

# Measurements of Higgs boson properties in the diphoton decay channel with $36 \text{ fb}^{-1}$ of pp collision data at $\sqrt{s}=13 \text{ TeV}$ with the ATLAS detector

On behalf of ATLAS experiment

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2016-21/>

Submitted to PRD

- Production modes and couplings
- Fiducial and differential cross-sections

$\mu, \mu_i, \sigma_i, \mu_i, \sigma_{\text{fid}}, d\sigma_{\text{fid}}/dX, \text{STXS}$

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# Introduction

- Characterize the Higgs production with the  $H \rightarrow \gamma\gamma$  channel : measure various POIs (Parameters of Interest)

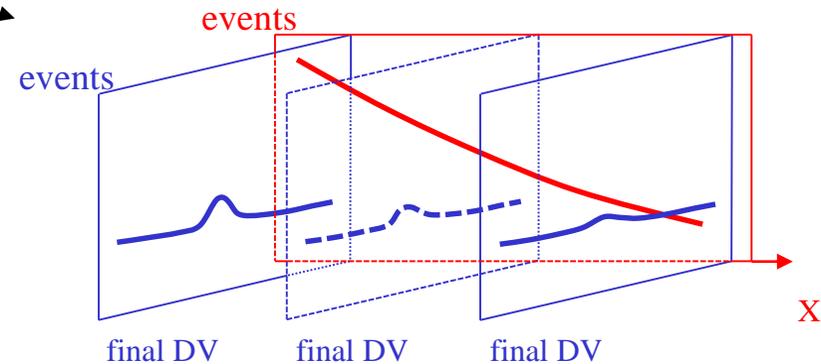
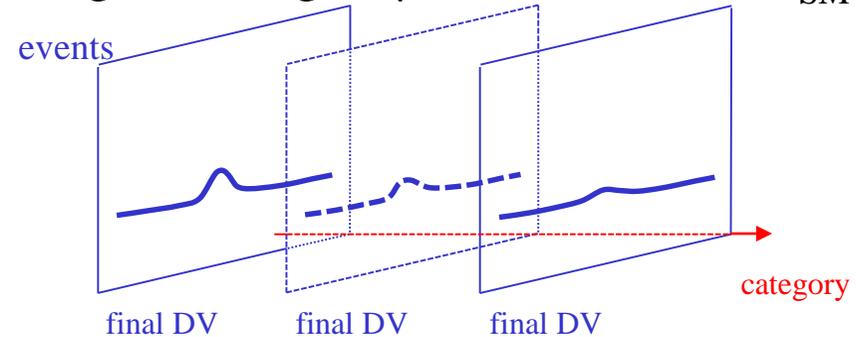
-cross-section : absolute ( $\sigma$ ) or relative to SM : signal strength ( $\mu = (\sigma \times BR) / (\sigma \times BR)_{SM}$ )

-per production mode :  $\sigma_i, \mu_i$

-in phase space of Higgs topology:  $\sigma_{SXTS}$   
(Simplified Template Cross-Sections)

-strengths on 'scattering amplitude' :  $\kappa$

-in fiducial regions: integrated:  $\sigma_{fid}$ , differential :  $d\sigma_{fid}/dX$   
(no extrapolation to total phase space)



(final DV : final discriminant variable :  $m_{\gamma\gamma}$ )

# Observables

- Traditional measurements on cross-sections

-cross-sections  $\sigma$ , inclusive +  $d\sigma/dX$

-  $\sigma$  in phase space of Higgs: Simplified Template Cross-Sections:  $\sigma_{STXS}$

-strengths on signal rate  $\mu=(\sigma \times BR)/(\sigma \times BR)_{SM}$

**Already discussed on previous slide**

- $\kappa$ -framework

-strengths on ‘scattering amplitude’:  $\kappa$

$$\sigma(i \rightarrow H \rightarrow f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_H^2 \Gamma_H^{SM}}$$

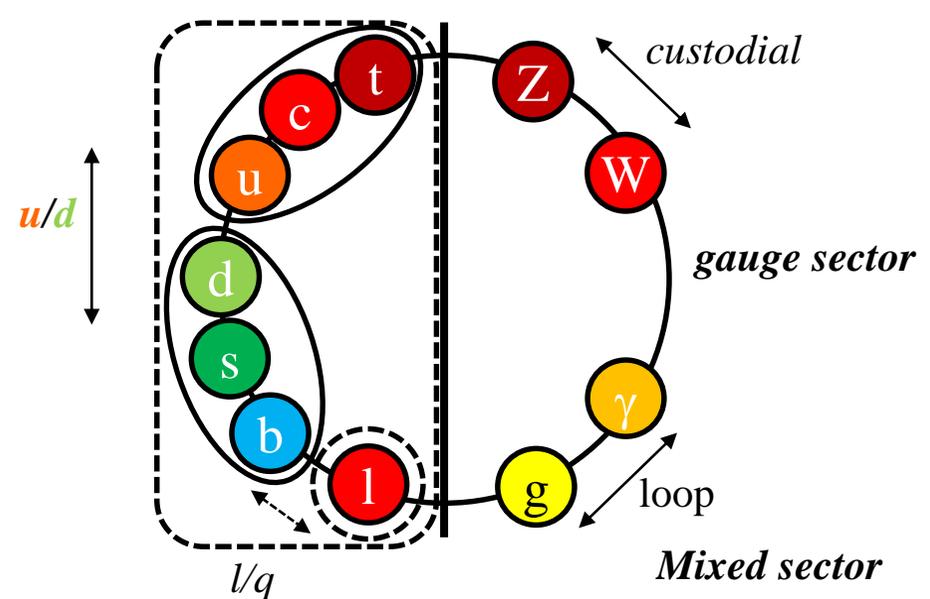
-Ratio of coupling modifiers:  $\lambda_{ij}=\kappa_i/\kappa_j$   
 (whenever a ratio is chosen, a reference coupling modifier is also considered, for the scaling : typically  $\kappa_{ij}=\kappa_i \cdot \kappa_j/\kappa_H$ )

- EFT : generalization of strengths w/  $J^{PC}$

Various benchmarks

(fermion/bosons)

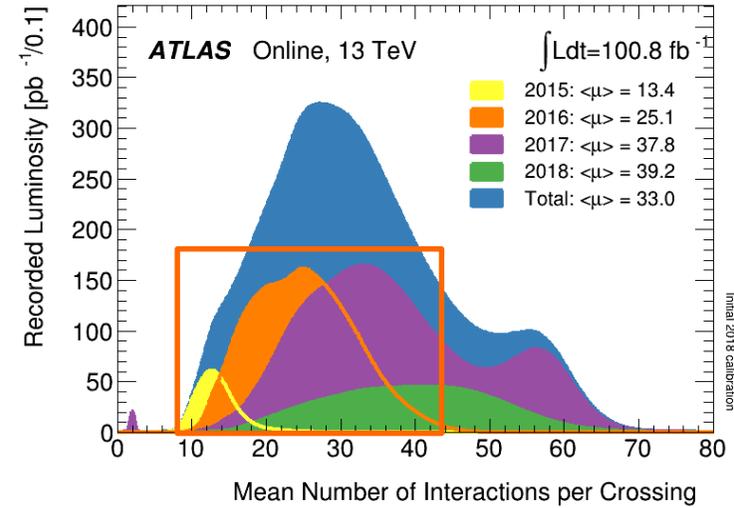
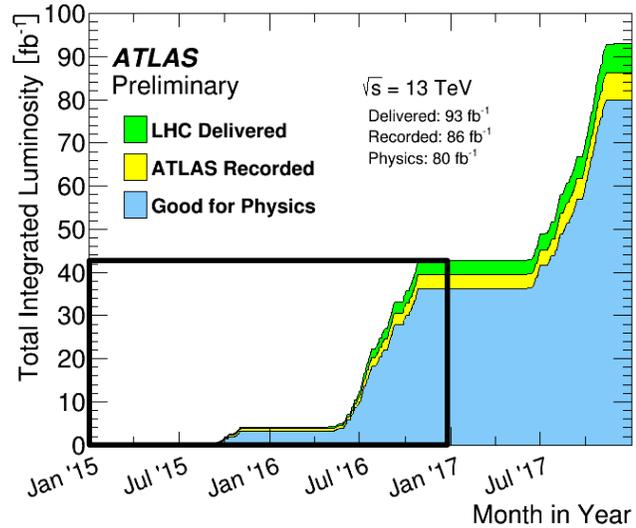
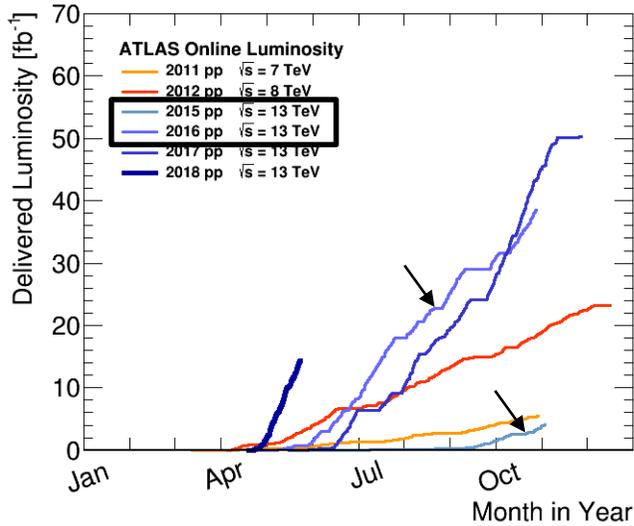
Yukawa sector



# Context of analysis in the LHC data-taking

- Data

ATLAS recorded 2015+2016: 36.1 fb<sup>-1</sup>, trigger : g35\_loose\_g25\_loose, eff=99.0 ± 0.5 %



- MC : normalization cross-section up to N<sup>3</sup>LO QCD+NLO(EW)

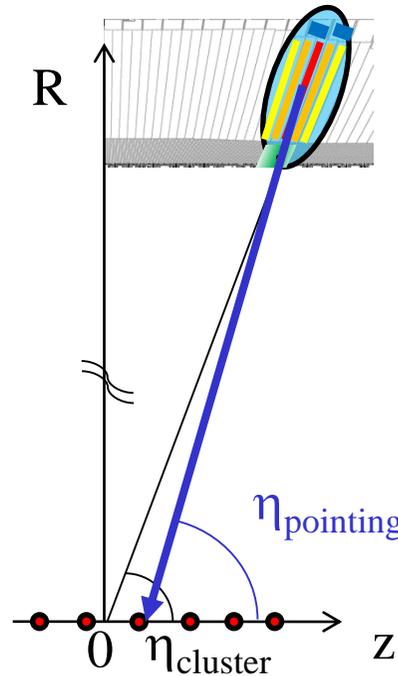
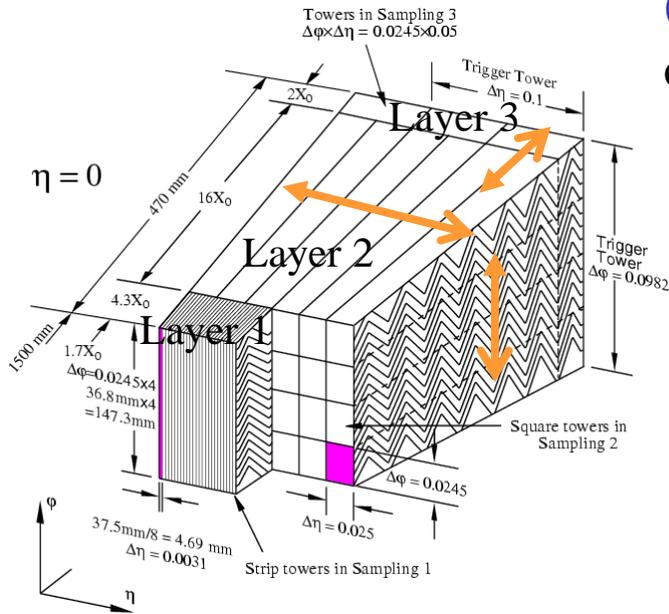
Process	Generator	Showering	PDF set	$\sigma$ [pb] $\sqrt{s} = 13$ TeV	Order of calculation of $\sigma$
ggH	POWHEG NNLOPS	PYTHIA8	PDF4LHC15	48.52	N <sup>3</sup> LO(QCD)+NLO(EW)
VBF	POWHEG-Box	PYTHIA8	PDF4LHC15	3.78	NNLO(QCD)+NLO(EW)
WH	POWHEG-Box	PYTHIA8	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$q\bar{q}' \rightarrow ZH$	POWHEG-Box	PYTHIA8	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$gg \rightarrow ZH$	POWHEG-Box	PYTHIA8	PDF4LHC15	0.12	NLO+NLL(QCD)
$t\bar{t}H$	MG5_AMC@NLO	PYTHIA8	NNPDF3.0	0.51	NLO(QCD)+NLO(EW)
$b\bar{b}H$	MG5_AMC@NLO	PYTHIA8	CT10	0.49	5FS(NNLO)+4FS(NLO)
$t$ -channel $tH$	MG5_AMC@NLO	PYTHIA8	CT10	0.07	4FS(LO)
$W$ -associated $tH$	MG5_AMC@NLO	HERWIG++	CT10	0.02	5FS(NLO)
$\gamma\gamma$	SHERPA	SHERPA	CT10		
$V\gamma\gamma$	SHERPA	SHERPA	CT10		

# Selection of photons

- exploits segmentation of electromagnetic calorimeter in order to :

(1) measure direction :  
calorimeter pointing

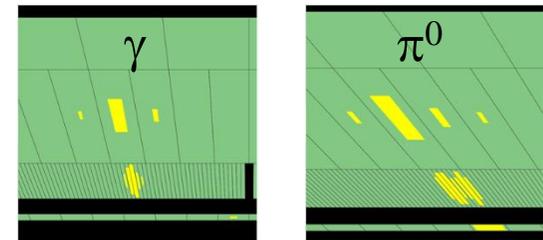
(2) identify photons  
(suppress fake photons)



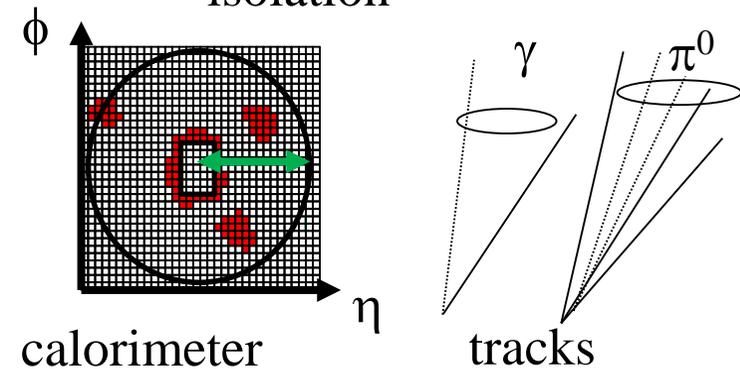
Neural Network:  
{ calorimeter pointing pull +  
pointing (pull),  $\Sigma p_T^2$ ,  $\Sigma p_T$ ,  $\Delta\phi(\text{trk}, \gamma\gamma)$  }

Layer 3  
Layer 2  
Layer 1

-shower shapes



-isolation



(3) measure energy

# Selection of photons (flashed)

Good quality events ('GRL'),  $\geq 1$  PV

- Primary objects : Photons

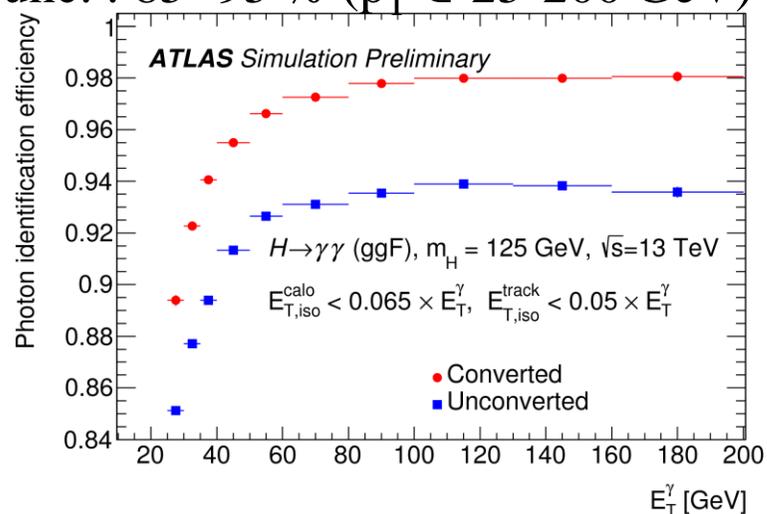
-2 photons,  $|\eta| < 2.37$ , exclude calorimeter barrel-endcap transition region  $1.37 < |\eta| < 1.52$

- $E_T/m_{\gamma\gamma} > 0.35$ , 0.25, tight ID, isolated

- $\text{eff}_{\text{ID}}$  (Identification 'quality') :  
from shower shapes

conv. : 90- 98 % ( $p_T \in 25$ -200 GeV)

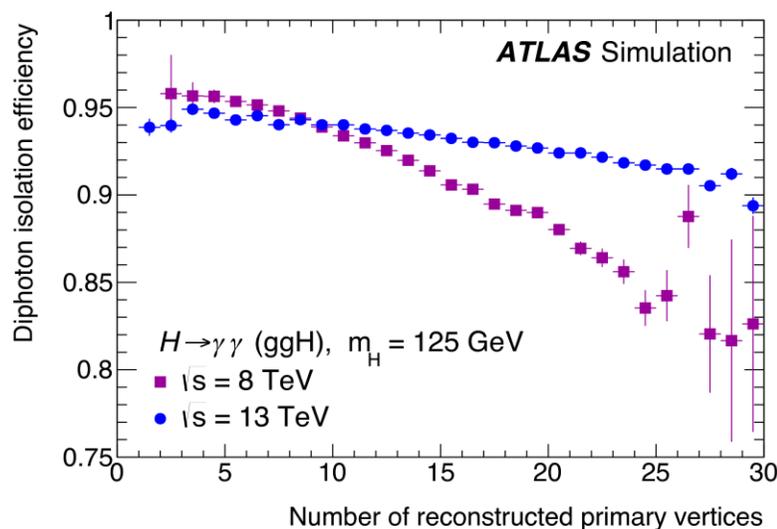
unc. : 85- 95 % ( $p_T \in 25$ -200 GeV)



-Isolation (calorimeter+track)

Calo : Topo  $E_T$  cone 20  $< 0.065 \times E_T$  ('FixedCutLoose')

Trk : Pt cone 20 :  $< 0.05 \times E_T$



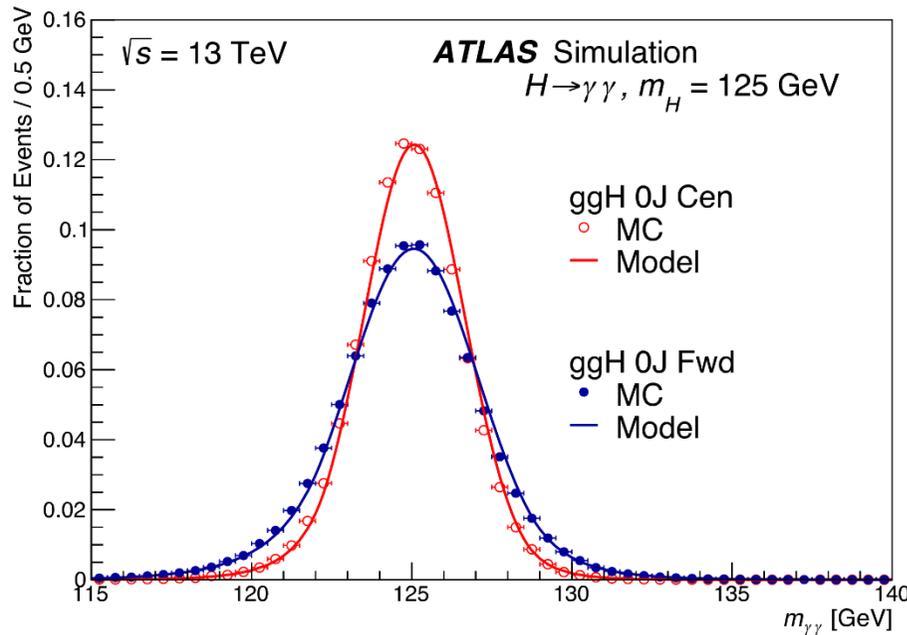
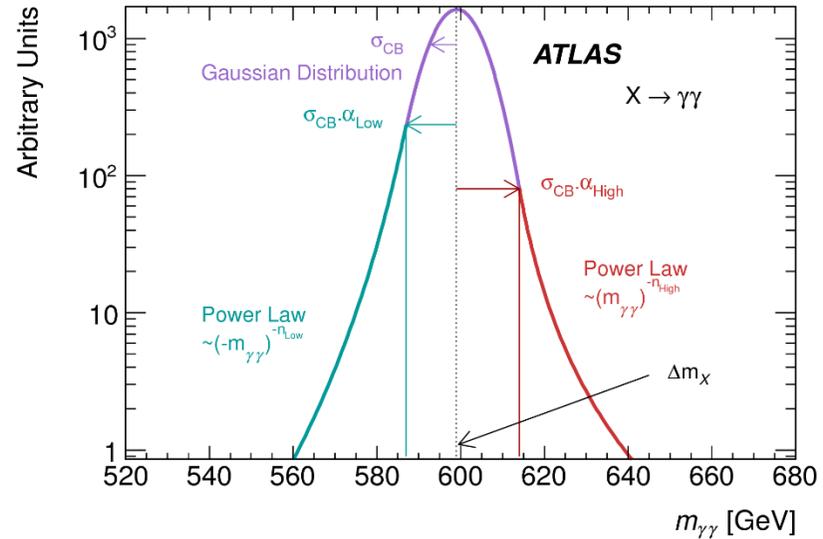
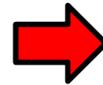
-Direction : NN :  $\{\Sigma p_T^2, \Sigma p_T, \Delta\phi\{\text{trk}, \gamma\gamma\} + \text{extended calo pointing}$

Eff( $|z_{\gamma\gamma} - z_{H \rightarrow \gamma\gamma}| < 0.3$  mm) : 79 % for ggH (others : 84-97 % : f(#j, #leptons)

- $m_{\gamma\gamma} \in [105 ; 160]$  GeV

# Signal modelling

- **Shape**  $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$   
-Double-sided Crystall-Ball function



- same shape used for all processes
- different for each reconstructed category
- $m_H=125$  GeV MC samples for all processes
- Statistics analysis made at  $m_H=125.09$  GeV
- shift  $\mu_{CB}$  by 0.09 GeV:  $m_H + \Delta\mu_{CB}$

- **Yields**

Per reconstructed category (r)  
(details : per phase space ('truth bin (t)') of STXS)

Expected (SM) Higgs bosons to pass selection: 1733 events

# Background modelling : method

(simplified explanation here : more details in backup)

- **Bkg model** : choice of functional forms for  $m_{\gamma\gamma}$
- **Fit a background-only dataset** with model bkg+signal

Residual fitted signal: spurious signal ( $n_{sp}$ )

Spurious signal taken as positive (absolute value) : no correction: systematics

- **Test various bkg functional forms (small variant for low stat MC)**

Choose one w/ smallest dof among those respecting criteria on  $|n_{sp}|$

<20 % expected stat. uncertainty on signal

→too #dofs  $\Leftrightarrow$  bkg model catches all stat. fluctuations: no discovery

<10 % expected signal yield

Spurious signal : max of fitted signal w/ signal model in 121-129 GeV

- **Test chosen functions on data w/ fit on sidebands** (exclude 121-129 GeV) w/ extra dof of same family: computes compatibility  $\chi^2$  (F-test). Reject simpler model if  $p(\chi^2) < 5\%$

# Systematics

- Bkg

bkg **fitted directly on data**

→ no direct systematics on bkg yield

**but** : spurious signal due to **choice of bkg functional** : for each category

systematic : residual yield on bkg-only sample

- **Signal: yields**

-theory : cross-section (scales, PDF+ $\alpha_s$ ), BR

-experim : luminosity, eff: trigger, photon ID, isolation, objects

- **Signal: shape**

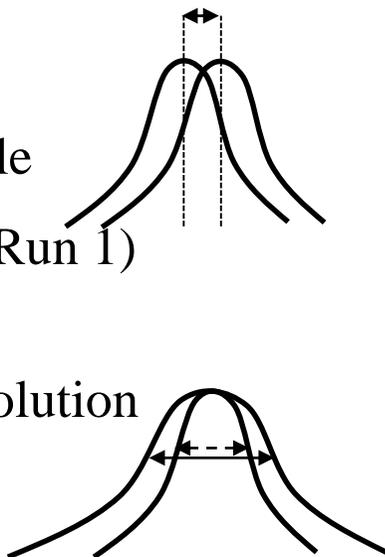
-peak position

≈ photon energy scale

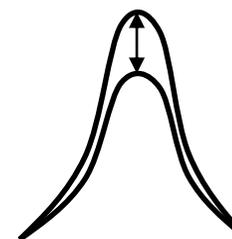
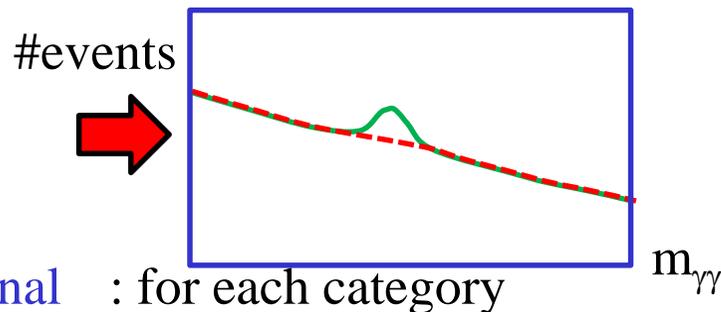
+240 MeV (A+C Run 1)

-peak resolution

≈ photon energy resolution

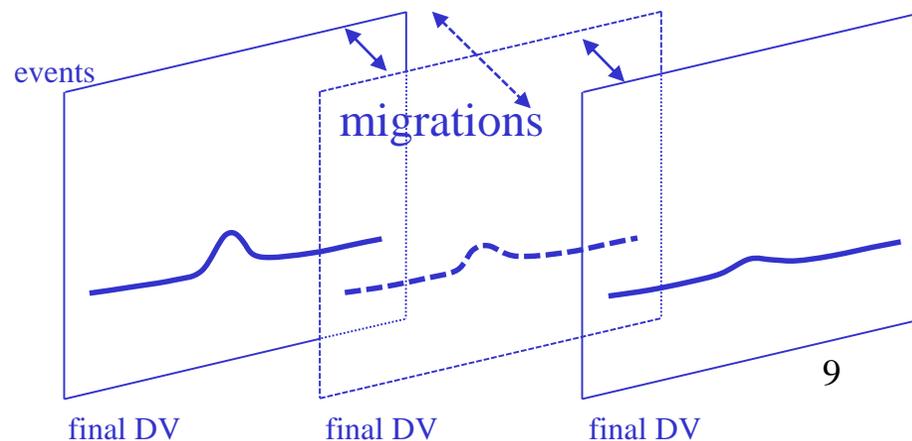


(final DV : final discriminant variable :  $m_{\gamma\gamma}$ )



- **migrations**

btw categories (prod. modes)



# Systematics: overview

Systematic uncertainty source		$N_{\text{NP}}$	Constraint	Category Likelihood	Fiducial Likelihood	
Theory	ggH QCD	9	$N_{\text{S}}^{\text{ggH}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-	
	Missing higher orders (non-ggH)	6	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-	
	$B(H \rightarrow \gamma\gamma)$	1	$N_{\text{S}}^{\text{tot}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-	
	PDF	30	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-	
	$\alpha_{\text{S}}$	1	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-	
	UE/PS	5	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-	
Experimental	Yield	Heavy flavor content	1	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Luminosity	1	$N_{\text{S}}^{\text{tot}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Trigger	1	$N_{\text{S}}^{\text{tot}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Photon identification	1	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Photon isolation	2	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
	Migration	Flavor tagging	14	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Jet	20	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Jet flavor composition	7	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Jet flavor response	7	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Electron	3	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Muon	11	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Missing transverse momentum	3	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Pileup	1	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
		Photon energy scale	40	$N_{\text{S}}^{\text{P}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	-
Mass	ATLAS-CMS $m_H$	1	$\mu_{\text{CB}} F_{\text{G}}(\sigma_i, \theta_i)$	✓	✓	
	Photon energy scale	40	$\mu_{\text{CB}} F_{\text{G}}(\sigma_i, \theta_i)$	✓	✓	
	Photon energy resolution	9	$\sigma_{\text{CB}} F_{\text{LN}}(\sigma_i, \theta_i)$	✓	✓	
Background	Spurious signal	Varies	$N_{\text{spur},c} \theta_{\text{spur},c}$	✓	✓	

Uncertainty Group	$\sigma_{\mu}^{\text{syst.}}$
Theory (QCD)	0.041
Theory ( $B(H \rightarrow \gamma\gamma)$ )	0.028
Theory (PDF+ $\alpha_{\text{S}}$ )	0.021
Theory (UE/PS)	0.026
Luminosity	0.031
Experimental (yield)	0.017
Experimental (migrations)	0.015
Mass resolution	0.029
Mass scale	0.006
Background shape	0.027

# Coupling analysis

# From $\mu, \kappa, \sigma$ to STXS

## Signal strengths, scale factor $\mu, \kappa$ framework

- Direct (dis-)agreement SM 😞
- f(ref.): model, precision 😞
- higher sys. error 😞

## Simplified Template Cross-Section (STXS)

- ‘Simplified’ : indep. decay mode 😊  
→ easy to combine
- Reduced th. sys. error 😊
- region detector acceptance  $|y_H| < 2.5$  😊  
→ reduced model dependency
- Allow to test various BSM models 😊

## Fiducial / differential cross-sections

- Specific to decay mode 😞  
→ not easy to combine
- region detector acceptance 😊  
→ tiny model dependency
- Reduced th. syst. error 😊

### For more information:

‘Template’ : SM templates to fit prod. modes

‘Truth bins’ of phase space (=granularity)

exclusive kinematic fiducial regions

=subdivision of prod. mode processes

chosen to minimize dependence on th. uncert,  
isolate BSM, maximize exp. sensitivity

-specific to topology (Higgs, environment [jets, etc.]

-Splitting by theoretical property  
(typically prod. mode)

-Merging of fiducial regions

Several levels of granularity: stage 0, 1, etc.

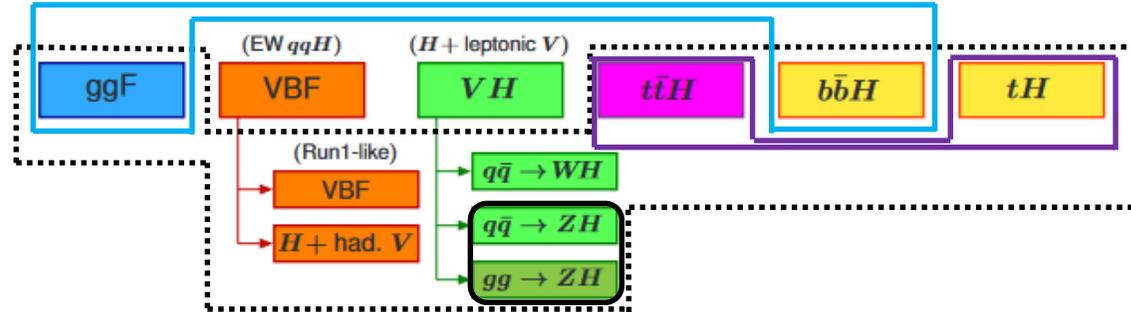
Merging truth bins if low statistics

$$n_{\text{sig}}^r = \sum_t \underbrace{\overbrace{\mu \sigma_t^{\text{SM}}}^{\mu \sigma_t^{\text{SM}}} \underbrace{A_{\text{tr}}^{\text{SM}} L}_{n_t}}_{n_{\text{tr}}}$$

# STXS 'stage 0'

(Flashed)

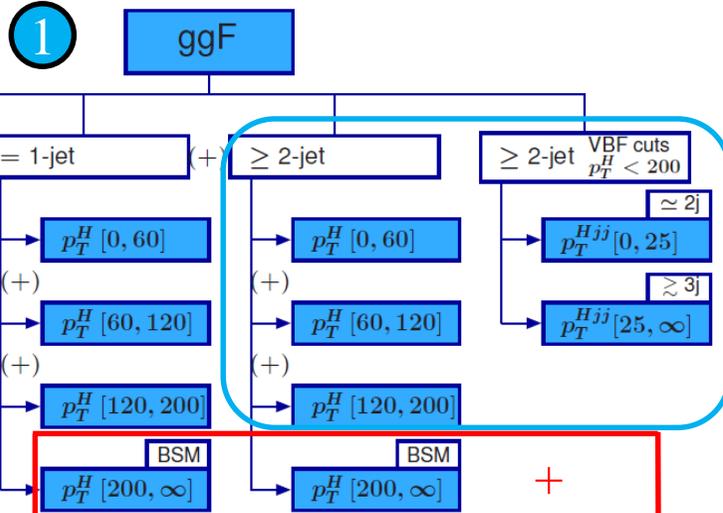
- Stage 0 : truth bins probed :  merged : 



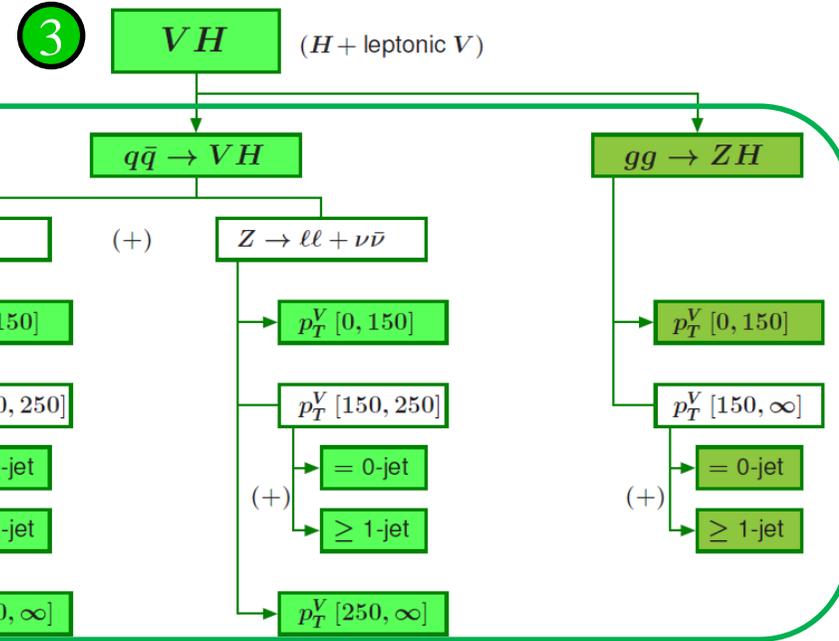
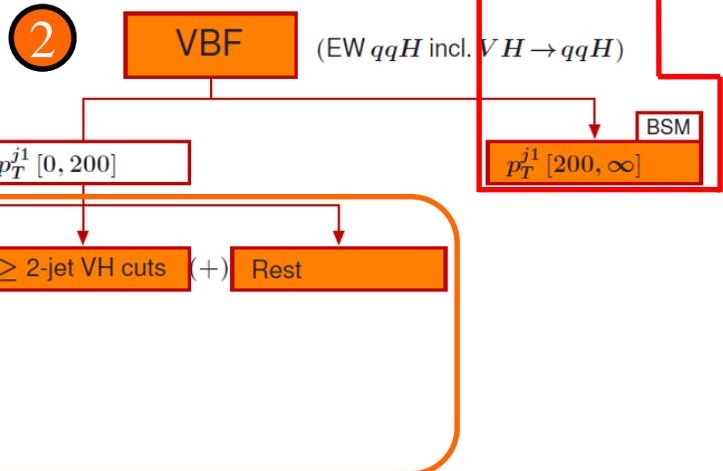
# STXS 'stage 1'

(units in [GeV])

Amount of data : no sensitivity to full stage-1  $\rightarrow$  merging of lower-rate regions



Sensitive to BSM



$ggH + VBF$  : anti-correlated  
 $\rightarrow$  measure sum : precise measurement  
 (subtraction : nuisance parameter : little sensitivity)

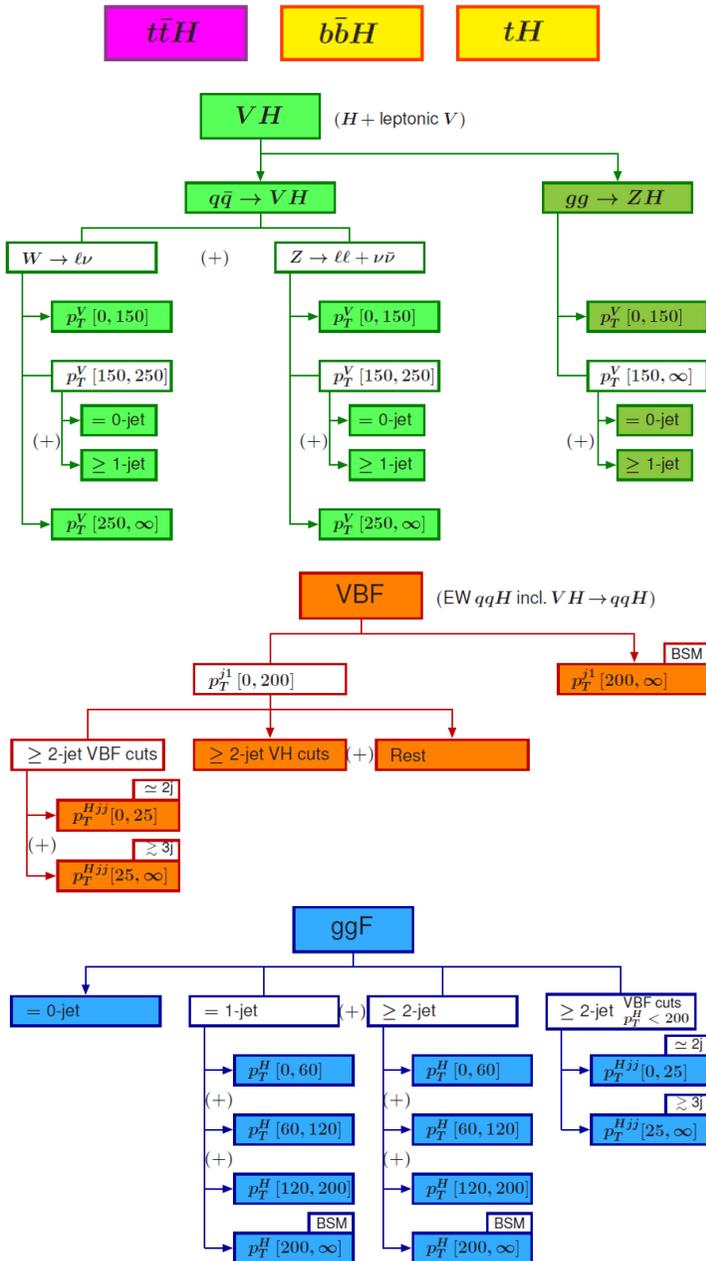


$\hookrightarrow$  in  $ggH$  truth bins

Strong merging

('+' means 'merge if not enough statistics' in the original scenario)

# Truth-level STXS ‘stage 1’ & reco-level categorization



Category	Selection
tH lep 0fwd	$N_{\text{lep}} = 1, N_{\text{jets}}^{\text{cen}} \leq 3, N_{b\text{-tag}} \geq 1, N_{\text{jets}}^{\text{fwd}} = 0 (p_T^{\text{jet}} > 25 \text{ GeV})$
tH lep 1fwd	$N_{\text{lep}} = 1, N_{\text{jets}}^{\text{cen}} \leq 4, N_{b\text{-tag}} \geq 1, N_{\text{jets}}^{\text{fwd}} \geq 1 (p_T^{\text{jet}} > 25 \text{ GeV})$
ttH lep	$N_{\text{lep}} \geq 1, N_{\text{jets}}^{\text{cen}} \geq 2, N_{b\text{-tag}} \geq 1, Z_{\ell\ell} \text{ veto } (p_T^{\text{jet}} > 25 \text{ GeV})$
ttH had BDT1	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, \text{BDT}_{\text{ttH}} > 0.92$
ttH had BDT2	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.83 < \text{BDT}_{\text{ttH}} < 0.92$
ttH had BDT3	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.79 < \text{BDT}_{\text{ttH}} < 0.83$
ttH had BDT4	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.52 < \text{BDT}_{\text{ttH}} < 0.79$
tH had 4j1b	$N_{\text{lep}} = 0, N_{\text{jets}}^{\text{cen}} = 4, N_{b\text{-tag}} = 1 (p_T^{\text{jet}} > 25 \text{ GeV})$
tH had 4j2b	$N_{\text{lep}} = 0, N_{\text{jets}}^{\text{cen}} = 4, N_{b\text{-tag}} \geq 2 (p_T^{\text{jet}} > 25 \text{ GeV})$
VH dilep	$N_{\text{lep}} \geq 2, 70 \text{ GeV} \leq m_{\ell\ell} \leq 110 \text{ GeV}$
VH lep High	$N_{\text{lep}} = 1,  m_{e\gamma} - 89 \text{ GeV}  > 5 \text{ GeV}, p_T^{\ell + E_T^{\text{miss}}} > 150 \text{ GeV}$
VH lep Low	$N_{\text{lep}} = 1,  m_{e\gamma} - 89 \text{ GeV}  > 5 \text{ GeV}, p_T^{\ell + E_T^{\text{miss}}} < 150 \text{ GeV}, E_T^{\text{miss}} \text{ significance} > 1$
VH MET High	$150 \text{ GeV} < E_T^{\text{miss}} < 250 \text{ GeV}, E_T^{\text{miss}} \text{ significance} > 9 \text{ or } E_T^{\text{miss}} > 250 \text{ GeV}$
VH MET Low	$80 \text{ GeV} < E_T^{\text{miss}} < 150 \text{ GeV}, E_T^{\text{miss}} \text{ significance} > 8$
jet BSM	$p_{T,j1} > 200 \text{ GeV}$
VH had tight	$60 \text{ GeV} < m_{jj} < 120 \text{ GeV}, \text{BDT}_{\text{VH}} > 0.78$
VH had loose	$60 \text{ GeV} < m_{jj} < 120 \text{ GeV}, 0.35 < \text{BDT}_{\text{VH}} < 0.78$
VBF tight, high $p_T^{Hjj}$	$ \Delta\eta_{jj}  > 2,  \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})  < 5, p_T^{Hjj} > 25 \text{ GeV}, \text{BDT}_{\text{VBF}} > 0.47$
VBF loose, high $p_T^{Hjj}$	$ \Delta\eta_{jj}  > 2,  \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})  < 5, p_T^{Hjj} > 25 \text{ GeV}, -0.32 < \text{BDT}_{\text{VBF}} < 0.47$
VBF tight, low $p_T^{Hjj}$	$ \Delta\eta_{jj}  > 2,  \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})  < 5, p_T^{Hjj} < 25 \text{ GeV}, \text{BDT}_{\text{VBF}} > 0.87$
VBF loose, low $p_T^{Hjj}$	$ \Delta\eta_{jj}  > 2,  \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})  < 5, p_T^{Hjj} < 25 \text{ GeV}, 0.26 < \text{BDT}_{\text{VBF}} < 0.87$
ggH 2J BSM	$\geq 2 \text{ jets}, p_T^{\gamma\gamma} \geq 200 \text{ GeV}$
ggH 2J High	$\geq 2 \text{ jets}, p_T^{\gamma\gamma} \in [120, 200] \text{ GeV}$
ggH 2J Med	$\geq 2 \text{ jets}, p_T^{\gamma\gamma} \in [60, 120] \text{ GeV}$
ggH 2J Low	$\geq 2 \text{ jets}, p_T^{\gamma\gamma} \in [0, 60] \text{ GeV}$
ggH 1J BSM	$= 1 \text{ jet}, p_T^{\gamma\gamma} \geq 200 \text{ GeV}$
ggH 1J High	$= 1 \text{ jet}, p_T^{\gamma\gamma} \in [120, 200] \text{ GeV}$
ggH 1J Med	$= 1 \text{ jet}, p_T^{\gamma\gamma} \in [60, 120] \text{ GeV}$
ggH 1J Low	$= 1 \text{ jet}, p_T^{\gamma\gamma} \in [0, 60] \text{ GeV}$
ggH 0J Fwd	$= 0 \text{ jets, one photon with }  \eta  > 0.95$
ggH 0J Cen	$= 0 \text{ jets, two photons with }  \eta  \leq 0.95$

Improve mass resolution

# Signal in various categories

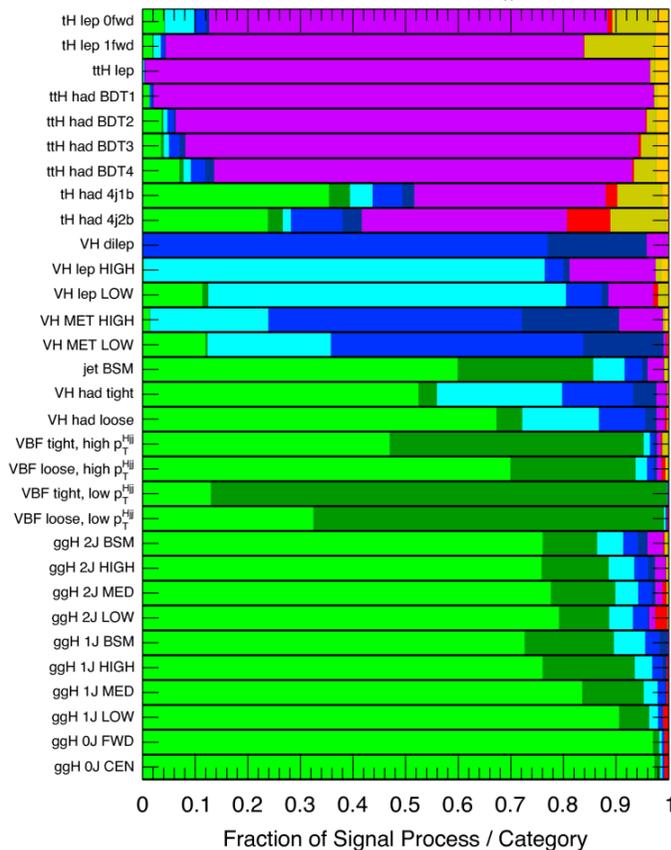
- Categorization to probe various production modes

- Signal purity

-Per production mode

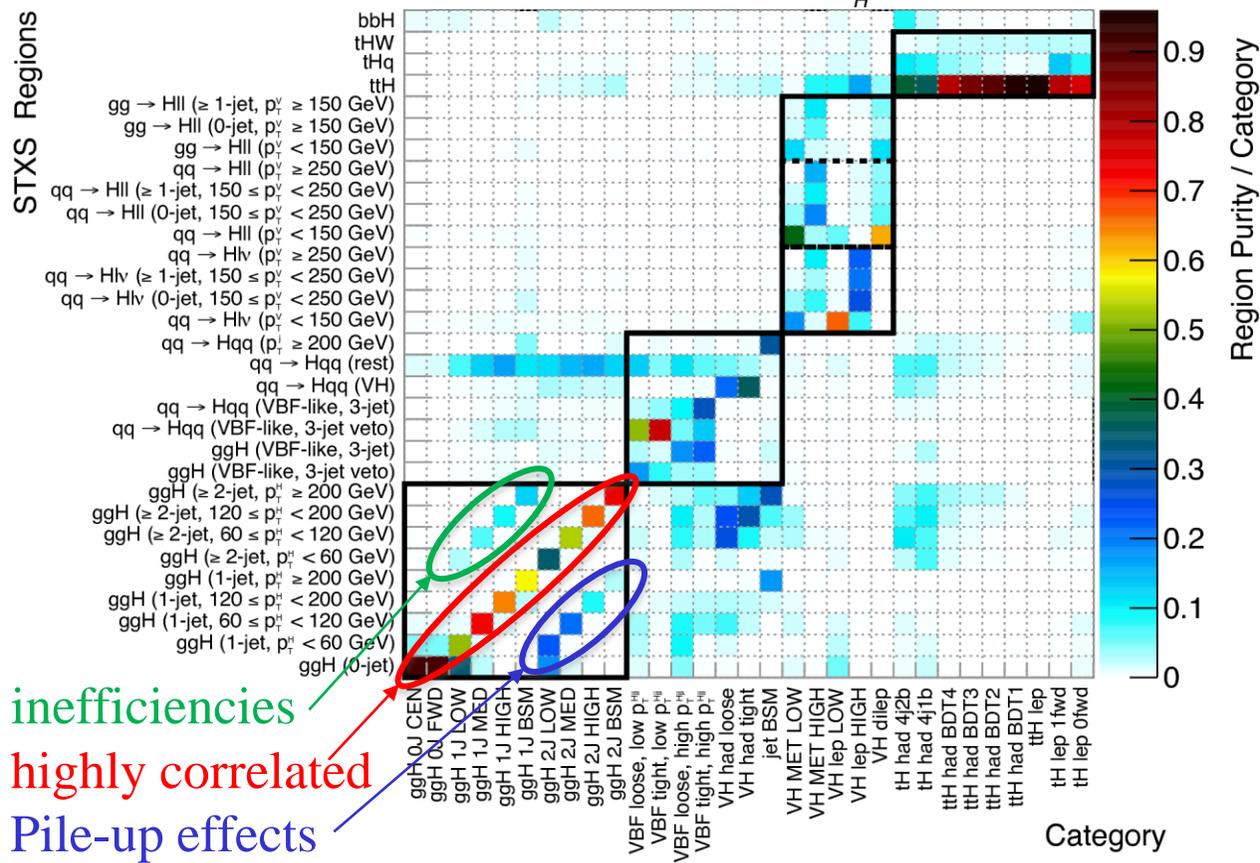


ATLAS Simulation  $H \rightarrow \gamma\gamma, m_H = 125.09$  GeV



-per truth bin STXS

ATLAS Simulation  $H \rightarrow \gamma\gamma, m_H = 125.09$  GeV



# Results: signal strengths

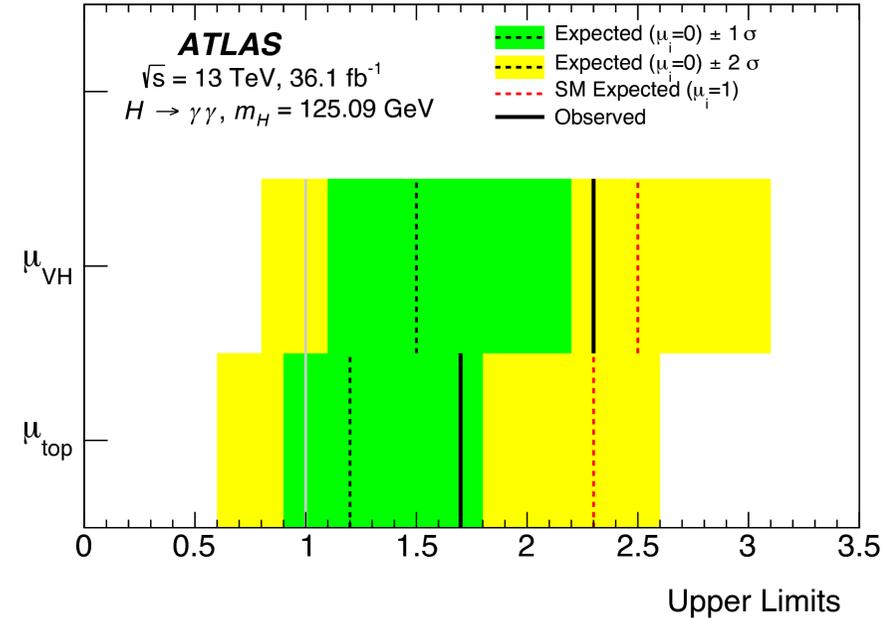
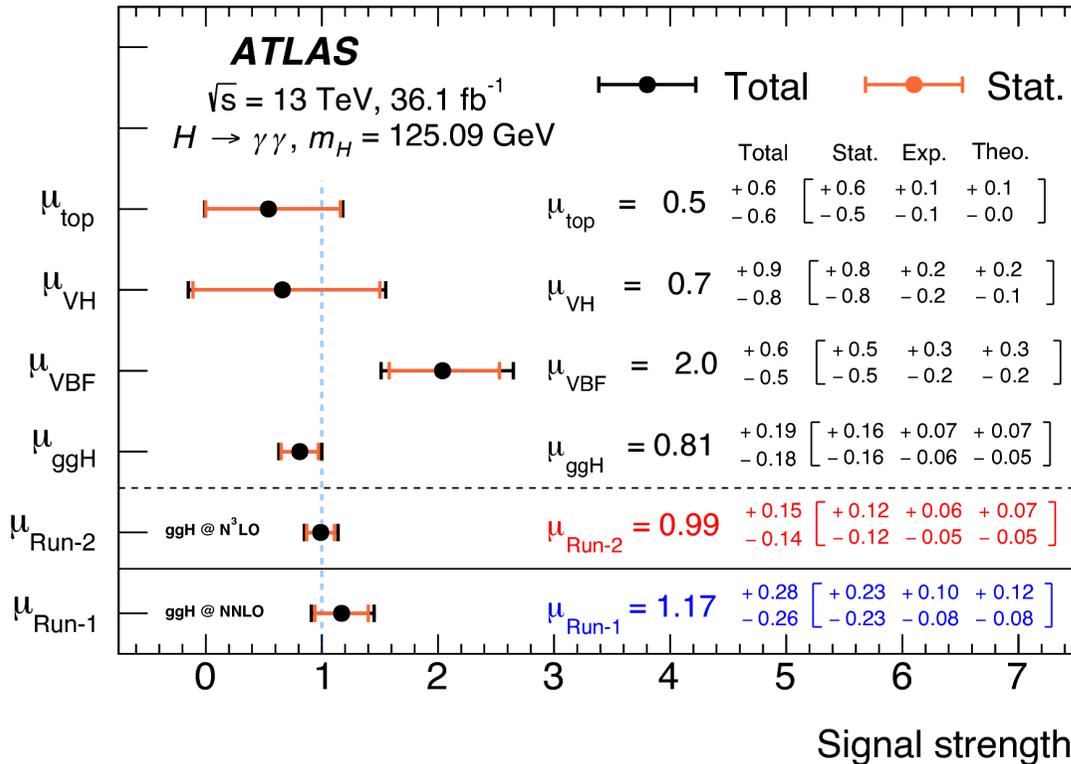
- Inclusive signal strength

( $|y_H| < 2.5$ )

$$\mu = 0.99 \pm 0.12 \text{ (stat.) } \begin{matrix} +0.06 \\ -0.05 \end{matrix} \text{ (exp.) } \begin{matrix} +0.07 \\ -0.05 \end{matrix} \text{ (th.)}$$

- Prod. Modes  $\mu_i$

- Limits & significance



Measurement	Exp. $Z_0$	Obs. $Z_0$
$\mu_{\text{VBF}}$	2.6 $\sigma$	4.9 $\sigma$
$\mu_{\text{VH}}$	1.4 $\sigma$	0.8 $\sigma$
$\mu_{\text{top}}$	1.8 $\sigma$	1.0 $\sigma$

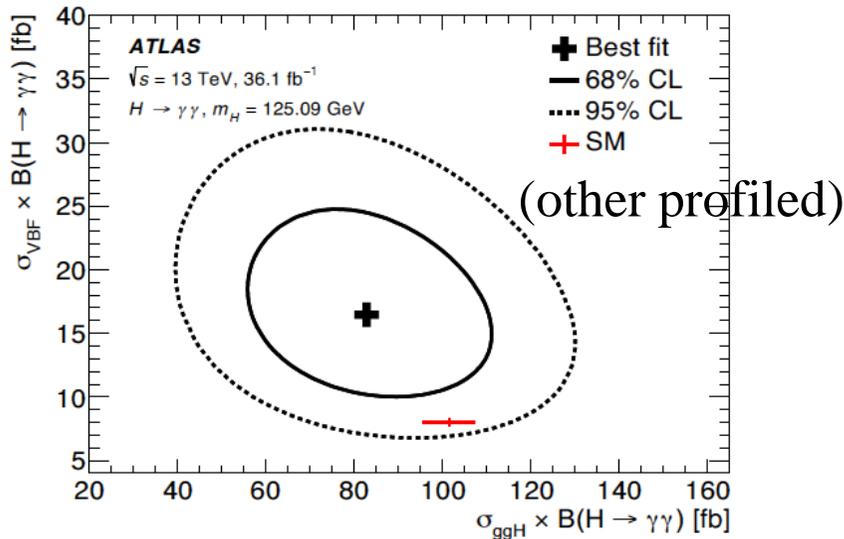
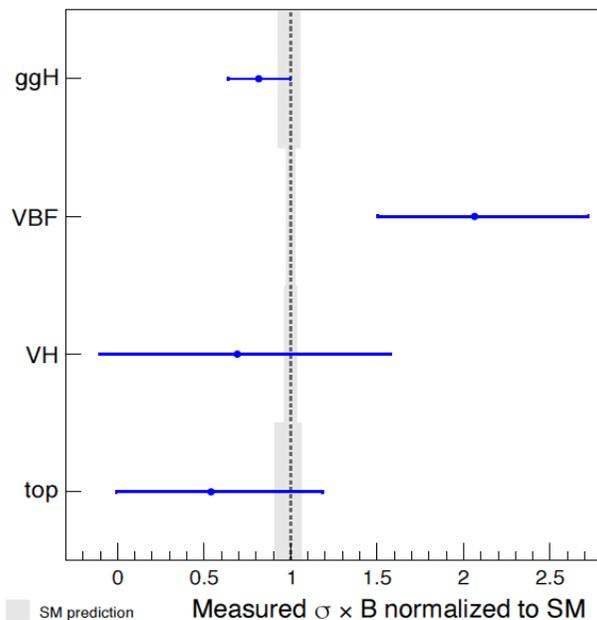
VBF close to 5  $\sigma$

# Results: cross-sections

- XS<sub>x</sub>BR

**ATLAS**

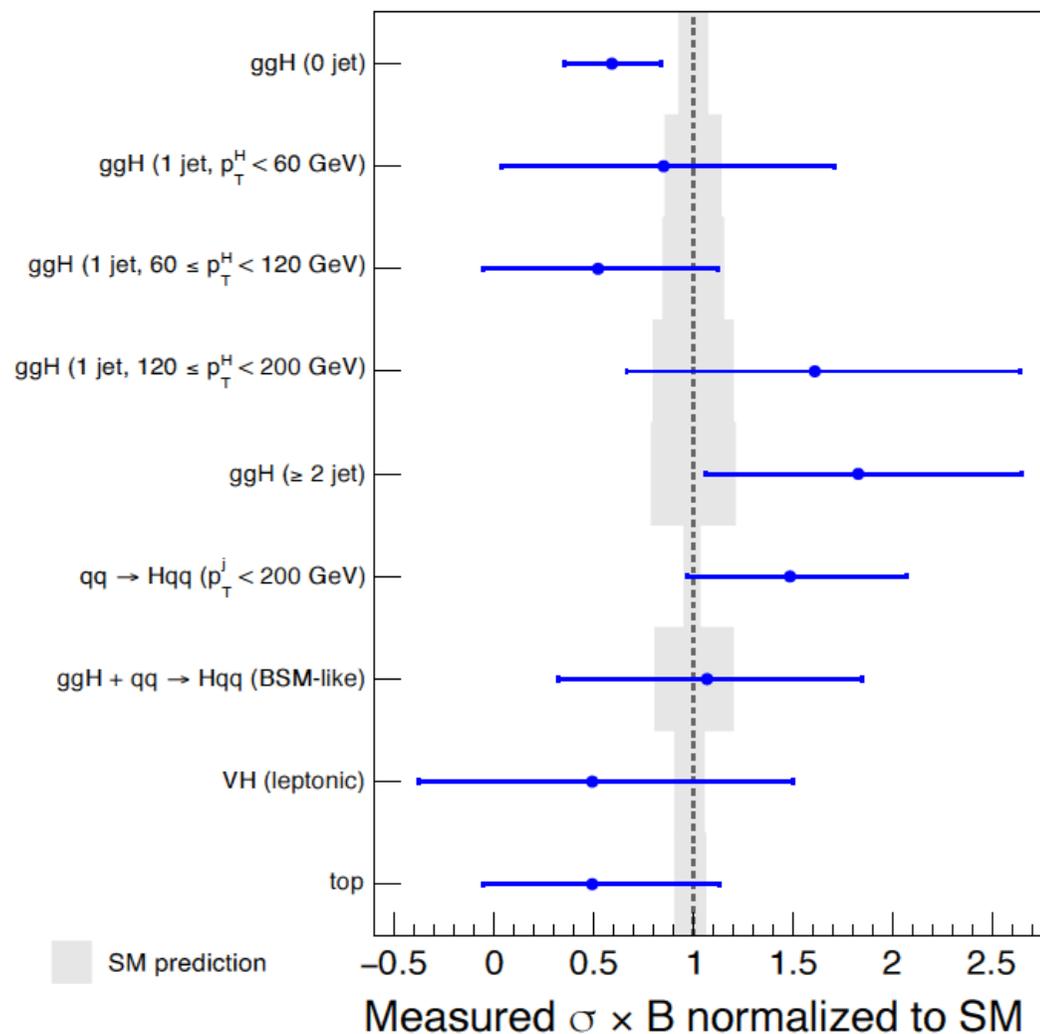
$\sqrt{s}=13$  TeV,  $36.1 \text{ fb}^{-1}$   
 $H \rightarrow \gamma\gamma$ ,  $m_H=125.09$  GeV



- STXS (strong merging)

**ATLAS**

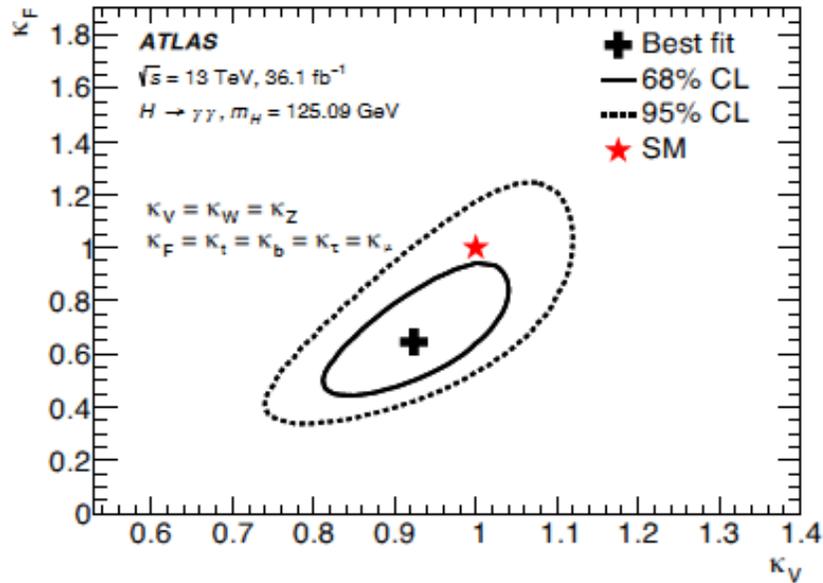
$\sqrt{s}=13$  TeV,  $36.1 \text{ fb}^{-1}$   
 $H \rightarrow \gamma\gamma$ ,  $m_H=125.09$  GeV



# Results: $\kappa$ -framework

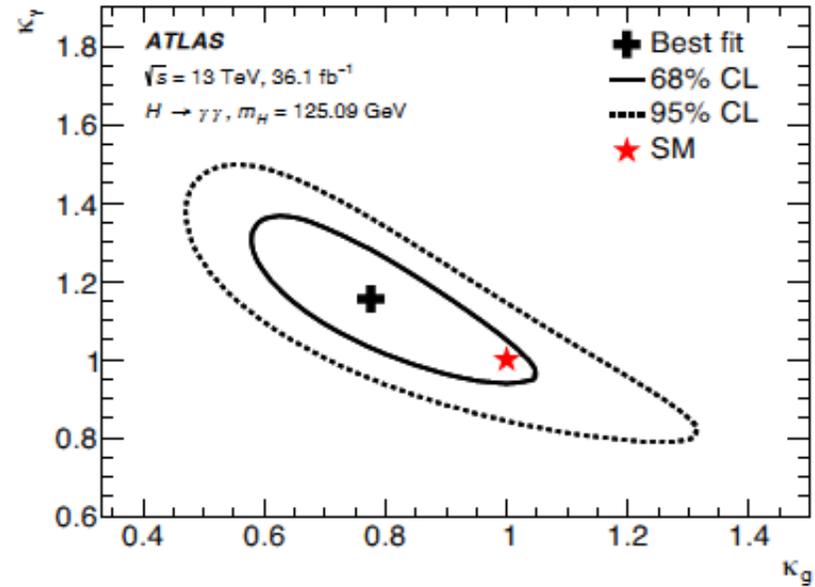
- Boson-fermion

$$\kappa_V = 0.92^{+0.08}_{-0.07} \quad \kappa_F = 0.64^{+0.18}_{-0.14}$$



- Loops using  $\kappa_V = \kappa_W = \kappa_Z, \kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

$$\kappa_g = 0.76^{+0.17}_{-0.14} \quad \kappa_\gamma = 1.16^{+0.14}_{-0.14}$$



# Fiducial and differential cross-sections

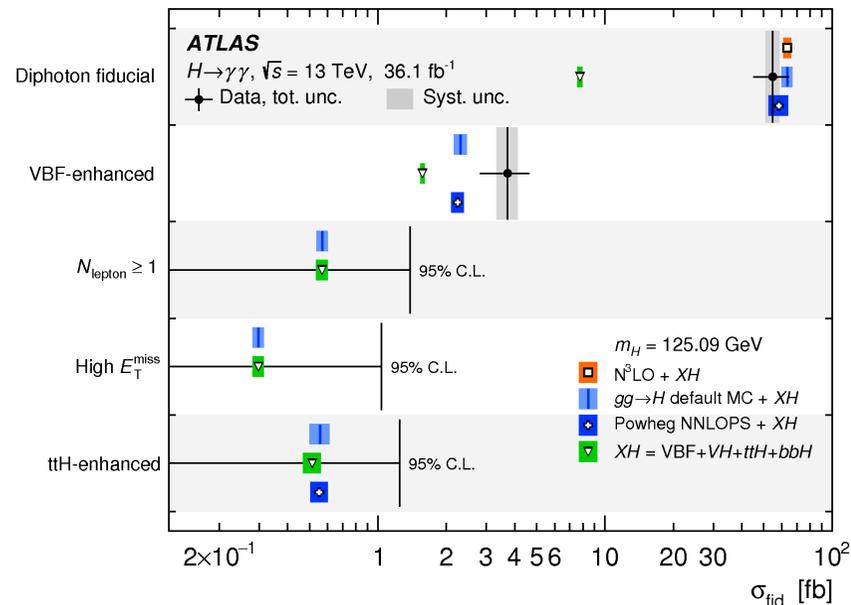
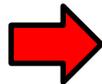
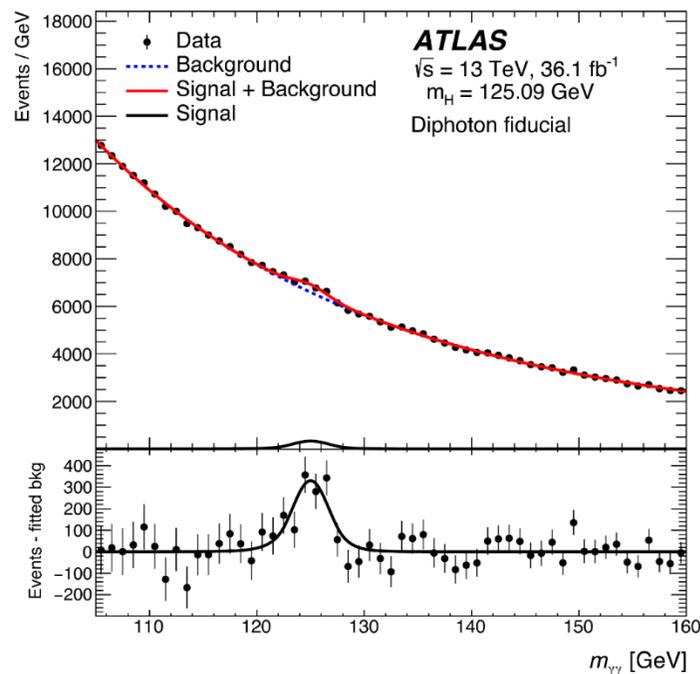
# Fiducial cross-sections: results

$$\sigma_i = \frac{N_i^{\text{sig}}}{c_i \int L dt}$$

**c** : reco eff + correction truth-level  $\leftrightarrow$  reco-level: bin-to-bin migration

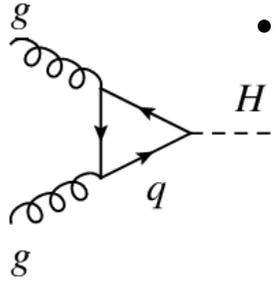
Fiducial region	Definition
$c_i = 0.75 \pm 0.03$ $\leftarrow$ (~PID & isolation)	Diphoton fiducial $N_\gamma \geq 2$ , $p_T^{\gamma 1} > 0.35 m_{\gamma\gamma} = 43.8 \text{ GeV}$ , $p_T^{\gamma 2} > 0.25 m_{\gamma\gamma} = 31.3 \text{ GeV}$ VBF-enhanced Diphoton fiducial, $N_j \geq 2$ with $p_T^{\text{jet}} > 25 \text{ GeV}$ , $m_{jj} > 400 \text{ GeV}$ , $ \Delta y_{jj}  > 2.8$ , $ \Delta\phi_{\gamma\gamma, jj}  > 2.6$
$N_{\text{lepton}} \geq 1$	Diphoton fiducial, $N_\ell \geq 1$
High $E_T^{\text{miss}}$	Diphoton fiducial, $E_T^{\text{miss}} > 80 \text{ GeV}$ , $p_T^{\gamma\gamma} > 80 \text{ GeV}$
$t\bar{t}H$ -enhanced	Diphoton fiducial, $(N_j \geq 4, N_{b\text{-jets}} \geq 1)$ or $(N_j \geq 3, N_{b\text{-jets}} \geq 1, N_\ell \geq 1)$

$m_{\gamma\gamma} \in [105 ; 160] \text{ GeV}$

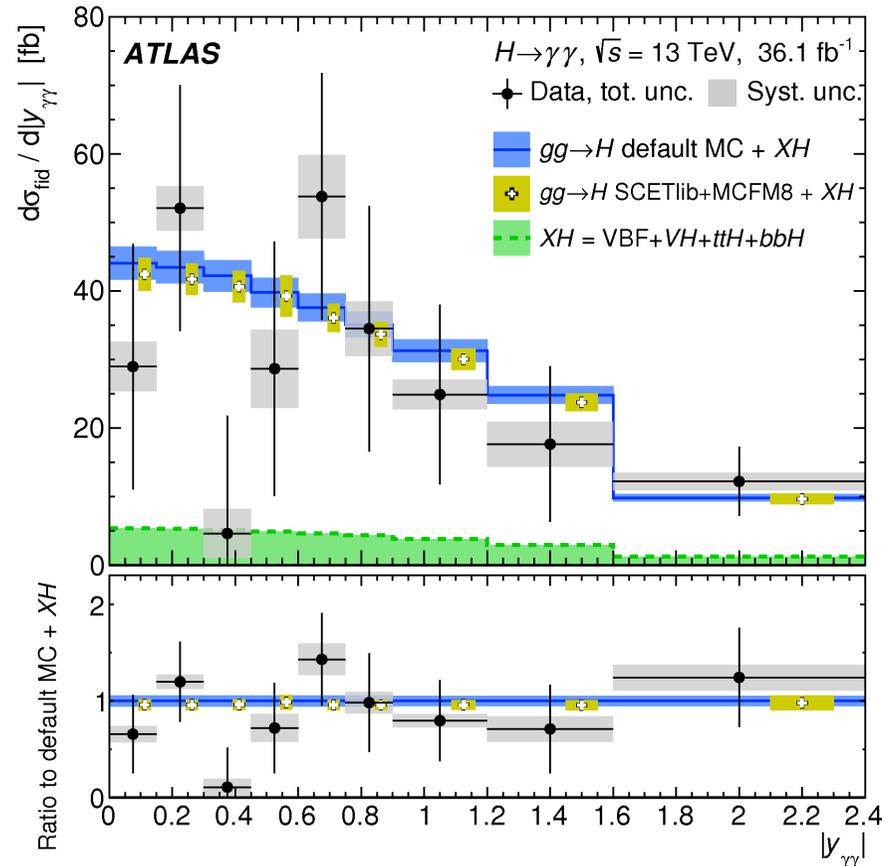
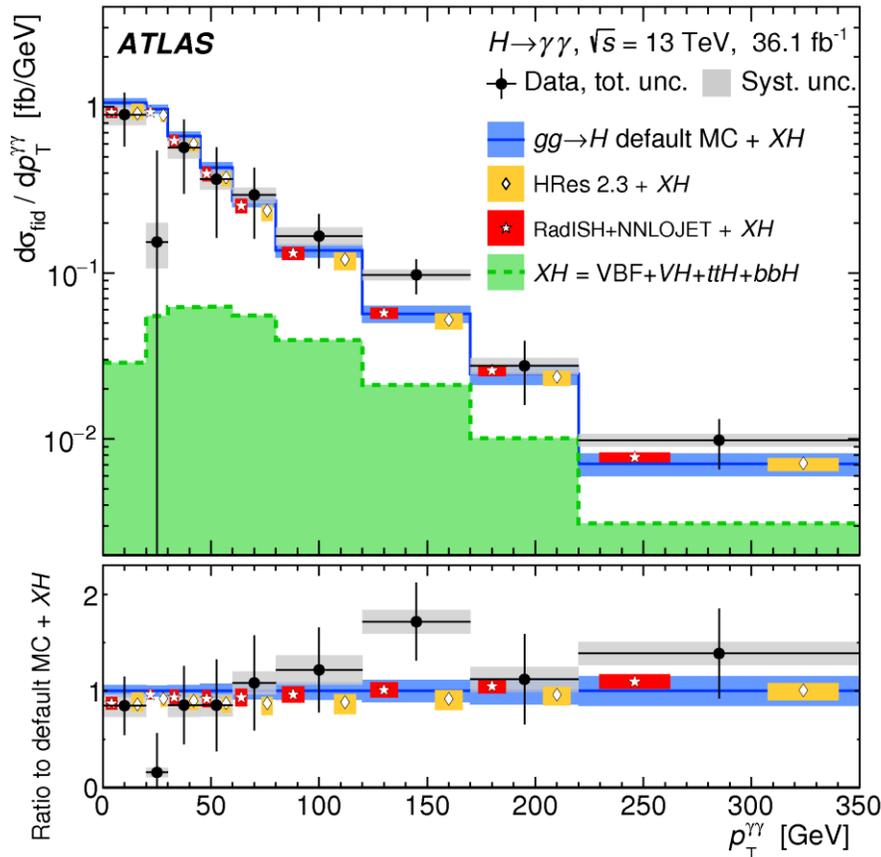


$d\sigma/dX$  : an example in next slide

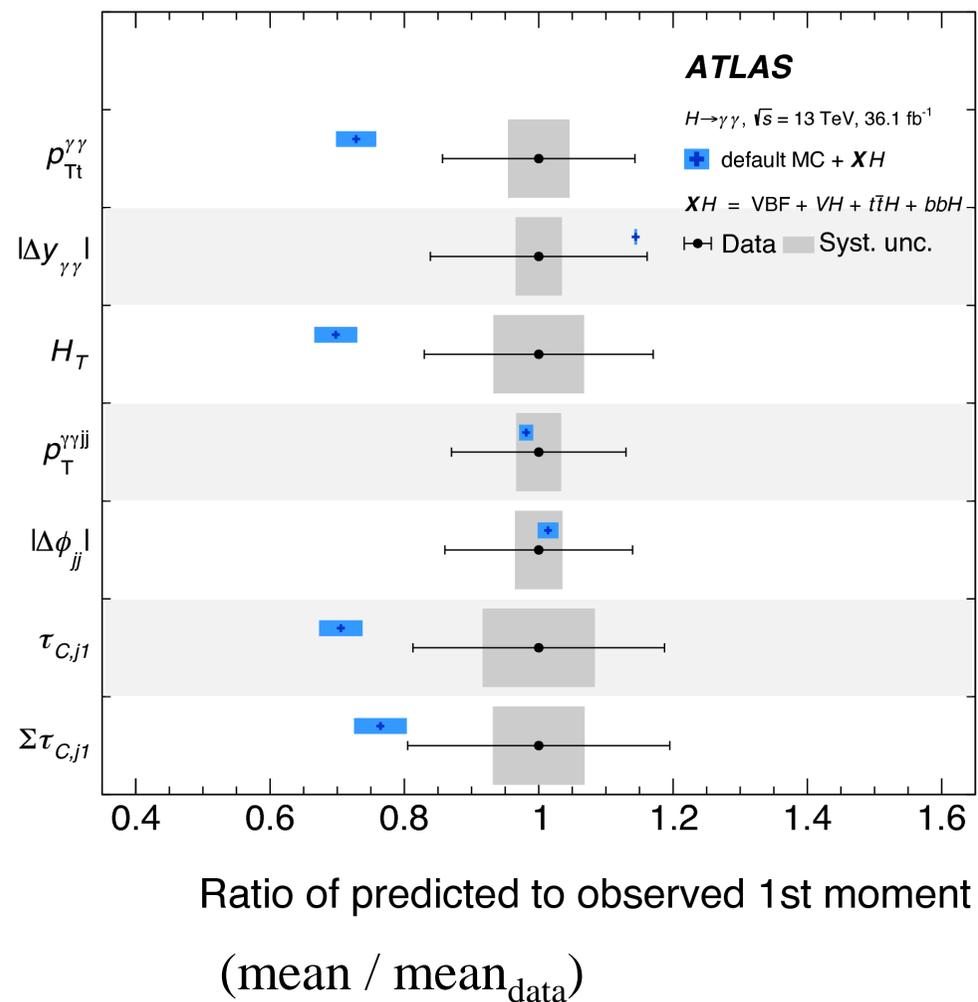
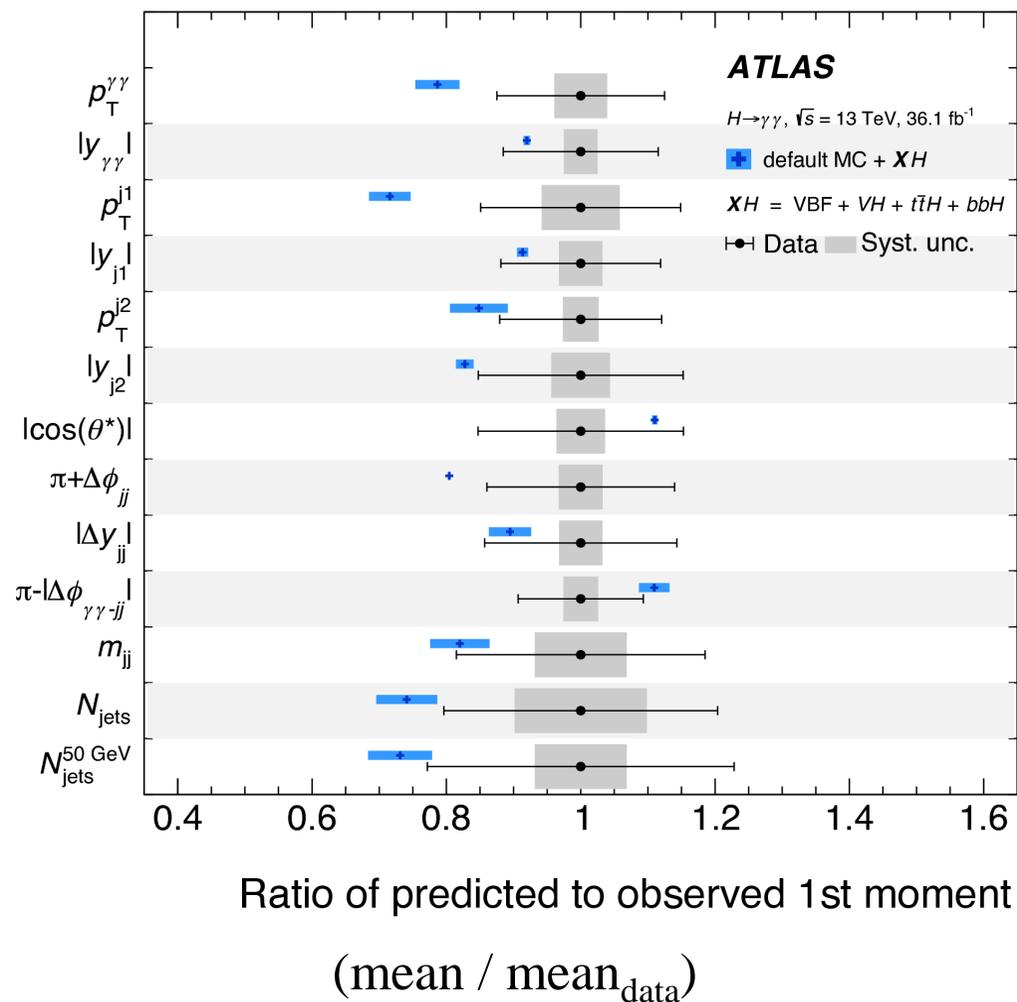
# Higgs kinematics



- $p_T^H$  :
  - $p_T \ll m_H$ : non-pert. QCD, soft & collinear corr.  $\alpha_S^n \ln^{2n}(m_H^2/q_T^2)$  resum. cancel divergences
  - $p_T \approx m_H, p_T \gg m_H$ : pert. QCD: emission soft gluons & quarks  $N^k \text{LO}$
  - BSM particles
- $|y_H|$  : QCD radiative correction, pdf



# $d\sigma/dX$ : overview



+double differential (backup)

# Tensor structure w/ SILH

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \underbrace{\sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)}}_{\text{violates L}} + \underbrace{\sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)}}_{\text{Leading BSM}} + \underbrace{\sum_i \frac{c_i^{(7)}}{\Lambda^3} O_i^{(7)}}_{\text{violates B-L}} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} O_i^{(8)} + \dots$$

(as all odd d)

-odd d suppressed at a level not experimentally accessible to LHC

-d=6 leading BSM, suppressed wrt SM at level  $(v/\Lambda)^2$

Constraints on parameters  $\Leftrightarrow$  constraints on new particles in BSM  
(but connection not obvious)

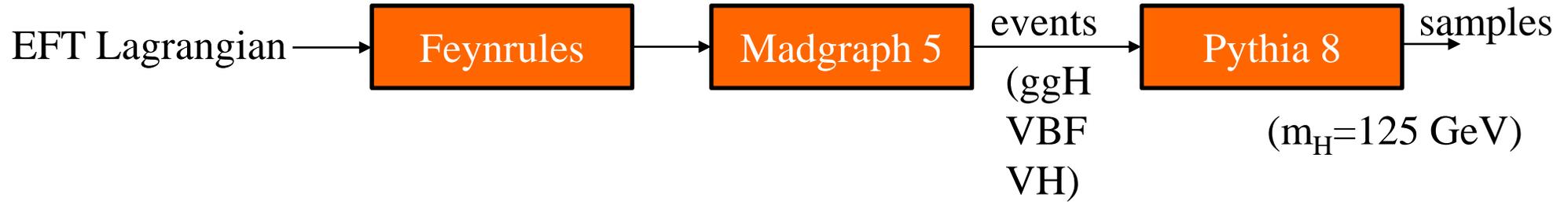
EFT, SILH basis, BSM dim-6 even operators

$$\mathcal{L}_{eff} = \underbrace{\bar{c}_g O_g + \tilde{c}_g \tilde{O}_g}_{\text{CP-even}} + \underbrace{\bar{c}_{HW} O_{HW} + \tilde{c}_{HW} \tilde{O}_{HW}}_{\text{CP-odd}} + \underbrace{\bar{c}_{HB} O_{HB} + \tilde{c}_{HB} \tilde{O}_{HB}}_{\text{CP-odd}}$$

Interactions $\longrightarrow$	<b>Hgg</b>	HWW, HZZ, HZ $\gamma$	HZZ, HZ $\gamma$
Probed by	ggH	VBF+VH	VBF+VH

# Tensor structure w/ SILH

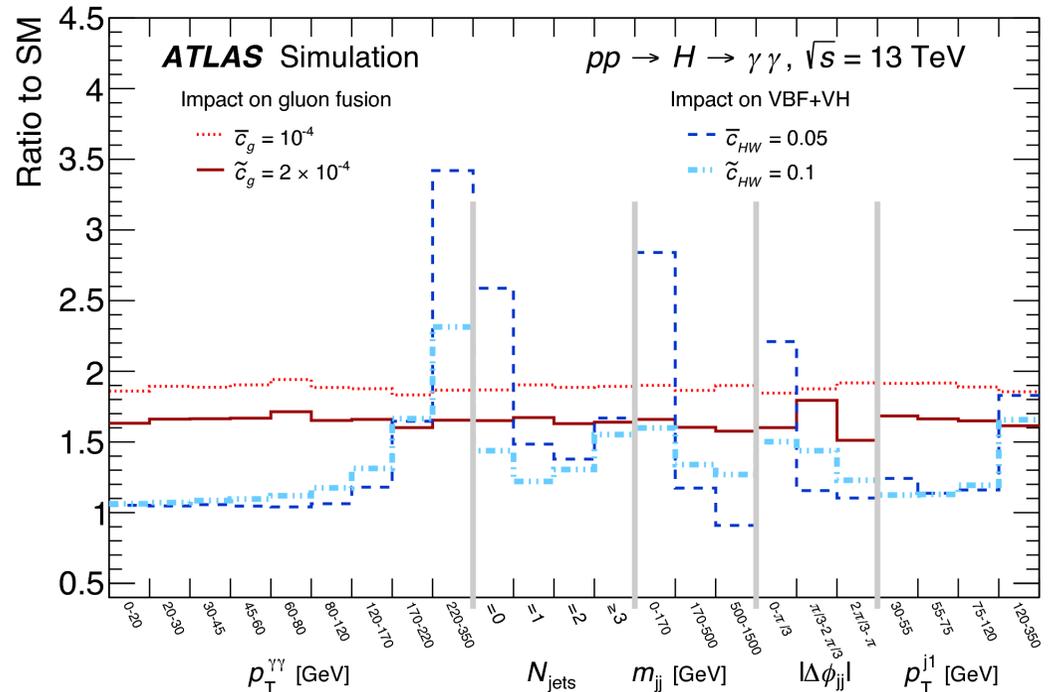
- Anomalous coupling : change rate/kinematics of Higgs events
- For each  $c_i$  (Wilson coefficient) in a given set



samples  $\rightarrow$   $d\sigma/dX$   $\rightarrow$  QCD corrections

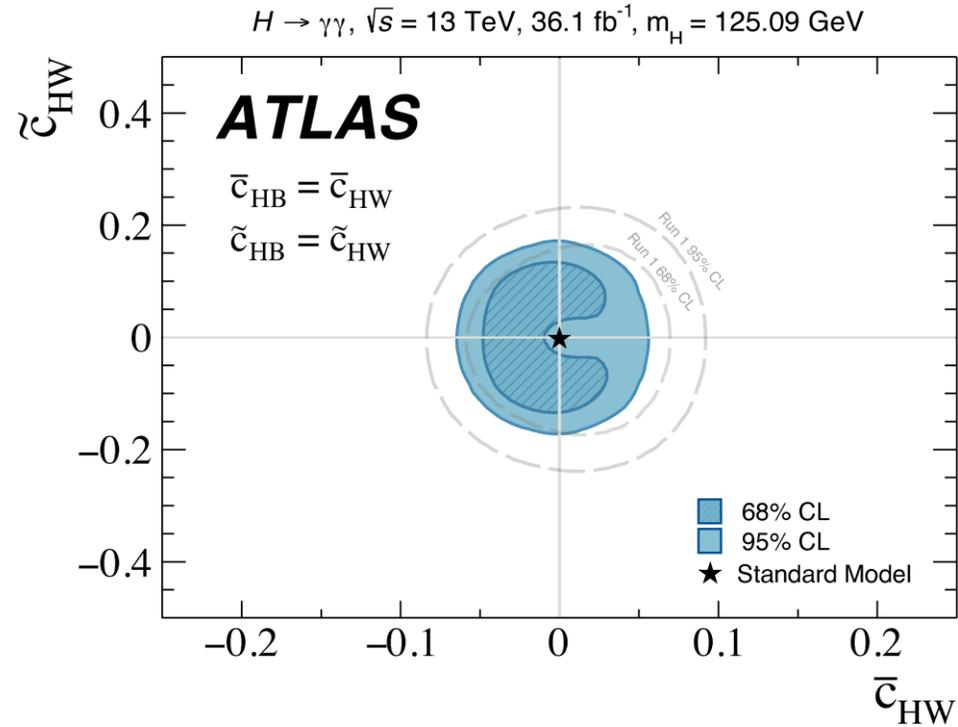
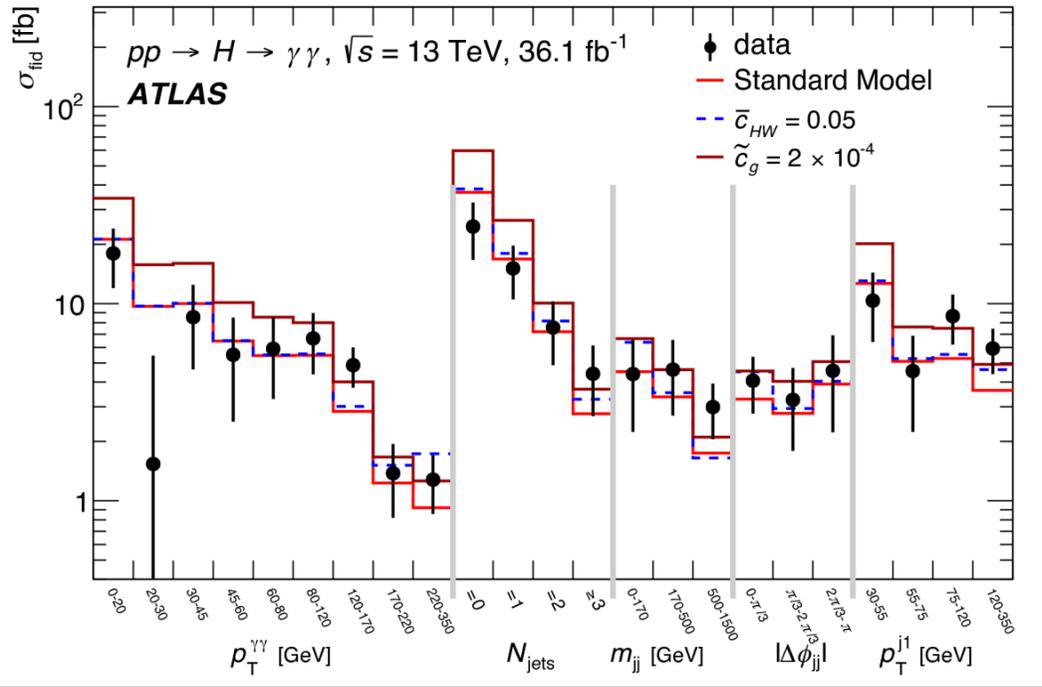
$$\frac{d\sigma}{dX} = \sum_j \left( \frac{d\sigma_j}{dX} \right)^{\text{ref}} \cdot \left( \frac{d\sigma_j}{dX} \right)_{c_i}^{\text{MG5}} / \left( \frac{d\sigma_j}{dX} \right)_{c_i=0}^{\text{MG5}}$$

- interpolate btw samples: Professor
- Illustration: effect of  $c_i$  on  $d\sigma/dX$



# Tensor structure w/ SILH

## Measured $d\sigma/dX$



## Results

Coefficient	Observed 95% CL limit	Expected 95% CL limit
$\bar{c}_g$	$[-0.8, 0.1] \times 10^{-4} \cup [-4.6, -3.8] \times 10^{-4}$	$[-0.4, 0.5] \times 10^{-4} \cup [-4.9, -4.1] \times 10^{-4}$
$\tilde{c}_g$	$[-1.0, 0.9] \times 10^{-4}$	$[-1.4, 1.3] \times 10^{-4}$
$\bar{c}_{HW}$	$[-5.7, 5.1] \times 10^{-2}$	$[-5.0, 5.0] \times 10^{-2}$
$\tilde{c}_{HW}$	$[-0.16, 0.16]$	$[-0.14, 0.14]$

# Tensor structure w/ SILH: ATLAS

$H \rightarrow ZZ^{(*)} \rightarrow 4l + H \rightarrow \gamma\gamma$

ATLAS

ATLAS-PHYS-PUB-2017-018

EFT, SILH basis, BSM dim-6 even operators

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i c_i^{(6)} O_i^{(6)}$$

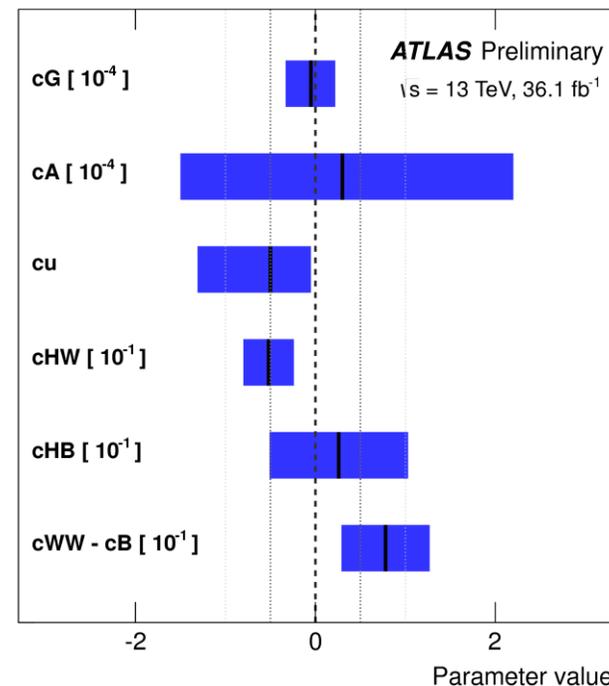
d=6: 6 operators considered for  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^*$

$$\bar{c}_i^{(d)} = c_i^{(d)} / \Lambda^d$$

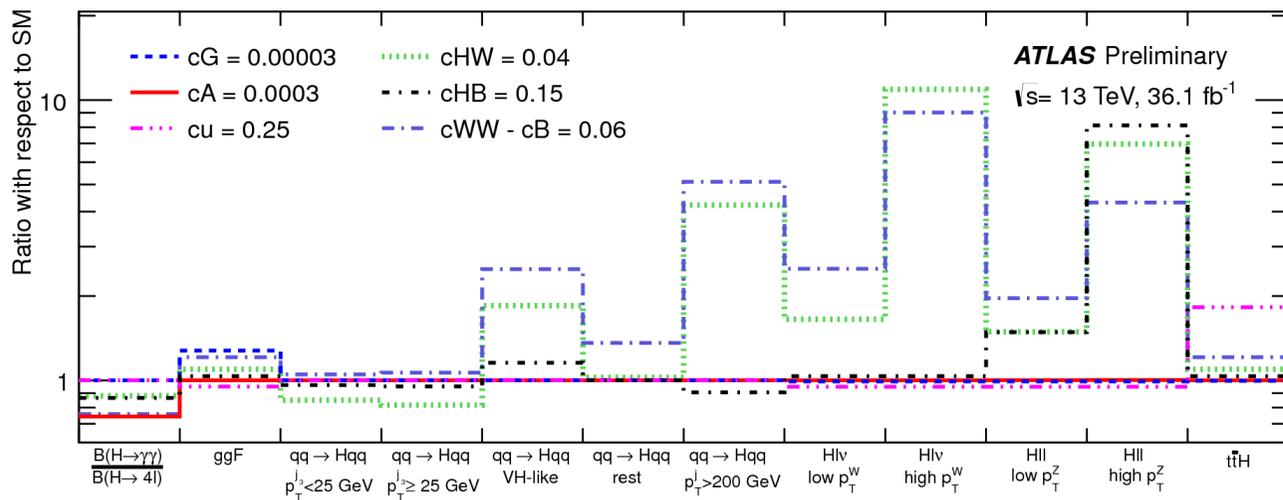
Operator	Expression	HEL coefficient	Vertices
$\mathcal{O}_g$	$ H ^2 G_{\mu\nu}^A G^{A\mu\nu}$	$cG = \frac{m_W^2}{g_s^2} \bar{c}_g$	$Hgg$
$\mathcal{O}_\gamma$	$ H ^2 B_{\mu\nu} B^{\mu\nu}$	$cA = \frac{m_W^2}{g'^2} \bar{c}_\gamma$	$H\gamma\gamma, HZZ$
$\mathcal{O}_u$	$y_u  H ^2 \bar{u}_l H u_R + \text{h.c.}$	$cu = v^2 \bar{c}_u$	$Ht\bar{t}$
$\mathcal{O}_{HW}$	$i (D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$	$cHW = \frac{m_W^2}{g} \bar{c}_{HW}$	$HWW, HZZ$
$\mathcal{O}_{HB}$	$i (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$cHB = \frac{m_W^2}{g'} \bar{c}_{HB}$	$HZZ$
$\mathcal{O}_W$	$i (H^\dagger \overleftrightarrow{D}^\mu H) D^\nu W_{\mu\nu}^a$	$cWW = \frac{m_W^2}{g} \bar{c}_W$	$HWW, HZZ$
$\mathcal{O}_B$	$i (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}$	$cB = \frac{m_W^2}{g'} \bar{c}_B$	$HZZ$

## Results

Observed HEL constraints with  $H \rightarrow ZZ^*$  and  $H \rightarrow \gamma\gamma$



## Connect STXS values to 7 EFT operators



# Conclusion

Used data 2015+2016 recorded by ATLAS ( $36.1 \text{ fb}^{-1}$ )

in order to measure :

-Inclusive signal strength  $\mu$

-Production mode cross-sections  $s_i$  and signal strength :  $\sigma_i \times \text{BR}(H \rightarrow \gamma\gamma)$ ,  $\mu_i$

-STXS w/ strong merging scenario :  $\sigma_{\text{STXS}}$

- Interpreted  $d\sigma/dX$  results in term of EFT (backup)
- No significative deviation from SM expectation
- Looking for more data (2015+2016+2017, then 2018)

backup



# Tensor structure w/ SILH: ATLAS in nutshell

$H \rightarrow \gamma\gamma$ , EFT, SILH basis, BSM dim-6 even operators

$$\mathcal{L}_{\text{eff}} = \underbrace{\bar{c}_g O_g + \tilde{c}_g \tilde{O}_g}_{\text{CP-even}} + \underbrace{\bar{c}_{HW} O_{HW} + \tilde{c}_{HW} \tilde{O}_{HW}}_{\text{CP-odd}} + \underbrace{\bar{c}_{HB} O_{HB} + \tilde{c}_{HB} \tilde{O}_{HB}}_{\text{CP-odd}}$$

CP-even

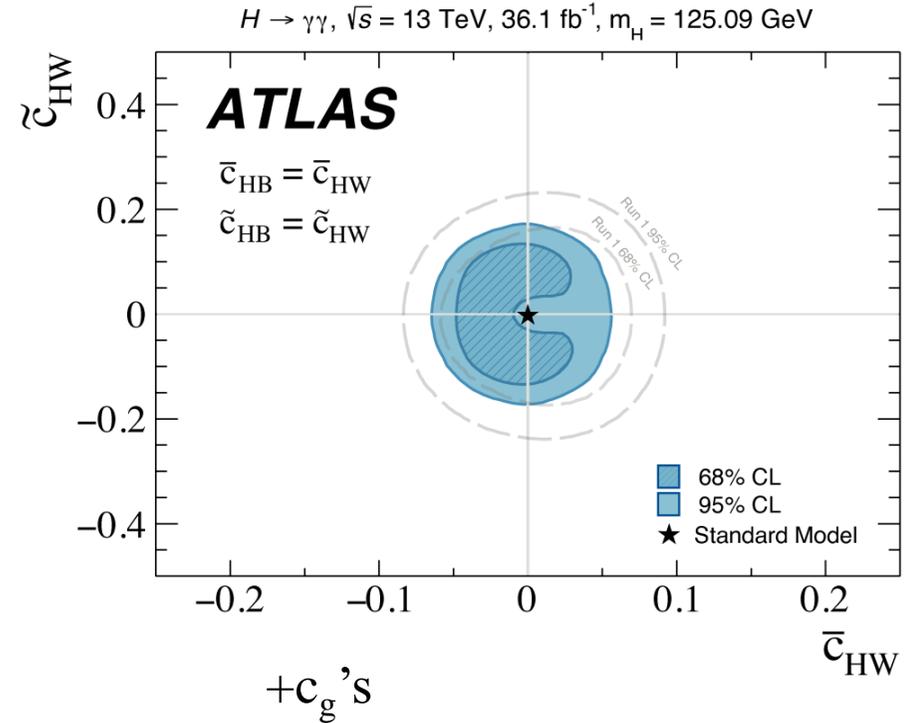
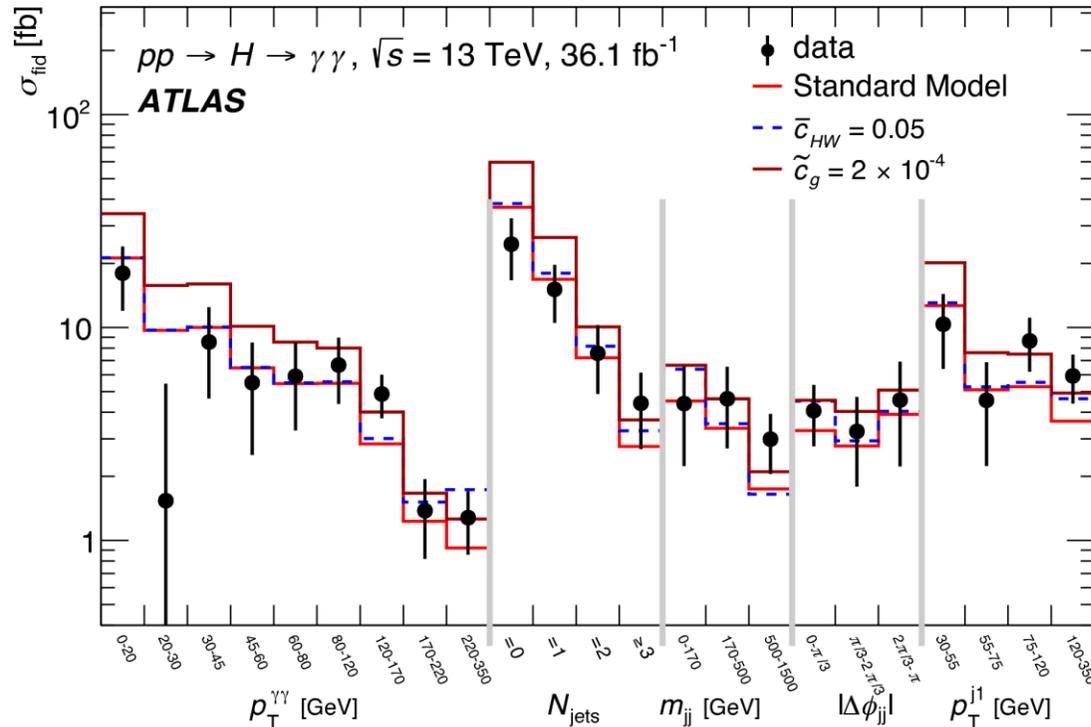
CP-odd

Anomalous coupling :  
change rate/kinematics  
of Higgs events

Interactions  $\longrightarrow$  **Hgg**      **HWW, HZZ, HZ $\gamma$**       **HZZ, HZ $\gamma$**   
 Probed by  $\longrightarrow$  **ggH**      **VBF+VH**      **VBF+VH**

- Simultaneous fit to data w/ 5  $d\sigma/dX$  distributions :

- Results



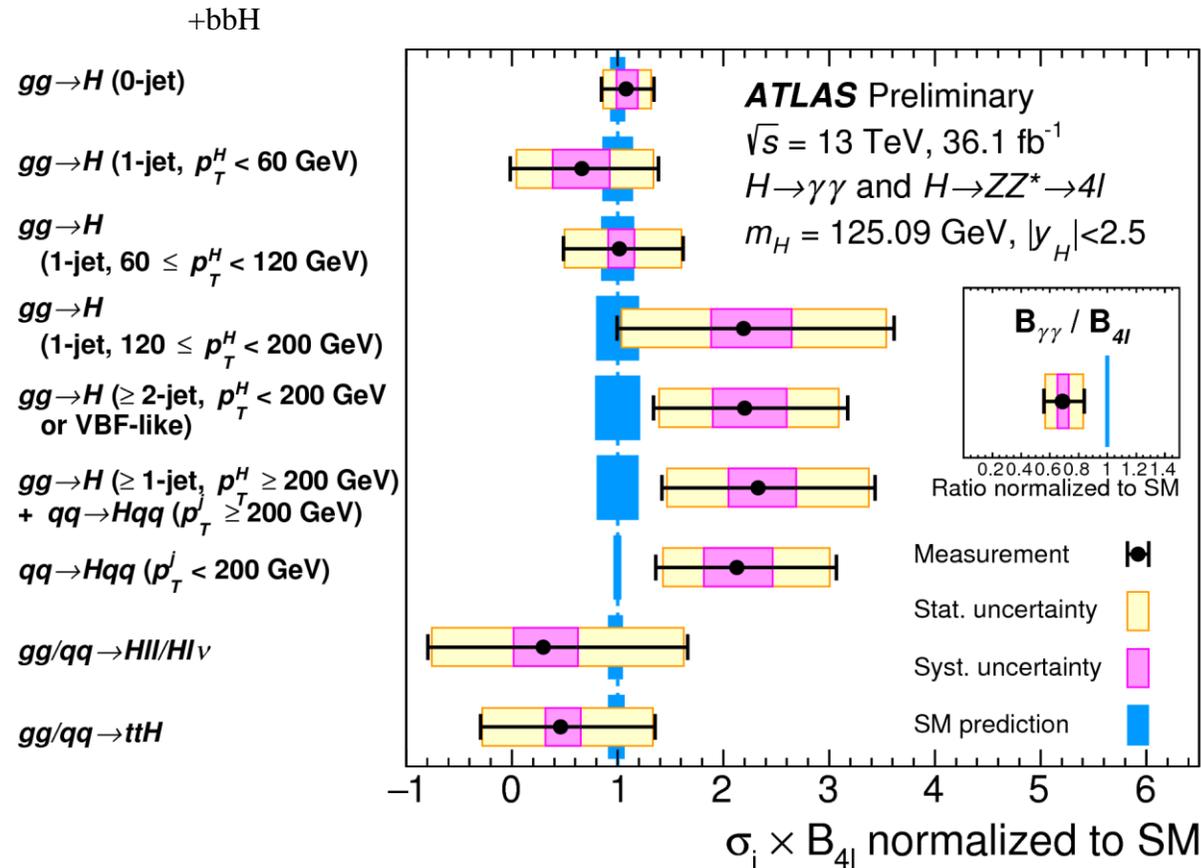
# STXS combination

ATLAS

STXS stage 1, merged

ATLAS-CONF-2017-047

Combination:  $H \rightarrow \gamma\gamma, H \rightarrow ZZ^{(*)} \rightarrow 4l$



# Tensor structure w/ SILH: ATLAS

$H \rightarrow ZZ^{(*)} \rightarrow 4l + H \rightarrow \gamma\gamma$

ATLAS

EFT, SILH basis, BSM dim-6 even operators

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i c_i^{(6)} O_i^{(6)}$$

ATLAS-PHYS-PUB-2017-018

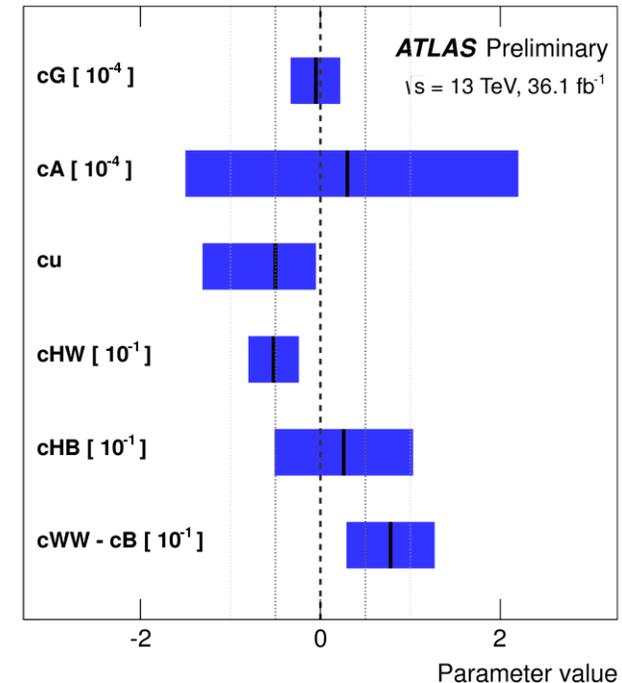
d=6: 6 operators considered for  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^*$

$$\bar{c}_i^{(d)} = c_i^{(d)} / \Lambda^d$$

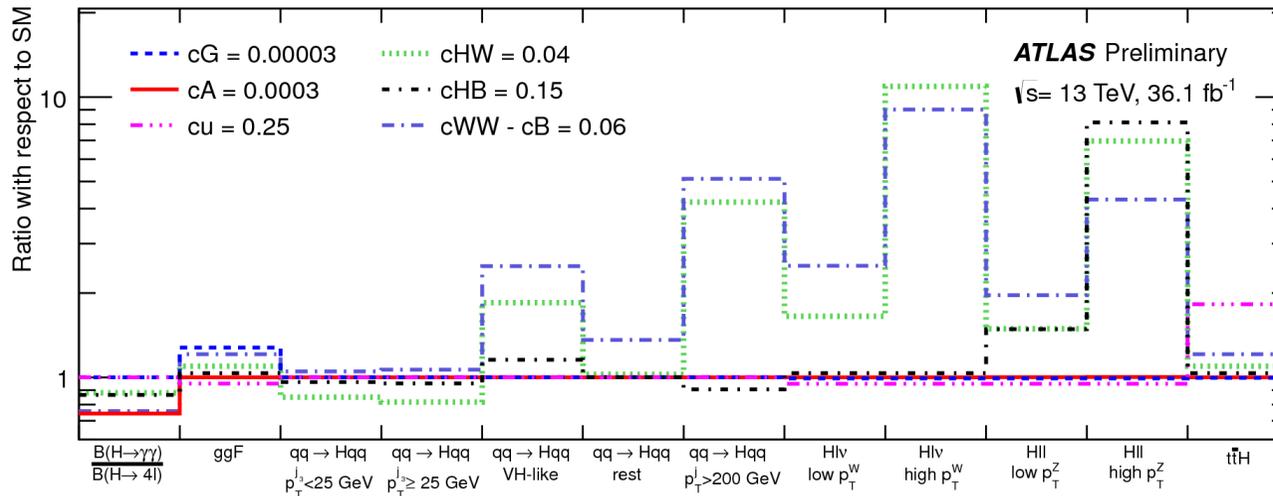
Operator	Expression	HEL coefficient	Vertices
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$\mathcal{O}_{HB}$	$i (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$cHB = \frac{m_W^2}{g'} \bar{c}_{HB}$	$HZZ$
$\mathcal{O}_W$	$i (H^\dagger \overleftrightarrow{D}^\mu H) D^\nu W_{\mu\nu}^a$	$cWW = \frac{m_W^2}{g} \bar{c}_W$	$HWW, HZZ$
$\mathcal{O}_B$	$i (H^\dagger \overleftrightarrow{D}^\mu H) \partial^\nu B_{\mu\nu}$	$cB = \frac{m_W^2}{g'} \bar{c}_B$	$HZZ$

## Results

Observed HEL constraints with  $H \rightarrow ZZ^*$  and  $H \rightarrow \gamma\gamma$

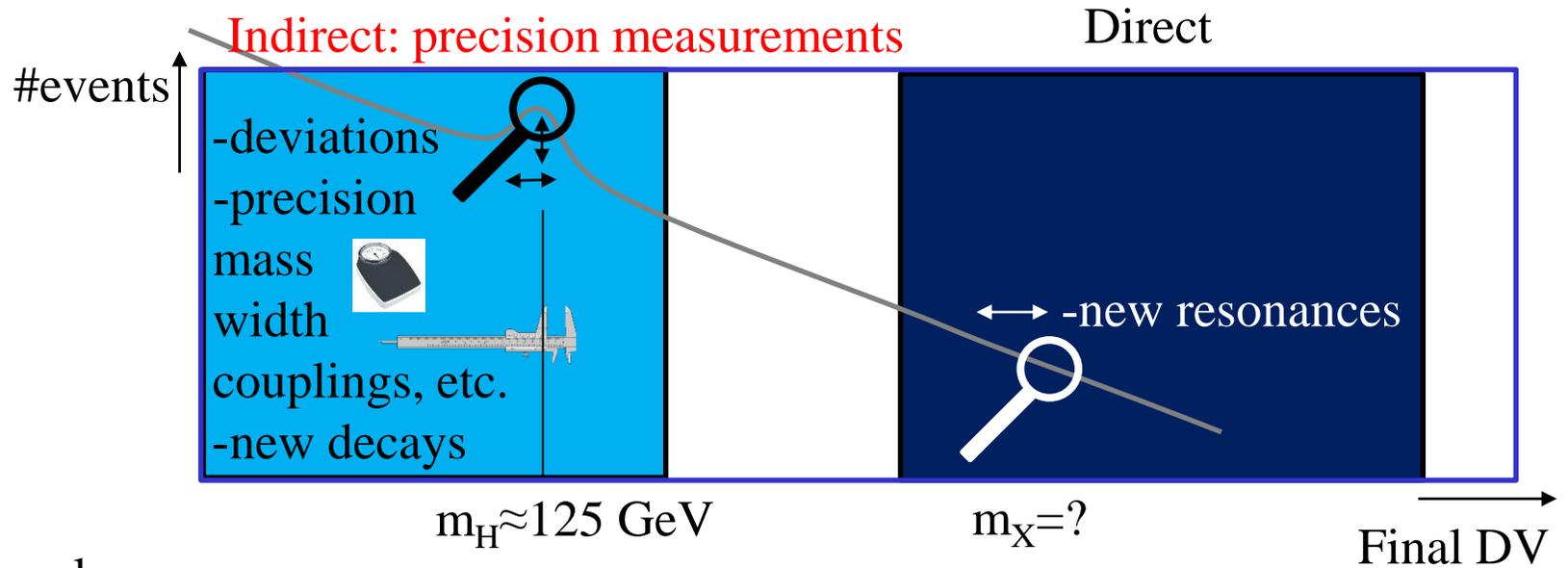


## Connect STXS values to 7 EFT operators



# Introduction

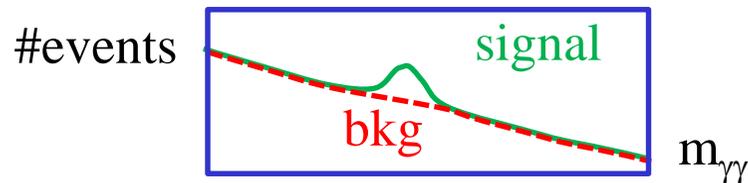
- Search for BSM



- $H \rightarrow \gamma\gamma$  channel

(final DV : final discriminant variable :  $m_{\gamma\gamma}$ )

Search for a **resonant system** of two high-pt photons above a **continuum bkg**



# Introduction

- Characterize the Higgs production with the  $H \rightarrow \gamma\gamma$  channel : measure various POIs (Parameters of Interest)

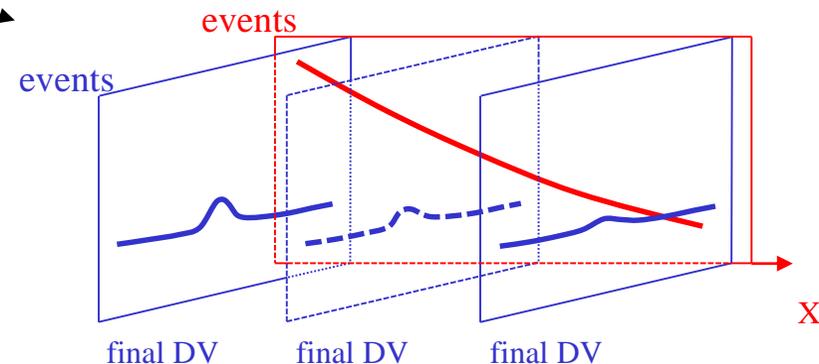
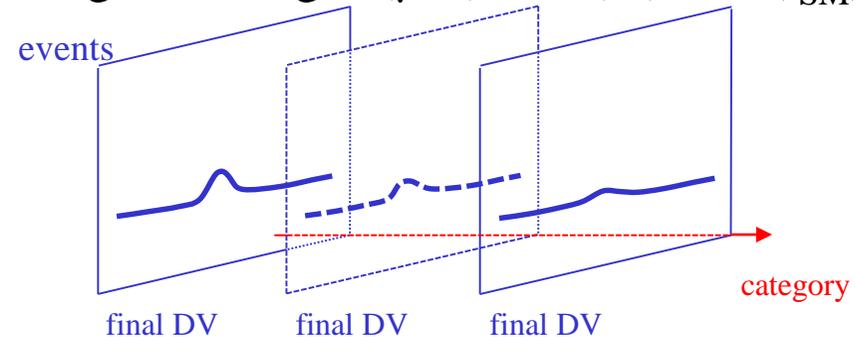
-cross-section : absolute ( $\sigma$ ) or relative to SM : signal strength ( $\mu = (\sigma \times BR) / (\sigma \times BR)_{SM}$ )

-per production mode :  $\sigma_i, \mu_i$

-in phase space of Higgs topology:  $\sigma_{SXTS}$   
(Simplified Template Cross-Sections)

-strengths on 'scattering amplitude' :  $\kappa$

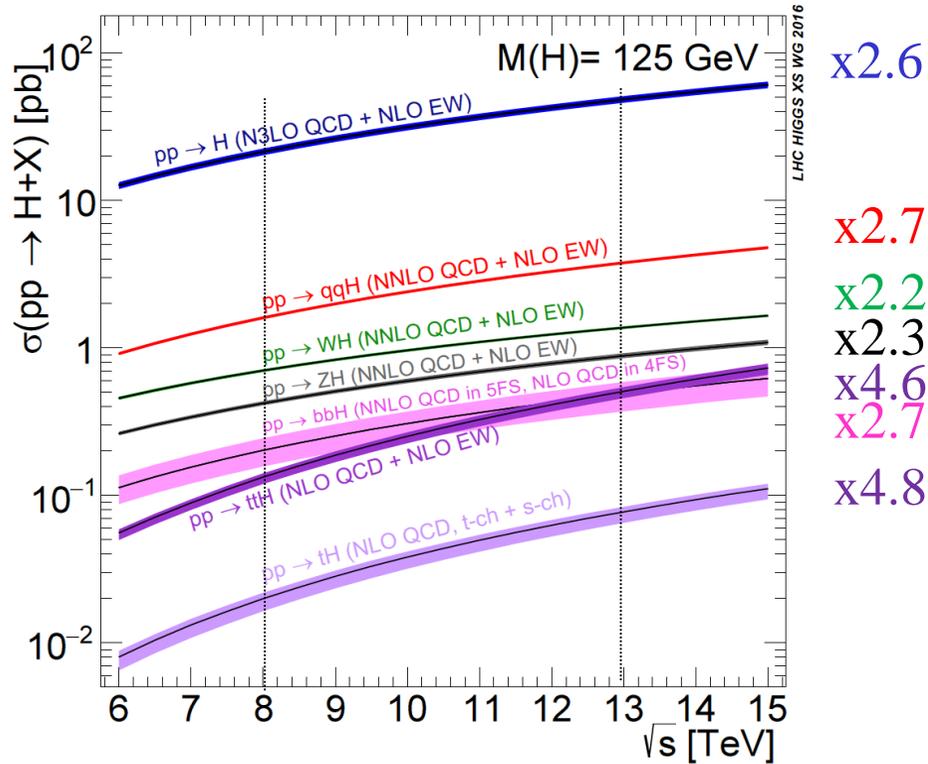
-in fiducial regions: integrated:  $\sigma_{fid}$ , differential :  $d\sigma_{fid}/dX$   
(no extrapolation to total phase space)



(final DV : final discriminant variable :  $m_{\gamma\gamma}$ )

# Context of analysis in the LHC data-taking

- Improved precision wrt previous combination (ATLAS-CMS Run 1)

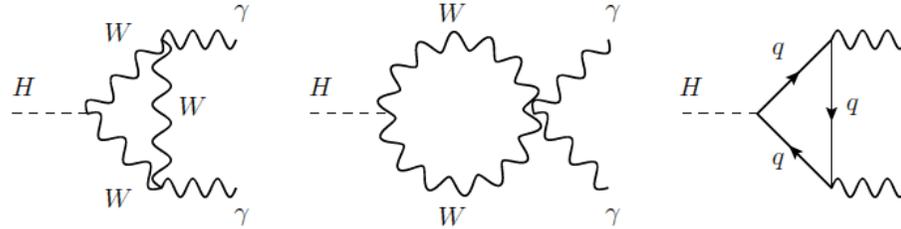


Improved theoretical prediction :

-ggH : NNLO  $\rightarrow$  N<sup>3</sup>LO

-VBF, VH, ttH: add EW corrections

# Interference

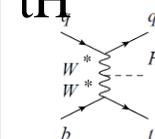
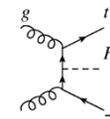
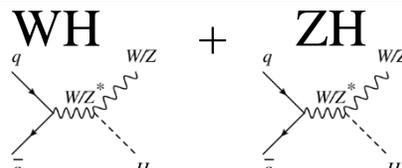
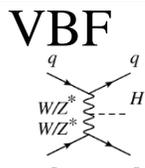
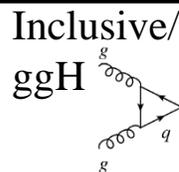


Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(\text{ggH})$	✓	b - t	$\kappa_g^2$	$1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-		$0.73 \cdot \kappa_W^2 + 0.27 \cdot \kappa_Z^2$
$\sigma(\text{WH})$	-	-		$\kappa_W^2$
$\sigma(\text{qq/qg} \rightarrow \text{ZH})$	-	-		$\kappa_Z^2$
$\sigma(\text{gg} \rightarrow \text{ZH})$	✓	Z - t		$2.46 \cdot \kappa_Z^2 + 0.47 \cdot \kappa_t^2 - 1.94 \cdot \kappa_Z \kappa_t$
$\sigma(\text{ttH})$	-	-		$\kappa_t^2$
$\sigma(\text{gb} \rightarrow \text{WtH})$	-	W - t		$2.91 \cdot \kappa_t^2 + 2.40 \cdot \kappa_W^2 - 4.22 \cdot \kappa_t \kappa_W$
$\sigma(\text{qb} \rightarrow \text{tHq})$	-	W - t		$2.63 \cdot \kappa_t^2 + 3.58 \cdot \kappa_W^2 - 5.21 \cdot \kappa_t \kappa_W$
$\sigma(\text{bbH})$	-	-		$\kappa_b^2$
Partial decay width				
$\Gamma_{\text{ZZ}}$	-	-		$\kappa_Z^2$
$\Gamma_{\text{WW}}$	-	-		$\kappa_W^2$
$\Gamma_{\gamma\gamma}$	✓	W - t	$\kappa_\gamma^2$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W \kappa_t$
$\Gamma_{\tau\tau}$	-	-		$\kappa_\tau^2$
$\Gamma_{\text{bb}}$	-	-		$\kappa_b^2$
$\Gamma_{\mu\mu}$	-	-		$\kappa_\mu^2$
Total width for $\text{BR}_{\text{BSM}} = 0$				
$\Gamma_{\text{H}}$	✓	-	$\kappa_{\text{H}}^2$	$0.58 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.08 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_t^2 + 0.026 \cdot \kappa_Z^2 + 0.029 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0015 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.00025 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

# Status of Higgs prod. modes observation at LHC

- Observation
- Evidence
- Analysis exists

prod. mode



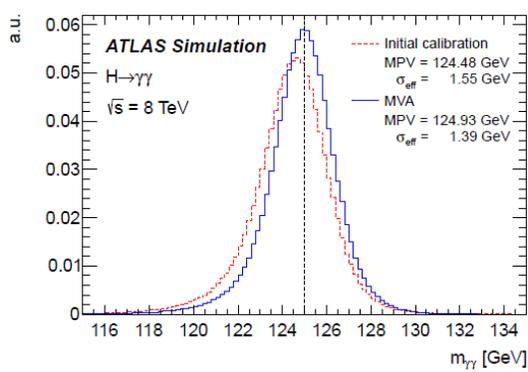
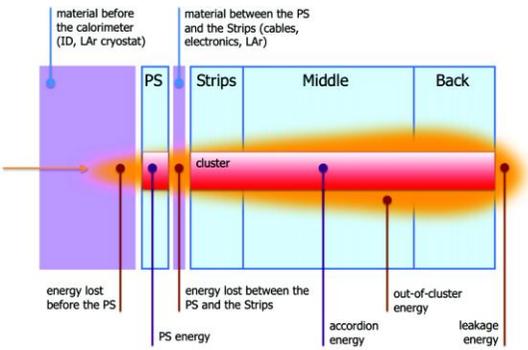
Decay channel

Decay channel	Inclusive/ ggH	VBF	WH + ZH	ttH	tH
combination	A+C: <input checked="" type="checkbox"/>	A+C: <input checked="" type="checkbox"/>	A+C: <input checked="" type="checkbox"/>	A: <input checked="" type="checkbox"/> , C: <input checked="" type="checkbox"/> A+C: <input checked="" type="checkbox"/>	
H → γγ	A: <input checked="" type="checkbox"/> C: <input checked="" type="checkbox"/>	A: <input checked="" type="checkbox"/>	A: <input type="checkbox"/>	A: <input type="checkbox"/>	A: <input type="checkbox"/> C: <input type="checkbox"/>
H → Zγ	A: <input type="checkbox"/> C: <input type="checkbox"/>				
H → ZZ(*) → 4l	A: <input checked="" type="checkbox"/> C: <input checked="" type="checkbox"/>	A: <input type="checkbox"/> C: <input type="checkbox"/>	A: <input type="checkbox"/> C: <input type="checkbox"/>	A: <input type="checkbox"/> C: <input type="checkbox"/>	
H → WW(*) → lνlν	A: <input checked="" type="checkbox"/> C: <input checked="" type="checkbox"/>	A: <input checked="" type="checkbox"/> C: <input type="checkbox"/>	A: <input type="checkbox"/> C: <input type="checkbox"/>	A: <input type="checkbox"/> C: <input type="checkbox"/>	C: <input type="checkbox"/>
H → bb	C: <input type="checkbox"/> boosted	A: <input type="checkbox"/> C: <input type="checkbox"/>	A: <input checked="" type="checkbox"/> C: <input checked="" type="checkbox"/>	A: <input type="checkbox"/> C: <input type="checkbox"/>	C: <input type="checkbox"/>
H → Y(1S)γ	A: <input type="checkbox"/> C: <input type="checkbox"/>				
H → cc				A: <input type="checkbox"/>	
H → J/ψγ	A: <input type="checkbox"/>				
H → φγ	A: <input type="checkbox"/>				
H → ργ	A: <input type="checkbox"/>				
H → ττ	A+C: <input checked="" type="checkbox"/>			C: <input type="checkbox"/>	
H → μμ	A: <input type="checkbox"/> C: <input type="checkbox"/>				
H → ee	C: <input type="checkbox"/>				

# Photon reconstruction

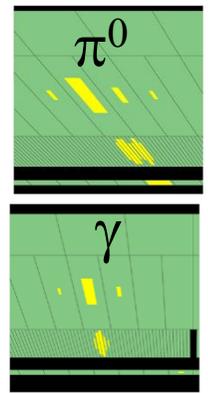
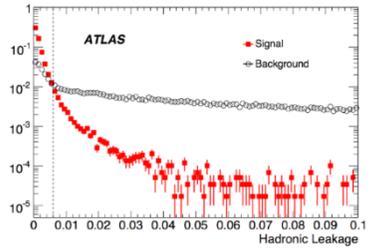
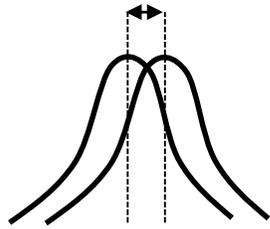
## calibration

- electronics
- cluster : MVA
- in situ :  $Z \rightarrow ee$
- validation :  $J/\Psi \rightarrow ee$ , rad. decays :  $Z \rightarrow ll\gamma$

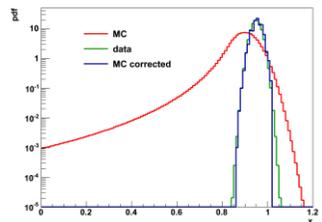


## identification

- development
- Fudge Factors
- cut-based
- MVA



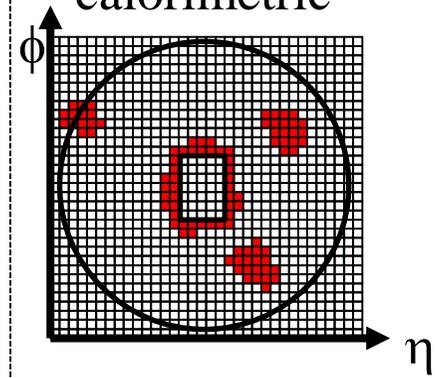
- data-driven measurement
- radiative
- matrix
- Smirnov transform



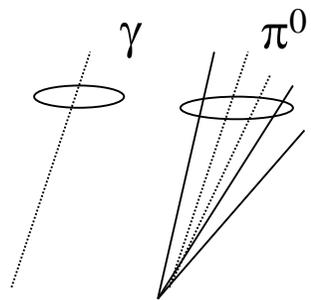
- $j \rightarrow \gamma$  rejection measurement
- pythia/sherpa
- q/g,  $f(p_T, \eta)$

## isolation

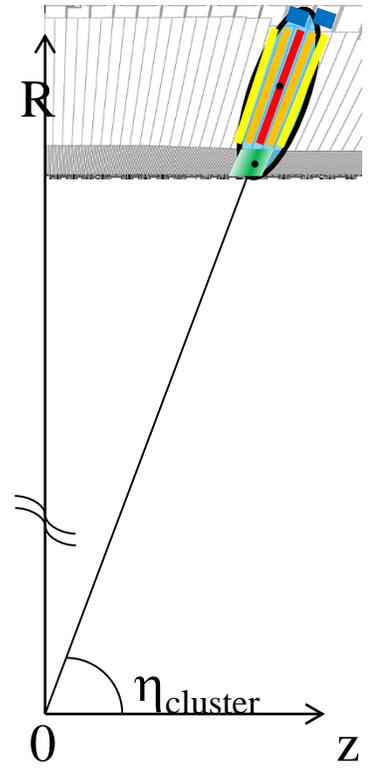
### calorimetric



### tracks



## direction



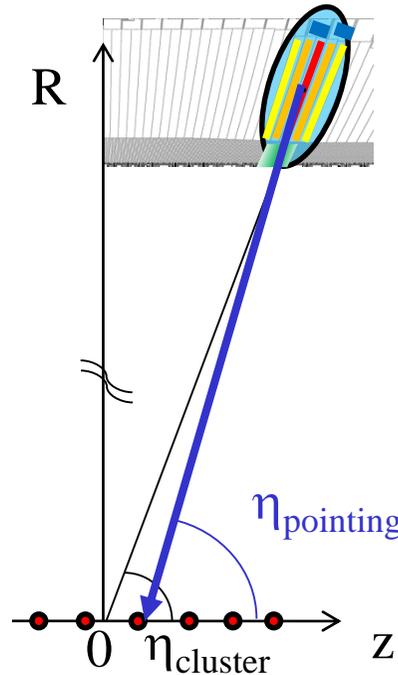
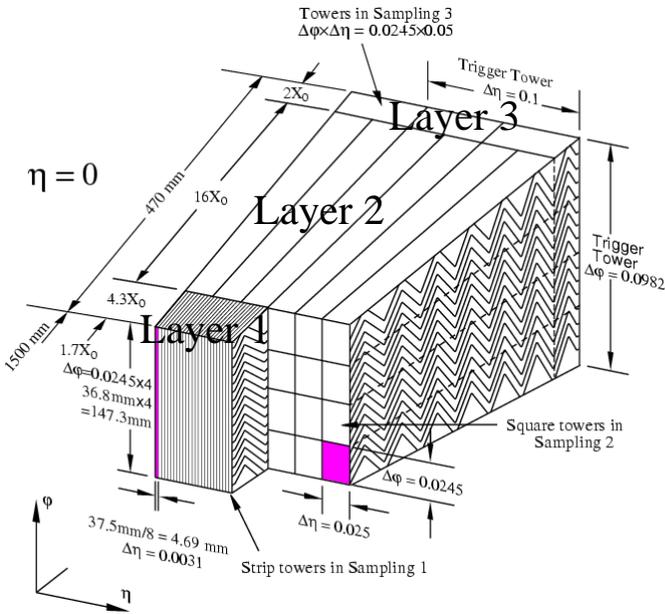
- balance
- MVA

# Selection of photons

- exploits segmentation of electromagnetic calorimeter in order to :

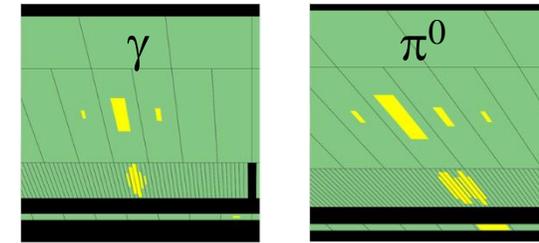
(1) **measure direction** : MVA :  
 { calorimeter pointing  
 + some variables }

(2) **identify photons**  
 (suppress fake photons)

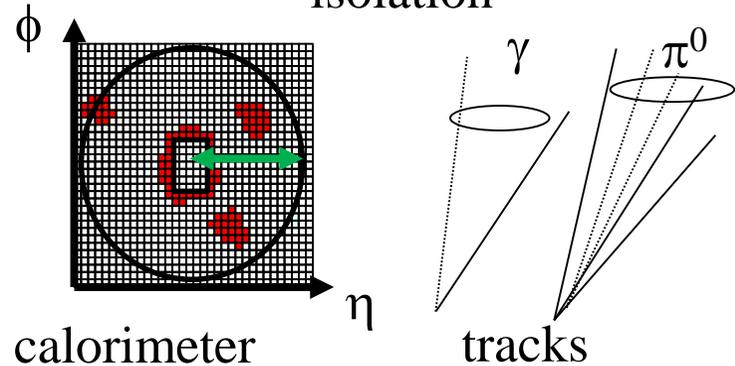


Layer 3  
 Layer 2  
 Layer 1

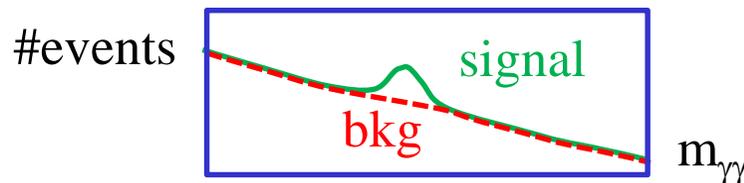
-shower shapes



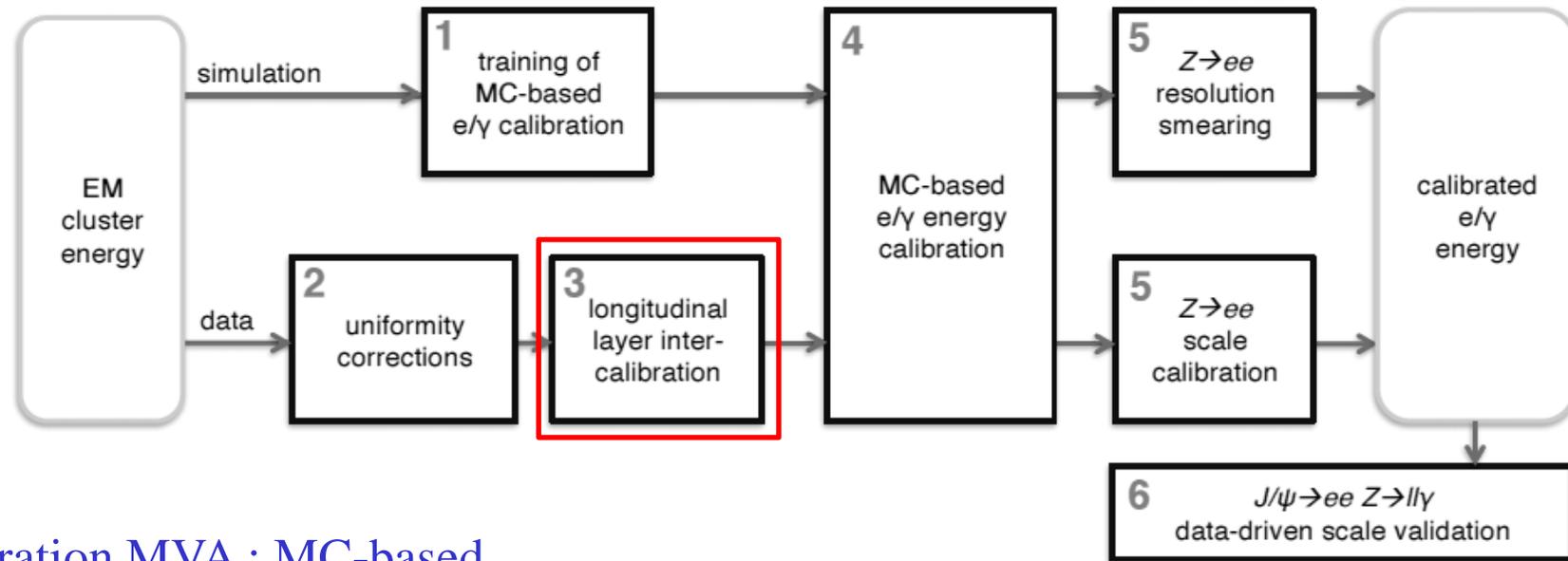
-isolation



- Search for a **resonant system** of two high-pt photons above a **continuum bkg**



# Calibration



- Calibration MVA : MC-based

Total energy in accordion :  $E_{acc}$

$E_0/E_{acc}$

Shower depth

eta cluster

Radius conversion

Ratio conversion pT / ET accordion

Fraction conversion pT carried by highest pT track

- detector geometry, simulation

Data :  $E_{1/2}$  : measure material

- Uniformity corrections

not included in simulation

-non optimal HV

-geometric effect : gravity-induced IMW

-biases from LAr electronic calibration

- Longitudinal intercalibration

Relative calibration of layers

no in-situ calibration of back

# Secondary objects

- **Jets**

AntiKt4EMTopoJets,  $p_T > 25$  GeV ( $|\eta| < 2.4$ ), then  $p_T > 30$  GeV

Kills jets not originating from primary vertex :  $JVT > 0.59$ ,  $|y| < 4.4$  ~Prob jet from PV

(JVT : 2D likelihood : corr JVF + ratio  $\{p_T \text{ trk} / p_T \text{ jet}\}$ )

**B-tagging** : MV2c10 tagger, efficiency : 70 % : rejection jets : c : 12 ; light : 380

Data-driven corrections (SFs) : accomodate differences of efficiencies (data vs MC)

- **Electrons**

$p_T > 10$  GeV,  $|\eta| < 2.47$ , remove crack  $1.37 < |\eta| < 1.52$

Distance wrt PV :  $|d_0/\sigma(d_0)| < 5$ ,  $|z_0 \sin \theta| < 0.5$  mm

-SF applied (J/ $\psi$ , Y)

-ID : Medium LH

-Isolation (calorimeter+track)

‘Topoetcone20  $< 0.02 \times p_T$  ; Trk : Pt cone 20 :  $< 0.15 \times E_T$

- **Muons**

$p_T > 10$  GeV,  $|\eta| < 2.7$

Distance wrt PV :  $|d_0/\sigma(d_0)| < 3$ ,  $|z_0 \sin \theta| < 0.5$  mm

medium quality, GradientLoose isolation (comb. eff. 25 GeV ~ 95 %)

- **MET** ( $E_T^{\text{miss}}$  in document)

Significance MET :  $E_T^{\text{miss}} / \sqrt{(\Sigma E_T)}$

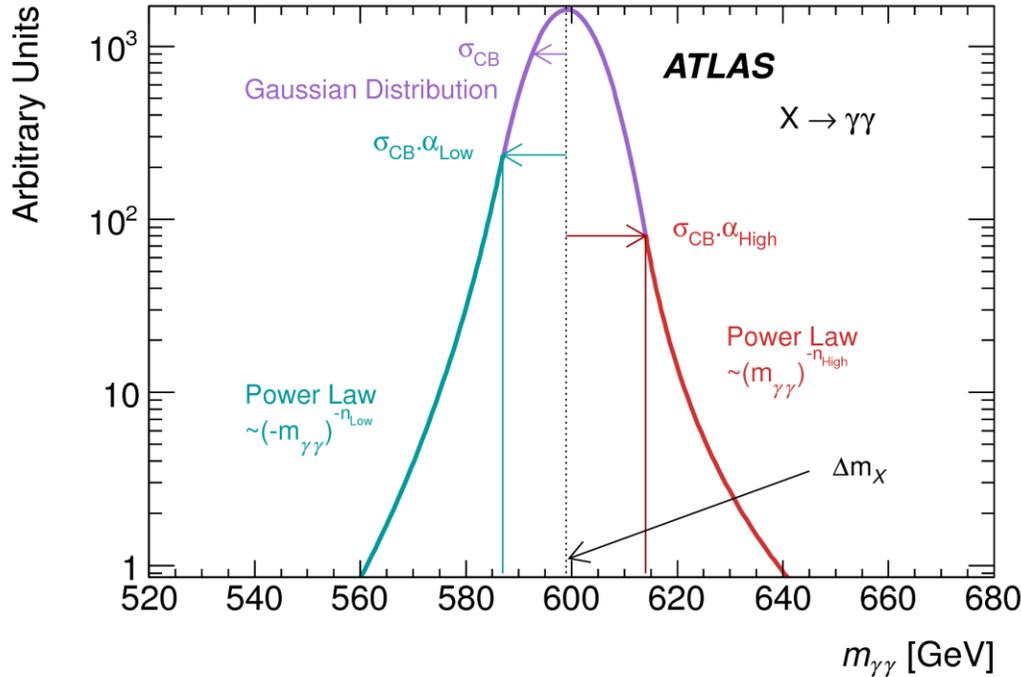
Soft term : ‘TST’ (Track-based soft-term) : more robust wrt pile-up than CST (calo)<sup>41</sup>

# Signal modelling

- Shape

-Double-sided Crystal-Ball function

$$f_i^{\text{sig}}(m_{\gamma\gamma}; \Delta\mu_{\text{CB},i}, \sigma_{\text{CB},i}, \alpha_{\text{CB},i}^{\pm}, n_{\text{CB},i}^{\pm}) = \mathcal{N}_c \begin{cases} e^{-t^2/2} & -\alpha_{\text{CB},i}^- \leq t \leq \alpha_{\text{CB},i}^+ \\ \left(\frac{n_{\text{CB},i}^-}{|\alpha_{\text{CB},i}^-|}\right)^{n_{\text{CB},i}^-} e^{-|\alpha_{\text{CB},i}^-|^2/2} \left(\frac{n_{\text{CB},i}^-}{\alpha_{\text{CB},i}^-} - \alpha_{\text{CB},i}^- - t\right)^{-n_{\text{CB},i}^-} & t < -\alpha_{\text{CB},i}^- \\ \left(\frac{n_{\text{CB},i}^+}{|\alpha_{\text{CB},i}^+|}\right)^{n_{\text{CB},i}^+} e^{-|\alpha_{\text{CB},i}^+|^2/2} \left(\frac{n_{\text{CB},i}^+}{\alpha_{\text{CB},i}^+} - \alpha_{\text{CB},i}^+ - t\right)^{-n_{\text{CB},i}^+} & t > \alpha_{\text{CB},i}^+ \end{cases}$$



# Signal modelling

## Yield signal

Category	ggH		VBF		WH		ZH		ttH		bbH		tHq		tHW		All $N_S$
	$\epsilon$ [%]	$f$ [%]															
ggH 0J Cen	8.9	97.3	1.2	1.1	1.4	0.4	1.9	0.4	nil	nil	8.2	0.9	nil	nil	nil	nil	333.5
ggH 0J Fwd	15.5	97.0	2.4	1.2	3.0	0.5	3.7	0.4	nil	nil	14.7	0.9	0.2	nil	0.1	nil	579.5
ggH 1J Low	7.2	90.5	5.7	5.7	5.0	1.7	4.4	1.0	0.1	nil	9.1	1.1	0.5	nil	0.2	nil	289.9
ggH 1J Med	3.6	83.5	6.4	11.7	4.2	2.6	4.1	1.6	0.1	nil	1.9	0.4	0.6	nil	0.3	nil	156.2
ggH 1J High	0.7	76.0	1.9	17.5	1.1	3.4	1.4	2.7	0.1	0.1	0.3	0.3	0.2	nil	0.1	nil	31.5
ggH 1J BSM	nil	72.4	0.1	16.9	0.1	6.0	0.2	4.2	nil	0.3	nil	nil	nil	0.1	nil	nil	2.2
ggH 2J Low	1.8	79.1	2.7	9.6	3.7	4.5	4.1	3.1	2.2	1.1	5.4	2.3	3.9	0.3	1.9	nil	81.1
ggH 2J Med	1.5	77.6	3.1	12.2	3.2	4.4	3.8	3.2	2.6	1.5	1.6	0.7	4.5	0.4	2.4	nil	72.4
ggH 2J High	0.6	75.8	1.3	12.8	1.4	4.9	1.9	4.0	1.4	2.0	0.1	0.1	2.2	0.4	1.6	0.1	29.2
ggH 2J BSM	0.2	76.2	0.3	10.3	0.4	4.9	0.6	4.6	0.6	3.0	0.1	0.2	0.8	0.6	1.3	0.2	7.6
VBF Hjj Low loose	0.2	32.3	4.5	66.7	0.1	0.3	0.1	0.3	nil	nil	0.1	0.2	0.3	0.1	nil	nil	19.4
VBF Hjj Low tight	nil	12.9	4.2	86.7	nil	0.1	nil	0.1	nil	nil	nil	nil	0.3	0.1	nil	nil	13.8
VBF Hjj High loose	0.3	69.9	1.4	23.8	0.4	2.2	0.5	1.8	0.4	0.9	0.4	0.7	1.8	0.6	0.5	nil	16.5
VBF Hjj High tight	0.3	47.0	3.4	48.2	0.2	1.2	0.4	1.3	0.4	0.8	0.2	0.3	4.4	1.2	0.6	nil	20.2
VHhad loose	0.3	67.2	0.3	4.9	2.4	14.6	2.9	11.0	0.6	1.6	0.2	0.4	0.8	0.3	0.8	0.1	16.5
VHhad tight	0.2	52.4	0.1	3.4	3.0	23.8	3.5	18.0	0.6	1.9	nil	0.1	0.5	0.2	1.0	0.1	12.3
jet BSM	0.4	59.9	2.4	25.8	1.6	5.9	1.9	4.4	2.0	3.0	0.1	0.1	3.1	0.6	5.1	0.2	26.7
VHMET Low	nil	11.9	nil	0.4	0.1	23.4	0.6	63.2	nil	0.5	nil	0.3	nil	0.2	nil	nil	0.6
VHMET High	nil	1.3	nil	0.1	0.3	22.8	1.4	66.2	0.3	8.3	nil	nil	0.1	0.6	0.8	0.7	1.3
VHlep Low	nil	11.4	nil	1.1	4.4	68.0	0.8	8.1	1.3	8.5	0.2	0.9	1.8	1.6	2.2	0.4	6.4
VHlep High	nil	0.2	nil	nil	1.2	76.5	0.1	4.6	0.6	16.2	nil	nil	0.3	1.2	1.6	1.3	1.5
VHdilep	nil	nil	nil	nil	nil	nil	1.4	95.8	0.1	4.0	nil	nil	nil	0.1	0.2	0.9	0.9
tHhad 4j2b	nil	23.8	nil	2.8	nil	1.6	0.1	13.5	0.6	39.0	0.1	8.2	1.2	10.5	0.3	0.6	0.6
tHhad 4j1b	nil	35.4	nil	4.0	0.1	4.3	0.3	7.9	2.2	36.3	0.2	2.2	3.8	8.5	2.6	1.3	2.5
ttHhadBDT4	nil	7.0	nil	0.8	nil	1.4	0.2	4.5	4.8	79.4	nil	0.3	1.9	4.3	4.7	2.4	2.5
ttHhadBDT3	nil	3.5	nil	0.5	nil	1.0	nil	3.1	1.3	86.1	nil	0.5	0.3	3.1	1.1	2.2	0.6
ttHhadBDT2	nil	3.6	nil	0.3	nil	0.8	nil	1.6	3.8	89.3	nil	0.2	0.6	1.8	3.4	2.4	1.8
ttHhadBDT1	nil	1.2	nil	0.1	nil	0.1	nil	0.7	3.4	95.0	nil	0.1	0.2	0.7	2.5	2.1	1.4
ttHlep	nil	nil	nil	nil	nil	0.2	nil	0.1	5.6	96.0	nil	0.1	0.4	1.0	5.0	2.6	2.4
tHlep 1fwd	nil	1.8	nil	0.2	nil	1.4	nil	0.9	2.1	79.4	nil	0.2	2.6	13.5	2.3	2.6	1.1
tHlep 0fwd	nil	4.1	nil	0.2	0.1	5.6	nil	2.8	1.9	75.7	nil	0.9	1.5	8.2	2.1	2.5	1.0
Total $\epsilon$ [%]	41.8	-	41.3	-	37.6	-	40.5	-	39.1	-	42.8	-	38.9	-	44.5	-	41.8
Events	1518.4		119.1		37.1		25.2		16.0		14.8		2.2		0.5		1733.2

# Measuring background for H( $\gamma\gamma$ ) analysis

Components of background :  $\gamma\gamma$ ,  $\gamma j$ ,  $jj$

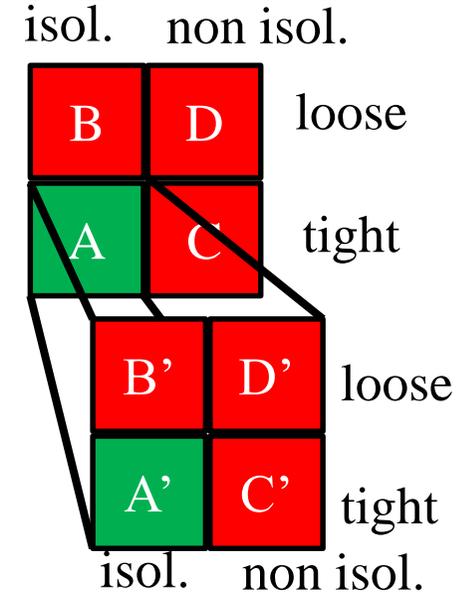
- $A = \frac{B}{D} * C$  method

leading  $\gamma$  candidate  
(highest  $p_T$ )

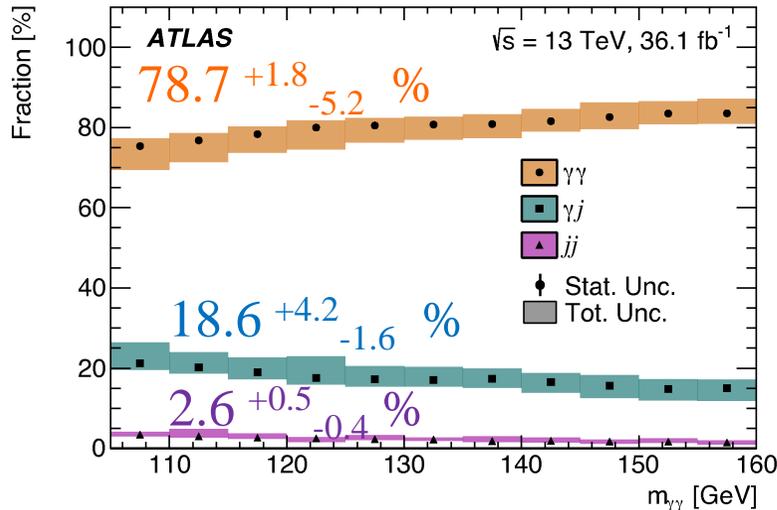
signal region : O( $\gamma$ )

control region : O( $j$ )

sub-leading  $\gamma$



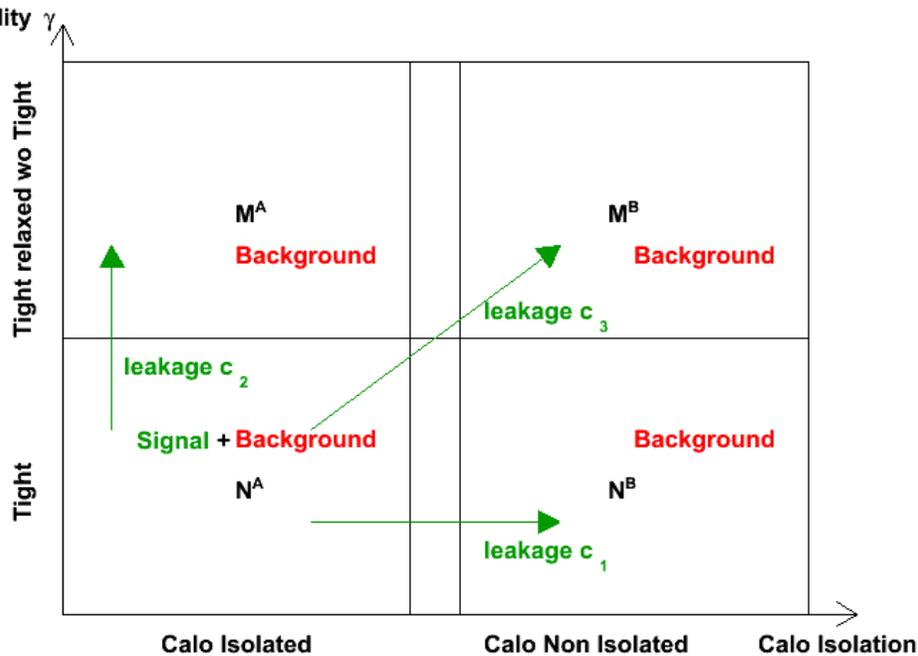
Connection of each region with bkg processes



Drell-Yan (<1 % of bkg) : neglected: inside other components

# 1D-ABCD method

1) **Introduction** : let's consider the case with one photon only



a) simplified case : no signal leakage

$$N_{\text{bkg}}^A = N^B \times \frac{M^A}{M^B}$$

b) w/ signal leakage ( $c_i = O(5\%)$ )

$$N_{\text{bkg}}^A = \left[ (N^B - c_1 N_{\text{sig}}^A) \frac{M^A - c_2 N_{\text{sig}}^A}{M^B - c_3 N_{\text{sig}}^A} \right]$$

c) phase space of  $M^A$ ,  $M^B$  may differ from  $N^A$ ,  $N^B$

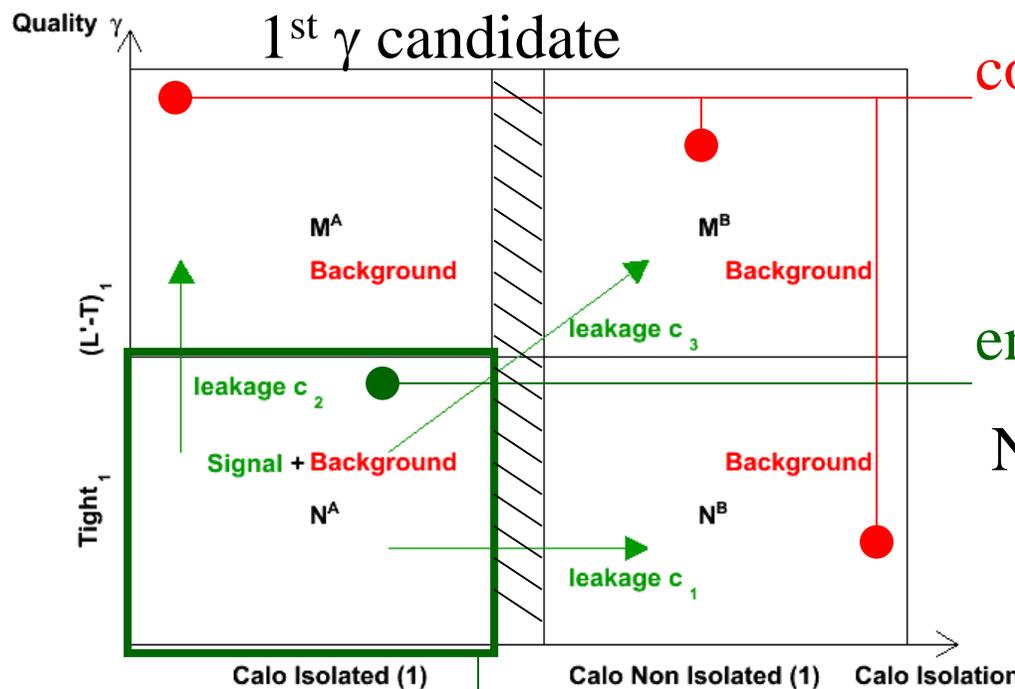
→ introduce a correction factor : ‘pseudo-correlation factor’

$$R = \frac{N_{\text{bkg}}^A M_{\text{bkg}}^B}{N_{\text{bkg}}^B M_{\text{bkg}}^A}$$

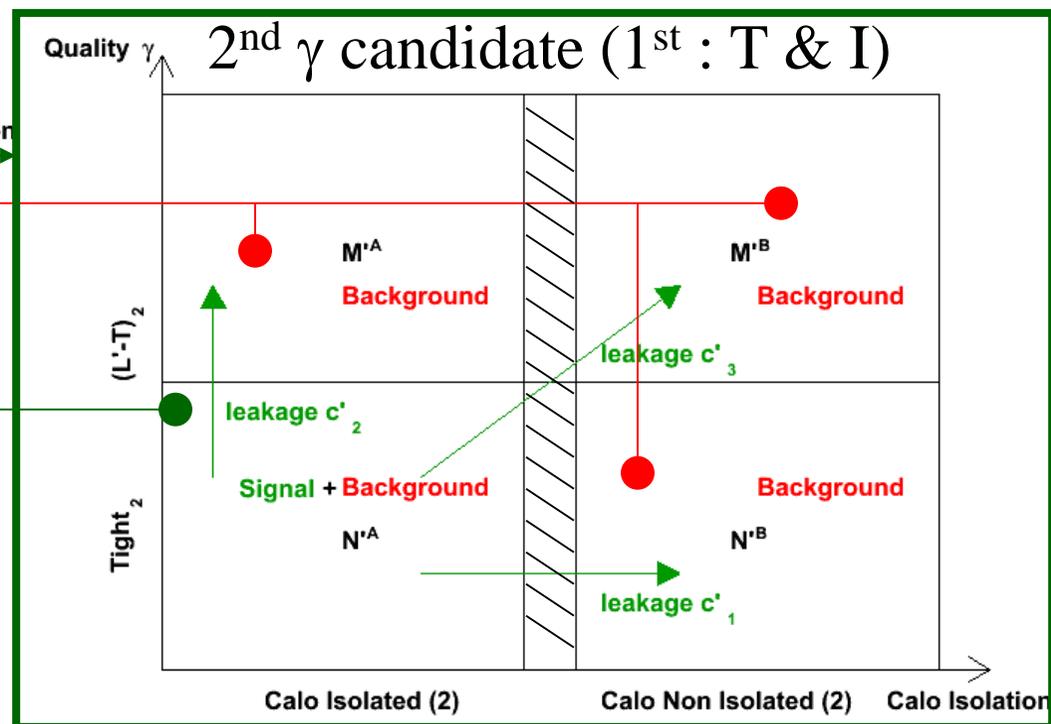
$$(< 1.15)$$

$$N_{\text{bkg}}^A = \left[ (N^B - c_1 N_{\text{sig}}^A) \frac{M^A - c_2 N_{\text{sig}}^A}{M^B - c_3 N_{\text{sig}}^A} \right] \left( \frac{N_{\text{bkg}}^A M_{\text{bkg}}^B}{N_{\text{bkg}}^B M_{\text{bkg}}^A} \right)$$

# 2D-ABCD method



gap region : not considered for the **nominal** measurement



# Background modelling : method

- **Bkg model** : choice of functional forms for  $m_{\gamma\gamma}$
- **Fit a background-only dataset** with model  $\text{bkg} + \text{signal}$

Residual fitted signal: spurious signal ( $n_{\text{sp}}$ )

$-n_{\text{sp}} > 0$  : harder to discover

$-n_{\text{sp}} < 0$  : harder to exclude

Limit on significance (Z) that could never exceeded

$$\frac{S}{\sqrt{B + n_{\text{spurious}}^2}} \xrightarrow{L \rightarrow \infty} \frac{S}{n_{\text{spurious}}}$$

Spurious signal taken as positive (absolute value) : no correction: systematics

- **Test various bkg functional forms** (small variant for low stat MC)

Choose one w/ smallest dof among those respecting criteria on  $|n_{\text{sp}}|$

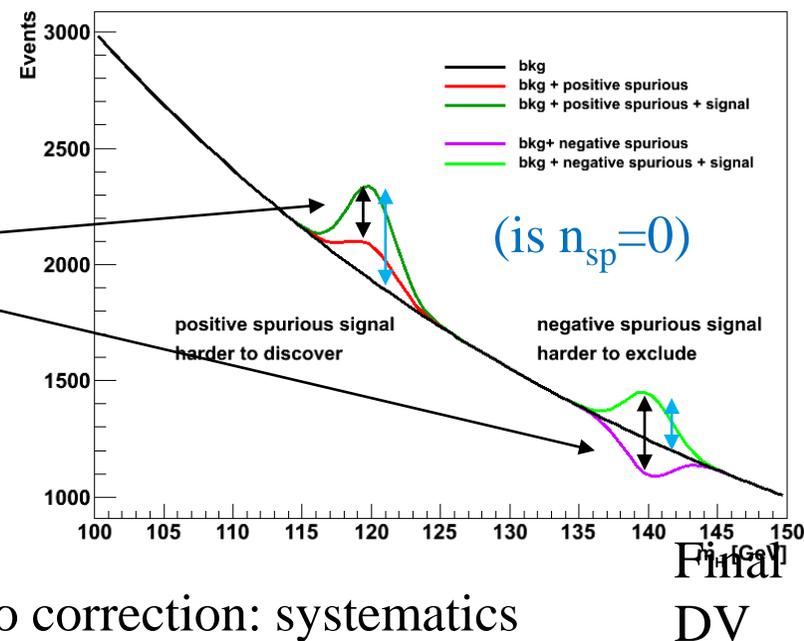
<20 % expected stat. uncertainty on signal

→ too #dofs  $\Leftrightarrow$  bkg model catches all stat. fluctuations: no discovery

<10 % expected signal yield

Spurious signal : max of fitted signal w/ signal model in 121-129 GeV

- **Test chosen functions on data w/ fit on sidebands** (exclude 121-129 GeV) w/ extra dof of same family: computes compatibility  $\chi^2$  (F-test). Reject simpler model if  $p(\chi^2) < 5\%$



# Background modelling

Functional forms for  $m_{\gamma\gamma}$  derived from MCs (or data CRs : ttH categories)

$\gamma\gamma, V\gamma\gamma$  : simulation ;  $\gamma j, jj$  : data CR w/ 1 or 2 photons failing ID or isolation

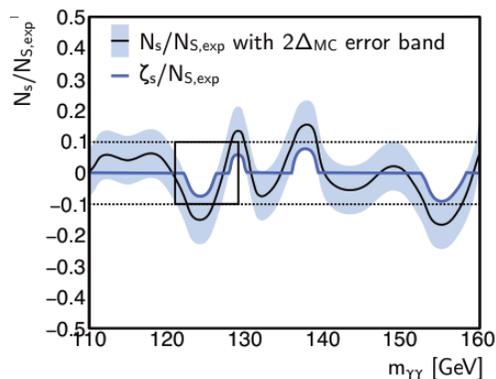
normalization : -rel. contrib from data-driven method (2xABCD method : ID, isol)

$-V\gamma\gamma : \sigma_{th}$

Fit representing bkg dataset w/ S+B model : residual fake signal : spurious signal

→ considered as estimate of bias on bkg model

- Choice of function form : minimize bias among those respecting criteria of selection
- Selection criteria : relaxed spurious signal:



$$\zeta_s(m_{\gamma\gamma}) = \begin{cases} N_s + 2\Delta_{MC}, & N_s + 2\Delta_{MC} < 0 \\ N_s - 2\Delta_{MC}, & N_s - 2\Delta_{MC} > 0 \\ 0, & \text{otherwise} \end{cases}$$

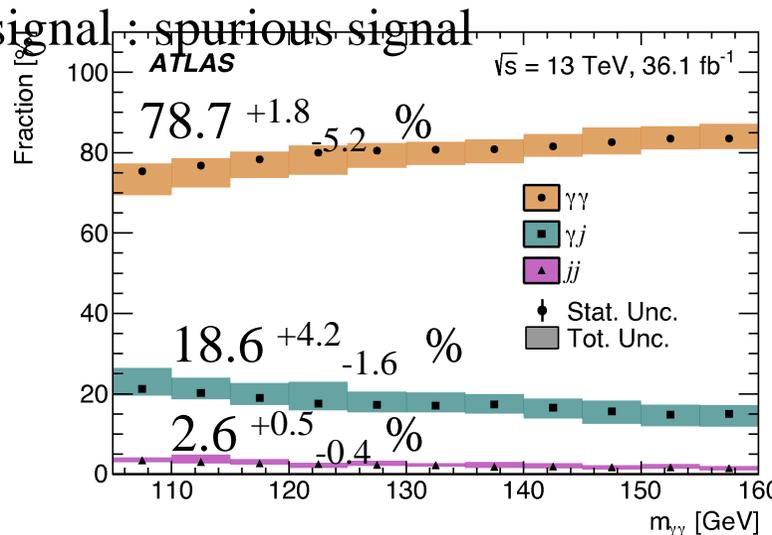
OR {  $\zeta_s < 20\%$  of bkg uncertainty( $m_H$ )  
 $\zeta_s < 10\%$  of expected signal yield( $m_H$ ) }

AND

p-value ( $\chi^2$ )  $> 5\%$ , from toys

null-hyp : current model ; model same family w/ one higher dof  
 if fails : choose model w/ one higher dof

- Spurious signal : maximum fitted signal yield w/  $m_H$  in [121 ; 129 GeV]



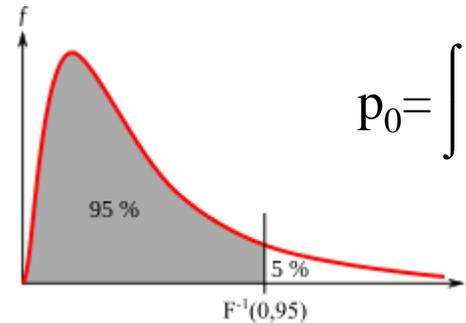
# Background modelling : method

F-test

$$F_{1,2} = \frac{\frac{\chi_1^2 - \chi_2^2}{p_1 - p_2}}{\frac{\chi_2^2}{n - p_2}}$$

$n$  : # bins data

$p_i$  : #dof in bkg model  $i$



$$p_0 = \int_{F_{1,2}}^{\infty} \text{Fischer cumulative}$$

# Systematics

## Signal and background modelling (shape)

- Signal

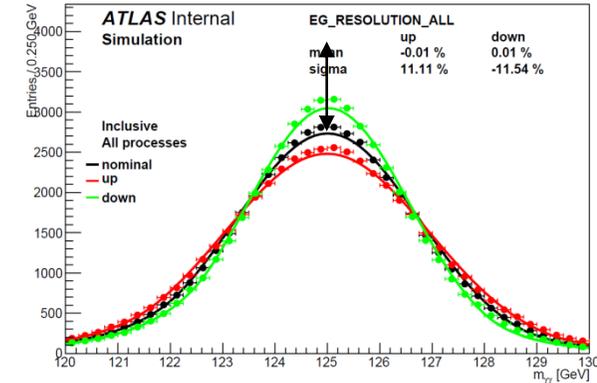
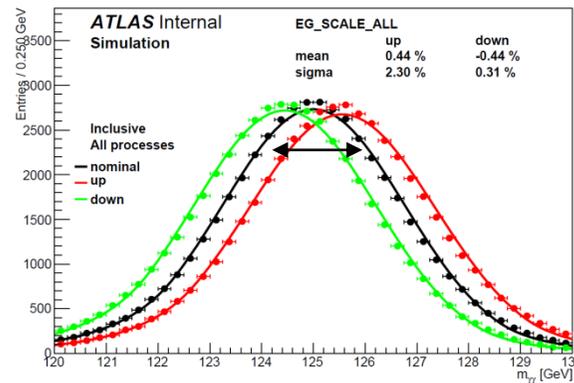
-PES, PER

using new egamma recommendation

PES : shift peak position by 0.21-0.36 %

PER : change width by 6-13 %

Illustrative purpose only



-ATLAS-CMS  $m_H$  : syst=240 MeV  $\Leftrightarrow$  0.19 %

- Background : spurious signal

# Systematics

Experimental efficiencies, acceptance, resolution effects on yield of signal

-Lumi : 3.2 %

-Pile-up

-Trigger : 0.4 %

Photon ID eff

Photon track isolation

B-tagging efficiency

-Electron, muon reco, id, isol.

-eff jVT

Migrations among

-Reco categories

-truth bins

due to calibration systematics :

Photon, jets, leptons

Vary parameters by measured  
uncertainty  
and inject in signal selection  
→ derive changes in signal yields

# Systematics

## Theoretical systematics on signal yields

- Perturbative QCD : change scales

correlate WH and ZH

$ggH : f(p_T^H, \#jets)$

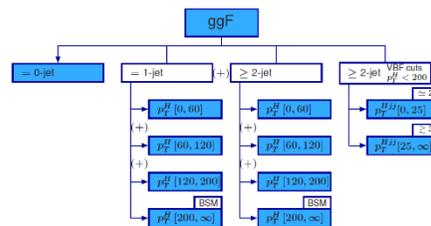
higher for high #jet and high  $p_T$

9 uncertainty sources : 4 on #jets

3 on  $p_T^H$

2 on VBF category :

normalization H+2j, H+≥3j, cut  $\Delta\phi_{\gamma\gamma, jj}$



Process	Perturbative QCD uncertainty [%]
ggF	(±3.9)
9 uncertainty sources	
VBF	+0.4 -0.3
WH	+0.5 -0.7
qq → ZH	+0.5 -0.6
gg → ZH	+25.1 -18.9
ttH	+5.8 -9.2
bbH	+20.1 -23.9
(QCD scale+PDF+ $\alpha_s$ )	
tHjb	+6.5 -14.7
tWH	+4.9 -6.7

- BR

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR>

(PU=Parametrised Uncertainty)  $\left( \begin{matrix} +1.73 \\ -1.72 \end{matrix} \right) \text{(THU)} \begin{matrix} +0.97 \\ -0.94 \end{matrix} \text{(PU}(m_q)) \begin{matrix} +0.66 \\ -0.61 \end{matrix} \text{(PU}(\alpha_s)) \right) \% \quad \Delta BR = \Delta BR + \sqrt{\Delta PU(m_q)^2 + \Delta PU(\alpha_s)^2}$   
 $\rightarrow +2.90_{-2.84} \%$

- Pdfs,  $\alpha_s$  : PDF4LHC15 recommendation

Set : PDF4LHC\_nlo\_30\_as

- UE+PS

Change from Pythia8 vs Herwig7

ggH, VBF, ttH

- ttH : 100 % uncertainty

Cmp data-simulation in ttbb, Wb production

# Systematics

Merging truth bins (QCD systematics)

Takes into account change in the systematics

[https://indico.cern.ch/event/628199/contributions/2565745/attachments/1453458/2242192/HComb\\_merge\\_STXS\\_bins.pdf](https://indico.cern.ch/event/628199/contributions/2565745/attachments/1453458/2242192/HComb_merge_STXS_bins.pdf)

PES : shift peak position between 0.21 % and 0.36 %

PER : change width between 6 and 13 %

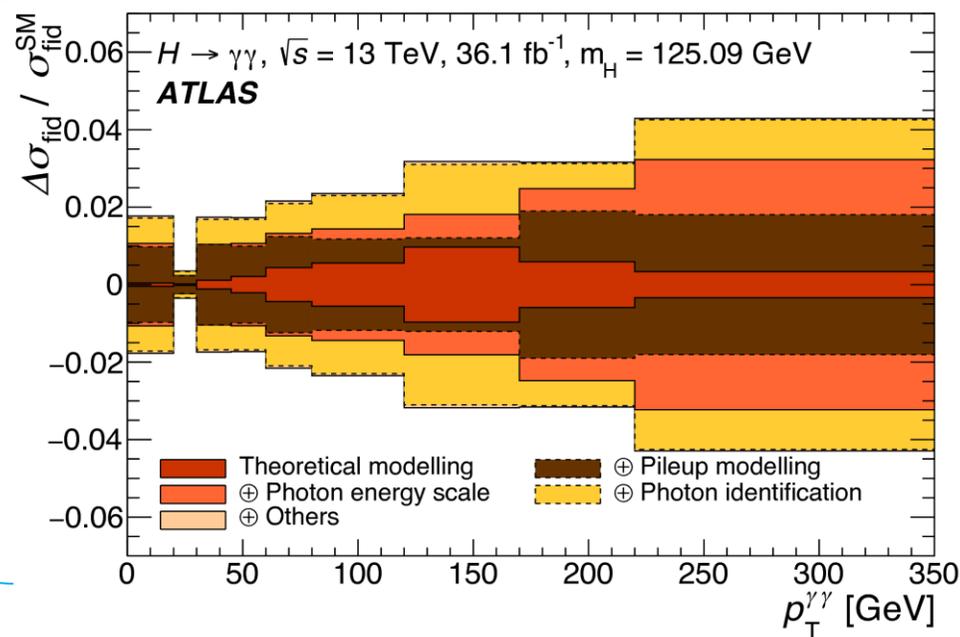
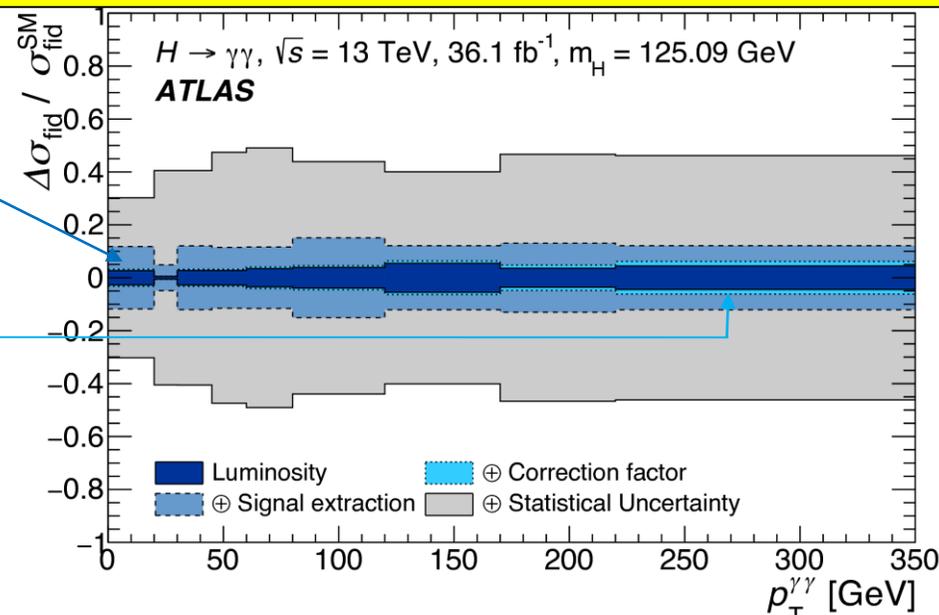
Uncertainty on Higgs mass : 0.24 GeV (LHC ATLAS-CMS)

# Systematics on fiducial cross-sections

$$\sigma_i = \frac{N_i^{\text{sig}}}{c_i \int L dt}$$

Stat uncertainty dominant

(same principle for  $d\sigma_{\text{fid}}/dX$ )



# Statistics model

- Likelihood function

$$L(\mu; \vec{\theta}) = e^{-(\mu s + b)} \frac{(\mu s + b)^n}{n!} \prod_{i=1}^n \mu \frac{s}{s+b} f_s(\{\overrightarrow{DV}_i\}, \vec{\theta}) + \frac{b}{s+b} f_b(\{\overrightarrow{DV}_i\}, \vec{\theta})$$

- Systematics

Gaussian  $X_k(1 + \sigma_k \theta_k)$

Log Normal  $X \exp(\sqrt{\ln(1 + \sigma_k^2 \theta_k)})$  +penalty function

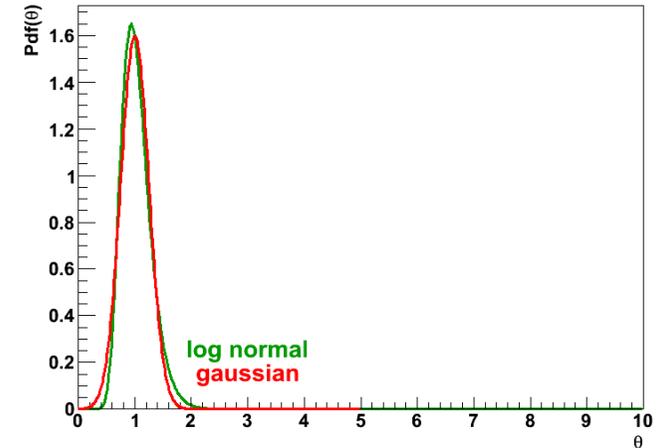
Migration systematics :

$$\left. \begin{array}{l} N_A = N_A^{SM}(1 + \sigma_A \theta) \\ N_B = N_B^{SM}(1 + \sigma_B \theta) \end{array} \right\} N_A \sigma_A - N_B \sigma_B = 0$$

- Test statistics

$$q_\mu = \begin{cases} -2 \ln \lambda(\mu) & 0 \leq \hat{\mu} \leq \mu, \\ -2 \ln 1 = 0 & \hat{\mu} > \mu \end{cases}$$

$$\lambda(\mu) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta}(\mu))}$$



$$L(\mu; \vec{\theta}) = \left\{ \prod_c \left[ \underbrace{\mu \sigma_{BR\epsilon L}}_{n_{sig}^{SM}} \prod_{k \in \vec{\theta}_{sig}} \overbrace{K_k(\theta_k)}^{syst. yield} + \overbrace{n_{sp} \theta_{sp}}^{syst. bkg} \right] Pdf_{sig}^c(\vec{\theta}) + n_{bkg} Pdf_{bkg} \right\} \times Pdf_{cstr}(\vec{\theta})$$

# Cross-sections

(X=observable)

	Integrated (over X) to a phase space (=fiducial volume/region)	differential
Integrated over fiducial & decay	Total: $\sigma_{\text{tot}}$ ●	$d\sigma_{\text{tot}}/dX$ ●
Fiducial (in a decay channel)	$\sigma_{\text{fid}} = \int d\sigma_{\text{fid}}/dX$ '(integrated) fiducial cross-section'	$d\sigma_{\text{fid}}/dX$ ●
STXS (in a decay channel)	$\int d\sigma_{\text{fid}}/dX$ over phase space <u>of Higgs topology</u> 'STXS cross-section'	

[Double differential:  $d^2\sigma/(dX dY)$ ]

Integrated fiducial cross-section:  $\sigma_{\text{fid}}$

Fiducial region:

- closely mimic detector-level selection to reduce model-dependence
- corrections to correct residual changes ('unfolding')
- enriched in a production mode

$$\sigma_{\text{tot}} = n_{\text{sig}} / (\mathbf{L} \mathbf{BR} \alpha \mathbf{c}) = \sigma_{\text{fid}} / (\mathbf{BR} \alpha)$$

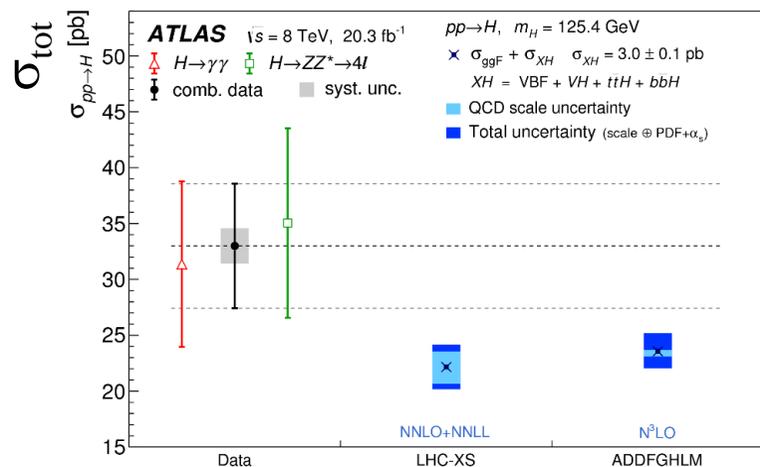
$\alpha$  : fiducial acceptance

$\mathbf{c}$  : correction to truth-level: detector effects :  
reco eff + bin-to-bin migration

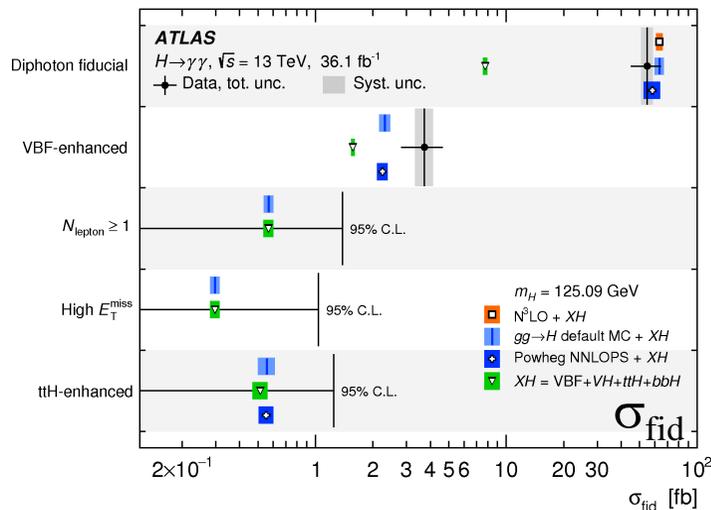
# Cross-sections (flashed)

(X=observable)

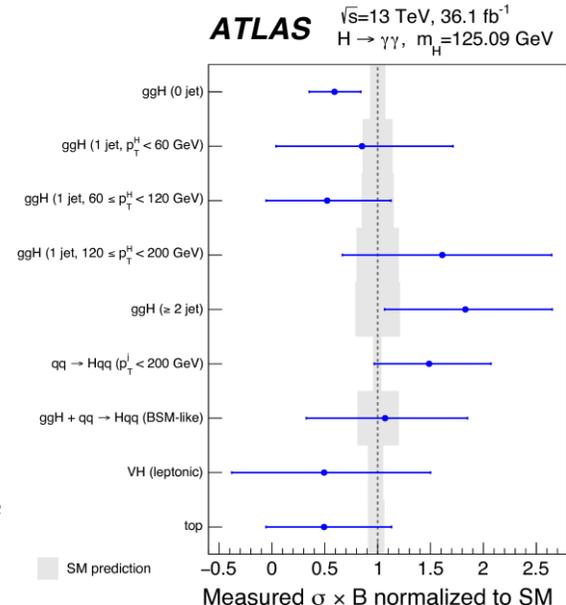
**H**  $\rightarrow \gamma\gamma + H \rightarrow ZZ^* \rightarrow 4l$ ,  
PRL 115, 091801 (2015)



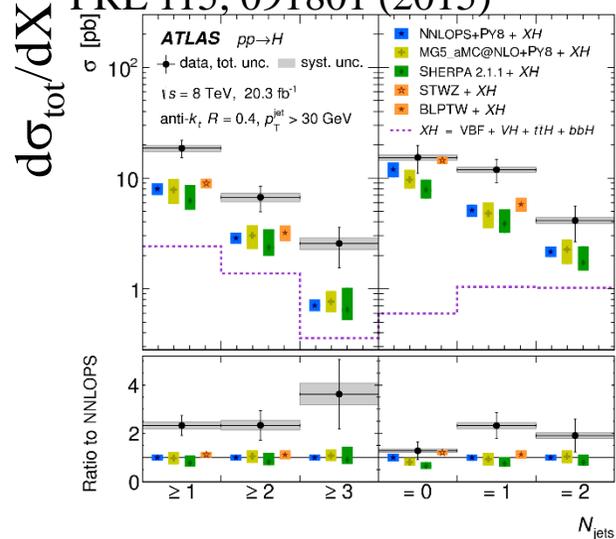
**H**  $\rightarrow \gamma\gamma$ , CERN-EP-2017-288



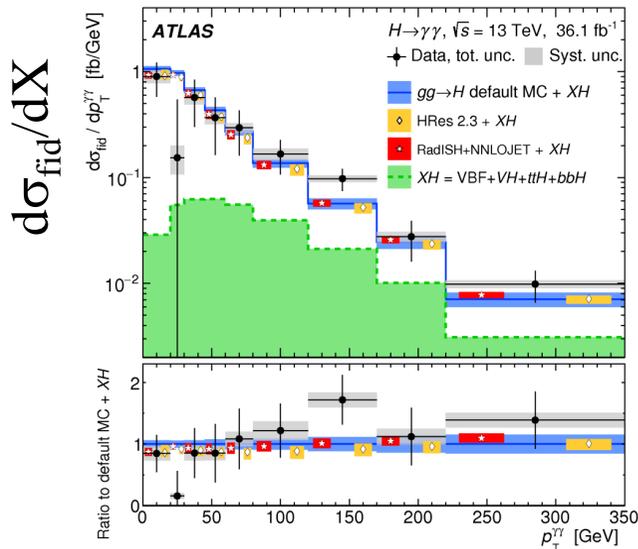
**H**  $\rightarrow \gamma\gamma$ , CERN-EP-2017-288



**H**  $\rightarrow \gamma\gamma + H \rightarrow ZZ^* \rightarrow 4l$ ,  
PRL 115, 091801 (2015)



**H**  $\rightarrow \gamma\gamma$ , CERN-EP-2017-288



$\int d\sigma_{\text{fid}}/dX$

# Fiducial region: mimic detector-level

Particle-level

Objects	Definition
Photons	$ \eta  < 1.37$ or $1.52 <  \eta  < 2.37$ , $p_T^{\text{iso},0.2} / p_T^\gamma < 0.05$
Jets	anti- $k_t$ , $R = 0.4$ , $p_T > 30$ GeV, $ y  < 4.4$
Leptons, $\ell$	$e$ or $\mu$ , $p_T > 15$ GeV, $ \eta  < 2.47$ for $e$ (excluding $1.37 <  \eta  < 1.52$ ) and $ \eta  < 2.7$ for $\mu$

Reco-level

photons,  $|\eta| < 2.37$ , exclude crack  $1.37 < |\eta| < 1.52$   
 $E_T / m_{\gamma\gamma} > 0.35, 0.25$ , tight ID, isolated(calorimeter+track)  
 Calo : Topo  $E_T$  cone 20  $< 0.065 \times E_T$  ('FixedCutLoose')  
 Trk : Pt cone 20 :  $< 0.05 \times E_T$

Jets, AntiKt4EMTopoJets,  $p_T > 25$  GeV ( $|\eta| < 2.4$ ), then  $p_T > 30$  GeV  
 Kills jets not originating from primary vertex :  $JVT > 0.59$ ,  $|y| < 4.4$   
 (JVT : 2D likelihood : corr JVF + ratio { $p_T$  trk /  $p_T$  jet}  
 B-tagging : MV2c10 tagger, efficiency : 70 %; rej. jets : c: 12; light : 380

Electrons,  $p_T > 10$  GeV,  $|\eta| < 2.47$ , remove crack  $1.37 < |\eta| < 1.52$   
 Distance wrt PV :  $|d_0 / \sigma(d_0)| < 5$ ,  $|z_0 \sin \theta| < 0.5$  mm  
 -SF applied (J/ $\psi$ , Y), ID : Medium LH, Isolation (calorimeter+track)  
 'Topoetcone20  $< 0.02 \times p_T$  ; Trk : Pt cone 20 :  $< 0.15 \times E_T$

Muons,  $p_T > 10$  GeV,  $|\eta| < 2.7$   
 Distance wrt PV :  $|d_0 / \sigma(d_0)| < 3$ ,  $|z_0 \sin \theta| < 0.5$  mm  
 medium quality, GradientLoose isolation (comb. eff. 25 GeV ~ 95 %)

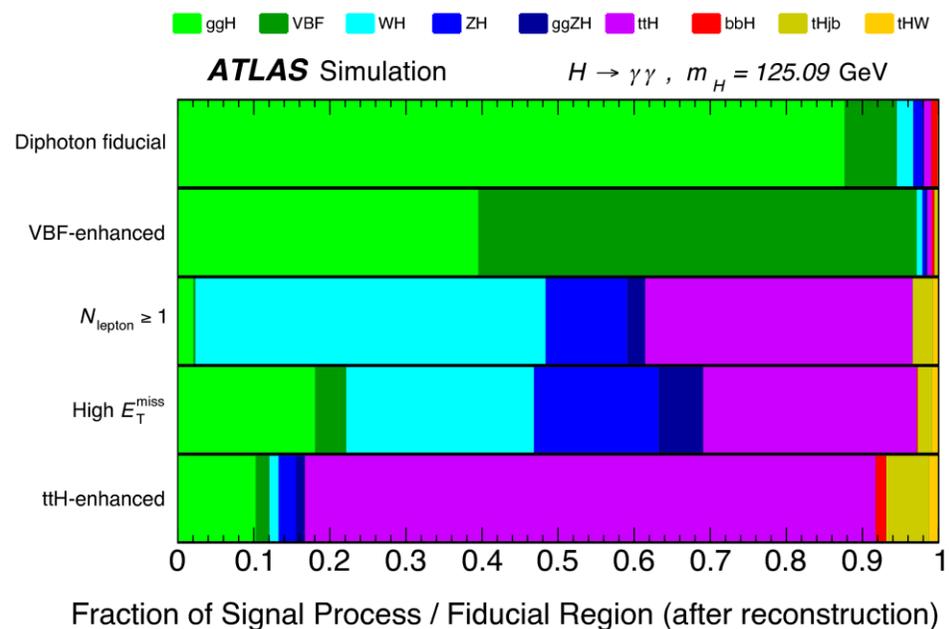
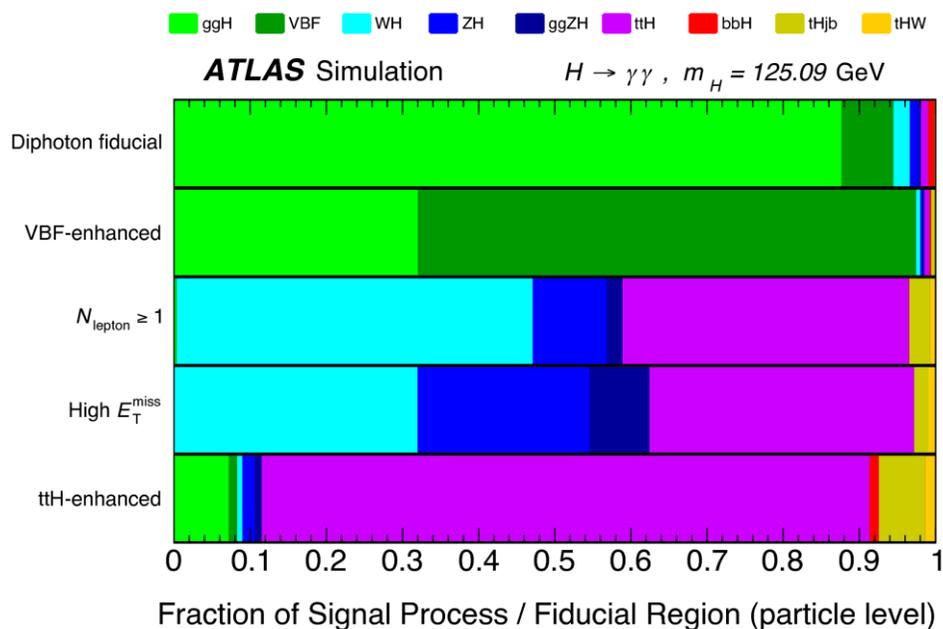
# Fiducial region: mimic detector-level

$c_i = 0.75 \pm 0.03$   
(~PID & isolation)

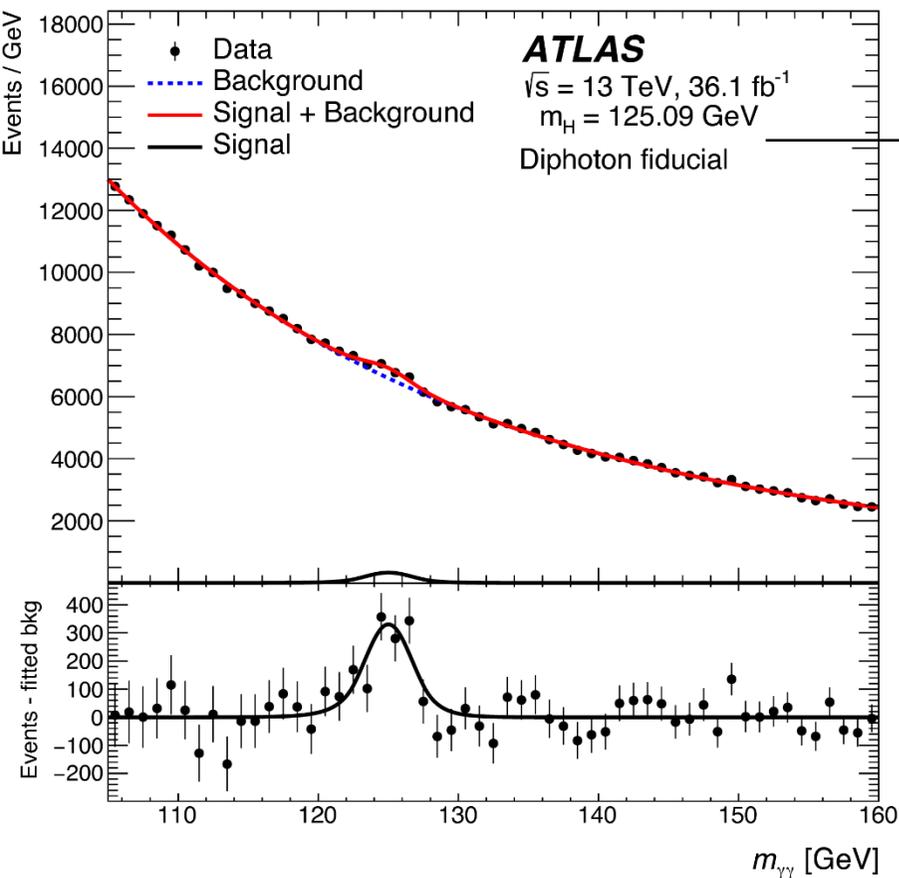
Fiducial region	Definition
Diphoton fiducial	$N_\gamma \geq 2$ , $p_T^{\gamma 1} > 0.35 m_{\gamma\gamma} = 43.8 \text{ GeV}$ , $p_T^{\gamma 2} > 0.25 m_{\gamma\gamma} = 31.3 \text{ GeV}$
VBF-enhanced	Diphoton fiducial, $N_j \geq 2$ with $p_T^{\text{jet}} > 25 \text{ GeV}$ , $m_{jj} > 400 \text{ GeV}$ , $ \Delta y_{jj}  > 2.8$ , $ \Delta\phi_{\gamma\gamma, jj}  > 2.6$
$N_{\text{lepton}} \geq 1$	Diphoton fiducial, $N_\ell \geq 1$
High $E_T^{\text{miss}}$	Diphoton fiducial, $E_T^{\text{miss}} > 80 \text{ GeV}$ , $p_T^{\gamma\gamma} > 80 \text{ GeV}$
$t\bar{t}H$ -enhanced	Diphoton fiducial, $(N_j \geq 4, N_{b\text{-jets}} \geq 1)$ or $(N_j \geq 3, N_{b\text{-jets}} \geq 1, N_\ell \geq 1)$

$m_{\gamma\gamma} \in [105 ; 160] \text{ GeV}$

Very close expected composition at truth and reco level



# Fiducial cross-sections: results



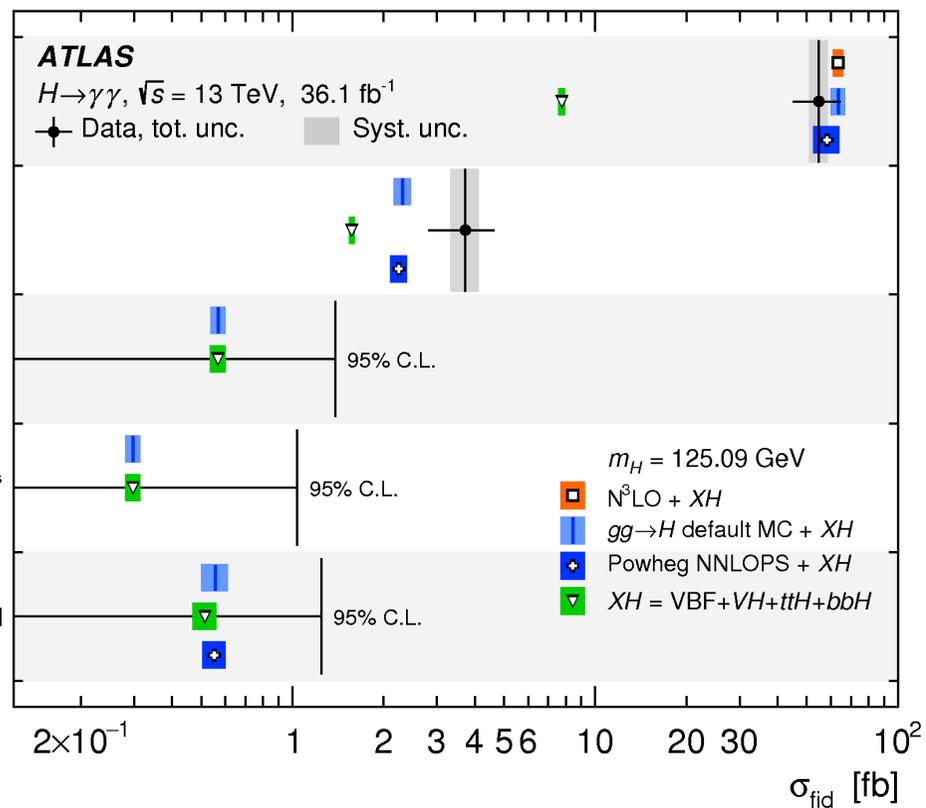
Diphoton fiducial

VBF-enhanced

$N_{\text{lepton}} \geq 1$

High  $E_T^{\text{miss}}$

ttH-enhanced



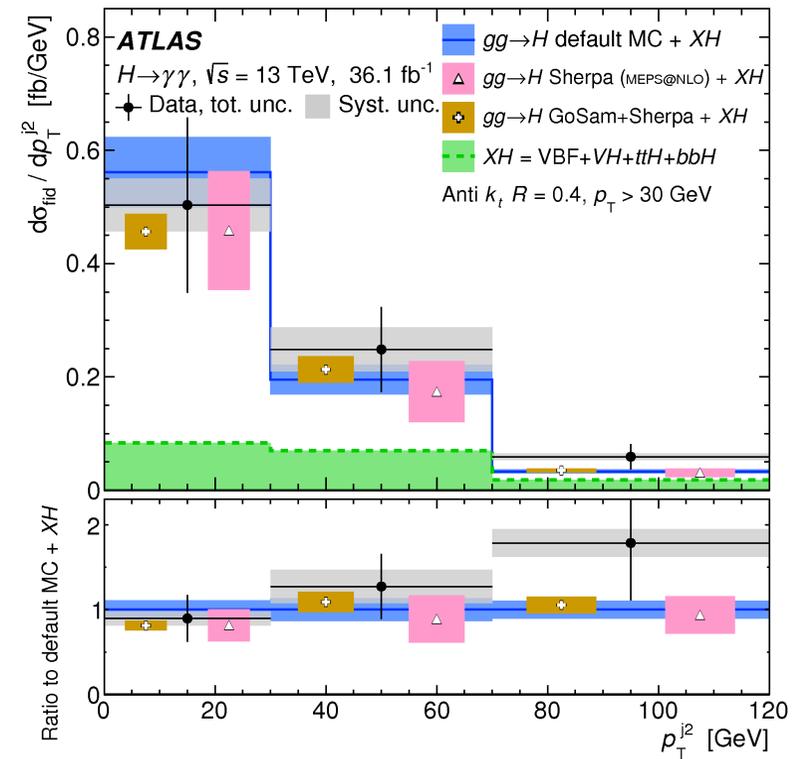
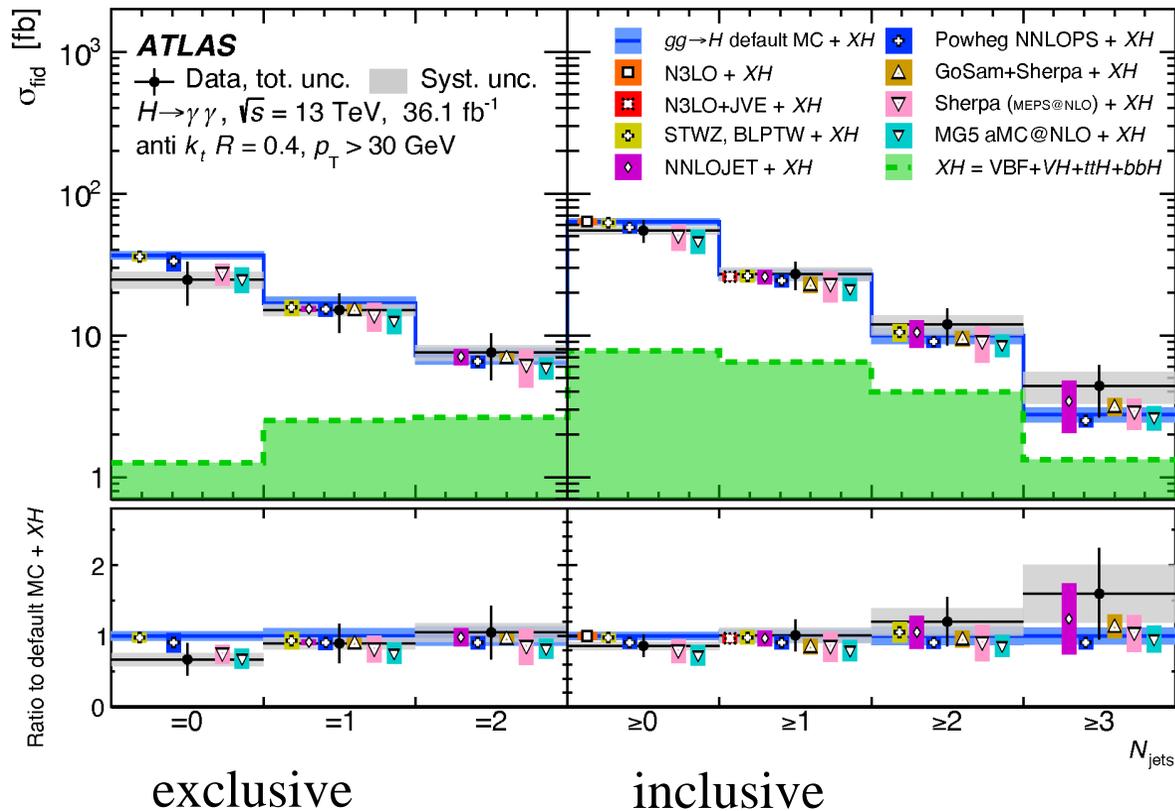
To merge with page 17 top ?

Differential cross-sections results: an example in next slide

# Jets multiplicities and kinematics

**Motivation:** theory modelling, contributions production modes

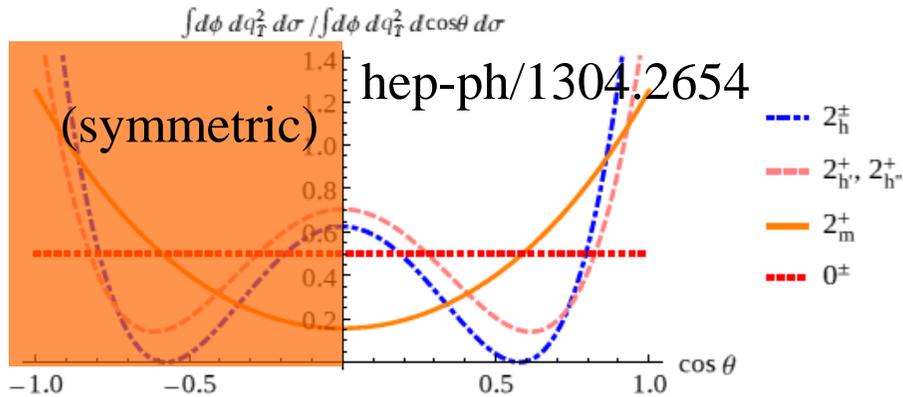
- $N_{\text{jets}}$  : ggH :  $\approx 0, 1$  jet ; VBF, WH, ZH:  $\geq 2$ -jets ; ttH:  $>2$ -jets, high for BSM scenarios
- $p_T^{j1}, p_T^{j2}, |y_{j1}|, H_T$  (scalar  $\Sigma_j p_T$ )



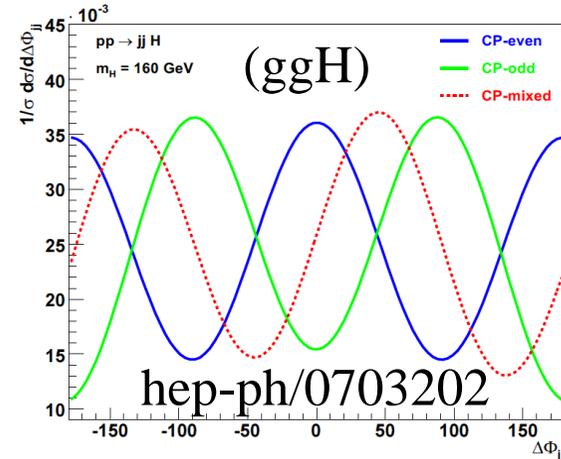


# Spin-CP variables: $J^{PC}$

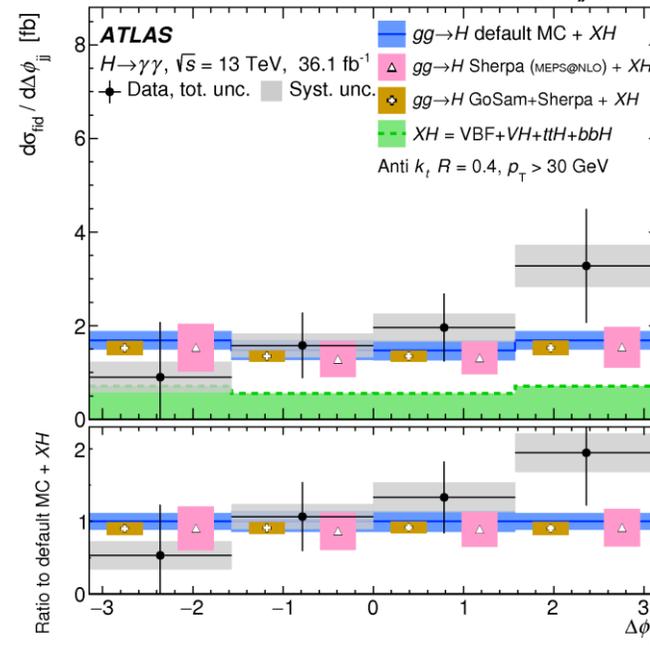
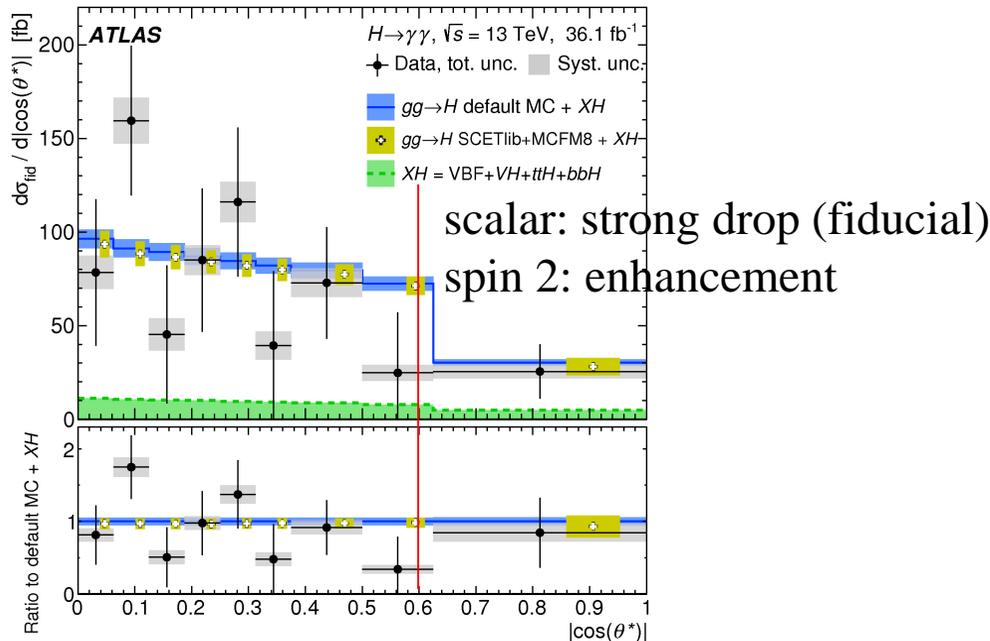
- $|\cos \theta^*|$ : polar angle: spin (J)



- $\Delta\phi_{jj}$ : azimuthal angle: quantum number CP



VBF: ~flat,  
slight increase at  
 $\pm\pi$



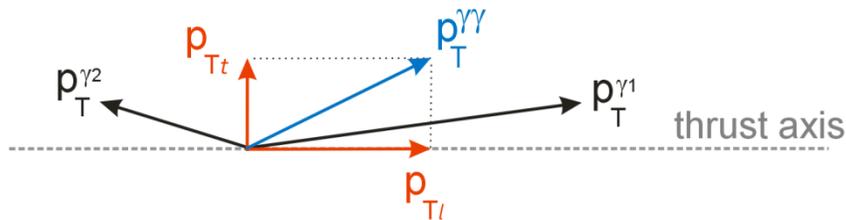
Consistent with  $J=0, PC=+$

# Additional

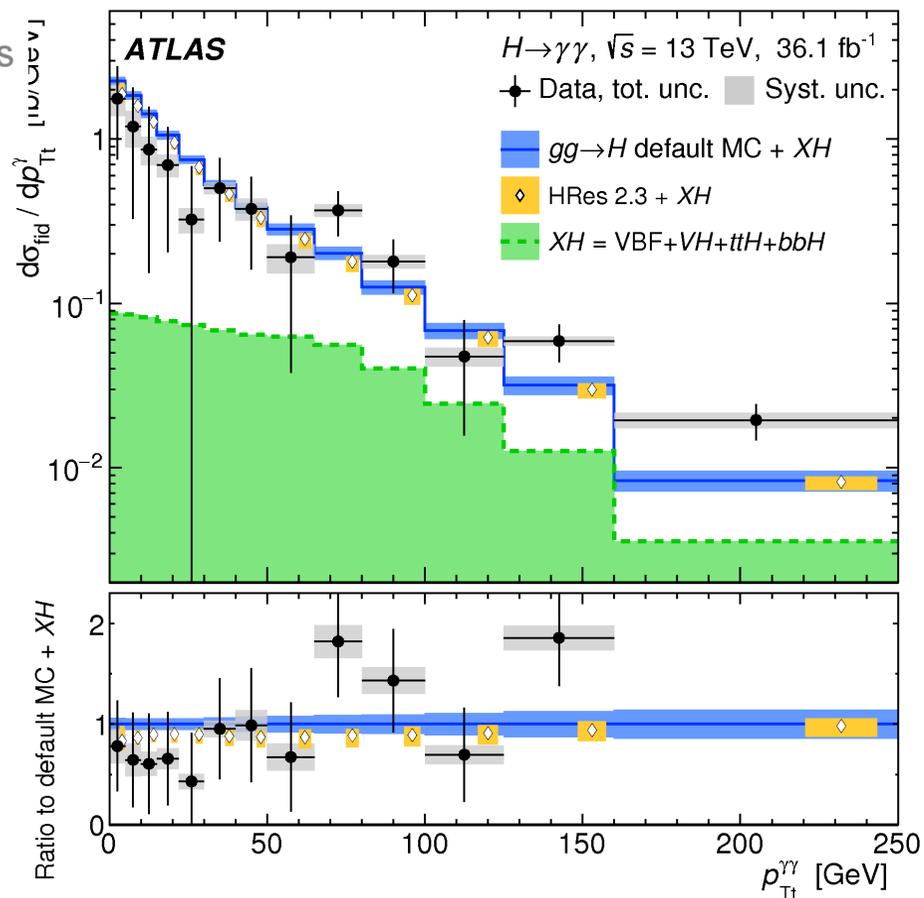
- $p_{T\gamma\gamma}$  category used historically for fermiophobic analysis  
drawback : turn-on effect on invariant mass

$$\hat{t} = (\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}) / |\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}|$$

- new variable :  $p_{Tt}$  : transverse projection of  $p_{T\gamma\gamma}$  on thrust axis



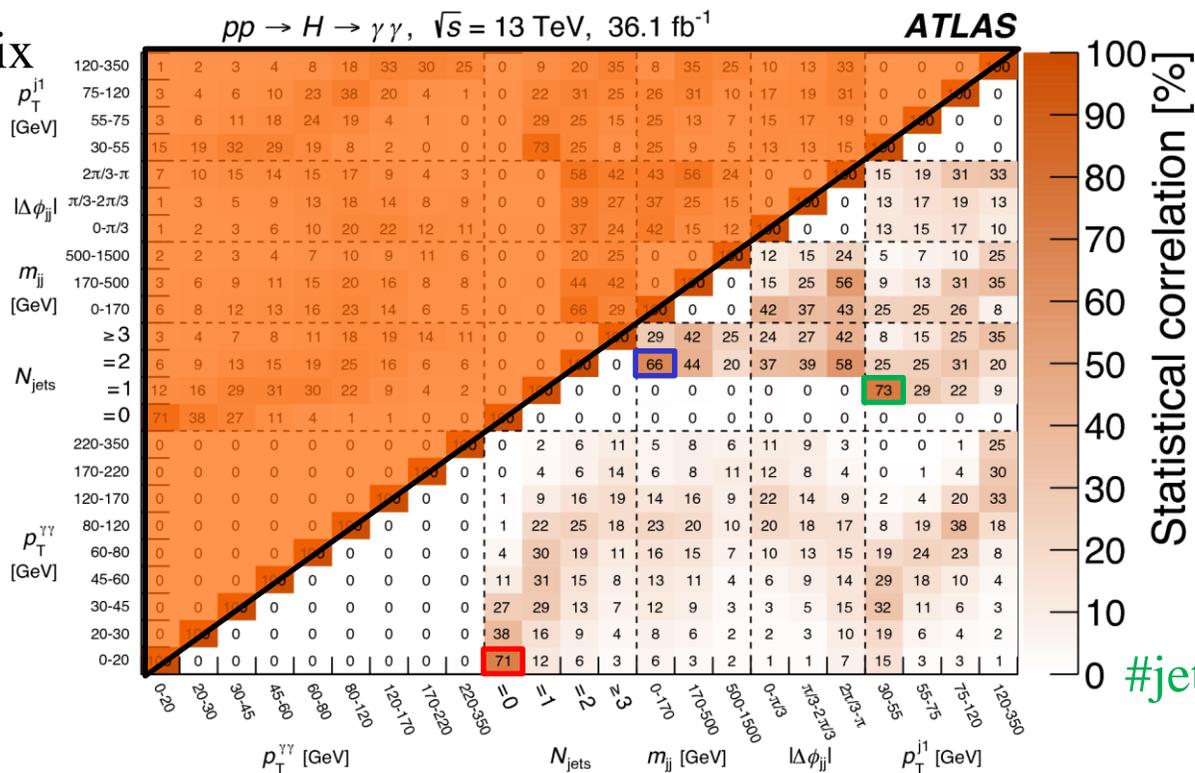
$p_{Tt}^{\gamma\gamma}$  : transverse component on thrust axis ( $\gamma_1$ - $\gamma_2$ )



# Correlations

Statistics correlations of Higgs cross-sections

Diagonal matrix

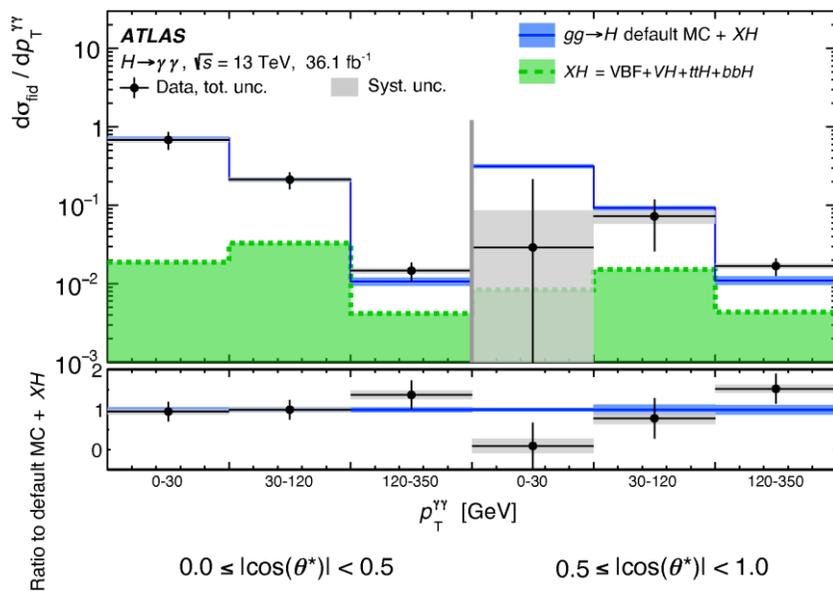
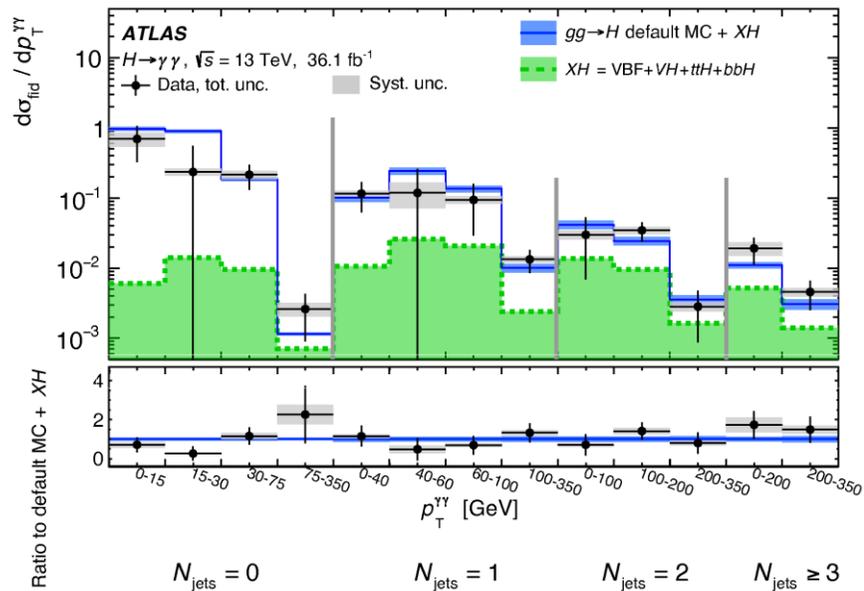


Low  $\#jet \Leftrightarrow$  low balance  $p_T^H$

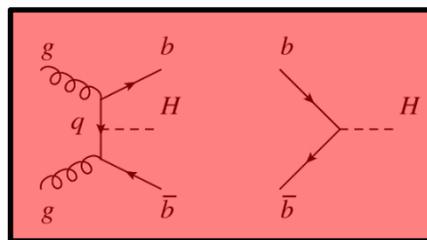
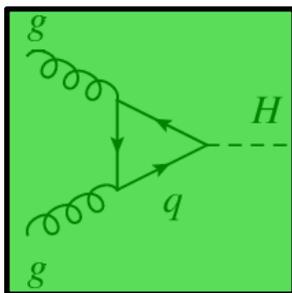
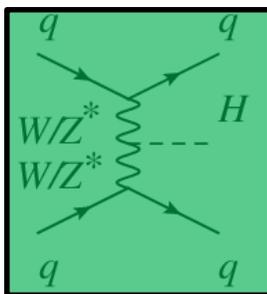
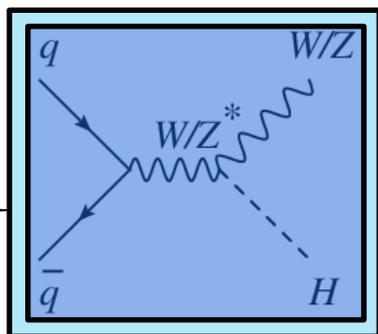
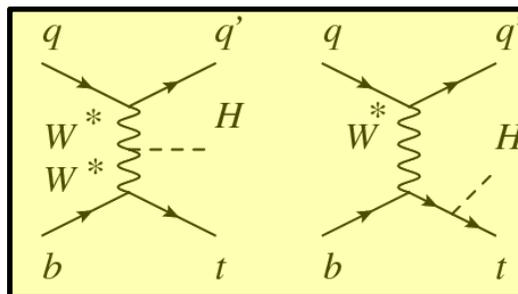
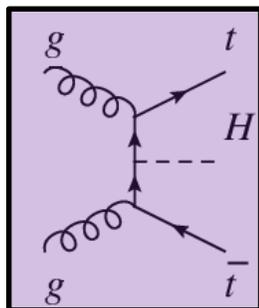
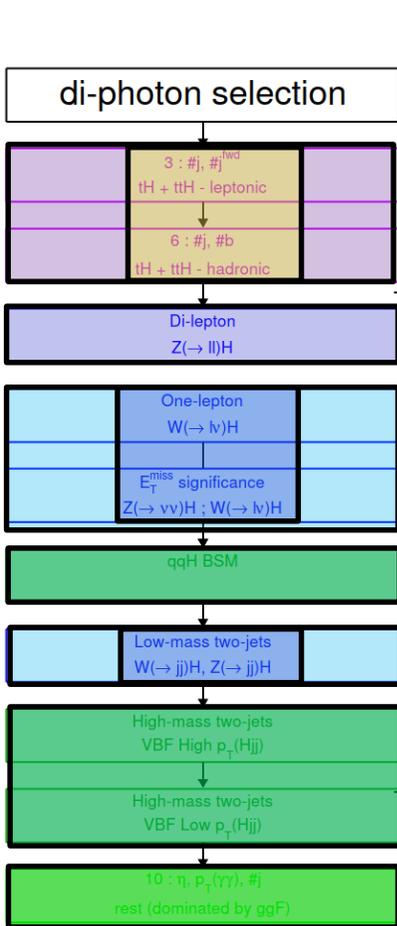
2 jets  $\Leftrightarrow m_{jj}$

- Correlations  $\geq 0$ : change of #events in a bin of given observable
  - Decrease in other bins of same observable : exactly null correlation (mutually exclusive bins)
  - change of #events in other observables in same direction: positive correlation
- (if shape of distribution of observable would have been measured, there would be a global normalisation, then there would be negative correlations for various bins of a given observable)

# Double differential

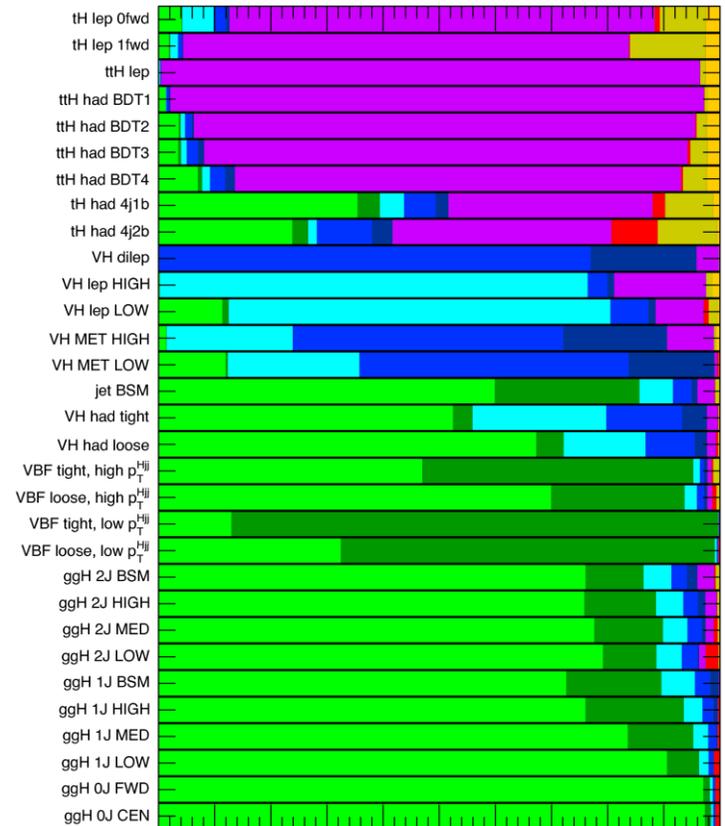


# Production modes categorization (flashed)



Legend for signal processes: ggH (green), VBF (dark green), WH (cyan), ZH (blue), ggZH (dark blue), ttH (magenta), bbH (red), tHq (yellow-green), tHW (yellow).

**ATLAS Simulation**  $H \rightarrow \gamma\gamma, m_H = 125.09 \text{ GeV}$

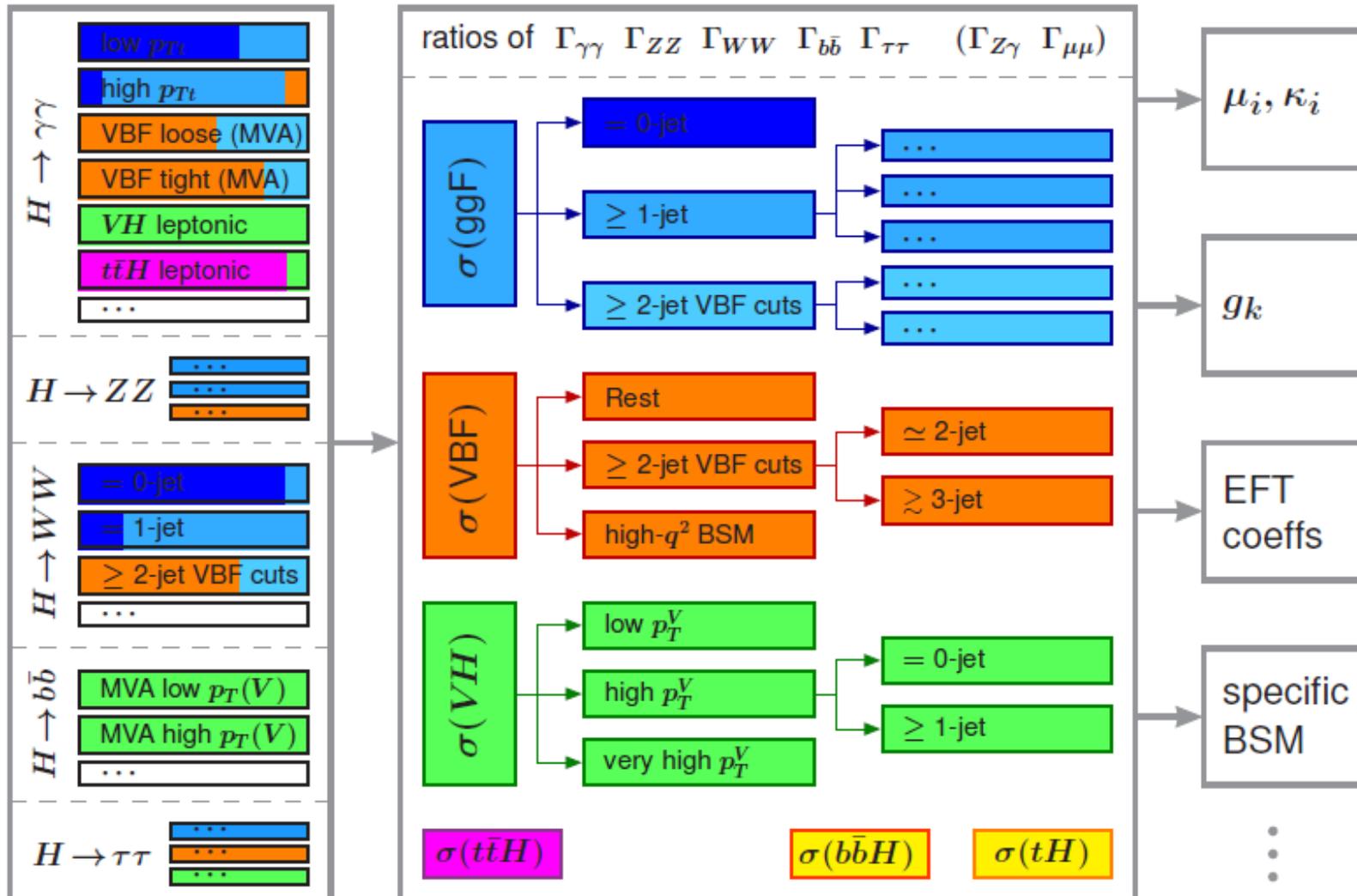


0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1  
Fraction of Signal Process / Category

# STXS : illustration

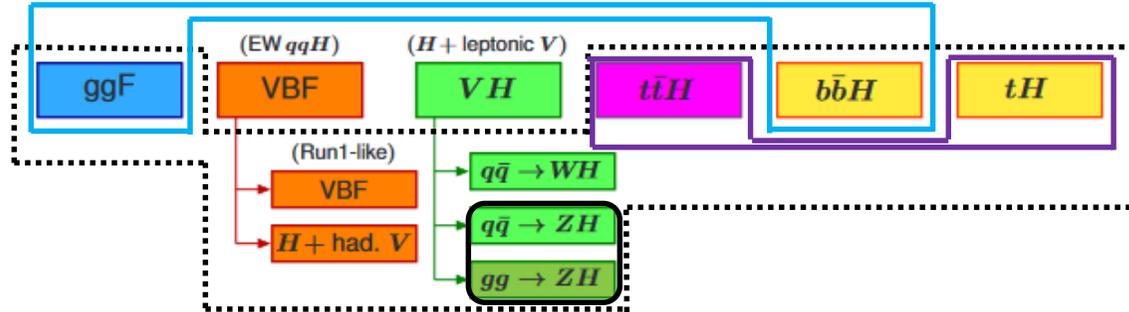
Various channels

Topology of the ‘mother’ (=H) of the channels  
 → allow combination



# STXS 'stage 0'

- Stage 0 : truth bins probed :  merged : 

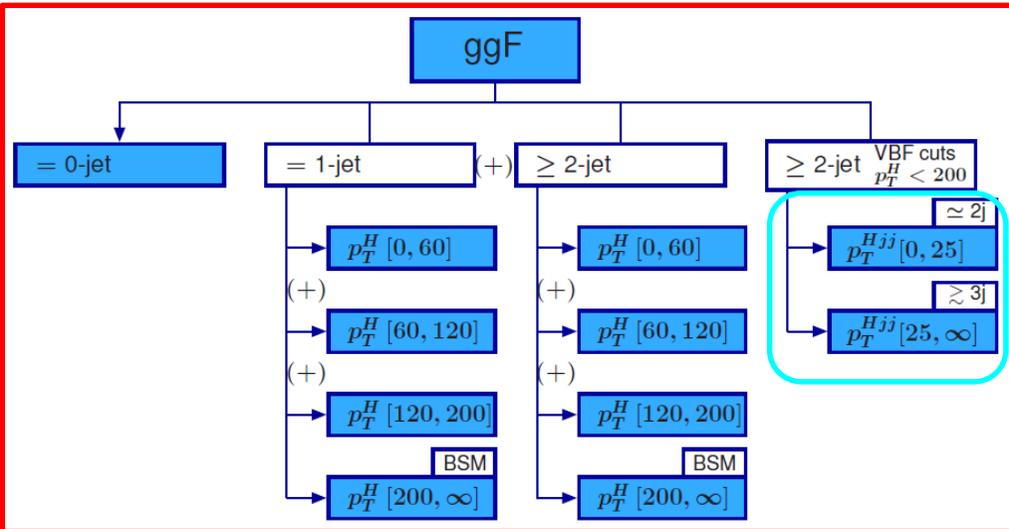


# STXS ‘strong merging’

merging

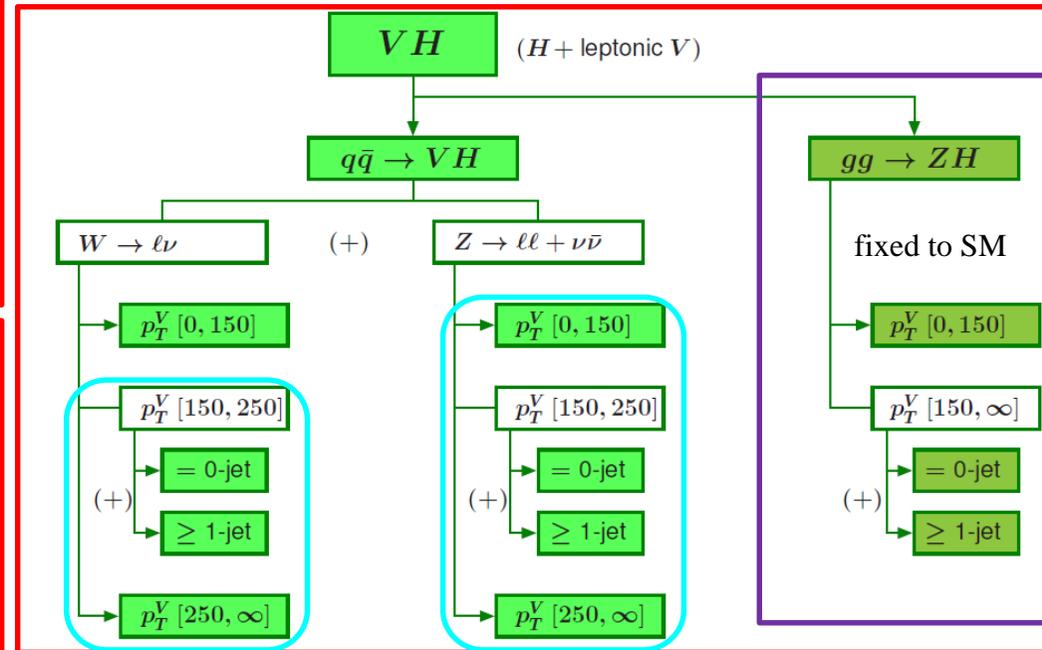
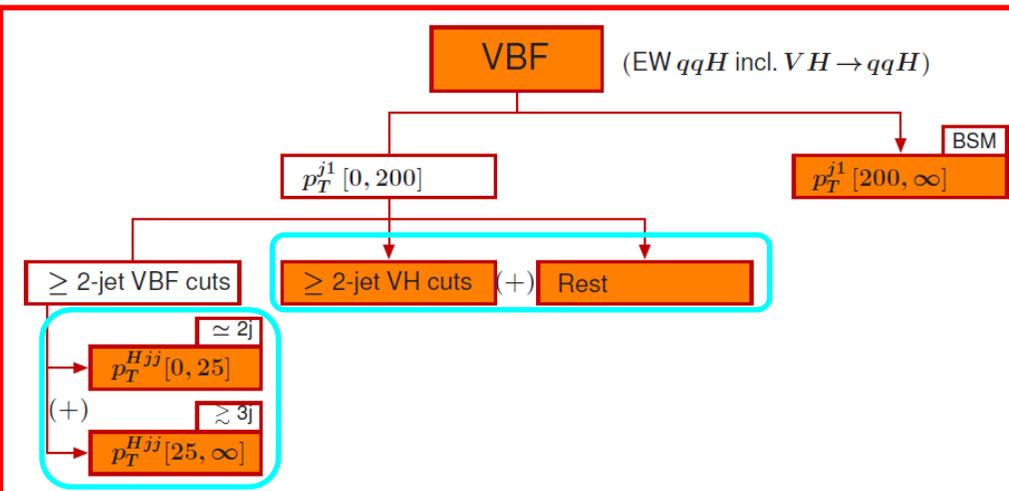
Process	Measurement region	Particle-level stage-1 region
ggH + gg → Z(→ qq)H	0-jet	0-jet
	1-jet, $p_T^H < 60 \text{ GeV}$ 1-jet, $60 \leq p_T^H < 120 \text{ GeV}$ 1-jet, $120 \leq p_T^H < 200 \text{ GeV}$ $\geq 1\text{-jet}, p_T^H > 200 \text{ GeV}$  $\geq 2\text{-jet}, p_T^H < 200 \text{ GeV}$ or VBF-like	1-jet, $p_T^H < 60 \text{ GeV}$ 1-jet, $60 \leq p_T^H < 120 \text{ GeV}$ 1-jet, $120 \leq p_T^H < 200 \text{ GeV}$ 1-jet, $p_T^H > 200 \text{ GeV}$ $\geq 2\text{-jet}, p_T^H > 200 \text{ GeV}$ $\geq 2\text{-jet}, p_T^H < 60 \text{ GeV}$ $\geq 2\text{-jet}, 60 \leq p_T^H < 120 \text{ GeV}$ $\geq 2\text{-jet}, 120 \leq p_T^H < 200 \text{ GeV}$ VBF-like, $p_T^{Hjj} < 25 \text{ GeV}$ VBF-like, $p_T^{Hjj} \geq 25 \text{ GeV}$
qq' → Hqq' (VBF + VH)	$p_T^j < 200 \text{ GeV}$	$p_T^j < 200 \text{ GeV}$ , VBF-like, $p_T^{Hjj} < 25 \text{ GeV}$ $p_T^j < 200 \text{ GeV}$ , VBF-like, $p_T^{Hjj} \geq 25 \text{ GeV}$ $p_T^j < 200 \text{ GeV}$ , VH-like $p_T^j < 200 \text{ GeV}$ , Rest
	$p_T^j > 200 \text{ GeV}$	$p_T^j > 200 \text{ GeV}$
VH (leptonic decays)	VH leptonic	$q\bar{q} \rightarrow ZH, p_T^Z < 150 \text{ GeV}$ $q\bar{q} \rightarrow ZH, 150 < p_T^Z < 250 \text{ GeV}$ , 0-jet $q\bar{q} \rightarrow ZH, 150 < p_T^Z < 250 \text{ GeV}$ , $\geq 1\text{-jet}$ $q\bar{q} \rightarrow ZH, p_T^Z > 250 \text{ GeV}$ $q\bar{q} \rightarrow WH, p_T^W < 150 \text{ GeV}$ $q\bar{q} \rightarrow WH, 150 < p_T^W < 250 \text{ GeV}$ , 0-jet $q\bar{q} \rightarrow WH, 150 < p_T^W < 250 \text{ GeV}$ , $\geq 1\text{-jet}$ $q\bar{q} \rightarrow WH, p_T^W > 250 \text{ GeV}$ $gg \rightarrow ZH, p_T^Z < 150 \text{ GeV}$ $gg \rightarrow ZH, p_T^Z > 150 \text{ GeV}$ , 0-jet $gg \rightarrow ZH, p_T^Z > 150 \text{ GeV}$ , $\geq 1\text{-jet}$
Top-associated production	top	$t\bar{t}H$ W-associated $tH$ ( $tHW$ ) t-channel $tH$ ( $tHq$ )
$b\bar{b}H$	merged w/ ggH	$b\bar{b}H$

# STXS weak merging



(‘+’ means ‘merge if not enough statistics’)

Purple : merging that is chosen so far)



$t\bar{t}H$

$b\bar{b}H$

fixed to SM

$tH$

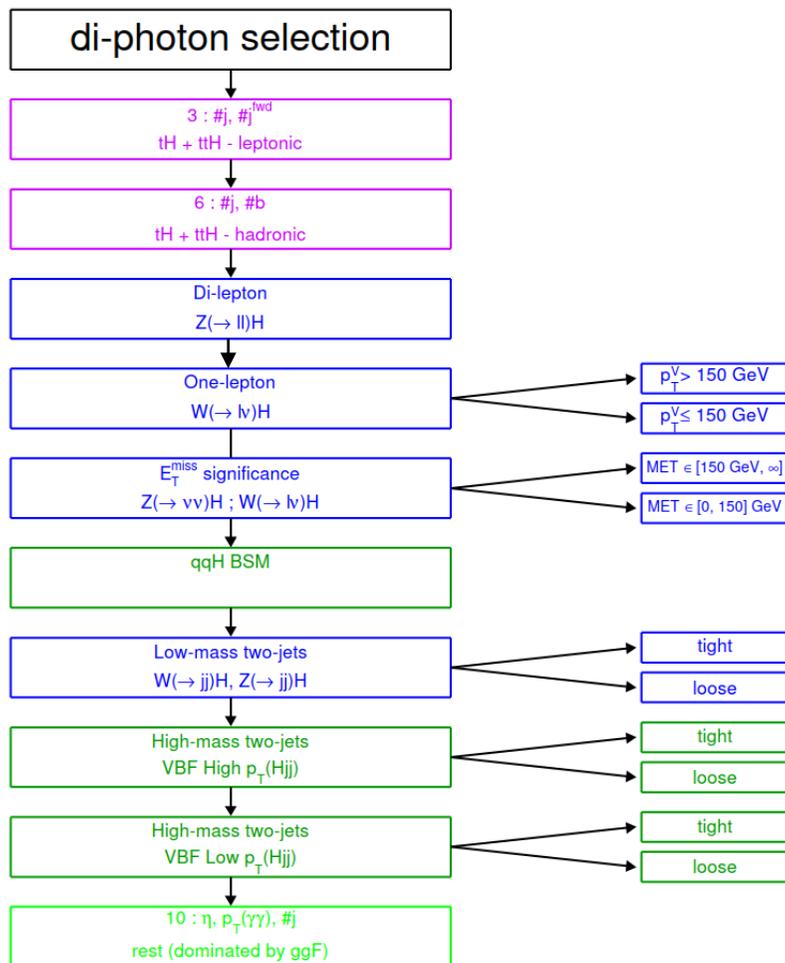
fixed to SM

# Categorization

Categorization optimized in order to highest granularity of STXS stage 1

31 categories

From the most rare to the least rare  
(to reduce contamination)



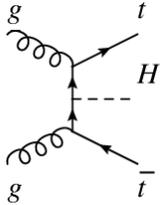
Category	Selection	
tH lep 0fwd	$N_{\text{lep}} = 1, N_{\text{jets}}^{\text{cen}} \leq 3, N_{b\text{-tag}} \geq 1, N_{\text{jets}}^{\text{fwd}} = 0 (p_T^{\text{jet}} > 25 \text{ GeV})$	tH
tH lep 1fwd	$N_{\text{lep}} = 1, N_{\text{jets}}^{\text{cen}} \leq 4, N_{b\text{-tag}} \geq 1, N_{\text{jets}}^{\text{fwd}} \geq 1 (p_T^{\text{jet}} > 25 \text{ GeV})$	
ttH lep	$N_{\text{lep}} \geq 1, N_{\text{jets}}^{\text{cen}} \geq 2, N_{b\text{-tag}} \geq 1, Z_{\ell\ell} \text{ veto } (p_T^{\text{jet}} > 25 \text{ GeV})$	
ttH had BDT1	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, \text{BDT}_{\text{ttH}} > 0.92$	ttH
ttH had BDT2	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.83 < \text{BDT}_{\text{ttH}} < 0.92$	
ttH had BDT3	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.79 < \text{BDT}_{\text{ttH}} < 0.83$	
ttH had BDT4	$N_{\text{lep}} = 0, N_{\text{jets}} \geq 3, N_{b\text{-tag}} \geq 1, 0.52 < \text{BDT}_{\text{ttH}} < 0.79$	
tH had 4j1b	$N_{\text{lep}} = 0, N_{\text{jets}}^{\text{cen}} = 4, N_{b\text{-tag}} = 1 (p_T^{\text{jet}} > 25 \text{ GeV})$	tH
tH had 4j2b	$N_{\text{lep}} = 0, N_{\text{jets}}^{\text{cen}} = 4, N_{b\text{-tag}} \geq 2 (p_T^{\text{jet}} > 25 \text{ GeV})$	
VH dilep	$N_{\text{lep}} \geq 2, 70 \text{ GeV} \leq m_{\ell\ell} \leq 110 \text{ GeV}$	
VH lep High	$N_{\text{lep}} = 1,  m_{e\gamma} - 89 \text{ GeV}  > 5 \text{ GeV}, p_T^{\ell+E_T^{\text{miss}}} > 150 \text{ GeV}$	
VH lep Low	$N_{\text{lep}} = 1,  m_{e\gamma} - 89 \text{ GeV}  > 5 \text{ GeV}, p_T^{\ell+E_T^{\text{miss}}} < 150 \text{ GeV}, E_T^{\text{miss}} \text{ significance} > 1$	
VH MET High	$150 \text{ GeV} < E_T^{\text{miss}} < 250 \text{ GeV}, E_T^{\text{miss}} \text{ significance} > 9 \text{ or } E_T^{\text{miss}} > 250 \text{ GeV}$	
VH MET Low	$80 \text{ GeV} < E_T^{\text{miss}} < 150 \text{ GeV}, E_T^{\text{miss}} \text{ significance} > 8$	
jet BSM	$p_{T,j1} > 200 \text{ GeV}$	
VH had tight	$60 \text{ GeV} < m_{jj} < 120 \text{ GeV}, \text{BDT}_{\text{VH}} > 0.78$	
VH had loose	$60 \text{ GeV} < m_{jj} < 120 \text{ GeV}, 0.35 < \text{BDT}_{\text{VH}} < 0.78$	
VBF tight, high $p_T^{Hjj}$	$ \Delta\eta_{jj}  > 2,  \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})  < 5, p_T^{Hjj} > 25 \text{ GeV}, \text{BDT}_{\text{VBF}} > 0.47$	
VBF loose, high $p_T^{Hjj}$	$ \Delta\eta_{jj}  > 2,  \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})  < 5, p_T^{Hjj} > 25 \text{ GeV}, -0.32 < \text{BDT}_{\text{VBF}} < 0.47$	
VBF tight, low $p_T^{Hjj}$	$ \Delta\eta_{jj}  > 2,  \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})  < 5, p_T^{Hjj} < 25 \text{ GeV}, \text{BDT}_{\text{VBF}} > 0.87$	
VBF loose, low $p_T^{Hjj}$	$ \Delta\eta_{jj}  > 2,  \eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})  < 5, p_T^{Hjj} < 25 \text{ GeV}, 0.26 < \text{BDT}_{\text{VBF}} < 0.87$	
ggH 2J BSM	$\geq 2 \text{ jets}, p_T^{\gamma\gamma} \geq 200 \text{ GeV}$	
ggH 2J High	$\geq 2 \text{ jets}, p_T^{\gamma\gamma} \in [120, 200] \text{ GeV}$	
ggH 2J Med	$\geq 2 \text{ jets}, p_T^{\gamma\gamma} \in [60, 120] \text{ GeV}$	
ggH 2J Low	$\geq 2 \text{ jets}, p_T^{\gamma\gamma} \in [0, 60] \text{ GeV}$	
ggH 1J BSM	$= 1 \text{ jet}, p_T^{\gamma\gamma} \geq 200 \text{ GeV}$	
ggH 1J High	$= 1 \text{ jet}, p_T^{\gamma\gamma} \in [120, 200] \text{ GeV}$	
ggH 1J Med	$= 1 \text{ jet}, p_T^{\gamma\gamma} \in [60, 120] \text{ GeV}$	
ggH 1J Low	$= 1 \text{ jet}, p_T^{\gamma\gamma} \in [0, 60] \text{ GeV}$	
ggH 0J Fwd	$= 0 \text{ jets, one photon with }  \eta  > 0.95$	
ggH 0J Cen	$= 0 \text{ jets, two photons with }  \eta  \leq 0.95$	

$p_T^j > 30 \text{ GeV}$  if not stated otherwise

# Categorization: coarse overview

Categorization optimized to probe STXS stage 1

Made from the most rare to the less rare (to reduce contamination)

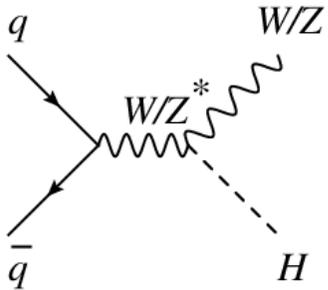


- ttH

decay of tops :

-‘leptonic’:  $\geq 1$  lepton for W from t

-‘hadronic’: no lepton decay for W from t

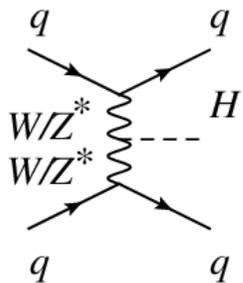


- VH

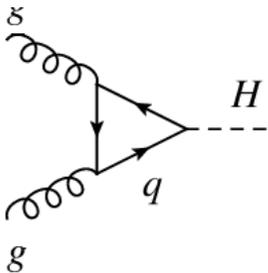
decay of tops :

-‘leptonic’:  $\geq 1$  lepton for W from t

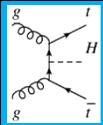
-‘hadronic’: no lepton decay for W from t



- VBF



- ggHd



# Categorization : ttH

• Truth bins

$t\bar{t}H$

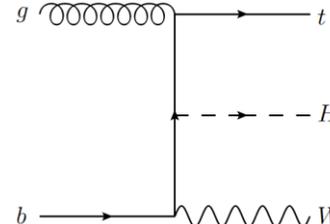
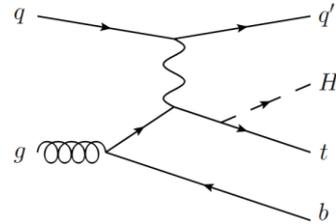
$tH$

• leptonic:  $\geq 1$  lepton,  $\geq 1$  b-jet

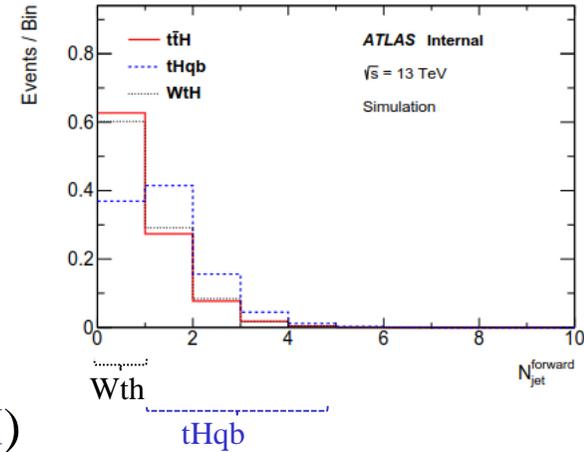
- $tH$  lep: veto event w/  $>1$  lepton, split categories w/ #fwd jets

→ disentangle

tHqb (#j fwd  $\approx 0$ ; 1) vs WtH (#j fwd  $\approx 0$ )



(no splitting in tH had: high #jets)

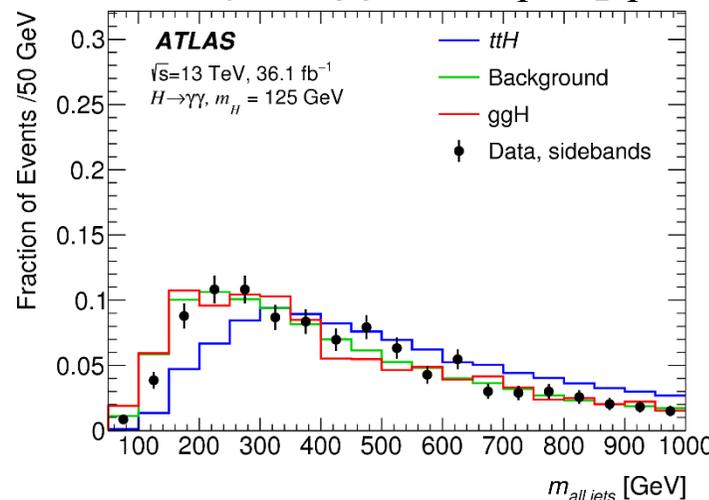
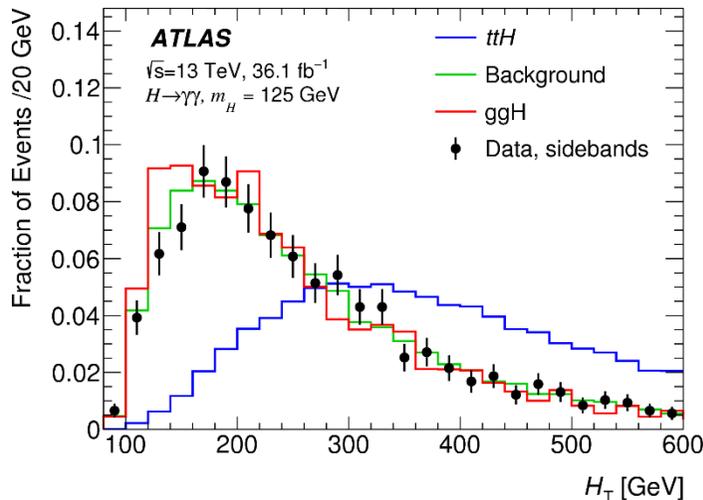


- $t\bar{t}H$  lep:  $\geq 2$  central jets

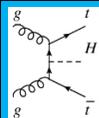
Veto event  $|m_{ll} - m_Z| < 10$  GeV with same flavor (suppr. ZH)

• Hadronic: - $t\bar{t}H$  hadronic:  $t\bar{t}H$  vs {QCD jets, ggH}:  $H_T = \sum p_T^j$ ,  $m_{\text{multijets}}$ , #j, #j cen, #b-jets

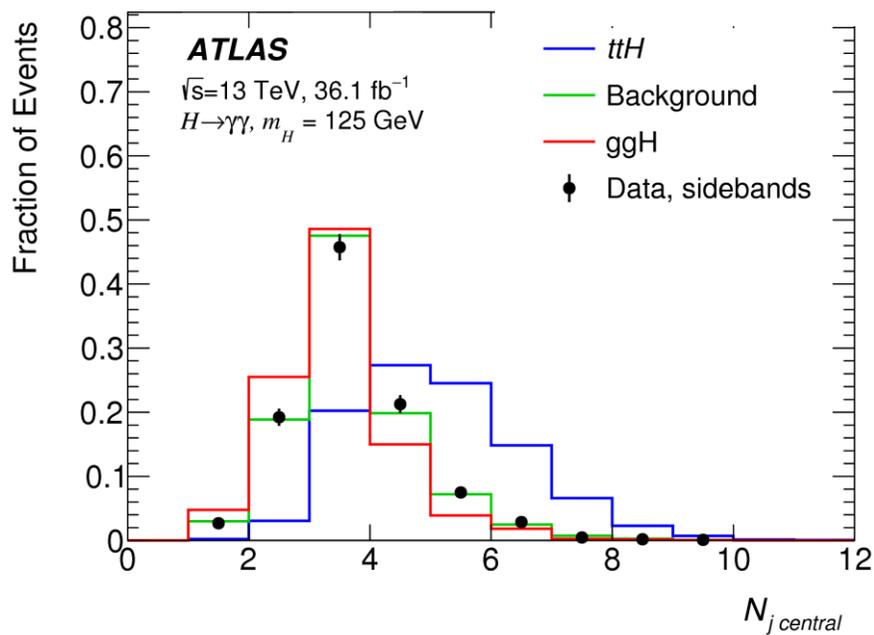
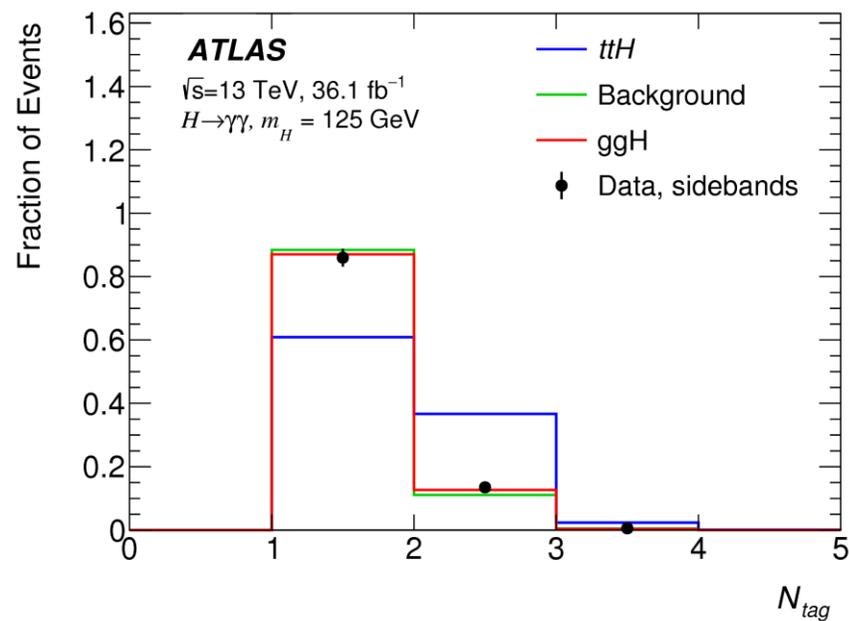
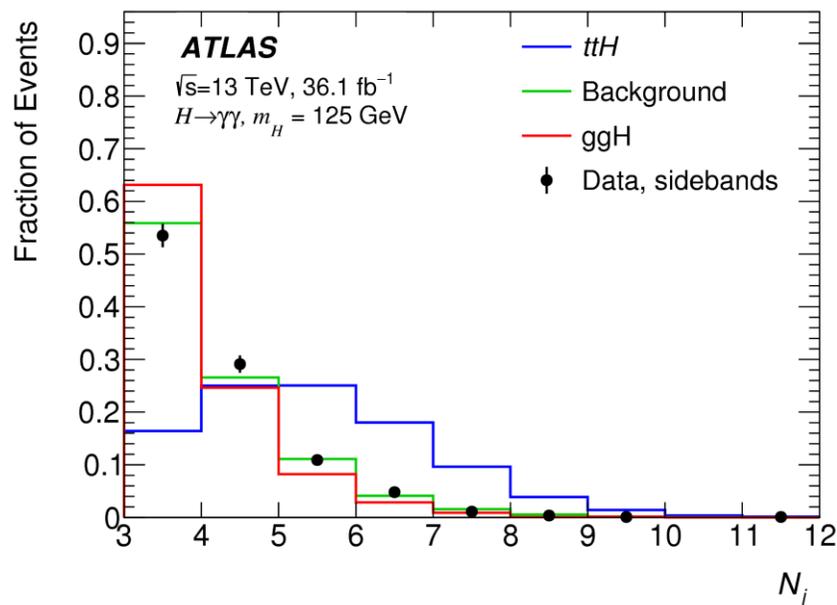
- $tH$  had: cut-based

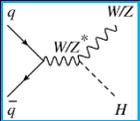


Not using photons in BDT, to be decorrelated from photons selection



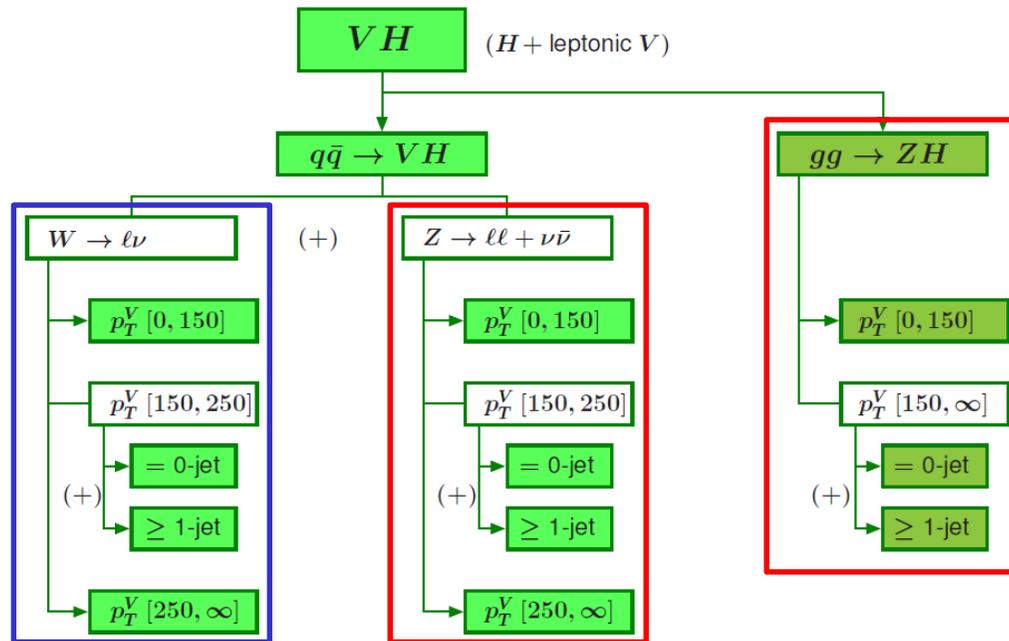
# Categorization : ttH



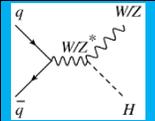


# Categorization : VH w/ leptons, MET

- Truth bins

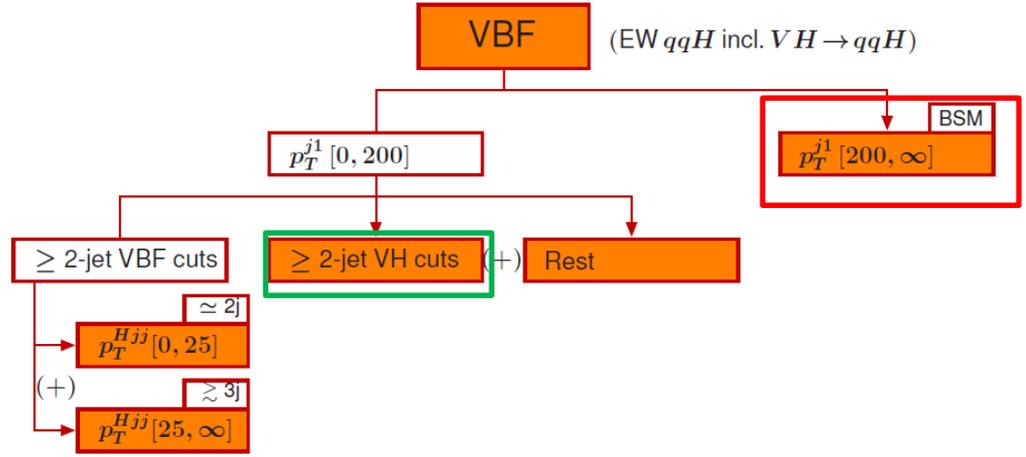


- VH dileptons: 2 SF OS leptons,  $70 \leq m_{ll} \leq 110$  GeV ■
- VH leptonic: 1 lepton, veto events w/  $84 \leq m_{e\gamma} \leq 94$  GeV (suppr.  $Z(ll)H$  w/  $e \rightarrow \gamma$ )  
split w/  $p_T(l+MET) >$  or  $< 150$  GeV ■  
low: additional cut on  $signi_{MET}$
- VH MET: 2 categories : ■ ■  
VH MET Low:  $80 < MET < 150$  GeV,  $signi_{MET} > 8$   
VH MET High:  $MET > 150$  GeV,  $\{signi_{MET} > 9$  or  $MET > 250$  GeV}



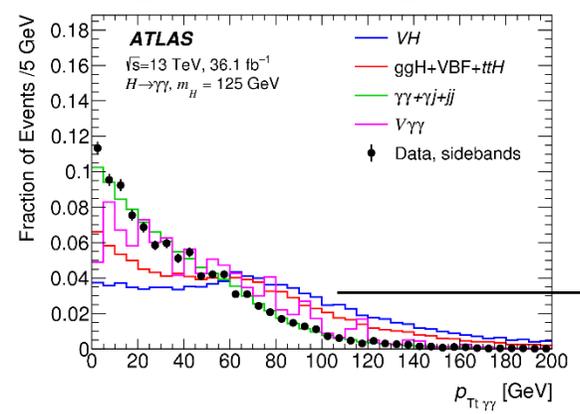
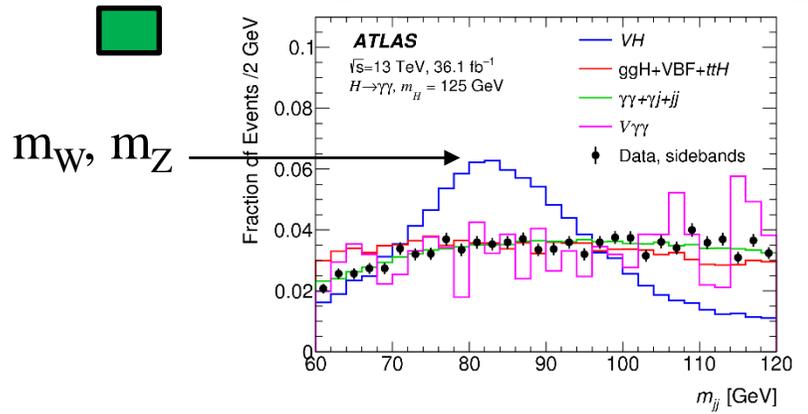
# Categorization : jet BSM, VH had

- Truth bins

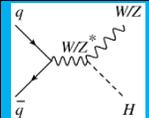


- Jet BSM: probe BSM (ggH & VBF, V(jj)H w/ boosted jets~reco 1-jet).  $p_T^j > 200$  GeV  
■  $\theta \sim m_{jj}/p_T$

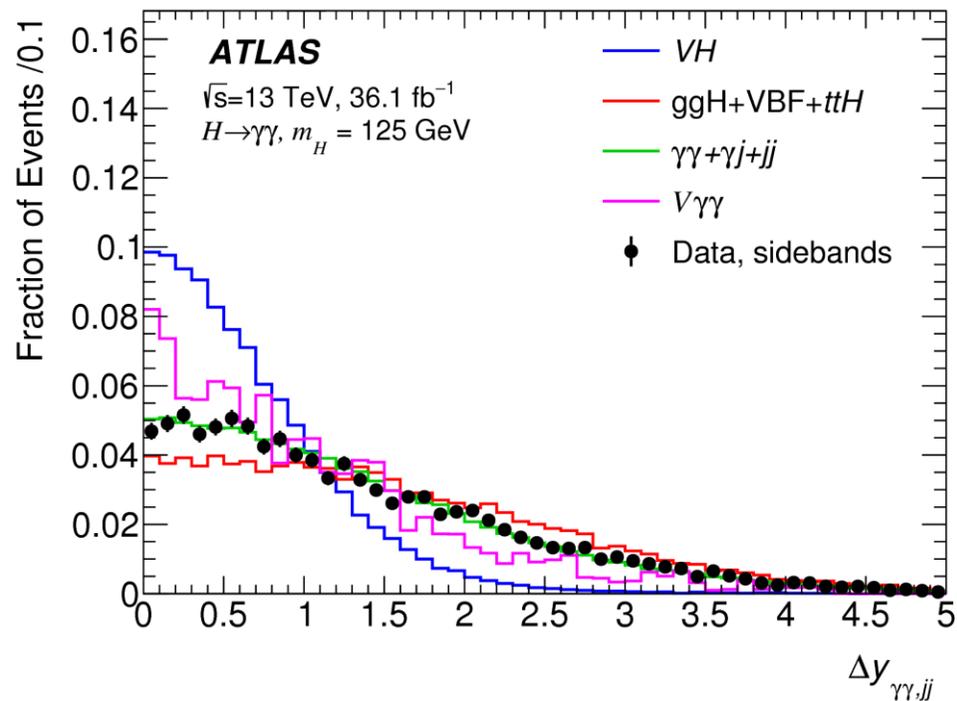
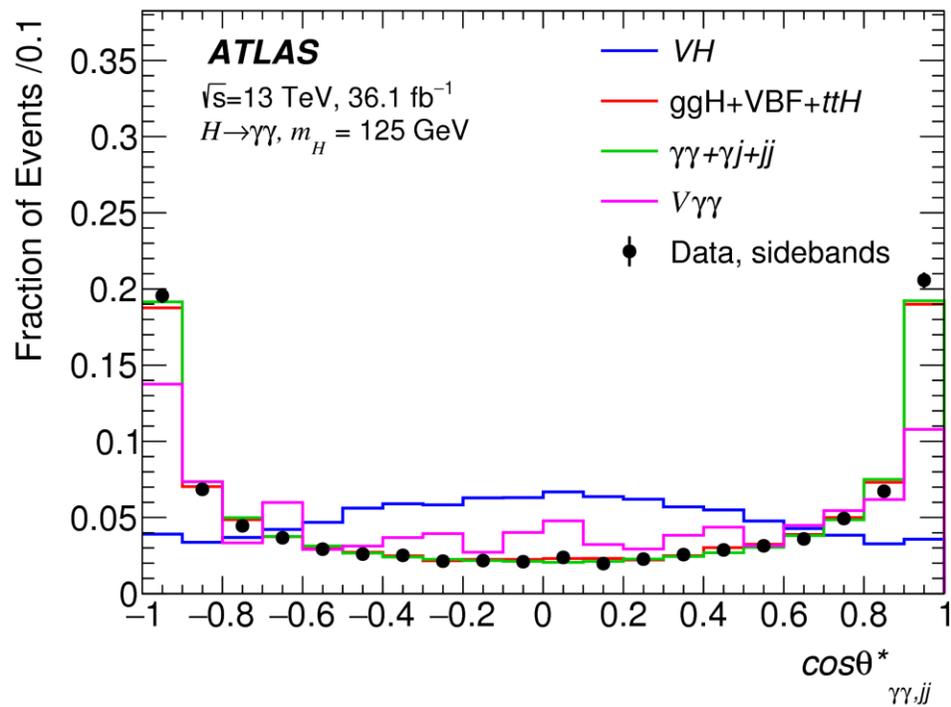
- VH had :  $60 < m_{jj} < 120$  GeV, BDT :  $m_{jj}, p_{T\gamma\gamma}, \Delta\eta_{jj, \gamma\gamma}, \cos \theta_{\gamma\gamma, jj}^*$

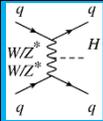


Training : VH vs { other signal, MC  $\gamma\gamma$ , CR :  $\gamma j, jj$  }  
 2 categories : purity in VH : 42 %, 25 %



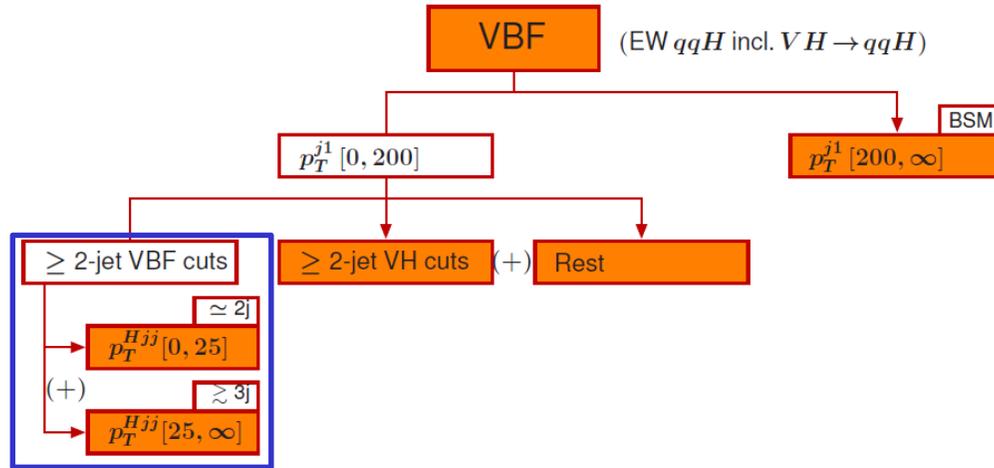
# Categorization : jet BSM, VH had





# Categorization : VBF

- Truth bins



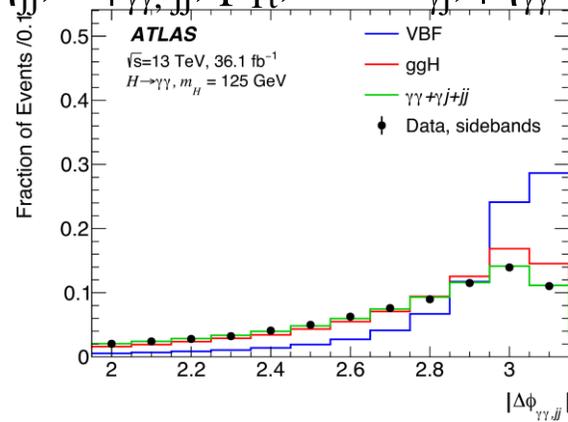
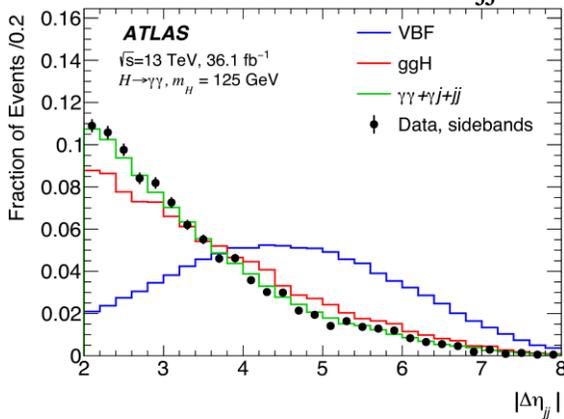
- VBF

$$|\Delta\eta_{jj}| > 2, |\eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})| > 5$$

Categories :  $p_T^{Hjj}$ :  $< 25$  GeV :  $\sim 2$ -jets ;  $> 25$  GeV:  $\geq 3$ -jets

$\rightarrow$  reduces ggH migration

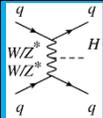
BDT :  $m_{jj}, \Delta\eta_{jj}, \Delta\phi_{\gamma\gamma, jj}, p_{Tt}, \Delta R^{\min}_{\gamma j}, |\eta_{\gamma\gamma} - 0.5(\eta_{j1} + \eta_{j2})|$



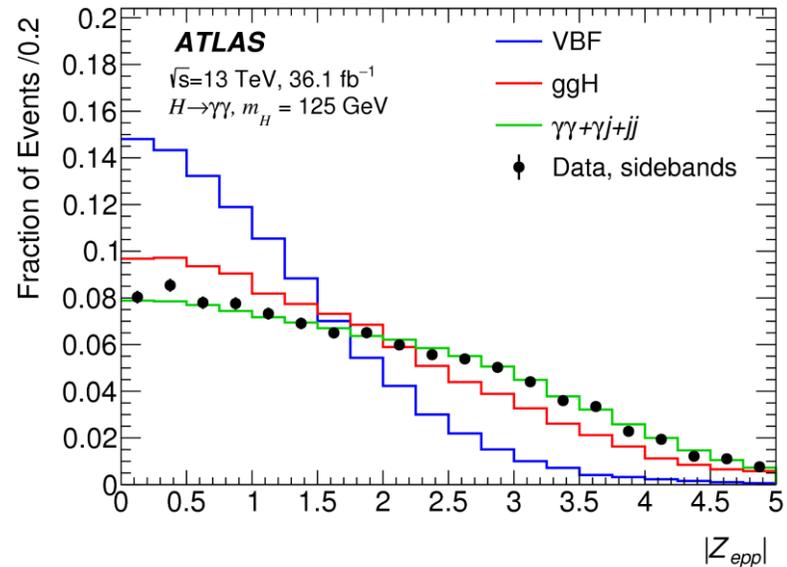
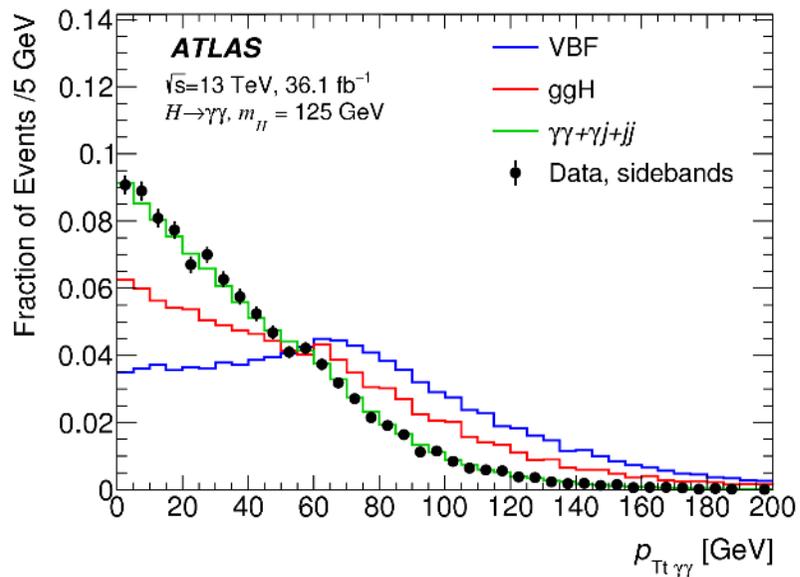
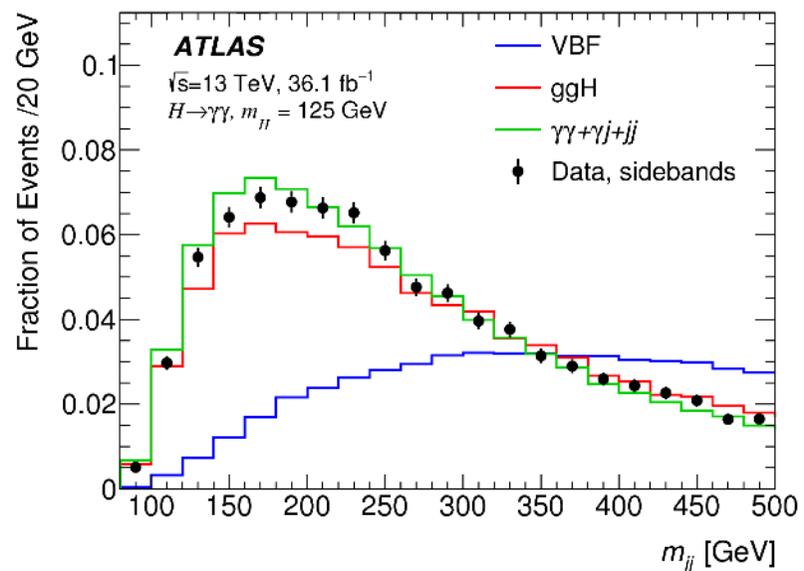
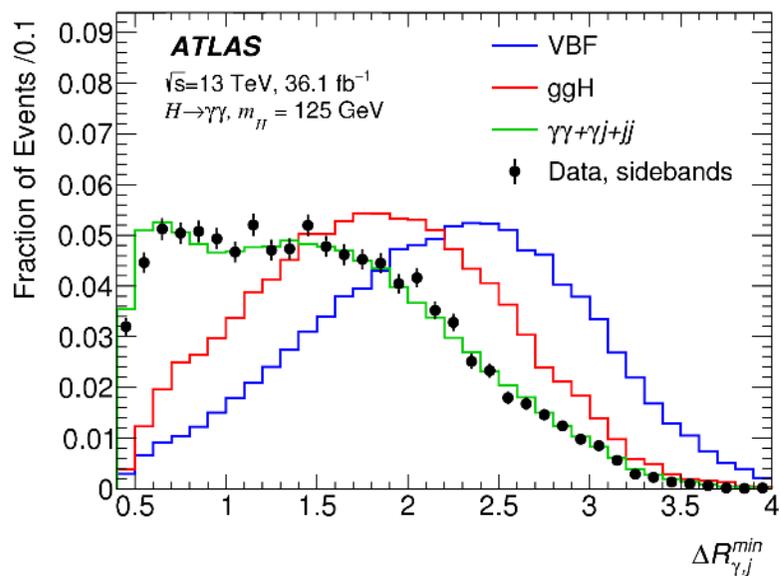
$\Delta\phi_{\gamma\gamma, jj}$   
Put all events of  $> 2.94$  in last bin  
To avoid large theoretical uncertainties

Training : VBF vs {ggH, MC  $\gamma\gamma$ , CR :  $\gamma j, jj$ }

2 categories x 2  $p_T^{Hjj}$



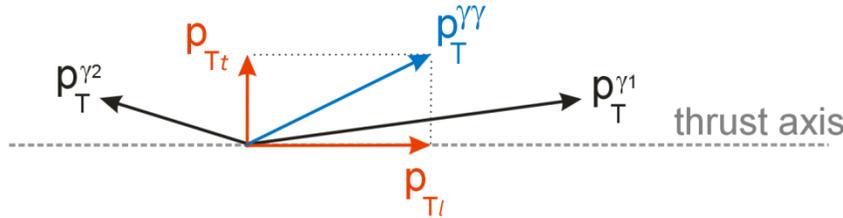
# Categorization : VBF



# $p_{Tt}$

- $p_{T\gamma\gamma}$  category used historically for fermiophobic analysis  
drawback : turn-on effect on invariant mass

- new variable** :  $p_{Tt}$  : transverse projection of  $p_{T\gamma\gamma}$  on thrust axis



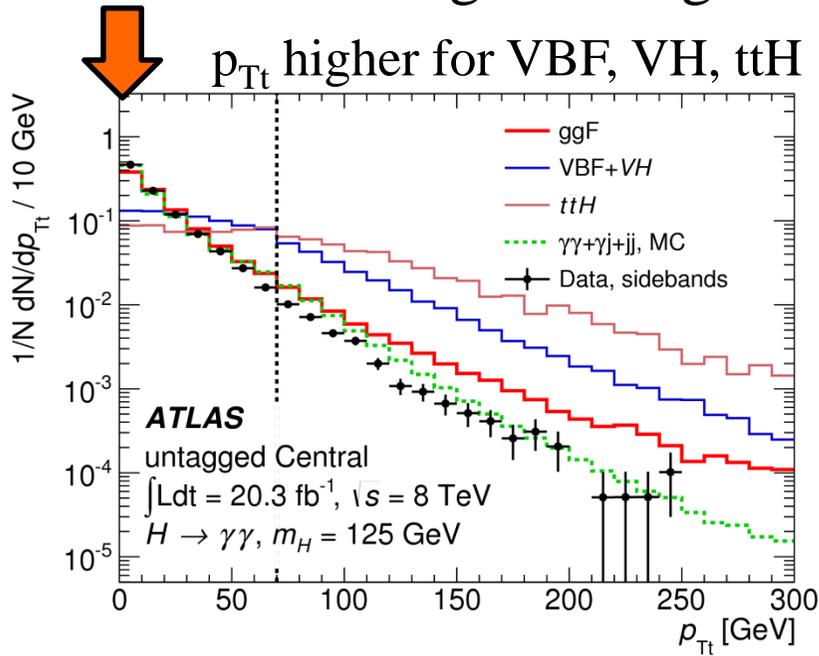
threshold  $p_{Tt} : 70 \text{ GeV}$

$$\hat{t} = (\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}) / |\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}|$$

Sensitivity gain : 5-10 % ( $f(m_H)$ )

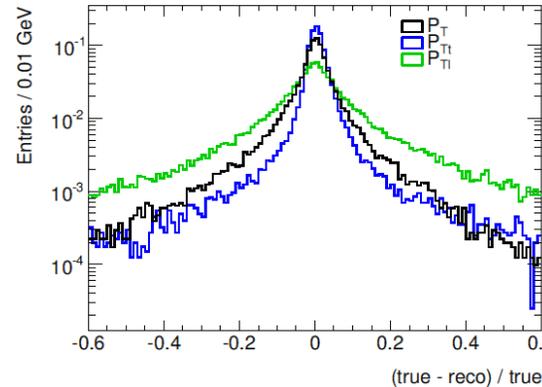
## Advantages

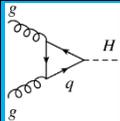
- discriminant against bkg



- Less correlated to  $m_{\gamma\gamma}$
- Less sensitive to resolution effects**

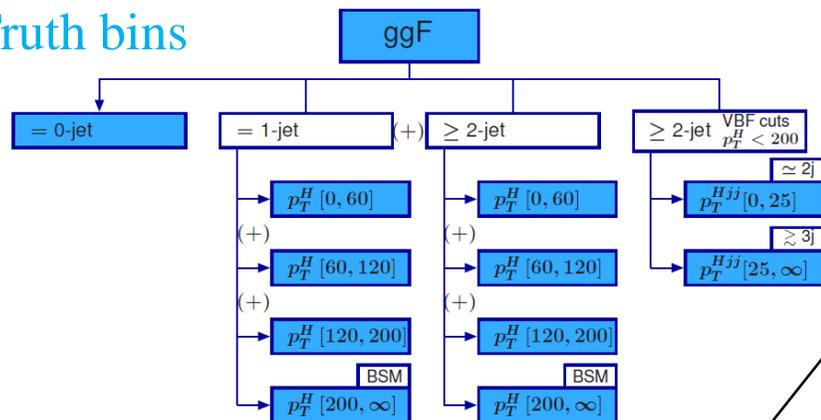
high  $p_{T\gamma\gamma}$  :  $\Delta\alpha \ll :$  similar to  $p_{T\gamma\gamma}$   
 low  $p_{T\gamma\gamma}$  :  $\Delta\alpha \gg \Leftrightarrow$  small angle {thrust ;  $\gamma\gamma$ }  
 -uncert. long.. :  $\delta p_T \times \cos$  (small angle)  
 -transv. :  $\delta p_T \times \sin$  (small angle)





# Categorization : un-tagged: $\approx$ ggH

## Truth bins



- ggH 2J BSM  $\geq 2$  jets,  $p_{T}^{\gamma\gamma} \geq 200$  GeV
- ggH 2J High  $\geq 2$  jets,  $p_{T}^{\gamma\gamma} \in [120, 200]$  GeV
- ggH 2J Med  $\geq 2$  jets,  $p_{T}^{\gamma\gamma} \in [60, 120]$  GeV
- ggH 2J Low  $\geq 2$  jets,  $p_{T}^{\gamma\gamma} \in [0, 60]$  GeV
- ggH 1J BSM = 1 jet,  $p_{T}^{\gamma\gamma} \geq 200$  GeV
- ggH 1J High = 1 jet,  $p_{T}^{\gamma\gamma} \in [120, 200]$  GeV
- ggH 1J Med = 1 jet,  $p_{T}^{\gamma\gamma} \in [60, 120]$  GeV
- ggH 1J Low = 1 jet,  $p_{T}^{\gamma\gamma} \in [0, 60]$  GeV
- ggH 0J Fwd = 0 jets, one photon with  $|\eta| > 0.95$
- ggH 0J Cen = 0 jets, two photons with  $|\eta| \leq 0.95$

## ggH: Mimic truth bins

+ : 0-jet : split with  $\eta$  region

Central ( $|\eta| \leq 0.95$ )

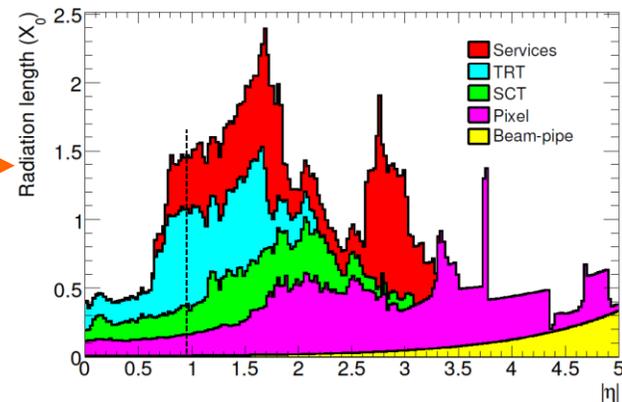
lower material: better energy/mass resolution

lower extension: artificially closer photons

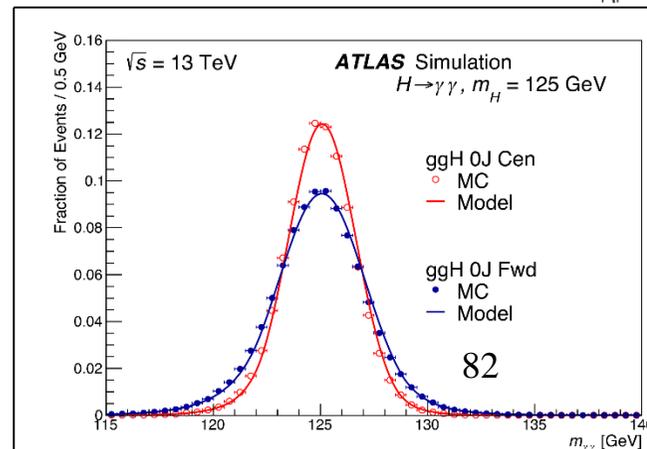
$\rightarrow$  higher  $p_T \rightarrow$  better S/B

Forward: worst mass resolution from previous, plus

position resolution : grazing direction of photon  
bit worst 1<sup>st</sup> samp. granularity



	Barrel		End-cap	
EM calorimeter				
Granularity $\Delta\eta \times \Delta\phi$ versus $ \eta $				
Presampler	0.025 × 0.1		0.025 × 0.1	
Calorimeter 1st layer	0.025/8 × 0.1	$ \eta  < 1.52$	0.025 × 0.1	$1.5 <  \eta  < 1.8$
	0.025 × 0.025	$ \eta  < 1.40$	0.050 × 0.1	$1.375 <  \eta  < 1.425$
		$1.40 <  \eta  < 1.475$	0.025 × 0.1	$1.425 <  \eta  < 1.5$
			0.025/8 × 0.1	$1.5 <  \eta  < 1.8$
		0.025/6 × 0.1	$1.8 <  \eta  < 2.0$	
		0.025/4 × 0.1	$2.0 <  \eta  < 2.4$	



# Categorization for historical mass measurement

24 categorization models considered

Compromise between best error on mass and simple model

Choice : 10 categories model

-conversion ( $0 ; \geq 1$   $\gamma$  converted)

unconv : better resolution on  $m_{\gamma\gamma}$

z vertex : converted more precise

E res : converted less precise

-direction

**central** [good] :  $|\eta| < 0.75$

better S/B

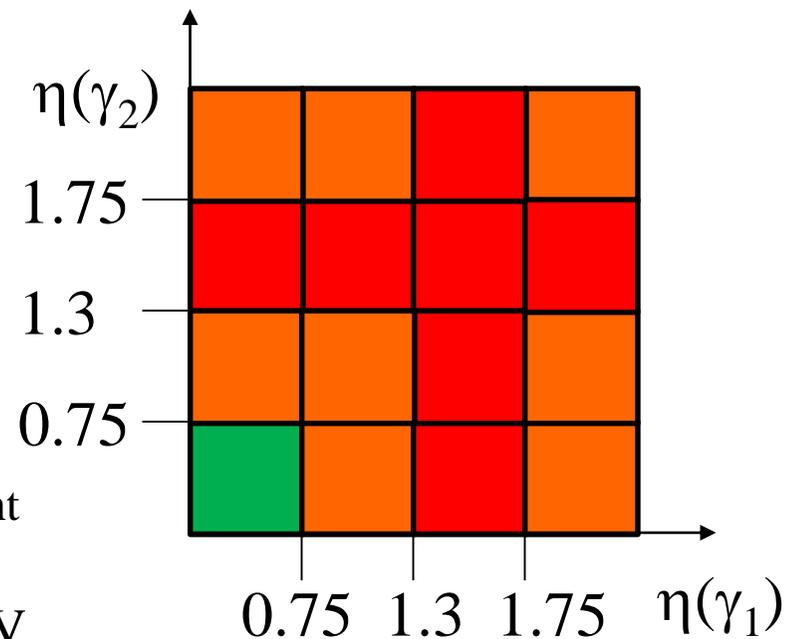
**medium** [rest] :  $1.3 < |\eta| < 1.75$

$\Delta\eta_{\gamma,\gamma} \uparrow \Leftrightarrow p_T \downarrow : S/B \downarrow$

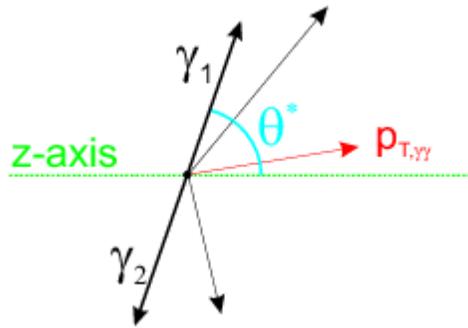
**bad** [transition]

degradation shower measurement

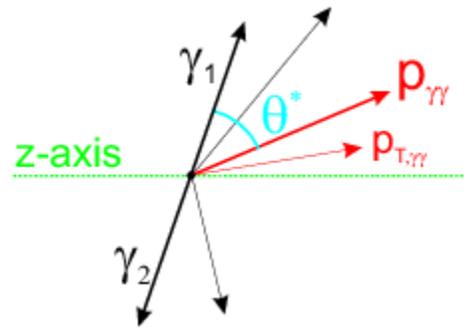
-transverse momentum of diphotons system :  $> / < 70$  GeV



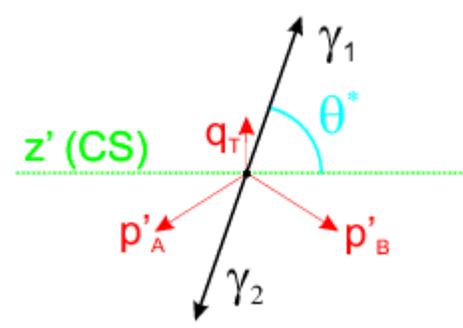
# Collins-Soper frame



wrt beam axis



wrt boost axis

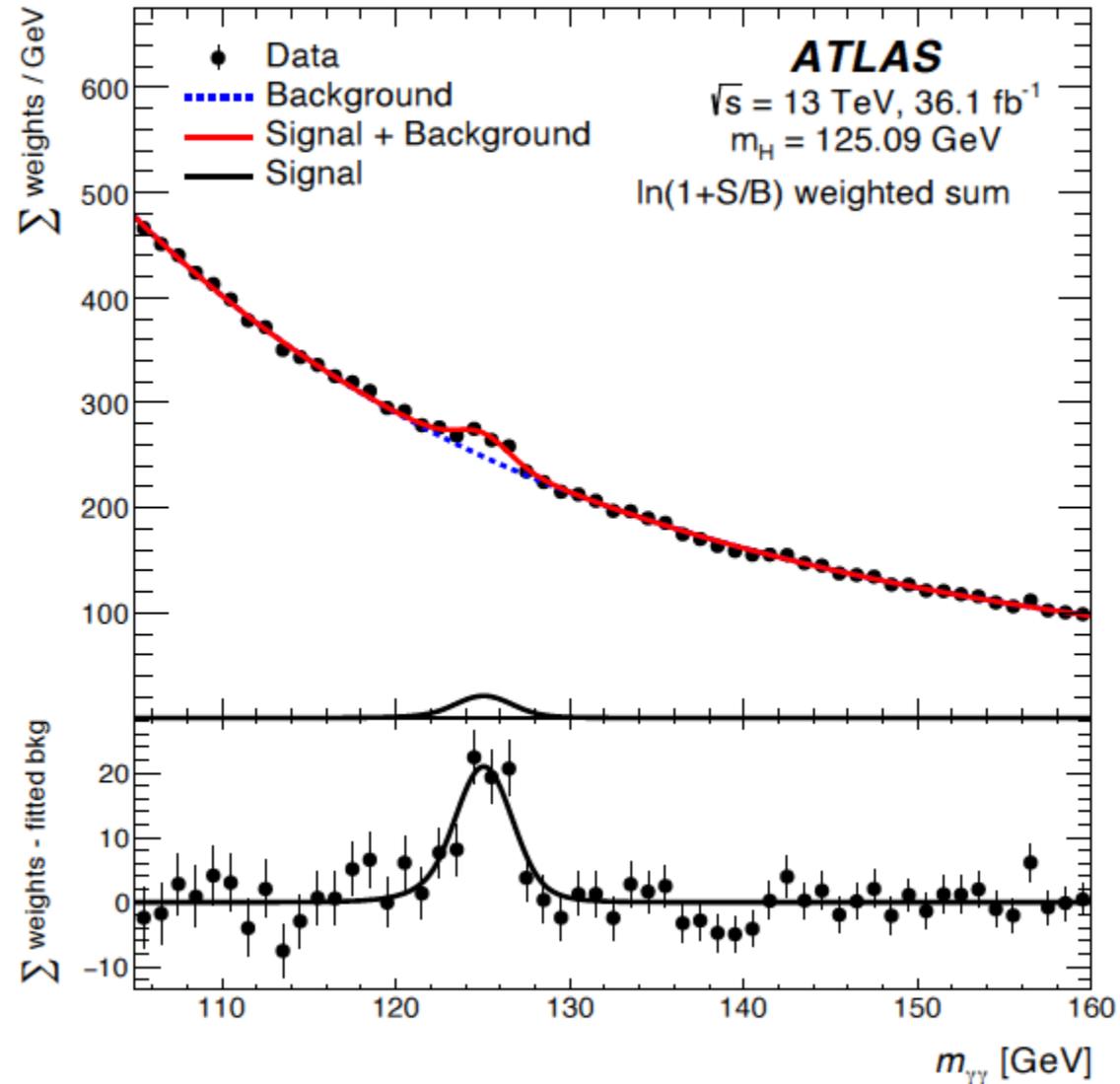


wrt Collins-Soper z axis

- Collins-Soper frame : z : bisector of beam axes in center-of-mass frame :  
 minimize effect of ISR  
 → better sensitivity to discriminate spin 0 from 2

# Final discriminant variables

inclusive

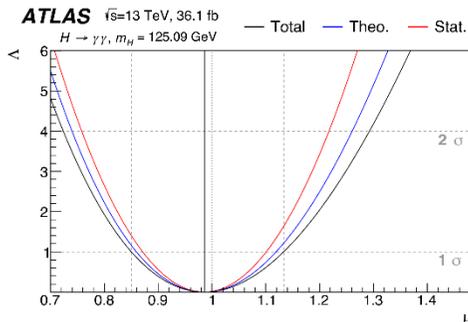


$$|y_H| < 2.5$$

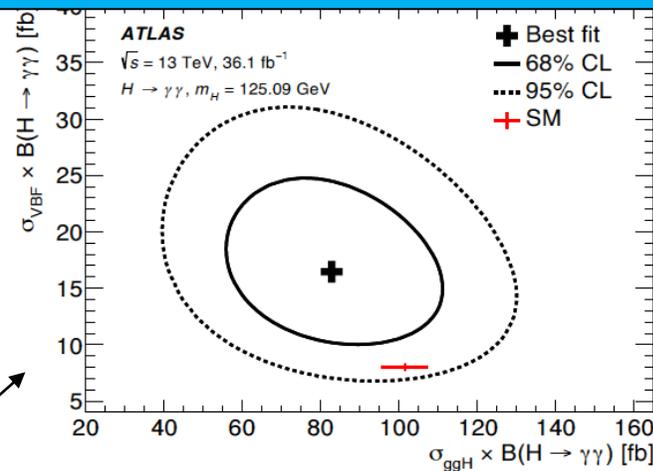
# Observed Results

## Inclusive signal strength

$$\mu = 0.99^{+0.15}_{-0.14} = 0.99^{+0.12}_{-0.12} \text{ (stat.) }^{+0.06}_{-0.05} \text{ (exp.) }^{+0.07}_{-0.05} \text{ (theory)}$$



Uncertainty Group	$\sigma_{\mu}^{\text{sys.}}$
Theory (QCD)	0.041
Theory ( $B(H \rightarrow \gamma\gamma)$ )	0.028
Theory (PDF+ $\alpha_S$ )	0.021
Theory (UE/PS)	0.026
Luminosity	0.031
Experimental (yield)	0.017
Experimental (migrations)	0.015
Mass resolution	0.029
Mass scale	0.006
Background shape	0.027



## $\mu_i$

$$\mu_{\text{ggH}} = 0.81^{+0.19}_{-0.18} = 0.81^{+0.16}_{-0.16} \text{ (stat.) }^{+0.07}_{-0.06} \text{ (exp.) }^{+0.07}_{-0.05} \text{ (theory)}$$

$$\mu_{\text{VBF}} = 2.0^{+0.6}_{-0.5} = 2.0^{+0.5}_{-0.5} \text{ (stat.) }^{+0.3}_{-0.2} \text{ (exp.) }^{+0.3}_{-0.2} \text{ (theory)}$$

$$\mu_{\text{VH}} = 0.7^{+0.9}_{-0.8} = 0.7^{+0.8}_{-0.8} \text{ (stat.) }^{+0.2}_{-0.2} \text{ (exp.) }^{+0.2}_{-0.1} \text{ (theory)}$$

$$\mu_{\text{top}} = 0.5^{+0.6}_{-0.6} = 0.5^{+0.6}_{-0.5} \text{ (stat.) }^{+0.1}_{-0.1} \text{ (exp.) }^{+0.1}_{-0.0} \text{ (theory)}$$

## Limits $\mu_i$

Measurement	Observed	Exp. Limit ( $\mu_i = 1$ )	Exp. Limit ( $\mu_i = 0$ )	+2 $\sigma$	+1 $\sigma$	-1 $\sigma$	-2 $\sigma$
$\mu_{\text{VH}}$	2.3	2.5	1.5	3.1	2.2	1.1	0.8
$\mu_{\text{top}}$	1.7	2.3	1.2	2.6	1.8	0.9	0.6

## Cancel out deviation in BR( $H \rightarrow \gamma\gamma$ )

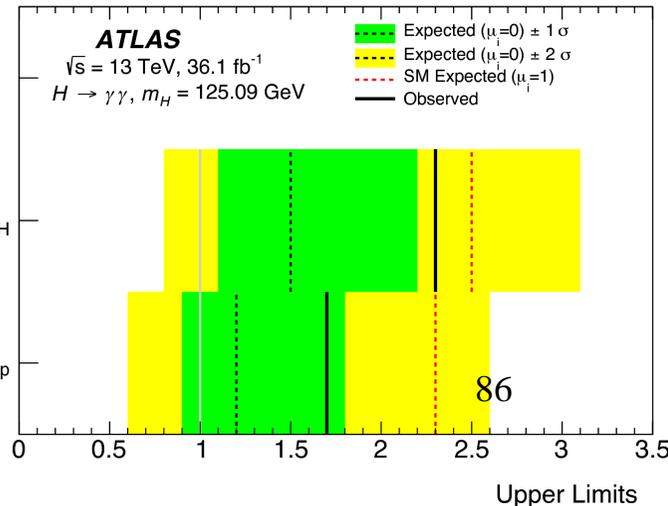
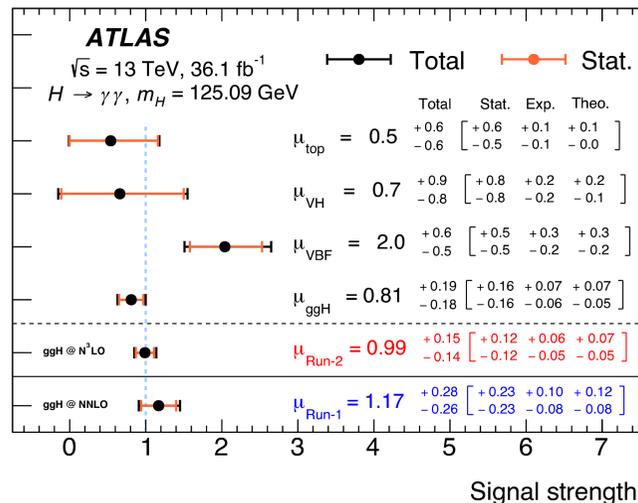
$$\frac{\sigma_{\text{VBF}}/\sigma_{\text{ggH}}}{(\sigma_{\text{VBF}}/\sigma_{\text{ggH}})_{\text{SM}}} = 2.5^{+1.3}_{-0.9} = 2.5^{+1.1}_{-0.8} \text{ (stat.) }^{+0.5}_{-0.3} \text{ (exp.) }^{+0.5}_{-0.3} \text{ (theory)}$$

$$\frac{\sigma_{\text{VH}}/\sigma_{\text{ggH}}}{(\sigma_{\text{VH}}/\sigma_{\text{ggH}})_{\text{SM}}} = 0.9^{+1.3}_{-1.0} = 0.9^{+1.2}_{-0.9} \text{ (stat.) }^{+0.3}_{-0.3} \text{ (exp.) }^{+0.2}_{-0.1} \text{ (theory)}$$

$$\frac{\sigma_{\text{top}}/\sigma_{\text{ggH}}}{(\sigma_{\text{top}}/\sigma_{\text{ggH}})_{\text{SM}}} = 0.7^{+0.8}_{-0.7} = 0.7^{+0.8}_{-0.7} \text{ (stat.) }^{+0.2}_{-0.1} \text{ (exp.) }^{+0.2}_{-0.0} \text{ (theory)}$$

Measurement	Exp. $Z_0$	Obs. $Z_0$
$\mu_{\text{VBF}}$	2.6 $\sigma$	4.9 $\sigma$
$\mu_{\text{VH}}$	1.4 $\sigma$	0.8 $\sigma$
$\mu_{\text{top}}$	1.8 $\sigma$	1.0 $\sigma$

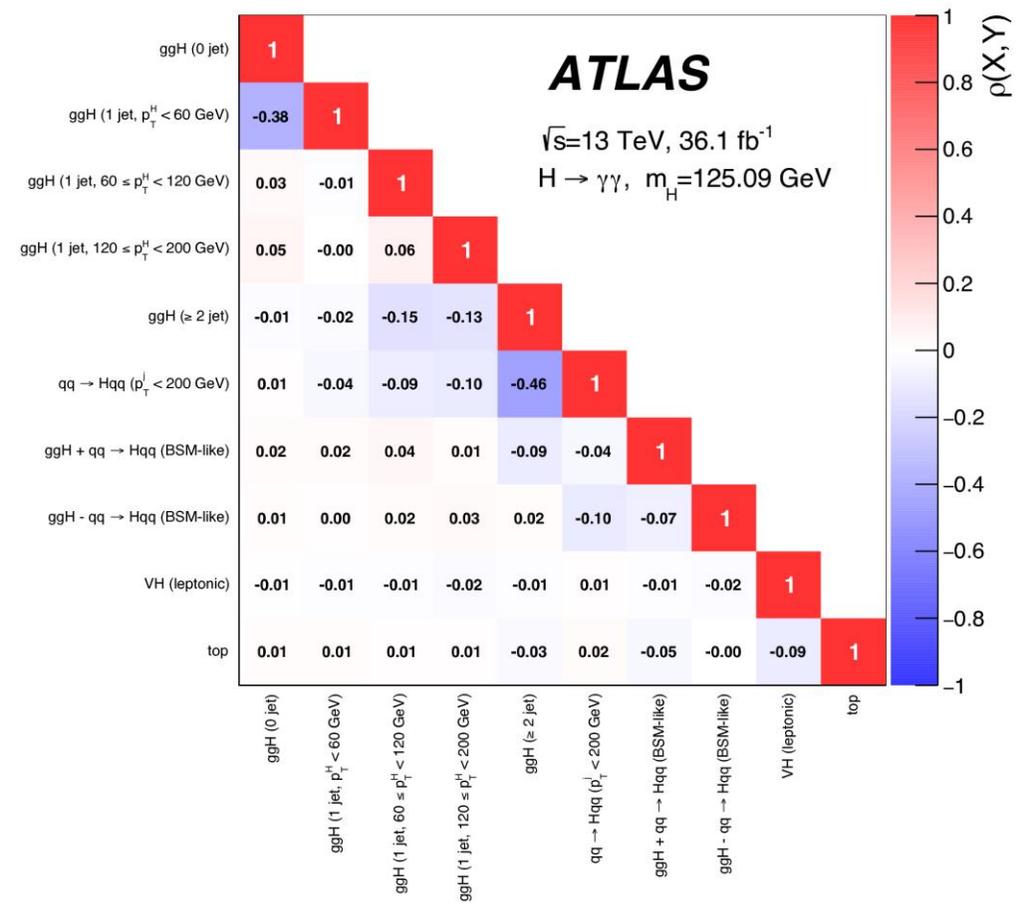
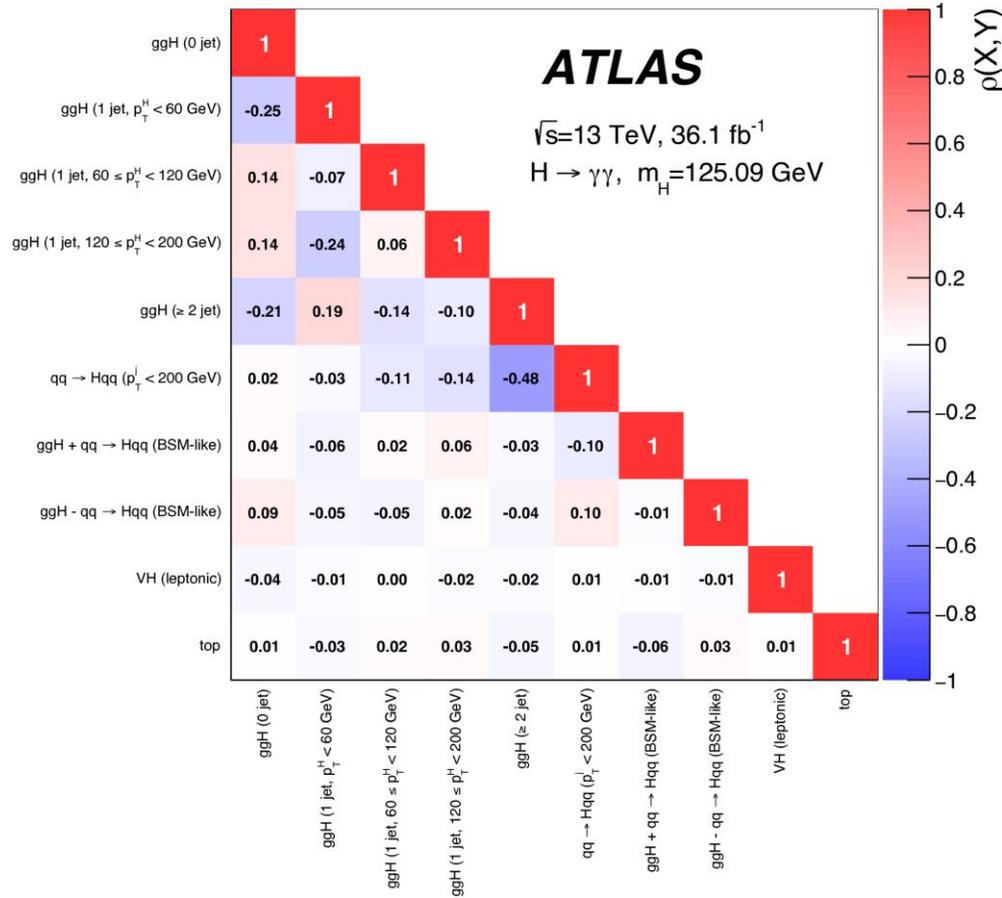
VBF close to 5  $\sigma$



# STXS ‘strong merging’: correlations

Observed

Expected



# $\kappa$ -framework

Initial state  $i \rightarrow$  intermediate state  $X$  ( $H$ )  $\rightarrow$  final state  $f$  ( $\mu = \kappa_i^2 \kappa_f^2 / \kappa_H^2$ )

$$\sigma(i \rightarrow H \rightarrow f) = \kappa_i^2 \sigma_i^{SM} \frac{\kappa_f^2 \Gamma_f^{SM}}{\kappa_H^2 \Gamma_H^{SM}}$$

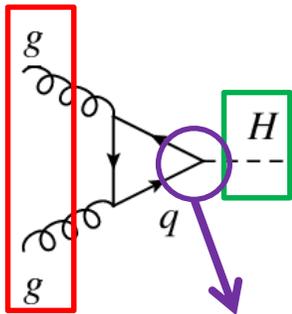
$\kappa$ : scale factor: 'amplitude' strength  
sensitivity to interference

$$\Gamma(H \rightarrow \gamma\gamma) / \Gamma_{SM}(H \rightarrow \gamma\gamma) = 1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t$$

can be formulated using :

- genuine SM coupling :  $f$ (SM coupling)
- effective coupling (BSM particles, etc.)

example :  $gg \rightarrow H \rightarrow \gamma\gamma$

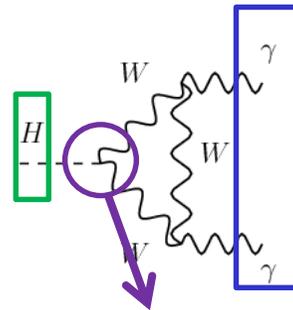


$$Htt \rightarrow \kappa_t$$

$$Hbb \rightarrow \kappa_b$$

$$ggH \rightarrow \kappa_g = f(\kappa_t, \kappa_b)$$

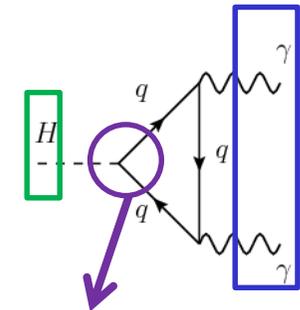
$$ggH \rightarrow \kappa_g$$



$$HWW \rightarrow \kappa_W$$

$$H\gamma\gamma \rightarrow \kappa_\gamma = f(\kappa_t, \kappa_b, \kappa_W, \kappa_\tau)$$

$$H\gamma\gamma \rightarrow \kappa_\gamma$$



$$Htt \rightarrow \kappa_t$$

$$Hbb \rightarrow \kappa_b$$

$$H\tau\tau \rightarrow \kappa_\tau$$

Explore various aspects of couplings  
 $\rightarrow$  'benchmarks' models

# $\kappa$ -framework: benchmarks scenarios

Explore various aspects of coupling structure

-Couplings modifiers on an amplitude:  $\kappa$

-Ratio of coupling modifiers:  $\lambda_{ij} = \kappa_i / \kappa_j$

(whenever a ratio is chosen, a reference coupling modifier is also considered, for the scaling : typically  $\kappa_{ij} = \kappa_i \cdot \kappa_j / \kappa_H$ )

-explore a given scaling

-Fermion-boson ( $\kappa_V, \kappa_F$ )

-Custodial symmetry : W/Z

-Fermion :

-up-down ( $\lambda_{du}$ ): BSM extended Higgs (2HDM, ...)

-q-l ( $\lambda_{lq}$ ): BSM extended Higgs (2HDM, ...)

-Loop (ggH,  $H \rightarrow \gamma\gamma, Z\gamma$ )

-resolved (SM):  $\kappa_{loop} = f(\kappa_i)$ , no BSM in  $\Gamma_H$  ( $BR_{BSM} = 0$ )

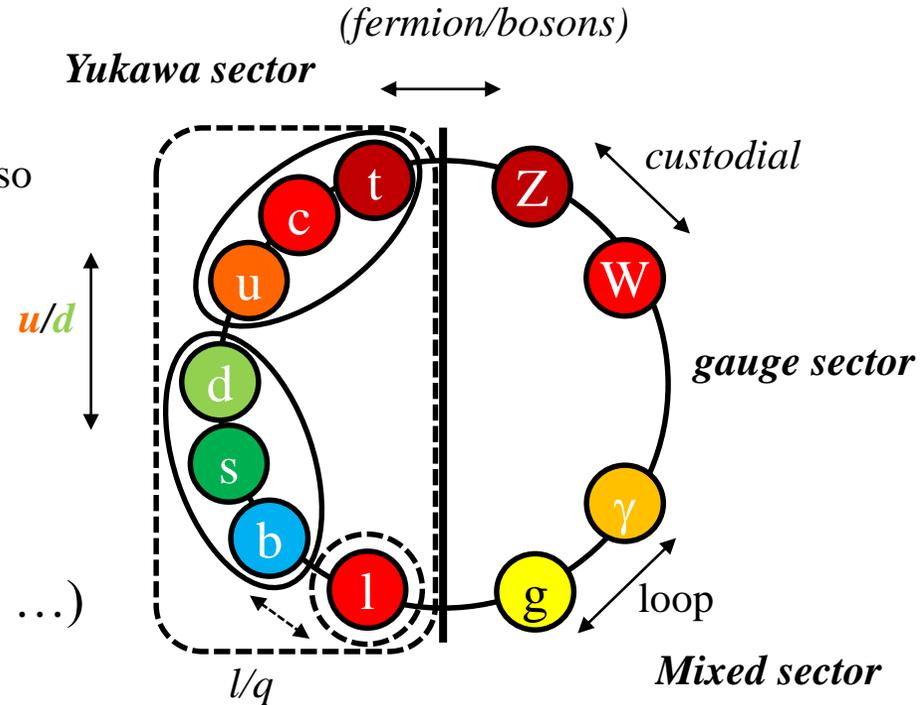
-unresolved (BSM):  $\kappa_{loop} \neq f(\kappa_i)$

-w/ or wo/ invisible decays

...

-Maximal parameterization

14 baseline benchmarks



Interpretation : phenomenological parametrization

$$SM : (M, \epsilon) = (v, 0) \quad \kappa_F = v \frac{m_F^\epsilon}{M^{1+\epsilon}}$$

$$\kappa_V = v \frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$$

# Results ICHEP ATLAS couplings $H \rightarrow \gamma\gamma$ in a nutshell

$L=13.3 \text{ fb}^{-1}$  (2015 :  $3.2 \text{ fb}^{-1}$ , 2016 :  $10.1 \text{ fb}^{-1}$ )

$\langle \mu \rangle = 13.7$

- Fixing  $m_H = 125.09 \text{ GeV}$

$$Z_{\text{obs}} = 4.7 \sigma \quad (Z_{\text{exp}} = 5.4 \sigma)$$

$$\mu = 0.85^{+0.22}_{-0.20}$$

- STXS, stage 0

$$\sigma_{ggH} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 63^{+30}_{-29} \text{ fb}$$

$$\sigma_{\text{VBF}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 17.8^{+6.3}_{-5.7} \text{ fb}$$

$$\sigma_{\text{VHlep}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 1.0^{+2.5}_{-1.9} \text{ fb}$$

$$\sigma_{\text{VHhad}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = -2.3^{+6.8}_{-5.8} \text{ fb}$$

$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \rightarrow \gamma\gamma) = -0.3^{+1.4}_{-1.1} \text{ fb}$$

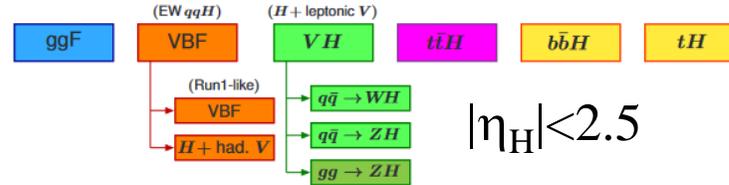
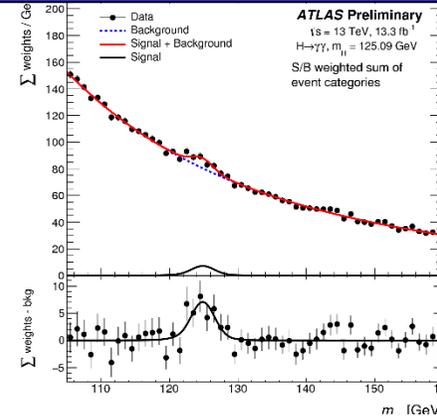
- Total production cross-section

$$\sigma_{ggH} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 65^{+32}_{-31} \text{ fb}$$

$$\sigma_{\text{VBF}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 19.2^{+6.8}_{-6.1} \text{ fb}$$

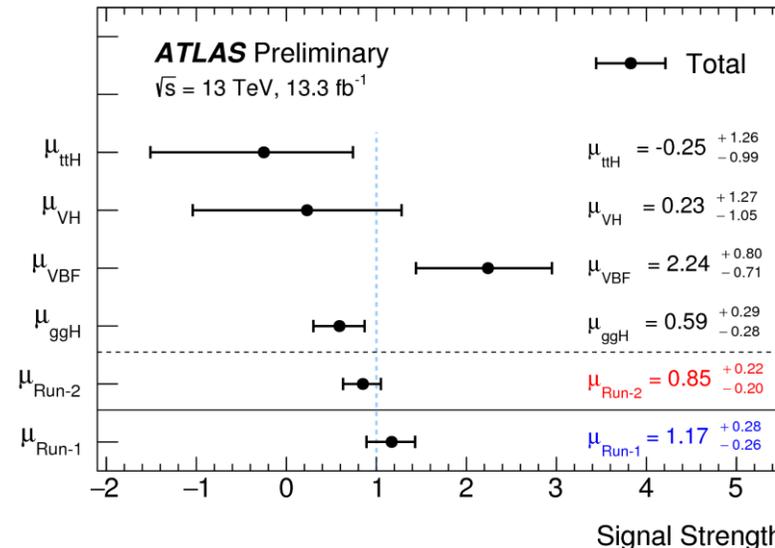
$$\sigma_{\text{VH}} \times \mathcal{B}(H \rightarrow \gamma\gamma) = 1.2^{+6.5}_{-5.4} \text{ fb}$$

$$\sigma_{t\bar{t}H} \times \mathcal{B}(H \rightarrow \gamma\gamma) = -0.3^{+1.4}_{-1.1} \text{ fb}$$



$$|\eta_H| < 2.5$$

- Signal strength



# Results: signal strengths

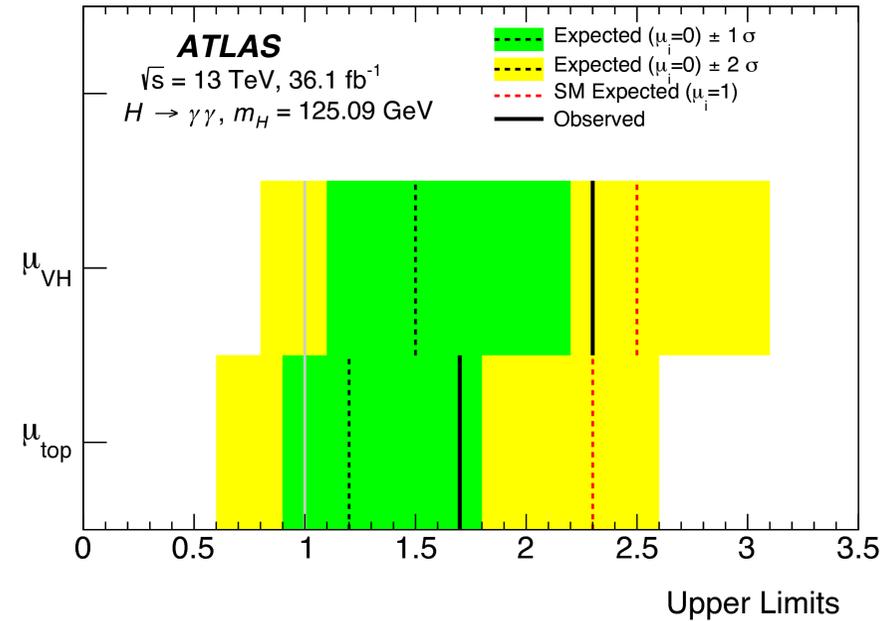
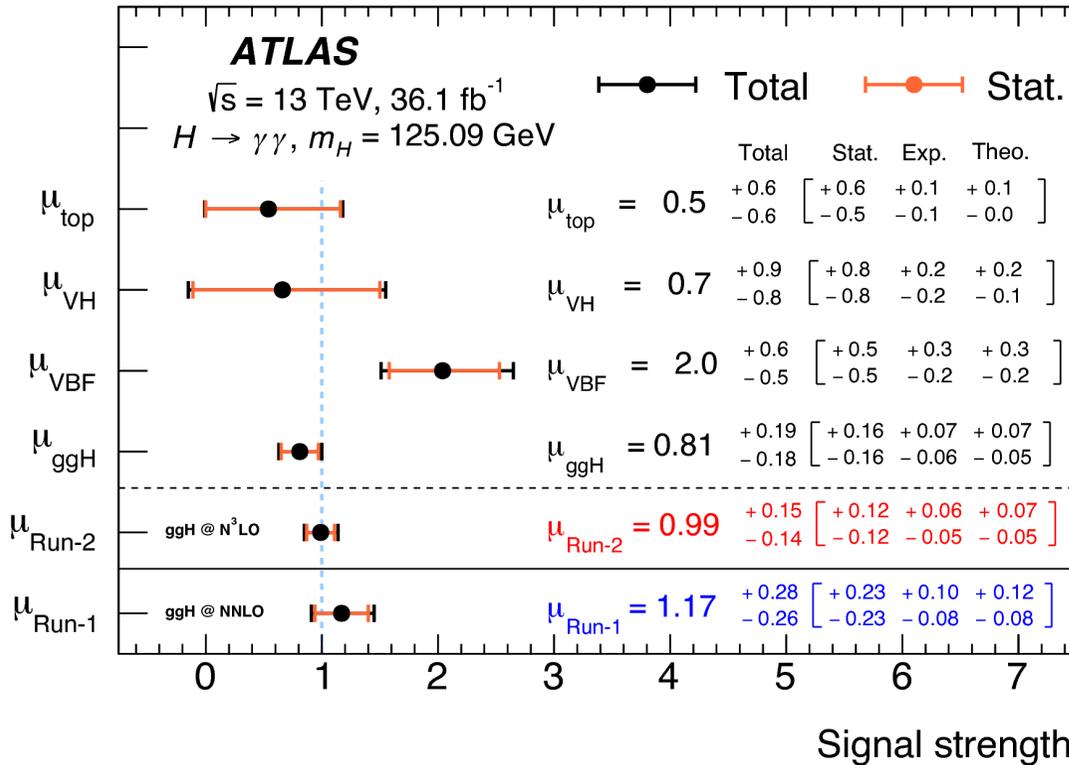
( $|y_H| < 2.5$ )

- Inclusive signal strength

$$\mu = 0.99^{+0.15}_{-0.14} = 0.99^{+0.12}_{-0.12} \text{ (stat.) }^{+0.06}_{-0.05} \text{ (exp.) }^{+0.07}_{-0.05} \text{ (theory)}$$

- Prod. Modes  $\mu_i$

- Limits & significance



Measurement	Exp. $Z_0$	Obs. $Z_0$
$\mu_{\text{VBF}}$	$2.6 \sigma$	$4.9 \sigma$
$\mu_{\text{VH}}$	$1.4 \sigma$	$0.8 \sigma$
$\mu_{\text{top}}$	$1.8 \sigma$	$1.0 \sigma$

VBF close to  $5 \sigma$

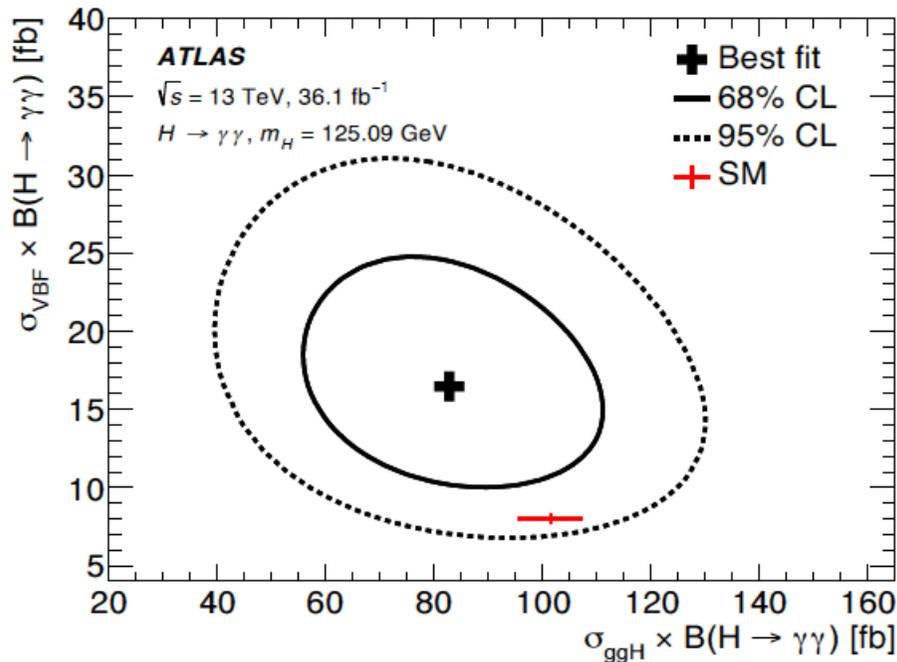
# Results: cross-sections

## • XSxBR

$\sigma_{ggH}^{STXS}(pp \rightarrow H) \times BR(H \rightarrow \gamma\gamma)$	$= 82 \pm 16$ (stat.)	$^{+7}_{-6}$ (Exp.)	$^{+5}_{-4}$ (Th.)	fb
$\sigma_{VBF}^{STXS}(pp \rightarrow H) \times BR(H \rightarrow \gamma\gamma)$	$= 16 \pm 4$ (stat.)	$\pm 2$ (Exp.)	$^{+3}_{-2}$ (Th.)	fb
$\sigma_{VH}^{STXS}(pp \rightarrow H) \times BR(H \rightarrow \gamma\gamma)$	$= 3^{+4}_{-3}$ (stat.)	$\pm 1$ (Exp.)	$^{+1}_{-0}$ (Th.)	fb
$\sigma_{tH+tH}^{STXS}(pp \rightarrow H) \times BR(H \rightarrow \gamma\gamma)$	$= 0.7^{+0.8}_{-0.7}$ (stat.)	$^{+0.2}_{-0.1}$ (Exp.)	$^{+0.2}_{-0.0}$ (Th.)	fb

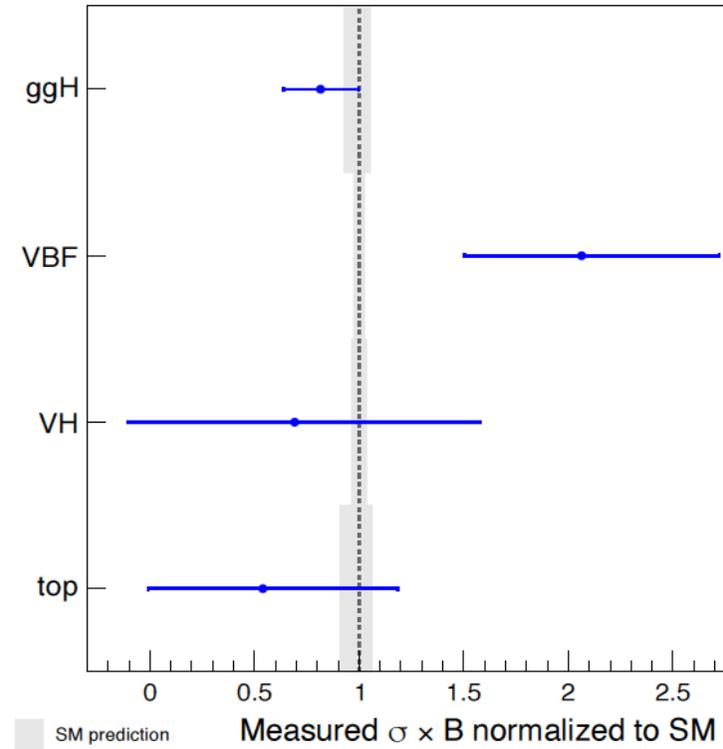
**SM :**

$\sigma_{ggH} \times B(H \rightarrow \gamma\gamma)$	$= 102^{+19}_{-18}$ fb	$= 102^{+17}_{-17}$ (stat.)	$^{+8}_{-6}$ (exp.)	$^{+4}_{-3}$ (theory)	fb
$\sigma_{VBF} \times B(H \rightarrow \gamma\gamma)$	$= 8^{+4}_{-3}$ fb	$= 8^{+3}_{-3}$ (stat.)	$^{+1}_{-1}$ (exp.)	$^{+1}_{-1}$ (theory)	fb
$\sigma_{VH} \times B(H \rightarrow \gamma\gamma)$	$= 5^{+4}_{-3}$ fb	$= 5^{+4}_{-3}$ (stat.)	$^{+1}_{-1}$ (exp.)	$^{+0}_{-0}$ (theory)	fb
$\sigma_{top} \times B(H \rightarrow \gamma\gamma)$	$= 1.3^{+0.9}_{-0.8}$ fb	$= 1.3^{+0.9}_{-0.8}$ (stat.)	$^{+0.2}_{-0.1}$ (exp.)	$^{+0.2}_{-0.1}$ (theory)	fb



**ATLAS**

$\sqrt{s}=13$  TeV, 36.1 fb  
 $H \rightarrow \gamma\gamma$ ,  $m_H=125.09$  GeV



- Ratio's: cancel out deviation in  $BR(H \rightarrow \gamma\gamma)$

$$\frac{\sigma_{VBF}/\sigma_{ggH}}{(\sigma_{VBF}/\sigma_{ggH})^{SM}} = 2.5^{+1.3}_{-0.9} = 2.5^{+1.1}_{-0.8} \text{ (stat.) } ^{+0.5}_{-0.3} \text{ (exp.) } ^{+0.5}_{-0.3} \text{ (theory)}$$

$$\frac{\sigma_{VH}/\sigma_{ggH}}{(\sigma_{VH}/\sigma_{ggH})^{SM}} = 0.9^{+1.3}_{-1.0} = 0.9^{+1.2}_{-0.9} \text{ (stat.) } ^{+0.3}_{-0.3} \text{ (exp.) } ^{+0.2}_{-0.1} \text{ (theory)}$$

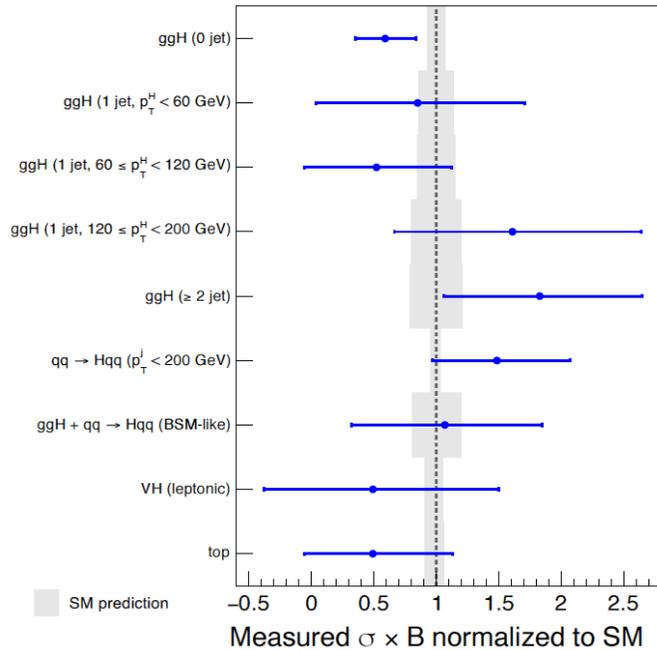
$$\frac{\sigma_{top}/\sigma_{ggH}}{(\sigma_{top}/\sigma_{ggH})^{SM}} = 0.7^{+0.8}_{-0.7} = 0.7^{+0.8}_{-0.7} \text{ (stat.) } ^{+0.2}_{-0.1} \text{ (exp.) } ^{+0.2}_{-0.0} \text{ (theory)} \quad 92$$

# Results: STXS

- strong merging STXS

- Minimally merged STXS

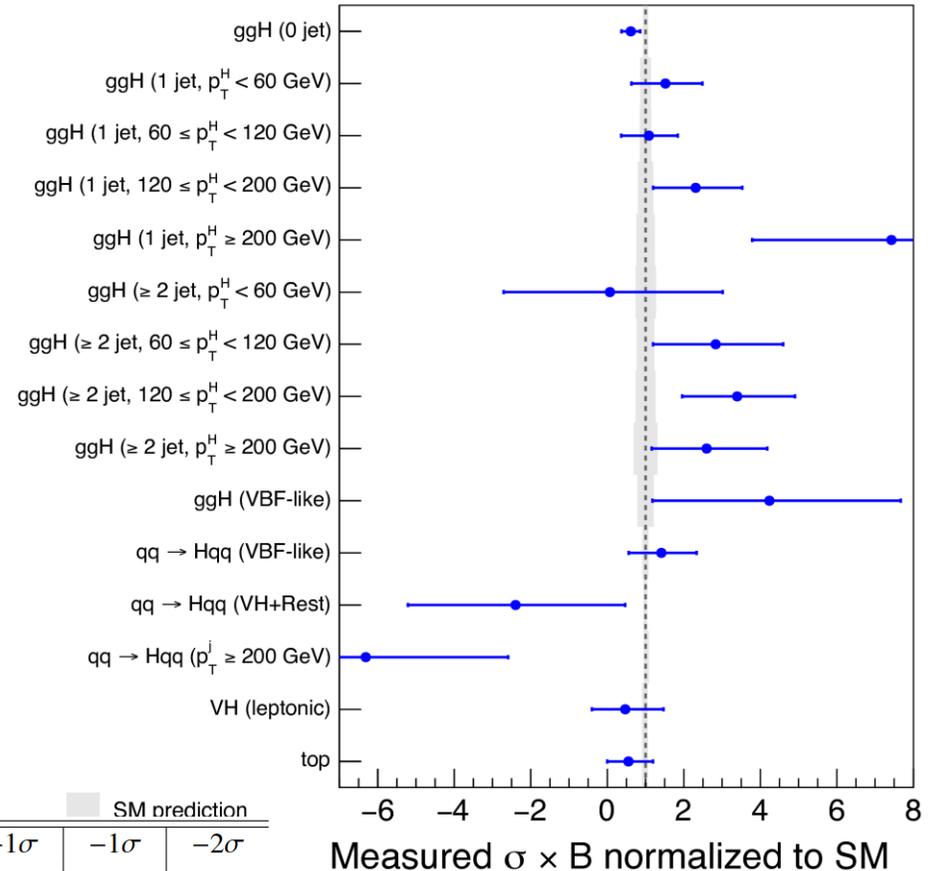
**ATLAS**  $\sqrt{s}=13$  TeV,  $36.1 \text{ fb}^{-1}$   
 $H \rightarrow \gamma\gamma$ ,  $m_H=125.09$  GeV



No significant discrepancy wrt SM

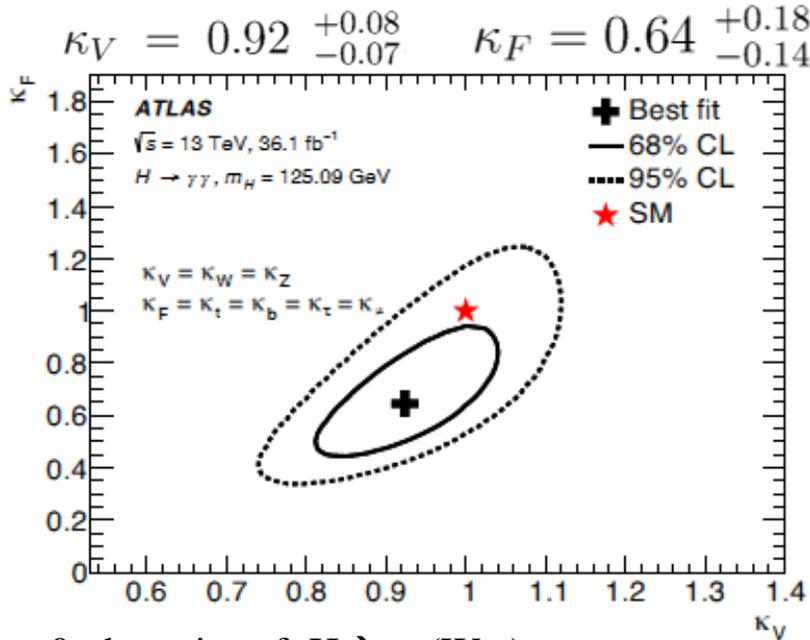
Measurement	Observed	Exp. Limit ( $\sigma = \sigma_{SM}$ )	Exp. Limit ( $\sigma = 0$ fb)	SM prediction			
				+2 $\sigma$	+1 $\sigma$	-1 $\sigma$	-2 $\sigma$
$ggH + qq \rightarrow Hqq$ , BSM-like	4.4 fb	4.3 fb	2.7 fb	5.3 fb	3.9 fb	2.0 fb	1.5 fb

**ATLAS**  $\sqrt{s}=13$  TeV,  $36.1 \text{ fb}^{-1}$   
 $H \rightarrow \gamma\gamma$ ,  $m_H=125.09$  GeV



# Results: $\kappa$ -framework

- Boson-fermion

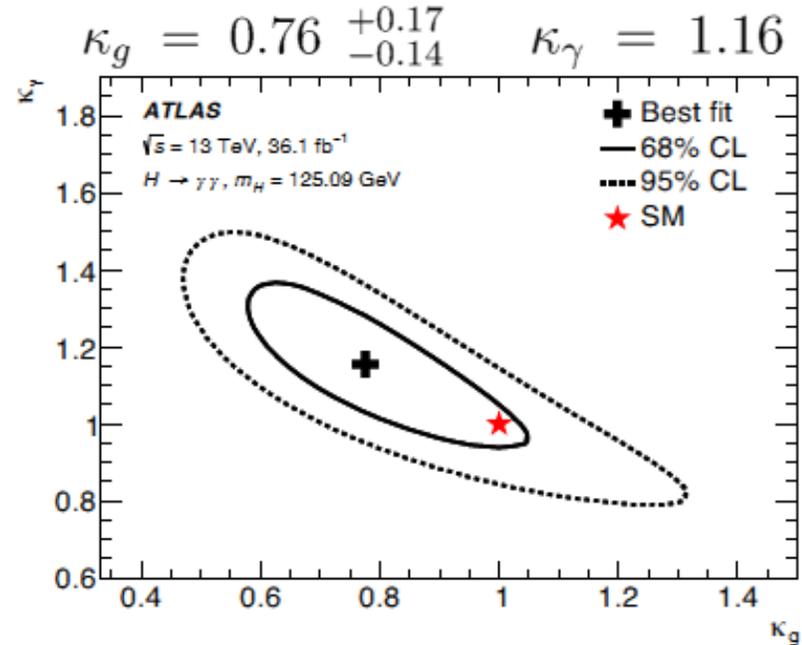


$\rho > 0$ : destr. interf.  $H \rightarrow \gamma\gamma$  (W, t)

degeneracy  $\kappa_f < 0$  excluded at  $>95\%$  CL

- Loops

using  $\kappa_V = \kappa_W = \kappa_Z, \kappa_F = \kappa_t = \kappa_b = \kappa_\tau$



- Loops, width, V, top

$$\kappa_{g\gamma} = \kappa_g \kappa_\gamma / \kappa_H$$

$$\lambda_{Vg} = \kappa_V / \kappa_g$$

$$\lambda_{tg} = \kappa_t / \kappa_g$$

Parameter	Result	Uncertainty			
		Total	Stat.	Exp.	Theo.
$\kappa_{g\gamma}$	0.90	$\pm 0.10$	$\left( \pm 0.09 \right)$	$\pm 0.04$	$\left( \begin{matrix} +0.04 \\ -0.03 \end{matrix} \right)$
$\lambda_{Vg}$	1.41	$\begin{matrix} +0.31 \\ -0.26 \end{matrix}$	$\left( \begin{matrix} +0.28 \\ -0.23 \end{matrix} \right)$	$\begin{matrix} +0.10 \\ -0.07 \end{matrix}$	$\left( \begin{matrix} +0.04 \\ -0.03 \end{matrix} \right)$
$\lambda_{tg}$	0.8	$\begin{matrix} +0.4 \\ -0.6 \end{matrix}$	$\left( \begin{matrix} +0.4 \\ -0.6 \end{matrix} \right)$	$\pm 0.1$	$\left( \begin{matrix} +0.1 \\ -0.0 \end{matrix} \right)$

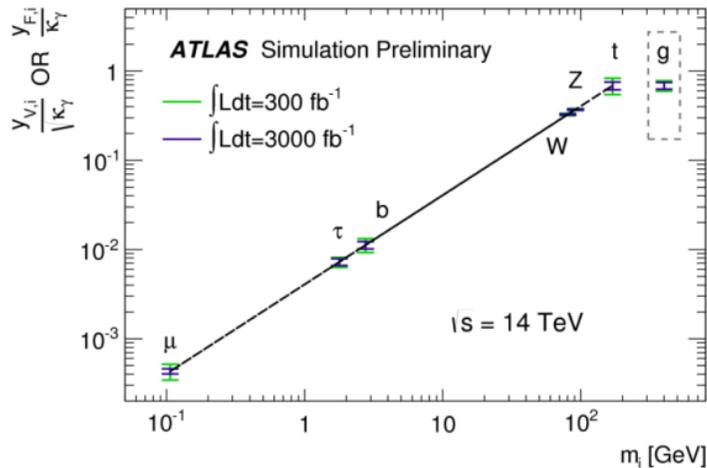
# Prospectives on couplings

ATLAS, HL-LHC,  $\sqrt{s}=14$  TeV,  $L=3000$  fb $^{-1}$ , ATL-PHYS-PUB-2014-016

- publication 2014 of  $H \rightarrow \gamma\gamma$ :  $\Delta\mu/\mu$  : 24 %  
(combination : 13 %)

- Run 2 : 100 fb $^{-1}$ ,  $\sqrt{s}=13-14$  TeV :
  - increase E : ( $\sigma$  x 2-3) [from  $\sqrt{s}=8$  TeV to 13 TeV]
  - increase L : x 4 [from 25 fb $^{-1}$  to 100 fb $^{-1}$ ]
- expect decrease stat. uncertainty by factor 3
- expect evidence of VBF, VH

- Longer term : better improvement

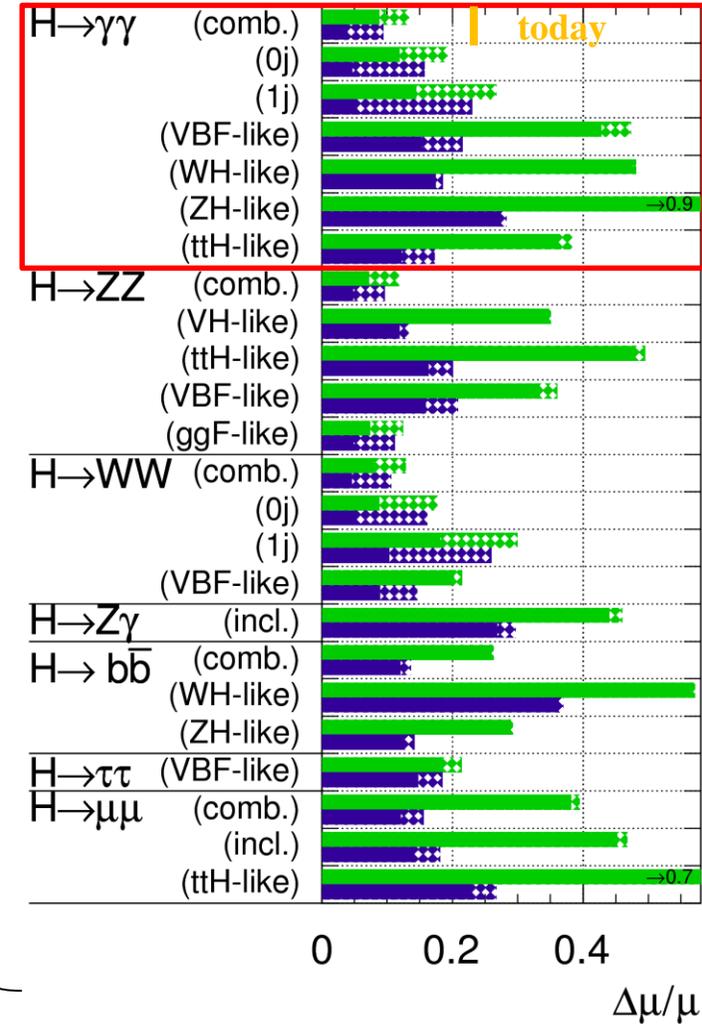


$$Y_V = \sqrt{\kappa_V} \frac{m_V}{v} \quad y_f = \kappa_f \frac{m_f}{v}$$

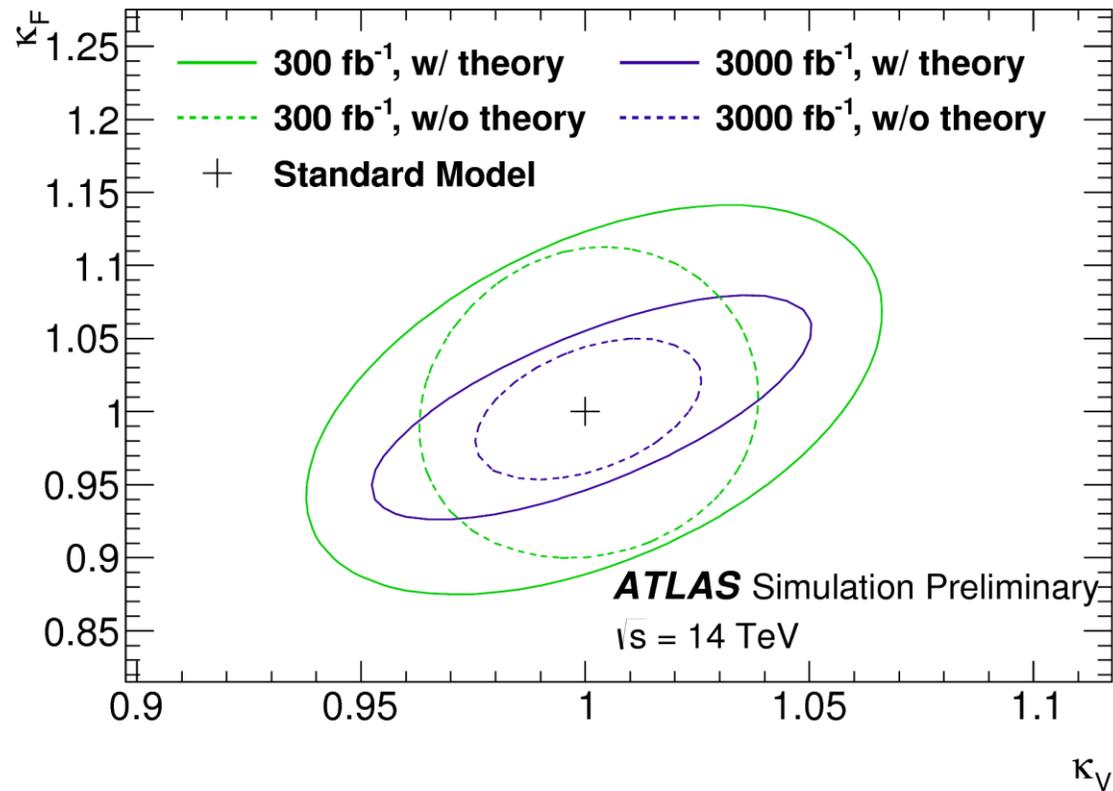


**ATLAS Simulation Preliminary**

$\sqrt{s} = 14$  TeV:  $\int L dt = 300$  fb $^{-1}$  ;  $\int L dt = 3000$  fb $^{-1}$



# Prospectives on couplings



+ many benchmarks models

# Prospectives on BSM from couplings

ATLAS, HL-LHC,  $\sqrt{s}=14$  TeV,  $L=3000$  fb $^{-1}$ , ATL-PHYS-PUB-2014-017

- inputs :  $h \rightarrow \gamma\gamma$ ,  $h \rightarrow ZZ^* \rightarrow 4l$ ,  $h \rightarrow WW^* \rightarrow l\nu l\nu$ ,  $h \rightarrow Z(l\nu)\gamma$ ,  $h \rightarrow \tau\tau$ ,  $h \rightarrow \mu\mu$ ,  $h \rightarrow b\bar{b}$

- Mass scaling of couplings

$$m_H = 125 \text{ GeV}$$

phenomenological parametrization

$$\text{SM} : (M, \epsilon) = (v, 0)$$

$$\kappa_F = v \frac{m_F^\epsilon}{M^{1+\epsilon}}$$

Deviation coupling from its strength =  $f(m^i)$

$$\kappa_V = v \frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$$

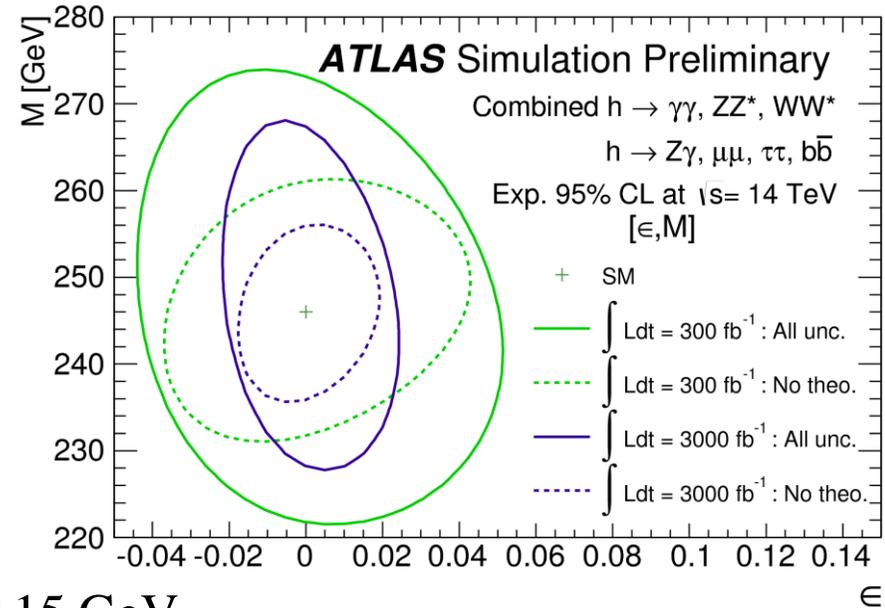
95 % exclusion expectations

300 fb $^{-1}$ : wo/ syst.  $|\epsilon| < 0.04$

3000 fb $^{-1}$ : wo/ syst.  $|\epsilon| < 0.02$

$M > v \pm 15$  GeV

$M > v \pm 10$  GeV



# Prospectives on BSM from couplings

## Minimal Composite Higgs Model

- Higgs is a composite Higgs
- Solves naturalness problem

Higgs couplings changed wrt to SM, w/ compositeness scale  $f$

Compositeness scale  $f$      $\xi = v^2/f^2$     SM:  $\xi \rightarrow 0$ ;  $f \rightarrow \infty$

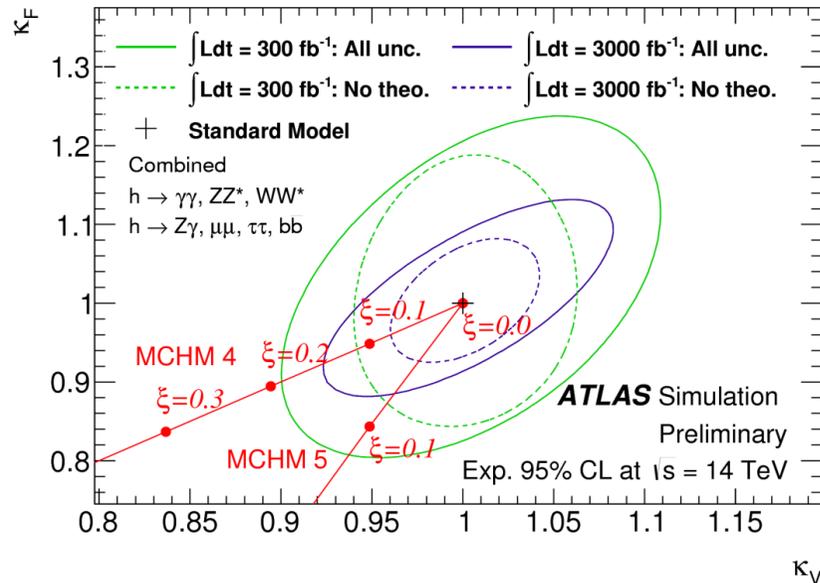
$f$ (representation fermions): spinorial: MCHM4

$$\kappa = \kappa_V = \kappa_F = \sqrt{1 - \xi}$$

fundamental: MCHM5

$$\kappa_V = \sqrt{1 - \xi}$$

$$\kappa_F = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$



95 % exclusion expectations

300 fb<sup>-1</sup>: w/ (wo/) syst.:  $\xi < 0.10$  (0.067)

$\Leftrightarrow f > 780$  GeV (950 GeV)

3000 fb<sup>-1</sup>: w/ (wo/) syst.:  $\xi < 0.060$  (0.039)

$\Leftrightarrow f > 1.0$  TeV (1.2 TeV)

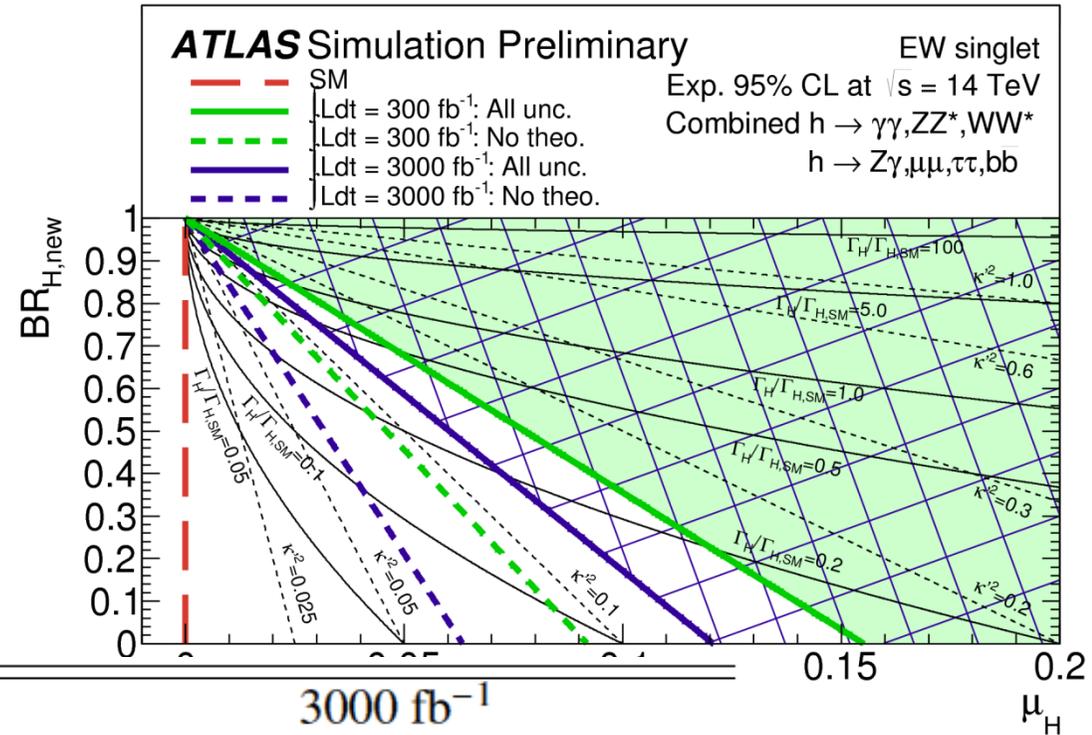
# Prospectives on BSM from couplings

- Additional electroweak singlet
- Additional scale EW singlet field to doublet Higgs field

$$\kappa, \kappa' : \kappa^2 + \kappa'^2 = 1 \quad \mu_H = \kappa^2$$

95 % exclusion expectations

Coupling	300 fb <sup>-1</sup>		3000 fb <sup>-1</sup>	
	All unc.	No theory unc.	All unc.	No theory unc.
$\kappa'^2$	0.17	0.10	0.13	0.06



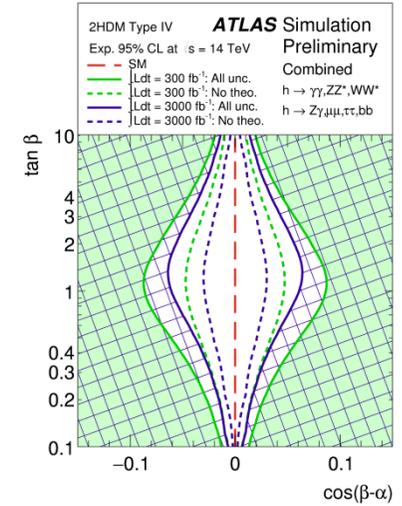
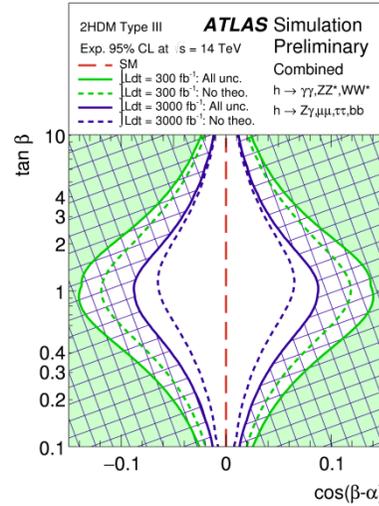
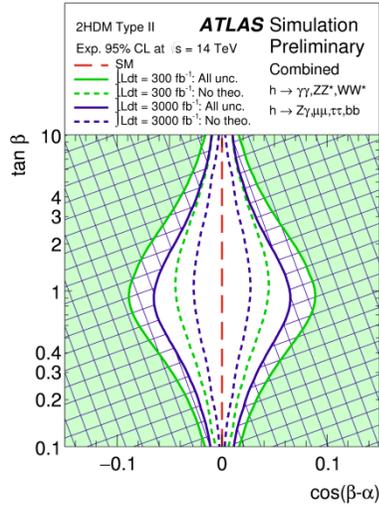
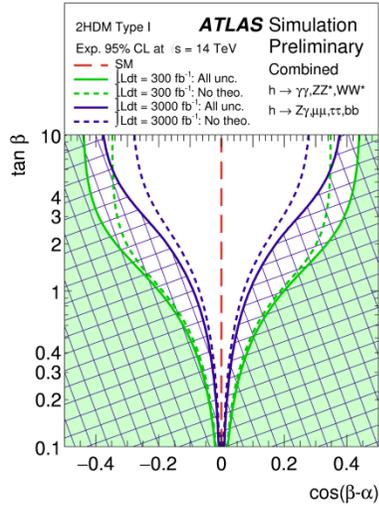
$\kappa$ :

300 fb<sup>-1</sup>: w/ (wo/) syst.: 4.2 % (2.4 %)

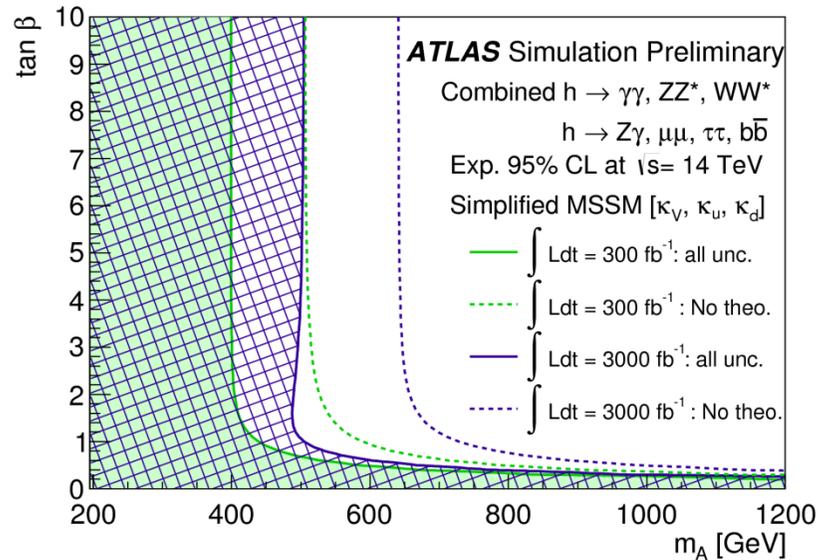
3000 fb<sup>-1</sup>: w/ (wo/) syst.: 3.2 % (1.7 %)

# Prospectives on BSM from couplings

- 2HDM ; 5 Higgs bosons : modify couplings



- hMSSM



# Prospectives on BSM from couplings

- 2HDM ; 5 Higgs bosons : modify couplings

Coupling scale factor	Type I	Type II	Type III	Type IV
$\kappa_V$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
$\kappa_u$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$	$\cos(\alpha) / \sin(\beta)$
$\kappa_d$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$
$\kappa_l$	$\cos(\alpha) / \sin(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$-\sin(\alpha) / \cos(\beta)$	$\cos(\alpha) / \sin(\beta)$

- hMSSM

$$\kappa_V = \frac{s_d(m_A, \tan \beta) + \tan \beta s_u(m_A, \tan \beta)}{\sqrt{1 + \tan^2 \beta}}$$

$$\kappa_u = s_u(m_A, \tan \beta) \frac{\sqrt{1 + \tan^2 \beta}}{\tan \beta}$$

$$\kappa_d = s_d(m_A, \tan \beta) \sqrt{1 + \tan^2 \beta},$$

$$s_u = \frac{1}{\sqrt{1 + \frac{(m_A^2 + m_Z^2)^2 \tan^2 \beta}{(m_Z^2 + m_A^2 \tan^2 \beta - m_h^2 (1 + \tan^2 \beta))^2}}}$$

$$s_d = \frac{(m_A^2 + m_Z^2) \tan \beta}{m_Z^2 + m_A^2 \tan^2 \beta - m_h^2 (1 + \tan^2 \beta)} s_u$$

# Prospectives on BSM from couplings

- Higgs Dark-matter portal

BR<sub>i</sub>:

300 fb<sup>-1</sup>: w/ (wo/) syst.: 0.22 (0.19)

3000 fb<sup>-1</sup>: w/ (wo/) syst.: 0.13 (0.09)

Translated to constraint on WIMP=f(spin)

