

What we have learned about the Higgs boson



Nicolas Berger (LAPP)
presenting results from the ATLAS and CMS collaborations

The Higgs Boson

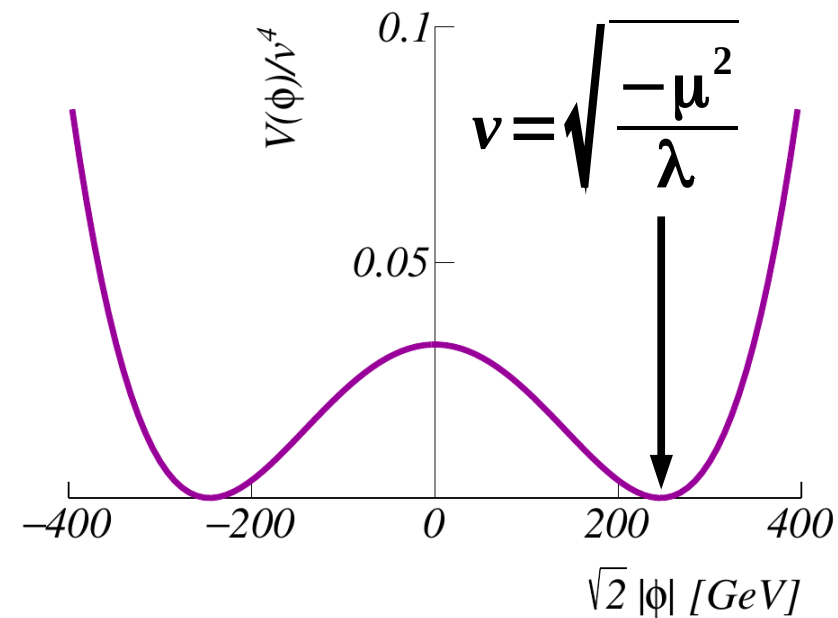
SM:

Scalar sector = single SU(2) doublet

→ acquires VEV $v \sim 246$ GeV:

- **EWSB**, **Gauge boson masses**
- **Fermion masses** through Yukawa couplings

→ One physical scalar left over: **Higgs boson**



$$\mathcal{L}_{\text{Scalar}} = |D_\mu \phi|^2 + \mu^2 |\phi|^2 + \lambda |\phi|^4 + y_{ij} \phi f_{L,i} f_{R,j}$$

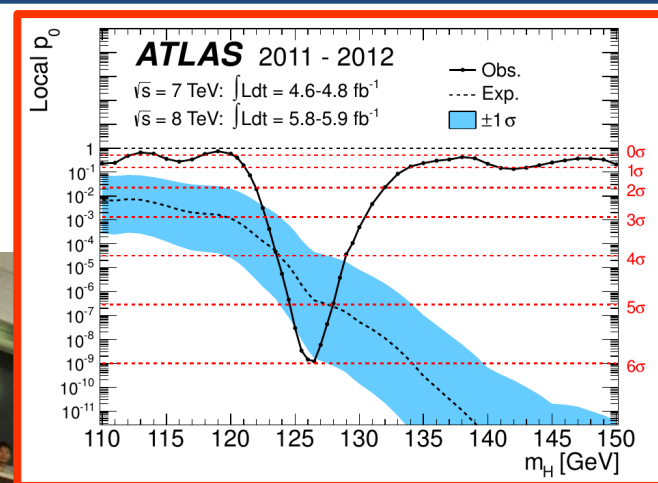
$$m_{W,Z}^2 = \frac{1}{2} g_{W,Z} v$$

$$m_H^2 = 2 \lambda v^2$$

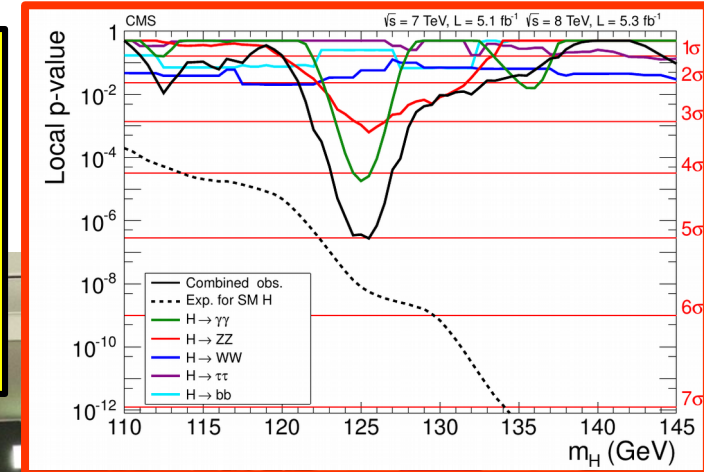
$$m_f = \frac{1}{\sqrt{2}} y_f v$$

Only **one parameter** specific to Higgs physics: **$m_H \sim 125$ GeV**

July 4th, 2012



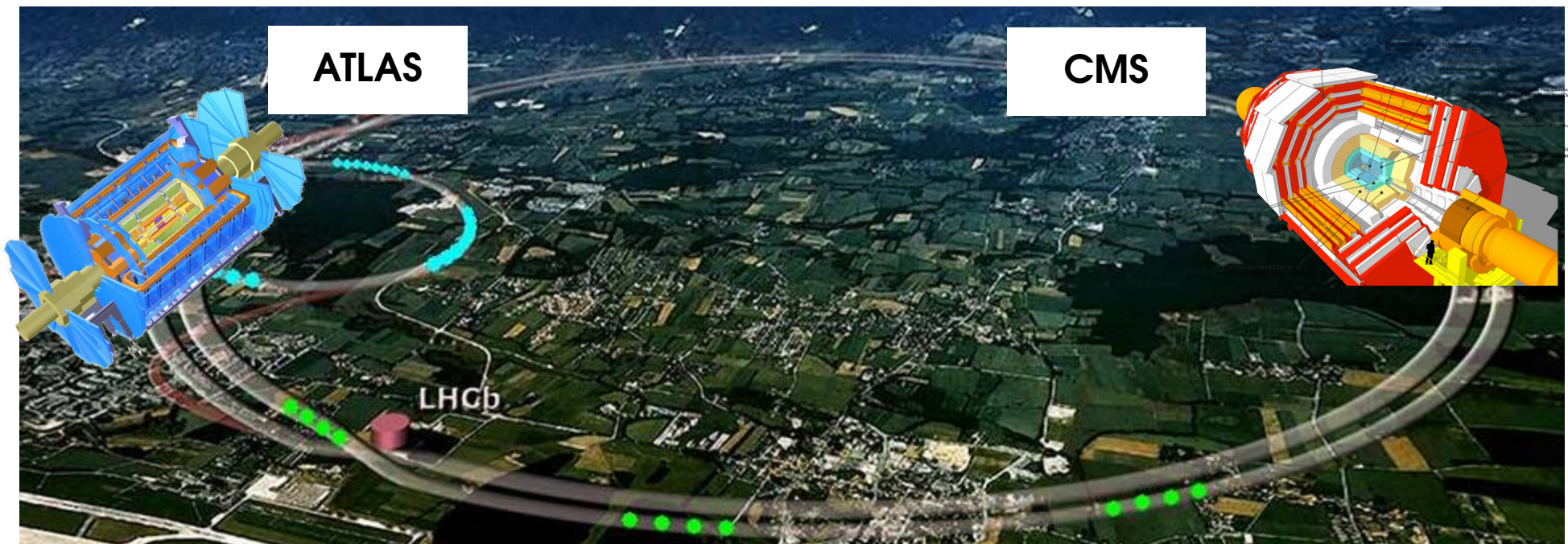
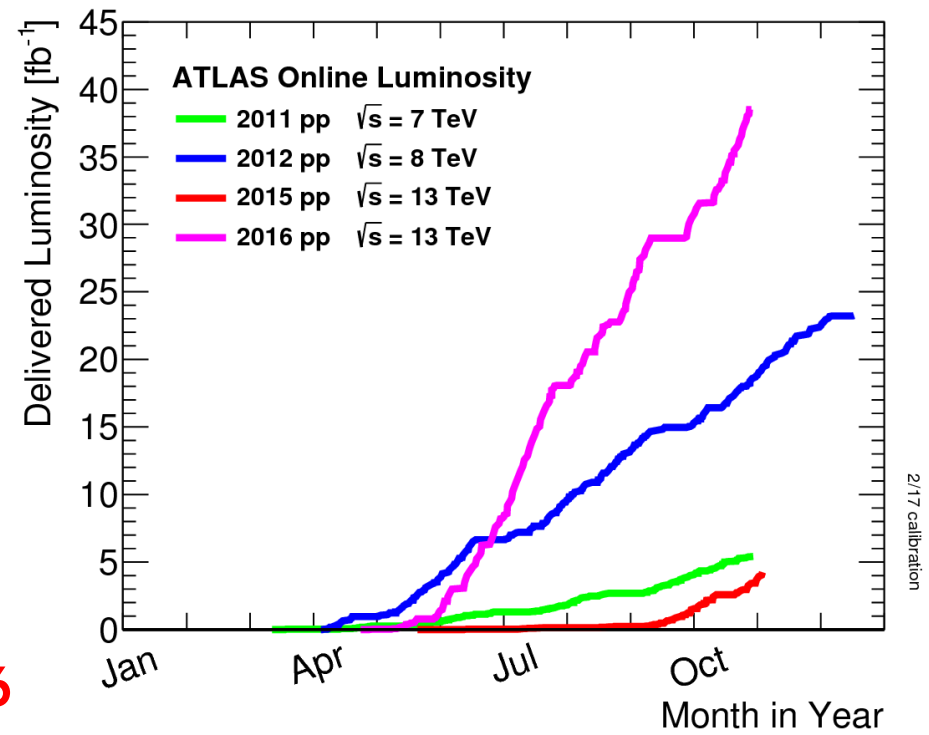
Higgs Discovery
“2 x 5 σ ” !



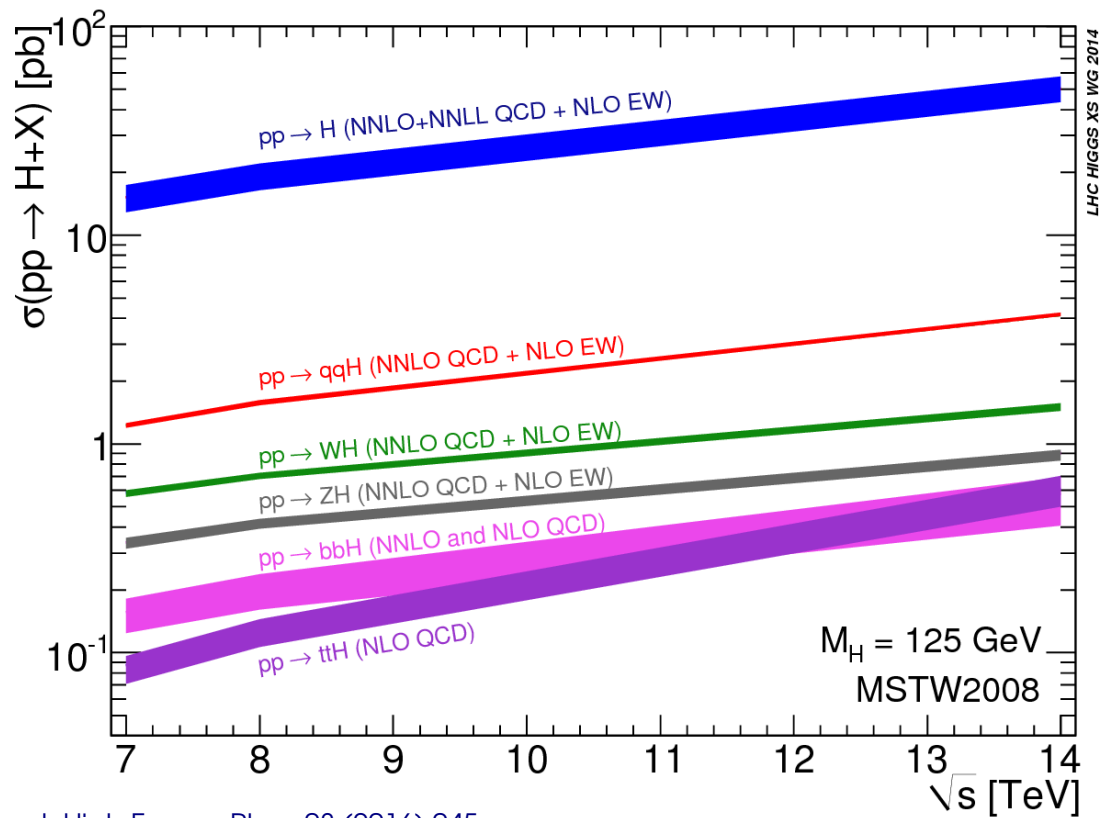
There is **a** Higgs boson! Is it **THE** Higgs boson ?
What have we learned since then ?

LHC

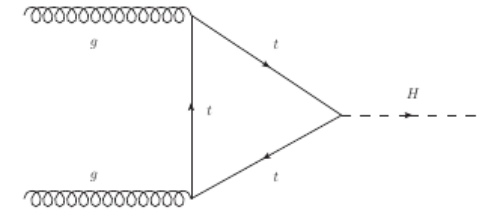
- **Run 1:**
 - $\sqrt{s} = 7$ TeV (~ 5 fb $^{-1}$)
 - $\sqrt{s} = 8$ TeV (~ 20 fb $^{-1}$)
- **Run 2:**
 - $\sqrt{s} = 13$ TeV. **~ 100 fb $^{-1}$ expected,**
 ~ 35 fb $^{-1}$ so far (2015 + 2016)
 - **Excellent LHC performance in 2015-16**
 - Peak lumi 1.4×10^{34} cm $^{-2}$ s $^{-1}$, **exceeds LHC design!**



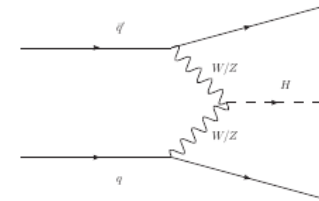
Higgs production at the LHC



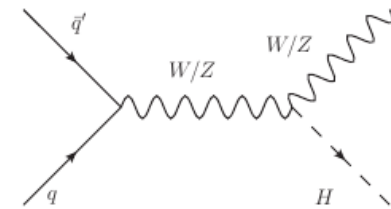
Gluon Fusion (ggF)



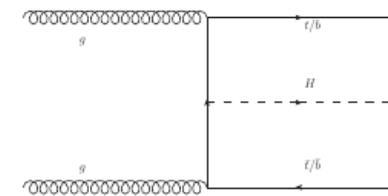
Weak Boson Fusion (VBF)



W/Z Association (VH)



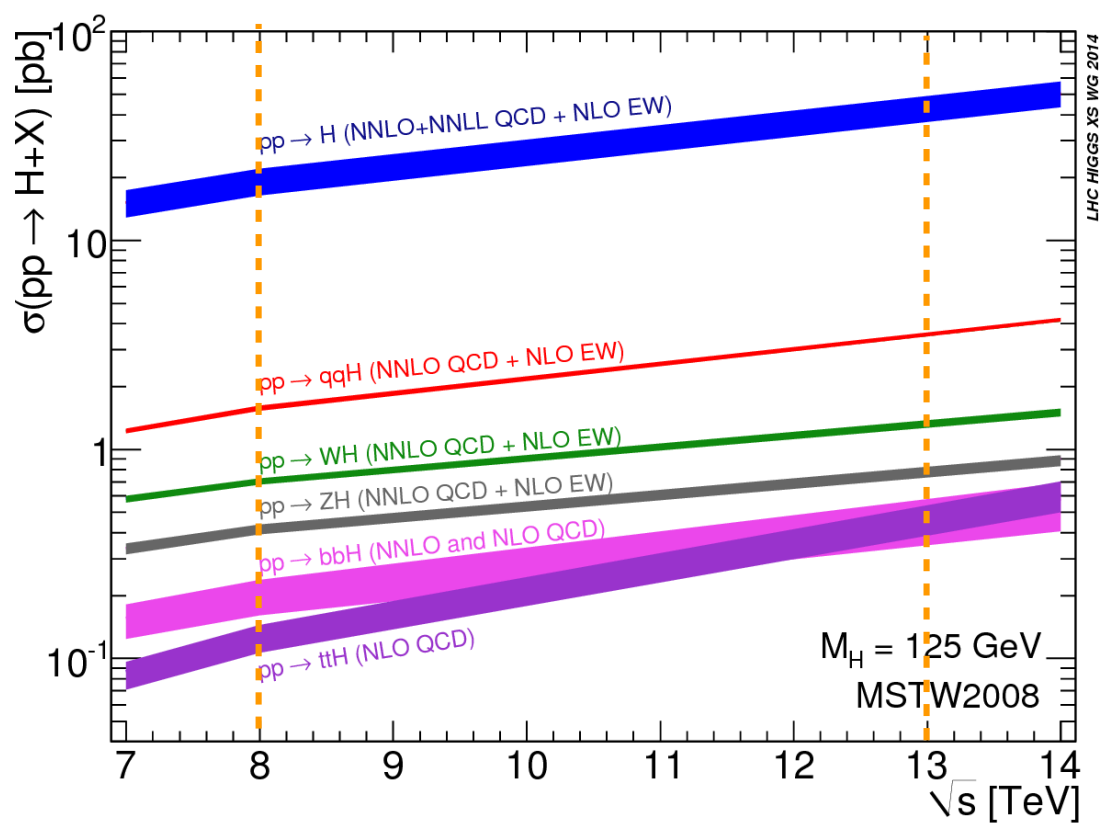
Top Association (ttH)



Run 1	Expected (σ)	Observed (σ)
VBF	4.6	5.4
VH	4.2	3.5
ttH	2.0	4.4

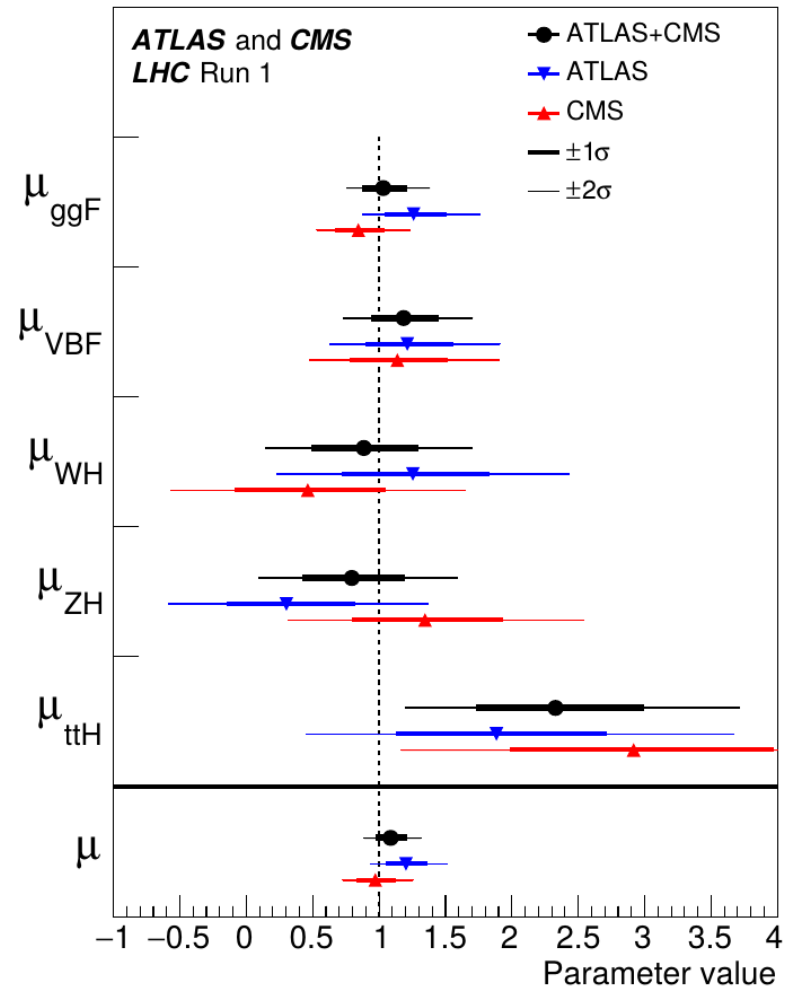
- Mainly ggF production, but many associate prod. modes also accessible
- 5 σ observation of VBF in Run 1**, **large significance also for ttH**

Higgs production at the LHC



$\times 2.3$

$\times 3.8$

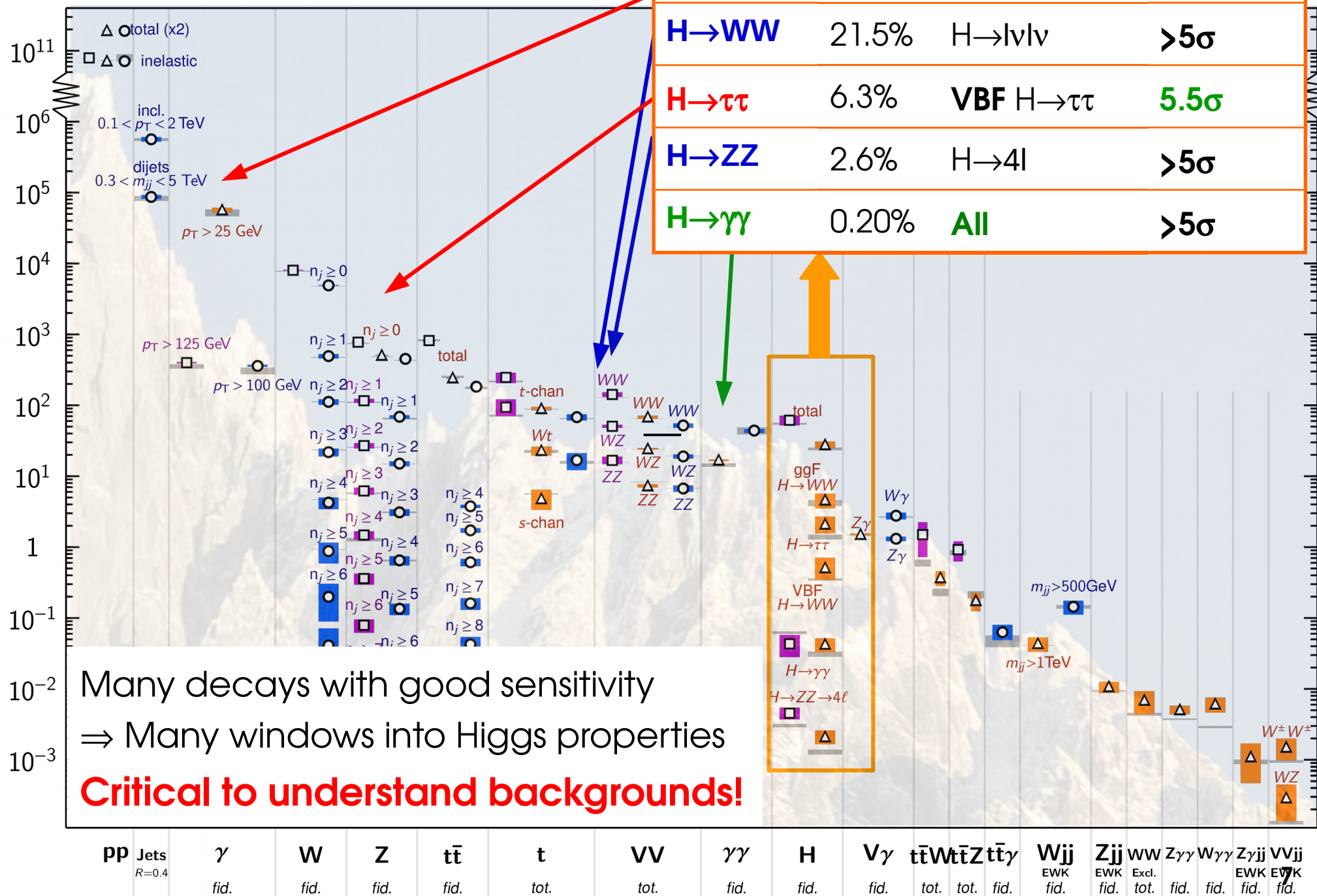


- **Run 1** : excellent agreement with SM,
ttH 2.3 σ higher than expected
- **Run 2** : Increased production cross-
sections from 8 to 13 TeV :
 - $\times 2.3$ for ggF,
 - $\times 3.8$ for ttH

Produced H	Run 1	Run 2 (35 fb ⁻¹)
Total	600k	2M
ttH	3k	18k

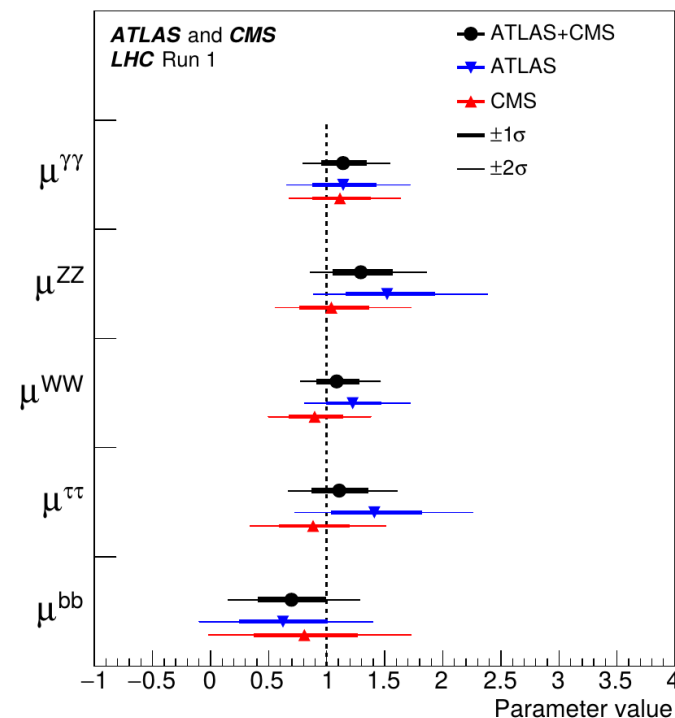
Decay modes

σ [pb]



What do we *want* to know ?

- **H(125) Properties : is it *the* SM Higgs ?**
 - “**Couplings measurements**” : $i \rightarrow H \rightarrow f$
yields, kinematics
 - Possible indirect evidence for new physics
 - **Couplings to gauge bosons** $\Rightarrow$ EWSB
 - **Yukawa couplings**
 - $t\bar{t}H$ higher, $H \rightarrow b\bar{b}$ lower (-2.5σ) than SM ?
 - **Spin/CP**
 - **Framework for comparison with the SM**
 - **Mass, width, lineshape**
 - **Higgs potential, λ**

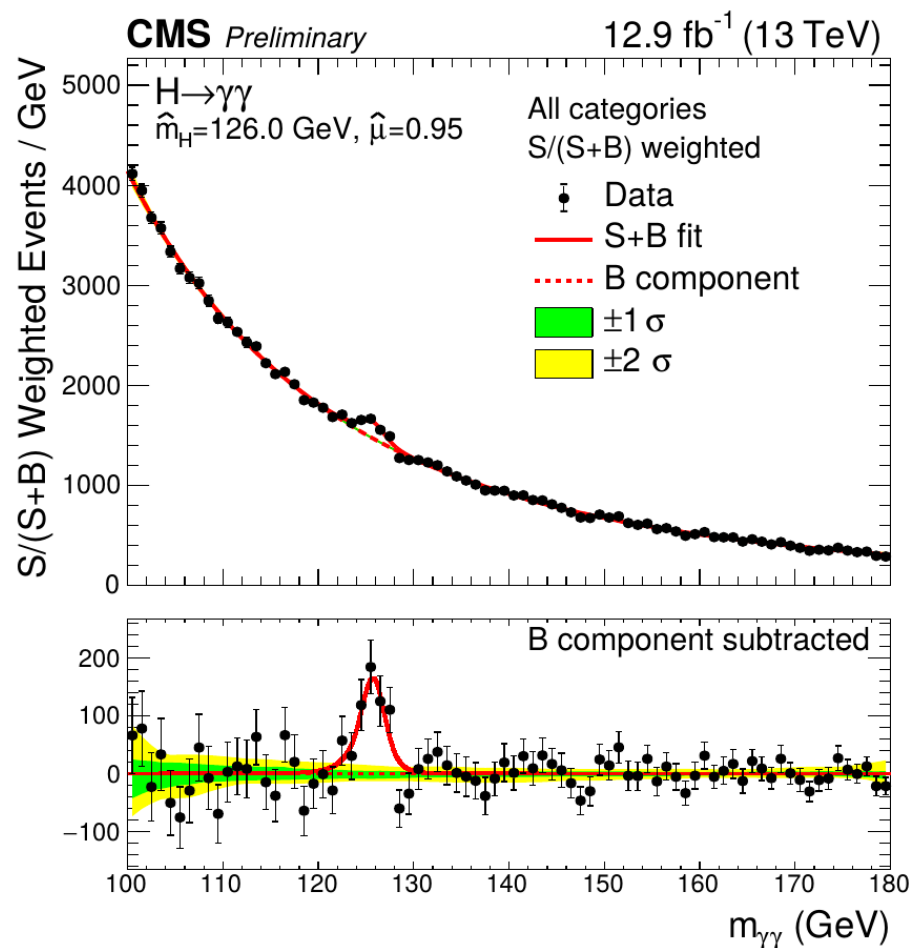
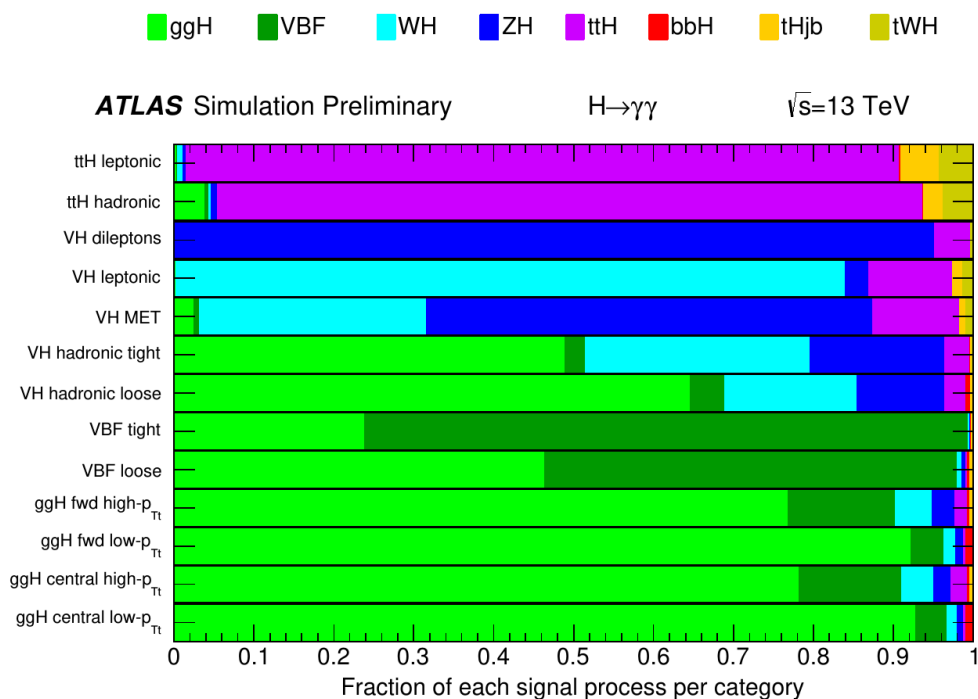


- **Direct evidence for New Physics ?**
 - Other Higgs bosons ?
 - Exotic decays
 - Production in association with new particles

$H \rightarrow \gamma\gamma, H \rightarrow ZZ^* \rightarrow 4l$ Cross-Section Measurements



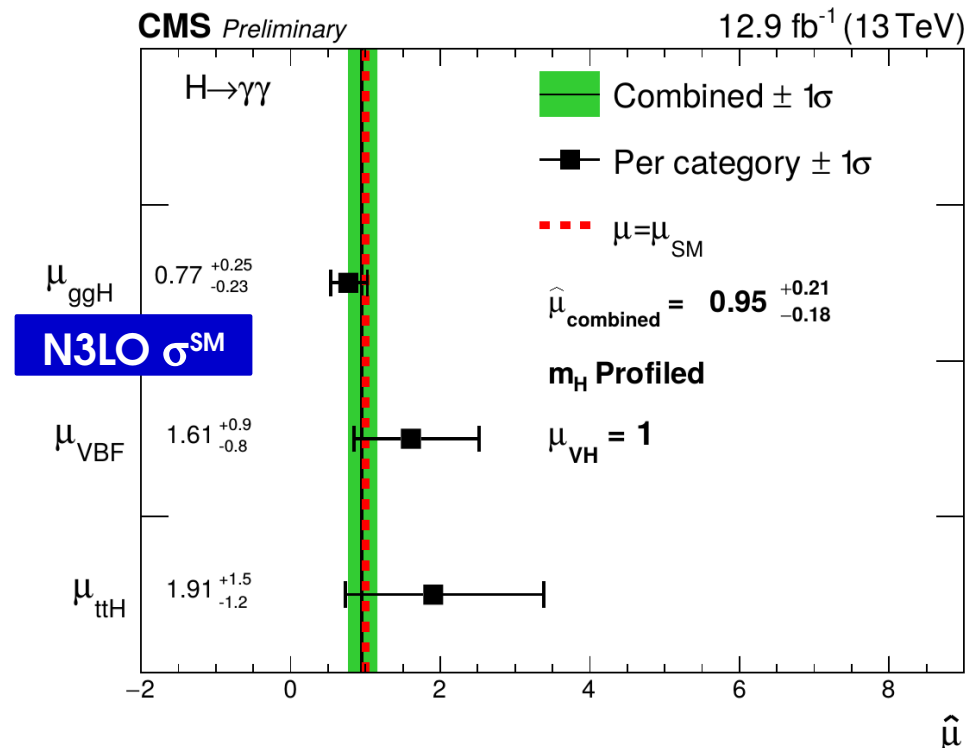
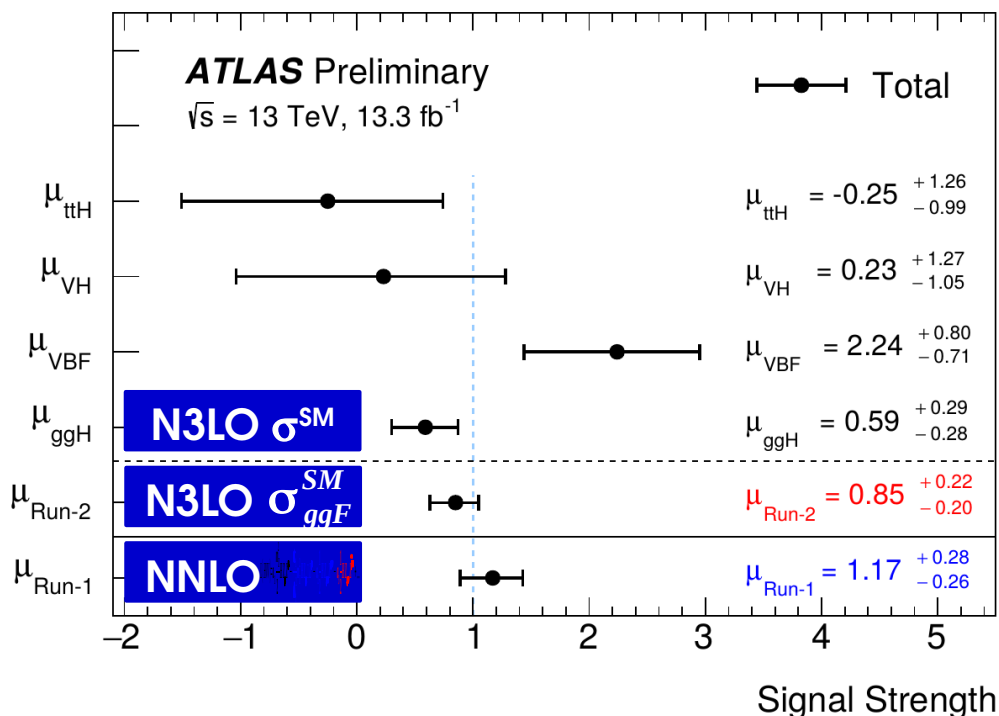
- Simple signature: 2 isolated photons
- **BR ~ 0.2%** but large acceptance $\Rightarrow$ sizable yield (~ 600 reco events in 13 fb^{-1})
- **S/B ~ 3%** $\Rightarrow$ Identify favorable regions
 - **ATLAS**: Higgs p_T , photon η
 - **CMS**: MVA of photon quantities
- Separate selections for **VBF, VH, $t\bar{t}H$**



$H \rightarrow \gamma\gamma$ Couplings Results

- Results for all 5 main production modes

→ Excellent agreement with SM



Run 2:

- New ggF N3LO computation : J. High Energ. Phys. (2016) 058
 - +3% change in σ_{ggF}^{SM}
 - QCD perturbative uncertainties $\sim 7.8\% \rightarrow 3.8\%$
 - PDF+ α_s uncertainties: $\sim 7\% \rightarrow 3.2\%$

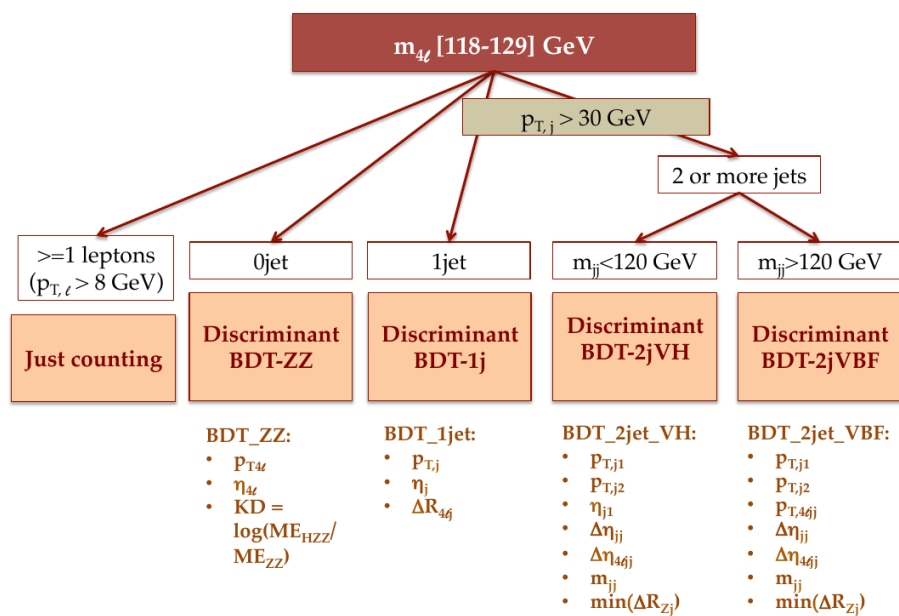
**Experimental precision
now needs to catch
up with theory!**

$H \rightarrow ZZ^* \rightarrow 4l$

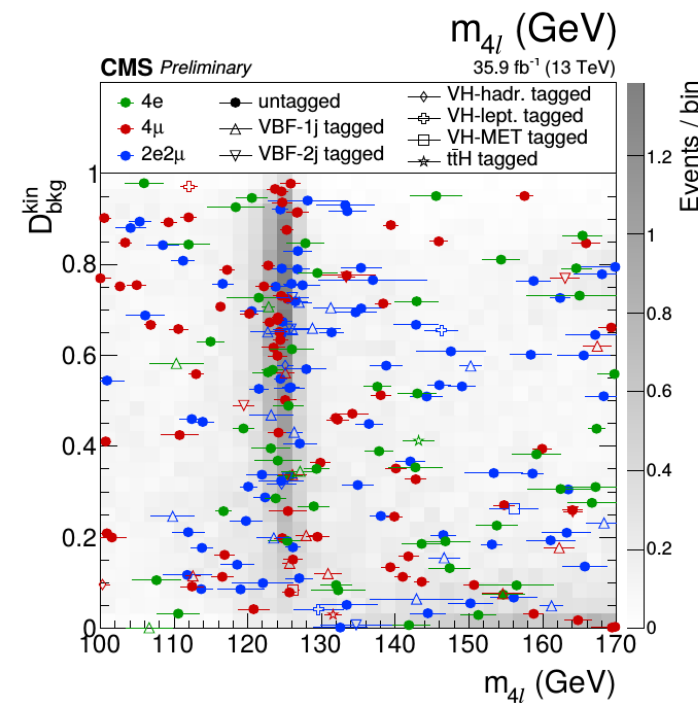
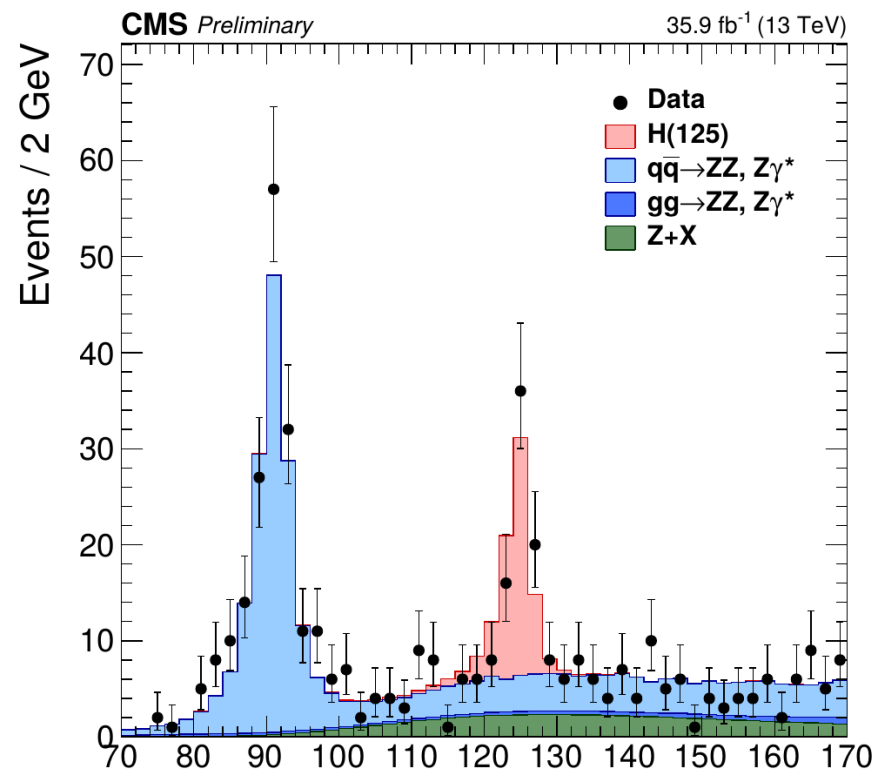
ATLAS-CONF-2016-079

CMS-PAS-HIG-16-041

- Require 4 leptons
 - $p_{T,l}$ reach down to **5(7) GeV** for $\mu(e)$
- Small yield (~ 60 exp. reco evts in 35 fb^{-1}) but large **S/B ~ 2** .
- Separate categories for
 - production modes
 - final states ($4\mu/2\mu 2e/4e$)
- fit MVAs (+ m_{4l} for CMS)



+ $\tau\tau H$ (CMS)



H → ZZ* → 4l Couplings results

• ATLAS:

$$\sigma_{\text{ggF}+b\bar{b}H+i\bar{l}H} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 1.80^{+0.49}_{-0.44} \text{ pb}$$

$$\sigma_{\text{VBF}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.37^{+0.28}_{-0.21} \text{ pb}$$

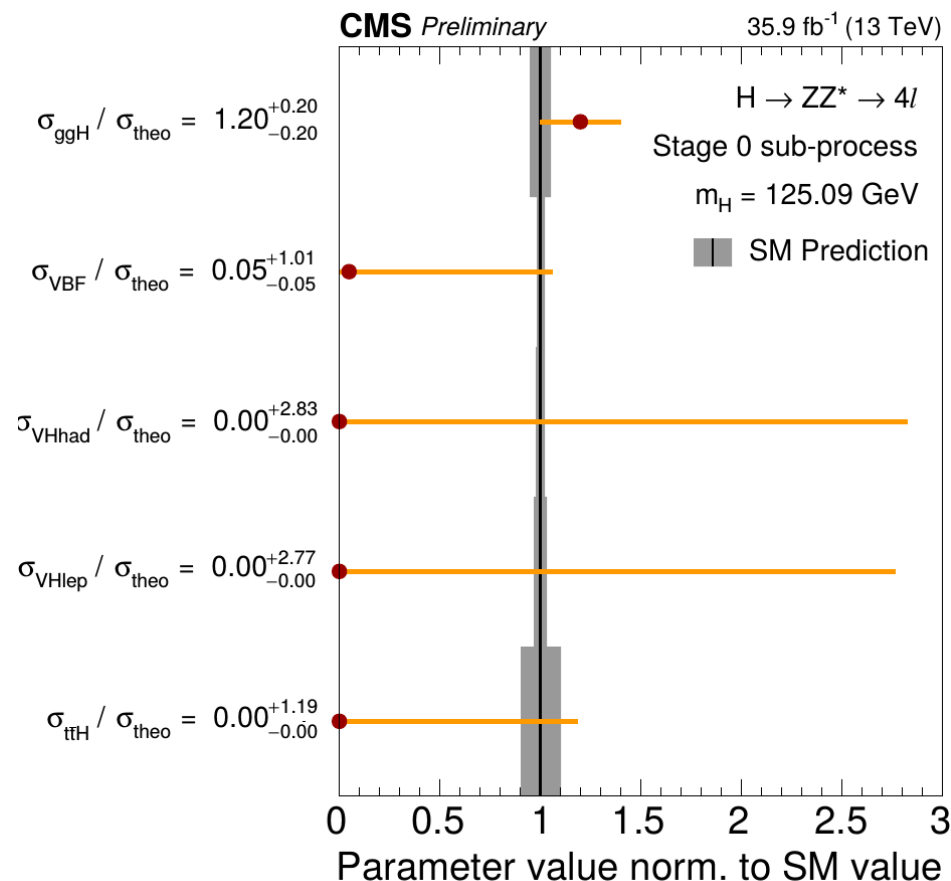
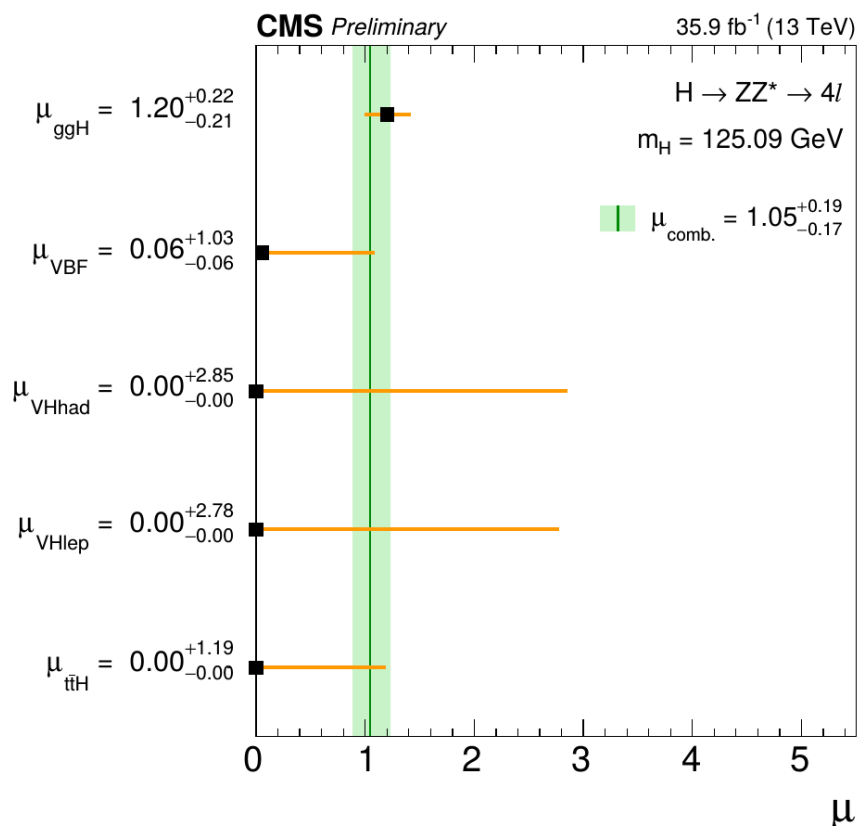
$$\sigma_{\text{VH}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0^{+0.15} \text{ pb}$$

$$\sigma_{\text{SM,ggF}+b\bar{b}H+i\bar{l}H} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 1.31 \pm 0.07 \text{ pb}$$

$$\sigma_{\text{SM,VBF}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.100 \pm 0.003 \text{ pb}$$

$$\sigma_{\text{SM,VH}} \cdot \mathcal{B}(H \rightarrow ZZ^*) = 0.059 \pm 0.002 \text{ pb}$$

• CMS



All in excellent agreement with the SM

H → ZZ and H → γγ Fiducial results

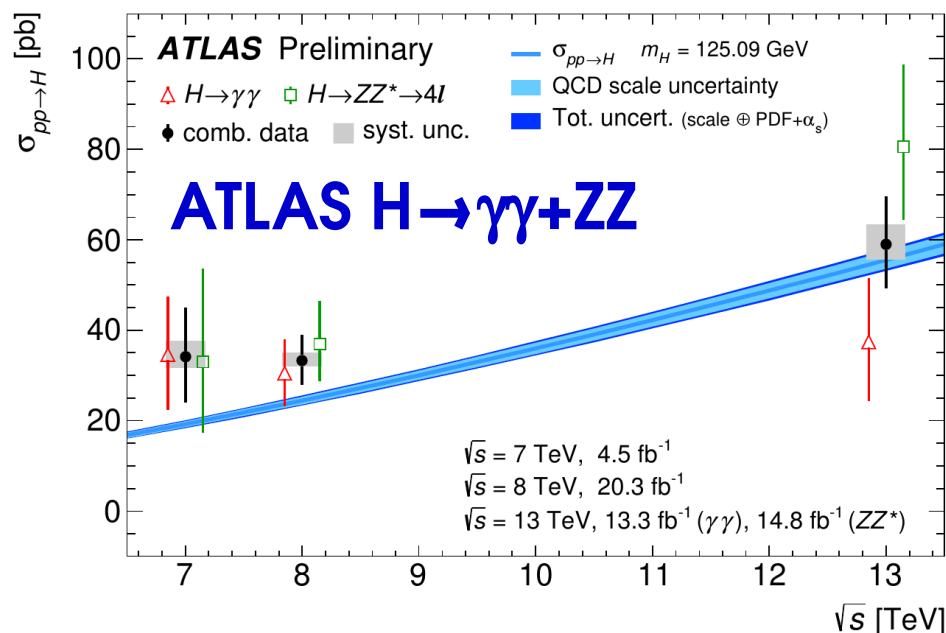
CMS-PAS-HIG-17-015

- Report cross-sections in **fiducial regions** matching reco acceptance ⇒ lower model-dependence
- ATLAS H → γγ : report σ in **VBF-like** and **VH-like** (lepton) regions

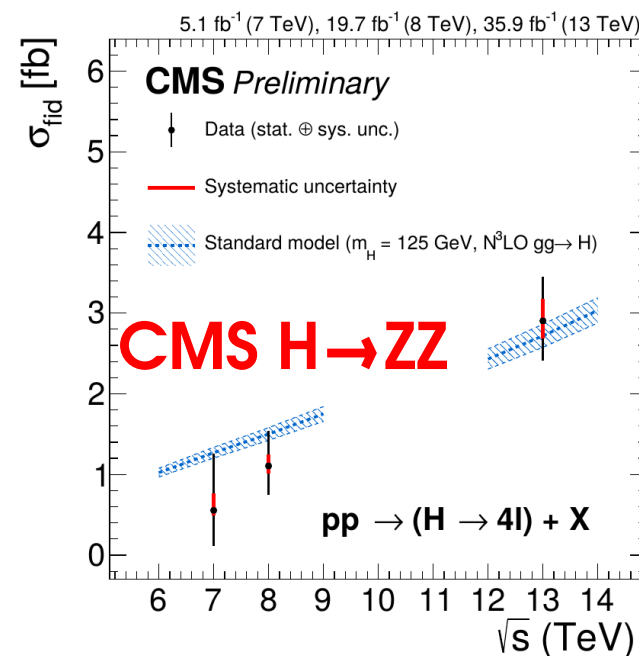
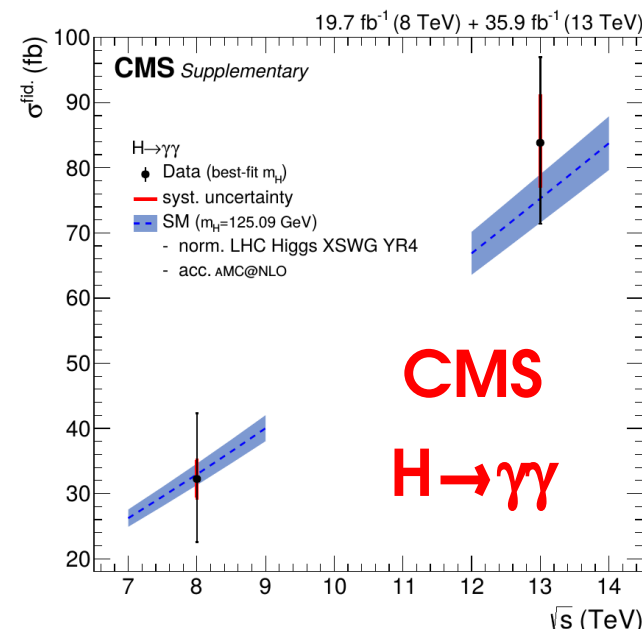
ATLAS H → γγ

ATLAS-CONF-2016-067

Fiducial region	Measured cross section (fb)	SM prediction (fb)
Baseline	43.2 ± 14.9 (stat.) ± 4.9 (syst.)	$62.8^{+3.4}_{-4.4}$ [N ³ LO + XH]
VBF-enhanced	4.0 ± 1.4 (stat.) ± 0.7 (syst.)	2.04 ± 0.13 [NNLOPS + XH]
single lepton	1.5 ± 0.8 (stat.) ± 0.2 (syst.)	0.56 ± 0.03 [NNLOPS + XH]



ATLAS-CONF-2016-081

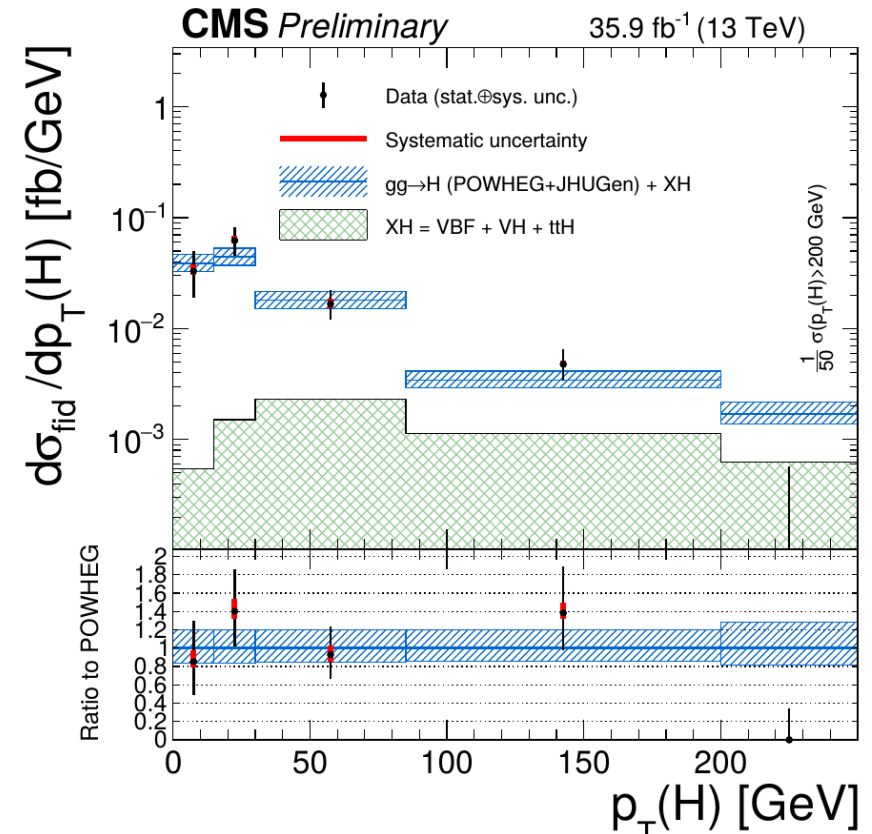
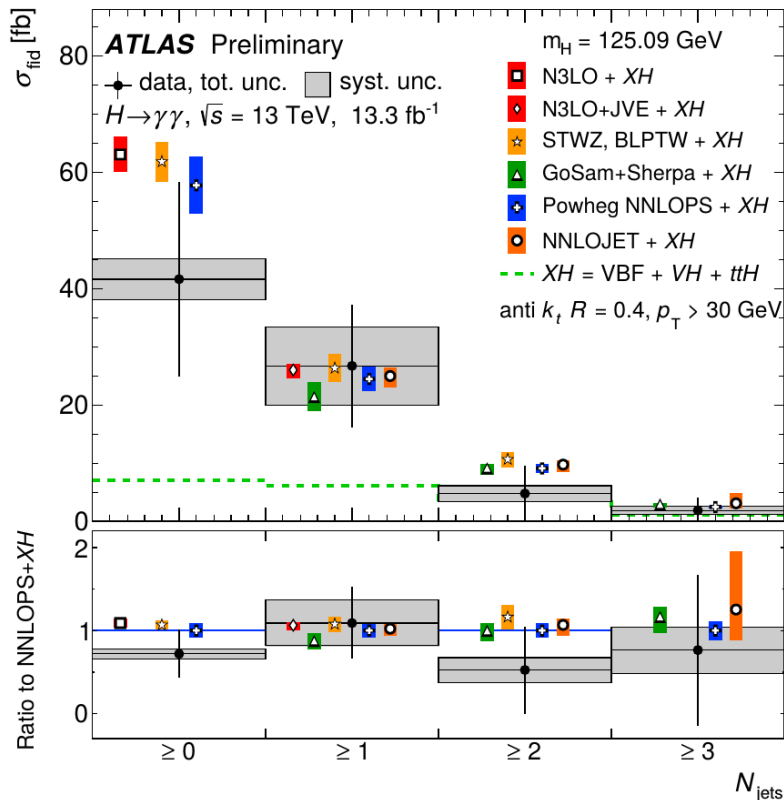


CMS-PAS-HIG-16-041

All in agreement with the SM!

$H \rightarrow \gamma\gamma/ZZ$ Differential Results

- Report fiducial σ in bins of given variables $\Rightarrow$ **Differential** cross-sections
- Variables considered: p_T^H , N_{jets} , 1-jet and 2-jet kinematic variables



All in agreement with the SM!

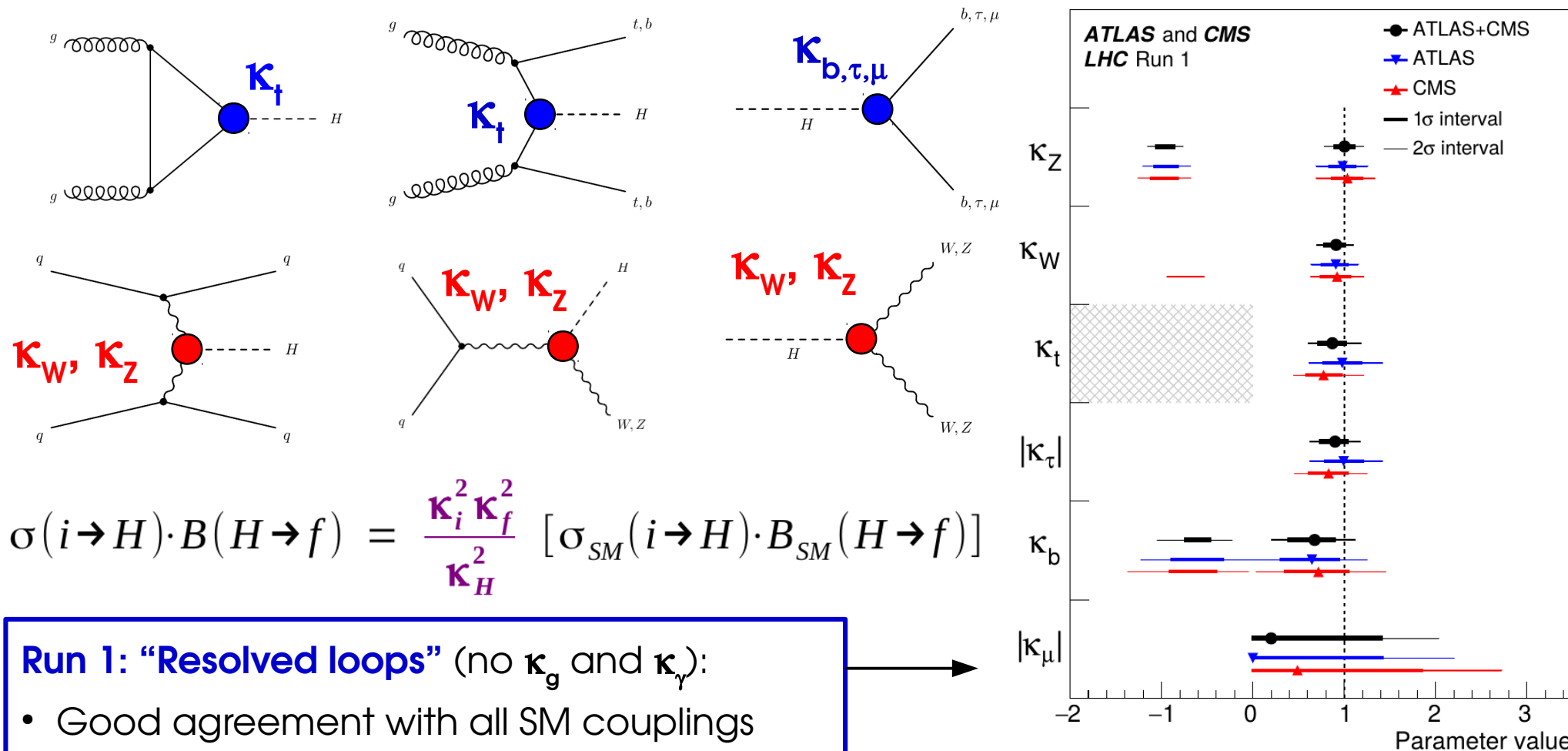
No large deviations from SM – how best to quantify them ?

$H \rightarrow \gamma\gamma, H \rightarrow ZZ^* \rightarrow 4l$ Couplings Measurements



In Run 1, Higgs couplings interpreted within the “ κ -framework”:

- κ_x modifiers for **all Hxx vertices**
 - also κ_g and κ_γ for effective **ggH** and **H $\gamma\gamma$** loops, κ_H for Higgs total width
- “**LO-inspired**” scaling for **$i \rightarrow H \rightarrow f$** (use the best available SM prediction for $\kappa=1$)

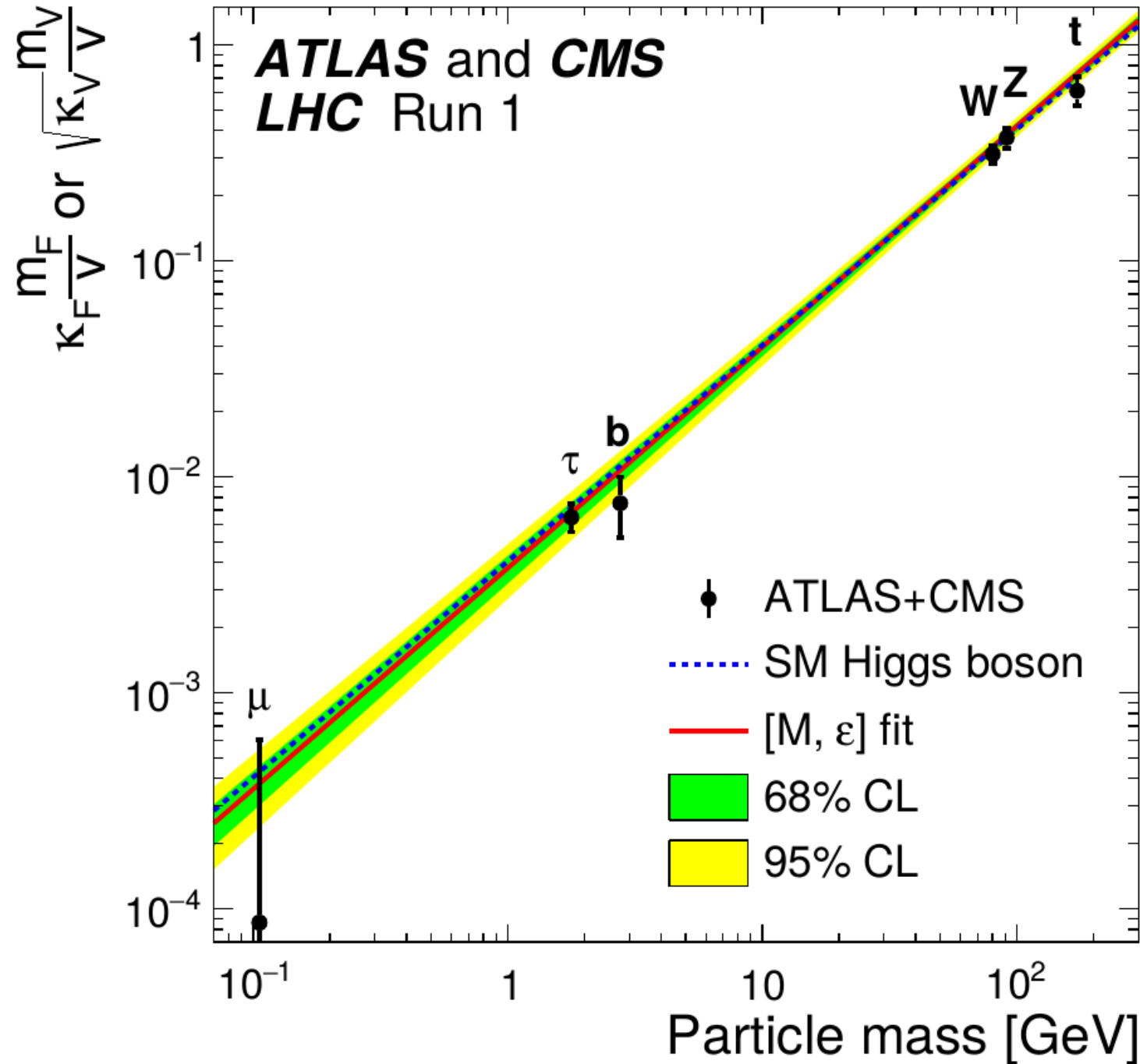


$$\sigma(i \rightarrow H) \cdot B(H \rightarrow f) = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} [\sigma_{SM}(i \rightarrow H) \cdot B_{SM}(H \rightarrow f)]$$

Run 1: “Resolved loops” (no κ_g and κ_γ):

- Good agreement with all SM couplings
- slightly low κ_b

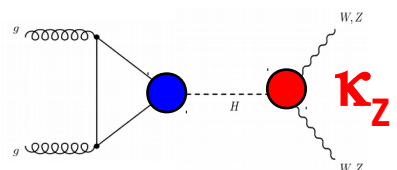
Same conclusion when including κ_g and κ_γ . 17



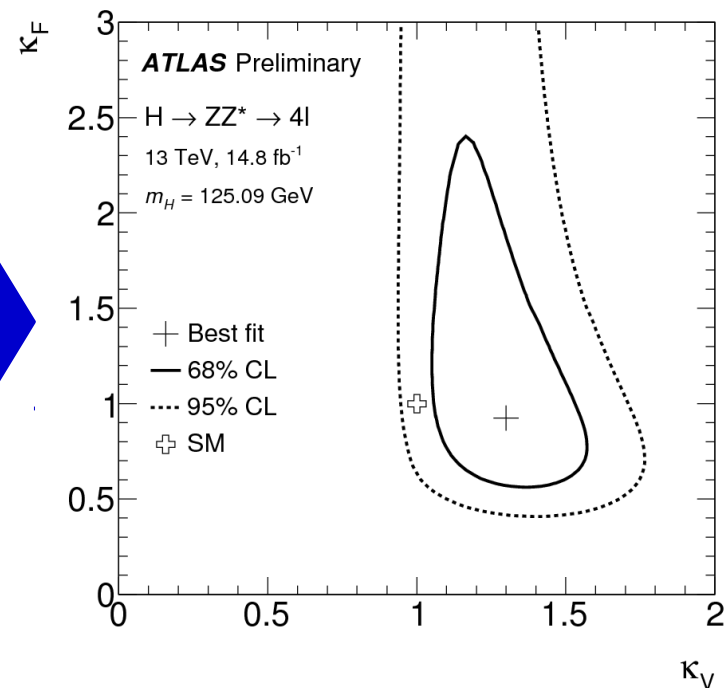
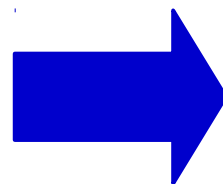
Run 2 κ -framework Results

$H \rightarrow ZZ$

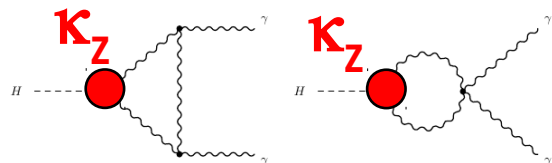
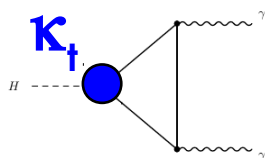
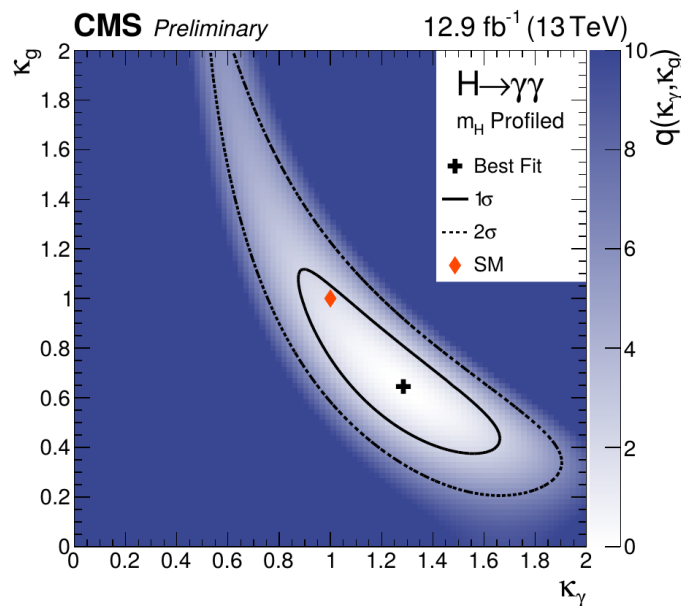
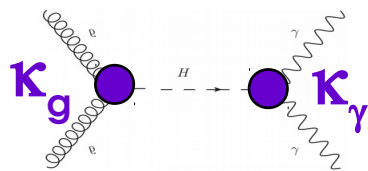
κ_f



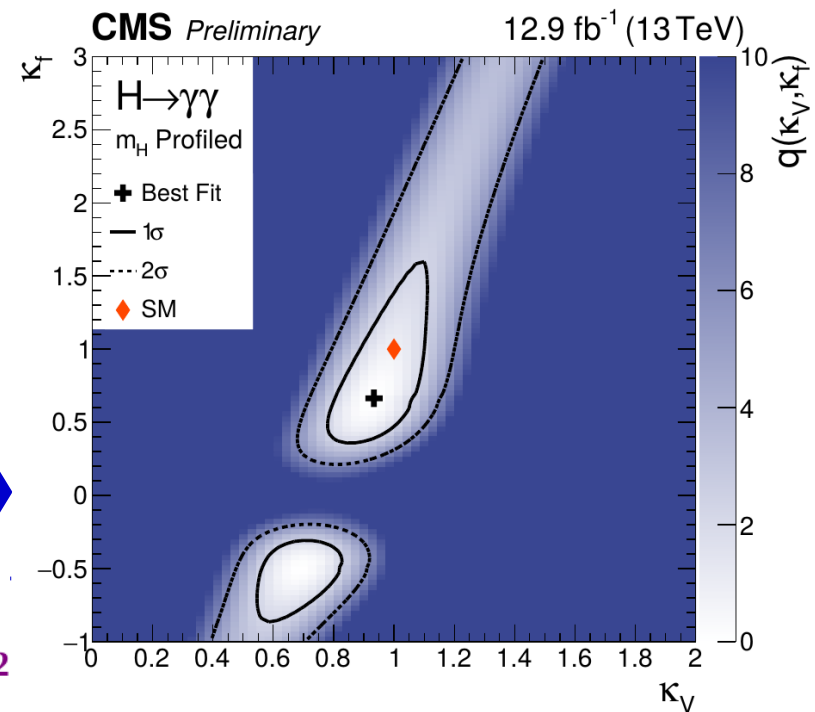
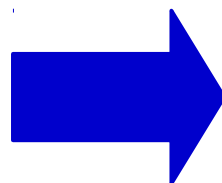
$$\frac{\sigma(gg \rightarrow H \rightarrow ZZ)}{\sigma^{SM}(gg \rightarrow H \rightarrow ZZ)} = \frac{\kappa_F^2 \kappa_V^2}{\kappa_H^2 \approx \kappa_F^2} = \kappa_V^2$$



$H \rightarrow \gamma\gamma$



$$\frac{\sigma(gg \rightarrow H \rightarrow \gamma\gamma)}{\sigma^{SM}(gg \rightarrow H \rightarrow \gamma\gamma)} = \frac{\kappa_F^2 \kappa_\gamma^2}{\kappa_H^2 \approx \kappa_F^2} = (1.3\kappa_V - 0.3\kappa_F)^2$$



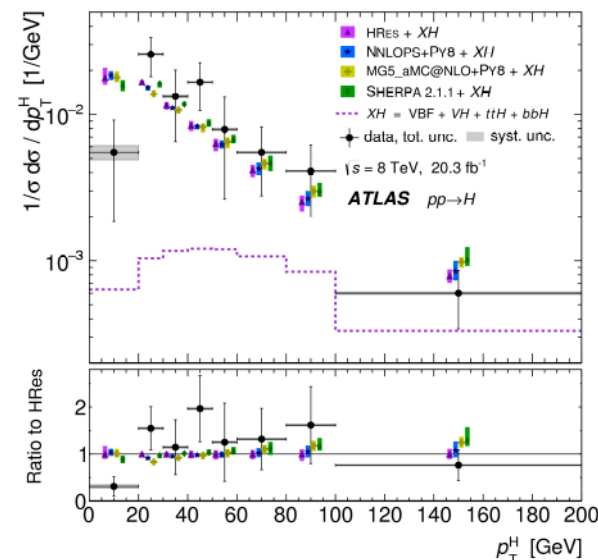
Beyond the κ Framework

- **Pros**

- Easy to implement
- Well-defined **near the SM limit** $\kappa_x \rightarrow 1$

- **Cons:**

- Depends on reference SM prediction (NNLO vs. N3LO)
 - Only well-defined at LO
 - Scaling inspired by LO diagrams, cannot be systematically extended to higher orders
 - e.g. breaks gauge symmetries $\Rightarrow$ Divergences
 - Does not include interactions not already in the SM
 - **CP-odd operators**
 - **Non-SM tensor structures**
- $\Rightarrow$ e.g. **no freedom for shape deviations in diff. measurements**



Run 2 : Simplified Template Cross-Sections

YR4 Section III.2

Similarities to fiducial cross-sections:

- measure cross-sections in **truth-level phase space regions**.
- Separate out regions to :
 - **Maximize sensitivity to SM or BSM effects**
 - **Minimize sensitivity to theory uncert., models**

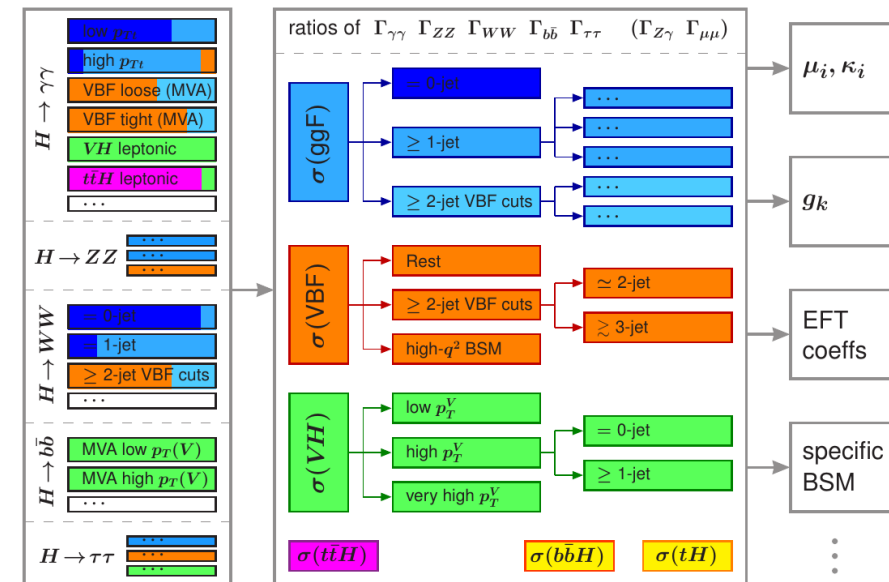
Differences:

- **Split production modes/final states**
- Partitions the **entire phase space** into **non-overlapping regions**
- **No strong matching between truth and reco-level selections**: compromise between
 - “complicated” reco selections (BDTs, etc.)
 - simple and well-defined theory selections

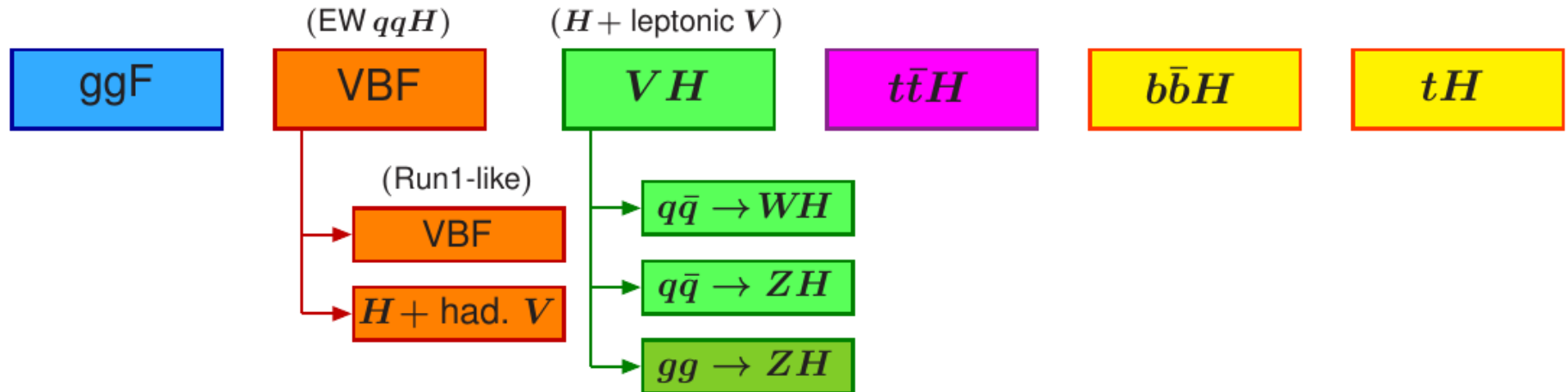
⇒ **Point of contact between theory and experiment**

Complementary to diff. measurements: fully exclusive split along many variables

- **No need for statistical correlations**
- **Coarser binning**

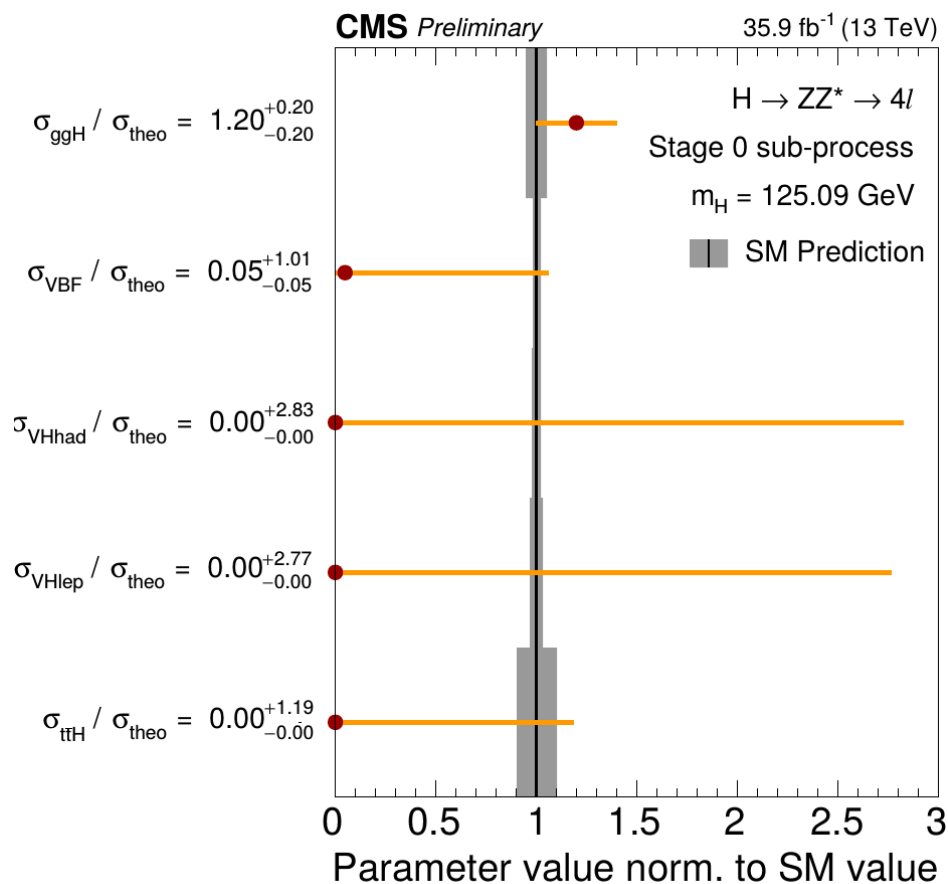


STXS Stage 0

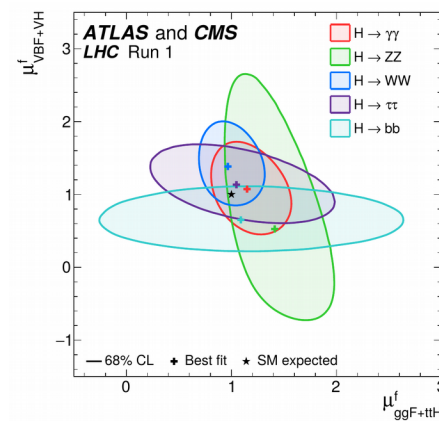
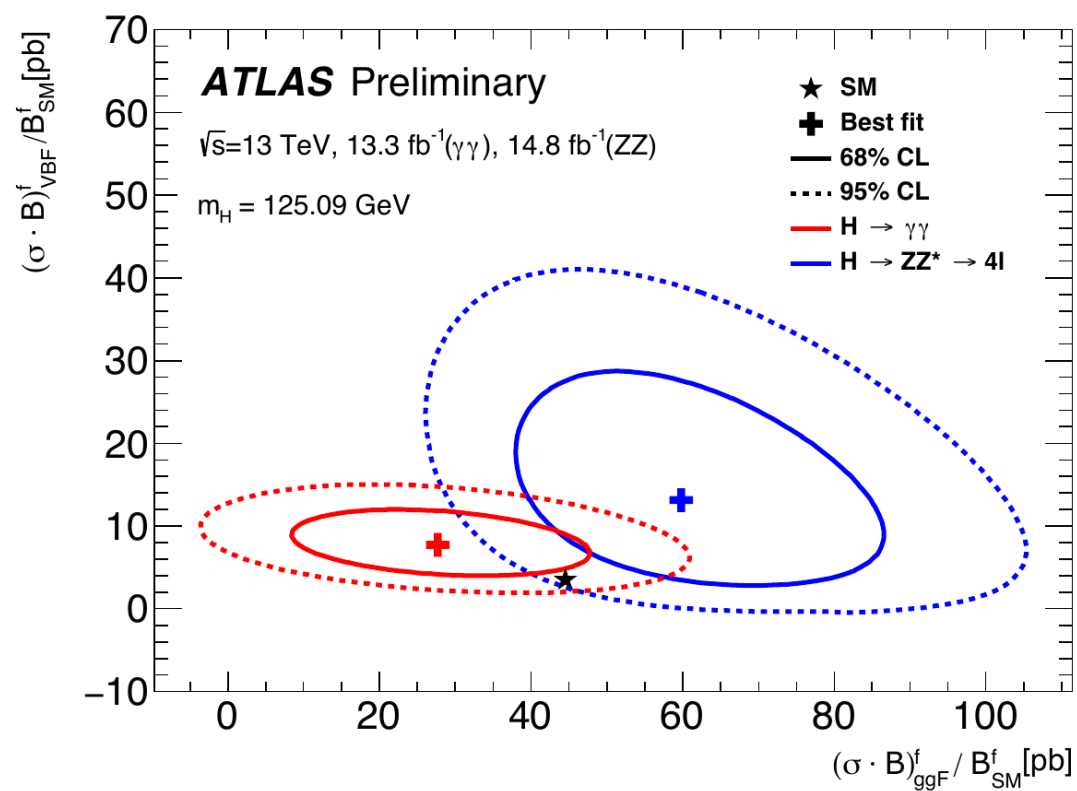


- **Splitting evolves with dataset size** (more data $\Rightarrow$ finer split)
- **“Stage 0”** based on “**production modes**” (**final states**) only
 - Relate **($V \rightarrow \text{had}$) H** to **VBF** since same final state
 - Restricted to **$|\mathbf{y}_H| < 2.5$** to avoid extrapolation
- Used for recent ATLAS and CMS Run 2 results

CMS H→4l Couplings



ATLAS Run 2 $\gamma\gamma$ /ZZ Combination

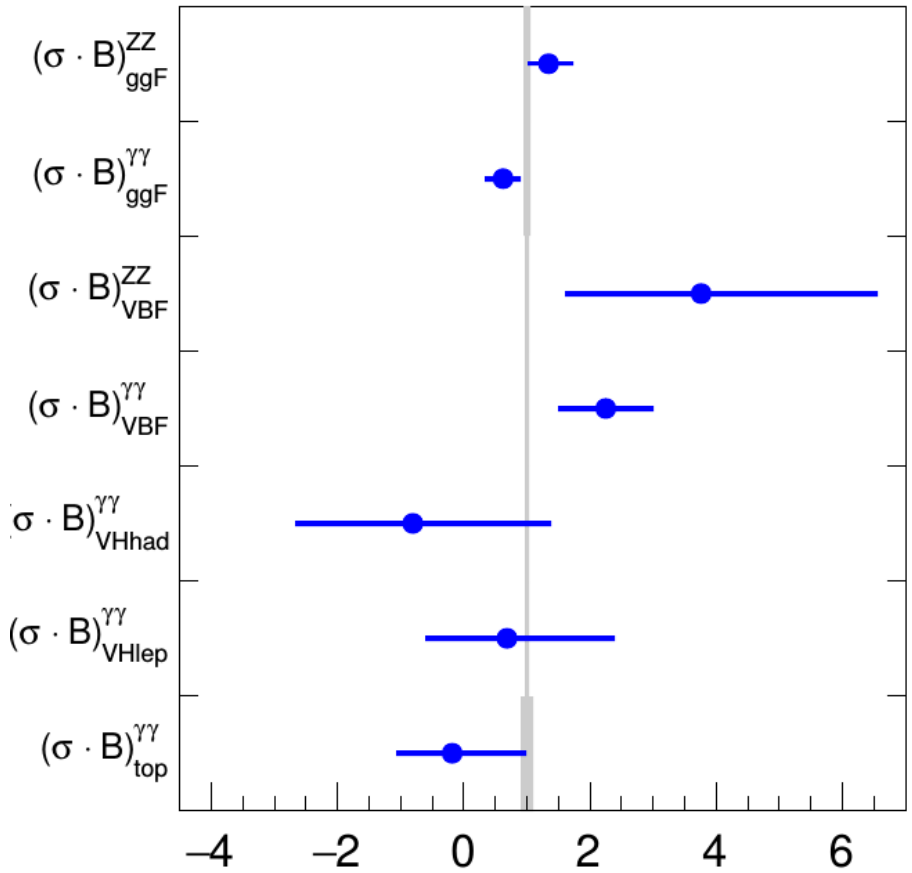


ATLAS Preliminary $m_H=125.09$ GeV
 $\sqrt{s}=13$ TeV, 13.3 fb^{-1} ($\gamma\gamma$), 14.8 fb^{-1} (ZZ)

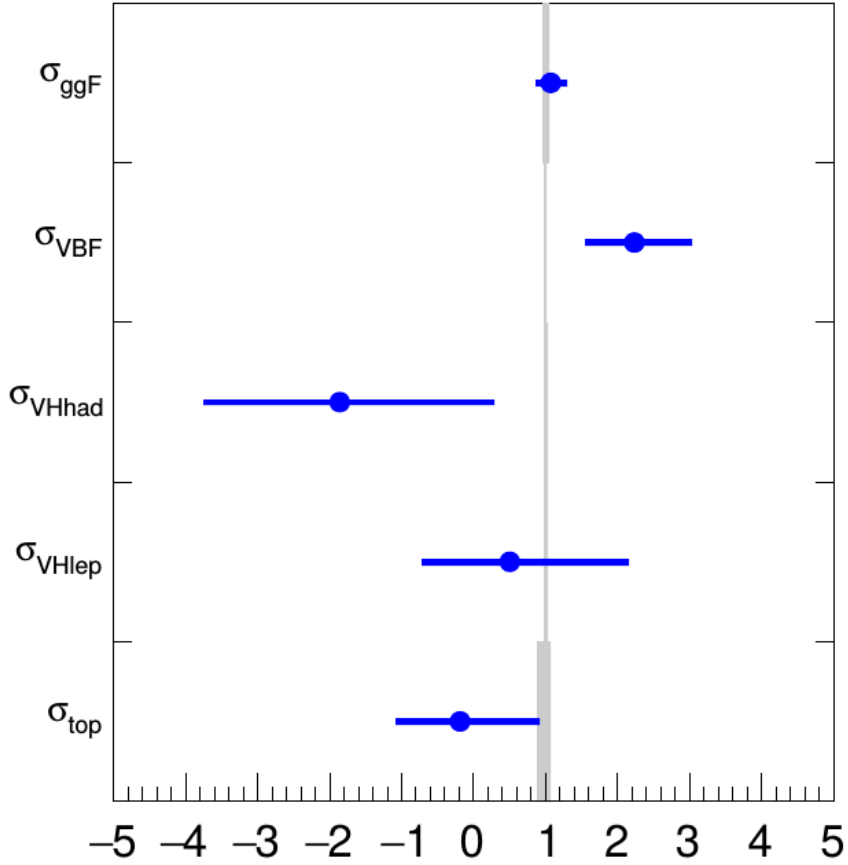
ATLAS Preliminary $m_H=125.09$ GeV
 $\sqrt{s}=13$ TeV, 13.3 fb^{-1} ($\gamma\gamma$), 14.8 fb^{-1} (ZZ)

—●— Observed 68% CL ■ SM Prediction

—●— Observed 68% CL ■ SM Prediction



Parameter value norm. to SM value



Parameter value norm. to SM value

bbH included in ggF
 $top = ttH + tH$

} Assuming SM values for relative fractions

Everything compatible with the SM

Effective Lagrangians

- **ATLAS: Higgs Characterization Model**

- includes HVV' and Hff couplings
- includes both CP-odd and CP-even interactions

α : CP-even/CP-odd mixing angle



$$L_0^V = \kappa_{SM} \frac{\cos \alpha g_{HZZ}}{2} H Z_\mu Z^\mu - \kappa_{H\partial Z} \frac{\cos \alpha}{\Lambda} H Z_\nu \partial_\mu Z^{\mu\nu} - \kappa_{HZZ} \frac{\cos \alpha}{4\Lambda} H Z_{\mu\nu} Z^{\mu\nu} - \kappa_{AZZ} \frac{\sin \alpha}{4\Lambda} H Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \dots$$

SM-like

Anomalous CP-even

Anomalous CP-odd

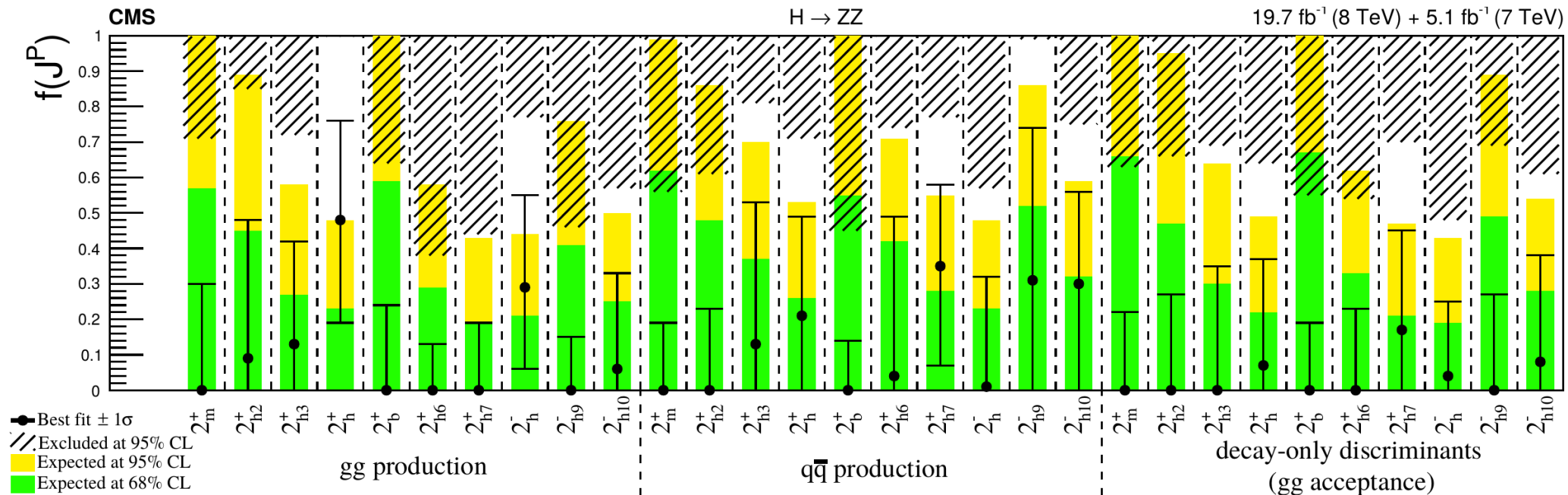
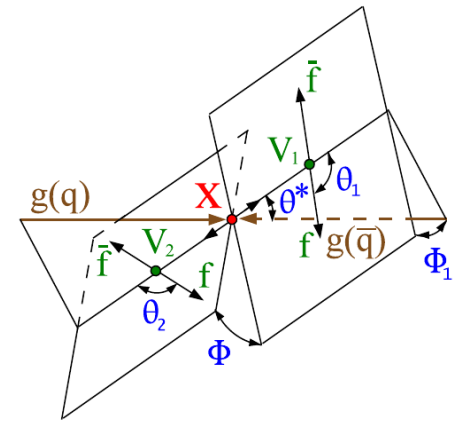
- **CMS: “JHU Model”**: based on Lorentz structure, follows

$$L(HVV) = a_1 \frac{m_Z^2}{2} H Z_\mu Z^\mu - \frac{\kappa_1}{\Lambda_1^2} m_Z^2 H Z_\mu \square Z^\mu - a_2 \frac{1}{2} H Z_{\mu\nu} Z^{\mu\nu} - a_3 \frac{1}{2} H Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \dots$$

- **Almost identical** – in both cases include “ κ ”-like scalings + modified HVV dynamics including CP-odd interactions
- More freedom than an EFT description (e.g. no gauge invariance)
⇒ **more parameters**
- Some **missing contributions** (e.g. HVff operators)

$H \rightarrow ZZ^* \rightarrow 4l$ Spin/Parity

- Sensitivity to **Higgs** J^{PC} from $H \rightarrow ZZ^* \rightarrow 4l$ final state kinematics
- Run 1: Many exotic models tested
→ Most scenarii of **pure** exotic J^{PC} excluded



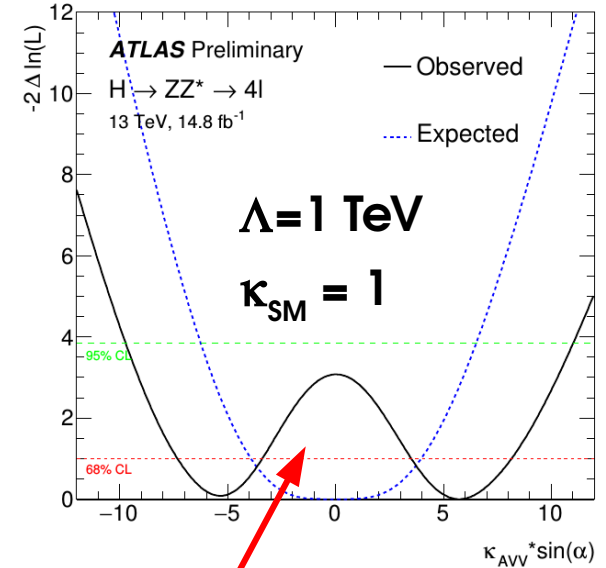
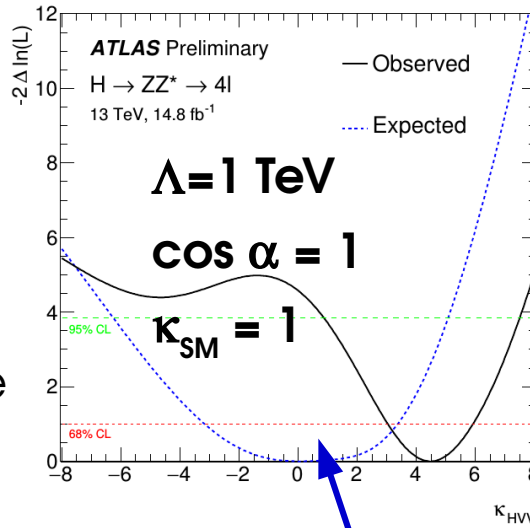
Still possible to have **admixture**s with small (or not) exotic components
⇒ use **effective Lagrangians** to parameterize

H → ZZ* → 4l Spin/Parity Results

CMS-PAS-HIG-17-011
ATLAS-CONF-2016-079

ATLAS :

- Same analysis as H → 4l
- couplings (VBF, VH selections)
- Float each κ_{BSM} in turn
- Central values away from 0 due to excess in 2-jet VBF selection

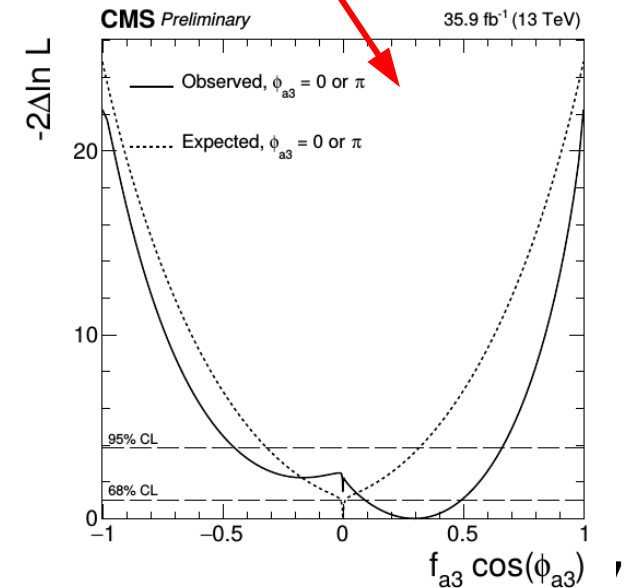
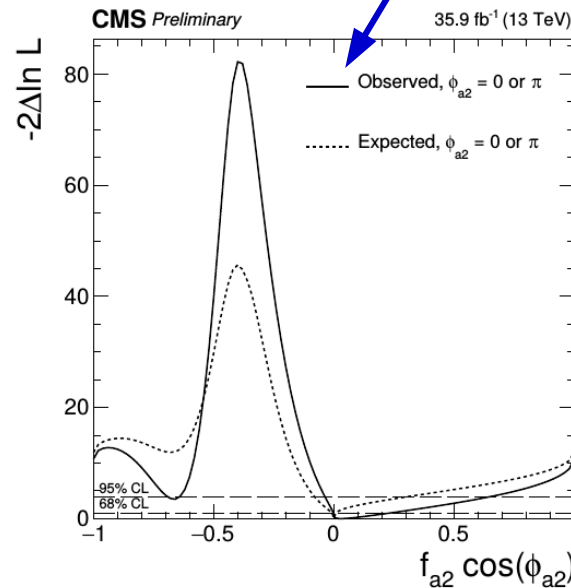


$$L_0^V = \kappa_{\text{SM}} \frac{\cos \alpha g_{\text{HZZ}}}{2} H Z_\mu Z^\mu - \kappa_{H\partial Z} \frac{\cos \alpha}{\Lambda} H Z_\nu \partial_\mu Z^{\mu\nu} - \kappa_{\text{HZZ}} \frac{\cos \alpha}{4\Lambda} H Z_{\mu\nu} Z^{\mu\nu} - \kappa_{\text{AZZ}} \frac{\sin \alpha}{4\Lambda} H Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \dots$$

$$L(\text{HVV}) = a_1 \frac{m_Z^2}{2} H Z_\mu Z^\mu - \frac{\kappa_1}{\Lambda^2} m_Z^2 H Z_\mu \square Z^\mu - a_2 \frac{1}{2} H Z_{\mu\nu} Z^{\mu\nu} - a_3 \frac{1}{2} H Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \dots$$

CMS:

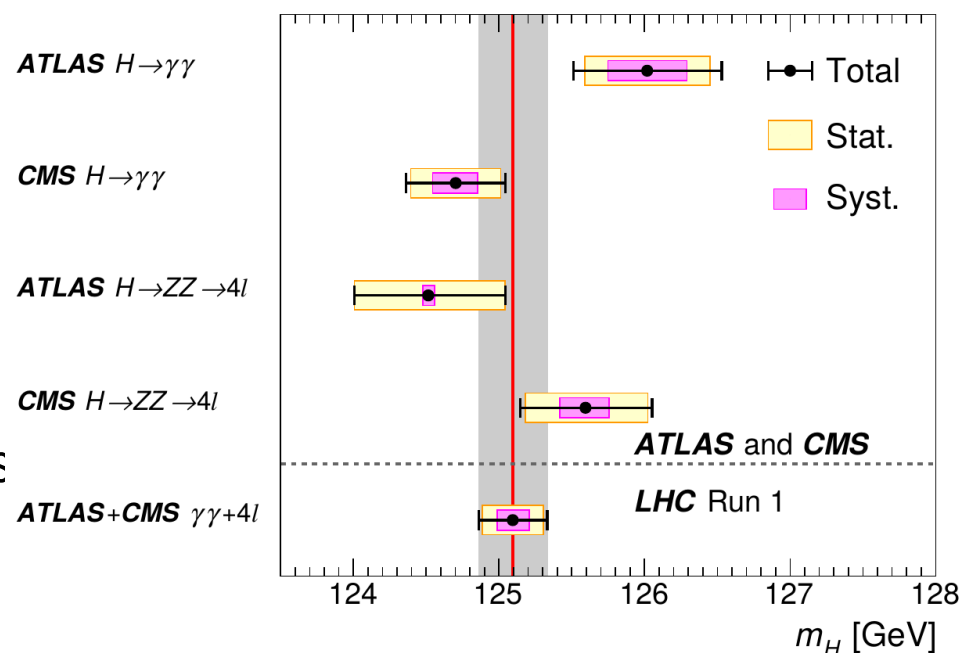
- VBF, VH selections + MVAs targeted to each BSM component
- Measure **fractions** of each BSM coupling: $f_{a_2}, f_{a_3}, \dots$



H $\rightarrow\gamma\gamma$ /ZZ Mass

Phys. Rev. Lett. 114, 191803
CMS-PAS-HIG-16-04

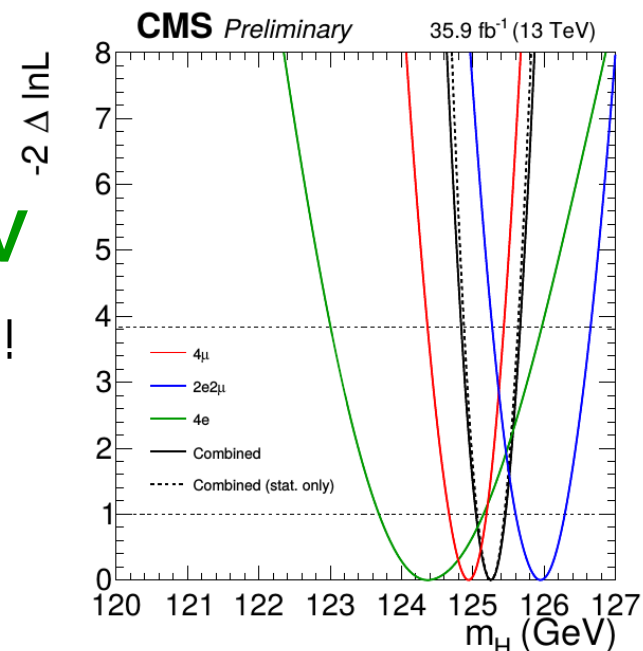
- Higgs mass:** almost completely from H $\rightarrow\gamma\gamma$ +ZZ combination
- Run 1:**
 $m_H = 125.09 \pm 0.240 \text{ GeV}$
($\pm 0.210 \text{ (stat)} \pm 0.110 \text{ (syst)} \text{ GeV}$)
- H $\rightarrow$ ZZ:** almost only statistical uncertainties
- H $\rightarrow\gamma\gamma$:** systematics from calo. response, material...



CMS: Preliminary **Run 2** result (35.9 fb $^{-1}$)

$$m_H = 125.26 \pm 0.200 \text{ (stat)} \pm 0.080 \text{ (syst)} \text{ GeV}$$

- Already $2\times$ more Higgs bosons than ATLAS+CMS Run 1 !
- "3D" measurement: m_{4l} + kinematic discriminant + per-event mass resolution model:
~20% improvement over m_{4l} alone



Γ_H : On- and Off-shell

- **Direct limit** from $H \rightarrow ZZ$ peak width:

$$\Gamma_H < 1.1 \text{ GeV}$$

→ includes interference with continuum

- **Off-shell $pp \rightarrow H \rightarrow 4l$ production** :

- Large $\sigma^{\text{off-shell}}$ due to Higgs $V_L V_L \rightarrow V_L V_L$ unitarization
- Off-shell production **independent of Γ_H** :

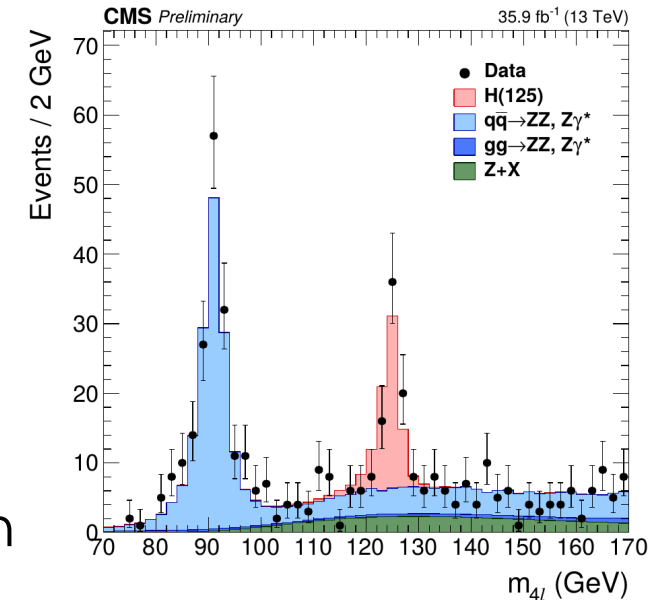
$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{off-shell}} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(2M_Z)^2}$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{m_H \Gamma_H}$$

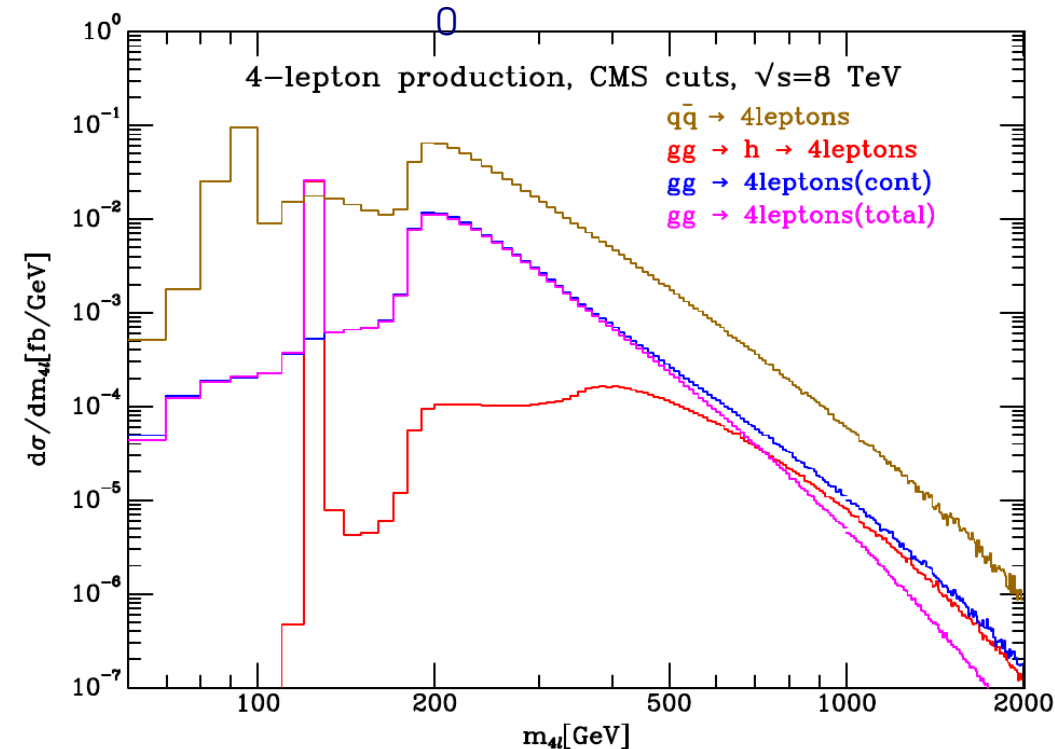
Then for $\kappa_{\text{on-shell}} \leq \kappa_{\text{off-shell}}$,

$$\Gamma_H < 41 \text{ MeV (exp. 32 MeV)}$$

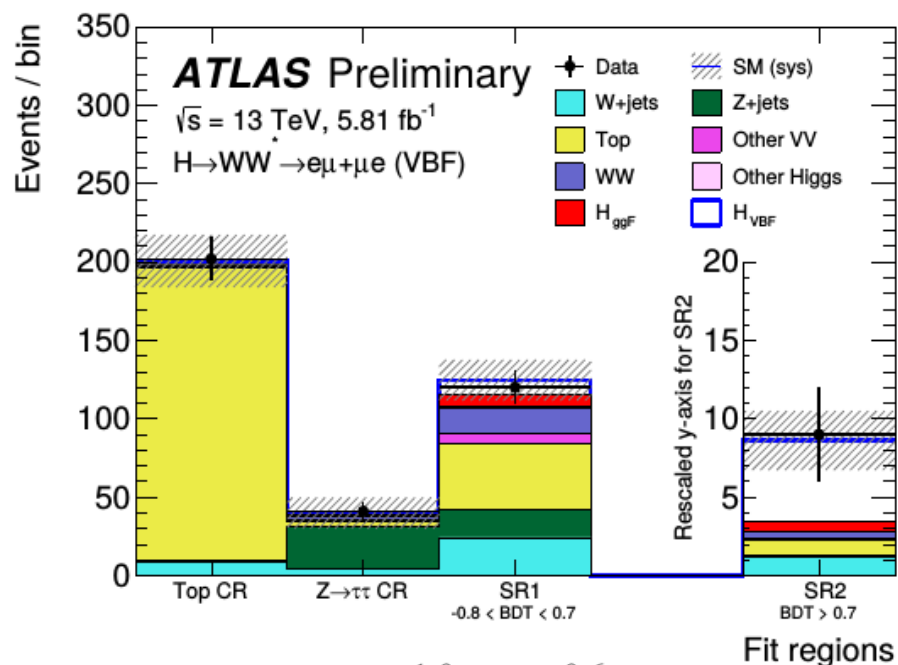
SM: $\Gamma_H = 4.1 \text{ MeV}$



Campbell et al., JHEP04 (2014) 06

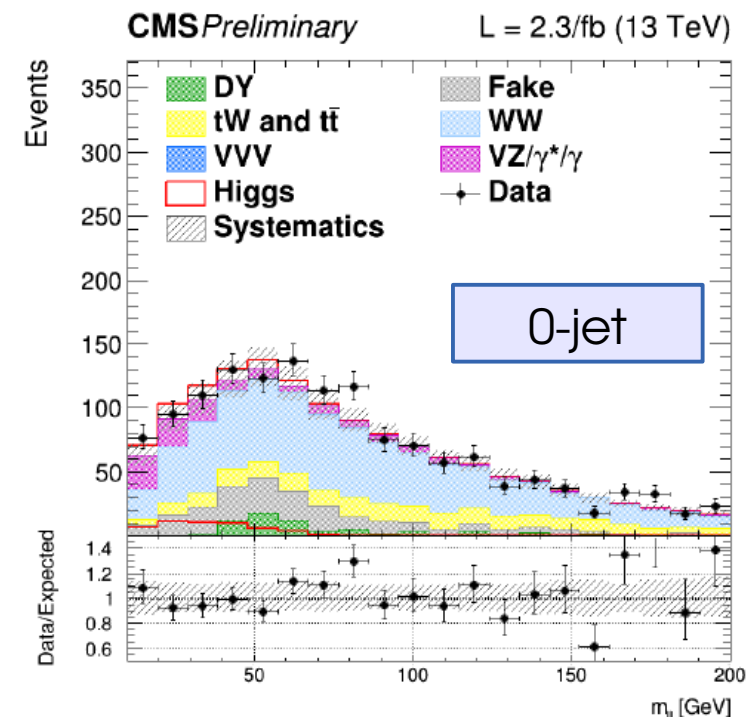


- Run 1**: best measurement of σ_{ggF} , σ_{VBF} & $\sigma_{\text{WH}} \Rightarrow 6.8\sigma$ (ATLAS), 4.8σ (CMS)
- Difficult measurement – large bkg from SM WW, top.
- 2l + MET signature
- CMS**: target ggF: $e\mu$ +MET, $N_{\text{jets}} \leq 1$ – shape analysis in $(m_{\parallel}, m_{\perp})$
- ATLAS**: target VBF ($e\mu$ +MET+2jets) and WH (3l+MET), counting
- Small datasets, precision still far from Run 1



$$\mu_{\text{VBF}} = 1.7^{+1.0}_{-0.8}(\text{stat})^{+0.6}_{-0.4}(\text{sys})$$

$$\mu_{\text{WH}} = 3.2^{+3.7}_{-3.2}(\text{stat})^{+2.3}_{-2.7}(\text{sys})$$

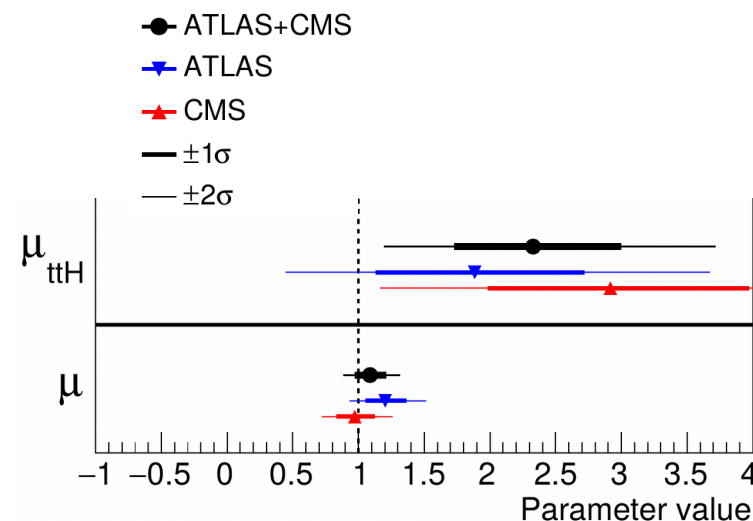
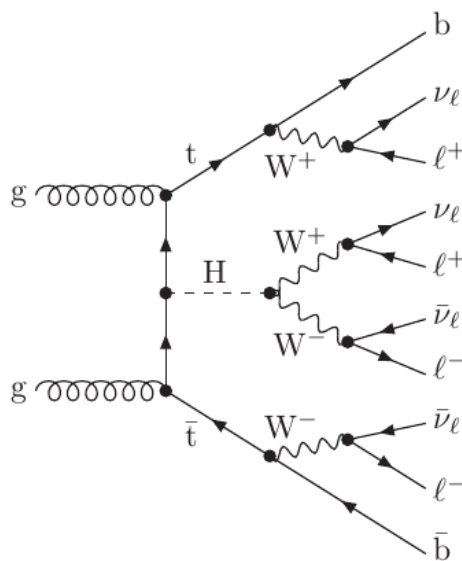
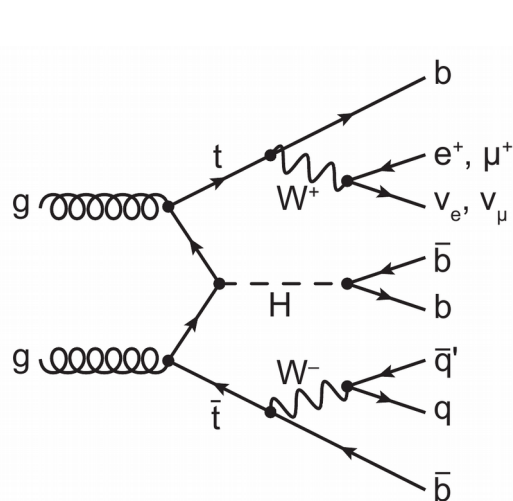
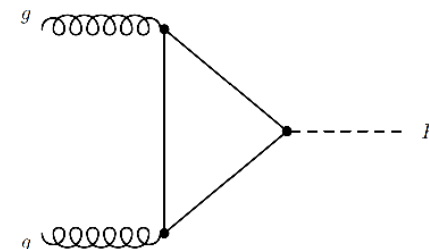
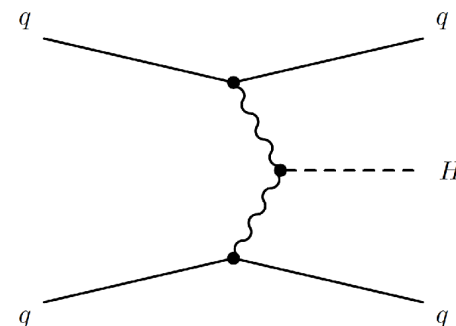


$$\mu = 0.3 \pm 0.5$$

Yukawa Couplings Measurements

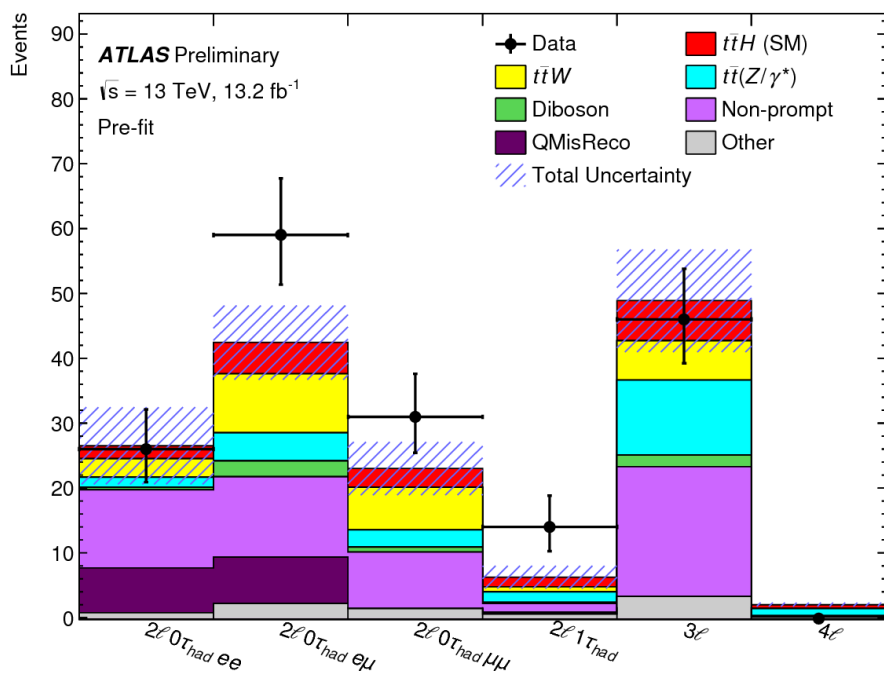


- **Direct measurement of top Yukawa coupling**
 - also probes BSM **loop contributions** in ggF
- Important early Run 2 measurement:
 - **x3.8** cross-section wrt 8 TeV
 - Intriguing excess in Run 1
- Experimentally challenging – Main channels:
 - **H→γγ**: category in the H→γγ analysis
 - **H→bb**
 - **H→leptons** (WW,ZZ,,ττ...)



$t\bar{t}H \rightarrow \text{leptons}$

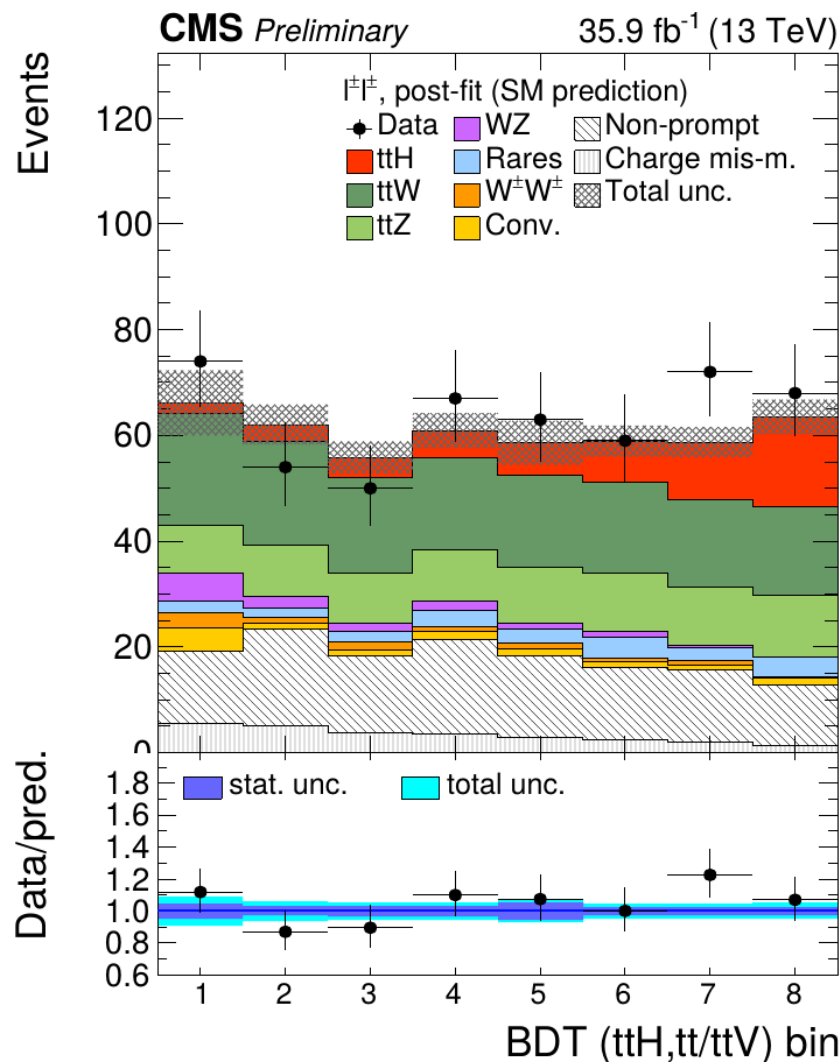
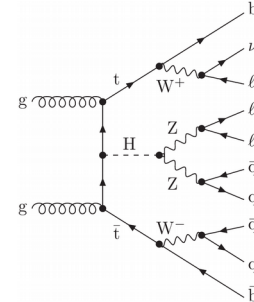
- Target $H \rightarrow WW$, $H \rightarrow \tau\tau$, $H \rightarrow ZZ$ decays
 $\Rightarrow$ Same-sign 2l (incl. 1τ), 3l and 4l signal regions
- Backgrounds:** $t\bar{t}V$, non-prompt leptons
- ATLAS:** Counting exp. in each bin
- CMS:** BDTs to reject $t\bar{t}/t\bar{t}V$;



$$\mu = 2.5 \pm 0.7 (\text{stat}) \pm 1.1 (\text{syst}) - 0.9$$

$$Z = 2.2 \sigma$$

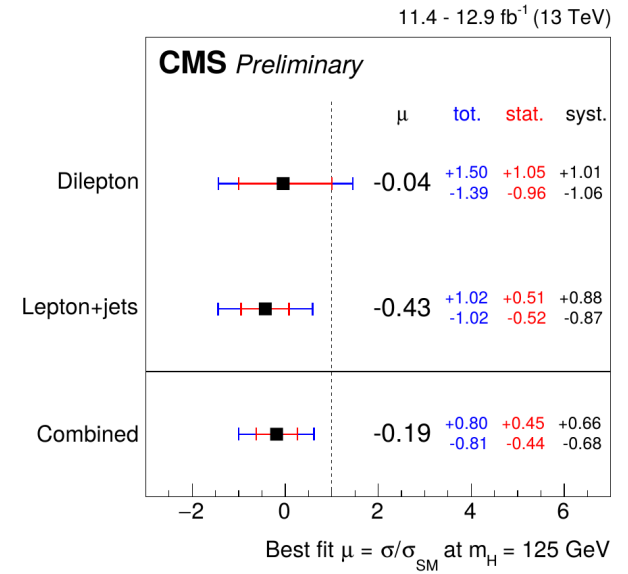
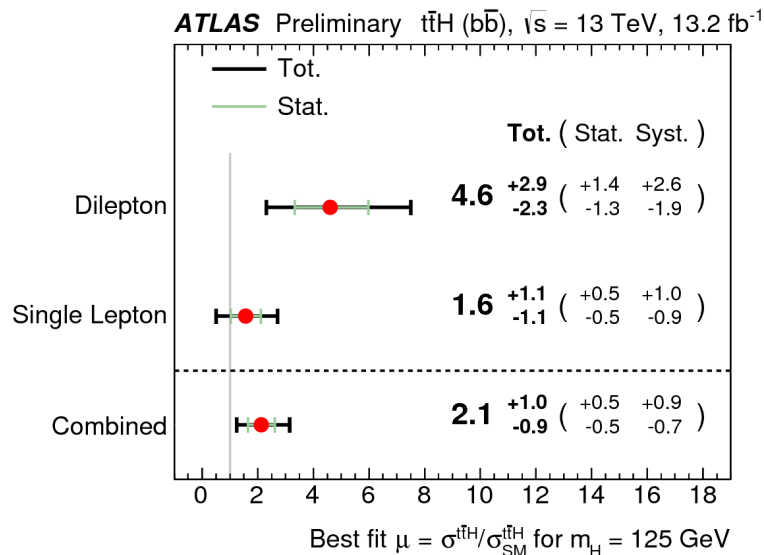
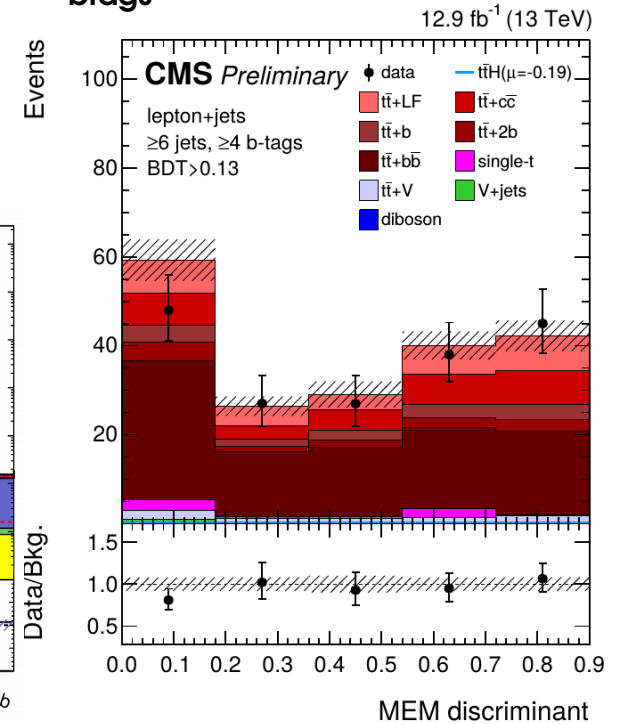
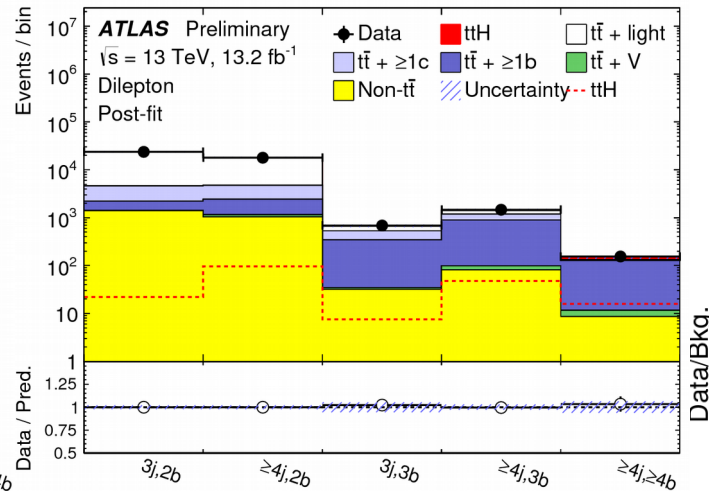
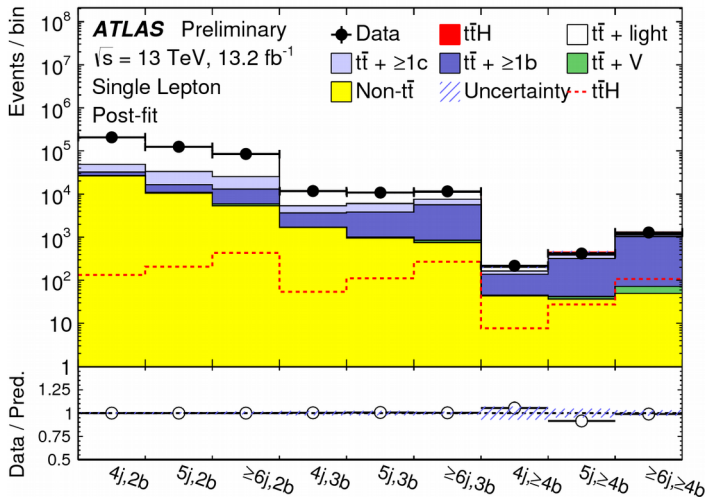
CMS-PAS-HIG-17-004
 CMS-PAS-HIG-17-003
 ATLAS-CONF-2016-058

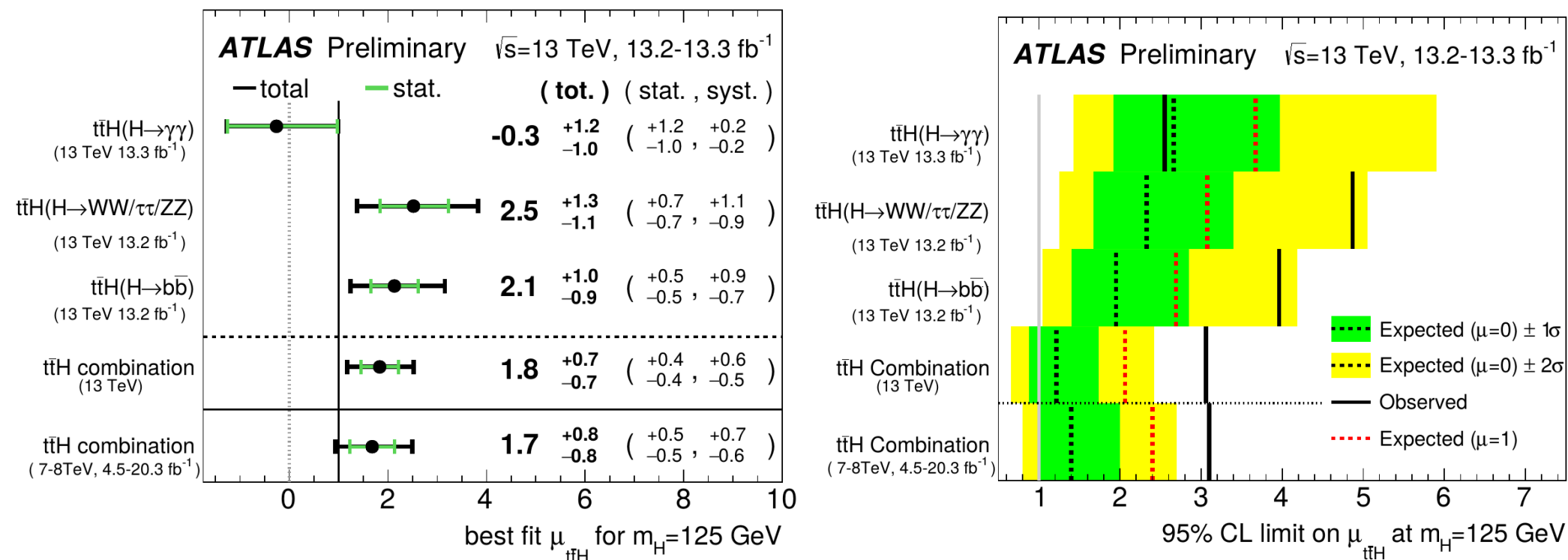


$$\mu = 1.5 \pm 0.29 (\text{stat}) \pm 0.32 (\text{syst}) \pm 0.24 (\text{theo})$$

$$\mu < 2.5 (0.8 \text{ exp.}) @ 95\% \text{ C.L.}$$

- Fine categorization in N_{leptons} (1 or 2) N_{jets} (3-6) and N_{btags} (3-4)
- Extensive use of MVA (BDT, MEM)
- Large systematics from bkg modeling ($t\bar{t}b\bar{b}$)





ATLAS still sees a (smaller) excess – but not CMS

Expected significance **1.8 σ** , exceeds Run 1 value (**1.5 σ**)

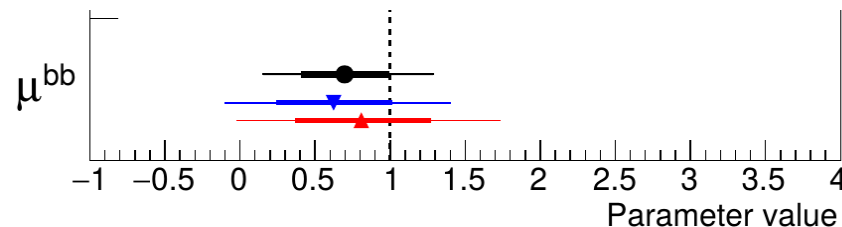
Still room for large improvements

- **x2** more 2016 data not yet included
- Improved understanding of systematic effects
- 2017 data coming soon

} CMS $t\bar{t}H \rightarrow$ leptons alone : **2.4 σ** exp.

H → bb

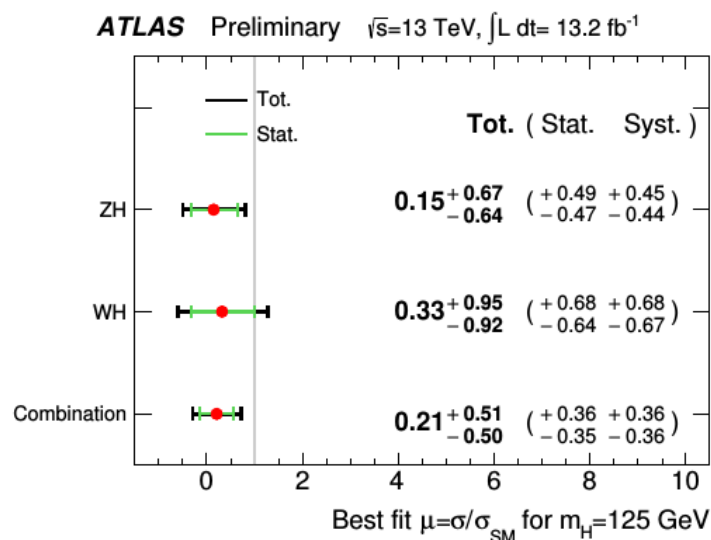
- **BR(H → bb) = 58%** , largest BR
- **Low** in Run 1: exp. **3.7σ**, observed **2.6σ**



ATLAS : VH → bb

ATLAS-CONF-2016-091

- Target $W \rightarrow lv$, $Z \rightarrow ll$ or $Z \rightarrow \nu\nu$ ($N_{lep} = 1/2/0$)
- Categories in N_{jets} , p_T^V
- MVAs trained against $t\bar{t}bar$, $V+HF$



- **Still below SM !**
- **Already stat=syst...**

CMS-PAS-HIG-16-003

CMS: VBF H → bb

Large QCD backgrounds,
Trigger $\epsilon = 6.2\%$, Overall $\epsilon = 2.2\%$

Run 1: $\mu = 1.03 \pm 0.43$, $Z = 2.6\sigma$

Run 2 (2.3 fb^{-1}): $\mu = -3.7 \pm 2.7$

Run 1+2: $\mu = 1.3^{+1.2}_{-1.1}$

ATLAS: VBF+γ H → bb

ATLAS-CONF-2016-063

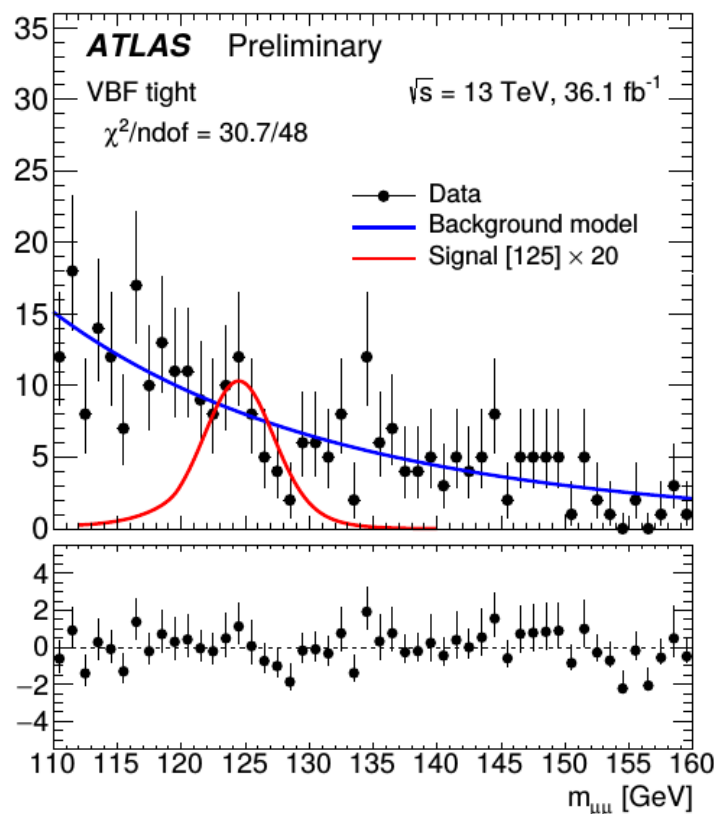
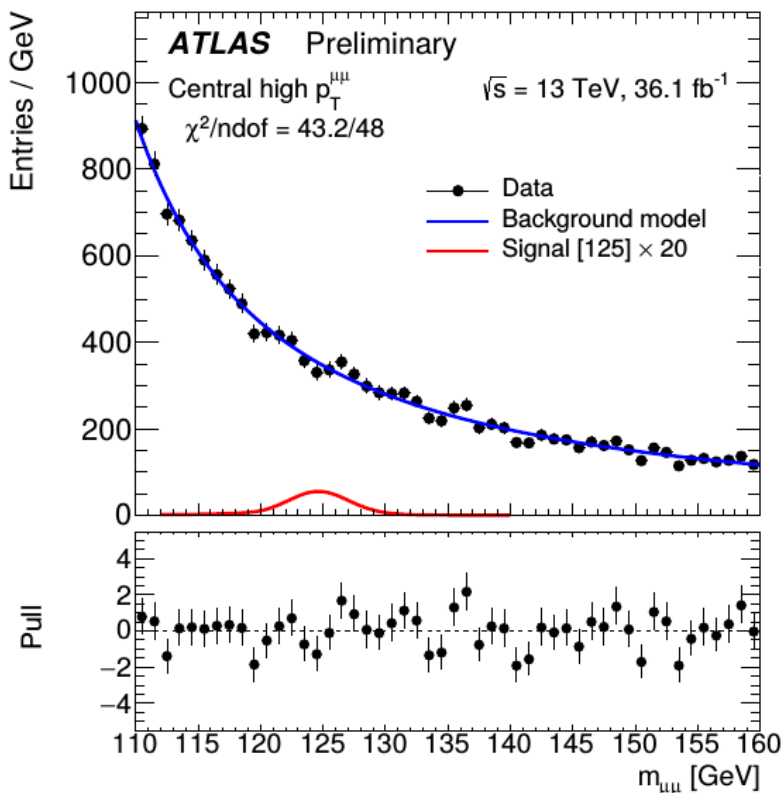
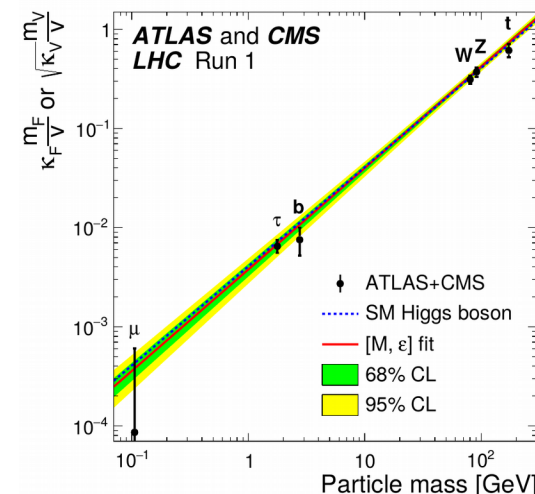
→ 2% of VBF, better S/B

• Run 2 (13.2 fb^{-1}): $\mu = -3.9^{+2.8}_{-2.7}$

$H \rightarrow \mu\mu$

ATLAS-CONF-2017-014

- **Main (only?) LHC window into non-3rd gen. Yukawas**
- Analysis similar to $H \rightarrow \gamma\gamma$
 - low S/B (BR $\sim 0.02\%$!)
 - Good mass resolution (FWHM ~ 6 -7 GeV)
 - Select VBF, split ggF along $p_T^{\mu\mu}, \eta_\mu$.
 - Stat-dominated: syst $\sim 5\%$ (ggF)



Results: (all @ $m_H = 125$ GeV)

Run 2

- $\mu = -0.1 \pm 1.5$
- $\mu < 3.0$ @ 95% CL

Run 1 + Run 2

$\mu < 2.8$ (2.9 exp)
@ 95% CL

→ Approaching SM
sensitivity

Double-Higgs Production

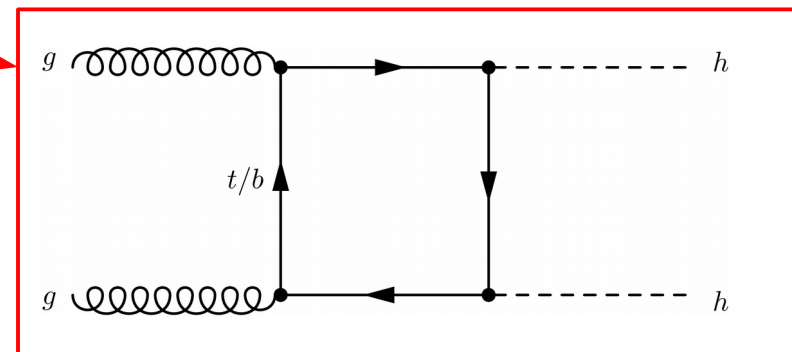
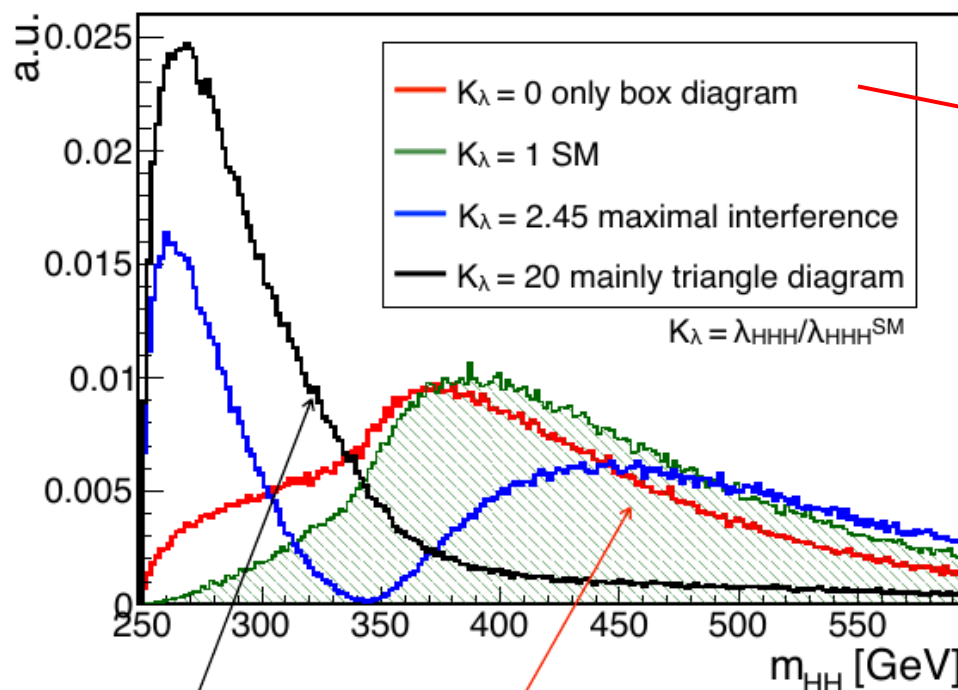
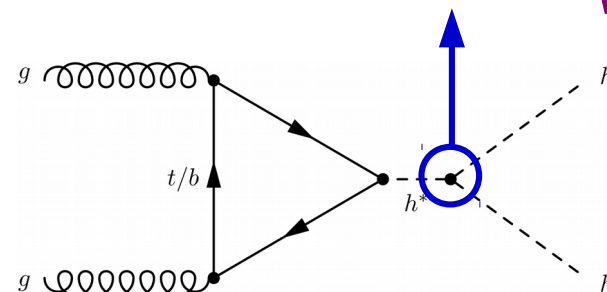


pp → HH

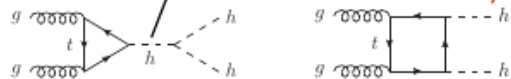
- HH sensitive to **Higgs self-interaction**
- → Within SM, **measure λ** , test consistency with m_H .
- **SM**: $\sigma(pp \rightarrow HH) \sim 37 \text{ fb}$ at $\sqrt{s} = 13 \text{ TeV}$ (90% $gg \rightarrow HH$)
 - Mostly from non- λ “box” contribution
 - **More sensitivity to λ at low m_{HH}**

$$\mathcal{L}_{\text{Scalar}} \supset \lambda |\phi|^4 - \frac{m_H^2}{2} |\phi|^2$$

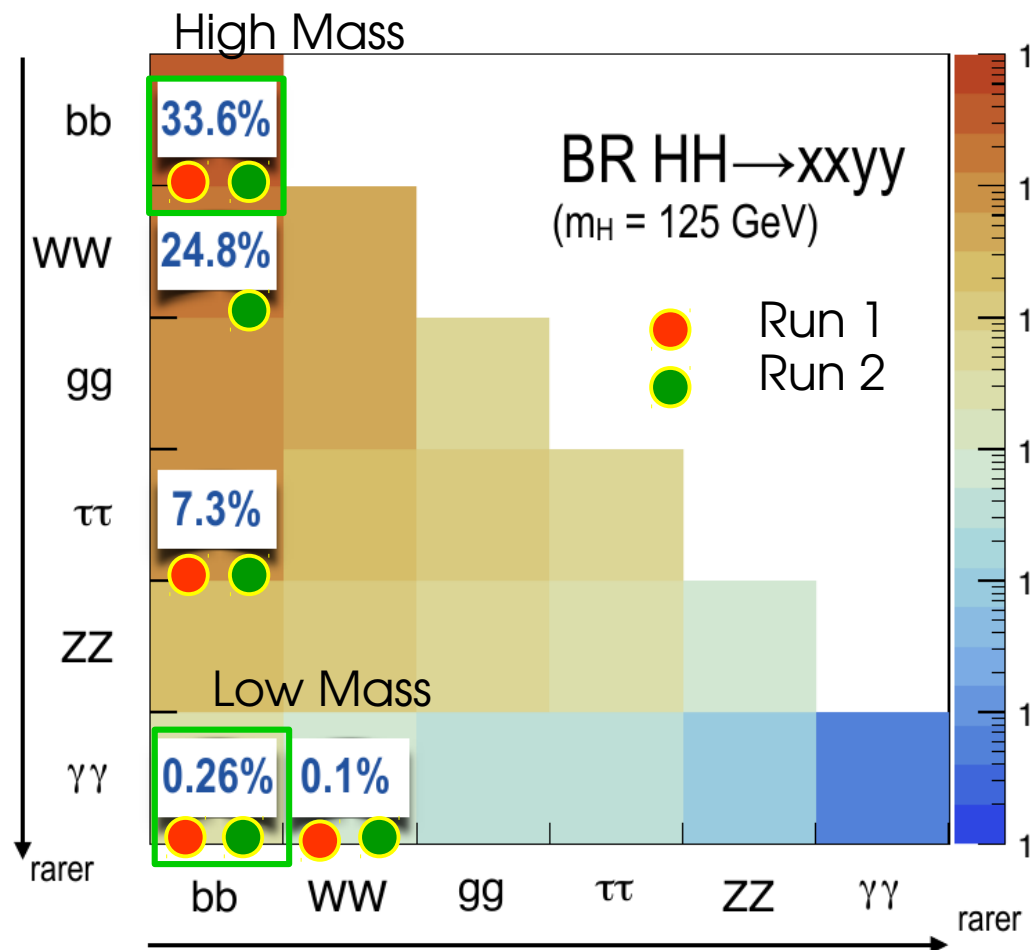
$$\lambda_{HHH} = 6\lambda v = \frac{3m_H^2}{v}$$



Roberto Salerno



- 2 Higgs bosons
6 decay modes
21 possibilities
- Tradeoff between clean modes and high BR
⇒ 5 channels tried so far
- **Run 1 limits ~ 50× SM**
- Also search for **resonances** in the m_{HH} spectrum



Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
Upper limit on the cross section [pb]					
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
Upper limit on the cross section relative to the SM prediction					
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

Phys. Rev. D 92, 092004 (2015)

HH→γγbb and HH→bbbb

CMS H→γγbb :

- Similar technique to H→γγ analysis, + 2 b-jets
- Extract signal in the 2D ($m_{\gamma\gamma}$, m_{bb}) plane

$$\Rightarrow \sigma(pp \rightarrow HH \rightarrow \gamma\gamma bb) < 7.90 \text{ (7.85) fb}$$

@ 95% CL at 13 TeV with 2.7 fb⁻¹ (**SM : 0.04 fb**)

ATLAS HH→bbbb

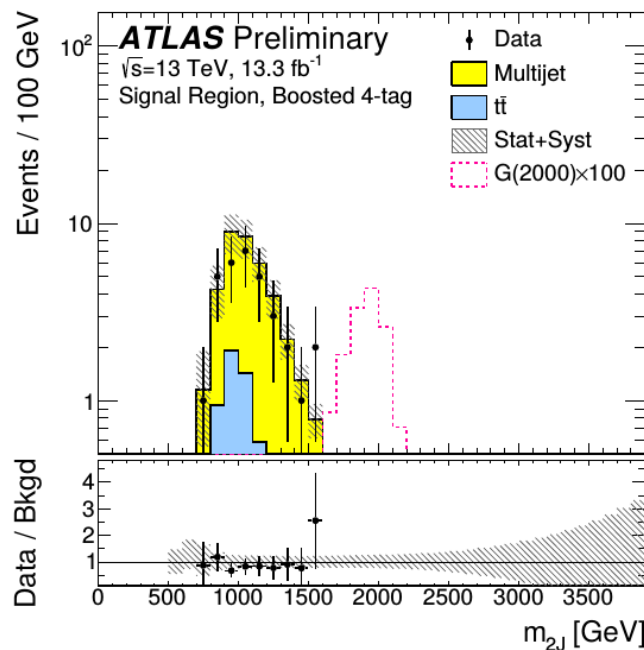
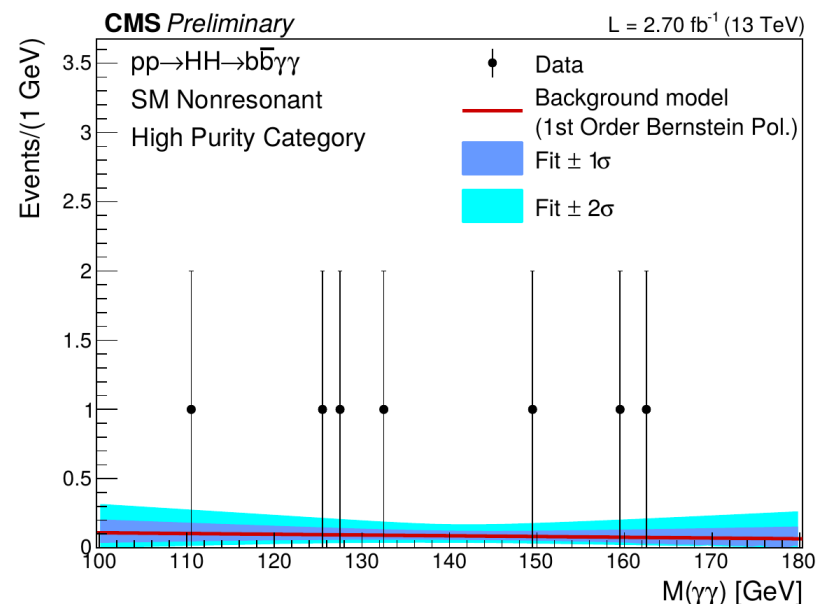
- Separate boosted and resolved analyses
- Use mass pairs ($m_{J(J)}^{\text{lead}}$, $m_{J(J)}^{\text{subl}}$) for selection
- Resonant + non-resonant searches in $m_{JJ(JJ)}$

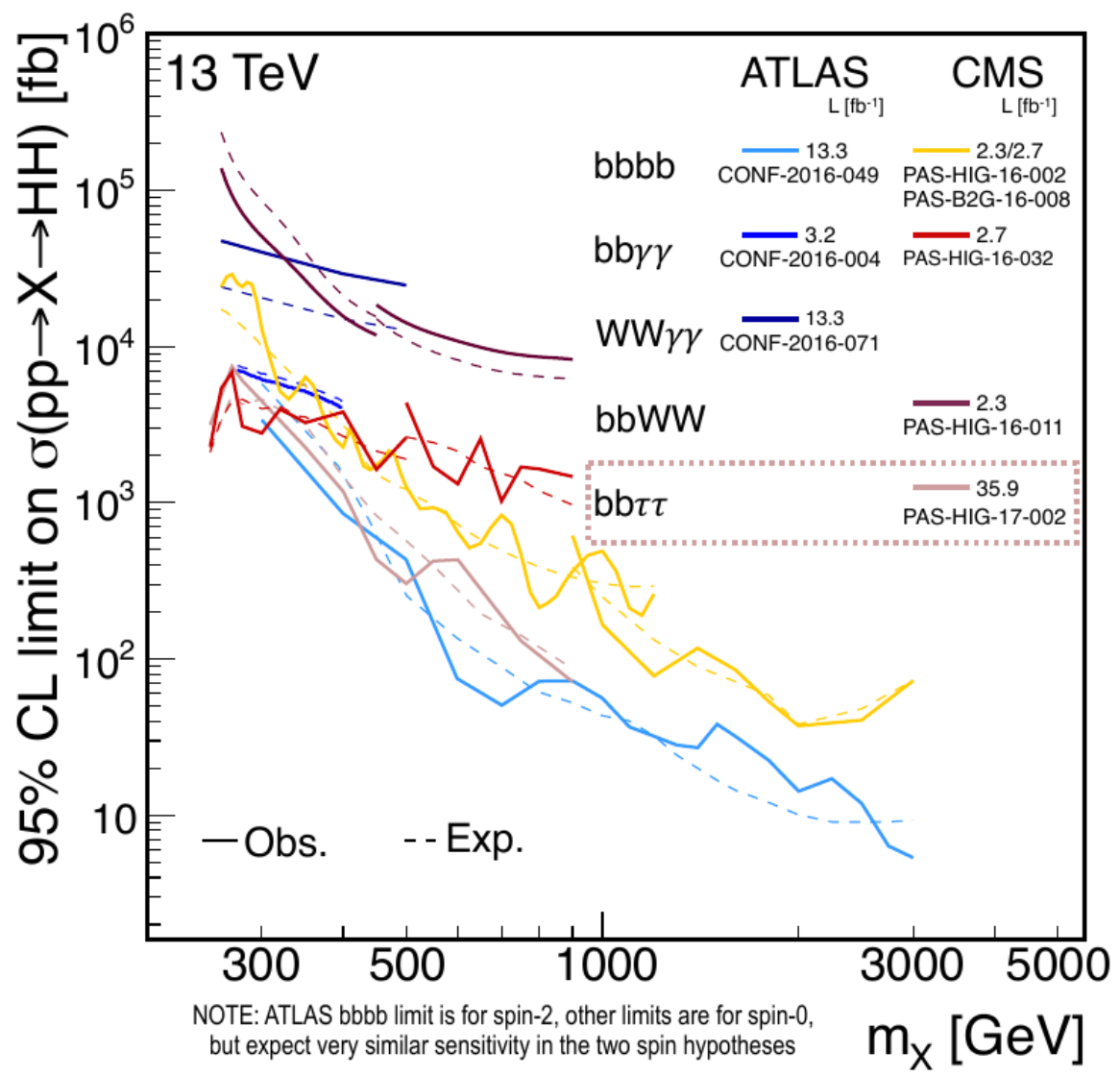
$$\Rightarrow \sigma(pp \rightarrow HH \rightarrow \gamma\gamma bb) < 330 \text{ (430) fb}$$

@ 95% CL at 13 TeV with 13.3 fb⁻¹ (**SM : 11.3 fb**)

$$\Rightarrow \text{Exclude } 480 \leq m_{G^*} \leq 910 \text{ GeV}$$

for Bulk-RS Graviton





New! CMS-PAS-HIG-17-006

Chan.	Obs. (exp.) 95% C.L. limit on σ/σ_{SM}	
bbbb	29 (38)	342 (308)
bbWW	-	79 (89)
bb $\tau\tau$	-	28 (25)
bb $\gamma\gamma$	117 (161)	91 (90)
WW $\gamma\gamma$	747 (386)	-
	2.3-3.2 fb ⁻¹	13.3 fb ⁻¹ 35.9 fb ⁻¹

▣: Test of anomalous HH couplings

Sensitivity to σ/σ_{SM} already better than Run 1 (→ New Run 2 CMS HH→bb $\tau\tau$!)

Still far from the SM!

High-Mass Searches



High-Mass Searches: $\gamma\gamma$

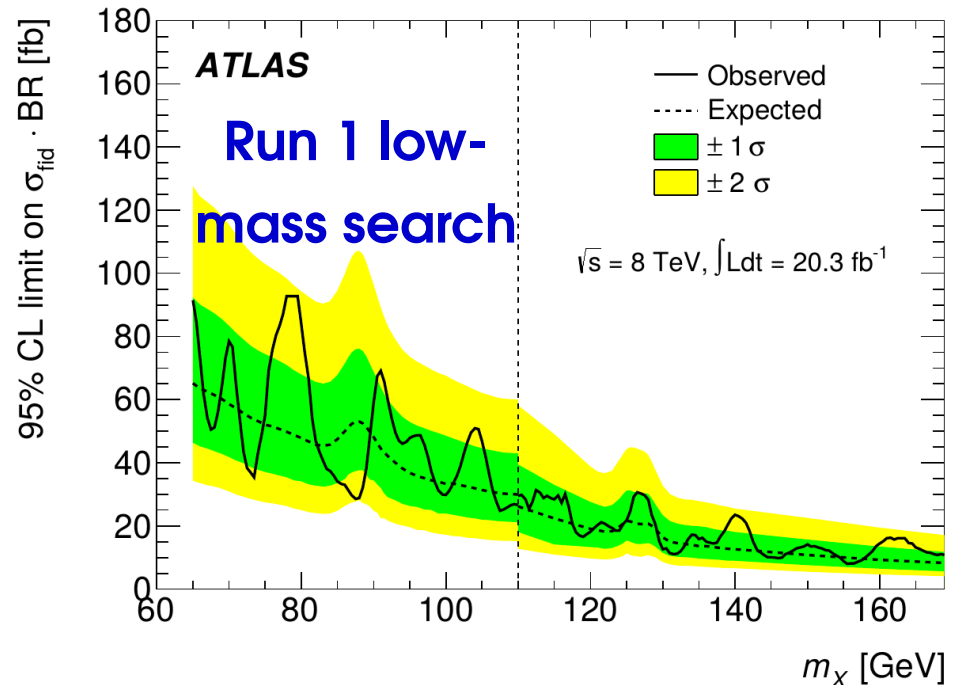
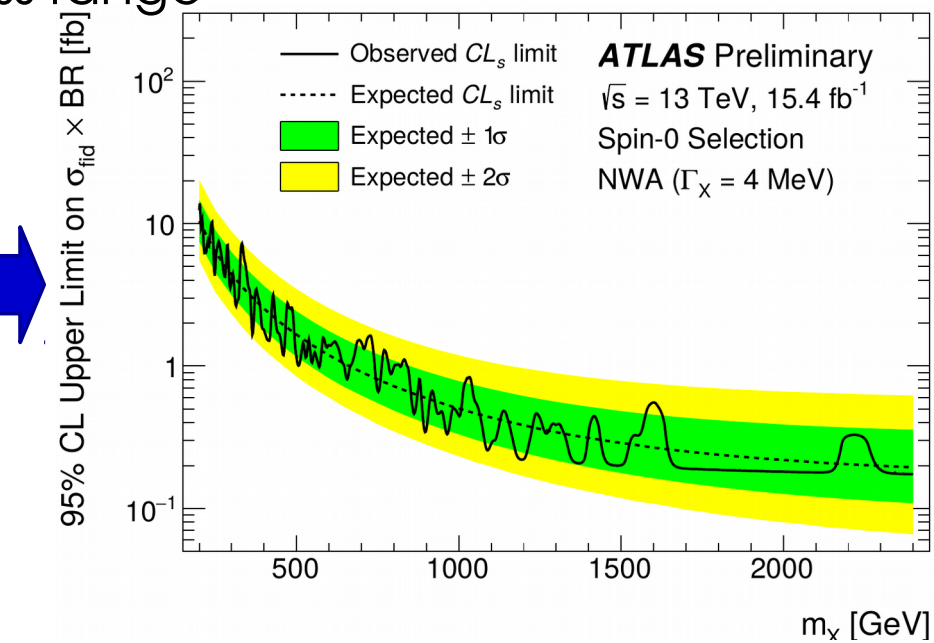
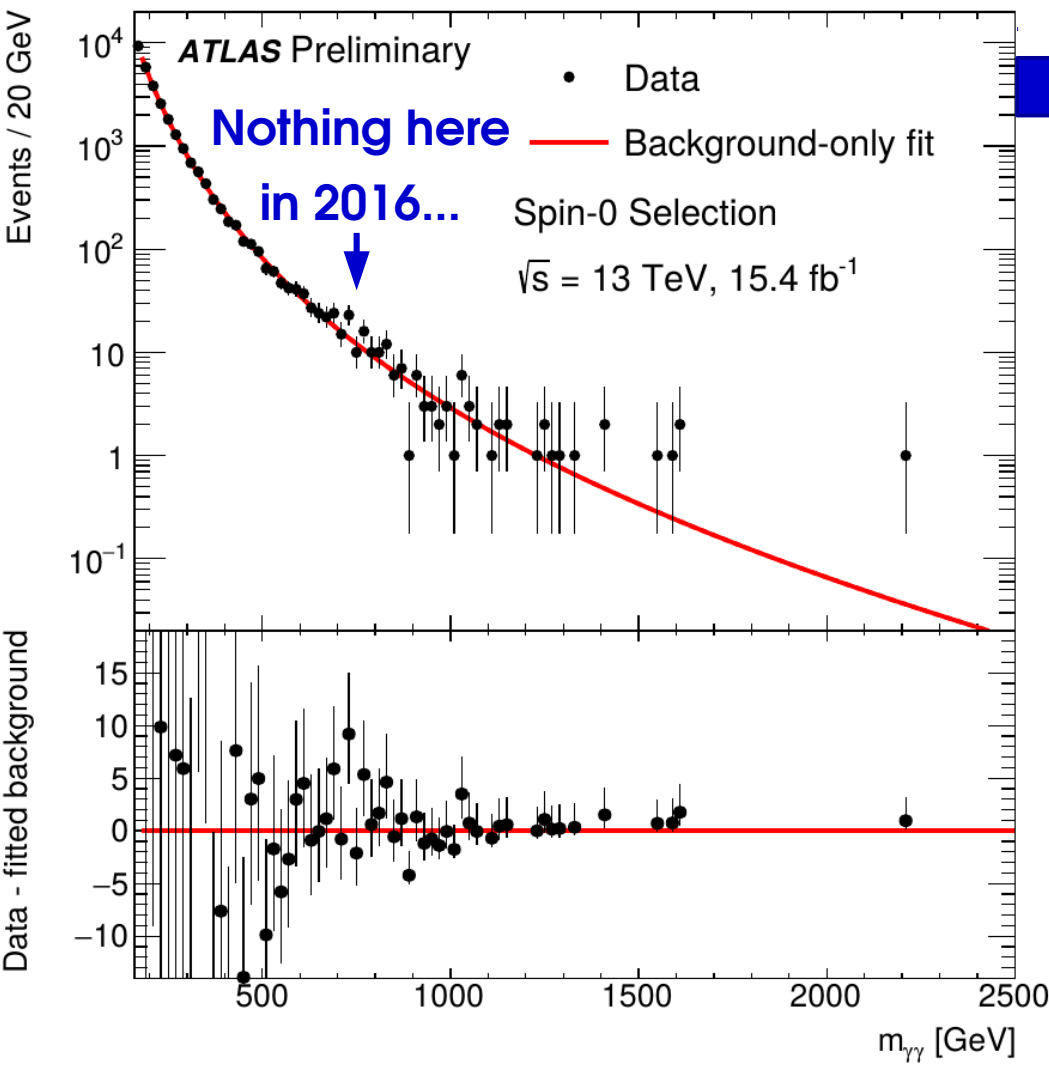
ATLAS-CONF-2016-059

Phys. Lett. B 767 (2017) 147

Phys. Rev. Lett. 113, 17180124

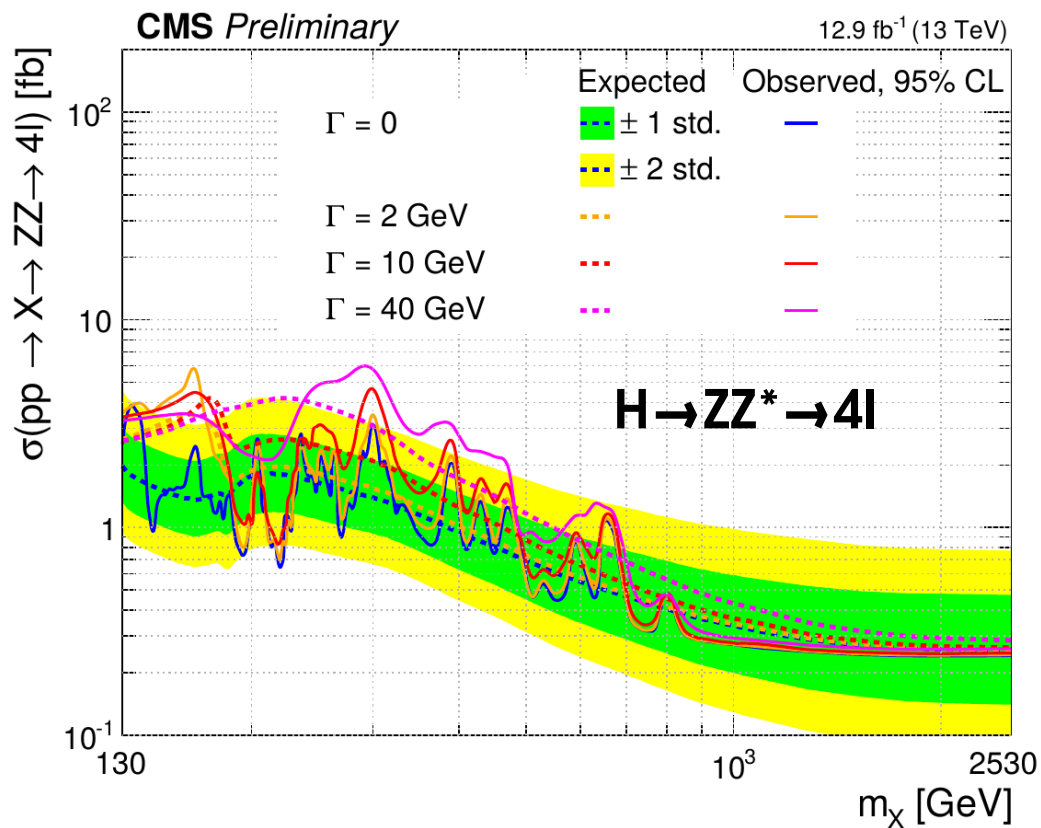
Idea: Extend Higgs searches to wider mass range

→ Search for e.g. Heavy/Light states from extended Higgs sectors



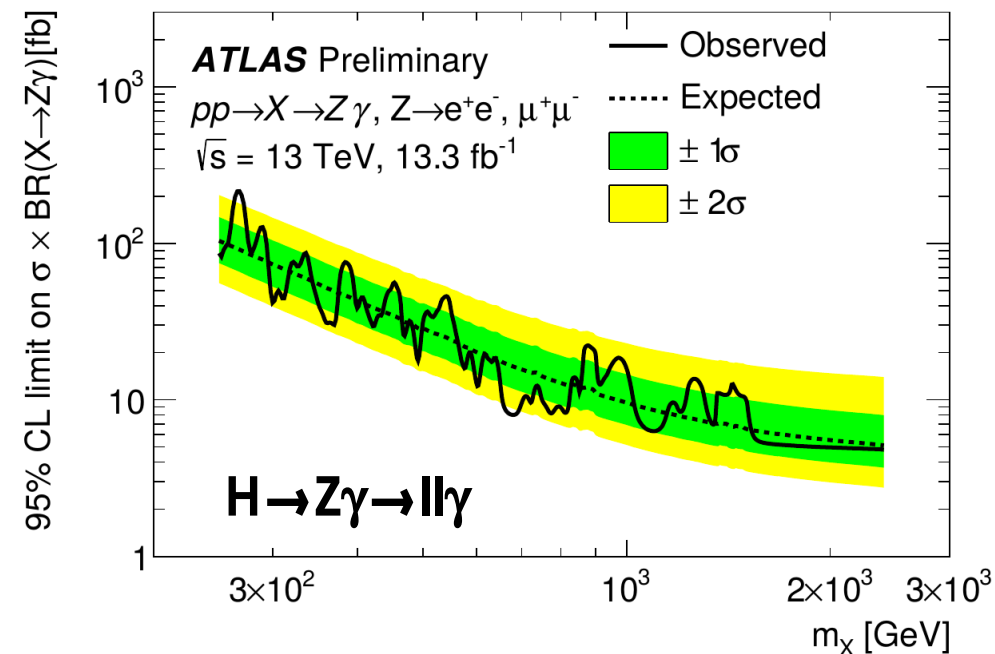
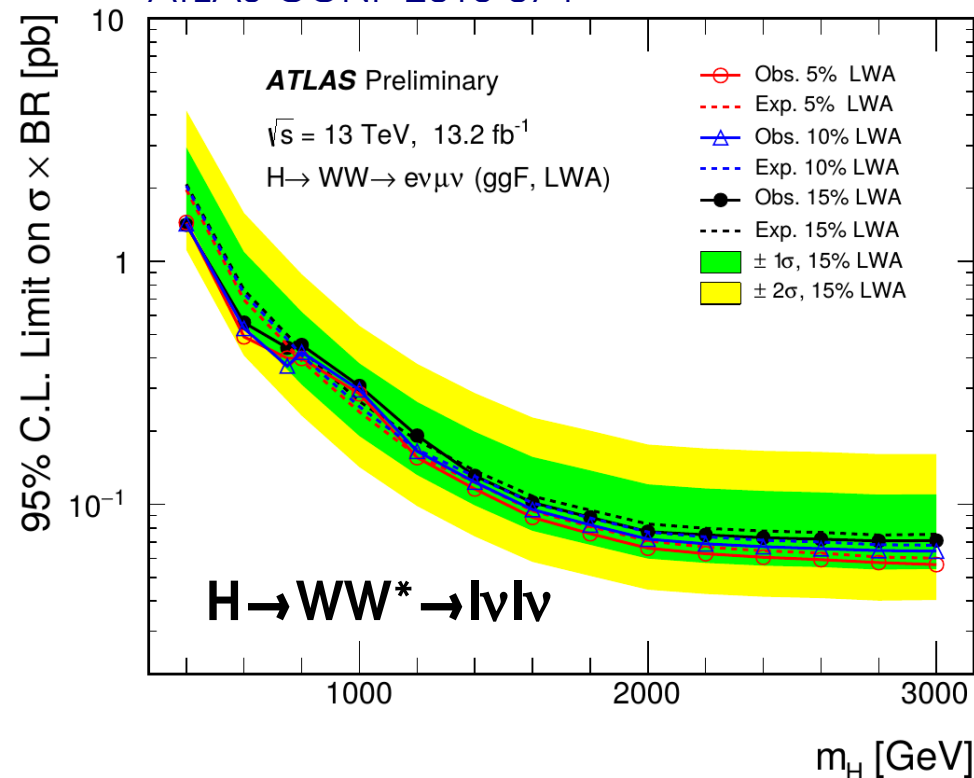
High-Mass Searches

CMS-PAS-HIG-16-033



Many more results not covered here!

ATLAS-CONF-2016-074



ATLAS-CONF-2016-044

So, what *have* we learned ?

Run 1

Run 2

Di-Higgs

$$\kappa_\lambda$$
$$-17 < \kappa_\lambda < 22.5$$

Searches

Nothing so far



Fermionic Channels

$$\kappa_t$$
$$\pm 24\%$$

$$\kappa_b$$
$$\pm 27\%$$

$$\kappa_\tau$$
$$\pm 15\%$$

$$\kappa_\mu$$
$$\pm 120\%$$

$$\text{BR}(H \rightarrow \text{invisible})$$
$$< 34\% \text{ (indirect)}$$
$$< 24\% \text{ (direct)}$$

Bosonic Channels

$$\kappa_g$$
$$\pm 13\%$$

$$\kappa_Z$$
$$\pm 10\%$$

$$\kappa_W$$
$$\pm 11\%$$

$$\kappa_\gamma$$
$$\pm 10\%$$

$$m_H$$
$$\pm 210 \text{ MeV}$$

$$\Gamma_H < 1.1 \text{ GeV (direct)}$$
$$< 13 \text{ MeV (indirect)}$$

$$J^{PC}$$
$$\text{Most pure } 1^{++}, 2^{++} \text{ excluded,}$$
$$0^- : f_{a3} < 17\%$$

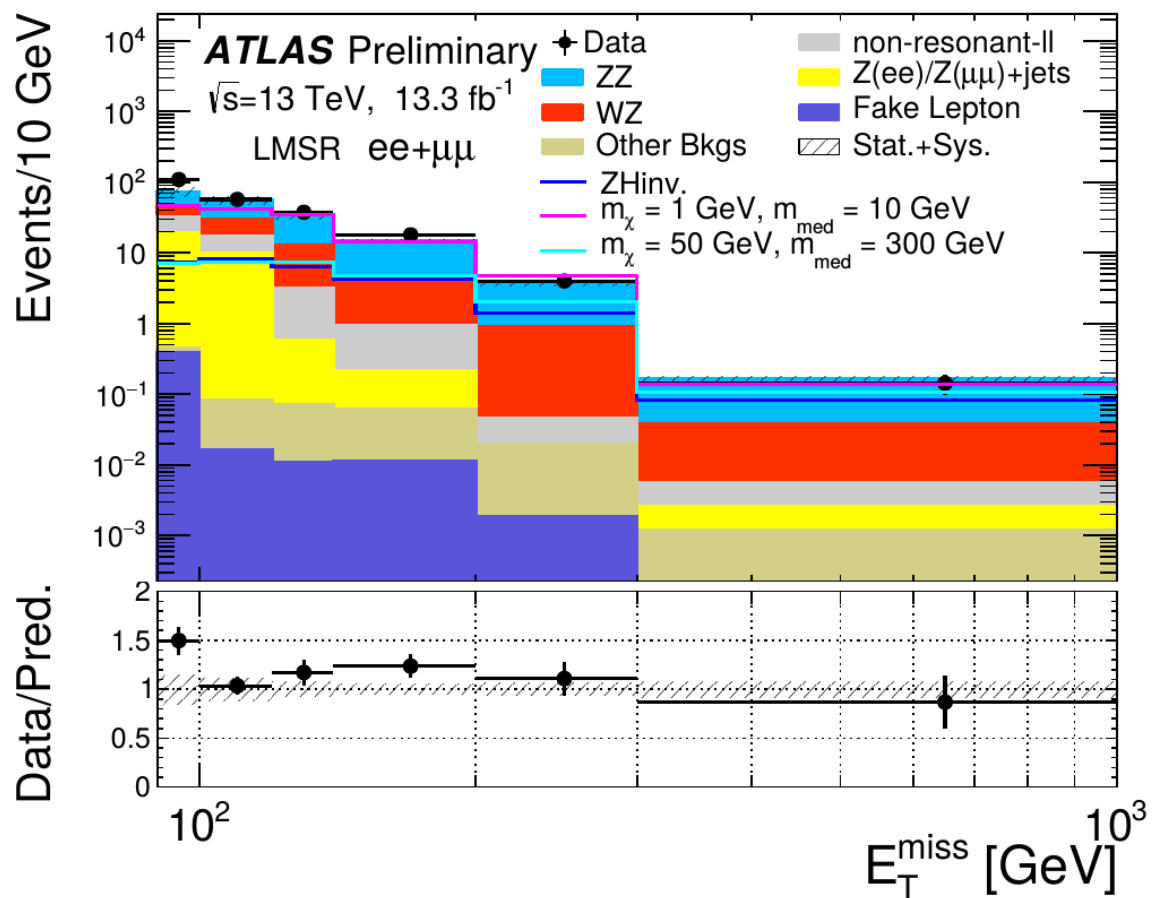
$$\text{fid/diff.}$$
$$\text{SM} \quad \checkmark$$

Conclusions

- **Higgs properties extensively tested by ATLAS and CMS**
 - Many results already re-produced in Run 2
- **What have we learned ?**
 - **Higgs seems very SM-like so far – no deviations from SM predictions**
 - **Not all equally well-known:**
 - **W,Z,g, γ couplings, spin/CP:** good precision already, moving to precision regime $\rightarrow$ New measurement frameworks: STXS, SMEFT, POs, ...
 - **Yukawas:** $H \rightarrow b\bar{b}$ or $t\bar{t}H$ not observed yet, could come in Run 2
 - **HH:** will need HL-LHC to approach SM sensitivity
 - **Still room for large deviations from SM!**
- **Full Run 2 statistics $\sim 3\times$ what we have now, another factor 30 for HL-LHC.**
 - **Can still hope for surprises**
 - High stat expose other limitation – some analyses already syst-limited
 $\rightarrow$ **will require more hard work (exp. + theory) to achieve full LHC potential**

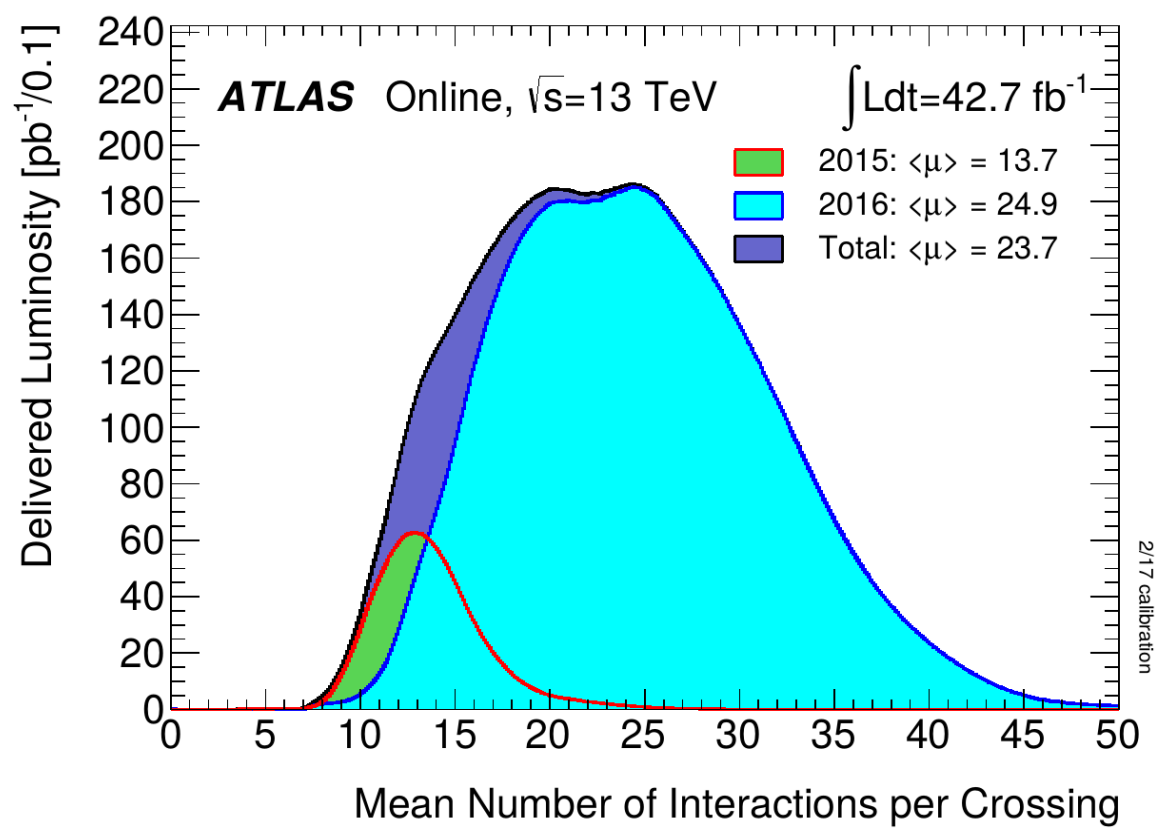
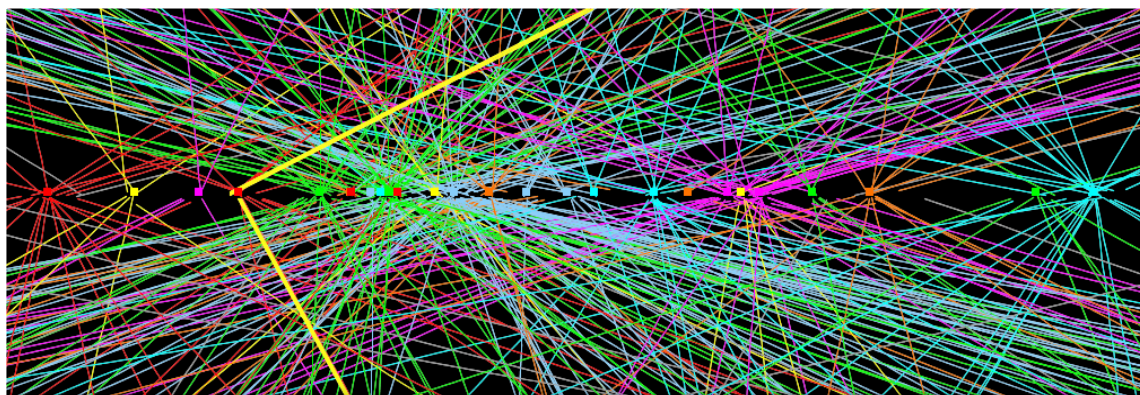
Additional Material





	Limits on $\sigma(Z(\rightarrow \ell\ell)H(\rightarrow \text{invisible}))$ [fb]		Limits on $\text{BF}(H \rightarrow \text{invisible})$	
	Expected	Observed	Expected	Observed
Central Value	58	88	65%	98%
($-1\sigma, +1\sigma$)	(41, 83)		(46%, 93%)	
($-2\sigma, +2\sigma$)	(30, 115)		(34%, 100%)	

Run1 : VBF H → inv BF < 28% (ATLAS), < 24% (CMS)



$$\begin{aligned}
\mathcal{L}_0^V = & \left\{ c_\alpha \kappa_{\text{SM}} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] \right. \\
& - \frac{1}{4} \left[c_\alpha \kappa_{H\gamma\gamma} g_{H\gamma\gamma} A_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{A\gamma\gamma} g_{A\gamma\gamma} A_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
& - \frac{1}{2} \left[c_\alpha \kappa_{HZ\gamma} g_{HZ\gamma} Z_{\mu\nu} A^{\mu\nu} + s_\alpha \kappa_{AZ\gamma} g_{AZ\gamma} Z_{\mu\nu} \tilde{A}^{\mu\nu} \right] \\
& - \frac{1}{4} \left[c_\alpha \kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + s_\alpha \kappa_{Agg} g_{Agg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \right] \\
& - \frac{1}{4} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \\
& - \frac{1}{2} \frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \\
& \left. - \frac{1}{\Lambda} c_\alpha \left[\kappa_{H\partial\gamma} Z_\nu \partial_\mu A^{\mu\nu} + \kappa_{H\partial Z} Z_\nu \partial_\mu Z^{\mu\nu} + (\kappa_{H\partial W} W_\nu^+ \partial_\mu W^{-\mu\nu} + h.c.) \right] \right\} X_0
\end{aligned}$$

$$\begin{aligned}
L(\text{HVV}) \sim & a_1 \frac{m_Z^2}{2} \text{HZ}^\mu Z_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \text{HZ}_\mu \square Z^\mu - \frac{1}{2} a_2 \text{HZ}^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \text{HZ}^{\mu\nu} \tilde{Z}_{\mu\nu} \\
& + a_1^{\text{WW}} m_W^2 \text{HW}^{+\mu} W_\mu^- - \frac{1}{(\Lambda_1^{\text{WW}})^2} m_W^2 \text{H} \left(\kappa_1^{\text{WW}} W_\mu^- \square W^{+\mu} + \kappa_2^{\text{WW}} W_\mu^+ \square W^{-\mu} \right) \\
& - a_2^{\text{WW}} \text{HW}^{+\mu\nu} W_{\mu\nu}^- - a_3^{\text{WW}} \text{HW}^{+\mu\nu} \tilde{W}_{\mu\nu}^- \\
& + \frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2} m_Z^2 \text{HZ}_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} \text{HF}^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} \text{HF}^{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} \text{HF}^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} \text{HF}^{\mu\nu} \tilde{F}_{\mu\nu}
\end{aligned}$$

H→γγ phase space

	diphoton baseline	VBF enhanced	single lepton
Photons	$ \eta < 1.37 \text{ or } 1.52 < \eta < 2.37$ $p_T^{\gamma_1} > 0.35 m_{\gamma\gamma} \text{ and } p_T^{\gamma_2} > 0.25 m_{\gamma\gamma}$		
Jets	- - -	$p_T > 30 \text{ GeV}, y < 4.4$ $m_{jj} > 400 \text{ GeV}, \Delta y_{jj} > 2.8$ $ \Delta\phi_{\gamma\gamma,jj} > 2.6$	- - -
Leptons	-	-	$p_T > 15 \text{ GeV}$ $ \eta < 2.47$

- $\frac{p_{T,gen}^{\gamma_{1,(2)}}}{m_{\gamma\gamma}} > \frac{1}{3}(\frac{1}{4})$ for the generator-level transverse momentum of the leading (subleading) photon,
- $|\eta_{gen}^\gamma| < 2.5$ for the generator-level pseudorapidities of both photon
- the generator-level isolation of the photons, calculated as the sum of the transverse momenta of all stable particles inside a cone of aperture $R = 0.3$ around the photon, is required to be smaller than 10 GeV.

H → ZZ phase space

Requirements for the H → 4ℓ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20 \text{ GeV}$
Next-to-leading lepton p_T	$p_T > 10 \text{ GeV}$
Additional electrons (muons) p_T	$p_T > 7(5) \text{ GeV}$
Pseudorapidity of electrons (muons)	$ \eta < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 \cdot p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 \text{ GeV} < m_{Z_1} < 120 \text{ GeV}$
Inv. mass of the Z_2 candidate	$12 \text{ GeV} < m_{Z_2} < 120 \text{ GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+ \ell^-} > 4 \text{ GeV}$
Inv. mass of the selected four leptons	$105 \text{ GeV} < m_{4\ell} < 140 \text{ GeV}$

Lepton definition

Muons: $p_T > 5 \text{ GeV}, |\eta| < 2.7$ Electrons: $p_T > 7 \text{ GeV}, |\eta| < 2.47$

Pairing

Leading pair: SFOS lepton pair with smallest $|m_Z - m_{\ell\ell}|$
Sub-leading pair: Remaining SFOS lepton pair with smallest $|m_Z - m_{\ell\ell}|$

Event selection

Lepton kinematics: Leading leptons $p_T > 20, 15, 10 \text{ GeV}$
Mass requirements: $50 < m_{12} < 106 \text{ GeV}; 12 < m_{34} < 115 \text{ GeV}$
Lepton separation: $\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same(opposite)-flavour leptons
 J/ψ veto: $m(\ell_i, \ell_j) > 5 \text{ GeV}$ for all SFOS lepton pairs
Mass window: $115 < m_{4\ell} < 130 \text{ GeV}$

H→ZZ and H→γγ Fiducial results

Fiducial region	Measured cross section (fb)	SM prediction (fb)
Baseline	43.2 ± 14.9 (stat.) ± 4.9 (syst.)	$62.8^{+3.4}_{-4.4}$ [N ³ LO + XH]
VBF-enhanced	4.0 ± 1.4 (stat.) ± 0.7 (syst.)	2.04 ± 0.13 [NNLOPS + XH]
single lepton	1.5 ± 0.8 (stat.) ± 0.2 (syst.)	0.56 ± 0.03 [NNLOPS + XH]

$$\hat{\sigma}_{\text{fiducial}} = 84 \pm 11 \text{ (stat)} \pm 7 \text{ (syst) fb}$$

$$\sigma_{\text{fiducial}}^{\text{theory}} = 75^{+4}_{-4} \text{ fb}$$

Excellent agreement with SM!

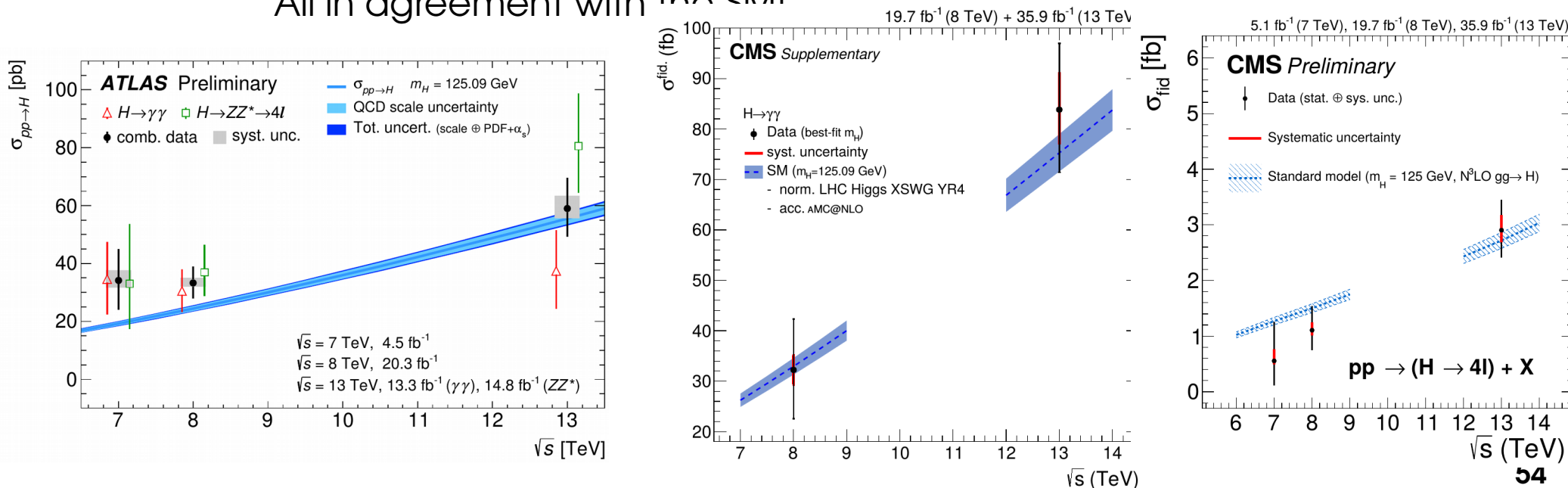
$$\sigma_{\text{fid,comb}}^{4\ell} = 4.54^{+1.02}_{-0.90} \text{ fb}$$

$$\sigma_{\text{fid.}} = 2.90^{+0.48}_{-0.44} \text{ (stat.)}^{+0.27}_{-0.22} \text{ (sys.) fb}$$

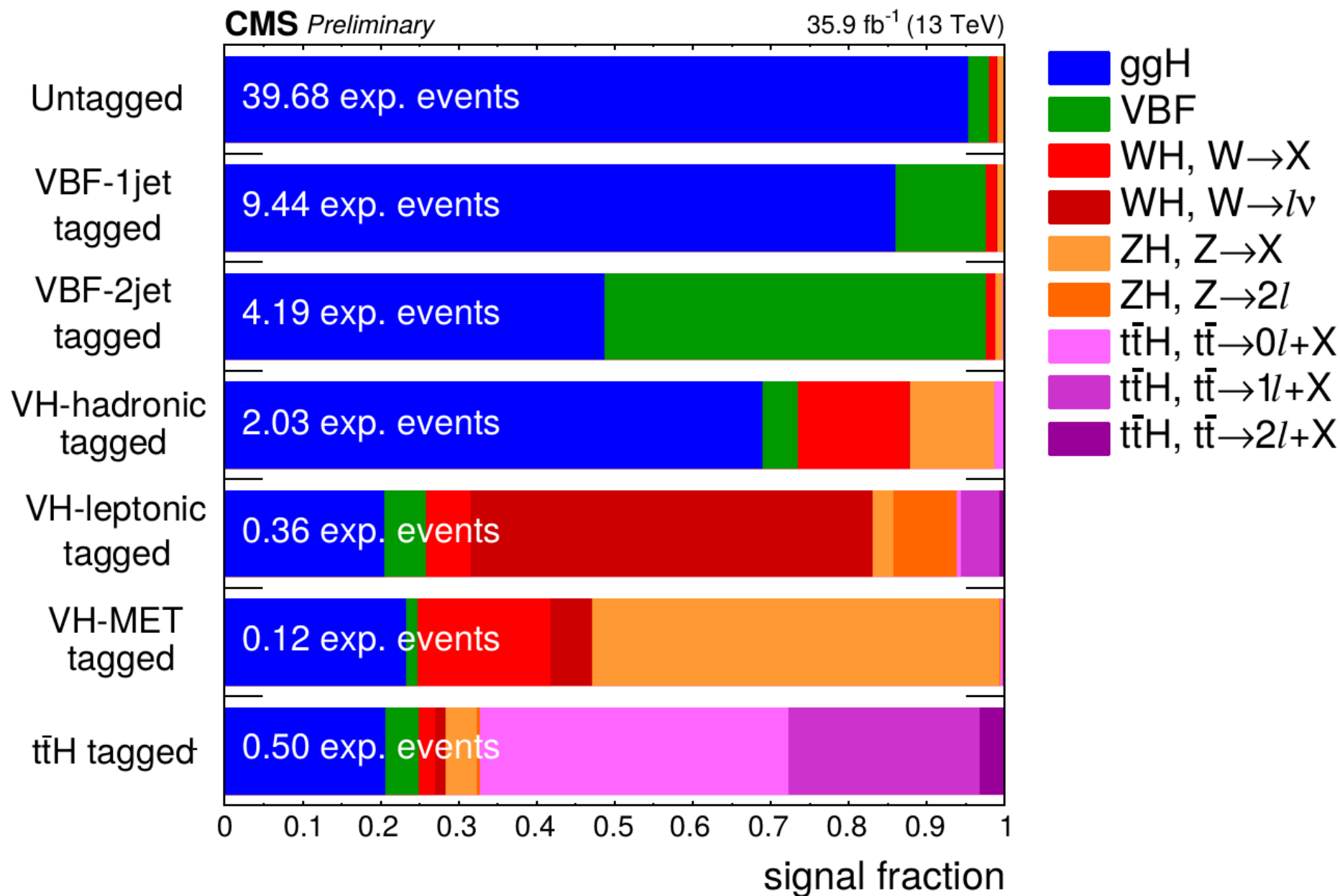
$$\sigma_{\text{fid,SM}}^{4\ell} = 3.07^{+0.21}_{-0.25} \text{ fb}$$

$$\sigma_{\text{fid.}}^{\text{SM}} = 2.72 \pm 0.14 \text{ fb}$$

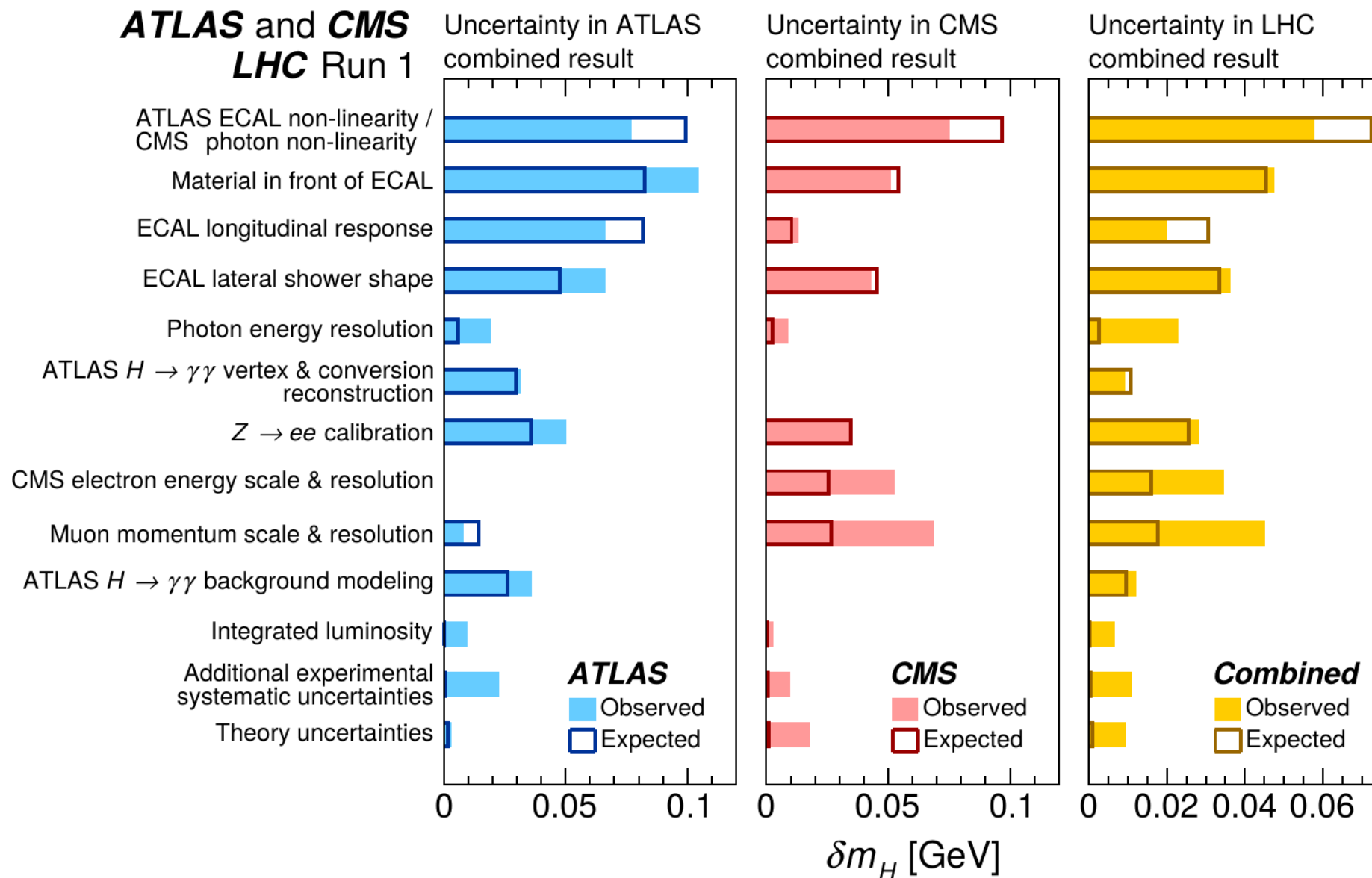
All in agreement with $\hat{\sigma}_{\text{fid.}}^{\text{SM}}$



CMS $H \rightarrow ZZ$ Category Splits

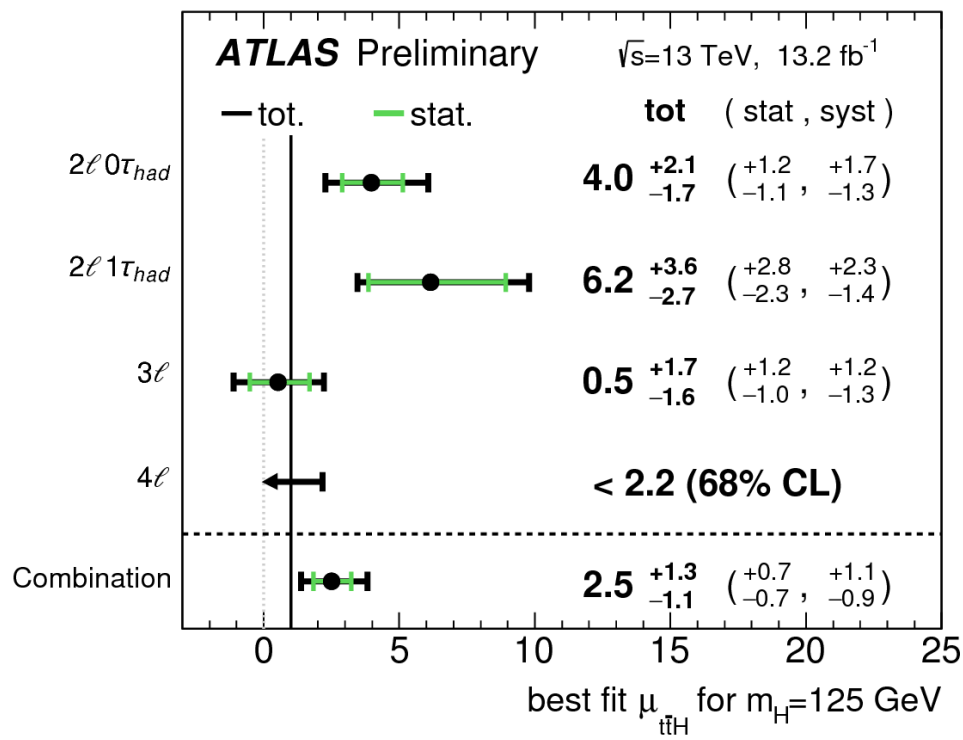


Mass Systematics



$t\bar{t}H \rightarrow \text{leptons}$

ATLAS-CONF-2016-058



CMS-PAS-HIG-17-004

Category	Measured signal rate $\pm 1\sigma$	Expected signal rate $\pm 1\sigma$
$1\ell + 2\tau_h$	$-1.20^{+1.50}_{-1.47}$	$1.00^{+1.75}_{-1.57}$
$2\ell ss + 1\tau_h$	$0.86^{+0.79}_{-0.66}$	$1.00^{+0.77}_{-0.64}$
$3\ell + 1\tau_h$	$1.22^{+1.34}_{-1.00}$	$1.00^{+1.41}_{-1.06}$
Combined	$0.72^{+0.62}_{-0.53}$	$1.00^{+0.67}_{-0.57}$

CMS-PAS-HIG-17-003

Category	Observed μ fit $\pm 1\sigma$	Expected μ fit $\pm 1\sigma$
Same-sign di-lepton	$1.7 (-0.5) (+0.6)$	$1.0 (-0.5) (+0.5)$
Three lepton	$1.0 (-0.7) (+0.8)$	$1.0 (-0.7) (+0.8)$
Four lepton	$0.9 (-1.6) (+2.3)$	$1.0 (-1.6) (+2.4)$
Combined (2016 data)	$1.5 (-0.5) (+0.5)$	$1.0 (-0.4) (+0.5)$
Combined (2015 data) [42]	$0.6 (-1.1) (+1.4)$	$1.0 (-1.1) (+1.3)$
Combined (2015+2016 data)	$1.5 (-0.5) (+0.5)$	$1.0 (-0.4) (+0.5)$

$t\bar{t}H \rightarrow \text{leptons}$

Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−0.15
Diboson modeling	+0.15	−0.14
Jet flavor tagging	+0.15	−0.12
Light lepton (e, μ) and τ_{had} ID, isolation, trigger	+0.12	−0.10
Other background modeling	+0.11	−0.11
Total systematic uncertainty	+1.1	−0.9

ttH → leptons

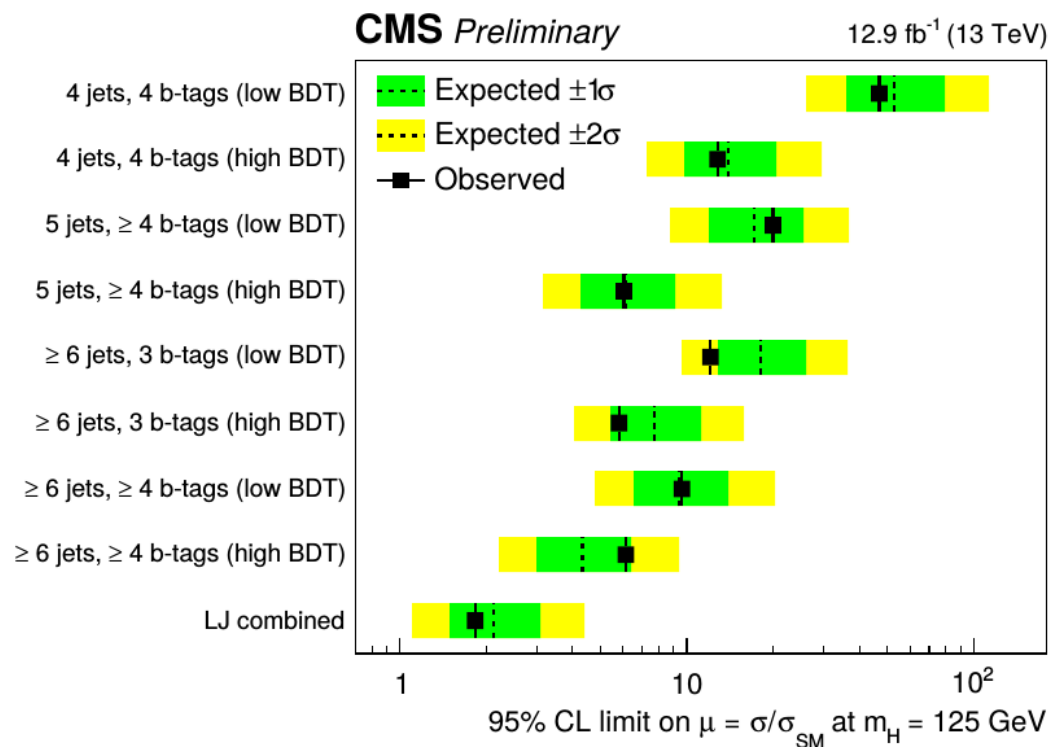
	$\mu\mu$	$e\mu$	ee
ttW	51.0 ± 0.6 (stat.) ± 6.9 (syst.)	72.8 ± 0.7 (stat.) ± 10.2 (syst.)	20.5 ± 0.4 (stat.) ± 3.1 (syst.)
ttZ/ γ^*	17.7 ± 0.8 (stat.) ± 2.9 (syst.)	47.3 ± 1.6 (stat.) ± 9.0 (syst.)	17.5 ± 1.0 (stat.) ± 3.6 (syst.)
WZ	4.2 ± 0.6 (stat.) ± 4.1 (syst.)	7.0 ± 0.8 (stat.) ± 6.8 (syst.)	1.8 ± 0.4 (stat.) ± 1.7 (syst.)
Rare SM bkg.	4.2 ± 1.5 (stat.) ± 3.0 (syst.)	13.3 ± 1.9 (stat.) ± 9.3 (syst.)	4.8 ± 1.1 (stat.) ± 3.6 (syst.)
WWss	3.5 ± 0.6 (stat.) ± 2.5 (syst.)	4.1 ± 0.6 (stat.) ± 3.2 (syst.)	1.4 ± 0.3 (stat.) ± 1.2 (syst.)
Conversions		7.8 ± 2.5 (stat.) ± 2.3 (syst.)	3.6 ± 3.5 (stat.) ± 1.7 (syst.)
Charge mis-meas.		16.4 ± 0.2 (stat.) ± 9.1 (syst.)	10.5 ± 0.2 (stat.) ± 5.9 (syst.)
Non-prompt leptons	38.7 ± 1.6 (stat.) ± 20.5 (syst.)	61.8 ± 2.0 (stat.) ± 13.0 (syst.)	17.7 ± 1.1 (stat.) ± 5.4 (syst.)
All backgrounds	120.3 ± 2.5 (stat.) ± 11.7 (syst.)	231.2 ± 4.3 (stat.) ± 13.3 (syst.)	77.9 ± 4.0 (stat.) ± 9.0 (syst.)
ttH signal	20.1 ± 0.5 (stat.) ± 2.1 (syst.)	27.9 ± 0.5 (stat.) ± 3.0 (syst.)	8.0 ± 0.3 (stat.) ± 1.1 (syst.)
Data	150	268	89

	3L	4L
ttW	32.8 ± 1.0 (stat.) ± 4.9 (syst.)	
ttZ/ γ^*	49.8 ± 3.9 (stat.) ± 11.1 (syst.)	2.15 ± 0.24 (stat.) ± 0.44 (syst.)
WZ	9.1 ± 0.9 (stat.) ± 4.0 (syst.)	
Rare SM bkg.	8.8 ± 4.3 (stat.) ± 5.9 (syst.)	0.27 ± 0.16 (stat.) ± 0.19 (syst.)
WWss		
Conversions	5.3 ± 1.2 (stat.) ± 4.0 (syst.)	
Charge mis-meas.		
Non-prompt leptons	30.8 ± 1.5 (stat.) ± 10.9 (syst.)	
All backgrounds	137.3 ± 6.2 (stat.) ± 12.4 (syst.)	2.42 ± 0.28 (stat.) ± 0.56 (syst.)
ttH signal	19.5 ± 1.0 (stat.) ± 3.0 (syst.)	1.00 ± 0.09 (stat.) ± 0.11 (syst.)
Data	148	3

Uncertainty source	$\Delta\mu$	
$t\bar{t}+ \geq 1b$ modelling	+0.53	−0.53
Jet flavour tagging	+0.26	−0.26
$t\bar{t}H$ modelling	+0.32	−0.20
Background model statistics	+0.25	−0.25
$t\bar{t}+ \geq 1c$ modelling	+0.24	−0.23
Jet energy scale and resolution	+0.19	−0.19
$t\bar{t}+\text{light}$ modelling	+0.19	−0.18
Other background modelling	+0.18	−0.18
Jet-vertex association, pileup modelling	+0.12	−0.12
Luminosity	+0.12	−0.12
$t\bar{t}Z$ modelling	+0.06	−0.06
Light lepton (e, μ) ID, isolation, trigger	+0.05	−0.05
Total systematic uncertainty	+0.90	−0.75
$t\bar{t}+ \geq 1b$ normalisation	+0.34	−0.34
$t\bar{t}+ \geq 1c$ normalisation	+0.14	−0.14
Statistical uncertainty	+0.49	−0.49
Total uncertainty	+1.02	−0.89

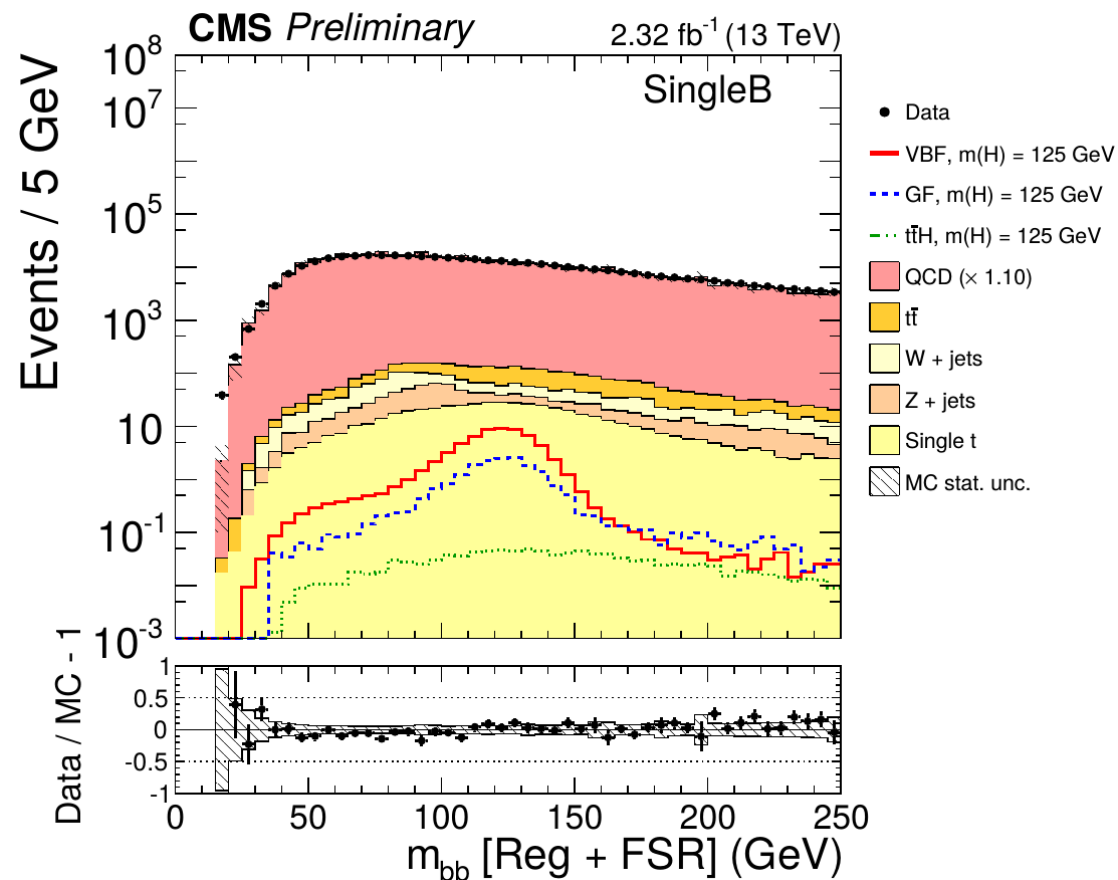
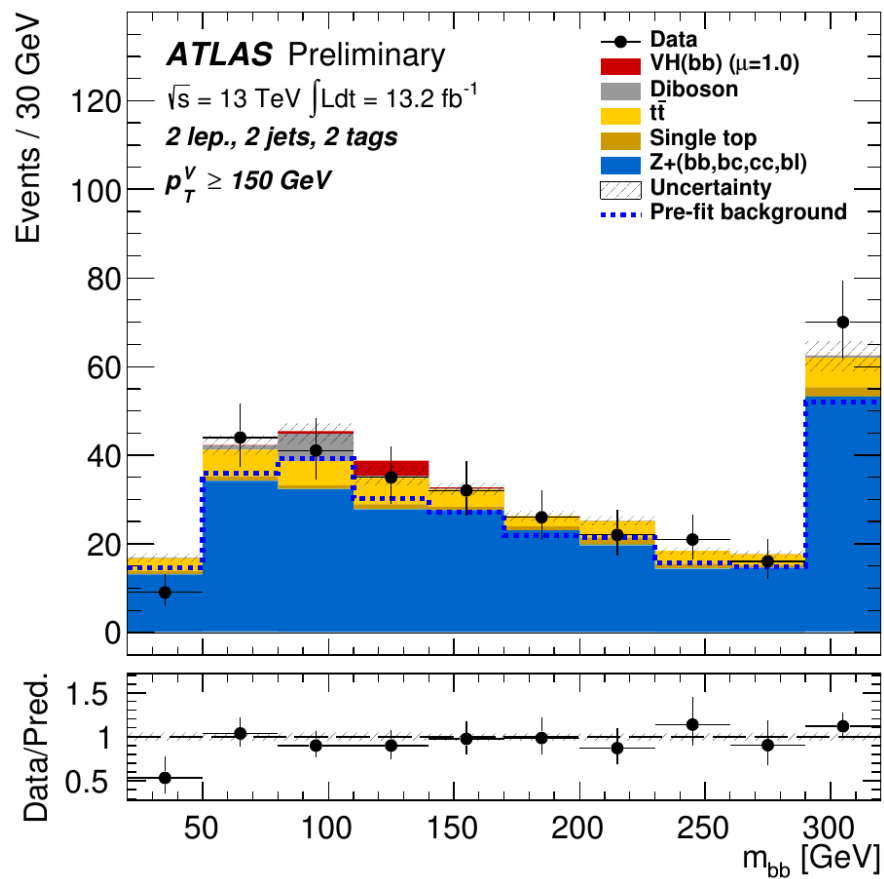
	Observed	Expected ($\mu = 0$)			Expected ($\mu = 1$)
		Median	+/-1 σ	+/-2 σ	
Dilepton	10.1	5.3	[3.8, 7.9]	[2.8, 12.6]	6.0
Single lepton	3.6	2.2	[1.6, 3.2]	[1.2, 4.7]	2.9
Combined	4.0	1.9	[1.4, 2.8]	[1.0, 4.2]	2.7

CMS $t\bar{t}H \rightarrow b\bar{b}$



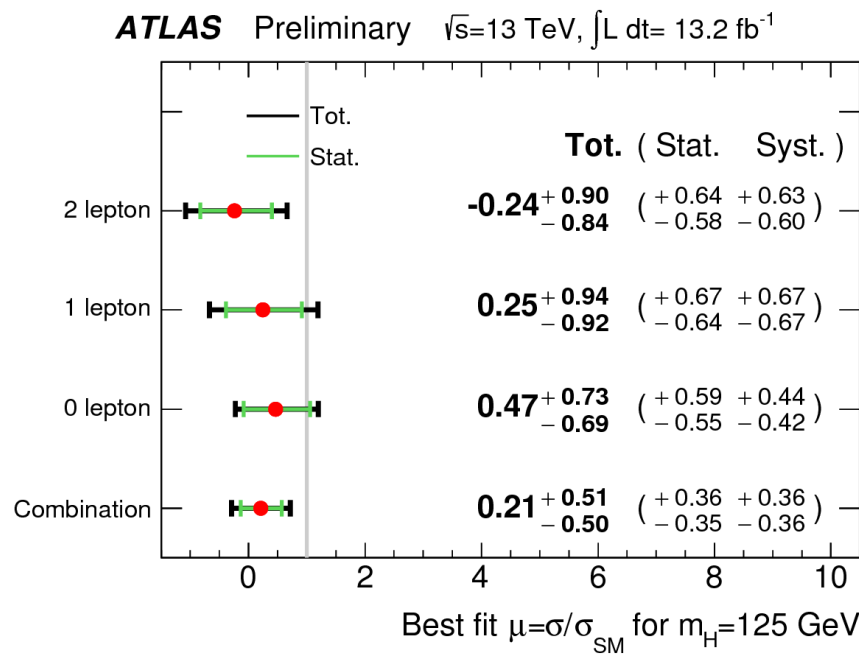
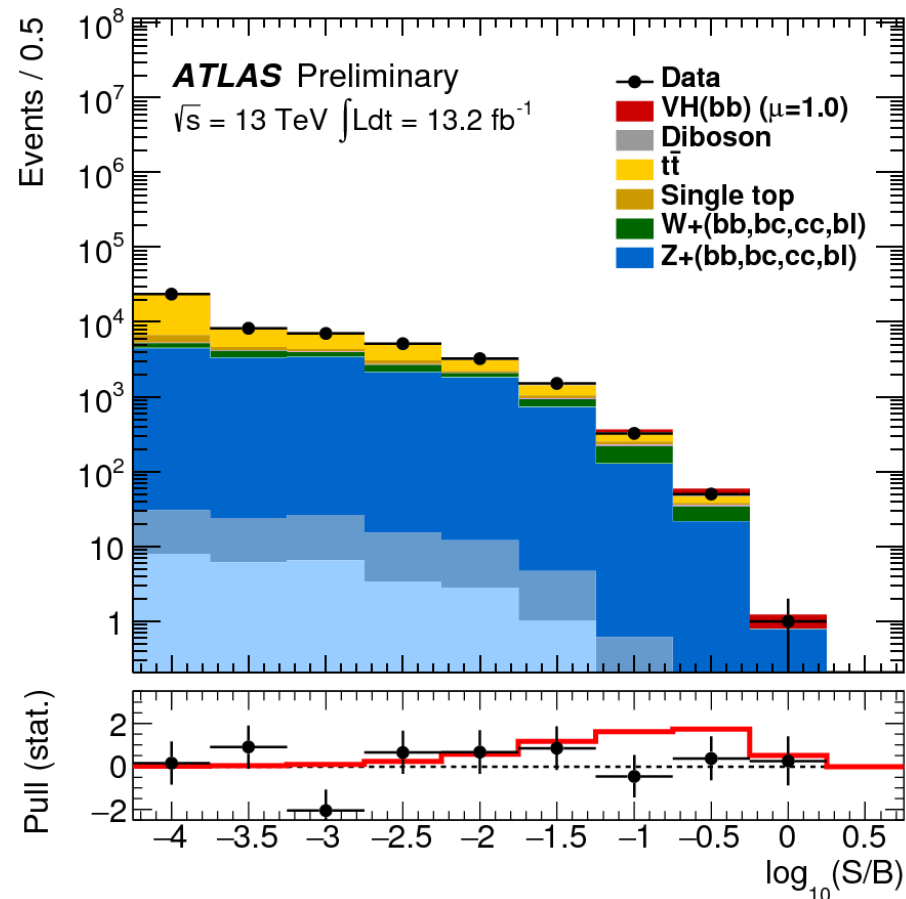
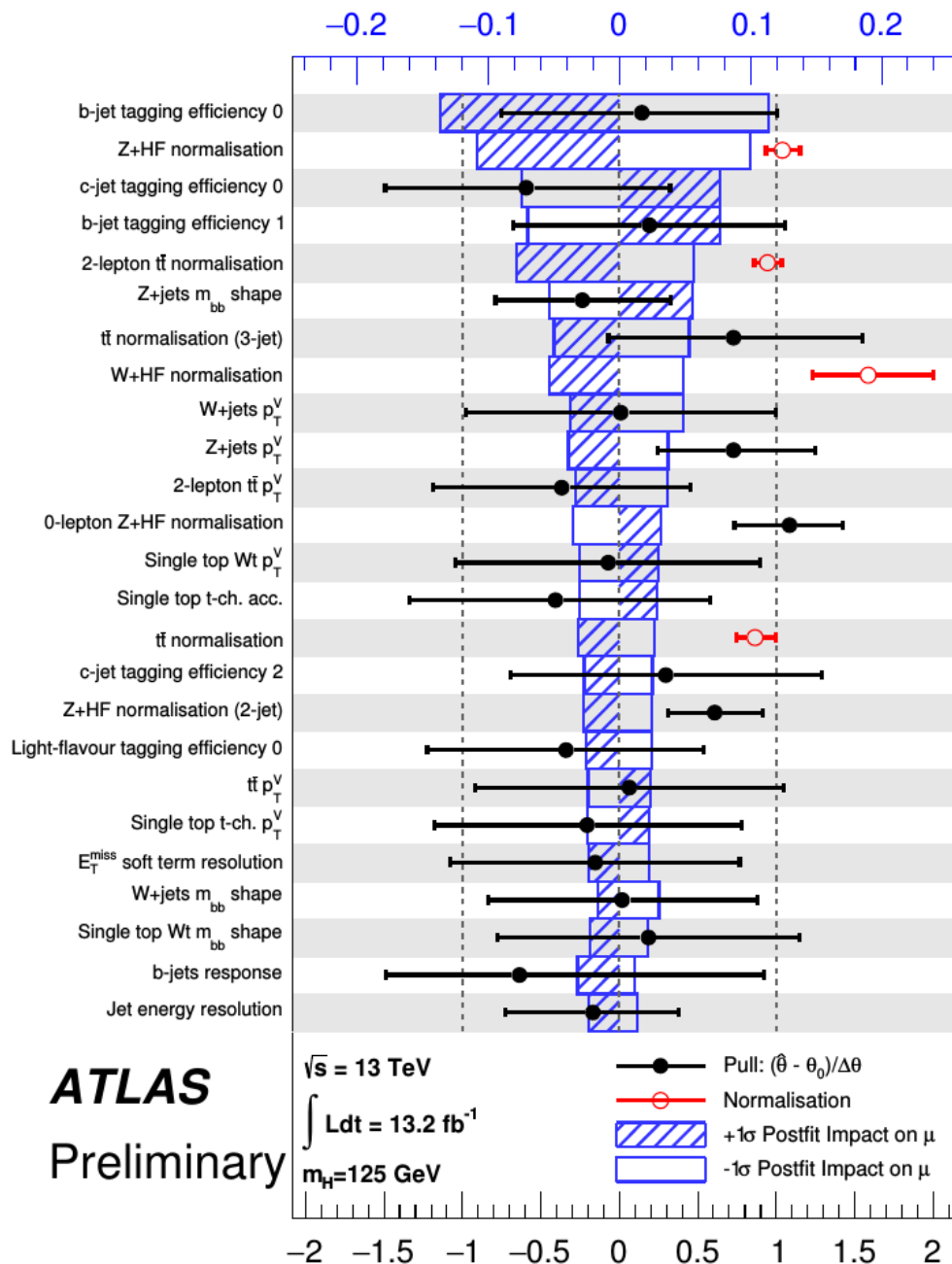
Process	$t\bar{t}$ rate up/down [%]	$t\bar{t}H$ rate up/down [%]
Jet energy scale	+12.6/ - 11.8	+8.4/ - 8.0
Jet energy resolution	+0.2/ - 0.3	-0.0/ - 0.1
Pile-up	+0.1/ - 0.1	-0.2/ + 0.1
Electron efficiency	+0.5/ - 0.5	+0.5/ - 0.5
Muon efficiency	+0.4/ - 0.4	+0.4/ - 0.4
Electron trigger efficiency	+1.2/ - 1.2	+1.3/ - 1.3
Muon trigger efficiency	+0.8/ - 0.8	+0.9/ - 0.9
b-Tag HF contamination	-9.4/ + 9.8	-2.6/ + 2.8
b-Tag HF stats (linear)	-3.1/ + 3.3	-2.5/ + 2.7
b-Tag HF stats (quadratic)	+2.6/ - 2.4	+2.4/ - 2.2
b-Tag LF contamination	+7.1/ - 5.2	+5.8/ - 4.5
b-Tag LF stats (linear)	-2.0/ + 4.4	+0.5/ + 1.5
b-Tag LF stats (quadratic)	+2.1/ + 0.2	+1.5/ + 0.5
b-Tag charm Uncertainty (linear)	-11.1/ + 14.9	-3.1/ + 4.1
b-Tag charm Uncertainty (quadratic)	+0.5/ - 0.5	-0.0/ + 0.0
Q^2 scale ($t\bar{t}+LF$)	-6.2/ + 7.5	-
Q^2 scale ($t\bar{t}+b$)	-1.7/ + 2.0	-
Q^2 scale ($t\bar{t}+2b$)	-1.1/ + 1.4	-
Q^2 scale ($t\bar{t}+b\bar{b}$)	-2.0/ + 2.5	-
Q^2 scale ($t\bar{t}+c\bar{c}$)	-4.3/ + 5.4	-
PS scale ($t\bar{t}+LF$)	+4.8/ - 9.0	-
PS scale ($t\bar{t}+b$)	-0.9/ + 0.7	-
PS scale ($t\bar{t}+2b$)	-0.8/ + 0.9	-
PS scale ($t\bar{t}+b\bar{b}$)	-1.5/ + 2.7	-
PS scale ($t\bar{t}+c\bar{c}$)	-3.9/ + 3.0	-

Channel	Observed UL	Expected UL	Best-fit μ		
Dilepton	3.2	$3.4^{+1.5}_{-1.0}$	$-0.04^{+1.50}_{-1.39}$ (tot.)	$+1.05$ (stat.)	$+1.01$ (syst.)
Lepton+jets	1.8	$2.1^{+1.0}_{-0.6}$	$-0.43^{+1.02}_{-1.02}$ (tot.)	$+0.51$ (stat.)	$+0.88$ (syst.)
Combined	1.5	$1.7^{+0.7}_{-0.5}$	$-0.19^{+0.80}_{-0.81}$ (tot.)	$+0.45$ (stat.)	$+0.66$ (syst.)



H → bb

$\Delta\mu$



	Signal
Cross section (scale)	0.7% ($q\bar{q}$), 27% (gg)
Cross section (PDF)	1.9% ($q\bar{q} \rightarrow WH$), 1.6% ($q\bar{q} \rightarrow ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance (scale)	1.4%–5%
3-jet acceptance (scale)	1.4%–4.7%
p_T^V shape (scale)	S
Acceptance (PDF)	0.3%–0.7%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	4%–7.5%

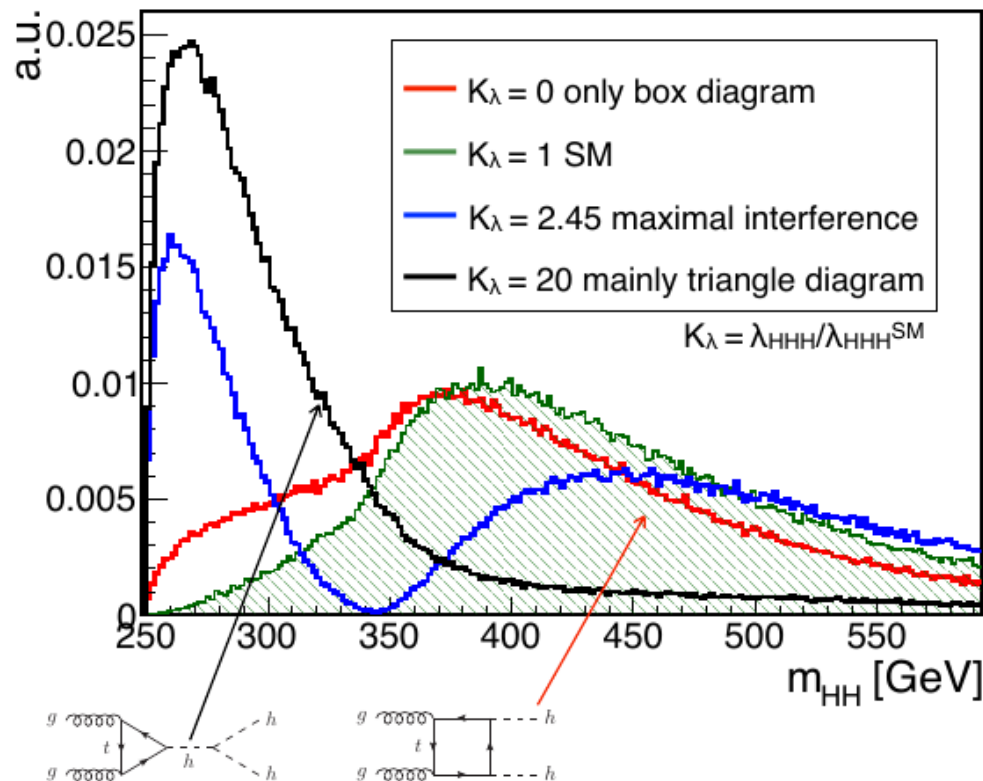
Uncertainty source	Uncertainty $\Delta\mu$
Non-resonant background uncertainty in medium-BDT region	0.22
Non-resonant background uncertainty in high-BDT region	0.21
Non-resonant background uncertainty in low-BDT region	0.17
Parton shower uncertainty on $H + \gamma$ acceptance	0.16
QCD scale uncertainty on $H + \gamma$ cross section	0.13
Jet energy uncertainty from calibration across η	0.10
Jet energy uncertainty from flavour composition in calibration	0.09
Integrated luminosity uncertainty	0.08

H $\rightarrow\mu\mu$

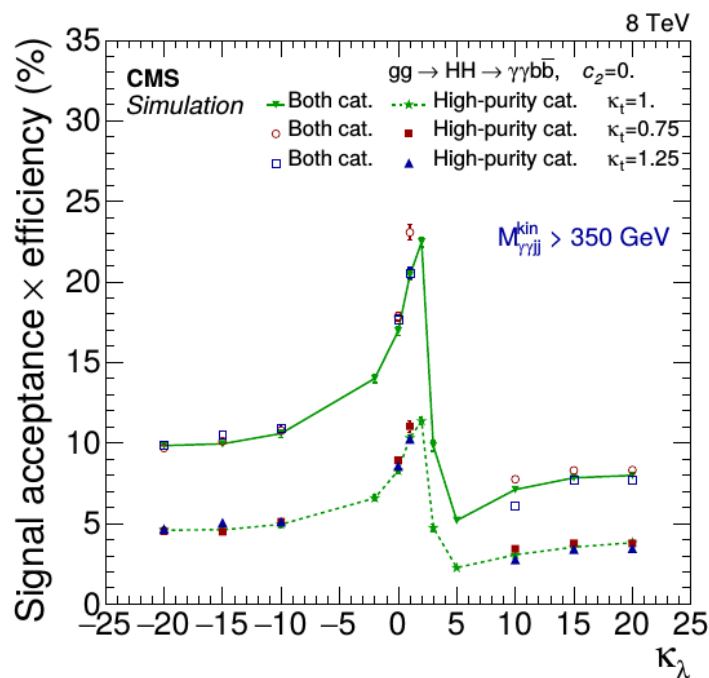
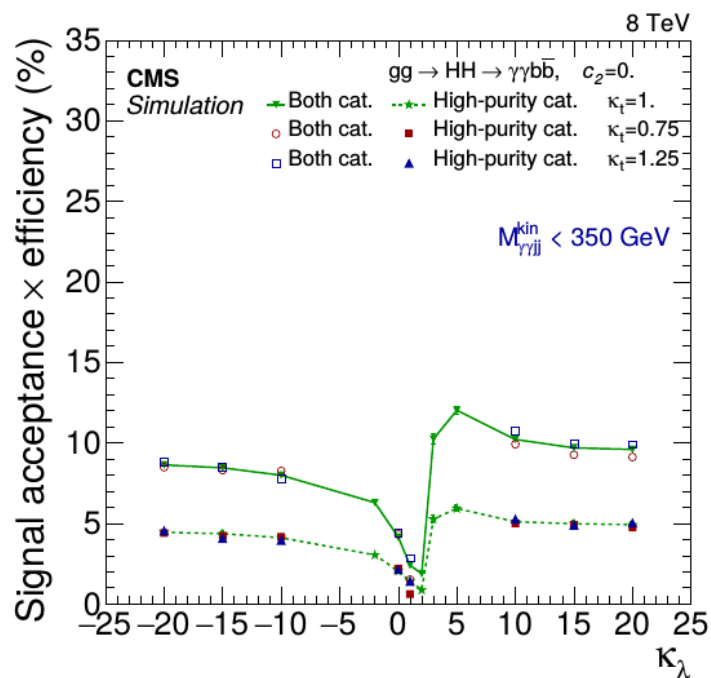
	Signal	Background	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	10.9	7400	0.13	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	31.6	36000	0.17	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23.4	6200	0.30	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66.5	29000	0.39	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	15.5	3300	0.27	6.3 GeV	3160
Non-central high $p_T^{\mu\mu}$	39.7	13000	0.35	7.7 GeV	12829
VBF loose	3.4	250	0.22	7.6 GeV	274
VBF tight	3.4	71	0.40	7.5 GeV	79

CMS $HH \rightarrow \gamma\gamma b\bar{b}$

Roberto Salerno

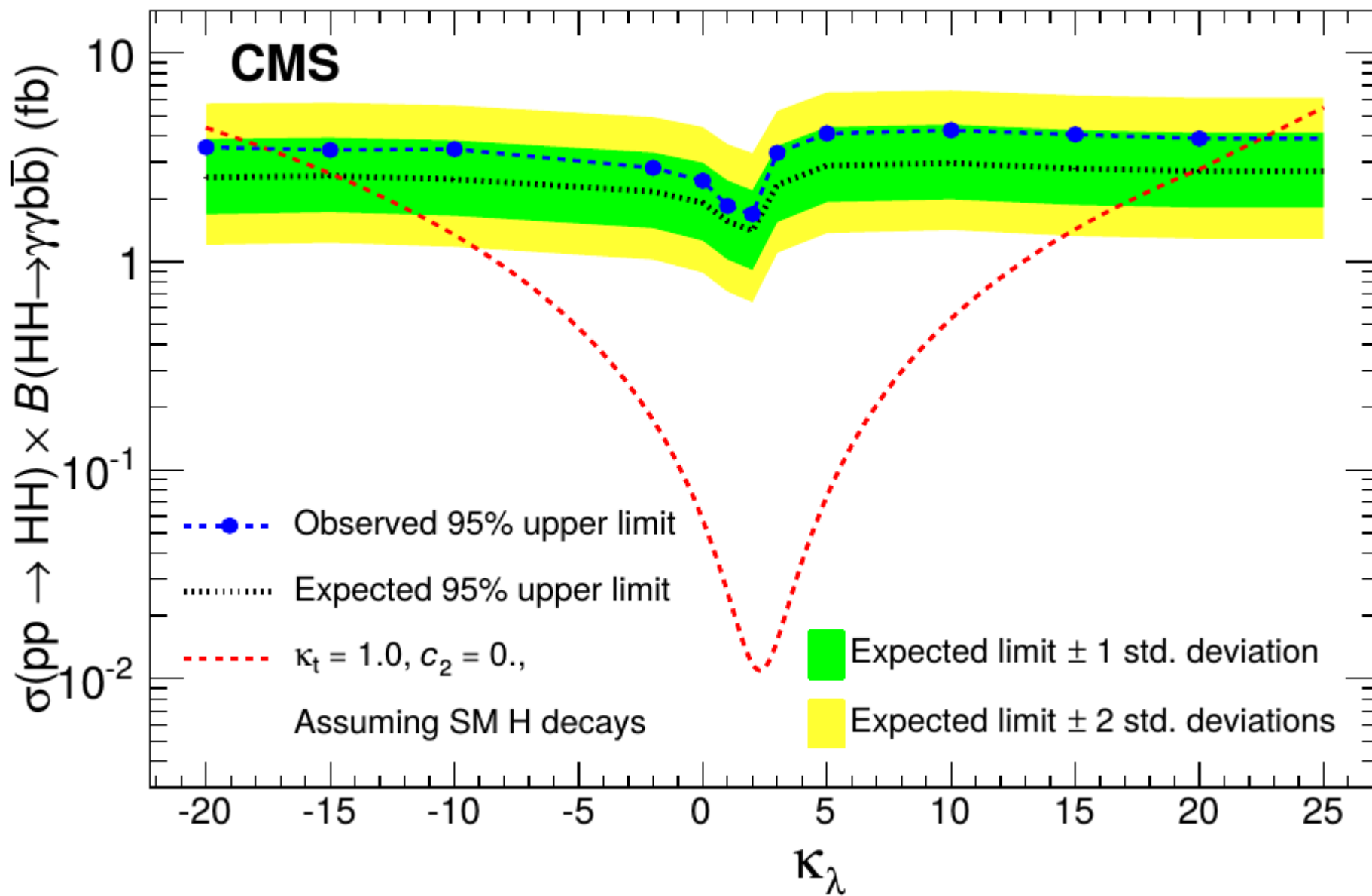


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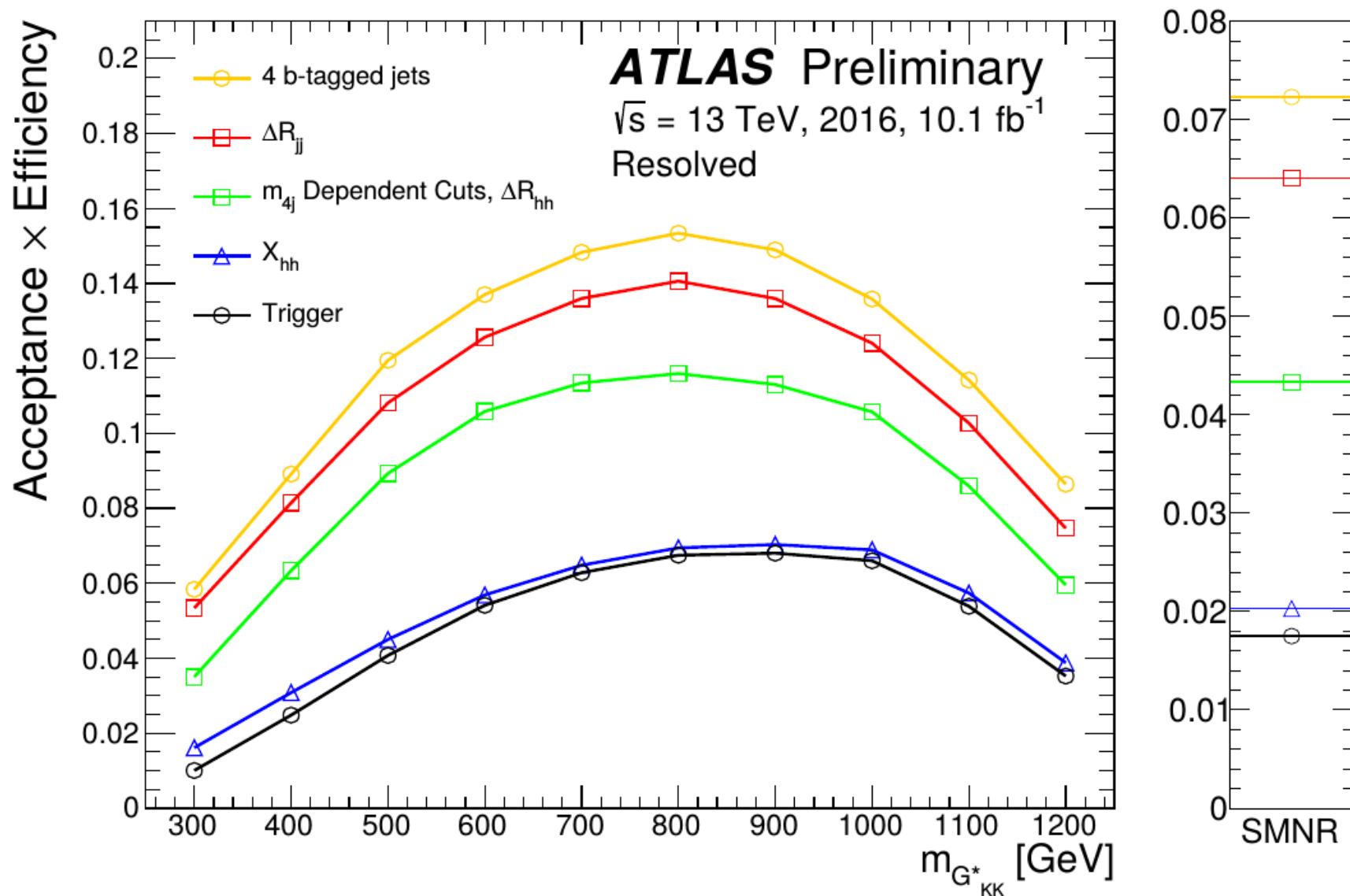


CMS $HH \rightarrow \gamma\gamma b\bar{b}$

19.7 fb⁻¹ (8 TeV)



HH $\rightarrow$ bbbb

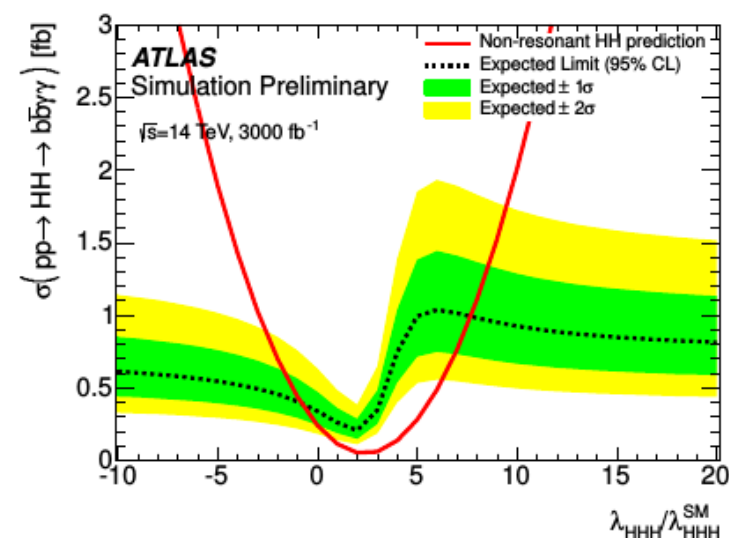


Future prospects

- Measurement of σ_{HH} and determination of λ_{HHH} are one of the main points of the physics programme at the HL-LHC (3 ab⁻¹ of data)
- Two alternative approaches to estimate the sensitivity to HH production



- parametric simulation of upgraded detector response



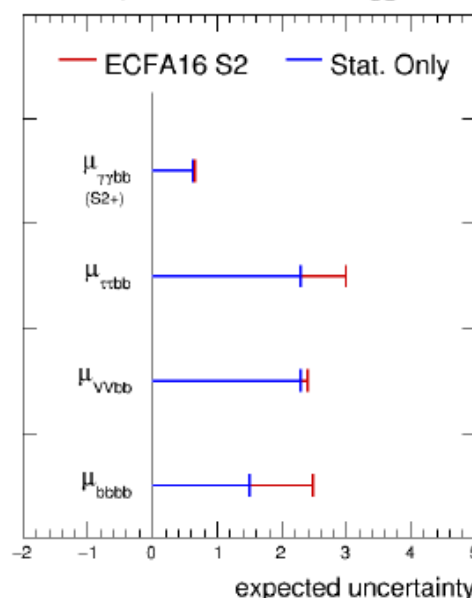
$bb\gamma\gamma$,
 $bb\tau\tau$ and
 $bbbb$
 studied

- Best significance is 1.05σ from $bb\gamma\gamma$

- extrapolation of results from 13 TeV, 2.3/2.7 fb⁻¹ to HL-LHC (conservative: current results not optimal for high luminosity)



CMS Projection $\sqrt{s} = 13$ TeV SM $gg \rightarrow HH$



Significance

$bb\gamma\gamma$	1.6σ
$bb\tau\tau$	0.39σ
$bbVV$	0.45σ
$bbbb$	0.39σ

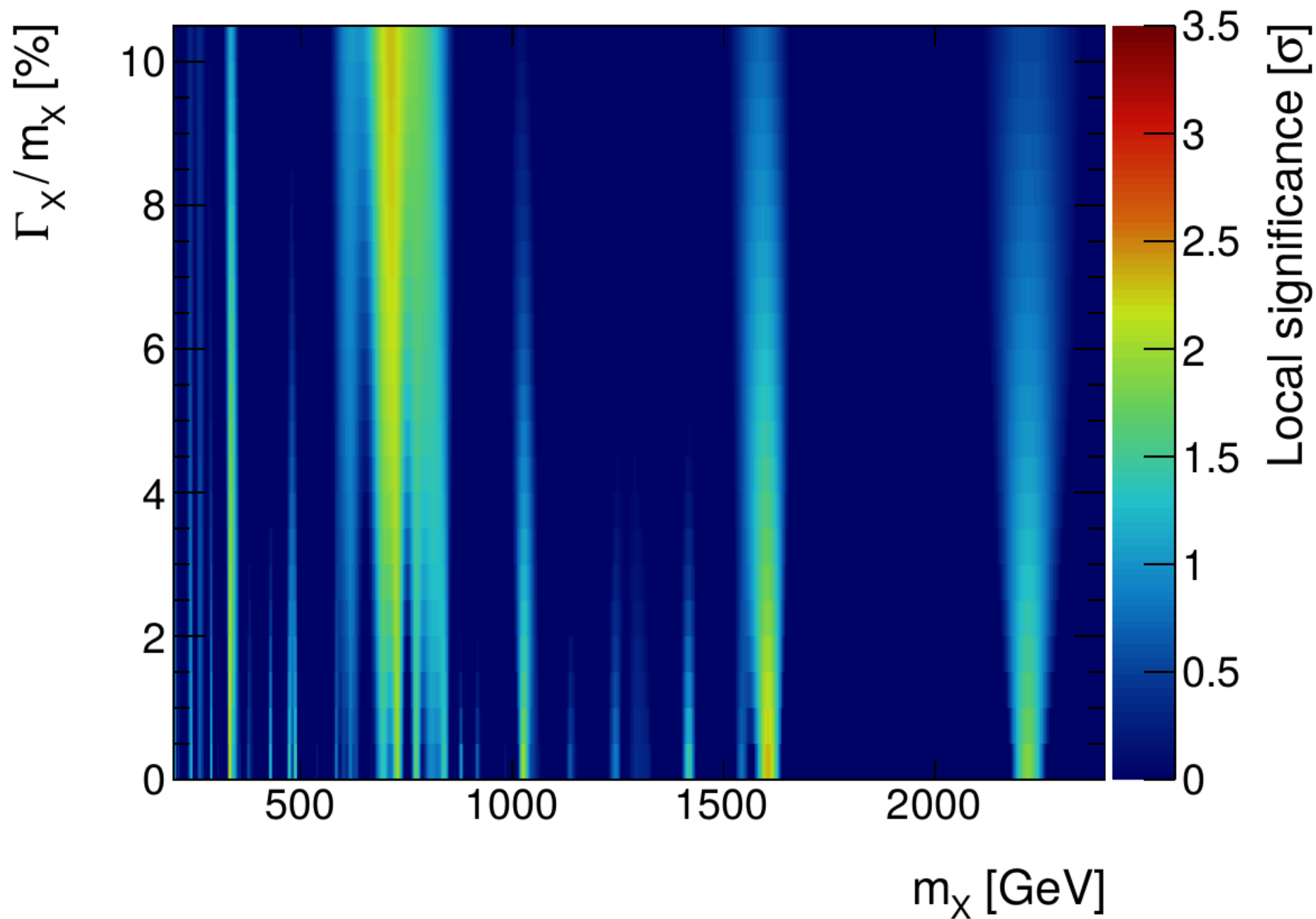
Combination of final states and of ATLAS and CMS will be crucial to observe HH production

High-Mass $\gamma\gamma$

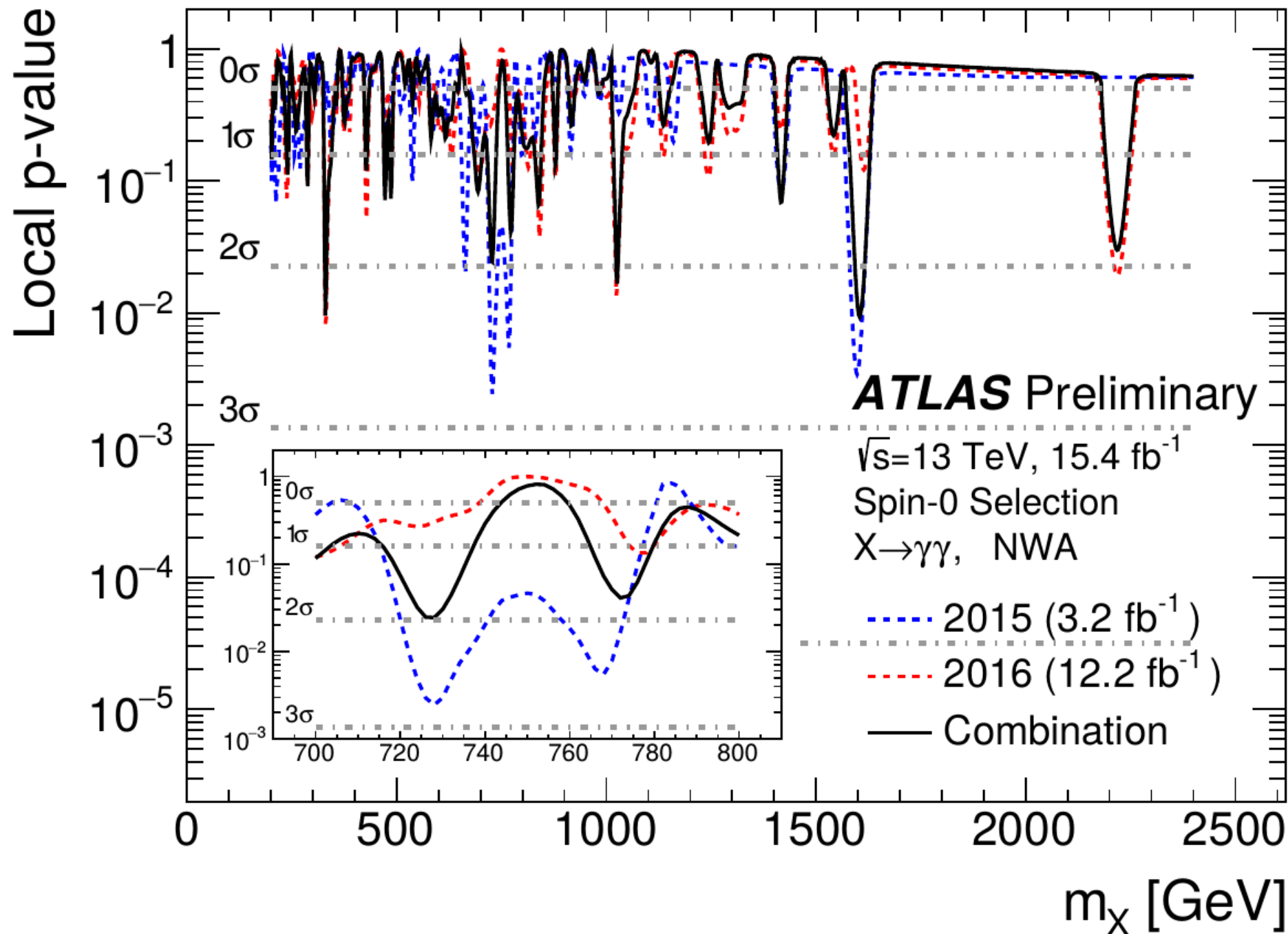
ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}, 15.4 \text{ fb}^{-1}$

Spin-0 Selection



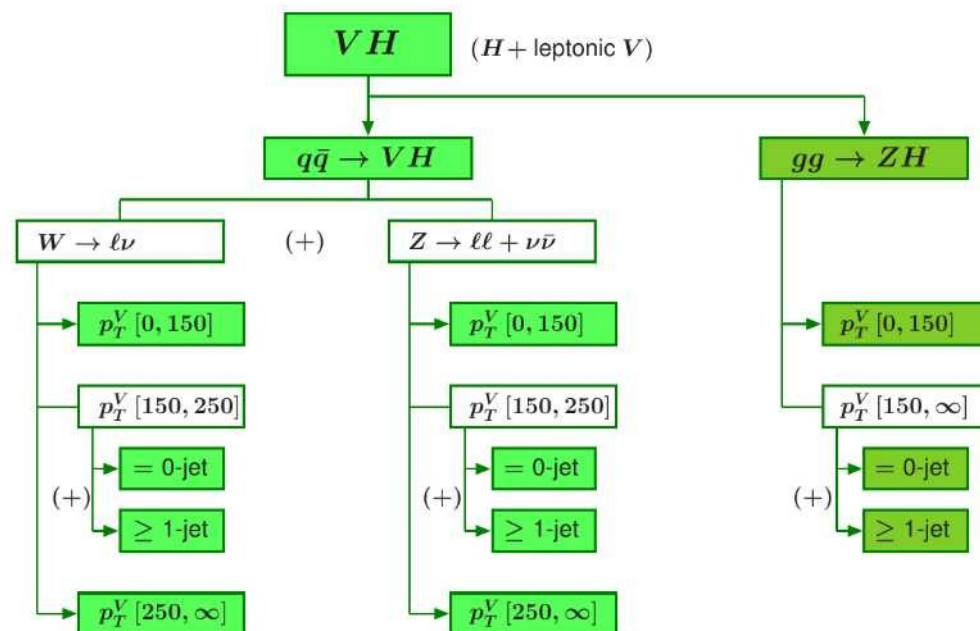
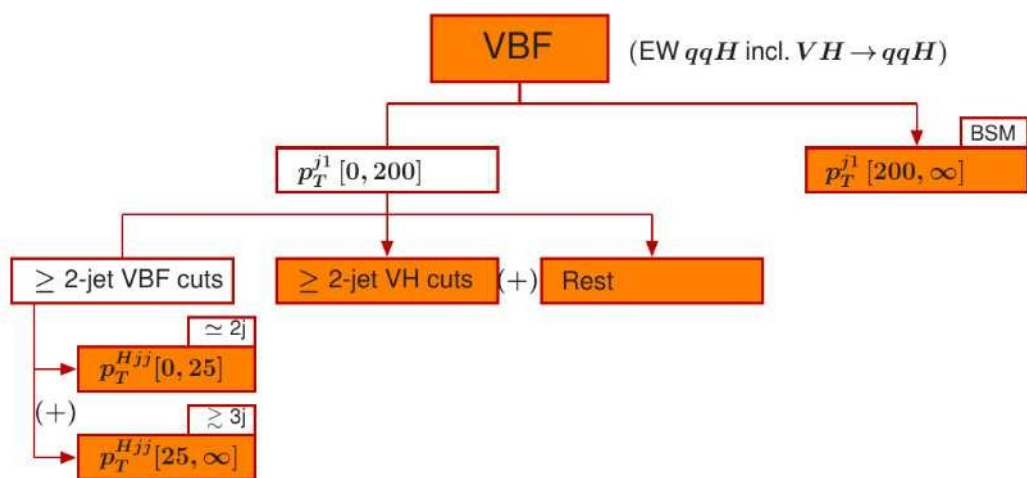
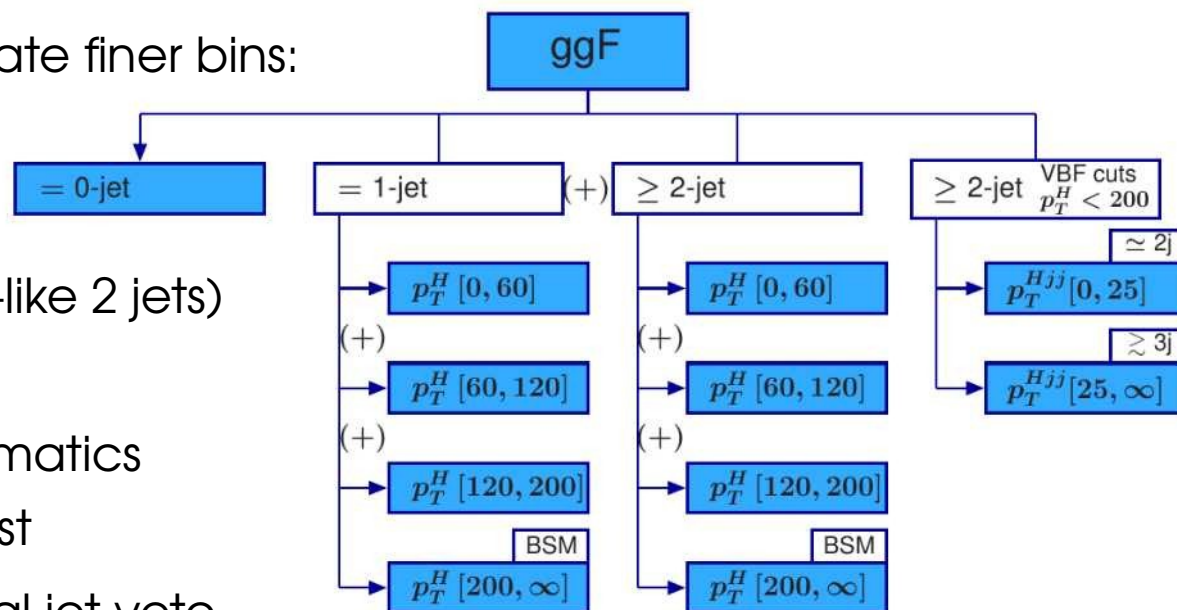
High-Mass $\gamma\gamma$



Measurement Frameworks for Run 2 and Beyond

Larger 2016 dataset $\Rightarrow$ Can populate finer bins:

- **ggF** :
 1. N_{jets} split
 2. p_T^H split for 1,2 jets (p_T^{Hjj} for VBF-like 2 jets)
- **VBF & (V $\rightarrow$ had)H** :
 1. Split **VBF**, **(V $\rightarrow$ had)H** from kinematics
 2. split off “**BSM**” (high p_T) and rest
- 3. p_T^{Hjj} split to match experimental jet veto
- **(V $\rightarrow$ lep)H** :
 - Split **W $\rightarrow$ lv** and **Z $\rightarrow$ ll/vv** from qq/gg
- p_T^V , N_{jets}



SMEFT

- SM scale $\sim v = 246 \text{ GeV}$, no BSM physics seen below $\Lambda \sim 1 \text{ TeV}$
 $\Rightarrow$ parameterize the BSM using an **EFT extension of the SM**

$$L = L_{SM}^{(d \leq 4)} + \frac{1}{\Lambda^2} \sum_i c_i^{(d=6)} O_i^{(d=6)} + \frac{1}{\Lambda^4} \sum_i c_i^{(d=8)} O_i^{(d=8)} + \dots$$

- Usually(*) leading effect from **interference of d=6 and SM** $\sim (v/\Lambda)^2$ and can **neglect d $\geq$ 8** and $|c^{(d=6)}|^2$.
 $\Rightarrow$ **Report experimental constraints on the c_i** , compare to model predictions
- Straightforward to extend to higher orders in SM couplings
- Many operators: 2499** for $n_{\text{gen}}=3$
 - For $n_{\text{gen}}=1$ (or MFV): “only” **59**
 - Operators **involving the Higgs boson** can be reduced to **17**.
- Many ways to define the operator basis on which to expand: **SILH** basis, **Warsaw** basis, **Higgs** basis etc. (*) Some restrictions may apply, see [YR4](#) Section II.2.2 for details

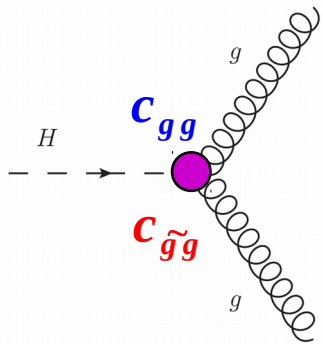
A Bestiary of SMEFT Operators (1)

YR4 Section II.2.1

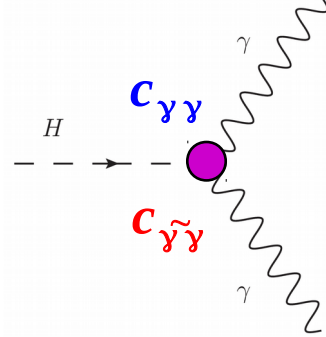
Using **Higgs Basis**, as defined in YR4, ignoring flavor ($n_{\text{gen}}=1$ or MFV)

→ **17 operators (10 CP-even + 7 CP-odd)** involving the Higgs boson

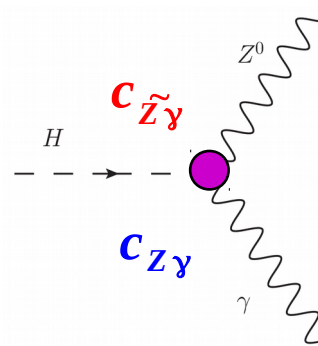
Tree-level ggH (κ_g)



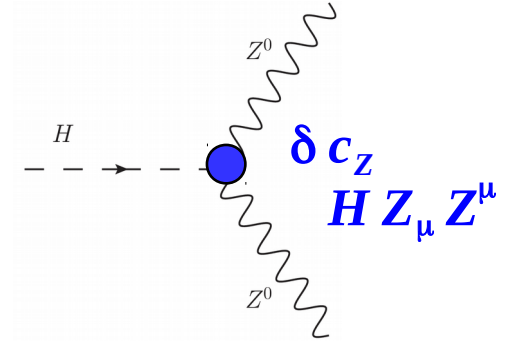
Tree-level $H\gamma\gamma$ (κ_γ)



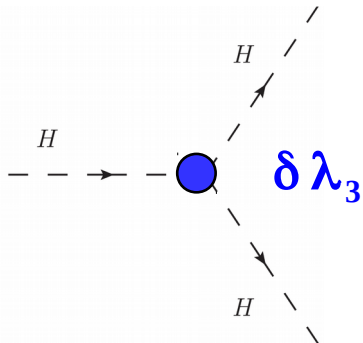
Tree-level $HZ\gamma$



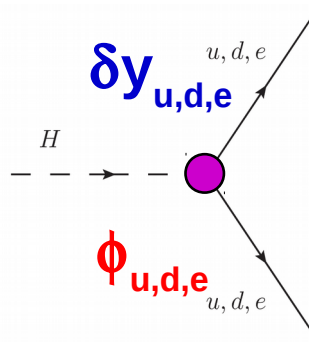
HZZ coupling modifier (κ_Z)



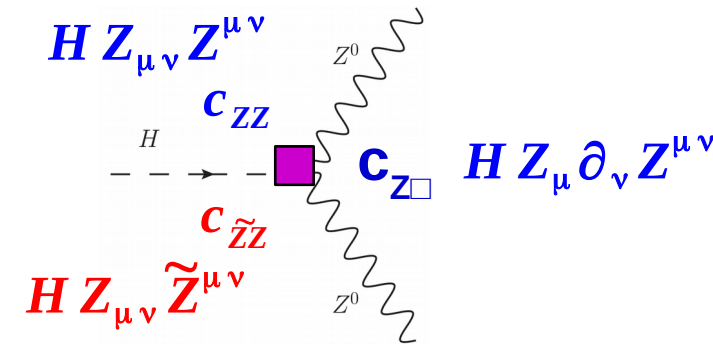
Modified H^3 Coupling



Modified Yukawa coupling magnitudes (κ_f) and phases



Modified HZZ interaction with derivative couplings



⇒ κ framework with effective (κ_g, κ_γ) + CP-odd couplings + modified HZZ structure

A Bestiary of SMEFT Operators (2)

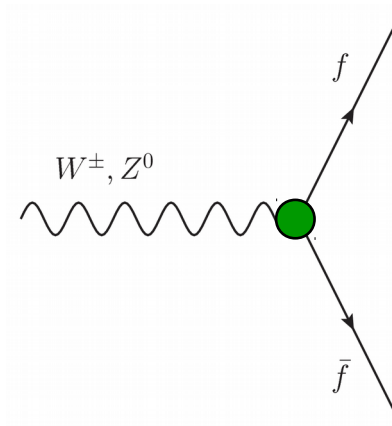
YR4 Section II.2.1

→ **46** operators not involving the Higgs boson

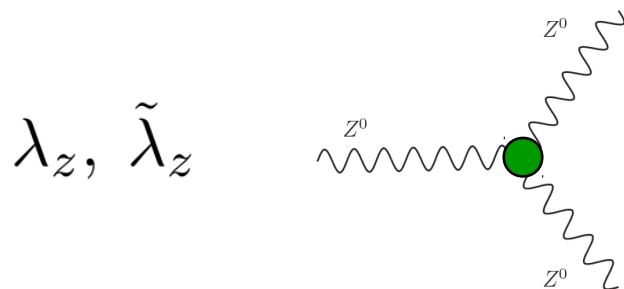
• **16 W,Z→ff couplings modifiers + W mass shift δm**

$$\delta m, [\delta g_L^{Ze}]_{ij}, [\delta g_R^{Ze}]_{ij}, [\delta g_L^{W\ell}]_{ij}, [\delta g_L^{Zu}]_{ij}, [\delta g_R^{Zu}]_{ij}, [\delta g_L^{Zd}]_{ij}, [\delta g_R^{Zd}]_{ij}, [\delta g_R^{Wq}]_{ij},$$

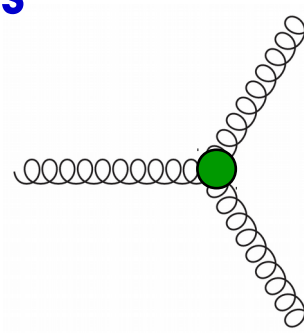
$$[dGu]_{ij}, [dGd]_{ij}, [dAe]_{ij}, [dAu]_{ij}, [dAd]_{ij}, [dZe]_{ij}, [dZu]_{ij}, [dZd]_{ij}.$$



• **4 corrections to triple-Z and triple-g couplings**



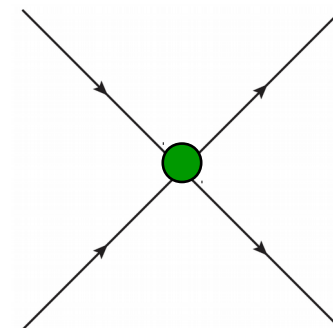
$$c_{3G}, \tilde{c}_{3G}$$



• **25 four-fermion couplings**

$$c_{ll}, c_{qq}, c'_{qq}, c_{lq}, c'_{lq}, c_{quqd}, c'_{quqd}, c_{lequ}, c'_{lequ}, c_{ledq},$$

$$c_{le}, c_{lu}, c_{ld}, c_{qe}, c_{qu}, c'_{qu}, c_{qd}, c'_{qd}, c_{ee}, c_{uu}, c_{dd}, c_{eu}, c_{ed}, c_{ud}, c'_{ud}$$



Can be constrained using **precision EW** and **flavor** measurements

⇒ **Global SM fits are critical to fully constrain the SMEFT**

⇒ For **Higgs measurements**, can focus on the other 17 operators

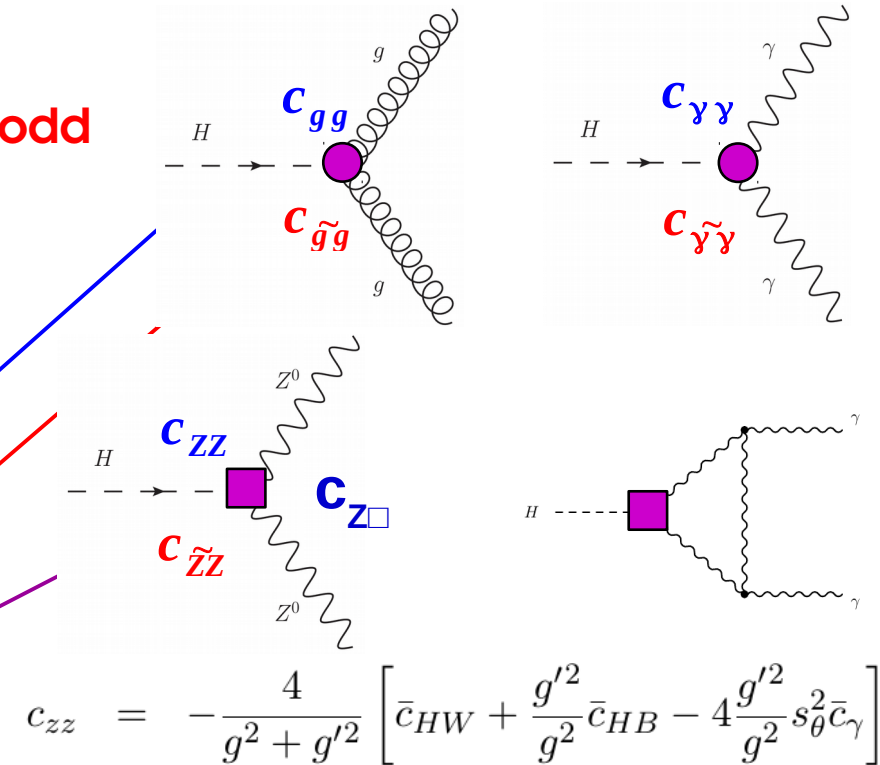
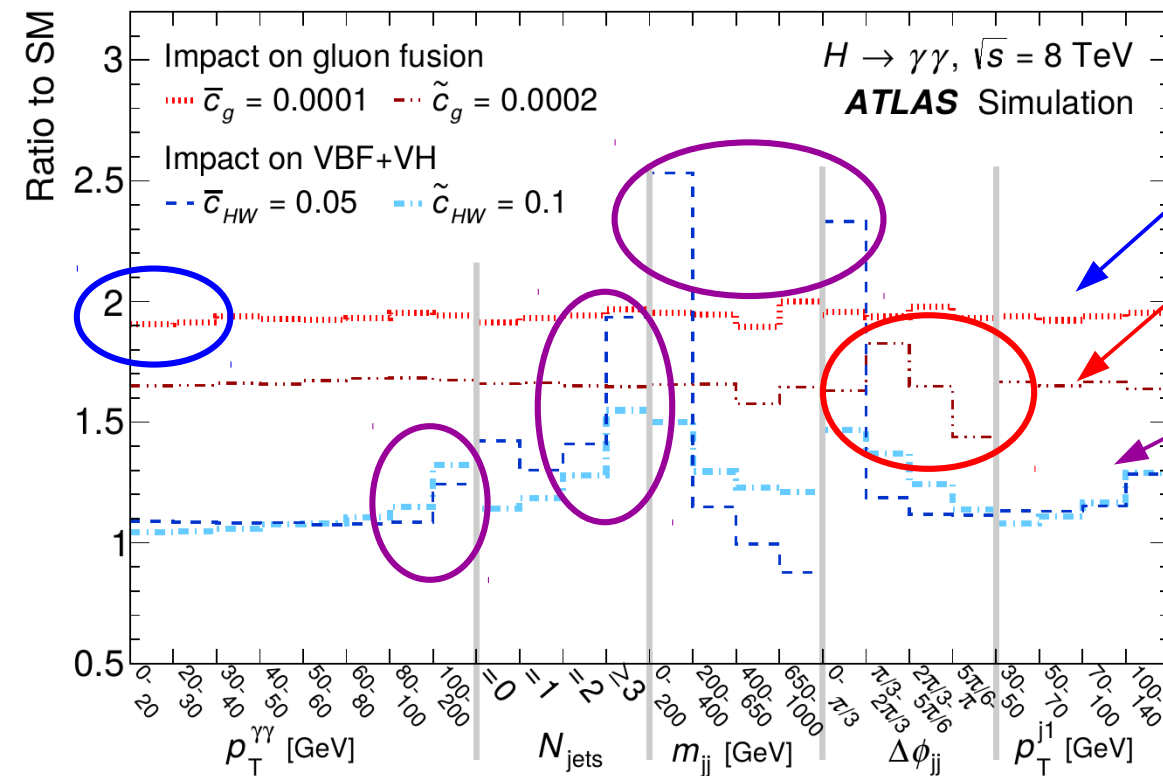
Effective Lagrangian Interpretation of $H \rightarrow \gamma\gamma$ Differential Results

PLB 753 (2016) 69-85

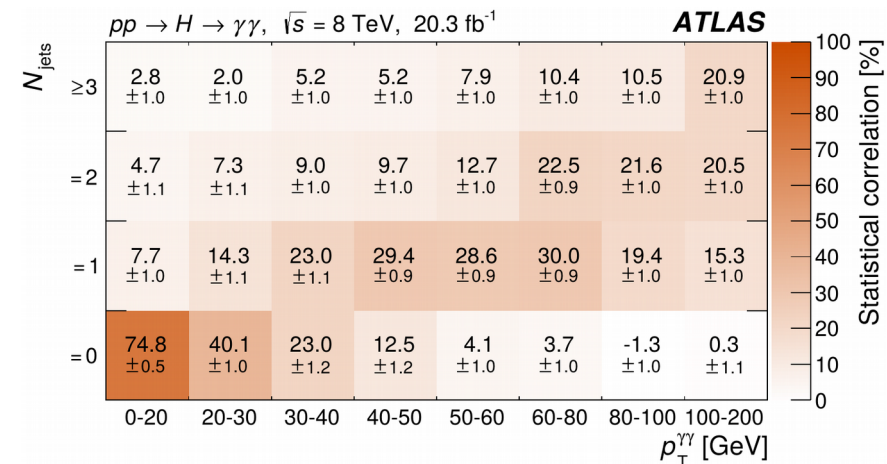
Reinterpret ATLAS Run 1 $H \rightarrow \gamma\gamma$ differential results in SMEFT-inspired effective Lagrangian

Use 5 distributions : p_T^H , N_{jets} , m_{jj} , $\Delta\phi_{jj}$, p_T^{j1} , 24 bins

Consider 6 coefficients: c_γ , c_g , c_{HW} + matching CP-odd

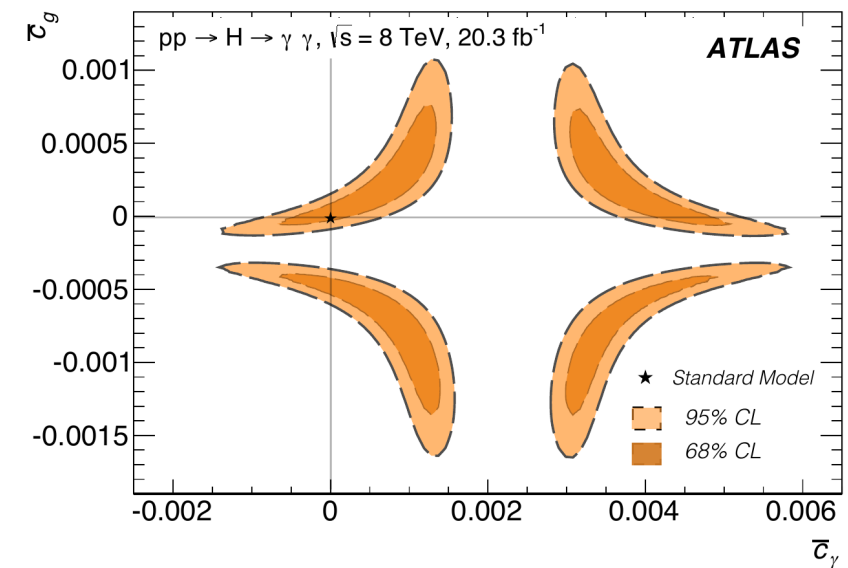
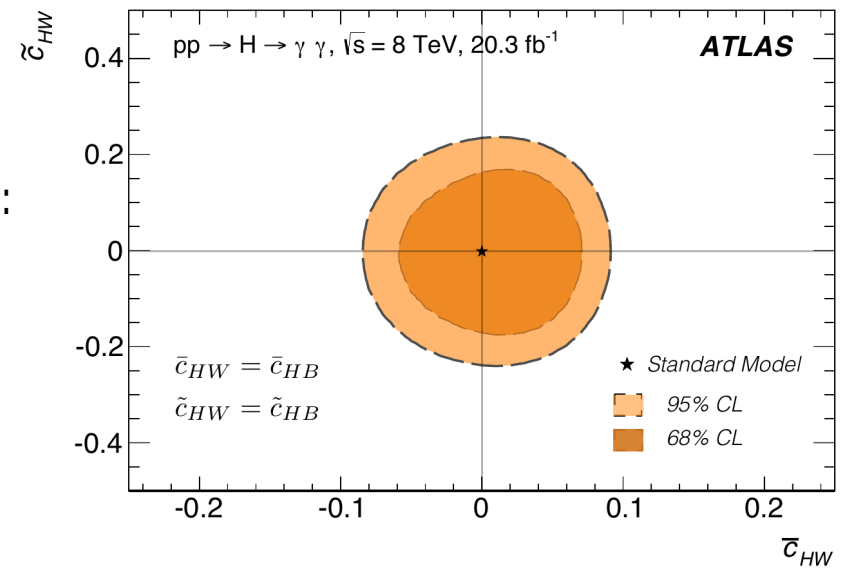
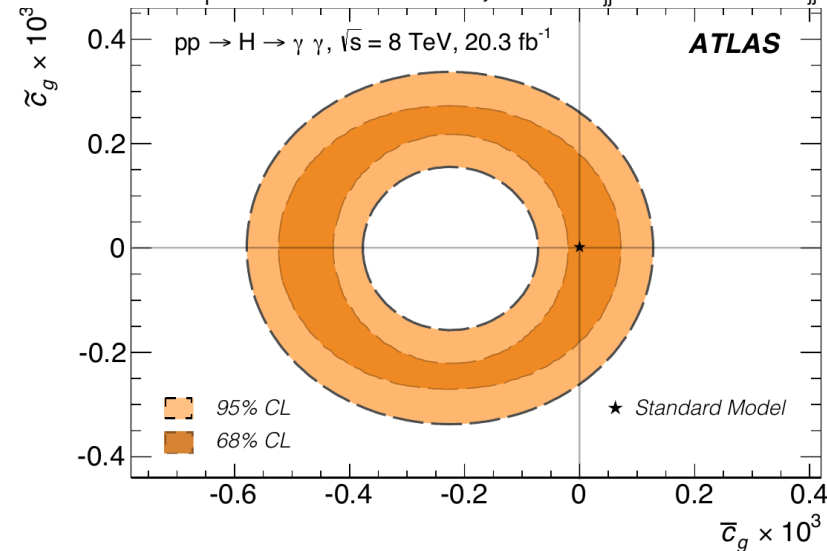
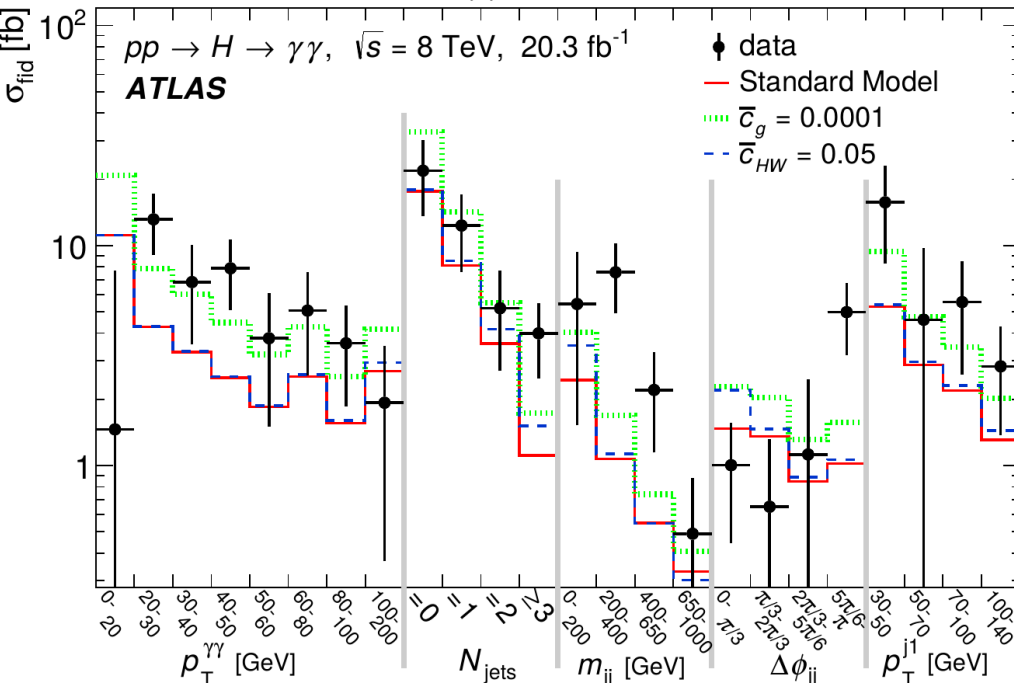


Same data for each of the 5 distributions
 $\Rightarrow$ Include correlations, measured in data using bootstrap.



Effective Lagrangian (2)

Fit deviations in $H \rightarrow \gamma\gamma$ differential measurements:



Most information still coming from rates

⇒ Strong constraints on odd+even c_g , c_γ

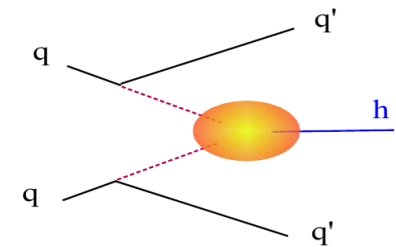
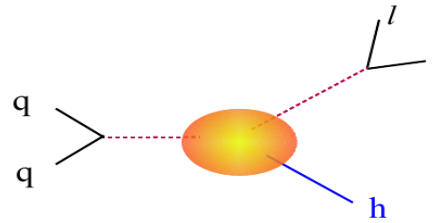
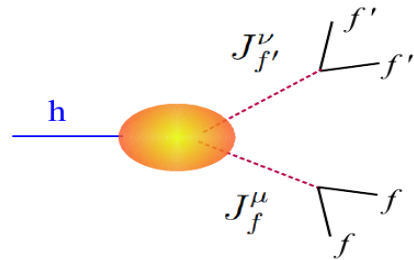
⇒ Weak constraints on c_{HW} , and odd vs. even

Vary at most 2 parameters simultaneously

Need to include **all** relevant parameters simultaneously for a full SMEFT analysis

Higgs Pseudo-Observables

Idea: encode all the experimentally available information with only weak assumptions (e.g. crossing symmetry)



- Report experimental measurements as POs, and compute them in specific models
 - One PO per accessible observable
 - $H \rightarrow \gamma\gamma$: $\Gamma(H \rightarrow \gamma\gamma)$, or $\kappa_{\gamma\gamma} = \Gamma(H \rightarrow \gamma\gamma) / \Gamma_{SM}(H \rightarrow \gamma\gamma)$
 - $H \rightarrow ff$: $\Gamma(H \rightarrow ff)$, or $\kappa_f = \Gamma(H \rightarrow ff) / \Gamma_{SM}(H \rightarrow ff)$
 - $H \rightarrow VV \rightarrow 4l$: Separate POs for
 - $H \rightarrow V_T V_T$ and $H \rightarrow V_L V_L$
 - Resonant and non-resonant contributions ($H \rightarrow Vff$)
- + CP-odd parameters where experimentally accessible
- Use the same “VV” POs for VBF and VH production

Higgs Pseudo-Observables

From YR4 and
G. Isidori's talk at HC16

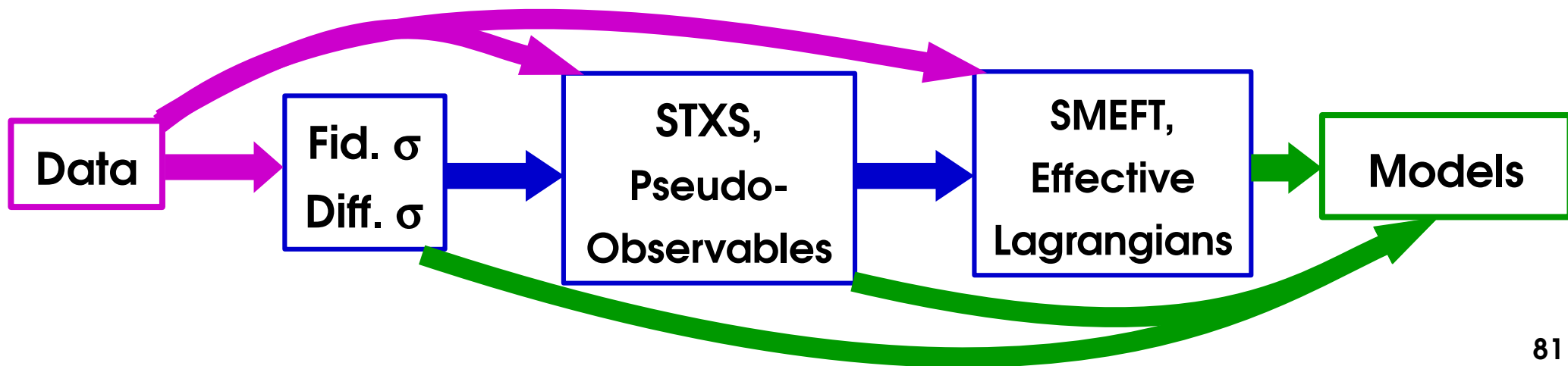
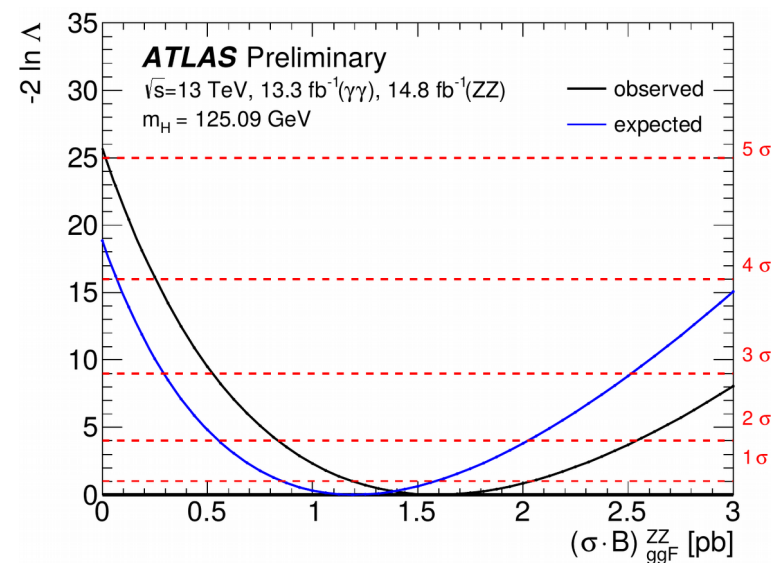
Process	CP-even	CP-odd
$H \rightarrow VV$ (no custodial symm.)	$\kappa_{ZZ}, \epsilon_{ZZ}, \kappa_{Z\gamma}, \kappa_{\gamma\gamma}$ $(\kappa_{WW}, \epsilon_{WW})$	$\epsilon_{ZZ}^{CP}, \delta_{Z\gamma}^{CP}, \delta_{\gamma\gamma}^{CP}$ (ϵ_{WW}^{CP})
$H \rightarrow V\ell\ell$ (no custodial symm.)	$\epsilon_{ZeL}, \epsilon_{ZeR}, \epsilon_{Z\nu}$ $(\text{Re } \epsilon_{WeL})$	$(\text{Im } \epsilon_{WeL})$
VBF, VH (no custodial symm.)	$\epsilon_{ZuL}, \epsilon_{ZuR}, \epsilon_{ZdL}, \epsilon_{ZdR}$ $(\text{Re } \epsilon_{WeL})$	$(\text{Im } \epsilon_{WeL})$
$H \rightarrow f\bar{f}$	$\kappa_f (f=t,b,\tau)$	δ_f^{CP}
ggF	κ_g	
Γ_H	κ_H	

Total : 17 CP-even + 6 CP-odd POs (no custodial symm. : 21 + 8)

Assuming flavor universality

Open Issues

- Need **MC generators** to provide predictions:
 - **HC/JHU**: used in Run 1
 - **SMEFT**: NLO generators being validated
 - **POs**: under development
- Tools for multidimensional measurements (Morphing)
- **How to report the likelihoods ?**
 - Last bins in distributions always have low statistics, not Gaussian
 - Not very Gaussian even now $\Rightarrow$ **Covariance matrix is not sufficient**
- Which framework to use for reporting ? Many possibilities:



Decay modes

