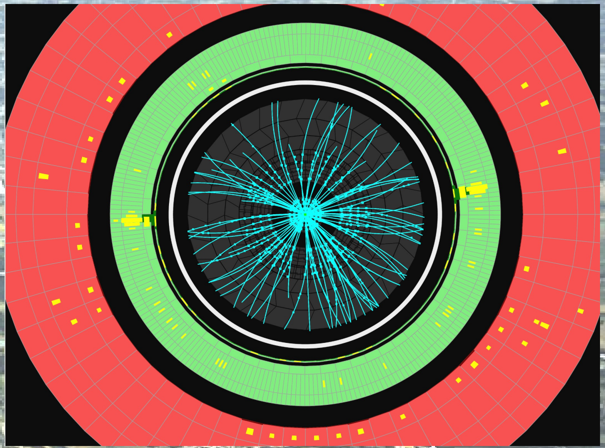
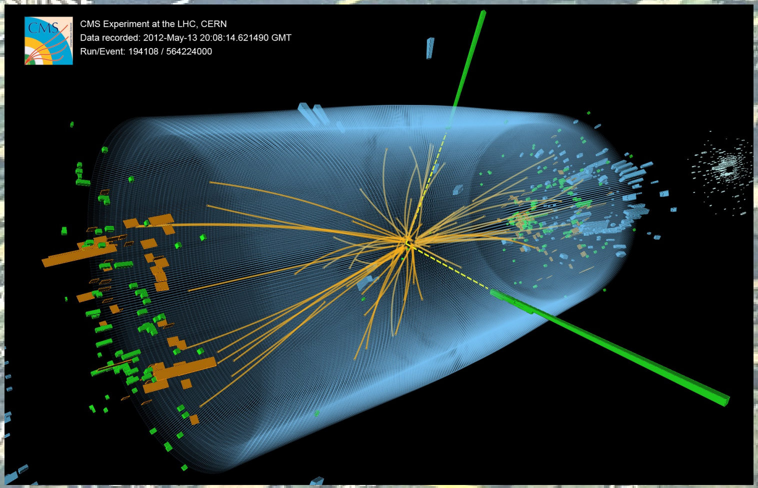
ATLAS and CMS $H \rightarrow \gamma\gamma$ Final Run1 Results

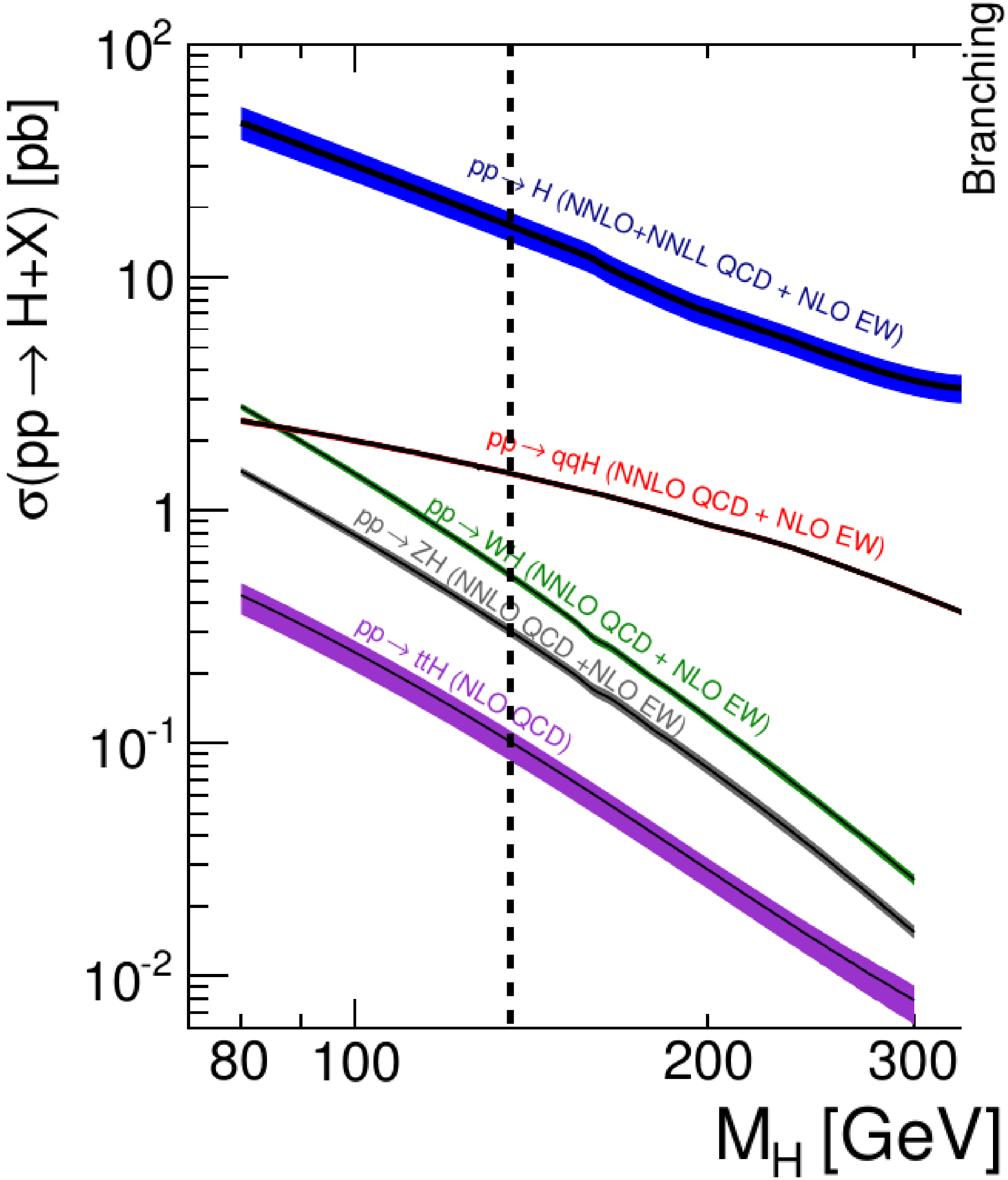


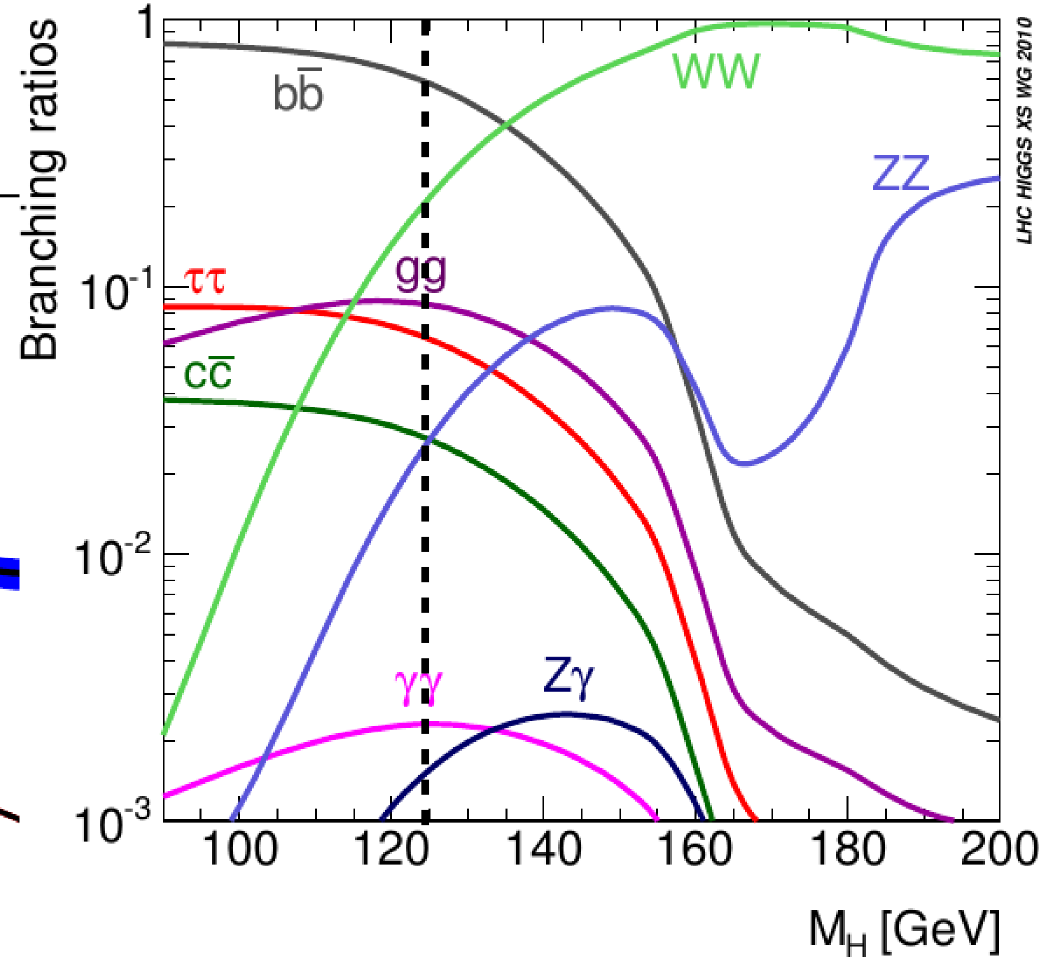


Nicolas Berger (LAPP)

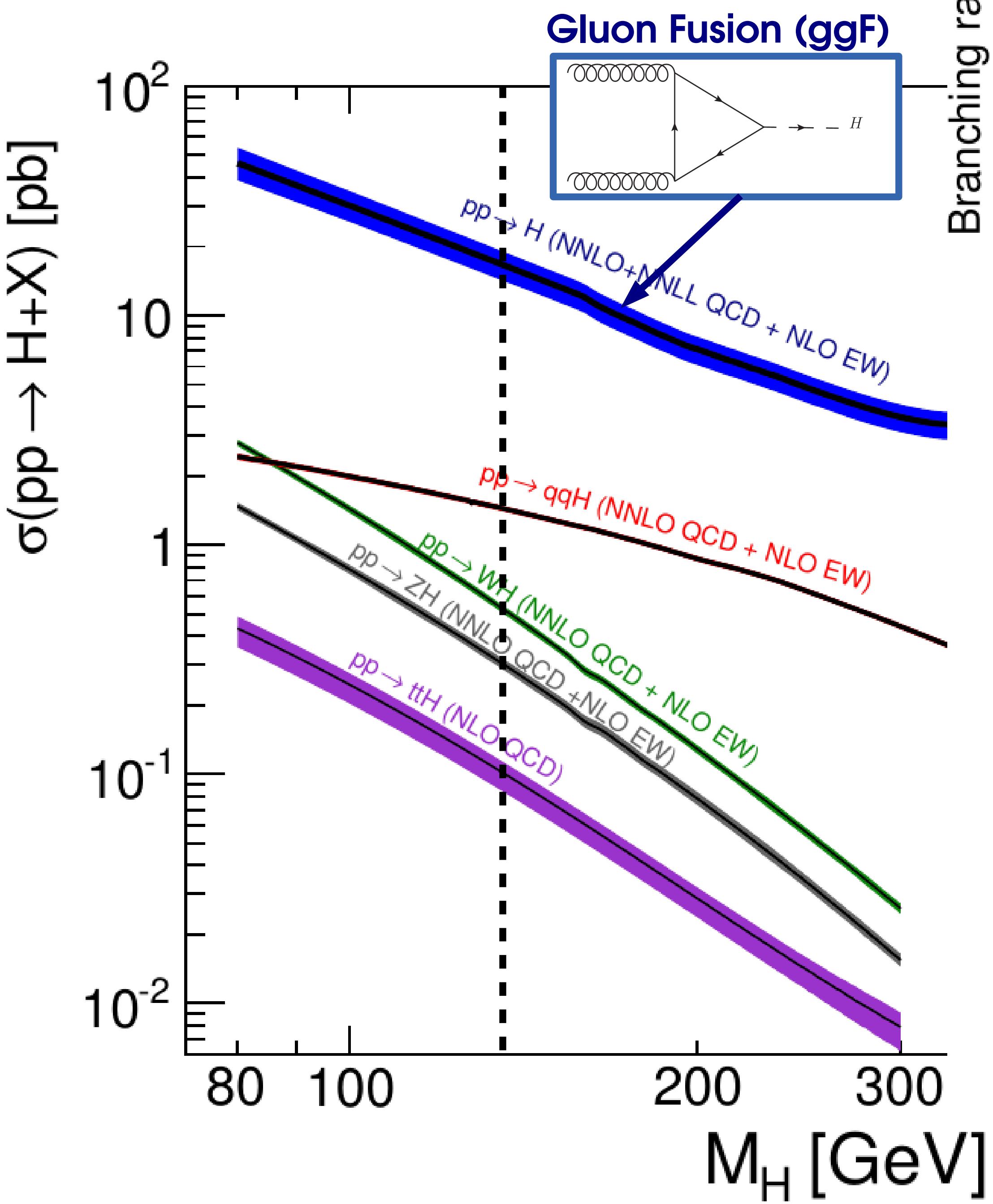
GDR Terascale @ Heidelberg, Dec. 11th-13th 2014

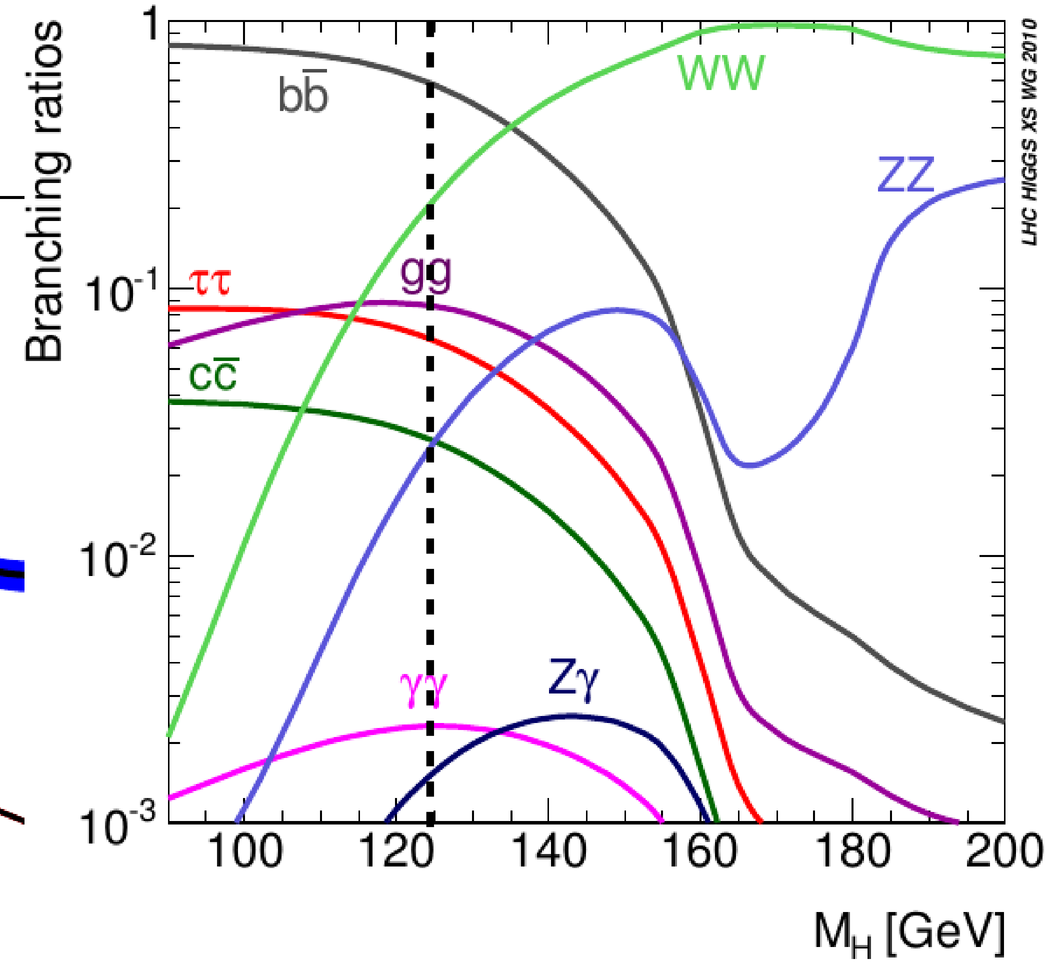
H→γγ at the LHC



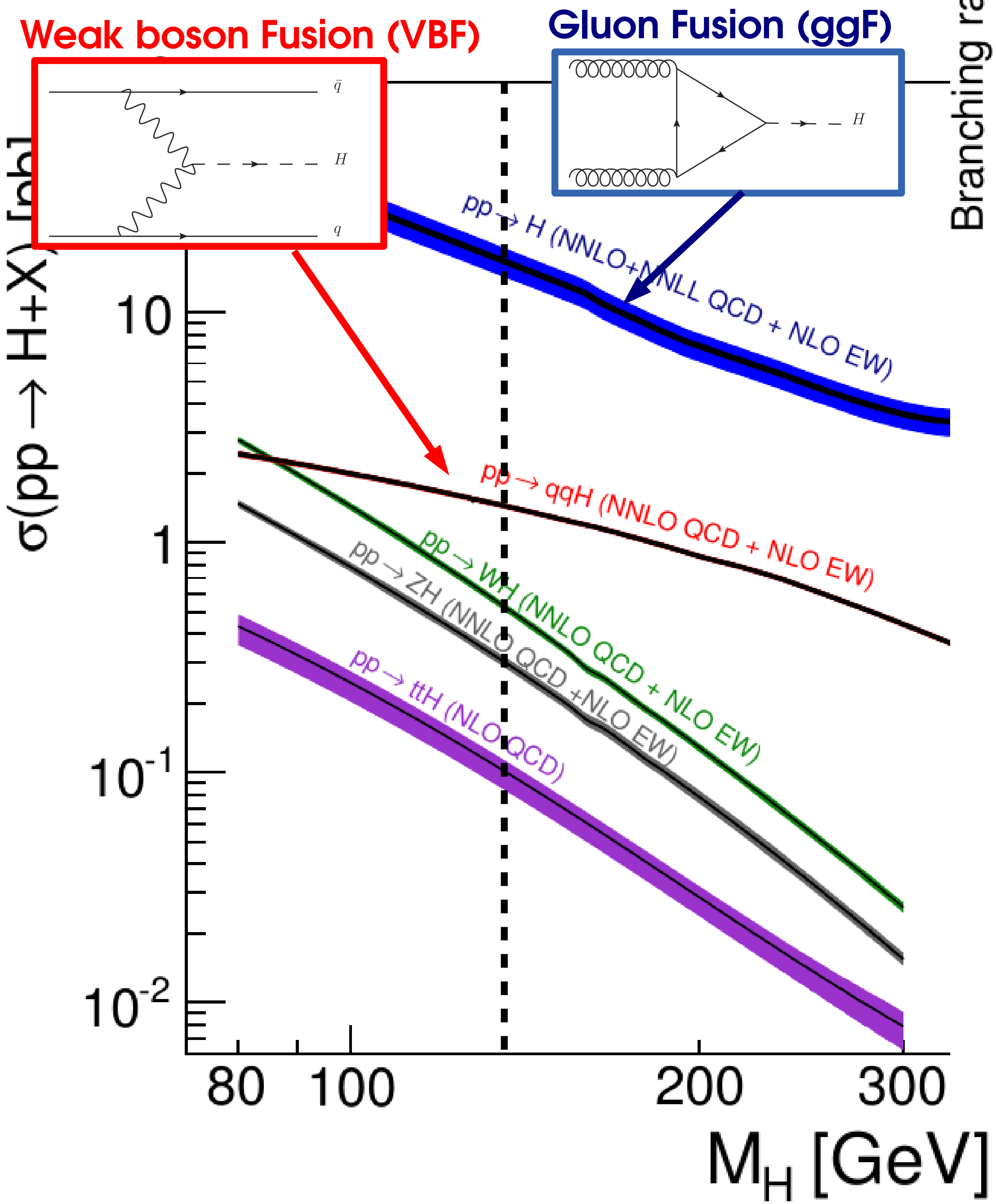


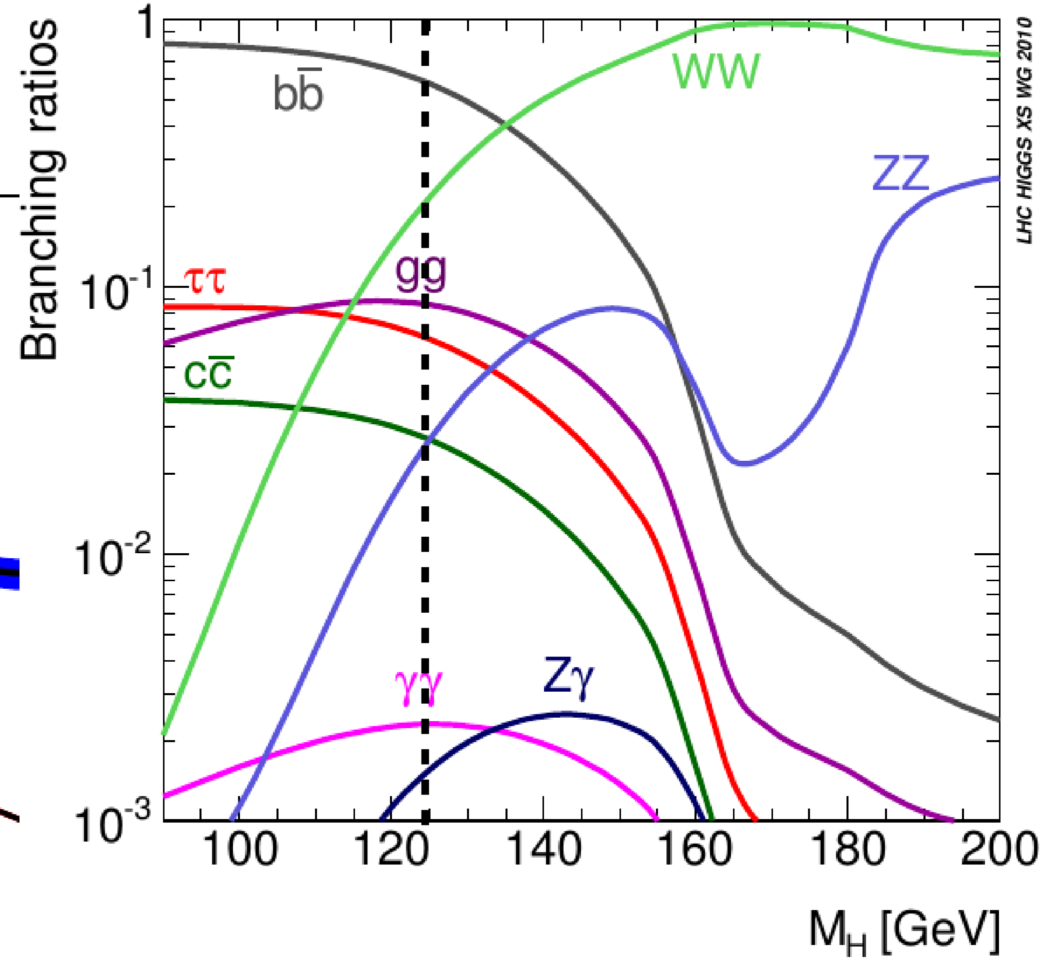
H→γγ at the LHC



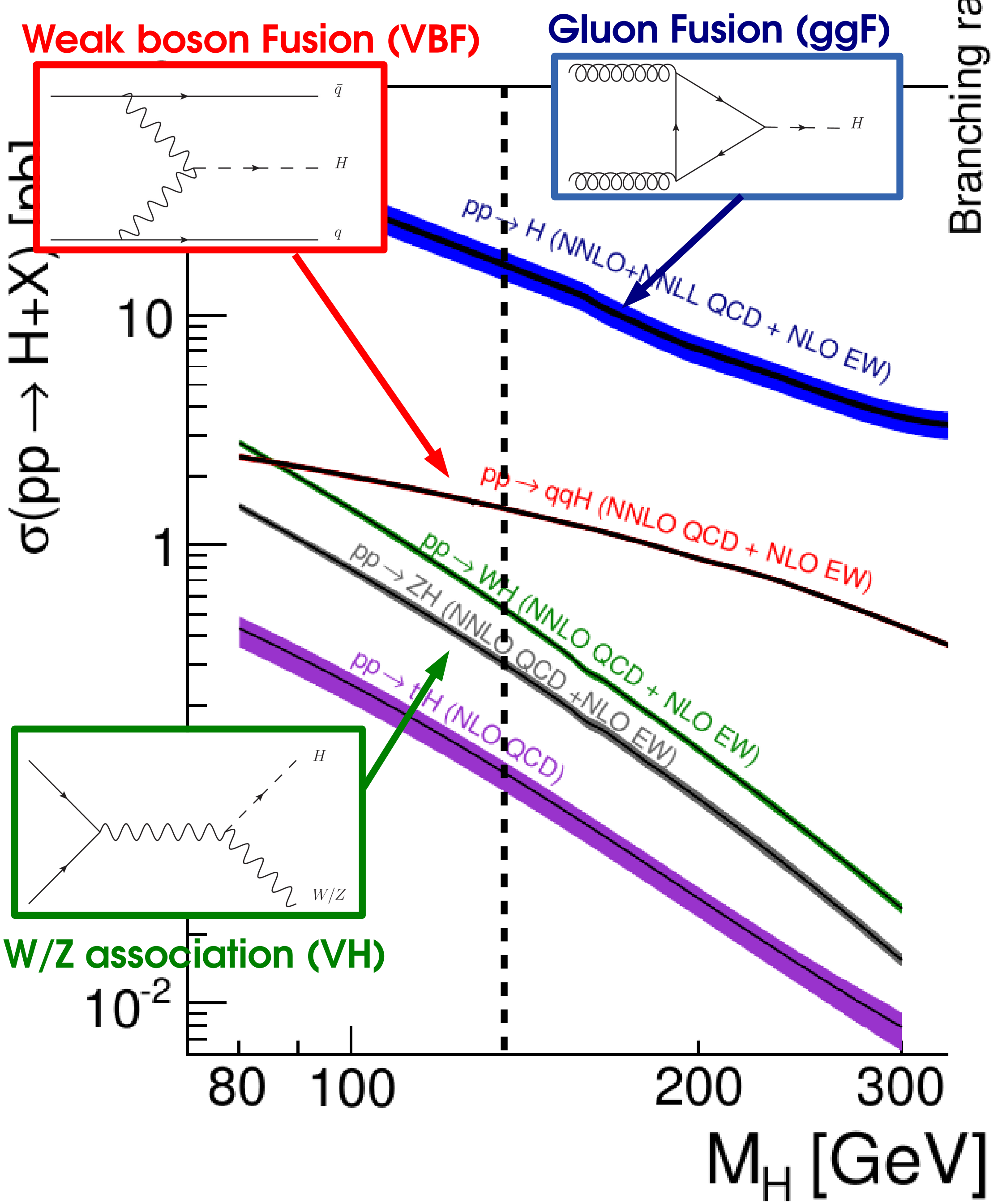


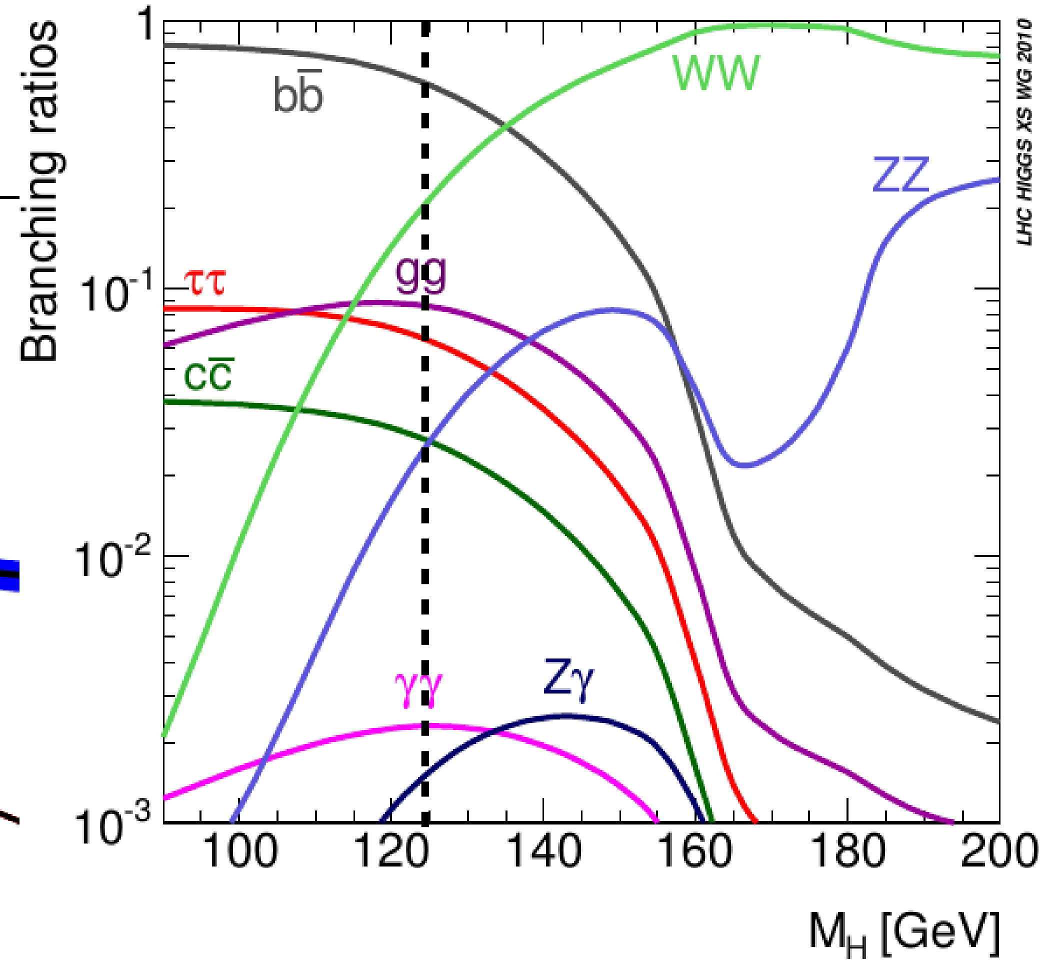
H→γγ at the LHC



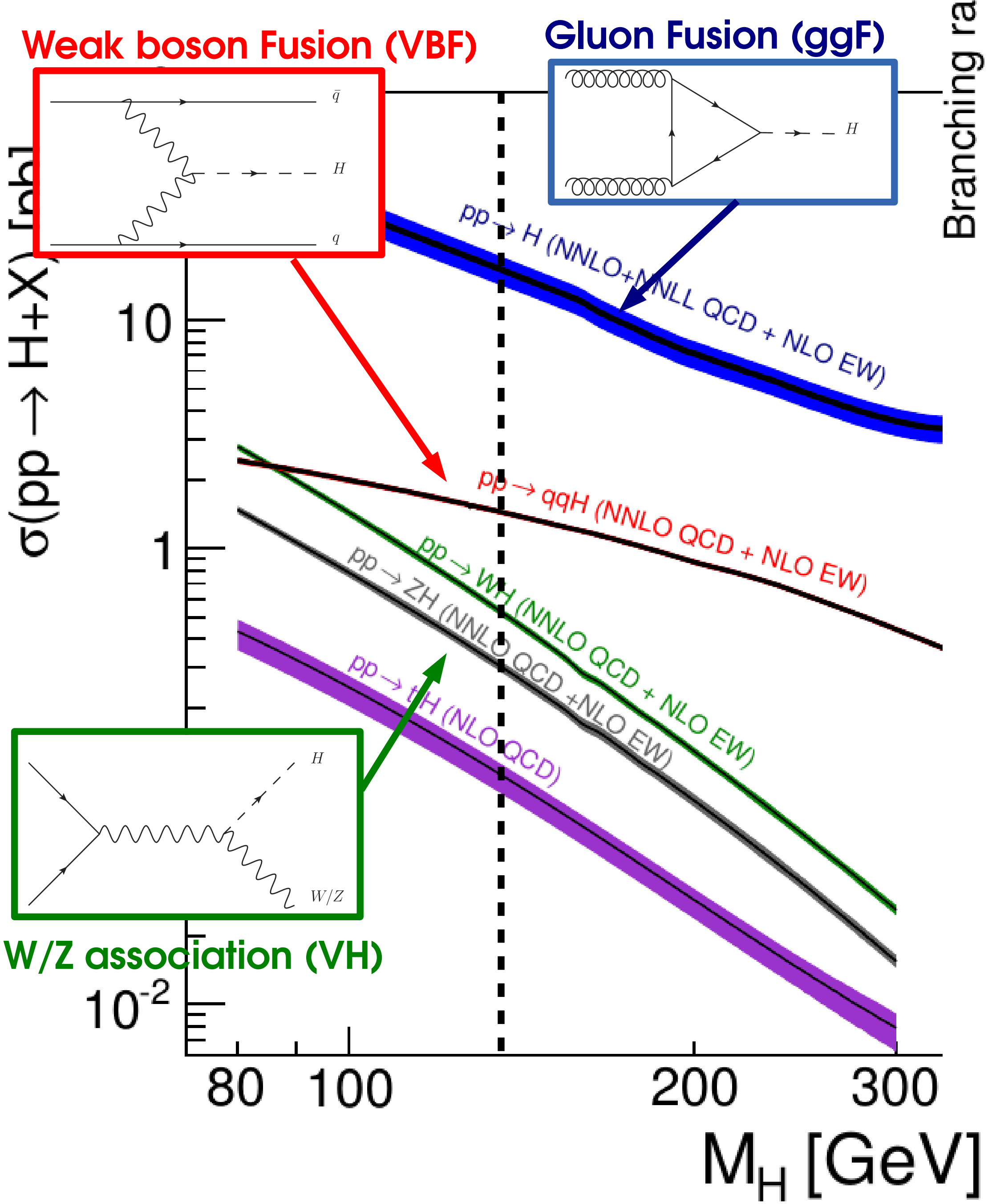


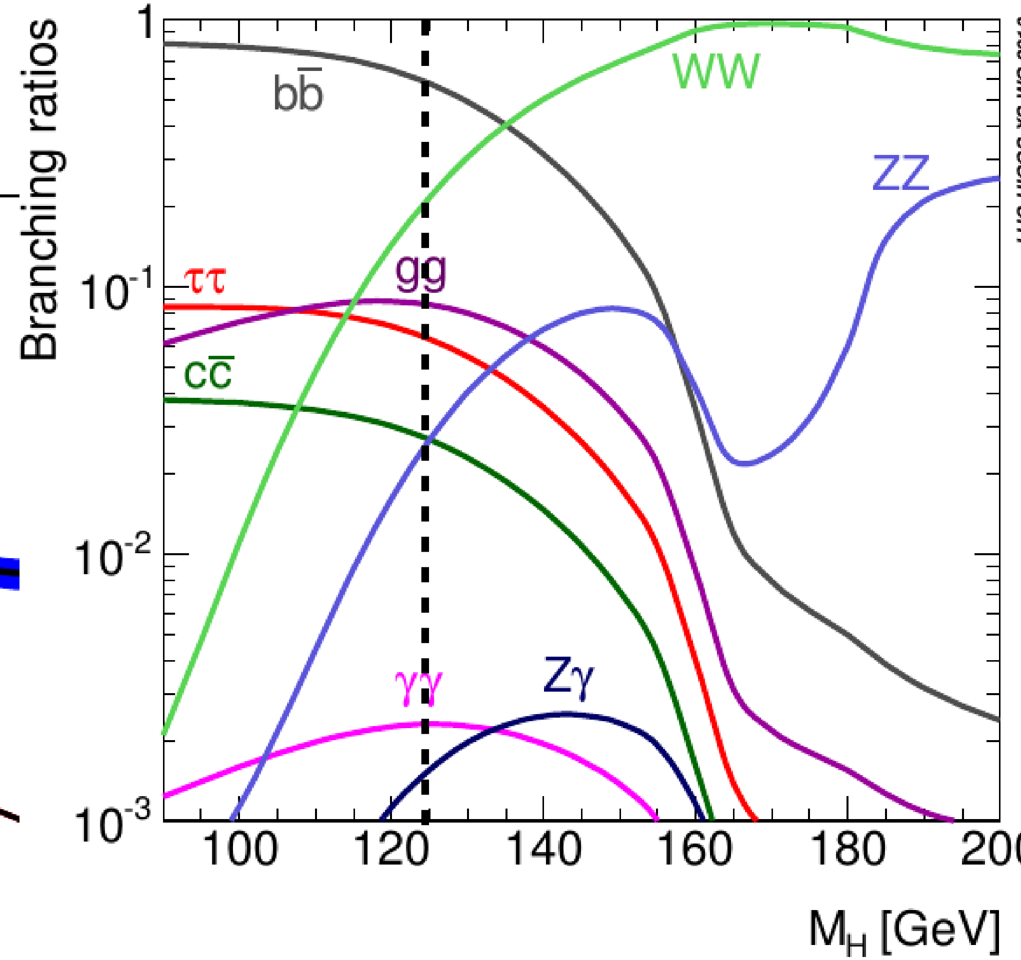
H→γγ at the LHC

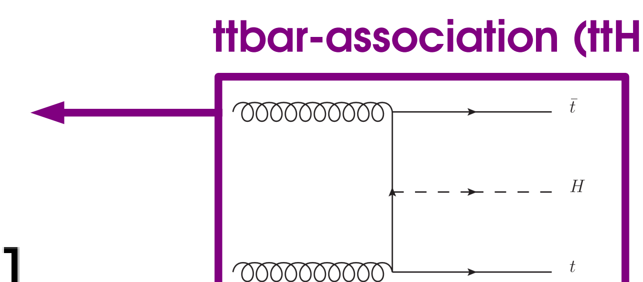




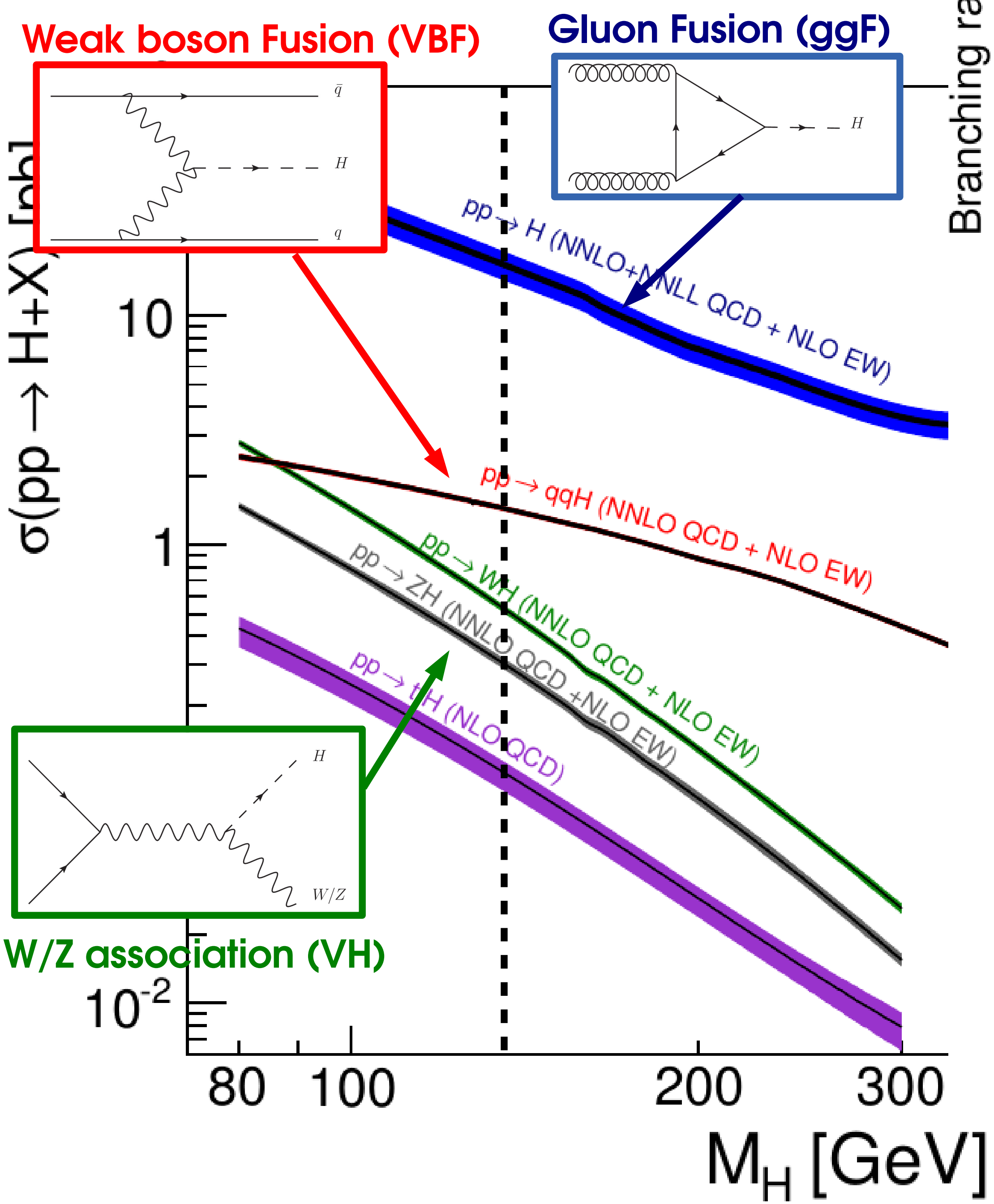
H→γγ at the LHC

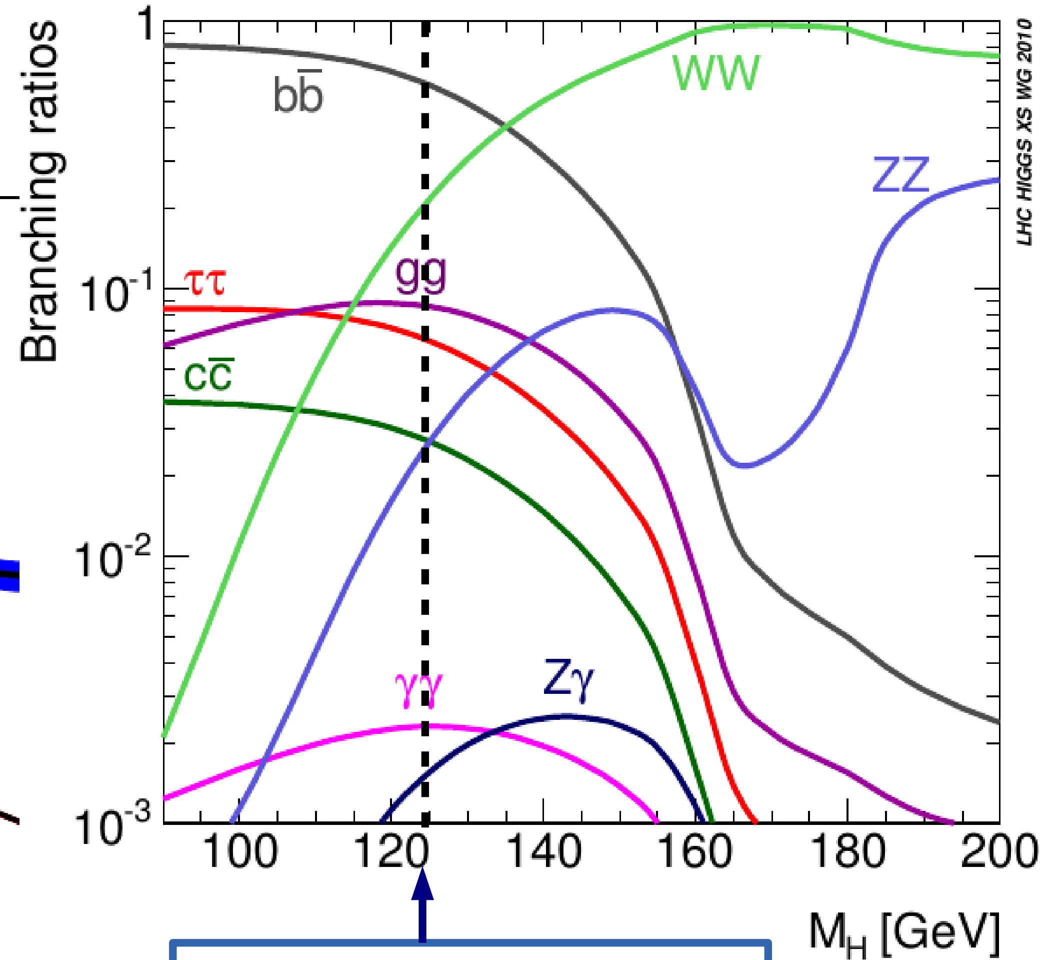






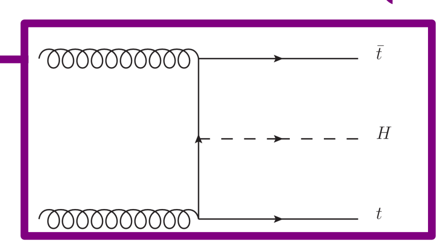
H→γγ at the LHC



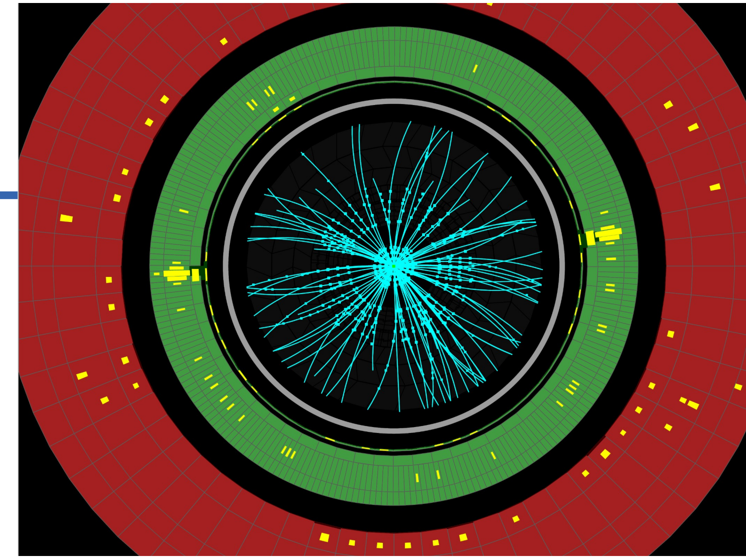


BF(H→γγ) = 0.23%

ttbar-association (ttH)



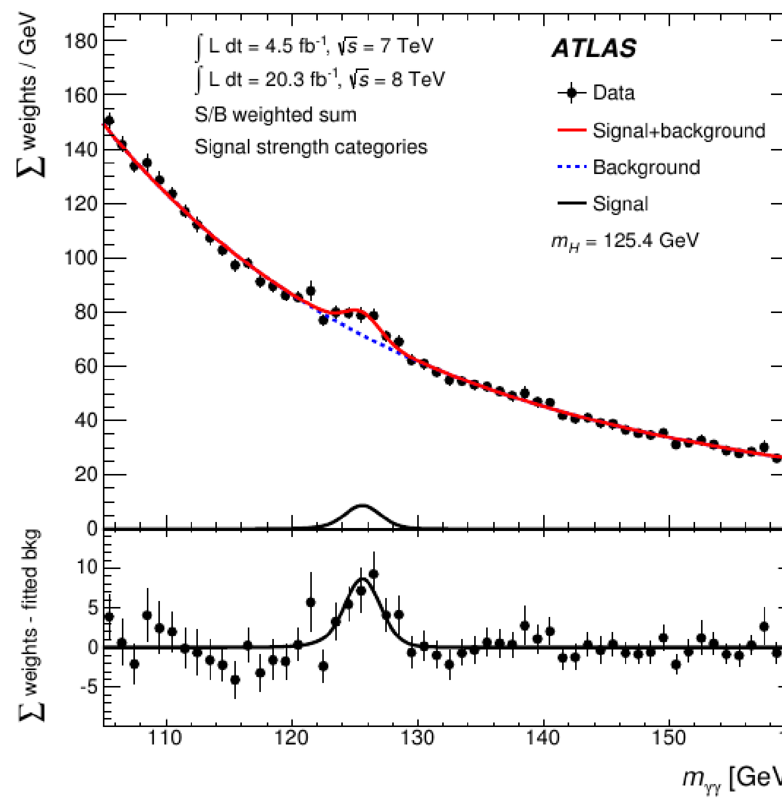
H→γγ



H→γγ:

- Low branching fraction
- Very clean final state at LHC (~80% bkg is irreducible γγ)
- Large but smooth bkg, estimated from wide sidebands
- S/B ~ 3%

Clear signal for discovery in 2012

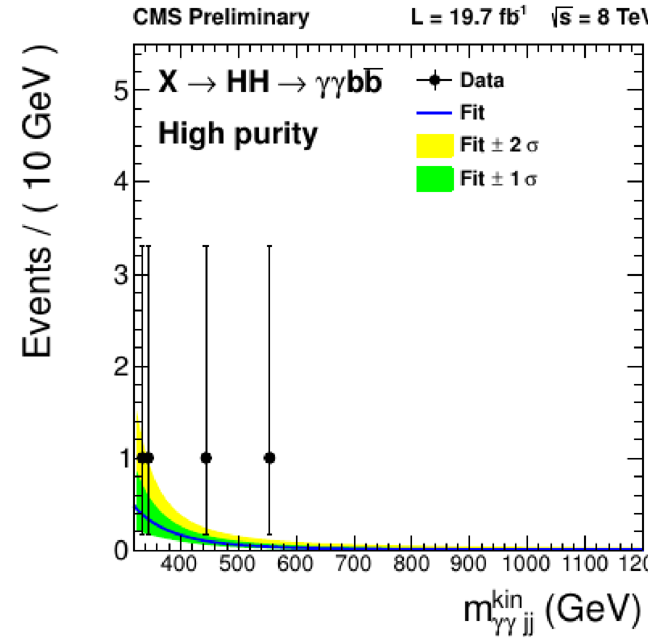


Flexible tool for additional selections:

- **Production modes**: VBF, VH, ttH, tH
- **Differential distributions**
- **Spin determination**
- **Associated production : H+jets, HH, t→cH, ...**
- Also straightforward to extend to other signal masses => **New resonances**

A Short History of Run1

Yesterday's sensation is today's calibration... R.P. Feynman



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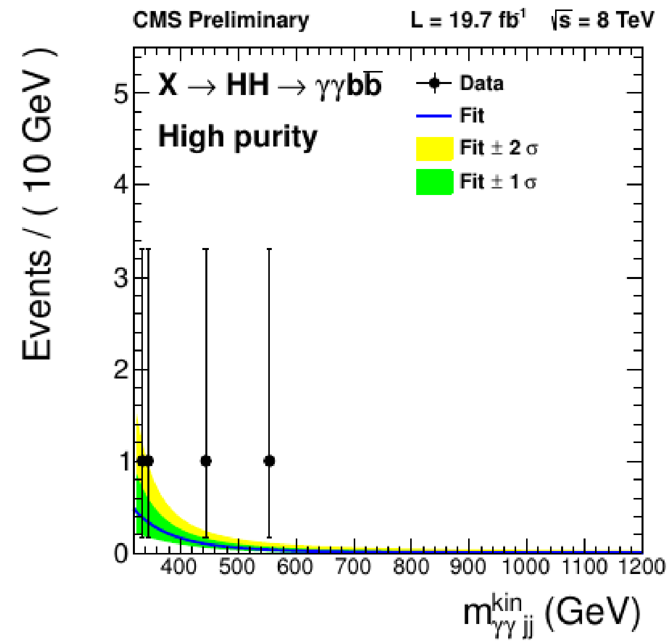


... and tomorrow's background V. L. Telegdi

> where both electrons are misidentified as photons. Two peaking backgrounds arise from the Z boson component of the DY and from $H \to \gamma\gamma$.
>
> Phys.Rev.Lett. 113 (2014) 171801

$H \rightarrow \gamma\gamma$ Couplings

Selection

arXiv:1408.7084, submitted to PRD

EPJC 74 (2014) 3076

ATLAS

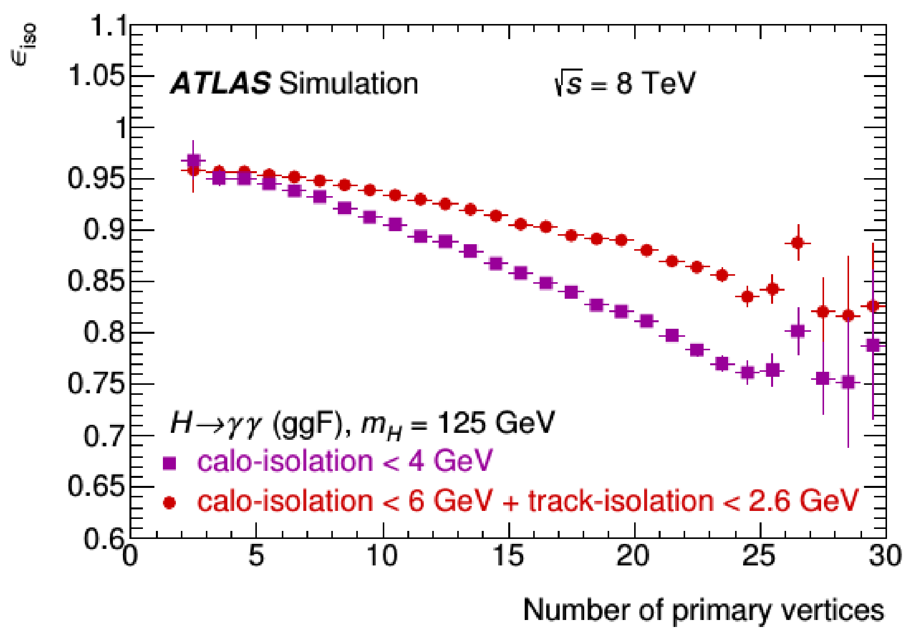
$E_{T1,2}/m_{\gamma\gamma}$ > 0.35, 0.25

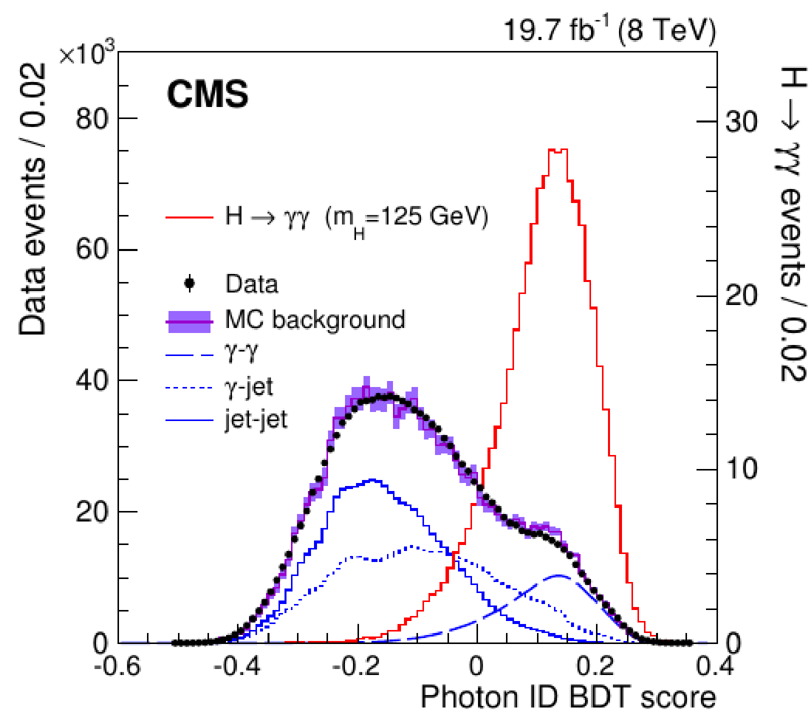
- Select unconverted, converted photons, veto electrons
- **Photon ID**: cuts on calo cluster shapes, tracks
- **Isolation**
  - $\Sigma\, p_T^{tracks,\, \Delta R<0.2} < 2.8$ GeV
  - $\Sigma\, E_T^{clusters,\, \Delta R<0.4} < 4$ GeV
- **Efficiency**: 39%
- **Bkg**: 84% γγ, 15% γj, 1% jj

CMS

$E_{T1,2}/m_{\gamma\gamma}$ > 1/3, 1/4

- Select unconverted, converted photons, veto electrons
- **Photon ID**: calo cluster shapes: loose cuts + included in a BDT
- **Isolation**: based on particle flow objects in ΔR<0.3 cone, included in γ-ID BDT
- **Efficiency**: 49%
- **Bkg**: ~70% γγ





Event Classification

Mode	Fraction	Exp.
ggF	88%	340
VBF	7%	28
WH	3%	11
ZH	2%	6
ttH	0.4%	2
bbH	0.9%	4

Mode	ATLAS	CMS
ttH→leptons	**ttH leptonic:** ≥1 lepton, ≥2 b-tag	**ttH lepton tag**: ≥1 lepton, ≥1 b-tag
ttH→hadrons	**ttH hadronic**: 0 leptons, ≥5 jets, ≥1 btag	**ttH multijet tag**: 0 leptons, ≥5 jets, ≥1 btag
(Z→ll)H	**VH dilepton**: $70 < m_{ll} < 110$ GeV	**VH tight lepton**: 2 l or l + (MET>45 GeV)
(W→lν)H	**VH l+MET**: l + (MET>20-30 GeV)	**VH loose lepton** : 1 lepton
(Z→νν)H	**VH MET**: MET > 70-100 GeV	**VH MET tag**: MET > 70 GeV
(W,Z→qq)H	**VH had**: $60 < m_{jj} < 110$ GeV	**VH dijet tag**: $60 < m_{jj} < 120$ GeV
VBF	**VBF tight**, **VBF loose** } BDT	**VBF dijet tag 0,1(,2)** } BDT
ggF/bbH	**Untagged**, 4 bins: $\|\eta\|$=0.95, p_{Tt}=70 GeV	**Untagged 0-4**, using diphoton BDT

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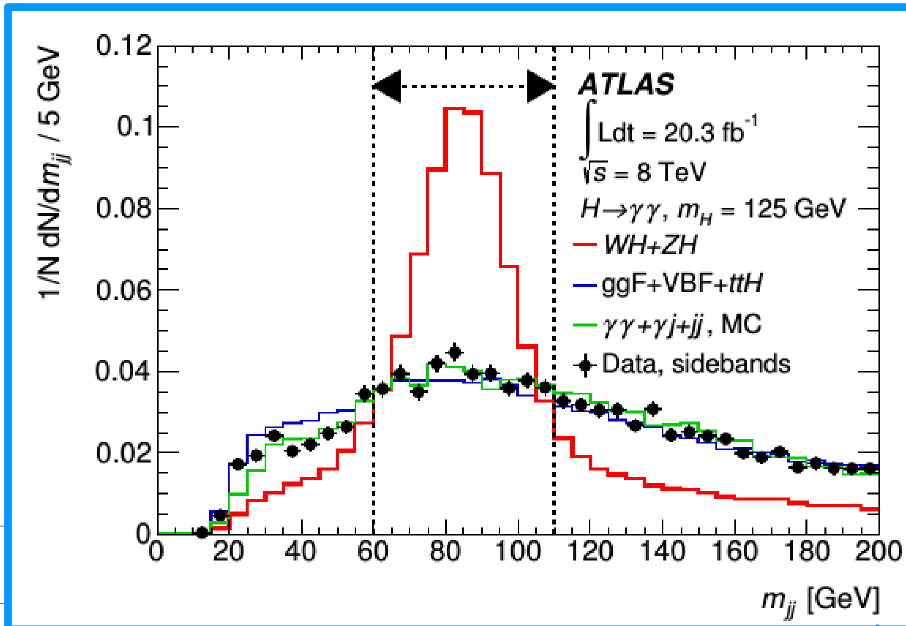

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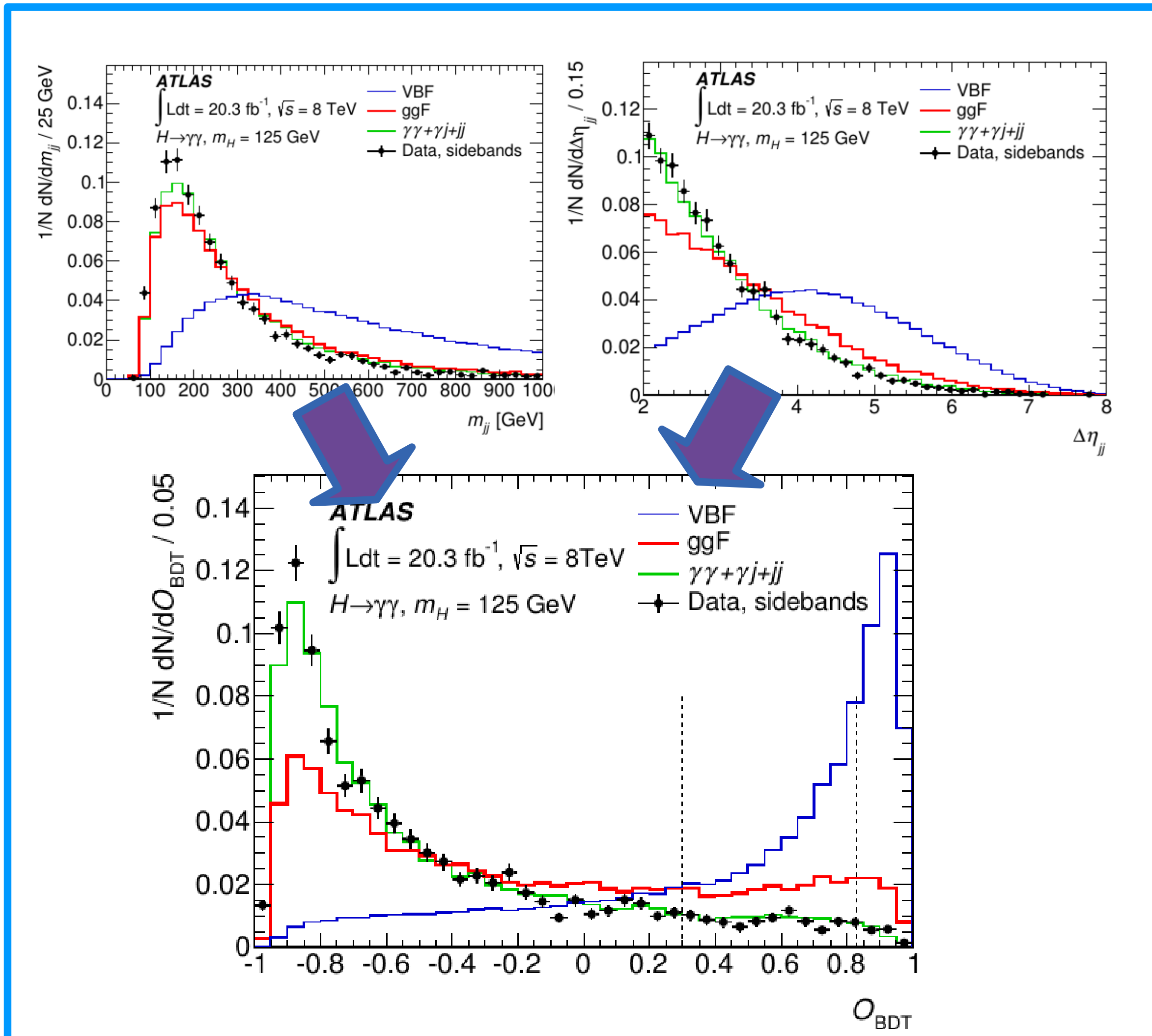

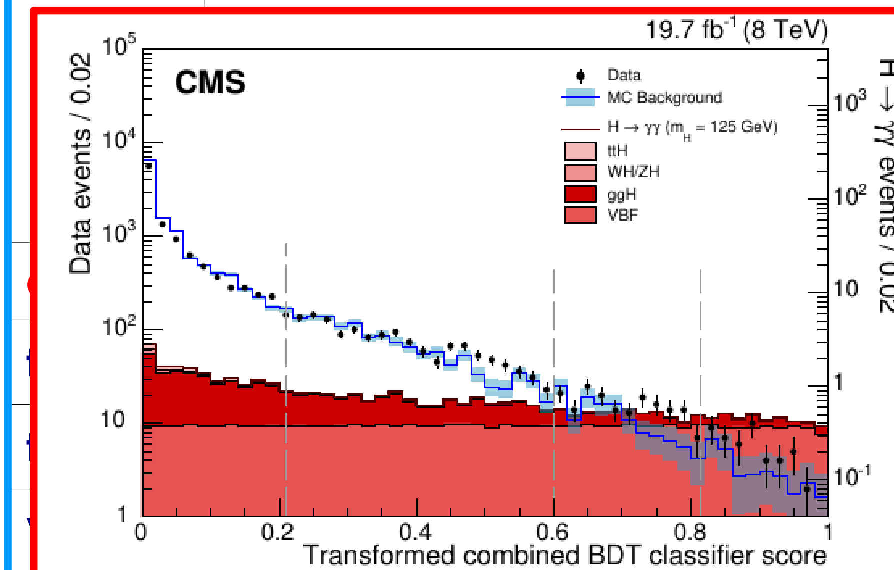

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VBF	**VBF tight** / **VBF loose** } BDT	**VBF dijet tag 0,1(,2)** } BDT
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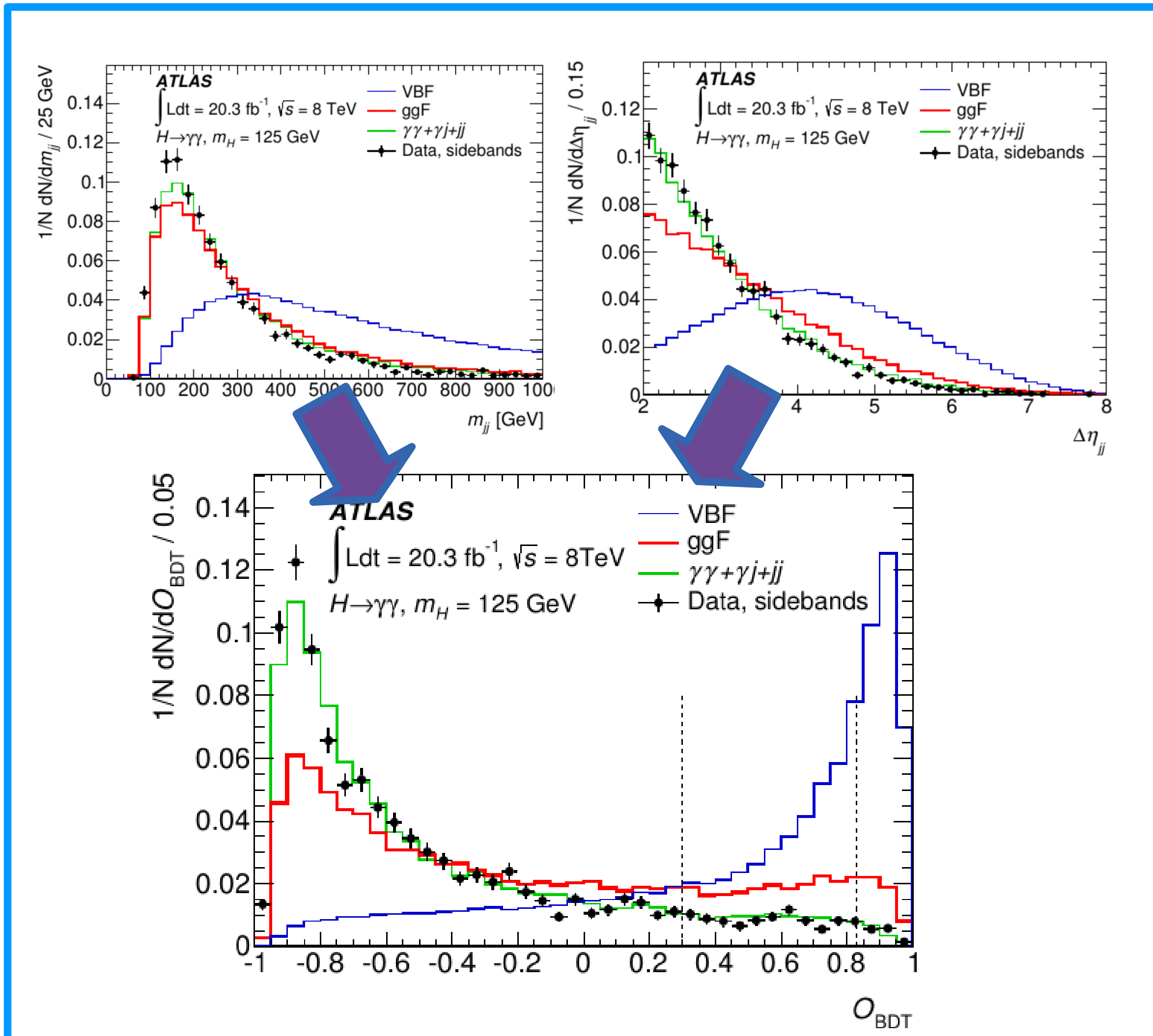

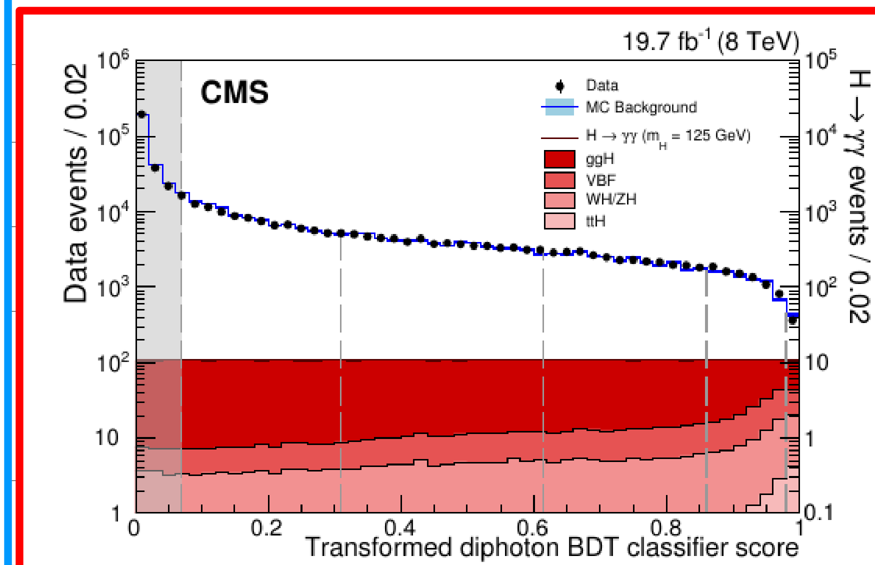

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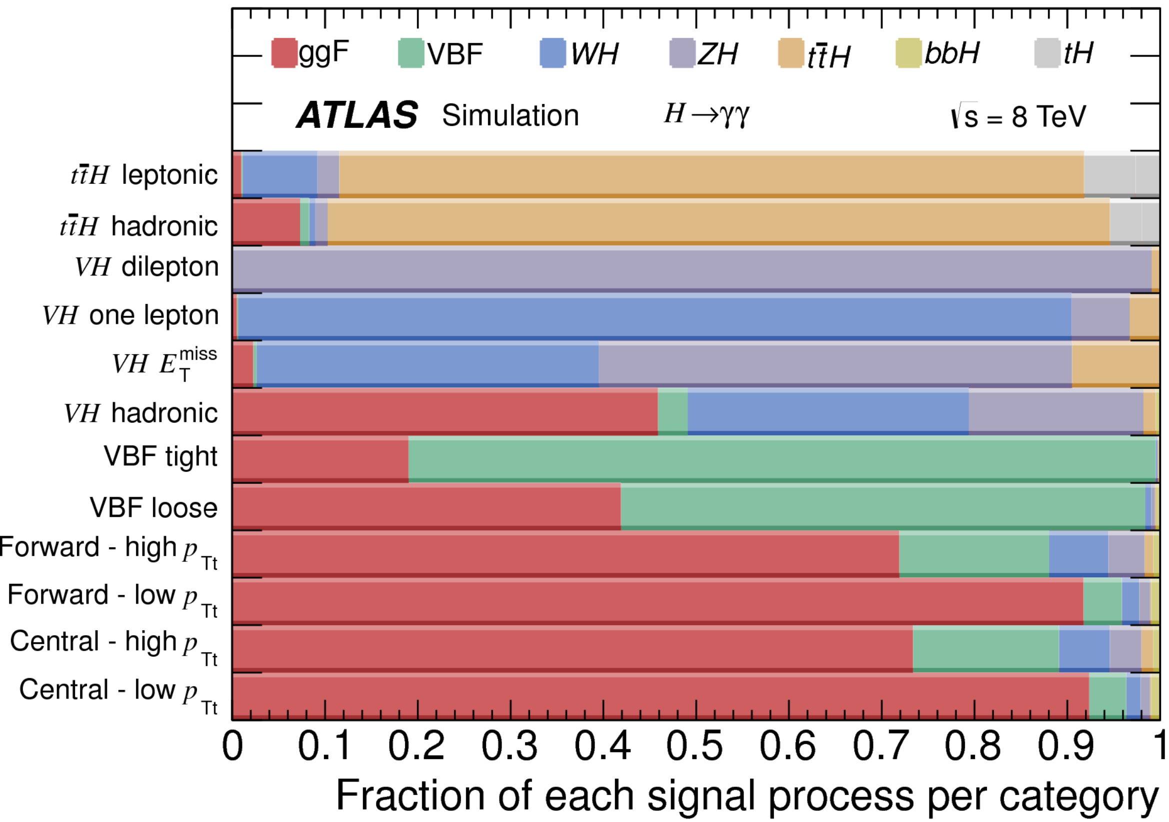
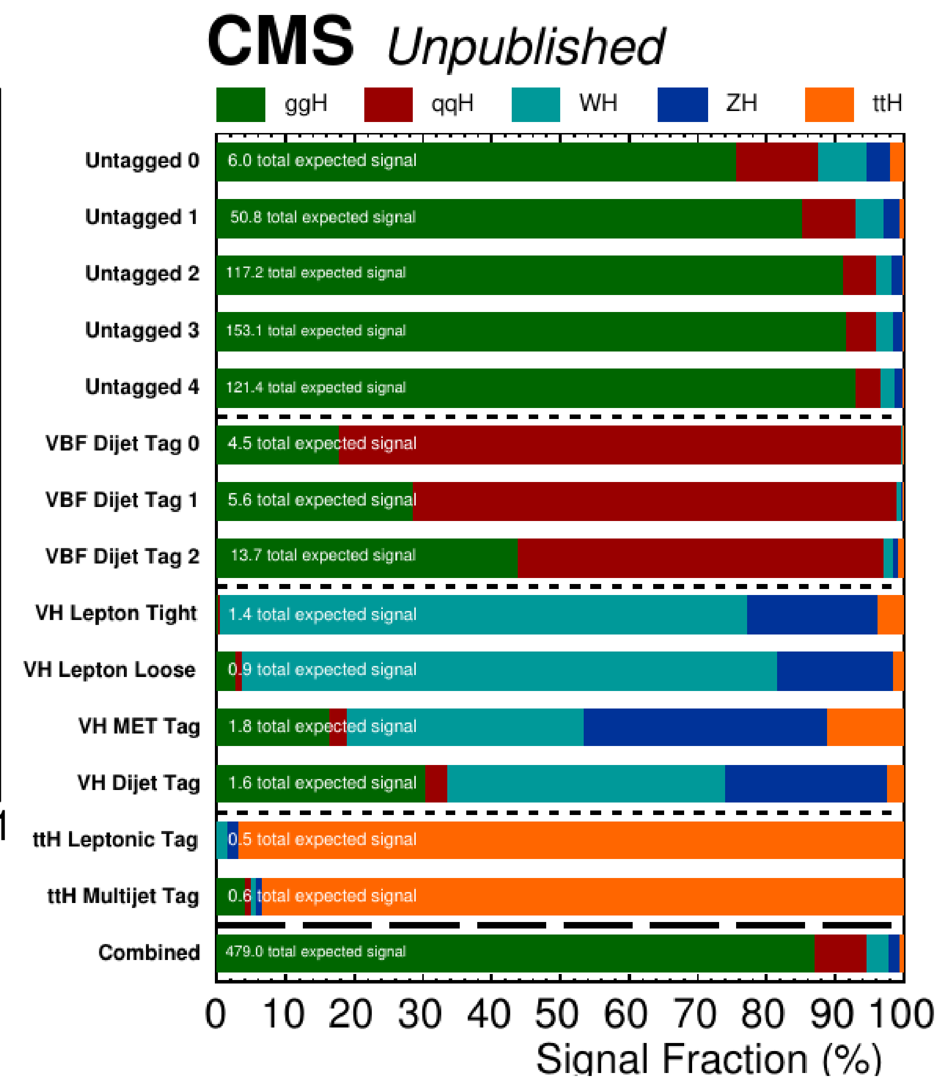
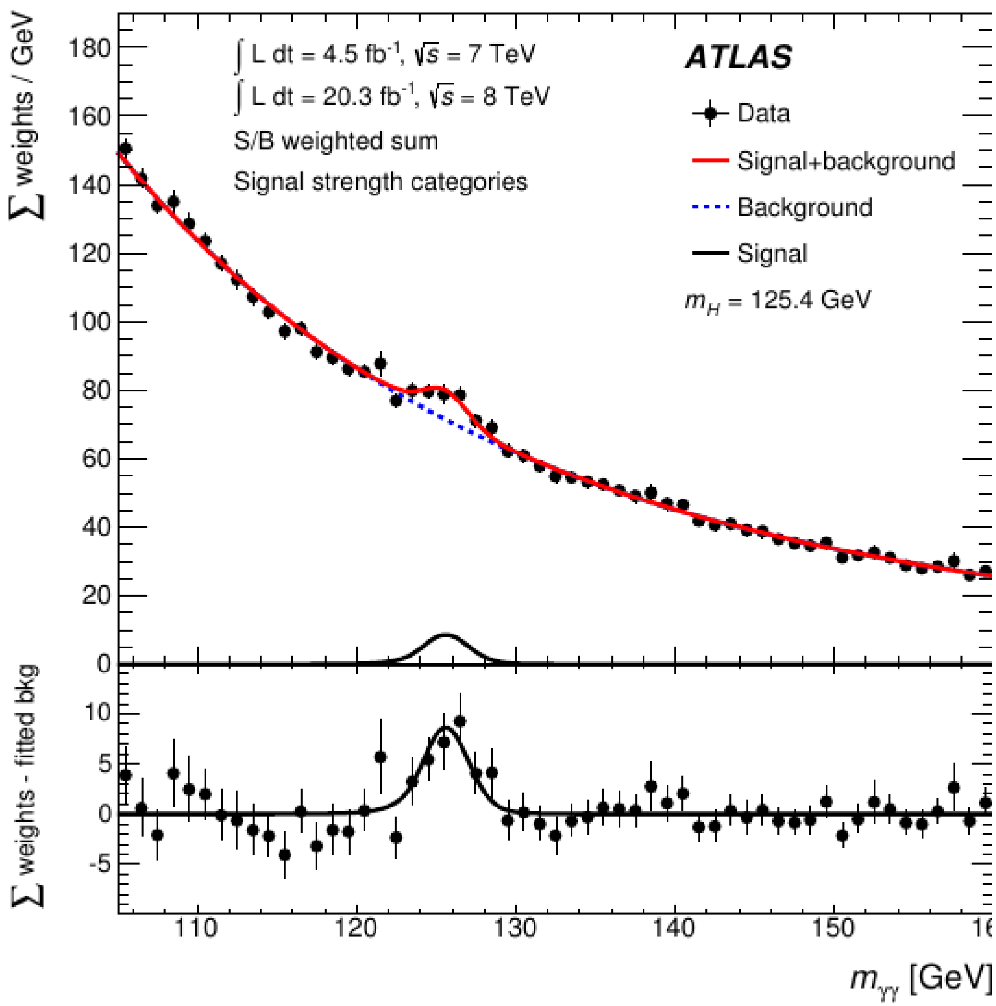
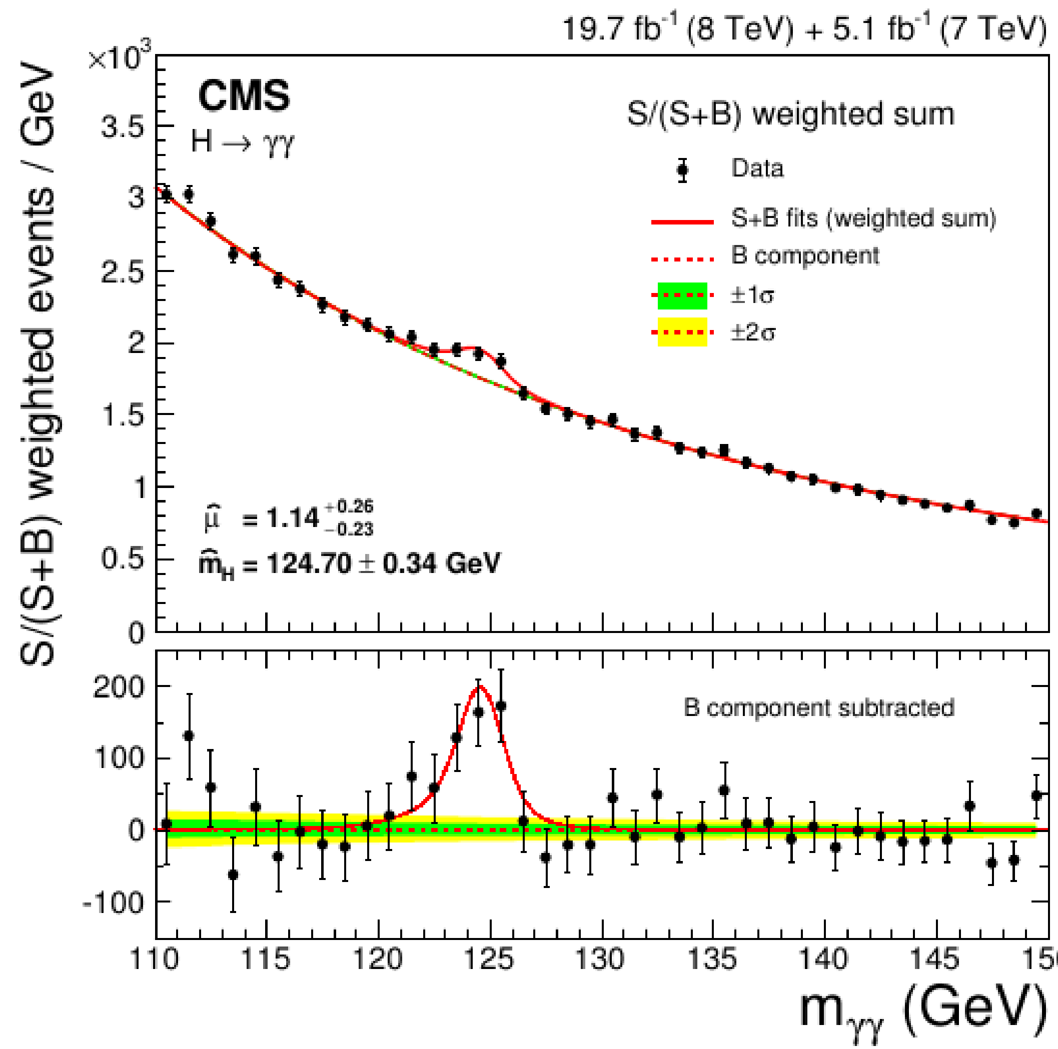
Classification





Mass Spectra



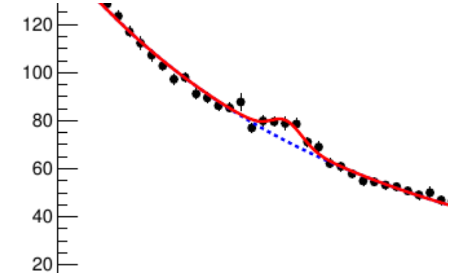


Fit using analytical shapes for signal and background components:

Signal : Gaussian with Power-law tail + Gaussian or Sum of Gaussians

Bkg: exponential, exp(poly2), polynomials, power-laws

Inclusive Signal Yield



$$\mu = \frac{N^{observed}_{signal}}{N^{SM}_{signal}}$$

$$\mu = 1.17 \pm 0.23\ (\text{stat.})\ ^{+0.10}_{-0.08}\ (\text{syst.})\ ^{+0.12}_{-0.08}\ (\text{theory})$$

ATLAS

CMS

$$1.14 \pm 0.21\,(\text{stat})\ ^{+0.09}_{-0.05}\,(\text{syst})\ ^{+0.13}_{-0.09}\,(\text{theo}),$$

Significance **5.2σ** (4.6σ expected)
Lower than previous H→γγ result (7.4σ), despite 10% better sensitivity

Observation

Significance **5.7σ** (5.2σ expected)

Observation

Results compatible at the 2.3σ level (74% correlation)

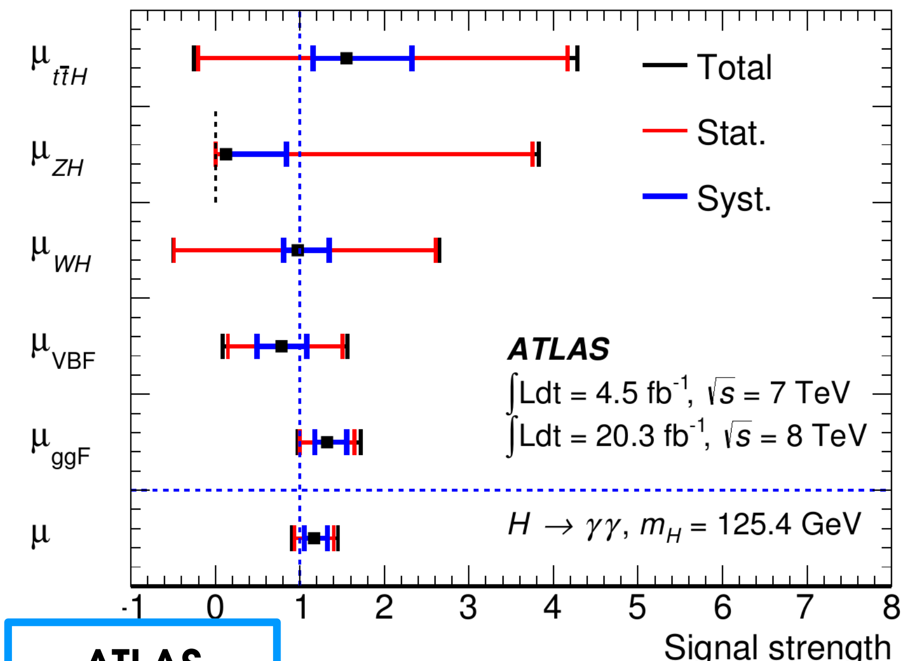
ATLAS	**1.8 ± 0.5**	**1.55 +0.33 –0.28**	**1.17 ± 0.27**
	Phys.Lett. B 716 (2012) 1-29	Phys. Lett. B 726 (2013) 88	accepted by PRD
CMS	**1.6 ± 0.4**	**1.56 ± 0.43**	**1.14 +0.26 -0.23**
	Phys. Lett. B 716 (2012) 30	JHEP 06 (2013) 081	Eur. Phys. J. C 74 (2014) 3076

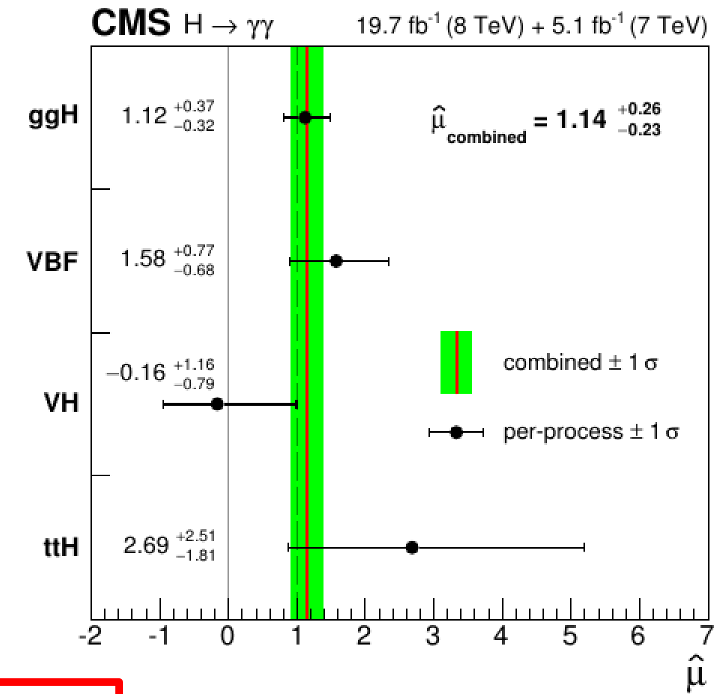
Small signal on large background, sensitive to analysis changes

Signal Yield Systematics

Source	ATLAS	CMS
ggF Theory scale	**-7.8 +7.2%**	
PDF	**-6.9 +7.5%**	
BF	**5%**	
Lumi	2.8%	2.6%
Photon ID	0.2% (trigger) + 1.0% (ID) + (1.3-2.3%) (isol)	1% (trigger) + 1% (vertex finding) **+6% (shower shape model)**
Energy scale, resolution	**7%**	2%
JES/JER	~(0-1)% (ggF), ~(4-9)% (VBF), ~7% (ttH had)	
MET	0.5% (VH-1lep), 1% (VH-MET)	2.6% (WH)
leptons		0.2 - 0.5%
b-tagging		1.1 - 1.3%

Signal Yield per Production Mode





ATLAS

$$\mu_{ggF} = 1.32 \pm 0.32\ (\text{stat.})\ ^{+0.13}_{-0.09}\ (\text{syst.})\ ^{+0.19}_{-0.11}\ (\text{theory})$$

$$\mu_{VBF} = 0.8 \pm 0.7\ (\text{stat.})\ ^{+0.2}_{-0.1}\ (\text{syst.})\ ^{+0.2}_{-0.3}\ (\text{theory})$$

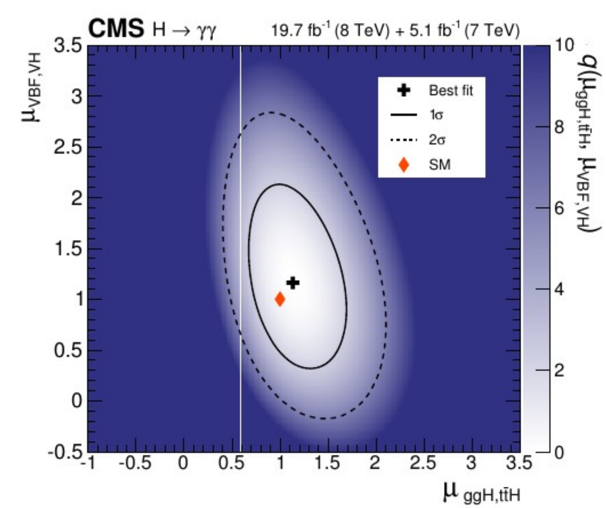
$$\mu_{WH} = 1.0 \pm 1.5\ (\text{stat.})\ ^{+0.3}_{-0.1}\ (\text{syst.})\ ^{+0.2}_{-0.1}\ (\text{theory})$$

$$\mu_{ZH} = 0.1\ ^{+3.6}_{-0.1}\ (\text{stat.})\ ^{+0.7}_{-0.0}\ (\text{syst.})\ ^{+0.1}_{-0.0}\ (\text{theory})$$

$$\mu_{t\bar{t}H} = 1.6\ ^{+2.6}_{-1.8}\ (\text{stat.})\ ^{+0.6}_{-0.4}\ (\text{syst.})\ ^{+0.5}_{-0.2}\ (\text{theory})$$

CMS

Process	$\hat{\mu}$	Uncertainty total	stat	systematic theo	systematic exp
ggH	$1.12^{+0.37}_{-0.32}$	0.34	0.30	0.13	0.09
VBF	$1.58^{+0.77}_{-0.68}$	0.73	0.69	0.20	0.15
VH	$-0.16^{+1.16}_{-0.79}$	0.97	0.97	0.08	
$t\bar{t}H$	$2.69^{+2.51}_{-1.81}$	2.2	2.1	0.4	



Measure μ for all 5 main production modes!
Agreement with SM within 0.7σ.

CMS Couplings Determination

ATLAS-CONF-2014-009

Interpret results in the "kappa framework", with leading-order modifications of Higgs couplings

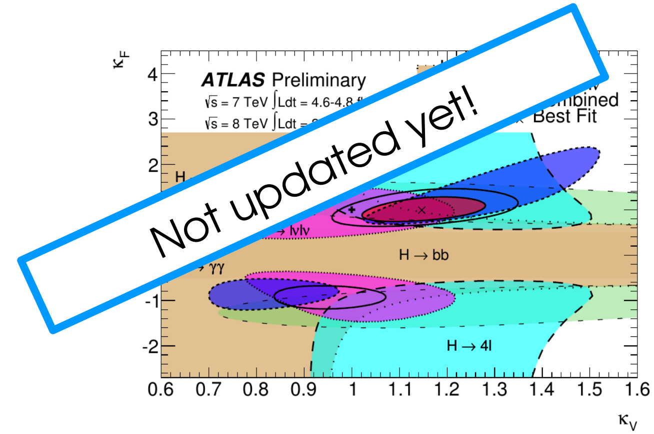
κ_f : anomalous coupling of H to fermions (mainly top)

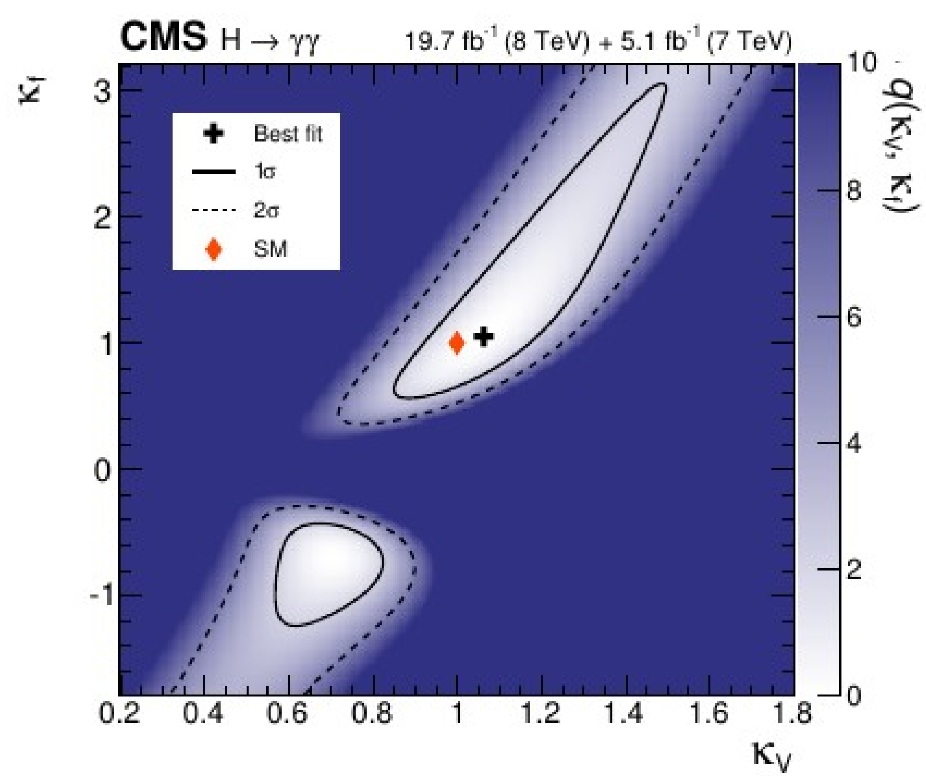
κ_V : anomalous coupling of H to W and Z

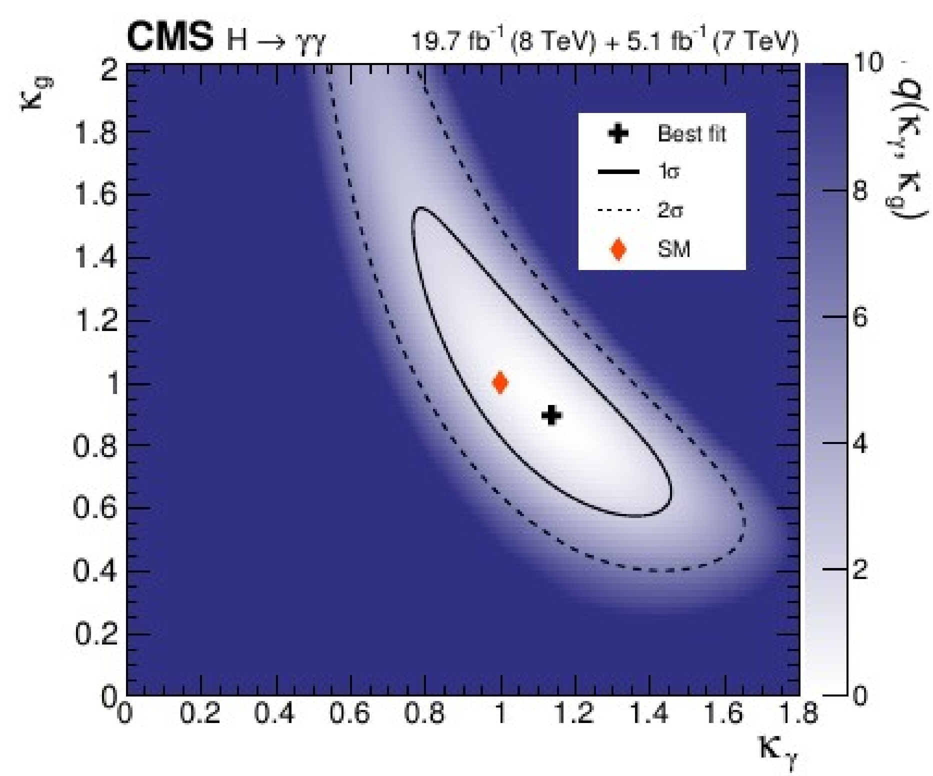
κ_g : anomalous coupling of H to gluons (loop in SM)

κ_γ : anomalous coupling of H to γ (loop in SM)

} Possible BSM contributions in loops







(t)tH Standalone Analyses

PAS HIG-14-001

ttH Analysis

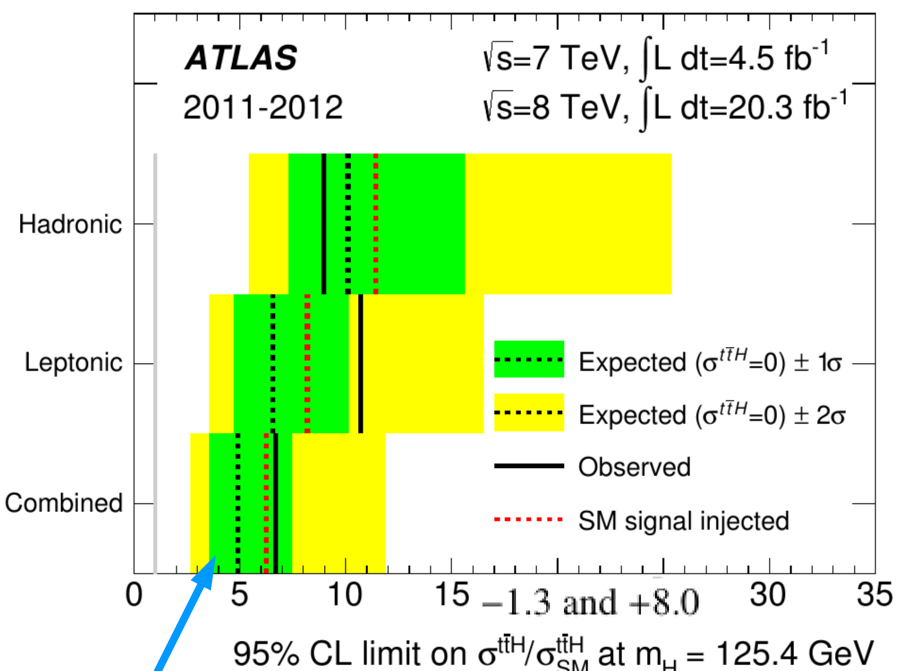
Phys. Lett. B (2015) 222-242

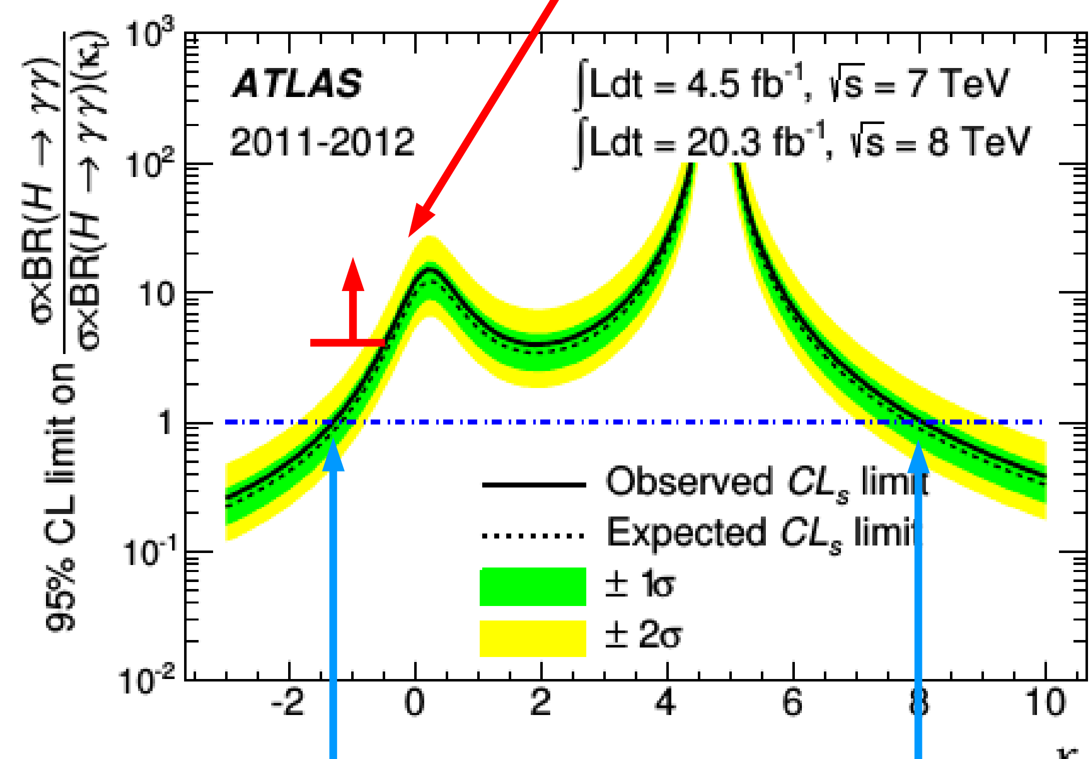
Use same ttH selection as $H \to \gamma\gamma$ main result
Set constraints on κ_t considering both tH and ttH production

Select $t(H \to \gamma\gamma)$ events with

- Semileptonic top decay: 2 jets, 1 b-tag, 1 lepton
- 2 photons, use $m_{\gamma\gamma}$ sidebands to subtract bkg.

$\mu < 4.1$ @ 95% C.L. for $\kappa_t = -1$





$\mu < 5.7$ (expected 3.8) @ 95% C.L. for $\kappa_t = +1$

Exclude regions **$\kappa_t < -1.3$ and $\kappa_t > 8.0$ @ 95% C.L.**

$H \rightarrow \gamma\gamma$ Mass and Width

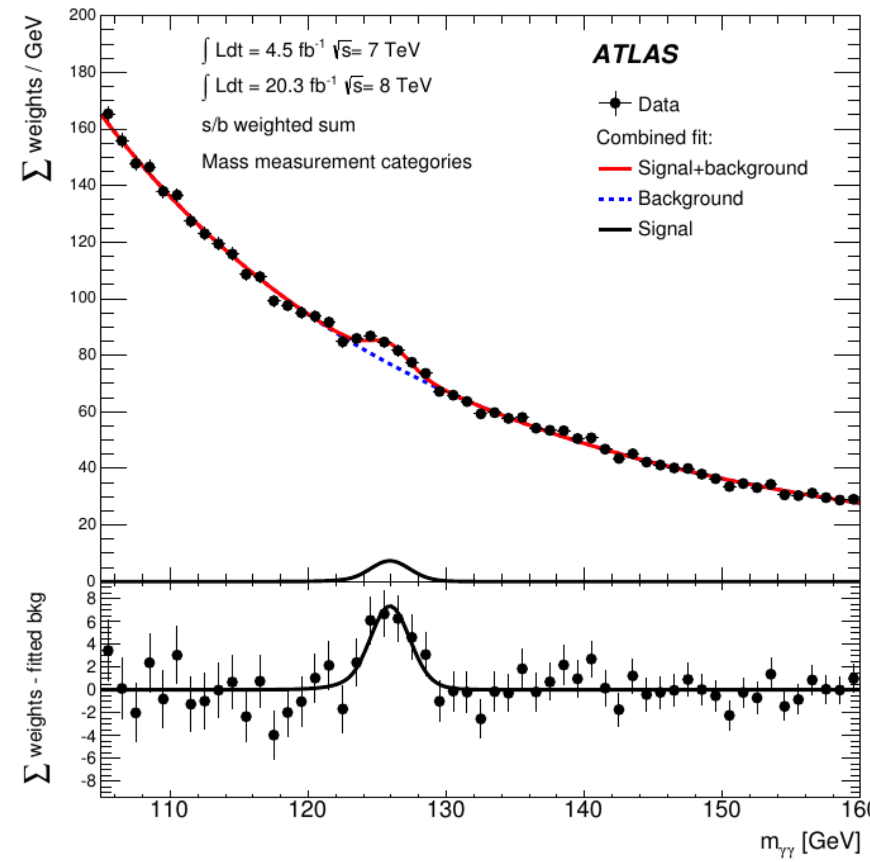
ATLAS Mass Categories

Phys.Rev. D90 (2014) 052004

Use 10 detector-driven categories for mass measurement,

- 3 |η| categories (|η|<0.75, 1.3 < |η| < 1.75, and rest)
- 2 p_{Tt} categories (> and <70 GeV)
- Separate converted and unconverted photons

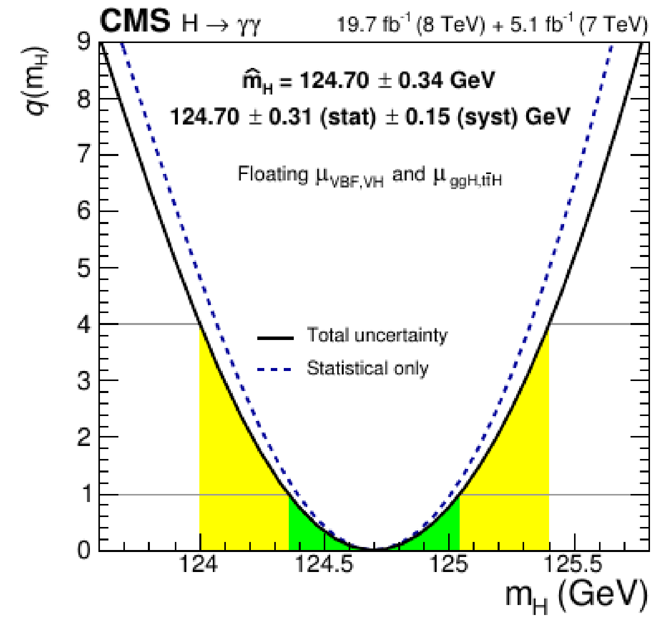
Category	n_{sig}	FWHM [GeV]	σ_{eff} [GeV]
	$\sqrt{s}$=8 TeV		
Inclusive	402.	3.69	1.67
Unconv. central low p_{Tt}	59.3	3.13	1.35
Unconv. central high p_{Tt}	7.1	2.81	1.21
Unconv. rest low p_{Tt}	96.2	3.49	1.53
Unconv. rest high p_{Tt}	10.4	3.11	1.36
Unconv. transition	26.0	4.24	1.86
Conv. central low p_{Tt}	37.2	3.47	1.52
Conv. central high p_{Tt}	4.5	3.07	1.35
Conv. rest low p_{Tt}	107.2	4.23	1.88
Conv. rest high p_{Tt}	11.9	3.71	1.64
Conv. transition	42.1	5.31	2.41



Mass and Width

Main uncertainties on m_H almost entirely from photon E resolution

$Z \to e^+e^-$ calibration	0.02 – 0.11%
Non-linearity	0.09 – 0.39%
Layer calibration	0.07 – 0.16%
Material	0.06% – 0.36%
Conversion Reconstruction	0.02% – 0.06%
Bkg Modeling	0.05% – 0.20%
Primary Vertex	0.03%
Total	0.21 – 0.59% => 0.22%



Source of uncertainty		Uncertainty in $\hat{m}_H$ (GeV)
Imperfect simulation of electron-photon differences	0.10	
Linearity of the energy scale	0.10	
Energy scale calibration and resolution	0.05	
Other	0.04	
All systematic uncertainties in the signal model	0.15	
Statistical		0.31
Total		0.34

Mass:

ATLAS: **m_H = 125.98 ± 0.42 (stat) ± 0.28 (syst) GeV**

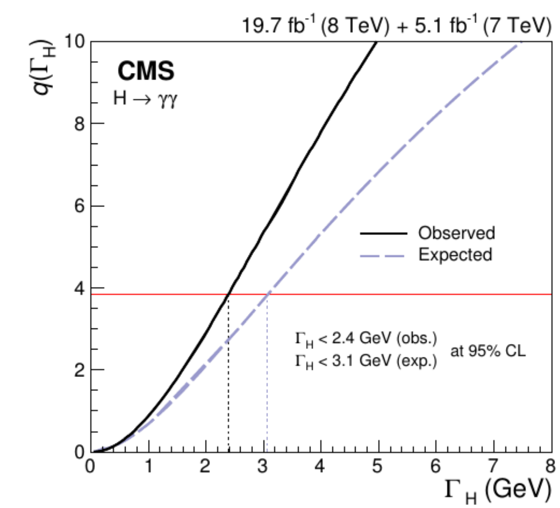
CMS: **m_H = 124.70 ± 0.31 (stat) ± 0.15 (syst) GeV**

Width: test using (SM signal shape) ⊗ BW signal model.

ATLAS: **Γ_H < 5.0 GeV** (expected 6.2 GeV)

CMS: **Γ_H < 2.4 GeV** (expected 3.1 GeV)

See next talk!



Other H→γγ Properties

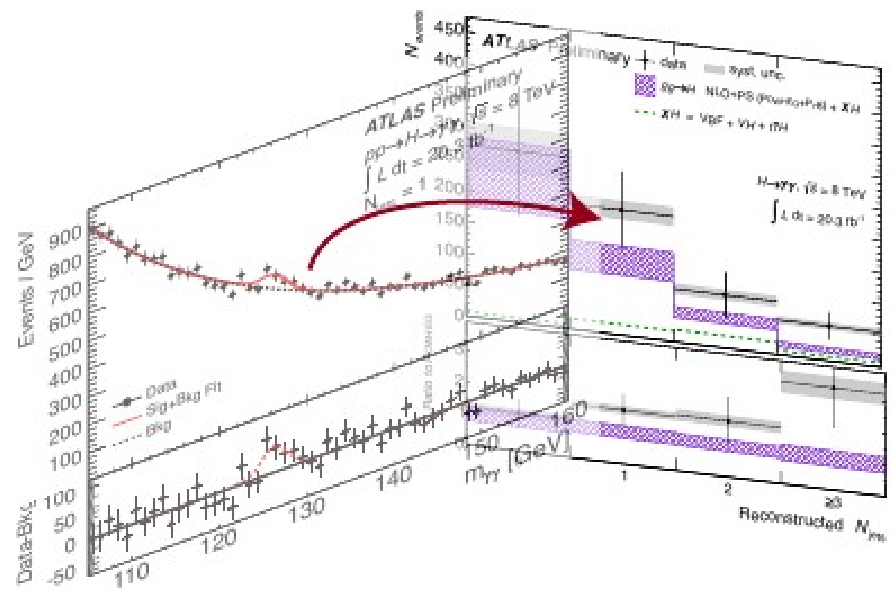
Differential Distributions

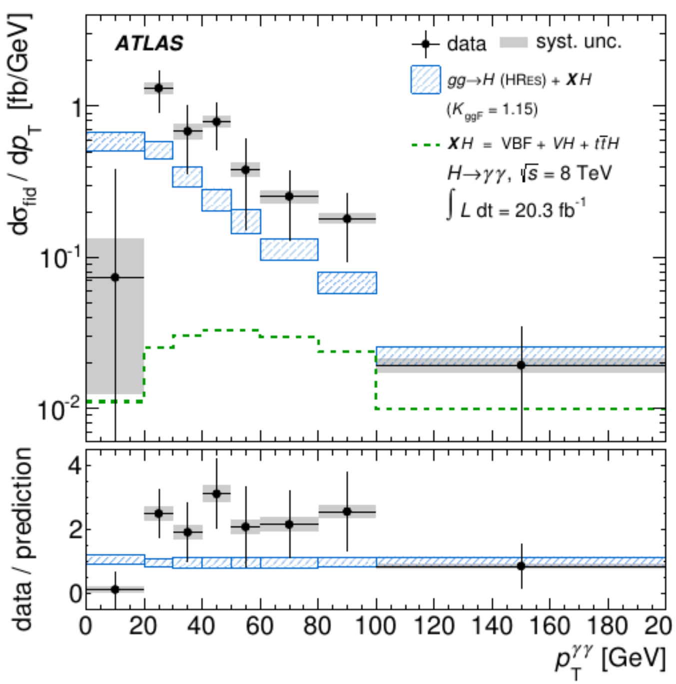
JHEP 1409 (2014) 112

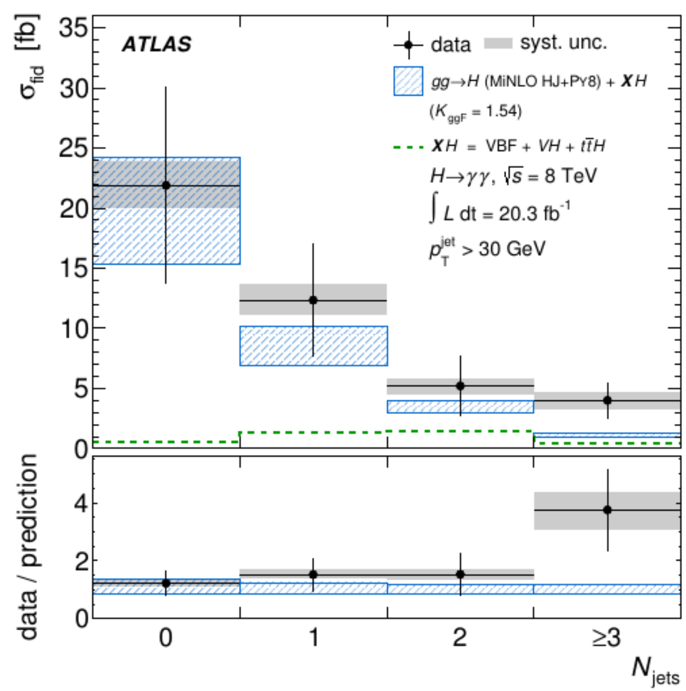
Idea: repeat the H→γγ analysis in "slices" of a given variable

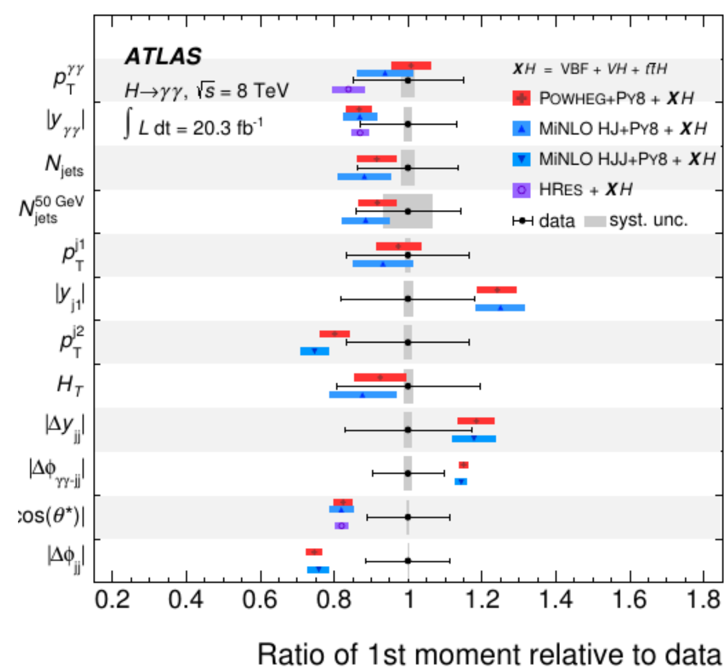
=> obtain a **binned distribution**

- Unfold to particle level within fiducial region
- Start to constrain MC, but errors still large
  - Precision dominated by statistical errors
- Promising to study Higgs properties in Run2
- 12 variables studied, available as HepData







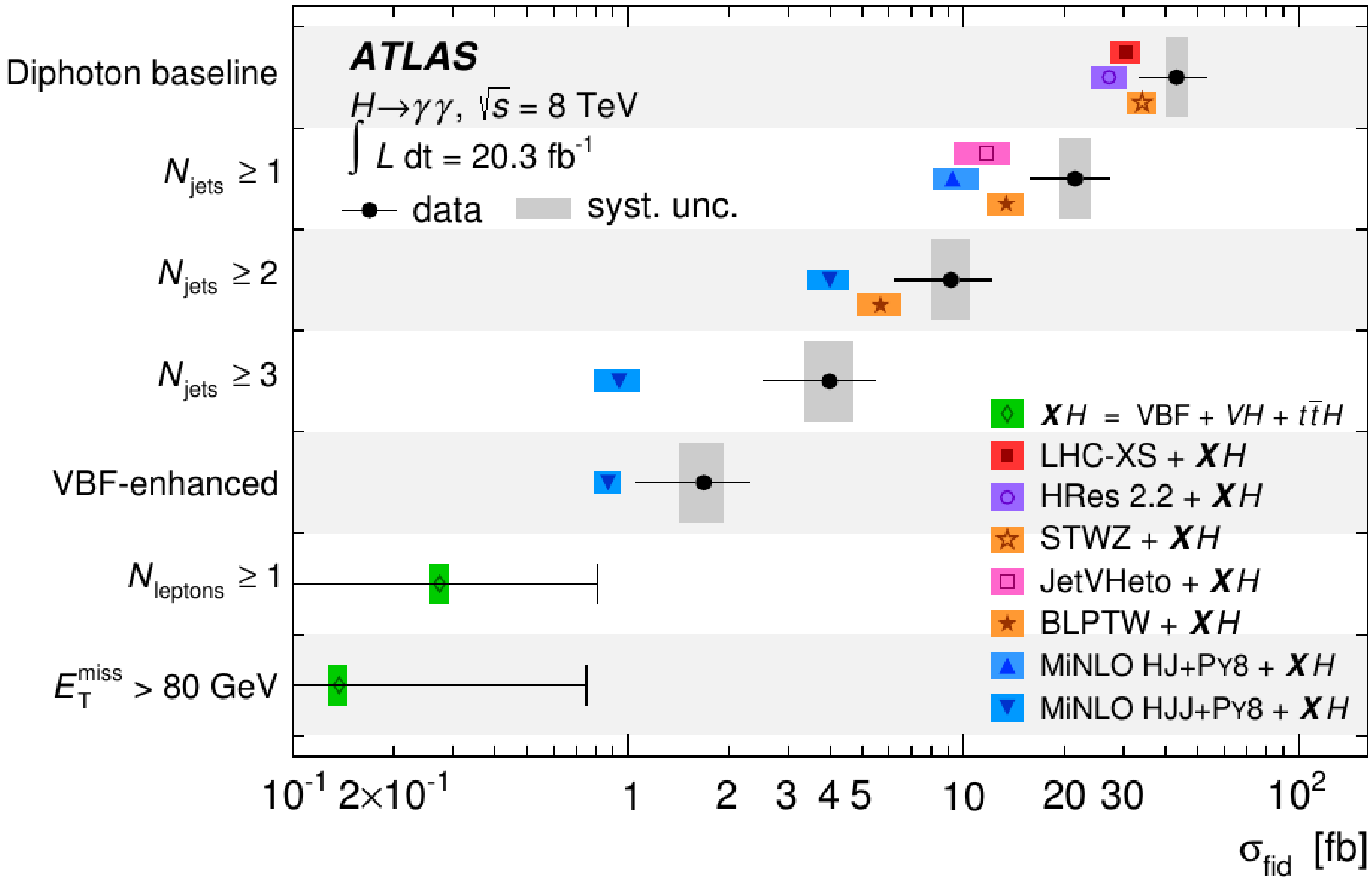


Fiducial Cross-Sections

JHEP 1409 (2014) 112

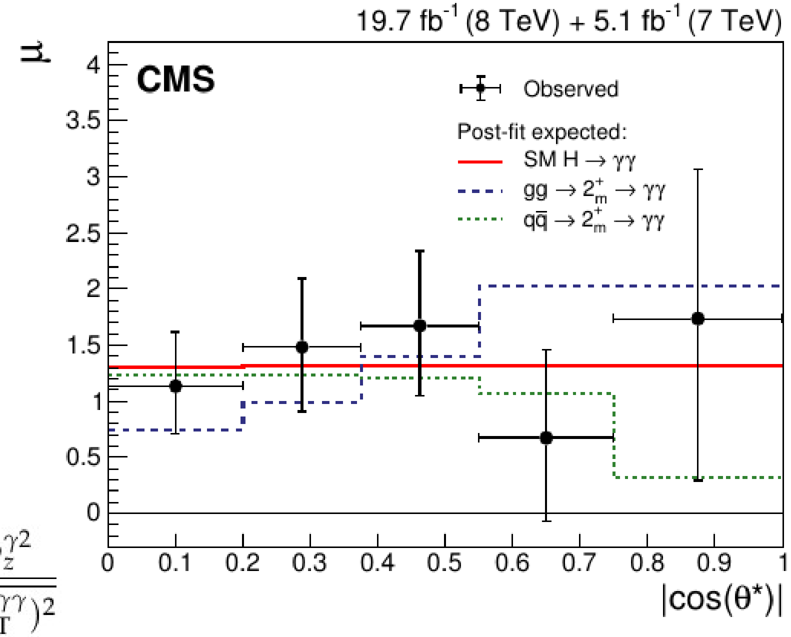
Report fiducial cross-sections within $|\eta_\gamma| < 2.37$, $E_{T1,2}/m_{\gamma\gamma} < 0.35, 0.25$

- Inclusive $H \to \gamma\gamma$
- Associated production: VBF-like topologies, jets, lepton, MET

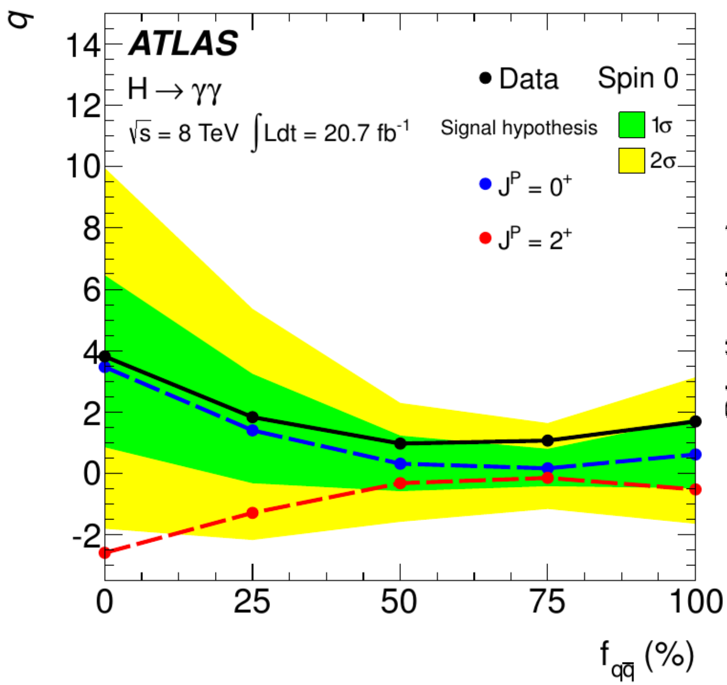


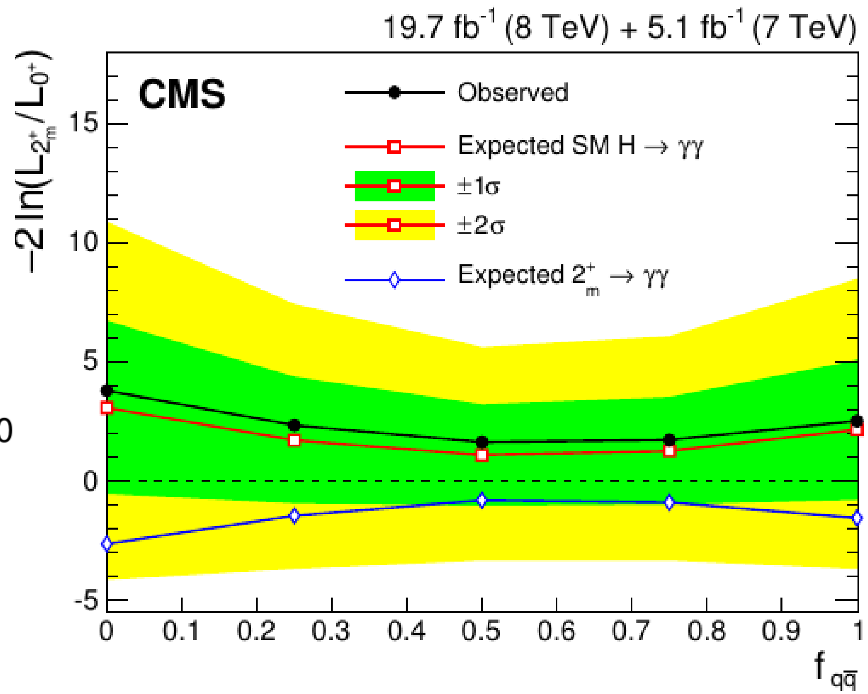
Spin

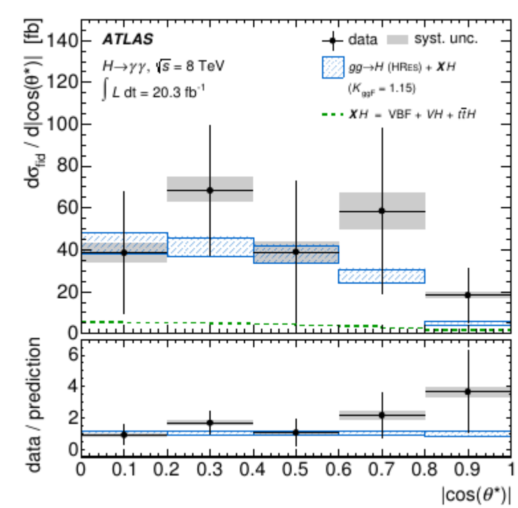
- Test 0^+ vs. "2^+_m" model. Fraction of $gg\to X$ and $qq\to X$ is a free parameter => vary f_{qq} over (0,1)
- Discriminating observable: decay angle in the Collins-Soper frame



$$\cos\theta^*_{CS} = 2 \times \frac{E^{\gamma 2} p_z^{\gamma 1} - E^{\gamma 1} p_z^{\gamma 2}}{m_{\gamma\gamma}\sqrt{m_{\gamma\gamma}^2 + (p_T^{\gamma\gamma})^2}}$$







Update ongoing with more realistic NLO models

Can also use the unfolded differential distribution of |cos θ*| (JHEP 1409 (2014) 112)

Spin

- Test 0^+ vs. "2^+_m" model. Fraction of gg→X and qq→X is a free parameter => vary f_{qq} over (0,1)
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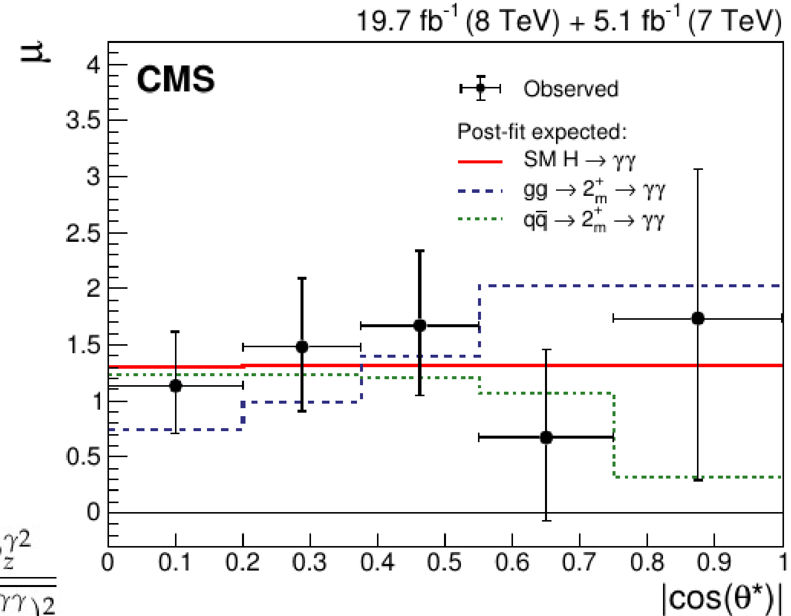
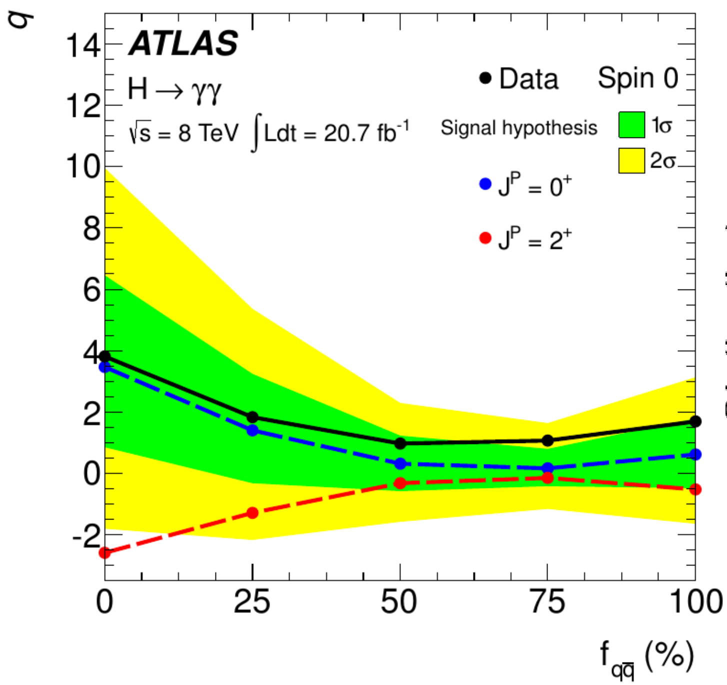
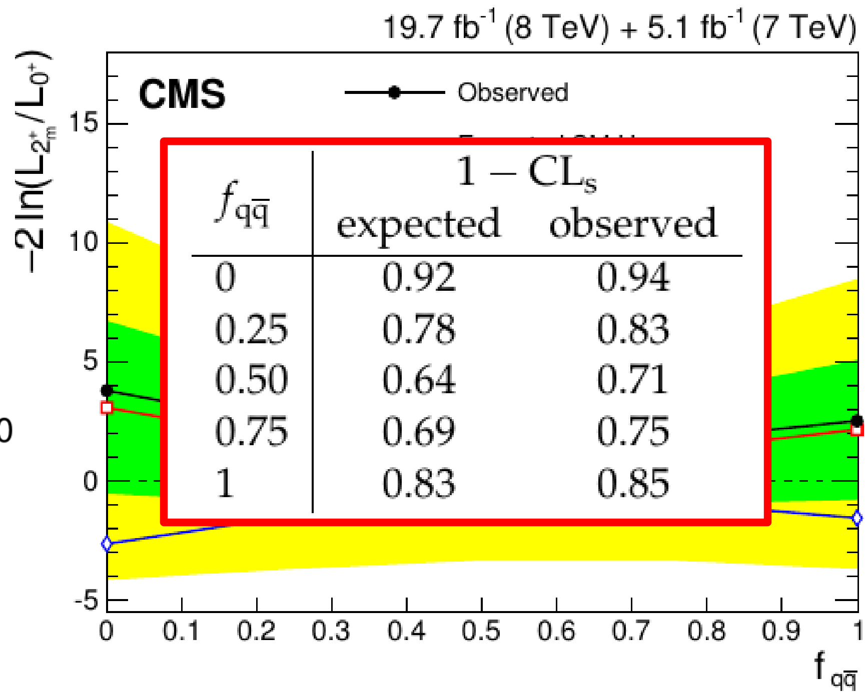
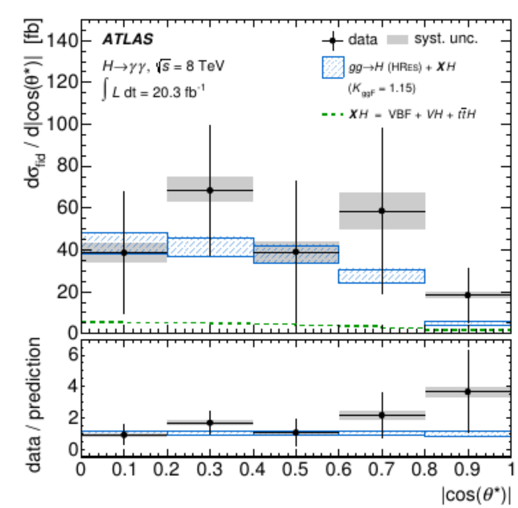


$$\cos\theta^*_{\rm CS} = 2 \times \frac{E^{\gamma 2} p_z^{\gamma 1} - E^{\gamma 1} p_z^{\gamma 2}}{m_{\gamma\gamma}\sqrt{m^2_{\gamma\gamma} + (p_{\rm T}^{\gamma\gamma})^2}}$$





$f_{q\bar{q}}$	$1-\mathrm{CL_s}$ expected	$1-\mathrm{CL_s}$ observed
0	0.92	0.94
0.25	0.78	0.83
0.50	0.64	0.71
0.75	0.69	0.75
1	0.83	0.85



Update ongoing with more realistic NLO models

Can also use the unfolded differential distribution of |cos θ*| (JHEP 1409 (2014) 112)

New Physics through $H \rightarrow \gamma\gamma$

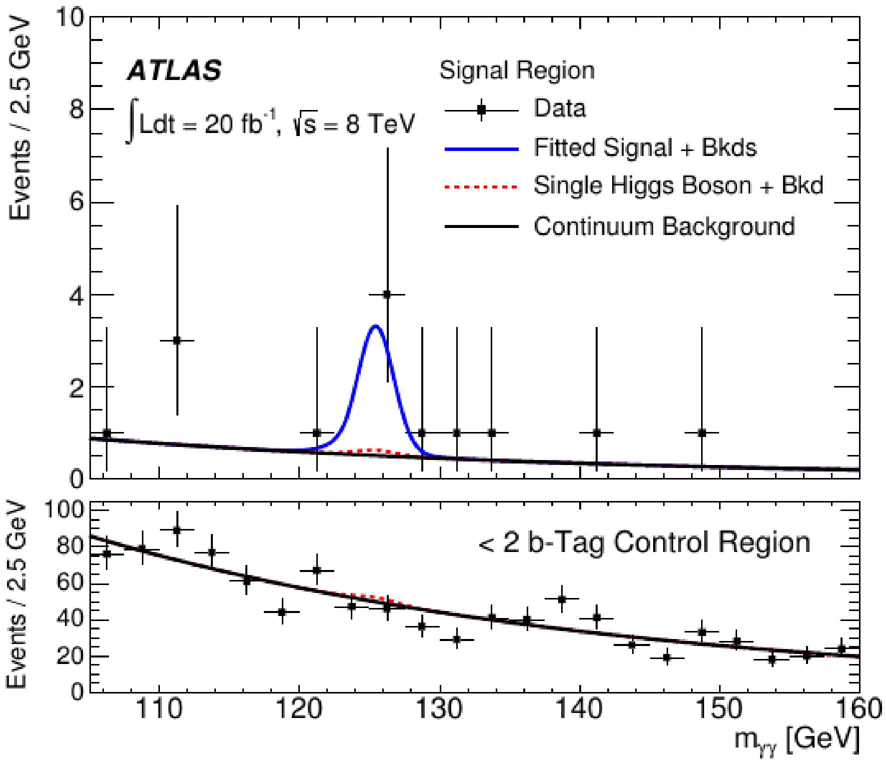
HH→γγbb

arXiv:1406.5053, submitted to PRL

CMS-PAS-HIG-13-032

- **HH** : window to λ parameter of the SM Higgs potential, but tiny SM rates (<0.1 bbγγ evts in Run1)
- Search for BSM enhancement in γγbb **final state : clear γγ signature + high bb BR**
- 2 b-tags, m_{bb} close to 125 GeV
- Search for **non-resonant excess or X→HH**

Non-Resonant σ < 2.2 pb @ 95% CL (1.0 expected)



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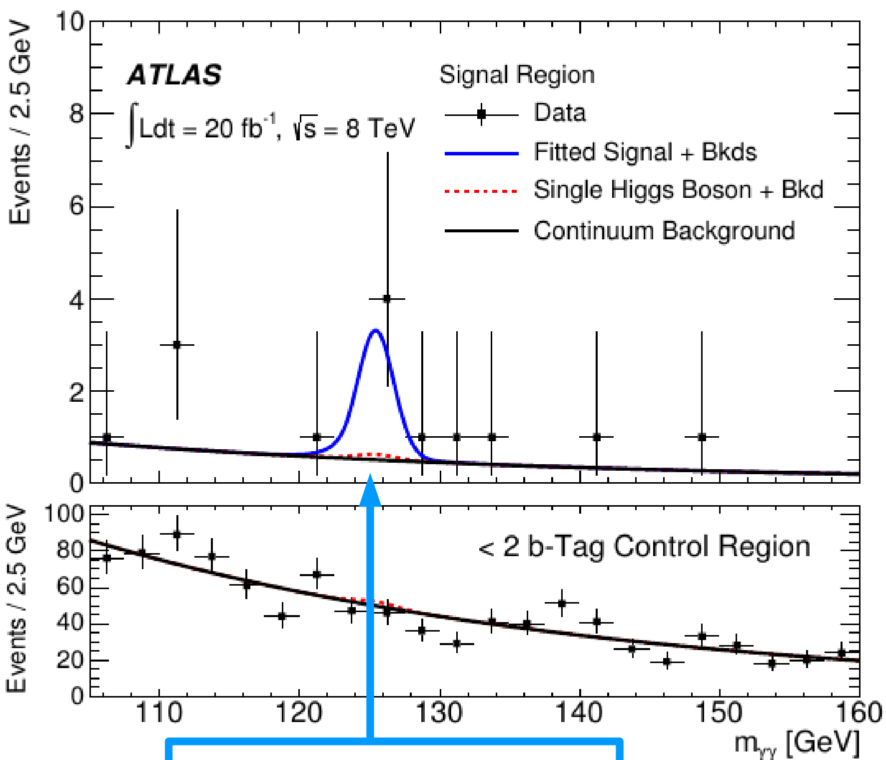

2.4σ excess

HH→γγbb

arXiv:1406.5053, submitted to PRL

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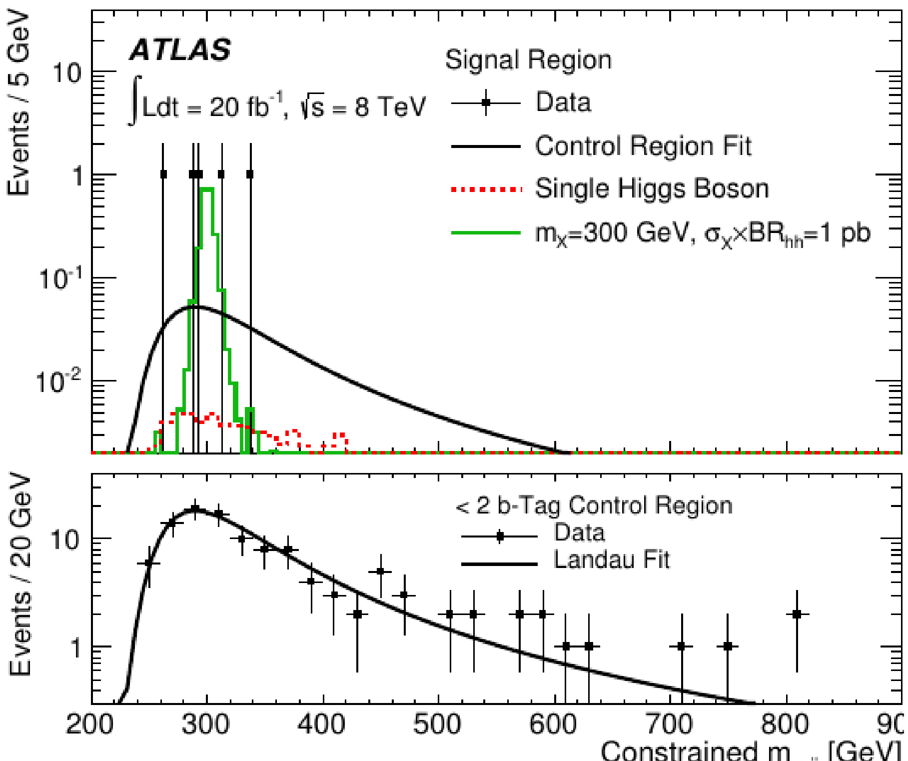

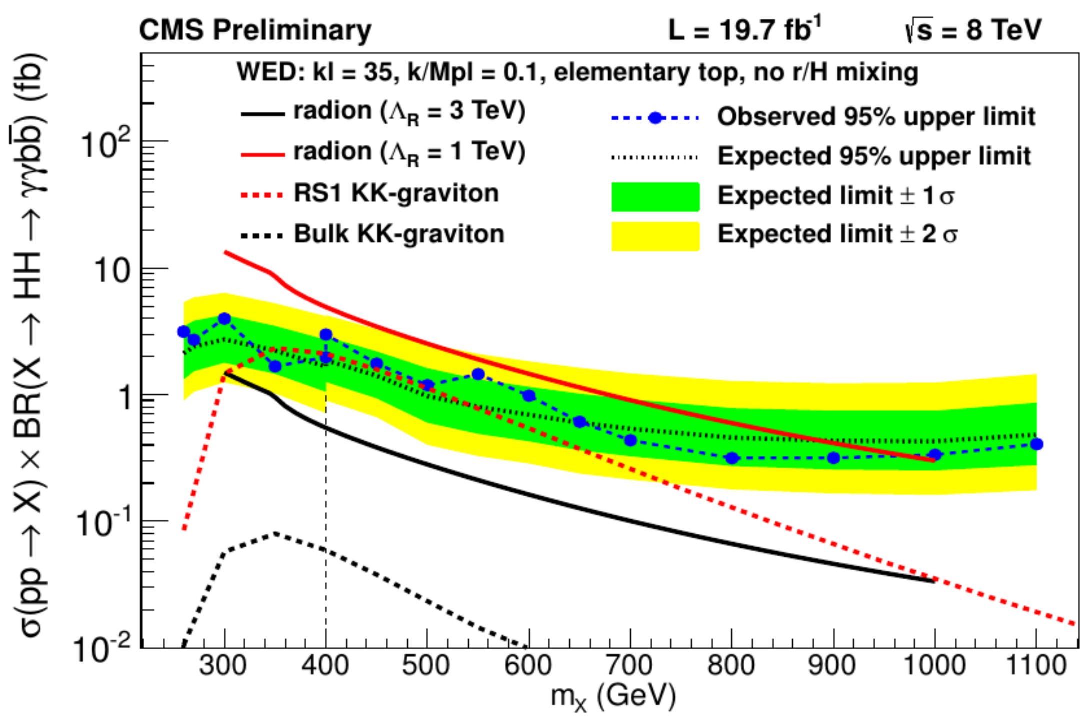

Resonant search: sensitive to Λ~1 TeV in ED-inspired models

HH→γγbb

arXiv:1406.5053, submitted to PRL

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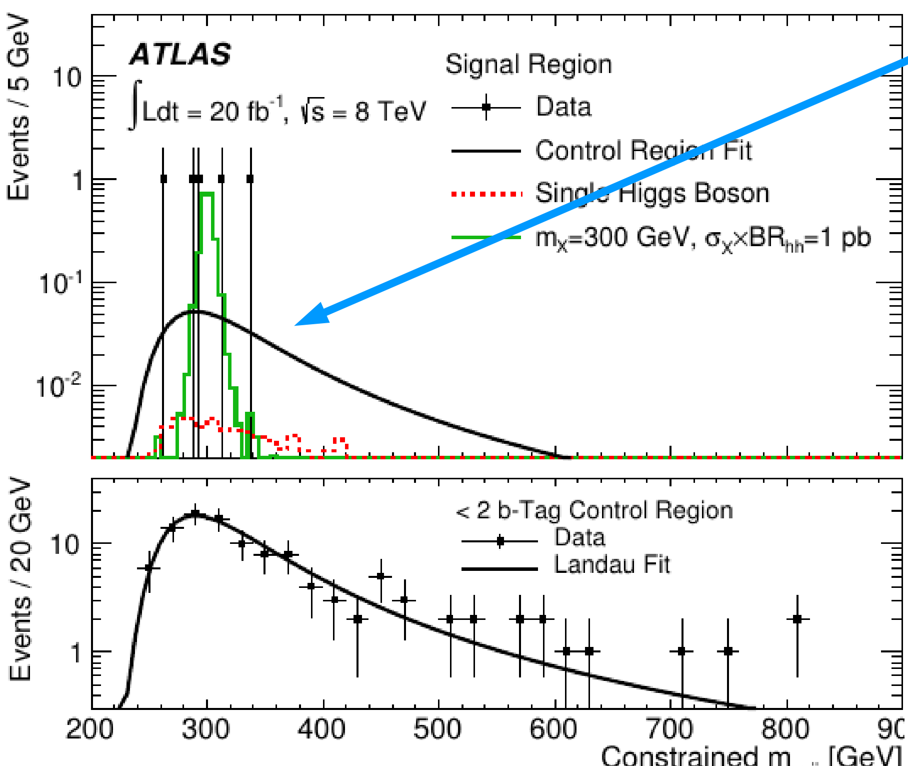
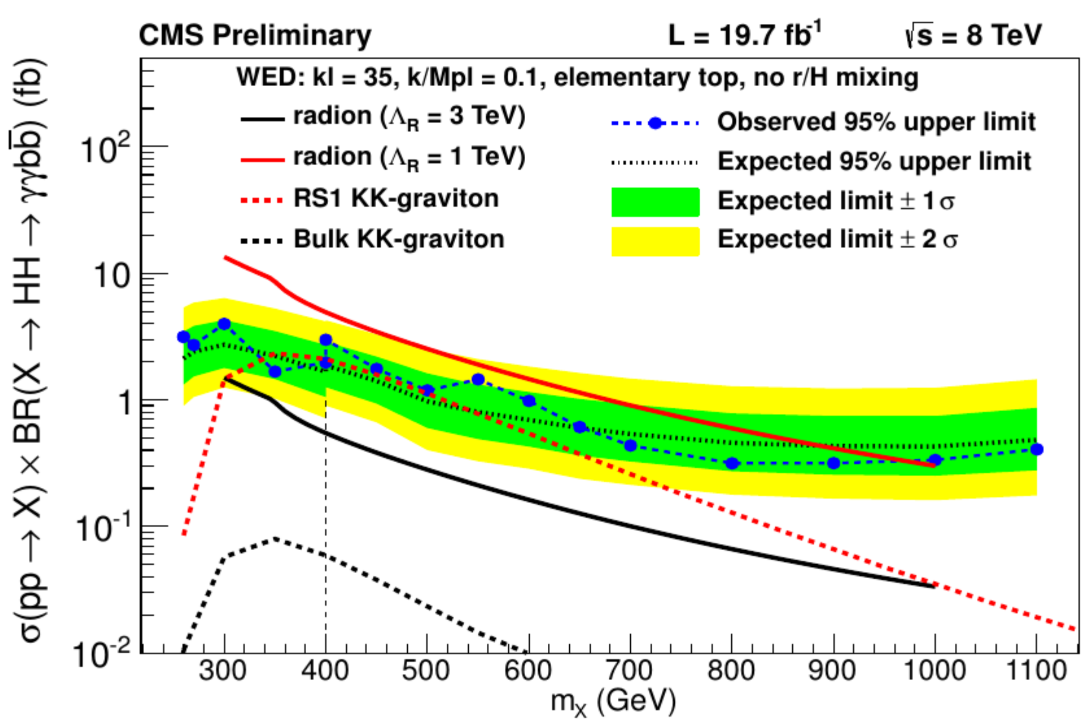


local 3σ excess @ m_X=300 GeV (2.1σ global)



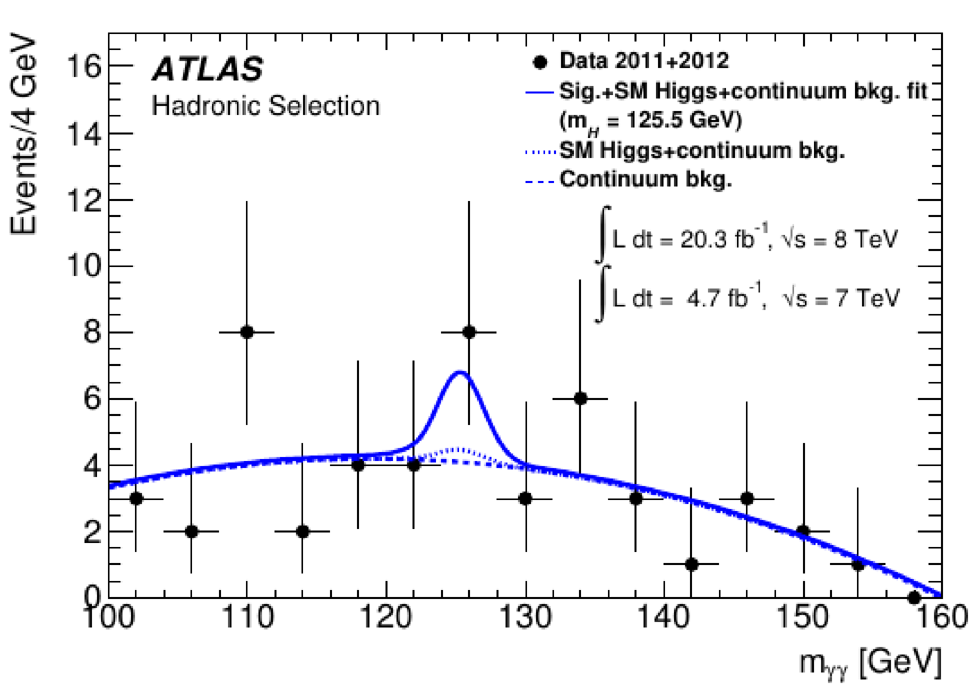
Resonant search: sensitive to Λ~1 TeV in ED-inspired models

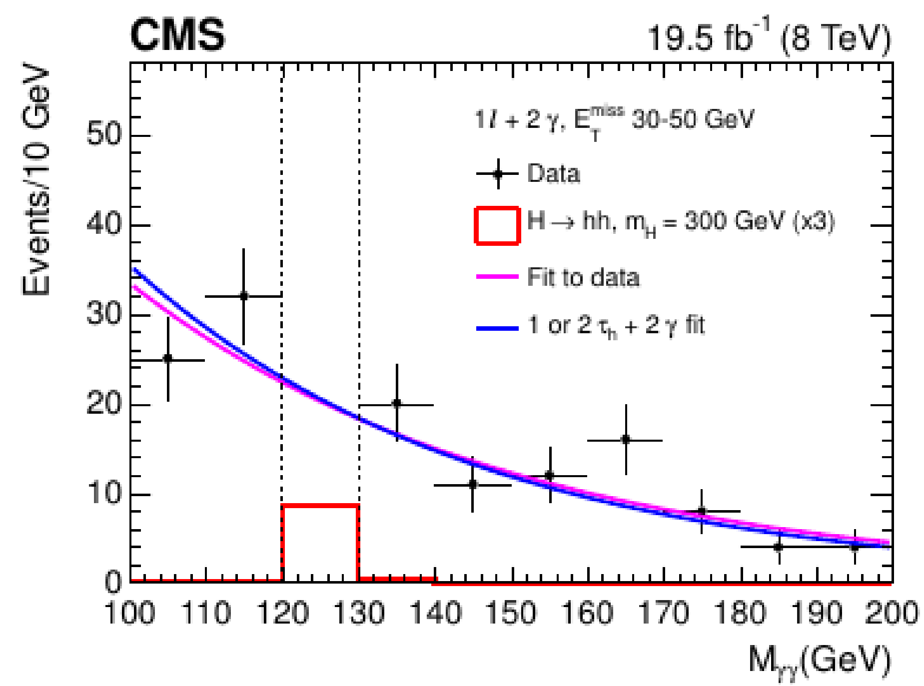
Search for t→qH

JHEP 1406 (2014) 008

arXiv:1410.2751, submitted to PRD

- Search for FCNC decay **t→qH**, mainly for q=c but also sensitive to q=u.
  - BF(t→cH) ~ 10^{-3} - 10^{-5} possible in some BSM models.
- **Use H→γγ : clean signal, can use sidebands to remove bkg**





BF(t→qH) < 0.79% @ 95% C.L. (0.51% exp.)

$$\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17 \quad \text{(0.14 exp.)}$$

BF(t→cH) < 0.56% @ 95% C.L. (0.65% exp.)

$$\sqrt{|\lambda^{\rm h}_{\rm tc}|^2 + |\lambda^{\rm h}_{\rm ct}|^2} < 0.14.$$

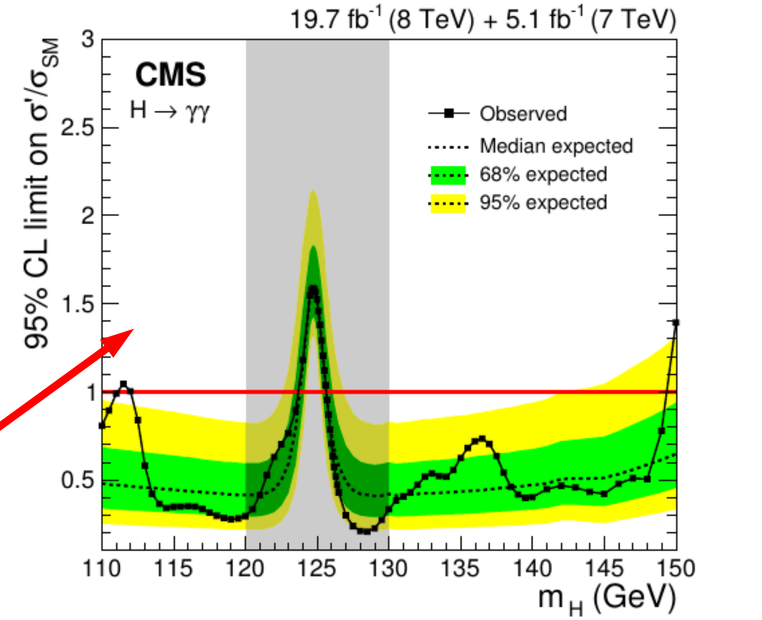
New $X \to \gamma\gamma$ Resonances

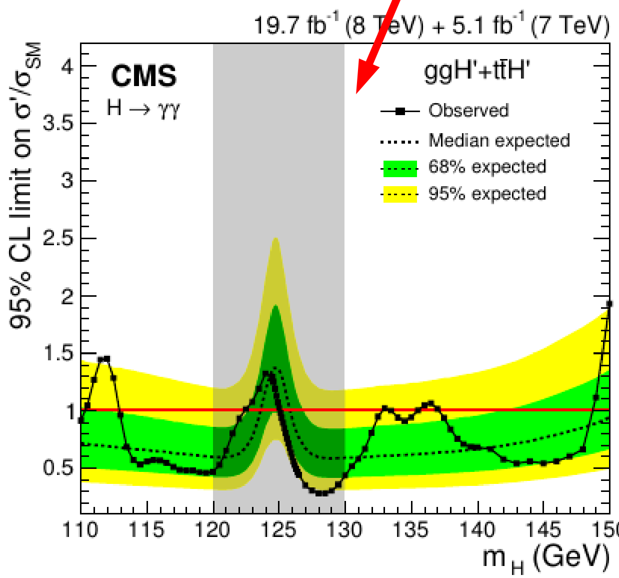
CMS Additional Resonance Search near 125 GeV

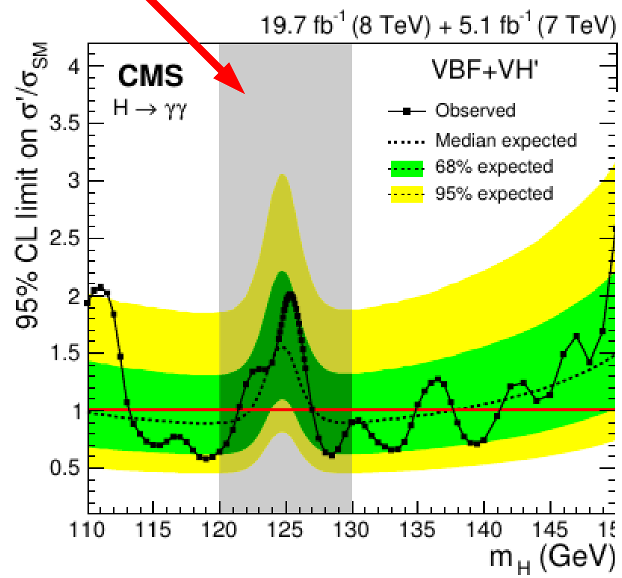
Additional narrow γγ resonances: occur in various BSM extensions, in particular extended Higgs sectors : (N)MSSM, 2HDM, ...

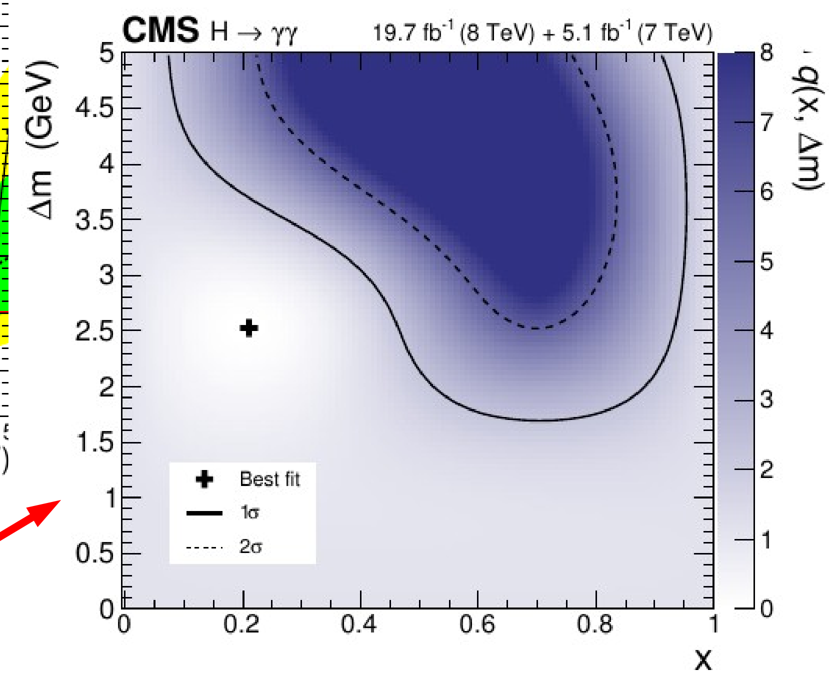
CMS: search within the original H→γγ search window:

- Separate second peak: H-like
- Second resonance partially overlapping with H
- Consider **ggF-only**, and **VBF+VH** only, and **H-like prod.**









Search for overlapping resonance:

x: fraction of events in 2nd peak

Δm : mass separation between the 2 peaks

Low/High-Mass Resonance Search

Search for new γγ resonances up to 850 GeV (CMS), down to 65 GeV (ATLAS)

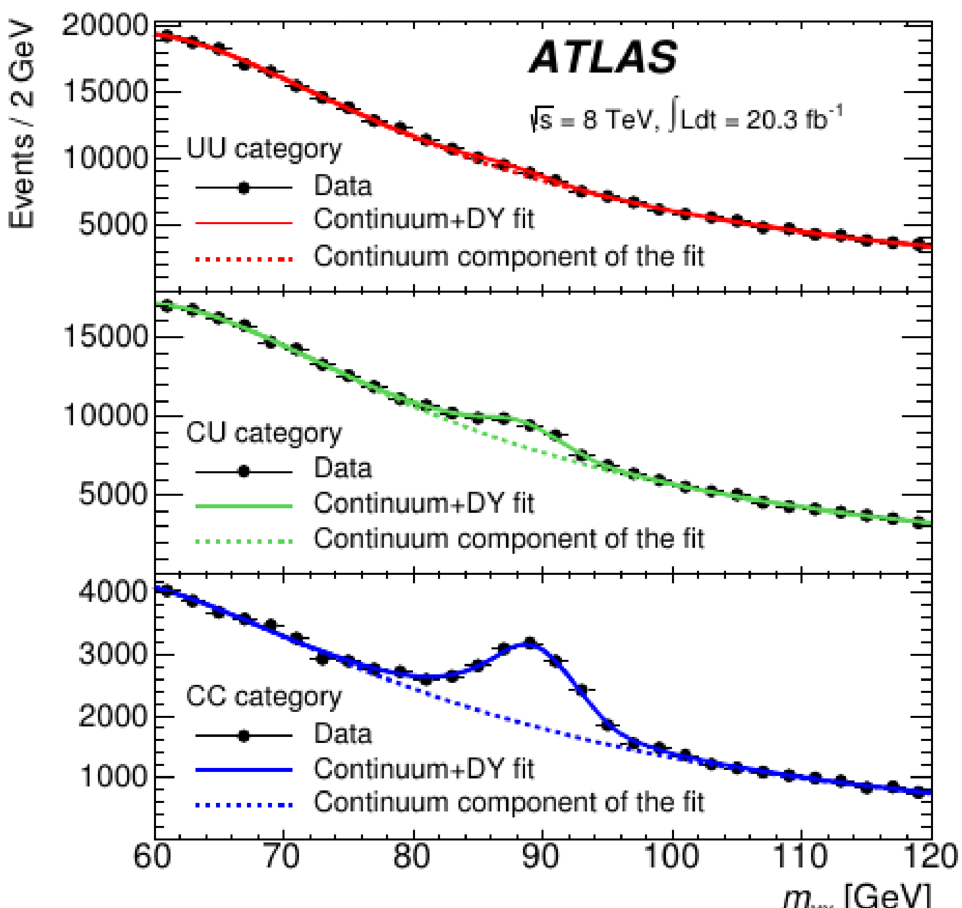
ATLAS: Model-independent search (fiducial σ), narrow resonances

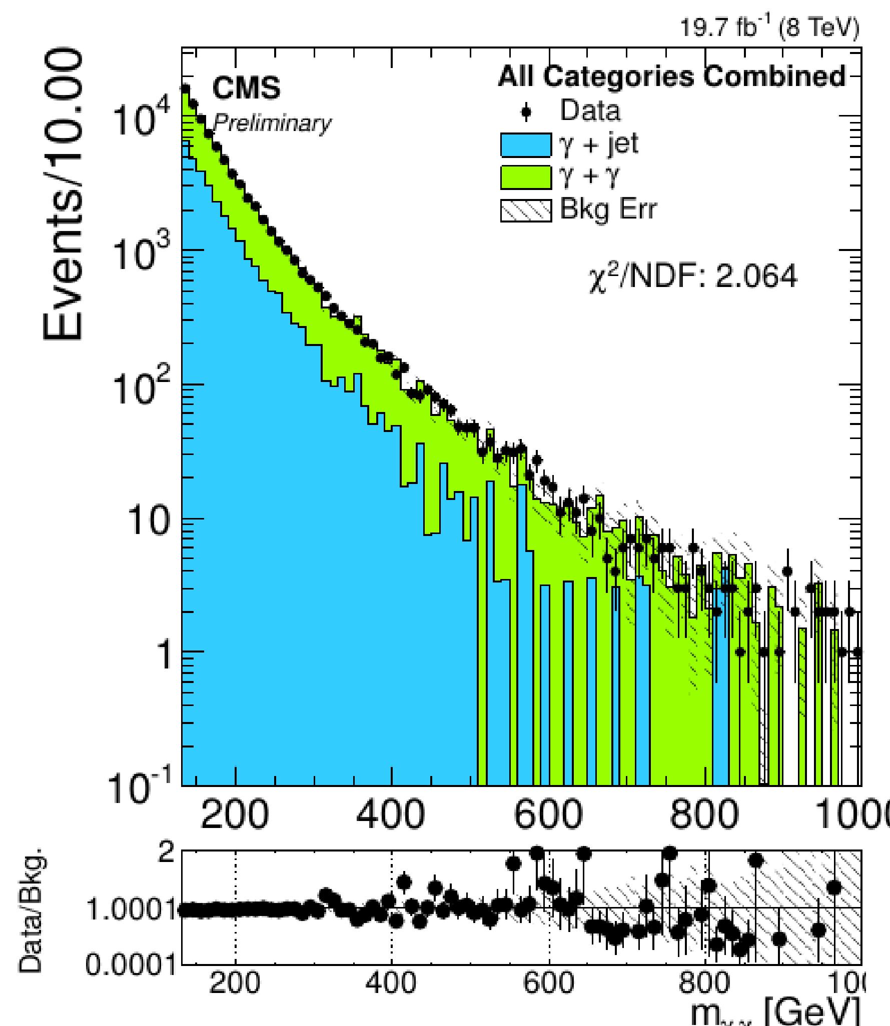
CMS: gluon fusion and VBF scenarii, consider larger widths

Need to consider **$Z \to e^+e^-$** and **$H \to \gamma\gamma$** backgrounds

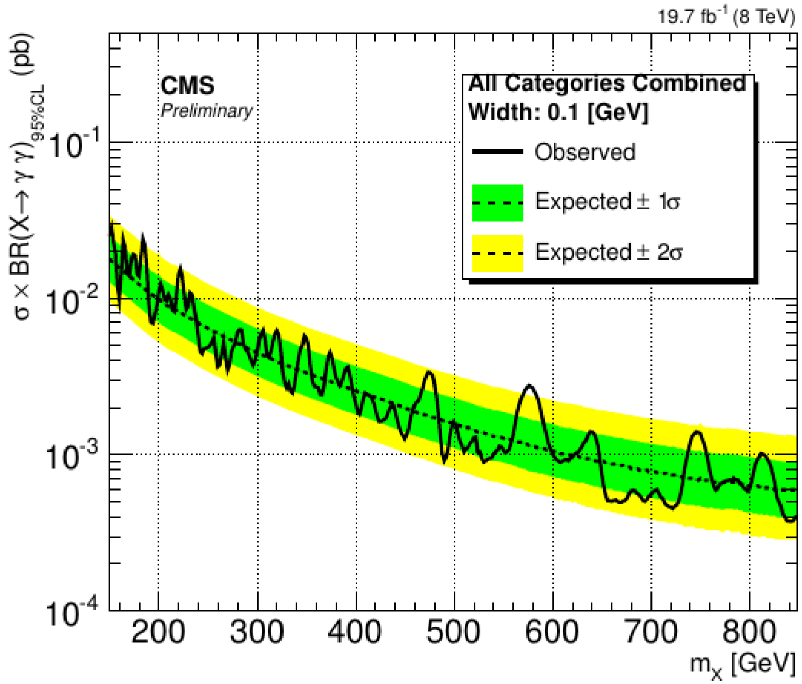
CMS-PAS-HIG-14-006

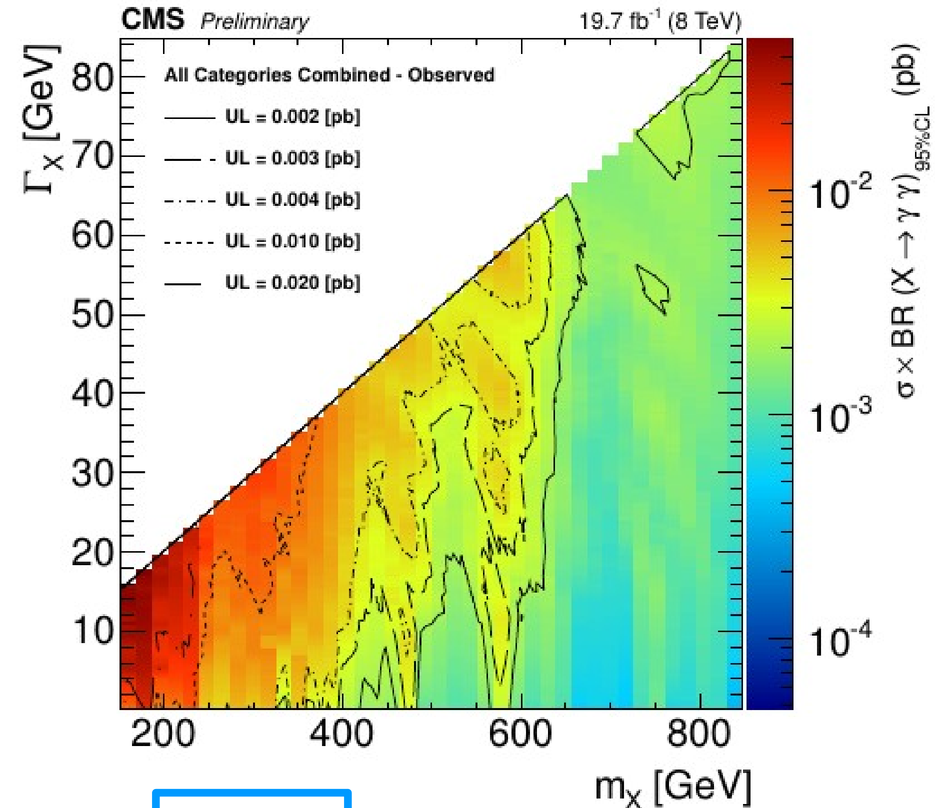
Phys.Rev.Lett. 113 (2014) 171801

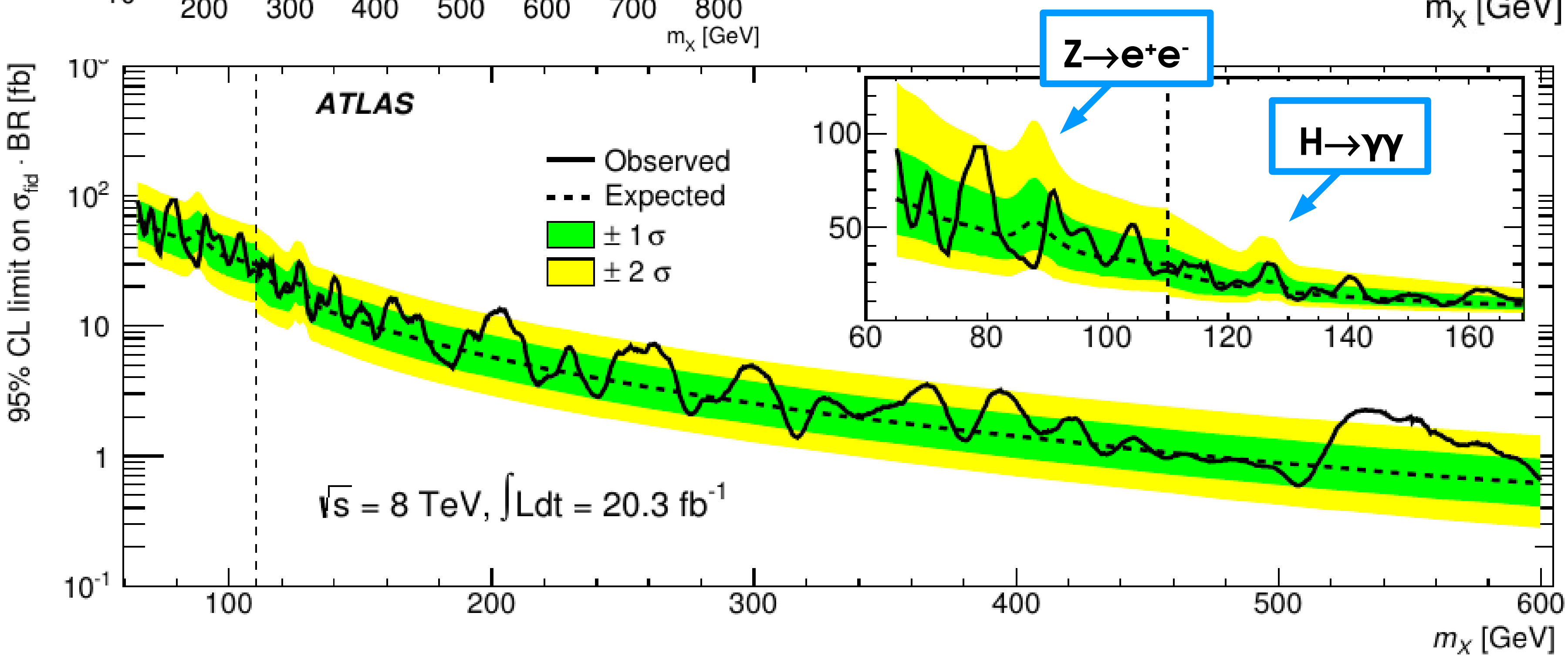




Low/High Mass Results







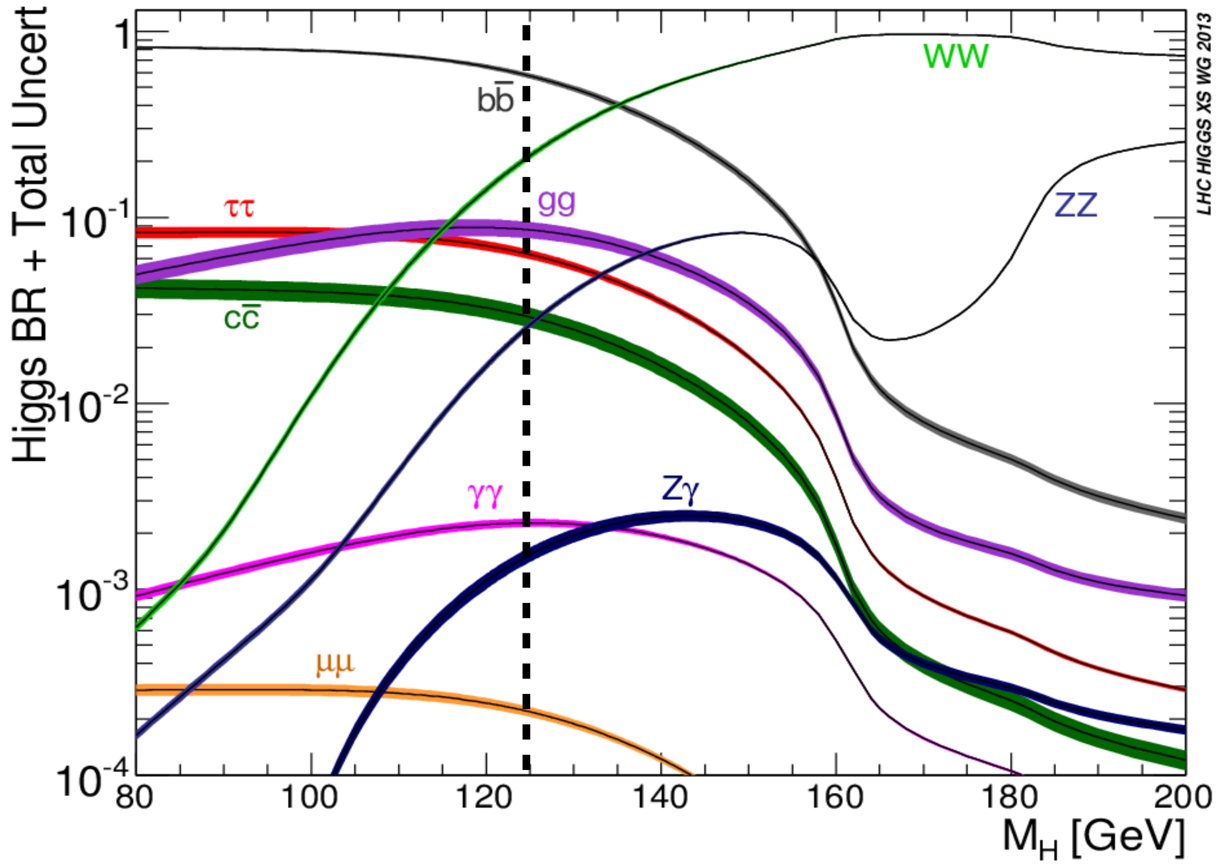
Conclusion

- γγ mode was crucial for Higgs discovery
- Now a useful tool to
  - Study Higgs properties, in particular associated production
  - Search for new physics ("Higgs portal")
- Looking forward to improved statistical precision in Run2

Additional Information

Higgs Decays / Overview

Many decay modes accessible for m_H=125 GeV



Higgs Decays / Overview

H→γγ : 0.23%
σ=50 fb @ 8 TeV
~1300 events **5.2σ**

New

H→WW : 22%
Main mode H→WW→lνlν:
σ~240 fb @ 8 TeV (6k evts) **3.8σ**

H→ZZ : 2.3%
Main mode H→ZZ→4l
σ~2.9 fb @ 8 TeV (70 evts) **8.2σ**

New

Discovery using diboson modes: easier, probe EWSB

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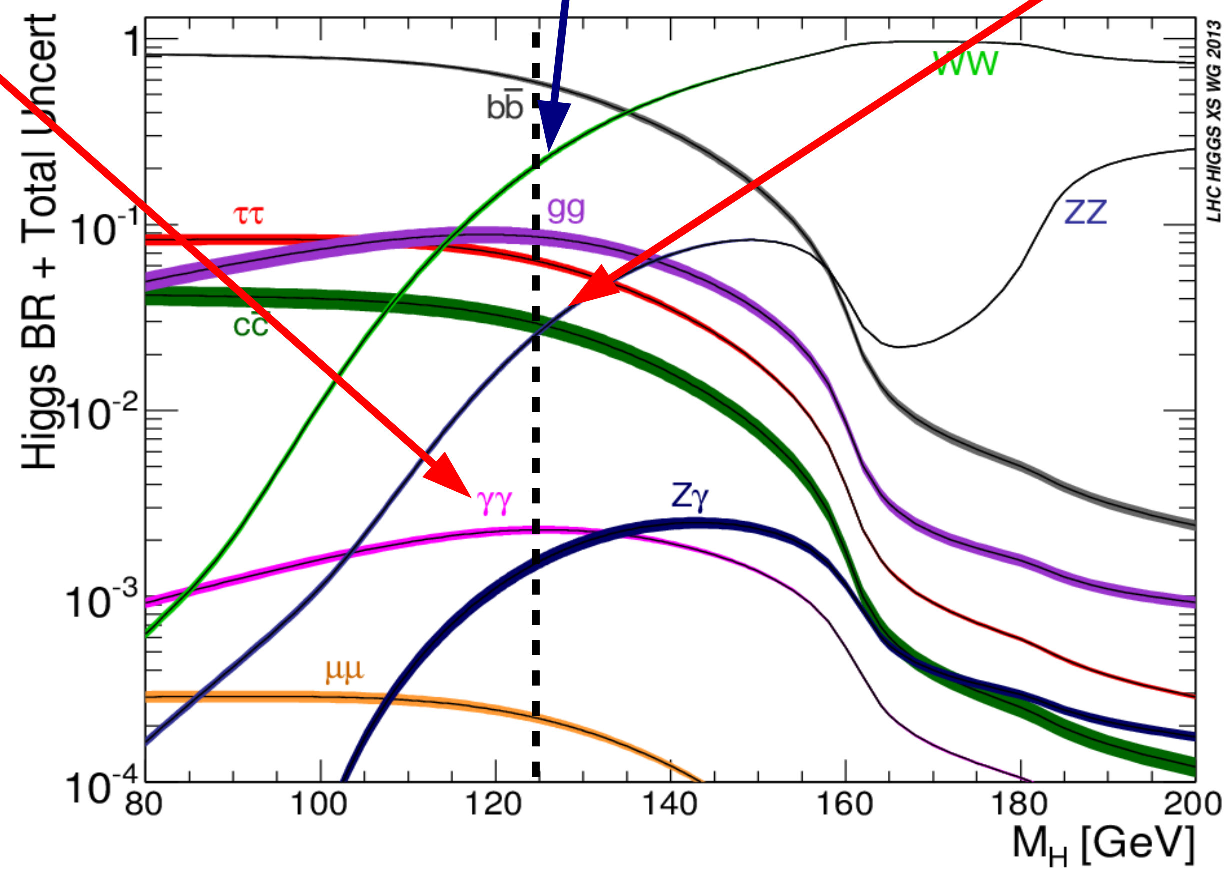

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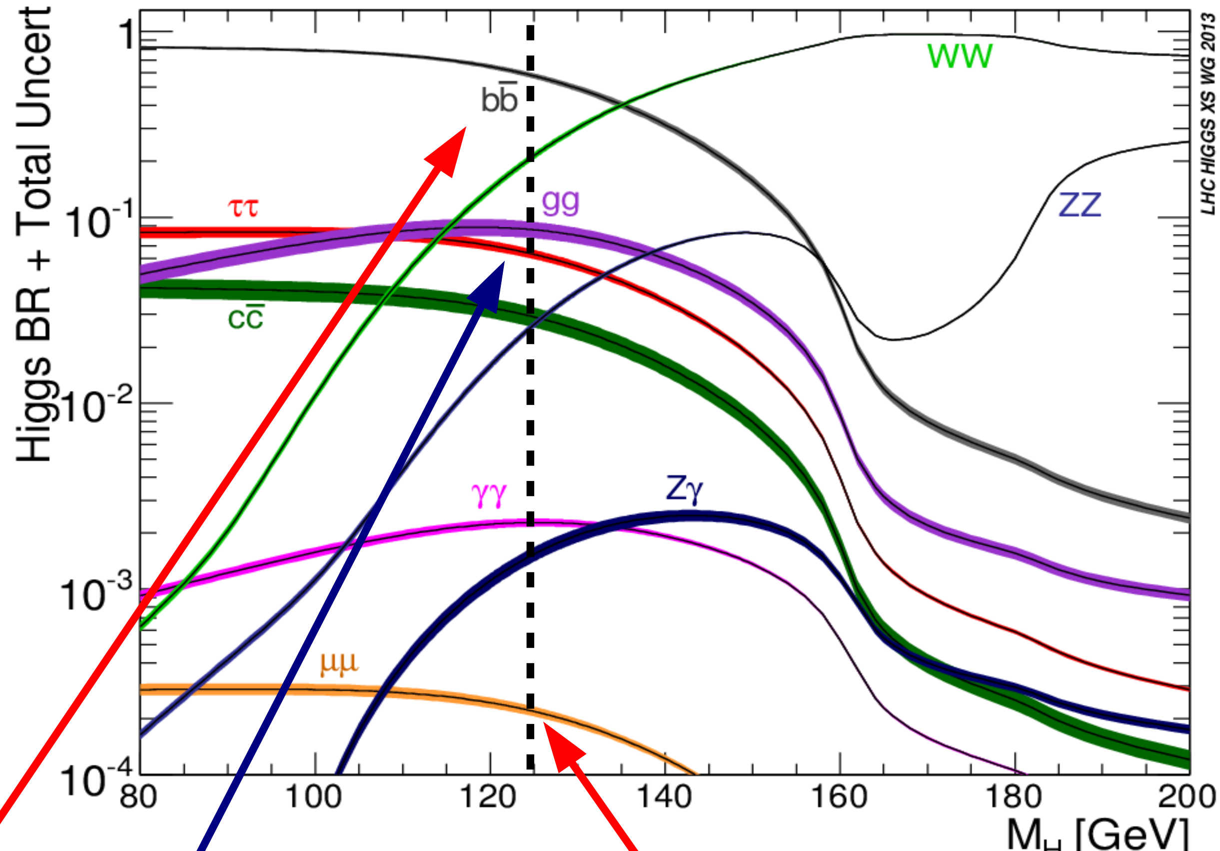
Recent progress focused on difermion modes: more challenging, probe Yukawa sector



H→bb : 57% New
only (V→leptons)H
σ~200 fb @ 8 TeV ~5k evts **1.4σ**

H→ττ : 6.2%
Consider VBF+high pT only
σ~O(10^2 fb) @ 8 TeV **4.1σ**

H→μμ : 0.02% New
σ=4 fb @ 8 TeV, 100 events

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H→WW
Main m
σ~240 fb

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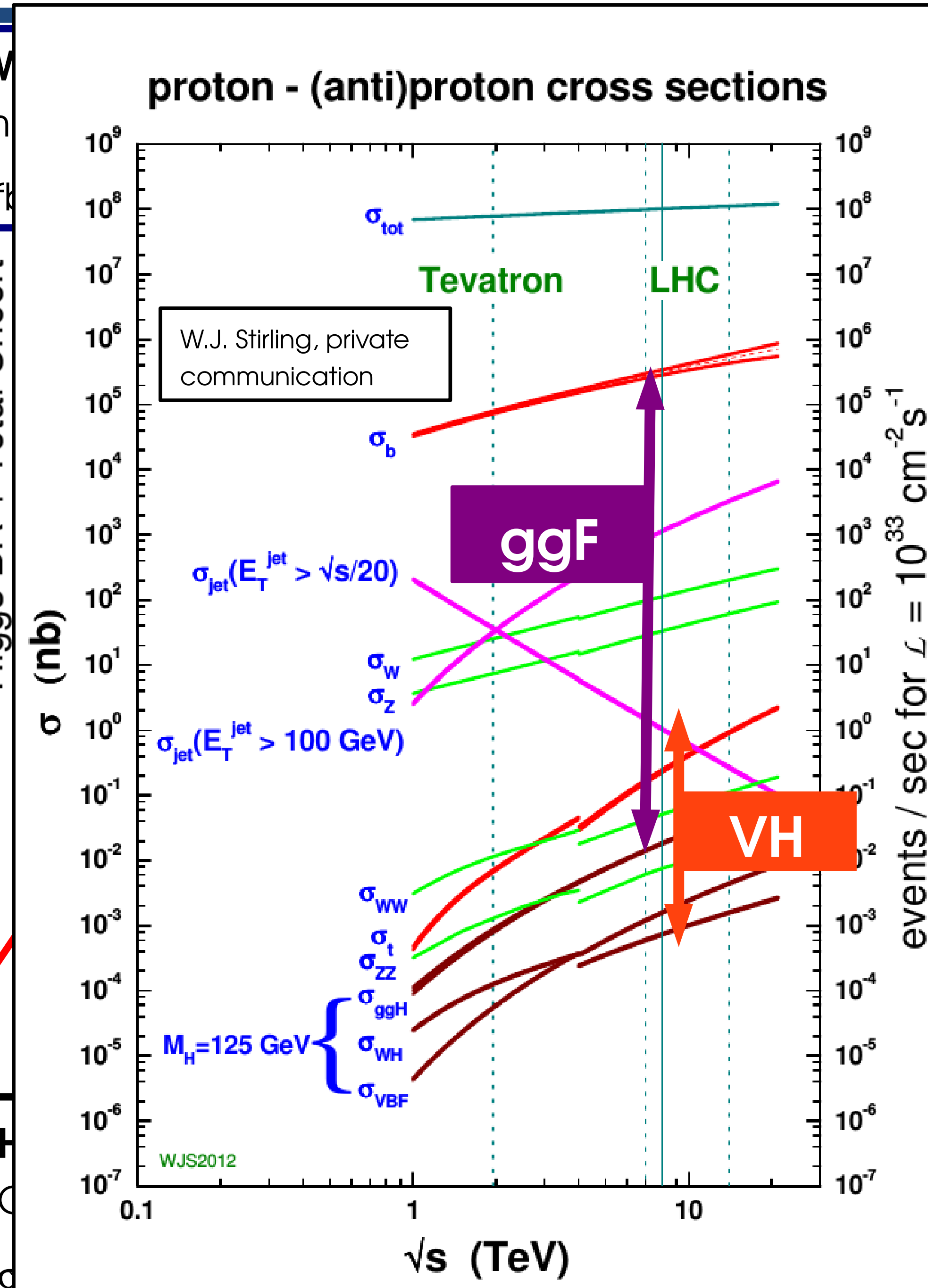

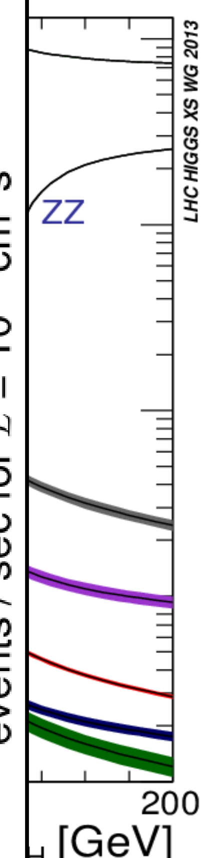

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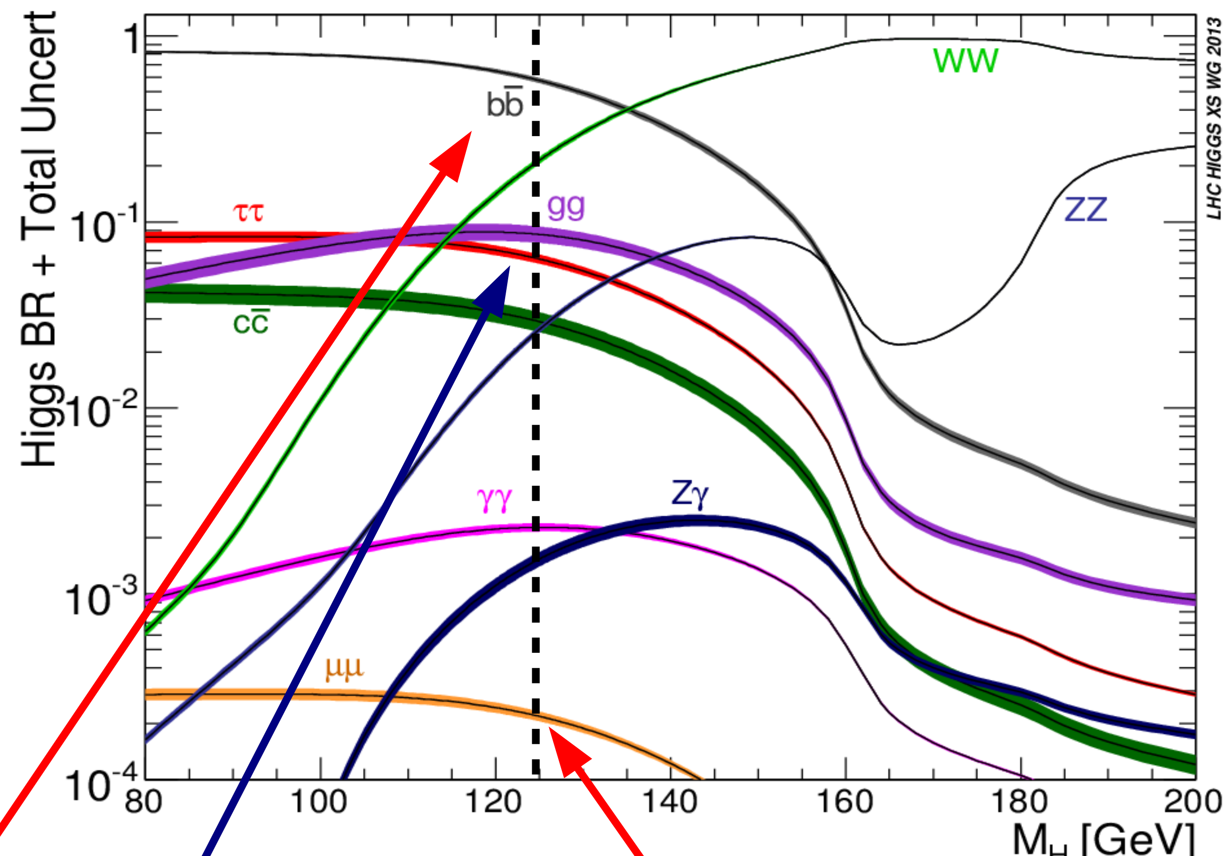

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New

H→ττ : 6.2%
Consider VBF+high pT only
σ~O(10^2 fb) @ 8 TeV **4.1σ**

H→μμ : 0.02%
σ=4 fb @ 8 TeV, 100 events
New

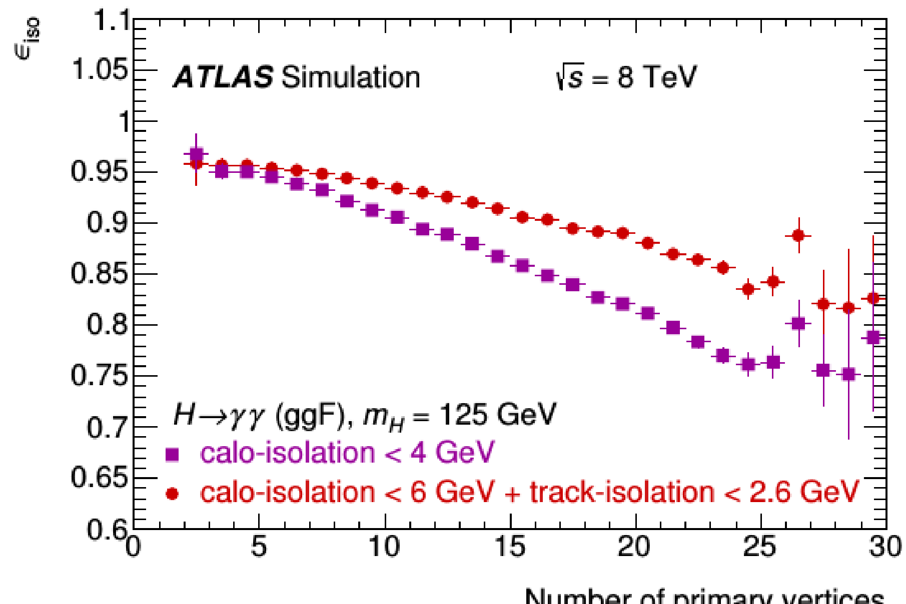
Selection

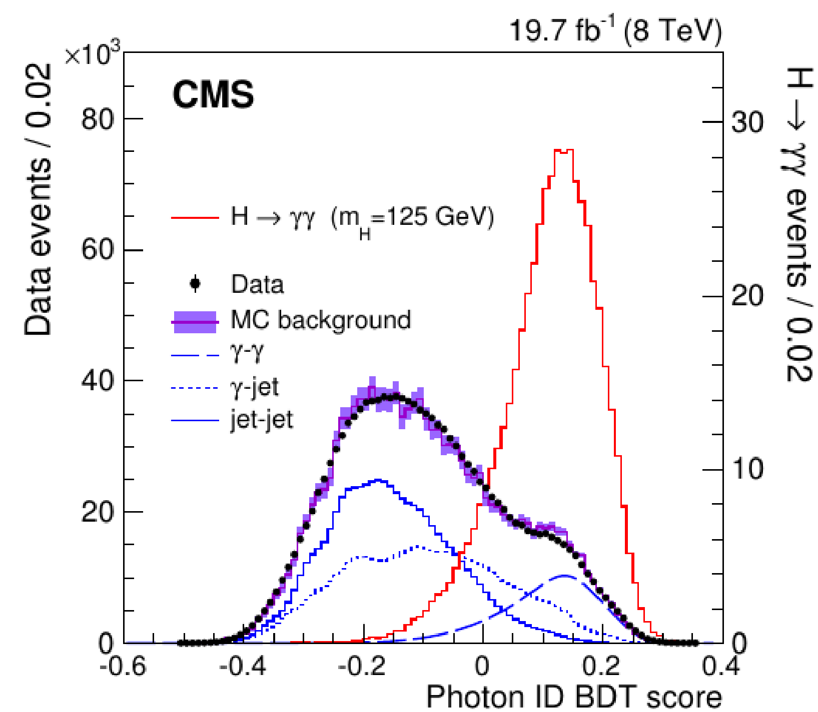
$p_{T1,2}/m_{\gamma\gamma} < 0.35, 0.25$

- Select unconverted, converted photons, veto electrons
- **Photon ID**: cuts on calo cluster shapes, tracks
- **Isolation**
  - $\Sigma\, p_T^{\text{tracks}, \Delta R<0.2} < 2.8$ GeV
  - $\Sigma\, E_T^{\text{clusters}, \Delta R<0.4} < 4$ GeV
- **Efficiency**: 39%
- **Bkg**: 84% γγ, 15% γj, 1% jj

$p_{T1,2}/m_{\gamma\gamma} < 1/3, 1/4$

- Select unconverted, converted photons, veto electrons
- **Photon ID**: calo cluster shapes: loose cuts + included in a BDT
- **Isolation**: based on particle flow objects in ΔR<0.3 cone, included in γ-ID BDT
- **Efficiency**: 49%
- **Bkg**: ~70% γγ





Primary Vertex

Two requirements:

- **Mass resolution**: $m^2 = 2E_1E_2(1 - \cos\alpha)$, and α depends on vertex choice
  - Need only ~1-2cm resolution on z_{vtx} to make this negligible
- **Pileup suppression**: only use tracks from γγ vertex for track isolation, associated jets
  - Needs **the** correct vertex

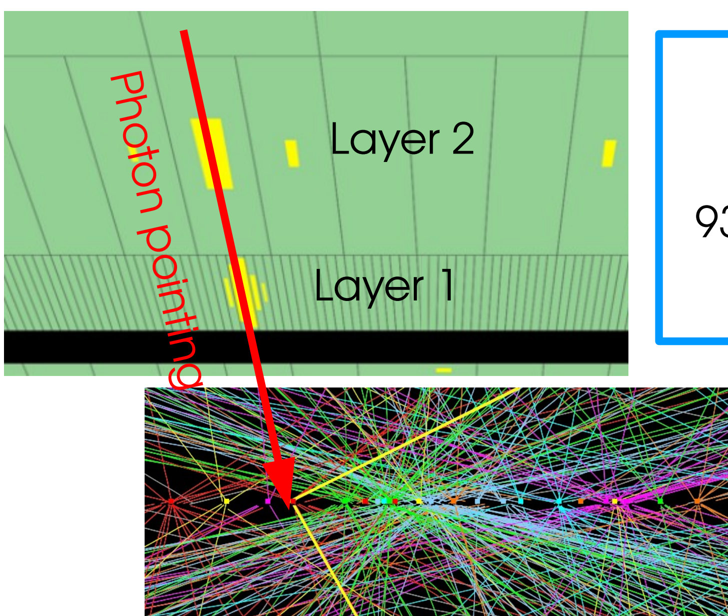
Photon pointing: σ~15 mm : enough for mass

- NN combination using pointing
- per-vertex Σp_T, Σp_T^2, $\Delta\varphi$(tracks, photons)

BDT using per-vertex

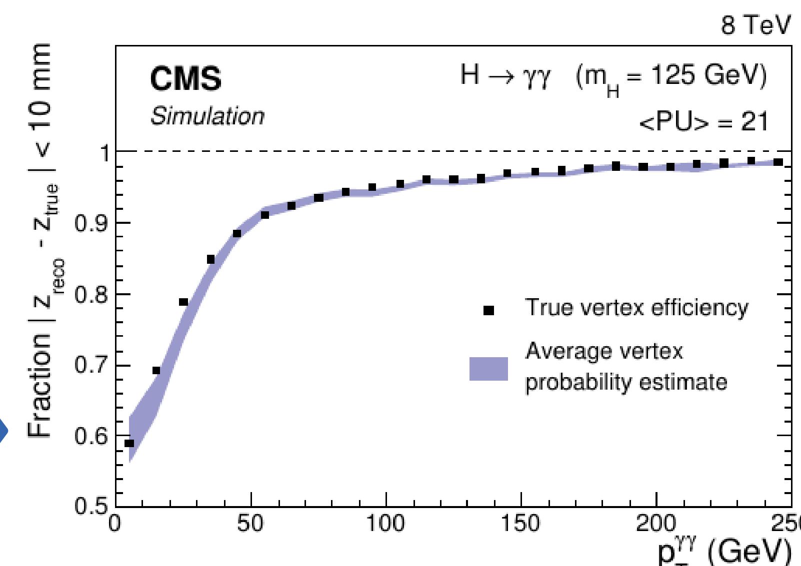
1. $\sum \vec{p}_T^{\,2}$
2. $-\sum(\vec{p}_T \cdot \frac{\vec{p}_T^{\,\gamma\gamma}}{|\vec{p}_T^{\,\gamma\gamma}|})$, and
3. $(|\sum \vec{p}_T| - |\vec{p}_T^{\,\gamma\gamma}|)/(|\sum \vec{p}_T| + |\vec{p}_T^{\,\gamma\gamma}|)$,

- misID prob. included in classification

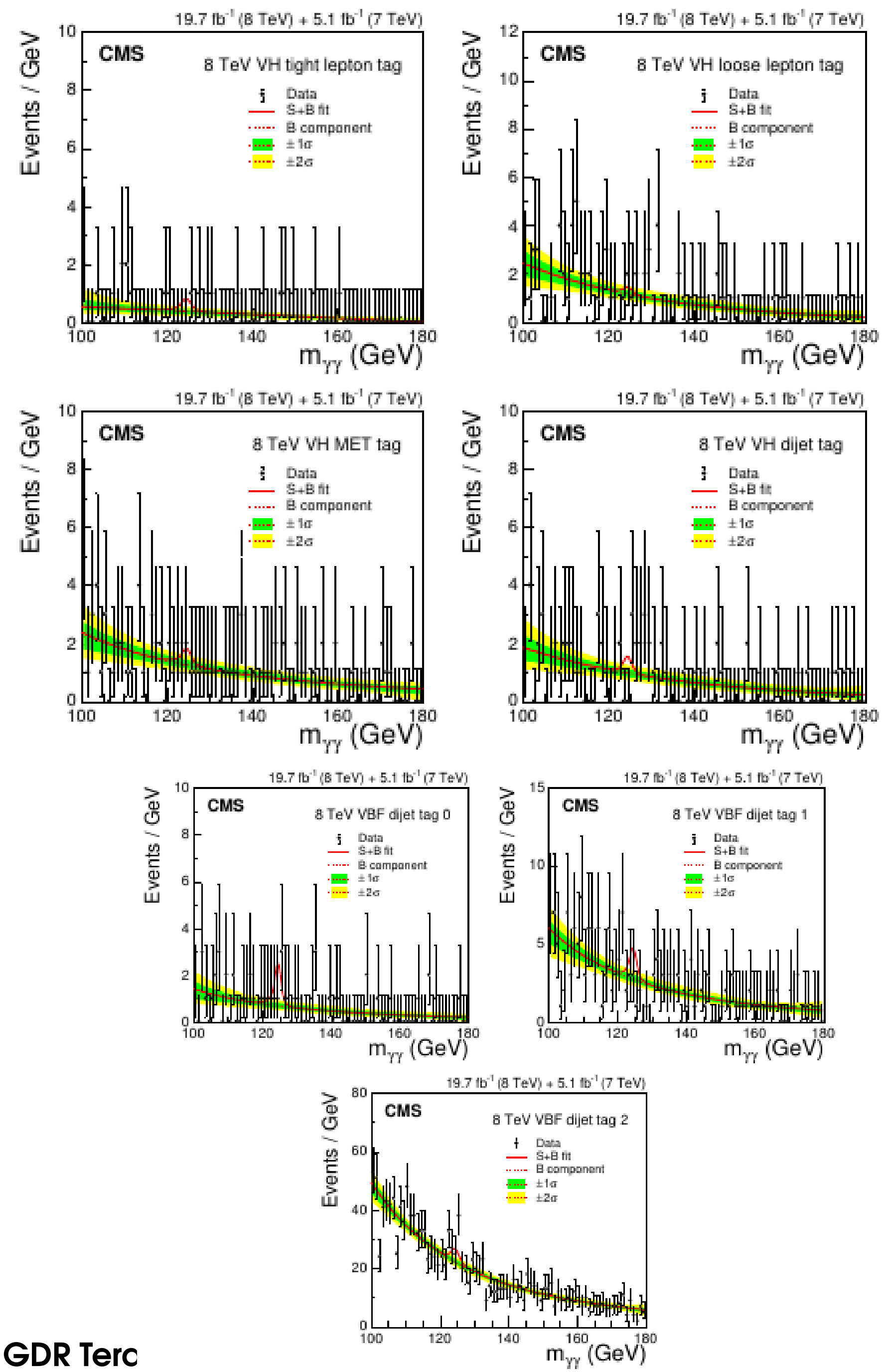


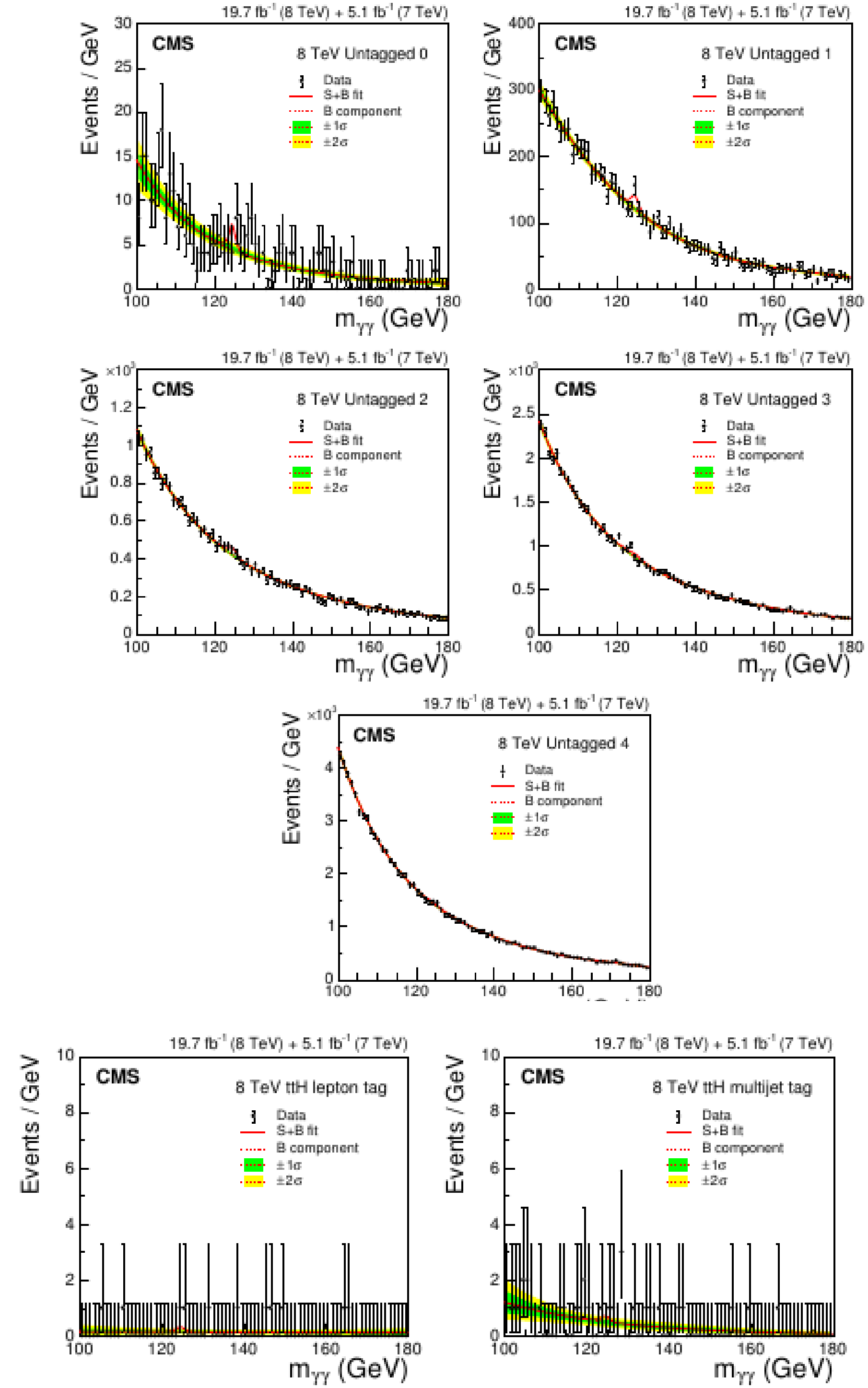
85% of events within 0.3 mm
93% within 10mm
(8 TeV)

80% of events within 10mm
(8 TeV)

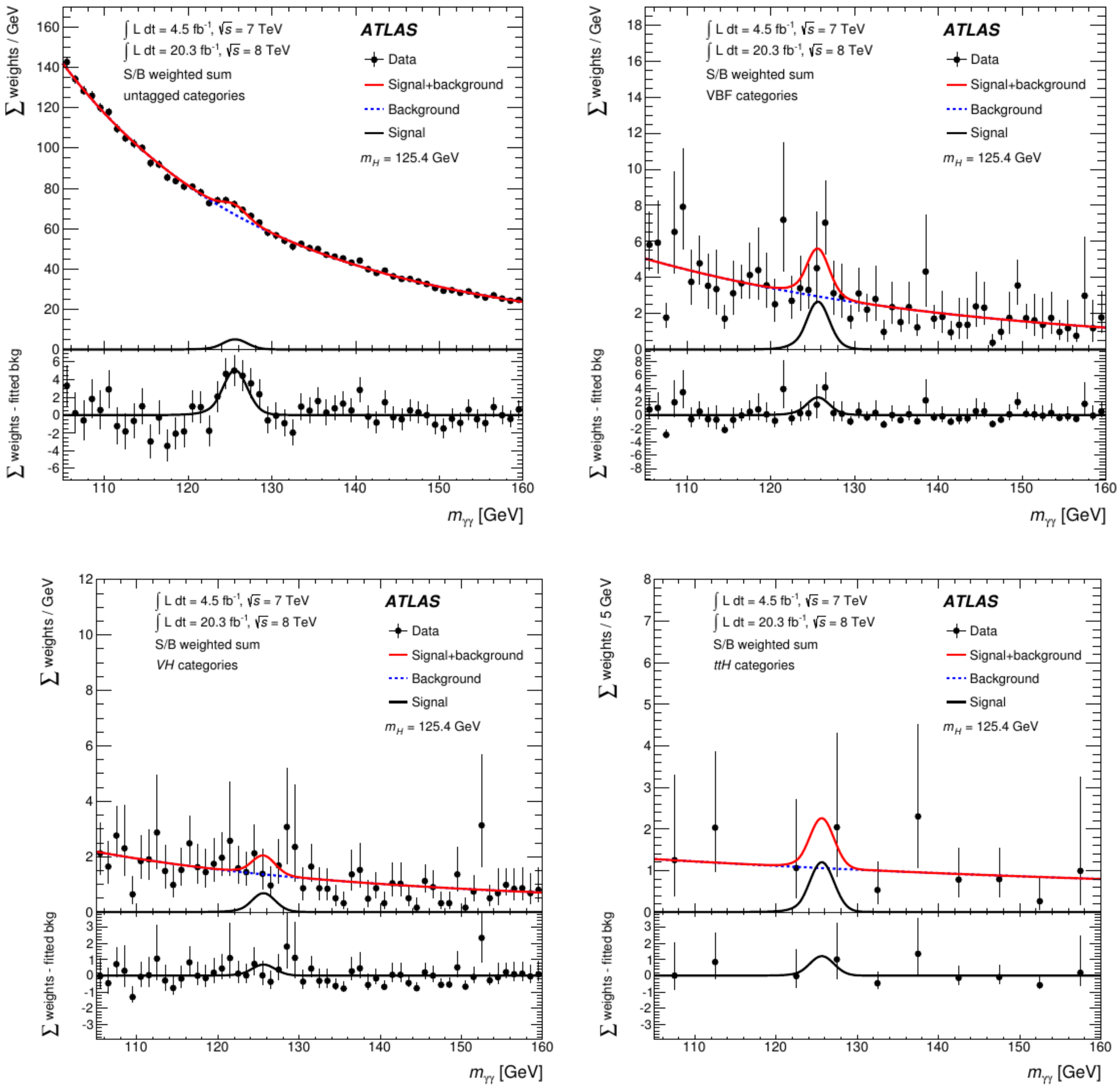


Mass Spectra





Mass Spectra

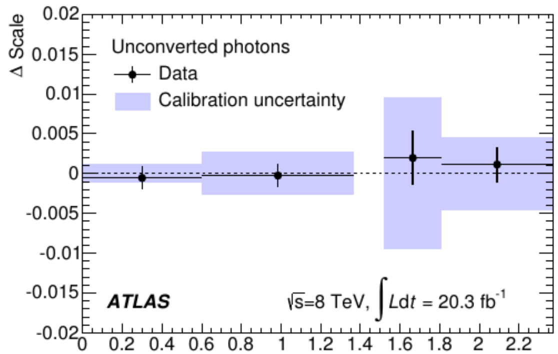


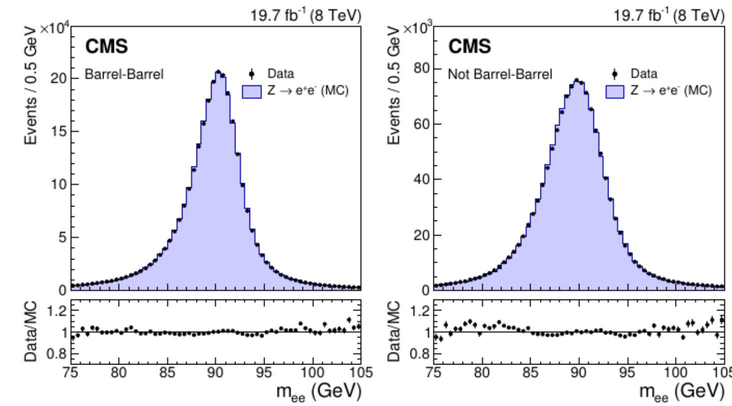
Photon Energy Calibration

Photon energy calibration using MVA – inputs: shower shapes, η...

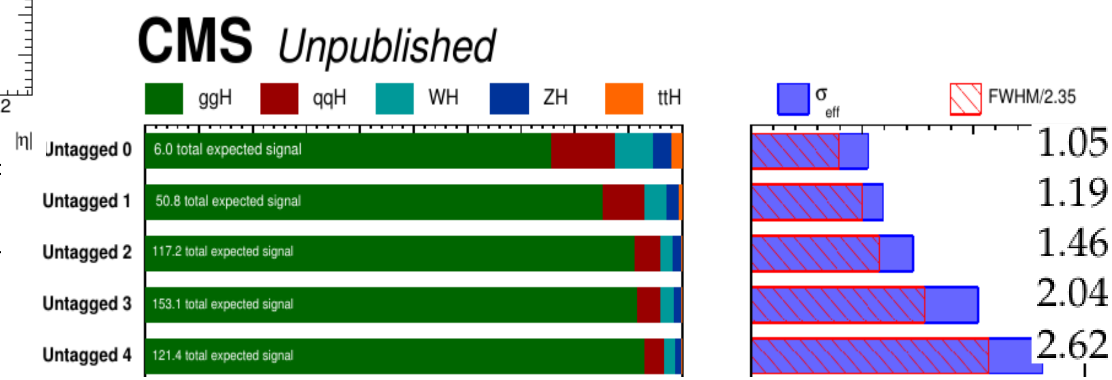
- In-situ adjustment using $Z \to e^+e^-$ peak
  - extrapolate to photons using simulation => need precise knowledge of material
  - extrapolate to Higgs mass => non-linearity

- Photon E calib : Eur. Phys. J. C74 (2014) 10, 3071
- Improved intercalibration of calorimeter layers (to within 1-2%)
- Improved determination of upstream material (to ~5%)
- Effective constant term ~0.7%





Category	$\sqrt{s}$=7 TeV σ_{68} [GeV]	$\sqrt{s}$=7 TeV σ_{90} [GeV]	$\sqrt{s}$=8 TeV σ_{68} [GeV]	$\sqrt{s}$=8 TeV σ_{90} [GeV]
Central - low p_{Tt}	1.36	2.32	1.47	2.50
Central - high p_{Tt}	1.21	2.04	1.32	2.21
Forward - low p_{Tt}	1.69	3.03	1.86	3.31
Forward - high p_{Tt}	1.48	2.59	1.64	2.88



σ_{eff} ~ 1.32-1.86 GeV => ~1.56 GeV

σ_{eff} ~ 1.05-2.62 GeV => ~1.46 GeV

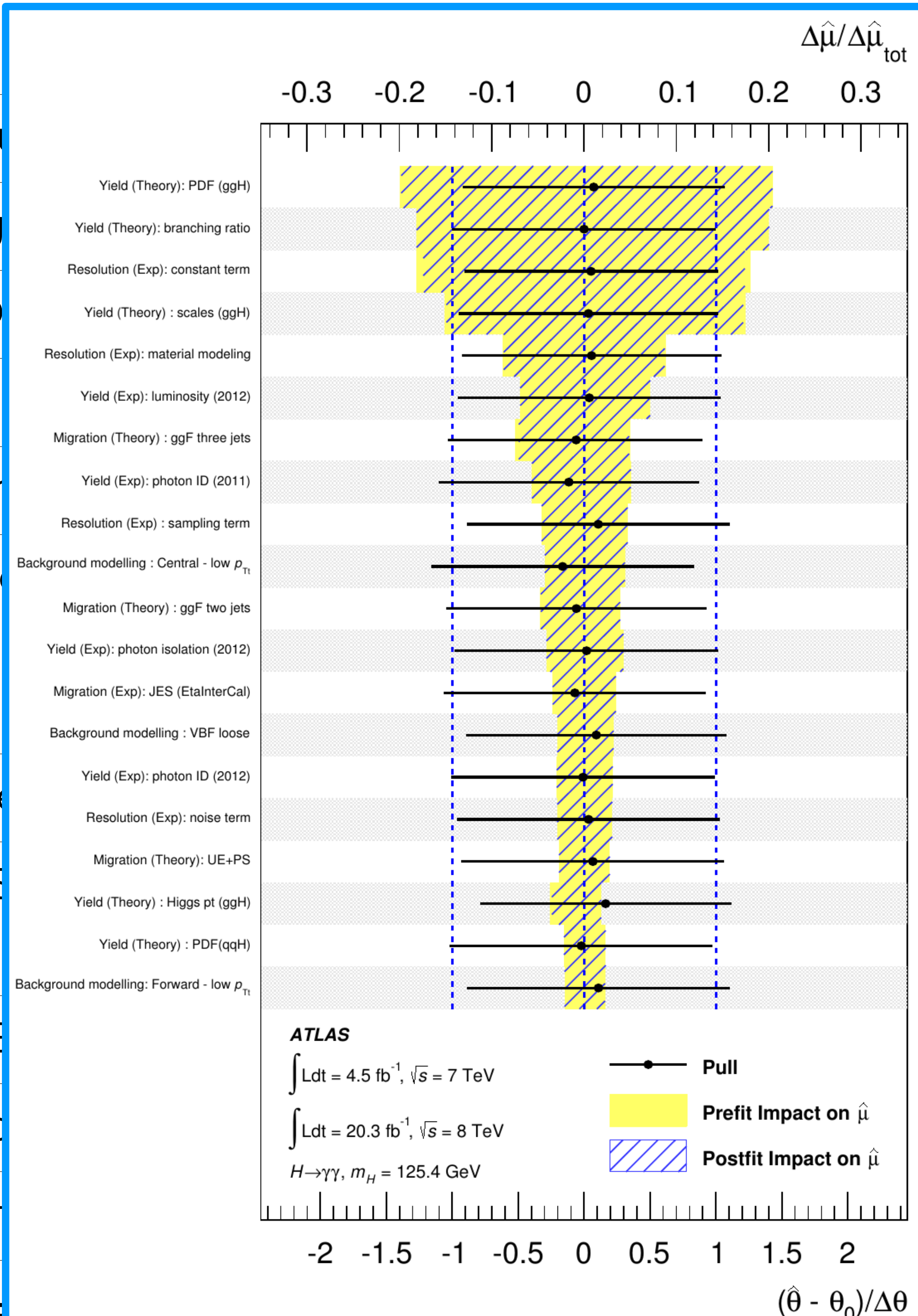
σ_{eff} : smallest interval containing 68% of signal

$$\frac{1}{\overline{\sigma}_{eff}} \sum_{i=1}^{n_{cat}} \frac{S_i^2}{B_i} = \sum_{i=1}^{n_{cat}} \frac{S_i^2}{\sigma_{eff,i} B_i}$$

Signal Yield Systematics

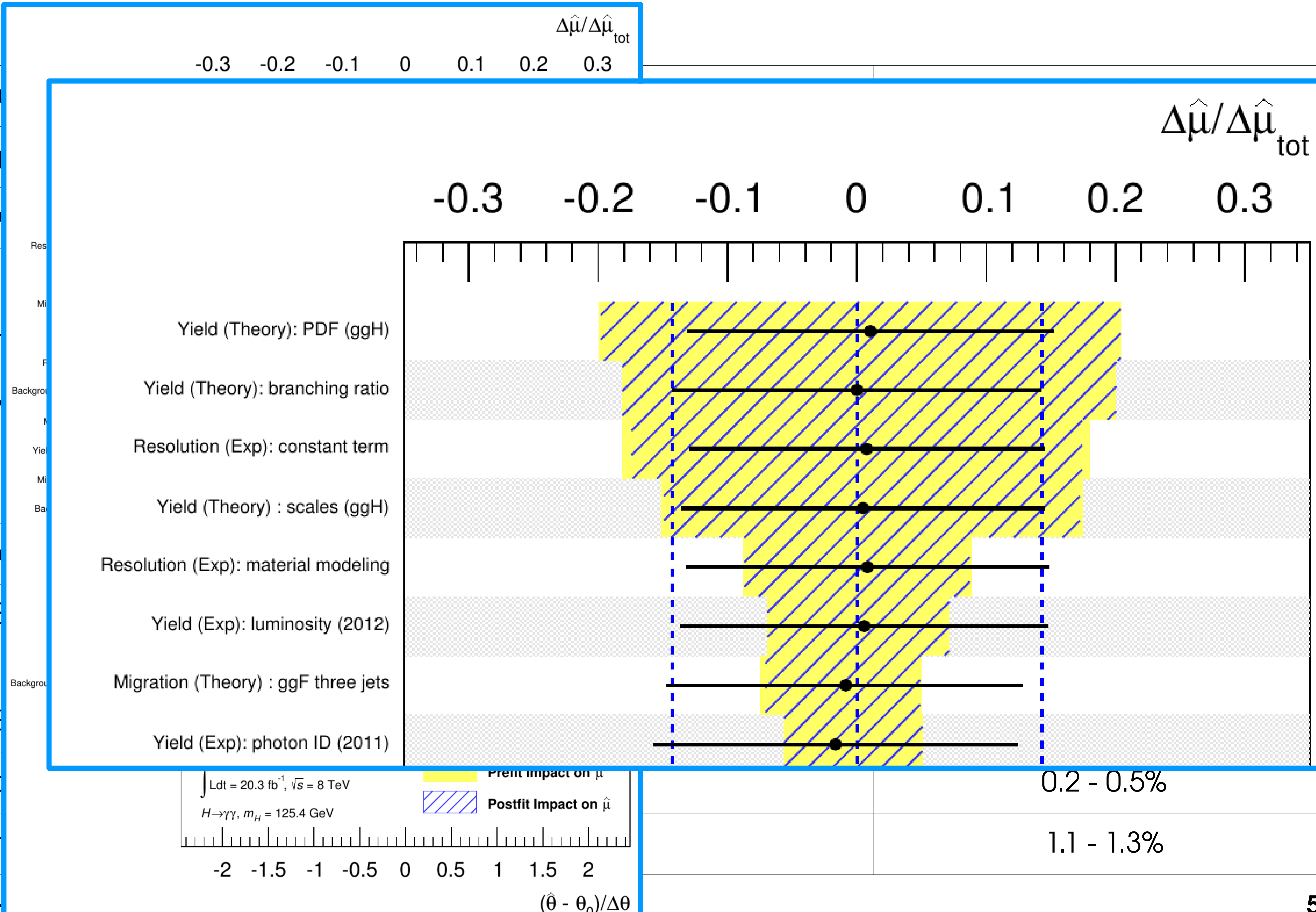
Source	ATLAS	CMS
ggF Theory scale	**-7.8 +7.2%**	
PDF	**-6.9 +7.5%**	
BF	**5%**	
Lumi	2.8%	2.6%
Photon ID	0.2% (trigger) + 1.0% (ID) + (1.3-2.3%) (isol)	1% (trigger) + 1% (vertex finding) **+6% (shower shape model)**
Energy scale, resolution	**7%**	2%
JES/JER	~(0-1)% (ggF), ~(4-9)% (VBF), ~7% (ttH had)	
MET	0.5% (VH-1lep), 1% (VH-MET)	2.6% (WH)
leptons		0.2 - 0.5%
b-tagging		1.1 - 1.3%

Signal Yield Systematics



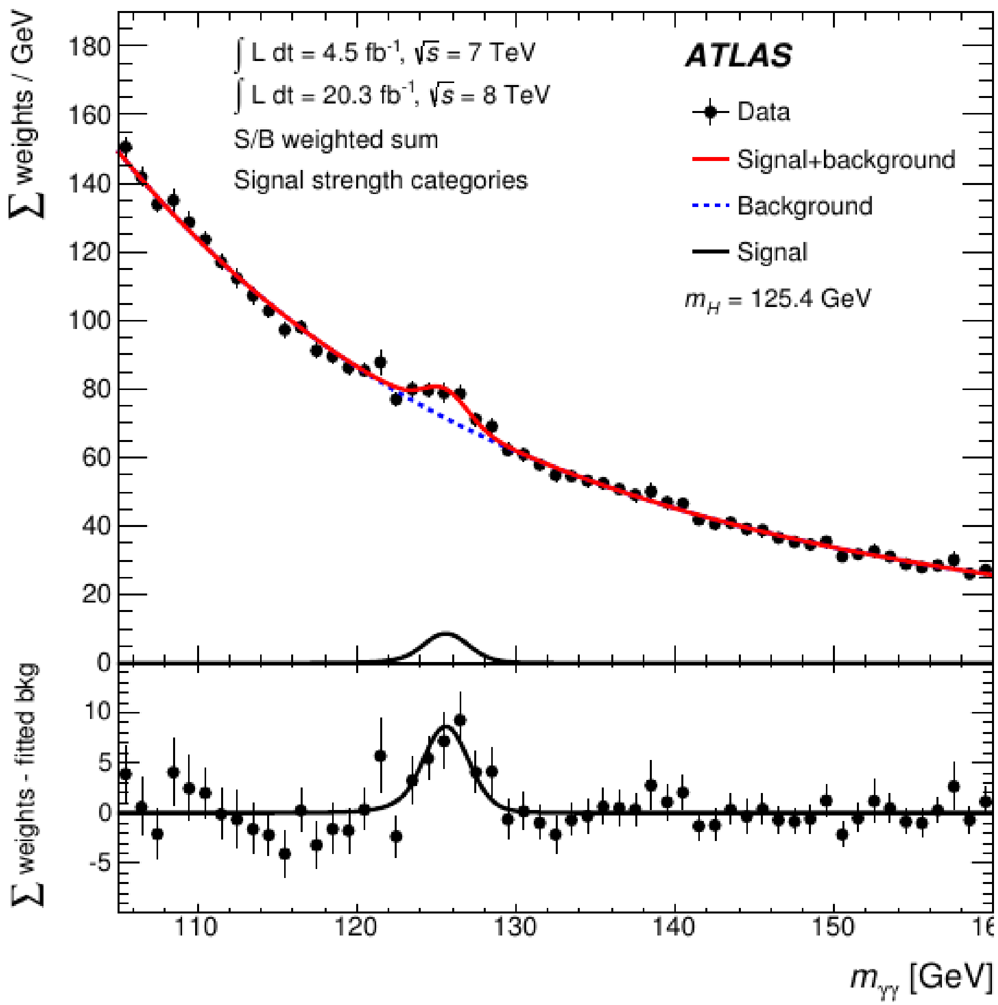
So	LAS	CMS
gg	-7.8 +7.2%	
PD	-6.9 +7.5%	
BF	5%	
Lu	3%	2.6%
Ph	rigger) % (ID) 3%) (isol)	1% (trigger) + 1% (vertex finding) **+6% (shower shape model)**
En	%	2%
JES	~(4-9)% (VBF), H had)	
ME	), 1% (VH-MET)	2.6% (WH)
lep		0.2 - 0.5%
b-t		1.1 - 1.3%

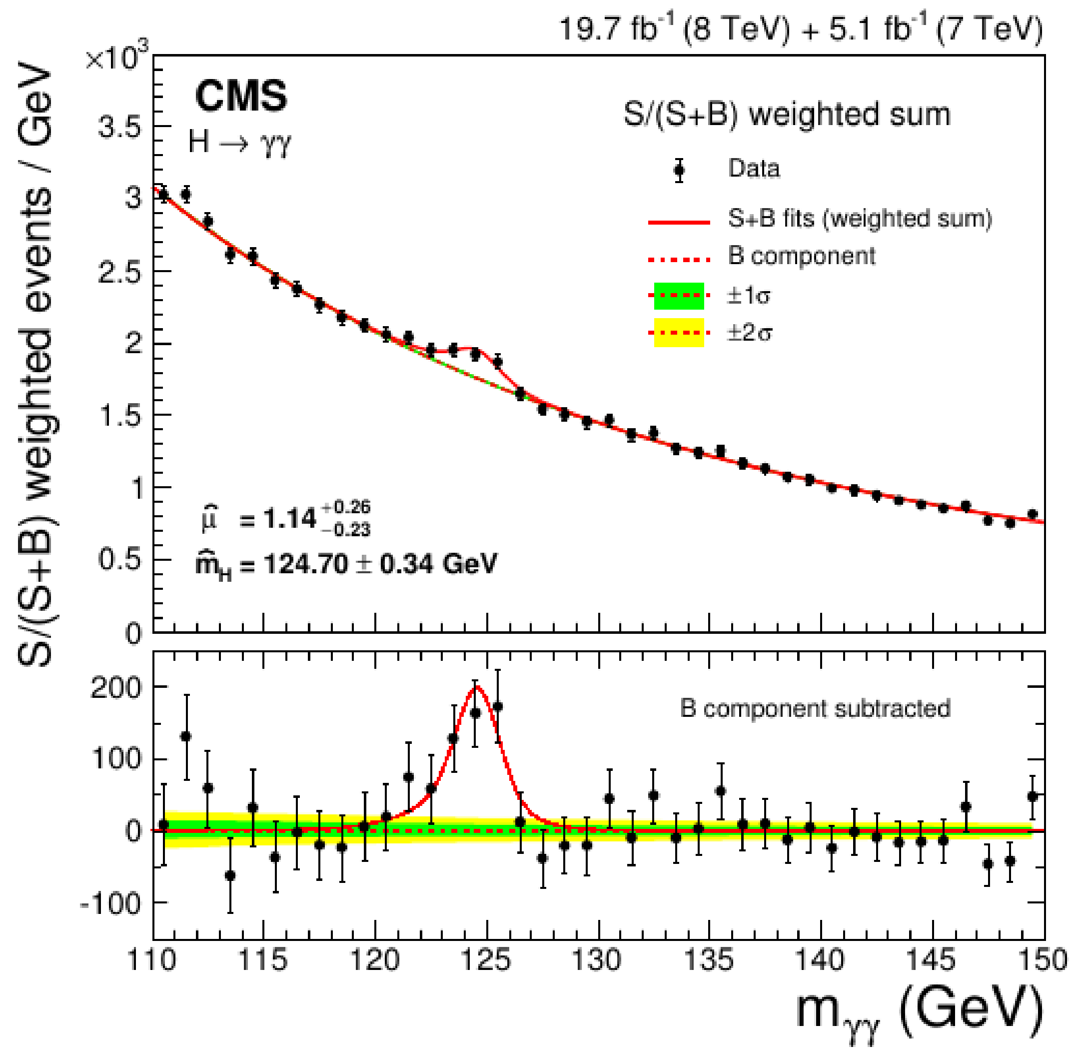
Signal Yield Systematics



Sou	
gg	
PD	
BF	
Lur	
Ph	
Ene	
JES	
ME	
lep	0.2 - 0.5%
b-t	1.1 - 1.3%

Mass Spectra



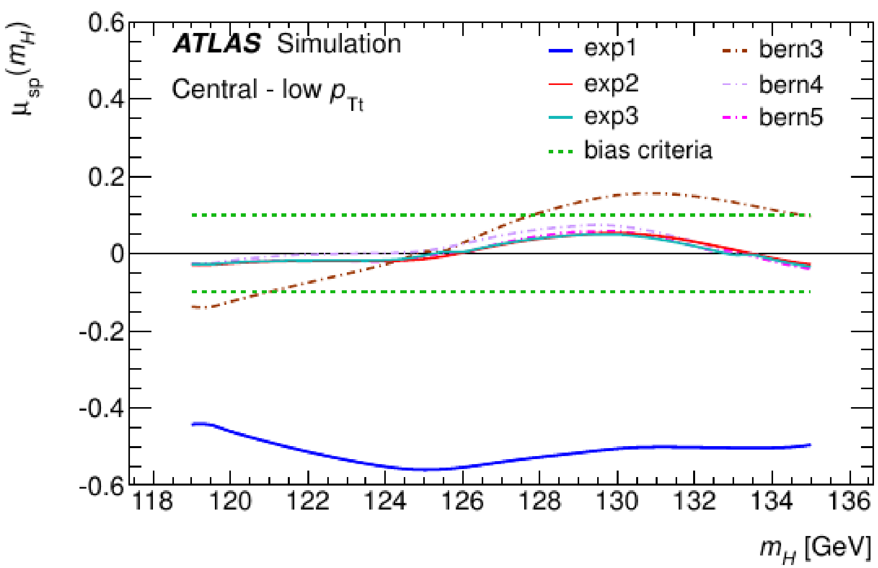


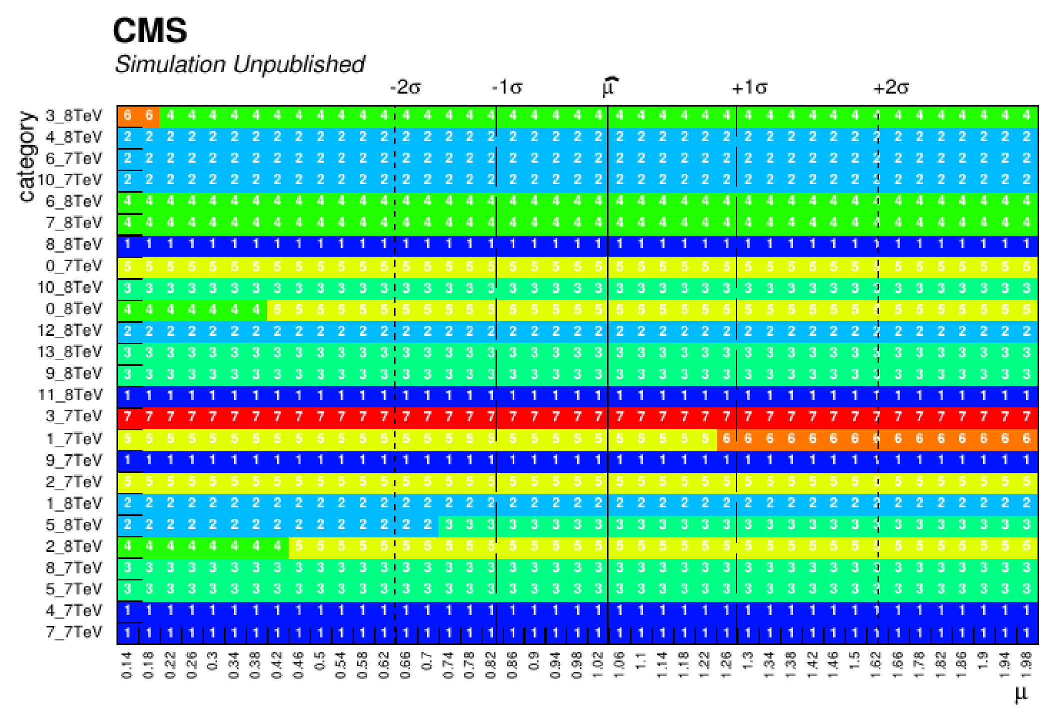
Data modeling

Use closed-form analytic shapes to describe both signal and background

- Fit range $100 < m_{\gamma\gamma} < 160$ GeV
- Signal: Crystal Ball + Gaussian
- Background
  - Shapes: Bernstein polynomials, exp, exp(poly2)
  - measure bias on high-stats bkg MC (max over (119, 135) GeV)
    - Select function with least N_{dof} passing bias criteria : <10% of N_{sig}, <20% of $\sigma_{stat}(N_{sig})$

- Fit range $100 < m_{\gamma\gamma} < 180$ GeV
- Signal: Sum of Gaussians (up to 5)
- Background
  - Shapes: Bernstein polynomials, exp, power laws, Laurent terms
  - "Discrete Profiling" : choice of functional form done as part of the fit
    - Select best-fit function, penalty for N_{dof}





Data modeling

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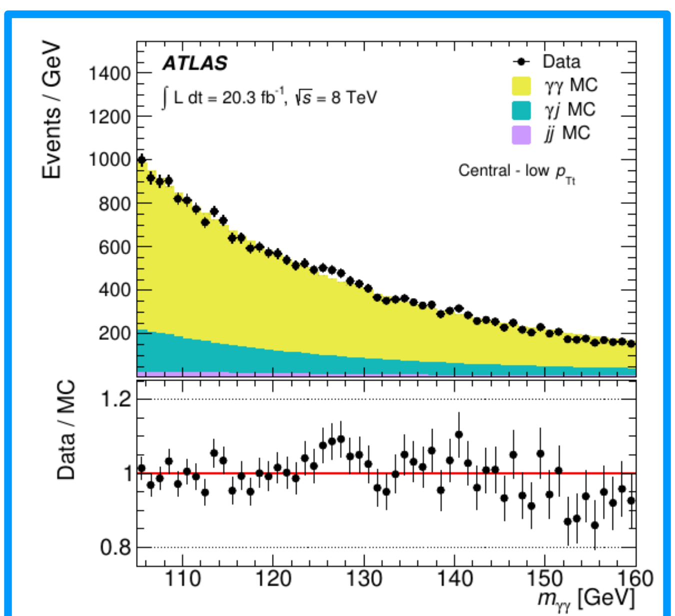
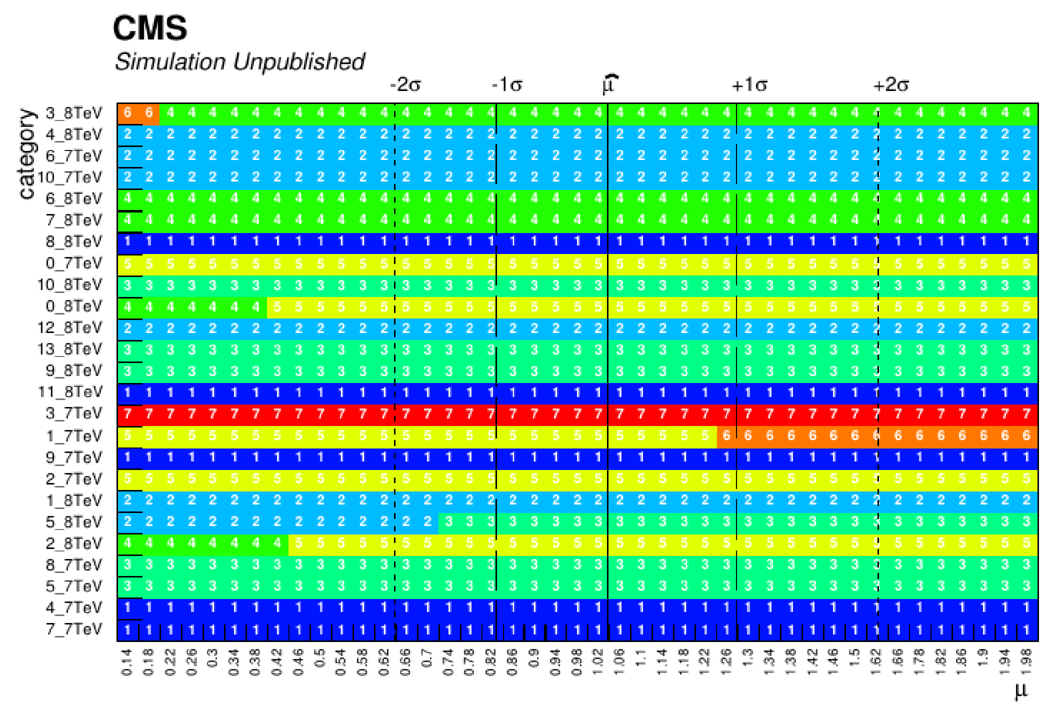
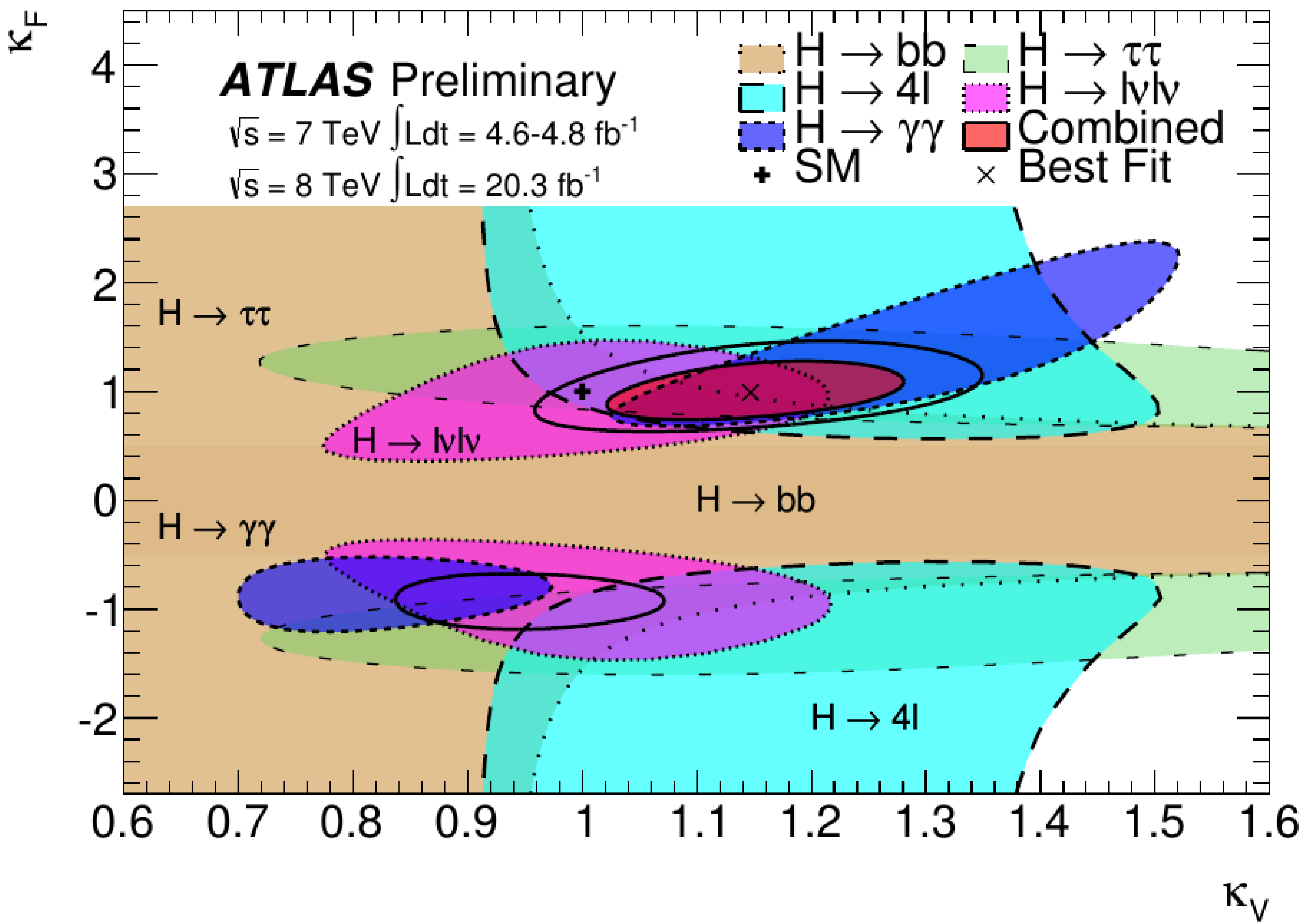




ATLAS Couplings (to be updated)

ATLAS-CONF-2014-009



$HH \to bb\gamma\gamma$

- Search for BSM enhancement in $bb\gamma\gamma$ **final state : clear $\gamma\gamma$ signature + high bb BR**
- 2 b-tags, m_{bb} mass window cut around 125 GeV.

arXiv:1406.5053, submitted to PRL

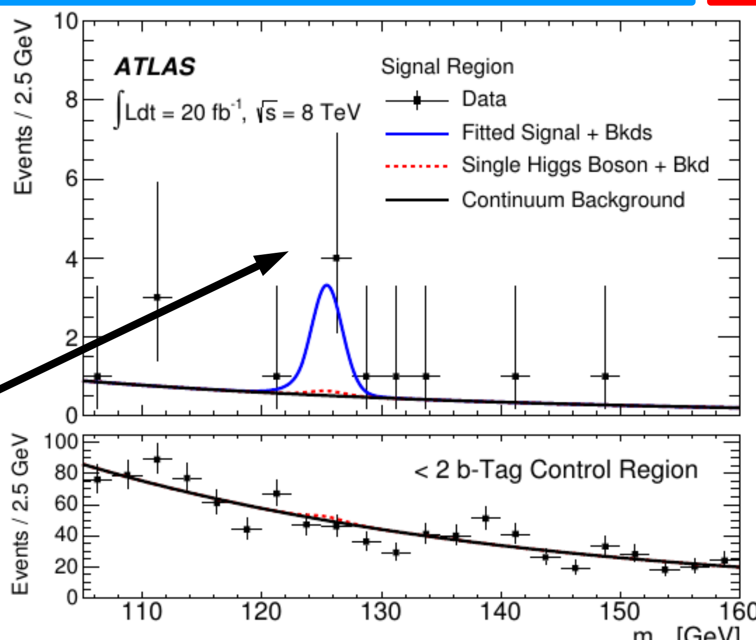
- **Non-resonant HH : similar technique to $H \to \gamma\gamma$**
- **Resonance** ($X \to HH$): counting analysis in $m_{bb\gamma\gamma}$
  - Cut on $m_{\gamma\gamma}$, m_{bb}, consider 260 < $m_{bb\gamma\gamma}$ < 500 GeV
  - Rescale m_{bb} to 125 GeV to compute $m_{bb\gamma\gamma}$
  - Assume SM BRs for H
  - Bkg from $m_{\gamma\gamma}$ sidebands and non-b-tagged CRs

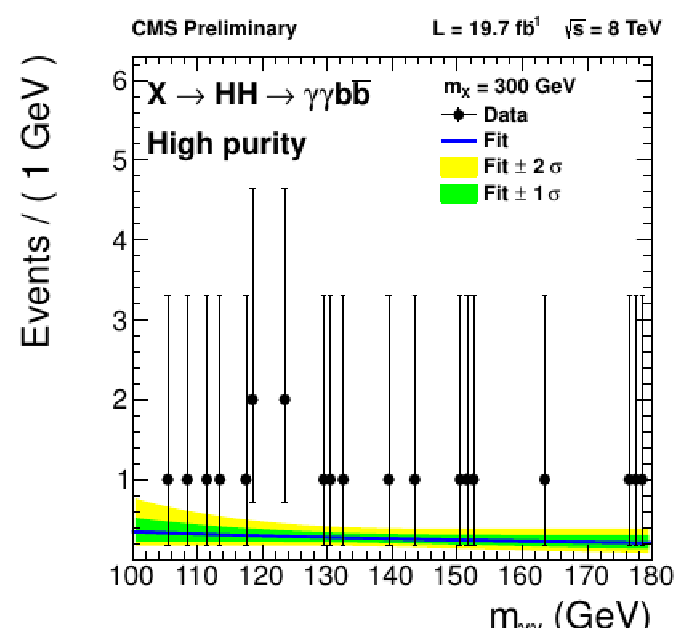
CMS-PAS-HIG-13-032

- **Resonant analysis only**
  - Consider 260 < $m_{bb\gamma\gamma}$ < 1100 GeV
  - Use kinematic fit to constrain m_{bb}
  - Shape analysis >400 GeV (C&C below)
  - Categories in N_{btags}
  - **~50% better sensitivity**, mainly due to looser bjet cuts (p_T>25 vs. 55/35 GeV)

Non-Resonant
σ < 2.2 pb
@ 95% CL
(1.0 expected)

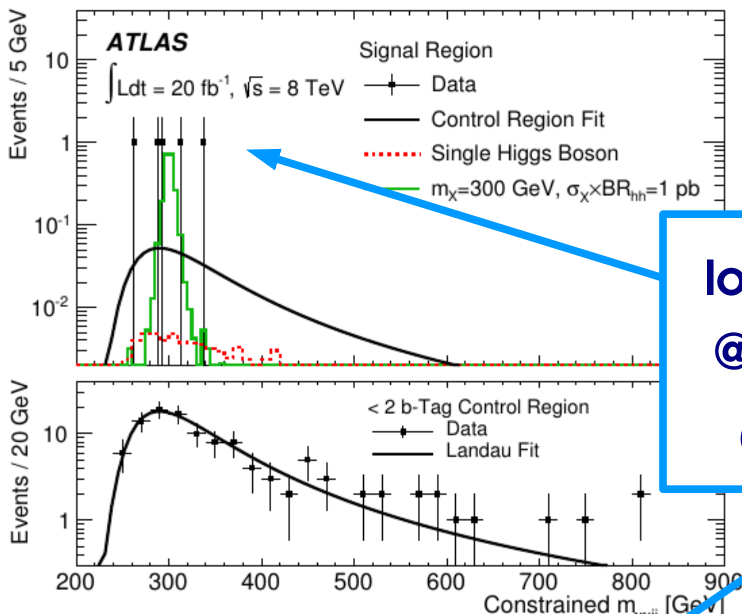
2.4σ excess



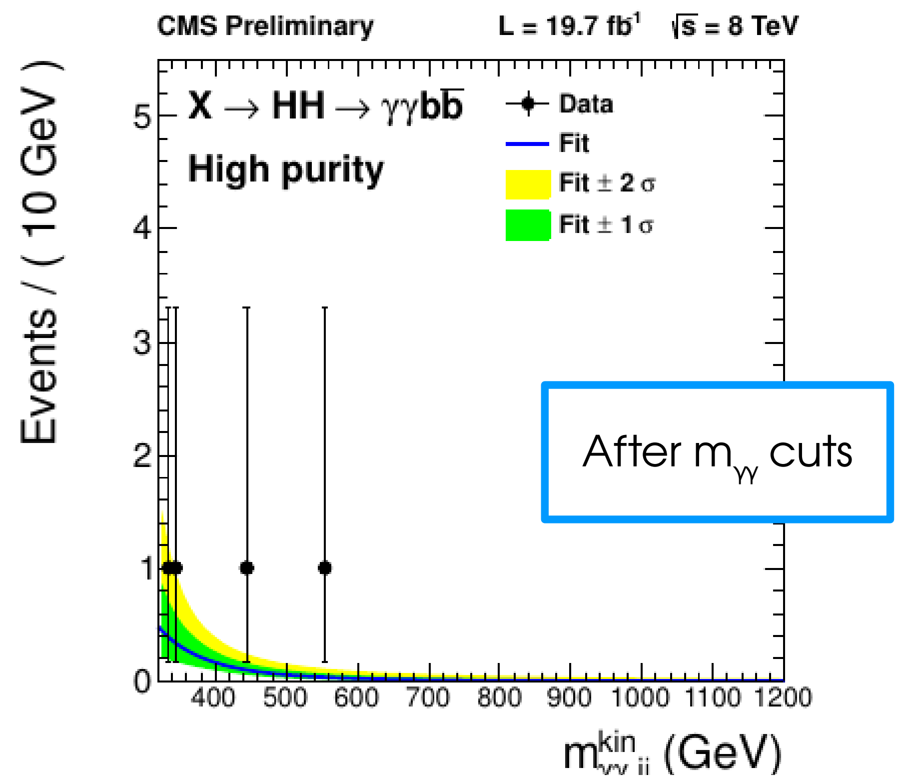


HH→bbγγ

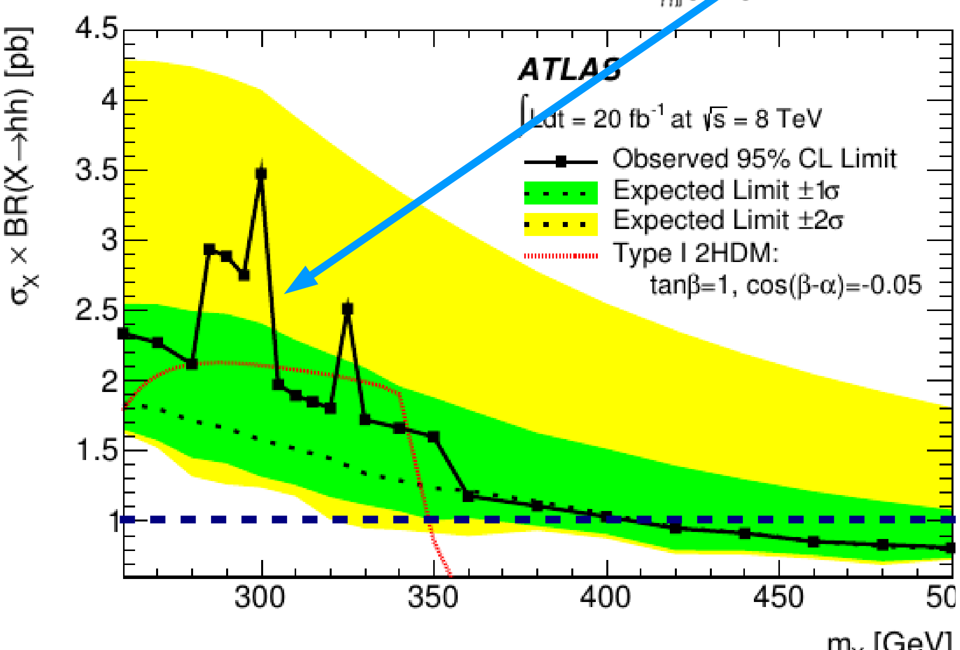
Resonance Search

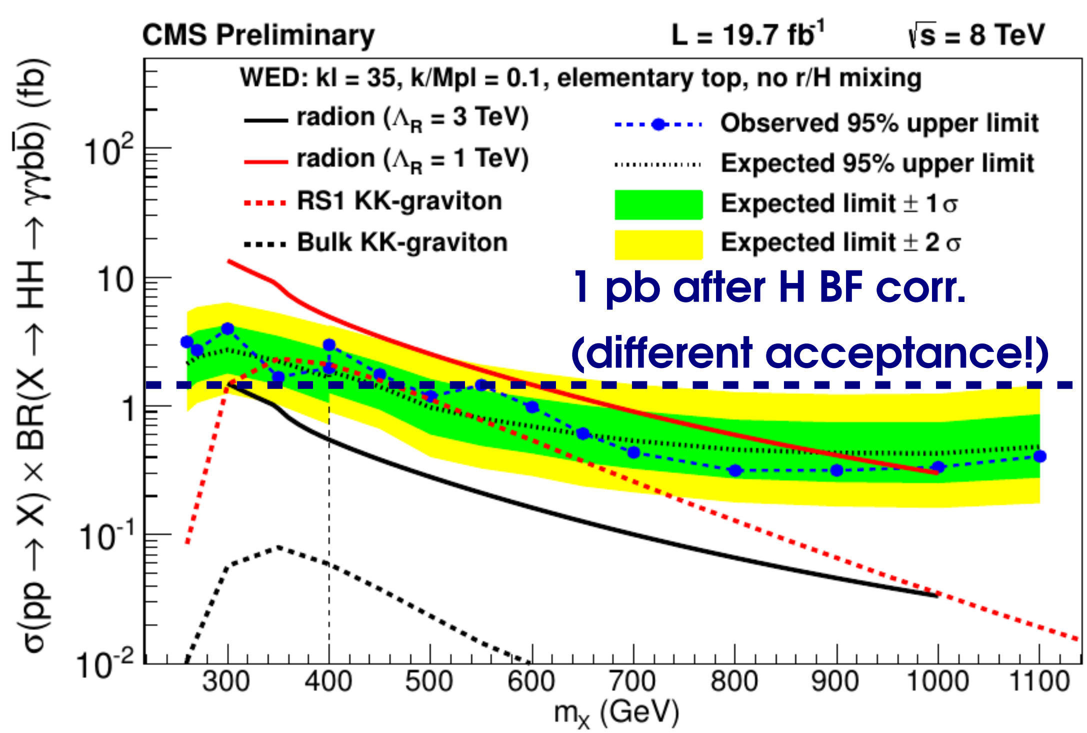


local 3σ excess @ m_X=300 GeV (2.1σ global)



After $m_{\gamma\gamma}$ cuts





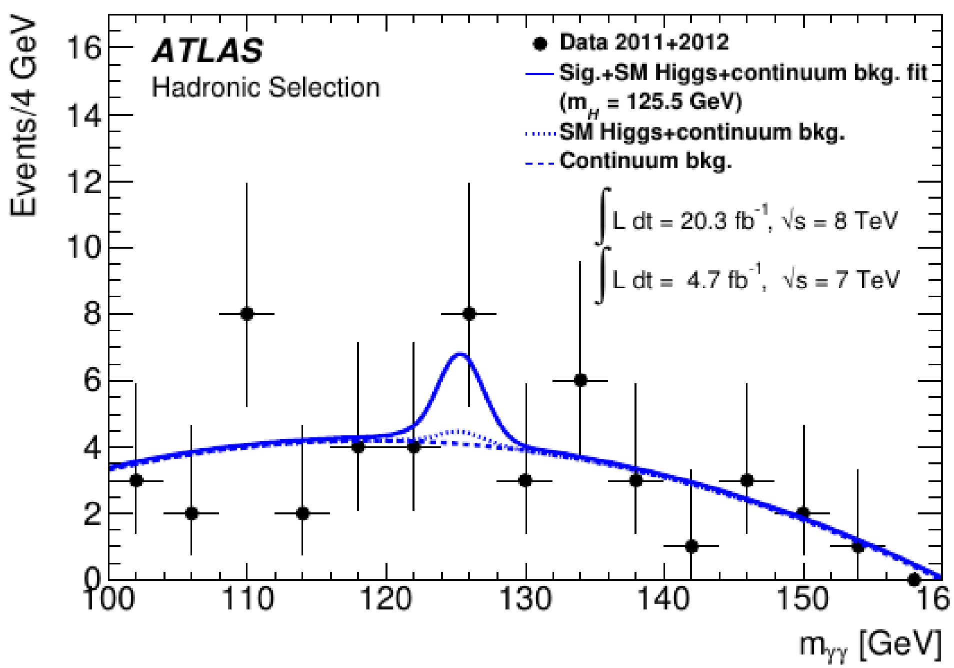
1 pb after H BF corr.

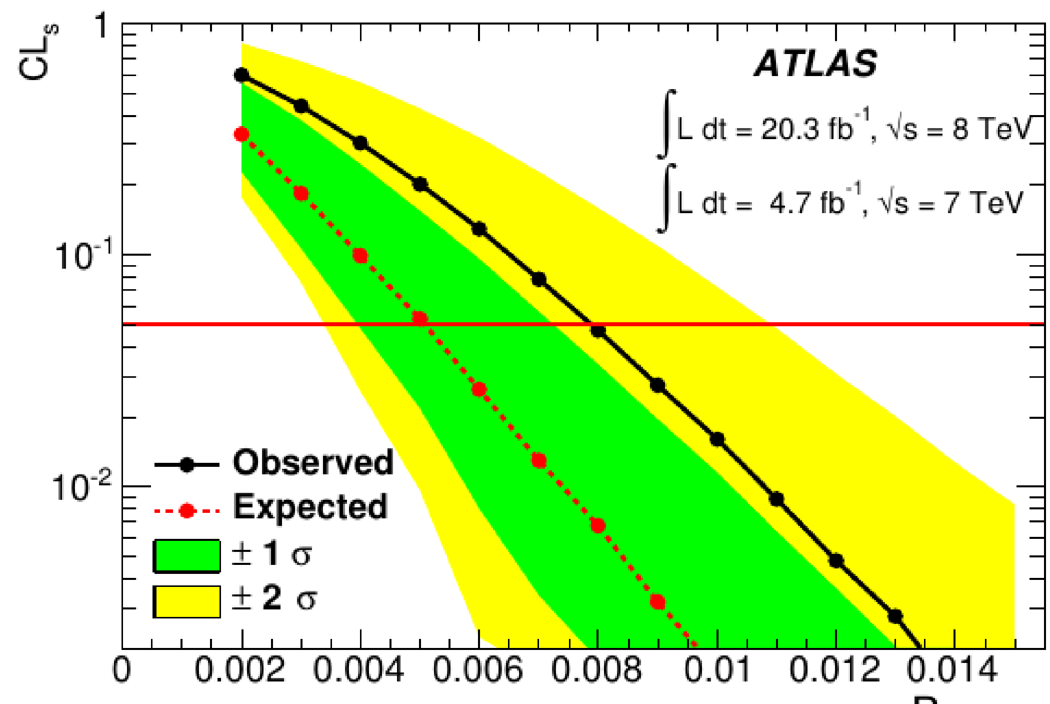
(different acceptance!)

ATLAS t→qH

JHEP 1406 (2014) 008

- Search for FCNC decay t→qH, mainly for q=c but also sensitive to q=u.
  - BF(t→cH) ~ 10^{-3} - 10^{-5} possible in some BSM models.
- Use H→γγ : clean signal, can use sidebands to remove bkg
- Selection
  - **Hadronic channel**: ≥ 4 jets, ≥ 1 b-tag, = 0 lepton, top candidates from γγj and jjj.
  - **Leptonic channel**: ≥ 2 jets, ≥ 1 b-tag, = 1 lepton, tops from γγj and jlν (M_W constraint)





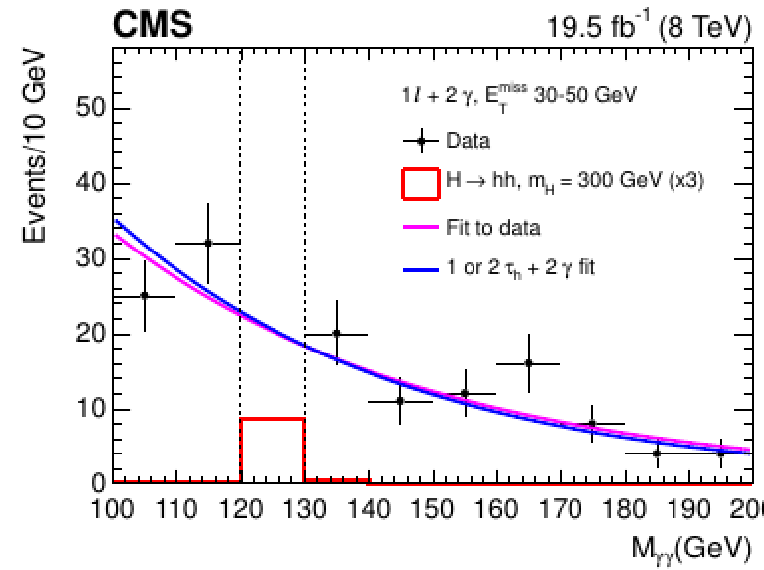
BF(t→qH) < 0.79% @ 95% C.L. (0.51% expected) $\sqrt{\lambda_{tcH}^2 + \lambda_{tuH}^2} < 0.17$ (0.14 expected)

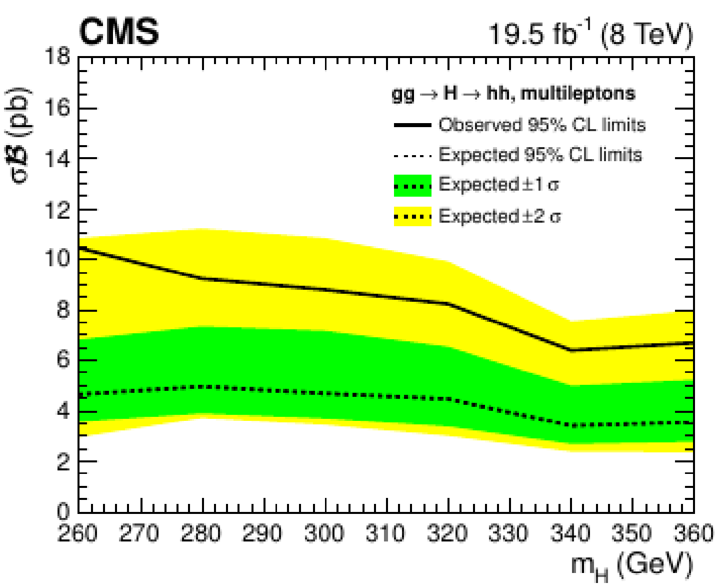
CMS ($H\to\gamma\gamma$) l(l)

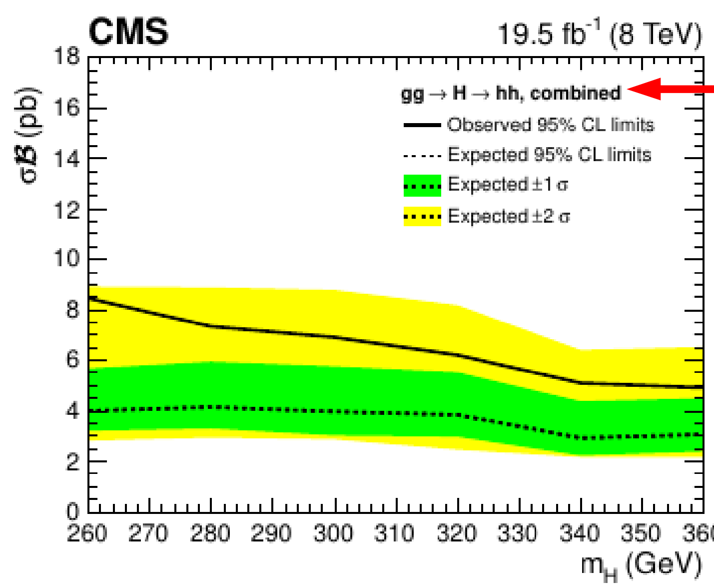
arXiv:1410.2751, submitted to PRD

Search for **H→hh** and **t→cH** in (H→γγ) l(l) signatures

- $120<m_{\gamma\gamma}<130$ GeV, use sideband to subtract bkg.
- Consider γγ ll, γγ lτ_h, γγ l, γγ τ_h with l=e,μ
- γγll : separate according to OSSF 2l pairs to mitigate Z→ll :
  0 OSSF, 1 OSSF off-Z, 1 OSSF on-Z
- γγl/τ_h : separate 0/1 b-tag
- MET bins in both cases







No standalone γγ H→hh result

Shown here combined with multilepton channel

BF(t→cH) < 0.56% @ 95% C.L. (0.65% expected)

$$\sqrt{|\lambda^{\rm h}_{\rm tc}|^2 + |\lambda^{\rm h}_{\rm ct}|^2} < 0.14.$$

Low/High-Mass Search

Phys Rev Lett. 113 (2014) 171801

CMS-PAS-HIG-14-006

Model-independent search for narrow resonances – report a fiducial cross-section

Separate analyses for

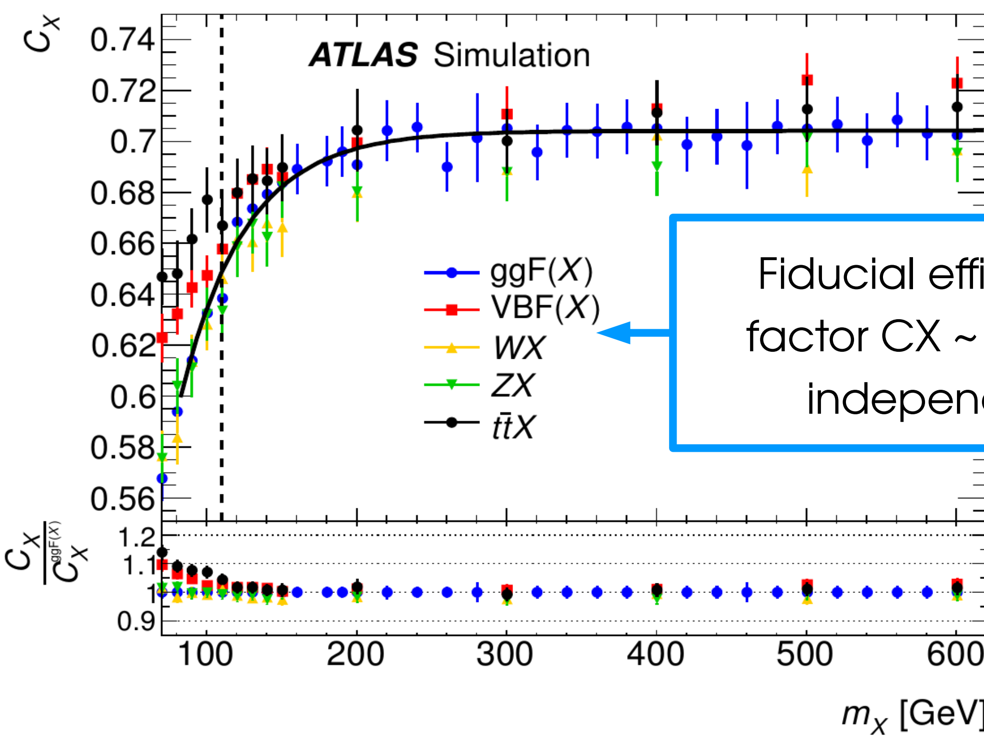
- low-mass $60 < m_X < 100$ GeV,
- high-mass $100 < m_X < 600$ GeV
- only conversion categories (UU/CU/CC) in low-mass region for model-independence.

Need to model DY bkg in low-mass region

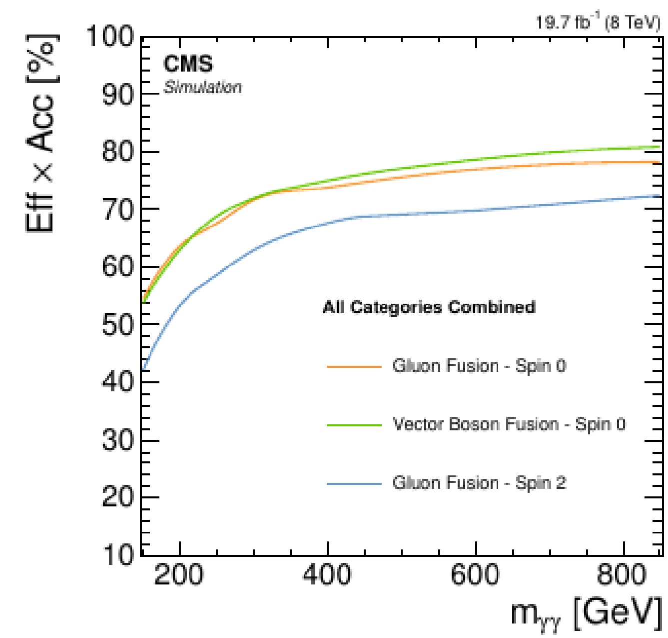
Search for new Higgs-like resonances, within $150 < m_X < 850$ GeV

Consider various width hypotheses

cat 0	Both photons in barrel	$\min(R_9) > 0.94$
cat 1	Both photons in barrel	$\min(R_9) < 0.94$
cat 2	One or more in endcap	$\min(R_9) > 0.94$
cat 3	One or more in endcap	$\min(R_9) < 0.94$

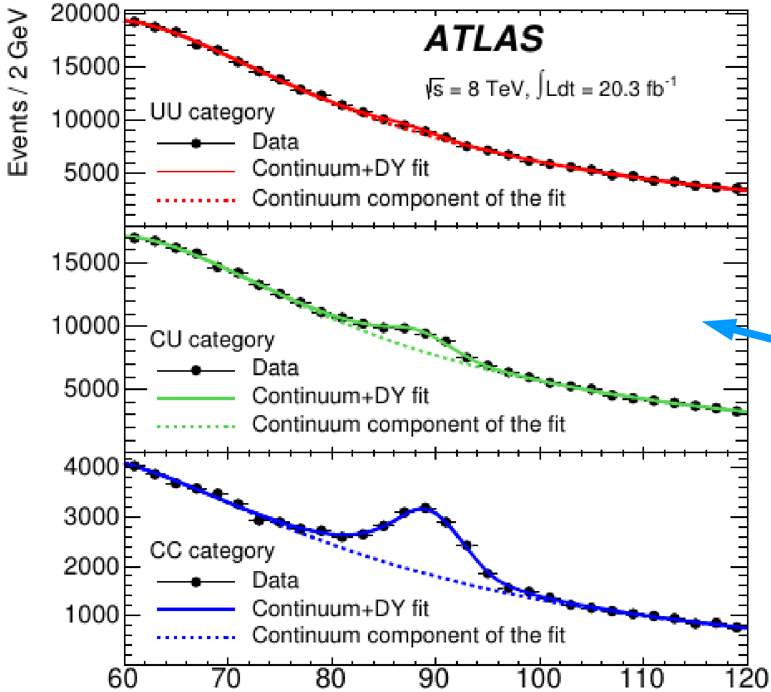


Fiducial efficiency factor CX ~ model-independent

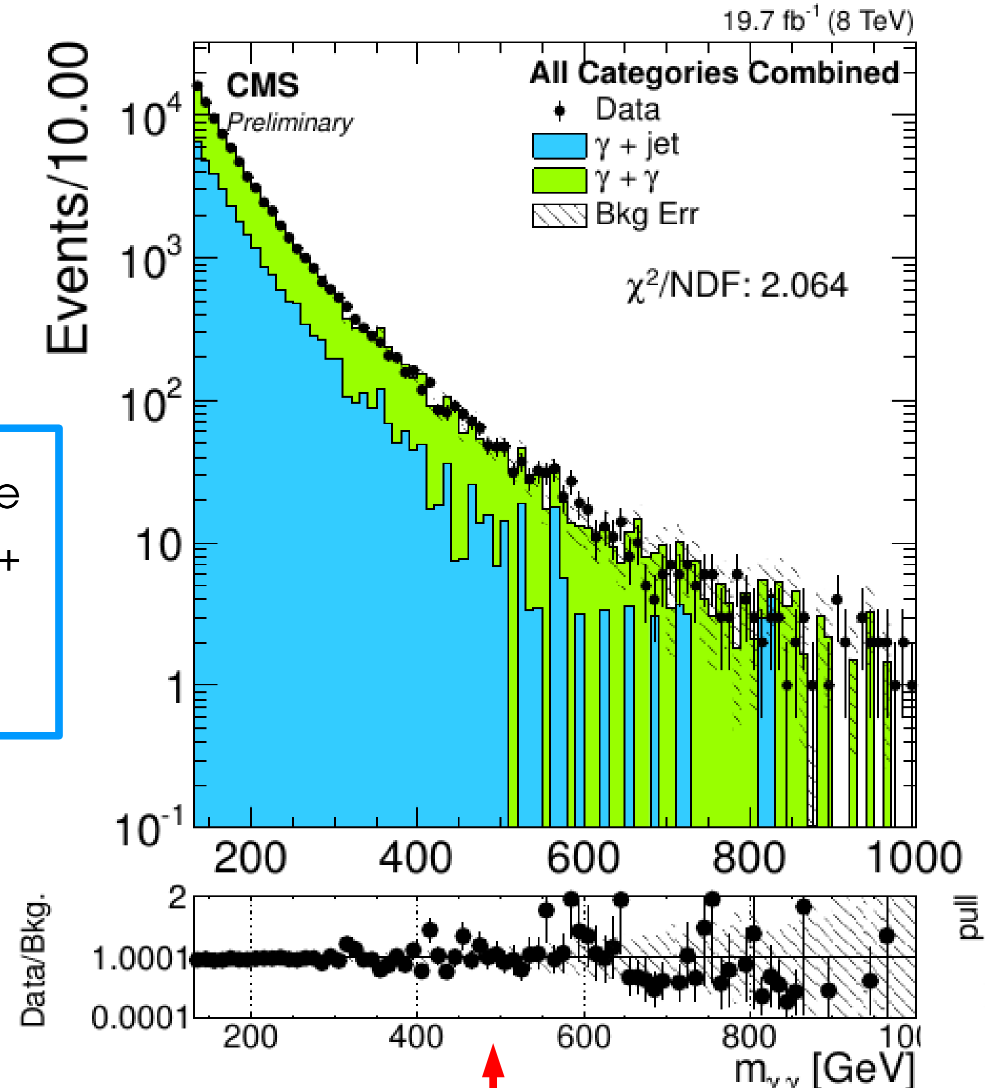


high efficiency achieved, ~60-80%

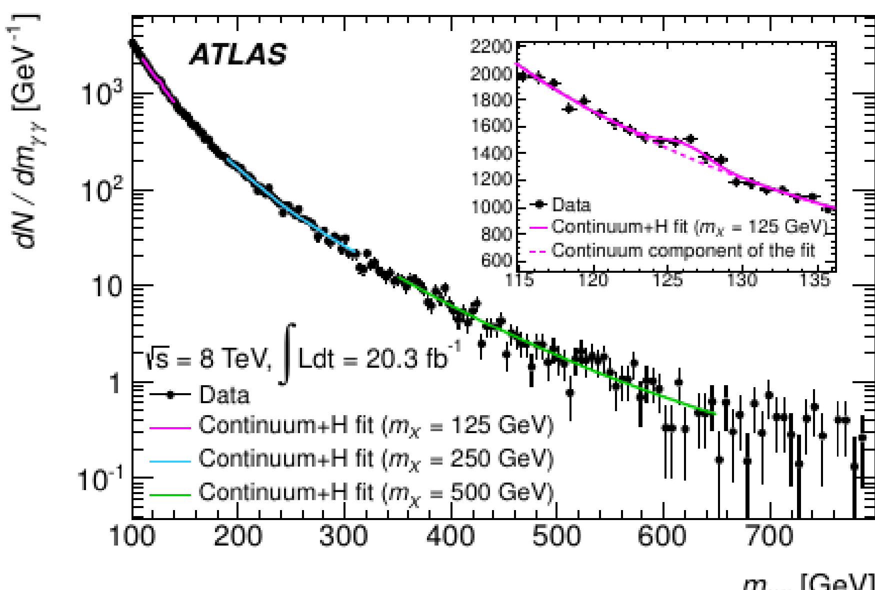
Low/High-Mass Spectra



Low-mass: use DY templates + continuum (Landau+exp)

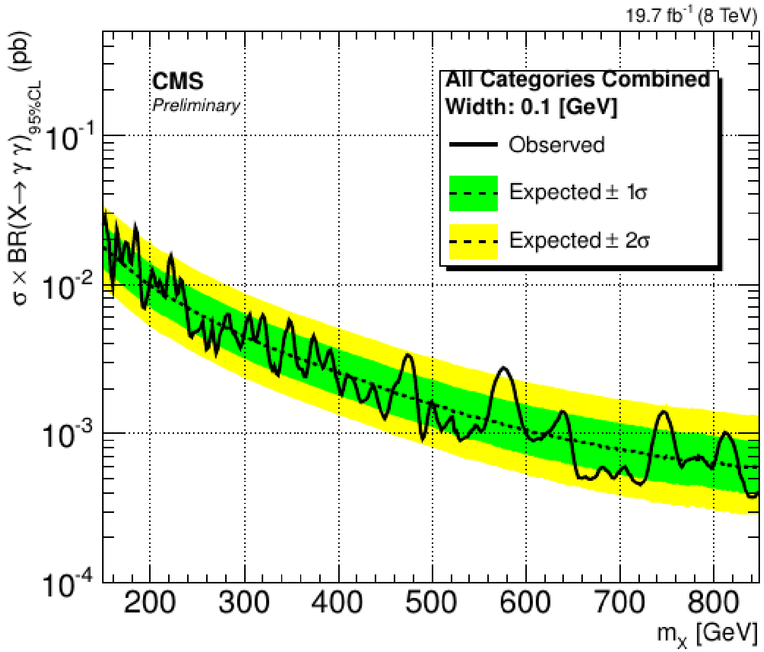


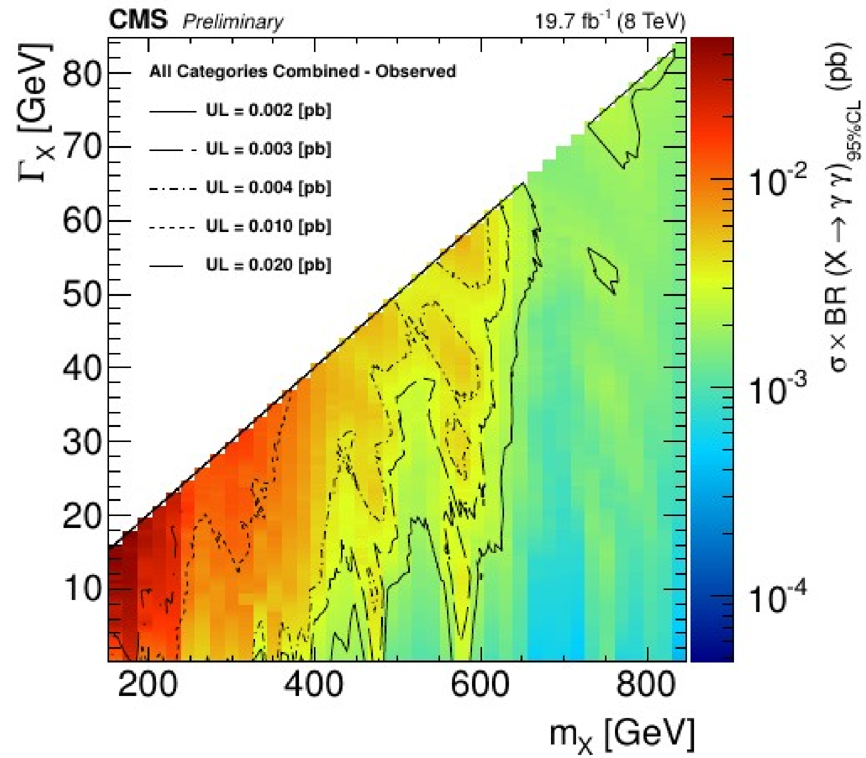
Fit within sliding window, size~300-400 GeV
use exp x power-law bkg shape

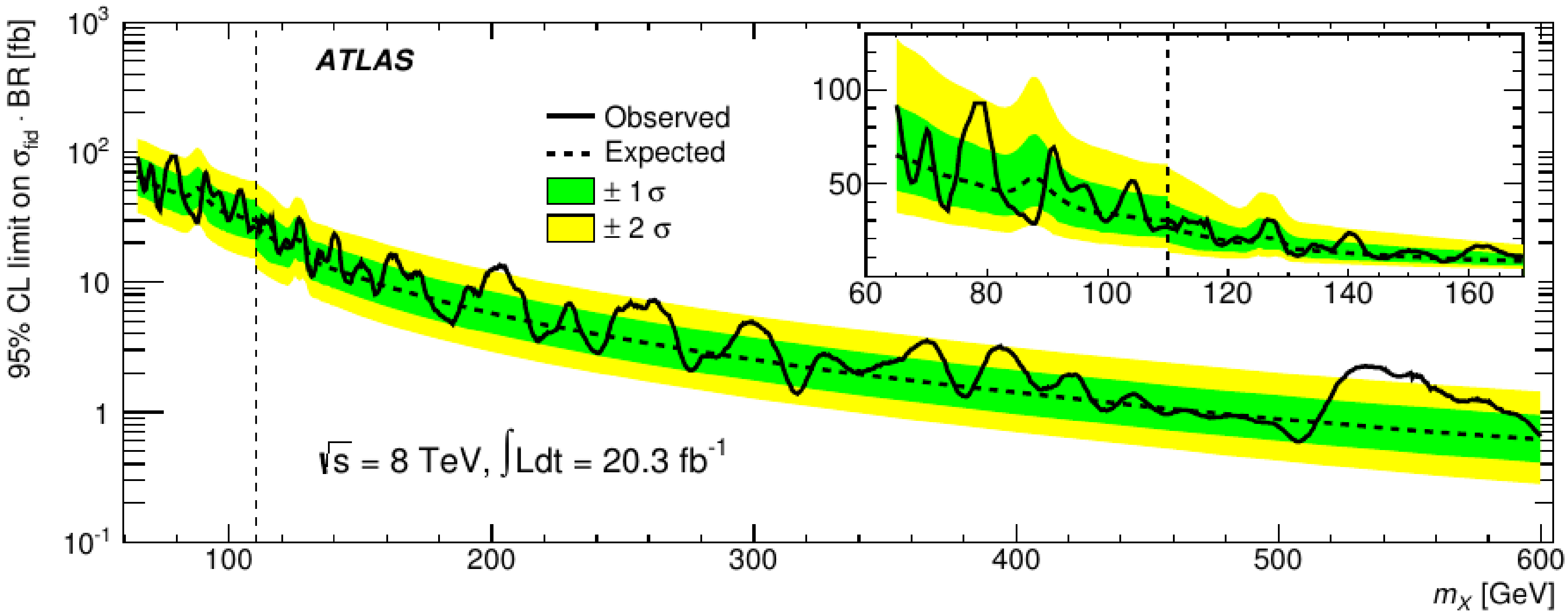


High-mass: Fit within sliding window, ~100-300 GeV
use exp(poly2) bkg shape
+ Higgs peak with μ=1, m_H=125.9 GeV

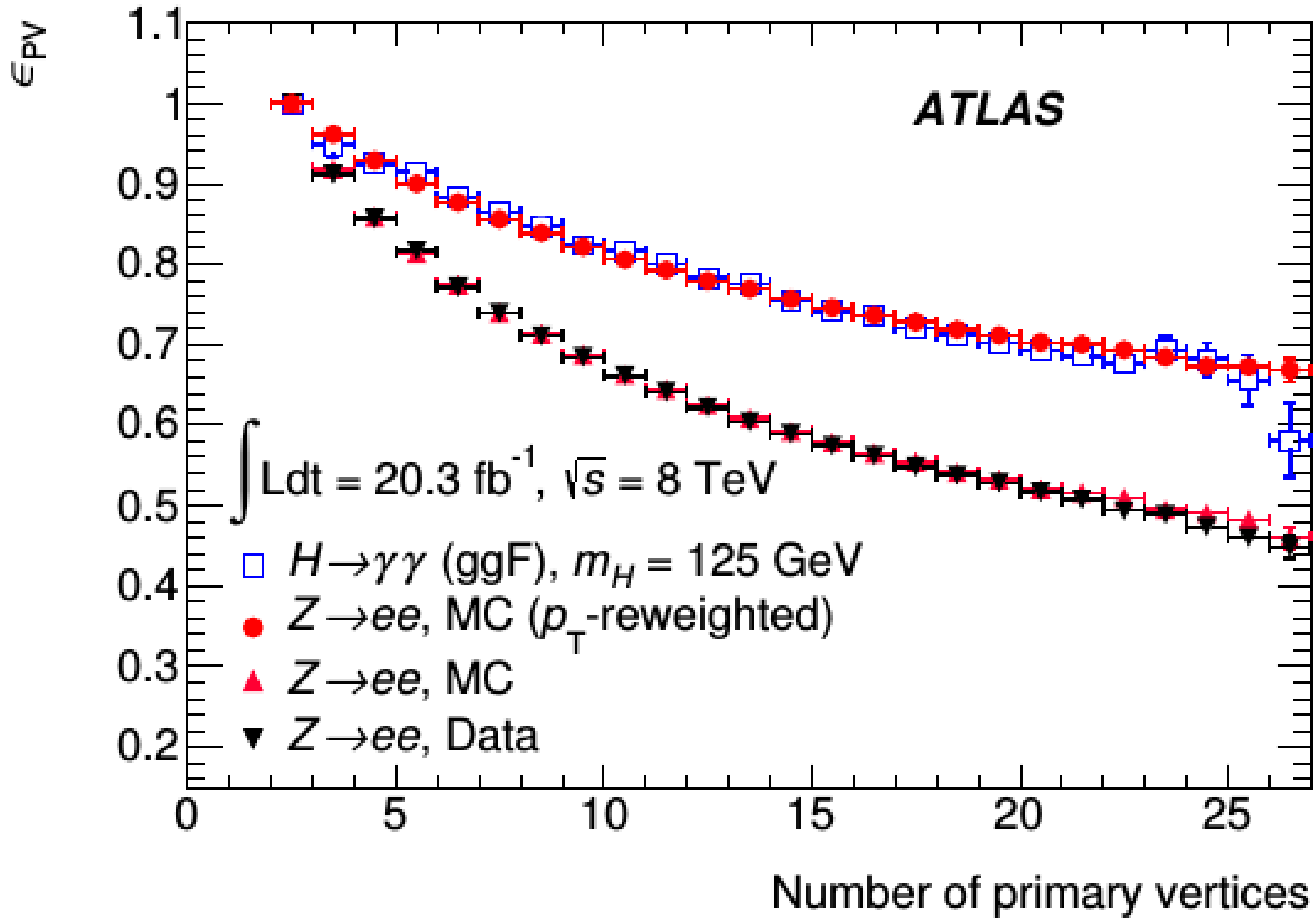
Low/High Mass Results

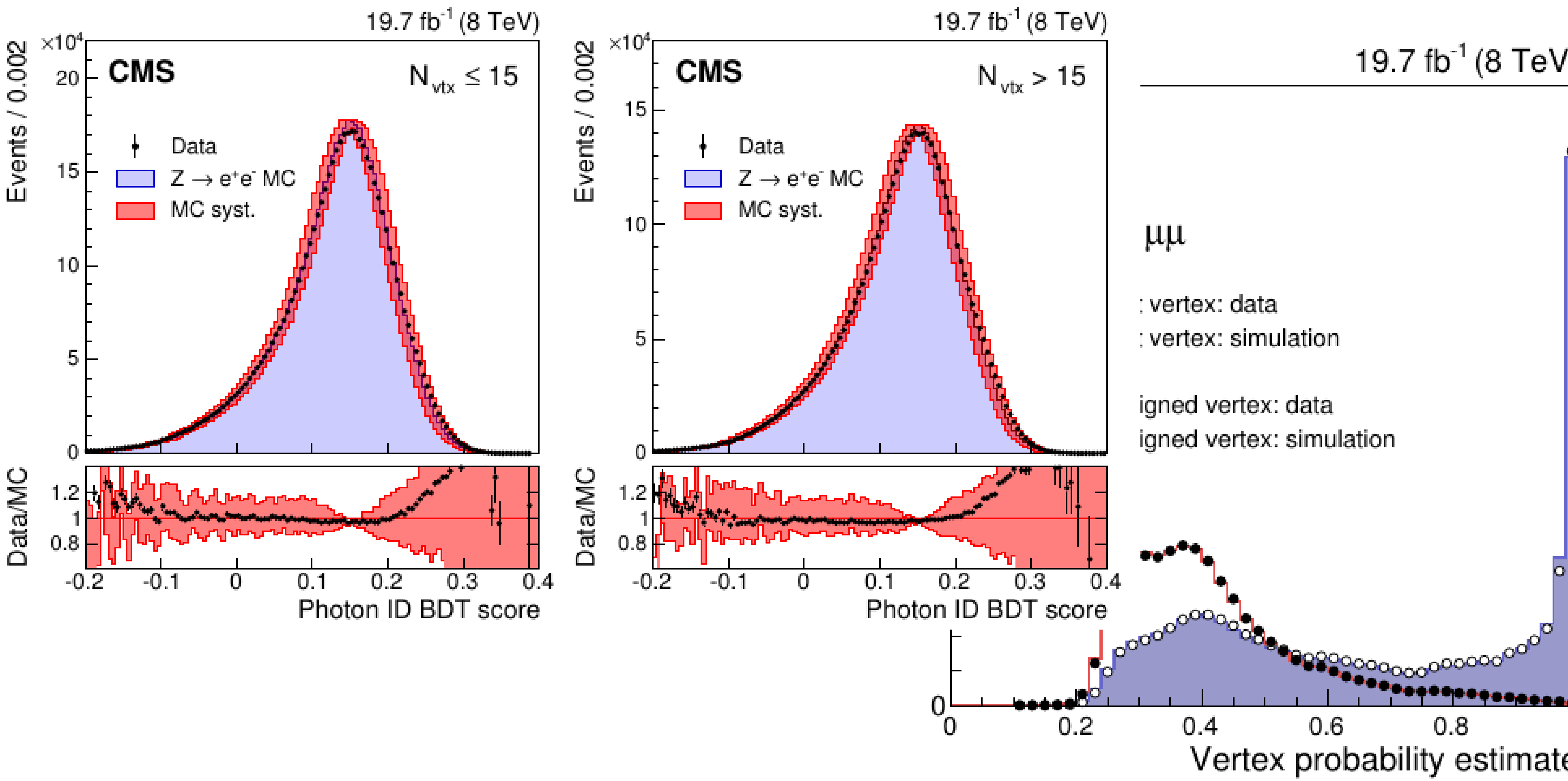


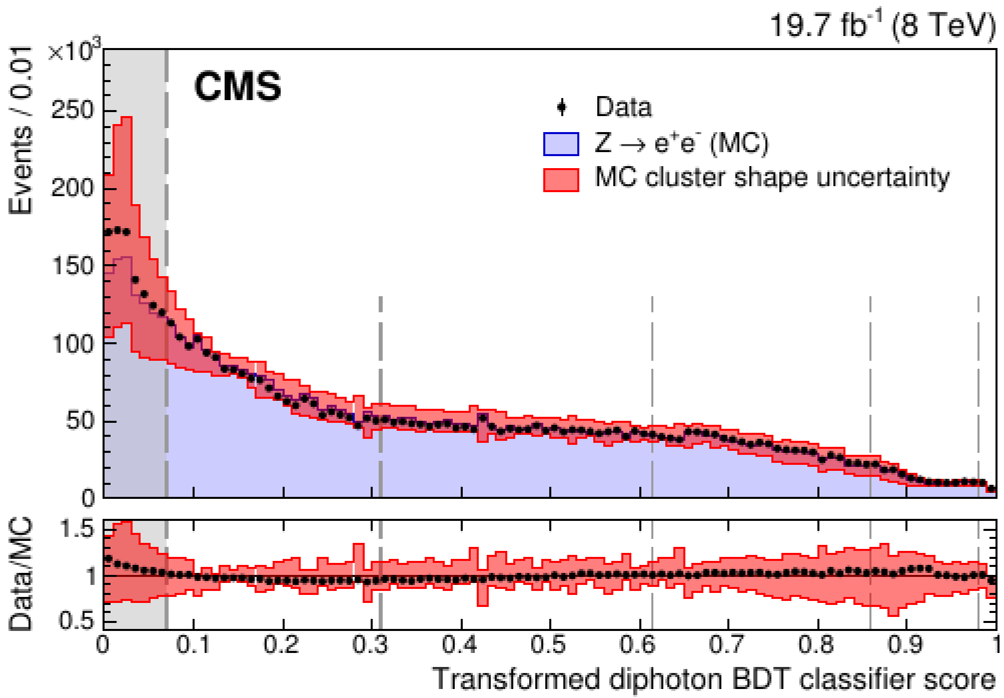


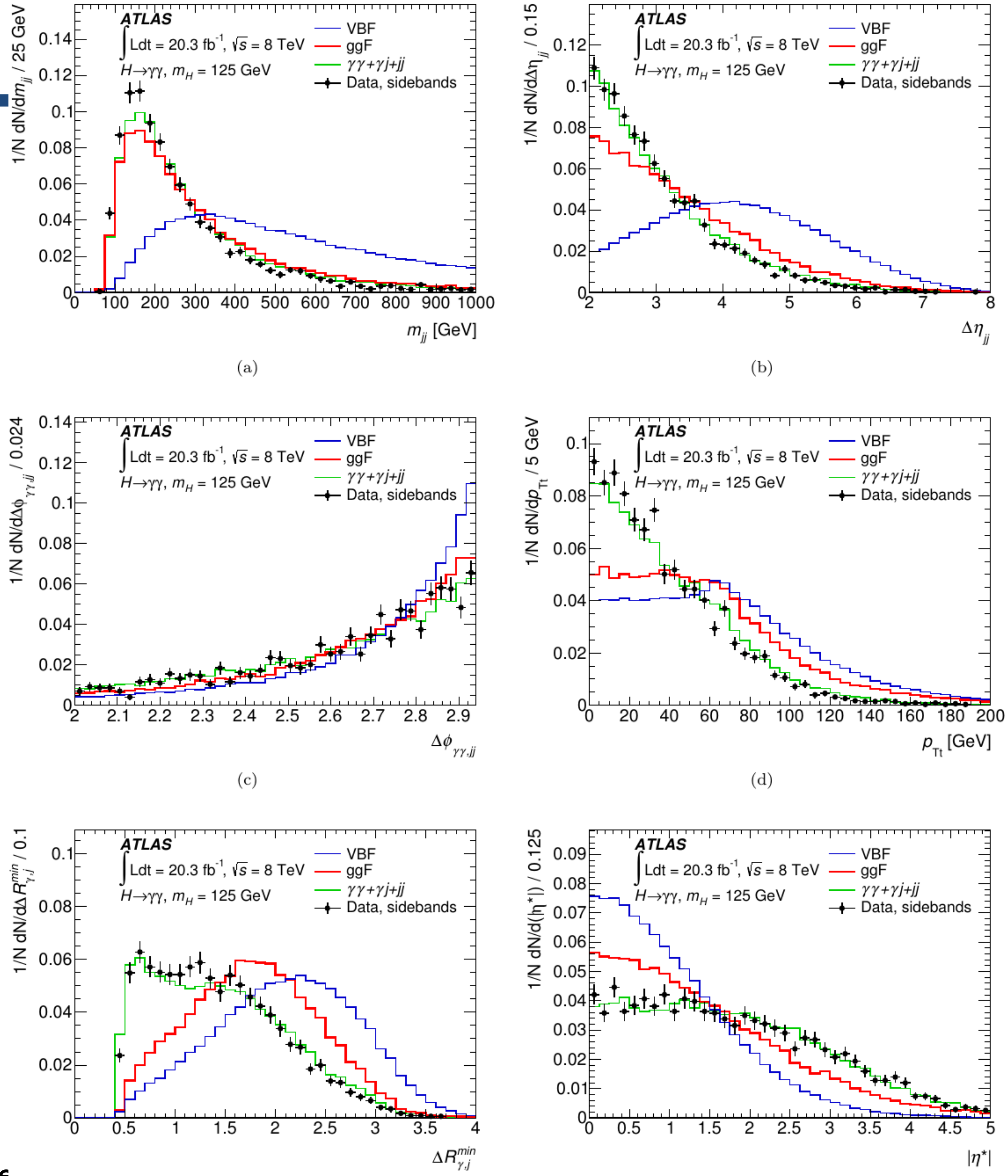


Backup

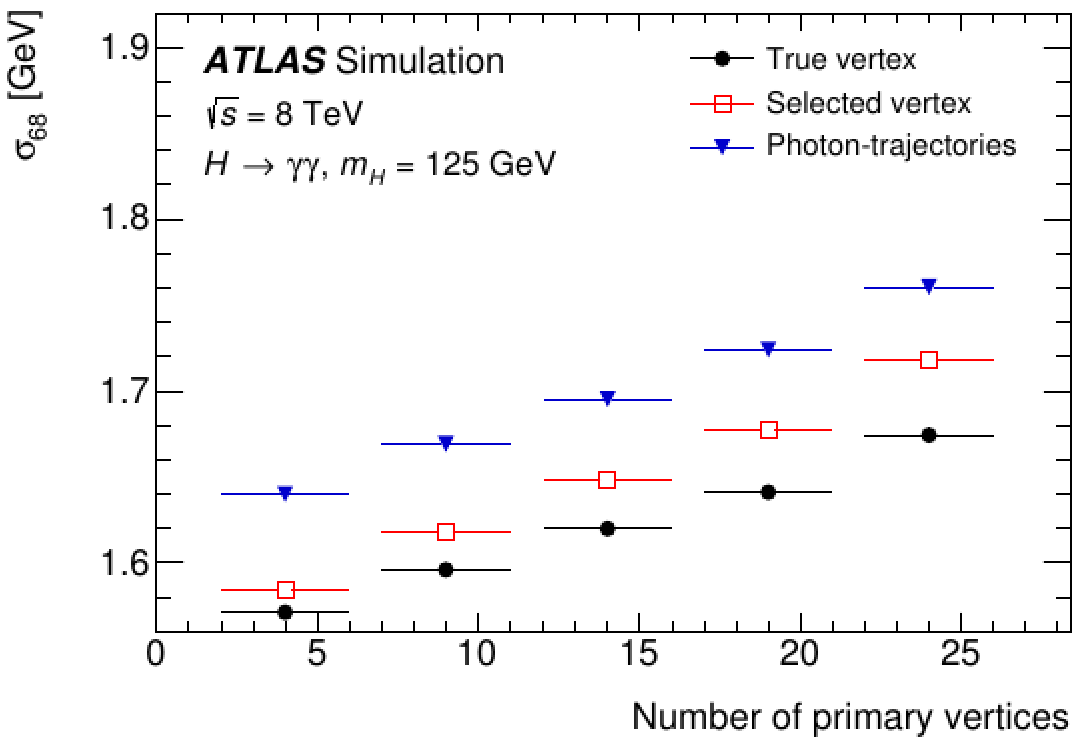

ATLAS
ϵ_{PV}
$\int Ldt = 20.3\ fb^{-1}$, $\sqrt{s} = 8$ TeV
$H\rightarrow\gamma\gamma$ (ggF), $m_H = 125$ GeV
$Z\rightarrow ee$, MC (p_T-reweighted)
$Z\rightarrow ee$, MC
$Z\rightarrow ee$, Data
Number of primary vertices
0
5
10
15
20
25
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1


19.7 fb-1 (8 TeV)
CMS
Nvtx ≤ 15
Data
Z → e+e- MC
MC syst.
Events / 0.002
×10^4
Data/MC
Photon ID BDT score
19.7 fb-1 (8 TeV)
CMS
Nvtx > 15
Data
Z → e+e- MC
MC syst.
Events / 0.002
×10^4
Data/MC
Photon ID BDT score
19.7 fb-1 (8 TeV)
μμ
: vertex: data
: vertex: simulation
igned vertex: data
igned vertex: simulation
Vertex probability estimate

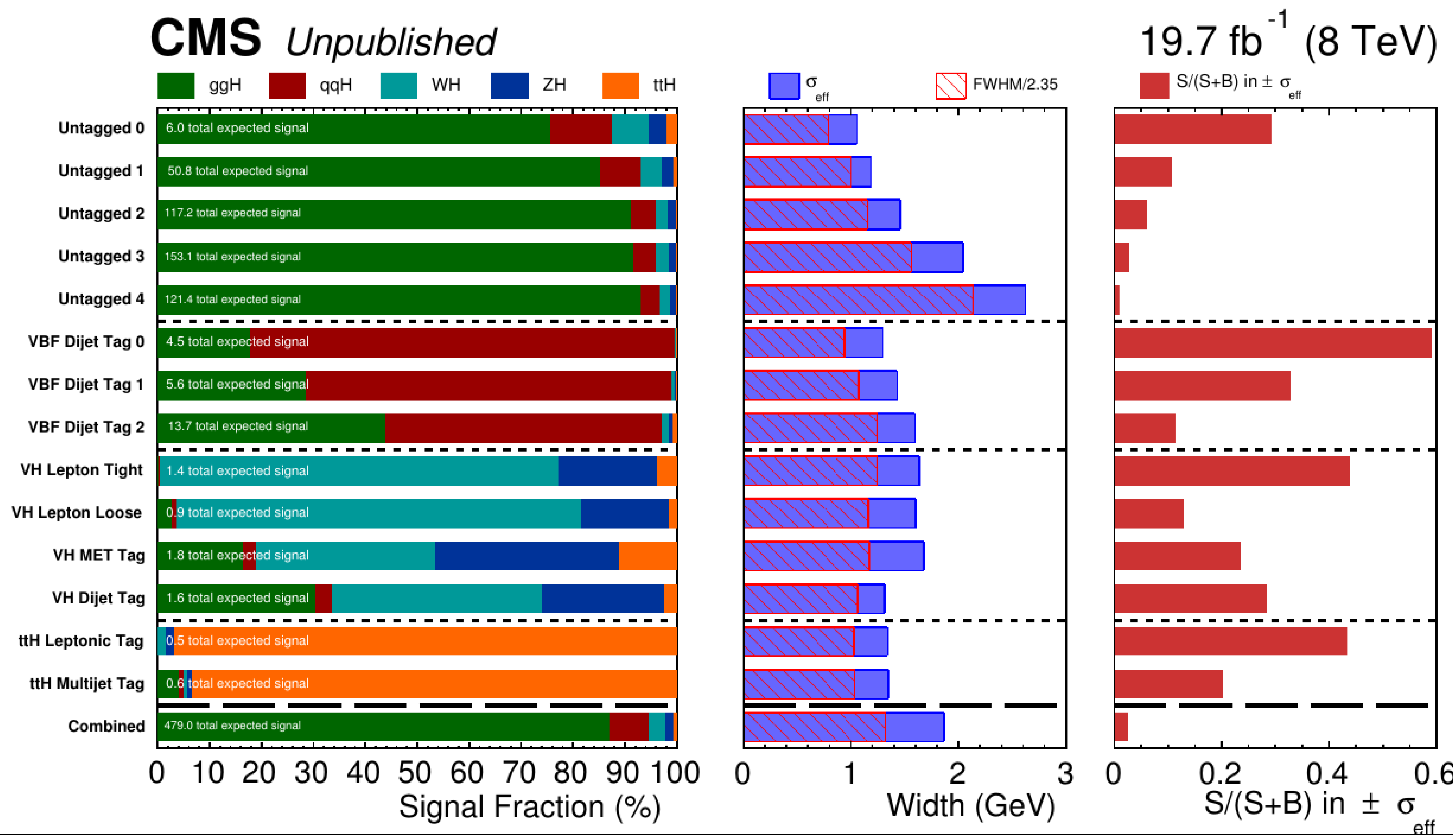

19.7 fb-1 (8 TeV)
CMS
Data
Z → e+e- (MC)
MC cluster shape uncertainty
×10^3
Events / 0.01
Data/MC
Transformed diphoton BDT classifier score


ATLAS
∫Ldt = 20.3 fb^-1, √s = 8 TeV
H→γγ, m_H = 125 GeV
VBF
ggF
γγ+γj+jj
Data, sidebands
1/N dN/dm_jj / 25 GeV
m_jj [GeV]
1/N dN/dΔη_jj / 0.15
Δη_jj
1/N dN/dΔφ_γγ,jj / 0.024
Δφ_γγ,jj
1/N dN/dp_Tt / 5 GeV
p_Tt [GeV]
1/N dN/dΔR^min_γ,j / 0.1
ΔR^min_γ,j
1/N dN/d(|η*|) / 0.125
|η*|

(a) (b) (c) (d) (e) (f)

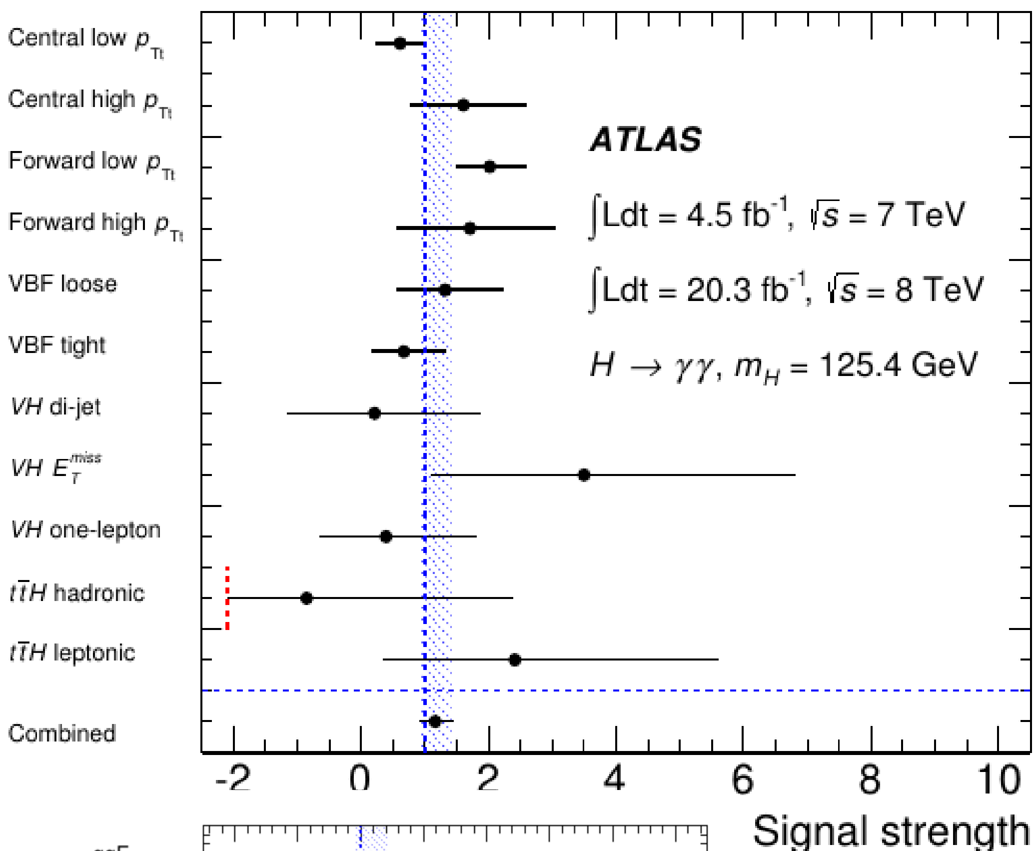

σ68 [GeV]
1.9
1.8
1.7
1.6
ATLAS Simulation
√s = 8 TeV
H → γγ, m_H = 125 GeV
True vertex
Selected vertex
Photon-trajectories
0
5
10
15
20
25
Number of primary vertices

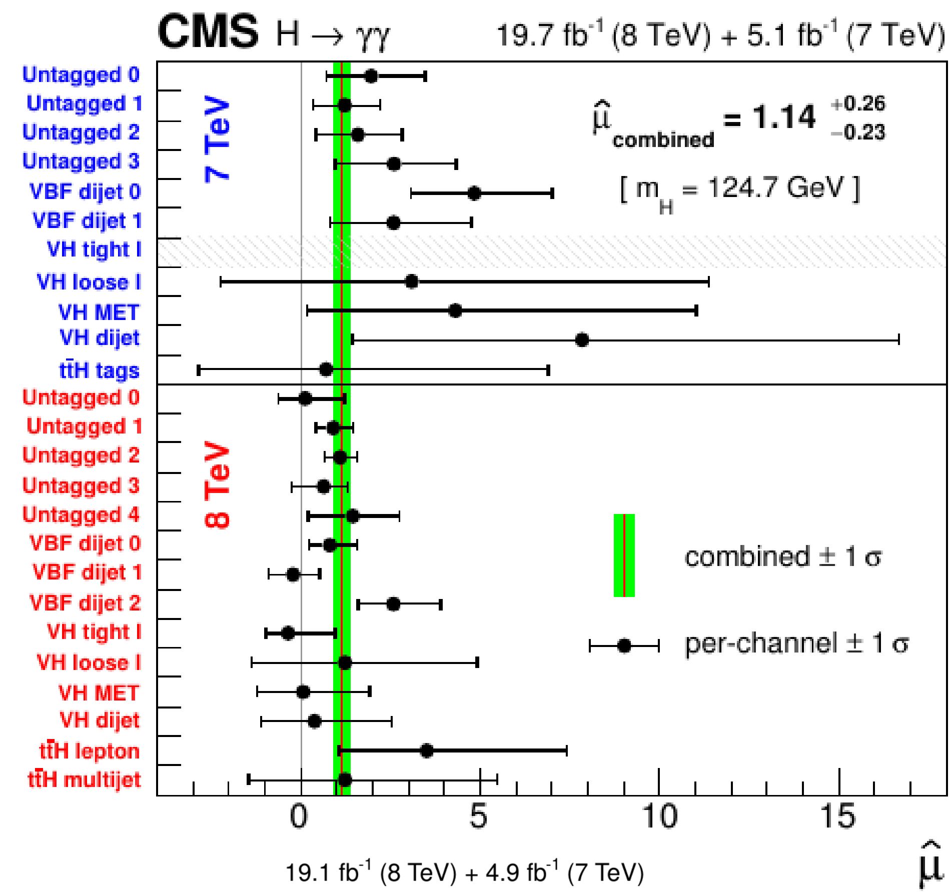
CMS Category Summary Plot

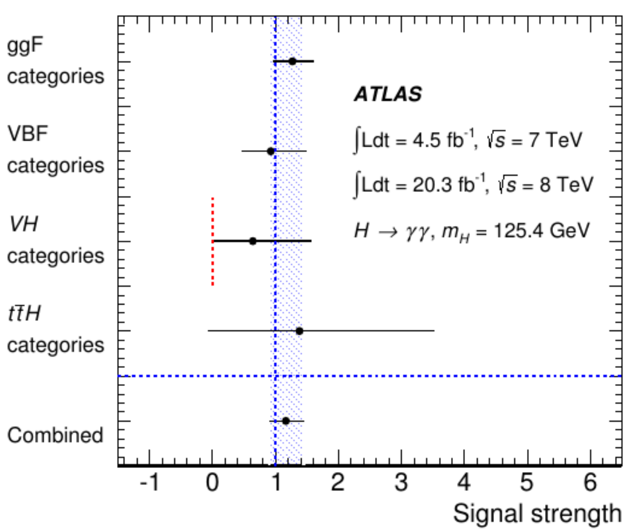


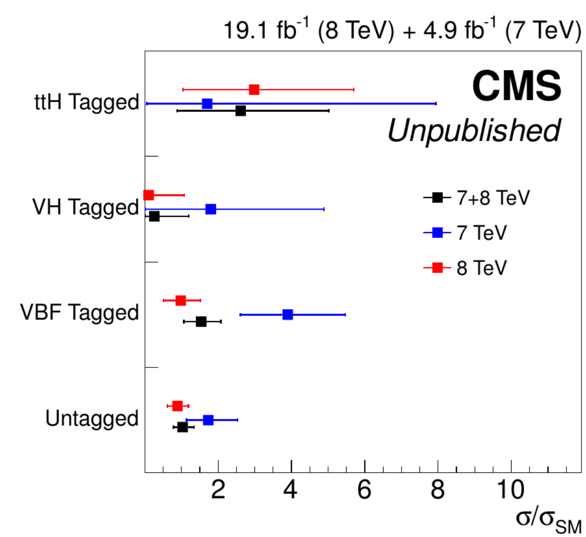
CMS Category Summary

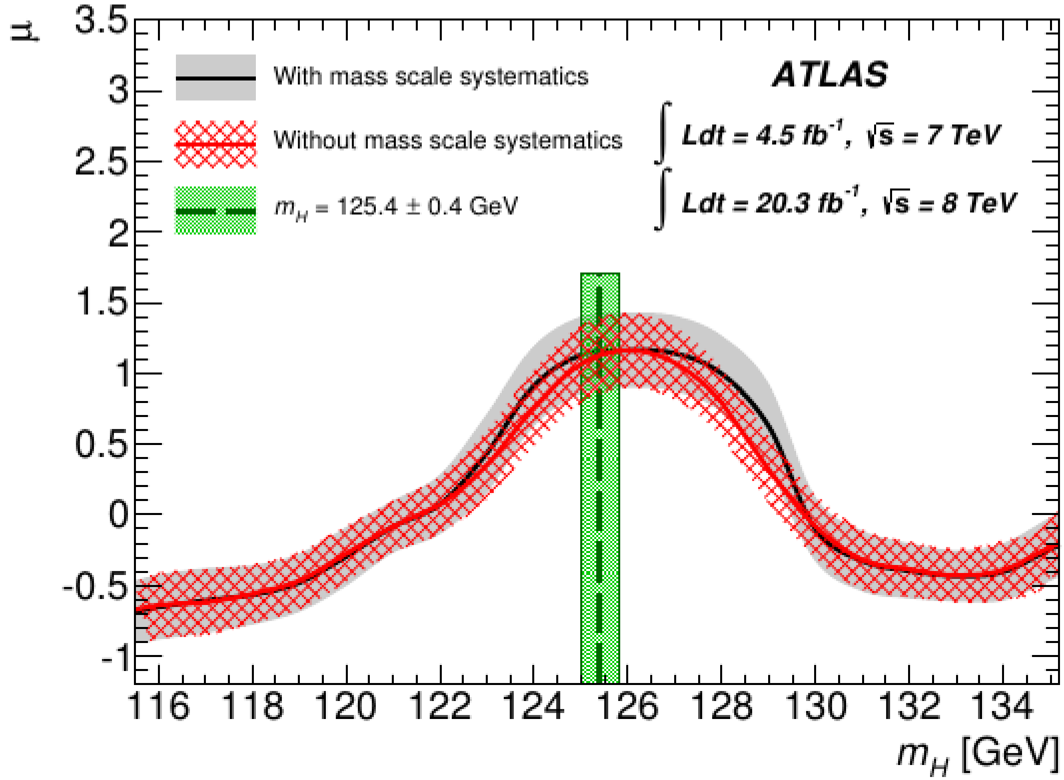
Event classes		Expected SM Higgs boson signal yield (m_H=125 GeV)								Bkg. (GeV^{-1})
		Total	ggH	VBF	WH	ZH	$t\bar{t}$H	σ_{eff} (GeV)	σ_{HM} (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	5.8	**79.8%**	9.9%	6.0%	3.5%	0.8%	1.11	0.98	11.0
	Untagged 1	22.7	**91.9%**	4.2%	2.4%	1.3%	0.2%	1.27	1.09	69.5
	Untagged 2	27.1	**91.9%**	4.1%	2.4%	1.4%	0.2%	1.78	1.40	135.
	Untagged 3	34.1	**92.1%**	4.0%	2.4%	1.3%	0.2%	2.36	2.01	312.
	VBF dijet 0	1.6	19.3%	**80.1%**	0.3%	0.2%	0.1%	1.41	1.17	0.5
	VBF dijet 1	3.0	38.1%	**59.5%**	1.2%	0.7%	0.4%	1.65	1.32	3.5
	VH tight ℓ	0.3	—	—	**77.2%**	20.6%	2.2%	1.61	1.31	0.1
	VH loose ℓ	0.2	3.6%	1.1%	**79.1%**	15.2%	1.0%	1.63	1.32	0.2
	VH E_T^{miss}	0.3	4.5%	1.1%	41.5%	**44.6%**	8.2%	1.60	1.14	0.2
	VH dijet	0.4	27.1%	2.8%	**43.7%**	24.3%	2.1%	1.54	1.24	0.5
	$t\bar{t}$H tags	0.2	3.1%	1.1%	2.2%	1.3%	**92.3%**	1.40	1.13	0.2
8 TeV 19.7 fb^{-1}	Untagged 0	6.0	**75.7%**	11.9%	6.9%	3.6%	1.9%	1.05	0.79	4.7
	Untagged 1	50.8	**85.2%**	7.9%	4.0%	2.4%	0.6%	1.19	1.00	120.
	Untagged 2	117.	**91.1%**	4.7%	2.5%	1.4%	0.3%	1.46	1.15	418.
	Untagged 3	153.	**91.6%**	4.4%	2.4%	1.4%	0.3%	2.04	1.56	870.
	Untagged 4	121.	**93.1%**	3.6%	2.0%	1.1%	0.2%	2.62	2.14	1400.
	VBF dijet 0	4.5	17.8%	**81.8%**	0.2%	0.1%	0.1%	1.30	0.94	0.8
	VBF dijet 1	5.6	28.5%	**70.5%**	0.6%	0.2%	0.2%	1.43	1.07	2.7
	VBF dijet 2	13.7	43.8%	**53.2%**	1.4%	0.8%	0.8%	1.59	1.24	22.1
	VH tight ℓ	1.4	0.2%	0.2%	**76.9%**	19.0%	3.7%	1.63	1.24	0.4
	VH loose ℓ	0.9	2.6%	1.1%	**77.9%**	16.8%	1.5%	1.60	1.16	1.2
	VH E_T^{miss}	1.8	16.3%	2.7%	34.4%	**35.4%**	11.1%	1.68	1.17	1.3
	VH dijet	1.6	30.3%	3.1%	**40.6%**	23.4%	2.6%	1.31	1.06	1.0
	$t\bar{t}$H lepton	0.5	—	—	1.6%	1.6%	**96.8%**	1.34	1.03	0.2
	$t\bar{t}$H multijet	0.6	4.1%	0.9%	0.8%	0.9%	**93.3%**	1.34	1.03	0.6

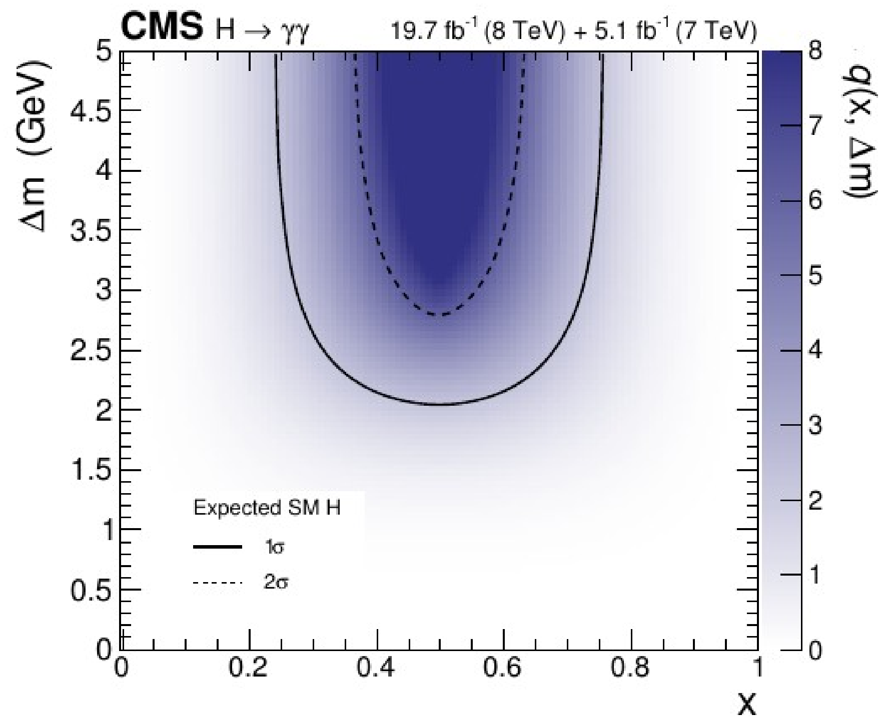

Central low p_{Tt}
Central high p_{Tt}
Forward low p_{Tt}
Forward high p_{Tt}
VBF loose
VBF tight
VH di-jet
VH E_T^{miss}
VH one-lepton
$t\bar{t}H$ hadronic
$t\bar{t}H$ leptonic
Combined
ATLAS
$\int Ldt = 4.5\ fb^{-1}$, $\sqrt{s} = 7$ TeV
$\int Ldt = 20.3\ fb^{-1}$, $\sqrt{s} = 8$ TeV
$H \rightarrow \gamma\gamma$, $m_H = 125.4$ GeV
-2 0 2 4 6 8 10
Signal strength


CMS $H \rightarrow \gamma\gamma$
$19.7\ fb^{-1}$ (8 TeV) + $5.1\ fb^{-1}$ (7 TeV)
7 TeV
Untagged 0
Untagged 1
Untagged 2
Untagged 3
VBF dijet 0
VBF dijet 1
VH tight l
VH loose l
VH MET
VH dijet
$t\bar{t}$H tags
8 TeV
Untagged 0
Untagged 1
Untagged 2
Untagged 3
Untagged 4
VBF dijet 0
VBF dijet 1
VBF dijet 2
VH tight l
VH loose l
VH MET
VH dijet
$t\bar{t}$H lepton
$t\bar{t}$H multijet
$\hat{\mu}_{combined} = 1.14\ ^{+0.26}_{-0.23}$
[m_H = 124.7 GeV]
combined ± 1 σ
per-channel ± 1 σ
0 5 10 15
$\hat{\mu}$

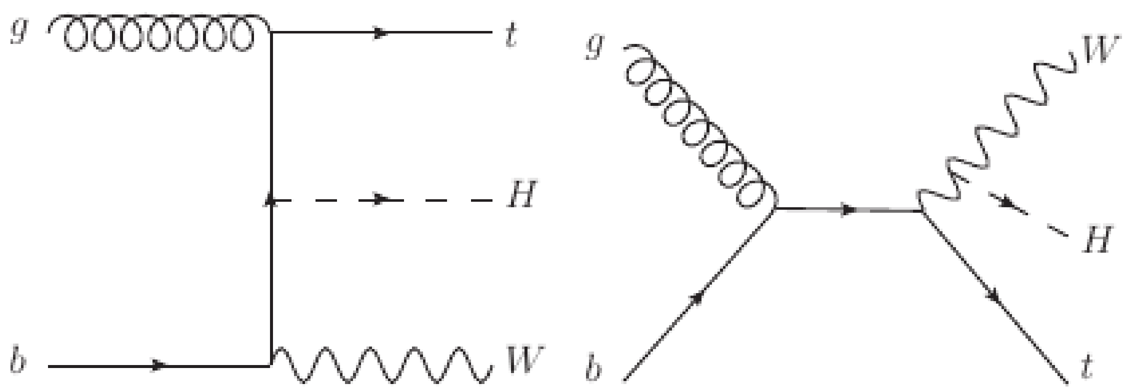

ggF categories
VBF categories
VH categories
$t\bar{t}H$ categories
Combined
ATLAS
$\int Ldt = 4.5\ fb^{-1}$, $\sqrt{s} = 7$ TeV
$\int Ldt = 20.3\ fb^{-1}$, $\sqrt{s} = 8$ TeV
$H \rightarrow \gamma\gamma$, $m_H = 125.4$ GeV
-1 0 1 2 3 4 5 6
Signal strength


$19.1\ fb^{-1}$ (8 TeV) + $4.9\ fb^{-1}$ (7 TeV)
CMS
Unpublished
ttH Tagged
VH Tagged
VBF Tagged
Untagged
7+8 TeV
7 TeV
8 TeV
2 4 6 8 10
σ/σ_{SM}

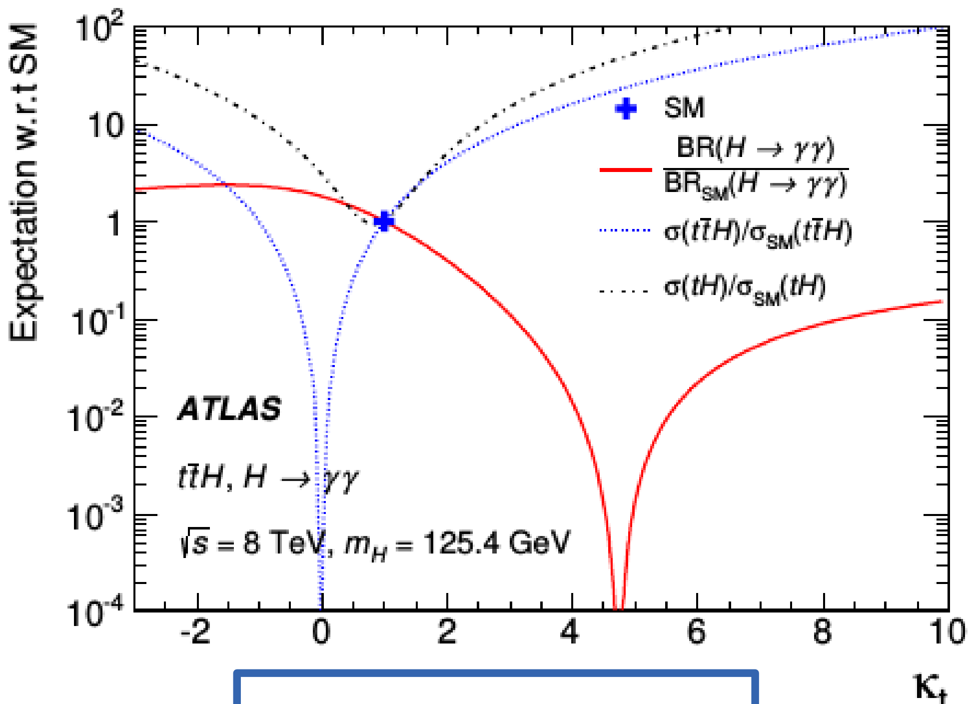

ATLAS
With mass scale systematics
Without mass scale systematics
m_H = 125.4 ± 0.4 GeV
$\int Ldt = 4.5\ fb^{-1}, \sqrt{s} = 7\ TeV$
$\int Ldt = 20.3\ fb^{-1}, \sqrt{s} = 8\ TeV$
μ
m_H [GeV]

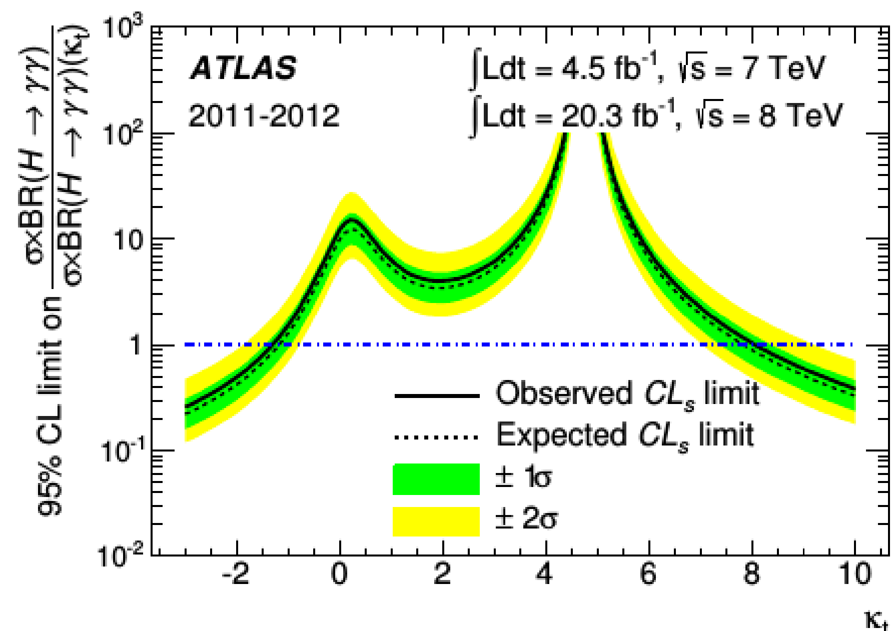

CMS H → γγ
19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
Δm (GeV)
x
q(x, Δm)
Expected SM H
1σ
2σ

tH->γγ Process



$$\frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to \gamma\gamma)_{SM}} \approx \left|0.26\,\kappa_f - 1.26\,\kappa_W\right|^2$$





ttH(SM) ~ 6xtH(SM)

ggbb Comparison

	ATLAS	CMS
Jet p_T	55/35 GeV	25 GeV
Tag requirement	≥ 2tag	Separate 1tag and ≥2tag regions for signal
m_{jj} range	95-135 GeV	85-155 GeV
m_{jj} method	4-vector scaling	Kinematic fit
Resonance limit method	Counting experiment	Sideband fit
Non-resonance limit	Yes	No
Signal at 300 GeV	CMS ~50% larger in 2-tag channel	
Background at 300 GeV	CMS ~400% larger in 2-tag channel	
Limit at 300 GeV	CMS ~50% better (expected)	

ggll Analysis

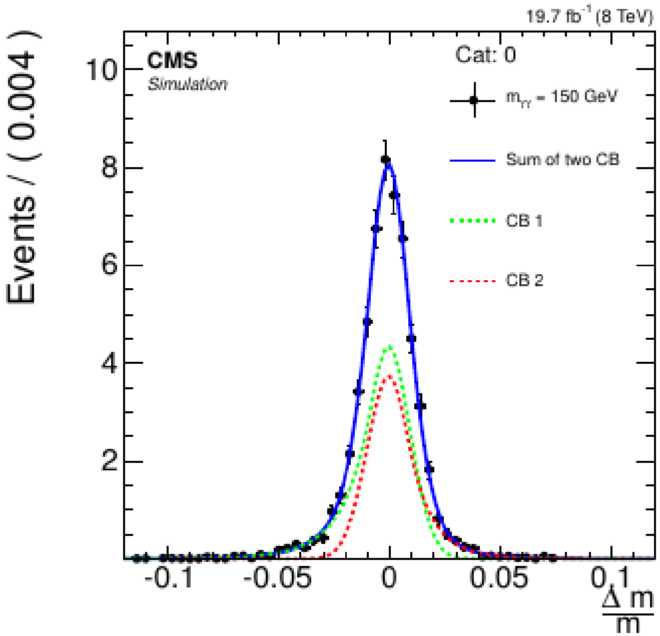
Channel	E_T^{miss} (GeV)	Obs.	Exp.
$\gamma\gamma\ell\ell$ (OSSF1, off-Z)	$(50, \infty)$	0	$0.19^{+0.25}_{-0.19}$
	$(30, 50)$	1	$0.17^{+0.25}_{-0.17}$
	$(0, 30)$	1	1.20 ± 0.74
$\gamma\gamma\ell\ell$ (OSSF1, on-Z)	$(50, \infty)$	0	$0.10^{+0.17}_{-0.10}$
	$(30, 50)$	1	0.33 ± 0.28
	$(0,30)$	0	1.01 ± 0.55
$\gamma\gamma\ell\ell$ (OSSF0)	All	0	$0.00^{+0.17}_{-0.00}$
$\gamma\gamma\ell\tau_h$	$(50, \infty)$	0	$0.16^{+0.66}_{-0.16}$
	$(30, 50)$	0	$0.50^{+0.57}_{-0.50}$
	$(0, 30)$	0	0.76 ± 0.60

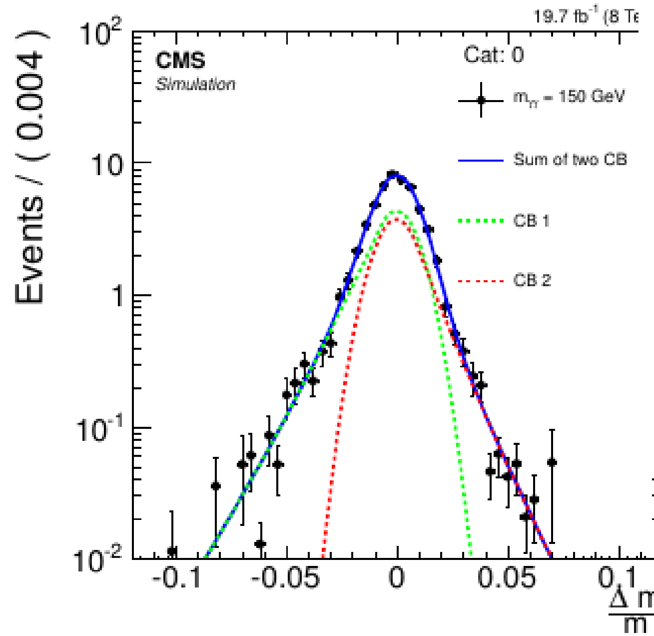
Channel	E_T^{miss} (GeV)	$N_b = 0$		$N_b \geq 1$	
		Obs.	Exp.	Obs.	Exp.
$\gamma\gamma\ell$	$(100, \infty)$	1	2.2 ± 1.0	0	0.5 ± 0.4
	$(50, 100)$	7	9.5 ± 4.4	1	2.3 ± 1.2
	$(30, 50)$	29	21 ± 10	2	1.1 ± 0.6
	$(0, 30)$	72	77 ± 38	2	2.1 ± 1.1
$\gamma\gamma\tau_h$	$(100, \infty)$	1	$0.24^{+0.25}_{-0.24}$	0	0.35 ± 0.28
	$(50, 100)$	14	9.3 ± 4.7	1	1.5 ± 0.8
	$(30, 50)$	71	67 ± 34	2	2.1 ± 1.2
	$(0, 30)$	229	235 ± 117	6	6.4 ± 3.3

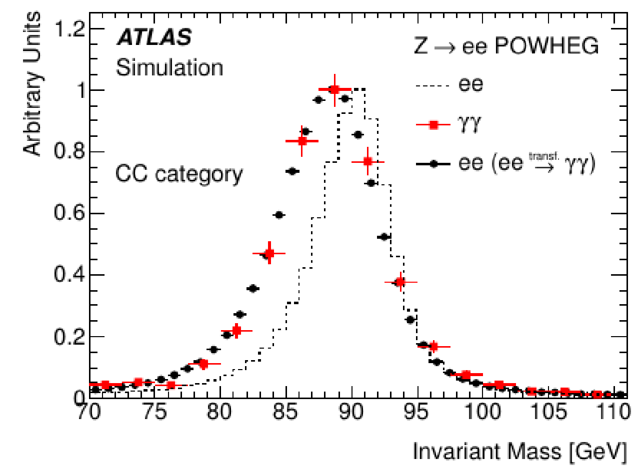
Spin

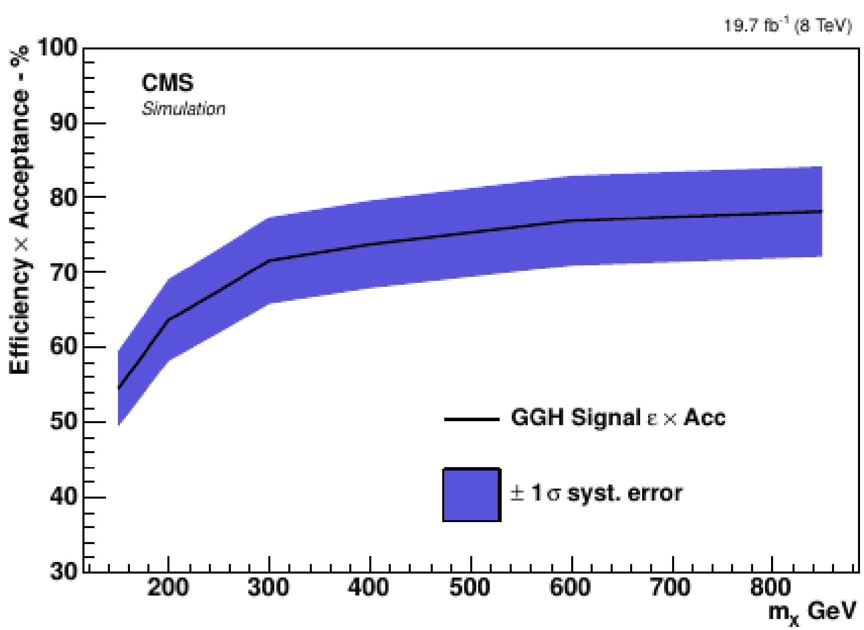
$H \rightarrow \gamma\gamma$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.148	0.135	0.798	0.025	0.124
75%	0.319	0.305	0.902	0.033	0.337
50%	0.198	0.187	0.708	0.076	0.260
25%	0.052	0.039	0.609	0.021	0.054
0%	0.012	0.005	0.588	0.003	0.007

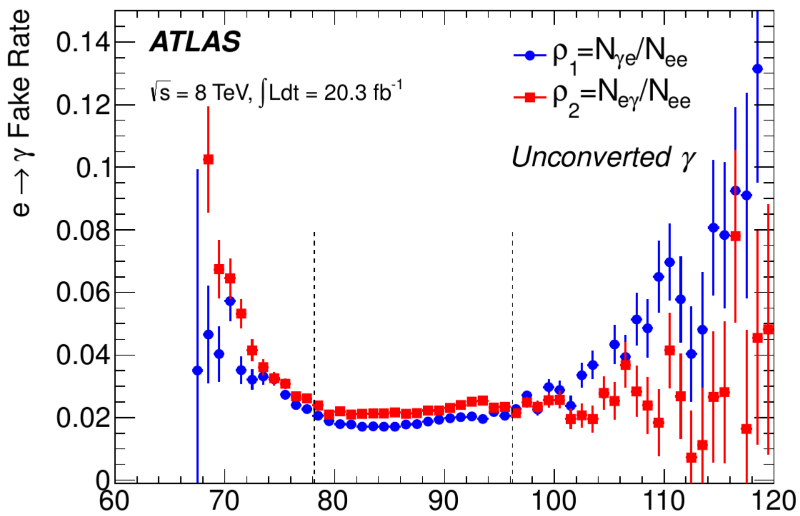

19.7 fb^{-1} (8 TeV)
CMS
Simulation
Cat: 0
$m_{\gamma\gamma}$ = 150 GeV
Sum of two CB
CB 1
CB 2
Events / (0.004)
$\frac{\Delta m}{m}$

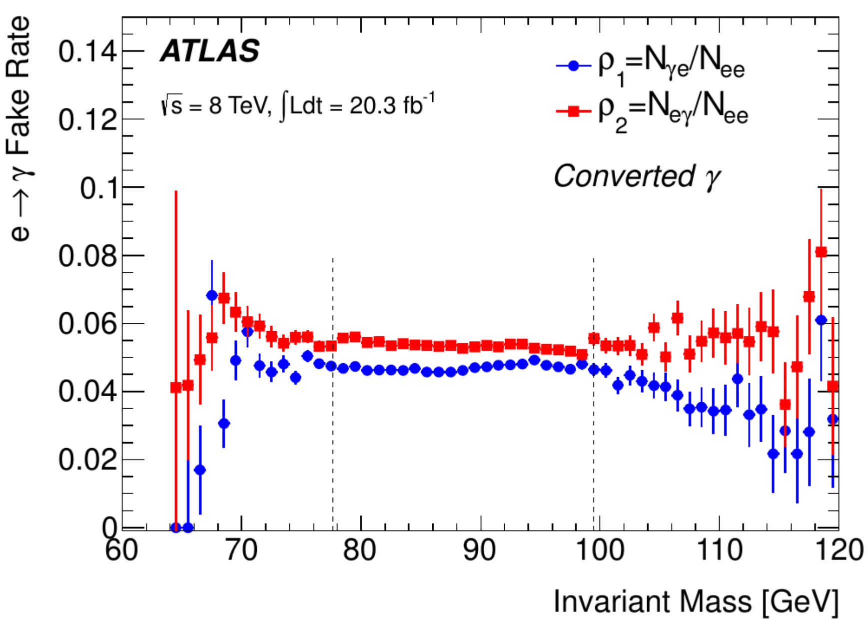

19.7 fb^{-1} (8 Te
CMS
Simulation
Cat: 0
$m_{\gamma\gamma}$ = 150 GeV
Sum of two CB
CB 1
CB 2
Events / (0.004)
$\frac{\Delta m}{m}$

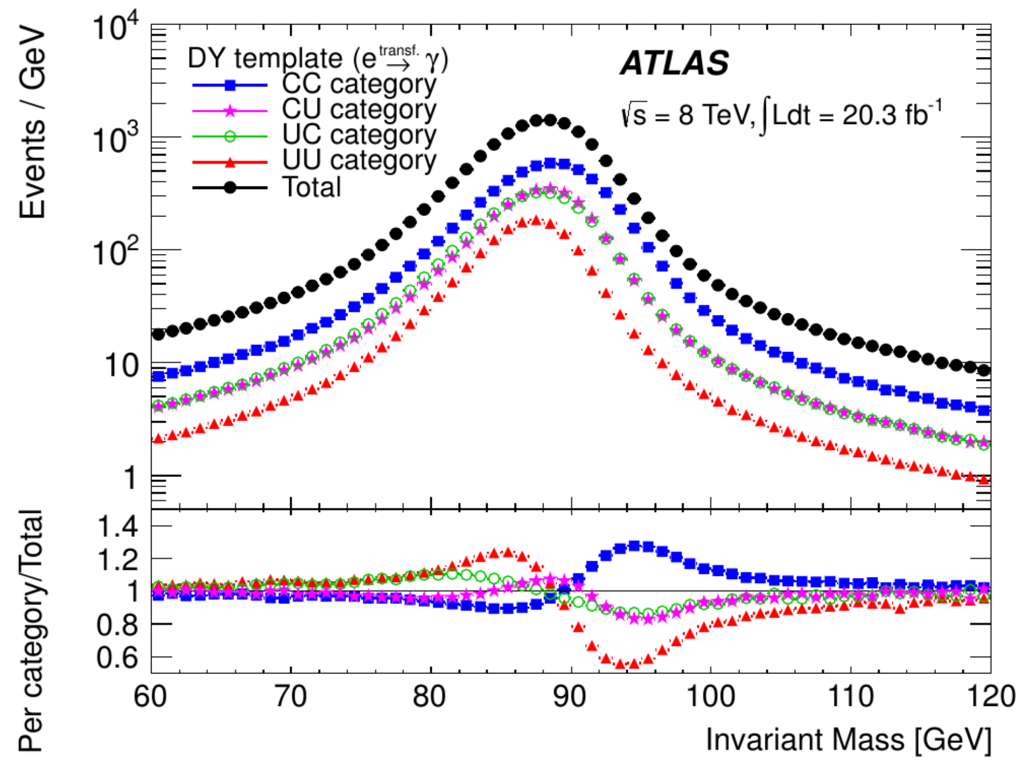

ATLAS
Simulation
CC category
Z → ee POWHEG
ee
γγ
ee (ee $\xrightarrow{\text{transf.}}$ γγ)
Arbitrary Units
Invariant Mass [GeV]


19.7 fb^{-1} (8 TeV)
CMS
Simulation
GGH Signal ε × Acc
± 1 σ syst. error
Efficiency × Acceptance - %
m_X GeV

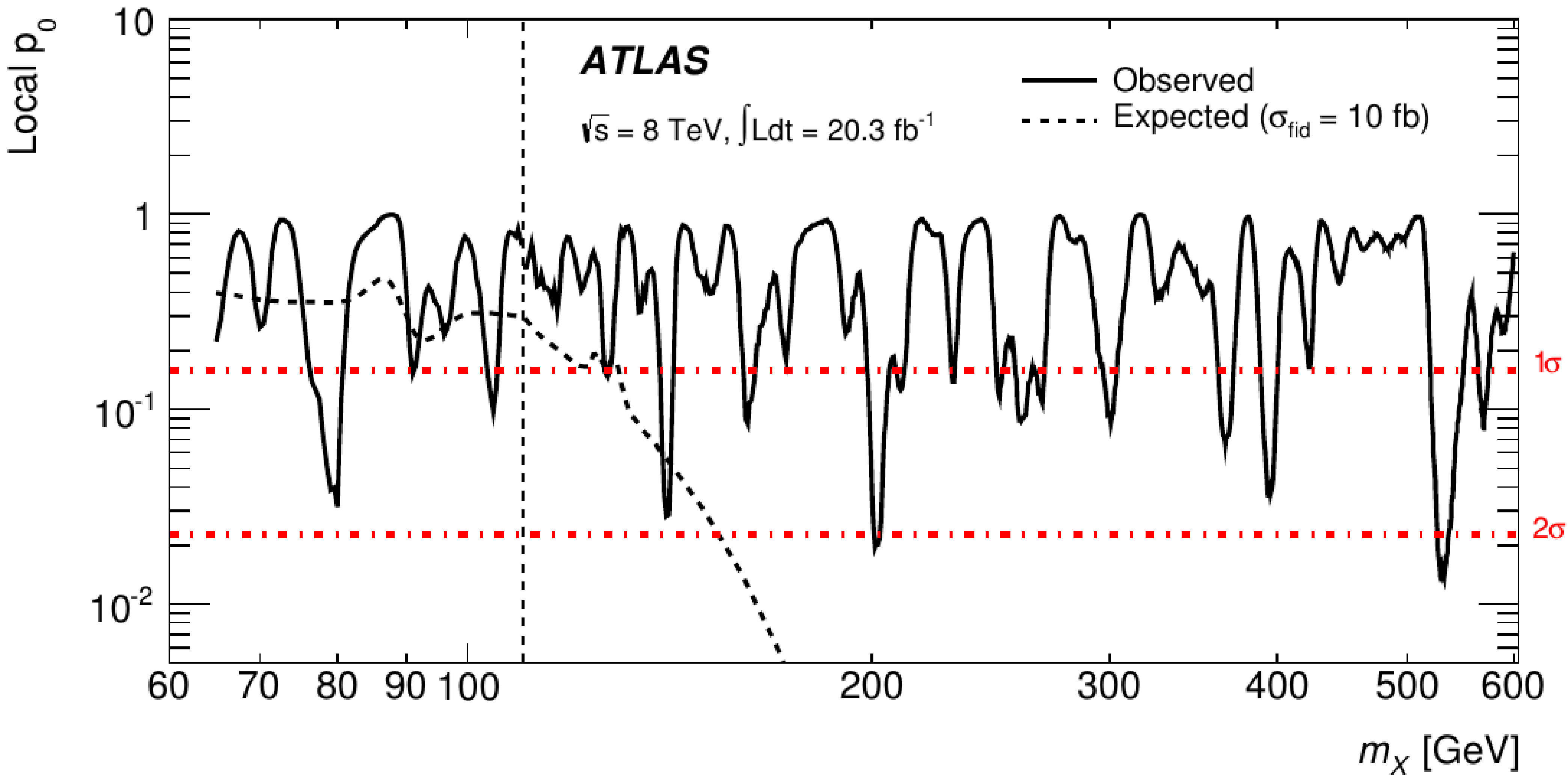
DY


ATLAS
√s = 8 TeV, ∫Ldt = 20.3 fb⁻¹
ρ1=Nγe/Nee
ρ2=Neγ/Nee
Unconverted γ
e → γ Fake Rate
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
60
70
80
90
100
110
120


ATLAS
√s = 8 TeV, ∫Ldt = 20.3 fb⁻¹
ρ1=Nγe/Nee
ρ2=Neγ/Nee
Converted γ
e → γ Fake Rate
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
60
70
80
90
100
110
120
Invariant Mass [GeV]

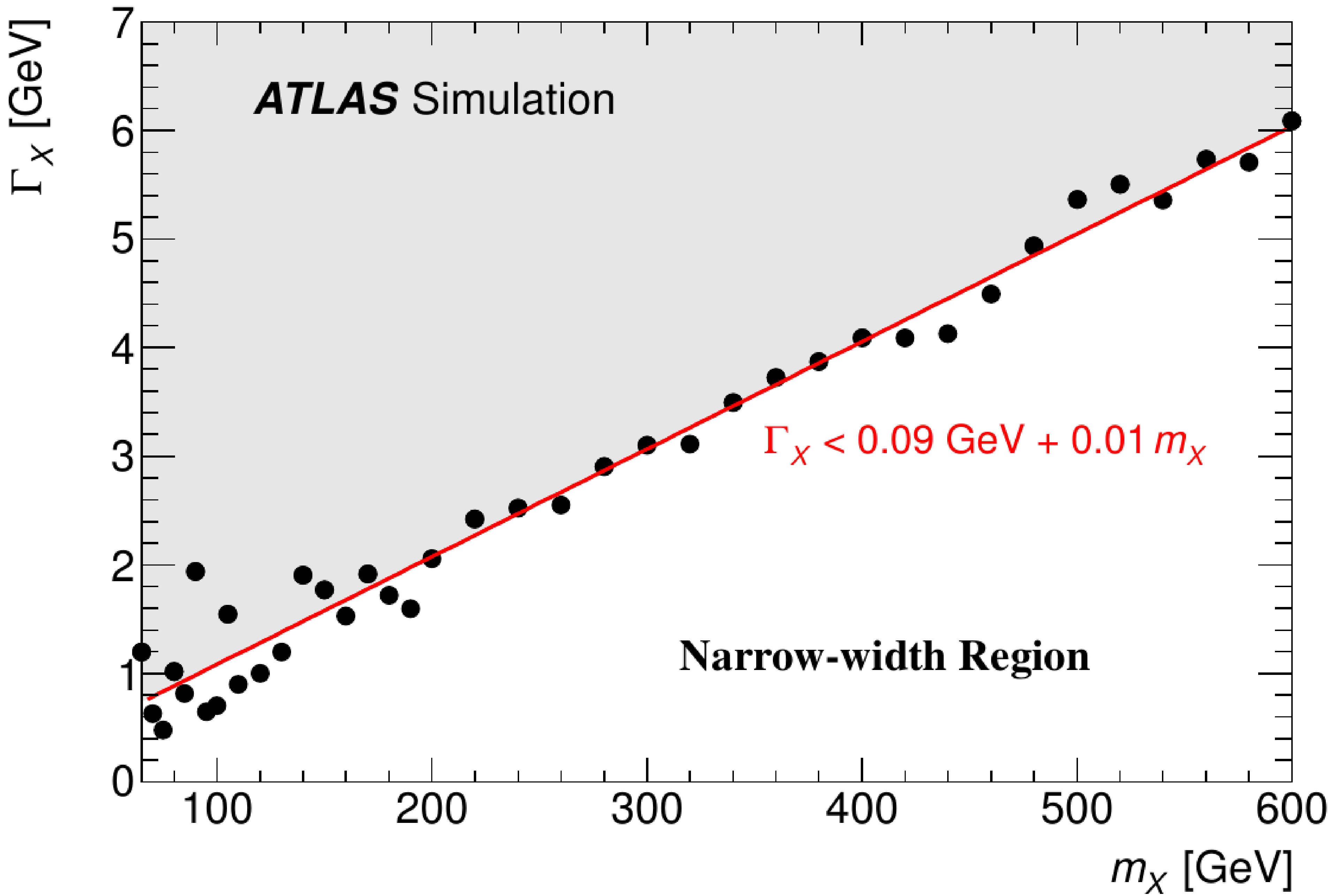

DY template (e transf.→ γ)
CC category
CU category
UC category
UU category
Total
ATLAS
√s = 8 TeV, ∫Ldt = 20.3 fb⁻¹
Events / GeV
10⁴
10³
10²
10
1
Per category/Total
1.4
1.2
1
0.8
0.6
60
70
80
90
100
110
120
Invariant Mass [GeV]

p0



Local p0
10
1
10^-1
10^-2
ATLAS
√s = 8 TeV, ∫Ldt = 20.3 fb^-1
Observed
Expected (σfid = 10 fb)
1σ
2σ
60
70
80
90
100
200
300
400
500
600
mX [GeV]

Narrow-Width Approx

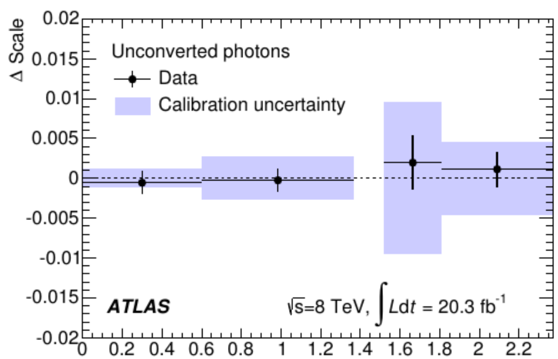


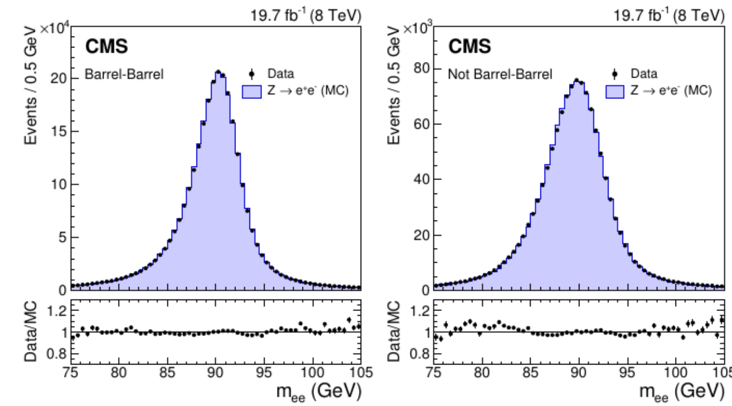
Photon Energy Calibration

Photon energy calibration using MVA – inputs: shower shapes, η…

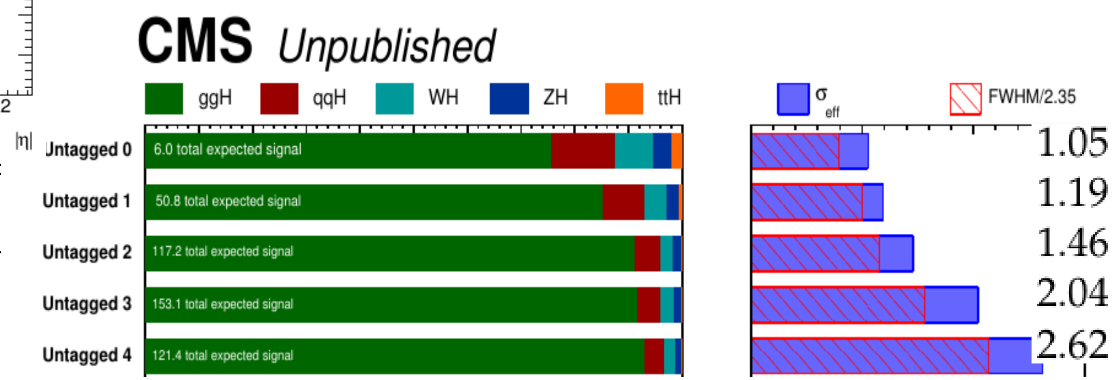
- In-situ adjustment using $Z \to e^+e^-$ peak
  - extrapolate to photons using simulation => need precise knowledge of material
  - extrapolate to Higgs mass => non-linearity

- Photon E calib : Eur. Phys. J. C74 (2014) 10, 3071
- Improved intercalibration of calorimeter layers (to within 1-2%)
- Improved determination of upstream material (to ~5%)
- Effective constant term ~0.7%





Category	$\sqrt{s}$=7 TeV σ_{68} [GeV]	$\sqrt{s}$=7 TeV σ_{90} [GeV]	$\sqrt{s}$=8 TeV σ_{68} [GeV]	$\sqrt{s}$=8 TeV σ_{90} [GeV]
Central - low p_{Tt}	1.36	2.32	1.47	2.50
Central - high p_{Tt}	1.21	2.04	1.32	2.21
Forward - low p_{Tt}	1.69	3.03	1.86	3.31
Forward - high p_{Tt}	1.48	2.59	1.64	2.88



σ_{eff} ~ 1.32-1.86 GeV => ~1.56 GeV

σ_{eff} ~ 1.05-2.62 GeV => ~1.46 GeV

σ_{eff} : smallest interval containing 68% of signal

$$\frac{1}{\bar{\sigma}_{eff}} \sum_{i=1}^{n_{cat}} \frac{S_i^2}{B_i} = \sum_{i=1}^{n_{cat}} \frac{S_i^2}{\sigma_{eff,i} B_i}$$