Higgs Boson: Experimental Review

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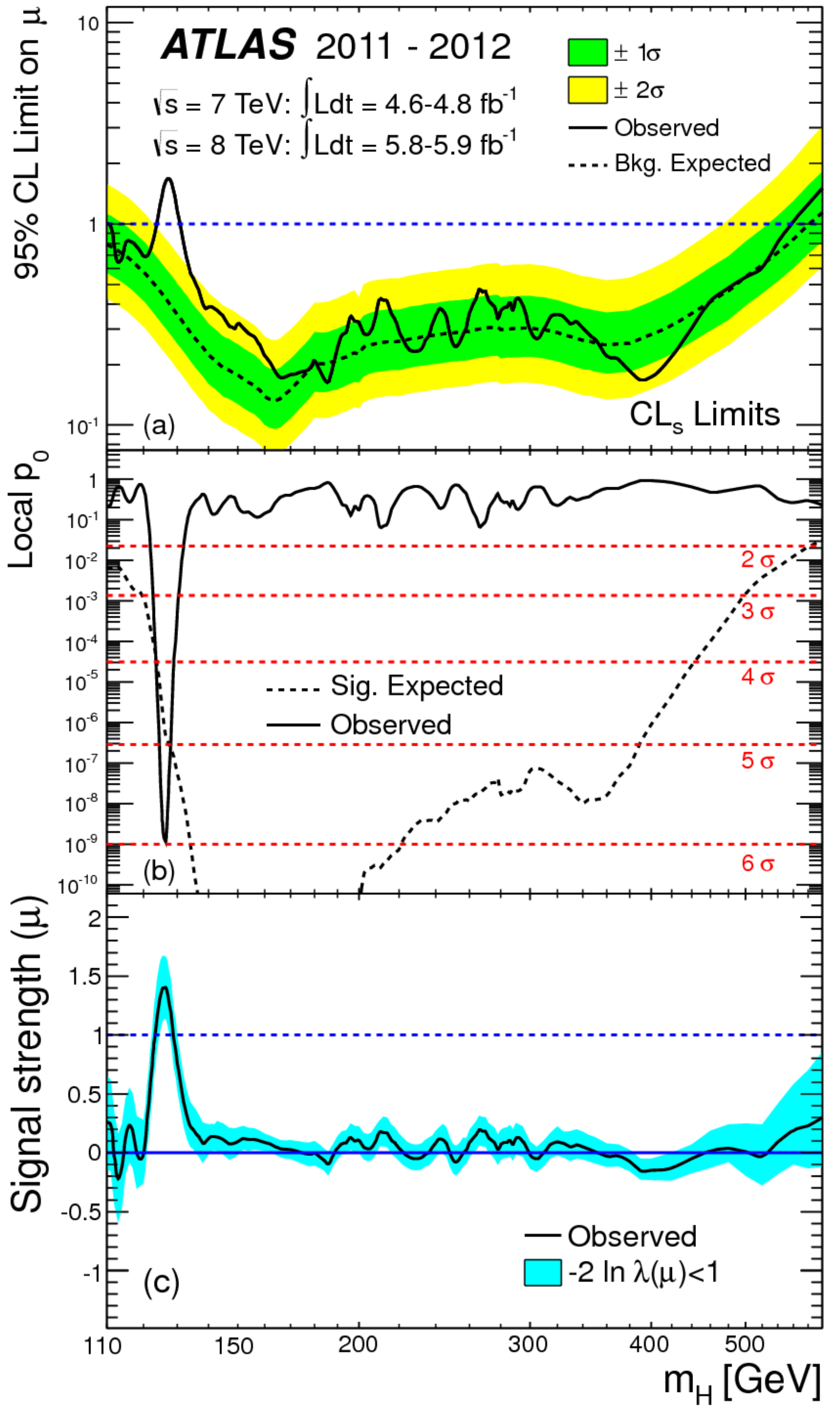
Outline

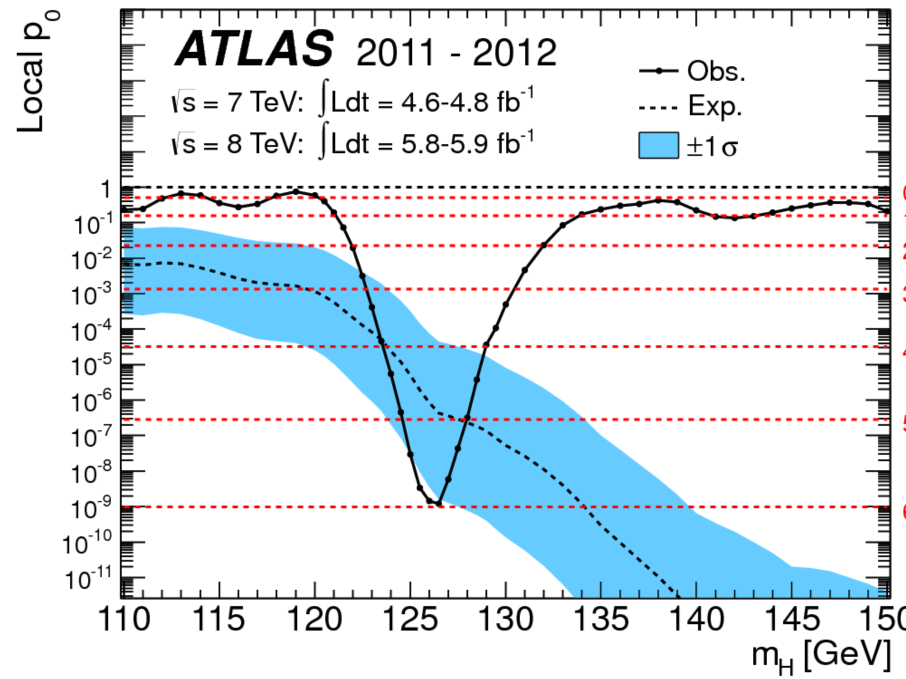
- ❑ **Habemus Novum Boson**
- ❑ **Production mechanisms and decay**
- ❑ **Mass**
- ❑ **Signal/coupling strength**
- ❑ **Spin-CP quantum numbers**



Habemus novum Boson

Phys.Lett. B716 (2012) 1-29

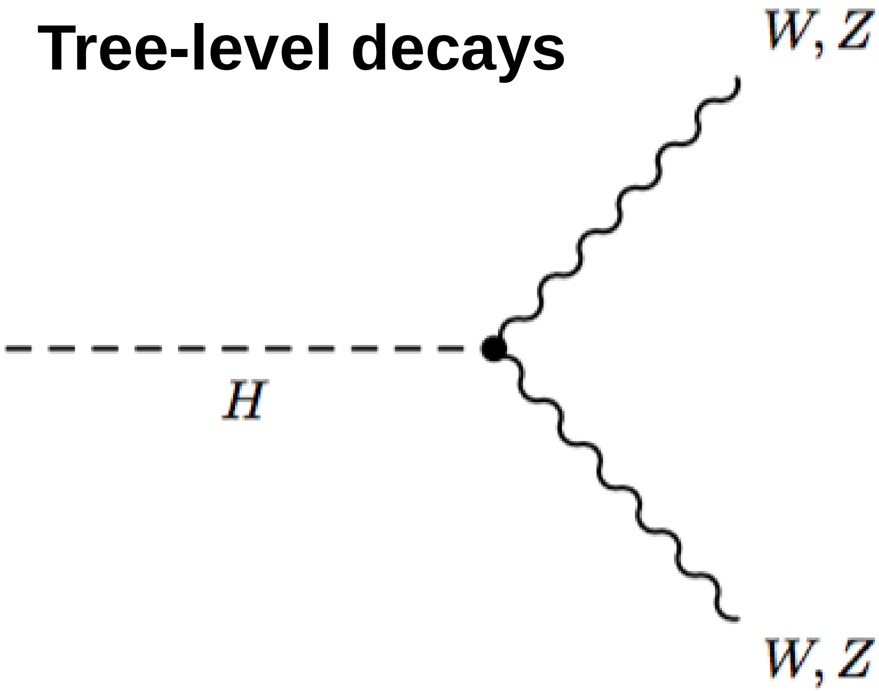
On July 4th reported 5σ.
With the addition of WW a 6σ effect is reached and reported in the final paper.

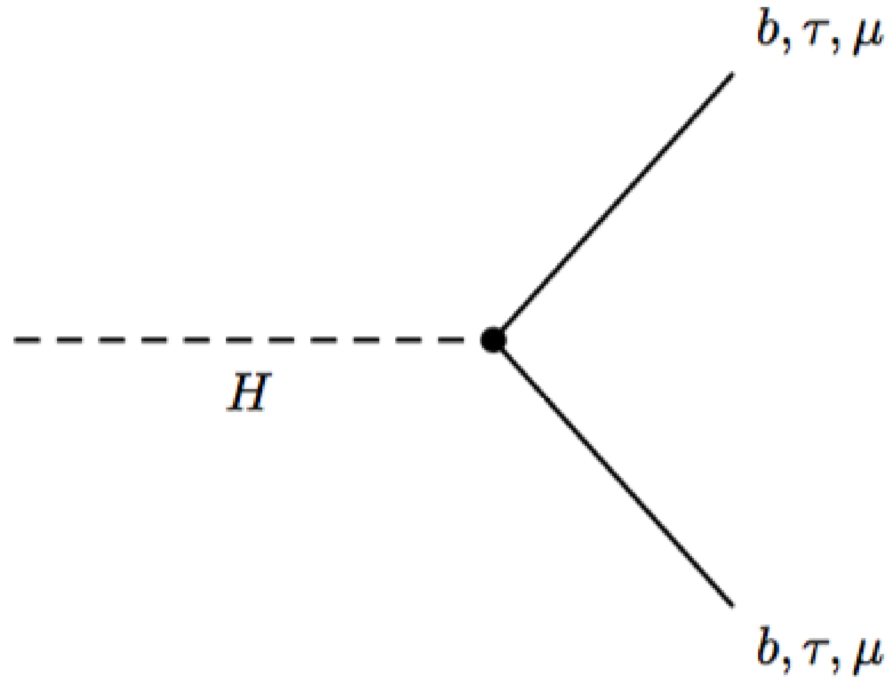


In this presentation we review progress since discovery with Run I

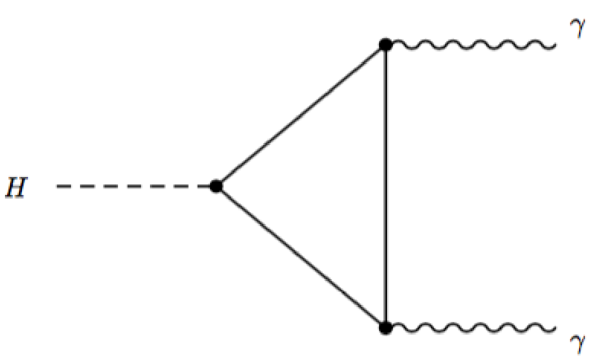
Higgs boson Decays

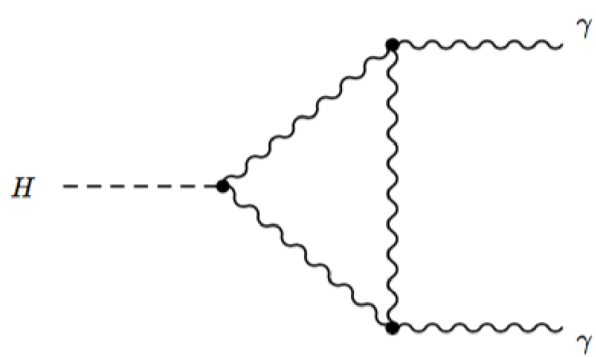
Tree-level decays

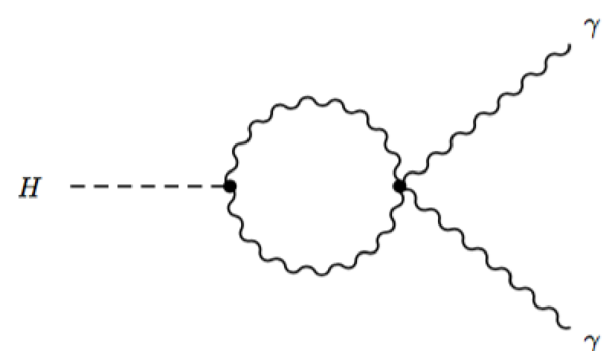




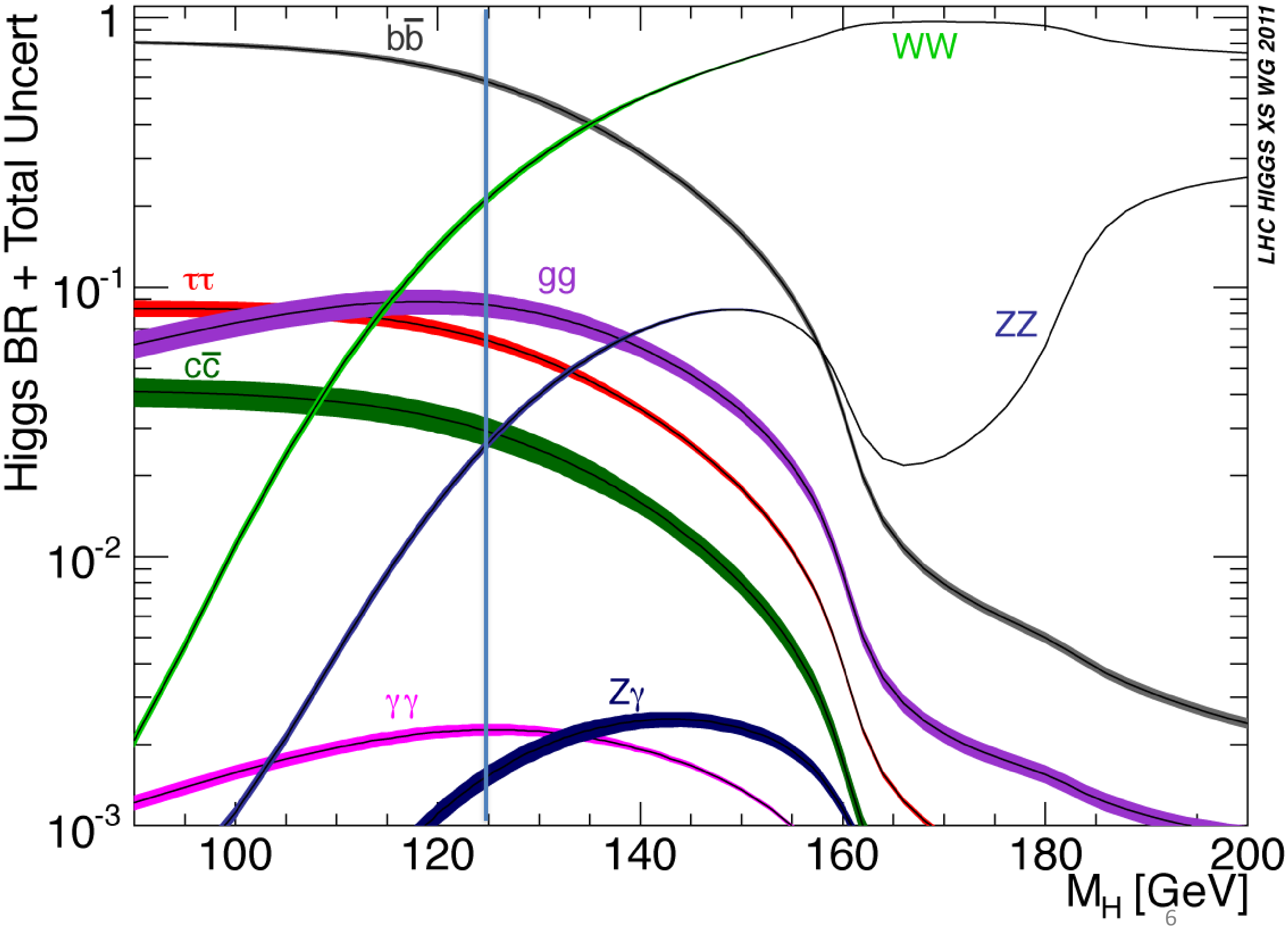
Loop-induced decays



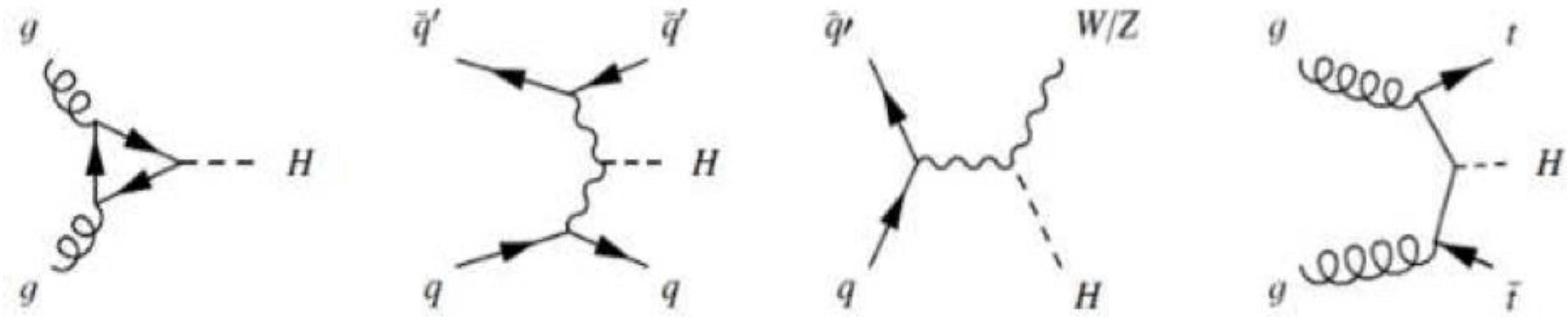




Main Decay Modes



Higgs production at Hadron Colliders

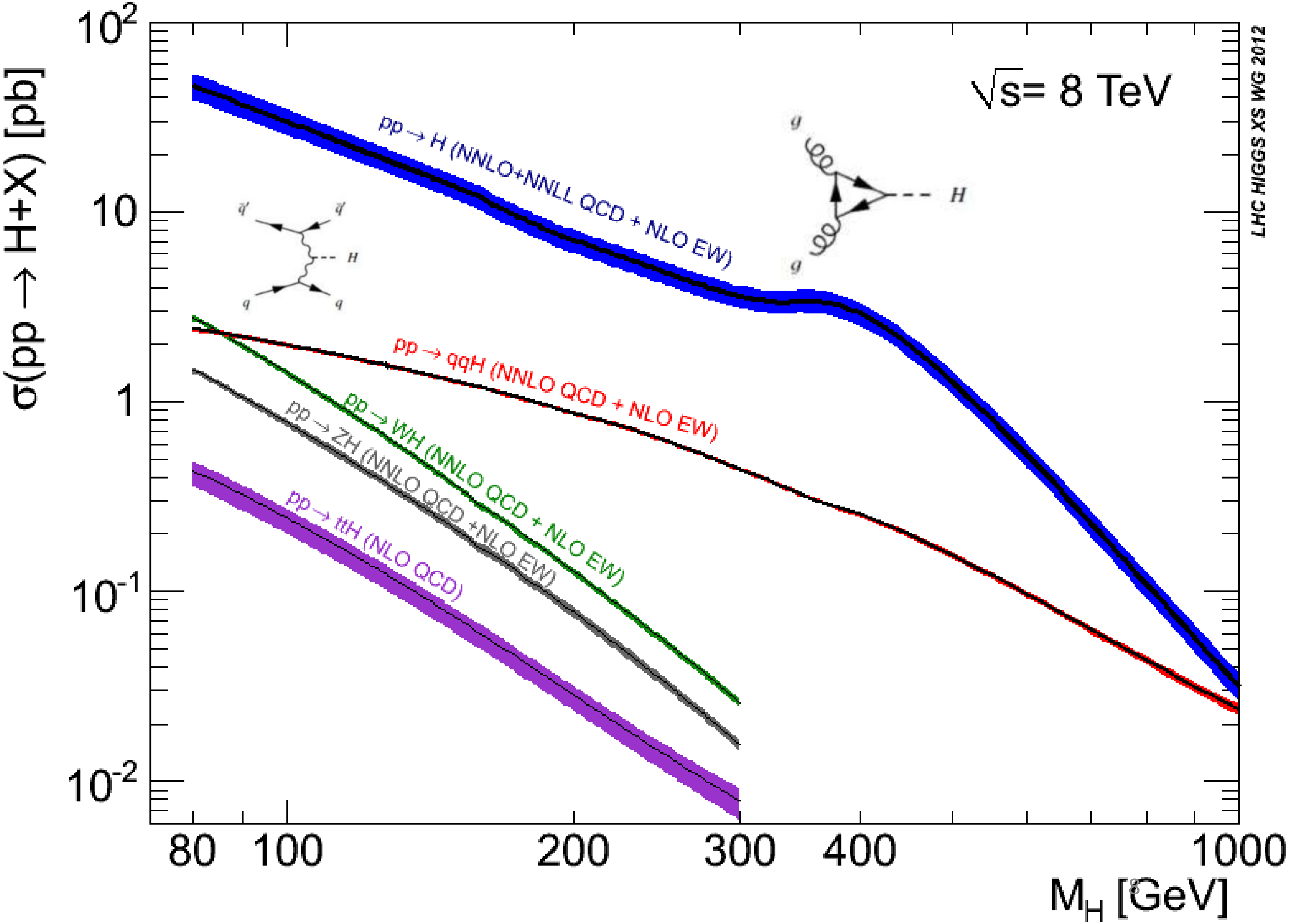


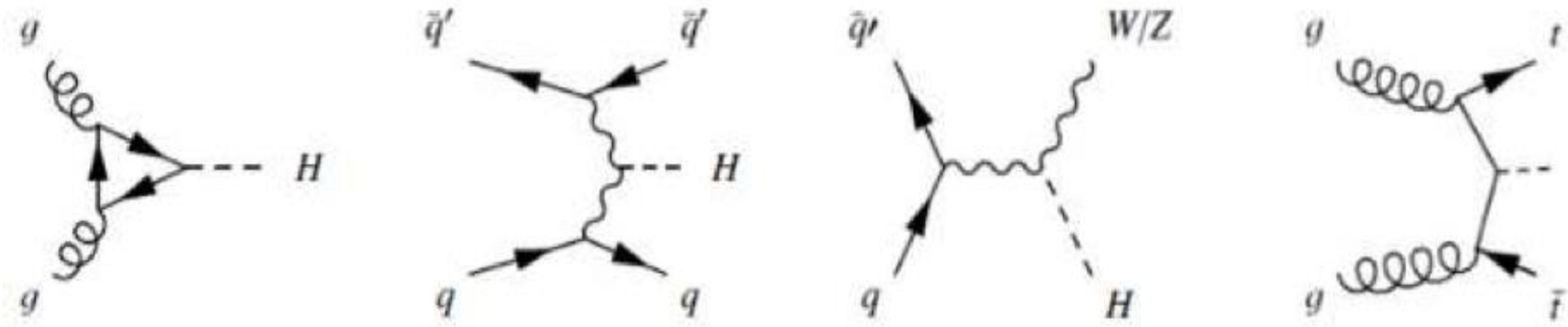
Gluon-gluon fusion

Vector Boson Fusion

Associated Production

Higgs Cross-Sections at LHC

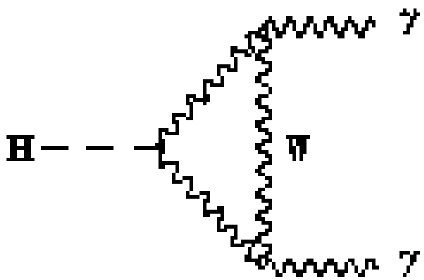


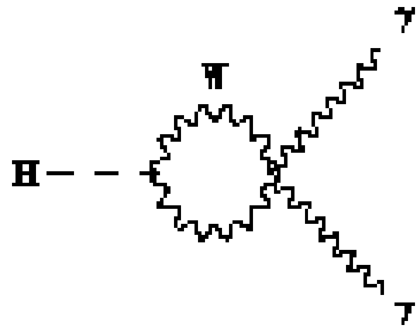


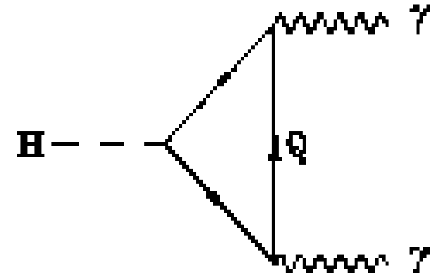
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
*gg*F	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD) + NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW) + APPROX. NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD) + NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD) + NLO(EW)
[*ggZH*]	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

The Main Channels

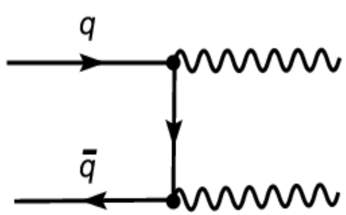
Higgs decay to $\gamma\gamma$

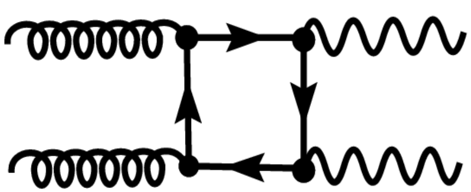


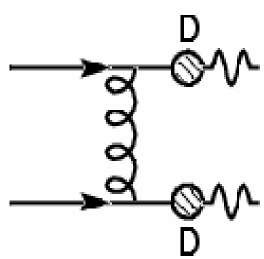


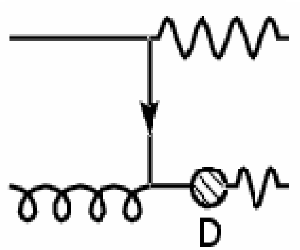


$\gamma\gamma$ Backgrounds

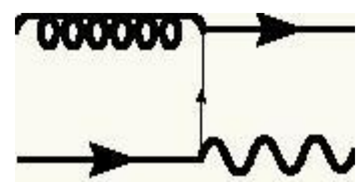


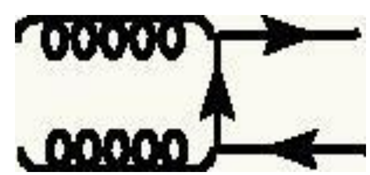






Reducible γj and jj Backgrounds

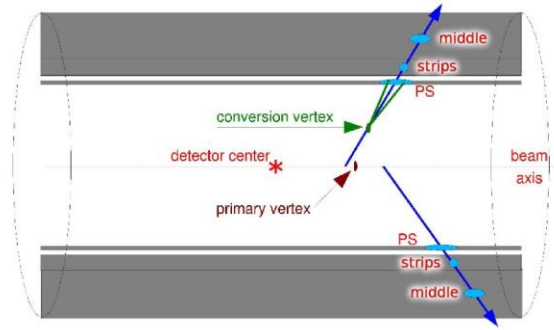




$q \rightarrow \pi^0$

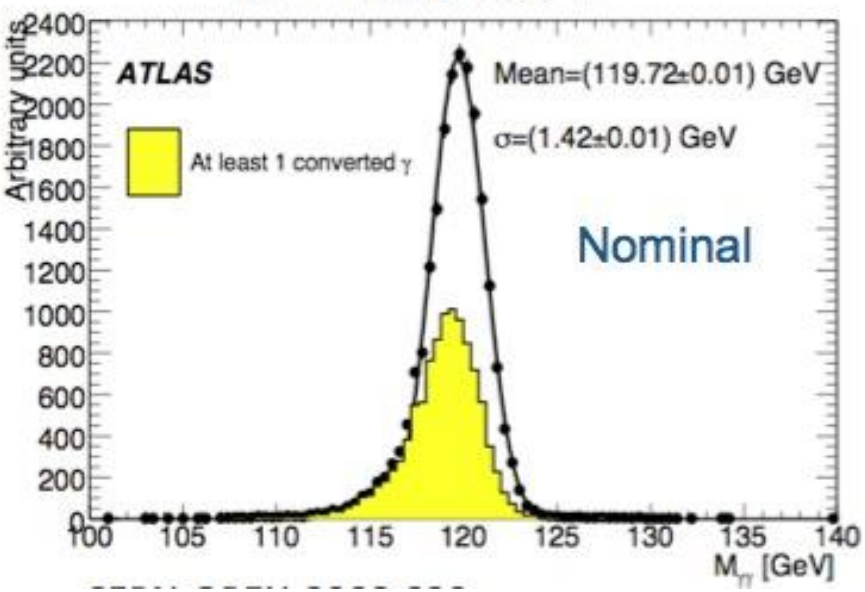
Diphoton Invariant Mass

- Primary vertex reconstruction :
    - Photon calorimeter pointing
    - Use conversion tracks when available

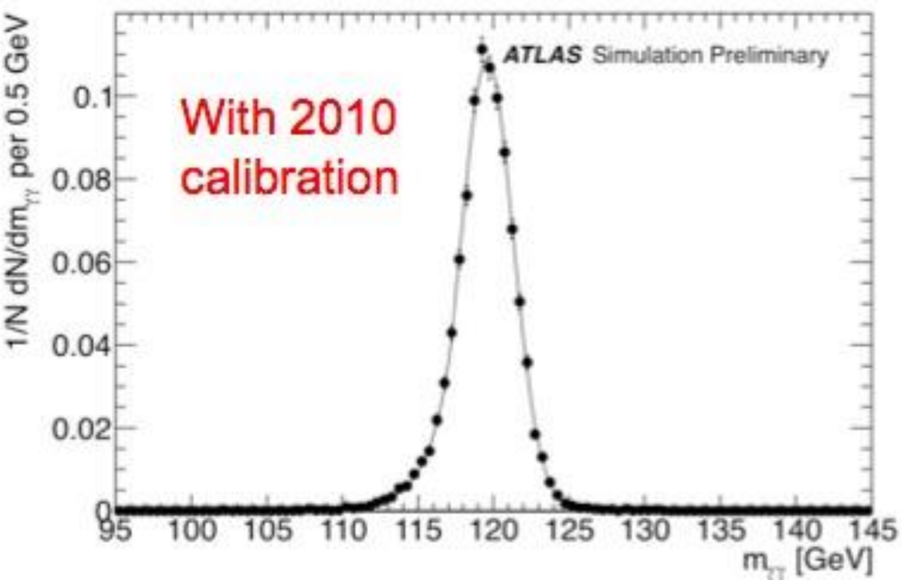


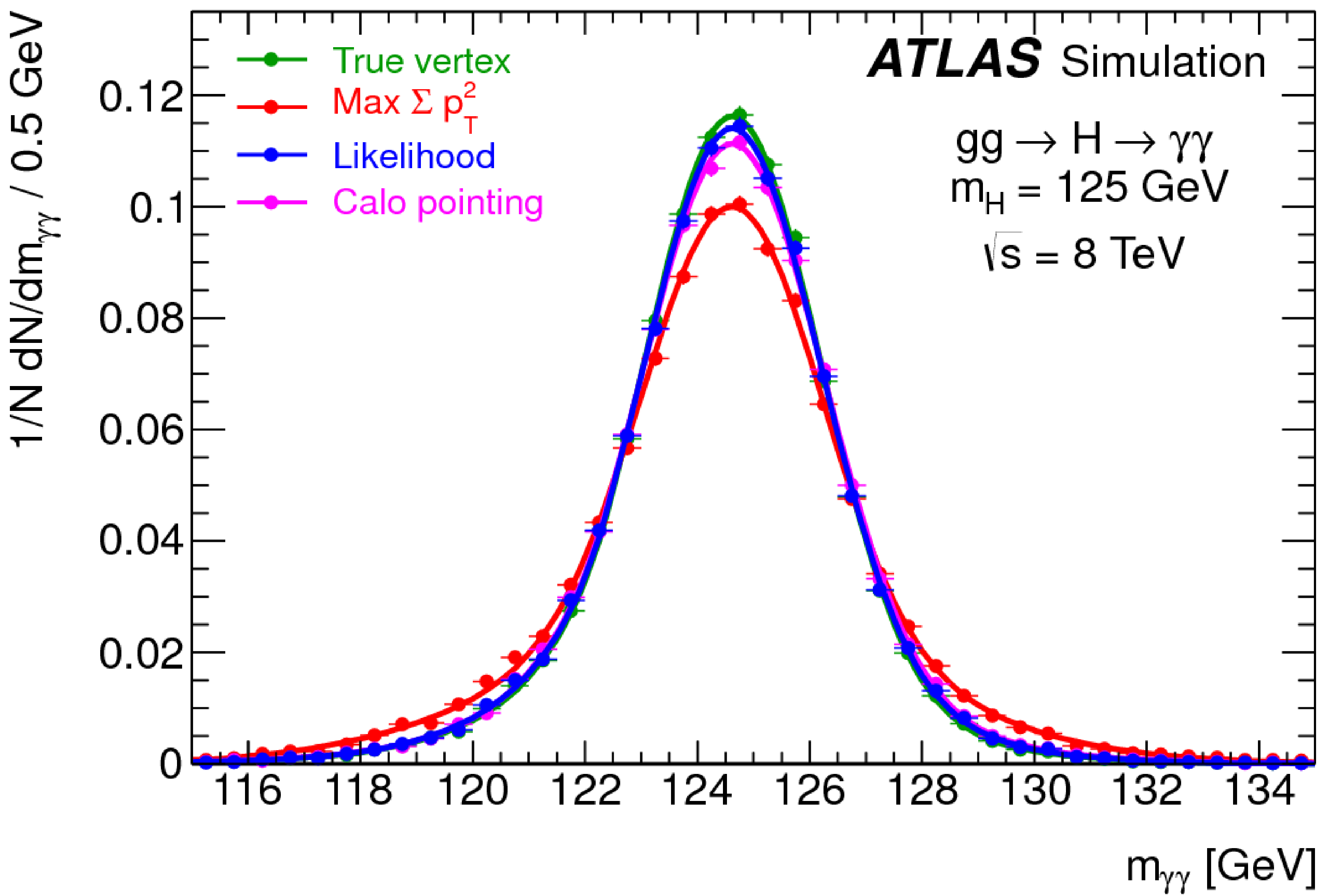
- Energy scale calibration from Z to electrons applied
- Crystal Ball + Gaussian model with narrow widths (of the core of the distribution) :

$\sigma \sim 1.4$ GeV

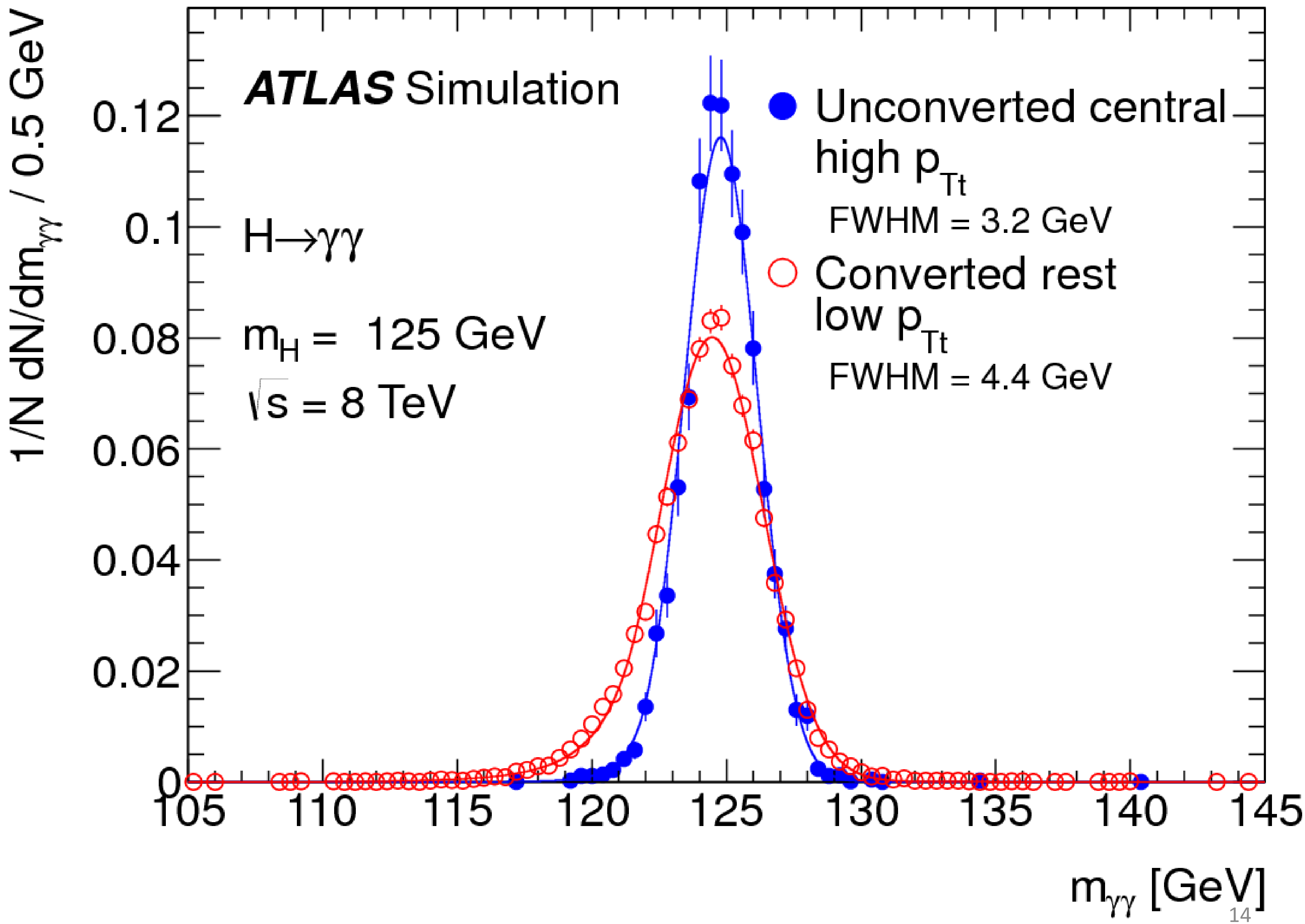


$\sigma \sim 1.7$ GeV



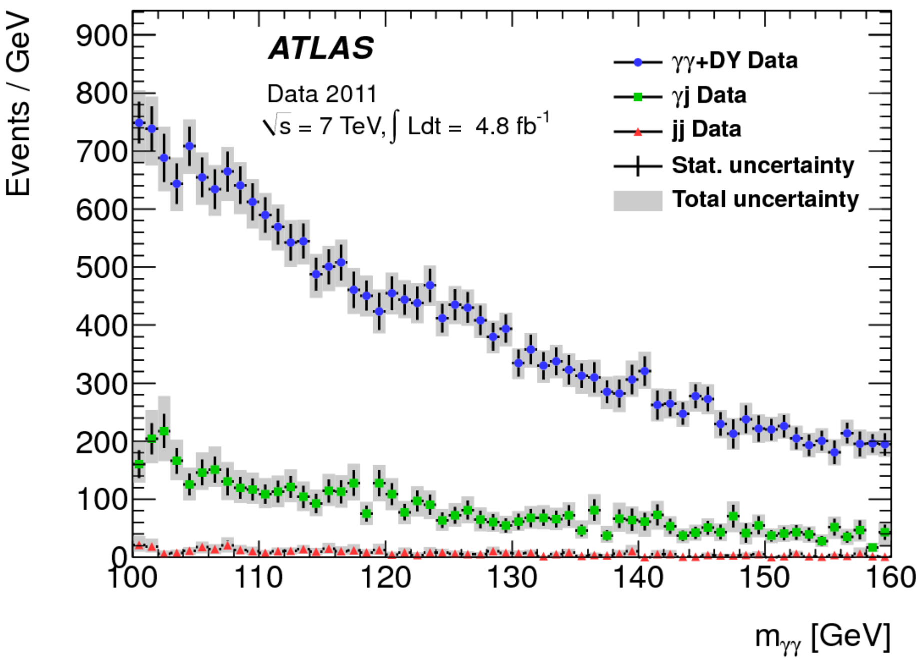


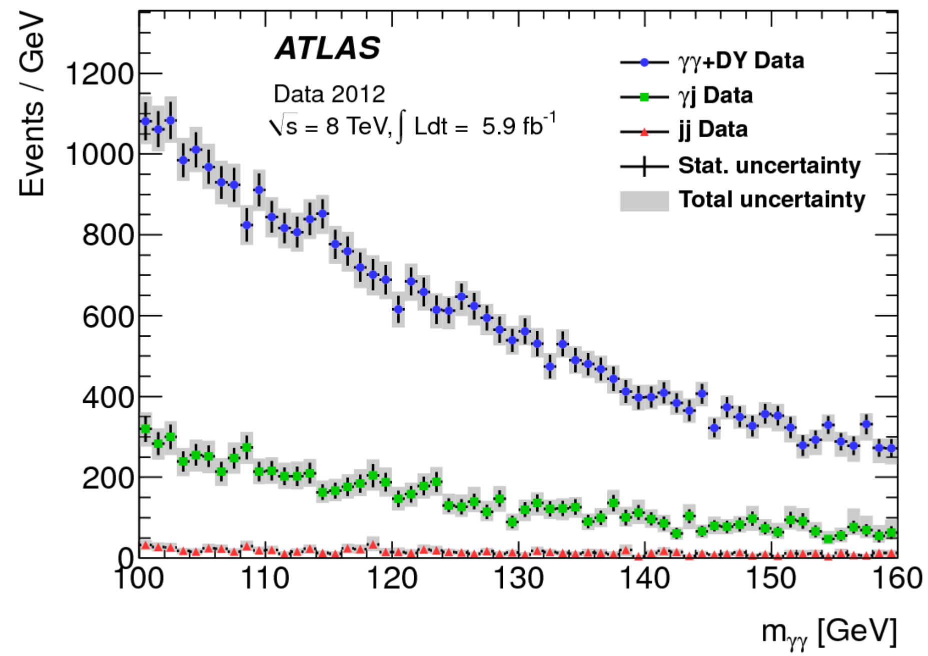
ATLAS Simulation
True vertex
Max $\Sigma\ p_T^2$
Likelihood
Calo pointing
$gg \rightarrow H \rightarrow \gamma\gamma$
m_H = 125 GeV
$\sqrt{s}$ = 8 TeV
$1/N\ dN/dm_{\gamma\gamma}$ / 0.5 GeV
0
0.02
0.04
0.06
0.08
0.1
0.12
116
118
120
122
124
126
128
130
132
134
$m_{\gamma\gamma}$ [GeV]


ATLAS Simulation
H→γγ
m_H = 125 GeV
$\sqrt{s}$ = 8 TeV
Unconverted central high p_{Tt}
FWHM = 3.2 GeV
Converted rest low p_{Tt}
FWHM = 4.4 GeV
1/N dN/d$m_{\gamma\gamma}$ / 0.5 GeV
$m_{\gamma\gamma}$ [GeV]
0
0.02
0.04
0.06
0.08
0.1
0.12
105
110
115
120
125
130
135
140
145

Background Composition

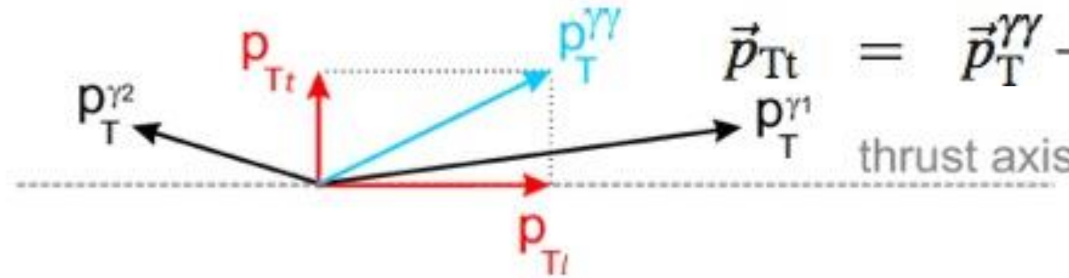
Composition	$\gamma\gamma$	γj	jj	Drell-Yan
Events	$16000 \pm 200 \pm 1100$	$5230 \pm 130 \pm 880$	$1130 \pm 50 \pm 600$	$165 \pm 2 \pm 8$
Relative fraction	$(71 \pm 5)\,\%$	$(23 \pm 4)\,\%$	$(5 \pm 3)\,\%$	$(0.7 \pm 0.1)\,\%$



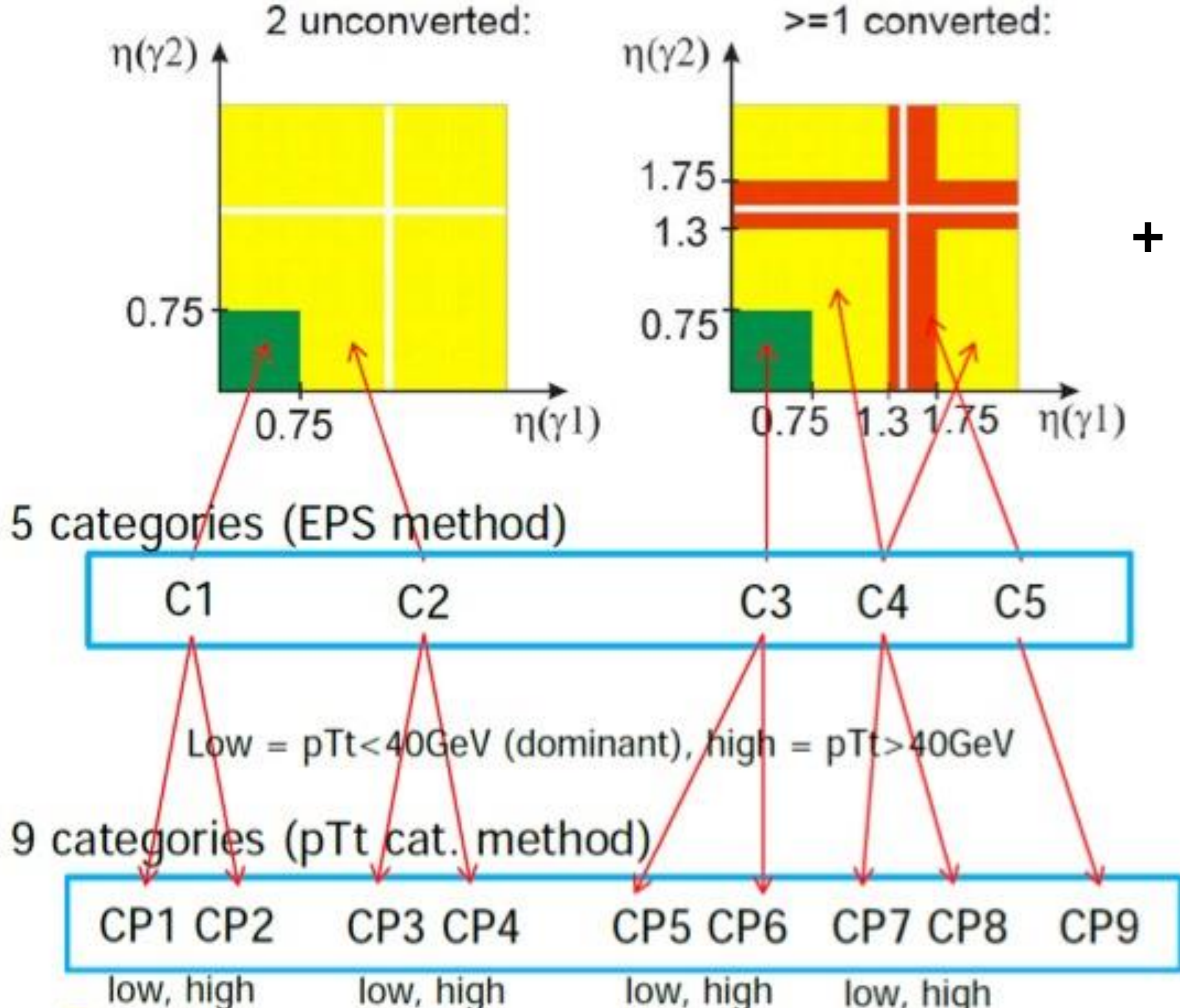


Categorization

$$\hat{t} = \frac{\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}}{|\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}|}$$



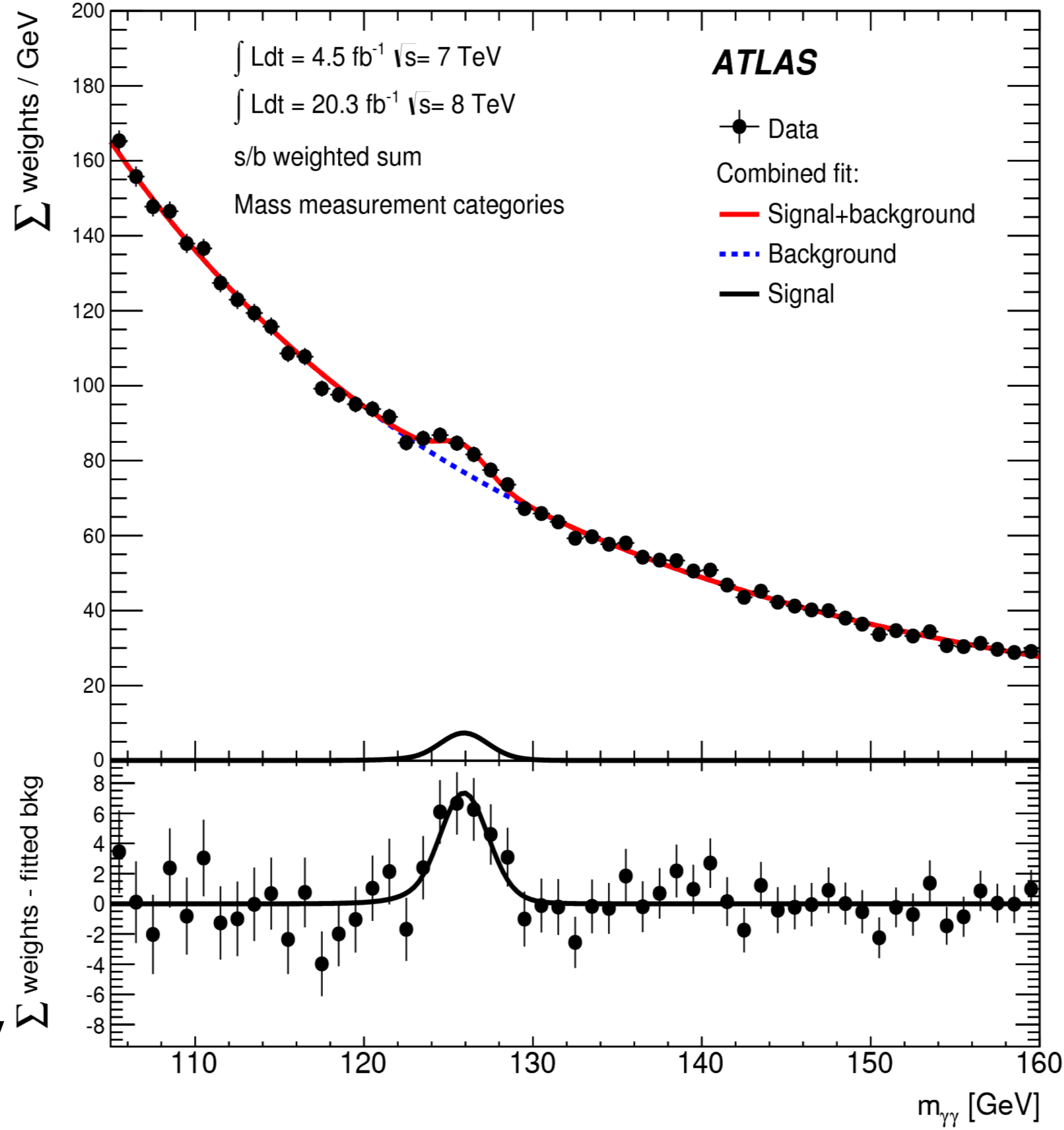
$$\vec{p}_{Tt} = \vec{p}_T^{\gamma\gamma} - (\vec{p}_T^{\gamma\gamma} \cdot \hat{t}) \cdot \hat{t},$$



+ 2j (VBF)

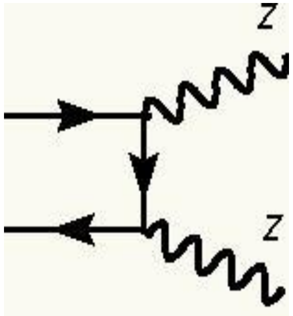
$$H \to \gamma\gamma$$

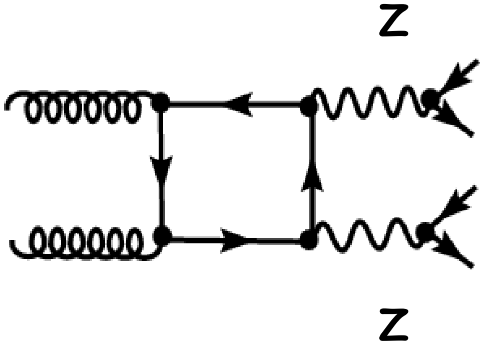
Di-photon Invariant mass distribution; analysis for data, showing weighted data points with errors, and the result of the simultaneous fit to all categories. The fitted signal plus background is shown, along with the background-only component of this fit.



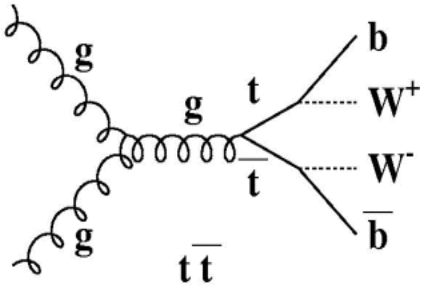
Higgs decay to Z^0Z^0

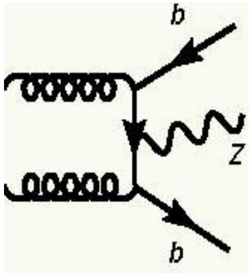
Irreducible Z^0Z^0 backgrounds



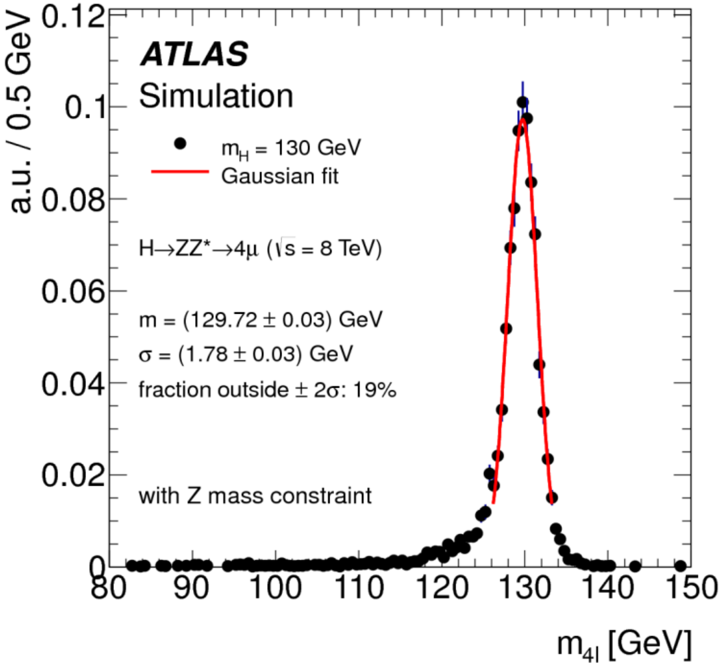


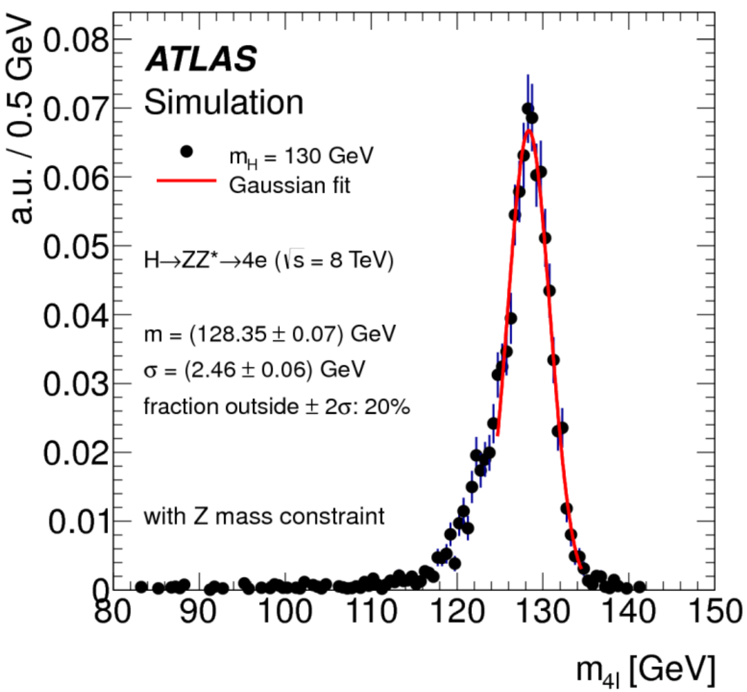
Reducible 4l backgrounds

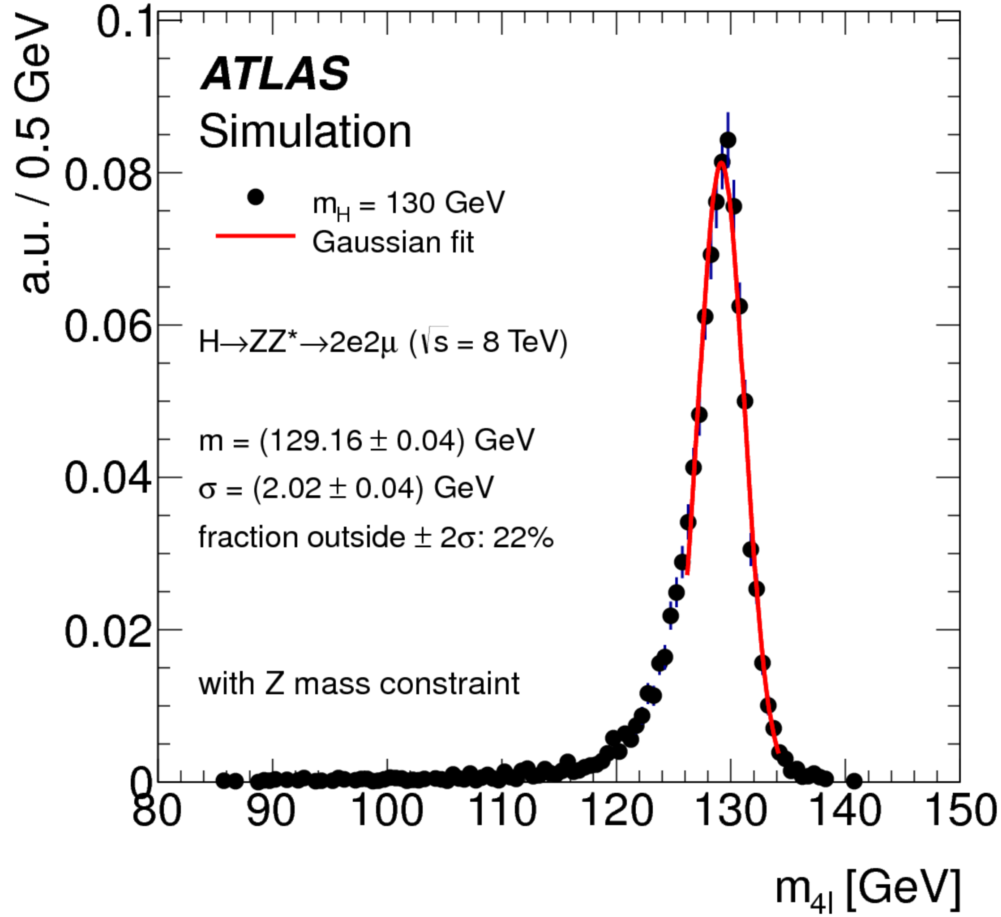




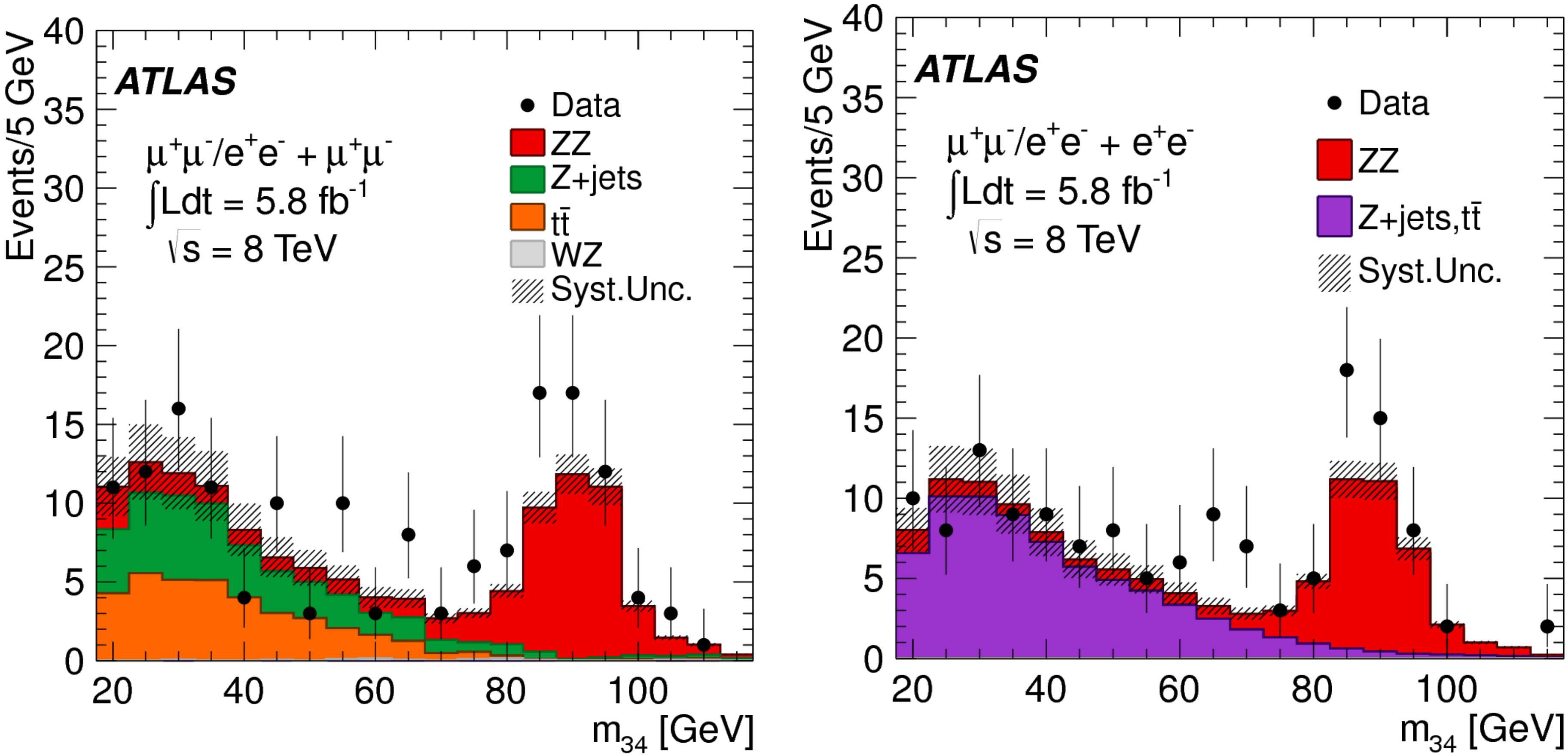
Mass resolution plots after the application of a mass constraint.
Gain in resolution ~15-20%



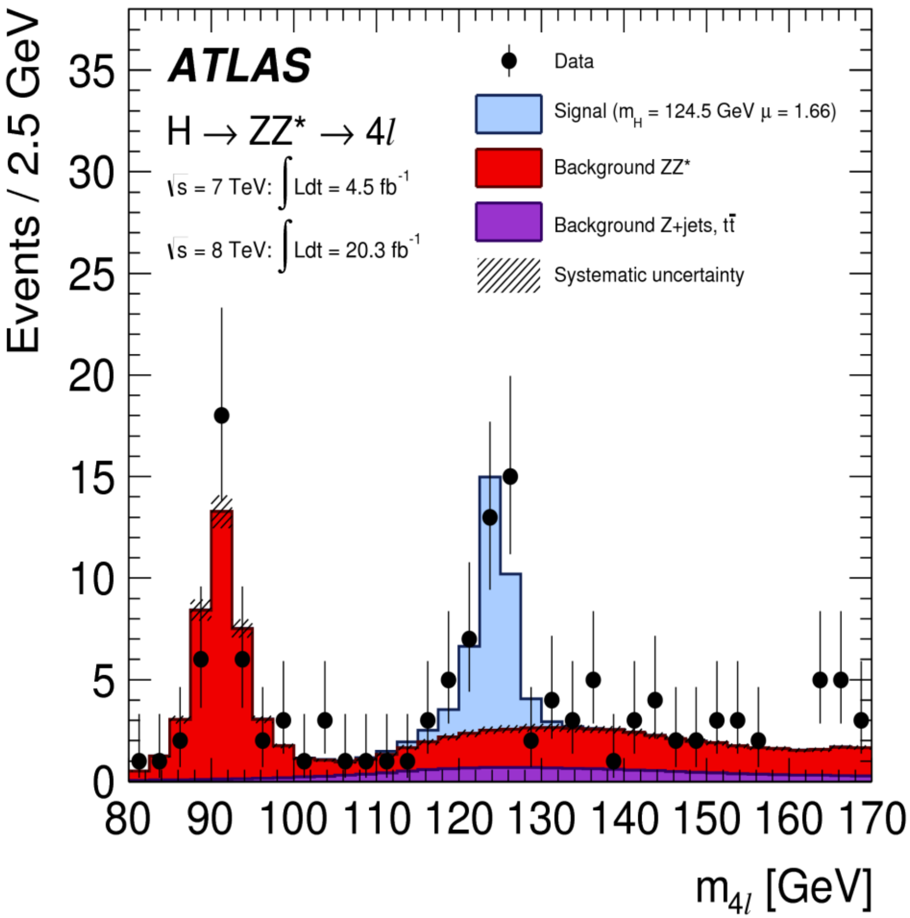




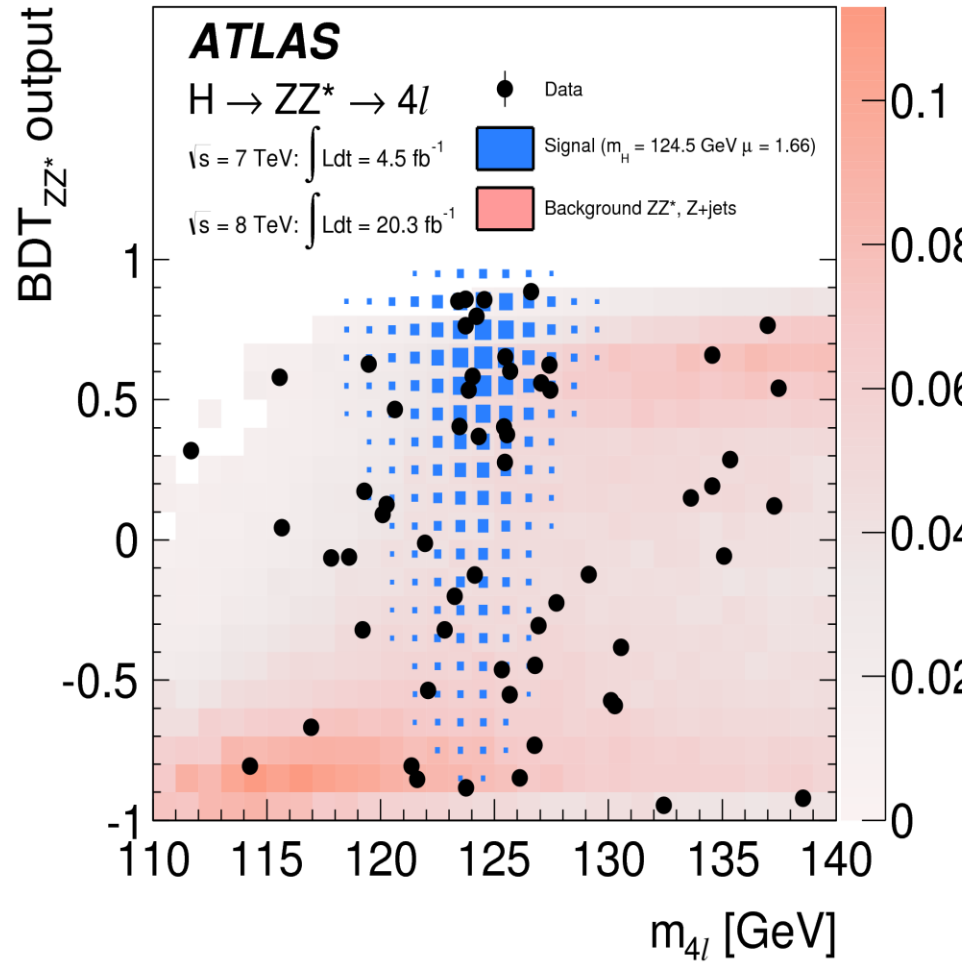
Invariant mass distribution of the second lepton pair: μμ and *ee.* The kinematic selections of the analysis have been applied. Isolation requirements have been applied on the first lepton pair. No charge requirements were applied to the second lepton pair.



$$H \to ZZ^* \to 4\ell$$



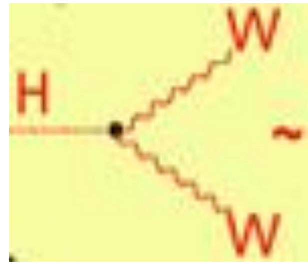
Distribution of the four-lepton invariant mass for the selected candidates in the m_{4l} range 80--170 GeV



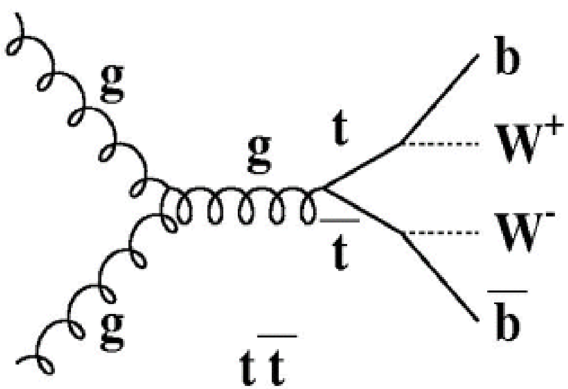
Distribution of the MVA (BDT) ZZ* output, versus m_{4l}; for the selected candidates in the m_{4l} range of 110--140 GeV

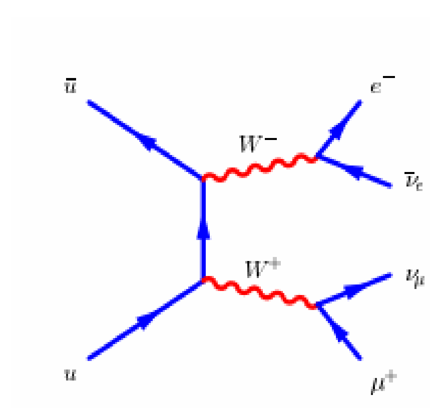
Higgs decay to W^+W^-

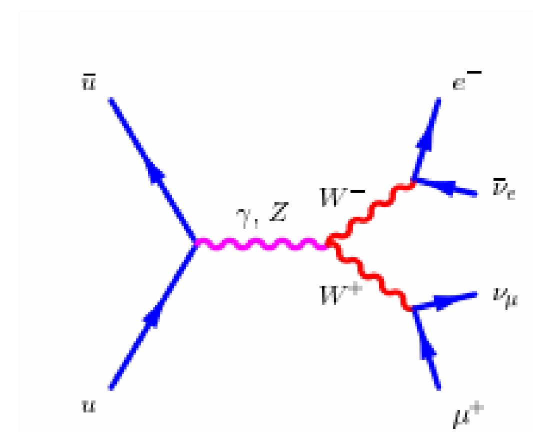
Two leptons + neutrinos
No mass peak
Event counting experiment



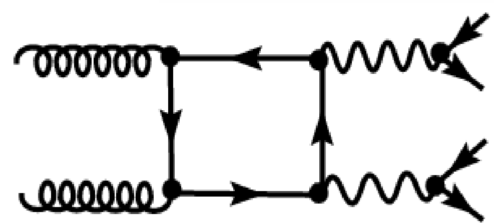
W^+W^- backgrounds







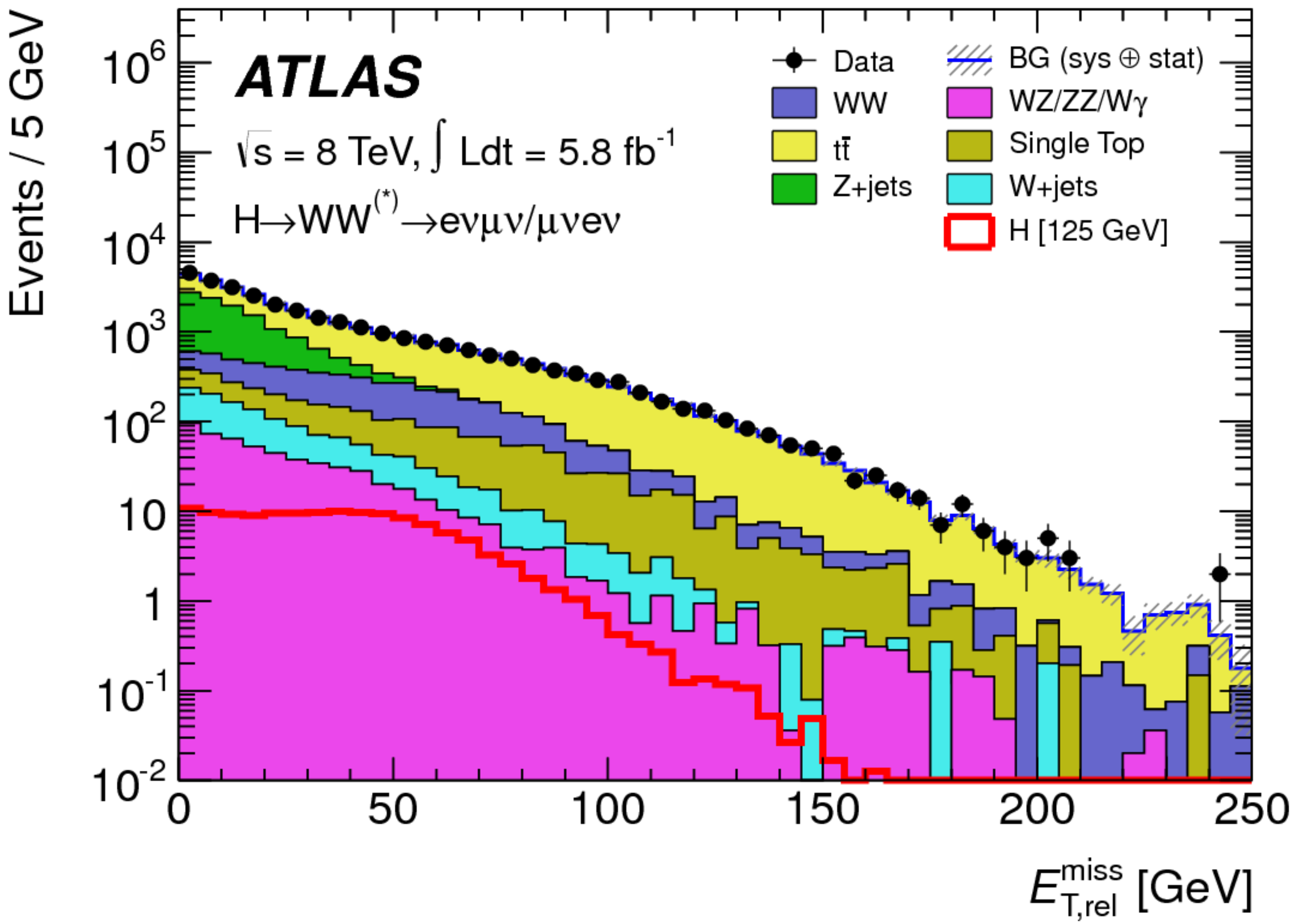
+ Single top
& non-resonant WWbb



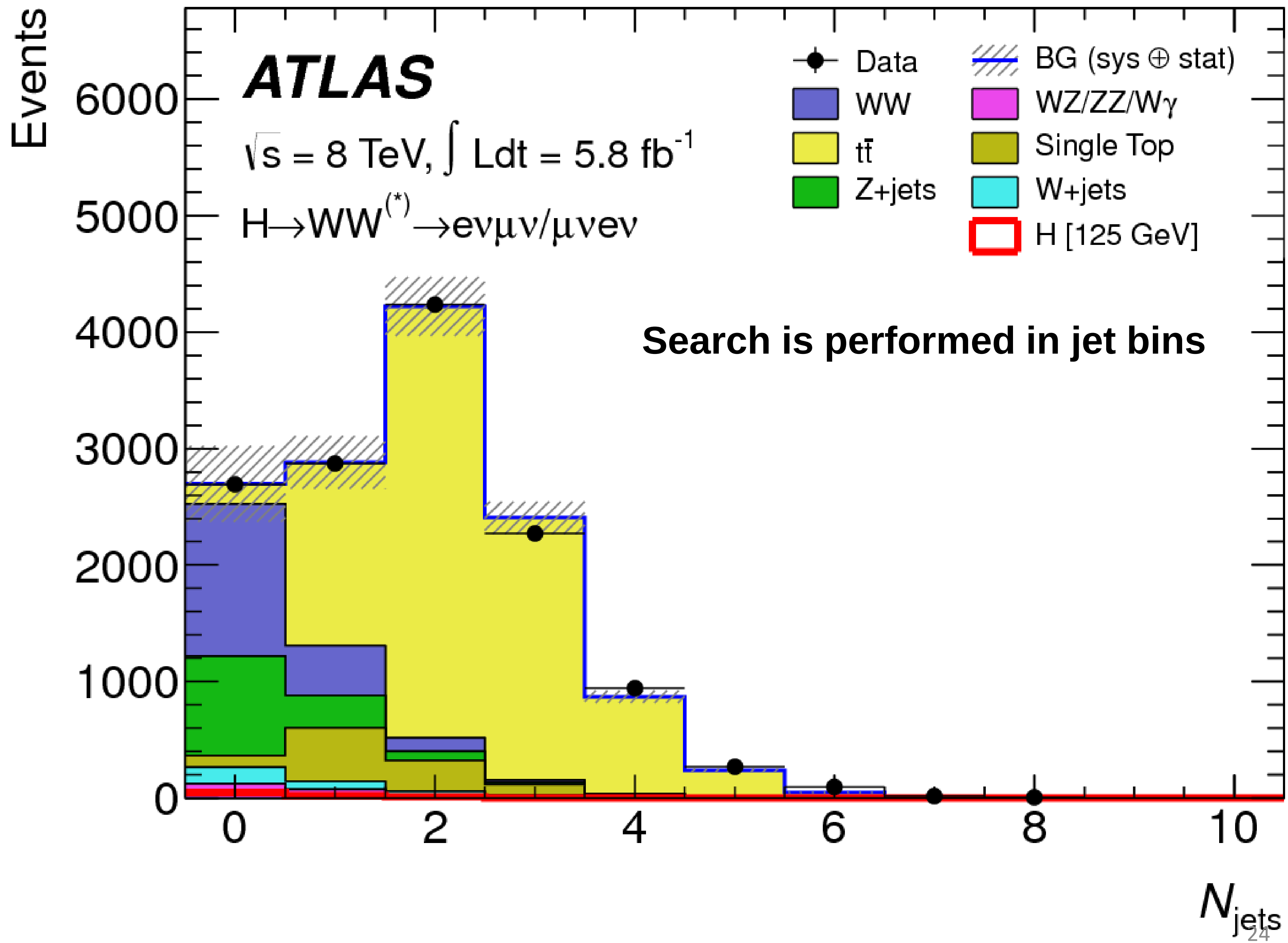
The reconstruction of missing energy is real is a crucial element to the search. Shown are the METRel distribution of the neutrino momenta in the presence of two charged leptons

Overall, good control of the data

$$E_{\mathrm{T,rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \cdot \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$

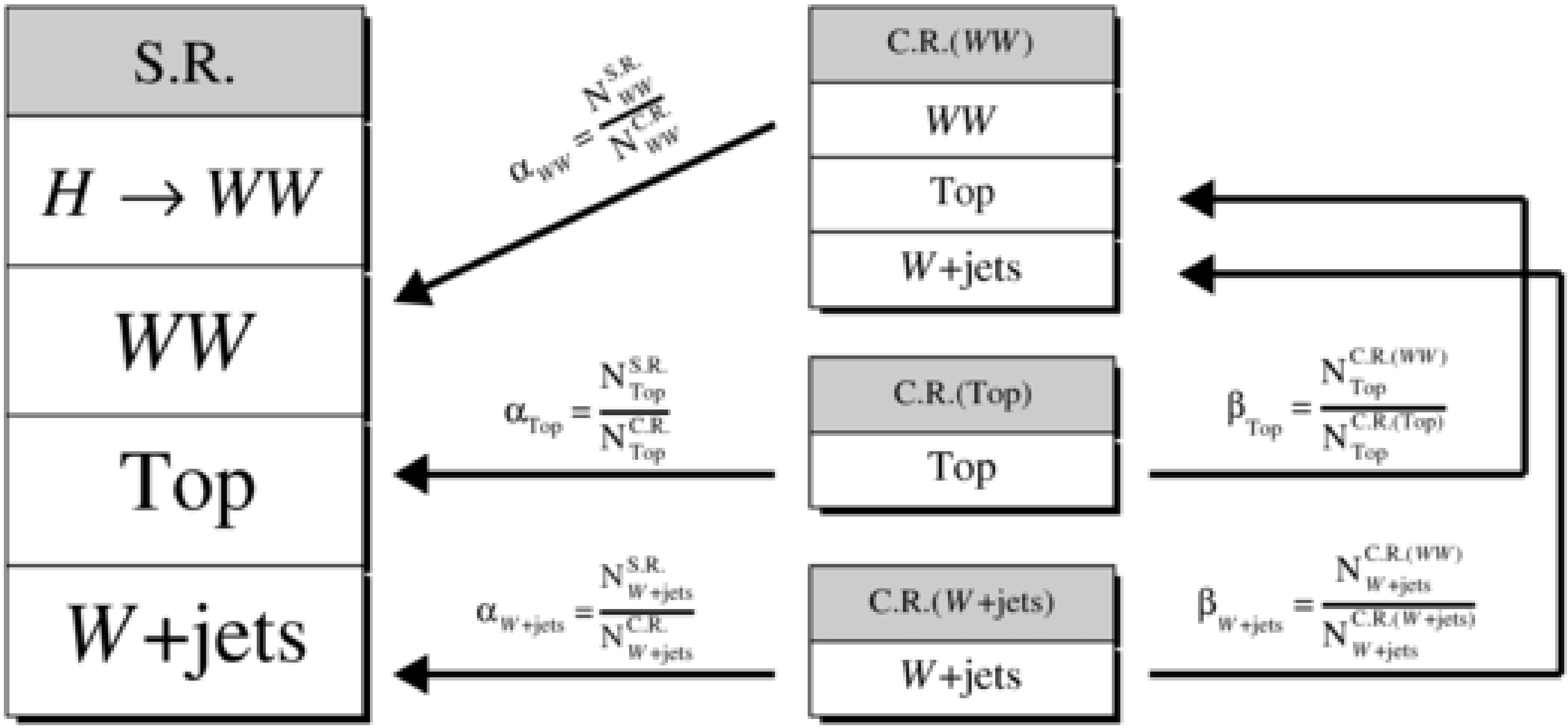


A real challenge this time around!



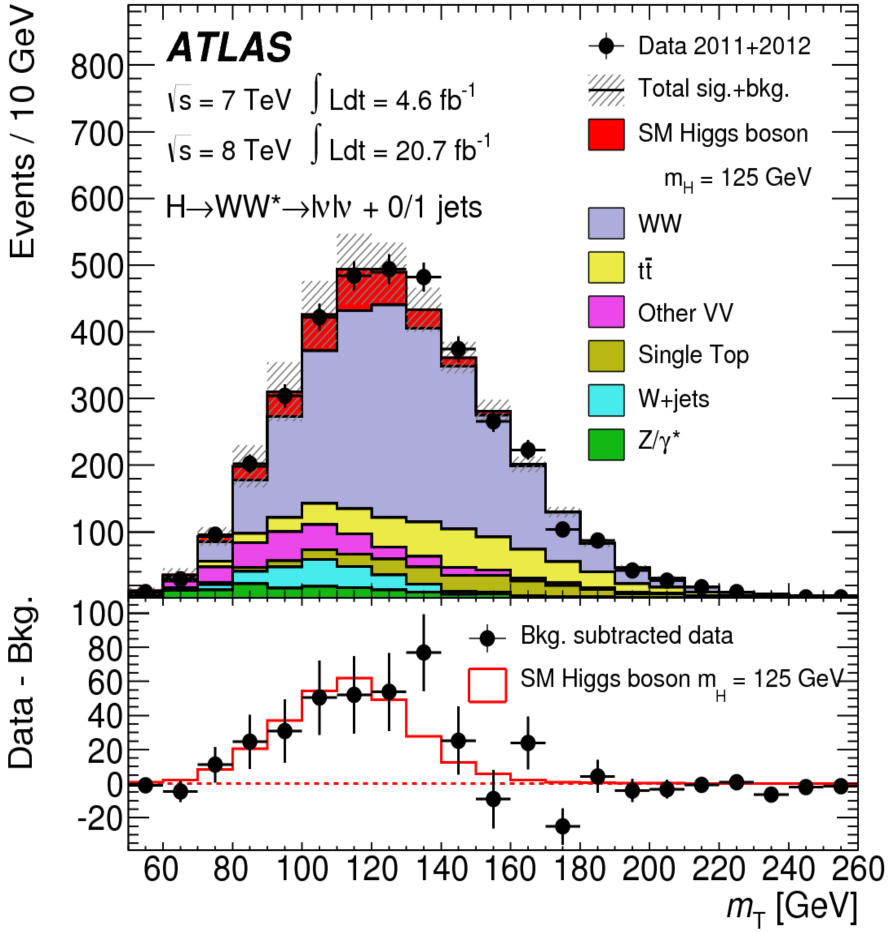
ATLAS
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 5.8 fb^{-1}
H→WW$^{(*)}$→eνμν/μνeν
Data
BG (sys ⊕ stat)
WW
WZ/ZZ/Wγ
$t\bar{t}$
Single Top
Z+jets
W+jets
H [125 GeV]
Search is performed in jet bins
Events
N_{jets}
0
1000
2000
3000
4000
5000
6000
0
2
4
6
8
10

Flow chart for Back. Extraction

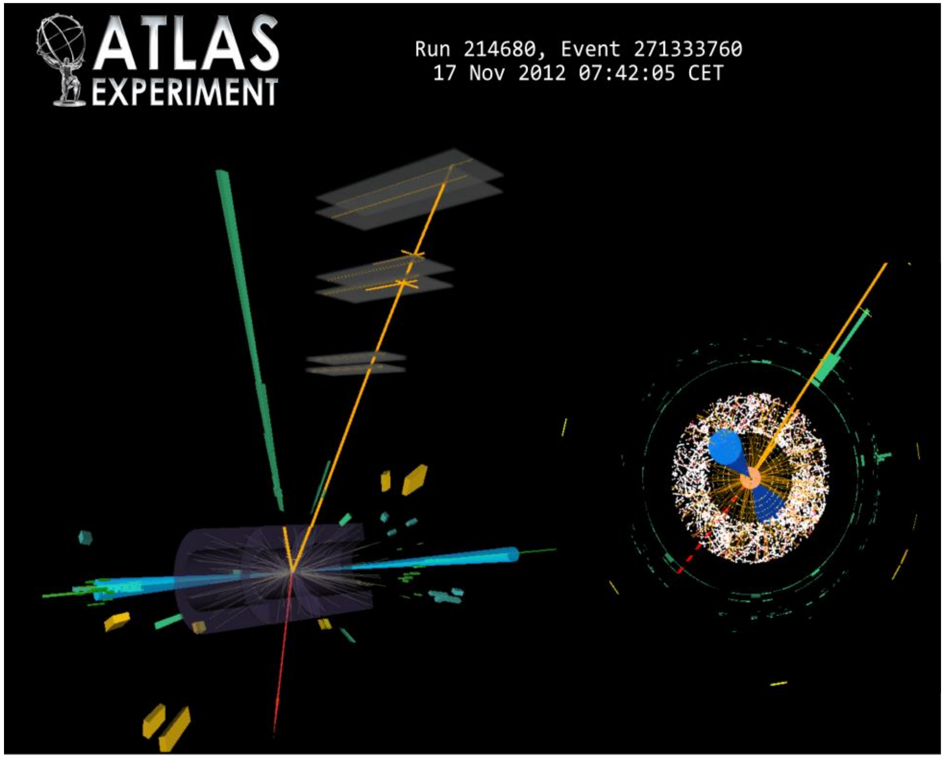


Complete propagation of systematic errors

$$H \to WW^* \to \ell\nu\ell\nu$$

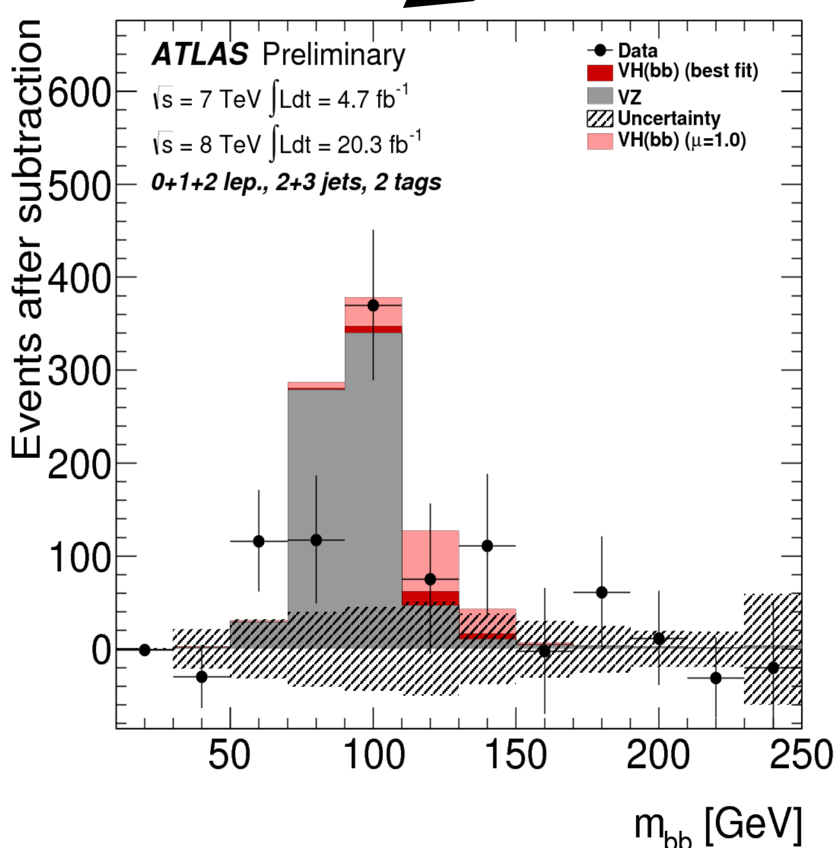


Candidate for VBF production

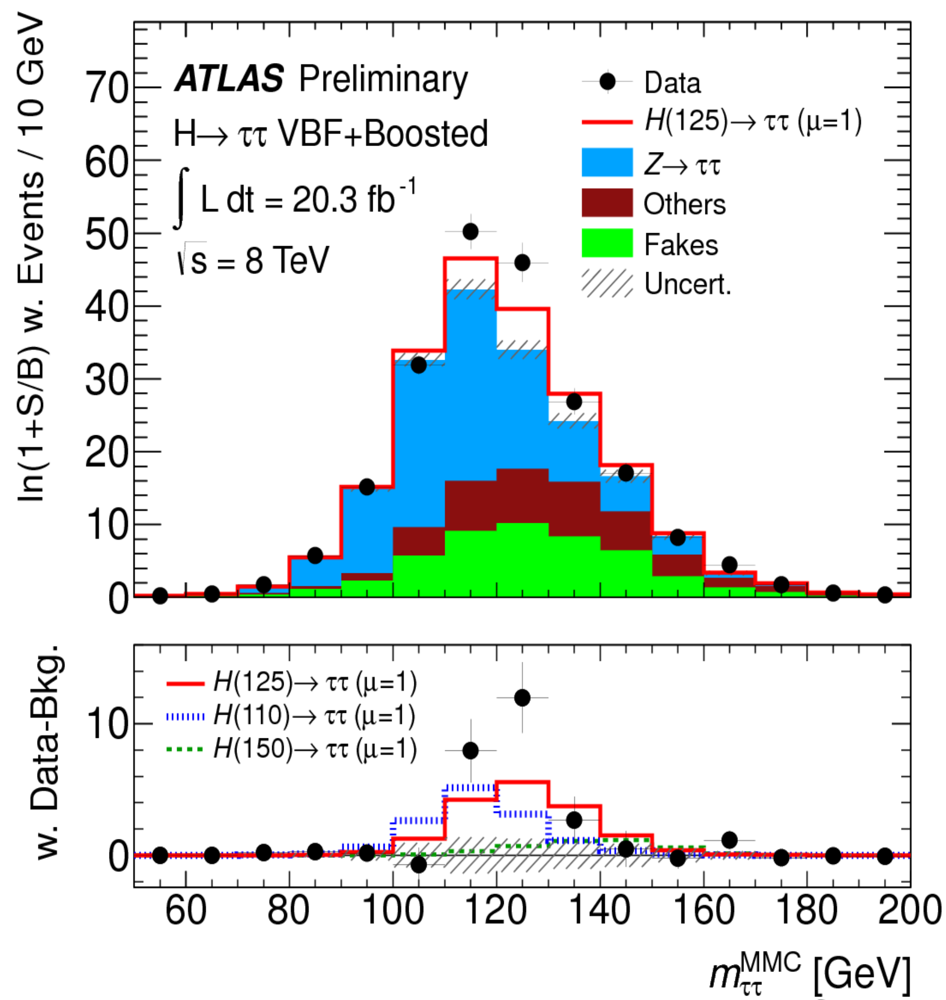


Require two isolated leptons and large MET. Reconstruct transverse mass. Categorization in jet multiplicity.

$VH(\to b\bar{b}), H \to \tau\tau$



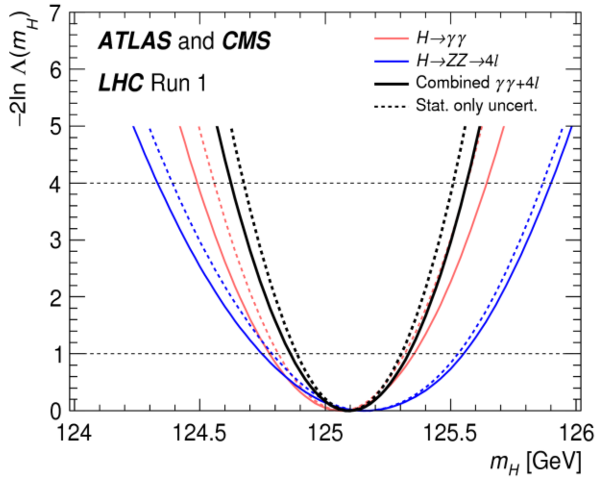
Di-b invariant mass after background subtraction except for di-boson processes, for all channels



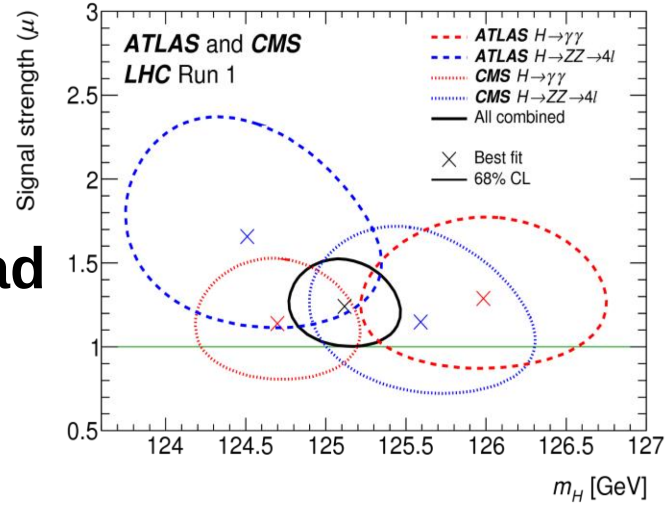
Di-tau invariant mass before and after background extraction

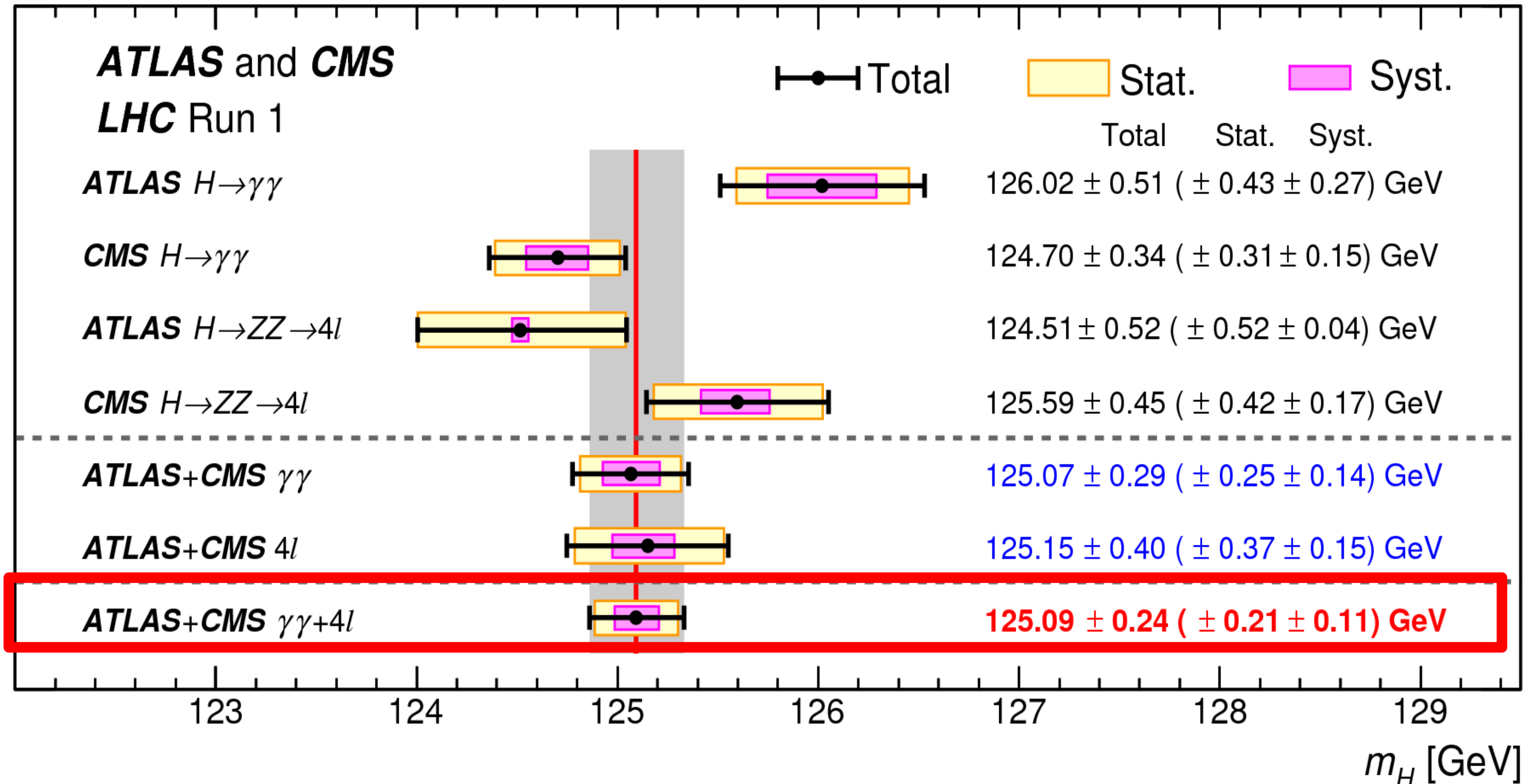
Mass measurement

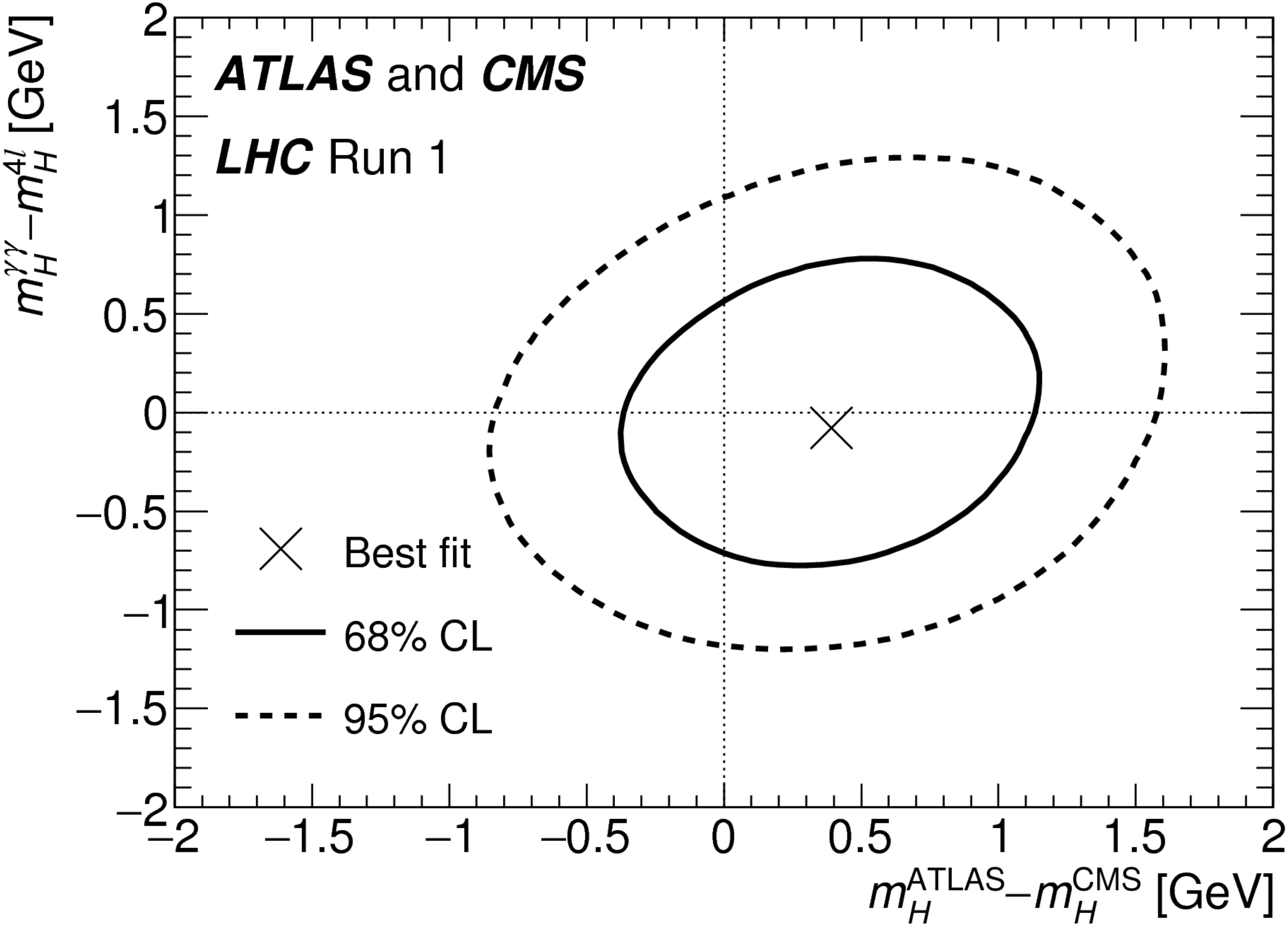
The Higgs boson mass is a fundamental parameter of nature that is not predicted by the theory



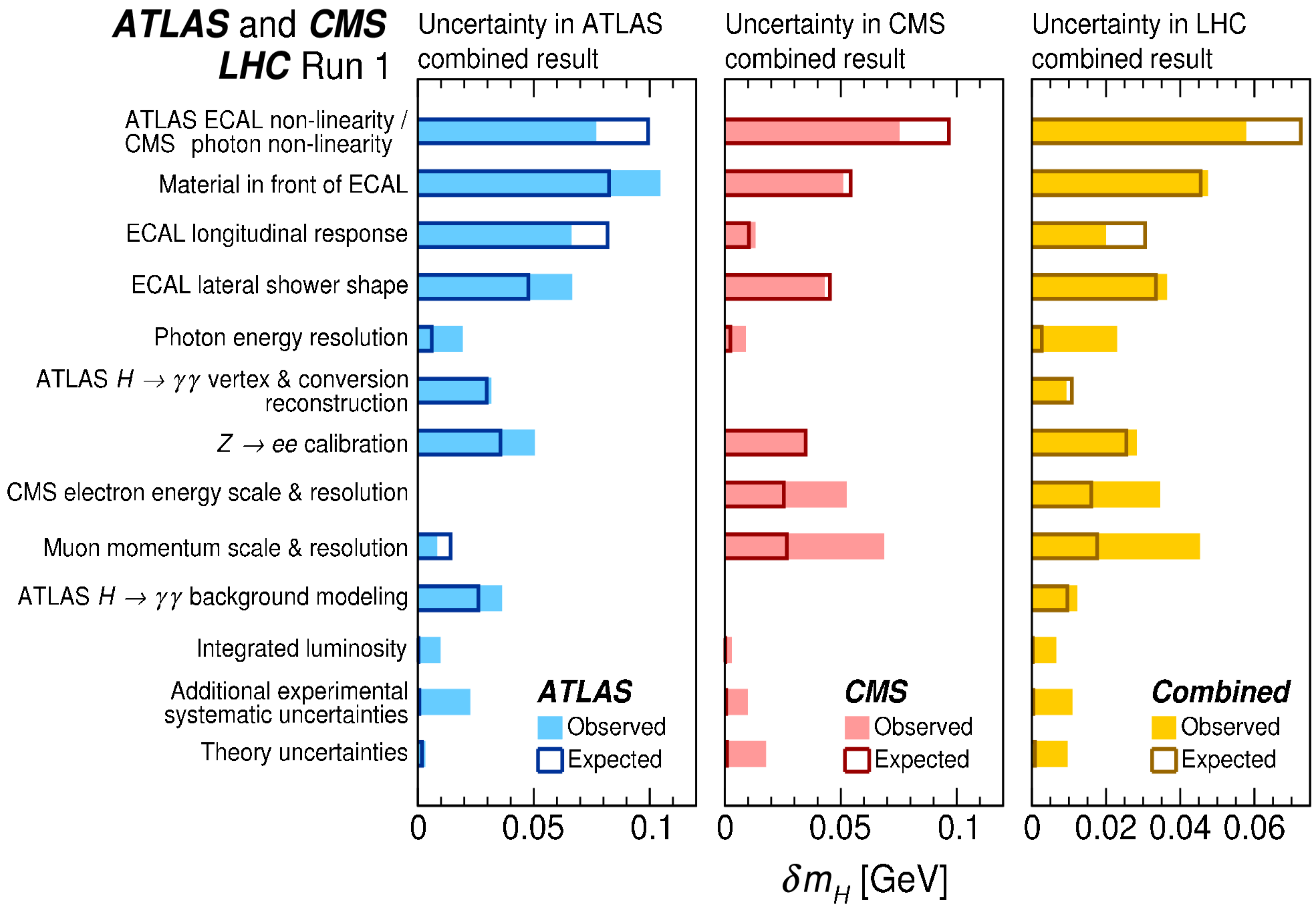
ATLAS and CMS measurements are compatible and lead to 0.2% accuracy measurement







ATLAS and CMS
LHC Run 1
Best fit
68% CL
95% CL
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
$m_H^{\gamma\gamma} - m_H^{4l}$ [GeV]
$m_H^{\mathrm{ATLAS}} - m_H^{\mathrm{CMS}}$ [GeV]



ATLAS and CMS
LHC Run 1
Uncertainty in ATLAS combined result
Uncertainty in CMS combined result
Uncertainty in LHC combined result
ATLAS ECAL non-linearity / CMS photon non-linearity
Material in front of ECAL
ECAL longitudinal response
ECAL lateral shower shape
Photon energy resolution
ATLAS $H \to \gamma\gamma$ vertex & conversion reconstruction
$Z \to ee$ calibration
CMS electron energy scale & resolution
Muon momentum scale & resolution
ATLAS $H \to \gamma\gamma$ background modeling
Integrated luminosity
Additional experimental systematic uncertainties
Theory uncertainties
ATLAS
Observed
Expected
CMS
Observed
Expected
Combined
Observed
Expected
0
0.05
0.1
0
0.05
0.1
0
0.02
0.04
0.06
δm_H [GeV]

Sensitivity to Coupling Strength

Preprint including ATLAS/CMS combination available at arXiv:1606.02266v1

Signal Strengths

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{B}^f}{(\mathrm{B}^f)_{\mathrm{SM}}}$$

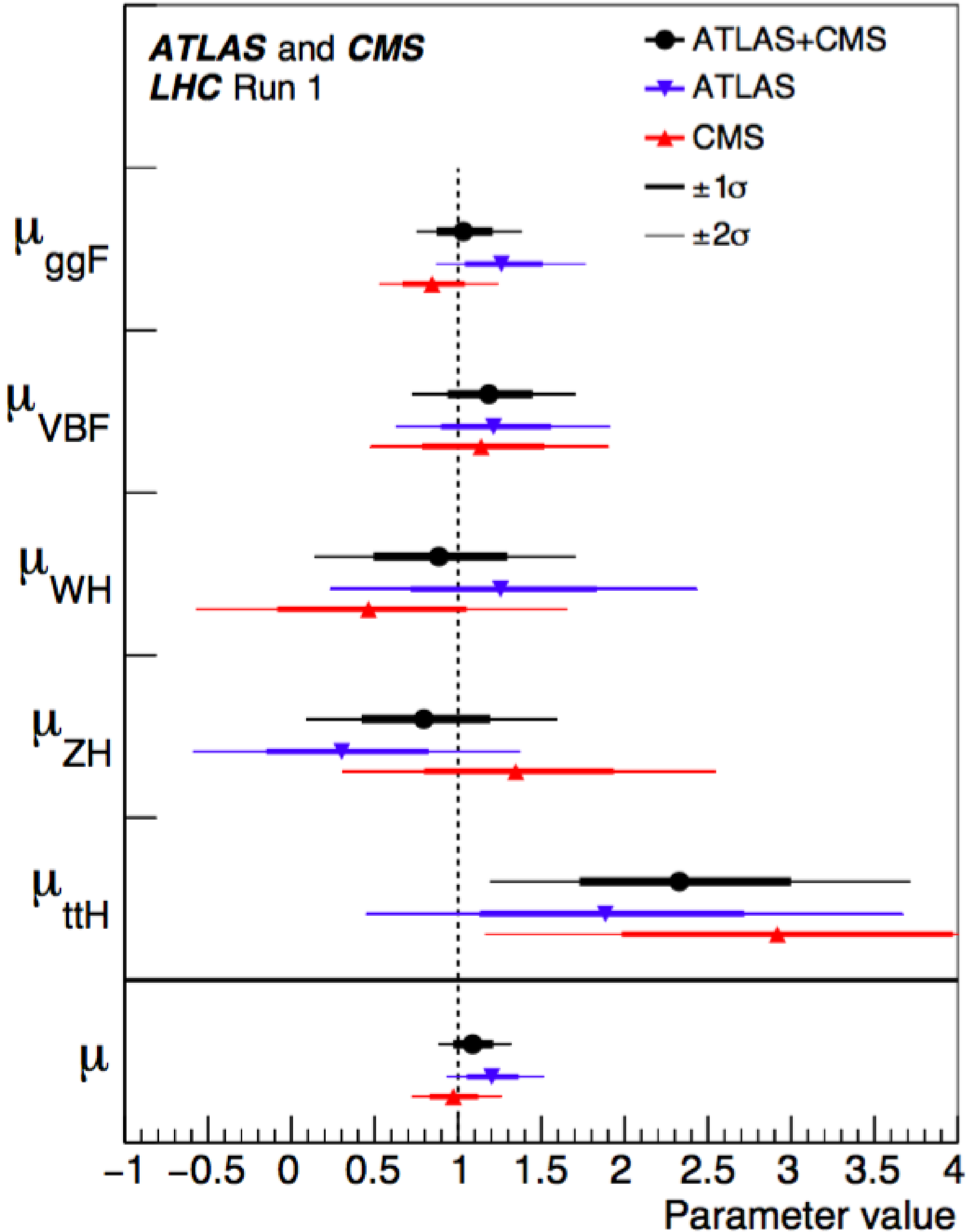
$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

Coupling Modifiers

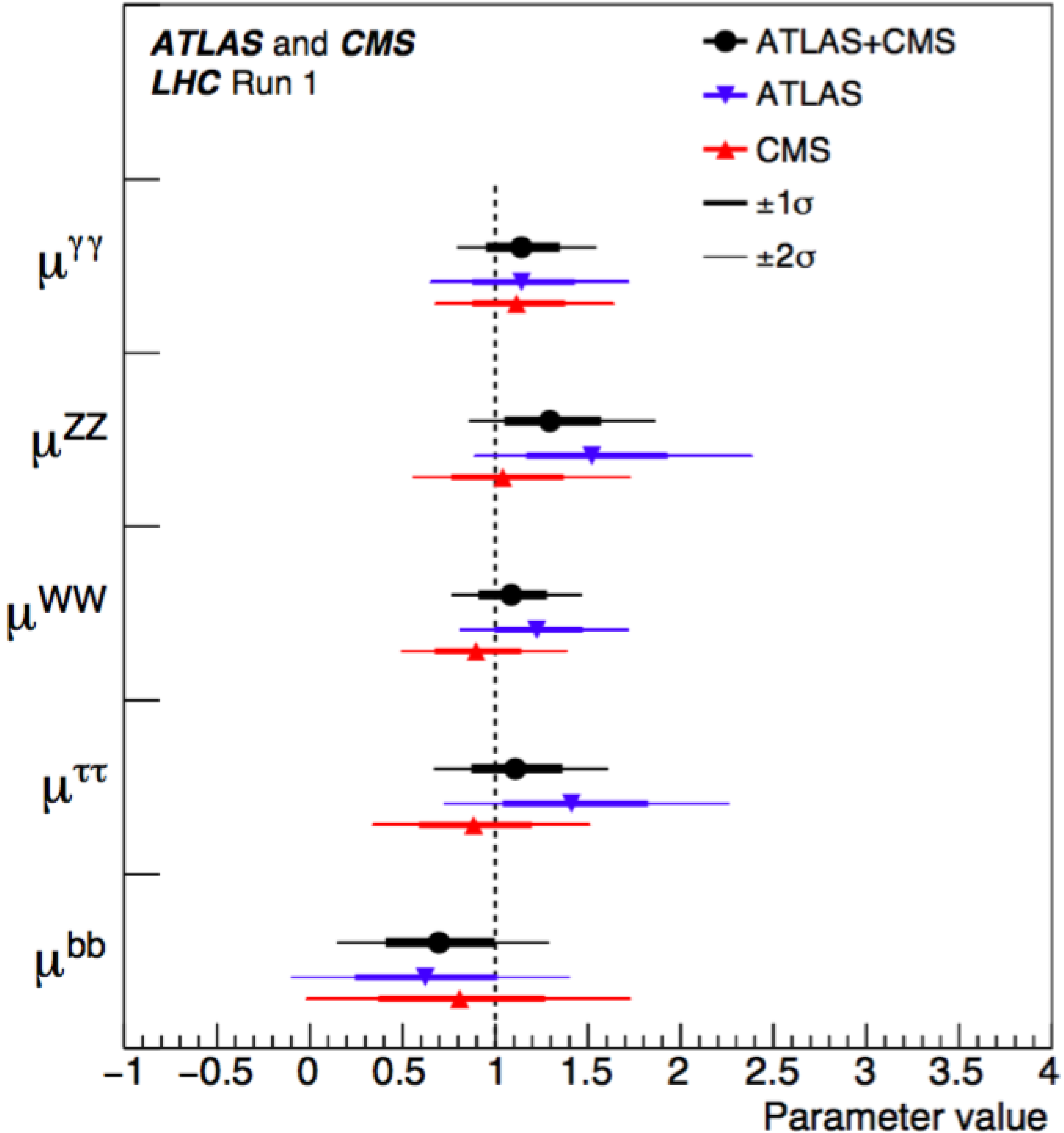
$$\sigma_i \cdot \mathrm{B}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H} \qquad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Channel	References for individual publications		Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ] from results in this paper (Section 5.2)	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[91]	[92]	$1.14\,^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11\,^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	[93]	[94]	$1.52\,^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04\,^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	[95, 96]	[97]	$1.22\,^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90\,^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	[98]	[99]	$1.41\,^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88\,^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	[100]	[101]	$0.62\,^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81\,^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	[102]	[103]	$-0.6\,^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9\,^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	[77, 104, 105]	[107]	$1.9\,^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9\,^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)

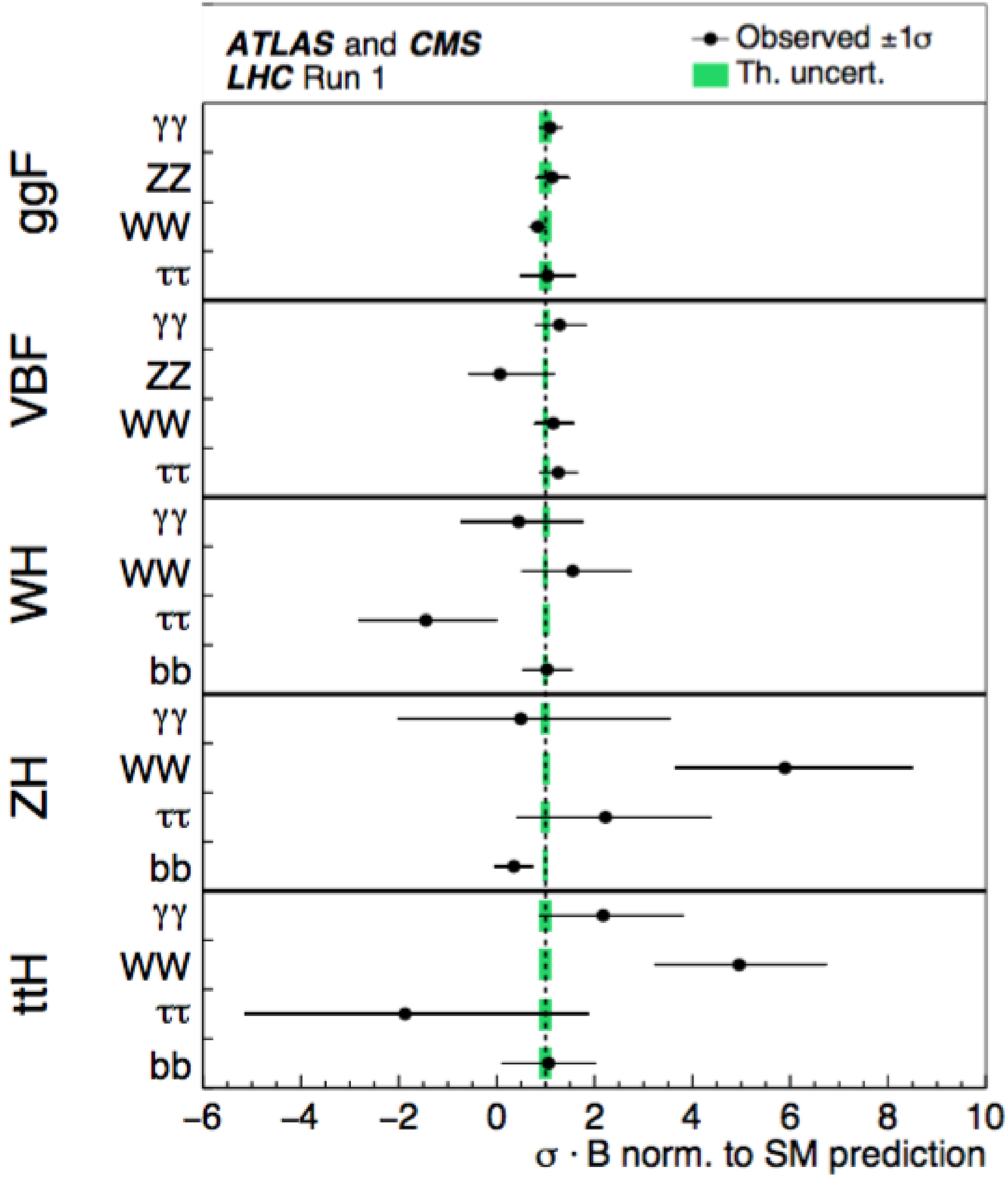


ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
μ ggF
μ VBF
μ WH
μ ZH
μ ttH
μ
−1
−0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
Parameter value



ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
$\mu^{\gamma\gamma}$
μ^{ZZ}
μ^{WW}
$\mu^{\tau\tau}$
μ^{bb}
−1
−0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
Parameter value

Production process		$H \to \gamma\gamma$ [fb]			$H \to ZZ$ [fb]			$H \to WW$ [pb]			$H \to \tau\tau$ [fb]			$H \to bb$ [pb]		
		Best fit value	Uncertainty Stat	Uncertainty Syst	Best fit value	Uncertainty Stat	Uncertainty Syst	Best fit value	Uncertainty Stat	Uncertainty Syst	Best fit value	Uncertainty Stat	Uncertainty Syst	Best fit value	Uncertainty Stat	Uncertainty Syst
ggF	Measured	$48.0\,^{+10.0}_{-9.7}$	$^{+9.4}_{-9.4}$	$^{+3.2}_{-2.3}$	$580\,^{+170}_{-160}$	$^{+170}_{-160}$	$^{+40}_{-40}$	$3.5\,^{+0.7}_{-0.7}$	$^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	$1300\,^{+700}_{-700}$	$^{+400}_{-400}$	$^{+500}_{-500}$	–		
		$\left(^{+9.7}_{-9.5}\right)$	$\left(^{+9.4}_{-9.4}\right)$	$\left(^{+2.5}_{-1.6}\right)$	$\left(^{+150}_{-130}\right)$	$\left(^{+140}_{-130}\right)$	$\left(^{+30}_{-20}\right)$	$\left(^{+0.7}_{-0.7}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+0.5}_{-0.5}\right)$	$\left(^{+700}_{-700}\right)$	$\left(^{+400}_{-400}\right)$	$\left(^{+500}_{-500}\right)$	–		
	Predicted	44 ± 5			510 ± 60			4.1 ± 0.5			1210 ± 140			11.0 ± 1.2		
	Ratio	$1.10\,^{+0.23}_{-0.22}$	$^{+0.22}_{-0.21}$	$^{+0.07}_{-0.05}$	$1.13\,^{+0.34}_{-0.31}$	$^{+0.33}_{-0.30}$	$^{+0.09}_{-0.07}$	$0.84\,^{+0.17}_{-0.17}$	$^{+0.12}_{-0.12}$	$^{+0.12}_{-0.11}$	$1.0\,^{+0.6}_{-0.6}$	$^{+0.4}_{-0.4}$	$^{+0.4}_{-0.4}$	–		
VBF	Measured	$4.6\,^{+1.9}_{-1.8}$	$^{+1.8}_{-1.7}$	$^{+0.6}_{-0.5}$	$3\,^{+46}_{-26}$	$^{+46}_{-25}$	$^{+7}_{-7}$	$0.39\,^{+0.14}_{-0.13}$	$^{+0.13}_{-0.12}$	$^{+0.07}_{-0.05}$	$125\,^{+39}_{-37}$	$^{+34}_{-32}$	$^{+19}_{-18}$	–		
		$\left(^{+1.8}_{-1.6}\right)$	$\left(^{+1.7}_{-1.6}\right)$	$\left(^{+0.5}_{-0.4}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+60}_{-39}\right)$	$\left(^{+8}_{-5}\right)$	$\left(^{+0.15}_{-0.13}\right)$	$\left(^{+0.13}_{-0.12}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+39}_{-37}\right)$	$\left(^{+34}_{-32}\right)$	$\left(^{+19}_{-18}\right)$	–		
	Predicted	3.60 ± 0.20			42.2 ± 2.0			0.341 ± 0.017			100 ± 6			0.91 ± 0.04		
	Ratio	$1.3\,^{+0.5}_{-0.5}$	$^{+0.5}_{-0.5}$	$^{+0.2}_{-0.1}$	$0.1\,^{+1.1}_{-0.6}$	$^{+1.1}_{-0.6}$	$^{+0.2}_{-0.2}$	$1.2\,^{+0.4}_{-0.4}$	$^{+0.4}_{-0.3}$	$^{+0.2}_{-0.2}$	$1.3\,^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$	–		
WH	Measured	$0.7\,^{+2.1}_{-1.9}$	$^{+2.1}_{-1.8}$	$^{+0.3}_{-0.3}$	–			$0.24\,^{+0.18}_{-0.16}$	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.08}$	$-64\,^{+64}_{-61}$	$^{+55}_{-50}$	$^{+32}_{-34}$	$0.42\,^{+0.21}_{-0.20}$	$^{+0.17}_{-0.16}$	$^{+0.12}_{-0.11}$
		$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+1.9}_{-1.8}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.14}_{-0.13}\right)$	$\left(^{+0.08}_{-0.07}\right)$	$\left(^{+67}_{-64}\right)$	$\left(^{+60}_{-54}\right)$	$\left(^{+30}_{-32}\right)$	$\left(^{+0.22}_{-0.21}\right)$	$\left(^{+0.18}_{-0.17}\right)$	$\left(^{+0.12}_{-0.11}\right)$
	Predicted	1.60 ± 0.09			18.8 ± 0.9			0.152 ± 0.007			44.3 ± 2.8			0.404 ± 0.017		
	Ratio	$0.5\,^{+1.3}_{-1.2}$	$^{+1.3}_{-1.1}$	$^{+0.2}_{-0.2}$	–			$1.6\,^{+1.2}_{-1.0}$	$^{+1.0}_{-0.9}$	$^{+0.6}_{-0.5}$	$-1.4\,^{+1.4}_{-1.4}$	$^{+1.2}_{-1.1}$	$^{+0.7}_{-0.8}$	$1.0\,^{+0.5}_{-0.5}$	$^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$
ZH	Measured	$0.5\,^{+2.9}_{-2.4}$	$^{+2.8}_{-2.3}$	$^{+0.5}_{-0.2}$	–			$0.53\,^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$^{+0.10}_{-0.07}$	$58\,^{+56}_{-47}$	$^{+52}_{-44}$	$^{+20}_{-16}$	$0.08\,^{+0.09}_{-0.09}$	$^{+0.08}_{-0.08}$	$^{+0.04}_{-0.04}$
		$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+2.3}_{-1.9}\right)$	$\left(^{+0.1}_{-0.1}\right)$	–			$\left(^{+0.17}_{-0.14}\right)$	$\left(^{+0.16}_{-0.14}\right)$	$\left(^{+0.05}_{-0.04}\right)$	$\left(^{+49}_{-40}\right)$	$\left(^{+46}_{-38}\right)$	$\left(^{+16}_{-12}\right)$	$\left(^{+0.10}_{-0.09}\right)$	$\left(^{+0.09}_{-0.08}\right)$	$\left(^{+0.05}_{-0.04}\right)$
	Predicted	0.94 ± 0.06			11.1 ± 0.6			0.089 ± 0.005			26.1 ± 1.8			0.238 ± 0.012		
	Ratio	$0.5\,^{+3.0}_{-2.5}$	$^{+3.0}_{-2.5}$	$^{+0.5}_{-0.2}$	–			$5.9\,^{+2.6}_{-2.2}$	$^{+2.3}_{-2.1}$	$^{+1.1}_{-0.8}$	$2.2\,^{+2.2}_{-1.8}$	$^{+2.0}_{-1.7}$	$^{+0.8}_{-0.6}$	$0.4\,^{+0.4}_{-0.4}$	$^{+0.3}_{-0.3}$	$^{+0.2}_{-0.2}$
ttH	Measured	$0.64\,^{+0.48}_{-0.38}$	$^{+0.48}_{-0.38}$	$^{+0.07}_{-0.04}$	–			$0.14\,^{+0.05}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$-15\,^{+30}_{-26}$	$^{+26}_{-22}$	$^{+15}_{-15}$	$0.08\,^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.06}_{-0.06}$
		$\left(^{+0.45}_{-0.34}\right)$	$\left(^{+0.44}_{-0.33}\right)$	$\left(^{+0.10}_{-0.05}\right)$	–			$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.02}_{-0.02}\right)$	$\left(^{+31}_{-26}\right)$	$\left(^{+26}_{-22}\right)$	$\left(^{+16}_{-13}\right)$	$\left(^{+0.07}_{-0.06}\right)$	$\left(^{+0.04}_{-0.04}\right)$	$\left(^{+0.06}_{-0.05}\right)$
	Predicted	0.294 ± 0.035			3.4 ± 0.4			0.0279 ± 0.0032			8.1 ± 1.0			0.074 ± 0.008		
	Ratio	$2.2\,^{+1.6}_{-1.3}$	$^{+1.6}_{-1.3}$	$^{+0.2}_{-0.1}$	–			$5.0\,^{+1.8}_{-1.7}$	$^{+1.5}_{-1.5}$	$^{+1.0}_{-0.9}$	$-1.9\,^{+3.7}_{-3.3}$	$^{+3.2}_{-2.7}$	$^{+1.9}_{-1.8}$	$1.1\,^{+1.0}_{-1.0}$	$^{+0.5}_{-0.5}$	$^{+0.8}_{-0.8}$

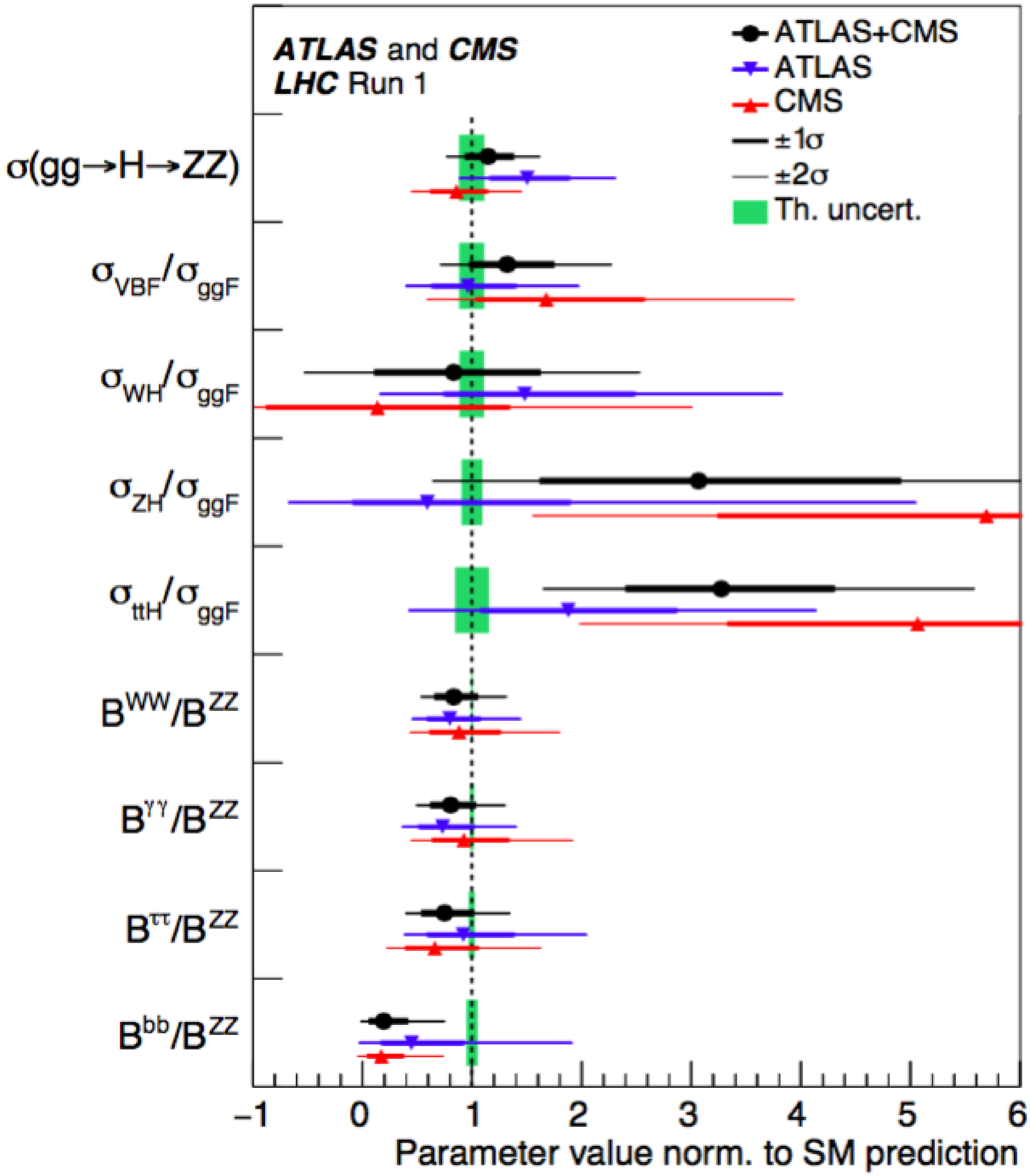


ATLAS and CMS
LHC Run 1
Observed ±1σ
Th. uncert.
ggF
VBF
WH
ZH
ttH
γγ
ZZ
WW
ττ
bb
−6
−4
−2
0
2
4
6
8
10
σ · B norm. to SM prediction

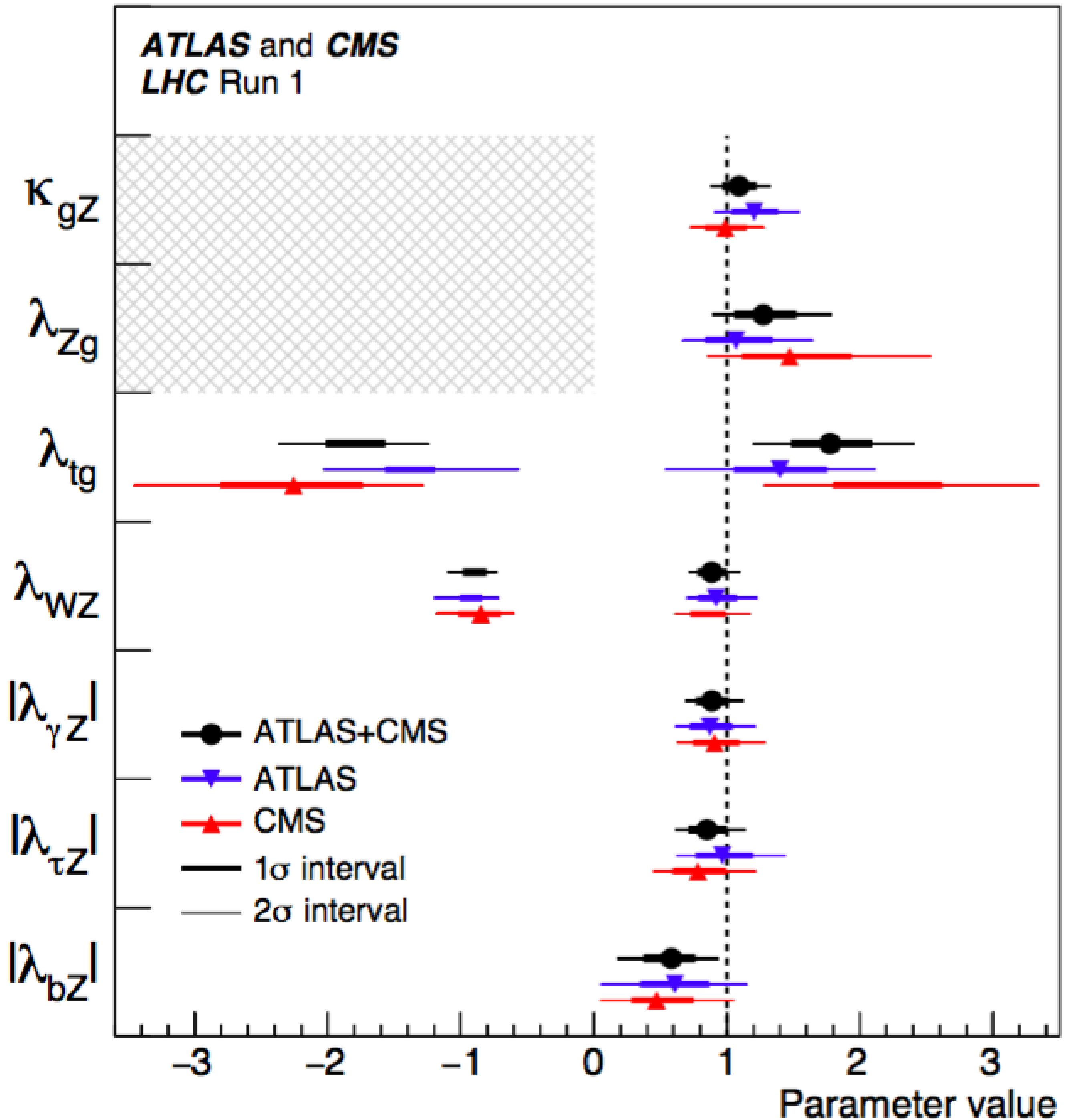
Introducing ratios. Has some advantages such as cancellation of experimental and some theoretical uncertainties, such as the lack of knowledge of total width and others

σ and B ratio parameterisation	Coupling modifier ratio parameterisation
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\sigma_{\mathrm{VBF}}/\sigma_{gg\mathrm{F}}$	
$\sigma_{WH}/\sigma_{gg\mathrm{F}}$	
$\sigma_{ZH}/\sigma_{gg\mathrm{F}}$	$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\sigma_{ttH}/\sigma_{gg\mathrm{F}}$	$\lambda_{tg} = \kappa_t/\kappa_g$
$\mathrm{B}^{WW}/\mathrm{B}^{ZZ}$	$\lambda_{WZ} = \kappa_W/\kappa_Z$
$\mathrm{B}^{\gamma\gamma}/\mathrm{B}^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$\mathrm{B}^{\tau\tau}/\mathrm{B}^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
$\mathrm{B}^{bb}/\mathrm{B}^{ZZ}$	$\lambda_{bZ} = \kappa_b/\kappa_Z$

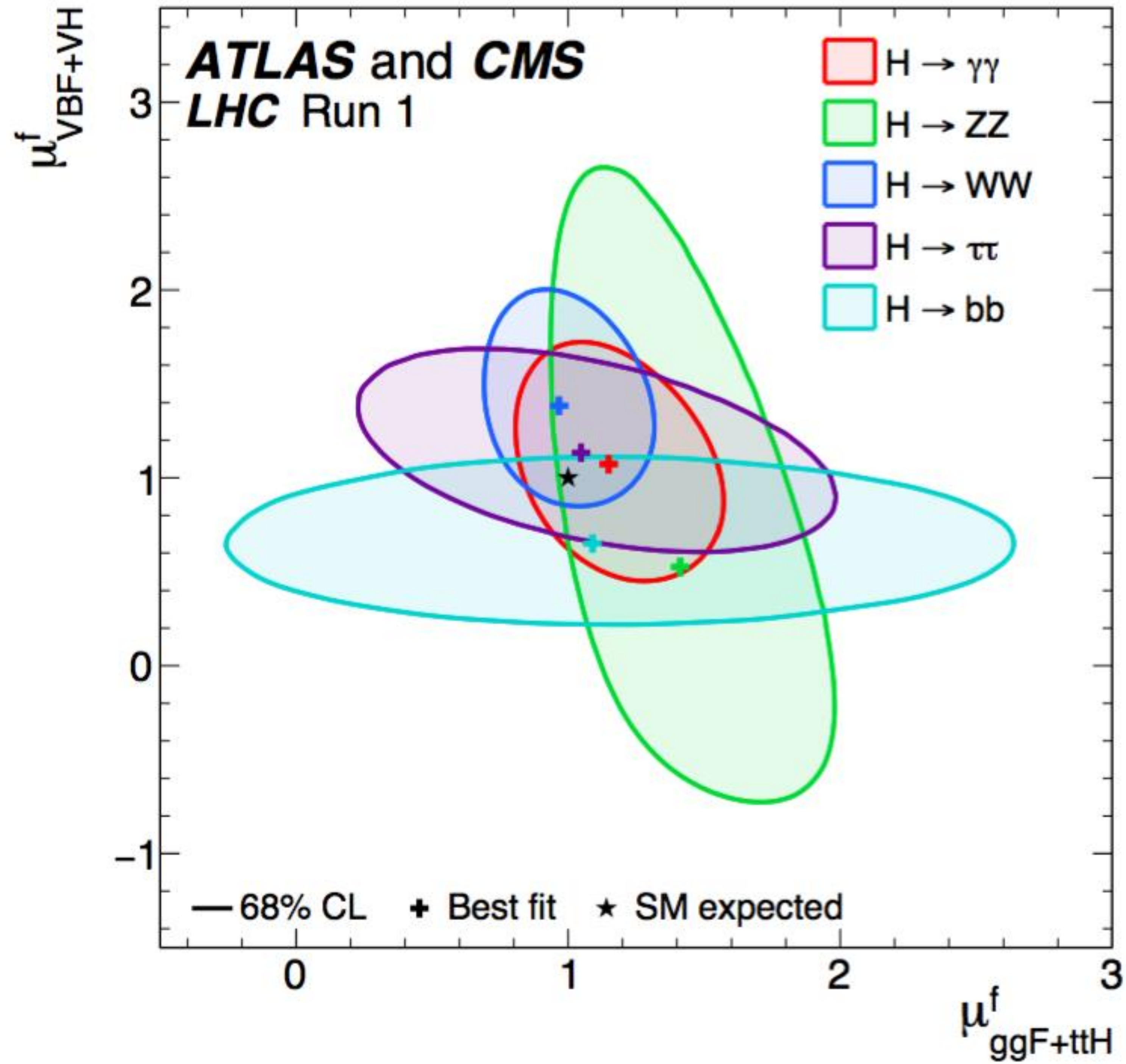
Parameter	SM prediction	Best fit value	Uncertainty		Best fit value	Uncertainty		Best fit value	Uncertainty	
			Stat	Syst		Stat	Syst		Stat	Syst
		ATLAS+CMS			ATLAS			CMS		
$\sigma(gg \to H \to ZZ)$ [pb]	0.51 ± 0.06	$0.59^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.09}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.03}_{-0.02}\right)$	$0.77^{+0.19}_{-0.17}$ $\left(^{+0.16}_{-0.14}\right)$	$^{+0.19}_{-0.16}$ $\left(^{+0.16}_{-0.13}\right)$	$^{+0.05}_{-0.03}$ $\left(^{+0.03}_{-0.02}\right)$	$0.44^{+0.14}_{-0.12}$ $\left(^{+0.15}_{-0.13}\right)$	$^{+0.13}_{-0.11}$ $\left(^{+0.15}_{-0.13}\right)$	$^{+0.05}_{-0.03}$ $\left(^{+0.04}_{-0.03}\right)$
$\sigma_{\mathrm{VBF}}/\sigma_{gg\mathrm{F}}$	0.082 ± 0.009	$0.109^{+0.034}_{-0.027}$ $\left(^{+0.029}_{-0.024}\right)$	$^{+0.029}_{-0.024}$ $\left(^{+0.024}_{-0.020}\right)$	$^{+0.018}_{-0.013}$ $\left(^{+0.016}_{-0.012}\right)$	$0.079^{+0.035}_{-0.026}$ $\left(^{+0.042}_{-0.031}\right)$	$^{+0.030}_{-0.023}$ $\left(^{+0.036}_{-0.028}\right)$	$^{+0.019}_{-0.012}$ $\left(^{+0.022}_{-0.014}\right)$	$0.138^{+0.073}_{-0.051}$ $\left(^{+0.043}_{-0.033}\right)$	$^{+0.061}_{-0.046}$ $\left(^{+0.037}_{-0.029}\right)$	$^{+0.039}_{-0.023}$ $\left(^{+0.023}_{-0.015}\right)$
$\sigma_{WH}/\sigma_{gg\mathrm{F}}$	0.037 ± 0.004	$0.031^{+0.028}_{-0.026}$ $\left(^{+0.021}_{-0.017}\right)$	$^{+0.024}_{-0.022}$ $\left(^{+0.019}_{-0.015}\right)$	$^{+0.015}_{-0.014}$ $\left(^{+0.011}_{-0.007}\right)$	$0.054^{+0.036}_{-0.026}$ $\left(^{+0.033}_{-0.022}\right)$	$^{+0.031}_{-0.023}$ $\left(^{+0.029}_{-0.020}\right)$	$^{+0.020}_{-0.013}$ $\left(^{+0.015}_{-0.009}\right)$	$0.005^{+0.044}_{-0.037}$ $\left(^{+0.032}_{-0.022}\right)$	$^{+0.037}_{-0.028}$ $\left(^{+0.027}_{-0.020}\right)$	$^{+0.023}_{-0.024}$ $\left(^{+0.017}_{-0.010}\right)$
$\sigma_{ZH}/\sigma_{gg\mathrm{F}}$	0.0216 ± 0.0024	$0.066^{+0.039}_{-0.031}$ $\left(^{+0.016}_{-0.011}\right)$	$^{+0.032}_{-0.025}$ $\left(^{+0.014}_{-0.010}\right)$	$^{+0.023}_{-0.018}$ $\left(^{+0.009}_{-0.004}\right)$	$0.013^{+0.028}_{-0.014}$ $\left(^{+0.027}_{-0.014}\right)$	$^{+0.021}_{-0.012}$ $\left(^{+0.023}_{-0.013}\right)$	$^{+0.018}_{-0.007}$ $\left(^{+0.014}_{-0.005}\right)$	$0.123^{+0.076}_{-0.053}$ $\left(^{+0.024}_{-0.013}\right)$	$^{+0.063}_{-0.046}$ $\left(^{+0.020}_{-0.012}\right)$	$^{+0.044}_{-0.026}$ $\left(^{+0.014}_{-0.006}\right)$
$\sigma_{ttH}/\sigma_{gg\mathrm{F}}$	0.0067 ± 0.0010	$0.022^{+0.007}_{-0.006}$ $\left(^{+0.004}_{-0.004}\right)$	$^{+0.005}_{-0.005}$ $\left(^{+0.003}_{-0.003}\right)$	$^{+0.004}_{-0.003}$ $\left(^{+0.003}_{-0.002}\right)$	$0.013^{+0.007}_{-0.005}$ $\left(^{+0.006}_{-0.004}\right)$	$^{+0.005}_{-0.004}$ $\left(^{+0.005}_{-0.004}\right)$	$^{+0.004}_{-0.003}$ $\left(^{+0.004}_{-0.003}\right)$	$0.034^{+0.016}_{-0.012}$ $\left(^{+0.007}_{-0.005}\right)$	$^{+0.012}_{-0.010}$ $\left(^{+0.005}_{-0.004}\right)$	$^{+0.010}_{-0.006}$ $\left(^{+0.004}_{-0.004}\right)$
$\mathrm{B}^{WW}/\mathrm{B}^{ZZ}$	$8.09 \pm < 0.01$	$6.7^{+1.6}_{-1.3}$ $\left(^{+2.2}_{-1.7}\right)$	$^{+1.5}_{-1.2}$ $\left(^{+2.0}_{-1.6}\right)$	$^{+0.6}_{-0.5}$ $\left(^{+0.9}_{-0.7}\right)$	$6.5^{+2.1}_{-1.6}$ $\left(^{+3.5}_{-2.4}\right)$	$^{+2.0}_{-1.4}$ $\left(^{+3.3}_{-2.2}\right)$	$^{+0.8}_{-0.6}$ $\left(^{+1.2}_{-0.9}\right)$	$7.1^{+2.9}_{-2.1}$ $\left(^{+3.2}_{-2.2}\right)$	$^{+2.6}_{-1.8}$ $\left(^{+2.9}_{-2.0}\right)$	$^{+1.3}_{-0.9}$ $\left(^{+1.4}_{-1.0}\right)$
$\mathrm{B}^{\gamma\gamma}/\mathrm{B}^{ZZ}$	0.0854 ± 0.0010	$0.069^{+0.018}_{-0.014}$ $\left(^{+0.025}_{-0.019}\right)$	$^{+0.018}_{-0.014}$ $\left(^{+0.024}_{-0.019}\right)$	$^{+0.004}_{-0.003}$ $\left(^{+0.006}_{-0.004}\right)$	$0.062^{+0.024}_{-0.018}$ $\left(^{+0.040}_{-0.027}\right)$	$^{+0.023}_{-0.017}$ $\left(^{+0.039}_{-0.027}\right)$	$^{+0.007}_{-0.005}$ $\left(^{+0.010}_{-0.006}\right)$	$0.079^{+0.034}_{-0.023}$ $\left(^{+0.035}_{-0.025}\right)$	$^{+0.032}_{-0.023}$ $\left(^{+0.034}_{-0.024}\right)$	$^{+0.010}_{-0.006}$ $\left(^{+0.008}_{-0.005}\right)$
$\mathrm{B}^{\tau\tau}/\mathrm{B}^{ZZ}$	2.36 ± 0.05	$1.8^{+0.6}_{-0.5}$ $\left(^{+0.9}_{-0.7}\right)$	$^{+0.5}_{-0.4}$ $\left(^{+0.8}_{-0.6}\right)$	$^{+0.3}_{-0.2}$ $\left(^{+0.5}_{-0.3}\right)$	$2.2^{+1.1}_{-0.7}$ $\left(^{+1.5}_{-1.0}\right)$	$^{+0.9}_{-0.6}$ $\left(^{+1.3}_{-0.9}\right)$	$^{+0.6}_{-0.4}$ $\left(^{+0.8}_{-0.5}\right)$	$1.6^{+0.9}_{-0.6}$ $\left(^{+1.2}_{-0.9}\right)$	$^{+0.8}_{-0.5}$ $\left(^{+1.0}_{-0.7}\right)$	$^{+0.5}_{-0.3}$ $\left(^{+0.7}_{-0.4}\right)$
$\mathrm{B}^{bb}/\mathrm{B}^{ZZ}$	21.5 ± 1.0	$4.2^{+4.4}_{-2.6}$ $\left(^{+16.8}_{-9.0}\right)$	$^{+2.8}_{-2.0}$ $\left(^{+13.9}_{-7.9}\right)$	$^{+3.4}_{-1.6}$ $\left(^{+9.5}_{-4.4}\right)$	$9.6^{+10.1}_{-5.7}$ $\left(^{+29.3}_{-11.8}\right)$	$^{+7.4}_{-4.4}$ $\left(^{+24.2}_{-10.5}\right)$	$^{+6.9}_{-3.6}$ $\left(^{+16.6}_{-5.3}\right)$	$3.7^{+4.1}_{-2.4}$ $\left(^{+29.4}_{-11.9}\right)$	$^{+3.1}_{-2.0}$ $\left(^{+23.4}_{-10.4}\right)$	$^{+2.7}_{-1.4}$ $\left(^{+17.8}_{-5.9}\right)$



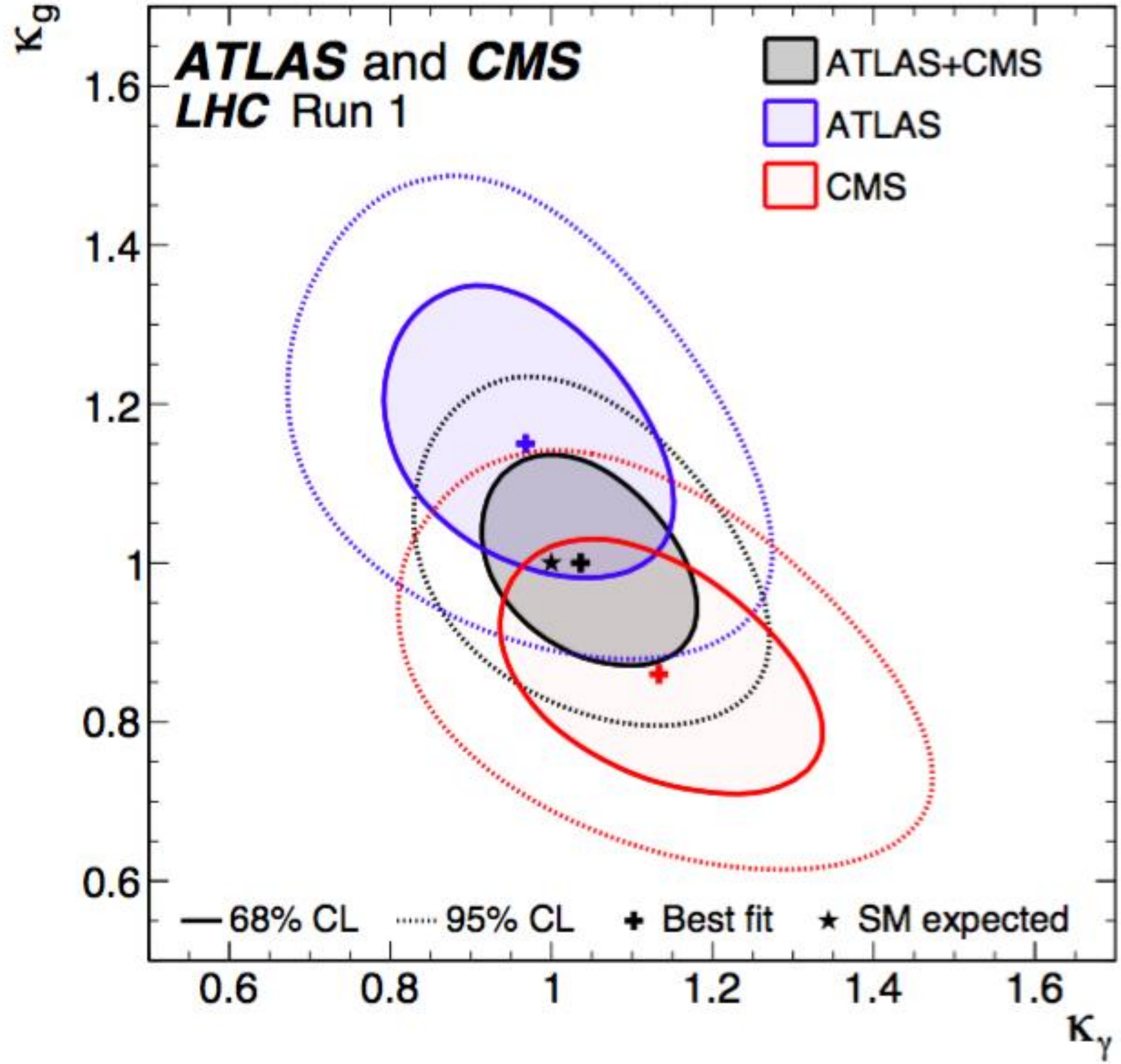
ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
Th. uncert.
σ(gg→H→ZZ)
σ_VBF/σ_ggF
σ_WH/σ_ggF
σ_ZH/σ_ggF
σ_ttH/σ_ggF
B^WW/B^ZZ
B^γγ/B^ZZ
B^ττ/B^ZZ
B^bb/B^ZZ
−1 0 1 2 3 4 5 6
Parameter value norm. to SM prediction



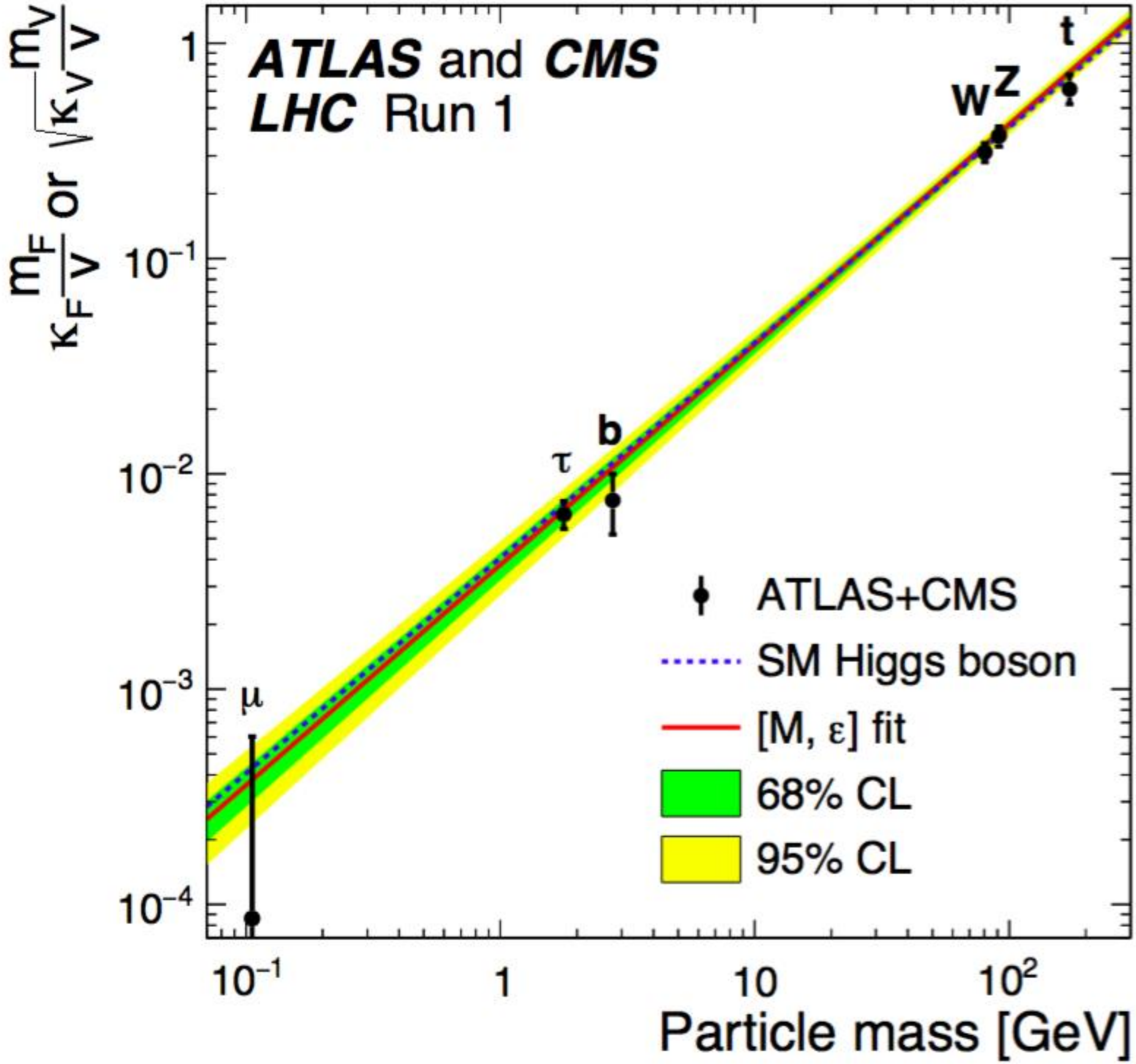
ATLAS and CMS
LHC Run 1
κ_{gZ}
λ_{Zg}
λ_{tg}
λ_{WZ}
$|\lambda_{\gamma Z}|$
$|\lambda_{\tau Z}|$
$|\lambda_{bZ}|$
ATLAS+CMS
ATLAS
CMS
1σ interval
2σ interval
−3
−2
−1
0
1
2
3
Parameter value



ATLAS and CMS
LHC Run 1
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
— 68% CL
✚ Best fit
★ SM expected
μ^f_{VBF+VH}
$\mu^f_{ggF+ttH}$
3
2
1
0
−1
0
1
2
3



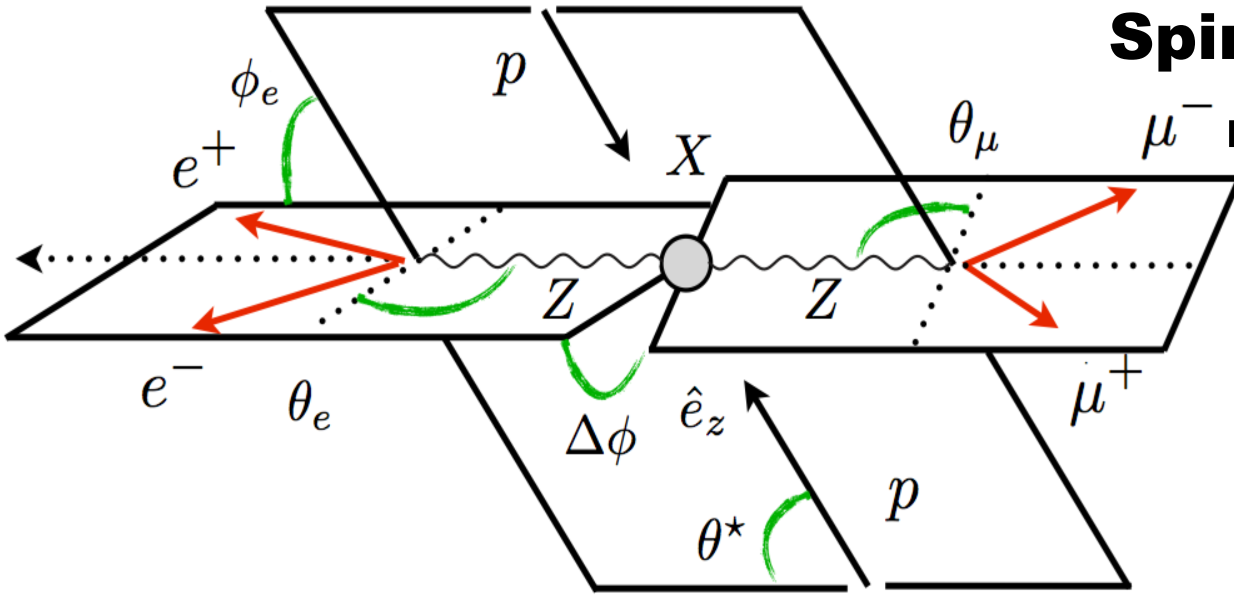
ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
68% CL
95% CL
Best fit
SM expected
κ_g
κ_γ
1.6
1.4
1.2
1
0.8
0.6
0.6
0.8
1
1.2
1.4
1.6


ATLAS and CMS
LHC Run 1
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V} \frac{m_V}{v}$
Particle mass [GeV]
t
W
Z
b
τ
μ
ATLAS+CMS
SM Higgs boson
[M, ε] fit
68% CL
95% CL

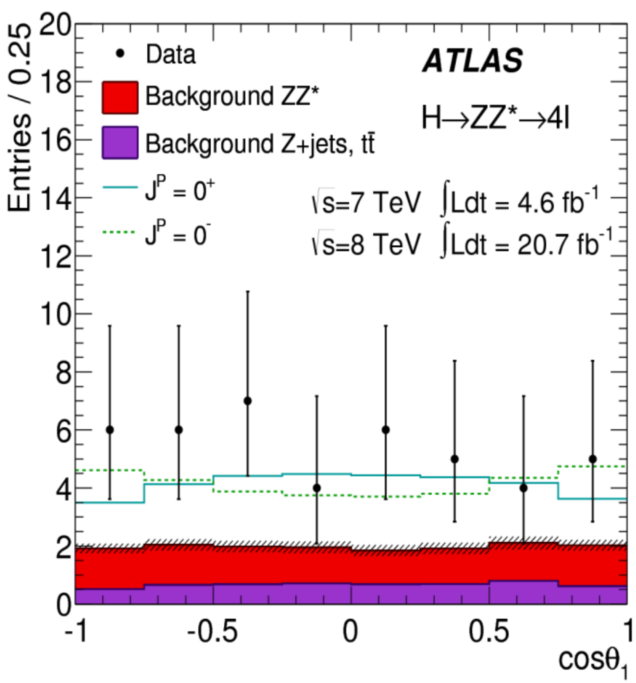
Spin/CP Quantum numbers: Exploration in Decay

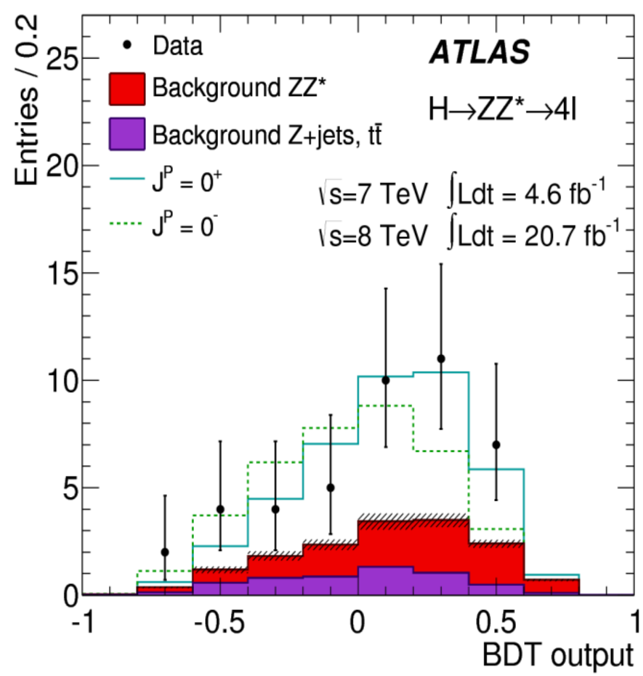
Spin/CP in H->ZZ->4l

Phys.Lett. B726 (2013) 120-144



Exploit full 4-lepton kinematics, combined into a multivariate analysis (BDT)



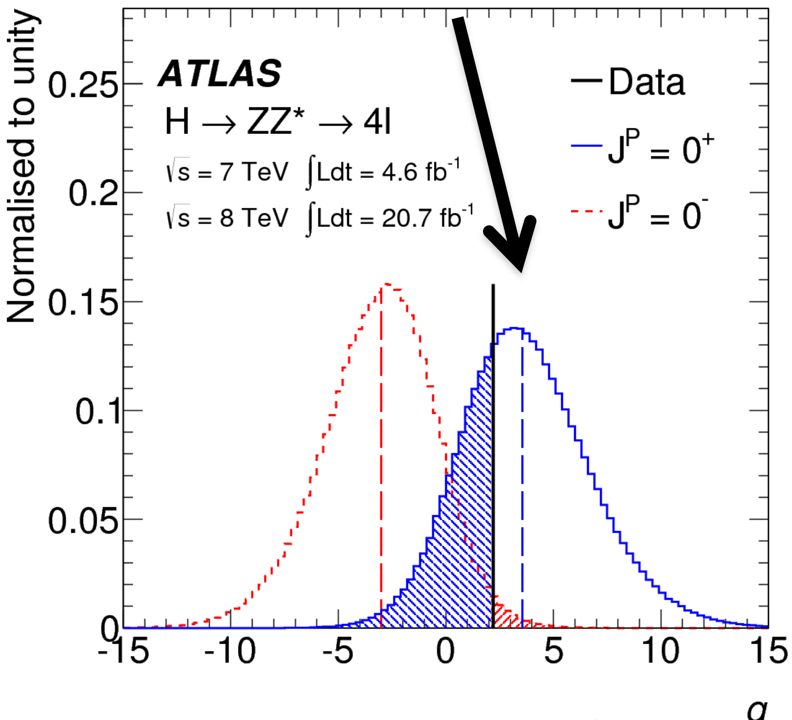


Most sensitive channel in decay to 0^-

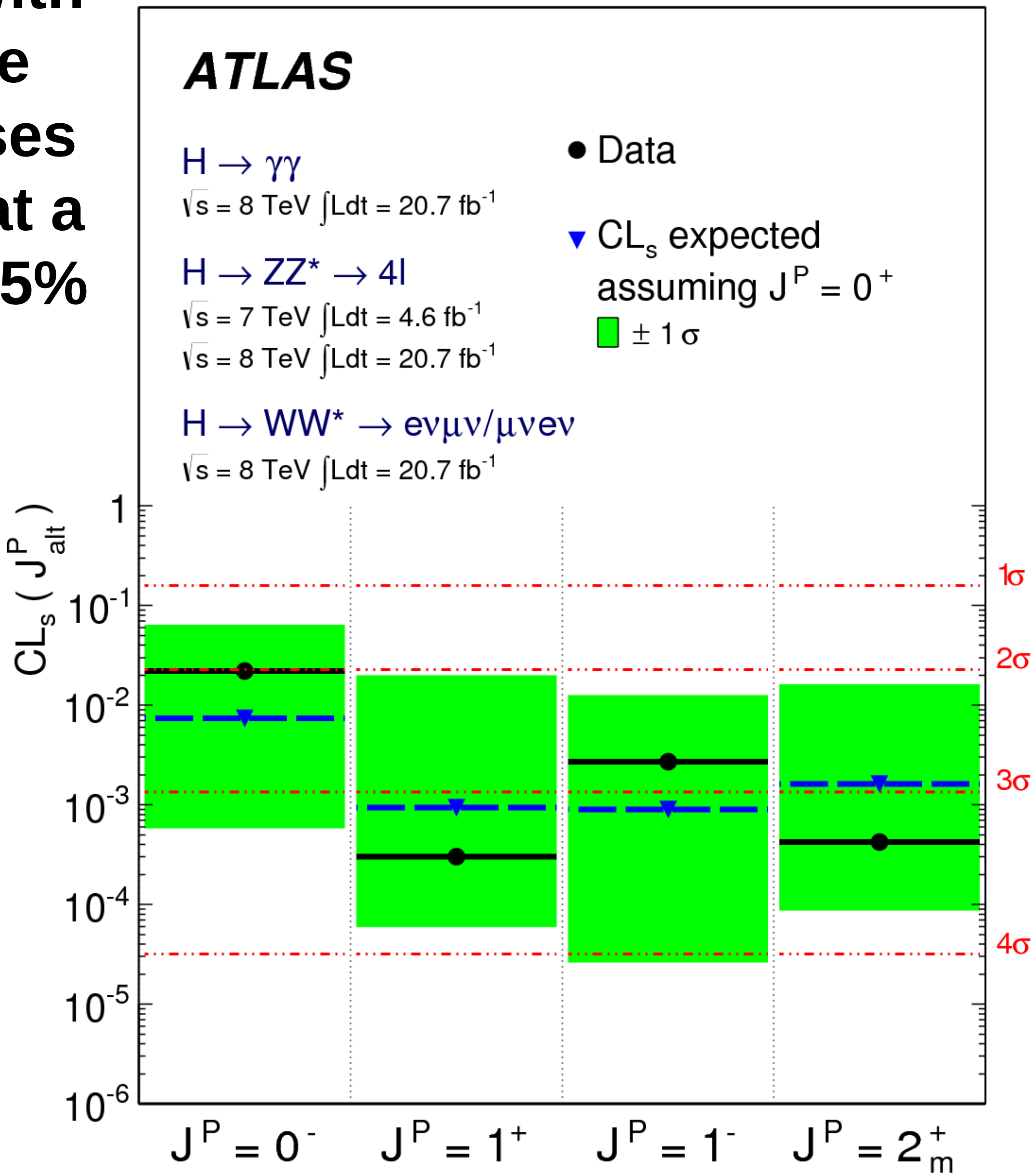
Phys.Lett. B726 (2013) 120-144

Data show compatibility with the SM 0^+ hypothesis while other alternative hypotheses considered are excluded at a confidence levels above 95%

Observation



$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$



$$
\begin{aligned}
A(X_{J=0} \to V_1 V_2) \;\sim\; & v^{-1} \Bigg(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \\
+ \; & a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\
+ \; & a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\
+ \; & a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \Bigg)
\end{aligned}
$$

CMS-PAS-HIG-14-014

CP-violating $f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4}$ $\phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$

CP-conserving $f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4}$ $\phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$

Λ - Scale of new physics $f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4}$ $\phi_{\Lambda 1}$,

Spin-1

$$f_{b2} = \frac{|b_2|^2\sigma_2}{|b_1|^2\sigma_1 + |b_2|^2\sigma_2}$$

$$A(X_{J=1} \to V_1 V_2) \sim b_1 \left[\left(\epsilon^*_{V_1} q\right) \left(\epsilon^*_{V_2} \epsilon_X\right) + \left(\epsilon^*_{V_2} q\right) \left(\epsilon^*_{V_1} \epsilon_X\right) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon^\alpha_X \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} \tilde{q}^\beta$$

Spin-2

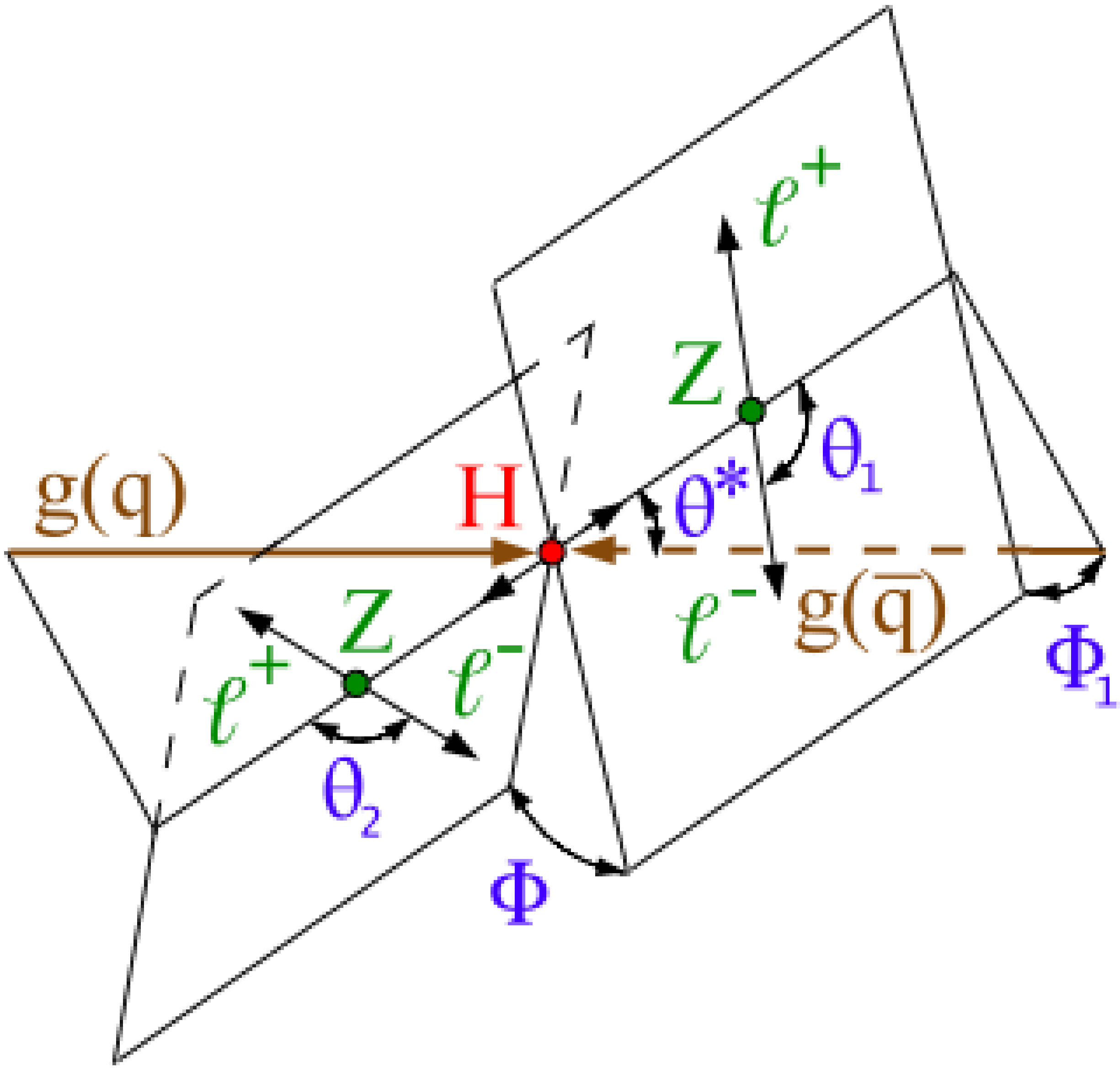
$$A(X_{J=2} \to V_1 V_2) \sim \Lambda^{-1} \Big[2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta}$$

$$+ c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} (f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$

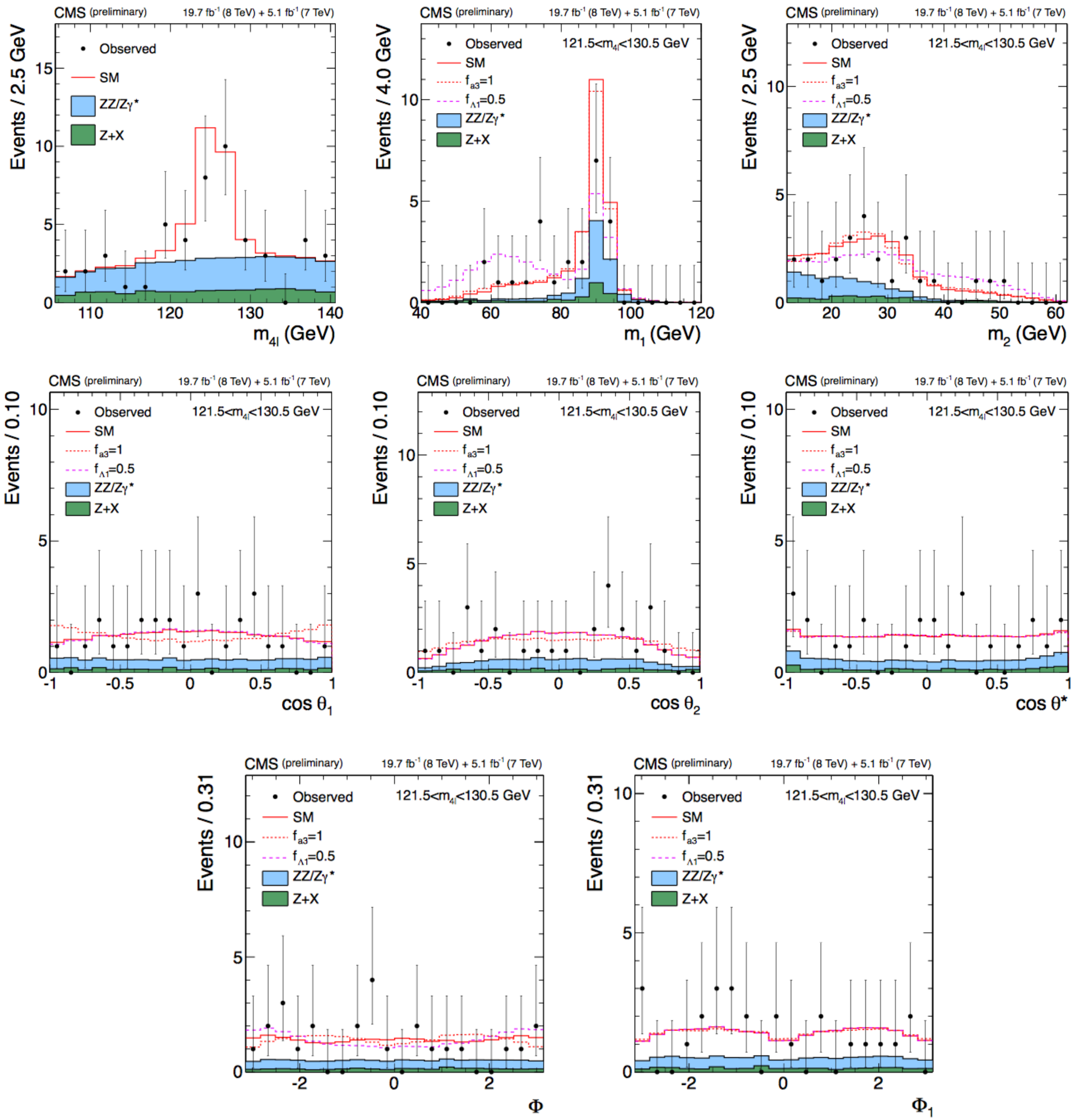
$$+ m_V^2 \left(2c_5 t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2} \right) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_{V_1} \epsilon^*_{V_2} \right)$$

$$+ c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma$$

$$+ \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V_1} (q \epsilon^*_{V_2}) + \epsilon^{*\nu}_{V_2} (q \epsilon^*_{V_1}) \right) \Big] \,,$$



g(q)
H
ℓ^+
Z
θ_1
θ^*
Z
ℓ^-
$g(\bar{q})$
ℓ^+
ℓ^-
Φ_1
θ_2
Φ


CMS (preliminary) 19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
Events / 2.5 GeV
Observed
SM
ZZ/Zγ*
Z+X
m4l (GeV)
Events / 4.0 GeV
121.5<m4l<130.5 GeV
fa3=1
fΛ1=0.5
m1 (GeV)
m2 (GeV)
Events / 0.10
cos θ1
cos θ2
cos θ*
Events / 0.31
Φ
Φ1

Probabilities build with LO ME from MCFM, MadGraph and FeynRules

Interference-related probabilities used in the Spin-0 study

$$\mathcal{P}_{\mathrm{SM}} = \mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) \times \mathcal{P}^{\mathrm{mass}}_{\mathrm{sig}}(m_{4\ell} | m_H)$$

$$\mathcal{P}_{\mathrm{J^P}} = \mathcal{P}^{\mathrm{kin}}_{\mathrm{J^P}}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) \times \mathcal{P}^{\mathrm{mass}}_{\mathrm{sig}}(m_{4\ell} | m_H)$$

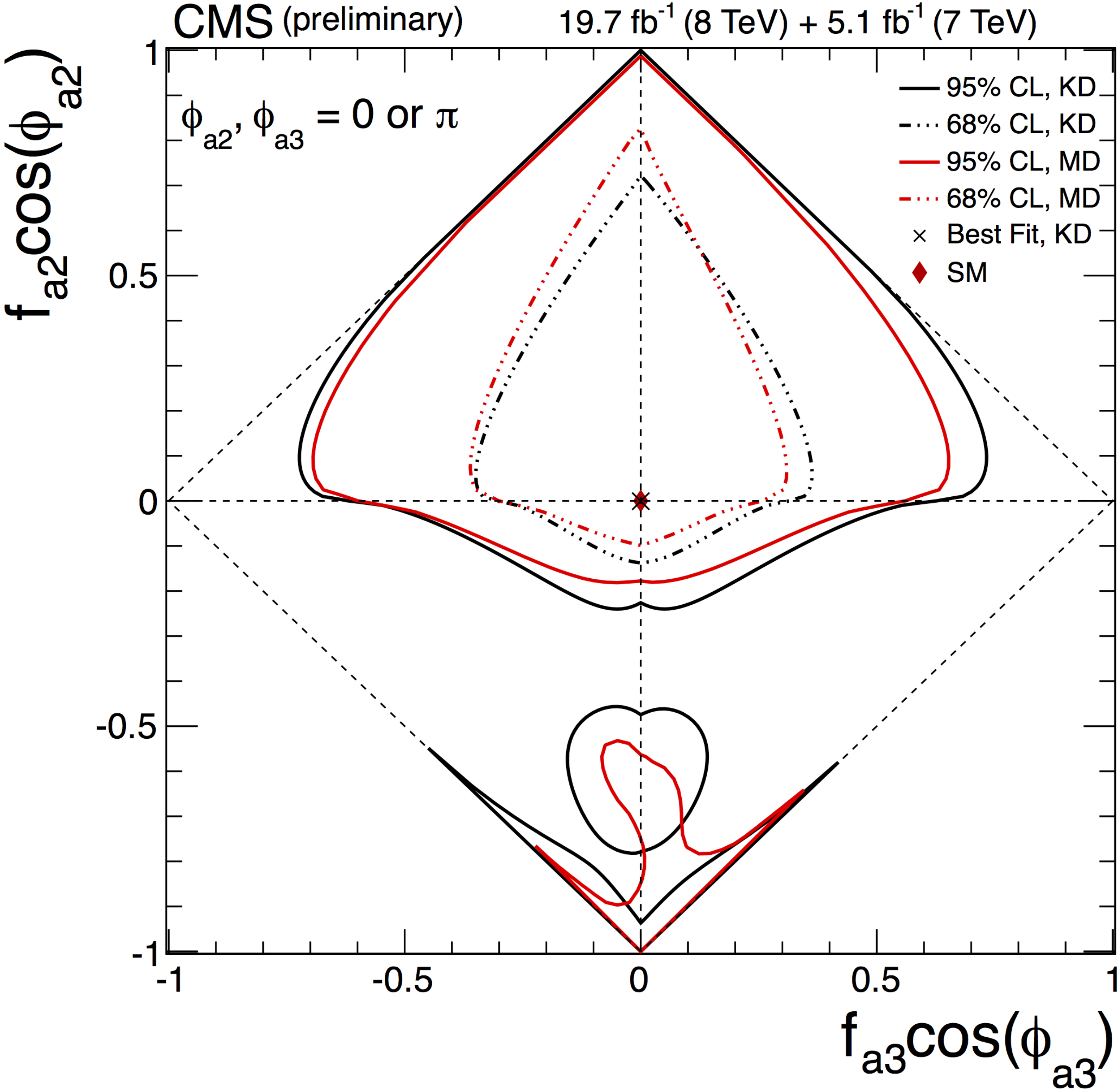
$$\boxed{\begin{aligned} \mathcal{P}^{\mathrm{kin}}_{\mathrm{interf}} &= \left(\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM+J^P}}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - g_{J^P}\mathcal{P}^{\mathrm{kin}}_{\mathrm{J^P}}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - \mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}}(\vec{\Omega}, m_1, m_2 | m_{4\ell})\right) \\ \mathcal{P}^{\mathrm{kin}}_{\mathrm{interf}\perp} &= \left(\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM+J^P}\perp}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - g_{J^P}\mathcal{P}^{\mathrm{kin}}_{\mathrm{J^P}}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - \mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}}(\vec{\Omega}, m_1, m_2 | m_{4\ell})\right) \end{aligned}}$$

$$\mathcal{P}_{q\bar{q}ZZ} = \mathcal{P}^{\mathrm{kin}}_{q\bar{q}ZZ}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) \times \mathcal{P}^{\mathrm{mass}}_{q\bar{q}ZZ}(m_{4\ell}),$$

$$\mathcal{D}_{\mathrm{bkg}} = \frac{\mathcal{P}_{\mathrm{SM}}}{\mathcal{P}_{\mathrm{SM}} + c \times \mathcal{P}_{\mathrm{bkg}}} = \left[1 + c(m_{4\ell}) \times \frac{\mathcal{P}^{\mathrm{kin}}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega} | m_{4\ell}) \times \mathcal{P}^{\mathrm{mass}}_{\mathrm{bkg}}(m_{4\ell})}{\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}}(m_1, m_2, \vec{\Omega} | m_{4\ell}) \times \mathcal{P}^{\mathrm{mass}}_{\mathrm{sig}}(m_{4\ell} | m_H)}\right]^{-1}$$

$$\mathcal{D}^{\mathrm{kin}}_{J^P} = \frac{\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}}}{\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}} + c_{J^P} \times \mathcal{P}^{\mathrm{kin}}_{J^P}} = \left[1 + c_{J^P} \times \frac{\mathcal{P}^{\mathrm{kin}}_{J^P}(m_1, m_2, \vec{\Omega} | m_{4\ell})}{\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}}(m_1, m_2, \vec{\Omega} | m_{4\ell})}\right]^{-1}$$

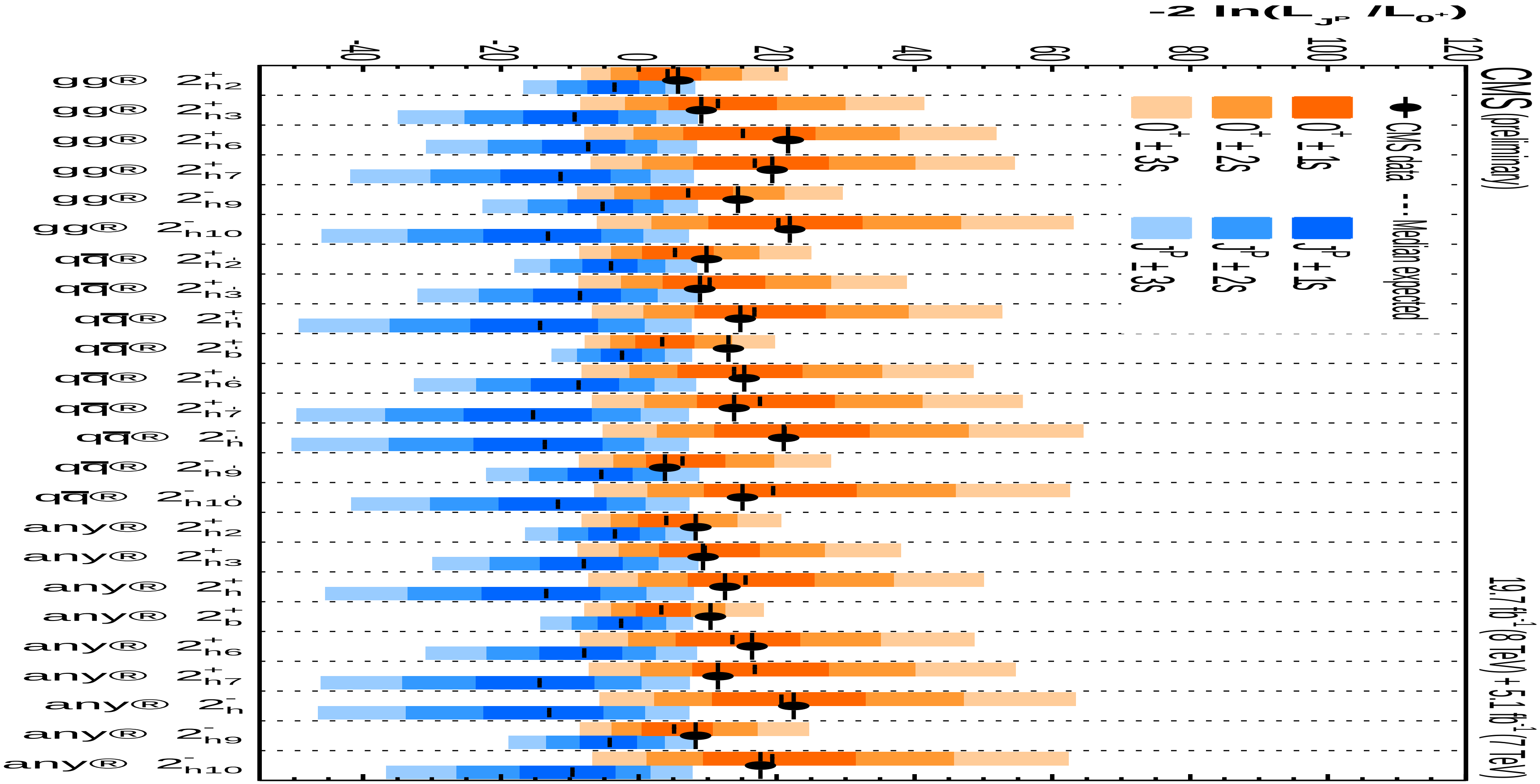
$$\mathcal{D}_{\mathrm{Interf}} = \frac{\left(\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM+J^P}} - g_{J^P}\mathcal{P}^{\mathrm{kin}}_{\mathrm{J^P}} - \mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}}\right)}{\mathcal{P}^{\mathrm{kin}}_{\mathrm{SM}} + c_{J^P} \times \mathcal{P}^{\mathrm{kin}}_{J^P}}.$$

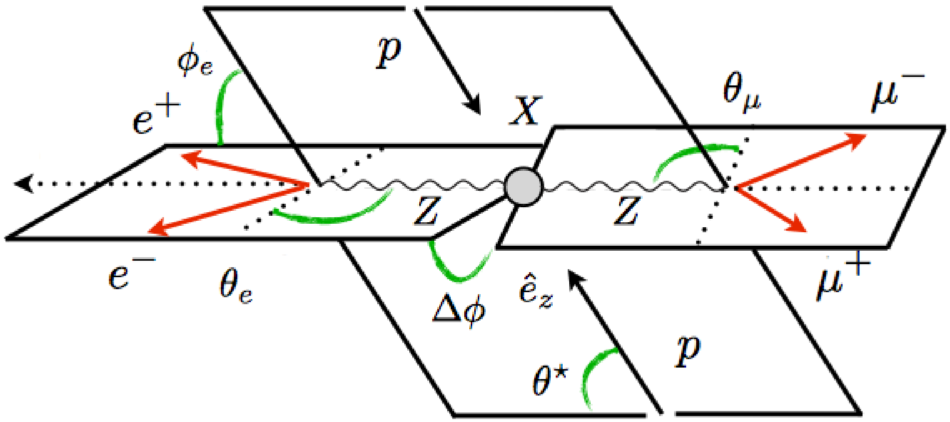

CMS (preliminary)
19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
ϕ_{a2}, ϕ_{a3} = 0 or π
95% CL, KD
68% CL, KD
95% CL, MD
68% CL, MD
Best Fit, KD
SM
$f_{a2}\cos(\phi_{a2})$
$f_{a3}\cos(\phi_{a3})$
1
0.5
0
-0.5
-1

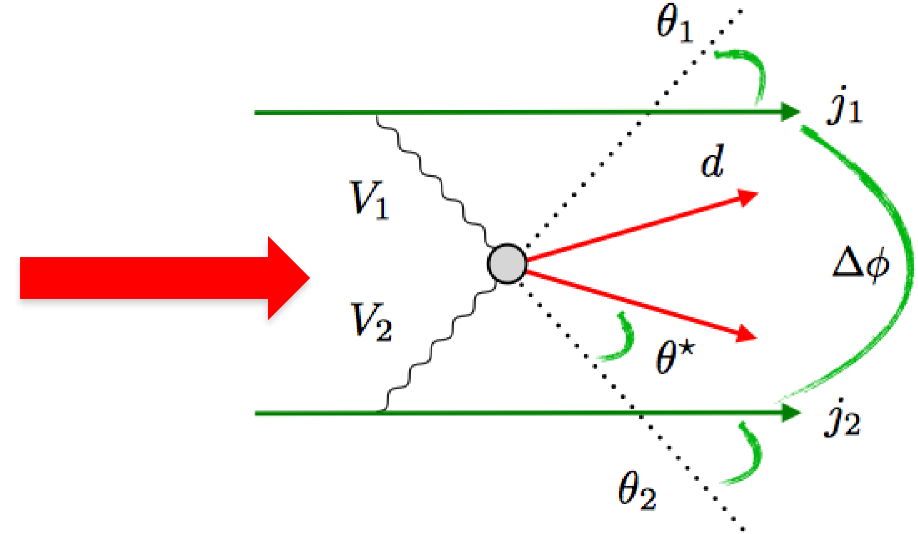
Exclusion of Spin-1 hypotheses

J^P model	J^P production	Expected (μ=1)	Obs. 0^+	Obs. J^P	CL_s	$f(J^P)$ CL=95% Obs(Exp)	$f(J^P)$ Best-Fit
1^-	any	$2.9\sigma(2.7\sigma)$	-2.0σ	$>4.5\sigma$	<0.01 %	0.37(0.79)	$0.00^{+0.12}_{-0.00}$
$f_{b2}=0.2$	any	$2.7\sigma(2.5\sigma)$	-2.2σ	$>4.5\sigma$	<0.01 %	0.38(0.82)	$0.00^{+0.12}_{-0.00}$
$f_{b2}=0.4$	any	$2.5\sigma(2.4\sigma)$	-2.3σ	$>4.5\sigma$	<0.01 %	0.39(0.84)	$0.00^{+0.13}_{-0.00}$
$f_{b2}=0.6$	any	$2.5\sigma(2.3\sigma)$	-2.4σ	$>4.5\sigma$	<0.01 %	0.39(0.86)	$0.00^{+0.13}_{-0.00}$
$f_{b2}=0.8$	any	$2.4\sigma(2.3\sigma)$	-2.3σ	$>4.5\sigma$	<0.01 %	0.40(0.86)	$0.00^{+0.13}_{-0.00}$
1^+	any	$2.5\sigma(2.3\sigma)$	-2.3σ	$>4.5\sigma$	<0.01 %	0.41(0.85)	$0.00^{+0.13}_{-0.00}$
1^-	$q\bar{q}\to X$	$2.9\sigma(2.8\sigma)$	-1.4σ	$>4.5\sigma$	<0.01 %	0.46(0.78)	$0.00^{+0.16}_{-0.00}$
$f_{b2}=0.2$	$q\bar{q}\to X$	$2.6\sigma(2.6\sigma)$	-1.4σ	$+4.6\sigma$	<0.01 %	0.49(0.81)	$0.00^{+0.17}_{-0.00}$
$f_{b2}=0.4$	$q\bar{q}\to X$	$2.5\sigma(2.4\sigma)$	-1.3σ	$+4.4\sigma$	<0.01 %	0.51(0.83)	$0.00^{+0.19}_{-0.00}$
$f_{b2}=0.6$	$q\bar{q}\to X$	$2.4\sigma(2.4\sigma)$	-1.2σ	$+4.1\sigma$	0.01 %	0.53(0.83)	$0.00^{+0.20}_{-0.00}$
$f_{b2}=0.8$	$q\bar{q}\to X$	$2.4\sigma(2.4\sigma)$	-1.0σ	$+3.9\sigma$	0.02 %	0.55(0.83)	$0.00^{+0.21}_{-0.00}$
1^+	$q\bar{q}\to X$	$2.4\sigma(2.4\sigma)$	-0.8σ	$+3.8\sigma$	0.04 %	0.57(0.81)	$0.00^{+0.22}_{-0.00}$

Exclusion of Spin-2 hypotheses

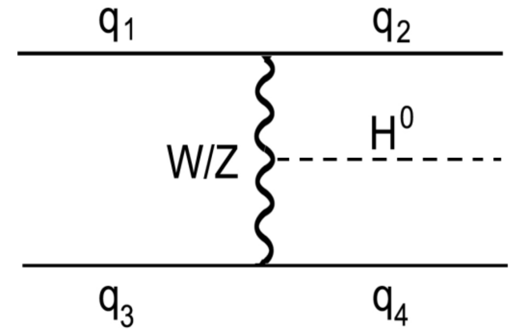






Spin/CP Quantum numbers: Exploration in Production

SM Higgs via VBF
Qualitative remarks



$$\sigma(fa \to f'X) \approx \int dx dp_T^2 P_{V/f}(x, p_T^2) \sigma(Va \to X)$$

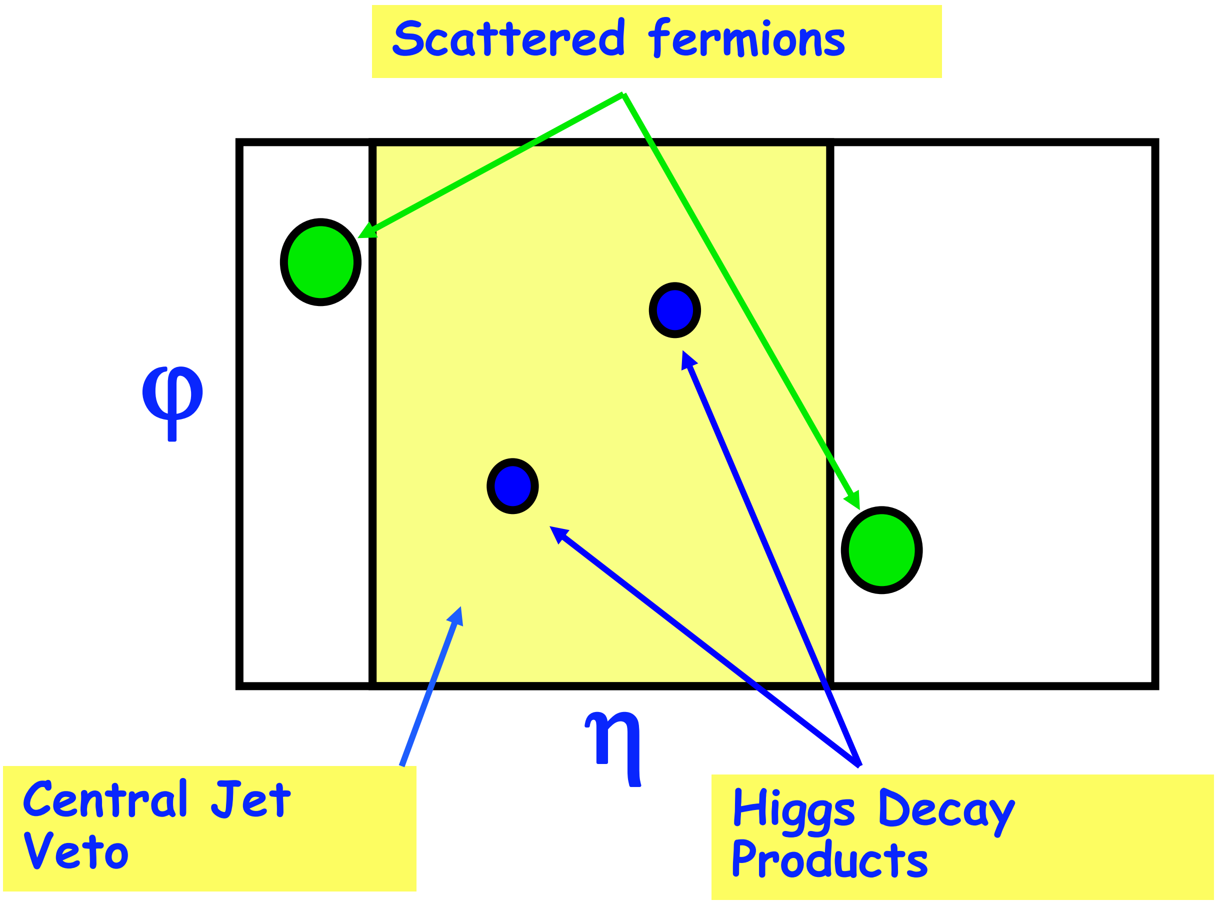
$$P_{V/f}^T(x, p_T^2) = \frac{g_V^2 + g_V^2}{8\pi^2} \frac{1 + (1-x)^2}{x} \frac{p_T^2}{(p_T^2 + (1-x)M_V^2)^2}$$

$$P_{V/f}^L(x, p_T^2) = \frac{g_V^2 + g_V^2}{4\pi^2} \frac{1-x}{x} \frac{(1-x)M_V^2}{(p_T^2 + (1-x)M_V^2)^2}.$$

- **Unlike QCD partons that scale like $1/P_T^2$, here P_T~sqrt(1-x)M_W**

- **Due to the 1/x behavior of the Weak boson the outgoing parton energy (1-x)E is large □ <u>forward jets</u>**
- **At high P_T** $P_{V/f}^T \sim 1/p_T^2$ and $P_{V/f}^L \sim 1/p_T^4$

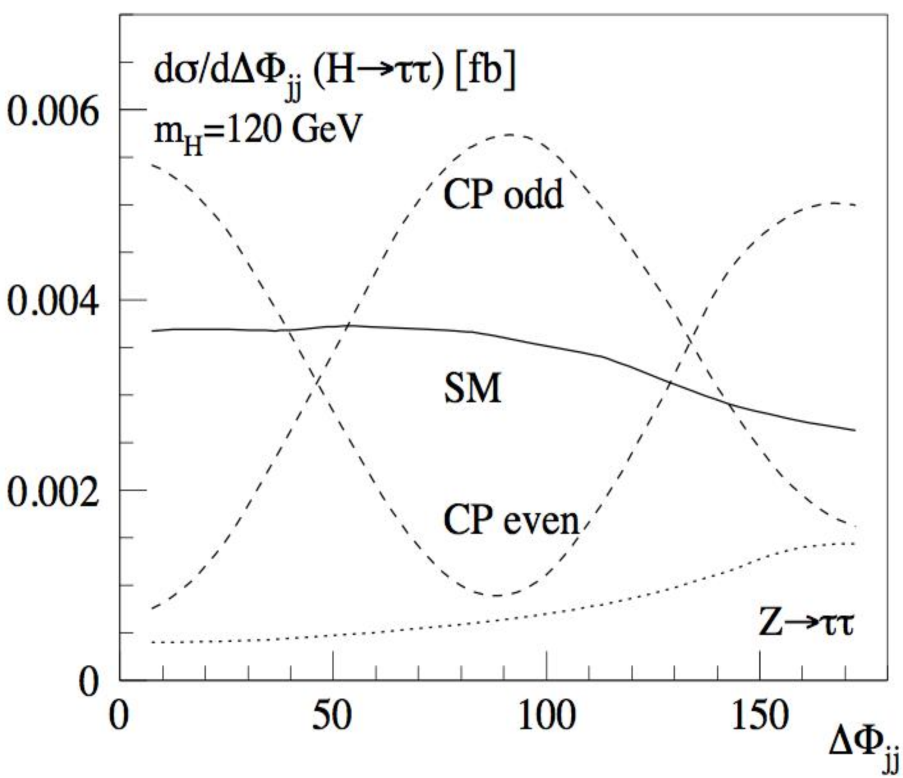
Well-defined prediction of the SM. Kinematics of scattered quarks, very sensitive to new physics

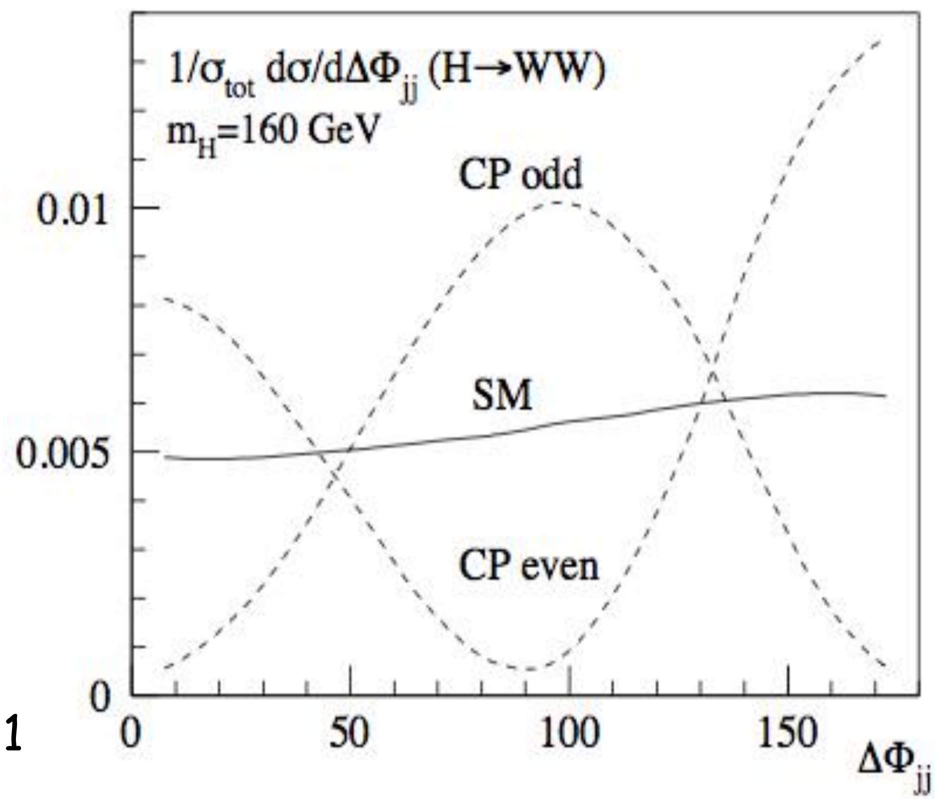


T.Plehn, D.Rainwater and D.Zeppenfeld
Phys.Rev.Lett. 88 (2002) 051801

$$pp \to qq'H \to qq'\tau\tau,\ qq'WW,\ qq'\gamma\gamma$$

$$p_{T_j} \geq 20\ \text{GeV} \qquad \Delta R_{jj} \geq 0.6 \qquad |\eta_j| \leq 4.5$$
$$|\eta_{j_1} - \eta_{j_2}| \geq 4.2 \qquad \eta_{j_1} \cdot \eta_{j_2} < 0$$





C. Englert, D. Gonsalves-Neto, K.Mawatari and T. Plehn, JHEP 1301 (2013) 148

A. Djouadi, R.M. Godbole, B.M., K.Mohan, Phys. Lett. B723 307-313

General tensor form of HVV coupling, where H is a scalar

SM

CP-conserving

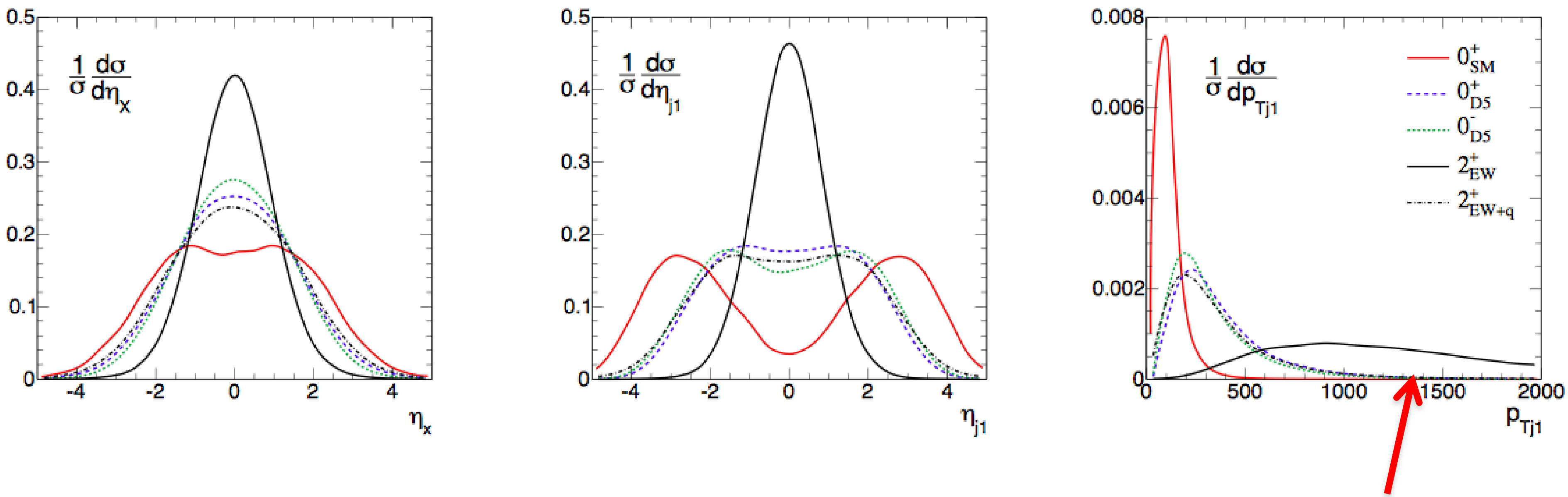
CP-violating

$$\Gamma_{\mu\nu}^{\mathrm{SM}} = -gM_V g_{\mu\nu}$$

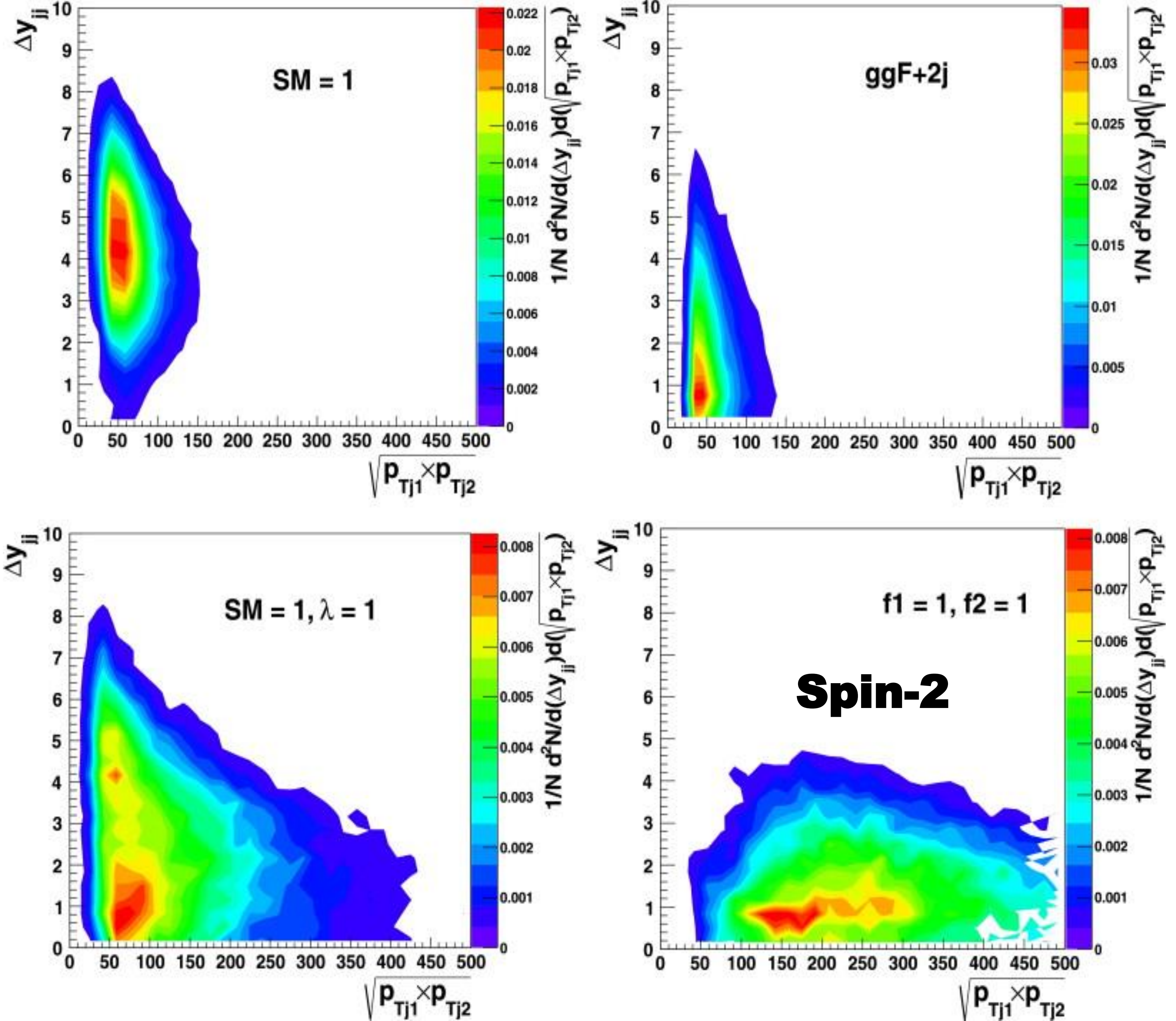
$$\Gamma_{\mu\nu}^{\mathrm{BSM}}(p,q) = \frac{g}{M_V}\left[\lambda(p\cdot q g_{\mu\nu} - p_\nu q_\mu) + \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma\right]$$

Extension of the SM high higher dimension operators. Where the Lambdas are effective coupling strengths.

In the above mention papers we realized that the kinematics of the scattered quarks have more information about the tensor structure of the HVV coupling than hitherto believed

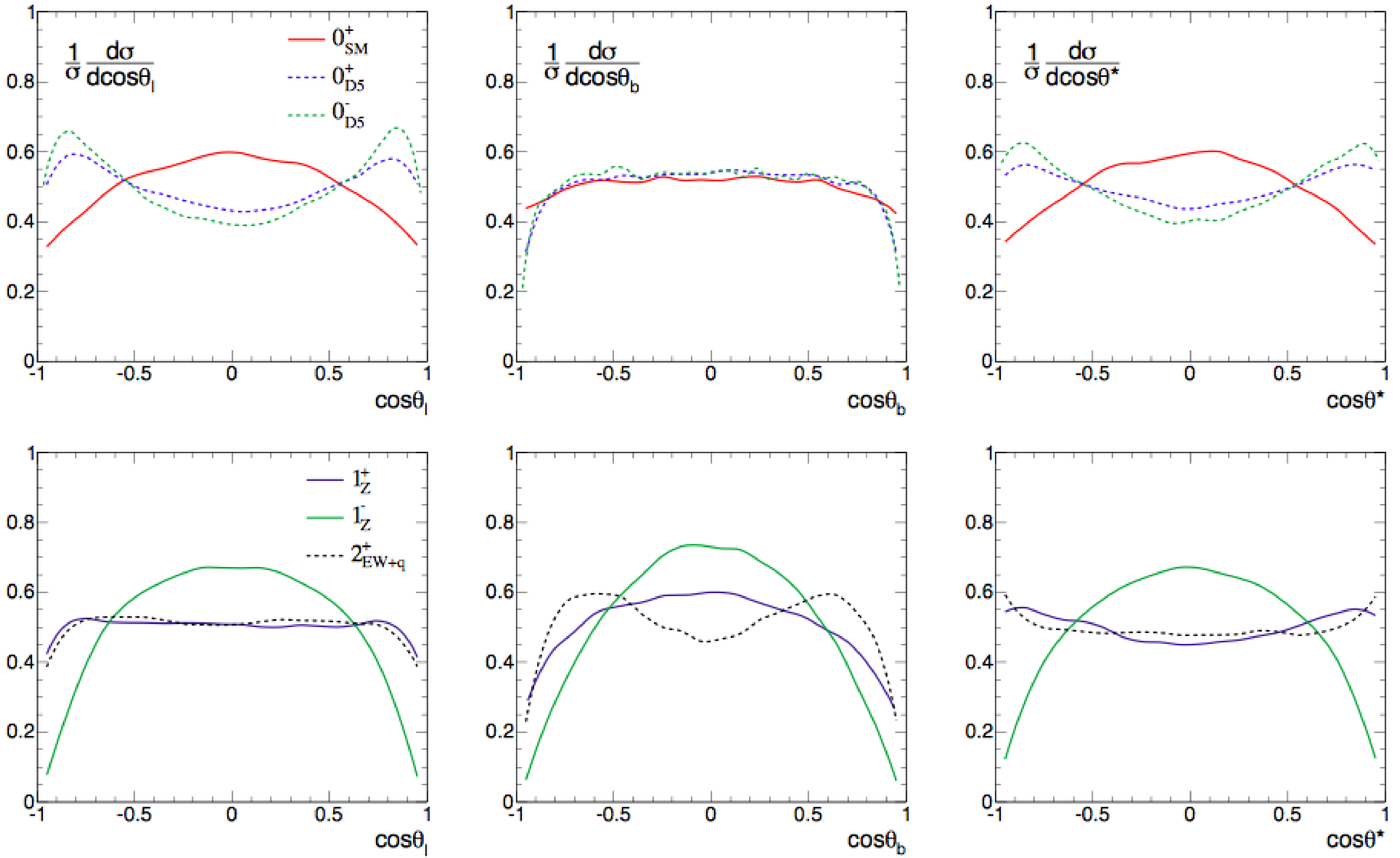


Problem with unitarization

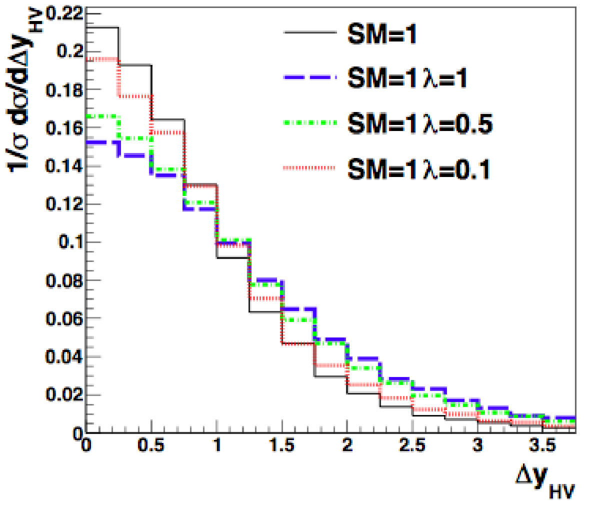


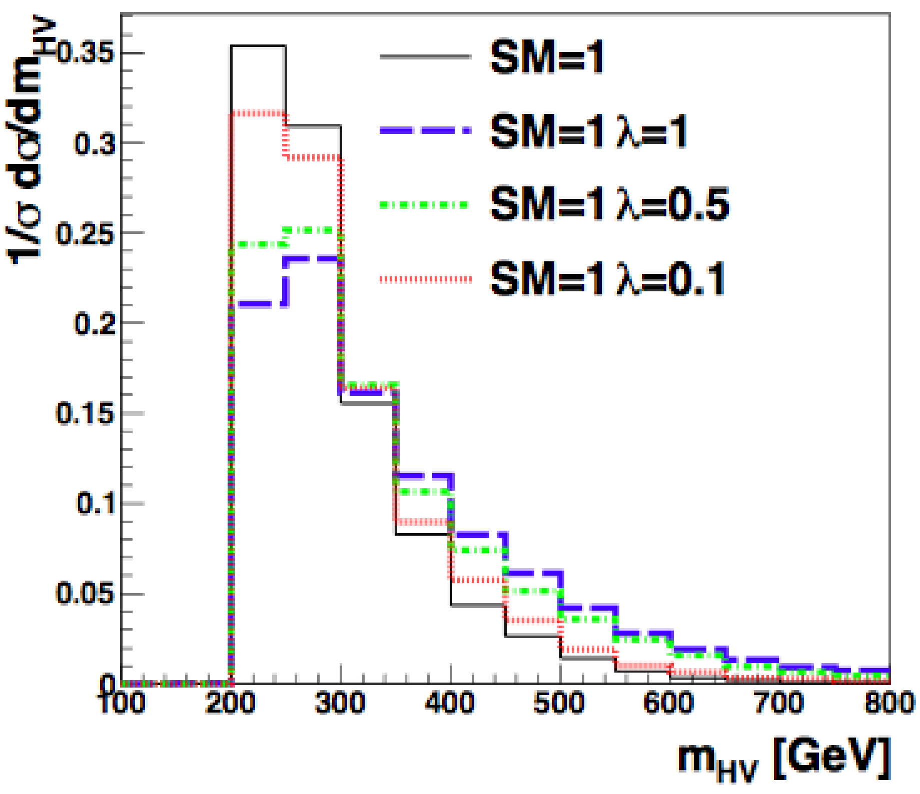
SM = 1
ggF+2j
SM = 1, λ = 1
f1 = 1, f2 = 1
Spin-2
Δy_{jj}
$\sqrt{p_{Tj1} \times p_{Tj2}}$
$1/N\ d^2N/d(\Delta y_{jj})d(\sqrt{p_{Tj1} \times p_{Tj2}})$

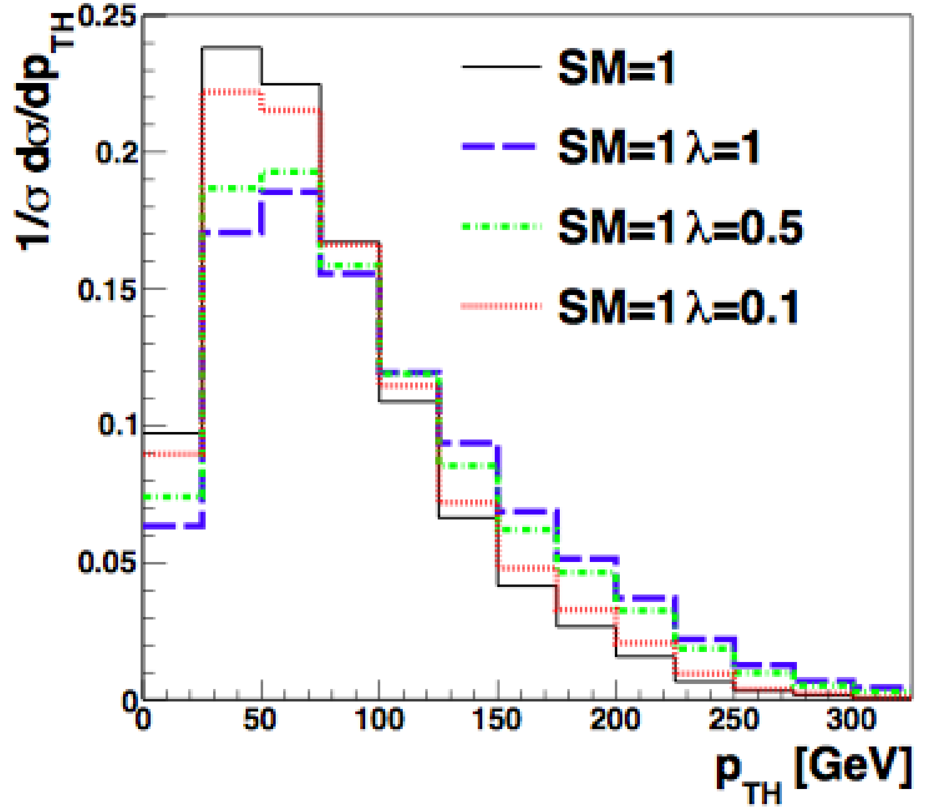
Associated VH production [Z(→ll)H(→bb)]



Associated VH production







Questions

- **How does one distinguish h→WW→ll+νs from h→$\tau\tau$→ll+νs**

- **Why is h→$\tau\tau$ observed and measured in VBF and boosted topologies?**

- **Why is the h→WW→ll+νs search and measurements performed jet bins?**

- **What are the shortcomings of the "kappa" framework?**