Higgs Boson: Experimental Review

B.Mellado
University of the Witwatersrand

2017 CTEQ School, University of Pittsburgh
26-27/07/2017

Outline

- ❑ The SM and the Higgs bsoon
- ❑ Habemus Novum Boson
- ❑ Production mechanisms and decay
- ❑ Mass
- ❑ Signal/coupling strength
- ❑ Spin-CP quantum numbers
- ❑ Fiducial cross-sections

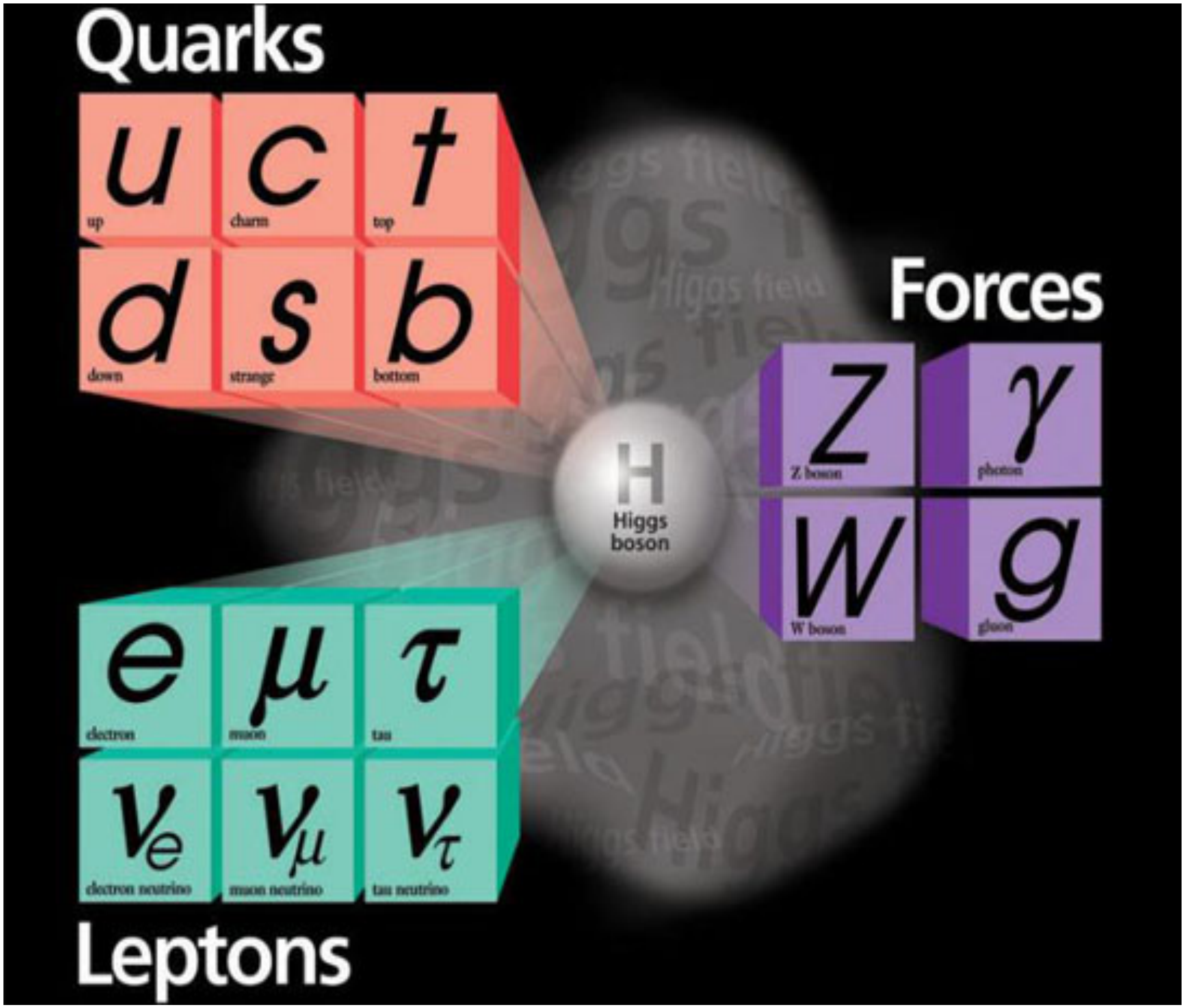
S. Dawson

The Standard Model of Physics

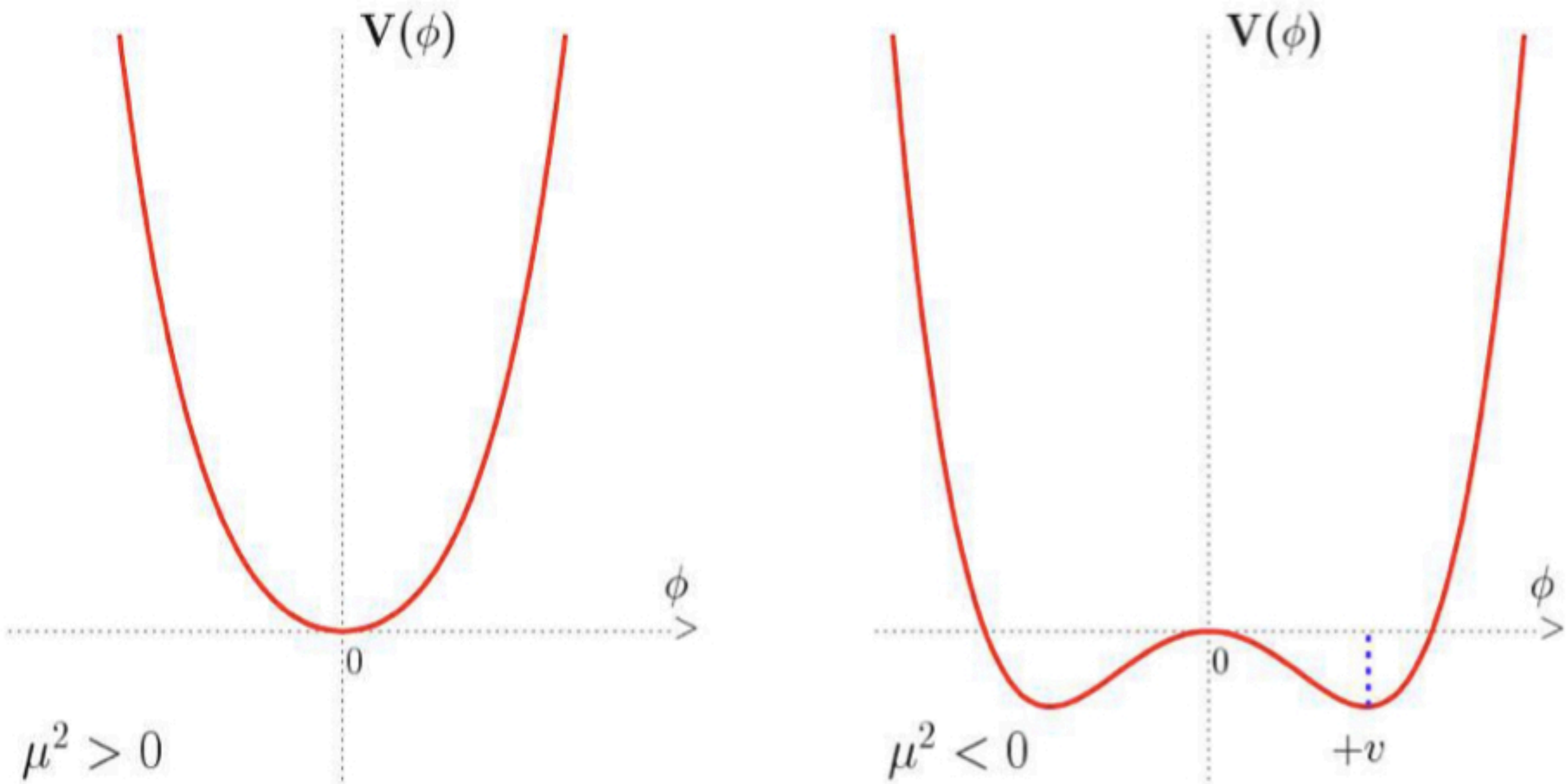
- Group: SU(3) x SU(2) x U(1)
  - SU(3): QCD
  - SU(2) x U(1): Electroweak
- Gauge bosons:
  - SU(3): G_μ^i, i=1…8
  - SU(2): W_μ^i, i=1,2,3
  - U(1): B_μ
- Gauge couplings: g_s, g, g'
- SU(2) Higgs doublet: Φ

Gauge symmetry forbids gauge boson masses: Spontaneous EW symmetry breaking and the Higgs Boson come to the rescue

The Higgs boson provides for explanation for the mass of quarks, leptons and weak bosons. It is a cornerstone of the theory of fundamental interactions.

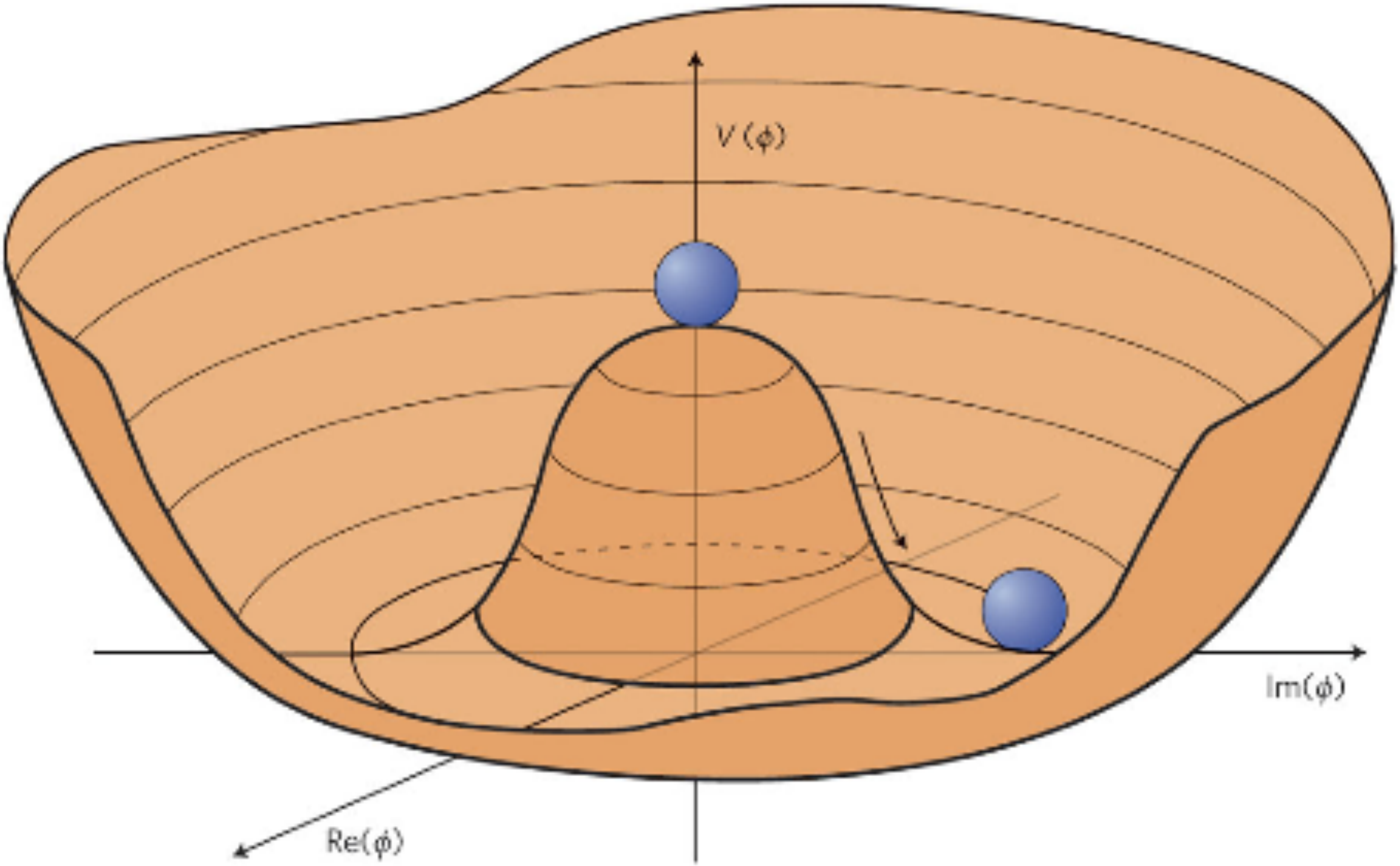


Spontaneous Symmetry Breaking



$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

Potential for a complex scalar field



$SU(2)_L \times U(1)_Y$ gauge symmetry

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 - i\phi_2 \\ \phi_3 - i\phi_4 \end{pmatrix}$$

$$V(\phi) = \mu^2 \phi^\dagger \phi - \lambda \left(\phi^\dagger \phi\right)^2$$

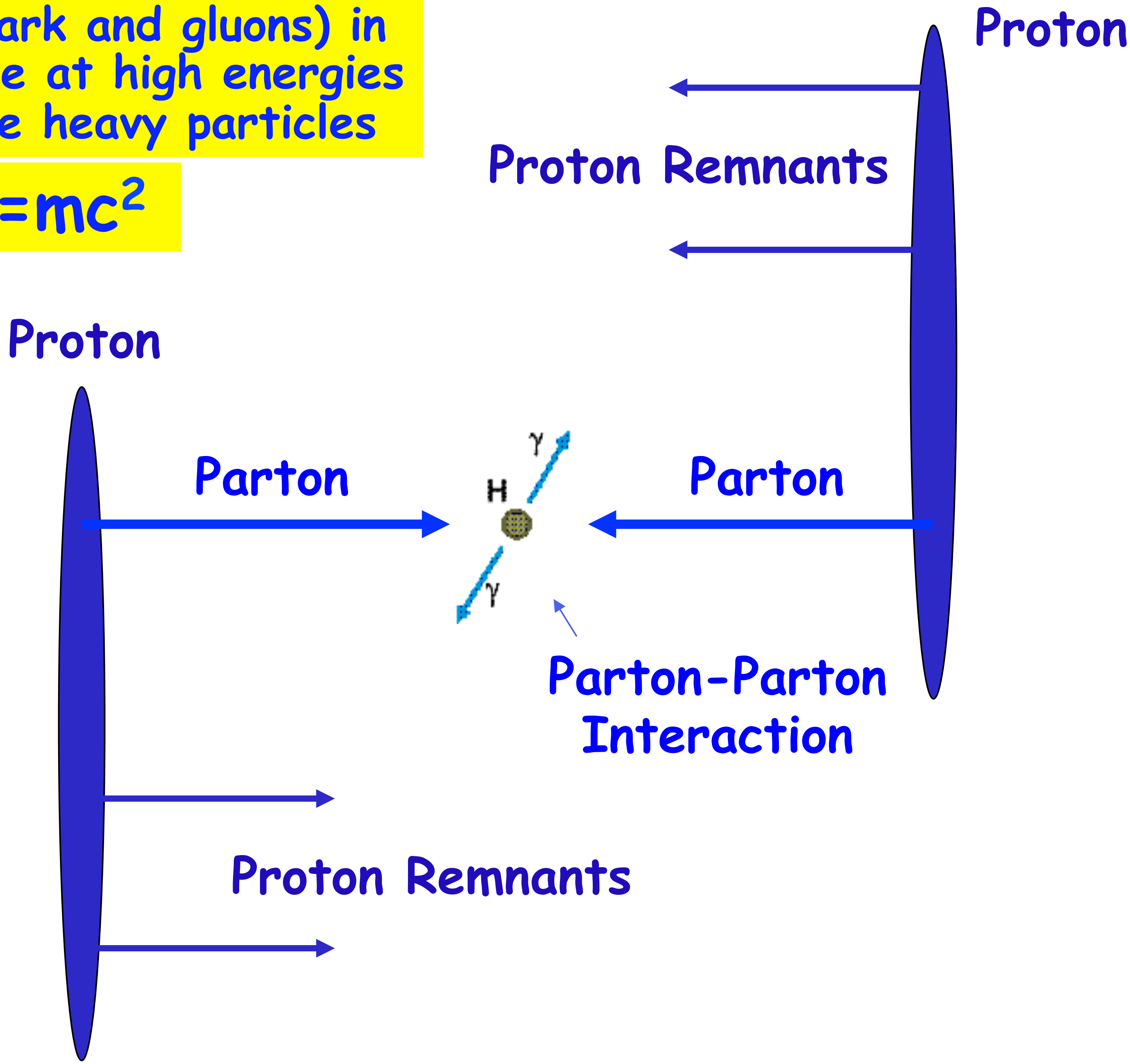
In the standard model there is a physical state, a Higgs boson with well defined couplings to weak bosons, fermions and self interactions

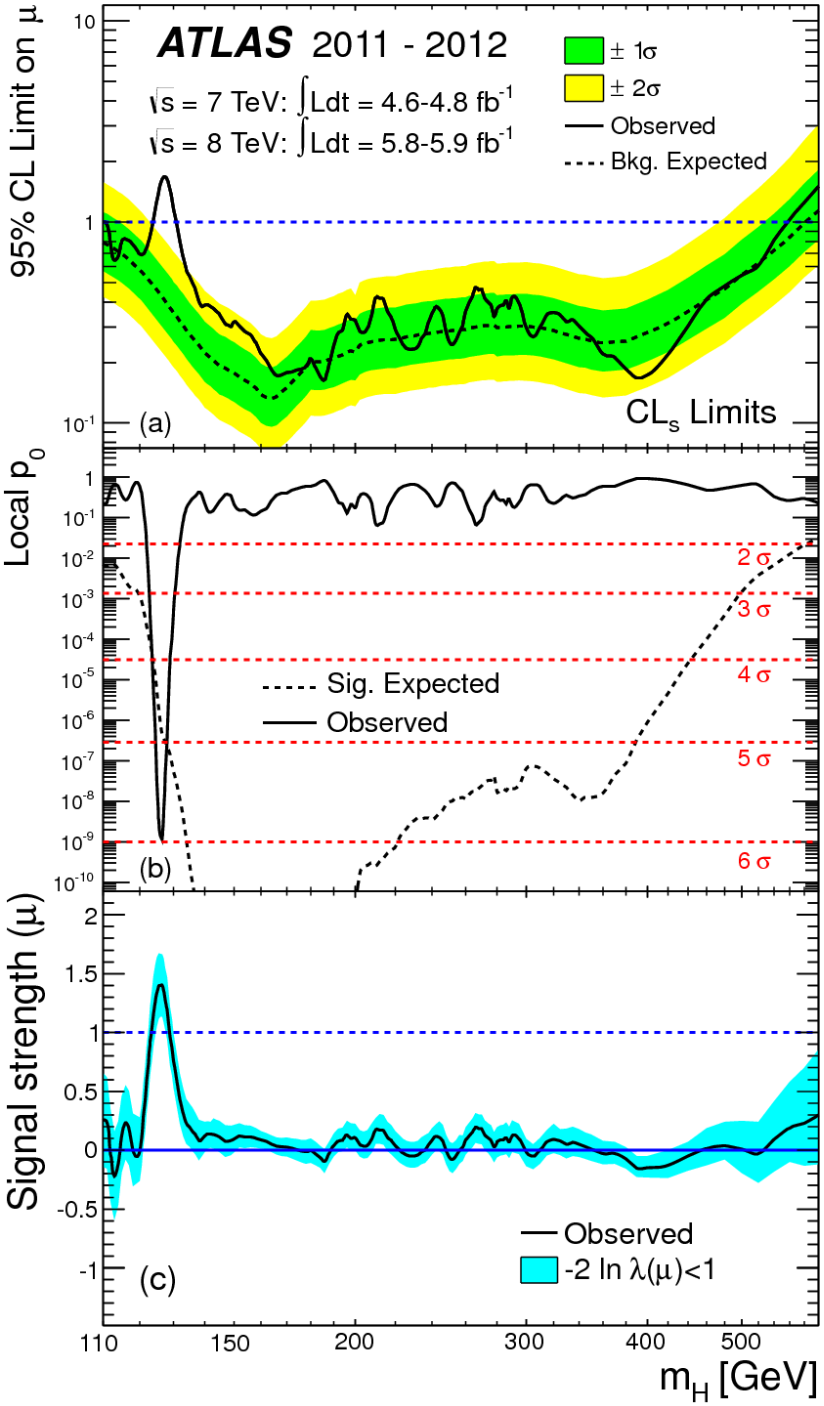
Gauge	Self-interaction	Fermion
$HW^+_\mu W^-_\nu : (-ig_{\mu\nu})2\frac{m_W^2}{\nu}$	$HHH : (i)3\frac{m_H^2}{\nu}$	$H\bar{f}f : (i)\frac{m_f}{\nu}$
$HZ_\mu Z_\nu : (-ig_{\mu\nu})2\frac{m_Z^2}{\nu}$	$HHHH : (i)3\frac{m_H^2}{\nu^2}$	
$HHW^+_\mu W^-_\nu : (-ig_{\mu\nu})2\frac{m_W^2}{\nu^2}$		
$HHZ_\mu Z_\nu : (-ig_{\mu\nu})2\frac{m_Z^2}{\nu^2}$		

The exploration of the coupling known particles plays now a pivotal role in understanding the nature of the scalar boson observed experimentally. New physics can be hidden in these couplings.

Partons (quark and gluons) in proton collide at high energies and produce heavy particles

$$E=mc^2$$

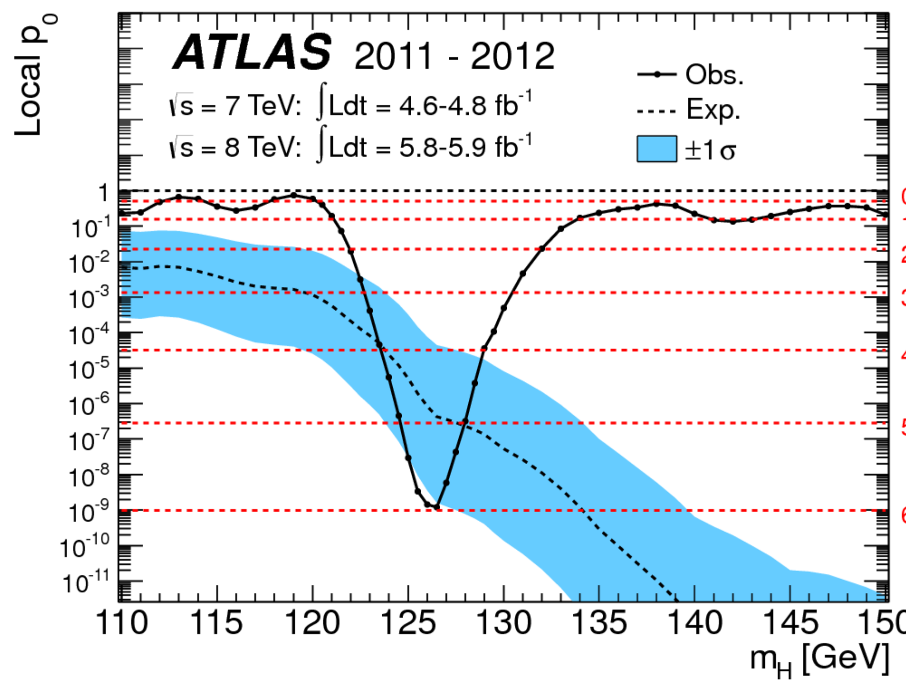




Habemus novum Boson

Phys.Lett. B716 (2012) 1-29

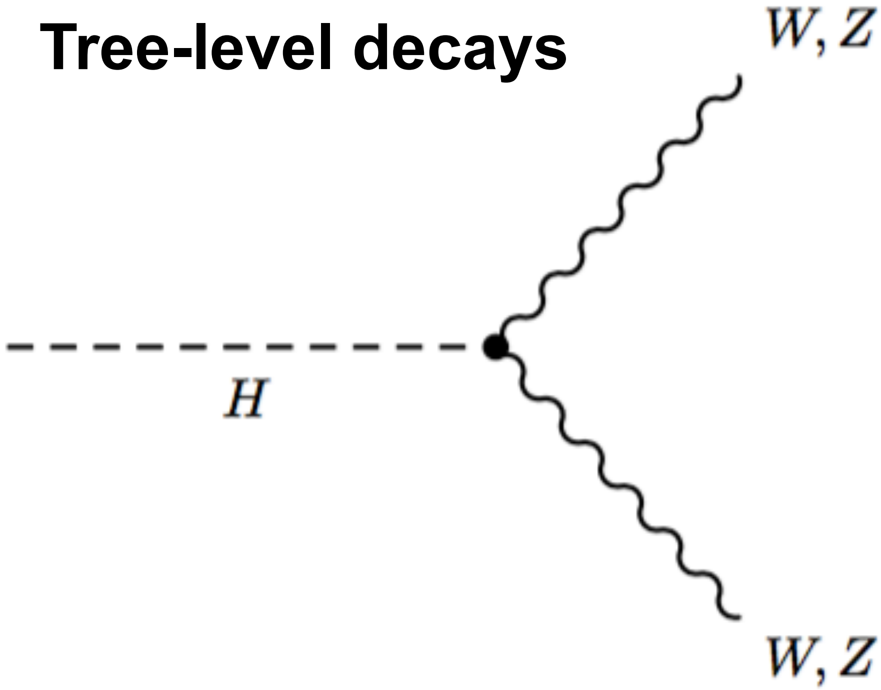
On July 4th reported 5σ.
With the addition of WW a 6σ effect is reached and reported in the final paper.

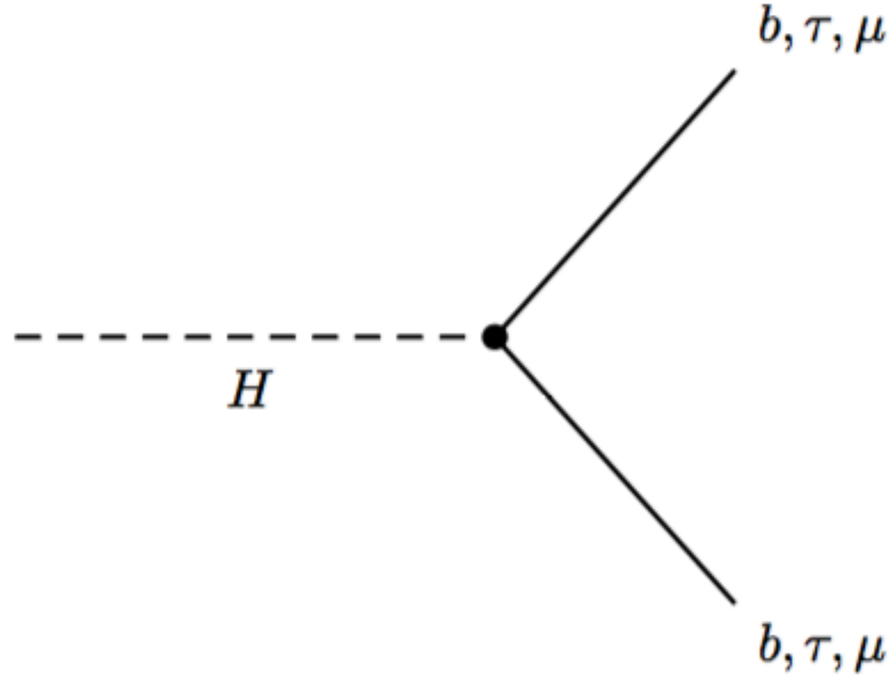


In this presentation we review progress since discovery with Run I

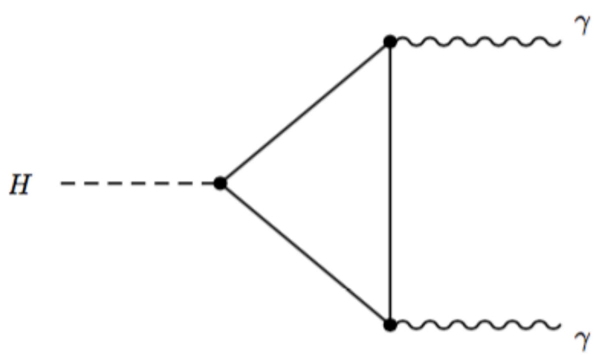
Higgs boson Decays

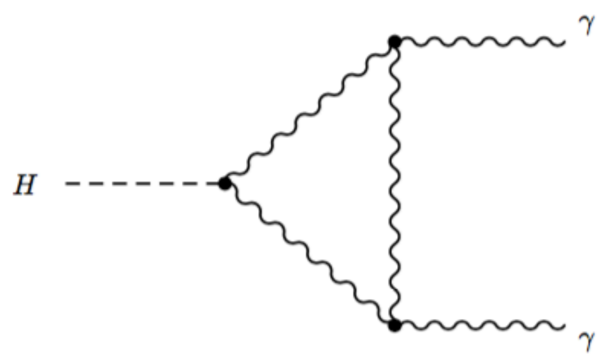
Tree-level decays

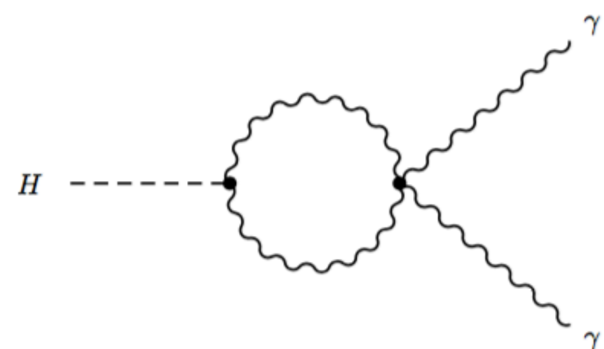




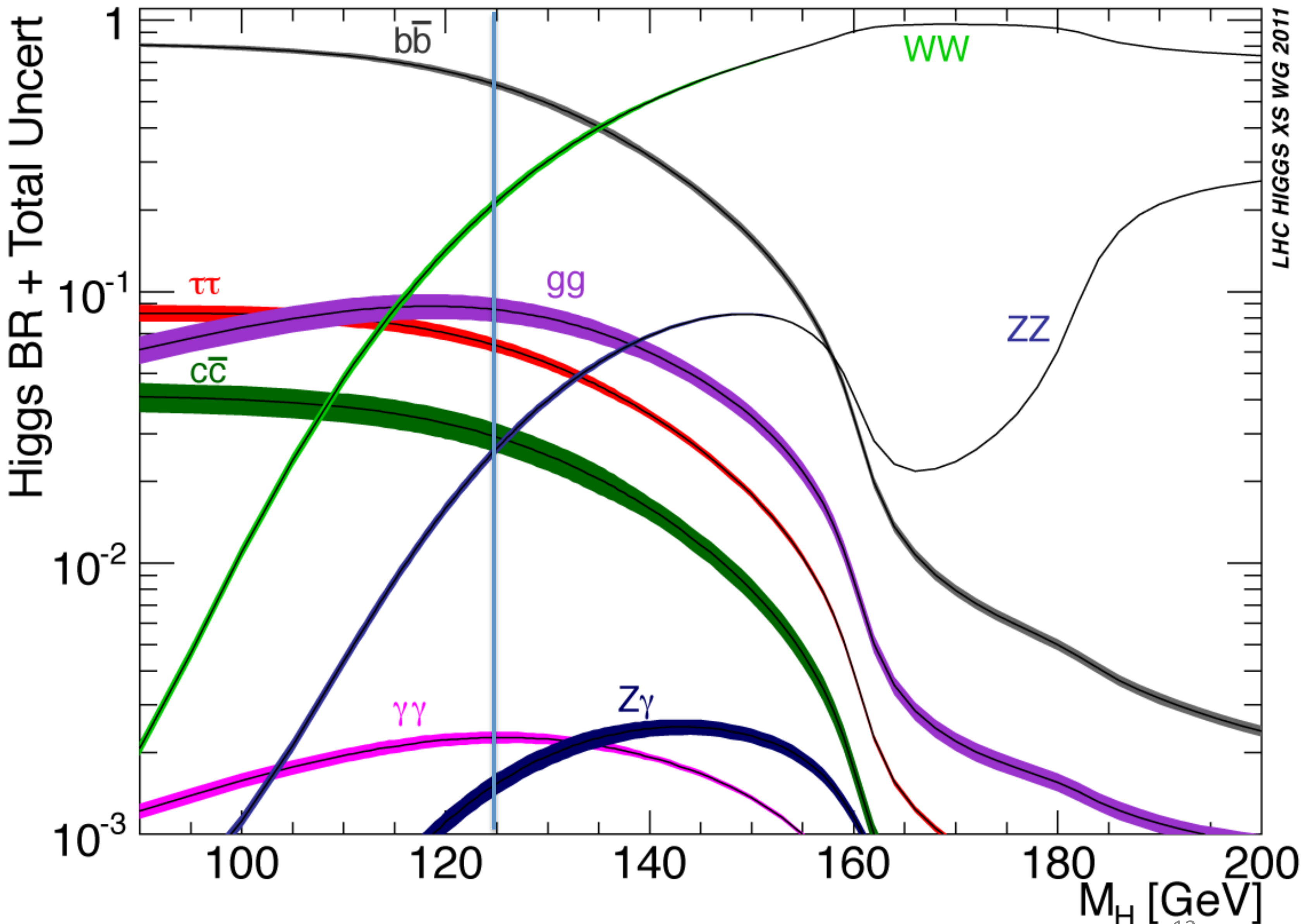
Loop-induced decays



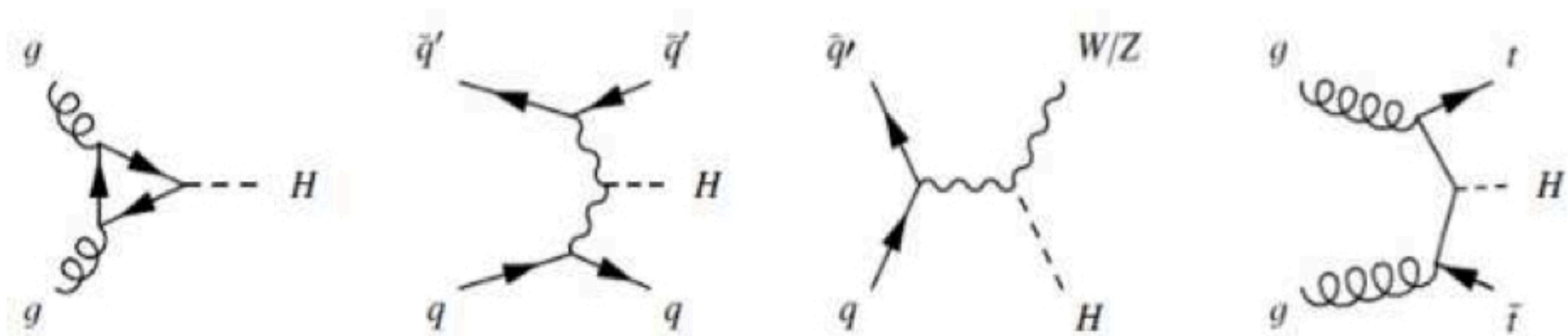




Main Decay Modes



Higgs production at Hadron Colliders

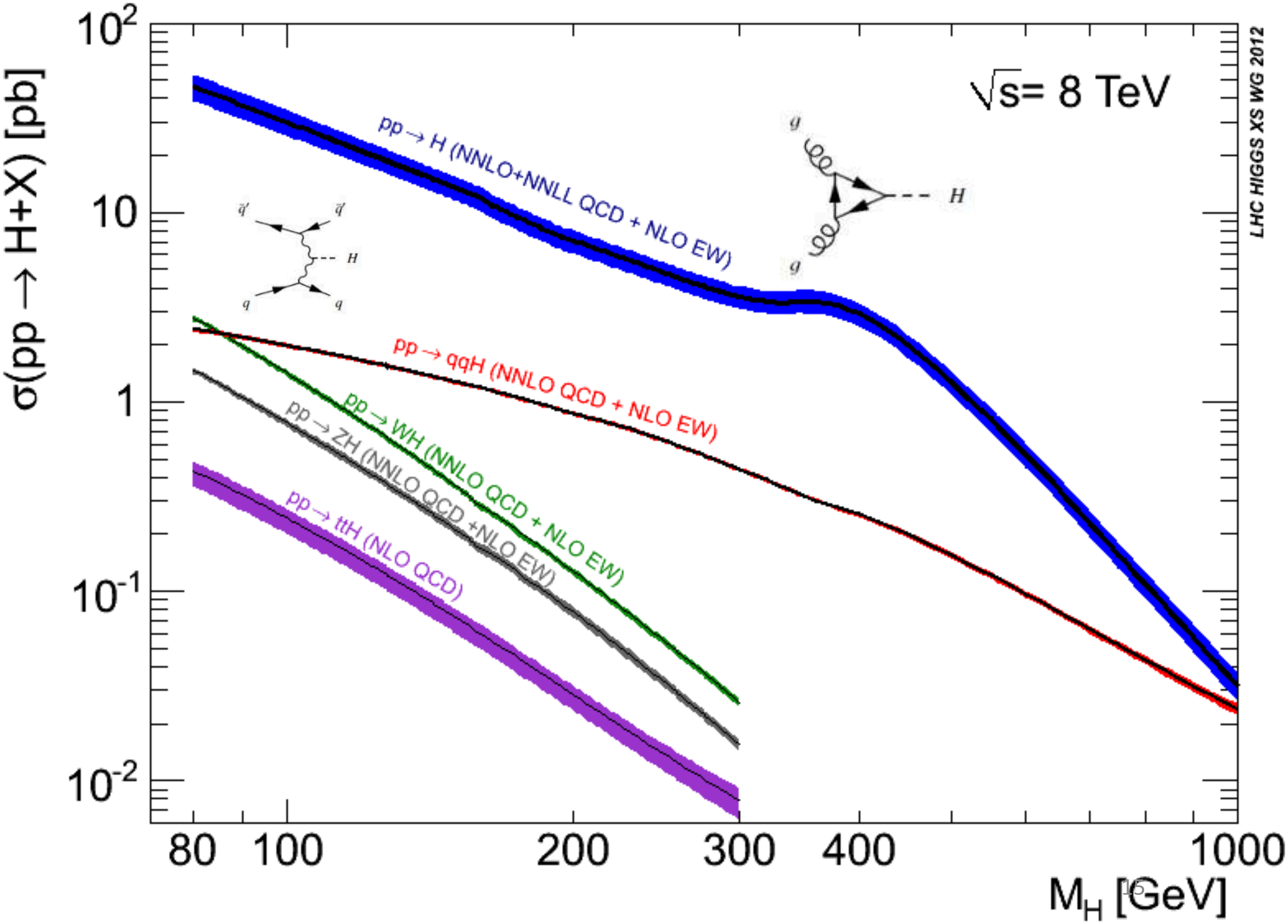


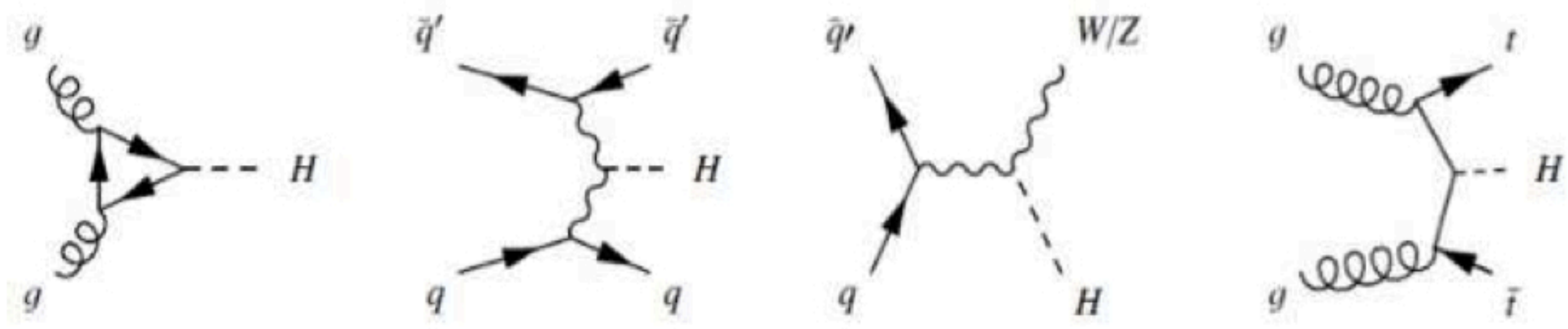
Gluon-gluon fusion

Vector Boson Fusion

Associated Production

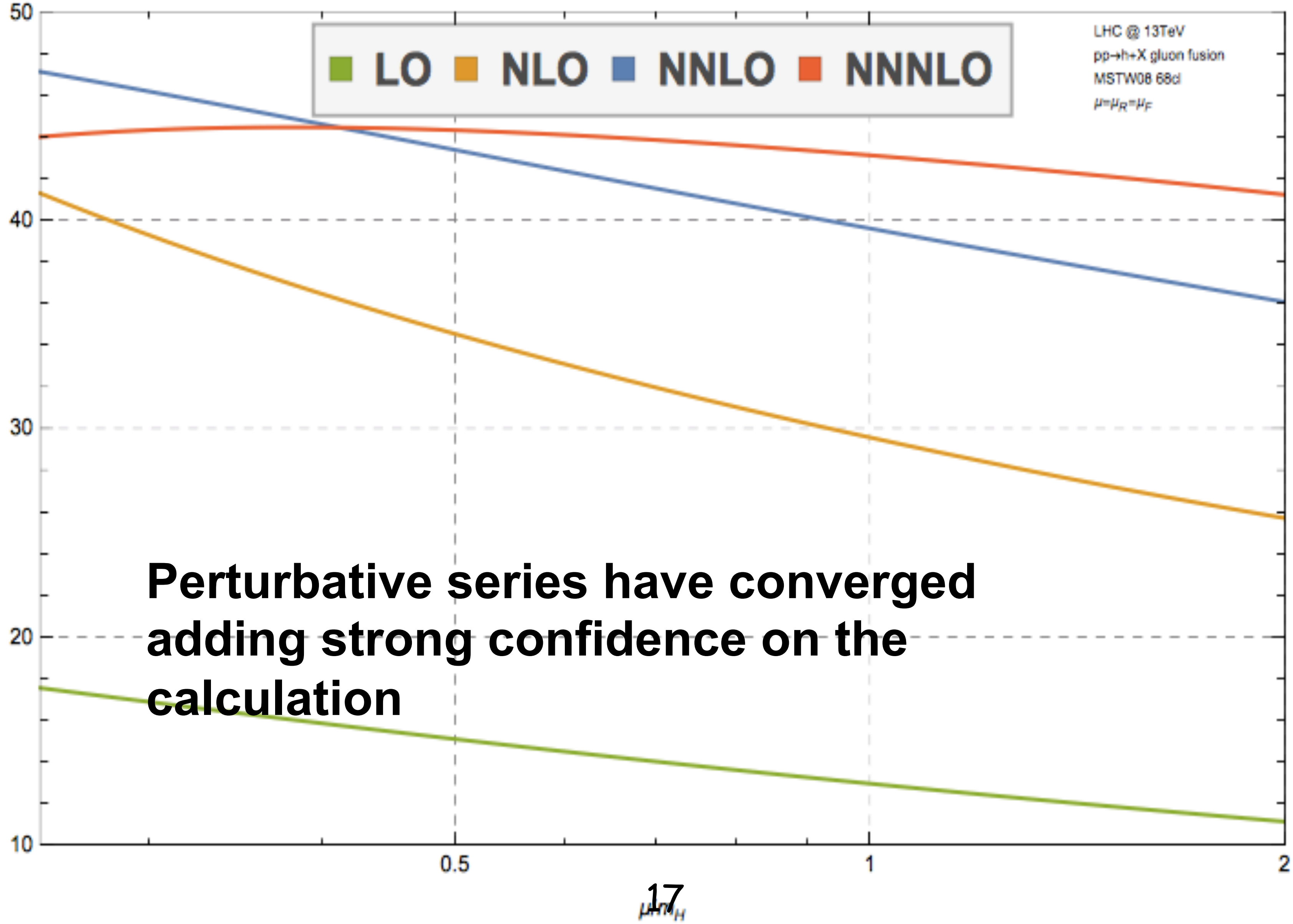
Higgs Cross-Sections at LHC





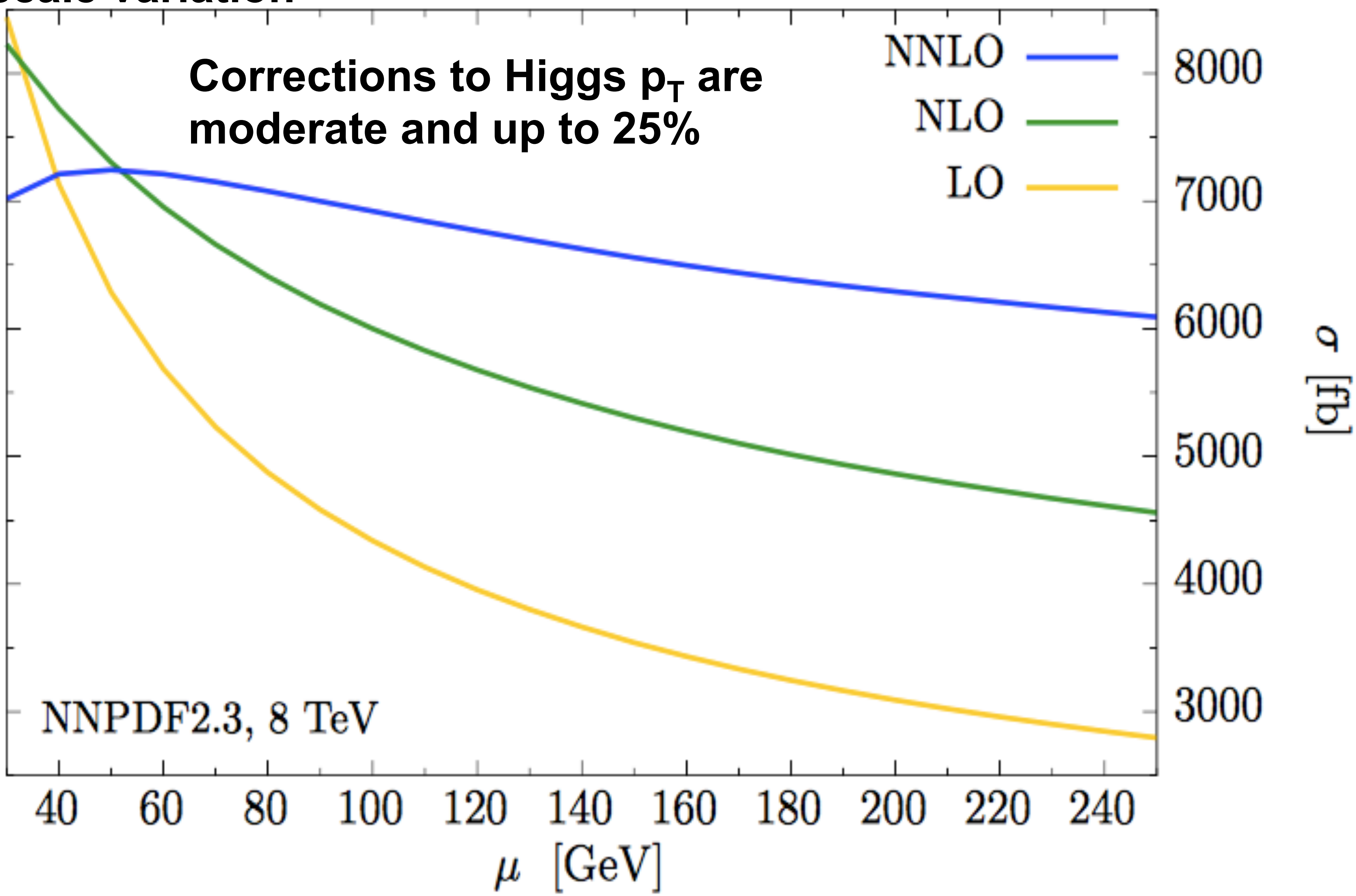
Production process	Cross section [pb]		Order of calculation
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD) + NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW) + APPROX. NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD) + NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD) + NLO(EW)
[$ggZH$]	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	

arXiv:1503.06056v1, C. Anastasiou et al.
First Complete N3LO calculation for the total gluon-gluon fusion cross-section showing small N3LO/NNLO corrections



Perturbative series have converged adding strong confidence on the calculation

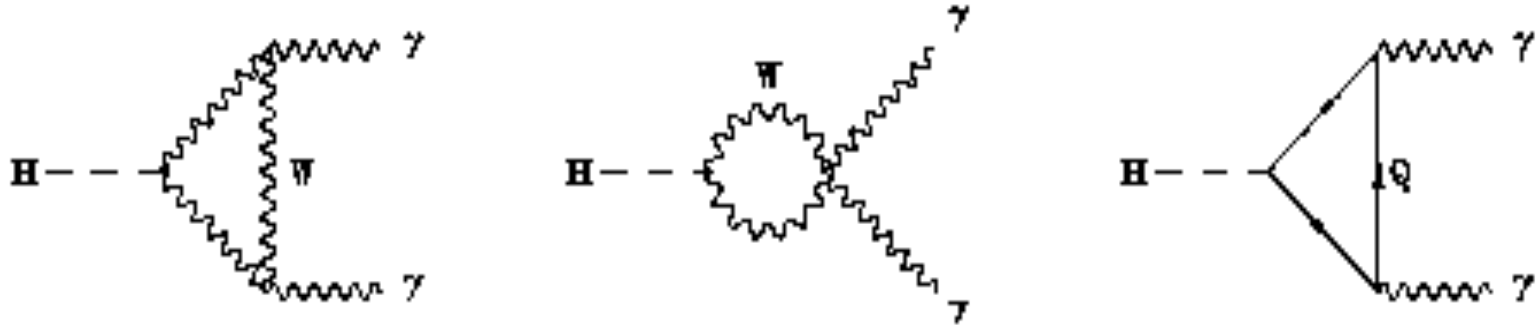
arXiv:1504.07922v1, R. Boughezal et al. First complete calculation of ggF+1j at NNLO, showing strong reduction of scale variation



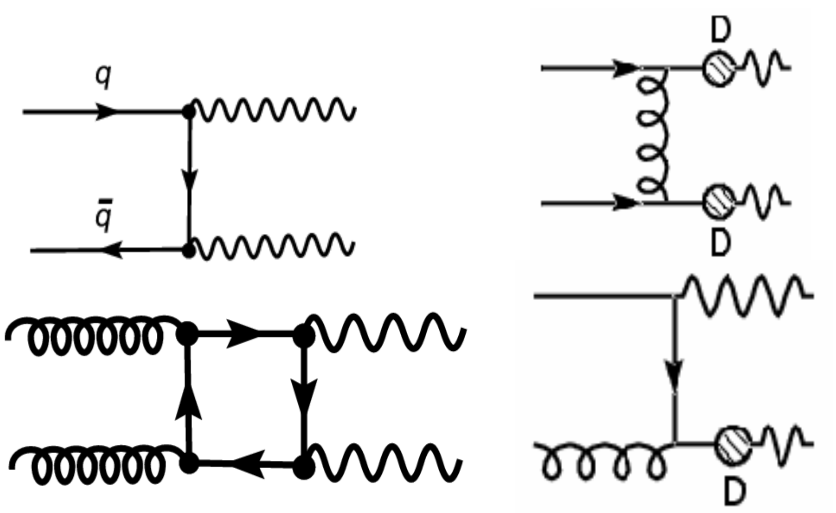
The Main Channels

Channels used in the measurement of properties

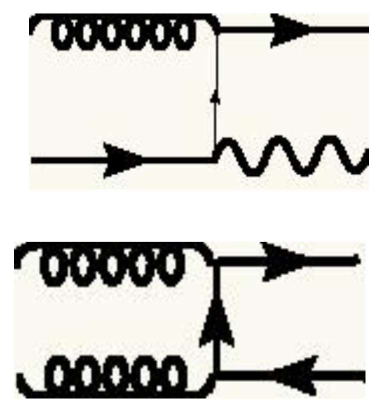
Higgs decay to γγ



γγ Backgrounds



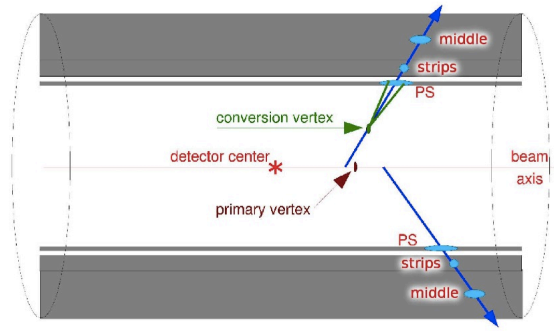
Reducible γj and jj Backgrounds



$q \rightarrow \pi^0$

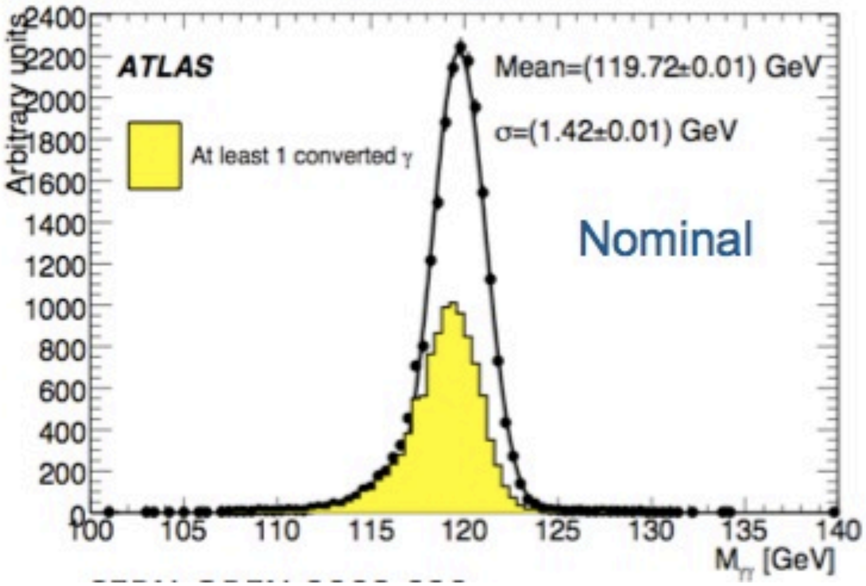
Diphoton Invariant Mass

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

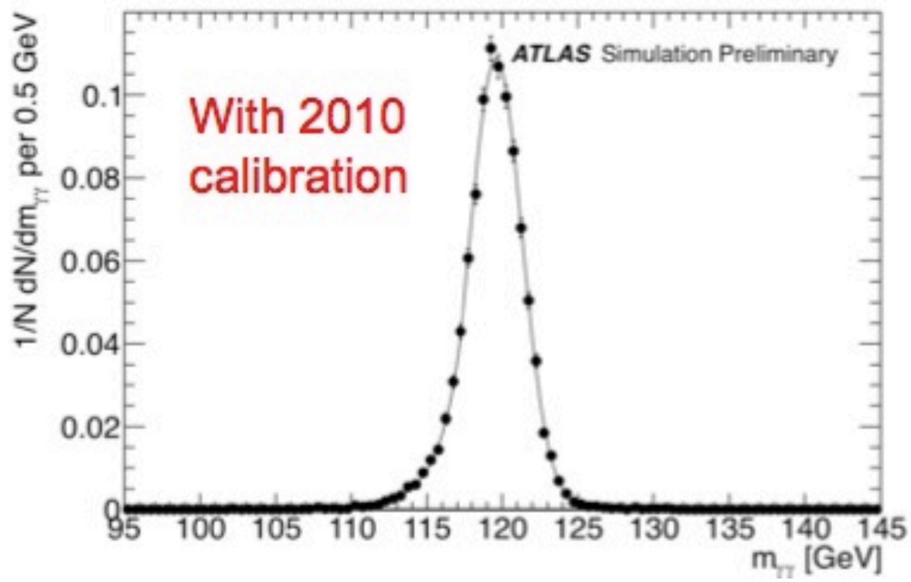


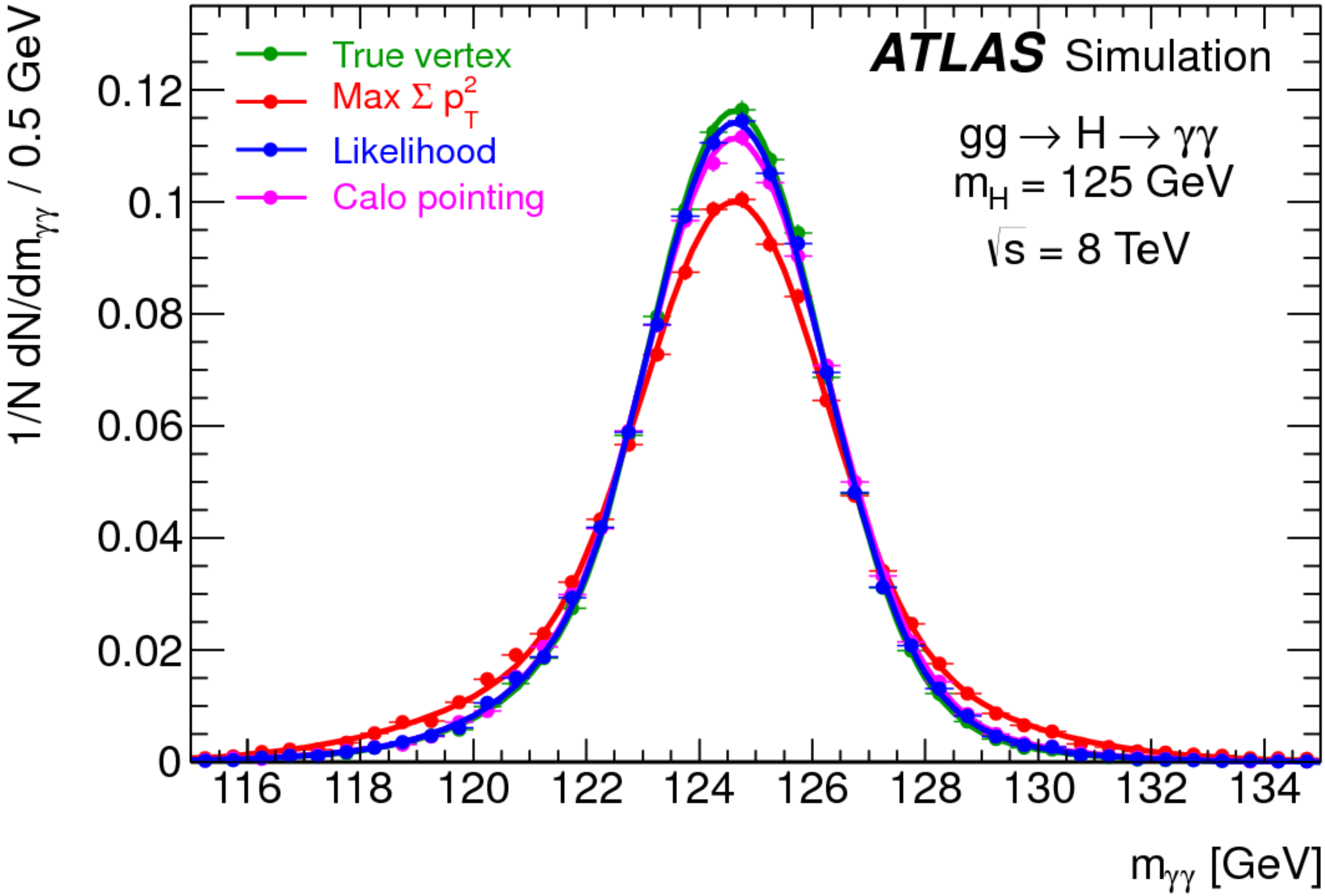
- Energy scale calibration from Z to electrons applied
- Crystal Ball + Gaussian model with narrow widths (of the core of the distribution) :

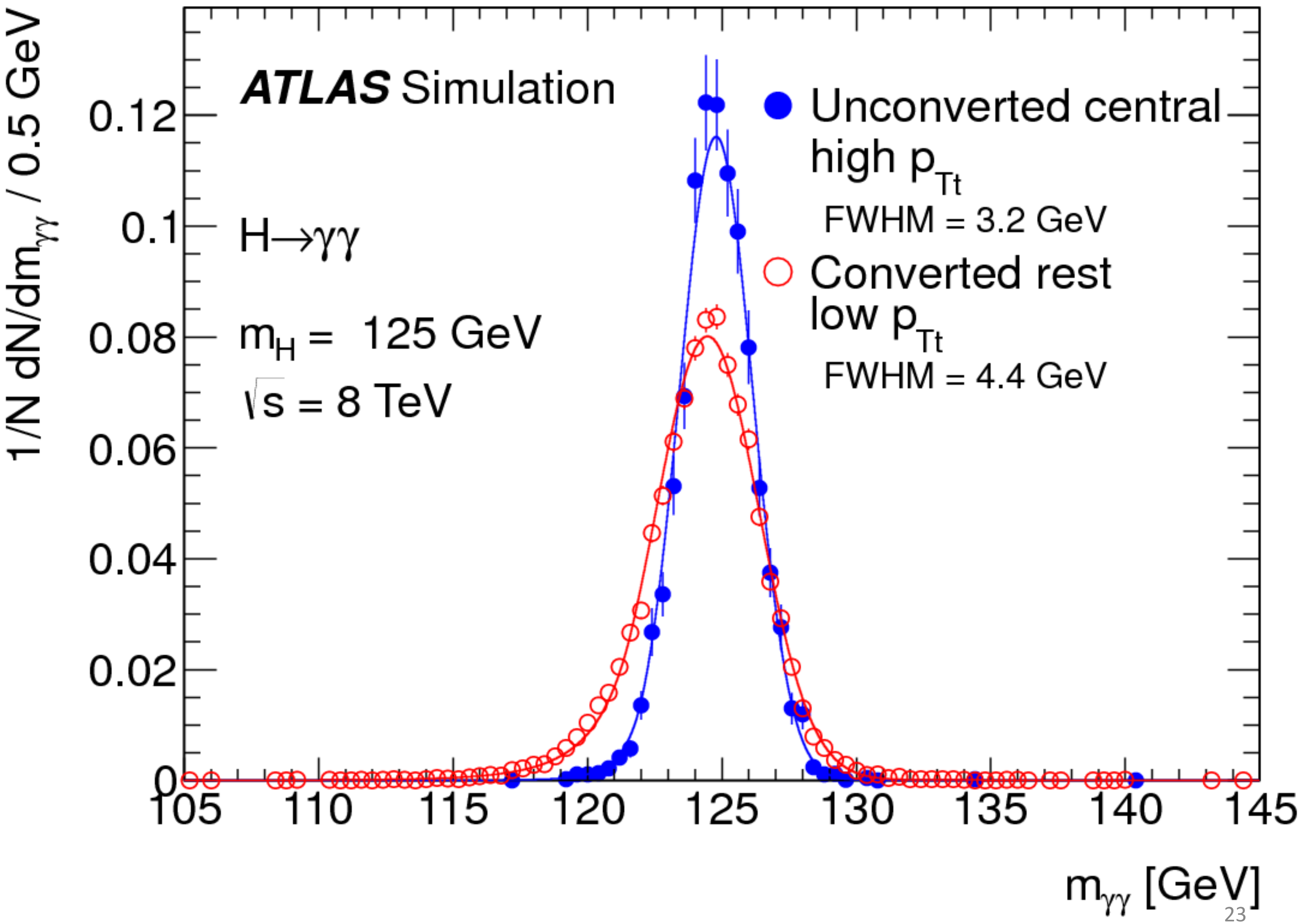
$\sigma \sim 1.4$ GeV



$\sigma \sim 1.7$ GeV



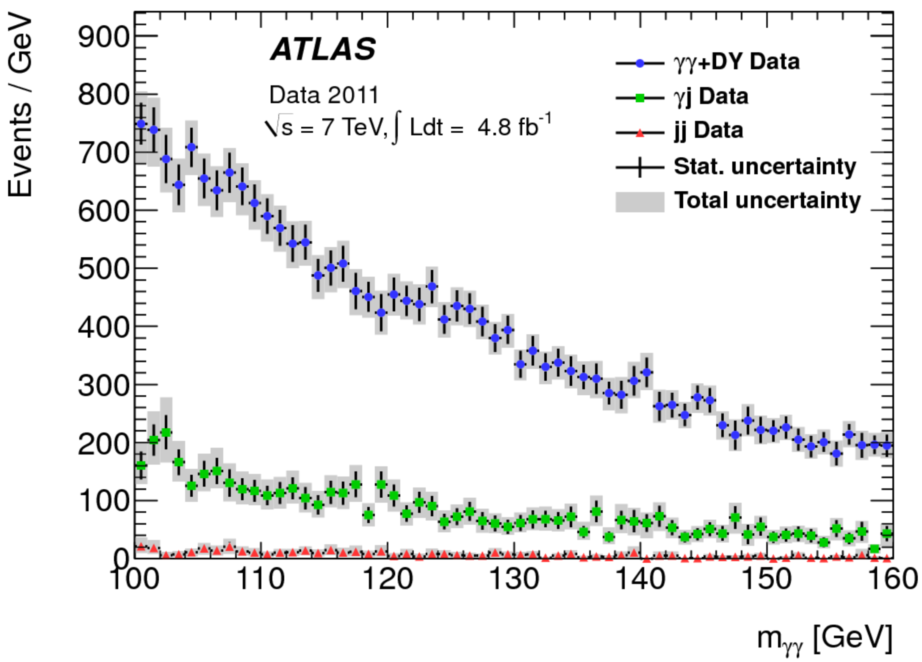

ATLAS Simulation
True vertex
Max Σ p_T^2
Likelihood
Calo pointing
$gg \rightarrow H \rightarrow \gamma\gamma$
m_H = 125 GeV
$\sqrt{s}$ = 8 TeV
1/N dN/d$m_{\gamma\gamma}$ / 0.5 GeV
0.12
0.1
0.08
0.06
0.04
0.02
0
116
118
120
122
124
126
128
130
132
134
$m_{\gamma\gamma}$ [GeV]

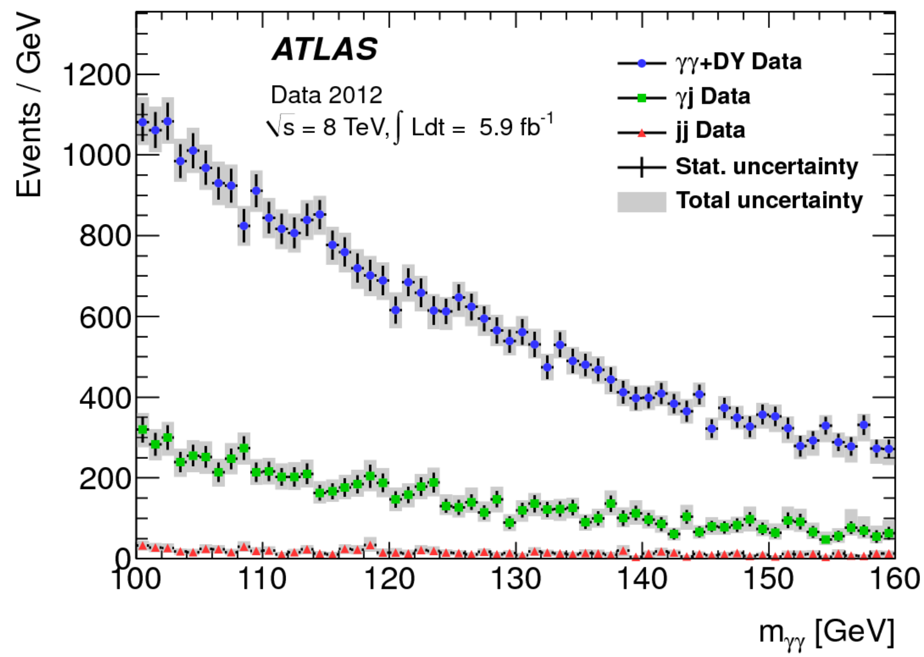


ATLAS Simulation
H→γγ
m_H = 125 GeV
$\sqrt{s}$ = 8 TeV
Unconverted central high p_{Tt}
FWHM = 3.2 GeV
Converted rest low p_{Tt}
FWHM = 4.4 GeV
1/N dN/d$m_{\gamma\gamma}$ / 0.5 GeV
$m_{\gamma\gamma}$ [GeV]
0
0.02
0.04
0.06
0.08
0.1
0.12
105
110
115
120
125
130
135
140
145

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	$(71 \pm 5)\,\%$	$(23 \pm 4)\,\%$	$(5 \pm 3)\,\%$	$(0.7 \pm 0.1)\,\%$

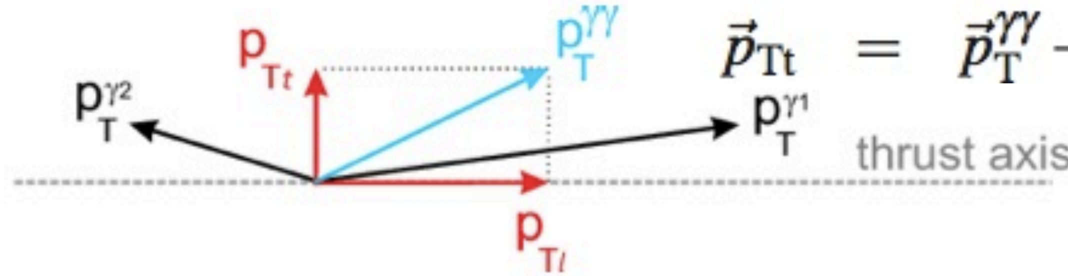


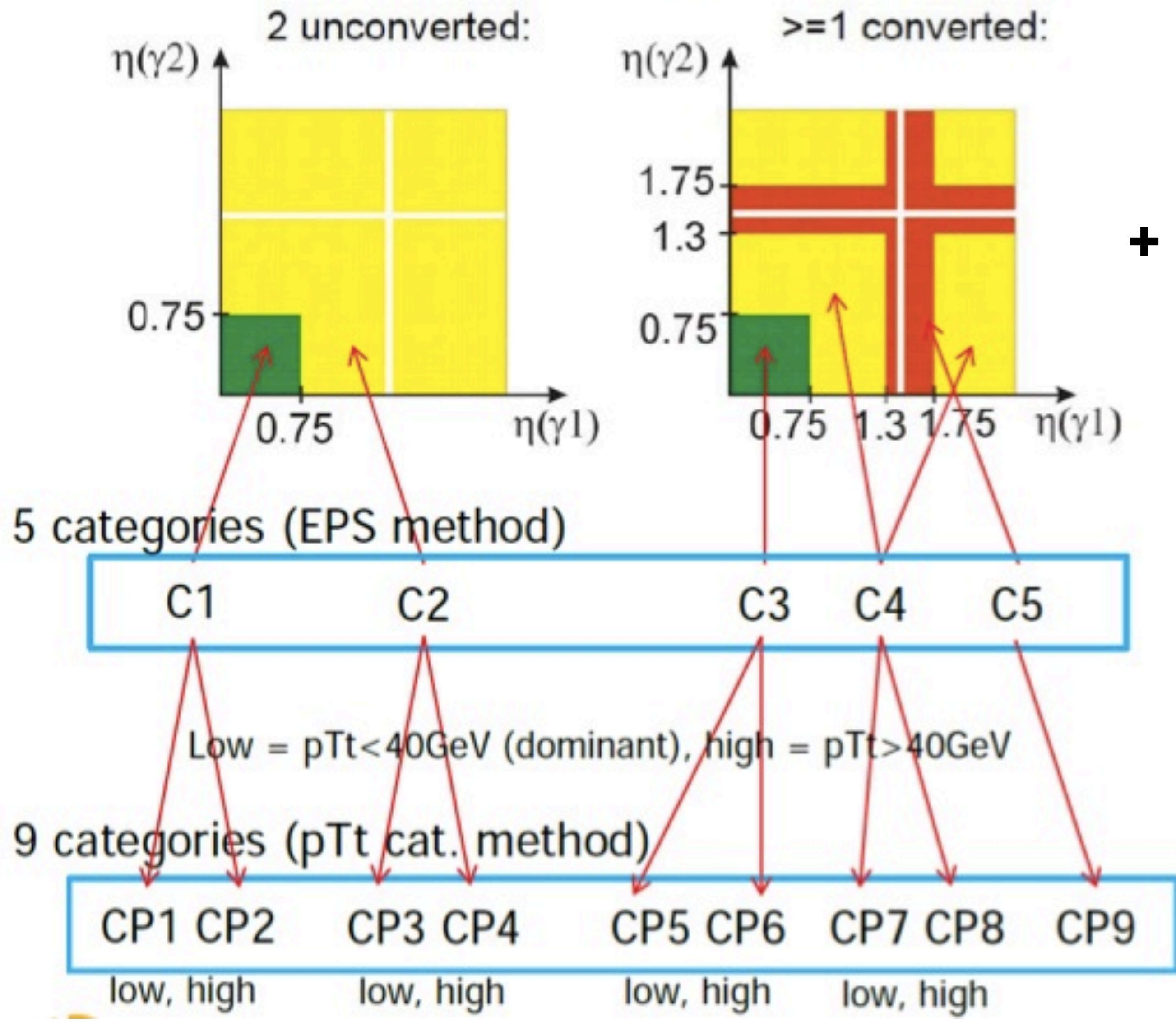


Categorization

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

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

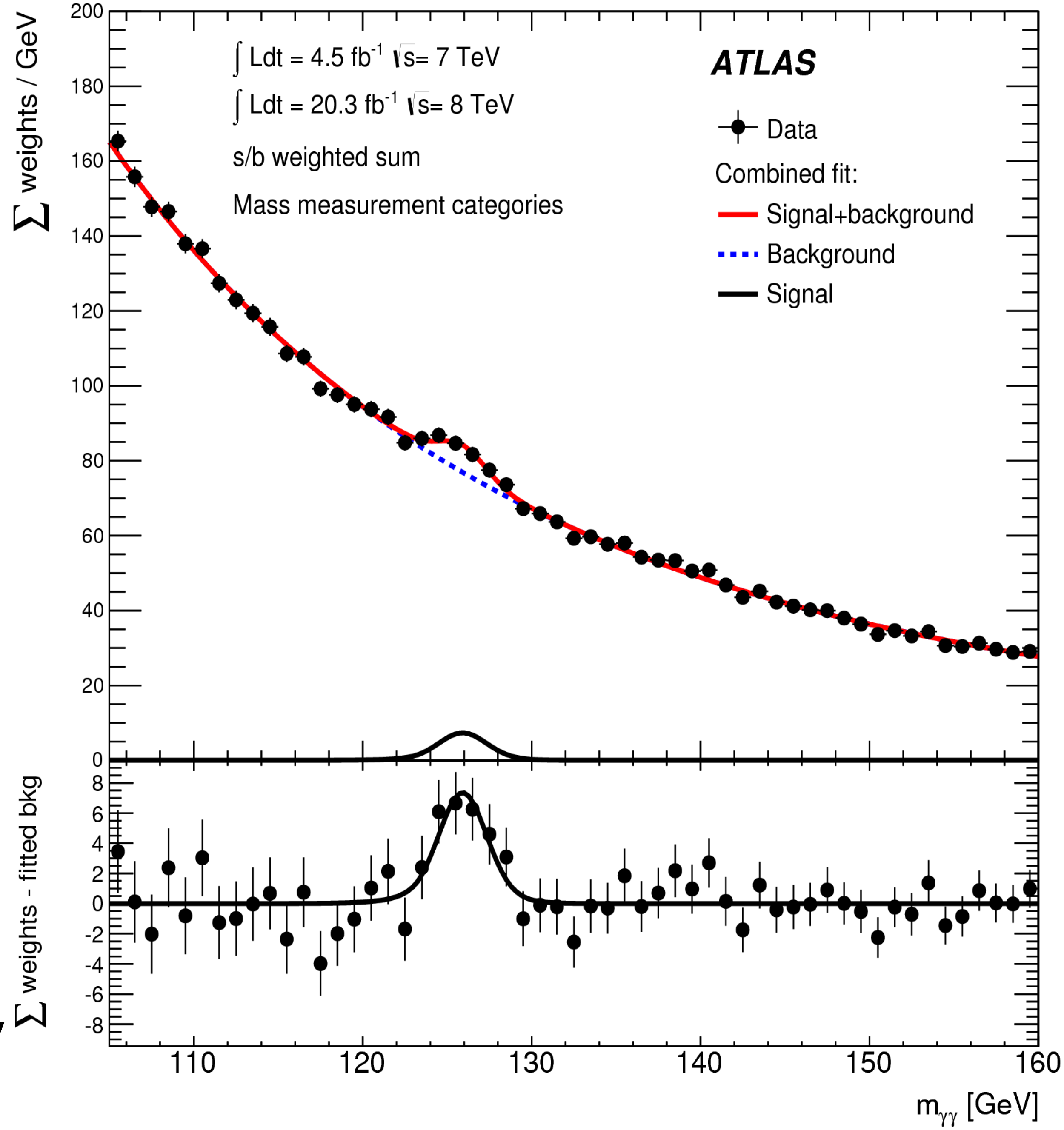




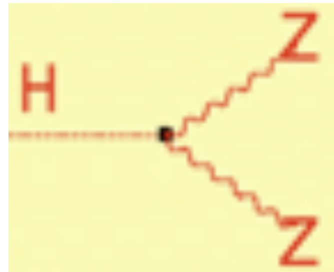
+ 2j (VBF)

$$H \rightarrow \gamma\gamma$$

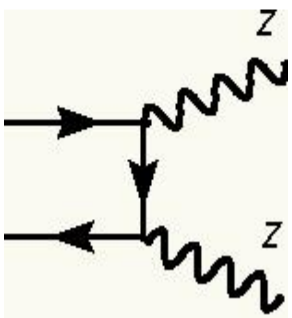
Di-photon Invariant mass distribution; analysis for data, showing weighted data points with errors, and the result of the simultaneous fit to all categories. The fitted signal plus background is shown, along with the background-only component of this fit.

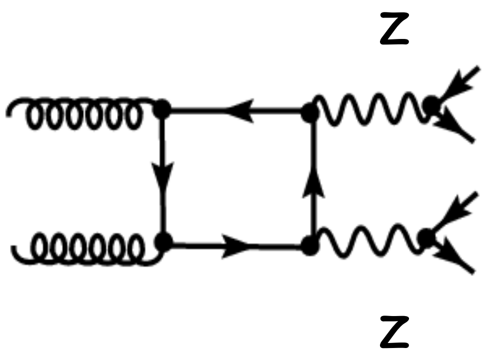


Higgs decay to Z^0Z^0

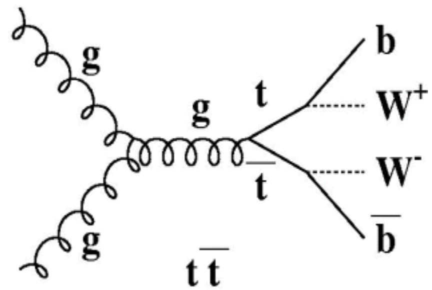


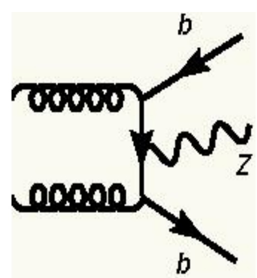
Irreducible Z^0Z^0 backgrounds

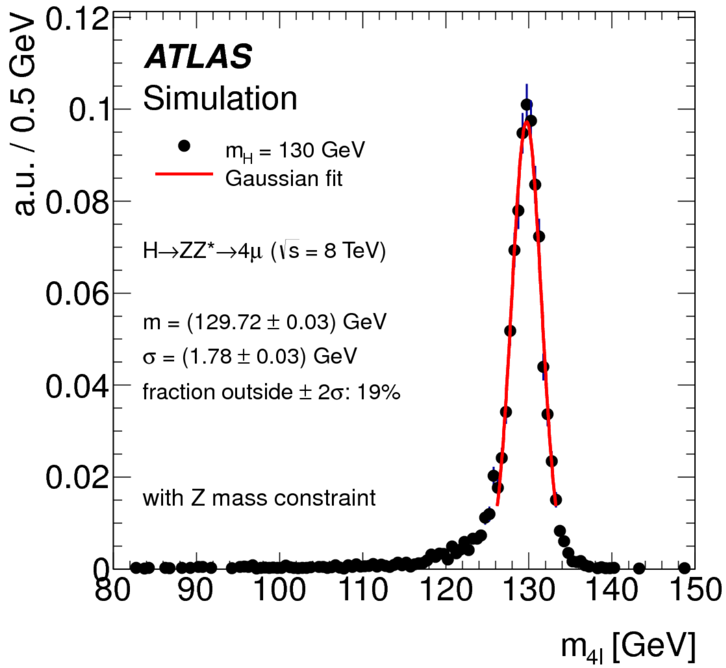




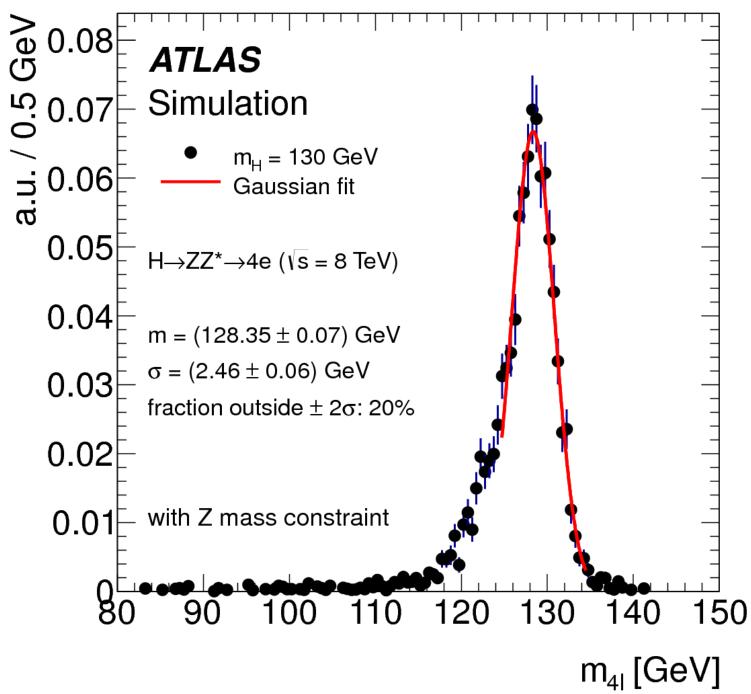
Reducible 4l backgrounds

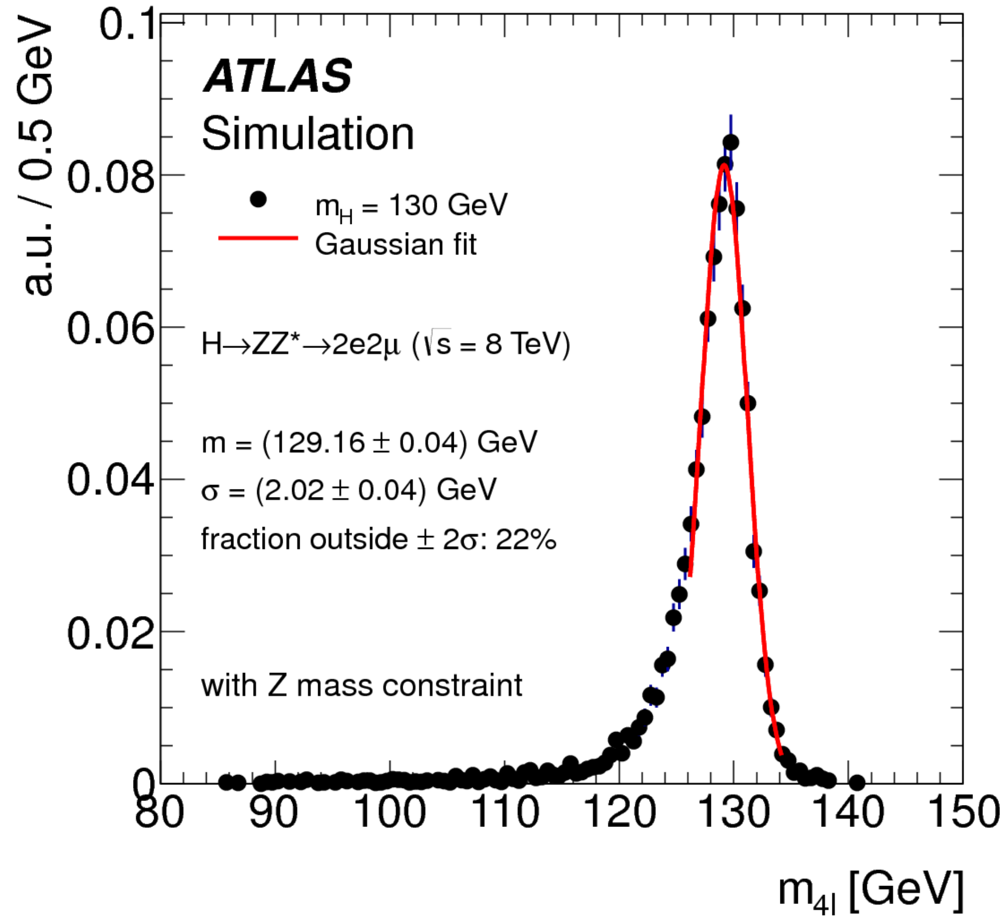




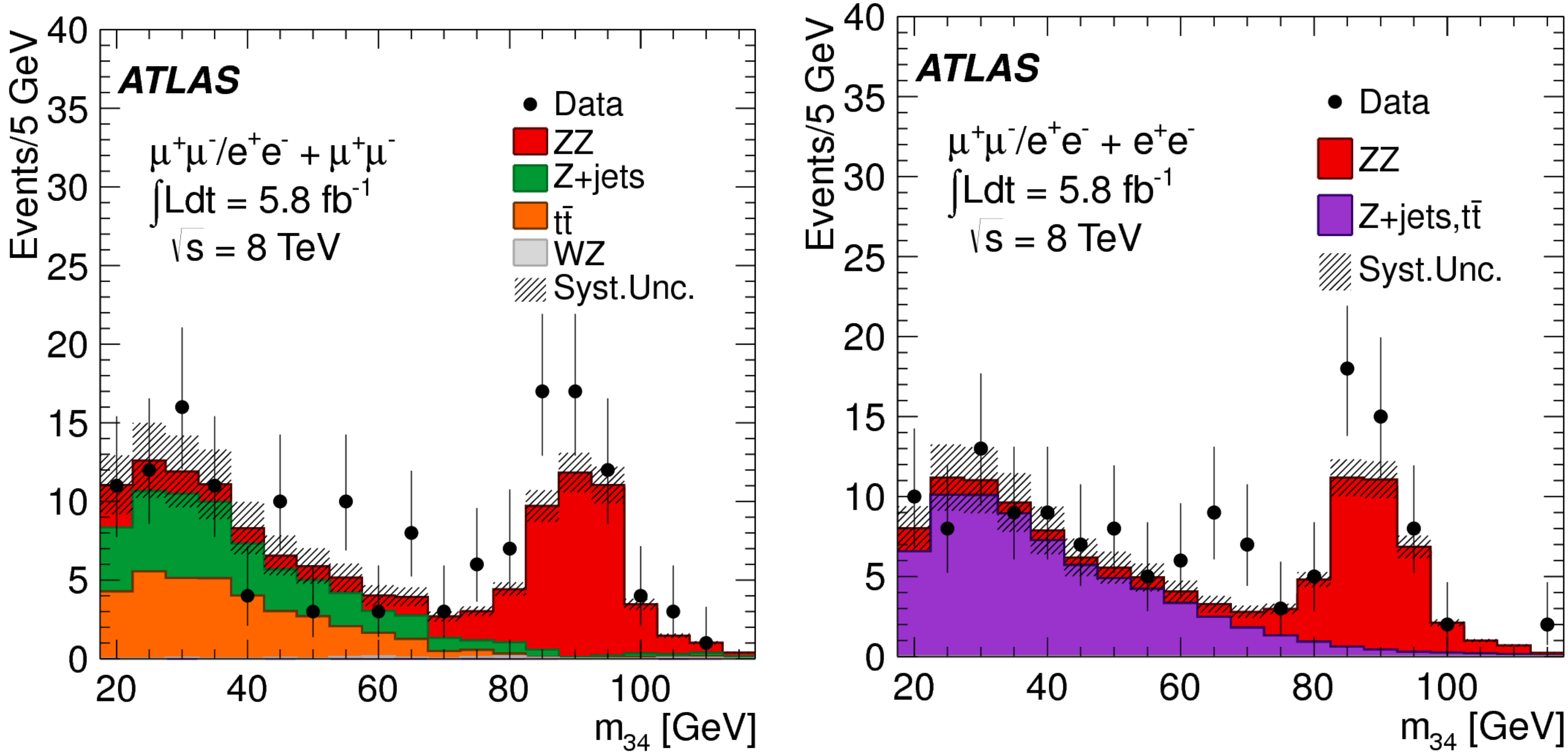


Mass resolution plots after the application of a mass constraint.
Gain in resolution ~15-20%

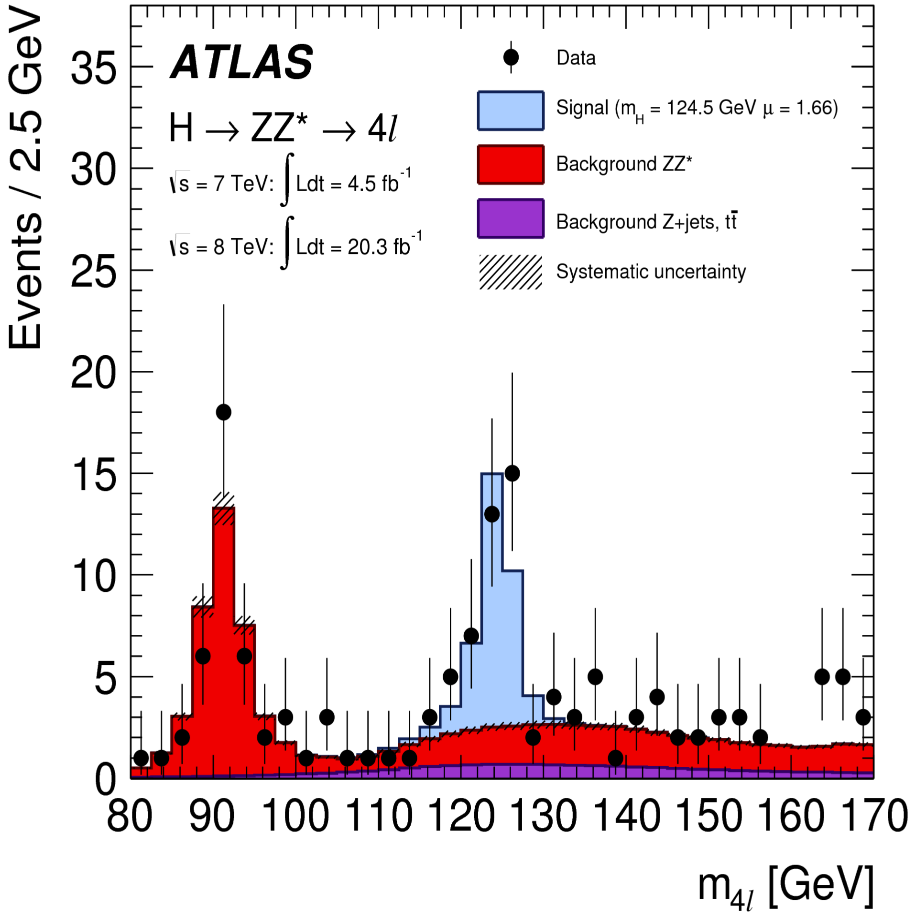




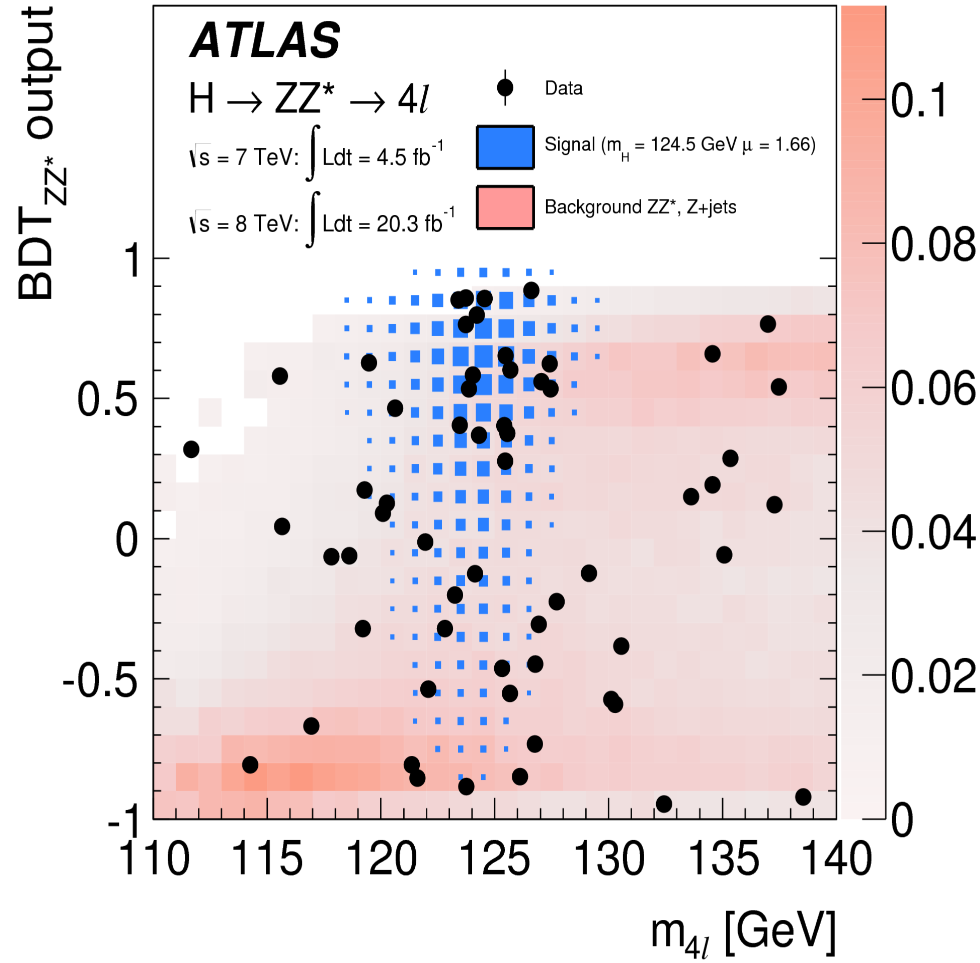
Invariant mass distribution of the second lepton pair: μμ and *ee.* The kinematic selections of the analysis have been applied. Isolation requirements have been applied on the first lepton pair. No charge requirements were applied to the second lepton pair.



$H \rightarrow ZZ^{*} \rightarrow 4\ell$



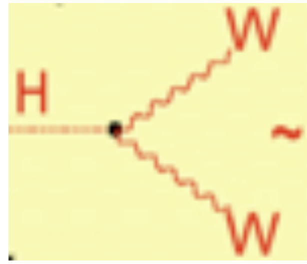
Distribution of the four-lepton invariant mass for the selected candidates in the m_{4l} range 80--170 GeV



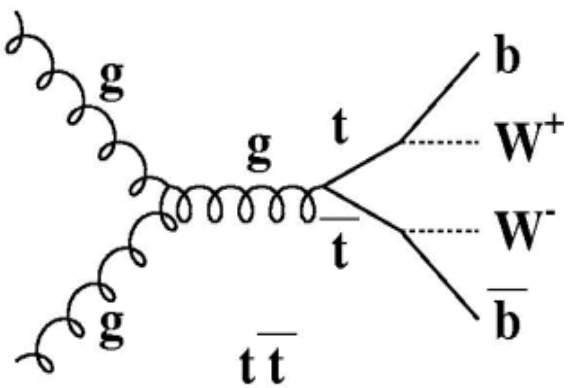
Distribution of the MVA (BDT) ZZ* output, versus m_{4l}; for the selected candidates in the m_{4l} range of 110--140 GeV

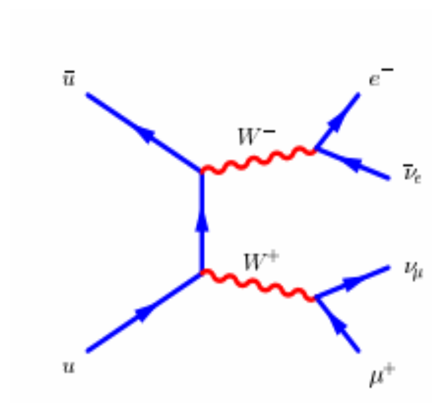
Higgs decay to W^+W^-

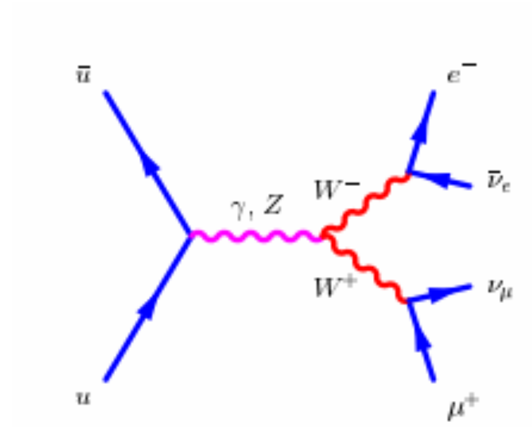
Two leptons + neutrinos
No mass peak
Event counting experiment

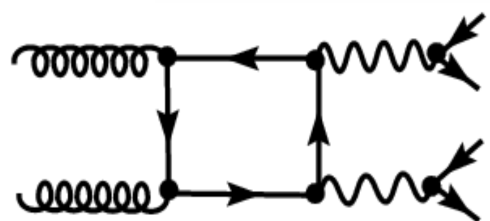


W^+W^- backgrounds





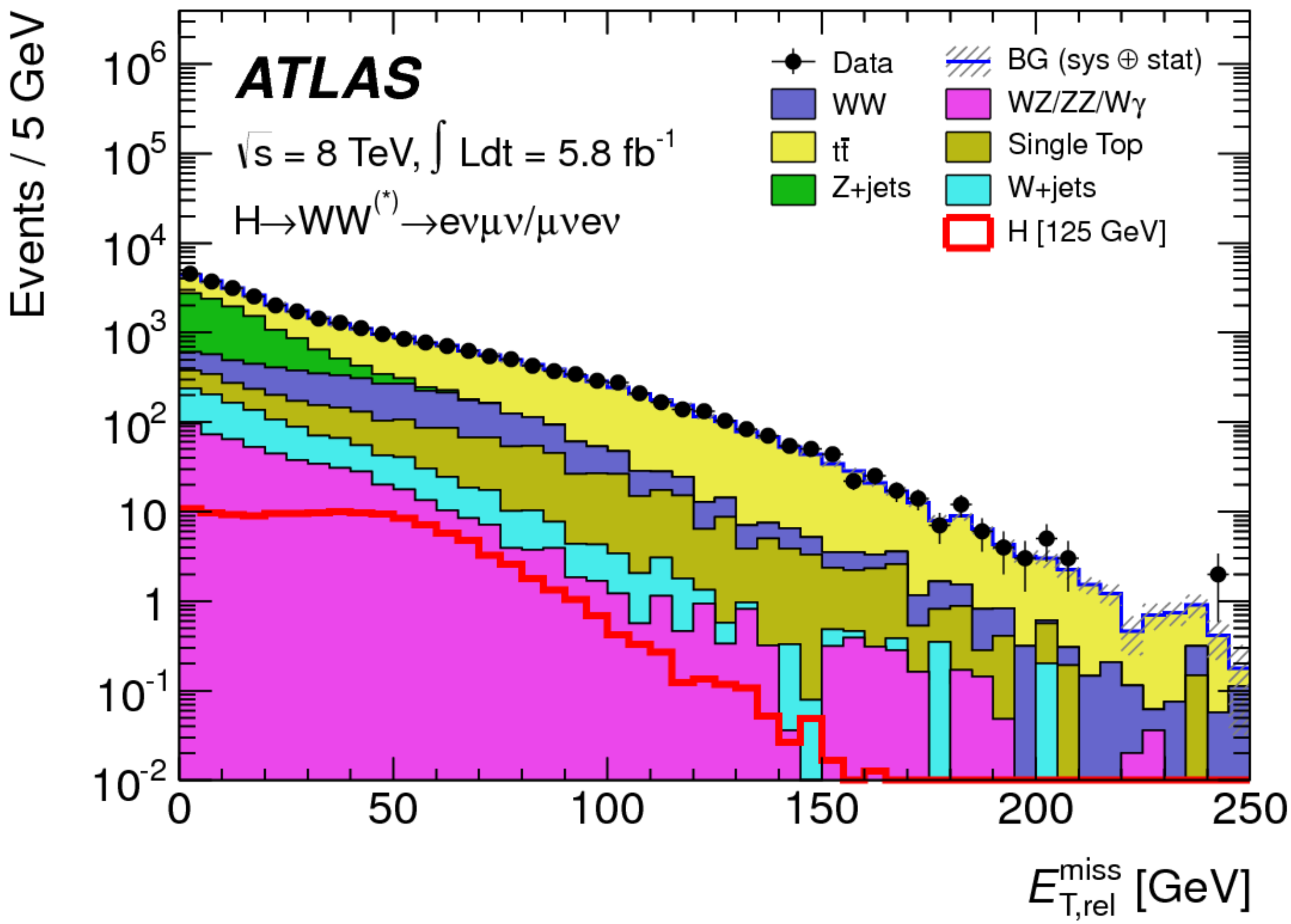




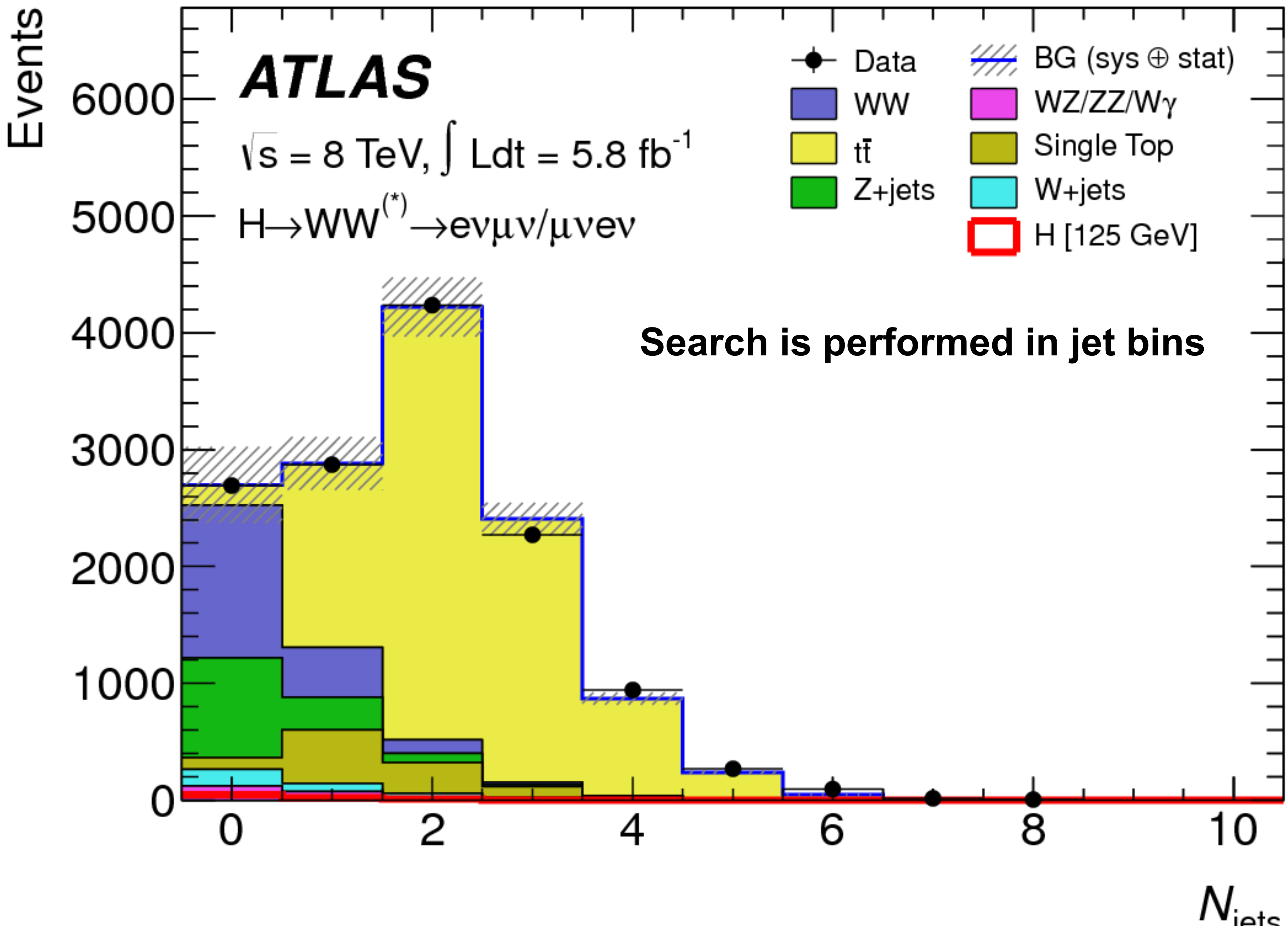
+ Single top
& non-resonant WWbb

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

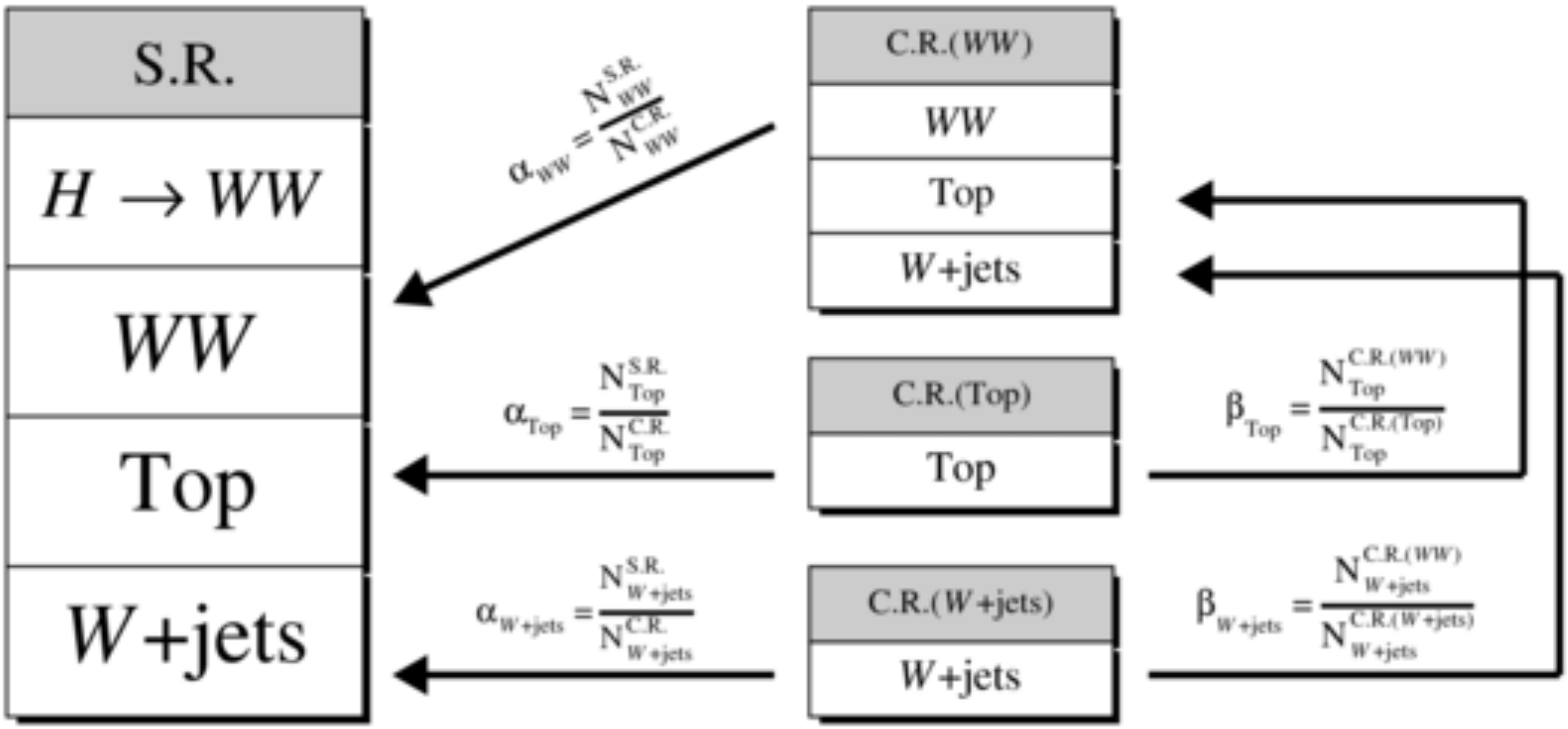
$$E_{\mathrm{T,rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \cdot \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$



A real challenge this time around!

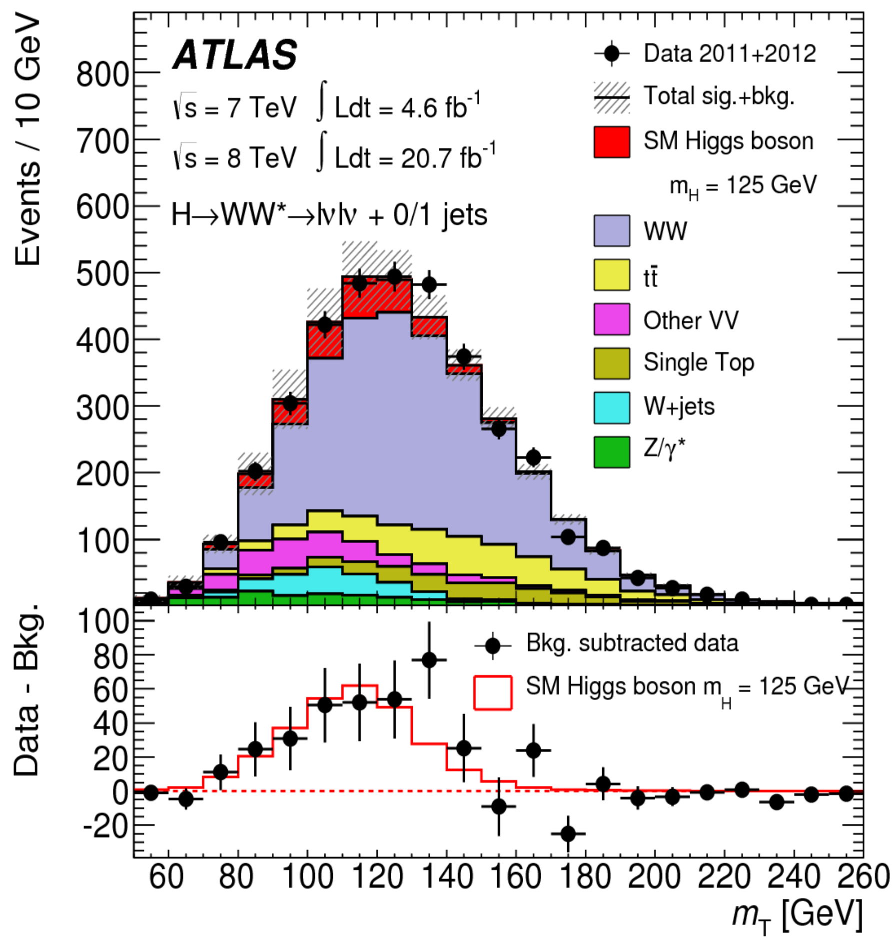

ATLAS
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 5.8 fb^{-1}
$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu/\mu\nu e\nu$
Data
WW
$t\bar{t}$
Z+jets
BG (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
H [125 GeV]
Search is performed in jet bins
Events
0
1000
2000
3000
4000
5000
6000
0
2
4
6
8
10
N_{jets}

Flow chart for Back. Extraction

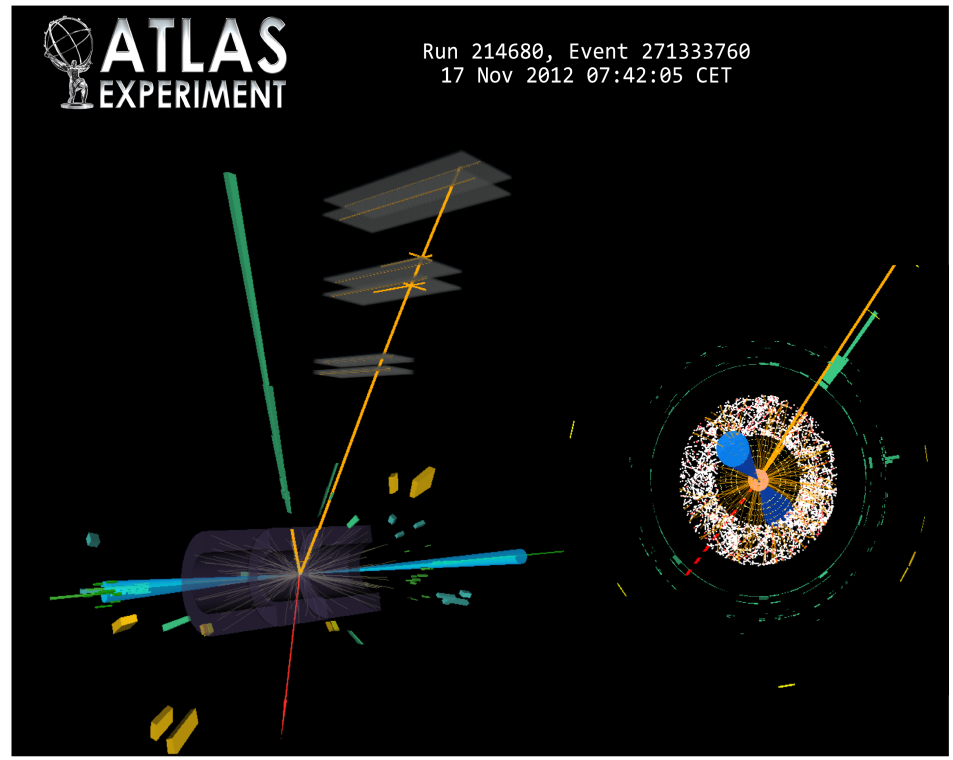


Complete propagation of systematic errors

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

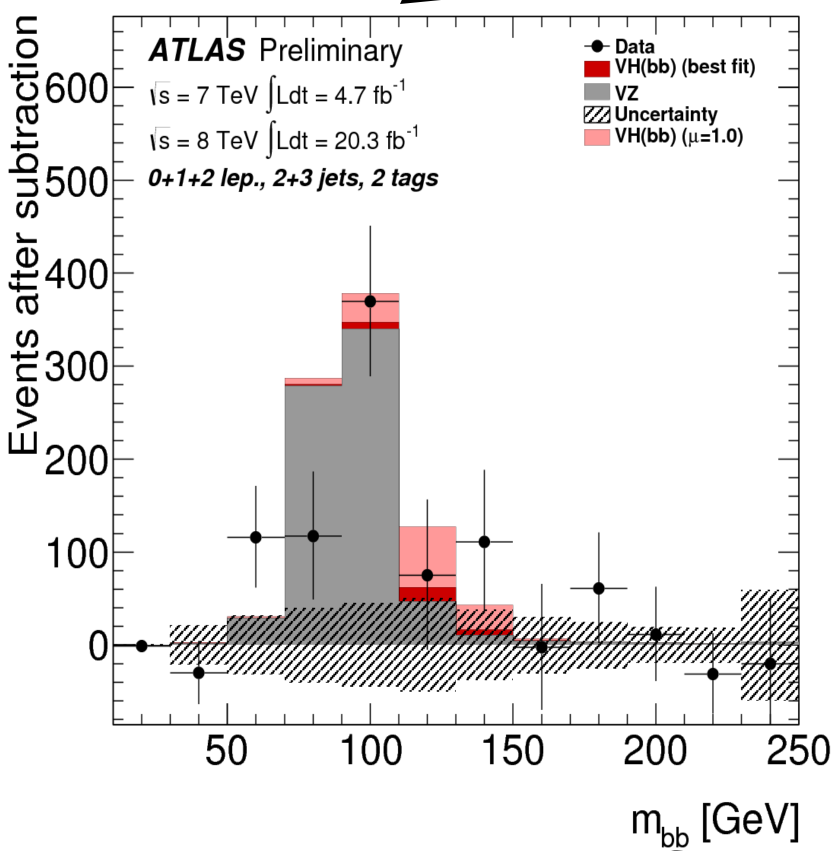


Candidate for VBF production

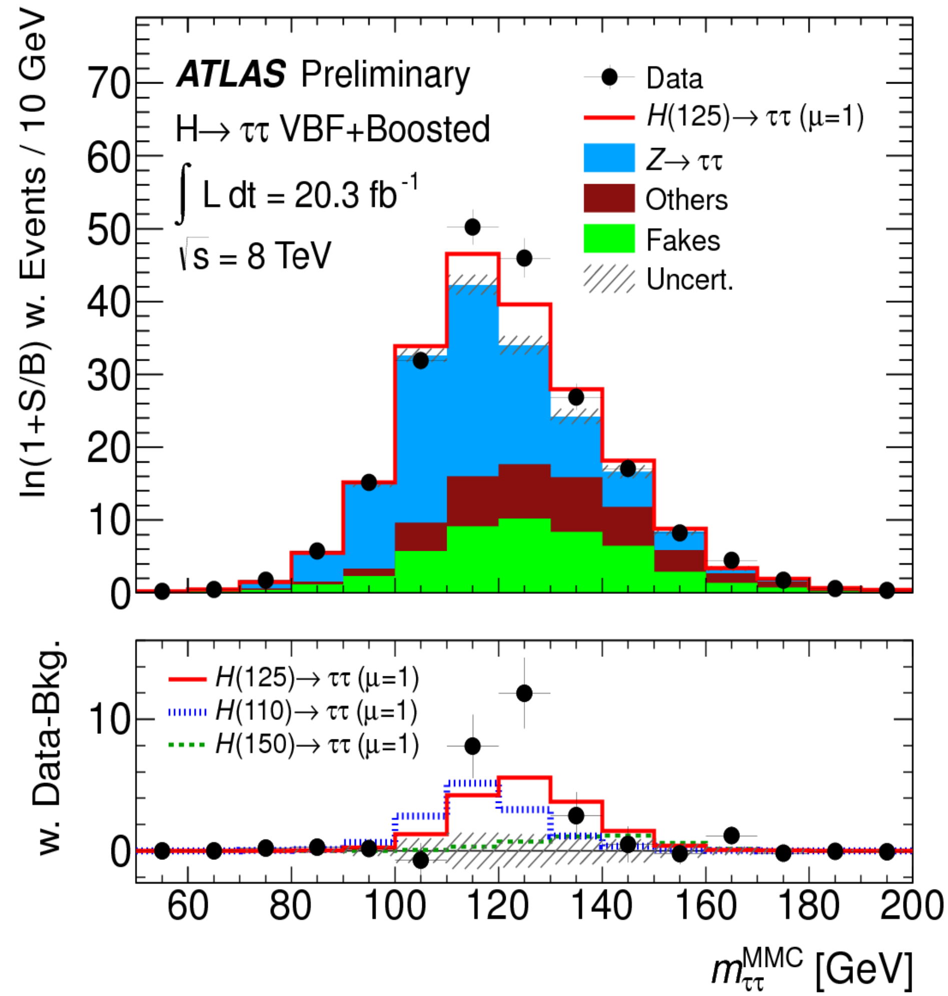


Require two isolated leptons and large MET. Reconstruct transverse mass. Categorization in jet multiplicity.

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



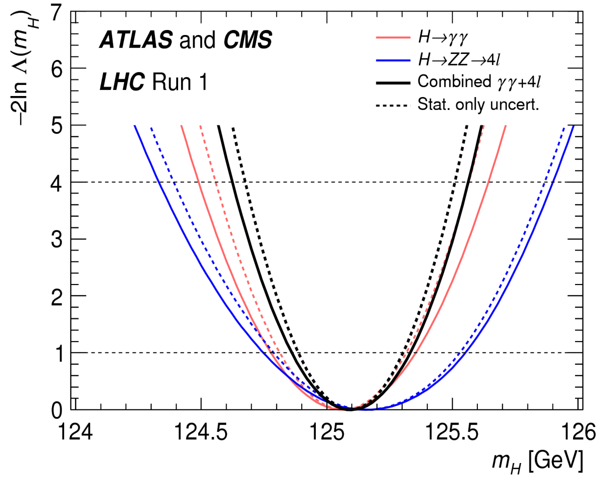
Di-b invariant mass after background subtraction except for di-boson processes, for all channels



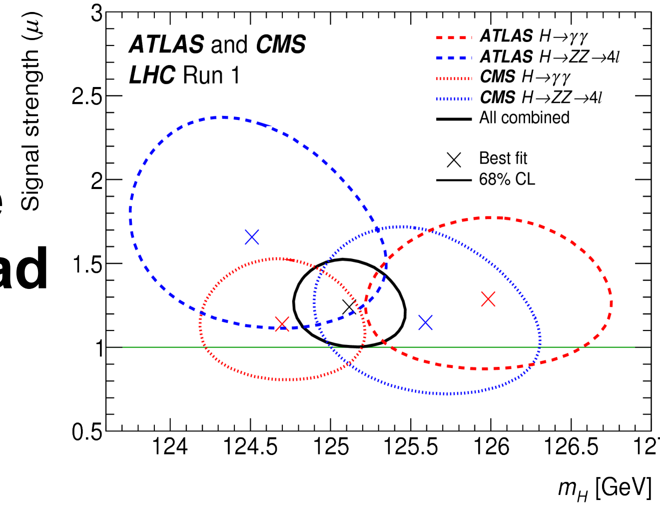
Di-tau invariant mass before and after background extraction

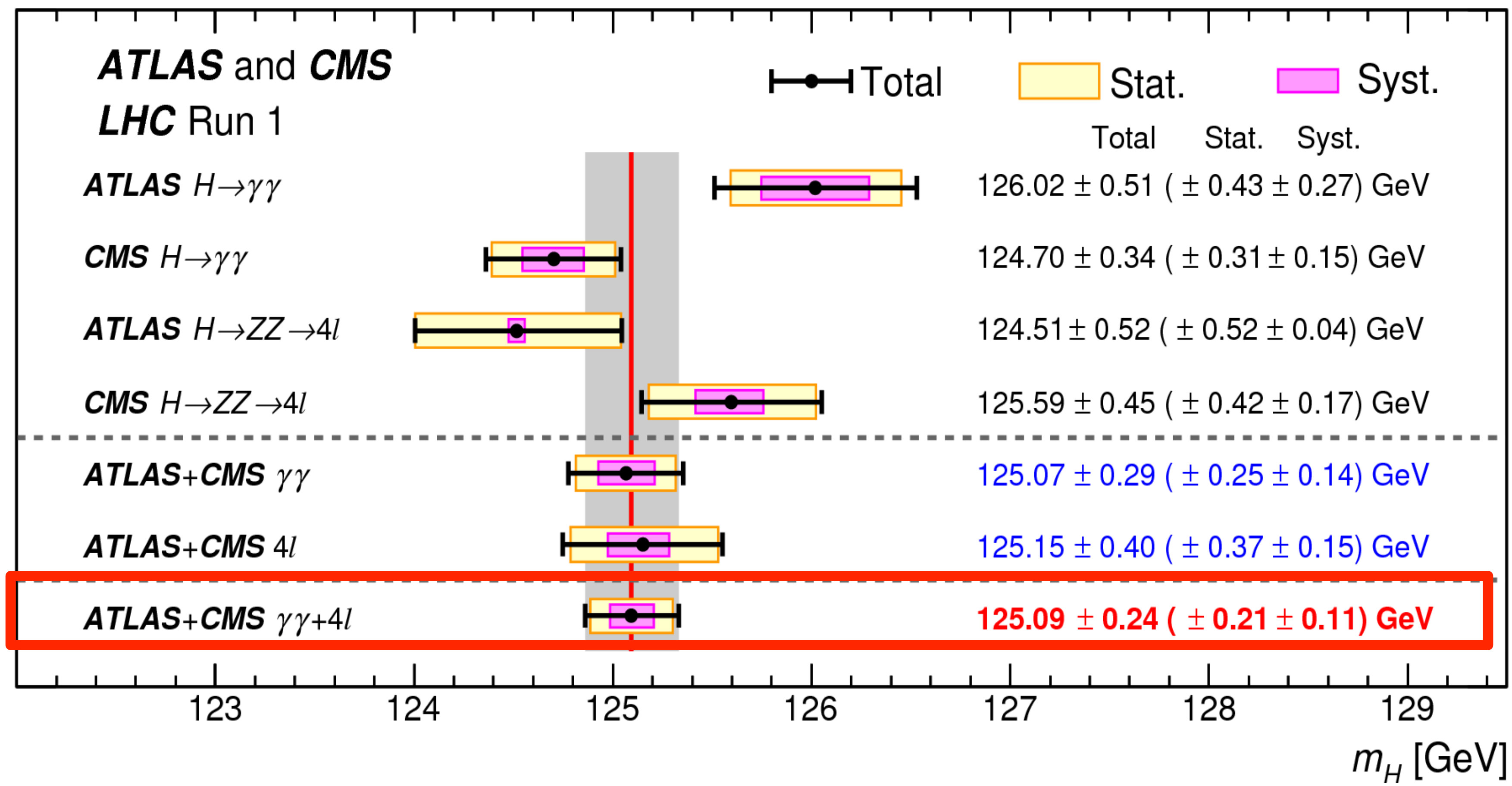
Mass measurement

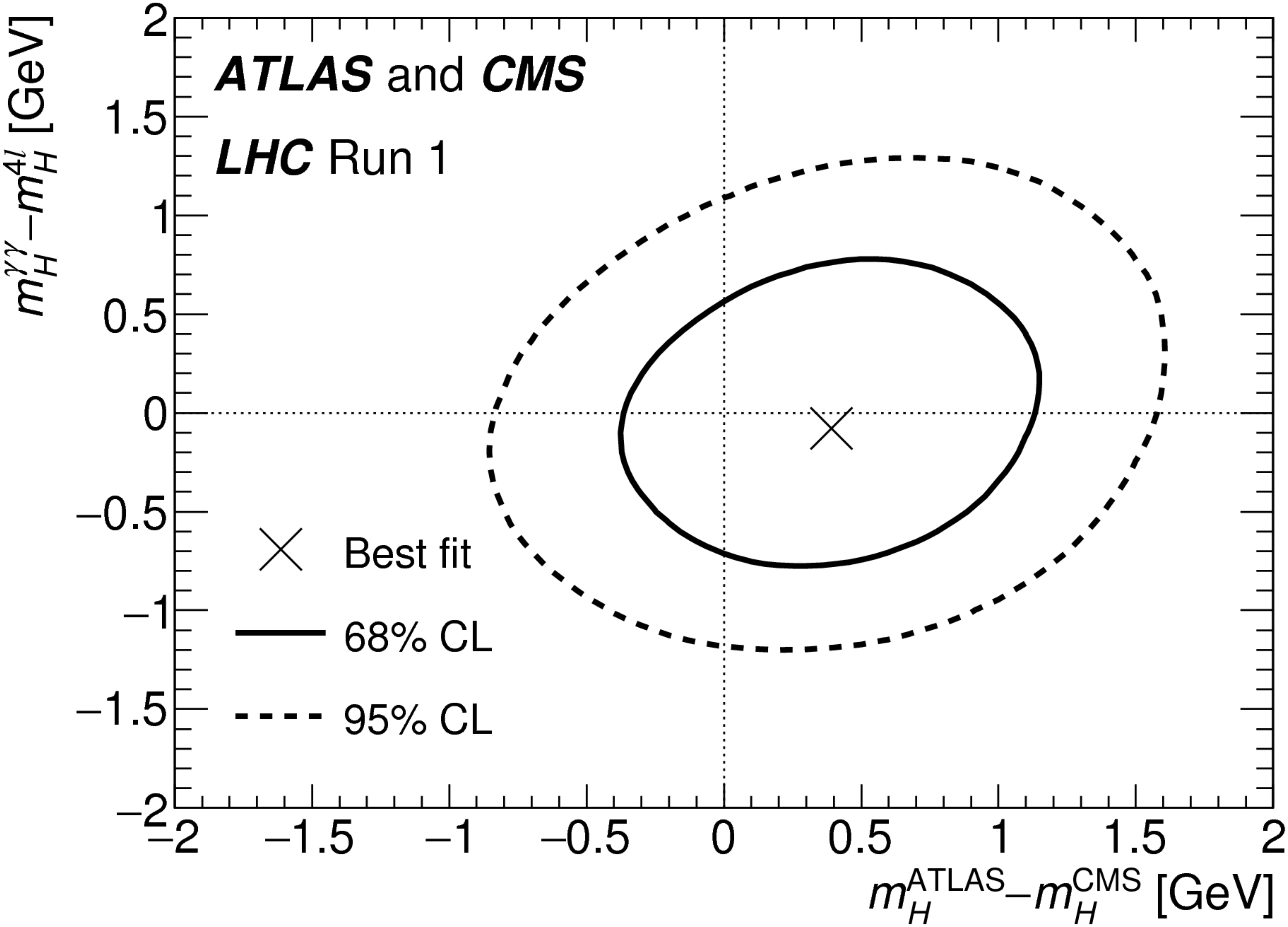
The Higgs boson mass is a fundamental parameter of nature that is not predicted by the theory

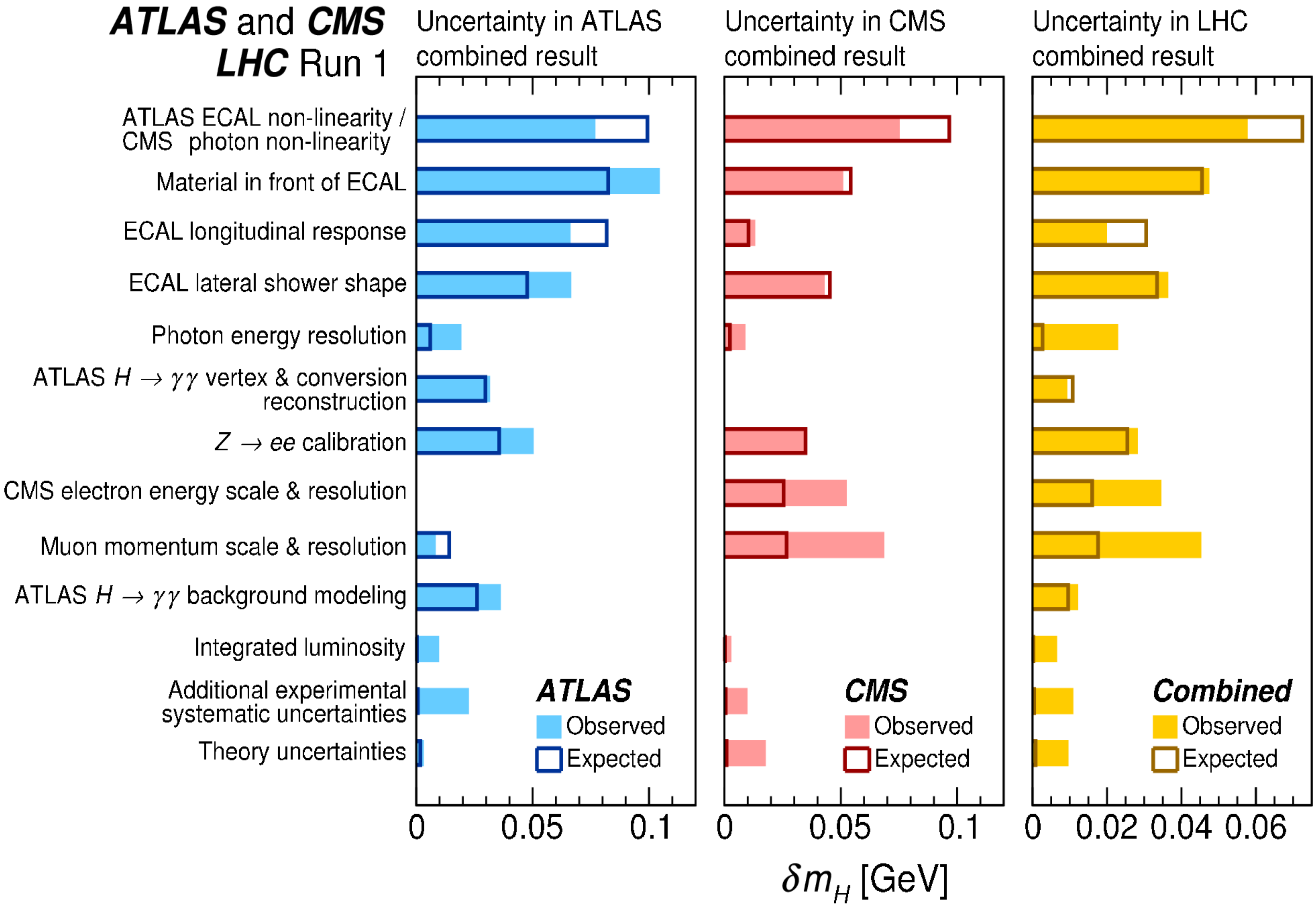


ATLAS and CMS measurements are compatible and lead to 0.2% accuracy measurement






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


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

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

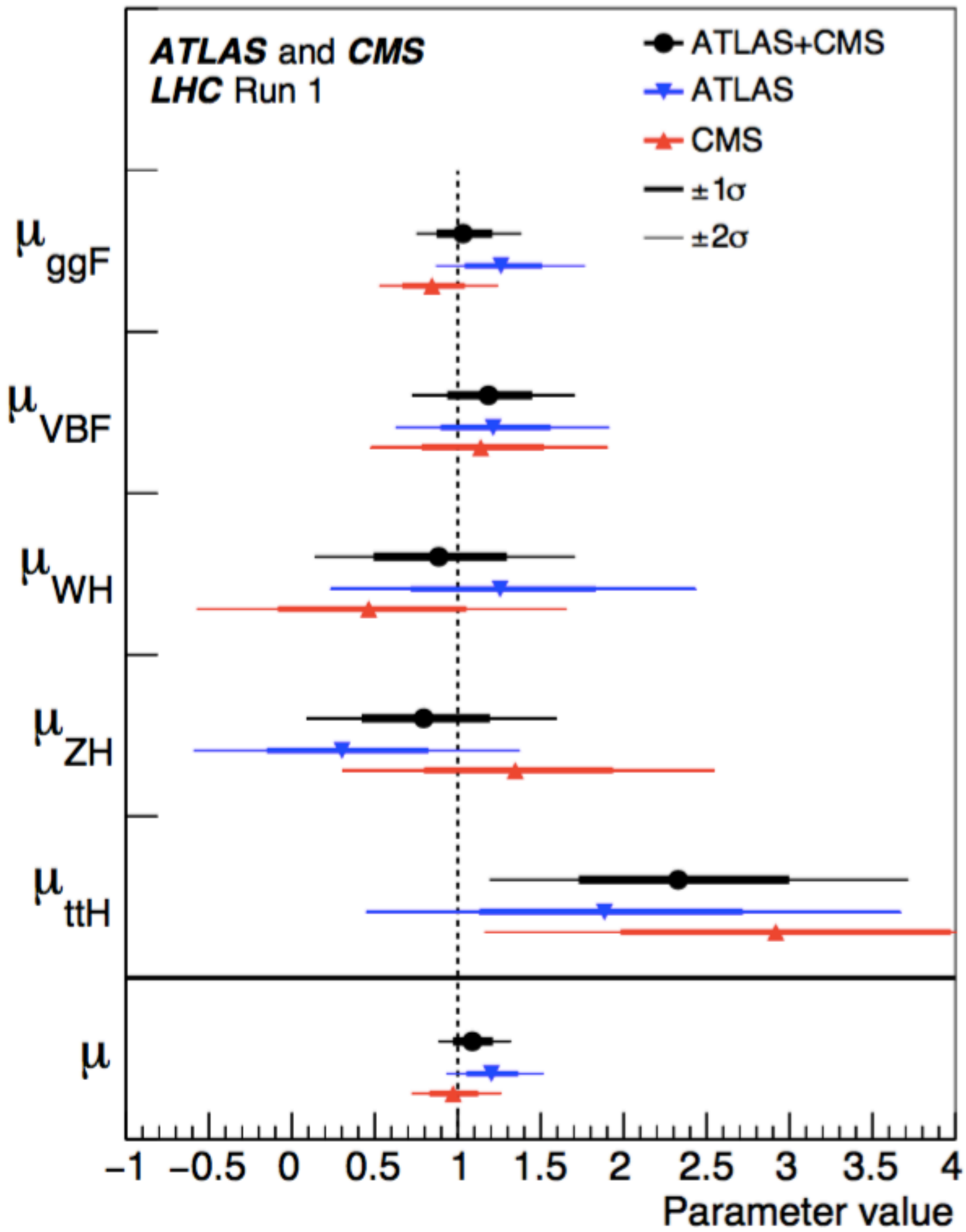
$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

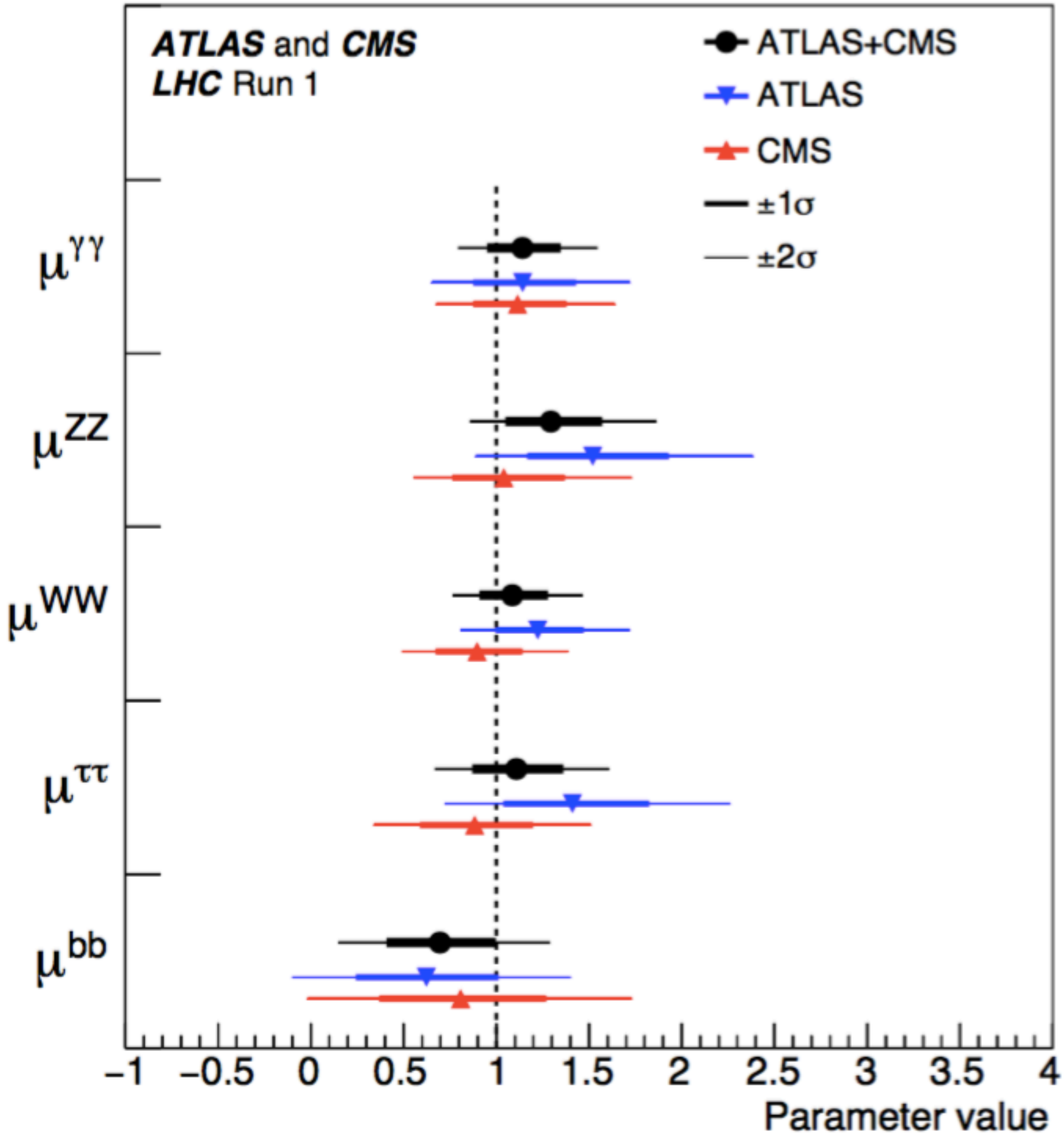
Coupling Modifiers

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

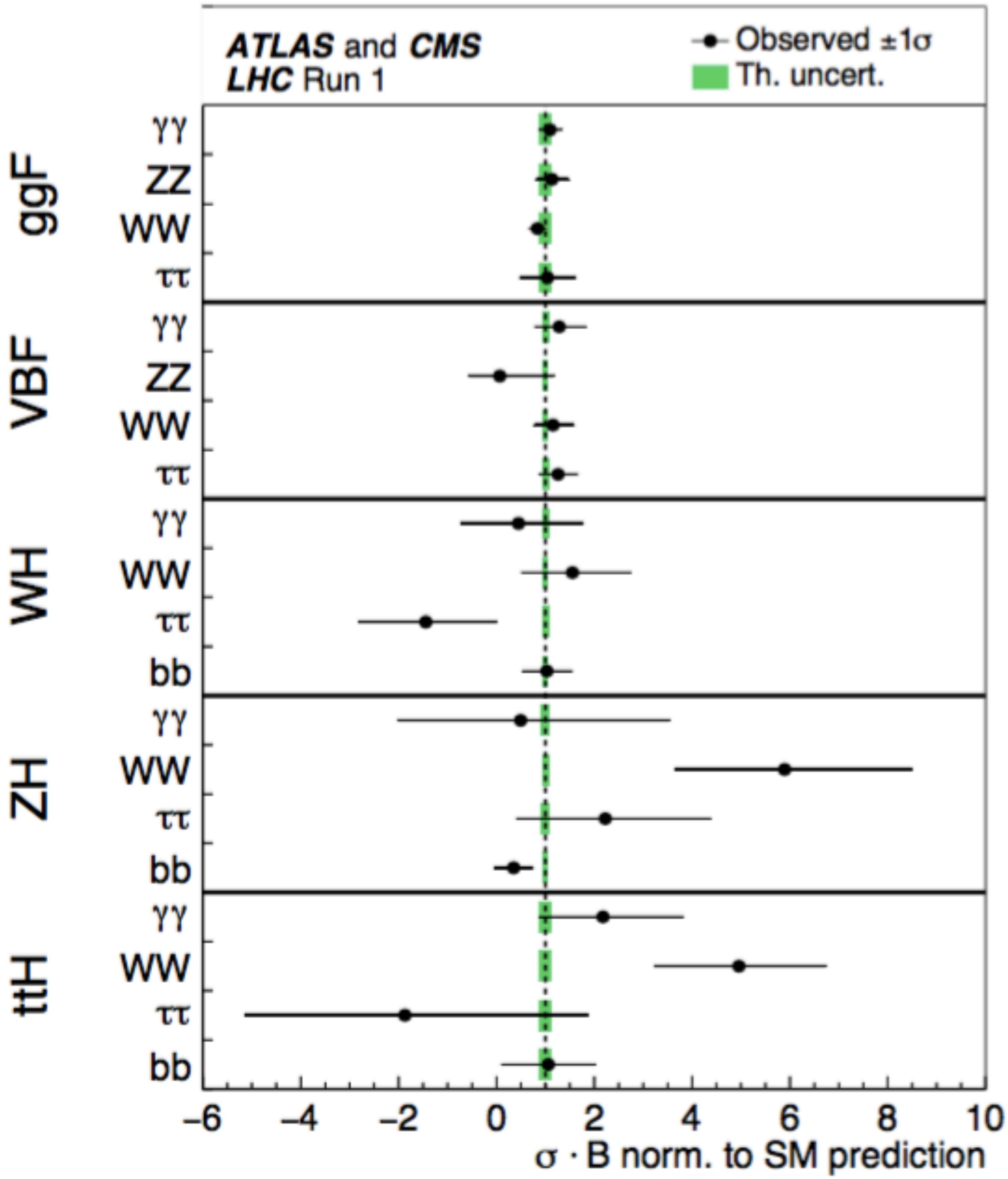
Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		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]	
	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
μggF
μVBF
μWH
μZH
μttH
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

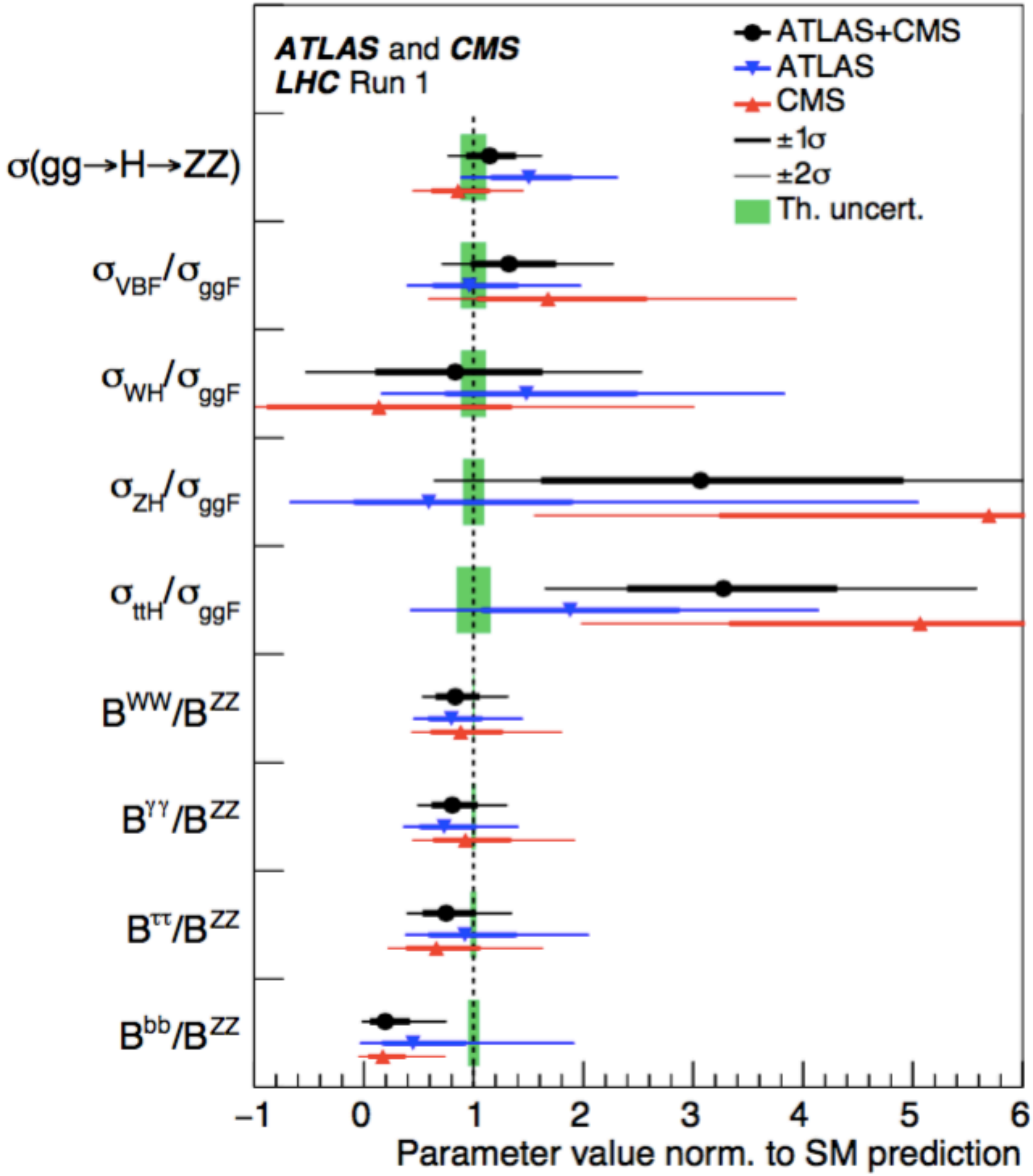
Production process		Decay mode														
		$H \to \gamma\gamma$ [fb]			$H \to ZZ$ [fb]			$H \to WW$ [pb]			$H \to \tau\tau$ [fb]			$H \to bb$ [pb]		
		Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	Syst	Best fit value	Uncertainty Stat	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

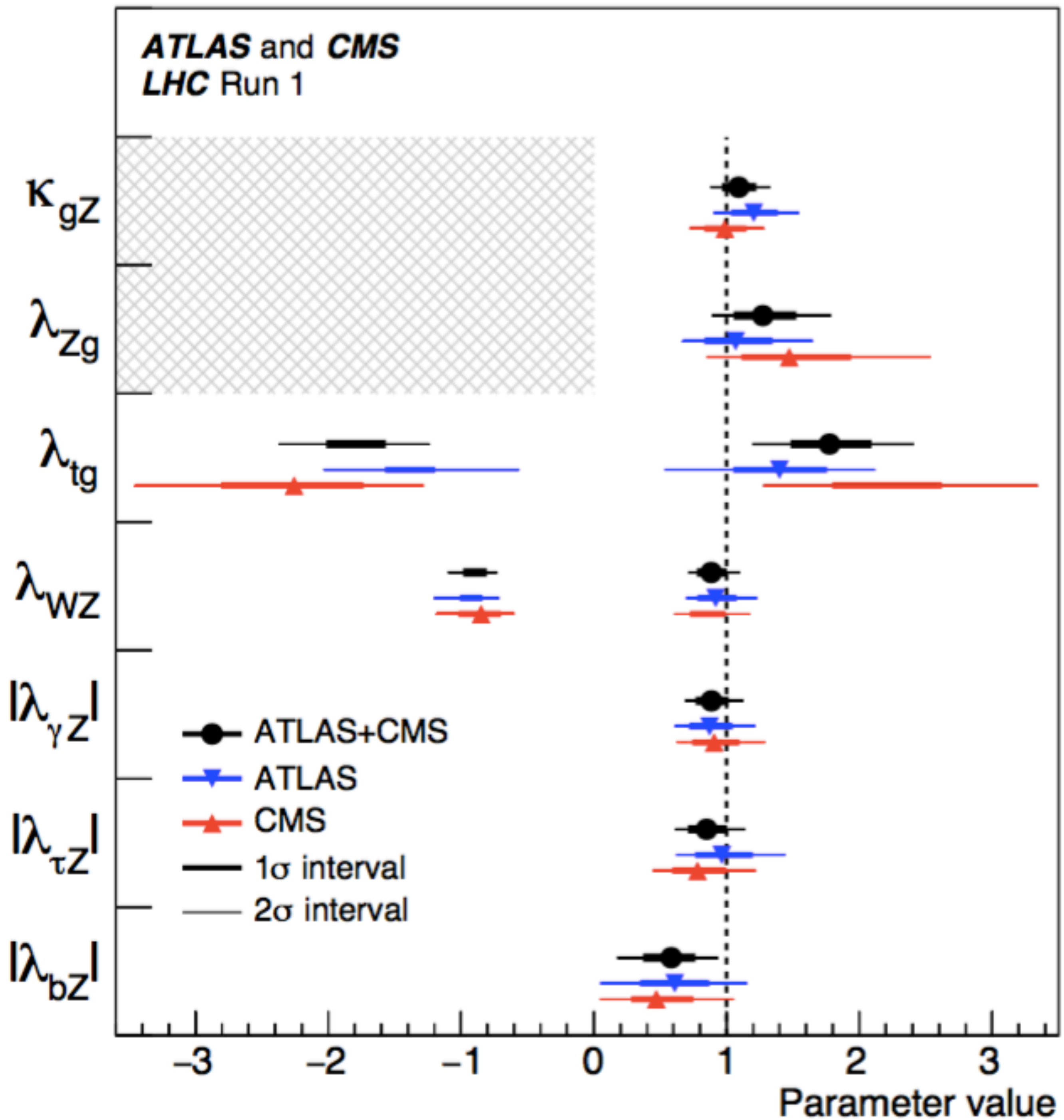
Introducing ratios. Has some advantages such as cancellation of experimental and some theoretical uncertainties, such as the lack of knowledge of total width and others

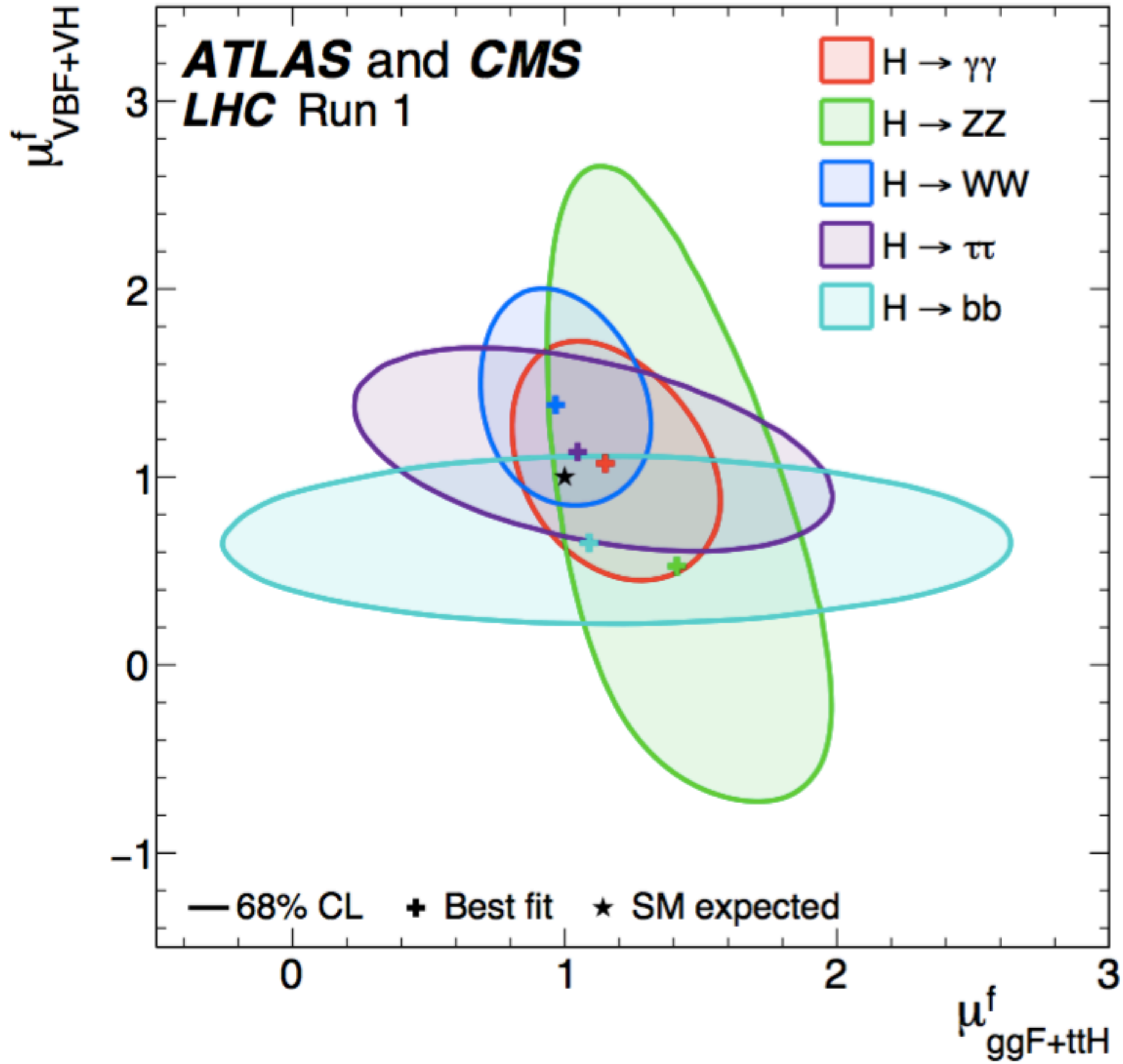
σ and B ratio parameterisation	Coupling modifier ratio parameterisation
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$
$\sigma_{\mathrm{VBF}} / \sigma_{gg\mathrm{F}}$	
$\sigma_{WH} / \sigma_{gg\mathrm{F}}$	
$\sigma_{ZH} / \sigma_{gg\mathrm{F}}$	$\lambda_{Zg} = \kappa_Z /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

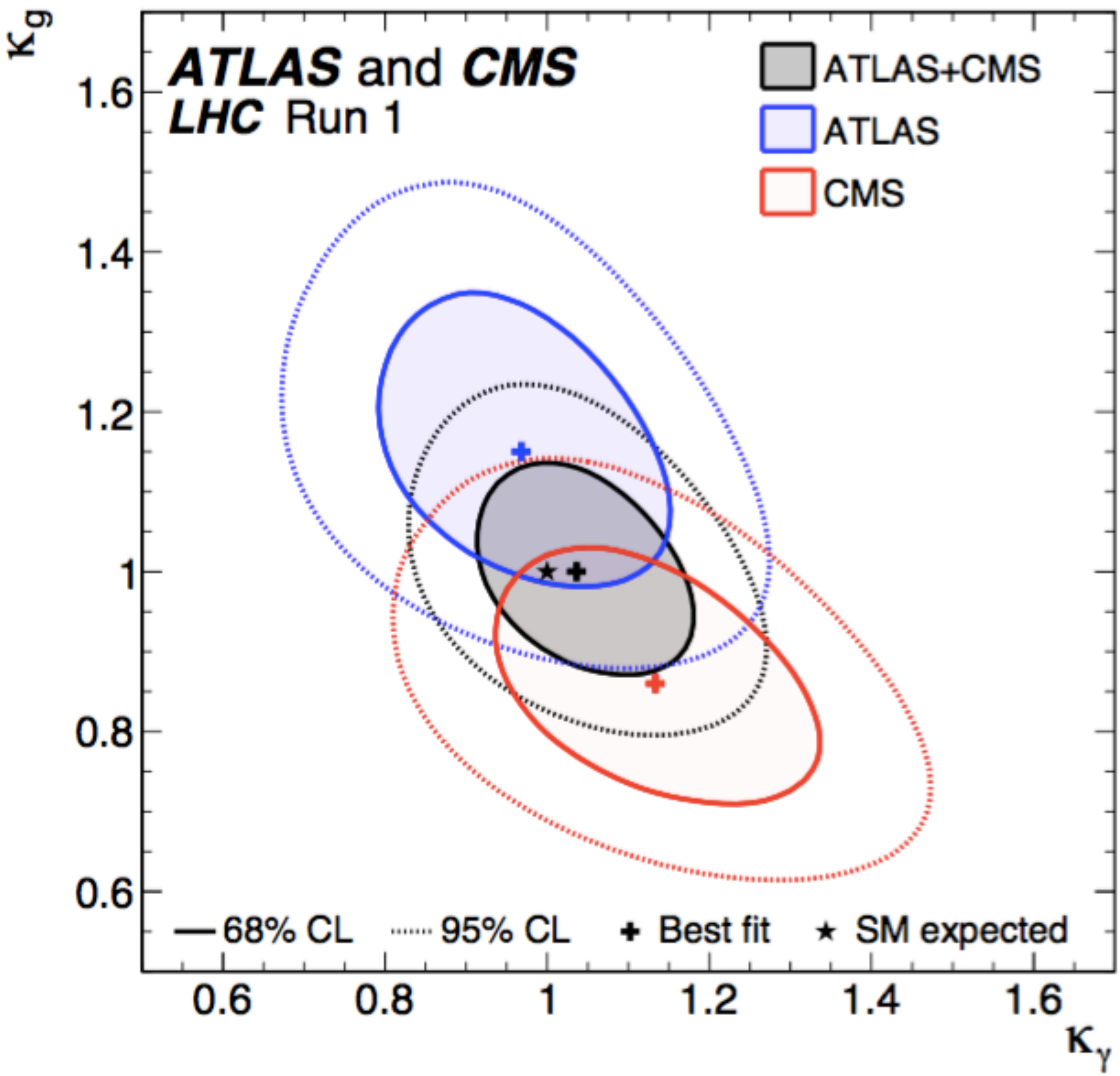
Parameter	SM prediction	Best fit value	Uncertainty		Best fit value	Uncertainty		Best fit value	Uncertainty	
			Stat	Syst		Stat	Syst		Stat	Syst
		ATLAS+CMS			ATLAS			CMS		
$\sigma(gg \to H \to ZZ)$ [pb]	0.51 ± 0.06	$0.59^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.10}\right)$	$^{+0.11}_{-0.10}$ $\left(^{+0.11}_{-0.09}\right)$	$^{+0.02}_{-0.02}$ $\left(^{+0.03}_{-0.02}\right)$	$0.77^{+0.19}_{-0.17}$ $\left(^{+0.16}_{-0.14}\right)$	$^{+0.19}_{-0.16}$ $\left(^{+0.16}_{-0.13}\right)$	$^{+0.05}_{-0.03}$ $\left(^{+0.03}_{-0.02}\right)$	$0.44^{+0.14}_{-0.12}$ $\left(^{+0.15}_{-0.13}\right)$	$^{+0.13}_{-0.11}$ $\left(^{+0.15}_{-0.13}\right)$	$^{+0.05}_{-0.03}$ $\left(^{+0.04}_{-0.03}\right)$
$\sigma_{\rm VBF}/\sigma_{gg\rm F}$	0.082 ± 0.009	$0.109^{+0.034}_{-0.027}$ $\left(^{+0.029}_{-0.024}\right)$	$^{+0.029}_{-0.024}$ $\left(^{+0.024}_{-0.020}\right)$	$^{+0.018}_{-0.013}$ $\left(^{+0.016}_{-0.012}\right)$	$0.079^{+0.035}_{-0.026}$ $\left(^{+0.042}_{-0.031}\right)$	$^{+0.030}_{-0.023}$ $\left(^{+0.036}_{-0.028}\right)$	$^{+0.019}_{-0.012}$ $\left(^{+0.022}_{-0.014}\right)$	$0.138^{+0.073}_{-0.051}$ $\left(^{+0.043}_{-0.033}\right)$	$^{+0.061}_{-0.046}$ $\left(^{+0.037}_{-0.029}\right)$	$^{+0.039}_{-0.023}$ $\left(^{+0.023}_{-0.015}\right)$
$\sigma_{WH}/\sigma_{gg\rm F}$	0.037 ± 0.004	$0.031^{+0.028}_{-0.026}$ $\left(^{+0.021}_{-0.017}\right)$	$^{+0.024}_{-0.022}$ $\left(^{+0.019}_{-0.015}\right)$	$^{+0.015}_{-0.014}$ $\left(^{+0.011}_{-0.007}\right)$	$0.054^{+0.036}_{-0.026}$ $\left(^{+0.033}_{-0.022}\right)$	$^{+0.031}_{-0.023}$ $\left(^{+0.029}_{-0.020}\right)$	$^{+0.020}_{-0.013}$ $\left(^{+0.015}_{-0.009}\right)$	$0.005^{+0.044}_{-0.037}$ $\left(^{+0.032}_{-0.022}\right)$	$^{+0.037}_{-0.028}$ $\left(^{+0.027}_{-0.020}\right)$	$^{+0.023}_{-0.024}$ $\left(^{+0.017}_{-0.010}\right)$
$\sigma_{ZH}/\sigma_{gg\rm F}$	0.0216 ± 0.0024	$0.066^{+0.039}_{-0.031}$ $\left(^{+0.016}_{-0.011}\right)$	$^{+0.032}_{-0.025}$ $\left(^{+0.014}_{-0.010}\right)$	$^{+0.023}_{-0.018}$ $\left(^{+0.009}_{-0.004}\right)$	$0.013^{+0.028}_{-0.014}$ $\left(^{+0.027}_{-0.014}\right)$	$^{+0.021}_{-0.012}$ $\left(^{+0.023}_{-0.013}\right)$	$^{+0.018}_{-0.007}$ $\left(^{+0.014}_{-0.005}\right)$	$0.123^{+0.076}_{-0.053}$ $\left(^{+0.024}_{-0.013}\right)$	$^{+0.063}_{-0.046}$ $\left(^{+0.020}_{-0.012}\right)$	$^{+0.044}_{-0.026}$ $\left(^{+0.014}_{-0.006}\right)$
$\sigma_{ttH}/\sigma_{gg\rm F}$	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	$4.2^{+4.4}_{-2.6}$ $\left(^{+16.8}_{-9.0}\right)$	$^{+2.8}_{-2.0}$ $\left(^{+13.9}_{-7.9}\right)$	$^{+3.4}_{-1.6}$ $\left(^{+9.5}_{-4.4}\right)$	$9.6^{+10.1}_{-5.7}$ $\left(^{+29.3}_{-11.8}\right)$	$^{+7.4}_{-4.4}$ $\left(^{+24.2}_{-10.5}\right)$	$^{+6.9}_{-3.6}$ $\left(^{+16.6}_{-5.3}\right)$	$3.7^{+4.1}_{-2.4}$ $\left(^{+29.4}_{-11.9}\right)$	$^{+3.1}_{-2.0}$ $\left(^{+23.4}_{-10.4}\right)$	$^{+2.7}_{-1.4}$ $\left(^{+17.8}_{-5.9}\right)$



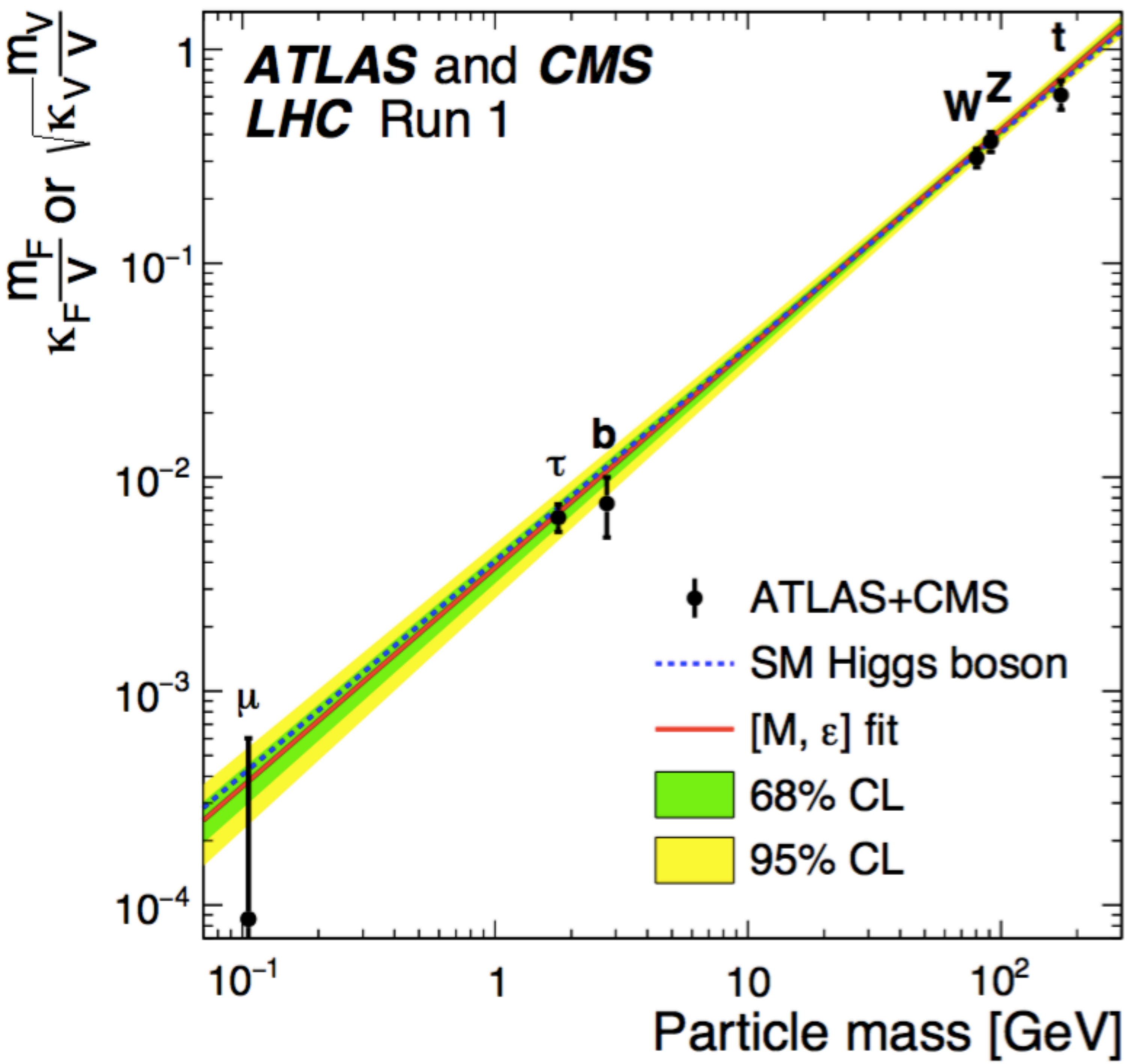
ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
Th. uncert.
σ(gg→H→ZZ)
σVBF/σggF
σWH/σggF
σZH/σggF
σttH/σggF
BWW/BZZ
Bγγ/BZZ
Bττ/BZZ
Bbb/BZZ
−1
0
1
2
3
4
5
6
Parameter value norm. to SM prediction


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

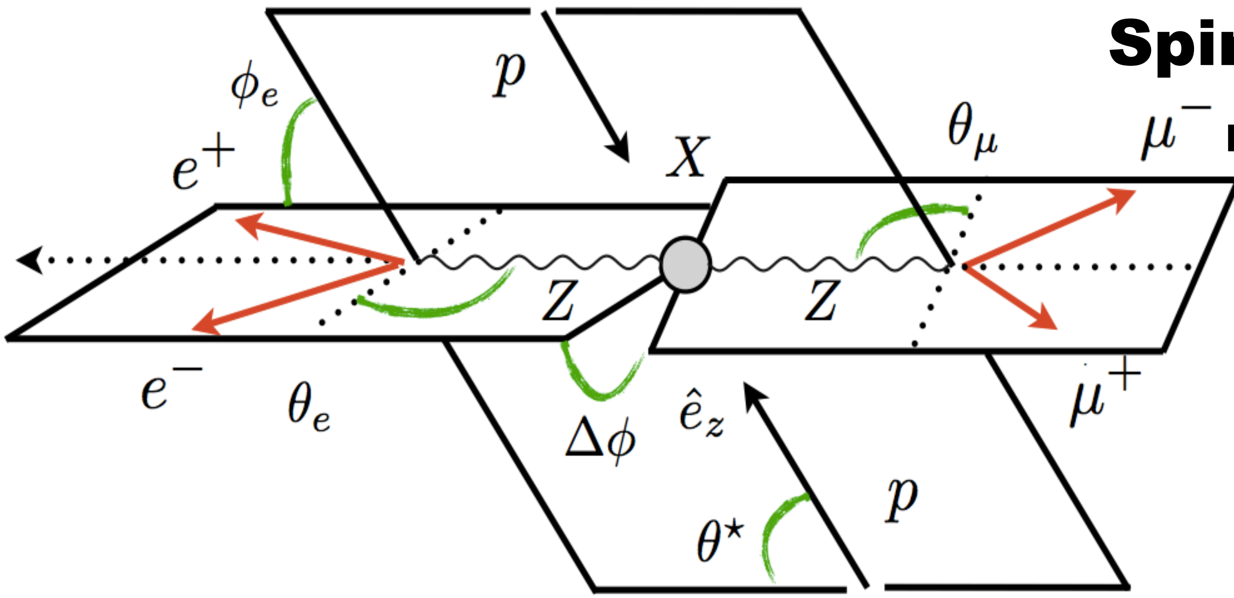

ATLAS and CMS
LHC Run 1
H → γγ
H → ZZ
H → WW
H → ττ
H → bb
— 68% CL
✚ Best fit
★ SM expected
μ^f_{VBF+VH}
$\mu^f_{ggF+ttH}$
3
2
1
0
−1
0
1
2
3



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


ATLAS and CMS
LHC Run 1
ATLAS+CMS
SM Higgs boson
[M, ε] fit
68% CL
95% CL
μ
τ
b
W
Z
t
Particle mass [GeV]

Spin/CP Quantum numbers: Exploration in Decay

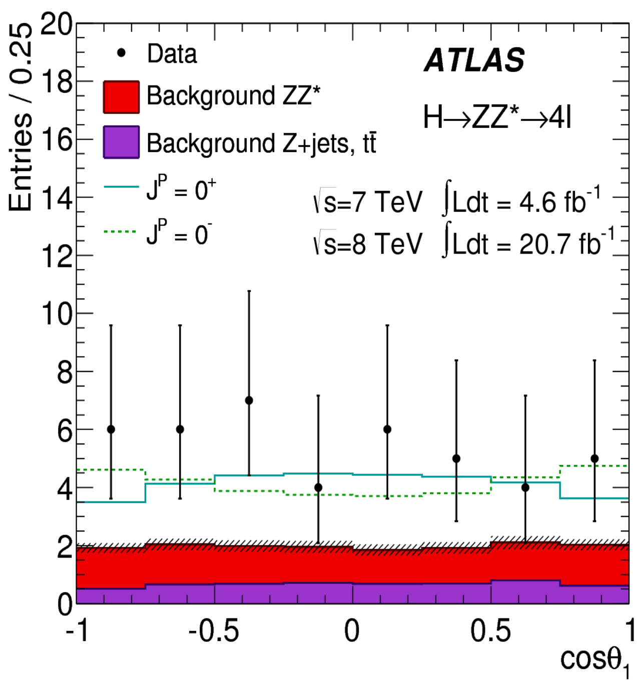


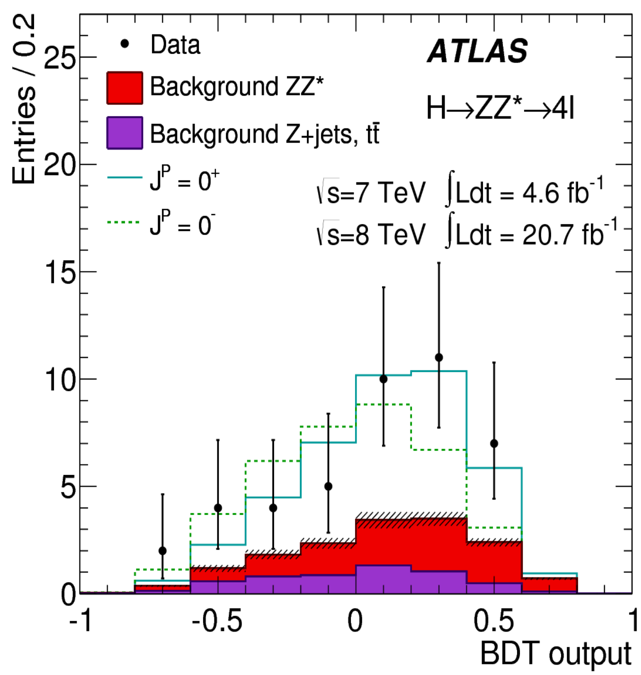
Spin/CP in H->ZZ->4l

Phys.Lett. B726 (2013) 120-144

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

Most sensitive channel in decay to 0-

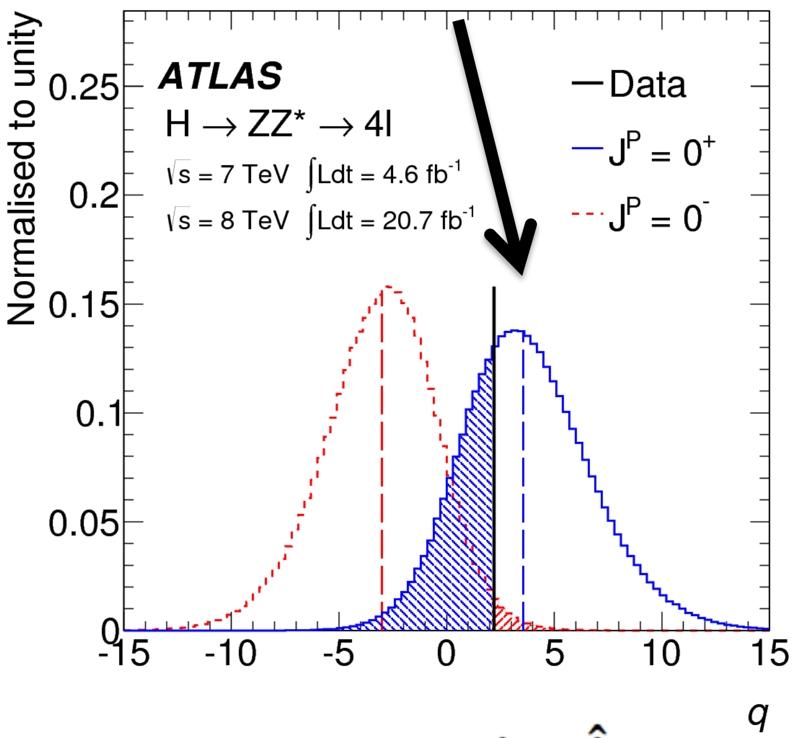




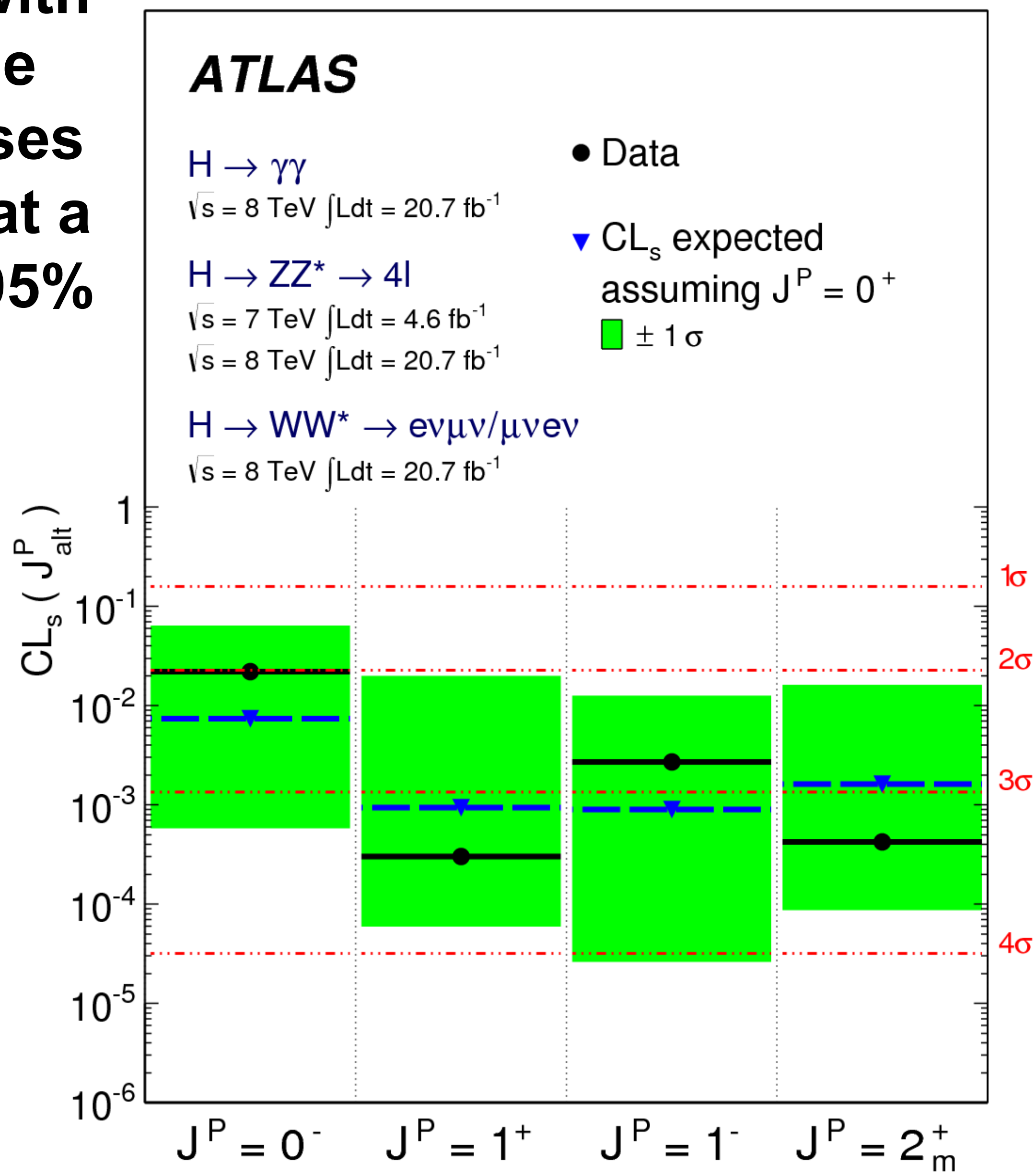
Phys.Lett. B726 (2013) 120-144

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

Observation



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



$$A(X_{J=0} \to V_1V_2) \sim v^{-1}\left(\left[a_1 - e^{i\phi_{\Lambda_1}}\frac{q^2_{Z_1}+q^2_{Z_2}}{(\Lambda_1)^2}\right] m_Z^2 \epsilon^*_{Z_1}\epsilon^*_{Z_2}\right.$$
$$+ a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu}$$
$$+ a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu}$$
$$\left. + a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu}\right)$$

CMS-PAS-HIG-14-014

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

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

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

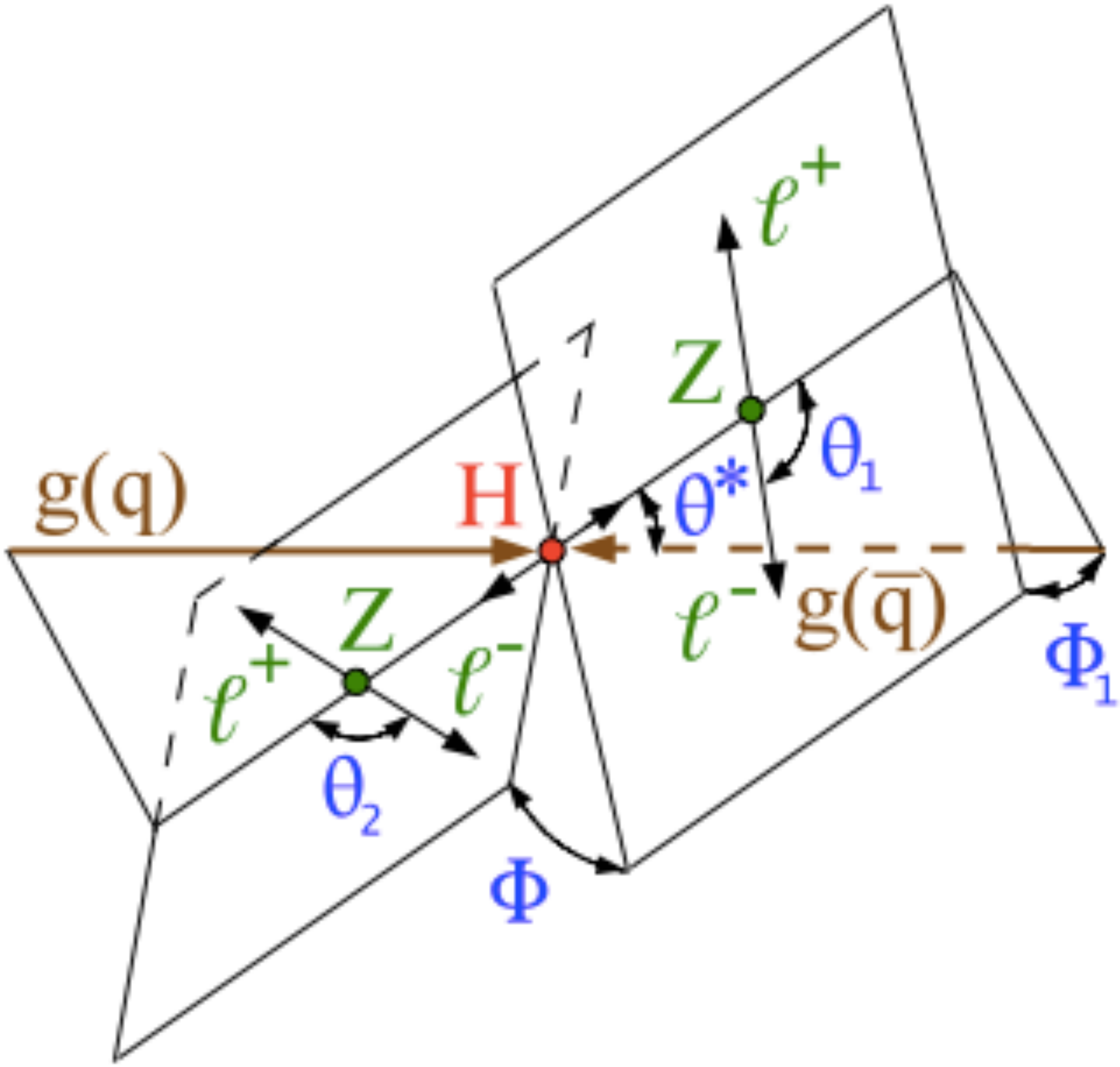
Spin-1

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

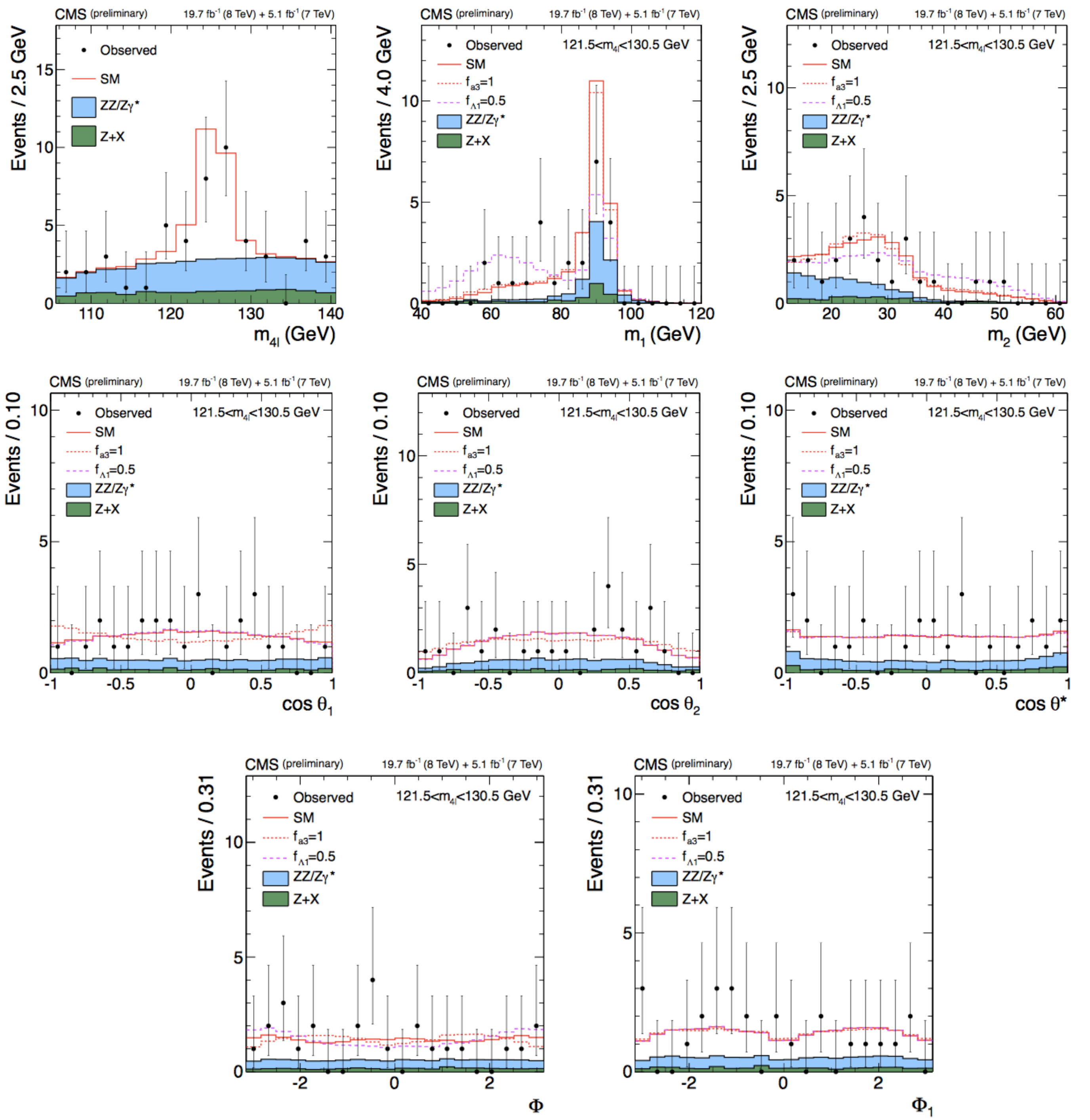
$$A(X_{J=1} \to V_1V_2) \sim b_1 \left[\left(\epsilon^*_{V_1} q\right) \left(\epsilon^*_{V_2} \epsilon_X\right) + \left(\epsilon^*_{V_2} q\right) \left(\epsilon^*_{V_1} \epsilon_X\right) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon^{\alpha}_X \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} \tilde{q}^{\beta}$$

Spin-2

$$\begin{aligned} A(X_{J=2} \to V_1V_2) \sim \Lambda^{-1} \Bigg[& 2c_1 t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2c_2 t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\ & + c_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha} \right) + c_4 \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\ & + m_V^2 \left(2c_5 t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2c_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2} \right) + c_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^*_{V_1} \epsilon^*_{V_2} \right) \\ & + c_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + c_9 t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma \\ & + \frac{c_{10} t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V_1} (q \epsilon^*_{V_2}) + \epsilon^{*\nu}_{V_2} (q \epsilon^*_{V_1}) \right) \Bigg] , \end{aligned}$$



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



CMS (preliminary)
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
Observed
SM
ZZ/Zγ*
Z+X
Events / 2.5 GeV
m4l (GeV)
121.5<m4l<130.5 GeV
fa3=1
fΛ1=0.5
Events / 4.0 GeV
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

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

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

$$\mathcal{P}^{\rm kin}_{\rm interf} = \left(\mathcal{P}^{\rm kin}_{\rm SM+J^P}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - g_{J^P}\mathcal{P}^{\rm kin}_{\rm J^P}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - \mathcal{P}^{\rm kin}_{\rm SM}(\vec{\Omega}, m_1, m_2 | m_{4\ell})\right)$$

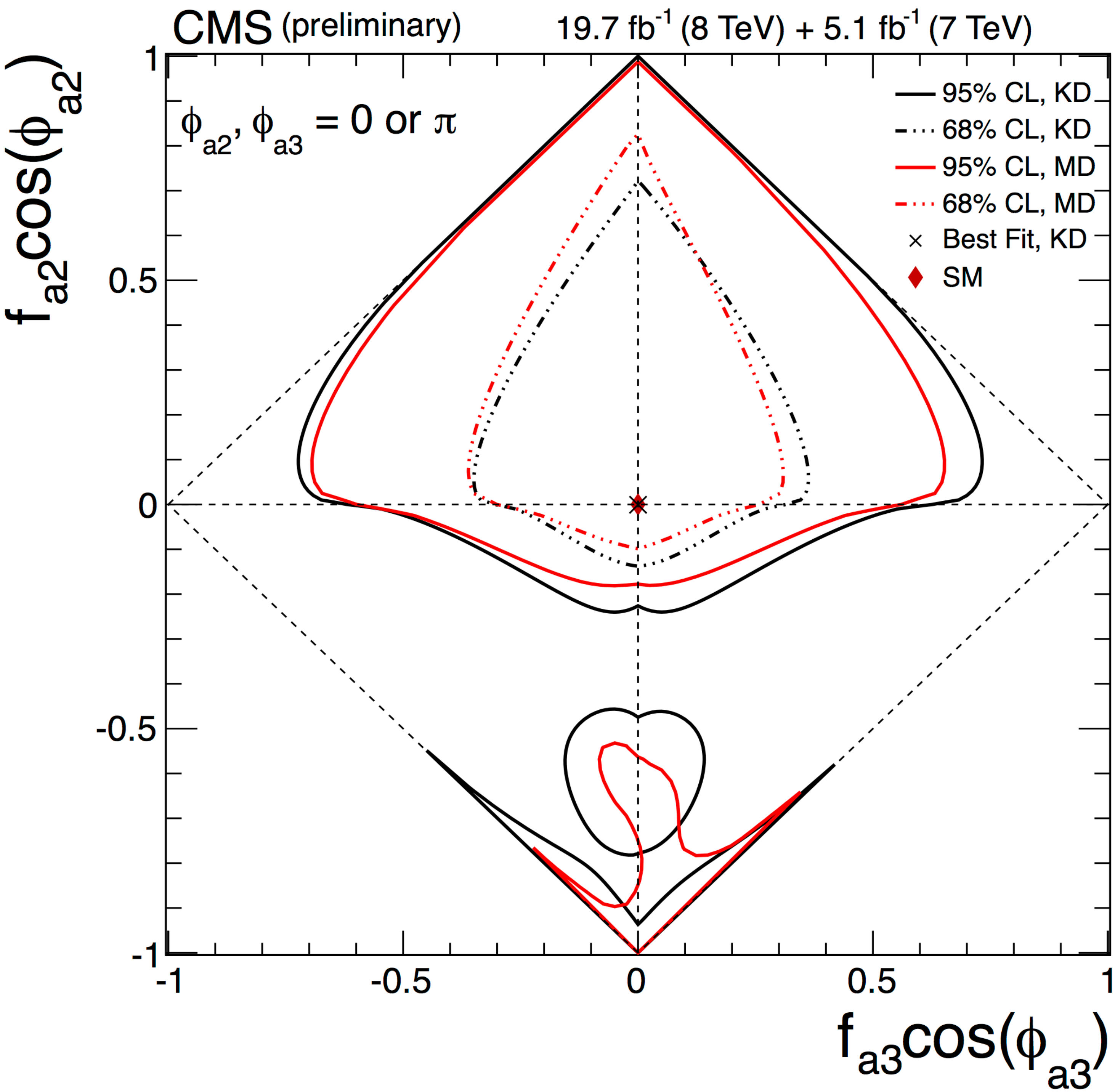
$$\mathcal{P}^{\rm kin}_{\rm interf\perp} = \left(\mathcal{P}^{\rm kin}_{\rm SM+J^P\perp}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - g_{J^P}\mathcal{P}^{\rm kin}_{\rm J^P}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - \mathcal{P}^{\rm kin}_{\rm SM}(\vec{\Omega}, m_1, m_2 | m_{4\ell})\right)$$

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

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

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

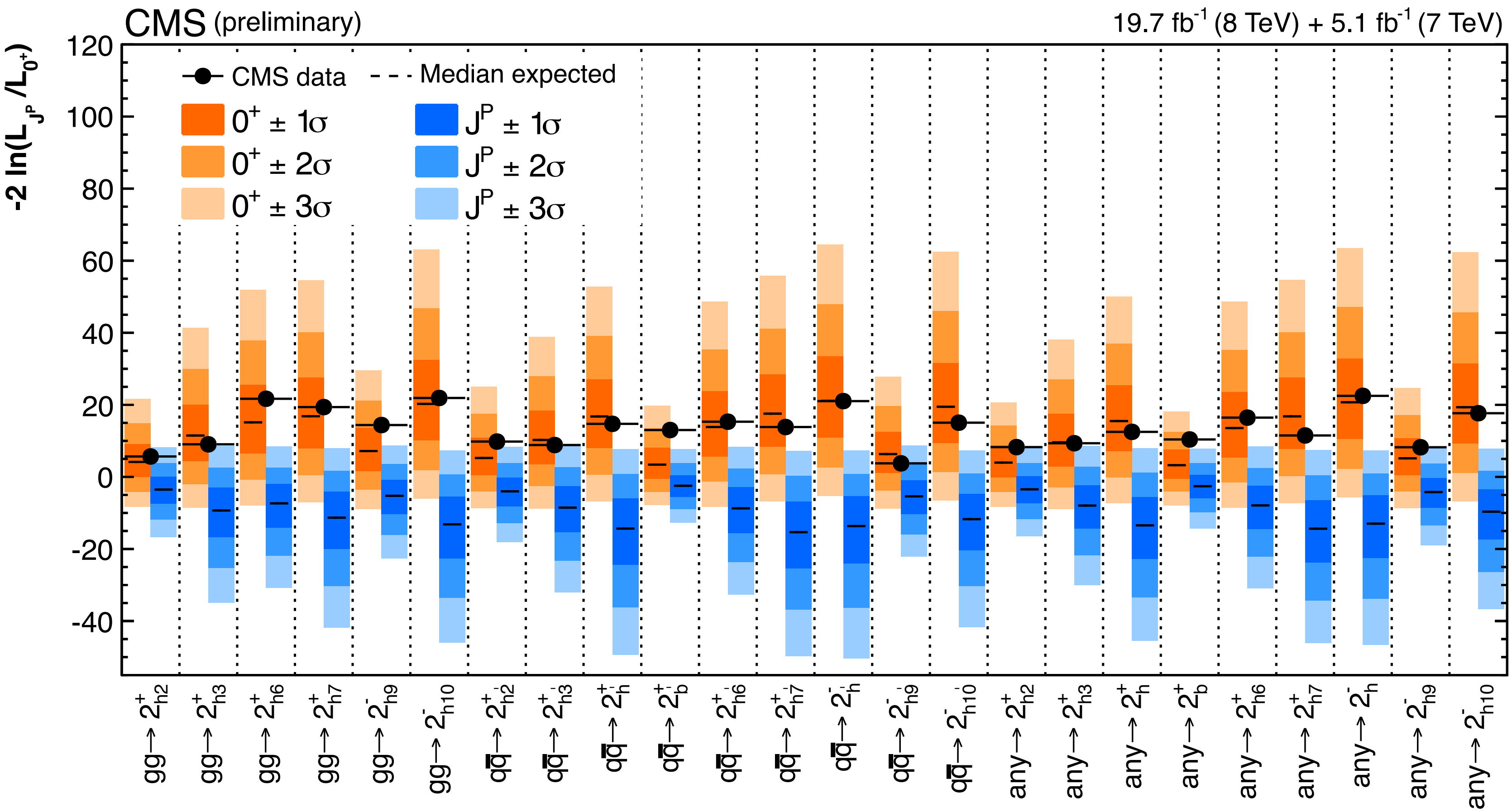
$$\mathcal{D}_{\rm Interf} = \frac{\left(\mathcal{P}^{\rm kin}_{\rm SM+J^P} - g_{J^P}\mathcal{P}^{\rm kin}_{\rm J^P} - \mathcal{P}^{\rm kin}_{\rm SM}\right)}{\mathcal{P}^{\rm kin}_{\rm SM} + c_{J^P} \times \mathcal{P}^{\rm kin}_{J^P}}.$$

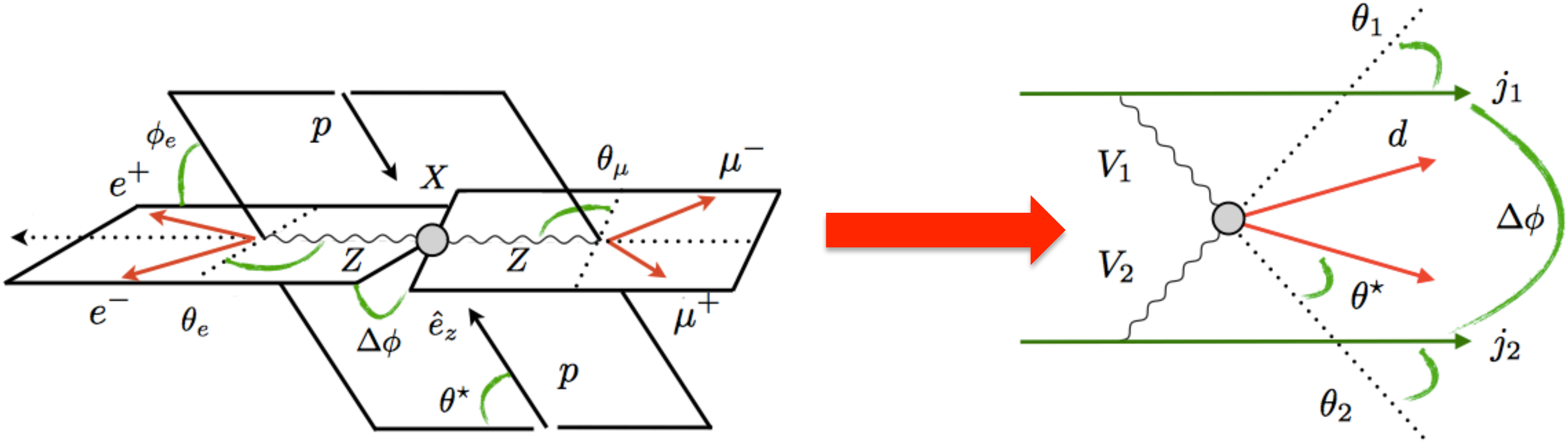

CMS (preliminary)
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
ϕa2, ϕa3 = 0 or π
95% CL, KD
68% CL, KD
95% CL, MD
68% CL, MD
Best Fit, KD
SM
fa2cos(ϕa2)
fa3cos(ϕa3)
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1

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)	$0.00^{+0.22}_{-0.00}$

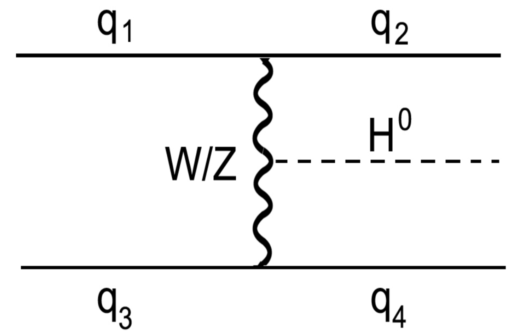
Exclusion of Spin-2 hypotheses





Spin/CP Quantum numbers: Exploration in Production

SM Higgs via VBF
Qualitative remarks



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

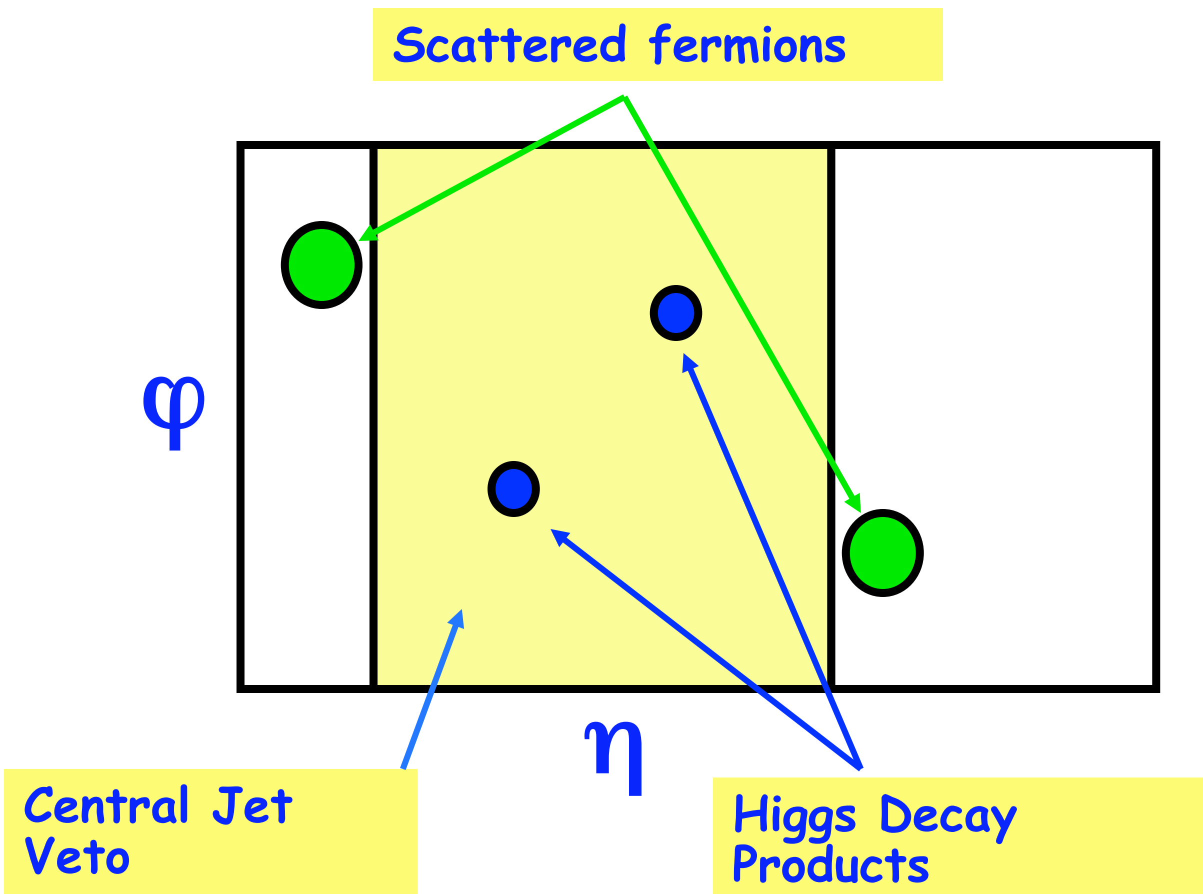
$$P^T_{V/f}(x, p_T^2) = \frac{g_V^2 + g_A^2}{8\pi^2} \frac{1+(1-x)^2}{x} \frac{p_T^2}{\left(p_T^2 + (1-x)M_V^2\right)^2}$$

$$P^L_{V/f}(x, p_T^2) = \frac{g_V^2 + g_A^2}{4\pi^2} \frac{1-x}{x} \frac{(1-x)M_V^2}{\left(p_T^2 + (1-x)M_V^2\right)^2}.$$

- **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** $P^T_{V/f} \sim 1/p_T^2$ and $P^L_{V/f} \sim 1/p_T^4$.

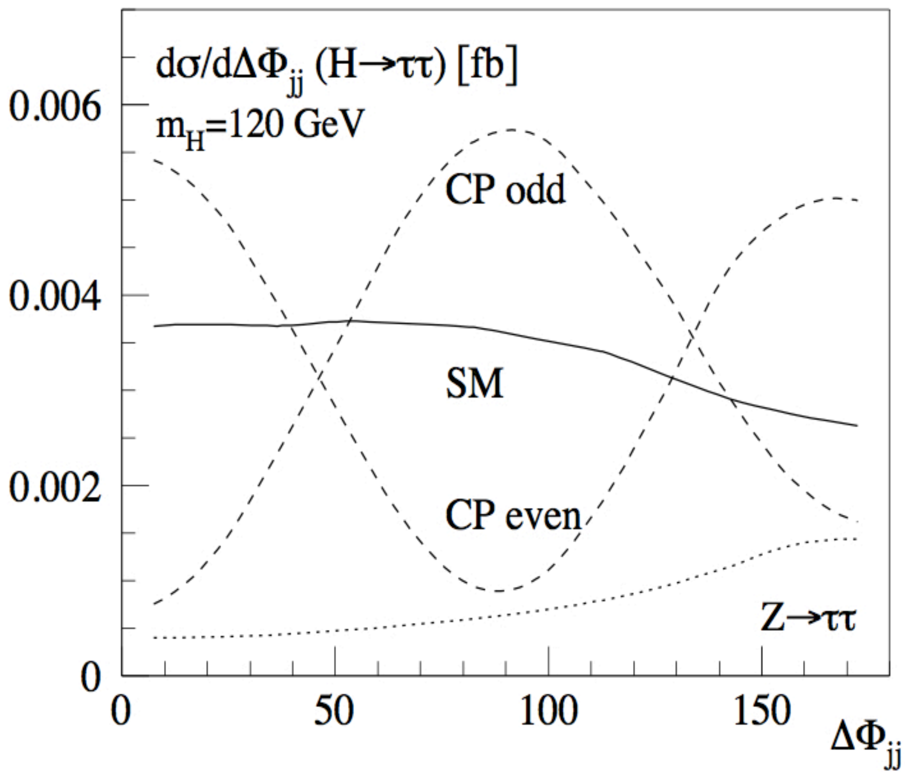
Well-defined prediction of the SM. Kinematics of scattered quarks, very sensitive to new physics

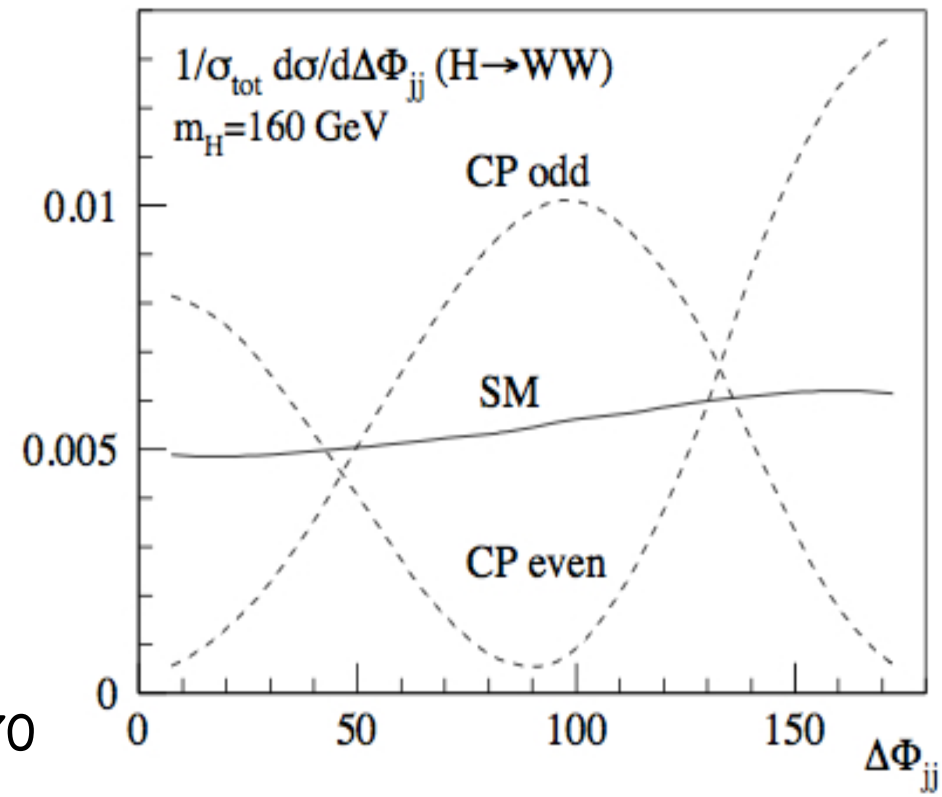


T.Plehn, D.Rainwater and D.Zeppenfeld
Phys.Rev.Lett. 88 (2002) 051801

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

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





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-violating

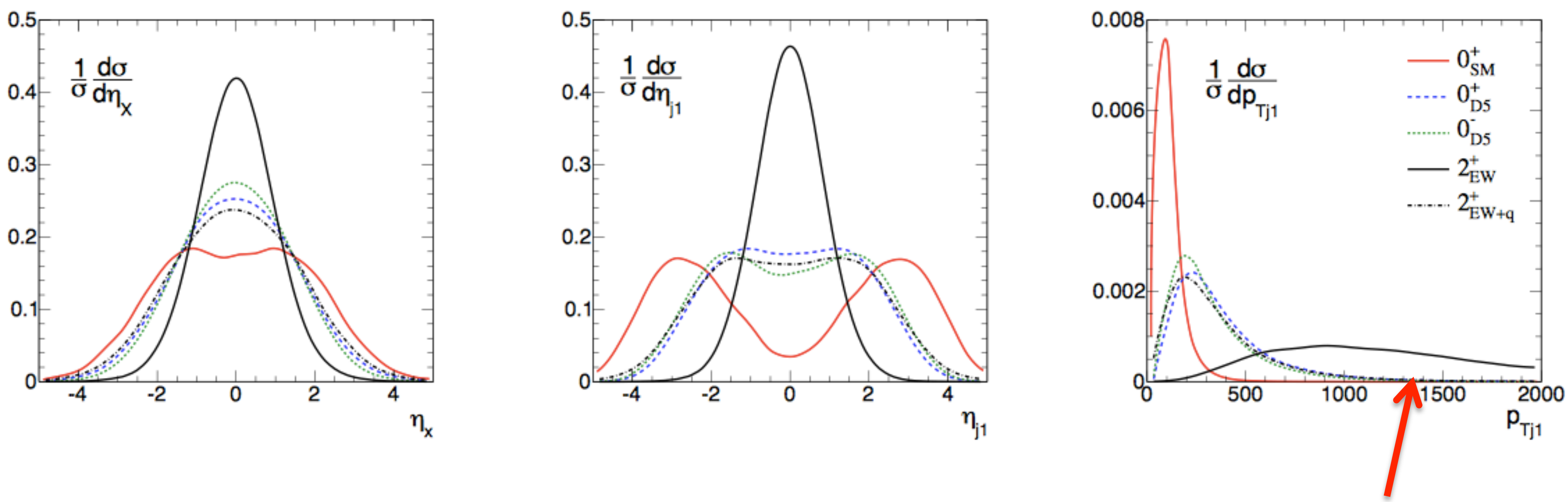
CP-conserving

$$\Gamma^{\rm SM}_{\mu\nu} = -g M_V g_{\mu\nu}$$

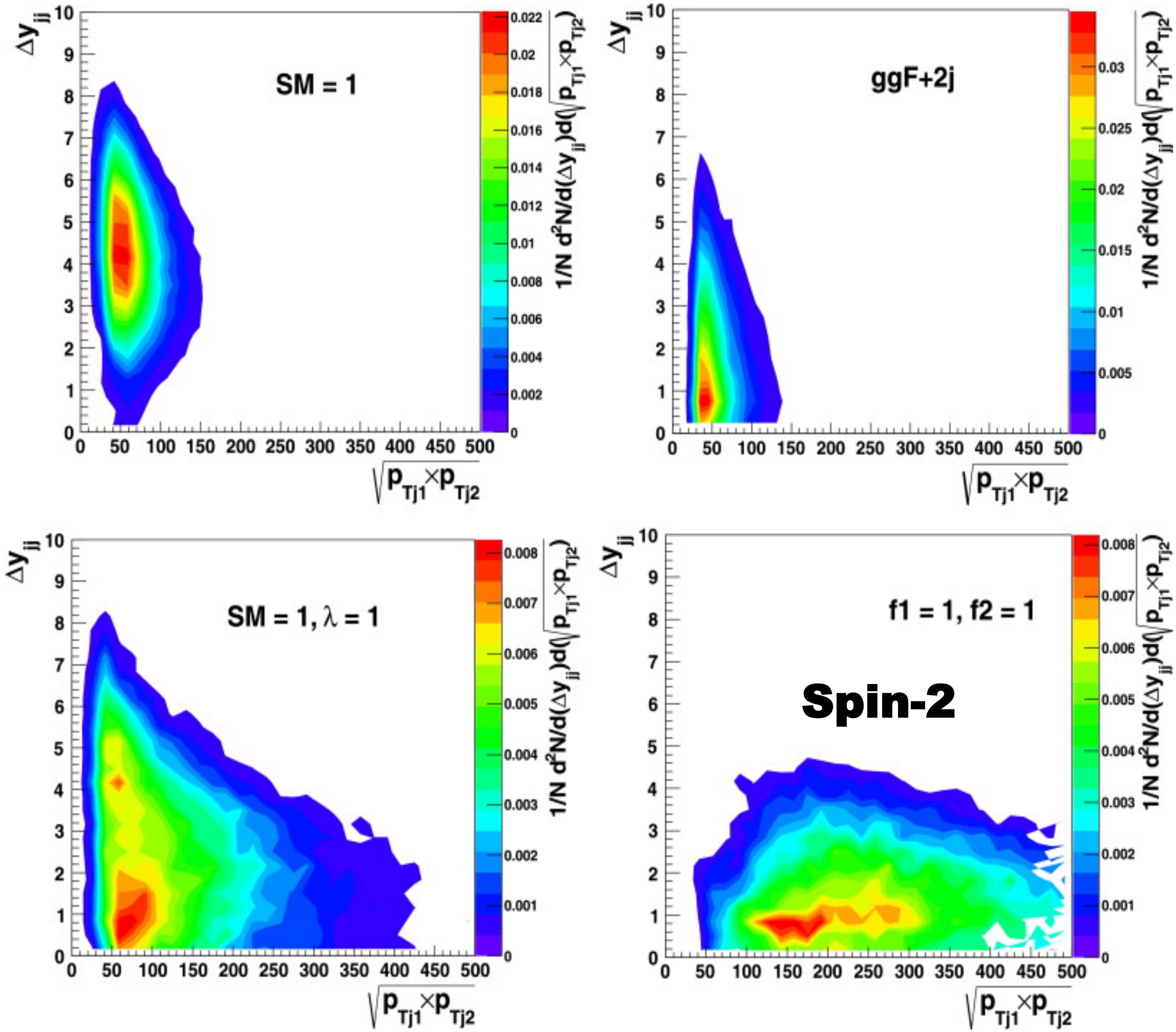
$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_V}\left[\lambda(p\cdot q g_{\mu\nu} - p_\nu q_\mu) + \lambda' \epsilon_{\mu\nu\rho\sigma} p^\rho q^\sigma\right]$$

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

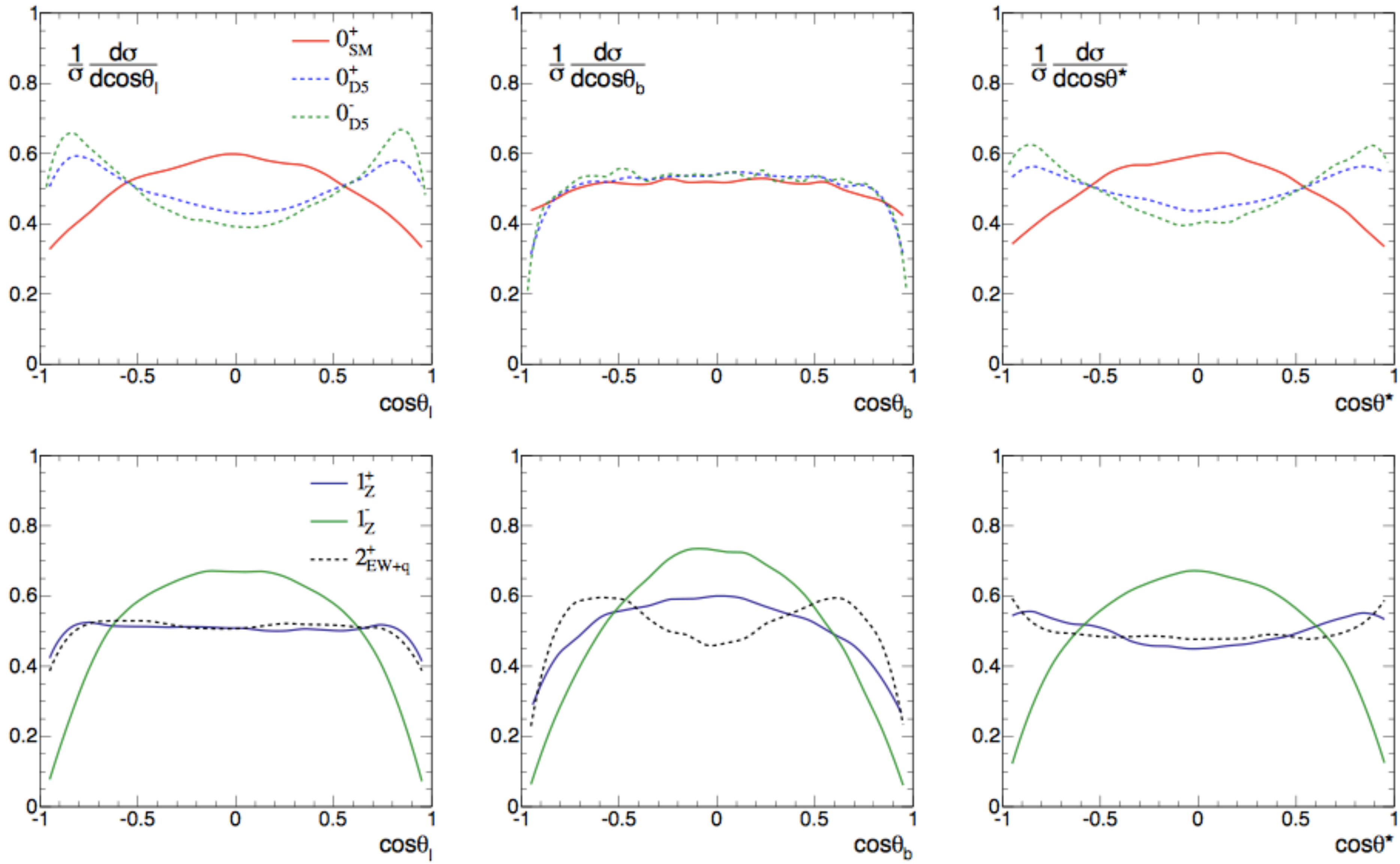


Problem with unitarization

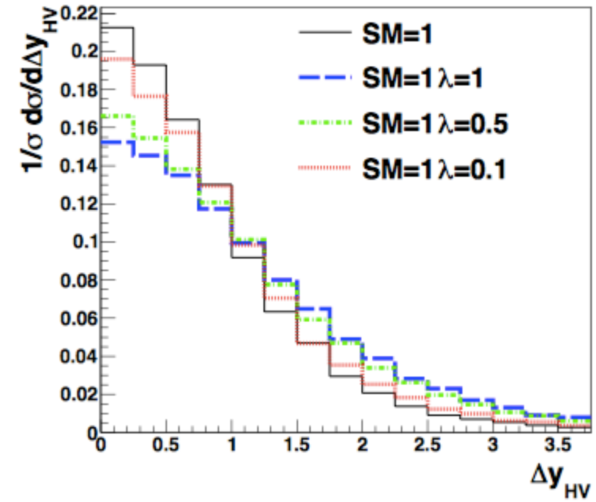


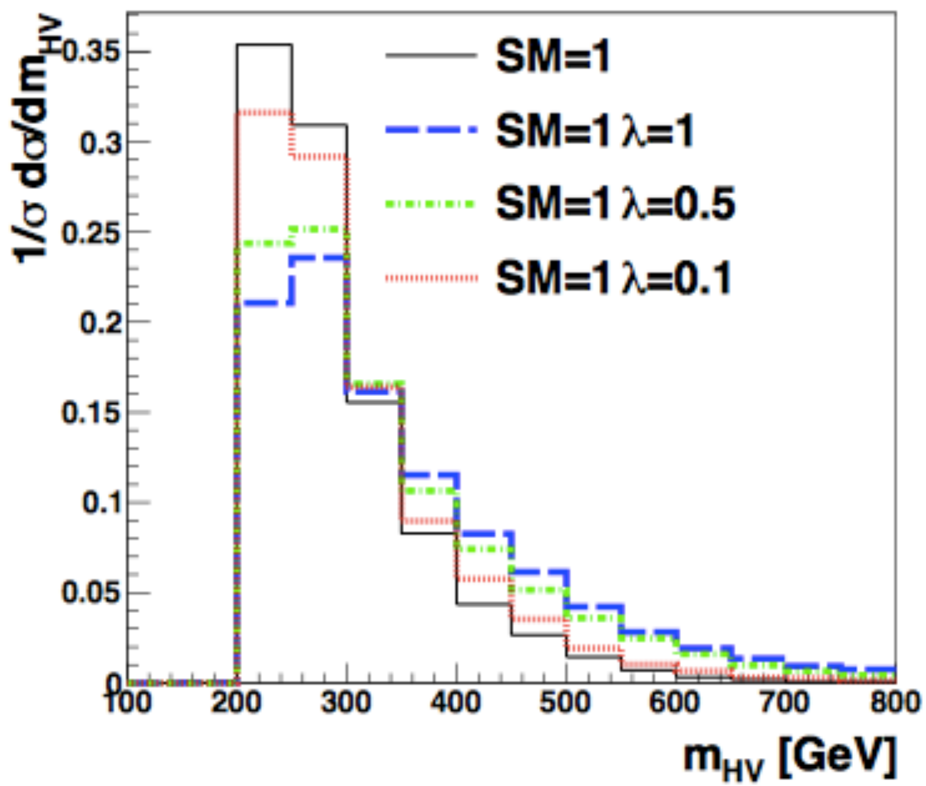
SM = 1
ggF+2j
SM = 1, λ = 1
f1 = 1, f2 = 1
Spin-2
Δy_{jj}
$\sqrt{p_{Tj1} \times p_{Tj2}}$
$1/N\ d^2N/d(\Delta y_{jj})d(\sqrt{p_{Tj1} \times p_{Tj2}})$

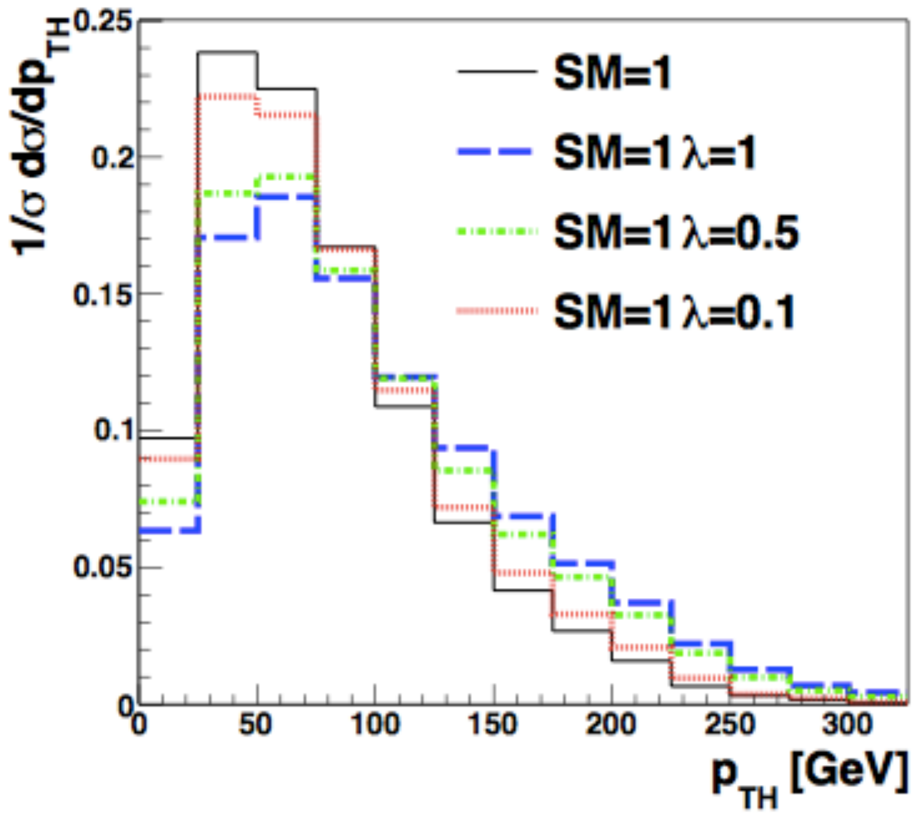
Associated VH production [Z(→ll)H(→bb)]



Associated VH production



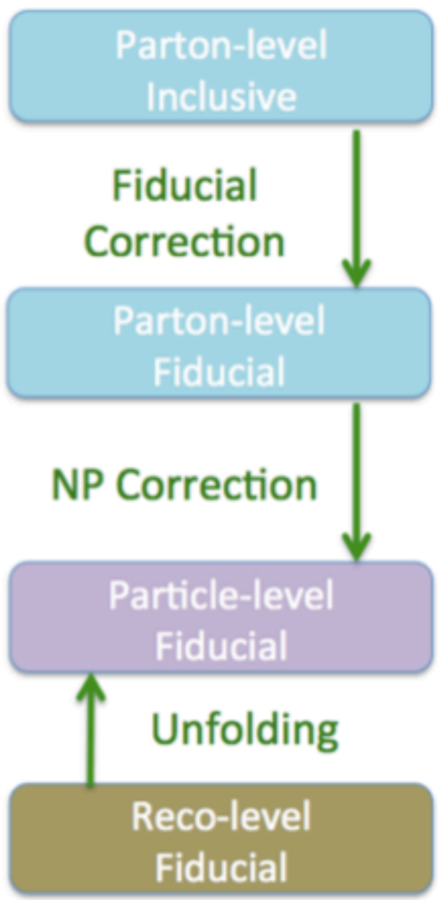




Fiducial Total and Differential Cross-sections

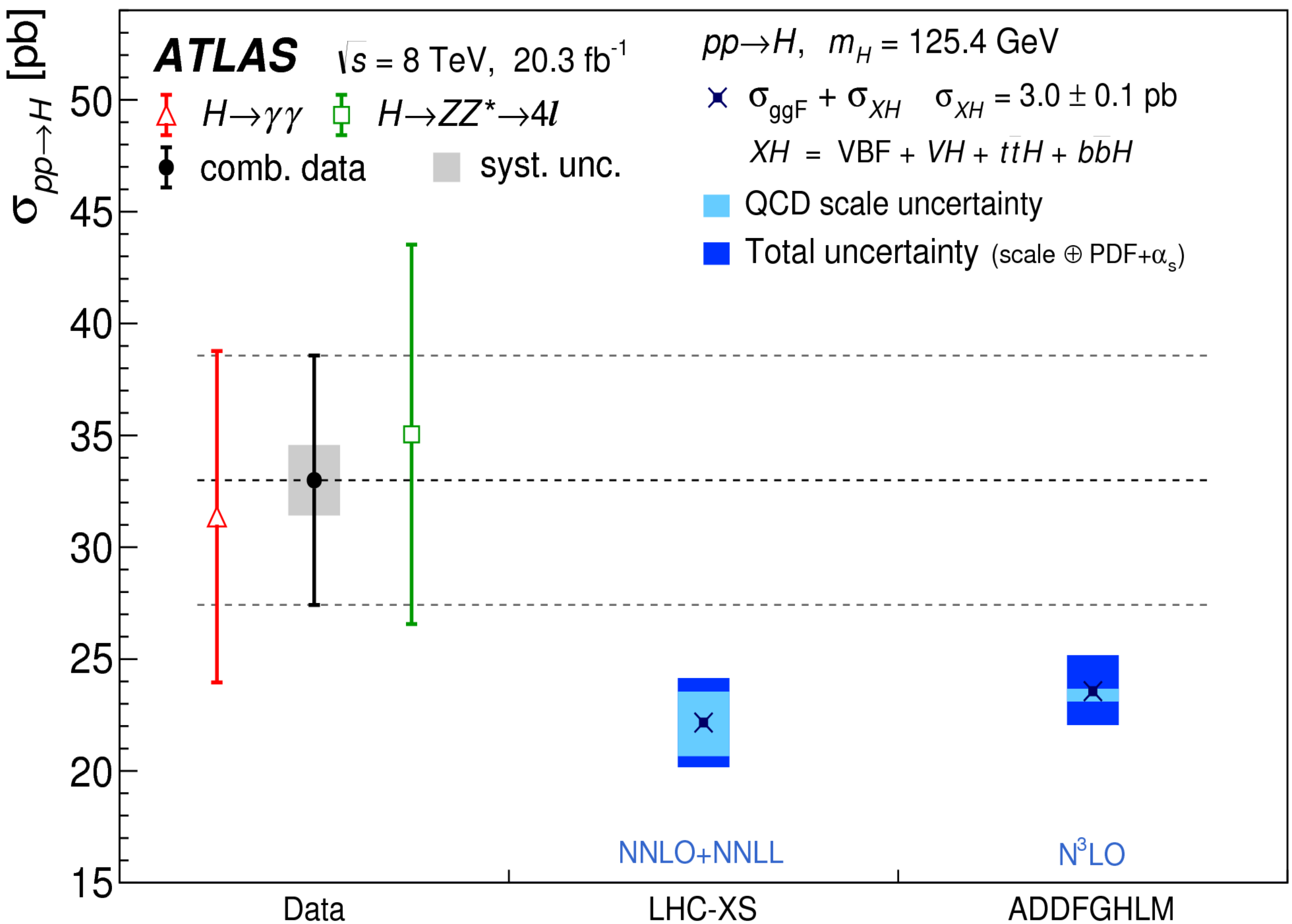
Differential Cross-section Measurements

- First Higgs differential cross section results
- Follows closely the coupling analysis strategy
- Allows to probe kinematics of Higgs boson
- As model-independent as possible



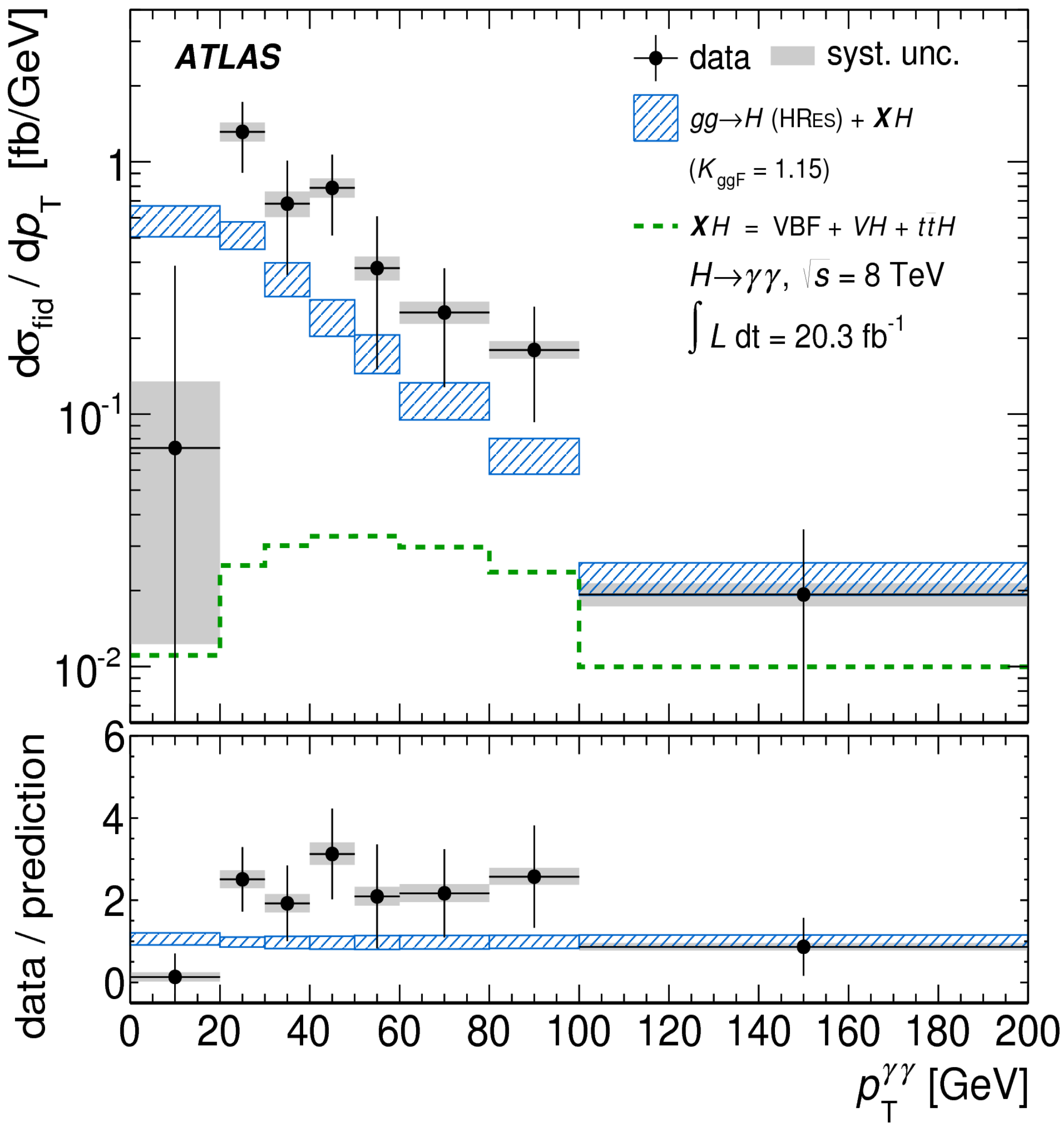
- Extract signal at reconstruction level
- Derive unfolding factors to unfold to particle level
- All results presented at particle level
- Also provide NP and fiducial correction factors for theorist use

When assuming the Standard Model the signal strength of H->γγ is 1.17 when releasing that condition we get 1.42. Still these two numbers are statistically compatible

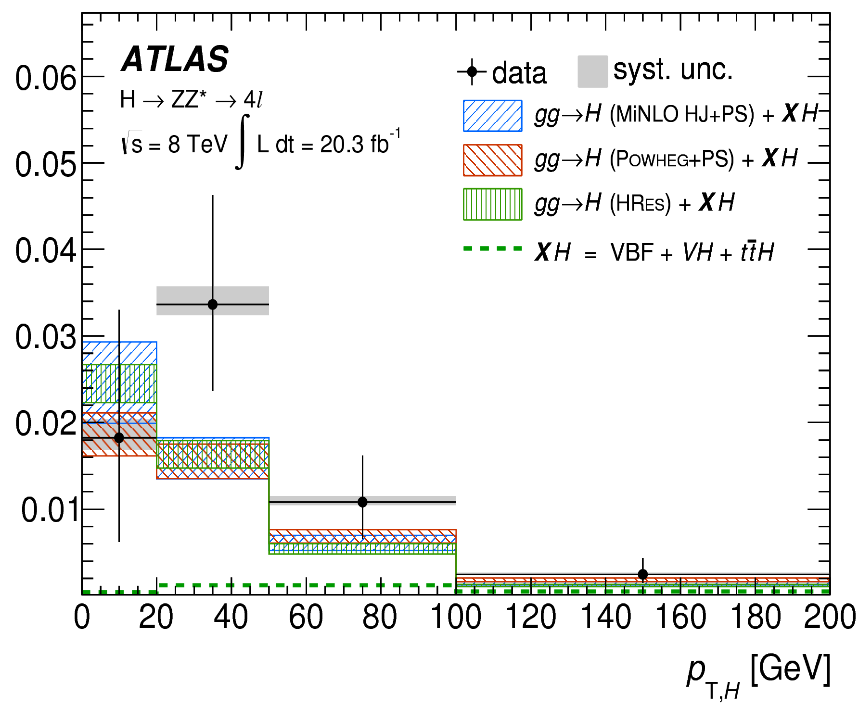


When measuring the Higgs boson transverse momentum certain discrepancies were found with the Standard Model

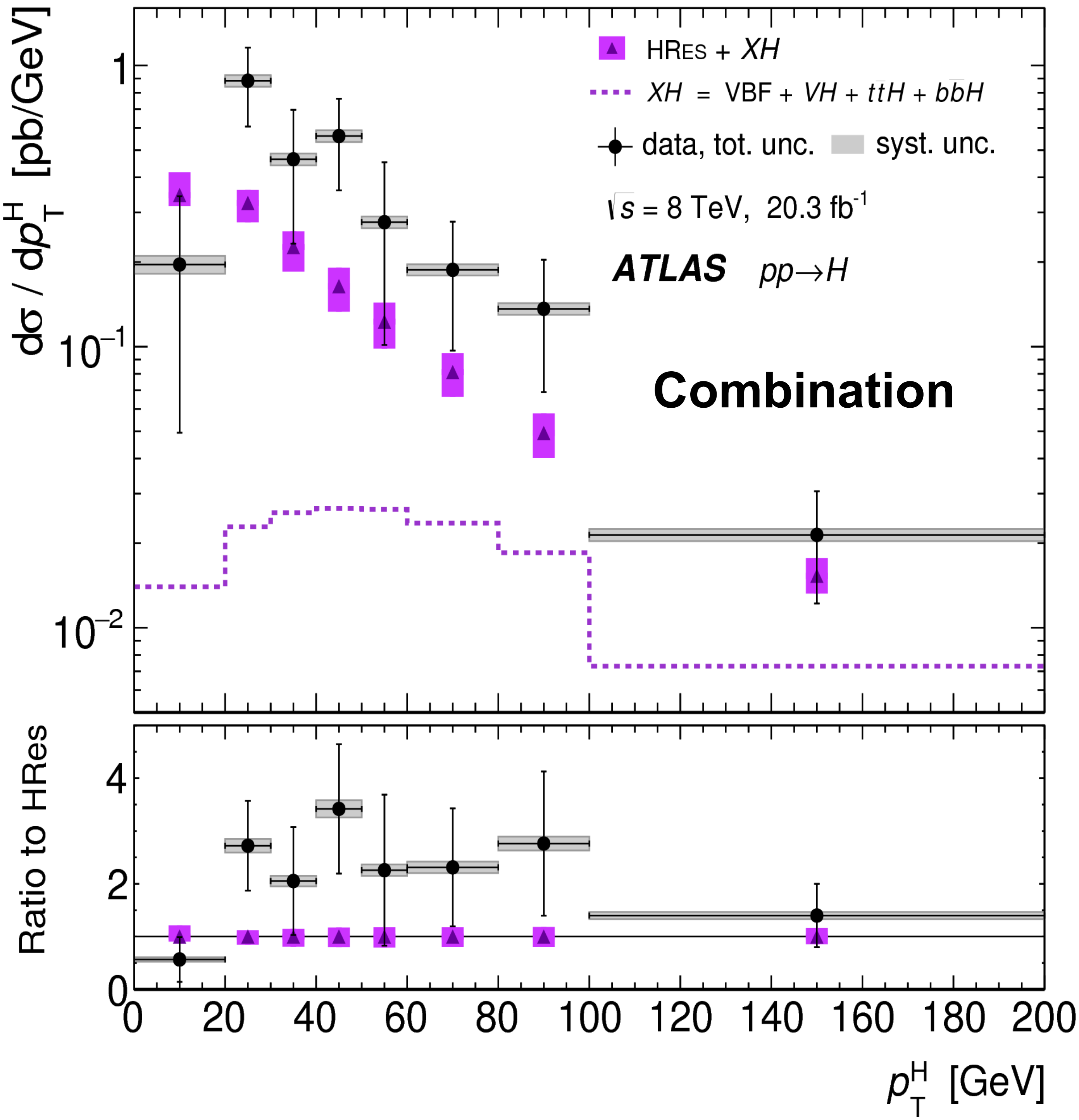
$H \to \gamma\gamma$

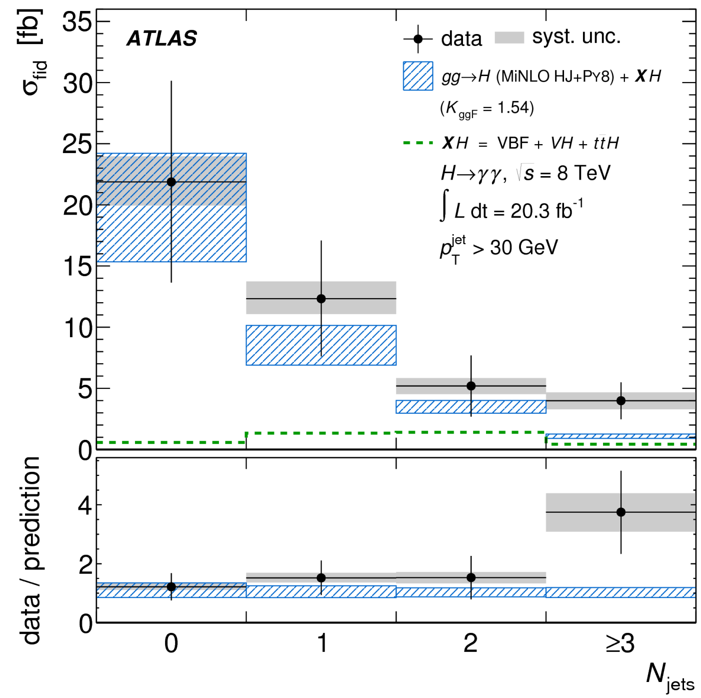


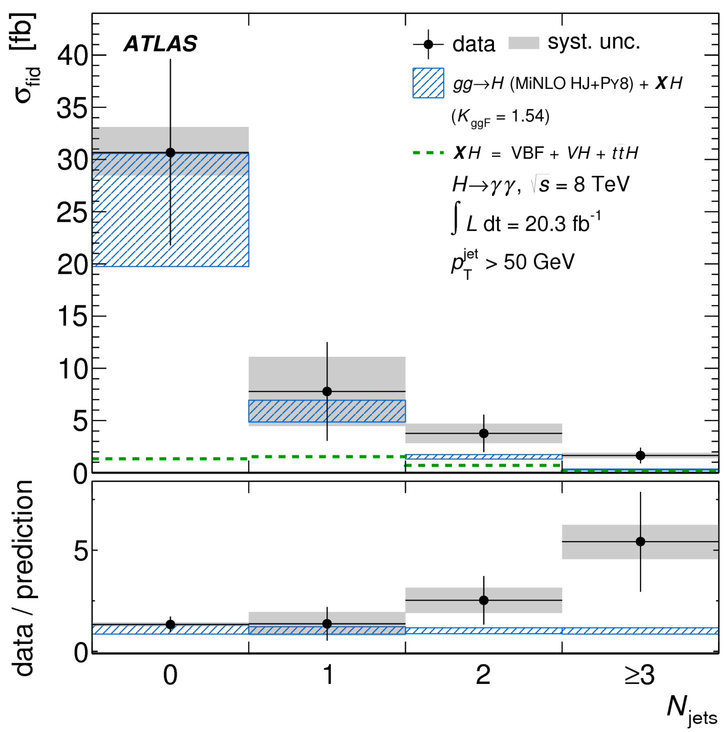
$H \to ZZ^* \to 4\ell$



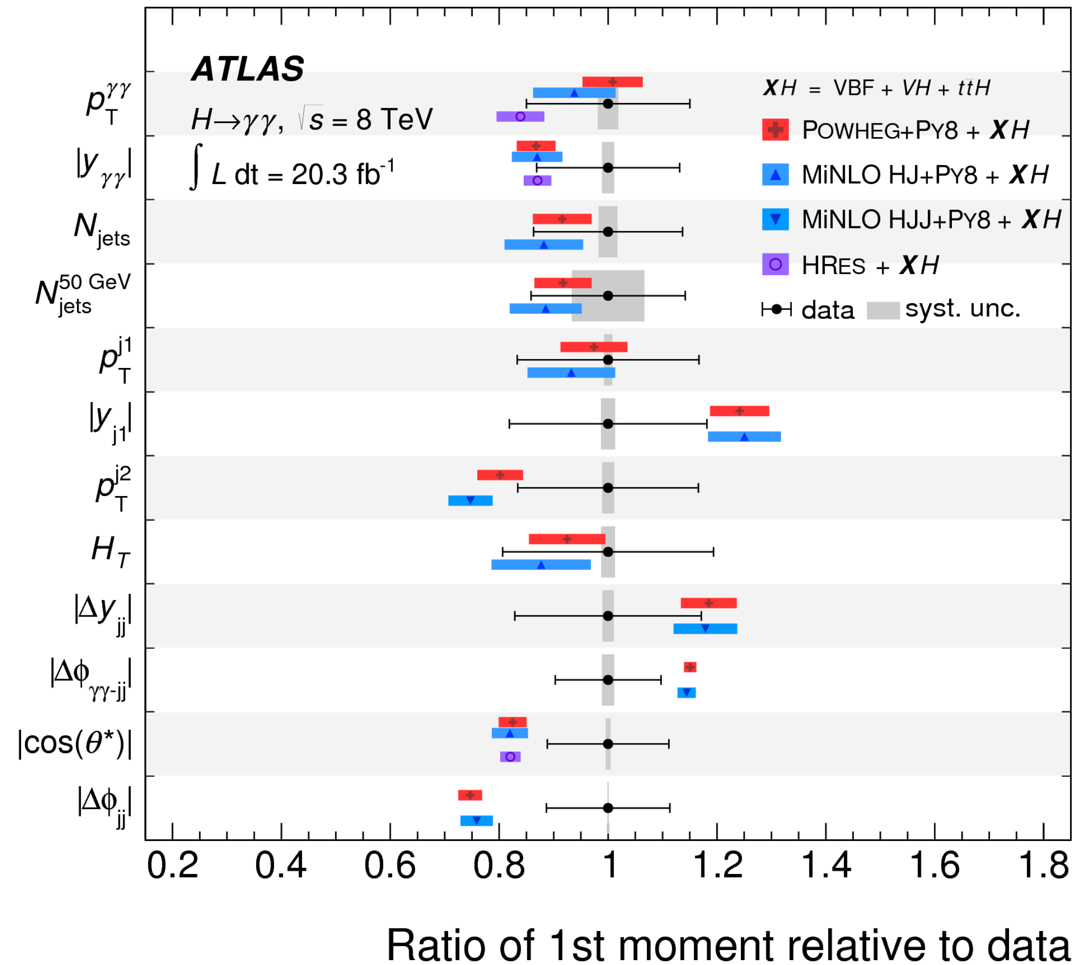
Compatibility with the SM (HRes) is 2%



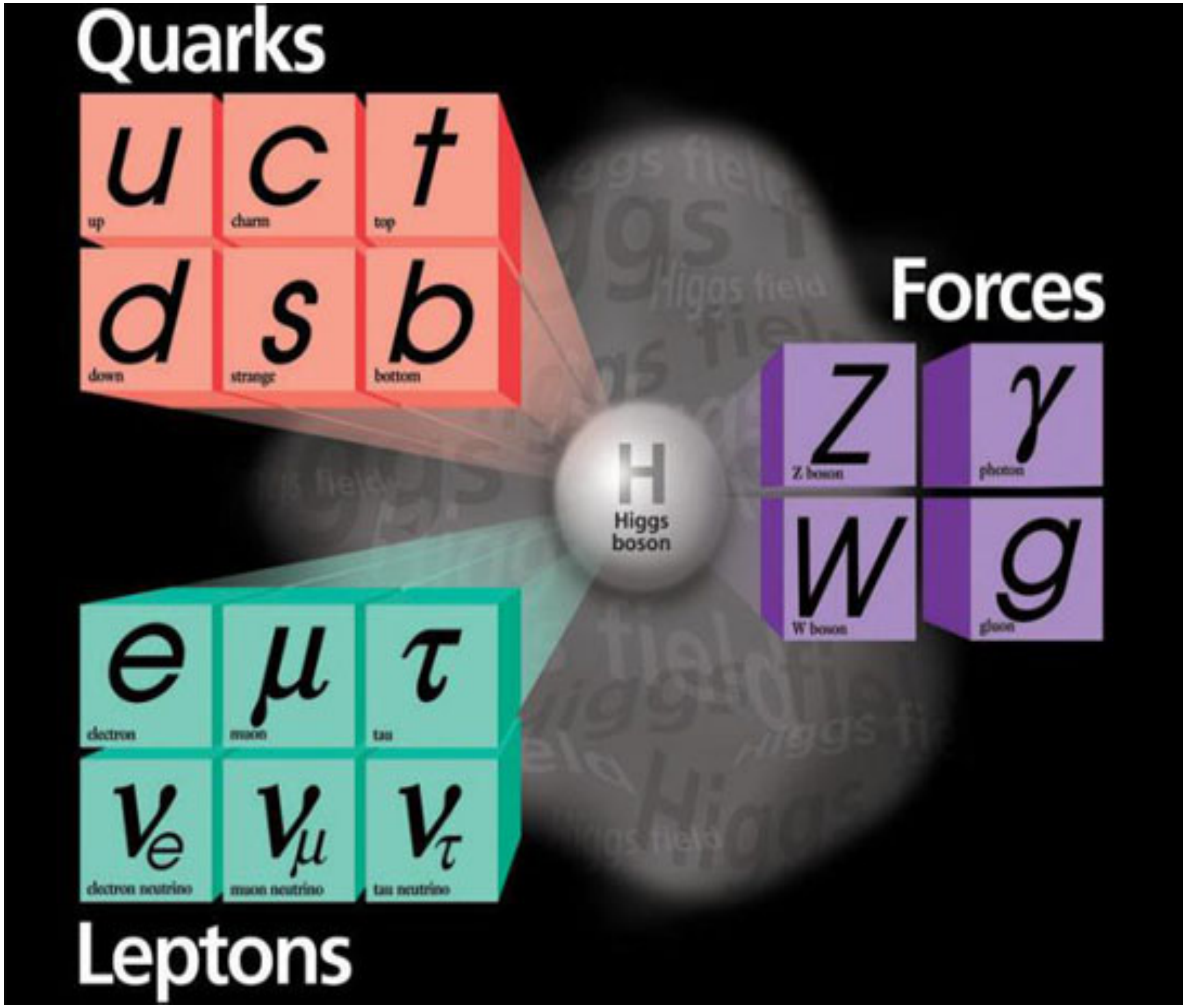




Comparison of the mean of the observable between data and MCs



Overall, reasonable agreement between data and the SM MC, but large errors. Future measurements very interesting s


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons