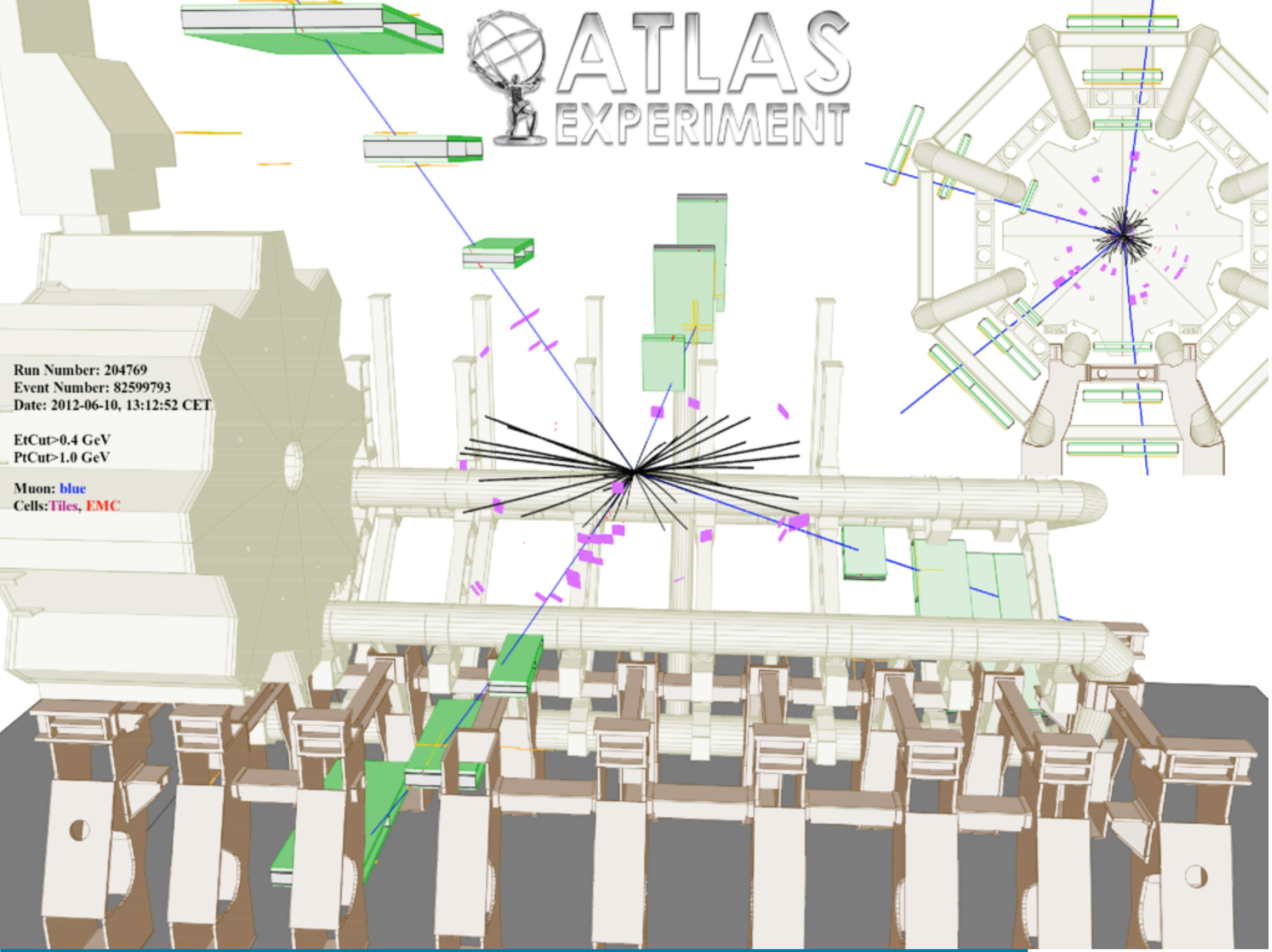


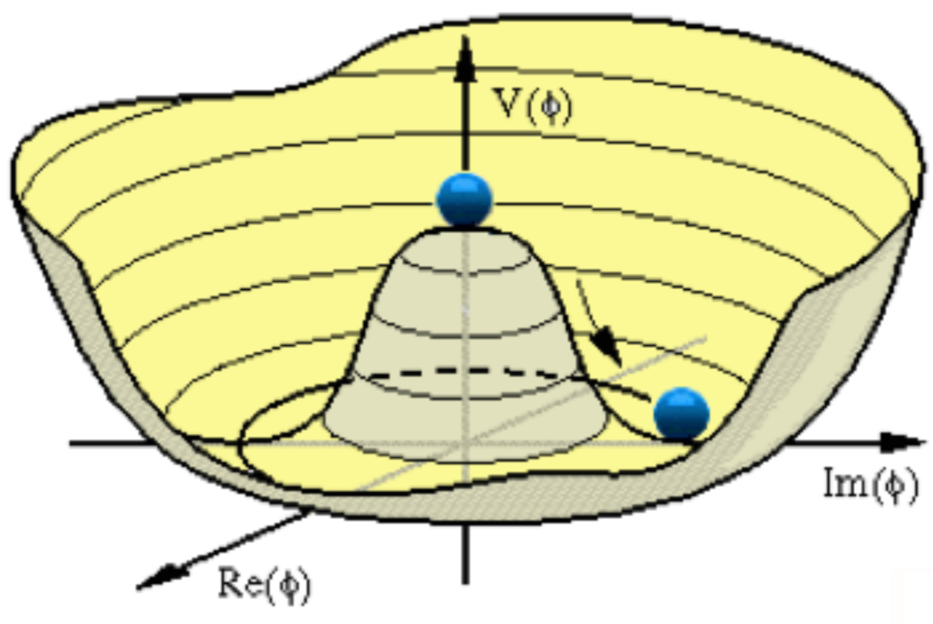
Higgs Boson Physics with ATLAS

K. Nikolopoulos
University of Birmingham

18th November 2013, Lisbon

UNIVERSITY OF BIRMINGHAM

The Standard Model Higgs boson



→ The SM unifies the electromagnetic and weak interactions through the symmetry $SU(2)_L \otimes U(1)_Y$, with massless carriers
→ This symmetry is spontaneously broken through the non-vanishing vacuum expectation value of the Higgs field
→ Three of the four degrees of freedom of the Higgs field are becoming the longitudinal polarizations of the vector bosons, the fourth is the Higgs boson.

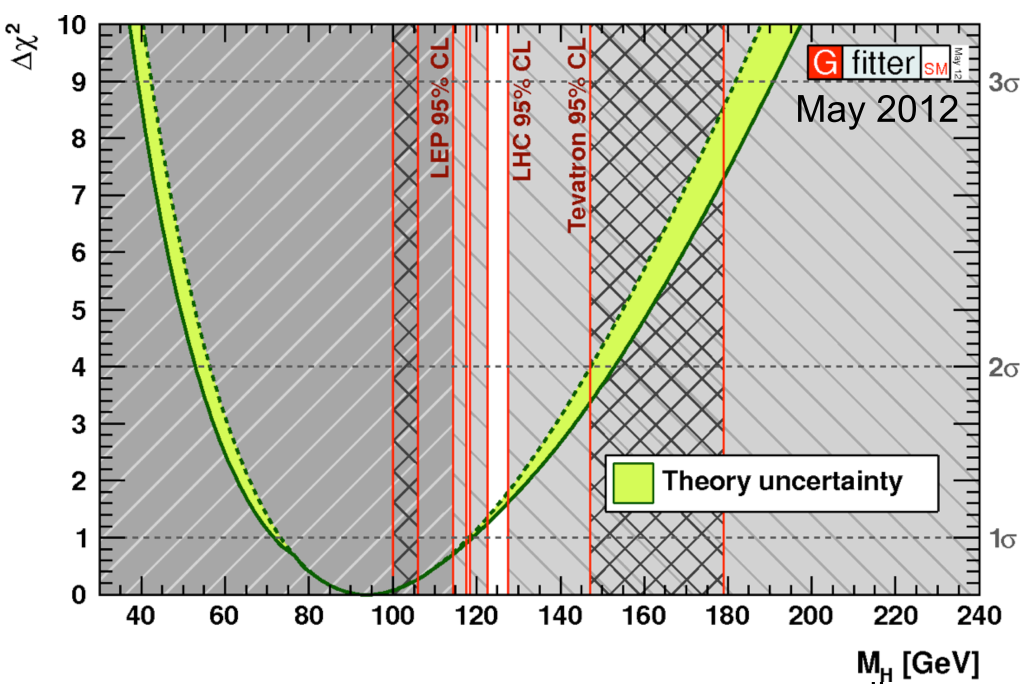
The Higgs boson has been one of the holy grails of particle physics for the past half century!

Global Electroweak Fit

→ The electro-weak observables depend on m_H through radiative corrections
→ Global fit performed providing information on the Higgs mass, assuming validity of the SM

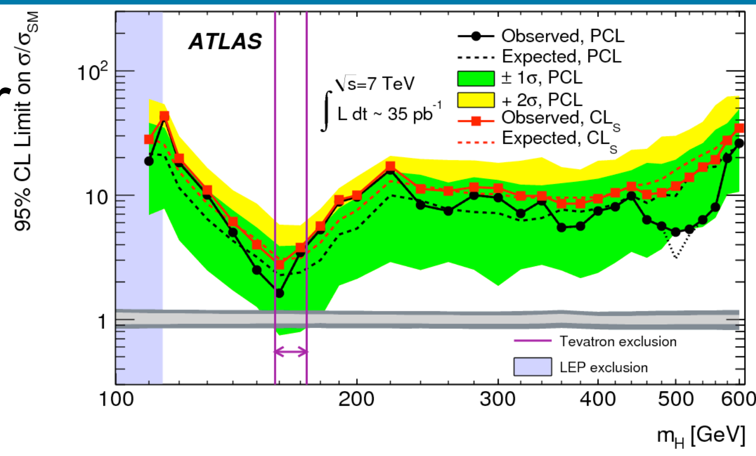
Non-LHC SM Higgs status

→ LEP m_H>114.4 GeV at 95% CL
→ Tevatron excluded 149 GeV<m_H<182 GeV at 95% CL
→ Large portion of allowed m_H uncovered
→ m_H>200 GeV not considered.



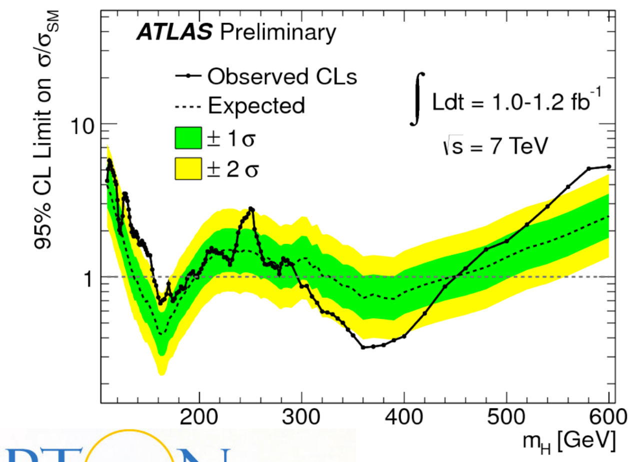
... a long way since then ...

40 pb^{-1} — Apr

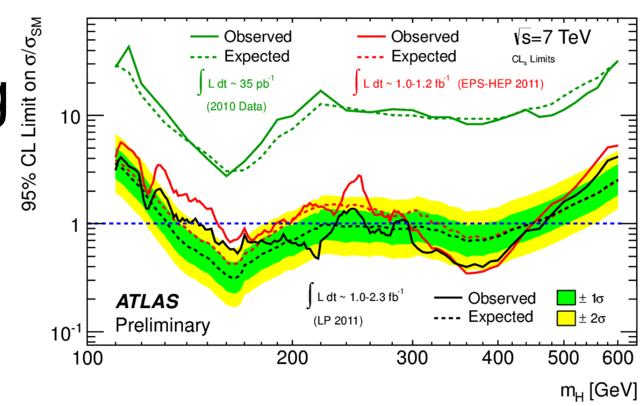


[Eur.Phys.J. C71 (2011) 1728]()

1 fb^{-1} — Jul

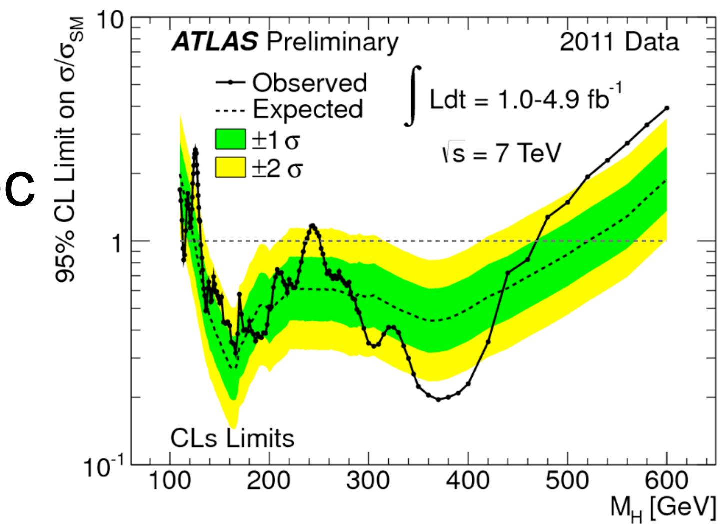


2 fb^{-1} — Aug



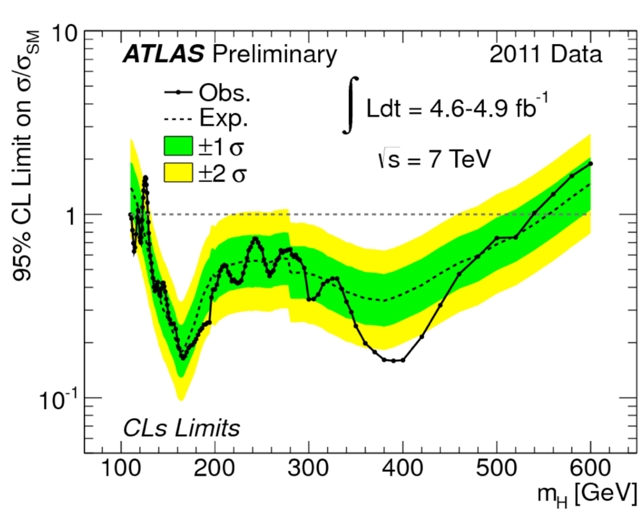
LEPTON PHOTON 2011
XXV International Symposium on Lepton and Photon Interactions at High Energies

5 fb^{-1} — Dec



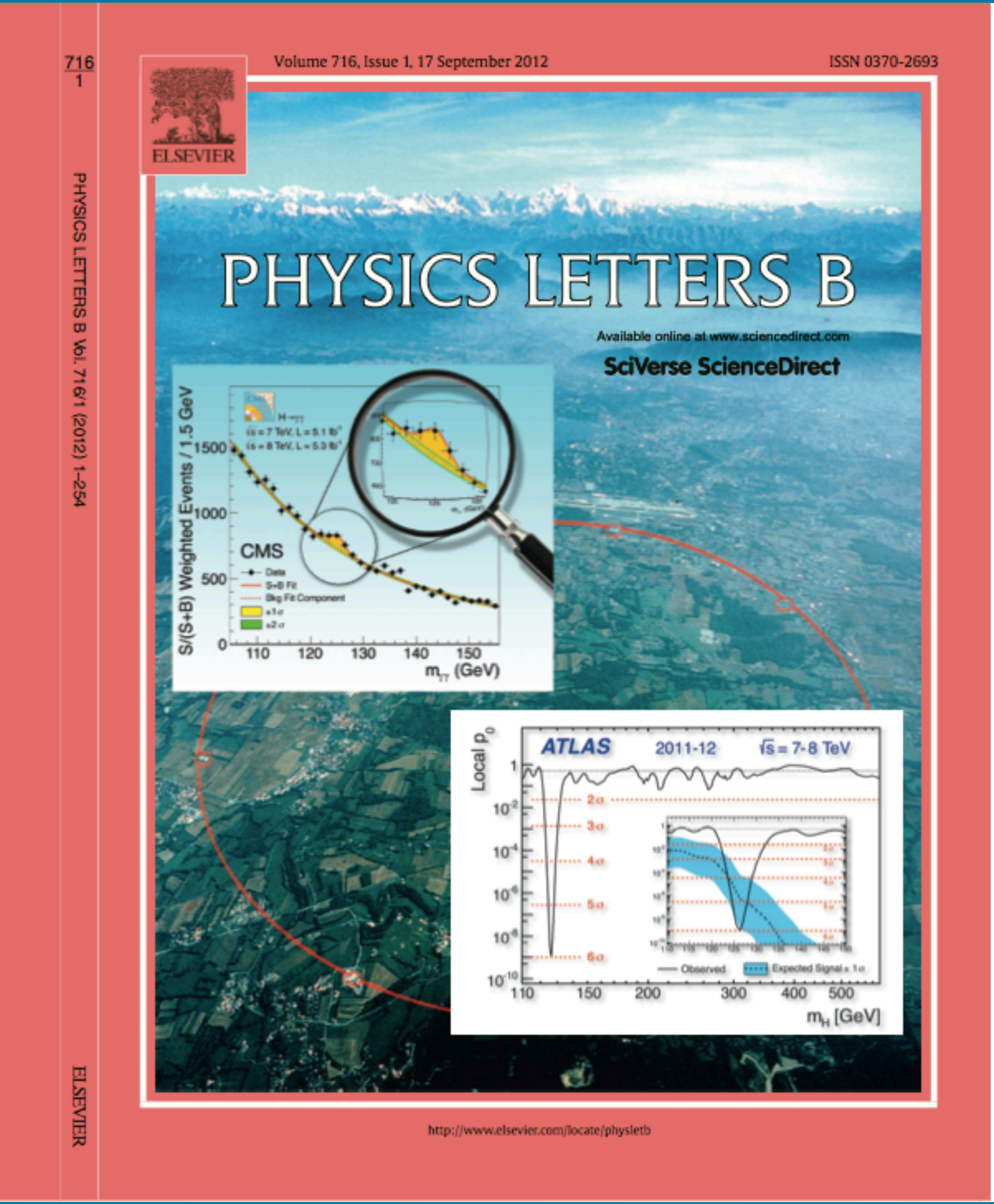
2012

Mar



47th RENCONTRES DE MORIOND
rencontres de Moriond

... the observation of a new particle ...



Physics Letters B 716 (2012) 1–29

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

Article history:
Received 31 July 2012
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ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s}=7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s}=8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Physics Letters B 716 (2012) 30–61

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

ARTICLE INFO

Article history:
Received 31 July 2012
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Accepted 11 August 2012
Available online 18 August 2012
Editor: W.-D. Schlatter

Keywords:
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ABSTRACT

Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s}=7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of $125.3 \pm 0.4(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})$ GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

... and a Nobel Prize

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

Volume 12, number 2 PHYSICS LETTERS 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

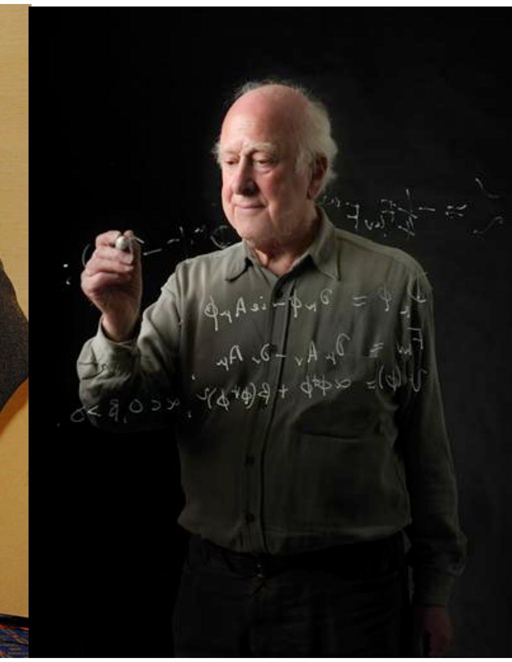
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

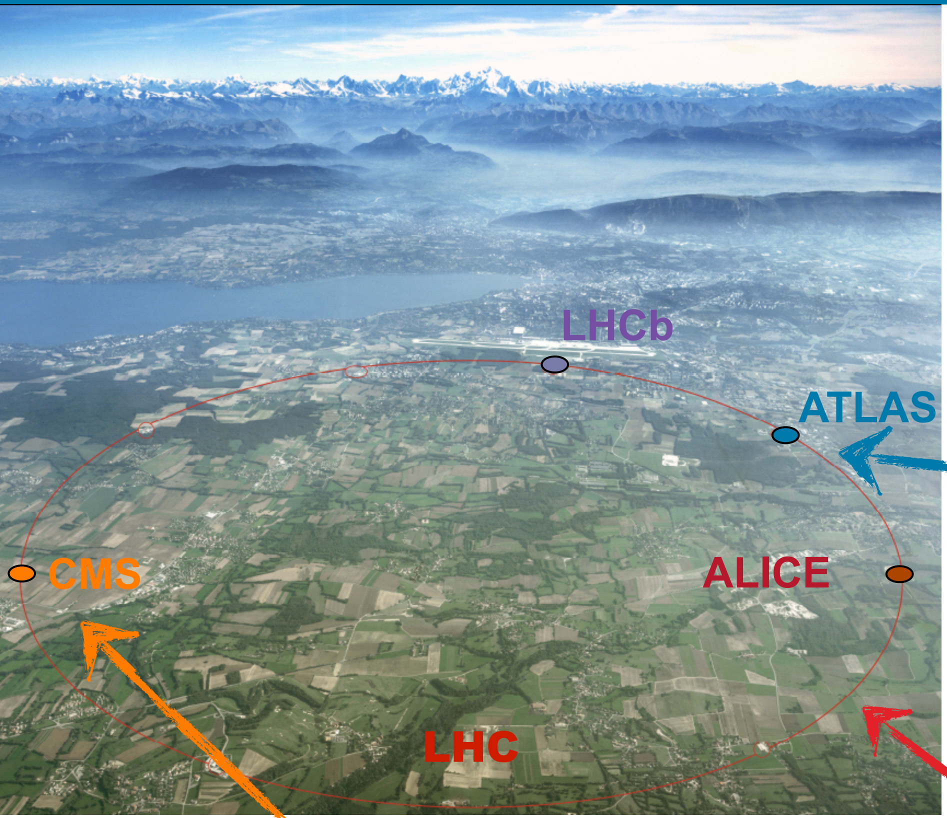
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

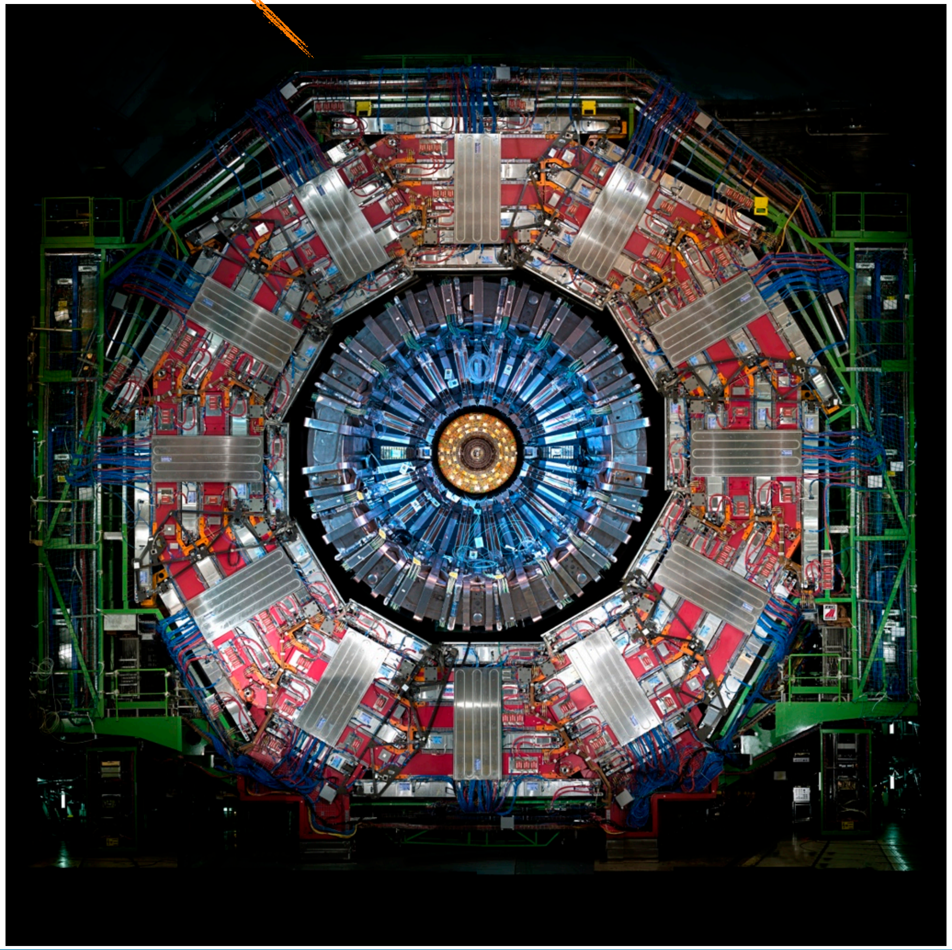


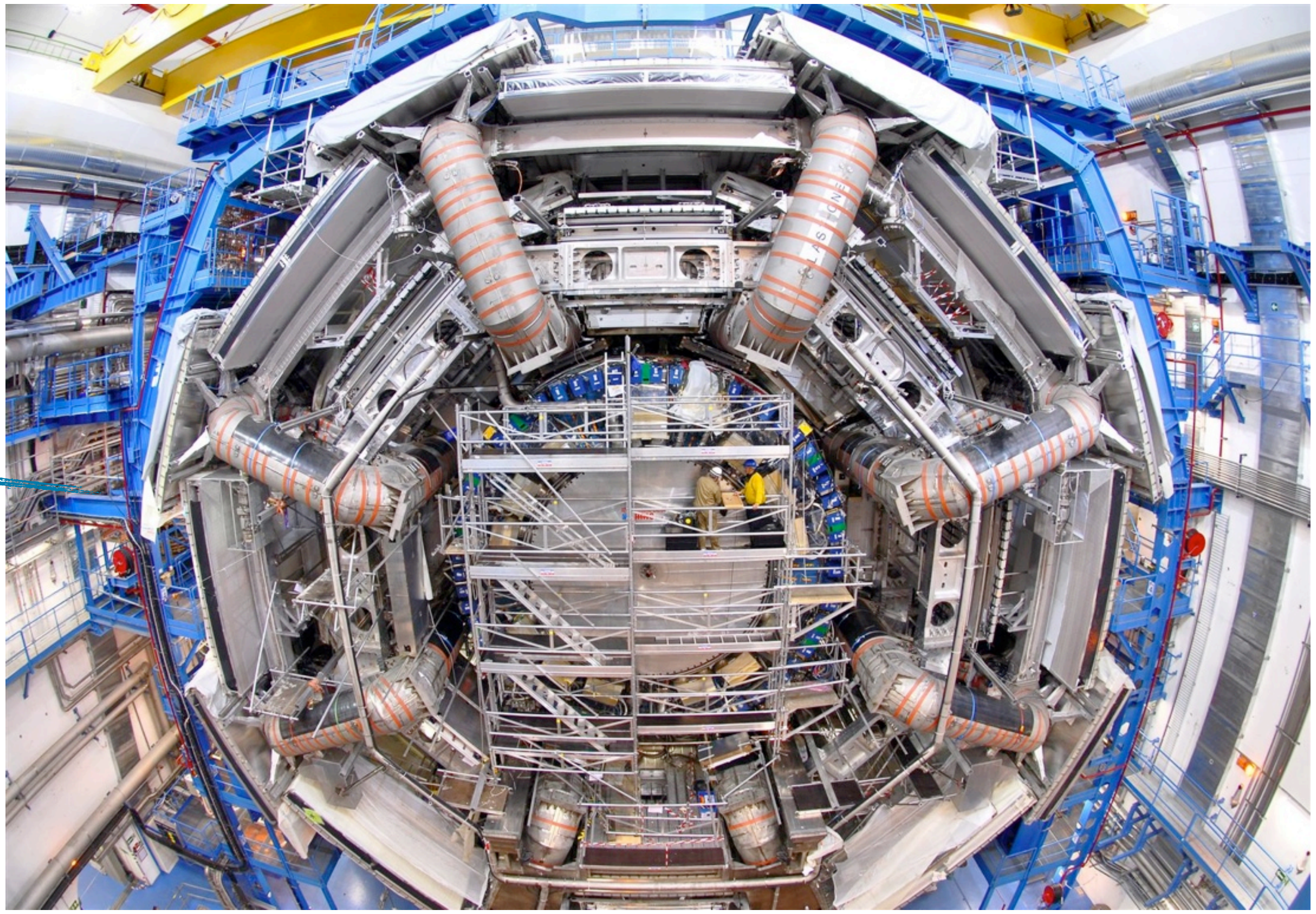
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs:

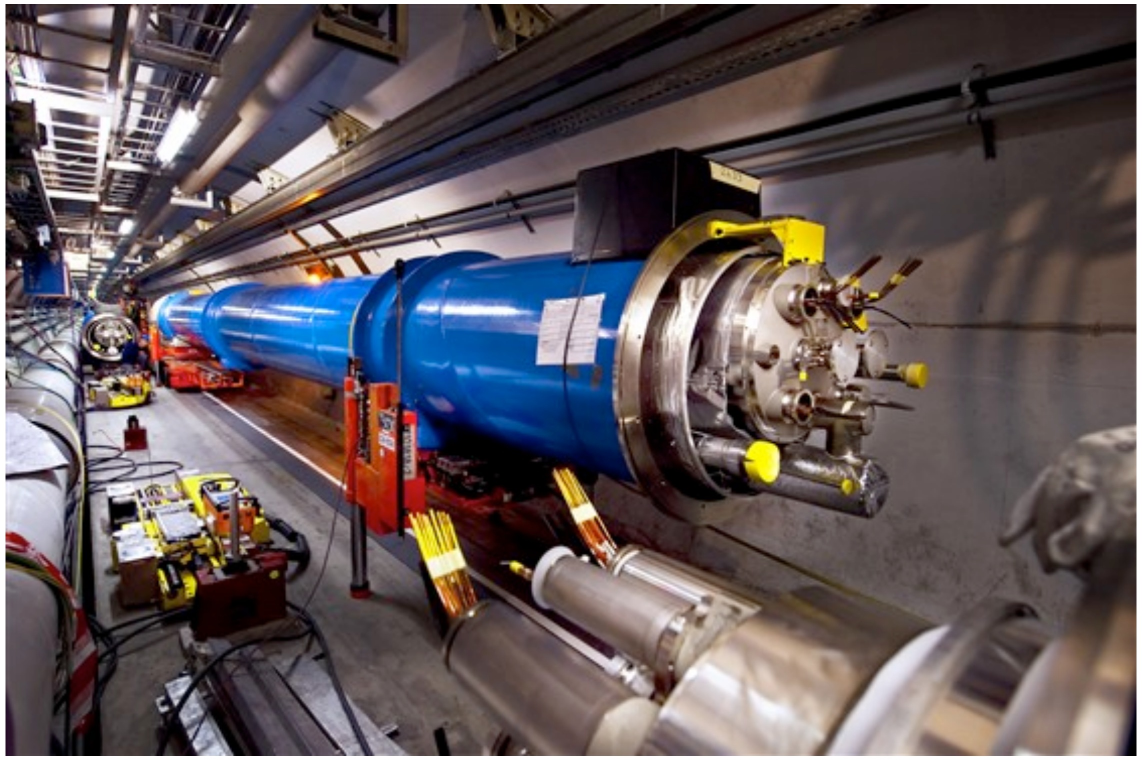
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The LHC and the detectors



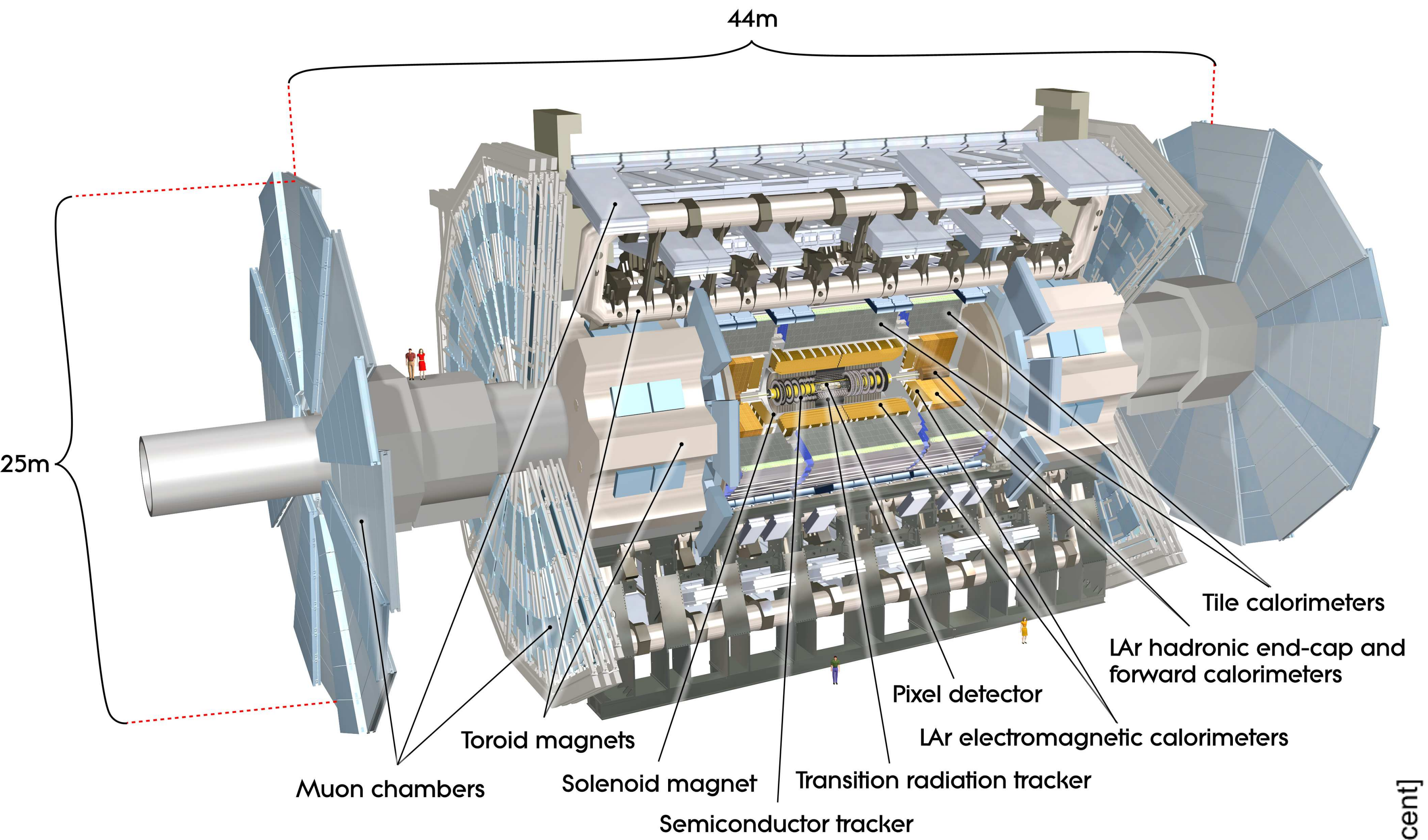






A Toroidal LHC ApparatuS

⇒ General purpose detector designed for the harsh LHC environment

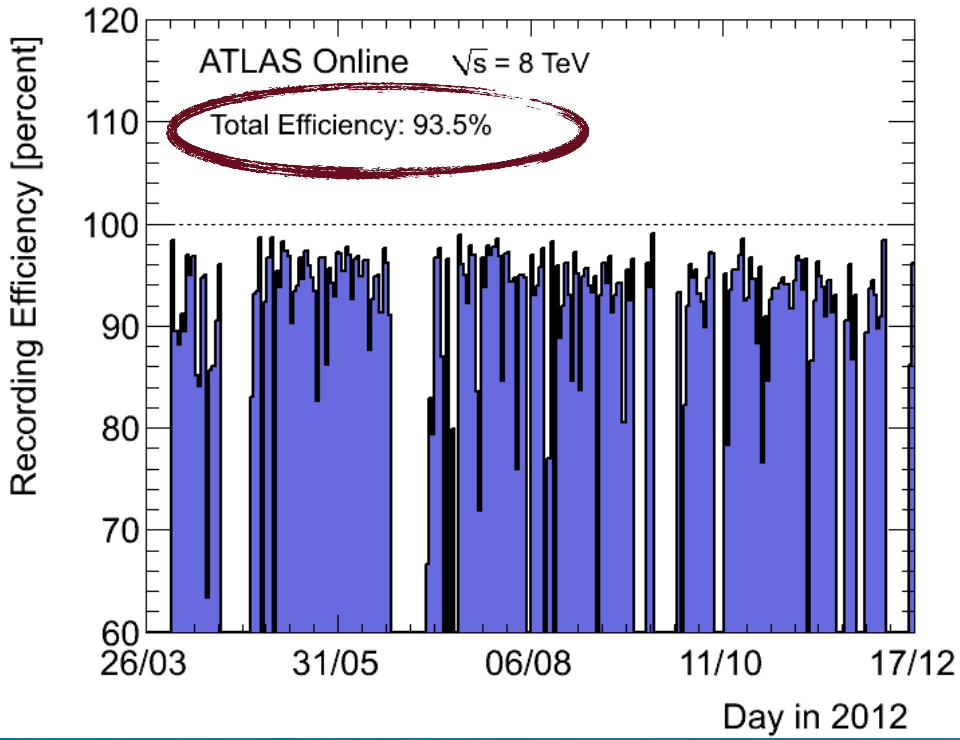


	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling LAr technology
Hadron Calorimetry	plastic scintillator (barrel) LAr technology (endcap)
Muon	independent system with trigger capabilities
Trigger	3 Level Implementation from 40 MHz to 400 Hz

⇒ Very important to ensure high data-taking efficiency/quality

ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.8%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at $\sqrt{s}$=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

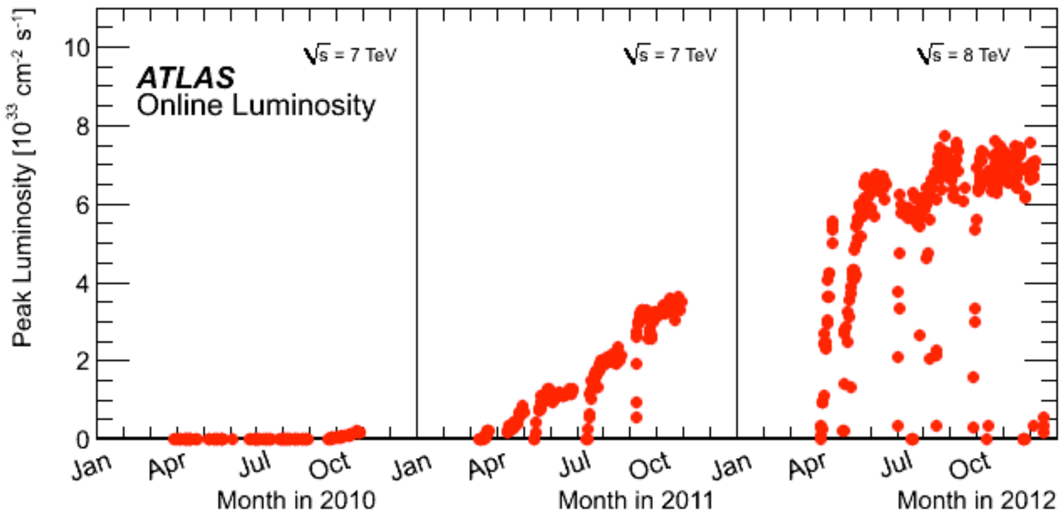


The LHC Run I dataset

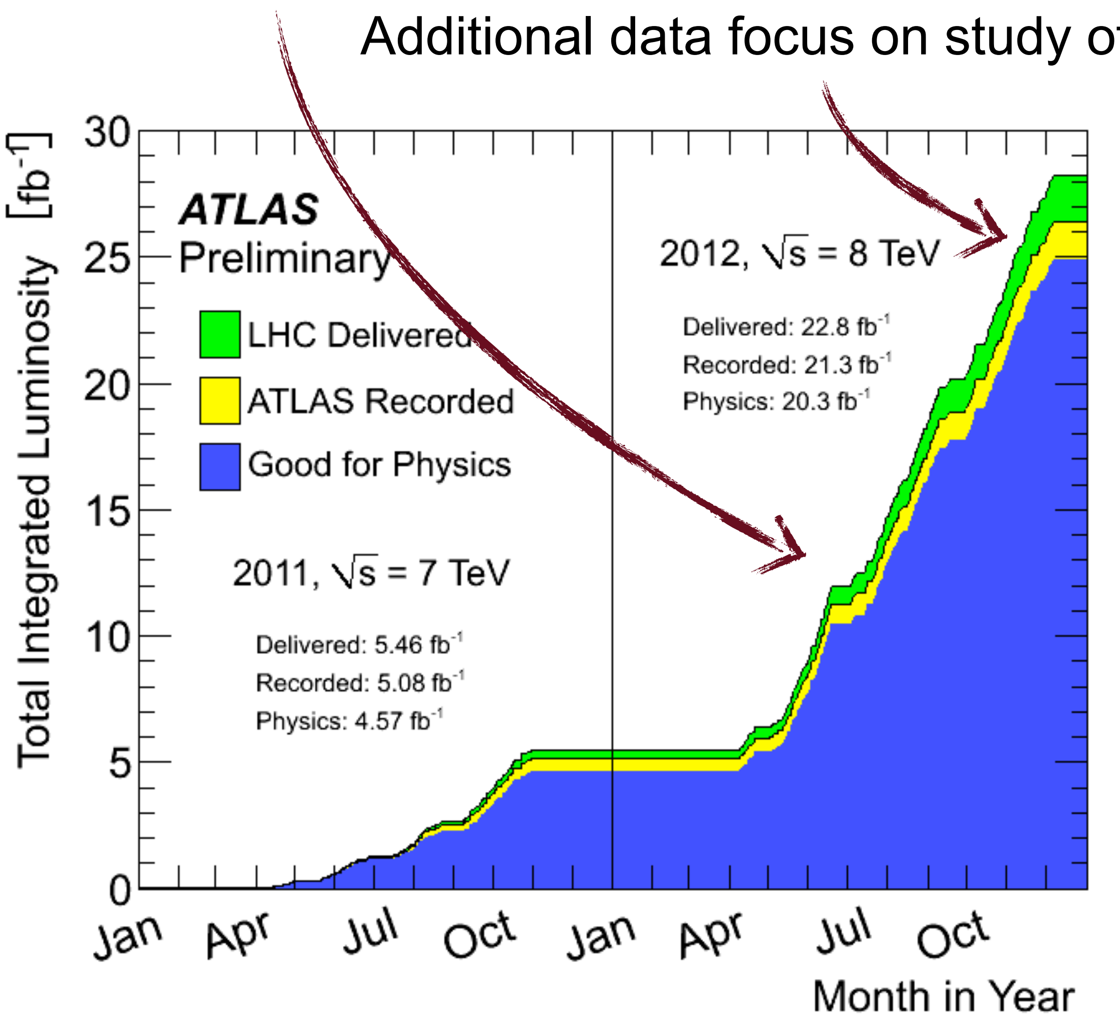
Excellent LHC performance during Run I :
4.8 fb^{-1} at 7 TeV and 20.7 fb^{-1} at 8 TeV
→ Pile-up in 2012 exceeding detector design specifications
→ Maintain excellent performance by improved algorithms
→ Proper modeling of experimental conditions essential

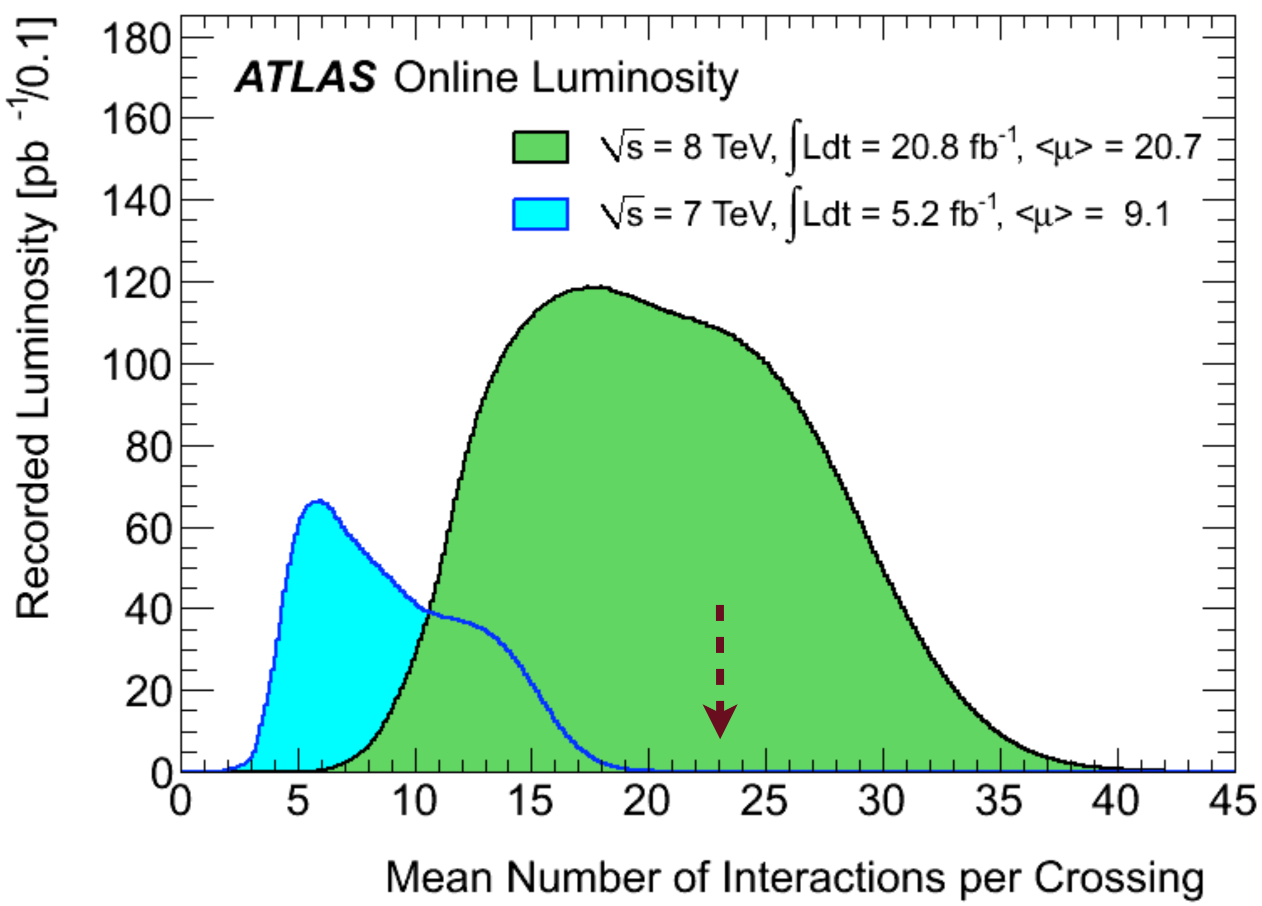
At the time of the discovery all we really knew:
"It is a boson which couples to bosons"

2.07×10^{32} 3.65×10^{33} $7.73\times10^{33}cm^{-2}s^{-1}$



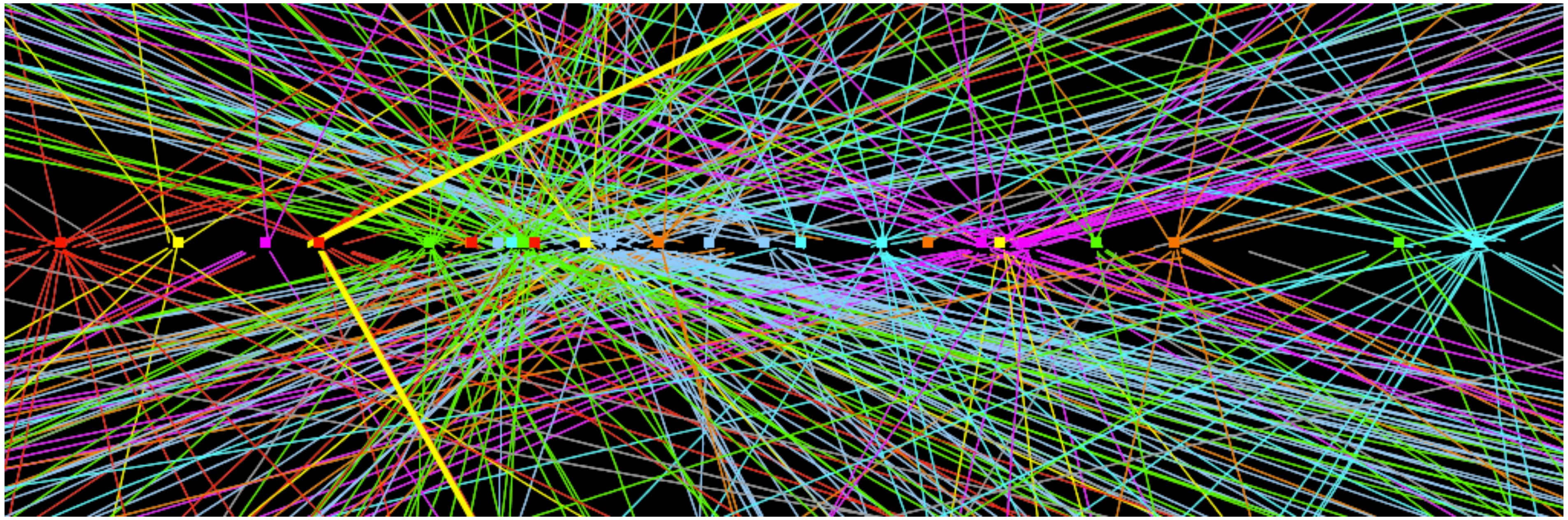
Additional data focus on study of properties

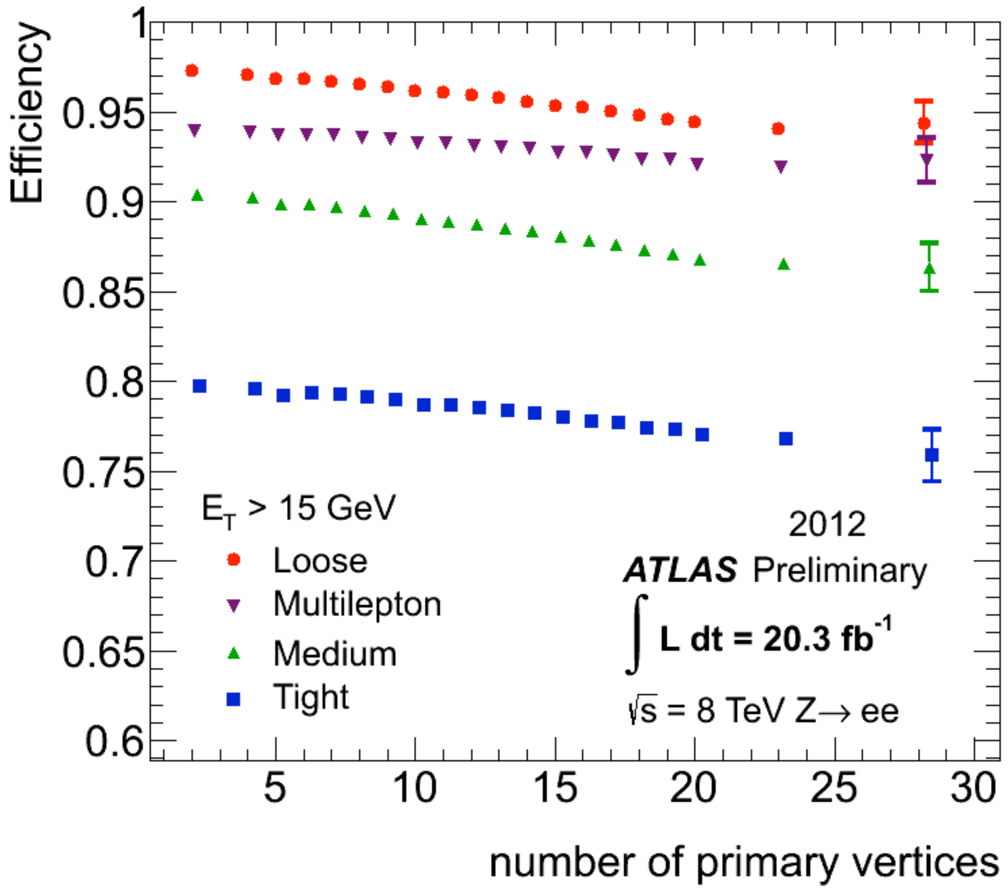


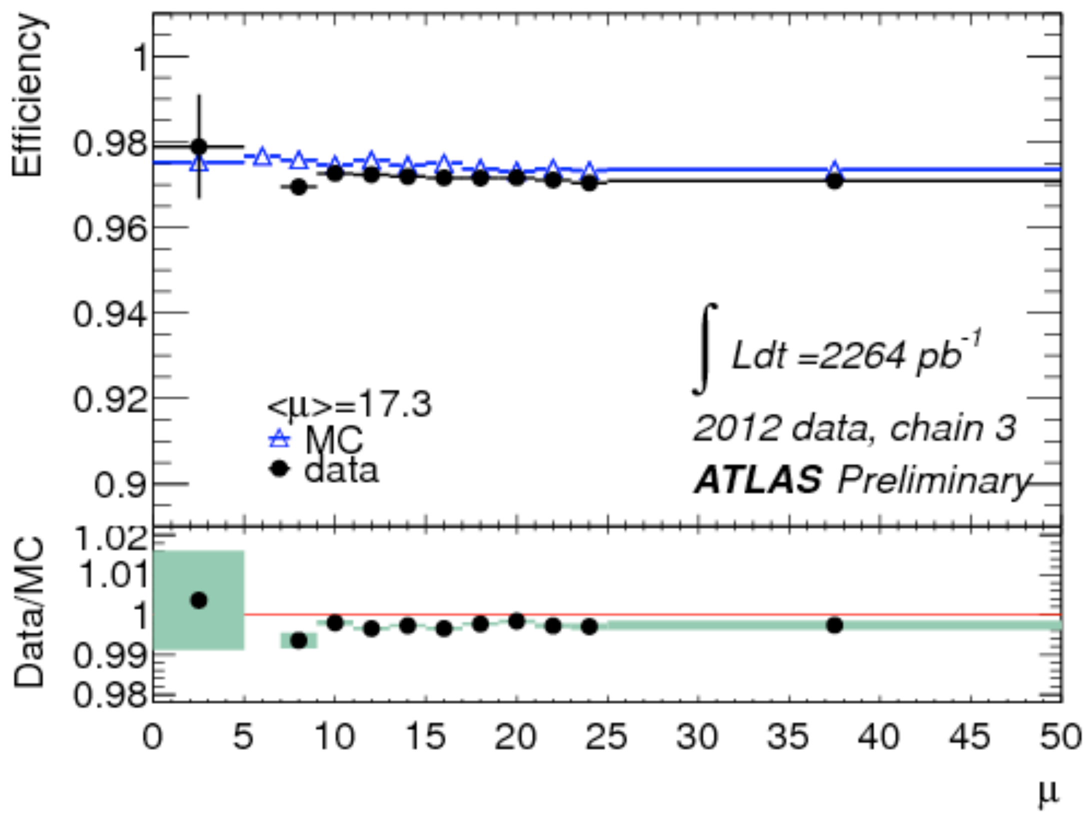


ATLAS Performance: Electrons and Muons

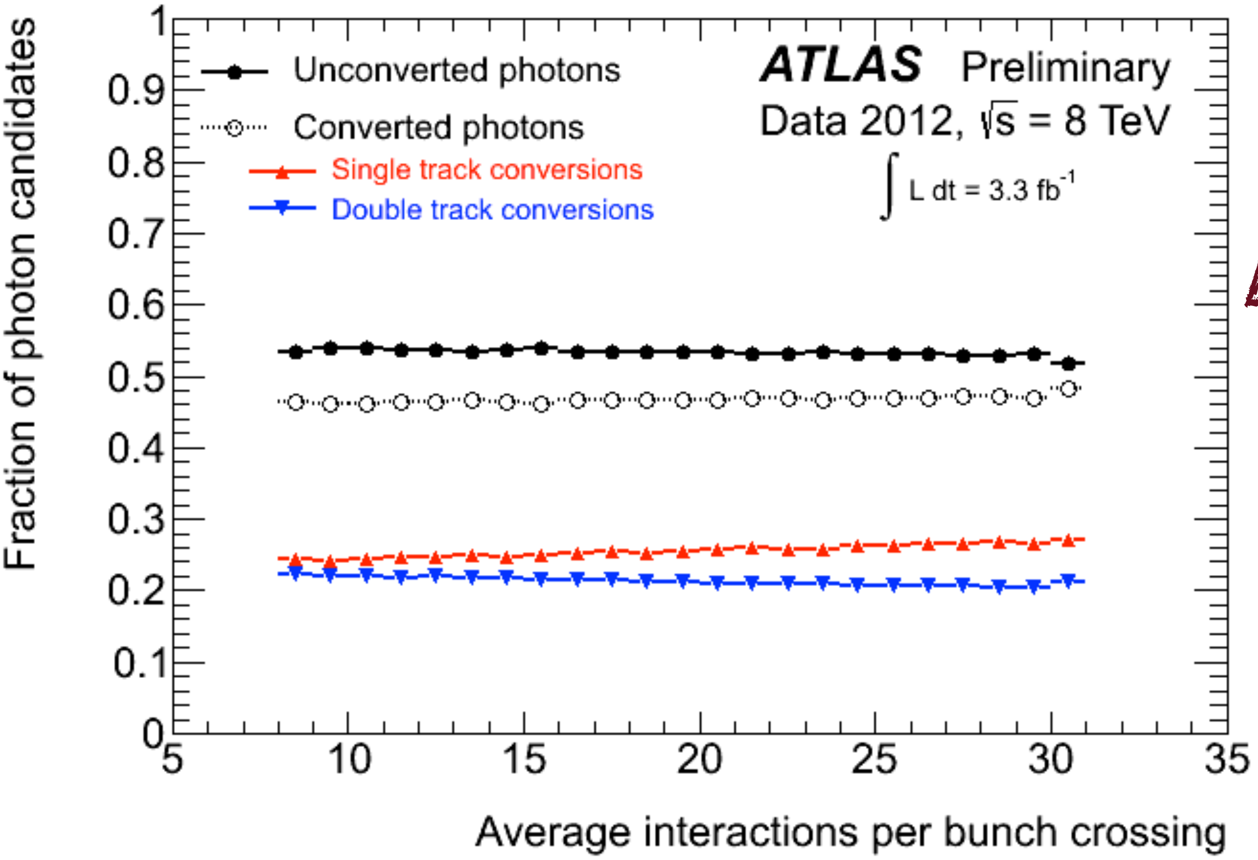
Z→μμ candidate with 25 reconstructed vertices from the 2012 run.
Only good quality tracks with pT>0.4GeV are shown





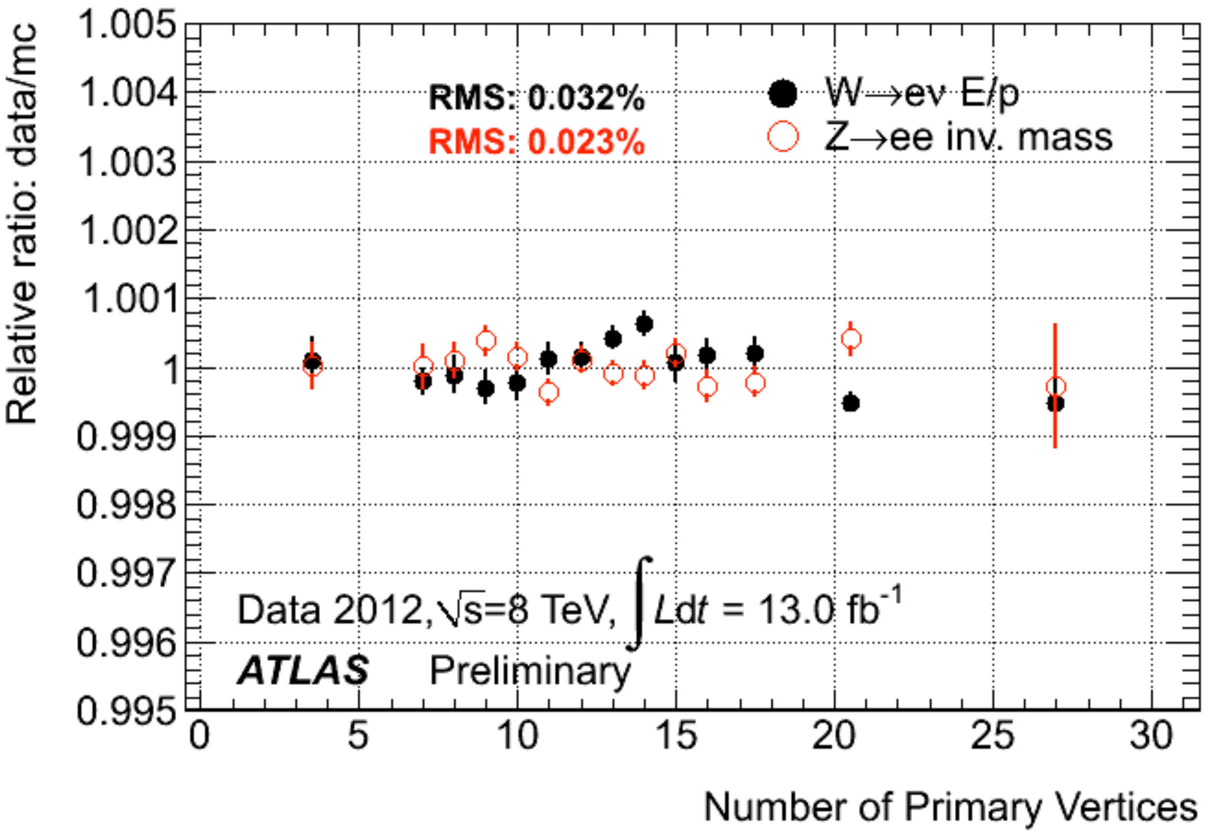


ATLAS Performance: Photons and EM response

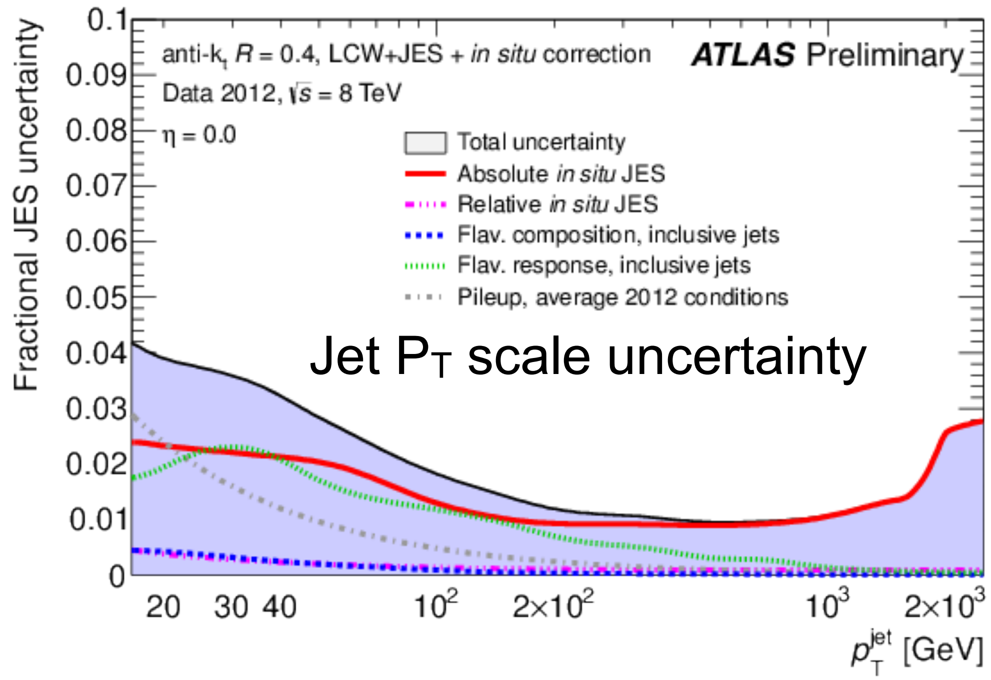


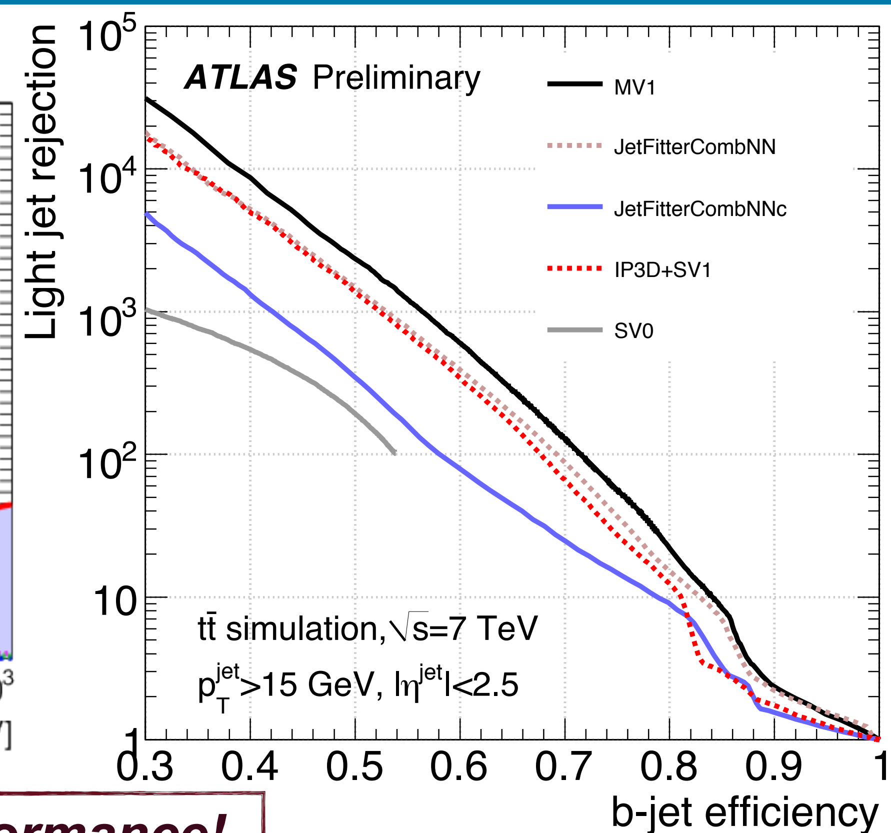
Stable photon reconstruction vs pile-up (within 1%)

- Excellent stability of the EM calorimeter response!
  - Studied with Z,J/ψ→ee and W→eν events
  - Energy scale at m_Z known to ~0.3%
  - Uniformity ~1% (2.5% for 1.37< |η|<1.8)

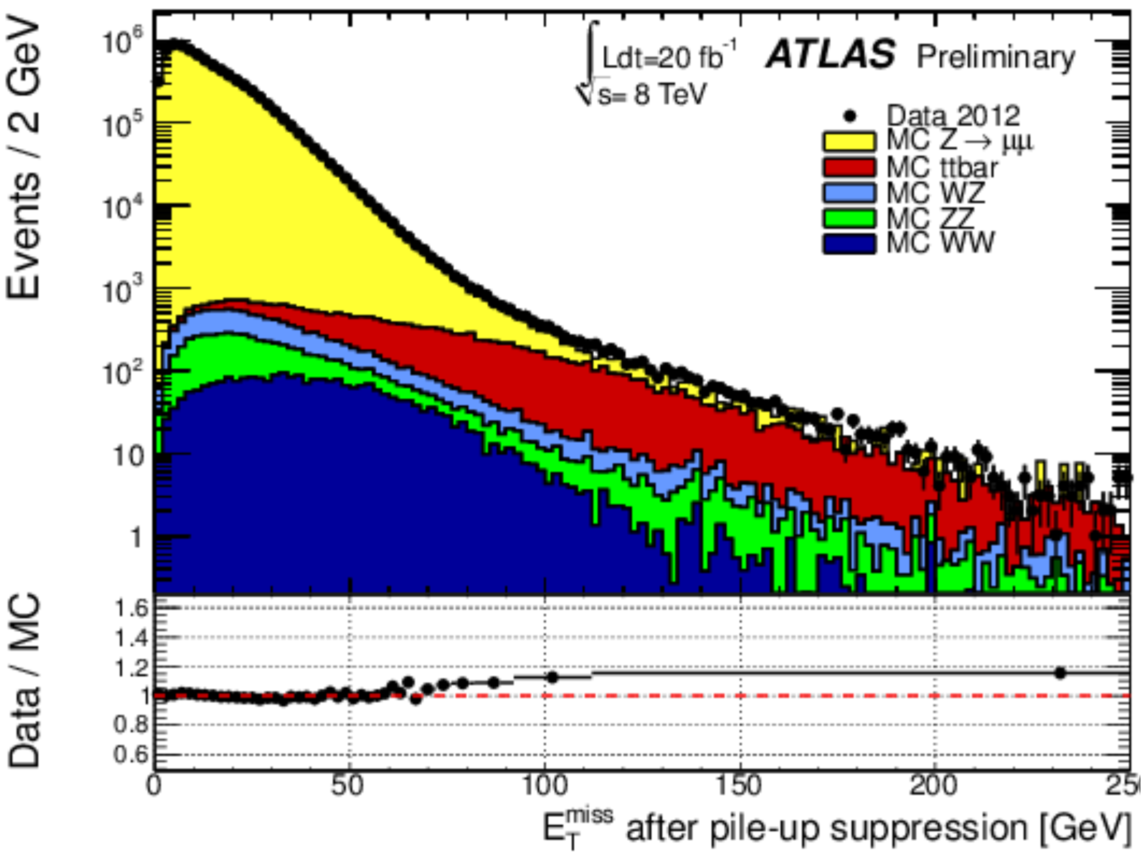


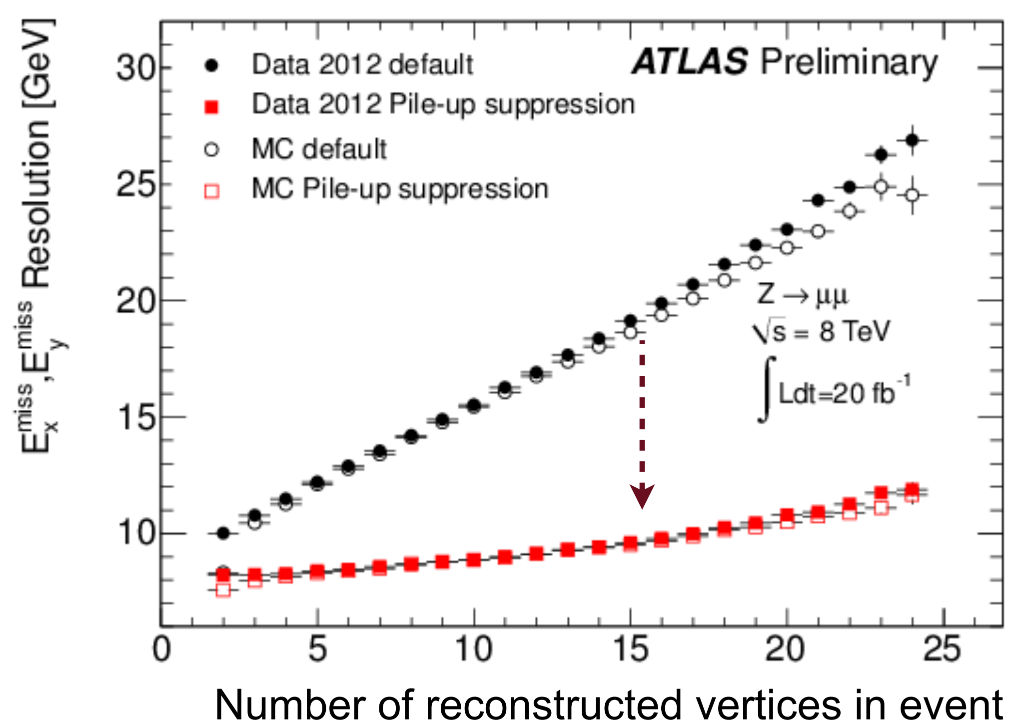
ATLAS Performance: Jets and Missing E_T



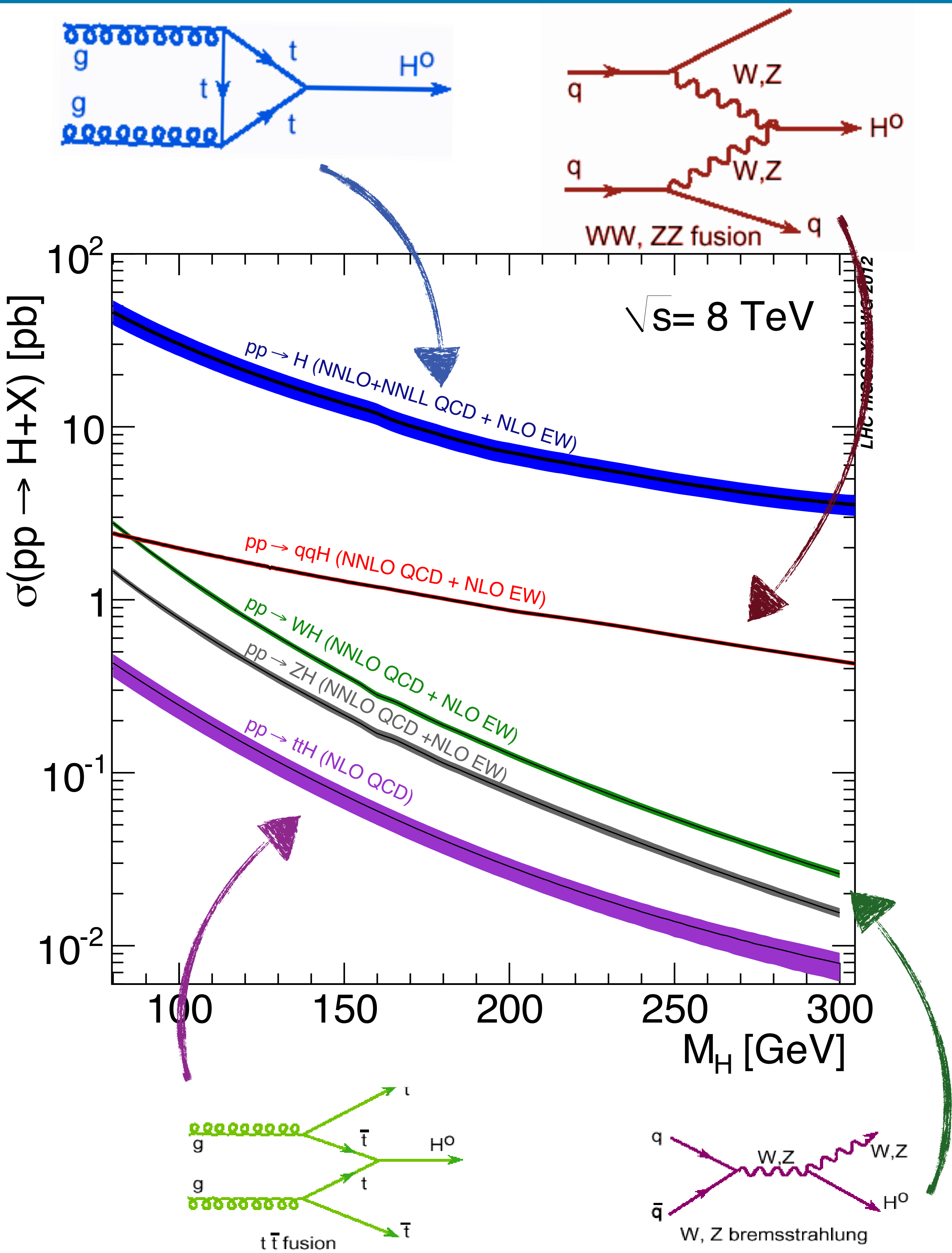


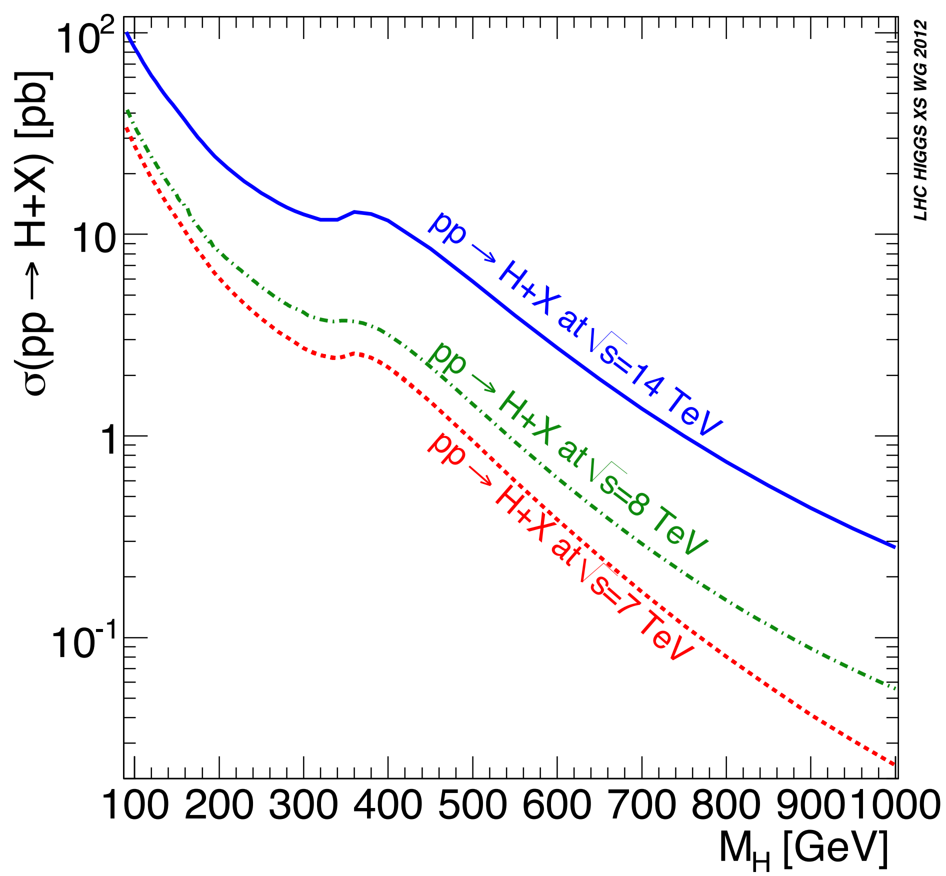
Excellent understanding of the detector performance!





Higgs boson production

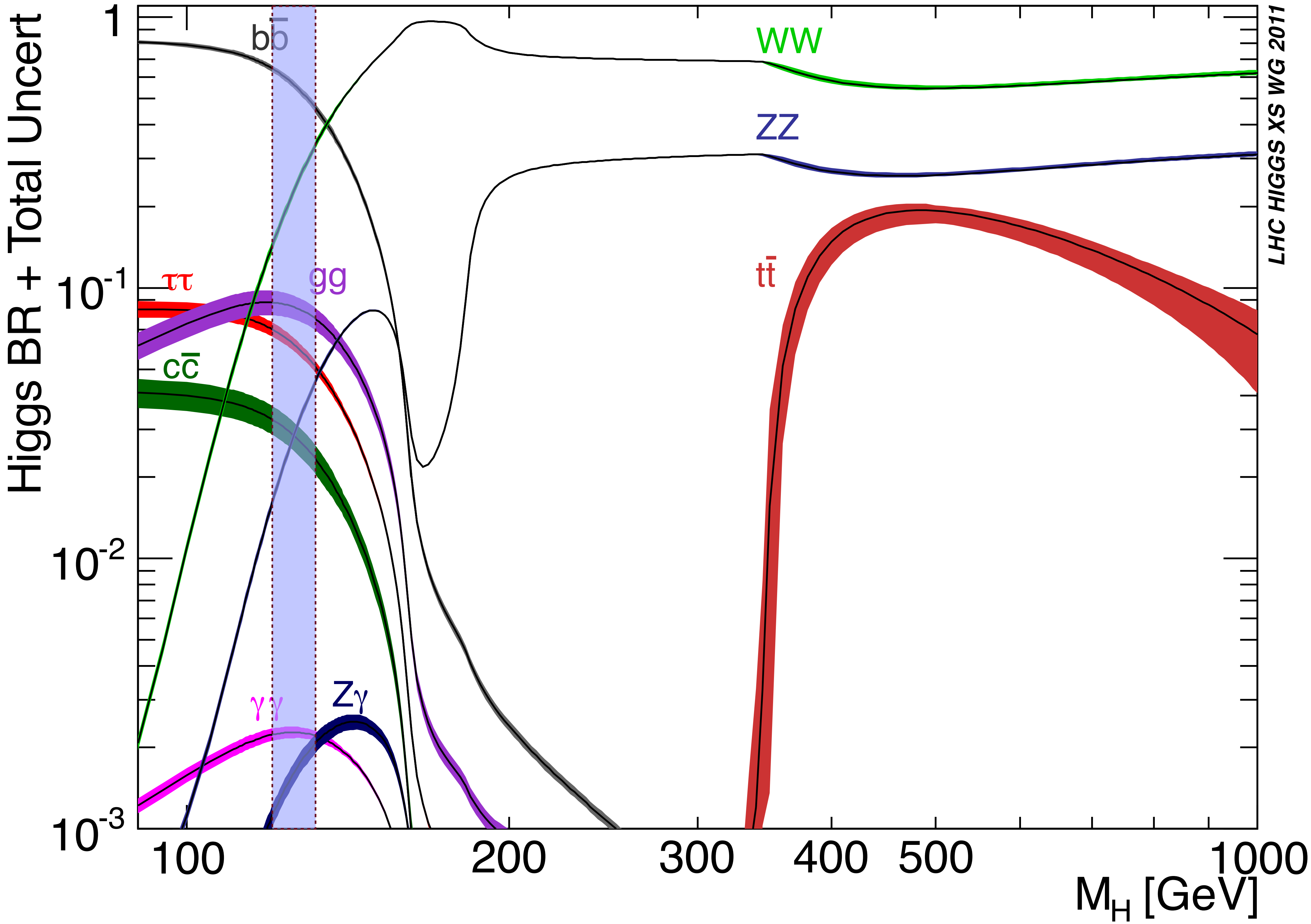




For m_H = 125 GeV cross-section increases
by ~1.3 when going from 7 to 8 TeV
by ~3.3 when going from 7 to 14 TeV

The LHC is a Higgs Factory

Higgs boson decays



m_H~125 GeV gives access to several decay channels

H→γγ

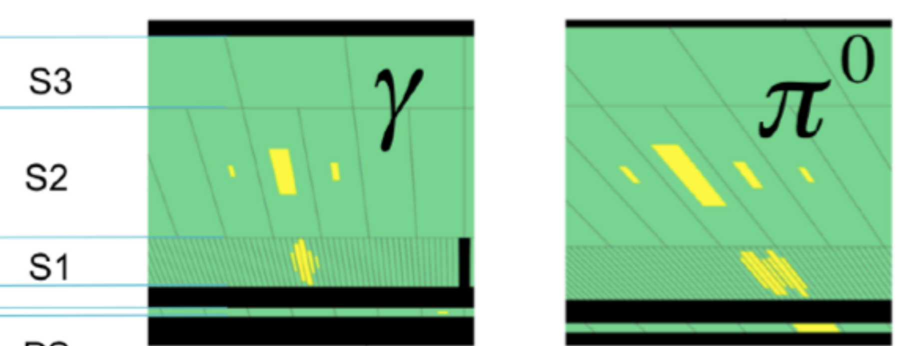
H→γγ

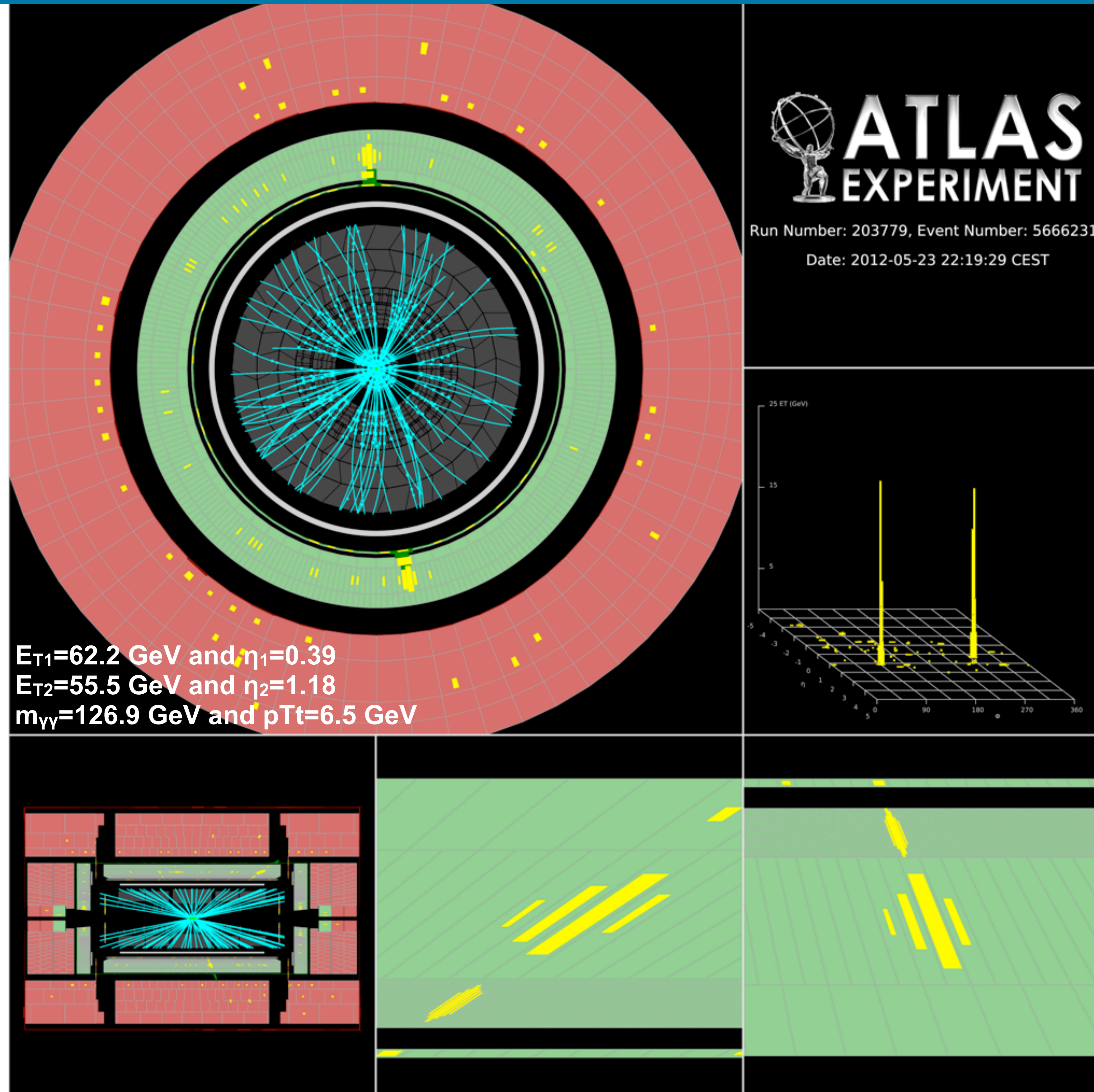
- Sensitive for low m_H (110 - 150 GeV)
- Search for narrow peak in $m_{\gamma\gamma}$
  - Background from data
- Main Backgrounds:
  - → di-photon ➛ $m_{\gamma\gamma}$ resolution
  - → jj and γj ➛ photon-ID

<u>Selection</u>

Two isolated photons with
E_T>40 GeV and 30 GeV respectively

π^0-γ Rejection



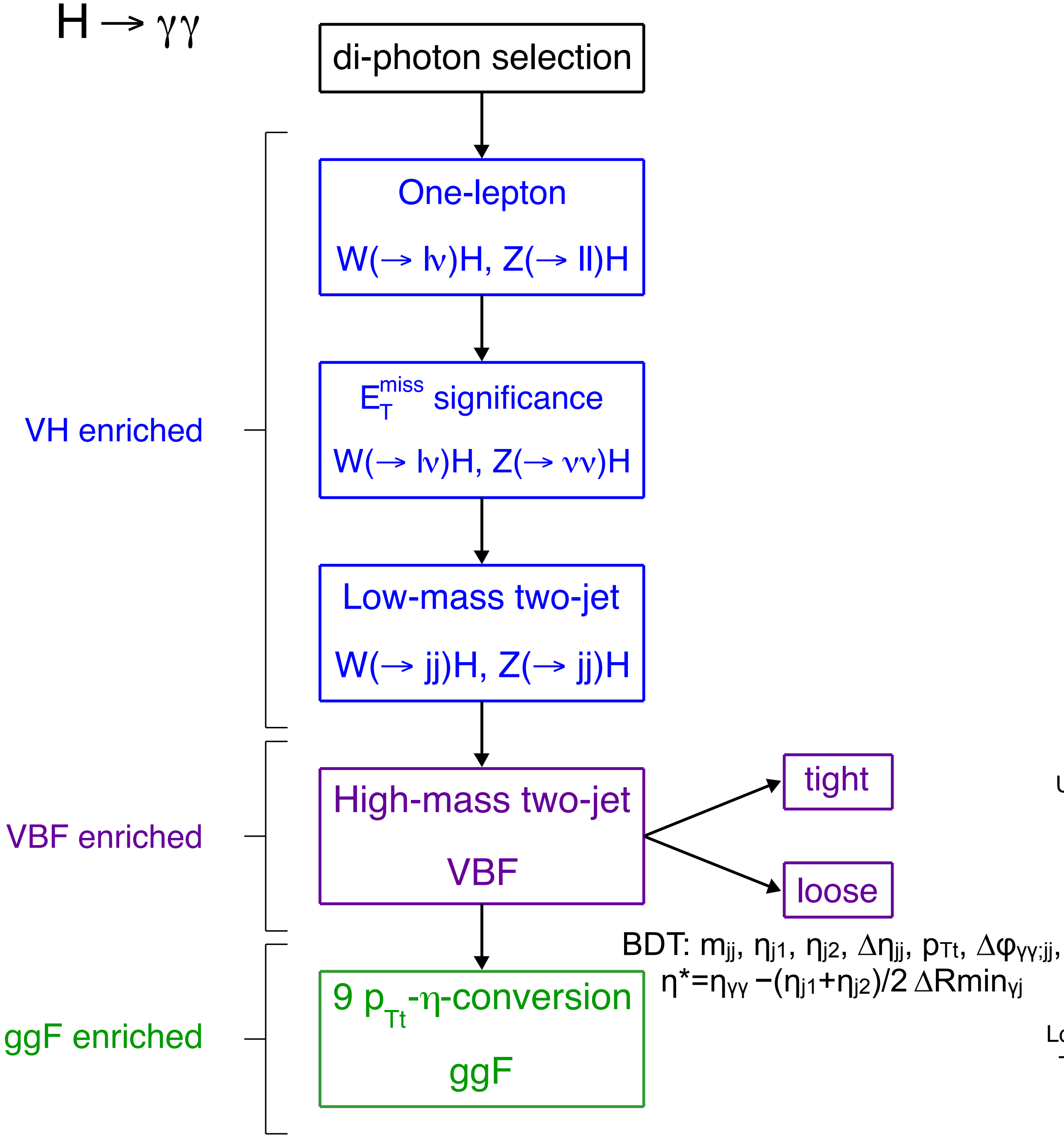


H→γγ: Event Categories

Improve the overall S/B of the analysis, and enhance particular signal contributions for properties studies

ATLAS Preliminary

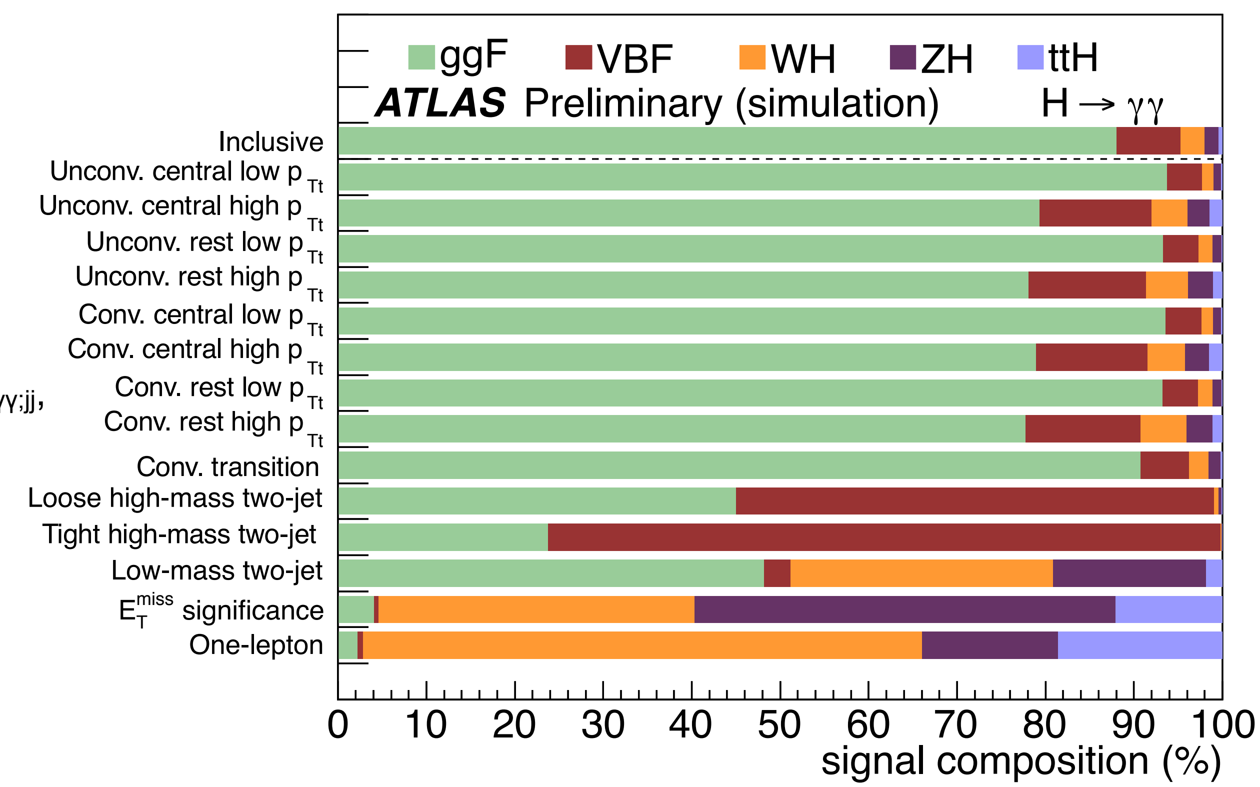
$H \rightarrow \gamma\gamma$



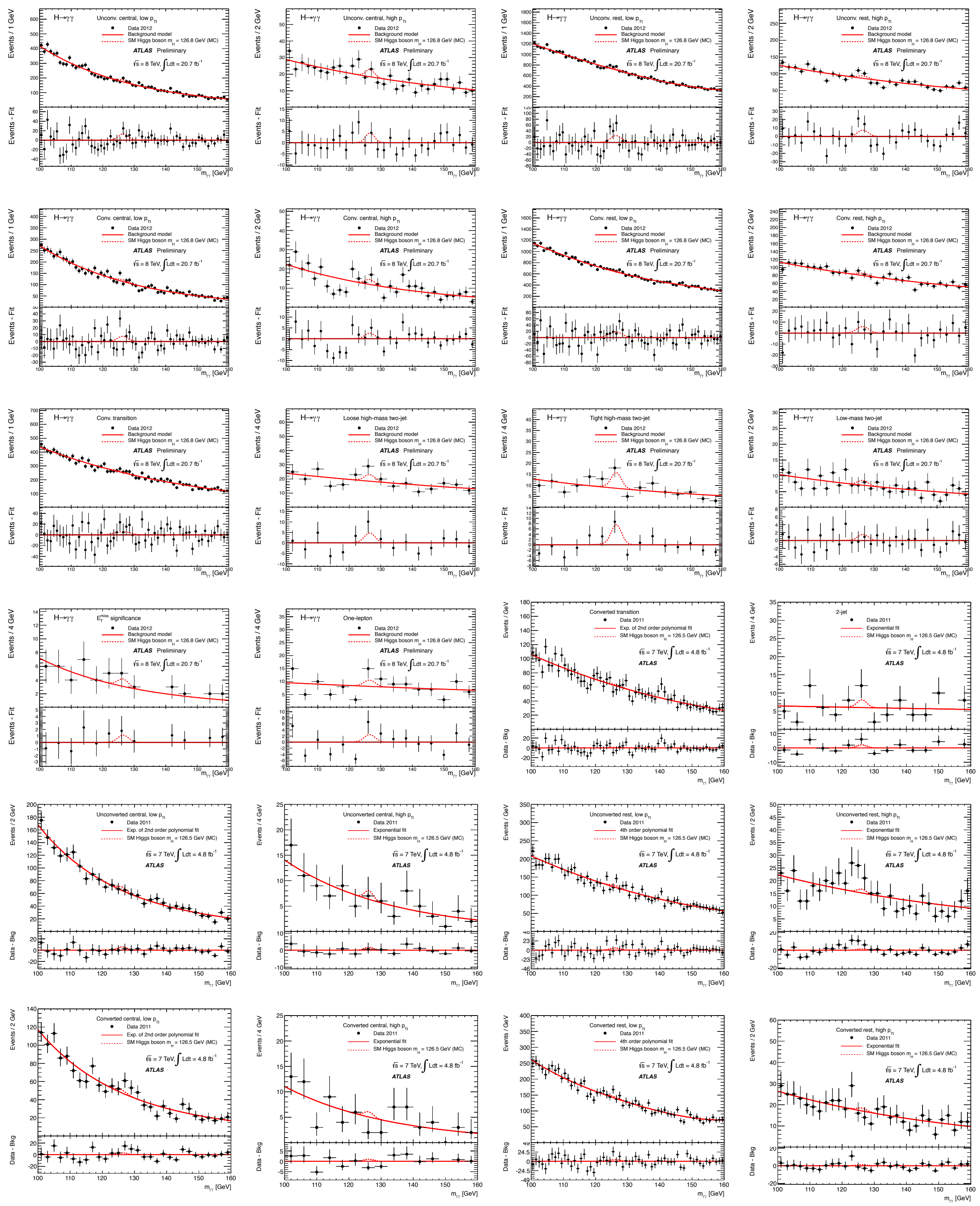
14 exclusive categories

8 TeV (90% signal window)

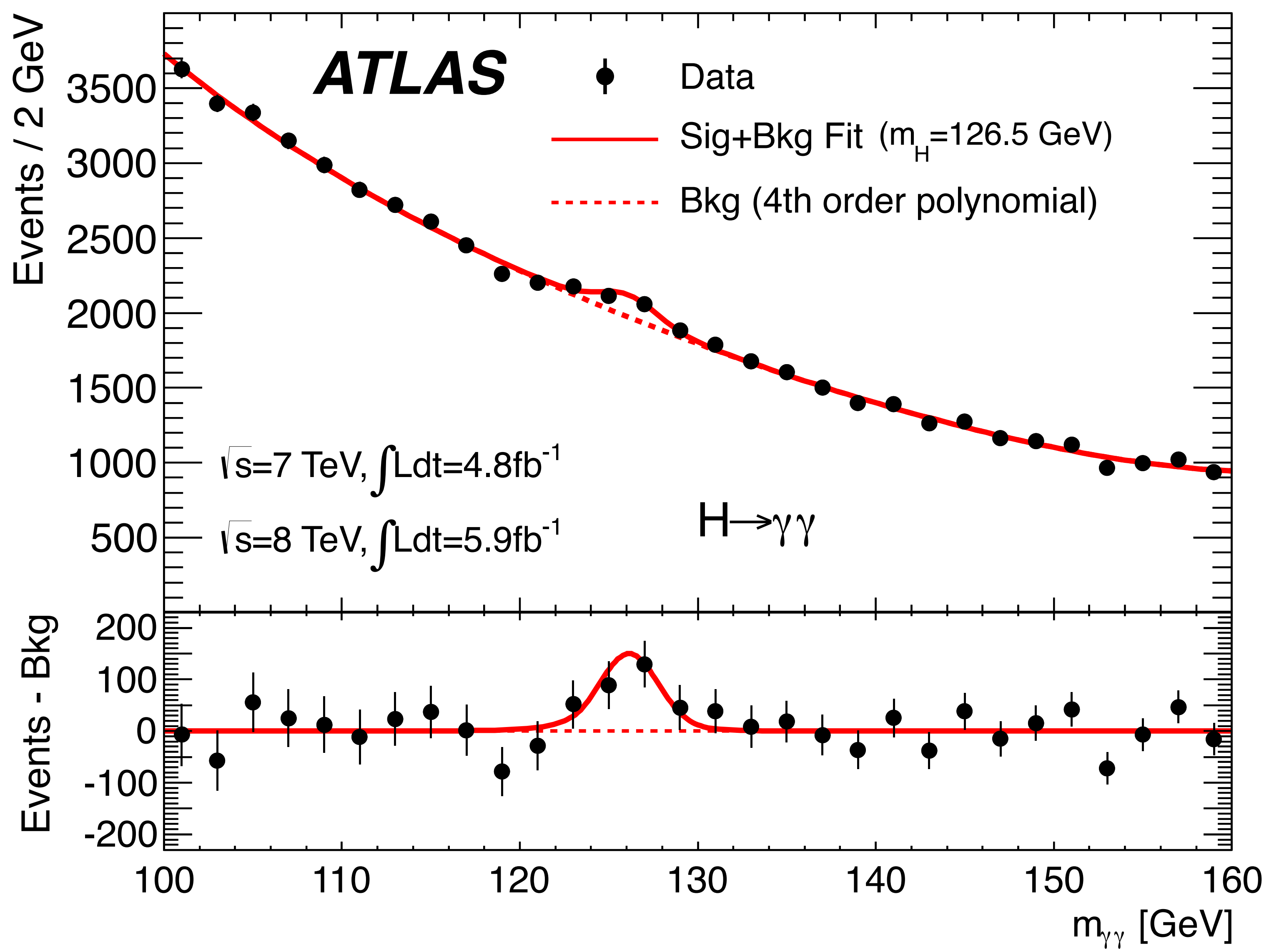
$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03



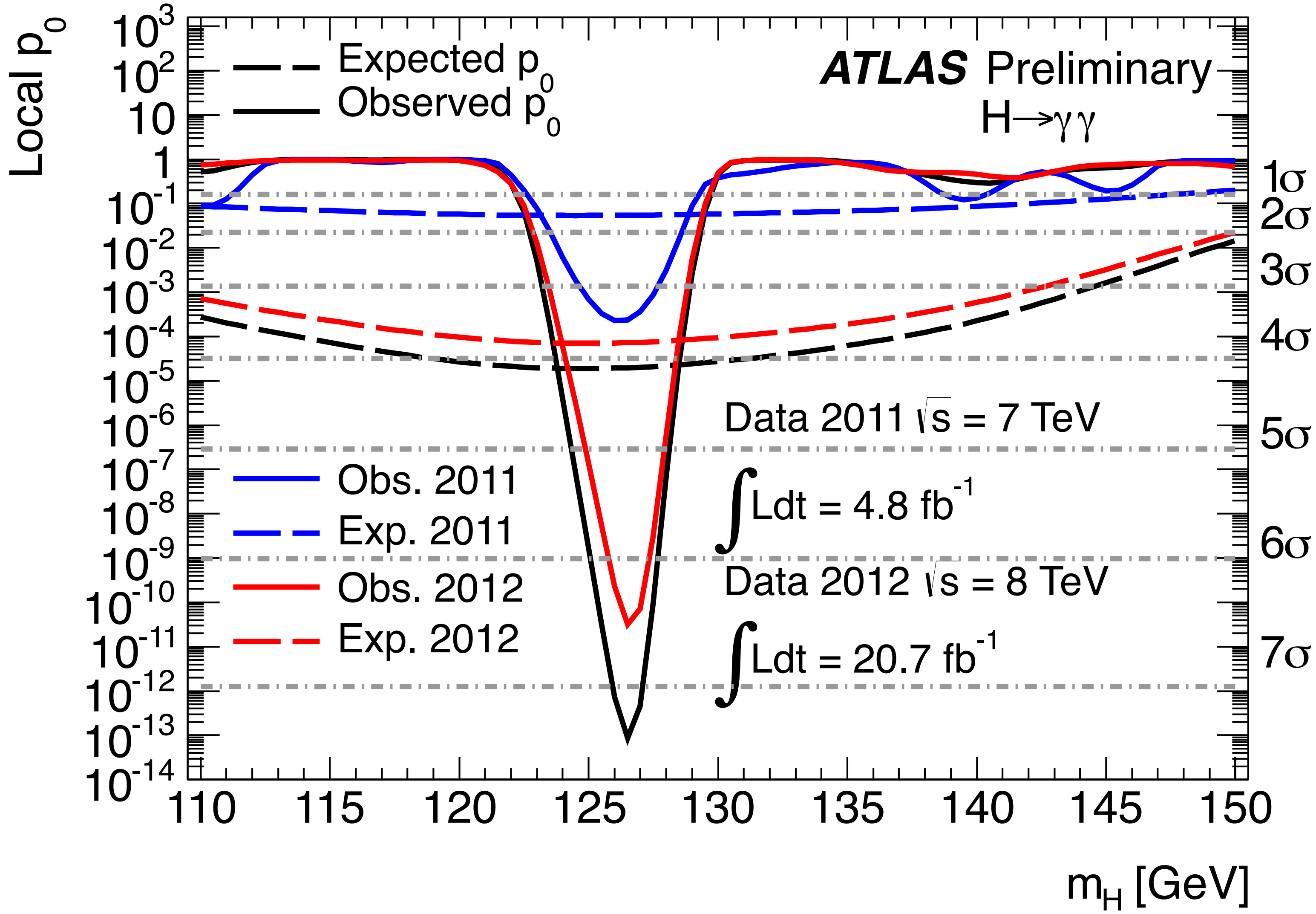
H→γγ: $m_{\gamma\gamma}$ spectra



all categories



H→γγ: Results



Statistics Treatment:

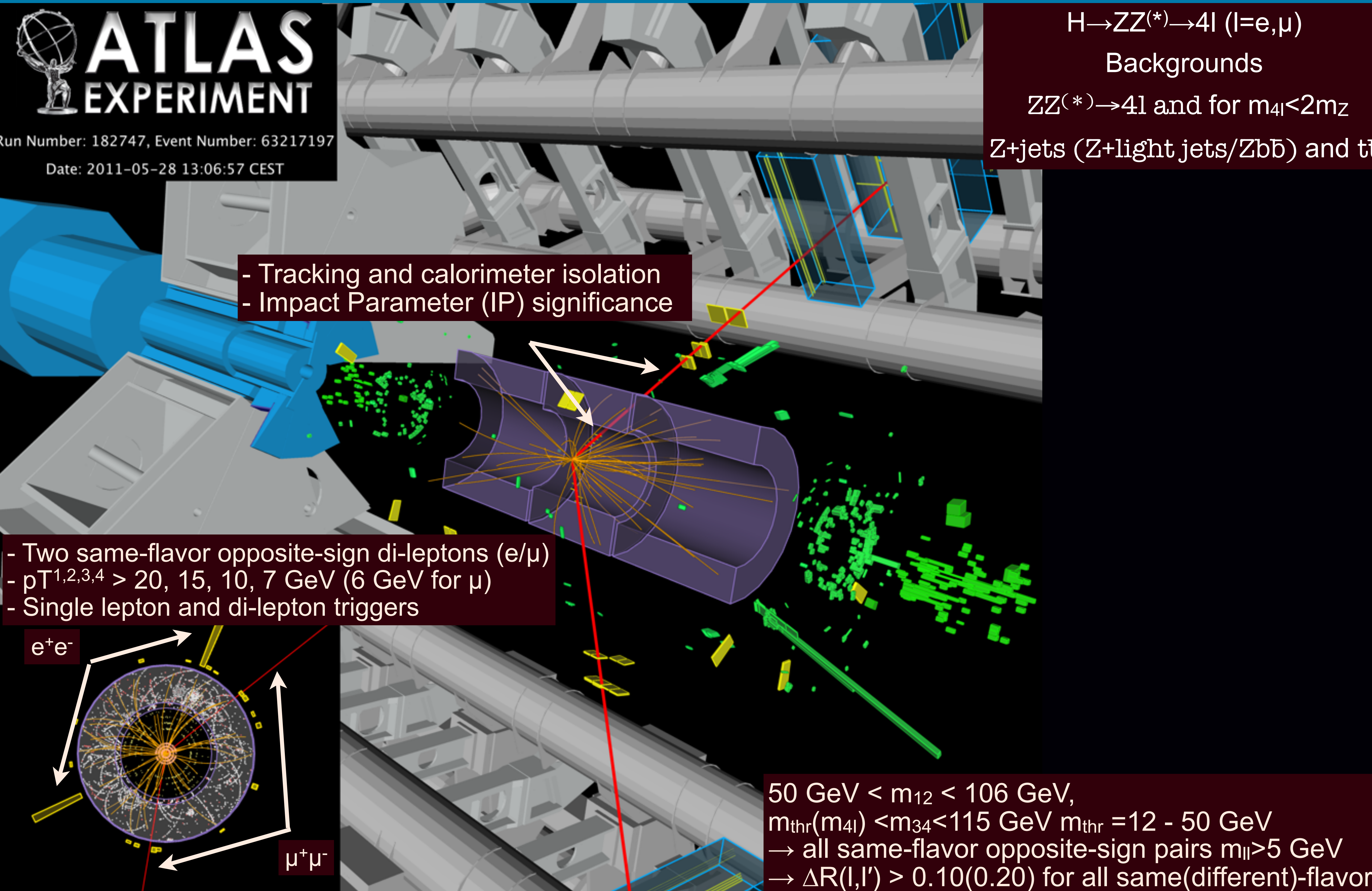
- profile likelihood ratio [Eur.Phys.J.C71:1554,2011]
  →systematic uncertainty as nuisance parameters
- CL_S exclusion limits [J.Phys.G28(2002)2693]

Most significant deviation from background only hypothesis at m_H =126.5 GeV:

- Local significance: **7.4σ** (with 4.1σ expected) @ m_H=126.5 GeV
  - Inclusive analysis: 6.1σ (with 2.9σ expected)
- Mass measurement: **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV**
  - Main systematics: γ energy scale from Z→ee, material modeling and presampler energy scale → 0.6 GeV
- Rate with respect to Standard Model: **1.65 ± 0.24 (stat)$^{+0.25}_{-0.18}$ (syst)**
  - 2.3σ deviation from the Standard Model

H→ZZ→4l

$H \to ZZ^{(*)} \to 4l$: Event Selection



$H \to ZZ^{(*)} \to 4l$ (l=e,μ)

Backgrounds

$ZZ^{(*)} \to 4l$ and for $m_{4l} < 2m_Z$

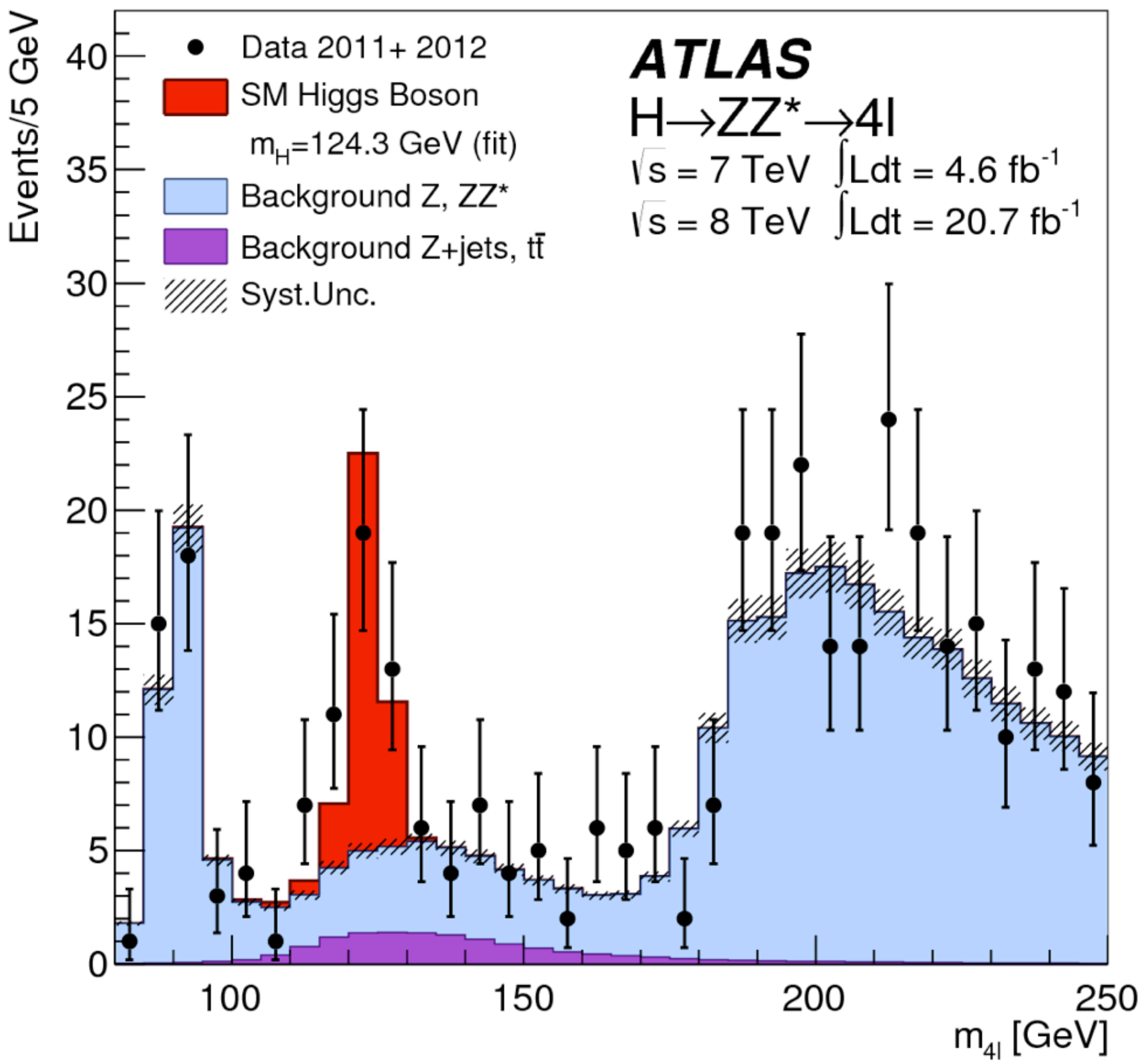
Z+jets (Z+light jets/$Zb\bar{b}$) and $t\bar{t}$

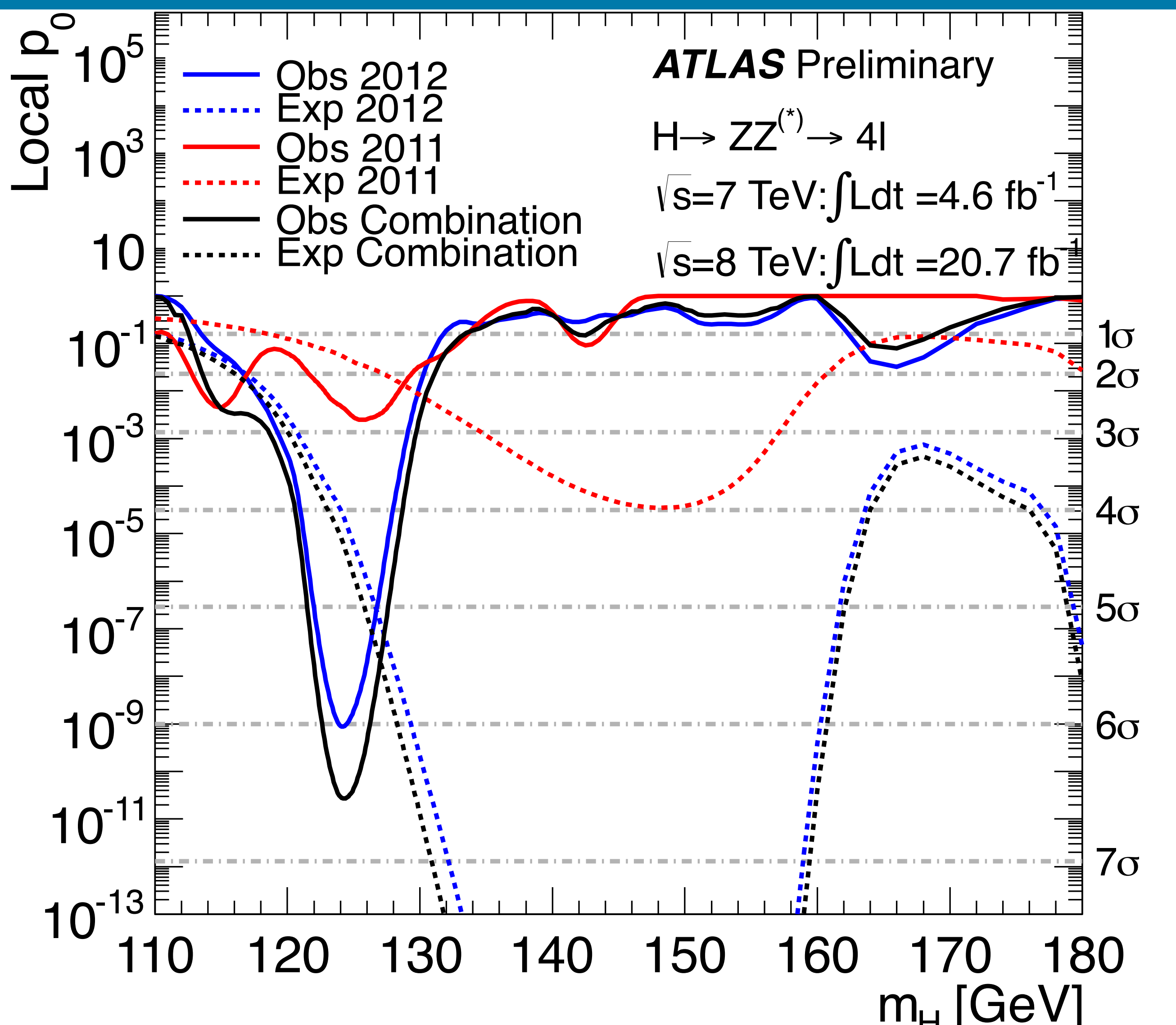
- Tracking and calorimeter isolation
- Impact Parameter (IP) significance

- Two same-flavor opposite-sign di-leptons (e/μ)
- $p_T^{1,2,3,4}$ > 20, 15, 10, 7 GeV (6 GeV for μ)
- Single lepton and di-lepton triggers

50 GeV < m_{12} < 106 GeV,
$m_{thr}(m_{4l})$ < m_{34} < 115 GeV m_{thr} = 12 - 50 GeV
→ all same-flavor opposite-sign pairs m_{ll} > 5 GeV
→ $\Delta R(l,l')$ > 0.10(0.20) for all same(different)-flavor

H→ZZ(*)→4l: Results





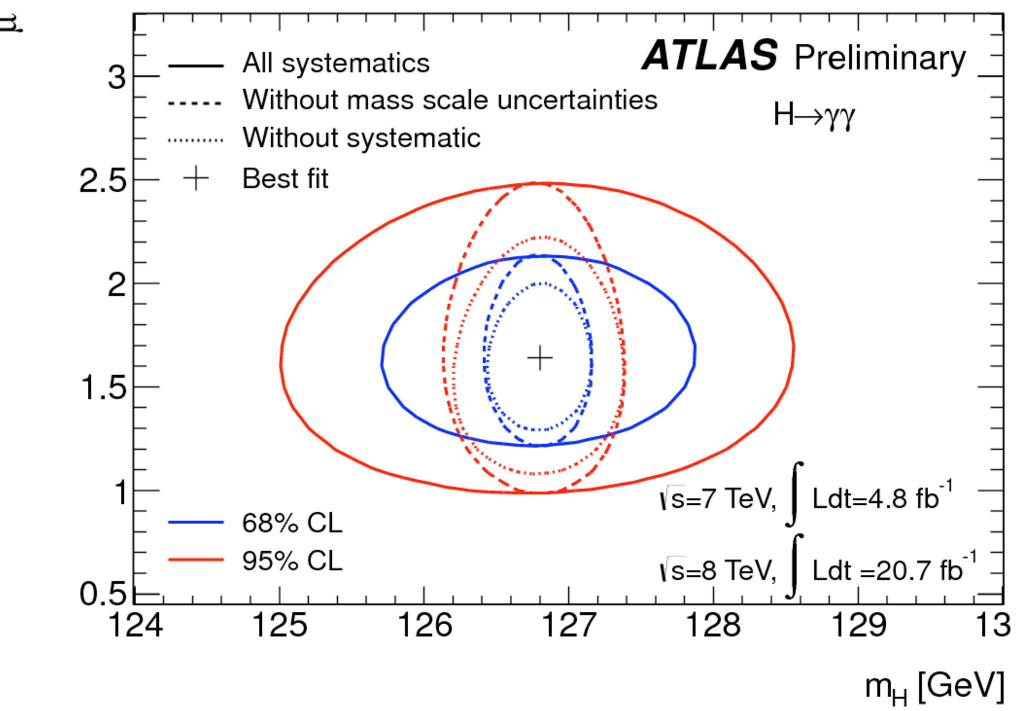
120-130 GeV

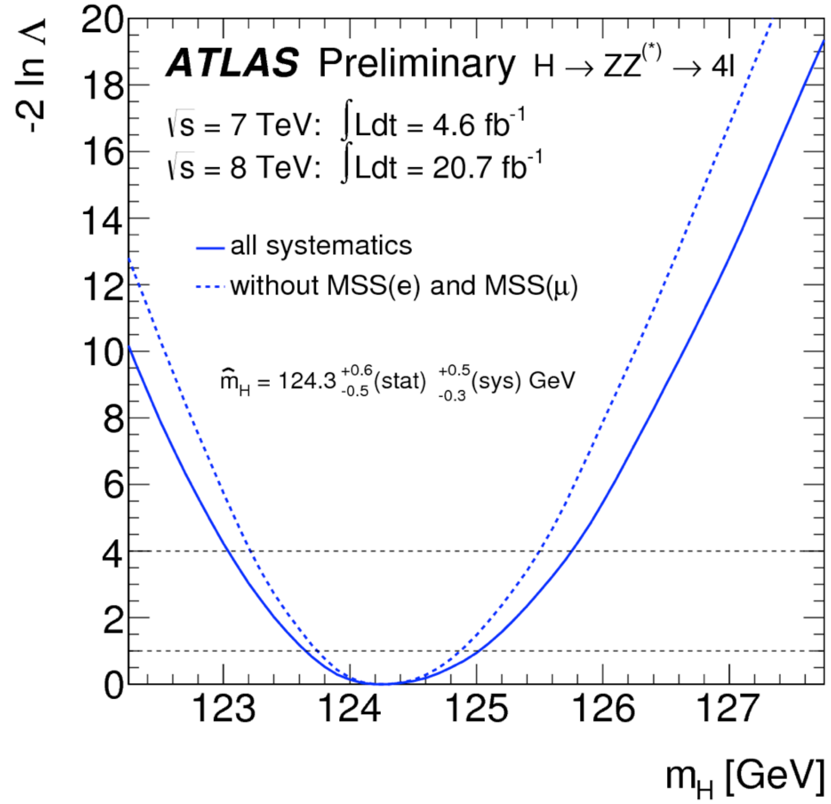
	Signal	ZZ(*)	Other Backgrounds	Observed	S/B
4μ	6.3±0.8	2.8±0.1	0.55±0.15	13	~1.9
2μ2e	3.0±0.4	1.4±0.1	1.56±0.33	5	~1.0
2e2μ	4.0±0.5	2.1±0.1	0.55±0.17	7	~1.5
4e	2.6±0.4	1.2±0.1	1.11±0.28	6	~1.1

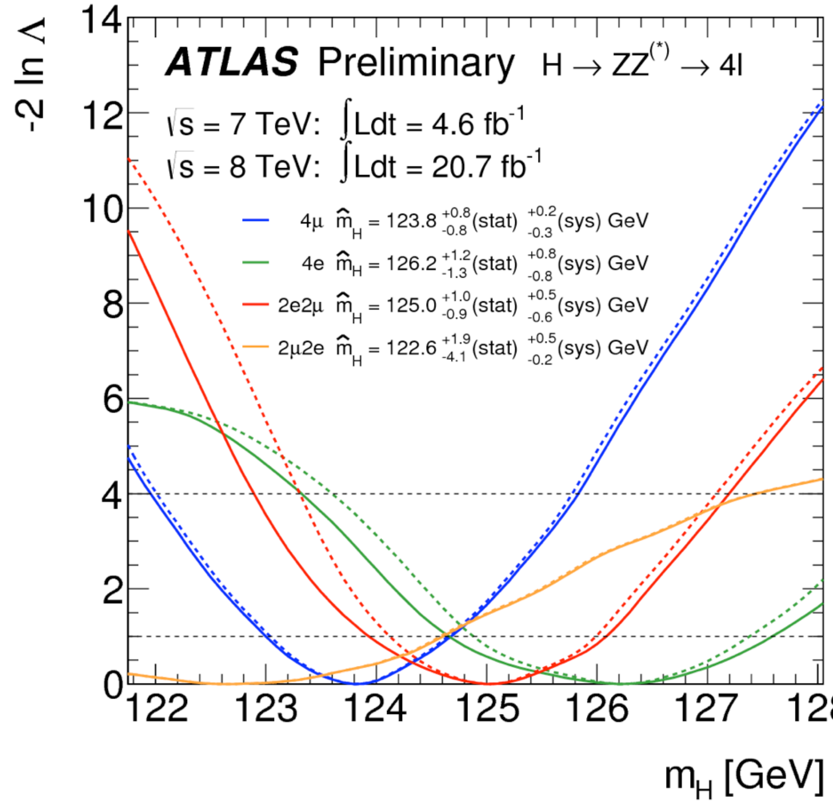
- Local significance:**6.6σ** (4.4σ)@m_H=124.3GeV
- Mass: **$124.3^{+0.6}_{-0.5}$(stat)$^{+0.5}_{-0.3}$(syst) GeV**
  - Main systematic uncertanty: e/μ E/P scale
- Rate with respect to SM: $1.7^{+0.5}_{-0.4}$
  - **1.5 ± 0.4 @ m_H=125.5 GeV**

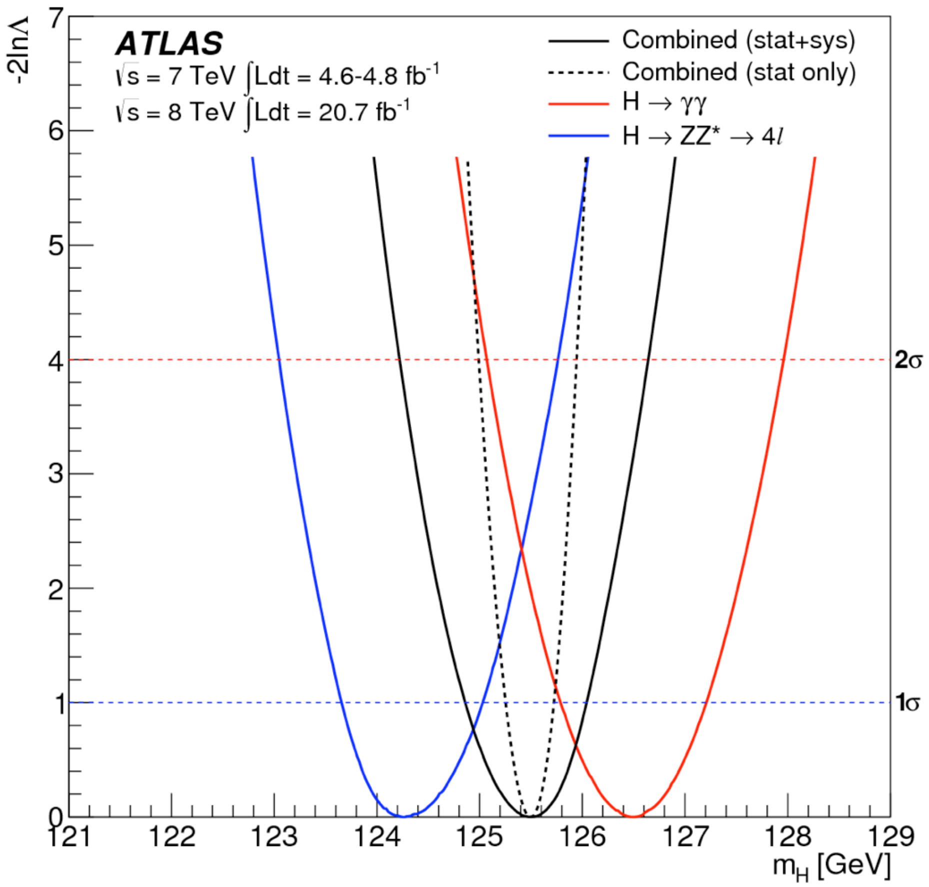
Further categorizing the observed events:
- VBF-like (two jets in VBF topology)
- VH-like (events with additional leptons)
- ggF-like(all remaining events)

The Higgs boson mass









Higgs boson mass measurement using:

- H→γγ : **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV**
- H→ZZ→4l : **$124.3^{+0.6}_{-0.5}$(stat)$^{+0.5}_{-0.3}$(syst) GeV**

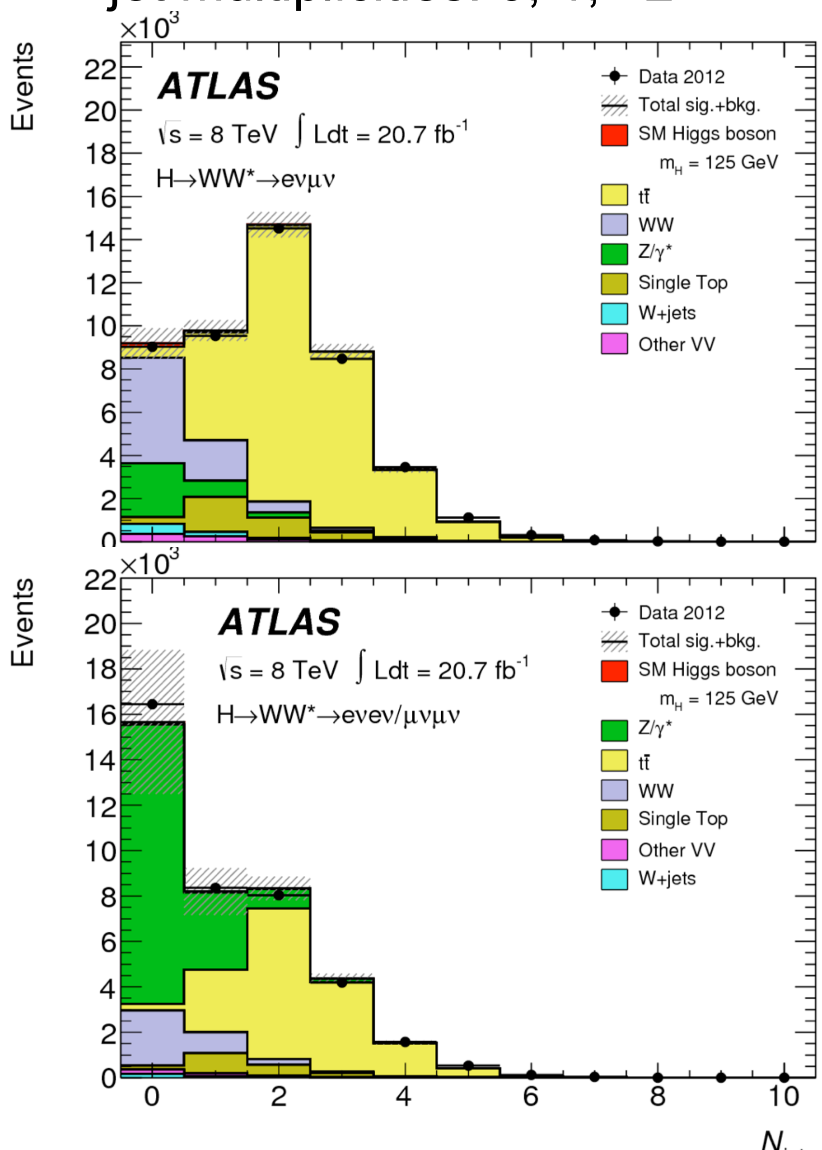
Combined m_H:**125.5 ± 0.2 (stat)$^{+0.5}_{-0.6}$ (syst) GeV**

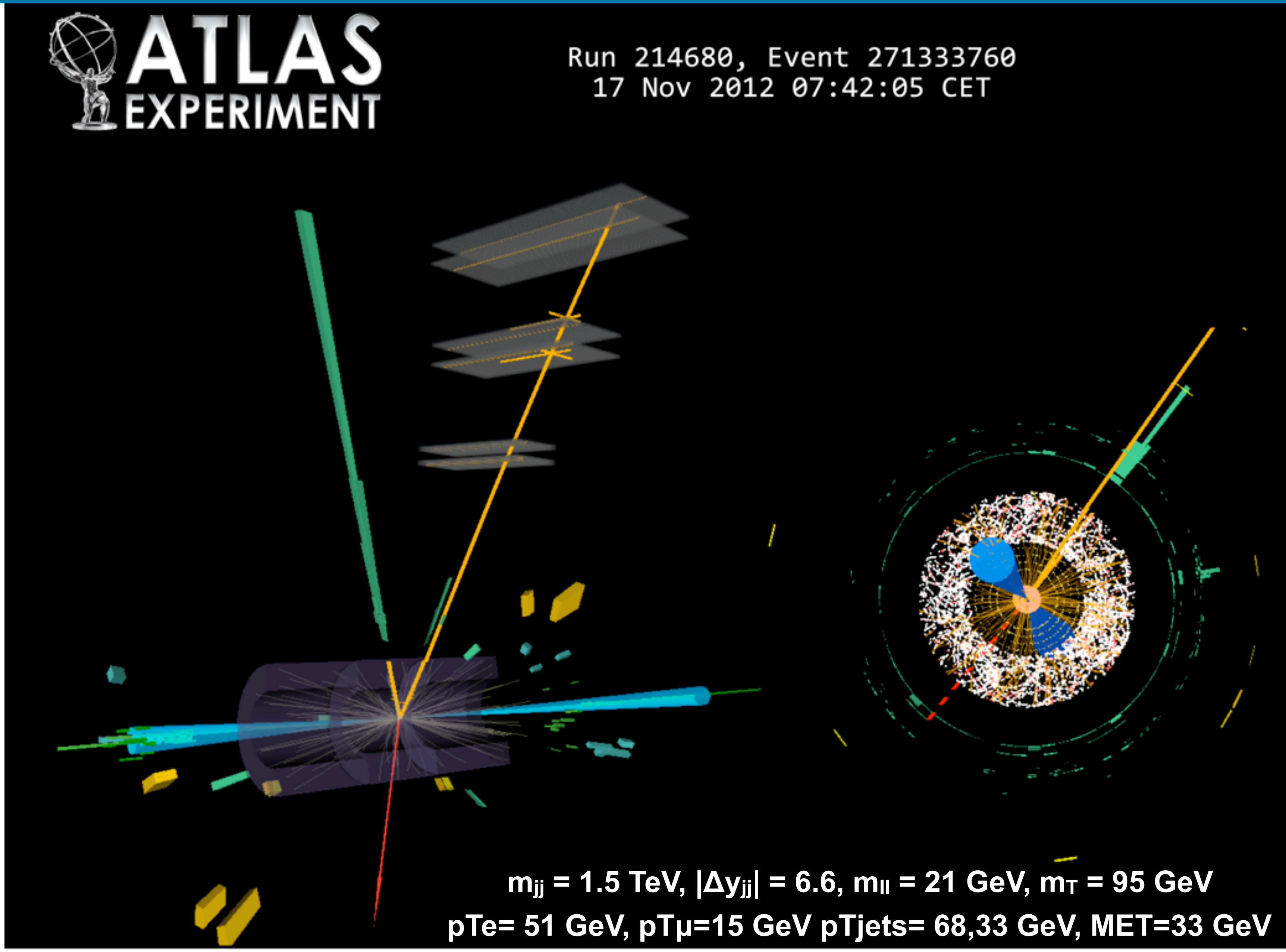
- single particle to give as much/more discrepant result 1.5% (2.4σ)
- by moving ±1σ the main systematics (calibration, upstream material, pre-samples energy scale) consistency increases up to 8%
- H→4l consistency leads to -0.8σ adjustment of e/γ energy scale
  - shift -350 MeV for H→γγ mass
- CMS : m_H = **125.7 ± 0.3 (stat) ± 0.3 (syst) GeV**

H→WW→lνlν

$H \to WW^{(*)} \to l\nu l\nu$

- Sensitive in wide mass range but:
  - no mass peak
  - uses all ATLAS components!
- Signature: ll + MET
- Observable: m_T
- Backgrounds: WW, top, W/Z+jets
- Separate final states:
  - dilepton mass: m_{ll}
  - lepton flavors: μe, eμ, μμ, ee
  - jet multiplicities: 0, 1, ≥2

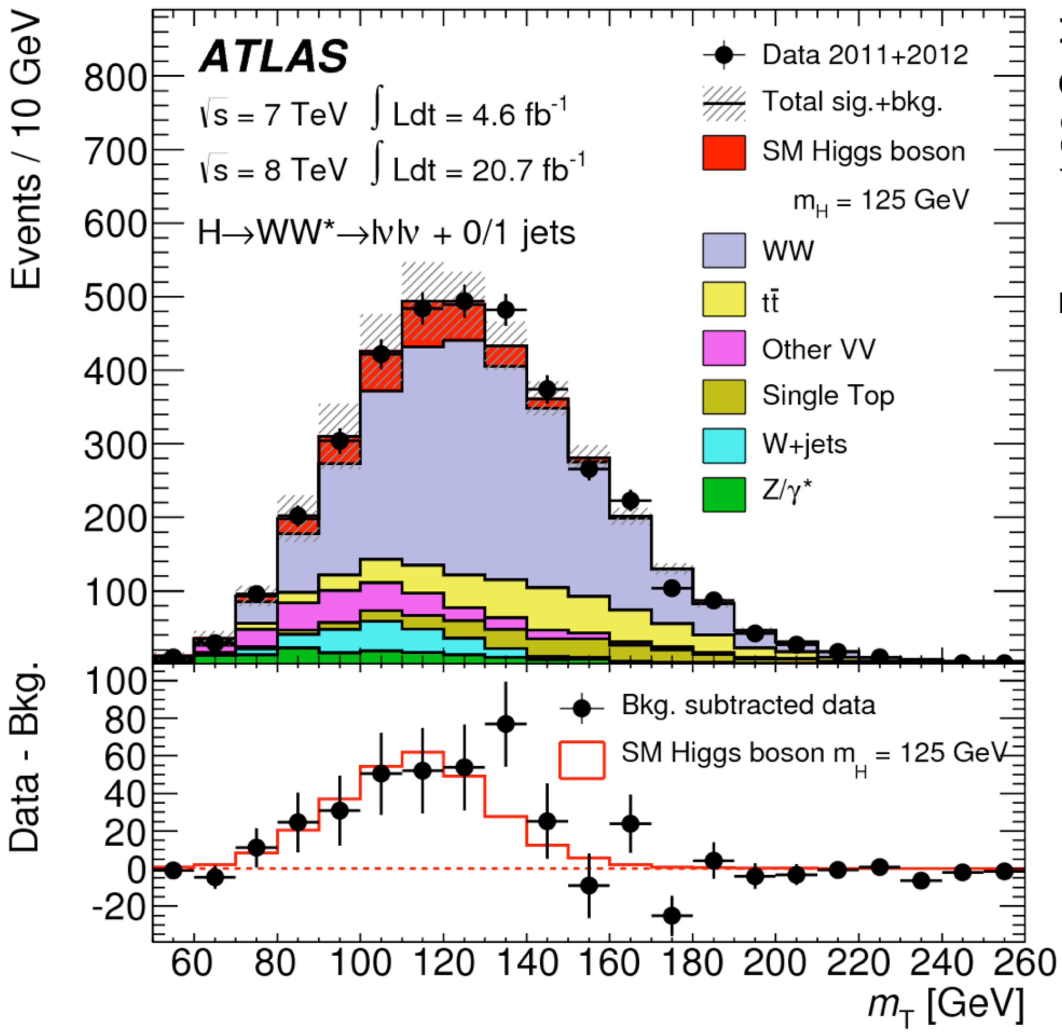


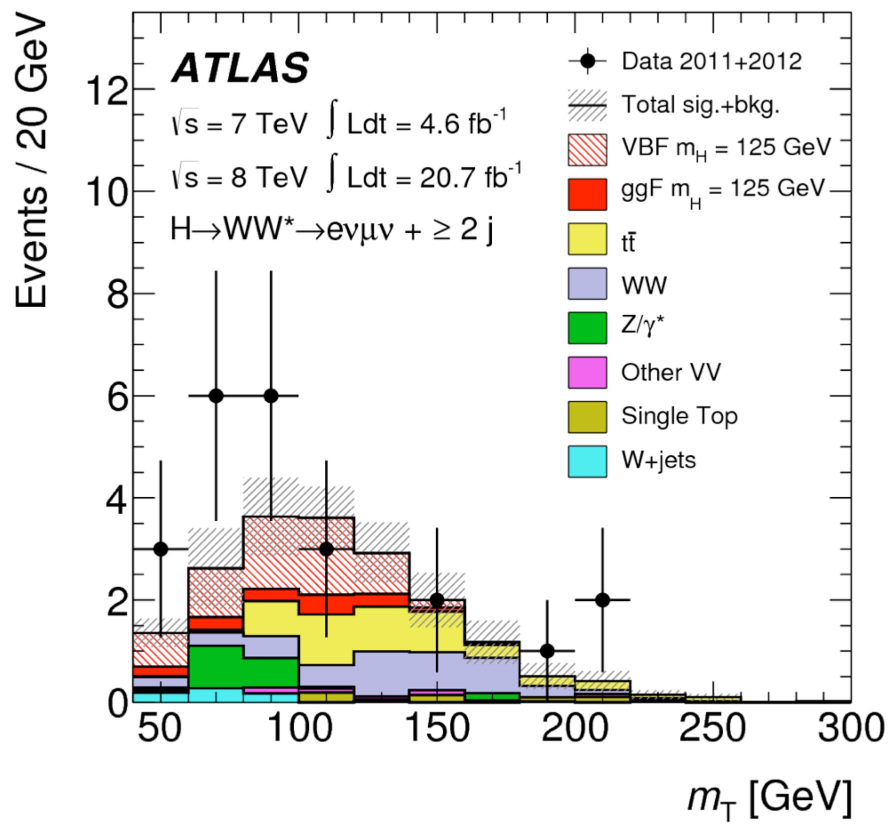


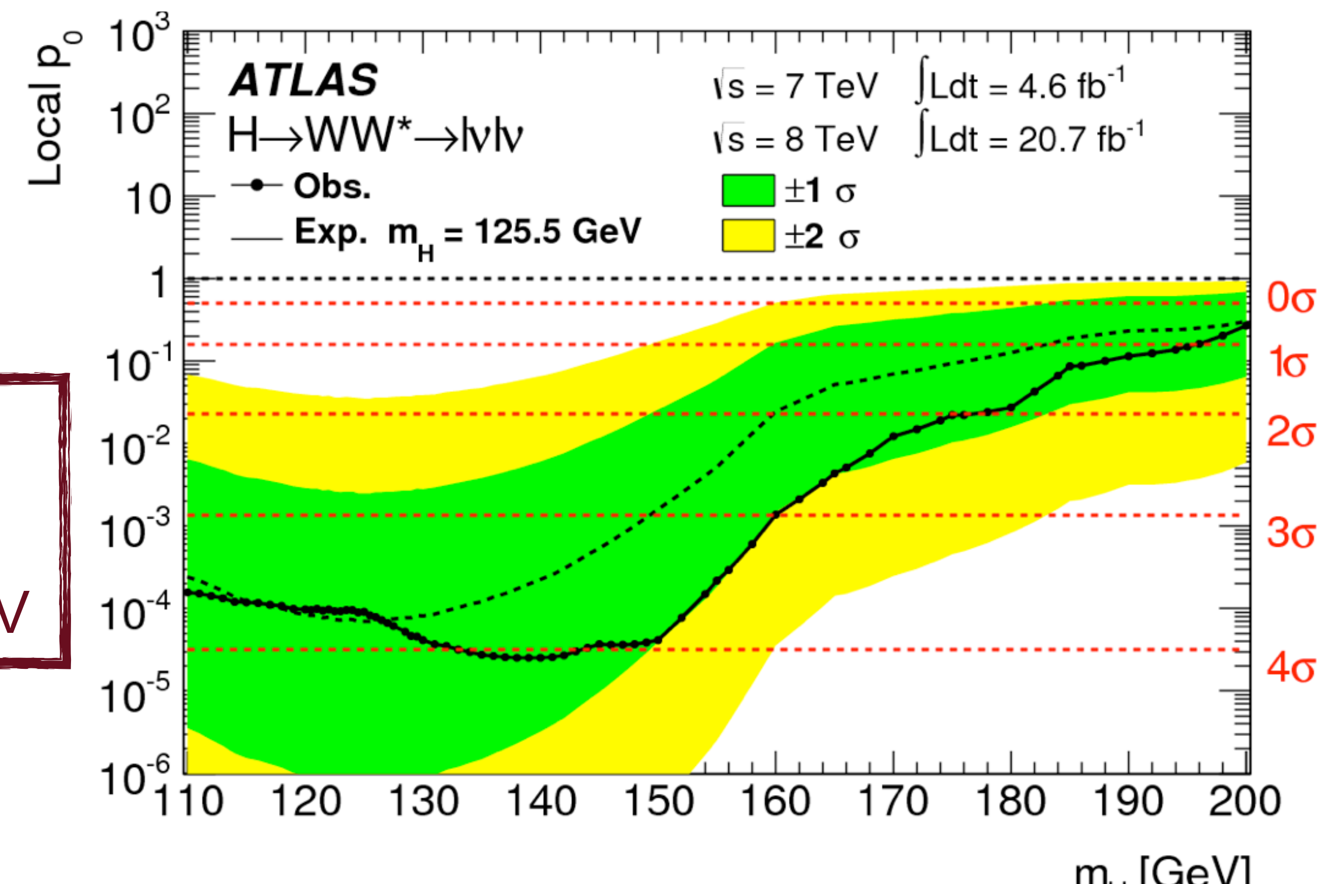
pT > 25 GeV, pT>15 GeV, m_{ll} upper threshold, ETMiss/ETMissRel and $\Delta\varphi_{ll}$ requirements, μe/eμ m_{ll}>10 GeV, μμ/ee m_{ll}>12 GeV and $|m_{ll}-m_Z|$>15 GeV b-tag jet veto

$$m_T = \left(\left(E_T^{\ell\ell} + E_T^{\rm miss}\right)^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\rm miss}|^2\right)^{1/2} \text{ with } E_T^{\ell\ell} = \left(|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2\right)^{1/2}$$

H→WW(*)→lνlν: Results 2011+2012







Local significance at m_H=140GeV is 4.1σ

Local significance at m_H=125GeV is 3.8σ

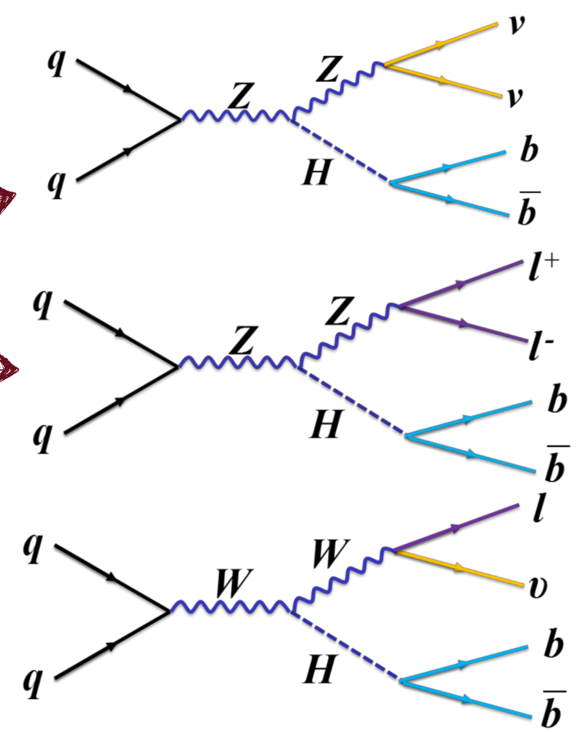
Rate with respect to SM: 1.01 ± 0.31 @ m_H=125 GeV

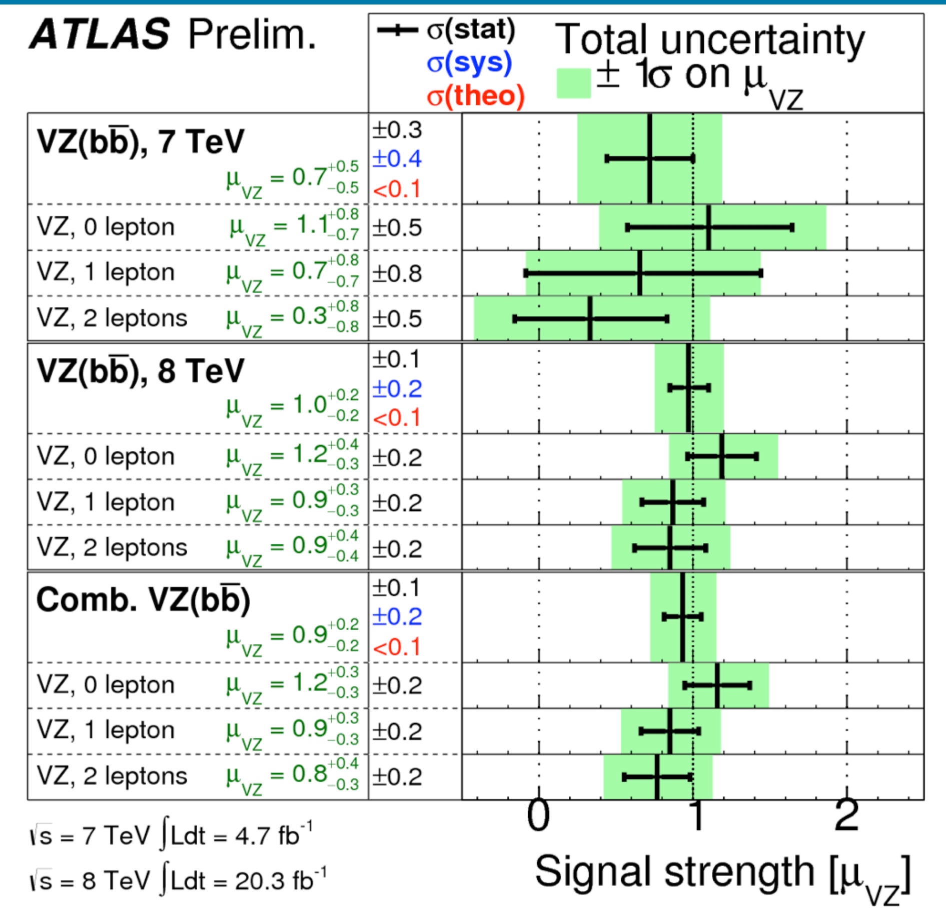
$H \rightarrow bb$

H→bb

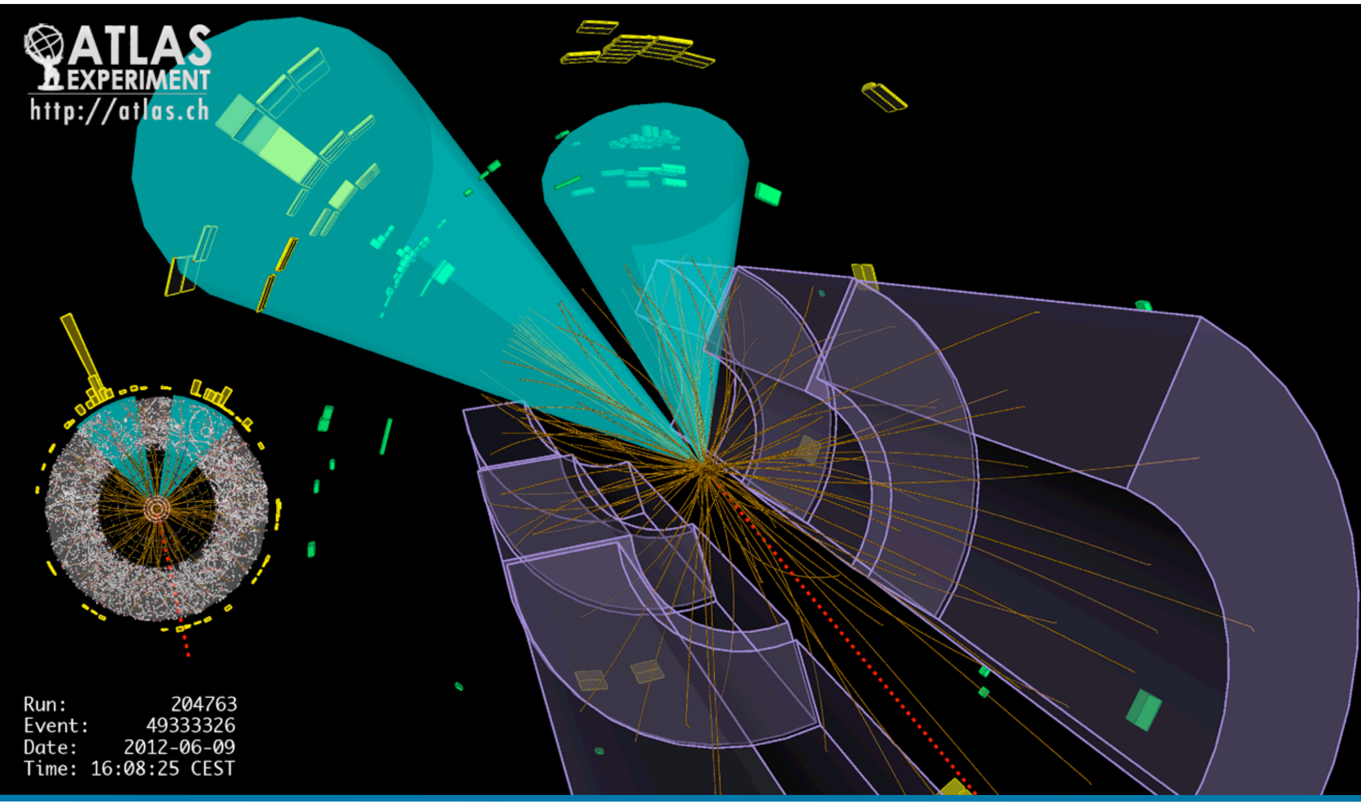
ATLAS-CONF-2013-079

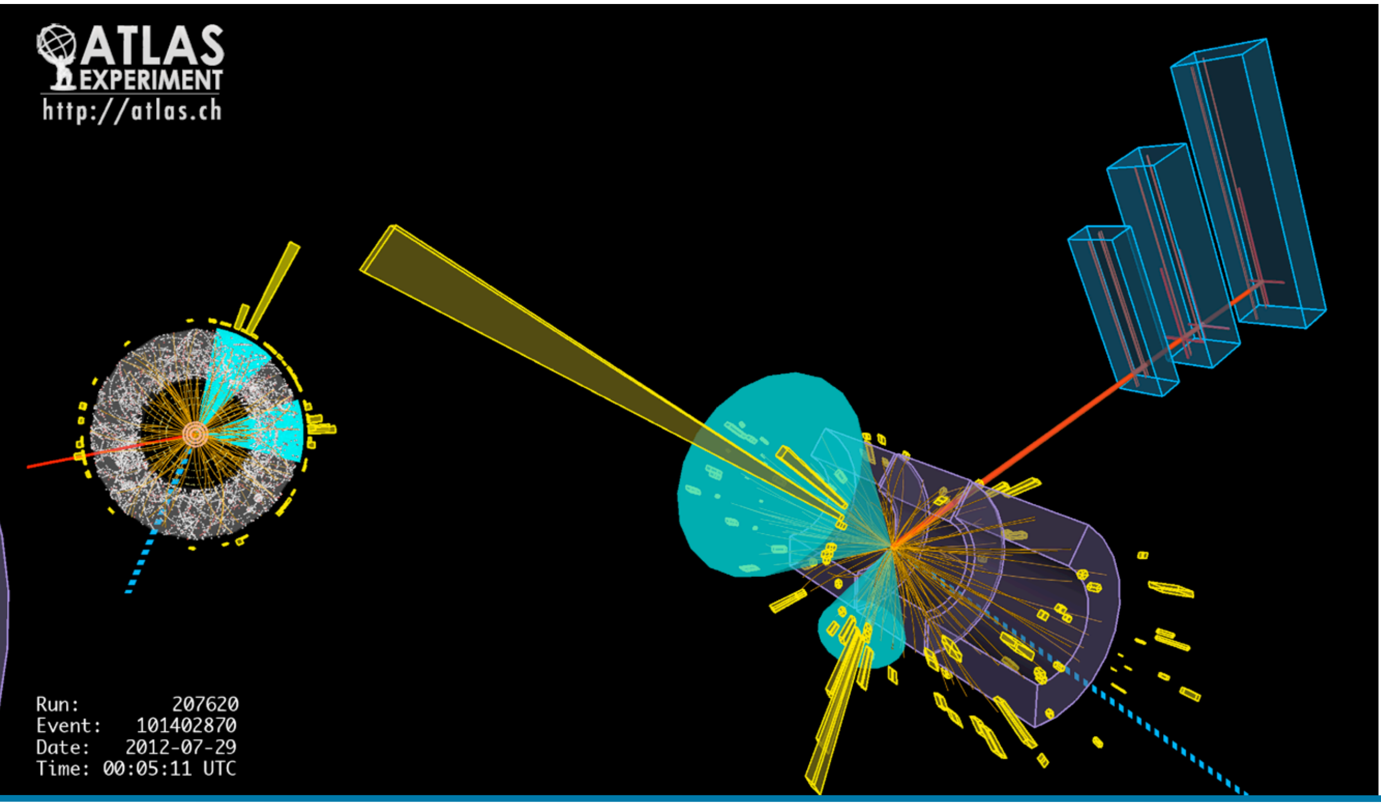
- Largest BR but very high background
- Exploit associated production with W or Z
  - Final states with leptons, MET and b-jets
- Backgrounds: W/Z+jets and top
- Final discriminant m_{bb}
- Separate final states:
  - number of leptons: 0, 1, 2
  - $P_T(V)$ or MET
  - number of jets
  - 26 signal bins in total
    - + 27 control regions



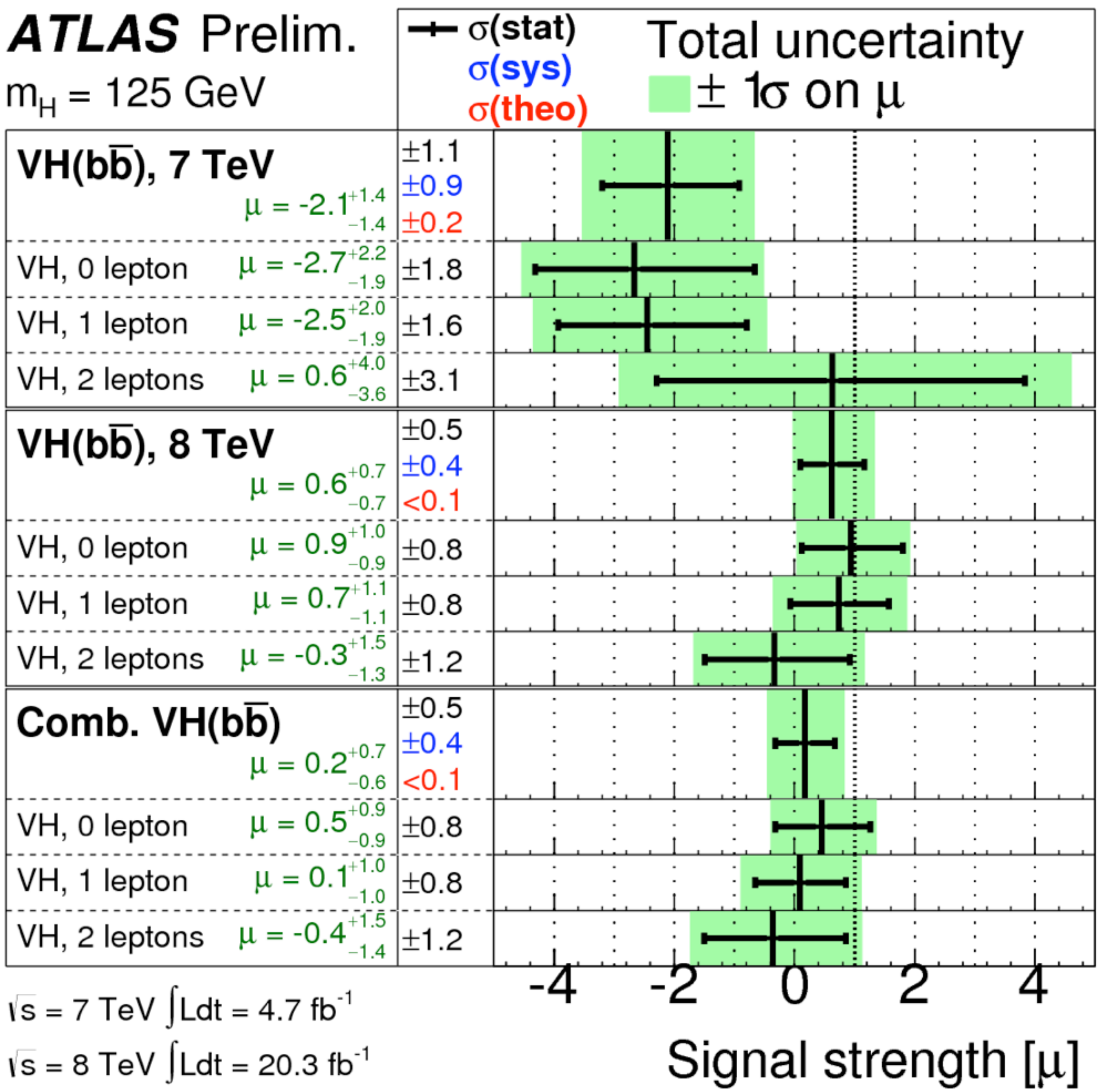


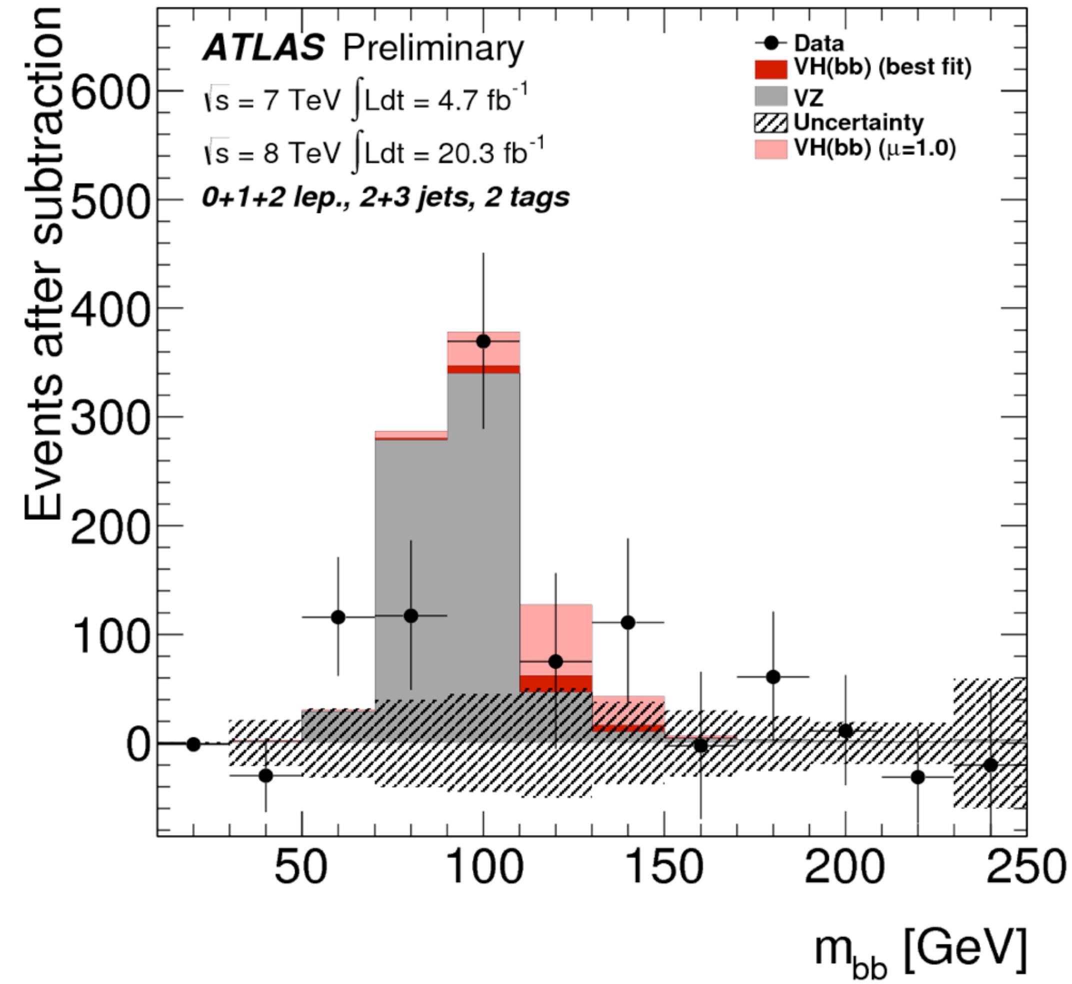
observation at 4.8σ(5.1σ) of VZ(→bb) production

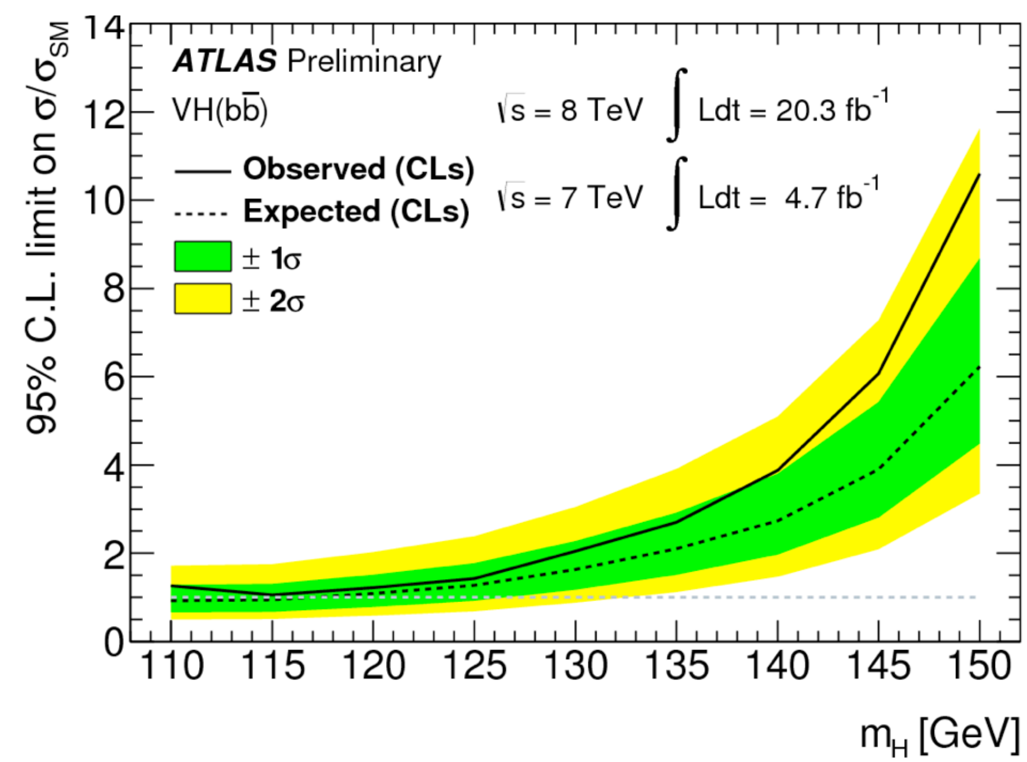




H→bb





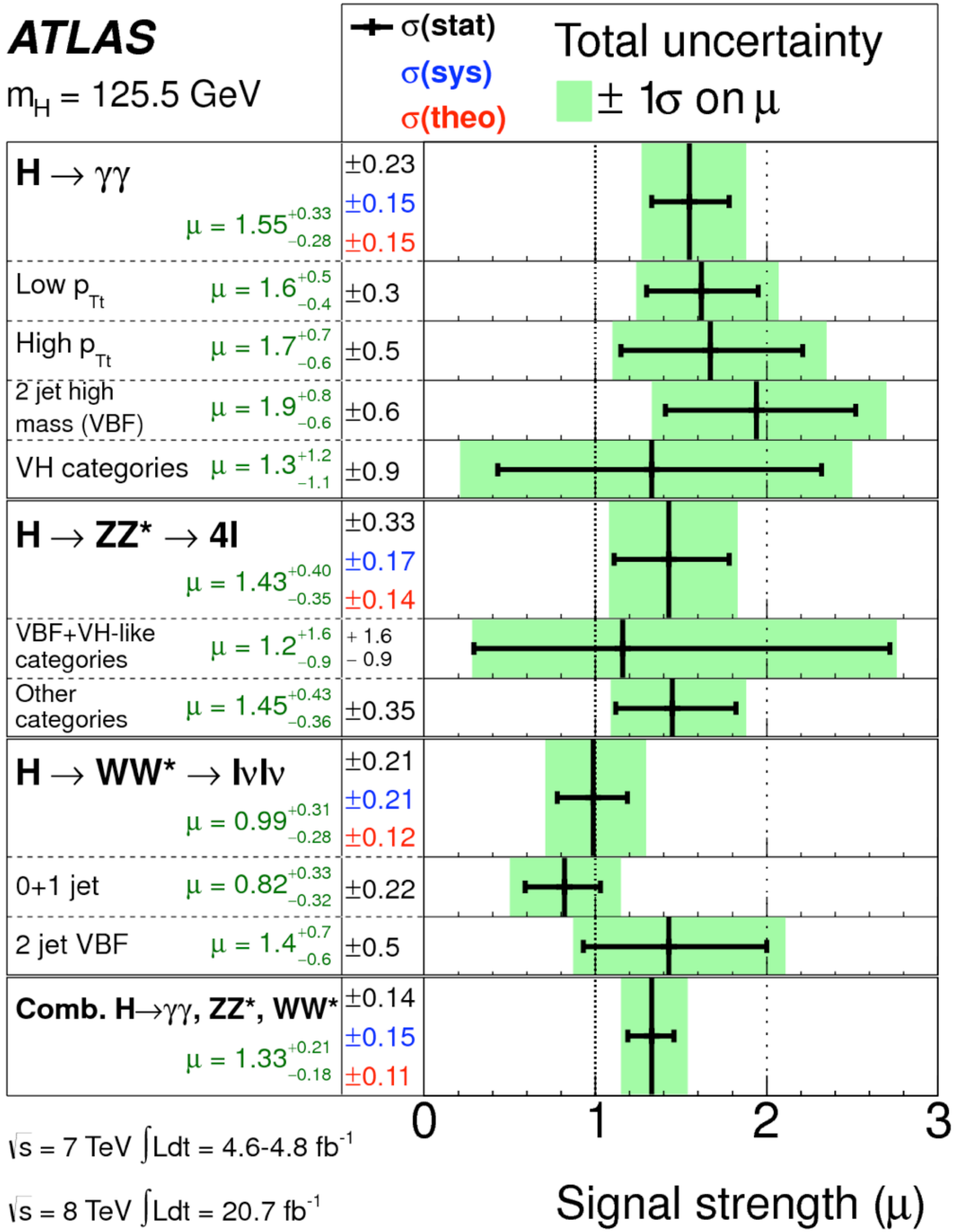


m_H=125 GeV
95% CL exclusion limit 1.4 (1.3) x SM
$\mu = 0.2 \pm 0.5$ (stat) ± 0.4 (syst)
CMS : significance 2.1(2.1)σ for m_H=125 GeV

Rates/Couplings

Phys. Lett. B 726 (2013), pp. 88-119

Signal strength

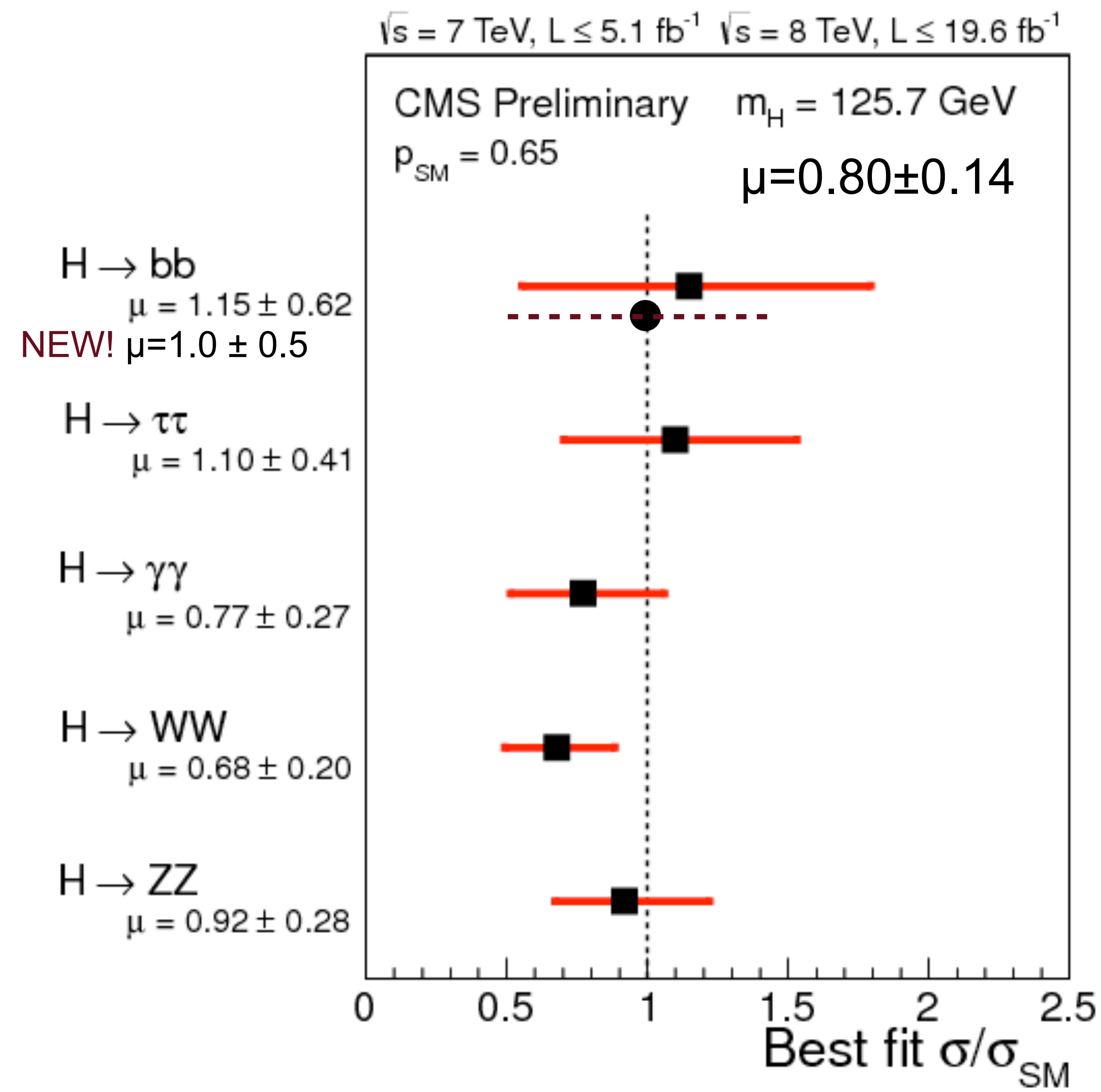


Higgs boson signal strength measurement

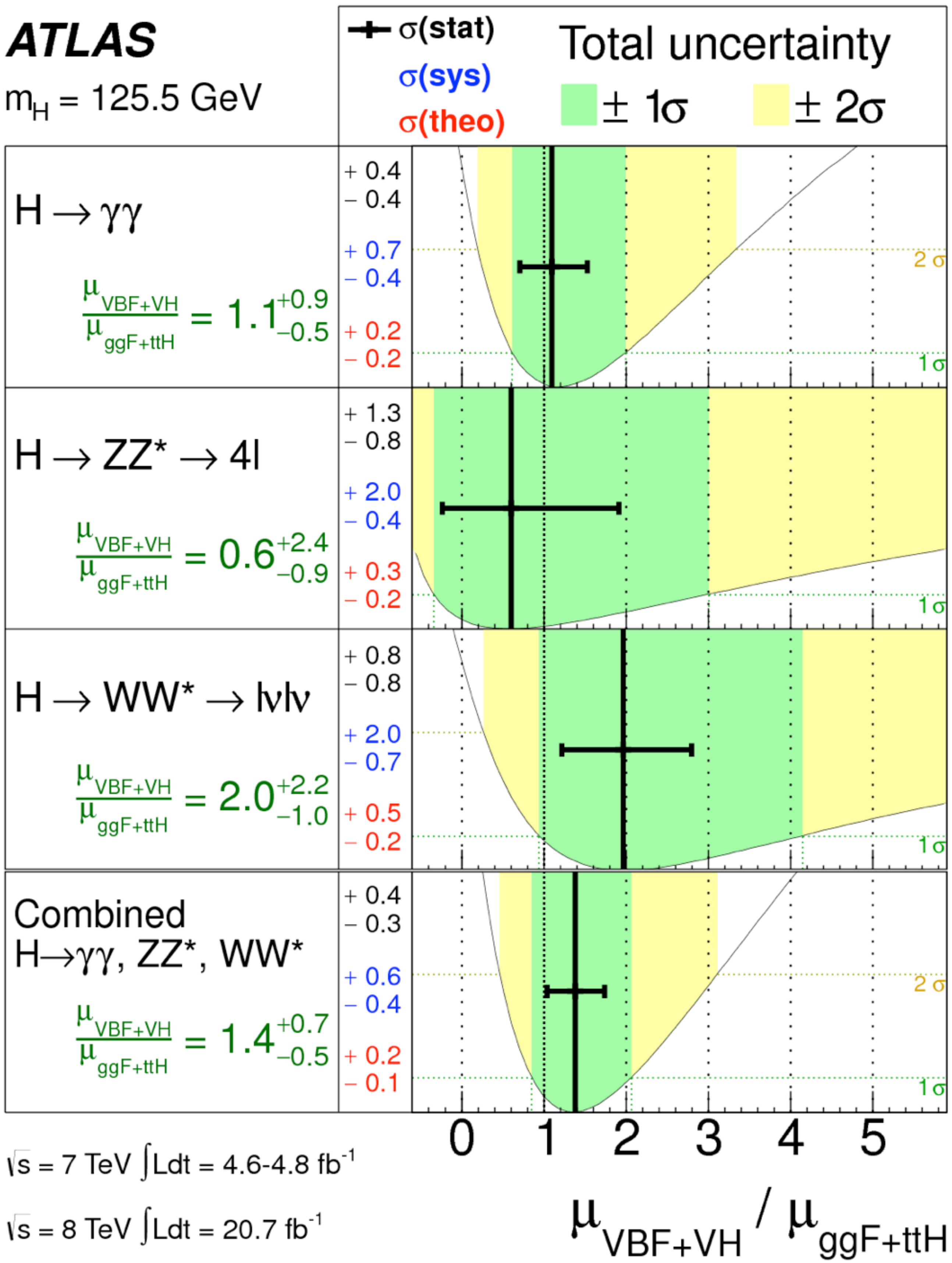
- using H→γγ, H→ZZ→4l and H→WW→lνlν
- $\mu = (\sigma \times BR) / (\sigma \times BR)_{SM}$
- $\mu = 1.33^{+0.21}_{-0.18}$ at m_H=125.5 GeV

[including preliminary/partial H→bb/H→ττ results gives 1.23±0.18]

- consistency with SM 7%



Signal strength for production mechanisms

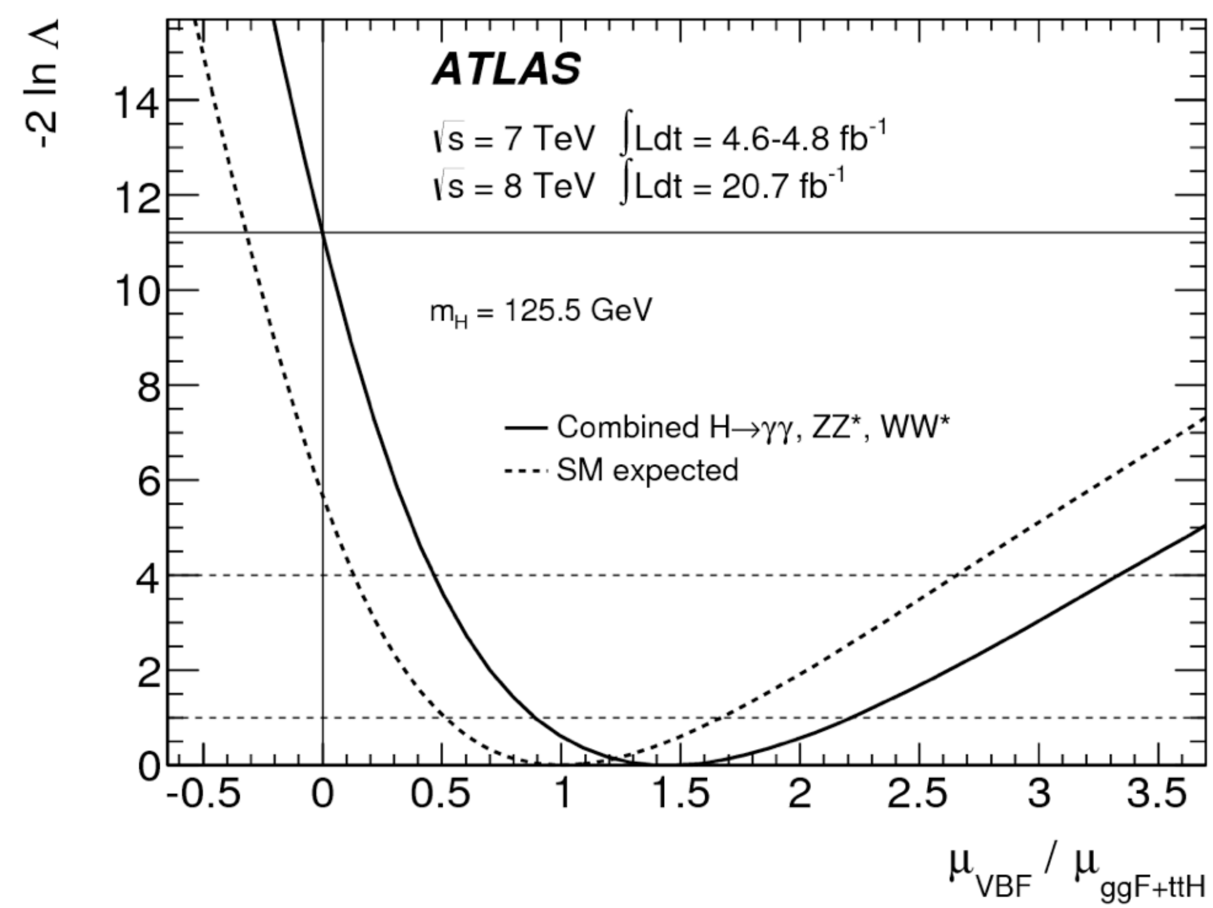


Overall Higgs boson signal strength measurement:

- no information on different production mechanisms
- assuming SM ratio of production cross-section

Separate vector-boson/gluon mediated processes:

- use two signal strengths μ_{VBF+VH} and $\mu_{ggF+ttH}$
- $\mu_{VBF+VH} / \mu_{ggF+ttH} = 1.4^{+0.4}_{-0.3}(\text{stat})^{+0.6}_{-0.4}(\text{sys})$
  - model independent (no assumption on branching ratios)
- 3.3σ evidence for VBF Higgs boson production



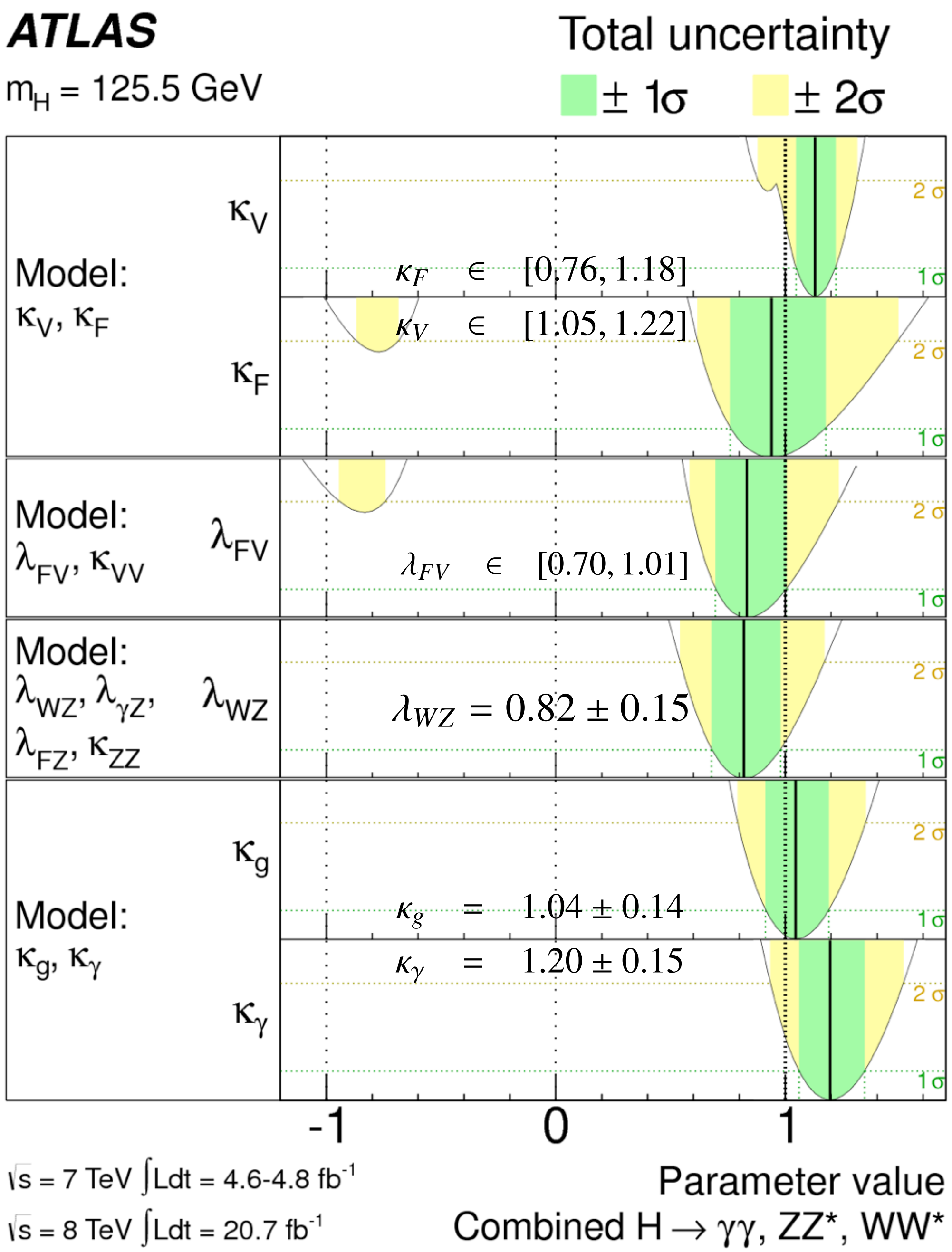
Higgs boson couplings

Table 10: Summary of the coupling benchmark models discussed in this paper, where $\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ii} = \kappa_i\kappa_i/\kappa_H$, and the functional dependence assumptions are: $\kappa_V = \kappa_W = \kappa_Z$, $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$ (and similarly for the other fermions), $\kappa_g = \kappa_g(\kappa_b, \kappa_t)$, $\kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)$, and $\kappa_H = \kappa_H(\kappa_i)$.

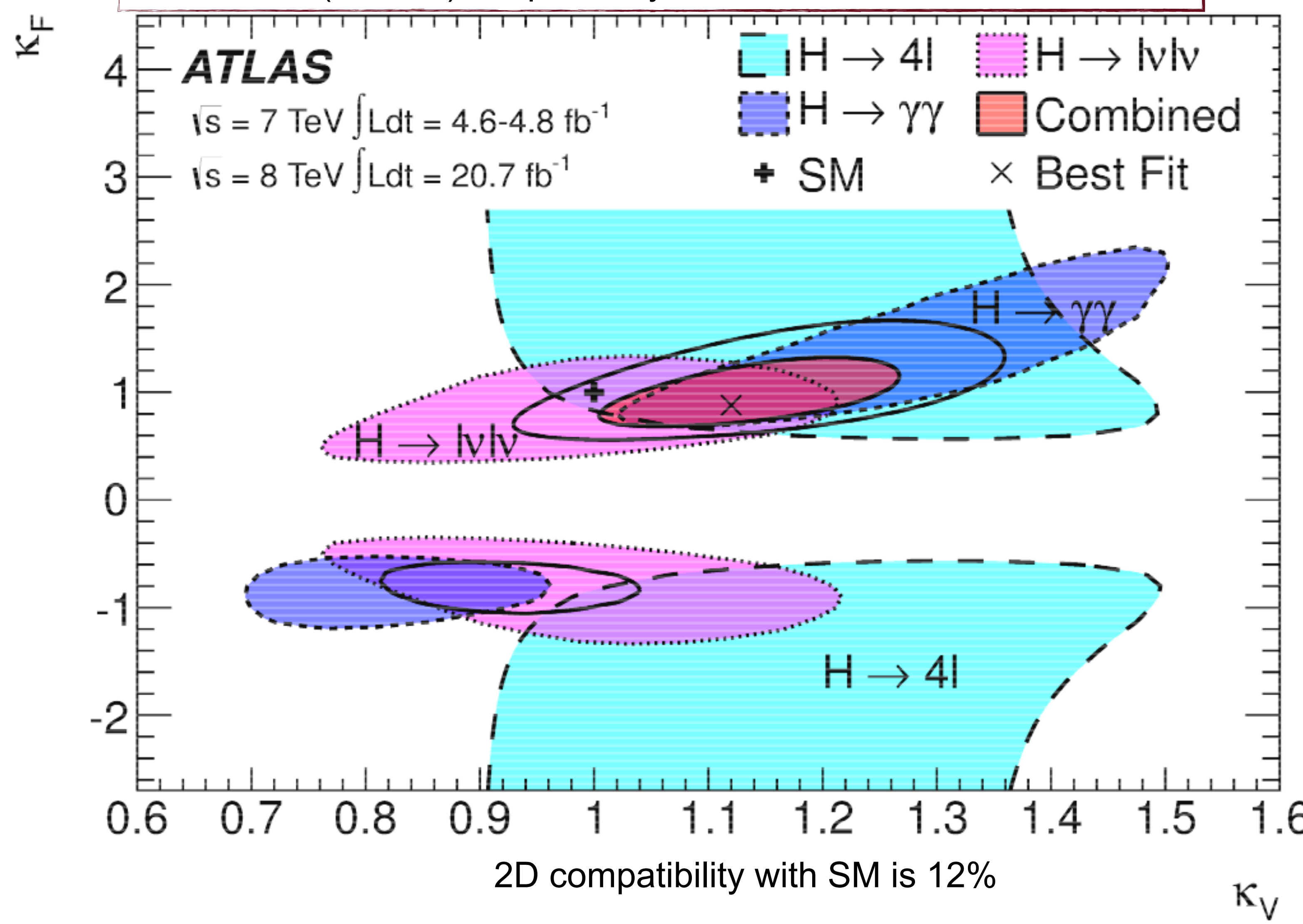
Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√

Higgs boson signal strength measurement following formalism of arXiv:1209.0040

- single resonance of 125.5 GeV
- narrow width approximation
- only modifications of the coupling strengths



Deviations described by overall scales kF (kV) for fermions (bosons), respectively, no BSM contribution



2D compatibility with SM is 12%

Spin/CP

ATLAS Spin/CP studies: The channels

Channel	$H \to ZZ^{(*)} \to 4\ell$	$H \to WW^{(*)} \to \ell\nu\ell\nu$	$H \to \gamma\gamma$
Dataset	20.7 fb^{-1} @ 8 TeV 4.8 fb^{-1} @ 7 TeV	20.7 fb^{-1} @ 8 TeV	20.7 fb^{-1} @ 8 TeV
Reference	ATLAS-CONF-2013-013	ATLAS-CONF-2013-031	ATLAS-CONF-2013-029
Signal	JHU$\oplus$PYTHIA	PowHeg/JHU$\oplus$PYTHIA	PowHeg/JHU$\oplus$PYTHIA
Tested Hypotheses			
0^-	✓	-	-
1^+	✓	✓	-
1^-	✓	✓	-
2^+	✓	✓	✓

- **Spin Combination**
  - ZZ+WW+γγ
  - ATLAS-CONF-2013-040
  - Phys. Lett. B 726 (2013), pp. 120-144

Production modes

spin-0 : ggF (qqbar annihilation negligible)

spin-1 : qqbar annihilation

spin-2 : ggF & qqbar annihilation

For the Graviton inspired tensor with minimal couplings to SM, ggF dominates with qqbar ~4%, but higher order QCD corrections may significantly modify this → scan f_{qqbar}

VBF and VH production modes:

γγ : included in the analysis

4l : VBF production does not modify kinematics

lvlv: negligible contribution

Statistical Treatment

$$\mathcal{L}\left(J^P,\mu,\theta\right) = \prod_{j}^{N_{channel}} \prod_{i}^{N_{bins}} P\left(N_{i,j}|\mu_j S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)\right) \times \mathcal{A}_j(\theta)$$

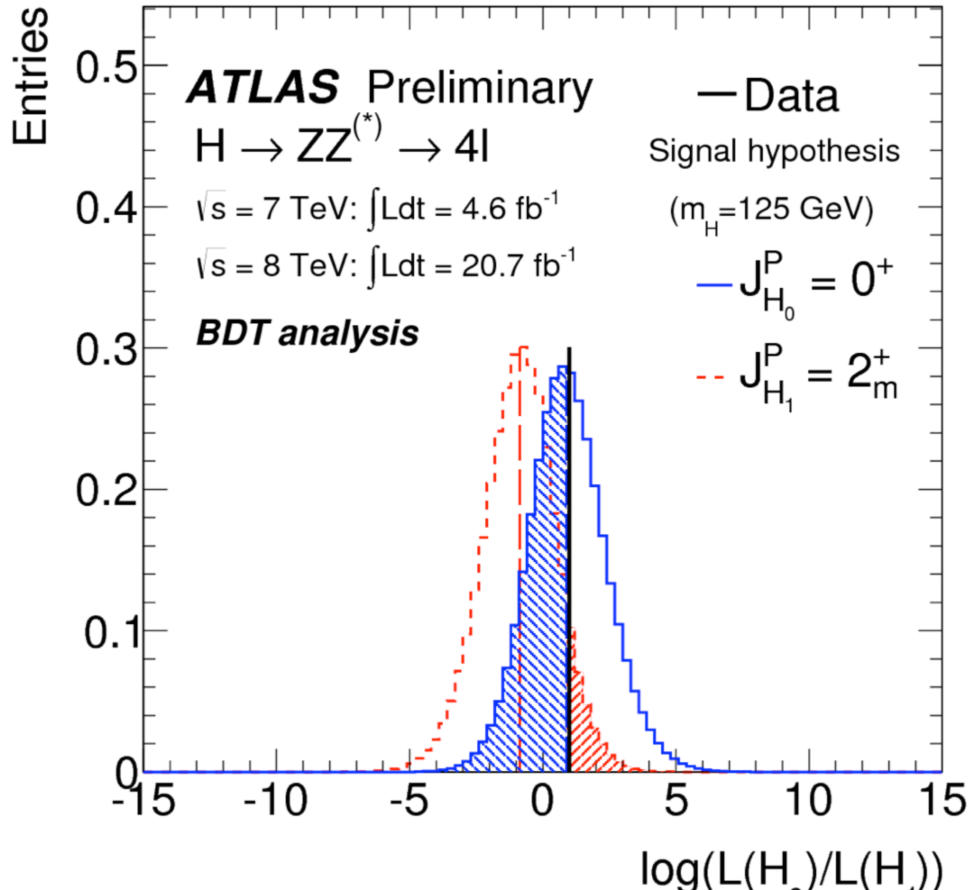
The test statistic is the ratio of profiled likelihoods (LLR) between the two hypotheses, nuisance parameters profiled separately for each hypothesis

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

The test statistic distribution for each hypothesis is extracted from ensemble tests (pseudo-experiments using the profiled values for nuisance parameters) and the CLs is built

$$\mathrm{CL_s}(J^P_{\mathrm{alt}}) = \frac{p_0(J^P_{\mathrm{alt}})}{1 - p_0(0^+)}$$

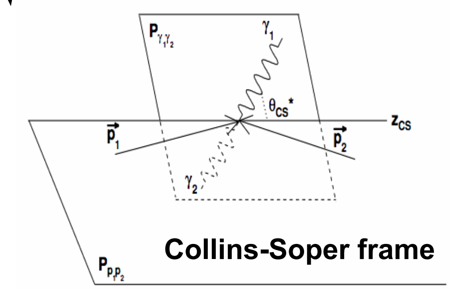
Note: μ_{SM} and μ_{JP} profiled independently (ie no assumptions on production rates)



H→γγ : Introduction

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma 1} p_T^{\gamma 2}}{m_{\gamma\gamma}^2}$$

Discriminating variable: polar angle of the photons with respect to the z-axis of the Collins-Soper frame (minimize effect of ISR)

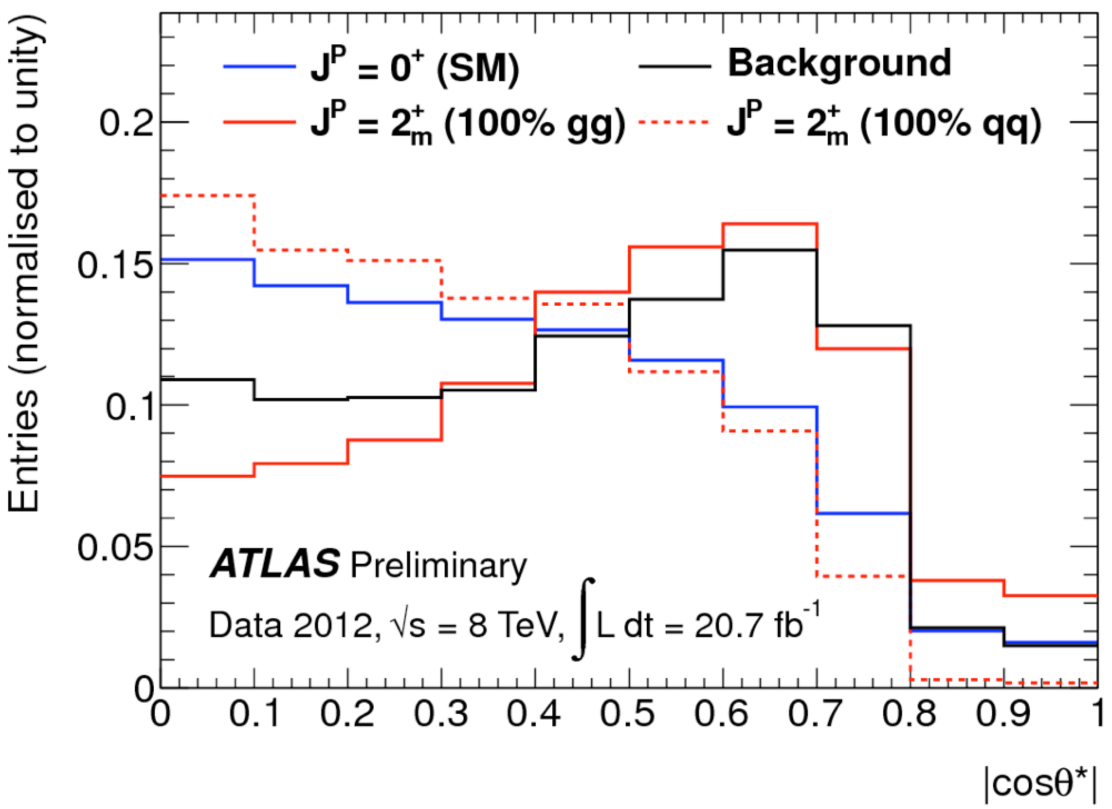


Before acceptance requirements:
- spin 0 : isotropic decay
- spin 2 : distribution depends on the qq/gg fractions:

$$100\%\ gg\ :\ \frac{dN}{d\cos\theta*} = 1 - 6\cos^2\theta^* + \cos^4\theta^*$$

$$100\%\ q\bar{q}\ :\ \frac{dN}{d\cos\theta*} = 1 - \cos^4\theta^*$$

- Background : peaking in the forward-backward direction

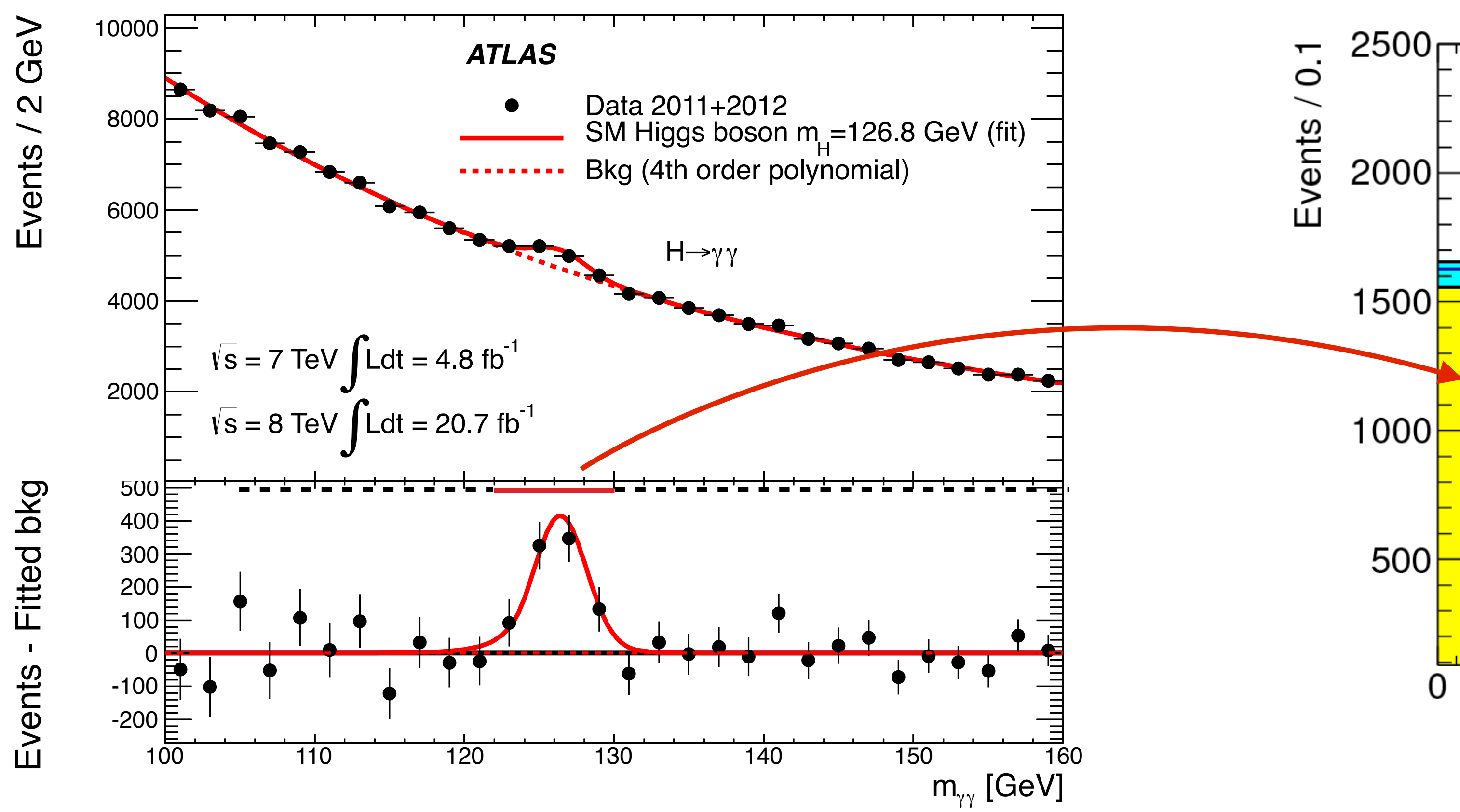


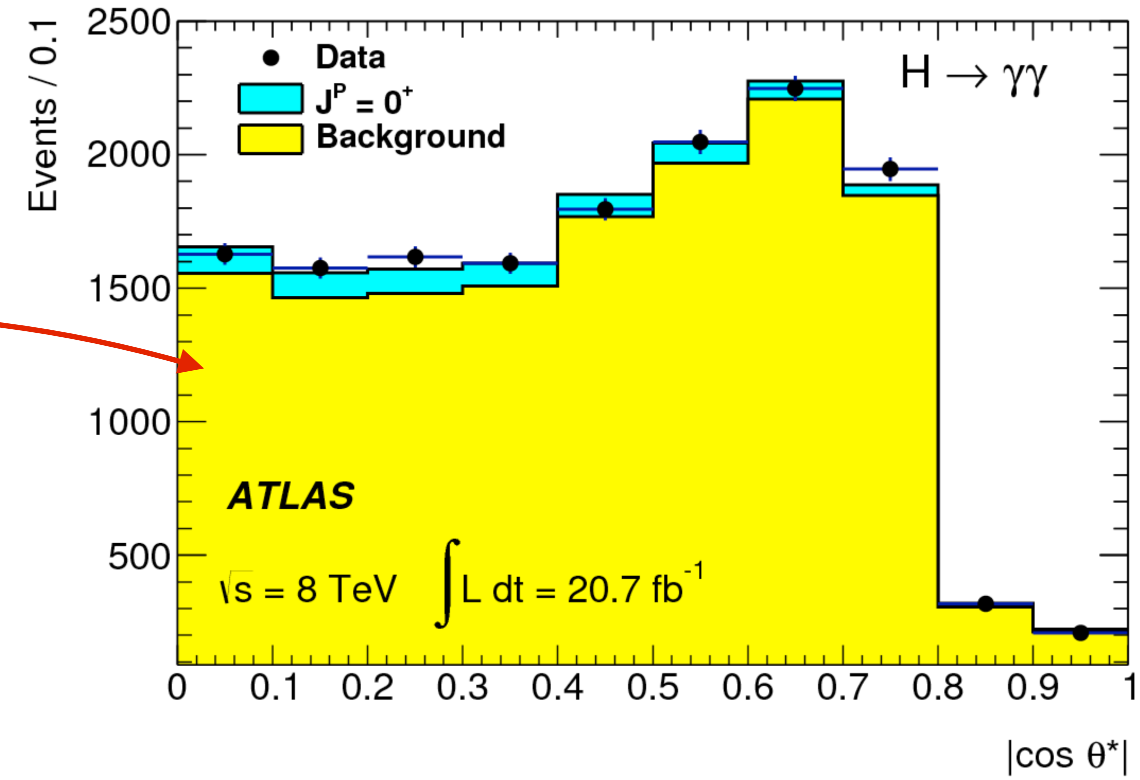
- Analysis similar to “rate/mass” analysis but optimized selection:
  - $p_{T\gamma 1}>0.35\ m_{\gamma\gamma}$ and $p_{T\gamma 2}>0.25\ m_{\gamma\gamma}$

  [Minimize $m_{\gamma\gamma}$ and cosθ* correlations for background]

H→γγ : Fit Procedure

H→γγ is a low S/B final state (inclusive ~3%)
- Simultaneous fit to $m_{\gamma\gamma}$ and |cosθ*| in signal region
- $m_{\gamma\gamma}$ in side-bands



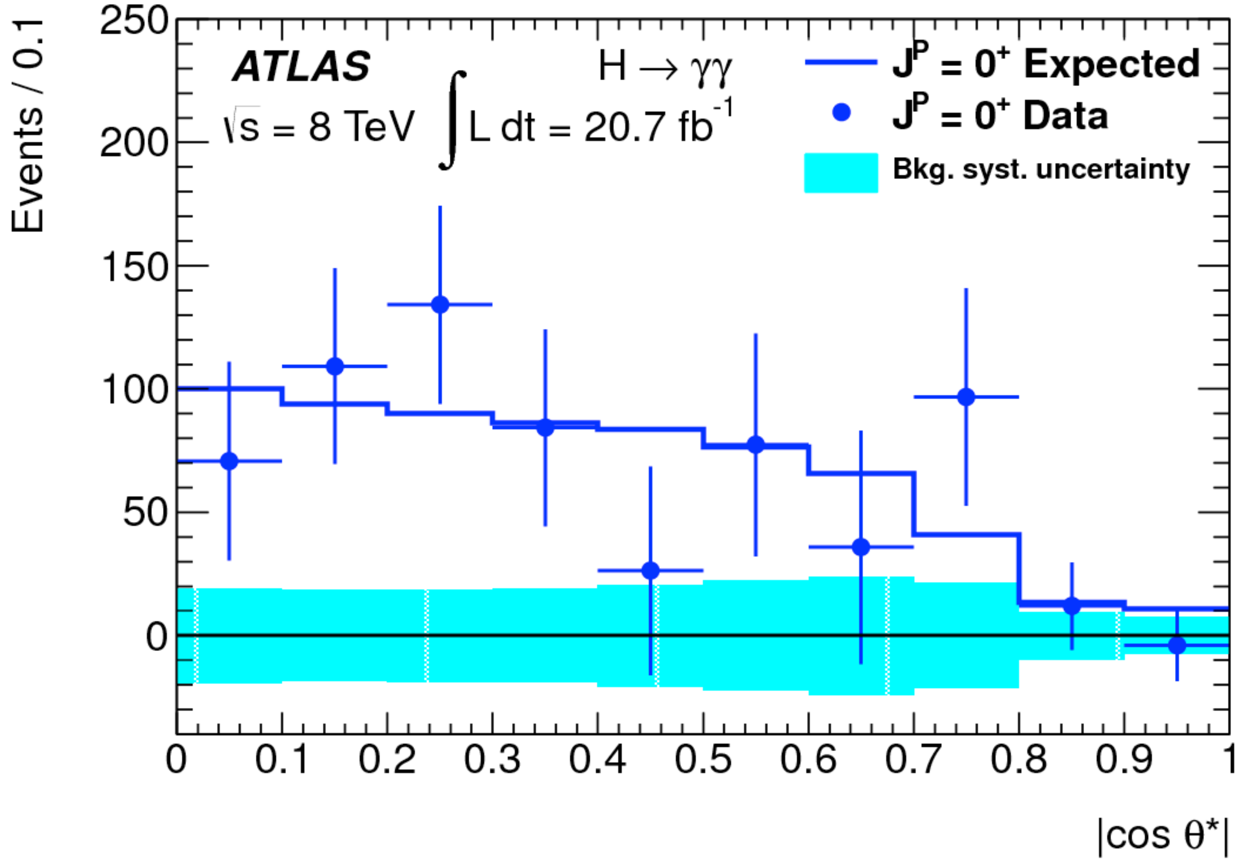


For 105 GeV < m_{4l} < 160 GeV
14977 candidate events
~14300 background events
~370 SM Higgs boson signal

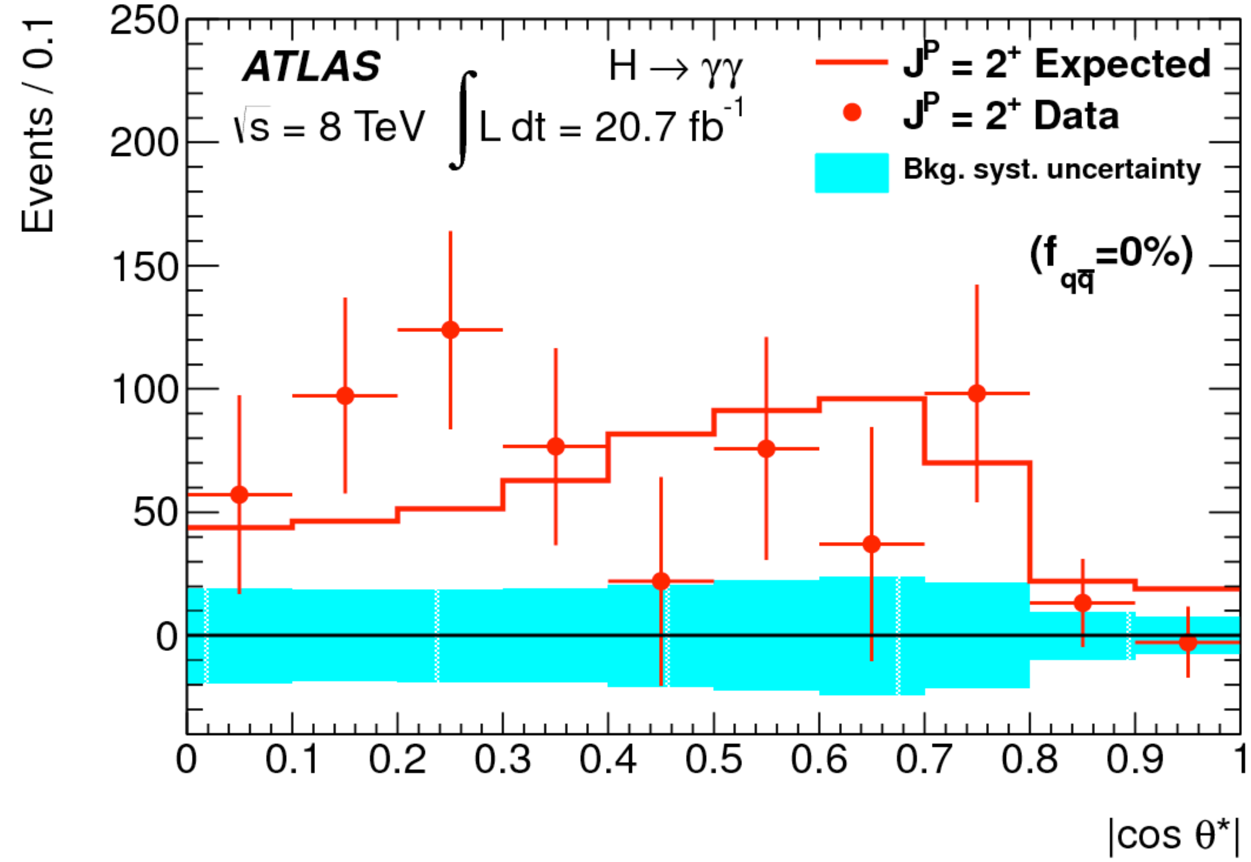
H→γγ : Fit results 0^+ vs 2^+

Background subtracted distributions

Fit assuming 0^+

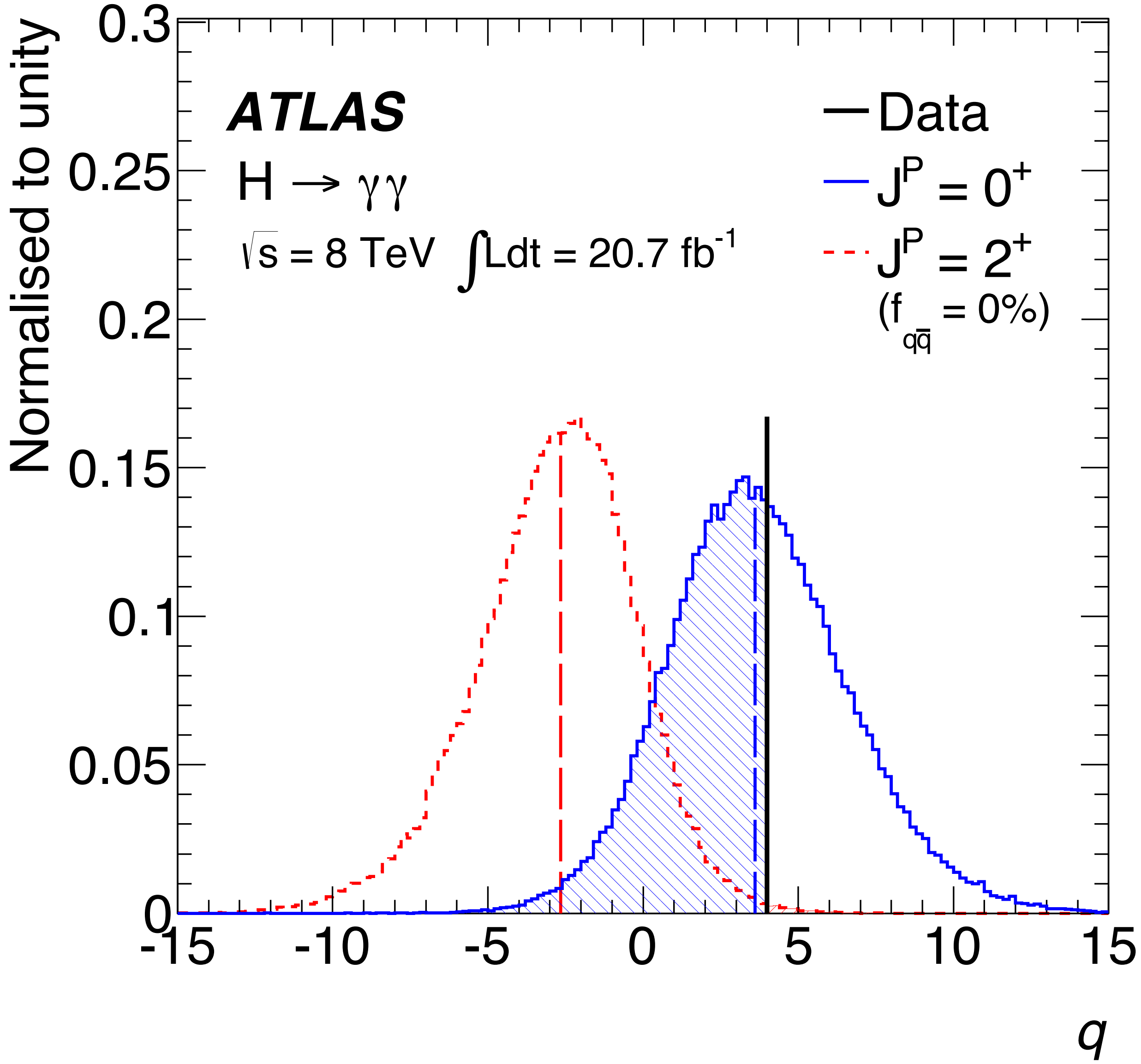


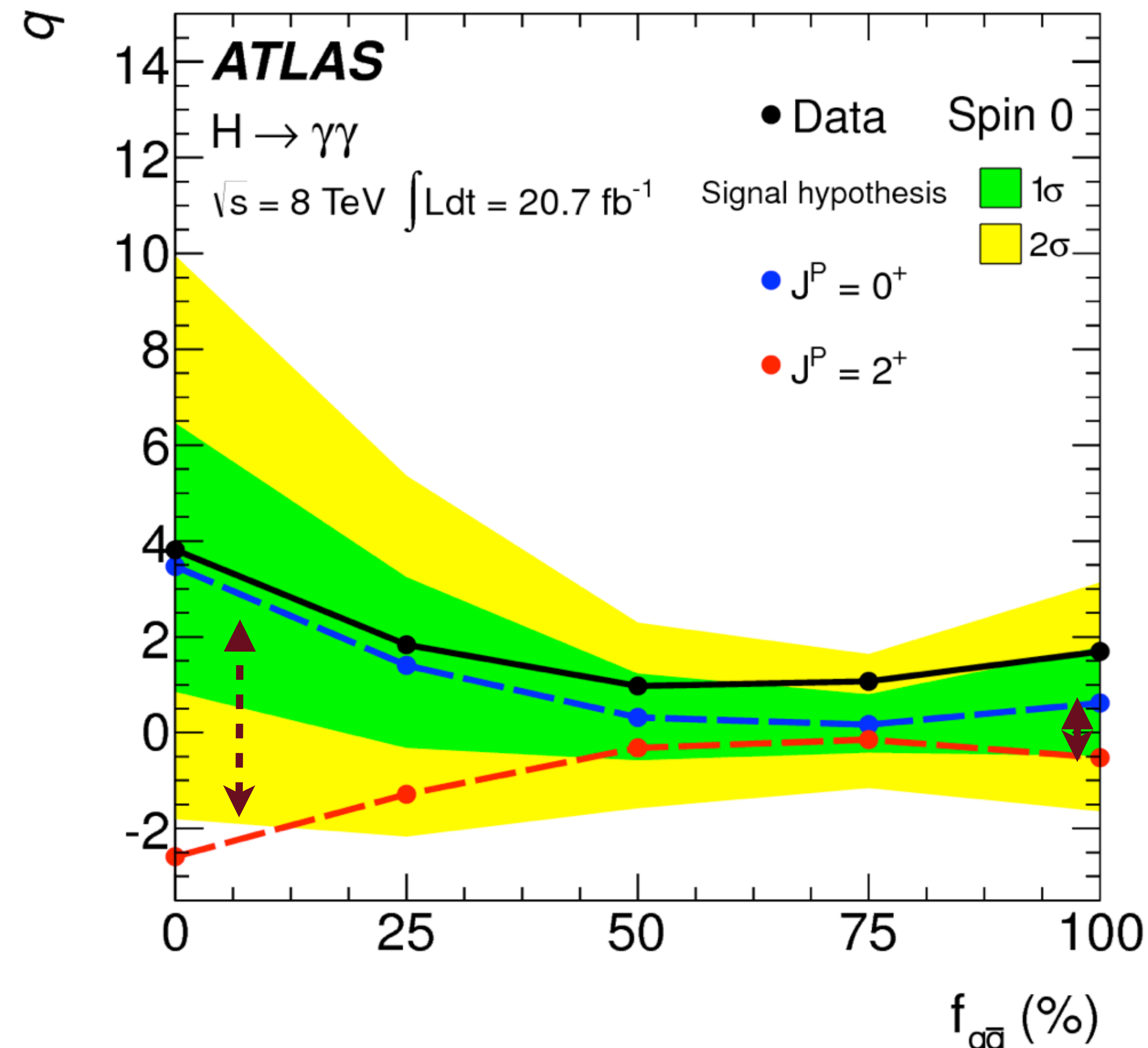
Fit assuming 2^+ (100% gg)



Data differ slightly, owing to the background being determined separately for each spin hypothesis

H→γγ: LLR 0^+ vs 2^+



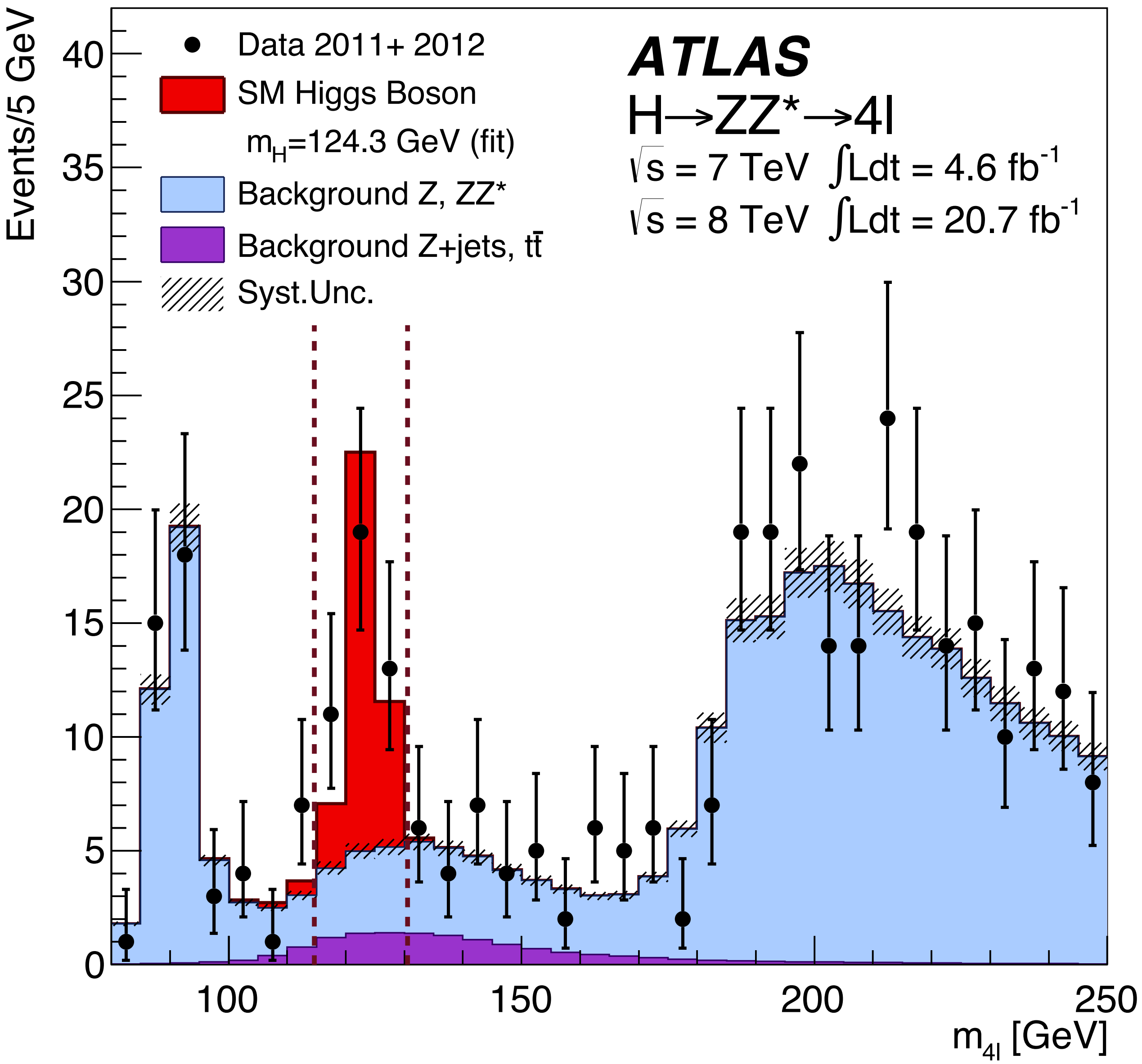


$H \to \gamma\gamma$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$	
100%	0.148	0.135	0.798	0.025	0.124	87.6%
75%	0.319	0.305	0.902	0.033	0.337	66.3%
50%	0.198	0.187	0.708	0.076	0.260	74.0%
25%	0.052	0.039	0.609	0.021	0.054	94.6%
0%	0.012	0.005	0.588	0.003	0.007	99.3%

The 2^+ hypothesis is disfavored with respect to the 0^+ hypothesis.

H→ZZ→4l: Introduction



Ideal channel for spin/CP studies

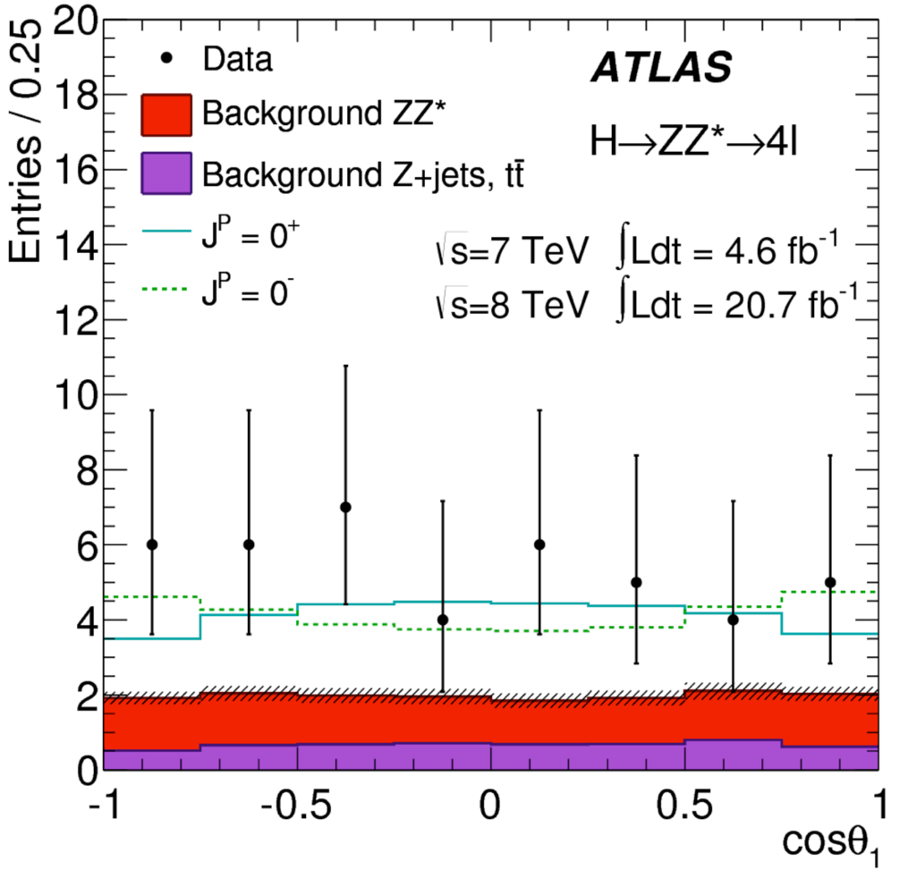
- Complete reconstruction of the event topology
- Clean (S/B ~1 to 2 depending on final state)
- Several observable depending on spin/CP available

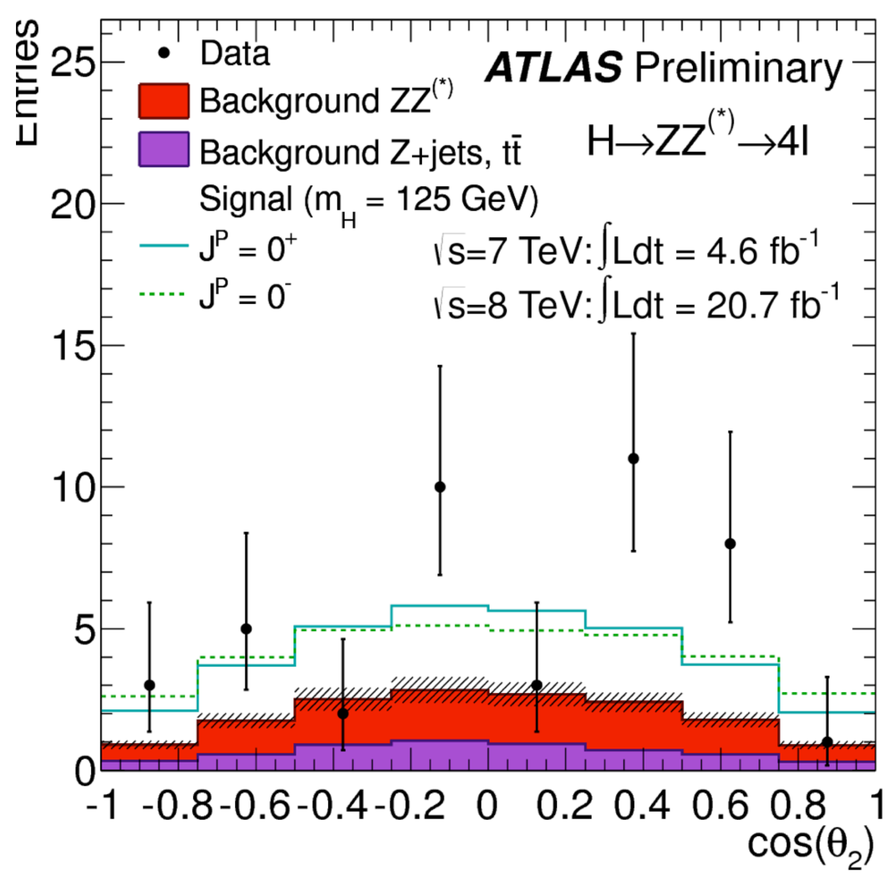
For 115 GeV < m_{4l} < 130 GeV
43 candidate events
16 background events
18 SM Higgs boson events expected

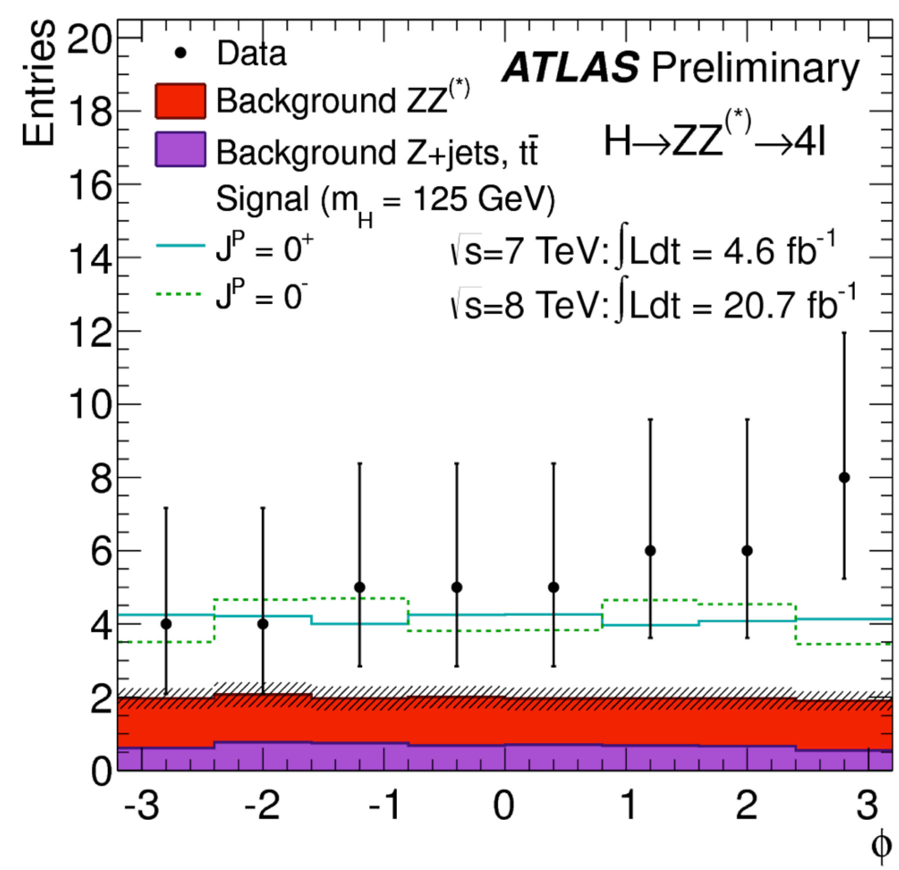
Split signal region [in GeV] → 6% sensitivity improvement:
- High S/B [121,127]
- Low S/B (115,121) ∪ (127,130)

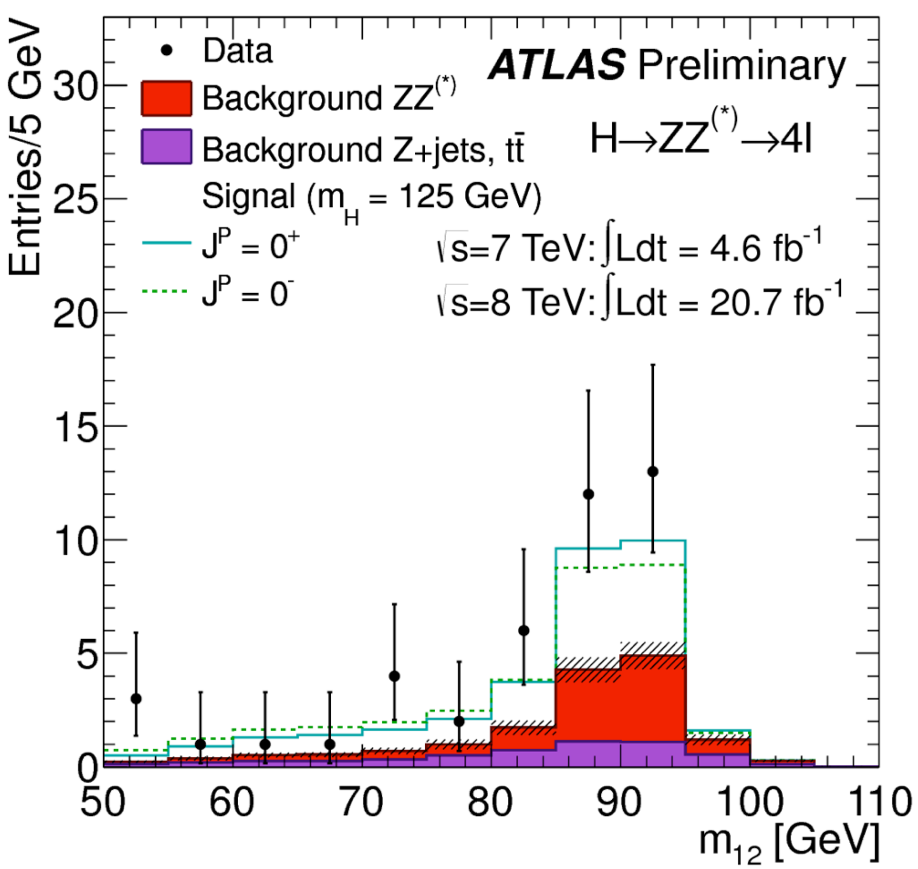
Two approaches:
- Train BDT separately for each hypothesis
- Use ME corrected for acceptance and pairing effects

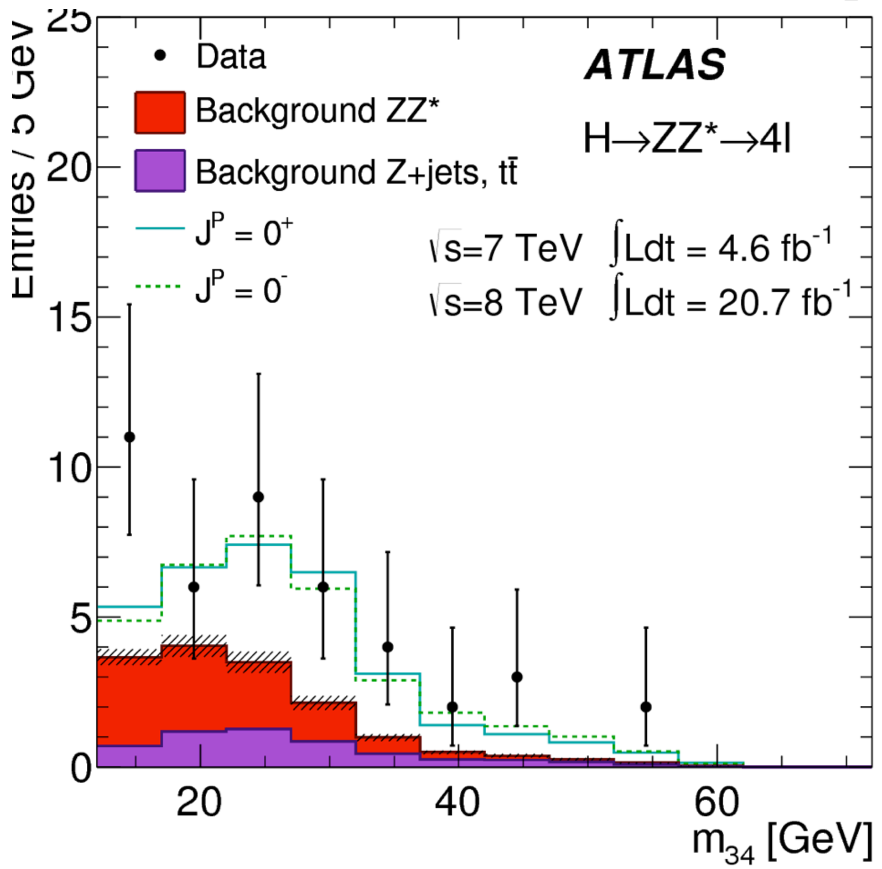
H→ZZ→4l: Input Variables





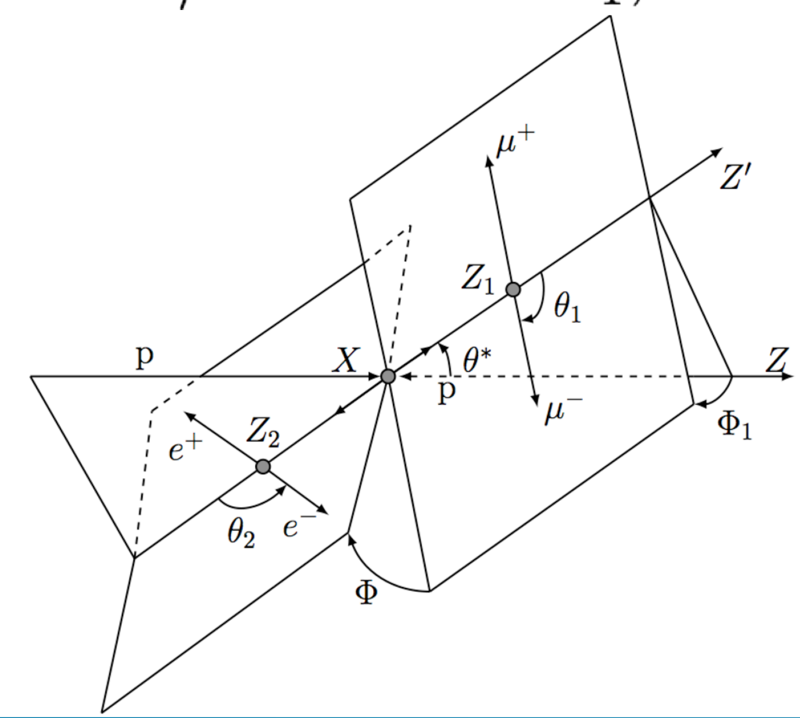




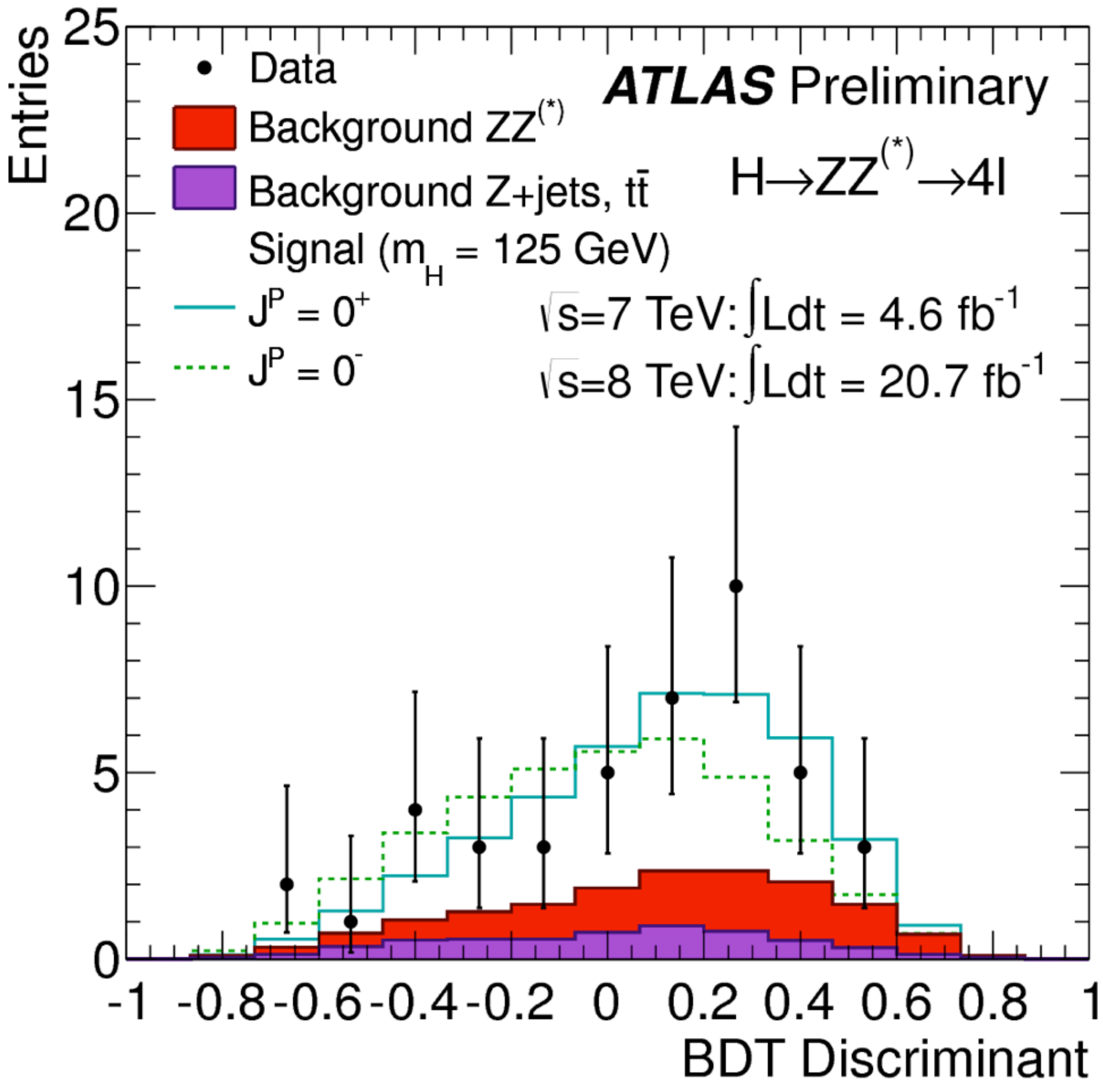


For $0^+/0^-$: $\Phi, \theta_1, \theta_2, m_{12}, m_{34}$

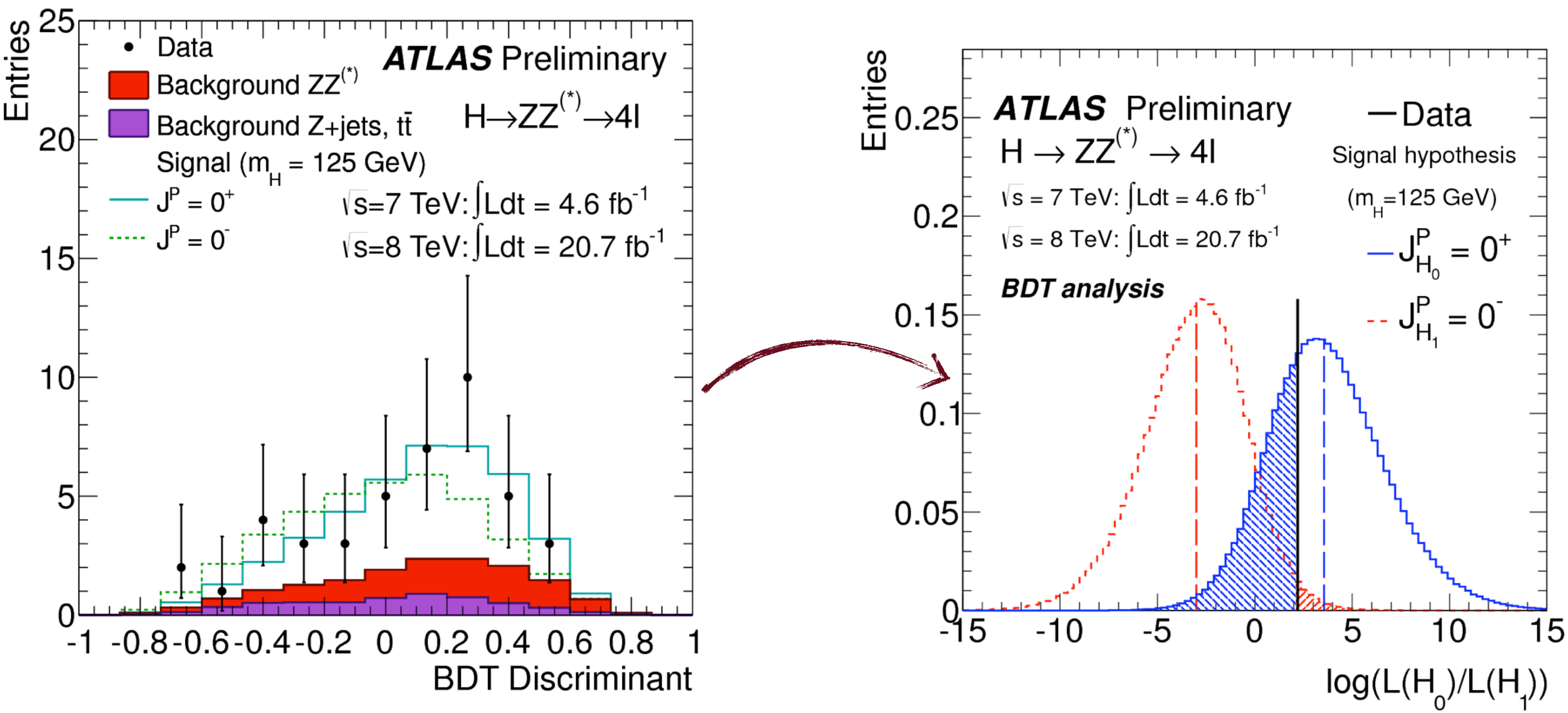
For 0^+/other add : Φ_1, θ^*



H→ZZ→4l : Distribution of discriminant

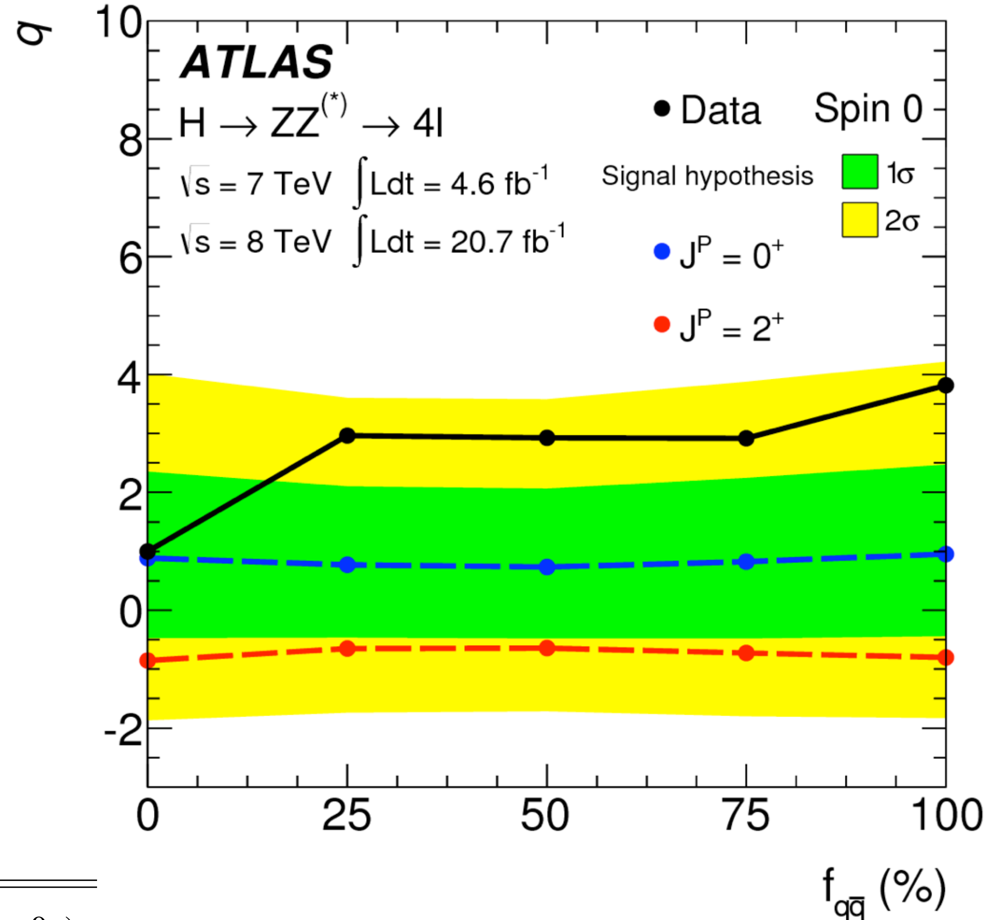


H→ZZ→4l : LLR 0^+ vs 0^-



H→ZZ→4l : Results Overview

Main Systematic:
- High S/B vs Low S/B regions normalization (~10%) owing to the uncertainty on m_H



Channel	0^- assumed Exp. $p_0(J^P=0^+)$	0^+ assumed Exp. $p_0(J^P=0^-)$	Obs. $p_0(J^P=0^+)$	Obs. $p_0(J^P=0^-)$	$CL_s(J^P=0^-)$	
$H\rightarrow ZZ^*$	$1.5\cdot10^{-3}$	$3.7\cdot10^{-3}$	0.31	0.015	0.022	97.8%

Channel	1^- assumed Exp. $p_0(J^P=0^+)$	0^+ assumed Exp. $p_0(J^P=1^-)$	Obs. $p_0(J^P=0^+)$	Obs. $p_0(J^P=1^-)$	$CL_s(J^P=1^-)$	
$H\rightarrow ZZ^*$	$0.9\cdot10^{-3}$	$3.8\cdot10^{-3}$	0.15	0.051	0.060	94.0%

Channel	1^+ assumed Exp. $p_0(J^P=0^+)$	0^+ assumed Exp. $p_0(J^P=1^+)$	Obs. $p_0(J^P=0^+)$	Obs. $p_0(J^P=1^+)$	$CL_s(J^P=1^+)$	
$H\rightarrow ZZ^*$	$4.6\cdot10^{-3}$	$1.6\cdot10^{-3}$	0.55	$1.0\cdot10^{-3}$	$2.0\cdot10^{-3}$	99.8%

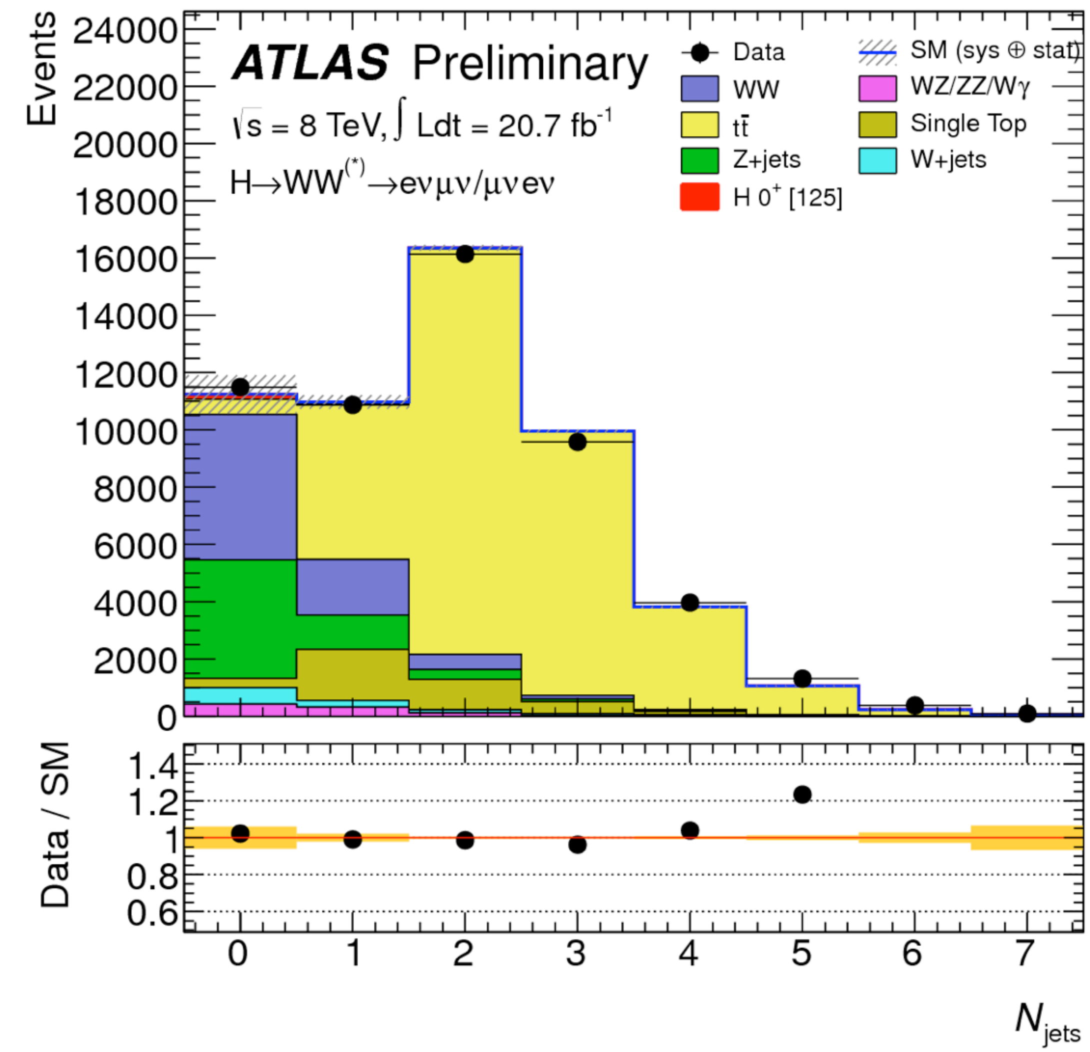
$H\rightarrow ZZ^*$

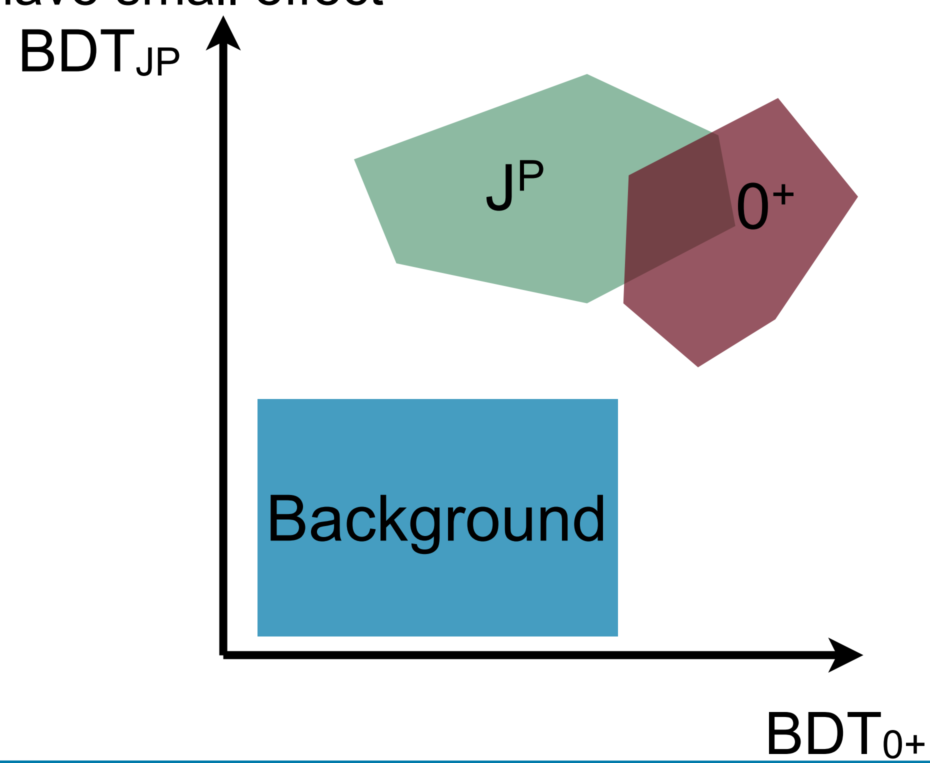
$f_{q\bar{q}}$	2^+ assumed assumed Exp. $p_0(J^P=0^+)$	0^+ assumed Exp. $p_0(J^P=2^+)$	Obs. $p_0(J^P=0^+)$	Obs. $p_0(J^P=2^+)$	$CL_s(J^P=2^+)$	
100%	0.102	0.082	0.962	0.001	0.026	97.4%
75%	0.117	0.099	0.923	0.003	0.039	96.1%
50%	0.129	0.113	0.943	0.002	0.035	96.5%
25%	0.125	0.107	0.944	0.002	0.036	96.4%
0%	0.099	0.092	0.532	0.079	0.169	83.1%

All alternative hypotheses are disfavored with respect to the 0^+ hypothesis.

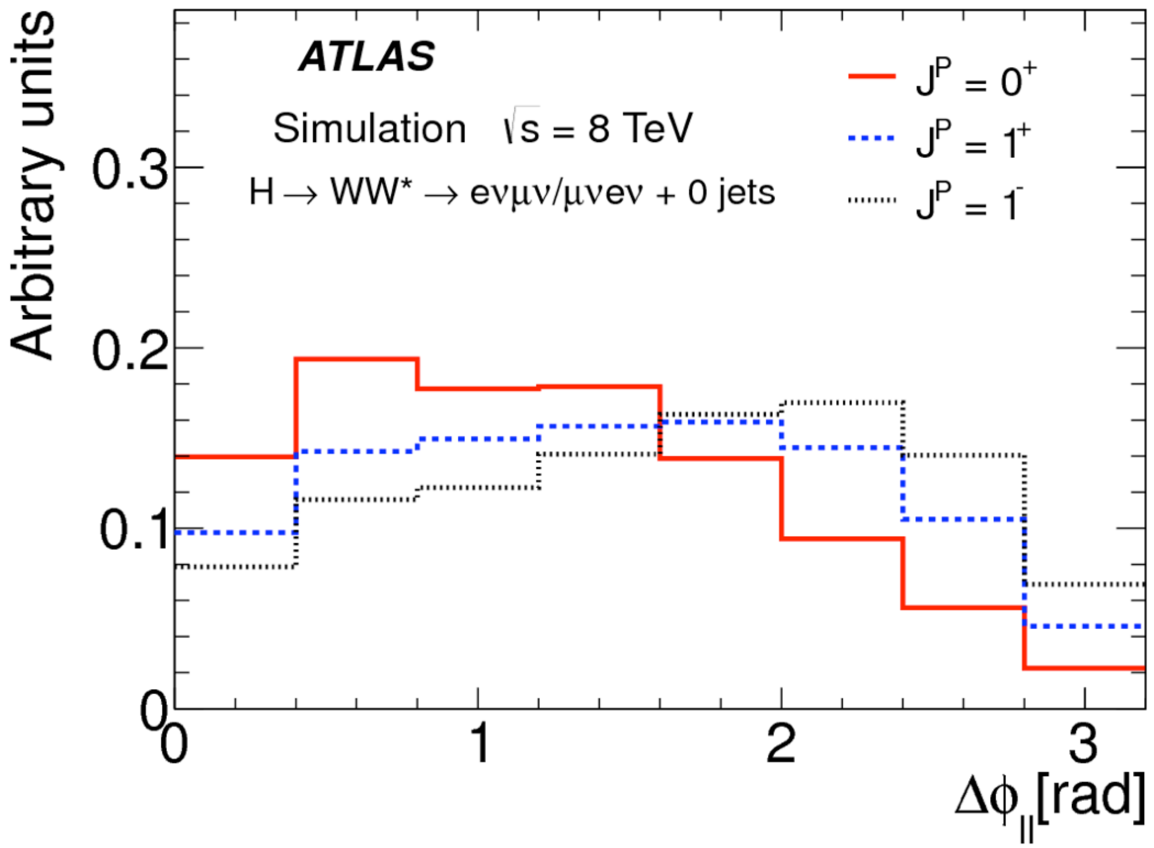
H→WW→lνlν: Introduction

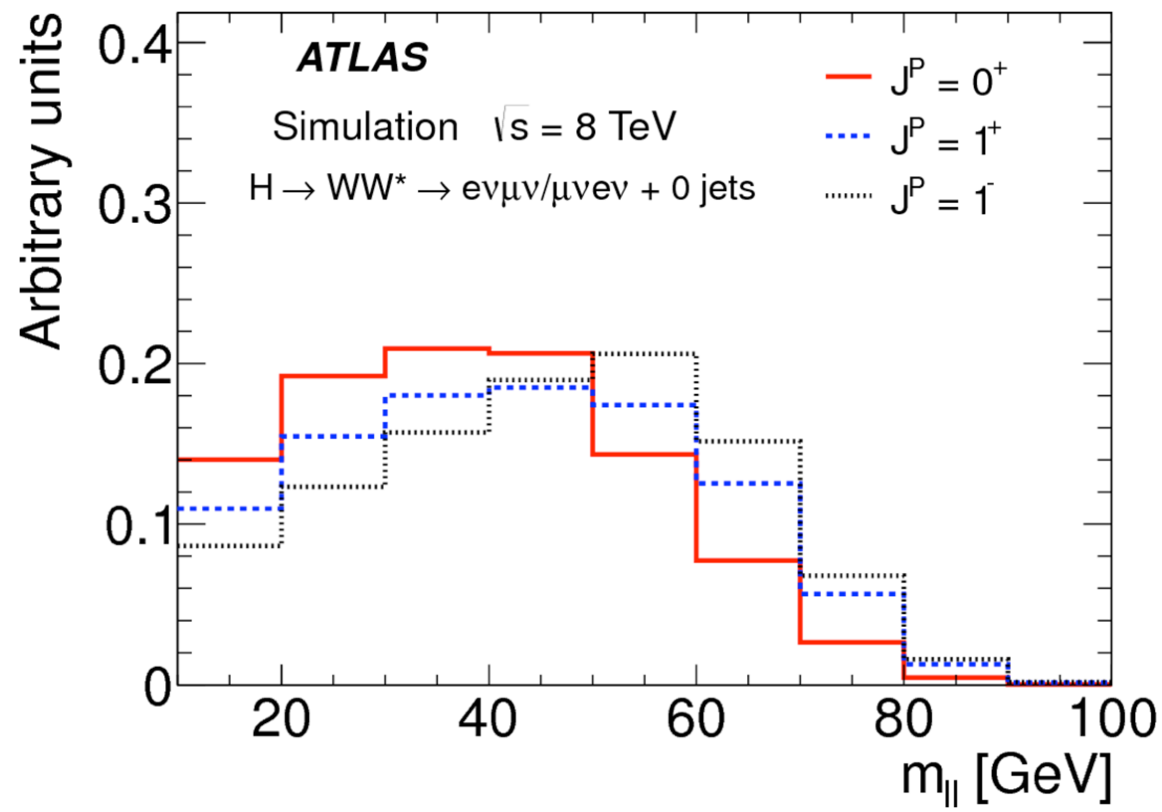
- Restricted to "different flavour" (eμ) events and no jets
  - p_{Tl1}>25 GeV and p_{Tl2}>15 GeV
  - p_{Tj}>25 GeV for |η|<2.5 (p_{Tj}>30 GeV for 2.5<|η|<4.5)
- Rate analysis already exploits spin-0 nature of SM Higgs boson
  - Relax spin-sensitive requirements
  (allow spin study while keeping backgrounds under control)
  - E_TMissRel > 20 GeV
  - m_{ll} < 80 GeV
  - p_{Tll} > 20 GeV
  - $\Delta\varphi_{ll}$ < 2.8
- m_{ll}, $\Delta\varphi_{ll}$, p_{Tll}, m_T sensitive to spin
- Two BDT classifiers are used:
  - BDT_{0+}: SM Higgs signal against the sum of all backgrounds
  - BDT_{JP}: J^P signal against the sum of all backgrounds
  - Perform 2D-fit in (BDT_{0+},BDT_{JP})
- pT spectrum uncertainties found to have small effect

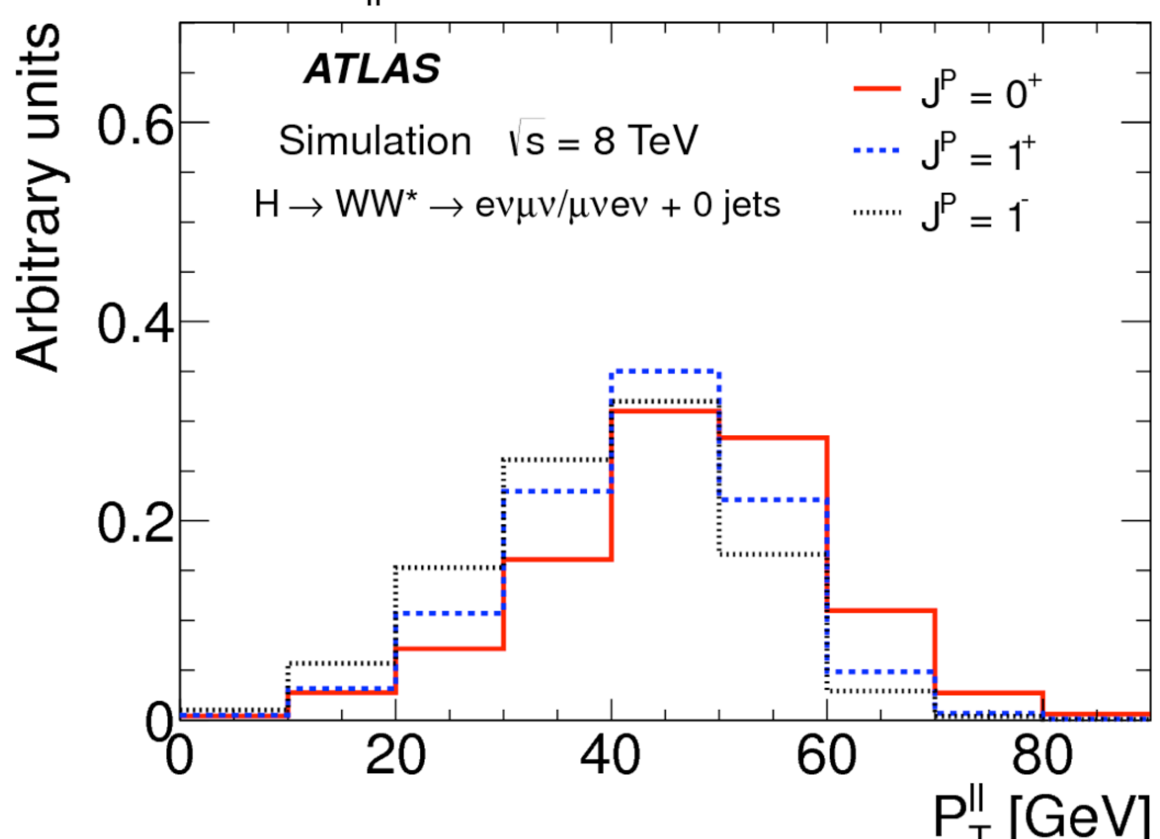




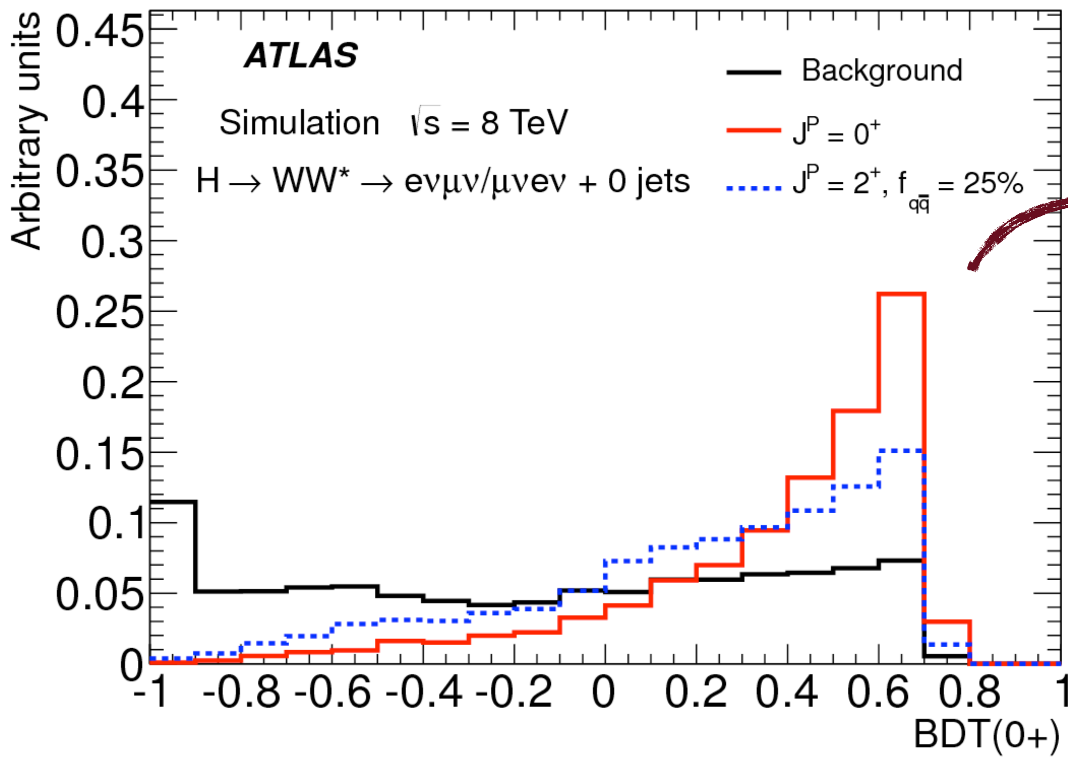
H→WW→lνlν: Spin/CP sensitive variables

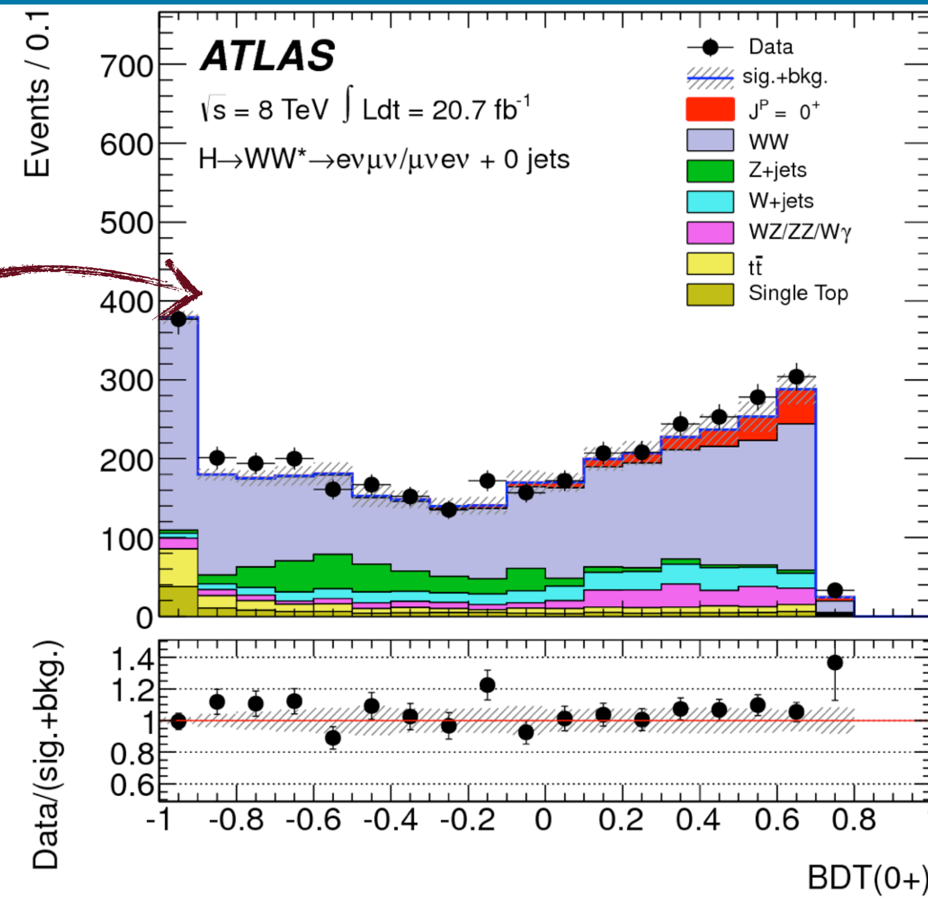




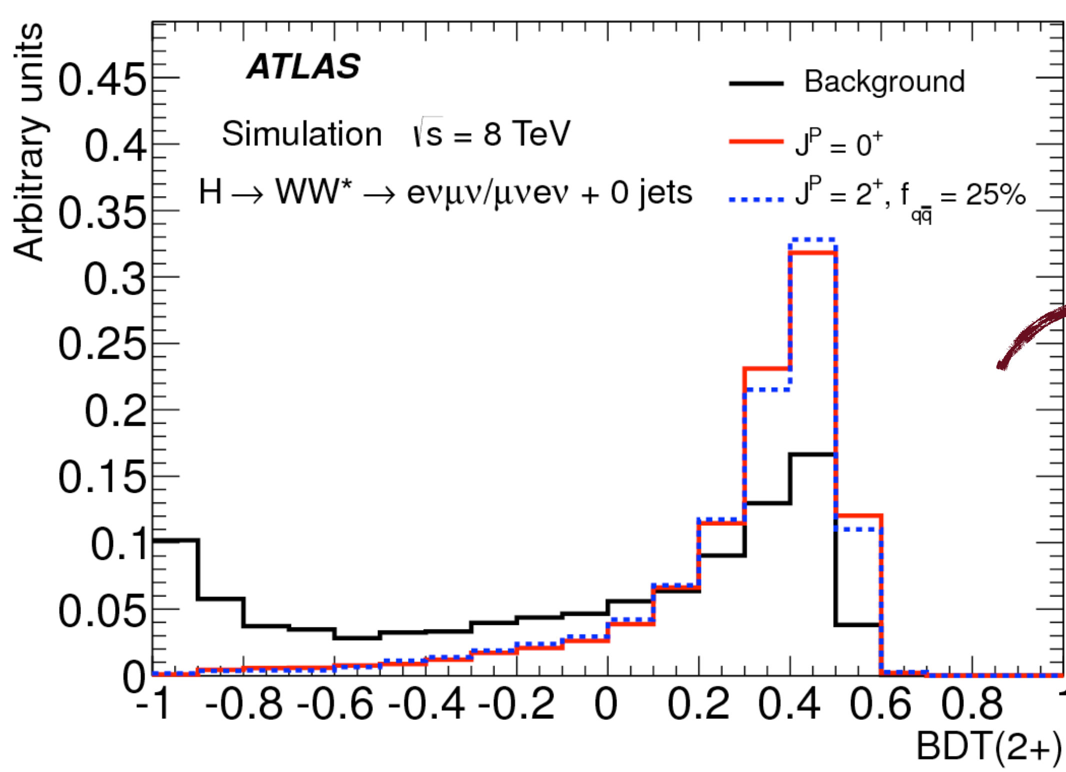


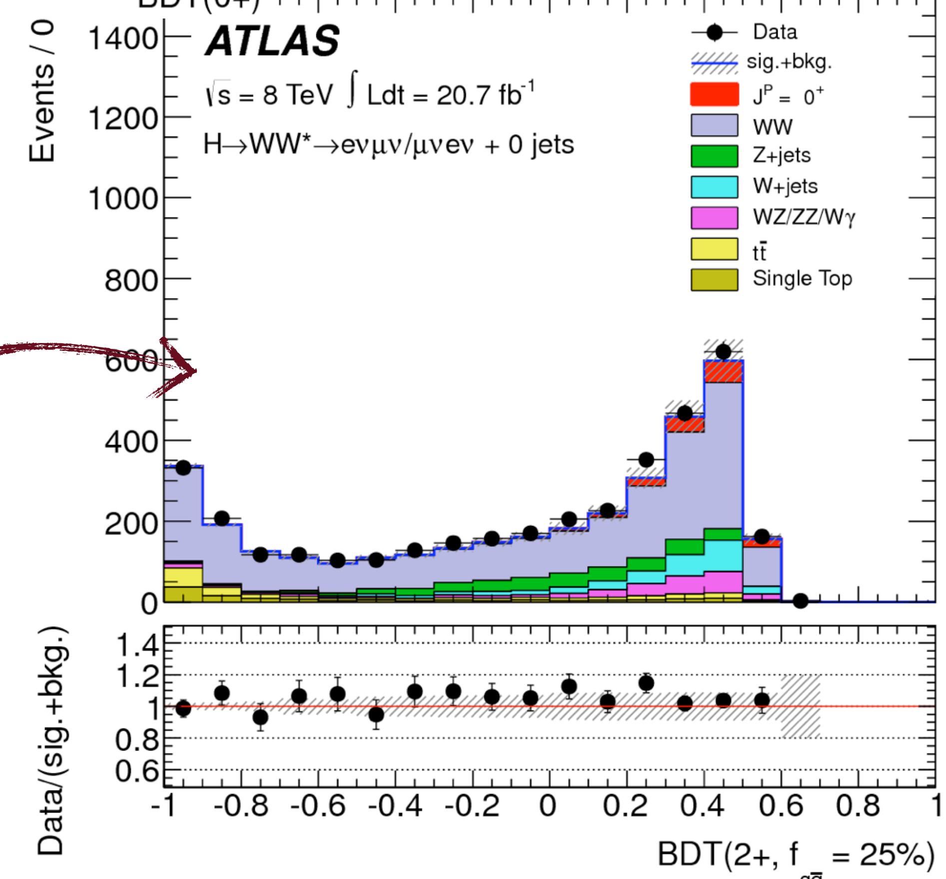
H→WW→lνlν: BDT output



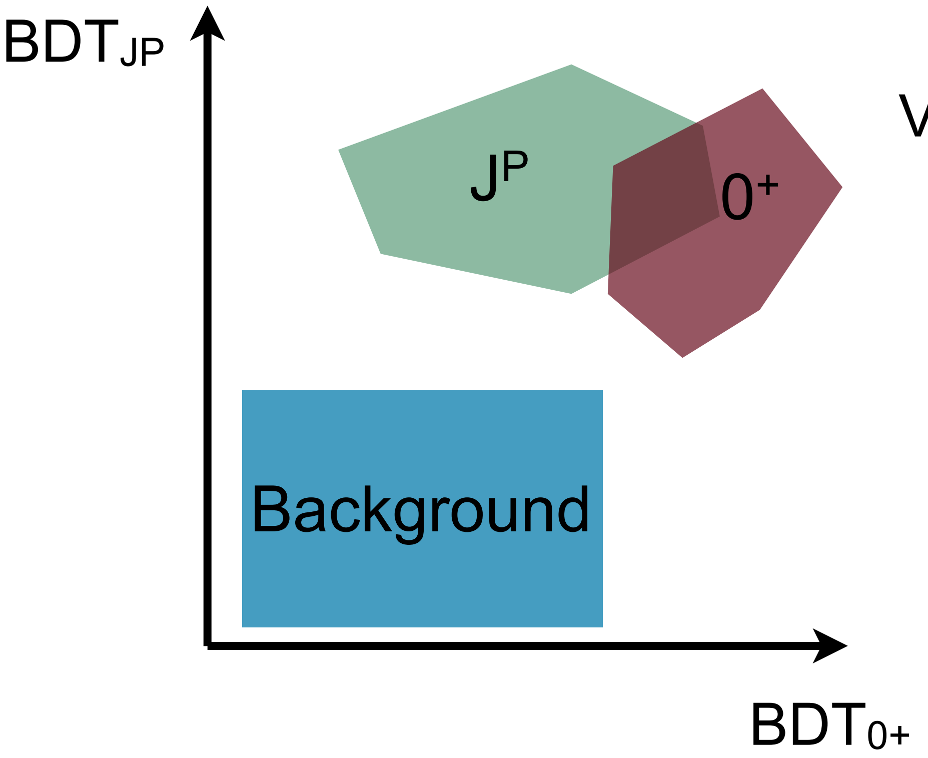


After full selection
3615 candidate events
3300 exp. background
170 exp. SM Higgs boson





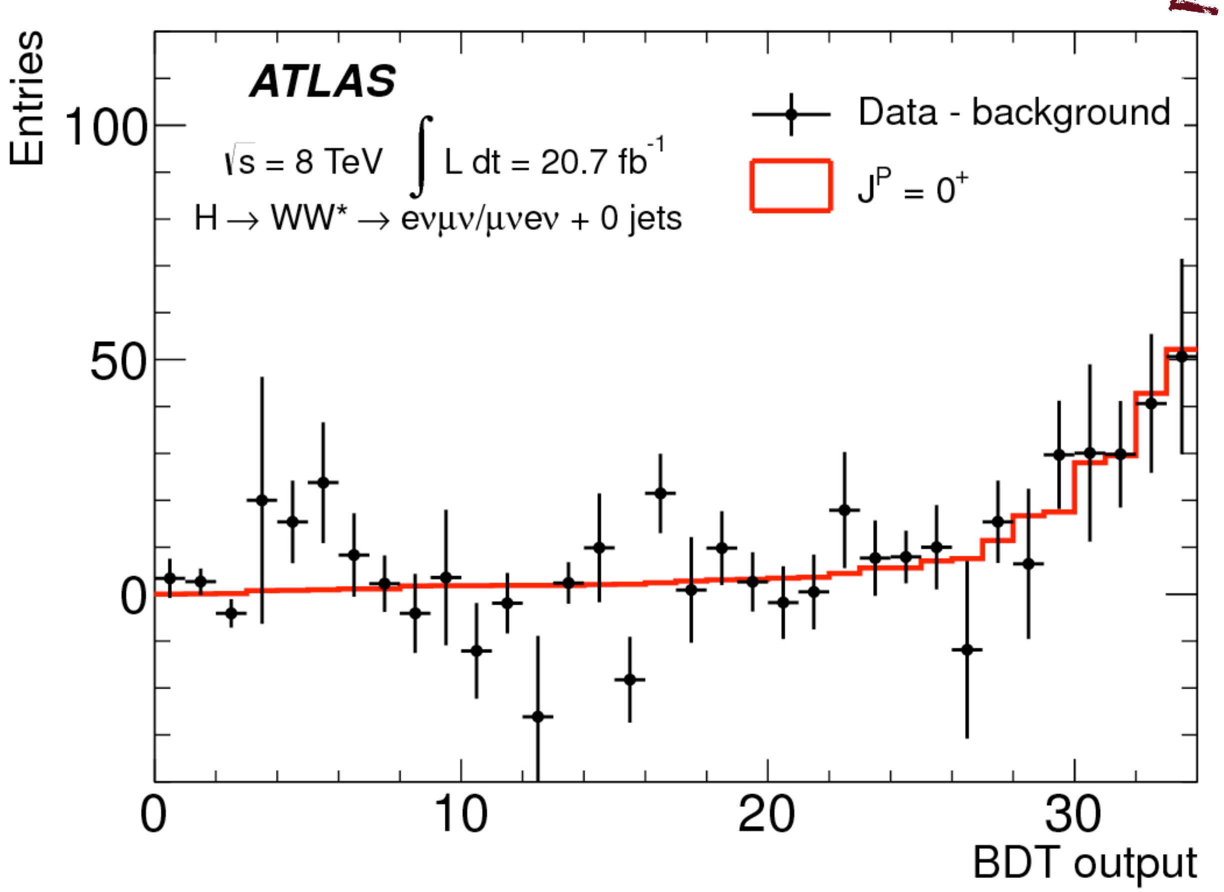
H→WW→lνlν : Post-fit output

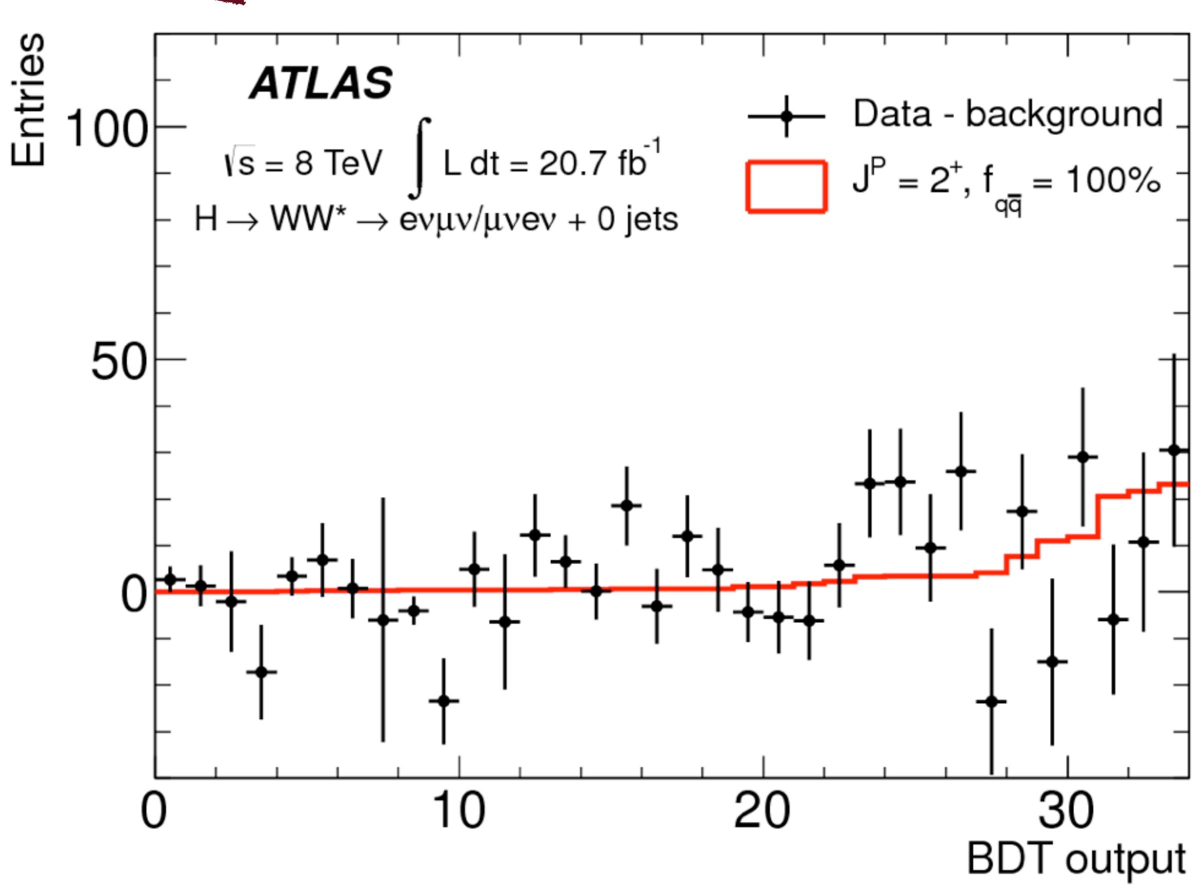


Visualization of the results in the post-fit background-subtracted plots

Data more consistent with spin-0 with respect to spin-2

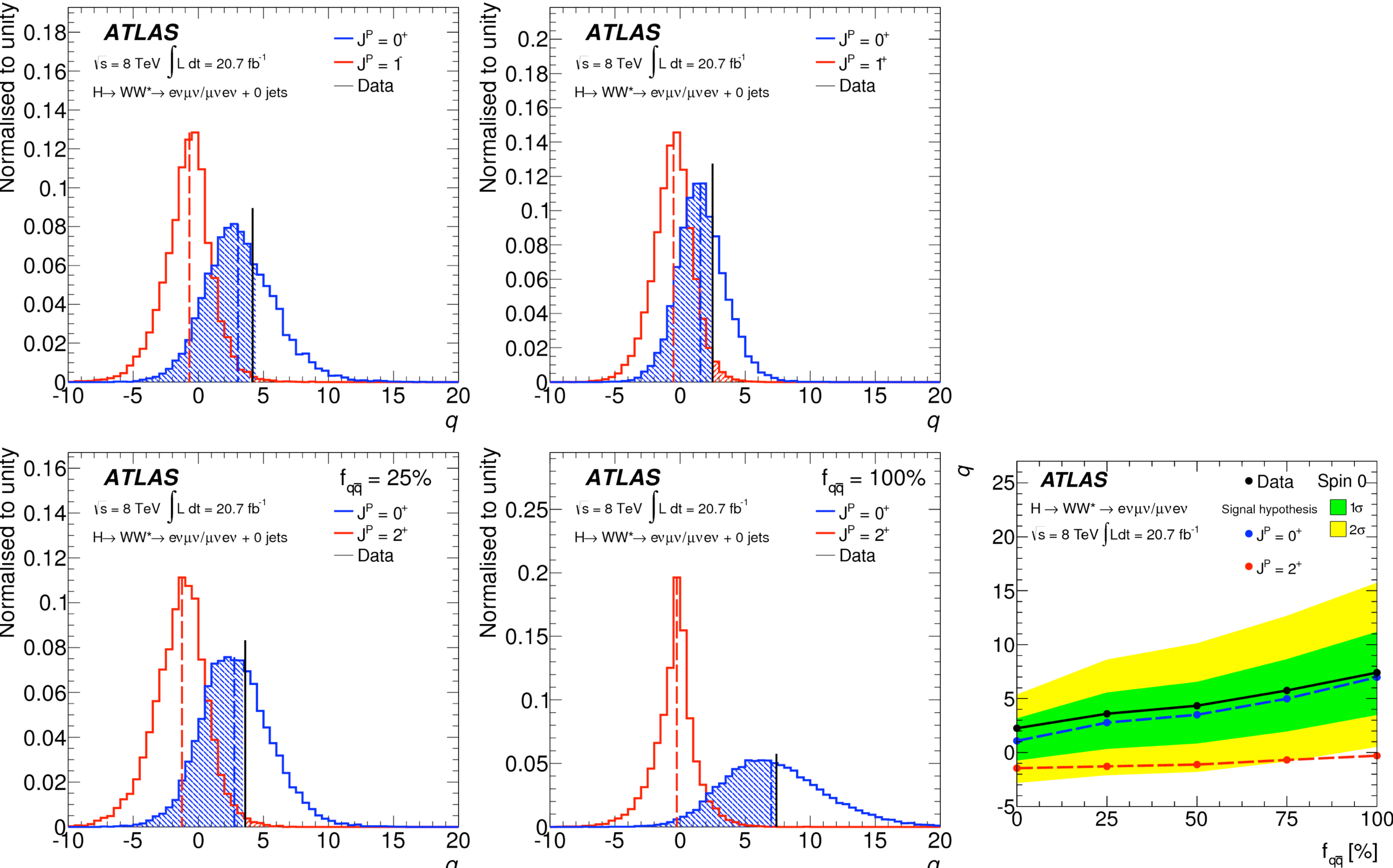
The (BDT_0,BDT_{JP}) distribution is remapped into an 1D distribution by ordering the bins by increasing expected signal. Empty bins (expected content <0.1) are removed.





Data described better by spin-0 with respect to spin-2 (100% qqbar)

H→WW→lνlν: LLR 0⁺ vs 1± and 2⁺



H→WW→lνlν: Results Overview

Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$\mathrm{CL_s}(J^P = 1^+)$	
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08	92%

Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$\mathrm{CL_s}(J^P = 1^-)$	
$H \to WW^*$	0.06	0.02	0.66	0.006	0.017	98.3%

$H \to WW^*$

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$\mathrm{CL_s}(J^P = 2^+)$	
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$	>99.9%
75%	0.028	0.003	0.586	0.001	0.003	99.7%
50%	0.042	0.009	0.616	0.003	0.008	99.2%
25%	0.048	0.019	0.622	0.008	0.020	98.0%
0%	0.086	0.054	0.731	0.013	0.048	95.2%

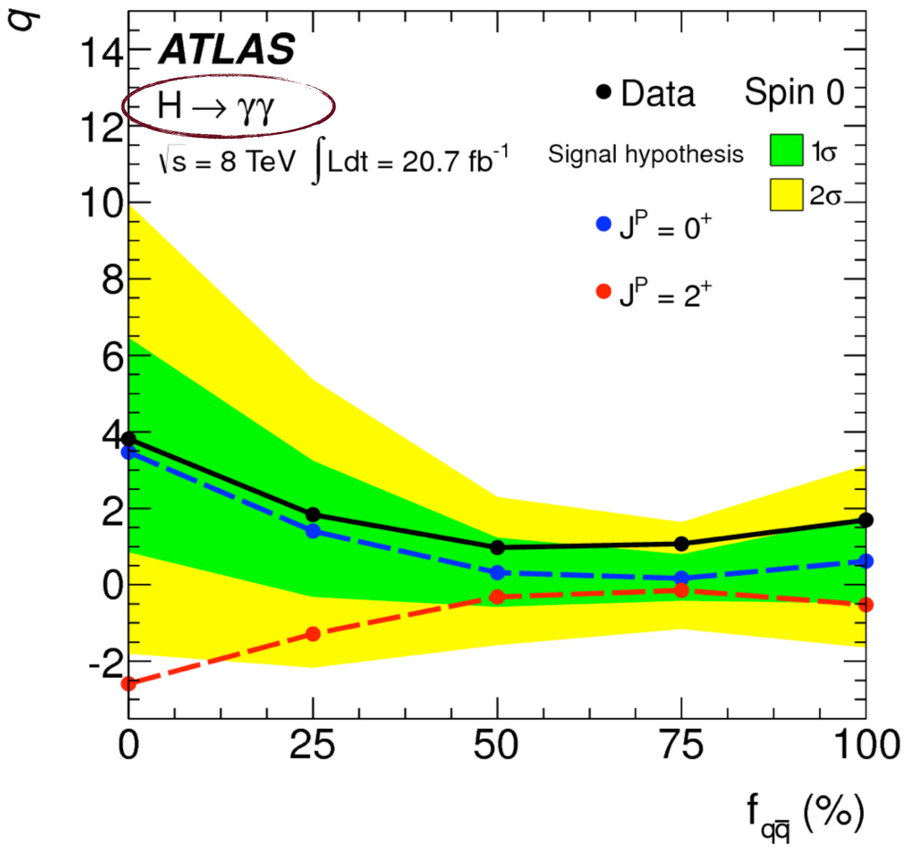
All alternative hypotheses are disfavored with respect to the 0^+ hypothesis.

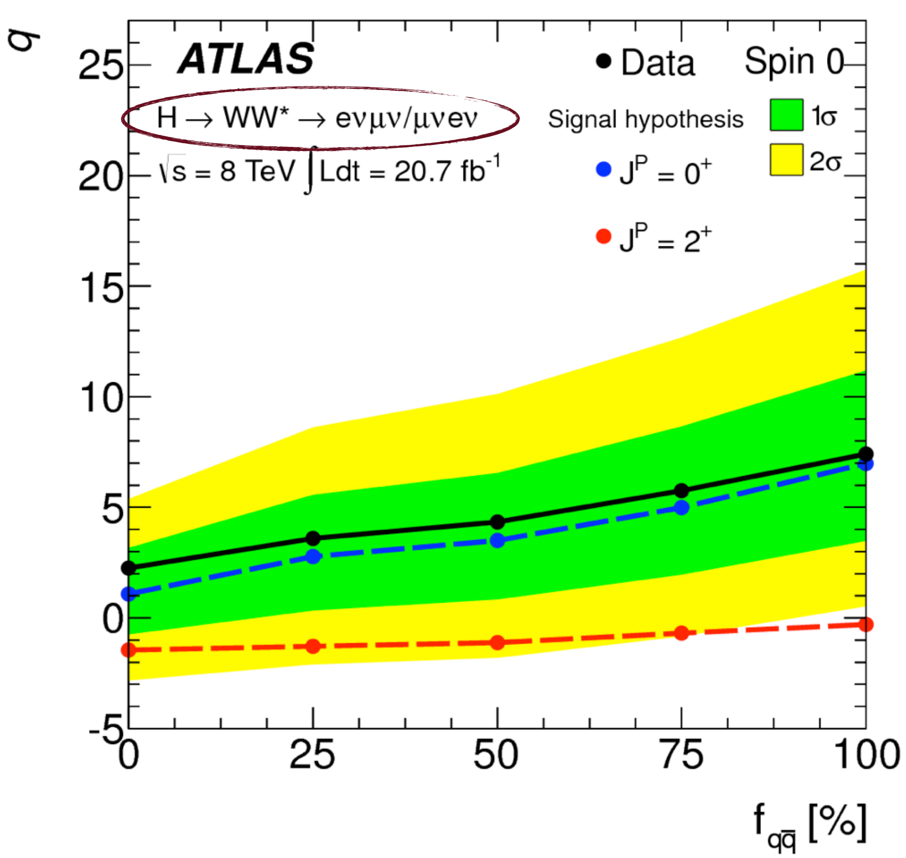
Combination

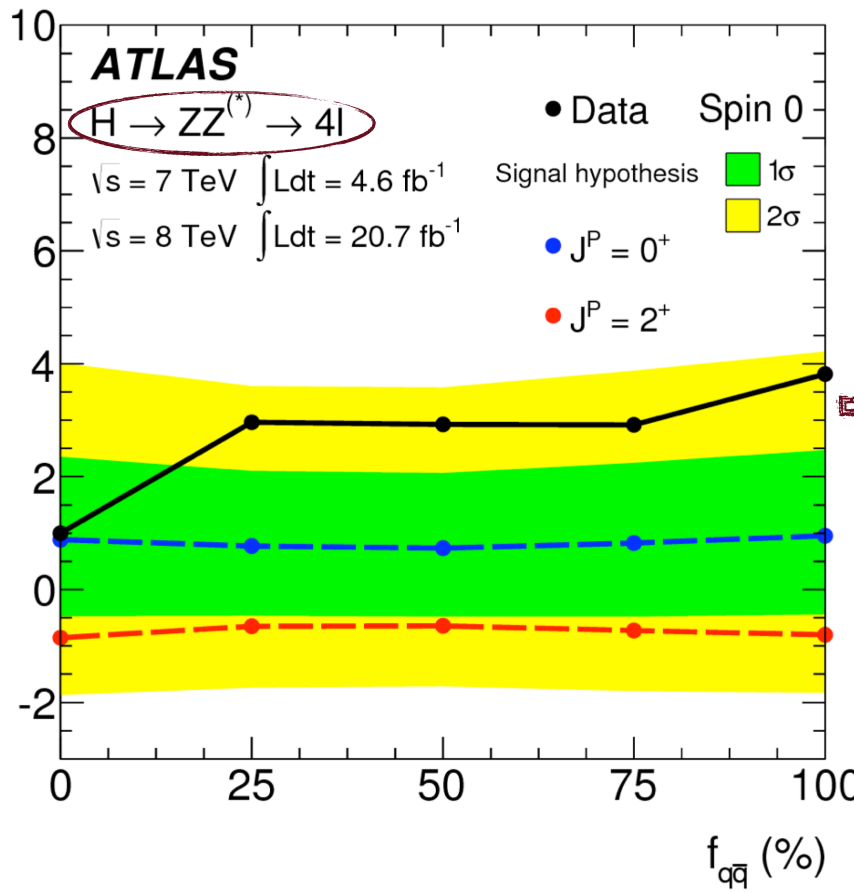
Channel	$H \to ZZ^{(*)} \to 4\ell$	$H \to WW^{(*)} \to \ell\nu\ell\nu$	$H \to \gamma\gamma$
Dataset	20.7 fb^{-1} @ 8 TeV 4.8 fb^{-1} @ 7 TeV	20.7 fb^{-1} @ 8 TeV	20.7 fb^{-1} @ 8 TeV
Reference	ATLAS-CONF-2013-013	ATLAS-CONF-2013-031	ATLAS-CONF-2013-029
Signal	JHU⊕PYTHIA	PowHeg/JHU⊕PYTHIA	PowHeg/JHU⊕PYTHIA
0^-	✓	-	-
1^+	✓	✓	-
1^-	✓	✓	-
2^+	✓	✓	✓

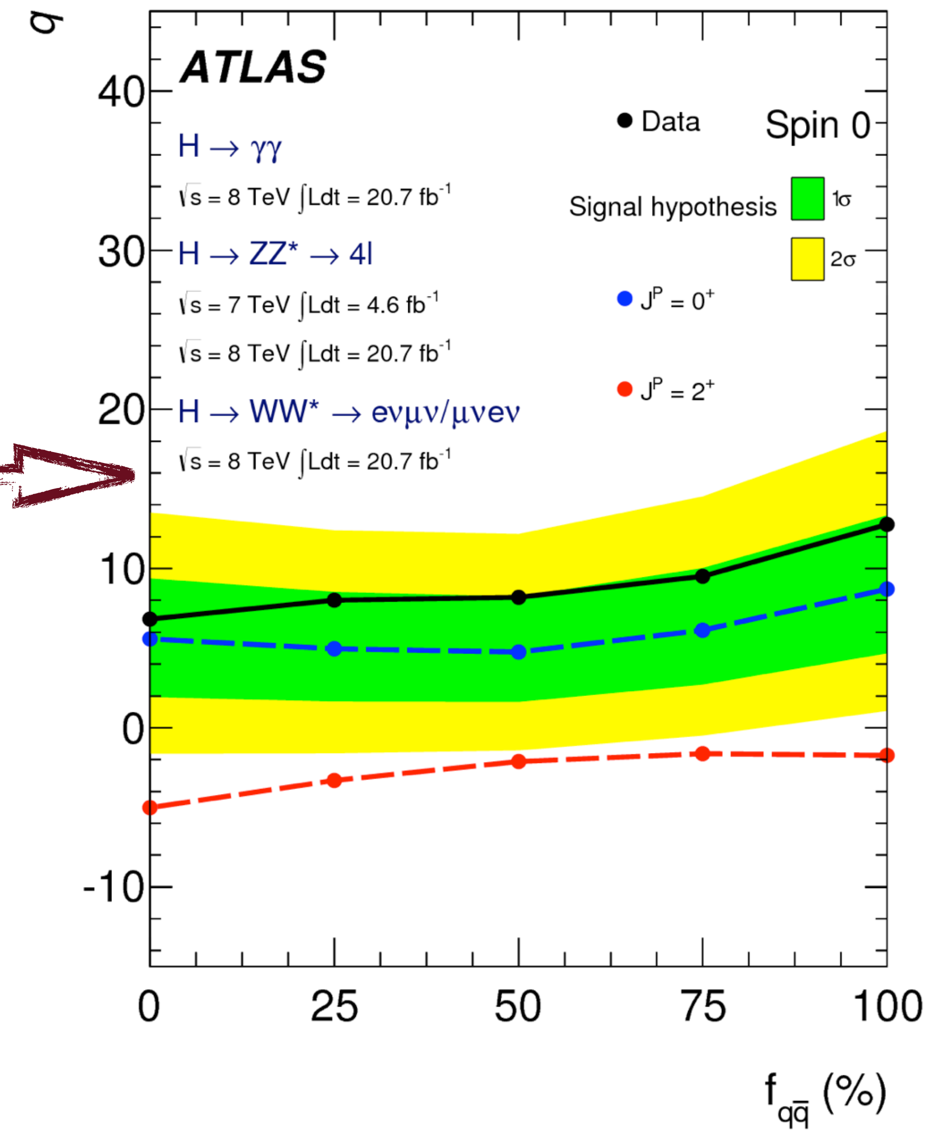
A note on systematic uncertainties:
- e/μ reconstruction,identification and trigger efficiencies and energy/momentum resolution uncertainties correlated between H→ZZ*→4l and H→WW*→lvlv
- e/γ energy scale correlated across all channels
- effect of mass measurement uncertainty negligible
- overall impact (by comparing results w/ and w/o profiling) estimated to be <0.3σ
- Higgs boson p_T spectrum small effect <0.1σ

Combination: The case of 0^+ vs 2^+

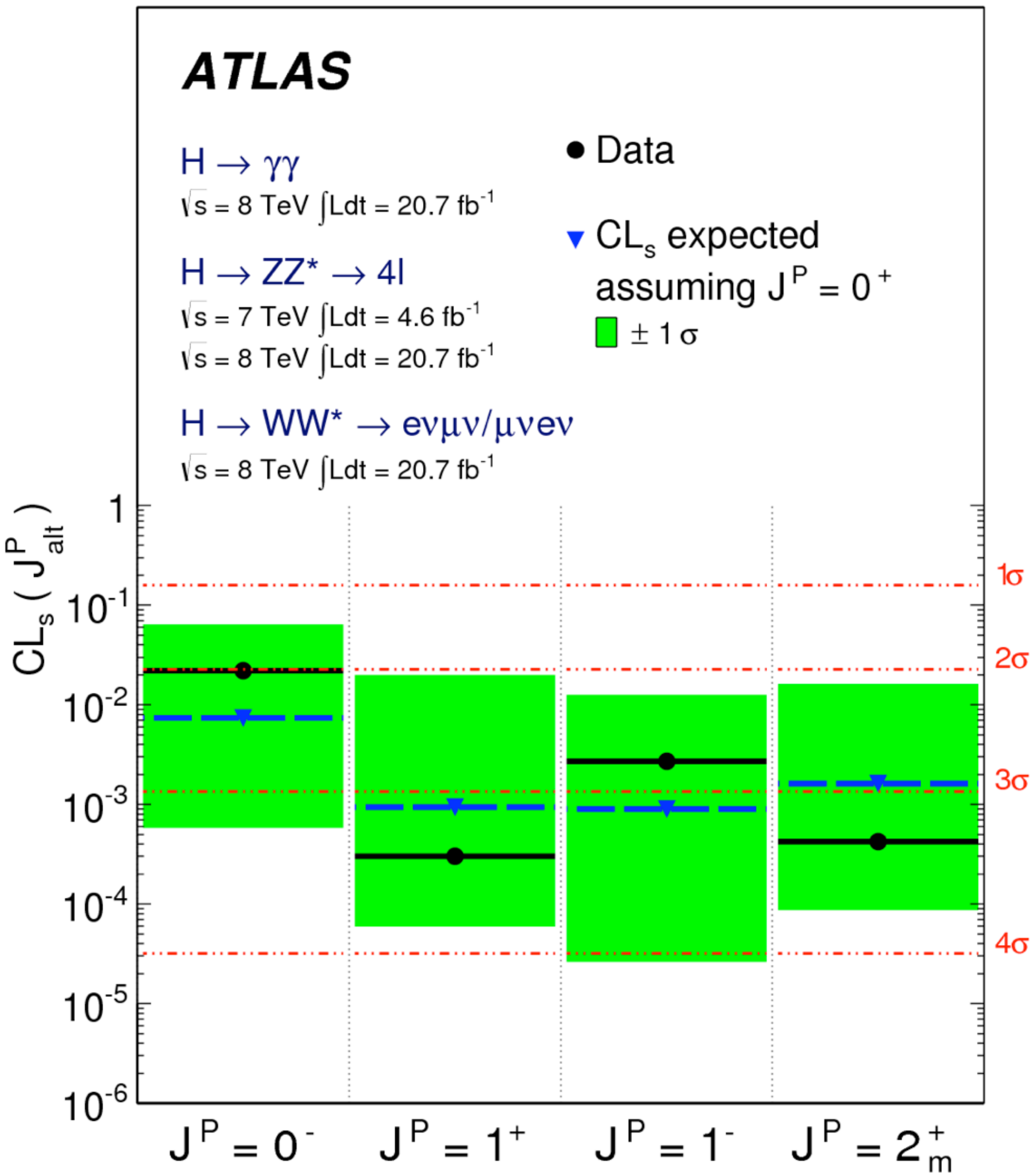


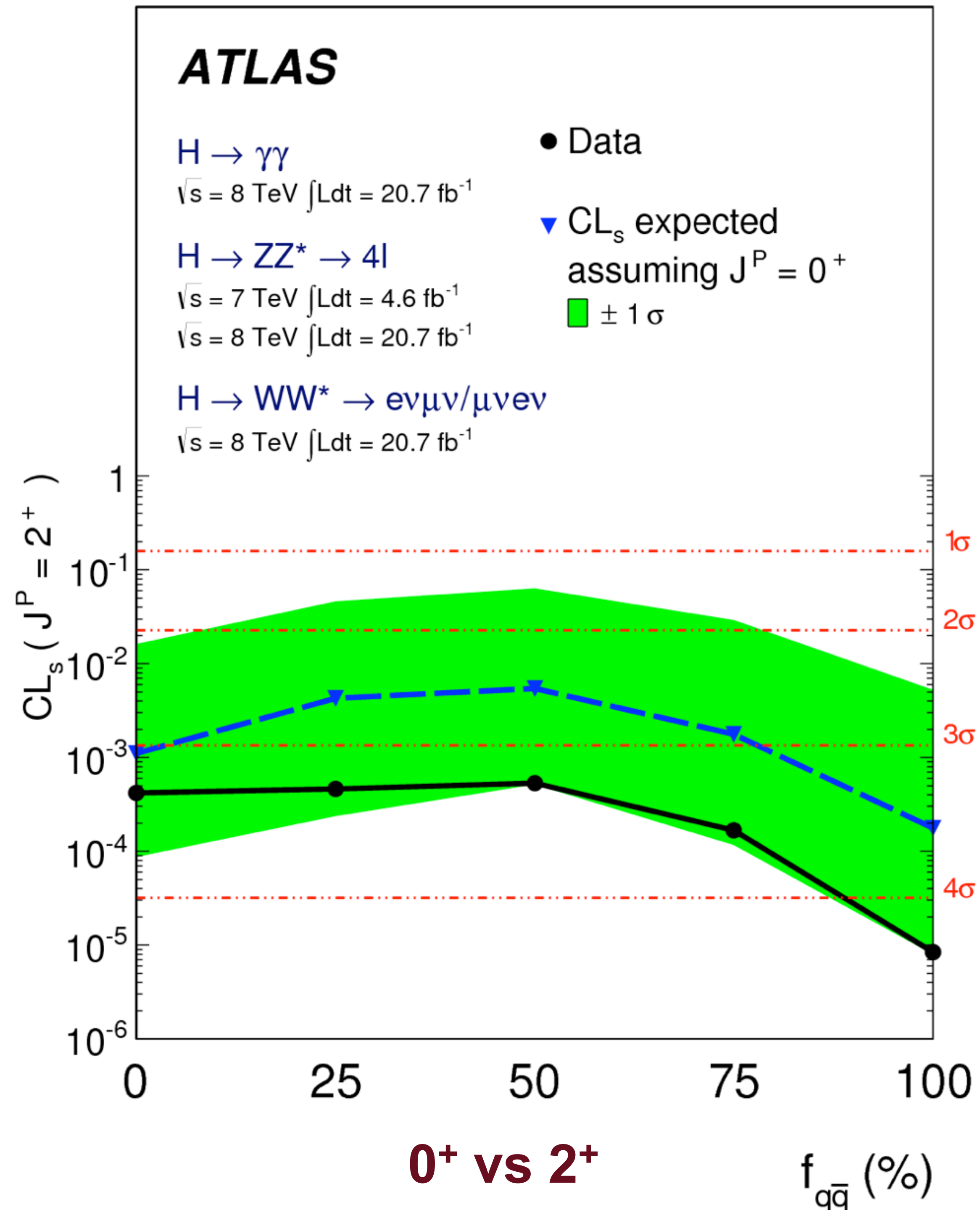






Combination: Results Overview





0^+ vs 0^-	0^+ vs 1^+	0^+ vs 1^-	0^+ vs 2^+
97.8%	>99.9%	99.7%	>99.9% for all f_{qq}

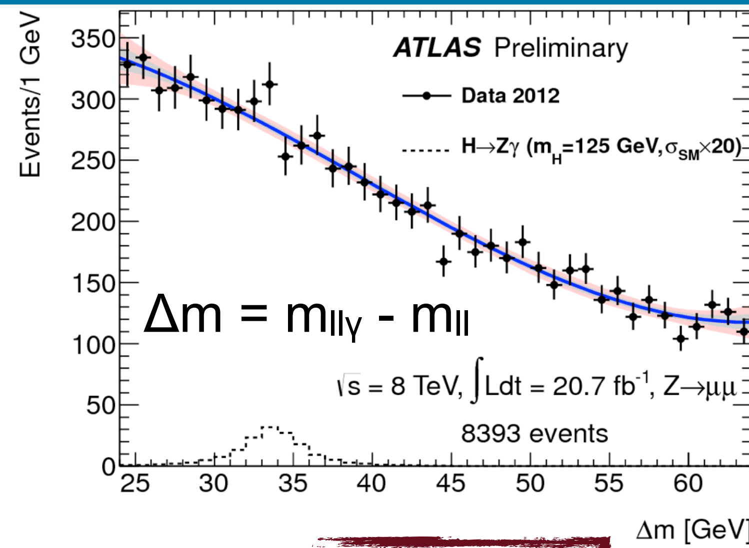
All alternative hypotheses are strongly disfavored with respect to the 0^+ hypothesis.

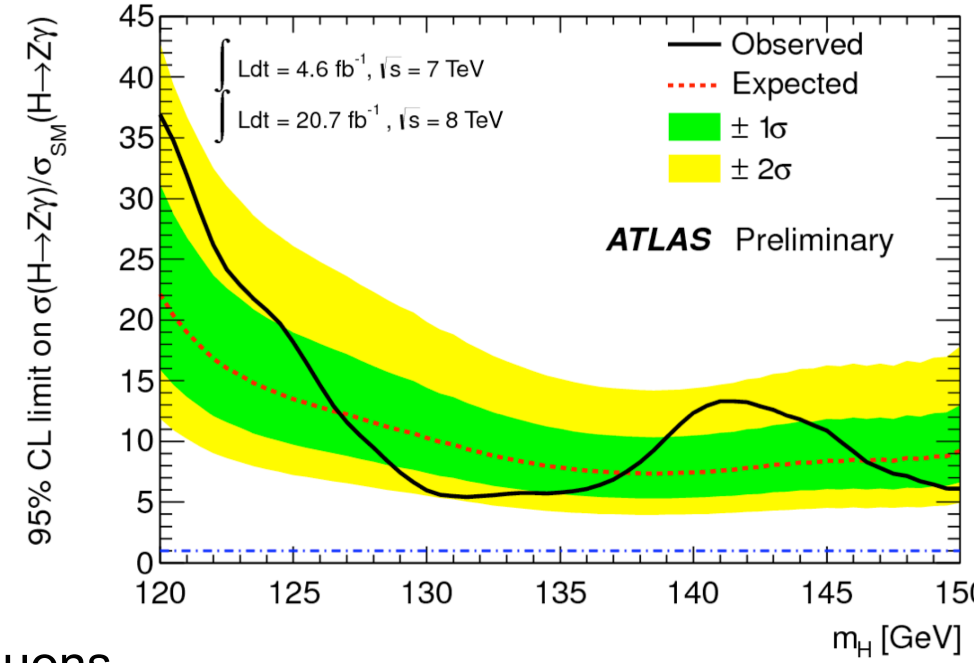
Rare/Anomalous decays

"Rare" Higgs boson decays

H→Zγ

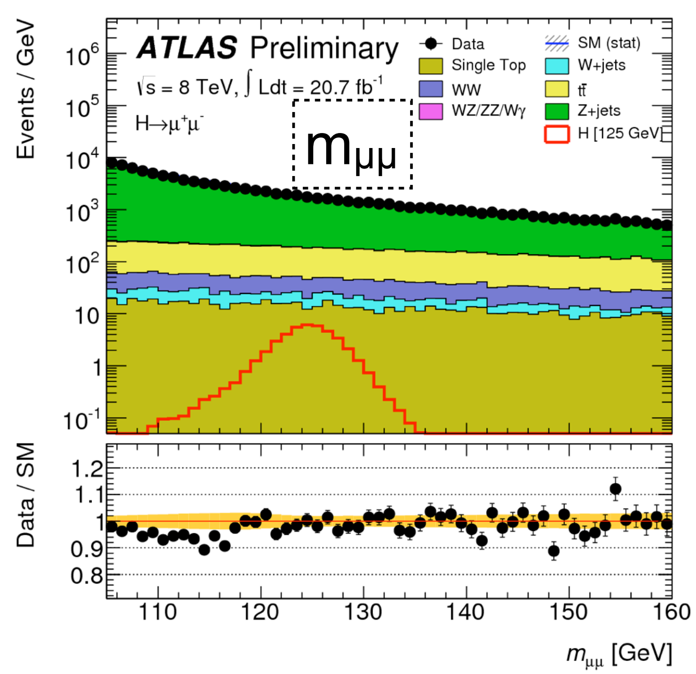
- loop induced → sensitive to new physics
- small BR; S/B~0.01
- signature: same-flavour opposite-charge isolated leptons + photon
- m_H=125 GeV:
  95% CL upper limit 18.5 (13.5) x SM

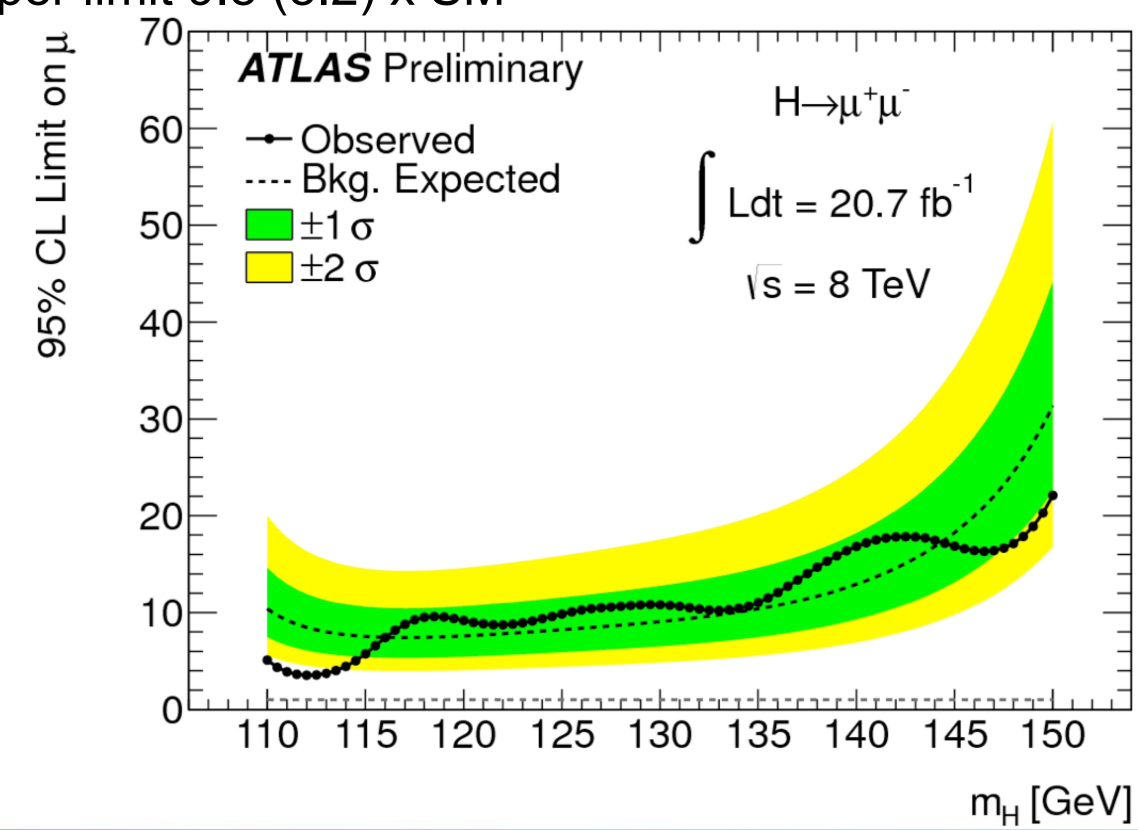




H→μμ

- probe directly the coupling to muons
- small BR; S/B ~ 0.002
- select two opposite-charge muons (pT>25,15 GeV, $pT_{\mu\mu}$>15 GeV)
- backgrounds: Z/γ*→μμ, top, dibosons
- m_H=125 GeV: 95% CL upper limit 9.8 (8.2) x SM

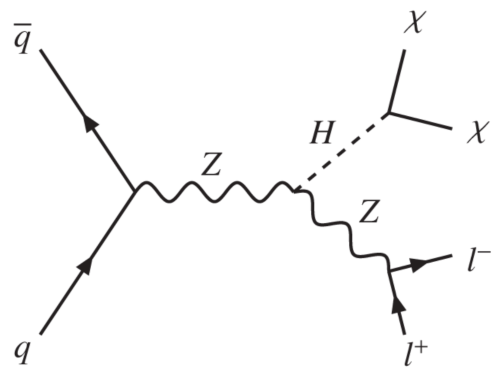




more channels being looked at:
ttH, with H→bb, H→γγ,
VBF H→bb, etc

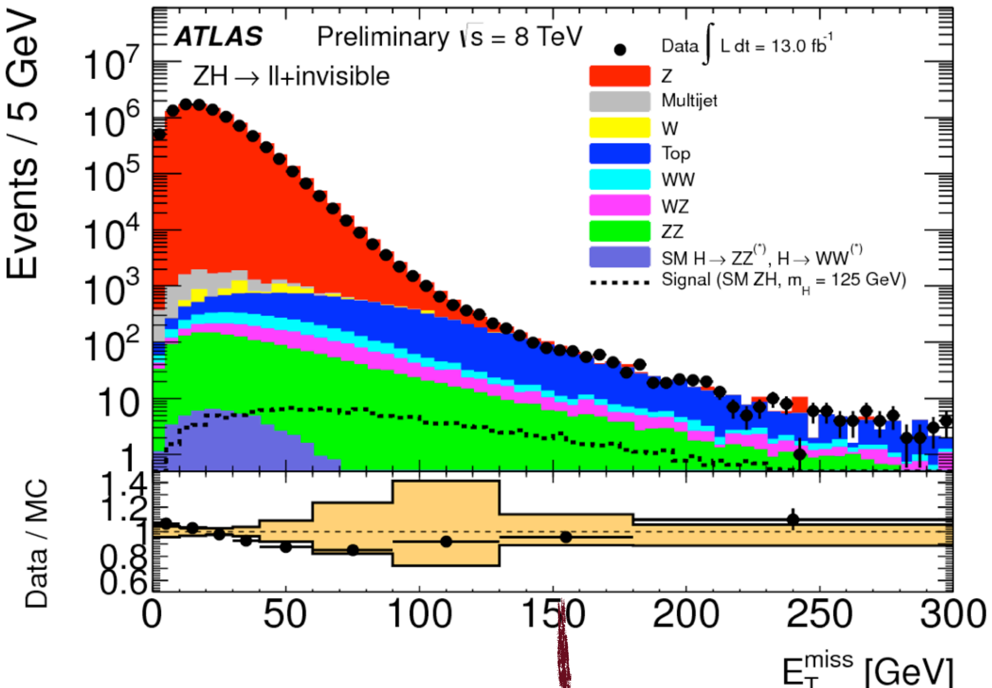
“Invisible” Higgs boson decays

“Invisible” decays are suppressed in SM → Observation would be direct indication of New Physics!

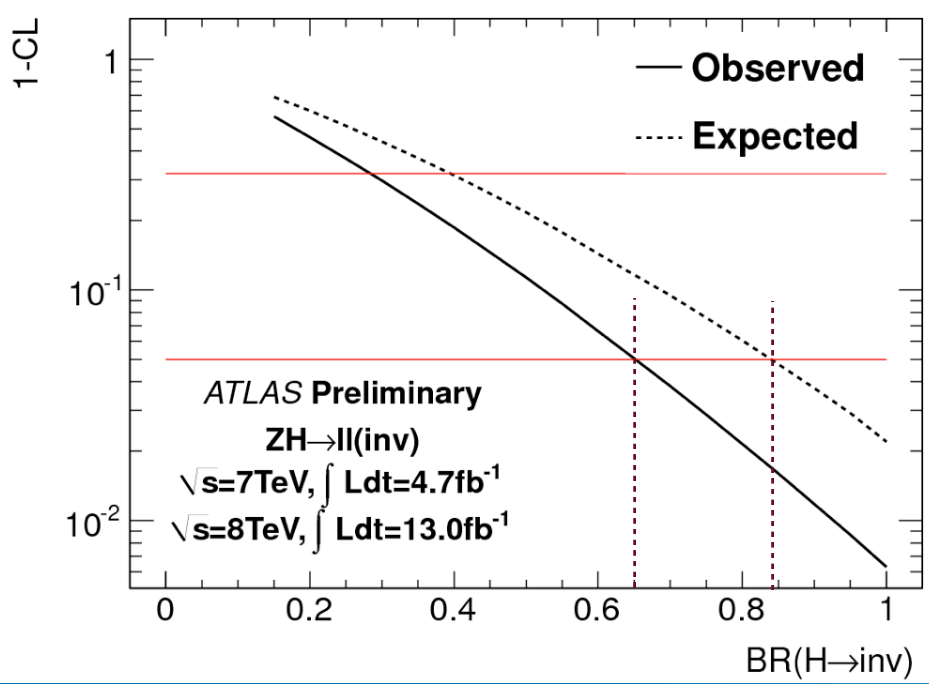


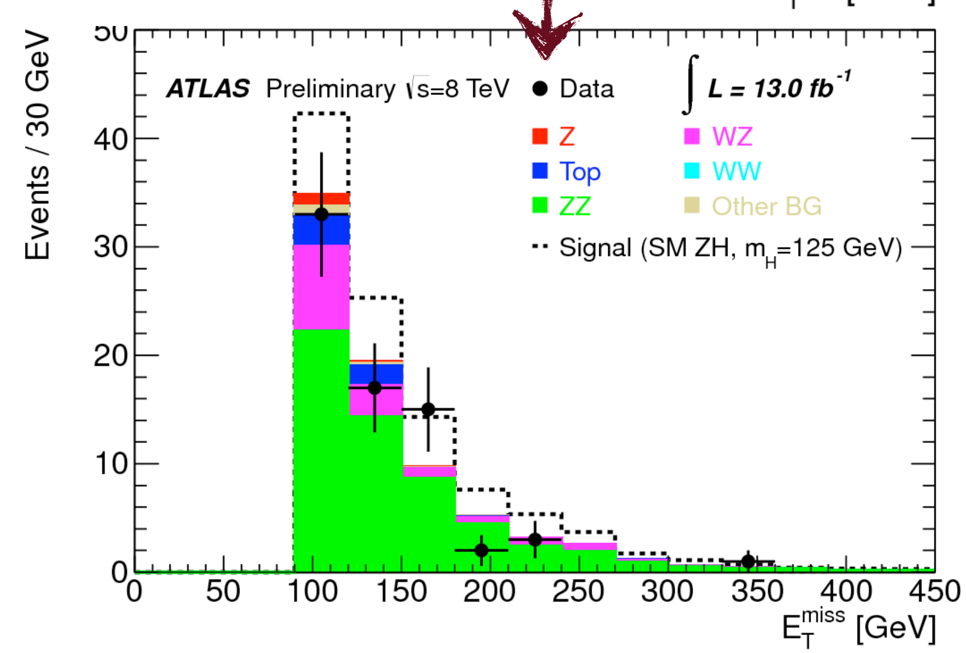
- Signature : Z→ee/μμ + large MET
- Main Backgrounds: ZZ→llνν, WZ→lνll, WW→lνlν
- Require MET > 90 GeV and optimize selection for ZH-like events

	Expected SM Backgrounds	Observed
7 TeV/4.7 fb^{-1}	32.7 ± 1.0 (stat) ± 2.6 (syst)	27
8 TeV/13.0 fb^{-1}	78.0 ± 2.0 (stat) ± 6.5 (syst)	71

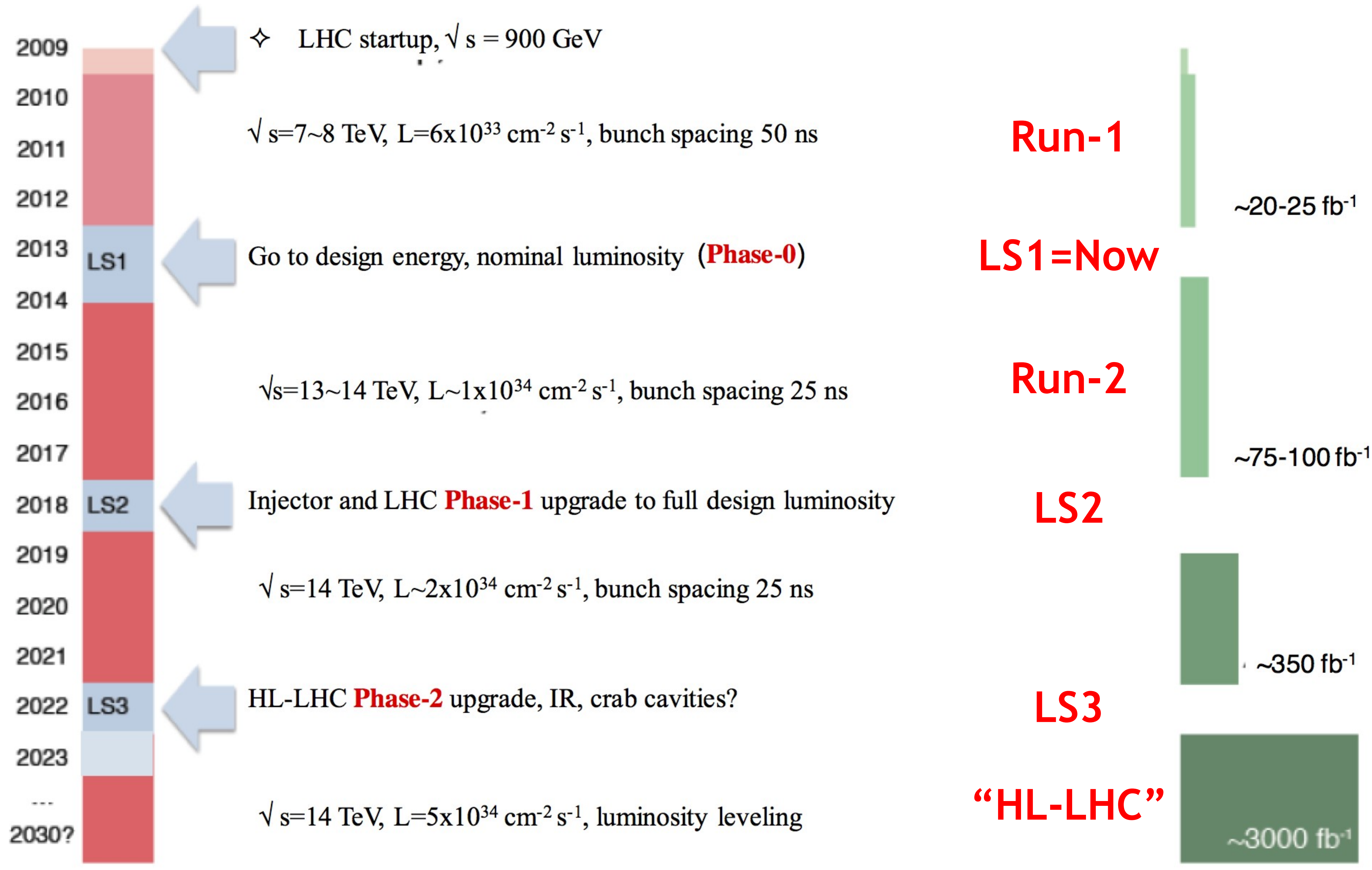


95% CL Upper Limit on the BR(H→invisible) for m_H=125 GeV: is <65% with <84% expected





Higgs boson physics prospects

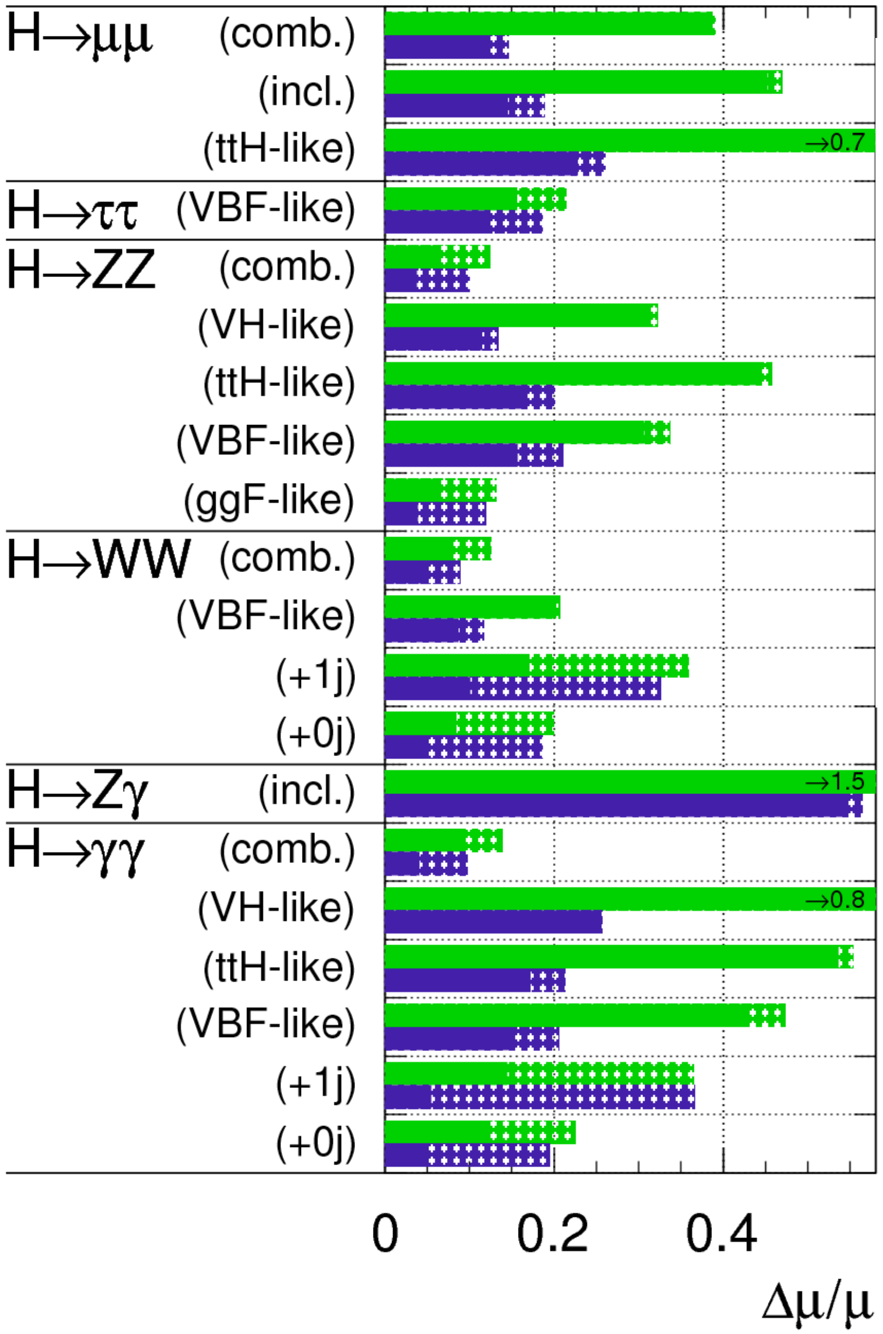


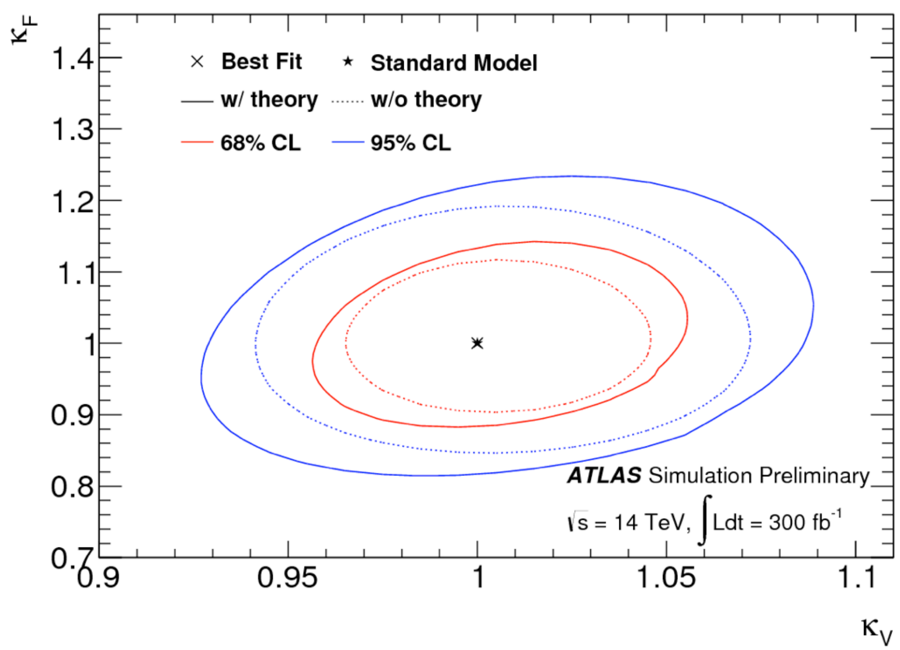
Prospects for Run II/III and HL-LHC

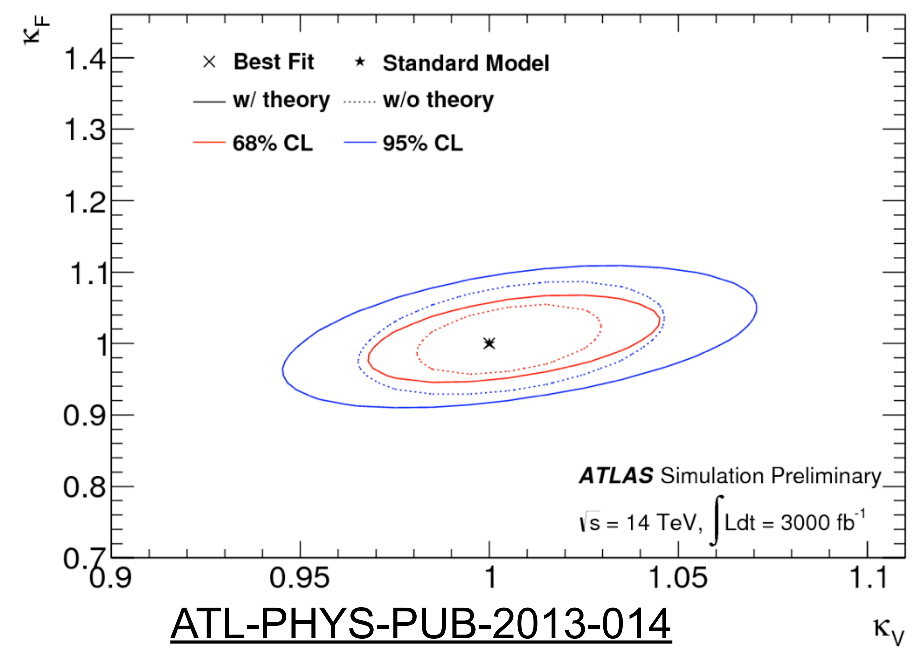
ATL-PHYS-PUB-2013-014

Several open topics in the Higgs sector for future studies:

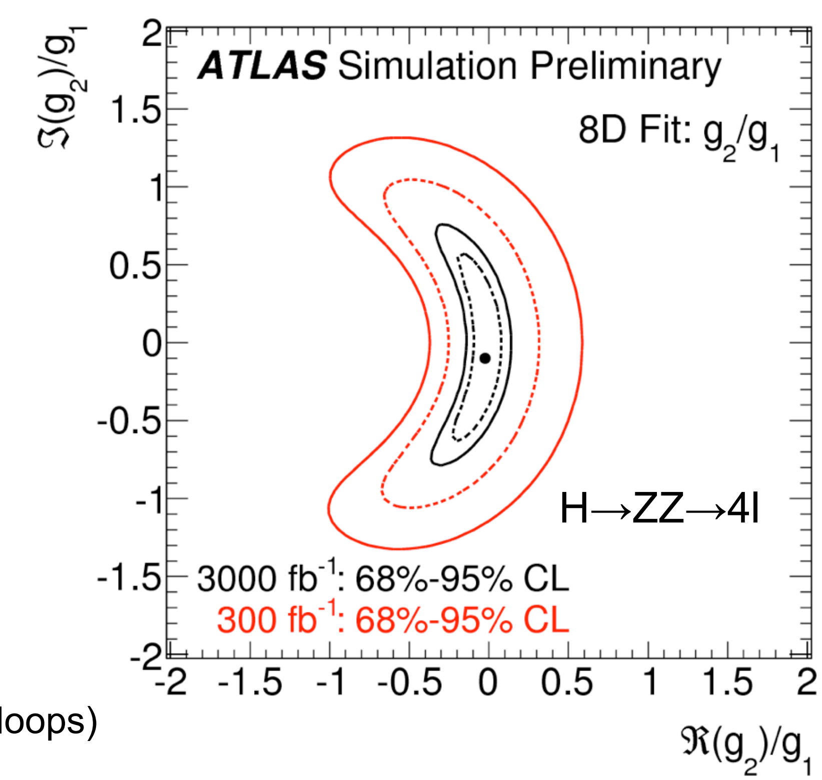
- Rare decays & Couplings
- CP studies
- BSM Higgs boson searches
- Higgs boson pair production

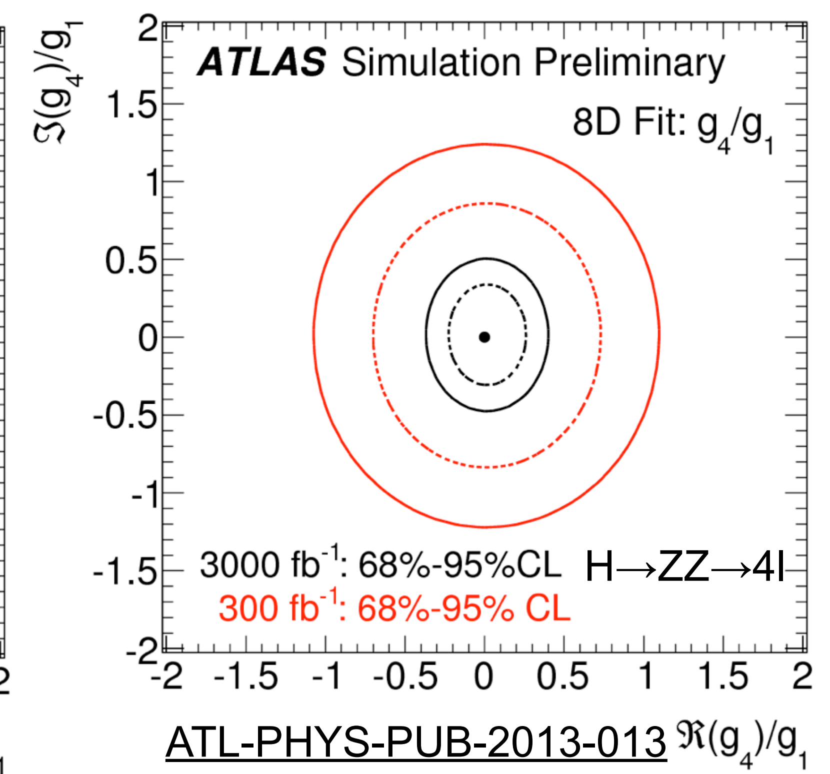






ATL-PHYS-PUB-2013-014





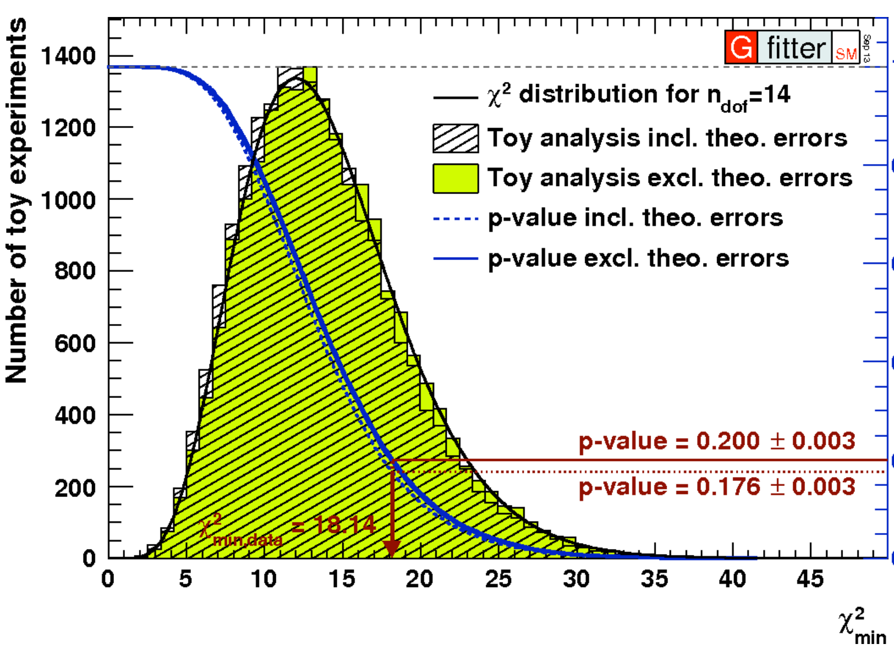
ATL-PHYS-PUB-2013-013

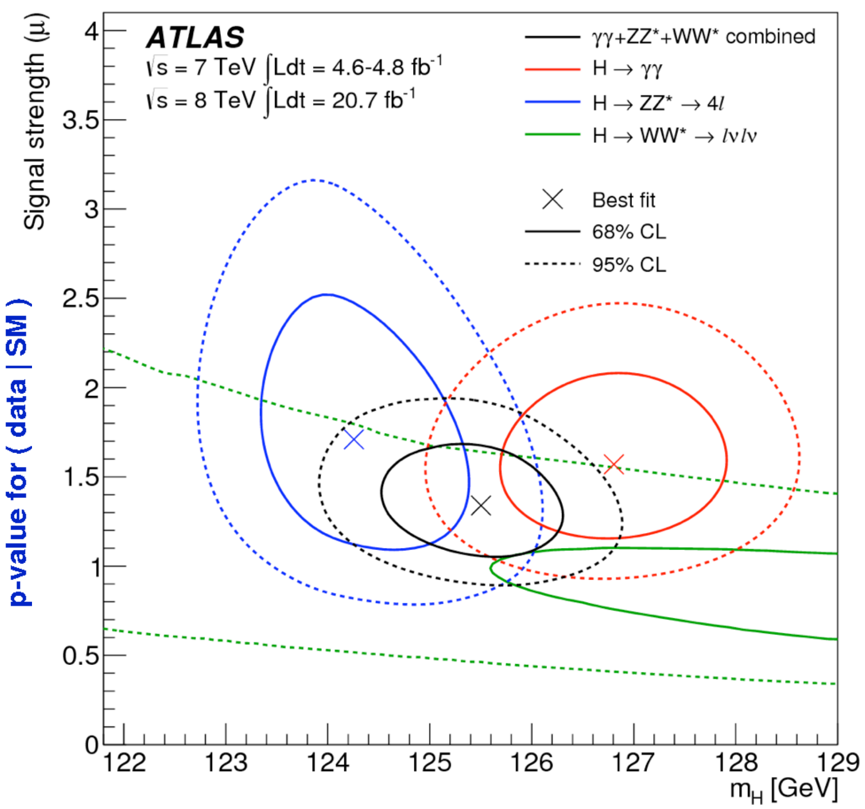
g_1 CP-even HZZ coupling
g_2 CP-even HZZ coupling (loops)
g_4 CP-odd HZZ coupling

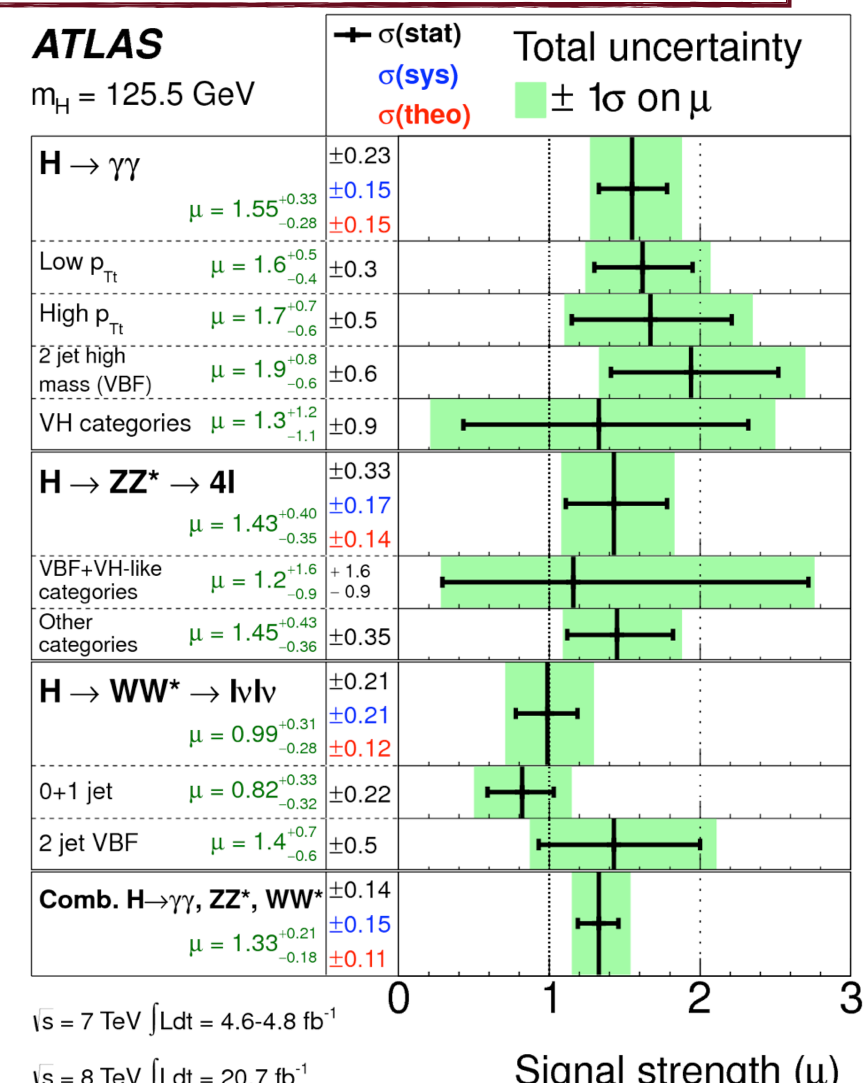
Summary

Convinced, beyond reasonable doubt, of the observation of a boson with m_H~125.5 GeV
Production rates in channels involving vector bosons in good agreement with Standard Model expectation.
$\mu = 1.33^{+0.21}_{-0.18}$ and $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.4^{+0.7}_{-0.5}$
[3.3σ evidence for VBF Higgs boson production, >5σ (indirect) evidence for Higgs coupling to fermions]
Searches for rare/anomalous decays and differential cross-sections have begun to appear

Spin studies strongly disfavor the hypothesis of non 0^+ pure state
- 0^- rejected at 97.8% CL
- $1^+/1^-$ rejected at >99.9% (99.7%) CL
- 2^+ rejected at >99.9% CL for all f_{qq}





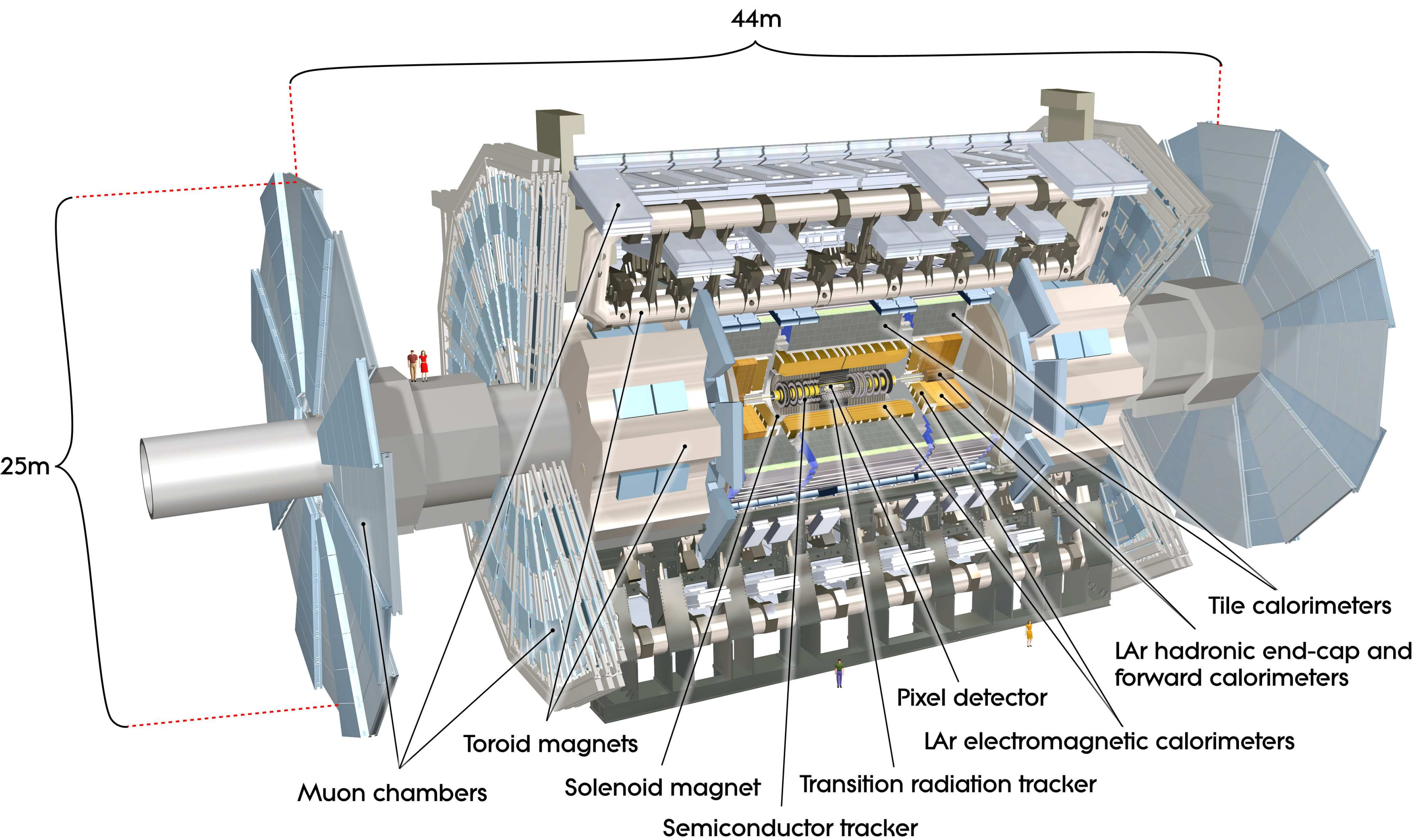


The new particle is a SM-like Higgs boson
No the end of the story... just a new window to understand Nature!
Is it the only Higgs boson? Do its properties deviate from the SM predictions?
At which level? Does it couple to dark matter?
LHC Run II/III and HL-LHC could provide answers to some of these questions

Additional Slides

A Toroidal LHC ApparatuS (2011)

⇒ General purpose detector designed for the harsh LHC environment

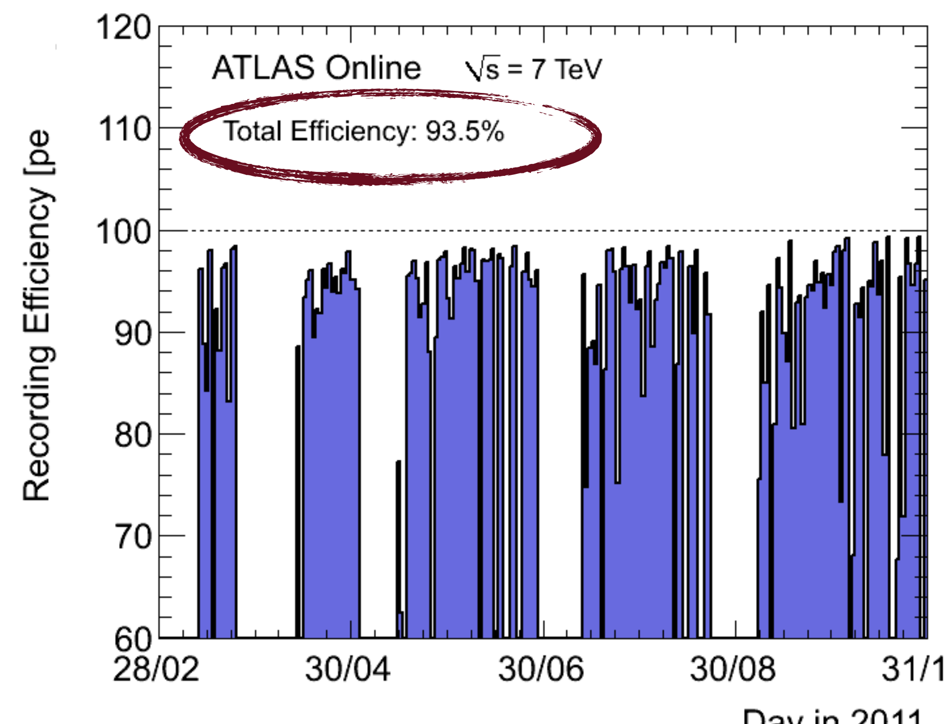


	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling LAr technology
Hadron Calorimetry	plastic scintillator (barrel) LAr technology (endcap)
Muon	independent system with trigger capabilities
Trigger	3 Level Implementation from 40 MHz to 400 Hz

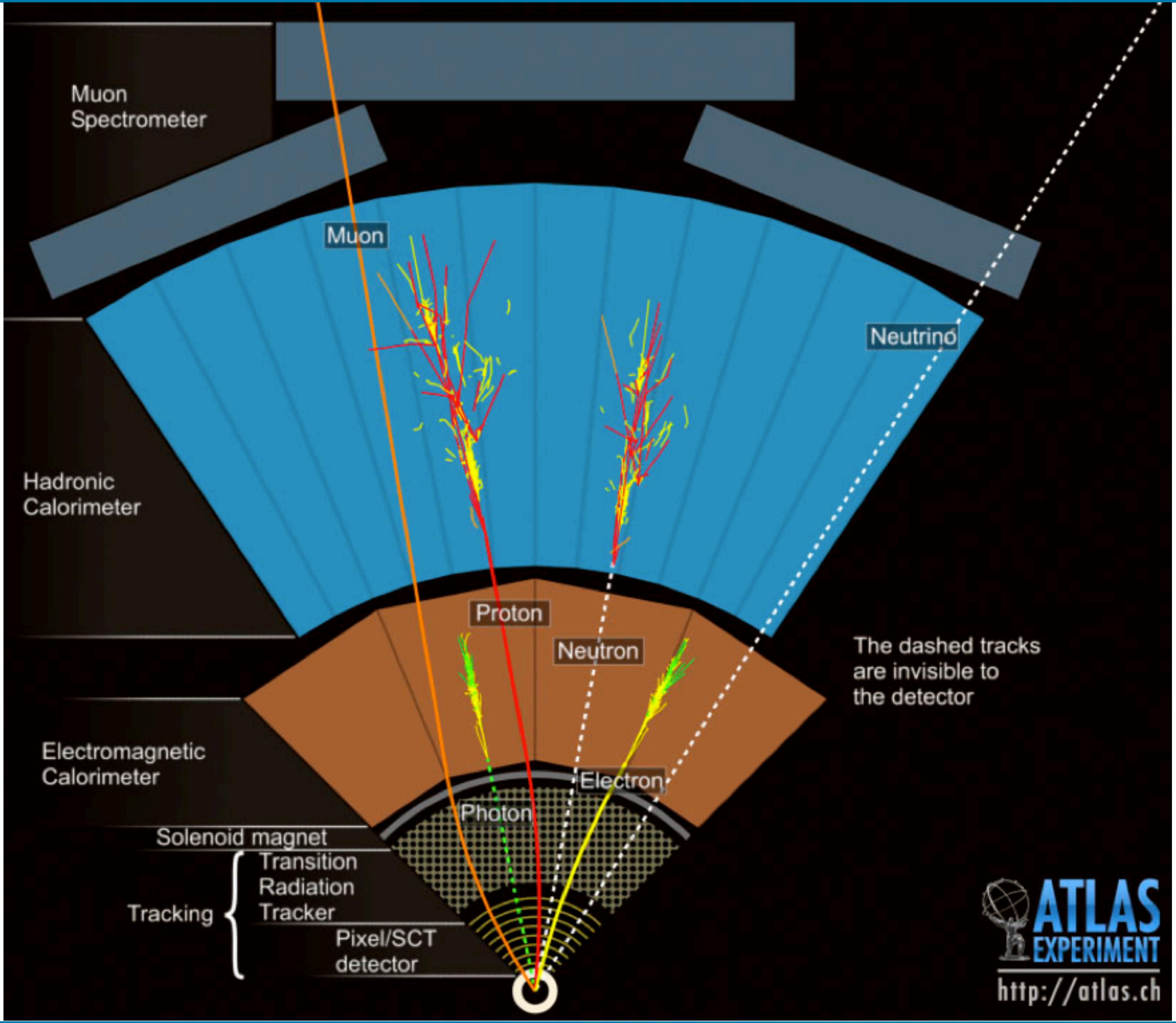
⇒ Very important to ensure high data-taking efficiency/quality

ATLAS p-p run: March-October 2011										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	96.9	99.2	99.4	98.8	99.4	99.1	99.8	99.3
All good for physics: 89.9%										

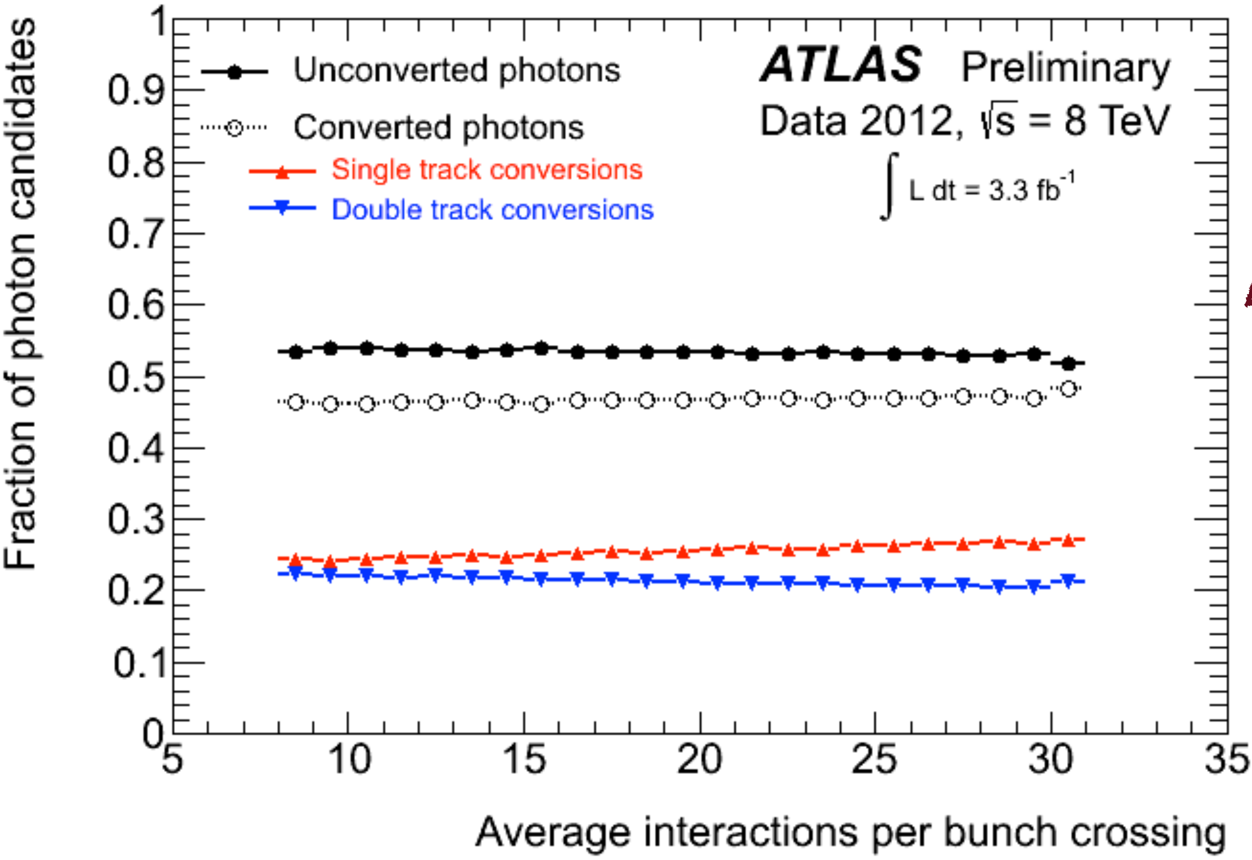
Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and October 30th (in %) - corresponding to 5.2 fb^{-1} of recorded data. This data quality status refers to the data after the summer reprocessing campaign.



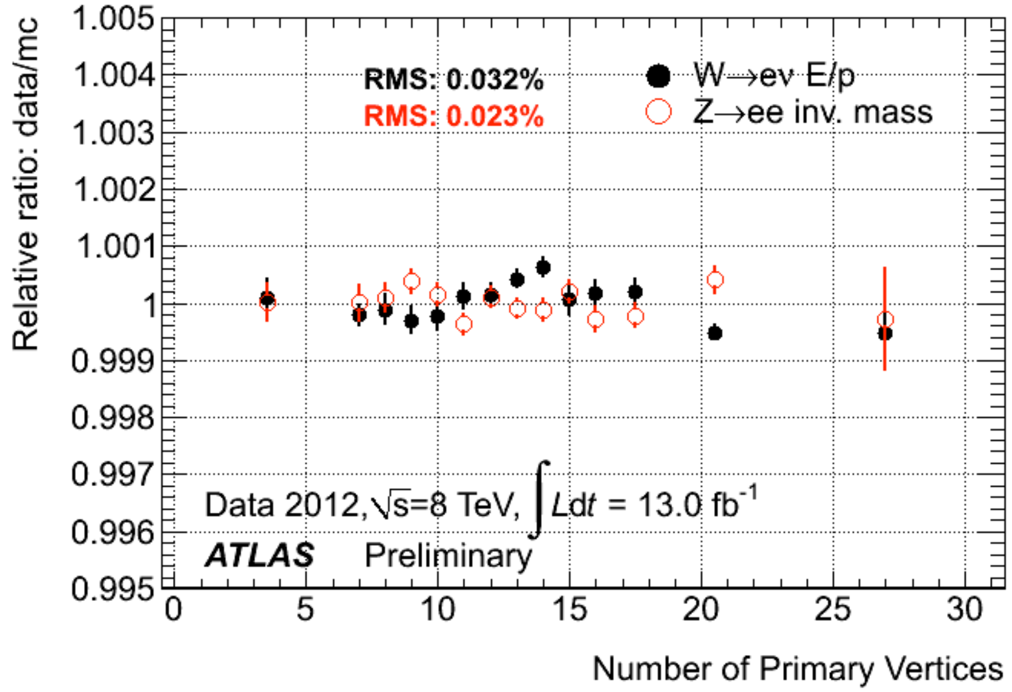
High Energy Physics Particle detectors



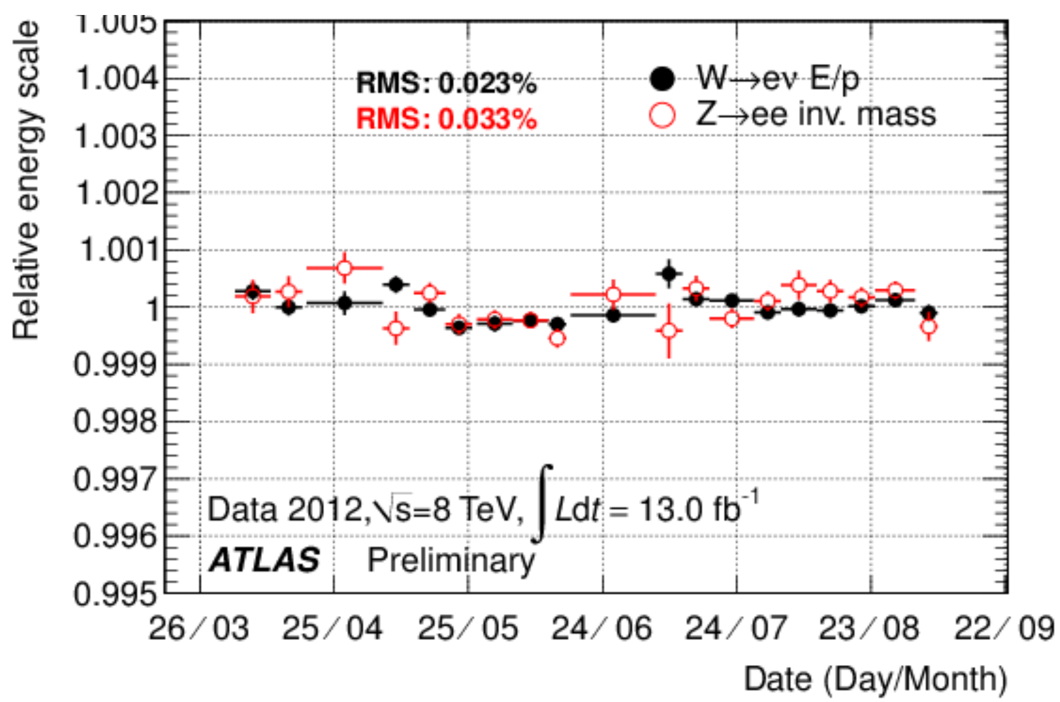
ATLAS Performance: Photons and EM response



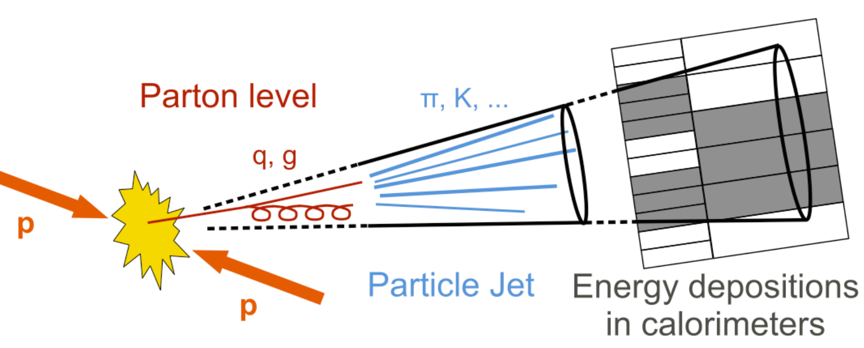
Stable photon reconstruction vs pile-up (within 1%)

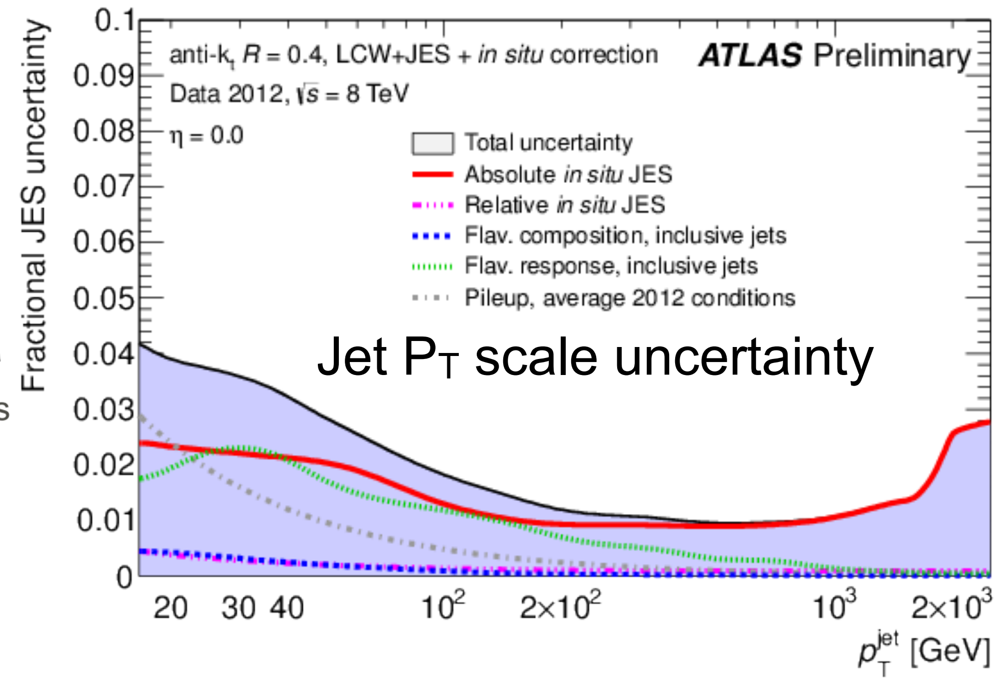


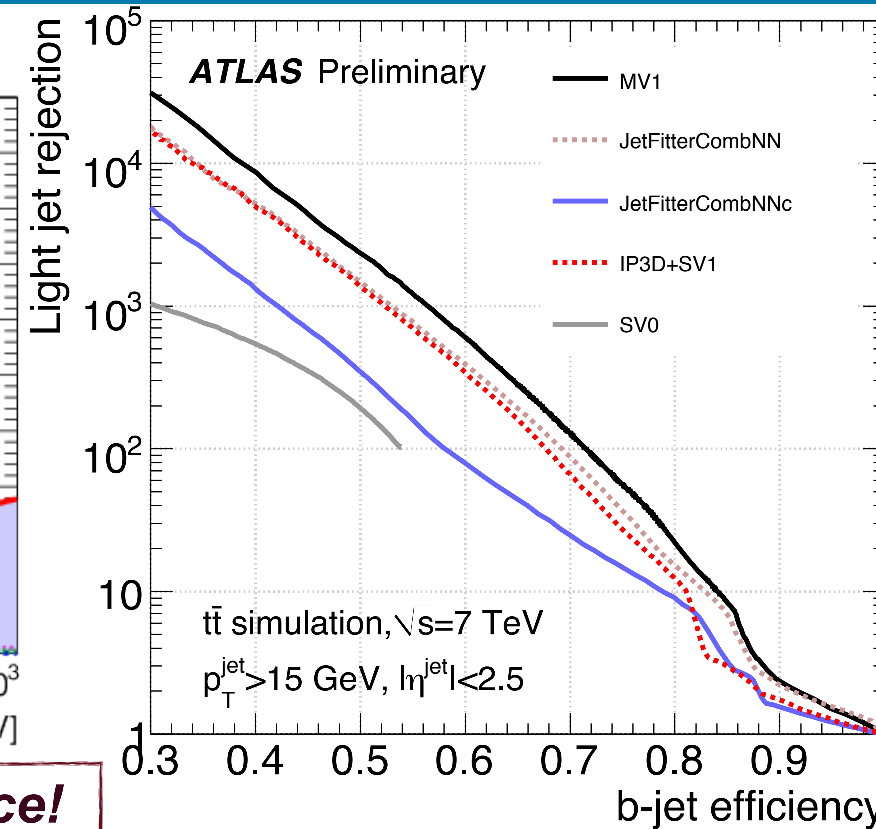
- Excellent stability of the EM calorimeter response!
  - Studied with Z,J/ψ→ee and W→eν events
  - Energy scale at m_Z known to ~0.3%
  - Uniformity ~1% (2.5% for 1.37< |η|<1.8)



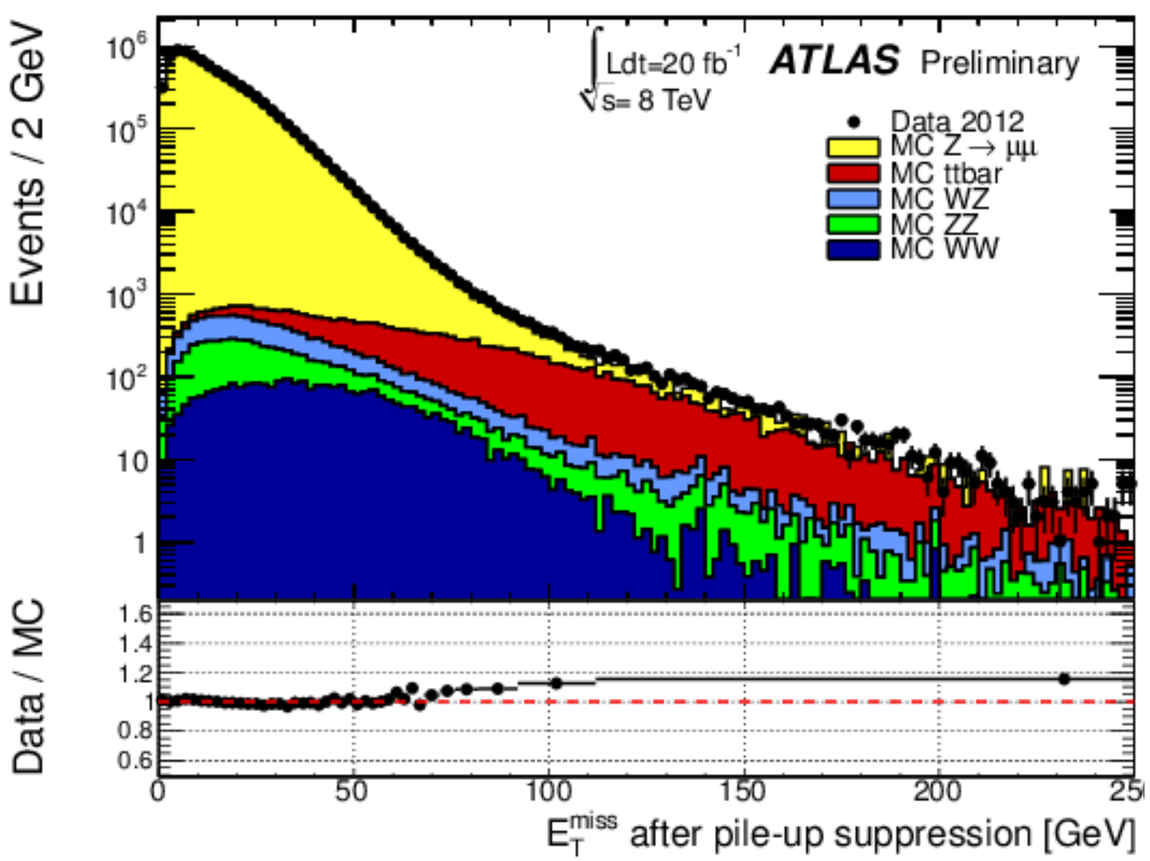
ATLAS Performance: Jets and Missing E_T

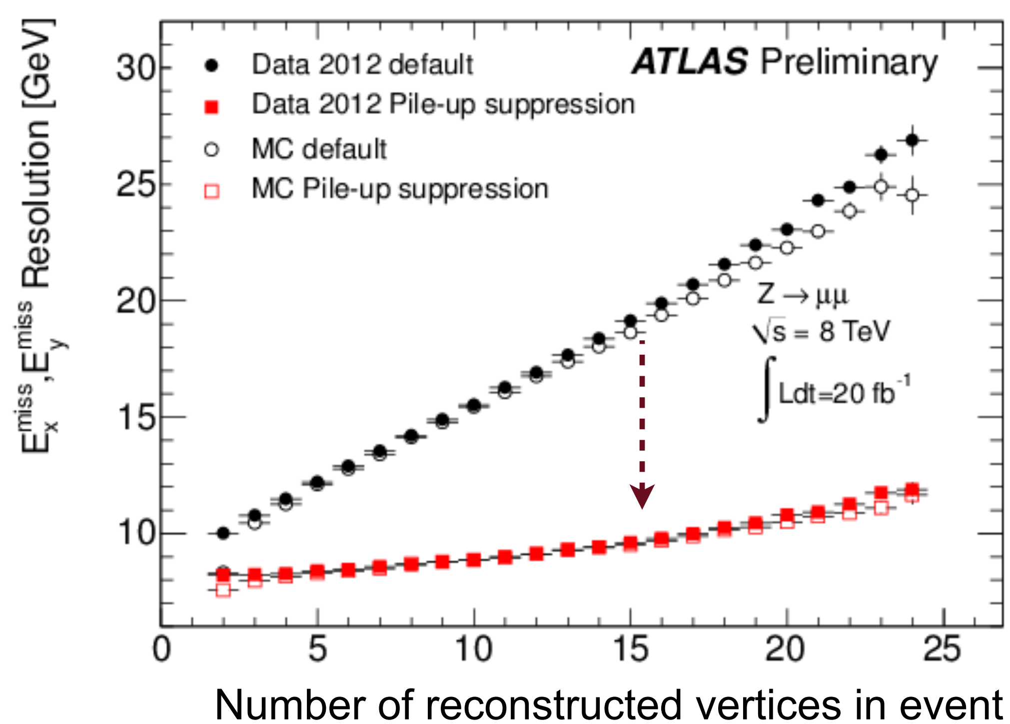


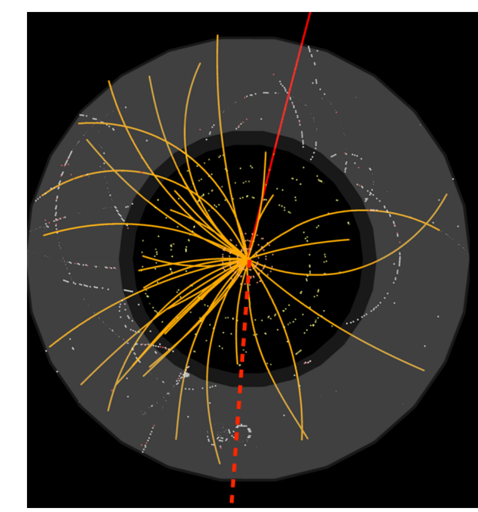




Excellent understanding of the detector performance!







W→μν candidate

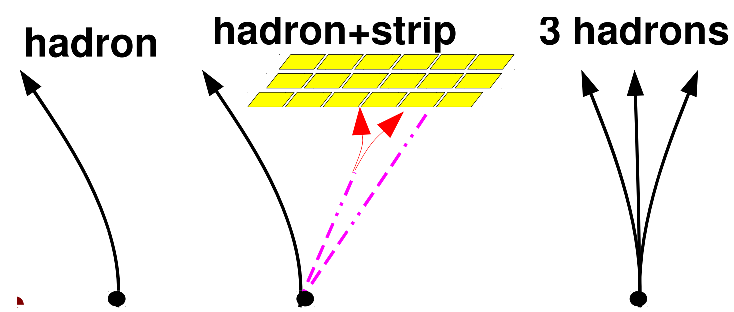
τ-leptons and b-jets

The τ-lepton is special!

Mass of 1.78 GeV and cτ = 87.1 μm, **the only lepton that decays in our detector**, in various ways...

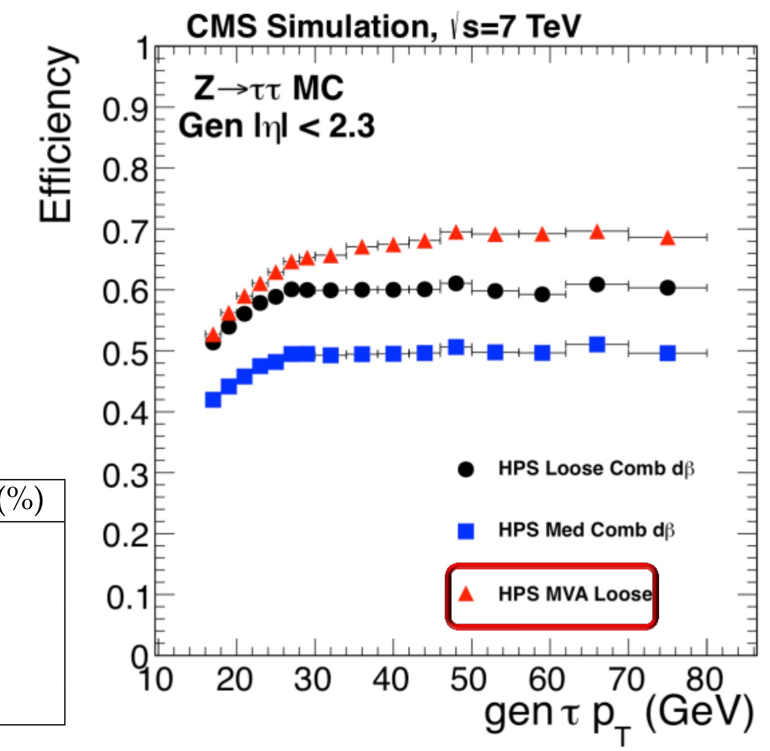
τ → lνν ~35%

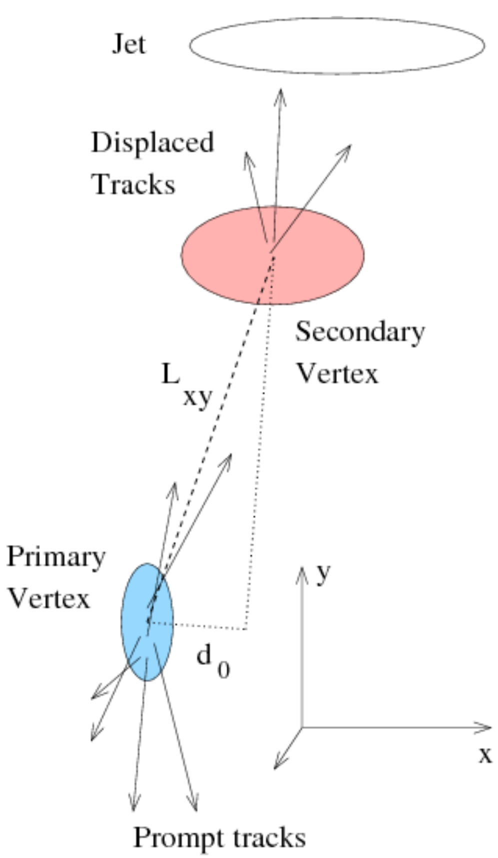
τ → hadrons ~ 65%



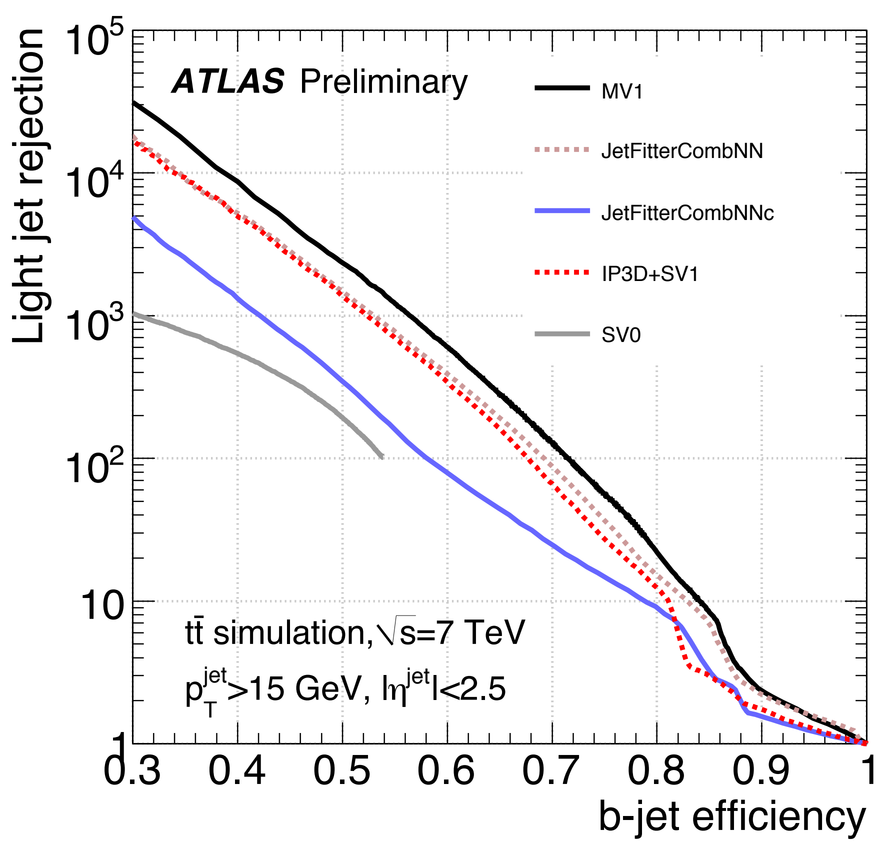
dominant hadronic decay modes

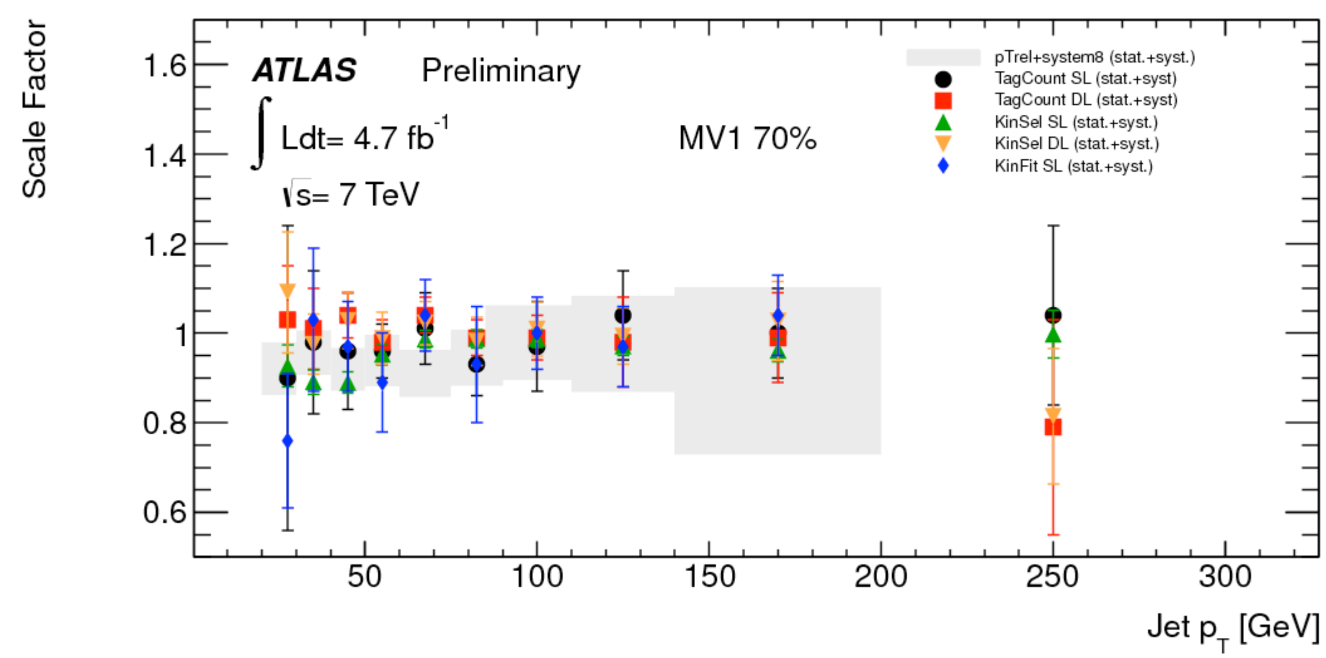
Decay mode	Resonance	Mass (MeV/c^2)	Branching fraction (%)
$\tau^- \to h^- \nu_\tau$			11.6%
$\tau^- \to h^- \pi^0 \nu_\tau$	ρ^-	770	26.0%
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	a_1^-	1200	9.5%
$\tau^- \to h^- h^+ h^- \nu_\tau$	a_1^-	1200	9.8%
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8%



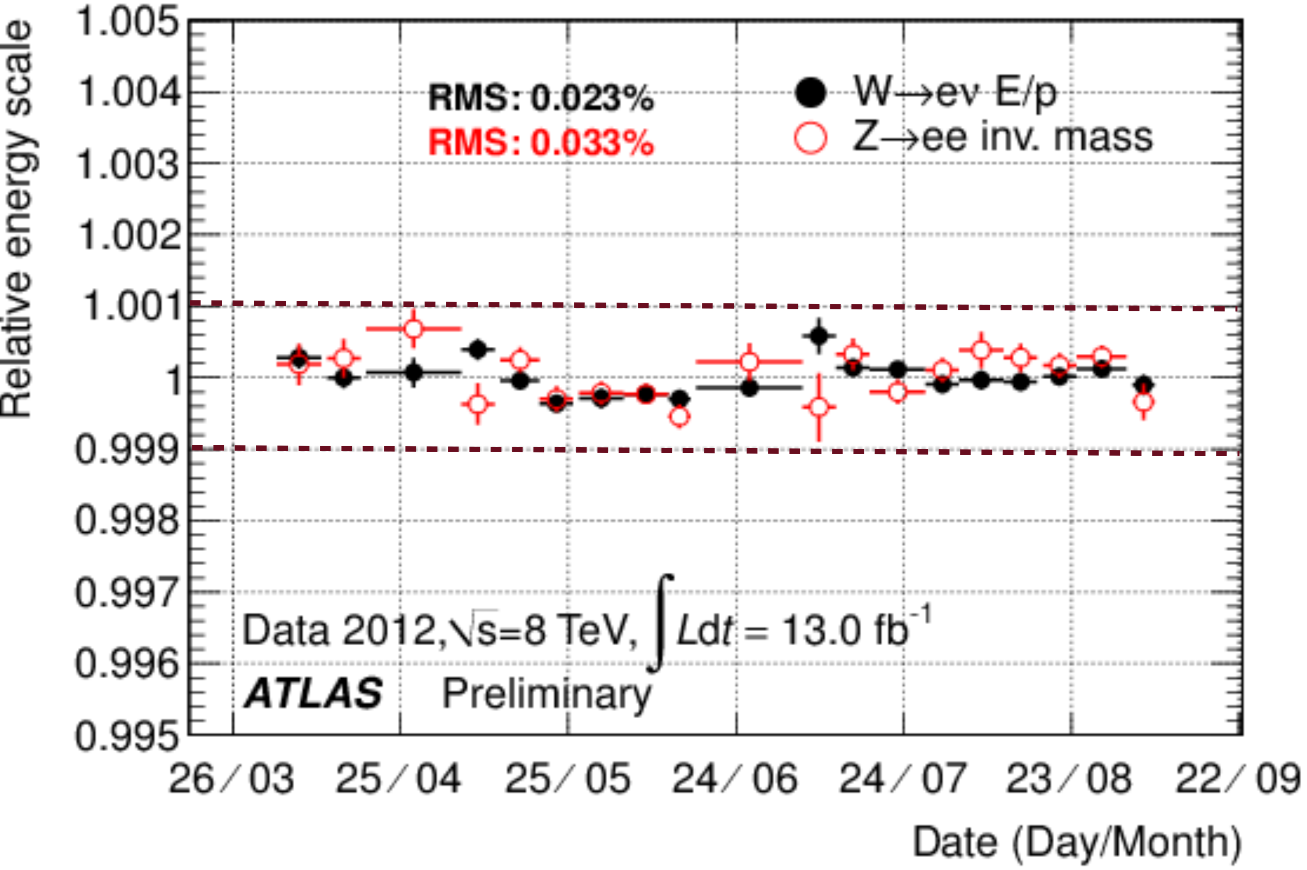


cτ = 492 μm



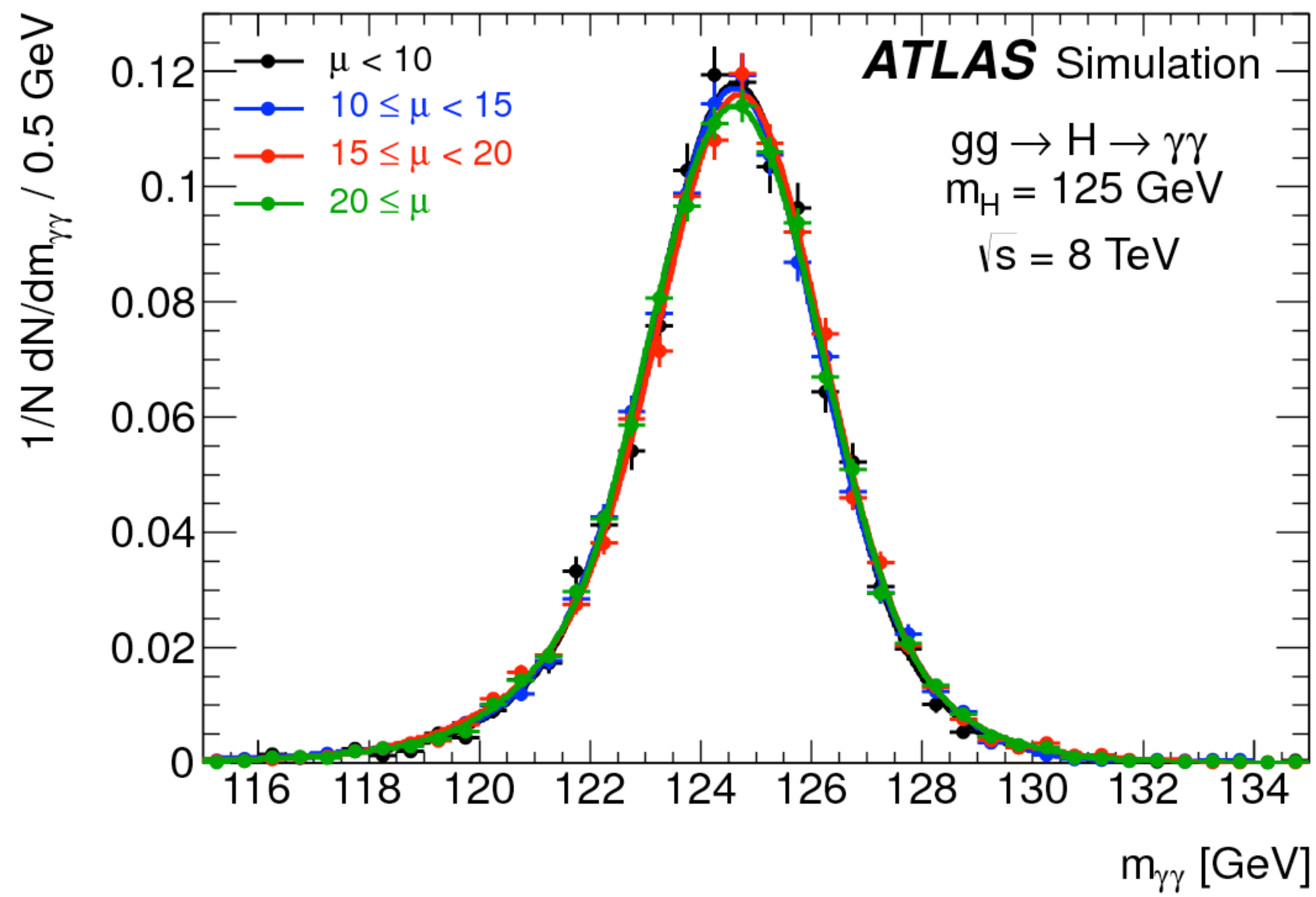


H→γγ: $m_{\gamma\gamma}$ resolution



$$m^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)$$

- Excellent stability of the EM calorimeter response!
  - Studied with Z,J/ψ→ee and W→eν events
  - Energy scale at m_Z known to ~0.3%
  - Uniformity ~1% (2.5% for 1.37< |η|<1.8)
- Resolution of inclusive sample ~1.6 GeV
  - ~90% of events within ±2σ
- Mass resolution immune to pile-up



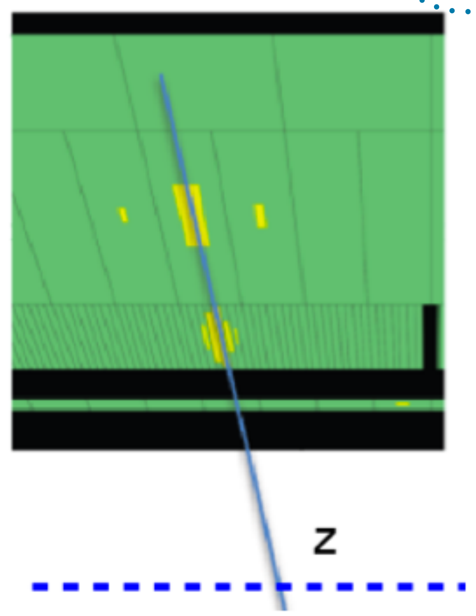
H→γγ: $m_{\gamma\gamma}$ resolution

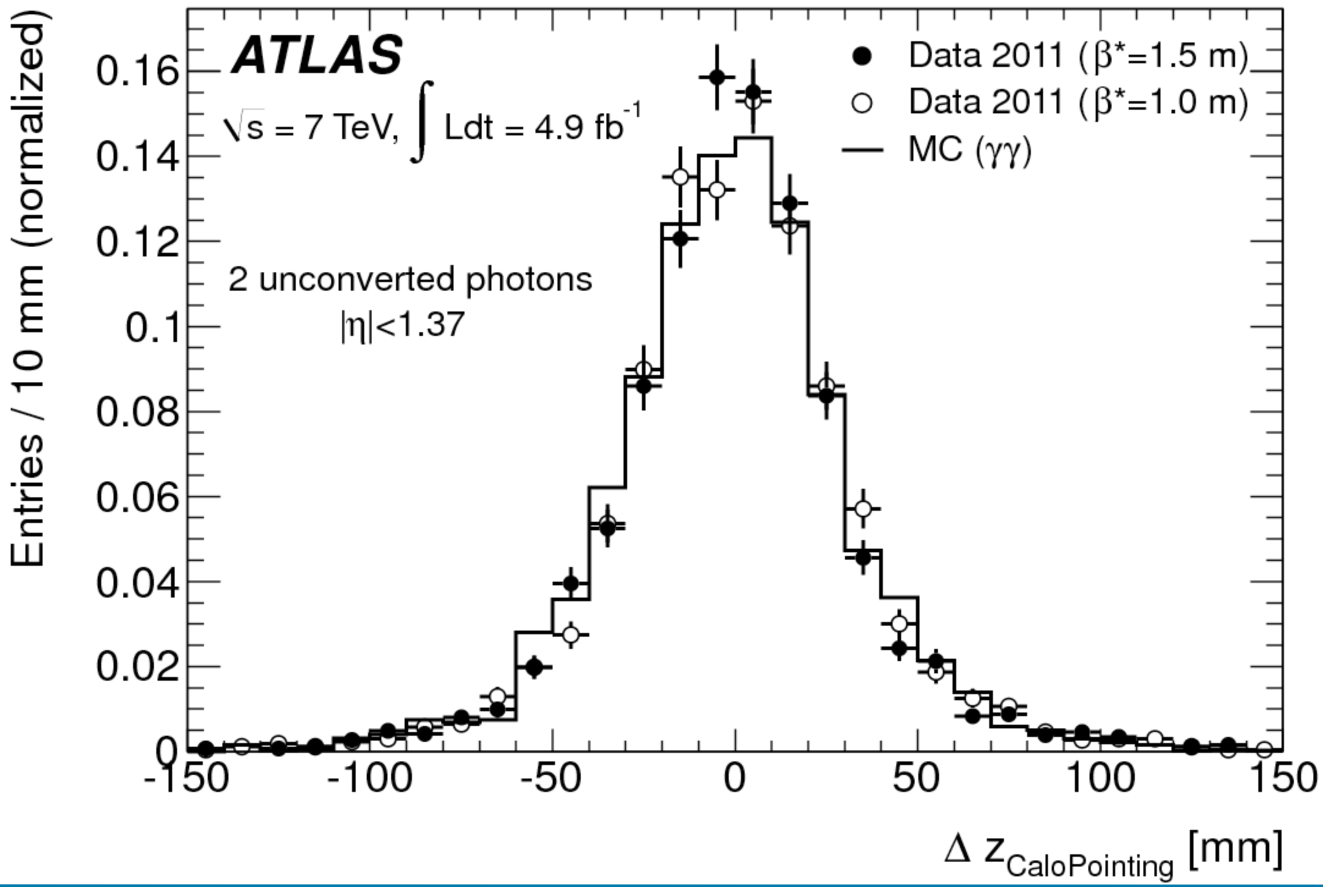
$$m^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)$$

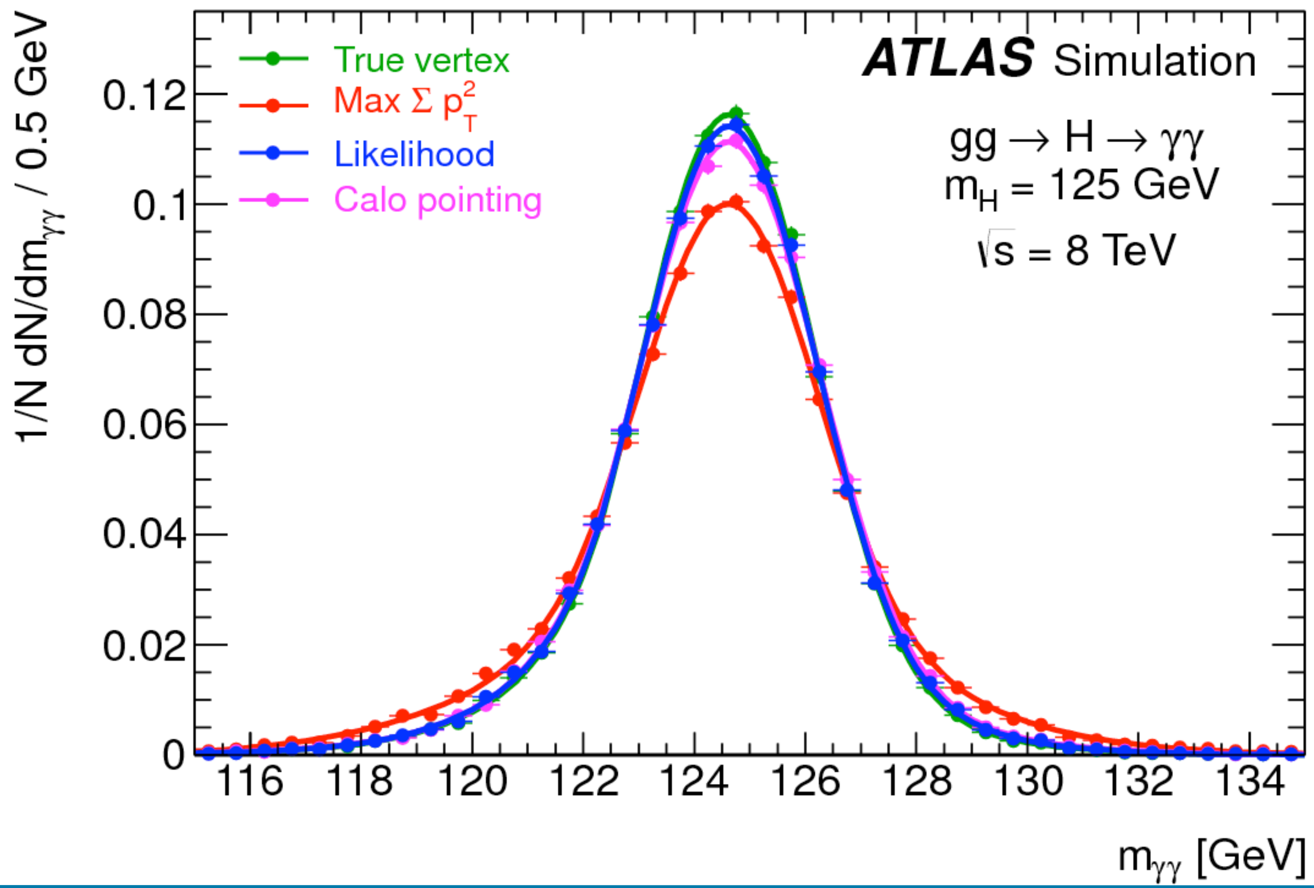
- LHC beam spot σ_z~5-6 cm and O(20) vertices → identify "primary" vertex challenging

Use the strengths of the detector!

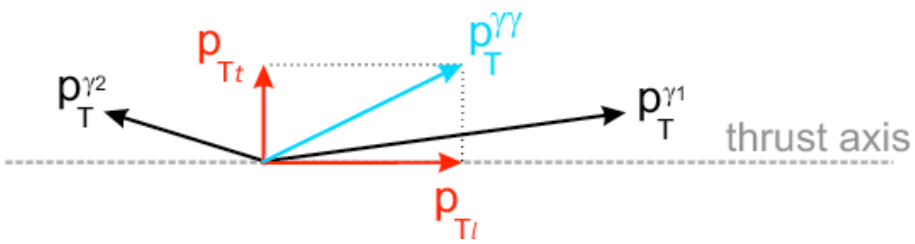
- Build likelihood to identify the primary vertex using
  - longitudinal/lateral segmentation of EM calorimeter (photon pointing) → **σ_z~1.5 cm**
  - use beam-spot constraint/converted photon tracks
  - reconstructed vertex $\Sigma(pT)^2$
- Recently a Neural Network has ben employed (including also the Σ(pT), Δφ between the direction of the tracks and the di-photon system)
- pile-up robust
- contribution of angular term to $m_{\gamma\gamma}$ resolution negligible





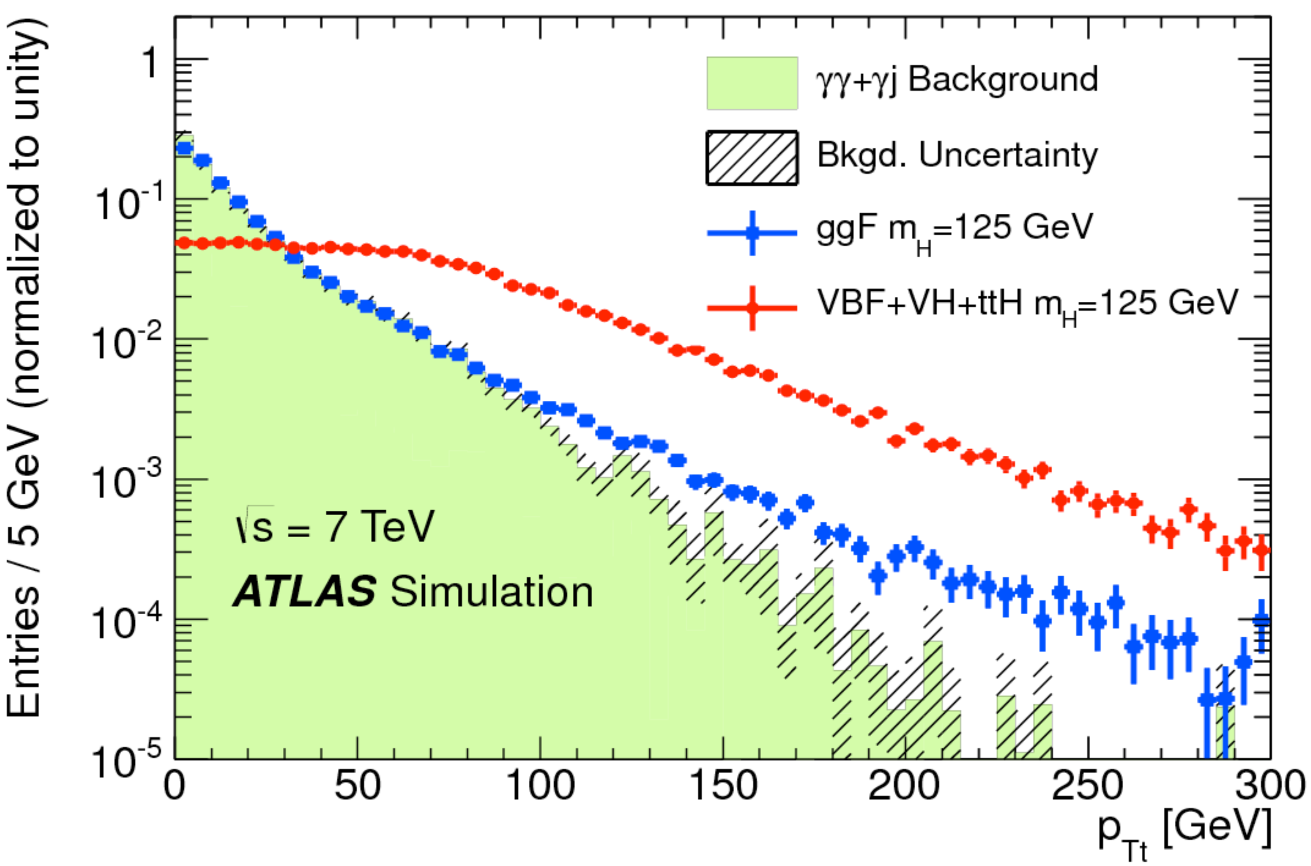


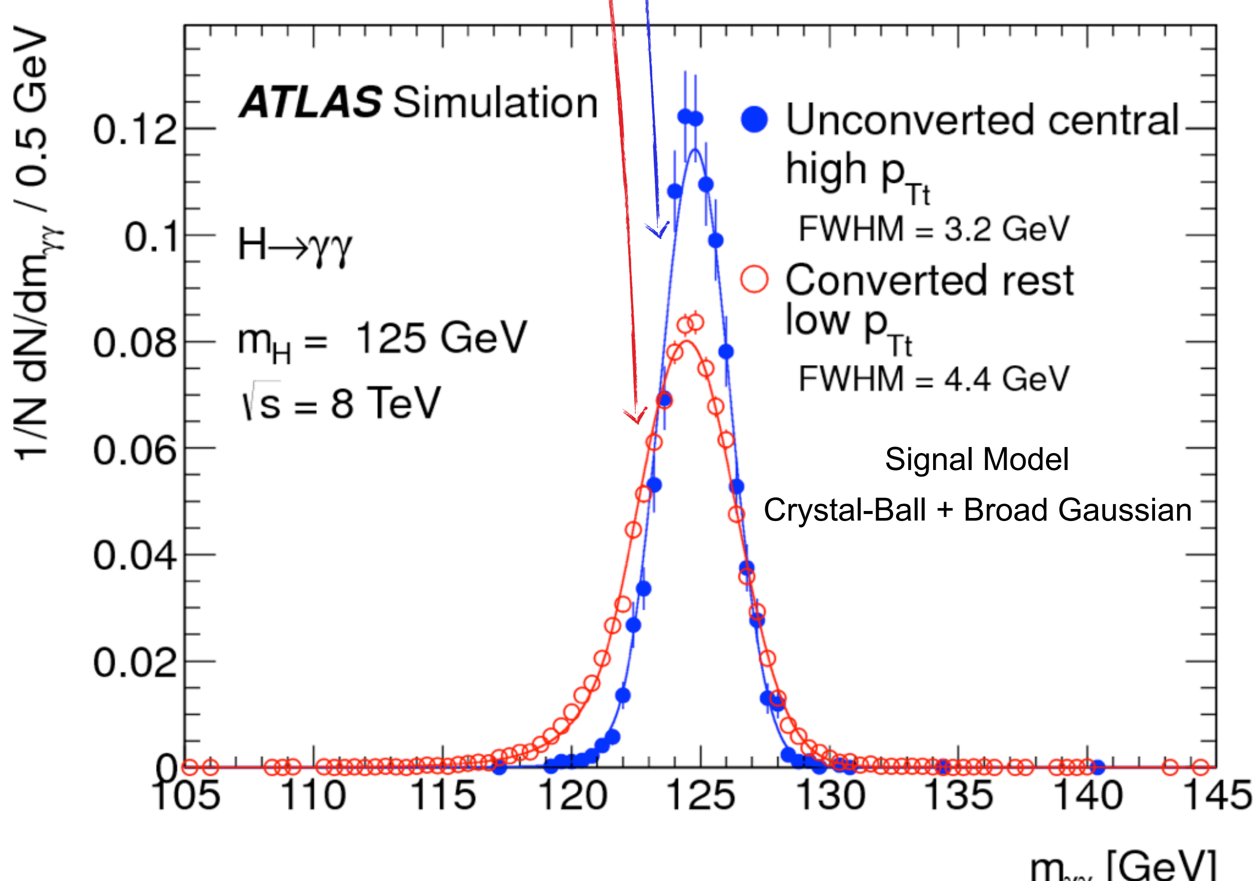
H→γγ: Event Categories



8 TeV (90% signal window)

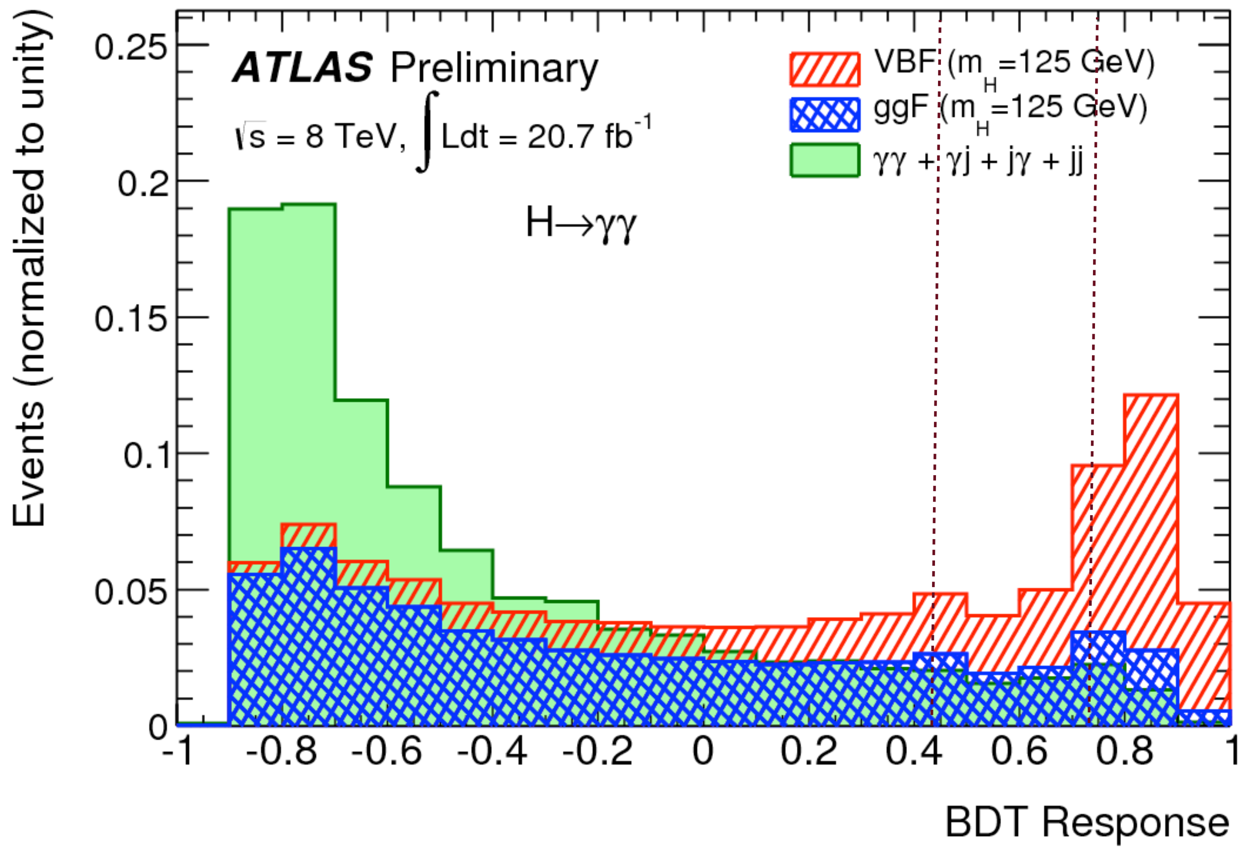
$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03

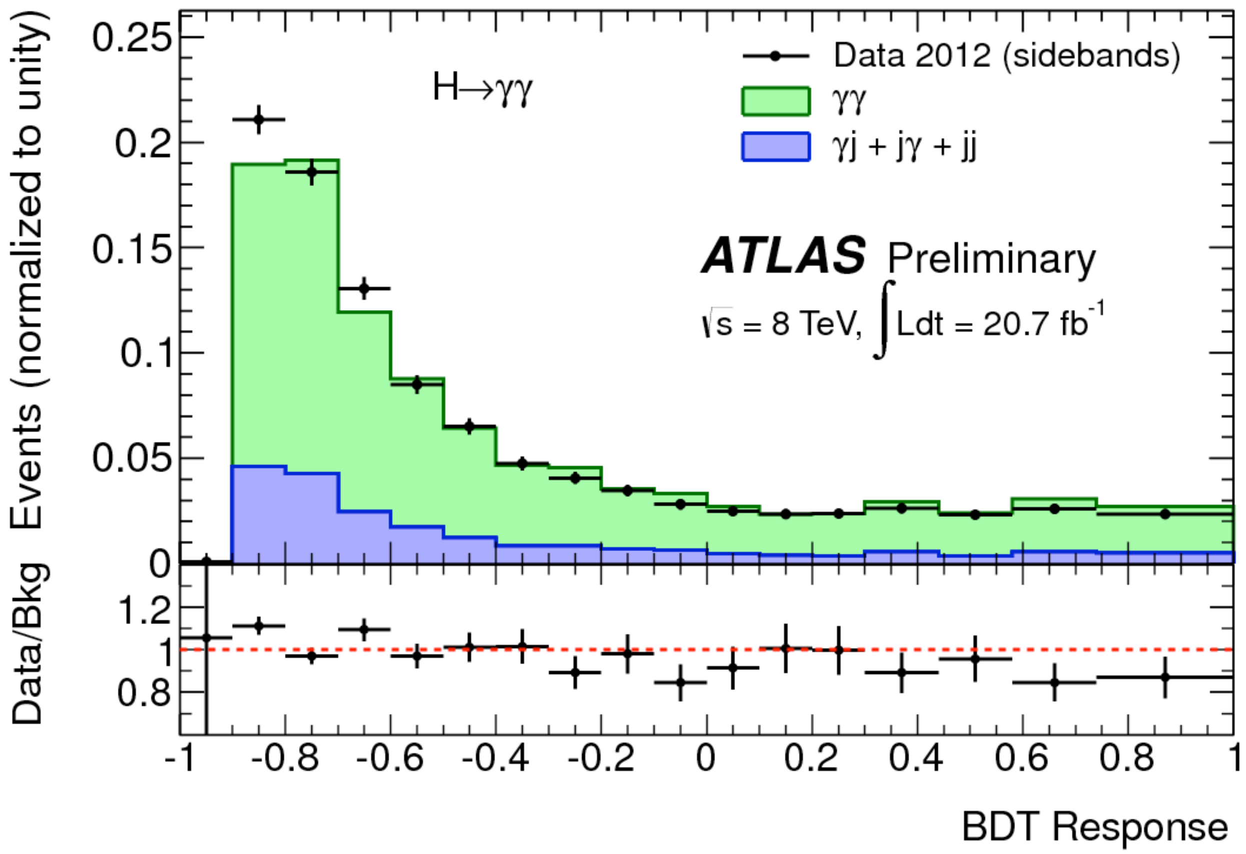




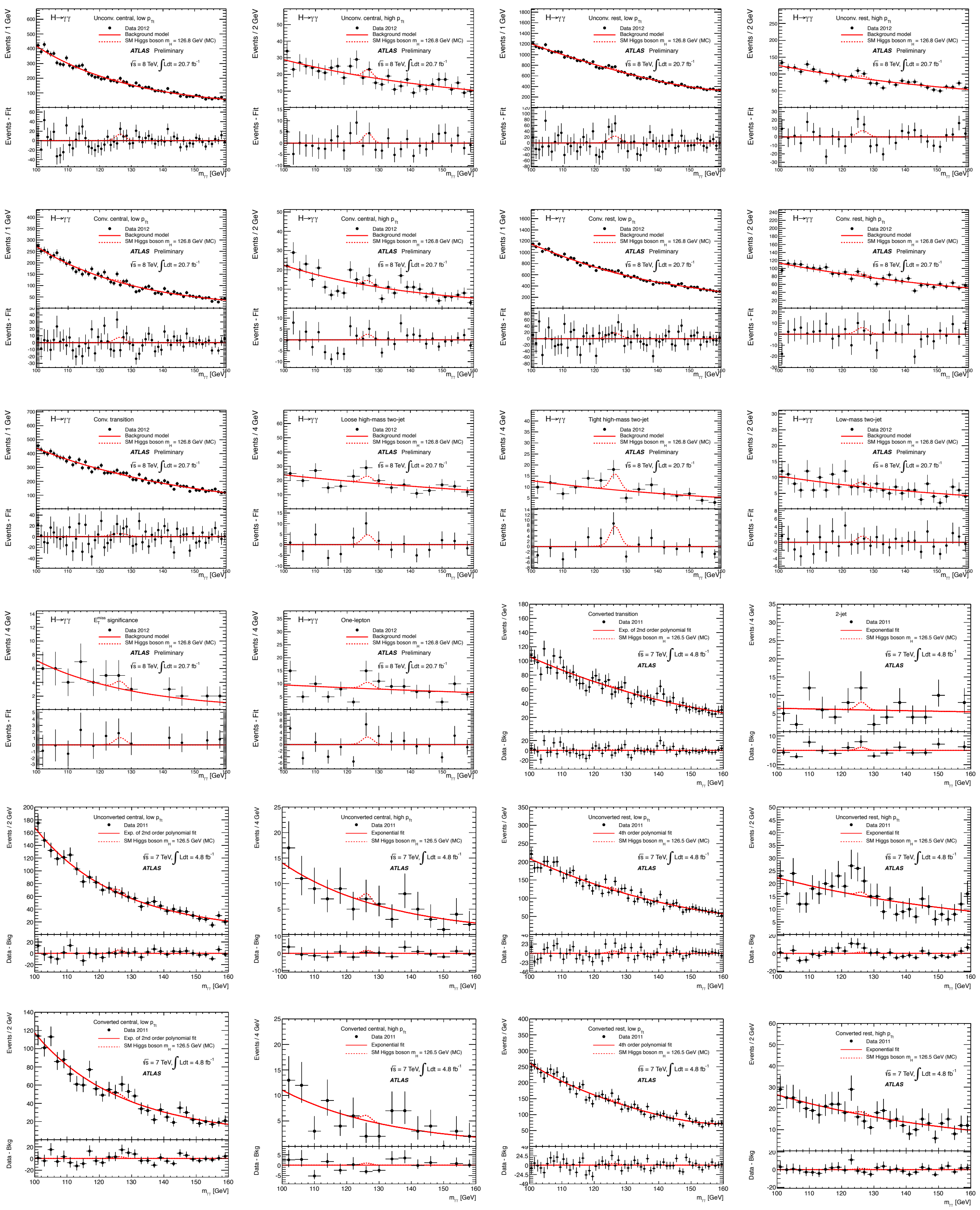
H→γγ: BDT Response

BDT: m_{jj}, η_{j1}, η_{j2}, $\Delta\eta_{jj}$, p_{Tt}, $\Delta\varphi_{\gamma\gamma;jj}$, $\eta^{*}=\eta_{\gamma\gamma}-(\eta_{j1}+\eta_{j2})/2$ $\Delta R min_{\gamma j}$

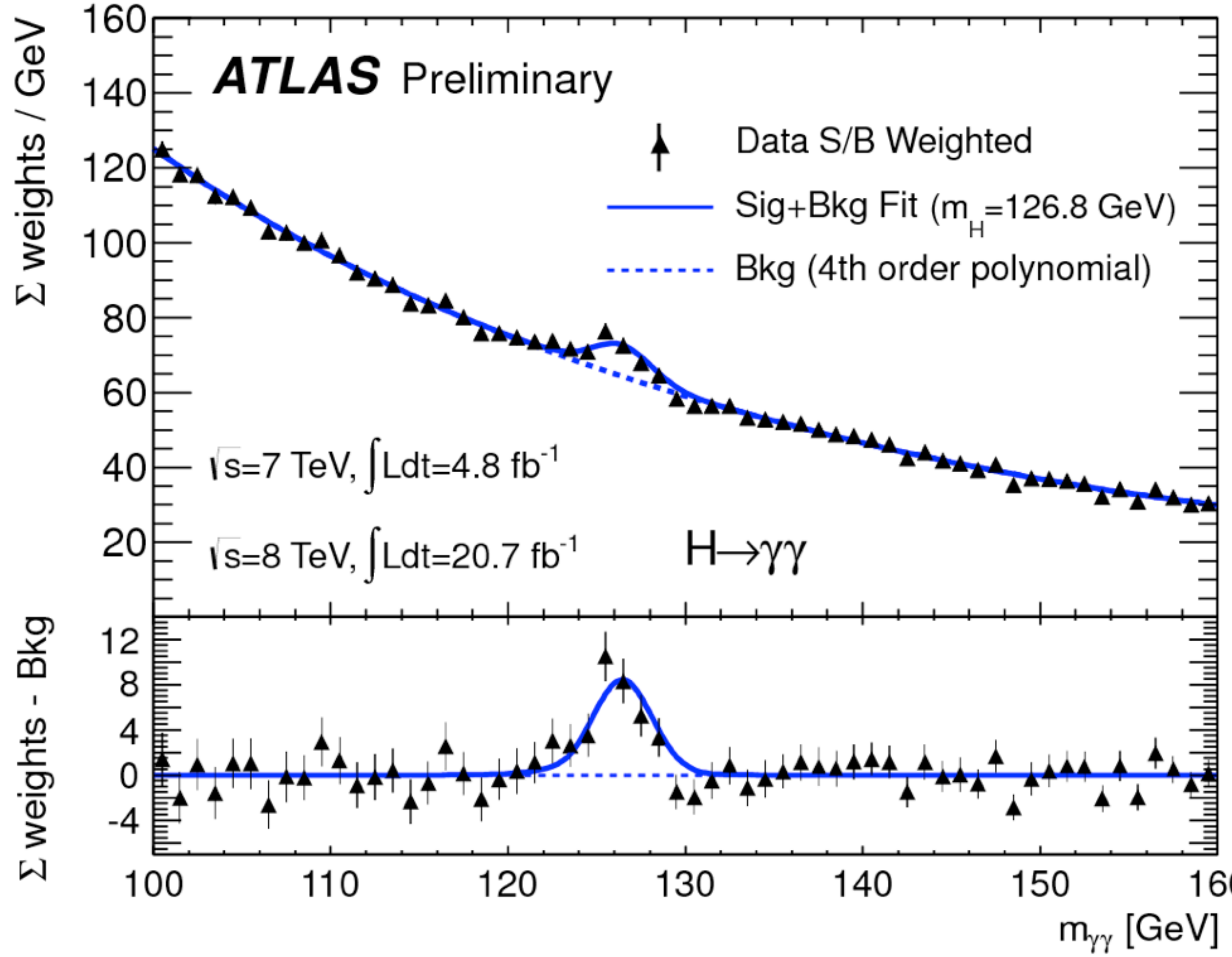




H→γγ: $m_{\gamma\gamma}$ spectra

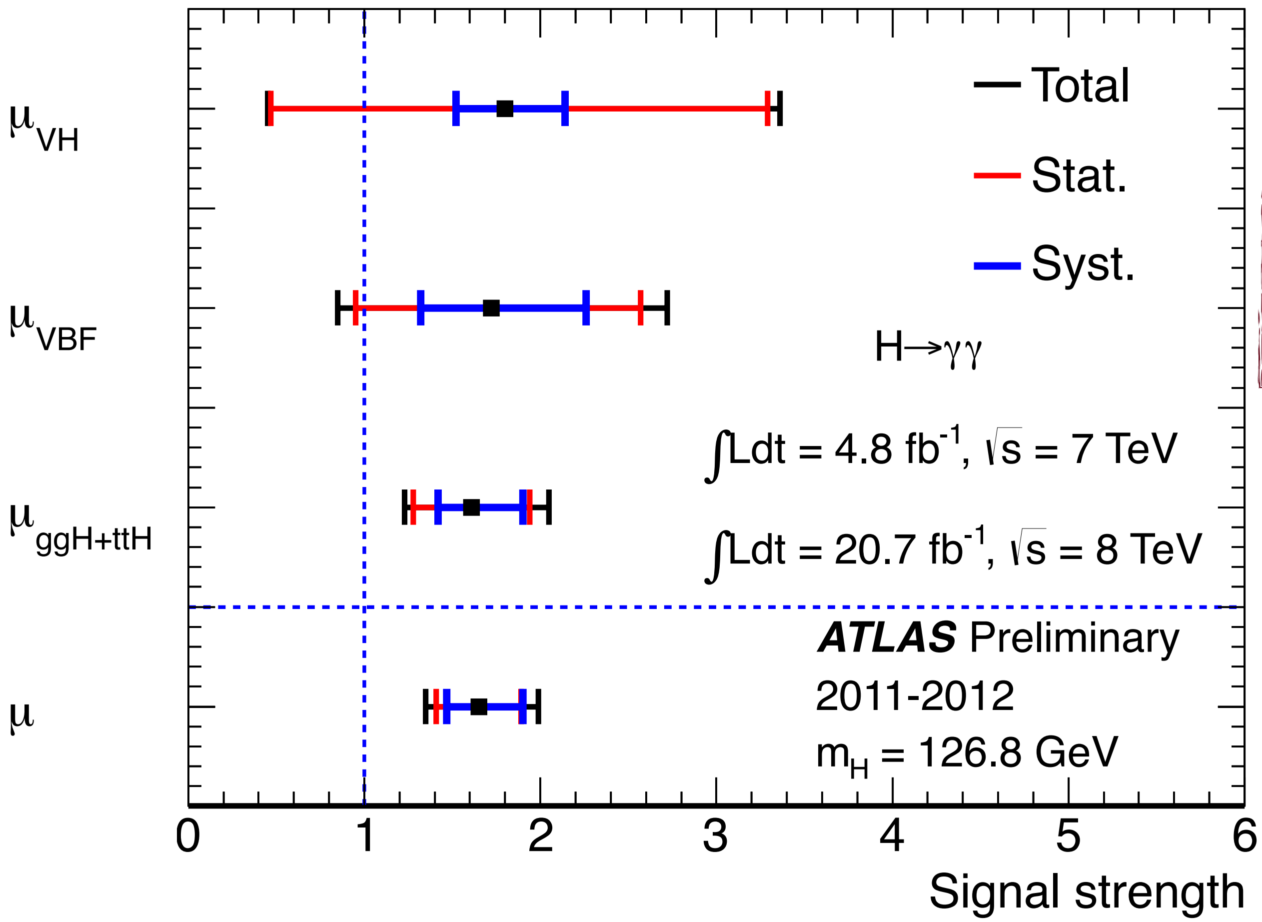


all categories



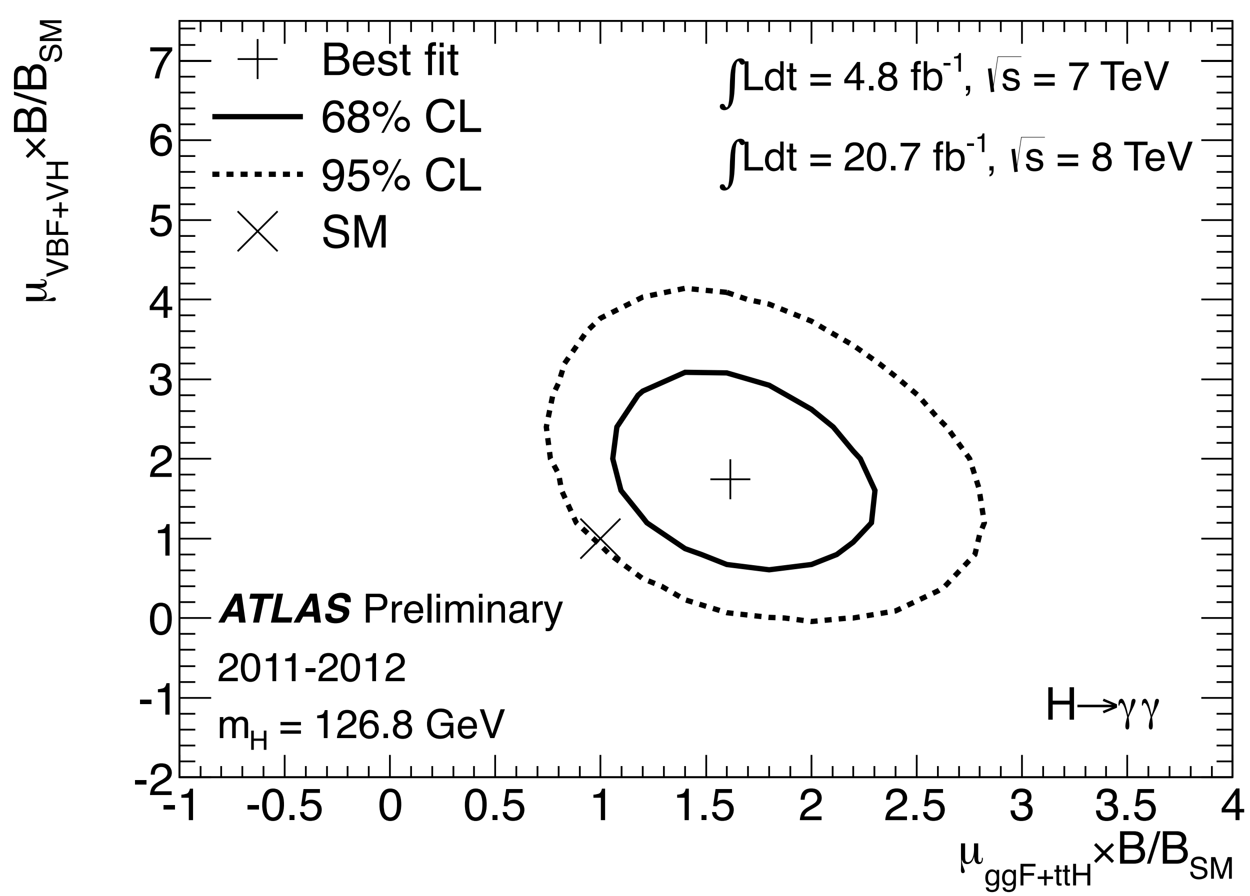
H→γγ: Signal Strength

Signal strength (μ) = (signal rate from data) / (expected SM signal rate at m_H)

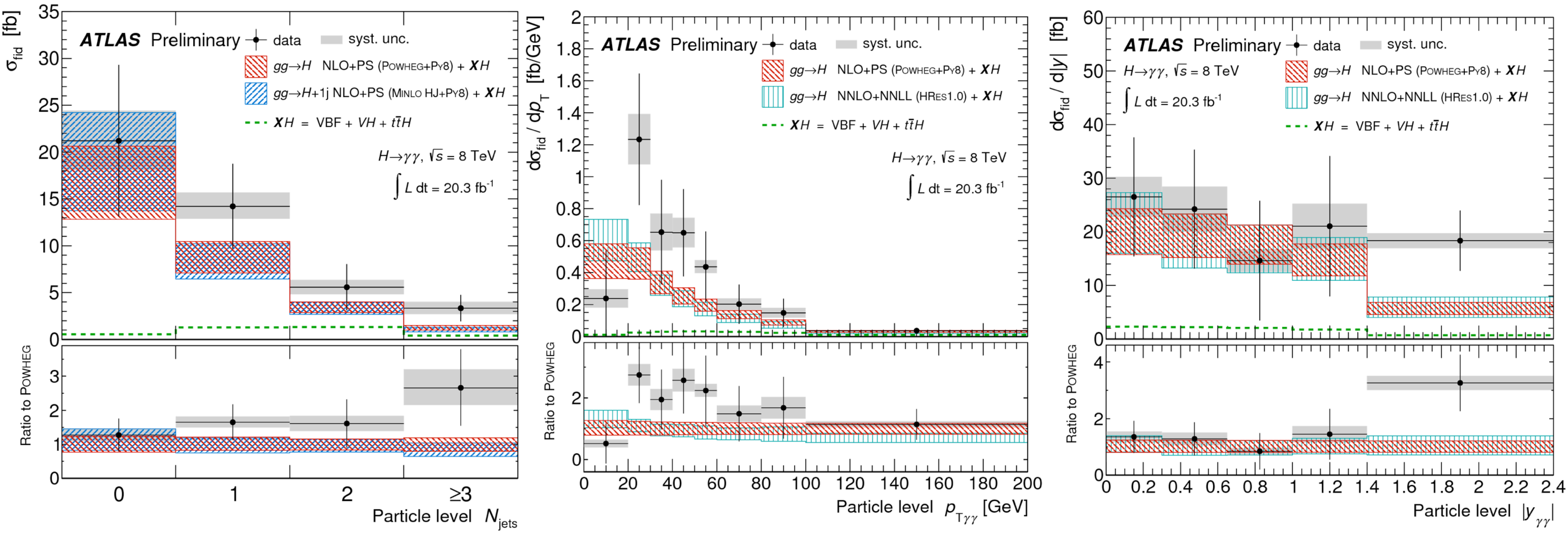


- Best-fit value for m_H =126.8 GeV: **$\mu=1.65^{+0.34}_{-0.30}$**
- 2.3σ deviation from the Standard Model

Fiducial cross-section defined for the kinematic range $E^{\gamma 1}_T > 40$ GeV, $E^{\gamma 2}_T > 30$ GeV, $|\eta^{\gamma}| < 2.37$, measured using 20.7 fb^{-1} of data at $\sqrt{s}$ = 8 TeV, is 56.2 ± 10.5(stat) ± 6.5(syst) ± 2.0(lumi) fb.

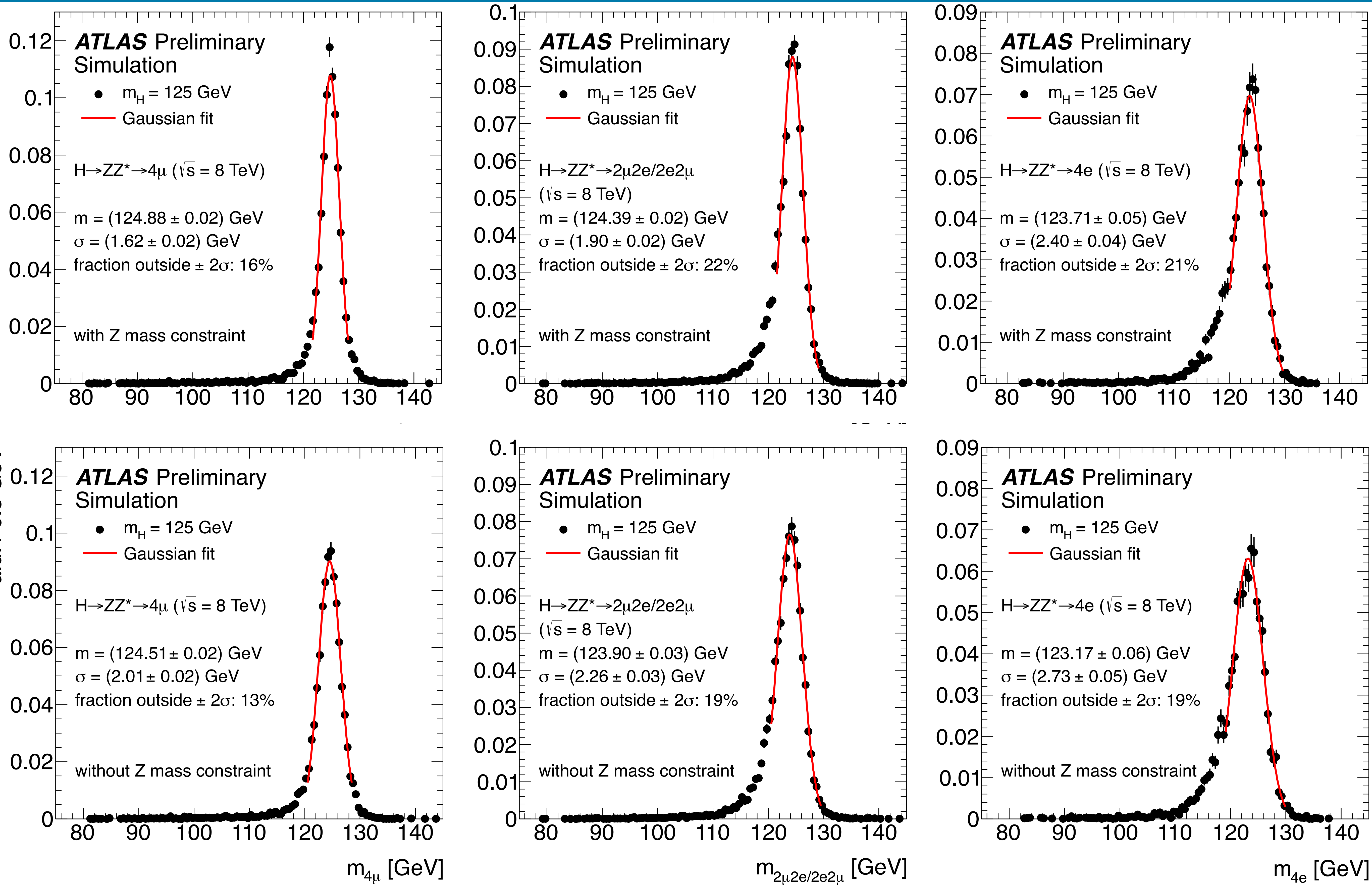


Higgs boson differential cross-sections

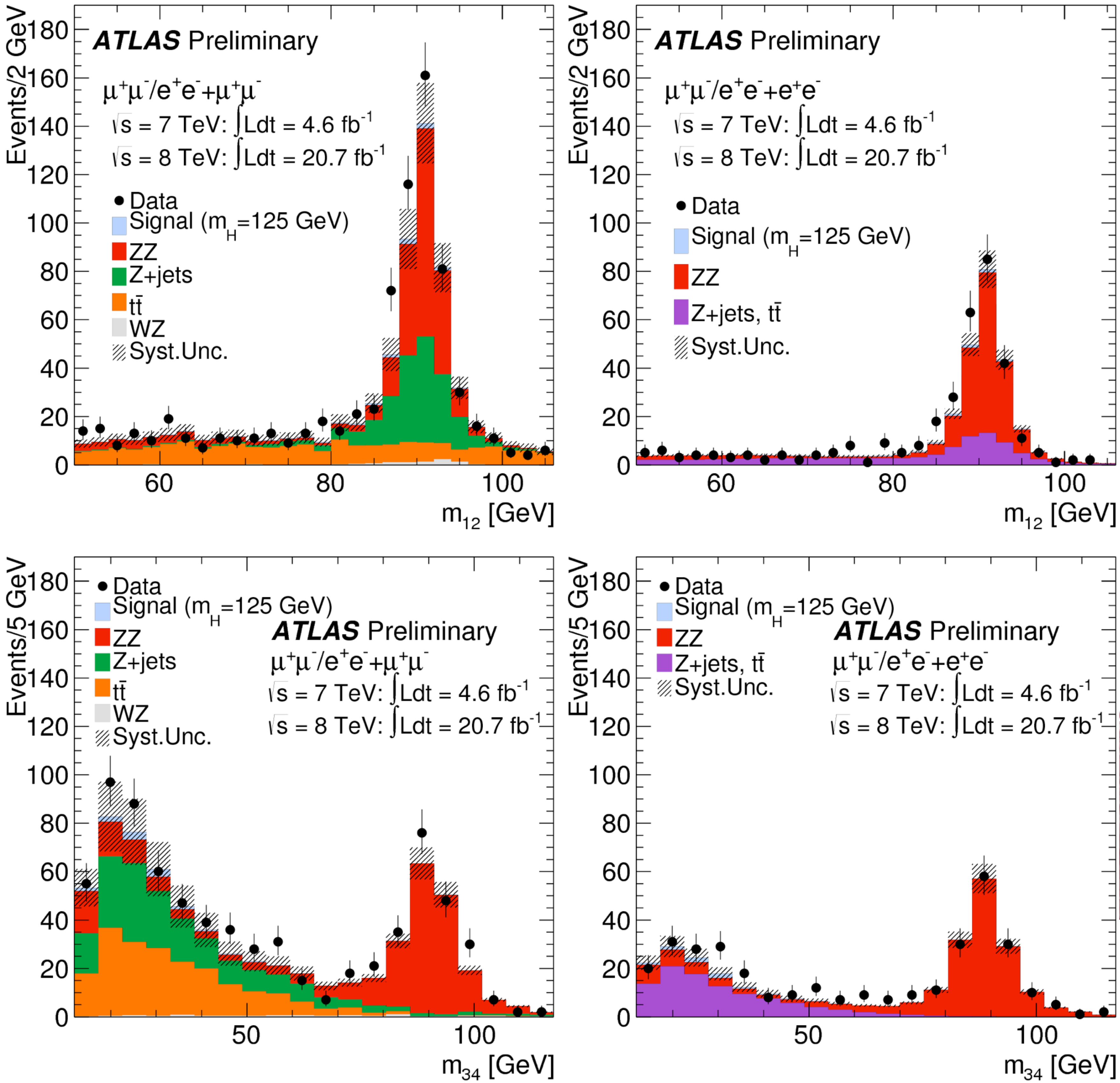


ATLAS-CONF-2013-072

H→ZZ(*)→4l: Mass resolution



H→ZZ(*)→4l: Backgrounds



Background-dominated Control Region

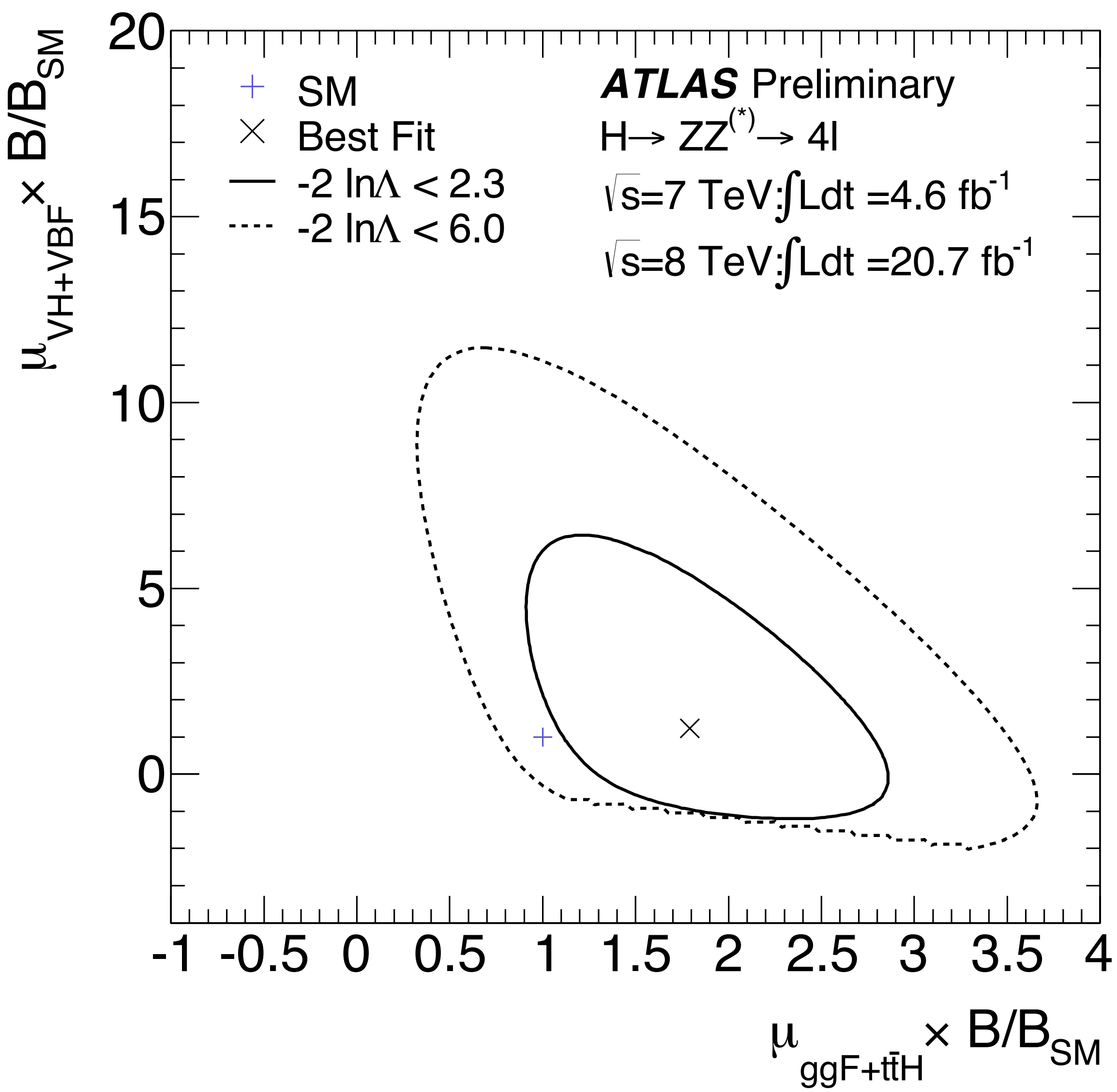
[Remove isolation/impact parameter requirements on sub-leading di-lepton and normalize to data-driven estimates]

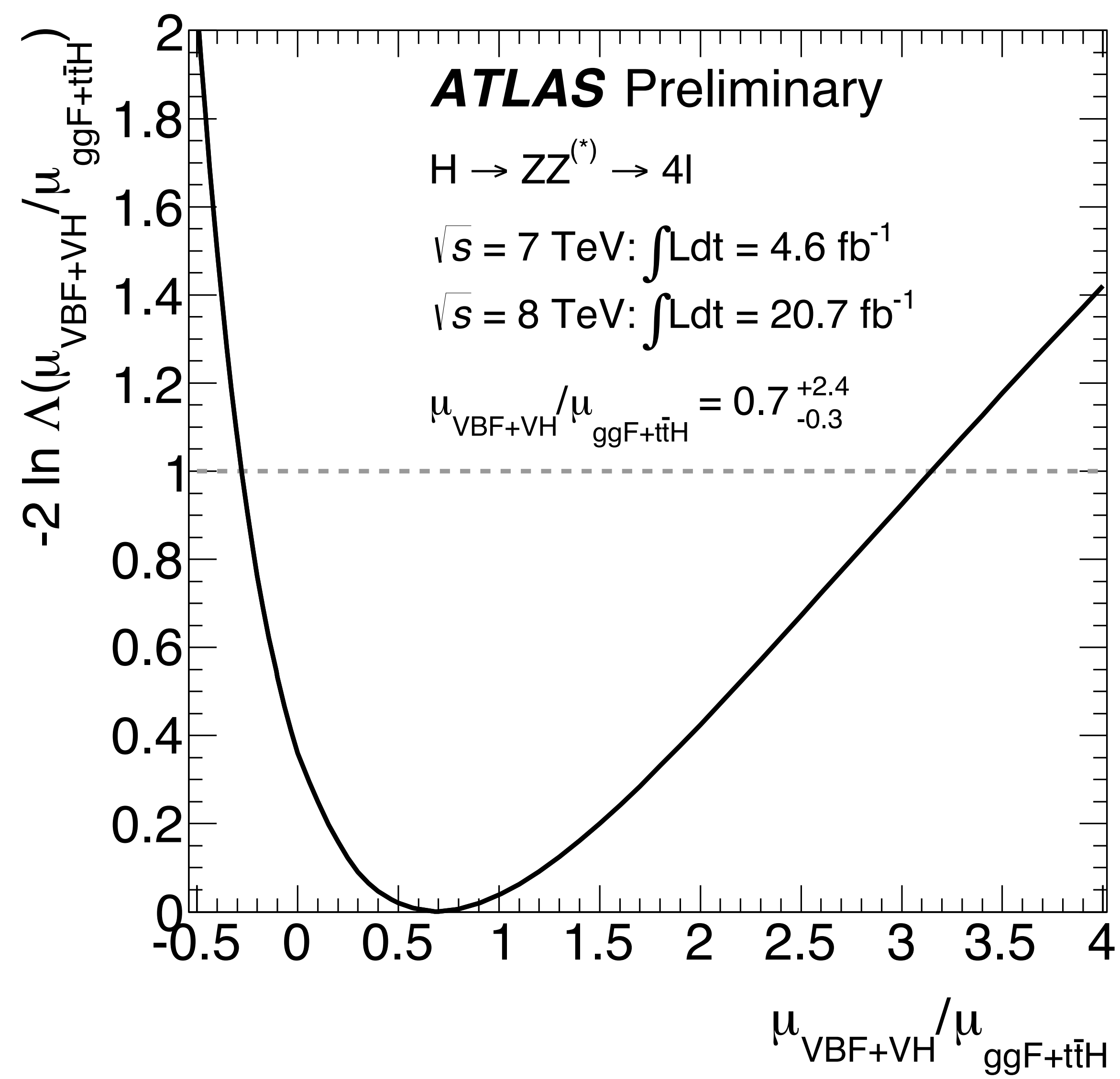
Normalization/shape of reducible backgrounds well described

H→ZZ(*)→4l: Couplings

The couplings of the Higgs boson are probed by further categorizing the observed events.

- VBF-like events : Events with at least two jets in VBF topology
- VH-like events : Events with additional leptons in the final state
- ggF-like events: All remaining events



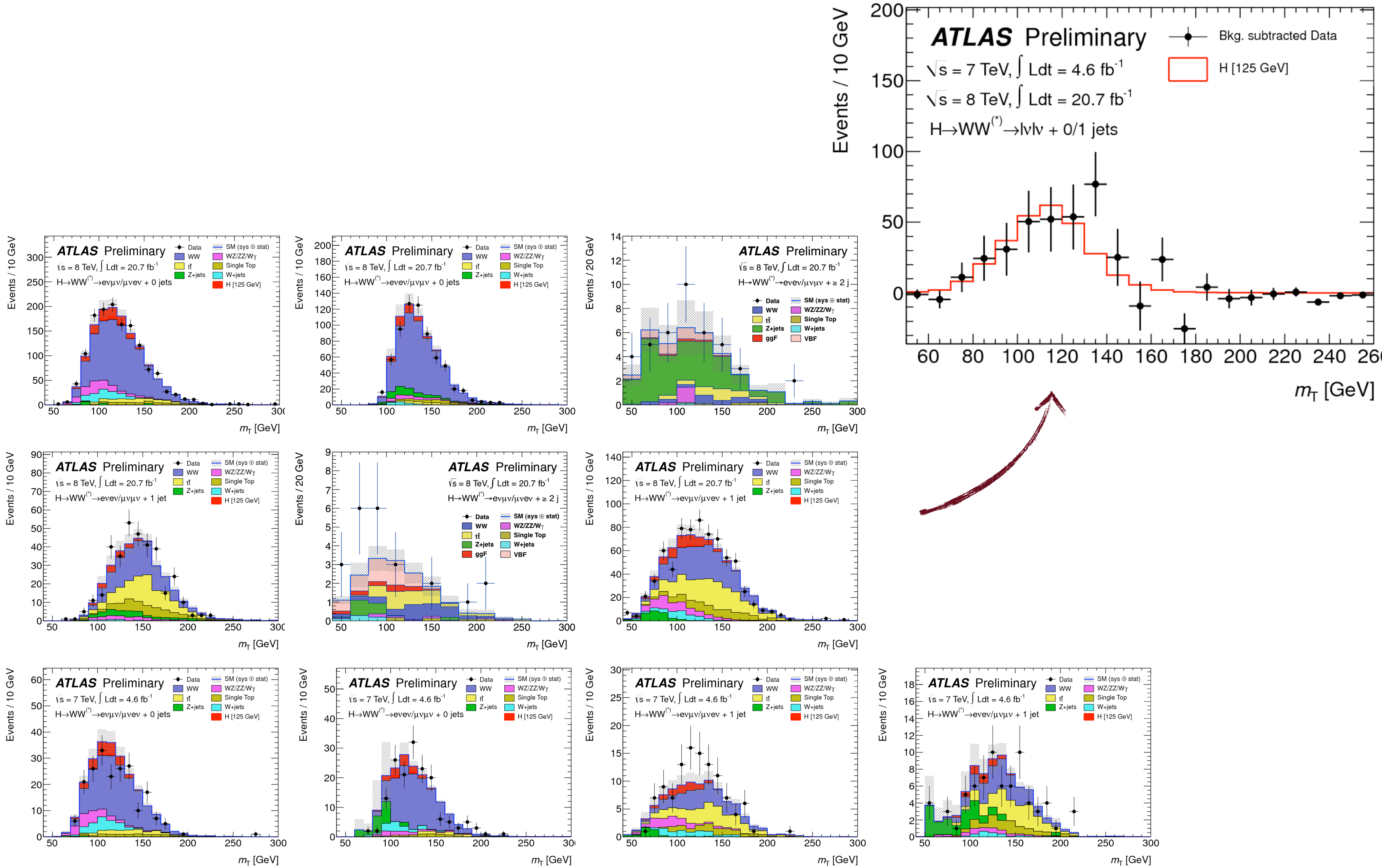


$H \to WW^{(*)} \to l\nu l\nu$: Event Selection

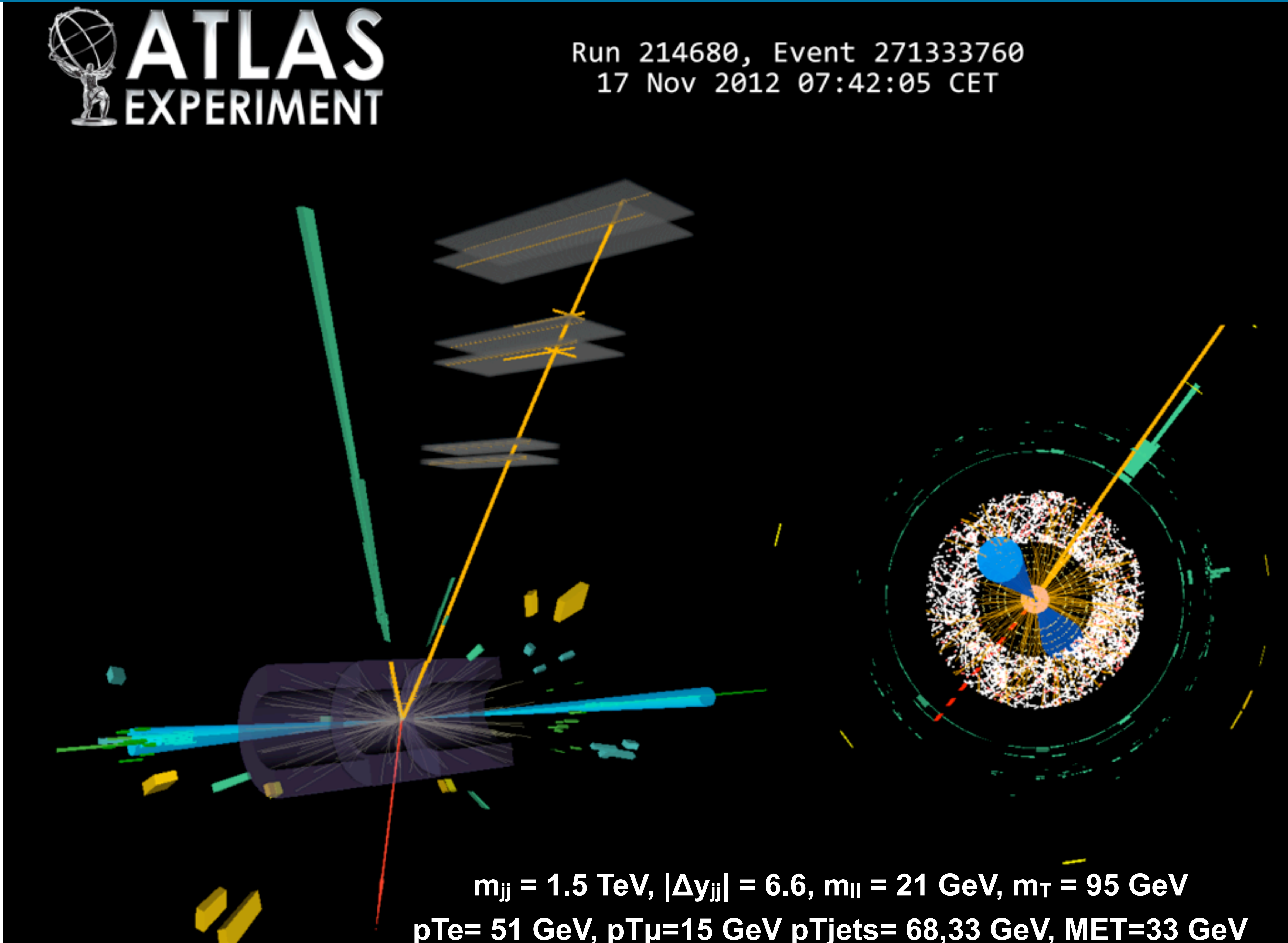
Table 2: Selection listing for 8 TeV data. The criteria specific to $e\mu + \mu e$ and $ee + \mu\mu$ are noted as such; otherwise, they apply to both. Pre-selection applies to all N_{jet} modes. The rapidity gap is the y range spanned by the two leading jets. The $m_{\ell\ell}$ split is at 30 GeV. The modifications for the 7 TeV analysis are given in Section 6 and are not listed here. Energies, masses, and momenta are in units of GeV.

Category	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_{\mathrm{T}}^{\text{lead}} > 25$ and $p_{\mathrm{T}}^{\text{sublead}} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{\mathrm{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\mathrm{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\mathrm{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.05$	$e\mu + \mu e$: $E_{\mathrm{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\mathrm{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\mathrm{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.2$	$e\mu + \mu e$: $E_{\mathrm{T}}^{\text{miss}} > 20$ $ee + \mu\mu$: $E_{\mathrm{T}}^{\text{miss}} > 45$ $ee + \mu\mu$: $E_{\mathrm{T,STVF}}^{\text{miss}} > 35$ -
General selection	- $\lvert \Delta\phi_{\ell\ell,MET} \rvert > \pi/2$ $p_{\mathrm{T}}^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_{\mathrm{T}}^{\text{tot}} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\lvert \Delta y_{jj} \rvert > 2.8$ No jets ($p_{\mathrm{T}} > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \to WW^{(*)} \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 60$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ - Fit m_{T}

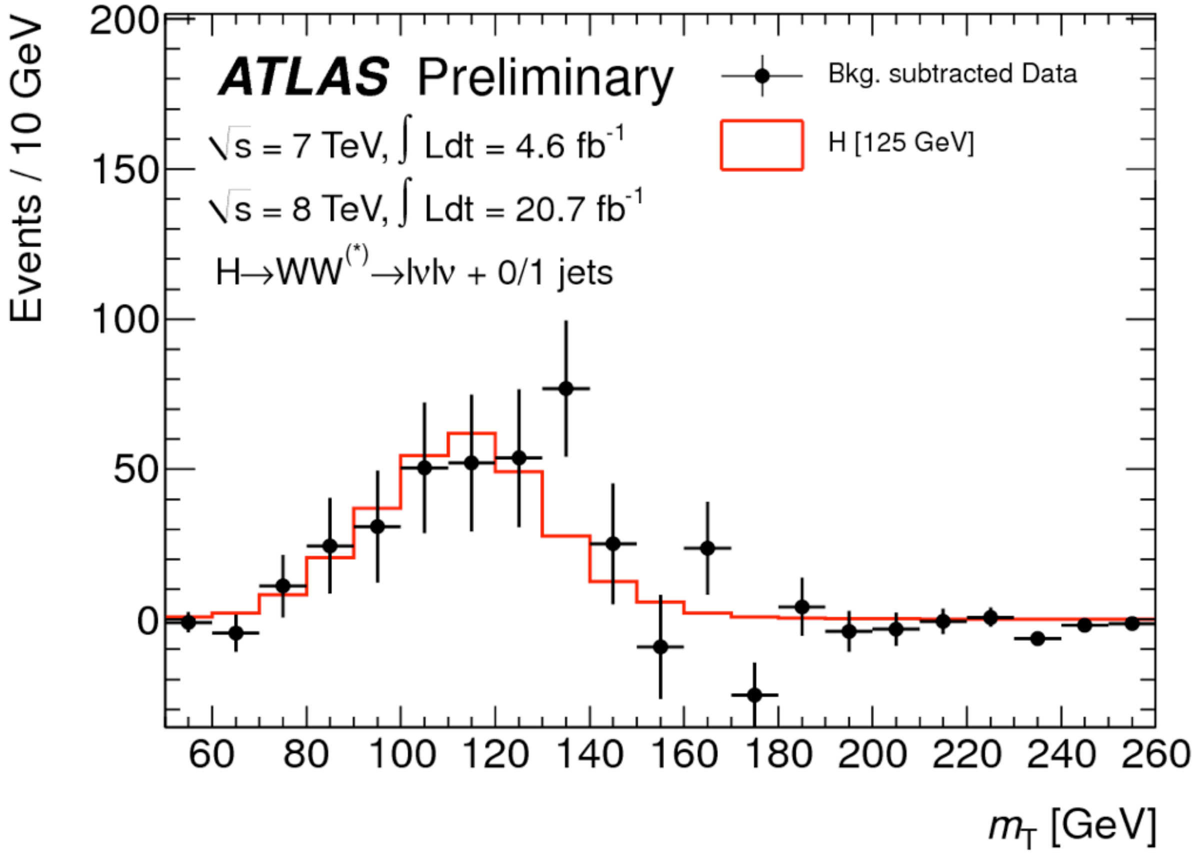
H→WW(*)→lνlν

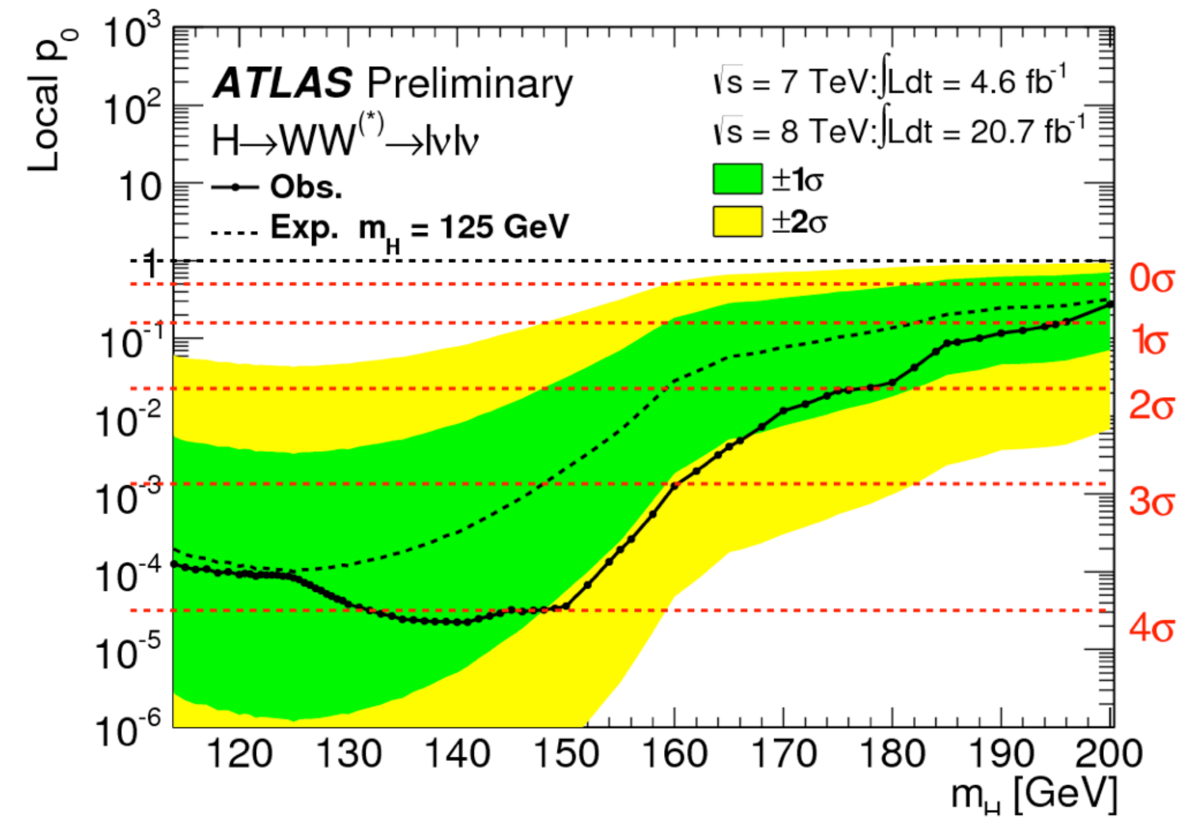

ATLAS Preliminary
√s = 7 TeV, ∫ Ldt = 4.6 fb-1
√s = 8 TeV, ∫ Ldt = 20.7 fb-1
H→WW(*)→lνlν + 0/1 jets
Bkg. subtracted Data
H [125 GeV]
Events / 10 GeV
mT [GeV]

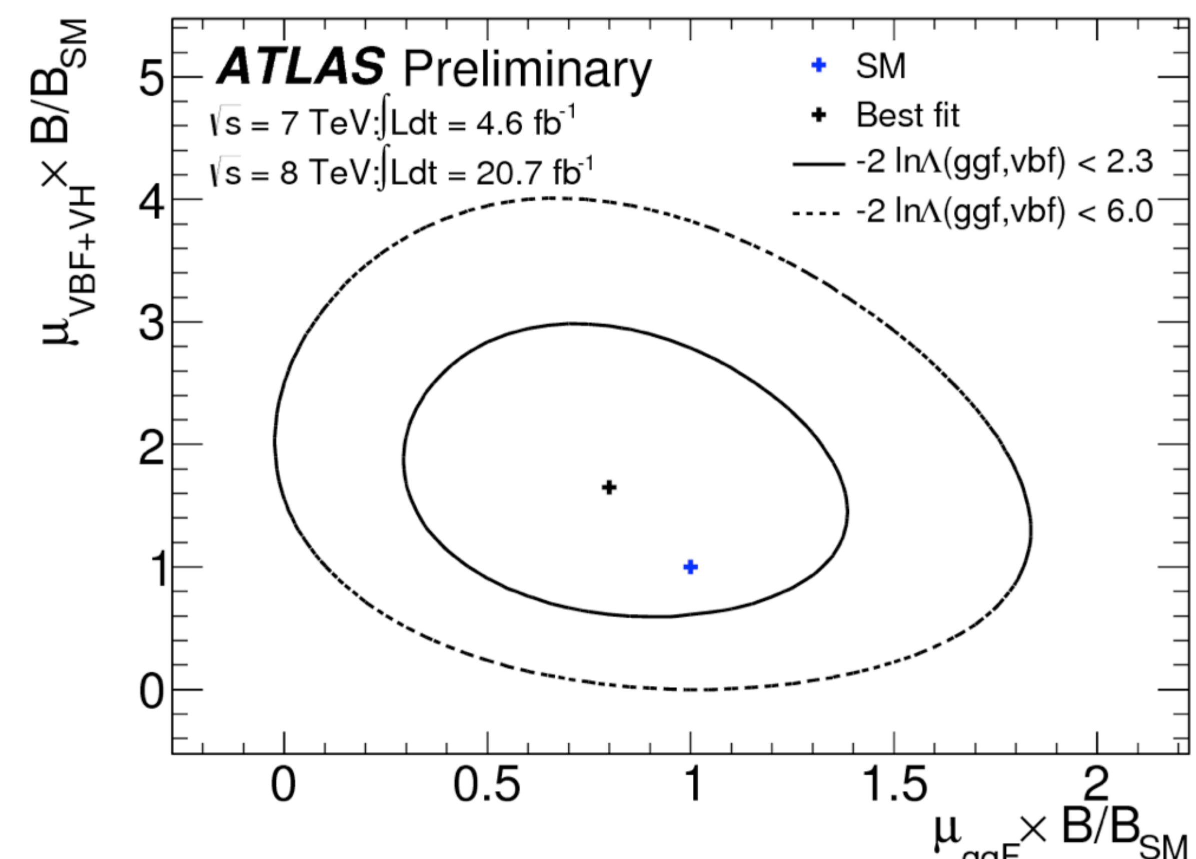
H→WW$^{(*)}$→eνμν +2 jet Event Display



H→WW(*)→lνlν: Results 2011+2012

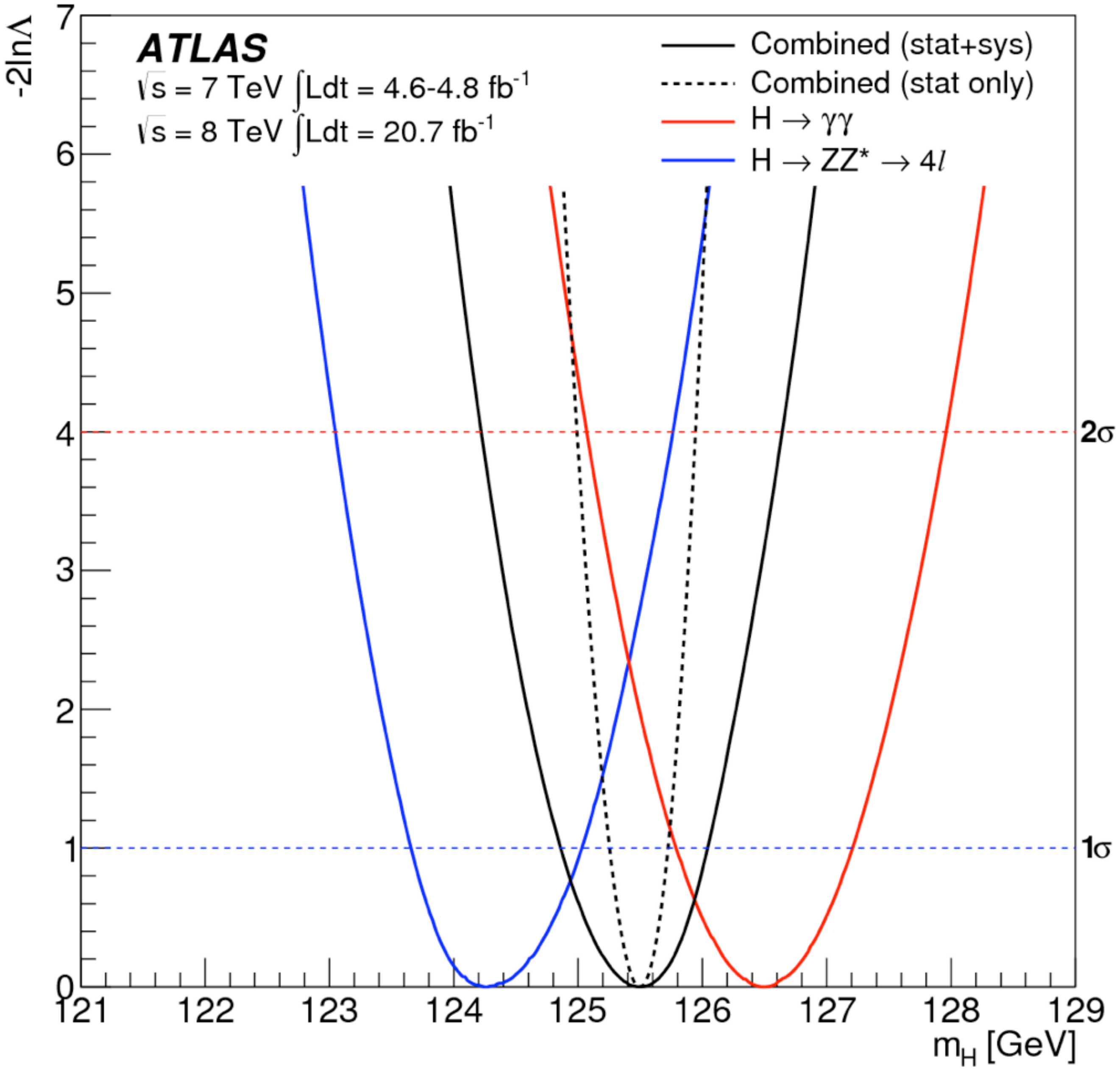




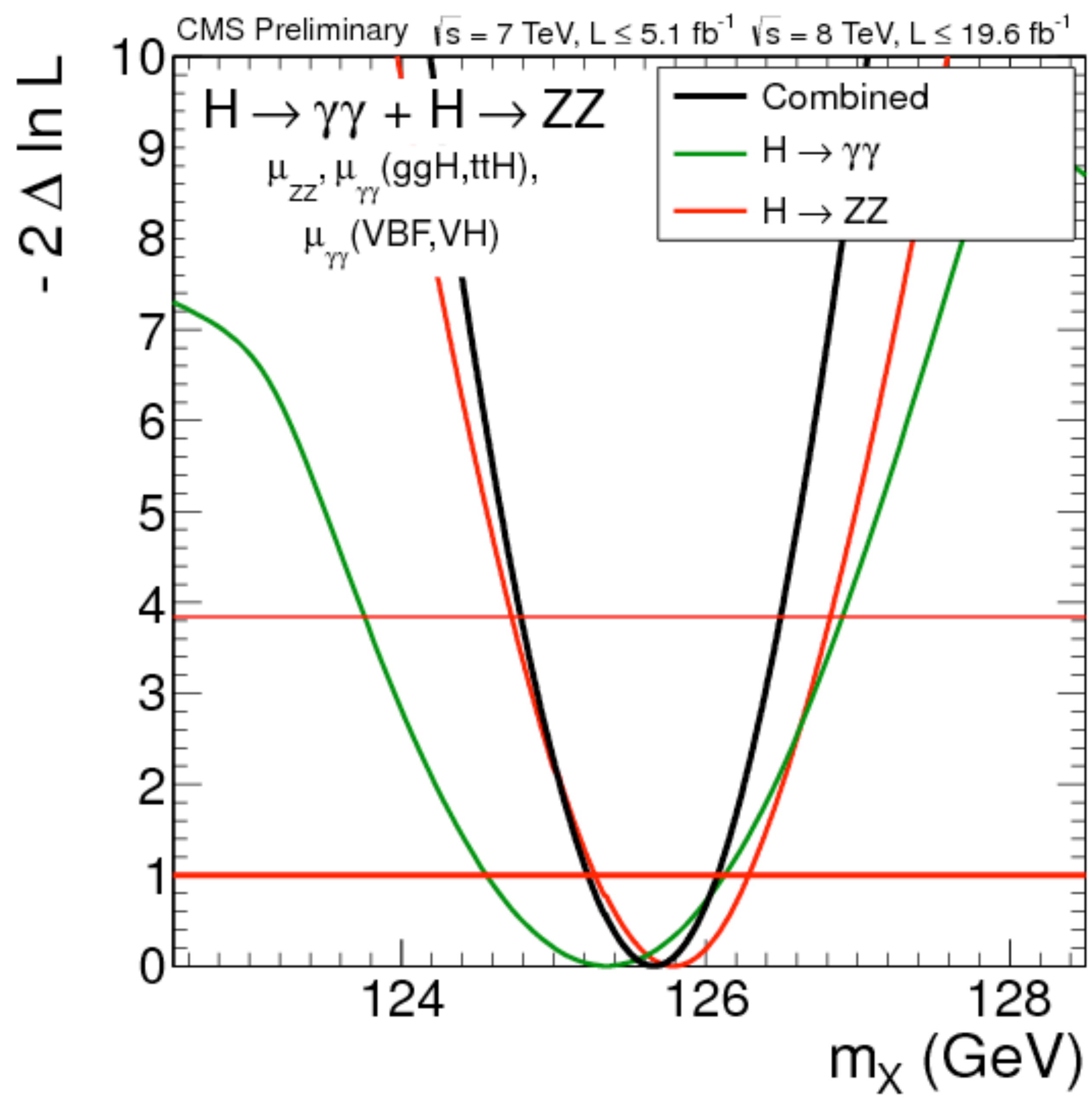


- Local significance at m_H=140GeV is 4.1σ
- Local significance at m_H=125GeV is 3.8σ
- Rate with respect to SM: 1.01 ± 0.31 @ m_H=125 GeV

Overview: Mass measurement



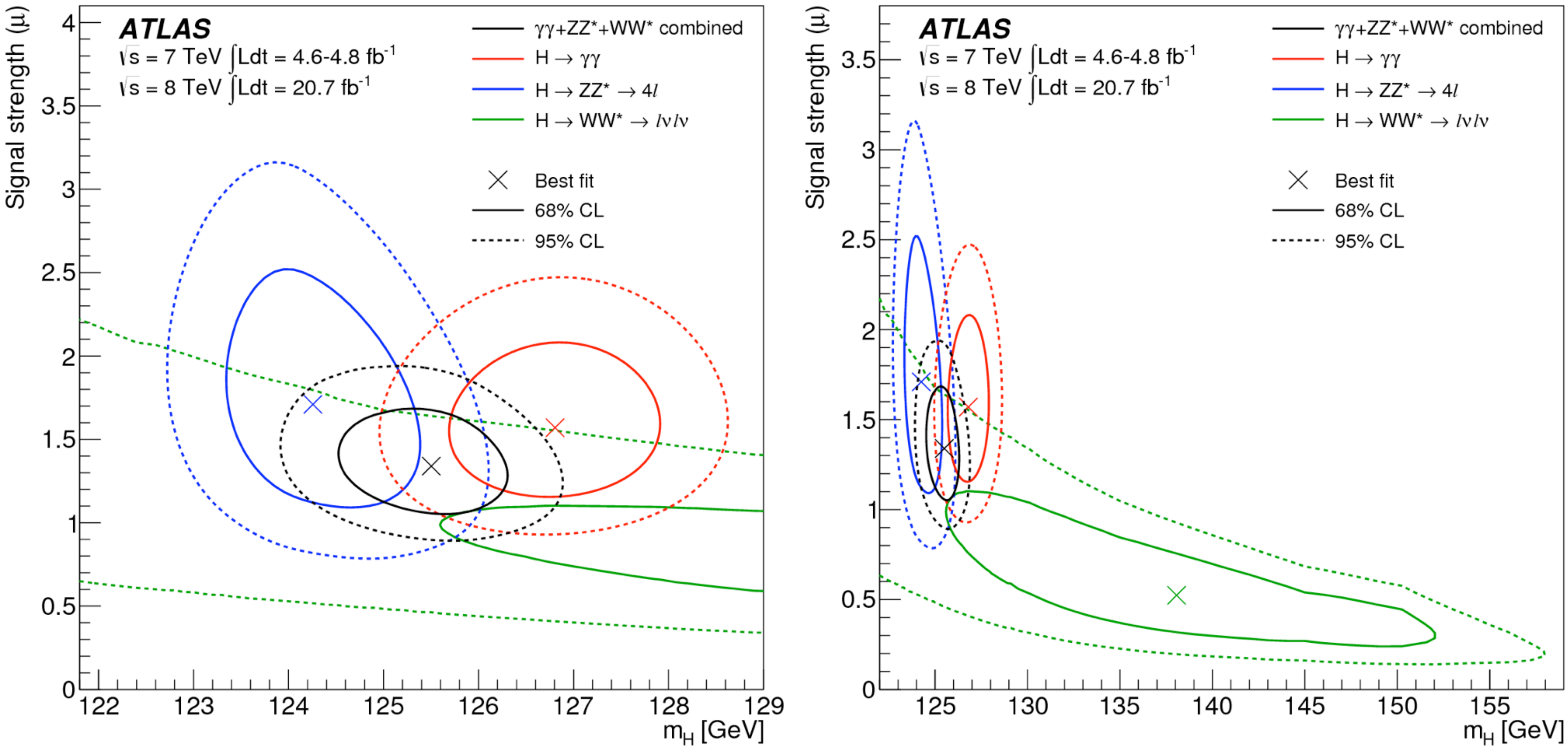
m_H = 125.5 ± 0.2 (stat)$^{+0.5}_{-0.6}$ (syst) GeV



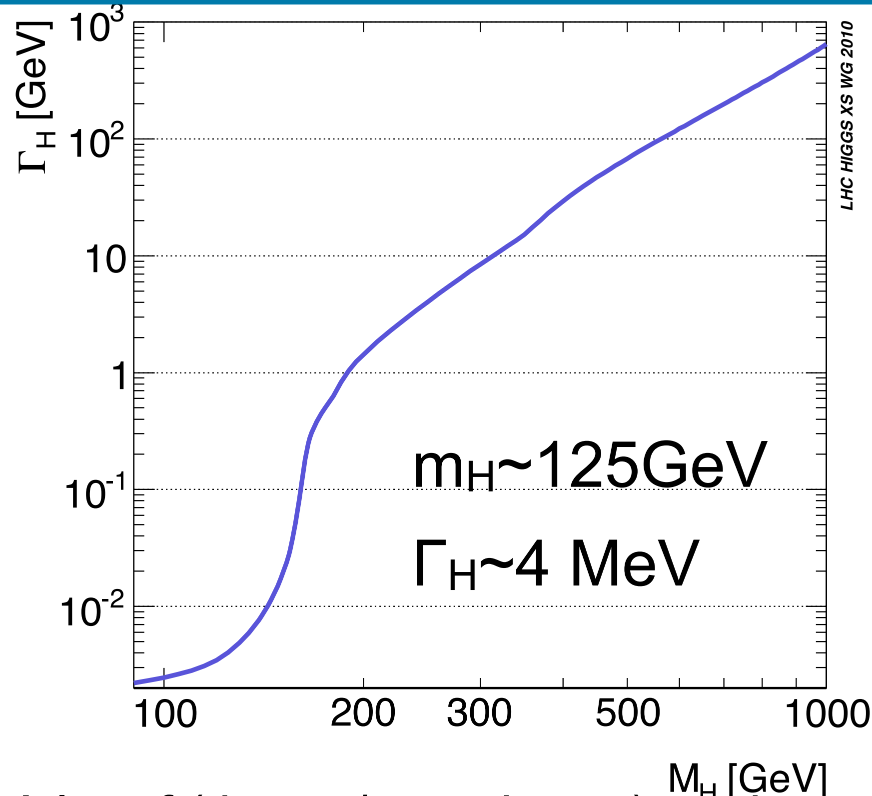
m_H = 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

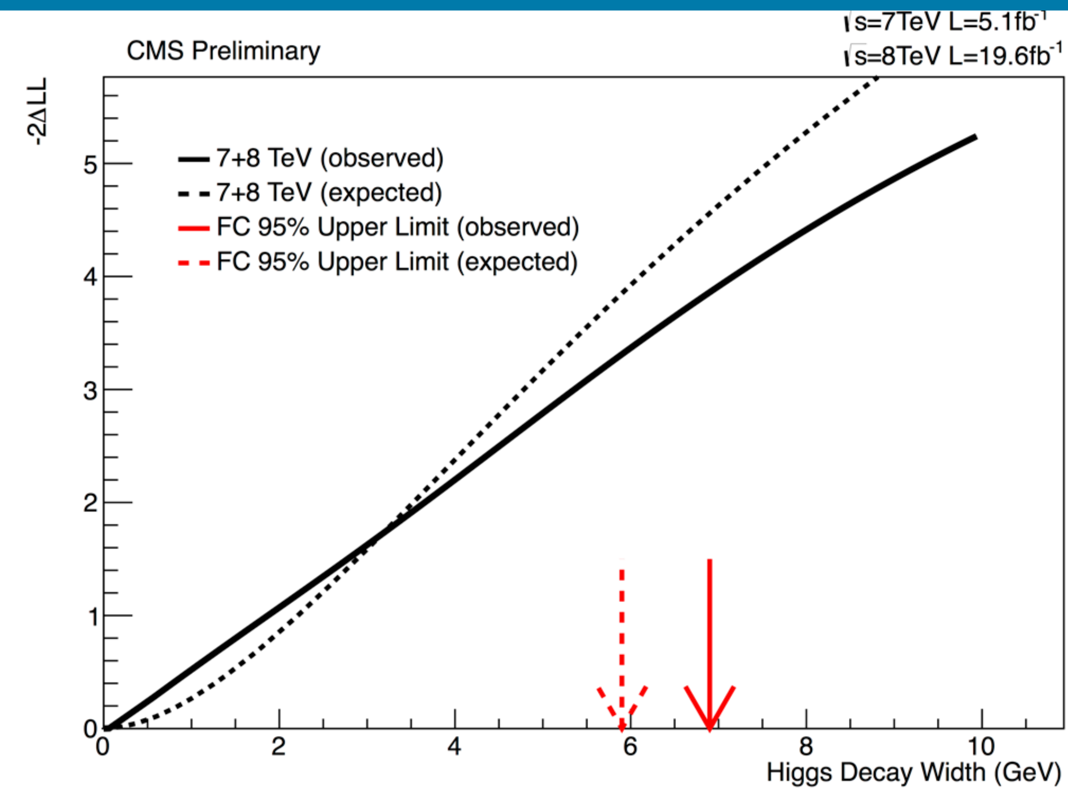
Using the high resolution channels only
The ATLAS and CMS mass combinations are in good agreement

The Higgs boson mass



Higgs Boson Width

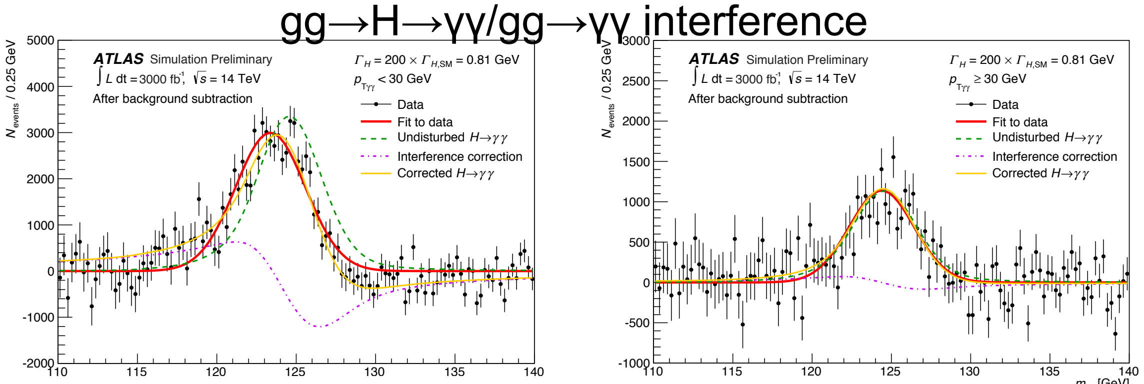


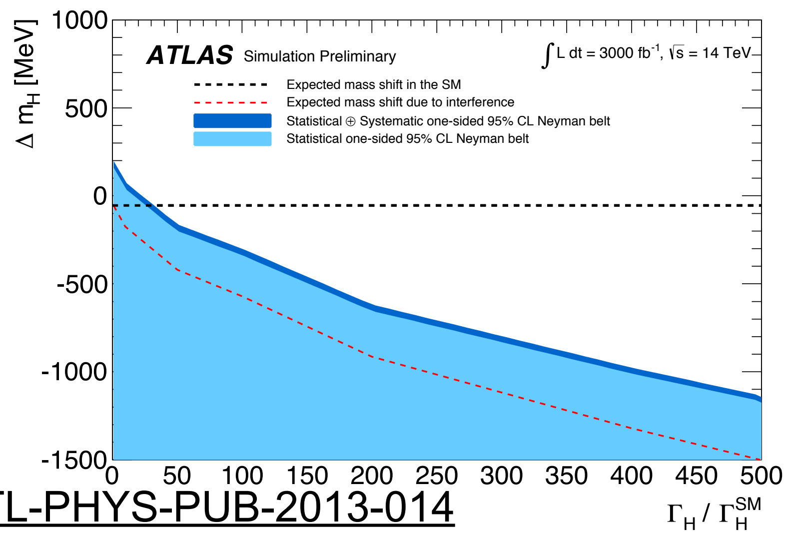


First direct limit to Higgs boson width from CMS H→γγ

A lot of (theory/experiment) work currently going towards Higgs boson width measurement through "interferometry"

gg→H→γγ/gg→γγ interference





ATL-PHYS-PUB-2013-014

gg→H→ZZ→4l/gg→ZZ→4l interference

Caola and Melnikov Phys.Rev. D88 (2013) 054024

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

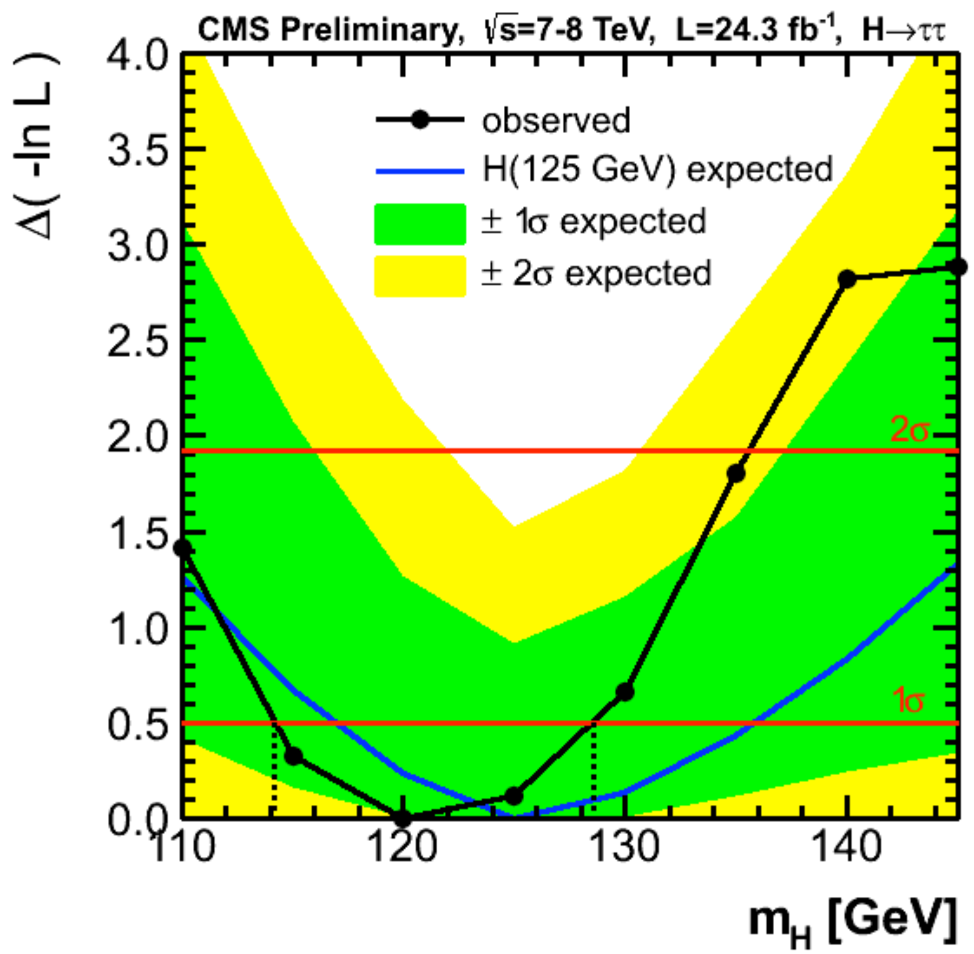
$$\Gamma_H \leq 21\ \Gamma_H^{\rm SM} \approx 88\ {\rm MeV}$$

with currently available dataset

L. J. Dixon and Y. Li, arXiv:1305.3854 [hep-ph]. Submitted to PRL.
S. P. Martin, arXiv:1303.3342 [hep-ph].

Higgs boson mass: CMS H→ττ

Mass 120^{+9}_{-7} GeV



H→ ττ

Small sensitivity to the Higgs boson mass

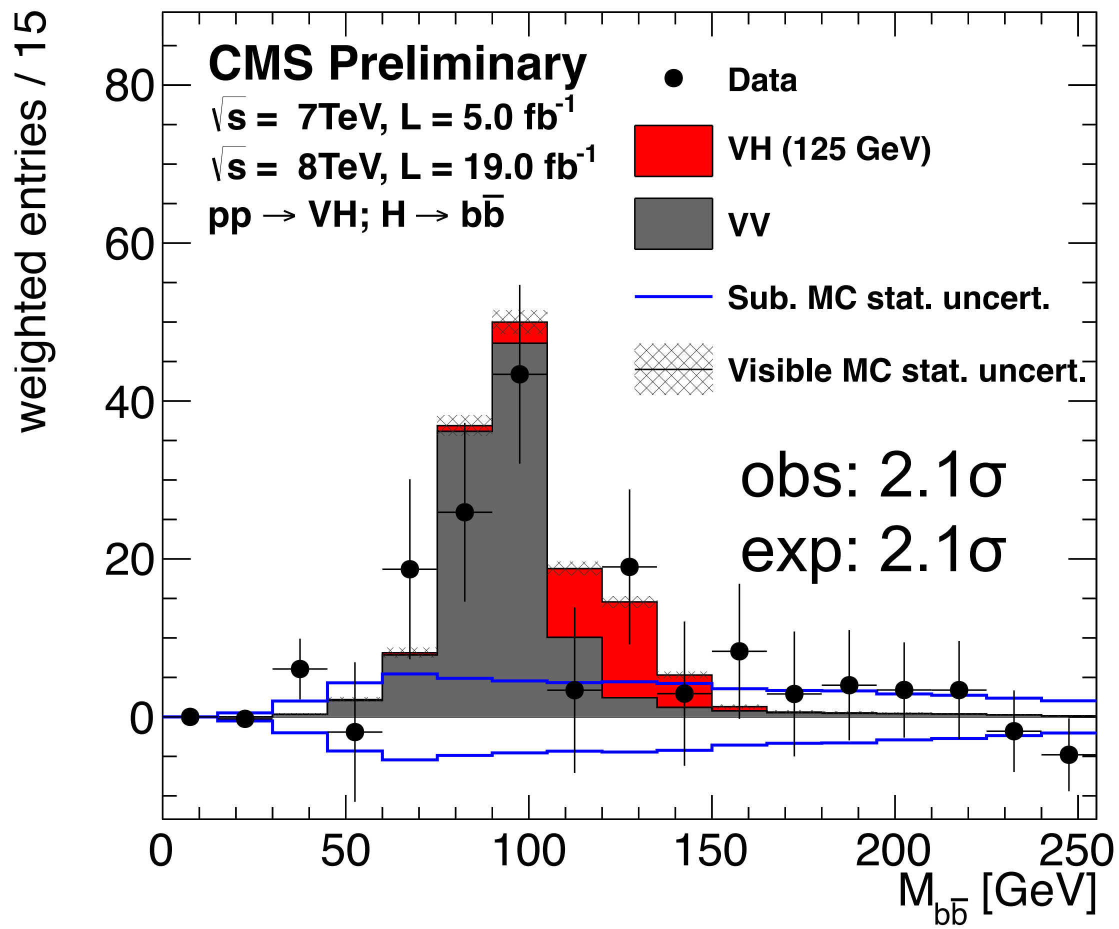
H→bb: Event Selection

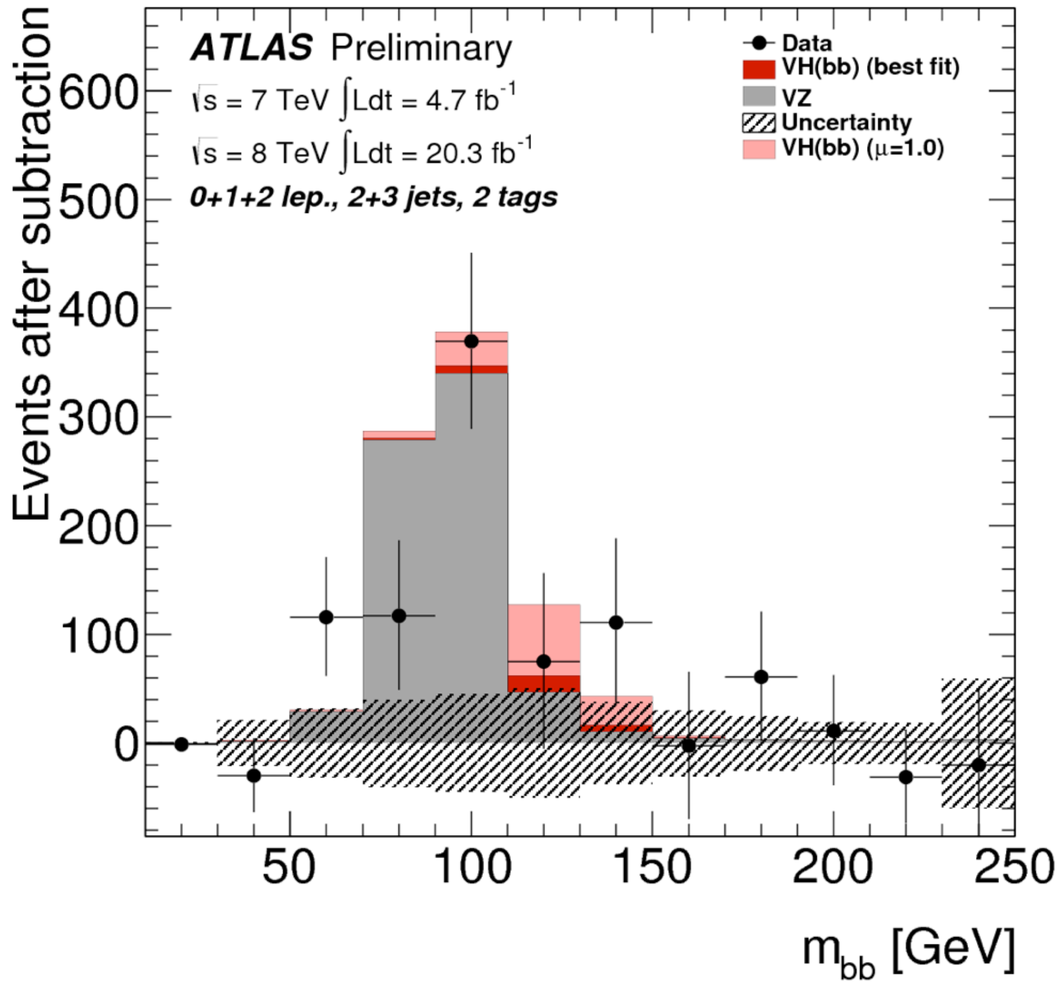
Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_{\mathrm{T}}^{\mathrm{jet}_1} > 45$ GeV $p_{\mathrm{T}}^{\mathrm{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \boldsymbol{p}_{\mathbf{T}}^{\mathbf{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_{\mathbf{T}}^{\mathbf{miss}}, b\bar{b}) > 2.8$	$E_{\mathrm{T}}^{\mathrm{miss}} > 25$ Gev	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_{\mathrm{T}}^{W} < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

Table 2: Further topological criteria in p_{T}^{V} intervals. The 0-lepton channel does not use the lowest two p_{T}^{V} intervals.

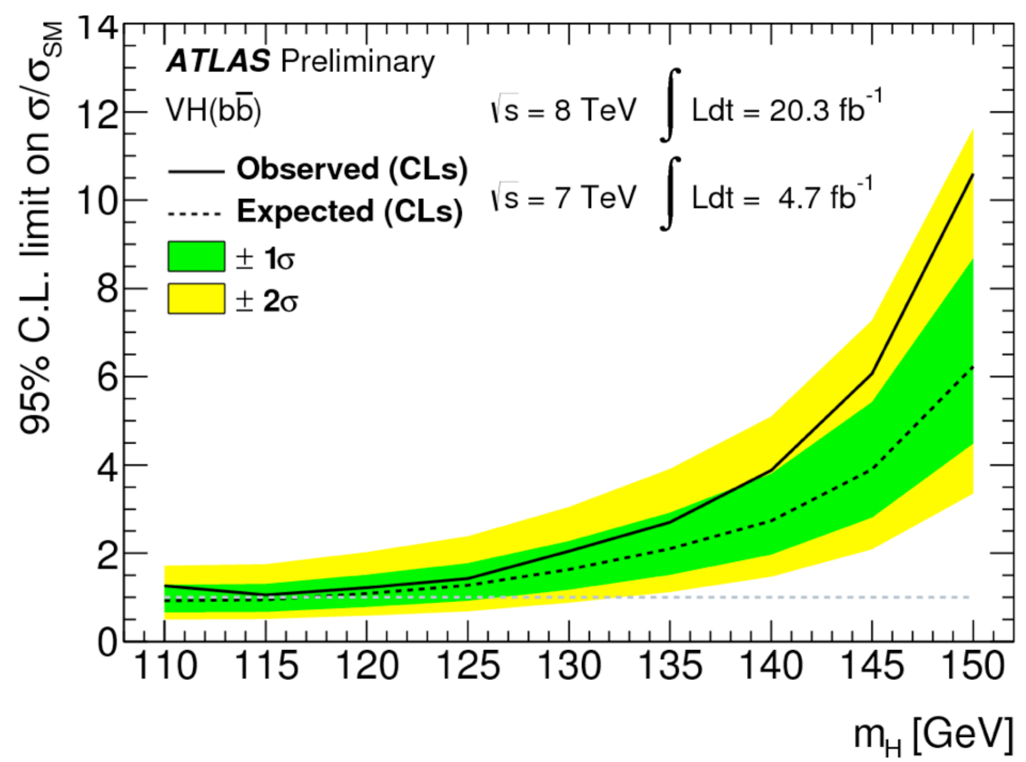
	p_{T}^{V} [GeV]	0-90	90-120	120-160	160-200	>200
All Channels	$\Delta R(b,\bar{b})$	0.7-3.4	0.7-3.0	0.7-2.3	0.7-1.8	<1.4
1-lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>25				>50
	m_{T}^{W} [GeV]	40-120			<120	

H→bb





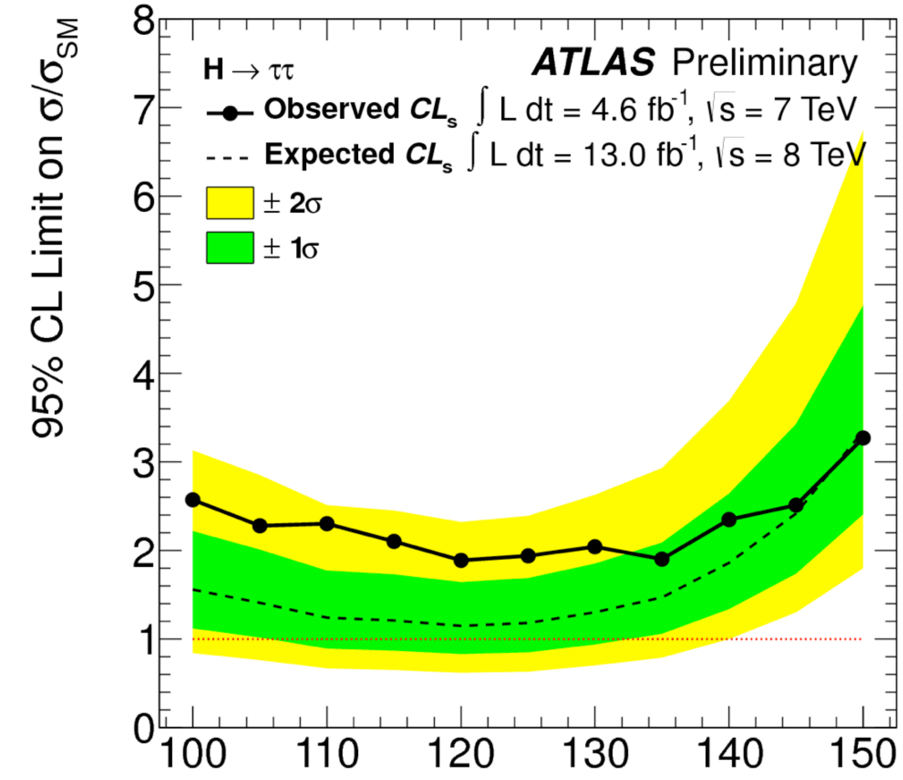
mH=125 GeV
95% CL exclusion limit 1.4 (1.3) x SM
μ = 0.2 ± 0.5 (stat) ± 0.4 (syst)



$H \rightarrow \tau\tau$

ATLAS-CONF-2012-160

- Direct probe of Higgs boson coupling to leptons
- Observable: $m_{\tau\tau}$
- Backgrounds: $Z\rightarrow\tau\tau$, diboson, top
- Poor mass resolution (~15%) due to neutrinos
- Separate final states:
  - τ-decays: μe, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
  - jet multiplicities
    - $\tau_l\tau_l$: 2j VBF, Boosted, 2j VH, 1j
    - $\tau_l\tau_h$: 2j VBF, Boosted, 1j, 0j
    - $\tau_h\tau_h$: VBF, Boosted

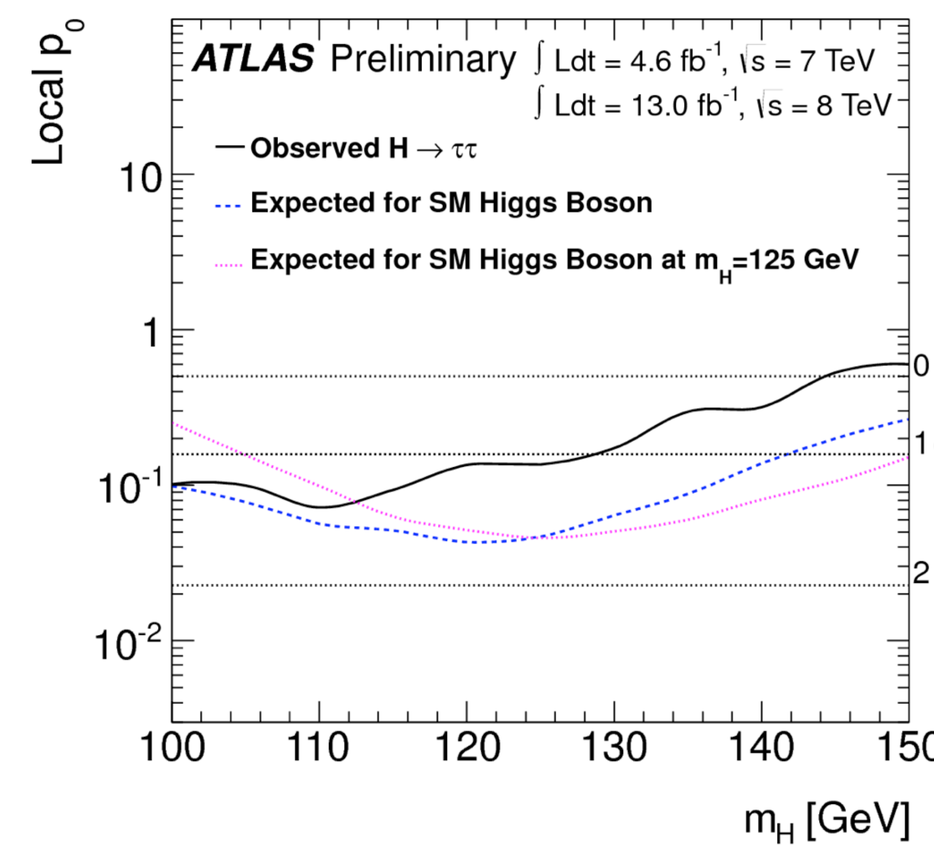


95% CL exclusion limit at m_H=125GeV is 1.9(1.2) x SM expectation

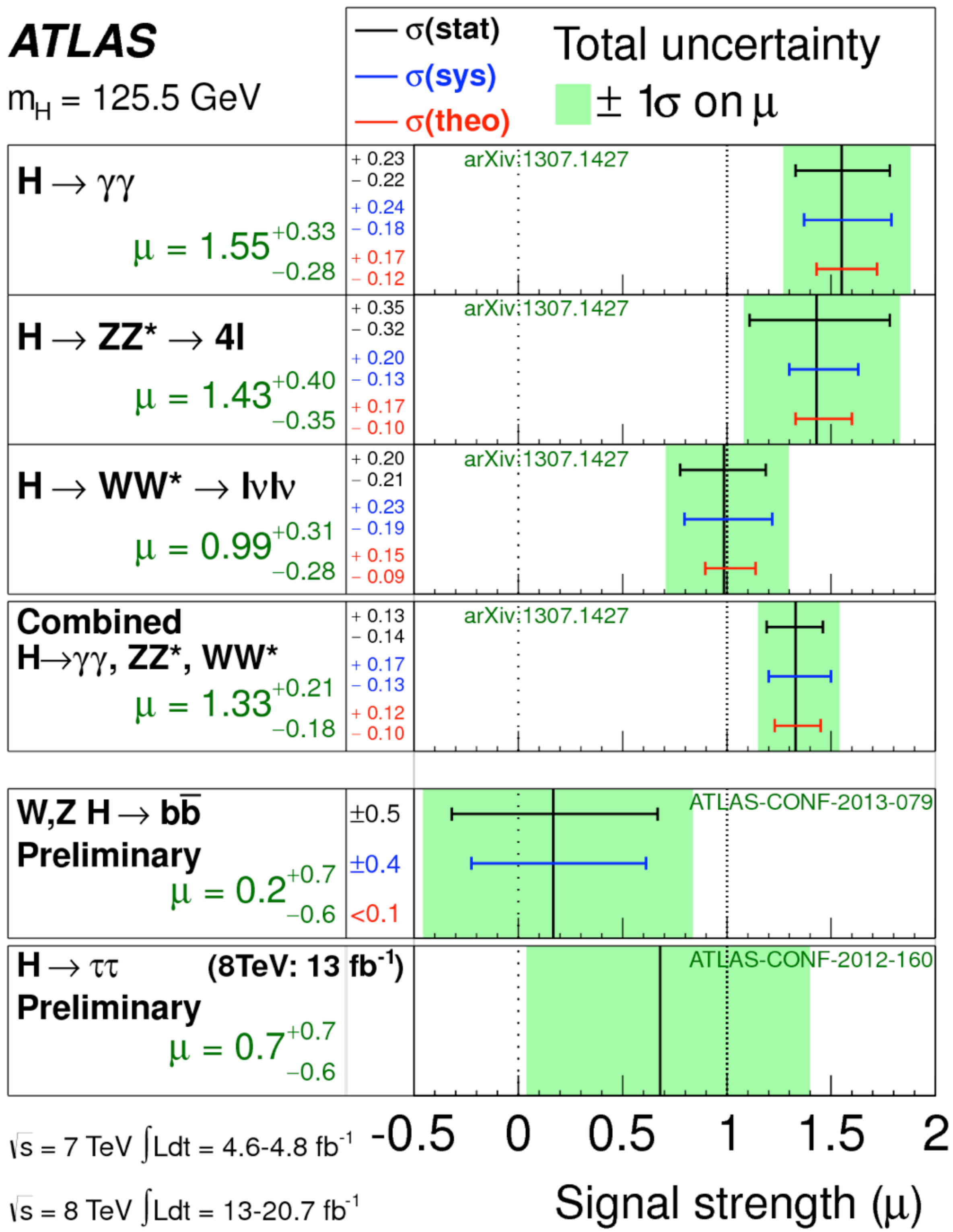
Local significance at **m_H=125GeV is 1.1σ (1.7σ)**

CMS Local significance at **m_H=125GeV is 2.85σ (2.62σ)**

CMSRate with respect to SM: **1.1 ± 0.4 @ m_H=125 GeV**



Overview of Signal Strength measurements



$H \rightarrow \tau_l \tau_l$

Table 2: The categorization of the $H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$ analysis. The JVF cut is $|JVF| > 0.75$ for 7 TeV data, the lepton centrality is not applied for 7 TeV analysis, and the 0-jet category is not used for 8 TeV data analysis.

<table>
<tr><th>2-jet VBF</th><th>Boosted</th><th>2-jet VH</th><th>1-jet</th></tr>
<tr><td colspan="4">Pre-selection: exactly two leptons with opposite charges</td></tr>
<tr><td colspan="4">30 GeV $< m_{\ell\ell} <$ 75 GeV (30 GeV $< m_{\ell\ell} <$ 100 GeV)
for same-flavor (different-flavor) leptons, and $p_{T,\ell 1} + p_{T,\ell 2} > 35$ GeV</td></tr>
<tr><td colspan="4">At least one jet with $p_T > 40$ GeV ($|JVF_{\text{jet}}| > 0.5$ if $|\eta_{\text{jet}}| < 2.4$)</td></tr>
<tr><td colspan="4">$E_{\text{T}}^{\text{miss}} > 40$ GeV ($E_{\text{T}}^{\text{miss}} > 20$ GeV) for same-flavor (different-flavor) leptons</td></tr>
<tr><td colspan="4">$H_{\text{T}}^{\text{miss}} > 40$ GeV for same-flavor leptons</td></tr>
<tr><td colspan="4">$0.1 < x_{1,2} < 1$</td></tr>
<tr><td colspan="4">$0.5 < \Delta\phi_{\ell\ell} < 2.5$</td></tr>
<tr><td>$p_{T,j2} > 25$ GeV (JVF)</td><td>excluding 2-jet VBF</td><td>$p_{T,j2} > 25$ GeV (JVF)</td><td>excluding 2-jet VBF, Boosted and 2-jet VH</td></tr>
<tr><td>$\Delta\eta_{jj} > 3.0$</td><td>$p_{T,\tau\tau} > 100$ GeV</td><td>excluding Boosted</td><td>$m_{\tau\tau j} > 225$ GeV</td></tr>
<tr><td>$m_{jj} > 400$ GeV</td><td>b-tagged jet veto</td><td>$\Delta\eta_{jj} < 2.0$</td><td>b-tagged jet veto</td></tr>
<tr><td>b-tagged jet veto</td><td rowspan="2">–</td><td>30 GeV $< m_{jj} <$ 160 GeV</td><td rowspan="2">–</td></tr>
<tr><td>Lepton centrality and CJV</td><td>b-tagged jet veto</td></tr>
<tr><td colspan="4">0-jet (7 TeV only)</td></tr>
<tr><td colspan="4">Pre-selection: exactly two leptons with opposite charges</td></tr>
<tr><td colspan="4">Different-flavor leptons with 30 GeV $< m_{\ell\ell} <$ 100 GeV and $p_{T,\ell 1} + p_{T,\ell 2} > 35$ GeV</td></tr>
<tr><td colspan="4">$\Delta\phi_{\ell\ell} > 2.5$</td></tr>
<tr><td colspan="4">b-tagged jet veto</td></tr>
</table>

$H \rightarrow \tau_l \tau_h$

Table 3: Event requirements applied in the different categories of the $H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$ analysis. Requirements marked with a triangle (▹) are categorization requirements, meaning that if an event fails that requirement it is still considered for the remaining categories. Requirements marked with a bullet (•) are only applied to events passing all categorization requirements in a category; events failing such requirements are discarded.

7 TeV		8 TeV	
VBF Category	Boosted Category	VBF Category	Boosted Category
▹ $p_{\mathrm{T}}^{\tau_{\text{had-vis}}}$ >30 GeV	–	▹ $p_{\mathrm{T}}^{\tau_{\text{had-vis}}}$ >30 GeV	▹ $p_{\mathrm{T}}^{\tau_{\text{had-vis}}}$ >30 GeV
▹ $E_{\mathrm{T}}^{\text{miss}}$ >20 GeV	▹ $E_{\mathrm{T}}^{\text{miss}}$ >20 GeV	▹ $E_{\mathrm{T}}^{\text{miss}}$ >20 GeV	▹ $E_{\mathrm{T}}^{\text{miss}}$ >20 GeV
▹ ≥ 2 jets	▹ $p_{\mathrm{T}}^{H} > 100$ GeV	▹ ≥ 2 jets	▹ $p_{\mathrm{T}}^{H} > 100$ GeV
▹ $p_{\mathrm{T}}^{j1}, p_{\mathrm{T}}^{j2} > 40$ GeV	▹ $0 < x_1 < 1$	▹ $p_{\mathrm{T}}^{j1} > 40$, p_{T}^{j2} >30 GeV	▹ $0 < x_1 < 1$
▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$	▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$
▹ $m_{jj} > 500$ GeV	▹ Fails VBF	▹ $m_{jj} > 500$ GeV	▹ Fails VBF
▹ centrality req.	–	▹ centrality req.	–
▹ $\eta_{j1} \times \eta_{j2} < 0$	–	▹ $\eta_{j1} \times \eta_{j2} < 0$	–
▹ $p_{\mathrm{T}}^{\text{Total}} < 40$ GeV	–	▹ $p_{\mathrm{T}}^{\text{Total}} < 30$ GeV	–
–	–	▹ p_{T}^{ℓ} >26 GeV	–
• m_{T} <50 GeV	• m_{T} <50 GeV	• m_{T} <50 GeV	• m_{T} <50 GeV
• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 1.6$	• $\sum \Delta\phi < 2.8$	–
–	–	• b-tagged jet veto	• b-tagged jet veto
1 Jet Category	0 Jet Category	1 Jet Category	0 Jet Category
▹ ≥ 1 jet, p_{T} >25 GeV	▹ 0 jets p_{T} >25 GeV	▹ ≥ 1 jet, p_{T} >30 GeV	▹ 0 jets p_{T} >30 GeV
▹ $E_{\mathrm{T}}^{\text{miss}}$ >20 GeV	▹ $E_{\mathrm{T}}^{\text{miss}}$ >20 GeV	▹ $E_{\mathrm{T}}^{\text{miss}}$ >20 GeV	▹ $E_{\mathrm{T}}^{\text{miss}}$ >20 GeV
▹ Fails VBF, Boosted	▹ Fails Boosted	▹ Fails VBF, Boosted	▹ Fails Boosted
• m_{T} <50 GeV	• m_{T} <30 GeV	• m_{T} <50 GeV	• m_{T} <30 GeV
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_{\mathrm{T}}^{\ell} - p_{\mathrm{T}}^{\tau} < 0$	–	• $p_{\mathrm{T}}^{\ell} - p_{\mathrm{T}}^{\tau} < 0$

Table 4: Summary of the event selection and categories for the $H \to \tau_{\text{had}}\tau_{\text{had}}$ channel.

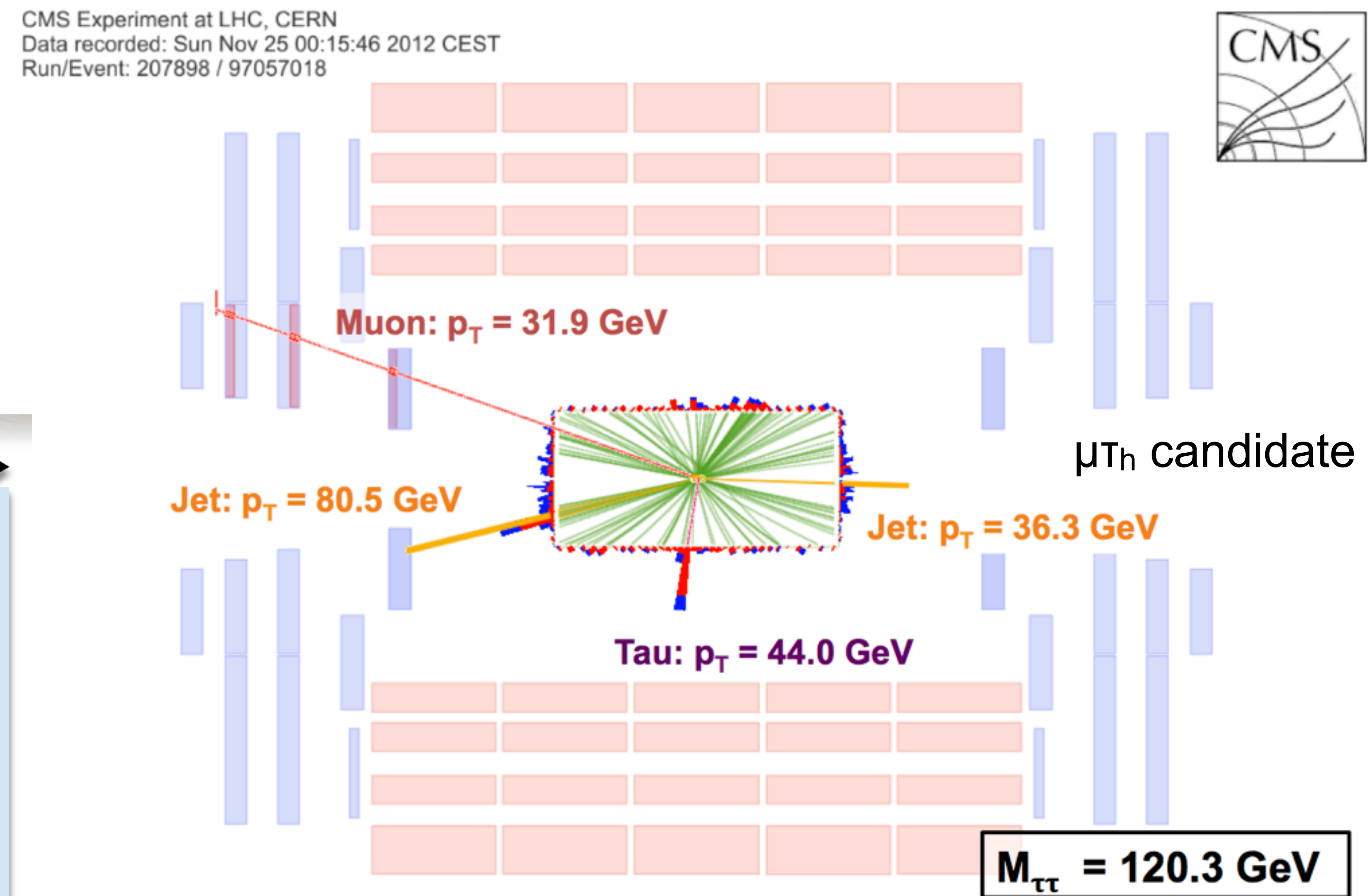
Cut	Description
Preselection	No muons or electrons in the event
	Exactly 2 medium τ_{had} candidates matched with the trigger objects
	At least 1 of the τ_{had} candidates identified as tight
	Both τ_{had} candidates are from the same primary vertex
	Leading $\tau_{\text{had-vis}}$ $p_T > 40$ GeV and sub-leading $\tau_{\text{had-vis}}$ $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
	τ_{had} candidates have opposite charge and 1- or 3-tracks
	$0.8 < \Delta R(\tau_1, \tau_2) < 2.8$
	$\Delta\eta(\tau, \tau) < 1.5$
	if $E_{\text{T}}^{\text{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_1), \Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_2)\right\} < 0.2\pi$
VBF	At least two tagging jets, j_1, j_2, leading tagging jet with $p_{\text{T}} > 50$ GeV
	$\eta_{j1} \times \eta_{j2} < 0$, $\Delta\eta_{jj} > 2.6$ and invariant mass $m_{jj} > 350$ GeV
	$\min(\eta_{j1}, \eta_{j2}) < \eta_{\tau1}, \eta_{\tau2} < \max(\eta_{j1}, \eta_{j2})$
	$E_{\text{T}}^{\text{miss}} > 20$ GeV
Boosted	Fails VBF
	At least one tagging jet with $p_{\text{T}} > 70(50)$ GeV in the 8(7) TeV dataset
	$\Delta R(\tau_1, \tau_2) < 1.9$
	$E_{\text{T}}^{\text{miss}} > 20$ GeV
	if $E_{\text{T}}^{\text{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_1), \Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_2)\right\} < 0.1\pi$.

H→ττ

- Direct probe of Higgs boson coupling to leptons
- Observable: $m_{\tau\tau}$
- Backgrounds: Z→ττ, diboson, top
- Poor mass resolution (~15%) due to neutrinos
- Separate final states:
  - τ-decays: μe, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
  - jet multiplicities: 1, 2

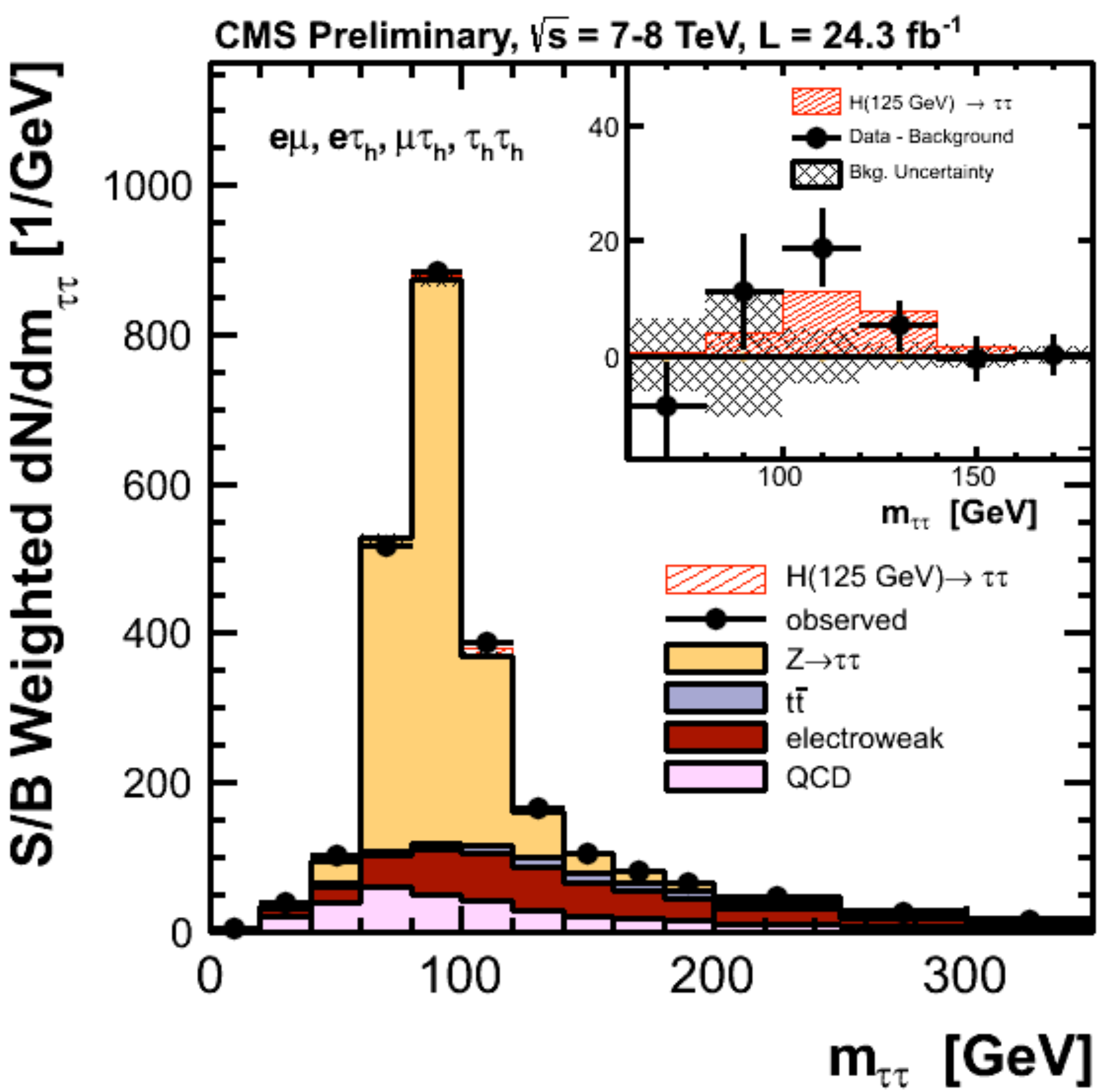
number of jets → ; τ p_T ↓ ; $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$

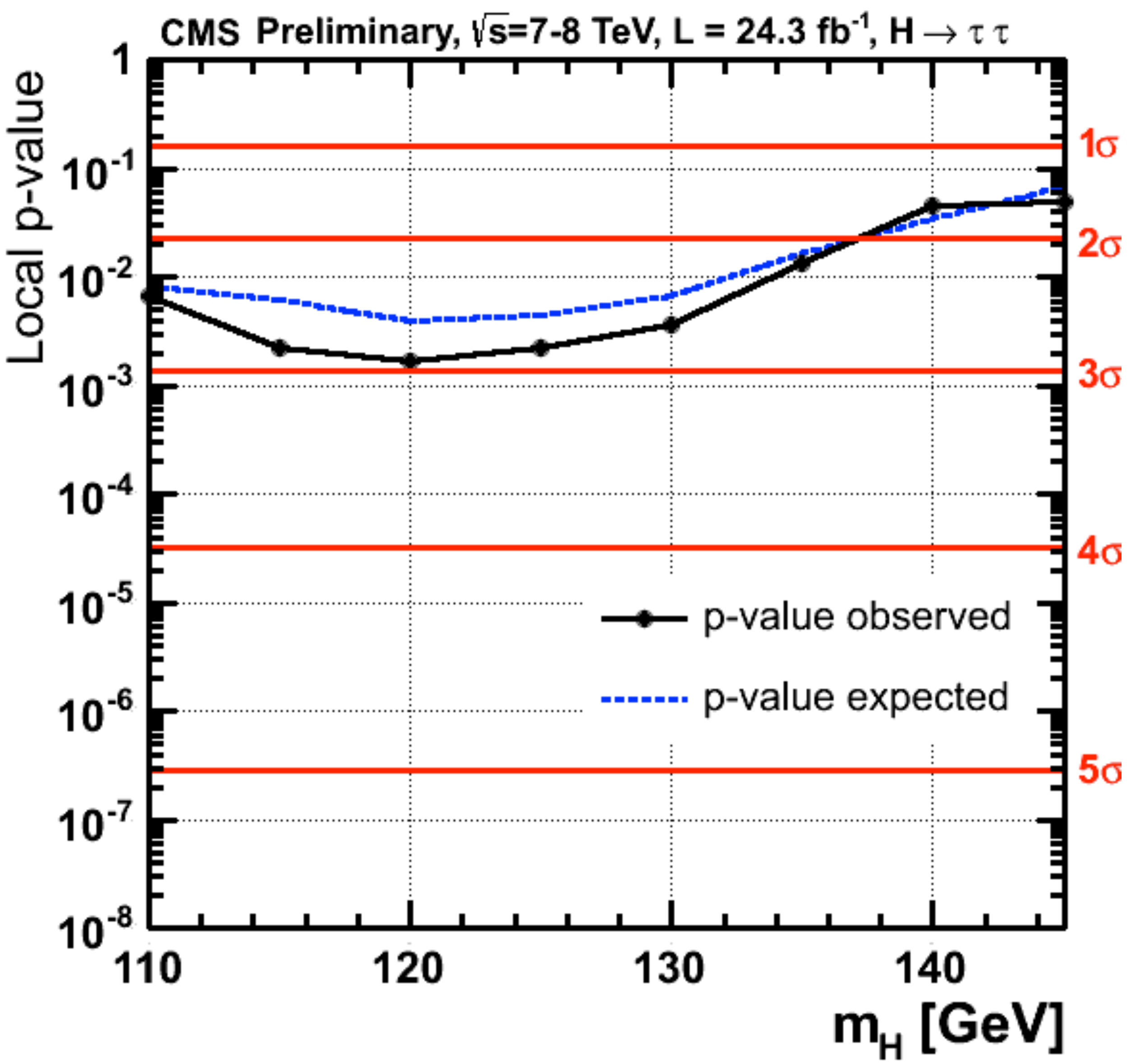
0-jet, low p_T ▪ High background, constrains nuisance parameters ▪ No fit for signal	**1-jet, low p_T** ▪ Enhancement from jet requirement	**2-jet (VBF)** ▪ ≥2 jets, no jet in rapidity gap ▪ m(jj) > 500 GeV, $\lvert\Delta\eta(jj)\rvert > 3.5$
0-jet, high p_T ▪ High background, constrains nuisance parameters ▪ No fit for signal	**1-jet, high p_T** ▪ Enhancement from jet and p_T requirement	
	$\tau_h\tau_h$ 1-jet 1 jet, high p_T(H) requirement	**$\tau_h\tau_h$ 2-jet (VBF)** 2 jets, high p_T(H) requirement, m(jj) > 250 GeV, $\lvert\Delta\eta(jj)\rvert > 2.5$



$\mu\tau_h$ candidate

H→ττ: Results





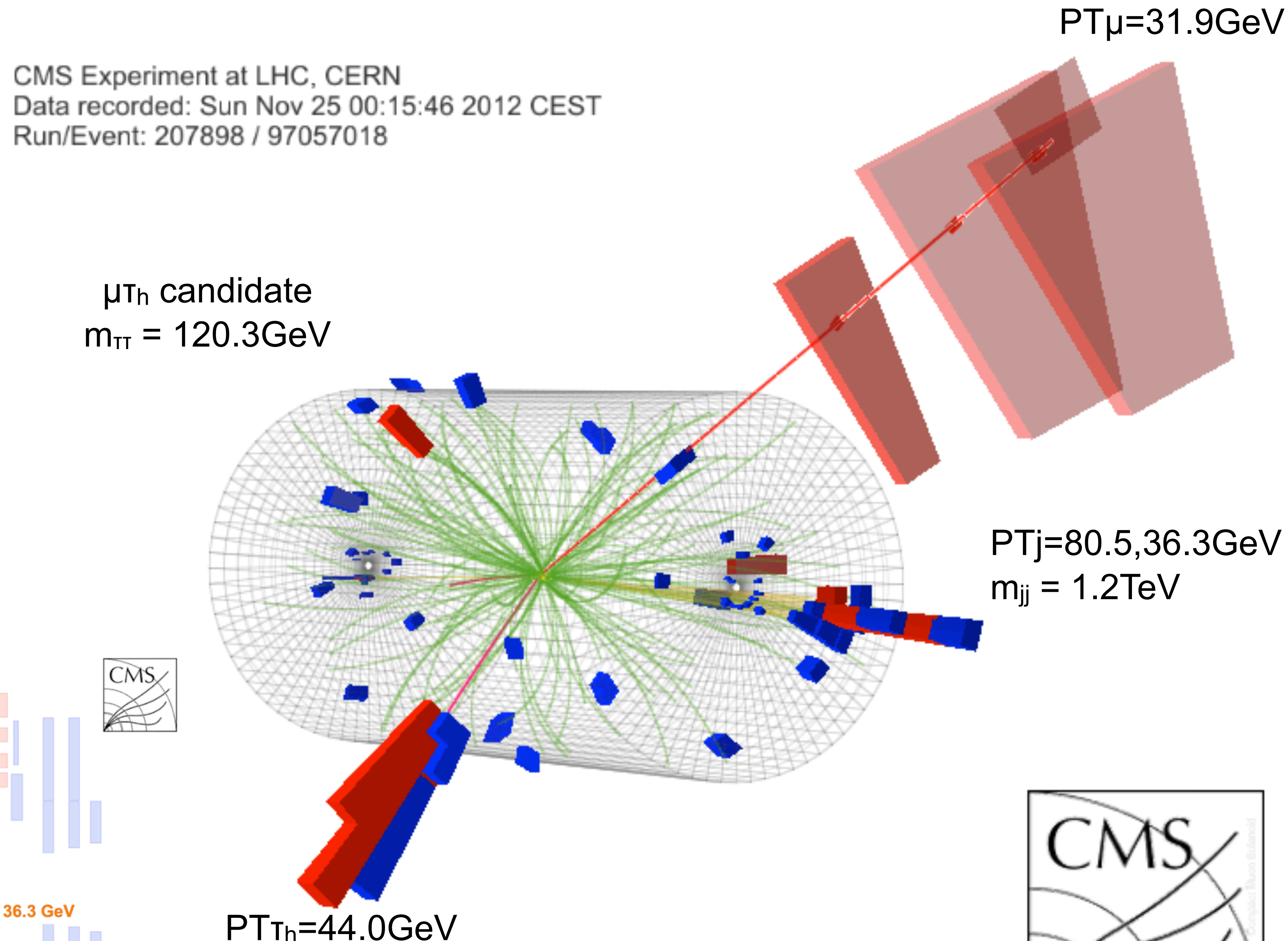
Local significance at m_H=120GeV is 2.93σ (2.65σ)

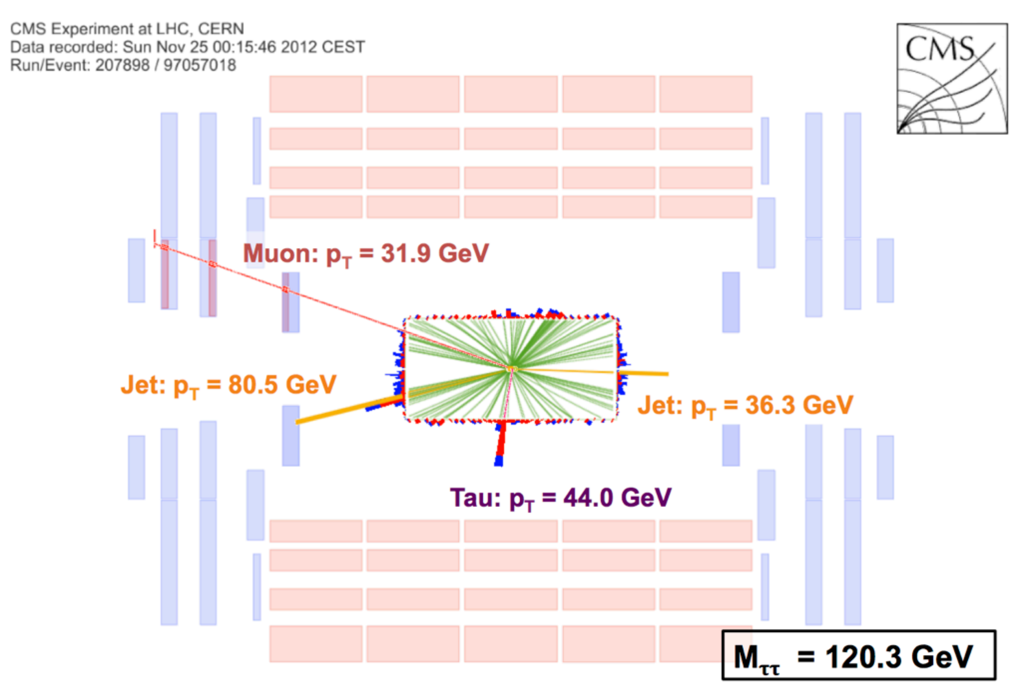
Local significance at **m_H=125GeV is 2.85σ (2.62σ)**

Consistent picture across different channels

Rate with respect to SM: **1.1 ± 0.4 @ m_H=125 GeV**

H→ττ: Event Display VBF-like candidate





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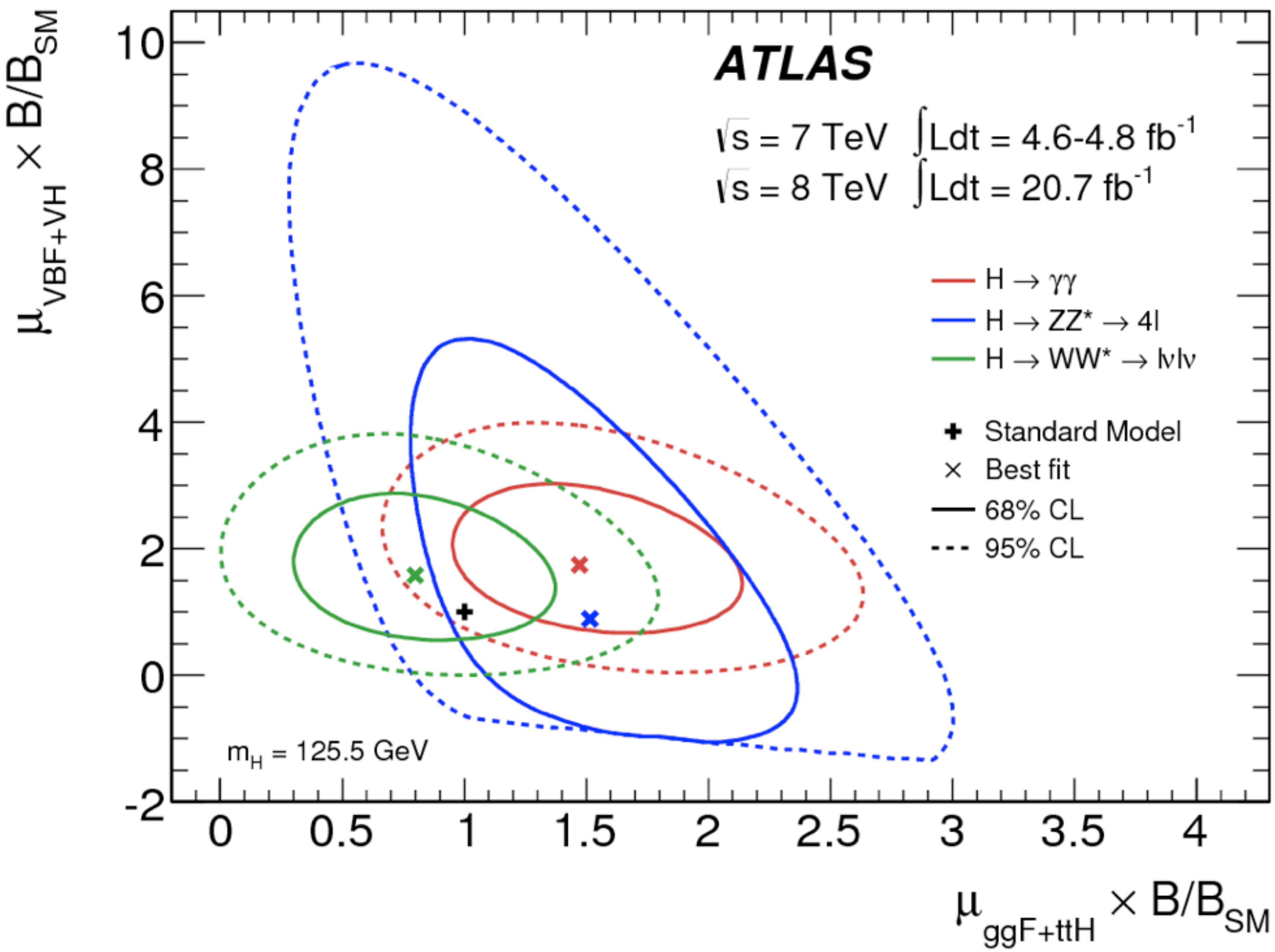

ATLAS
$\sqrt{s}$ = 7 TeV $\int$Ldt = 4.6-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int$Ldt = 20.7 fb^{-1}
H → γγ
H → ZZ* → 4l
H → WW* → lνlν
Standard Model
Best fit
68% CL
95% CL
m_H = 125.5 GeV
$\mu_{VBF+VH} \times B/B_{SM}$
$\mu_{ggF+ttH} \times B/B_{SM}$

ATLAS Spin/CP studies: The scenarios

Spin/CP studies following formalism of arXiv:1001.3396 and arXiv:1208.4018

- Currently study pure spin/CP states
- Ultimate goal: determine helicity amplitudes and observe/ constraint admixtures (potentially CP-violation)

arXiv:1001.3396

Spin determination of single-produced resonances at hadron colliders

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We study the production of a single resonance at the LHC and its decay into a pair of Z bosons. We demonstrate how full reconstruction of the final states allows us to determine the spin and parity of the resonance and restricts its coupling to vector gauge bosons. Full angular analysis is illustrated with the simulation of the production and decay chain including all spin correlations and the most general couplings of spin-zero, -one, and -two resonances to Standard Model matter and gauge fields. We note implications for analysis of a resonance decaying to other final states.

PACS numbers: 12.60.-i, 13.88.+e, 14.80.Bn

spin-0 $$A(X \to V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta \right)$$

TABLE I: The list of scenarios chosen for the analysis of the production and decay of an exotic X particle with quantum numbers J^P. For the two 2^+ cases, the superscripts m (minimal) and L (longitudinal) distinguish two scenarios, as discussed in the last column. When relevant, the relative fraction of gg and $q\bar{q}$ production is taken to be 1:0 at $m_X = 250$ GeV and 3:1 at $m_X = 1$ TeV. The spin-zero X production mechanism does not affect the angular distributions and therefore is not specified.

	scenario (J^P)	$X \to ZZ$ decay parameters	X production parameters	comments
✔	0^+	$a_1 \neq 0$ in Eq. (2)	$gg \to X$	SM Higgs-like scalar
✔	0^-	$a_3 \neq 0$ in Eq. (2)	$gg \to X$	pseudo-scalar
✔	1^+	$g_{12} \neq 0$ in Eq. (4)	$q\bar{q} \to X$: $\rho_{11}, \rho_{12} \neq 0$ in Eq. (9)	exotic pseudo-vector
✔	1^-	$g_{11} \neq 0$ in Eq. (4)	$q\bar{q} \to X$: $\rho_{11}, \rho_{12} \neq 0$ in Eq. (9)	exotic vector
✔	2^+_m	$g_1^{(2)} = g_5^{(2)} \neq 0$ in Eq. (5)	$gg \to X$: $g_1^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: $\rho_{21} \neq 0$ in Eq. (10)	Graviton-like tensor with minimal couplings
✘	2^+_L	$c_2 \neq 0$ in Eq. (6)	$gg \to X$: $g_2^{(2)} = g_3^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: $\rho_{21}, \rho_{22} \neq 0$ in Eq. (10)	Graviton-like tensor longitudinally polarized and with $J_z = 0$ contribution
✘	2^-	$g_8^{(2)} = g_9^{(2)} \neq 0$ in Eq. (5)	$gg \to X$: $g_1^{(2)} \neq 0$ in Eq. (5) $q\bar{q} \to X$: $\rho_{21}, \rho_{22} \neq 0$ in Eq. (10)	"pseudo-tensor"

$H \rightarrow \gamma\gamma$: Analysis procedure

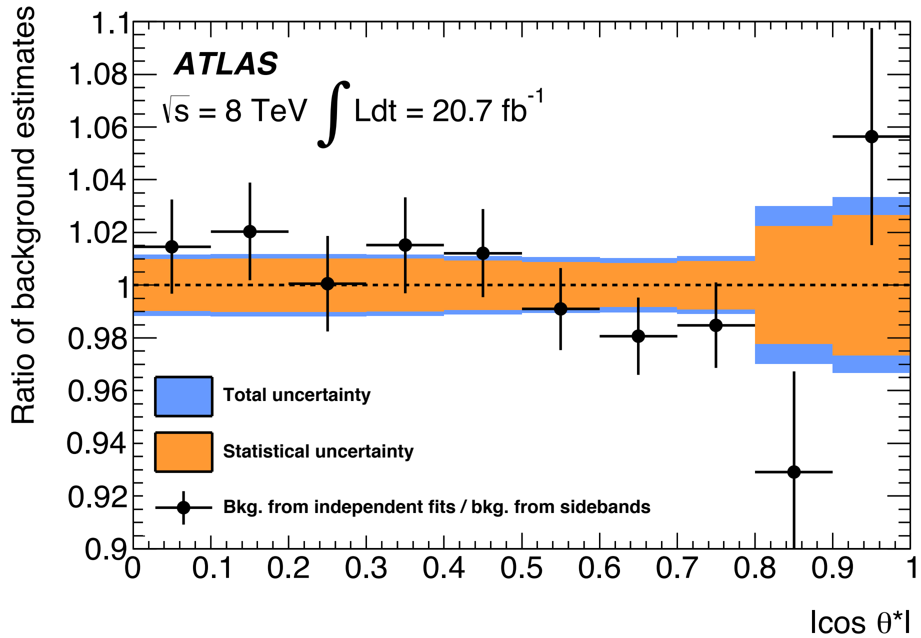
- Analysis similar to "rate/mass" analysis but optimized selection:
  - $p_{T\gamma 1} > 0.35\ m_{\gamma\gamma}$ and $p_{T\gamma 2} > 0.25\ m_{\gamma\gamma}$
  - Minimize $m_{\gamma\gamma}$ and $\cos\theta^*$ correlations for background
  - Residual correlations at 0.6% (2%) level for $|\cos\theta^*|<(>)0.8$
- $H \rightarrow \gamma\gamma$ is a low S/B final state (inclusive ~3%)
  - Simultaneous fit to $m_{\gamma\gamma}$ and $|\cos\theta^*|$ in signal region
  - $m_{\gamma\gamma}$ in side-bands
- $m_{\gamma\gamma}$ modeling similar to rate analysis
  - Signal : Crystal-Ball (describe ~95% of events) and Gauss
  - Background : 5^{th} order polynomial
- $\cos\theta^*$ modeling
  - Signal : derived from MC

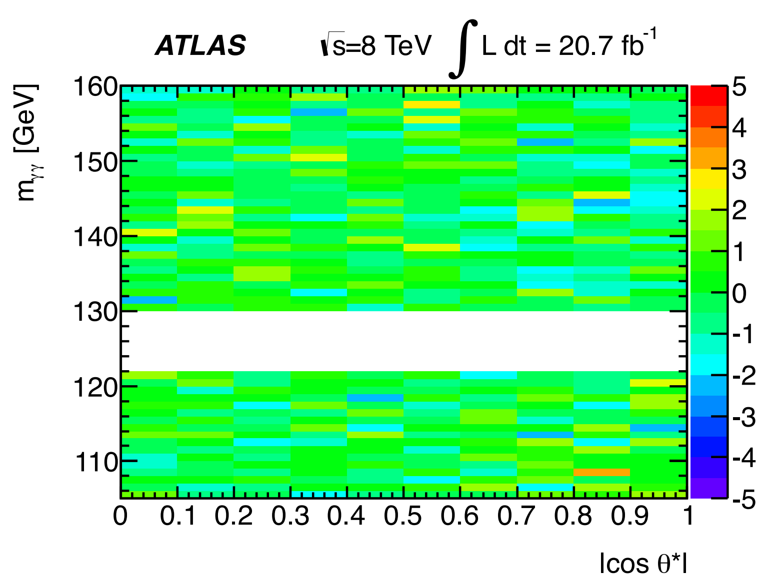
    For SM correct for interference between $gg \rightarrow \gamma\gamma$ and signal (important for $|\cos\theta^*| > 0.8$)

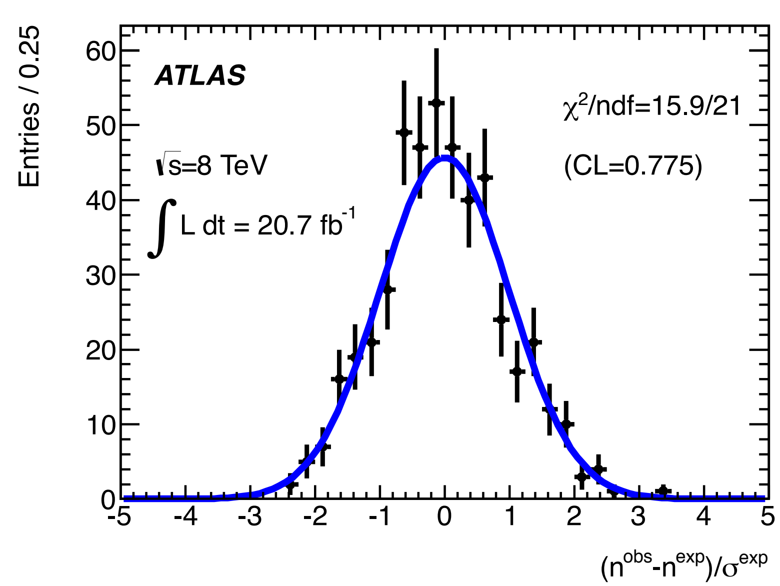
    For 2^+ no description for such effect, neglect.
  - Background : $|\cos\theta^*|$ distribution from $m_{\gamma\gamma}$ side-bands
- p_T spectrum: reweight spin-2 state to SM PowHeg (HqT), full size of correction as systematic

side-band statistics: 1% (3%) for $|\cos\theta^*|<(>)0.8$

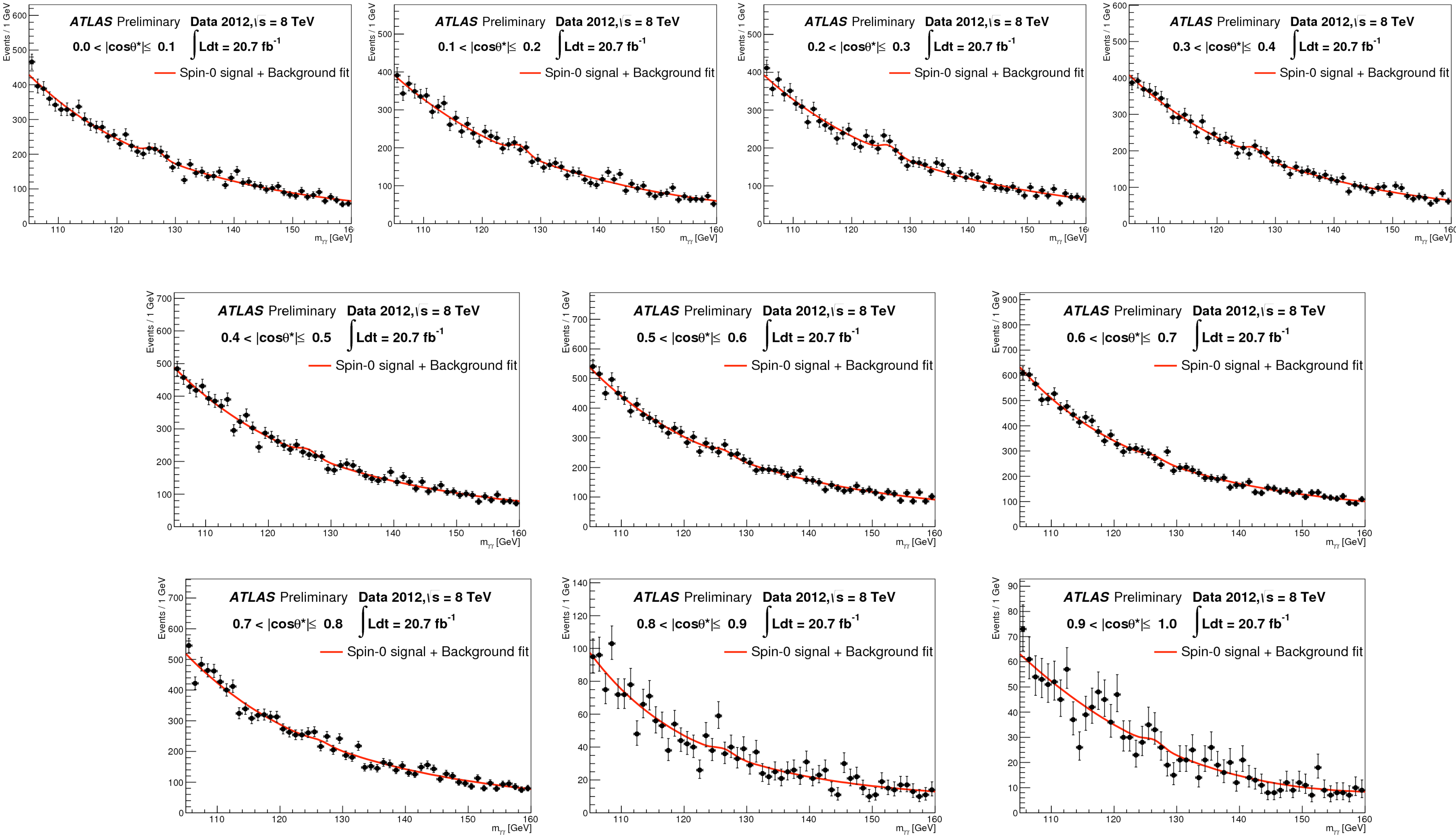
residual correlations: 0.6% (2%) for $|\cos\theta^*|<(>)0.8$





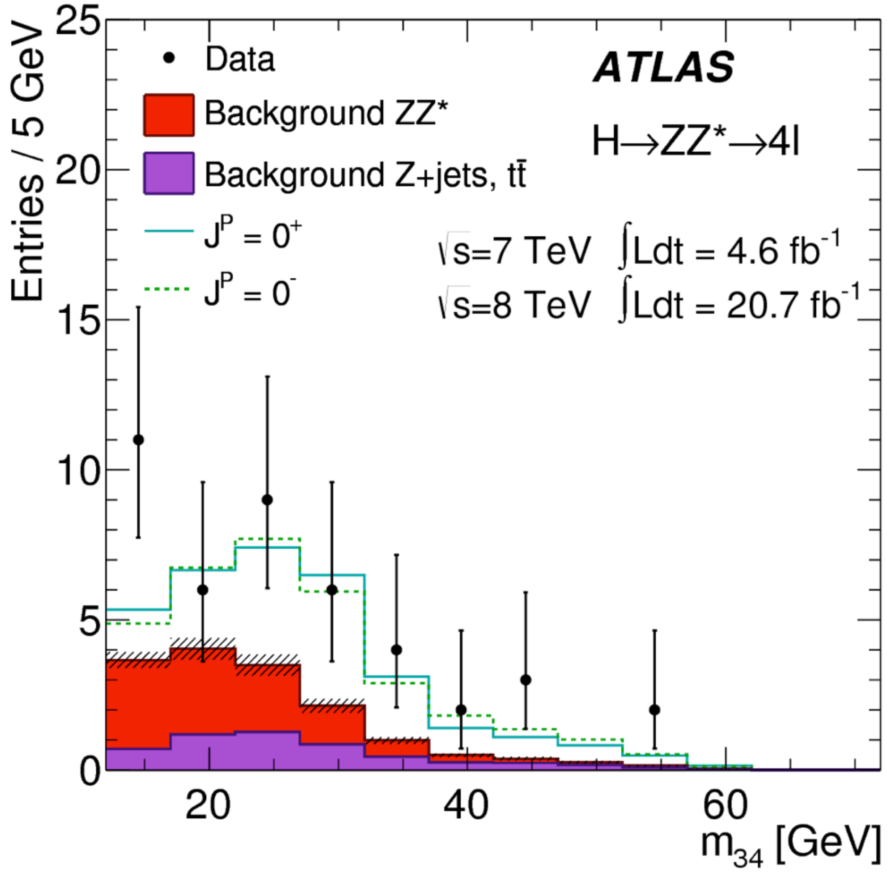


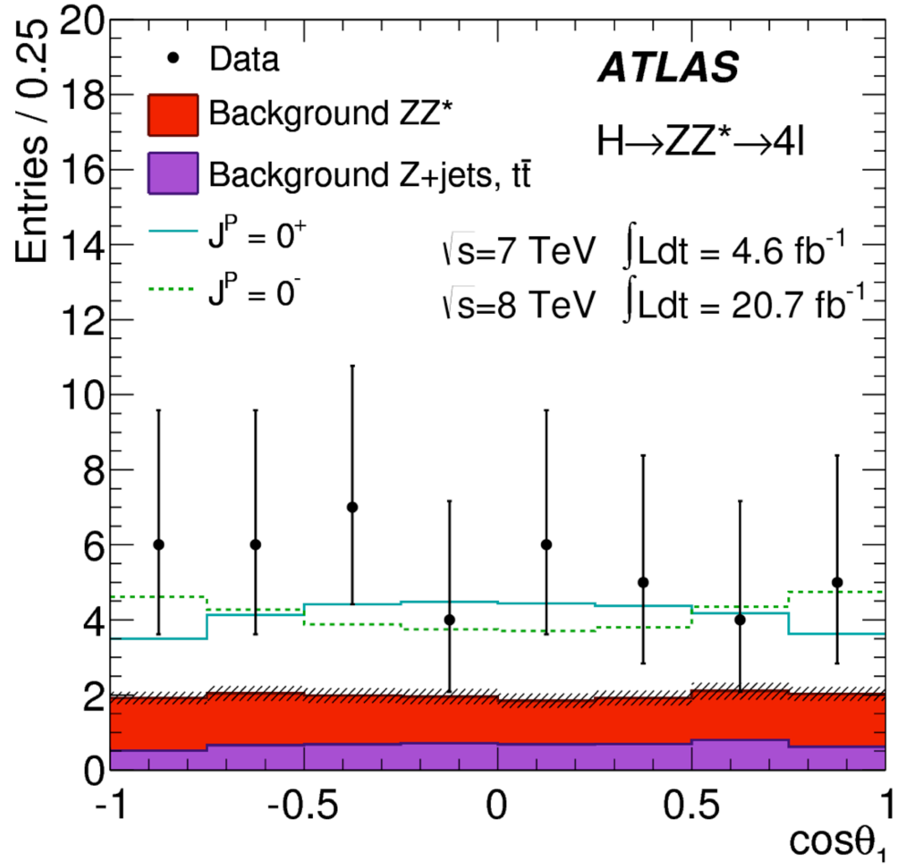
H→γγ : Alternative method

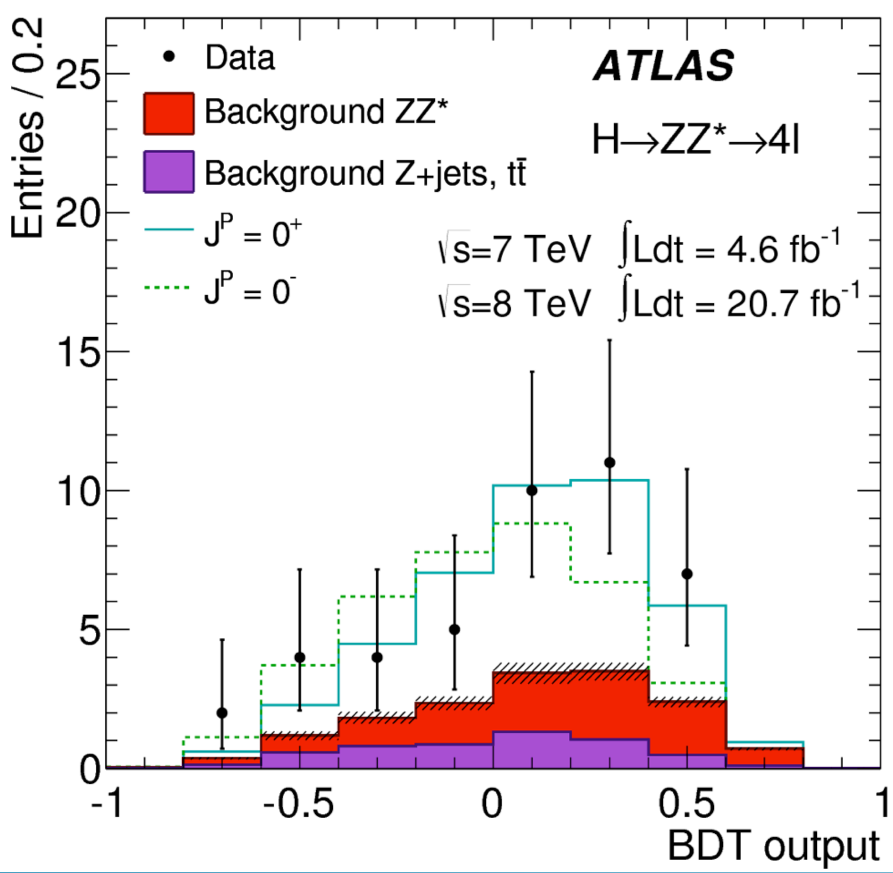


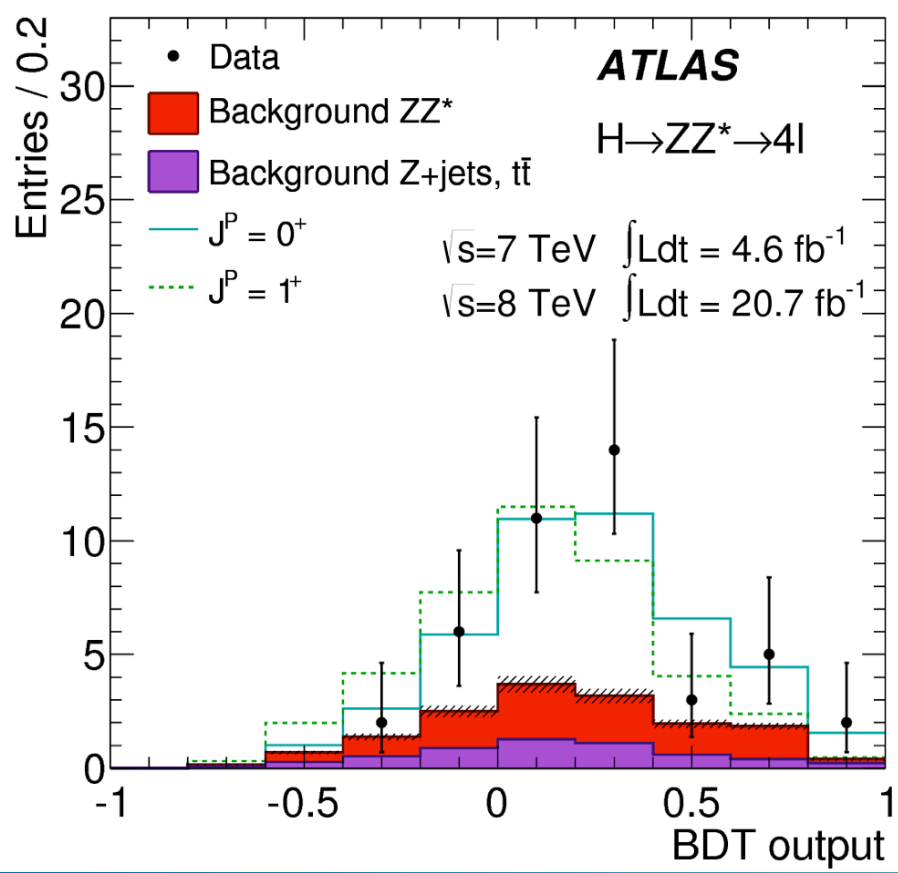
Fit separately S+B in bins of |cosθ*|

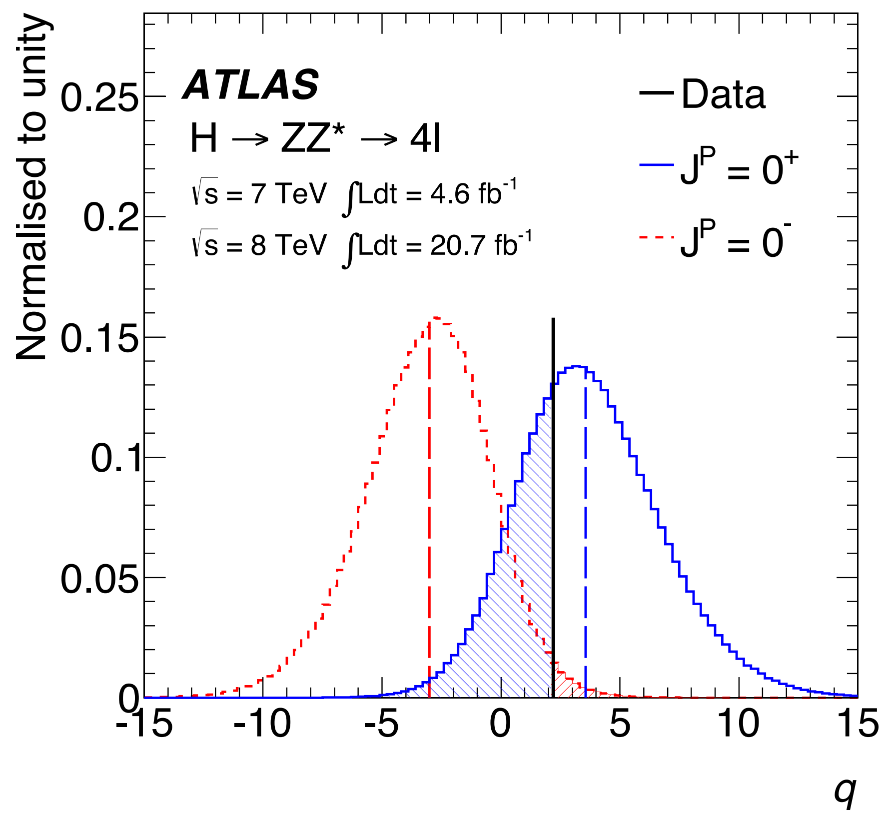
H→ZZ→4l : Publication



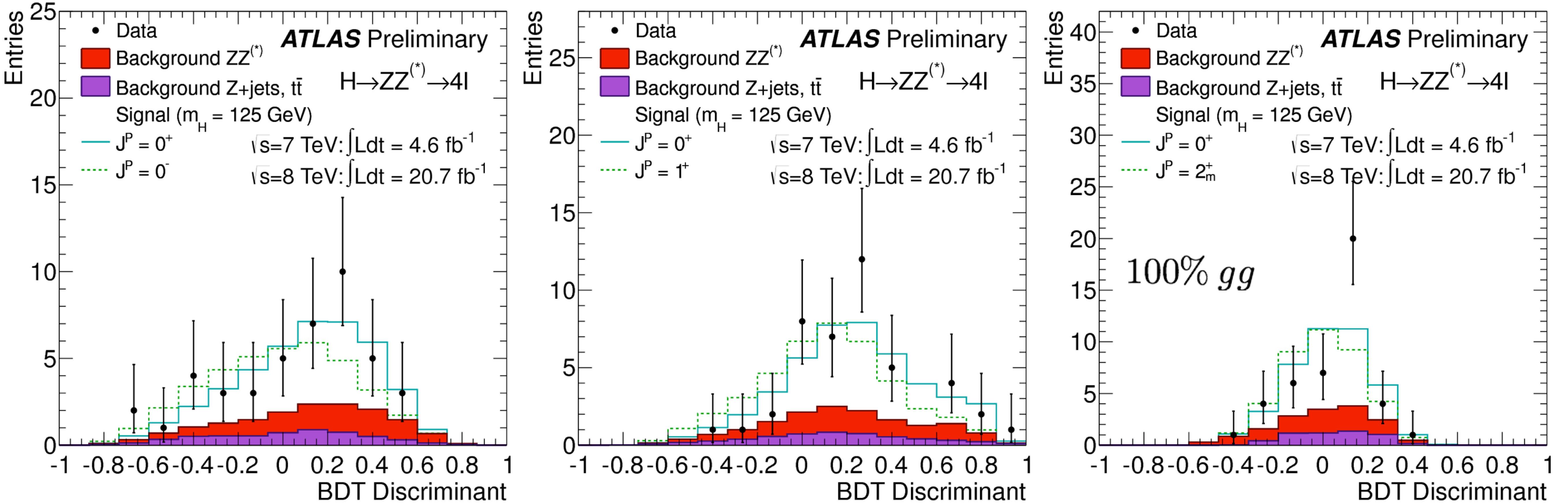




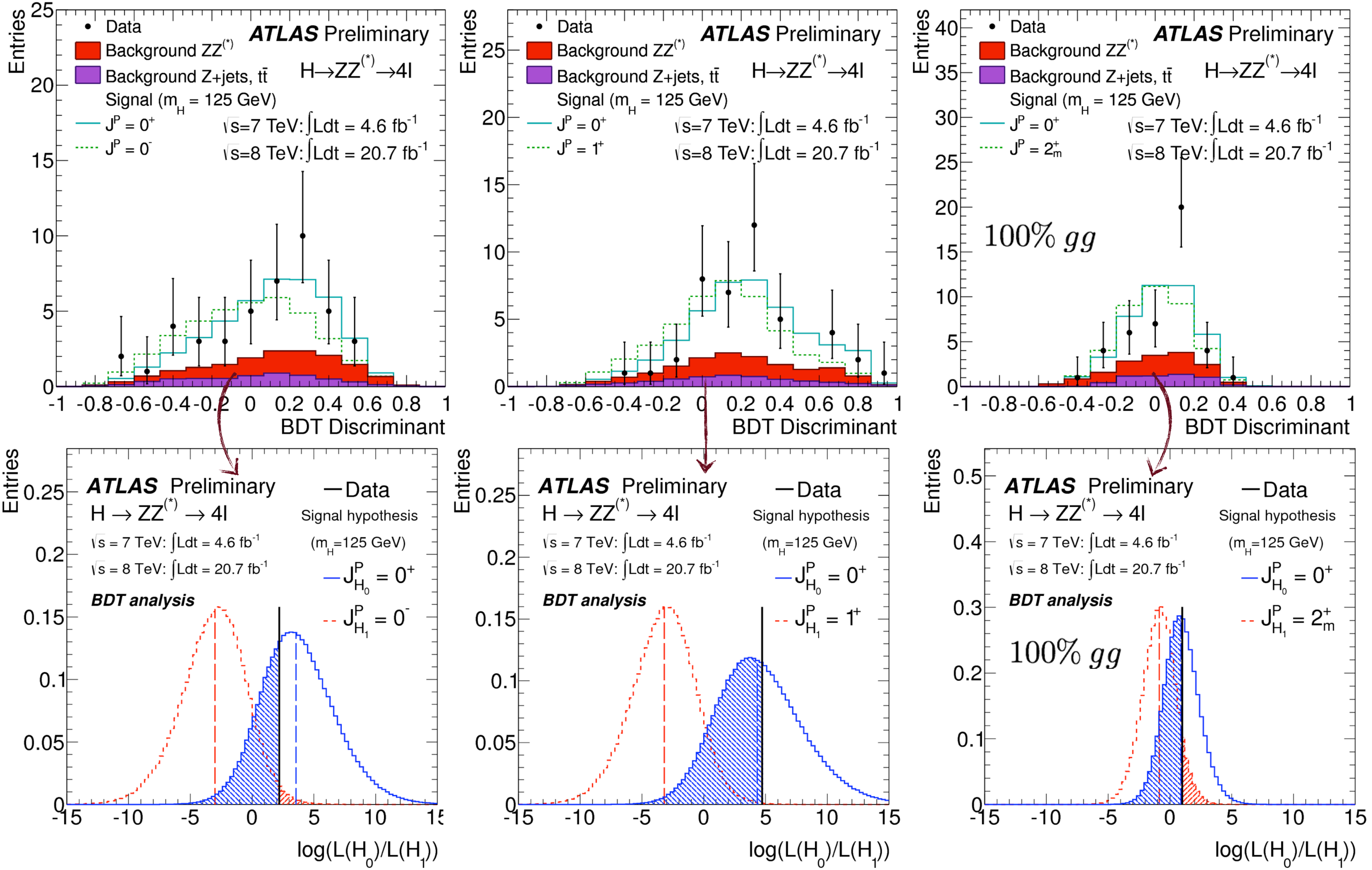




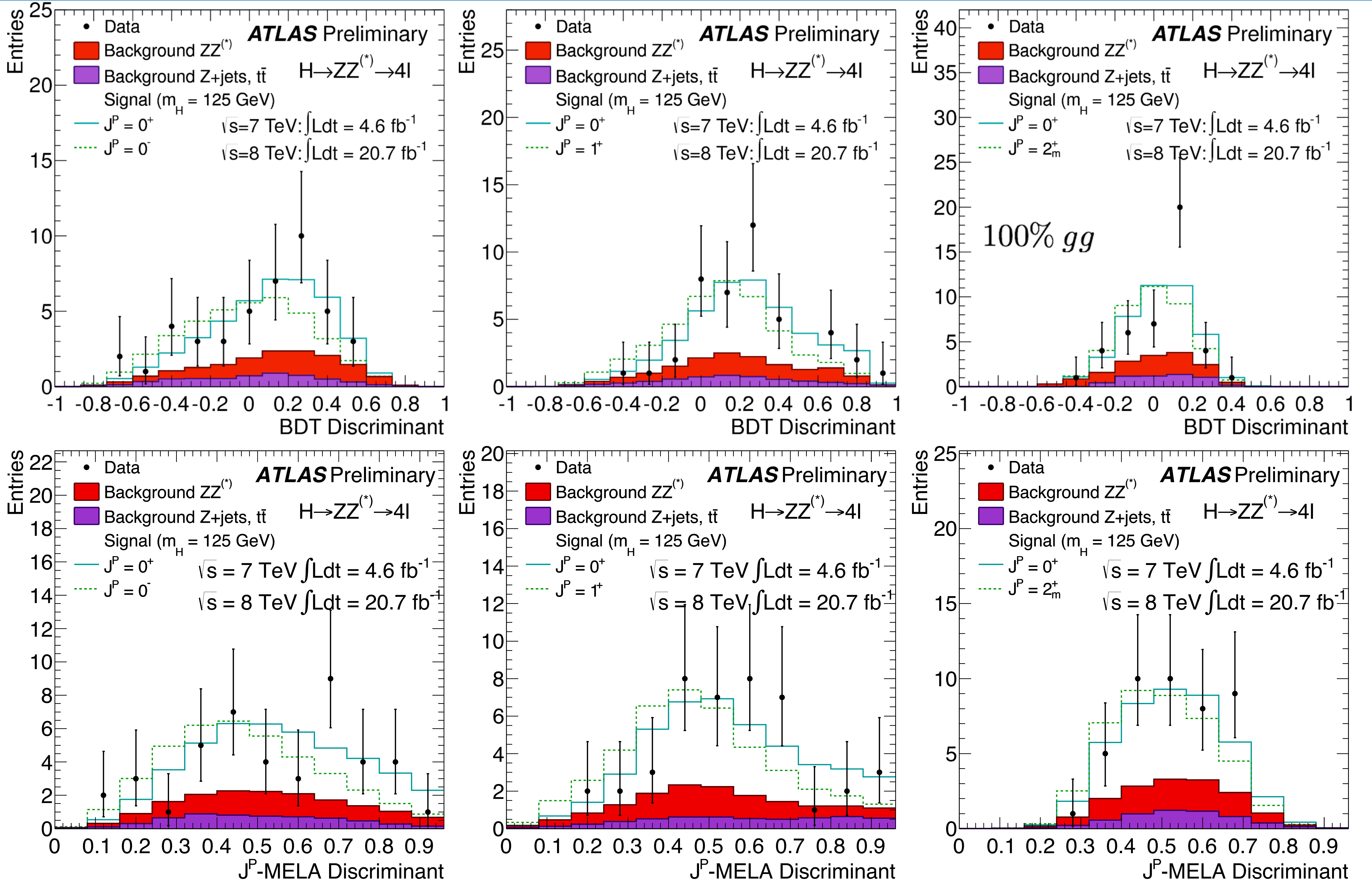
H→ZZ→4l : Distributions of discriminants



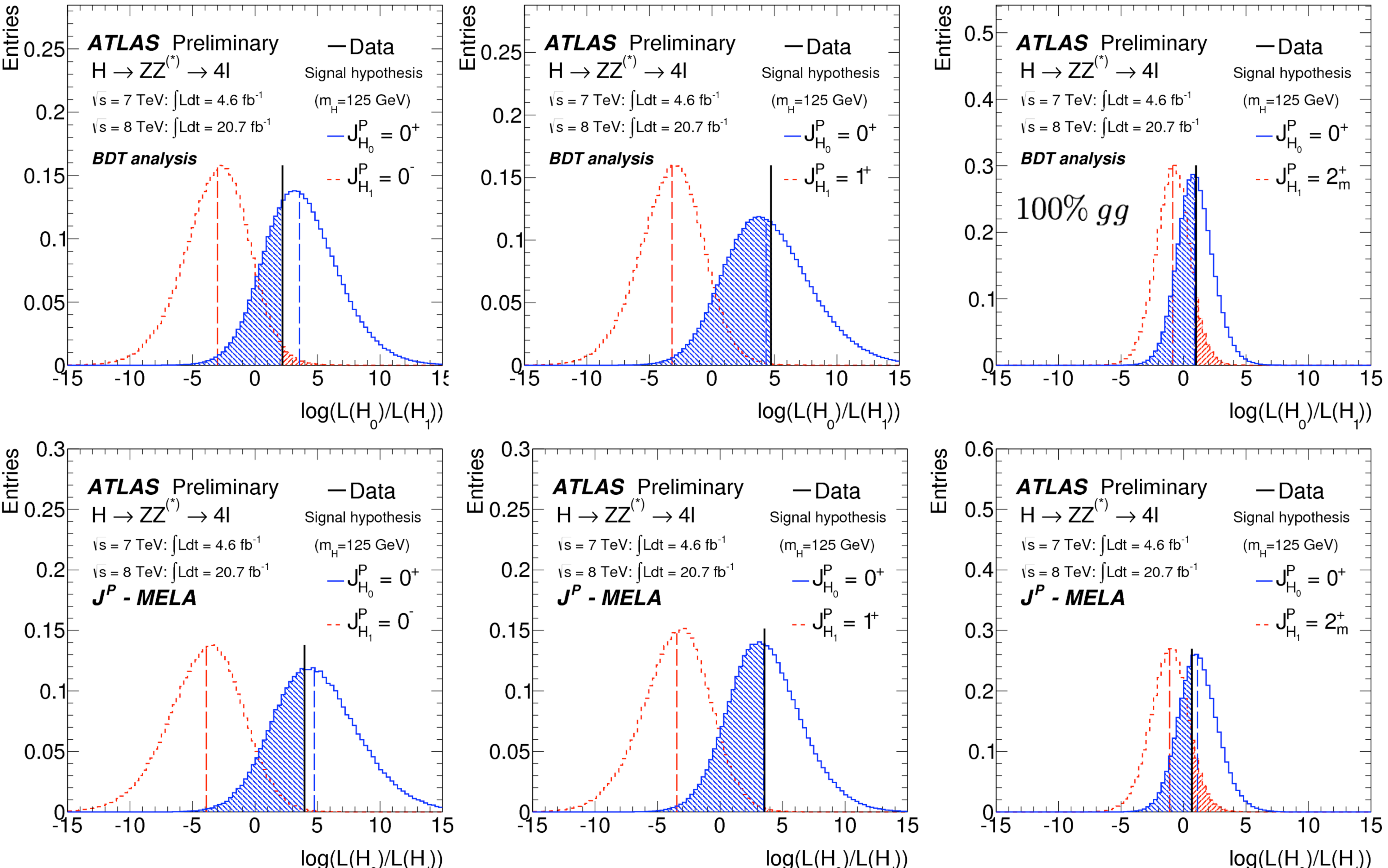
H→ZZ→4l : LLR 0+ vs 0-, 1+, 2+



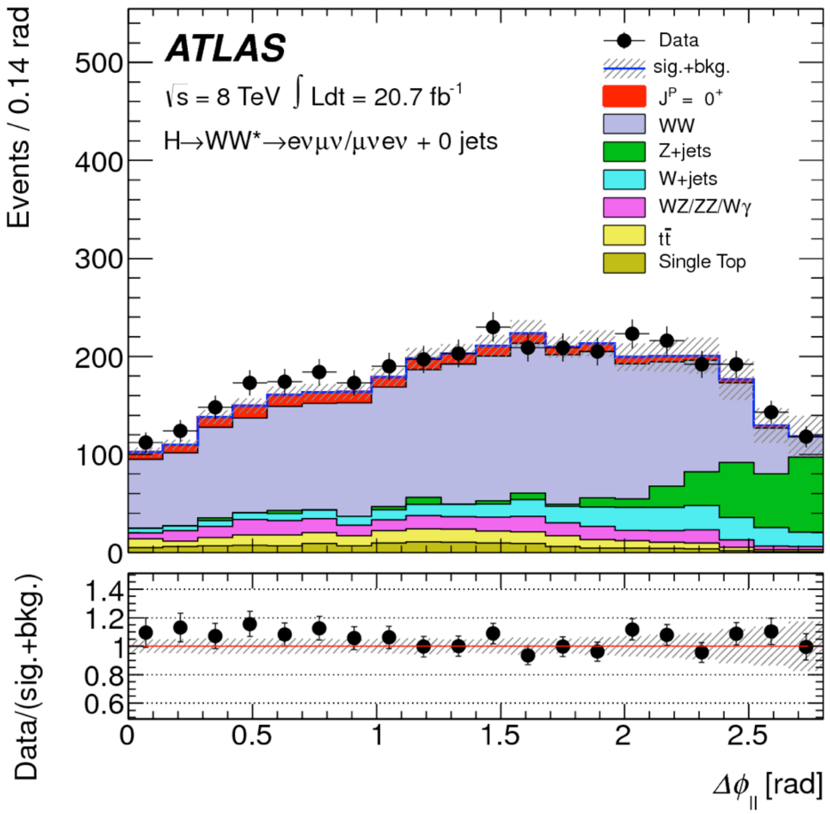
$H \to ZZ \to 4l$: BDT and J^P-MELA discriminants

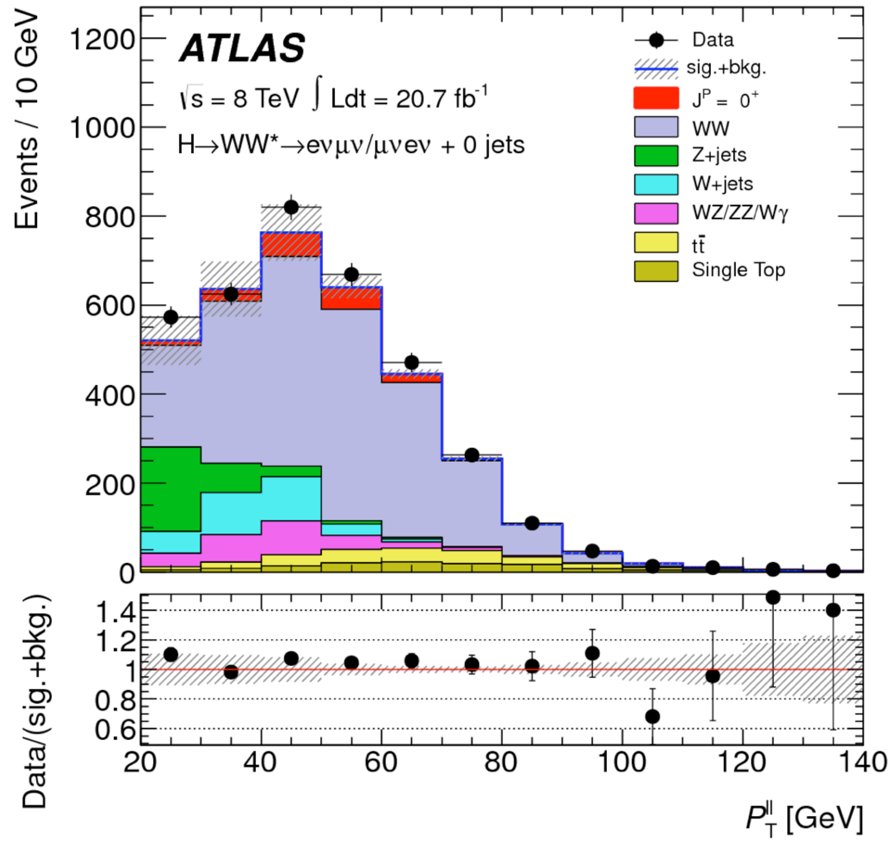


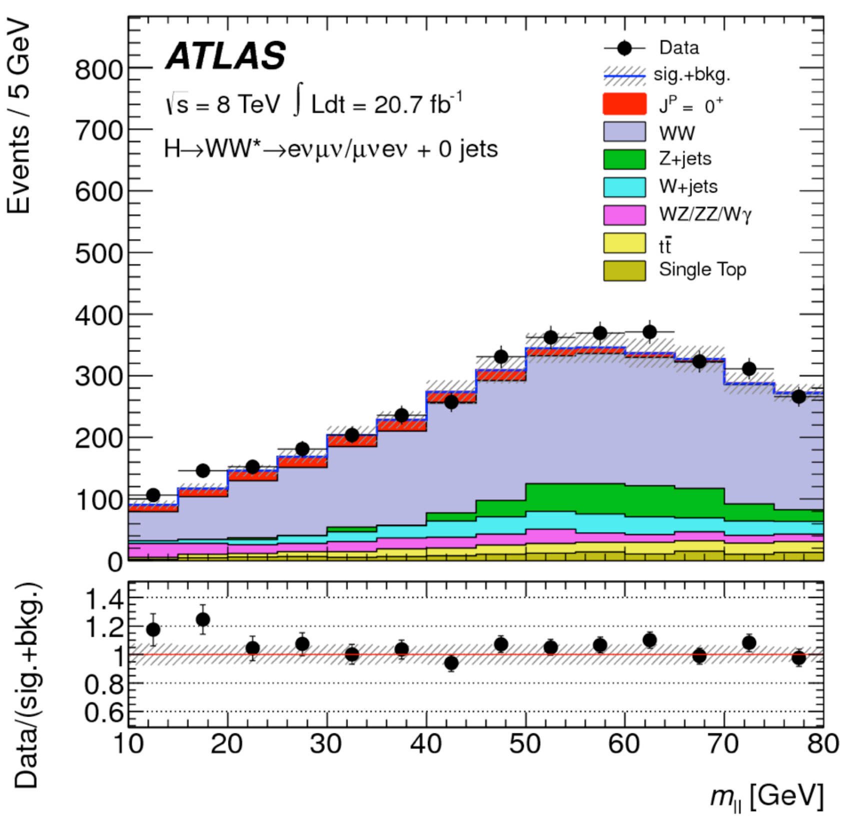
$H \rightarrow ZZ \rightarrow 4l$: LLR 0^+ vs 0^-, 1^+, 2^+

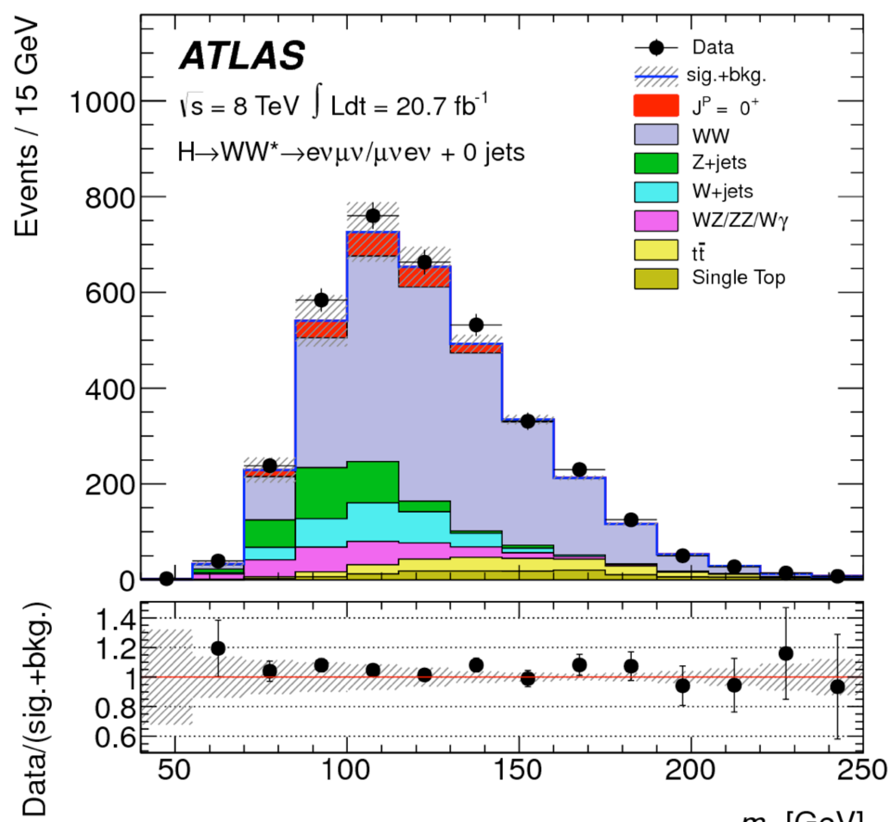


H→WW→lνlν: Data/MC in the Signal Region



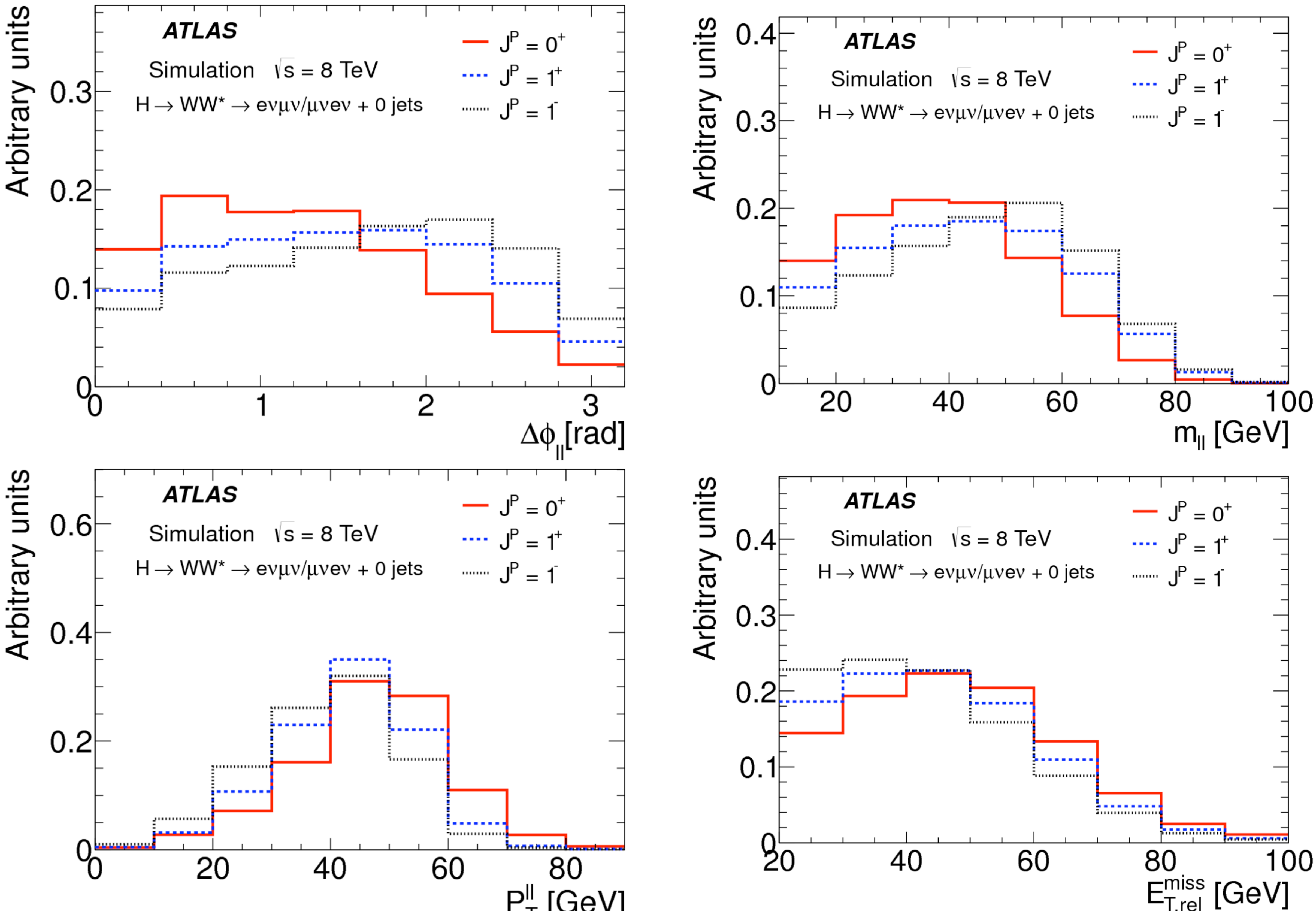




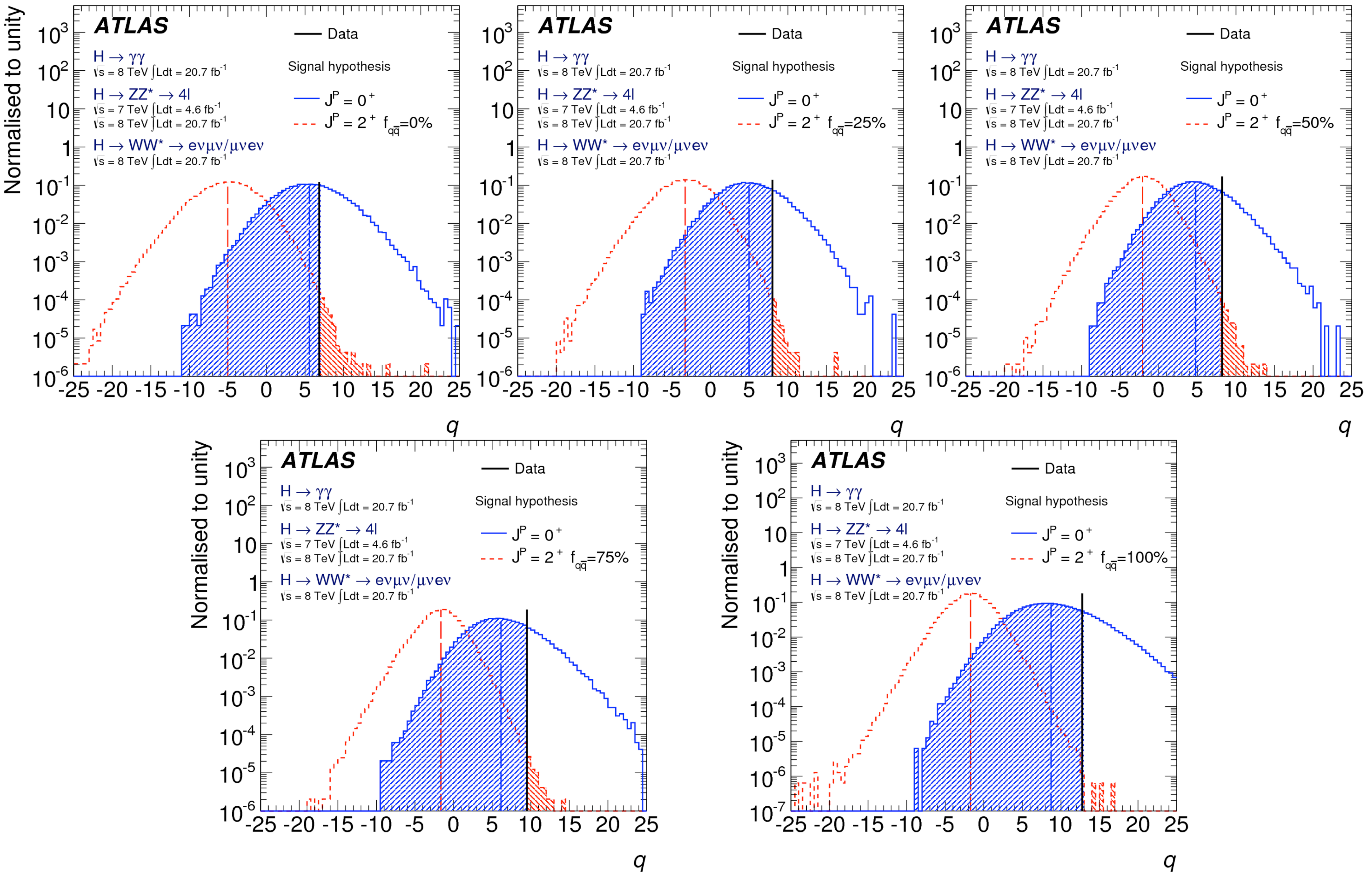


After full selection
3615 candidate events
3300 background expected
170 SM Higgs boson expected

H→WW→lνlν: Spin/CP sensitive variables



Combination: The case of 0^+ vs 2^+



Amplitudes

Spin-0 $\rightarrow$ two gauge bosons

$$A(X \to VV) = v^{-1}\epsilon_1^{*\mu}\epsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_X^2 + a_2\, q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta}\, q_1^\alpha q_2^\beta\right)$$

Spin-1$\rightarrow$ two gauge bosons

$$A(X \to ZZ) = g_1^{(1)}\left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X)\right] + g_2^{(1)} \epsilon_{\alpha\mu\nu\beta}\epsilon_X^\alpha \epsilon_1^{*,\mu}\epsilon_2^{*,\nu}\tilde{q}^\beta$$

Spin-2 $\rightarrow$ two gauge bosons

$$A(X \to VV) = \Lambda^{-1}\Big[2g_1^{(2)} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2g_2^{(2)} t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}$$

$$+g_3^{(2)}\frac{\tilde{q}^\beta\tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}\left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}\right) + g_4^{(2)}\frac{\tilde{q}^\nu\tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$

$$+m_V^2\left(2g_5^{(2)} t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2g_6^{(2)}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}\left(\epsilon_1^{*\nu}\epsilon_2^{*\alpha} - \epsilon_1^{*\alpha}\epsilon_2^{*\nu}\right) + g_7^{(2)}\frac{\tilde{q}^\mu\tilde{q}^\nu}{\Lambda^2} t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right)$$

$$+g_8^{(2)}\frac{\tilde{q}_\mu\tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha}\tilde{q}^\alpha\epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma} q^\rho\tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right)\Big]$$

Spin-1 $\rightarrow$ two fermions

$$A(X_{J=1} \to q\bar{q}) = \epsilon^\mu \bar{u}_{q_1}\left(\gamma_\mu\left(\rho_1^{(1)} + \rho_2^{(1)}\gamma_5\right) + \frac{m_q\tilde{q}_\mu}{\Lambda^2}\left(\rho_3^{(1)} + \rho_4^{(1)}\gamma_5\right)\right) v_{q_2},$$

Spin-2 $\rightarrow$ two fermions

$$A(X_{J=2} \to q\bar{q}) = \frac{1}{\Lambda} t^{\mu\nu}\bar{u}_{q_1}\left(\gamma_\mu\tilde{q}_\nu\left(\rho_1^{(2)} + \rho_2^{(2)}\gamma_5\right) + \frac{m_q\tilde{q}_\mu\tilde{q}_\nu}{\Lambda^2}\left(\rho_3^{(2)} + \rho_4^{(2)}\gamma_5\right)\right) v_{q_2}$$

Combination: Results Overview

0^+ vs 0^-

Channel	0^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 0^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 0^-)$	$CL_s(J^P = 0^-)$
$H \to ZZ^*$	$1.5 \cdot 10^{-3}$	$3.7 \cdot 10^{-3}$	0.31	0.015	0.022

97.8%

0^+ vs 1^+

Channel	1^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^+)$	$CL_s(J^P = 1^+)$
$H \to ZZ^*$	$4.6 \cdot 10^{-3}$	$1.6 \cdot 10^{-3}$	0.55	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
$H \to WW^*$	0.11	0.08	0.70	0.02	0.08
Combination	$2.7 \cdot 10^{-3}$	$4.7 \cdot 10^{-4}$	0.62	$1.2 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$

>99.9%

0^+ vs 1^-

Channel	1^- assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 1^-)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 1^-)$	$CL_s(J^P = 1^-)$
$H \to ZZ^*$	$0.9 \cdot 10^{-3}$	$3.8 \cdot 10^{-3}$	0.15	0.051	0.060
$H \to WW^*$	0.06	0.02	0.66	0.006	0.017
Combination	$1.4 \cdot 10^{-3}$	$3.6 \cdot 10^{-4}$	0.33	$1.8 \cdot 10^{-3}$	$2.7 \cdot 10^{-3}$

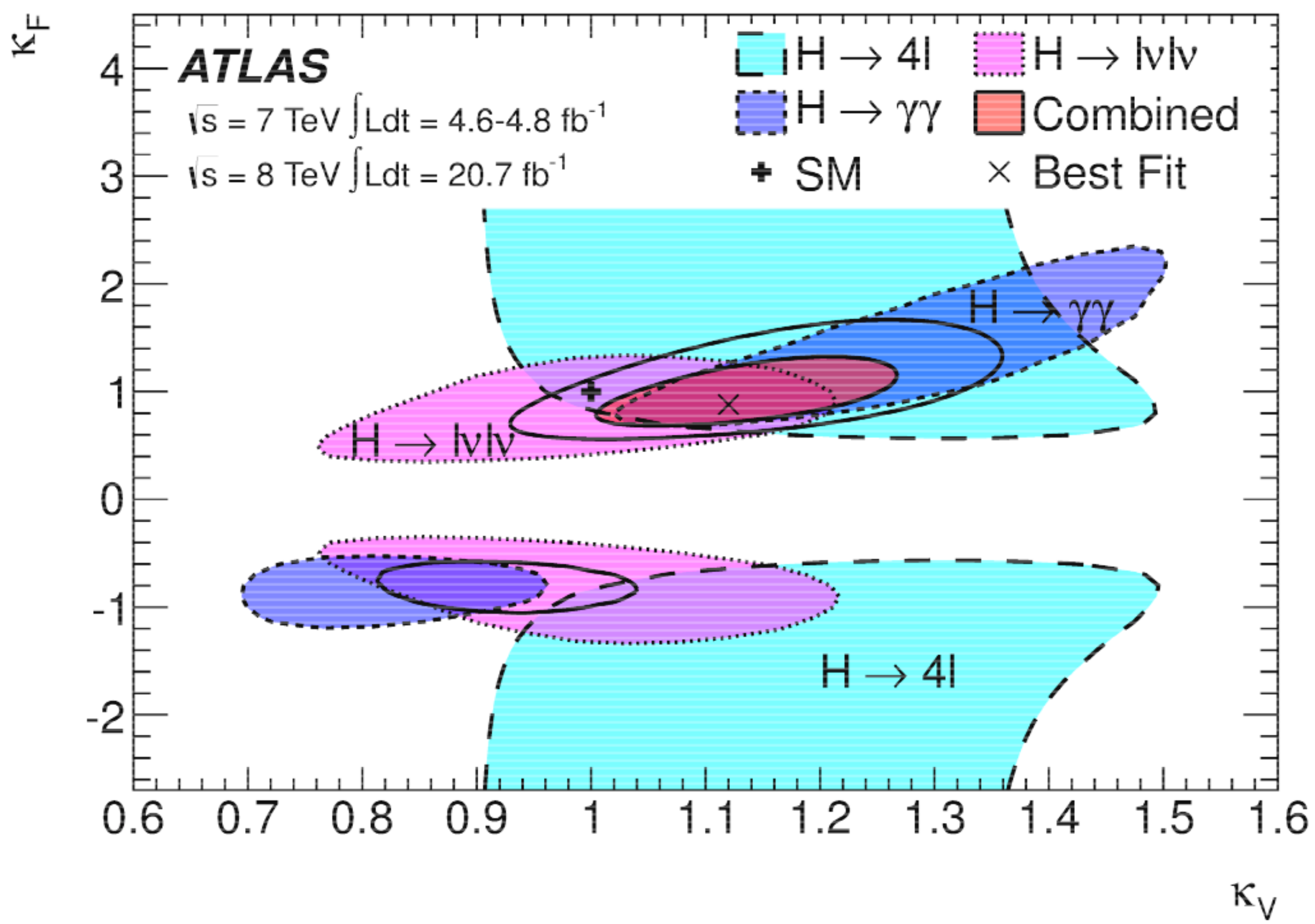
99.7%

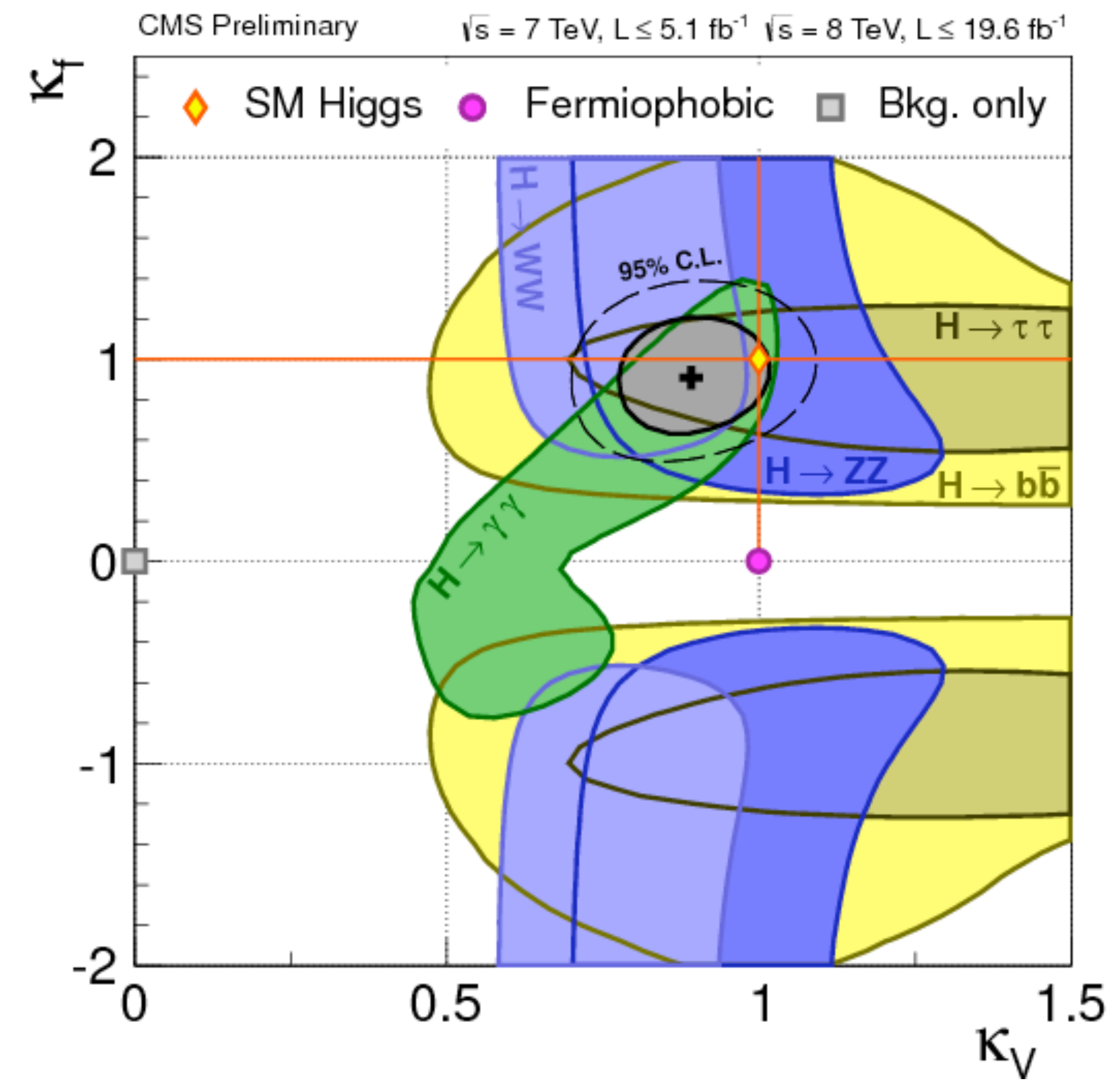
0^+ vs 2^+

$f_{q\bar{q}}$	2^+ assumed Exp. $p_0(J^P = 0^+)$	0^+ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	$3.0 \cdot 10^{-3}$	$8.8 \cdot 10^{-5}$	0.81	$1.6 \cdot 10^{-6}$	$0.8 \cdot 10^{-5}$
75%	$9.5 \cdot 10^{-3}$	$8.8 \cdot 10^{-4}$	0.81	$3.2 \cdot 10^{-5}$	$1.7 \cdot 10^{-4}$
50%	$1.3 \cdot 10^{-2}$	$2.7 \cdot 10^{-3}$	0.84	$8.6 \cdot 10^{-5}$	$5.3 \cdot 10^{-4}$
25%	$6.4 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$	0.80	$0.9 \cdot 10^{-4}$	$4.6 \cdot 10^{-4}$
0%	$2.1 \cdot 10^{-3}$	$5.5 \cdot 10^{-4}$	0.63	$1.5 \cdot 10^{-4}$	$4.2 \cdot 10^{-4}$

>99.9% for all f_{qq}

Overview: Coupling studies





Assuming that:
- the resonance corresponds to a CP-even boson
- no contributions beyond the Standard Model
- deviations of vector boson couplings to the Higgs described by one overall scaling (κ_V)
- deviations of fermion couplings to the Higgs described by one overall scaling (κ_F)

Data compatible with the Standard Model expectation for both experiments

Higgs boson couplings

Higgs boson signal strength measurement following formalism of arXiv:1209.0040

- single resonance of 125.5 GeV
- narrow width approximation
- only modifications of the coupling strengths

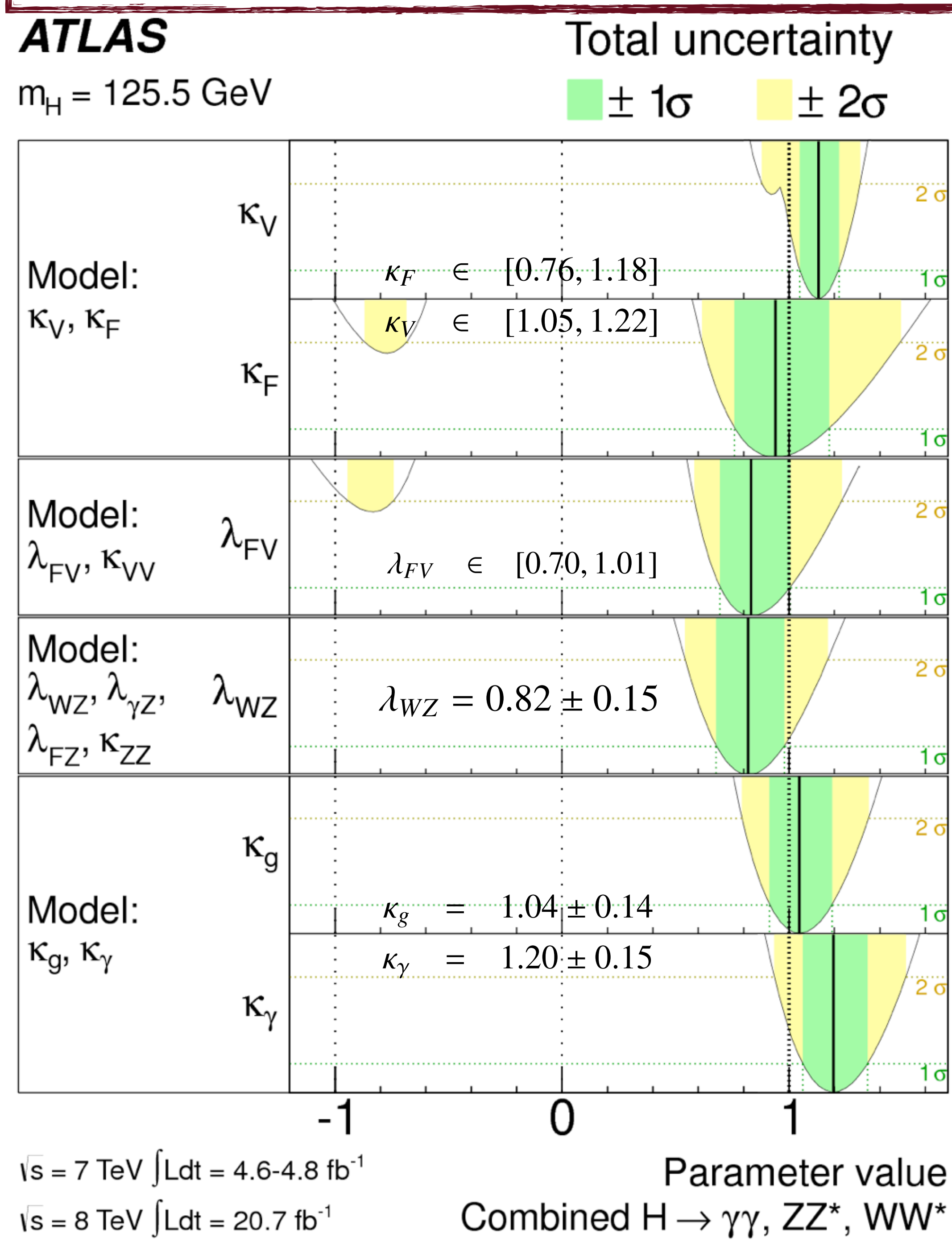
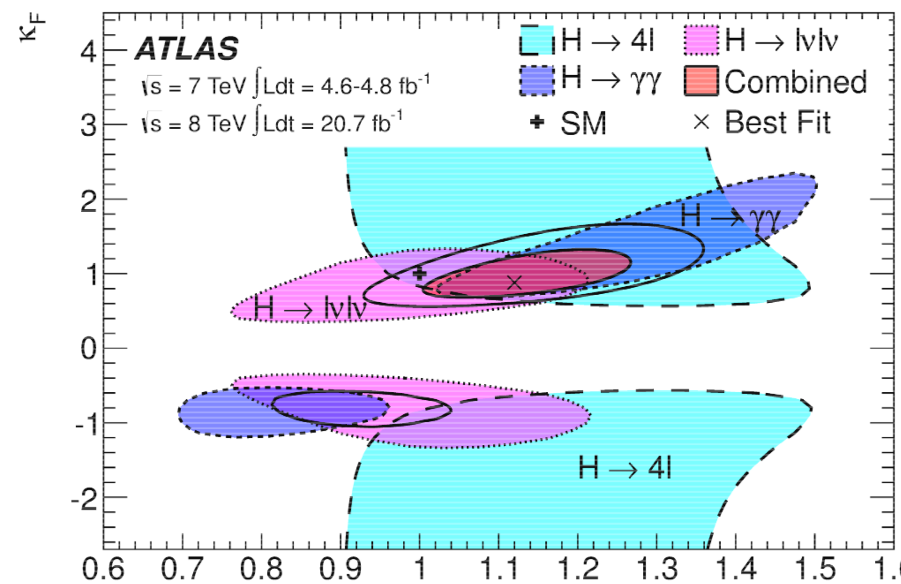


Table 10: Summary of the coupling benchmark models discussed in this paper, where $\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ii} = \kappa_i\kappa_i/\kappa_H$, and the functional dependence assumptions are: $\kappa_V = \kappa_W = \kappa_Z$, $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$ (and similarly for the other fermions), $\kappa_g = \kappa_g(\kappa_b, \kappa_t)$, $\kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W)$, and $\kappa_H = \kappa_H(\kappa_i)$.

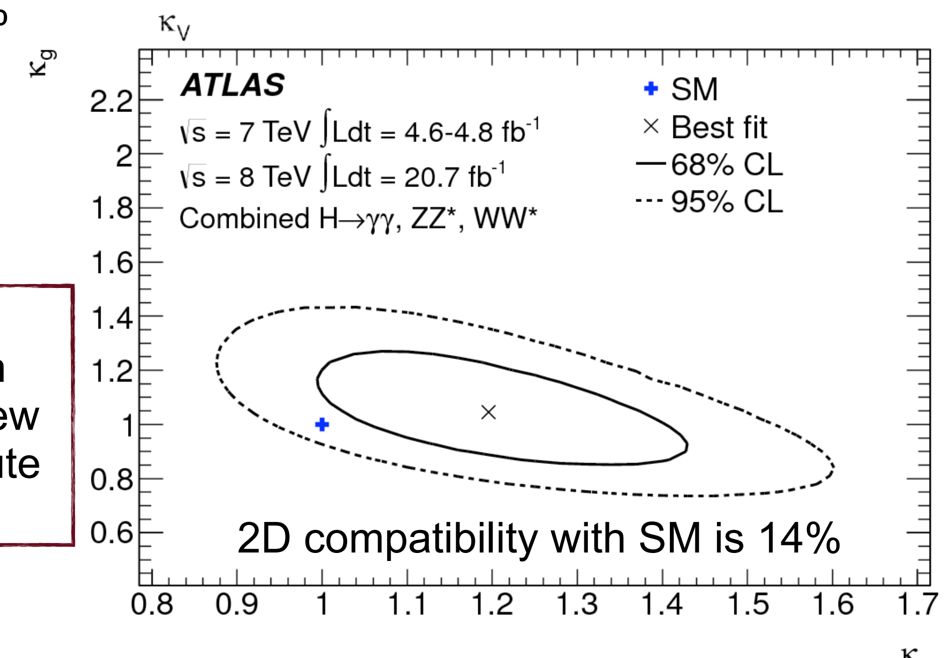
Model	Probed couplings	Parameters of interest	Functional assumptions				
			κ_V	κ_F	κ_g	κ_γ	κ_H
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√



2D compatibility with SM is 12%

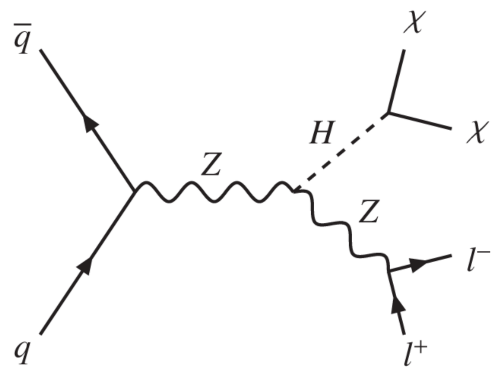
Deviations described by overall scales kF (kV) for fermions (bosons), respectively, no BSM contribution

Constrain contributions to production/decay loops. Known particles fixed to SM strength. New particles assumed to not contribute to Higgs width



"Invisible" Higgs boson decays prospects

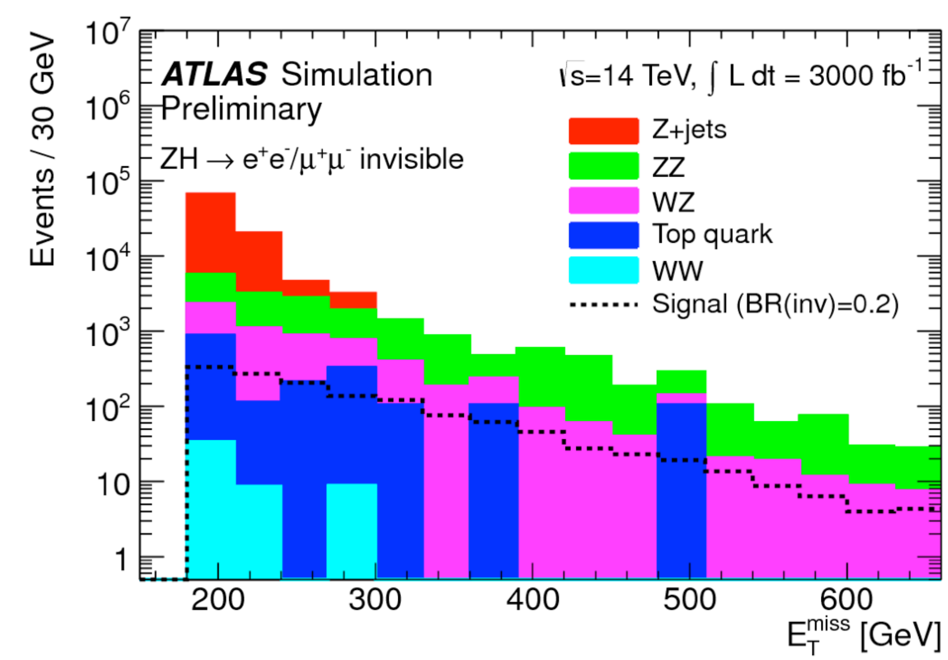
"Invisible" decays are suppressed in SM → Observation would be direct indication of New Physics!



- Signature : Z→ee/μμ + large MET
- Main Backgrounds: ZZ→llνν, WZ→lνll, WW→lνlν

Cut variables	Thresholds
E_T^{miss}	> 180 GeV
$d\phi(\ell,\ell)$	< 1.2
$d\phi(\vec{p}_T^{\,\ell,\ell}, \vec{E}_T^{miss})$	> 2.7
$\lvert E_T^{miss} - p_T^{\ell,\ell}\rvert / p_T^{\ell,\ell}$	< 0.6
Jet veto	> 25 GeV

Expected yields	300 fb^{-1}	3000 fb^{-1}
ZZ	1321 ± 53	12000 ± 500
WZ	440 ± 2	4501 ± 22
WW	0.9 ± 0.9	52 ± 21
Top	127 ± 37	1810 ± 440
Z+jets	172 ± 87	82000 ± 6100
Signal (125 GeV, BR($H \to$ inv.)=20%)	154 ± 2	1379 ± 21



BR(H →inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)

Prospects for Run II/III and HL-LHC

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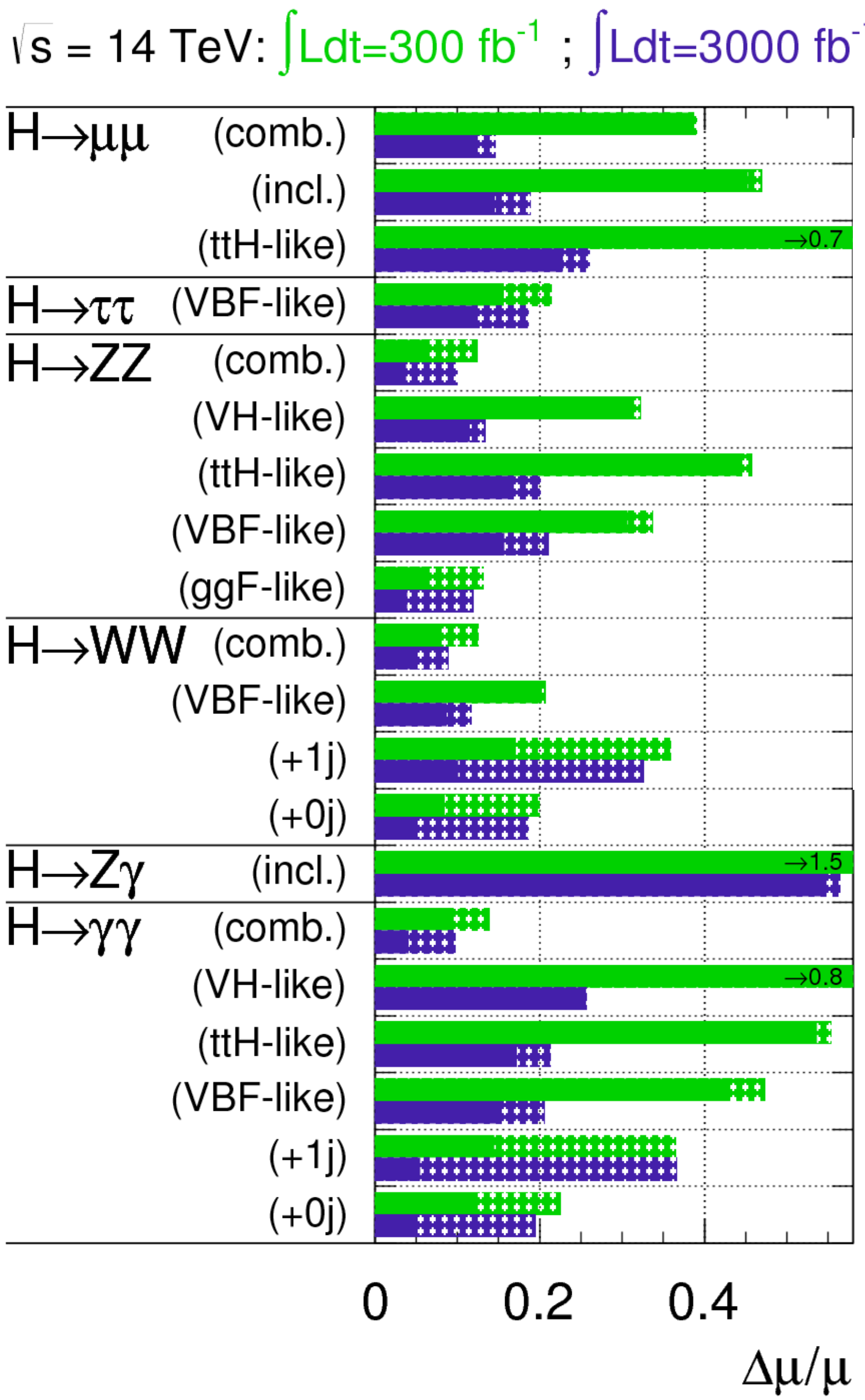
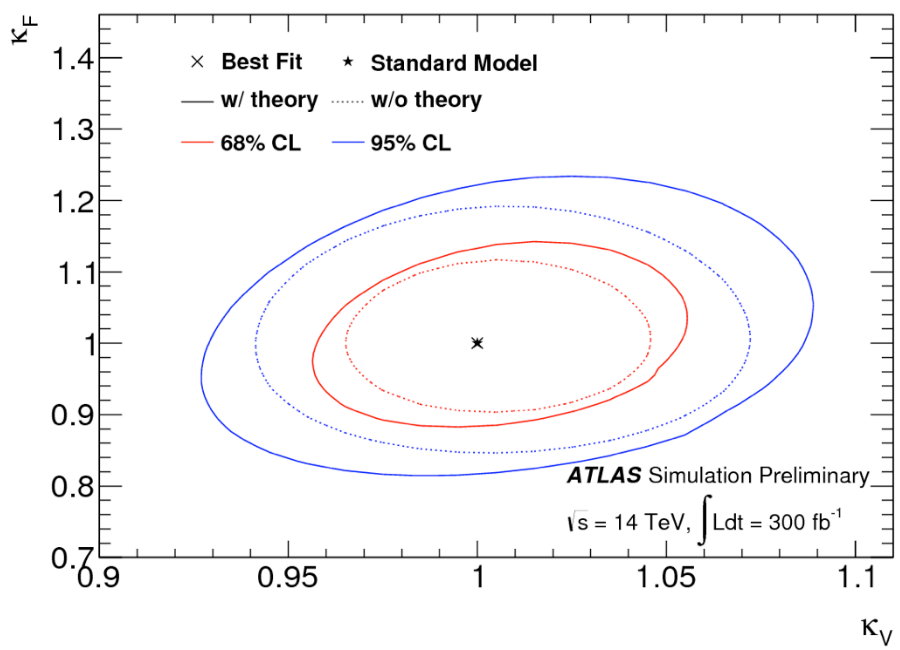
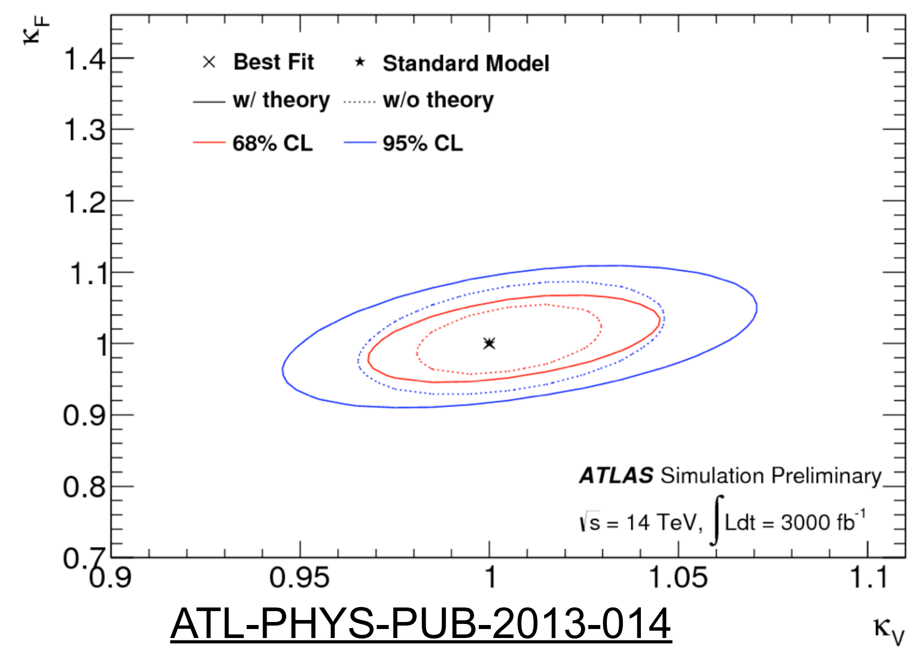


Several open topics in the Higgs sector for future studies:

- Rare decays & Couplings - CP studies
- BSM Higgs boson searches - Higgs boson pair production





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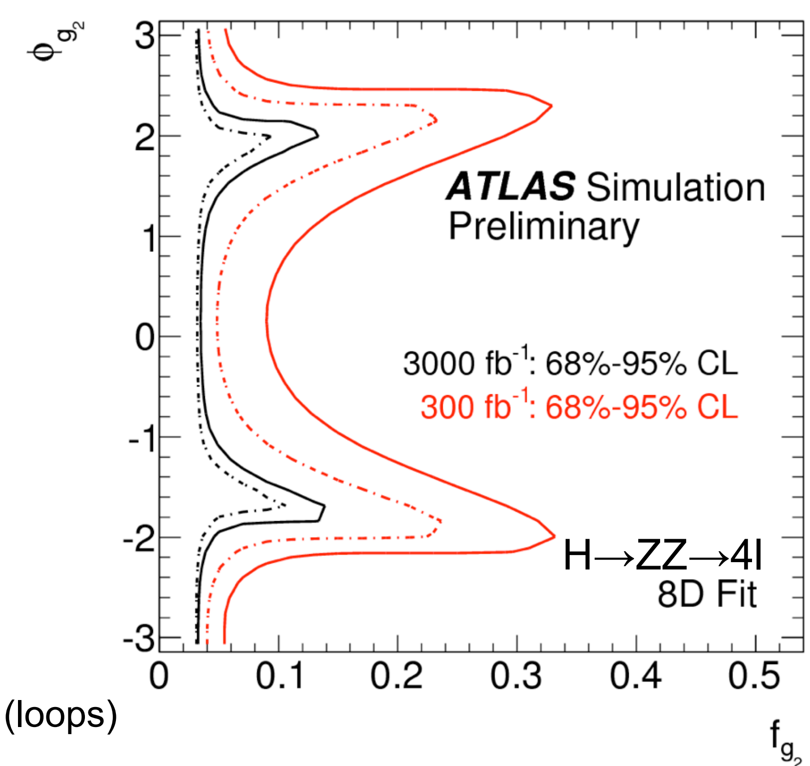
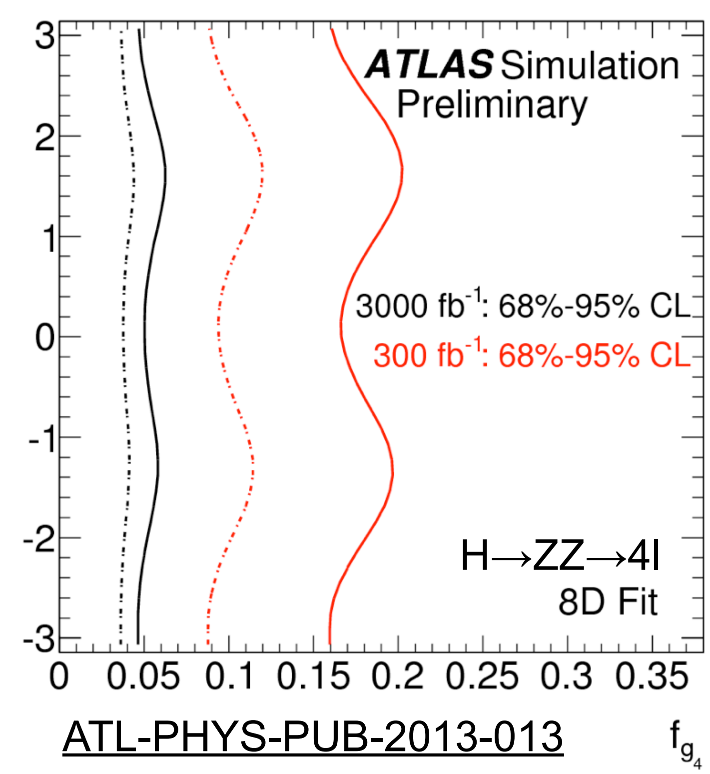




g_1 CP-even HZZ coupling
g_2 CP-even HZZ coupling (loops)
g_3 CP-odd HZZ coupling

ATL-PHYS-PUB-2013-013

Prospects for Run II/III and HL-LHC

$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \mu\mu$ (comb.)	0.39	0.38	0.15	0.12
(incl.)	0.47	0.45	0.19	0.15
(ttH-like)	0.73	0.72	0.26	0.23
$H \to \tau\tau$ (VBF-like)	0.22	0.16	0.19	0.12
$H \to ZZ$ (comb.)	0.12	0.06	0.10	0.04
(VH-like)	0.32	0.31	0.13	0.12
(ttH-like)	0.46	0.44	0.20	0.16
(VBF-like)	0.34	0.31	0.21	0.16
(ggF-like)	0.13	0.06	0.12	0.04
$H \to WW$ (comb.)	0.13	0.08	0.09	0.05
(VBF-like)	0.21	0.20	0.12	0.09
(+1j)	0.36	0.17	0.33	0.10
(+0j)	0.20	0.08	0.19	0.05
$H \to Z\gamma$ (incl.)	1.47	1.45	0.57	0.54
$H \to \gamma\gamma$ (comb.)	0.14	0.09	0.10	0.04
(VH-like)	0.77	0.77	0.26	0.25
(ttH-like)	0.55	0.54	0.21	0.17
(VBF-like)	0.47	0.43	0.21	0.15
(+1j)	0.37	0.14	0.37	0.05
(+0j)	0.22	0.12	0.20	0.05

Table 17: Relative uncertainty on the signal strength μ for the combination of Higgs analysis at 14 TeV, 300 fb^{-1} (left) and 3000 fb^{-1} (right), assuming a SM Higgs Boson with a mass of 125 GeV. For both 300 and 3000 fb^{-1} the first column shows the results including current theory systematic uncertainties, while the second column shows the uncertainties obtained using only the statistical and experimental systematic uncertainties. The abbreviation "(comb.)" indicates that the precision on μ is obtained from the combination of the measurements from the different experimental sub-categories for the same final state, while "(incl.)" indicates that the measurement from the inclusive analysis was used.

Coupling Expectations

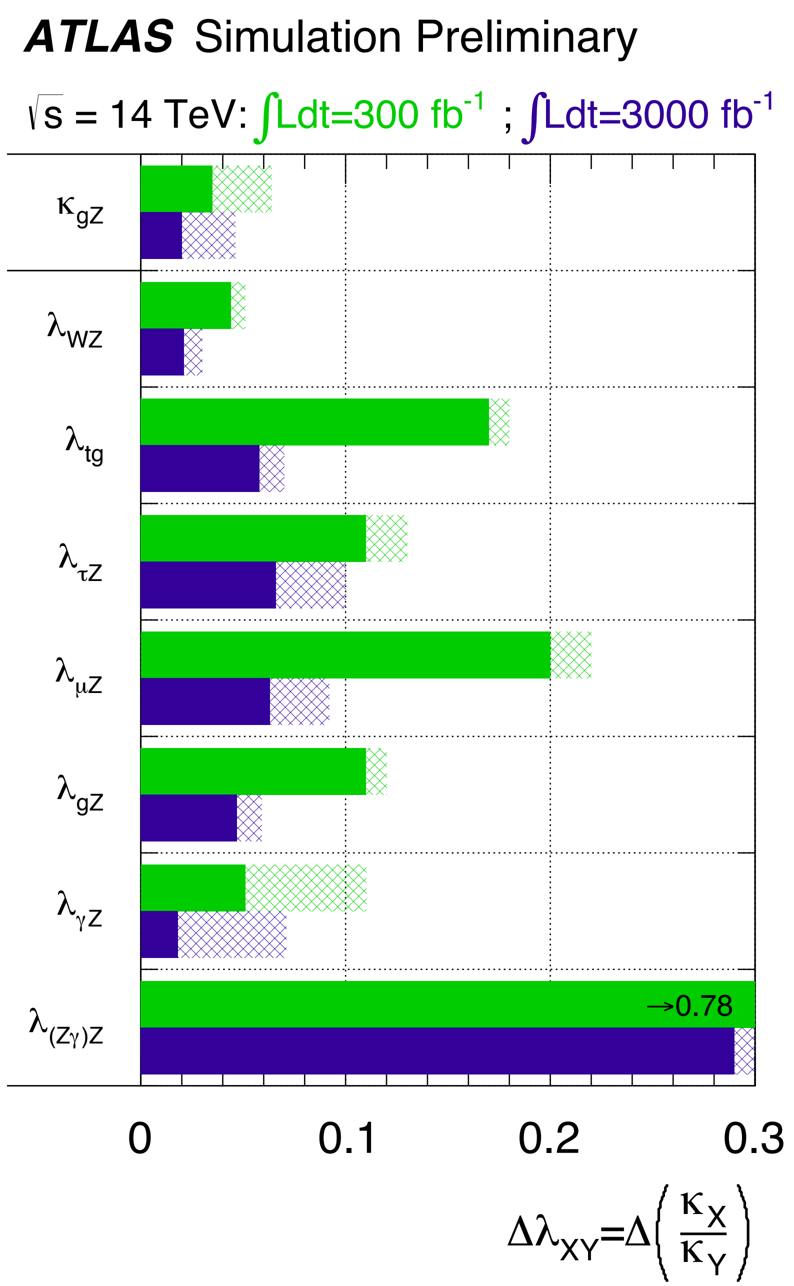


Figure 23: Relative uncertainty on the expected precision for the determination of coupling scale factor ratios λ_{XY} in a generic fit without assumptions, assuming a SM Higgs Boson with a mass of 125 GeV and LHC at 14 TeV, 300 fb^{-1} and 3000 fb^{-1}. The hashed areas indicate the increase of the estimated error due to current theory systematics uncertainties. The numerical values can be found in model Nr. 5 in Table 19.

Effective Lagrangian and Invariant Amplitudes

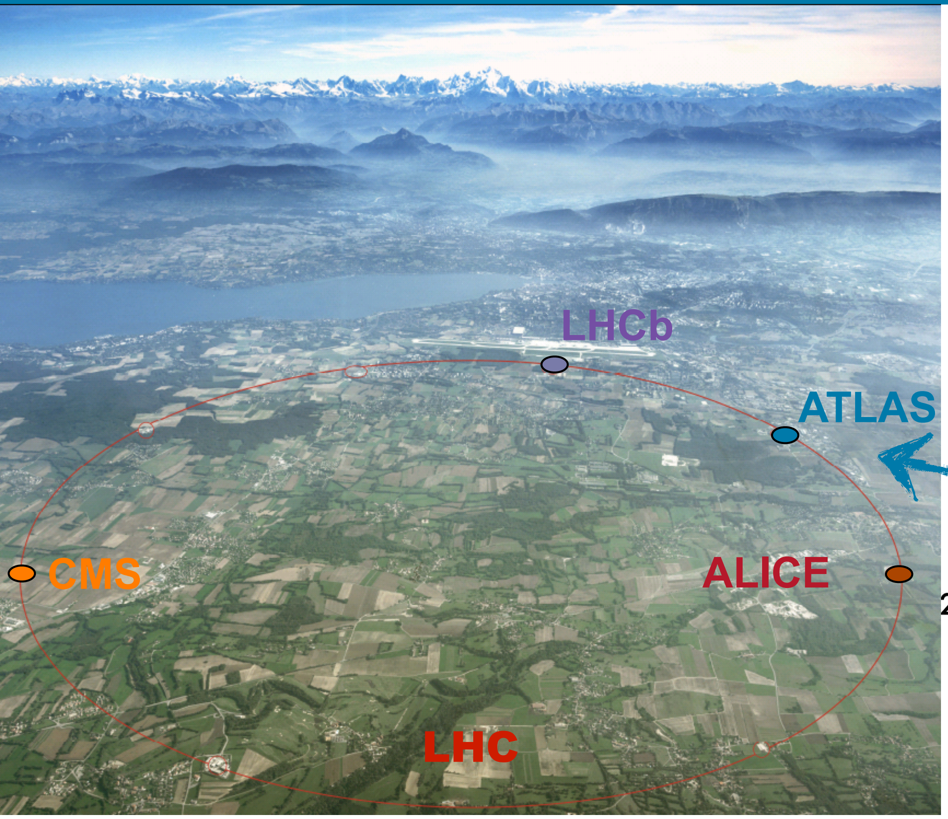
$$f_{a_i} = \frac{|a_i|^2\sigma_i}{|a_1|^2\sigma_1 + |a_i|^2\sigma_i}; \quad \phi_{a_i} = \arg\left(\frac{a_i}{a_1}\right)$$

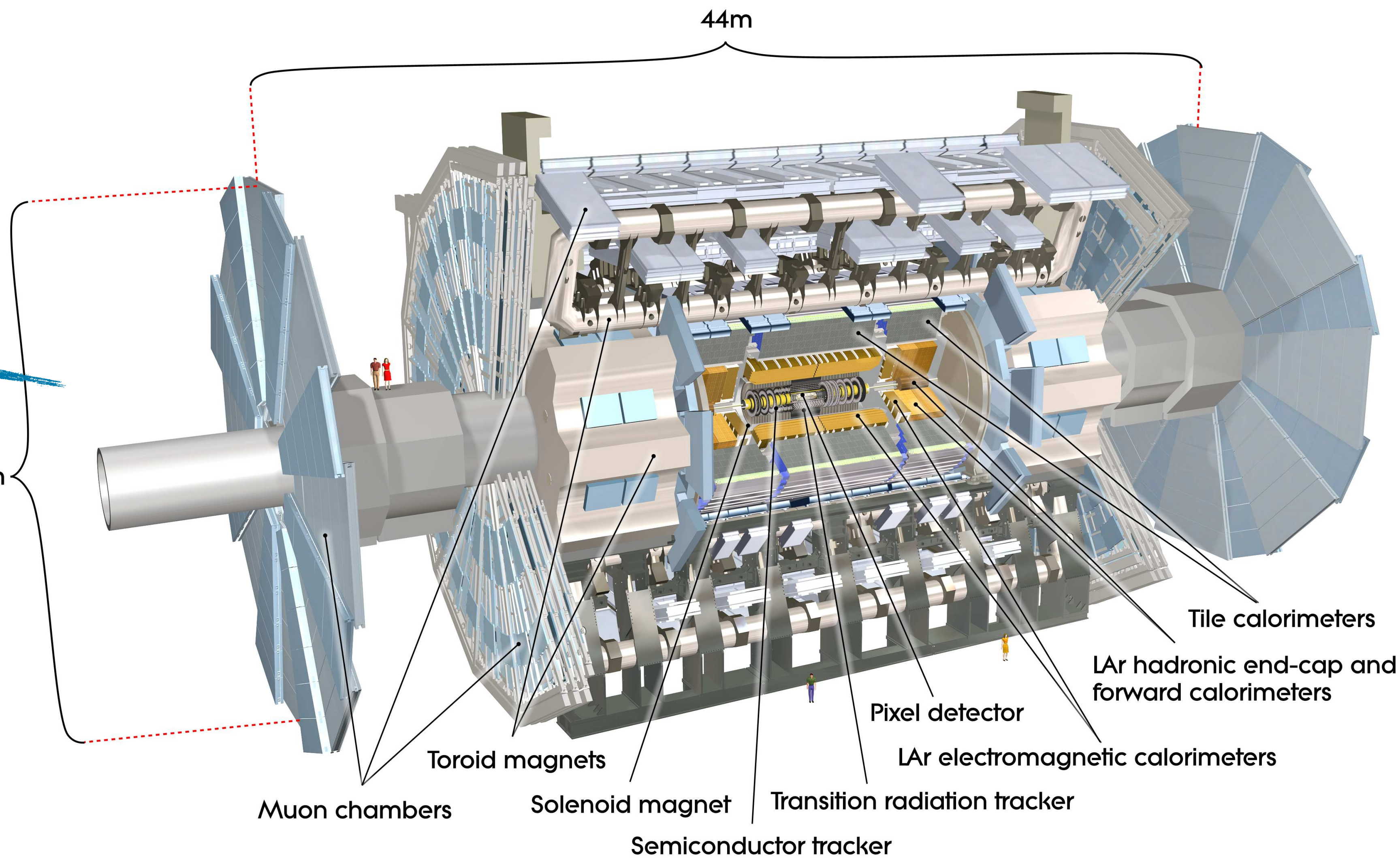
$$a_1 = g_1\frac{m_V^2}{m_H^2} + \frac{s}{m_H^2}\left(2g_2 + g_3\frac{s}{\Lambda^2}\right); \quad a_2 = -\left(2g_2 + g_3\frac{s}{\Lambda^2}\right); \quad a_3 = -2g_4$$

$$f_{g_i} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right)$$

$$f_{g_i} = \frac{r_{i1}^2}{1 + r_{i1}^2}, \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right), \quad \text{where} \quad r_{31}^2 \approx 0.16\frac{|g_4|^2}{|g_1|^2} \quad \text{and} \quad r_{21}^2 \approx 0.382\frac{|g_2|^2}{|g_1|^2}.$$

A Toroidal LHC ApparatuS





⇒ General purpose detector designed for the harsh LHC environment

	ATLAS
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling LAr technology
Hadron Calorimetry	plastic scintillator (barrel) LAr technology (endcap)
Muon	independent system with trigger capabilities

H→γγ: cosθ* / $m_{\gamma\gamma}$ residual correlations

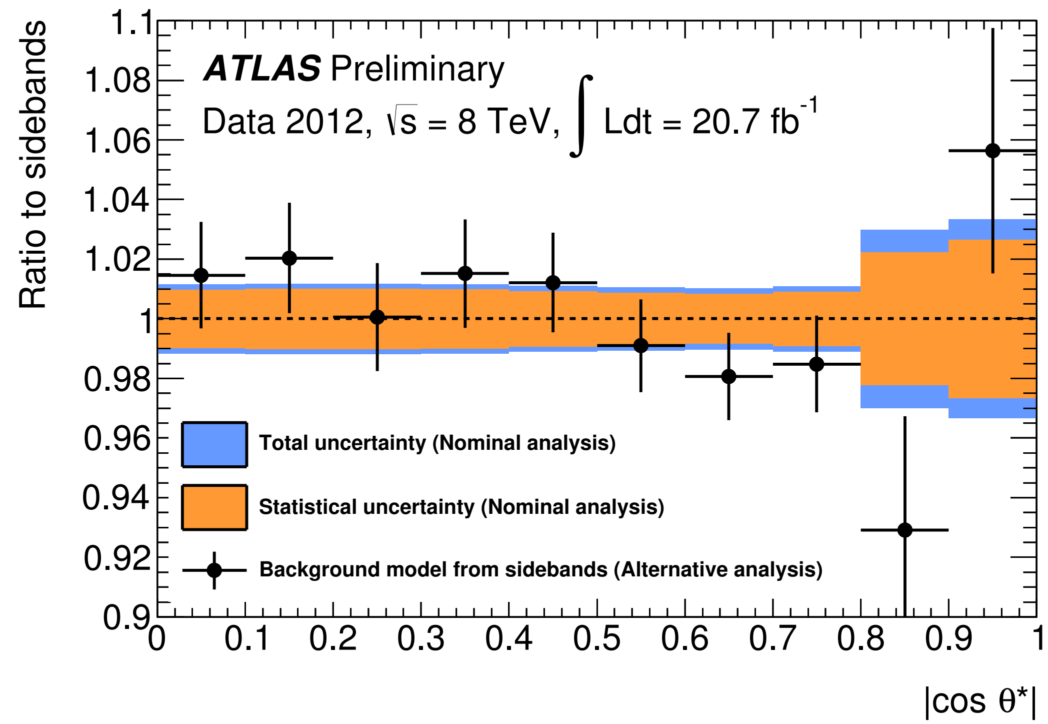


Figure 7: Residual correlations between the invariant mass $m_{\gamma\gamma}$ and $|\cos\theta^*|$, from the ratio of the background models of $|\cos\theta^*|$ in the alternative and the nominal analyses. The background model in the nominal analysis is given by the normalised distribution of $|\cos\theta^*|$, built from all events belonging to the sidebands (105 GeV $< m_{\gamma\gamma} <$ 122 GeV and 130 GeV $< m_{\gamma\gamma} <$ 160 GeV). For the alternative analysis, the distribution corresponds to the estimated number of background events in the signal region ($122 < m_{\gamma\gamma} < 130$ GeV) in each bin, normalised by their sum. The number of events in the signal region in each bin is estimated from a fit to the invariant mass sidebands, using exponentials of second degree polynomials for the first nine bins and a third degree polynomial for the last bin. The orange and blue bands correspond, respectively, to the statistical uncertainty from the sidebands and the total uncertainty on the background model in the nominal analysis. The total uncertainty includes, in addition to the statistical errors, systematic uncertainties from the residual correlations between the invariant mass $m_{\gamma\gamma}$ and $|\cos\theta^*|$ estimated from Monte Carlo simulations. The compatibility of the ratio with the line at one implies that no significant correlation between $m_{\gamma\gamma}$ and $|\cos\theta^*|$, within the current precision, is observed in the data.