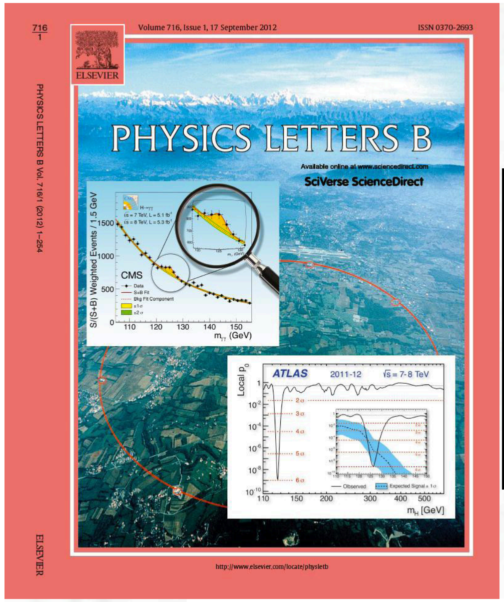


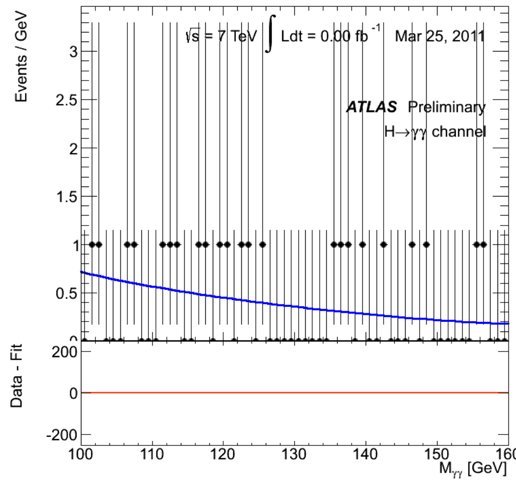
Higgs Boson Physics in ATLAS

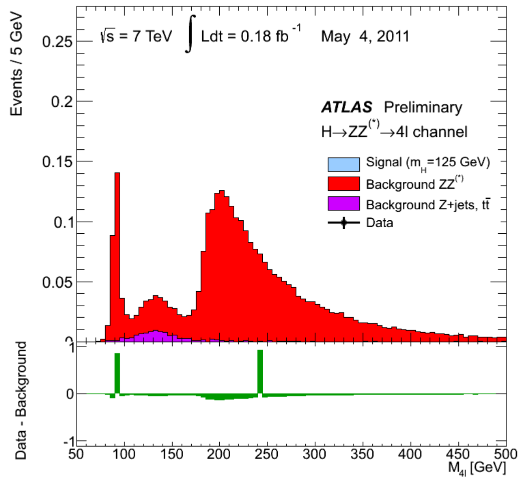
Decay observed into particles with same spin and electric charge sum = 0
→ A new neutral boson has been discovered

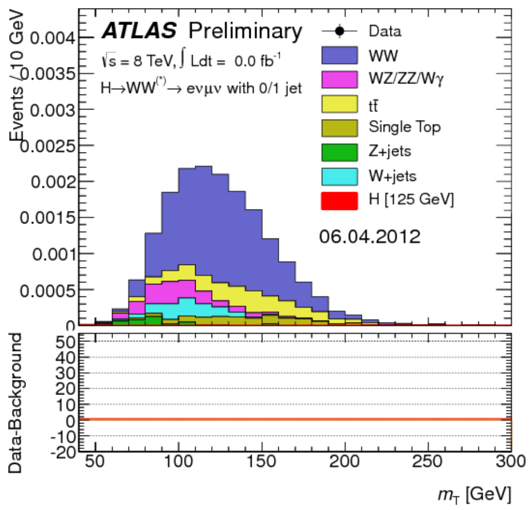
Submission to PLB on 31st July 2012

Outline*

- LHC and ATLAS
- Update since Discovery
- Properties







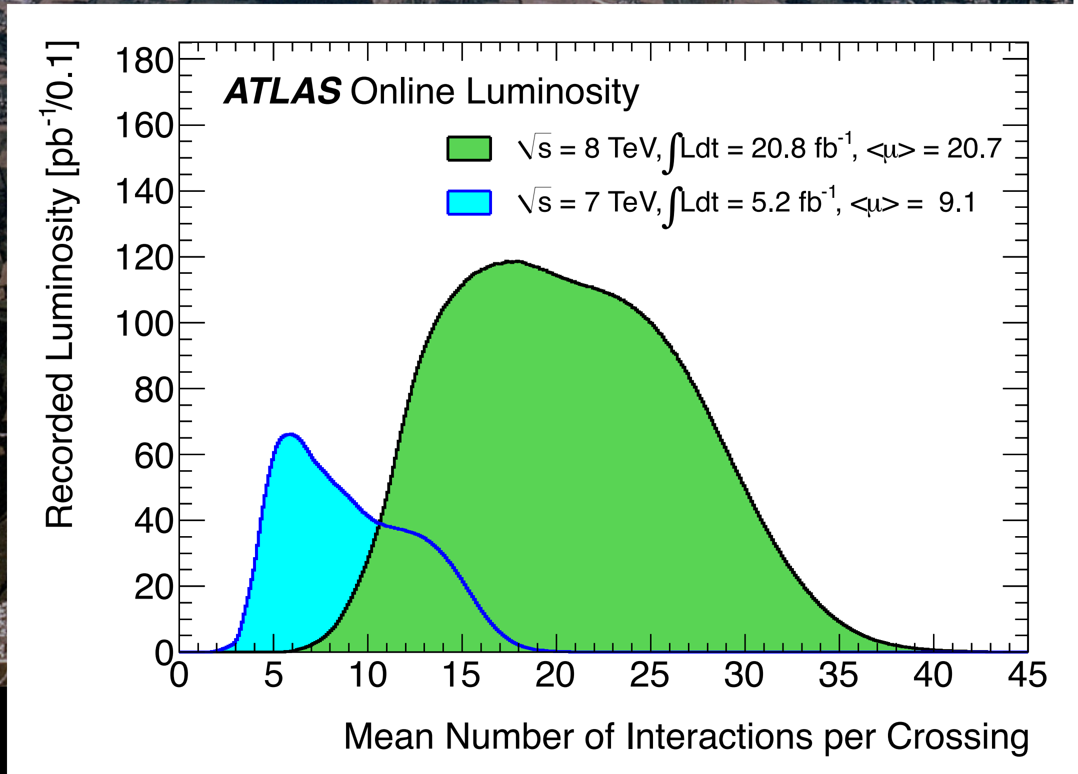
Richard St. Denis, University of Glasgow
-On behalf of the ATLAS Collaboration-

Sixteenth Lomonosov Conference on Elementary Particle Physics
Moscow State University, Moscow, 22-28 August, 2013

*Channels not yet seen by ATLAS in Joe Price's talk

The Large Hadron Collider

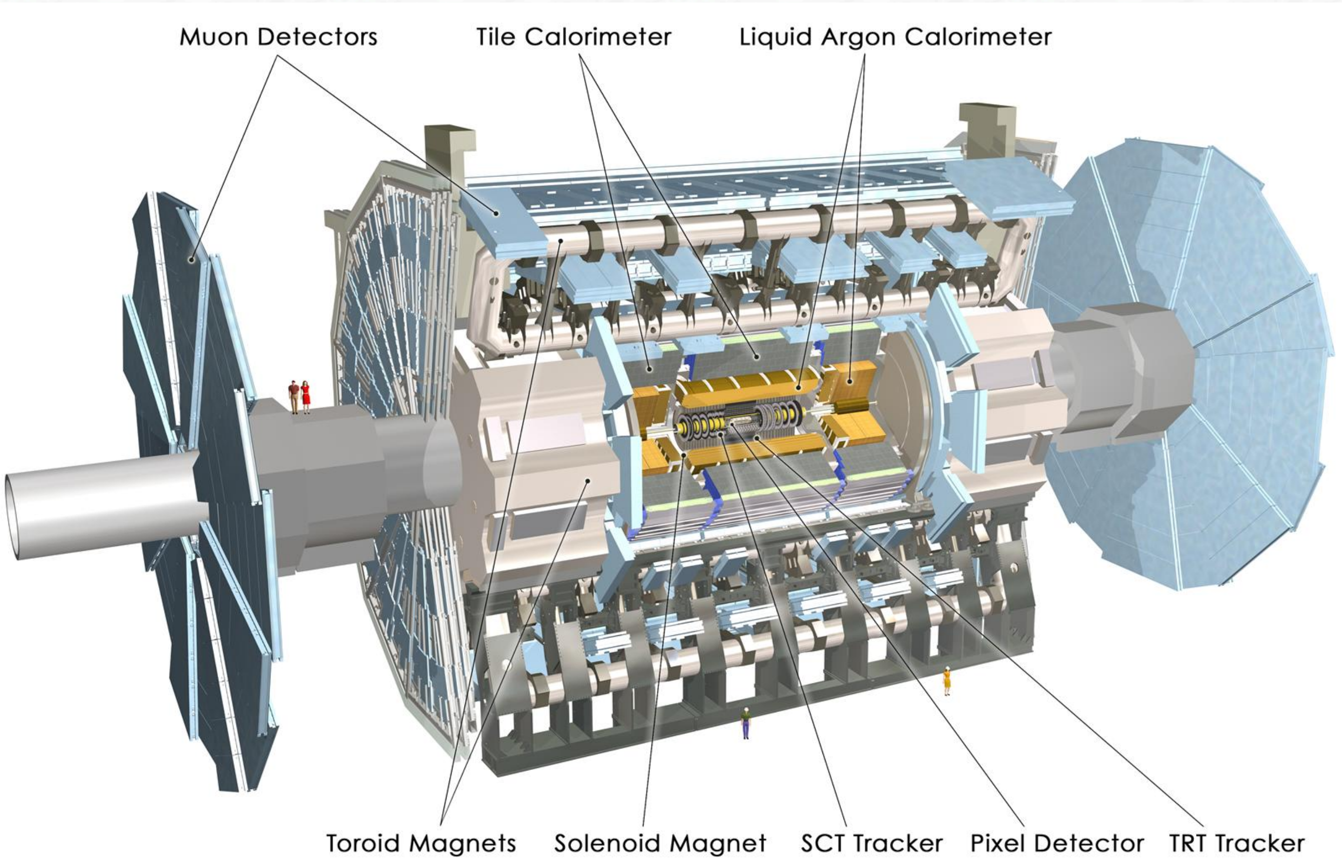
- Excellent LHC performance in 2011 and 2012
- Peak luminosities > 7×10^{33} cm^{-2} s^{-1}
- High level of pileup: ~21 interactions / beam crossing on average in 2012

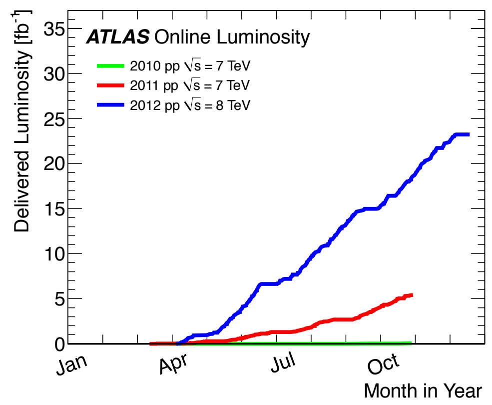


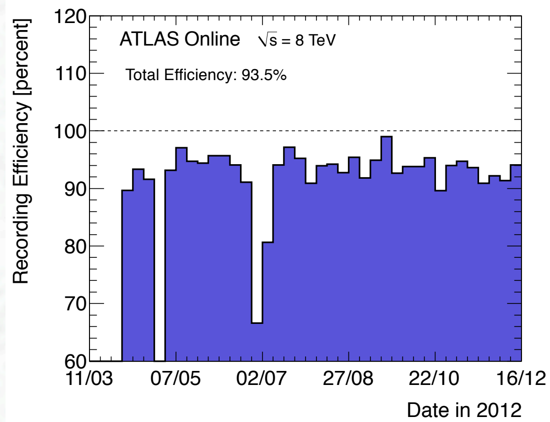
Steve Meyers PLHC 2012:

"The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics."

The ATLAS Experiment







- Axial magnetic field (2T) in the central region (momentum measurement)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons
Channels working	>99%
Fraction of Lumi Recorded	93.5%

- Energy measurement down to 1° to the beam line

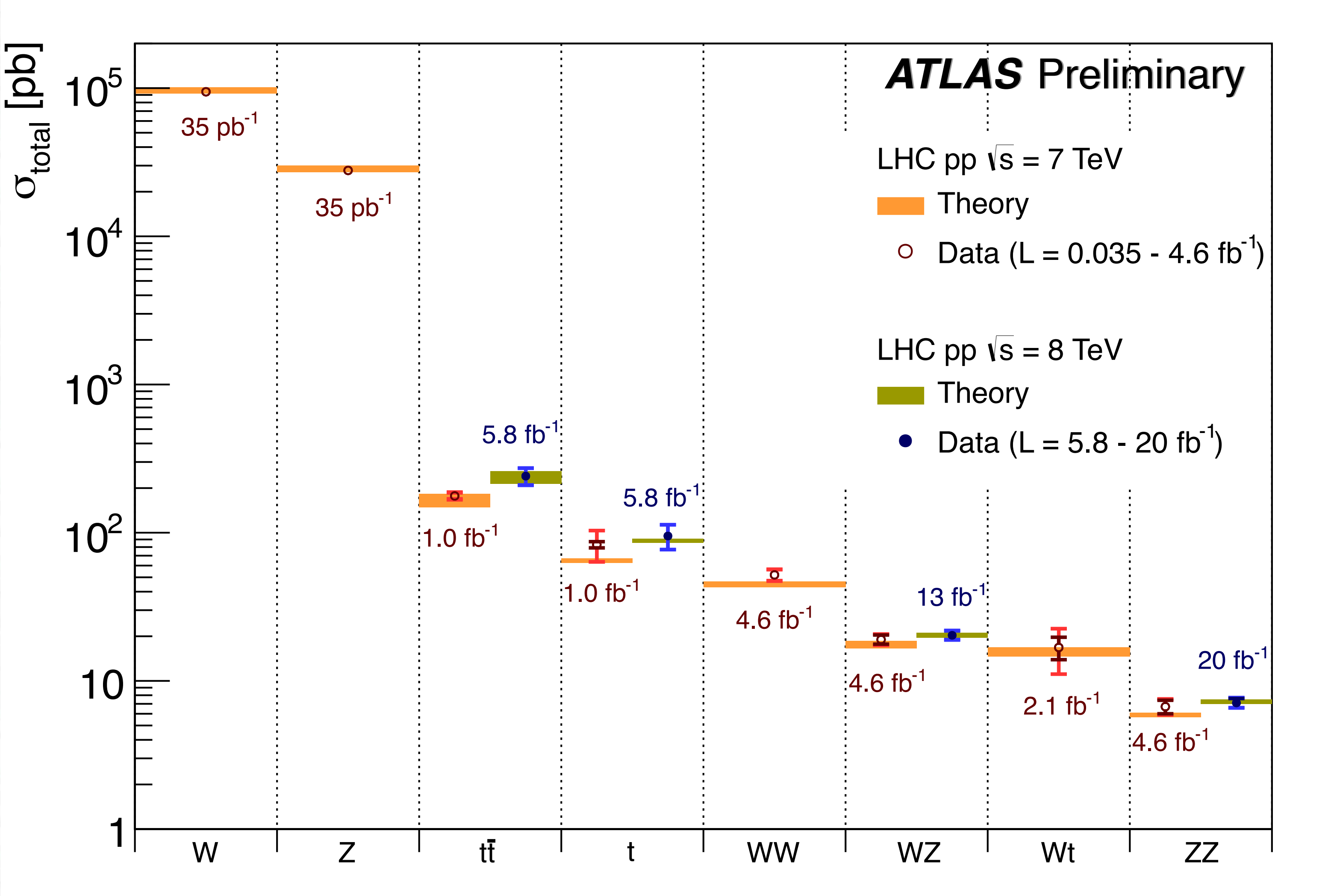
- Independent muon spectrometer (supercond. toroid system)

High resolution silicon detectors:

- 6 Mio. channels (80 μm x 12 cm)
- 100 Mio. channels (50 μm x 400 μm)

space resolution: ~ 15 μm

The Standard Model at the LHC

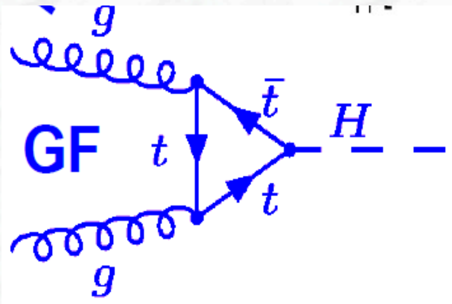


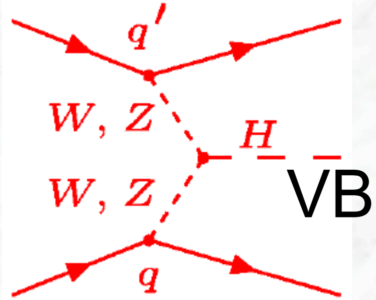
Experimental measurements of Standard Model process esand their theoretical predictions are well under control

Higgs Boson Production

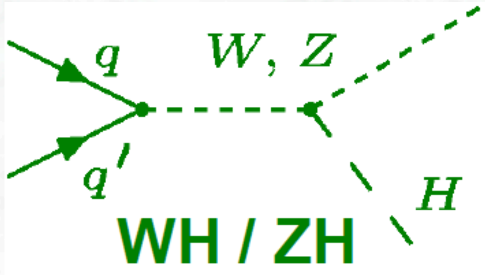
Boson fusion

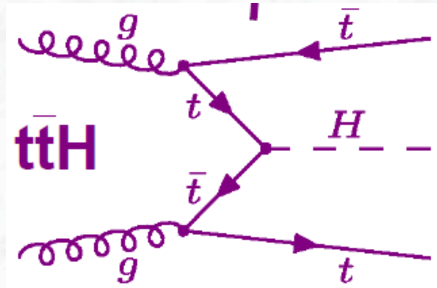
Associated production: Tag W, Z, T





VBF





0 Jets

2 Jets

σ= 19.27 pb

1.578 pb

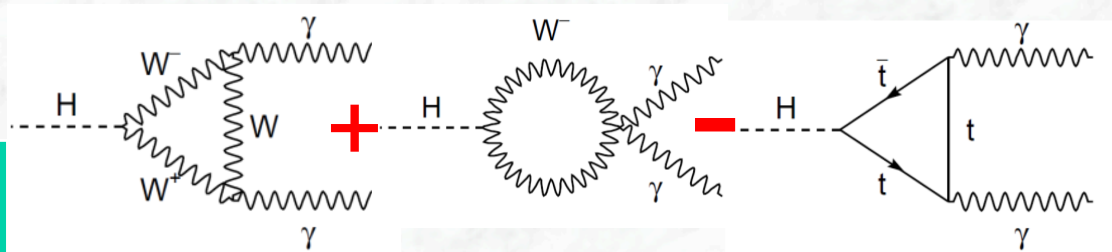
0.7046/0.4153 pb

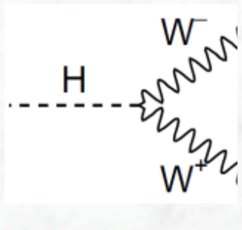
0.1293 pb

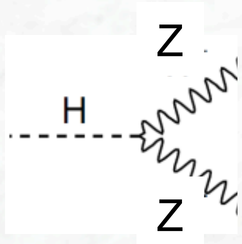
(√s=8 TeV)

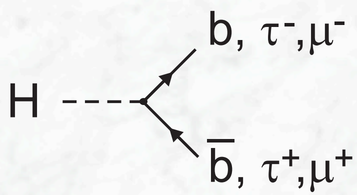
…and Decay

SM Branching Ratio H ➔X M_H=125 GeV			
bb	56.9%	ττ	6.2%
WW	22.3%	γγ	0.24%
ZZ	2.8%	μμ	0.022%



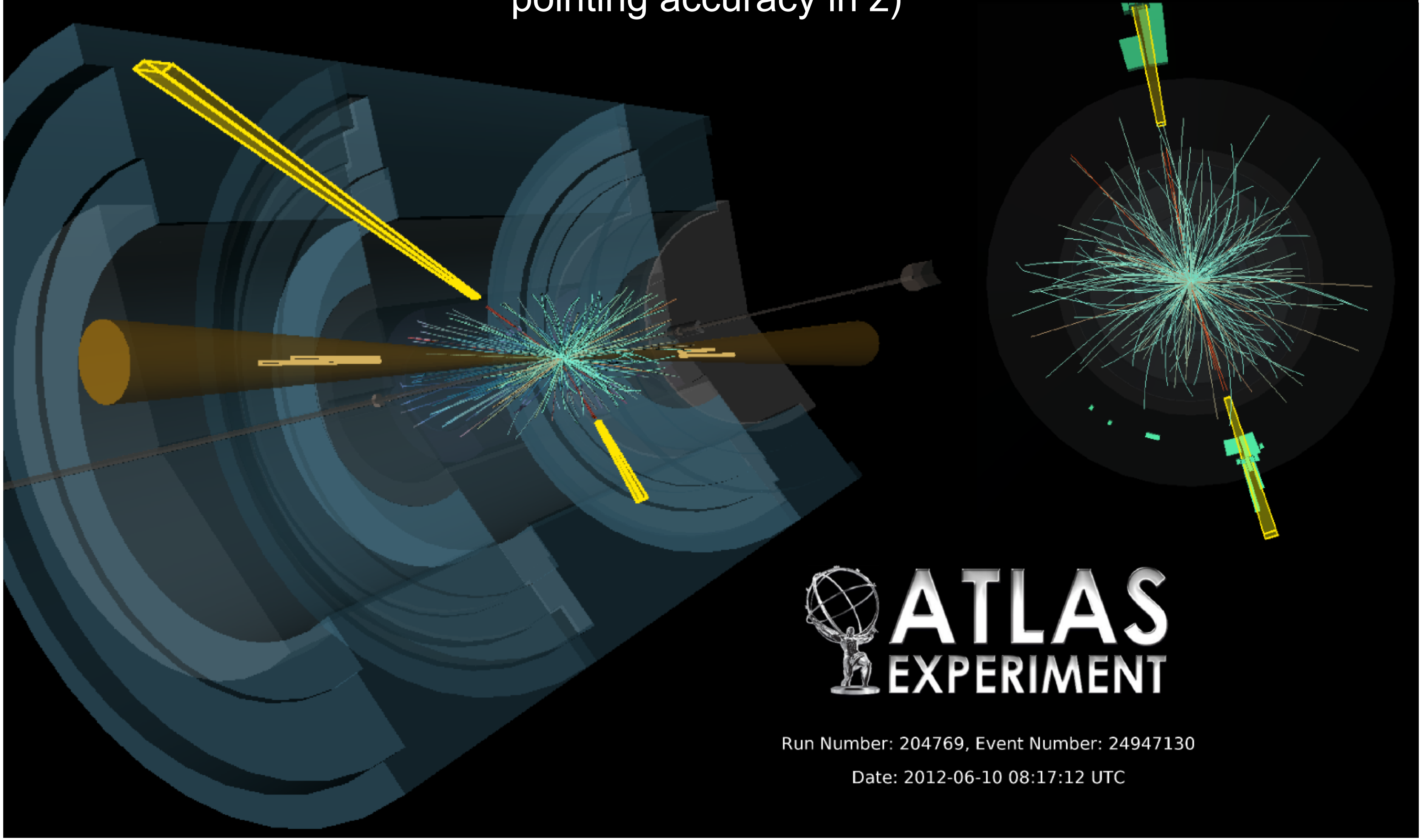


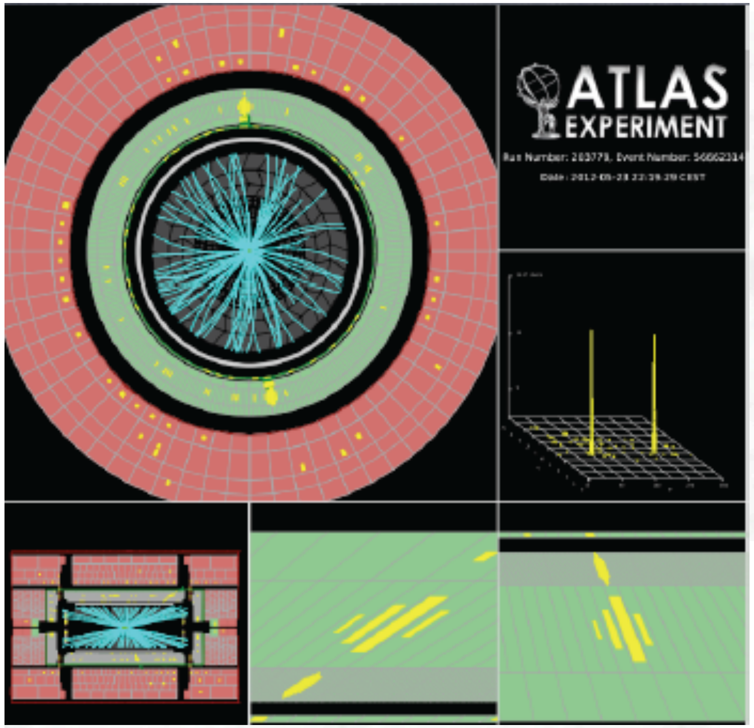




γγ Candidate event

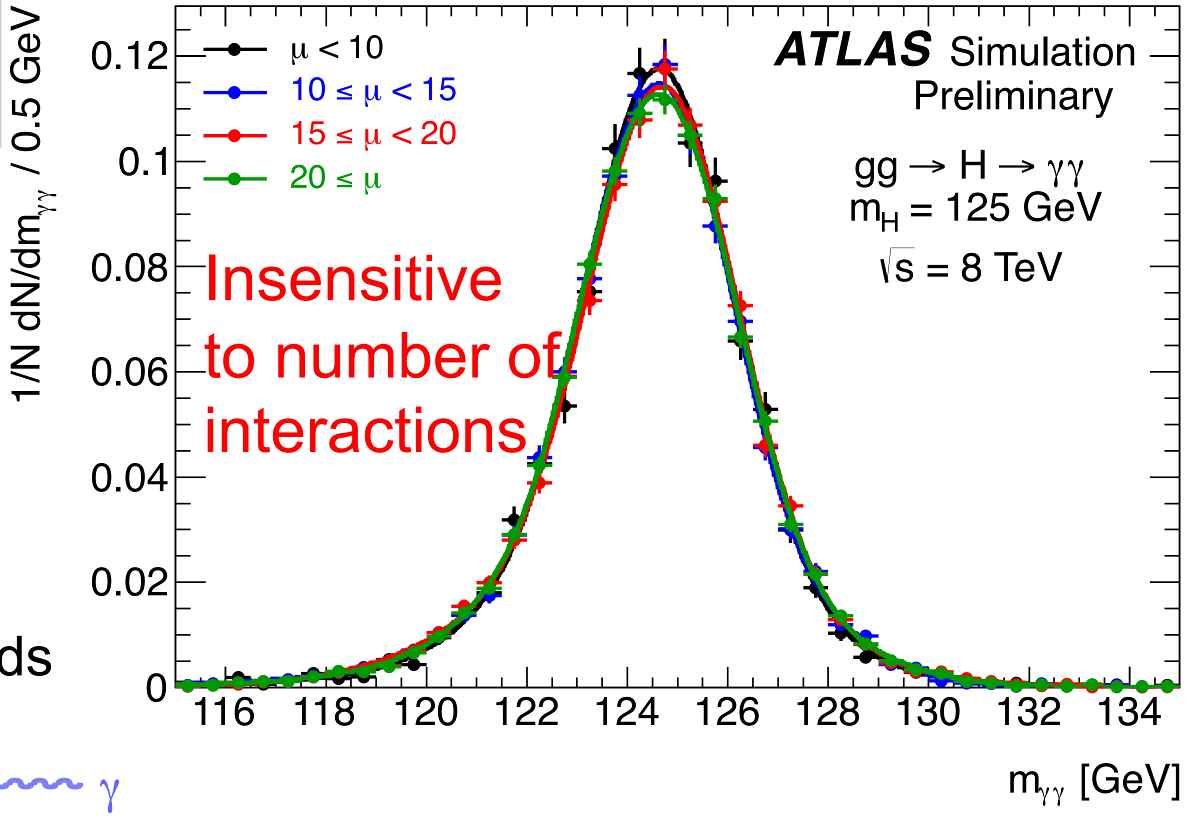
- Highly granular LAr electromagnetic calorimeter: cells pointing to the interaction region provides direction measurement: robust to pileup and good isolation to suppress jets faking photons. (15 mm pointing accuracy in z)





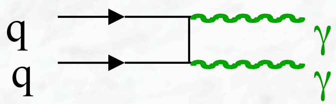
Search for H → γγ

- 2 isolated photons P_T > 40, 30 GeV
- Mass $m_{\gamma\gamma}$ of the Higgs boson reconstructed
- Mass resolution: ~1.7 GeV, m_H ~120 GeV

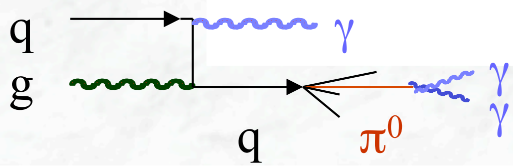


Challenges:

- Signal-to-background ratio 3%
- Smooth irreducible γγ background 75^{+3}_{-4}%



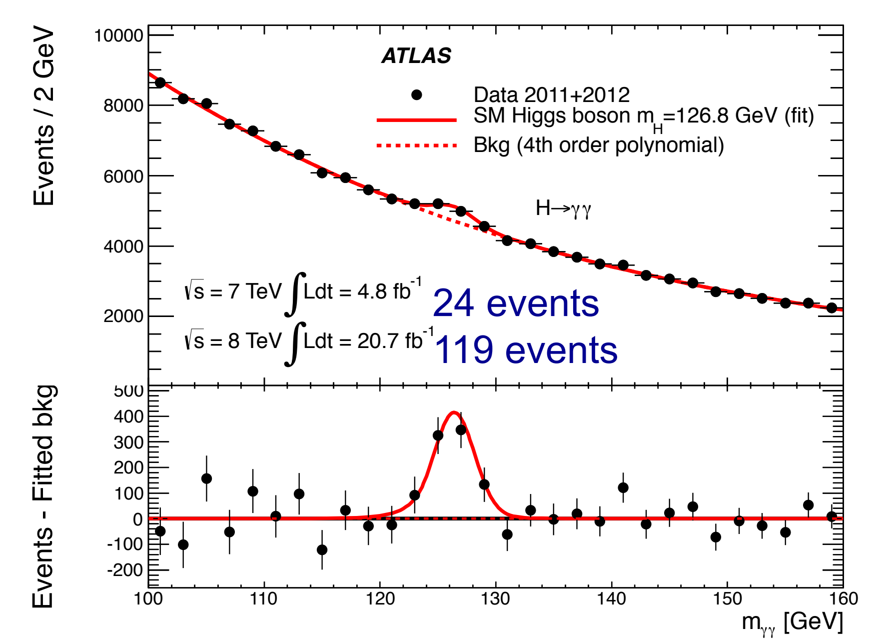
- Reducible huge backgrounds from γj (22%) and jj (3%)



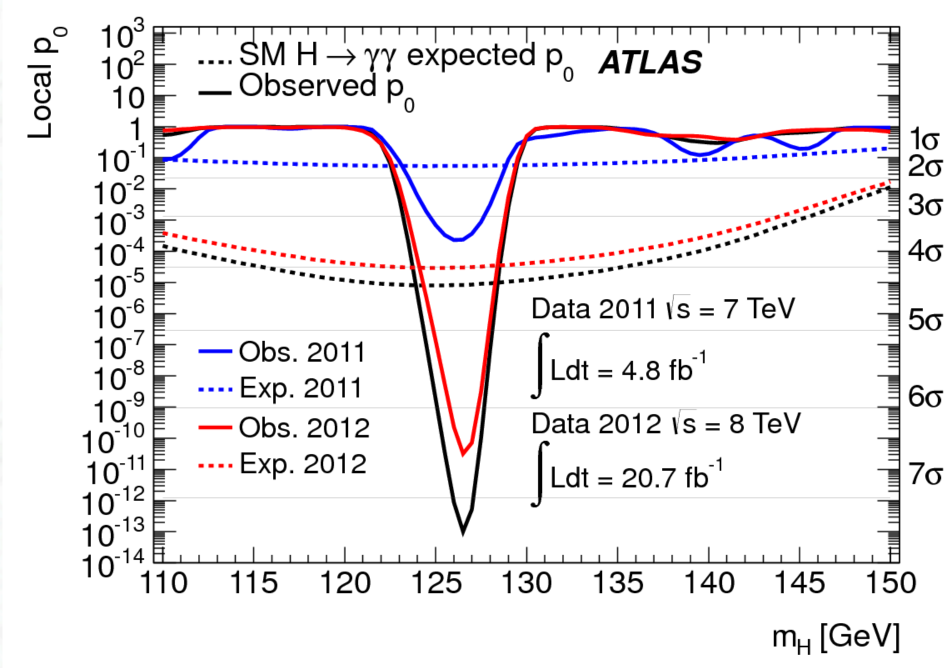
Result of the ATLAS Search for H → γγ

Establishes the discovery of the new particle in the γγ channel alone

Full dataset arXiv:1307.1427



arXiv:1307.1427



- p_0 value for consistency of data with background-only: ~ 10^{-13} : 7.4σ observed (4.3σ expected) 7 TeV and 8 TeV

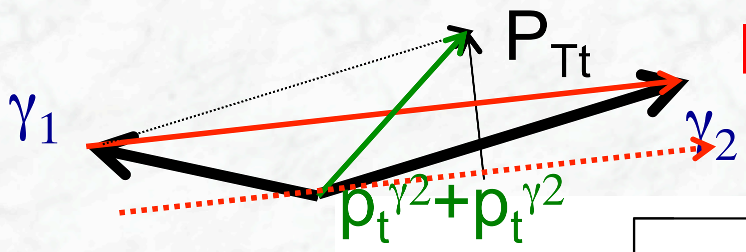
Mass

m_H = 126.8 ±0.2 (stat) ±0.7 (syst) GeV

Signal Strength

$\mu := \sigma/\sigma_{SM}$ = 1.55 ±0.23 (stat) ±0.15 (syst) ±0.15 (theo)

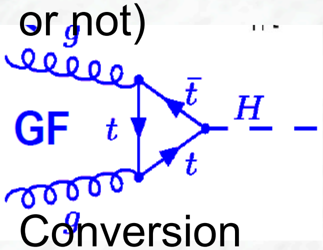
Categorisation of H → γγ Candidate Events to Separate Production Modes



Enhance VBF using component of **diphoton pt** orthogonal to **difference in photon momenta**

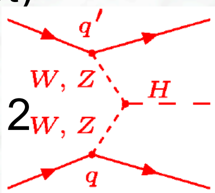
arXiv:1307.1427

No Conversion photon (Central or not)

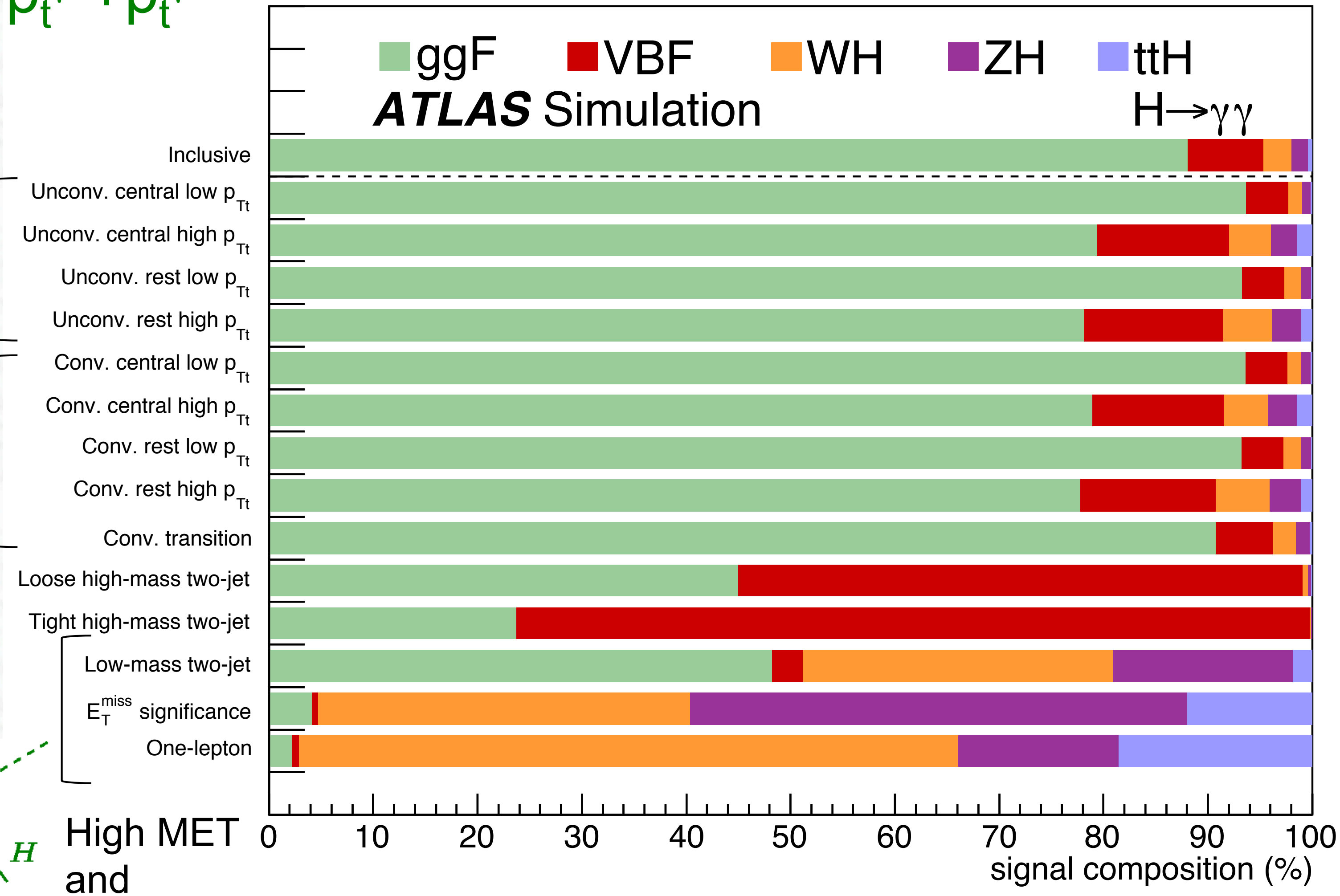


Conversion photon (Central or not)

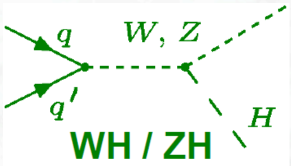
High mass 2 jet

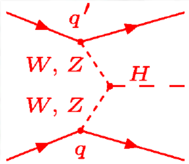


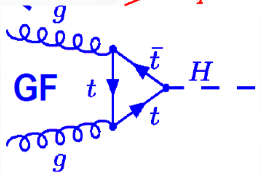
High MET and

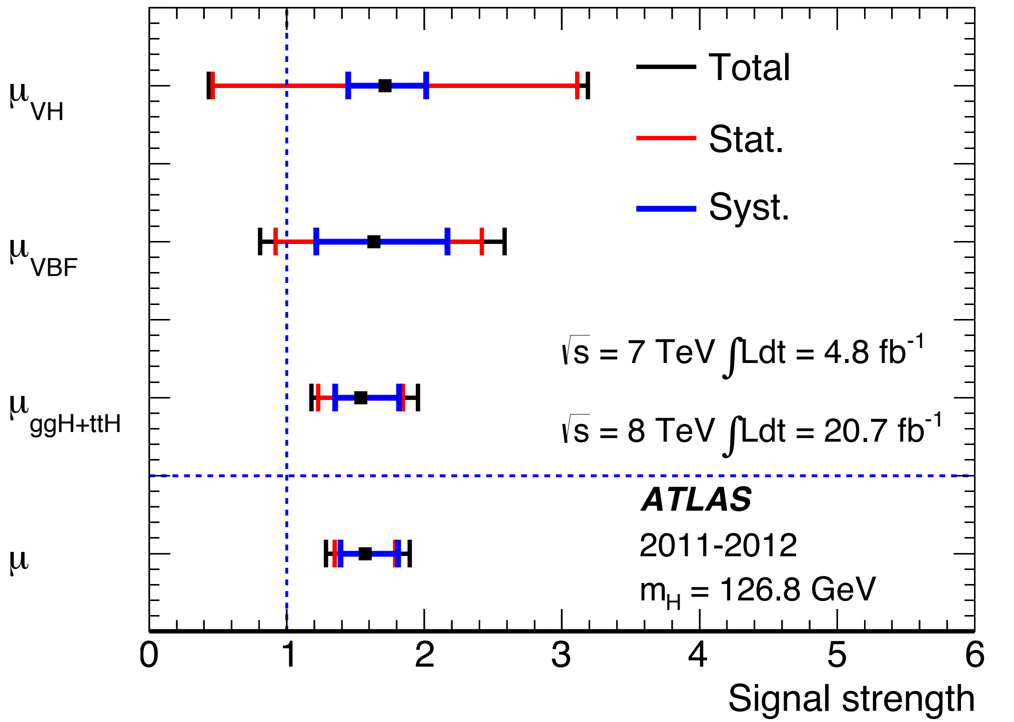


Signal Strength by Production Mode for H → γγ







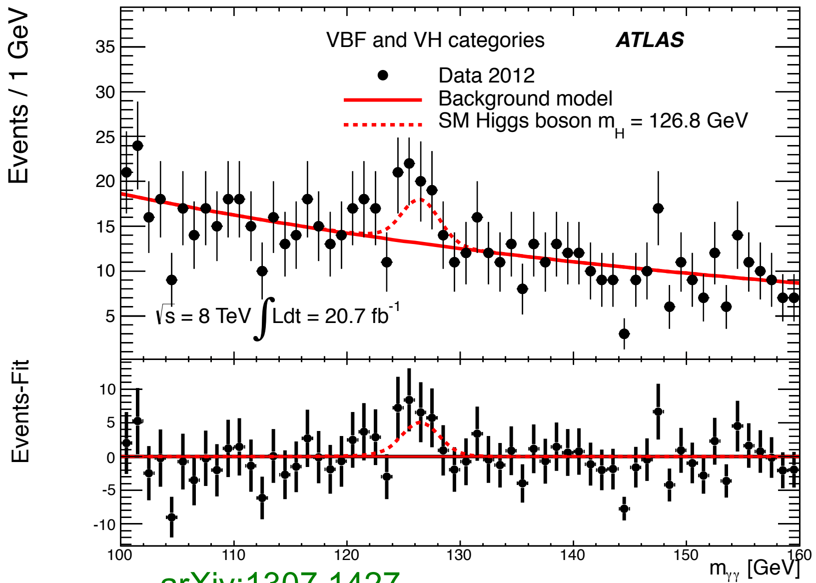


arXiv:1307.1427

VBF + VH categories

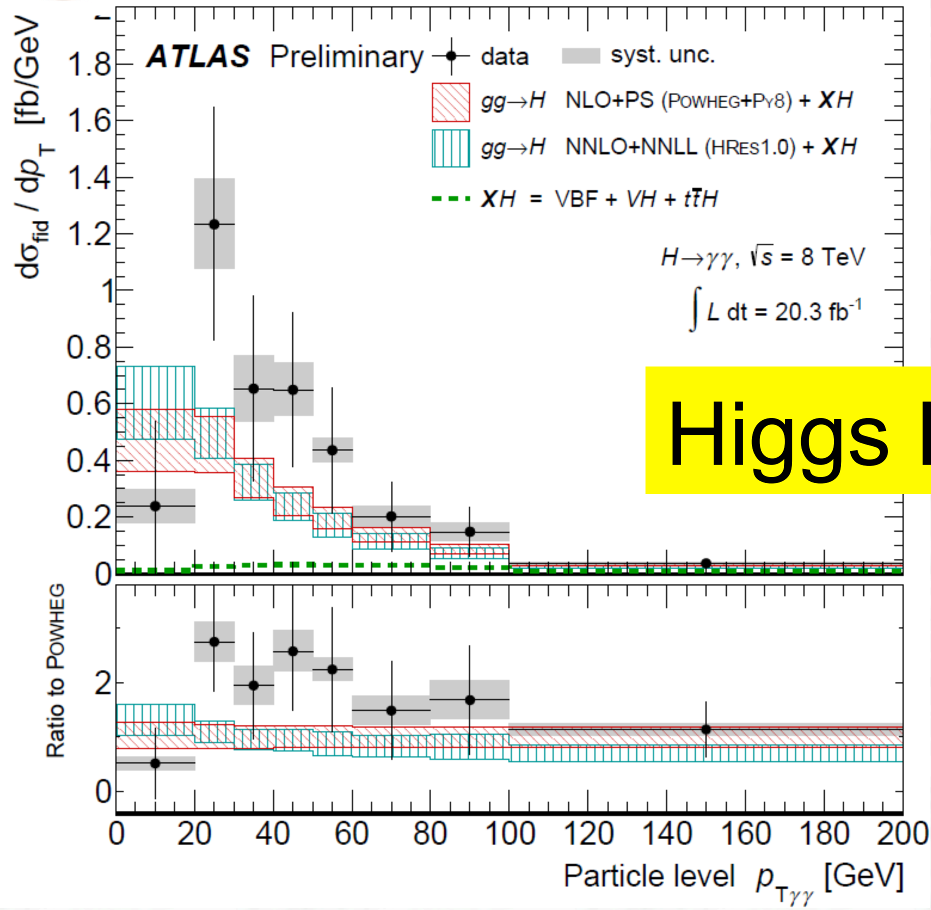
Can separate the production modes: set the stage for measurements of couplings

2.0 sigma



arXiv:1307.1427

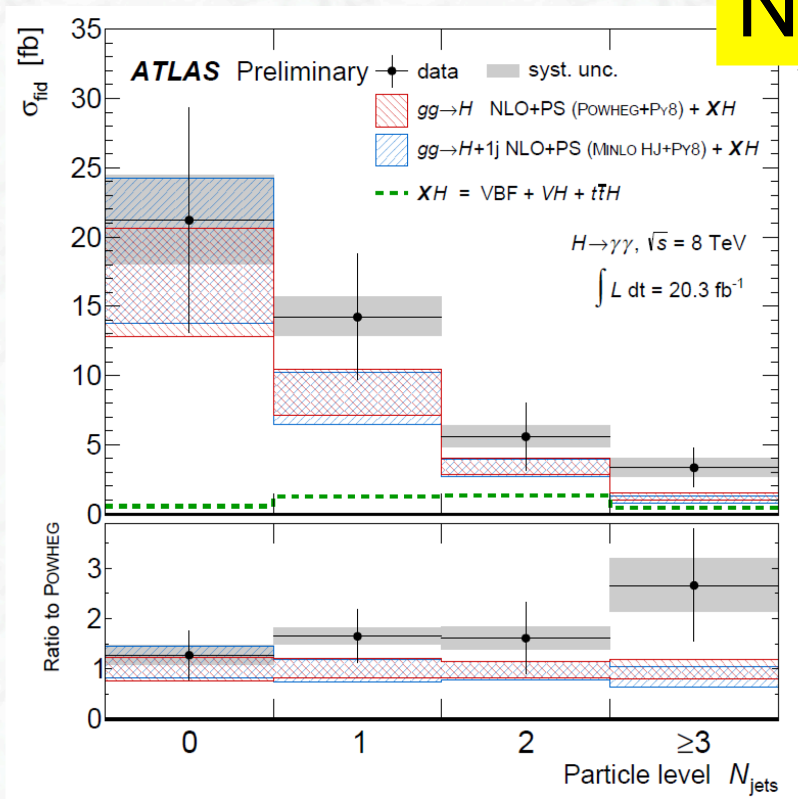
$H \rightarrow \gamma\gamma$ Differential distributions: Dawn of a New Era



Higgs P_t

Initial state jet radiation used to constrain production mechanism so that theoretical uncertainties can be reduced. Theoretical work is needed! … and statistics.

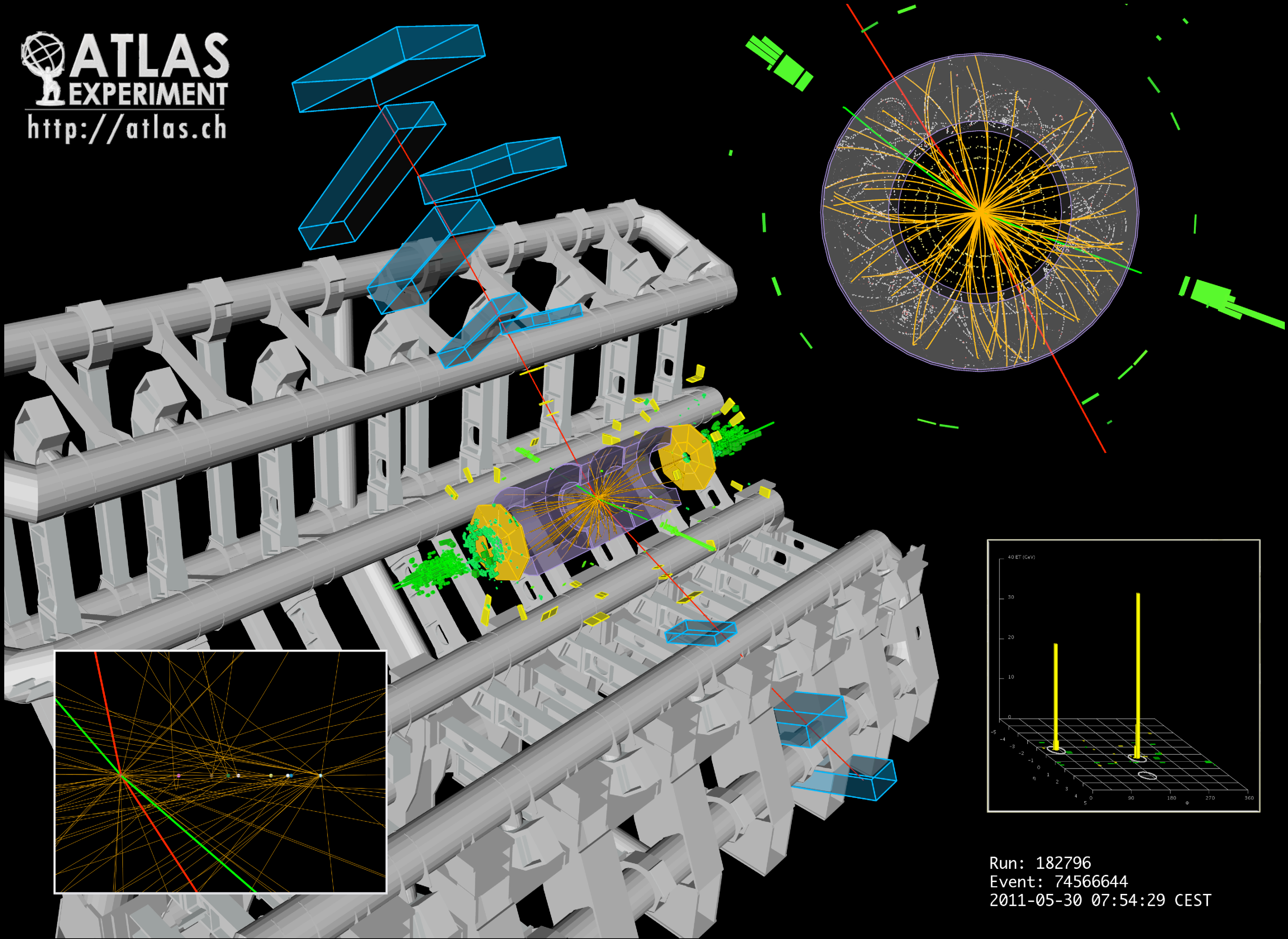
N_{jet}



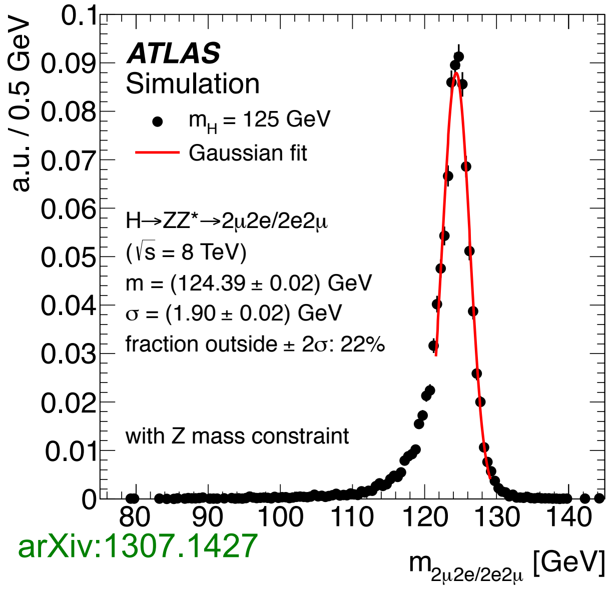
Distributions also available for
- Higgs rapidity,
- cosθ*,
- leading jet p_t,
- azimuthal angle between leading and subleading jet,
- p_t of Higgs and dijet system.

ATLAS-CONF-2013-029[11]

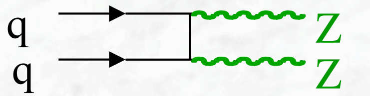
$H \rightarrow ZZ \rightarrow e^+e^- \mu^+ \mu^-$ Candidate Event



$H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- \ell^+\ell^-$



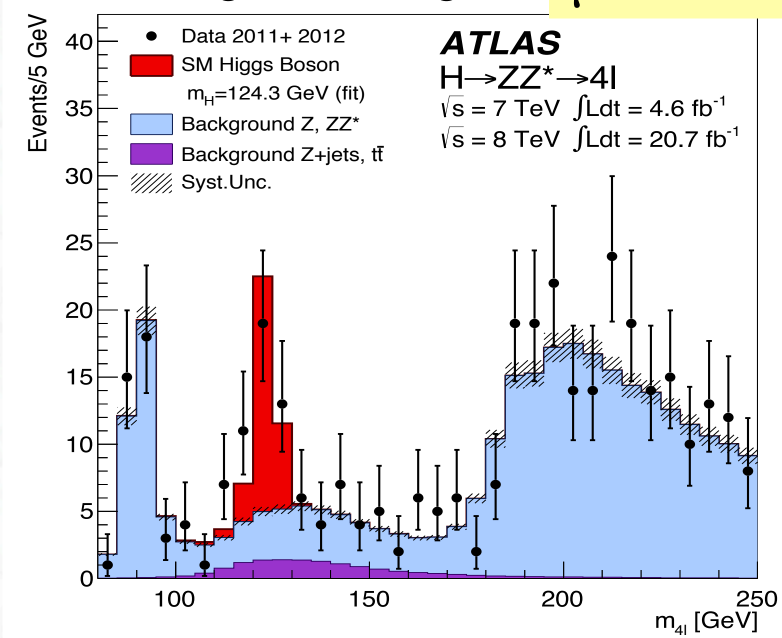
arXiv:1307.1427

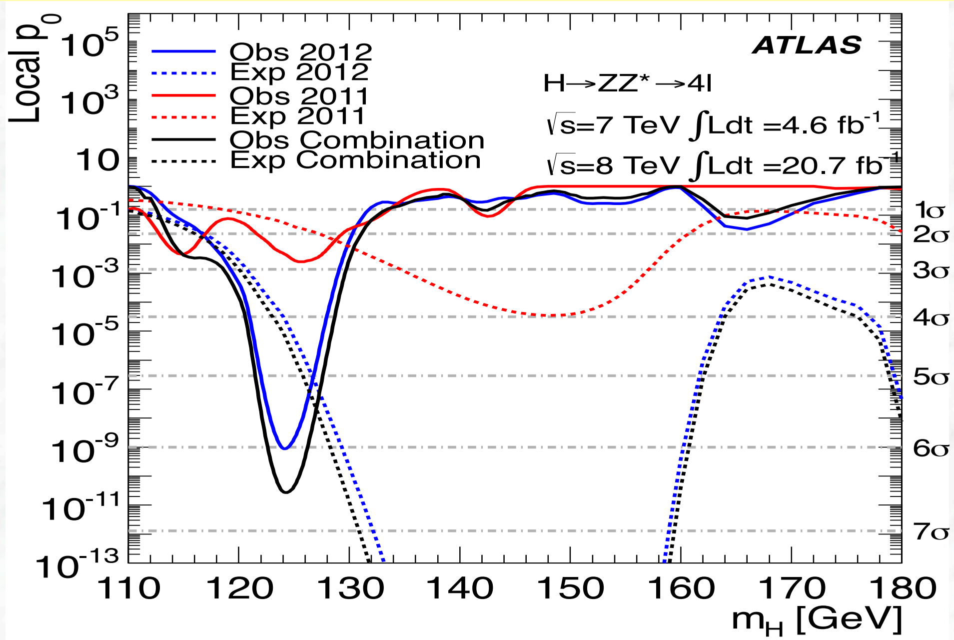
- 4 isolated leptons: Mass of Higgs boson: $m_{4\ell}$
- Optimize cuts to maximize acceptance ~ ε^4
- e: P_T > 20 , 15, 10, 7 GeV, $|\eta|$ < 2.47
- On-shell Z: One pair ~ Z mass (m_{12})
- Off-shell Z: Other pair: 12 < m_{34} < 115 GeV
- Low signal rate, but also low background from ZZ continuum,  Zbb

- p_0: ~2.7 10^{-11} or 6.6σ obs. (4.4σ exp.)

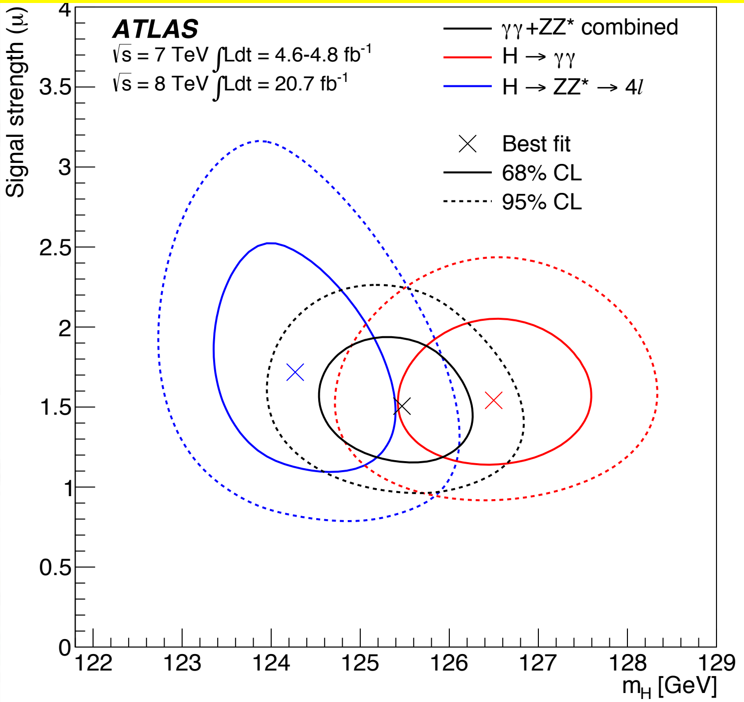
$$m_H = 124.3\ ^{+0.6}_{-0.5}\,(\text{stat})\ ^{+0.5}_{-0.3}\,(\text{syst})\ \text{GeV}$$

Signal strength: μ=1.43±0.33(stat)±0.17(syst) ±0.14(theo)



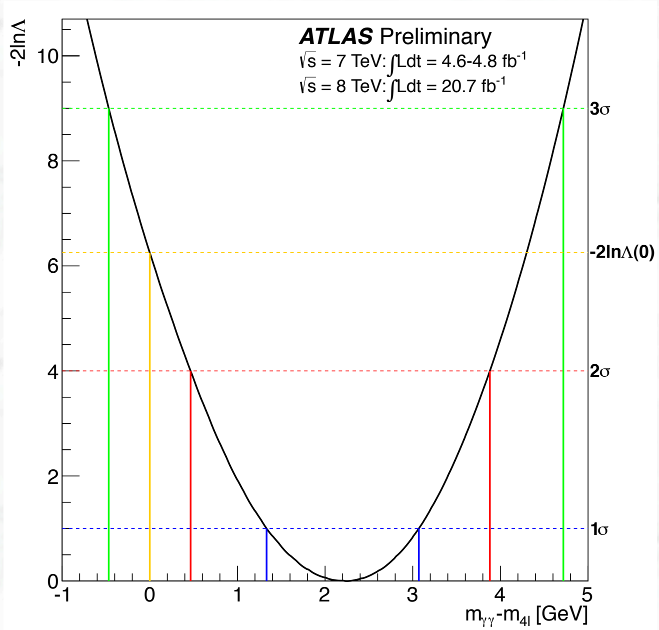


Compatibility of ZZ and γγ Channels and Determination of Mass



arXiv:1307.1427

ATLAS-CONF-2013-014

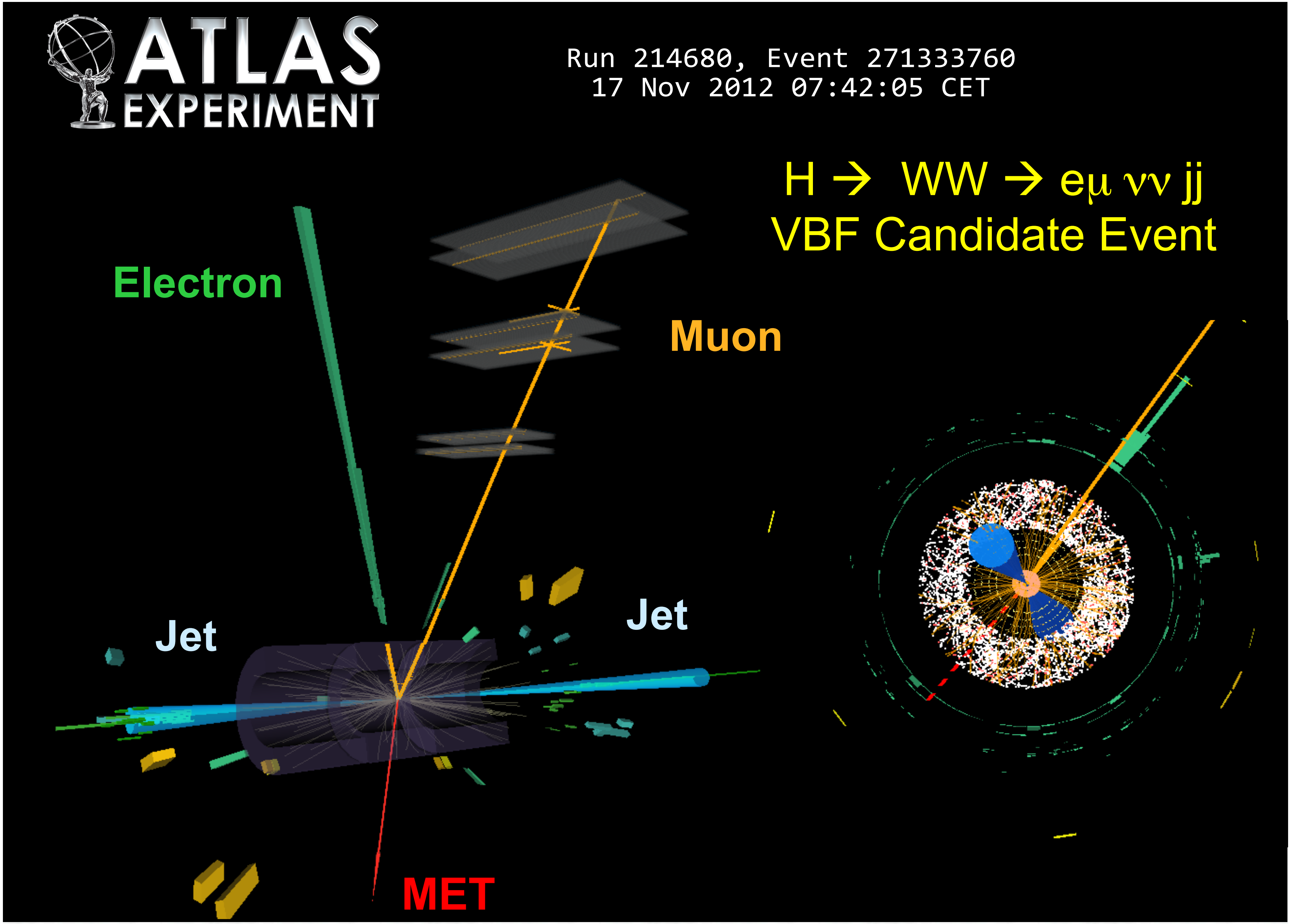


Consistency between the fitted masses: Likelihood for $\Delta m = 0$ vs best fit value for Δm:

$$\Delta m = 2.3^{+0.6}_{-0.7}\,(\text{stat}) \pm 0.6\,(\text{syst})$$ 2.4σ deviation (Agreement: 1.5%)

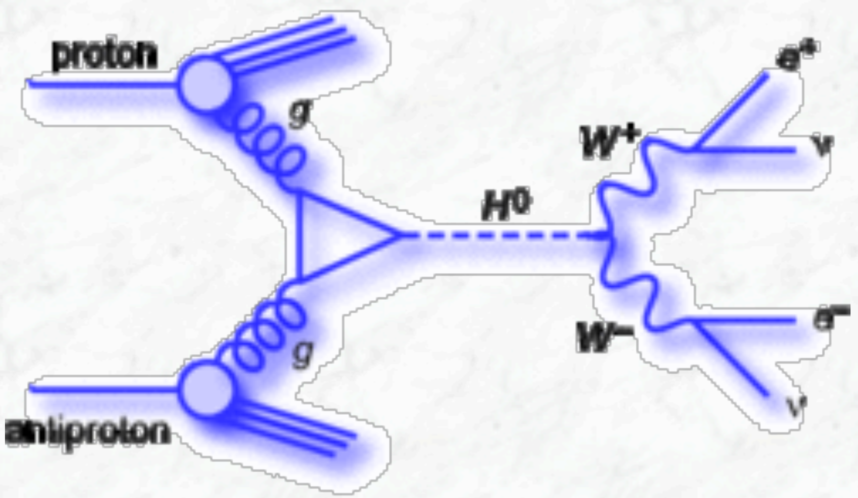
Agreement goes to 8% if we take rectangular instead of gaussian shapes for the three principle sources of e/γ energy scale uncertainty: material, pre-sampler energy scale, calibration procedure

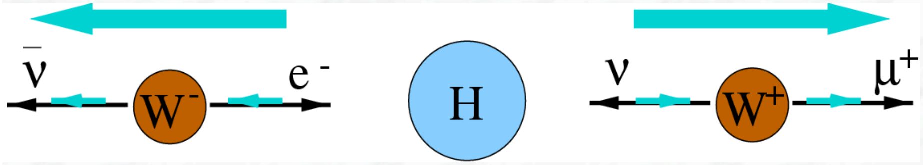
$$m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.6}_{-0.5}\,(\text{syst})\ \text{GeV}$$

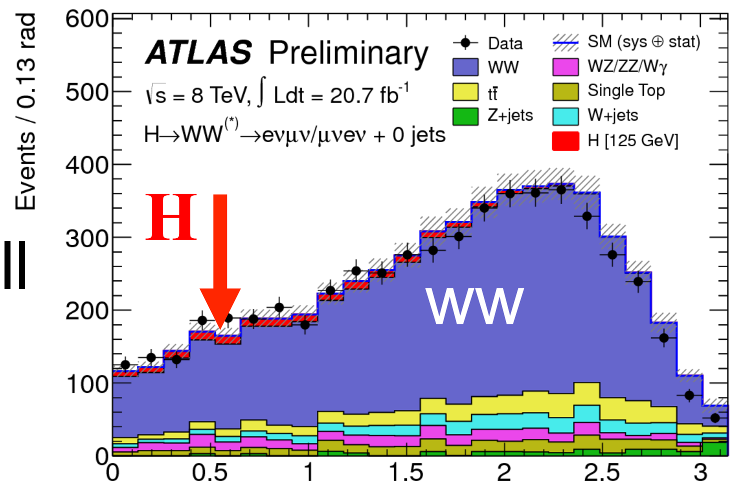

ATLAS
EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
H → WW → eμ νν jj
VBF Candidate Event
Electron
Muon
Jet
Jet
MET

H→WW Production Features

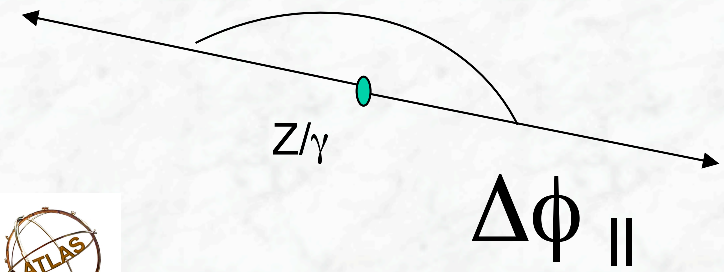
- 2 High Pt ee,eμ,μμ not back to back (as Drell Yan is)
- Spin 0 Higgs correlates spins of leptons: charged leptons (**low $\Delta\phi_{ll}$**), two neutrinos (**High MET**) tend to be closely aligned
- Modifies dilepton invariant mass
- Analyze vs N_{jet}: backgrounds, production modes differ





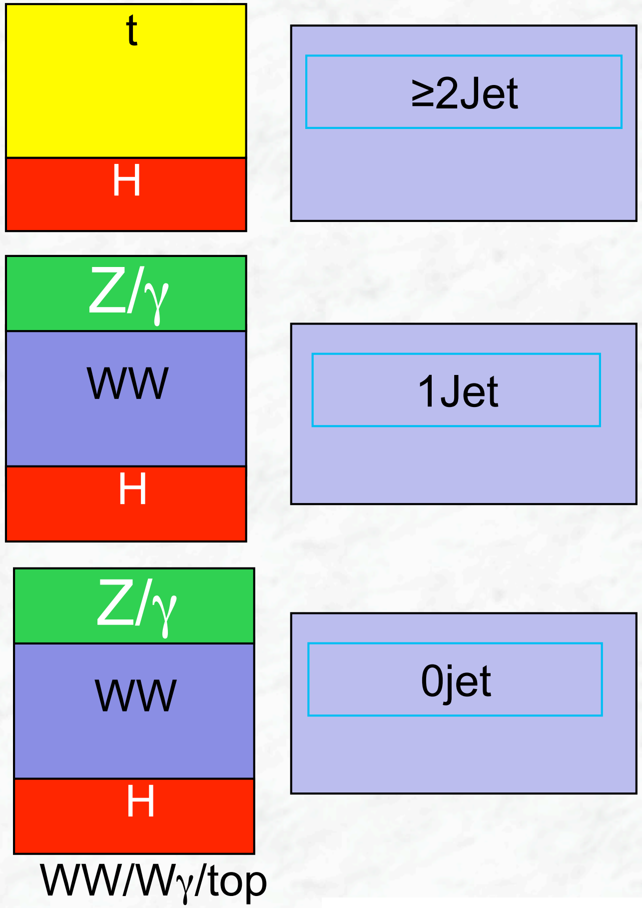


ATLAS-CONF-2013-030



Backgrounds

Search for H → WW → ℓν ℓν Decay

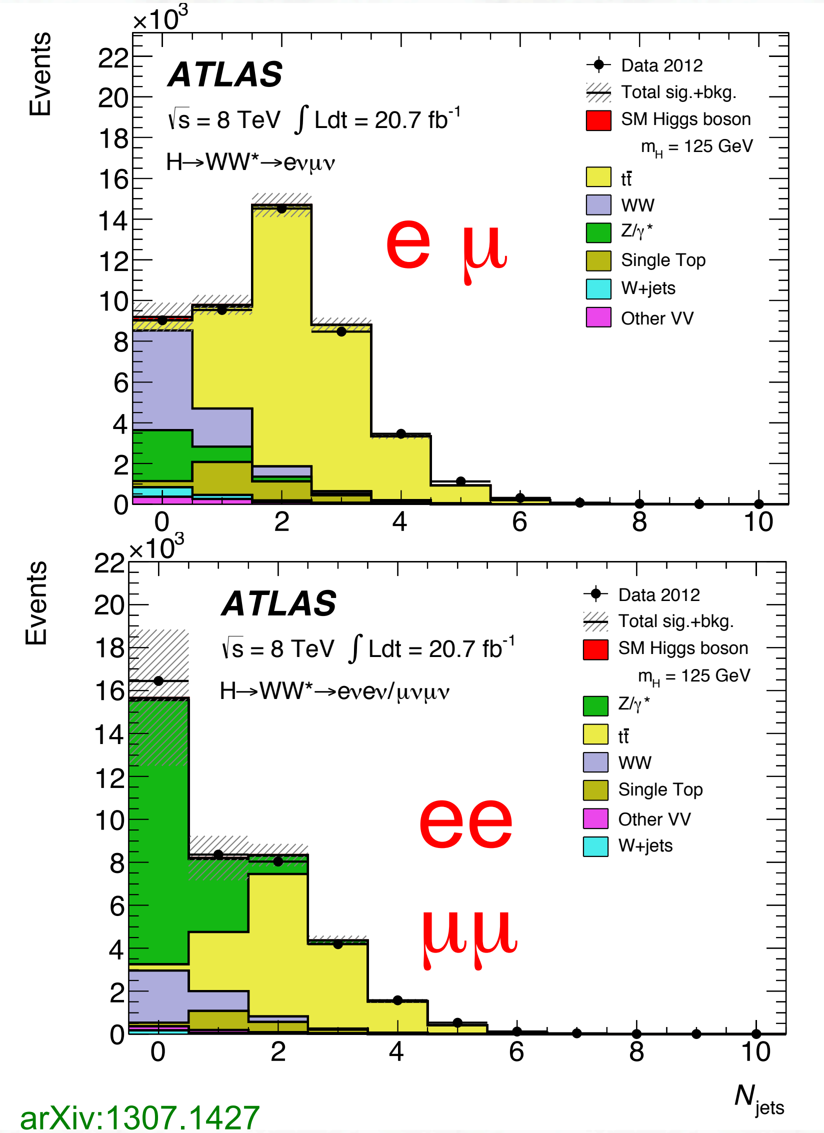


Major backgrounds:

(normalization in control regions)

- WW pair production (0 jet)
- tt background (2 jets)
- Z+jets (for ee/μμ pairs)

Jet multiplicity distr. after basic selection requirements

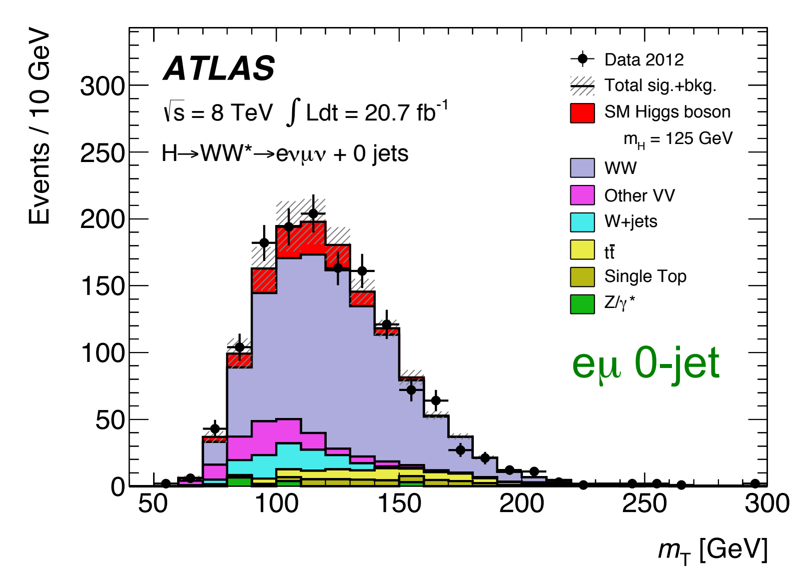


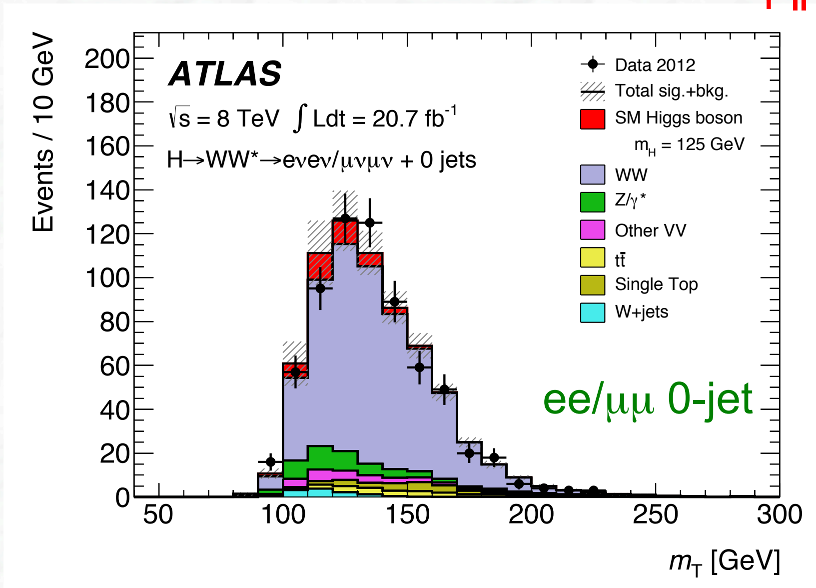
arXiv:1307.1427

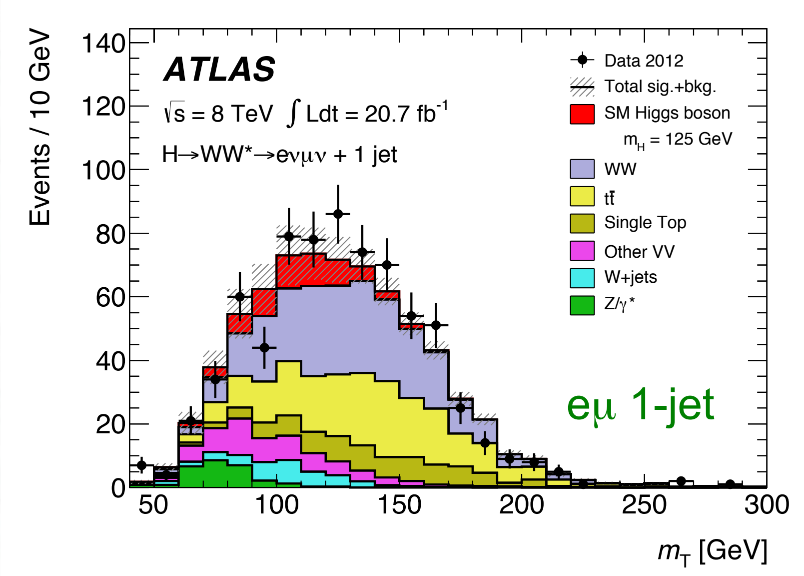
Transverse Mass Distributions*

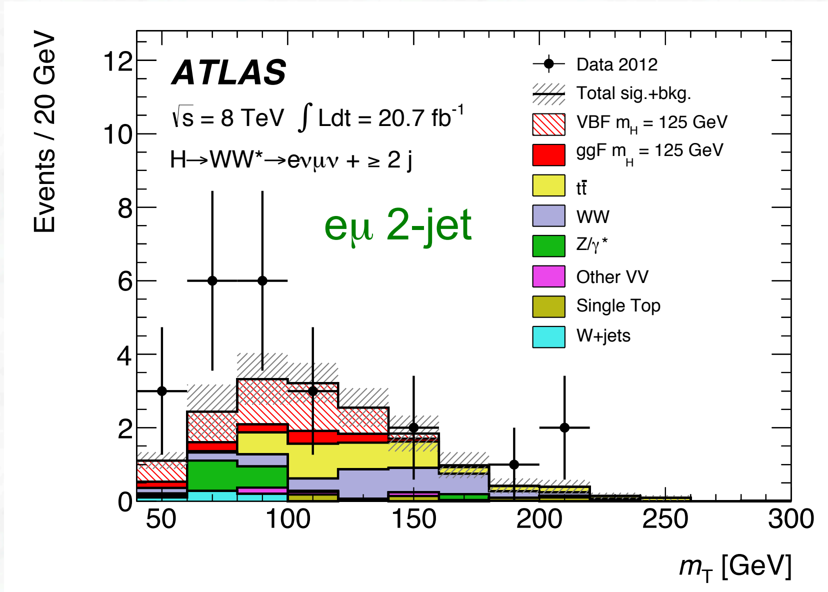
arXiv:1307.1427

*after cuts on $\Delta\phi_{ll}$, MET, m_{ll}







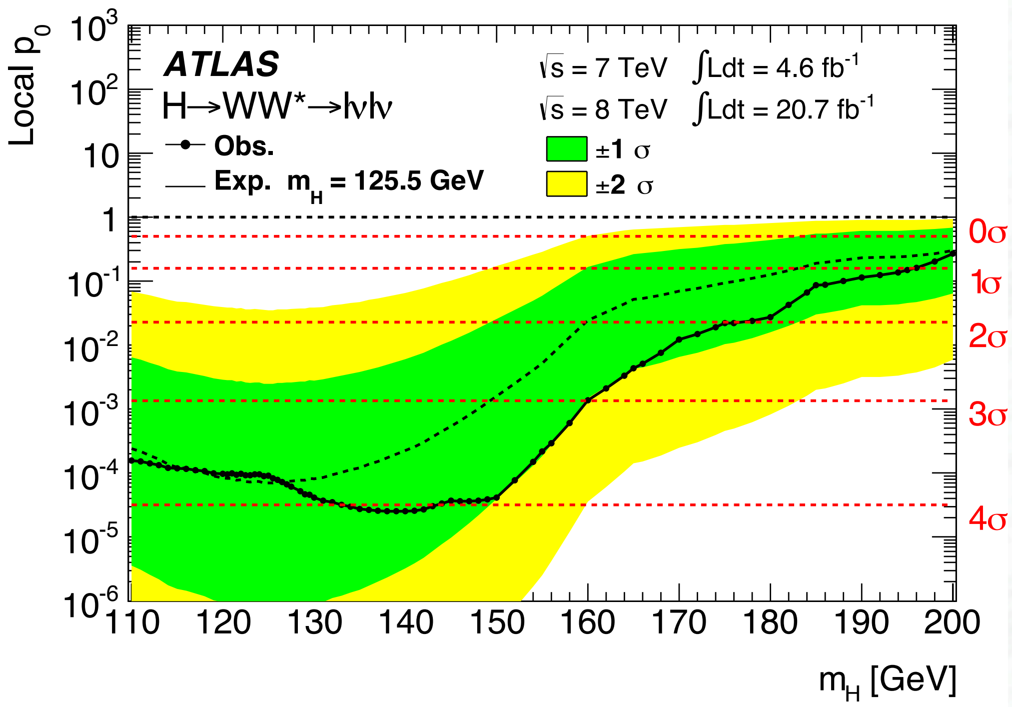


Clear excess above backgrounds for all Njet

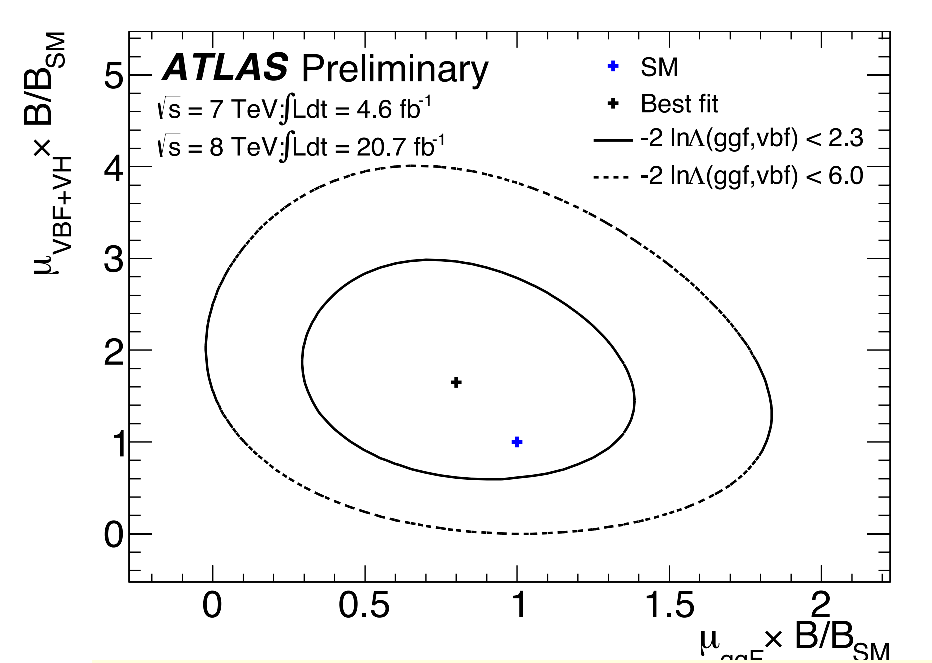
Results on the Search for H → WW → ℓν ℓν Decays

p_0 (125 GeV) = 8 10^{-5} or 3.8σ observed (3.7σ expected)

Signal strength: (7 TeV and 8 TeV 125 GeV)
μ = 0.99 ± 0.21 (stat) ± 0.12 (syst) ± 0.19 (theo)



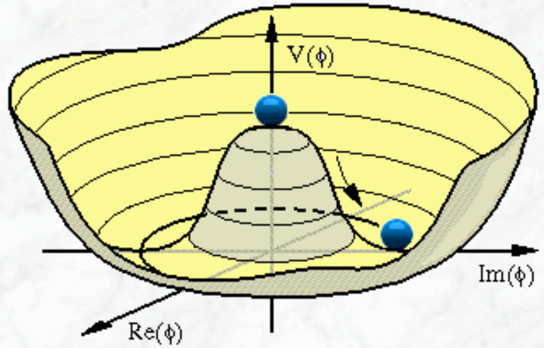
arXiv:1307.1427



Based on 2jet vs 0,1 jet:
μ_{VBF} = 1.66 ± 0.79
μ_{ggF} = 0.82 ± 0.36

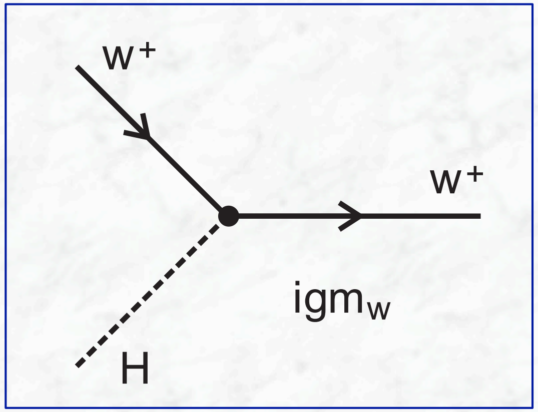
ATLAS-CONF-2013-030

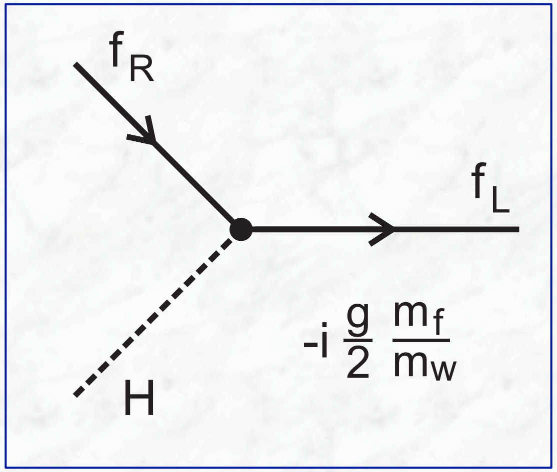
Is the New Particle the Higgs Boson ?



- Production rates ?

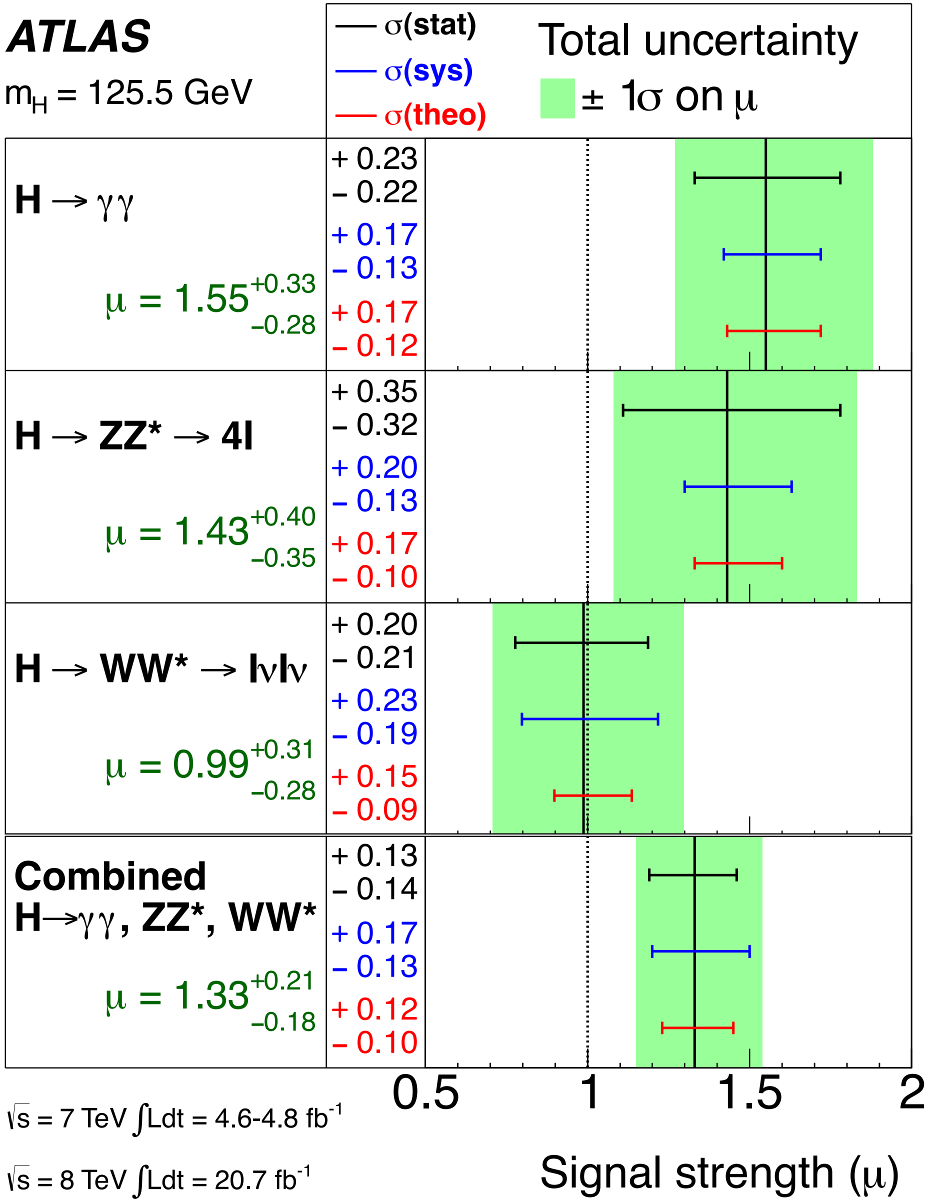
  Couplings to bosons and fermions





- Spin, J^P quantum number

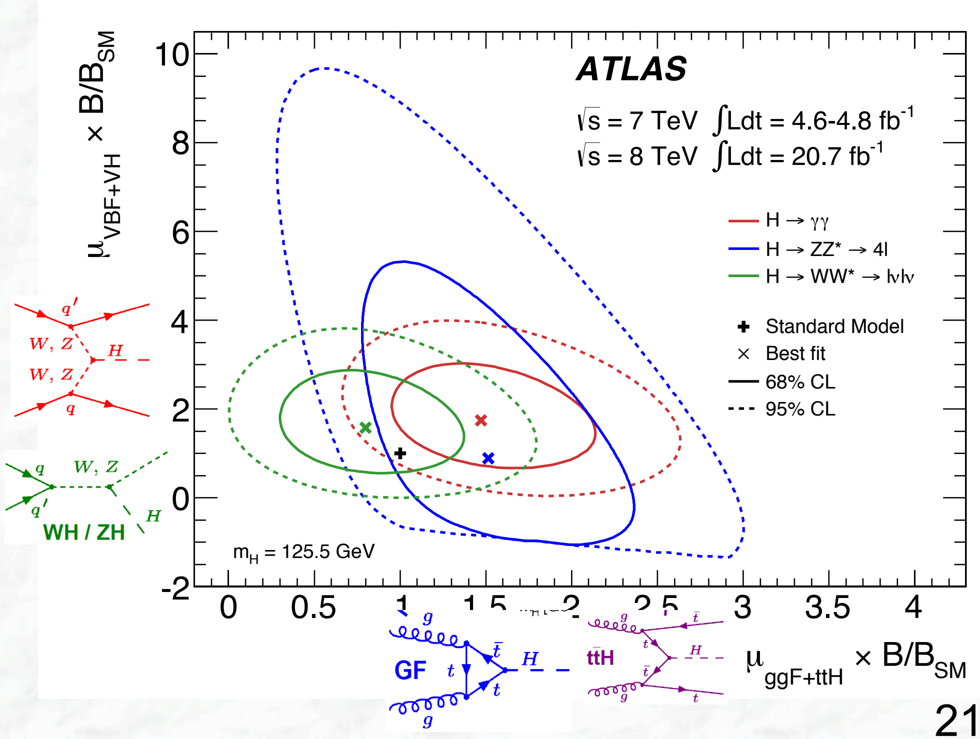
Signal Strength in Di-Boson Decay Modes
(full data set)



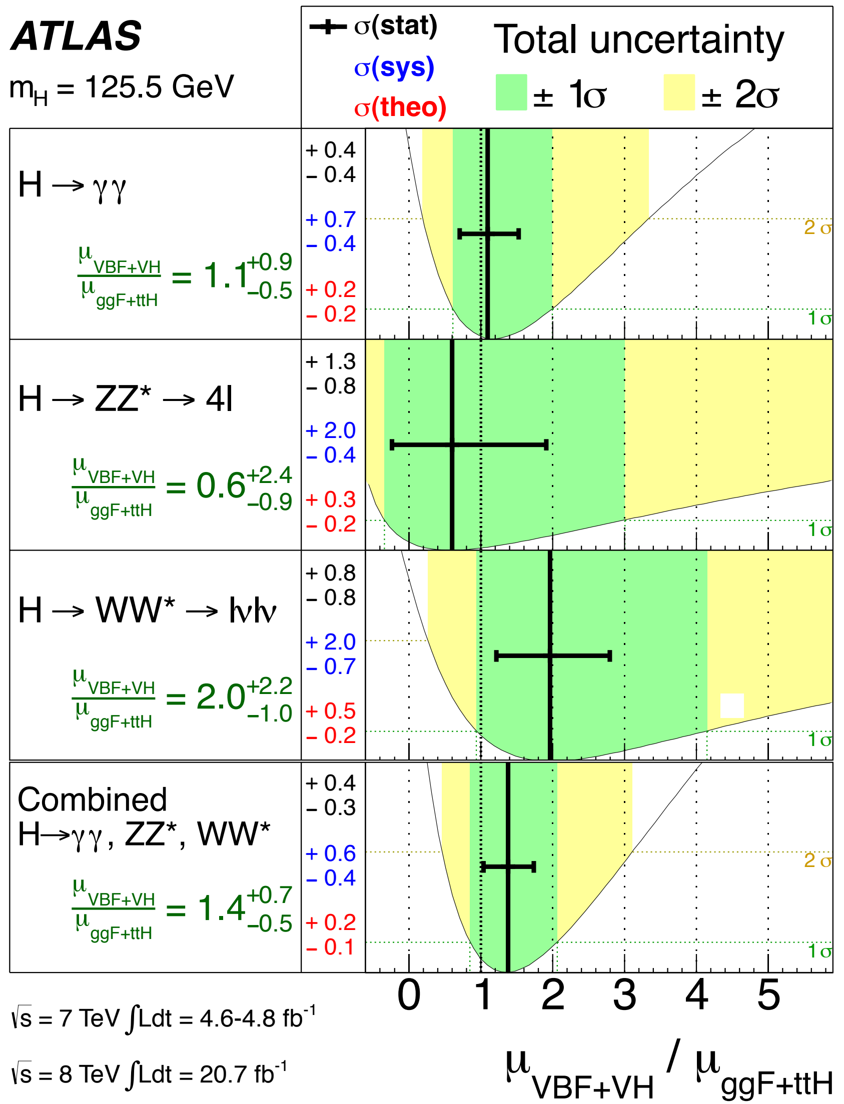
- Data consistent with the Standard Model Higgs boson:

μ=1.33 ± 0.14 (stat) ± 0.15 (syst)

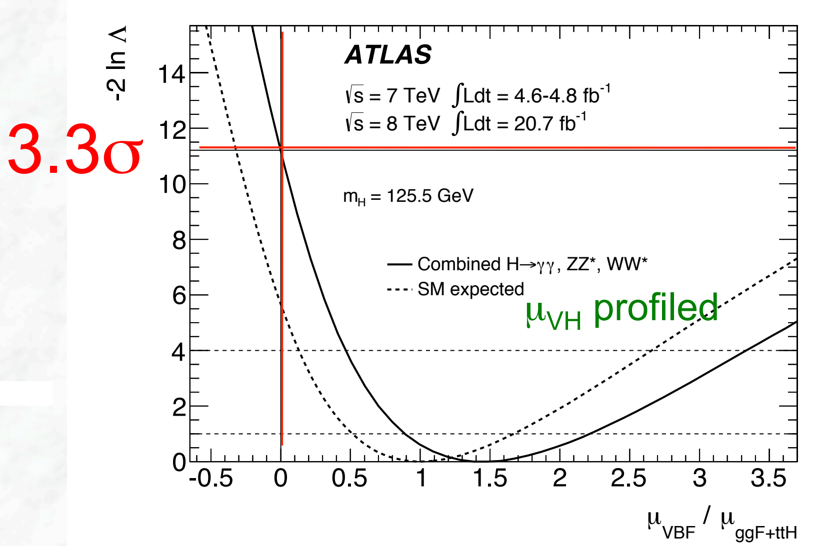
- Sensitivity to gluon-fusion (ggF + ttH) and (VBF+VH) production fractions, branching ratio factors B/B_{SM}



Evidence for production via vector boson fusion



- Fit for the ratio $\mu_{VBF+VH} / \mu_{ggF+ttH}$ for the individual channel (model independent)
- Results can be combined
- Good agreement with SM expectation for individual channels and the combination



$$\mu_{VBF} / \mu_{ggF+ttH} = 1.4\,^{+0.4}_{-0.3}\,(\text{stat})\,^{+0.6}_{-0.4}\,(\text{syst})$$

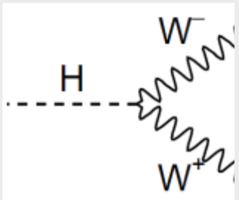
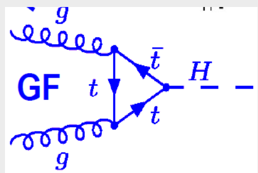
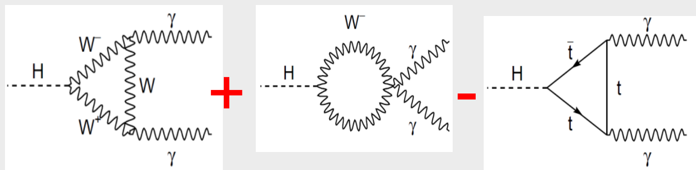
3.3σ evidence for VBF production

Couplings to Fermions and Bosons

- Assume single narrow resonance in a zero-width approximation: $\sigma \cdot BR(ii \to H \to ff) = \sigma_{ii} \cdot \Gamma_{ff} / \Gamma_H$

- All SM couplings fixed given m_H. Assume tensor structure unchanged: Higgs is a CP-even 0 scalar. No BSM particles.

- Add scaling κ_i of coupling:

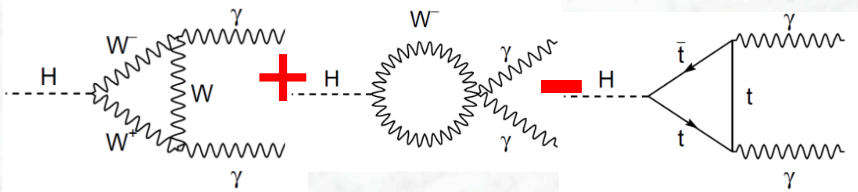
	 k_W=1(SM)	 K_g=1(SM)  K_γ=1(SM)
Production	$\sigma_{WH}/(\sigma_{WH})^{SM}=k_W^2$	$\sigma_{ggH}/(\sigma_{ggH})^{SM}=k_g^2 = k_g^2(k_b, k_t, m_H)$
Decay	$\Gamma_{WH}/(\Gamma_{WH})^{SM}=k_W^2$	$\sigma_{\gamma\gamma}/(\sigma_{\gamma\gamma})^{SM} = \kappa_\gamma^2 = \kappa_\gamma^2(k_b, k_t, k_\tau, k_W, m_H)$

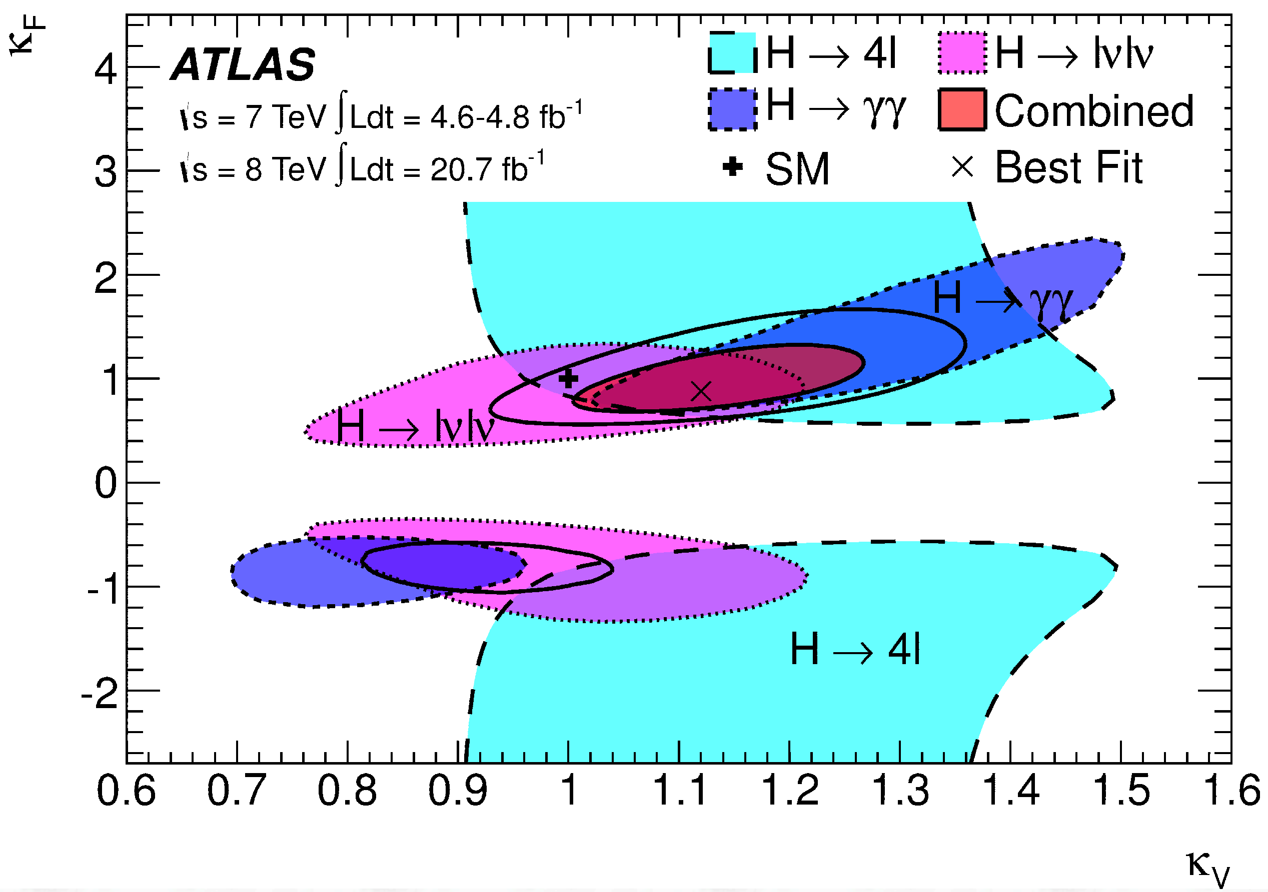
- Example: $H \to \gamma\gamma$

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Couplings to Fermions and Bosons

- Assume only one scale factor for fermion and vector couplings: $\kappa_V = \kappa_W = \kappa_Z$ $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- Sensitivity to relative sign between κ_F and κ_V only from interference term in H → γγ

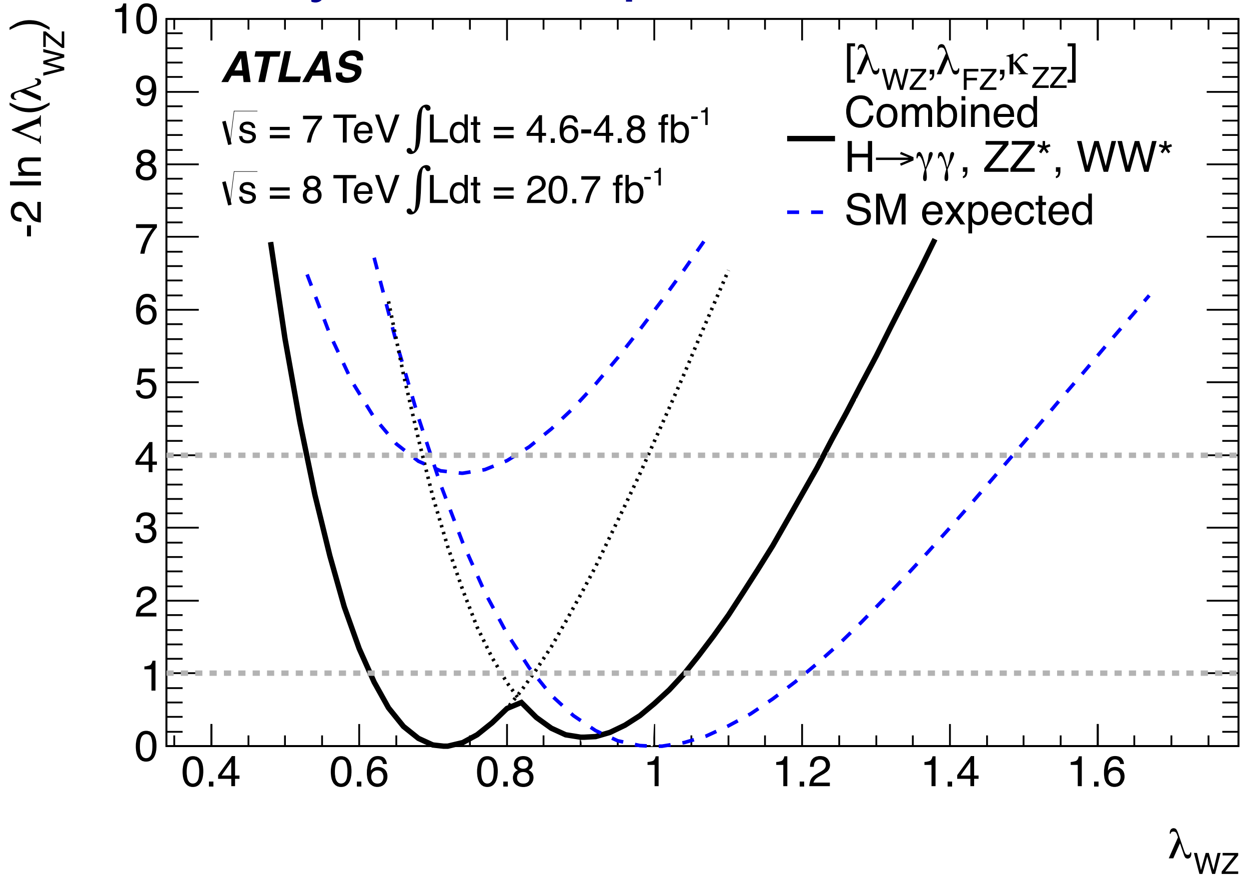




- Data consistent with the SM expectation
- Two-dimensional consistency: 12%
- 68% CL intervals:
  - κ_F : [0.76, 1.18]
  - κ_V : [1.05, 1.22]

Ratio of Couplings to the W and Z bosons

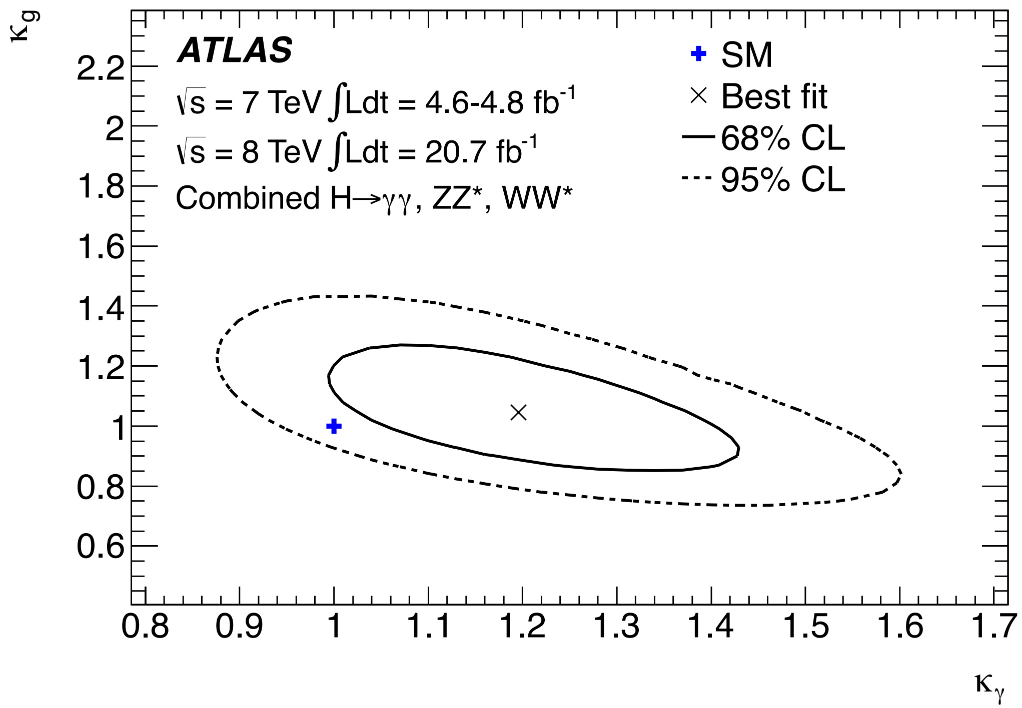
- Assume only one scale factor for fermions: $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- Custodial symmetry requires $\lambda_{WZ} := \kappa_W/\kappa_Z = 1$
- Sensitivity via VBF production and H → WW and H → ZZ



$\lambda_{WZ} = 0.82 \pm 0.15$

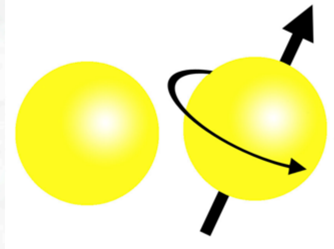
Constraints on Production and Decay Loops

- Test on contributions from other particles contributing to loop-induced processes
- Assume nominal couplings for all SM particles $\kappa_i = 1$ and that the new particles do not contribute to the Higgs boson width
- Introduce effective scale factors κ_g and κ_γ



- Best fit between 1σ and 2σ contours: 2d consistency with SM is 14%
- $\kappa_g = 1.04 \pm 0.14$
- $\kappa_\gamma = 1.20 \pm 0.15$

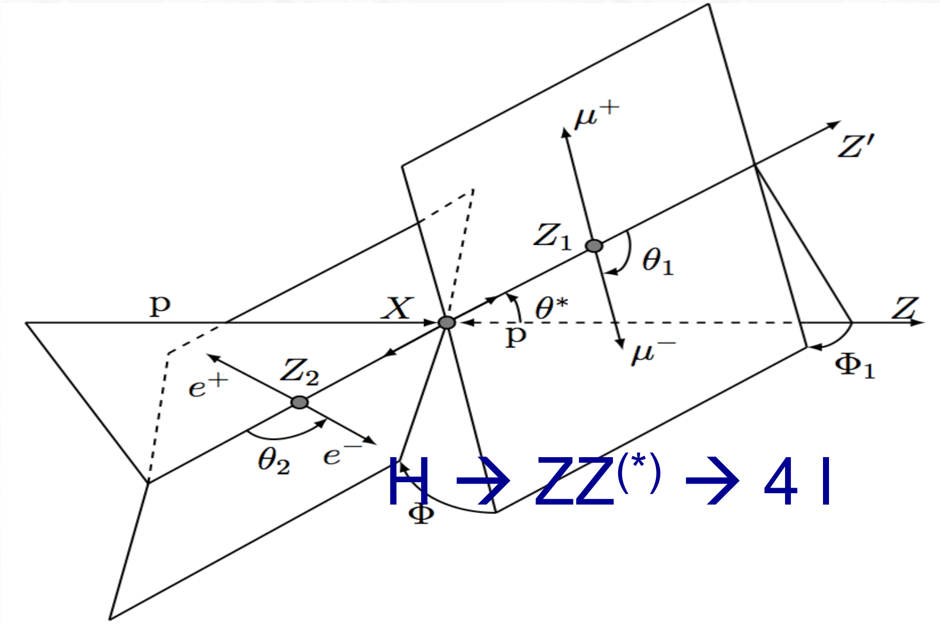
Spin and Parity

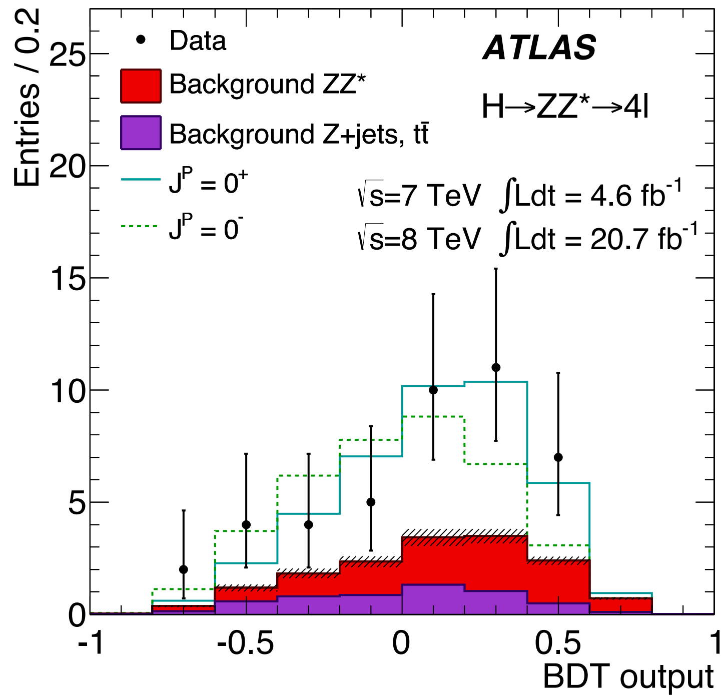


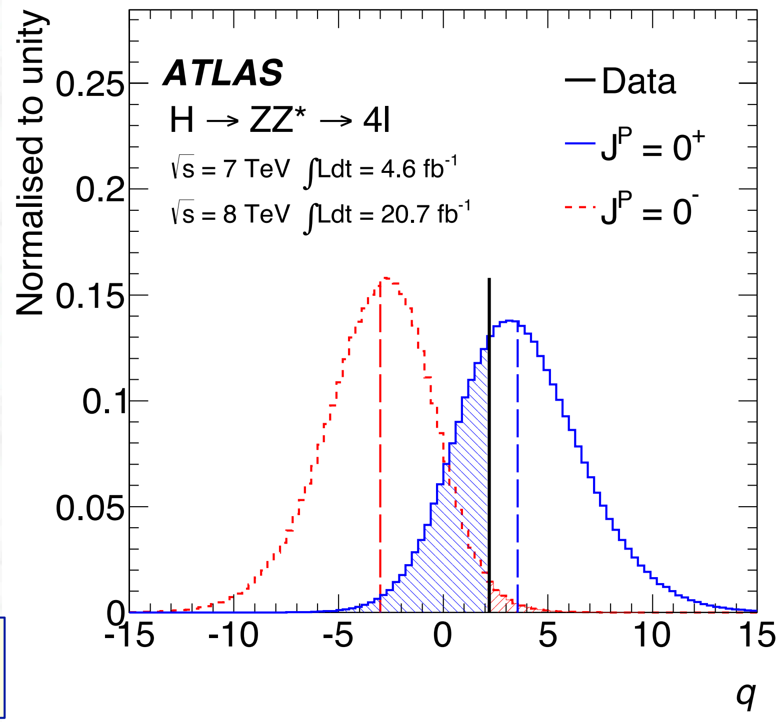
- If Standard Model Higgs boson: $J^P = 0^+$
- Strategy: falsify other hypotheses: (0^-, 1^-, 1^+, 2^-, 2^+) specific effective models *)
  - Spin 1: disfavoured by H → γγ decays (Landau-Yang theorem)
  - Spin 2: Many parameters, consider graviton-like tensor, equivalent to a Kaluza-Klein graviton
    - Production via gluon fusion and qq annihilation possible;
    - Studies are performed as a function of the qq annihilation fraction f_{qq} (= 4% at LO, however, large uncertainties)
    - Minimal coupling to SM particles: 2^+_m mode

*) ATLAS results used program in Y. Gao et al, Phys. Rev. D81 (2010) 075022

$J^P = 0^-$ versus $J^P=0^+$







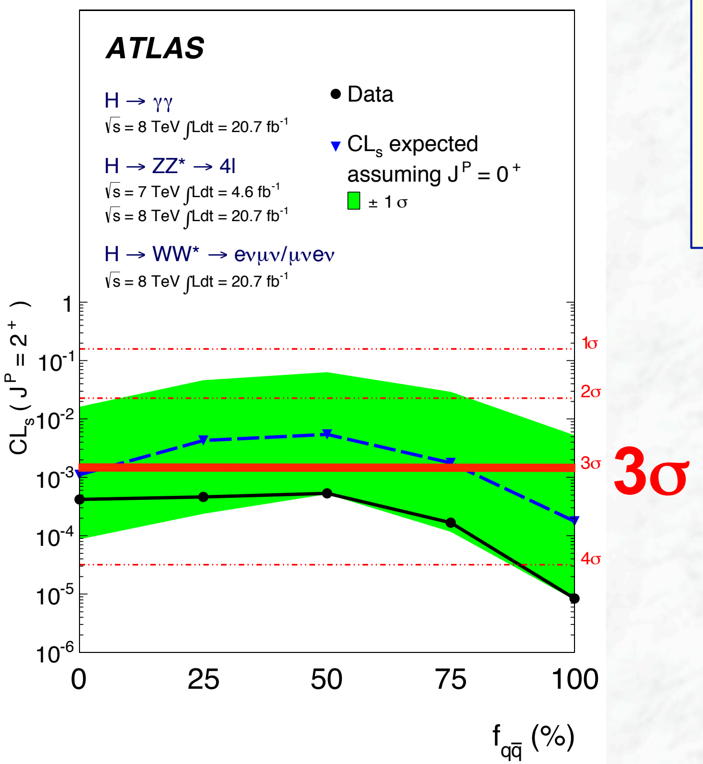
- Sensitive variables:
  - Masses of the two Z's
  - Production angle θ^*
  - Four decay angles Φ_1, Φ, θ_1 and θ_2
- Perform multivariate analysis (BDT)
- Compare Data to Log likelihood ratio

Exclude $J^P=0^-$ (vs. 0^+) with 97.8% CL

$J^P = 1^{+/-}$ versus $J^P=0^+$

	p_0 (0^+)	CL (1^+) Exclusion	p_0 (0^+)	CL (1^-) Exclusion
H → ZZ*	0.55	99.8%	0.15	94%
H → WW*	0.70	92%	0.66	98.3%
Combination	0.62	99.97%	0.33	99.7%

$J^P = 2^+$ versus $J^P=0^+$

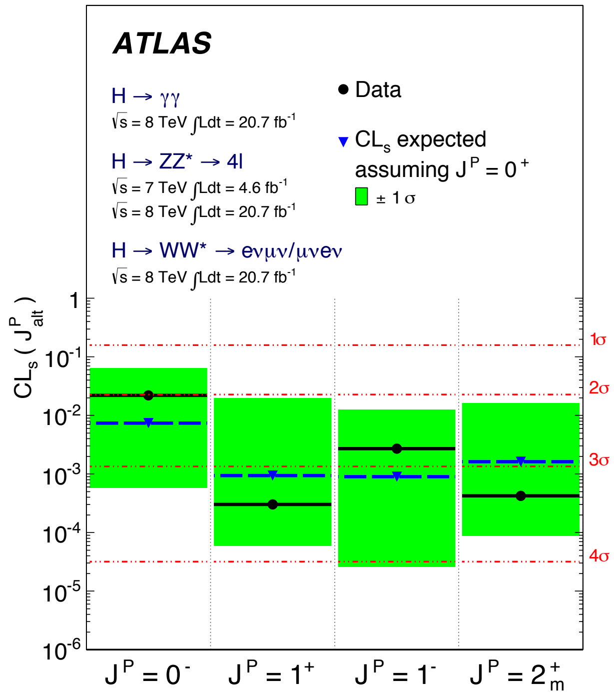


Exclude $J^P=2^+$ (produced via gluon fusion, $f_{qq}= 0$) (vs. 0^+) via H → γγ decays with 99.3% CL

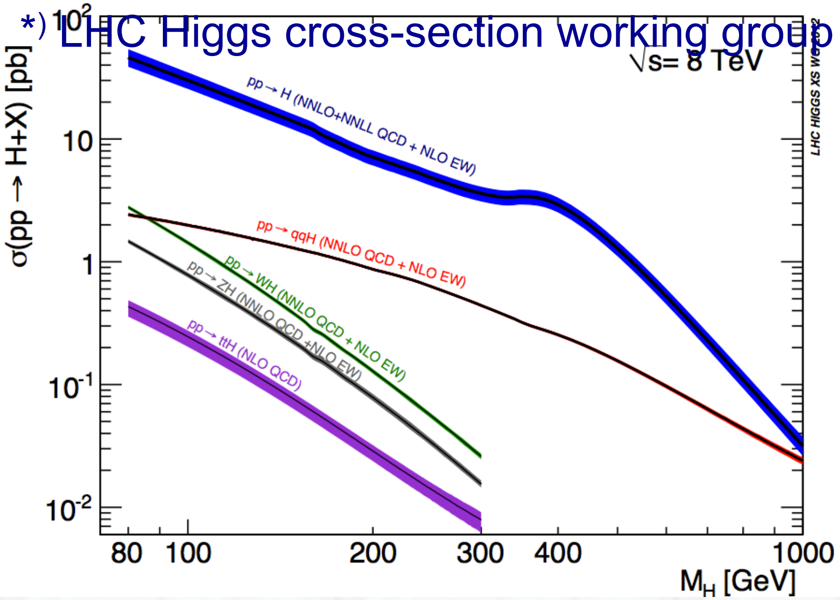
- Combination of H → γγ, H → ZZ* and H → WW* channels (complementary behaviour as function of f_{qq})
- Observed exclusion of $J^P = 2^+$ exceeds 99.9%, independent of f_{qq}

Conclusions

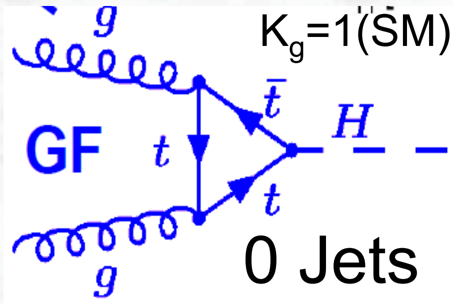
- A milestone discovery made on July 4th 2012
- Signals impressively confirmed with additional data; discovery phase turned into the measurement phase
- ATLAS data are consistent with the expectations for the Standard Model Higgs boson
  - Production rates and coupling strengths
  - Evidence for VBF production
  - Evidence for spin-0
- Exciting times ahead of us to study the Higgs boson with higher precision (> 2015) and look for surprises (deviations? more Higgs bosons?)
- More channels covered in Joe Price's talk: VH ➔Vbb, H ➔ττ, VH ➔VWW$^{(*)}$, H ➔Zγ, ttH ➔ttγγ, H ➔μμ, ZH ➔ll+inv



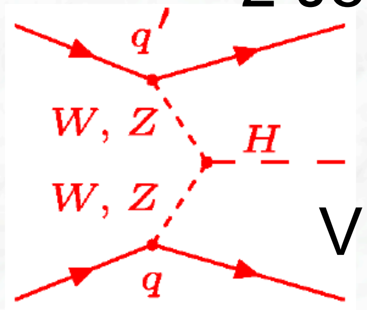
Higgs Boson Production



Boson Fusion

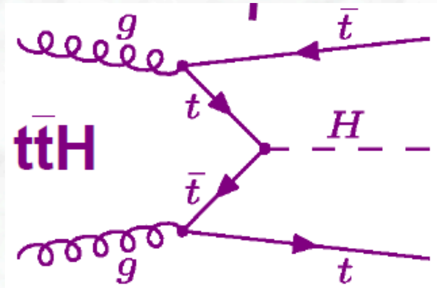


2 Jets



VBF

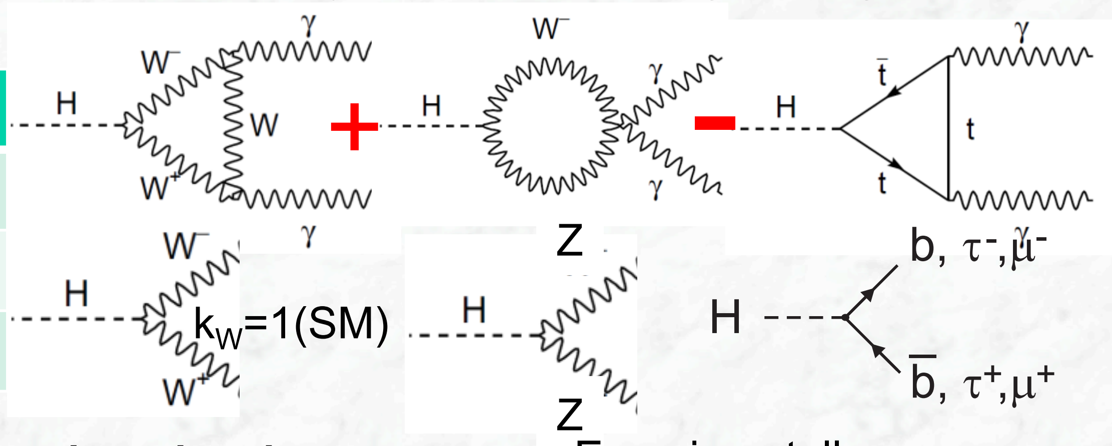
Associated production: Tag W, Z, T



Experimentally difficult: rare or high background

…and Decay

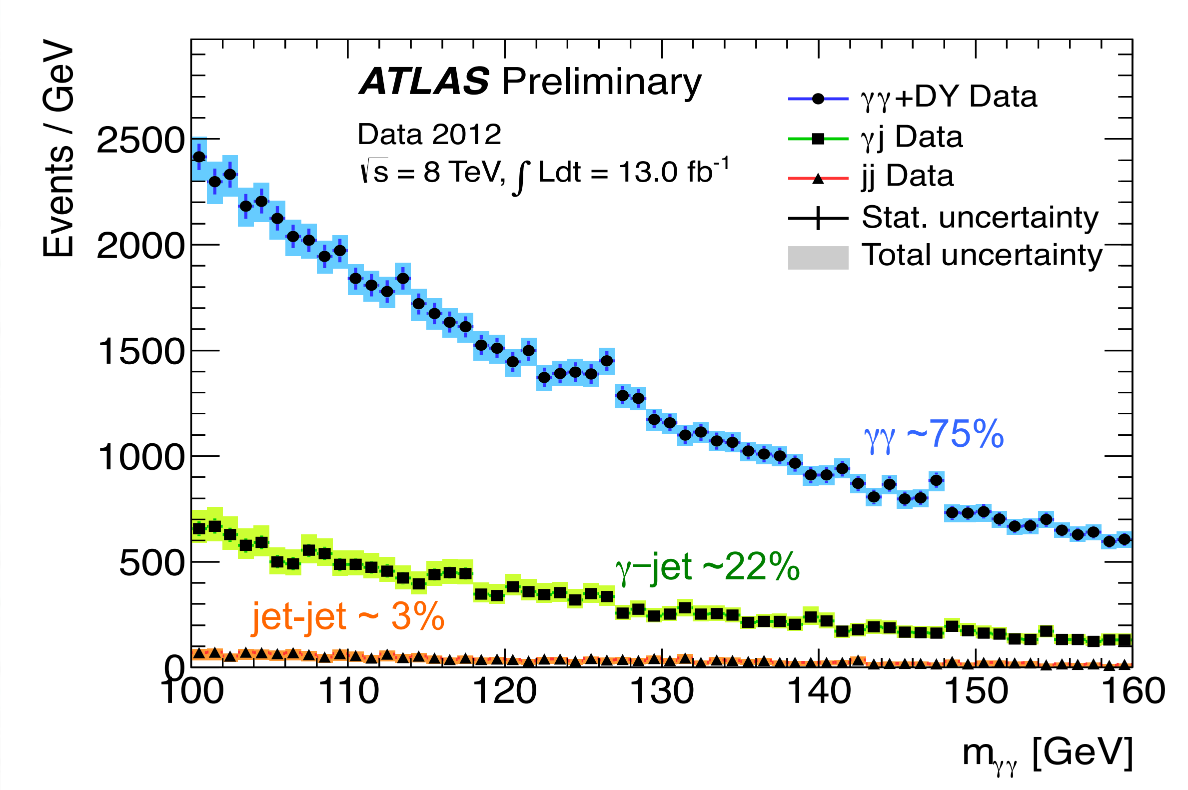
SM Branching Ratio H → X			
bb	56.9%	ττ	6.2%
WW	22.3%	γγ	0.24%
ZZ	2.8%	μμ	0.022%



Experimentally difficult: rare or high background

Characterize Higgs SM computing by k_X (=1 for SM), X=W,Z,b,t,c,τ,μ,γ,g

Composition of the $\gamma\gamma$ Background



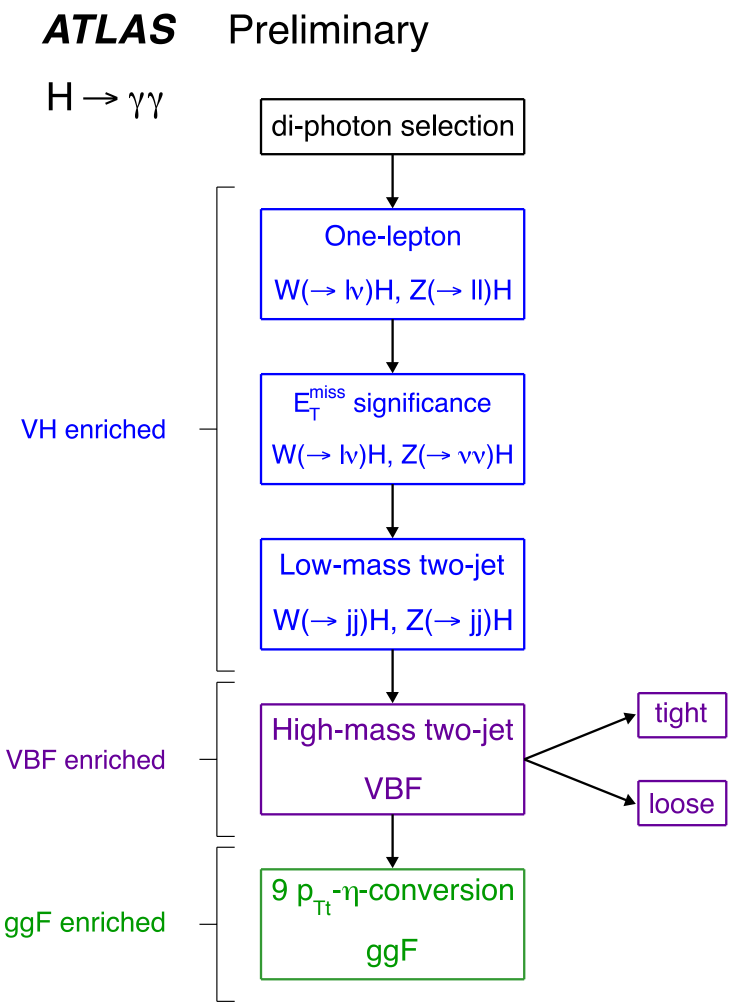
ATLAS-CONF-2012-168

- Reducible γ-jet and jet-jet background at the level of 25%

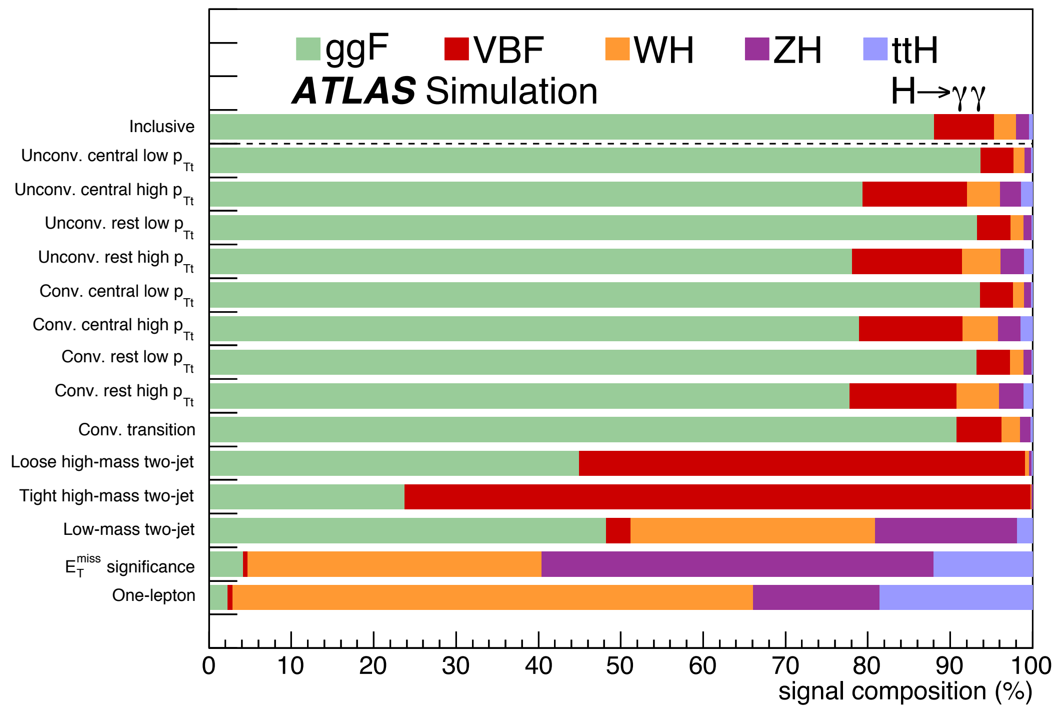
- Background extrapolation below the excess from sidebands (4th order polynomial)

Categorisation of H → γγ Candidate Events

ATLAS-CONF-2013-012



arXiv:1307.1427



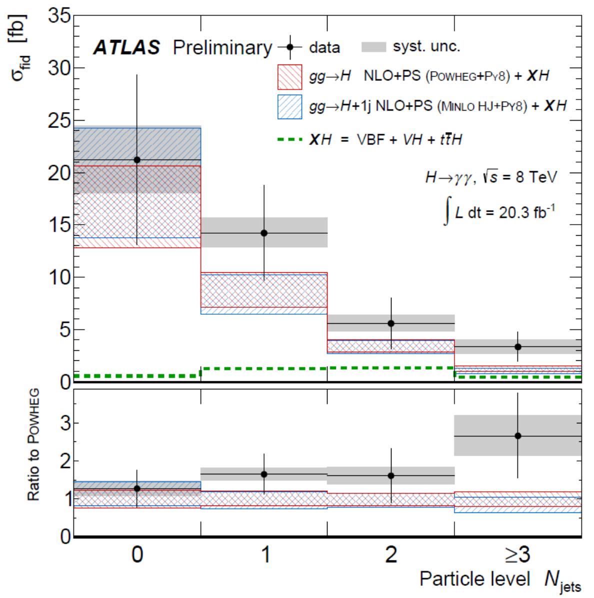
Categorisation: to increase overall sensitivity and sensitivity to different production modes (VBF, VH)

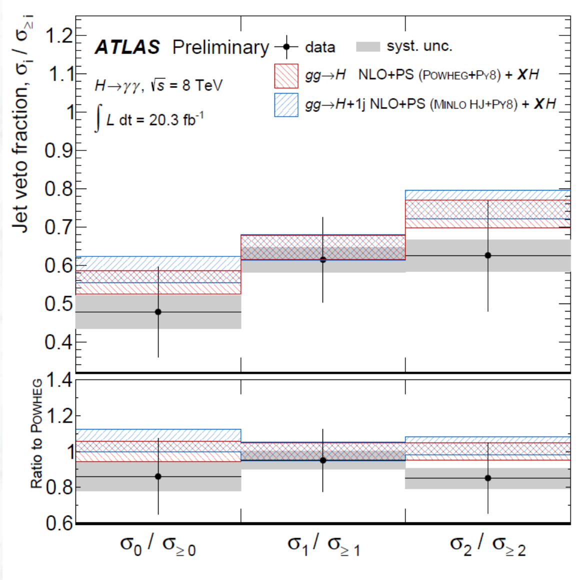
- VH enriched: one-lepton, E_T^{miss}
- VBF enriched (tag-jet configuration, $\Delta\eta$, m_{jj})
- gluon fusion: 9 categories, exploit different mass resolution for different detector regions, γγ conversion status and p_{Tt}

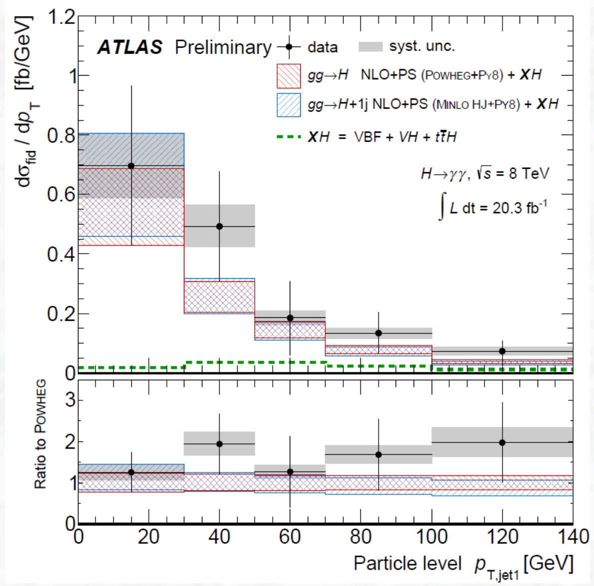
$H \rightarrow \gamma\gamma$ Differential Distributions

New!

ATLAS-CONF-2013-029

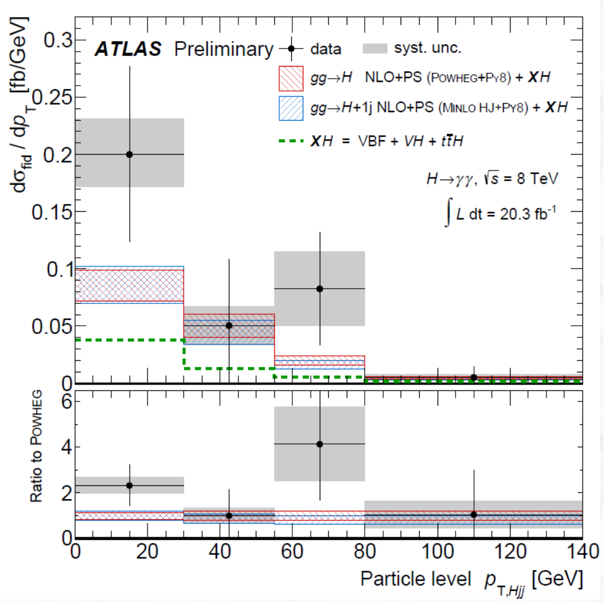


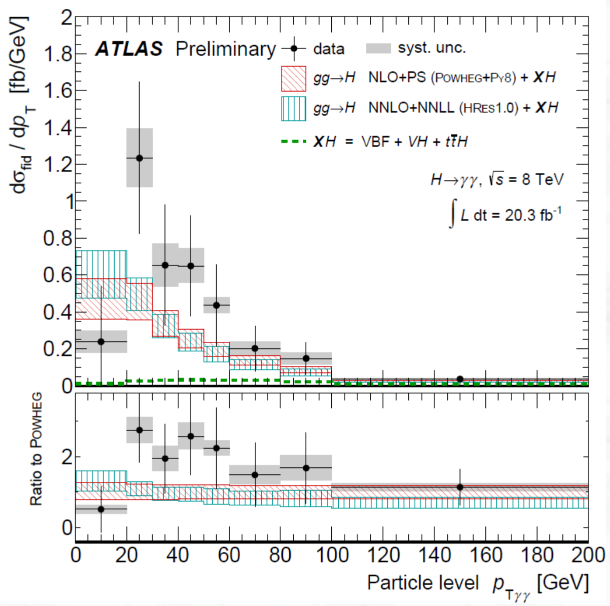




Initial state jet radiation used to constrain production mechanism

Higgs new dawn of σ measurements

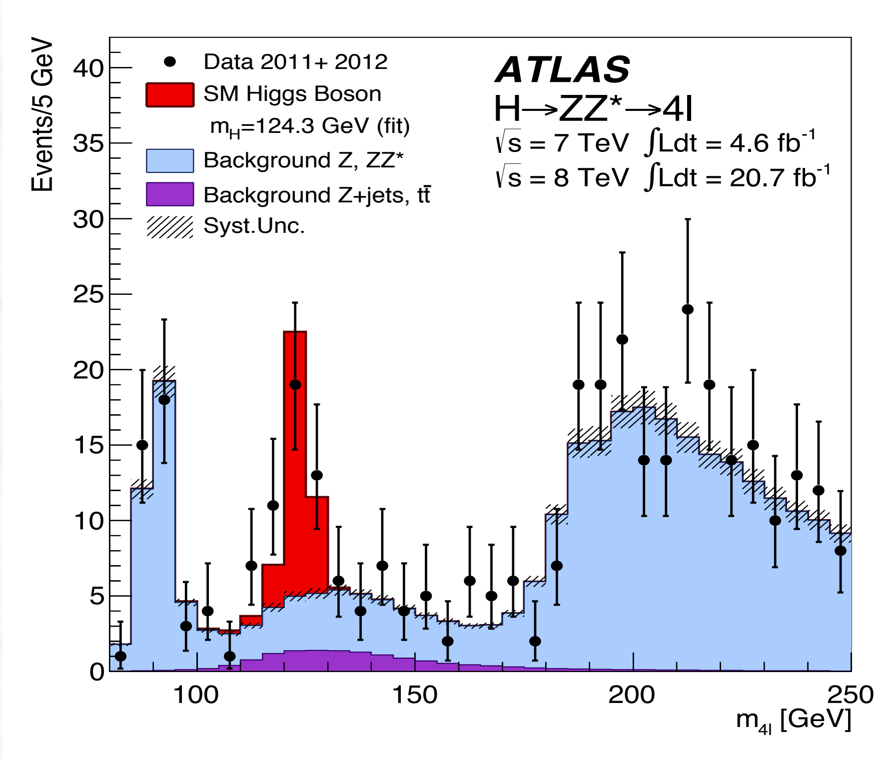




4ℓ Invariant Mass Spectra

Full dataset

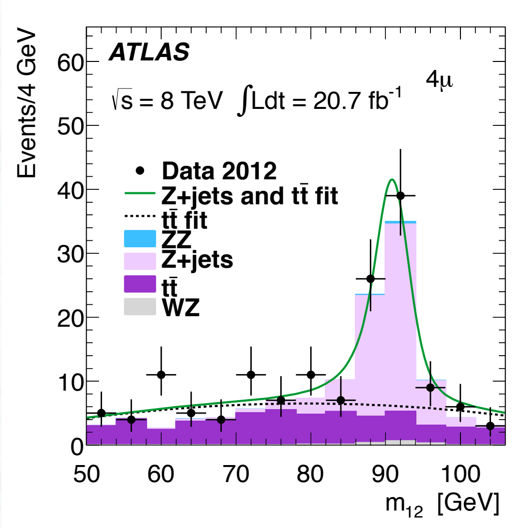
arXiv:1307.1427

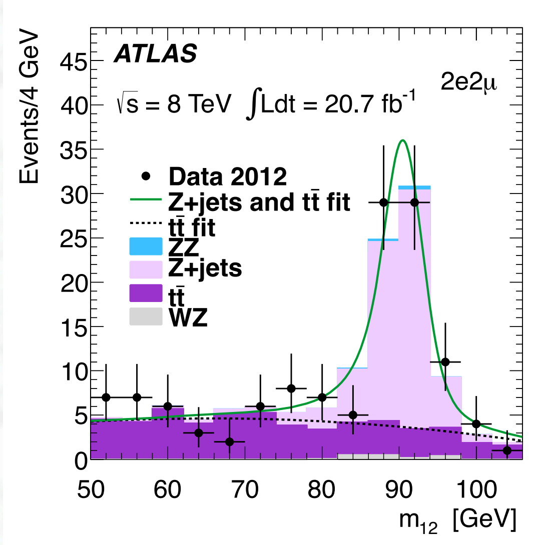


Mass range 120 – 130 GeV	Expected signal	Background	Data
$\sqrt{s}$ = 7 TeV	2.2	2.3	5
$\sqrt{s}$ = 8 TeV	13.7	8.8	27

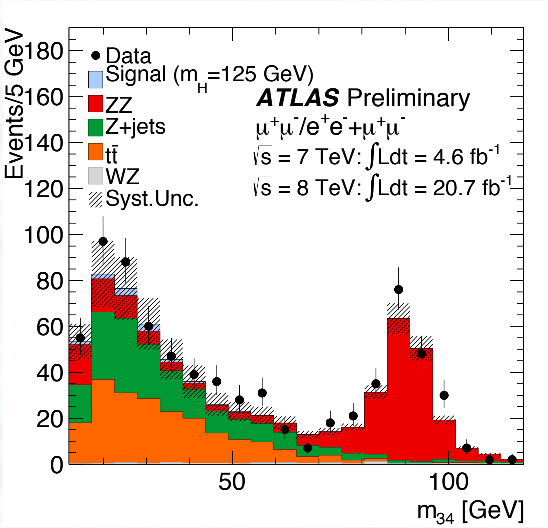
$m_{4\ell}$ > 160 GeV: 376 events observed
348 ± 26 expected from
$\sqrt{s}$ = 7 + 8 TeV background (mainly ZZ)

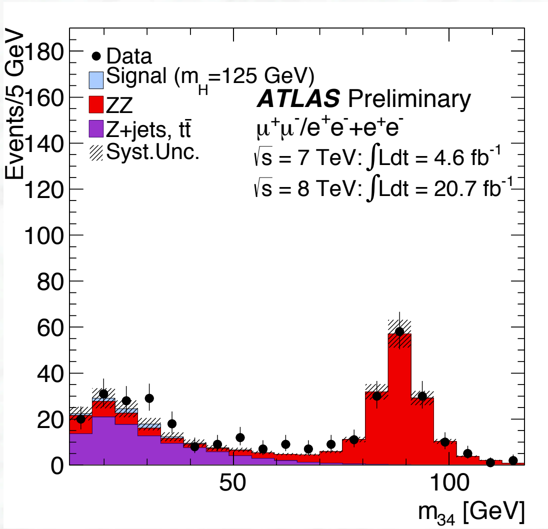
Background Estimates





arXiv:1307.1427

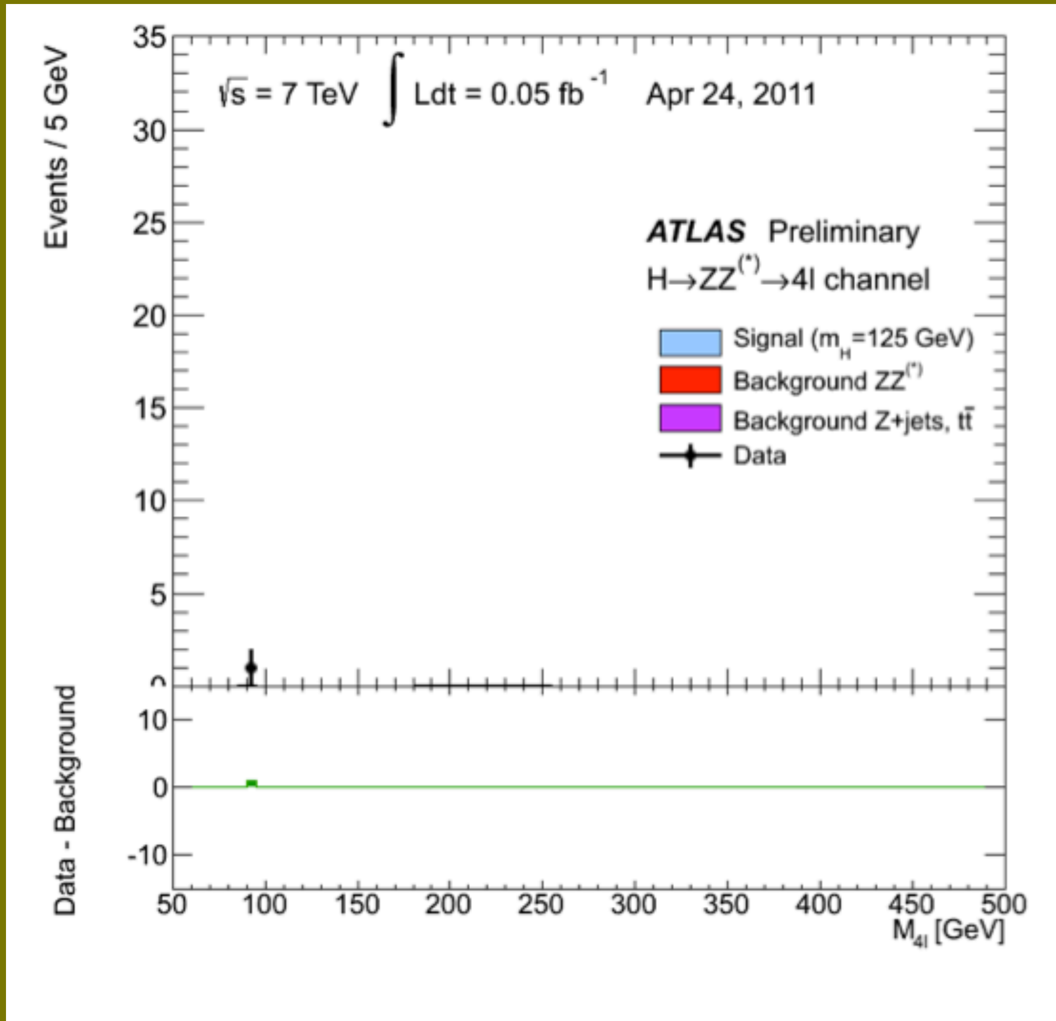




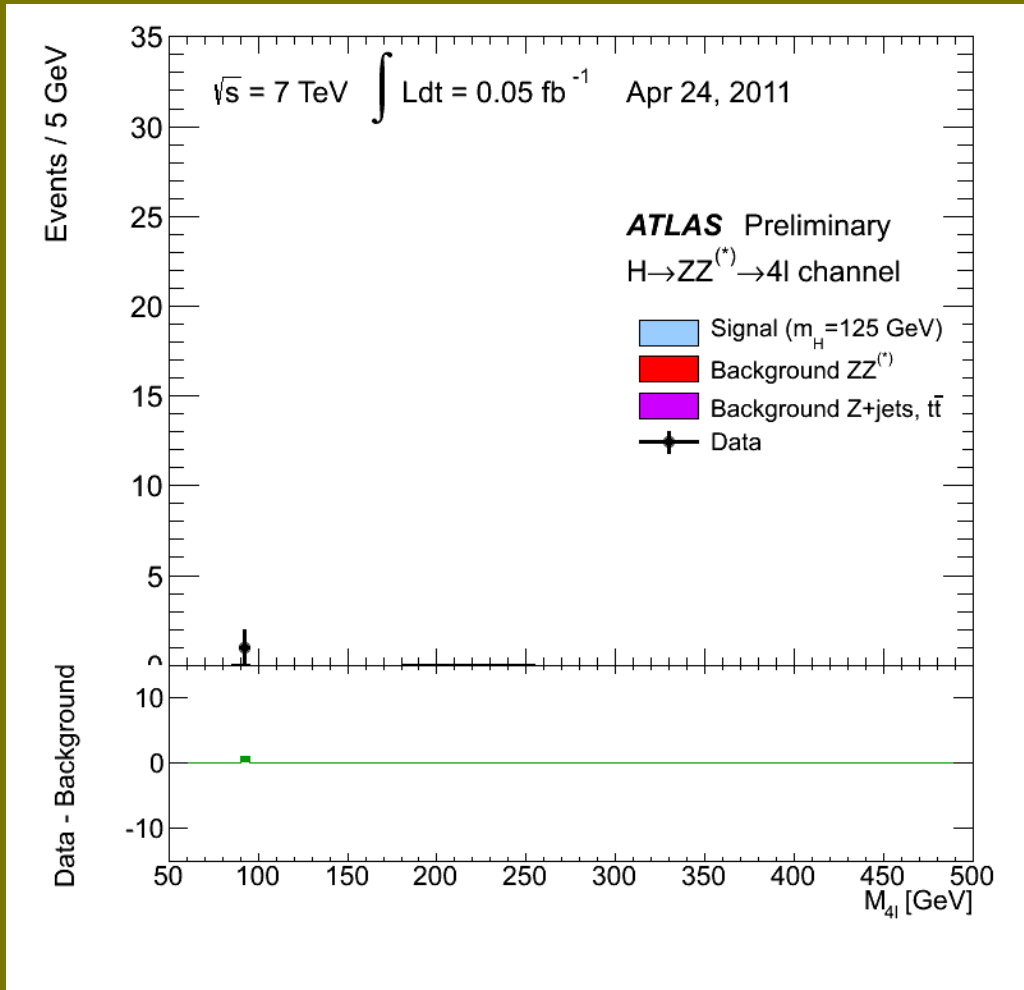
ATLAS-CONF-2013-013

- Irreducible ZZ* background taken from Monte Carlo simulation
- Reducible Z+jets and tt background: measured using various background-enriched control regions and transferred to signal region using Monte Carlo simulation

Time Evolution of the H → ZZ → 4ℓ Signal

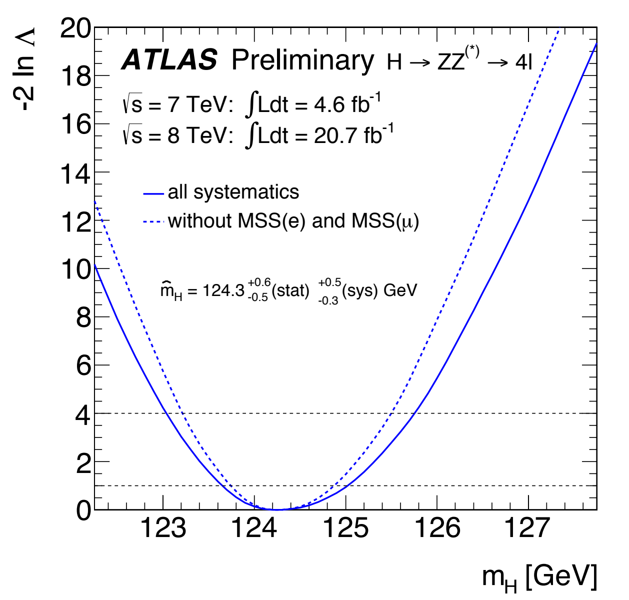


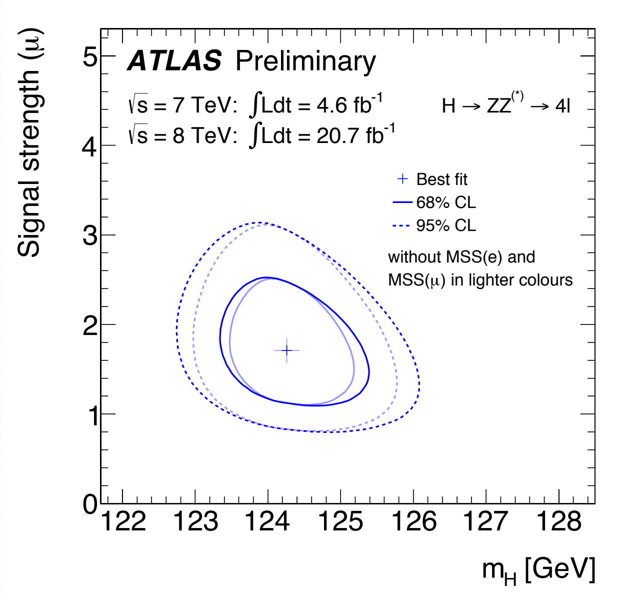
Time Evolution of the H → ZZ → 4ℓ Signal

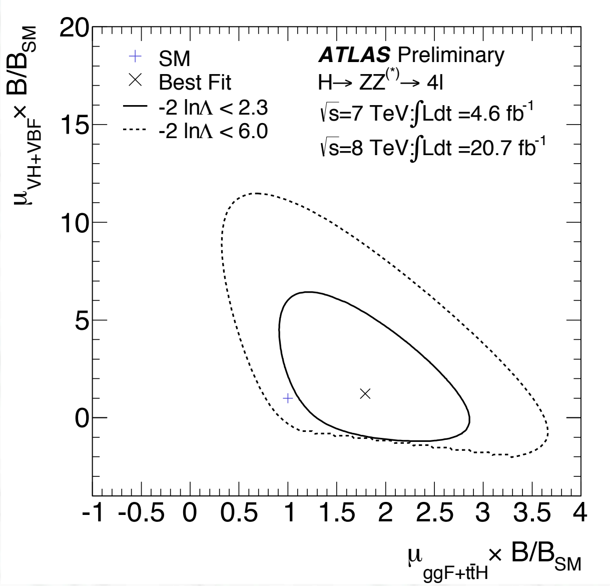


Mass and Signal Strength for H → ZZ*

ATLAS-CONF-2013-013







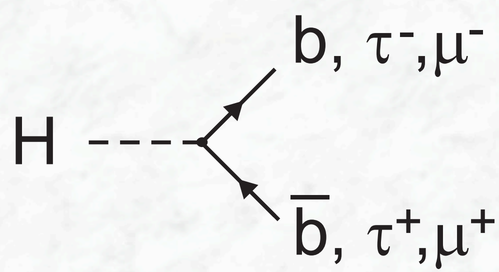
Mass: m_H = 124.3 ±0.6 (stat) ±0.4 (syst) GeV

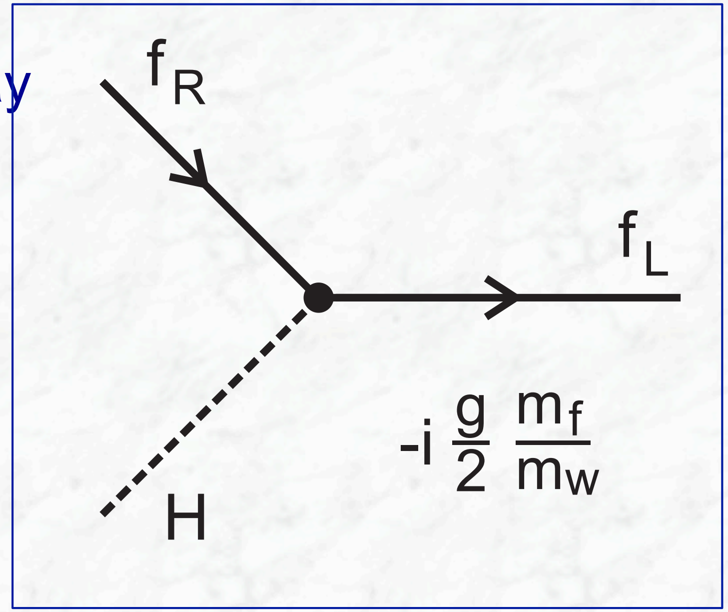
Signal strength: $\mu = 1.7 \pm 0.5$

Couplings to quarks and leptons ?

- Search for $H \rightarrow \tau\tau$ and $H \rightarrow bb$ decays

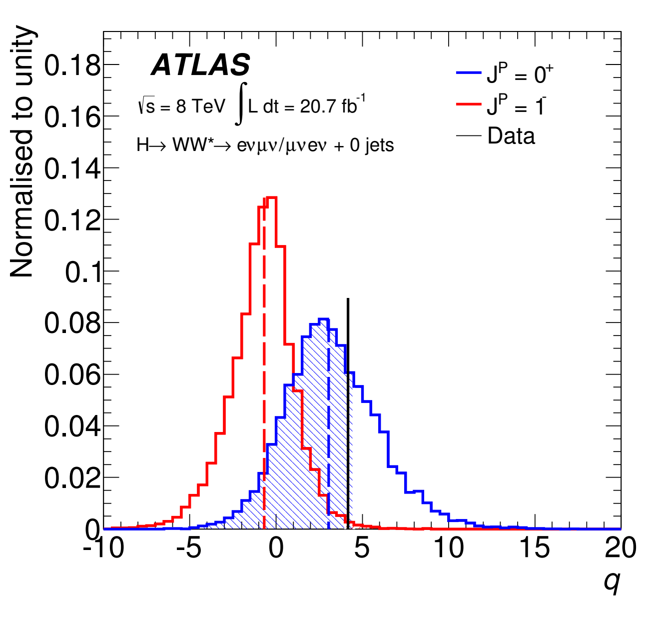
- Search for the rare $H \rightarrow \mu\mu$ decay

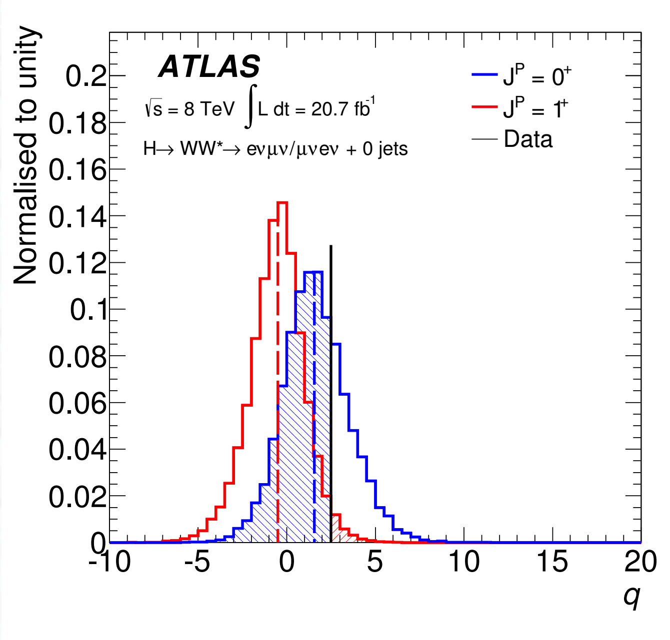




$J^P = 1^{+/-}$ versus $J^P=0^+$ using $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ events

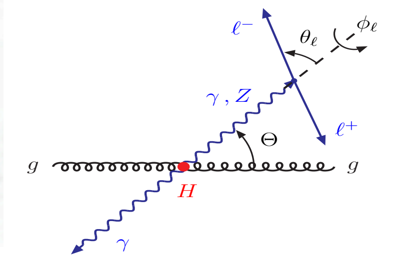
- $H \rightarrow ZZ^*$, as before: BDT separation based on masses and angles
- $H \rightarrow WW^*$: m_{ll}, $\Delta\phi_{ll}$ … carry information on spin
  Combine variables using BDT analysis



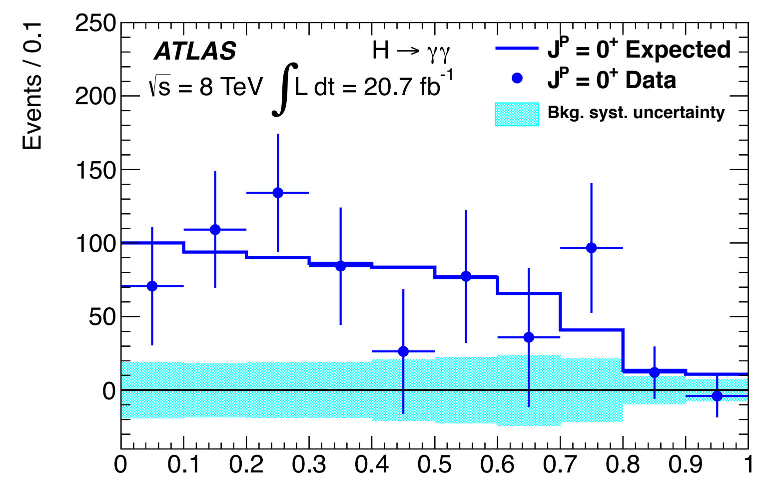


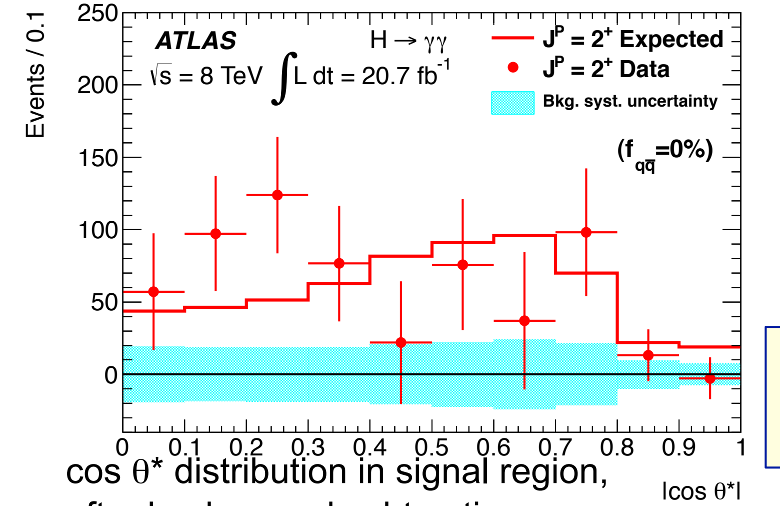
	p_0 (0^+)	CL (1^+) Exclusion	p_0 (0^+)	CL (1^-) Exclusion
$H \rightarrow ZZ^*$	0.55	99.8%	0.1	94%
$H \rightarrow WW^*$	0.70	92%	0.66	98%
Combination	0.62	99.97%	0.33	99.7%

$J^P = 2^+$ versus $J^P=0^+$ using $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, and $H \rightarrow WW^*$ events

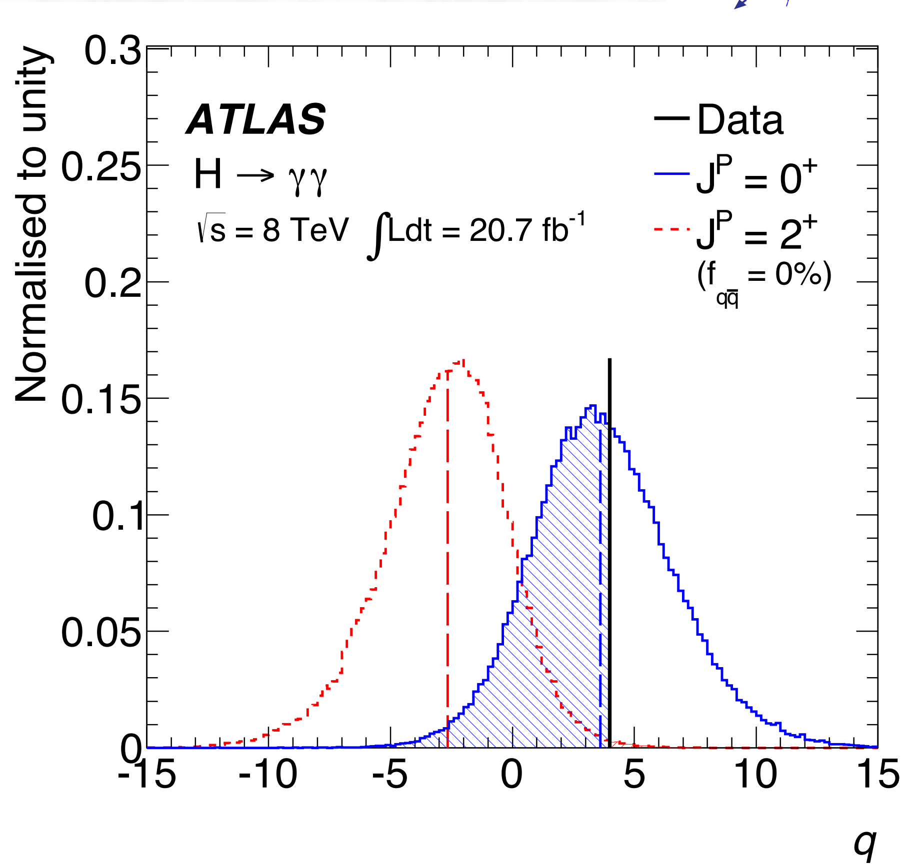


- $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ as before (BDT separation)
- $H \rightarrow \gamma\gamma$: use decay angle in Higgs boson rest frame (Collins-Soper angle)





$\cos\theta^*$ distribution in signal region, after background subtraction



Exclude $J^P=2^+$ (produced via gluon fusion, $f_{qq}= 0$) (vs. 0^+) via $H \rightarrow \gamma\gamma$ decays with 99.3% CL

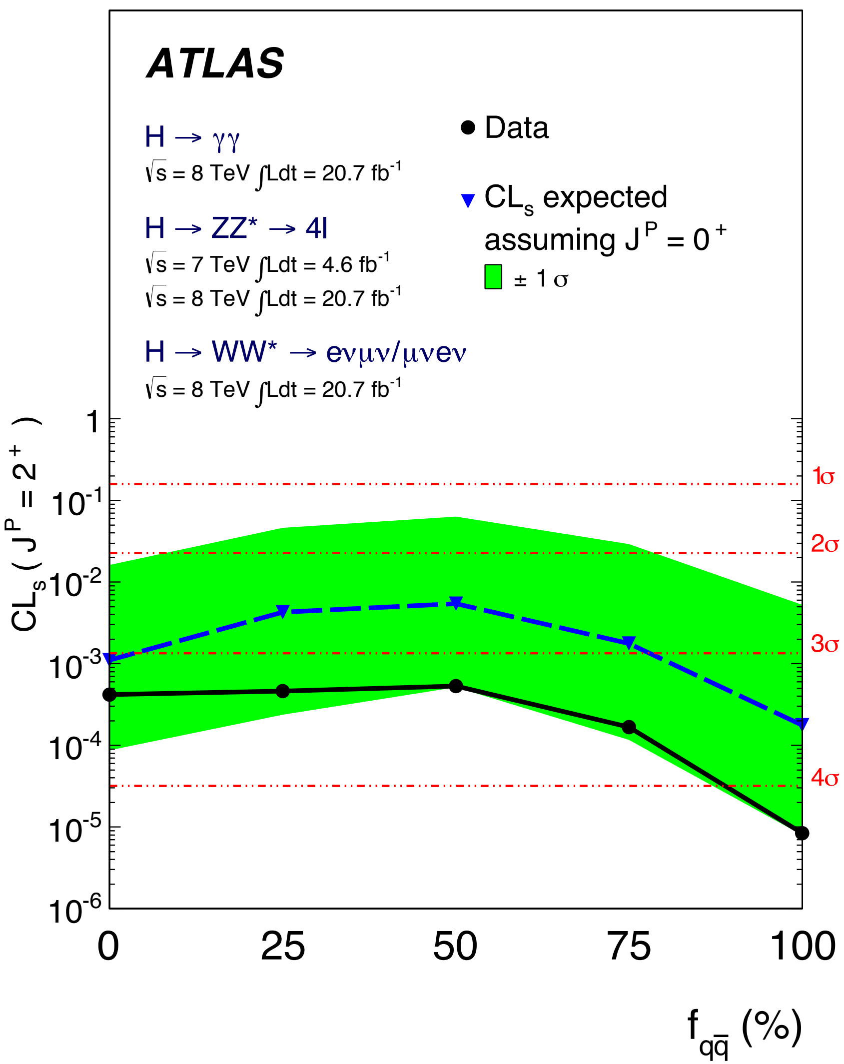
$J^P = 2^+$ Exclusion as Function of f_{qq}

arXiv:1307.1432

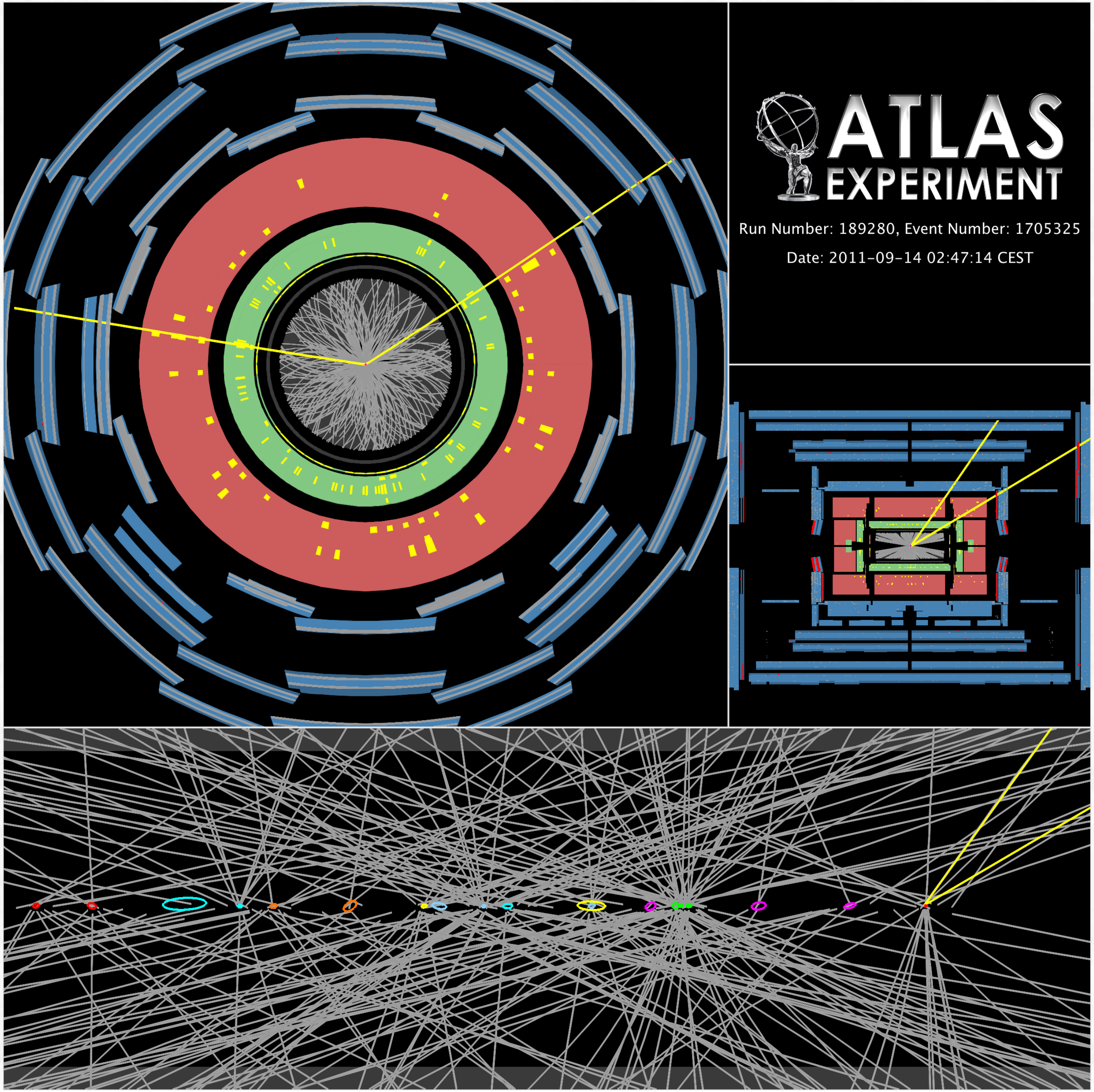
- Combination of H → γγ, H → ZZ* and H → WW* channels

(complementary behaviour as function of f_{qq})

- Observed exclusion of $J^P = 2^+$ (versus the SM $J^P = 0^+$) exceeds 99.9%, independent of f_{qq}

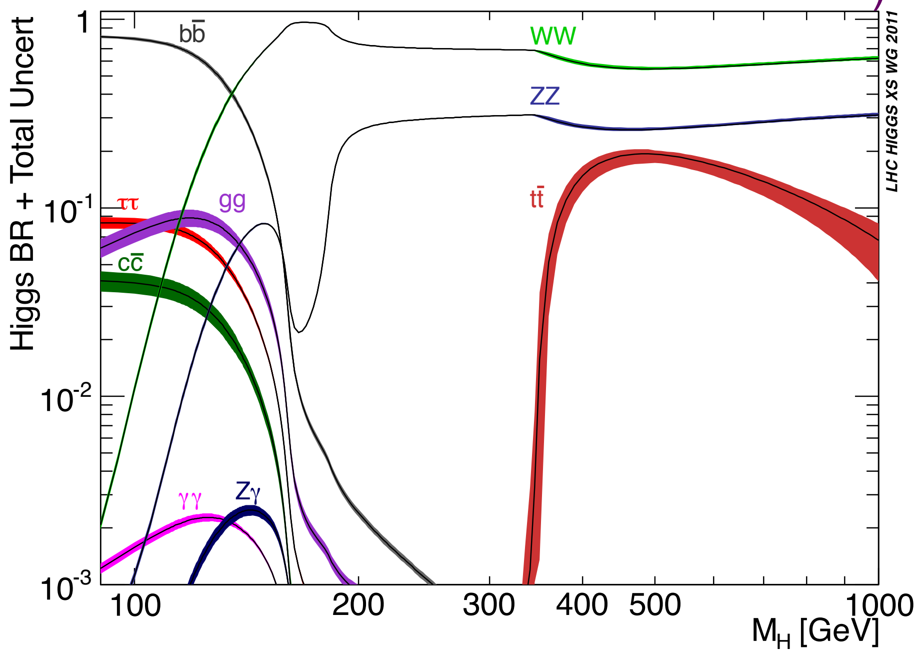


$Z \rightarrow \mu^+ \mu^-$ with 20 superimposed events



Higgs Boson Decays

*)

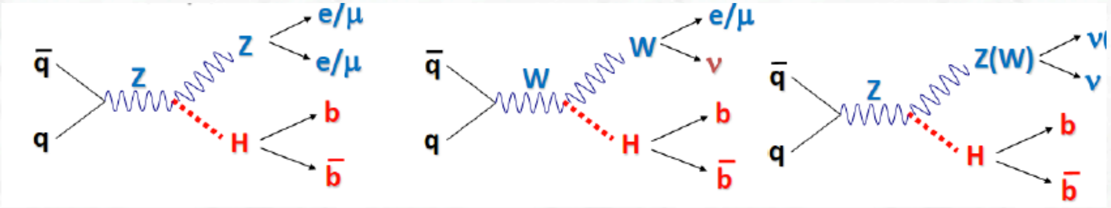


Useful decays at a hadron collider:

- Final states with leptons via WW and ZZ decays
- γγ final states (despite small branching ratio)
- ττ final states (more difficult)
- In addition: H → bb decays via associated lepton signatures (VBF, VH or ttH production)

*) LHC Higgs cross-section working group

Search for VH Production with H → bb decays



- Exploit three leptonic vector boson decay modes
  → split analysis in 0, 1, and 2-lepton categories

- Require 2 b-tagged jets
  (working point for 70% efficiency)

- Major background: W/Z bb, W+jets, tt

- Signal-to-background ratio improves for "boosted Higgs boson",
  split analysis in bins of $p_T(V)$

  in total: 15 categories (0,1,2 jets × p_T bins)

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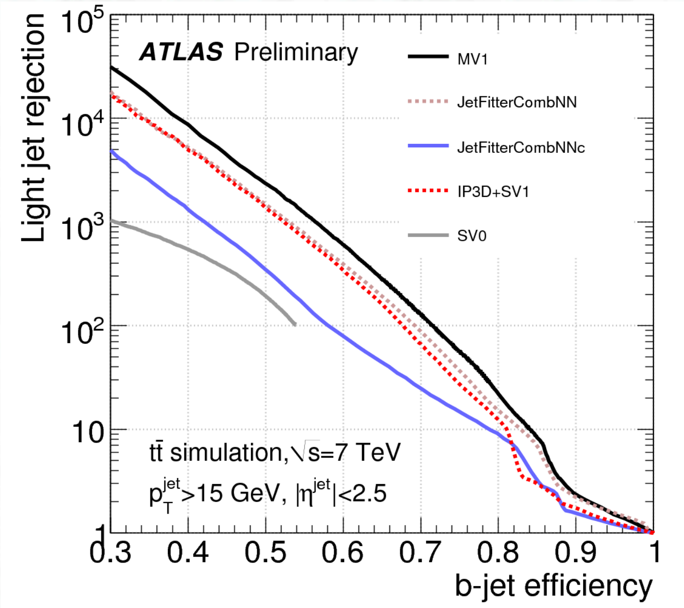
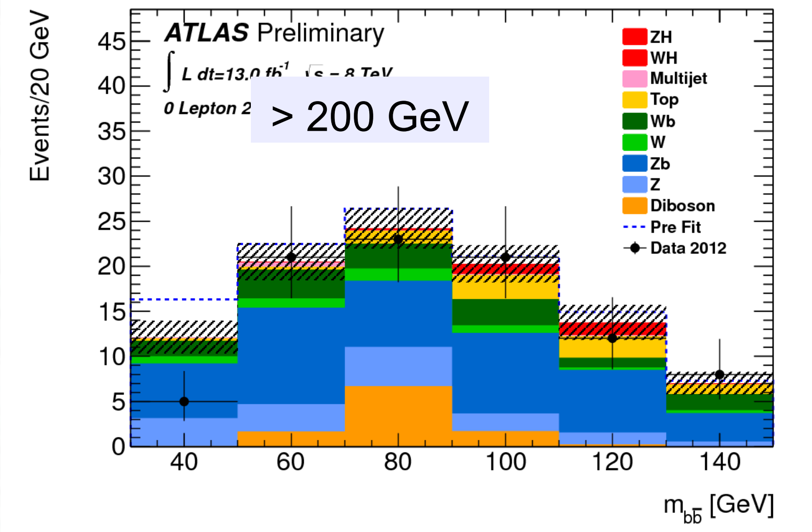


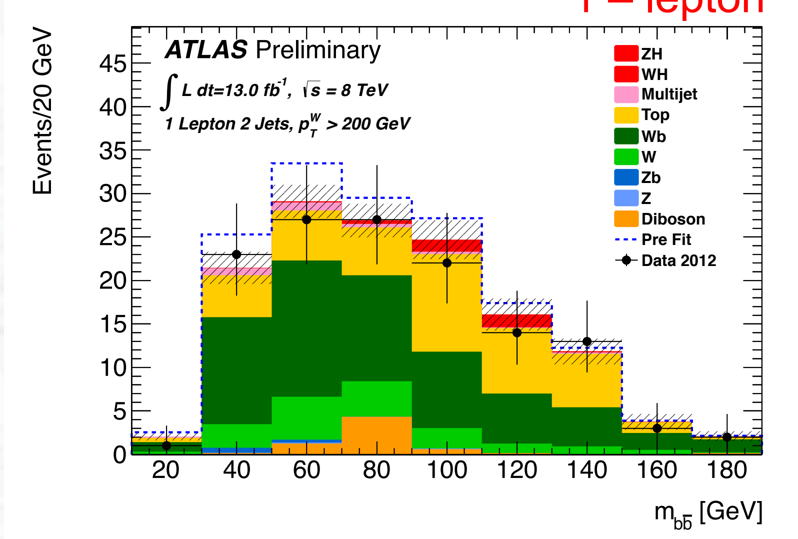
Reconstructed Mass Distributions

-8 TeV, L = 13 fb^{-1} (a selection)-

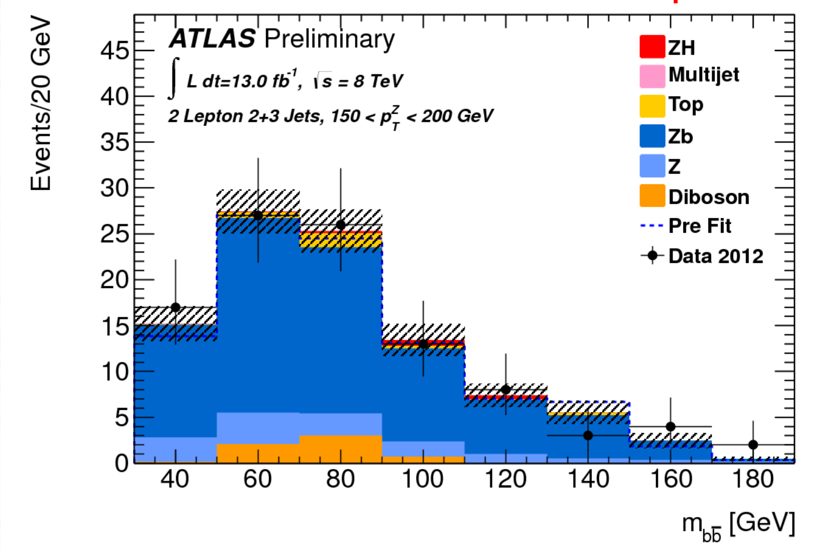
0 lepton



1 – lepton



2 leptons



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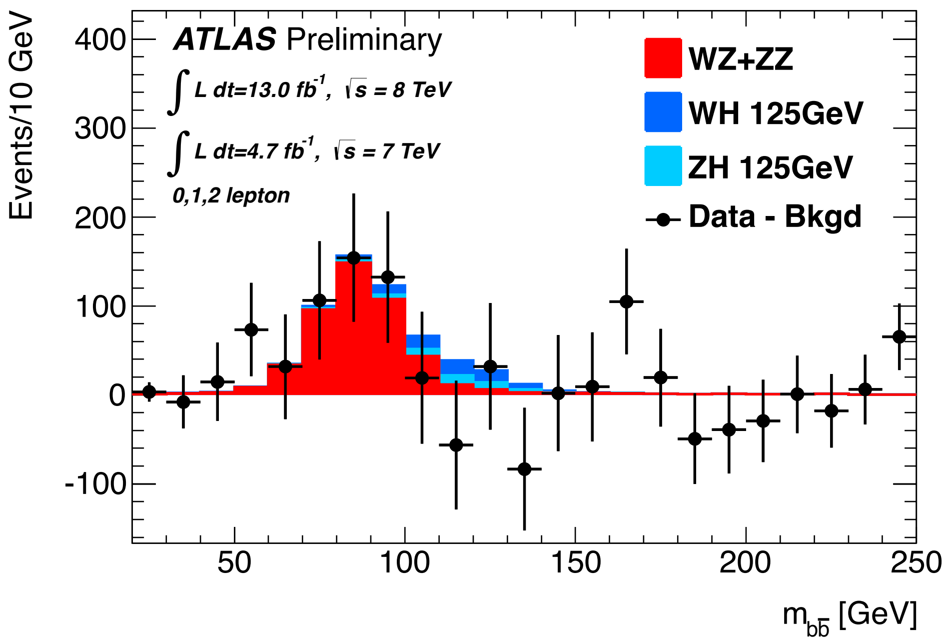
Results on the Search for H → bb decays

combination: data - background



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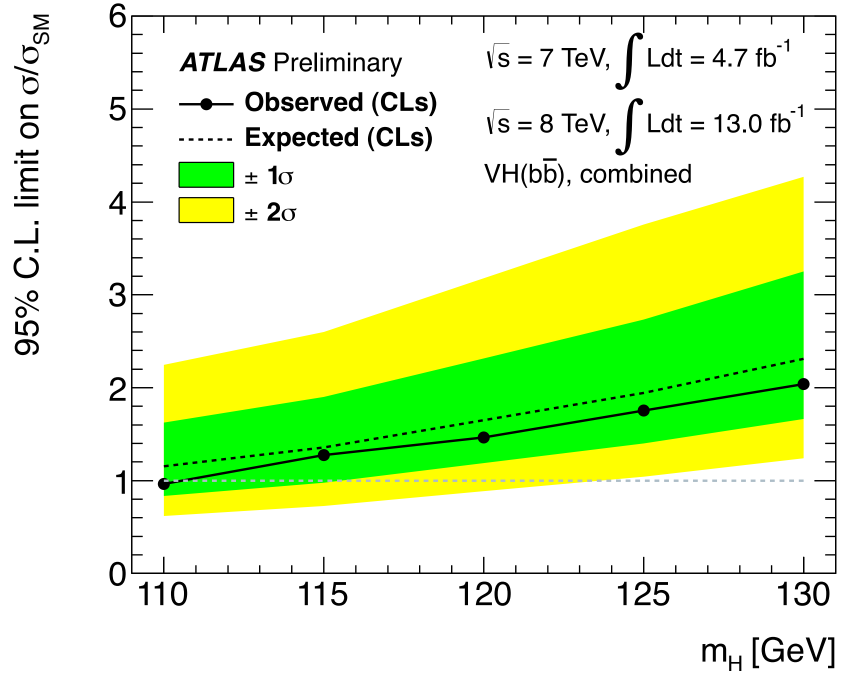


m_H = 125 GeV:

Observed 95% CL: 1.8 σ_{SM}
Expected 1.9 σ_{SM}

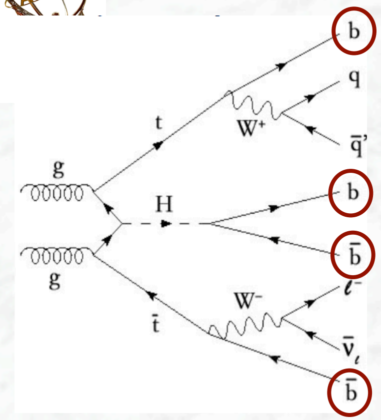
Di-boson signal established
(important "calibration" signal)

$\mu_{WZ+WW} = 1.09 \pm 0.20$ (stat) $\pm$ 0.22 (syst)

$\mu_H = -0.4 \pm 0.7$ (stat) $\pm$ 0.8 (syst)

Updated analysis, including the full data sample expected soon

Results on the Search for ttH, H→ bb



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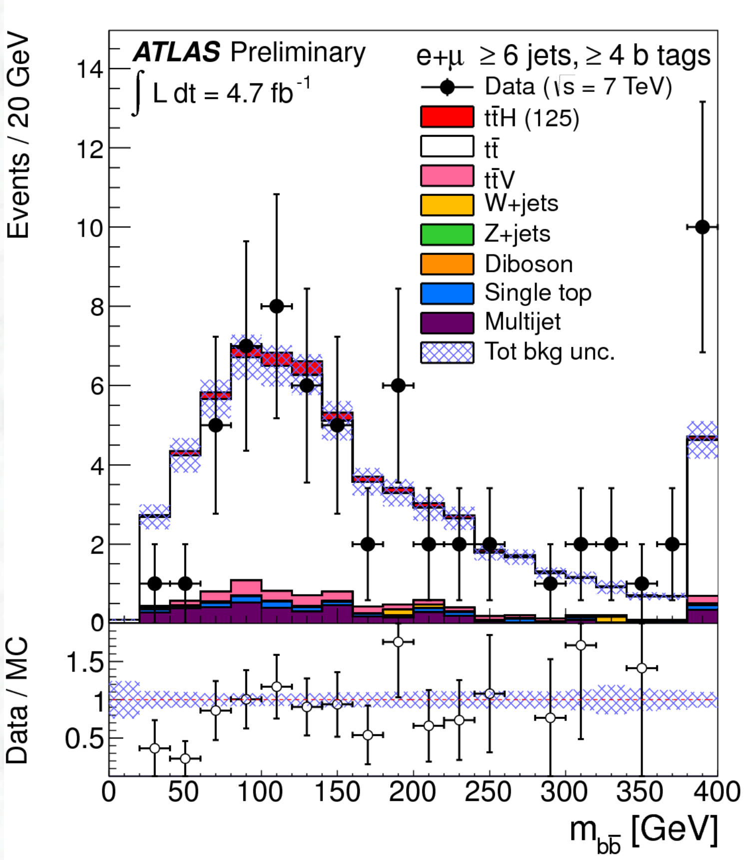
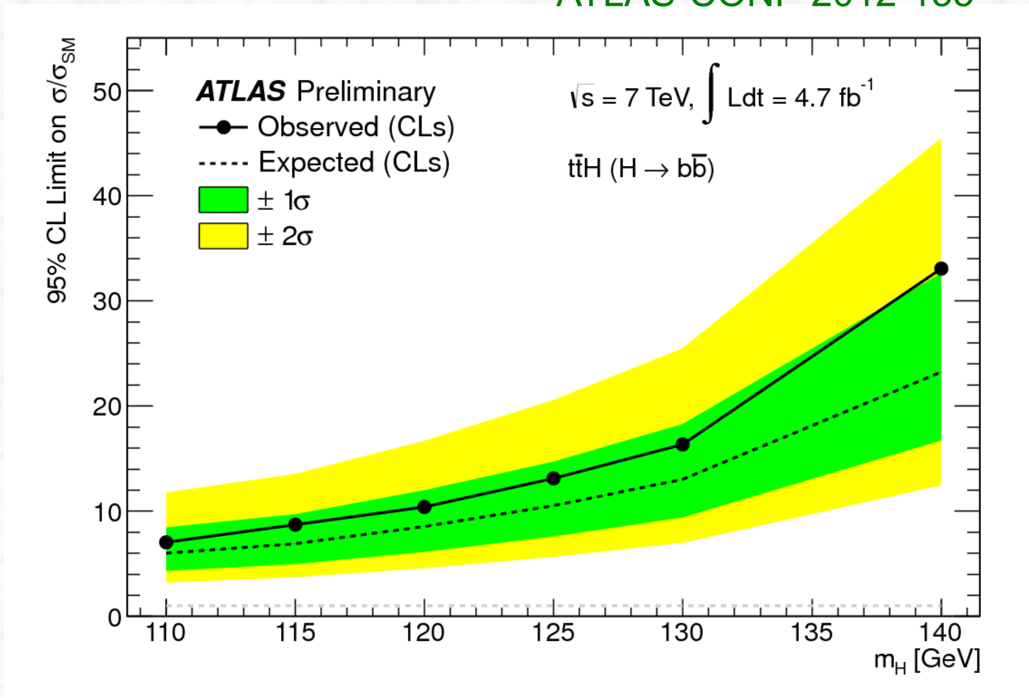


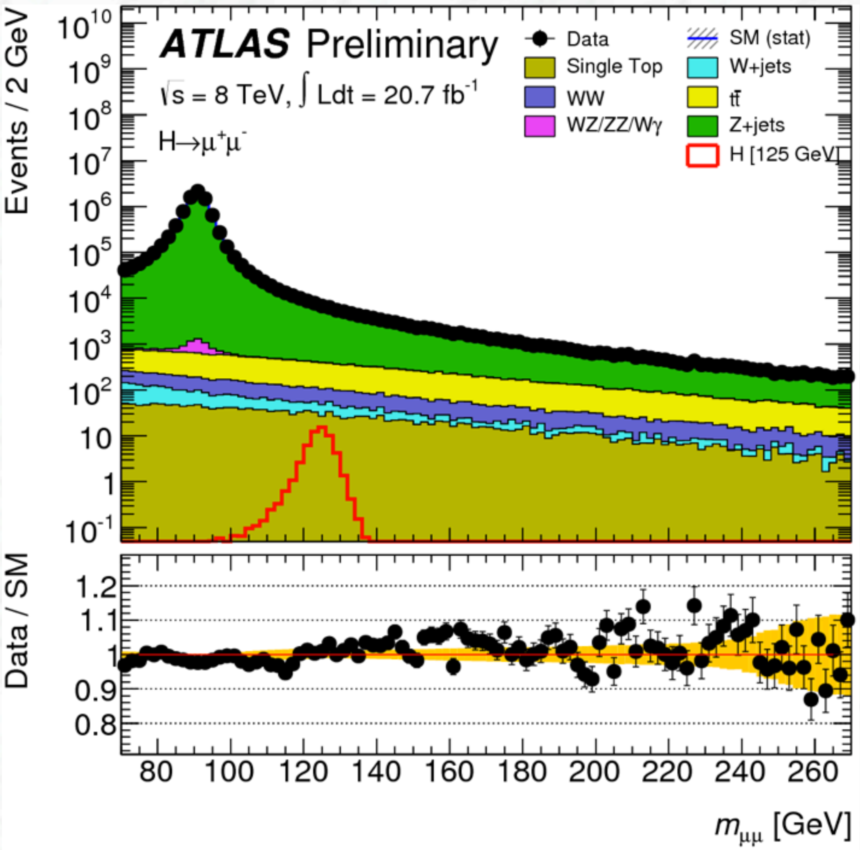


m_H = 125 GeV:

Observed 95% CL: 13.1 σ_{SM}

Expected 10.5 σ_{SM}

Results on the Search for H→ μμ



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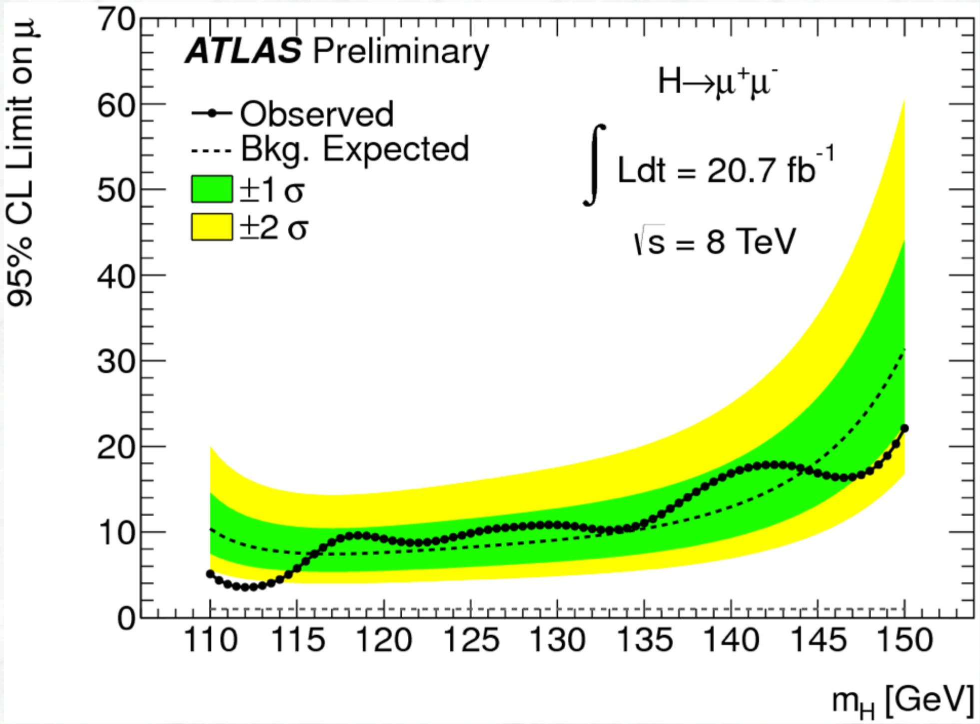
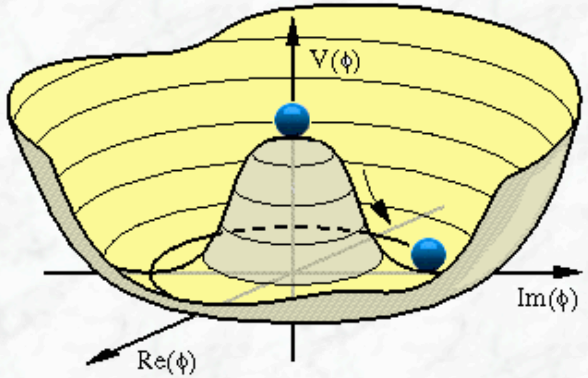


m_H = 125 GeV:

Observed 95% CL: $9.8\ \sigma_{SM}$
Expected $8.2\ \sigma_{SM}$

Electroweak Symmetry Breaking

-a cornerstone of the Standard Model-



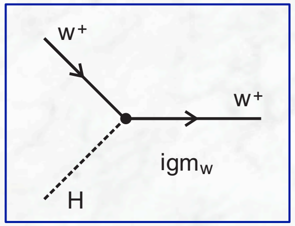
Complex scalar (spin 0) field ϕ with potential:

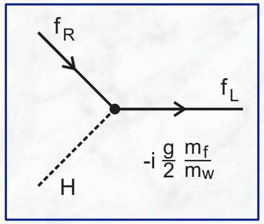
$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

$\lambda > 0$, $\mu^2 < 0$:

→ vacuum expectation value $v = 246$ GeV

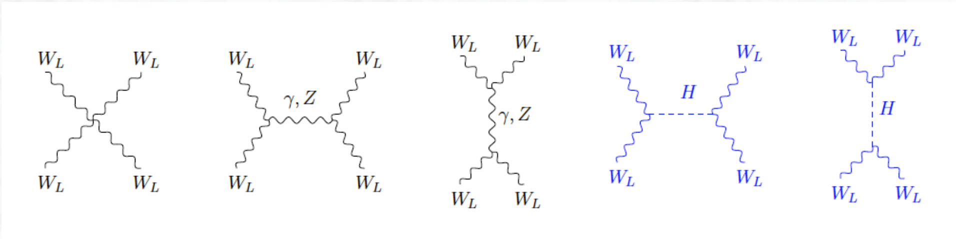
- Coupling proportional to mass of Standard Model particles





- Higgs boson, $m_H < \sim 1$ TeV

- "Ultraviolet regulator"



F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

Statistical Treatment

- All results are based on profile likelihood method

$$\Lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$

μ = parameter(s) of interest
θ = nuisance parameters

- $L(\hat{\mu}, \hat{\theta})$ Unconditional maximum likelihood estimate (μ and θ adjusted to maximise L)

- $L(\mu, \hat{\hat{\theta}}(\mu))$ Conditional maximum likelihood estimate: (a specific μ value (fixed), θ adjusted to maximise L for this μ)

- -2 ln $\Lambda(\mu)$ follows a χ^2 distribution with n d.o.f. ($\mu_{1, \ldots n}$)

- Nuisance parameters θ are constraint by probability density functions (Gaussian constraints, log-normal distributions, Poisson,… also explored: “rectangular” pdfs for some specific systematic uncertainties)

Categorisation of H → $\gamma\gamma$ Candidate Events, $\sqrt{s}$ = 8 TeV

$\sqrt{s}$	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

Signal mass resolution (σ_{CB}), signal (N_S) and background (N_B) numbers in a mass window around m_H = 126.5 GeV containing 90% of the expected signal events