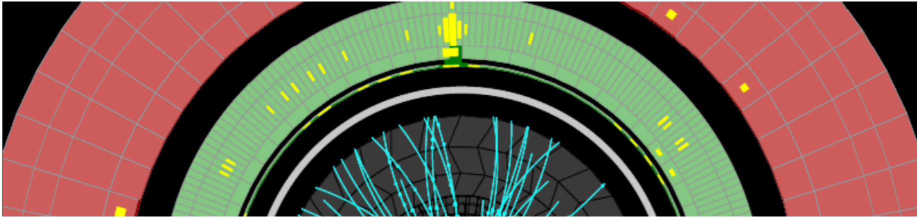
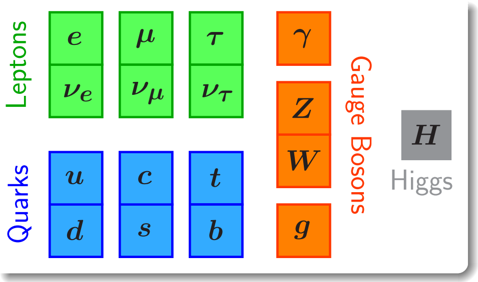
Study of Higgs boson properties in its decay to two photons with the ATLAS detector

Kerstin Tackmann (DESY)



DESY Physics Seminar

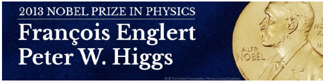
The Standard Model and the Higgs boson.



SM describes known elementary particles and their interactions

Local gauge invariance does not allow explicit mass terms in the Lagrangian – but experiment shows W and Z to have mass

- Elementary particles acquire mass through the Higgs (BEH) mechanism by interacting with the Higgs field
  - ⋆ Introduced 1964 by Brout, Englert and Higgs

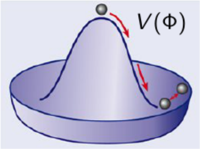


- Higgs mechanism predicts the existence of a new, neutral boson: the Higgs boson
  - ⋆ Candidate discovered by the LHC experiments (2012)

What do we expect a SM Higgs boson to look like?

Introduce a scalar field with vaccum expectation value $v \neq 0$

$$\phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix} \rightarrow \langle\phi\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$ (choose gauge)



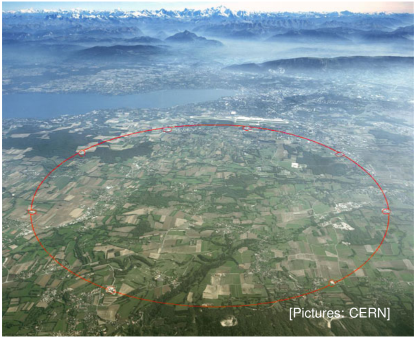
Mass terms from interaction between Higgs field and gauge bosons and fermions:

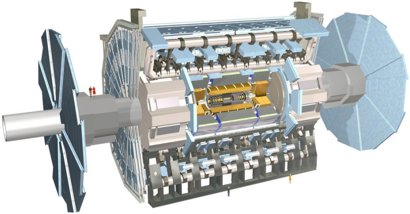
$$\mathcal{L}_\phi = (D^\mu\phi)^\dagger(D_\mu\phi) - g_f(\bar{\psi}_L\phi\psi_R + \bar{\psi}_R\phi\psi_L) - V(\phi)$$

- Gauge boson masses $m_{W^\pm} = \frac{gv}{2}$, $m_Z = \frac{v\sqrt{g^2+g'^2}}{2}$
- Charged fermion masses $m_f = \frac{g_f v}{\sqrt{2}}$
  - ⋆ Not needed for electroweak symmetry breaking, but convenient to generate fermion masses

Higgs mechanism predicts the existence of a new, neutral boson: the Higgs boson, coupling to particles proportional to their mass, $J^P = 0^+$

The Large Hadron Collider and the ATLAS experiment.





LHC

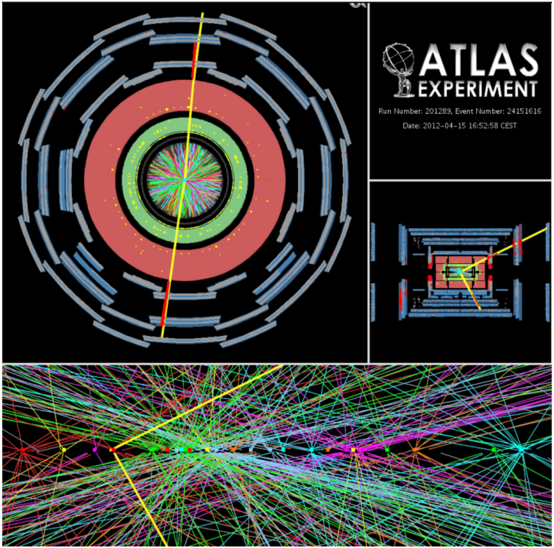
- Proton-proton collisions
  - ⋆ 2010/11 $\sqrt{s} = 7$ TeV (6 fb^{-1})
  - ⋆ 2012 $\sqrt{s} = 8$ TeV (23 fb^{-1})
- 2013/14 shutdown: machine and detector consolidation+upgrade
- 2015- pp collisions at 13-14 TeV

ATLAS

- Multipurpose detector: search for new physics, Higgs, top and SM measurements, ...

Outstanding performance of LHC and the experiments

The cost of high luminosity: pileup.

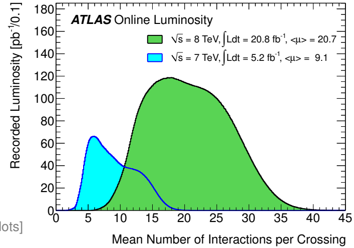


$Z \to \mu\mu$ with 25 interaction vertices

[ATLAS public plots]

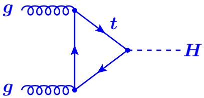
Challenge to trigger, software and analyses

- $\rightarrow$ Large amount of data to process and store
- $\rightarrow$ Identification and measurement of the “interesting” objects, including the primary vertex



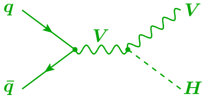
Higgs boson production at the LHC.

Gluon fusion: $\mathbf{19.5\,pb}$



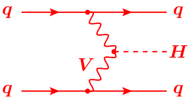
Higgs tends to have low p_T

Associated production: $\mathbf{1.1\,pb}$



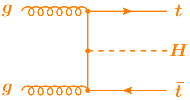
Clear signature: reconstruct W and Z in leptonic and/or hadronic decays

Vector boson fusion: $\mathbf{1.6\,pb}$



Distinct signature with 2 forward jets and little hadronic activity in between

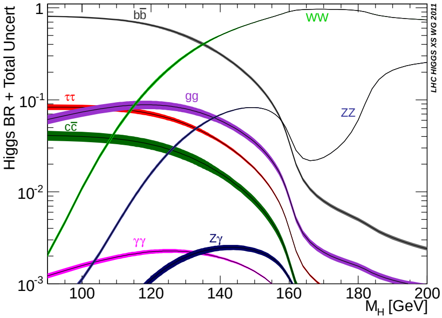
Associated production with $t\bar{t}$: $\mathbf{0.1\,pb}$



Tag presence of two top quarks

Production cross sections given at $m_H = \mathbf{125\,GeV}$ and $\sqrt{s} = \mathbf{8\,TeV}$

SM Higgs boson decays.



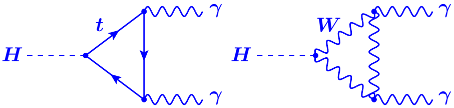
Higgs boson couples to mass

Decay branching fractions @ $m_H = 125\,\mathrm{GeV}$

$H \to b\bar{b}$	57.7%
$H \to WW$	21.5%
$H \to \tau\tau$	6.3%
$H \to ZZ$	2.6%
$H \to \gamma\gamma$	0.23%

$H \to \gamma\gamma$: Comparably simple final state: 2 energetic isolated photons

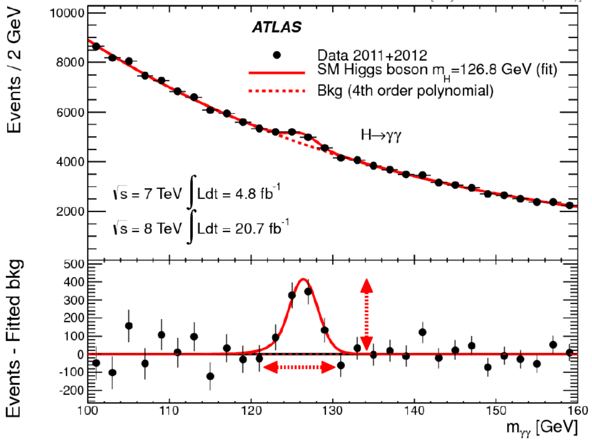
Large event yield despite low branching fractions expect to see 475 signal events in current dataset



Decay through loop processes $\to$ sensitive to new heavy particles

What do we need to discover and measure $H \to \gamma\gamma$?

[Phys. Lett. B 716 (2012)]



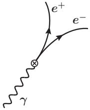
High and well-known efficiency

Good energy and angular resolution
Precise understanding of energy scale

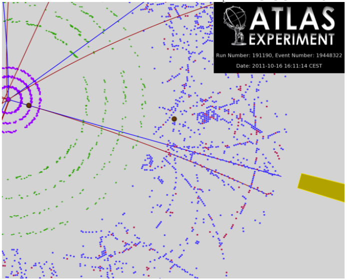
Photon reconstruction, identification and calibration

Photon reconstruction.

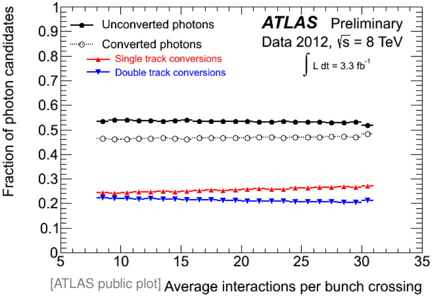
- Reconstruction seeded from electromagnetic clusters
- $\sim 40\%$ of photons convert to e^+e^- pairs in the material of the tracking detector



[ATLAS-CONF-2011-161]



- Reconstructed secondary vertices (and tracks) matched to clusters in calorimeter
  - ⋆ Separate reconstruction of converted and unconverted photons important for good calibration and identification, and separation from electrons

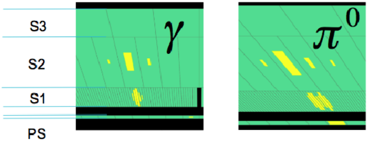


[ATLAS public plot]

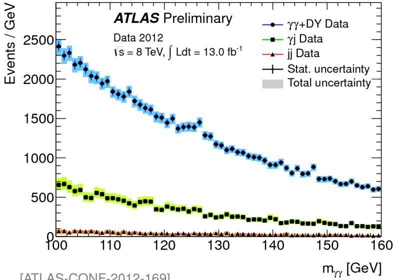
⋆ Reconstruction robust against pileup
  - ⋆ Substantial improvements made for 8 TeV

Photon identification.

- Powerful jet-rejection ($\mathcal{O}(10^4)$) needed to suppress dominant hadronic background
- Take advantage of fine granularity of electromagnetic calorimeter to look at width and internal structure of showers: Photon identification based on shower shape



[ATLAS public figure]



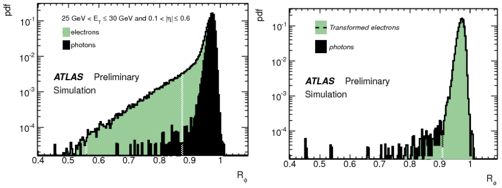
[ATLAS-CONF-2012-169]

After photon identification and requiring photon candidates to be isolated in calorimeter and tracker

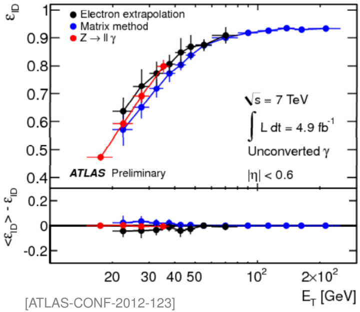
75% $\gamma\gamma$ events
22% γ-jet events
3% jet-jet events

Photon identification efficiency measurement.

"Electron extrapolation" selects a pure sample of electrons in $Z \to ee$ and applies transformations to correct for differences between electron and photon shower shapes



[ATLAS-CONF-2012-123]



[ATLAS-CONF-2012-123]

- "Electron extrapolation" results combined with results from other measurements
- Reduced uncertainty by a factor of 4 between discovery and now (8 TeV)

Summer 2012	10.8%
Winter 2013	2.4%

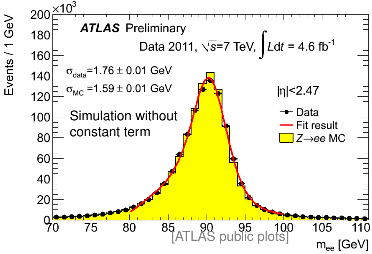
Uncertainty on expected $H \to \gamma\gamma$ signal yield

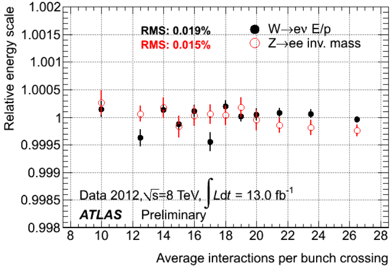
Energy calibration.

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

- MC-based calibration improved with energy scale and resolution corrections based on $Z \to e^+e^-$ ($W \to e\nu$, $J/\psi \to e^+e^-$ for cross checks)
- Energy response of the calorimeter is stable over time and varying pileup
- Understanding of photon energy scale requires understanding of inner detector material budget

  Cross checked with photon conversions, hadronic interactions, $e^{\pm}$ shower shapes and E/p, ...





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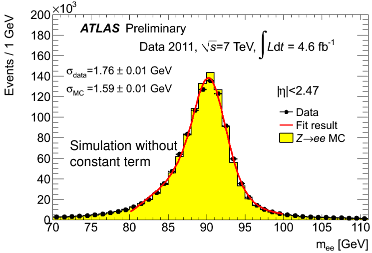
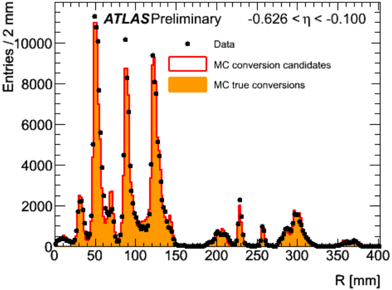
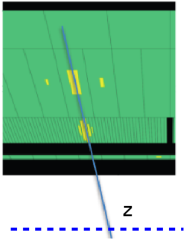


[ATLAS public plots]



Photon pointing and primary vertex selection.

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

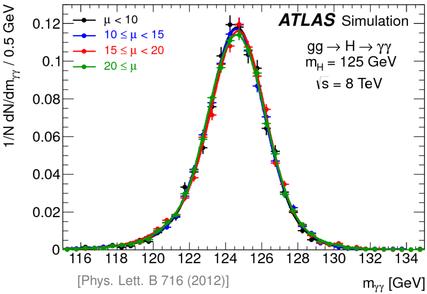


Improve photon angle measurement using

- Photon pointing
  - ⋆ Photon direction from calorimeter using longitudinal segmentation
  - ⋆ Position of conversion vertex for converted photons (with Si hits)
- $\sum p_T^2$, $\sum p_T$ (over tracks) and angular balance in ϕ between tracks and diphoton system (8 TeV)

→ Contribution of angle measurement to mass resolution negligible already without primary vertex information

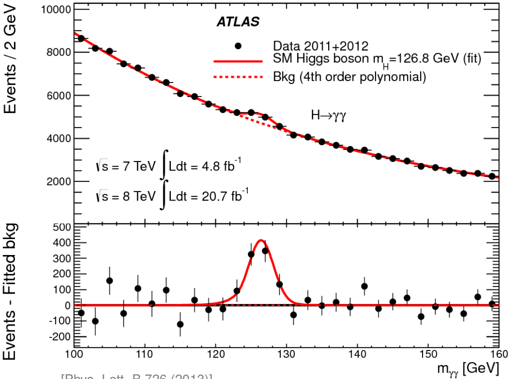
→ Good primary vertex selection needed for selection of signal jets



[Phys. Lett. B 716 (2012)]

Mass spectrum and background parametrization.

7 TeV + 8 TeV data



[Phys. Lett. B 726 (2013)]

Background+signal fit, signal fixed at 126.8 GeV

Signal clearly visible ($\sim 6\,\sigma$)

Diphoton selection

Identified and isolated photons
$p_T^{\gamma 1} > 40$ GeV, $p_T^{\gamma 2} > 30$ GeV

23788 events (7 TeV)
118893 events (8 TeV)

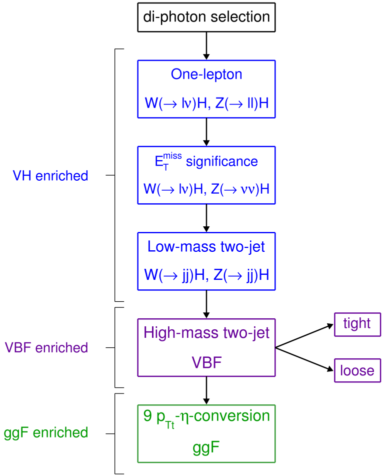
Background modelled by 4th order Bernstein polynomial

Studied on high-statistics MC and chosen to give good statistical power while keeping potential biases acceptable

Potential bias accounted for as systematic uncertainty

$H \to \gamma\gamma$ production and coupling studies

Categorization overview.



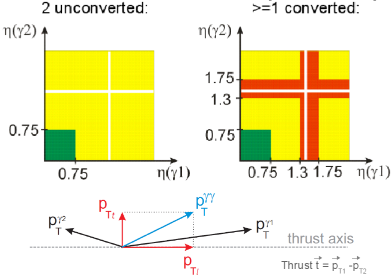
[ATLAS-CONF-2013-012]

$\sqrt{s}$ =8 TeV categories

(7 TeV: 1 VBF category)

- Dedicated categories for separation of production processes: VH, VBF, gluon fusion
- Remaining events split into categories of varying signal resolution and S/B
  - $\eta_{\gamma 1,2}$, conversions, p_{Tt}

[J. Schaarschmidt]

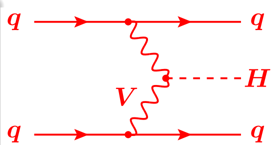


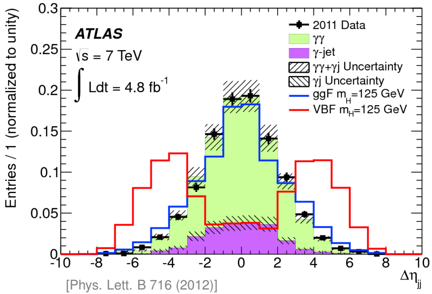
[ATLAS-CONF-2011-161]

VBF-enriched categories.

Select with 2 jets and VBF topology:

- 2 well-separated jets ($\eta_{j1,2}$, $\Delta\eta_{jj}$, m_{jj})
- Boosted diphoton system ($p_{Tt}^{\gamma\gamma}$)
- Jet-photon separation ($\Delta\phi_{\gamma\gamma;jj}$, $\eta^* = \eta_{\gamma\gamma} - 1/2(\eta_{j1} + \eta_{j2})$, $\Delta R_{\text{min}}^{\gamma j}$)



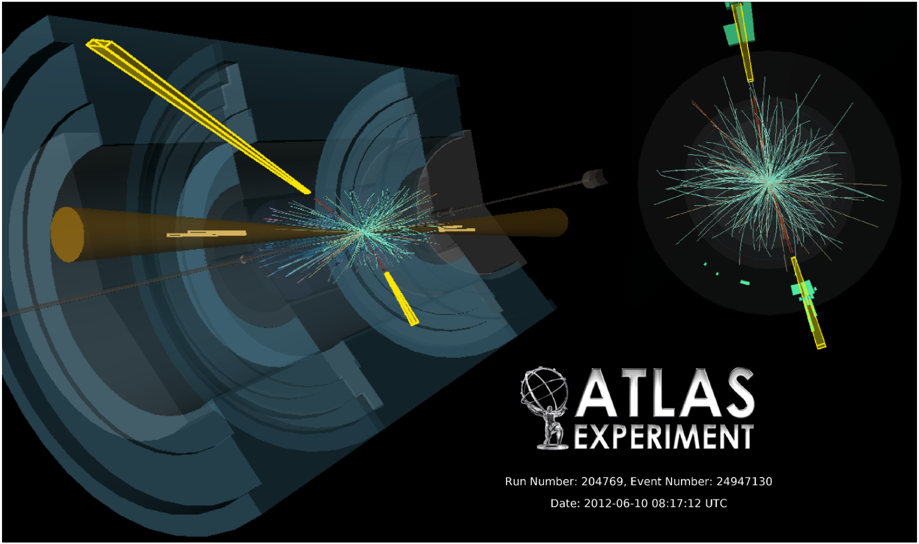


[Phys. Lett. B 716 (2012)]

- Variables combined in a boosted decision tree
- High purity of VBF events

	VBF purity	N_{sig}
tight	76%	8.1
loose	54%	5.3

2-Jets candidate.

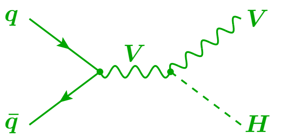


[Phys. Lett. B 726 (2013)]

VH-enriched categories.

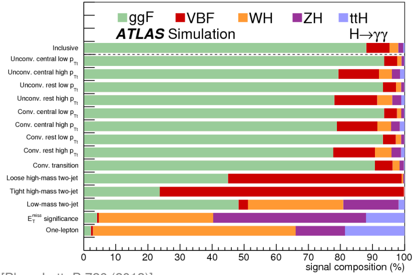
Inclusive leptons ($W \to \ell\nu$, $Z \to \ell\ell$)

$p_T^e > 15$ GeV or $p_T^\mu > 10$ GeV, isolated in tracker and calorimeter



Missing energy ($W \to \ell\nu$, $Z \to \nu\nu$)

E_T^{miss} significance $\frac{E_T^{\text{miss}}}{0.67\sum E_T} > 5$



[Phys. Lett. B 726 (2013)]

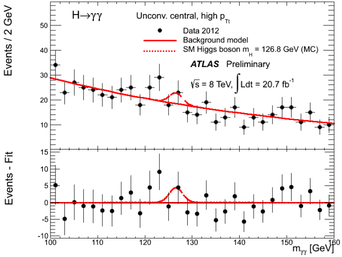
Dijet ($W \to jj$, $Z \to jj$)

60 GeV $< m_{jj} <$ 110 GeV,
$|\Delta\eta_{jj}| <$ 3.5

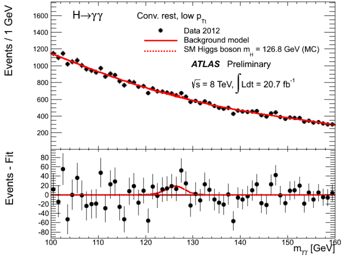
	VH purity	N_{sig}
lepton	82%	2.9
E_T^{miss}	83%	1.3
dijet	47%	3.3

Diphoton mass spectra for a few categories.

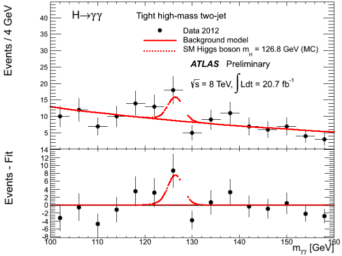
Unconverted central, high p_{Tt}



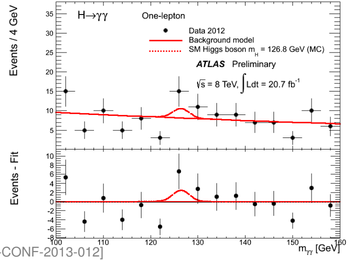
Converted rest, low p_{Tt}



Tight high-mass 2-jet

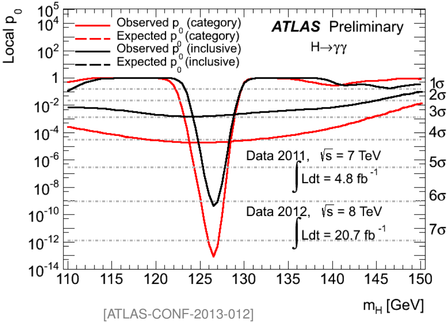


E_T^{miss} significance



[ATLAS-CONF-2013-012]

$H \to \gamma\gamma$ single channel discovery.



[ATLAS-CONF-2013-012]

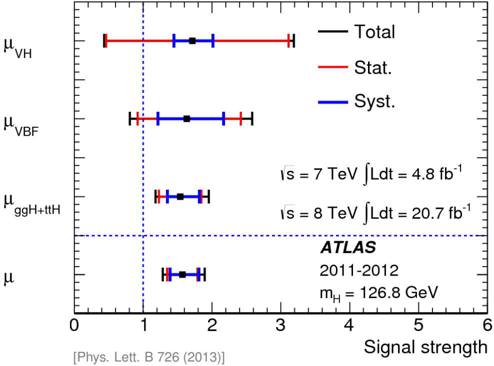
- (Local) significance of excess $\mathbf{7.4\,\sigma}$
  - ⋆ $\mathbf{4.1\,\sigma}$ expected for SM Higgs boson

  Single channel discovery

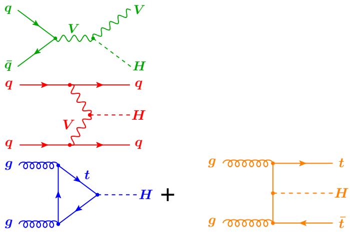
- $\mathbf{4.5\,\sigma}$ excess at the time of discovery (summer 2012)

- Measured mass $m_H = \mathbf{126.8 \pm 0.2(stat) \pm 0.7(syst)\,GeV}$
  - ⋆ Dominated by systematic uncertainties, mainly from photon energy calibration
- Measured signal strength $\mu = N_{\rm meas}/N_{\rm SM} = \mathbf{1.55^{+0.33}_{-0.28}}$ (at $m_H = \mathbf{125.5\,GeV}$, combined mass with $H \to 4\ell$)
  - ⋆ Data favors narrower signal shape than assumed for μ measurement, which would lower μ

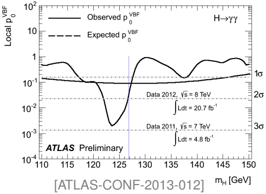
Separating production processes.



[Phys. Lett. B 726 (2013)]



$\mu = 1 \Rightarrow$ SM

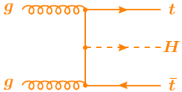


[ATLAS-CONF-2013-012]

Consistent with SM expectations

$\sim 2\,\sigma$ hint of VBF production

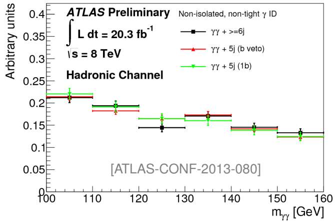
Search for production in association with $t\bar{t}$.



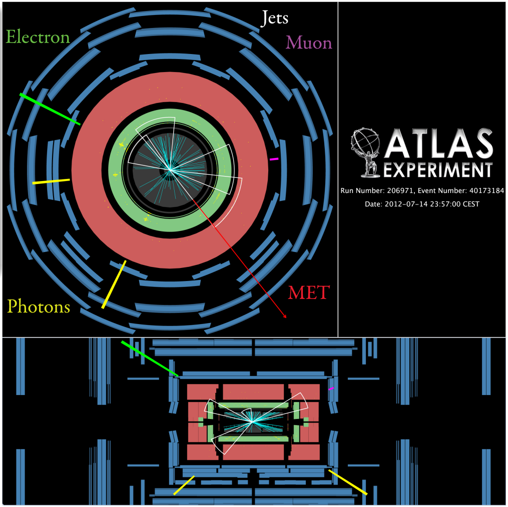
- Aim for high efficiency for $t\bar{t}H$, while suppressing other production modes

Search in two event categories

- Fully hadronic: 2 $t \rightarrow bjj'$
  - ★ $\geq$ 6 jets ($\geq$ 2 b-tagged)
  - ★ No leptons
- Leptonic: 1 or 2 $t \rightarrow b\ell\nu$
  - ★ $\geq$1 electron or muon
  - ★ $\geq$1 b-tagged jet
  - ★ $E_T^{miss} > 20$ GeV



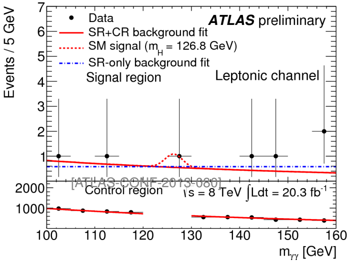
Bkgd shape constrained in control regions



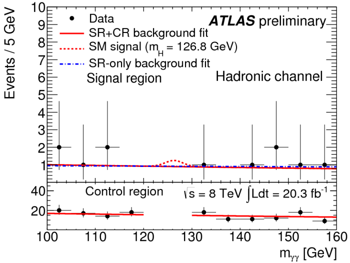
[ATLAS-CONF-2013-080]

Search for production in association with $t\bar{t}$.

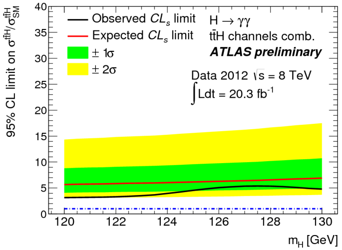
Leptonic



Hadronic



Leptonic		Hadronic
0.55	N_H	0.36
0.46	$N_{t\bar{t}H}$	0.33
83%	Purity	91%



- Assume SM for other production modes and BR$(H \to \gamma\gamma)$

$\sigma^{t\bar{t}H}/\sigma^{t\bar{t}H}_{\mathrm{SM}} < 5.3$ @ 95% CL

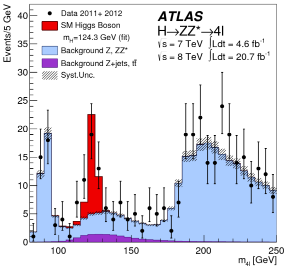
(6.4 expected) at m_H=126.8 GeV

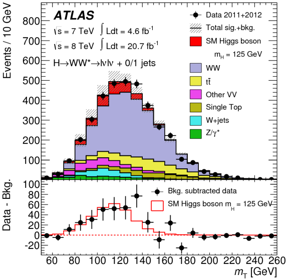
Detailed coupling studies: combination with the other decay channels

Combining with the other decay channels.

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

[Phys. Lett. B 726 (2013)]



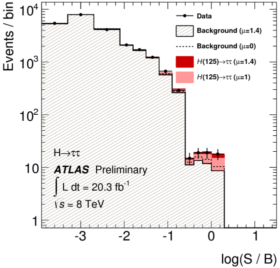


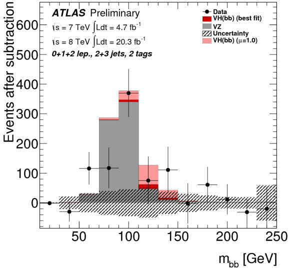
$H \to WW^* \to 2\ell 2\nu$

[Phys. Lett. B 726 (2013)]

$H \to \tau\tau$

[ATLAS-CONF-2013-108]



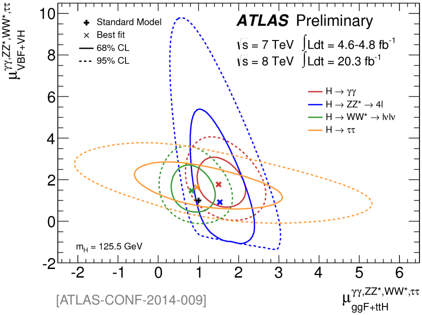


$H \to b\bar{b}$

[ATLAS-CONF-2013-079]

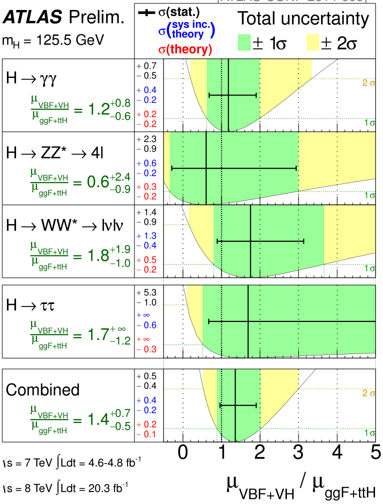
Separating production channels.

- Coupling to vector bosons
  use $\mu_{\mathrm{VBF+VH}} = \mu_{\mathrm{VBF}} = \mu_{\mathrm{VH}}$
- Coupling to fermions
  use $\mu_{\mathrm{ggF+ttH}} = \mu_{\mathrm{ggF}} = \mu_{\mathrm{ttH}}$



[ATLAS-CONF-2014-009]

[ATLAS-CONF-2014-009]



- Combination of decay channels (at level of μ) would need assumptions on BRs

4.1 σ evidence for VBF

(obtained profiling μ_{VH})

Detailed coupling studies.

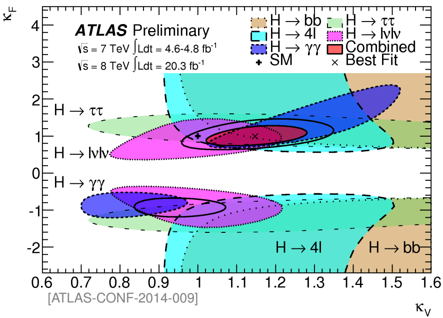
- LO-inspired coupling scale factors κ_j:

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu}\right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\overline{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\overline{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\overline{f} \right) H.$$

- Effective coupling scale factors κ_γ and κ_g treated as function of more fundamental scale factors κ_t, κ_b, κ_W, ... for some tests

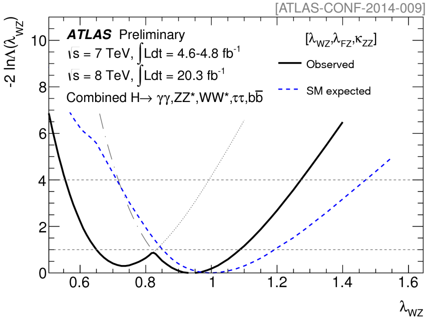
Specific benchmark models.

Probing fermion and boson couplings



- Simplest non-trivial model
- $H \rightarrow \gamma\gamma$ decay gives sensitivity to relative sign
- Agreement of SM hypothesis with data ∼10%

Probing custodial symmetry

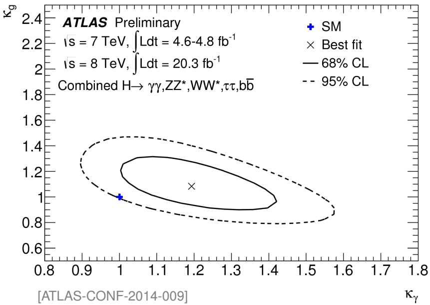


- $\lambda_{WZ} = \kappa_W / \kappa_Z$
  - ⋆ Common κ_F for fermion couplings
- Agreement of SM hypothesis with data ∼19%

Probing beyond SM contributions.

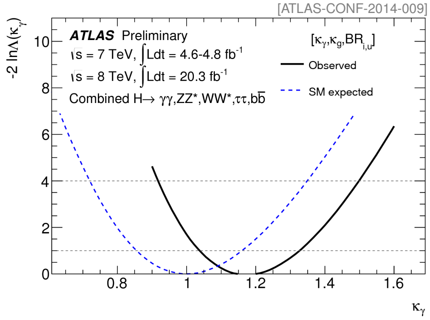
Effective scale factors κ_g and κ_γ allow for new contributions in loops

Only SM contributions to total width



- Agreement of SM hypothesis with data ∼9%

No assumptions on total width

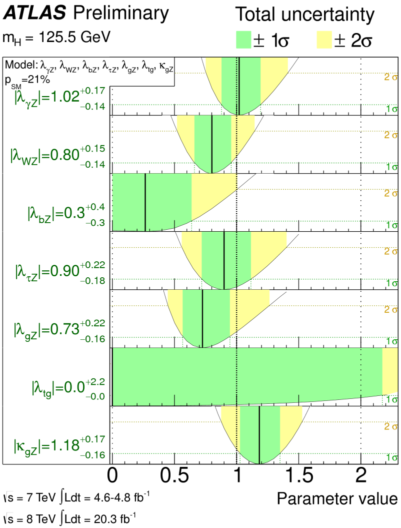


- Allow for undetected or invisible final states
- $BR_{i,u} < 0.41$ (at 95% CL) (expected: 0.55)
  - ⋆ Improved by inclusion of new $H \to b\bar{b}$, $H \to \tau\tau$

Most generic model.

...free couplings to SM particles and allowing for deviations in loops and additional contributions to total width

- No sensitivity to relative signs between couplings
- No sensitivity to Higgs-top coupling
  - ⋆ Degenerate with gluon-fusion loop
  - ⋆ Needs observation of ttH production
- Agreement of SM hypothesis with data ∼21%



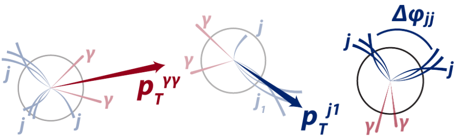
[ATLAS-CONF-2014-009]

Back to $H \to \gamma\gamma$

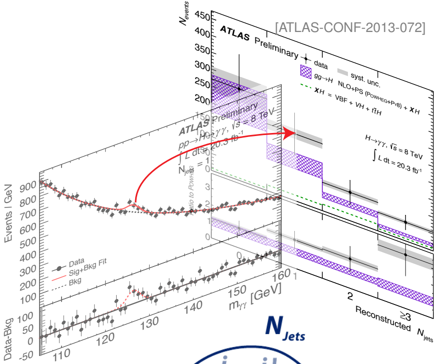
Differential cross section measurements.

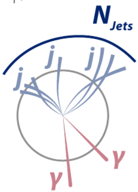
Full 8 TeV dataset allows to make first differential cross section measurements

- Almost model-independent measurements of production and decay kinematics
- Measure kinematic distributions of Higgs, of associated jets, ...



- $H \to \gamma\gamma$ decay well suited thanks to good resolution and “high” signal yield
- Background subtracted in a simultaneous signal-plus-background fit to all bins





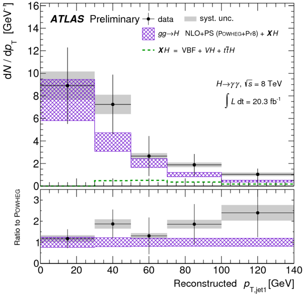
Correcting to fiducial cross sections.

- Bin-by-bin unfolding for detector acceptance, resolution and efficiency
- Unfold to fiducial region defined by photons (and jets)

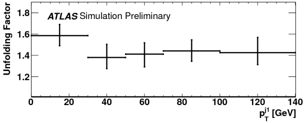
  ⋆ $p_T^{\gamma 1(\gamma 2)} > 0.35\ (0.25)\ m_{\gamma\gamma}$, $|\eta^{\gamma 1,2}| < 2.37$

  ⋆ $p_T^{j} > 30$ GeV, $|y^{j}| < 4.4$

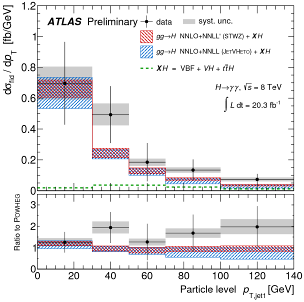
Reconstructed spectrum



Correction factors



Unfolded spectrum

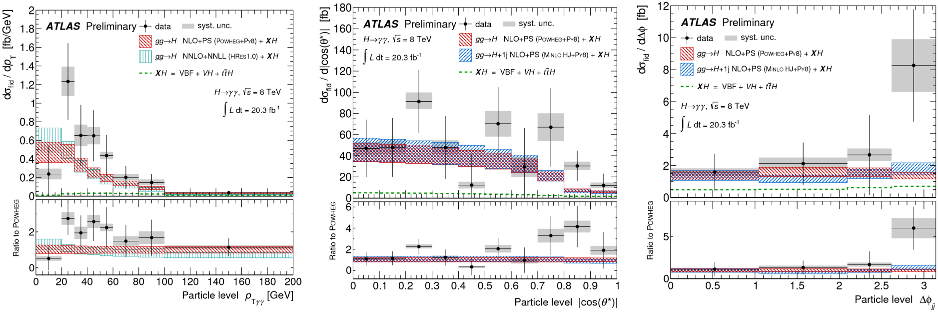


- Uncertainties dominated by statistical uncertainties

[ATLAS-CONF-2013-072]

- Allows for direct comparisons to precise theoretical calculations

A few more results.



[ATLAS-CONF-2013-072]

Agreement between data and SM prediction within current uncertainties

χ^2 probabilities comparing to several predictions

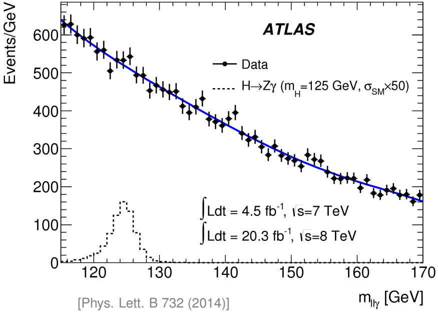
	$N_{\rm jets}$	$p_{\rm T}^{\gamma\gamma}$	$\lvert y^{\gamma\gamma}\rvert$	$\lvert\cos\theta^*\rvert$	$p_{\rm T}^{j_1}$	$\Delta\phi_{jj}$	$p_{\rm T}^{\gamma\gamma jj}$
POWHEG	0.54	0.55	0.38	0.69	0.79	0.42	0.50
MINLO	0.44	–	–	0.67	0.73	0.45	0.49
HRES 1.0	–	0.39	0.44	–	–	–	–

Looking for rare decay modes: $H \to Z\gamma$.

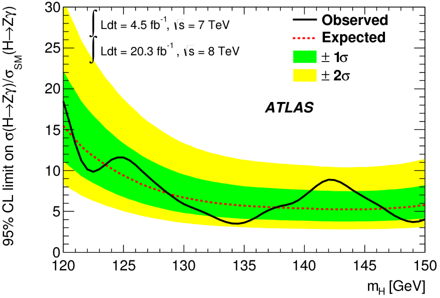
$H \to Z\gamma$ coupling could be modified e.g. from new particles in the loop

- ...although careful parameter tuning needed to enhance expected signal beyond $\sim 2\times$SM

- $Z \to \ell\ell$ with $\ell = e$ or μ
- Search assumes SM-like production
- Events classified by lepton flavor, p_{Tt}, $\Delta\eta_{Z\gamma}$



[Phys. Lett. B 732 (2014)]

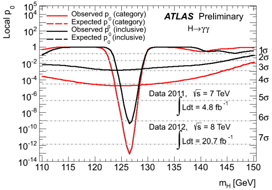


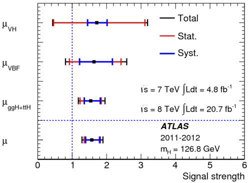
$<$11 $\times$ SM @ 95% CL

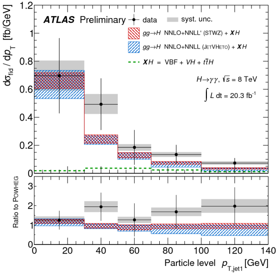
(expected 9) at m_H=125.5 GeV

Conclusions and Outlook.

- Successful transition from Higgs search to detailed measurements
  - ★ SM predictions consistent with data within present uncertainties
- Run 2 to start in 2015, expecting to collect 350 fb^{-1} until 2022
- Detailed studies of production channels and couplings
- Refine measurements of differential and fiducial cross sections
- Search for rare decay modes ($H \to Z\gamma$, $H \to \mu\mu$)
- Looking forward to LHC Run 2 for a detailed understanding of EWSB







Spin studies.

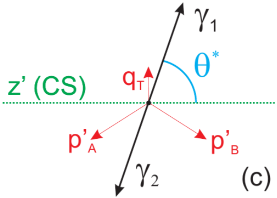
Polar angle θ^* in resonance rest frame sensitive to spin of resonance

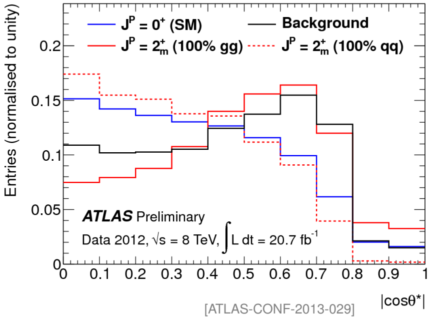
spin 0^+ $\mathrm{d}N/\mathrm{d}|\cos\theta^*| \sim$ const

spin 2^+ $\mathrm{d}N/\mathrm{d}|\cos\theta^*| \sim 1 + 6\cos^2\theta^* + \cos^4\theta^*$

(for spin 2 produced by gg fusion in minimal coupling model)

$\rightarrow$ strongly distorted by kinematic selection





[ATLAS-CONF-2013-029]

Background $|\cos\theta^*|$ shape interpolated from $m_{\gamma\gamma}$ sidebands into signal region (122 to 130 GeV)

- Decorrelate $m_{\gamma\gamma}$ and $|\cos\theta^*|$ by using $p_T^{1/2} >$ 35/25 $m_{\gamma\gamma}$
- Extract 690$\pm$150 (620$\pm$160) signal events under spin-0 (spin-2) assumption

Analysis performed on 20.7 fb^{-1} of $\sqrt{s}$ =8 TeV data

Spin studies.

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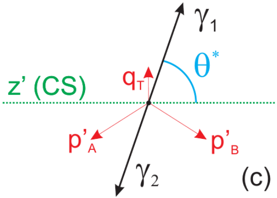

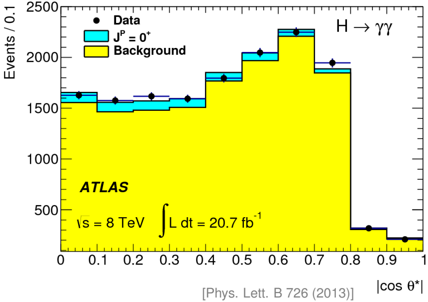

[Phys. Lett. B 726 (2013)]

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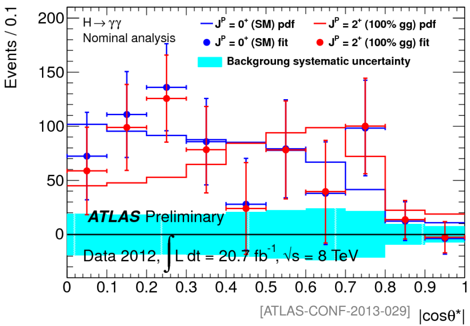
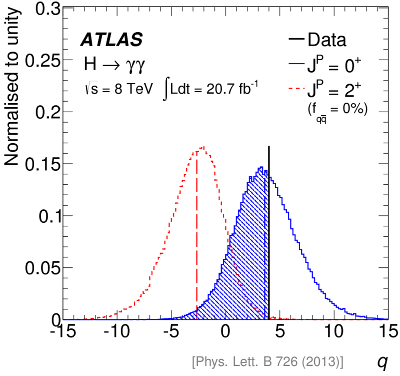
Analysis performed on 20.7 fb^{-1} of $\sqrt{s}$ =8 TeV data

Spin studies – results.



[ATLAS-CONF-2013-029]



[Phys. Lett. B 726 (2013)]

Compatibility of data with spin-0^+ signal plus background hypothesis and spin-2^+ signal plus background hypothesis estimated via likelihood ratio

$$q = -\ln\mathcal{L}(\text{spin0}, \hat{\theta})/\ln\mathcal{L}(\text{spin2}, \hat{\theta})$$

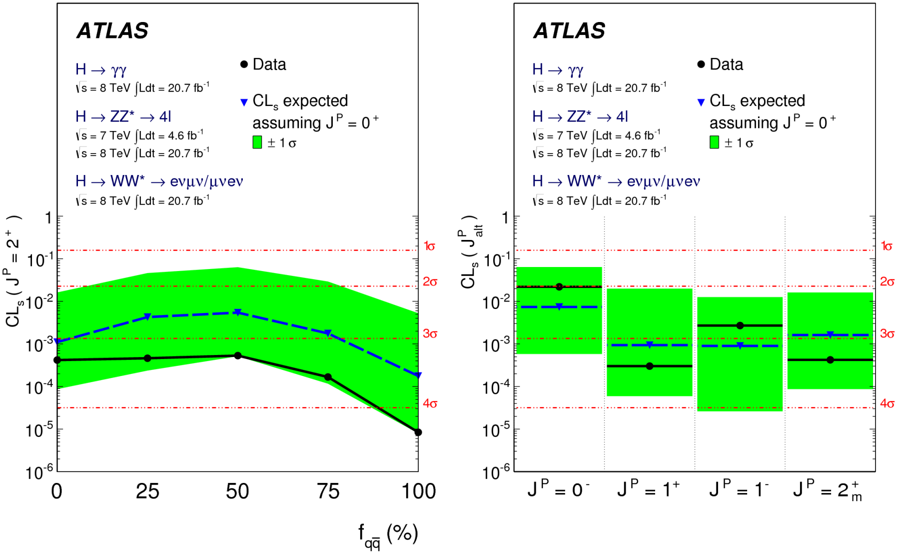
Expected p-values $p_{2+} = 0.5\%$ and $p_{0+} = 1.2\%$
Observed p-values $p_{2+} = 0.3\%$ and $p_{0+} = 58.8\%$

p value of 50% would be perfect agreement

Tested spin 2 model excluded at 99% CL

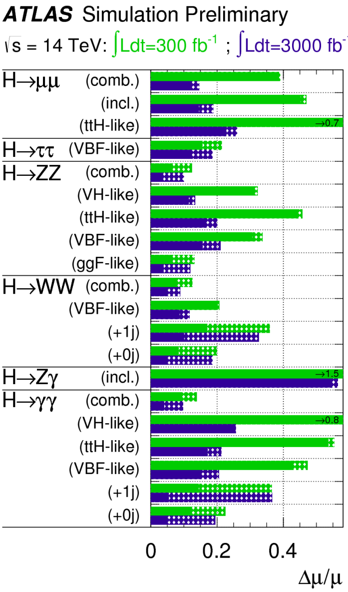
Exclusion can be significantly weaker for other models

Spin combination.



[Phys. Lett. B 726 (2013)]

Projections for 300 and 3000 fb^{-1}.



Projection for $H \to Z\gamma$

	300 fb^{-1}	3000 fb^{-1}
Exp. CL_s limit ($\times$SM)	2.53	0.74
p_0 (σ)	0.67	2.12

Limit on width from interference

- Measurement of mass shift between $p_T^{\gamma\gamma} < 30$ GeV and > 30 GeV

	300 fb^{-1}	3000 fb^{-1}
Exp. limit	880 MeV	160 MeV

[ATL-PHYS-PUB-2013-014]