ATLAS Higgs to diboson

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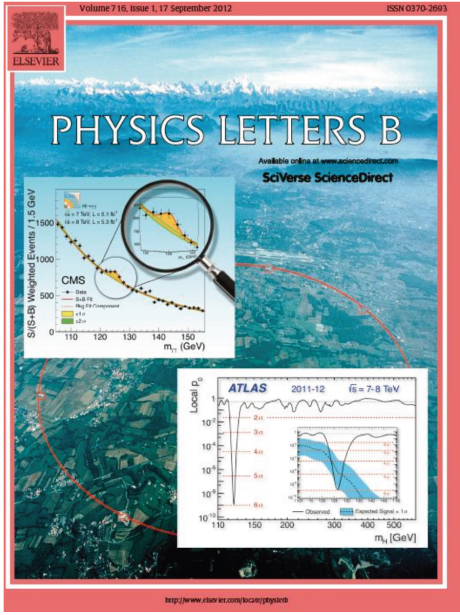
on behalf of the ATLAS collaboration

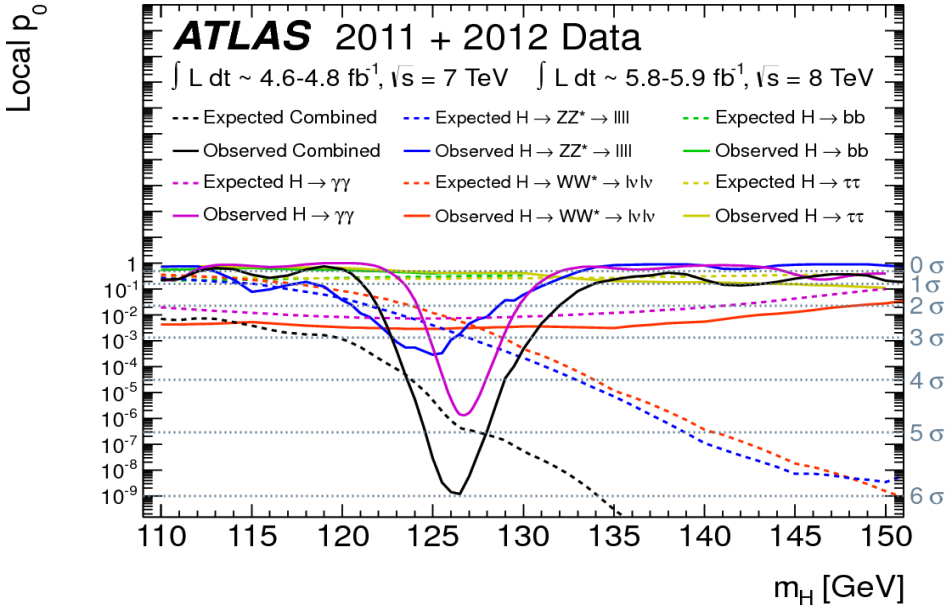
Higgs Hunting 2014

Results from bosonic decays in ATLAS



Discovery of new boson declared on July 2012:

- Observed excess driven by γγ, ZZ*, WW* decay channels

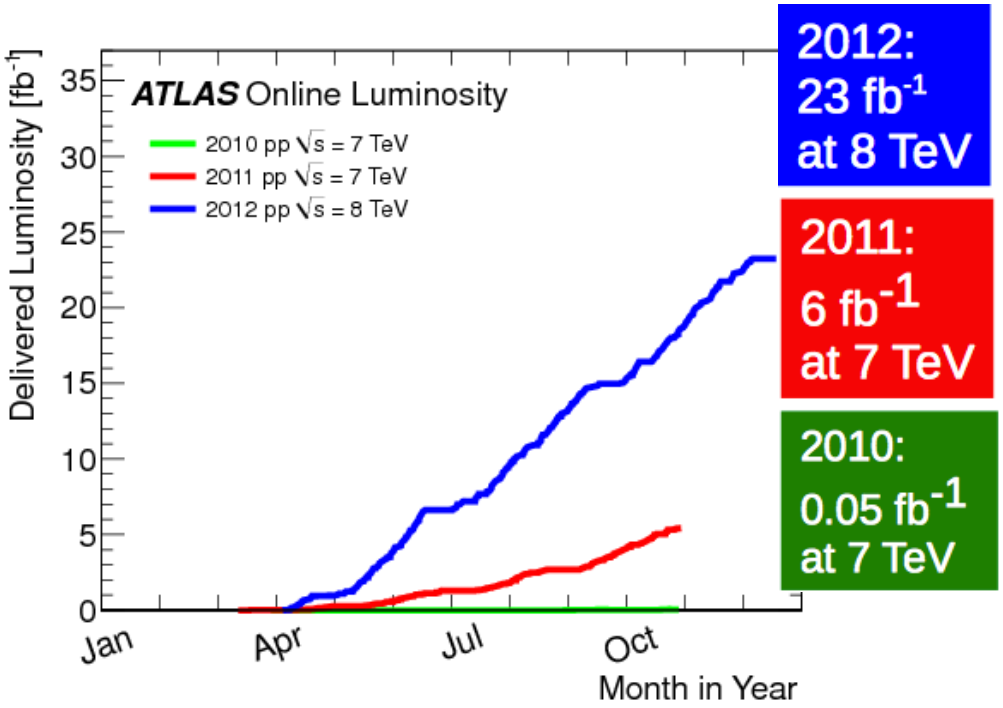


Since then measurements of the Higgs Boson properties

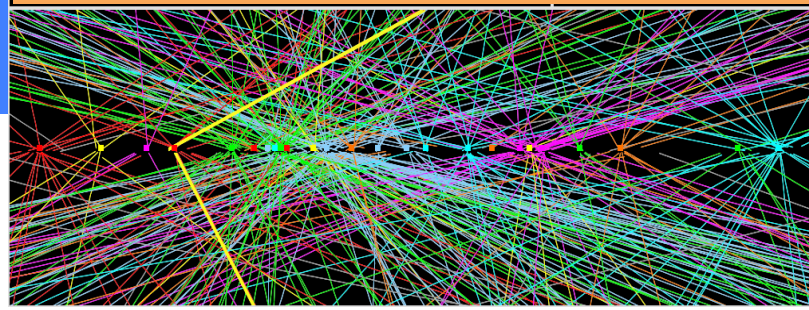
NEW

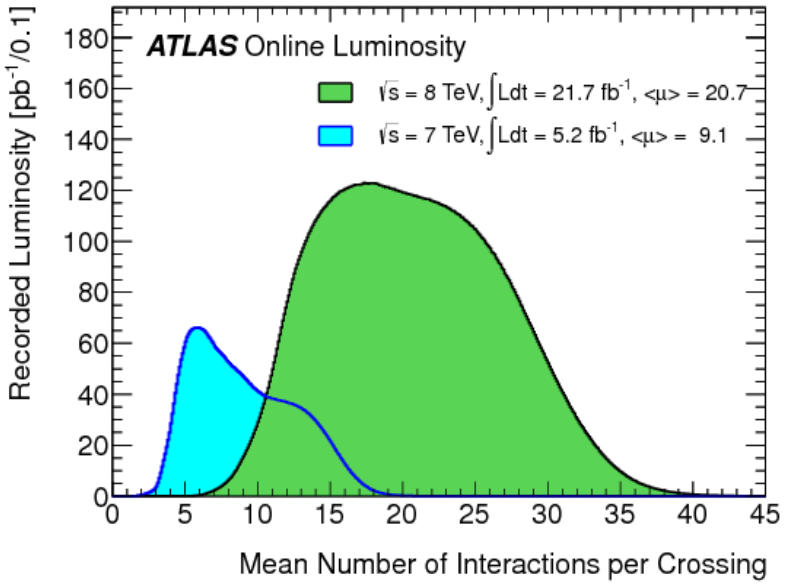
- **Mass** — from H→γγ and H→ZZ*
- **Couplings :** — boson+fermion channel
  - H→ZZ*→4l — new
  - H→γγ , H→WW* — old result from Moriond 2013
- **Spin and Parity** — from H→γγ and H→ZZ*, H→WW*
- **Differential cross section** — from H→γγ and H→ZZ*
- **Width (indirect measurement)** — from H→ZZ*

LHC and ATLAS performances



Z →μμ with 25 pile-up vertices

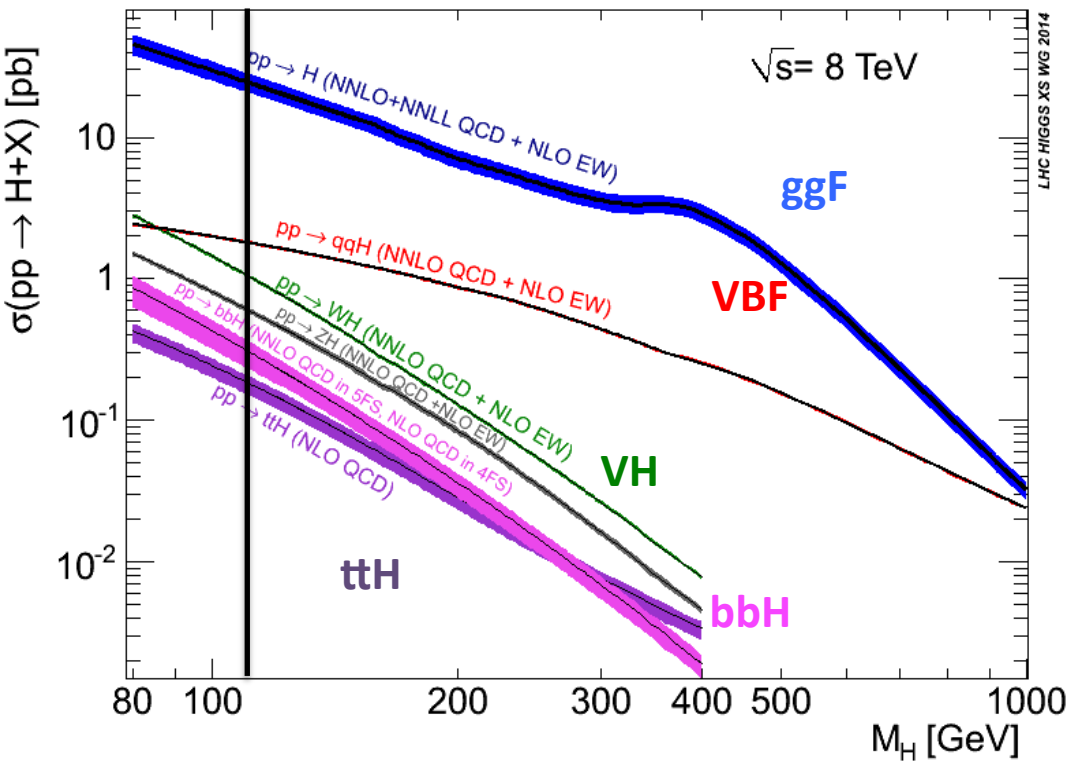


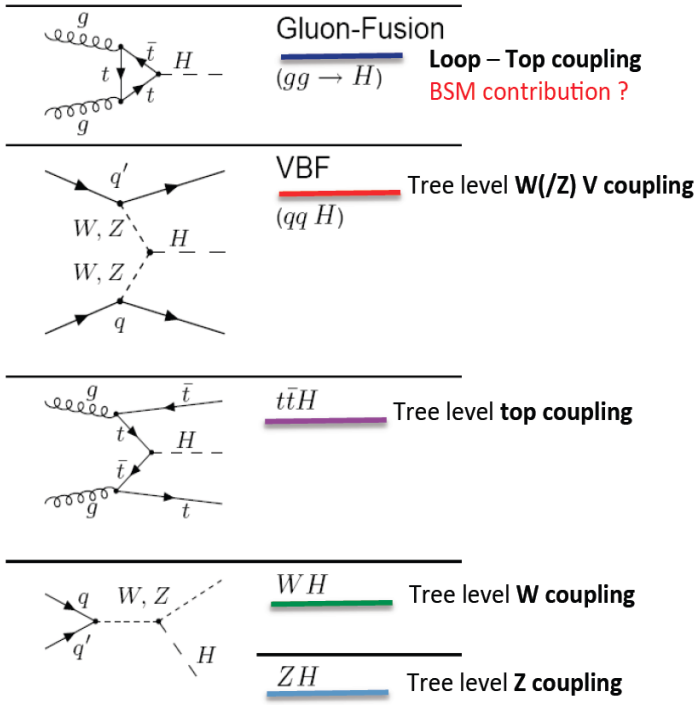


- L_{peak} up to 7.7×10^{33} cm^{-2} s^{-1} in 2012 at 8 TeV
- $L_{delivered}$ ~ 23 fb^{-1} (8 TeV) + 6 fb^{-1} (7 TeV)
- ~ 90% of delivered collisions are used in ATLAS physics analyses

- Pile-up level above design value (50 ns bunch crossing)
- Many challenges to mitigate its impact at all levels: trigger, computing, reco/identification of physics objects

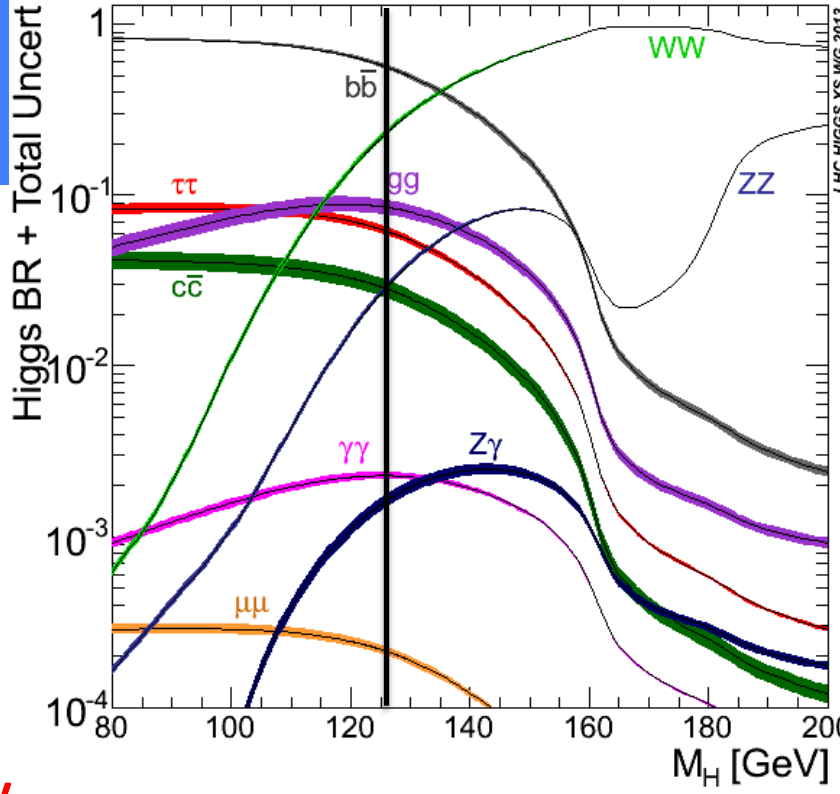
Higgs Boson production at LHC





- **Access to top(direct and loop),b,W and Z couplings via production cross section**
- **NNLO prediction for SM Higgs production cross section in most cases**
  - **theory uncertainties reduced to < 12%, dominated by QCD-scale and PDF +α_s**

Higgs Boson decay at LHC



- **Experimentally accessible:**
  - **$b\bar{b}$,ττ,WW*,ZZ*,γγ,Zγ,μμ**
  - **Theoretical uncertainty for di-boson decay <5%**
- **$\Gamma_H(125)$~ 4 MeV**
- **Boson decays have different yield and purity**

channel	σ(pp→H)@ 8 TeV	BR (H→VV)	BR(VV→4l)	Evt yield in 20 fb^{-1}	S/B
H→γγ	22.3 pb @m_H=125GeV	0.0023	-	1000	0.03
H→ZZ→4l		0.026	0.0044	50	2
H→WW→lυlυ		0.22	0.047	4700	0.1-0.4

→Different sensitivity for different analysis

H→γγ

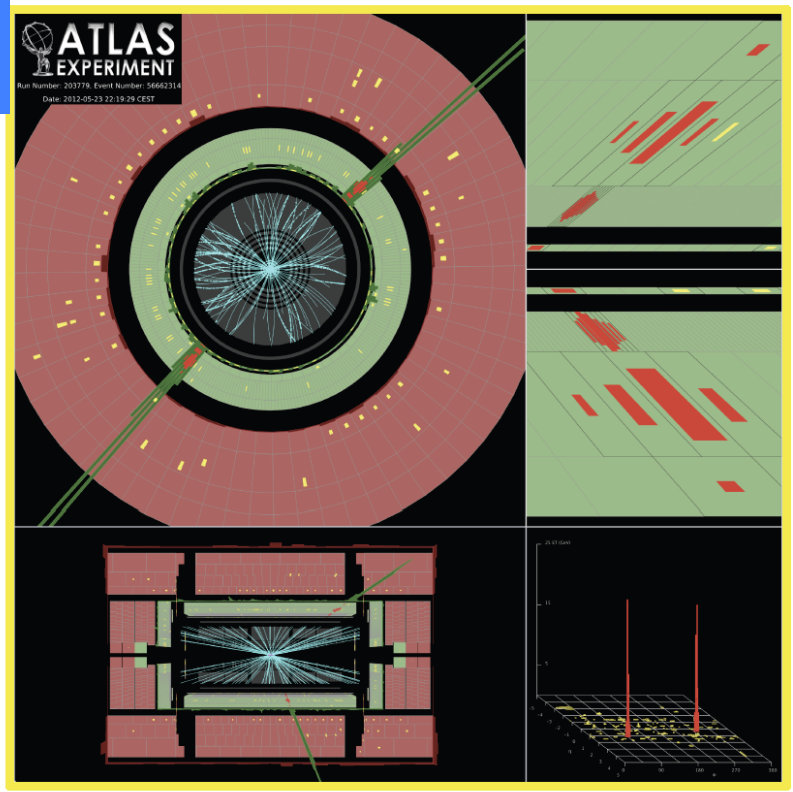
- σ × BR ~ 50 fb S/B~3%

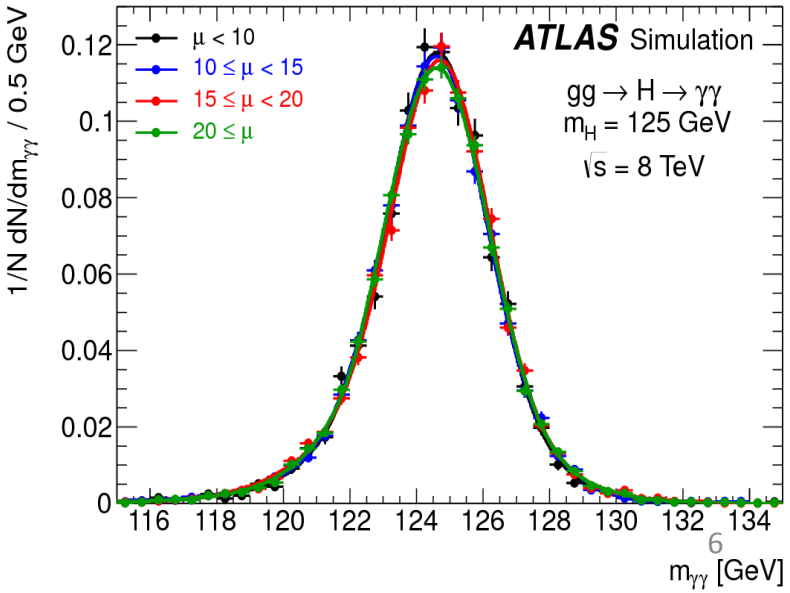
- Simple topology
  - Two high p_T isolated photons
  - background: γγ continuum, fakes

- Crucial experimental aspects
- excellent γγ mass resolution:

$m_{\gamma\gamma} = 2\sqrt{E_1 E_2}(1-\cos\alpha)$

- E_1, E_2: Control of Energy scale is crucial
  New calibration (arXiv:1407.5063)
  crucial for Higgs Boson mass measurement
  (see S.Heim talk)





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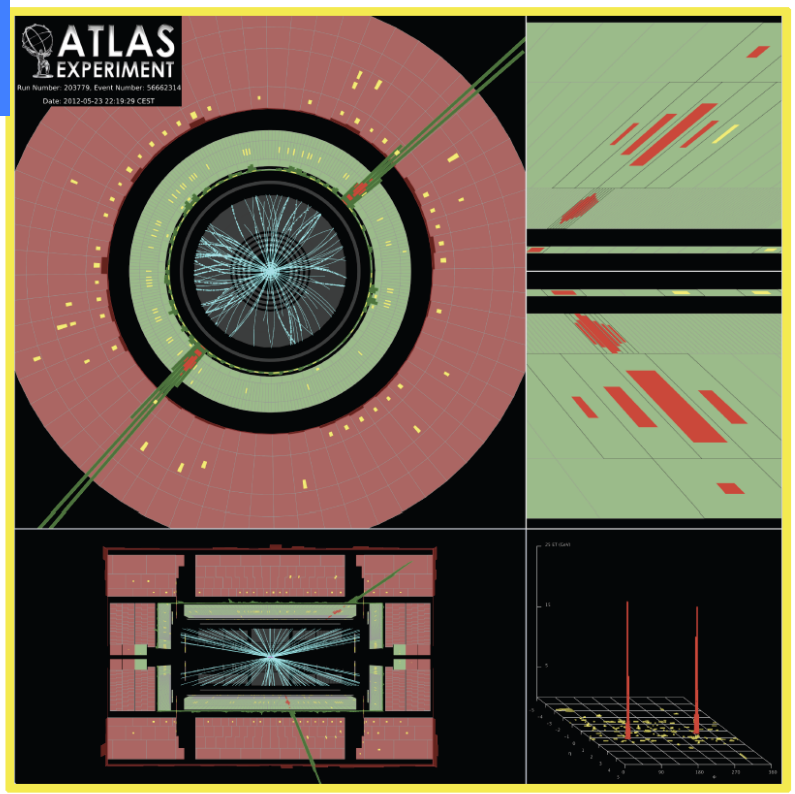
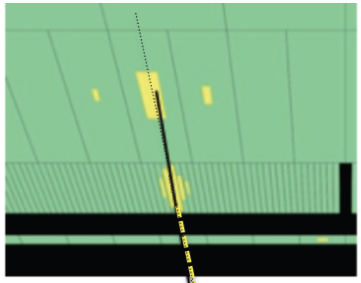
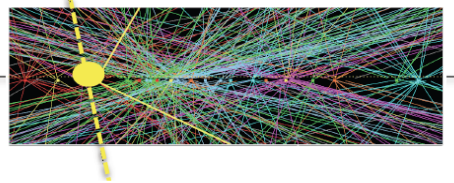
- cos α :
  - cluster position + primary vertex position
  - negligible impact of angular resolution from calorimeter pointing on $m_{\gamma\gamma}$ wrt to energy resolution





Independent Primary vertex position measurement in ATLAS



H→γγ

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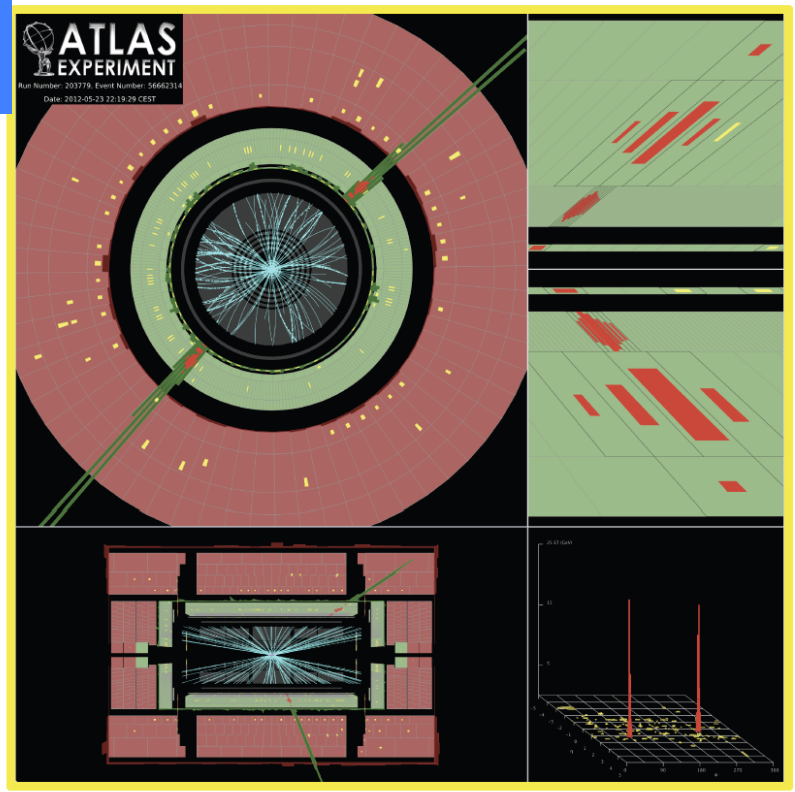
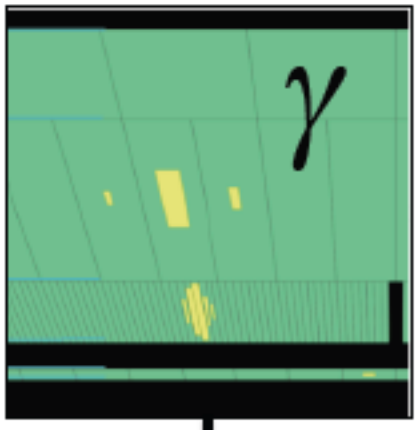
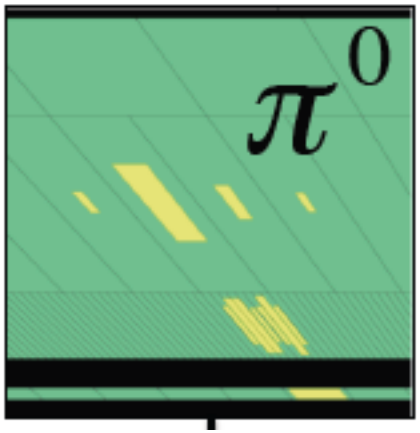
- Simple topology
  - Two high p_T isolated photons
  - background: γγ continuum, fakes



- Crucial experimental aspects
- excellent γγ mass resolution
- Powerful γ ID to suppress γj and jj with j→π^0→fake γ
  Xsec are 10^4-10^7 larger than γγ background

- Make use of fine calorimeter segmentation





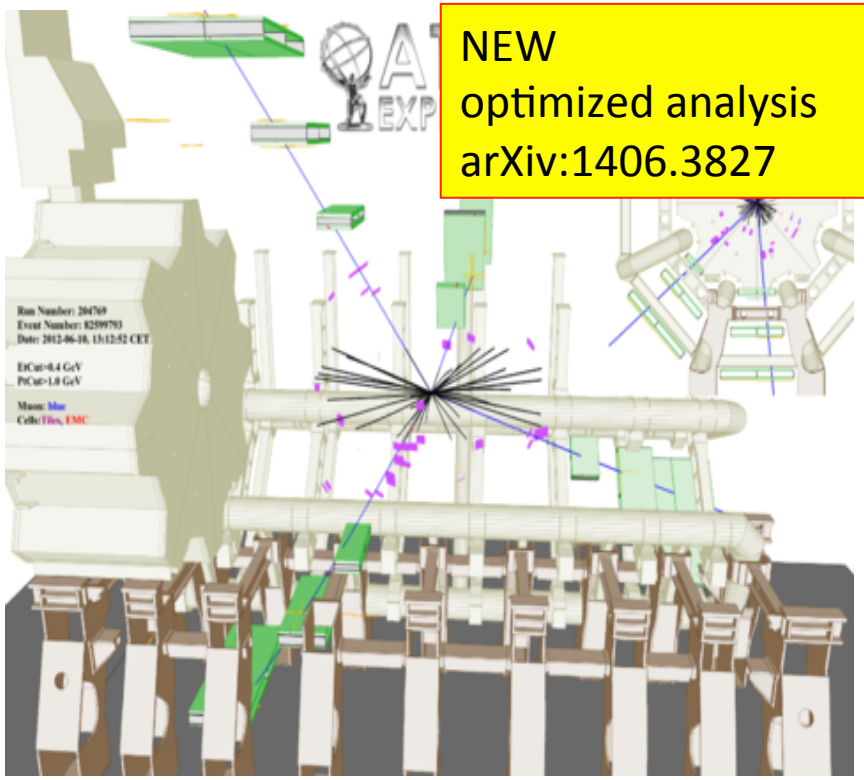
- γγ purity in the selected sample ≈ 80%

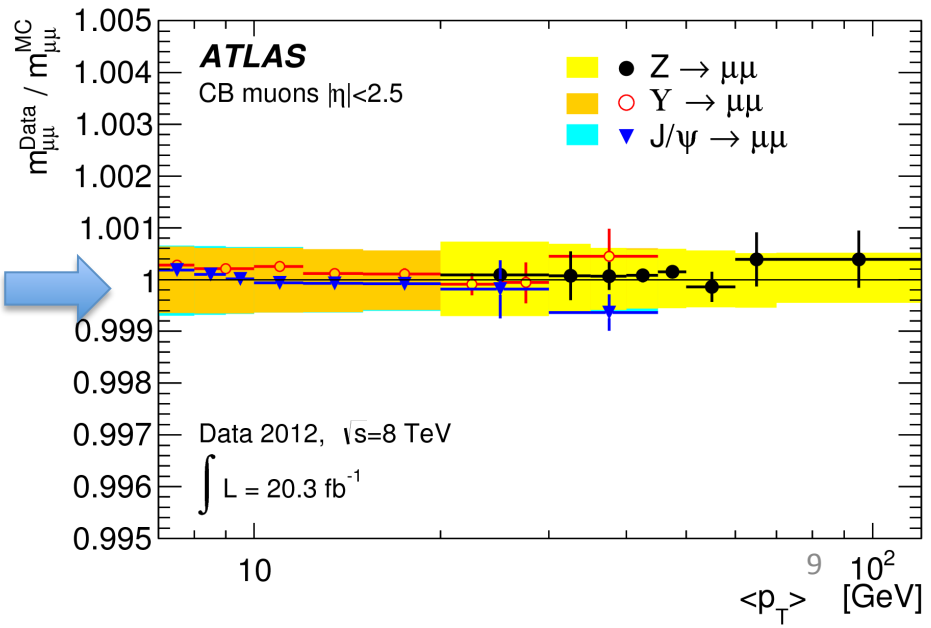
H→ZZ*→4l

- σ × BR ~ 2.5 fb S/B>1
- Small rate but clear topology
  → high purity
- Main background:
  - ZZ* (irreducible)
  - Zbb̄,Z+jets,tt̄
  - suppressed with isolation and impact parameters cuts

- Crucial experimental aspects
  - High lepton acceptances, reconstruction & identification efficiency down to low p_T
  - Good energy/momentum resolution
    New muon calibration with Z and J/ψ, checked with Y (arXiv:1407.3935)
    0.05%(0.2%) in barrel (|η|>2)
    New electron calibration
  - Good control of reducible background

NEW
optimized analysis
arXiv:1406.3827





H→ZZ*→4l ,H→γγ: Mass measurement

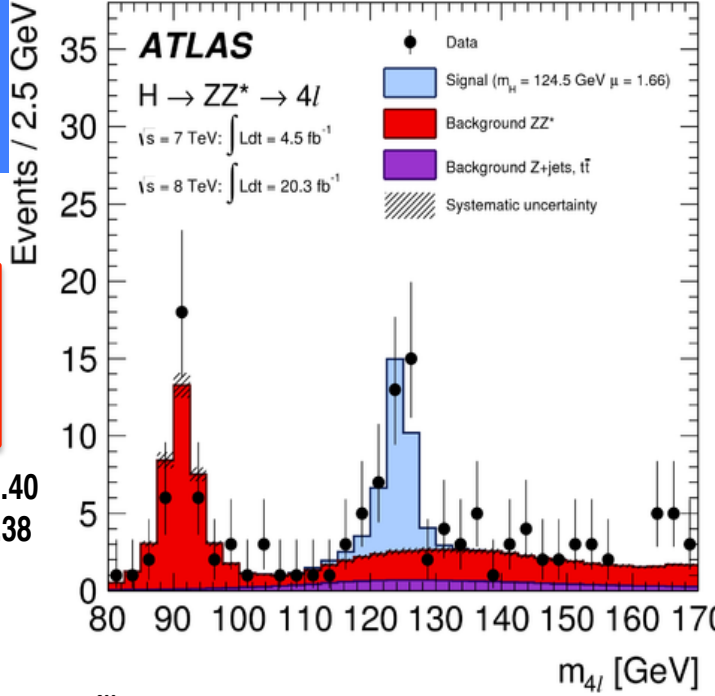
NEW
arXiv:1406.3827

H→ZZ→4l:

$$m_H = 125.51 \pm 0.52(\text{stat}) \pm 0.06(\text{syst})\ \text{GeV}$$
$$\mu = 1.66^{+0.45}_{-0.38}$$

Old result PLB726 $m_H = 124.3^{+0.6}_{-0.5}\ (\text{stat})\ ^{+0.5}_{-0.3}\ (\text{syst})\ \text{GeV}\ \mu = 1.43\ ^{+0.40}_{-0.38}$

- New e/μ calibration
  →negligible impact of scale uncertainties on m_H
- Better e-ID: 2x less fake for same efficiency

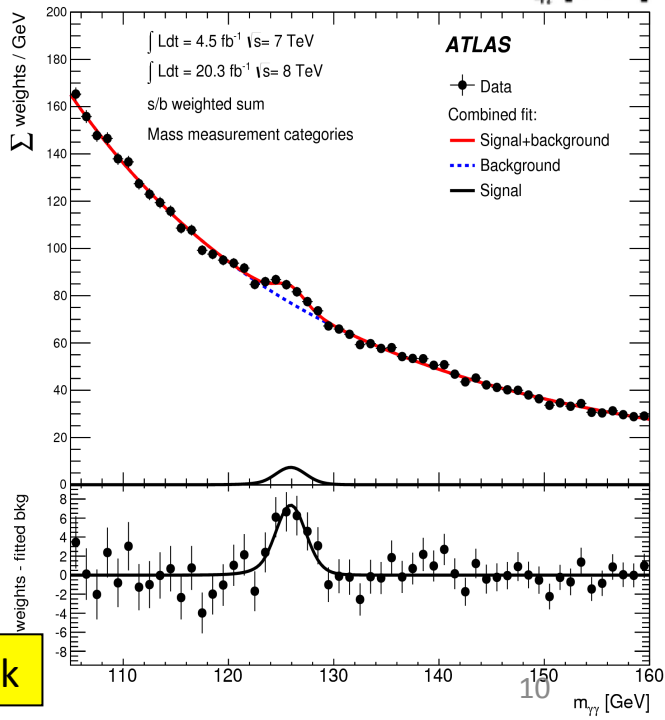


H→γγ:

$$m_H = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})\ \text{GeV}$$
$$\mu = 1.29 \pm 0.30$$

Old result PLB726 $m_H = 126.8 \pm 0.24\ (\text{stat}) \pm 0.7\ (\text{syst})\ \text{GeV}\ \mu = 1.55\ ^{+0.33}_{-0.28}$

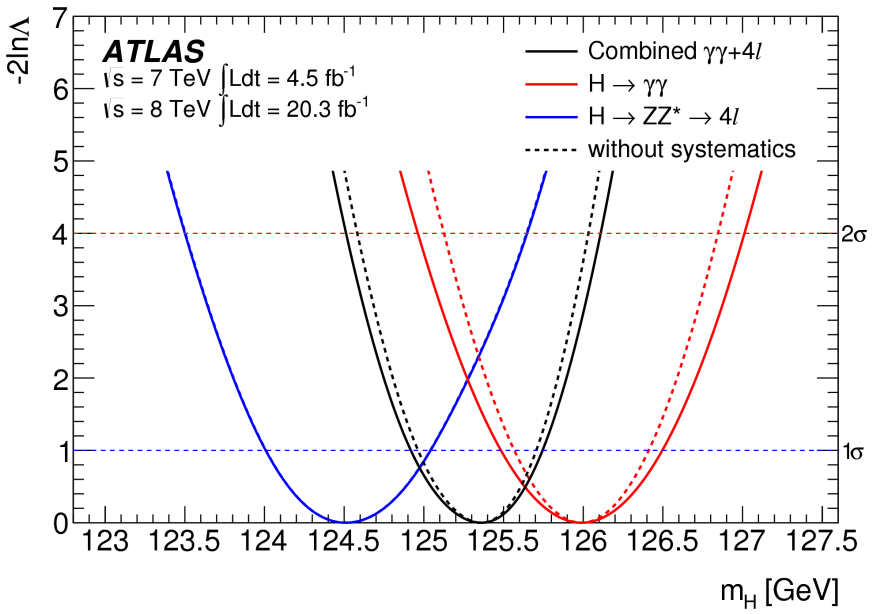
- Systematics uncertainty, dominated by γ E-scale , reduced by a factor 2.5
- Observed/expect shift from calibration change: 0.8 GeV/-0.45 ± 0 .35 GeV

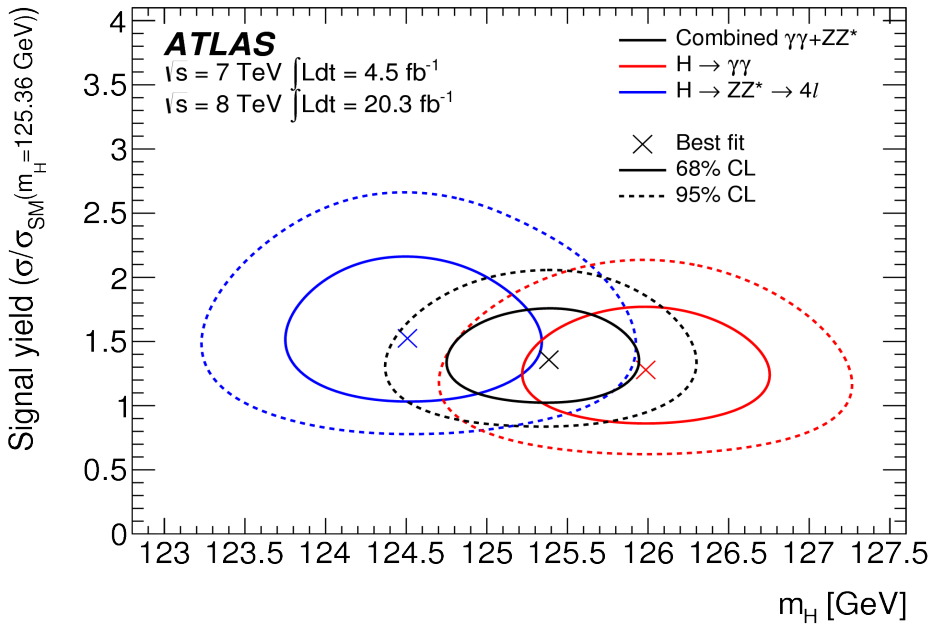


see S. Heim talk

Mass measurement Combination

NEW
arXiv:1406.3827





$$m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})\ \text{GeV}$$

Previous result (PLB 726) $m_H = 125.6 \pm 0.2\,(\text{stat})\ ^{+0.5}_{-0.6}\,(\text{syst})\ \text{GeV}$

see S. Heim talk

- **Total uncertainty reduced by 40%**
- **Systematic uncertainty reduced by factor ~ 3**
- **Compatibility between channels11 2.0σ**
  - **it was 2.5 σ in the previous measurement**

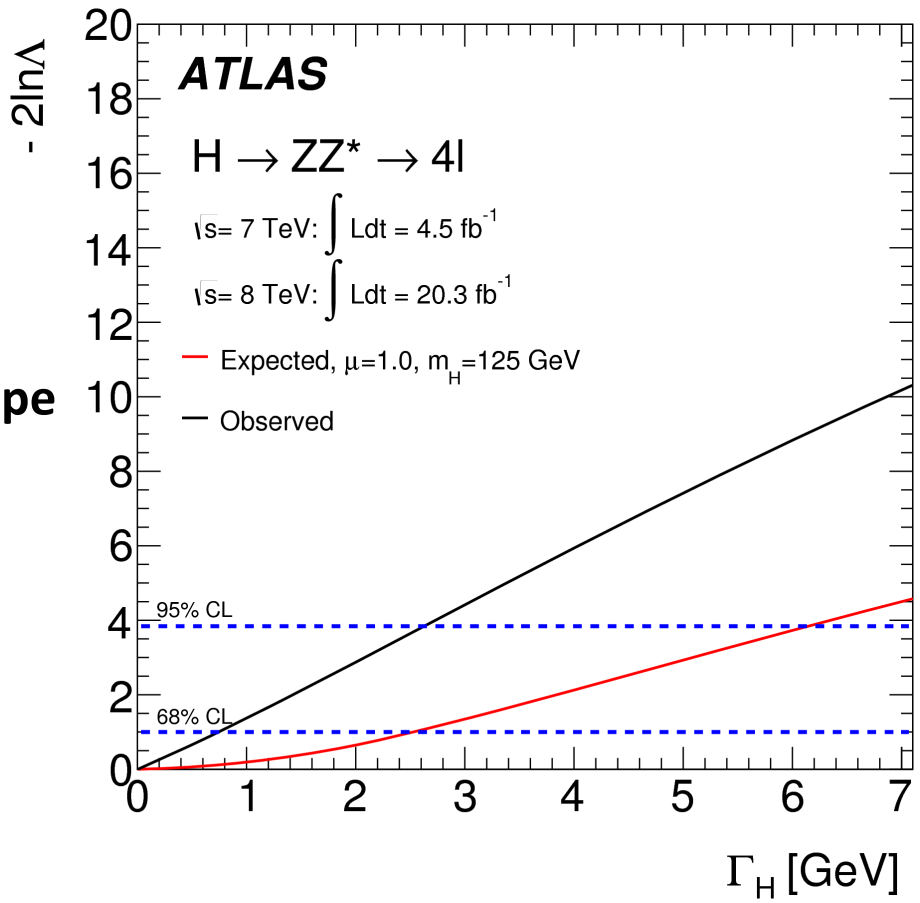
Direct Higgs width measurement

NEW
arXiv:1406.3827

- H → ZZ* →4l and H->γγ analysis to measure Higgs width
- Assumption: no interference with background processes

- H → ZZ* → 4l
  - Event-by-event convolution of detector response with line-shape
  - $\Gamma_H < 2.5$ GeV @ 95% CL (expected 6.2 with μ=1)

- H->γγ
  - $\Gamma_H < 5.0$ GeV @ 95% CL (expected 6.2 with μ=1)



- Far away from SM value of 4 MeV

- Alternative approaches possible:
  Indirect constraint on the Higgs boson width through the measurement of the off-shell signal strength

Indirect Measurement of Γ_H from off-shell H -> ZZ decay

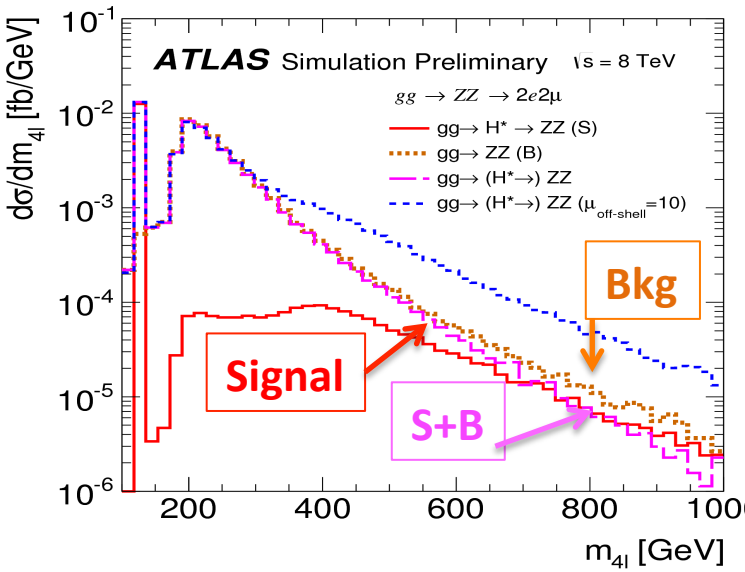
- **High-mass H→ZZ (m>2m$_Z$) provides constraints on Γ_H**

  Kauer and Passarino, JHEP 1208 (2012) 116
  Caola and Melnikov, PRD 88 (2013) 054024
  Campbell, Ellis, and Williams, PRD 89 (2014) 053011

- **Peak region with zero-width approximation**

$$\sigma^{gg\to H^*\to ZZ}_{on-shell} \propto \frac{g^2_{Hgg(on-shell)}\, g^2_{HVV(on-shell)}}{\Gamma_H / \Gamma^{SM}_H}$$

- **Off-shell region** $\sigma^{gg\to H^*\to ZZ}_{off-shell} \propto g^2_{Hgg(off-shell)}\, g^2_{HVV(off-shell)}$



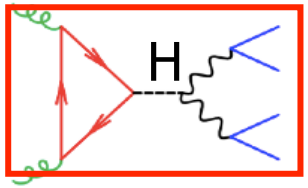
- **Assuming on-shell = off-shell couplings**

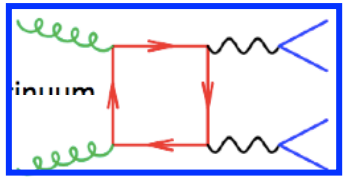
$$\frac{\sigma^{gg\to H\to ZZ}_{off-shell}}{\sigma^{gg\to H\to ZZ}_{on-shell}} \propto \frac{\Gamma_H}{\Gamma^{SM}_H}$$

- **For m_{ZZ}>2m_Z large and negative interference between gg →H→ ZZ signal and SM gg→ZZ background**
- **Large theory uncertainties**

  gg→ZZ known to LO: no (N)NLO K factor

  Results for $R_H^B = K_{gg\to ZZ}/K_{gg\to H\to ZZ}$=[0.5,2]
- **To increase statistics, both 4l and 2l2v final states exploited**

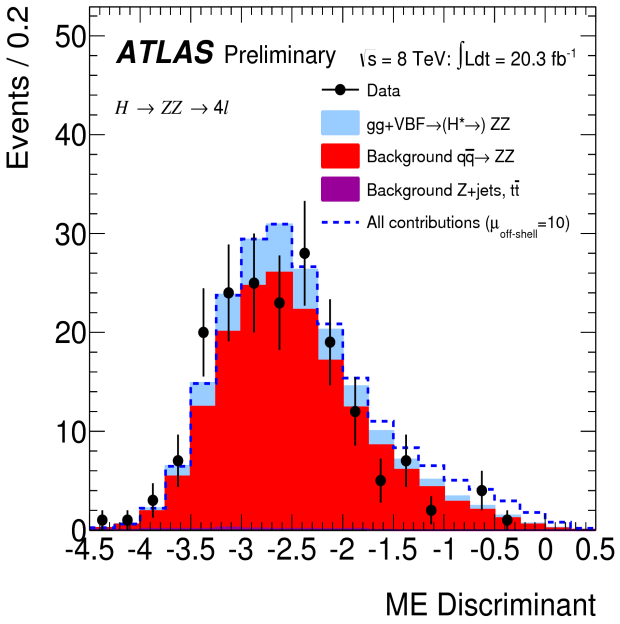


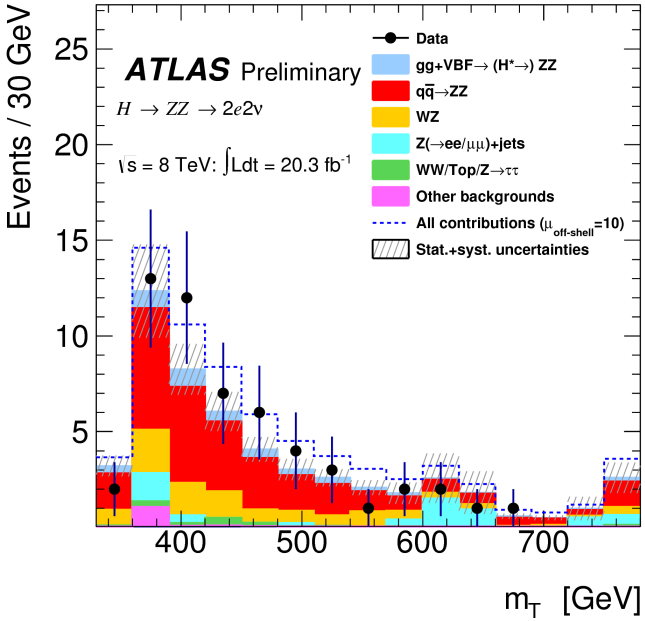


$\mu_{\text{off-shell}}$ from H→ZZ

NEW
ATLAS-CONF-2014-042

- **Analysis strategy: combination of**
  ZZ→4l and ZZ->2l2v
  - **Similar expected sensitivity**
- **ZZ→4l**
  - **Offpeak region m_{4l}=[220,1000] GeV**
  - **Matrix element (ME) kinematic discriminant to separate gg→H→ZZ from gg→ZZ and $q\bar{q}$→ZZ**
  - **fit to ME discriminant shape**
  - **limit on $\mu_{\text{off-shell}}$**
- **ZZ→2l2v**
  - **E_T^{miss}>150 GeV, 76<m_{ll}<106 GeV**
  - **Main backgrounds: $q\bar{q}$→ZZ + diboson**
  - **Off peak Signal region: m_T^{ZZ}>350 GeV**
  - **limit on $\mu_{\text{off-shell}}$**



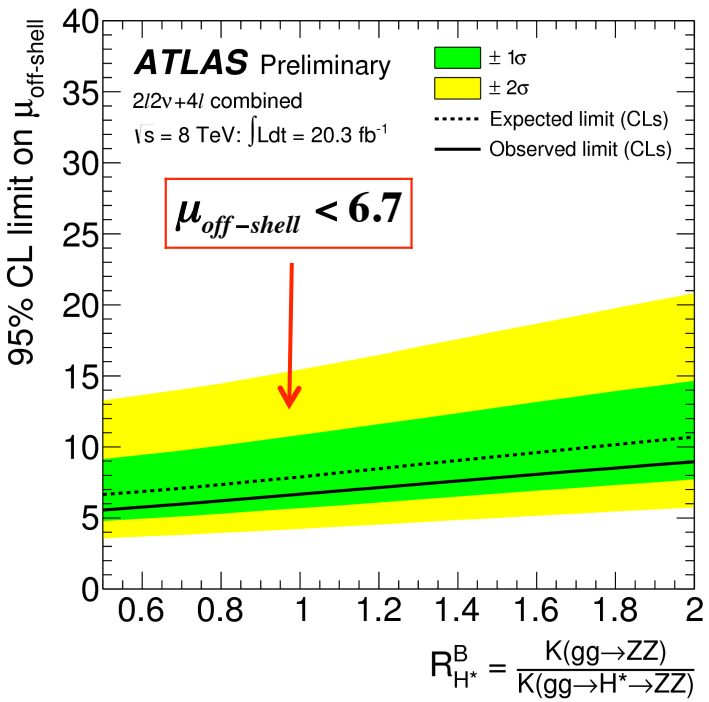


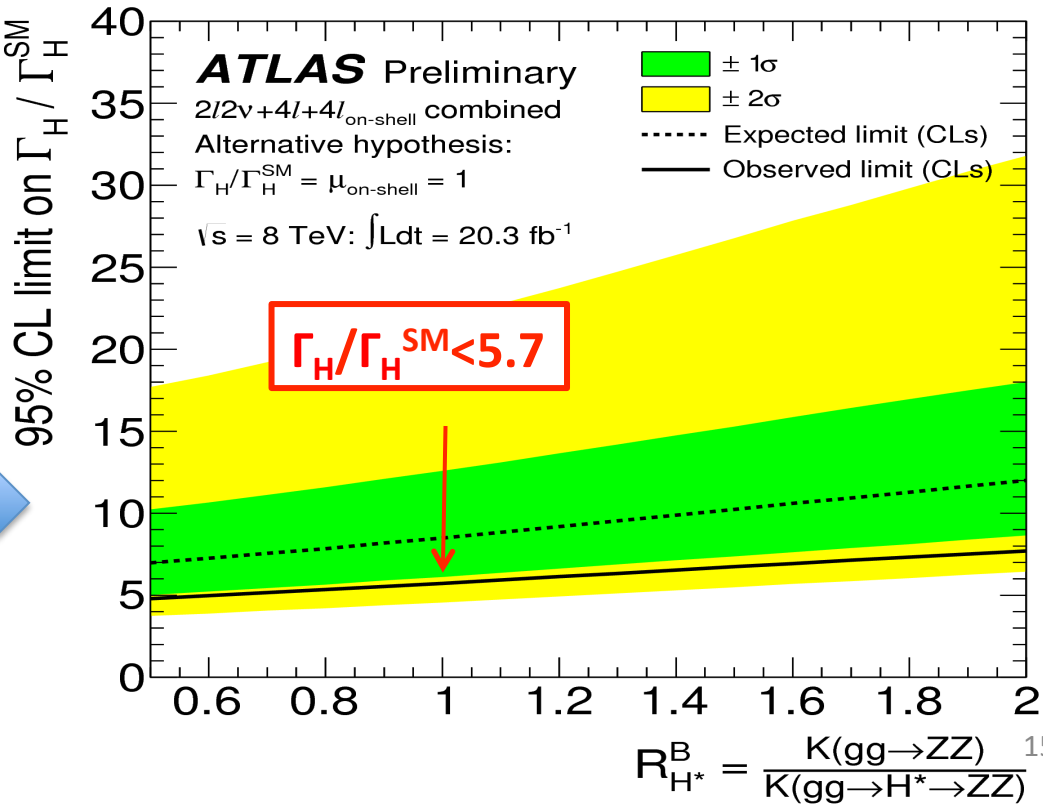
Indirect Measurement of Γ_H

NEW
ATLAS-CONF-2014-042

- **Combination of ZZ→4l and ZZ->2l2ν to fit $\mu_{off\text{-}shell}$**
  - **Small dependence on the ratio between gg→ ZZ and gg→H→ZZ k-factors**
  - **R_H^B is ~ 1 in the soft collinear approximation**
- **Include low-mass region (4l) to fit $\mu_{on\text{-}shell}$**
- **Ratio of $\mu_{on\text{-}shell}/\mu_{off\text{-}shell}$ yields Γ_H**

Γ_H/Γ_{SM}	Observed	Expected μ =1
R_H^B=0.5	4.8	7.0
R_H^B=1	5.7	8.5
R_H^B=2	7.7	12.0





Fiducial and differential cross section

NEW
ATLAS-CONF-2014-044
arXiv:1406.4222

- **Probe several properties of the Higgs boson**
  - **Kinematics, spin and parity, jet activity, production modes, BSM**
- **Analyses designed to minimize model-dependence**
  - **Fiducial region definition**
  - **Compare several theoretical predictions**

$$\sigma_{fid} \cdot BR = \frac{N_{sig}}{\varepsilon_{fid} \cdot L_{\text{int}}}$$

- **$d\sigma/dX$ with X= p_T^H, y_H, cos θ^*, m_{34}, p_T^{jet}, njets, VBF enriched,…**

- **Signal extraction:**
  - **H→ ZZ→4l: Cut-and-count method**
    - **Bin-by-bin yields estimated by subtracting expected background and correcting for detector efficiency and resolution effects**
  - **H→γγ: Fit to $m_{\gamma\gamma}$ in each bin**

- **m_H fixed to the combined γγ+4l value m_H = 125.4 GeV**

H→ZZ*→4l Fiducial and differential fiducial x-section

NEW
ATLAS-CONF-2014-044

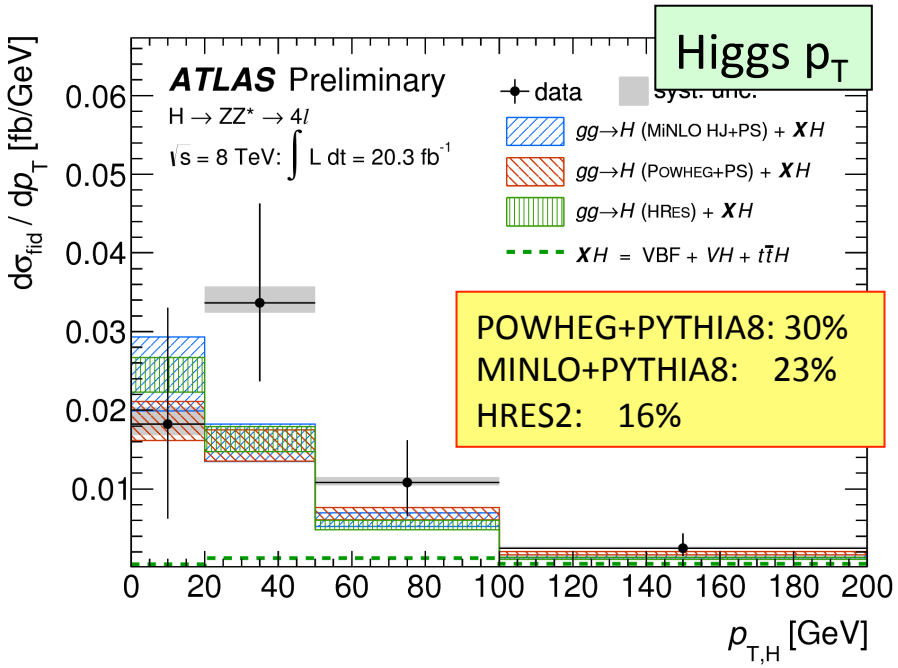
- **Cut in $p_T(l)$, η_l m_{ll} truth quantities**
  to mimic reco level selection cuts and m_{4l}=[118-129] GeV

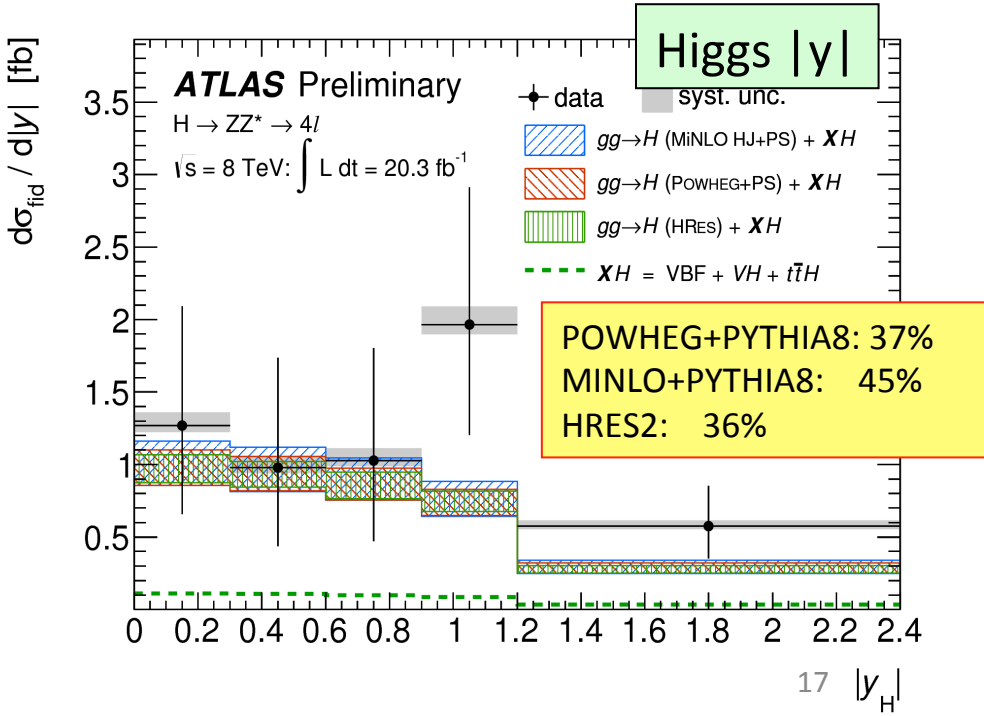
$$\sigma_{fid} = 2.11^{+0.53}_{-0.47}(stat) \pm 0.08(syst)\ fb$$

- **SM prediction**

$$\sigma^{SM}_{fid} = 1.30 \pm 0.13\ fb$$

Differential x-section in fiducial region



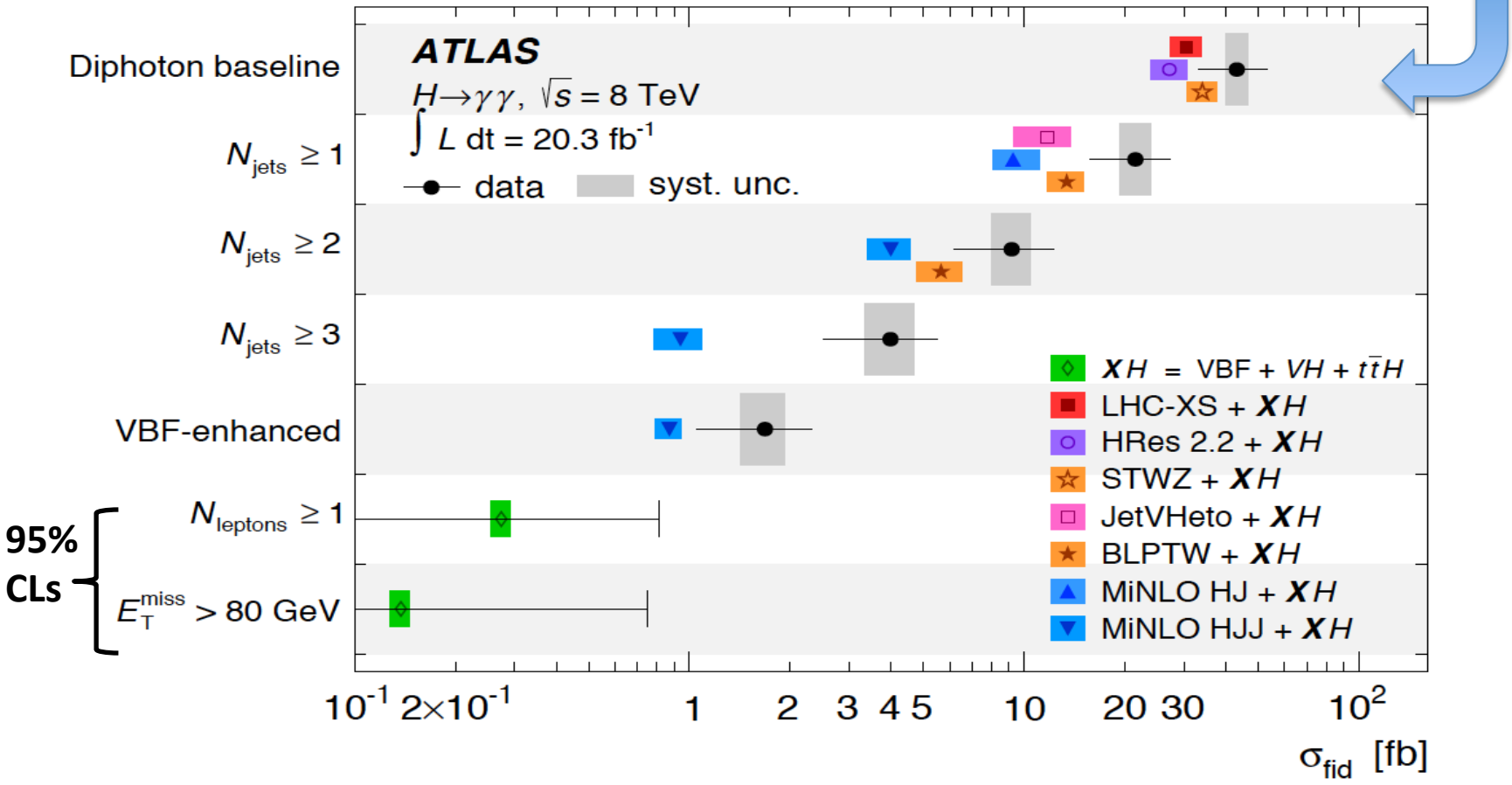


H→γγ fiducial x-section

NEW
arXiv:1406.4222

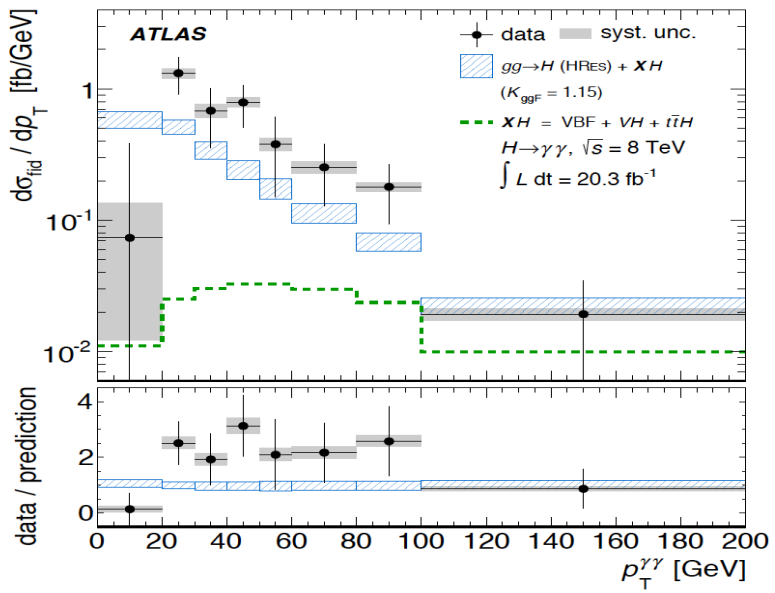
- **Analysis cuts: Two isolated photons with $p_{T1,2}/m_{\gamma\gamma} > 0.35(0.25)$ in $|\eta_\gamma| < 2.37$**
- **7 fiducial regions: inclusive,1,2,3 jets, VBF enhanced,1 lepton, $E_T^{miss} > 80$ GeV**

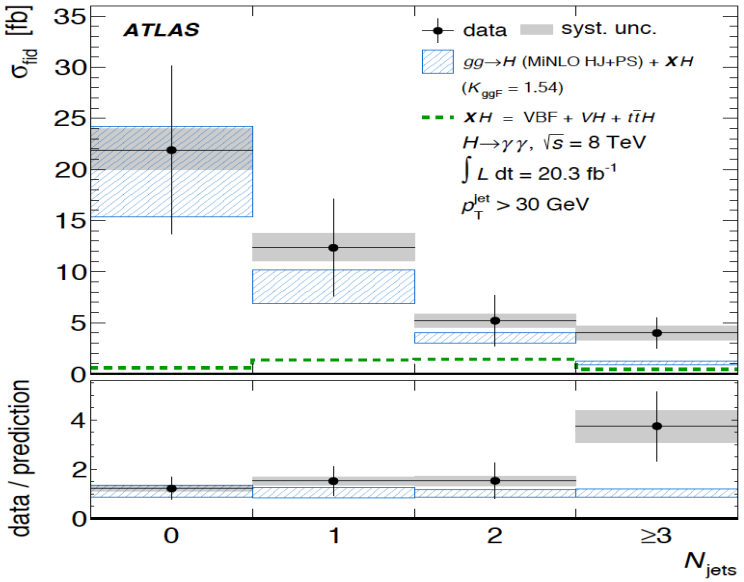
$$\sigma_{fid}(pp \to H \to \gamma\gamma) = 43.2 \pm 9.4(stat)^{+3.2}_{-2.9}(syst) \pm 1.2(lumi)\ fb$$



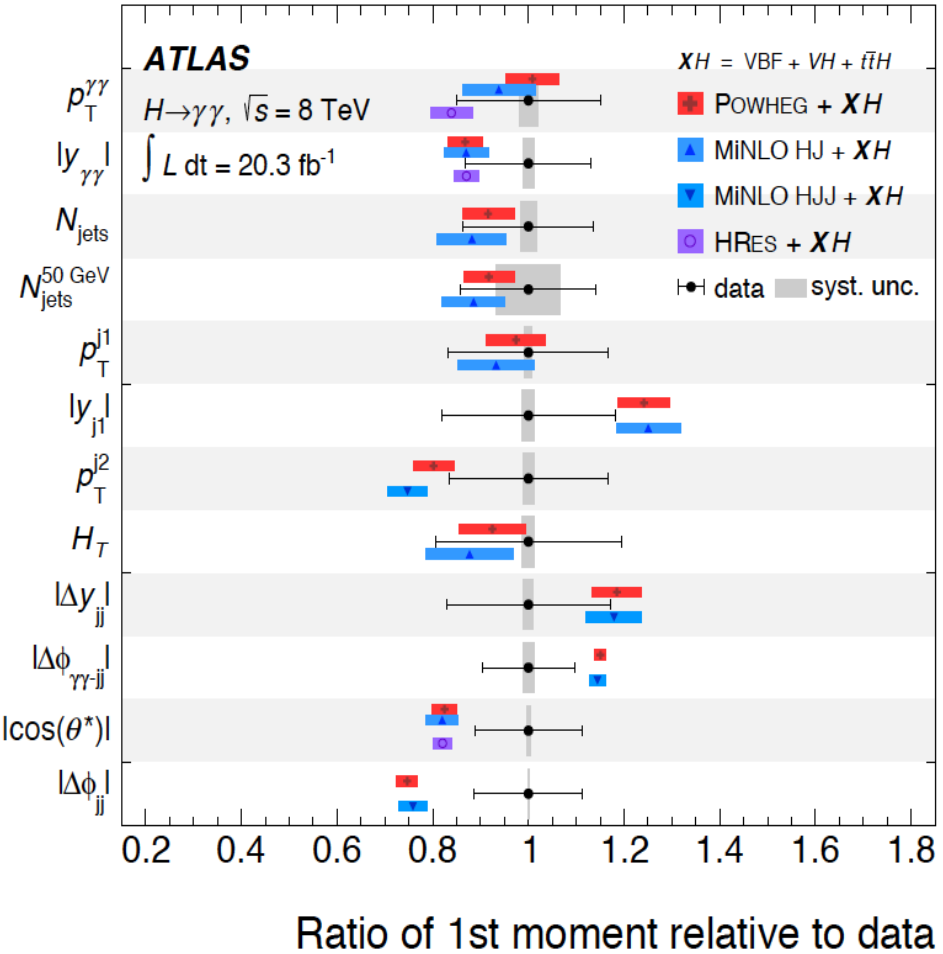
H→γγ differential x-section

NEW
arXiv:1406.4222





- **dσ/dX with X= p_T^H, y_H, cos θ*, φ_{jj}, p_T^{jet}, njets, ..12 differential distributions**
- **Reasonable agreement with SM prediction**



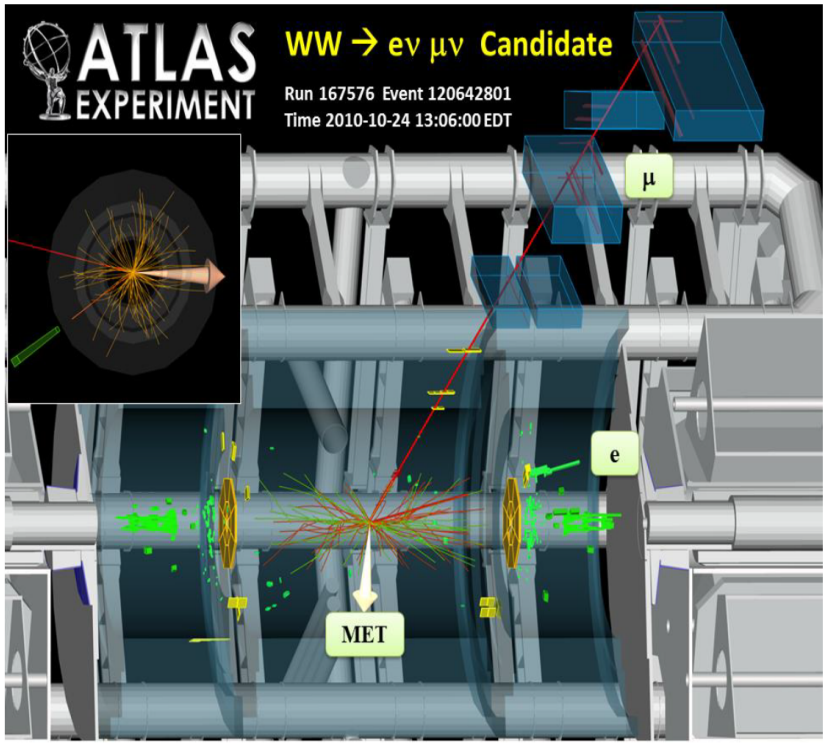
H→WW*→lνlν

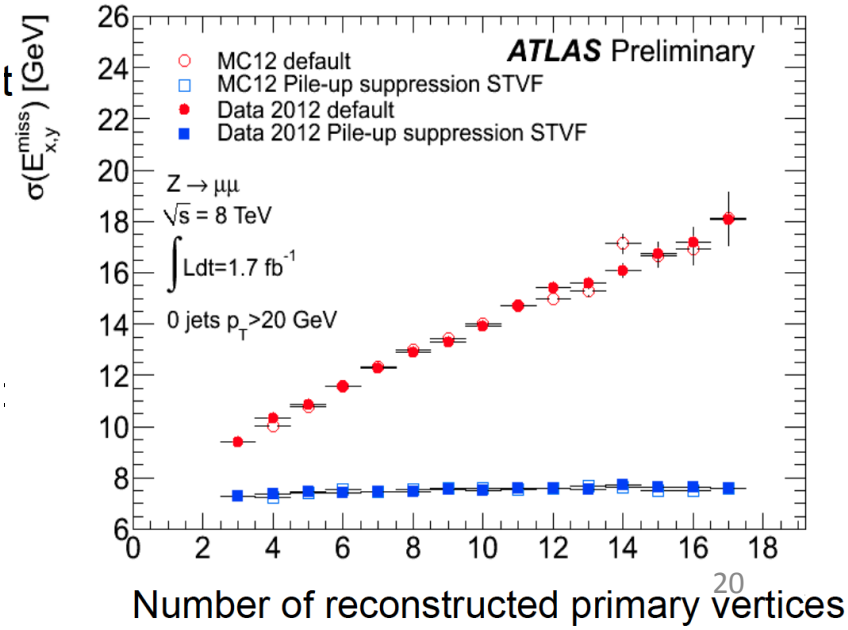
- σ × BR ~ 200 fb S/B = 0.1-0.4
- Signature : opposite-sign leptons (e,μ) and large missing transverse energy
- Large background:
  - Irredubile:Continuum WW
  - Reducible: W+jets, , Wγ(*),top,Z/γ

- Poor mass resolution (~ 20%)

$$m_T^2 = \left(\sqrt{m_{ll}^2 + |\vec{p}_{Tll}|^2} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_{Tll} + \vec{E}_T^{\text{miss}}\right)^2$$

- Crucial experimental aspects
- Missing transverse energy deterioration with PileUp
  - Resolution increases with √$N_{interactions}$
  - use tracks from the primary vertex

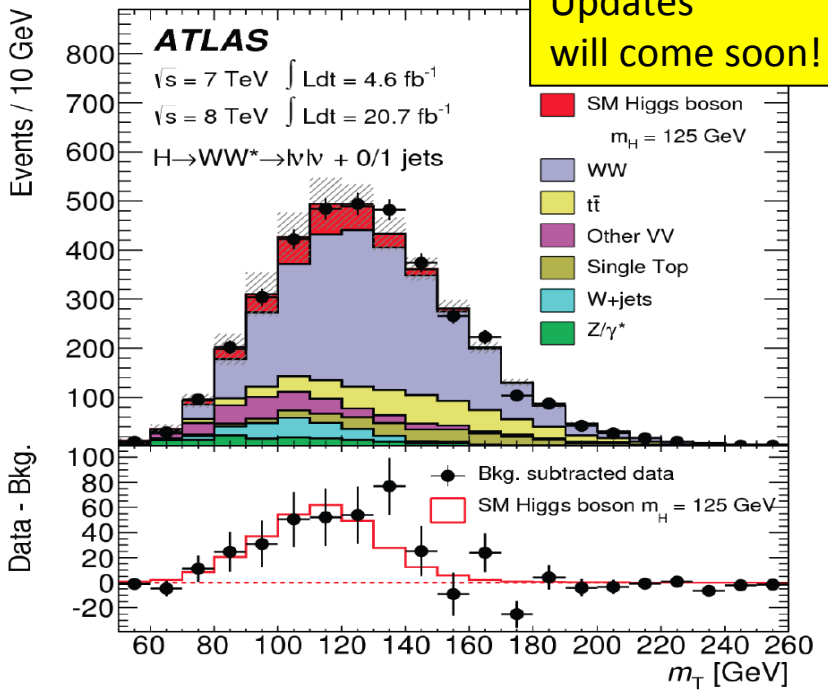




H→WW*→lνlν: cross section and signal strength

Updates will come soon!

- Two high p_T leptons (ee, μμ,eμ, μe)
- Large Missing E_T
- Crucial to understand background and normalize to control regions
- Binned in jet multiplicity
  - N_j = 0,1 optimized for ggF



$$\mu = 0.99 \pm 0.21(stat) \pm 0.21(sys)$$

$$(\sigma \cdot BR)_{obs,8TeV} = 6.0 \pm 1.1(stat.) \pm 0.8(theo.) \pm 0.7(\exp t.) \pm 0.3(lumi.)\, pb$$

$$= 6.0 \pm 1.6\, pb$$

$$(\sigma \cdot BR)_{\exp,8TeV} = 4.8 \pm 0.7\, pb$$

- Systematic uncertainty dominated by signal Xsec

Agreement with SM prediction

H→WW*→lνlν: Higgs boson production and couplings

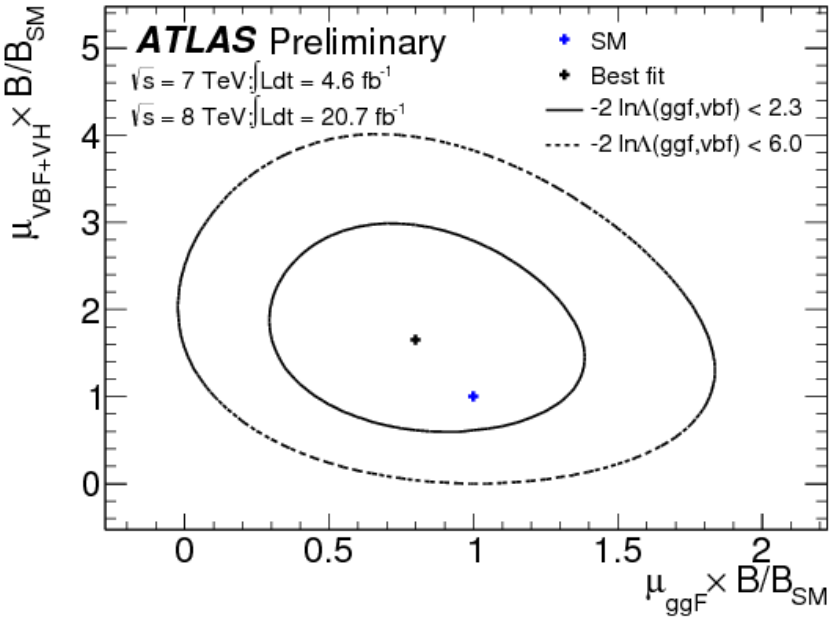
Updates will come soon!

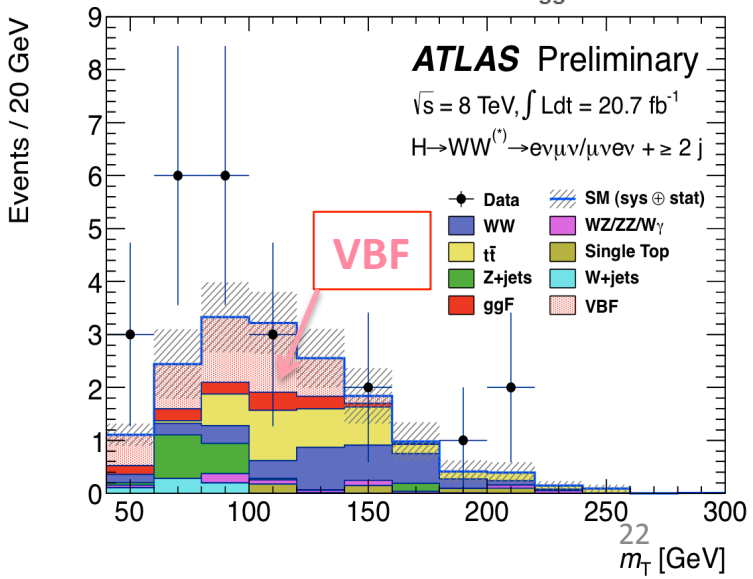
- Two high p_T leptons (ee, μμ,eμ, μe)
- Large Missing E_T
- Crucial to understand background and normalize to control regions
- Binned in jet multiplicity
  - N_j = 0,1 optimized for ggF
  - N_j >= 2 optimized for VBF
- 2D simultaneous ggF vs VBF fit:

$$\mu_{ggF} = 0.8 \pm 0.2(\text{stat}) \pm 0.3(\text{sys})$$
$$\mu_{VBF} = 1.7 \pm 0.7(\text{stat}) \pm 0.4(\text{sys})$$

- Uncertainty on μ_{VBF} dominated by statistics

Agreement with SM prediction

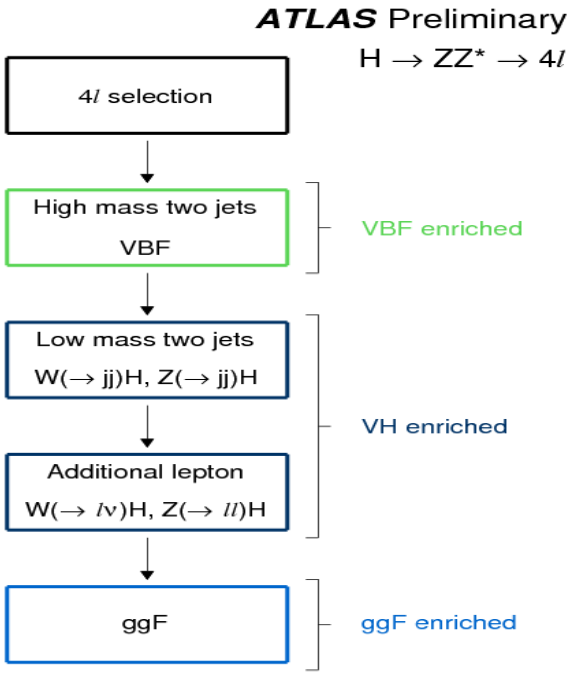


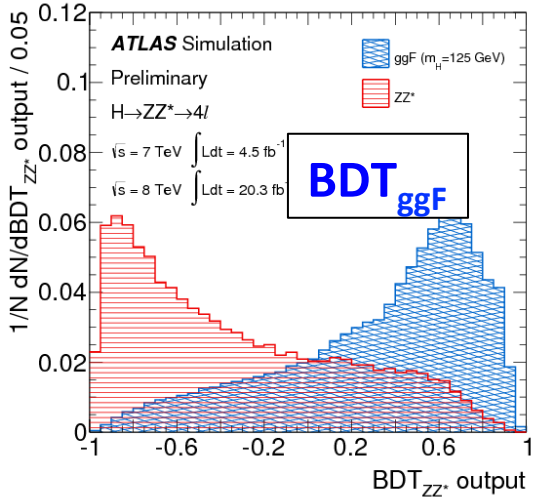


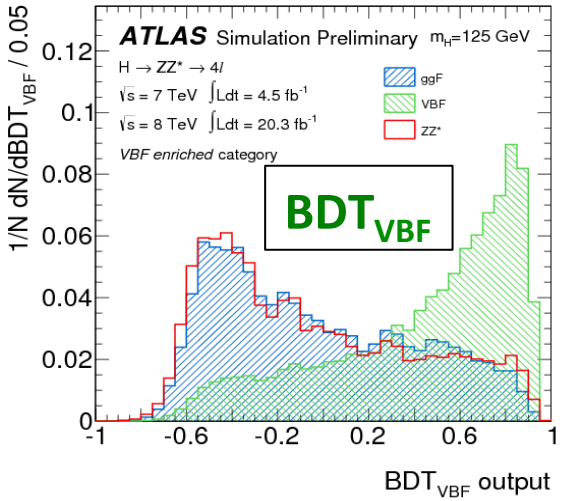
H→ZZ*→4l: Higgs boson production and couplings

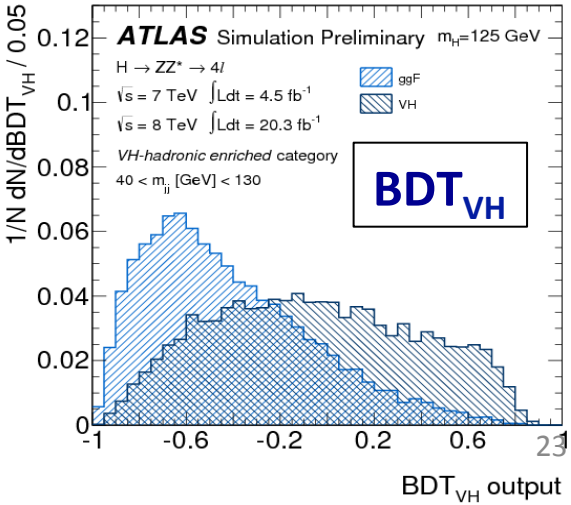
NEW for Higgs-Hunting 2014
To be submitted to PRD

- **Events are assigned to 4 mutually exclusive categories based on production modes**
- **New wrt to previous results (PLB 726)**
  - **Based on the new inclusive H4l analysis used for the mass measurement**
  - **2 VH categories, leptonic and hadronic**
  - **BDT discriminant against ZZ* for ggF**
  - **BDT discriminants for VBF and VH categories**
  - **FSR extended to non collinear photons**
  - **Reducible ll+jet and $t\bar{t}$ bkg determination improved**







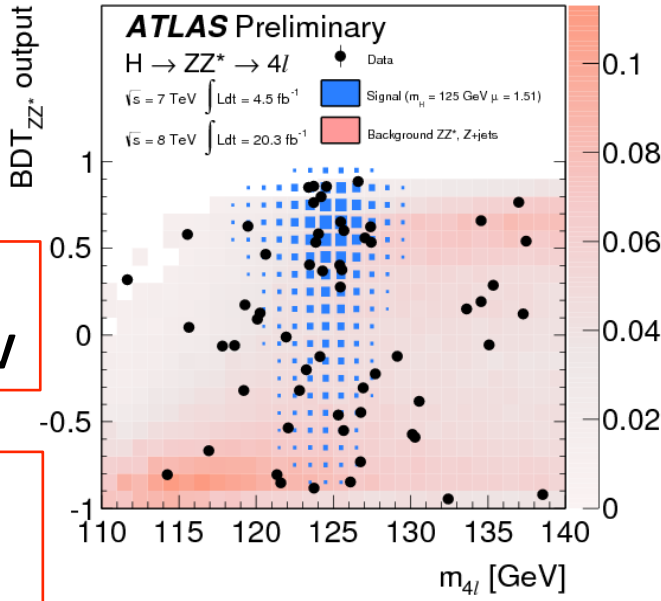


H→ZZ*→4l: inclusive analysis and categories results

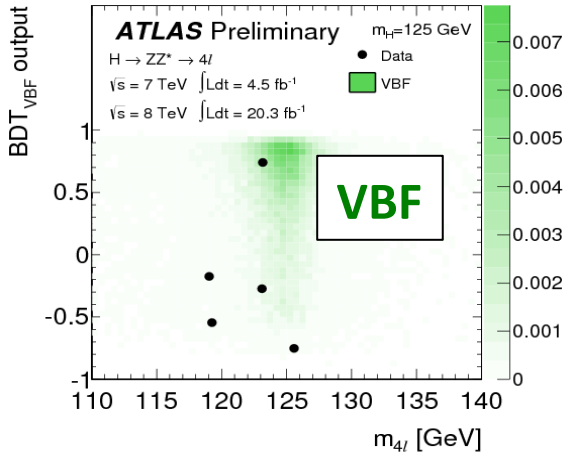
NEW for Higgs-Hunting 2014
To be submitted to PRD

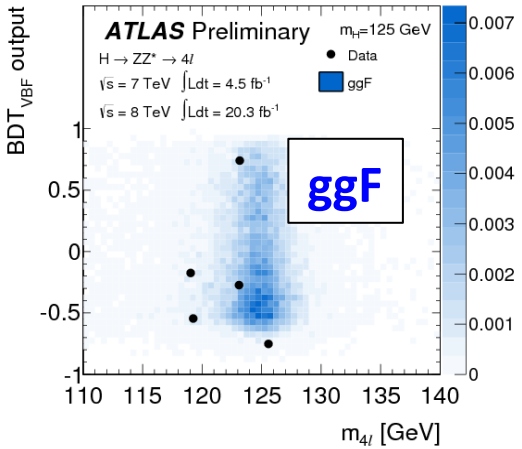
- **Inclusive analysis**
  - **Observed 37 with m_{4l}= [120-130] GeV**
    total expected = 26.5 ± 1.7, 16.2 ±1 .6 from SM Higgs

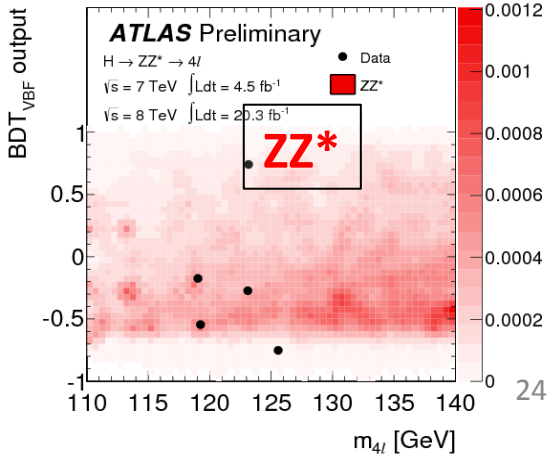
- **Local p_0-value:**
  Observed (expected) = 8.1 σ(6.2) at m_H=125.36 GeV



- **Categories:**
  - **Observed 1 VBF-like with high BDT_{VBF} with m_{4l}= 123.4 GeV, total expected = 1.26 ± 0.15**
  - **No VH candidate is found in m_{4l}[120-130] GeV**







H→ZZ*→4l: results on couplings

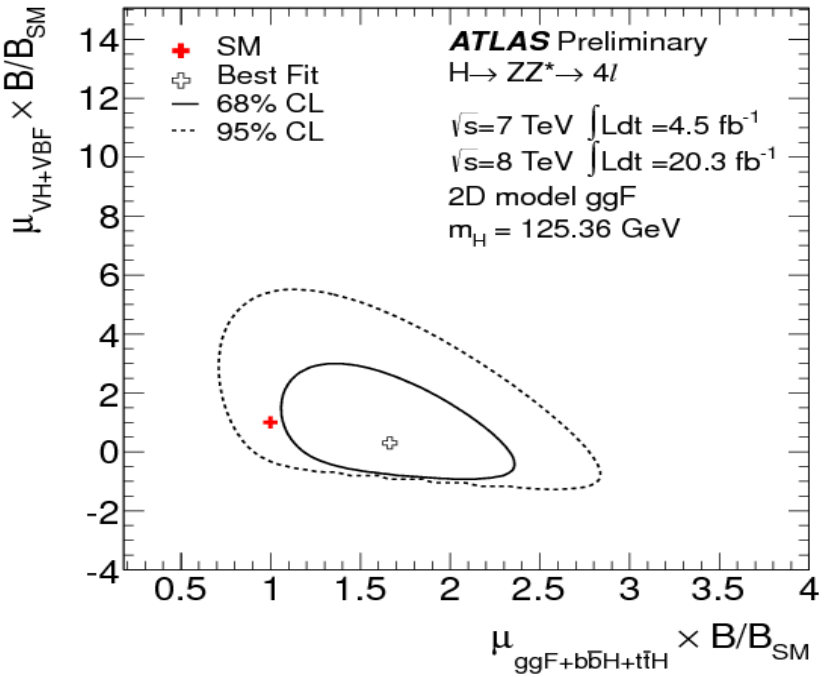
NEW for Higgs-Hunting 2014
To be submitted to PRD

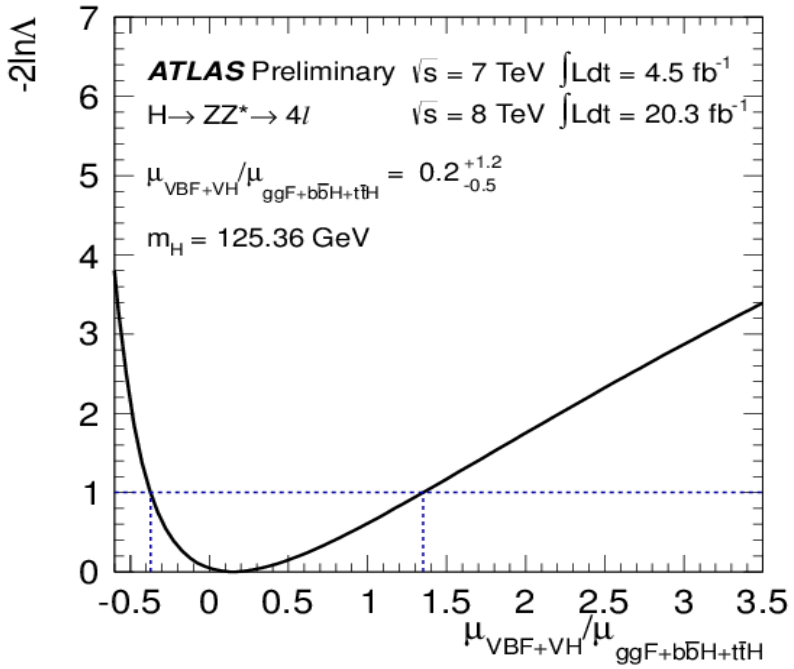
Production mechanism grouped into femionic (ggF,bb̄H,tt̄H) and bosonic (VBF,VH)

$$\mu_{ggF+b\bar{b}H+t\bar{t}H} \times B/B_{SM} = 1.66^{+0.45}_{-0.41}(\text{stat})^{+0.25}_{-0.15}(\text{sys})$$

$$\mu_{VBF+VH} \times B/B_{SM} = 0.26^{+1.60}_{-0.91}(\text{stat})^{+0.36}_{-0.23}(\text{sys})$$

$$\mu_{VBF+VH} / \mu_{ggF+b\bar{b}H+t\bar{t}H} = 0.2^{+1.2}_{-0.5}$$



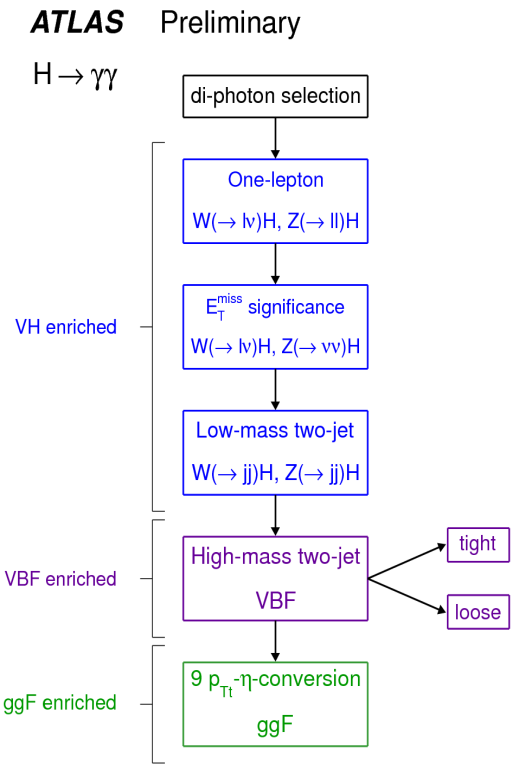


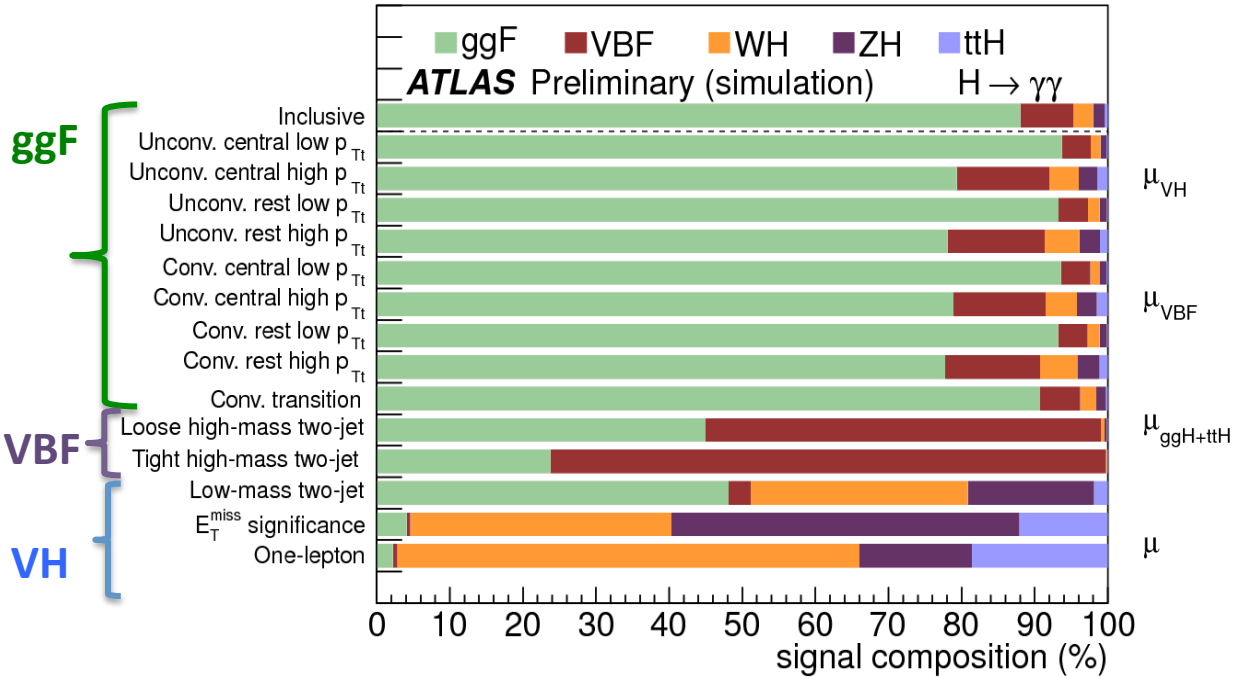
Agreement with SM prediction

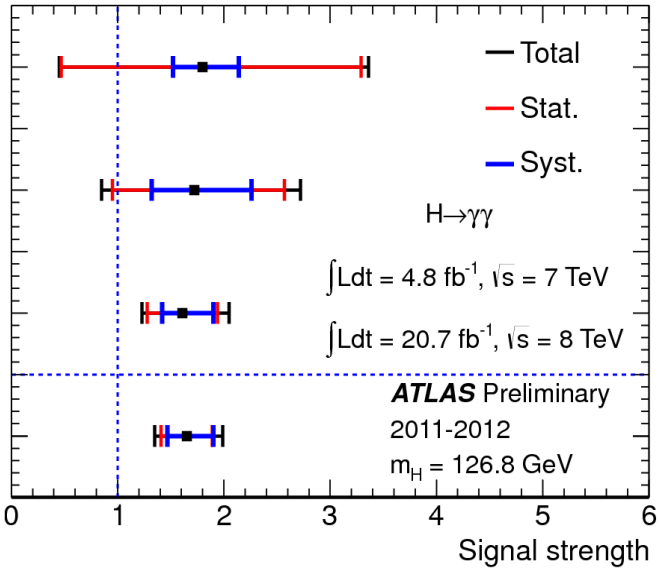
H→γγ: Higgs boson production and couplings

- **Events are assigned to 14 categories**
  - based on S/B, mass resolution, production modes
- **Increase sensitivity to production modes**

Updates will come soon!

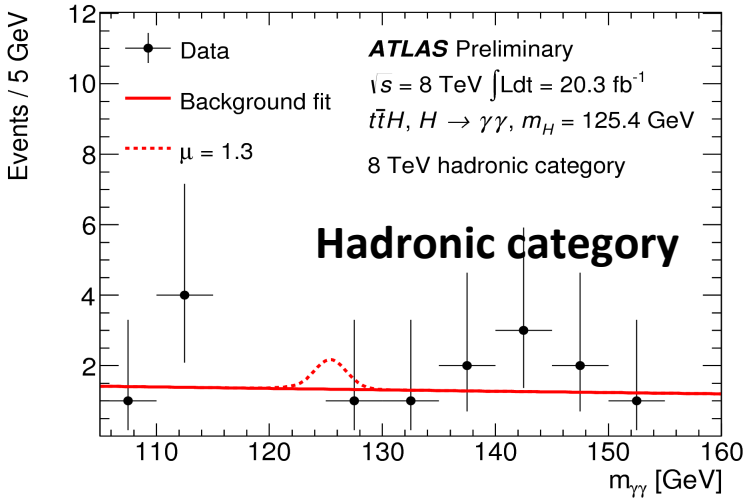


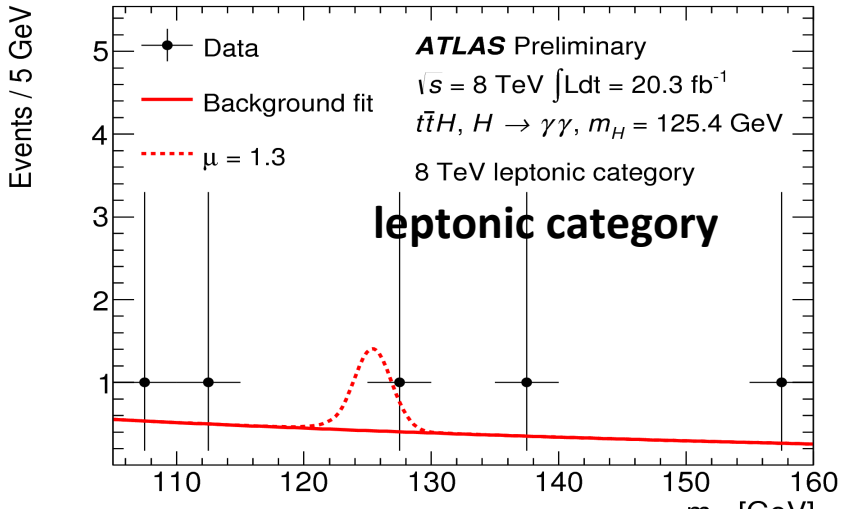




$t\bar{t}H \rightarrow \gamma\gamma$: test production mechanism

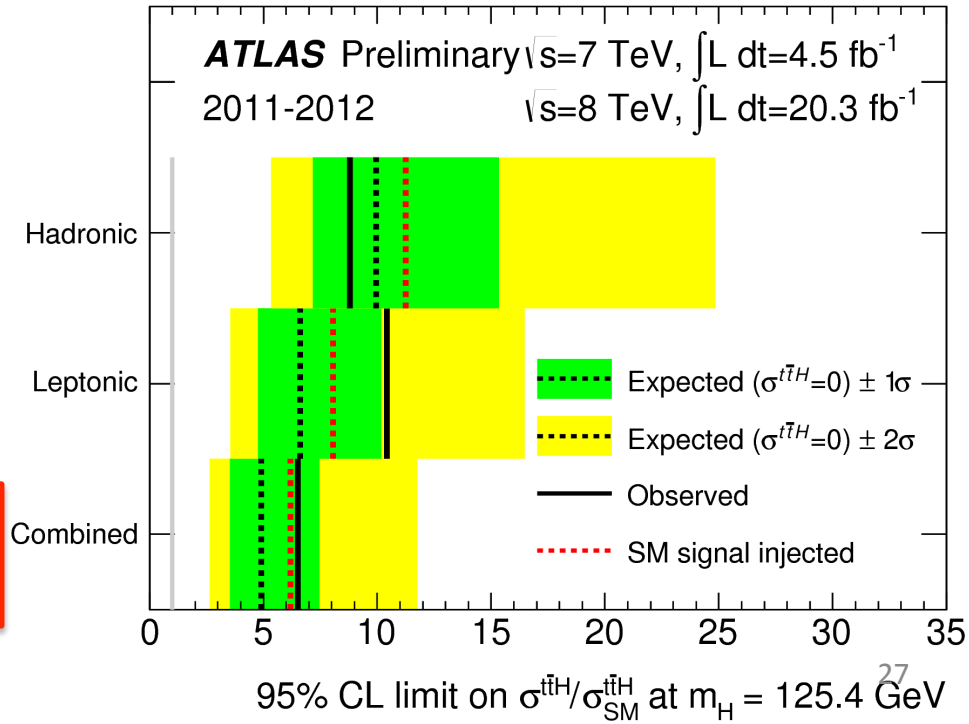
NEW
ATLAS-CONF-2014-043





- **Direct access to top couplings**
- **Analysis strategy:**
  - **Di-photon trigger**
    - **Hadronic $t\bar{t}$ category**
    - **Leptonic $t\bar{t}$ category**
- **Statistically limited**

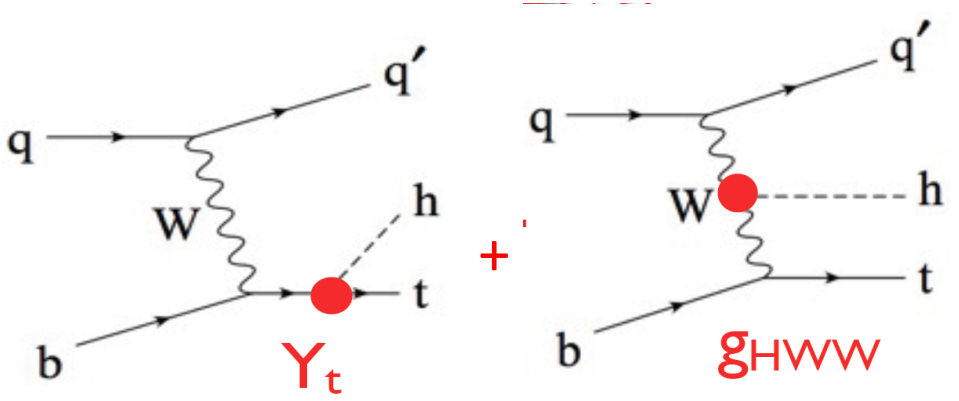
95% CL observed (expected) limit:
6.5 ×SM (4.9 ×SM) for m_H = 125.4 GeV

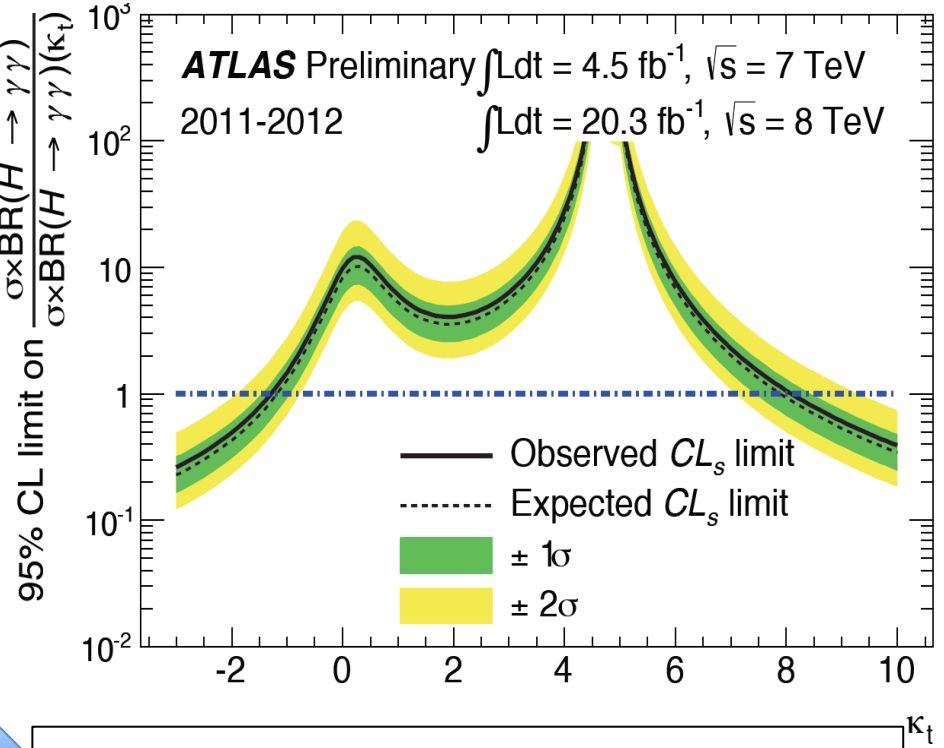


$t\bar{t}H \rightarrow \gamma\gamma$: top Yukawa coupling strength

NEW
ATLAS-CONF-2014-043

- Results on $t\bar{t}H$ x-sec can be interpreted as limits on the strength parameter $k_t = Y_t/Y_t^{SM}$ of the top-Higgs Yukawa coupling
- tH processes also sensitive to Y_t
  - destructive interference between diagrams with Higgs emitted from W or top
- In BSM theories Y_t and g_{HWW} relative sign can be flipped
- If $k_t<0$, tH contribution increases
- k_t changes x-sec of all production mode and BR($H\rightarrow\gamma\gamma$)
- Set limit on inclusive x-sec as a function of k_t





95% CL lower and upper observed (expected) limits on k_t:
-1.3 and +8.1 (-1.2 and +7.9)

Constrain models with negative sign of k_t

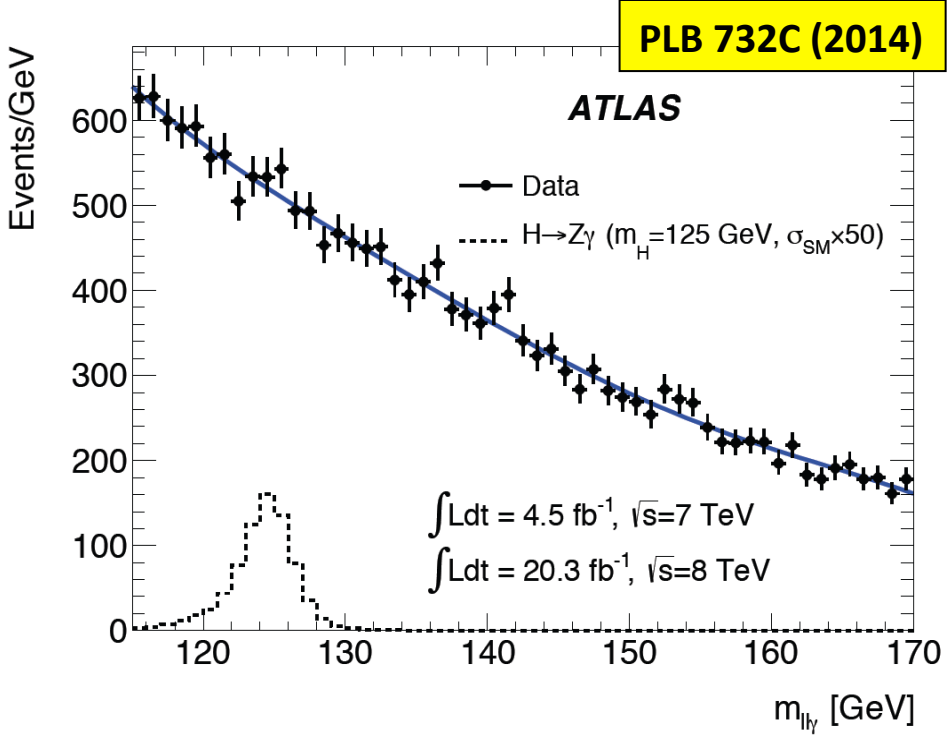
Rare decays: H→Zγ→llγ

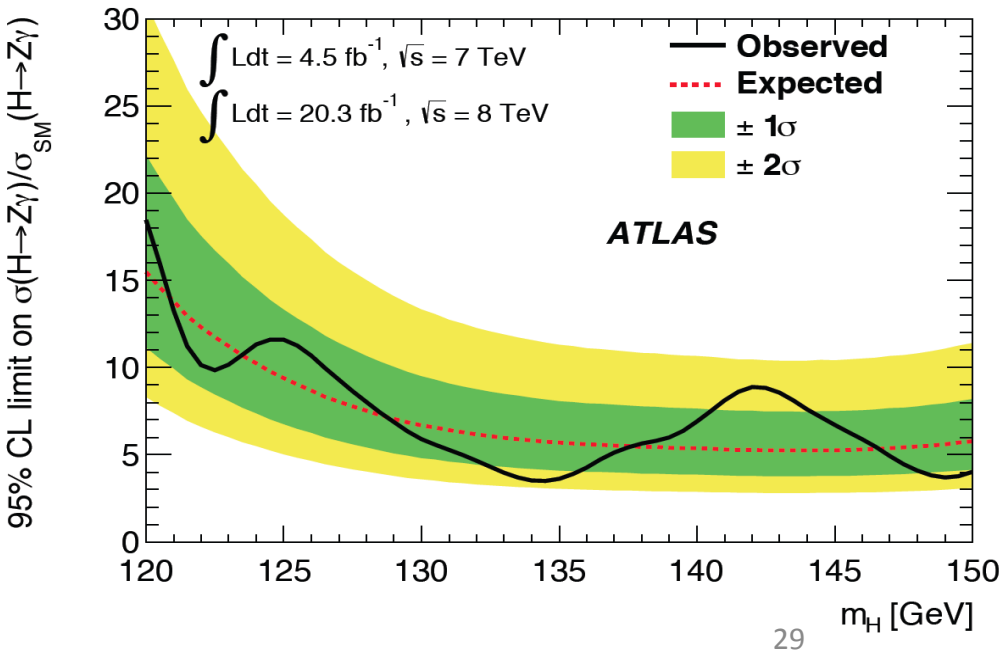
- σ × BR ~ 2.3 fb S/B<1%
- In SM, H→Zγ proceed though loops
  - Sensitive to BSM contributions
- Main background:
  - Zγ (82%), Z+jets (17%)
  - Modeled by analytical functions
- Categories:
  - ee,μμ
  - Δη(Zγ), p_T
- Results
  - 95% CL at m_H=125.5

  Obs. $\sigma(H\to Z\gamma)/\sigma_{SM}(H\to Z\gamma) < 11$

  Exp. $\sigma(H\to Z\gamma)/\sigma_{SM}(H\to Z\gamma) < 9$

PLB 732C (2014)





Conclusions

- **2 years after the discovery, the properties of the Higgs boson measured with increased precision**
- **Most of the measurements are dominated by boson decay channels:**
  - **Mass measured at the 3 per mill level**
  - **Evidence for V-mediated and VBF production**
  - **Evidence for scalar nature 0^+**
  - **Coupling test compatible with SM prediction**

- **In 2015 LHC will increase E_{CM} to 13 TeV and Luminosity to 10^{34} $cm^{-2}s^{-1}$**
  - **increase sensitivity of all the measurement above to test SM predictions**
  - **Search of rare production modes VH,ttH and rare decays (Zγ,..)**

Back-up

H→γγ: mass measurement: Improved calibration for electron and photons

NEW
arXiv:1406.3827

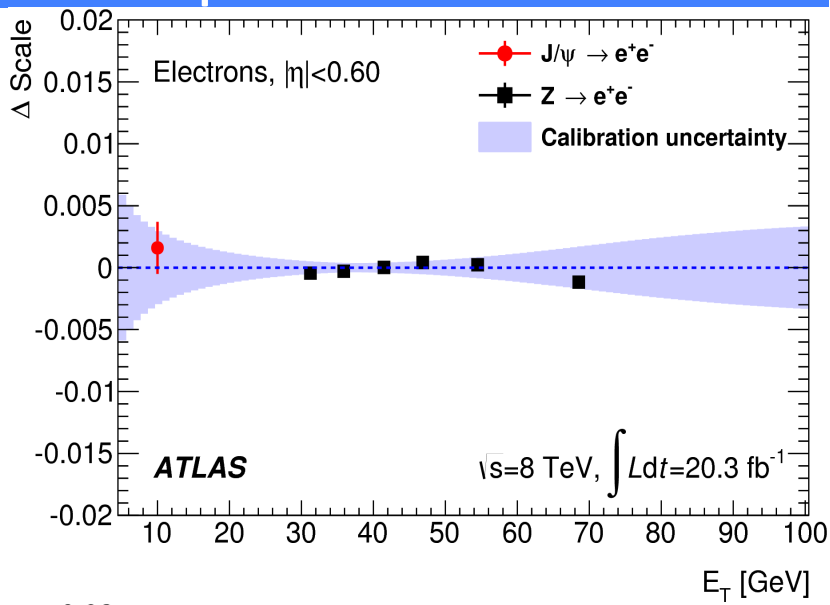
- **Critical for m_H measurement in H→γγ**

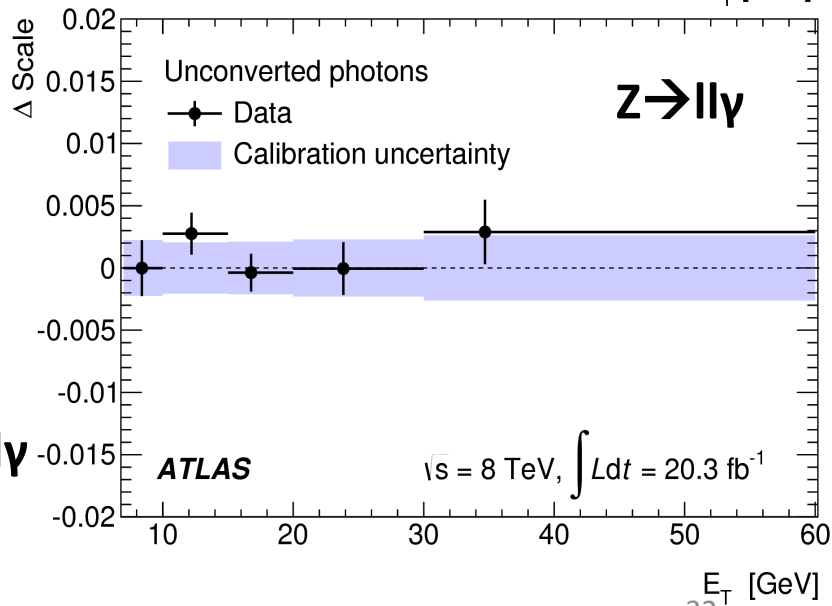
- **EM cluster energy via MVA regression**
  → 10% improvement on $m_{\gamma\gamma}$ resolution
- **layers intercalibration using Z→μμ:**
  →1-2 % for EM layers 1-2

- **Accurate knowledge of material in front of the EM calorimeter: 2-10 % X_0**

- **Energy scale and resolution from Z→ee :**
  - **scale accuracy: few 10^{-4}**
  - **resolution accuracy: few 10^{-3}**

- **Linearity and extrapolation to photons checked with Z→ee vs E_T(e), J /ψ→ ee, Z→llγ**
  - **0.03-0.05% for 40 GeV E_T electons**
  - **0.2-0.5% for photons**





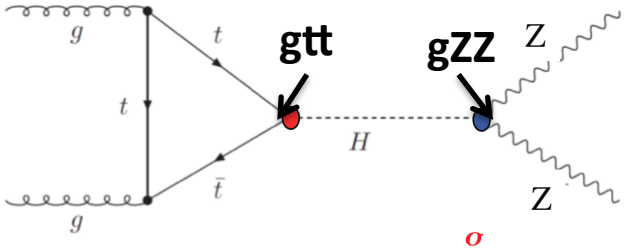
Test of Boson and Fermion Couplings

- **Follow recommendation from LHC HXSWG, assuming:**
  -1 resonance + zero width approximation+SM lagrangian tensor structure

$$\sigma \cdot BR(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{hh}}{\Gamma_H}$$

See N. Andari talk

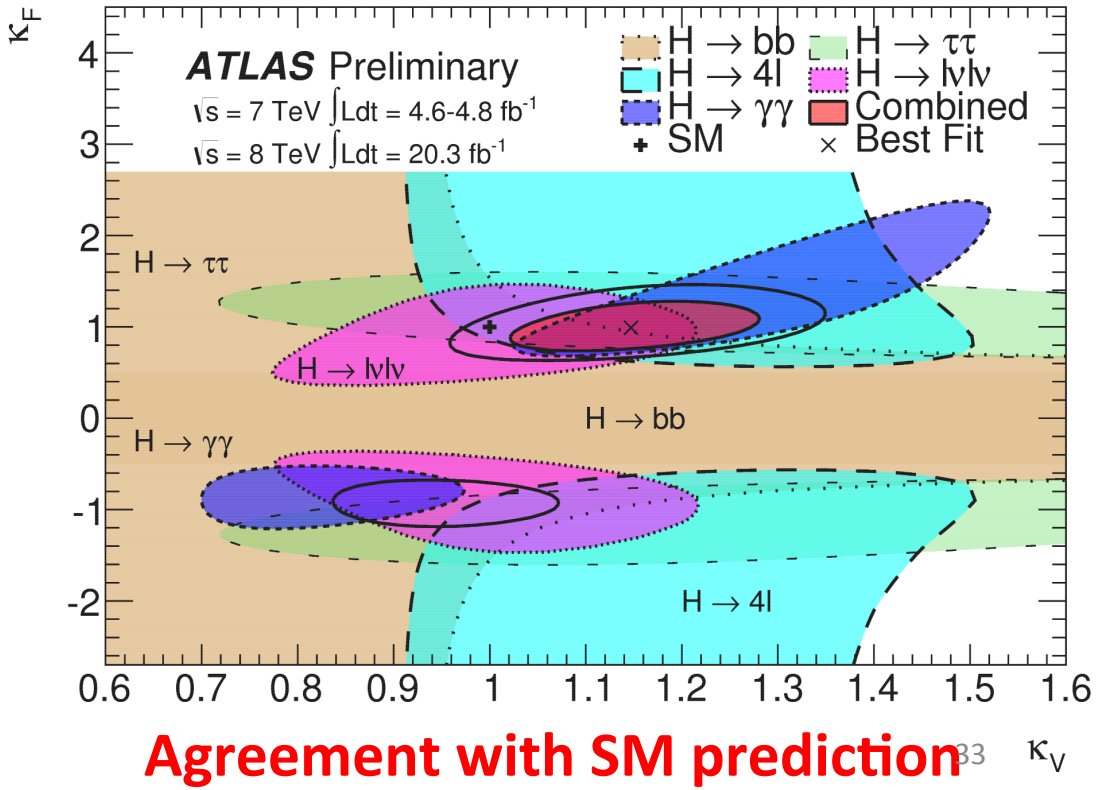
- **test SM predictions exploiting correlation between production and decay modes with current precision**



- **Test deviation from SM:**
  - **$\kappa = g/g_{SM}$**
- **Assume $\kappa_V(=\kappa_Z=\kappa_W), \kappa_F(=\kappa_b=\kappa_t=..)$**
- **$\kappa_{g,\gamma}$ loop scaling = $\kappa_{g,\gamma}(\kappa_F, \kappa_W)$**

$$\kappa_V = 1.15 \pm 0.08$$

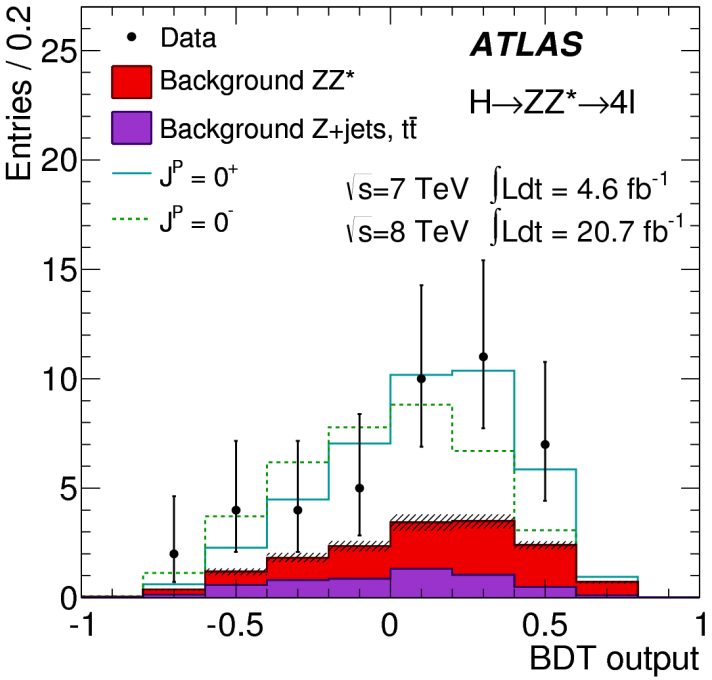
$$\kappa_F = 0.99^{+0.17}_{-0.15}$$



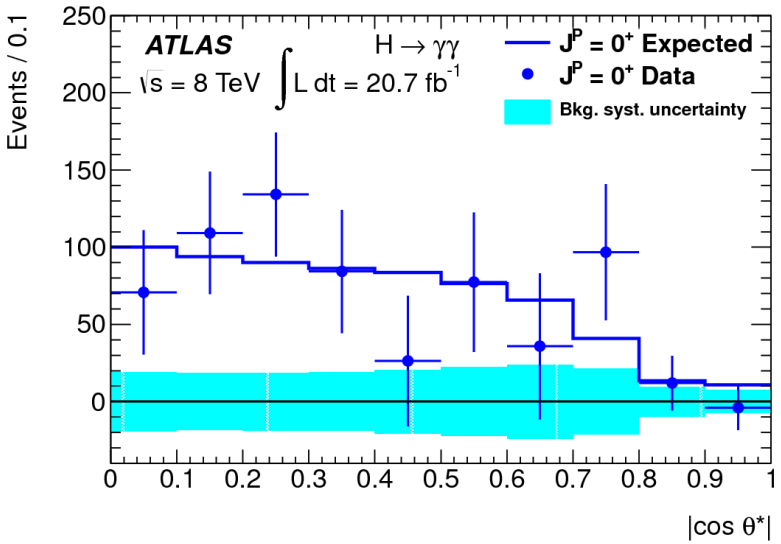
Agreement with SM prediction

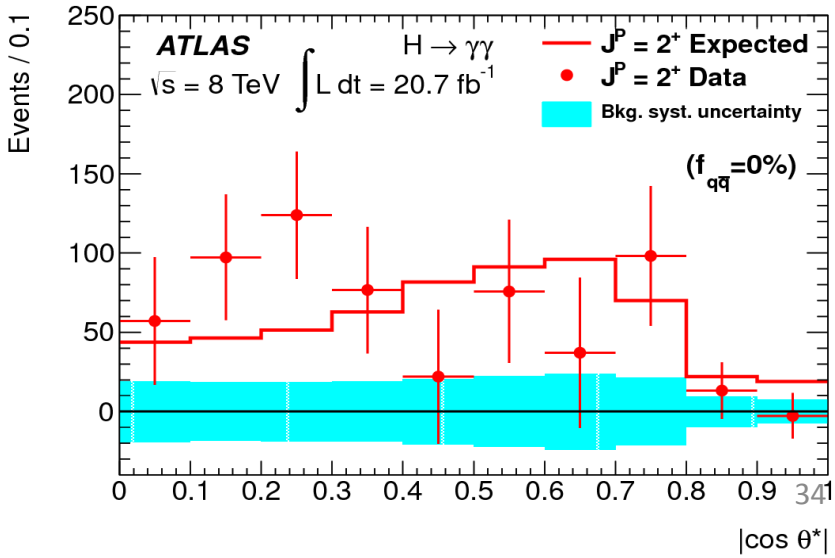
Spin-Parity Determination from Higgs to dibosons

- **SM Prediction: $J^P = 0^+$, tested against alternative specific models: $0^-, 1^+, 1^-, 2^+_m$ (graviton-like tensor)**
- **$H \to ZZ^* \to 4l$: 2 masses (MZ1,MZ2) and 5 angles combined with a BDT. Test $J^P = 0^+$ and 2^+_m**
- **$H \to \gamma\gamma$: decay angle $\cos\theta^*$, Test $J^P = 0^+$ and 2^+_m**
- **$H \to WW^* \to l\nu l\nu$: $\Delta\varphi_{ll}, M_{ll}$, ..combined with a BDT. Test $J^P = 0^+, 1^\pm$ and 2^+_m**
- **Combination: $0^-, 1^+, 1^-, 2^+_m$ models excluded at >95%CL**



See N. Andari talk

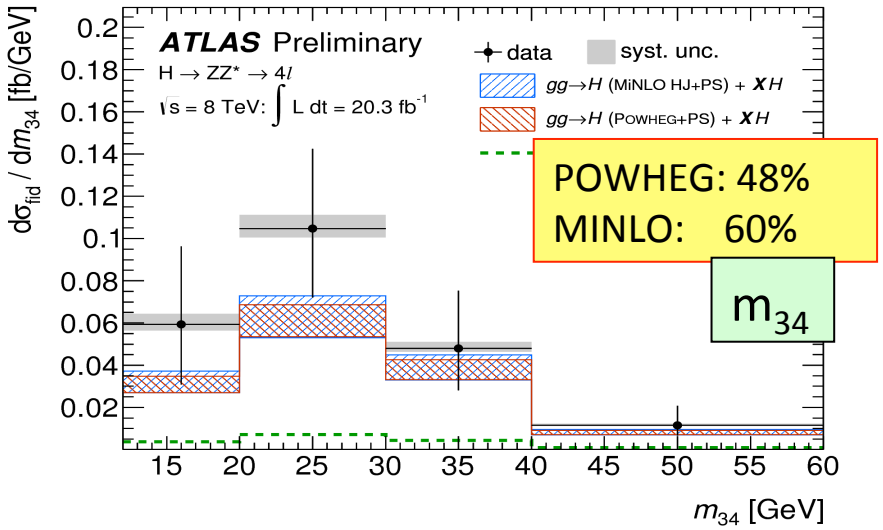


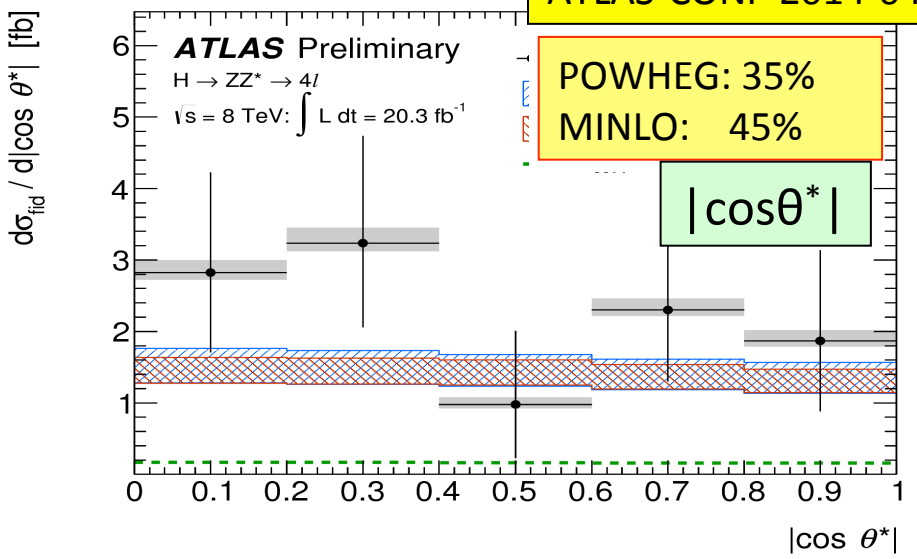


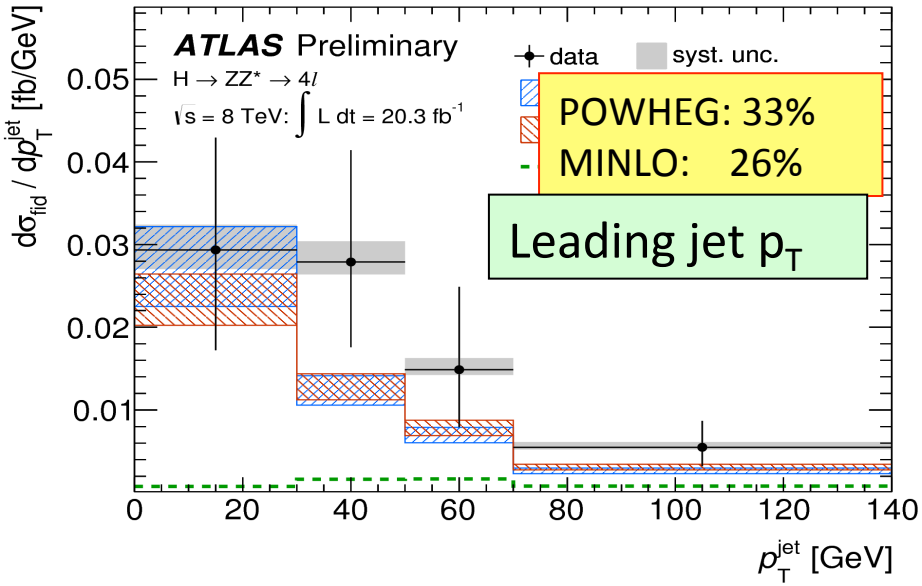
H→ZZ*→4l Differential fiducial cross-sections

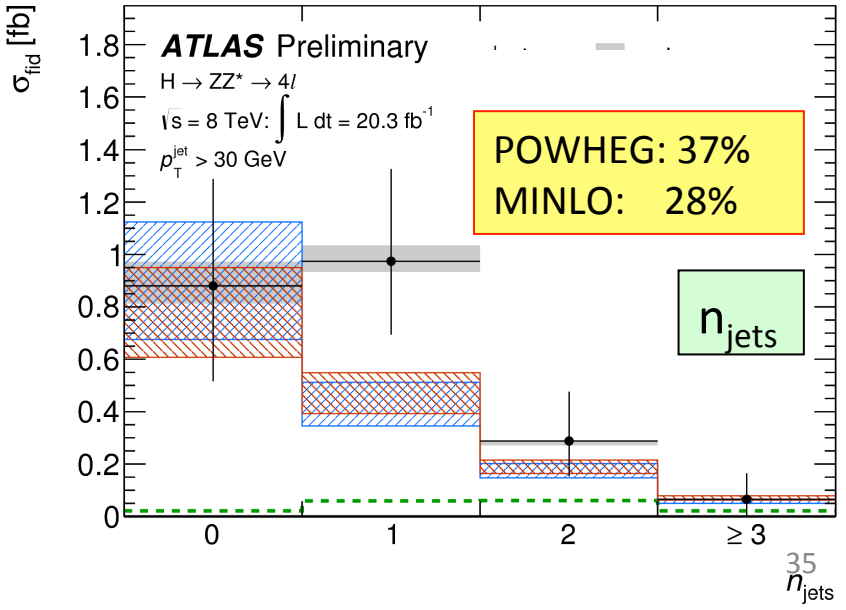
Reasonable agreement with SM prediction

NEW
ATLAS-CONF-2014-044







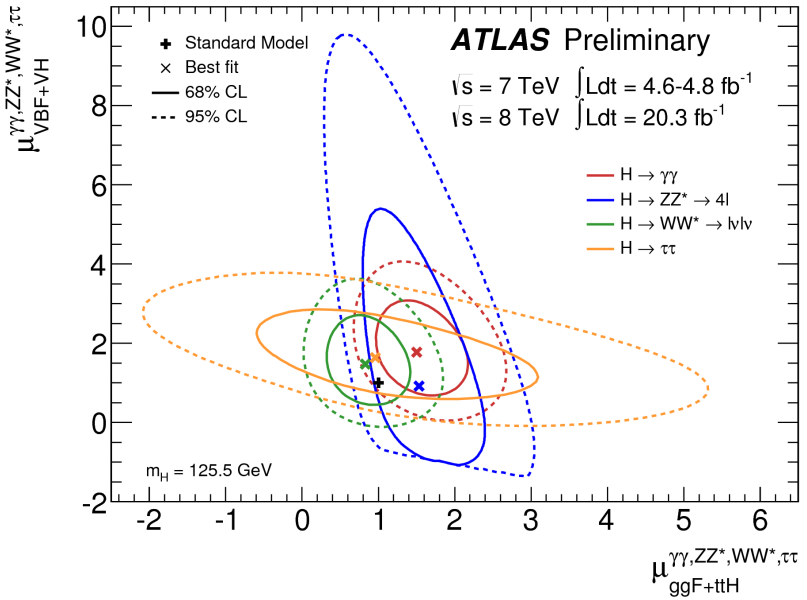


Combination: test Higgs production mechanism

- **Disentangle production modes:**
  -Vector-boson mediate (VBF+VH) from fermion mediated (ggH,ttH)
- **Fit to $\mu_{VBF+VH}/\mu_{gg+ttH}$ in different channels (BRs cancel out)**

- **VBF observed at 4.10σ**
- **VB mediated production compatible with SM prediction**

See N. Andari talk



Updates will come soon!