Overview of ATLAS Higgs Results

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on behalf of the ATLAS Collaboration

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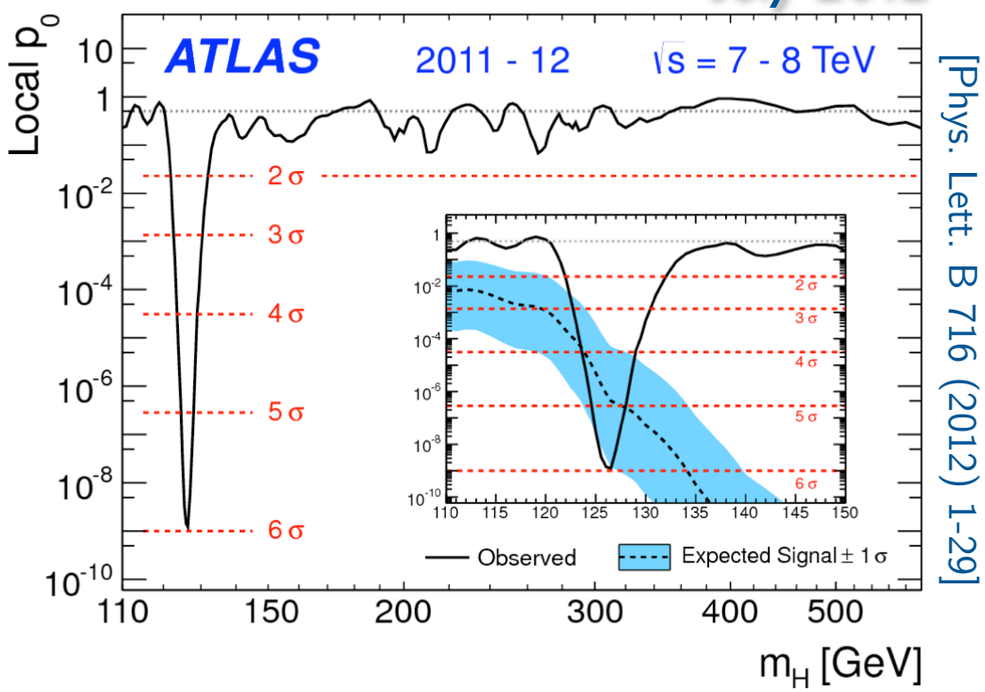
Higgs Searches after the Discovery

- **Combination of H→γγ, H→ZZ* and H→WW* results** with full data sample (25 fb^{-1}) to determine:
  - Mass and couplings [arXiv:1307.1427]
  - Spin and parity [arXiv:1307.1432]

July 2012



[Phys. Lett. B 716 (2012) 1-29]

- **Preliminary results**:

NEW ttH with H→γγ (20 fb^{-1}) [ATLAS-CONF-2013-080]

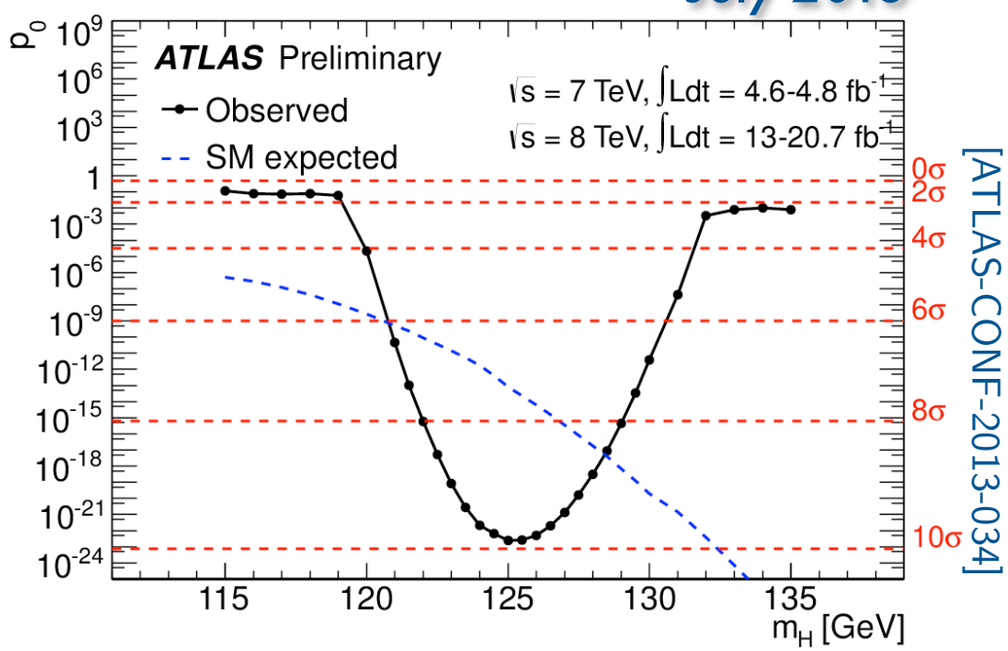
NEW H→γγ differential cross-sections (25 fb^{-1}) [ATLAS-CONF-2013-072]

- H→μμ (21 fb^{-1}) [ATLAS-CONF-2013-010]
- H→Zγ (25 fb^{-1}) [ATLAS-CONF-2013-009]

NEW VH with H→WW (25 fb^{-1}) [ATLAS-CONF-2013-075]

- ZH with H→invisible (18 fb^{-1}) [ATLAS-CONF-2013-011]
- High mass Higgs (25 fb^{-1})
  - H→ZZ→4 leptons [ATLAS-CONF-2013-013]
  - NEW H→WW→eνμν [ATLAS-CONF-2013-067]

July 2013



[ATLAS-CONF-2013-034]

Status of the Higgs Searches at Today

- **SM Higgs:** the resonance discovered last year is looking more and more like the SM Higgs boson
  - Spin/parity measurements favor SM $J^P = 0^+$
  - Coupling measurements show no disagreement with SM hypothesis
  - The overall compatibility with the SM hypothesis is $\mu = 1.33^{+0.21}_{-0.18}$
  - Evidence of Higgs boson production via VBF
  - Combined mass measurement $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ GeV

  → **H→γγ**, **H→ZZ*→4l**, **H→WW*→lνlν**

  - No evidence yet for fermionic decays, but results are consistent with the SM Higgs

  → **SM H→ττ**, **VH, H→bb**

  - No evidence for rare production decay modes and for H→invisible

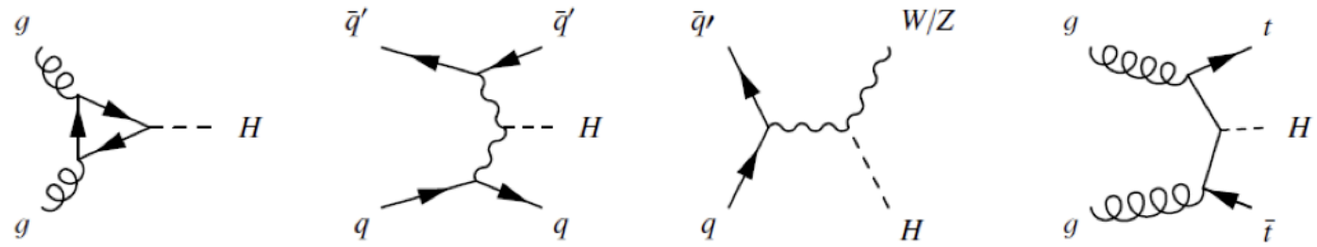
  → **SM VH, H→WW**, **H→μμ ZH, H→inv**, **.....**

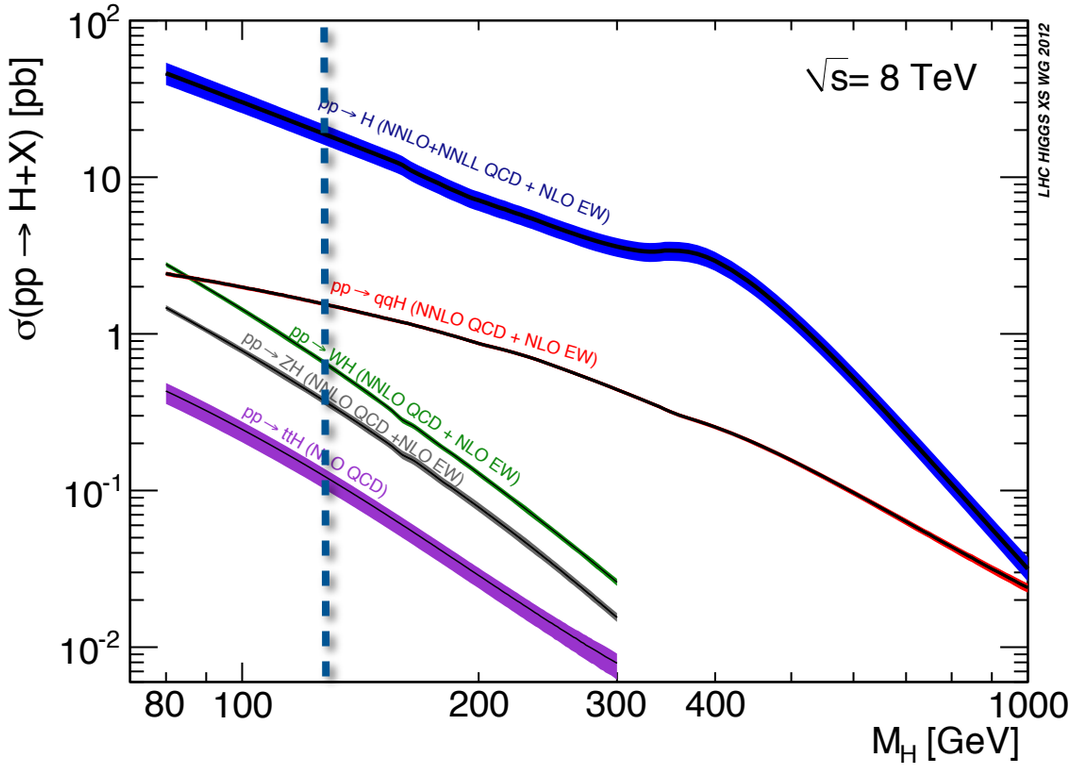
- **BSM Higgs Searches**
  - No evidence for high mass resonances
  - No evidence for charged Higgs bosons
  - Fermiophobic Higgs and 4th fermion generation ruled out

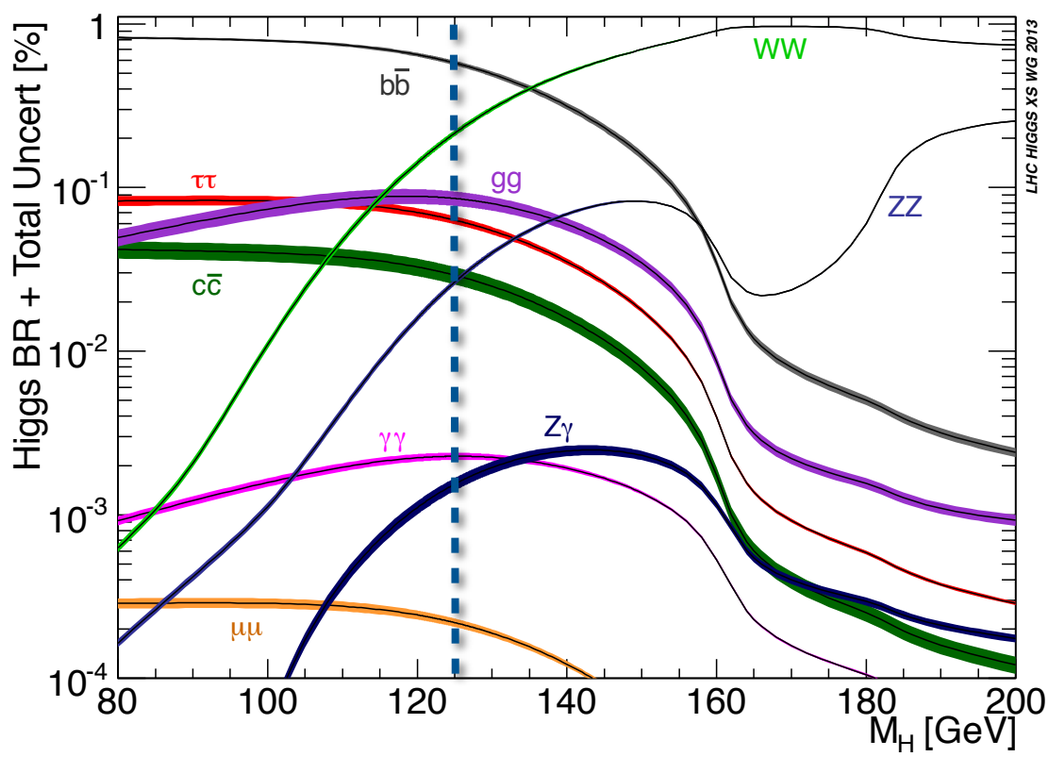
  → **$H^{\pm}$→τν + jets**, **H→ZZ*/WW***, **H→γγ**, **.....**

Higgs Production and Decays at LHC

[LHC Higgs Cross Section WG - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections and CERN Yellow Reports I, II and III [arXiv:1101.0593, arXiv:1201.3084 and arXiv:1307.1347]]







SM xsec [pb] for $m_H = 125.5$ GeV

ggF	VBF	WH	ZH	$t\bar{t}H$
19	1.6	0.7	0.41	0.13

BR [%] for $m_H = 125.5$ GeV

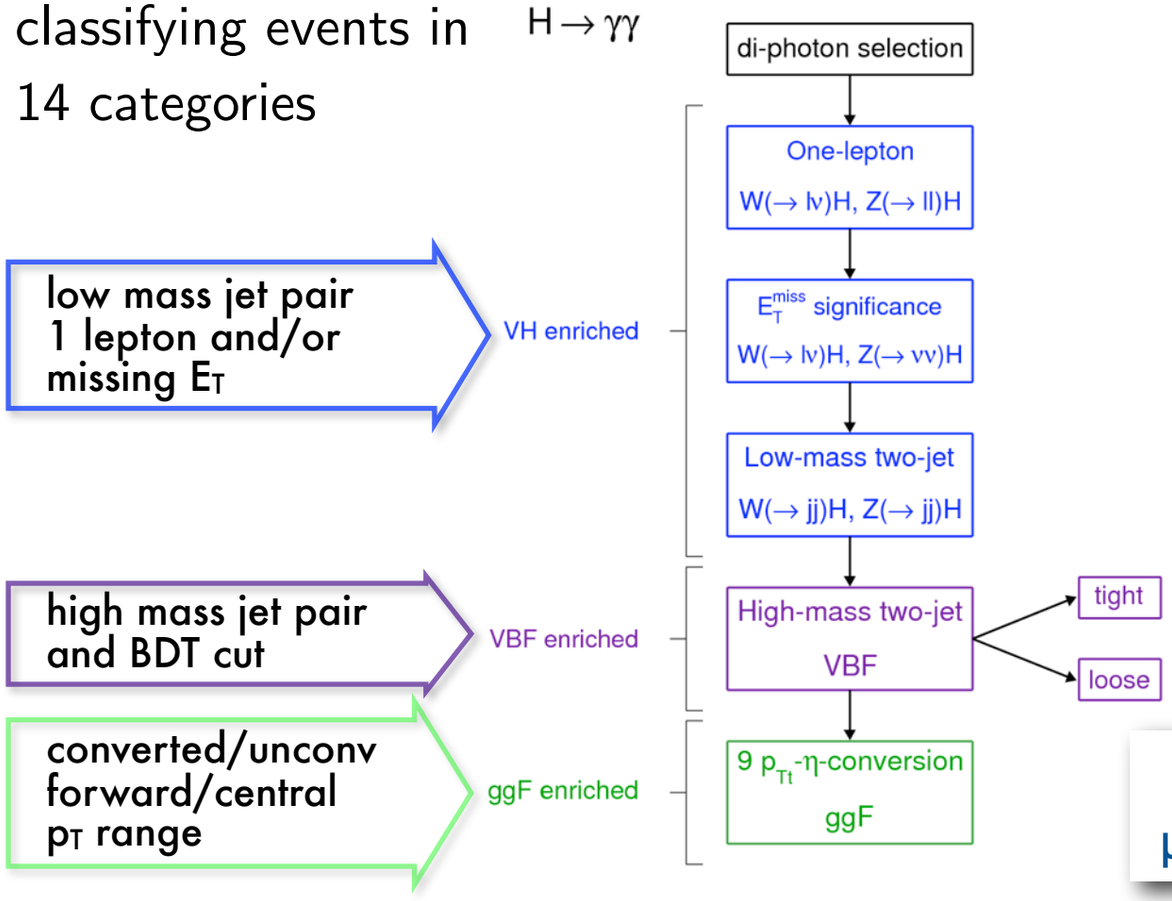
bb	ww	$\tau\tau$	Zz	$\gamma\gamma$	$Z\gamma$	$\mu\mu$
57	22	6.2	2.8	0.23	0.16	0.02

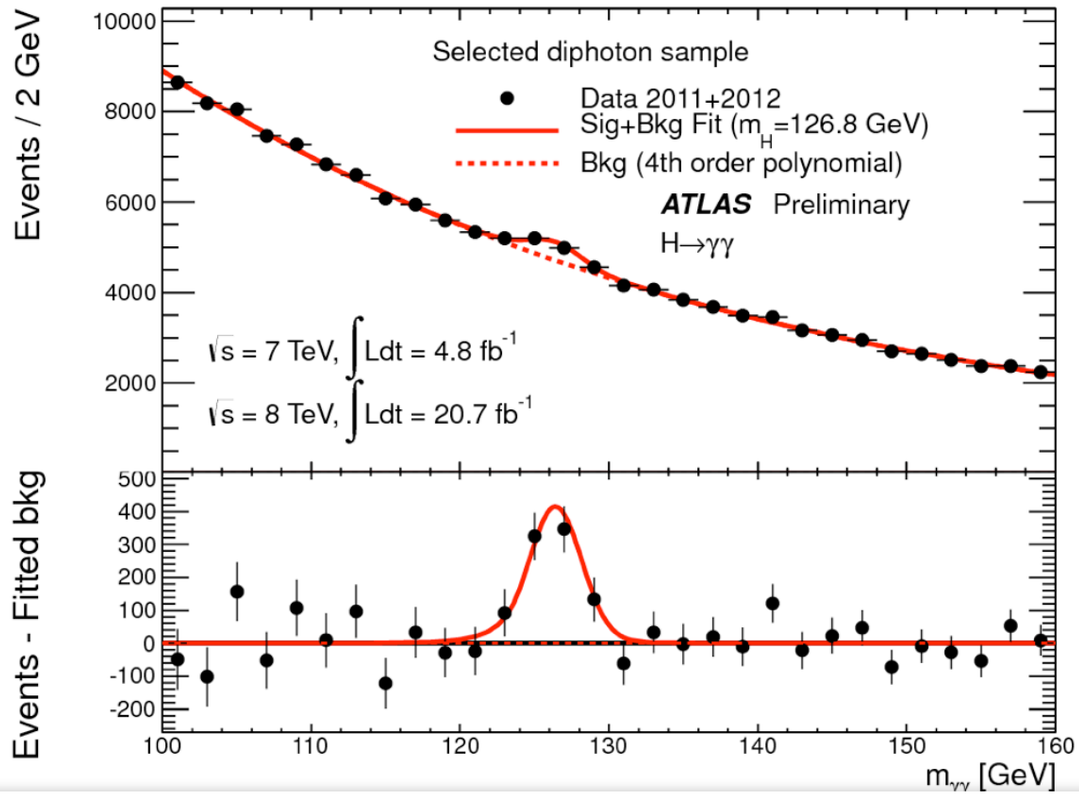
- A lot of recent progress on cross section and BR computation → up to NNLO in most cases - uncertainties O(20%) dominated by QCD scale and PDF+α_S in gg-fusion

Higgs Decays to Bosons: H→γγ

[ATLAS-CONF-2013-012, arXiv:1307.1427]

- Small σ x BR (50 fb, S/B = 3%) but clean signature: two isolated high-E_T photons (E_{T1} > 40 GeV; E_{T2} > 30 GeV)
- Photon identification based both on lateral and longitudinal segmentation of the ECal
- SM background -irreducible γγ (75%), reducible γj (22%) and jj(3%)- parameterized with analytic functions with functional form estimated from MC then fitted to data
- Invariant mass $m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\vartheta)}$ reconstructed - $\delta m/m = 1.77$ GeV at $m_H = 126.5$ GeV
- Analysis performed classifying events in 14 categories





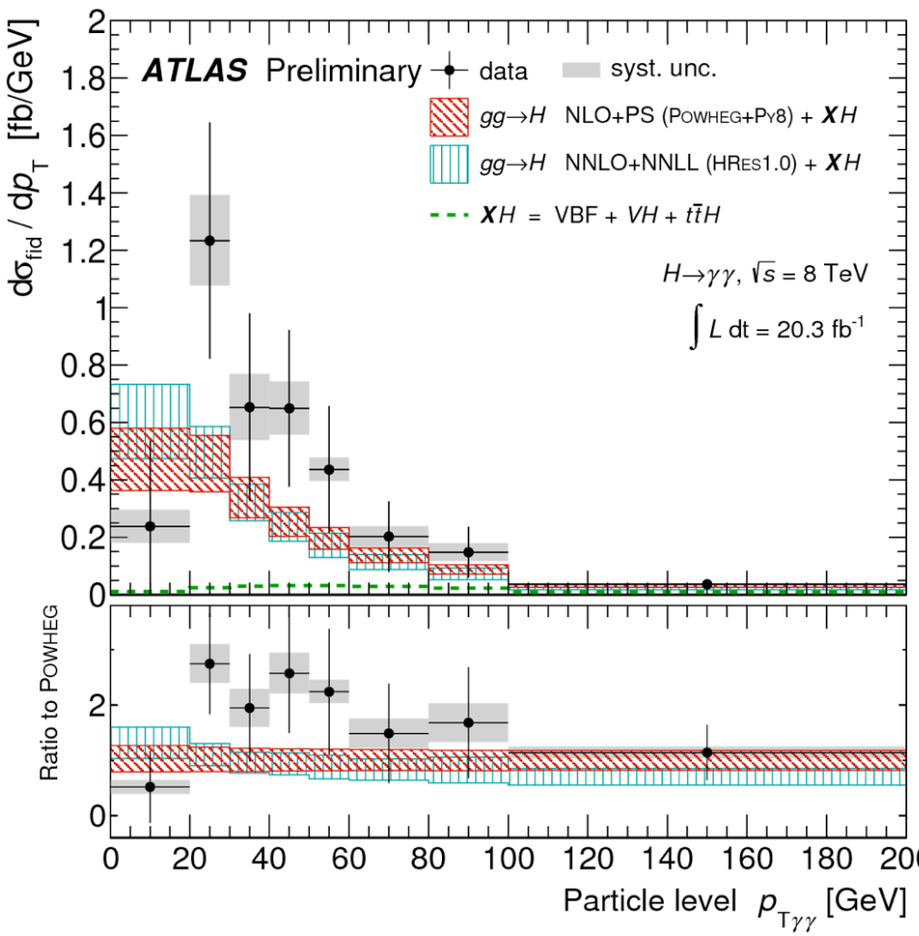
Obs.(Exp.) 7.4σ(4.3σ) - p_0 (B only)~10^{-13}

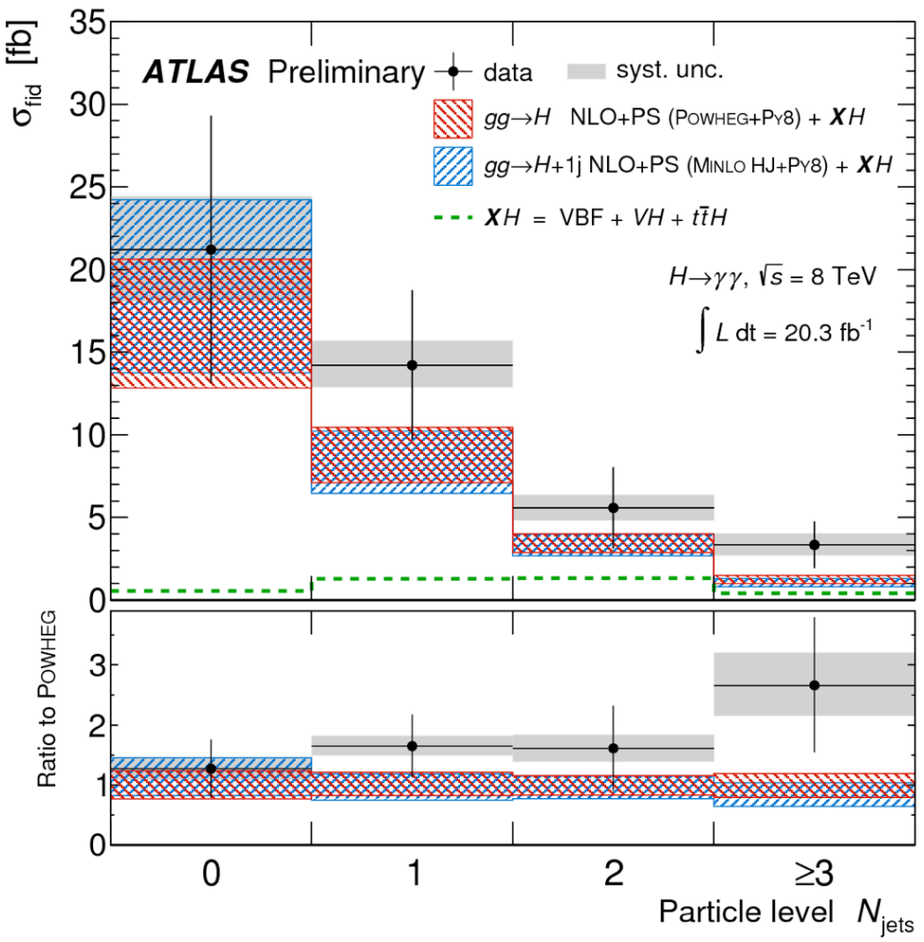
$\mu = \sigma/\sigma_{SM}$= 1.55 ± 0.23(stat) ± 0.15(syst) ± 0.15(th)

NEW H→γγ Differential Cross Section

[ATLAS-CONF-2013-072]

- Distributions studied for several Higgs observables (Higgs rapidity, cosθ*, leading jet p_T, etc.)
- Fit repeated to extract signal in each bin (signal model: ggF+VBF+VH+ttH at $m_H = 126.8$ GeV)
- Initial state jet radiation used to constrain production mechanism → *theoretical uncertainties can be reduced* - theoretical work (and statistics) needed





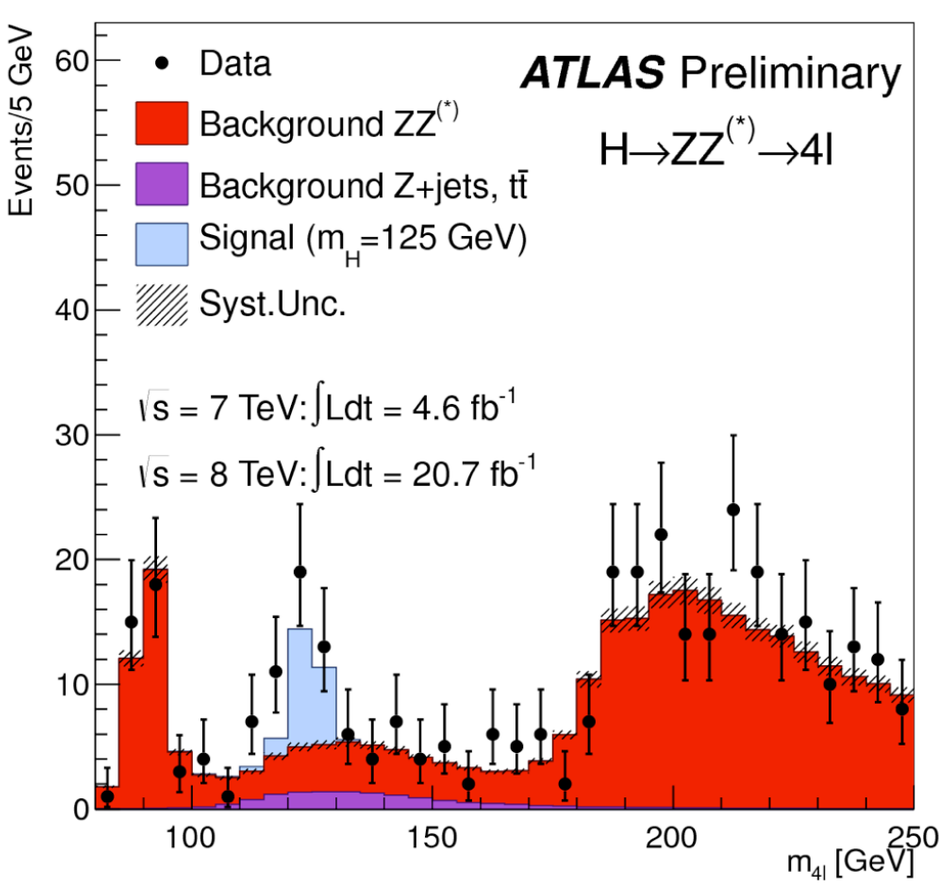
- p_T spectrum in data appears harder but errors (statistics and theory) are still large

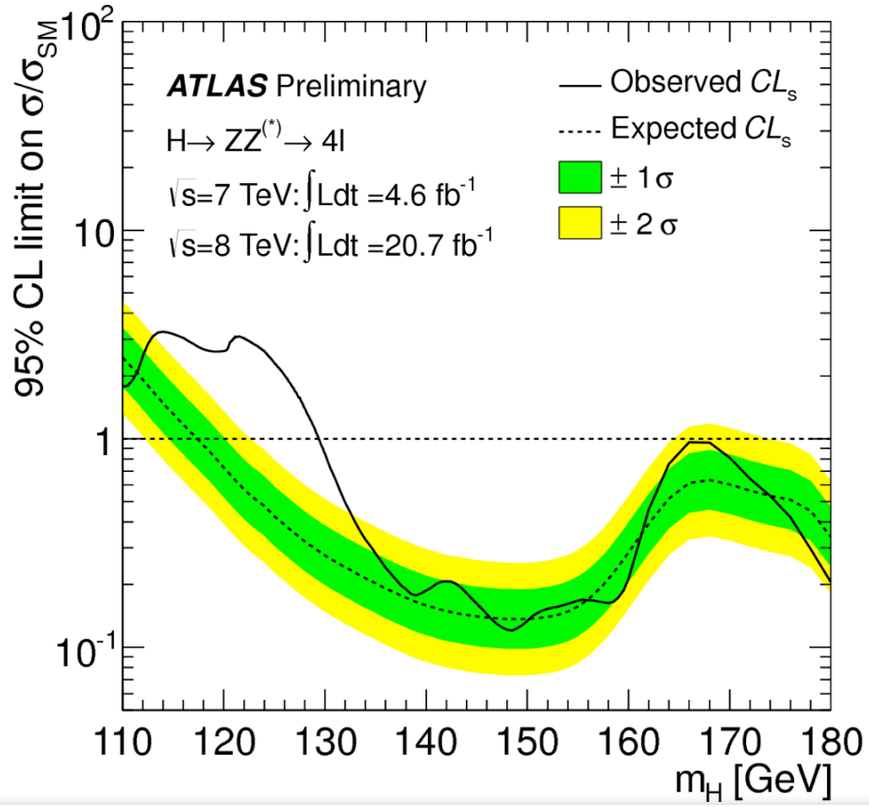
No significant disagreements with respect to SM Higgs expectation

Higgs Decays to Bosons: H→ZZ*→4l

[ATLAS-CONF-2013-013, arXiv:1307.1427]

- Small production rate (σ x BR ~2.5 fb), but very clean final state (4 isolated high p_T leptons) and good mass resolution ($\delta m/m = ^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$(syst) GeV at $m_H = 124.3$ GeV)
- Control regions in data for background estimations (ZZ continuum, Zbb, tt)
- Analysis subcategories: 4e, 4μ, 2e2μ/2μ2e - *VBF enhanced* (high mass jet pair, $|\Delta\eta|>3$) - *VH enhanced* (additional lepton) - *ggF dominated* (inclusive)
- Improvements in reconstruction efficiency, data/MC agreement, stability in pileup and time





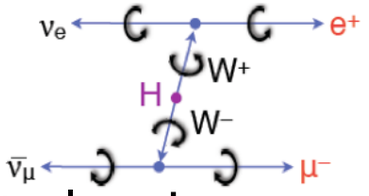
Obs.(Exp.) 6.6σ(4.4σ) - p_0 (B only)~10^{-11}

$\mu = \sigma/\sigma_{SM}$= 1.43 ± 0.33(stat) ± 0.17(syst) ± 0.14(th)

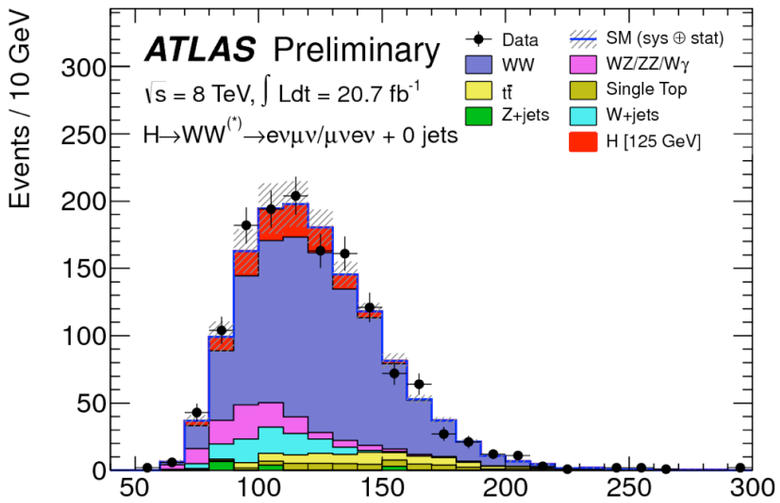
Higgs Decays to Bosons: H→WW*→lνlν

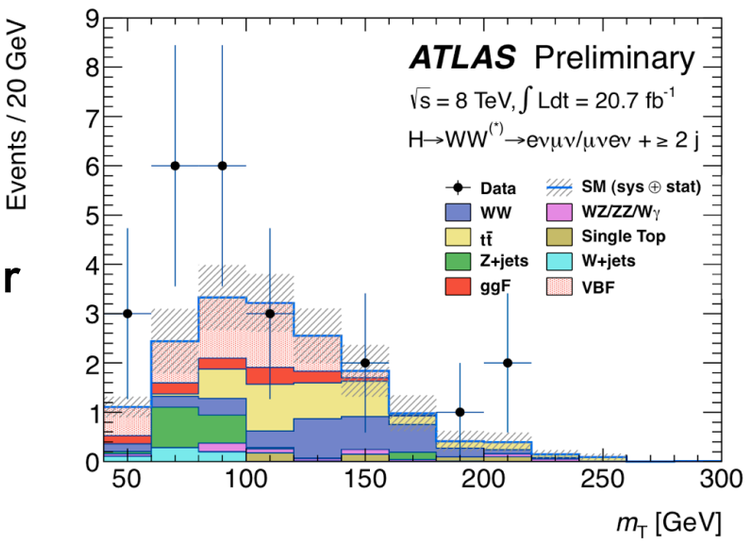
[ATLAS-CONF-2013-030, arXiv:1307.1427]

- High production rate (σ x BR ~200 fb) but limited mass resolution and significant backgrounds
- *Signal*: two high p_T leptons (ee, eμ, μμ) not back to back (small $\Delta\varphi_{ll}$ due to spin correlation) + two neutrinos (high missing E_T)

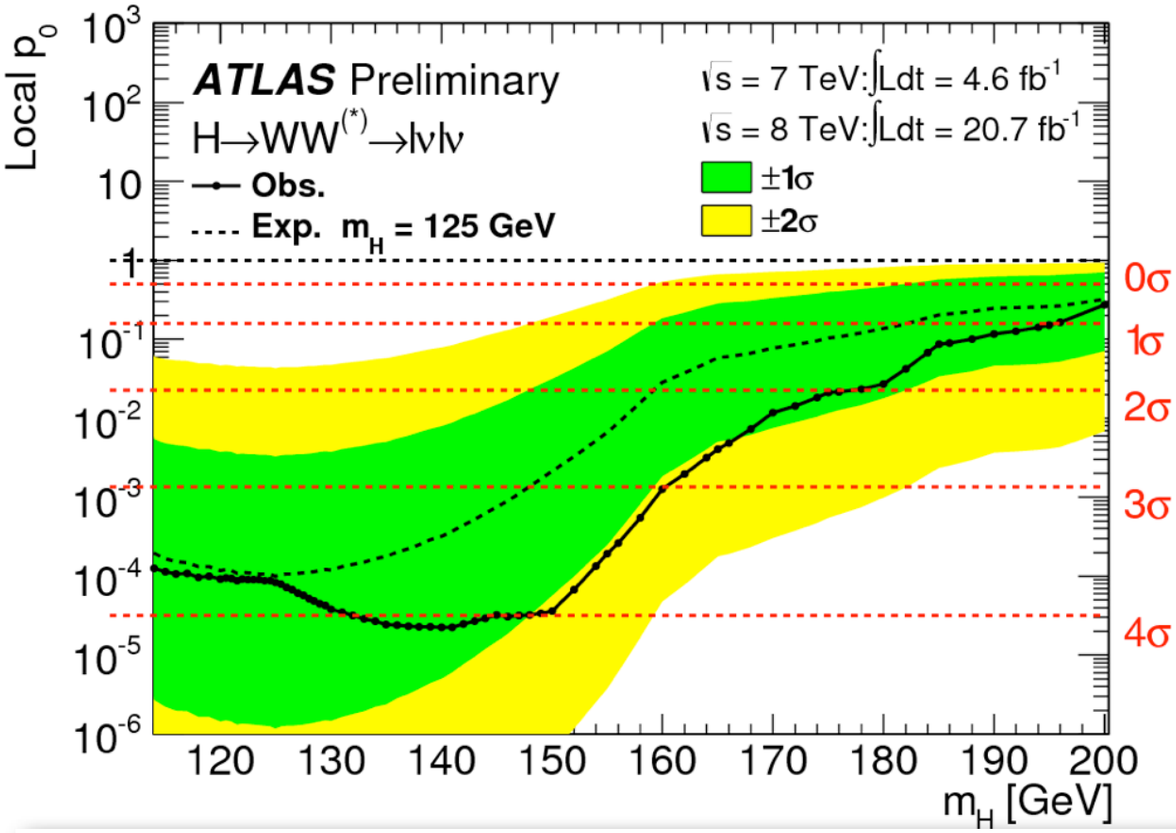


- Most backgrounds (WW irreducible, tt, single W, Wt) estimated from data control regions
- Analysis categories: ee, μμ or eμ - 0, 1 or ≥2 jets (backgrounds and production modes differ)





excess above background for all categories



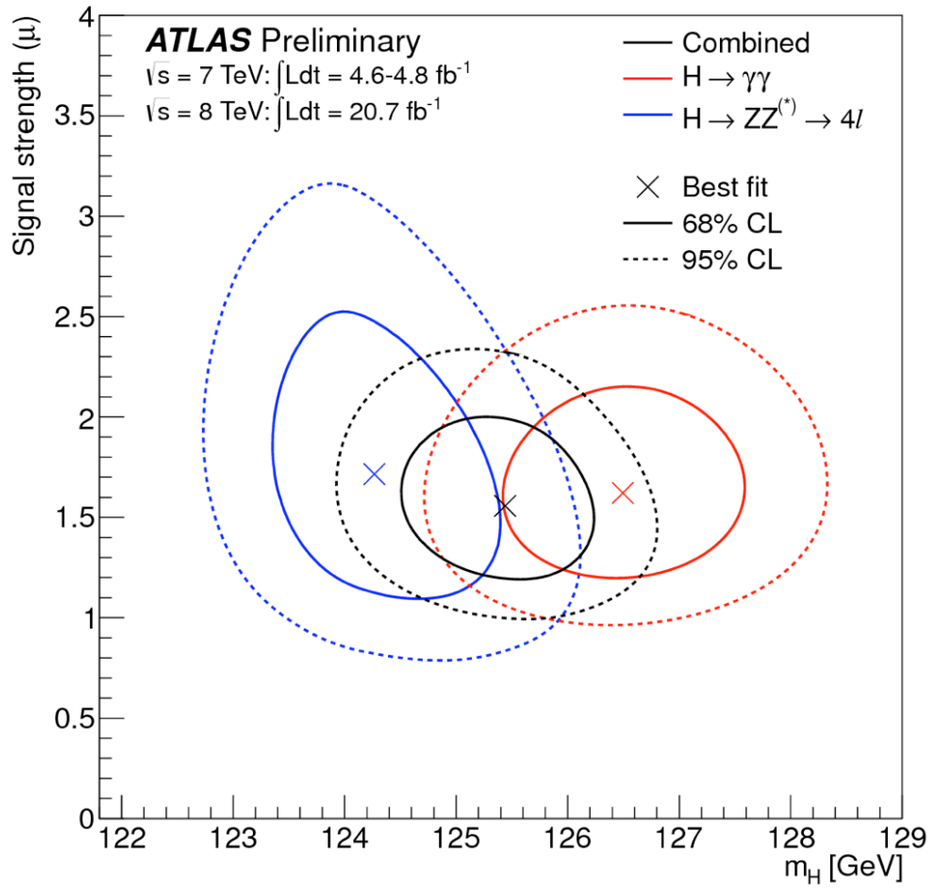
Obs.(Exp.) 3.8σ(3.7σ) - p_0 (B only)~10^{-4}

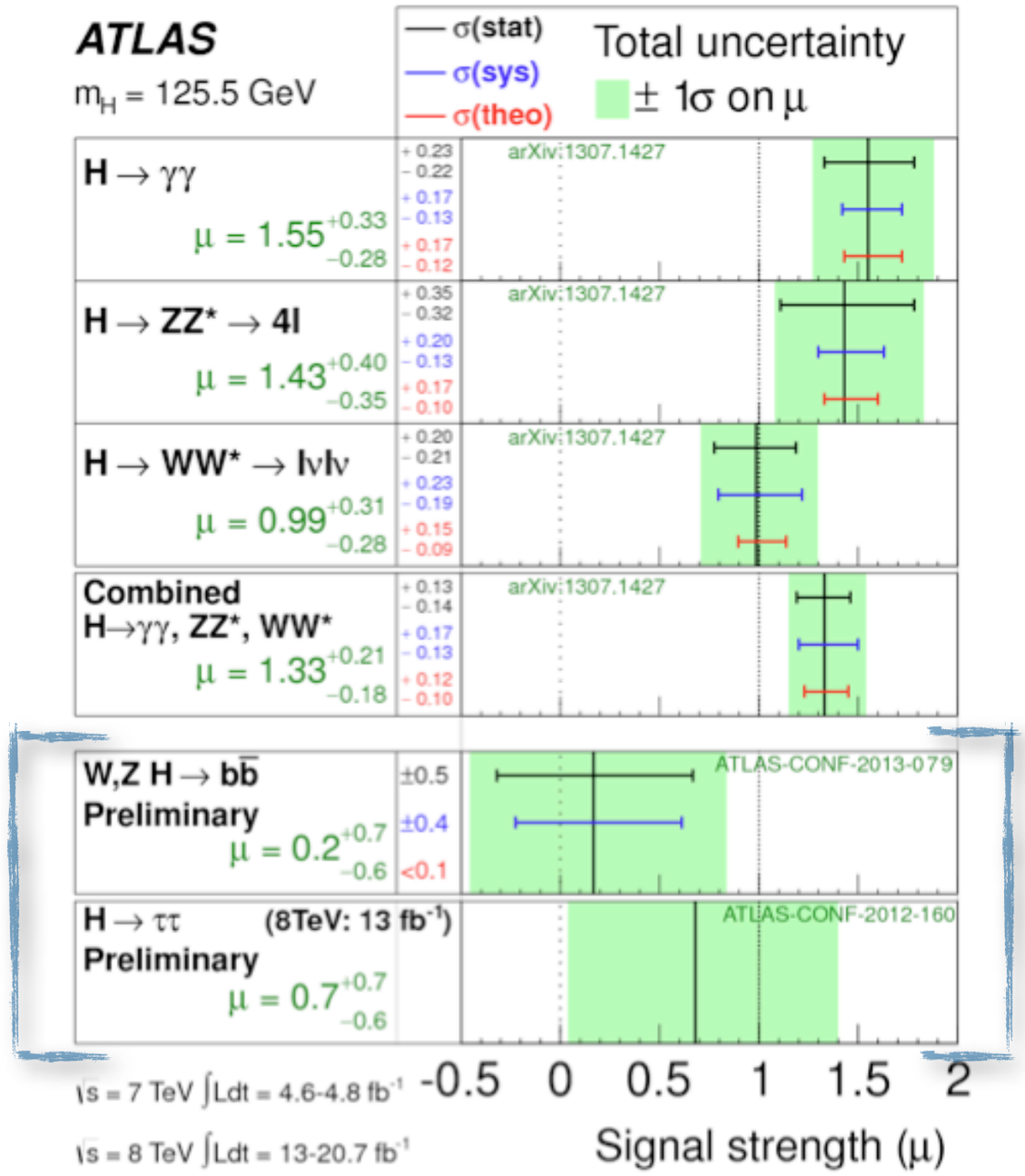
$\mu = \sigma/\sigma_{SM}$= 0.99 ± 0.21(stat) ± 0.21(syst) ± 0.12(th)

Higgs to Bosons Comb: Mass and Signal Strength

[ATLAS-CONF-2013-014, arXiv:1307.1427]

- $H\to\gamma\gamma$: m_H determined from combined fit in all categories $m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$ GeV
- $H\to 4$ leptons: m_H determined from unbinned likelihood fit $m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})$ GeV





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

Mass difference $2.4\sigma \rightarrow 1.5\%$ probability to occur

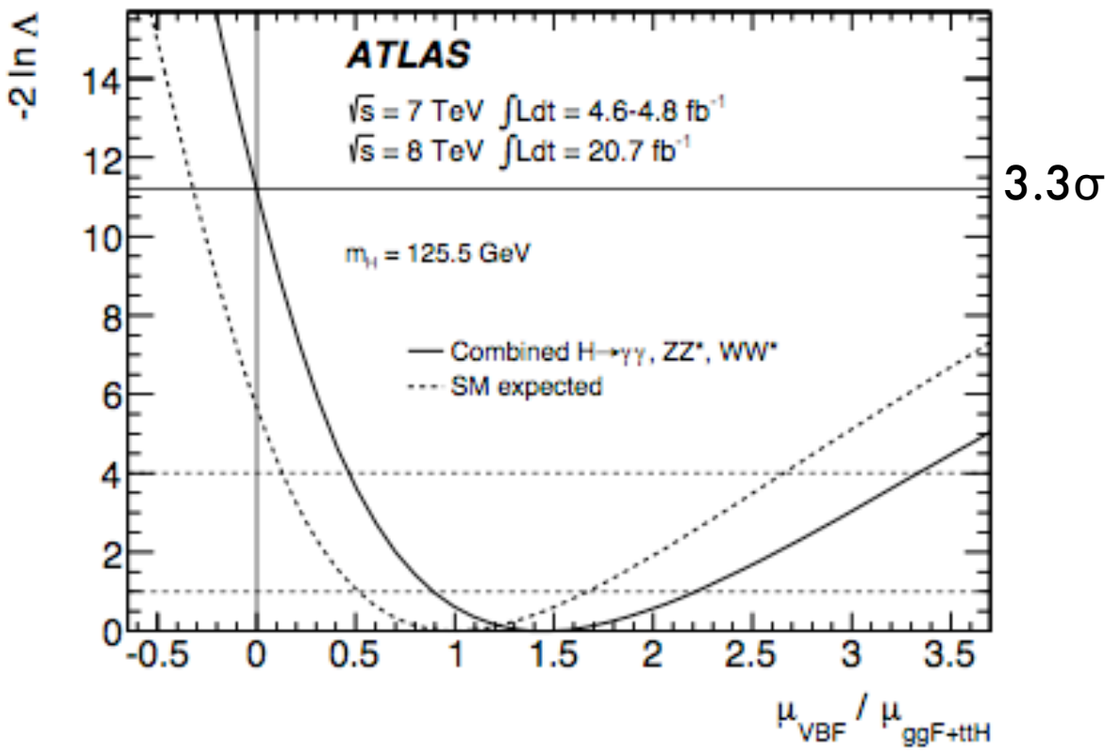
Overall signal strength $\mu = 1.33 \pm 0.14(\text{stat}) \pm 0.15(\text{syst})$

Compatibility with SM at 7% level

Higgs to Bosons Combined: VBF Evidence

[ATLAS-CONF-2013-014, arXiv:1307.1427]

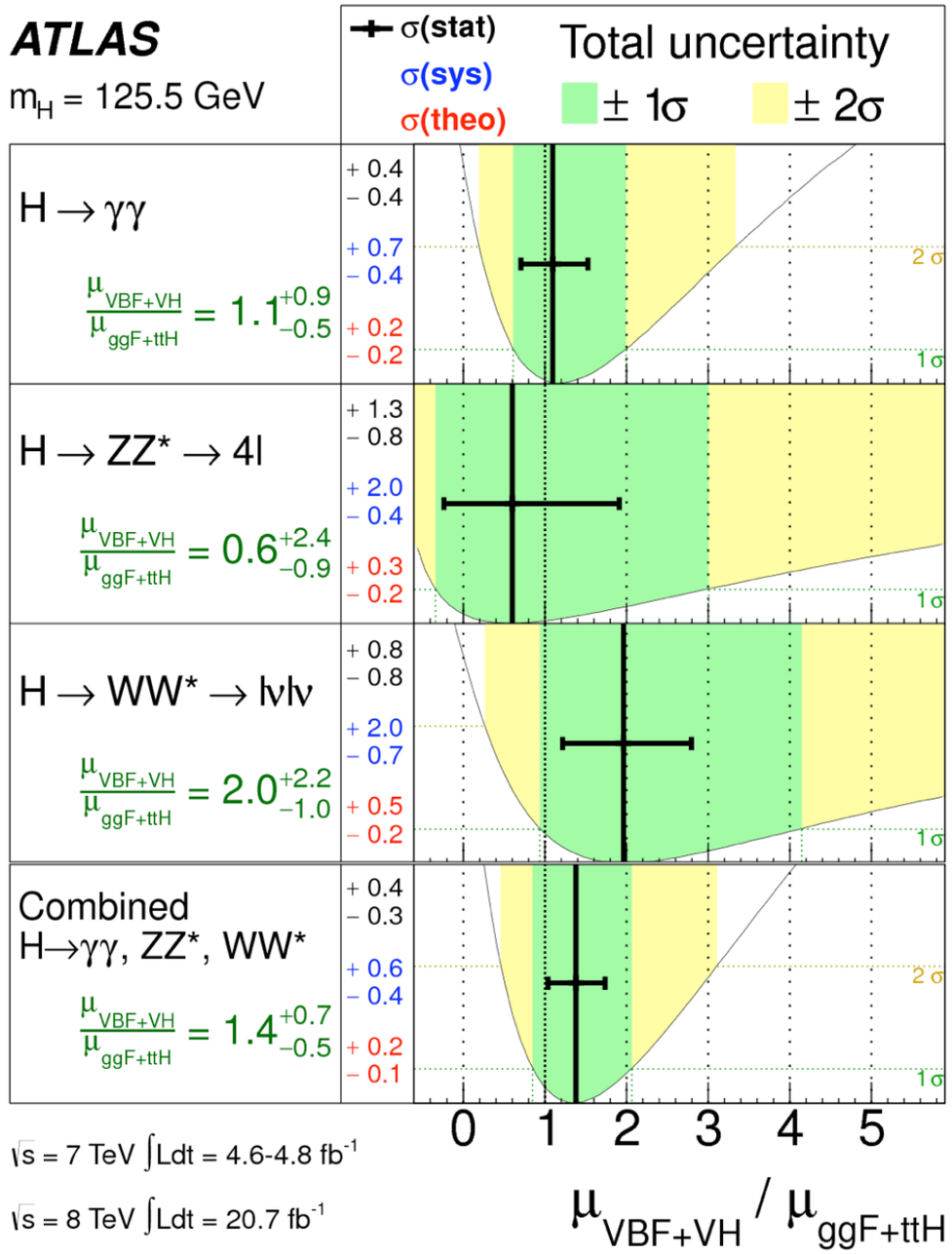
- Exploiting the sensitivity of production event categories in the H→γγ, H→ZZ*→4l and H→WW*→lνlν analyses, individual signal strength for ggF, VBF, VH and ttH can be extracted→ results can be then combined



3.3σ

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

3.3σ evidence for VBF production

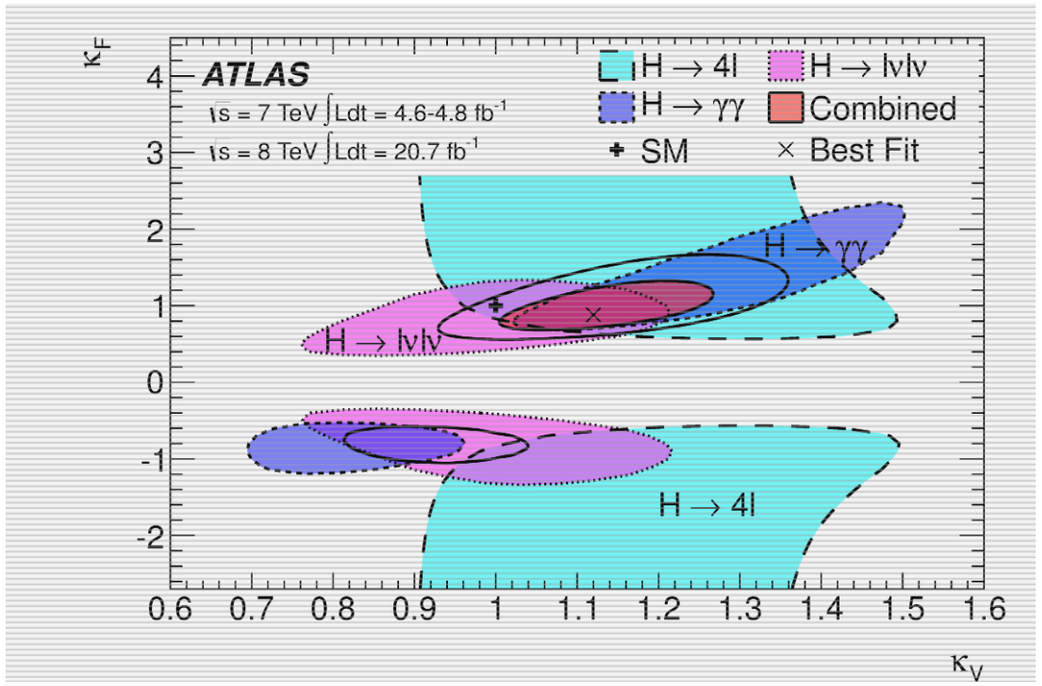


VBF enhanced analyses in H→γγ, H→ZZ*→4l and H→WW*→lνlν all find a VBF component consistent with the SM expectation

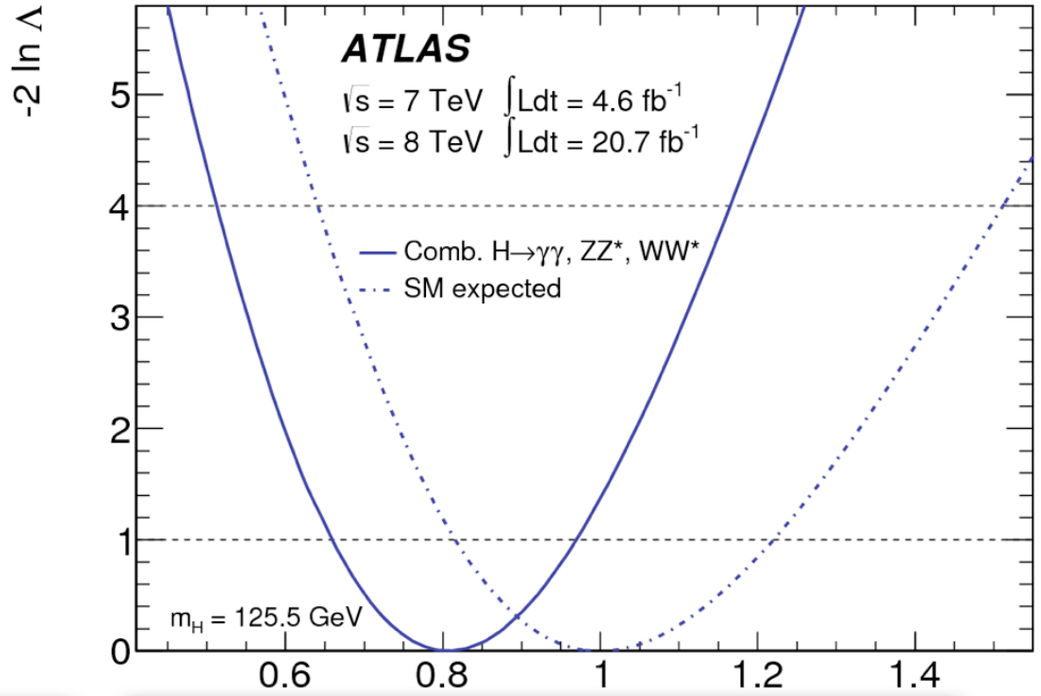
Higgs to Bosons Combined: Couplings

[arXiv:1307.1427, arXiv:1209.0040v1]

- Framework to parameterize coupling dependency of measured yields (under few assumptions)
  $\rightarrow$ LO coupling scale factors κ for partial widths
- Several benchmark parameterizations (i.e. nuisance parameters in the fit), for instance:
  1. Check the fundamental compatibility with SM hypothesis $\rightarrow$ one scale factor $\mu = \sigma/\sigma_{SM}$
  2. Assuming custodial symmetry $\rightarrow \kappa_V, \kappa_f$ (assumption on total width and loop content)
  3. Probing custodial symmetry $\rightarrow \lambda_{WZ} = \kappa_W/\kappa_Z$ with κ_Z and κ_f nuisance parameters
  4. Probing the fermion sector $\rightarrow$ distinct couplings for up-type and down-type fermions or consider quark and leptons separately, etc.



$\kappa_F = 0$ (fermiophobic H) excluded at $>5\sigma$ ($\kappa_F<0$ allowed at $\sim 2\sigma$)
2D Compatibility with SM at 12% level



Custodial symmetry $\lambda = 0.82 \pm 0.15$
Consistency with SM at 20% level

Higgs to Bosons Combined: Spin/Parity

[arXiv:1307.1432]

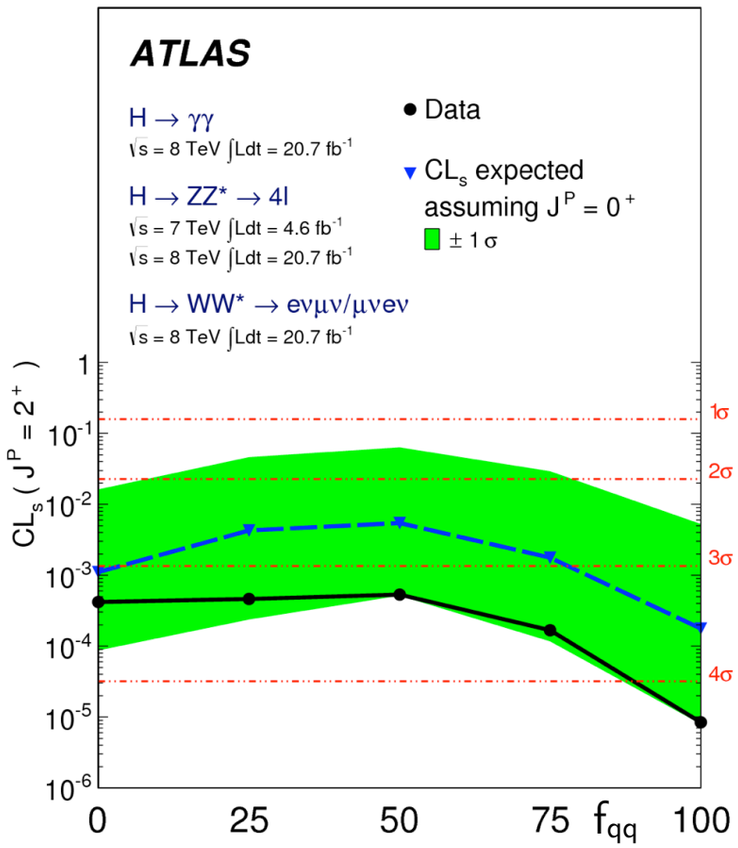
- Test various options (J^P=0^-, 0^+,1^-,1^+,2^+) using angular and kinematic distributions in $H\to\gamma\gamma$ (*sensitivity to 2^+, excludes spin 1*), $H\to ZZ^*\to 4l$ (*sensitivity to all spin/parity*) and $H\to WW^*\to l\nu l\nu$ (*sensitivity to spin 1/2*) to verify compatibility with SM hypothesis $J^P = 0^+$

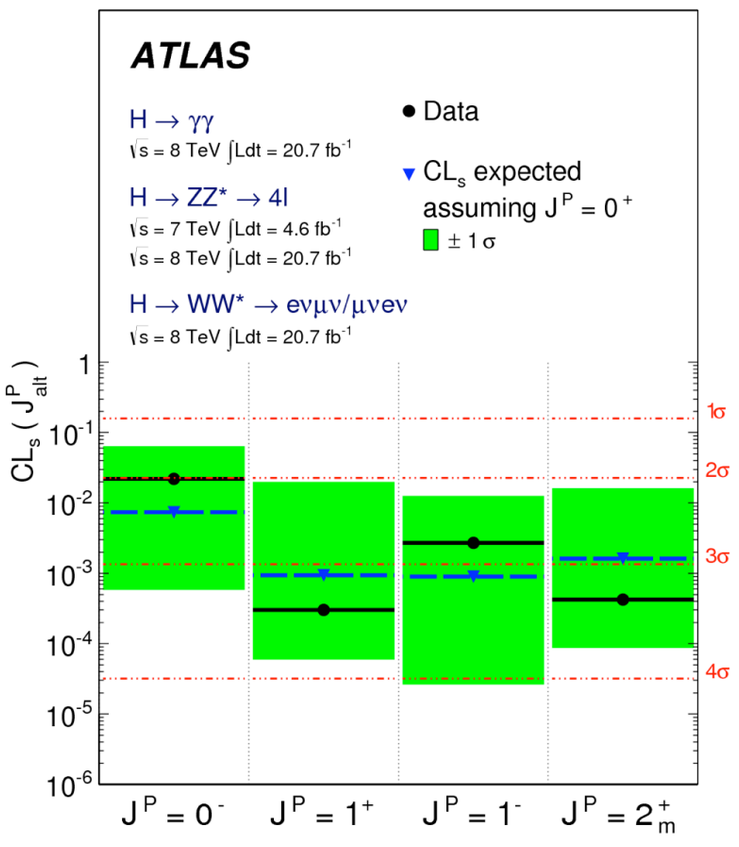
$$q = \log \frac{\mathcal{L}(J^P = 0^+)}{\mathcal{L}(J^P_{alt})}$$

f_{qq} = annihilation fraction

f_{qq} = 0% fully gluon induced

f_{qq} = 100% fully quark induced





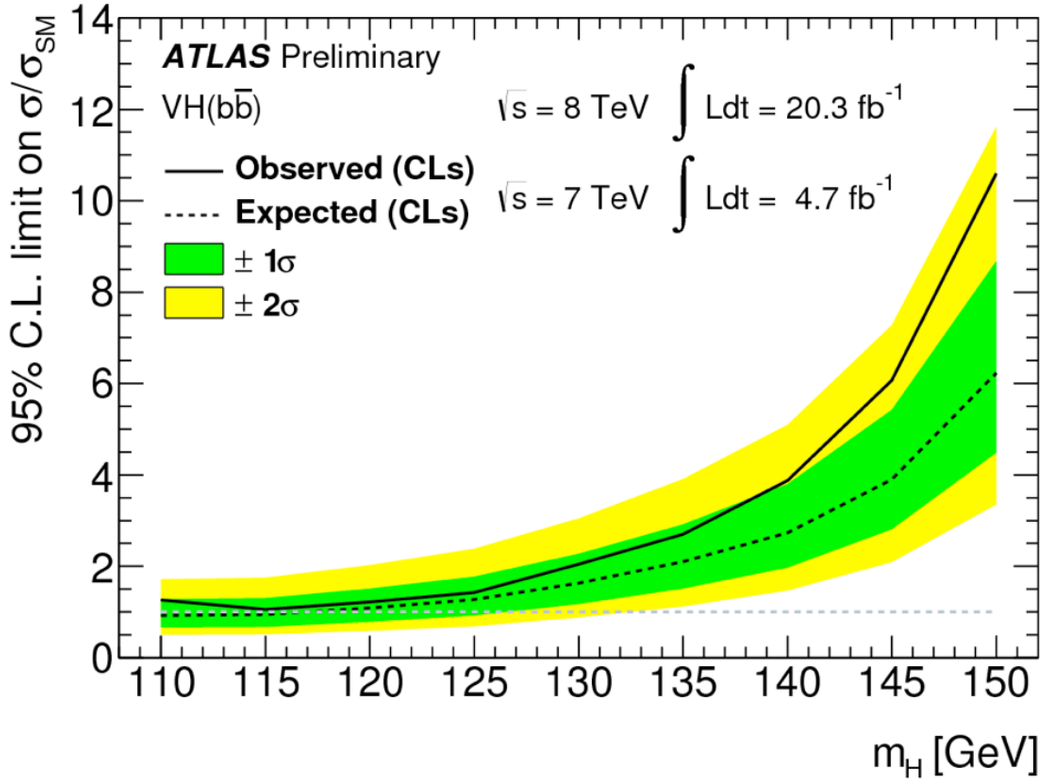
J^P hypo	Exclusion CL	Source	Channel
0^-	97.8%	$H \to ZZ^* \to 4l$	ggF only
1^-	99.7%	Combined ZZ^*/WW^*	VBF only
1^+	99.97%	Combined ZZ^*/WW^*	VBF only
2^+	99.9%	Combined $\gamma\gamma/ZZ^*/WW^*$	5 $f_{q\bar{q}}$ points

Combination of all Higgs decays to bosons clearly favors 0+ hypothesis

Higgs Decays to Fermions: VH, H→bb and H→ττ

NEW

VH, H→bb

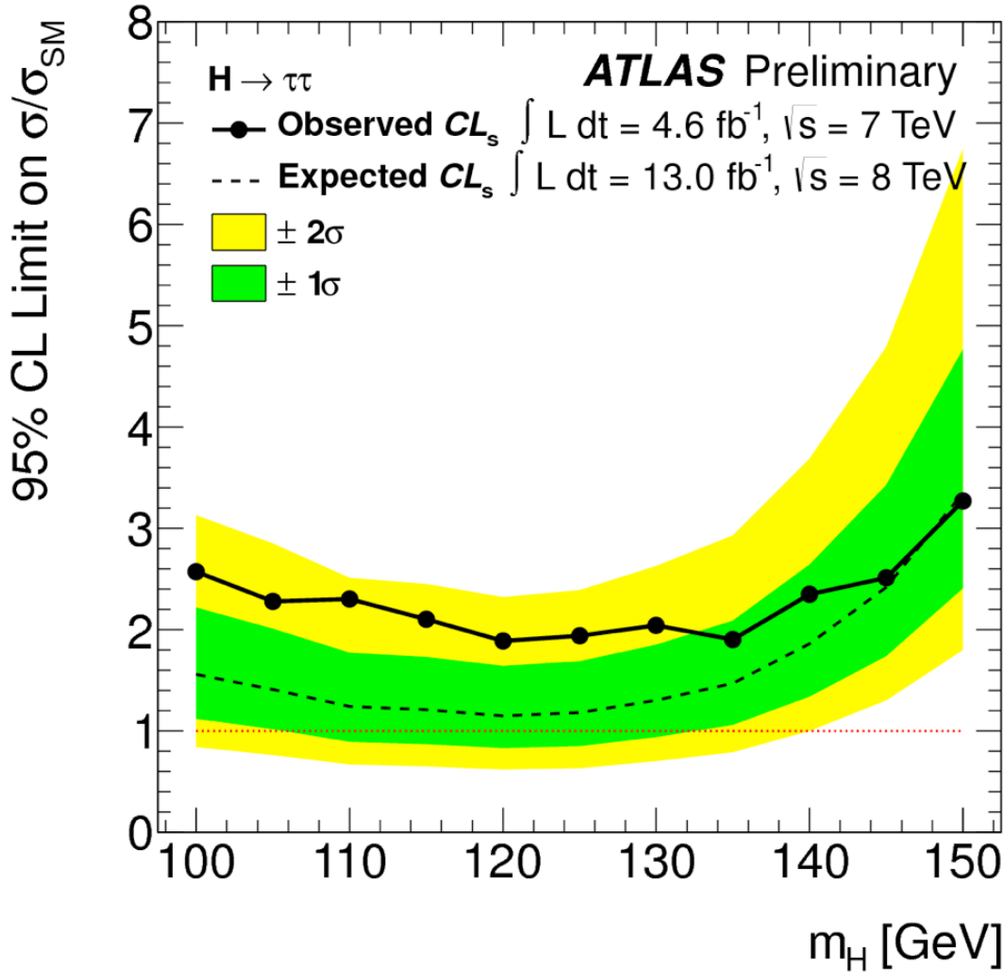


No significant excess observed: data consistent with either SM backgrounds only, and SM backgrounds + Higgs (1.4/1.3 x SM)

Best fit signal strength for m_H = 125 GeV:

$\mu = 0.2 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$

SM H→ττ



Analysis of full 2012 dataset still ongoing

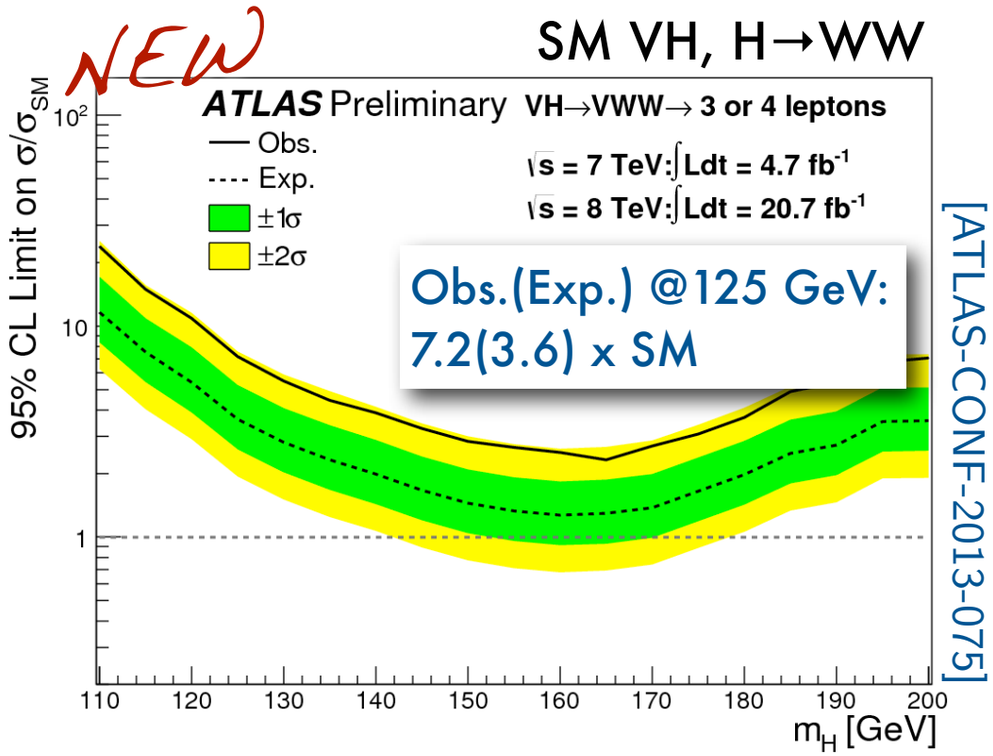
Obs.(Exp.) 1.9(1.2) x SM

Best fit signal strength for m_H = 125 GeV: $\mu = 0.7^{+0.7}_{-0.6}$

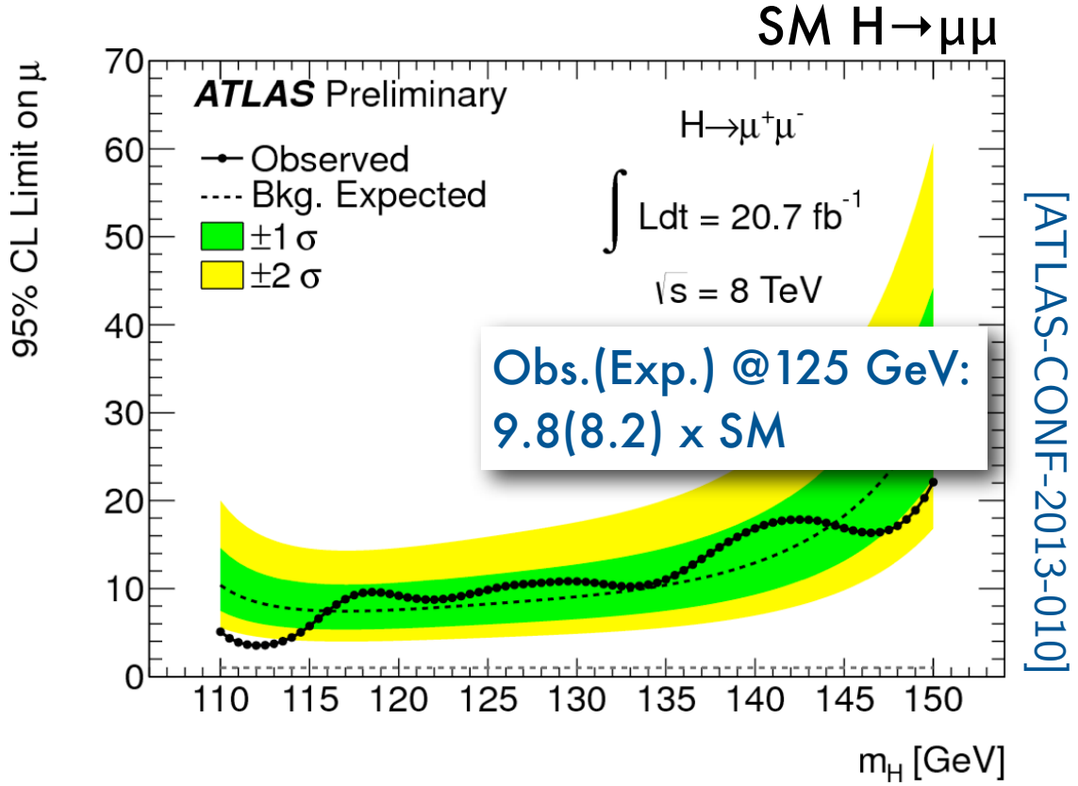
Rare Production/Decay Modes

SM VH, H→WW

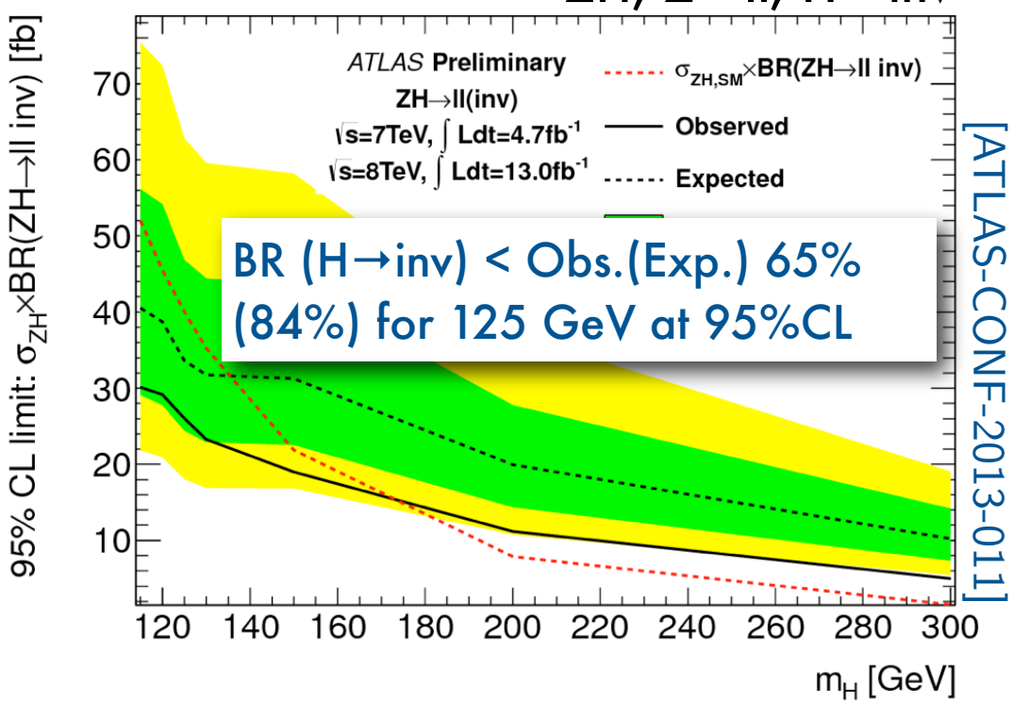
NEW



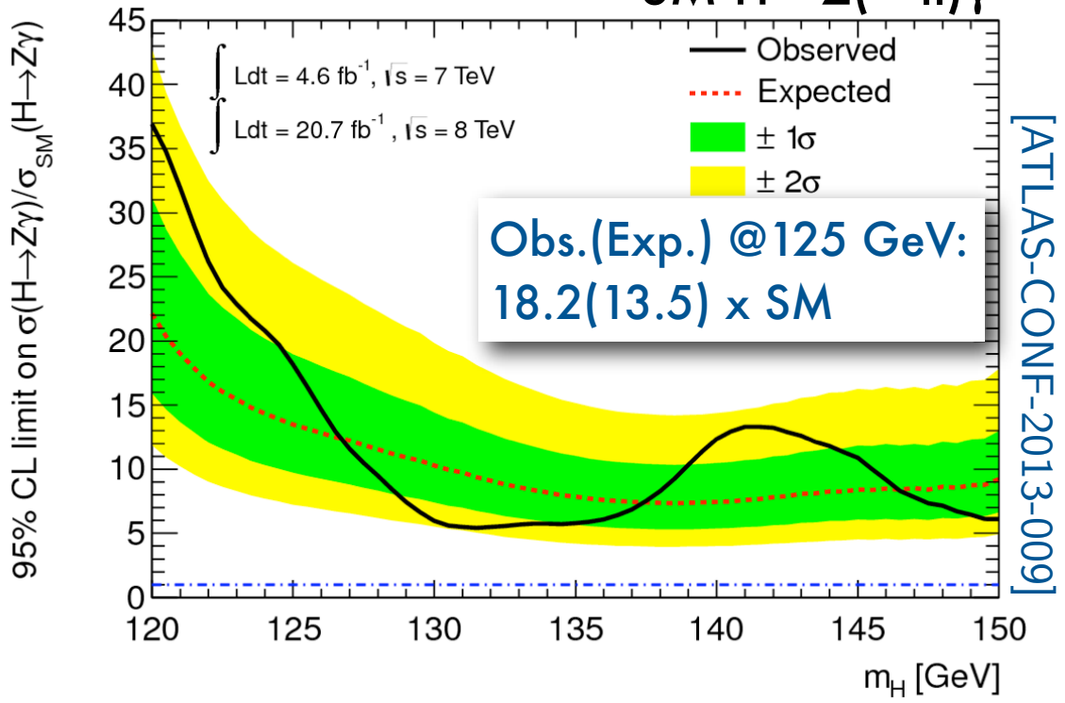
SM H→μμ



ZH, Z→ll, H→inv



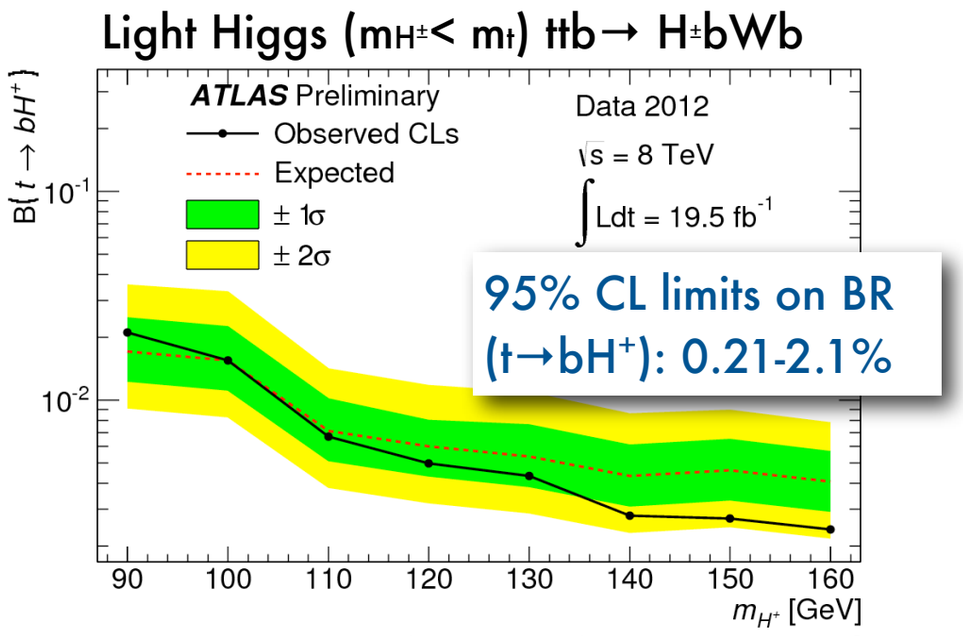
SM H→Z(→ll)γ

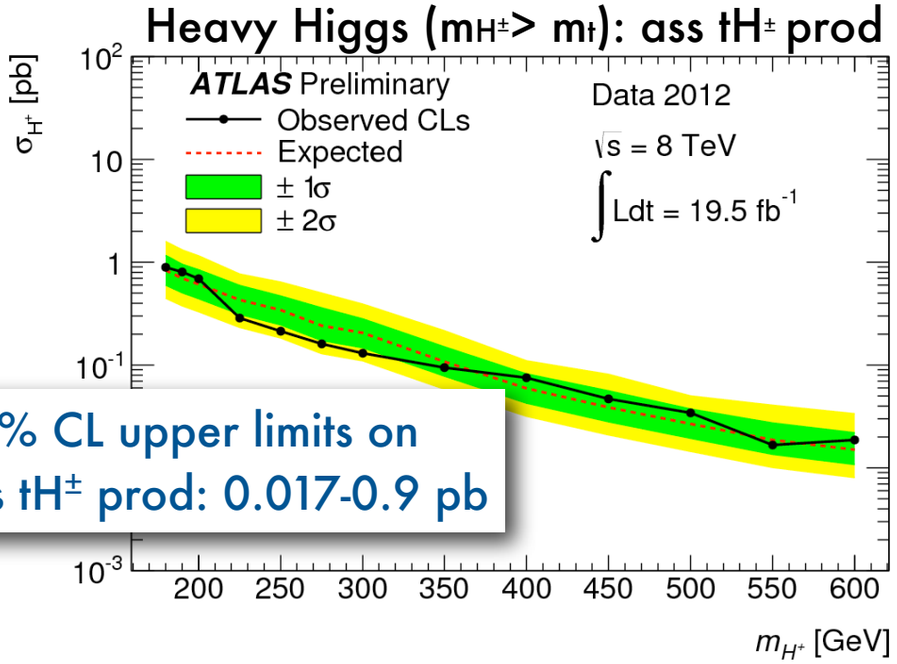


BSM Higgs - Recent Results

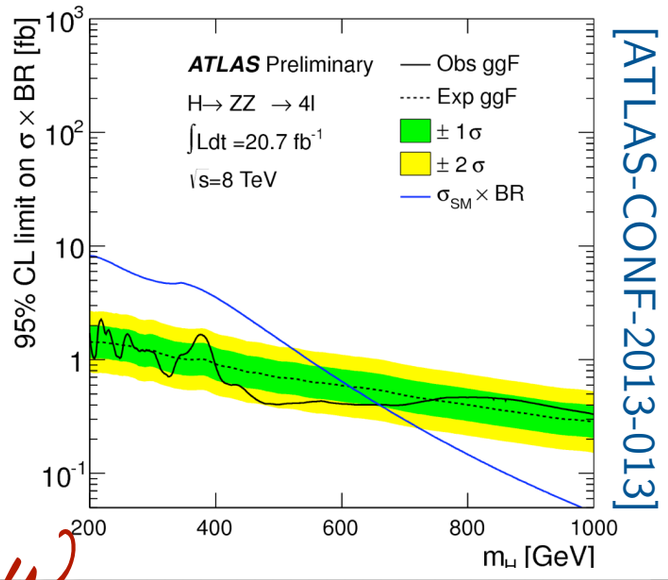
NEW

- Search for $H^{\pm} \to \tau\nu$ + jets in mass range 180 – 600 GeV [ATLAS-CONF-2013-090]





- Search for a high mass (additional) neutral Higgs in the ZZ and WW decay modes
- SM like Higgs with full description of width (both NWA and SM-like) and of interference



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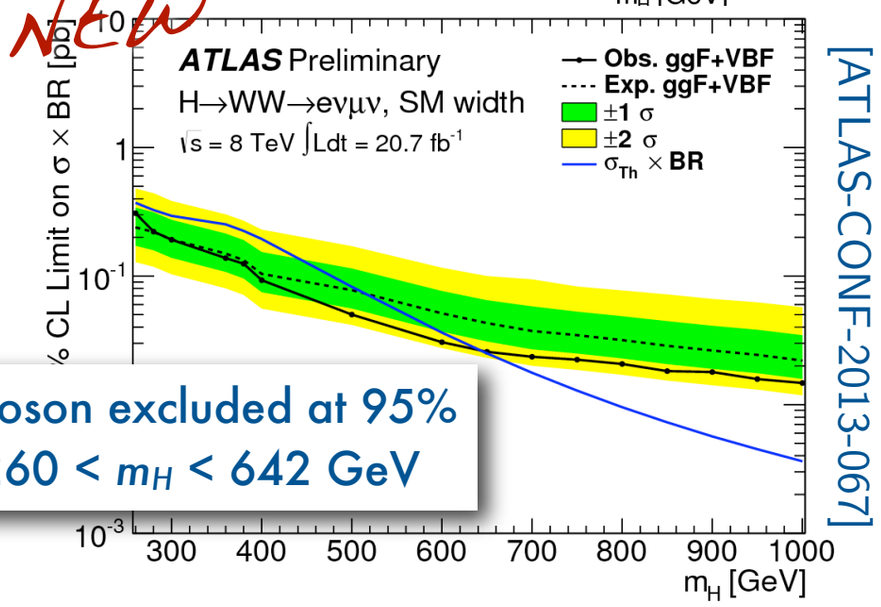


Higgs boson excluded at 95% CL for 260 < m_H < 642 GeV

Additional SM and BSM Higgs Searches

- NEW FCNC in t→cH, H→γγ - upper limit on BR: Obs.(Exp.): 0.83%(0.53%) x SM for 125 GeV at 95% CL [ATLAS-CONF-2013-081]
- NEW ttH, H→γγ: Obs.(Exp.): 5.3(6.4) x SM for 126.8 GeV at 95% CL [ATLAS-CONF-2013-080]
- H→ZZ→llνν: Excl. 320 - 560 GeV [ATLAS-CONF-2012-016]
- H→ZZ→llqq: Excl. 300 - 310, 360 - 400 GeV. at 145 GeV 3.5 x SM [ATLAS-CONF-2012-017]
- H→WW→lνjj: at 400 GeV Obs.(Exp.) 2.3(1.6) x SM [ATLAS-CONF-2012-018]
- WH→WWW(*)→lνlνlν and ZH →lllνlν: Obs.(Exp.): 7.3(3.2) x SM for 125 GeV at 95% CL [ATLAS-CONF-2012-078]
- Higgs in SM with 4th fermion generation: model ruled out [ATLAS-CONF-2011-135]
- Fermiophobic H to diphoton [ATLAS-CONF-2012-013]
- MSSM neutral H [ATLAS-CONF-2012-094]
- NMSSM a_1 to μμ [ATLAS-CONF-2011-020]
- NMSSM H to a_0a_0 to 4γ [ATLAS-CONF-2012-079]

Summary

LHC Run I has been a great success for the machine and for ATLAS...

- **SM Higgs**
  - The resonance discovered last year is looking like the SM Higgs boson
  - The combined mass measurement gives $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})$ GeV
  - The spin/parity measurements favor SM $J^P = 0^+$
  - No evidence yet for fermionic decays, but results are consistent with the SM Higgs
  - First results on various rare production decay modes and direct limits on H→invisible
  - The overall compatibility with the SM hypothesis is $\mu = 1.33^{+0.21}_{-0.18}$
- **BSM Higgs Searches**
  - Searches for high mass resonances with SM width and NWA
  - Direct limits on:
    - H^+ BR: BR(t→bH^+): 0.21 - 2.1% for $90 < m_{H+} < 160$ GeV
    - neutral Higgs tanβ: Best limit at $m_A = 130$ GeV: tanβ > 9.3 (exp. 10.3)
  - Upper limit on BR(t→cH)

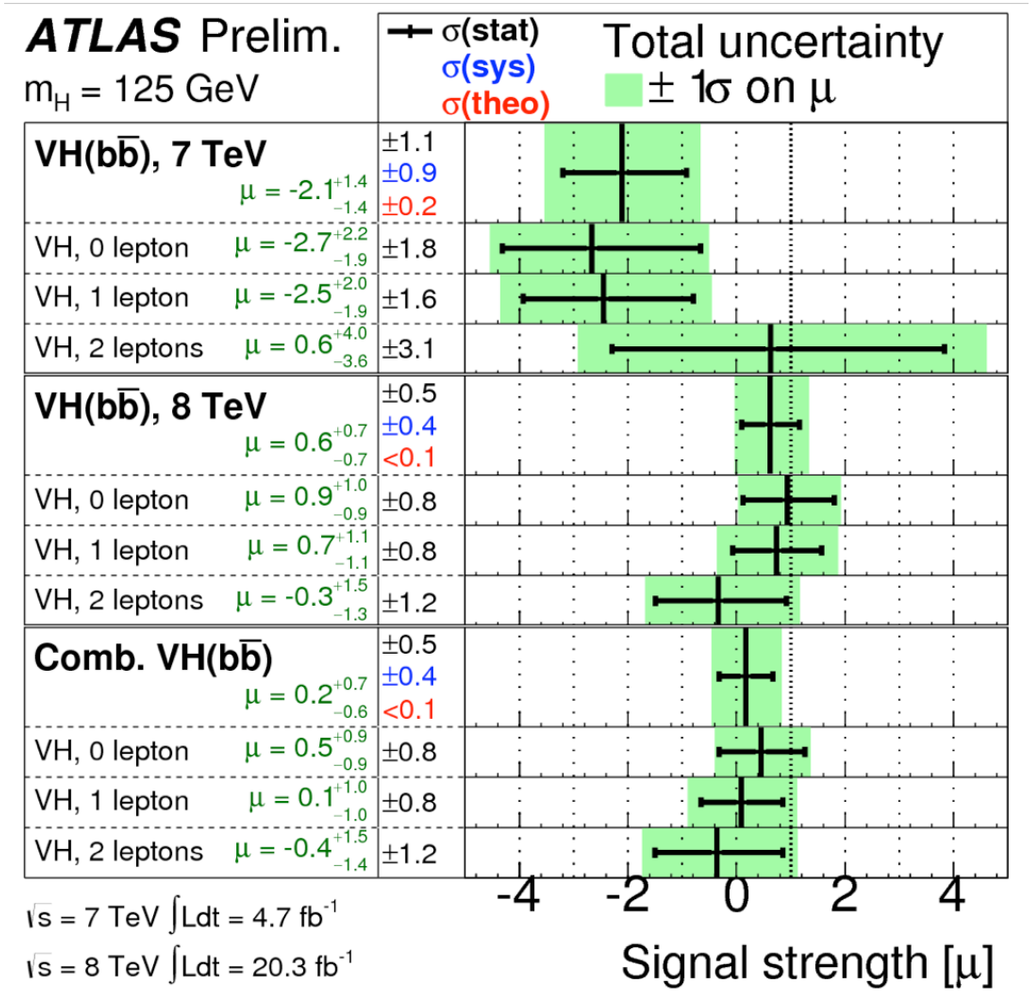
ATLAS is preparing for LHC Run II (13/14 TeV)
We are getting ready for Higgs boson studies with higher precision
and for other surprises... Still very exciting times ahead...

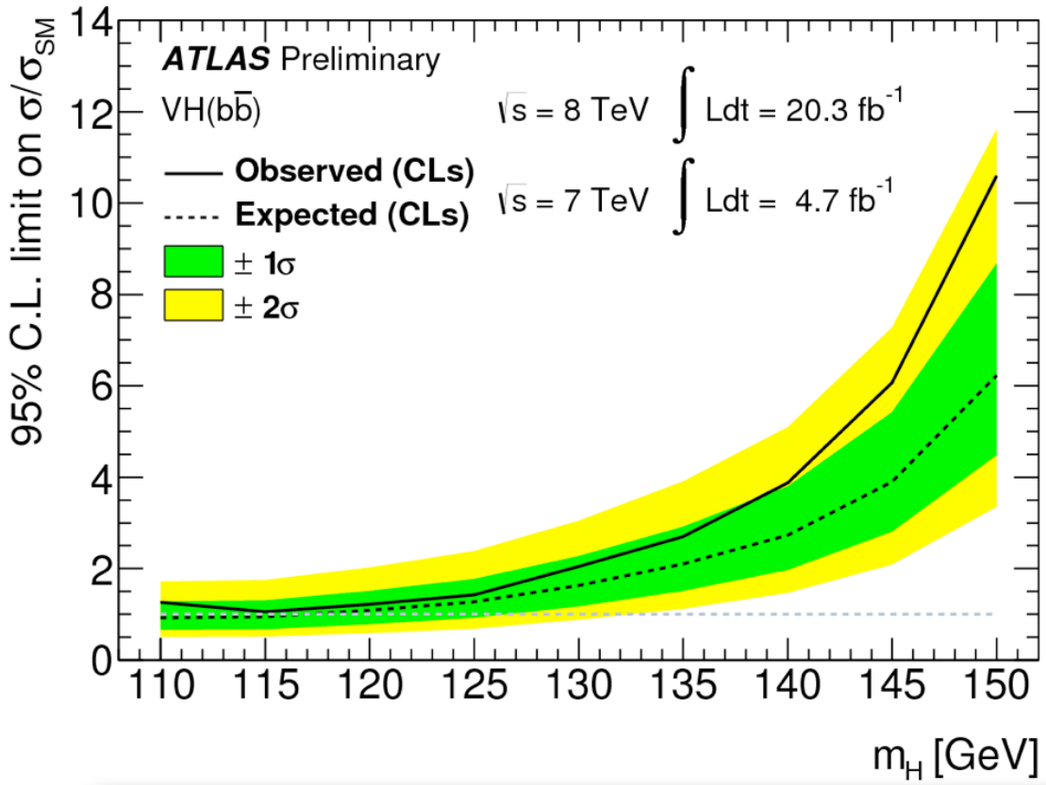
Backup slides

NEW Higgs Decays to Fermions: VH, H→bb

[ATLAS-CONF-2013-079]

- High BR (58%) but difficult backgrounds (WZ, WW, tt, single t, Wt, Wbb, Wcc, Zbb, multijet)
- Flavor composition of the main backgrounds determined from data
- Analysis categories in different p_T^V to improve sensitivity (0, 90, 120, 160 and 200 GeV) - further categorization used for background estimations from data: *number of leptons* (0,1,2), *number of jets* (2,3), *number of b-tagged jets* (1,2)





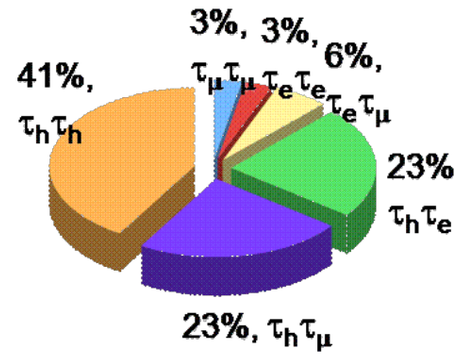
No significant excess observed: data consistent with either SM backgrounds only, and SM backgrounds + Higgs (1.4/1.3 x SM)

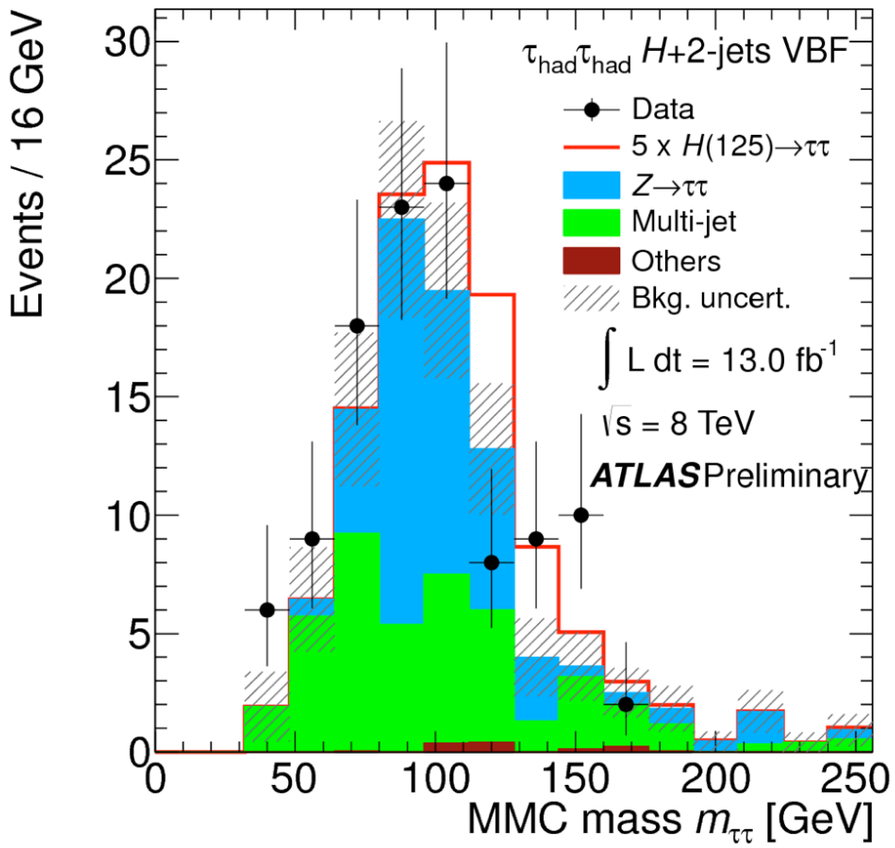
Best fit signal strength for m_H = 125 GeV: $\mu = 0.2 \pm 0.5(\text{stat}) \pm 0.4(\text{syst})$

Higgs Decays to Fermions: $H \to \tau\tau$

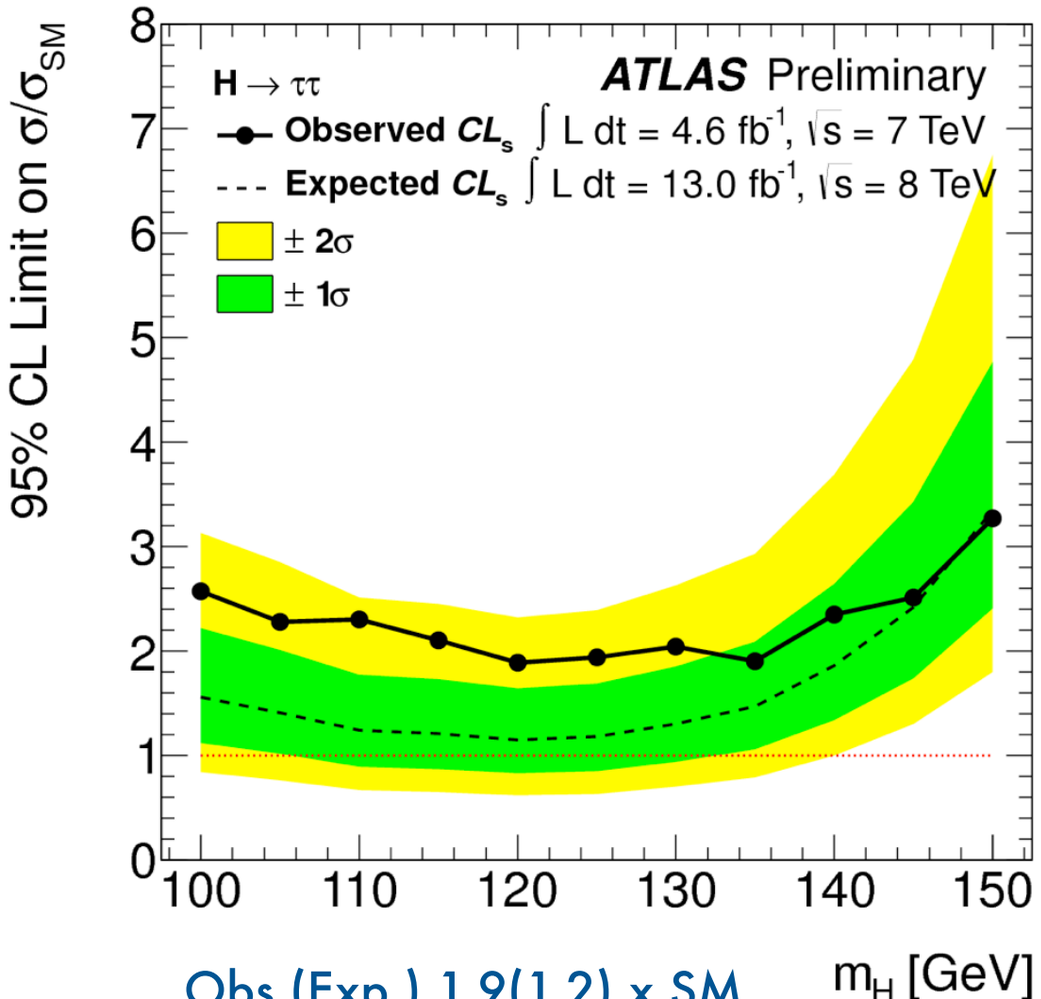
[ATLAS-CONF-2012-160]

- Search in lep-lep, lep-had and had-had channels - each channel affected by different backgrounds → cuts optimized separately
- Selected events (in each channel) split in 0, 1, 2 jet case (2 jet case optimized for VBF/VH)
- Invariant $m_{\tau\tau}$ obtained using the Collinear Approximation or the Missing Mass Calculator (MMC)





Analysis of full 2012 dataset still ongoing



Obs.(Exp.) 1.9(1.2) x SM

Best fit signal strength for m_H = 125 GeV: $\mu = 0.7^{+0.7}_{-0.6}$

VBF H→γγ Candidate

converted photon

high mass jet

high mass jet

converted photon

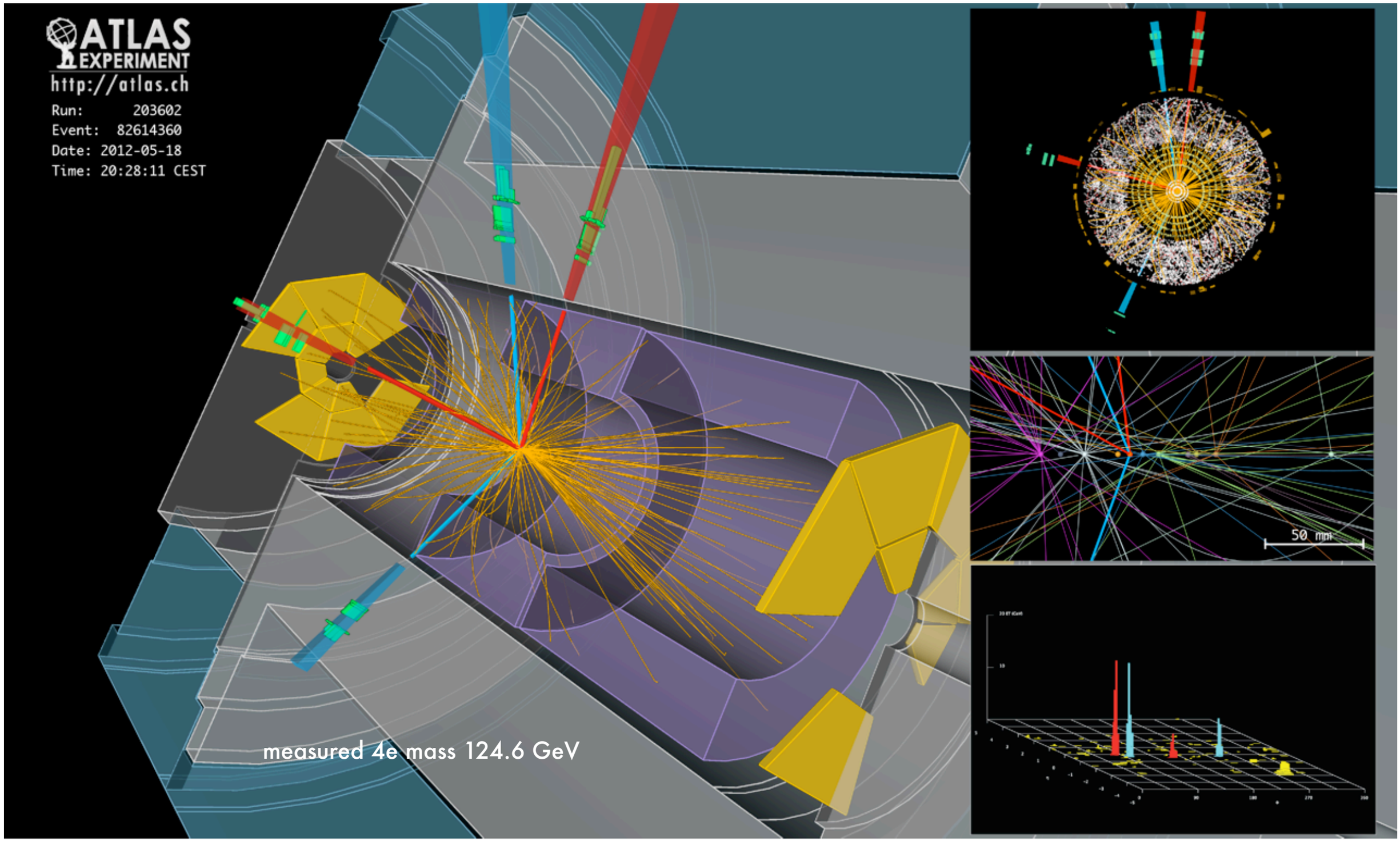
ATLAS EXPERIMENT

measured diphoton mass 126.9 GeV

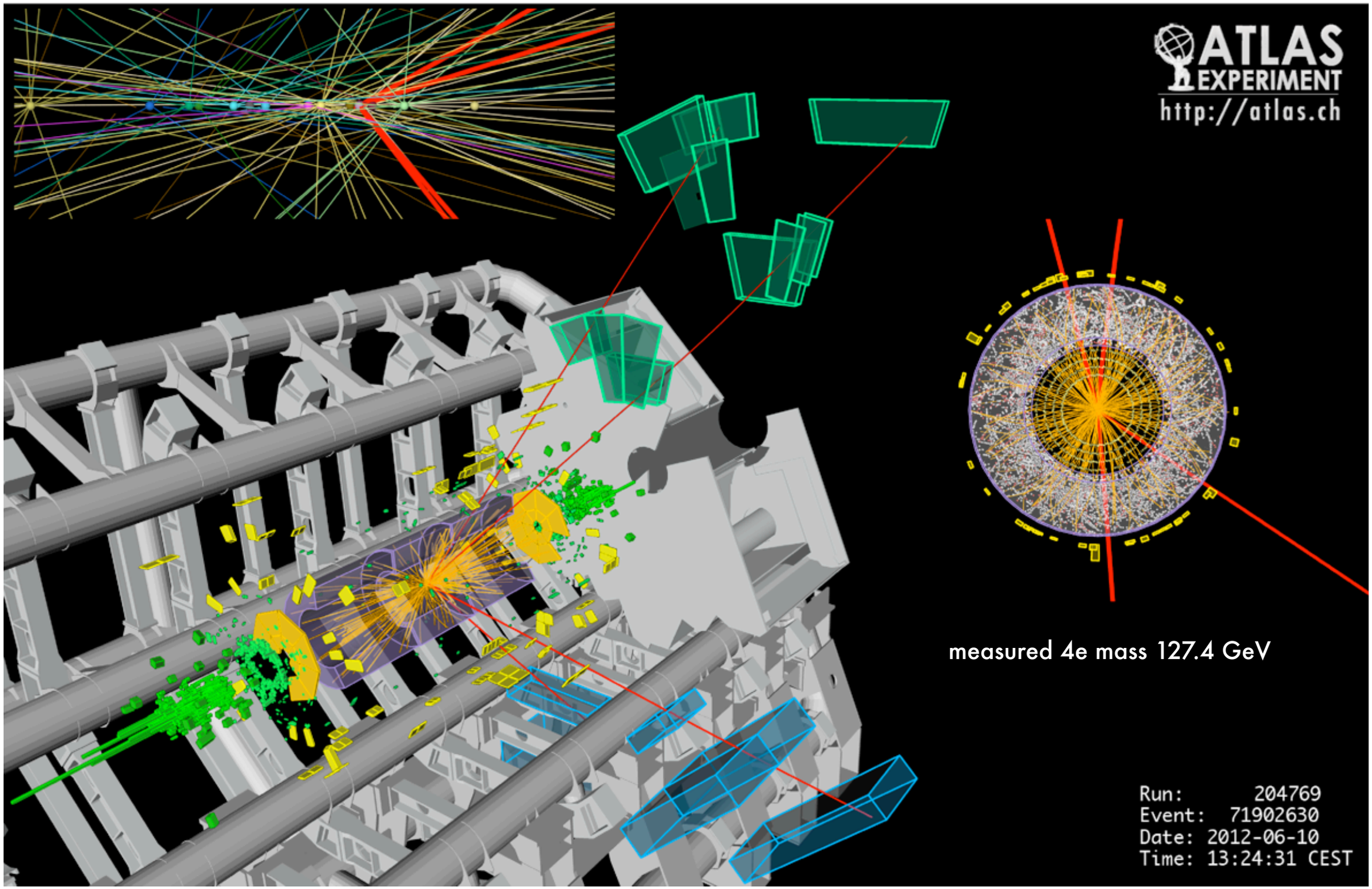
Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

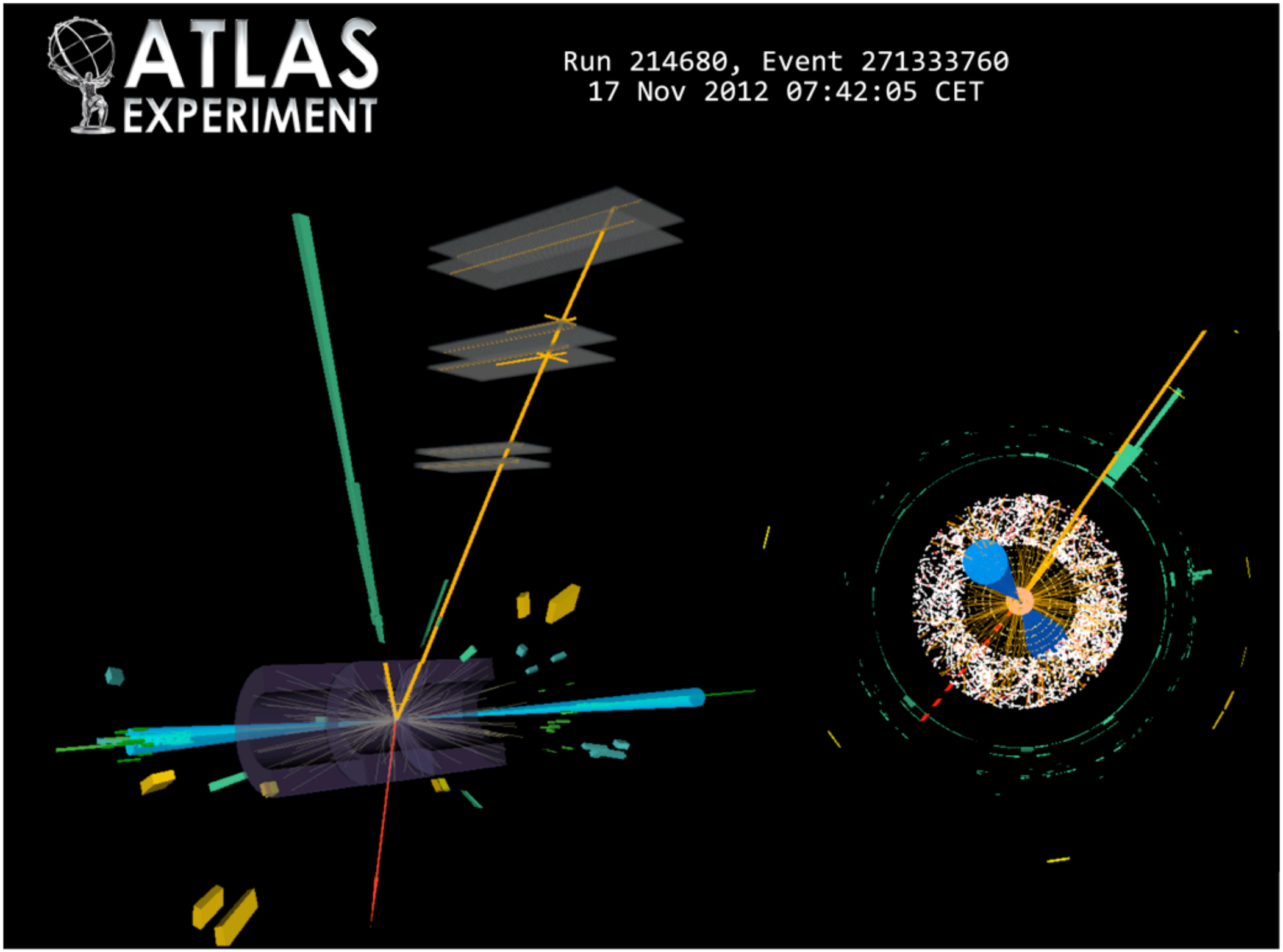
H→ZZ*→4e Candidate



H→ZZ*→4μ Candidate



VBF H→WW(*)→eνμν+2jets Candidate



Leptonic ttH → ttγγ Candidate