PROBING THE HIGGS PROPERTIES AT ATLAS

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1. Introduction
2. H decay channels
3. Property of the newly-discover H boson
4. Rare decay
5. Conclusion and prospects

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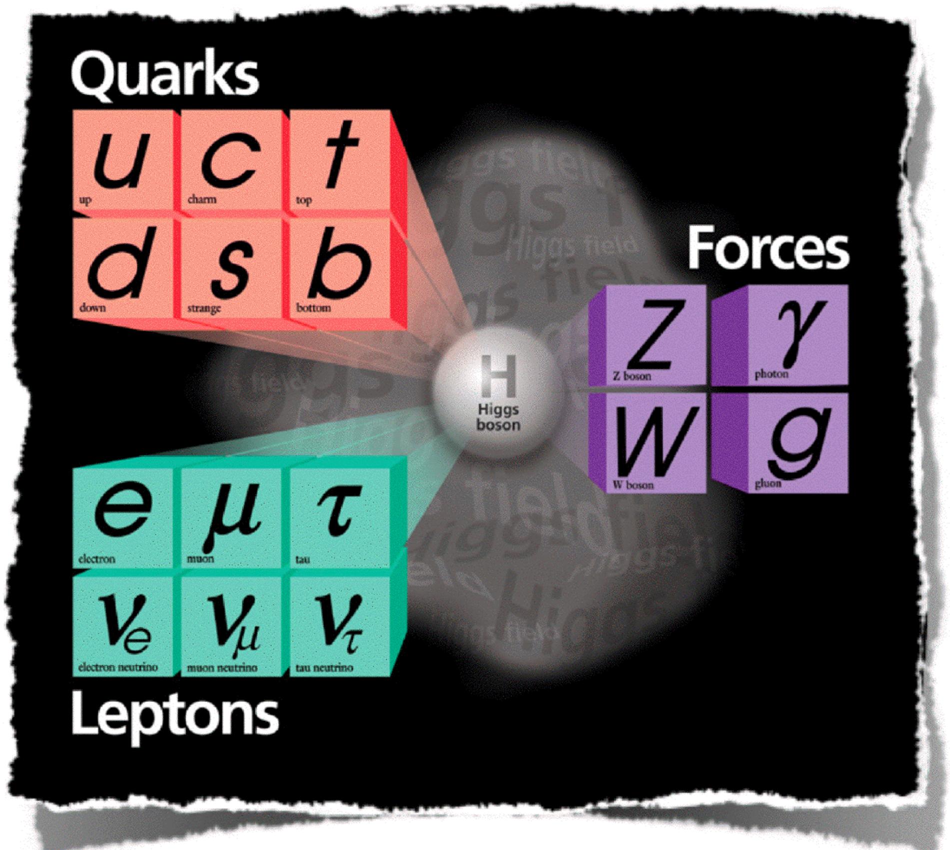
The Standard Model H boson



The Standard Model of particle physics is an impressively successful theory.

⇒ The Higgs mechanism was postulated in the mid-1960s to complete the Standard Model (SM) of particle interactions.

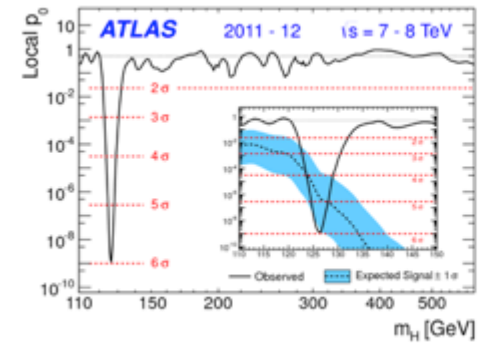
The Higgs boson has been the missing piece of SM puzzle for the past half century!

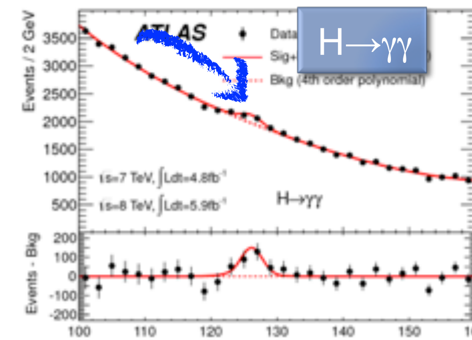
A long way since then ..

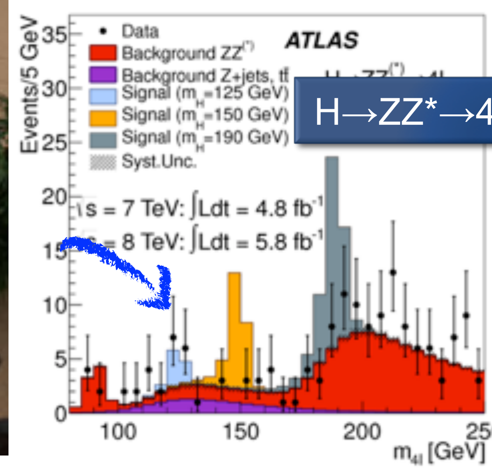
The observation of a new particle

PLB 716(2012) 1-29

4th July 2012 – The Discovery of the H

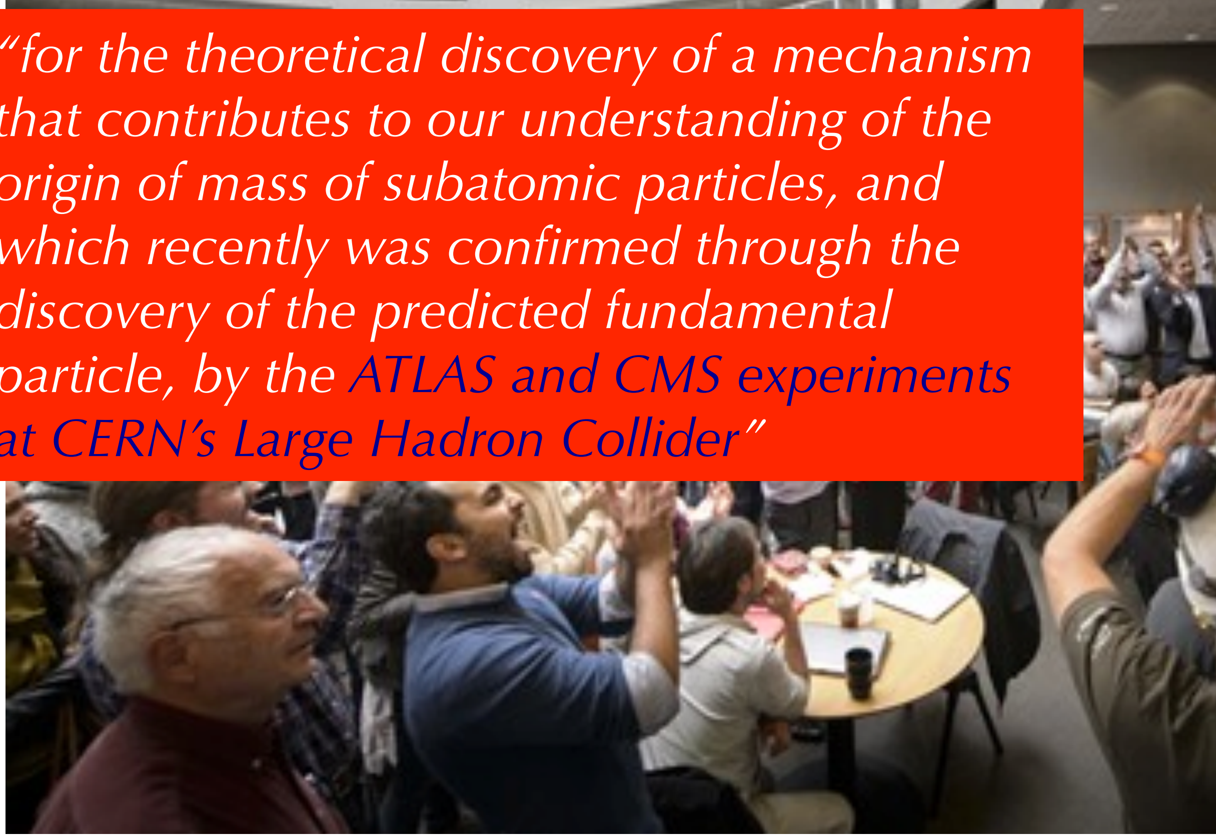






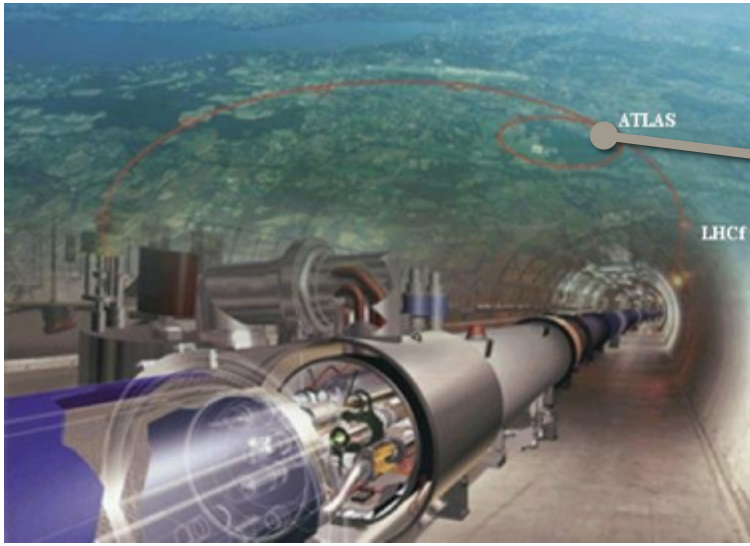
And Recently a Nobel Prize

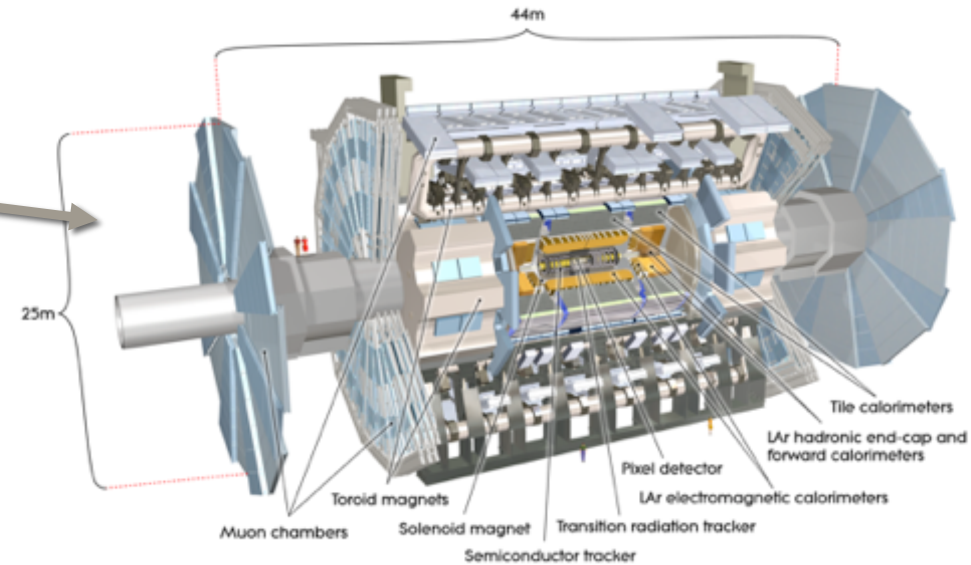
8th October 2013



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

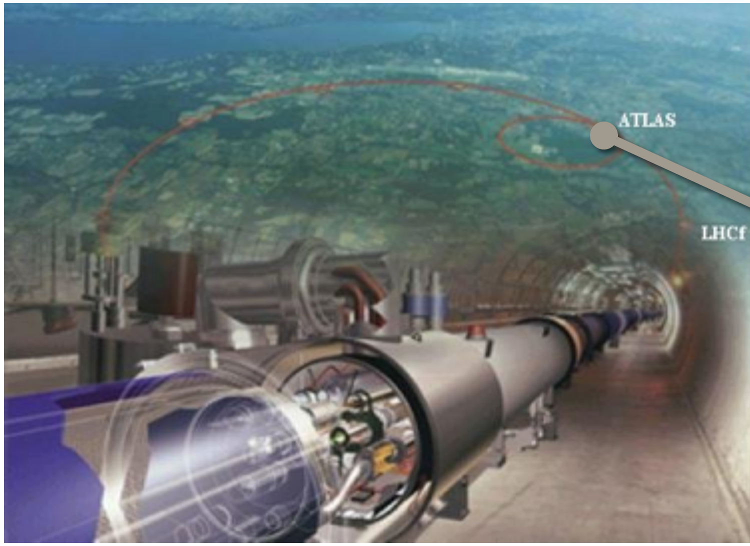
LHC performance and ATLAS detector



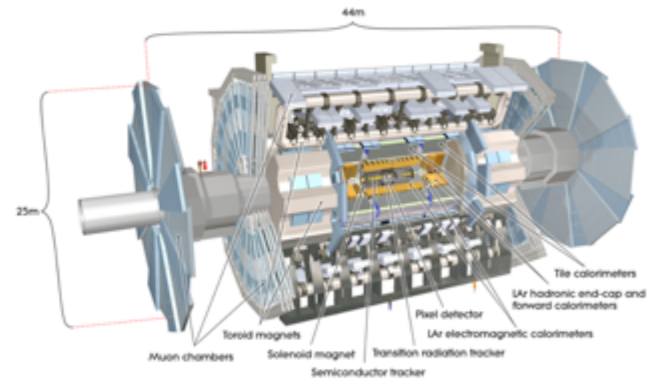


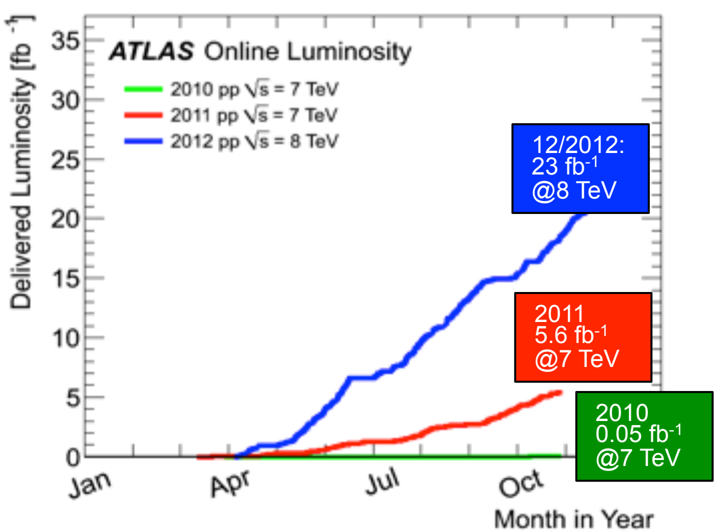
	A Toroidal **L**HC **A**pparatu**S**
Magnets	2T solenoid, 3 air-core toroids
Tracking	silicon + transition radiation tracker
EM Calorimetry	sampling LAr technology
Hadronic Calorimetry	plastic scintillator (barrel) LAr (endcaps)
Muon	independent system with trigger capabilities
Trigger	3 levels of trigger (first level hardwer)

LHC performance and ATLAS detector



A Toroidal **L**HC **A**pparatu**S**
Is a general purpose experiment
More then 95% of data taking efficiency/ quality





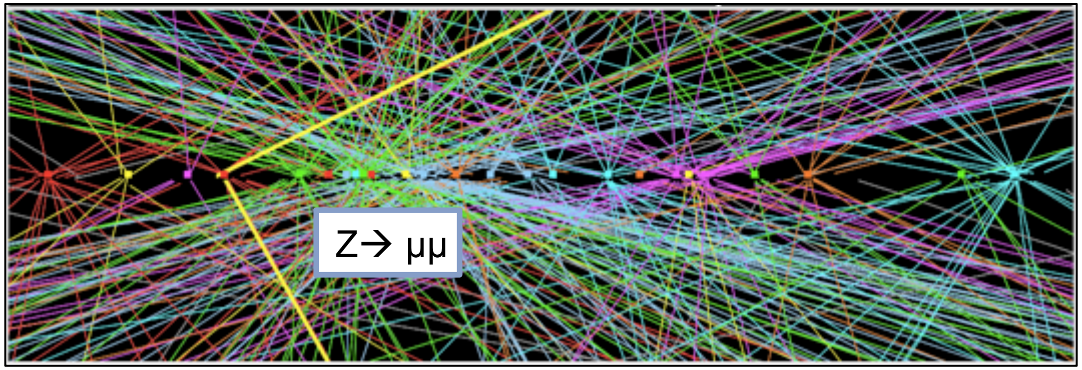
Excellent LHC performance during Run I

- 2011: 4.8 fb-1 at 7 TeV
- 2012: 20.7 fb-1 at 8 TeV

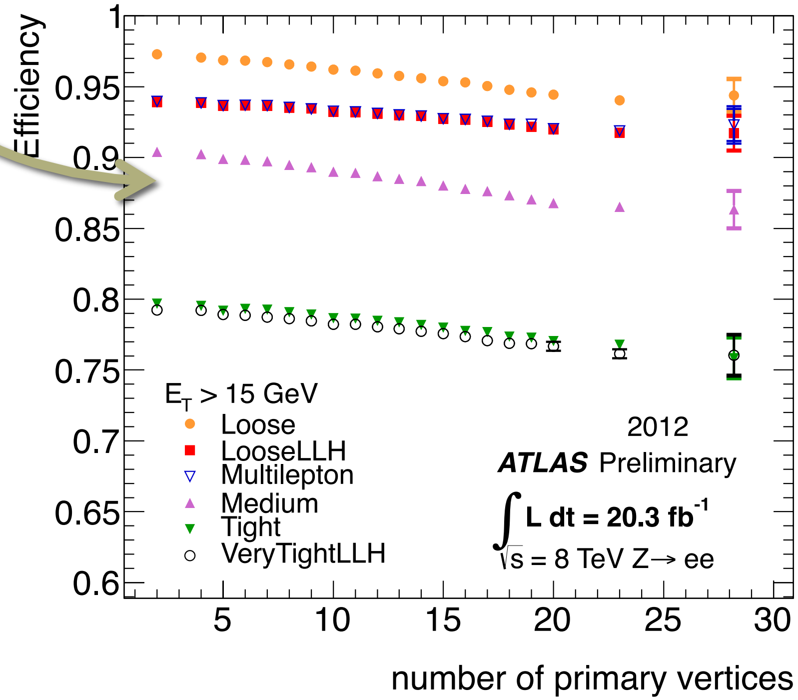
- Challenging data taking condition
  → Pile-up in 2012
  → Maintain excellent performance by improved algorithms

Lepton performance vs pileUp

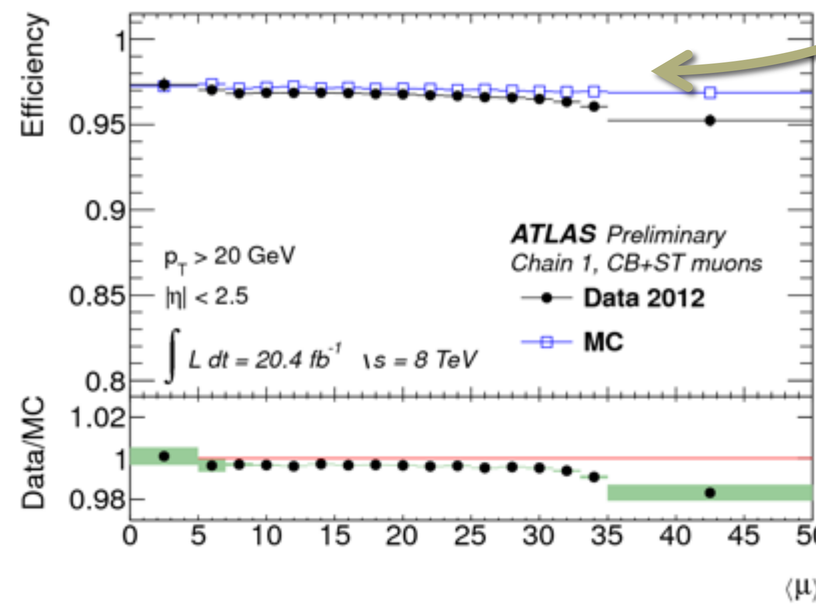
Z→ μμ event from 2012 data with 25 reconstructed vertices



Electron reconstruction

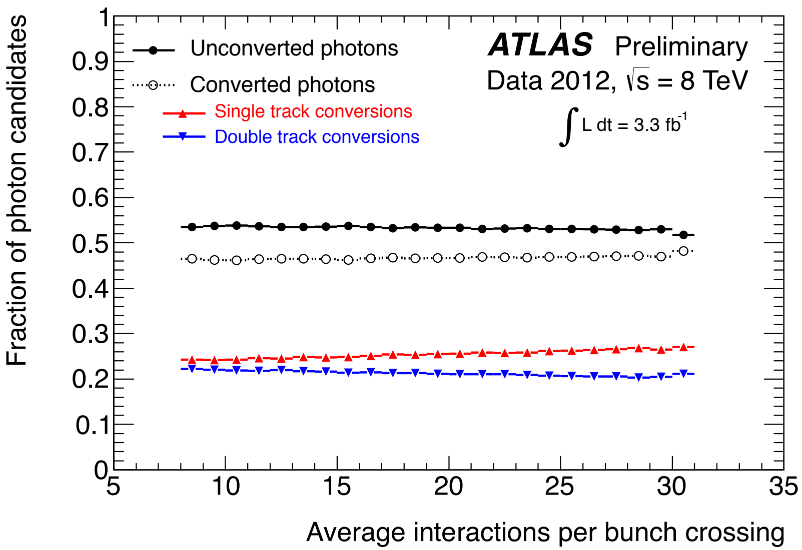


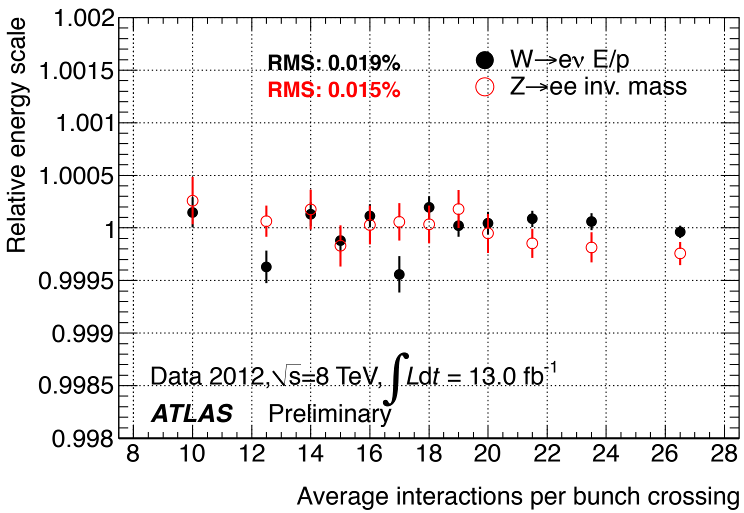
Muon reconstruction



Photon and Calorimeter performance

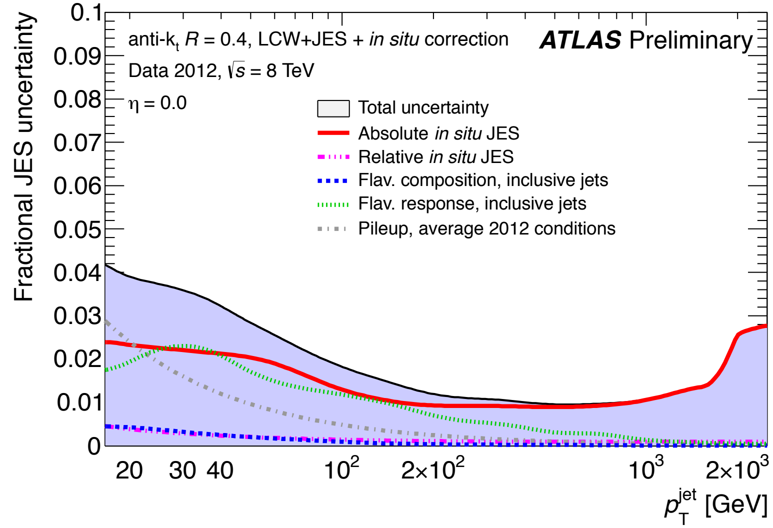
- Stable energy response vs number of primary vertex.
  - Excellent stability of the EM calorimeter response
    - Studied with Z,J/$\psi \rightarrow$ee and W$\rightarrow$eν events
    - Energy scale at m_Z known to ~0.3% and stable wrt pileup
    - Uniformity ~1% (2.5% for 1.37<|η|<1.8)
- Photon efficiency stable with time and pile-up.

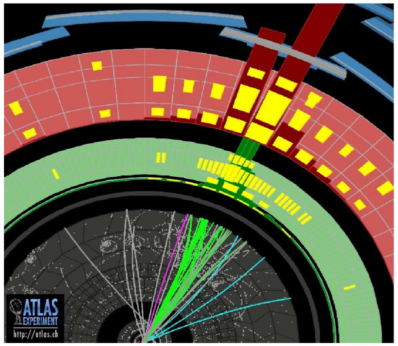


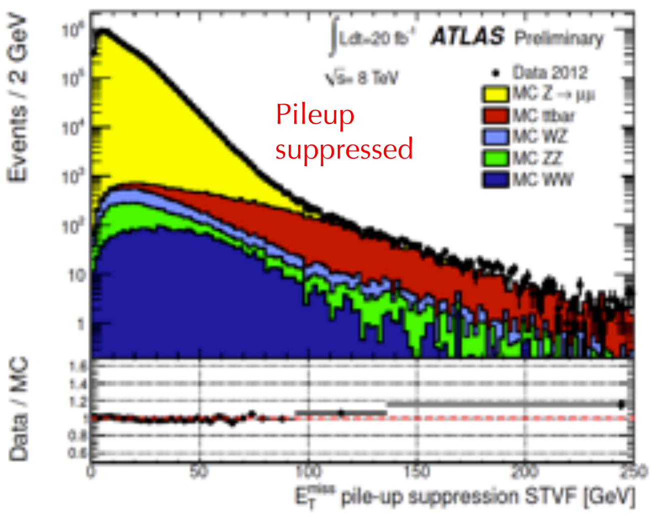


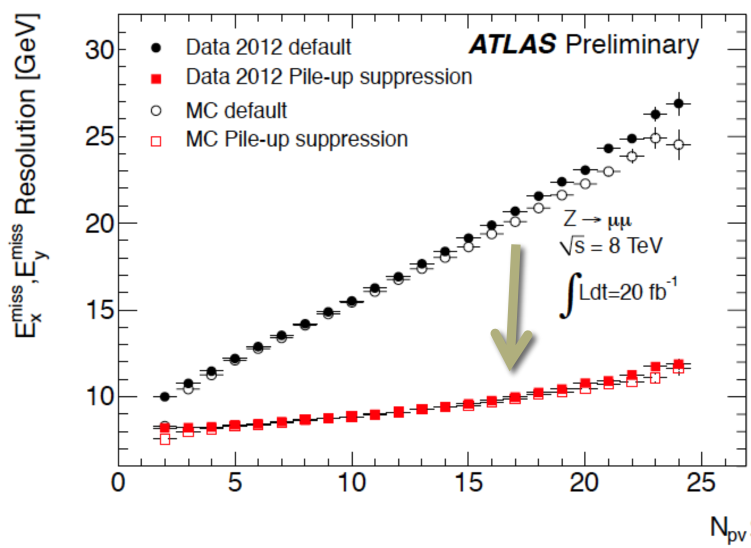
Jet - E_T miss performance

- JES uncertainties at the 1-2% level (absolute calibration)
- Missing ET well modeled: Pileup suppression improves E_{TMiss} resolution

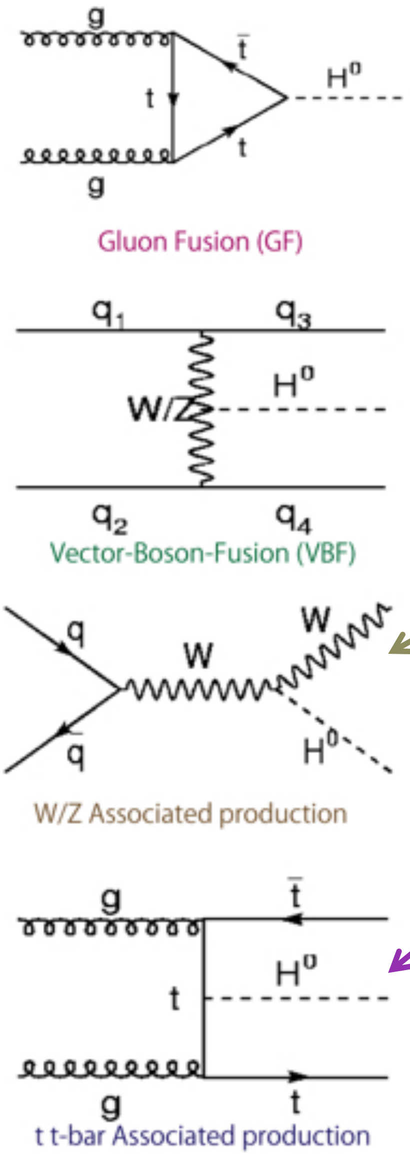








SM Higgs production at the LHC

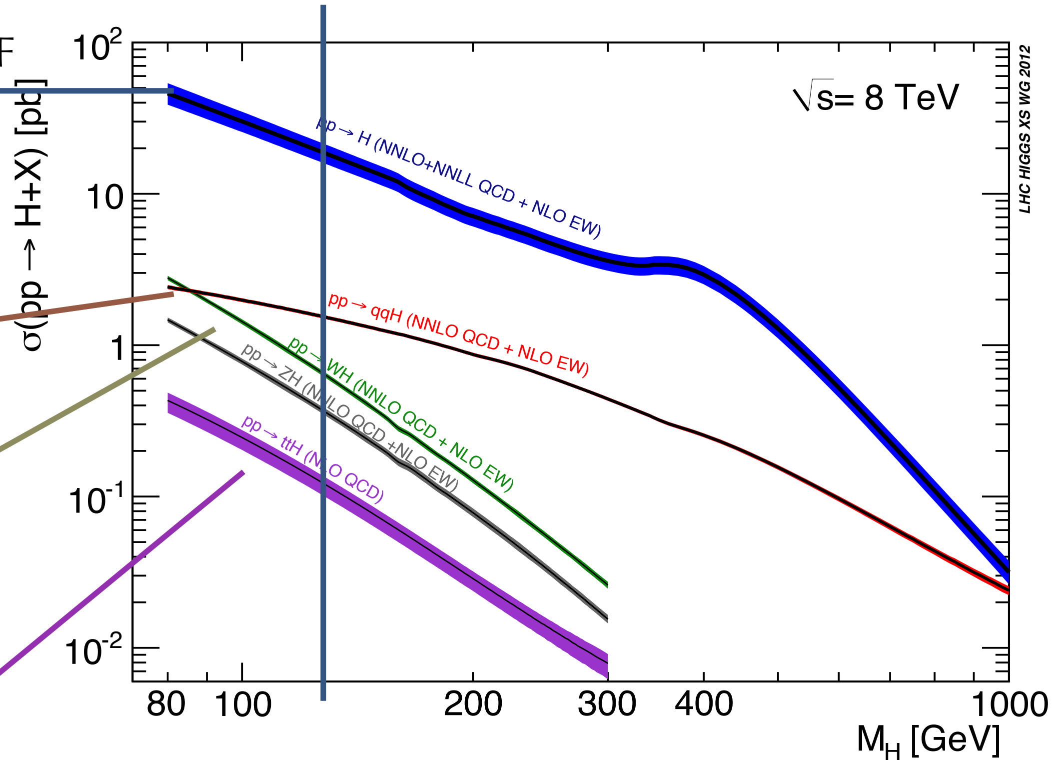


19.5 pb (87%) ggF

1.6 pb (7%) VBF

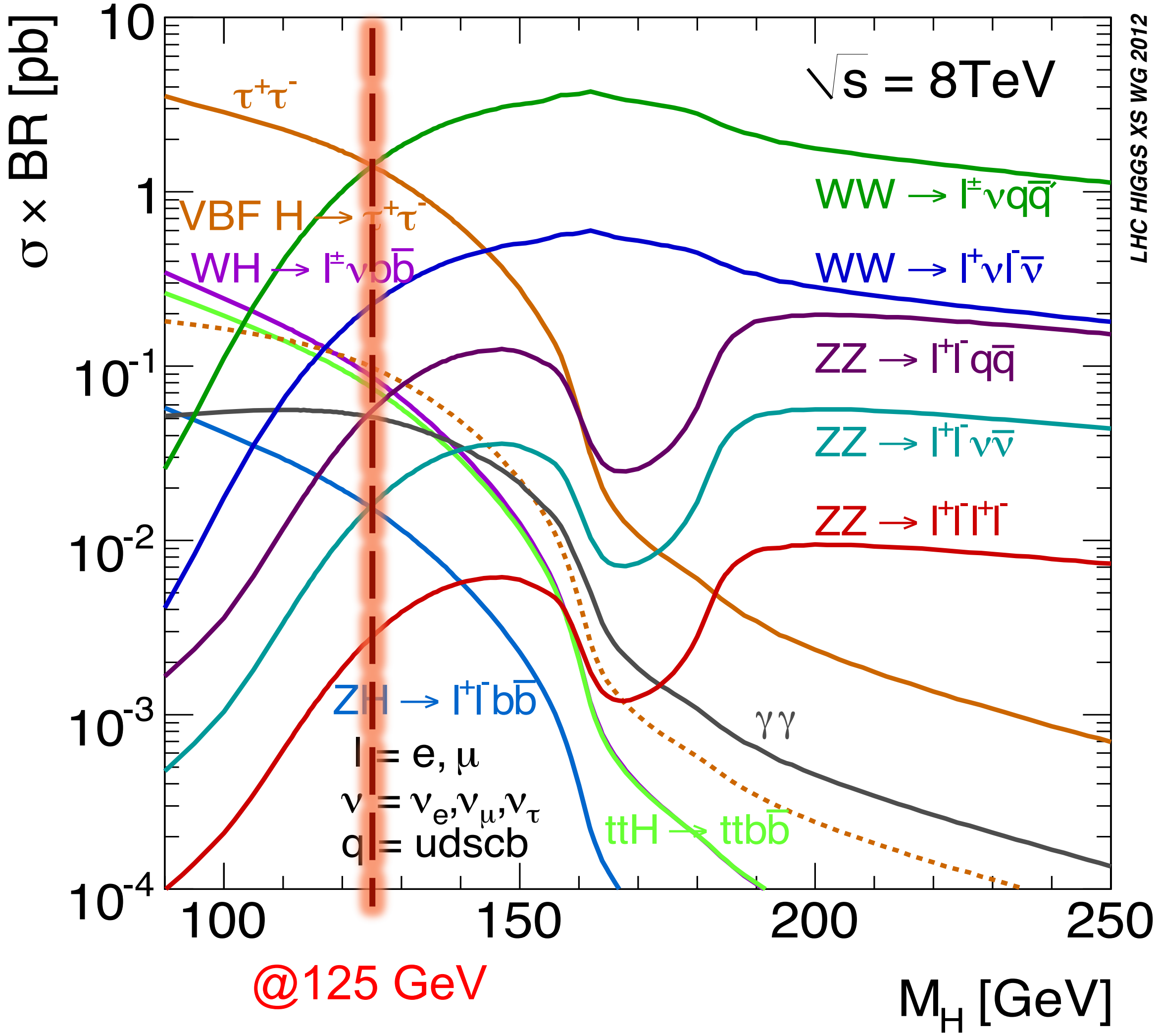
1.1 pb (5%) VH

0.1 pb (1%) ttH



σ (pb) @ m_H=125 GeV for pp $\sqrt{s}$ =8 TeV 22.3 pb

SM Higgs decay mode

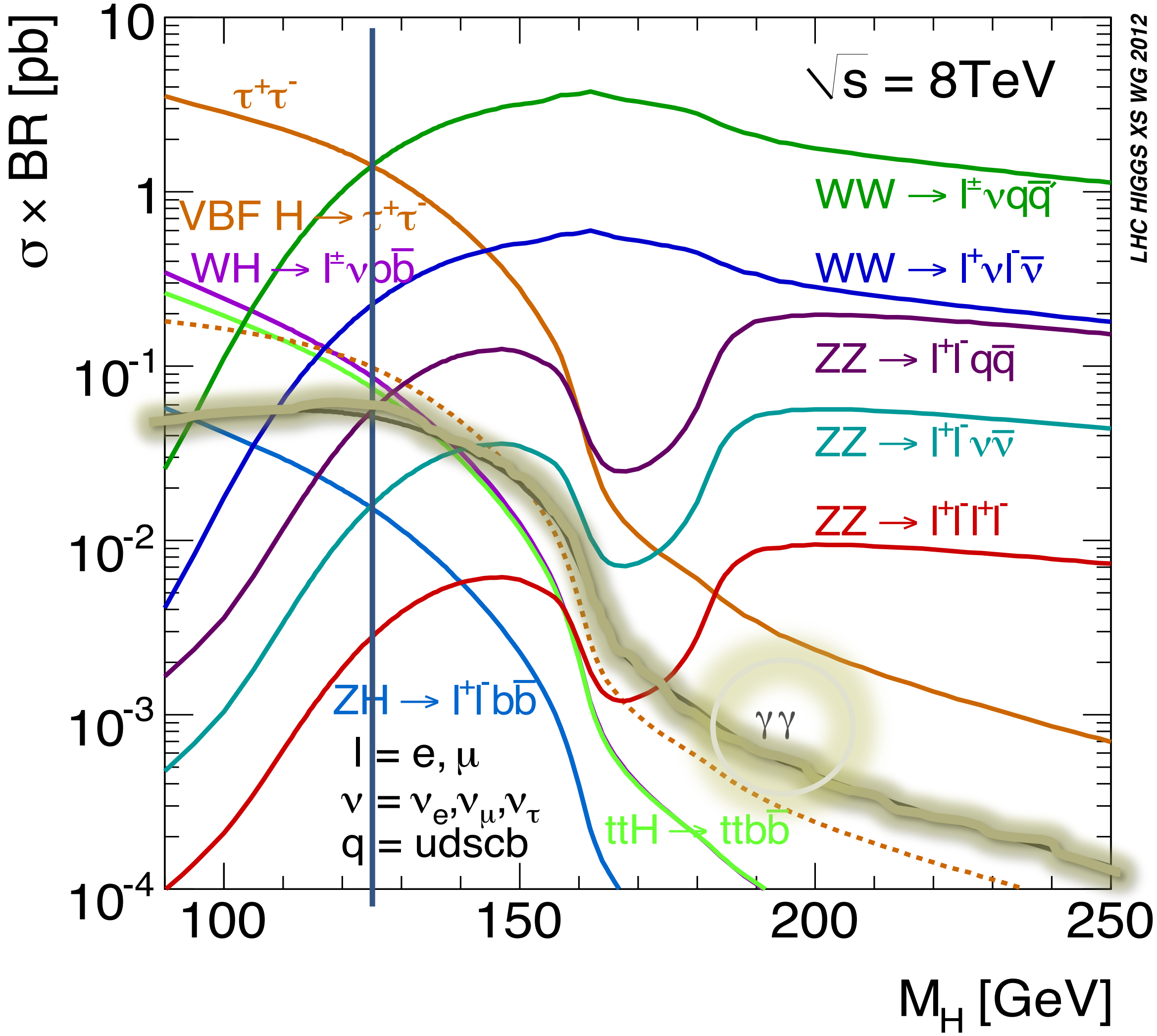


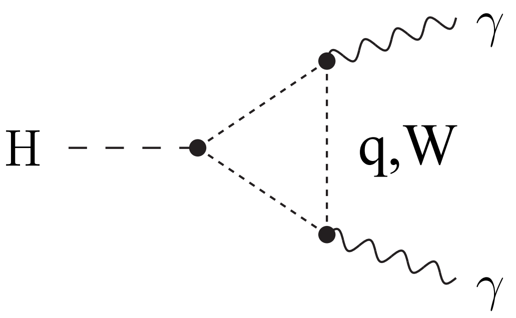
The σ BR for the different decay mode is highly m_H dependent.

@mH= 125 GeV several decay mode can be studied

- Bosonic mode:
  - γ γ, ZZ*, WW*
- Leptonic mode
  - bb, τ τ

$H \to \gamma\gamma$





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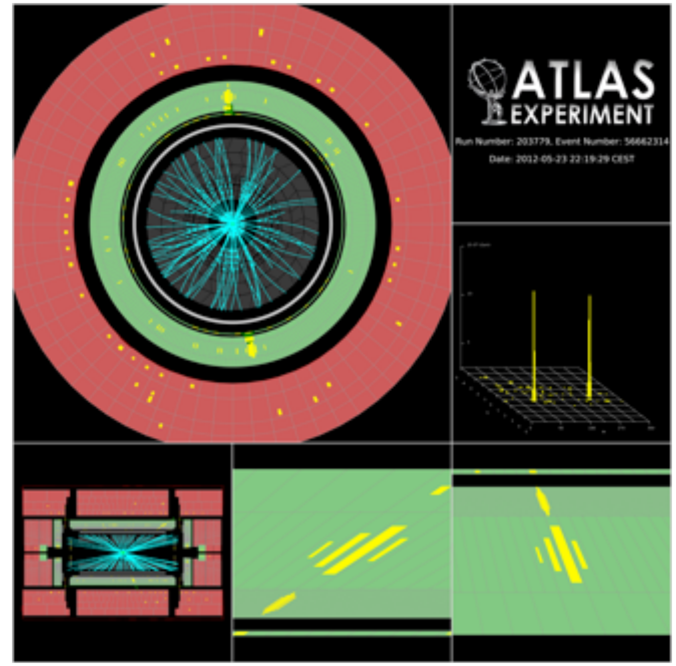
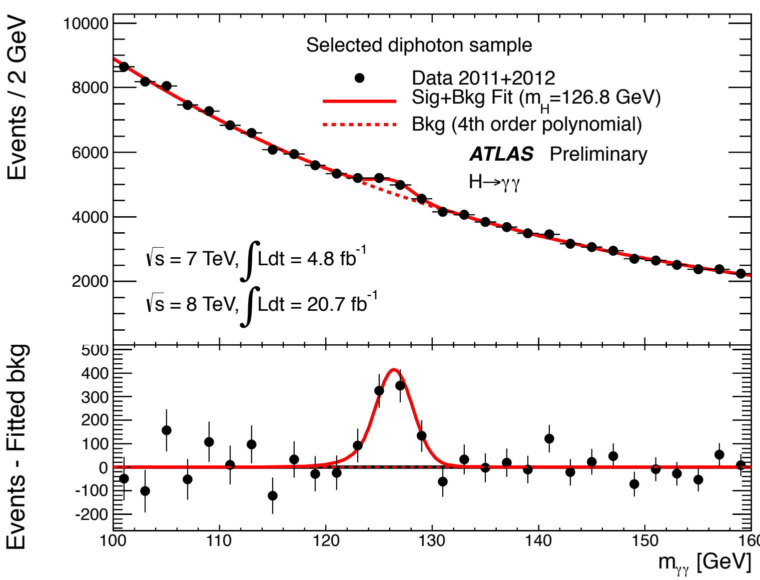
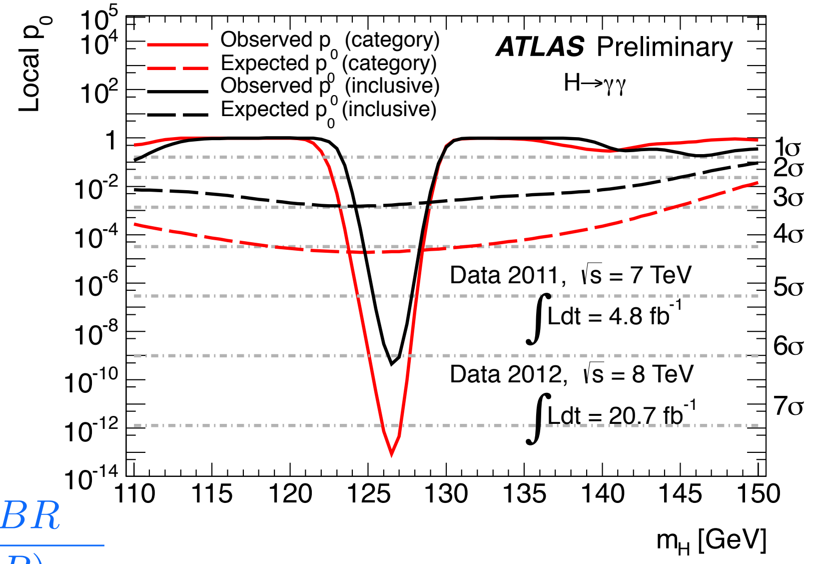
H→γγ

- Selection:
  - $E_T(\gamma 1)$> 40 (20) GeV @8TeV (7TeV)
  - $E_T(\gamma 2)$> 30 (20) GeV @8TeV (7TeV)
- Search narrow peak in $m_{\gamma\gamma}$
  - Very good mass resolution ~1.7 GeV.
- Background:
  - γγ [~75%], γ-jet and jet-jet [~25%]
- Analysis:
  - Simultaneous fit Signal + background to data
  - S/B~3%.
  - Classification 14 categories.
    - Enhance sensitivity (~40%).
    - Improve signal resolution (1.4-2.5 GeV).
    - Optimized for coupling measurements



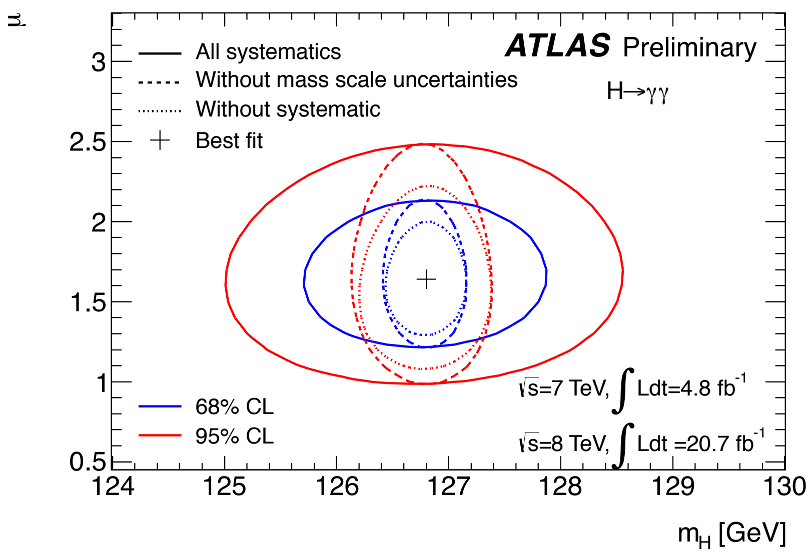


$H \rightarrow \gamma\gamma$: results

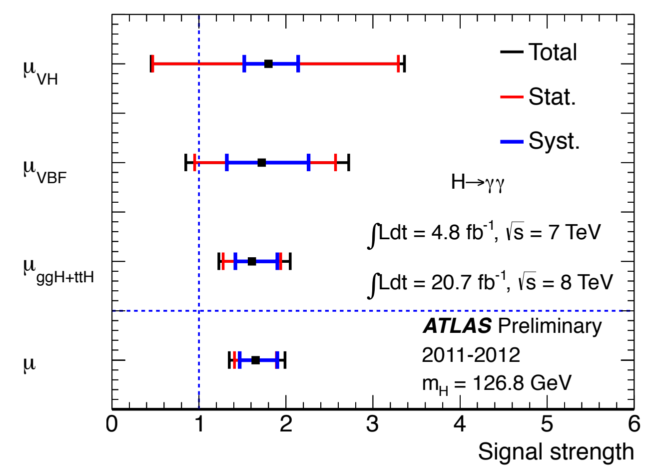


- Most significant deviation @ mH 126.5 GeV:
  - Local significance: **7.4 σ** (4.1 σ expected)
- Mass measurement:
  126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
  - Systematics dominated by photon energy scale
- Production rate:
  μ = **1.65 ± 0.24 (stat)$^{+0.25}_{-0.18}$ (syst)**
  - 2.3 σ deviation SM

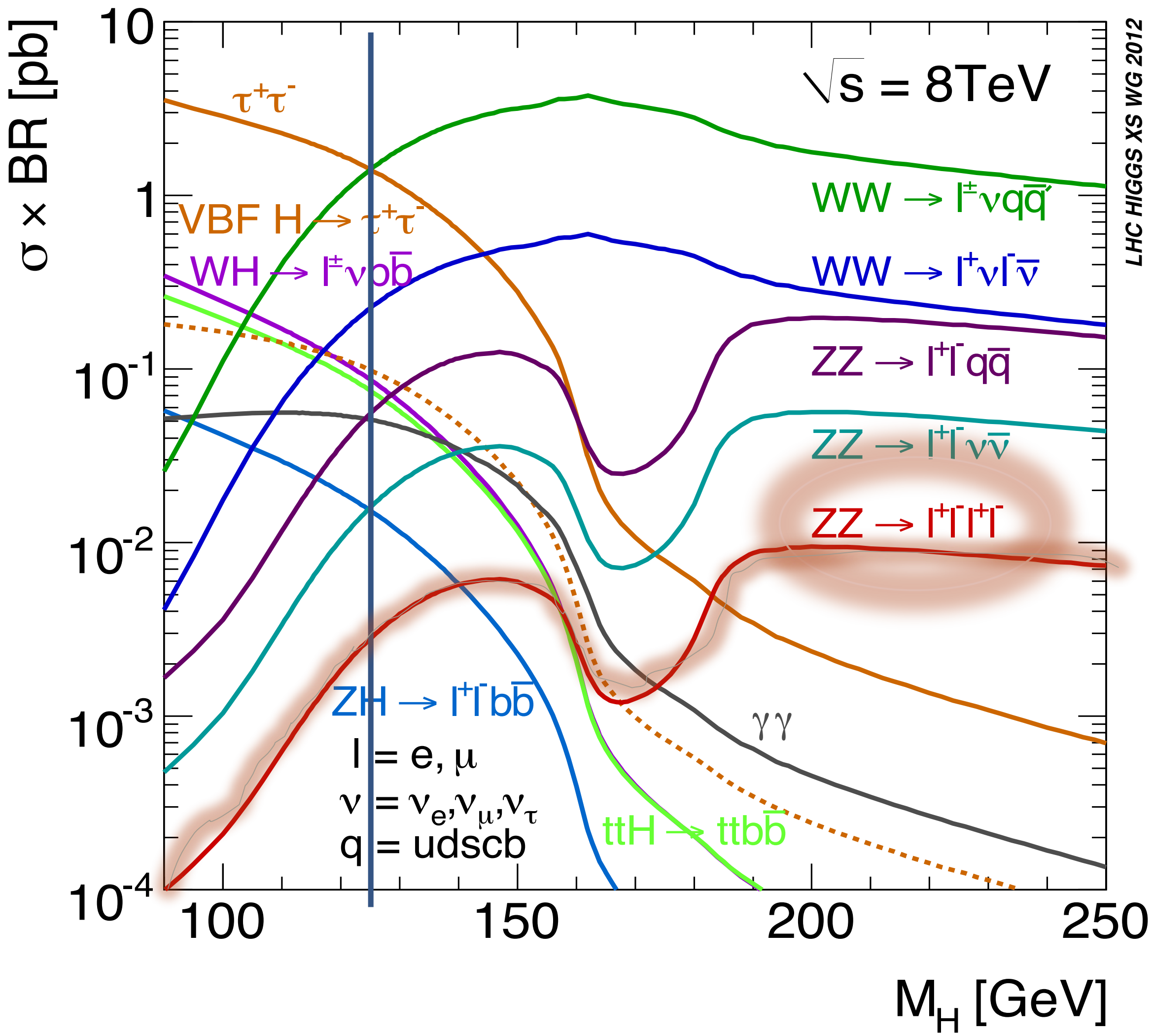
$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

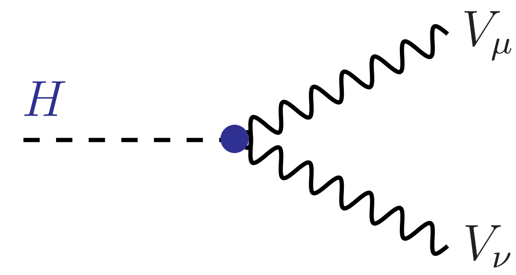


Couplings in agreement with SM expectation within 2 σ :



$H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$





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

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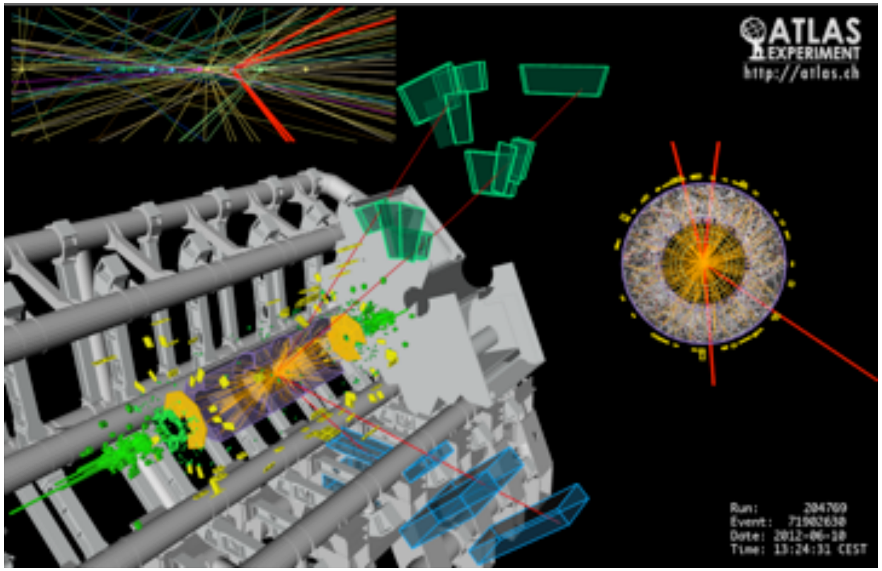
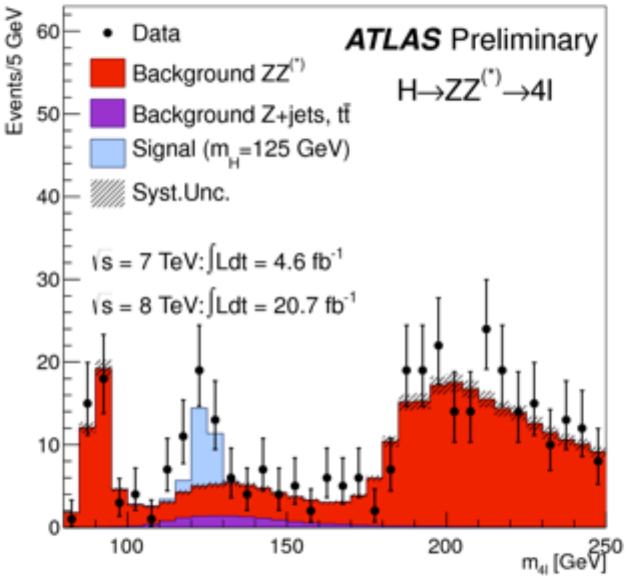
- Selection:
  - $p_T^{1,2,3,4}$ > 20, 15, 10, 7/6(e/μ) GeV
  - m_{12} =50-106 GeV; 115 > m_{34} > 12-50 GeV
- Main backgrounds:
  - $ZZ^{(*)}$ (irreducible)
  - Reducible: Zbb, Z+jets, tt with two leptons from b/q-jets ($m_H < 2m_Z$)
- *Golden channel:*
  - very good S/B = 1.6 for mH=125 GeV
  - mass resolution ~1.9 GeV
  - Signal acceptance x efficiency: 15-37 % @m_H125 GeV



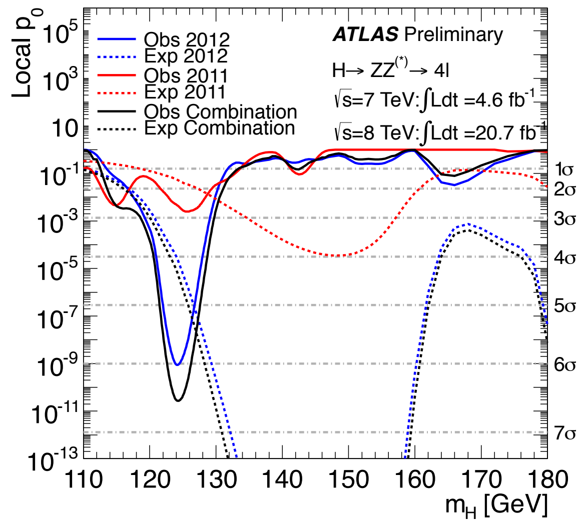
120-130 GeV

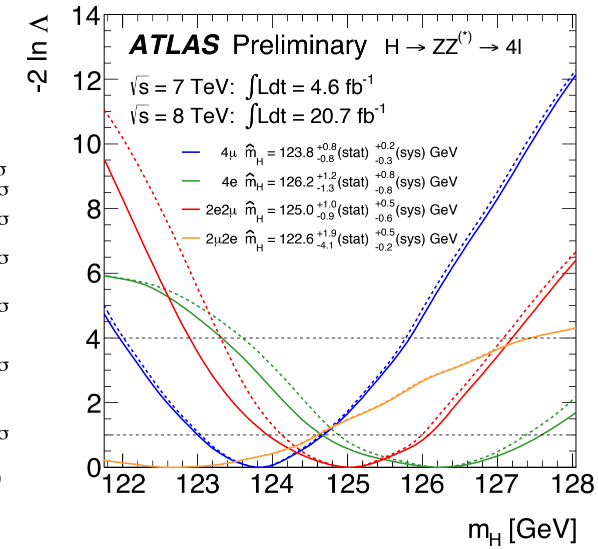
	Signal	ZZ(*)	Other Backgrounds	Observed	S/B
4μ	6.3±0.8	2.8±0.1	0.55±0.15	13	~1.9
2μ2e	3.0±0.4	1.4±0.1	1.56±0.33	5	~1.0
2e2μ	4.0±0.5	2.1±0.1	0.55±0.17	7	~1.5
4e	2.6±0.4	1.2±0.1	1.11±0.28	6	~1.1



$H\rightarrow ZZ^{*}\rightarrow 4\ell$ results

- Local significance:
  6.6 σ (4.4 σ exp)
  @mH=124.3GeV
- Mass:
  $124.3^{+0.6}_{-0.5}$(stat)$^{+0.5}_{-0.3}$(syst) GeV
  - Main systematic uncertainty: e/μ E/P scale
- **Production rate with respect to SM:**
  $\mu = 1.7^{+0.5}_{-0.4}$

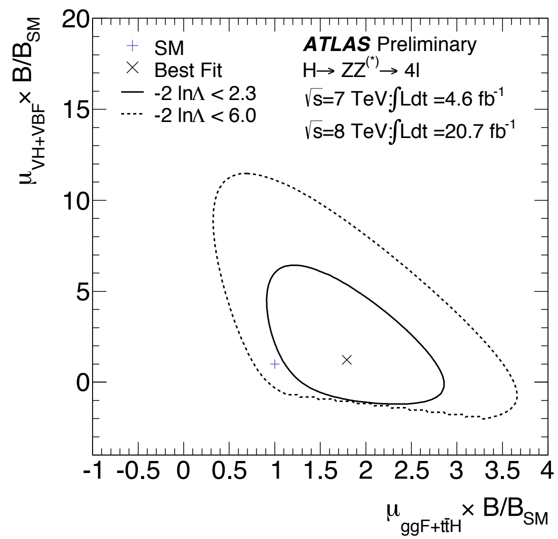




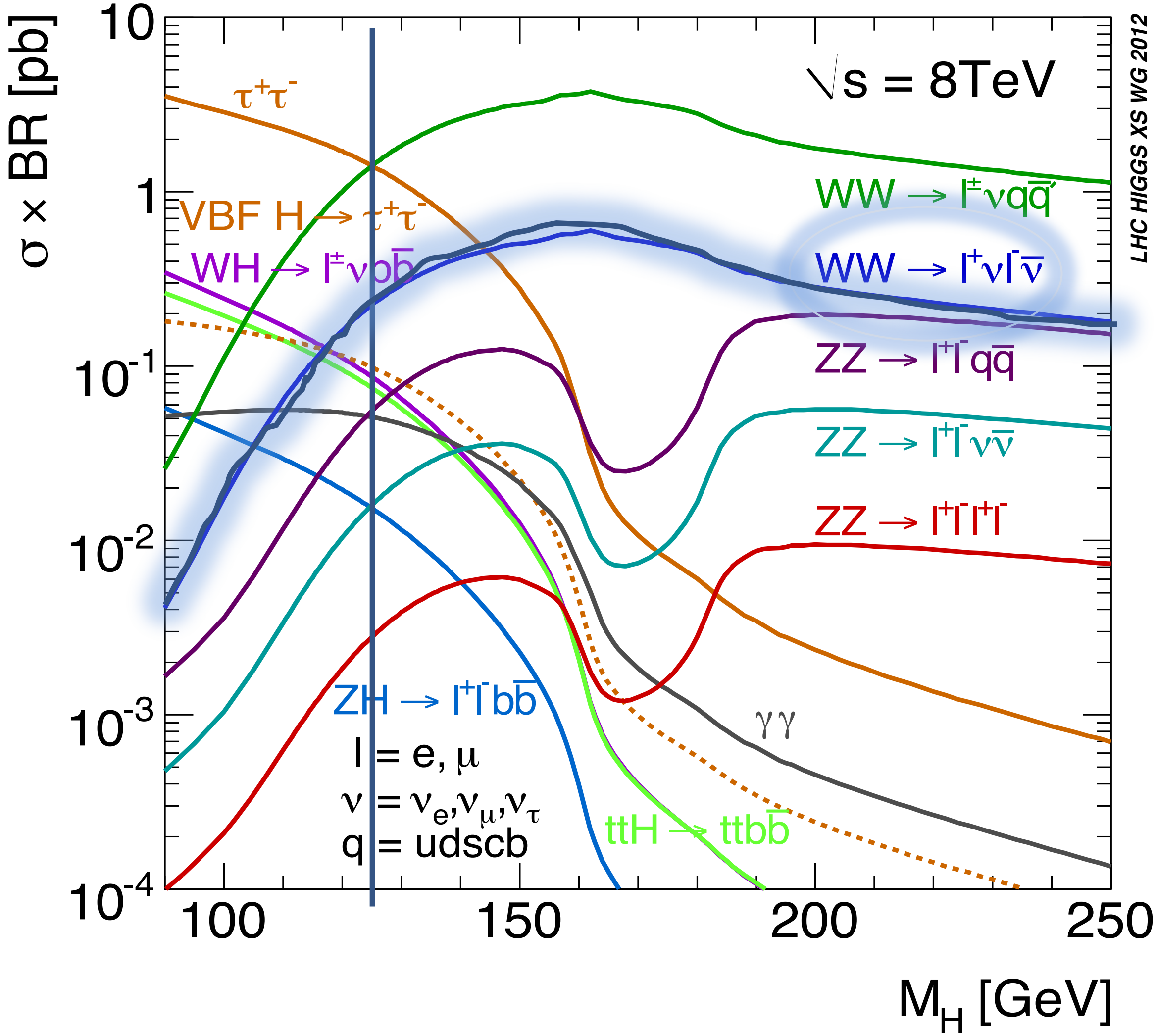
The events are further categorized as:

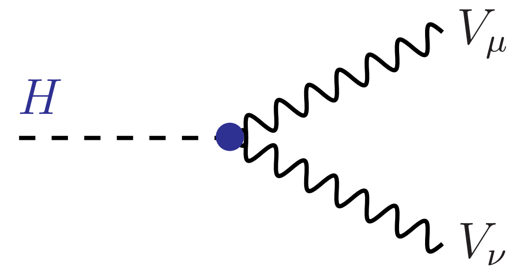
VBF-like (two jets in VBF topology)
VH-like (events with additional leptons)
ggF-like (all remaining events)

→ Coupling measurement consistent with SM expectation within 2 σ



$H \to WW^* \to l\nu l\nu$





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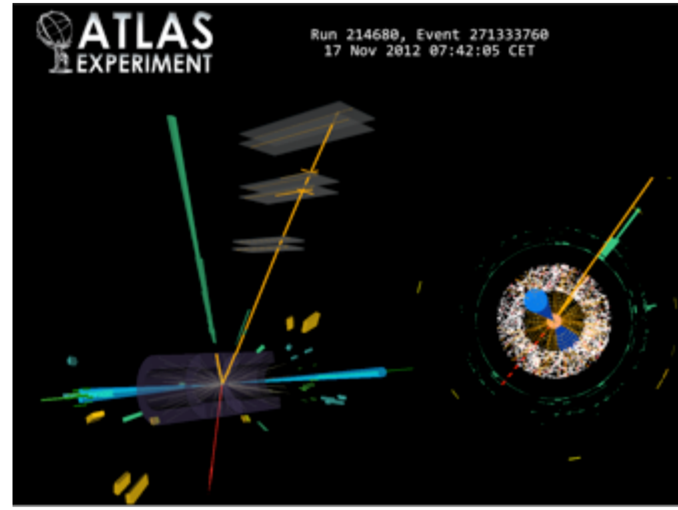
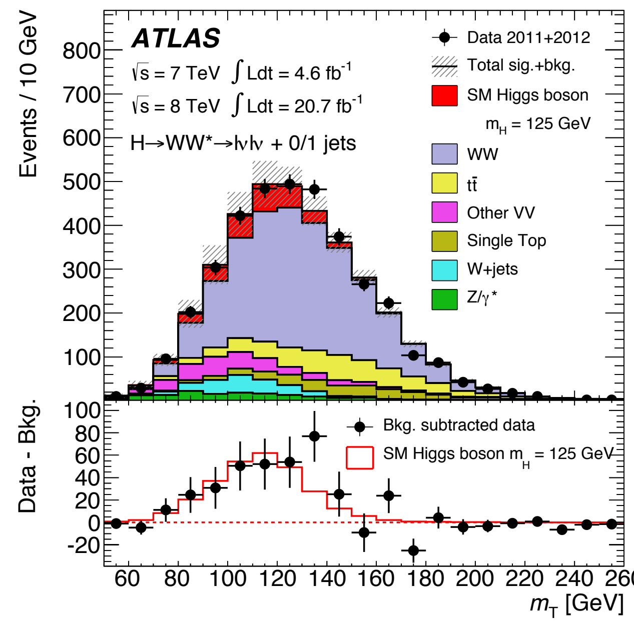
$H \rightarrow WW^* \rightarrow l\nu l\nu$

- Signature:
  - 2 isolated opposite-sign leptons & large E_{Tmiss}
- Sensitive channel in wide mass range ~ 125-180 GeV (σ ~ 200 fb)
  - Challenging: two missing ν → no mass reconstruction/peak
- Observable: m_T

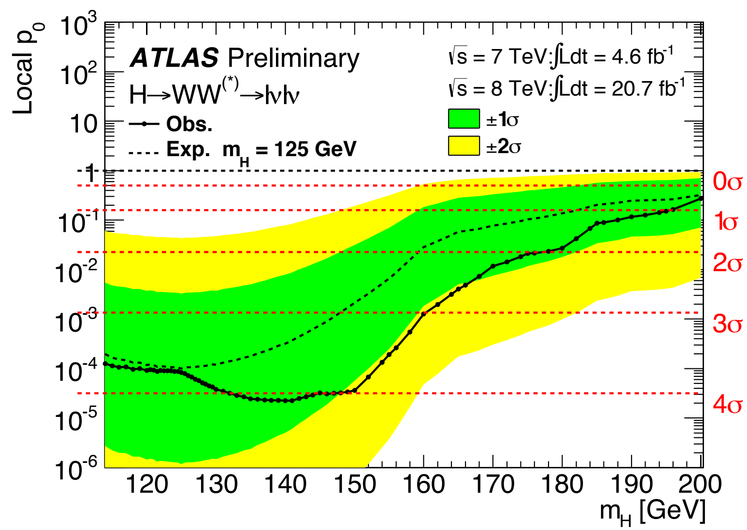
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

- Main backgrounds: WW, top, Z+jets, W+jets
  - Excellent understanding of background in signal region → use signal-free control regions in data to constrain MC → use MC to extrapolate to the signal region
- Further categorization to improve sensitivity:
  - Range dilepton mass: m_{ll}
  - lepton flavors: μe, eμ, $\mu\mu$, ee
  - jet multiplicities: 0, 1, ≥2

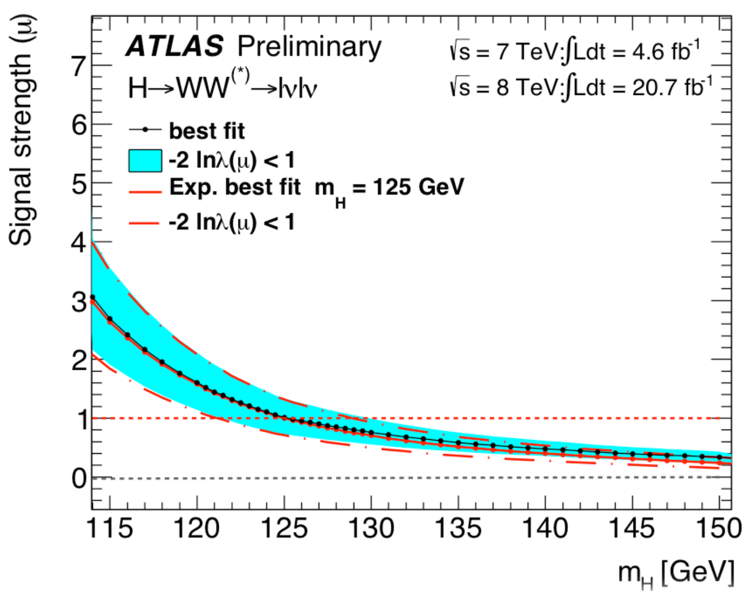


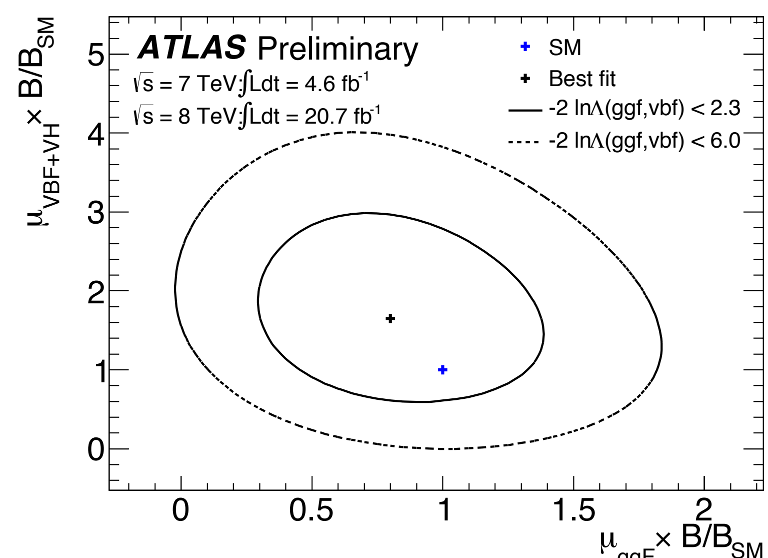


$H \to WW^* \to l\nu l\nu$ results

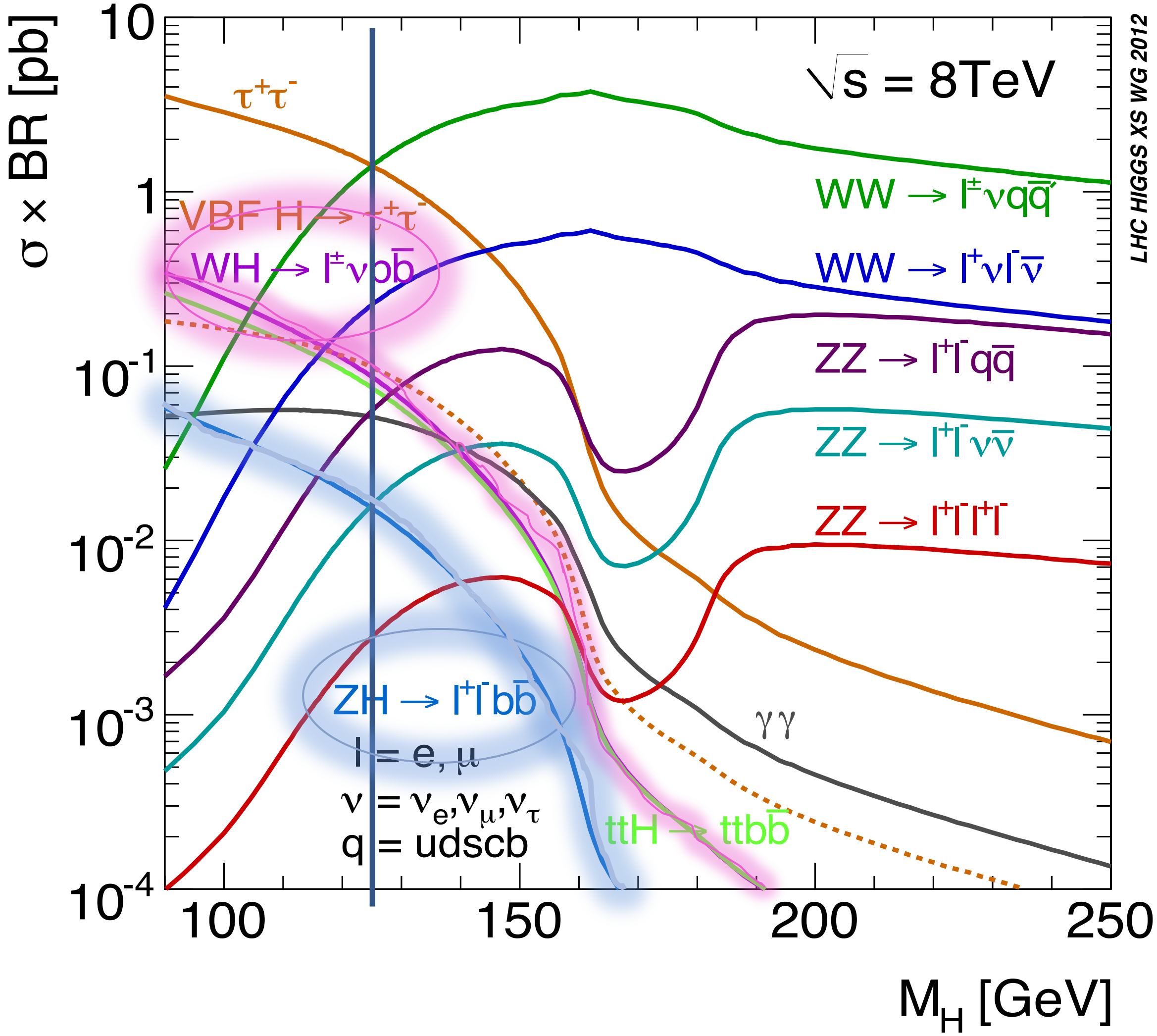


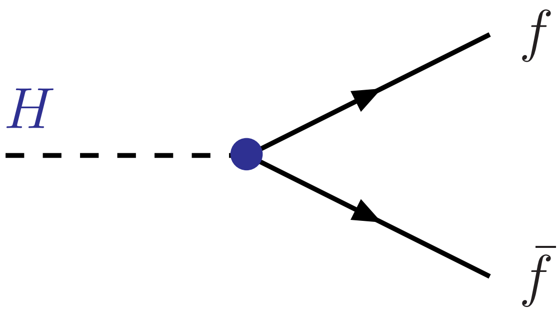
- Broad excess around 120 GeV
  - significance: 3.8 σ @125 GeV (3.7 σ exp)
- Best fit of signal strength:
  μ = 1.01 ±0.31 @125 GeV
  - Dominant contribution to the experimental systematic uncertainty from jet energy scale and resolution.
- Coupling measurement consistency with SM <1 σ level





H→bb (VH→bb)





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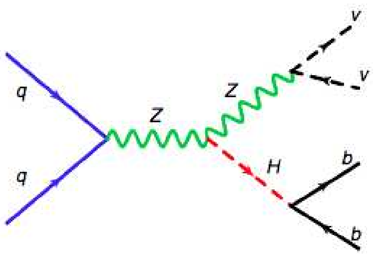
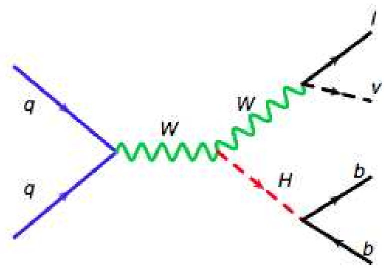
H→bb (VH→bb)

- Highest branching ratio (58% for 125 GeV) but large QCD bkg
- Associated production with W /Z to overcome dominant QCD background:
  - 3 final states: ZH->$\nu\nu$+bb, WH->lν+bb , ZH->ll+bb in the **VH production mode**

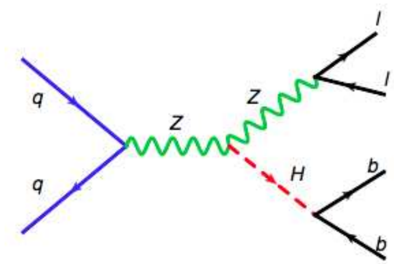
0 lepton

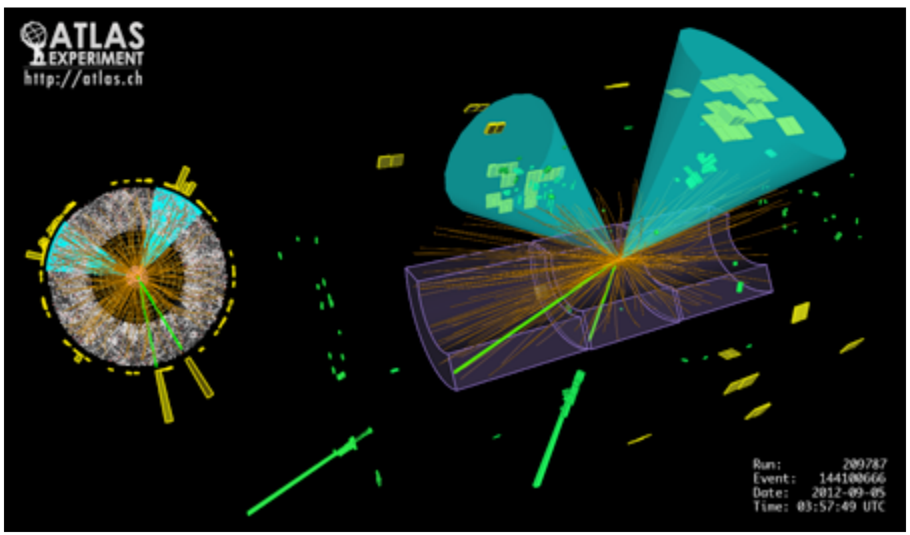


1 lepton



2 lepton

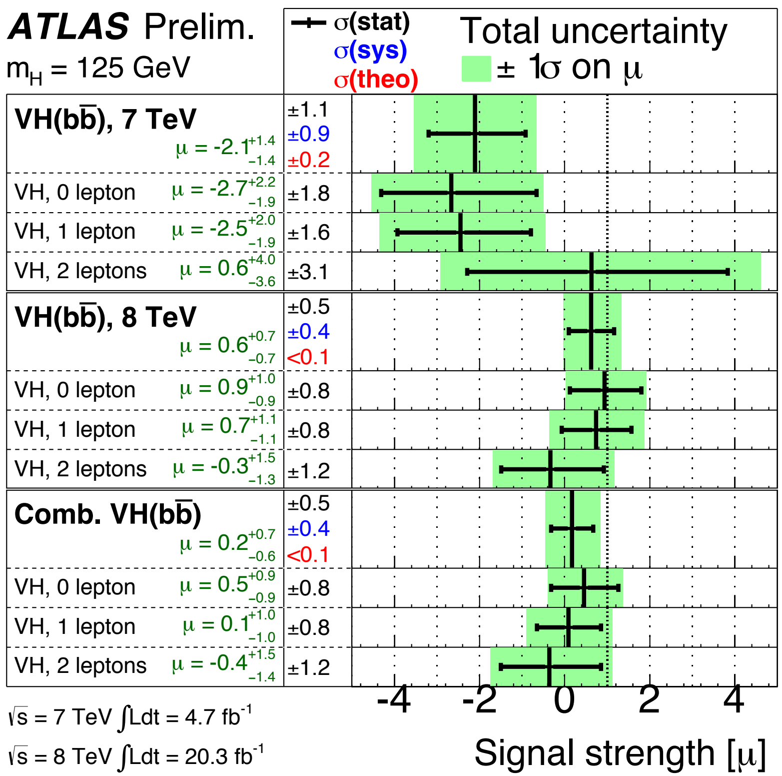


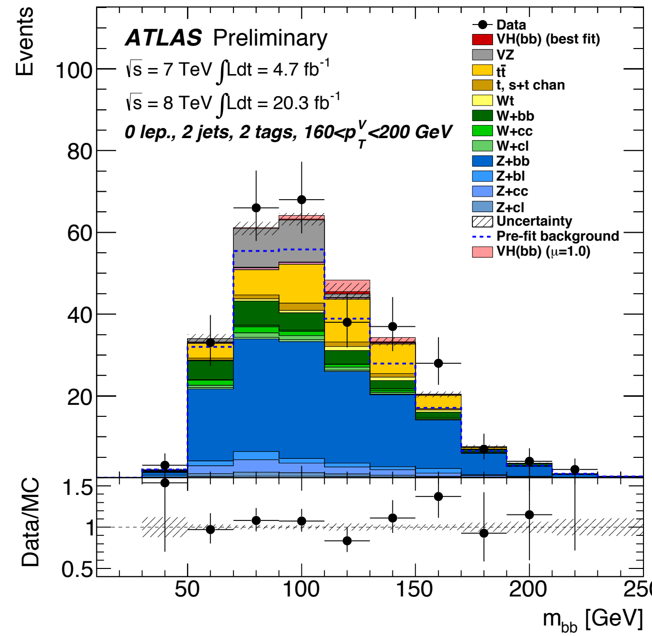


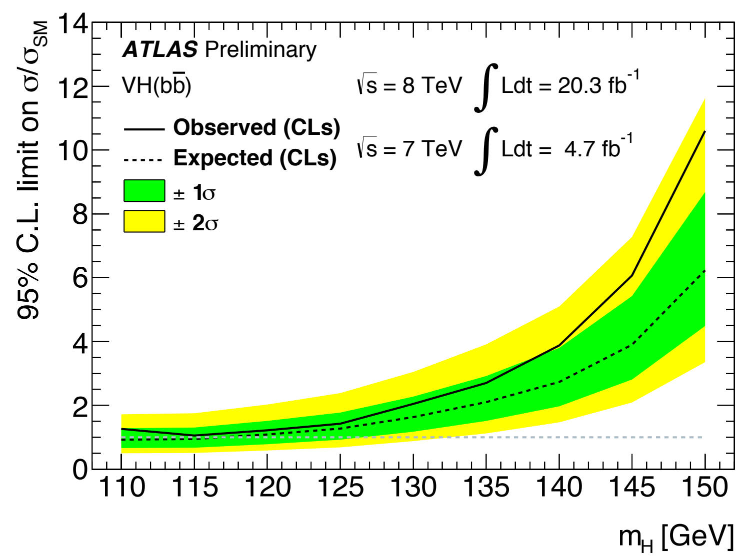
- Categories: to improve S/B and mass resolution (16%):
  - 26 2-b tags signal regions,
  - 31 bkg control regions
- Discriminant: m_{bb}
- *All regions fitted simultaneously*
  - Main backgrounds normalization free parameter in the fit.
- Fit validated on VZ production, observation Z→bb @ 4.8σ (5.1σ exp.)

VH→bb results:

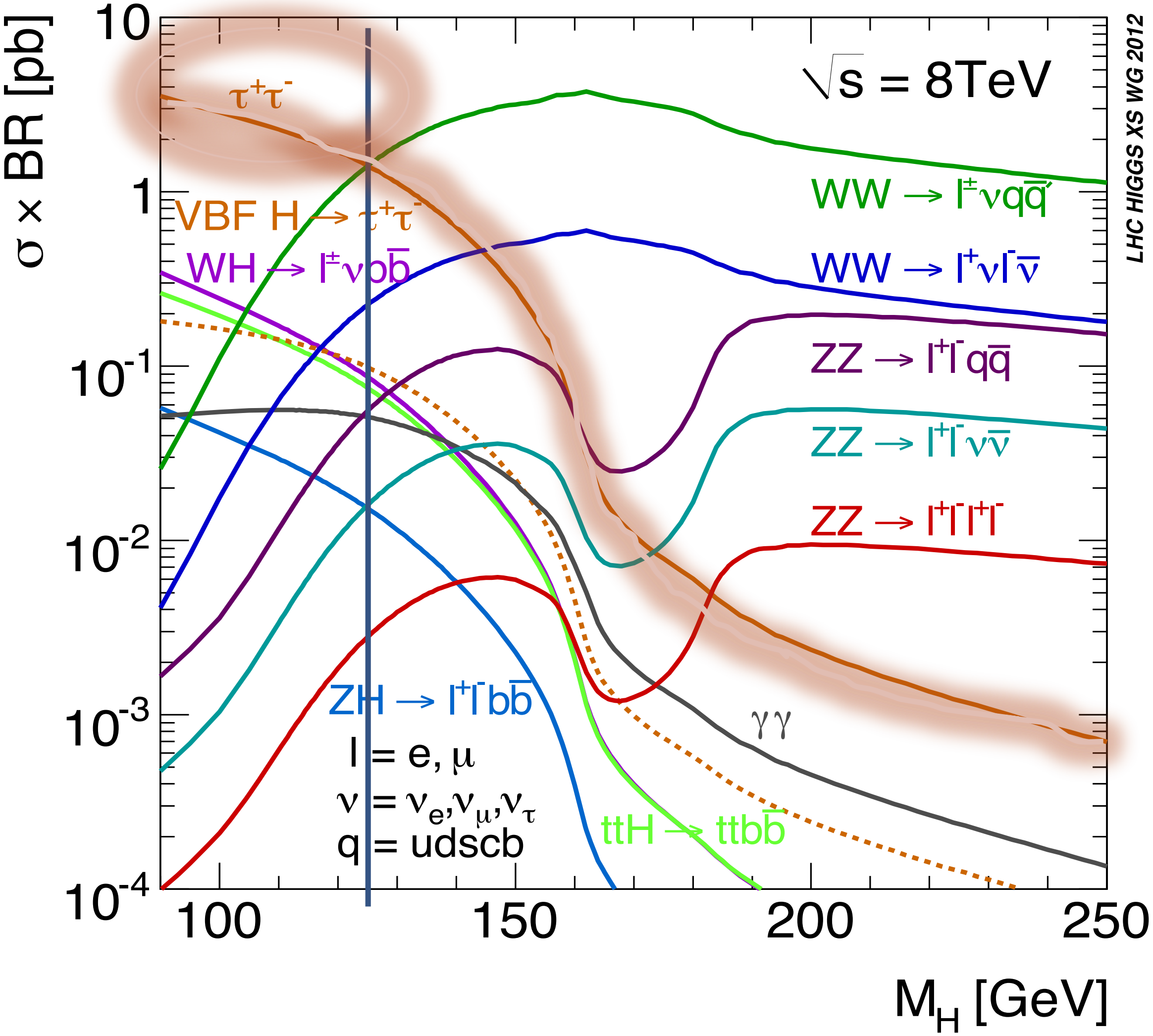
- mH=125 GeV
  95% CL exclusion limit 1.4 (1.3) x SM
- **μ = 0.2 ± 0.5 (stat) ± 0.4 (syst)**
  CMS : significance 2.1(2.1) σ for mH=125 GeV
- Overall compatibility with background (0) and Higgs (1) hypothesis: p0 = 36% p1 = 11%

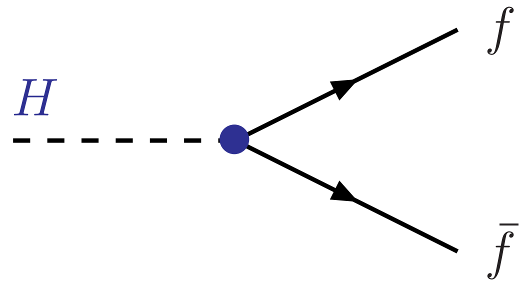






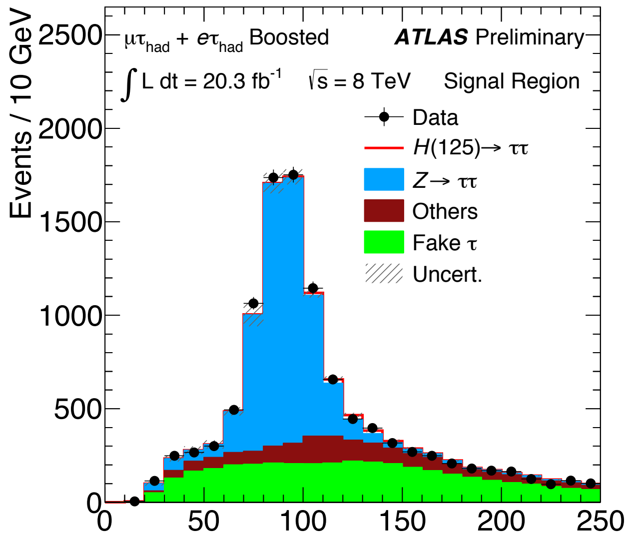
H→ τ τ





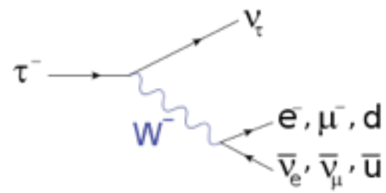
ATLAS-CONF-2013-108

$H \rightarrow \tau\ \tau$



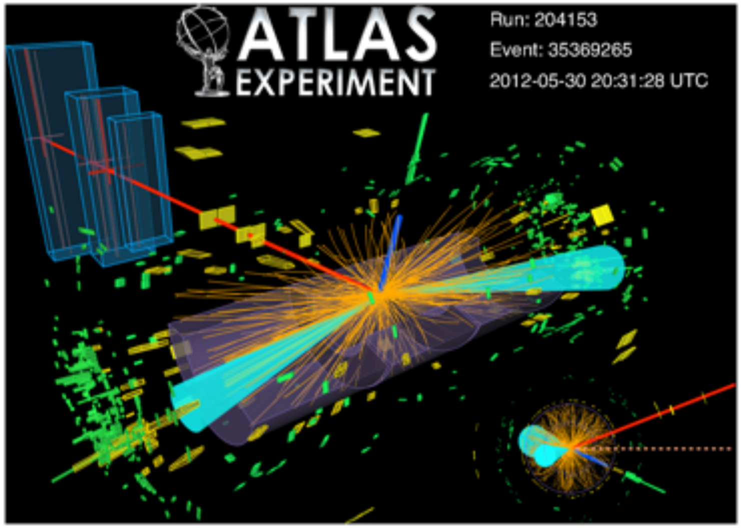
Mass reconstruction: $m_{\tau\tau}^{MMC}$ [GeV]
MMC *(missing mass calculator)*

- Sensitive to the τ Yukawa coupling
- Search includes the three different decay modes of the τ -pair:
  - $\tau_{lep}\ \tau_{lep}$ BR~12% → 2lepton
  - $\tau_{lep}\ \tau_{had}$ BR~46% → 1 lepton
  - $\tau_{had}\ \tau_{had}$ BR~42% → 0 lepton



- Background:
  - $Z \rightarrow \tau\ \tau$ dominant irreducible, estimated from data
  - "Fakes": Multijet, W+jets, top (with fake taus) modeled by data
  - "Other": Dibosons and H->WW* modeled by MC

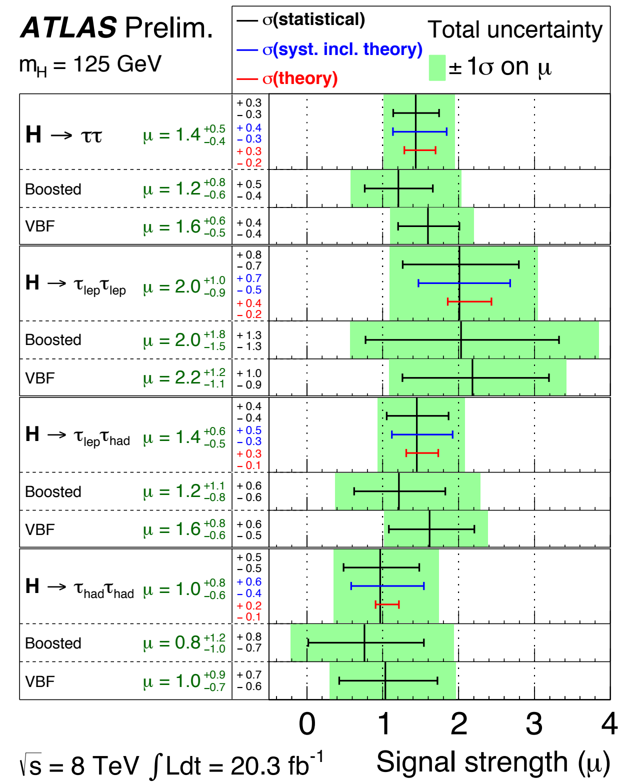
- Analysis performed using an MVA approach (Boosted Decision Tree).
  - BDT inputs based on resonance property, VBF topology (for VBF category) and event activity
- Two categories:
  - VBF: 2 jets with a large Pseudorapidity separation
  - Boosted: events failing VBF category, large p_T



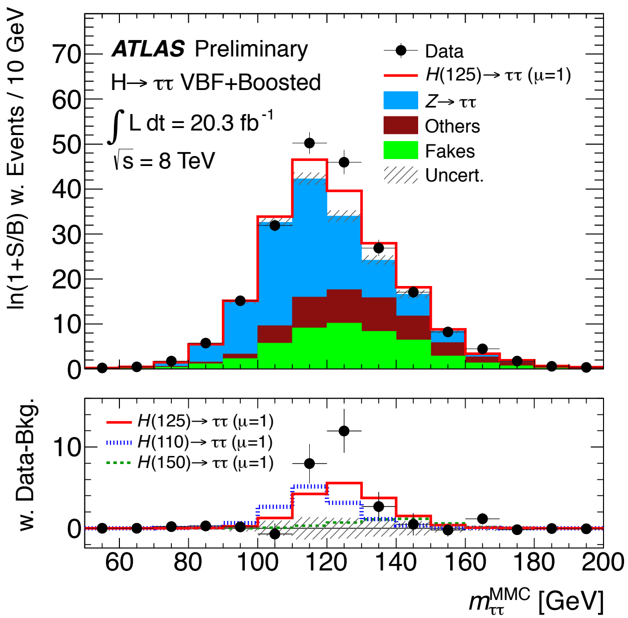
H→ τ τ results

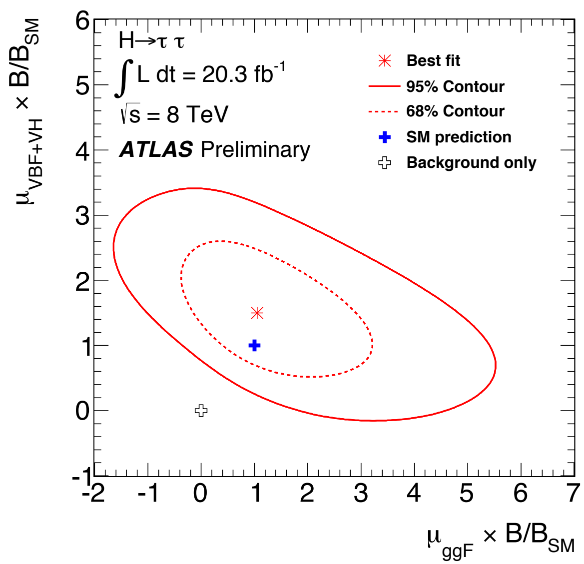
- Using a multivariate analysis ATLAS observes the first evidence of SM Higgs decaying to τ with a significance of **4.1σ (3.2σ exp.)**
- The fitted signal strength parameter is:

$$\mu = 1.43^{+0.31}_{-0.29}(stat)^{+0.41}_{-0.30}(syst) \ @m_H 125GeV$$



Excess consistent with presence of Higgs@125 GeV
Each event weighted by ln(1+S/B) for corresponding bin in BDT-score

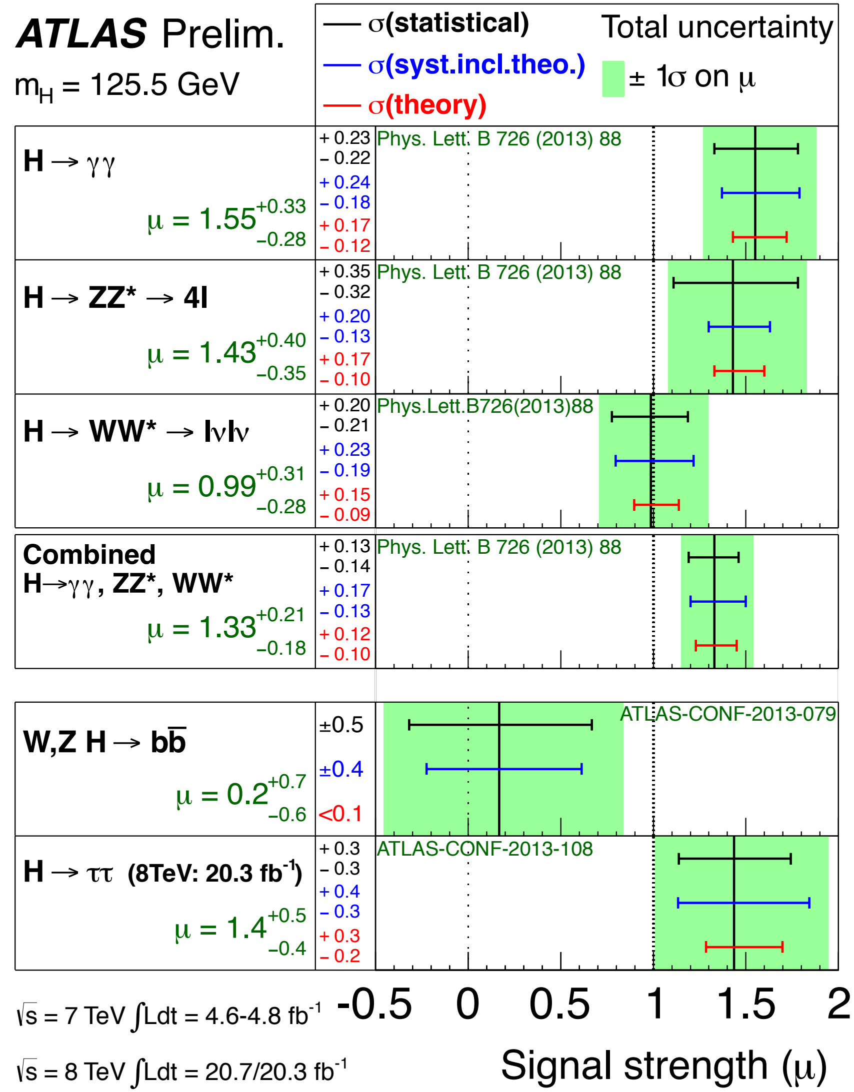




Couplings results consistent with SM predictions within 68% contour.

Summary of the H searches in ATLAS:

Production mode	ATLAS signal significance	CMS signal significance
H→γ γ	7.4σ (4.1σ)	3.2σ (4.2σ)
H→ZZ*→4l	6.6σ (4.4σ)	6.8σ, (7.2σ)
H→WW*	3.8σ (3.7σ)	4.0σ (5.2σ)
VH→bb	limit 1.4×SM	2.1σ (2.1σ)
H→τ τ	4.1σ (3.2σ)	3.4σ (3.6σ)



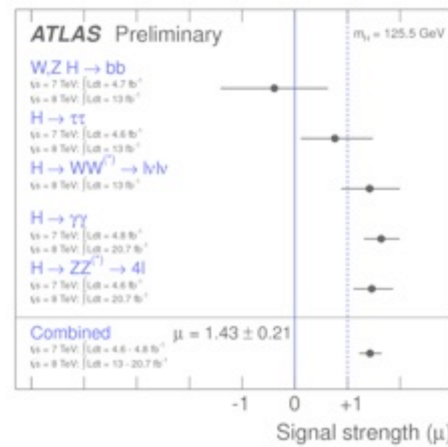
- Wide program of H analyses at ATLAS
- A lot of progress since the "Observation of a New Particle in the Search for the Standard Model Higgs Boson"

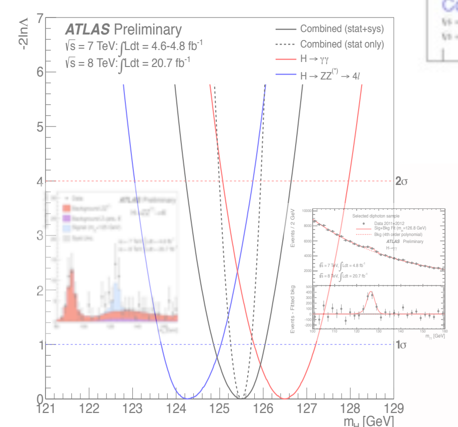
- With discovery well established

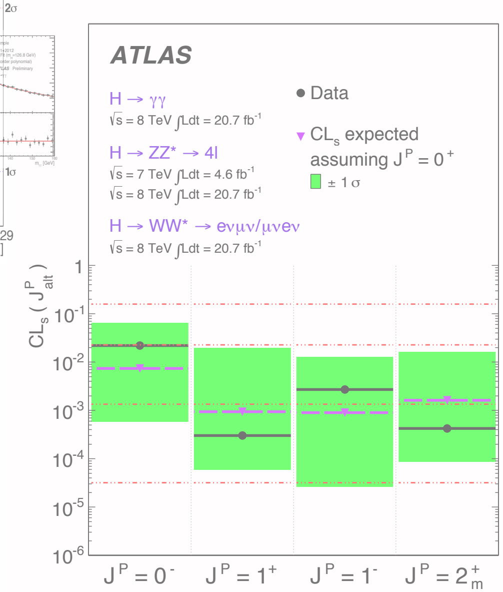
→ Explore the newly discovered particle

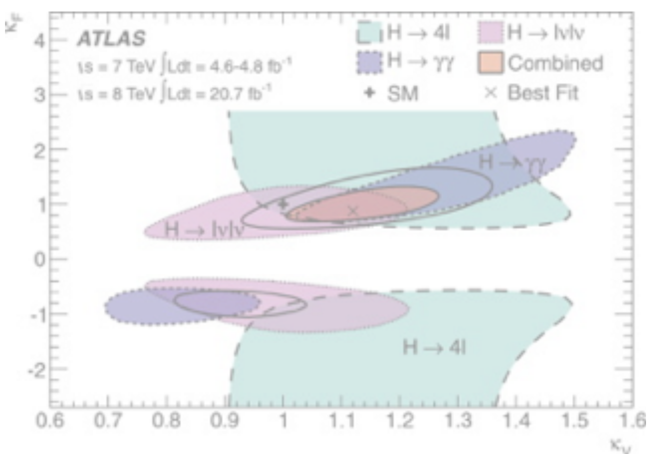
Entering Precision Higgs Physics

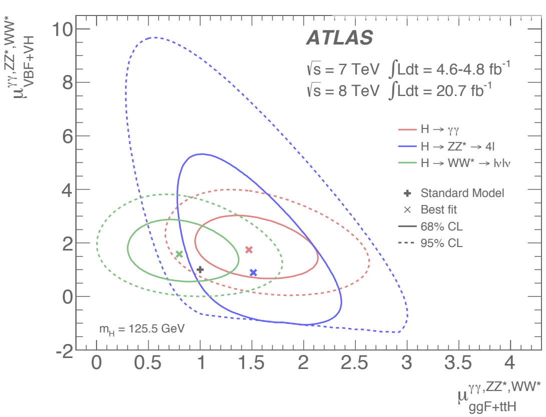
- Is it the Standard Model Higgs boson?
  - Never conclude that it is the SM Higgs boson,we can only demonstrate that it is (in)consistent with that hypothesis
  - Our "null hypothesis" is the SM Higgs sector: many predictions that can be tested:
    - Mass (the only parameter not fixed by SM)
    - Signal strength
    - Production mechanisms
    - Couplings
    - Spin



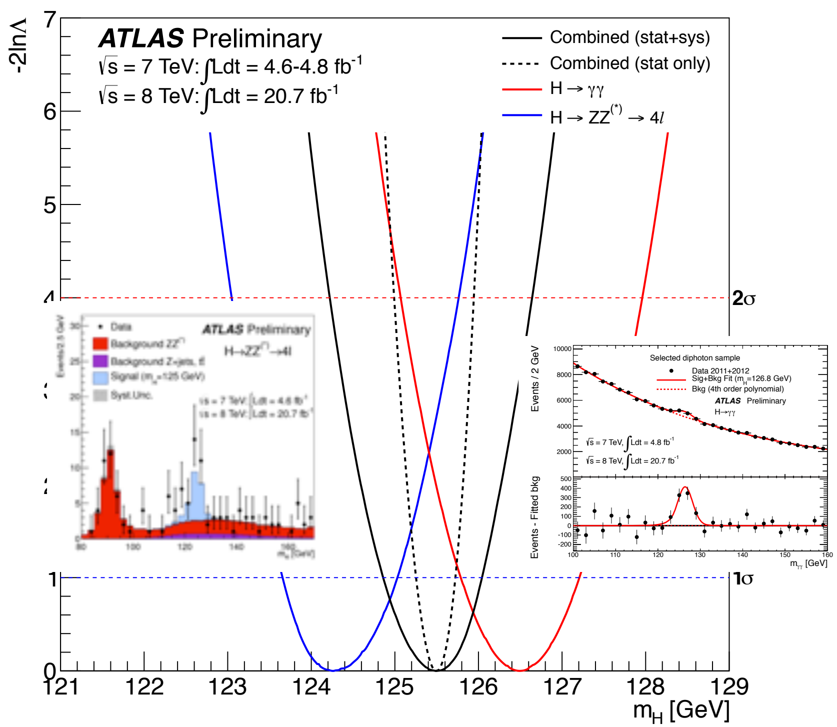


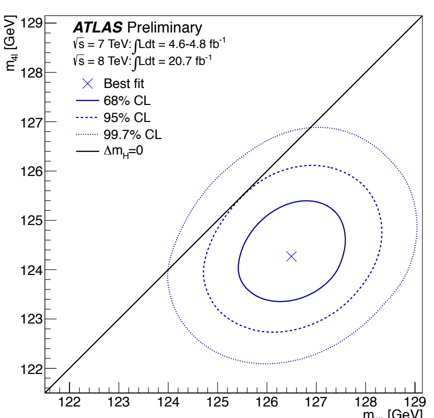






Mass combination





- Higgs boson mass measurement using:
- $H\rightarrow\gamma\gamma$: **126.8 ± 0.2(stat)± 0.7 (syst) GeV**
- $H\rightarrow ZZ\rightarrow 4l$: **$124.3^{+0.6}_{-0.5}$(stat)$^{+0.5}_{-0.3}$(syst) GeV**

- Combined m_H:

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

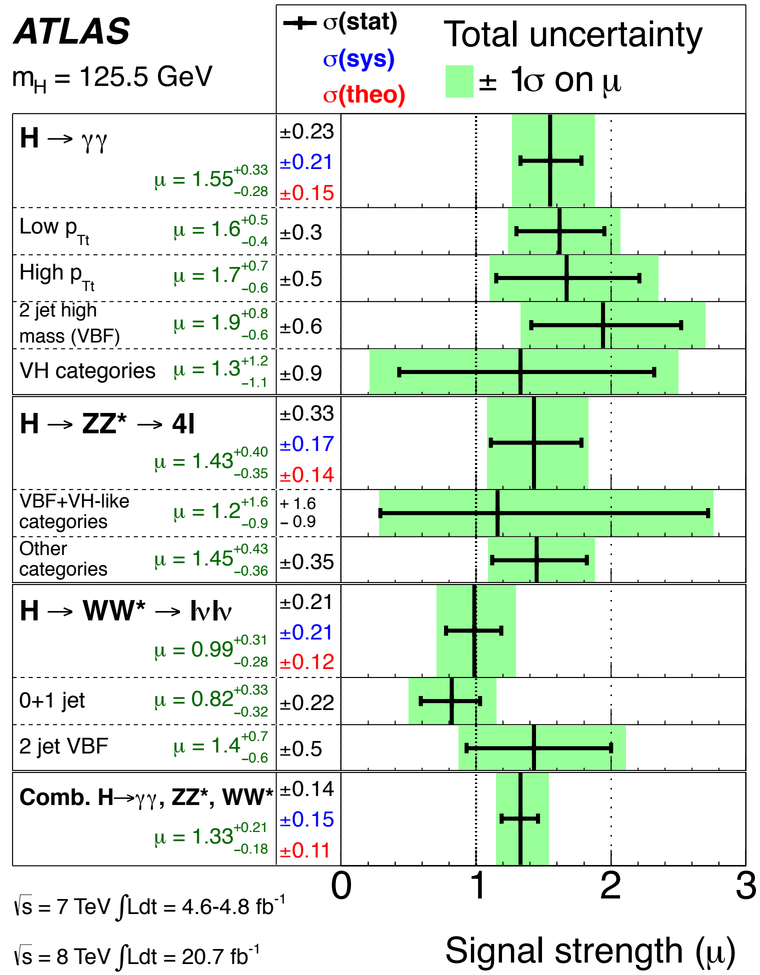
- Results compatible at ~1.5% level (~2.4 σ)
  - Can depend critically on energy resolution modeling
  - By moving ±1 σ the main systematics (calibration, upstream material, pre-samples energy scale) consistency increases up to 8%

CMS: m_H = **125.7 ± 0.3 (stat) ± 0.3 (syst) GeV**

Signal Strength

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

- Higgs boson signal strength measurement
  - Evaluated at m_H =125.5 GeV
  - using $H \to \gamma\gamma$, $H \to ZZ \to 4l$ and $H \to WW \to l\nu l\nu$
- $\boldsymbol{\mu = 1.33^{+0.21}_{-0.18}}$
  - [including preliminary/partial $H \to bb$/ $H \to \tau\tau$ results gives 1.23±0.18]
- Consistency with SM within 7%
- Theory uncertainty (QCD scale and PDF+α_s) comparable to experimental and statistical uncertainties.
- CMS combination (bosonic + fermionic): $\boldsymbol{\mu = 0.88 \pm 0.14}$



$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

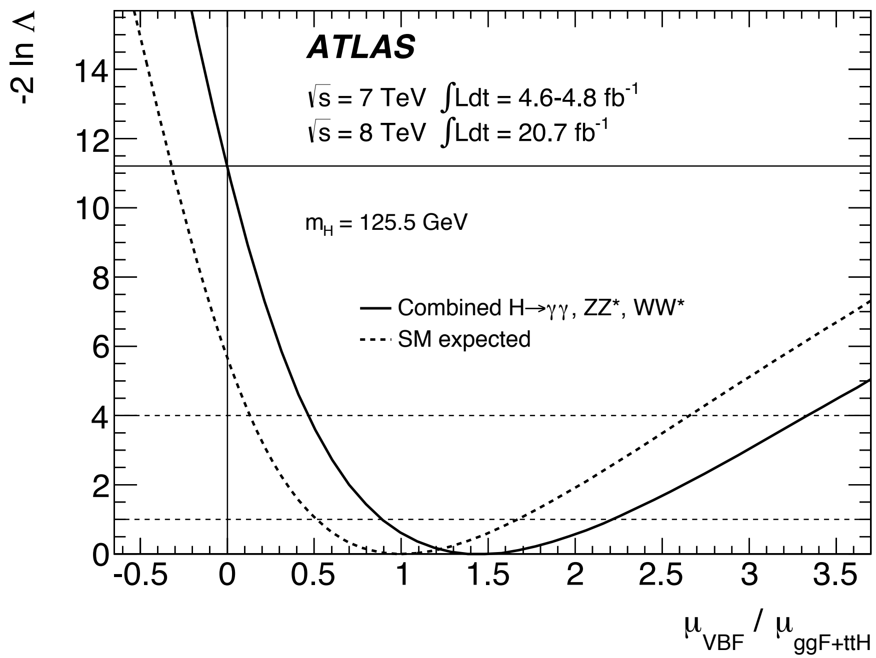
H production modes

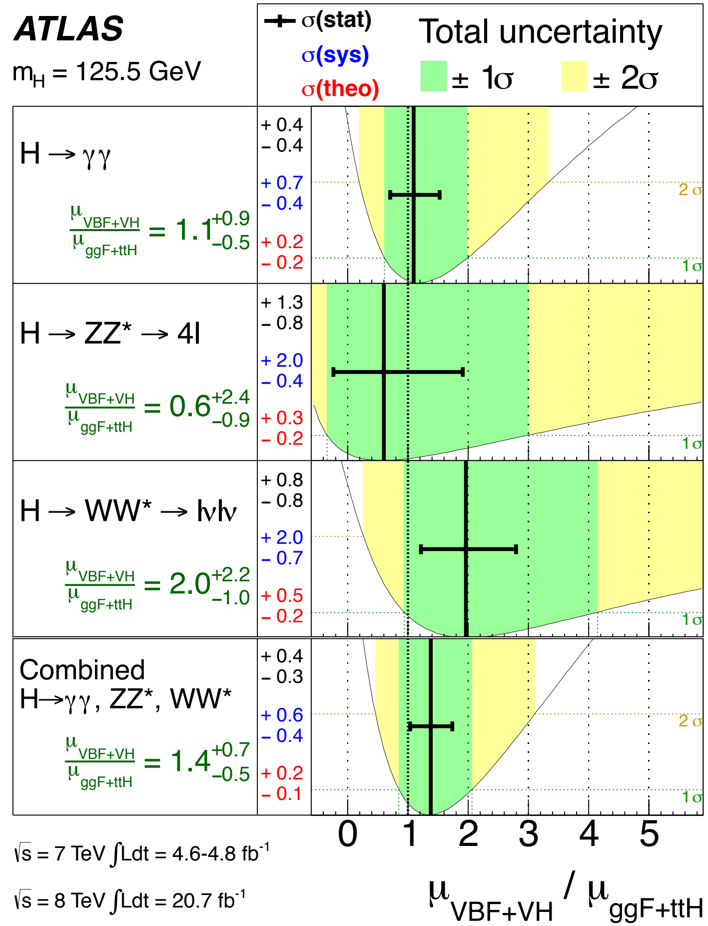
Phys. Lett. B 726 (2013), pp. 120-144

- Study SM compatibility of production modes in each decay channel:
  - Production process ratios (assuming SM ratio of production cross-section)
- Isolate VBF production process:

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

- 3.3 σ evidence for VBF production

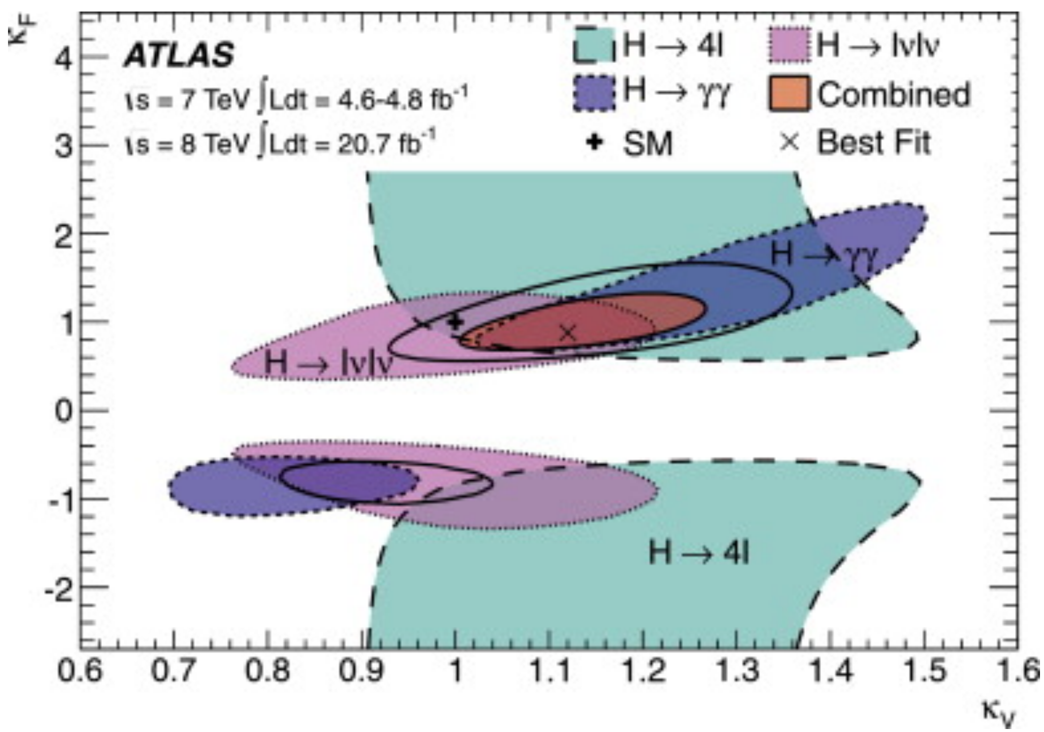




H boson coupling measurement

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

- The measurement of the H boson couplings are implemented following the assumption:
  - Single resonance @125.5 GeV,
  - SM tensor structure (spin 0, CP-even)
  - narrow width approximation



Minimal fit:

- Assume no BSM contributions to Γ_H
- Assume only two coupling scale factors: κ_F for all fermion couplings and κ_V for all vector boson couplings

2D contours of Vector vs Fermion couplings compatibility with SM is 12%

68% CL intervals:

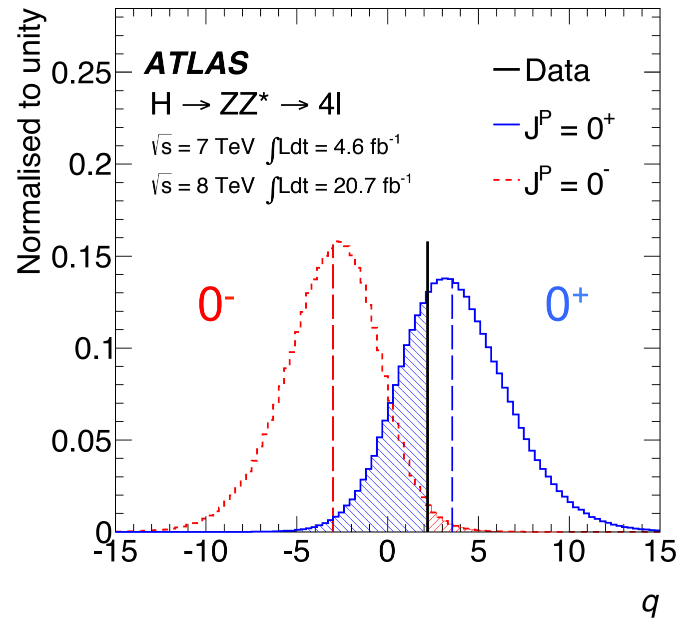
$$k_F \in [0.76, 1.18]$$

$$k_V \in [1.05, 1.22]$$

Spin/parity measurement

Phys. Lett. B 726 (2013), pp. 120-144

- Find observables in bosonic channels sensitive to spin and parity:
- Test several alternative spin-parity hypotheses J^P ($0^-, 1^+, 1^- 2^+$) compared to SM hypothesis: 0^+ and observe which is favored by data



The test statistic to distinguish between the 2 hyp: is the ratio of profiled likelihoods (LLR) between the two hypotheses, (nuisance parameters profiled separately for each hypothesis):

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

Exclusion of alternative model in favor of Standard Model 0+ hypothesis based on:

$$\text{CL}_s(J^P_{\text{alt}}) = \frac{p_0(J^P_{\text{alt}})}{1 - p_0(0^+)}$$

Where p_0 values are determined by integrating the distribution of the test-statistic q above the observed value. Typically, a value of 0.5 (corresponding to the median) is expected if the model agrees

Spin measurement combination

Phys. Lett. B 726 (2013), pp. 120-144

	$H \to ZZ^{(*)} \to 4\ell$	$H \to WW^{(*)} \to \ell\nu\ell\nu$	$H \to \gamma\gamma$
0^-	✓	-	-
1^+	✓	✓	-
1^-	✓	✓	-
2^+	✓	✓	✓

- On-shell X(J=1) → $\gamma\ \gamma$ not allowed by Landau-Yang theorem
  → still worth testing with other decay modes
- J =2: KK graviton as a consistent effective description of a spin-2 particle At LO in minimal model, produced via gluon fusion, but 4% contribution of qq annihilation Higher-order QCD corrections could largely change this ratio
  → consider models with different production modes admixture (scan fqq between 0 and 100%)

$H \rightarrow \gamma\gamma$: SPIN analysis

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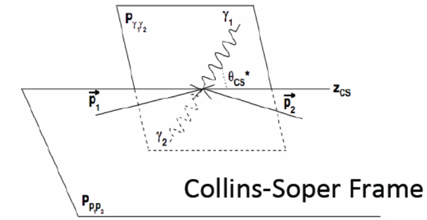
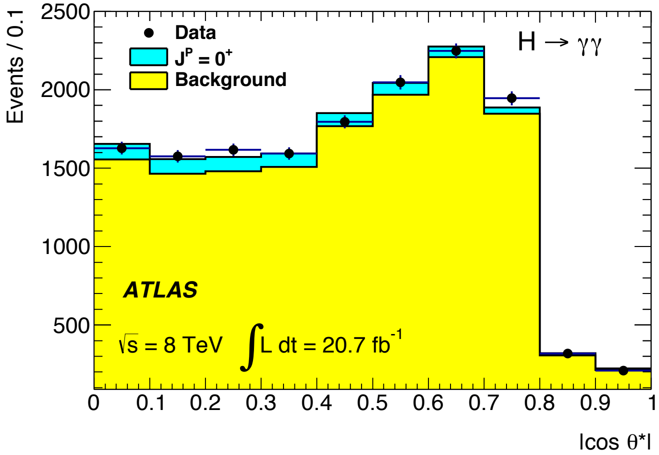
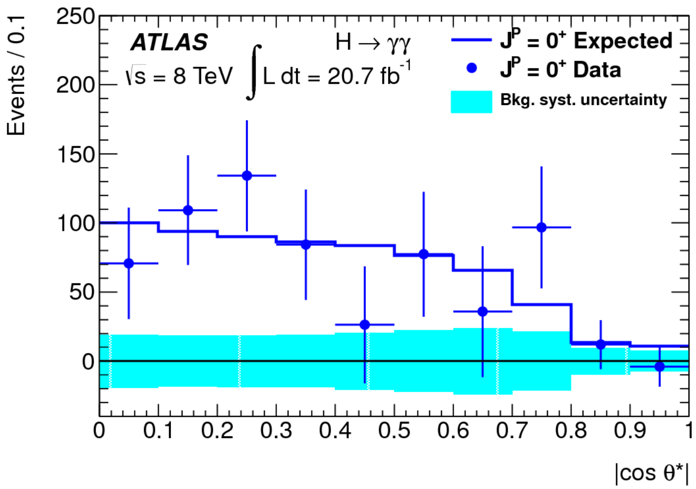
- Discriminating variable: polar angle of the photons with respect to the Z-axis of the Collins-Soper frame
- Analysis optimized for the Spin measurement
  - $H \rightarrow \gamma\gamma$ is a low S/B final state (inclusive ~3%)

→ Simultaneous fit to $m_{\gamma\gamma}$ and $|\cos\theta^*|$ in signal region & the bkg $m_{\gamma\gamma}$ in side-bands.

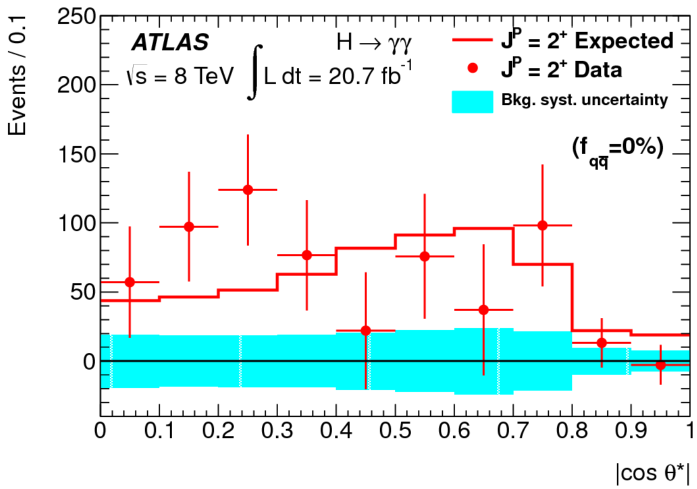




Fit assuming 0^+



Fit assuming 2^+



Background subtracted distributions:
Data differ slightly, owing to the background being determined separately for each spin hypothesis

H→γγ: SPIN analysis

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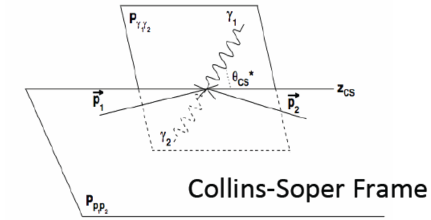
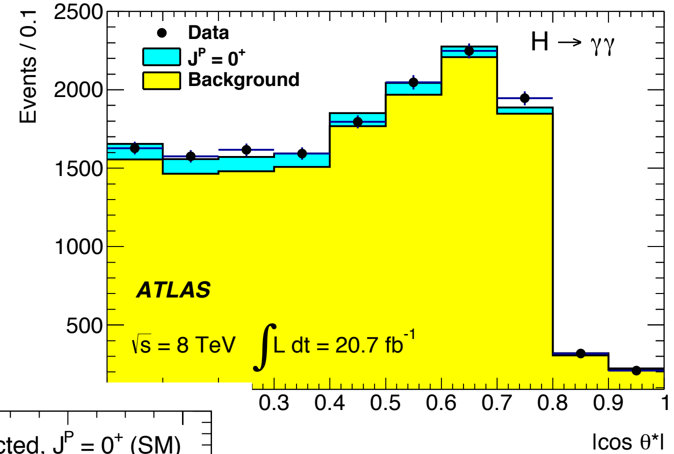
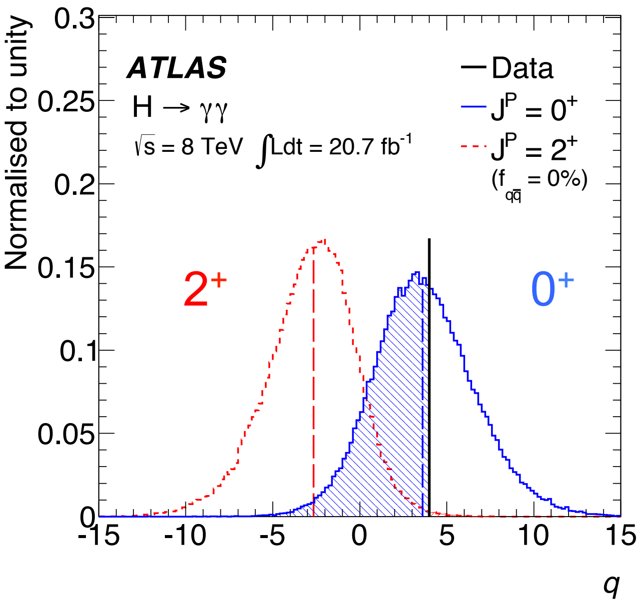
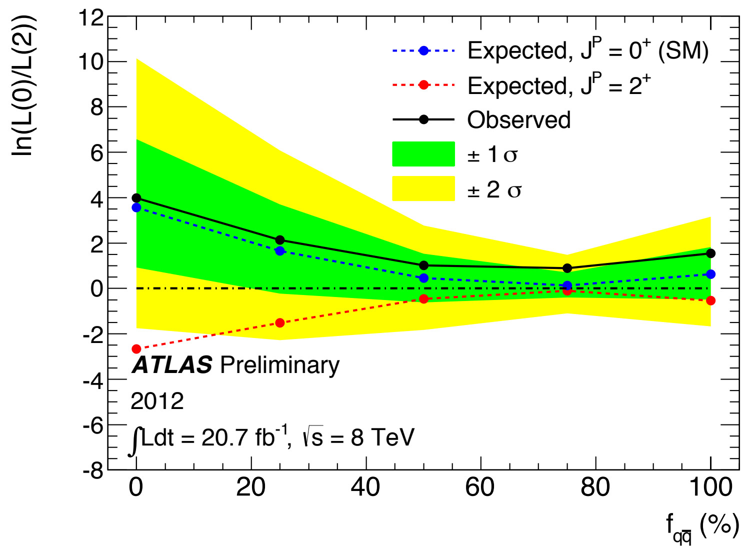


- Discriminating variable: polar angle of the photons with respect to the Z-axis of the Collins-Soper frame
- Analysis optimized for the Spin measurement
  - H→γγ is a low S/B final state (inclusive ~3%)

→ Simultaneous fit to mγγ and |cos θ*| in signal region & the bkg mγγ in side-bands.





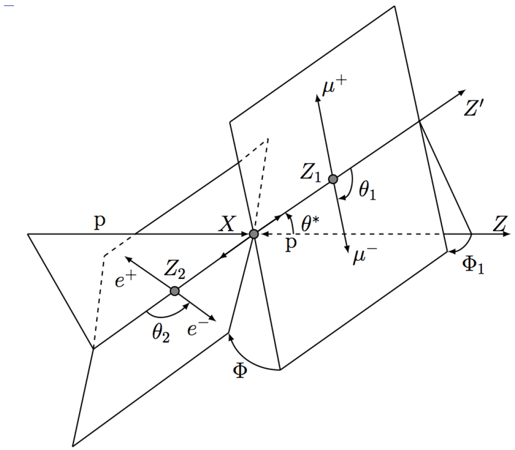


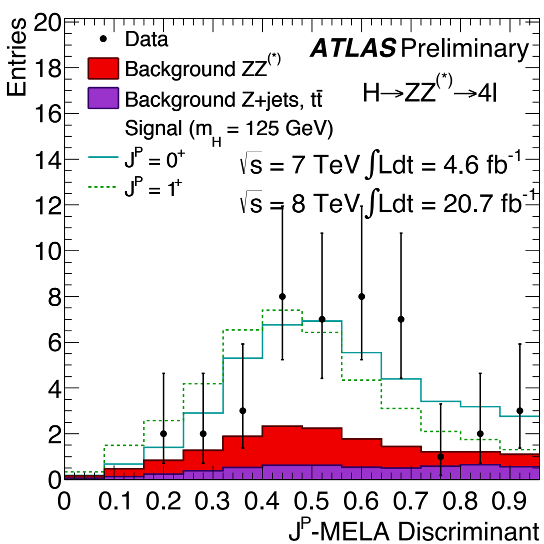
The 2⁺ hypothesis is disfavor with to respect the 0⁺

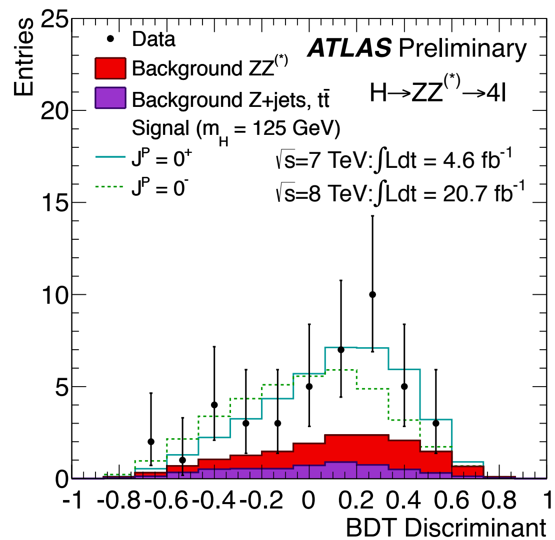
$H \to ZZ^* \to 4\ell$: SPIN analysis

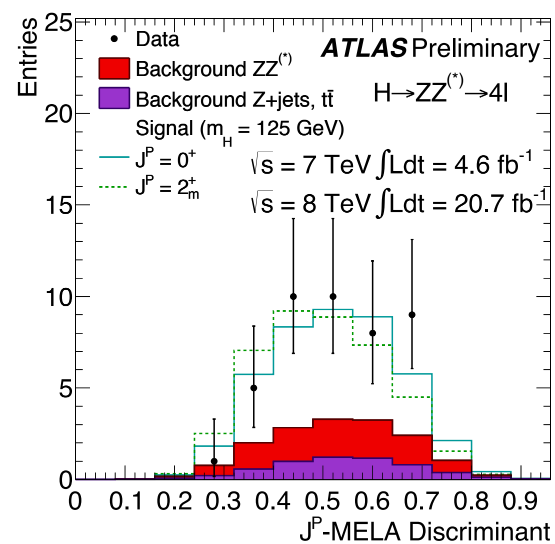
Phys. Lett. B 726 (2013), pp. 120-144

- Ideal channel for spin/CP studies
  - Complete reconstruction of the event topology
  - Clean (S/B ~1 to 2 depending on final state)
  - Several observable depending on spin/CP available
- Use 5 production and decay angles as well as two invariant masses to build the Multivariate discriminant
- Two approaches:
  - Train BDT separately for each hypothesis
  - Use Matrix Element approach corrected for acceptance and pairing effects









H→ZZ*→4ℓ : SPIN analysis

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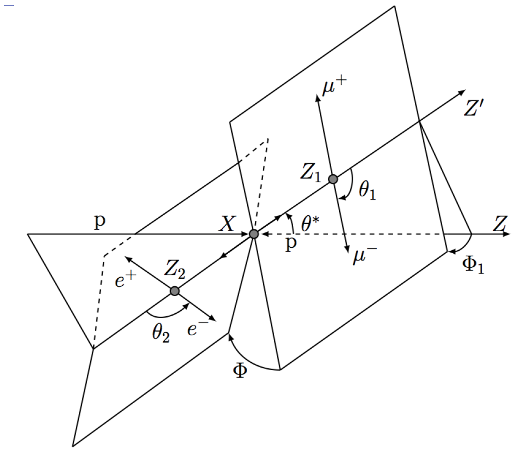

- Ideal channel for spin/CP studies
  - Complete reconstruction of the event topology
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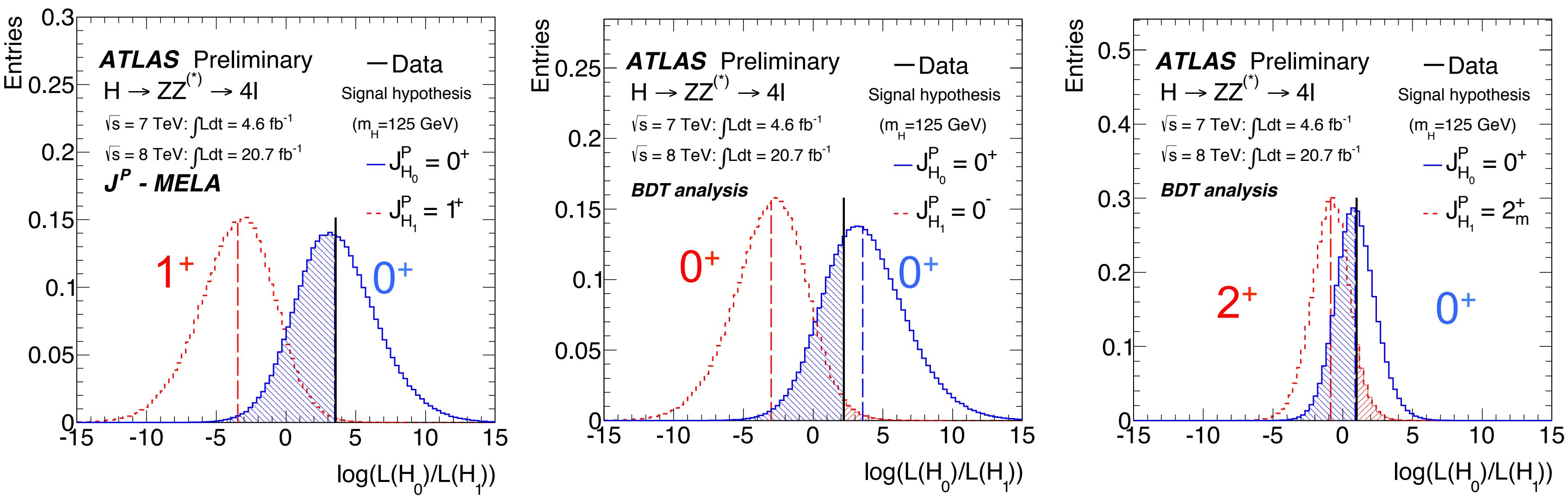
  - Several observable depending on spin/CP available
- Use 5 production and decay angles as well as two invariant masses to build the Multivariate discriminant
- Two approaches:
  - Train BDT separately for each hypothesis
  - Use ME corrected for acceptance and pairing effects



$H \rightarrow WW^{*} \rightarrow l\nu l\nu$: SPIN analysis

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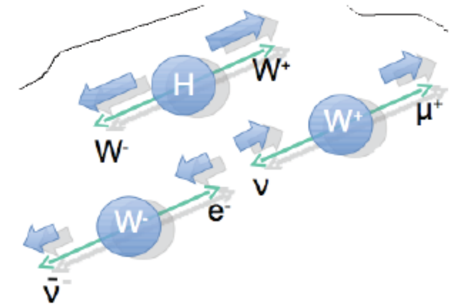
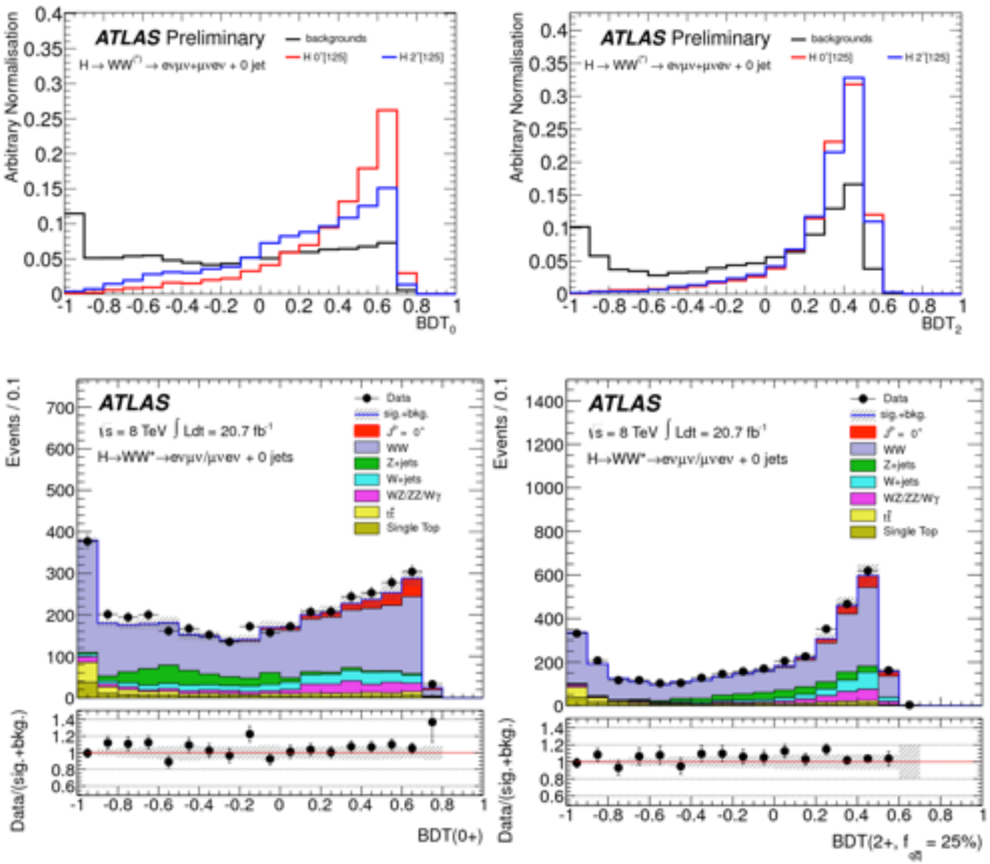
- Large sample statistics but no clear peak
- Restricted to "different flavor" ($e\mu$) events and no jets
- Use spin-sensitive variables ($\Delta\phi_{ll}$, m_{ll}, p_T^{ll}, m_T) to train BDTs and fit output of two BDTs (trained for each hypothesis).





- Two BDT classifiers are used:
  - BDT0^{+}: SM Higgs signal against the sum of all backgrounds
  - BDTJ^{P}: J^{P} signal against the sum of all backgrounds
- Perform 2D-fit in (BDT0^{+},BDTJ^{P})
- p_T spectrum uncertainties found to have small effect

$H \rightarrow WW^* \rightarrow l\nu l\nu$: SPIN analysis

Phys. Lett. B 726 (2013), pp. 120-144

- Large sample statistics but no clear peak
- Restricted to "different flavor" ($e\mu$) events and no jets
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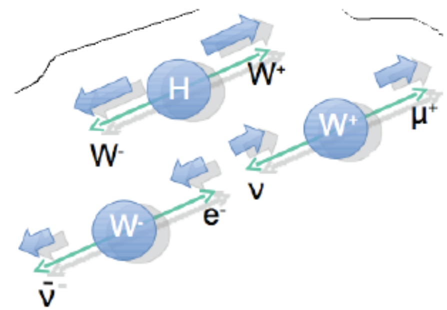
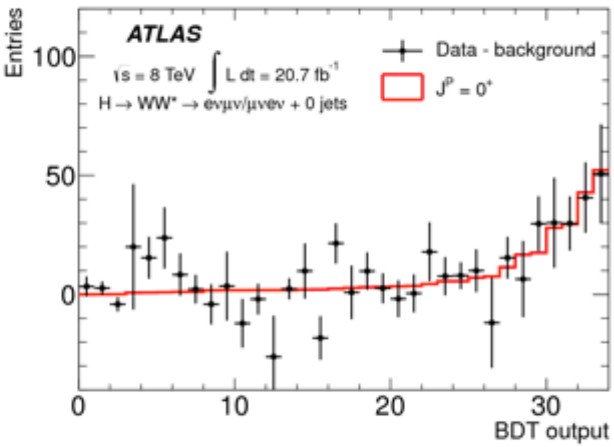
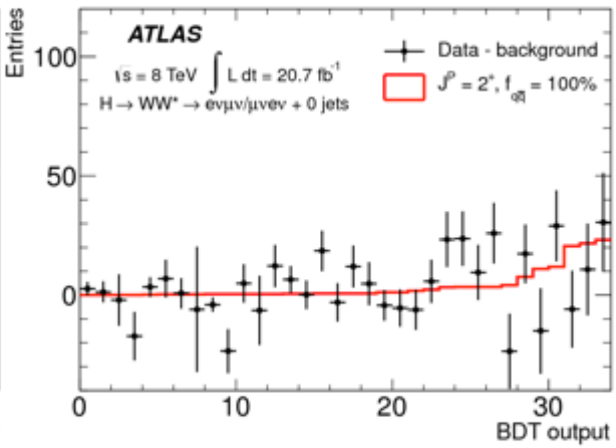


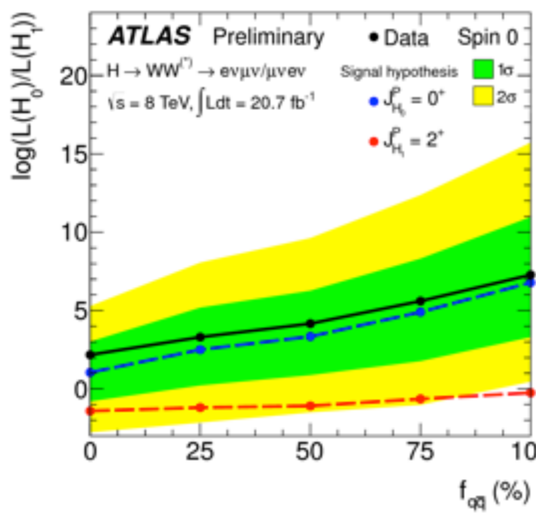




The 2D distribution (BDT0,BDTJ^P) is remapped into a 1D distribution, with the bins ordered in increasing number of expected signal events. Empty bins (expected content <0.1) are removed.

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

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



Spin/Parity combination:

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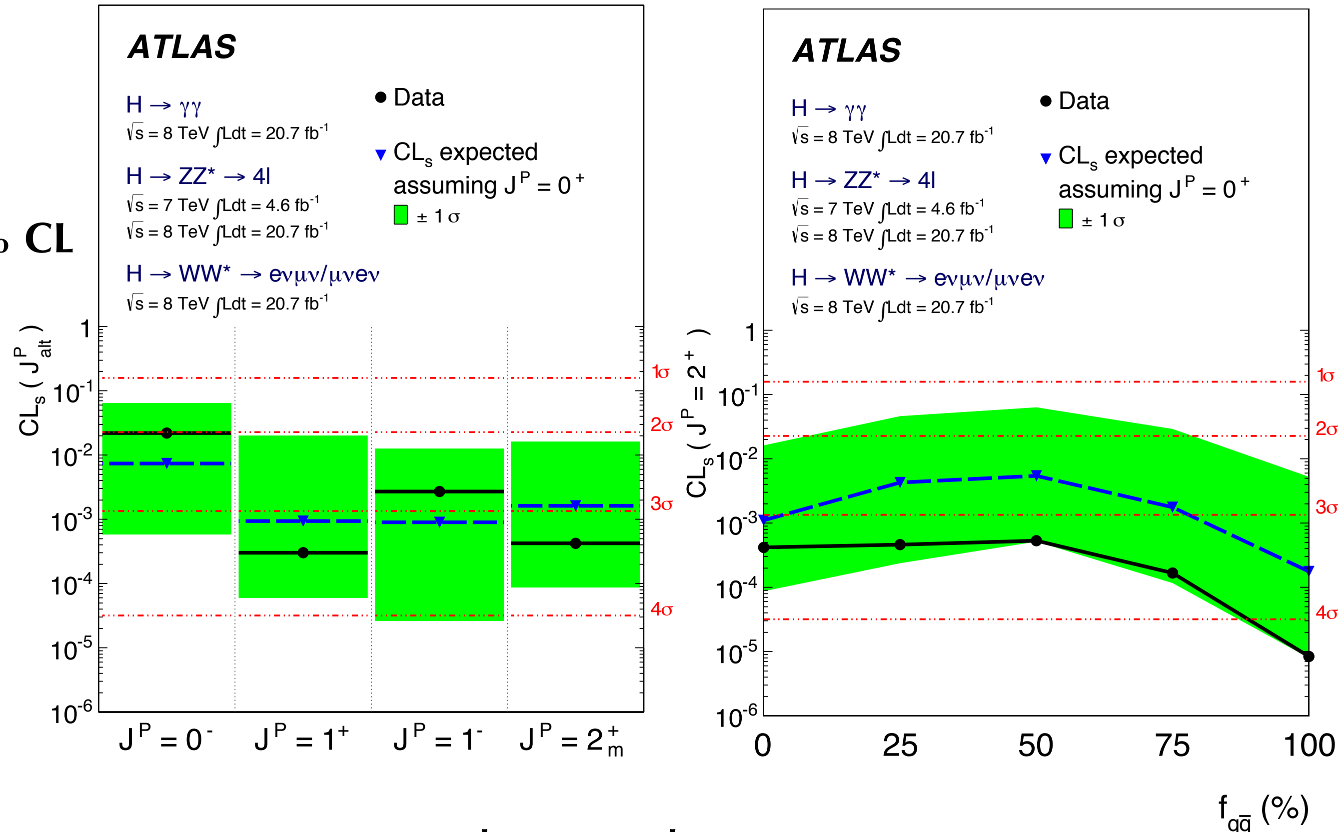
$0^+/0^-$ (ZZ): 97.8% CL
$0^+/1^+$ (ZZ+WW): 99.97% CL
$0^+/1^-$ (ZZ+WW): 99.7% CL
$0^+/2^+$ ($\gamma\gamma$+ZZ+WW)>99.9% CL



All spin hypotheses disfavored compared to 0^+ at > 95%

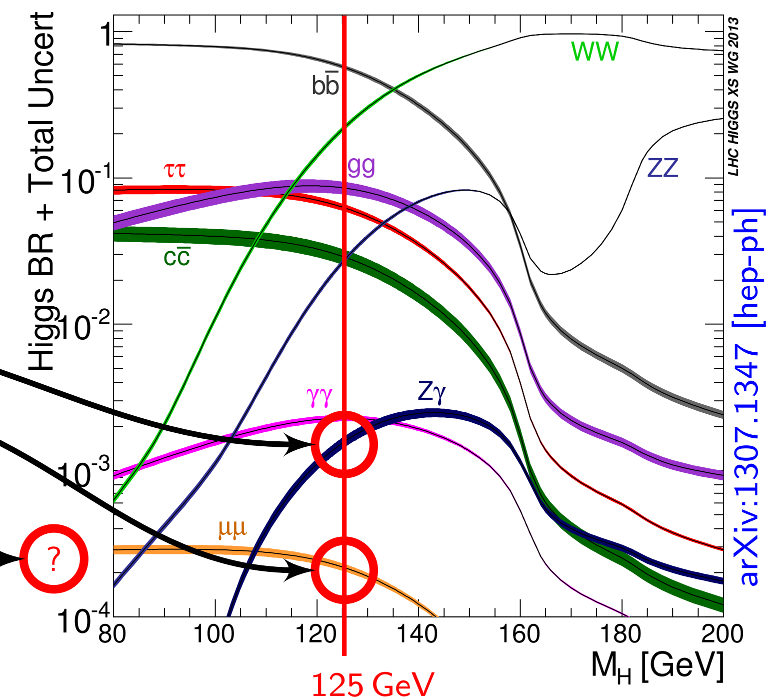
- A note on systematic uncertainties in the combination:
  - Common systematic correlated across the channels.
  - effect of mass measurement uncertainty negligible
    - overall impact (by comparing results w/ and w/o profiling) estimated to be <0.3 σ
  - Higgs boson pT spectrum small effect <0.1 σ

Rare decays

- **Properties of discovered Higgs boson consistent with Standard Model hypothesis.**
- But no definitive statement on its nature possible, yet.
- All possible decay channels need to be explored.
- Rare decay modes help to gain insight into its nature.

Even if channels are not expected to be sensitive, yet.
→ Observation of such signatures in current data would indicates BSM Higgs sector

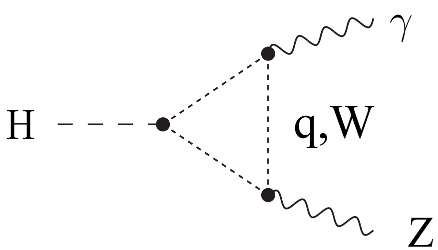
- $H \to Z\gamma$
- $H \to \mu^+\mu^-$
- $H \to$ invisible



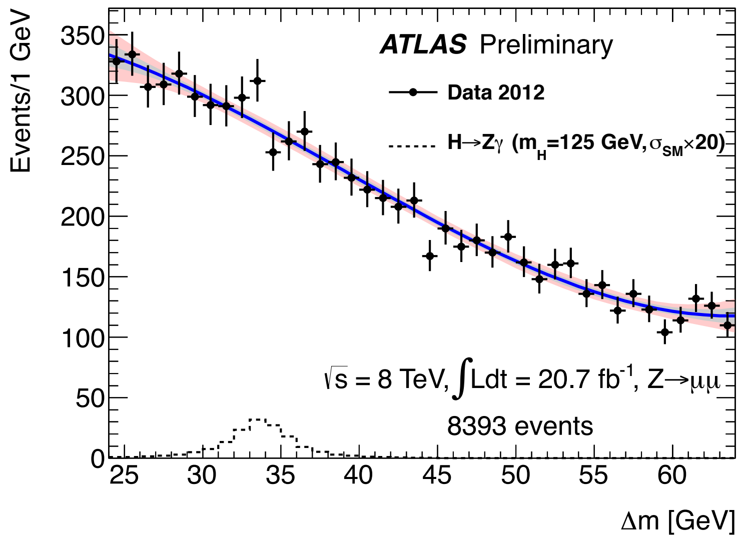
Rare decays: H→Zγ→llγ

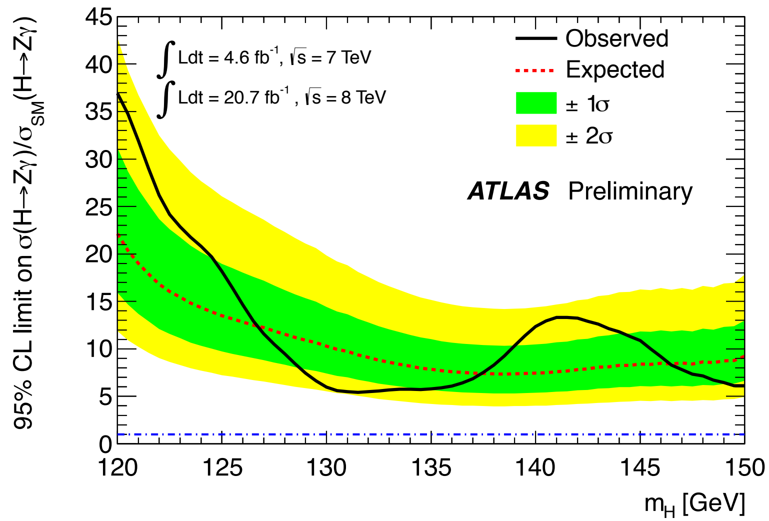
ATLAS-CONF-2013-009

- Loop-induced decay
  ⇒ sensitive to BSM particle



- Low yield (S_{exp}~15) and S/B (~0.25%)
- Good mass resolution (σ m/m~1.4%)
- Total bkg fitted to data (Δm = mllγ – mll)
- **no excess: μ<18.2(13.5) @95% CL for mH=125 GeV**

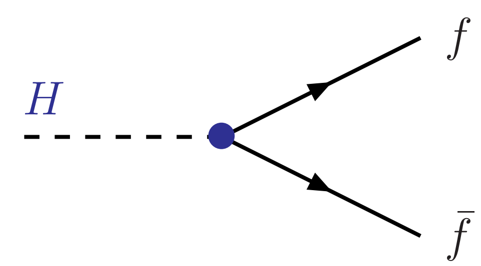


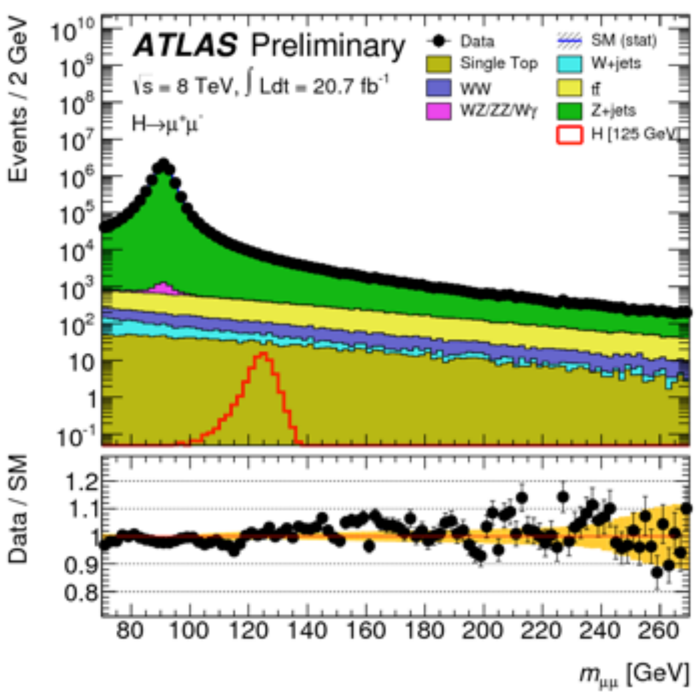


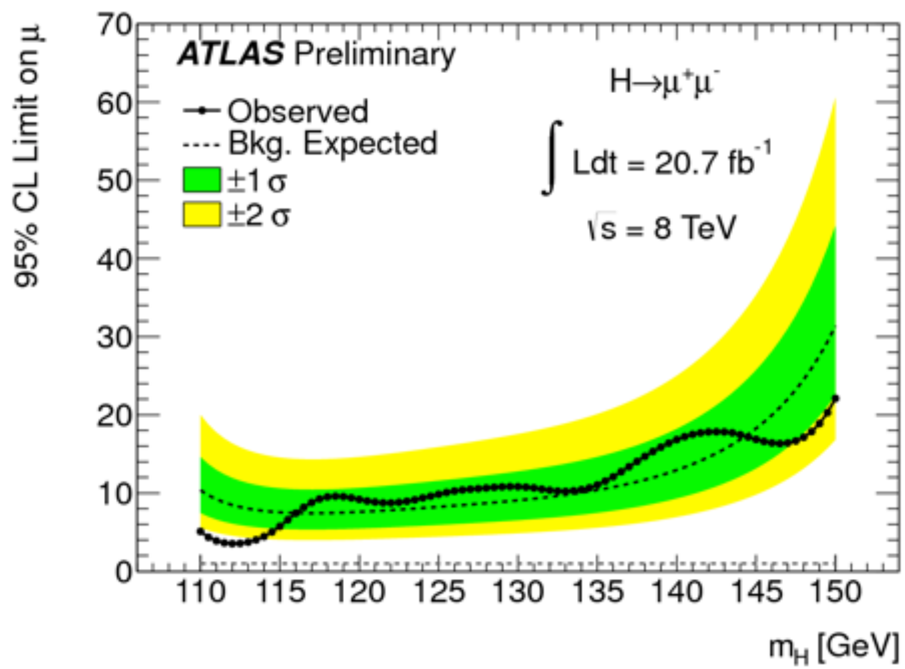
Rare decays: $H\to\mu\mu$

ATLAS-CONF-2013-010 [21 fb^{-1}]

- Direct measurement Yukawa coupling to 2[nd] gen fermions.
- Low yield (S_{exp}~38) and S/B (~0.2%)
- Good mass resolution (σ m/m~2%)
- S+B fit to $m_{\mu\mu}$
- **no excess: μ<9.8 (8.2) @95% CL for mH=125 GeV**



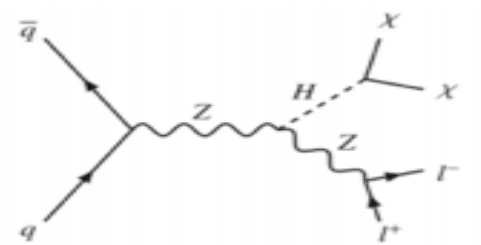


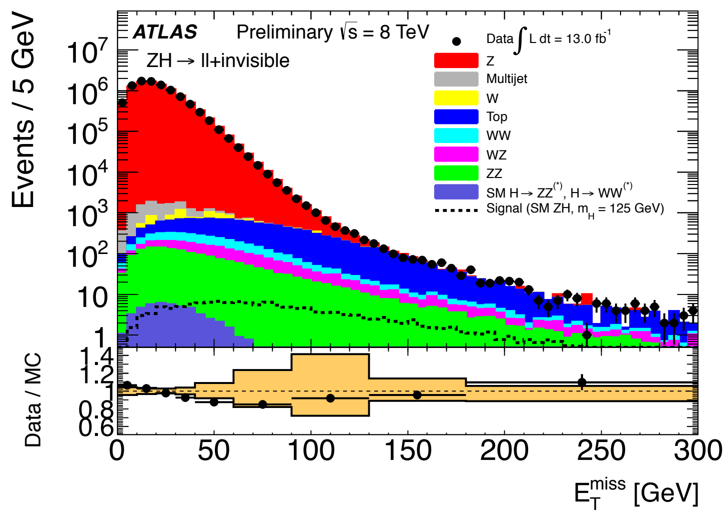


H to invisible

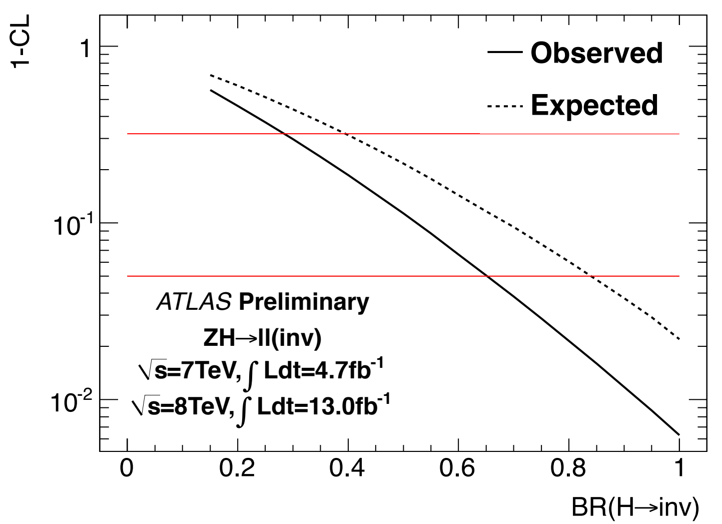
ATLAS-CONF-2013-011 [18 fb^{-1}]

- While the invisible branching fraction for a SM Higgs boson is too small to be accessible → Observation would be direct indication of New Physics!
  - Higgs couplings to non SM stable or long lived particles is excellent way to search for new physics, in particular Dark Matter through so called Higgs portal models.



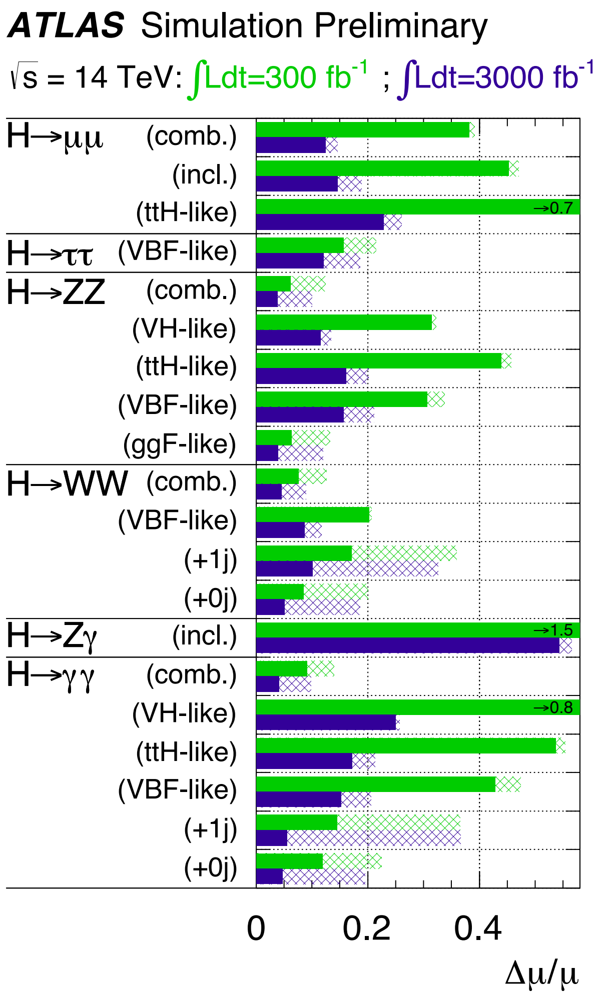


- Search for invisible decays of the Higgs boson produced in association with a Z boson.
- The search performed by looking for excess in events with 2 leptons and high E_T miss
- **no excess ⇒ σ*BRinv (<35 fb) for m_H=115-300 GeV and BRinv <65% obs (84% exp) @ 125 GeV**



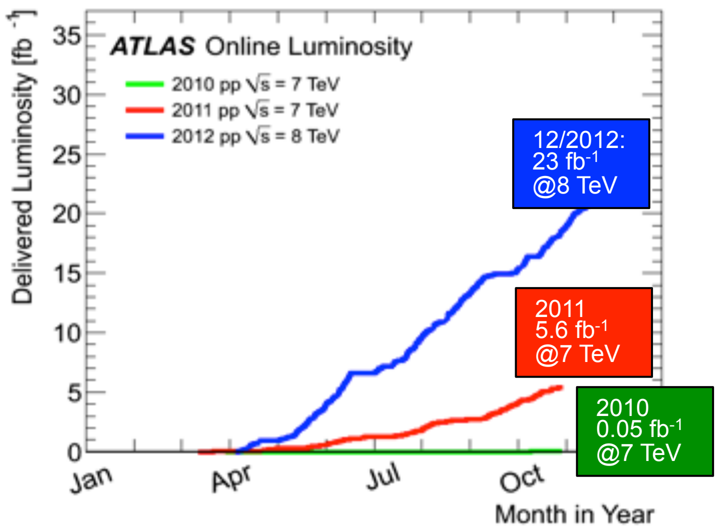
Conclusion

- Wide program of H analyses at ATLAS
- **A SM-like Higgs boson with mass ~125 GeV was discovered using LHC Run1 data**
- Measured spin/parity (0+) and couplings to SM particles are consistent with SM expectations No evidence of non-standard properties
  - No invisible decays
  - No hint of enhancements in suppressed channels ($\mu\mu$, $Z\gamma$)
  - No hint of additional 2HDM bosons with larger masses
- This particle opens up a fabulous new area of physics
- Look forward LHC Run II/III and HL-LHC
  - Factor ~5–6 more luminosity compared to Run 1
  - Factor ~2.1– 4.7 increase in cross section from 8TeV to 14TeV
  - Up to a factor of ~4–5 improvement in statistical sensitivity



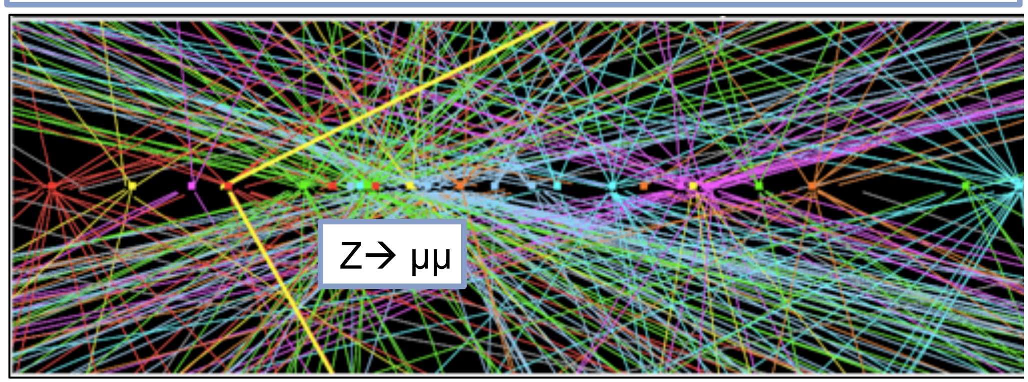
BACKUP

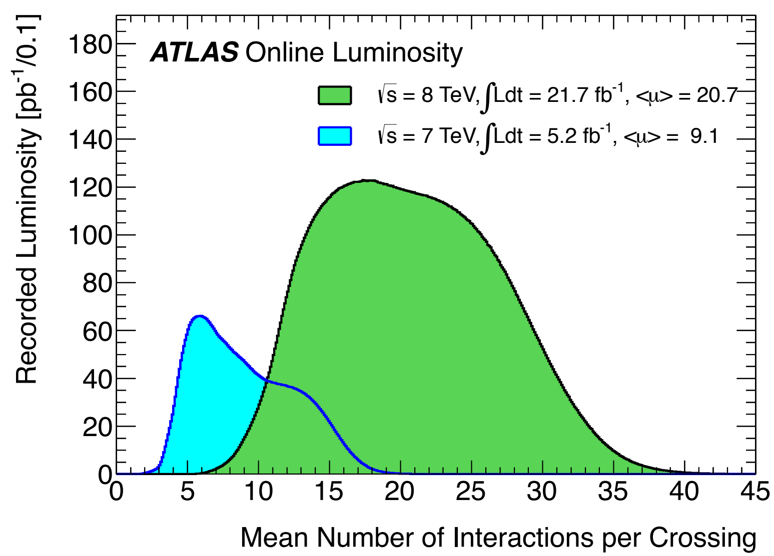
LHC and ATLAS performance



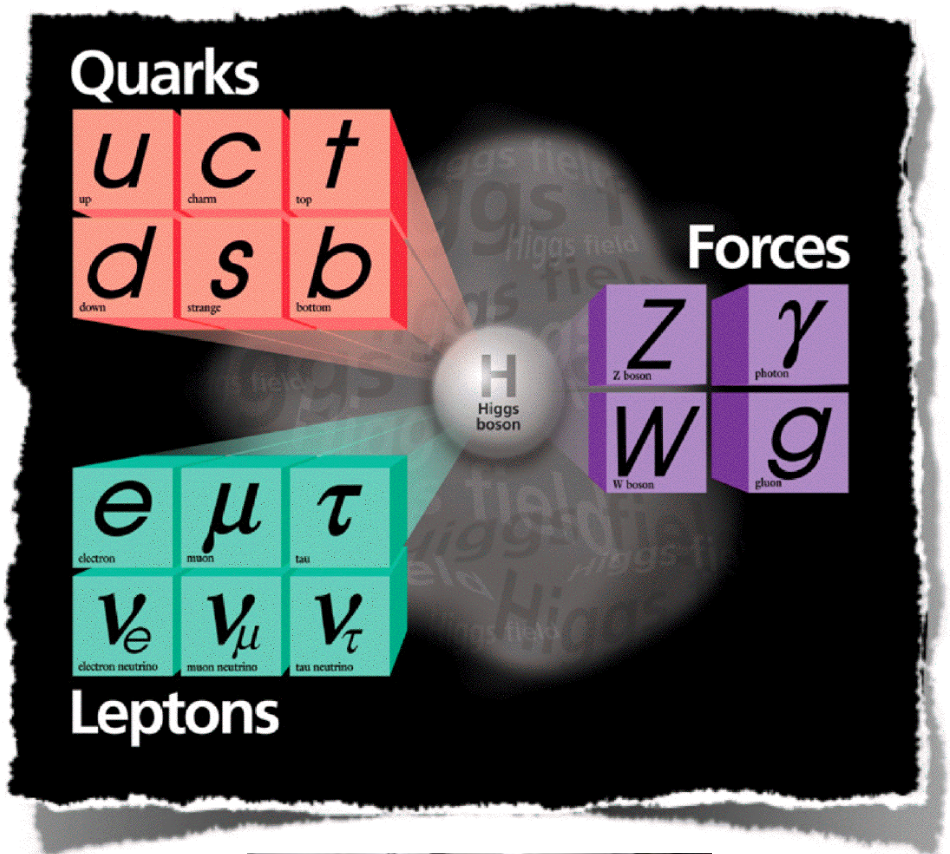
- Excellent LHC performance during Run I
  - 2011: 4.8 fb-1 at 7 TeV
  - 2012: 20.7 fb-1 at 8 TeV
- Challenging data taking condition
  → Pile-up in 2012
  → Maintain excellent performance by improved algorithms

Z→ μμ event from 2012 data with 25 reconstructed vertices





The Standard Model H boson

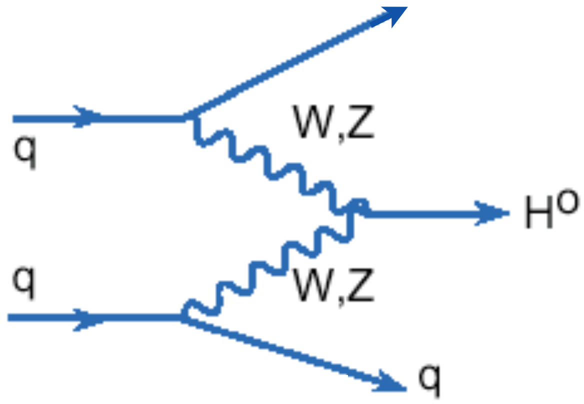


The Standard Model of particle physics is an impressively successful theory.
In the SM the electromagnetic and weak interactions are unified through the symmetry $SU(2)_L \otimes U(1)_Y$, where the carriers are massless.
→ This symmetry is spontaneously broken through the non-vanishing vacuum expectation value of the Higgs field
→ Three of the four degrees of freedom of the Higgs field are becoming the longitudinal polarizations of the vector bosons, the fourth is the Higgs boson.

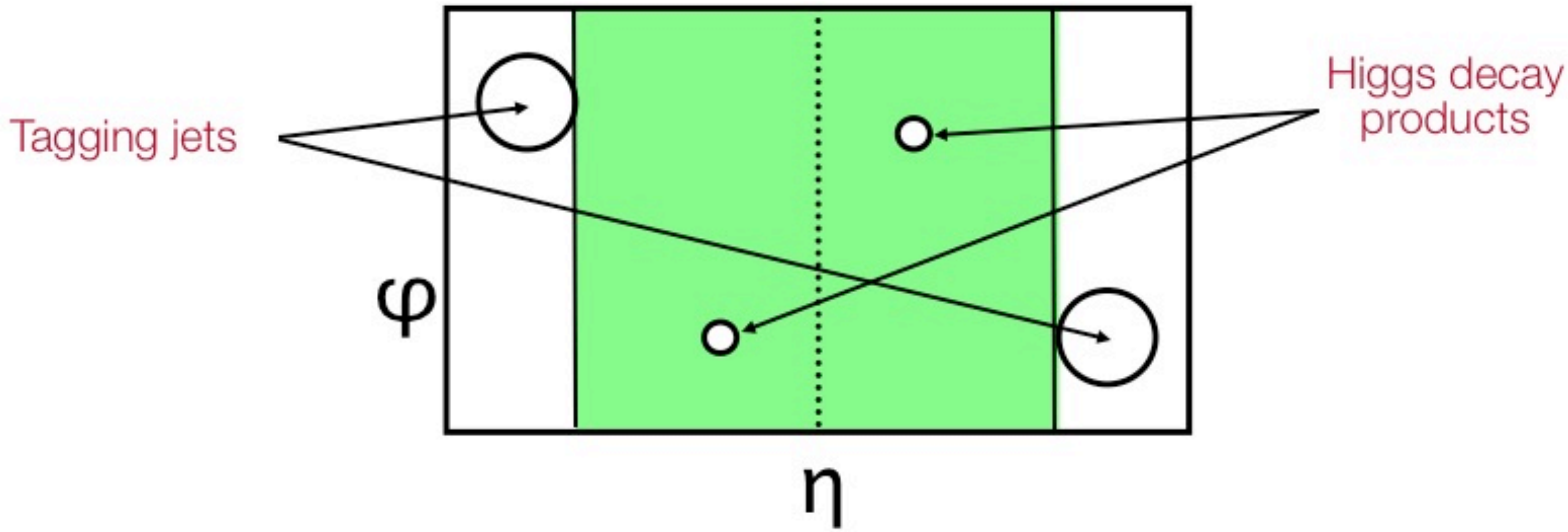
⇒ The Higgs boson is a particle postulated in the mid-1960s to complete the Standard Model (SM) of particle interactions.

A long way since then ..

VBF topology

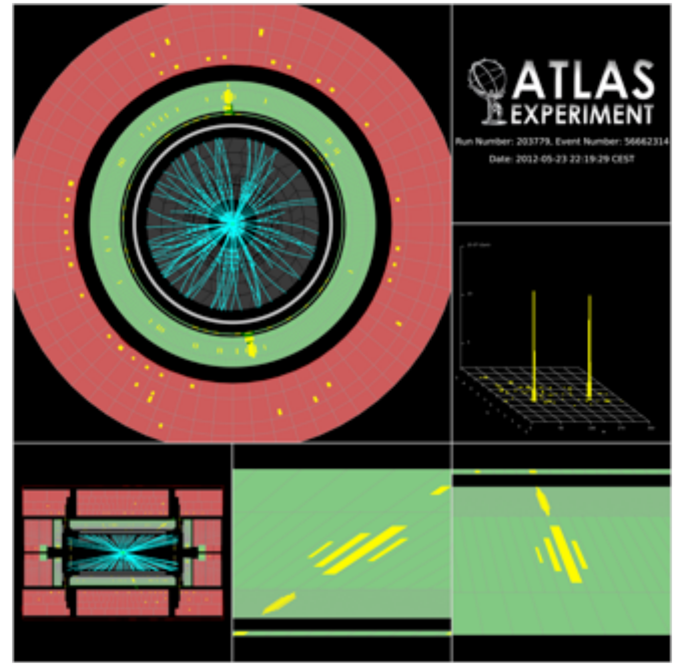


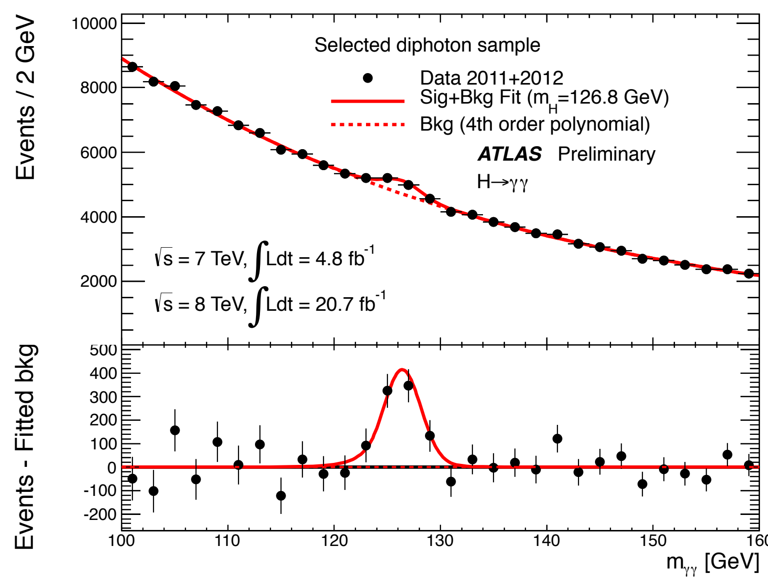
Distinctive signature:
- two forward jets (tagging jets)
- little (jet) activity in central region (central jet veto)



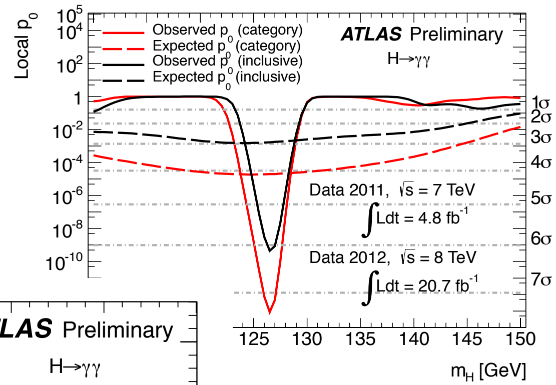
H→γγ

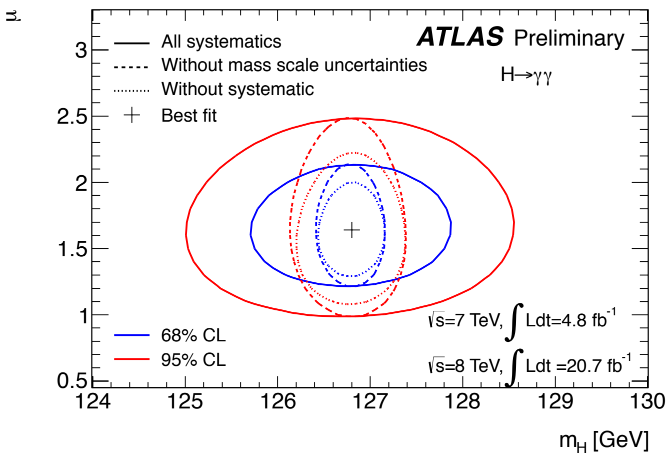
- Simple final state: 2 high-p_T isolated photons
  - E_T (γ1, γ2) > 40, 30 GeV (20/20 for 7 TeV)
- Search for narrow peak in $m_{\gamma\gamma}$
- Very good mass resolution ~1.7 GeV.
  - Stable with time and pile-up.
- Main background: γγ continuum
  - γγ [~75%], γ-jet and jet-jet [~25%]
  - Background extrapolated from side-bands in data:
- S/B~3% in mass window ~125 GeV with 90% signal
- To enhance the sensitivity (~40%): classification into 14 categories with different S/B (1-60%) and different resolutions (1.4-2.5 GeV) --> optimized for coupling measurements
  - background model for each category chosen on MC to minimize signal bias.
- Simultaneous fit Signal + background
  - Signal strength and H mass are free parameter on the fit

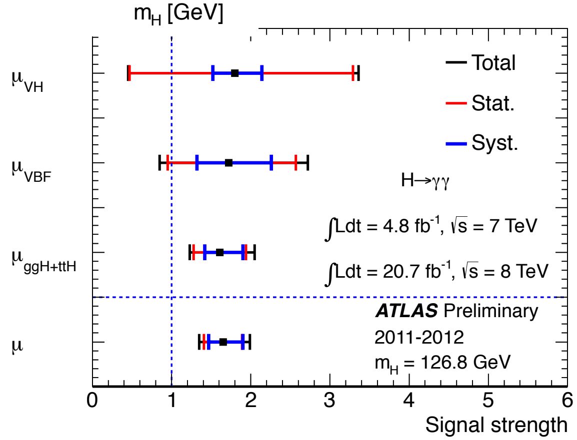




$H \rightarrow \gamma\gamma$: results

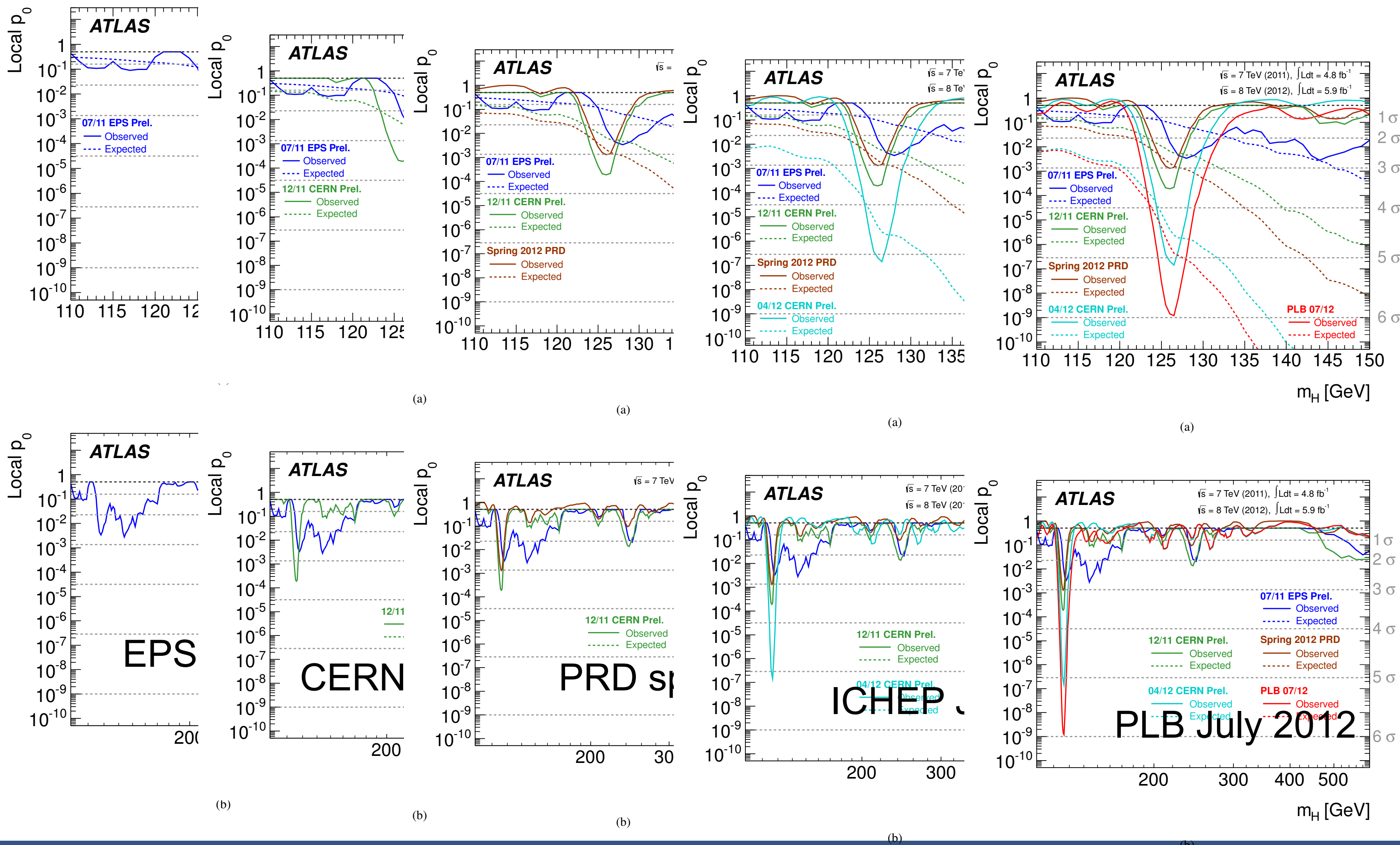




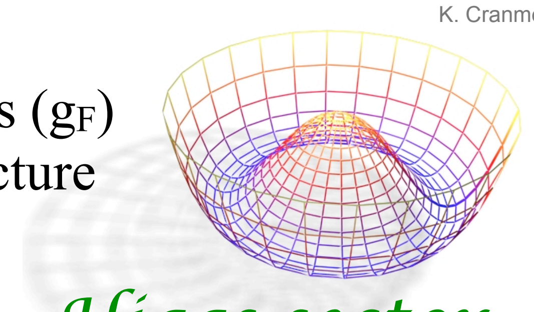


- Most significant deviation from background only hypothesis at mH =126.5 GeV:
- Local significance: **7.4 σ** (with 4.1 σ expected) @ mH=126.5 GeV
  - Inclusive analysis: 6.1 σ (with 2.9 σ expected)
- Mass measurement: **126.8 ± 0.2 (stat) ± 0.7 (syst) GeV**
- Systematics completely dominated by the photon energy scale uncertainty *(mainly from the extrapolation of the photon energy scale from Z->ee ,* presampler energy scale *and material modeling)*
- Rate with respect to Standard Model: μ = **1.65 ± 0.24 (stat)$^{+0.25}_{-0.18}$ (syst)**
  - 2.3 σ deviation from the Standard Model
- 2.0 σ excess for the VBF production mH=126.5 GeV
- Couplings in agreement with SM expectation within 2 σ

A Bit of History



Higgs Boson Property Measurements



1. Higgs boson mass (M_H) & decay width (Γ_H)
2. Higgs couplings to gauge bosons (g_V) and fermions (g_F)
3. Higgs boson quantum numbers J^{PC} and tensor structure
4. Higgs potential - Higgs self-coupling (λ)

The Standard Model Lagrangian - Higgs sector

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

Couplings to EW gauge bosons

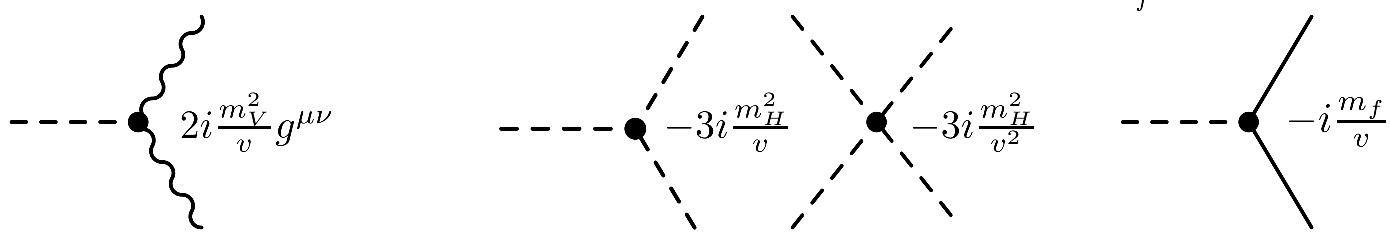
$$\left[m_W^2 W^{\mu+} W_\mu^- + \tfrac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \tfrac{h}{v}\right)^2$$

Higgs self-couplings

$$-\mu^2 h^2 - \tfrac{\lambda}{2} v h^3 - \tfrac{1}{8}\lambda h^4$$

Couplings to fermions

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$

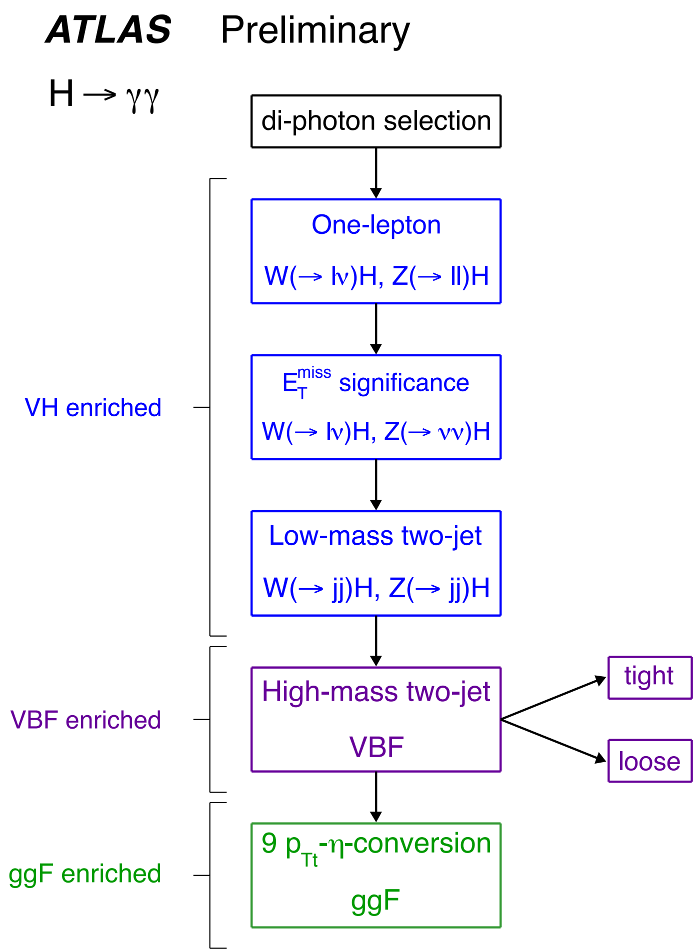


$$m_H = \sqrt{2}\mu = \sqrt{\lambda} v \ (v = \text{vacuum expectation value})$$

The ultimate goal of particle physics of today is to fix the Standard Model (SM) Lagrangian and find the physics beyond the Standard Model (BSM).

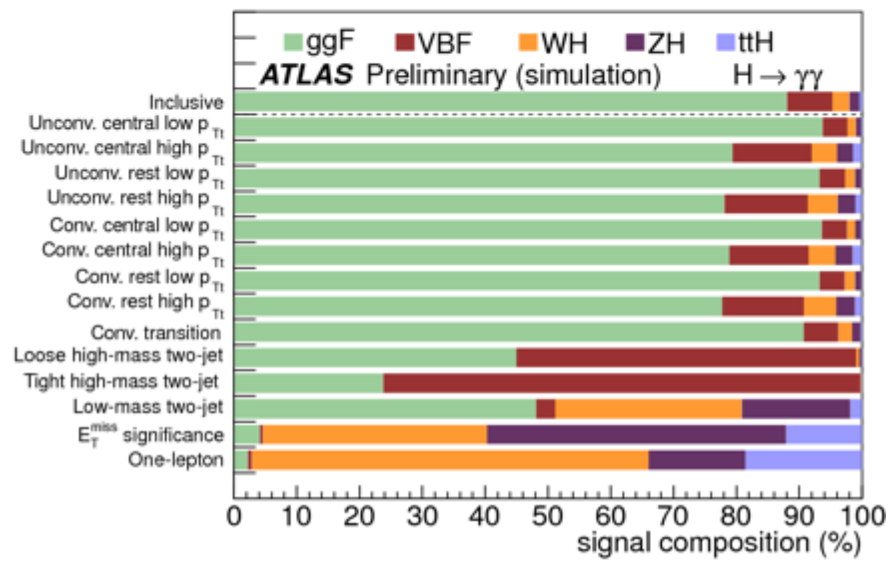
2

$H \rightarrow \gamma\gamma$: Event Categories



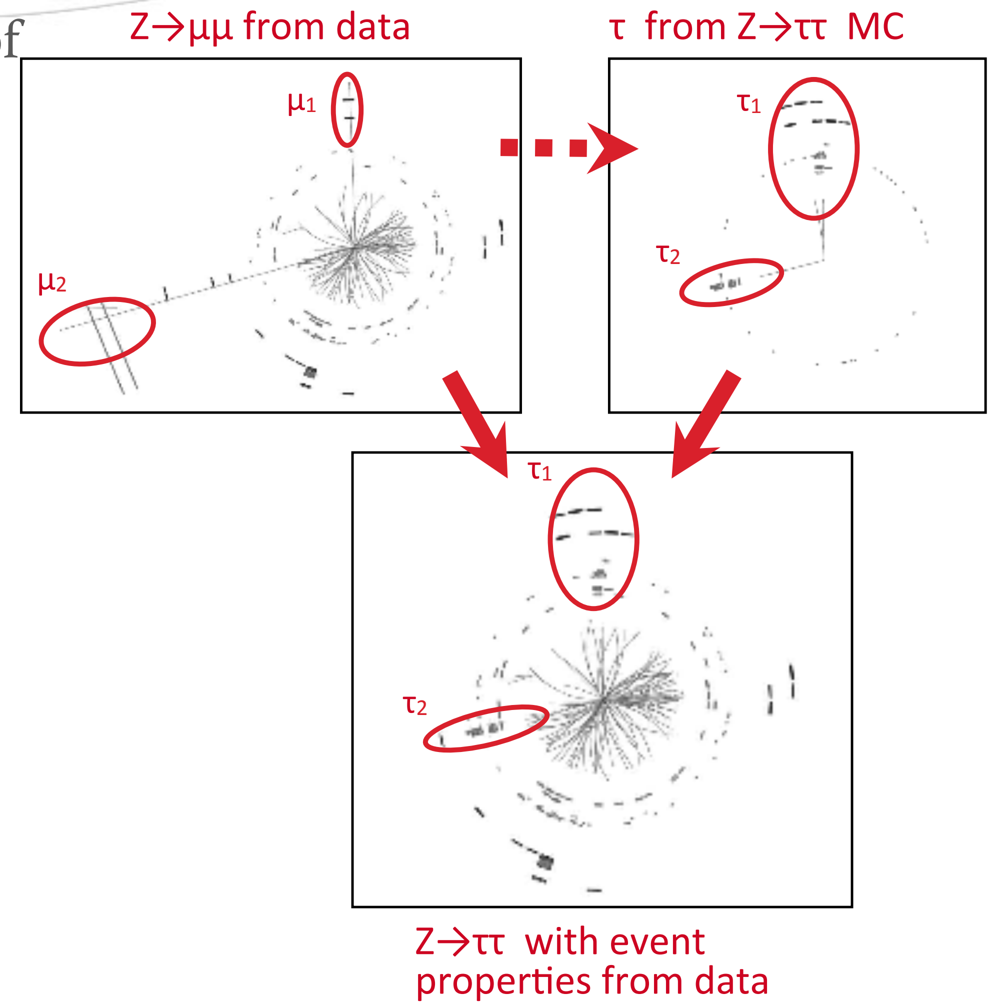
To enhance the sensitivity (~40%): classification into 14 categories with different S/B (1-60%) and different resolutions (1.4-2.5 GeV) --> optimized for coupling measurements

background model for each category chosen on MC to minimize signal bias



H→ τ τ : Embedding

- Embedding: all properties of a Z→ τ τ event except the taus are modeled by Z→ μ μ data
- Remove μ from data
  - Simulate τ including spin
  - Add τ in place of the μ
- **Major advantages of embedding**: Z-boson kinematics, jets, MET resolution, pile-up, and VBF/EWK production are directly modeled by data



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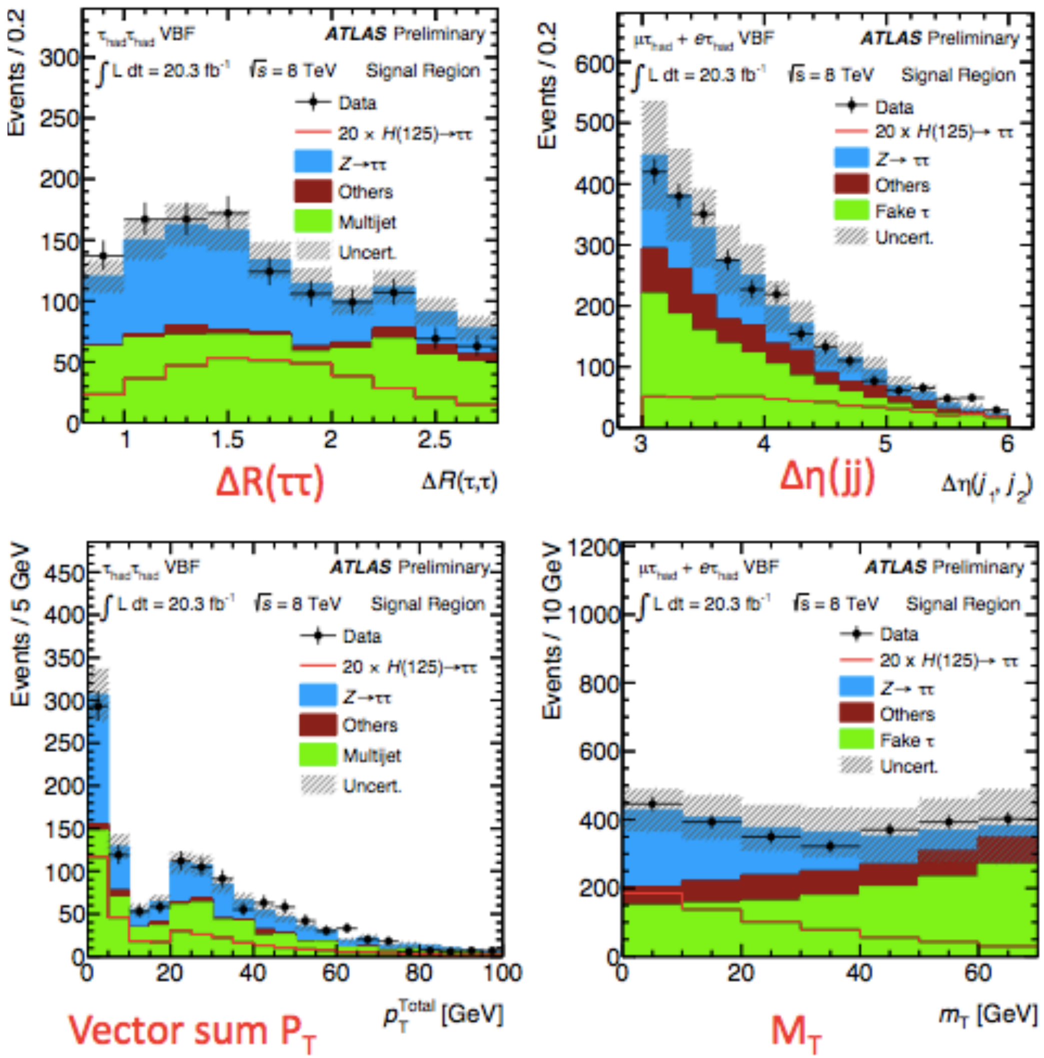
H→ τ τ : Inputs to the BDT



- Resonance properties
  - m(ττ), ΔR(ττ), etc
- VBF topology
  - m_{jj}, $\Delta\eta_{jj}$, etc
- Event activity
  - Scalar & vector P_T-sum
- Event topology
  - m_T, object centralities, $P_T(\tau_1)/P_T(\tau_2)$, etc
- Number of variables
  - VBF: 7-9
  - Boosted: 6-9

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Leading Systematic Uncertainties:

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \rightarrow \ell\ell$ normalization ($\tau_{\rm lep}\tau_{\rm had}$ boosted)	0.13
ggF $d\sigma/dp_T^H$	0.12
JES η calibration	0.12
Top normalization ($\tau_{\rm lep}\tau_{\rm had}$ VBF)	0.12
Top normalization ($\tau_{\rm lep}\tau_{\rm had}$ boosted)	0.12
$Z \rightarrow \ell\ell$ normalization ($\tau_{\rm lep}\tau_{\rm had}$ VBF)	0.12
QCD scale	0.07
di-$\tau_{\rm had}$ trigger efficiency	0.07
Fake backgrounds ($\tau_{\rm lep}\tau_{\rm lep}$)	0.07
$\tau_{\rm had}$ identification efficiency	0.06
$Z \rightarrow \tau^+\tau^-$ normalization ($\tau_{\rm lep}\tau_{\rm had}$)	0.06
$\tau_{\rm had}$ energy scale	0.06

$$\textit{Signal strength } \mu = \frac{\sigma_{measured}}{\sigma_{SM}}$$

- Leading theory uncertainty is due to effect of top, bottom, charm quark masses in gluon-gluon loop, affecting $P_T(H)$ spectrum in gluon fusion produced H (~30%)
- Working with the LHC Higgs Cross Section group to come up with the best way to treat these theory systematics
- Leading experimental uncertainties are due to background normalizations (up to ~20%)

$H \rightarrow \tau\ \tau$: Results BDT score

- The log(Signal/Bkgd) for each event's BDT-score bin

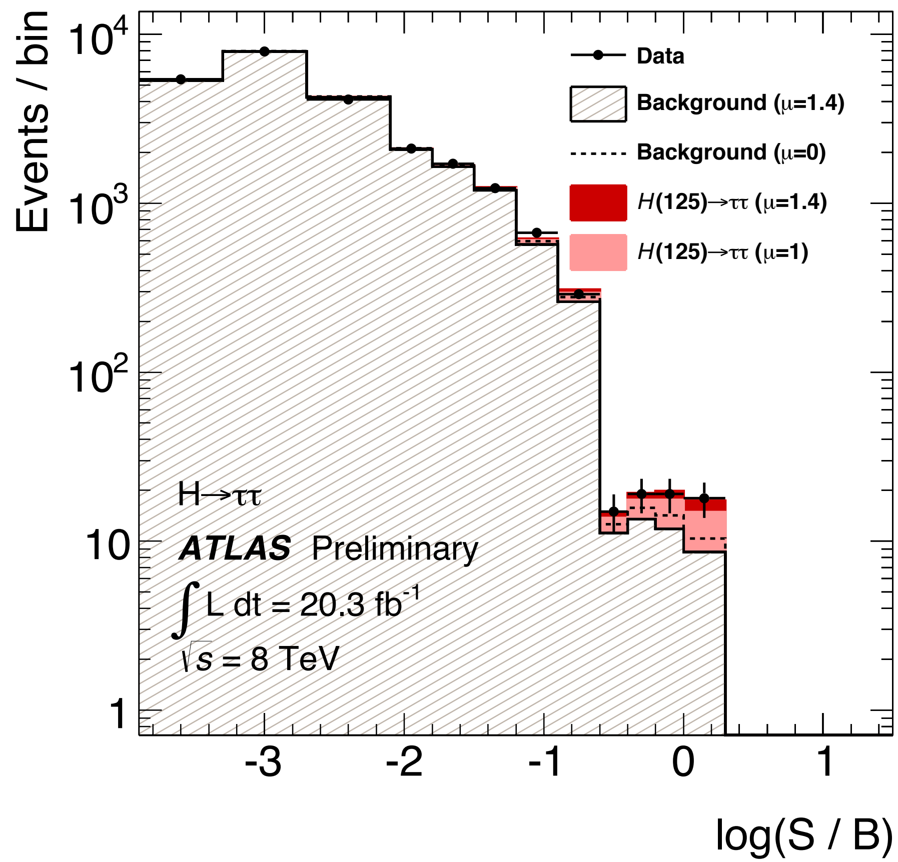
Numbers of events in highest BDT-score bin

VBF

	Lep-lep	**Lep-had**	**Had-had**
Signal	5.7±1.7	8.7±2.5	8.8±2.2
Bkgd	13.5±2.4	8.7±2.4	11.8±2.6
Data	**19**	**18**	**19**

Boosted

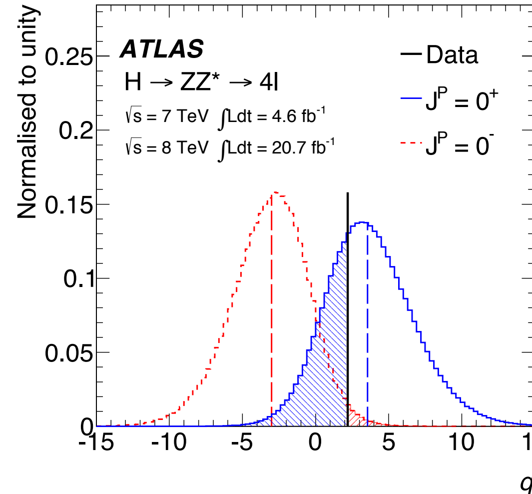
Signal	2.6±0.8	8.0±2.5	3.6±1.1
Bkgd	20.2±1.8	32±4	11.2±1.9
Data	20	34	15



Spin/parity measurement

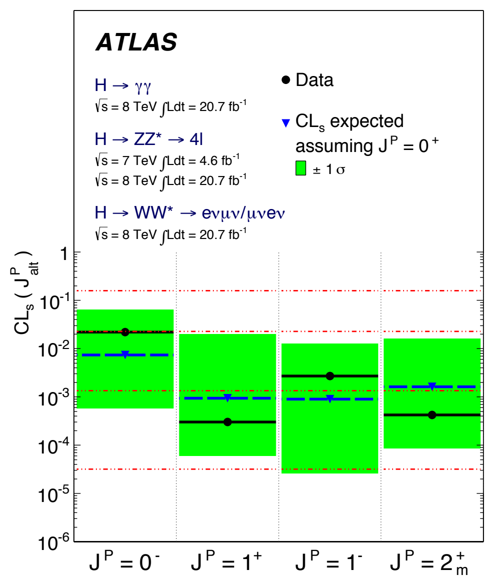
Phys. Lett. B 726 (2013), pp. 120-144

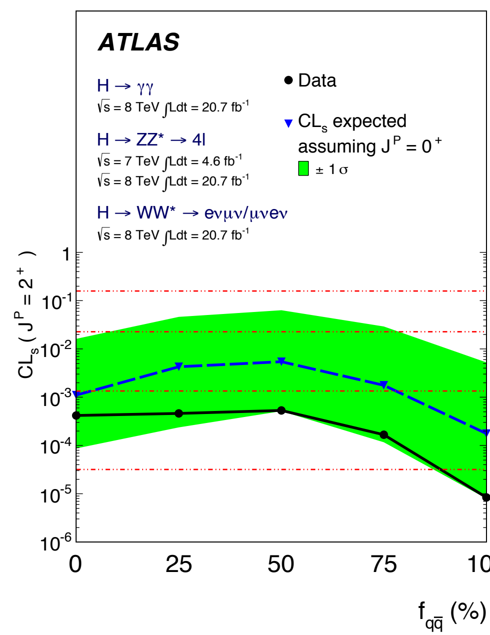
- Find observables in bosonic channels sensitive to spin and parity
- Test several alternative spin-parity hypotheses J^P (0^-,1^+,$1^-$$2^+$) compared to SM hypothesis: 0^+ and observe which is favored by data
- Production modes
  - spin-2 : test production mechanism via combination of ggF & qqbar annihilation
  - spin-1 :signal produce via qqbar annihilation (ggF forbidden)
  - spin-0 : ggF (qqbar annihilation negligible)



0+/0- (only ZZ): 97.8% CL
0+/1+ (ZZ +WW): 99.97% CL
0+/1- (ZZ+WW): 99.7% CL
0+/2+ ($\gamma\gamma$+ZZ+WW)>99.9% CL

All spin hypotheses disfavored compared to 0^+ at > 95%

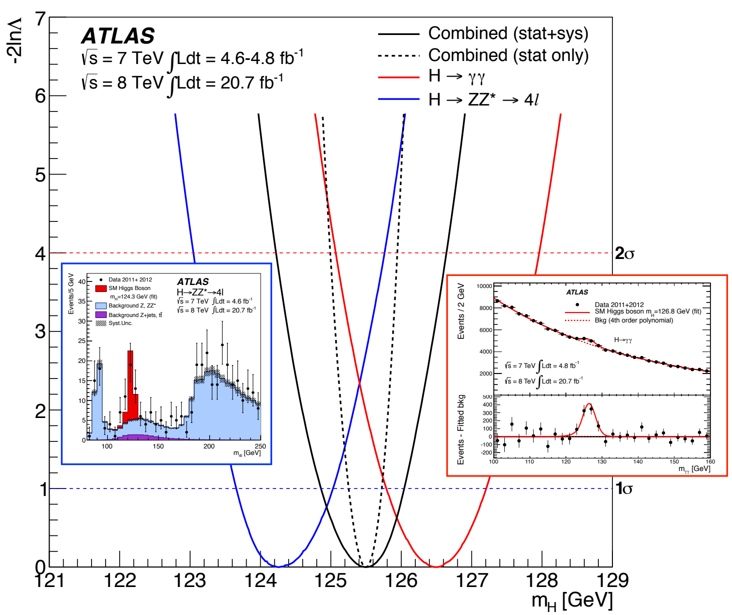




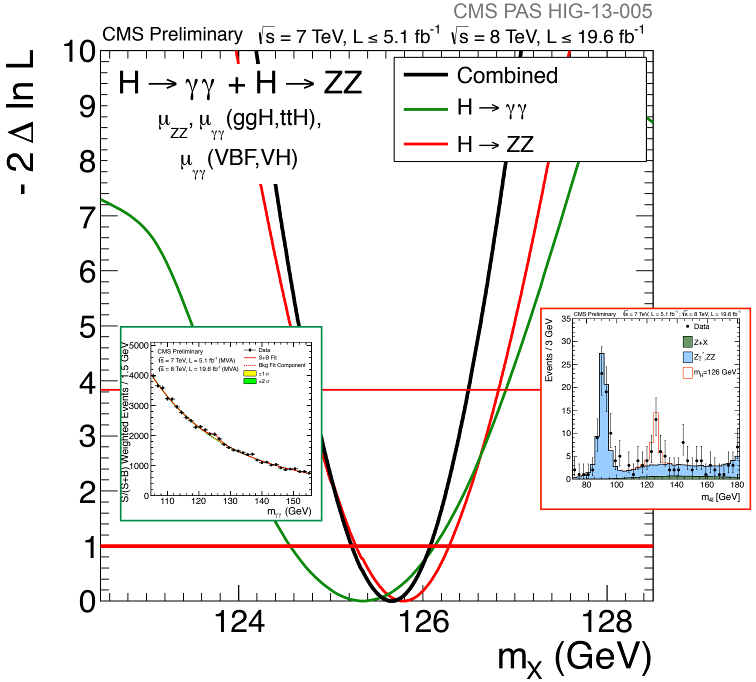
The H mass

- M_H - the only parameter not fixed in the Standard Model. Fixes $\lambda = \frac{M_H^2}{v^2}$.
- Most precisely determined with H→γγ and 4 lepton channels.
- δM_H precision at 0.3% level (PDG2013: δM_W 187ppm, δM_Z 23ppm, δM_{top} 0.5%).

CERN-PH-EP-2013-103



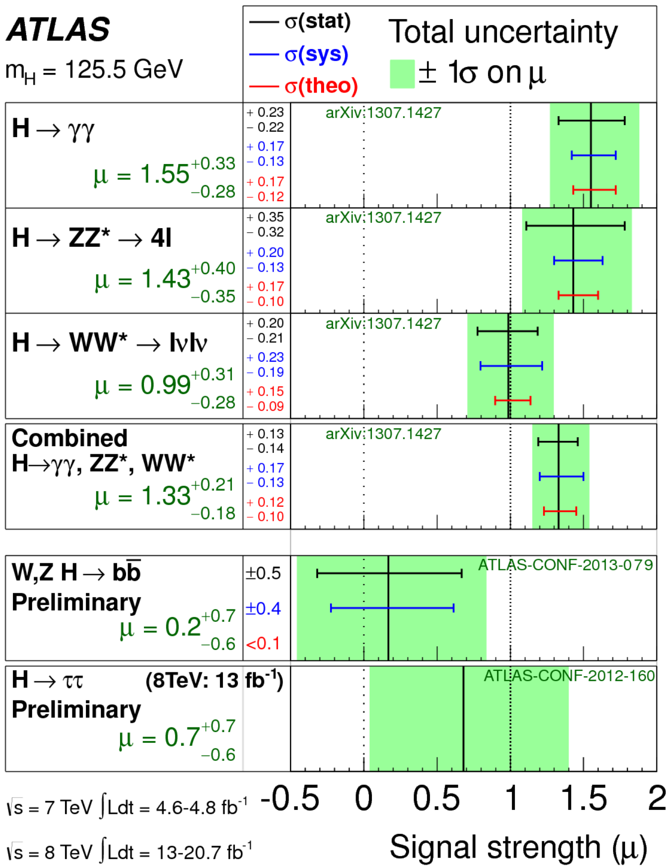
CMS PAS HIG-13-005

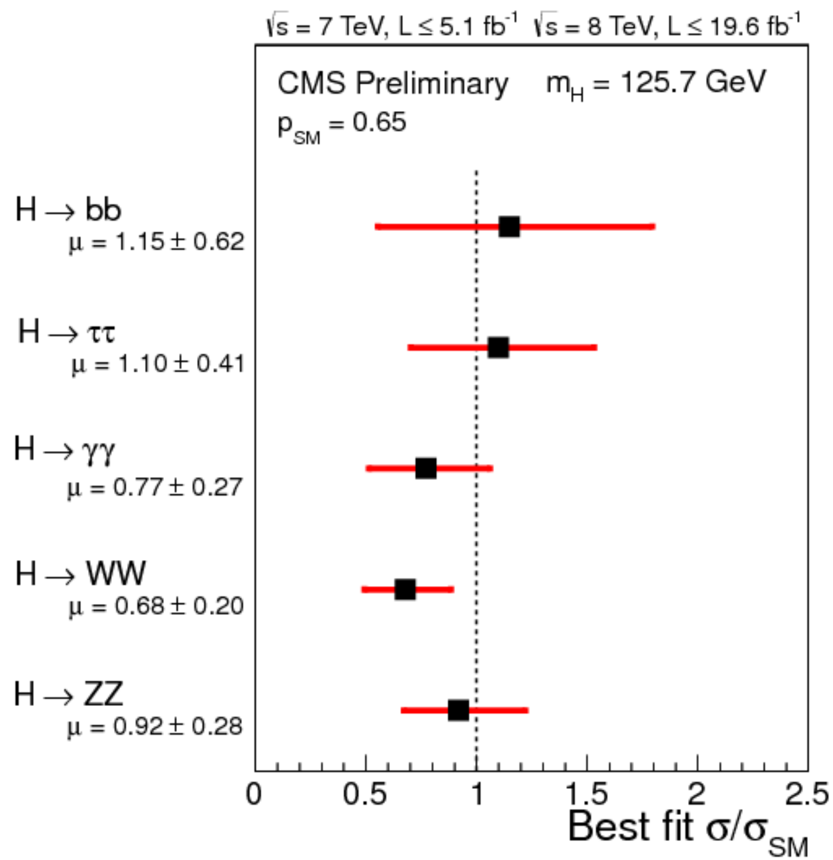


ATLAS: $M_H = 125.5 \pm 0.2$ (stat.) ± 0.6 (syst.) GeV
CMS: $M_H = 125.7 \pm 0.3$ (stat.) ± 0.3 (syst.) GeV

Signal Strength ATLAS-CMS

Consistent with the SM prediction for both ATLAS and CMS with precision about 15% level.

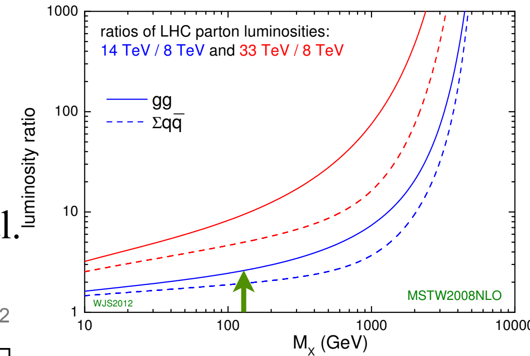




$\mu = 1.23 +/- 0.18$ $\mu = 0.88 +/- 0.14$

HL-LHC

- ECFA HL-LHC with $L=300\ fb^{-1}$ ($3\ ab^{-1}$) physics study.
- Higgs mass precision $\Delta M_H \sim 100$ (50) MeV.
- Access to top-Yukawa coupling via ttH, and rare decay $H\to\mu\mu$.
- Coupling precision of 10 to 5% reachable (even few% in κ_γ/κ_Z).
- Detector performances (trigger, lepton-id, fake, τ/b-id) are crucial.
- Theory uncertainty dominates - challenge for theorists!



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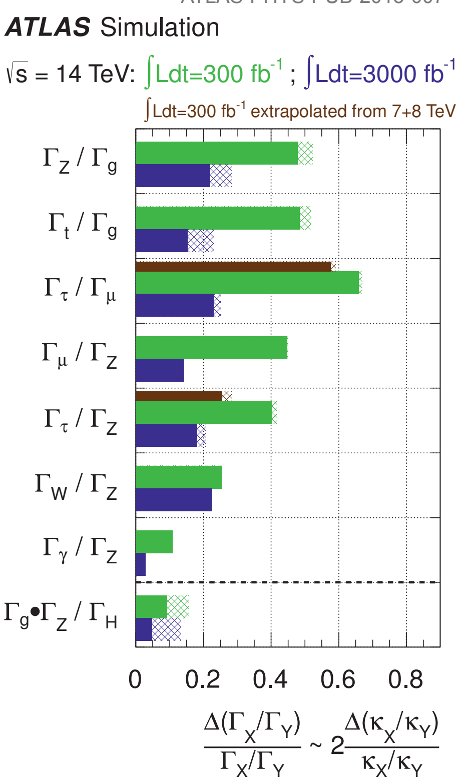
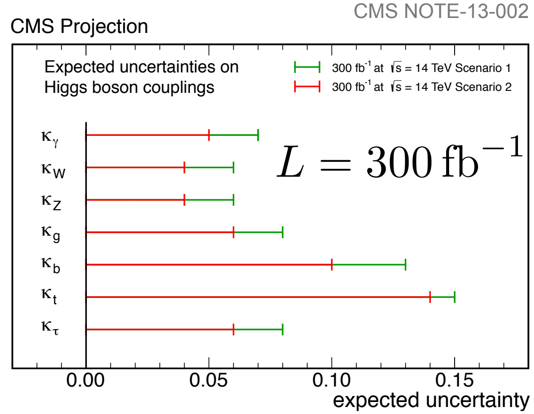
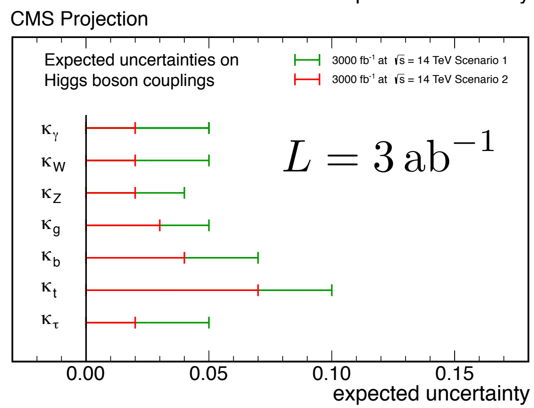


CMS NOTE-13-002





	σ(14TeV)/σ(8TeV)
gg→H	**2.6**
qq→qqH	**2.6** (sees high Mx)
qq→VH	**2.1**
gg→ttH	**4.7** (phase space)

Scenario 1
current systematic uncert.
Scenario 2
theory uncert. ↘ 1/2
other systematics ↘ 1/√L

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CMS summary

- CMS latest public result add by hends