

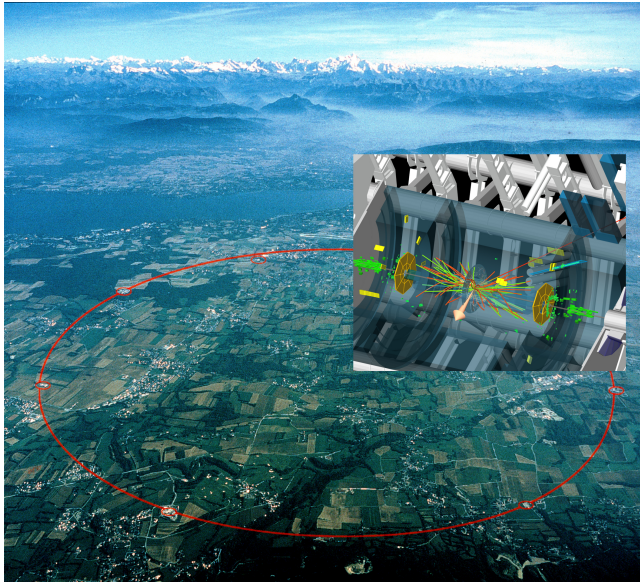
Is the Higgs boson  
natural?

What experiments  
can tell us.

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University of Pennsylvania

February 21, 2014

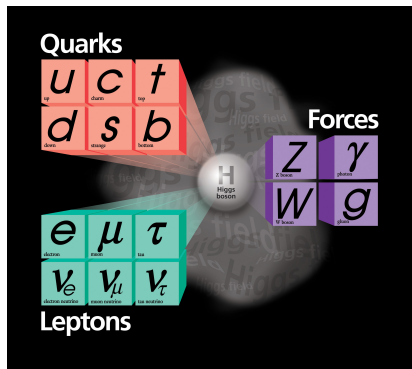


- ▶ Standard Model and Higgs boson
- ▶ LHC and ATLAS detector
- ▶ Higgs boson decays to W bosons
- ▶ Higgs boson decays to muons
- ▶ Future experimental outlook



# The Standard Model

- ▶ Standard Model is renormalizable quantum field theory of 12 fermions with 3 forces mediated by spin-1 gauge bosons
- ▶ Electroweak Symmetry is spontaneously broken by Brout-Englert-Higgs mechanism
- ▶ Neutral scalar particle: Higgs boson
- ▶ Very successful description of particle interactions



*"The renormalization theory is simply a way to sweep the difficulties of the divergences of electrodynamics under the rug. I am, of course, not sure of that."* - Richard Feynman.

# The Standard Model

*"[The Higgs boson is] a particle needed for theories to work"* - Gerard 't Hooft

Higgs boson discovery seminar  
at CERN on July 4th, 2012



2013 Nobel Physics Prize  
to Englert and Higgs

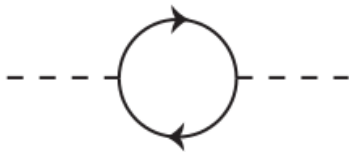


The Higgs boson discovery completes the SM,  
making the theory self-consistent up to very high energy scale.

## Some of open questions

- ▶ Dark matter and dark energy
- ▶ Higgs boson mass is sensitive to scale of new physics (up to  $\Lambda_{Planck}$ )
- ▶ Cosmological constant problem

### Quantum corrections to the Higgs mass term



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} [\Lambda_{UV}^2 + \dots].$$

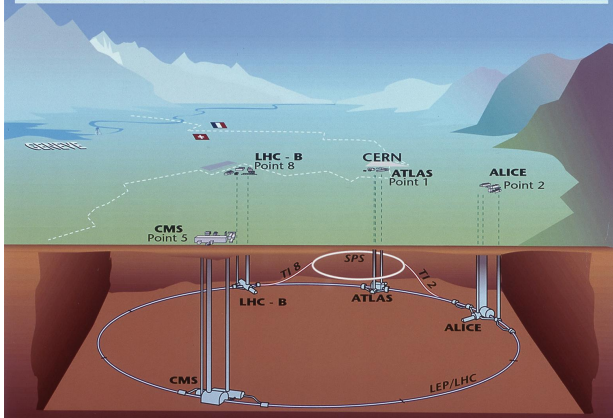
- ▶ Broad experimental program underway to look for new physics
- ▶ SM precisely predicts all Higgs boson properties for fixed  $m_H$
- ▶ Any deviations represent clear signs of new physics

## Road to the discovery

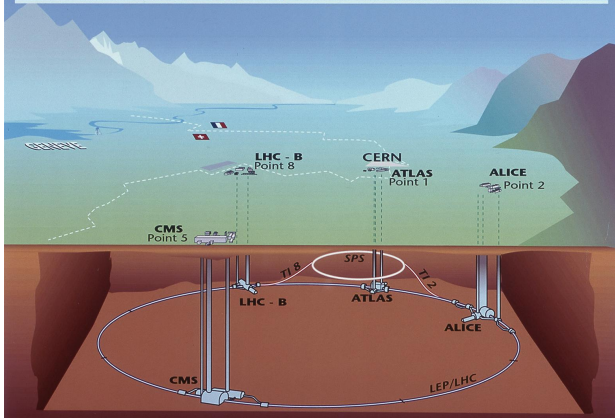


## Overall view of the LHC experiments.

- ▶ 27 km tunnel LHC
- ▶ 1232 superconducting dipoles at 1.9 K
- ▶ Proton-proton, proton-ion and ion-ion collisions
- ▶ 7-8 TeV pp collisions in 2011 and 2012
- ▶ LHC will restart in 2015 at  $\sim 14$  TeV



## Overall view of the LHC experiments.



### 4 large detectors to study:

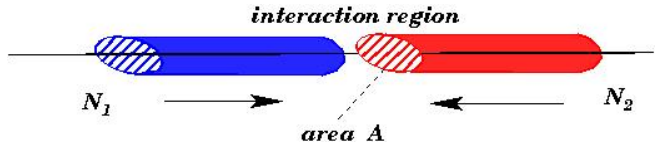
- ▶ Electroweak Symmetry Breaking
- ▶ Standard Model
- ▶ Searches for new physics
- ▶ Matter-antimatter asymmetry
- ▶ New states of matter



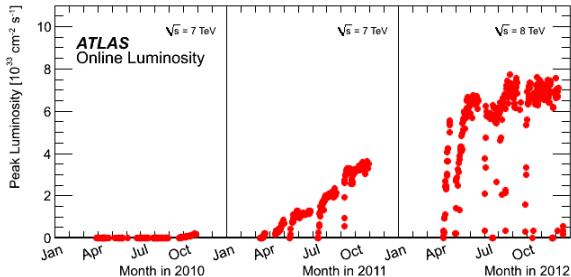
Colliding bunches:

$$\mathcal{L} = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A}$$

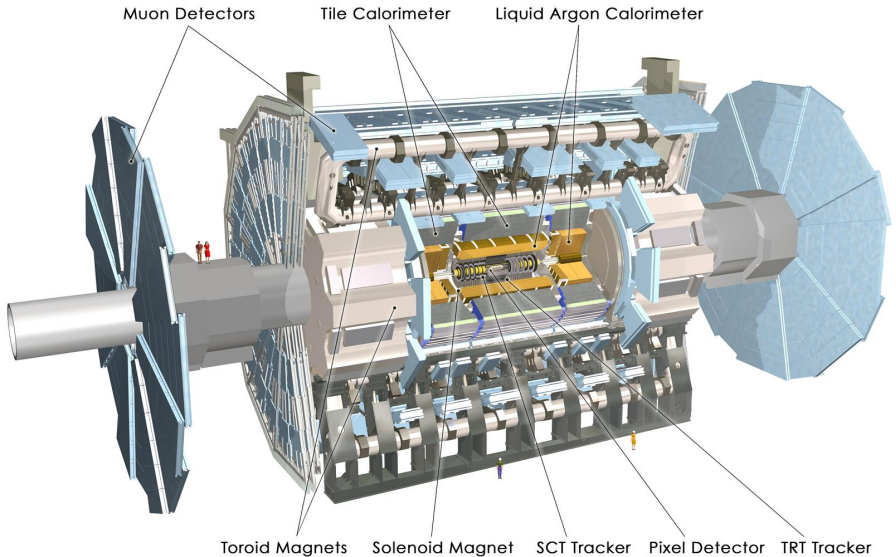
$$\text{Area } A = 4\pi \cdot \beta \cdot \epsilon$$



- ▶  $n_b$  - number of bunches
- ▶  $N_{1,2}$  - number of protons per bunch ( $\sim 1.15 \times 10^{11}$ )
- ▶  $f_{rev}$  - revolution frequency (11kHz)
- ▶  $\beta$  and  $\epsilon$  determined by interaction region focusing and injectors
- ▶ Run 1 - 1380 bunches at 50 ns:  $\mathcal{L}_{2012} = 0.77 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- ▶ Design - 2808 bunches at 25 ns:  $\mathcal{L}_{design} = 1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$



# ATLAS detector

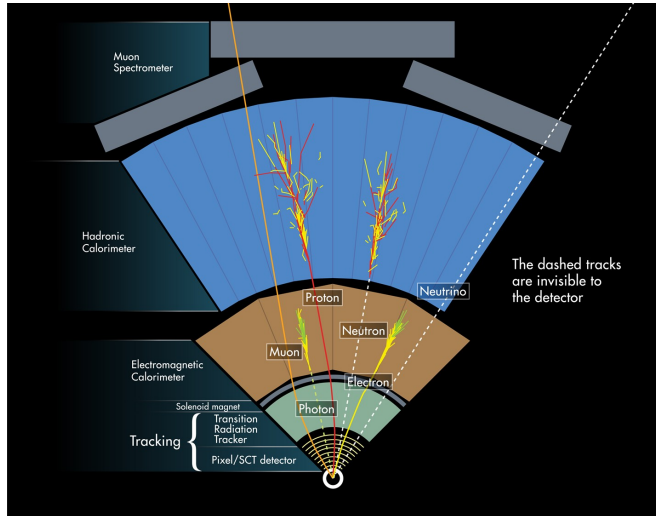
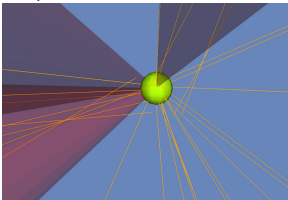




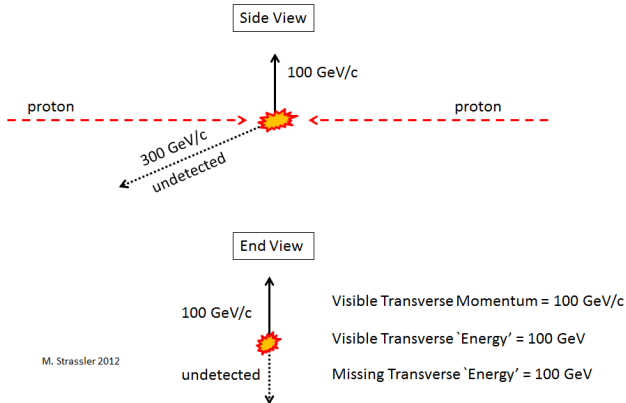
# Particle reconstruction and identification

- ▶ Hermetic detector
- ▶ Almost all particles are reconstructed
- ▶ Miss neutrinos and particles traveling very near beam axis

Displaced b-hadron vertex



# Missing transverse energy



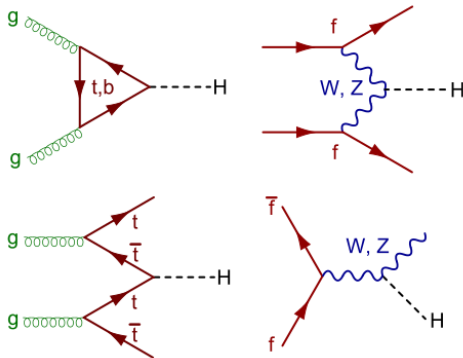
- ▶ Momentum is conserved only in transverse plane
- ▶ Missing transverse energy:

$$E_{T,miss} = - \sum_{jets} E_T - \sum_{leptons} p_T - \sum_{photons} E_T - \sum_{clusters} E_T$$

# Higgs boson production at the LHC

Higgs boson properties are fixed once  $m_H$  is known

- ▶ Gluon-gluon fusion (ggF)
  - ▶ Fermion couplings in the loop
- ▶ Vector boson fusion (VBF)
  - ▶ Two forward separated jets
- ▶ WH/ZH associated production:
  - ▶ Tag W/Z to reduce backgrounds
- ▶ ttH associated production:
  - ▶ Direct ttH coupling



Cross-sections and theory uncertainties for  $m_H = 126$  GeV at 8 TeV:

|                 | ggF       | VBF       | WH/ZH     | ttH       |
|-----------------|-----------|-----------|-----------|-----------|
| $\sigma$ (pb)   | 19.0      | 1.6       | 1.1       | 0.13      |
| QCD scale       | $\pm 8\%$ | $\pm 1\%$ | $\pm 1\%$ | +4% – 9%  |
| PDF+ $\alpha_S$ | $\pm 8\%$ | $\pm 4\%$ | $\pm 4\%$ | $\pm 8\%$ |

## Higgs decays: update to 126 GeV

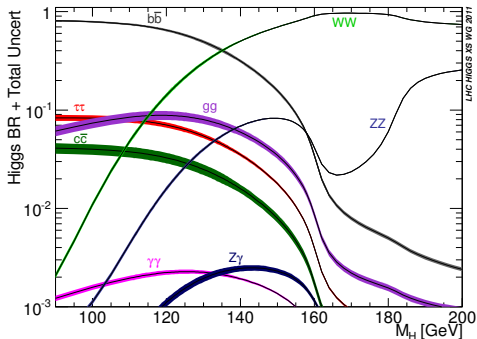
- ▶  $\Gamma_H = 4.1$  MeV - observed signal width is determined by detector resolution
- ▶  $WW$  and  $ZZ$  dominate when kinematically allowed
- ▶ 7 channels accessible at the LHC for  $m_H = 126$  GeV:

$$\begin{aligned} H &\rightarrow b\bar{b} \\ H &\rightarrow W W \\ H &\rightarrow \tau\tau \\ H &\rightarrow Z Z \\ H &\rightarrow \gamma\gamma \\ H &\rightarrow Z\gamma \\ H &\rightarrow \mu\mu \end{aligned}$$

- ▶  $H \rightarrow \gamma\gamma$  and  $H \rightarrow Z\gamma$  decay via loops - sensitive to new physics

$$\text{Fermion couplings} \propto \frac{m_f}{v}$$

$$\text{Gauge boson couplings} \propto \frac{2m_V^2}{v}$$



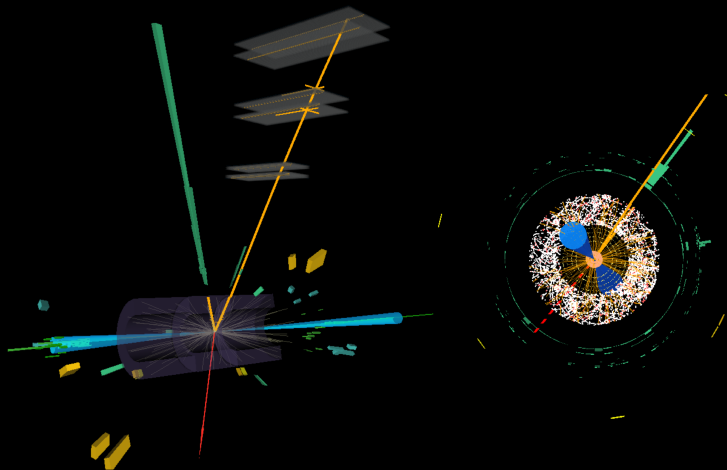
$H \rightarrow WW \rightarrow l\nu l\nu$

$\sigma \times BR \approx 0.24 \text{ pb}$  for  $m_H = 126 \text{ GeV}$

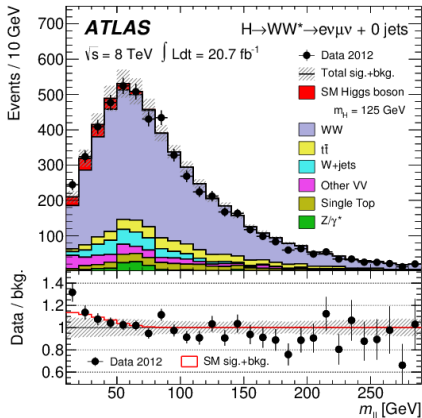
$\approx 4800$  signal events before selection



Run 214680, Event 271333760  
17 Nov 2012 07:42:05 CET



## $H \rightarrow WW$ : analysis strategy



### $H \rightarrow WW \rightarrow l\nu l\nu$ :

- ▶ 2 opposite sign leptons +  $E_T^{miss}$
- ▶ Only electrons and muons
- ▶ High rate, clean final state
- ▶ No mass peak because of  $\nu$

### Irreducible background:

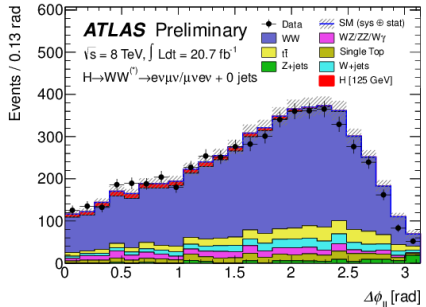
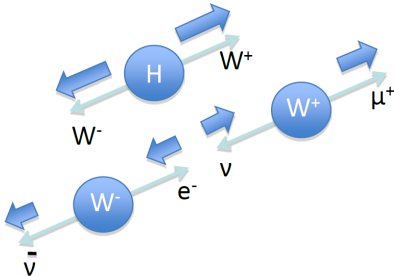
- ▶ Non-resonant WW
- ▶ Normalized from data

### Other backgrounds:

- ▶ Top quark
- ▶ Z+jets
- ▶ W+jets
- ▶ Di-bosons:  $WZ$ ,  $ZZ$ ,  $W\gamma^{(*)}$
- ▶ Normalized/validated from data

## $H \rightarrow WW \rightarrow l\nu l\nu$ : Spin-0 Higgs boson

- ▶ Irreducible non-resonant WW background:  $\sigma_H/\sigma_{WW} \approx 3\%$
- ▶ Spin-0: small opening angle for 2 charged leptons:
  - ▶  $|m_{ll}| < 50 \text{ GeV}$
  - ▶  $|\Delta\phi_{ll}| < 1.8$



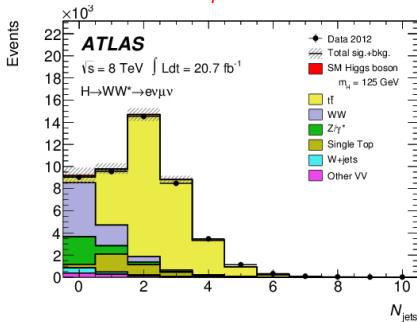
"... for the weak interactions parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence." - Lee and Yang, 1956.

# $H \rightarrow WW \rightarrow l\nu l\nu$ : jet multiplicity

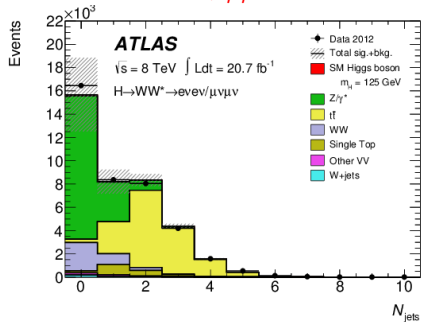
Categories based on number of jets and lepton flavor:

- ▶ Veto events with b-jets to reduce top quark background
- ▶ Improve S/B because of different background composition
- ▶ Increase sensitivity to VBF production mode (+)
- ▶ Increase theory and experimental uncertainties (-)

$e\mu$ :



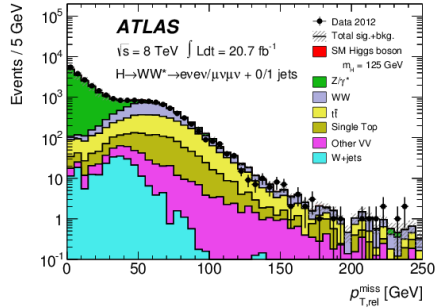
$ee + \mu\mu$ :



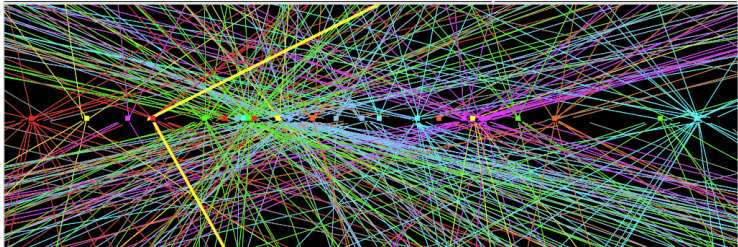


## $H \rightarrow WW \rightarrow l\nu l\nu$ : $p_{T,miss}$ performance

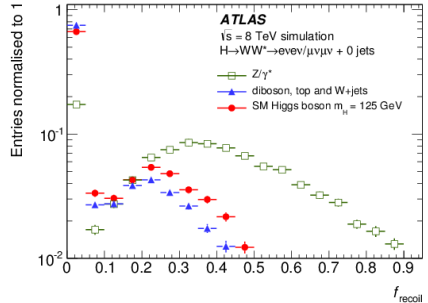
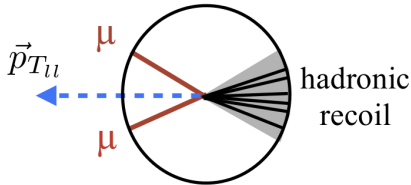
- ▶ Missing transverse momentum:  
$$p_{T,miss} = -\sum_{\text{charged particle}} p_T$$
- ▶ Use reconstructed charged particle tracks matching primary vertex - does not depend on pileup
- ▶ Miss neutral particles
- ▶ Suppress  $Z \rightarrow ll$  by factor of  $\sim 5$



## $Z \rightarrow \mu\mu$ with 25 vertexes



# $H \rightarrow WW \rightarrow l\nu l\nu$ : soft hadronic recoil veto



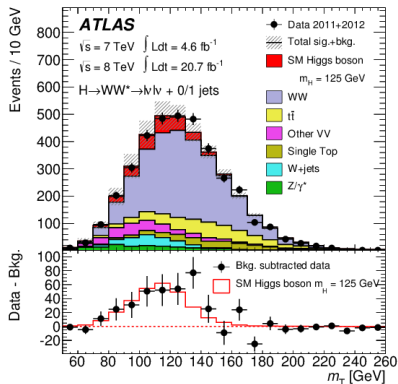
- ▶ Require that di-lepton system is boosted:  $p_{T,ll} > 30$  GeV
- ▶ Soft hadronic recoil fraction:  $f_{recoil} = E_{T,recoil} / p_{T,ll}$
- ▶  $H \rightarrow WW \rightarrow l\nu l\nu$  - recoil carried away by neutrinos
- ▶  $Z \rightarrow ll$  - boost requires hadronic recoil
- ▶  $Z \rightarrow ll$  estimated from regions with high  $f_{recoil}$  and Z peak
- ▶ Suppress  $Z \rightarrow ll$  by factor of  $\sim 5$

# $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ : results

- Probe transverse mass distribution
- Observed  $3.8 \sigma$  excess for  $m_H = 125$  GeV (expected  $3.8 \sigma$ )

| Category     | Source                                      | Uncertainty, up (%) | Uncertainty, down (%) |
|--------------|---------------------------------------------|---------------------|-----------------------|
| Statistical  | Observed data                               | +21                 | -21                   |
| Theoretical  | Signal yield ( $\sigma \cdot \mathcal{B}$ ) | +12                 | -9                    |
| Theoretical  | $WW$ normalisation                          | +12                 | -12                   |
| Experimental | Objects and DY estimation                   | +9                  | -8                    |
| Theoretical  | Signal acceptance                           | +9                  | -7                    |
| Experimental | MC statistics                               | +7                  | -7                    |
| Experimental | $W$ + jets fake factor                      | +5                  | -5                    |
| Theoretical  | Backgrounds, excluding $WW$                 | +5                  | -4                    |
| Luminosity   | Integrated luminosity                       | +4                  | -4                    |
| Total        |                                             | +32                 | -29                   |

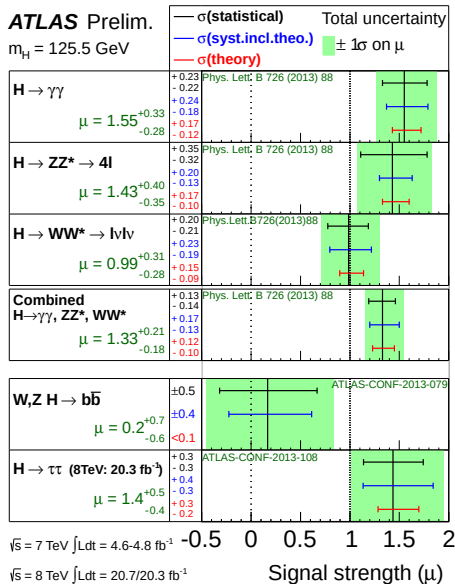
$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{\text{miss}}|^2}$$



At the summit



# Summary of Higgs boson measurements



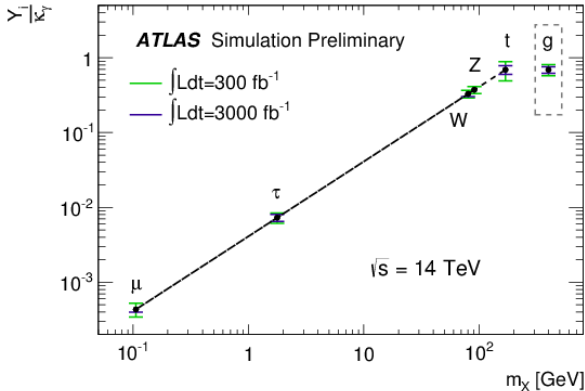
- Signal strength  $\mu = \frac{\sigma \times BR}{\sigma_{SM} \times BR_{SM}}$
- Clear evidence for Higgs boson decays to gauge bosons with properties consistent with the SM predictions
- Strong evidence for  $H \rightarrow \tau\tau$  decays

What's next?



# Higgs couplings to fermions

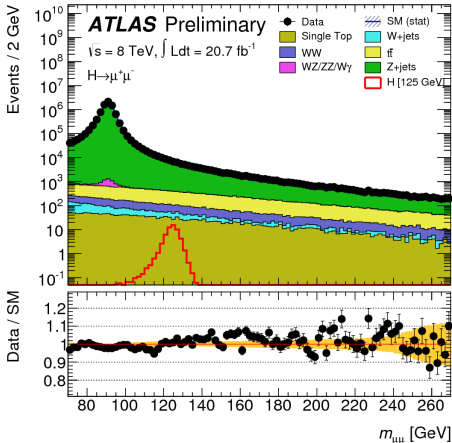
$$Y_f \sim m_f/v, \quad Y_V \sim m_V/v, \quad v = 246 \text{ GeV}$$



- ▶ Explore flavor physics in Higgs boson decays to fermions
- ▶  $H \rightarrow \tau\tau$  and  $t\bar{t}H$  test 3rd generation couplings
- ▶  $H \rightarrow \mu\mu$  tests 2nd generation coupling
- ▶ What is a reason for the fermion mass hierarchy?

# $H \rightarrow \mu\mu$ search

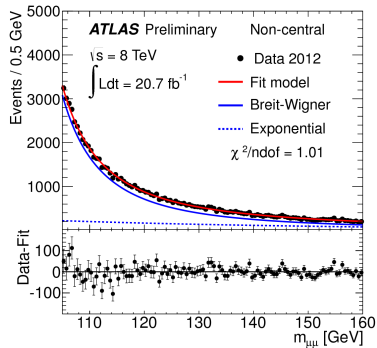
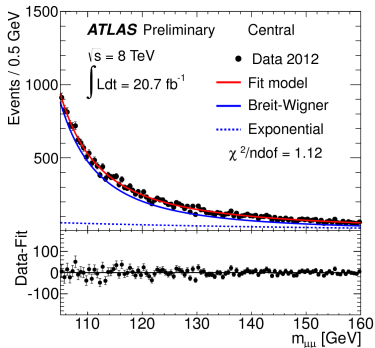
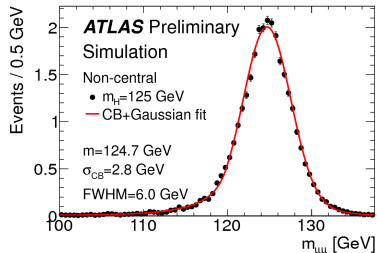
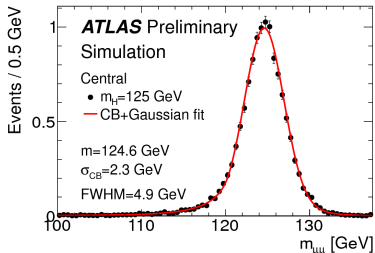
- Goal: set limit on  $B(H[125] \rightarrow \mu\mu)$  and search for new resonances
- $H \rightarrow \mu\mu$  probes directly SM Higgs coupling to 2nd generation fermions
- $B(H[125] \rightarrow \mu\mu) = 2.2 \times 10^{-4} \rightarrow 2.6 \text{ events/fb}^{-1}$  ( $\approx 55\%$  efficiency)
- Dominant irreducible background is Z+jet (also  $t\bar{t}$  and di-bosons)



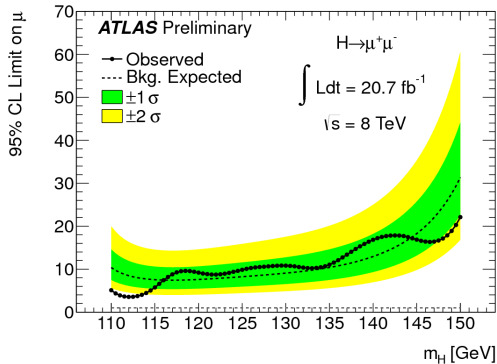
|                  | $ m_H - m_{\mu\mu}  \leq 5 \text{ GeV}$ |
|------------------|-----------------------------------------|
| Signal [125 GeV] | $37.7 \pm 0.2$                          |
| WW               | $250 \pm 4$                             |
| WZ/ZZ/W $\gamma$ | $30 \pm 1$                              |
| $t\bar{t}$       | $1374 \pm 13$                           |
| Single Top       | $151 \pm 5$                             |
| Z+jets           | $15806 \pm 125$                         |
| W+jets           | $88 \pm 6$                              |
| Total Bkg.       | $17697 \pm 126$                         |
| Observed         | 17442                                   |



## $H \rightarrow \mu\mu$ : two resolution categories



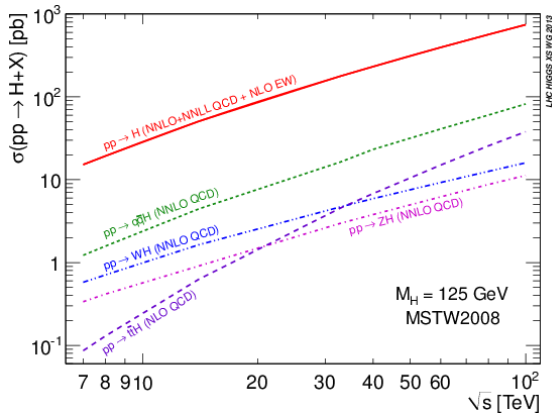
## Results



- ▶ No evidence of significant enhancement in the  $H \rightarrow \mu\mu$  production
- ▶ Observed (expected) limit at the 95% CL for the Higgs boson with a mass of 125 GeV is 9.8 (8.2) times the Standard Model prediction

# Higgs boson measurements at 14 TeV

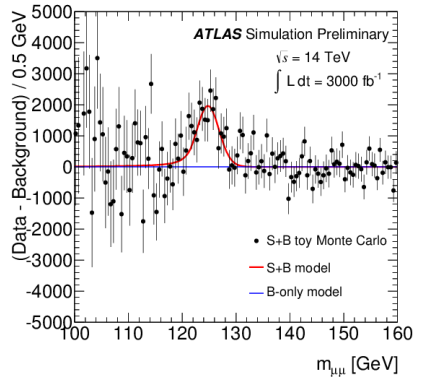
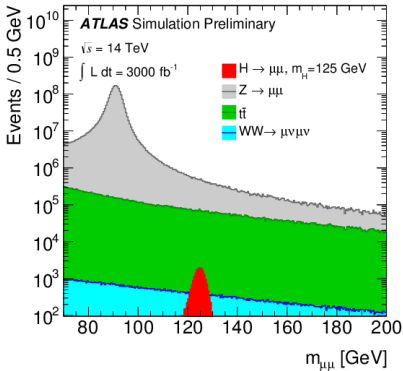
- ▶ High Luminosity LHC will provide up to  $3000 \text{ fb}^{-1}$
- ▶ Extensive ATLAS detector upgrades
- ▶ Expand sensitivity of searches for new physics
- ▶ Expect  $\approx 5 - 10\%$  statistical precision on Higgs boson couplings



|                      | $\sigma(14\text{TeV})/\sigma(8\text{TeV})$ |   |
|----------------------|--------------------------------------------|---|
| $gg \rightarrow H$   | 2.6 ( $M_X = M_H$ )                        | ● |
| $qq \rightarrow qqH$ | 2.6 (probes high $M_X$ )                   | ● |
| $qq \rightarrow VH$  | 2.1 ( $M_X = M_V + M_H$ )                  | ● |
| $gg \rightarrow ttH$ | 4.7 (phase space + $M_X$ )                 | ● |

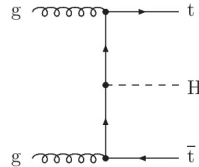
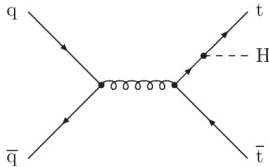
# $H \rightarrow \mu\mu$ at HL-LHC

- ▶ Measurement of Higgs couplings to 2nd generation fermions
- ▶ Expect  $\sim 10\%$  statistical uncertainty on  $H \rightarrow \mu\mu$  with HL-LHC



## $t\bar{t}H$ cross-section and branching ratios

- ▶  $t\bar{t}H$  allows to measure directly the top quark Yukawa coupling
- ▶ Probe for new physics contributions in  $gg \rightarrow H$  and  $H \rightarrow \gamma\gamma$  loops



Examples of LO Feynman diagrams for the partonic processes  $q\bar{q}, gg \rightarrow t\bar{t}H$ .

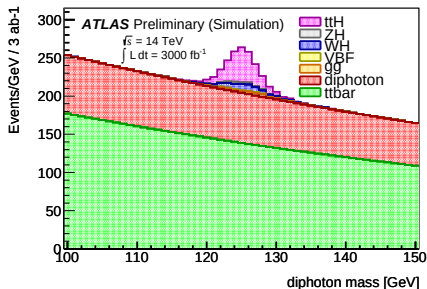
$t\bar{t}H, H \rightarrow b\bar{b}$

- ▶ Dominant decay mode
- ▶ Large irreducible  $t\bar{t} + b\bar{b}$  QCD background
- ▶ Boosted techniques at 14 TeV

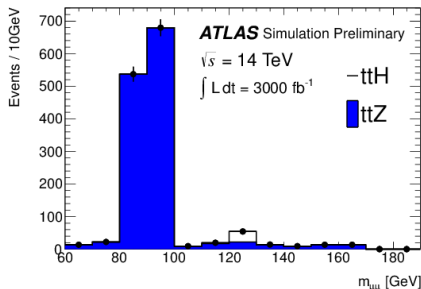
## $t\bar{t}H$ at HL-LHC

- ▶  $\sim 20\%$  statistical precision on  $t\bar{t}H$  in  $H \rightarrow \mu\mu$ ,  $H \rightarrow ZZ \rightarrow 4l$  and  $H \rightarrow \gamma\gamma$  decay modes
- ▶  $t\bar{t}H$ ,  $H \rightarrow WW$  can potentially improve precision of  $t\bar{t}H$  coupling measurement

$t\bar{t}H \rightarrow 1 \text{ lepton} + \text{jets} + \gamma\gamma$



$t\bar{t}H \rightarrow t\bar{t} + \mu\mu$



## Summary and outlook

- ▶ The Higgs boson discovery completes the SM
- ▶ Yet the SM does not explain full range of the observed phenomena
- ▶ Extensive searches at the LHC and other facilities so far have found no evidence for new physics
- ▶ Upcoming LHC runs will expand reach of new physics searches and allow precision measurements of Higgs boson properties
- ▶ Studies for future high energy colliders are underway
- ▶ SM precisely predicts all Higgs boson properties for fixed  $m_H$
- ▶ Any deviations represent clear signs of new physics

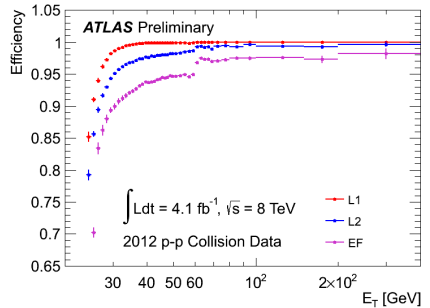
Is the Higgs boson natural?  
Only future experiments can tell.

BACKUP

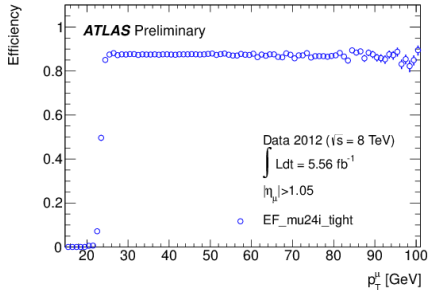


## Single lepton triggers

- ▶ Single electron trigger with  $p_T > 24 \text{ GeV}$
- ▶ Shower shapes for electron id and isolation
- ▶ Match Inner Detector track to calorimeter cluster
- ▶ Acceptance  $|\eta| < 2.5$  and efficiency 90%



- ▶ Single muon trigger with  $p_T > 24 \text{ GeV}$
- ▶ Match Muon Spectrometer track to Inner Detector track
- ▶ Trigger acceptance  $|\eta| < 2.5$
- ▶ Trigger efficiency: 90% in endcap and 70% in barrel (geometric coverage of muon trigger chambers)
- ▶ Di-muon efficiency  $> 95\%$



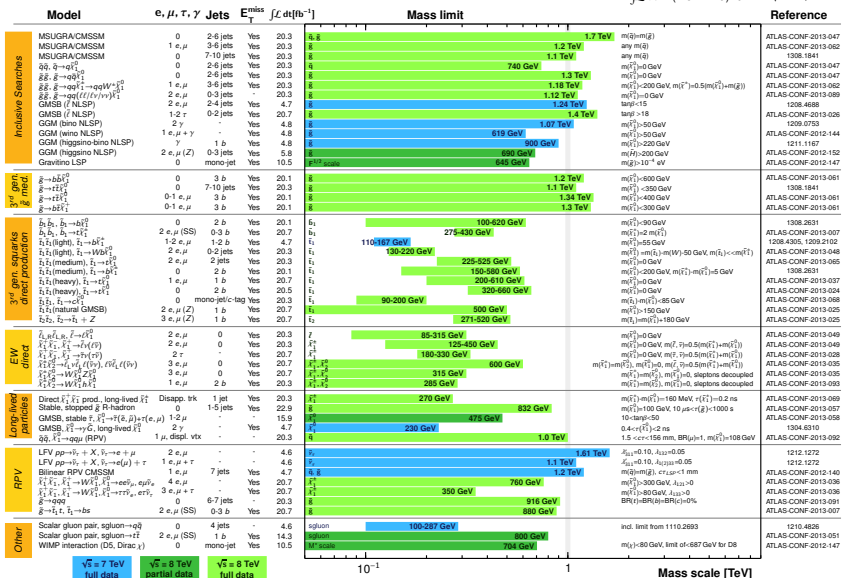
# Supersymmetry

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: SUSY 2013

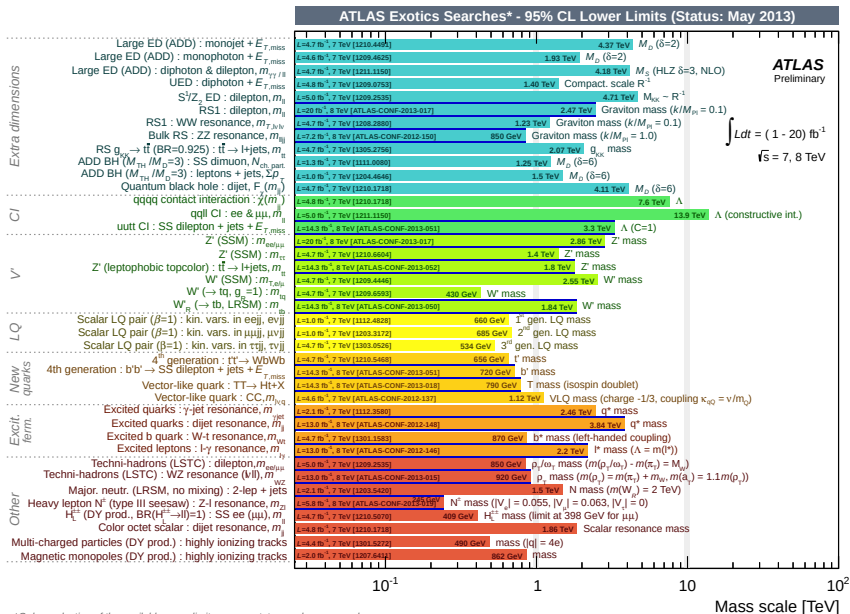
ATLAS Preliminary

$$\int \mathcal{L} dt = (4.6 - 22.9) \text{ fb}^{-1} \quad \sqrt{s} = 7, 8 \text{ TeV}$$



\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.

# Exotics

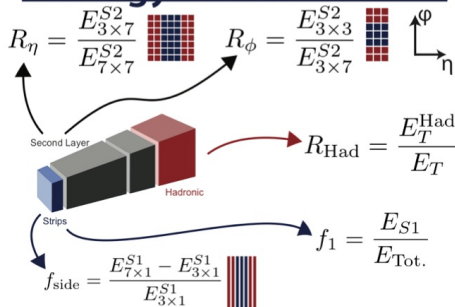


# Graphical illustration

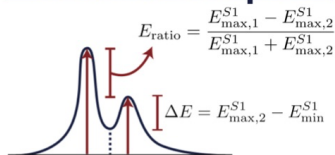
## Variables and Position

|        | Strips                       | 2nd                    | Had.                |
|--------|------------------------------|------------------------|---------------------|
| Ratios | $f_1, f_{\text{side}}$       | $R_\eta^*, R_\phi$     | $R_{\text{Had.}}^*$ |
| Widths | $w_{s,3}, w_{s,\text{tot}}$  | $w_{\eta,2}^*$         | -                   |
| Shapes | $\Delta E, E_{\text{ratio}}$ | * Used in PhotonLoose. |                     |

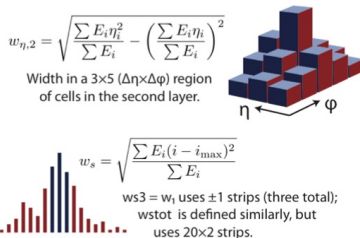
## Energy Ratios



## Shower Shapes

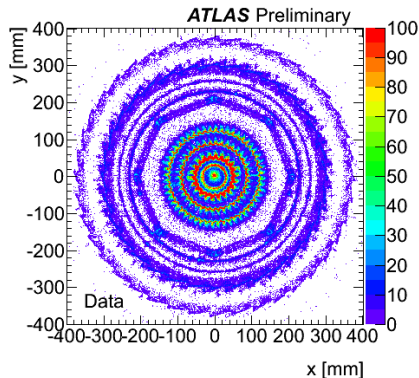
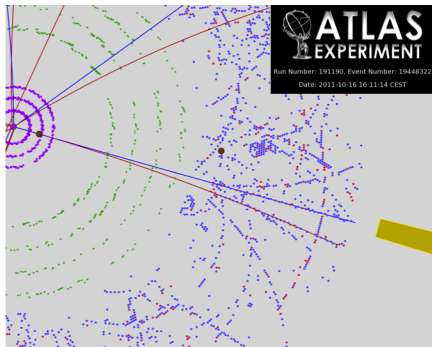


## Widths

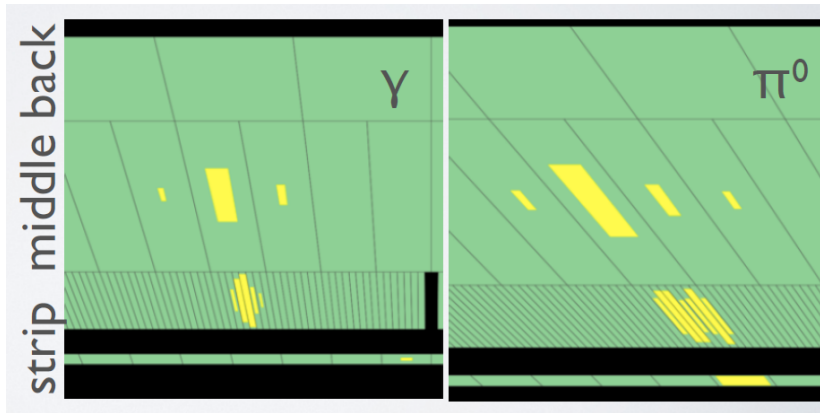


## $H \rightarrow \gamma\gamma$ : photon conversion

- ▶ Photons convert into electron and positron pairs in the tracker material
- ▶ Reconstruct as displaced Inner Detector track(s) matched to electromagnetic cluster
- ▶ Measure amount of Inner Detector material with conversion vertex density
- ▶ 52% of signal events contain at least one converted photon
- ▶ Uncertainty on event migration between converted/unconverted is 4%

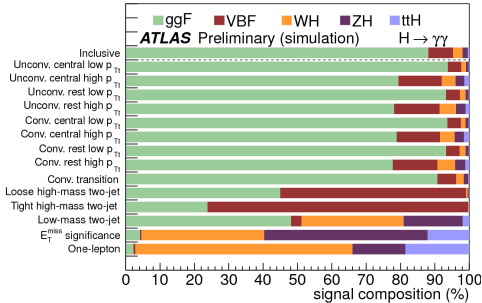


$H \rightarrow \gamma\gamma$ : photon identification



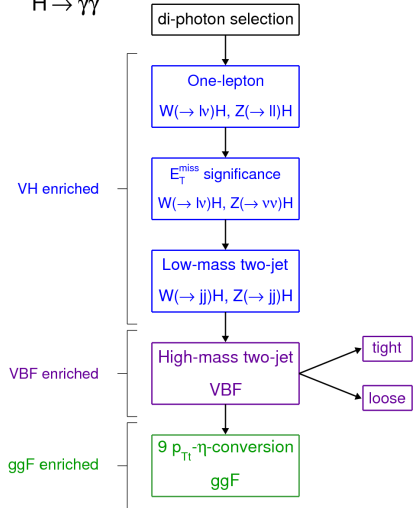
# $H \rightarrow \gamma\gamma$ : selection categories

- Categories to increase sensitivity to different production modes
- 9 resolution categories to increase ggF signal significance



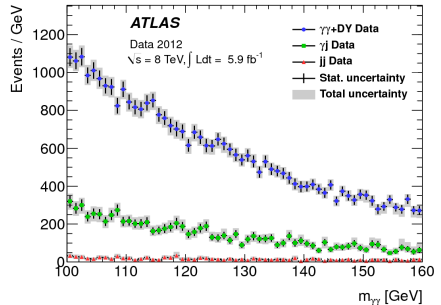
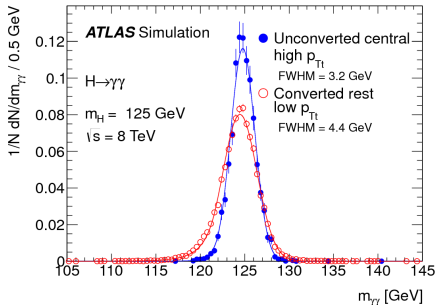
**ATLAS** Preliminary

$H \rightarrow \gamma\gamma$



## $H \rightarrow \gamma\gamma$ : analysis strategy

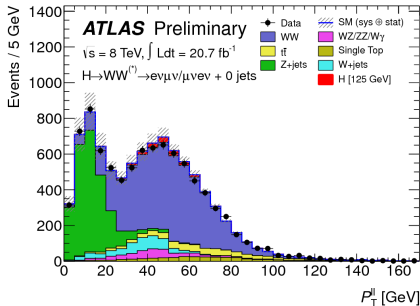
- ▶ Two isolated photons with  $p_T > 40, 30$  GeV
- ▶ Search for a narrow mass peak in di-photon mass spectrum
- ▶ Requires excellent photon energy resolution
- ▶ Multiple categories to optimize signal significance and to increase sensitivity for different production modes
- ▶ Irreducible SM backgrounds are fitted from sidebands
- ▶ Observed  $7.4\sigma$  excess (expected  $4.3\sigma$ )



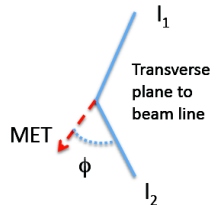


# $H \rightarrow WW \rightarrow \nu\nu/\nu\nu$ : Drell-Yan background - $(e\mu, \mu e) \otimes (0\text{-jet}, 1\text{-jet})$

- ▶  $Z/\gamma^* \rightarrow \tau\tau \rightarrow e\mu + \text{neutrinos}$
- ▶ Relative  $E_{T,miss}$
- ▶ Apply  $m_{\tau\tau}$  veto
- ▶ Boosted events  $p_{T,ll} > 30 \text{ GeV}$
- ▶ Normalize from data using events with back to back leptons



$E_{\text{rel}}^{\text{miss}} = \text{MET}$   
 If closest object  
 within  $90^\circ$ ,  
 $E_{\text{rel}}^{\text{miss}} = \text{MET} \sin \phi$



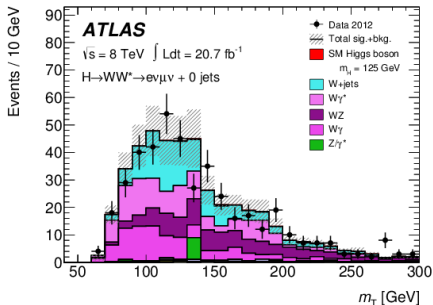
$H \rightarrow WW \rightarrow l\nu l\nu$ : W+jet, WZ, ZZ,  $W\gamma$  backgrounds

W+jet background - data driven:

- ▶ Jets reconstructed as leptons
- ▶ Suppress with tight isolation and tight lepton id
- ▶ Estimated from control regions with loosened lepton selection:
  - ▶  $\approx 50\%$  uncertainty for W+jets

$WZ/ZZ/W\gamma^{(*)}$  backgrounds are taken from MC simulation and validated with sign di-lepton events

Same sign validation region



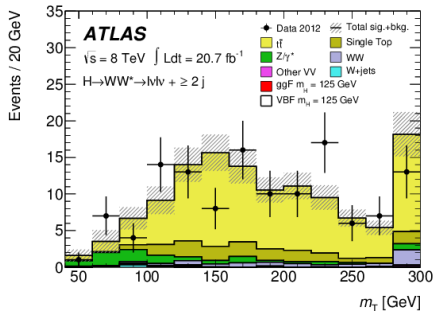
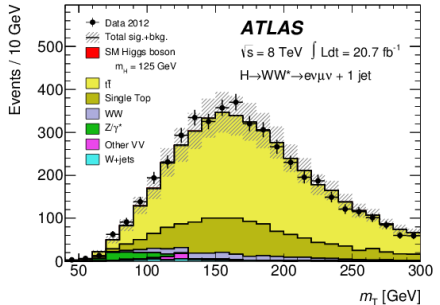
# $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ : top backgrounds

## 0-jet top background:

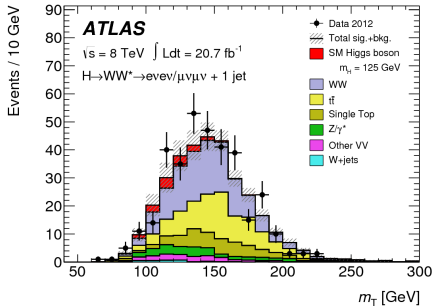
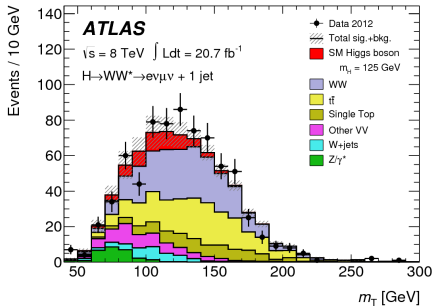
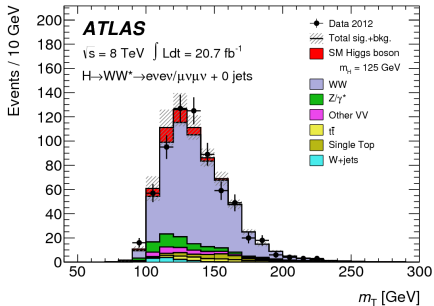
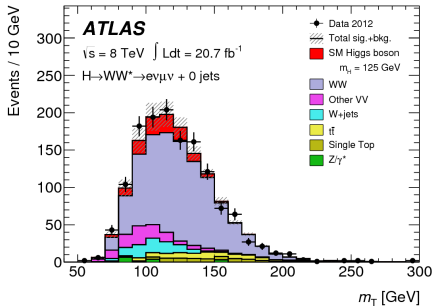
- ▶ Estimate from inclusive di-lepton sample using MC extrapolation factor with data driven corrections
- ▶  $1.07 \pm 0.03$  (stat)  $\pm 0.14$  (sys)

## 1-jet and 2-jet top backgrounds:

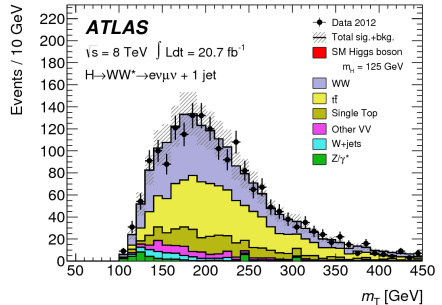
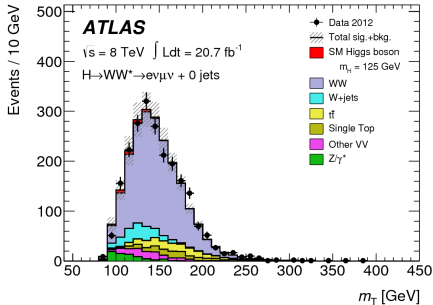
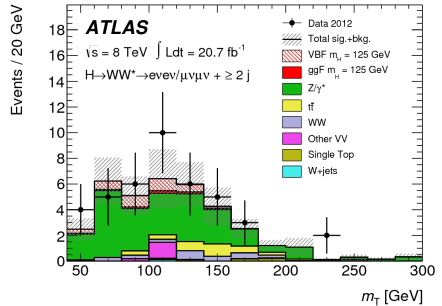
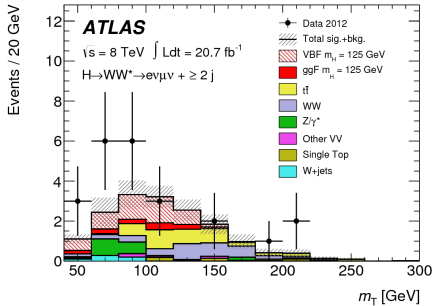
- ▶ Estimated from data control regions with b-tagged events
- ▶ 1-jet:  $1.04 \pm 0.02$  (stat)  $\pm 0.30$  (sys)
- ▶ 2-jet:  $0.59 \pm 0.07$  (stat)  $\pm 0.23$  (sys)



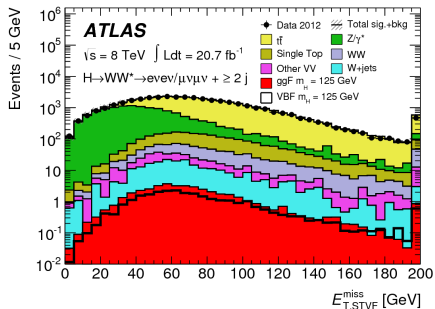
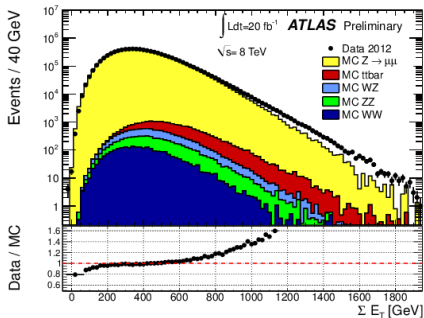
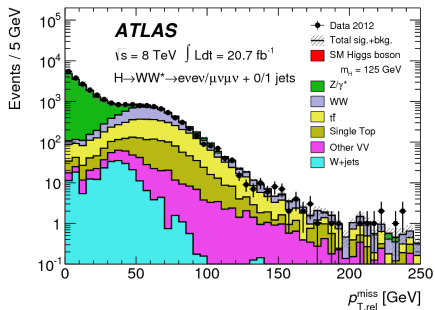
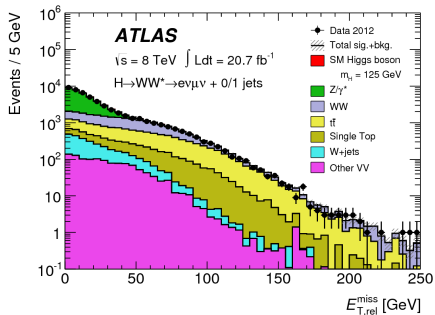
# $H \rightarrow WW \rightarrow l\nu l\nu$ : SR MT



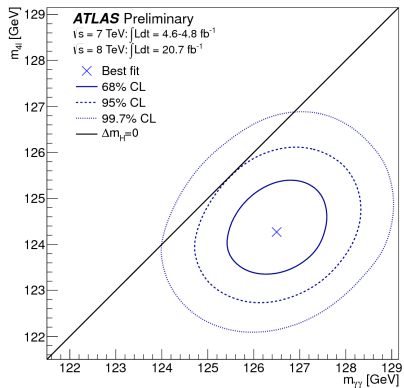
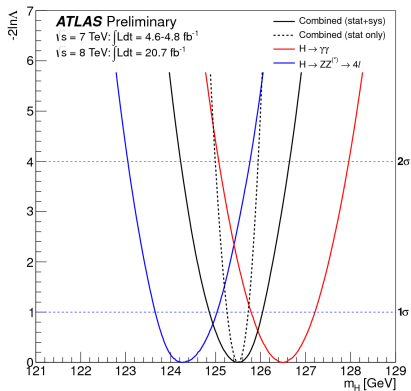
# $H \rightarrow WW \rightarrow l\nu l\nu$ : 2-jet SR and SM WW CR



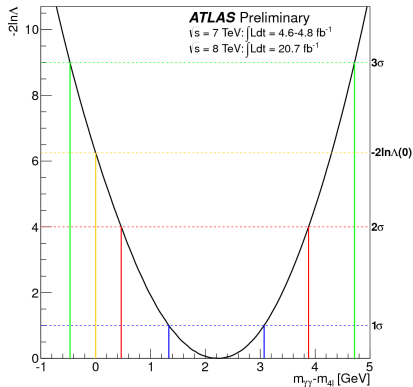
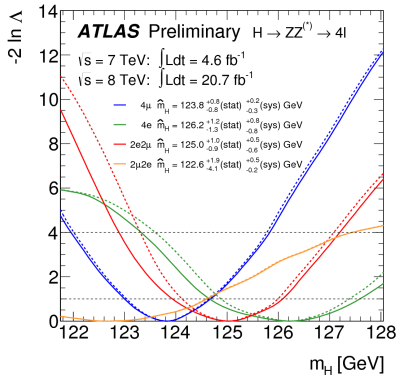
# $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ : $E_{T,miss}$ performance



# Mass measurements



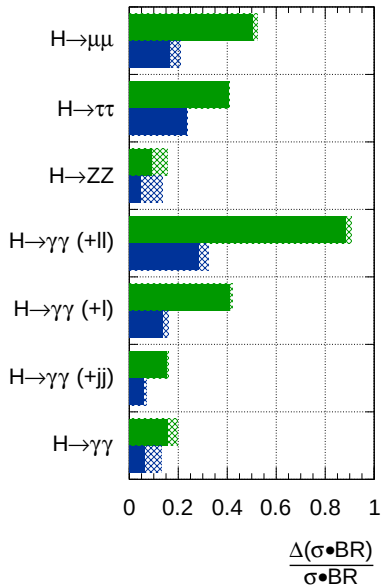
# Mass measurements





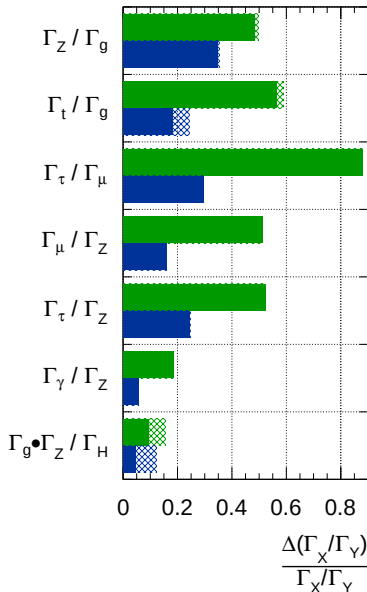
**ATLAS Preliminary (Simulation)**

$\sqrt{s} = 14$  TeV:  $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ ;  $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$

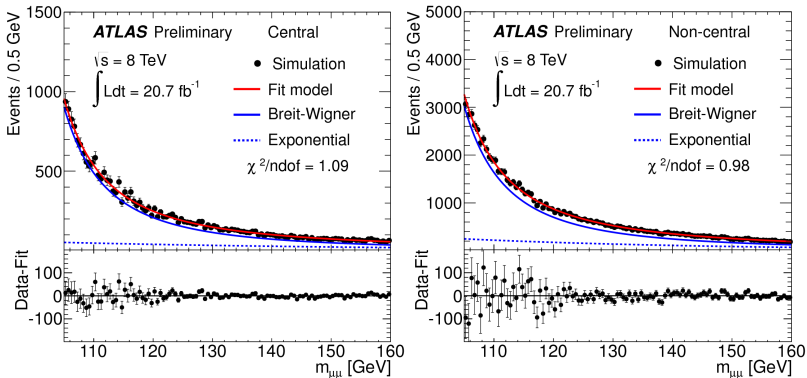


**ATLAS Preliminary (Simulation)**

$\sqrt{s} = 14$  TeV:  $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$ ;  $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



## Background model: MC signal regions



- ▶ The background model fits to the di-muon mass distribution  $m_{\mu\mu}$  for the central (left) and non-central (right) signal categories
- ▶ Shown are MC signal regions

$H \rightarrow \mu\mu$ : systematic uncertainties: acceptance and experimental

| Uncertainty     | Upward [%] | Downward [%] |
|-----------------|------------|--------------|
| Ren./Fac. Scale | 0.1        | -0.3         |
| ISR             | 1.3        | -2.5         |
| FSR             | -0.4       | 0.1          |
| PDF             | 0.2        | 0.2          |
| Total inclusive | +1.3       | -2.6         |

**Table:** Summary of the signal acceptance uncertainties due to the theory sources.

| Source of Uncertainty              | Treatment in the analysis                |
|------------------------------------|------------------------------------------|
| Luminosity                         | 3.6%                                     |
| Muon Selection Efficiency          | 0.3-1% as a function of $\eta$ and $p_T$ |
| Muon Momentum Scale and Resolution | < 1%                                     |
| Muon Trigger                       | < 1%                                     |
| Muon Track Isolation               | < 1%                                     |
| Pile-up reweighting                | < 1%                                     |

**Table:** Summary of the signal normalization uncertainties due to the experimental sources.

# $H \rightarrow \mu\mu$ : systematic uncertainties: theory

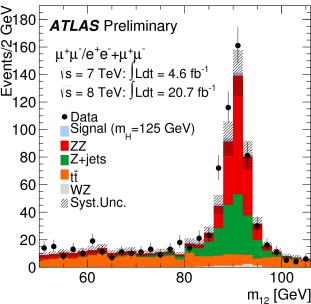
| $m_H[\text{GeV}]$ | gluon fusion        |                 |       | vector boson fusion |                 |      | BR                                |                 |      |
|-------------------|---------------------|-----------------|-------|---------------------|-----------------|------|-----------------------------------|-----------------|------|
|                   | $\sigma[\text{pb}]$ | uncertainty [%] |       | $\sigma[\text{pb}]$ | uncertainty [%] |      | $\text{BR}(H \rightarrow \mu\mu)$ | uncertainty [%] |      |
|                   |                     | up              | down  |                     | up              | down |                                   | up              | down |
| 110               | 25.04               | +15.3           | -14.9 | 1.809               | +2.7            | -3.0 | $2.76 \times 10^{-4}$             | +7.0            | -6.8 |
| 115               | 22.96               | +15.0           | -14.9 | 1.729               | +2.7            | -3.0 | $2.63 \times 10^{-4}$             | +6.7            | -6.6 |
| 120               | 21.13               | +14.8           | -14.8 | 1.649               | +2.8            | -3.0 | $2.44 \times 10^{-4}$             | +6.4            | -6.3 |
| 125               | 19.52               | +14.7           | -14.7 | 1.578               | +2.8            | -3.0 | $2.20 \times 10^{-4}$             | +6.0            | -5.9 |
| 130               | 18.07               | +14.6           | -14.6 | 1.511               | +2.8            | -2.9 | $1.90 \times 10^{-4}$             | +5.5            | -5.4 |
| 135               | 16.79               | +14.4           | -14.7 | 1.448               | +2.8            | -2.9 | $1.55 \times 10^{-4}$             | +5.0            | -4.9 |
| 140               | 15.63               | +14.3           | -14.5 | 1.389               | +2.7            | -2.9 | $1.22 \times 10^{-4}$             | +3.7            | -3.8 |
| 145               | 14.59               | +14.1           | -14.4 | 1.333               | +2.8            | -2.8 | $9.06 \times 10^{-5}$             | +3.4            | -3.4 |
| 150               | 13.65               | +14.1           | -14.4 | 1.280               | +2.8            | -2.9 | $6.19 \times 10^{-5}$             | +3.1            | -3.2 |

**Table:** SM Higgs production cross sections at 8 TeV and SM Higgs branching ratios  $\text{BR}(H \rightarrow \mu\mu)$

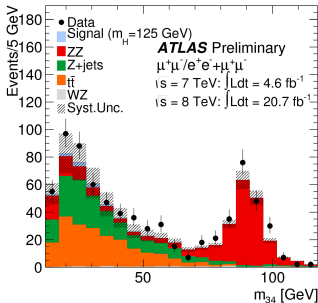
# $H \rightarrow ZZ \rightarrow 4l$ : backgrounds

- ▶ Normalize  $ZZ^{(*)}$  from simulation
- ▶ Normalize reducible backgrounds from control regions
- ▶ Z+jets background - relax/reverse lepton selections
- ▶  $t\bar{t}$  - from  $e\mu$  channel
- ▶ Lepton momentum scale and efficiency from  $Z, J/\psi$

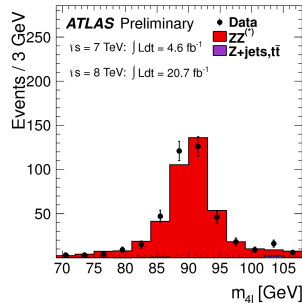
## Relax $lep_{34}$ selection



## Relax $lep_{34}$ selection



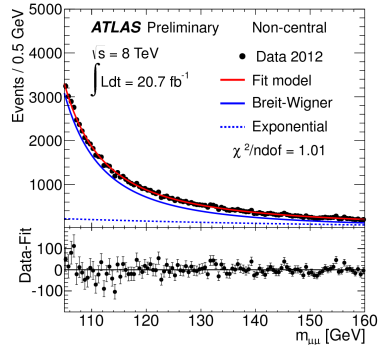
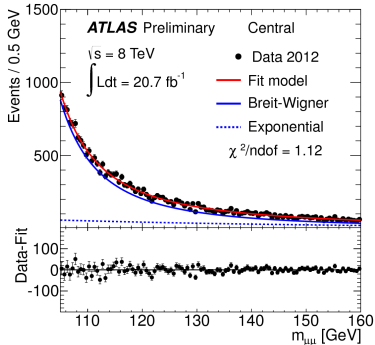
## Single resonant $Z \rightarrow 4l$



## Background model

- ▶ All backgrounds have continuous  $m_{\mu\mu}$  distribution in the search window
- ▶ Model background as a sum of Breit-Wigner (BW) and exponential pdfs:  
$$F_{BG} = f_{BW} \cdot BW(x, M_Z, \Gamma_Z) + (1 - f_{BW}) \cdot P(e^{B \cdot x})$$
- ▶  $M_Z$  and  $\Gamma_Z$  are fixed to the LEP/SLD average values
- ▶ Validated by fitting di-muon invariant mass distributions for different background MC samples and the data control regions

Measure background PDF directly from data signal regions

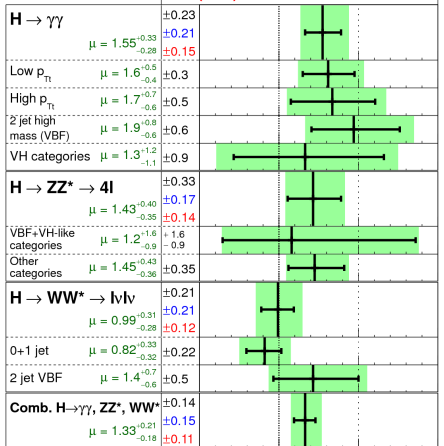


# Combined VBF results

**ATLAS**

$m_H = 125.5 \text{ GeV}$

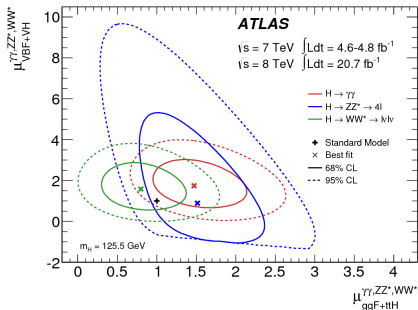
$\blacktriangle$   $\sigma(\text{stat})$   
 $\color{blue}\triangle$   $\sigma(\text{sys})$   
 $\color{red}\triangle$   $\sigma(\text{theo})$   
 Total uncertainty  
 $\color{green}\square$   $\pm 1\sigma$  on  $\mu$



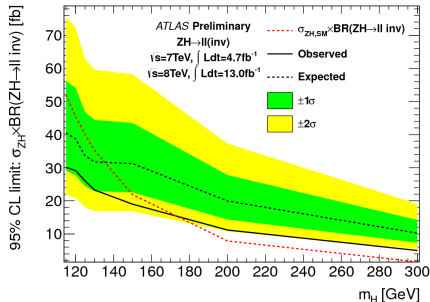
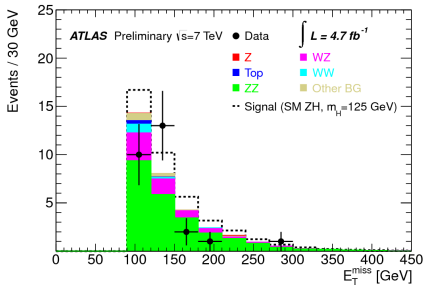
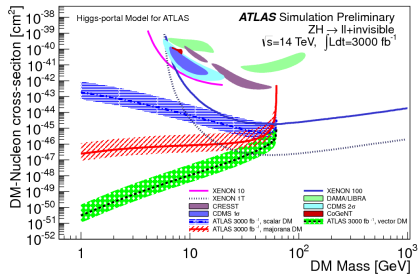
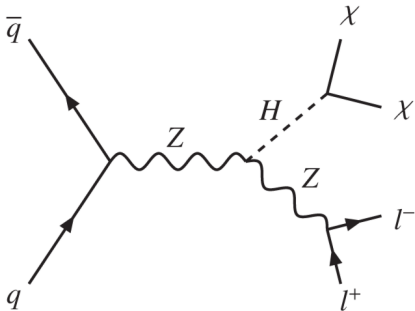
$\sqrt{s} = 7 \text{ TeV} \int \mathcal{L} dt = 4.6\text{-}4.8 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV} \int \mathcal{L} dt = 20.7 \text{ fb}^{-1}$

Signal strength ( $\mu$ )



# Higgs to invisible decays





## Event pre-selection

|                                     | $\mu\mu$       | ee             | $e\mu$         | $3\ell$         | $4\ell$         |
|-------------------------------------|----------------|----------------|----------------|-----------------|-----------------|
| $t\bar{t}H, H \rightarrow WW$       | $2.0 \pm 0.3$  | $0.9 \pm 0.1$  | $2.7 \pm 0.4$  | $3.2 \pm 0.6$   | $0.28 \pm 0.05$ |
| $t\bar{t}H, H \rightarrow ZZ$       | $0.1 \pm 0.0$  | $0.0 \pm 0.0$  | $0.1 \pm 0.0$  | $0.2 \pm 0.0$   | $0.09 \pm 0.02$ |
| $t\bar{t}H, H \rightarrow \tau\tau$ | $0.6 \pm 0.1$  | $0.3 \pm 0.0$  | $0.9 \pm 0.1$  | $1.0 \pm 0.2$   | $0.15 \pm 0.02$ |
| $t\bar{t}W$                         | $8.2 \pm 1.5$  | $3.4 \pm 0.6$  | $13.0 \pm 2.2$ | $9.2 \pm 1.9$   | -               |
| $t\bar{t}Z/\gamma^*$                | $2.5 \pm 0.5$  | $1.6 \pm 0.3$  | $4.2 \pm 0.9$  | $7.9 \pm 1.7$   | $1.25 \pm 0.88$ |
| $t\bar{t}WW$                        | $0.2 \pm 0.0$  | $0.1 \pm 0.0$  | $0.3 \pm 0.1$  | $0.4 \pm 0.1$   | $0.04 \pm 0.02$ |
| $t\bar{t}\gamma$                    | -              | $1.3 \pm 0.3$  | $1.9 \pm 0.5$  | $2.9 \pm 0.8$   | -               |
| WZ                                  | $0.8 \pm 0.9$  | $0.5 \pm 0.5$  | $1.2 \pm 1.3$  | $4.2 \pm 0.9$   | -               |
| ZZ                                  | $0.1 \pm 0.1$  | $0.0 \pm 0.0$  | $0.1 \pm 0.1$  | $0.4 \pm 0.1$   | $0.45 \pm 0.09$ |
| rare SM bkg.                        | $1.1 \pm 0.0$  | $0.4 \pm 0.0$  | $1.5 \pm 0.0$  | $0.8 \pm 0.0$   | $0.01 \pm 0.00$ |
| non-prompt                          | $10.8 \pm 4.8$ | $8.9 \pm 4.5$  | $21.2 \pm 8.1$ | $33.2 \pm 12.3$ | $0.53 \pm 0.32$ |
| charge flip                         | -              | $1.9 \pm 0.6$  | $2.4 \pm 0.8$  | -               | -               |
| all signals                         | $2.7 \pm 0.4$  | $1.2 \pm 0.2$  | $3.7 \pm 0.6$  | $4.4 \pm 0.8$   | $0.52 \pm 0.09$ |
| all backgrounds                     | $23.7 \pm 5.2$ | $18.0 \pm 4.7$ | $45.9 \pm 8.6$ | $58.9 \pm 12.7$ | $2.28 \pm 0.94$ |
| data                                | 41             | 19             | 51             | 68              | 1               |

Table 1: Expected and observed yields after the selection in all five final states. The rare SM backgrounds include triboson production,  $t\bar{t}Z$ ,  $W^\pm W^\pm qq$ , and  $WW$  produced in double-parton interactions. A '-' indicates a negligible yield. Non-prompt and charge-flip backgrounds are described in Sec. 8.

# $t\bar{t}H \rightarrow \text{leptons} - \text{jet multiplicity and background composition}$

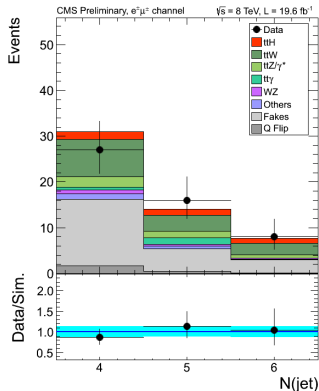
## $t\bar{t}W/Z$

- ▶  $\approx 10 - 20\%$  theory uncertainty
- ▶ Measure with control regions

## $t\bar{t} + \text{jets}$

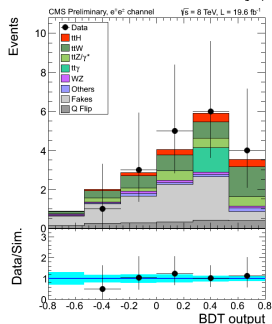
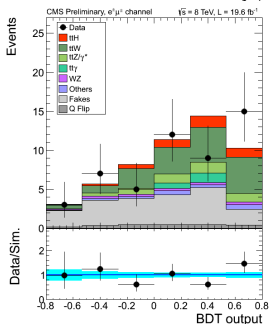
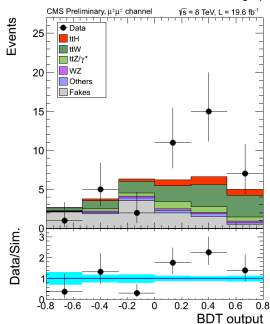
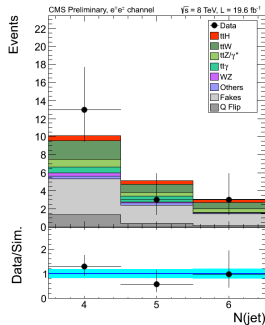
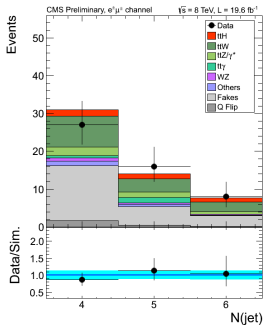
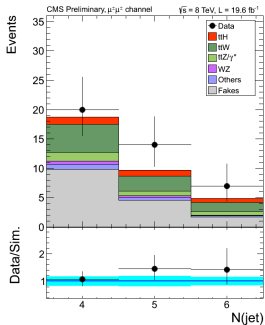
- ▶ Dominant background
- ▶ Jets mis-identified as leptons
- ▶ Suppressed with lepton id and isolation
- ▶ CMS:  $t\bar{t} + \text{jets}$  uncertainty  $\gtrsim 2 \times$  signal

## CMS HIG-13-020

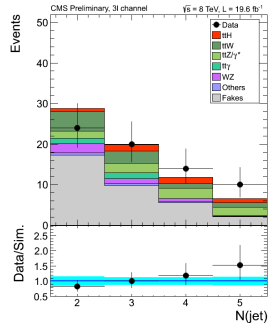
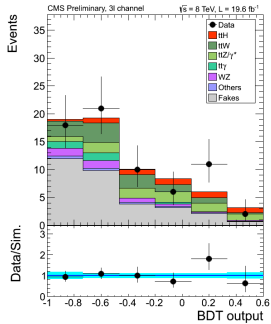
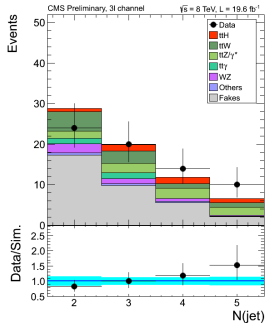


|     | $\sigma$ 8 TeV [fb] | $\sigma$ 14 TeV [fb] | Ratio |
|-----|---------------------|----------------------|-------|
| ttH | 130                 | 611                  | 4.7   |
| ttW | 232                 | 769                  | 3.3   |
| tt  | $2.5 \times 10^5$   | $9.8 \times 10^5$    | 3.9   |

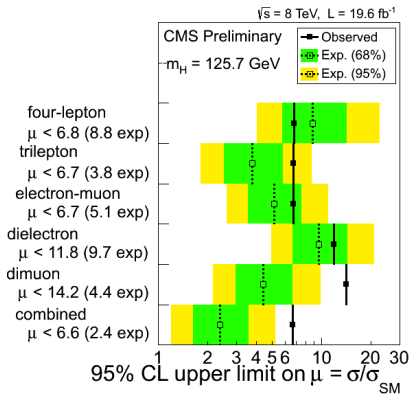
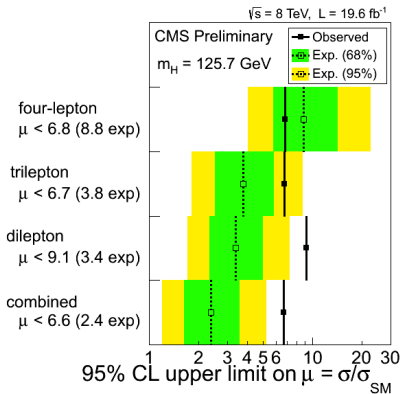
## 2 same sign leptons



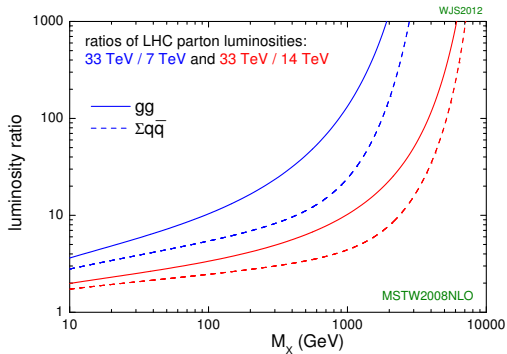
## 3 and 4 leptons



# Results



# Higgs physics reach



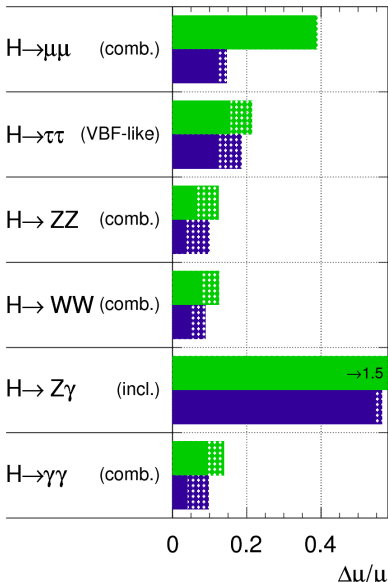
|                      | $\sigma(14\text{TeV})/\sigma(8\text{TeV})$ |   |
|----------------------|--------------------------------------------|---|
| $gg \rightarrow H$   | 2.6 ( $M_X = M_H$ )                        | ● |
| $qq \rightarrow qqH$ | 2.6 (probes high $M_X$ )                   | ● |
| $qq \rightarrow VH$  | 2.1 ( $M_X = M_V + M_H$ )                  | ● |
| $gg \rightarrow ttH$ | 4.7 (phase space + $M_X$ )                 | ● |

# Higgs physics at a High Luminosity LHC with ATLAS

**ATLAS** Simulation Preliminary

$\sqrt{s} = 14$  TeV:  $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$  ;  $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$

- ▶  $\sim 5\%$  statistical uncertainty on  
 $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ \rightarrow 4l$  and  
 $H \rightarrow WW$
- ▶ Improvement in theory uncertainties  
will be necessary
- ▶ With  $300 \text{ fb}^{-1}$  spin/CP quantum  
numbers of non-mixed states can be  
measured at  $5\sigma$  level



# Theory uncertainty on BR

**Table 1-4.** *Uncertainties on  $M_H = 126$  GeV Standard Model branching ratios arising from the parametric uncertainties on  $\alpha_s$ ,  $m_b$ , and  $m_c$  and from theory uncertainties [16, 17].*

| Decay                        | Theory Uncertainty | Parametric Uncertainty | Total Uncertainty<br>on Branching Ratios | Central Value        |
|------------------------------|--------------------|------------------------|------------------------------------------|----------------------|
|                              | (%)                | (%)                    | (%)                                      |                      |
| $H \rightarrow \gamma\gamma$ | $\pm 2.7$          | $\pm 2.2$              | $\pm 4.9$                                | $2.3 \times 10^{-3}$ |
| $H \rightarrow b\bar{b}$     | $\pm 1.5$          | $\pm 1.9$              | $\pm 3.4$                                | $5.6 \times 10^{-1}$ |
| $H \rightarrow c\bar{c}$     | $\pm 3.5$          | $\pm 8.7$              | $\pm 12.2$                               | $2.8 \times 10^{-2}$ |
| $H \rightarrow gg$           | $\pm 4.3$          | $\pm 5.8$              | $\pm 10.1$                               | $8.5 \times 10^{-2}$ |
| $H \rightarrow \tau^+\tau^-$ | $\pm 3.5$          | $\pm 2.1$              | $\pm 5.6$                                | $6.2 \times 10^{-2}$ |
| $H \rightarrow WW^*$         | $\pm 2.0$          | $\pm 2.1$              | $\pm 4.1$                                | $2.3 \times 10^{-1}$ |
| $H \rightarrow ZZ^*$         | $\pm 2.1$          | $\pm 2.1$              | $\pm 4.2$                                | $2.9 \times 10^{-2}$ |
| $H \rightarrow Z\gamma$      | $\pm 6.8$          | $\pm 2.2$              | $\pm 9.0$                                | $1.6 \times 10^{-3}$ |
| $H \rightarrow \mu^+\mu^-$   | $\pm 3.7$          | $\pm 2.2$              | $\pm 5.9$                                | $2.1 \times 10^{-4}$ |