# SM and BSM Higgs results from the ATLAS experiment

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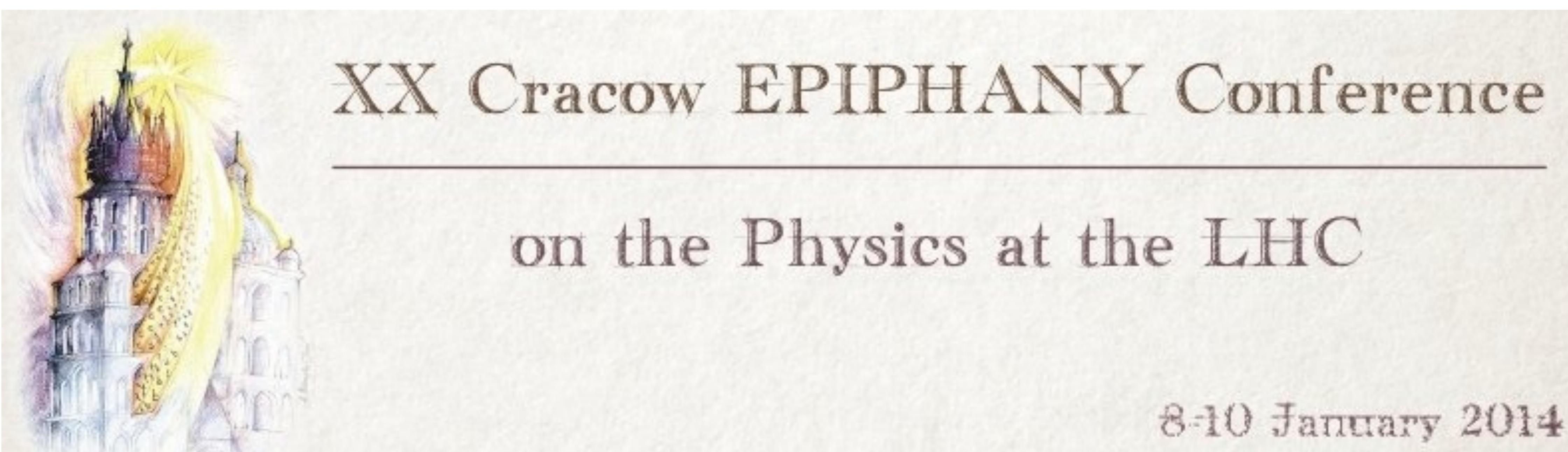
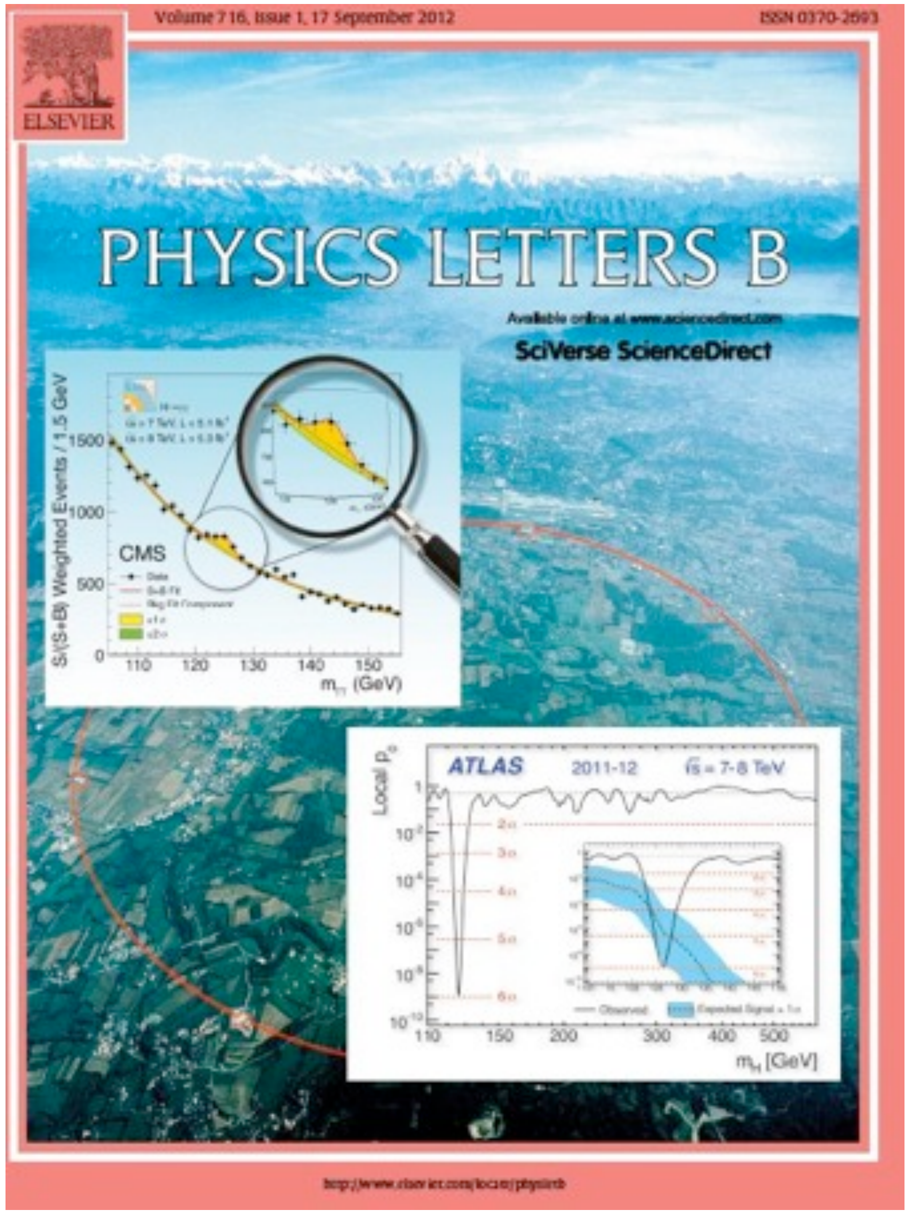
On behalf of the ATLAS collaboration



# Introduction: Higgs discovery




After the discovery, an important question to answer:

**– Is this particle the SM Higgs boson, responsible for the EW symmetry breaking mechanism?**

This talk will review the recent results on Higgs searches (SM and BSM) and properties measurements of this new particle.


ATLAS and CMS experiments announced the discovery of a new boson at LHC on 4 July 2012

# Outline

1. Observation/evidence of a Higgs boson

   $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ\rightarrow 4l$, $H\rightarrow WW\rightarrow l\nu l\nu$

   $H\rightarrow\tau\tau$ NEW!

2. Properties measurements:

   Mass, signal strength and couplings

   Spin and parity

   - Differential cross section in the $H\rightarrow\gamma\gamma$ channel

3. Other Higgs boson searches

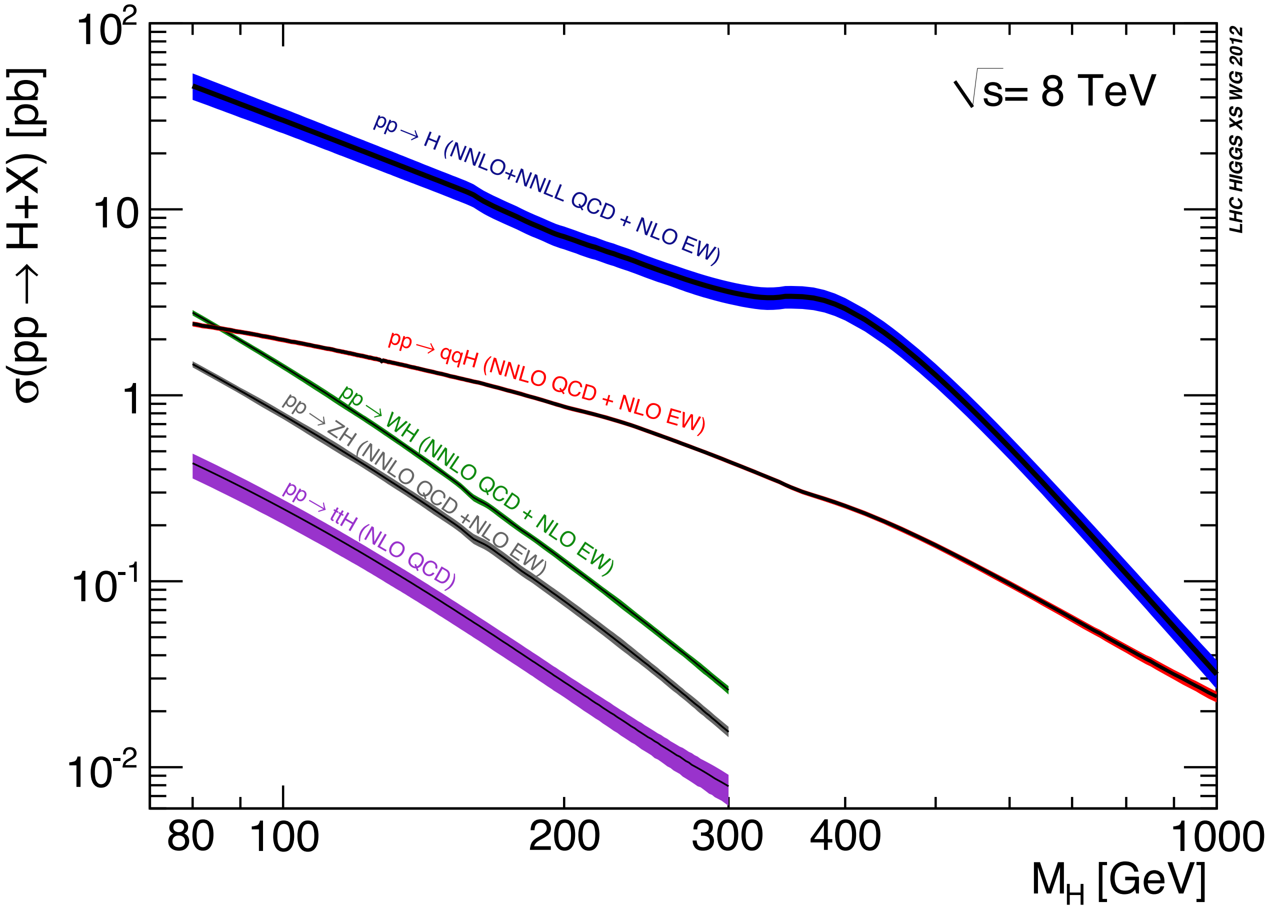
   - $H\rightarrow bb$ & Rare decays

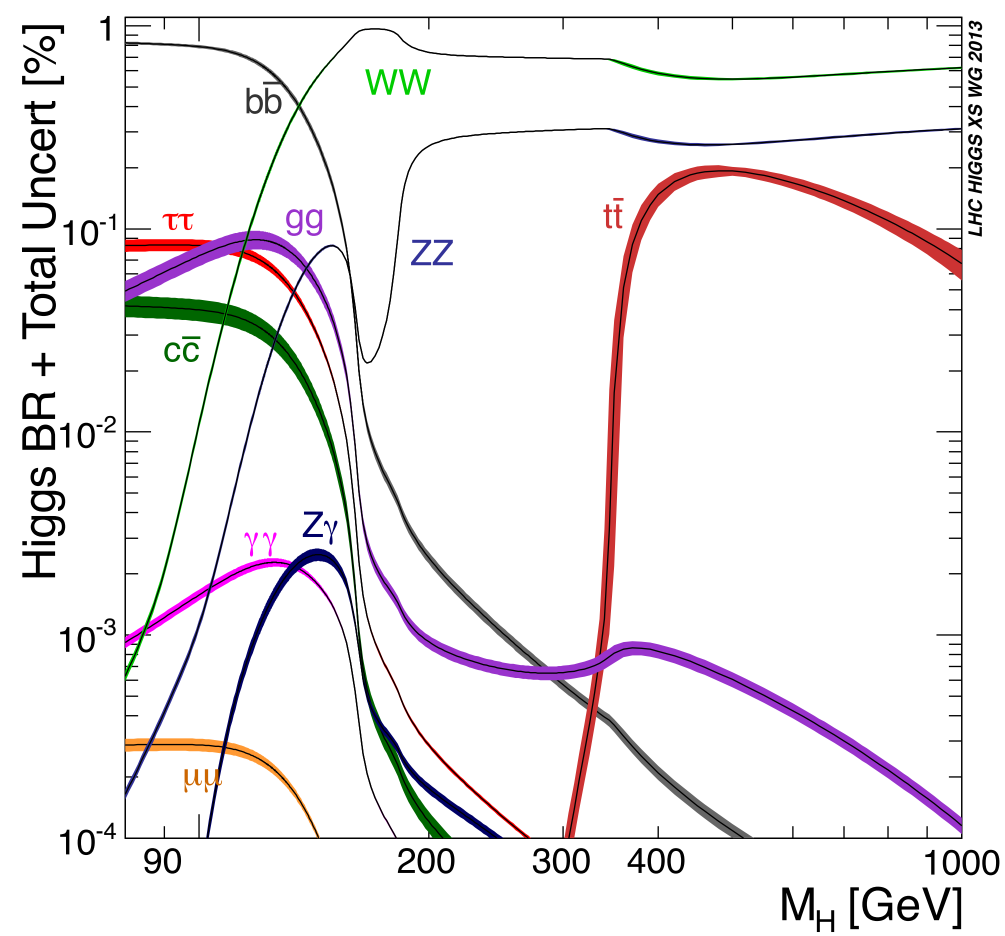
   - Recent BSM Higgs searches

4. Summary

Note: Most results presented in this talk use the complete dataset of the fist LHC run.

# The Higgs at the LHC


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

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

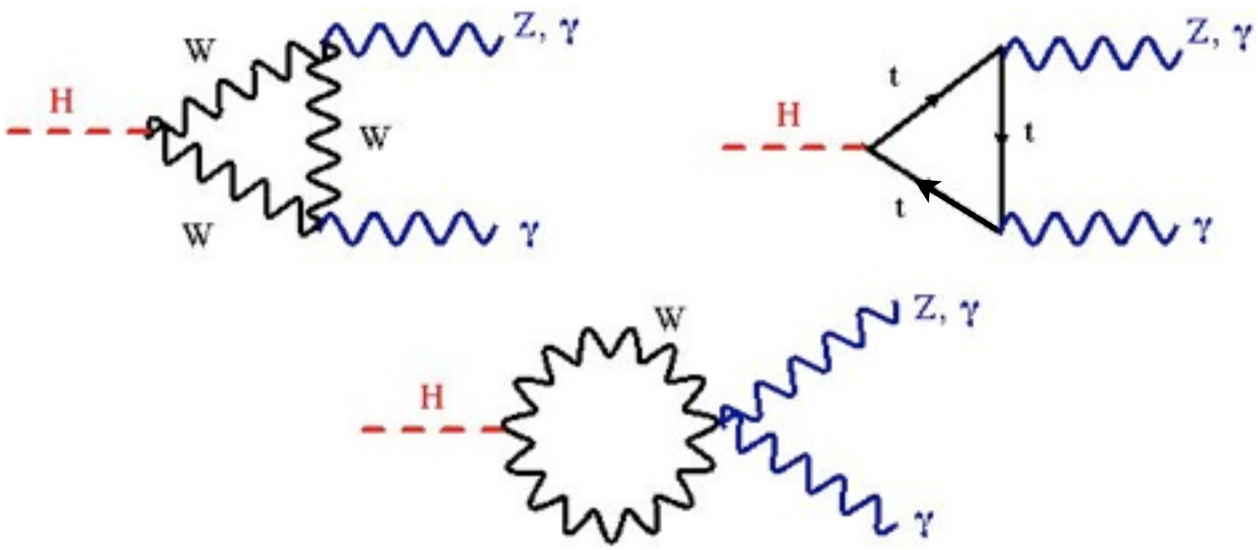
**BR [%] for $m_H$ = 125.5 GeV**

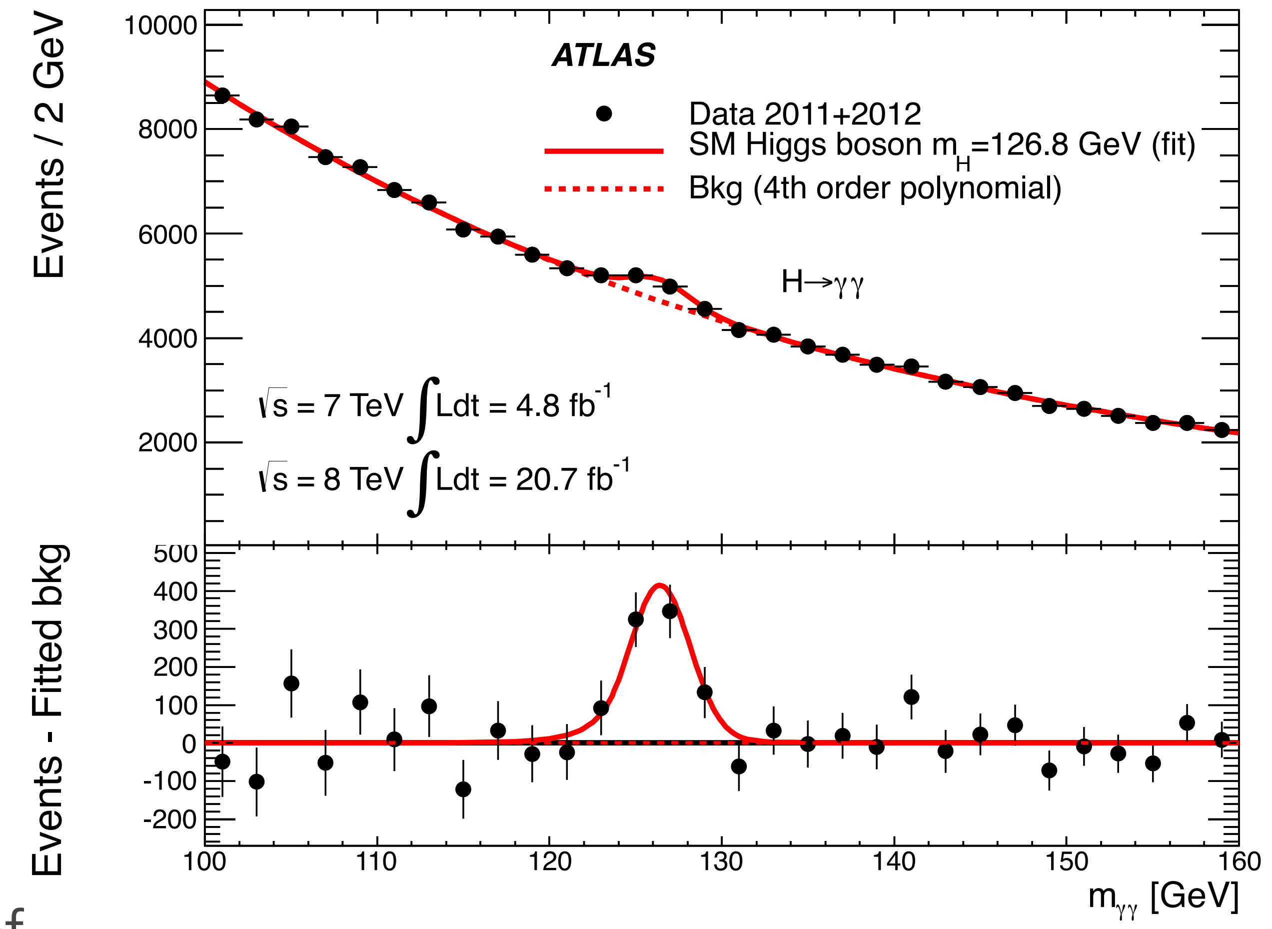
| $bb$ | $ww$ | $\tau\tau$ | $Zz$ | $\gamma\gamma$ | $Z\gamma$ | $\mu\mu$ |
|---|---|---|---|---|---|---|
| 57 | 22 | 6.2 | 2.8 | 0.23 | 0.16 | 0.02 |

# Higgs observation channels

# H→γγ channel

- Decay due to W and top loops: Sensitive to vector boson and top couplings both in production and decay; sensitive to BSM physics




- Despite low BR (0.2%), H→γγ was one of the most promising for channels of Higgs search in the low mass range: clean signature (good mass resolution) to discriminate QCD backgrounds.

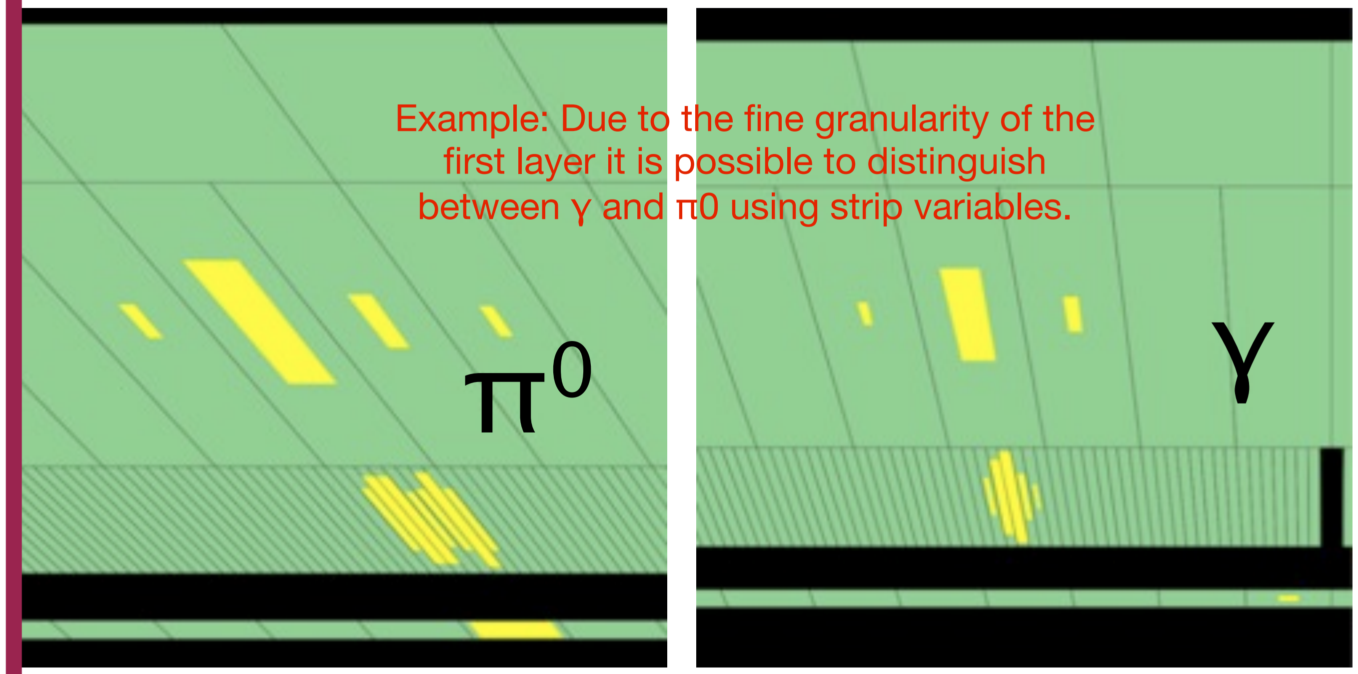
Backgrounds: 75% irreducible γγ QCD background, 25% reducible γj, jj background

# H→γγ channel

**Selection**: 2 tightly identified isolated photons, Pt > 40 / 30 GeV, $|\eta| < 1.37$ or $1.56 < |\eta| < 2.37$

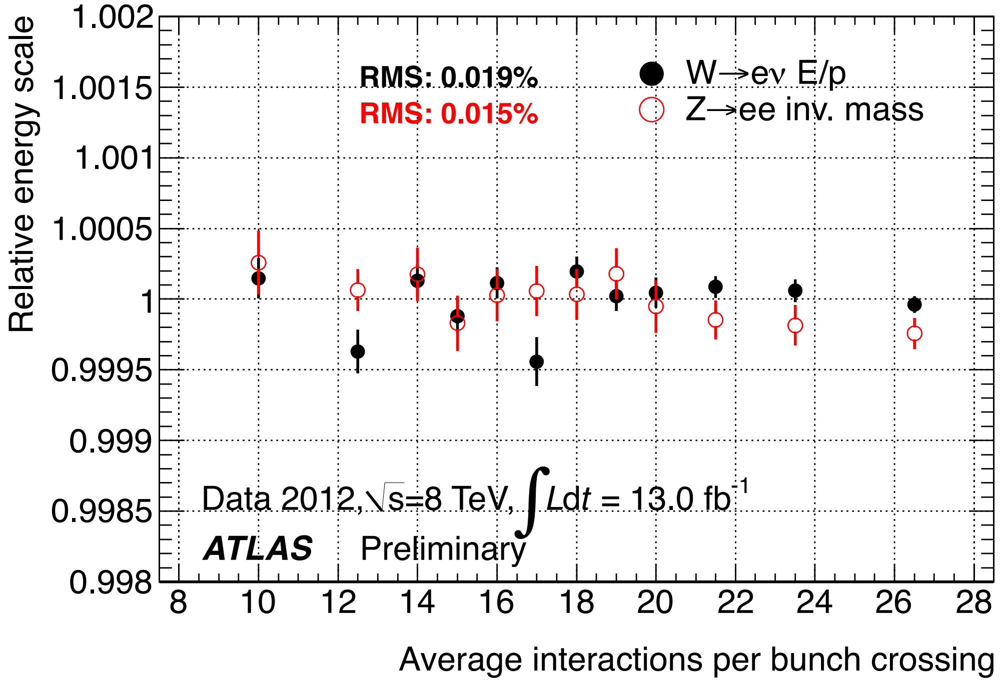
**Photon identification:**

Cuts on shower shape variables to discriminate isolated photons from QCD jets.




**Photon energy reconstruction:**

Validated with Z->ee and corrected with MC for e-γ translation effects.

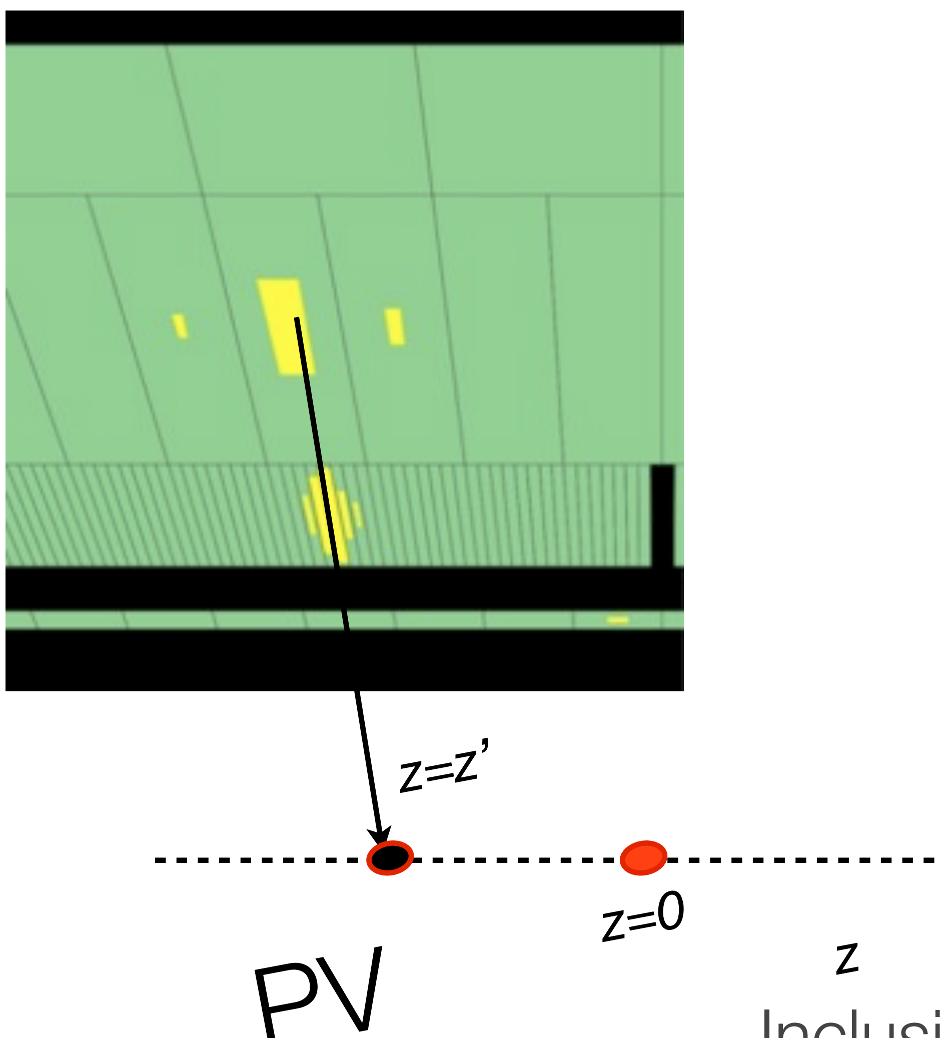


# H→γγ: Invariant mass reconstruction

- Evaluated from the following expression:

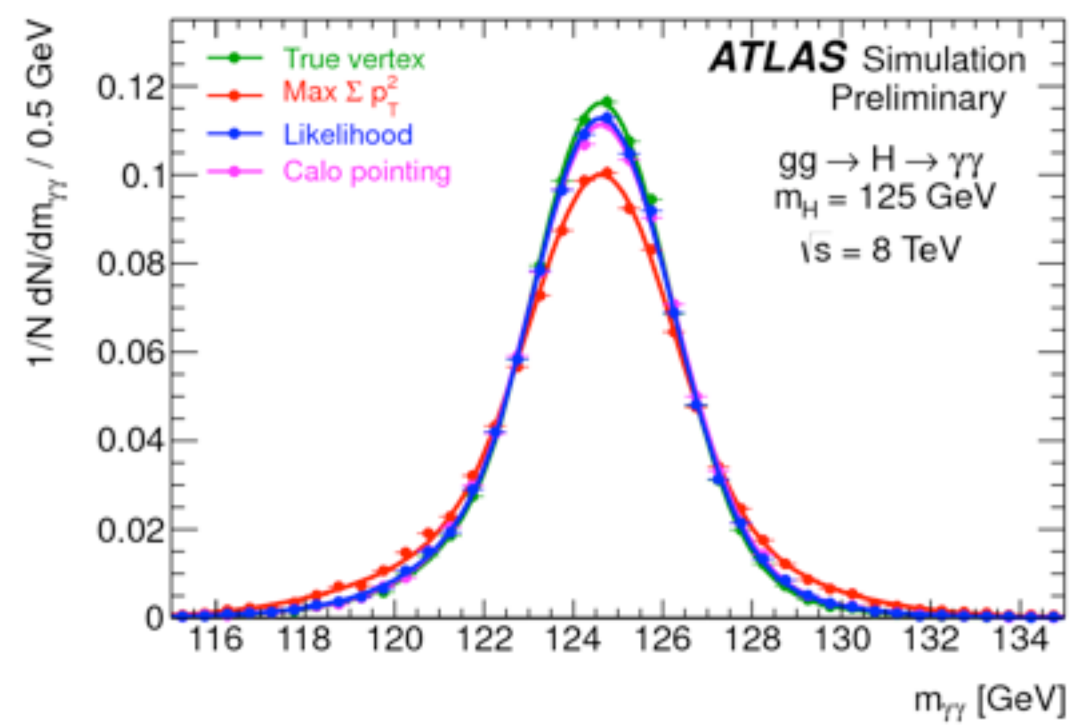
$$M_{\gamma\gamma} = \sqrt{2E_{\mathrm{T}}^{1}E_{\mathrm{T}}^{2}\left[\cosh(\eta_1-\eta_2)-\cos(\phi_1-\phi_2)\right]},$$

Photon pseudo-rapidity **η** has to be corrected by the primary vertex (PV).




The PV is identified by building a likelihood, which includes:

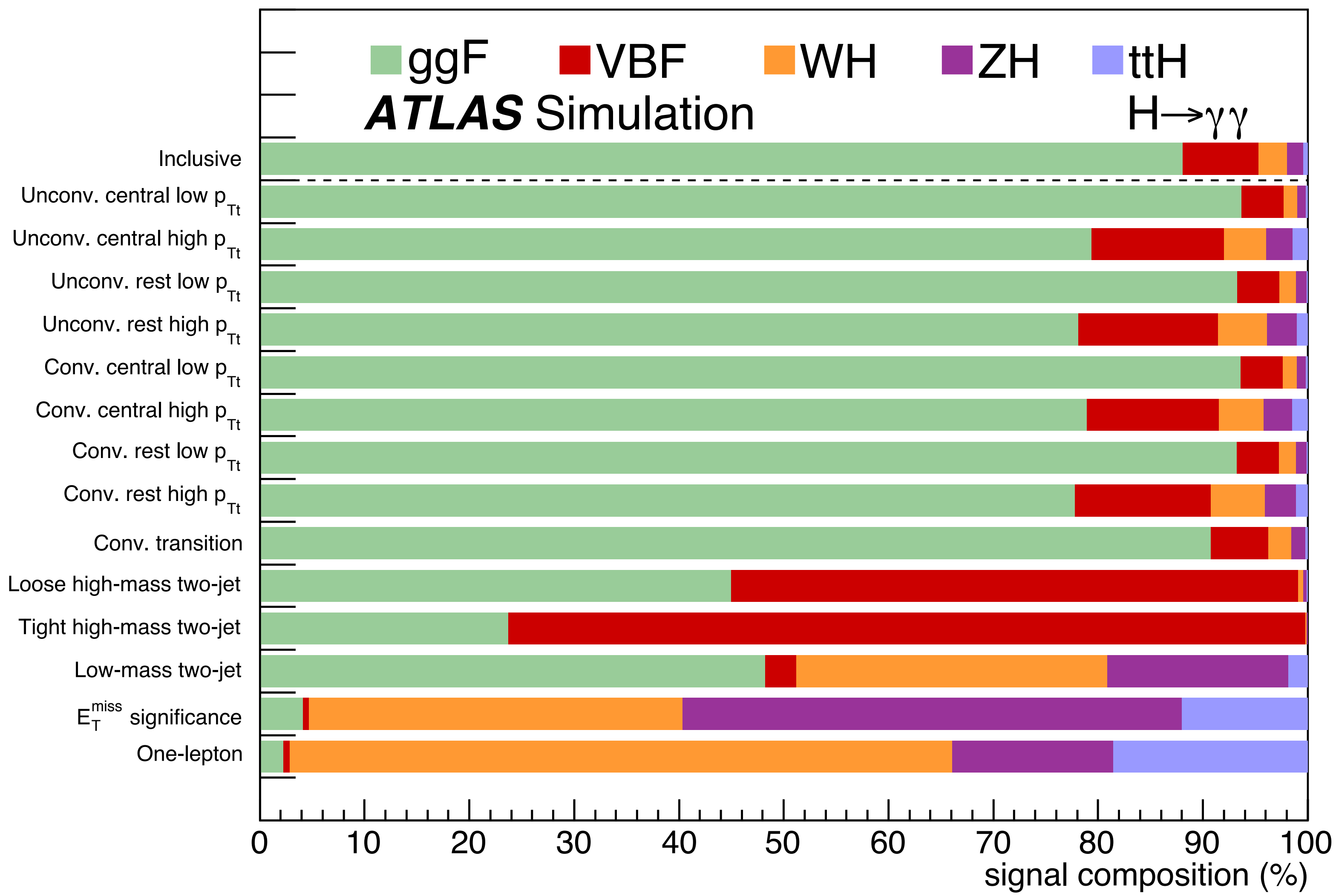
- Flight direction of the photons (using calo-pointing technique).
- Average beam spot position
- Sum of $|pT|^2$ of the tracks associated to the PV

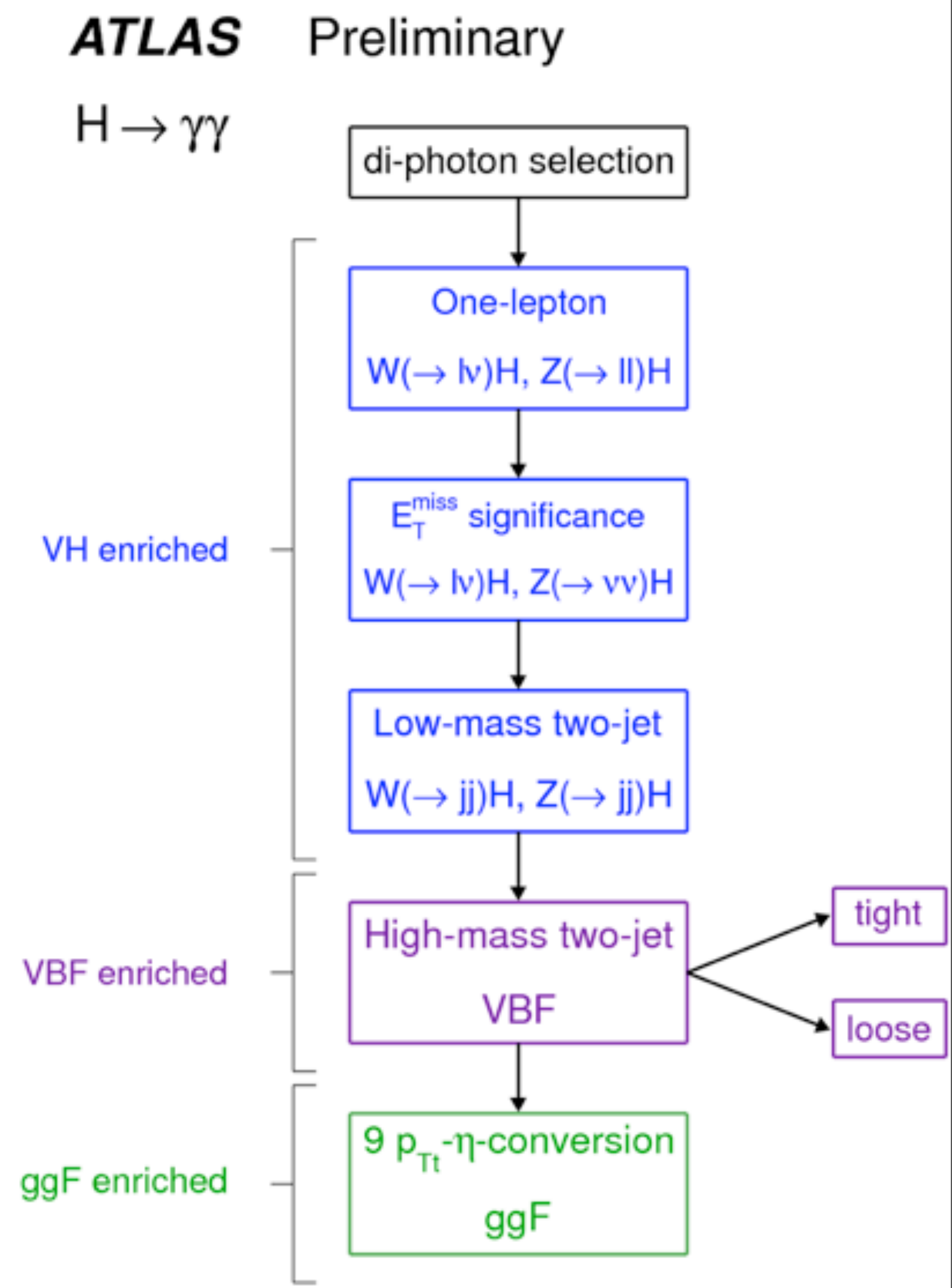



Inclusive mass resolution ~1.8 GeV.

# H→γγ: Categories

Perform the analysis of the data classifying the events in 14 categories exploiting process signature (VH, VBF or ggF enriched) and differences in mass resolutions.

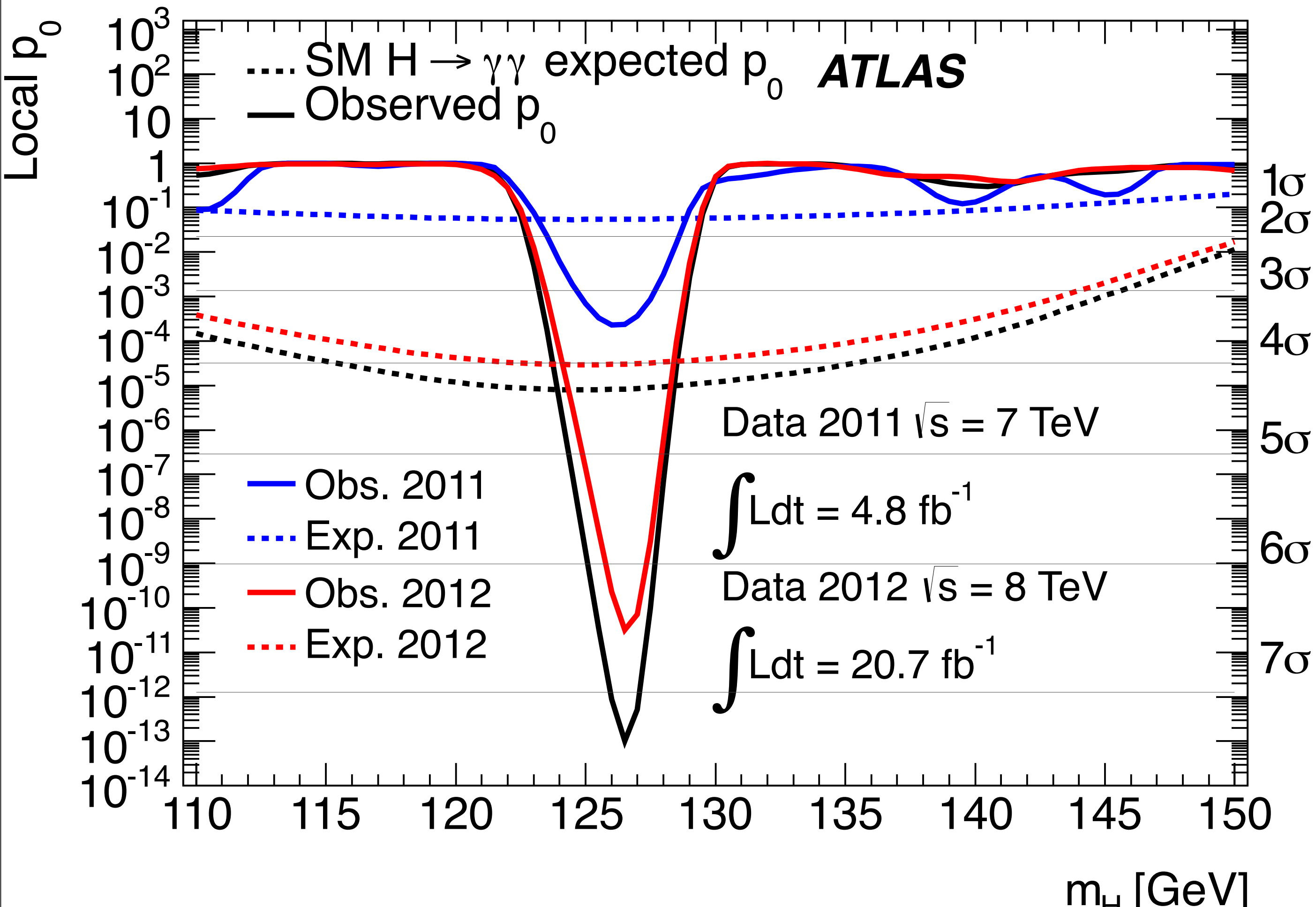


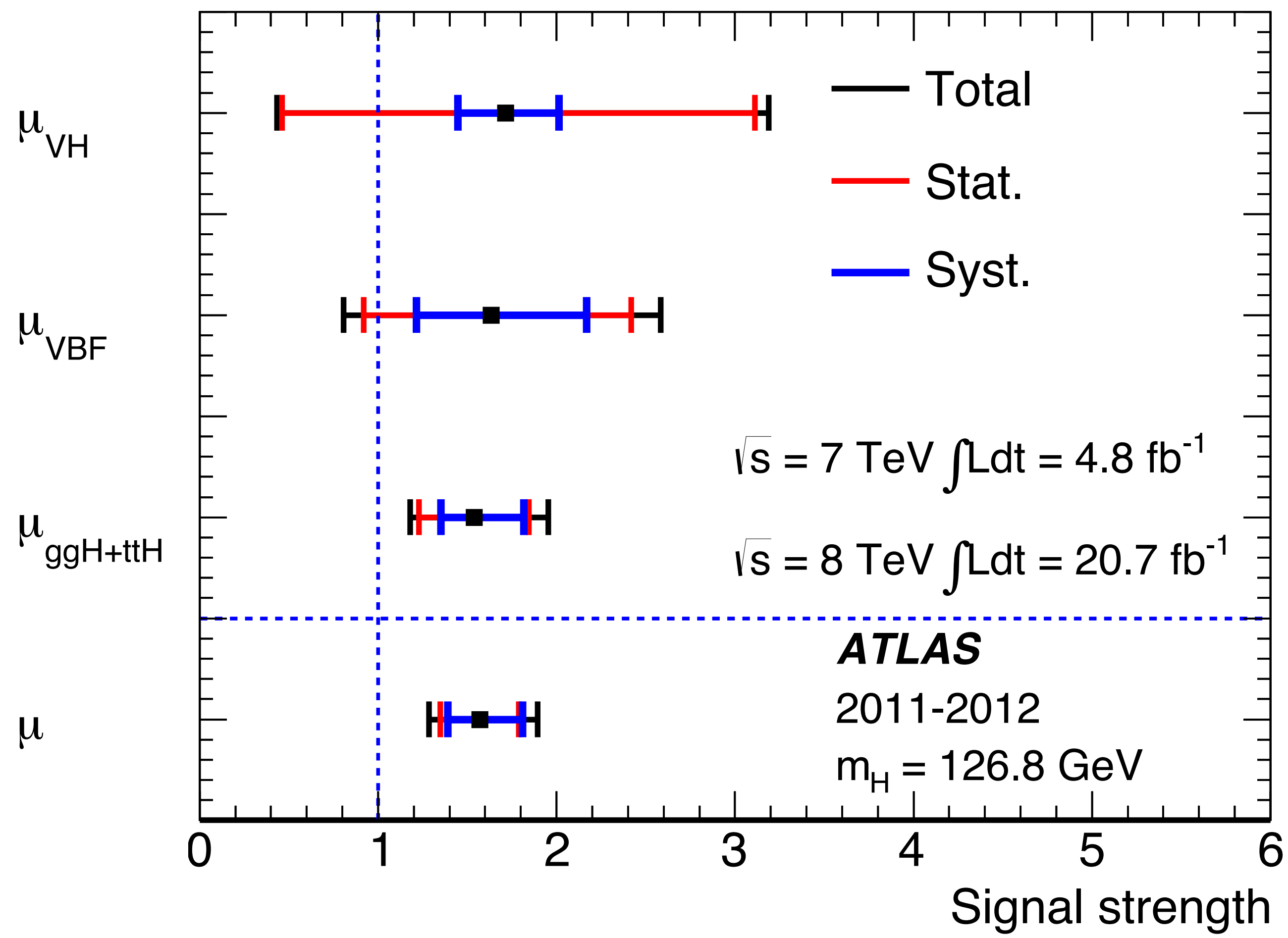



# H→γγ: Results

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

**Discovery-level signal only in this channel!**

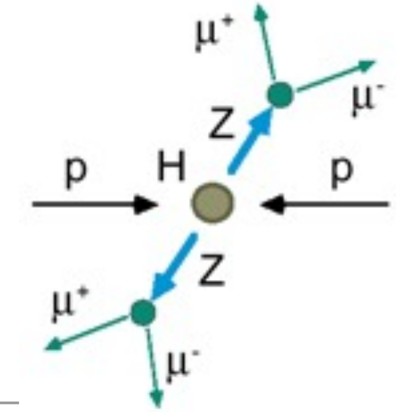



Obs. (Exp.) 7.4**σ** (4.3**σ**) @ $m_H$=126.5 GeV

Signal strength @ $m_H$ = 126.6 GeV:
$\mu$ = 1.55 ± 0.23(stat) ± 0.15 (sys) ± 0.15 (th)

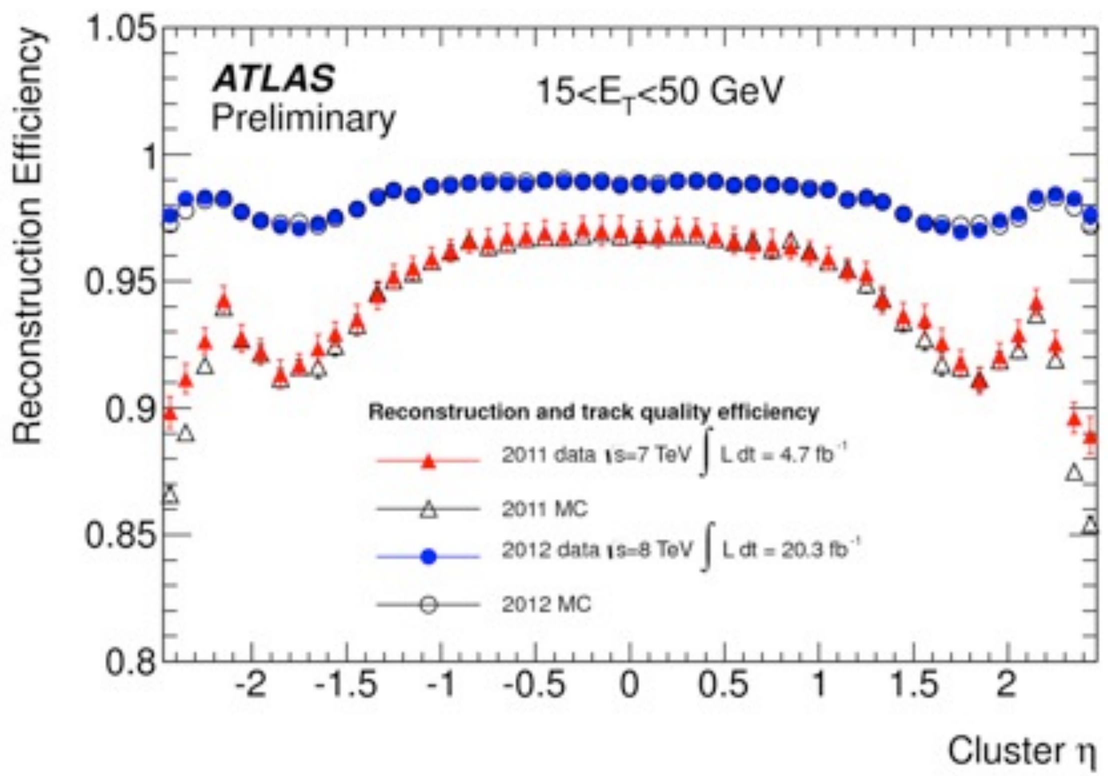
# H→ZZ→4l channel




- Events can be fully reconstructed with high efficiency and purity
- Signal/background ratio ~ 1
- However: low σ*BR

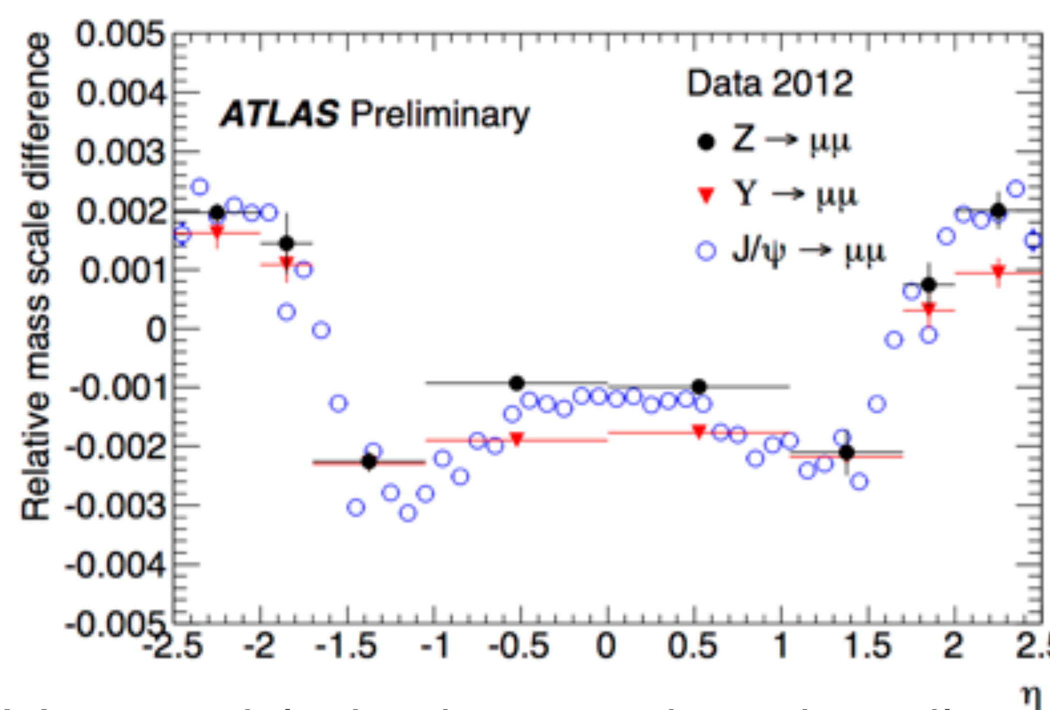
**Efficiencies:**

- Electrons: Significant improvements of the reconstruction efficiency for the 2012 dataset.



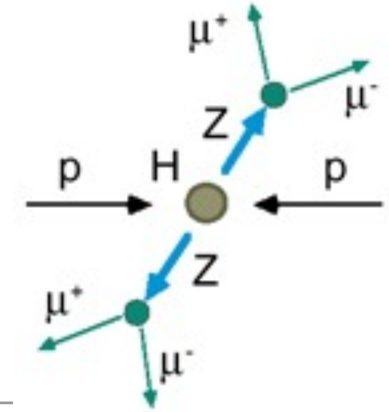

**Energy/momentum scale:**

- Muons: Different input objects (Z/W/Upsilon/J/Psi) give comparable results.




-Very stable in time and under pile-up both for Electrons (shown for H→γγ) and Muons.

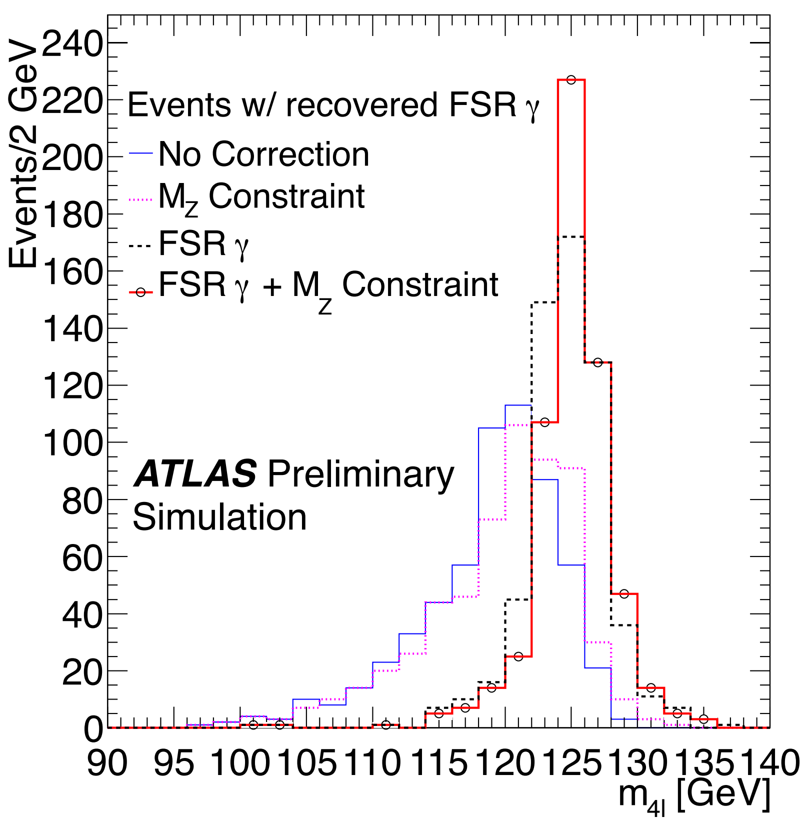
# H→ZZ→4l: Improvement in the invariant mass

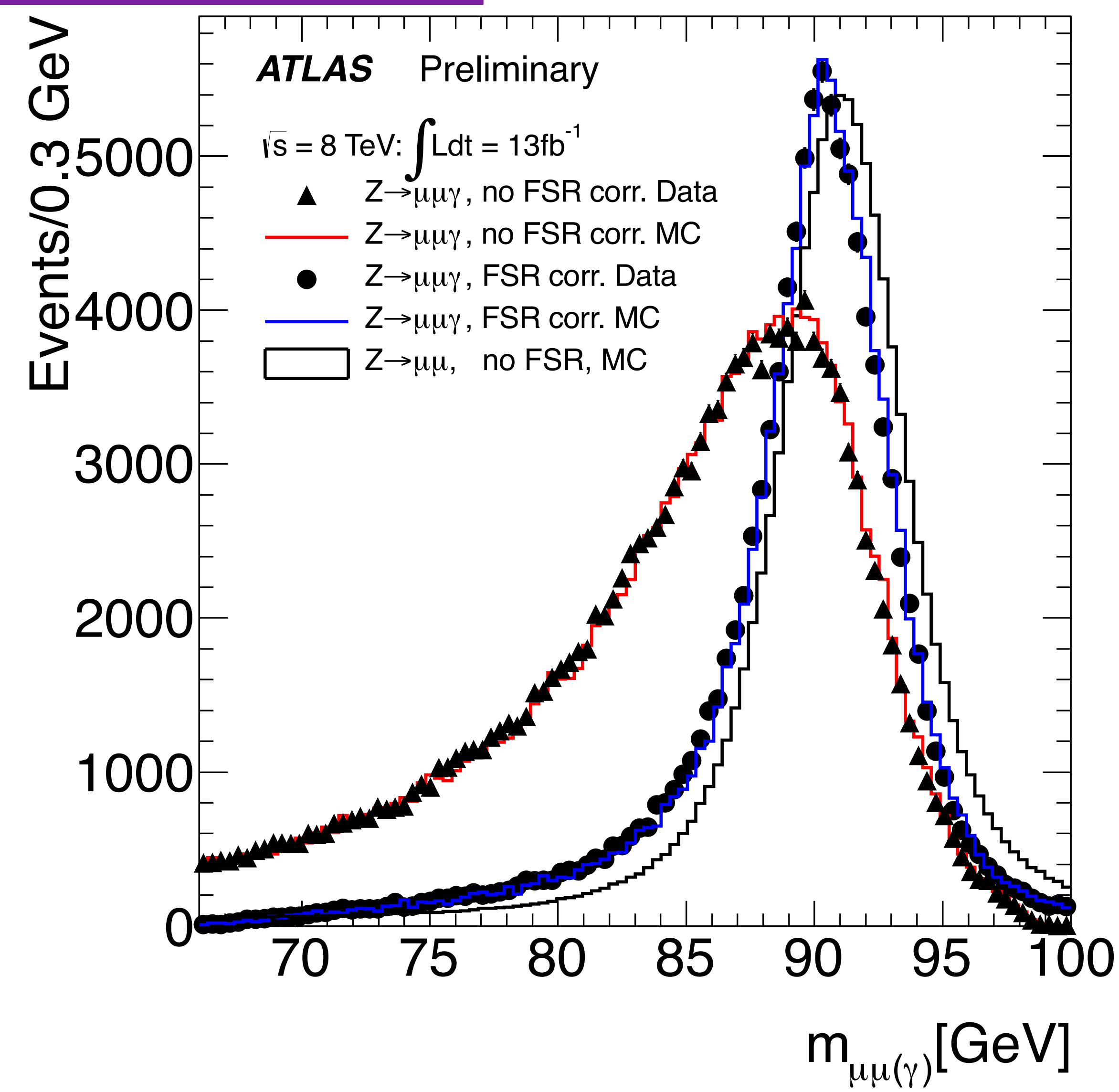



Search for 4 leptons (e,μ): 4e, 2e2μ, 4μ

Improvement in the invariant mass:

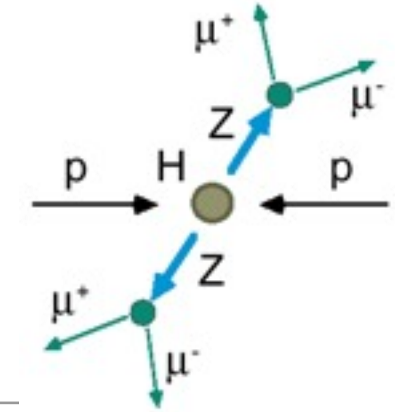
- FSR correction to muon momentum
  Photons with ET > 1 GeV
  and $\Delta R_{cluster,\,\mu} < 0.15$
  Affects 4% of the events




- Z-mass constraint on the leading di-lepton (highest pT, opposite sign, same flavour), 15% of improvement in the mass resolution

# H→ZZ→4l:



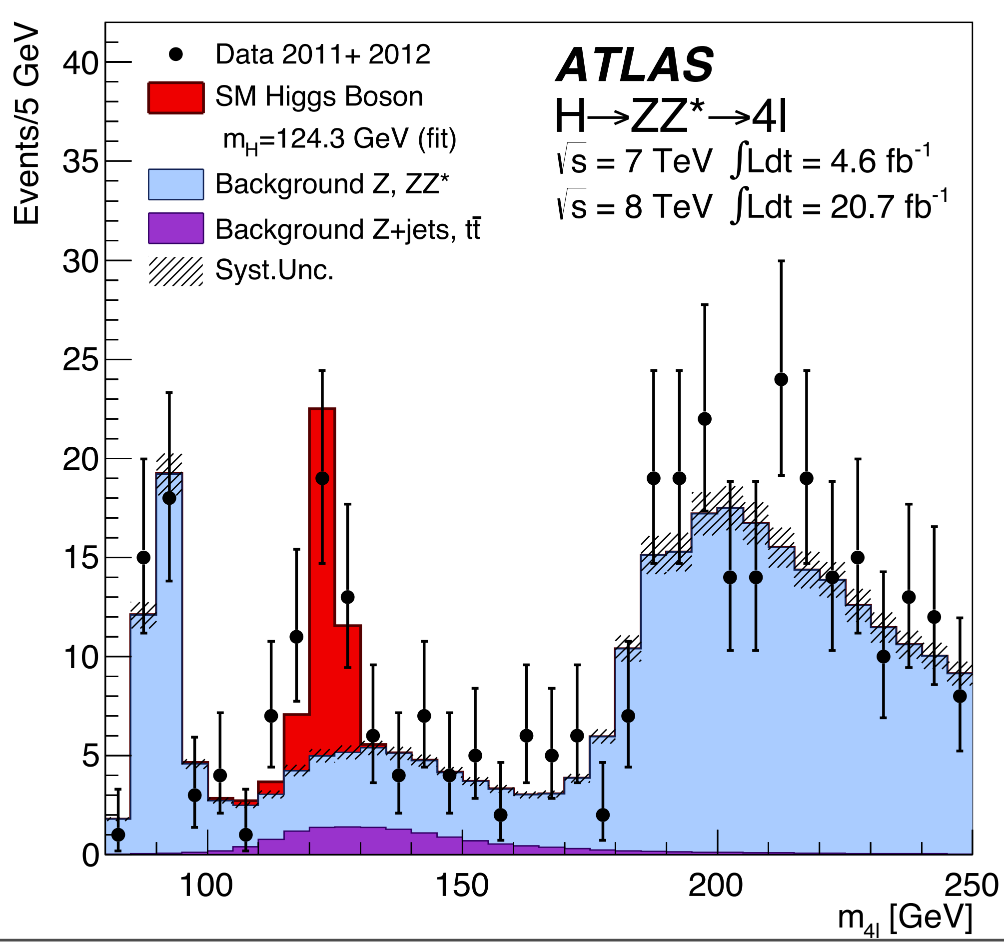

**Backgrounds:**

**Main irreducible background:**

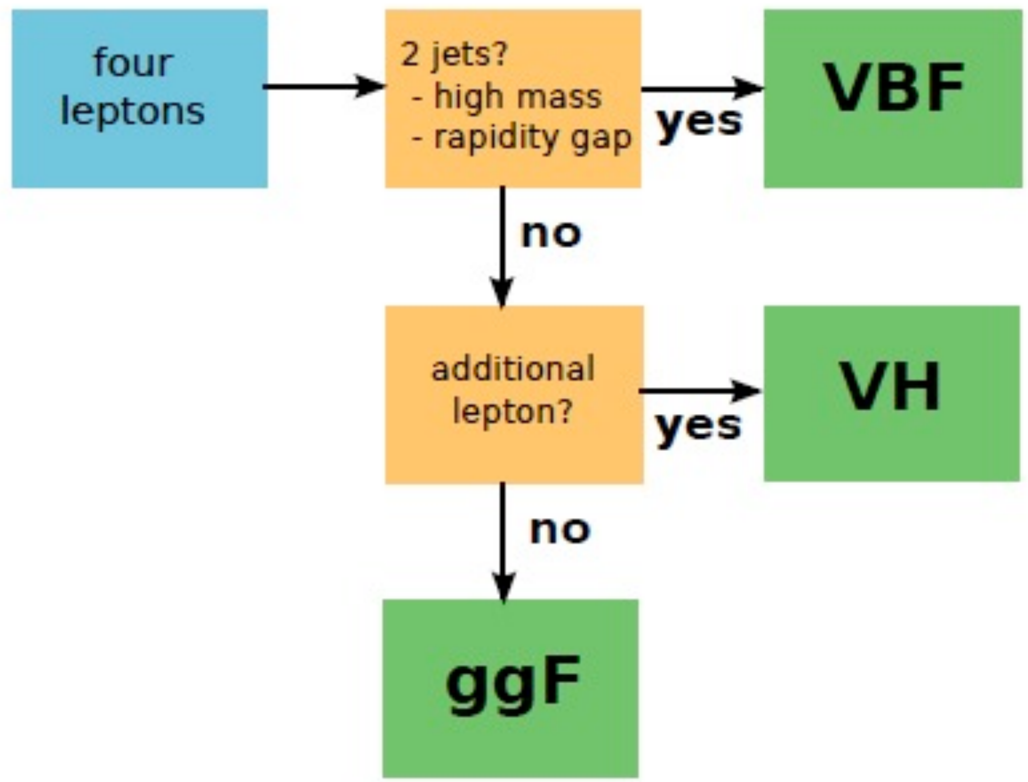
ZZ*, estimated from MC

**Reducible background:**

Z + jets, ttbar, data-driven methods, transfer factors to extrapolate from control regions to the signal regions from MC and cross-checked with data.




## Event Categorisation:




Expected number of signal events in each category +ZZ background events.

| category | $gg \to H, q\bar{q}/gg \to t\bar{t}H$ | $qq' \to Hqq'$ | $q\bar{q} \to W/ZH$ | $ZZ^{(*)}$ |
|---|---|---|---|---|
| | | $\sqrt{s} = 8$ TeV | | |
| ggF-like | 13.5 | 0.79 | 0.65 | 320.4 |
| VBF-like | 0.28 | 0.43 | 0.01 | 3.58 |
| VH-like | 0.06 | - | 0.14 | 0.69 |

# H→ZZ→4l: Results

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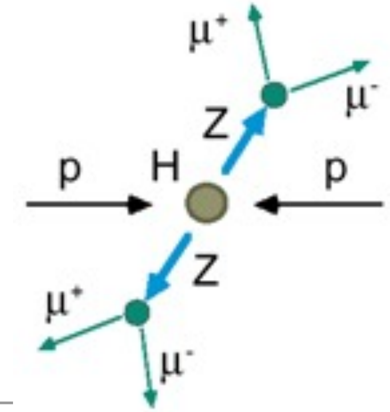
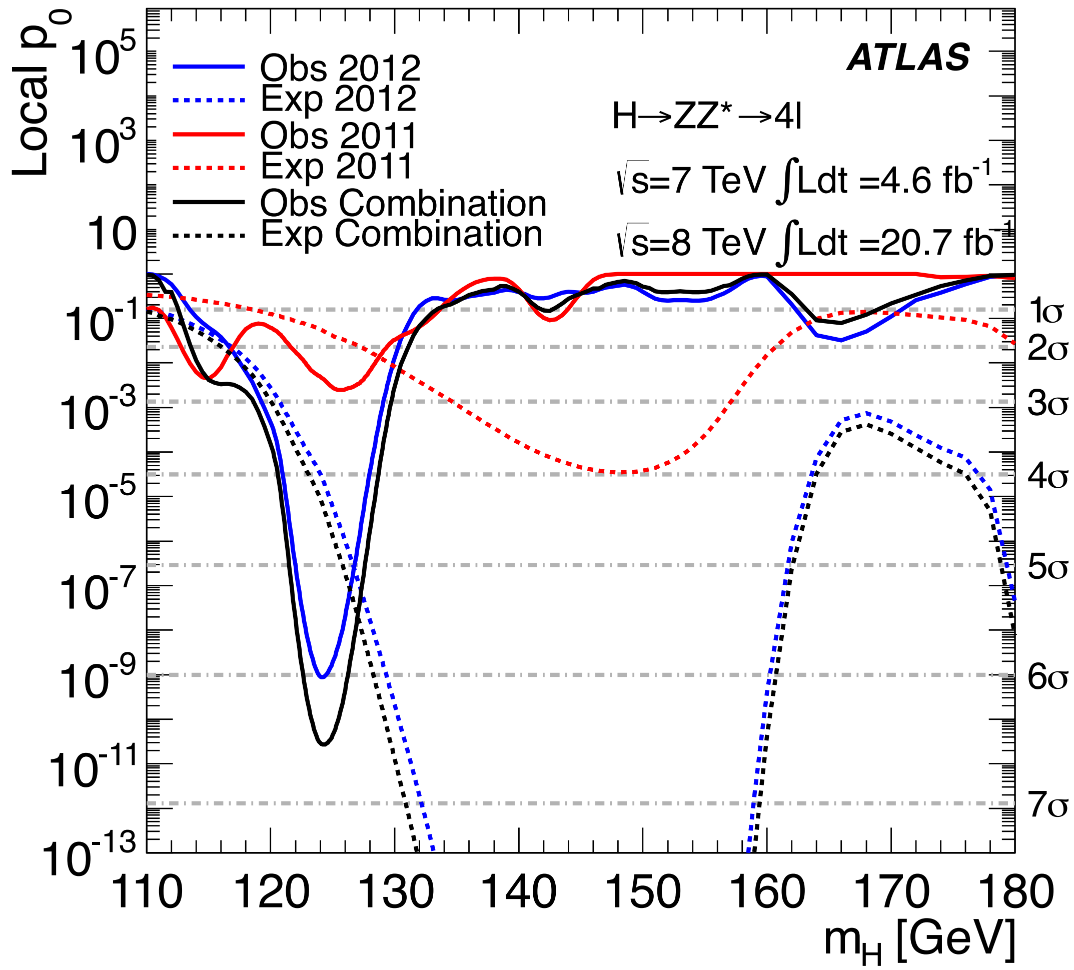



Single channel discovery: 6.6σ (4.4σ) observed (expected) significance

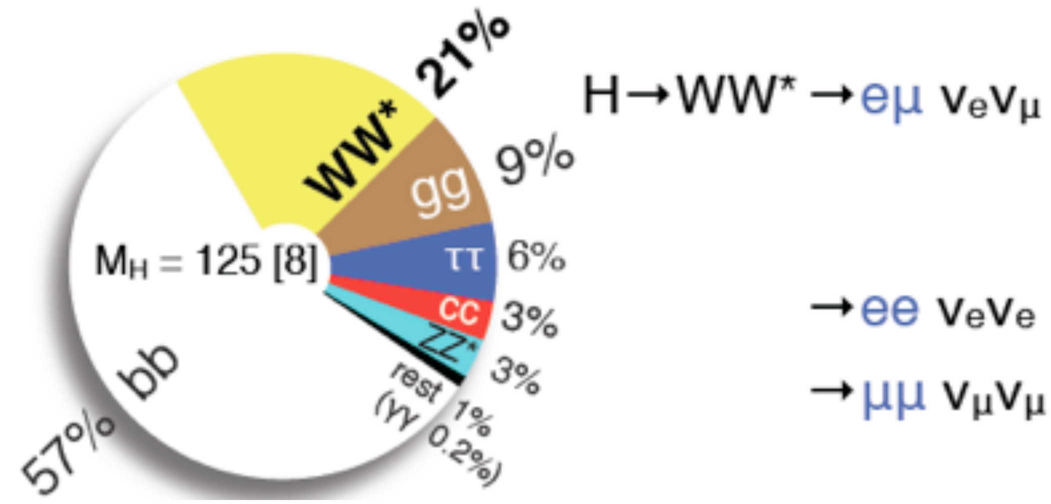
Signal strength: $\mu = 1.7^{+0.5}_{-0.4}$ for mH = 124.3 GeV



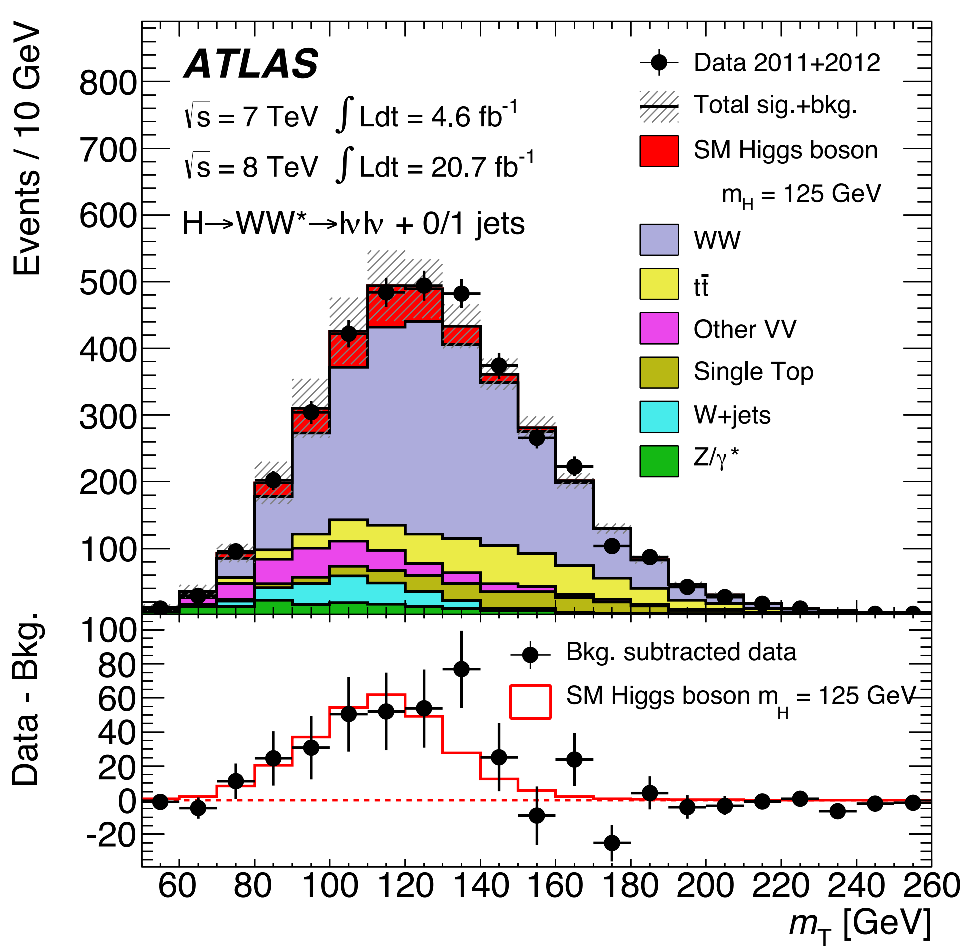

Expected and observed number of signal and background events in a window of 5 GeV around 125 GeV

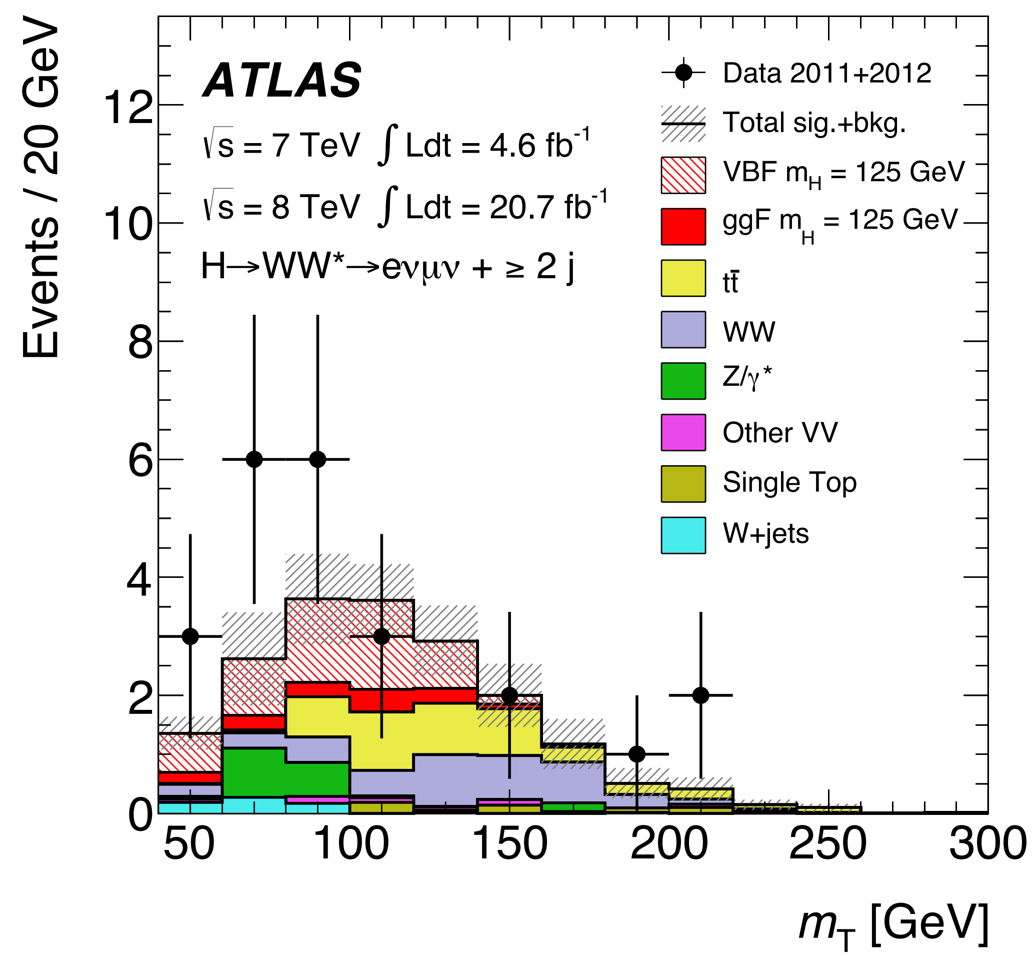
| | Signal | $ZZ^*$ | $Z+\text{jets}, t\bar{t}$ | Observed |
|---|---|---|---|---|
| $4\mu$ | $6.3 \pm 0.8$ | $2.8 \pm 0.1$ | $0.55 \pm 0.15$ | 13 |
| $2e2\mu/2\mu2e$ | $7.0 \pm 0.6$ | $3.5 \pm 0.1$ | $2.11 \pm 0.37$ | 13 |
| $4e$ | $2.6 \pm 0.4$ | $1.2 \pm 0.1$ | $1.11 \pm 0.28$ | 6 |

# H→WW→lνlν channel




- High production rate (σ x BR ~200 fb) but limited mass resolution and large backgrounds
- The analysis is divided into Njet = 0, = 1, and ≥ 2.

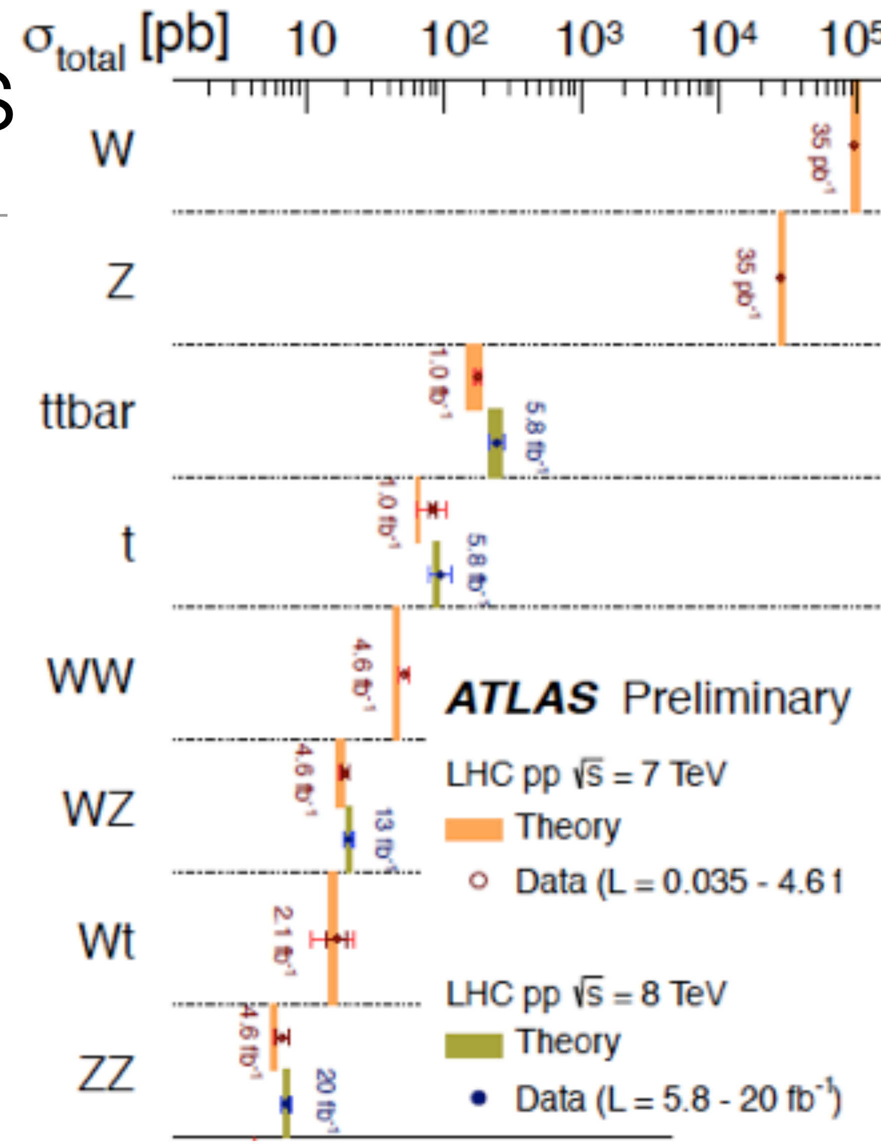


# H→WW→lνlν Backgrounds

Illustration from TM Hong

Most backgrounds (WW irreducible, tt, single W, Wt) estimated from data control regions →




| How it fakes signal | | Estimate |
|---|---|---|
| W → ℓν | Jet fakes ℓ | Data |
| Z → ℓℓ<br>Z → ττ | Fake MET<br>Real MET | Data |
| t → bℓν | Lose b | Data |
| Irreducible | Large | Data |
| WZ → ℓνℓℓ | Lose ℓ | MC |
| W → ℓν | Lose b | Data |
| Irreducible | Small | MC |

| | $N_{jet} = 0$ | $N_{jet} = 1$ | $N_{jet} \geqslant 2$ |
|---|---|---|---|
| Observed | 831 | 309 | 55 |
| Signal | 100 ± 21 | 41 ± 14 | 10.9 ± 1.4 |
| Total background | 739 ± 39 | 261 ± 28 | 36 ± 4 |
| WW | 551 ± 41 | 108 ± 40 | 4.1 ± 1.5 |
| *Other VV* | 58 ± 8 | 27 ± 6 | 1.9 ± 0.4 |
| Top-quark | 39 ± 5 | 95 ± 28 | 5.4 ± 2.1 |
| Z+jets | 30 ± 10 | 12 ± 6 | 22 ± 3 |
| W +jets | 61 ± 21 | 20 ± 5 | 0.7 ± 0.2 |

Numbers of events observed in the data and expected from signal ($m_H$=125.5GeV) and backgrounds inside the regions $0.75m_H<m_T<m_H$ for Njet≤1 and $m_T<1.2m_H$ for Njet =2 .

# H➞WW➞lνlν channel Results

More details about this analysis in V. Bortolotto's talk this afternoon!

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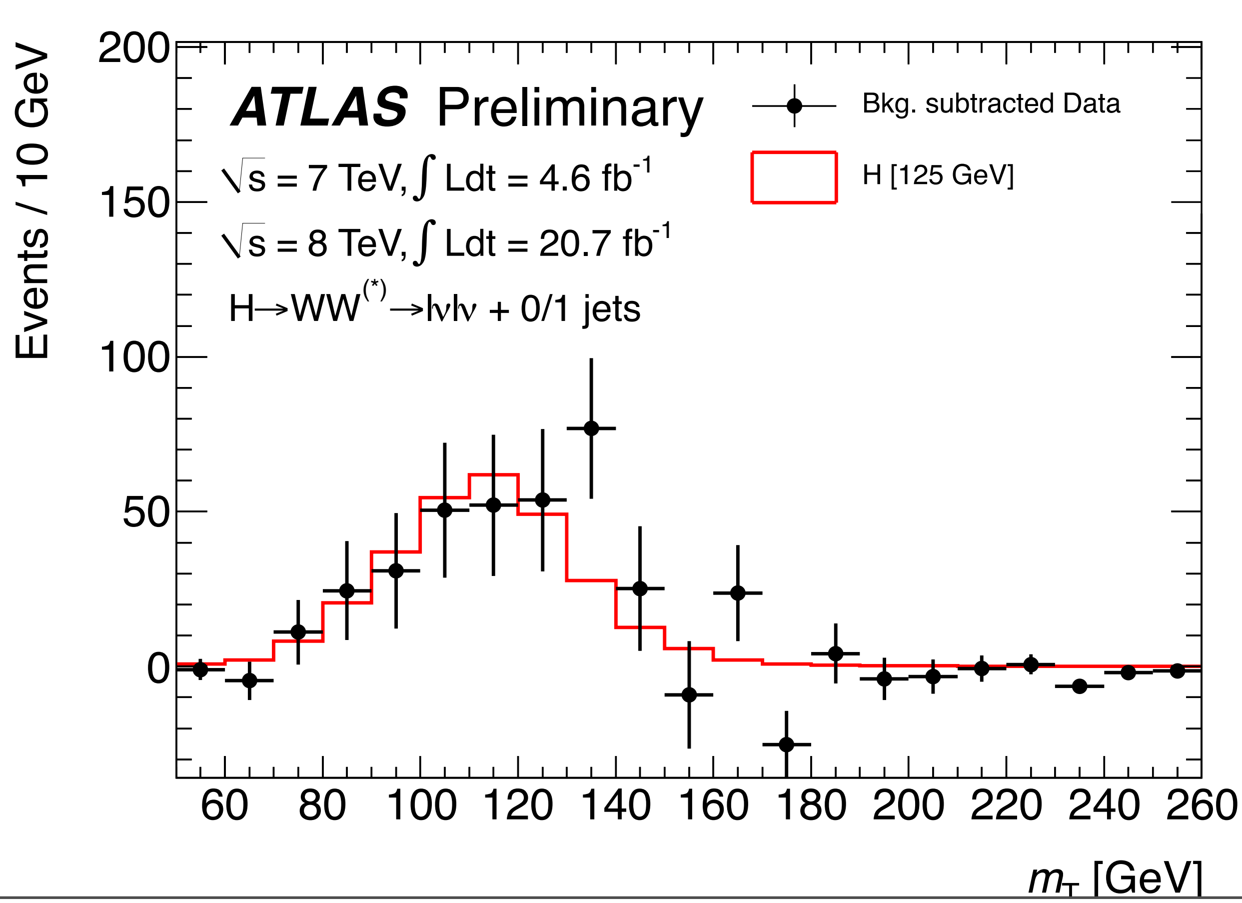
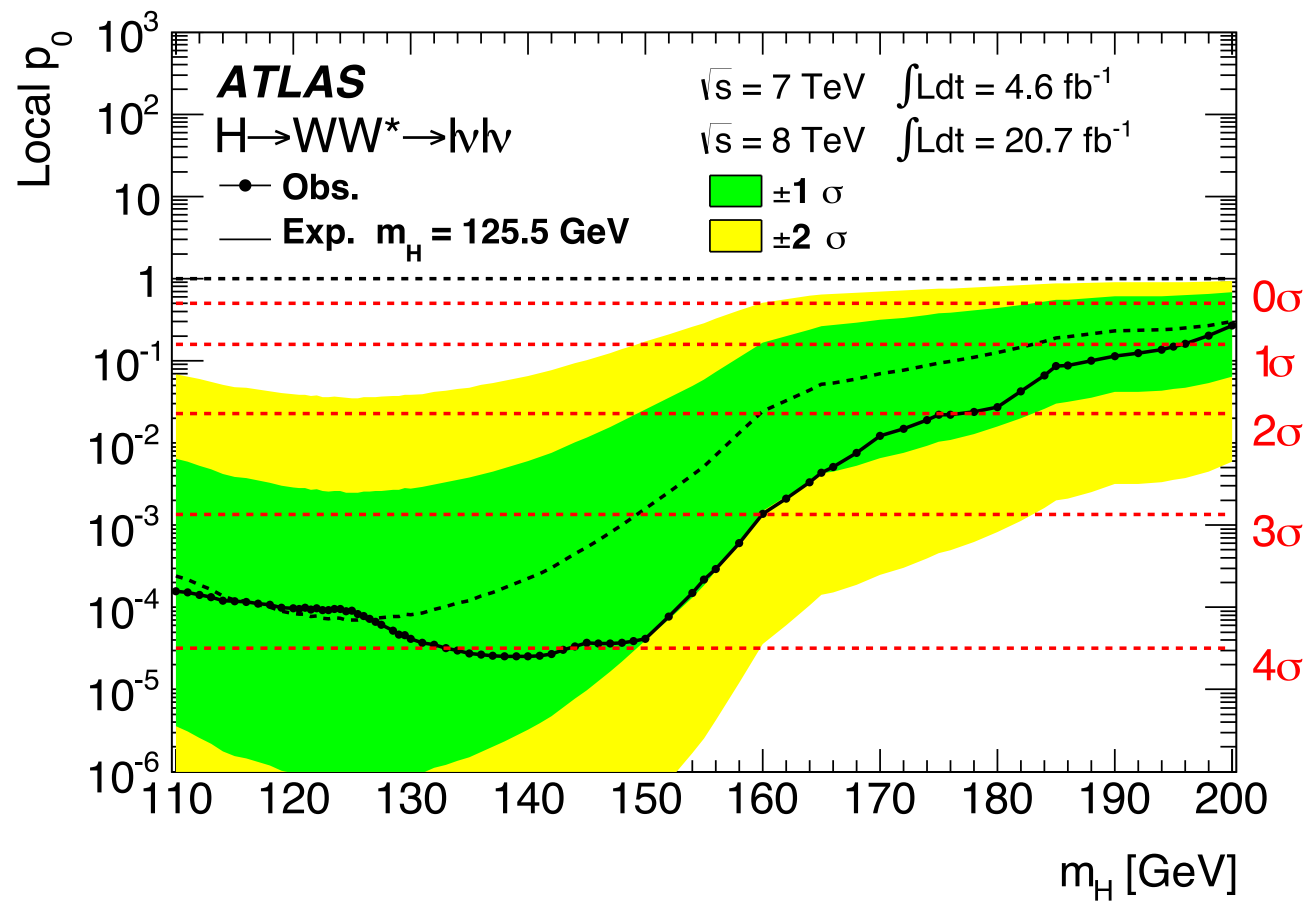
Significance of the signal with mH = 125GeV is 3.8(3.7) observed (expected) standard deviations. With a signal strength:

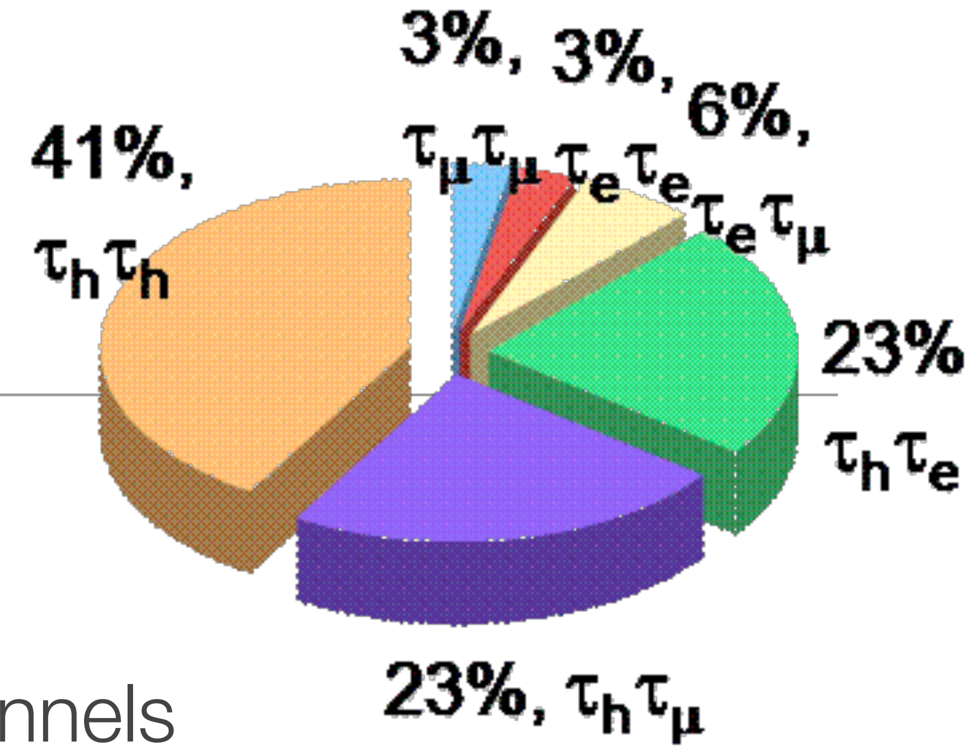
$\mu_{obs}$ = 1.01 ± 0.21 (stat.) ± 0.19 (theo. syst.) ± 0.12 (expt. syst.) ± 0.04 (lumi.)
$\mu_{obs}$ = 1.01 ± 0.31.

Results are consistent with the predictions for the Standard Model Higgs boson decaying to a pair of W bosons.



# H→ττ channel




## Analysis strategy:

✓ Search in $\tau_{lep}$-$\tau_{lep}$, $\tau_{lep}$-$\tau_{had}$ and $\tau_{had}$-$\tau_{had}$ channels

- Major backgrounds: Z→ττ (irreducible), $Z_{(ee/\mu\mu)}$+jets, W+jets, top, multi-jets,di-bosons (each channel is affected differently by the backgrounds → cuts optimised separately).

✓ Two analysis categories are defined in an exclusive way:

- VBF: Presence of two jets with a large pseudo-rapidity separation.
- Boosted: targeted at events with a boosted Higgs boson from ggF (Higgs $P_T$>100 GeV).

✓ BDTs are used in each category to extract the Higgs signal from the large backgrounds.

# H→ττ channel: Inputs to BDT

Resonance properties

– m(ττ), ΔR(ττ) ...

- VBF topology

– mjj, Δηjj ...

- Event activity

– Scalar & vector PT-sum

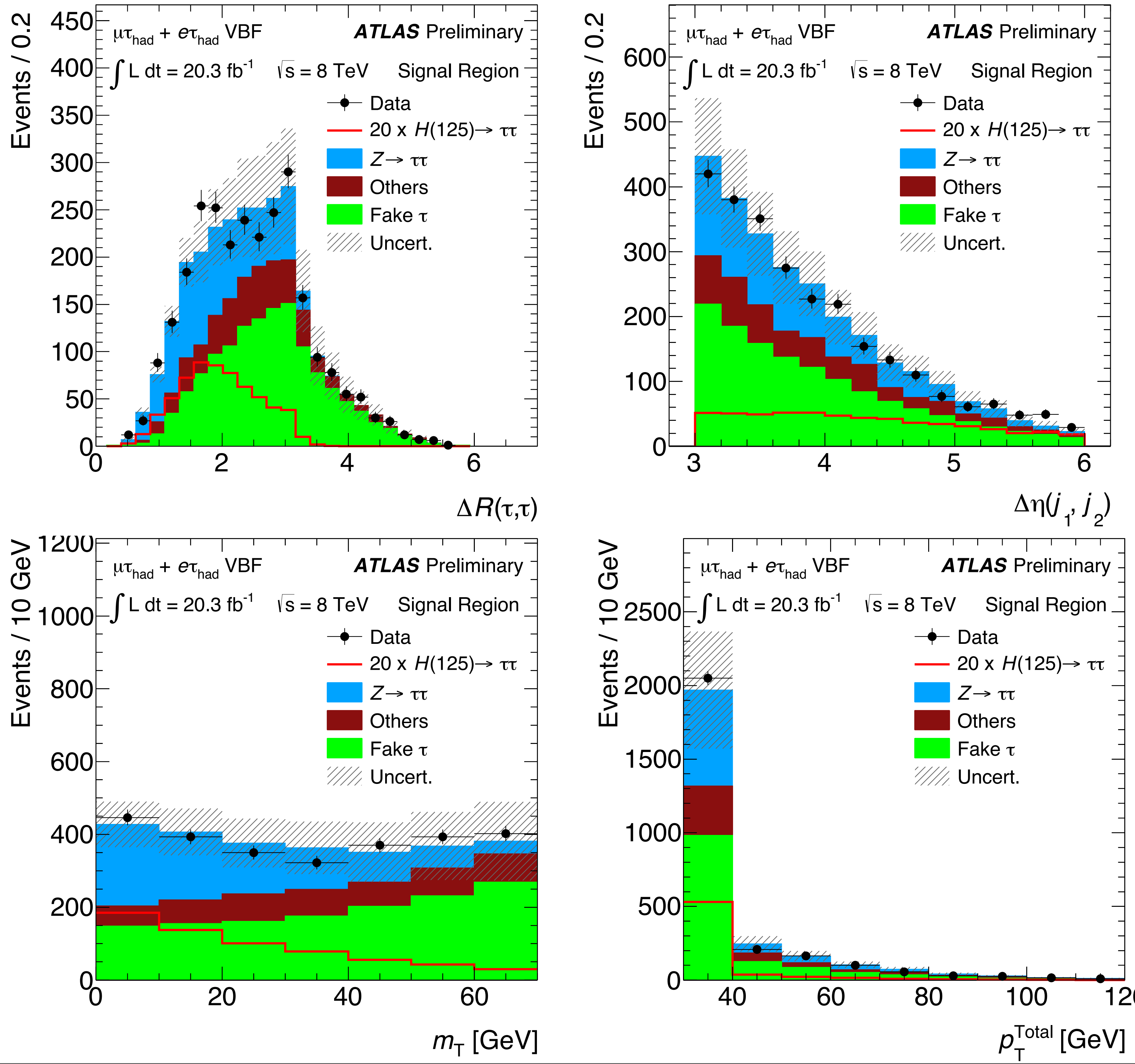
- Event topology

– mT, object centralities, PT(τ1)/PT(τ2), etc

- Number of variables

– VBF: 7 - 9

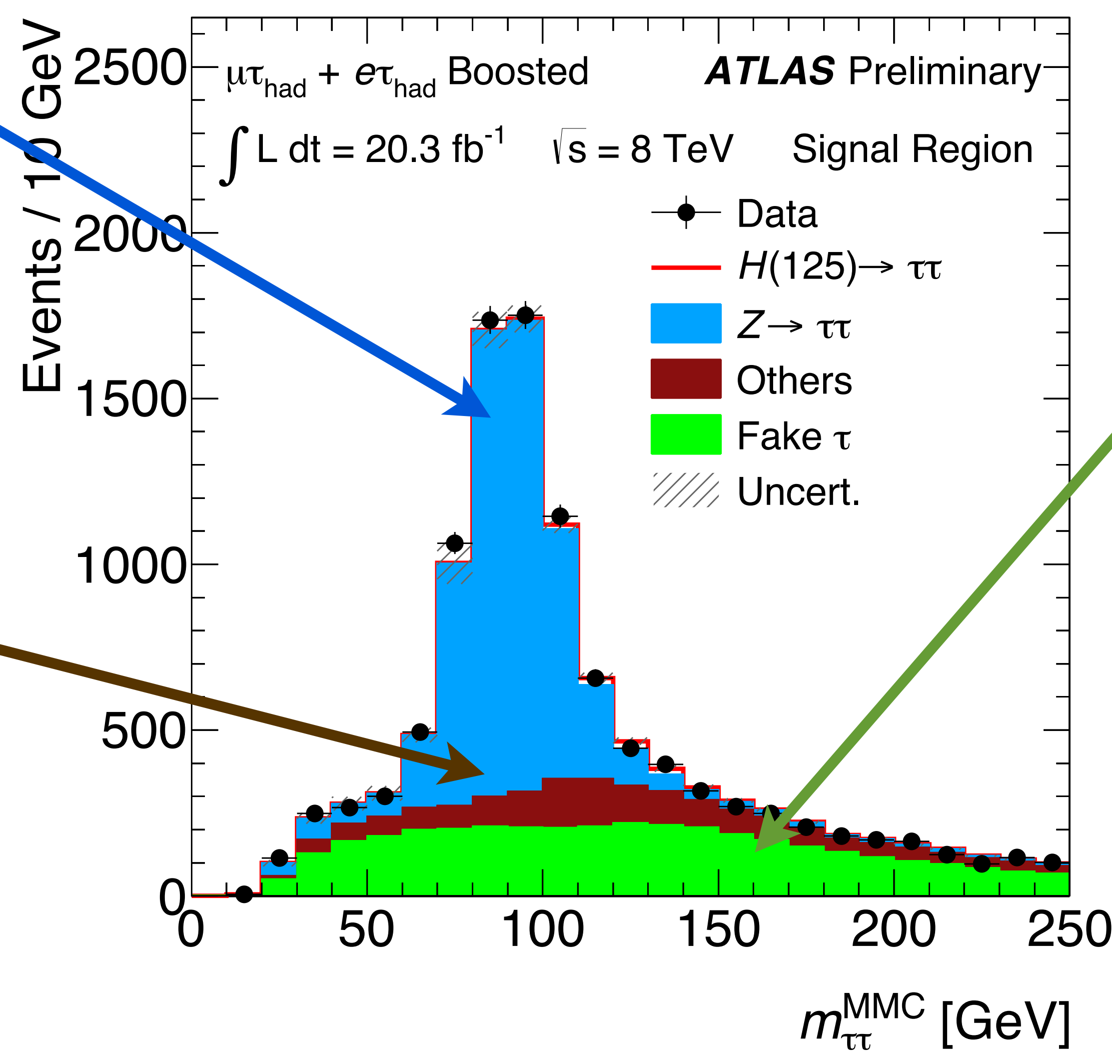
– Boosted: 6 - 9



# H→ττ channel: Background estimation

- All major backgrounds are either directly estimated from data or normalised to data in dedicated control regions

Z→ττ: major background; modelled by data/MC hybrid estimate




"Fakes": multijet, W+jets, top (with fake tau); modelled by data

"Others": dibosons, H→WW;modelled by MC. Z →ee, μμ& top modeled by MC, normalized to data.

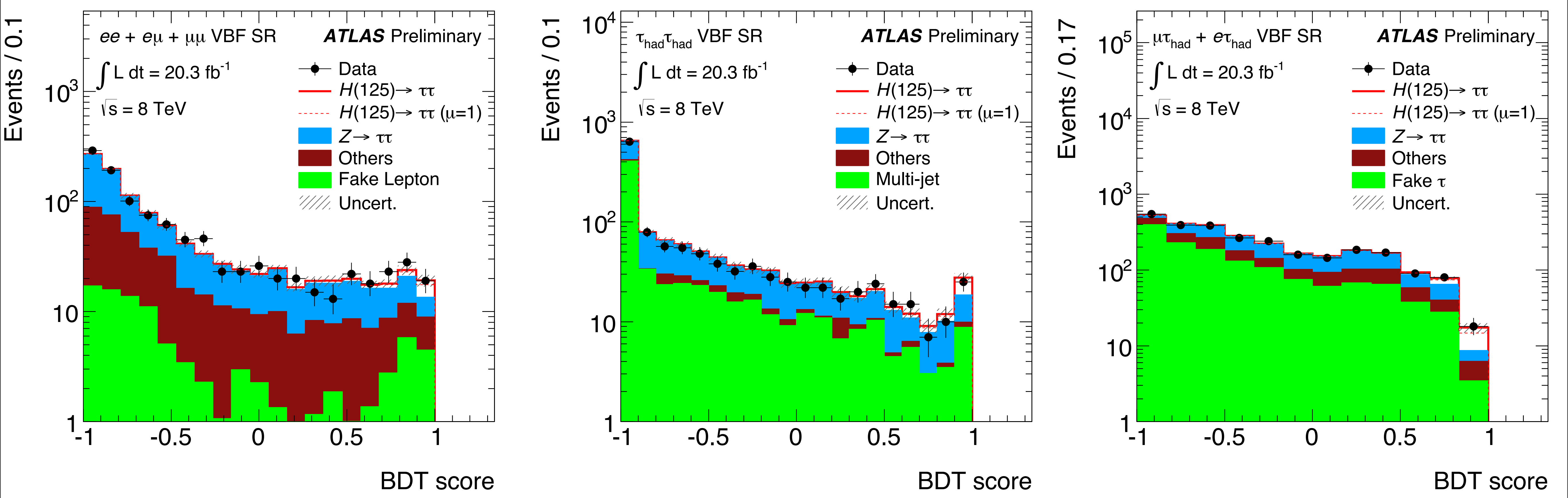
Background model is validated by control regions defined separately to each channel:

# $H \rightarrow \tau\tau$ channel: Signal extraction

Maximum likelihood fit extracts signal strength μ by performing a simultaneous fit in 6 SR (VBF+Boosted categories per channel) and 5 CR with common nuisance parameters.

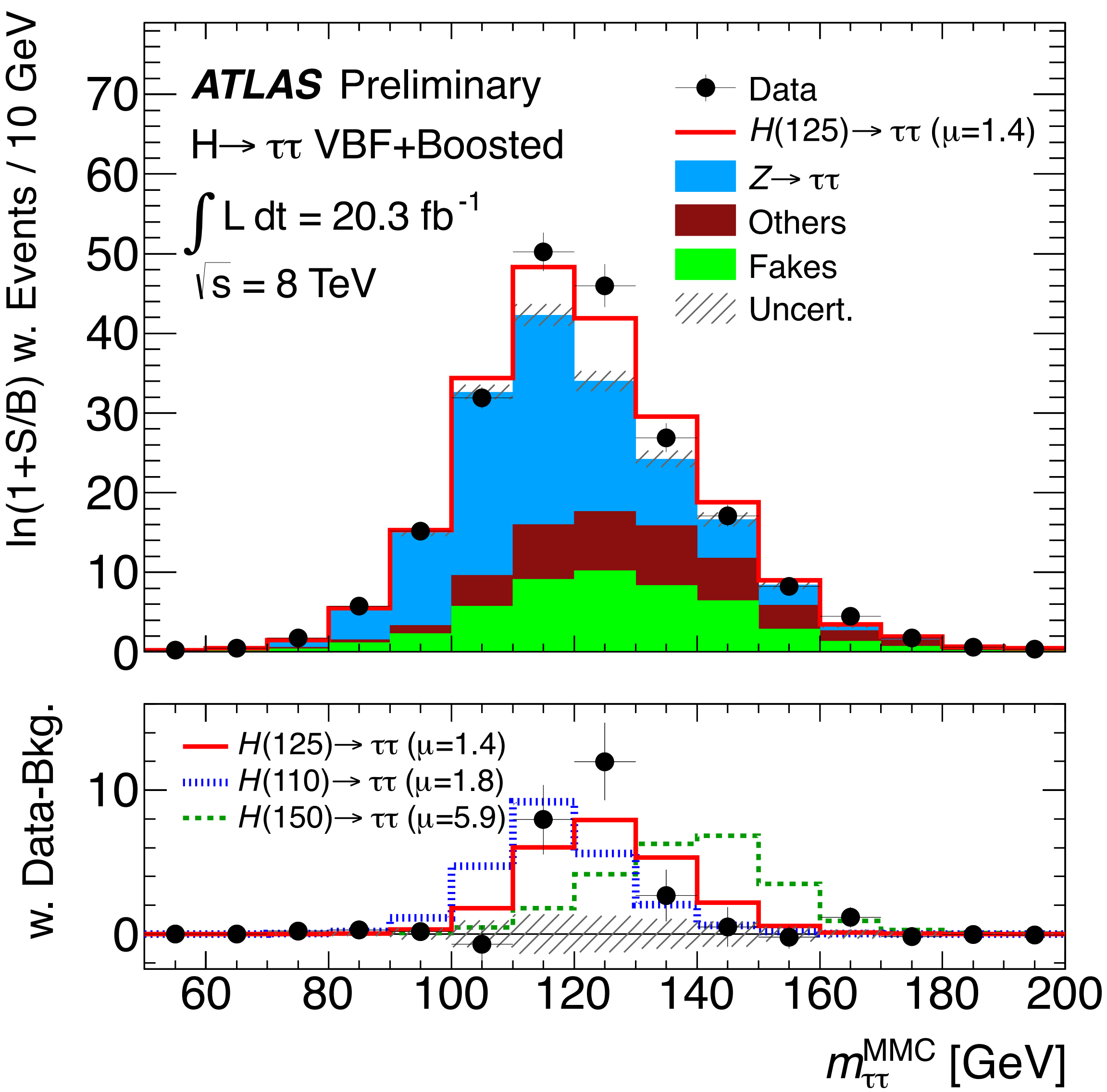
Inputs for maximum likelihood:

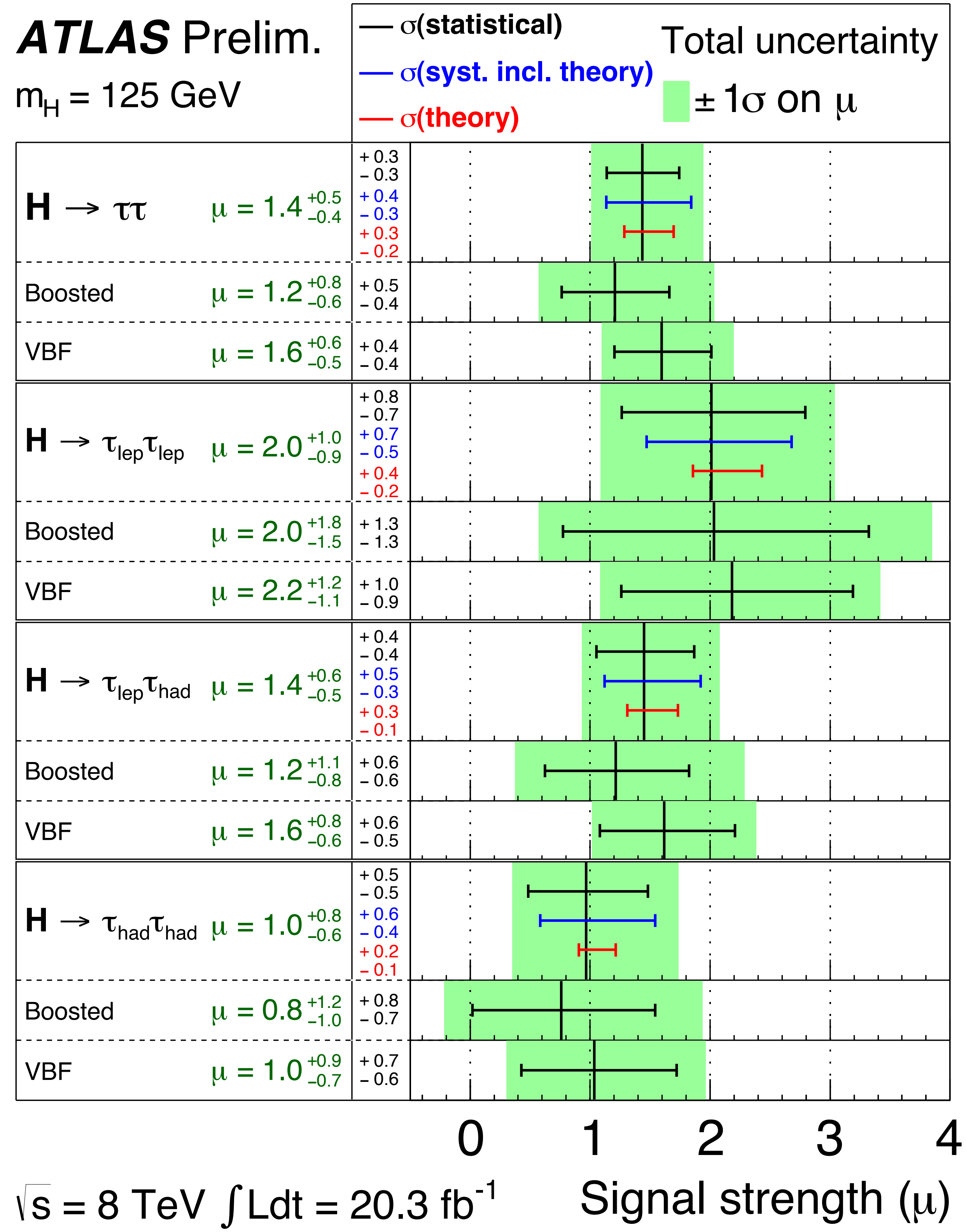
- BDT score in the 6 SR
- Event yields Z→ll and top CR ($\tau_{lep}$-$\tau_{lep}$ and $\tau_{lep}$-$\tau_{had}$)
- "Rest" category CR in bins of $\Delta\eta(\tau_{had}, \tau_{had})$ (failed VBF&Boosted cuts)



# H→ττ channel: Results

An excess is observed in the three channels, with an observed (expected) significance of 4.1σ (3.2)σ.




The fitted signal strength@125 GeV:

$\mu=1.43^{+0.31}_{-0.29}(\text{stat.})^{+0.41}_{-0.30}(\text{syst.})$

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# Higgs properties

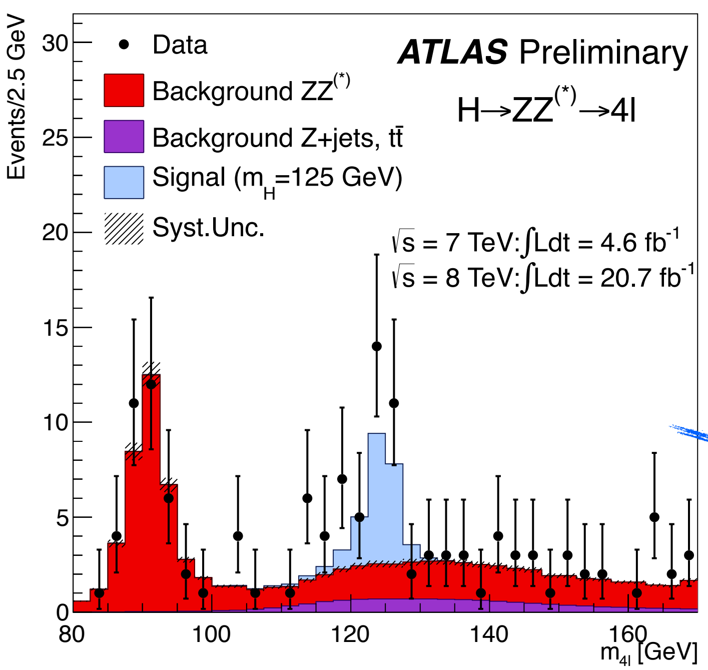
# Mass of the Higgs boson

ATLAS-CONF-2013-014

Precise measurement of mH from channels with entirely reconstructed final state and good object resolution:

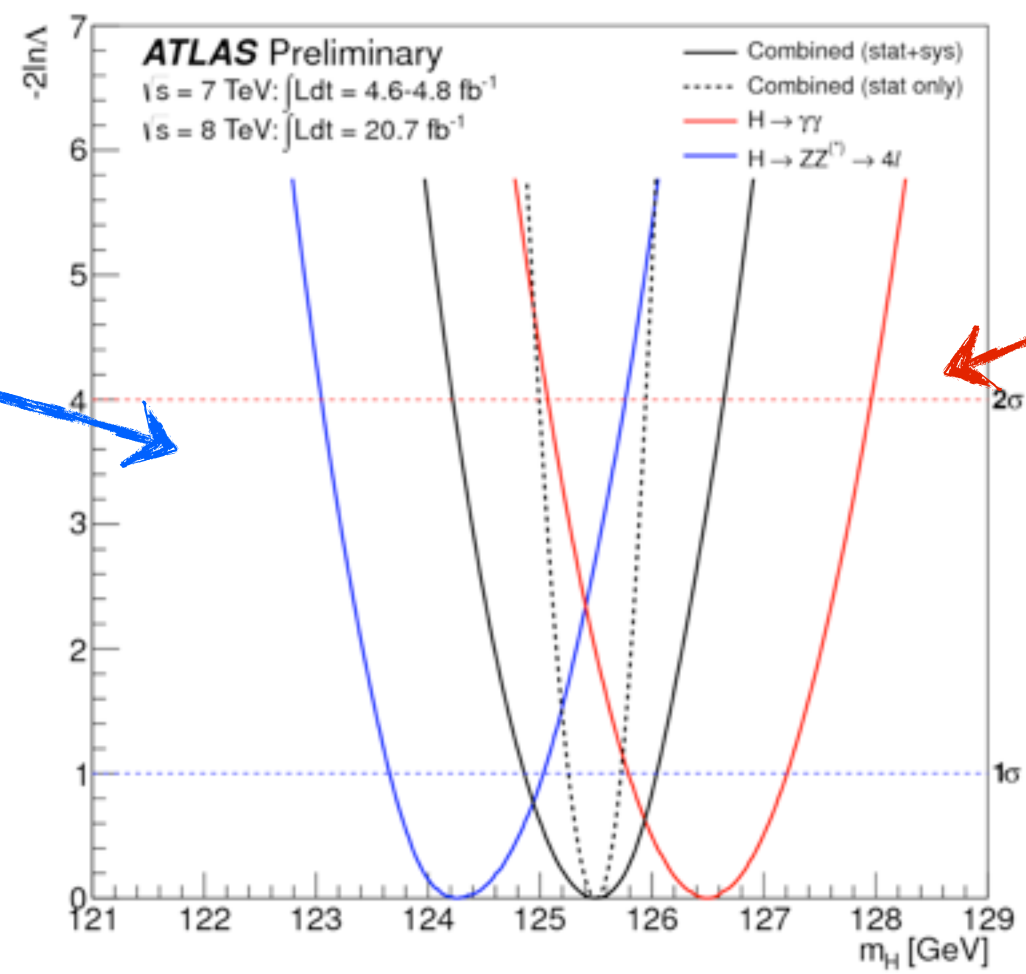
**H→γγ, H→ZZ**

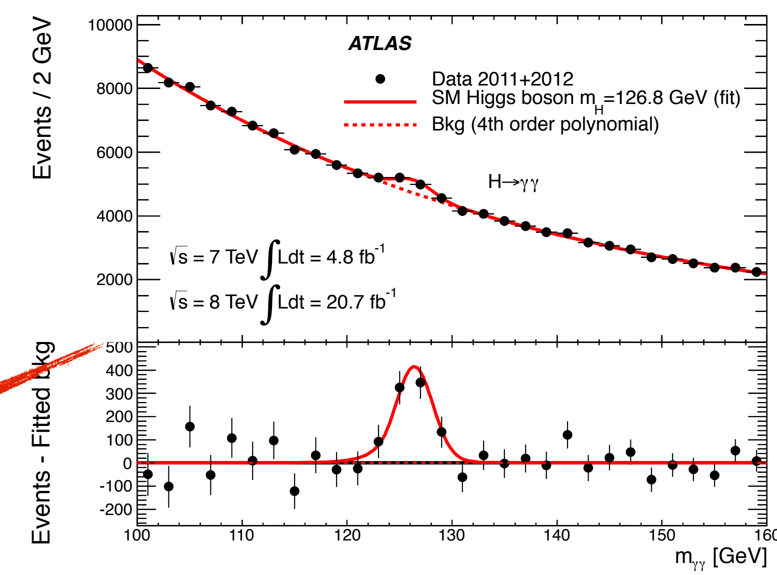
Dominant uncertainties: photon energy scale (H→γγ), lepton energy and momentum scale, statistics (H→4l)




mH = 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.6}$(sys) GeV

(H→ ZZ(*)→ 4l)




mH = 126.8 ± 0.2(stat) ± 0.7(sys) GeV

(H→γγ)

**Combined mass: mH=125.5 ± 0.2(stat) $^{+0.5}_{-0.6}$(sys) GeV**

Mass difference 2.4 σ (p-value 1.5% ).

# Signal strength

Measure the ratio between observed rate and SM Higgs expectation for **σ** *x BR:*

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

where **μ**=1 ➞ SM Higgs

Systematic, statistical and theoretical uncertainties are already comparable.

NEW!

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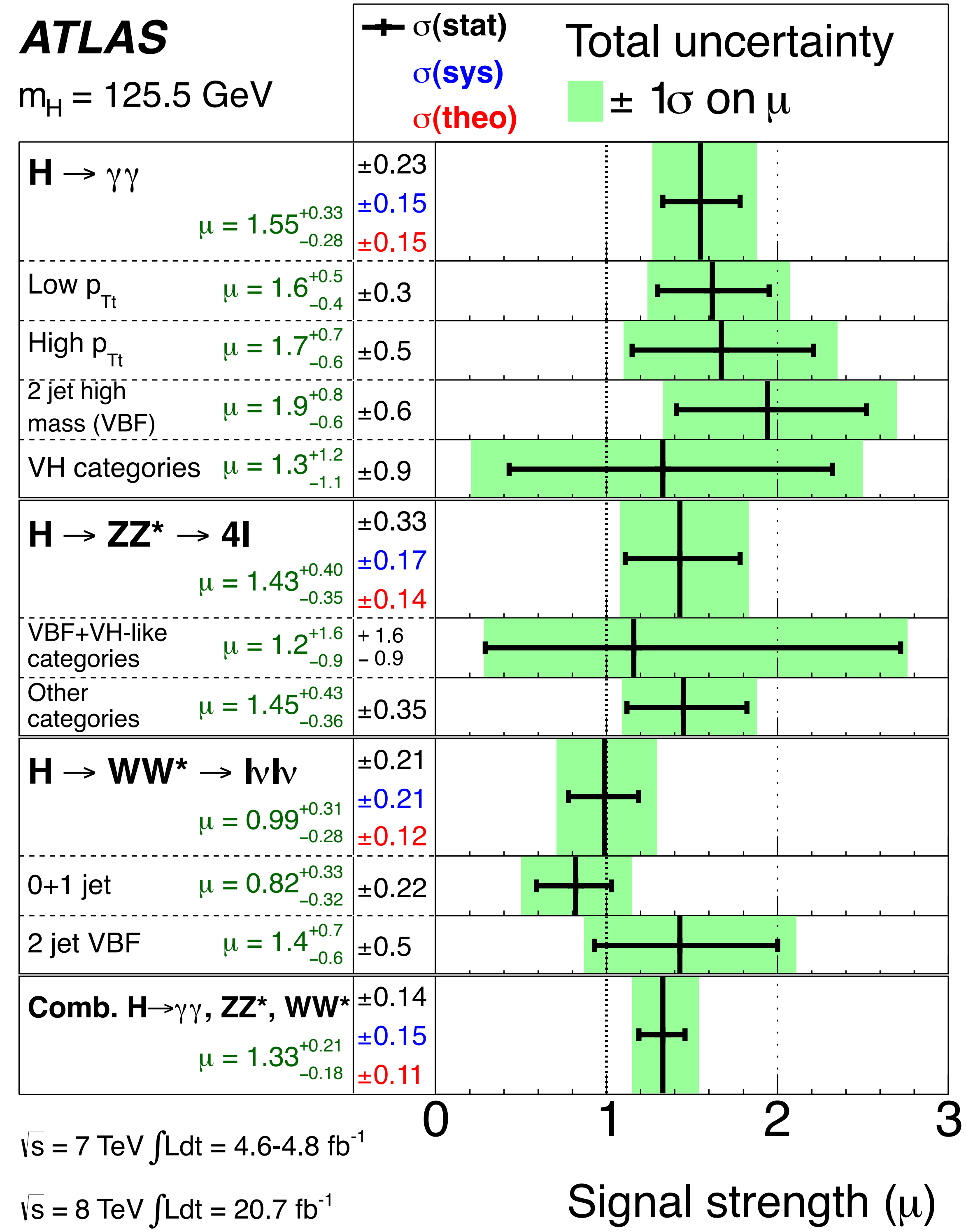


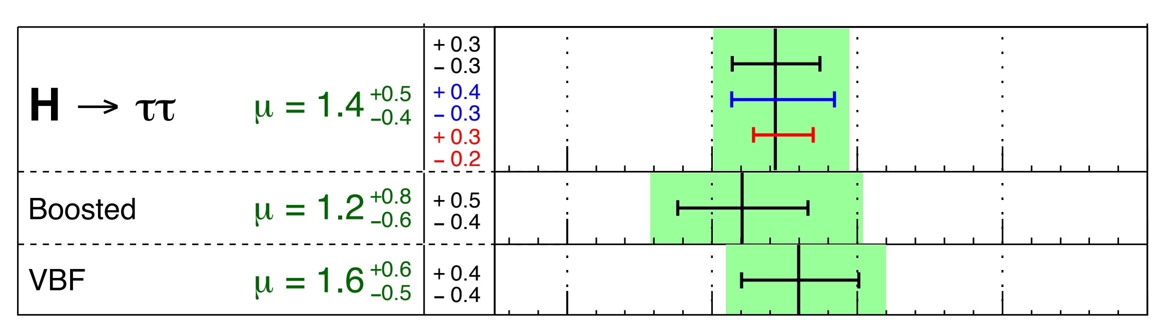


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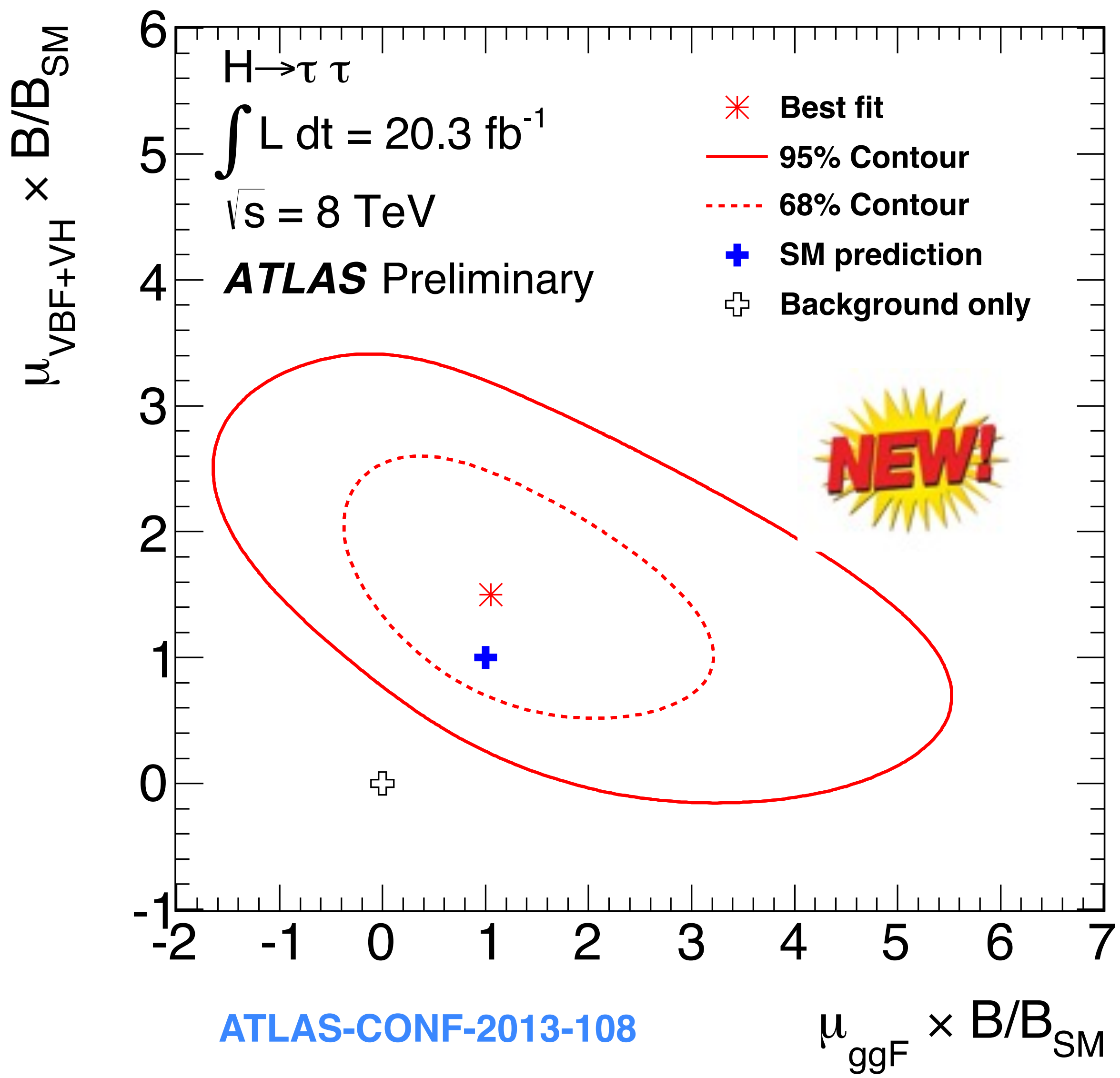
# Higgs production modes

Exploiting the categorisations, the signal strength the data is fitted separating the vector-boson mediating processes VBF and VH from ggF and ttH.

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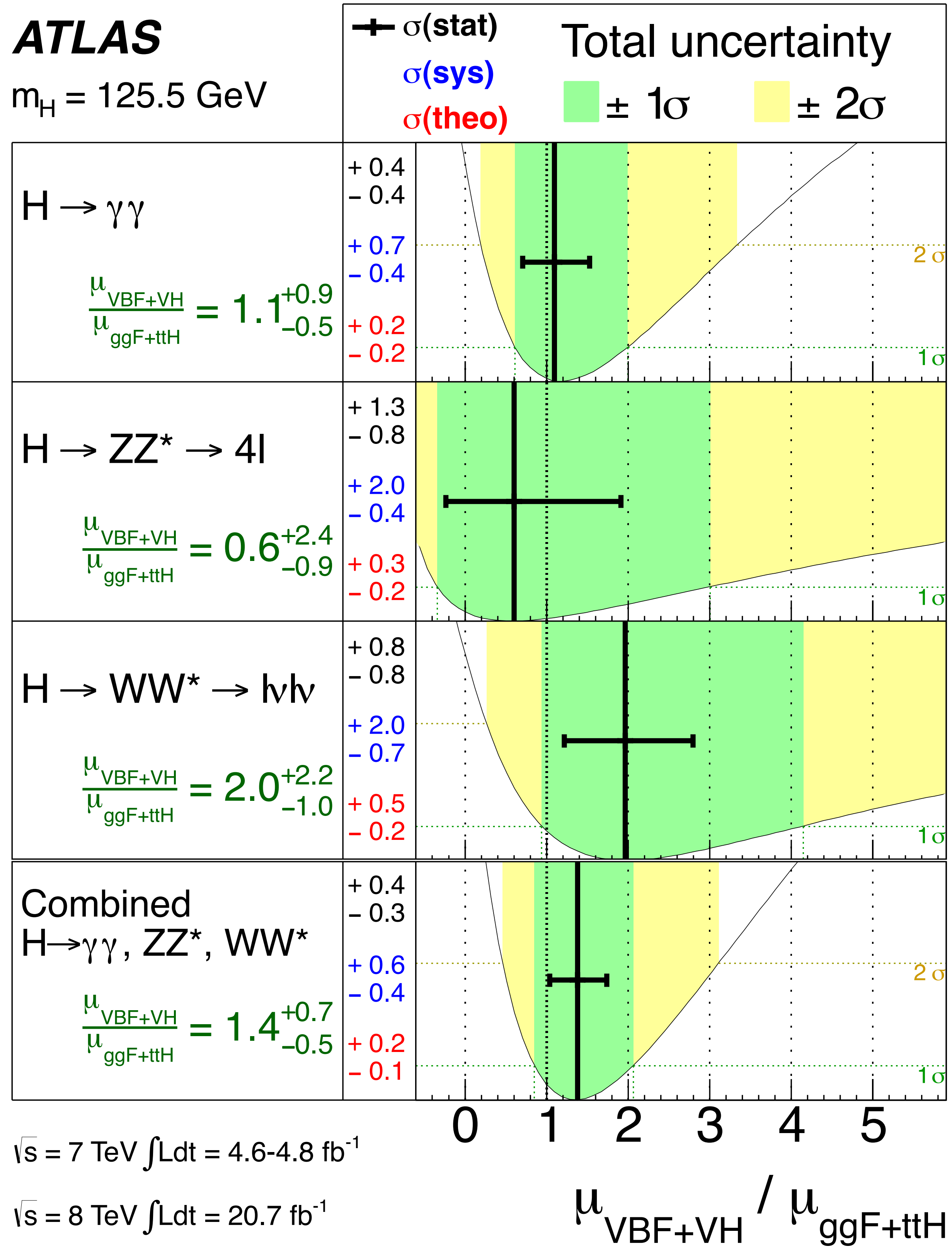


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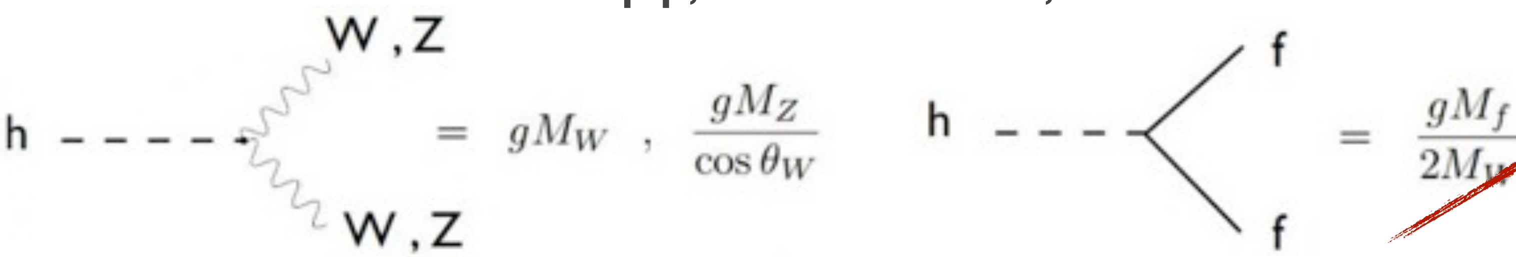
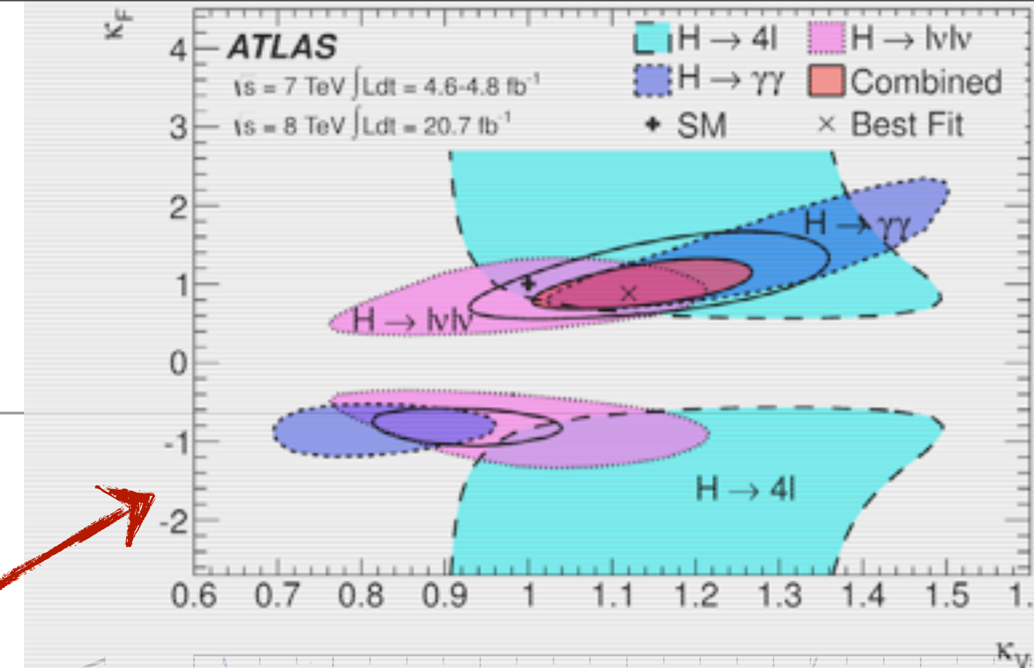
# Higgs Couplings

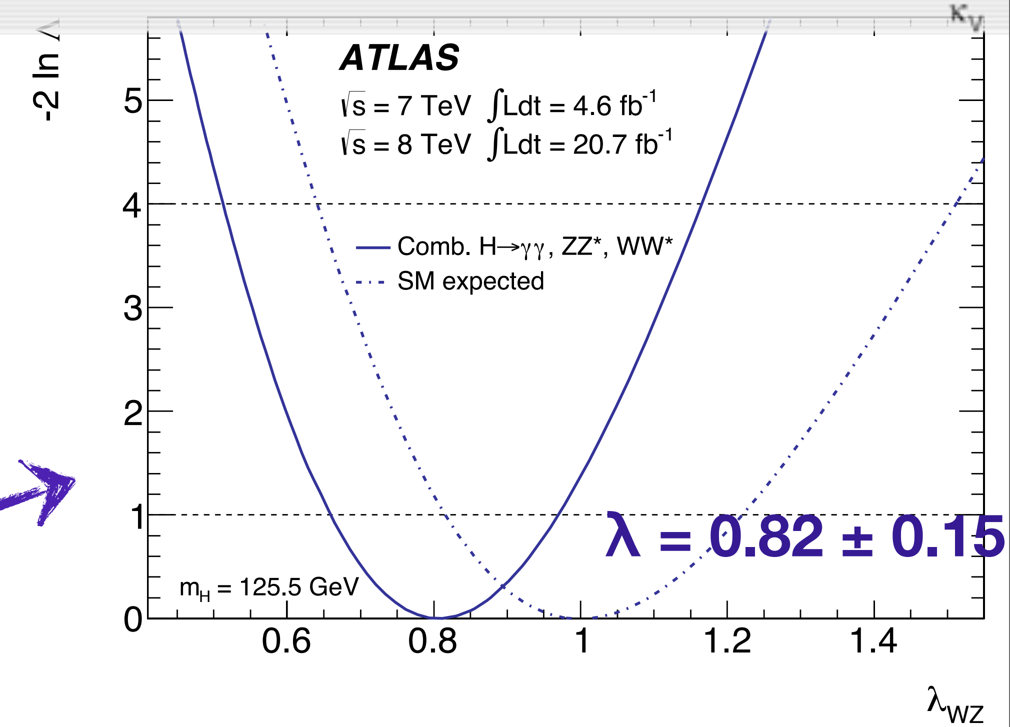
Combined H→γγ, H→ZZ→4l, H→WW→lvlv:



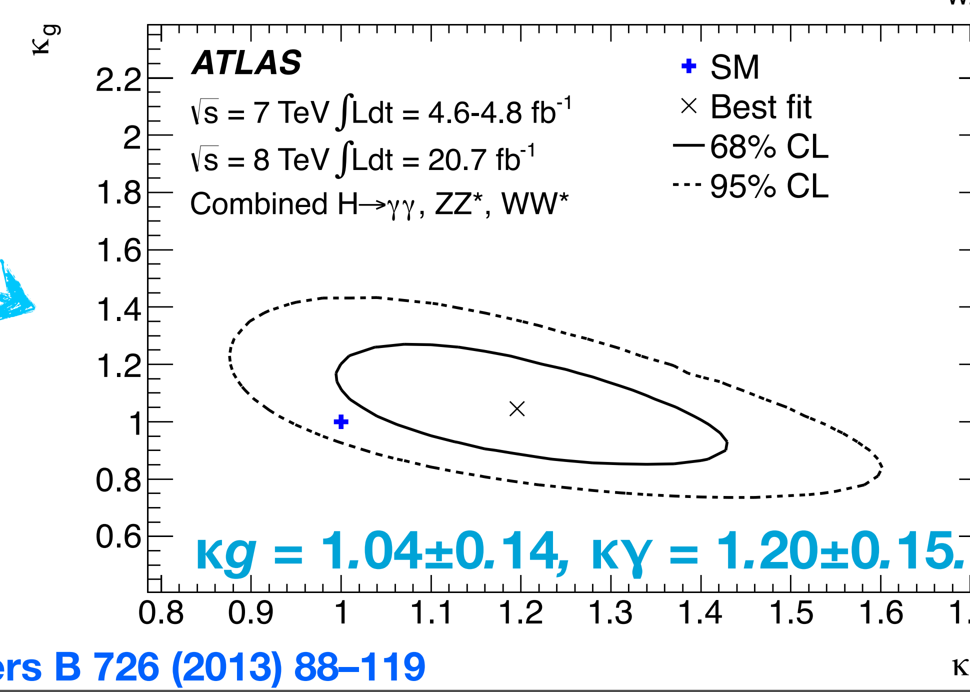

**Coupling to fermions and bosons:** One coupling scale factor for fermions, and one for bosons

**κF = 0 (vanishing fermion couplings) excluded at >5σ**
**2D Compatibility with SM at 12% level**




**Ratio of couplings to the W and Z bosons**
**$\lambda_{WZ}=k_W/k_Z$:** Test custodial symmetry.

**Consistency with SM at 20% level**



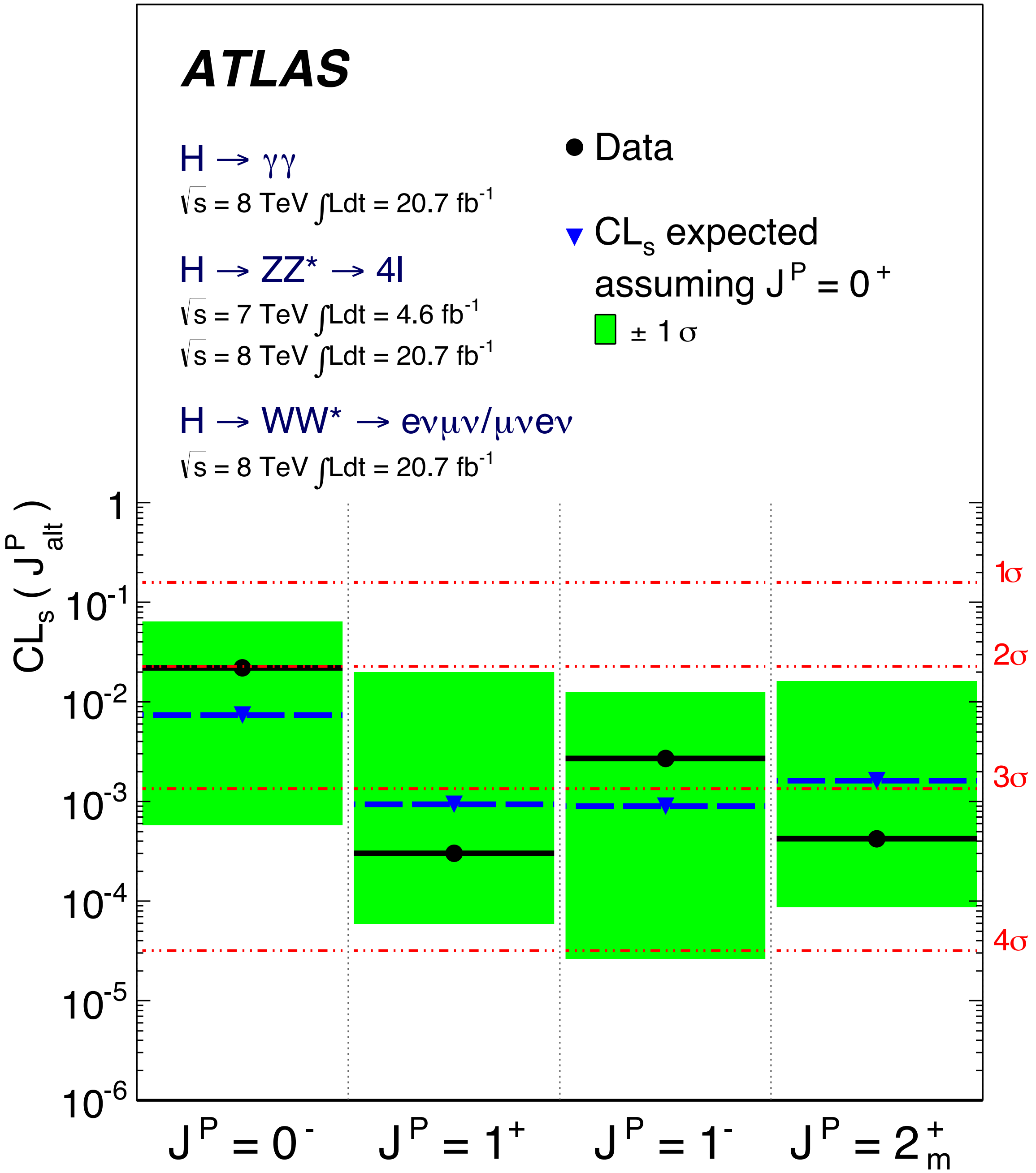

**Constrains on production and decay rates:** Test the existence of new heavy particles, that contribute to loop-induced processes (i.e gg→H and H→γγ)

**2D Compatibility with SM at 14% level**

Physics Letters B 726 (2013) 88–119

# Higgs spin/parity measurement

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

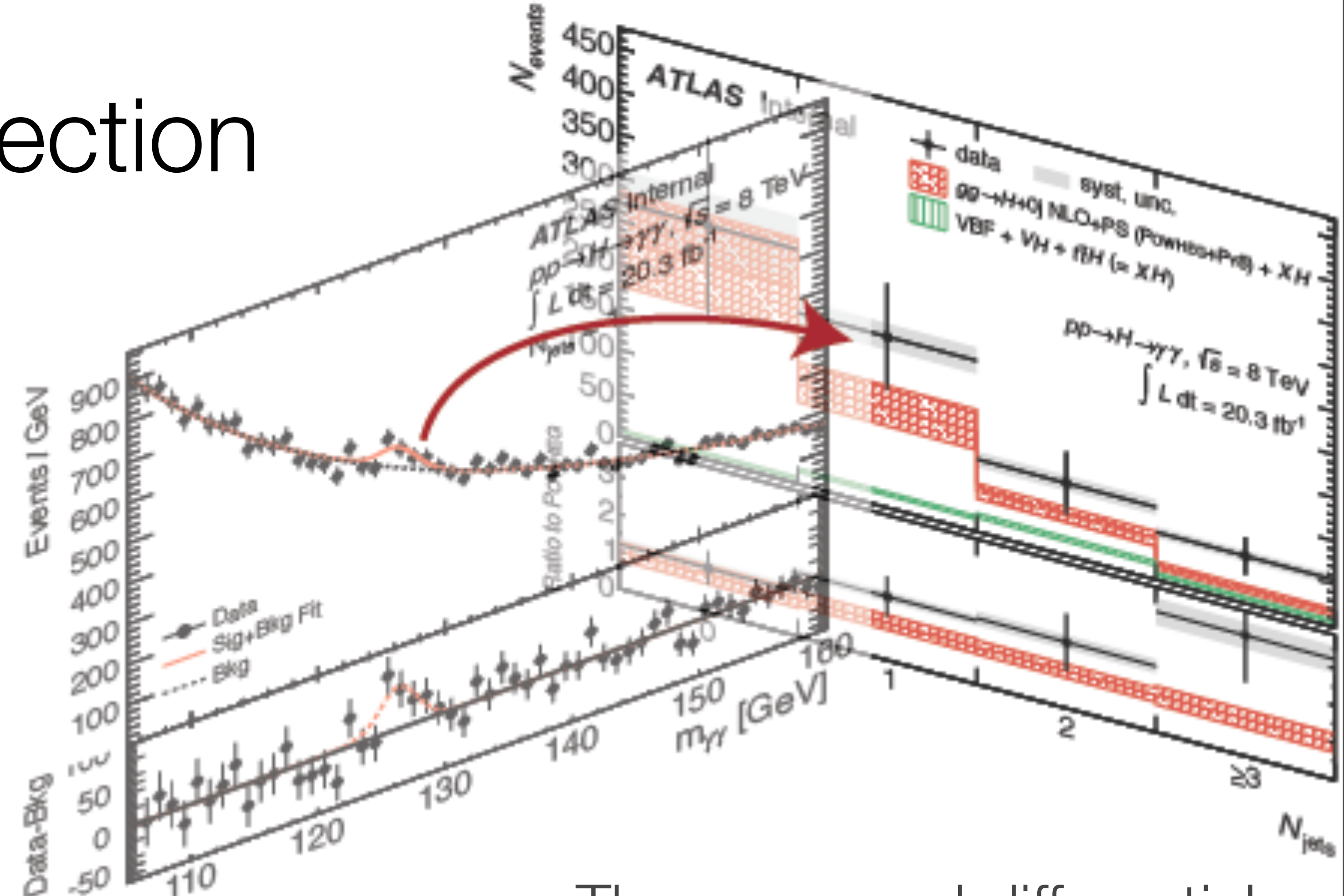



| $J^P$ hypo | Exclusion CL | Source | Channel |
|---|---|---|---|
| $0^-$ | 97.8% | $H \rightarrow ZZ^* \rightarrow 4l$ | ggF only |
| $1^-$ | 99.7% | Combined $ZZ^*/WW^*$ | VBF only |
| $1^+$ | 99.97% | Combined $ZZ^*/WW^*$ | VBF only |
| $2^+$ | 99.9% | Combined $\gamma\gamma/ZZ^*/WW^*$ | 5 $f_{q\bar{q}}$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

Combination favours $0^+$ hypothesis!

Physics Letters B 726 (2013) 120–144

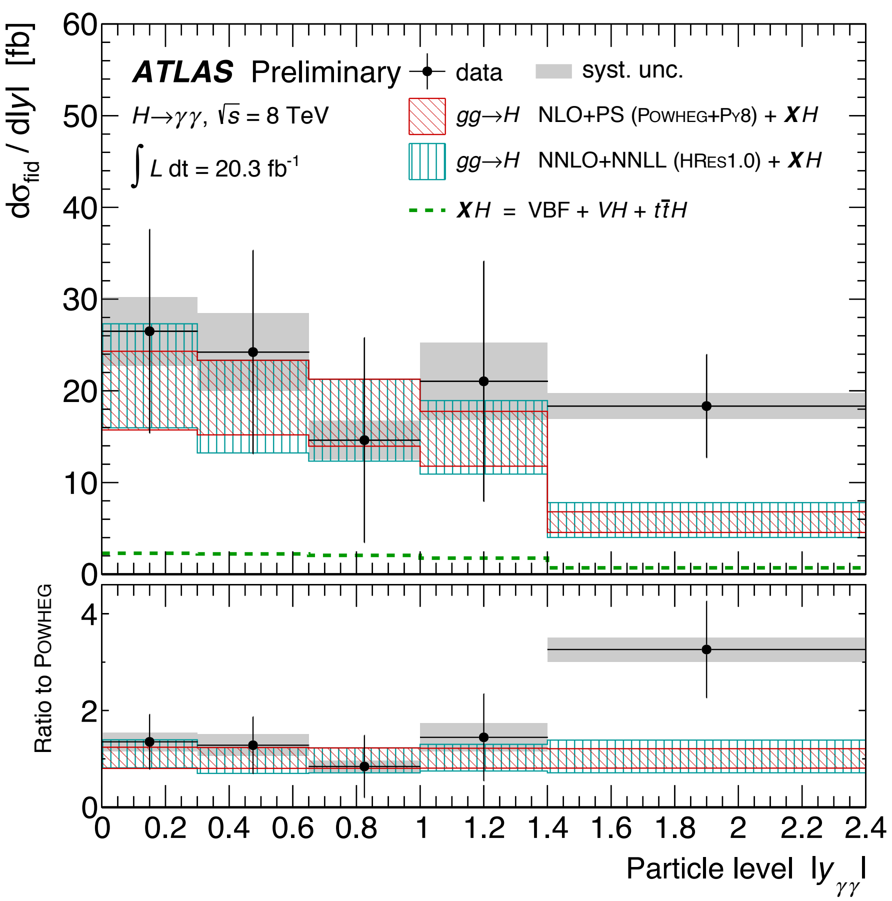
# Differential cross-section in the H→γγ

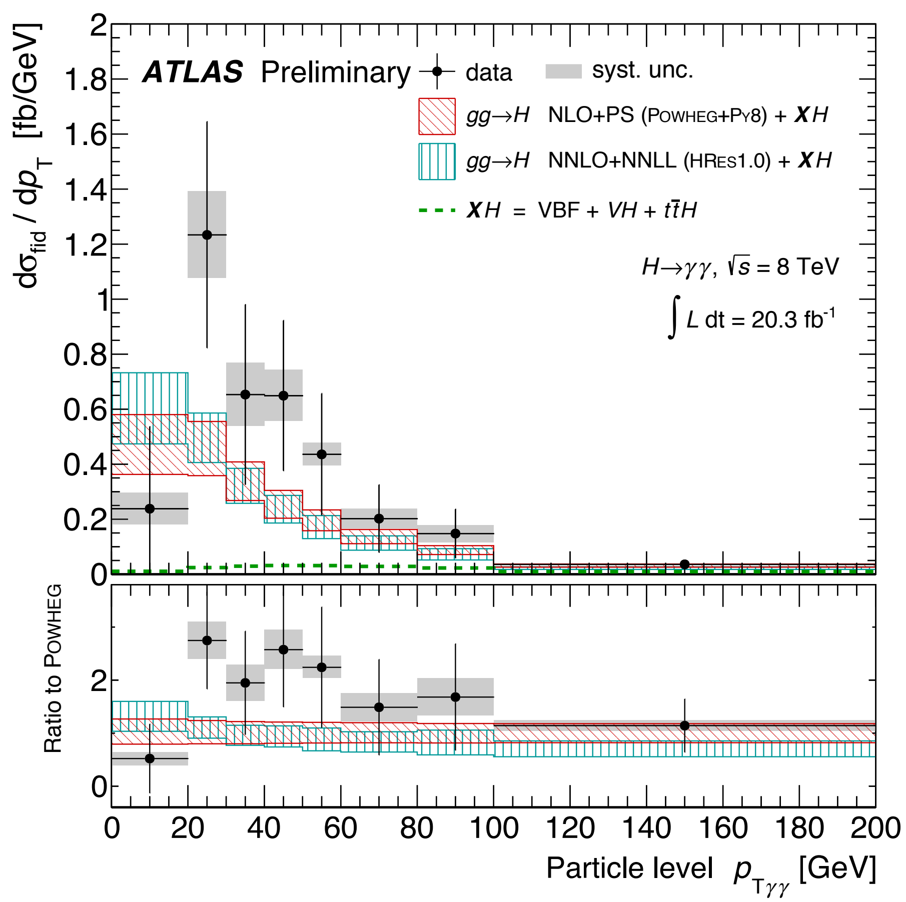



Define a binning for a variable ($Pt_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, cos(θ)*...):

- For each bin extract yield from fit to $m_{\gamma\gamma}$.
- For each bin, correct for acceptance, efficiency, resolution:“unfolding”

ATLAS-CONF-2013-072

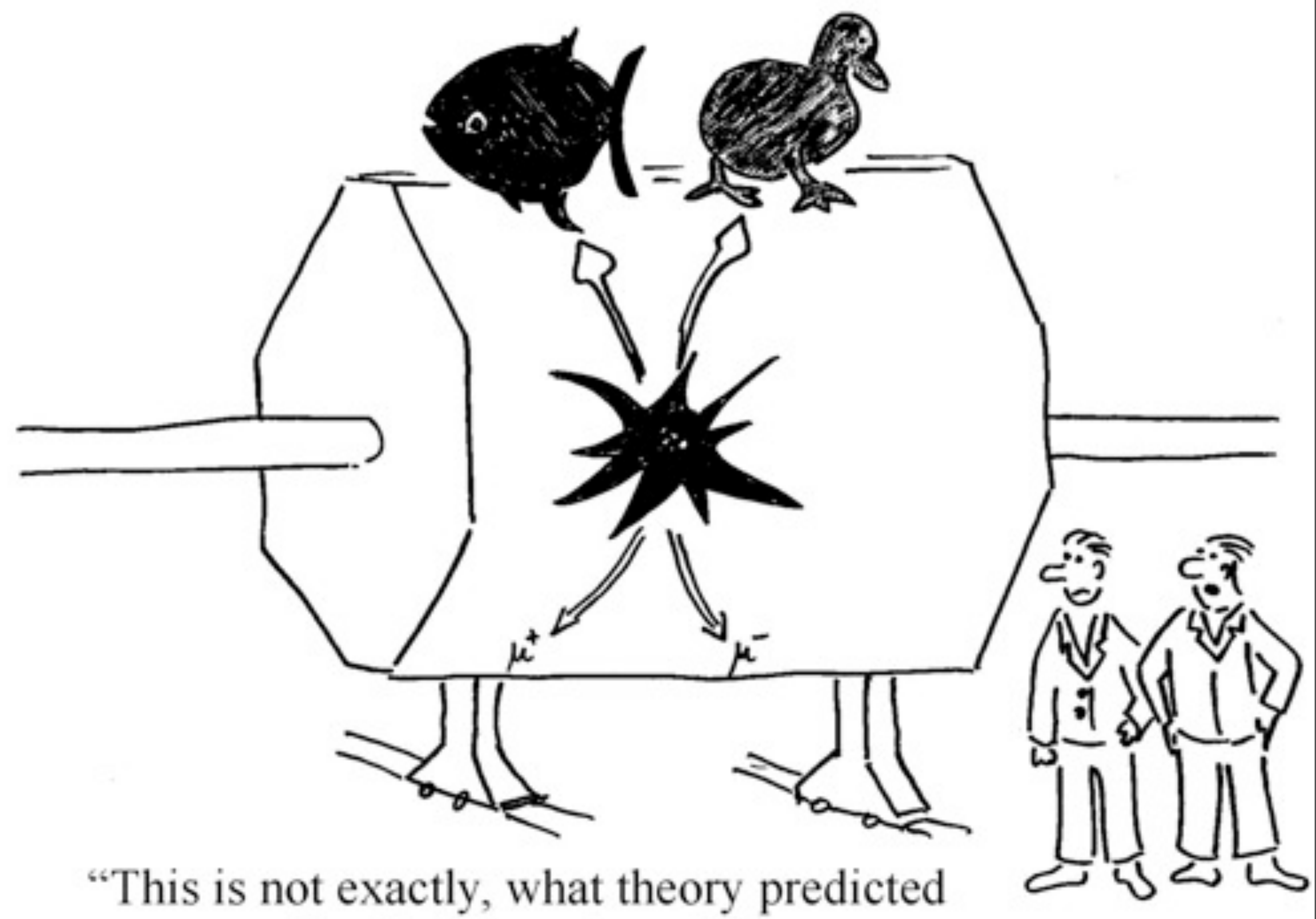



The measured differential cross sections are compared with various theoretical predictions (NLO Powheg NNLO+NNLL HRes).

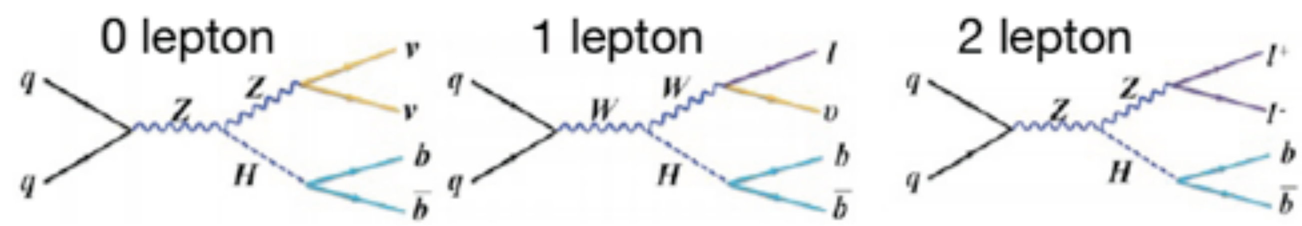
Within the experimental and theoretical uncertainties, no significant deviation from the SM expectation is observed.

# Other search channels (SM and BSM)

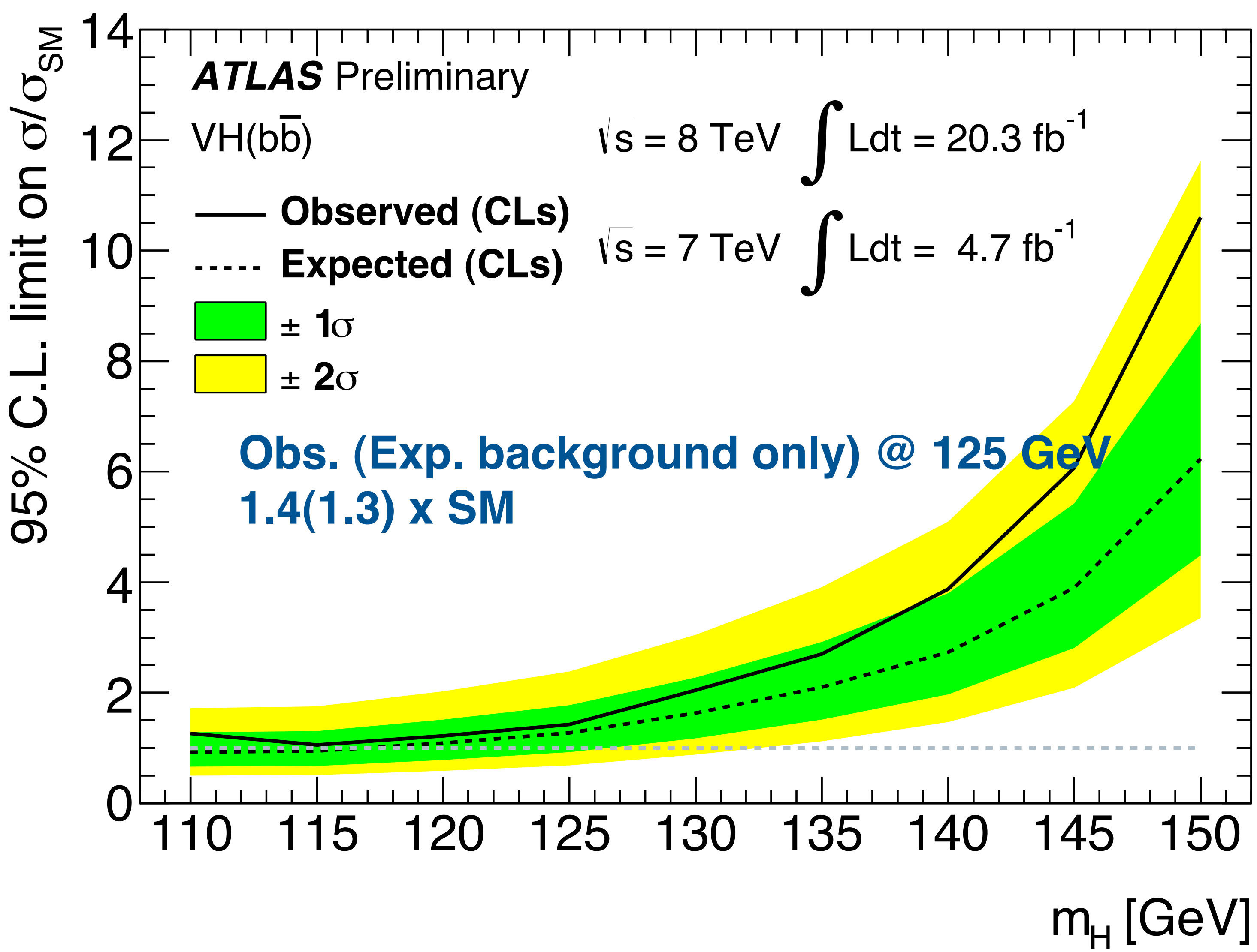


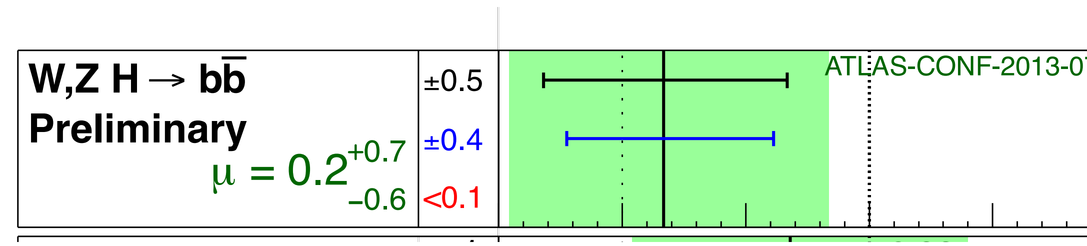
"This is not exactly, what theory predicted for the Higgs decay!"

# VH, H→bb




- High BR (57%) but difficult backgrounds:
  (WZ, WW, tt, single t, Wt, Wbb, Wcc, Zbb, multijet)
- Categories in different $p_T^V$ to improve sensitivity (0, 90, 120, 160 and 200 GeV)
- Further categorisation used for background estimations from data: number of leptons (0,1,2), number of jets (2,3), number of b-tagged jets (1,2).



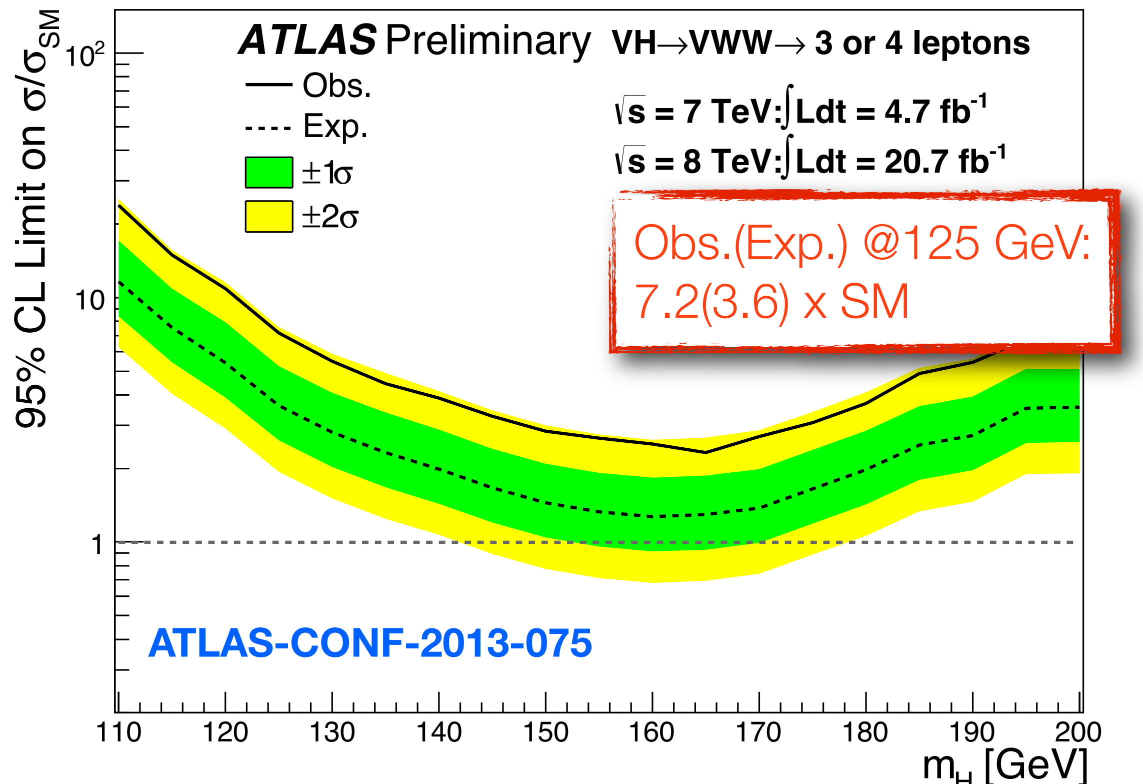




**ATLAS-CONF-2012-079**

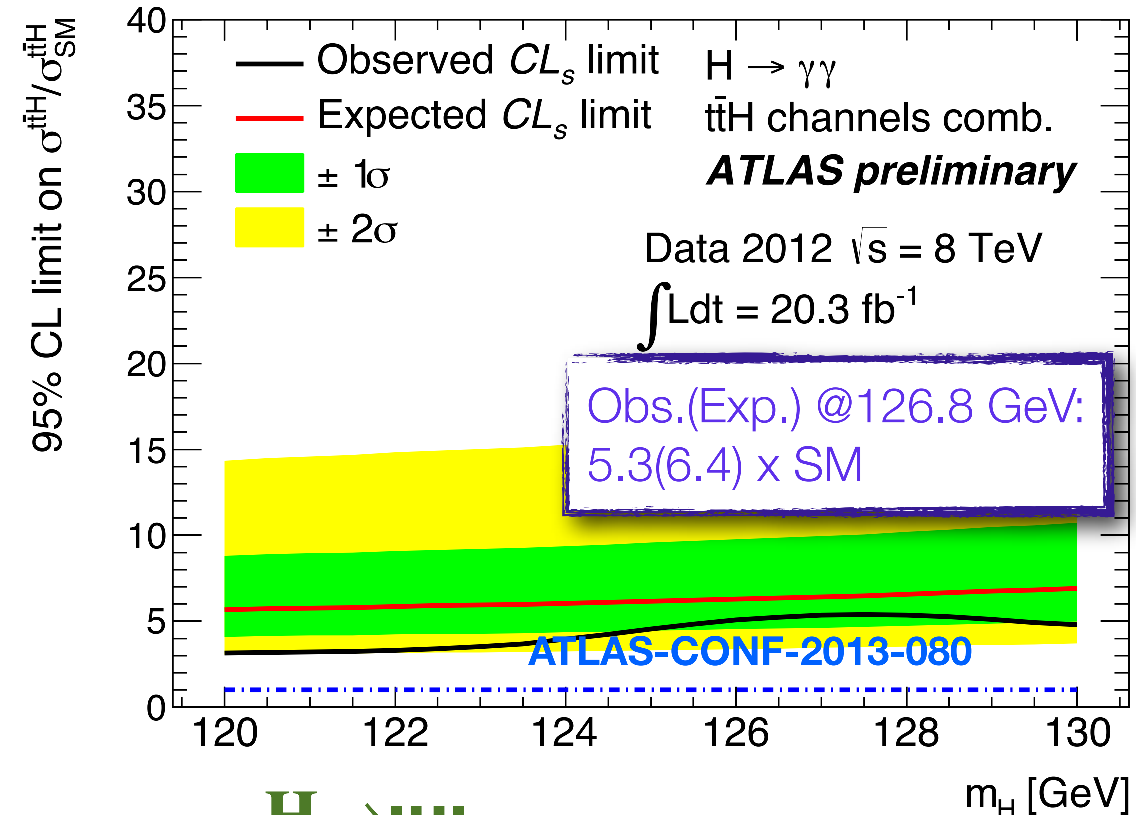
No significant excess observed: data consistent with either SM backgrounds only,and SM backgrounds + Higgs.

# Rare production/decays modes

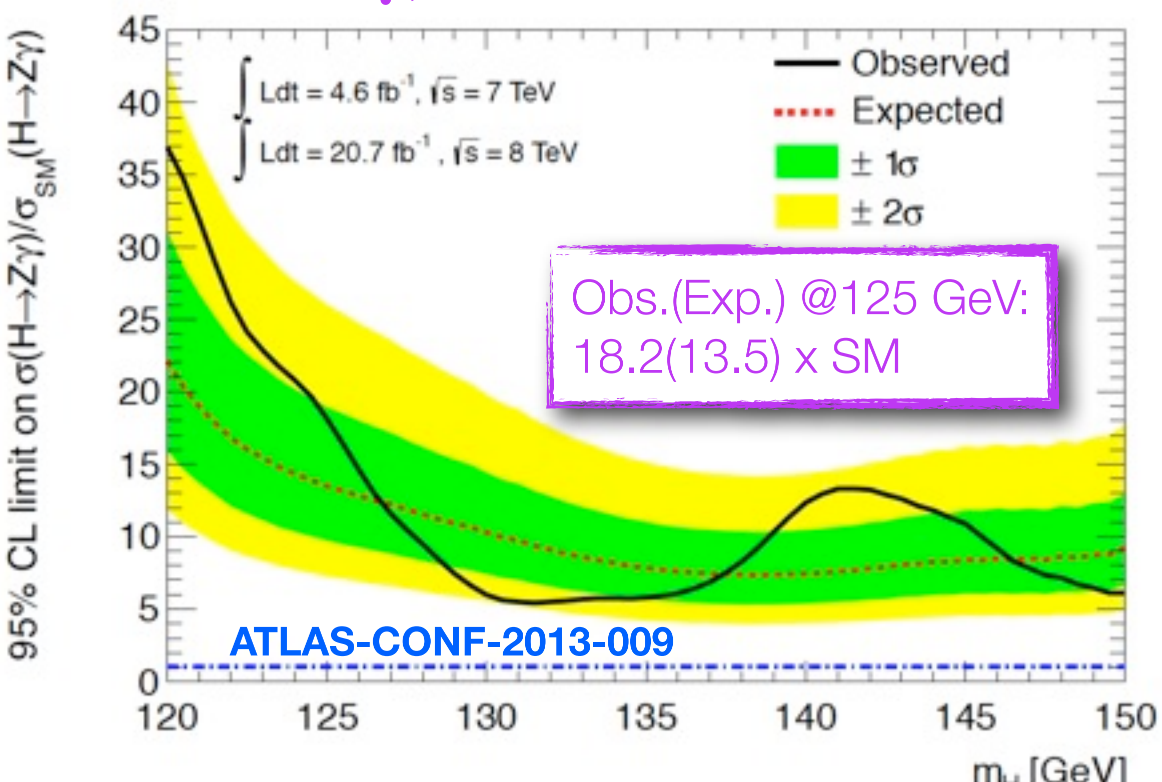
## VH, H→ WW(*) (leptonic W decay)



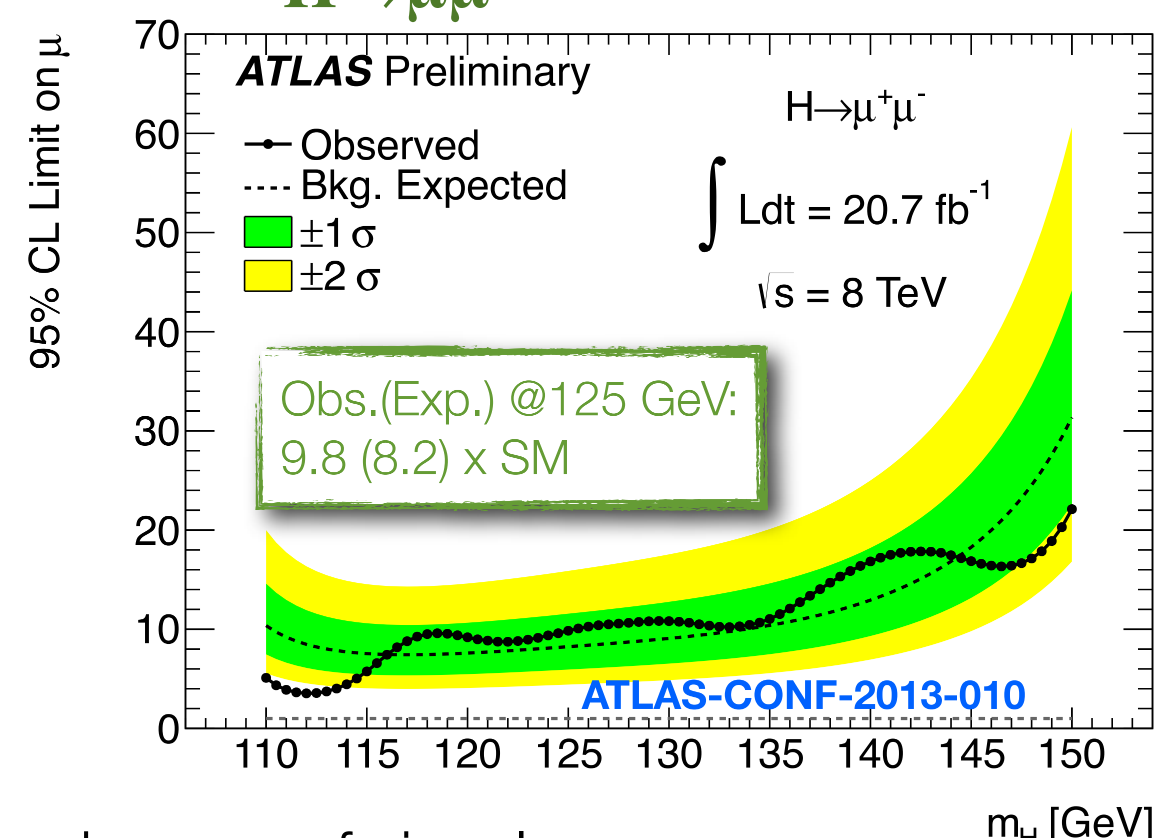

## ttH, H→γ γ




## H→Zγ, Z→ll




## H→μμ



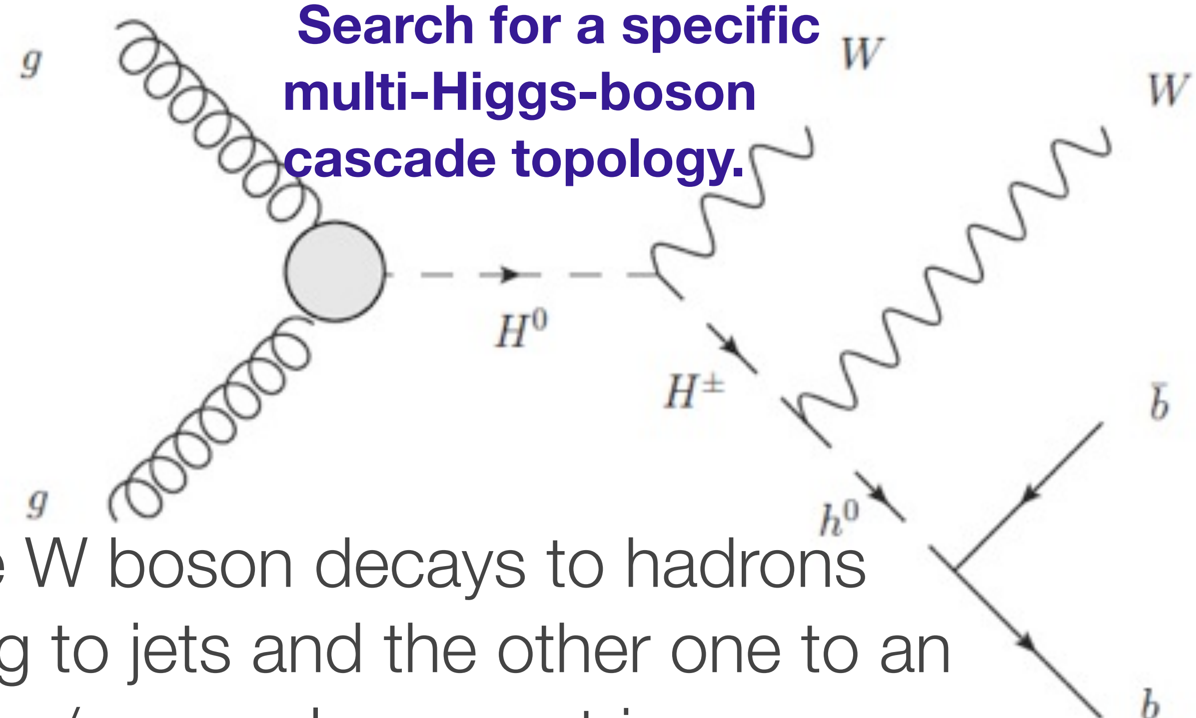

Exp. : Expected limit in the absence of signal

# BSM Higgs: Search for a multi-Higgs-boson cascade in $W^+W^-bb$ events

CERN-PH-EP-2013-173
Submitted to PRD

Extension to the SM: heavier neutral Higgs + charged Higgs + a light neutral Higgs boson, $h_0$ (with $m_{h0}$ = 125 GeV).

**Search for a specific multi-Higgs-boson cascade topology.**

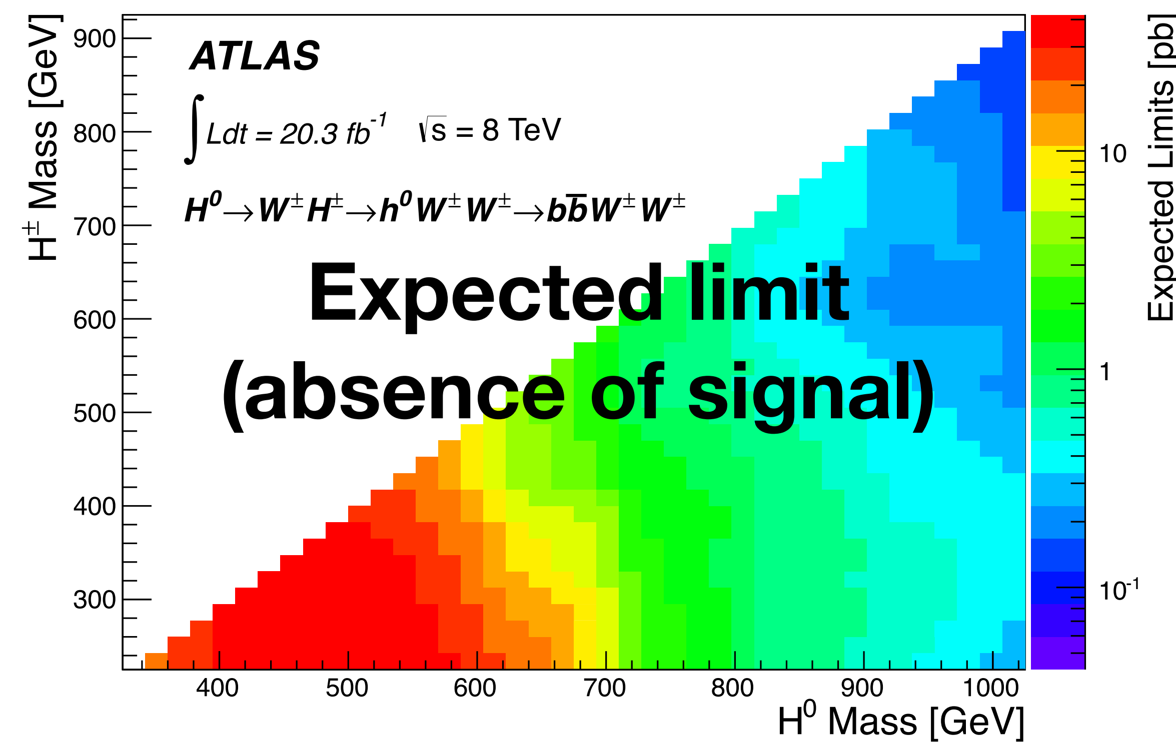


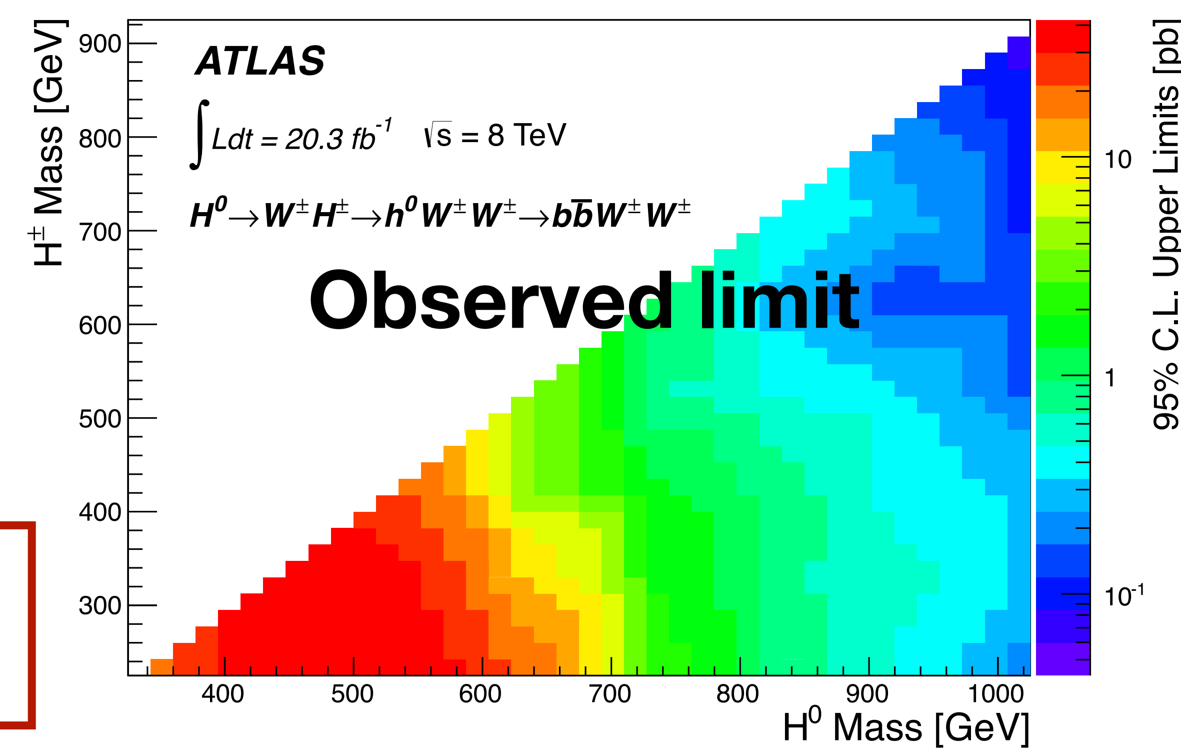

- One W boson decays to hadrons leading to jets and the other one to an electron/muon plus a neutrino.

- BDTs used to distinguish the signal cascade events from tt background.

No significant excess of events above the expectation from the SM background was found.

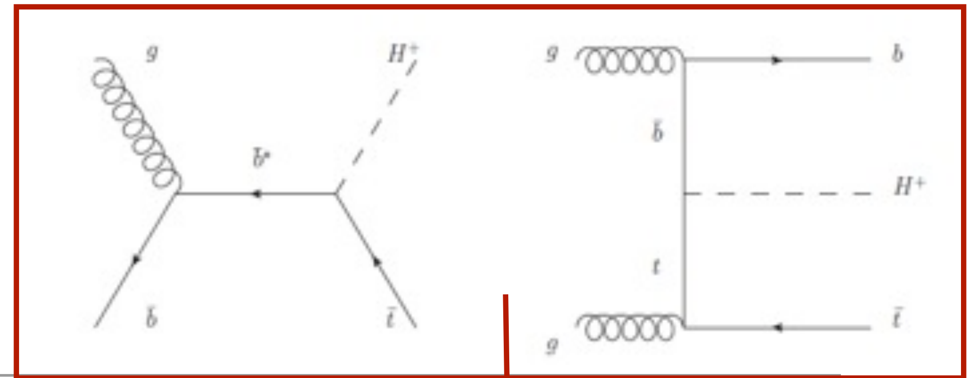
Limits on the observed XS:



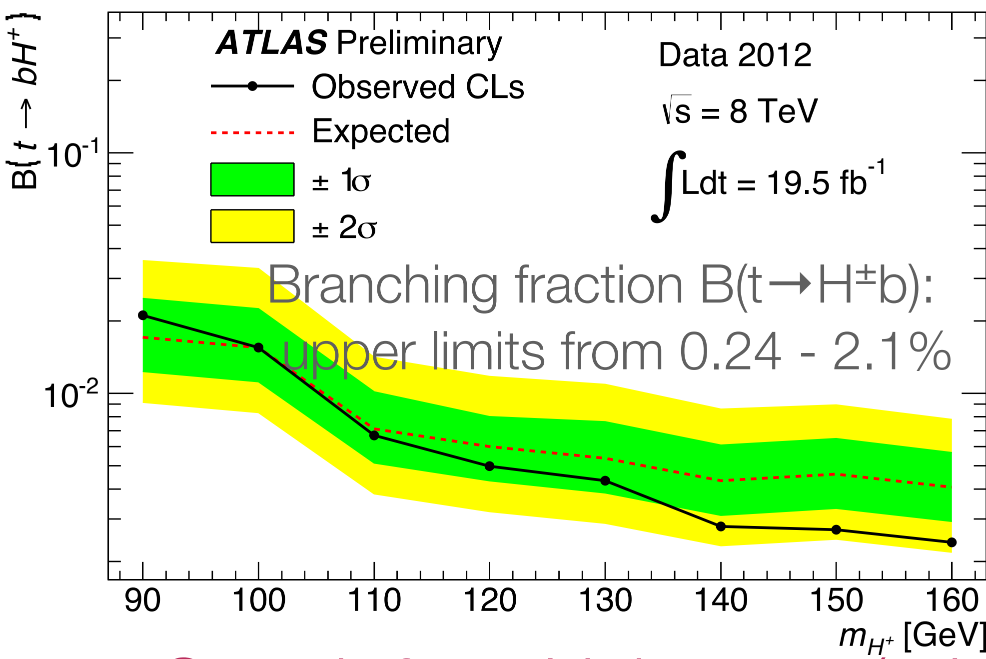
# BSM Higgs -Recent Results

Search for $H^{\pm} \rightarrow \tau\nu$ + jets (uses the assumption that $B(H^{\pm} \rightarrow \tau\nu = 1.)$:

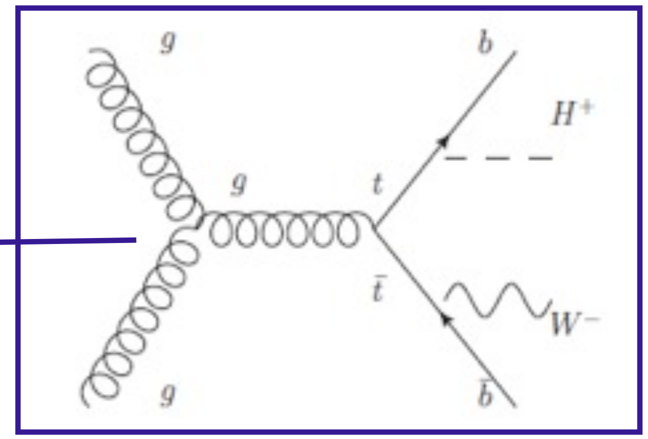



**Light Higgs ($mH^{\pm}$< mt) ttb→ $H^{\pm}bWb$:**

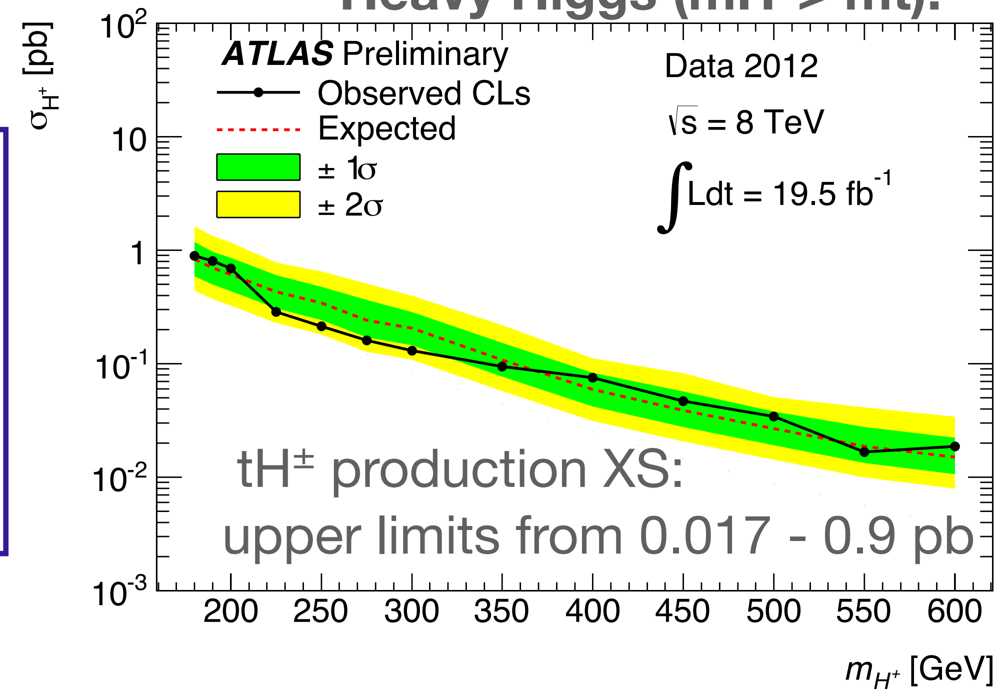
**ATLAS-CONF-2013-090**




Branching fraction $B(t \rightarrow H^{\pm}b)$: upper limits from 0.24 - 2.1%

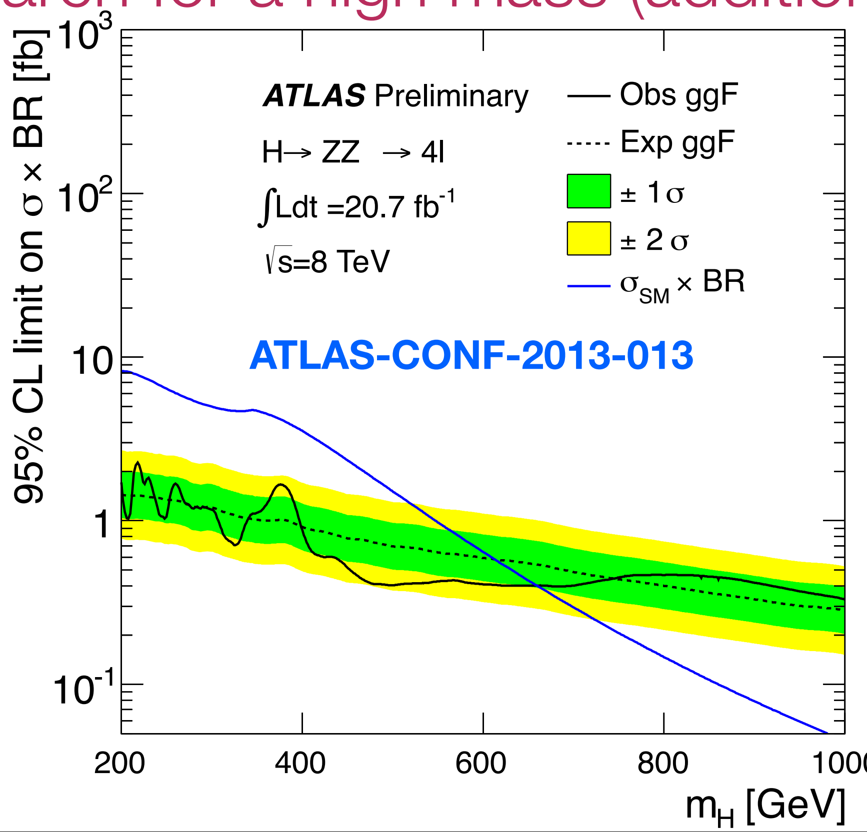


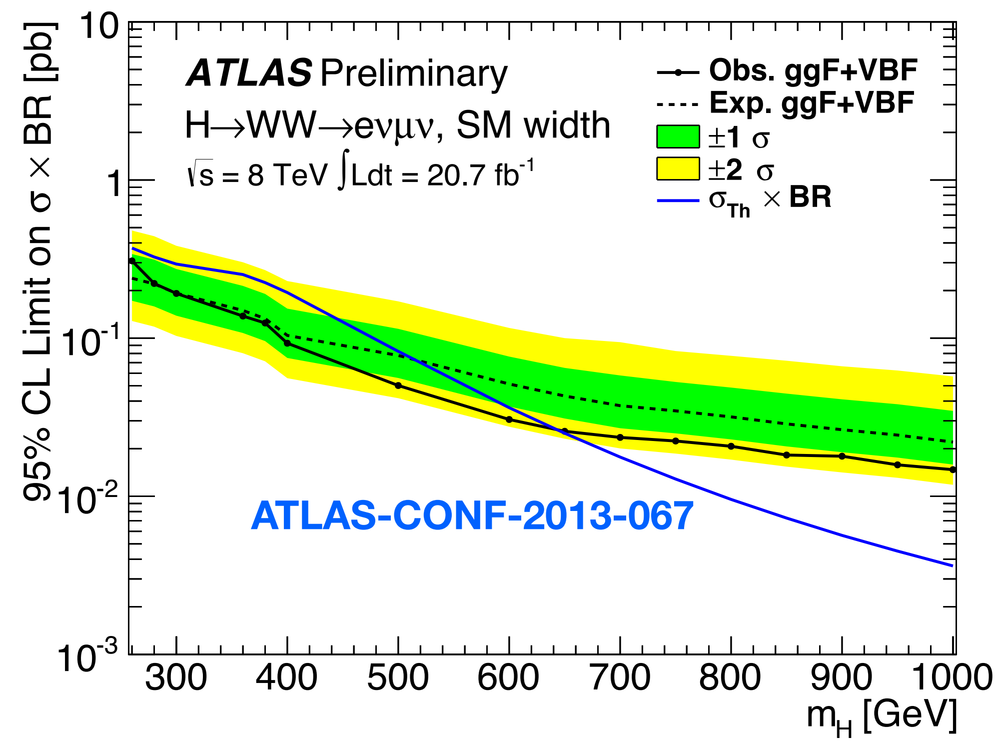

**Heavy Higgs ($mH^{\pm}$> mt):**




$tH^{\pm}$ production XS: upper limits from 0.017 - 0.9 pb

Search for a high mass (additional) neutral Higgs in the ZZ and WW decay modes:



# Additional SM and BSM Higgs searches

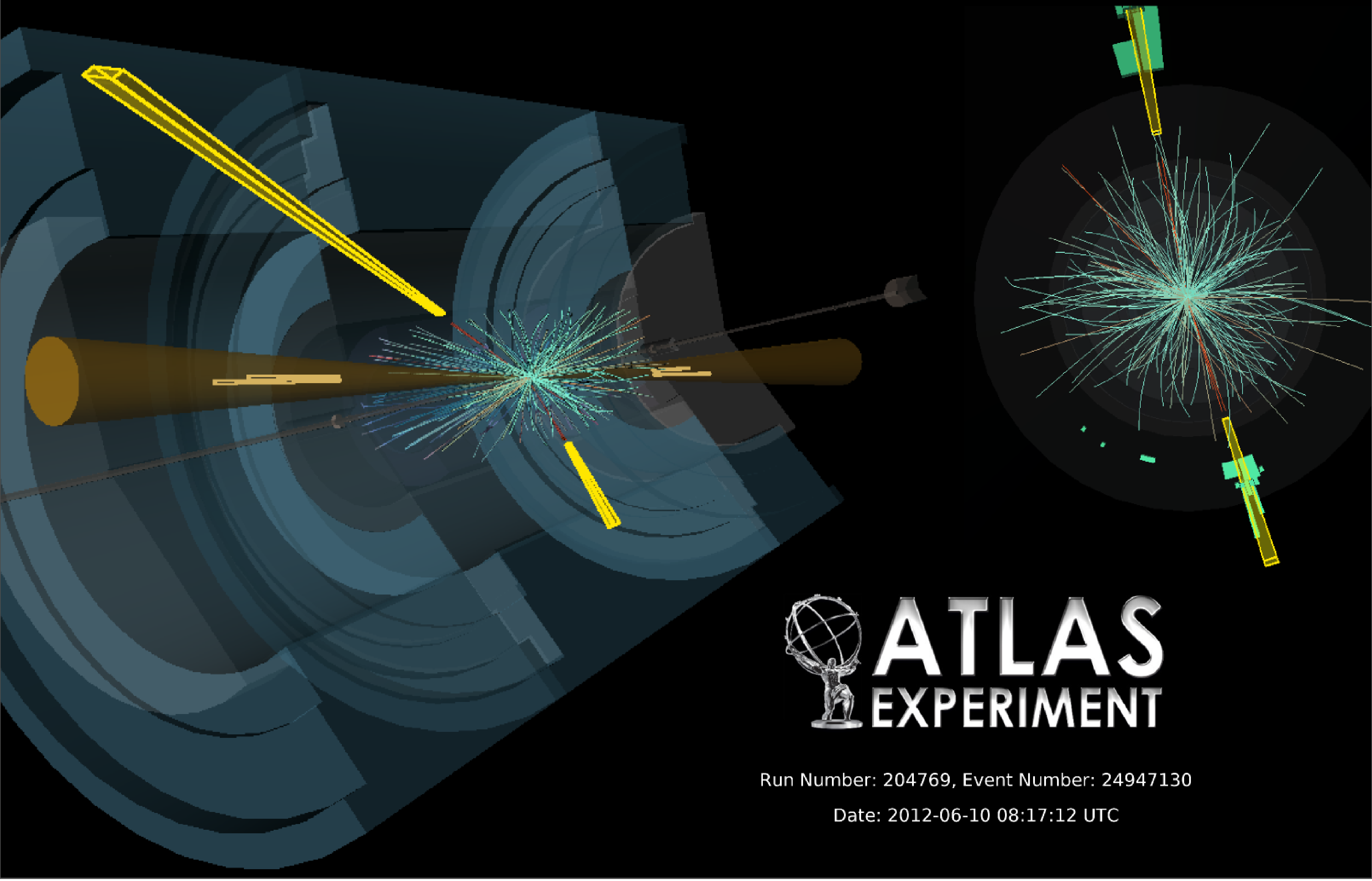
- FCNC in $t \to cH$, $H \to \gamma\gamma$ - upper limit on BR: Obs.(Exp.): 0.83%(0.53%) x SM for 125 GeV at 95% CL [ATLAS-CONF-2013-081]
- $H \to ZZ \to ll\nu\nu$: Excl. 320 - 560 GeV [ATLAS-CONF-2012-016]
- $H \to ZZ \to llqq$: Excl. 300 - 310, 360 - 400 GeV. at 145 GeV 3.5 x SM [ATLAS-CONF-2012-017]
- $H \to WW \to l\nu jj$: at 400 GeV Obs.(Exp.) 2.3(1.6) x SM [ATLAS-CONF-2012-018]
- Higgs in SM with 4th fermion generation: model ruled out [ATLAS-CONF-2011-135]
- Fermiophobic H to diphoton Model ruled out [ATLAS-CONF-2012-013]
- MSSM neutral H [JHEP: JHEP02(2013)095]
- NMSSM a1 to $\mu\mu$ [ATLAS-CONF-2011-020]
- NMSSM H to a0a0 to $4\gamma$ [ATLAS-CONF-2012-079]
- $H^{\pm} \to cs$ [EPJC73 (2013) 2465]
- 2HDM WW(lvlv) [ATLAS-CONF-2013-027]

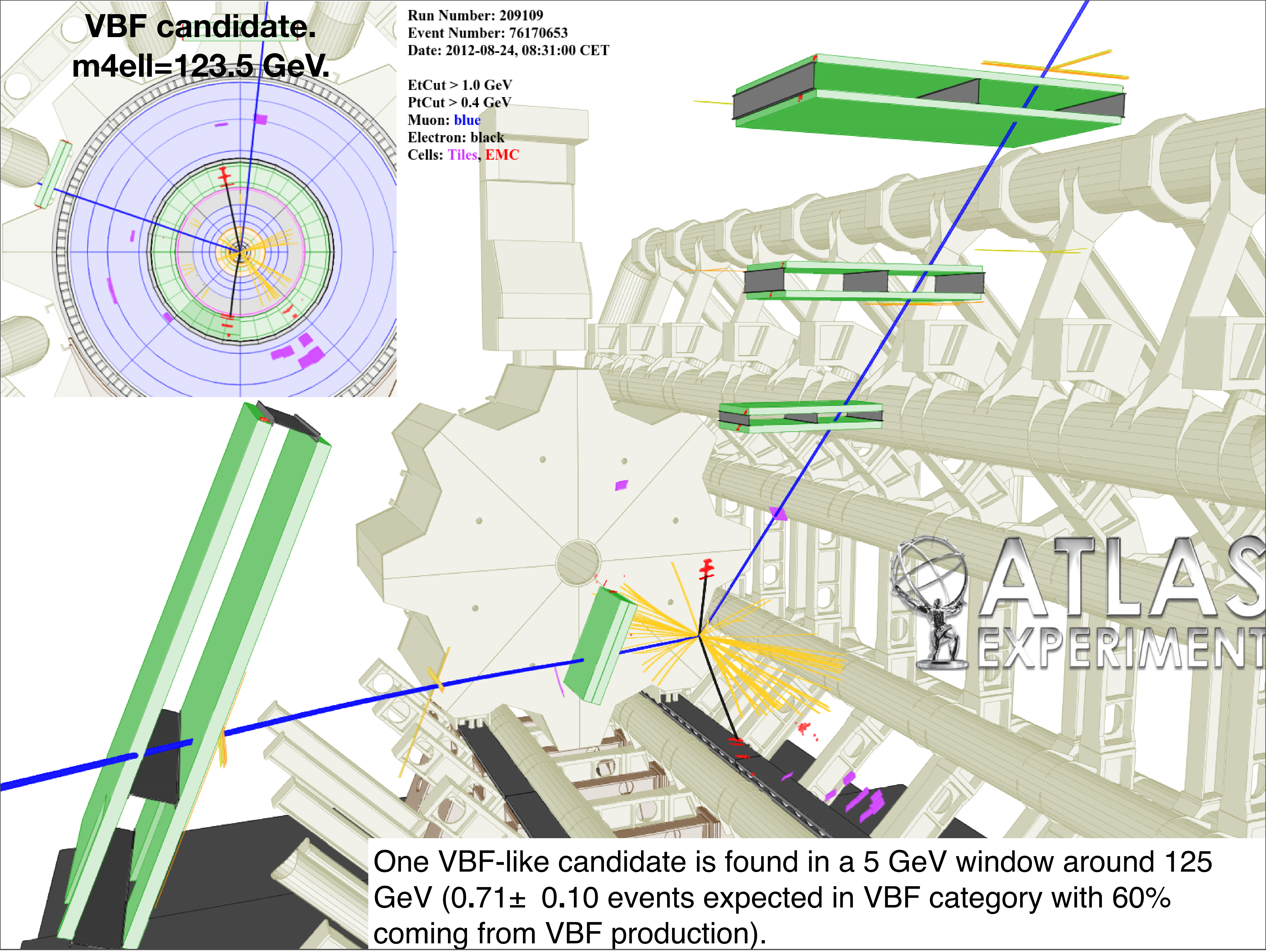
# Summary

- LHC-ATLAS Run 1 finished with great success
- After the discovery of the new boson, its properties are being measured. It is looking more like the SM Higgs boson:
  - Combined mass measurement mH=125.5 ± 0.2(stat) $^{+0.5}_{-0.6}$(sys) GeV
  - Combined signal strength $\mu$ = 1.3 ± 0.14(stat) ± 0.15 (sys)
  - The spin/parity measurements favour SM $J^P = 0^+$
  - Direct evidence for fermionic decays from $H \rightarrow \tau\tau$
  - First results on various rare production decay modes and BSM Higgs models.
- ATLAS is preparing for LHC Run II (13/14 TeV and $10^{34}$ cm$^{-2}$ s$^{-1}$):
  - Rare SM Higgs production/decays should achieve observation sensitivity.
  - More precise measurements to test/challenge the SM predictions
  - Look for surprises... Exciting times ahead, stay tuned!!...

Back-up

Event display of a VBF H→γγ candidate, containing two converted photons and two high-mass jets.





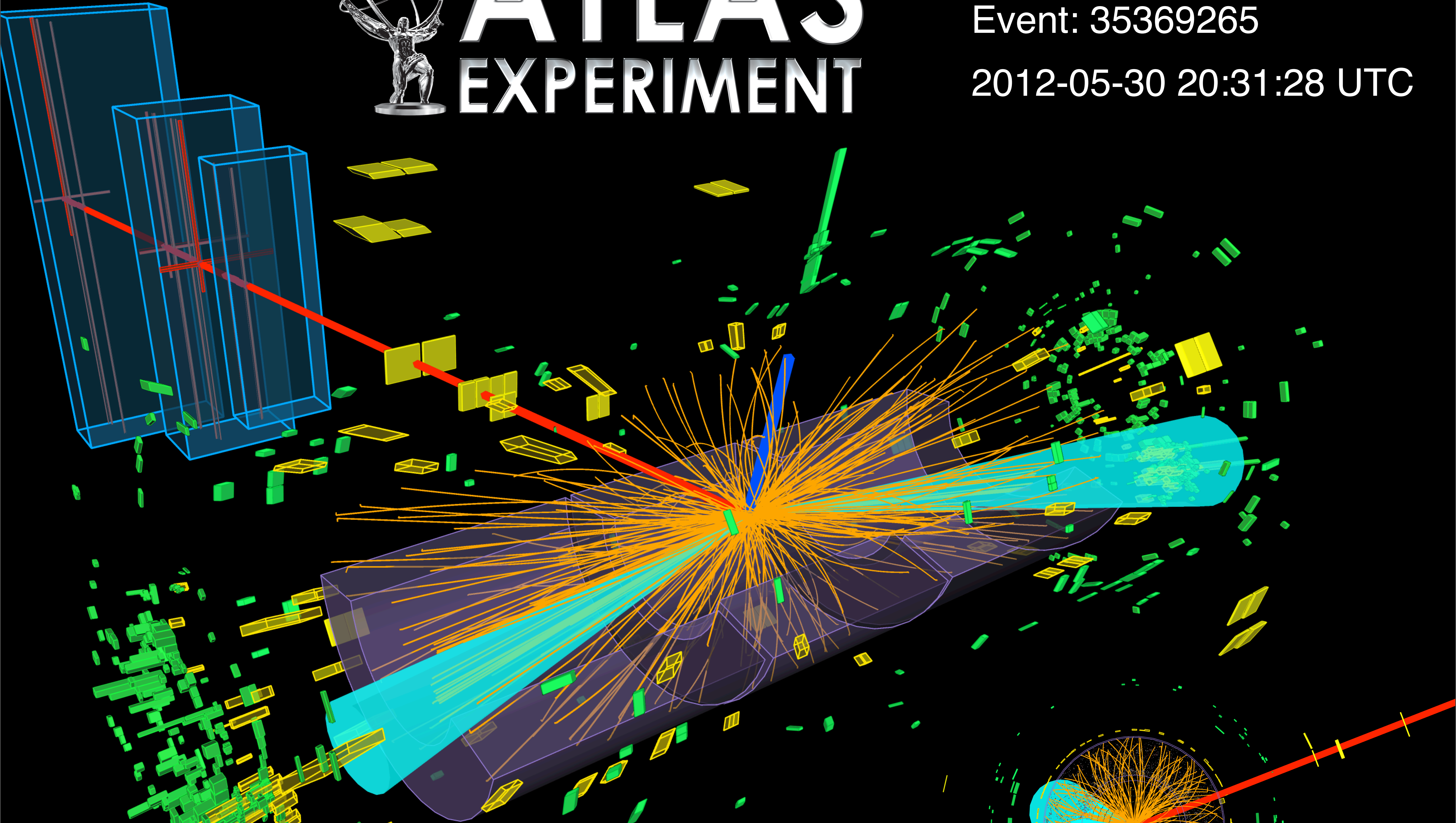

One VBF-like candidate is found in a 5 GeV window around 125 GeV (0.71± 0.10 events expected in VBF category with 60% coming from VBF production).

ATLAS EXPERIMENT

Run: 204153

Event: 35369265

2012-05-30 20:31:28 UTC



**$H \rightarrow \tau_{lep}\tau_{lep}$ channel candidate in the VBF category: One τ decays to a muon (red track) and the other to an electron (blue track). The dashed line in the R-ϕ view is the direction of the $E_{Tmiss}$ vector. There are two VBF jets (turquoise cones).**

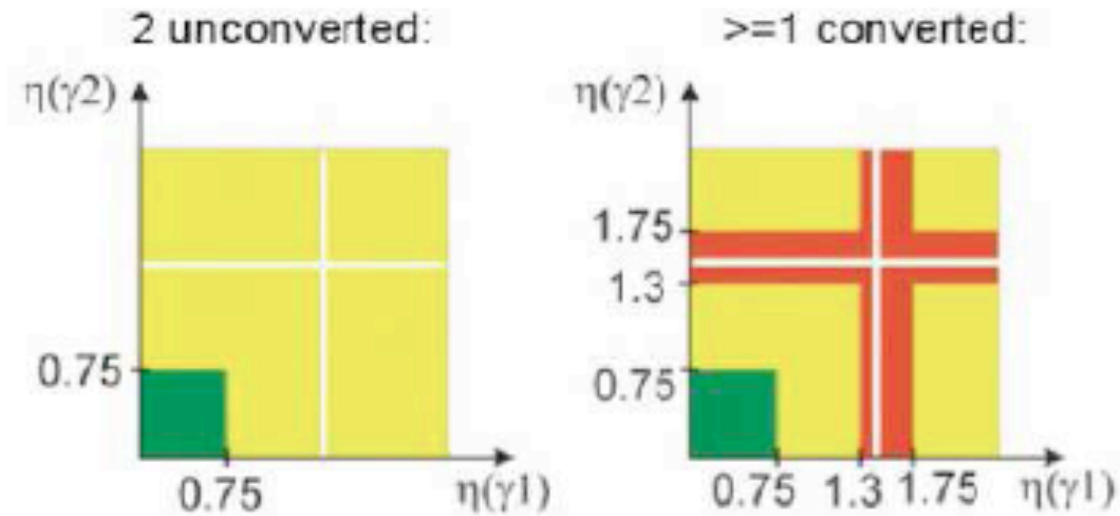
# Higgs to di-photon Categories

Both unconverted:

- Central
- Rest

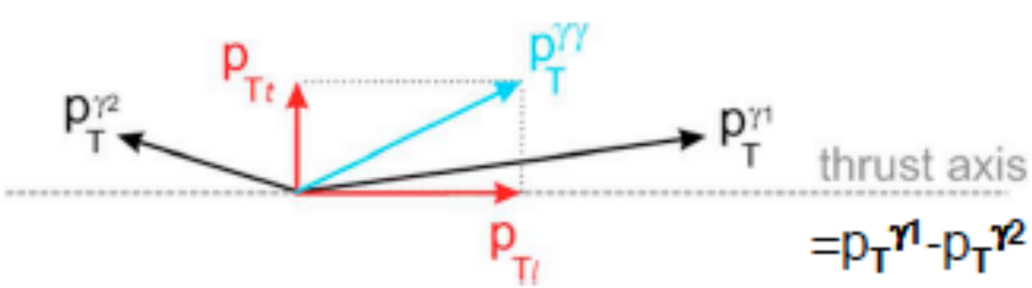
At least one converted:

- Central
- Transition
- Rest

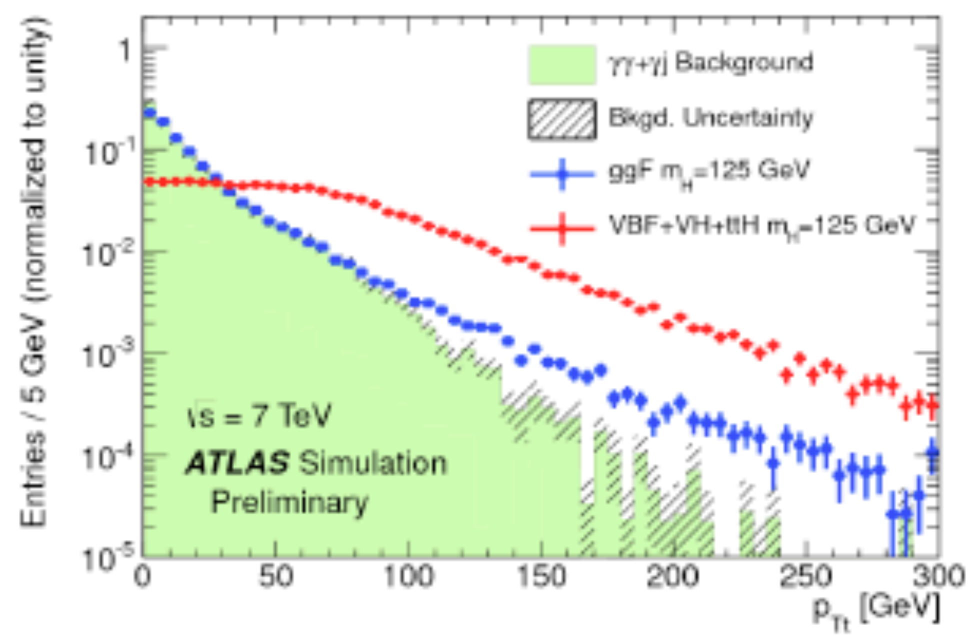



*Resolution:*

*Good*
*Medium*
*Poor*




Variable $p_{Tt}$ is strongly correlated with diphoton $p_T$ but has better detector resolution and retains a monotically falling invariant mass for background



# Higgs to di-photon Uncertainties

| Source | Uncertainty (%) |
|---|---|
| On signal yield | |
| Photon identification | $\pm 2.4$ |
| Trigger | $\pm 0.5$ |
| Isolation | $\pm 1.0$ |
| Photon energy scale | $\pm 0.25$ |
| ggF (theory), tight high-mass two-jet cat. | $\pm 48$ |
| ggF (theory), loose high-mass two-jet cat. | $\pm 28$ |
| ggF (theory), low-mass two-jet cat. | $\pm 30$ |
| Impact of background modelling | $\pm(2\text{–}14)$, cat.-dependent |
| On category population (migration) | |
| Material modelling | $-4$ (unconv), $+3.5$ (conv) |
| $p_{\mathrm{T}}$ modelling | $\pm 1$ (low-$p_{\mathrm{Tt}}$),<br>$\mp(9\text{–}12)$ (high-$p_{\mathrm{Tt}}$, jets),<br>$\pm(2\text{–}4)$ (lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$) |
| $\Delta\phi_{\gamma\gamma,jj}$, $\eta^*$ modelling in ggF | $\pm(9\text{–}12)$, $\pm(6\text{–}8)$ |
| Jet energy scale and resolution | $\pm(7\text{–}12)$ (jets),<br>$\mp(0\text{–}1)$ (others) |
| Underlying event two-jet cat. | $\pm 4$ (high-mass tight),<br>$\pm 8$ (high-mass loose),<br>$\pm 12$ (low-mass) |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | $\pm 4$ ($E_{\mathrm{T}}^{\mathrm{miss}}$ category) |
| On mass scale and resolution | |
| Mass measurement | $\pm 0.6$, cat.-dependent |
| Signal mass resolution | $\pm(14\text{–}23)$, cat.-dependent |

# Higgs to 4 leptons
# Uncertainties

| Source | Uncertainty (%) | | | |
|---|---|---|---|---|
| Signal yield | $4\mu$ | $2\mu 2e$ | $2e2\mu$ | $4e$ |
| Muon reconstruction and identification | ±0.8 | ±0.4 | ±0.4 | – |
| Electron reconstruction and identification | – | ±8.7 | ±2.4 | ±9.4 |
| Reducible background (inclusive analysis) | ±24 | ±10 | ±23 | ±13 |
| Migration between categories | | | | |
| ggF/VBF/VH contributions to VBF-like cat. | ±32/11/11 | | | |
| $ZZ^*$ contribution to VBF-like cat. | ±36 | | | |
| ggF/VBF/VH contributions to VH-like cat. | ±15/5/6 | | | |
| $ZZ^*$ contribution to VH-like cat. | ±30 | | | |
| Mass measurement | $4\mu$ | $2\mu 2e$ | $2e2\mu$ | $4e$ |
| Lepton energy and momentum scale | ±0.2 | ±0.2 | ±0.3 | ±0.4 |

# H→WW selection

| Category | $N_{\rm jet}=0$ | $N_{\rm jet}=1$ | $N_{\rm jet}\geq 2$ |
|---|---|---|---|
| Pre-selection | Two isolated leptons ($\ell = e,\mu$) with opposite charge<br>Leptons with $p_{\rm T}^{\rm lead} > 25$ and $p_{\rm T}^{\rm sublead} > 15$<br>$e\mu+\mu e$: $m_{\ell\ell} > 10$<br>$ee+\mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z\rvert > 15$ | | |
| Missing transverse momentum and hadronic recoil | $e\mu+\mu e$: $E_{\rm T,rel}^{\rm miss} > 25$<br>$ee+\mu\mu$: $E_{\rm T,rel}^{\rm miss} > 45$<br>$ee+\mu\mu$: $p_{\rm T,rel}^{\rm miss} > 45$<br>$ee+\mu\mu$: $f_{\rm recoil} < 0.05$ | $e\mu+\mu e$: $E_{\rm T,rel}^{\rm miss} > 25$<br>$ee+\mu\mu$: $E_{\rm T,rel}^{\rm miss} > 45$<br>$ee+\mu\mu$: $p_{\rm T,rel}^{\rm miss} > 45$<br>$ee+\mu\mu$: $f_{\rm recoil} < 0.2$ | $e\mu+\mu e$: $E_{\rm T}^{\rm miss} > 20$<br>$ee+\mu\mu$: $E_{\rm T}^{\rm miss} > 45$<br>$ee+\mu\mu$: $E_{\rm T,STVF}^{\rm miss} > 35$<br>- |
| General selection | -<br>$\lvert\Delta\phi_{\ell\ell,MET}\rvert > \pi/2$<br>$p_{\rm T}^{\ell\ell} > 30$ | $N_{b\text{-jet}} = 0$<br>-<br>$e\mu+\mu e$: $Z/\gamma^* \to \tau\tau$ veto | $N_{b\text{-jet}} = 0$<br>$p_{\rm T}^{\rm tot} < 45$<br>$e\mu+\mu e$: $Z/\gamma^* \to \tau\tau$ veto |
| VBF topology | -<br>-<br>-<br>- | -<br>-<br>-<br>- | $m_{jj} > 500$<br>$\lvert\Delta y_{jj}\rvert > 2.8$<br>No jets ($p_{\rm T} > 20$) in rapidity gap<br>Require both $\ell$ in rapidity gap |
| $H \to WW^{(*)} \to \ell\nu\ell\nu$ topology | $m_{\ell\ell} < 50$<br>$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$<br>$e\mu+\mu e$: split $m_{\ell\ell}$<br>Fit $m_{\rm T}$ | $m_{\ell\ell} < 50$<br>$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$<br>$e\mu+\mu e$: split $m_{\ell\ell}$<br>Fit $m_{\rm T}$ | $m_{\ell\ell} < 60$<br>$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$<br>-<br>Fit $m_{\rm T}$ |

Table 11: Summary selection table for 8 TeV data for events in the $m_{\rm T}$ range noted in Section 3.5. The uncertainty on $N_{\rm bkg}$ accounts for the correlations among the sources. More details are given in the caption of Table 7.

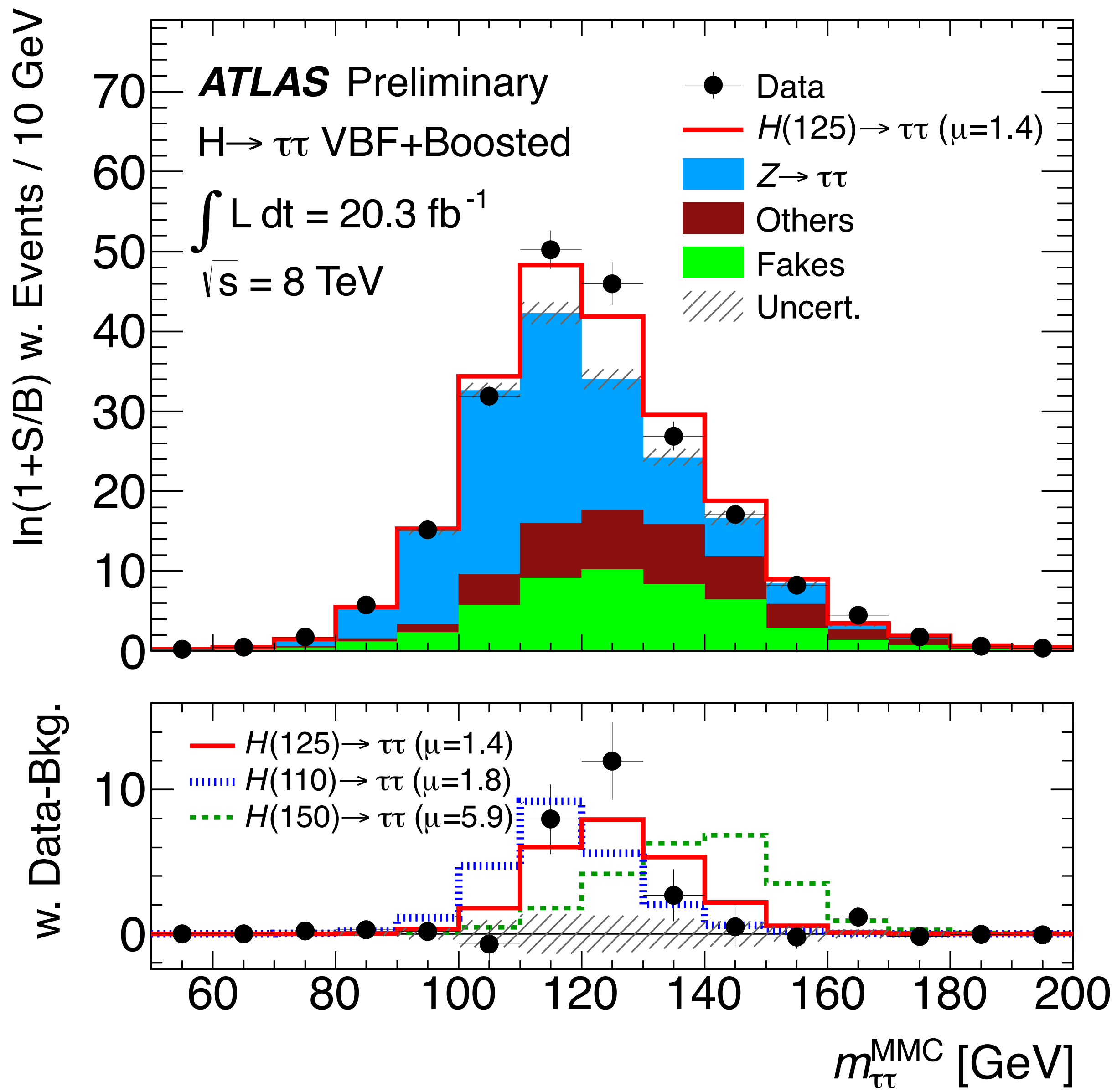
| $N_{\rm jet}$ | $N_{\rm obs}$ | $N_{\rm bkg}$ | $N_{\rm sig}$ | $N_{WW}$ | $N_{VV}$ | $N_{t\bar{t}}$ | $N_t$ | $N_{Z/\gamma^*}$ | $N_{W+\rm jets}$ |
|---|---|---|---|---|---|---|---|---|---|
| $=0$ | 831 | $739\pm39$ | $97\pm20$ | $551\pm41$ | $58\pm8$ | $23\pm3$ | $16\pm2$ | $30\pm10$ | $61\pm21$ |
| $=1$ | 309 | $261\pm28$ | $40\pm13$ | $108\pm40$ | $27\pm6$ | $68\pm18$ | $27\pm10$ | $12\pm6$ | $20\pm5$ |
| $\geq 2$ | 55 | $36\pm4$ | $10.6\pm1.4$ | $4.1\pm1.5$ | $1.9\pm0.4$ | $4.6\pm1.7$ | $0.8\pm0.4$ | $22\pm3$ | $0.7\pm0.2$ |

# Missing Mass Calculator

Due to neutrinos there is a limited mass resolution. With the MMC 13-20% of mass resolution is achieved.

The method allows to partially compensate the effects of MET resolution.

MMC defines an event global likelihood which will constrain the kinematics of the decays: requiring that relative orientations of the neutrinos and other decay products are consistent with the mass and kinematics of the τ decay.




http://arxiv.org/pdf/1012.4686v2.pdf

# H→ττ channel: Inputs to BDT per categories

| Variable | VBF | | | Boosted | | |
|---|---|---|---|---|---|---|
| | $\tau_{\rm lep}\tau_{\rm lep}$ | $\tau_{\rm lep}\tau_{\rm had}$ | $\tau_{\rm had}\tau_{\rm had}$ | $\tau_{\rm lep}\tau_{\rm lep}$ | $\tau_{\rm lep}\tau_{\rm had}$ | $\tau_{\rm had}\tau_{\rm had}$ |
| $m_{\tau\tau}^{\rm MMC}$ | • | • | • | • | • | • |
| $\Delta R(\tau,\tau)$ | • | • | • | | • | • |
| $\Delta\eta(j_1,j_2)$ | • | • | • | | | |
| $m_{j_1,j_2}$ | • | • | • | | | |
| $\eta_{j_1}\times\eta_{j_2}$ | | • | • | | | |
| $p_{\rm T}^{\rm Total}$ | | • | • | | | |
| sum $p_{\rm T}$ | | | | | • | • |
| $p_{\rm T}(\tau_1)/p_{\rm T}(\tau_2)$ | | | | | • | • |
| $E_{\rm T}^{\rm miss}\phi$ centrality | | • | • | • | • | • |
| $x_{\tau 1}$ and $x_{\tau 2}$ | | | | | | • |
| $m_{\tau\tau,j_1}$ | | | | • | | |
| $m_{\ell_1,\ell_2}$ | | | | • | | |
| $\Delta\phi_{\ell_1,\ell_2}$ | | | | • | | |
| sphericity | | | | • | | |
| $p_{\rm T}^{\ell_1}$ | | | | • | | |
| $p_{\rm T}^{j_1}$ | | | | • | | |
| $E_{\rm T}^{\rm miss}/p_{\rm T}^{\ell_2}$ | | | | • | | |
| $m_{\rm T}$ | | • | | | • | |
| $\min(\Delta\eta_{\ell_1\ell_2,{\rm jets}})$ | • | | | | | |
| $j_3$ $\eta$ centrality | • | | | | | |
| $\ell_1\times\ell_2$ $\eta$ centrality | • | | | | | |
| $\ell$ $\eta$ centrality | | • | | | | |
| $\tau_{1,2}$ $\eta$ centrality | | | • | | | |

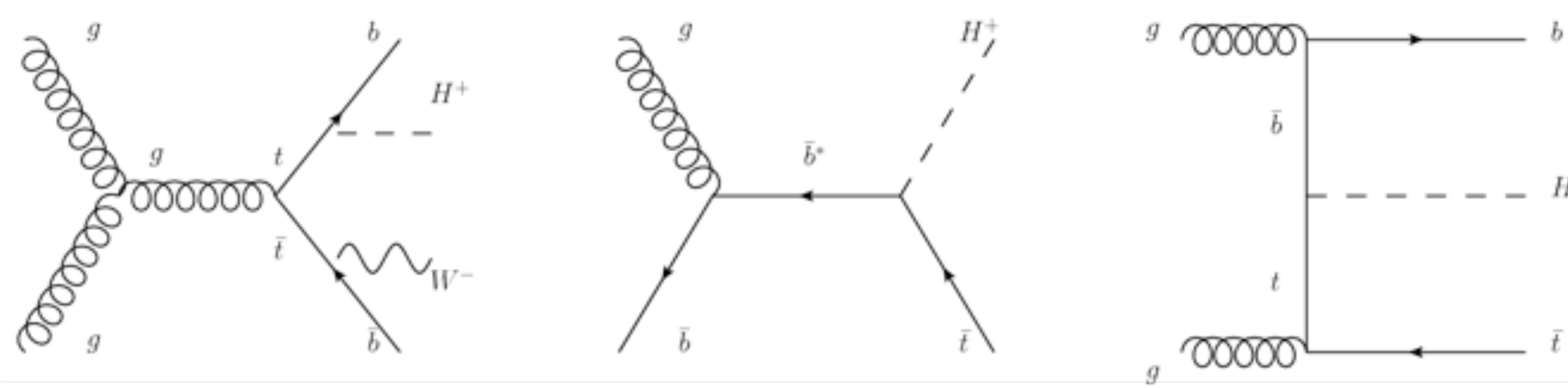
Table 3: Discriminating variables used for each channel and category. The filled circles identify which variables are used in each decay mode. Note that variables such as $\Delta R(\tau,\tau)$ are defined either between the two leptons, between the lepton and $\tau_{\rm had}$, or between the two $\tau_{\rm had}$ candidates, depending on the decay mode.

# H→ττ channel: Uncertainties

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

Table 7: The important sources of uncertainty on the measured signal strength parameter $\mu$, given as absolute uncertainties on $\mu$.

# BSM Higgs -Recent Results




Search for H± ➝ τν + jets in mass range 180 – 600 GeV (uses the the assumption that B(H± ➝ τν = 1)):

The exclusion limits for the light and heavy H± are also interpreted in terms of the MSSM $m_h^{max}$ scenario with the Higgsino mass parameter μ = 200 GeV. For this interpretation, the assumption of B(H± ➝ τν = 1) is no longer held.