# Selected Highlights from Higgs Results at the LHC-ATLAS Experiment

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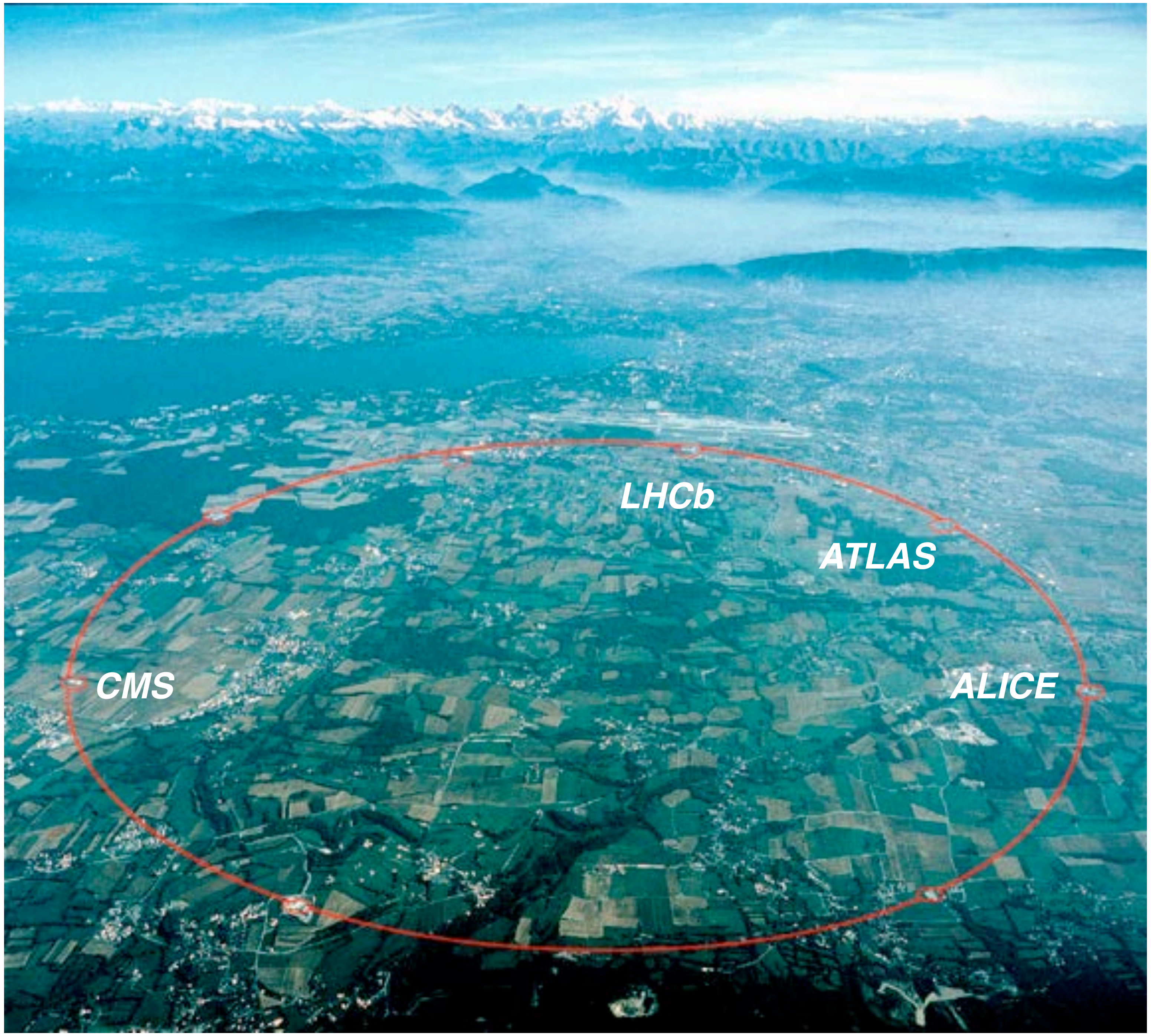
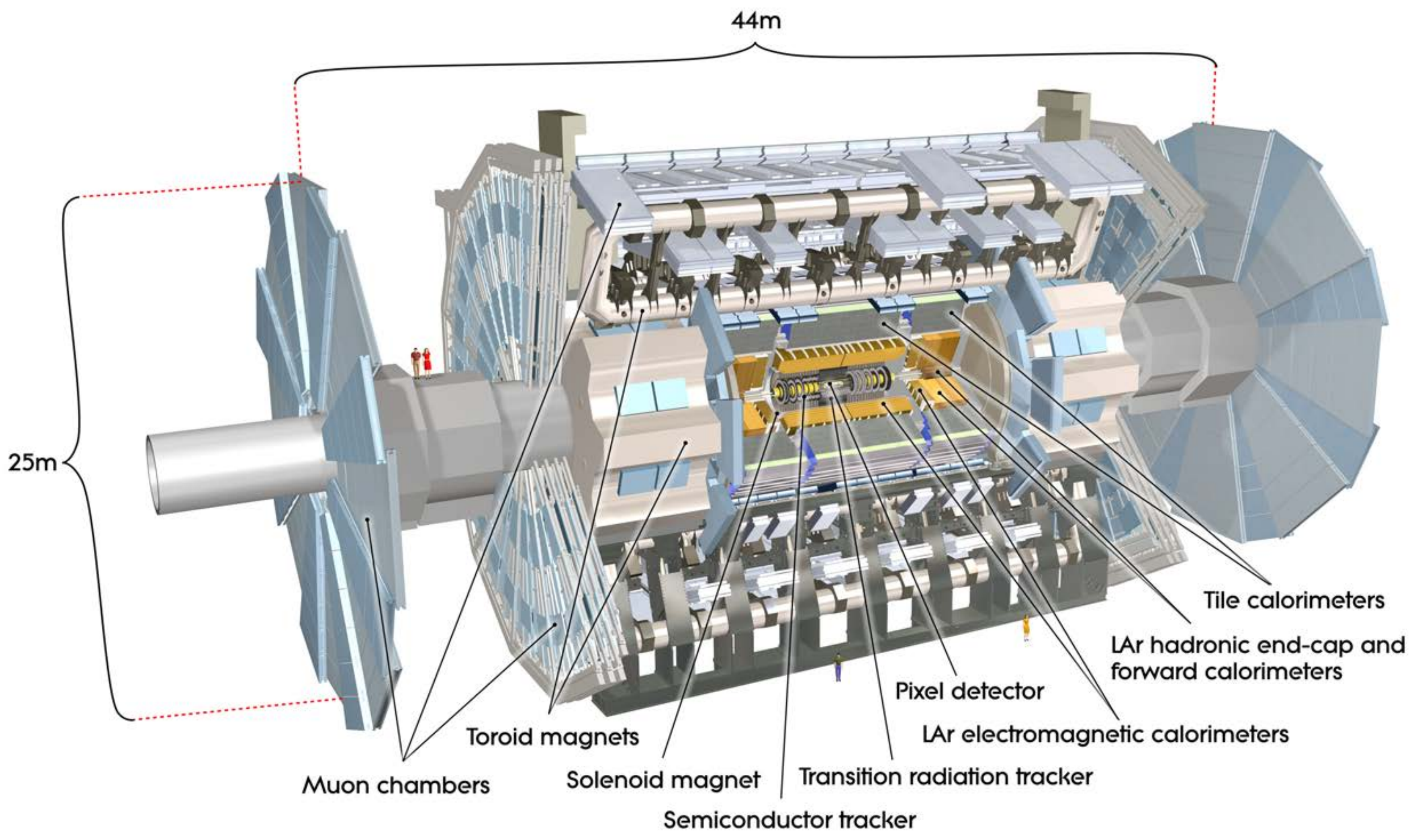
# CERN & LHC

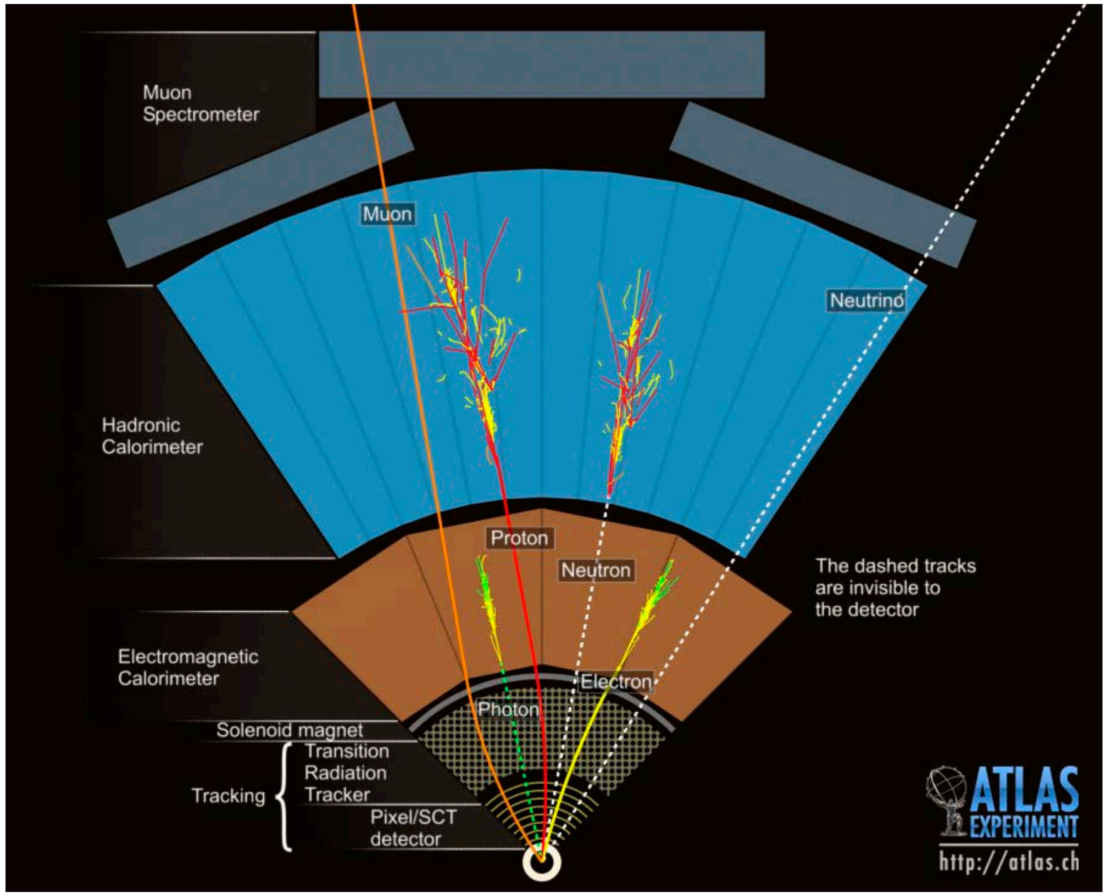



- Large Hadron Collider (LHC) is a pp-collider located at CERN in Geneva, Switzerland.
- Only operating collider at the energy frontier.
- Four interaction points at the LHC, where two are for generic purpose detectors (ATLAS & CMS), and the others for b-physics (LHCb) & heavy ion (ALICE).

# ATLAS Experiment

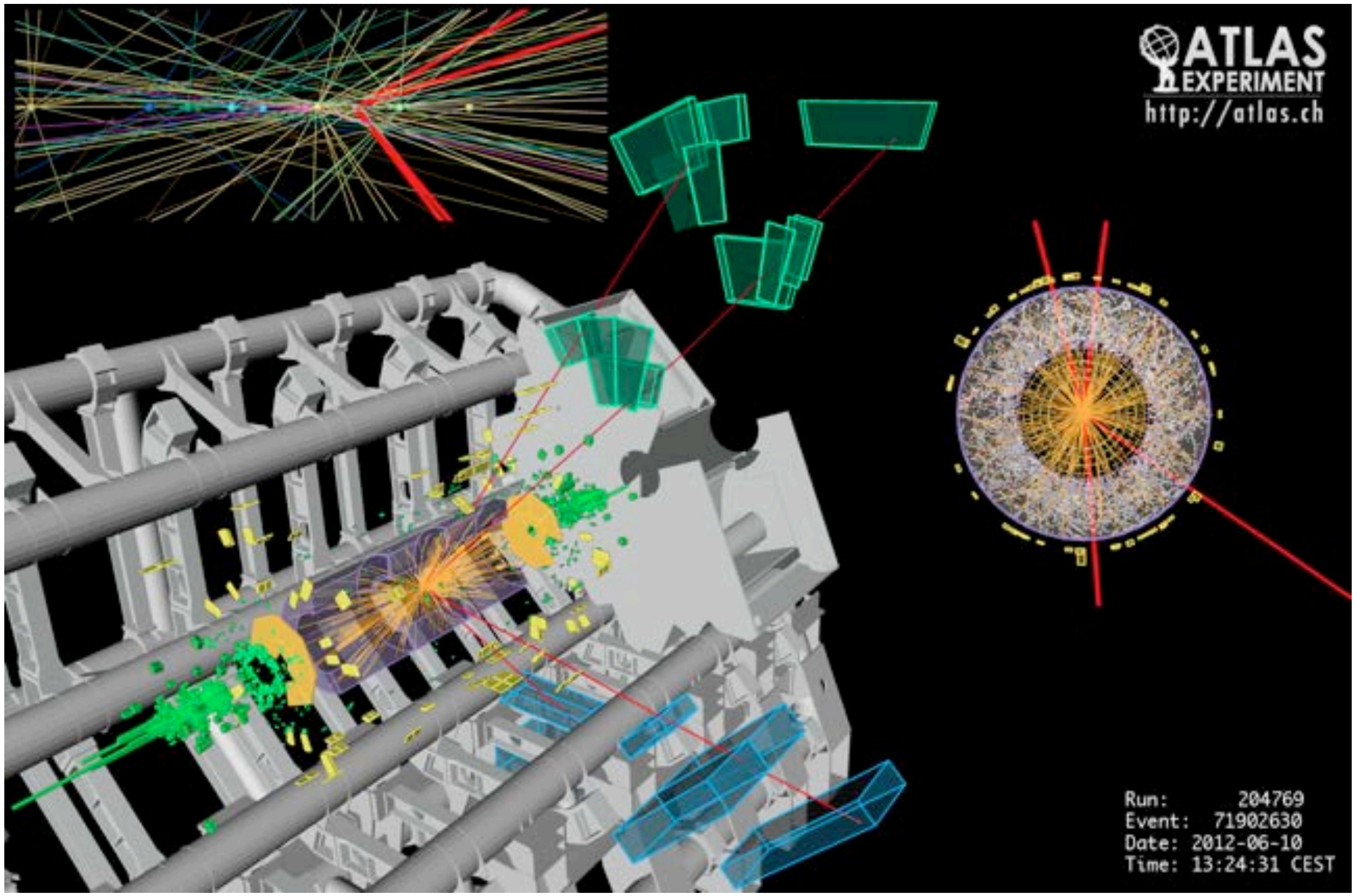


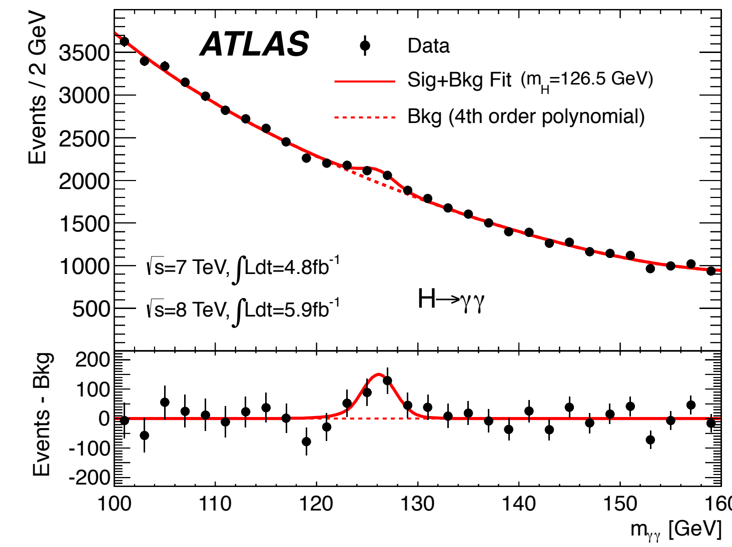

- Generic detector located ~100m underground.
- Inner Detector: Surrounded by 2T solenoid. Gigantic silicon detector + TRT.

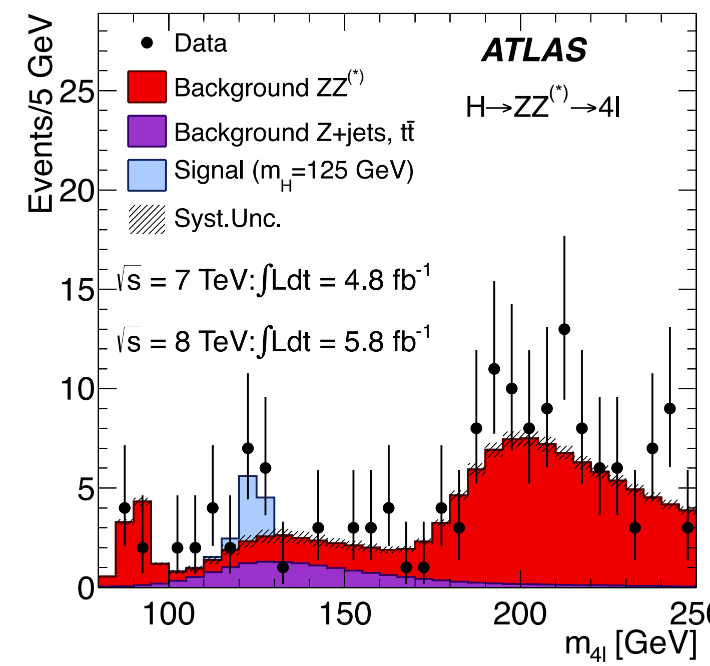



- Calorimeter: high granularity & hermeticity.
- Muon spectrometer: surrounded by air-core toroidal magnets.
- 3-level trigger system (L1, L2, EF)

# Higgs Discovery@LHC

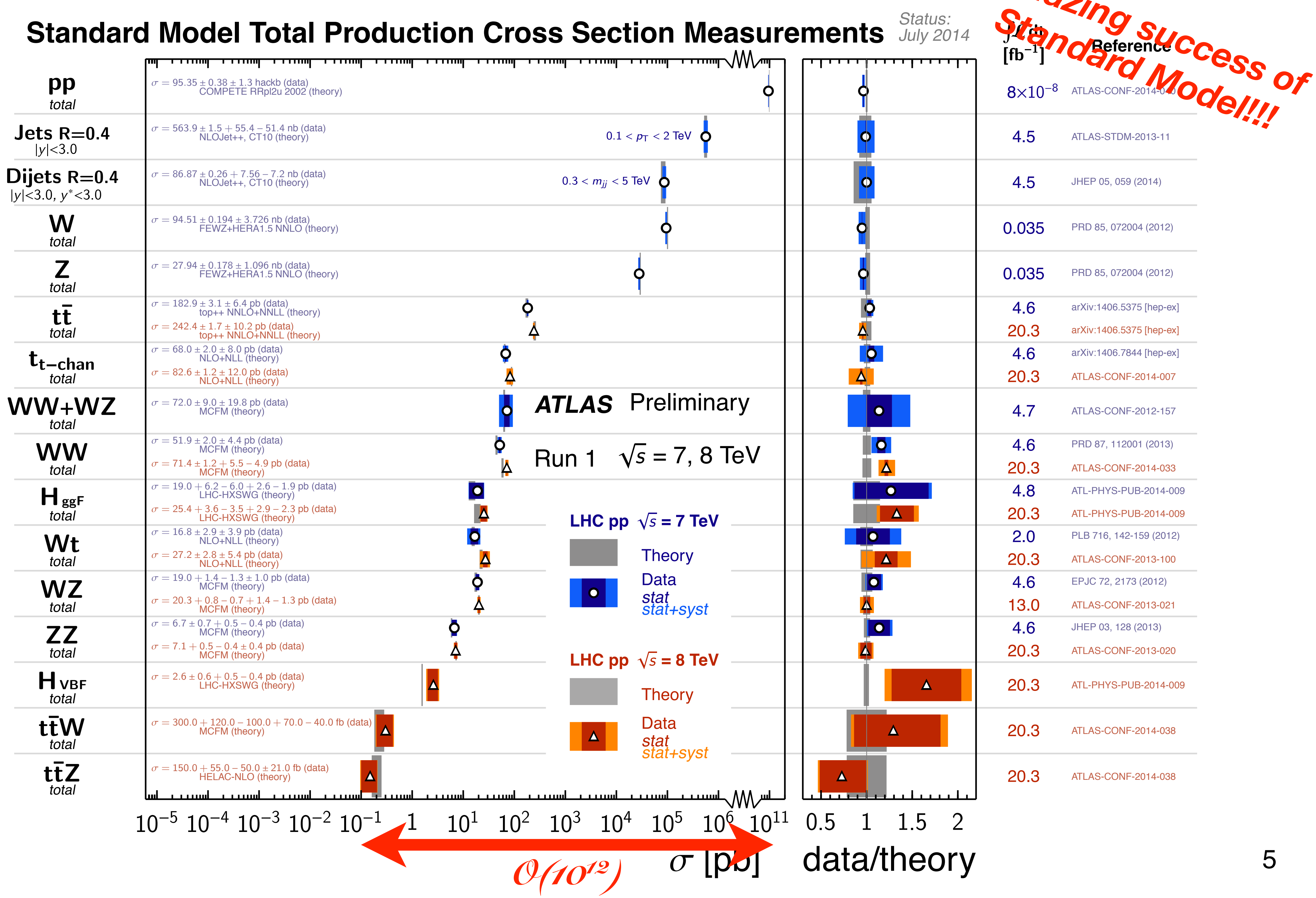



- **A Higgs boson was discovered at LHC in July 2012.** *Phys. Lett. B 716 (2012) 1*
- **Last missing piece of Standard Model (SM) or does it also imply BSM?**

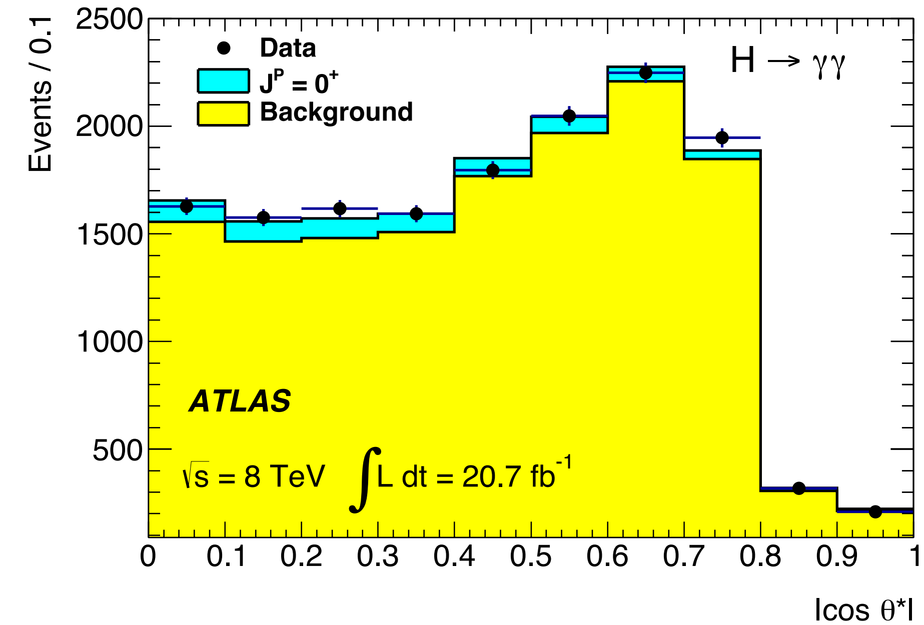
# Standard Model@LHC



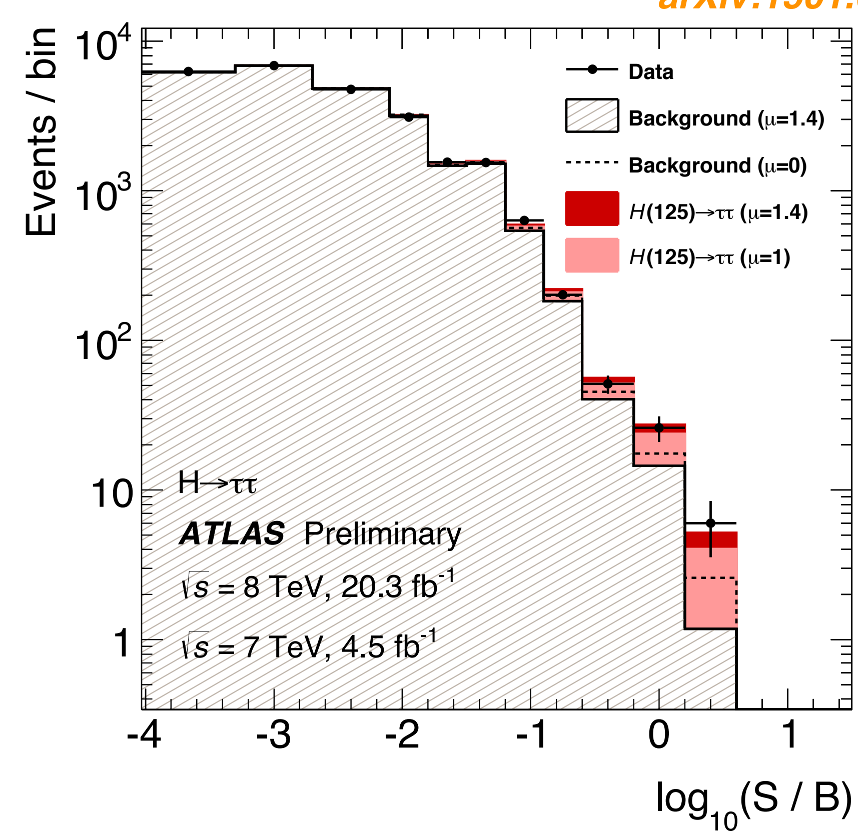
# After Higgs Discovery

- Is it really the Standard Model Higgs boson?
  - Results are consistent with **scalar**.
  - **Signal strengths** for main channels are **consistent w/ Standard Model**.
- $H \to \tau^+\tau^-$ is also observed. **What about $H \to b\bar{b}$?**
- Any exotic decays? Does the Higgs boson just decay as expected from the Standard Model? ($\gamma\gamma$, ZZ, $W^+W^-$, $\tau^+\tau^-$, bb,...)
  - **Constraint on the Higgs boson width**
  - **Invisible decays of Higgs**
- **Are there more Higgs bosons?**

Phys. Lett. B 726 (2013) 120



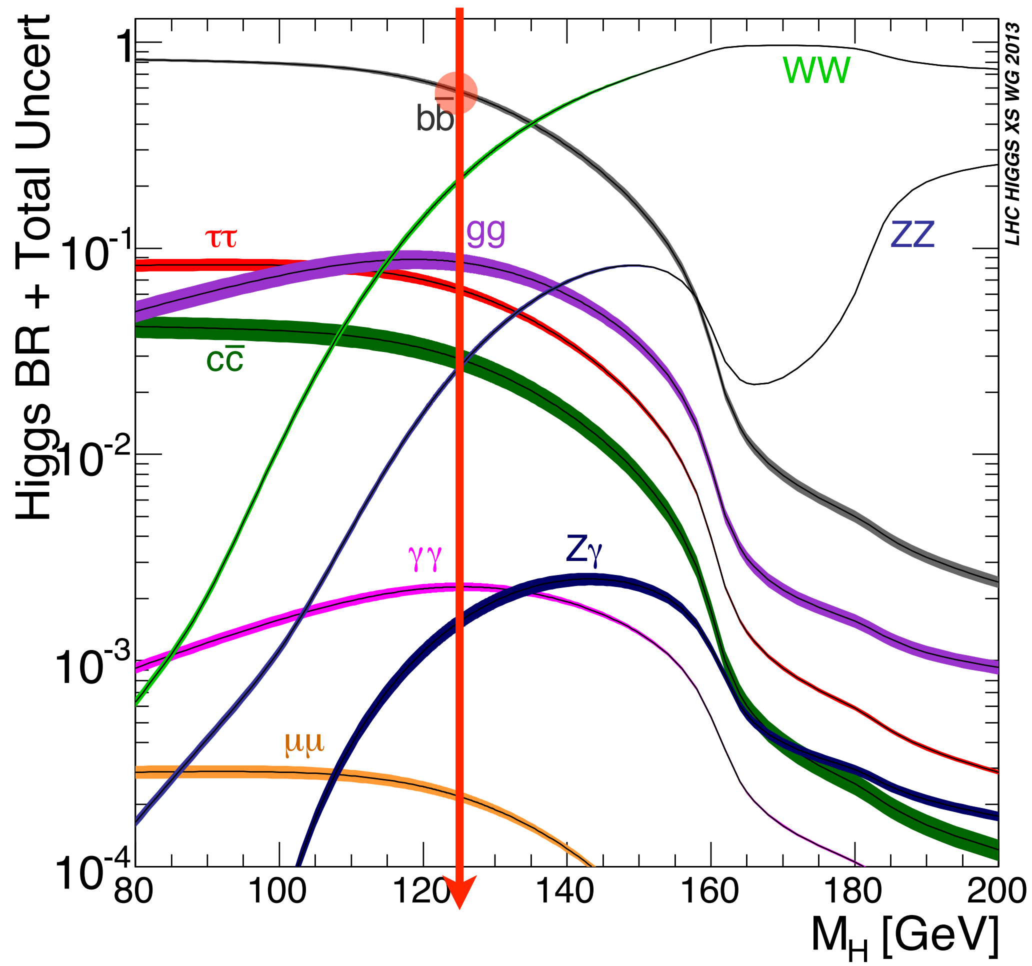

arXiv:1501.04943



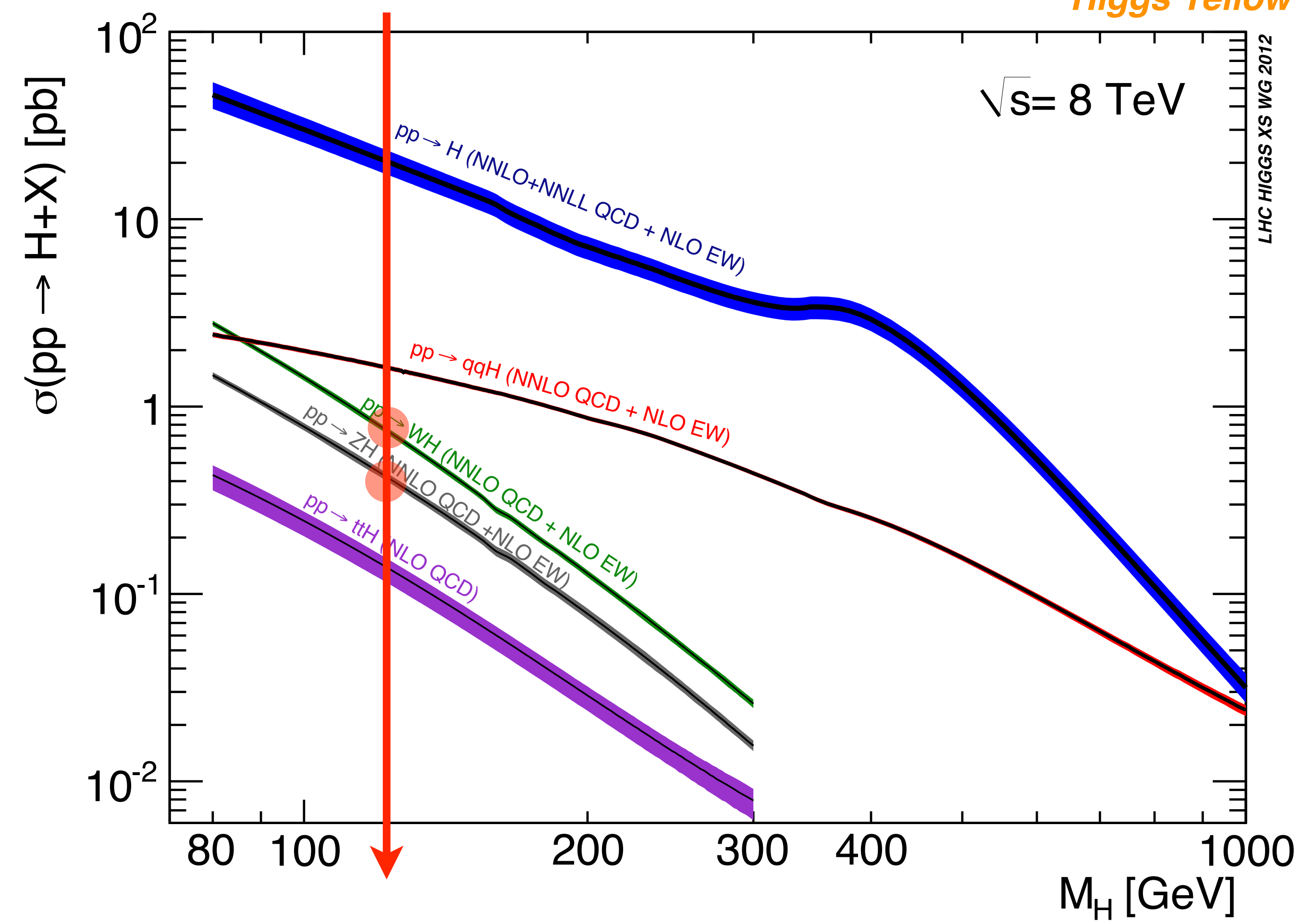
# $H \rightarrow b\bar{b}$ Measurement

*JHEP01(2015)069*

# $VH(\rightarrow b\bar{b})$

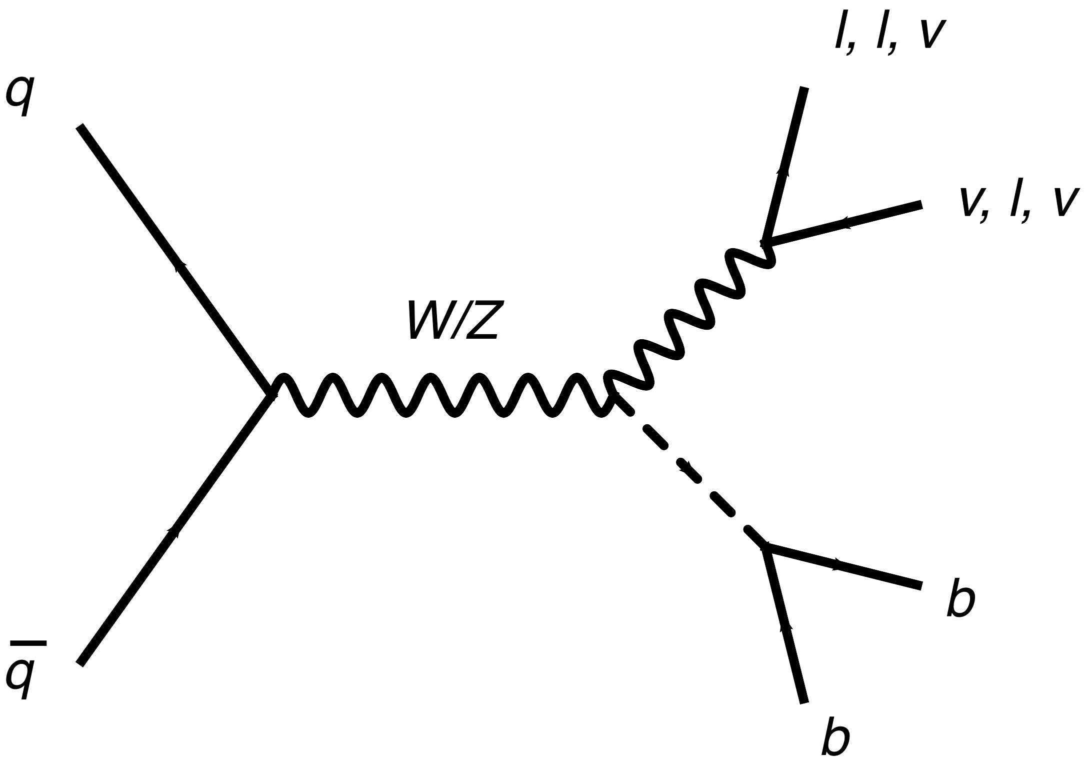



Higgs Yellow Report




- $H\rightarrow b\bar{b}$ has the largest BR (58%) among all the decay channels.
- Need to look at the VH production, since ggF and VBF suffer from large multijet background.
- Current results from other experiments: Tevatron 2.8σ, CMS 2.1σ.

# VH(→b$\bar{b}$)

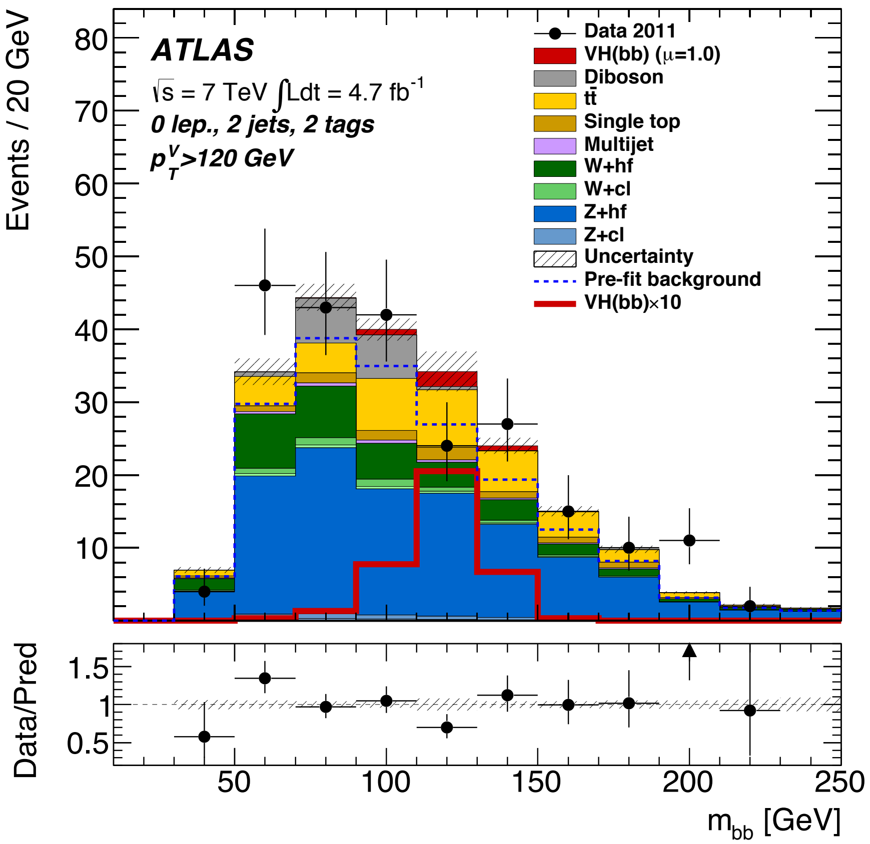



| Variable | Dijet-mass analysis | | | | | Multivariate analysis | |
|---|---|---|---|---|---|---|---|
| **Common selection** | | | | | | | |
| $p_T^V$ [GeV] | 0–90 | $90^{(*)}$–120 | 120–160 | 160–200 | $>200$ | 0–120 | $>120$ |
| $\Delta R(\text{jet}_1, \text{jet}_2)$ | 0.7–3.4 | 0.7–3.0 | 0.7–2.3 | 0.7–1.8 | $<1.4$ | $>0.7$ ($p_T^V$<200 GeV) | |
| **0-lepton selection** | | | | | | | |
| $p_T^{miss}$ [GeV] | NU | $>30$ | $>30$ | | | NU | $>30$ |
| $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{miss} vec)$ | | $<\pi/2$ | $<\pi/2$ | | | | $<\pi/2$ |
| $\min[\Delta\phi(\vec{E}_T^{miss}, \text{jet})]$ | | – | $>1.5$ | | | | $>1.5$ |
| $\Delta\phi(\vec{E}_T^{miss}, \text{dijet})$ | | $>2.2$ | $>2.8$ | | | | $>2.8$ |
| $\sum_{i=1}^{N_{jet}=2(3)} p_T^{jet_i}$ [GeV] | | $>120$ (NU) | $>120$ (150) | | | | $>120$ (150) |
| | | See text | – | | | | – |
| **1-lepton selection** | | | | | | | |
| $m_T^W$ [GeV] | $<120$ | | | | | – | |
| $H_T$ [GeV] | $>180$ | | – | | | $>180$ | – |
| $E_T^{miss}$ [GeV] | – | | $>20$ | | $>50$ | – | $>20$ |
| **2-lepton selection** | | | | | | | |
| $m_{\ell\ell}$ [GeV] | 83-99 | | | | | 71-121 | |
| $E_T^{miss}$ [GeV] | $<60$ | | | | | – | |

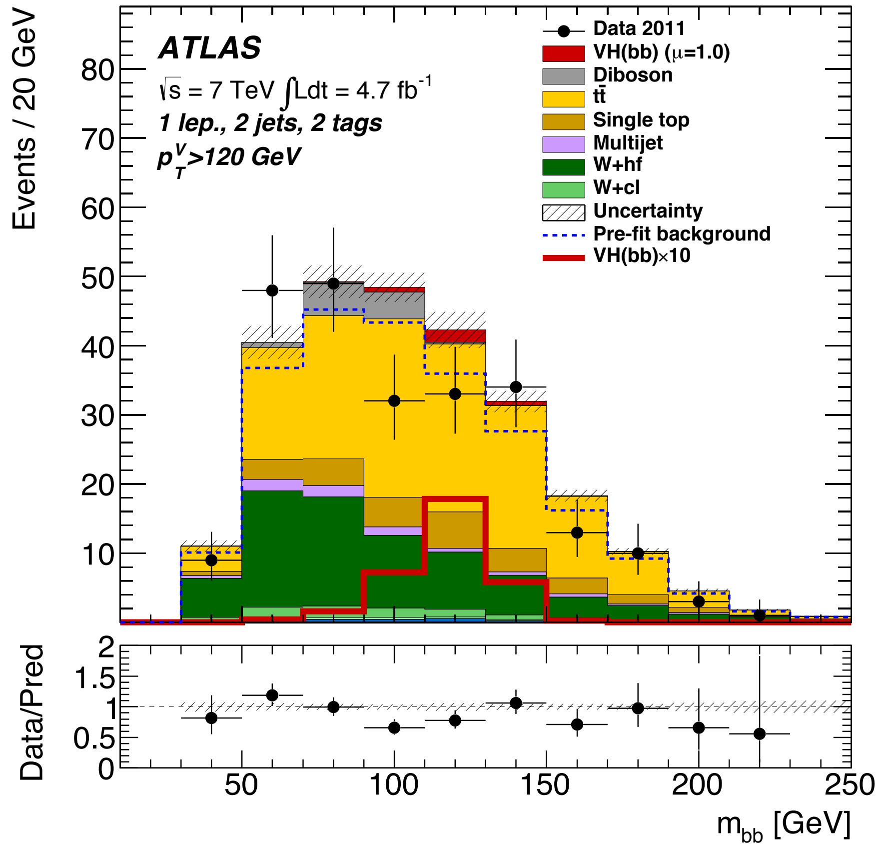
- 3 channels to be considered regarding the lepton multiplicity (0, 1, 2-leptons for **ZH→ν$\bar{\nu}$b$\bar{b}$, WH→l$\bar{\nu}$b$\bar{b}$, ZH→l$^+$l$^-$b$\bar{b}$**).
- Both cut-based & multivariate (BDT) analyses considered.
- Require 1 or 2 b-tagged jet(s). Categorize with $p_T^V$ ranges.

# VH(→$b\bar{b}$)

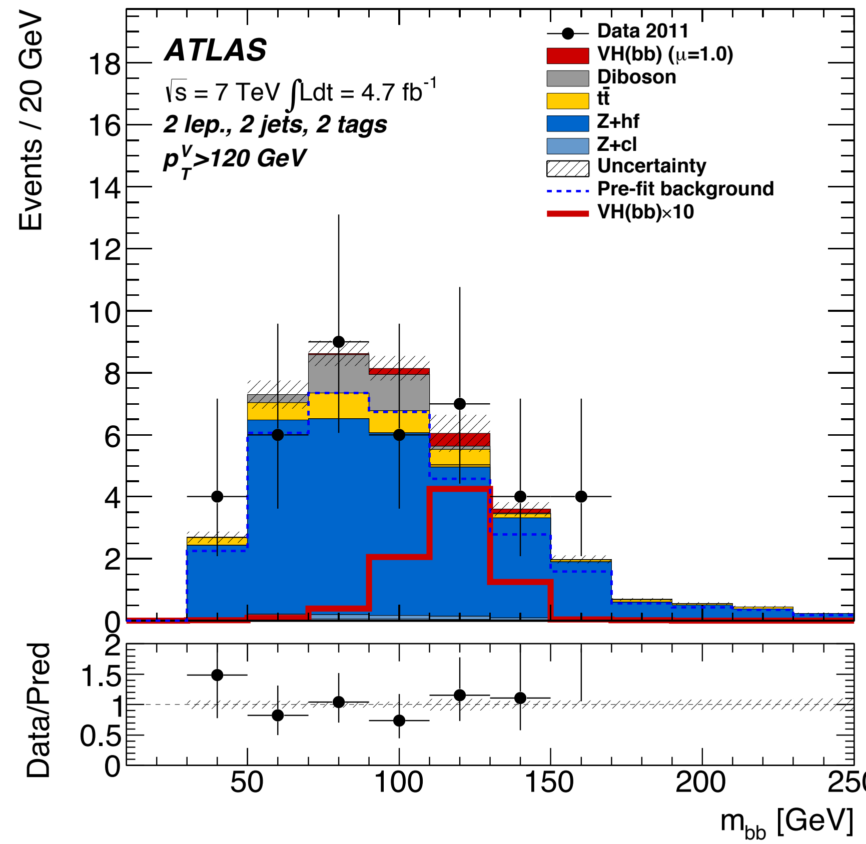
0-lepton




1-lepton

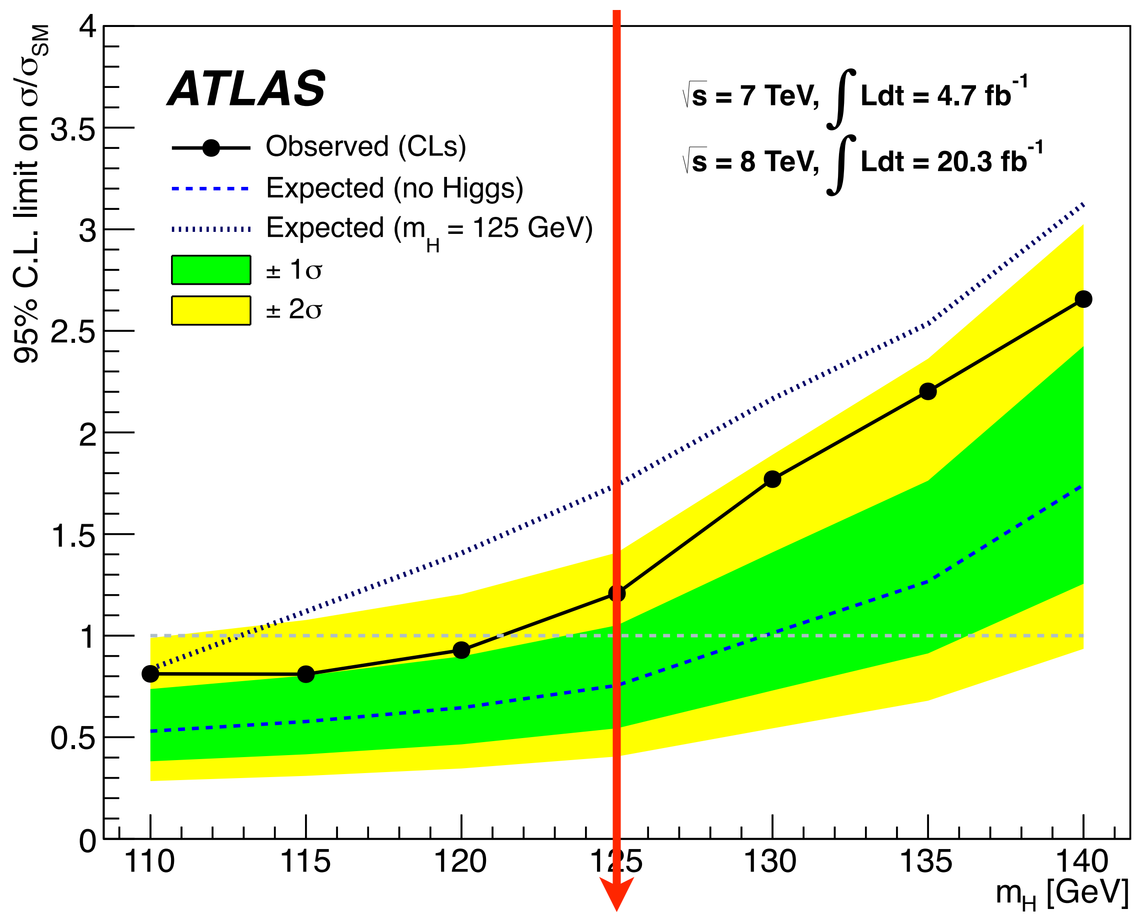


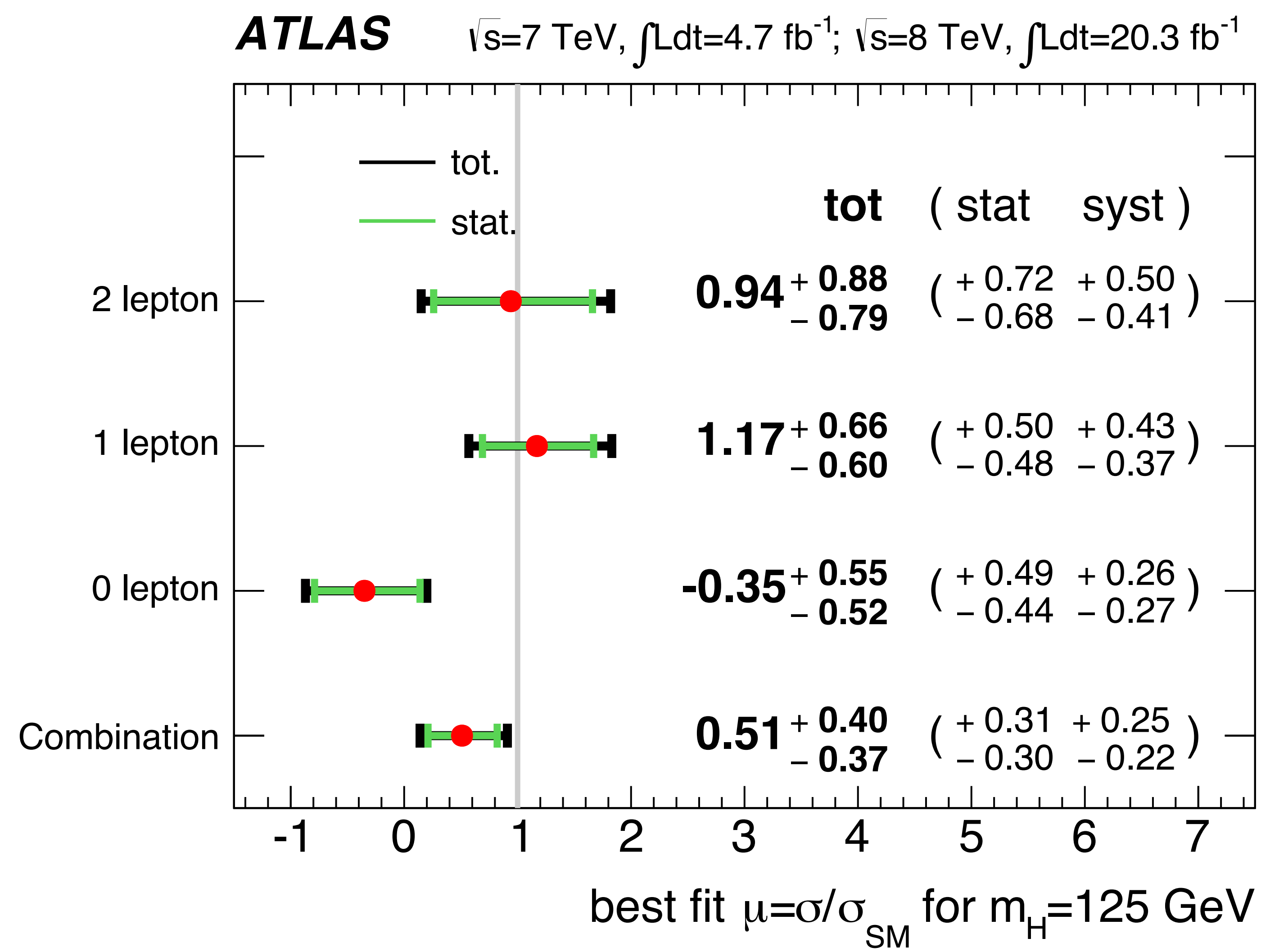

2-leptons




- Main backgrounds: Z+jets, W+jets, $t\bar{t}$, diboson, multijet.
- Backgrounds are estimated with data-driven methods or simulation with corrections derived from data (e.g. Δϕ(j,j) reweighting for W +jets).

# VH(→$b\bar{b}$)



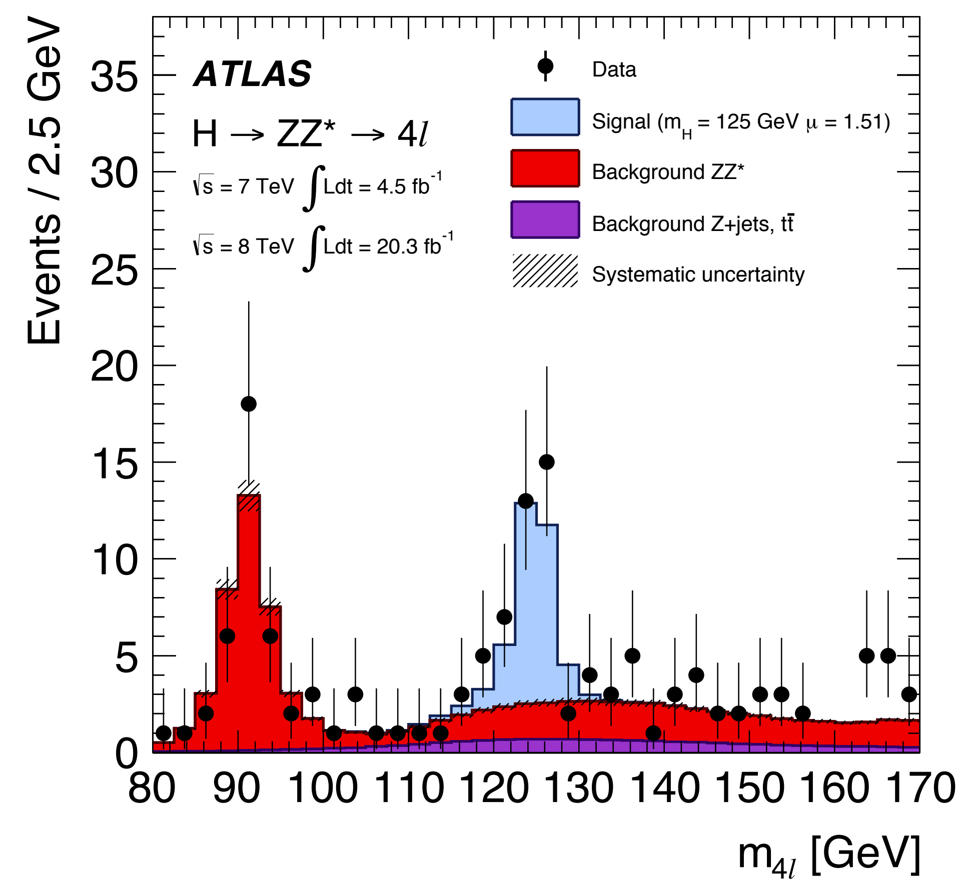

- Measurement is still consistent with the Standard Model, but H→$b\bar{b}$ is not observed yet.
- Overall signal strength is **0.51±0.31±0.24** for $m_H$=125 GeV. Observed significance of 1.4σ.

# Higgs Width

*arXiv:1503.01060*

# Higgs Total Width

- We cannot directly measure the width of the Higgs boson ($\Gamma_H$=4.1 MeV) due to the detector resolution.
  - Mass resolution@ATLAS is ~2 GeV.
- **Current Higgs measurement does not provide constraints on the width.**
  **→ If the width & couplings scale at the same time, the signal yields stay the same.**



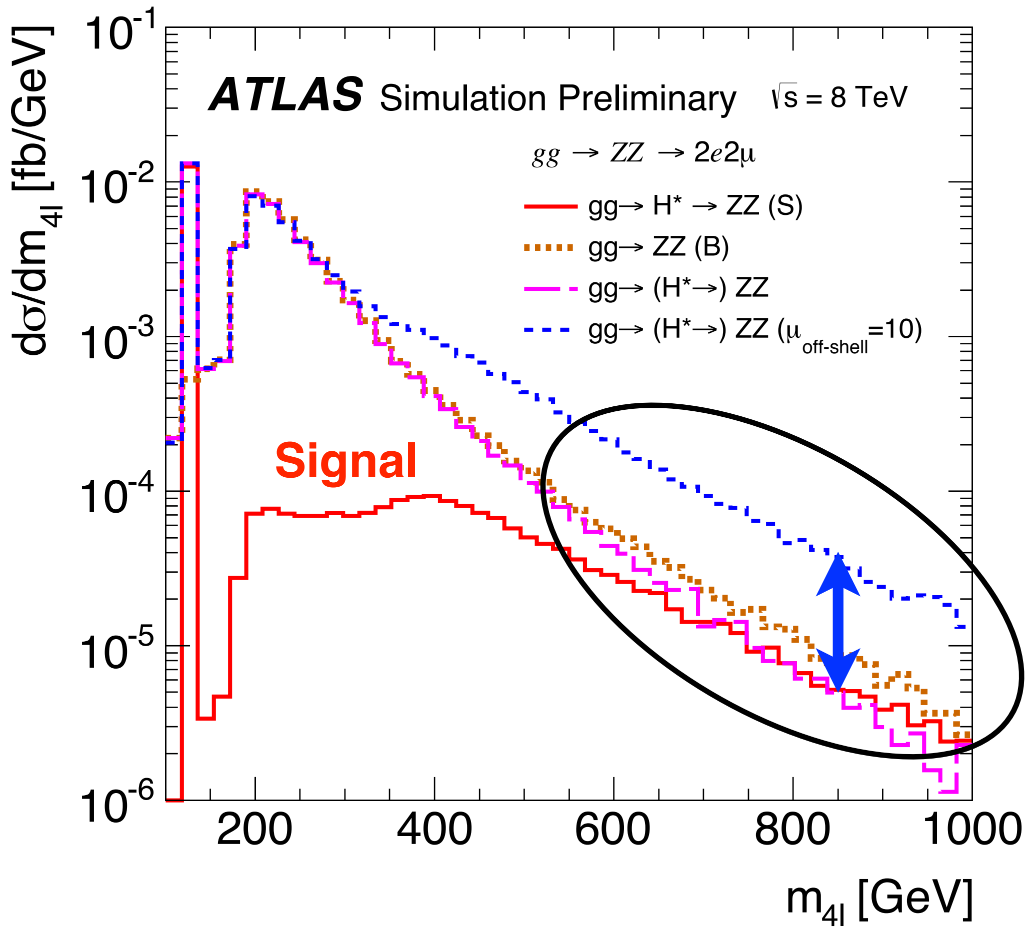

$$\sigma_{i \to H \to f} \sim \frac{\kappa_i^2 \kappa_f^2}{\Gamma_H}$$

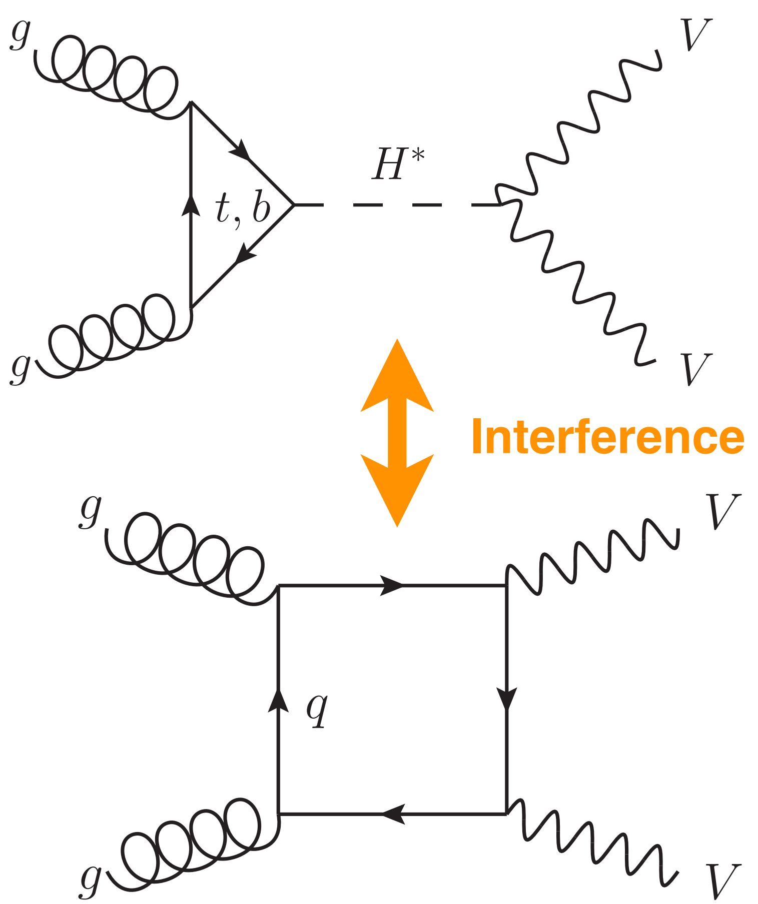
- $\sigma_{i \to H \to f}$: Cross section of Higgs production i, decay pattern f
- $\kappa_i$: Higgs coupling to particle i
- $\kappa_f$: Higgs coupling to particle f
- $\Gamma_H$: Total Higgs width

***Larger total width is a sign of BSM decays.***

# Off-Shell Higgs Boson

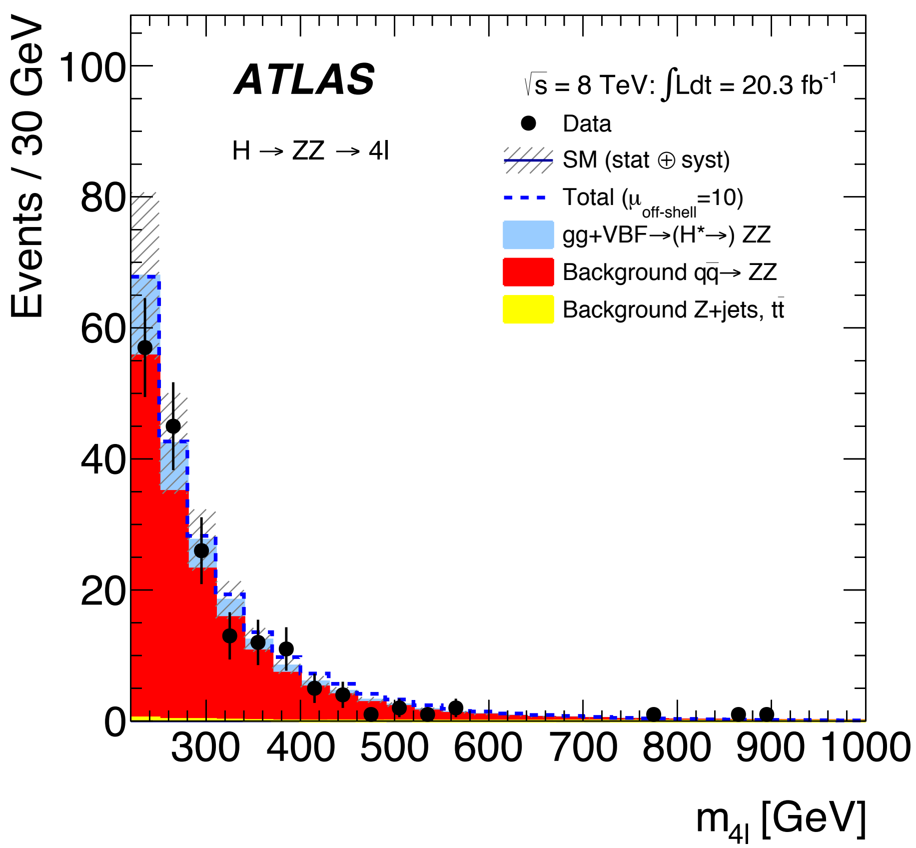
arXiv:1503.01060

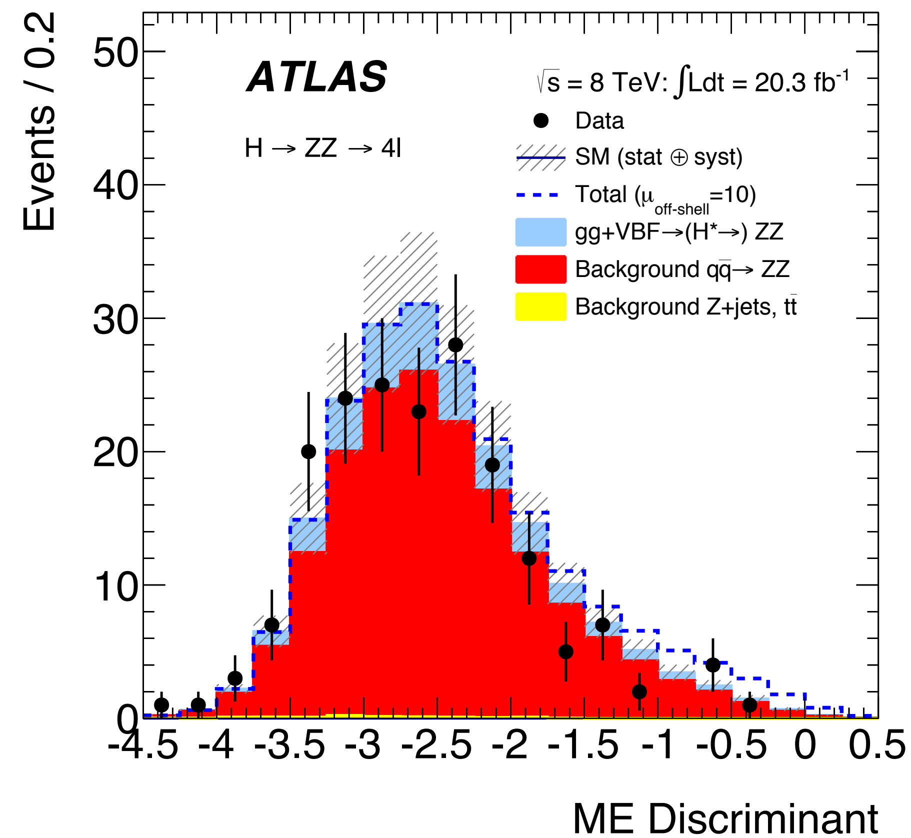


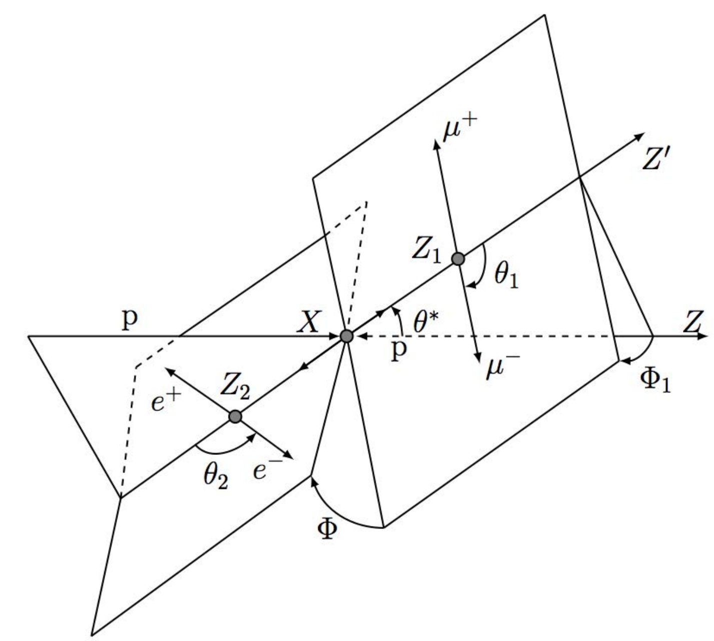




- Off-shell production of the Higgs boson shows up in the tail of the $m_{4l}$ distribution & **its yield greatly enhances with the Higgs total width**!
- **H→ZZ & W⁺W⁻ are promising decay channels for this measurement.**

# H*→ZZ→4l



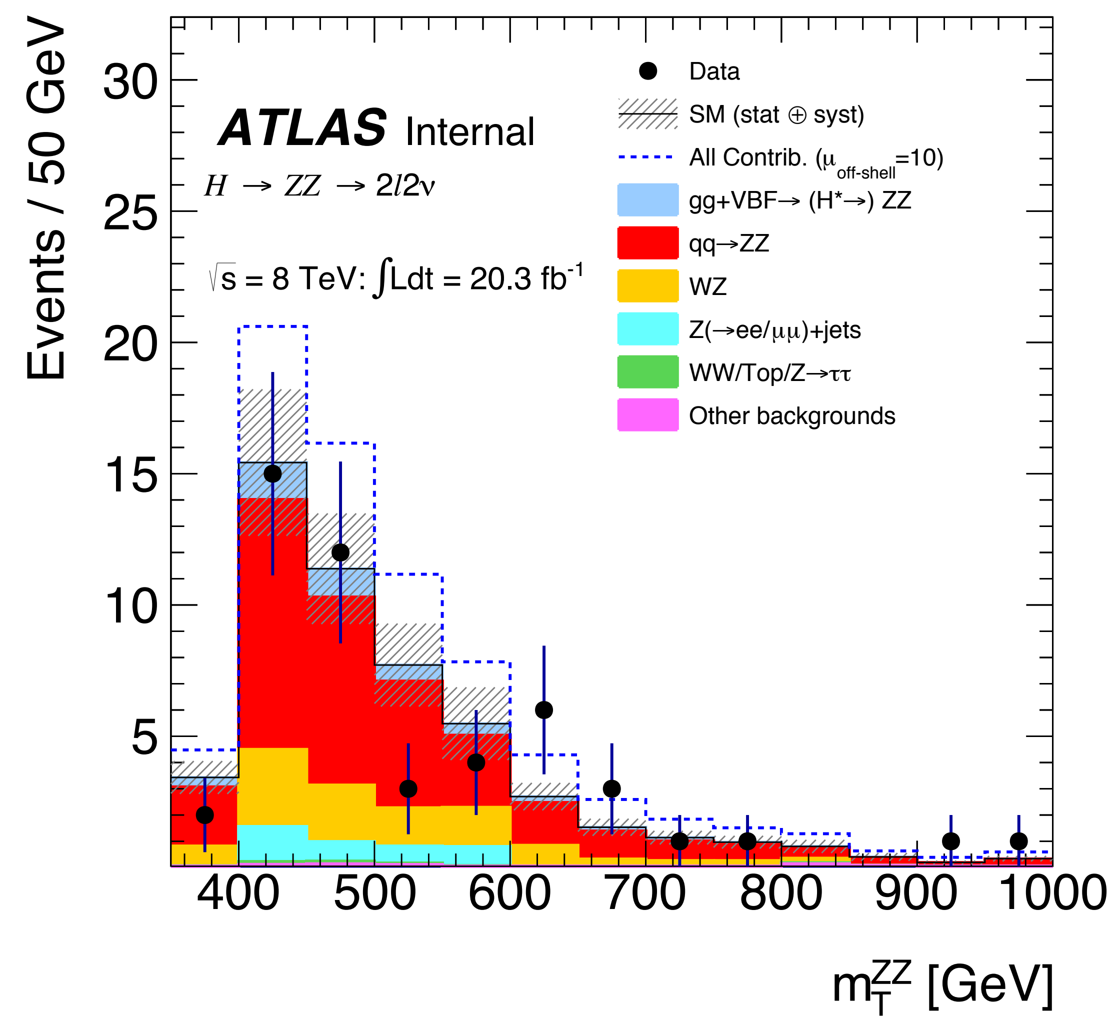



- Same strategies as the coupling measurement with the H→ZZ*→4l.
- $50 < m_{12} < 106$ GeV, $50 < m_{34} < 115$ GeV, **$220 < m_{4l} < 1000$ GeV.**
- Exploits the Matrix Element using 8 kinematic variables (**$m_{4l}$, $m_{12}$, $m_{34}$, $\cos\theta_1$, $\cos\theta_2$, $\phi$, $\cos\theta^*$, $\phi_1$**) to discriminate gluon-gluon initiated signals.

# $H^* \to ZZ \to l^+l^-\nu\bar{\nu}$

- Cut-based analysis with the **Z+Missing $E_T$ final state**.
- Basically the same strategies (e.g. BG estimation methods) as the previously published ZH invisible search (Phys. Rev. Lett.112, 201802 (2014)), but the event selection is optimized for the off-shell signals.
  - e.g. **$E_T^{miss}$ > 180 GeV, $m_T^{ZZ}$> 380 GeV.**
- **$m_T^{ZZ}$** is used as the final discriminant.



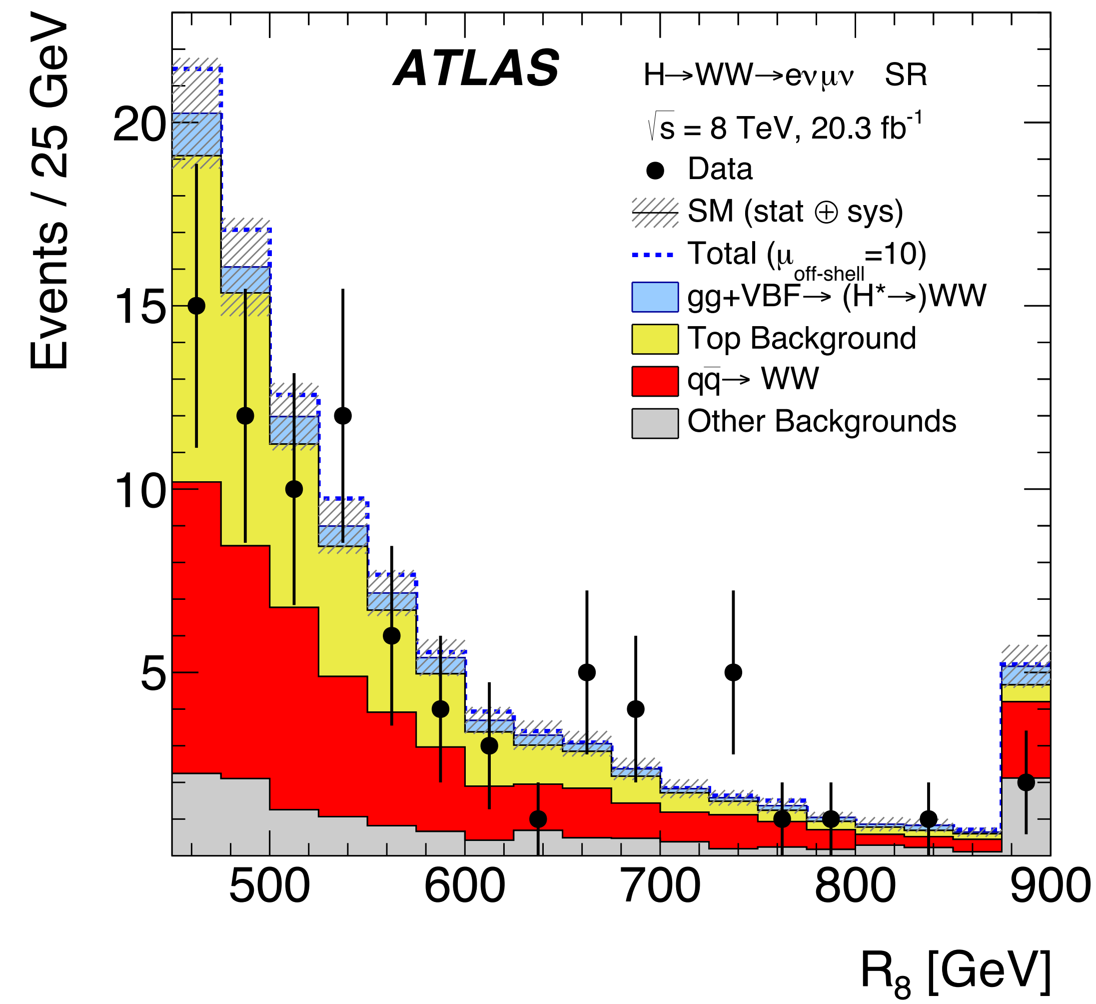

$$m_T^{ZZ} \equiv \sqrt{\left(\sqrt{m_Z^2 + \left|\boldsymbol{p}_T^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|\boldsymbol{E}_T^{\text{miss}}\right|^2}\right)^2 - \left|\boldsymbol{p}_T^{\ell\ell} + \boldsymbol{E}_T^{\text{miss}}\right|^2}$$

# $H^* \rightarrow W^{\pm}W^{\mp} \rightarrow e^{\pm}\nu\mu^{\mp}\nu$

- Cut-based analysis using $e^{\pm}\mu^{\mp}$ final state.
- Baseline strategies are the same as the SM $H \rightarrow WW^*$ measurement, but no jet binning is performed.
- **$R_8$** is used as the final discriminant.

$$m_{\mathrm{T}}^{WW} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + p_{\mathrm{T}}^{\nu\nu}\right)^2 - \left|\boldsymbol{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{p}_{\mathrm{T}}^{\nu\nu}\right|^2},$$

$$\mathrm{R}_8 = \sqrt{m_{\ell\ell}^2 + \left(a \cdot m_{\mathrm{T}}^{WW}\right)^2}.$$

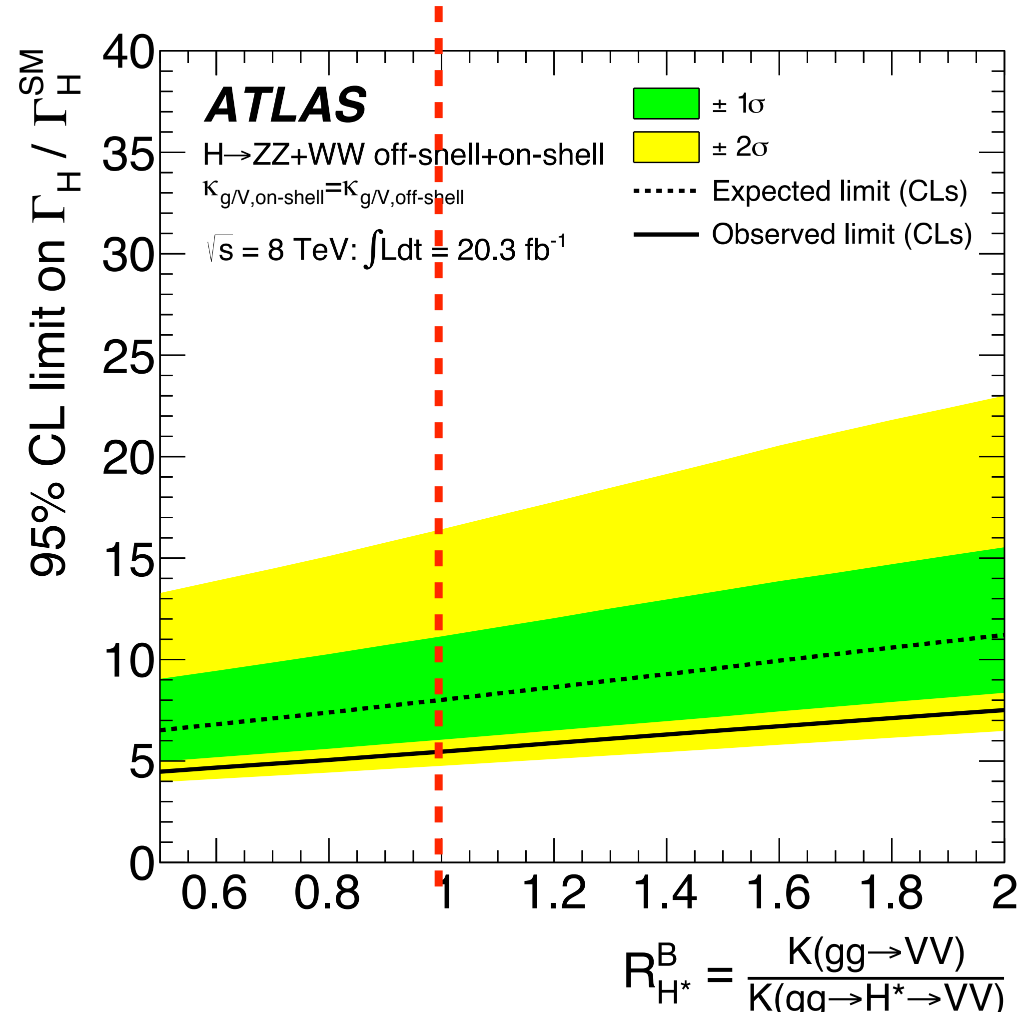



- **$a$ = 0.8 & $R_8$ > 450 GeV** were adopted from optimization.
- Dominant BGs: Top quark & $qq \rightarrow WW$ events.

# Combined Results

| Process | $ZZ \to 4\ell$ | $ZZ \to 2\ell 2\nu$ | $WW \to e\nu\,\mu\nu$ |
|---|---|---|---|
| $gg \to H^* \to VV$ (S) | 1.1 ± 0.3 | 3.2 ± 1.0 | 1.5 ± 0.4 |
| $gg \to VV$ (B) | 2.8 ± 0.8 | 5.3 ± 1.6 | 3.6 ± 1.1 |
| $gg \to (H^* \to)VV$ | **2.4 ± 0.7** | **3.9 ± 1.2** | **2.4 ± 1.2** |
| $gg \to (H^* \to)VV$ ($\mu_{\text{off-shell}} = 10$) | 9.2 ± 2.5 | 24.0 ± 7.3 | 10 ± 4 |
| VBF $H^* \to VV$ (S) | 0.12 ± 0.01 | 0.48 ± 0.04 | 0.42 ± 0.05 |
| VBF $VV$ (B) | 0.71 ± 0.04 | 1.2 ± 0.2 | 1.6 ± 0.2 |
| **VBF** $(H^* \to)VV$ | **0.59 ± 0.03** | **0.7 ± 0.1** | **1.1 ± 0.1** |
| VBF $(H^* \to)VV$ ($\mu_{\text{off-shell}} = 10$) | 1.17 ± 0.06 | 2.9 ± 0.2 | 2.8 ± 0.3 |
| $q\bar{q} \to ZZ$ | 21.3 ± 2.1 | 31.5 ± 3.5 | 2.0 ± 0.2 (with $q\bar{q} \to WZ$) |
| $q\bar{q} \to WZ$ | - | 10.6 ± 1.4 | |
| $q\bar{q} \to WW$ | - | 0.4 ± 0.2 (with $t\bar{t}$, $Wt$, $t\bar{b}/tq\bar{b}$ and $Z \to \tau\tau$) | 40 ± 5 |
| $t\bar{t}$, $Wt$, and $t\bar{b}/tq\bar{b}$ | - | | 35 ± 4 |
| $Z \to \tau\tau$ | - | | 1.4 ± 0.2 |
| $Z \to ee, \mu\mu$ | - | 3.5 ± 3.0 | - |
| Other backgrounds | - | 0.8 ± 0.2 | 8.7 ± 1.3 |
| Total Expected (SM) | 24.4 ± 2.2 | 51 ± 6 | 90 ± 4 |
| Observed | 18 | 48 | 82 |

| | Observed | | | Median expected | | |
|---|---|---|---|---|---|---|
| $\mathrm{R}^{B}_{H^*}$ | 0.5 | **1.0** | 2.0 | 0.5 | **1.0** | 2.0 |
| $ZZ \to 4\ell$ analysis | 6.1 | **7.3** | 10.0 | 9.1 | **10.6** | 14.8 |
| $ZZ \to 2\ell 2\nu$ analysis | 9.9 | **11.0** | 12.8 | 9.1 | **10.6** | 13.6 |
| $WW \to e\nu\,\mu\nu$ analysis | 15.6 | **17.2** | 20.3 | 19.6 | **21.3** | 24.7 |



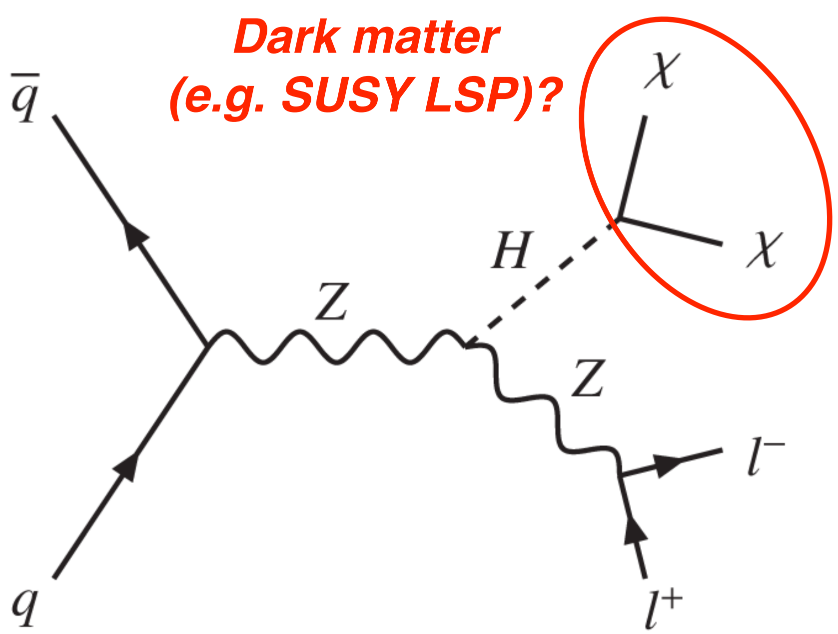

- Good agreement with Standard Model prediction.
- Stringent constraint on the off-shell signal strength & total Higgs width.
  - **$\Gamma_H/\Gamma_H^{SM}$ < 4.5-7.5 (obs)**, 6.5-11.2 (exp) @95% CL.
- However, **still allows for sizable contributions from BSM.**

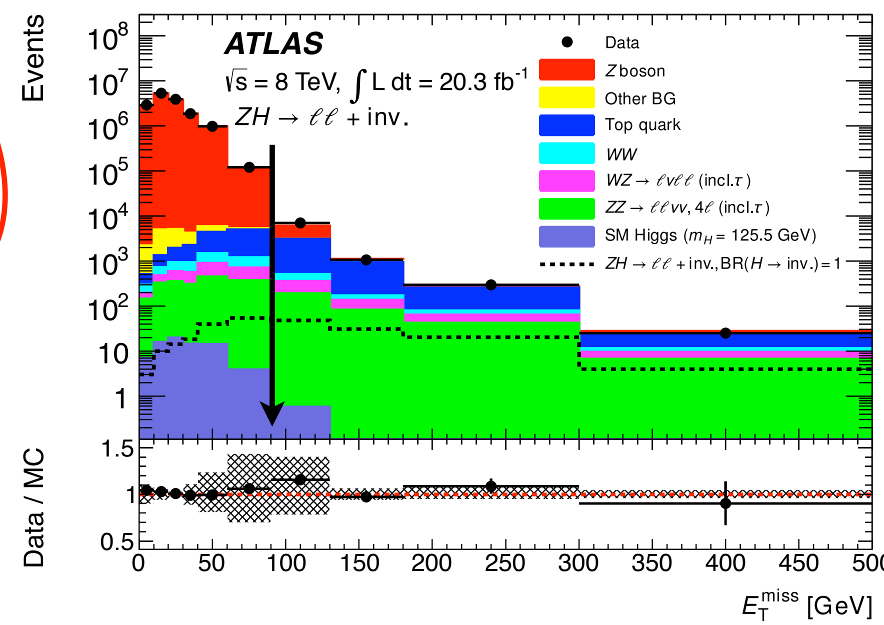
# BSM Decays of Higgs

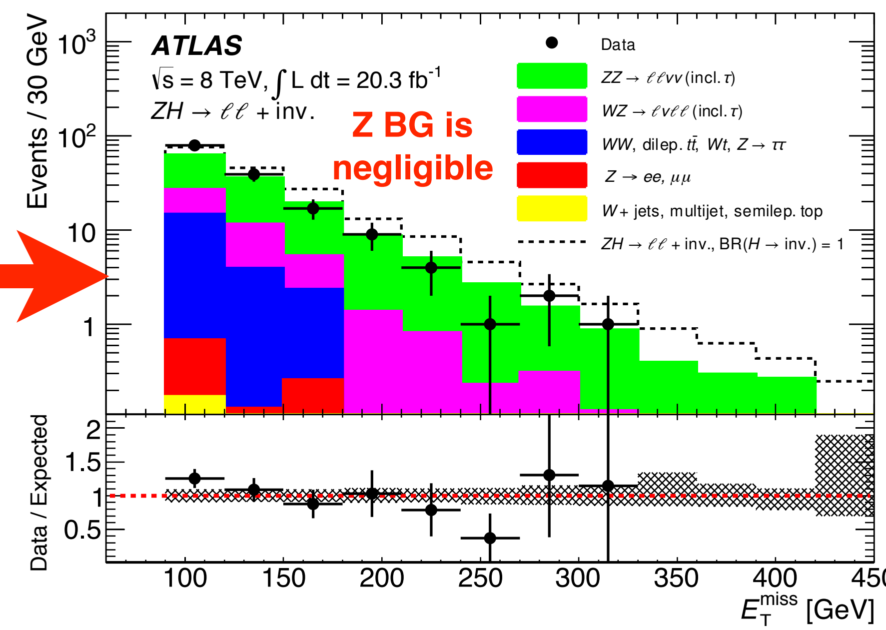
# ZH→l⁺l⁻+invisible

**BSM decay of Higgs boson to dark matter. Expected from Supersymmetry, etc.**

*Phys. Rev. Lett.112, 201802 (2014)*




- $e^+e^-$ or $\mu^+\mu^-$ w/ $76 < M_{ll} < 106$ GeV; 3rd lepton veto ($p_T$>7 GeV)
- $d\phi(l,l) < 1.7$
- Jet veto (w/ $p_T$>25 GeV)

$p_T^{miss}$: Missing $E_T$ reconstructed from ID tracks

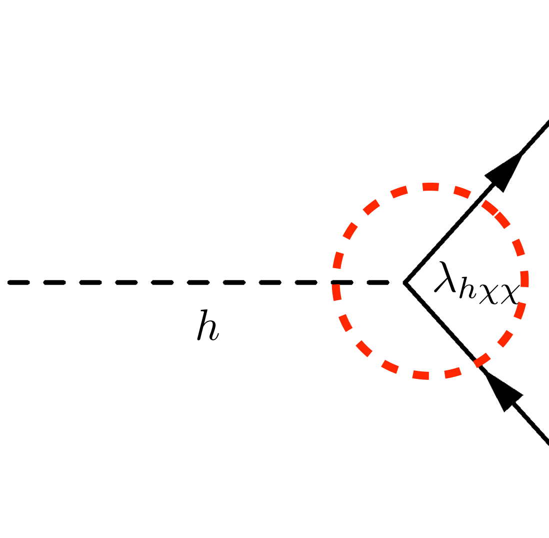
- $E_T^{miss} > 90$ GeV
- $|E_T^{miss} - p_T^{ll}| / p_T^{ll} < 0.2$
- $d\phi(E_T^{miss}, p_T^{miss}) < 0.2$
- $d\phi(Z, E_T^{miss}) > 2.6$

# ZH→l⁺l⁻+invisible

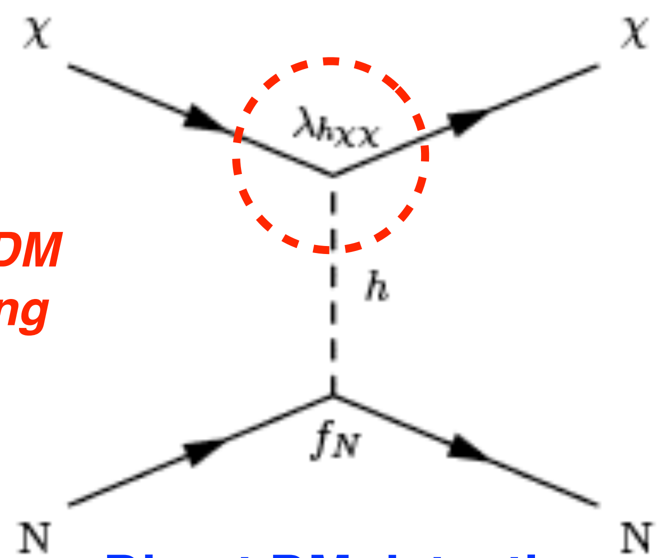
- <u>**Limit on BR(H→invisible)<0.75 (observed)**</u> **& 0.62 (expected)** @ 95% confidence level. assuming $m_H$ = 125.5 GeV & $\sigma_{ZH} = \sigma_{ZH}^{SM}$.
- The BR(H→inv) limit was interpreted within Higgs-portal dark matter model. <u>**The ATLAS result shows outstanding sensitivity in the low DM mass region, exceeding current DM detection experiments**</u>**.**

| *Higgs invisible decay* | | *Higgs-DM coupling* | | *DM-nucleon xsec* |
|---|---|---|---|---|
| $\Gamma(h \to \chi\chi)$ | $\Leftrightarrow$ | $\lambda^2_{h\chi\chi}$ | $\Leftrightarrow$ | $\sigma_{N\chi}$ |

$$BR(h \to \chi\chi) = \frac{\Gamma(h \to \chi\chi)}{\Gamma(h \to \chi\chi) + \Gamma(h \to SM)}$$

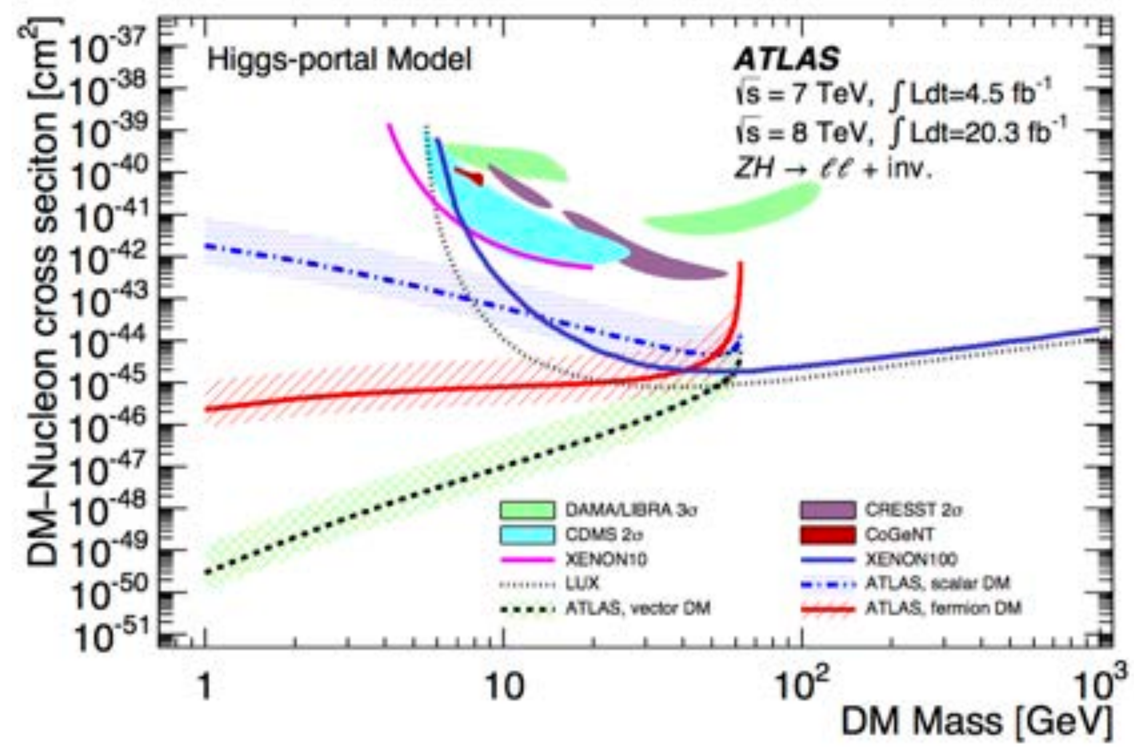



**Higgs-DM coupling**



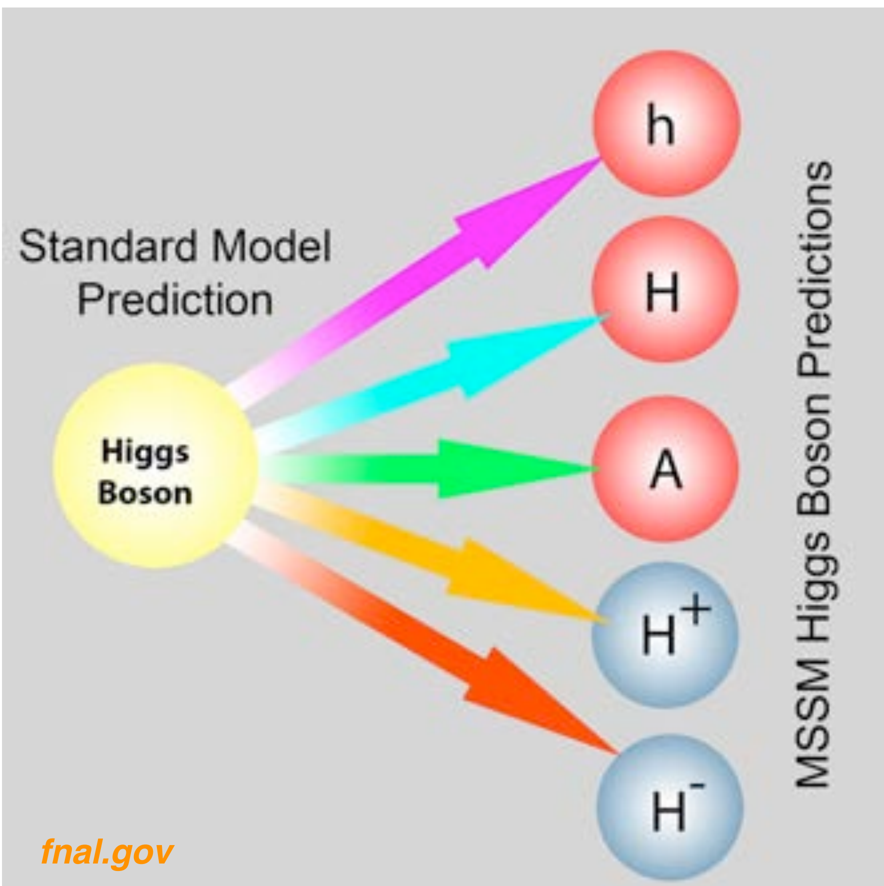

**Our analysis**

**Direct DM detection experiments**



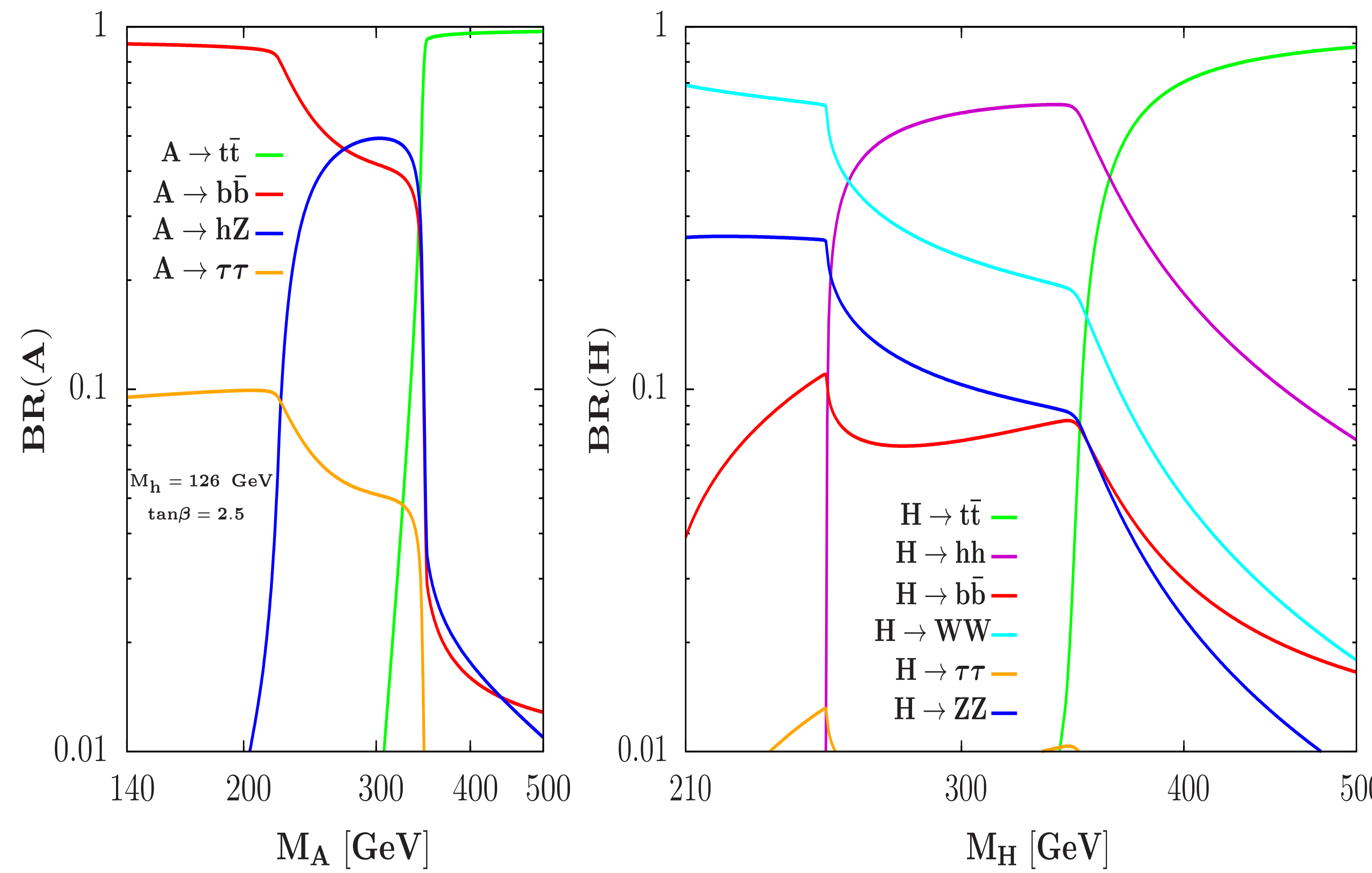
# Heavy Higgs Boson Searches

# Heavy Higgs Bosons




**low tan β (=2.5) case**

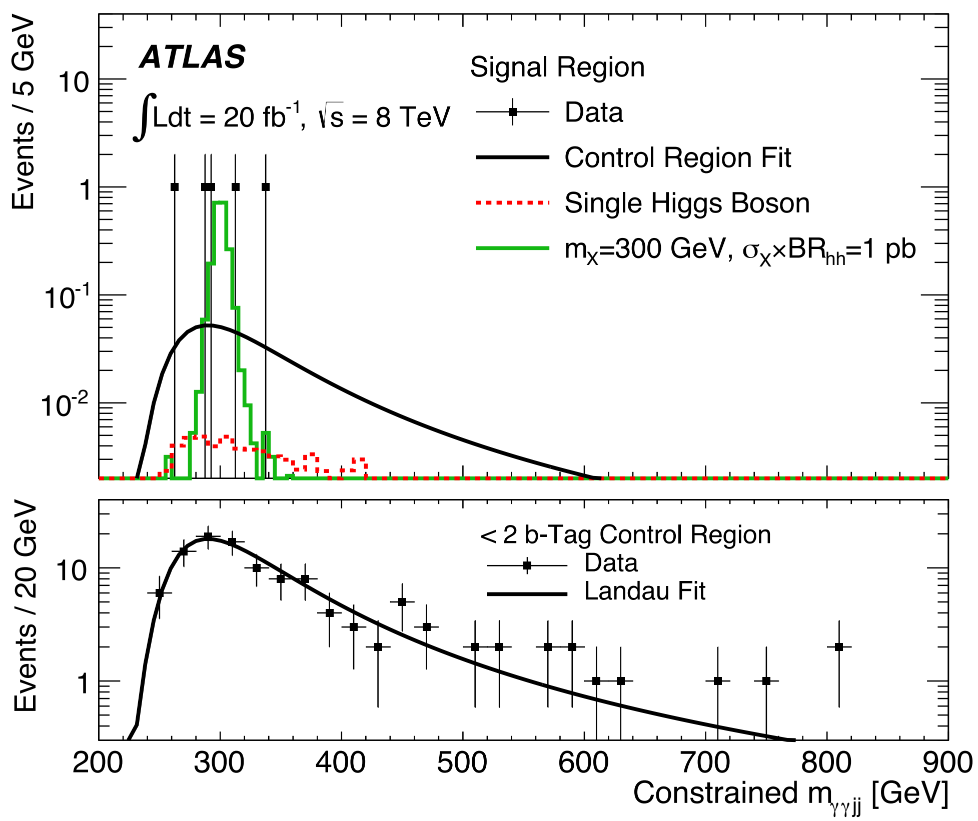
*A. Djouadi & J. Quevillon, LPT-ORSAY-13-26, arXiv:1304.1787*

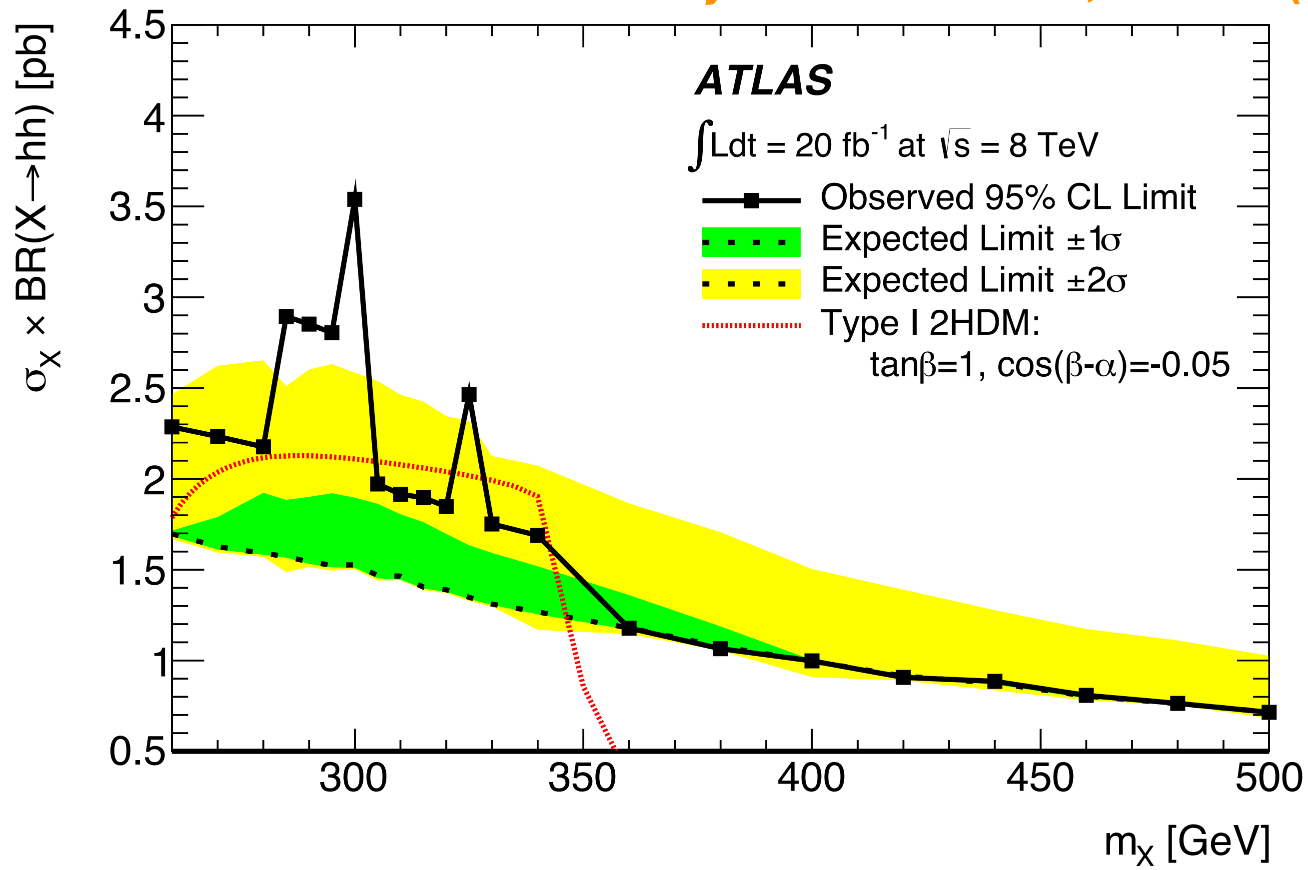



- Many BSM models **predict the existence of multiple Higgs bosons**.
- Their decay modes & branching ratios highly depend on mass & tan β (vacuum expectation values of the Higgs bosons).

# $H \to hh \to b\bar{b}\gamma\gamma$ (low tan β)

*Phys. Rev. Lett. 114, 081802 (2015)*



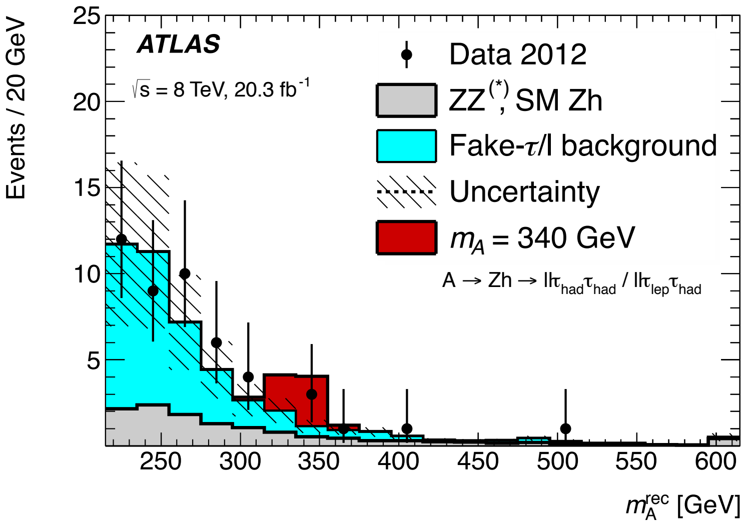




- Small BR (~0.003), but very clean signature.
- Two γ's following the SM $h \to \gamma\gamma$ analysis. 2 b-jets (w/ $p_T > 55/35$ GeV), $95 < m_{bb} < 135$ GeV & $105 < m_{\gamma\gamma} < 160$ GeV. Events from diphoton trigger.
- 1.5 events expected from the SM, 5 events observed (2.4σ excess).
- $H \to hh \to b\bar{b}b\bar{b}$ also published. $H \to hh \to b\bar{b}\tau^+\tau^-$ & $b\bar{b}W^+W^-$ under way.

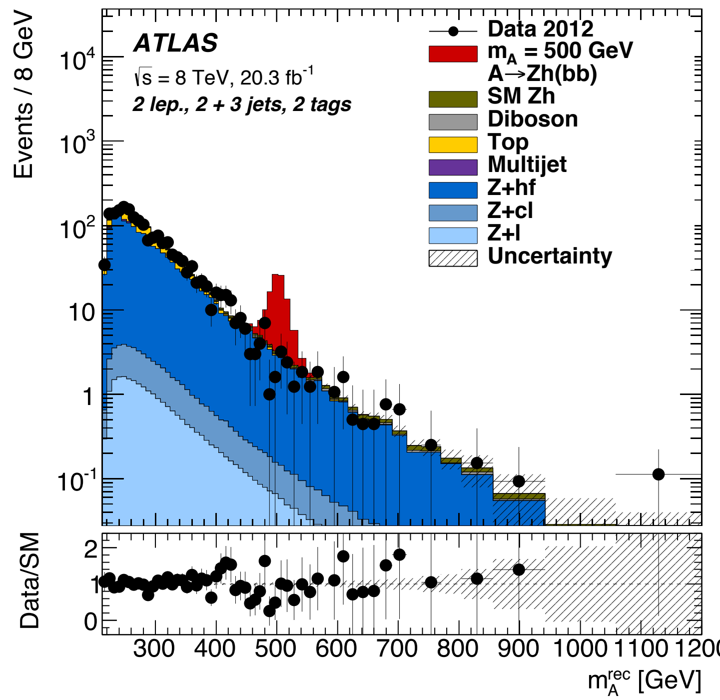
# A→Zh→l⁺l⁻τ⁺τ⁻/llb$\bar{b}$ (low tan β)

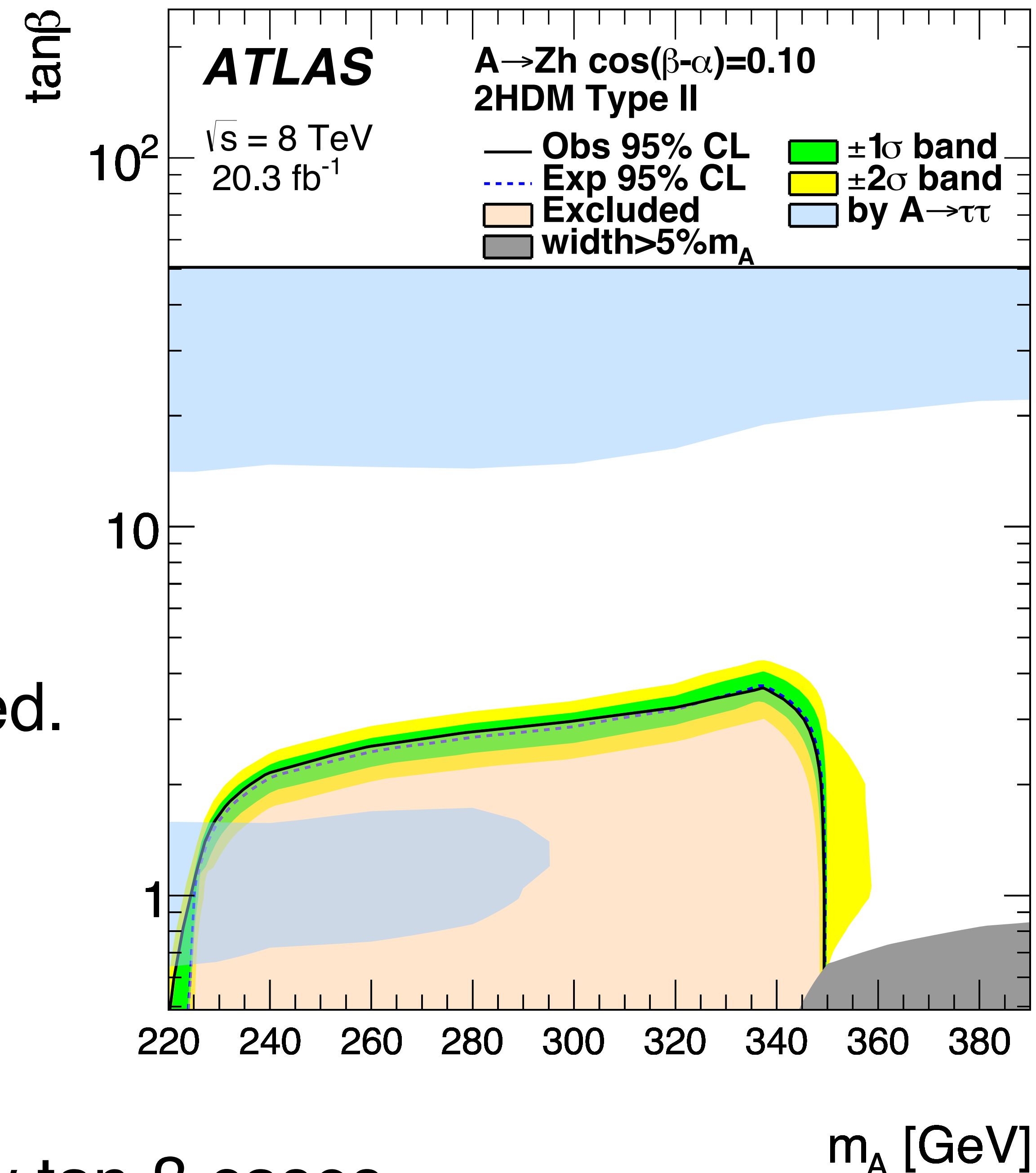
arXiv:1502.04478

A→Zh→llττ




A→Zh→llbb

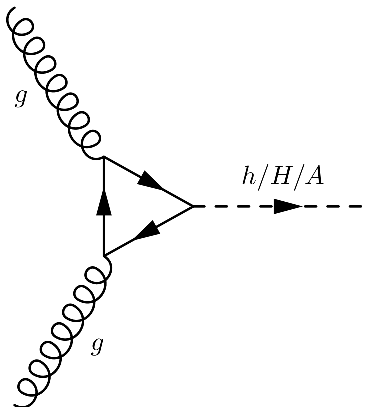


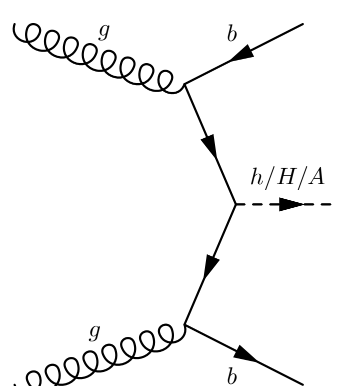



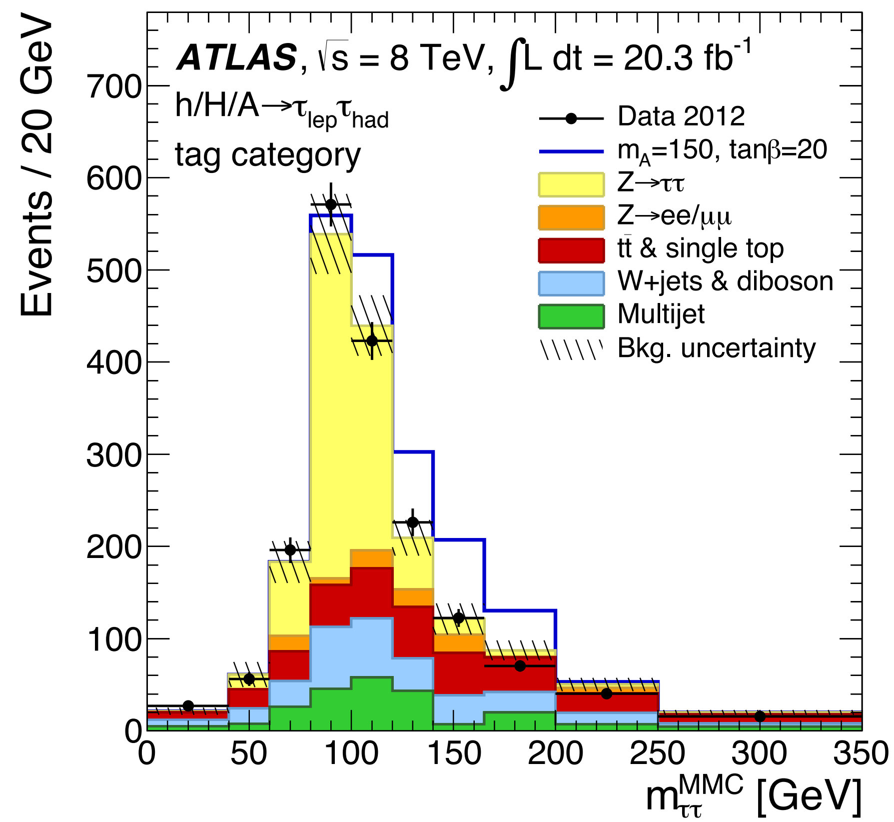

- A→Zh→l⁺l⁻τ⁺τ⁻, l⁺l⁻b$\bar{b}$, ν$\bar{\nu}$b$\bar{b}$ are considered.
- No excess observed.
- Width effects are ignored in the signals, but its impact on the limits are checked.
- 230 < $m_A$ < 350 GeV are excluded for low tan β cases.

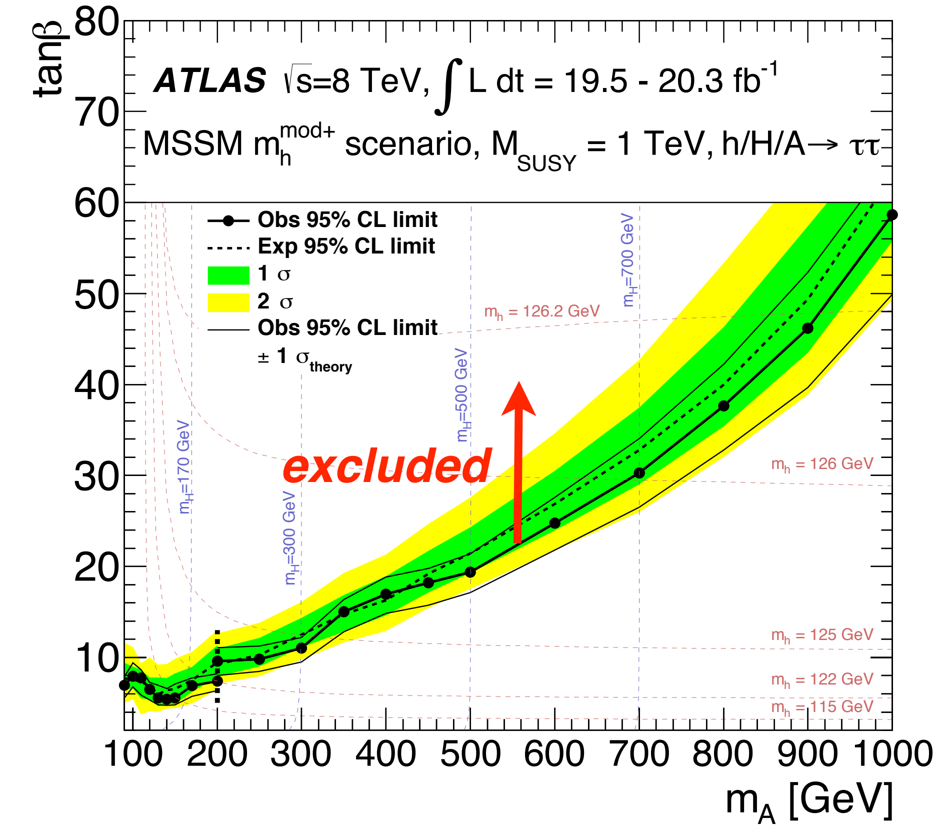
# h/A/H→τ⁺τ⁻ (high tan β)

[JHEP11(2014)056](JHEP11(2014)056)



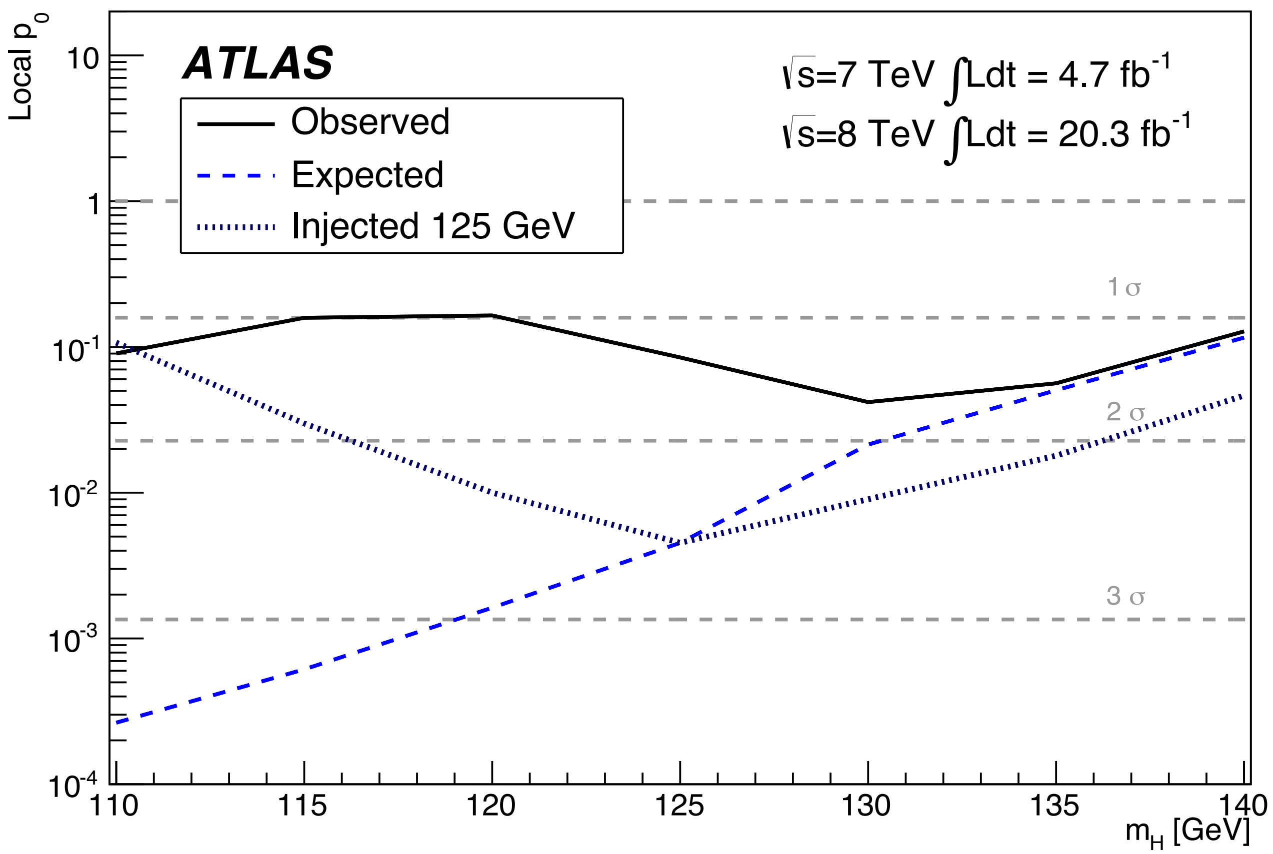

- No b-tag & b-tagged signal regions to search for ggF & b-associated production. Uses all combinations of tau decays ($\tau_{lep}$-$\tau_{lep}$, $\tau_{lep}$-$\tau_{had}$, $\tau_{had}$-$\tau_{had}$)
- $m_{\tau\tau}$ is calculated using the missing mass calculator (MMC). Does not assume collinear approximation & estimate neutrino momentum using a set of equations & likelihood computation.

# Summary

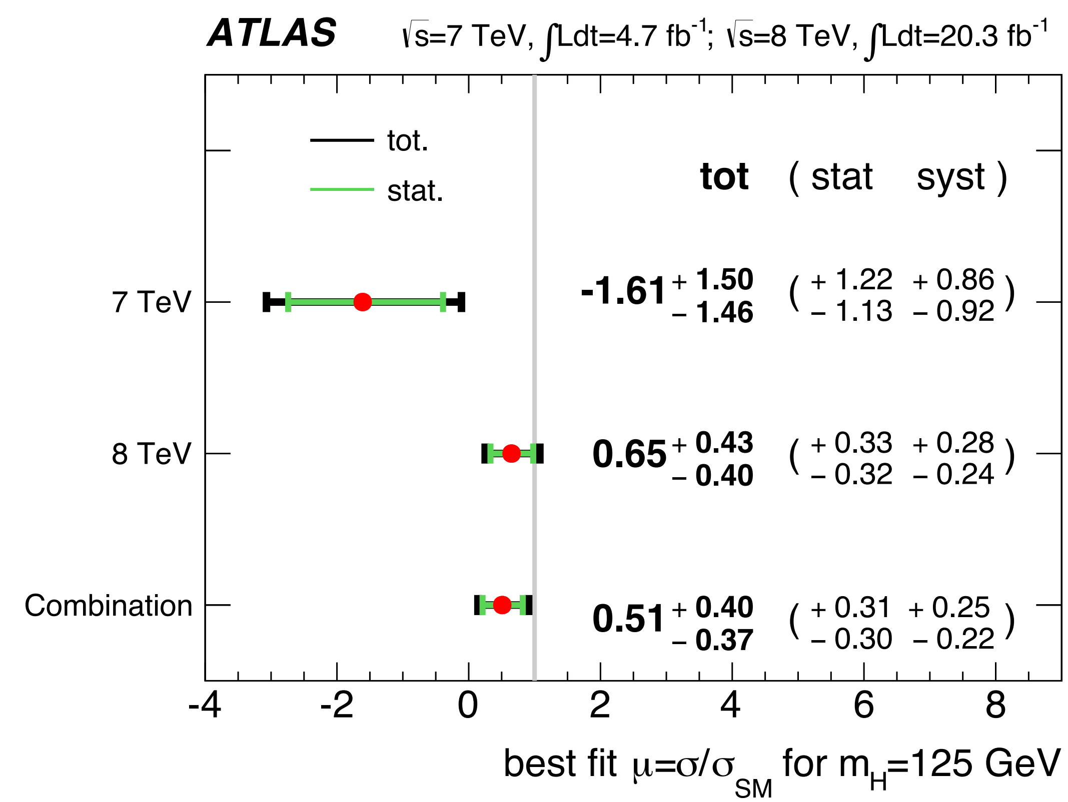
- Presented selected highlights on the Higgs results from the LHC-ATLAS Experiement.
- After the discovery of the Higgs boson, we are progressing with promising programs to understand the Higgs sector from various perspective.
- The efforts will continue for Run-2.
- Run-2 is about to start!
    - 6.5 TeV training is ongoing & has already been successful in many sectors.
    - First beam expected in late March; test collisions expected in late May; 13 TeV data taking will likely to occur in June (50 ns & then to 25 ns).

# backups

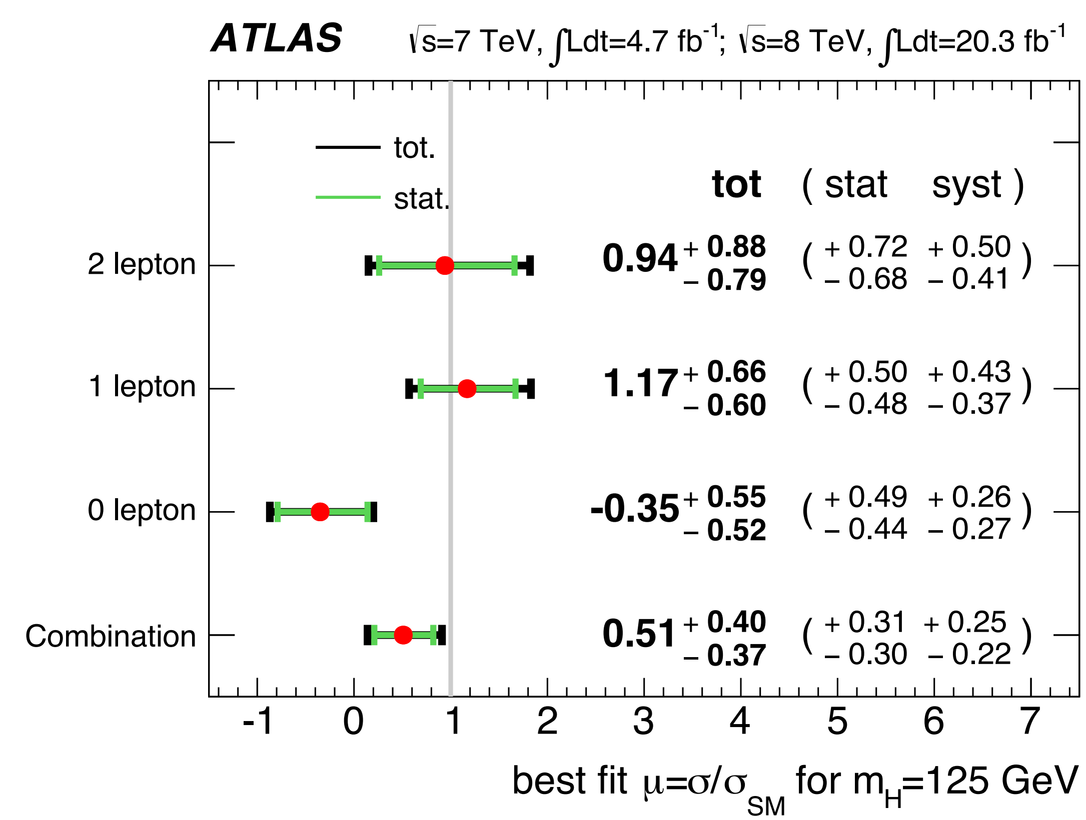
# VH(→b$\bar{b}$)



ATLAS
Observed
Expected
Injected 125 GeV
√s=7 TeV ∫Ldt = 4.7 fb⁻¹
√s=8 TeV ∫Ldt = 20.3 fb⁻¹
Local p0
mH [GeV]

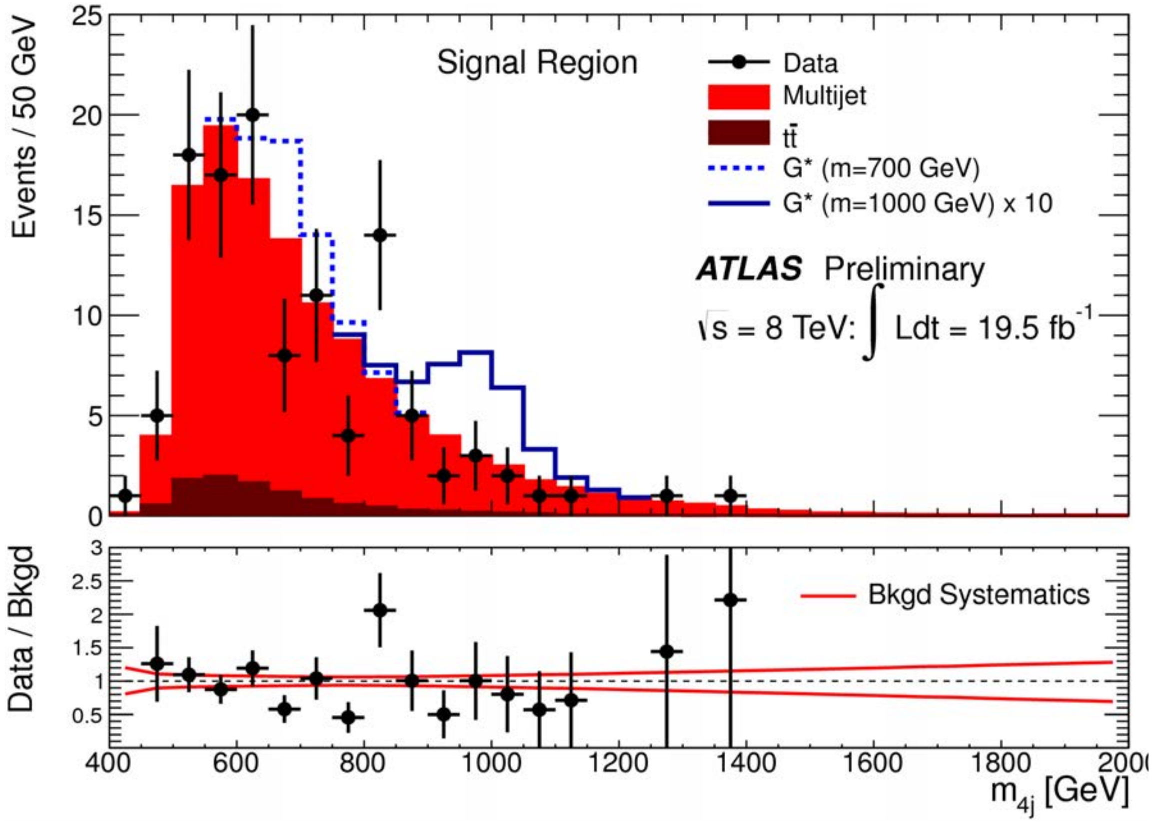



ATLAS
√s=7 TeV, ∫Ldt=4.7 fb⁻¹; √s=8 TeV, ∫Ldt=20.3 fb⁻¹
tot.
stat.
tot ( stat syst )
7 TeV -1.61 +1.50 −1.46 ( +1.22 −1.13 +0.86 −0.92 )
8 TeV 0.65 +0.43 −0.40 ( +0.33 −0.32 +0.28 −0.24 )
Combination 0.51 +0.40 −0.37 ( +0.31 −0.30 +0.25 −0.22 )
best fit μ=σ/σSM for mH=125 GeV

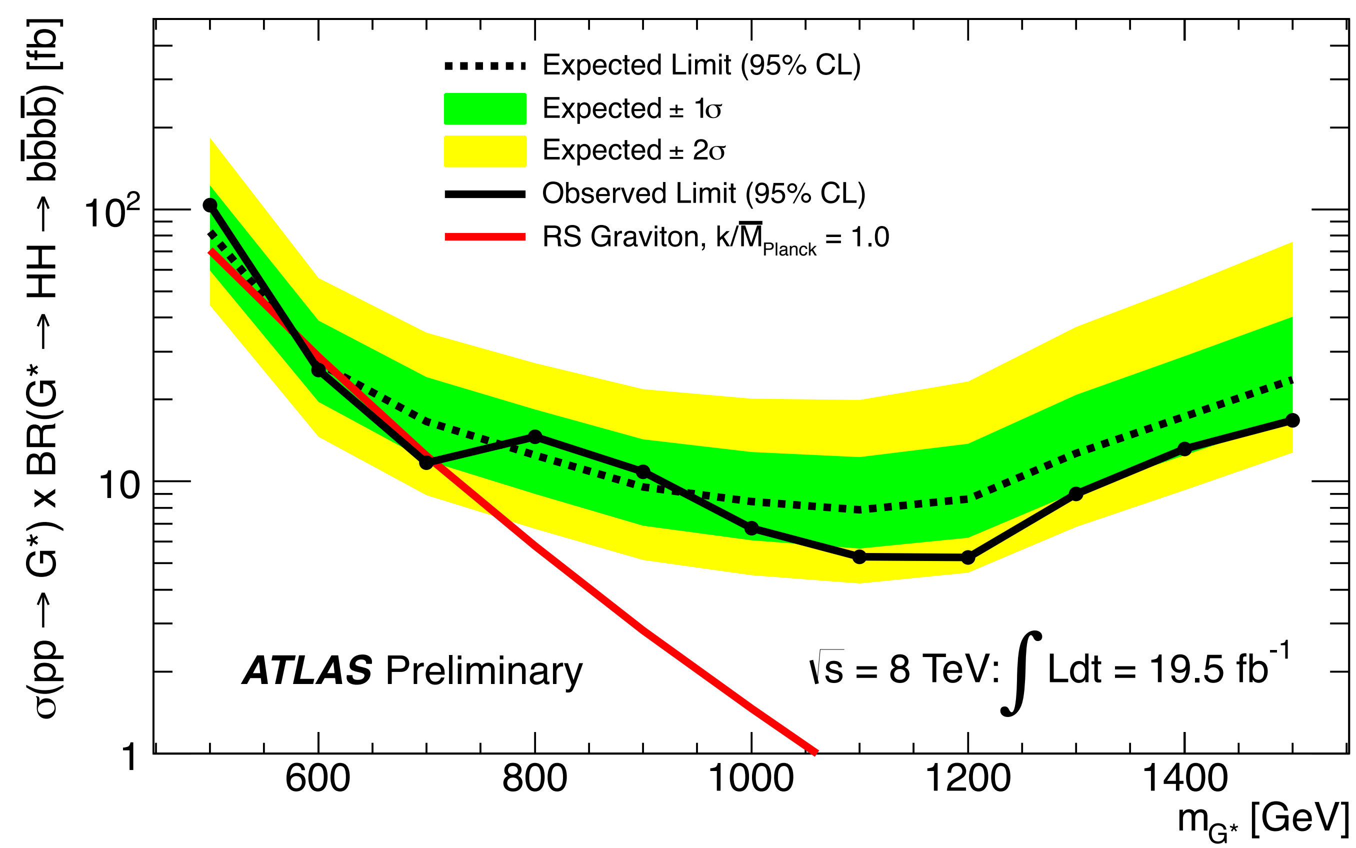



ATLAS
√s=7 TeV, ∫Ldt=4.7 fb⁻¹; √s=8 TeV, ∫Ldt=20.3 fb⁻¹
tot.
stat.
tot ( stat syst )
2 lepton 0.94 +0.88 −0.79 ( +0.72 −0.68 +0.50 −0.41 )
1 lepton 1.17 +0.66 −0.60 ( +0.50 −0.48 +0.43 −0.37 )
0 lepton -0.35 +0.55 −0.52 ( +0.49 −0.44 +0.26 −0.27 )
Combination 0.51 +0.40 −0.37 ( +0.31 −0.30 +0.25 −0.22 )
best fit μ=σ/σSM for mH=125 GeV

# hh→bbbb



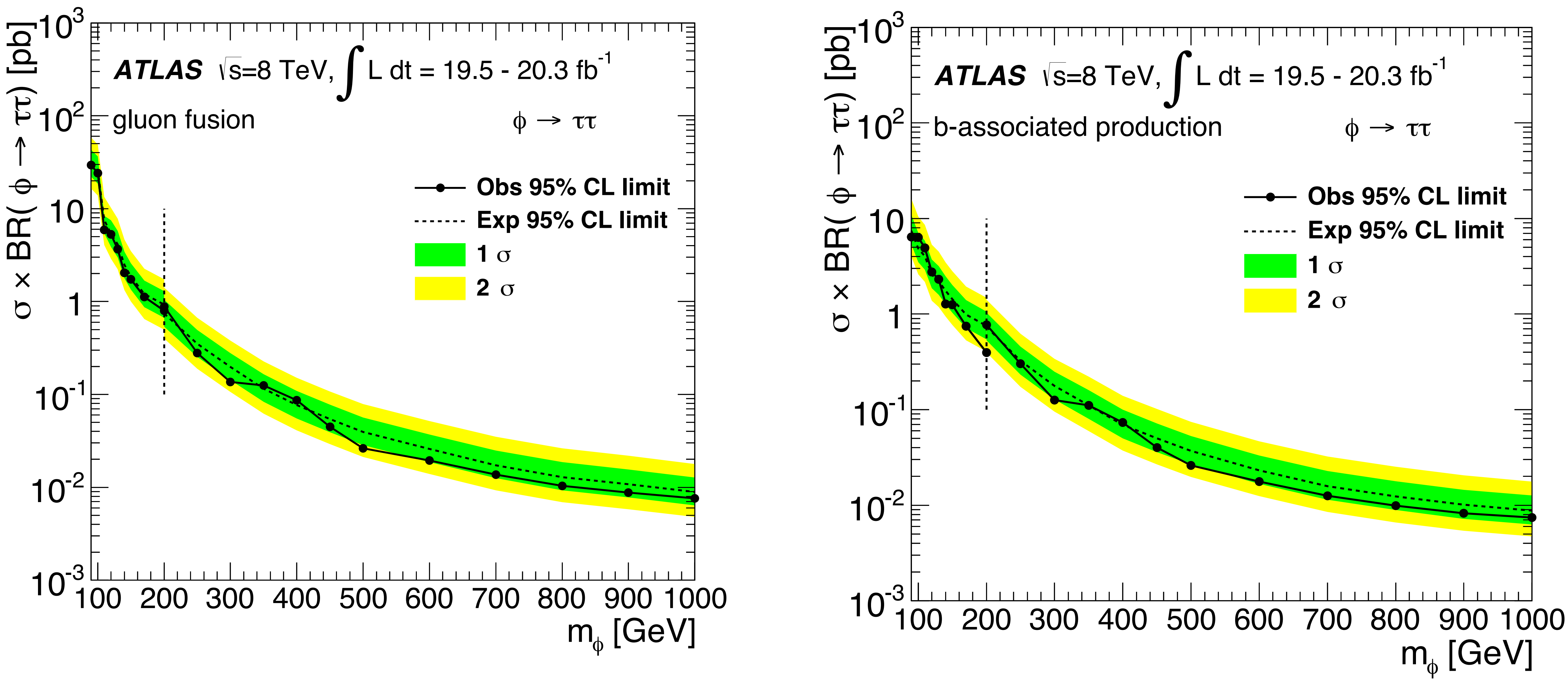
Signal Region
Data
Multijet
tt̄
G* (m=700 GeV)
G* (m=1000 GeV) x 10
ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb⁻¹
Events / 50 GeV
Data / Bkgd
Bkgd Systematics
m4j [GeV]

Expected Limit (95% CL)
Expected ± 1σ
Expected ± 2σ
Observed Limit (95% CL)
RS Graviton, k/M̄Planck = 1.0
ATLAS Preliminary
√s = 8 TeV: ∫ Ldt = 19.5 fb⁻¹
σ(pp → G*) x BR(G* → HH → bb̄bb̄) [fb]
mG* [GeV]

# h/A/H→τ⁺τ⁻ (high tan β)

JHEP11(2014)056



# $h/A/H \to \tau^+\tau^-$ (high tan β)

JHEP11(2014)056