Searches for the Higgs at the LHC in the ZZ decay channel (non 4l)

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(on behalf of the ATLAS and CMS Collaborations)

Higgs Hunting 2012
July 18-20, 2012, Orsay-France

Outline

ATLAS and CMS accumulated ~5fb^{-1} data both at $\sqrt{s}=7\,\mathrm{TeV}$ in 2011 and at $\sqrt{s}=8\,\mathrm{TeV}$ in 2012, and searched for the Standard Model Higgs boson in various decay channels. This talk reports the searches for the SM Higgs in ZZ decay channels (non-4l) mainly in the high mass region (>200GeV).

- Introduction
- $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ in ATLAS and CMS
- $H \to ZZ^{(*)} \to \ell^+\ell^- qq$ in ATLAS and CMS
- $H \to ZZ \to \ell^+\ell^-\tau^+\tau^-$ in CMS
- Summary

Introduction

Search Processes for $H \to ZZ$ (non 4ℓ)

- $H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$

  ATLAS: arXiv:1205.6744 (submitted to Phys. Lett. B)

  CMS: JHEP 1203 (2012) 040, arXiv:1202.3478 (7TeV)

  CMS-PAS-HIG-12-023 (7TeV+8TeV)

- $H \to ZZ \to \ell^+\ell^- q\bar{q}$

  ATLAS: arXiv:1206.2443 (submitted to Phys. Lett. B)

  $H \to ZZ^{(*)} \to \ell^+\ell^- q\bar{q}$

  CMS: JHEP 1204 (2012) 036, arXiv:1202.1416

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

  CMS: JHEP 1203 (2012) 081, arXiv:1202.3617 (7TeV)

  CMS-PAS-HIG-12-016 (7TeV+8TeV combined with 4l analysis)

- Analyses are based on 2011 data at $\sqrt{s} = 7$ TeV and 2012 data at 8 TeV

  ATLAS: 4.7 fb^{-1}(7 TeV)

  CMS: 4.6 fb^{-1}(7 TeV) for $\ell^+\ell^- q\bar{q}$

  5.0 fb^{-1}(7 TeV) $+ 5.0$ fb^{-1}(8 TeV) for $\ell^+\ell^-\nu\bar{\nu}$

  5.05 fb^{-1}(7 TeV) $+ 5.26$ fb^{-1}(8 TeV) for $\ell^+\ell^-\tau^+\tau^-$

SM Higgs Boson $\sigma \times \mathrm{BR}$

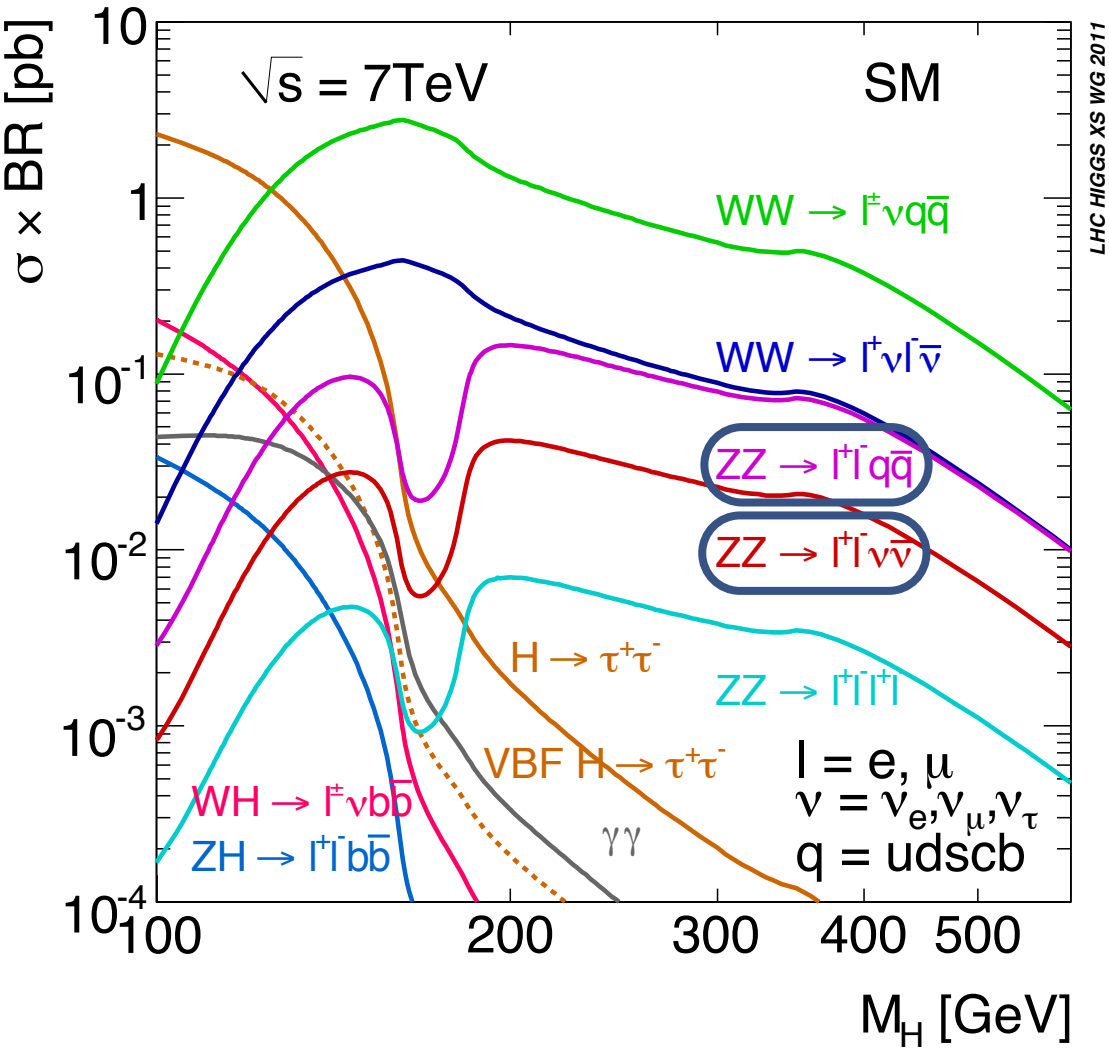
- Cross-sections, branching ratios and theoretical uncertainties are based on: "LHC Higgs Cross Section Working Group" arXiv:1101.0593, arXiv:1201.3084

- Uncertainty of mass line shape:

$$\sim (150\%) \times \left(\frac{M_{\mathrm{H}}}{\mathrm{TeV}} \right)^3$$

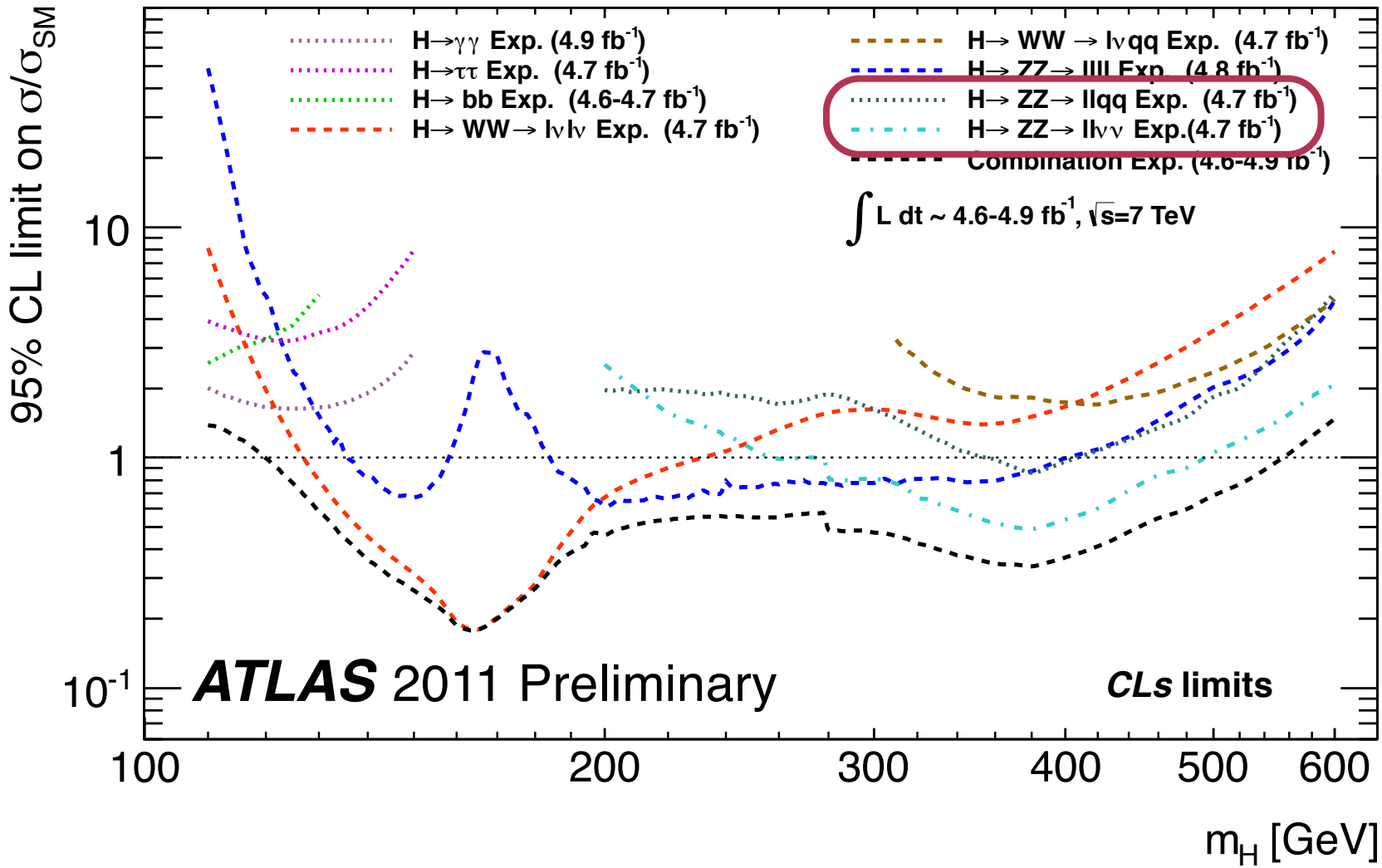
for $M_{\mathrm{H}} \geq 300\ \mathrm{GeV}$

- Main decay modes of the high mass SM Higgs boson are decays to vector boson pairs.



Sensitivity of the Search

- In the high Higgs mass region, $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ has the largest sensitivity.



Analyses

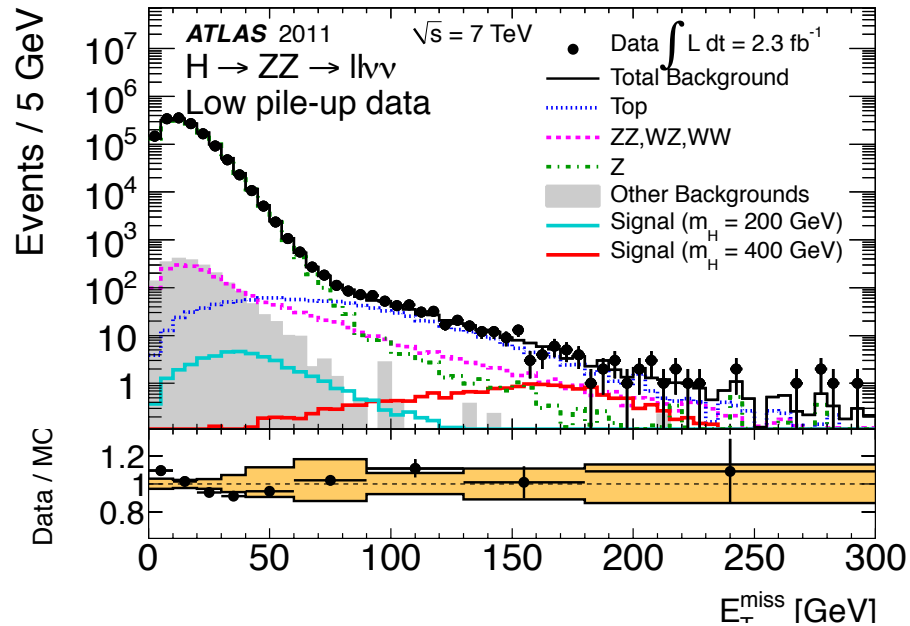
$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (ATLAS)

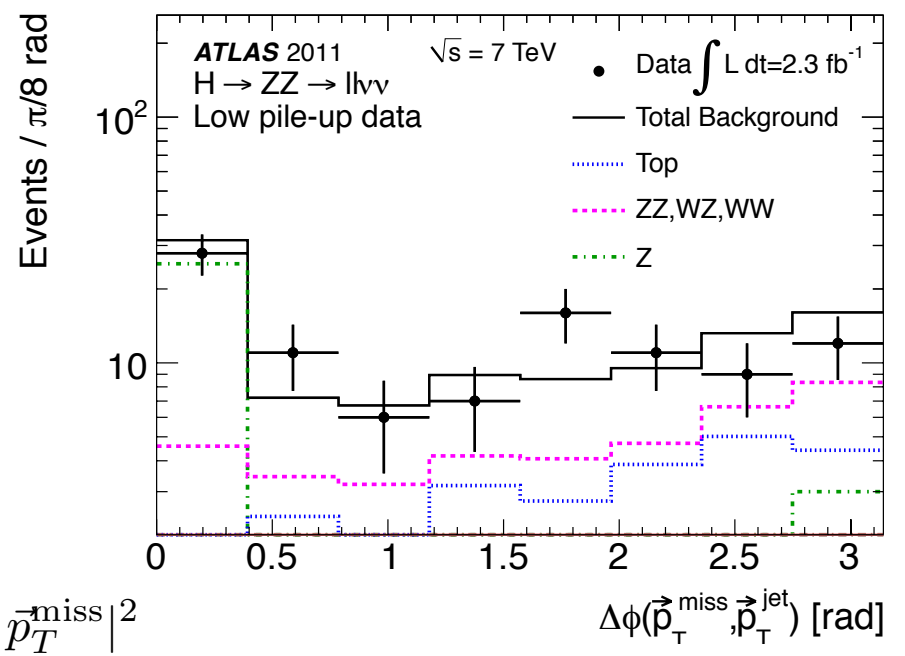
- High p_{T} lepton pair and large $E_{\mathrm{T}}^{\mathrm{miss}}$ from Z decays.
- Exactly two oppositely charged leptons $p_{\mathrm{T}} > 20\,\mathrm{GeV}\,(\mathrm{e}^+\mathrm{e}^-, \mu^+\mu^-)$ (3rd lepton veto with $p_T > 10$ GeV)
- $|m_Z - m_{\ell\ell}| < 15$ GeV
- m_H in [200, 600] GeV, 4-sub channels: $(ee, \mu\mu) \otimes$ (high , low) pile-up periods
- b-jet veto: $p_T > 20$ GeV, $|\eta| < 2.5$
- Optimize selections for two m_H regions:

$200 < m_{\mathrm{H}} < 280$ GeV	$280 \le m_{\mathrm{H}} < 600$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} > 66$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 82$ GeV
$1 < \Delta\phi(\ell,\ell) < 2.64$	$\Delta\phi(\ell,\ell) < 2.25$
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{jet}}) > 1.5$	$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{jet}}) > 0.5$
	$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\ell\ell}) > 1$

- Transverse mass:

$$m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\,\mathrm{miss}}|^2}\right]^2 - |\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\mathrm{miss}}|^2$$





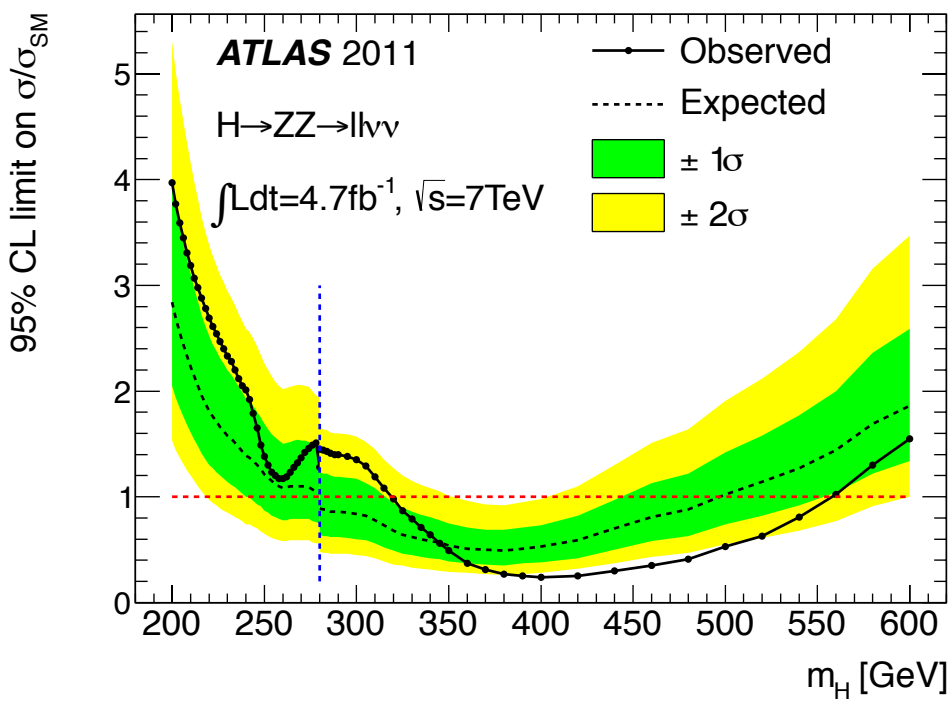
$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (ATLAS)

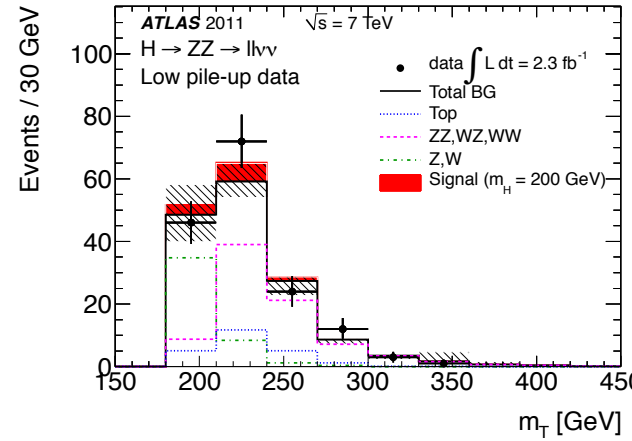
Most BG estimated from MC and verified with data.

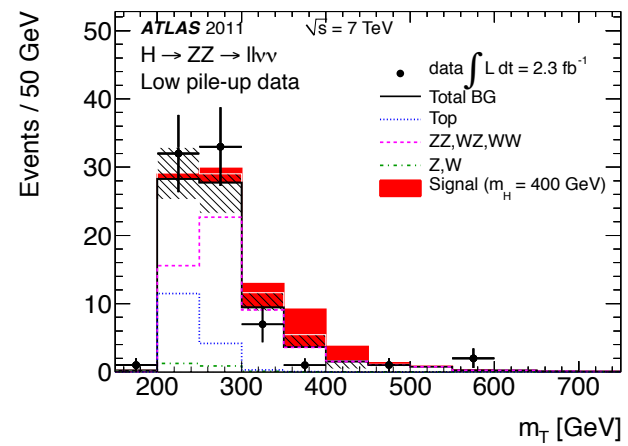
- WZ: verified with three-lepton events
- Top: verified in two control samples: $(e^{\pm}\mu^{\mp})$, and *b*-jet + $m_{\ell\ell}$ side-band.
- W + jets: verified with like-sign $(e^{\pm}e^{\pm}, \mu^{\pm}\mu^{\pm})$
- Z + jets: verified with events rejected by $\Delta\phi(\vec{p}_T^{\,\mathrm{miss}}, \vec{p}_T^{\,\mathrm{jet}})$

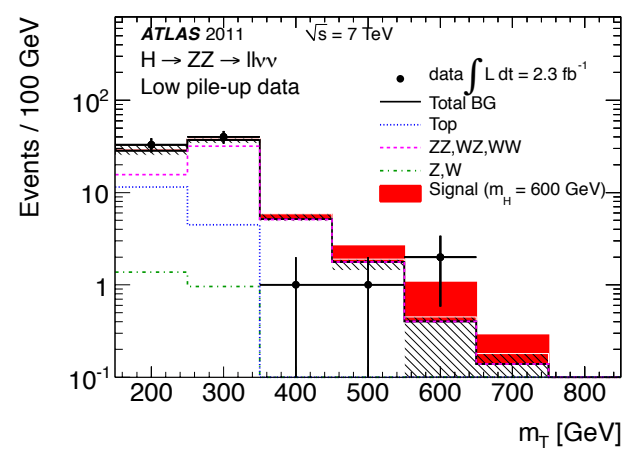
- No indication of excess is seen in m_T distributions.

$319 < m_H < 558$ GeV excluded at the 95% CL.









$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (CMS)

- Two sub-categories

  VBF: two or more jets $|\Delta\eta_{jj}| > 4,\ m_{jj} > 500\ \mathrm{GeV}$

  leptons are in between jets, no jets in the central

  Gluon Fusion: all other events (0-, 1- and ≥2 jets)
- $|m_Z - m_{\ell\ell}| < 30\ \mathrm{GeV},\ \ p_T^{\ell\ell} > 55\ \mathrm{GeV}$ and $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{jet}}) > 0.5$ with 3rd lepton veto

  $p_T > 10\ \mathrm{GeV}$
- Top rejection

  b-jet veto: $p_T > 30\ \mathrm{GeV}, |\eta| < 2.4$

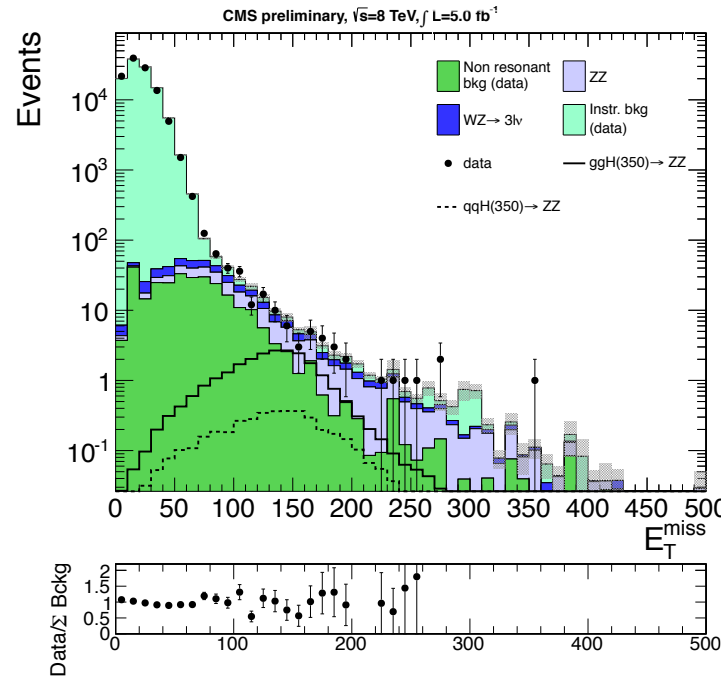
  soft μ veto: $p_T > 3\ \mathrm{GeV}$
- m_{H} dependent cuts on $E_{\mathrm{T}}^{\mathrm{miss}}$ and m_{T} for "Gluon Fusion". Fixed $E_{\mathrm{T}}^{\mathrm{miss}} > 70\ \mathrm{GeV}$ cut for "VBF".

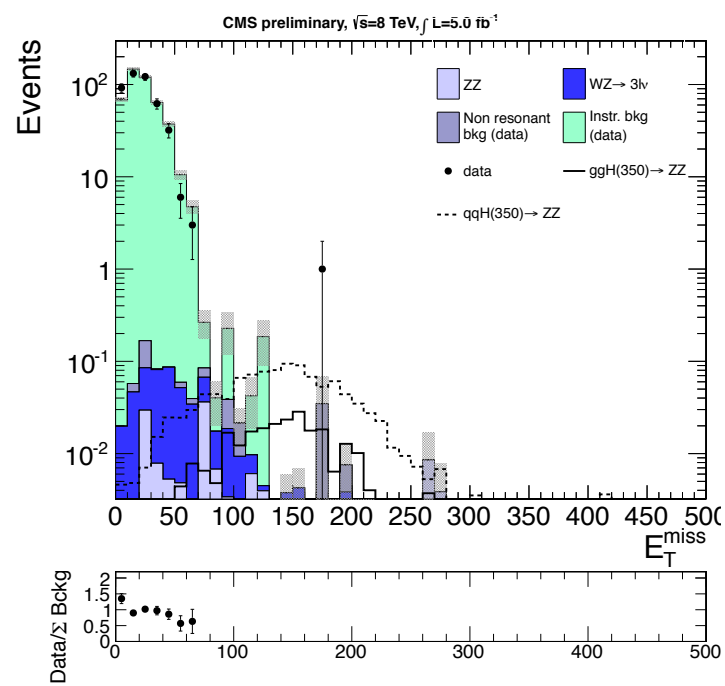
Backgrounds:

- ZZ and WZ from MC
- Z + jets modeled with γ + jets events
- Non-resonant backgrounds (no Z included)

  from $(e^{\pm}\mu^{\mp})$ control sample with scale factors

  obtained from number of events in m_Z side-bands

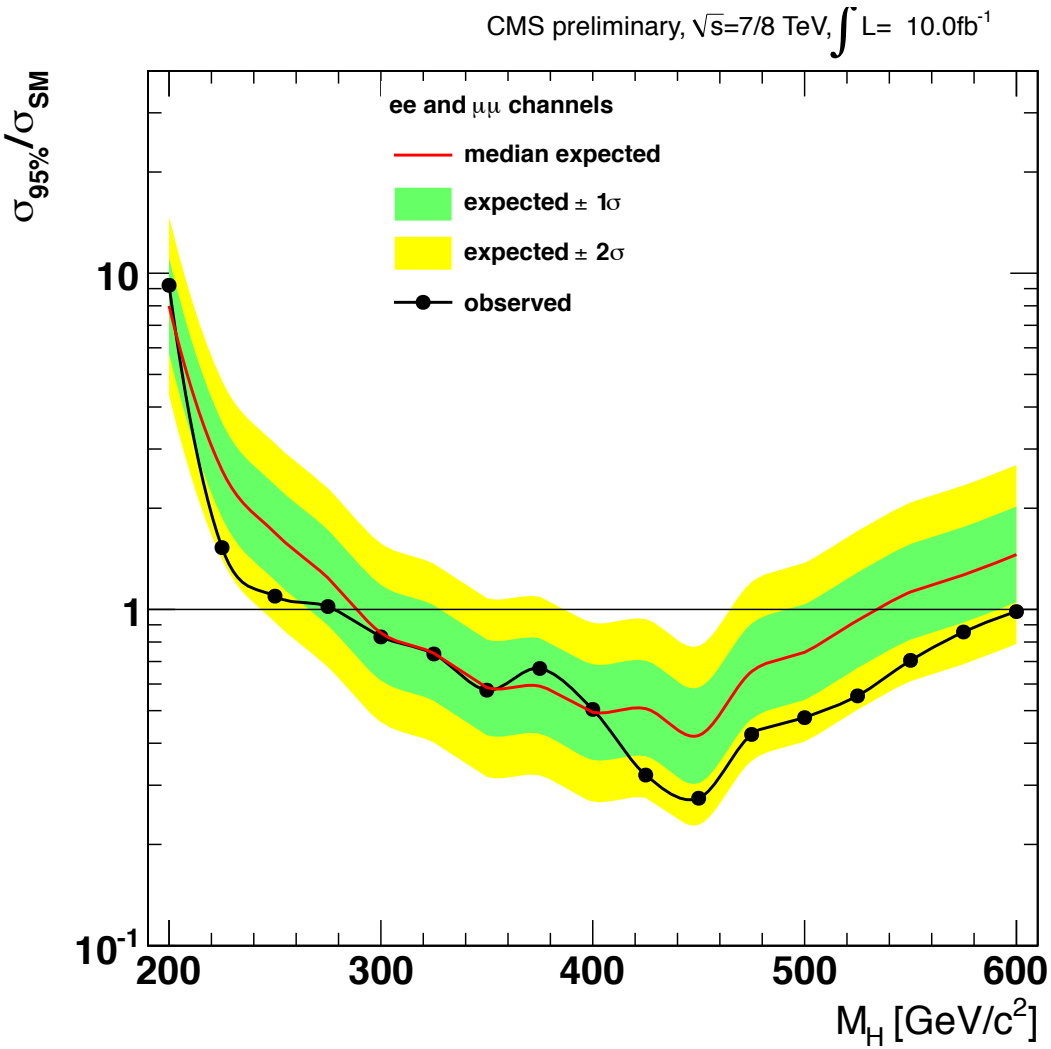




$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (CMS)

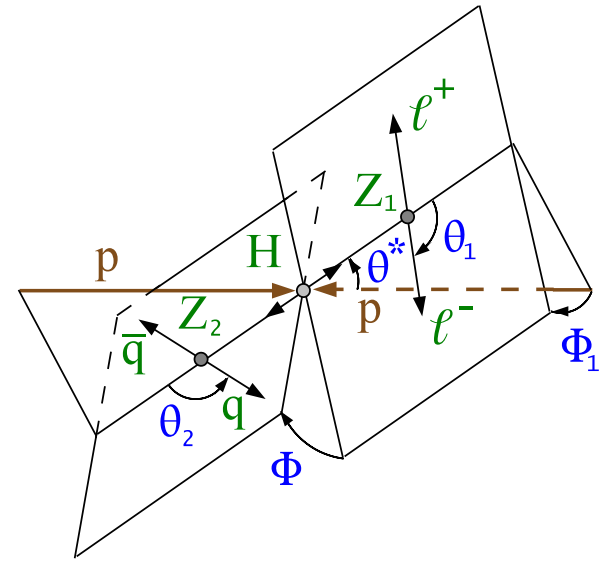
- No significant excess of events is observed
- The SM Higgs boson is excluded at 95% confidence level:

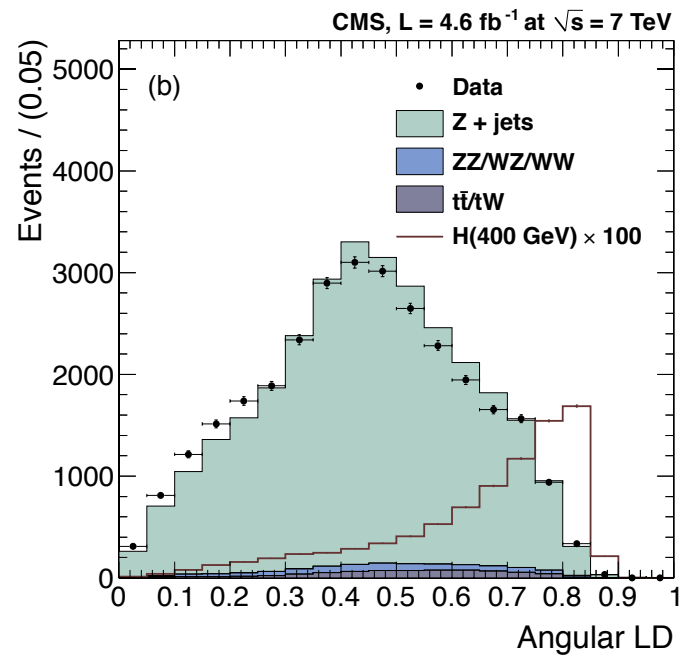
$$278\ \mathrm{GeV} < m_{\mathrm{H}} < 600\ \mathrm{GeV}$$



$H \to ZZ^{(*)} \to \ell^+\ell^- q\bar{q}$ (CMS)

- Highest $\sigma \times \mathrm{Br}$ of all $H \to ZZ$ modes
- m_H regions: [125,170], [183,800] GeV
- lepton:
  low m_H: $p_T^{\ell} > 20,\ 10\ \mathrm{GeV},\ m_{\ell\ell} < 80\ \mathrm{GeV}$
  high m_H: $p_T^{\ell} > 40,\ 20\ \mathrm{GeV},\ 70 < m_{\ell\ell} < 110\ \mathrm{GeV}$
- jet: $p_T^{\mathrm{jet}} > 30\ \mathrm{GeV},\ 75 < m_{jj} < 105\ \mathrm{GeV}$
- Events categorized by 0, 1, 2 *b*-jets
- Higgs decay angles: angular likelihood discriminant (LD) based on $(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$
- Quark-gluon LD for 0 *b*-jets: no. of charged tracks, no. of photon and neutral hadrons, and $\mathrm{PTD} = \sqrt{\sum p_T^2 / \left(\sum p_T\right)^2}$
- Missing E_T discriminant for top: $E_T^{\mathrm{miss}} \sim 0$



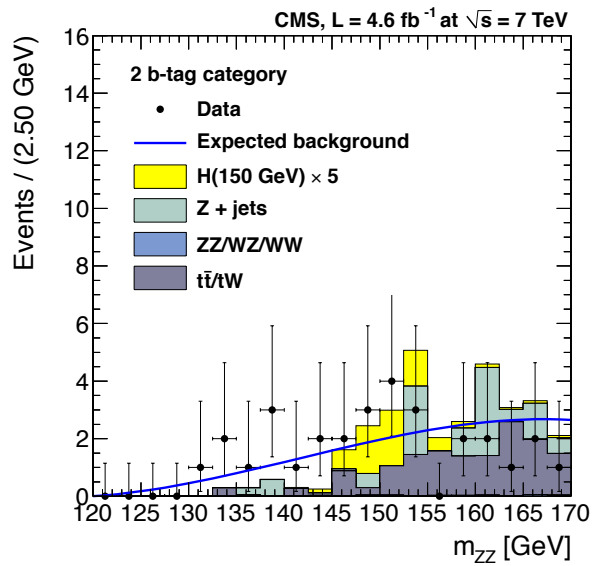


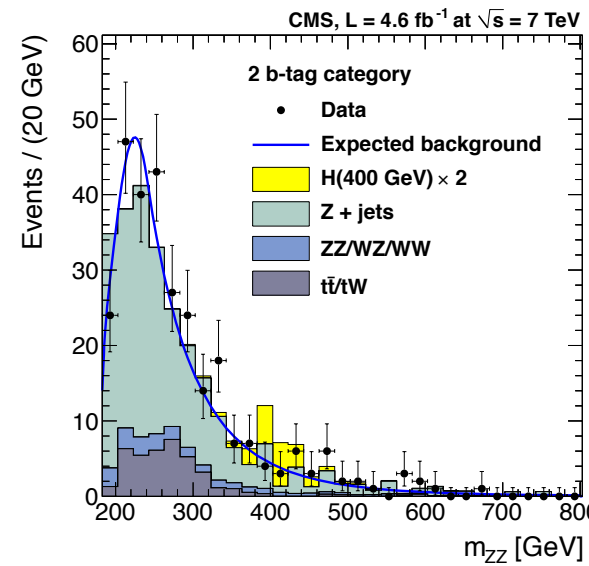
Background

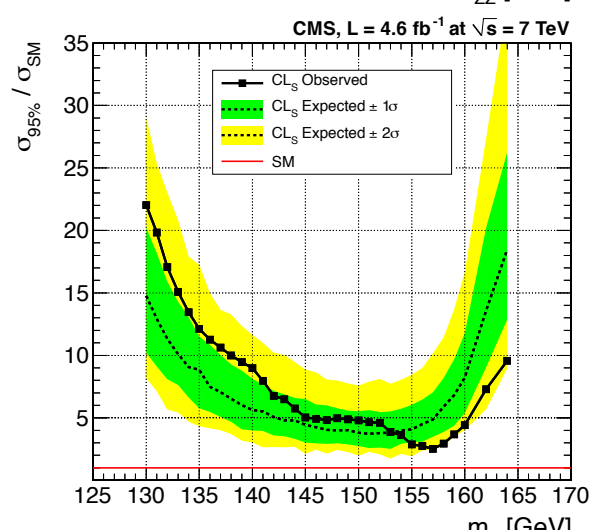
- m_{jj} sidebands: $60 < m_{jj} < 75\ \mathrm{GeV}$ and $105 < m_{jj} < 130\ \mathrm{GeV}$

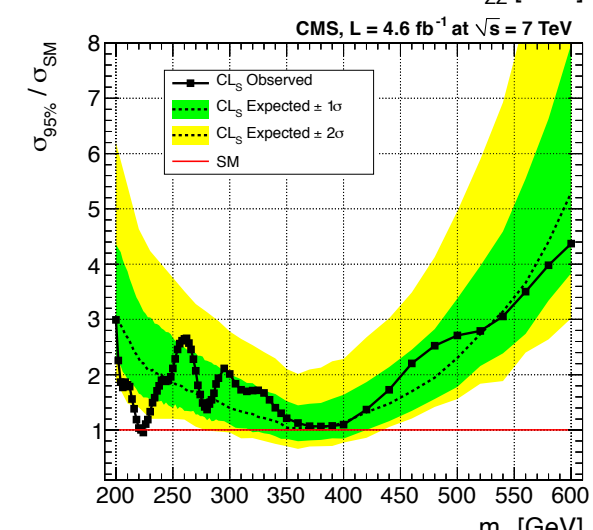
$H \to ZZ^{(*)} \to \ell^+\ell^- q\bar{q}$ (CMS)

- SM Higgs: the upper limit of cross section at the 95% CL for the search regions.
- A Higgs model with four fermion generations: [154,161] GeV and [200, 470] GeV are excluded at 95% CL.









$H \to ZZ \to \ell^+\ell^- q\bar{q}$ (ATLAS)

- High p_{T} lepton pair and jet pair from Z decays. Small $E_{\mathrm{T}}^{\mathrm{miss}}$
- m_H region: 200-600 GeV
- $e, \mu : p_T^{\ell} > 20\ \mathrm{GeV},\ 83 < m_{\ell\ell} < 99\ \mathrm{GeV}$

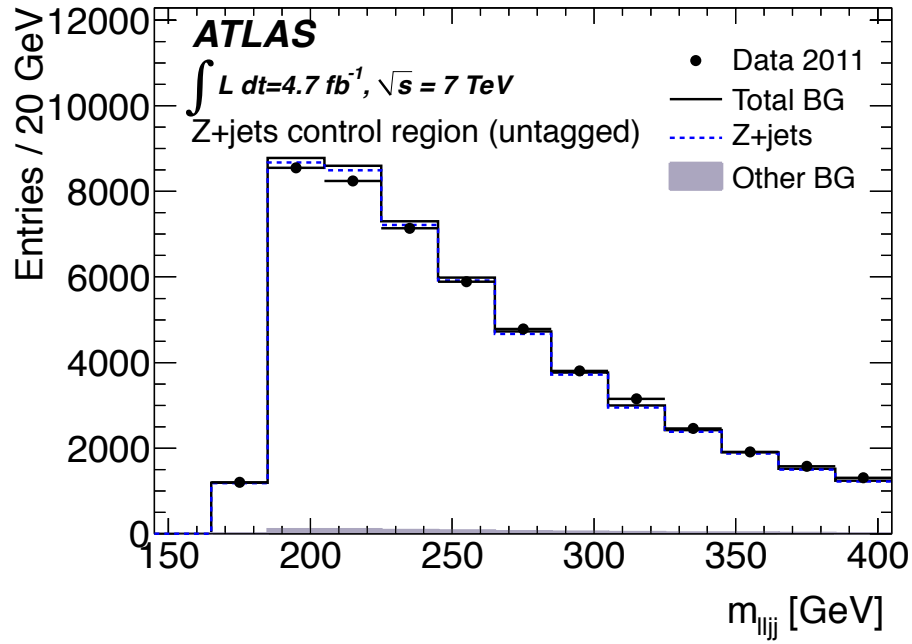
  $\mathrm{jet} : p_T^{\mathrm{jet}} > 20\ \mathrm{GeV},\ 70 < m_{jj} < 105\ \mathrm{GeV}$

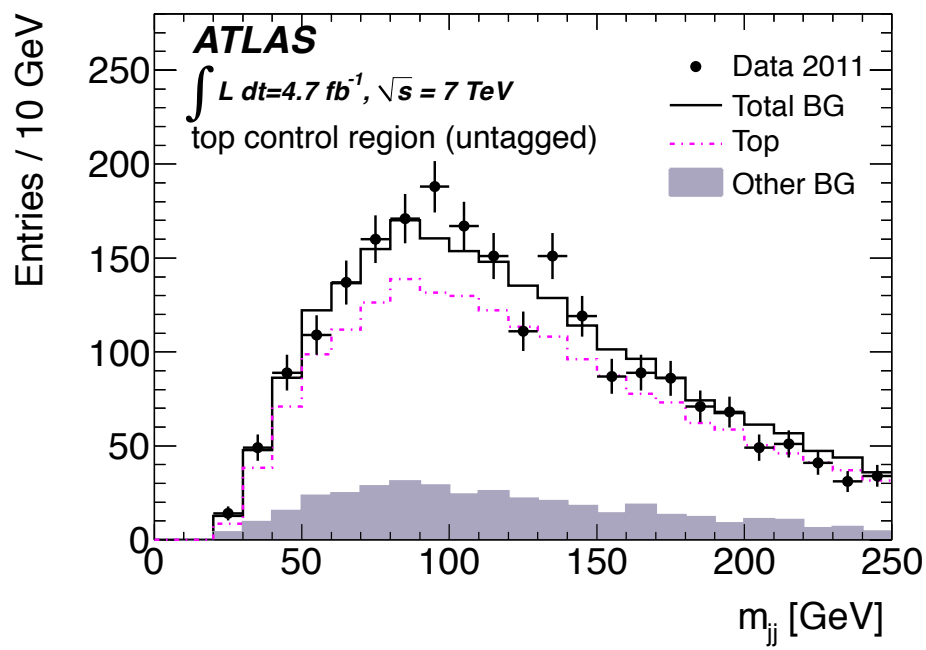
  $\Delta R_{jj} > 0.7$
- $E_T^{\mathrm{miss}} < 50\ \mathrm{GeV}$
- Two sub-channels: untagged ($< 2\,b$ jets) & tagged ($= 2\,b$ jets)
- For high m_H ($> 300\ \mathrm{GeV}$)

  $p_T^{\mathrm{jet}} > 45\ \mathrm{GeV},\ \Delta\phi_{\ell\ell} < \frac{\pi}{2},\ \Delta\phi_{jj} < \frac{\pi}{2}$

Backgrounds

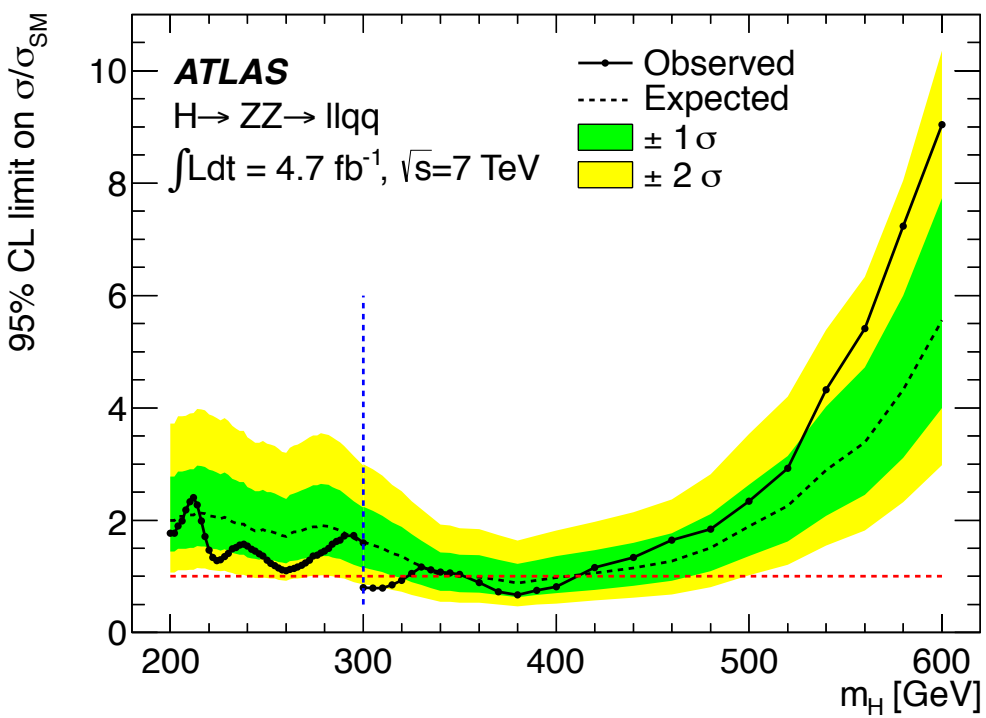
- Z + jets: m_{jj} sidebands: [40,70]. [105,150] GeV
- Top: $m_{\ell\ell}$ sidebands: [60,76], [106,150] GeV and E_T^{miss} selection reversed.
- Di-boson: from MC simulation
- Multi-jet: events with loose electron-ID

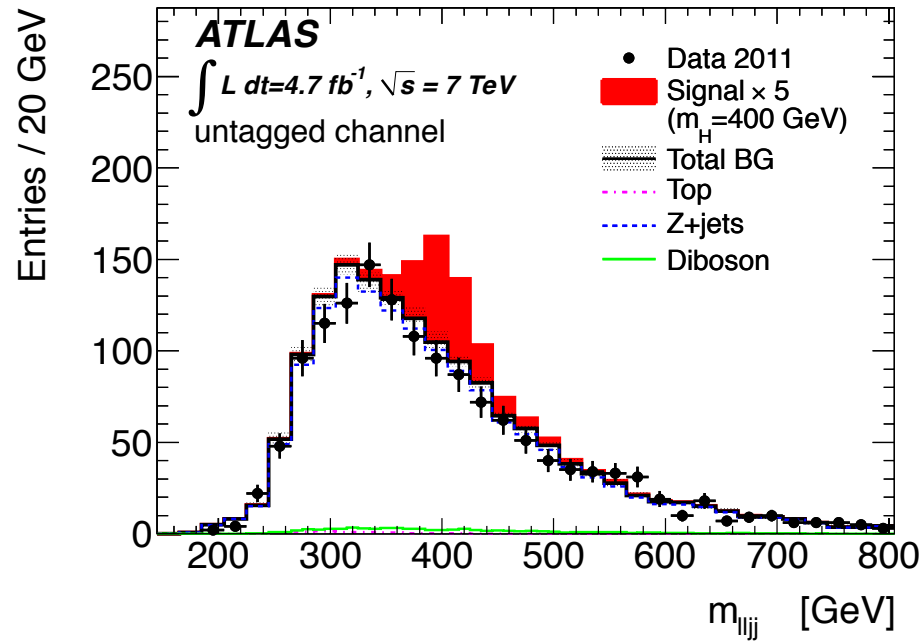


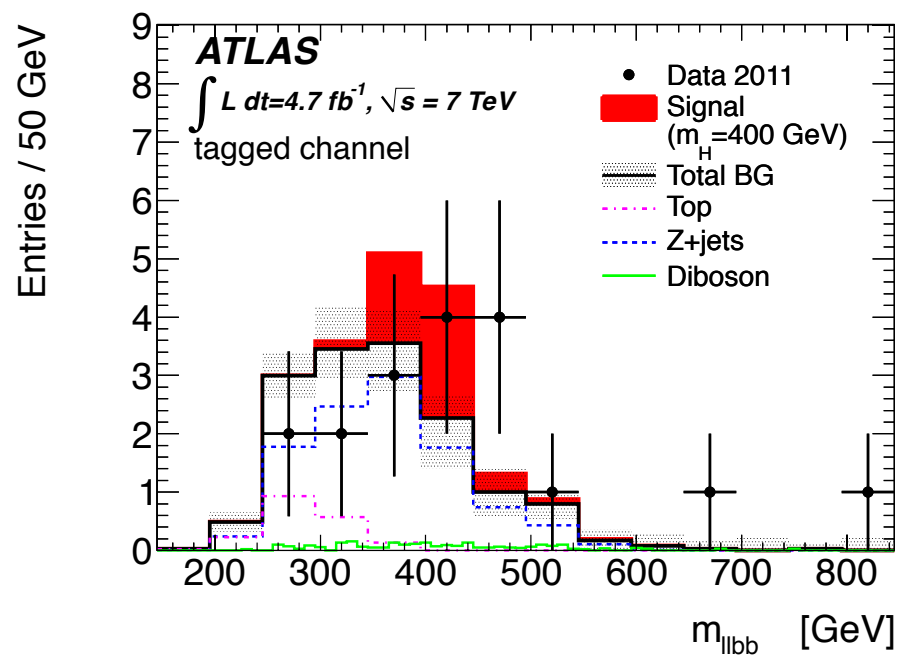


$H \to ZZ \to \ell^+\ell^- q\bar{q}$ (ATLAS)

- $m_{\ell\ell jj}$ distributions: no significant excess of events is seen.
- $300 \leq m_{\mathrm{H}} \leq 322\,\mathrm{GeV}$ and $353 \leq m_{\mathrm{H}} \leq 410\,\mathrm{GeV}$ excluded at the 95% CL.







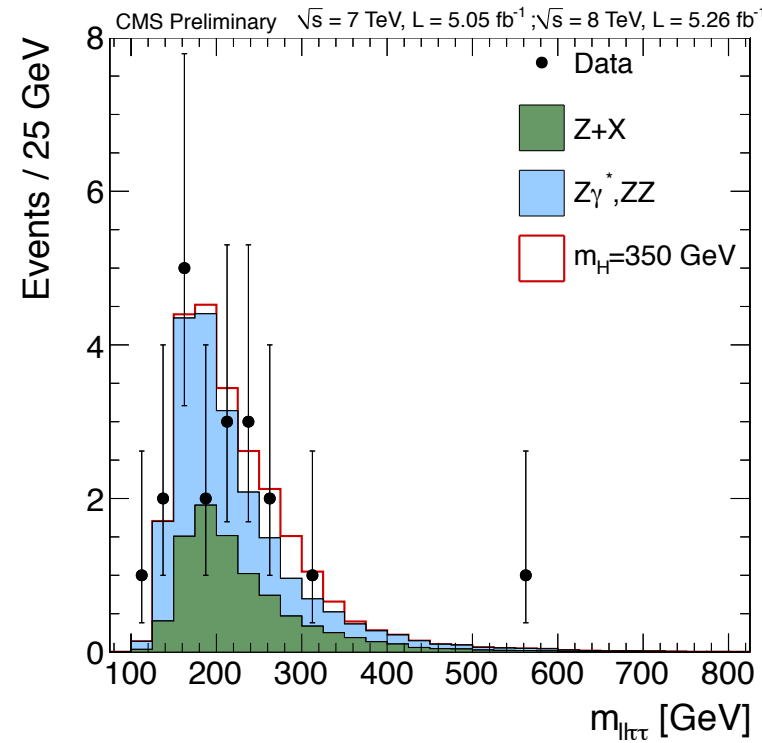
$H \to ZZ \to \ell^+\ell^-\tau^+\tau^-$ (CMS)

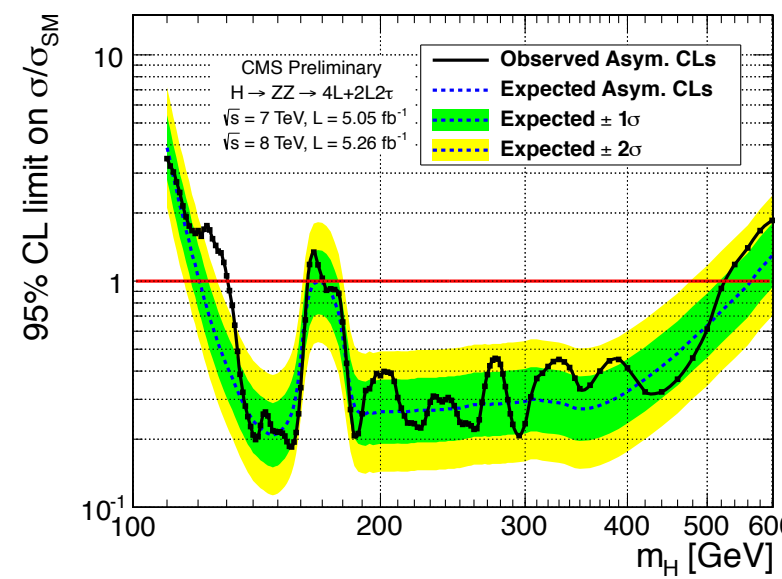
- This analysis becomes a part of $ZZ \to 4\ell$ analysis for 7+8 TeV data.

- One Z: $Z \to \ell^+\ell^-(\ell = e, \mu)$
  $60 < m_{\ell\ell} < 120$ GeV
  $(p_{\mathrm{T}}^{\ell} > 20$ GeV and 10 GeV$)$

- The other: $Z \to \tau^+\tau^-$
  $\tau_h\tau_h$, $\tau_e\tau_h$, $\tau_\mu\tau_h$ and $\tau_e\tau_\mu$ are considered.
  Visible mass: $m_{\tau\tau} < 90$ GeV
  $(p_{\mathrm{T}}^{\ell} > 10$ GeV and $p_{\mathrm{T}}^{\tau_h} > 20$ GeV$)$

- Results combined with 4l-channel:
  The SM Higgs boson excluded to 525 GeV
  95% CL. (tau-channel contribution is small)
  (Corresponding number from ZZ->4l by ATLAS: 460 GeV)

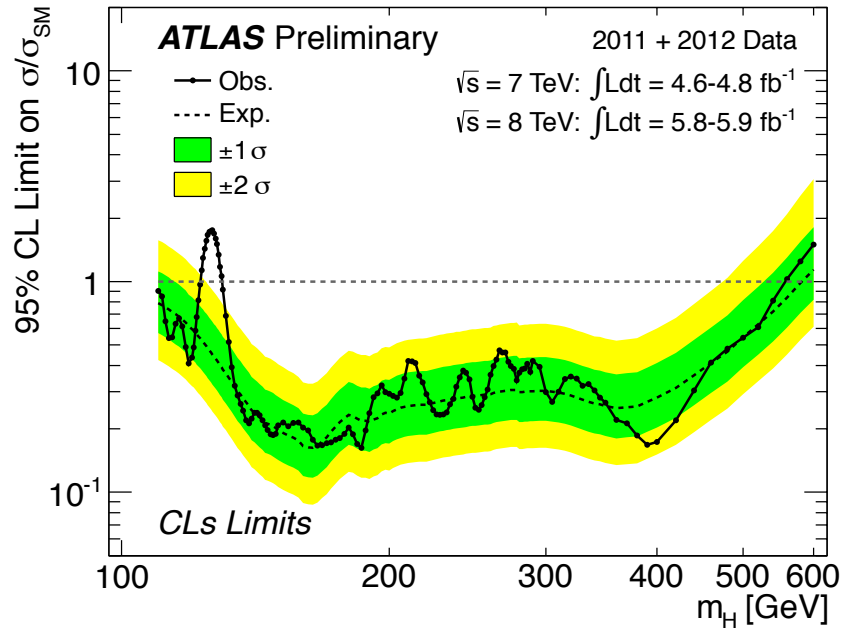


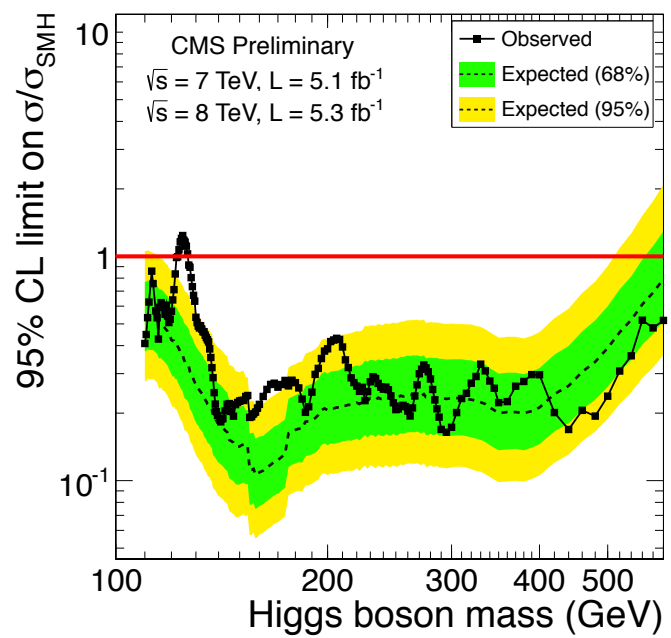


Summary and Outlook

• SM Higgs boson searches in the high mass region have been performed by ATLAS and CMS, using the H to ZZ decay channel. In combination with other channels a SM Higgs boson is excluded up to 600 GeV.

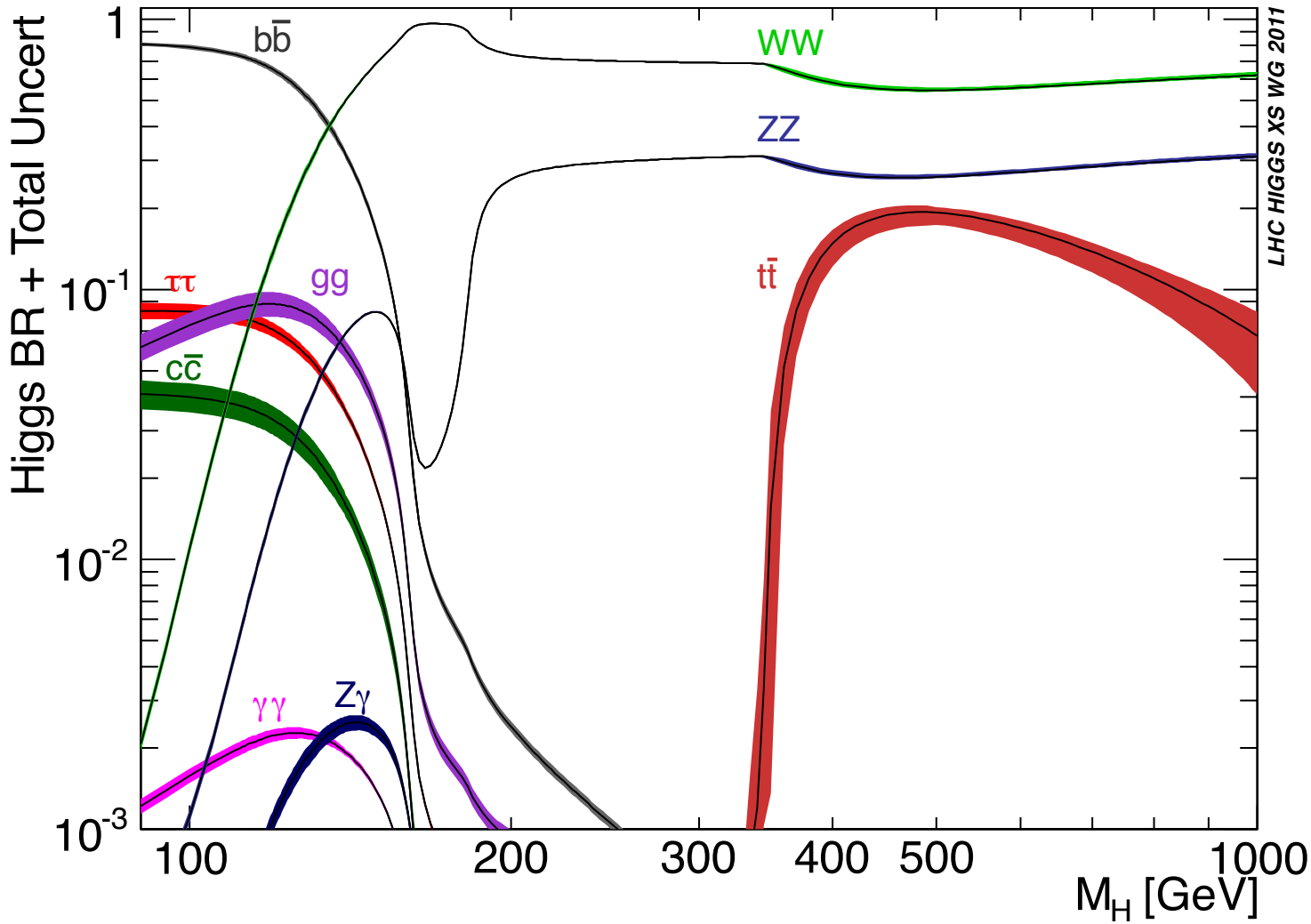
• As the next step:
  - to probe higher mass region, and
  - to search for non-SM signals.



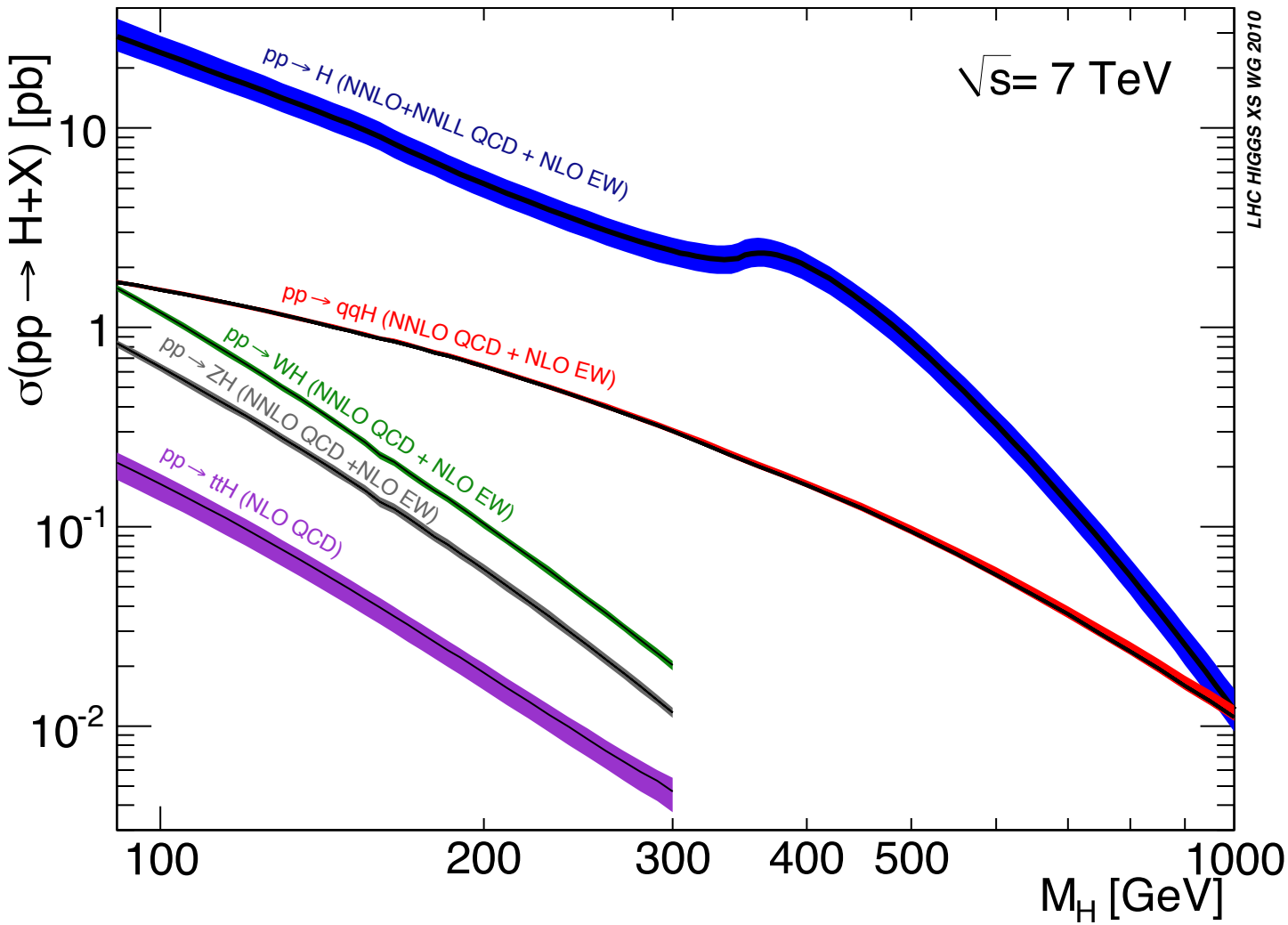


Backups

SM Higgs Boson Decays

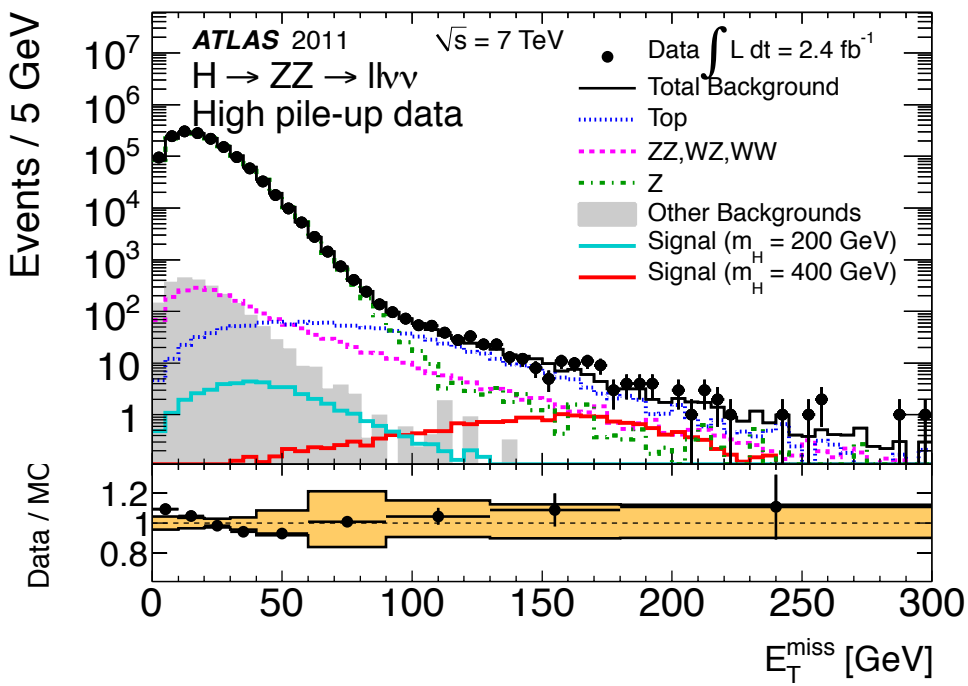


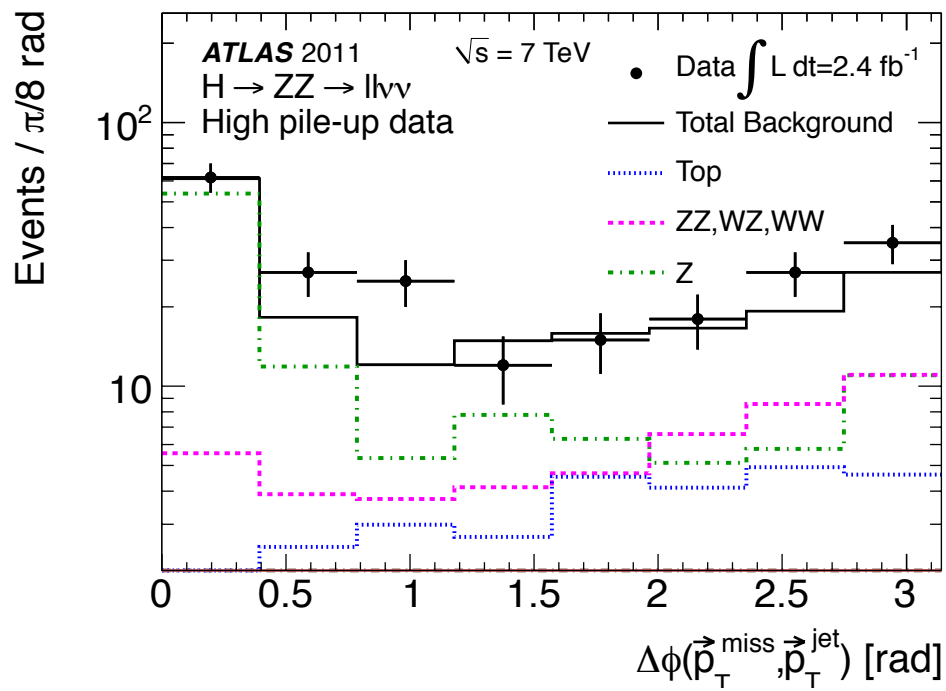
SM Higgs Boson Production



$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (ATLAS)

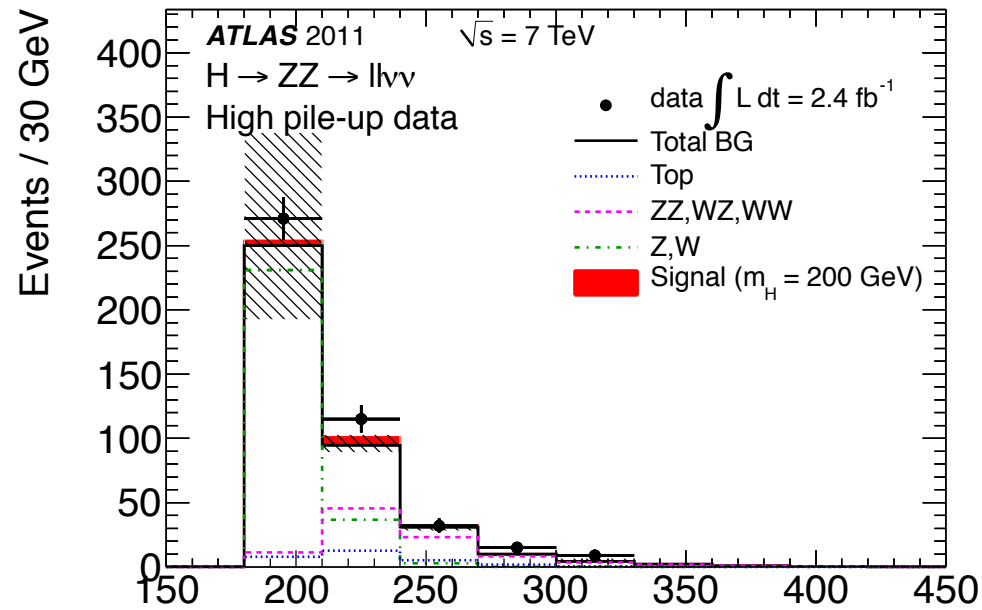
- High pile-up plots

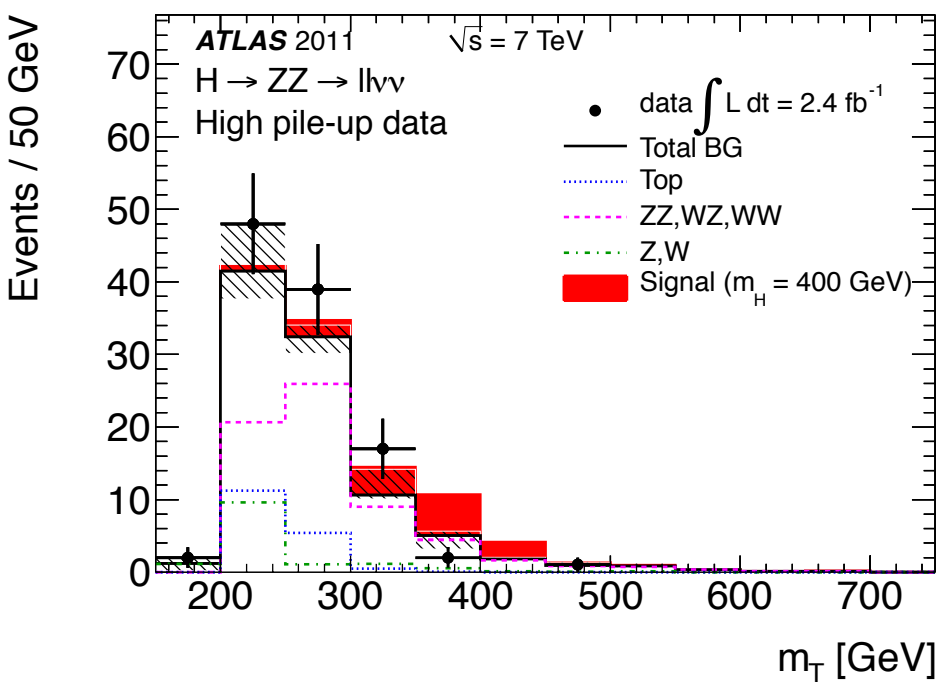


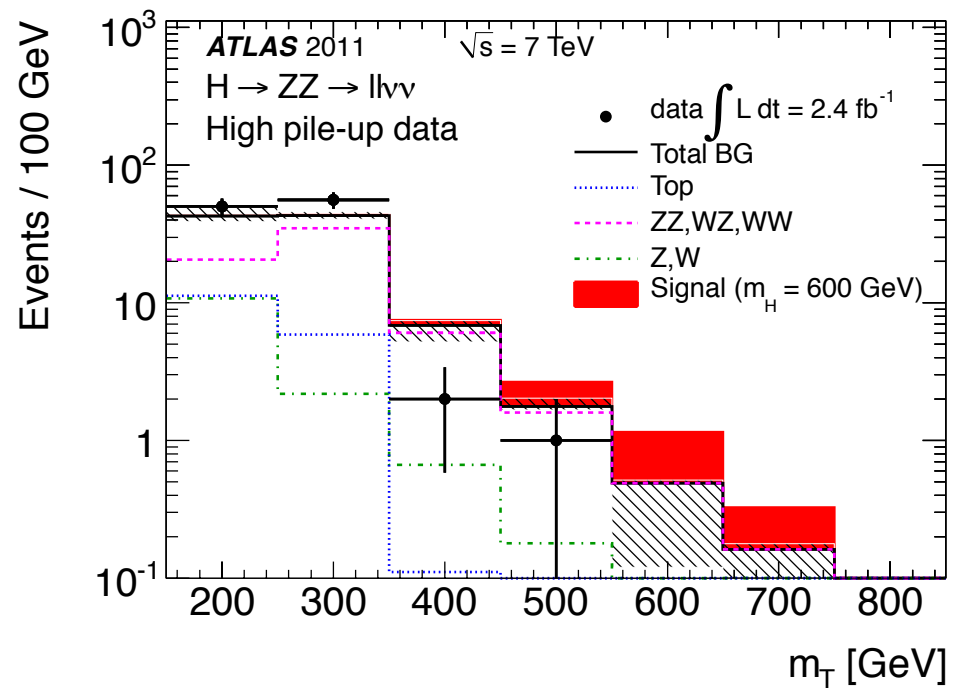


$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (ATLAS)

- High pile-up plots

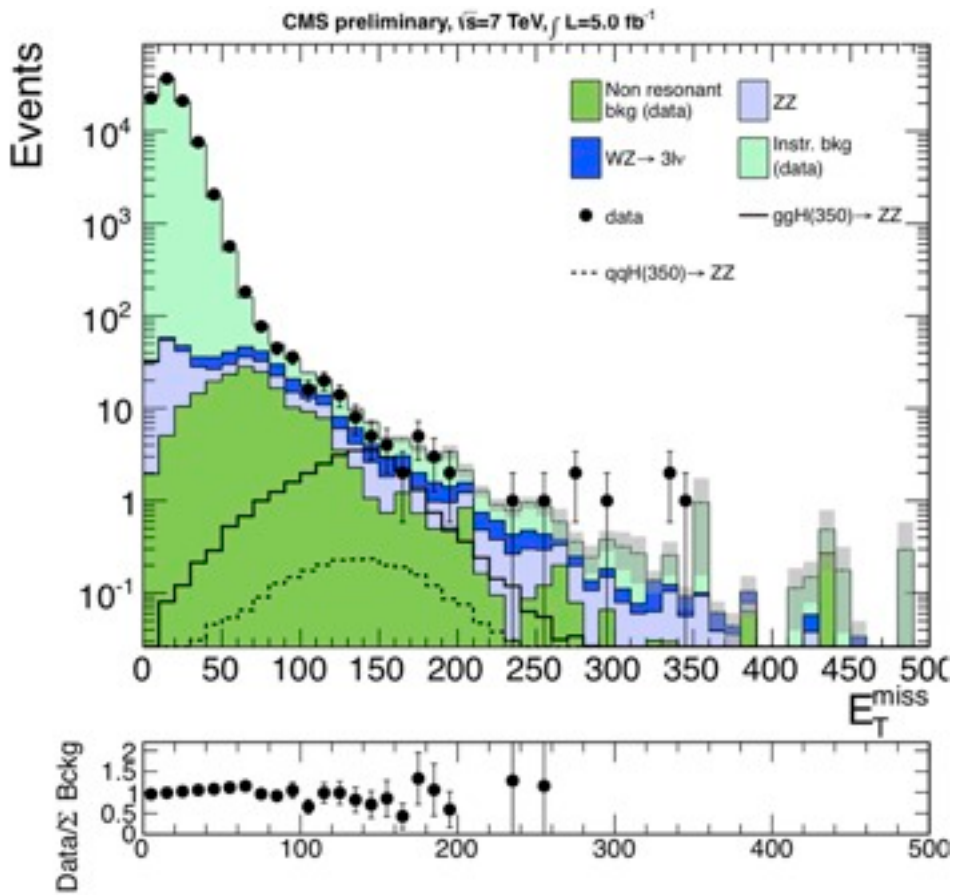


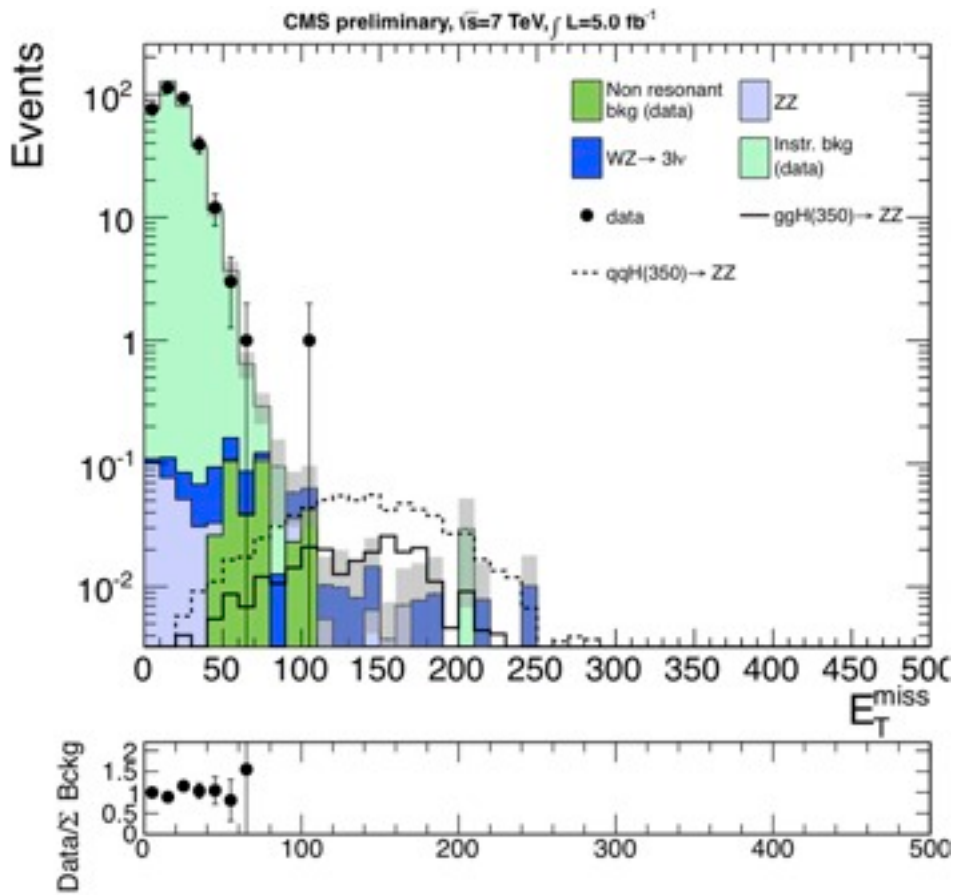




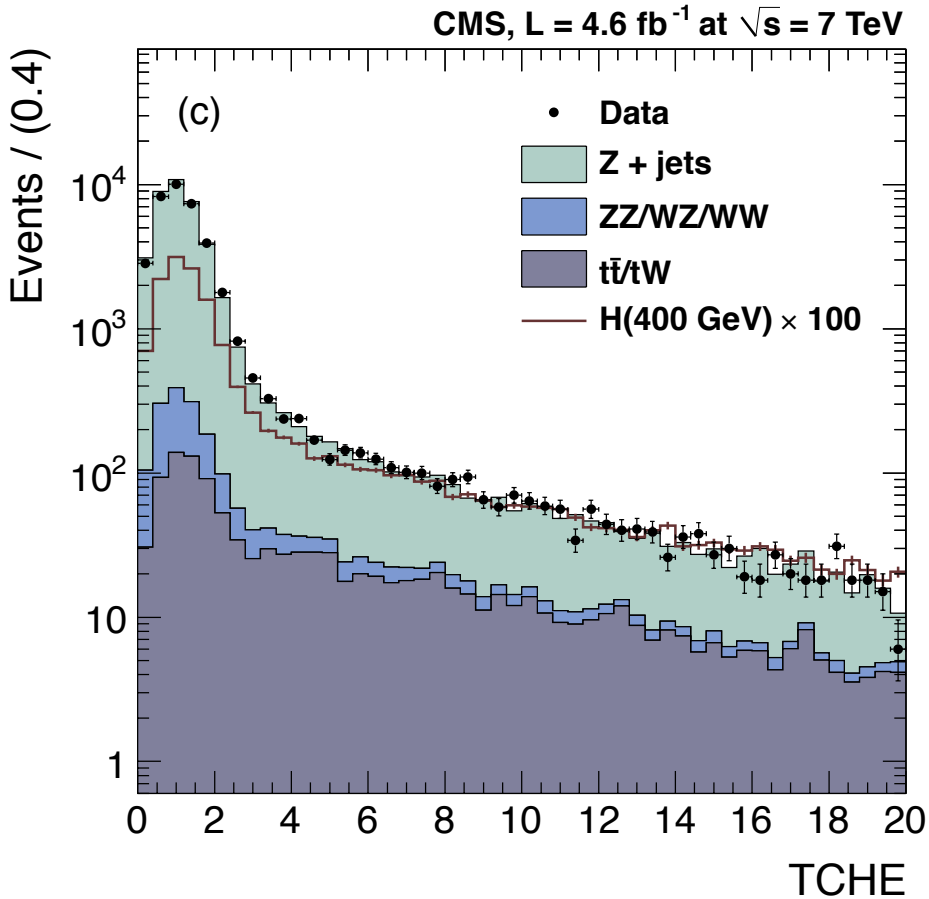
$H \to ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (CMS)

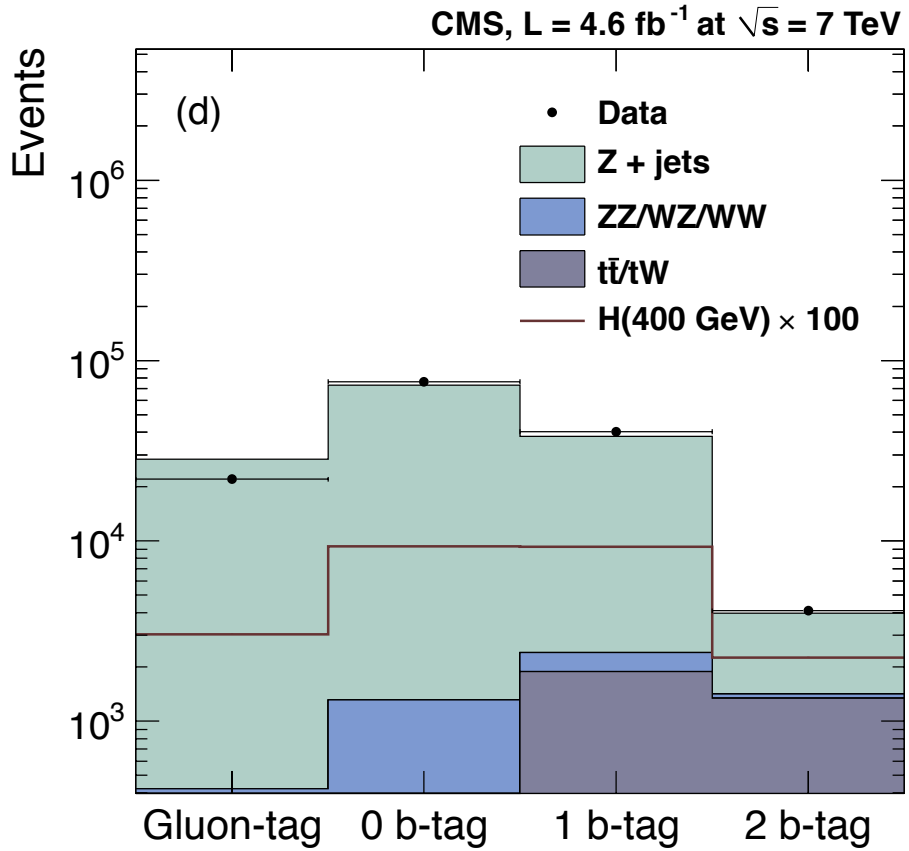
- 7TeV Plots



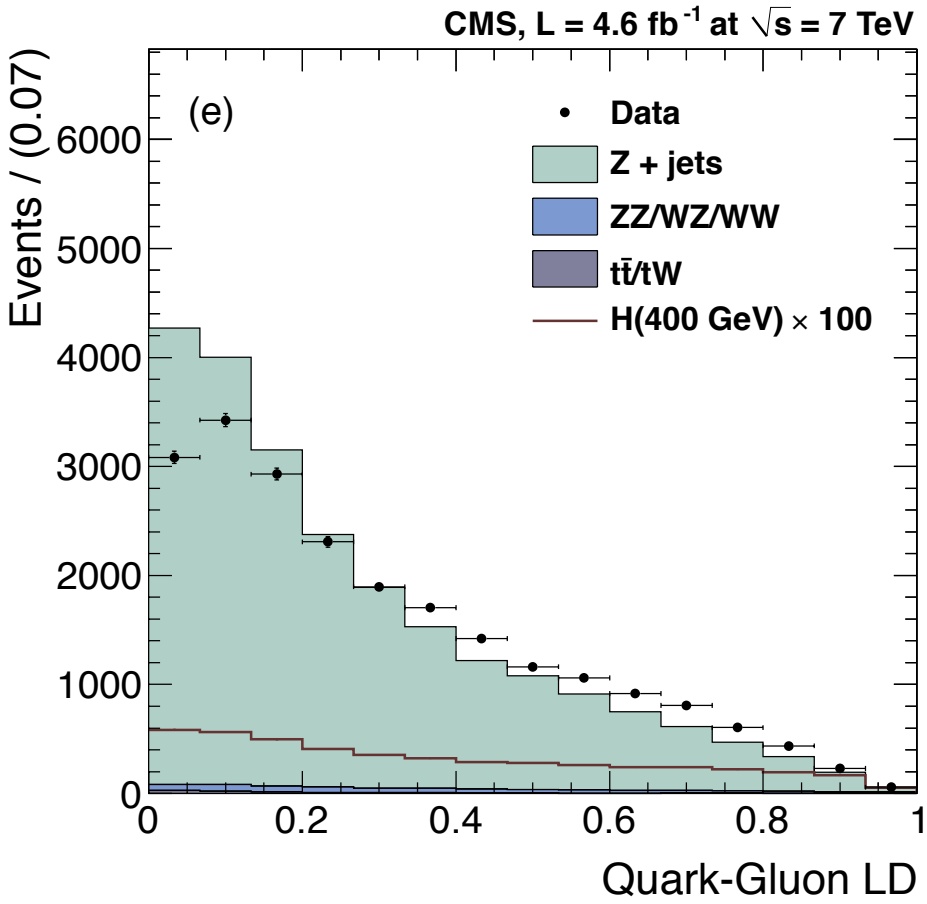


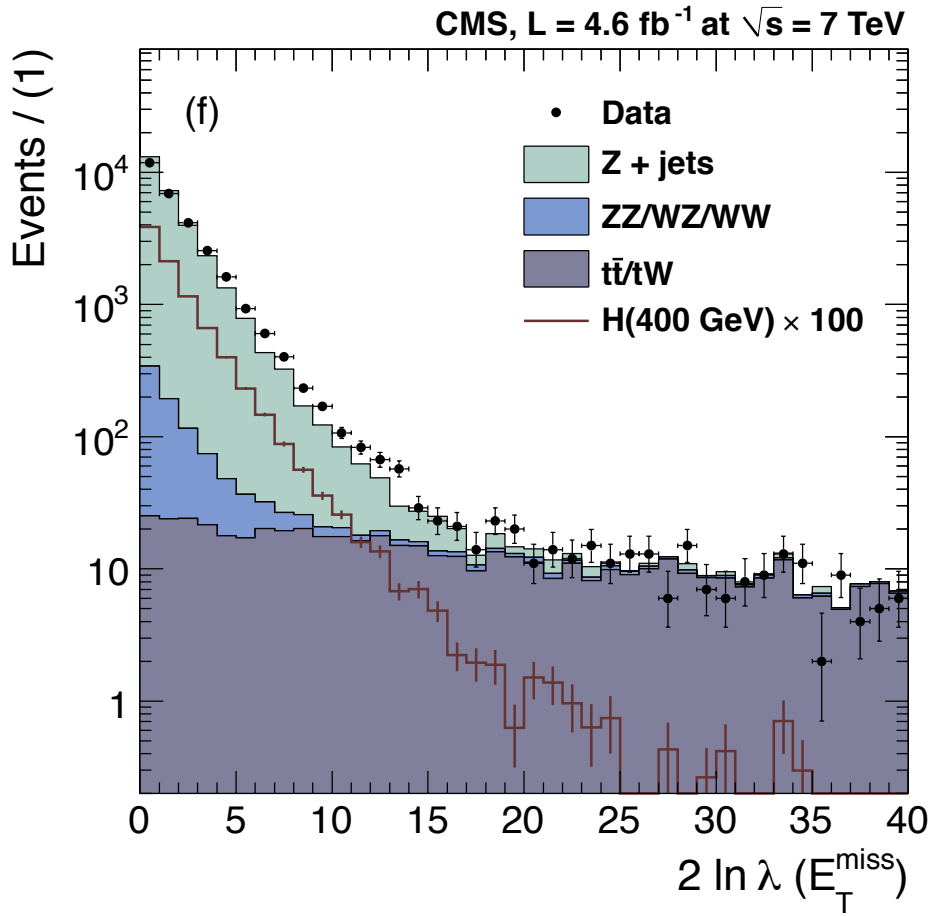
$H \to ZZ^{(*)} \to \ell^+\ell^- q\bar{q}$ (CMS)





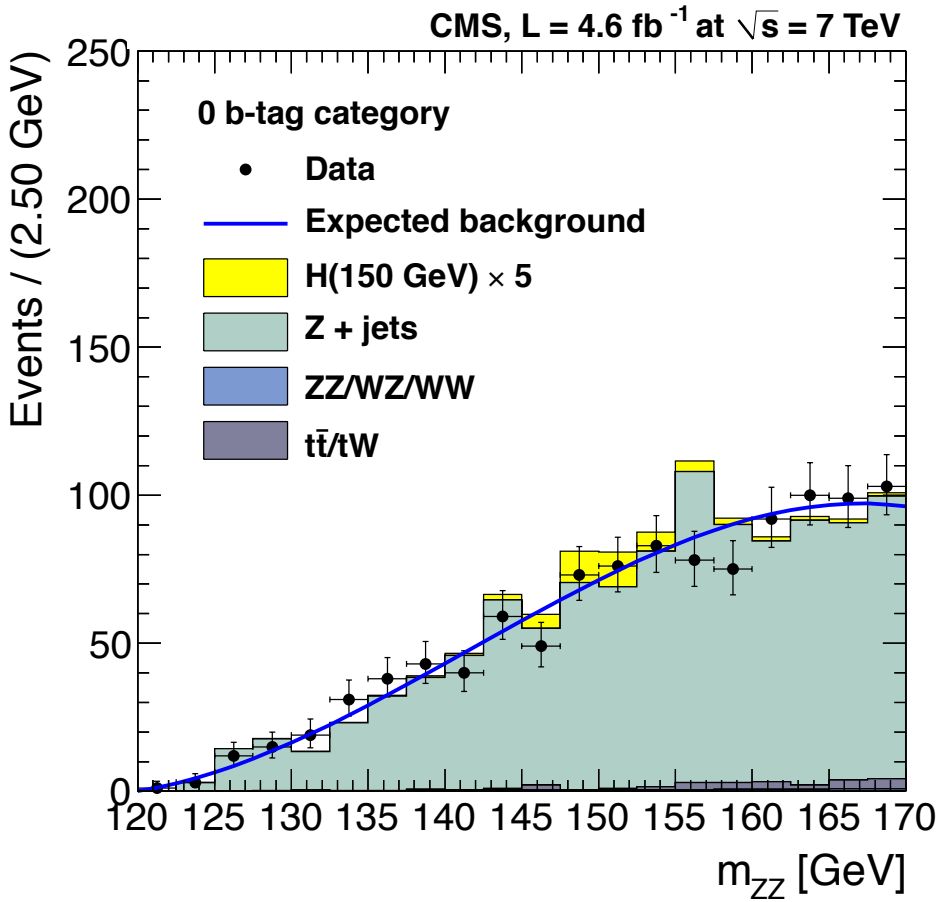
$H \to ZZ^{(*)} \to \ell^+\ell^- q\bar{q}$ (CMS)

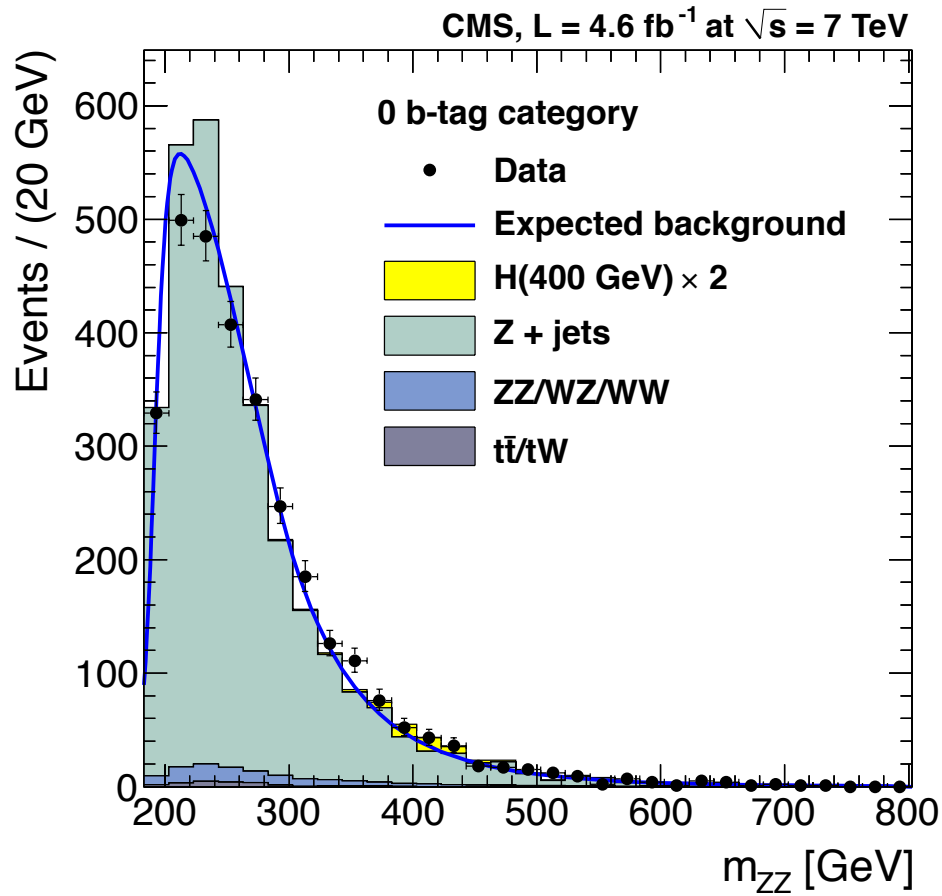




$H \to ZZ^{(*)} \to \ell^+\ell^- q\bar{q}$ (CMS)

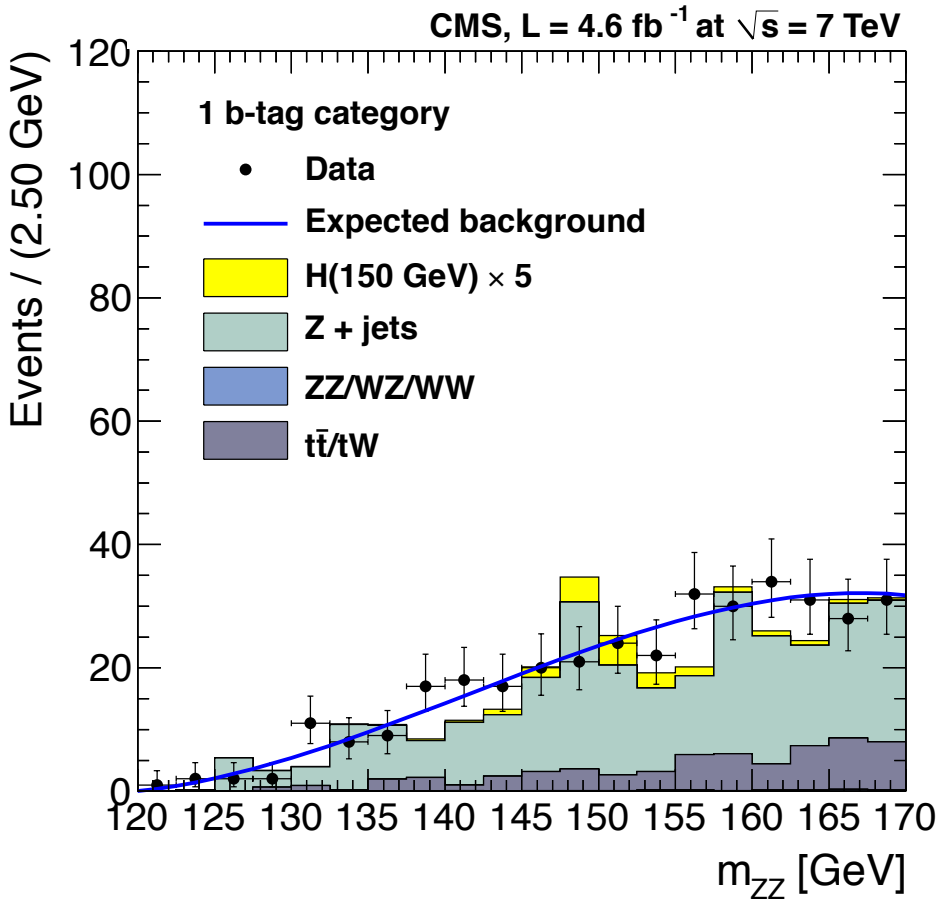
- 0 b-tag Category

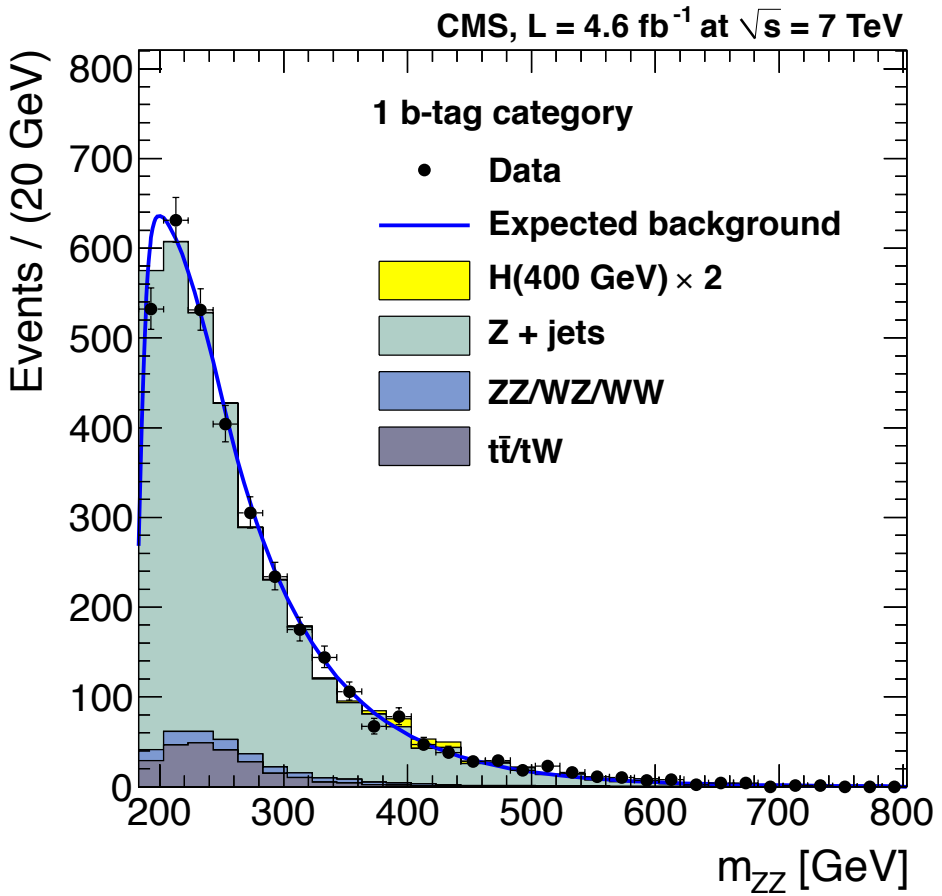




$H \to ZZ^{(*)} \to \ell^+\ell^- q\bar{q}$ (CMS)

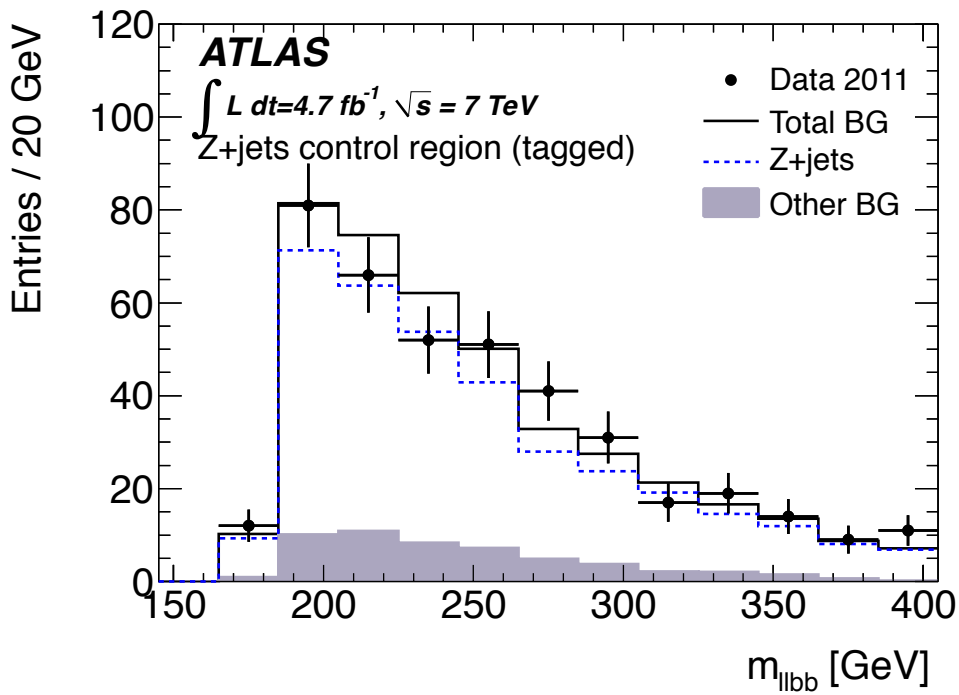
- 1 b-tag Category

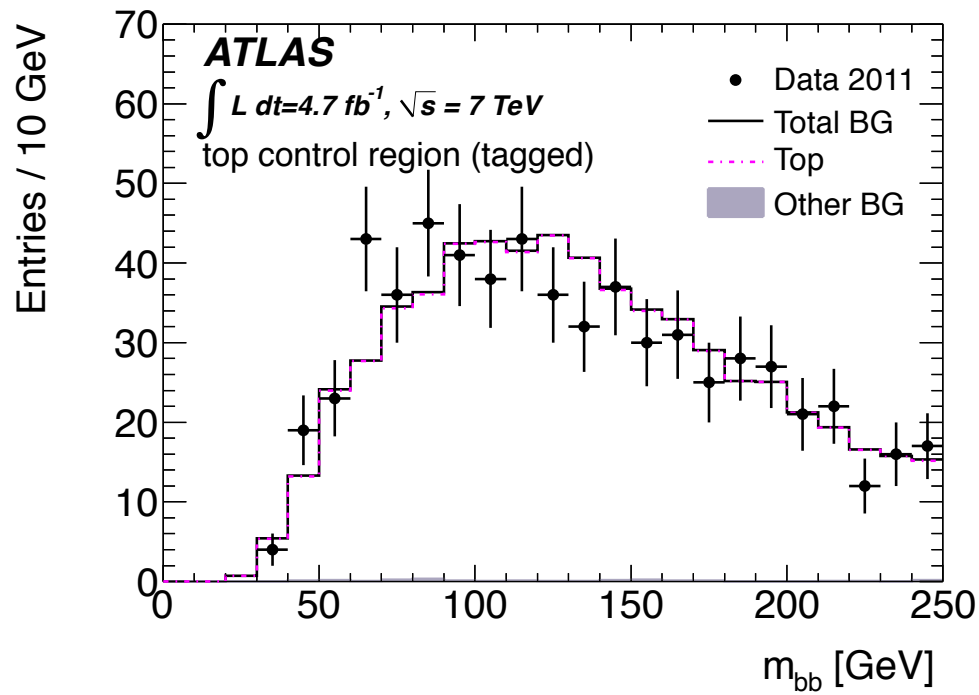




$H \to ZZ \to \ell^+\ell^- q\bar{q}$ (ATLAS)

- Tagged control plots





$H \to ZZ \to \ell^+\ell^- q\bar{q}$ (ATLAS)

- m_H = 200 GeV