High mass Higgs searches at LHC

6th February 2012
CERN Winter school

S.Bolognesi (Johns Hopkins University)
on behalf of ATLAS & CMS collaborations

Outline

- **The Higgs role in the EWSB mechanism**

- **The LHC results**

  input: theoretical description of the signal: Higgs xsec and differential distributions

  object reconstruction and identification (leptons, jet, btag, MET, …)

  output: **H->ZZ->llνν**

  H->ZZ->lljj , H->WW->lνjj, H->ZZ->llττ

  H->ZZ->4l, H->WW->lνlν

- **Summary and future prospects**

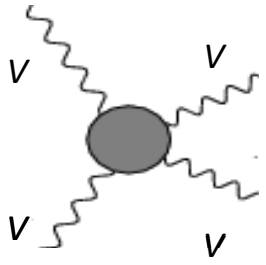
Higgs and unitarity in VBF

EWSB: W, Z mass (-> longitudinal dof) arise from the Higgs mechanism

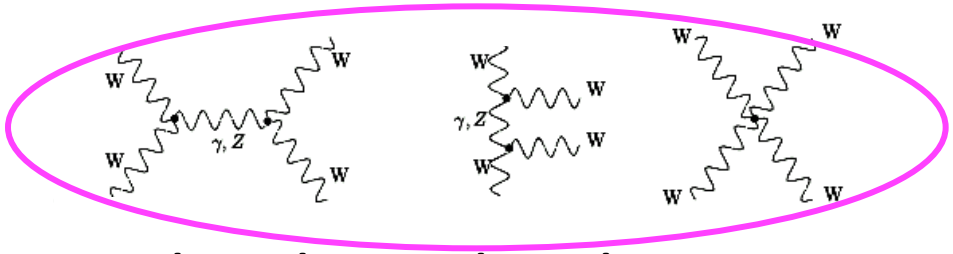
without Higgs, $W^+_L W^-_L \to W^+_L W^-_L$ would break unitarity

$$A\left(W_L^+W_L^- \to W_L^+W_L^-\right) \approx \frac{1}{v^2}\left(-s-t+\frac{s^2}{s-m_H^2}+\frac{t^2}{t-m_H^2}\right)$$

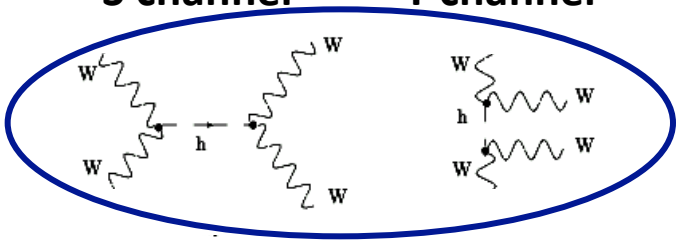
Vector Boson Fusion (VBF)



VV -> VV



S channel **T channel** **QGC**

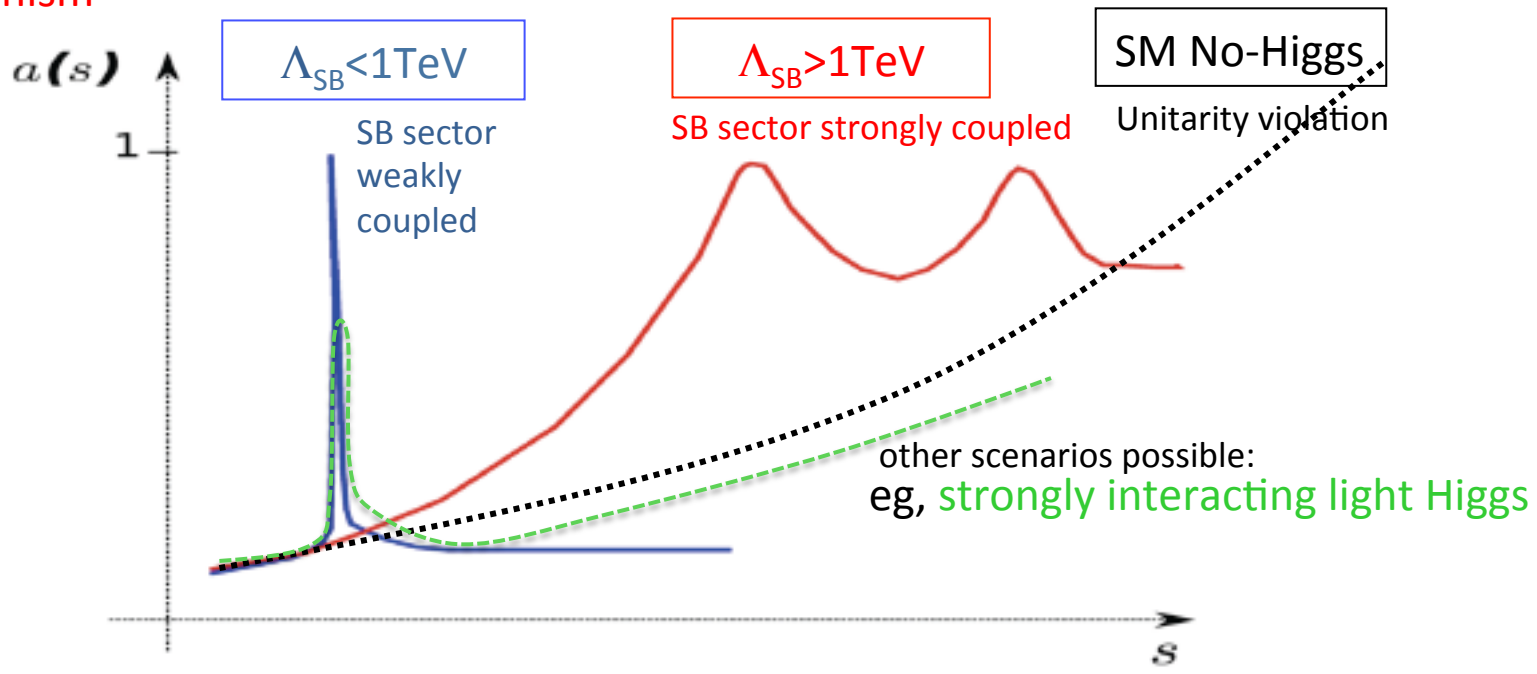


VBF is the smoking gun of the EWSB !

VBF and VV scattering

- **VV scattering spectrum σ(VV->VV) vs M(VV)**

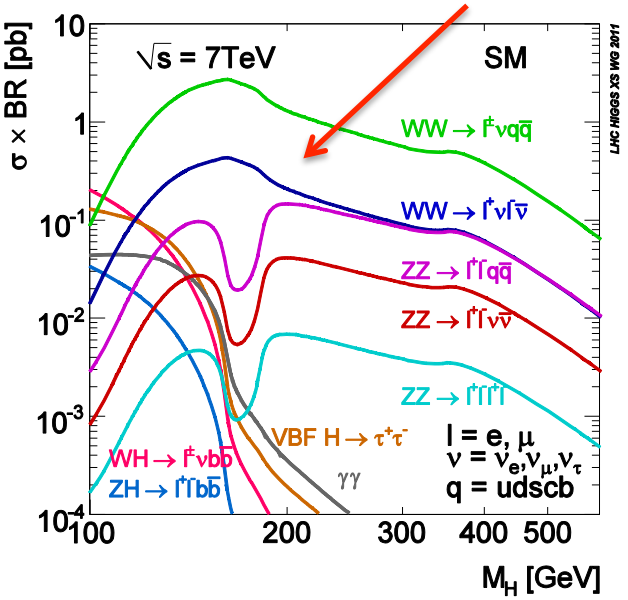
  is the fundamental probe to test nature of Higgs boson or to find alternative EWSB mechanism

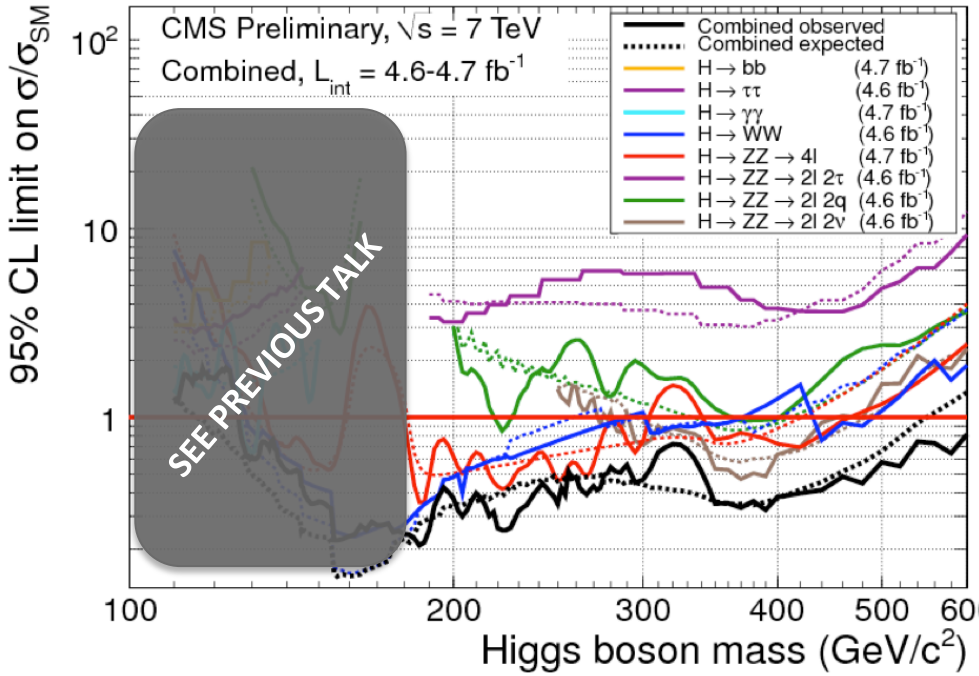


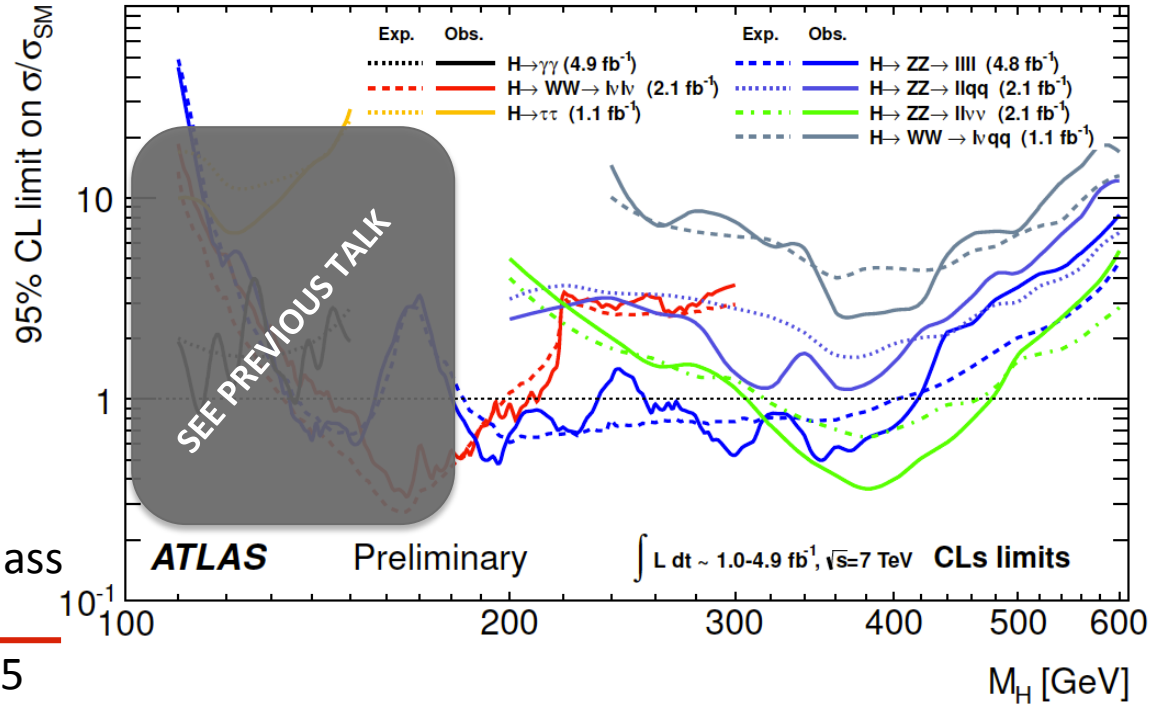
- Whatever we will see or not see at low mass (<2×m_W), the EWSB mechanism must be probed in the VV final state

LHC results

"High mass" Higgs: mH>2*mV







ATLAS: 2fb^{-1} (4.8 fb^{-1} for 4lep)

CMS: 4.6-4.7 fb^{-1}

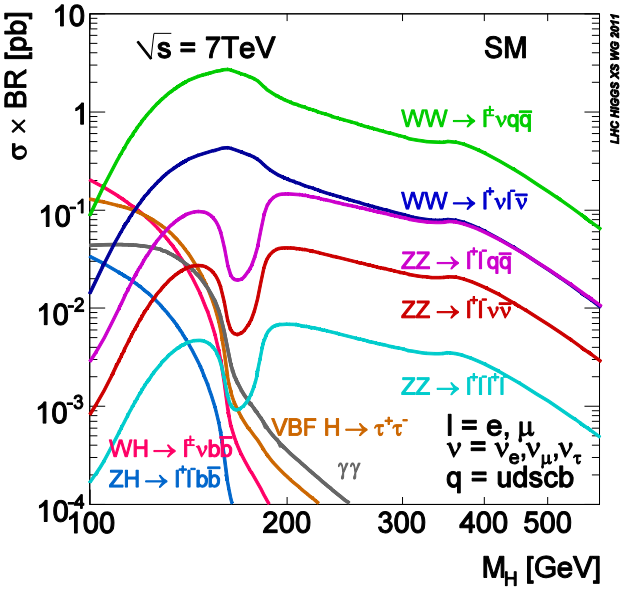
H->ZZ->2l2τ CMS only

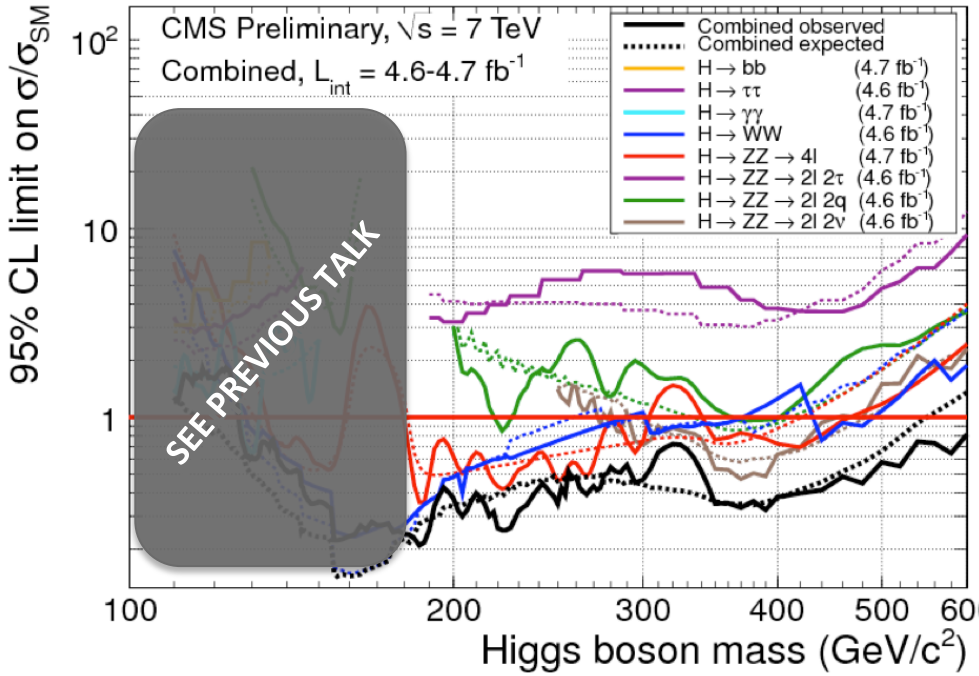
H->WW->lνjj ATLAS only

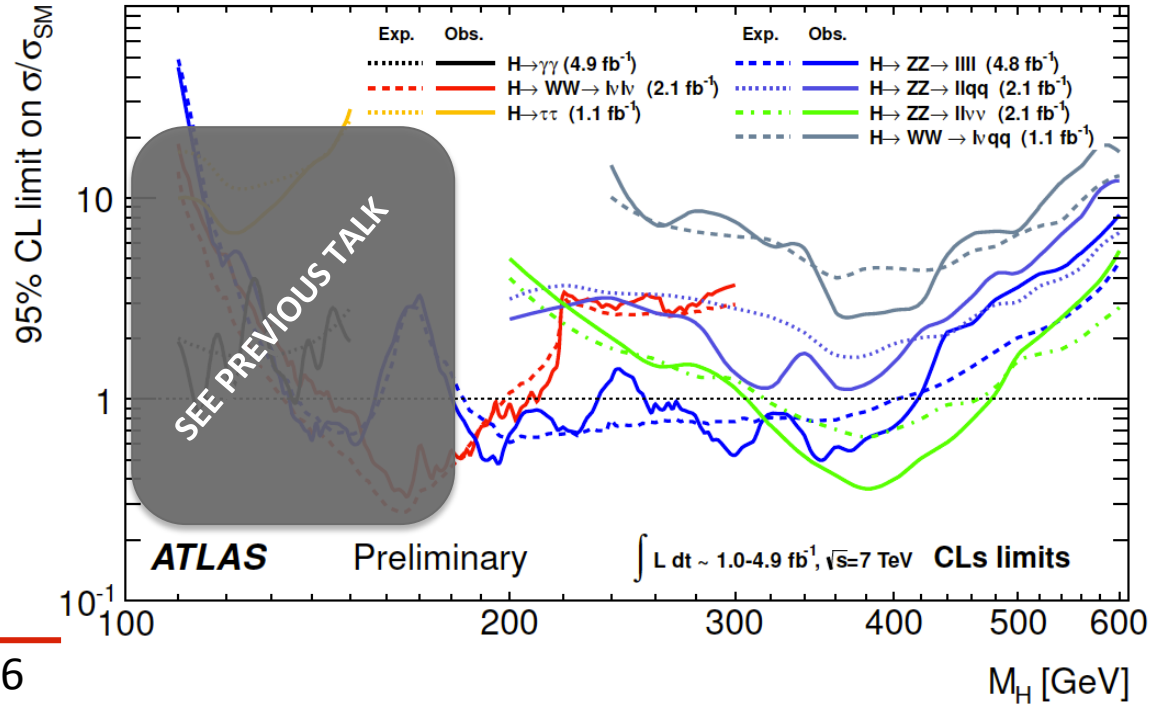
H->WW->lνlν CMS also at high mass

LHC results

"High mass" Higgs: mH>2*mV





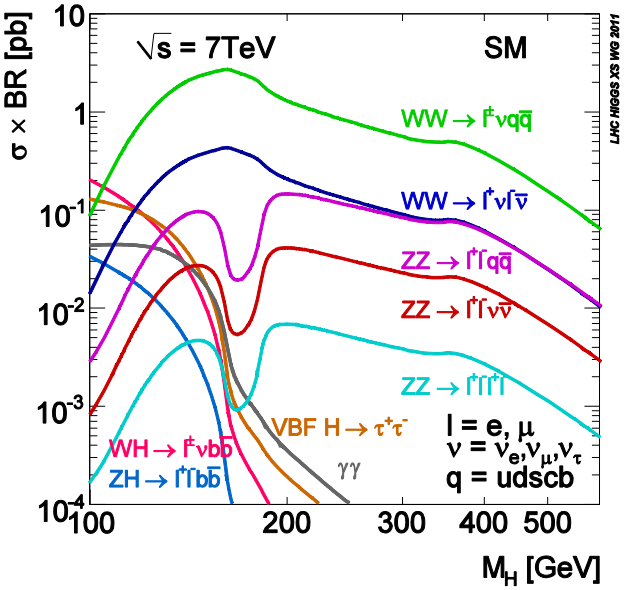


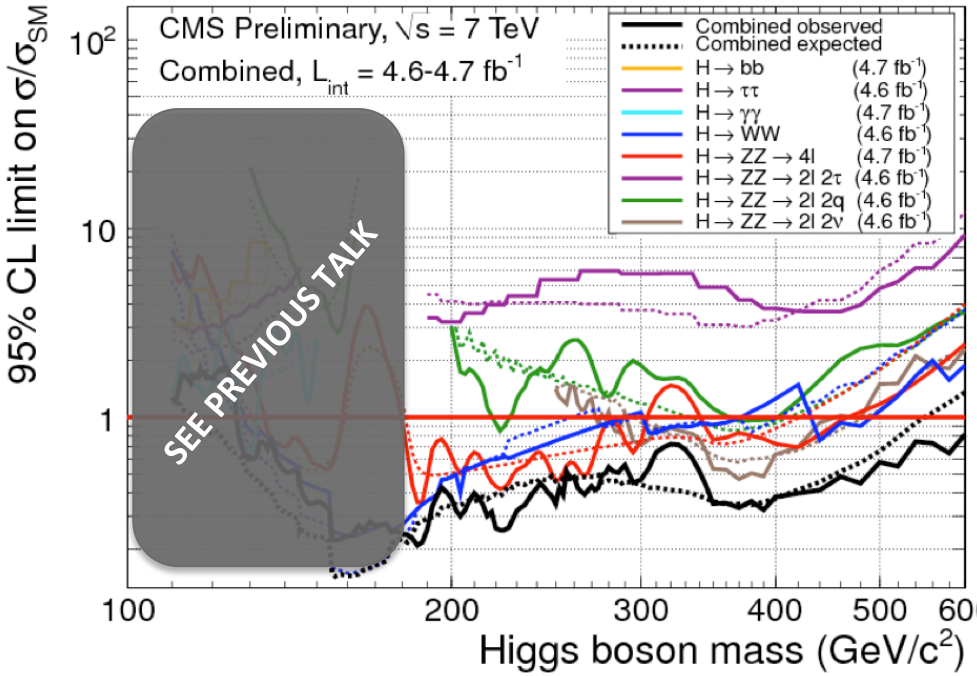
- semileptonic: larger statistics but lower sensitivity
- H->ZZ->2l2ν: drives the UL in 300-400 GeV

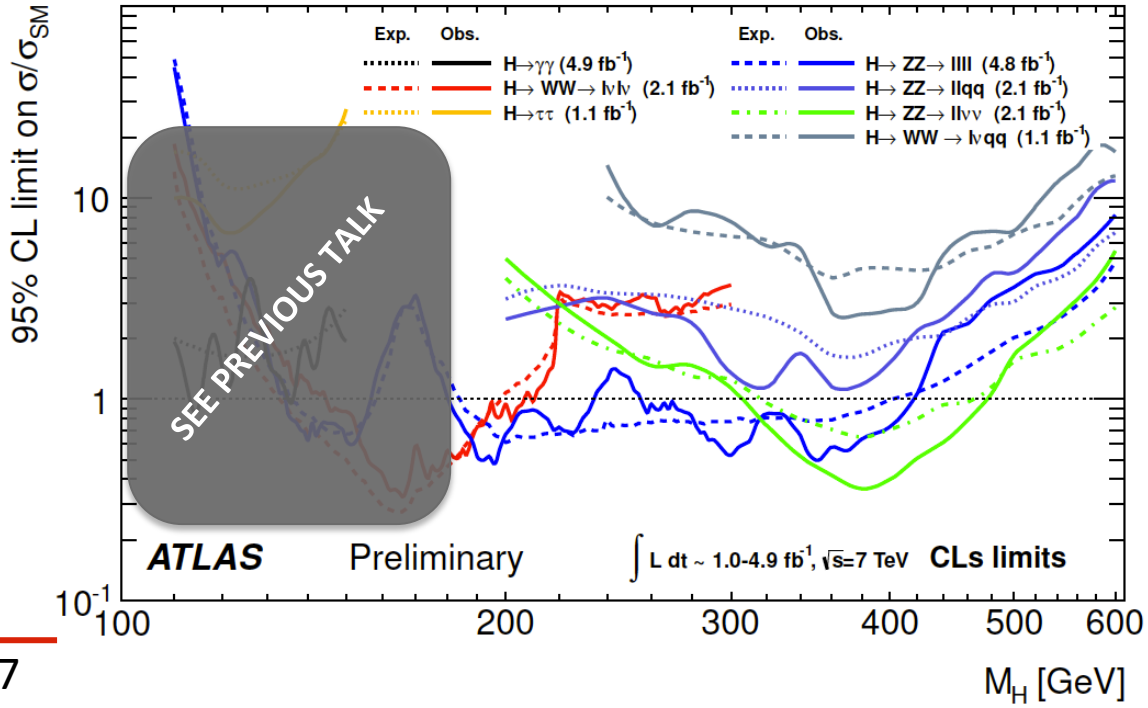
the name of the game: control of background (V+jets, top)

LHC results

"High mass" Higgs: mH>2*mV







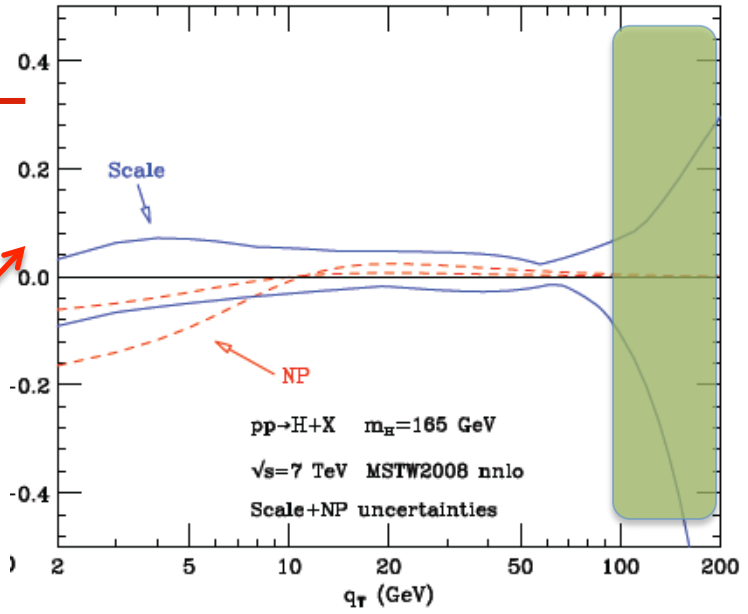
- H->ZZ->4l and H->WW->lnln high sensitivity everywhere

The input: signal description

Common effort CMS-ATLAS-theoreticians:
Higgs Xsec working group
(2 yellow reports published: **arXiv:1101.0593 [hep-ph]**
arXiv:1201.3084 [hep-ph])

❑ Higgs p_T reweighted at NNLO+NNLL (Powheg+HqT+HNNLO)

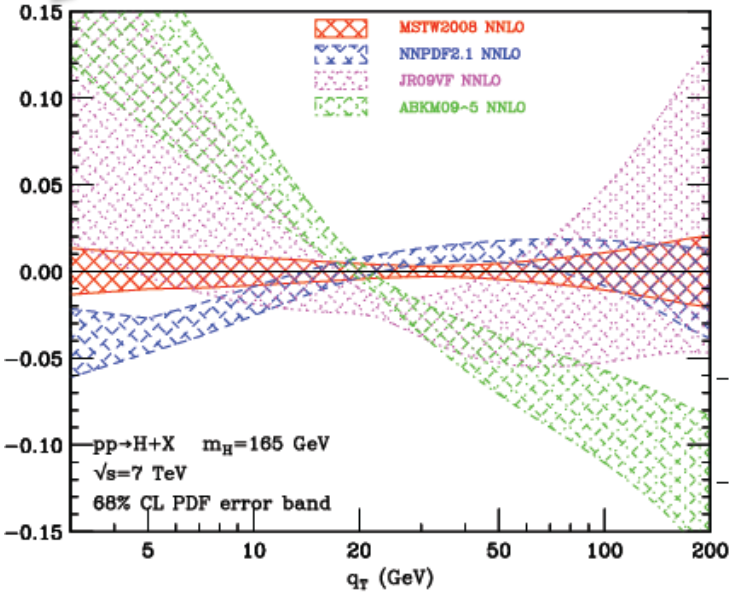
uncertainties: • factor/renorm scale
• non perturb. effects, PDF



❑ Mass shape uncertainty at high mass:

• xsec for on-shell Higgs production and decay in zero width approx

• acceptance from MC with ad-hoc BW distribution



10-30% uncertainty on xsec for mH 400–600 GeV

Now shape from proper (QFT-consistent) Higgs propagator available!

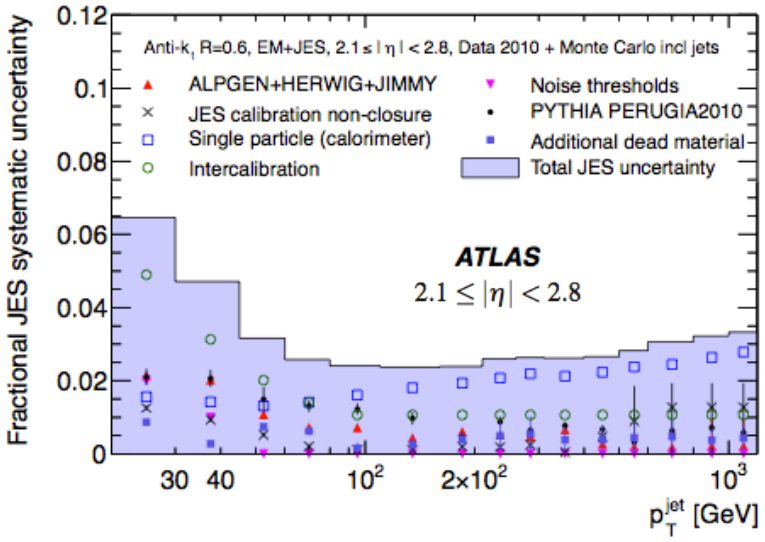
The input: object reconstruction

- Leptons (e,μ) from V: p_T>20 GeV, isolated, if from Z then M(ll)~91 GeV

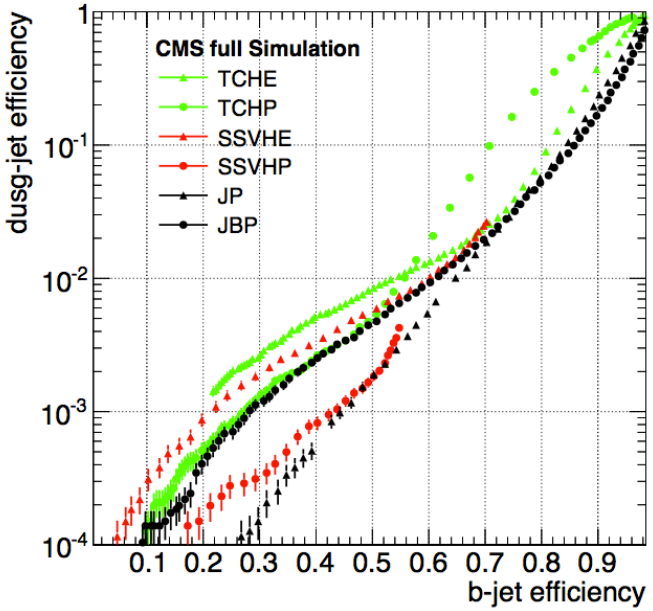
  -> optimal performances, see previous lecturer

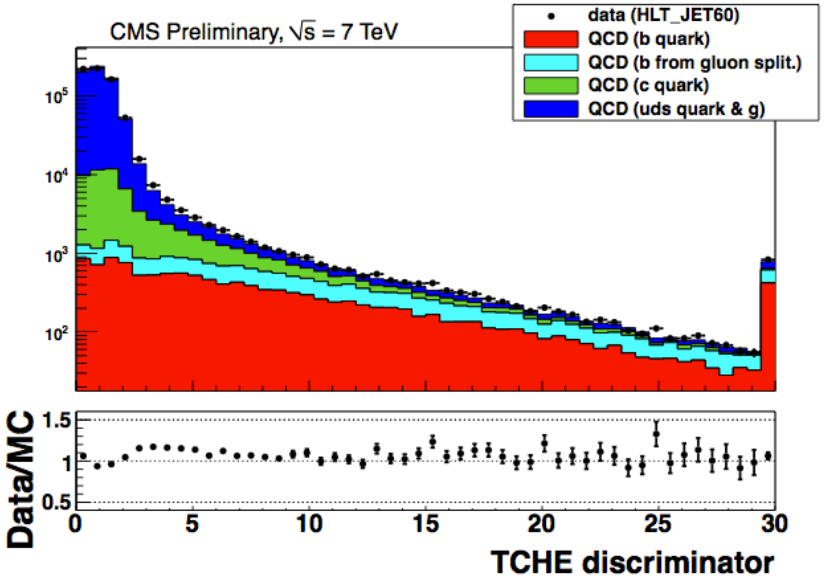
- Jets: ATLAS: clusters of calorimeter deposits, p_T>25 GeV

  CMS: particle-flow (full particle identification with tracker+calo), p_T>30 GeV



- B-tagging

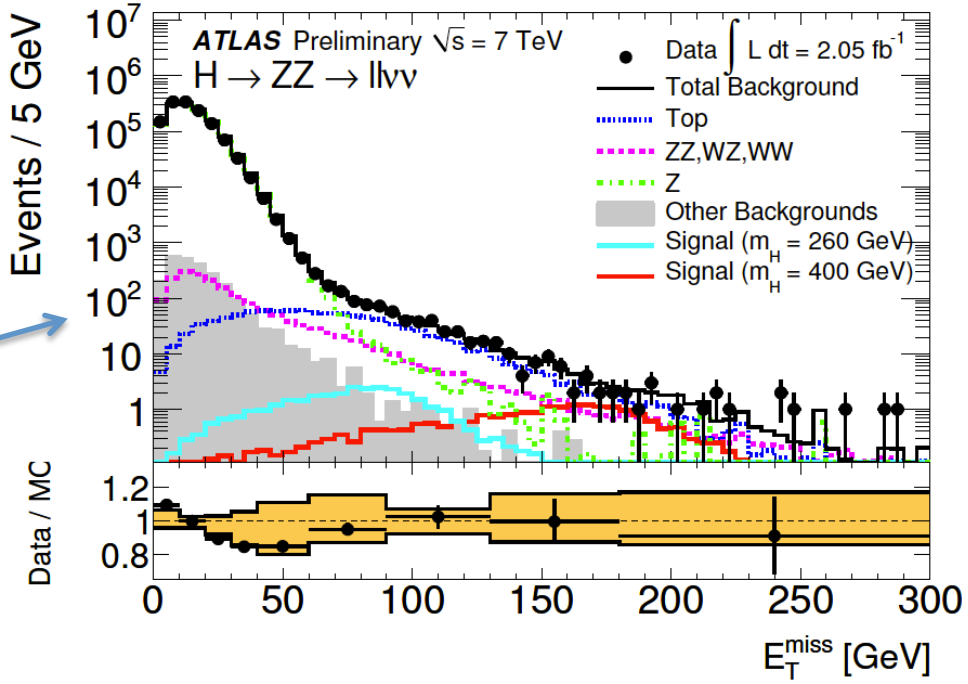




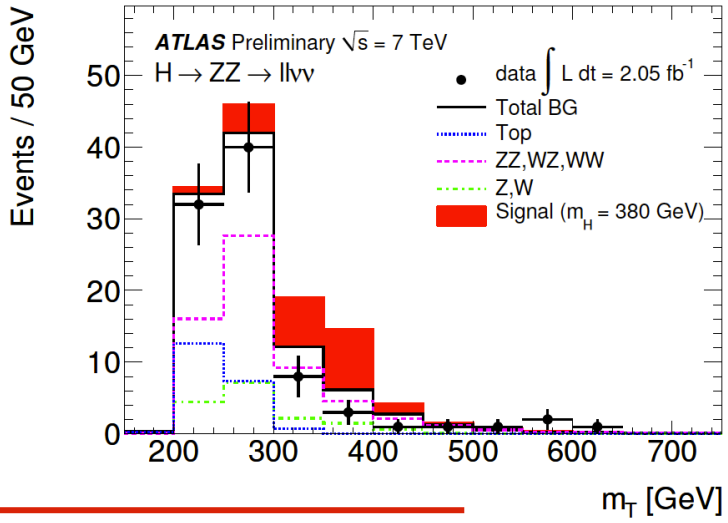
- MET : calorimeter deposits (in CMS also part. flow)

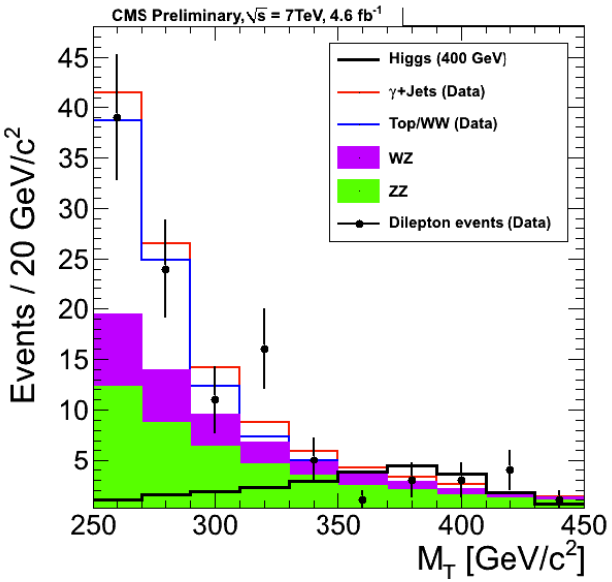
H->ZZ->llνν

- 2 leptons from Z + MET.
  - **Backgrounds:**
    - Z+jets removed asking for high, "real" MET
      high Δϕ(jet-MET, Z-MET)
    - ttbar removed vetoing b-tag jets
    - VV mainly irreducible
    - W+jets with lepton fake or from HF
  - **Final cuts:**
    - high MET
    - high Δϕ(ll) or $p_T Z$ -> for high mH
    - UL from fit to m_T
      broad distribution
      but pretty good S/B



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





H->ZZ->llνν: Z+jets control

- **Z+jets is 10^5 × signal and steeply falling** with MET and $p_T Z$
  - high MET tail dominated by fake MET (difficult to simulate)
  - cut on Z boost depends on Z+jets modeling

ATLAS

MET shape comparison pythia-alpgen (5-20%)

JES systematics on MET

normalization data-MC comparison m(ll) (2.5%)

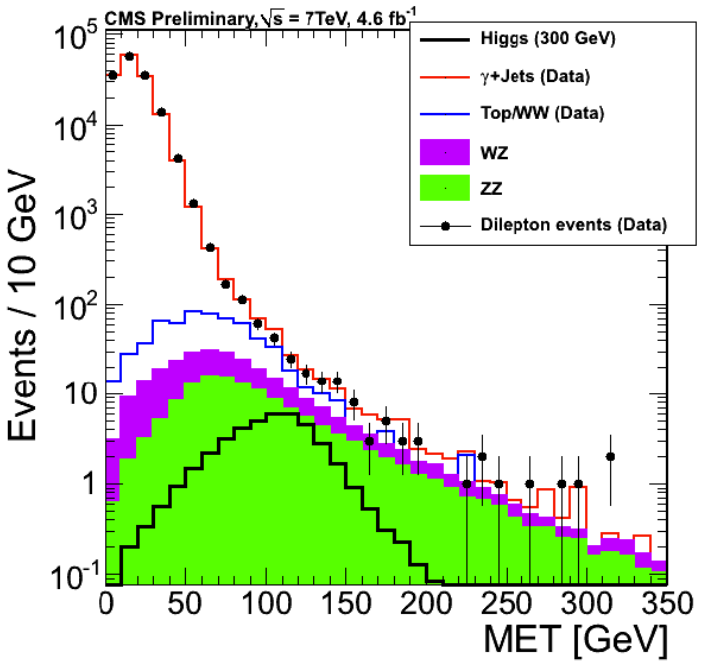
↓

7% uncertainty

CMS: fully data-driven

γ+jets reweighted vs N jets, boson p_T, N vertices

boson mass by sampling Z line-shape from fit to data



Main systematics: contamination from γ + real MET

↓

Z+jets left float btw 0 and γ+jet prediction **(-100%,+0% uncertainty)**

H->ZZ->llνν: non resonant backgrounds

❑ **ATLAS:**

- ttbar from MC
  - xcheck in control regions (mll sidebands, e+mu)
  - systematics btag eff and mistag rate

-> 9% uncertainty

- W+jets normalization from control region (same-sign ll + MET)

-> 100% uncertainty

❑ **CMS:**

- non resonant from data: e+mu and m(ll) sidebands

$$N_{\mu\mu} = \frac{N^{SB}_{\mu\mu}}{N^{SB}_{e\mu}} \times N_{e\mu}$$

systematics from statistics in e+mu data

-> 15-100% uncertainty

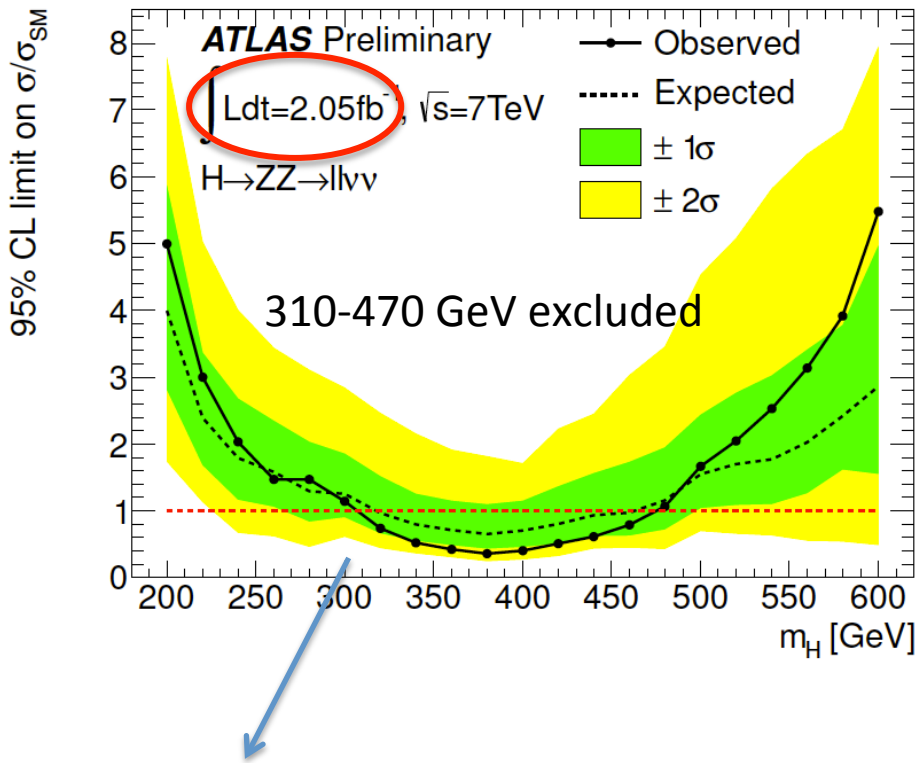
- VV from MC ->systematics on norm from PDF, scale, missing VZ*

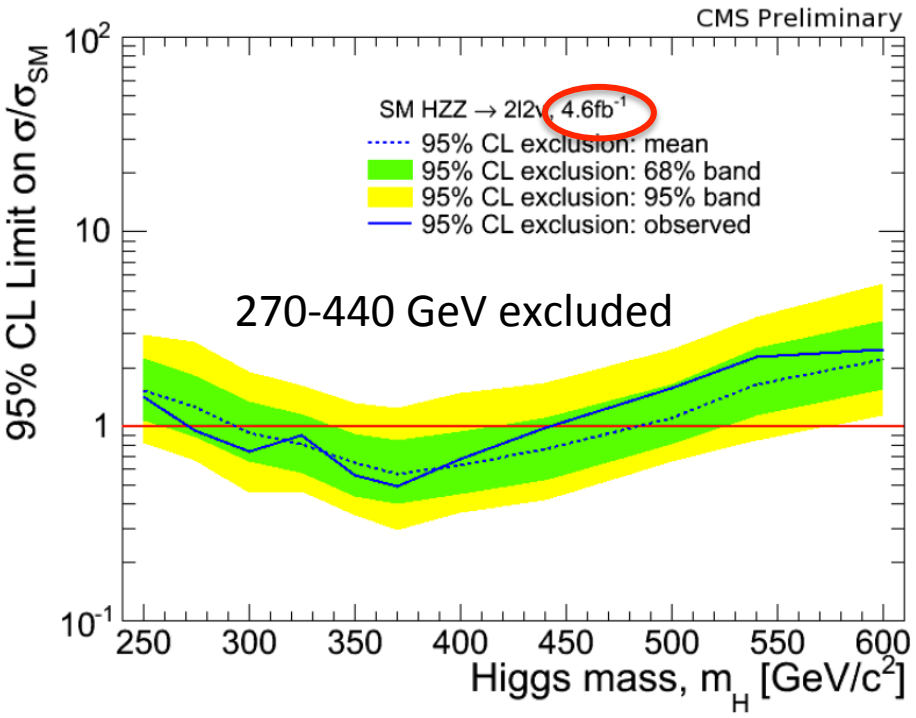
-> 5-10% uncertainty

CMS 4.6 fb^{-1}

m_H (GeV/c^2)	ZZ	WZ	Top/WW/ W+jets/Z→ ττ	Z+Jets	Total	Signal	Data
400	$12 \pm 0.13 \pm 0.87$	$4.6 \pm 0.14 \pm 0.39$	0	2.7 ± 2.7	$19 \pm 0.19 \pm 2.9$	17 ± 1.6	18

H->ZZ->llνν: results





ATLAS includes H->WW->lνlν (13%-77%) and H->ZZ->4l, H->ZZ->2l2q

(exclusive cuts wrt to dedicated analysis to avoid double counting in combination)

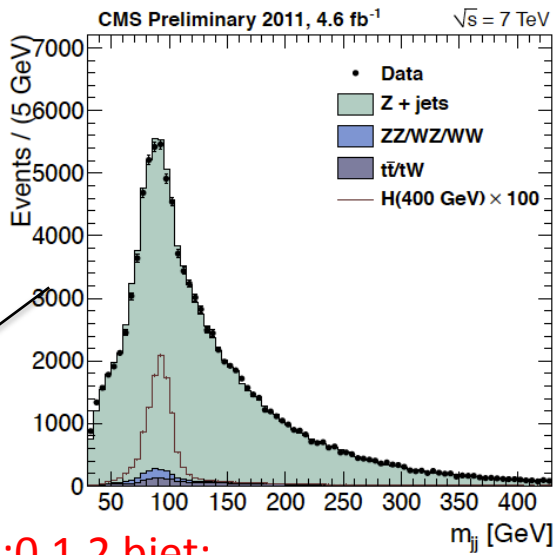
H->ZZ->lljj

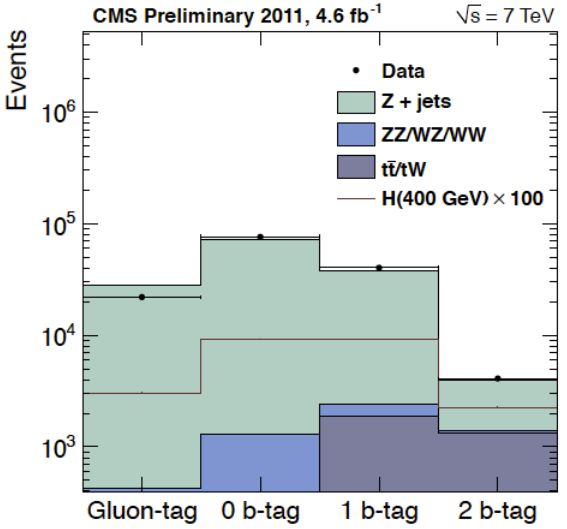
- 2l from Z + 2jets from Z

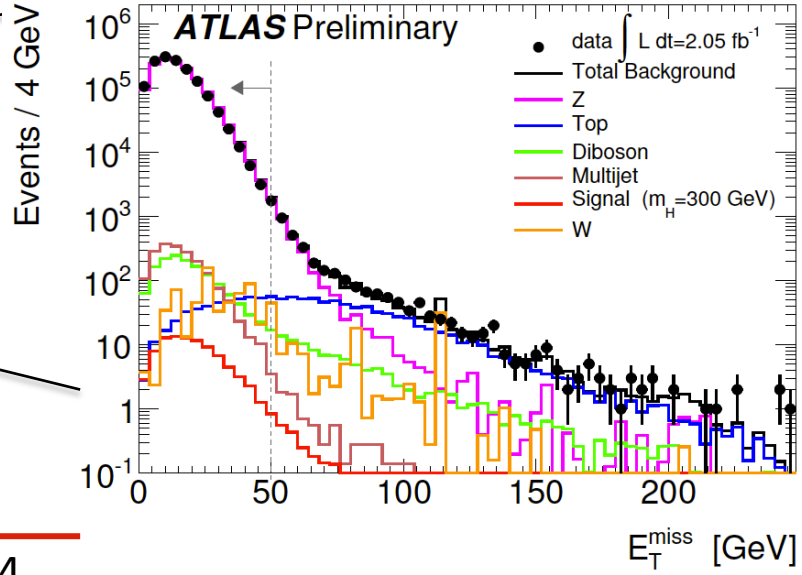
  (to improve mH resolution: kinematic fit M(Z->jj) in CMS, mZ/mjj rescaling in ATLAS)

- Main background Z+jets
  - still peaking ~M_Z because of kinematic pT cuts
  - no b-jets -> b categories (CMS:0,1,2 bjet; ATLAS: 2 bjets or less)
  - (CMS remove jet from gluons with qg-likelihhod discriminant)

- In 2 btag ttbar relevant -> MET cut (MET significance in CMS)







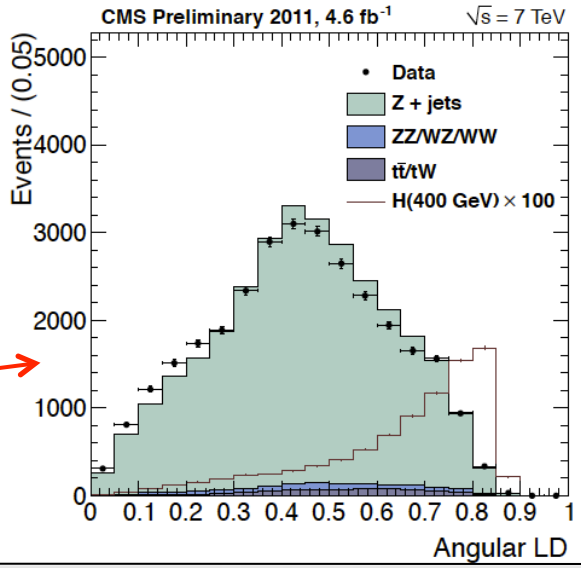
H->ZZ->lljj: final cuts

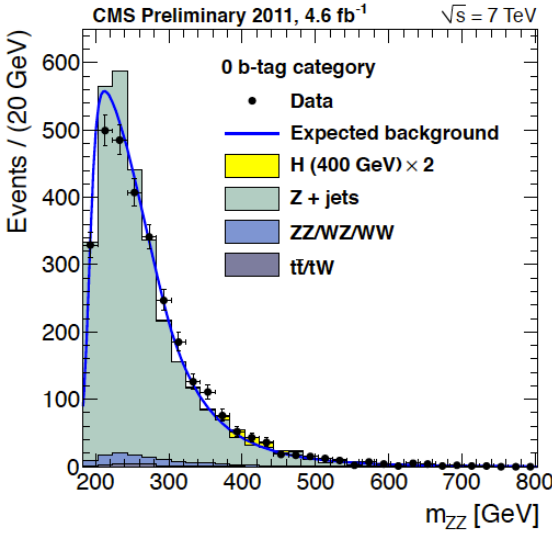
- **ATLAS**: higher p_T jets + small $\Delta\phi(jj)$, $\Delta\phi(ll)$ -> high Z p_T for high mass Higgs
- **CMS**: exploit full angular info H(spin0) -> ZZ ->4f :

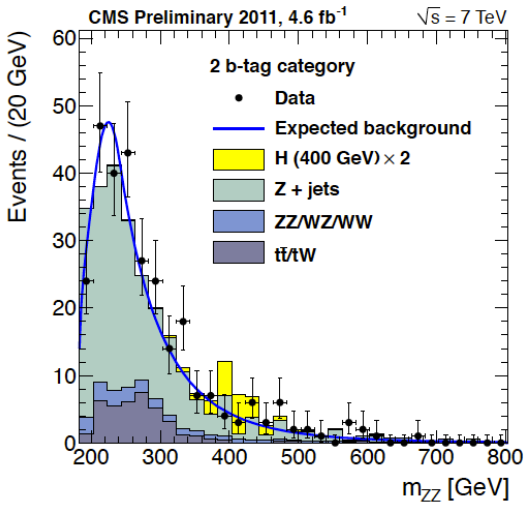
  likelihood discriminant built with angles distributions

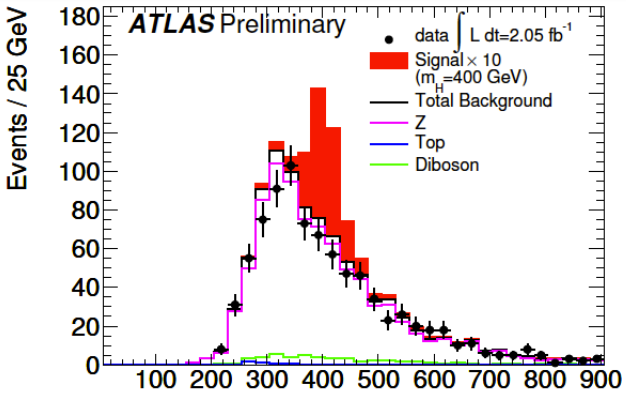
  ->no m(jj) bias -> background from sidebands

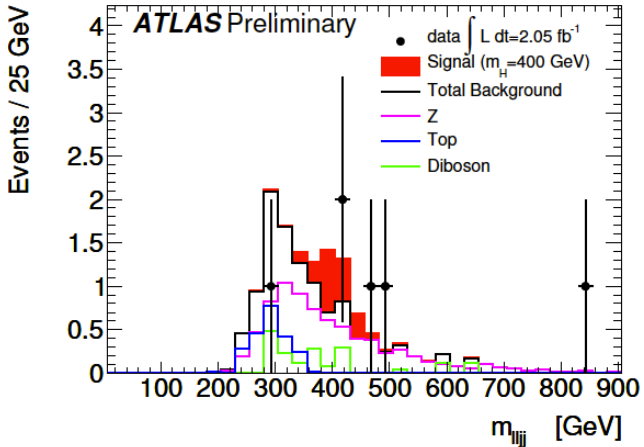
- UL from fit to m(lljj)











H->ZZ->lljj: background control

❑ **ATLAS:**

- **Z+jets**
  - shape from MC -> uncertainty from Pythia-Alpgen comparison
  - normalization from data M(jj) sidebands -> uncertainty from data statistics: 1-12% depend. on mH and untagged (16%)
- **ttbar from MC**
  - xcheck in MET>50 GeV, M(ll) sidebands

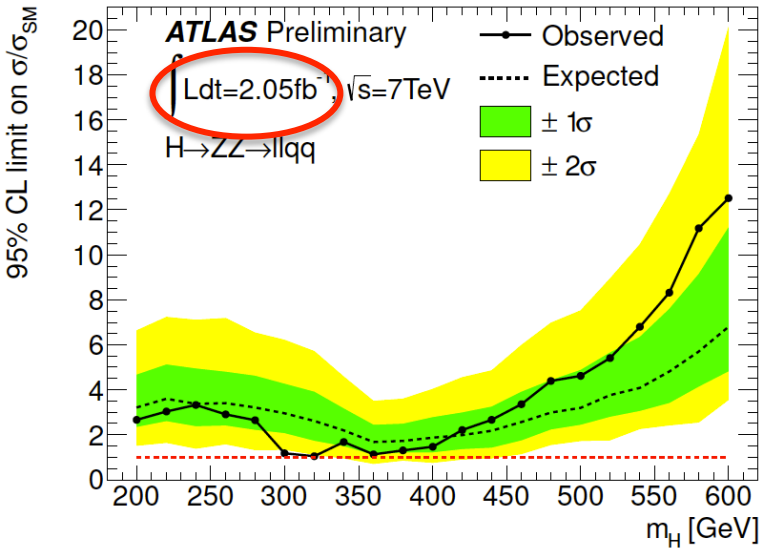
  -> uncertainty from data statistics + theoretical uncertainty (~15-20%)

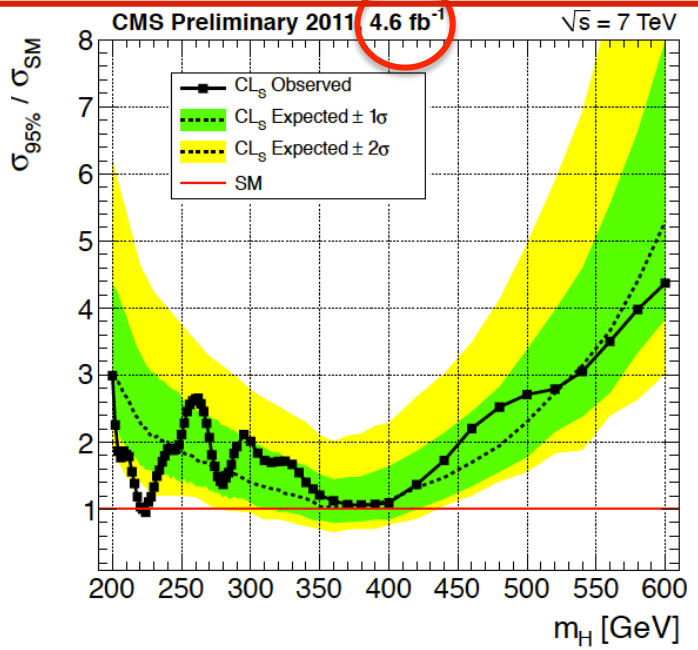
❑ **CMS:**

- **All background at once, data-driven** (highly dominated by Z+jets)
  - shape and normalization from data M(jj) sidebands
  - rescaled SB/SR from MC

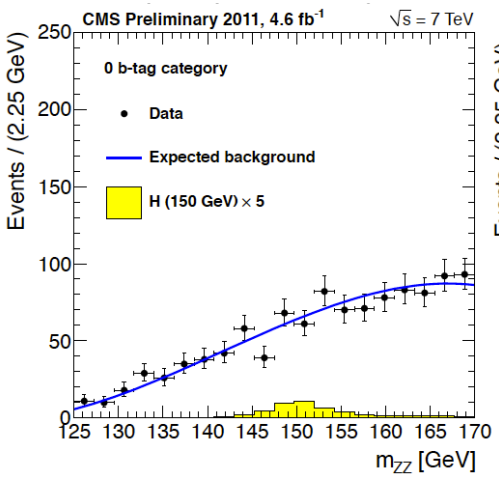
-> uncertainty from statistics

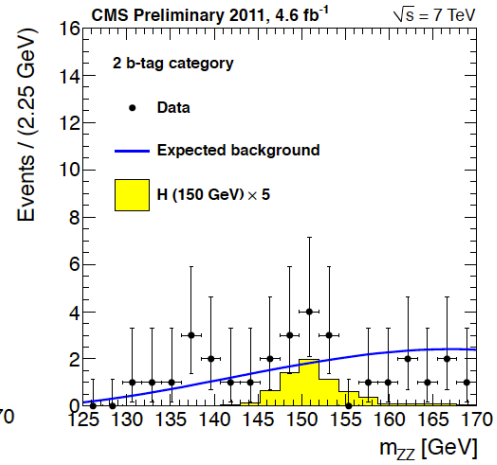
H->ZZ->2l2j: results

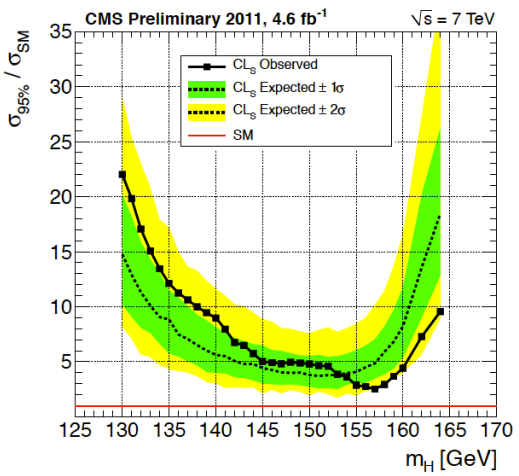




- CMS also applied similar analysis for low mass Higgs (130-165 GeV)
  - -> 2l from off-shell Z: lower signal xsec and lower Z+jets

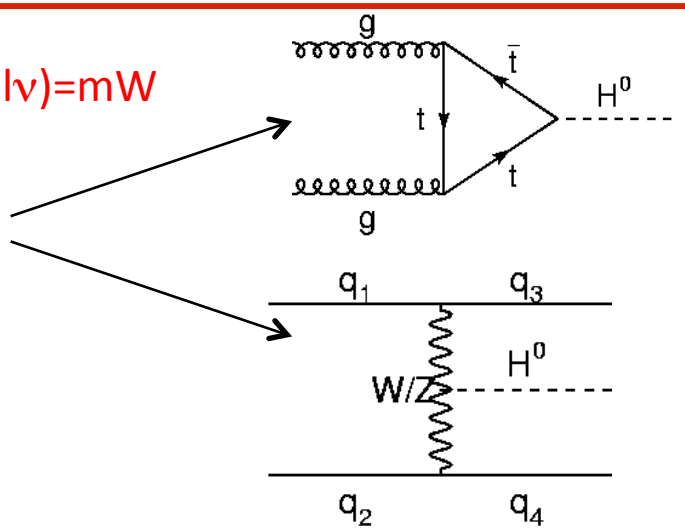




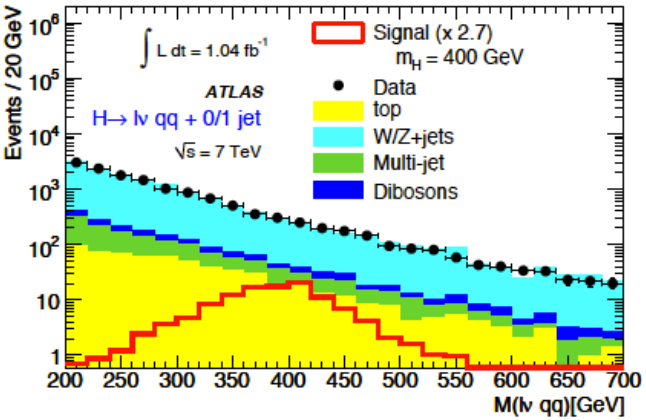


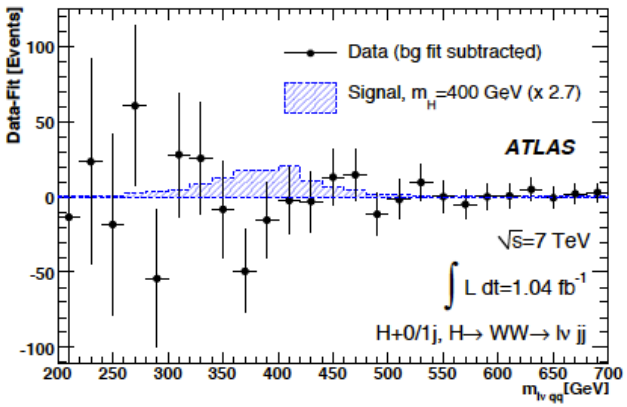
H->WW ->lνjj (ATLAS)

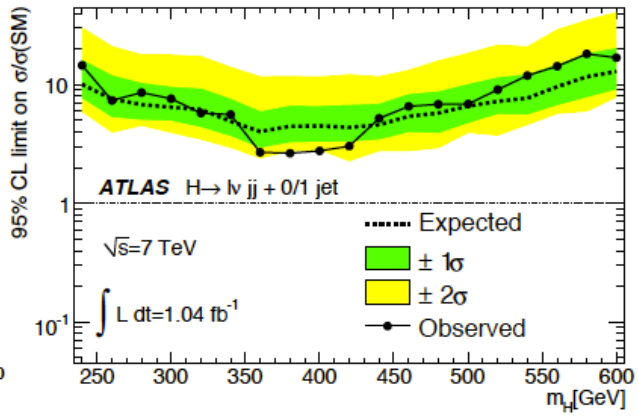
- neutrino constrained by p_T=MET (>30 GeV) and m(lν)=mW
  - 2 jets from W in central region (good JES)
  - + 0 or 1 jets -> 2 categories with different ggF/VBF



- Fit to m(lνjj)
  - background double expo (functional form chosen on the sidebands)
  - signal mass resolution 7.5% at 400 GeV mH





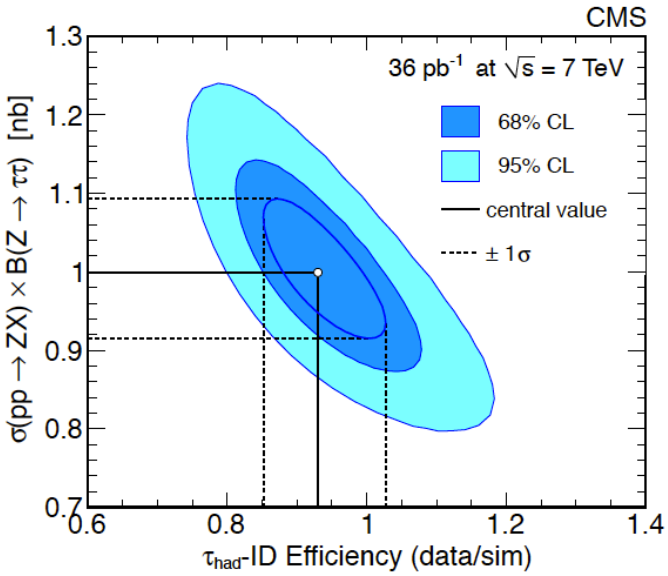


H->ZZ->llττ (CMS)

- Leading Z->ee/μμ + Z-> $\tau_h\tau_h/\tau_\mu\tau_h/\tau_e\tau_h$

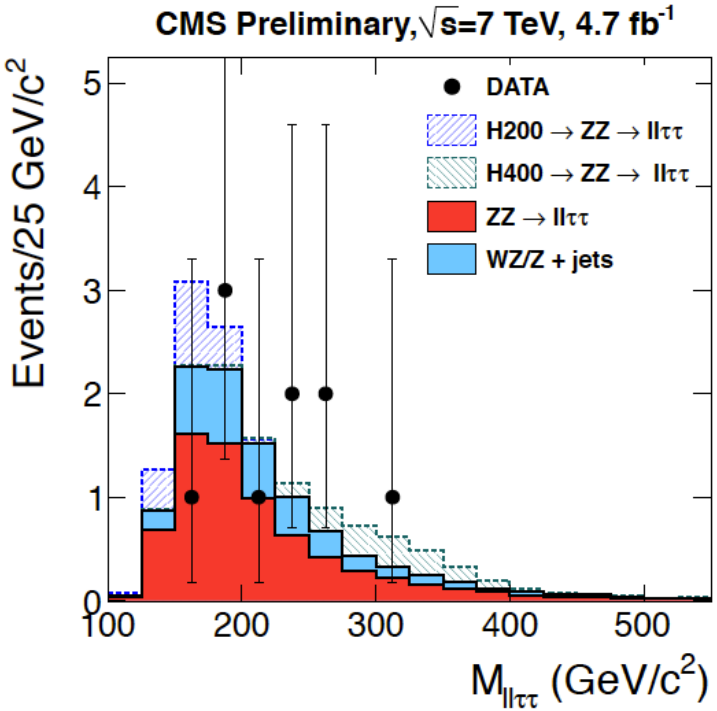
  τ_h reco through specific decay modes, using particle identification with part.flow techniques

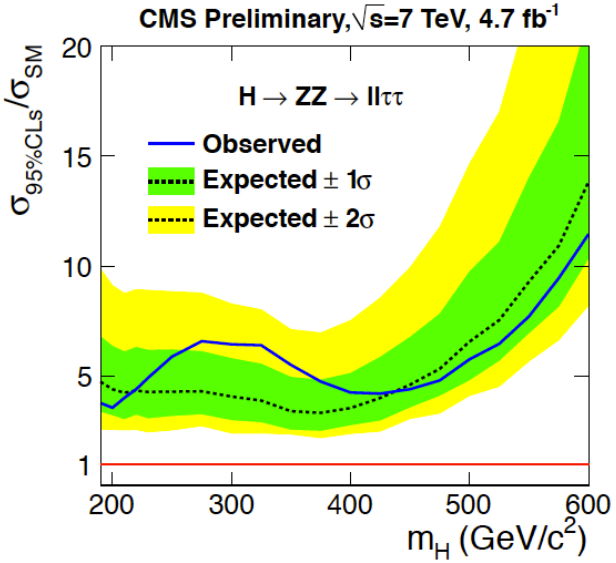
  τ_h systematics scale (4%) and eff (10%) extracted from Z->ττ



- Visible mass (15% reso). Backgrounds:
  - ZZ* normalized from ratio to Z: 10% uncertainty
  - Z+jets (with jets misid as τ_h): 30% uncertainty

    -> misid rate from data: $l^+l^-\tau_h\tau_h$ with SS τ_h



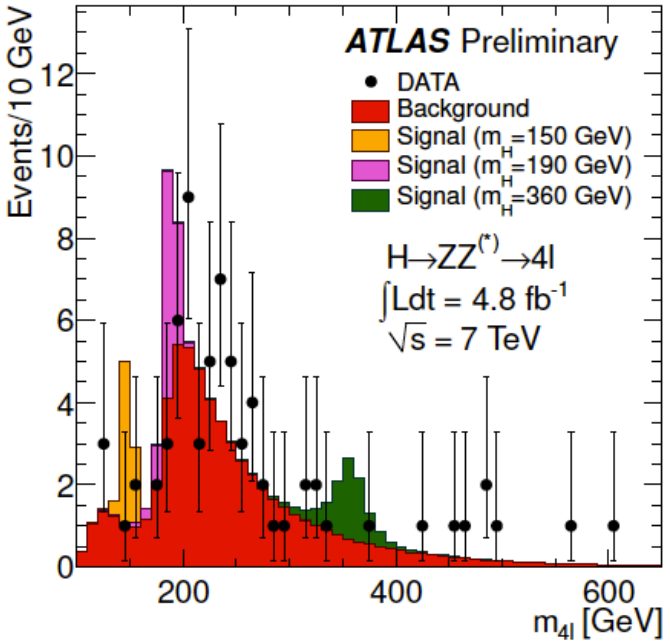


H->ZZ->4l at high mass

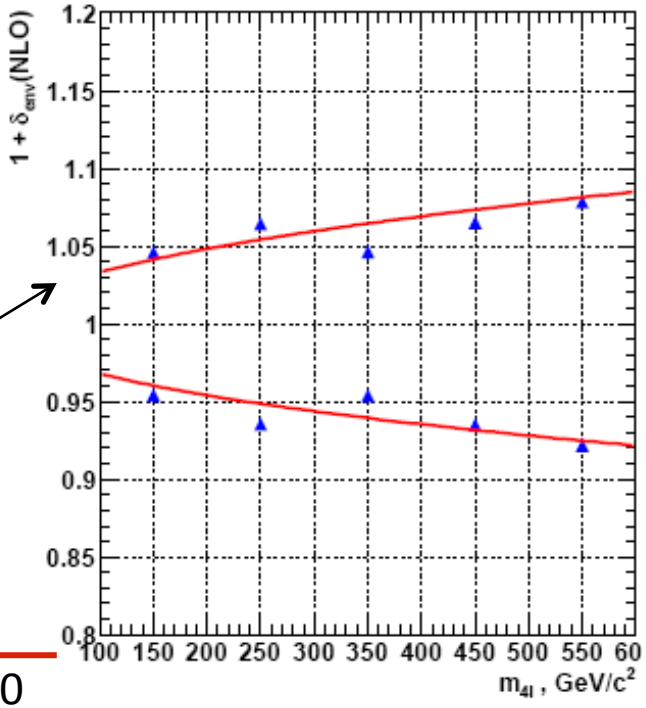
- Moving to **fully leptonic final state**
  - V+jets negligible
  - lepton performance well known from data (Z candle)
  - main uncertainty is statistical + signal theoretical systematics
  - main issue to face is the control of VV EWK continuum:

irreducible (no control regions in data)

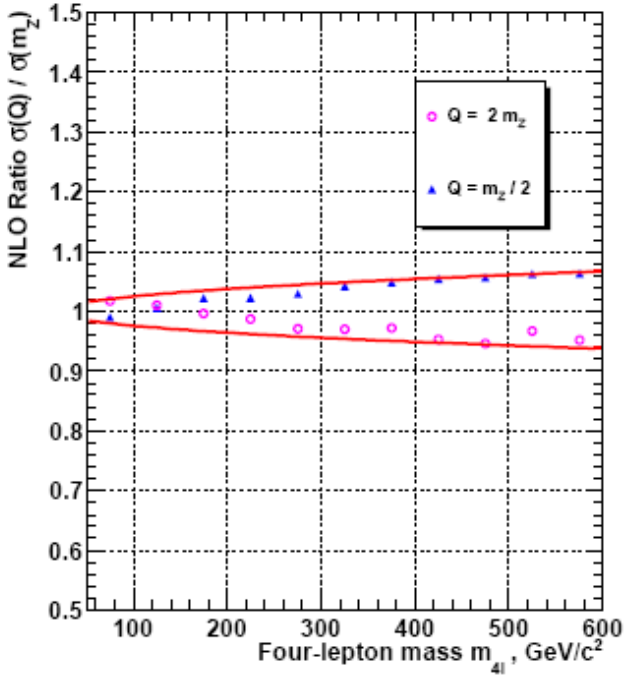
theoretical uncertainty
(Higgs xsec working group)



PDF



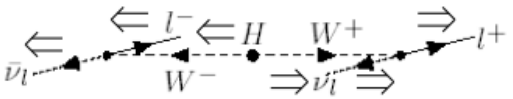
scale



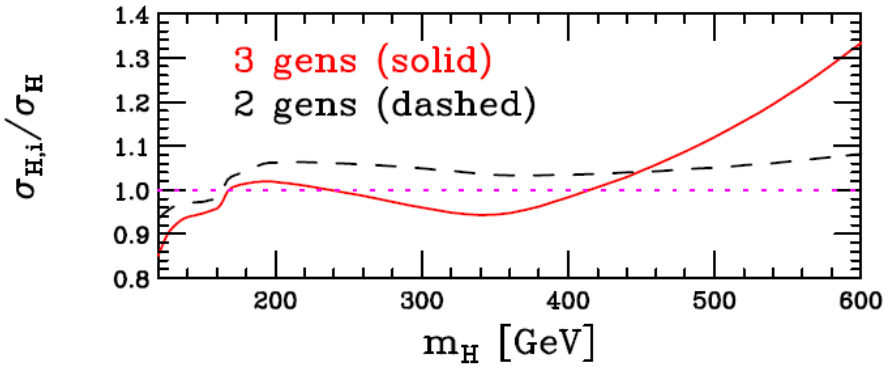
H->WW->lνlν high mass (CMS)

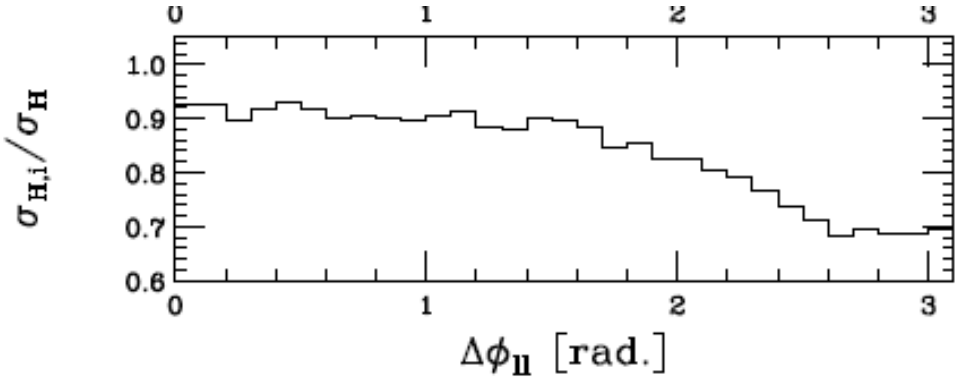
❑ **2l (ee,μμ,eμ) + MET + 0/1/2 jets** -> different ggF/VBF contribution

- Topological cuts (MET-ll, Δϕ(ll-j), m(ll)) -> useful against Z/W+j dominant at low mass
- High mass dominated by top and WW
  - anti-top tagging (b-tagging and soft-muon veto)
  - main cut against WW: H spin 0 -> low Δϕ(ll) only for low masses



WW irreducible and can only be extracted from MC: interferes with H signal

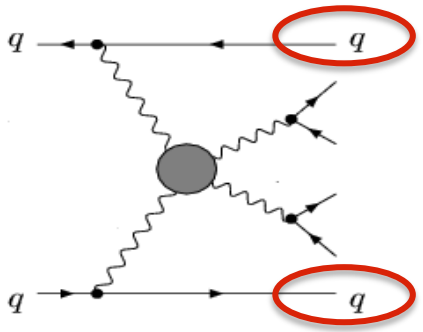




❑ 2 jet category: VBF search

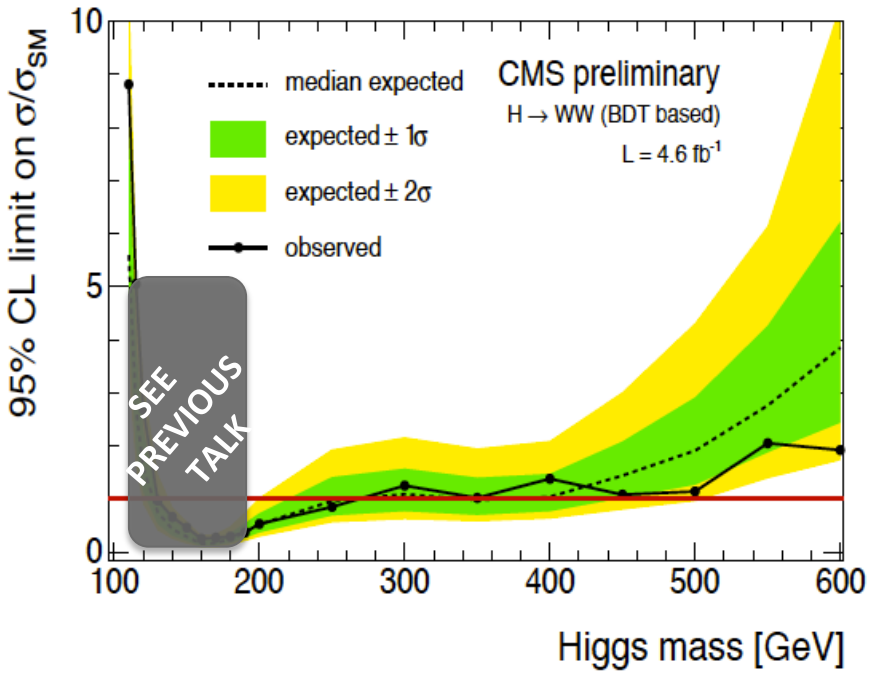
1/10 production xsec
but very peculiar kinematics:

- 2 jets forw-bkwd, high E (Δη>3.5, mjj>450 GeV)
- no color flow btw the jets

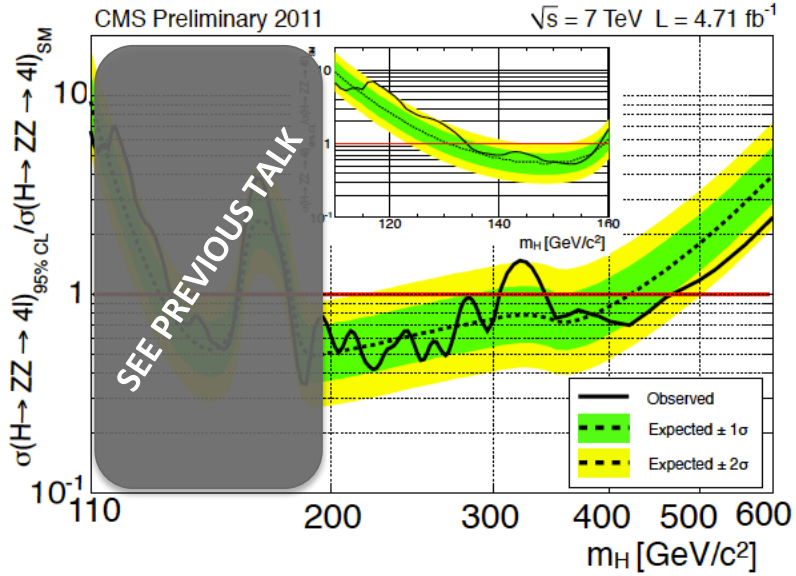


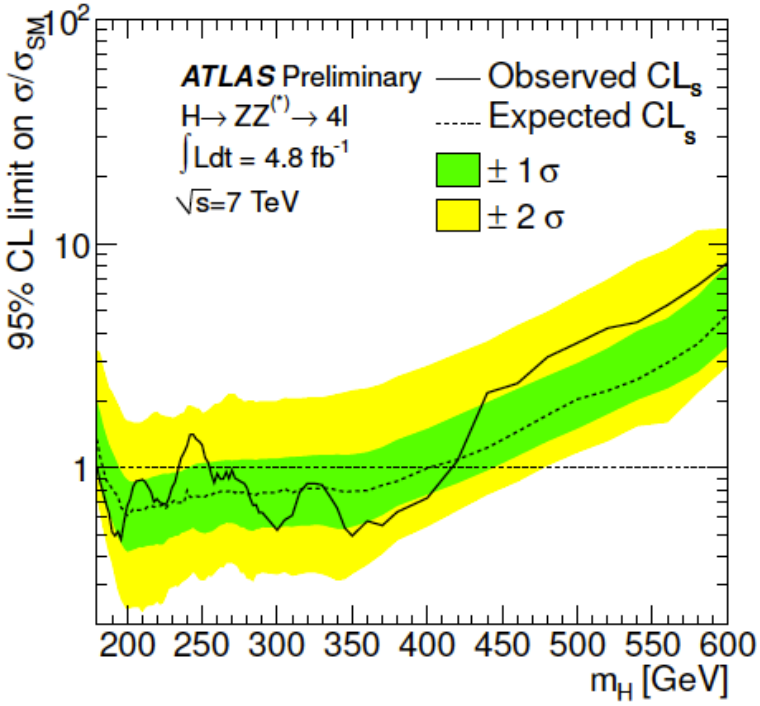
Fully leptonic results at high mass

- **WW:** cut based + fit m_T^H in VBF, fit to Boosted Decision Tree output in 0,1 categories



- **ZZ:** fit to mH





Summary

- **WW→lnqq, ZZ→llqq** limited by huge V+jets background, taken from simu/data with large theoretical/statistical error
- **WW→lnln** at high mass limited by WW background ($\Delta\phi$ not effective)
- **ZZ→llnn**: limited by Z+jets tail at high MET: not large but not well known

  ⇨ **drives the UL for mH>300-400**
- **ZZ→4l** limited by statistics (only ZZ background: small and well known)

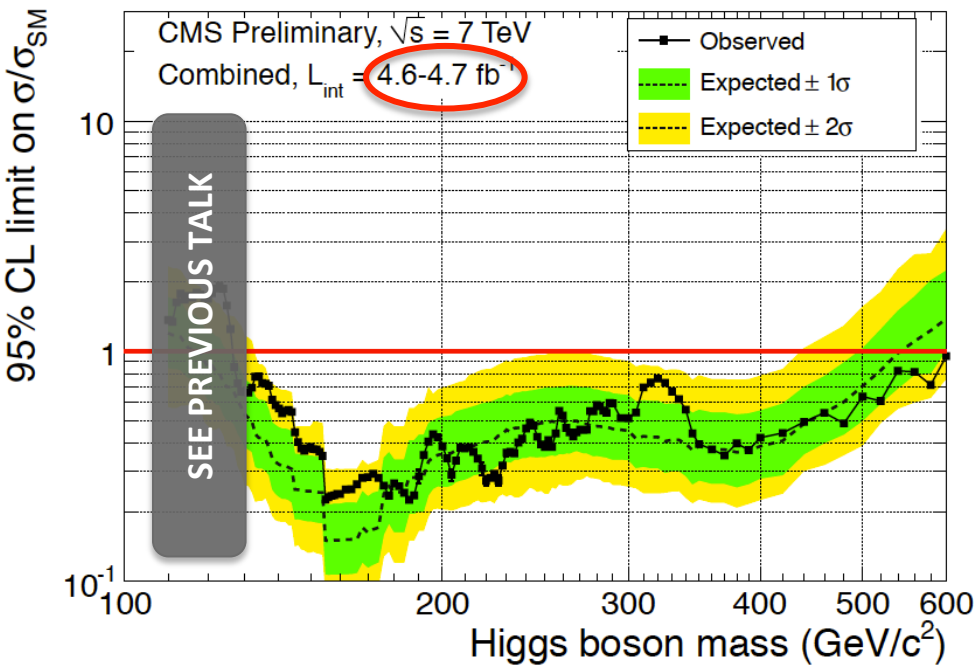
  ⇨ **drives the UL for mH 200-300**

❑ Combination of >5 different channels (ele, mu, btag, …) Robust!
Very optimized analyses, some space for further improvement. With higher lumi:

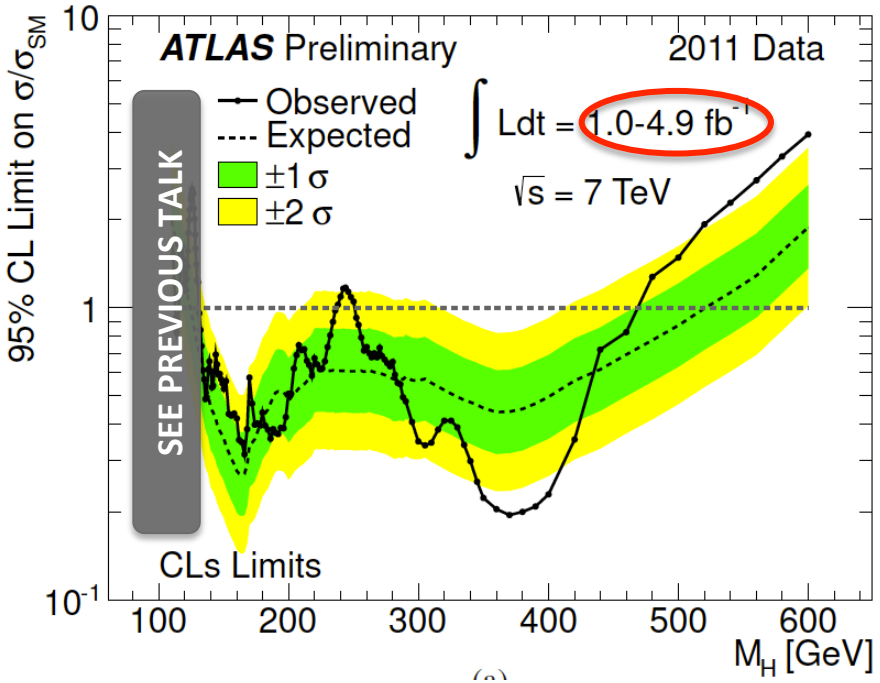
- use shape analyses (where not yet done)
- extract signal with multidimensional fit (now only mZZ fit)
- extract background (norm and shape) from data with lower uncertainty

Combined results: high mass

127-600 GeV 95% CL exclusion



131-237 251-468 GeV 95% CL exclusion



What's next?

- **Characterization of the signal** (if any) -> angular analysis
  xsec and BR (if different channels available)

- **Search for lower xsec at high mass:**

  many models provide high mass resonances (+ even together with a lower mass one)
  -> look specifically to VBF resonances

  the mechanism to give mass to the fermions (-> ggF H production)
  can be completely decoupled from EWSB: H coupling to VV

  Next year enough statistics to probe VBF Higgs in all semileptonic and 2l2ν final states

- **Make sure that the Higgs (if there) plays the expected role in EWSB:**

  the only definitive way to prove that an observed resonance is the Higgs
  is to look at the VV scattering spectrum

BACK-UP:
High mass Higgs searches at LHC

6th February 2012
CERN Winter school

S.Bolognesi (Johns Hopkins University)
on behalf of ATLAS & CMS collaborations

EWSB and the W, Z mass

$$L_{gauge} = -\frac{1}{4}W^i_{\mu\nu}W^{\mu\nu i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m^2 W^i_{\mu}W^{\mu i} + \frac{1}{2}m^2 B_{\mu}B^{\mu}$$

$$W^i_{\mu\nu} = \partial_\nu W^i_\mu - \partial_\mu W^i_\nu + g\varepsilon^{ijk}W^j_\mu W^k_\nu \quad \text{SU(2)} \times$$

$$B_{\mu\nu} = \partial_\nu B_\mu - \partial_\mu B_\nu \quad \text{U(1)}$$

Gauge invariance

scalar potential ($\lambda>0$, $\mu<0$) $V(\Phi) = \mu^2|\Phi^+\Phi| + \lambda(|\Phi^+\Phi|)^2$

complex scalar doublet of SU(2) $\Phi = \begin{pmatrix}\phi^+\\ \phi^0\end{pmatrix}$

with minimum **(= empty state)** at *(**v** = empty expectation value)*

$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}$ **or** ~~$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}v\\ 0\end{pmatrix}$~~ → ~~SU(2)~~

generic Gauge

$$\Phi = \frac{1}{\sqrt{2}}e^{i\frac{\omega^i\tau^i}{2v}}\begin{pmatrix}0\\ v+h\end{pmatrix}$$

1 physical scalar field $\langle h\rangle = 0$

3 Goldstone bosons ω_i

4 Gauge fields W^i_μ, B_μ

unitary Gauge

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h\end{pmatrix}$$

1 physical scalar field -> Higgs

4 Gauge fields combined into known vector bosons:
W,Z with mass, photon massless

$$W^\pm_\mu = \frac{1}{\sqrt{2}}\left(W^1_\mu \mp iW^2_\mu\right) \quad M^2_W = \frac{1}{4}g^2v^2$$

$$Z^\mu = \frac{-g'B_\mu + gW^3_\mu}{\sqrt{g^2+g'^2}} \quad M^2_Z = \frac{1}{4}\left(g^2+g'^2\right)v^2$$

$$A^\mu = \frac{-gB_\mu + g'W^3_\mu}{\sqrt{g^2+g'^2}} \quad M^2_A = 0 \quad \text{U(1)}_{\text{EM}}$$