# Higgs search by CMS

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Friday seminar
Warsaw, 4 November 2011

*AK is supported by the Homing Plus programme of Foundation for Polish Science, cofinanced from European Union Regional Development Fund

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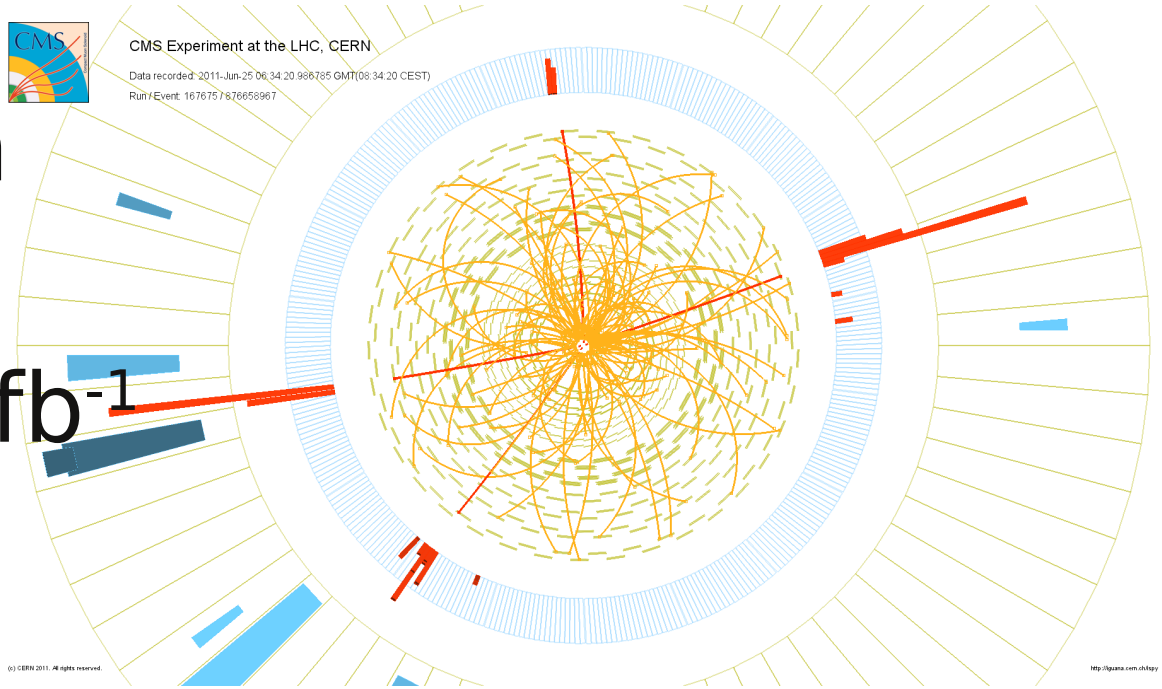
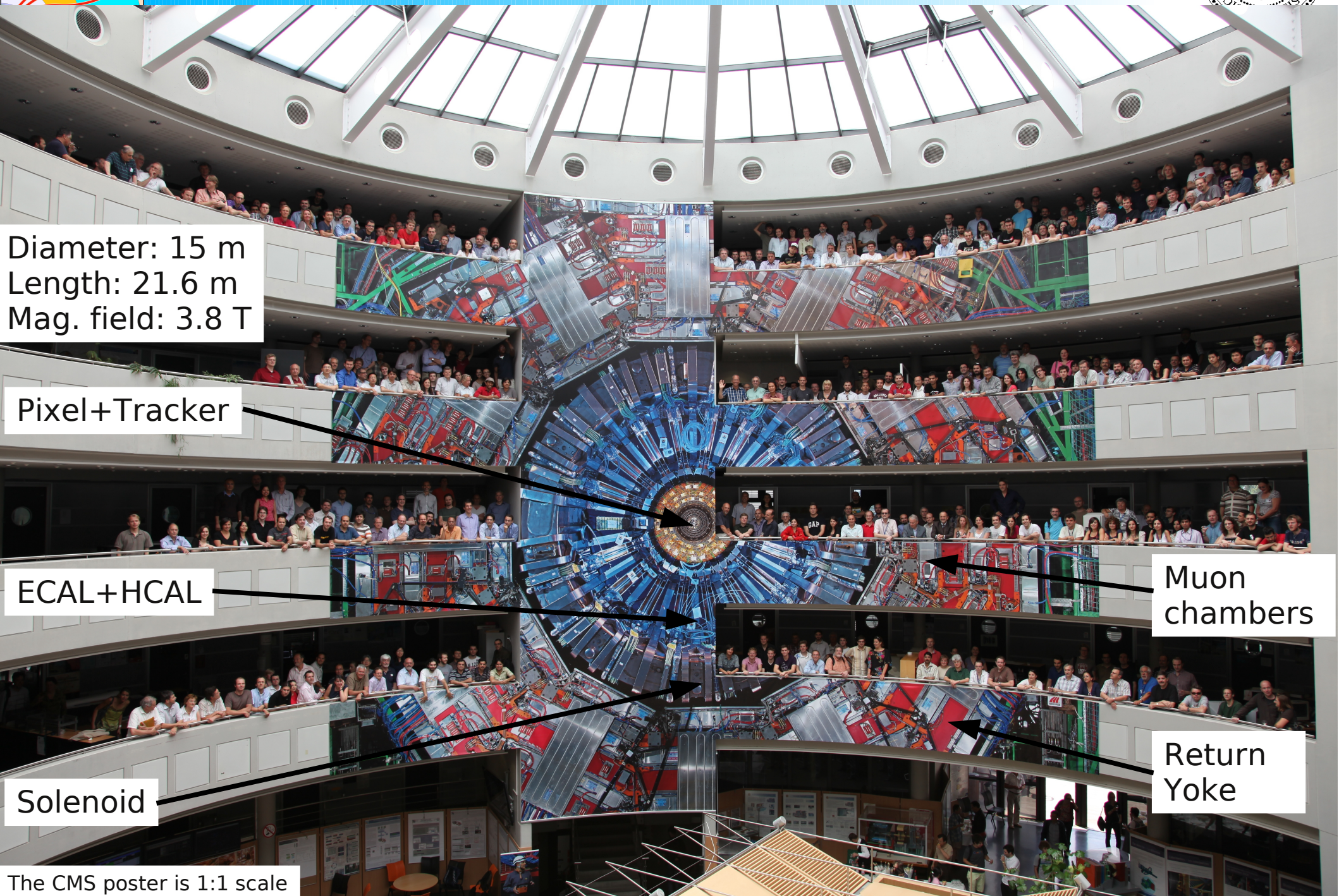
# Outline

- Higgs boson production at the LHC
- Search channels at CMS
- Exclusion limits for SM Higgs with up to 1.6 $fb^{-1}$
- Prospects with 5 $fb^{-1}$



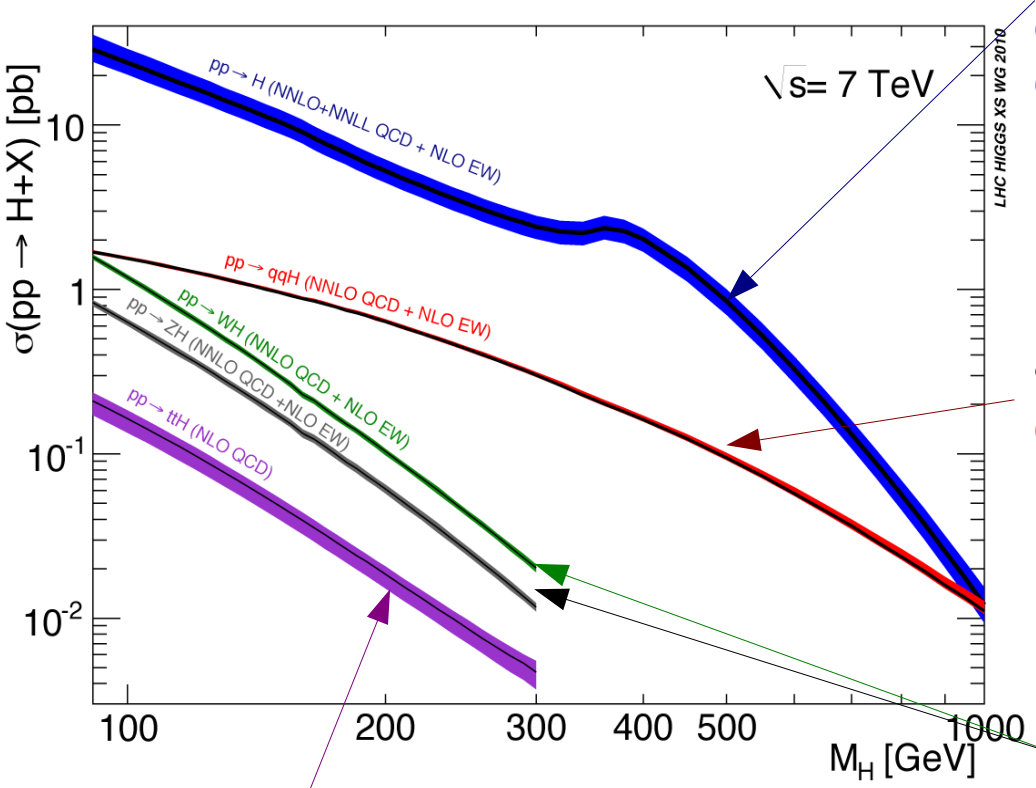

Candidate ZZ→4e event

# The CMS

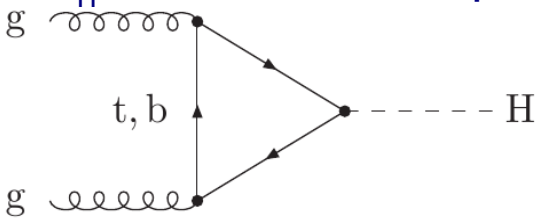



The CMS poster is 1:1 scale

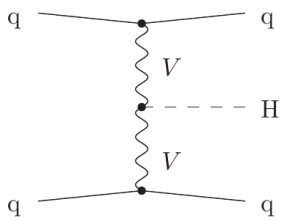
# Higgs production modes at LHC



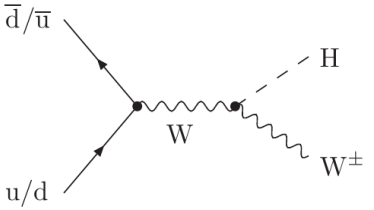

- Dominating production mode in pp collisions @7 TeV is gluon-gluon fusion
  gg→H: $\sigma(m_H=120) = 16.63$ pb



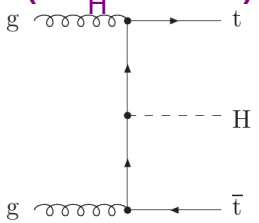

- Next is Vector Boson Fusion (VBF)
  qq→qqH: $\sigma(m_H=120) = 1.27$ pb



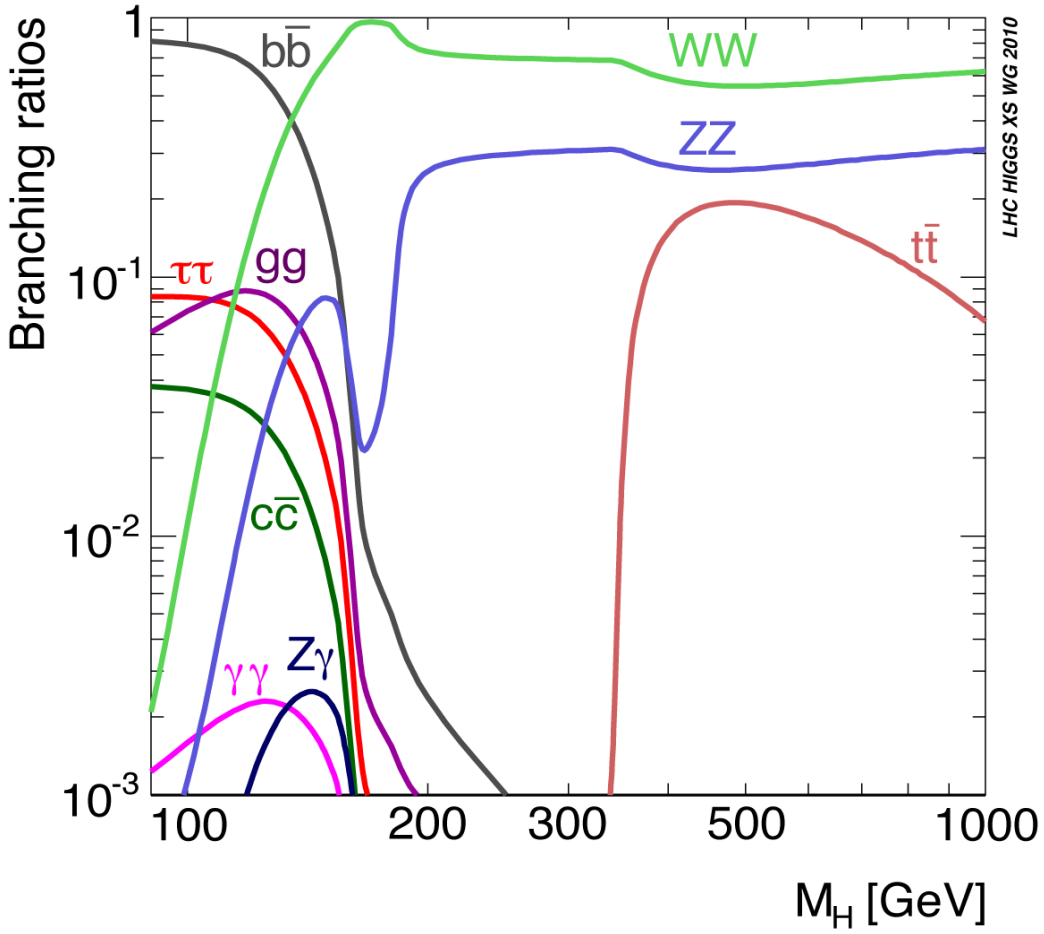

- then is VH associated production:
  qq'→WH $\sigma(m_H=120)$ =0.66 pb and
  qq→ZH $\sigma(m_H=120)$ = 0.36 pb

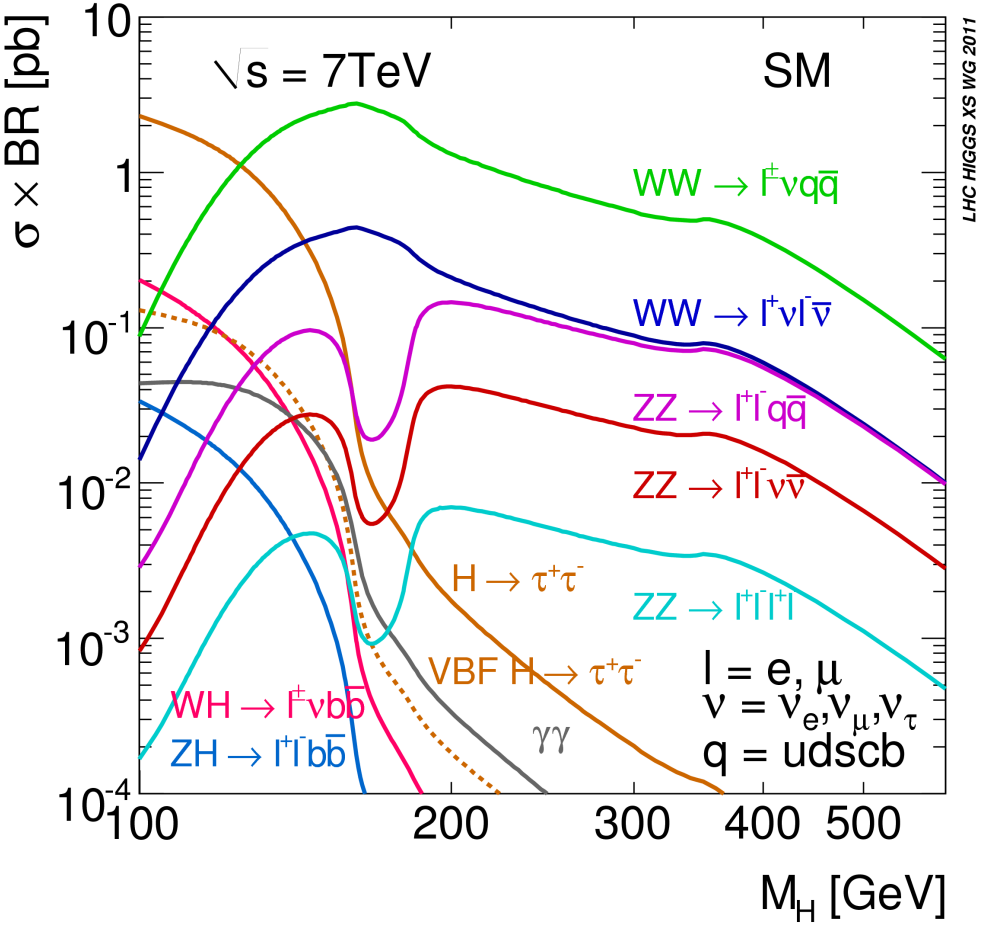



- Finally ttH associated production:
  qq→ttH $\sigma(m_H=120)$ =0.098 pb



# Main H decay modes




- channels important for low mass region, $m_H$<130: H→γγ, H→bb, H→ττ
- channels important for medium and high masses: H→WW, H→ZZ

# Channels investigated by CMS

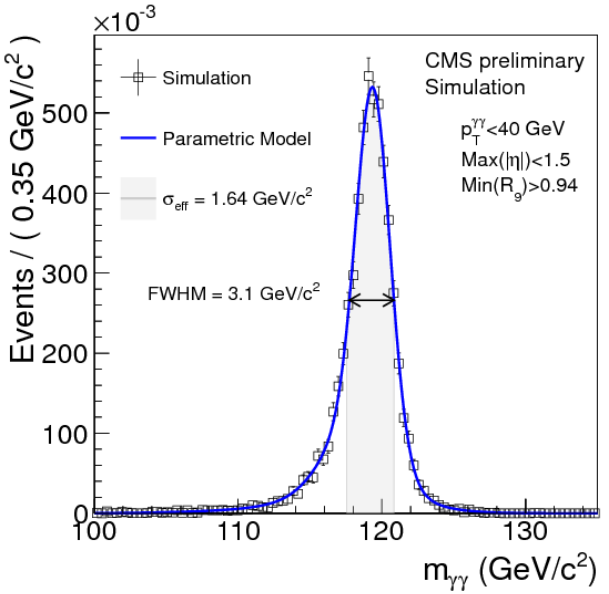
| channel | mass range ($\mathrm{GeV}/c^2$) | luminosity ($\mathrm{fb}^{-1}$) | number of sub-channels | type of analysis |
|---|---|---|---|---|
| $H \to \gamma\gamma$ | 110-150 | 1.7 | 8 | mass shape (unbinned) |
| $H \to \tau\tau$ | 110-140 | 1.1 | 6 | mass shape (binned) |
| $H \to bb$ | 110-135 | 1.1 | 5 | cut&count |
| $H \to WW \to 2\ell 2\nu$ | 110-600 | 1.5 | 5 | cut&count |
| $H \to ZZ \to 4\ell$ | 110-600 | 1.7 | 3 | mass shape (unbinned) |
| $H \to ZZ \to 2\ell 2\tau$ | 180-600 | 1.1 | 8 | mass shape (unbinned) |
| $H \to ZZ \to 2\ell 2\nu$ | 250-600 | 1.6 | 2 | cut&count |
| $H \to ZZ \to 2\ell 2q$ | 226-600 | 1.6 | 6 | mass shape (unbinned) |
| TOTAL (8) | 110-600 | 1.1-1.7 | 27 for low $m_H$<br>24 for high $m_H$ | |

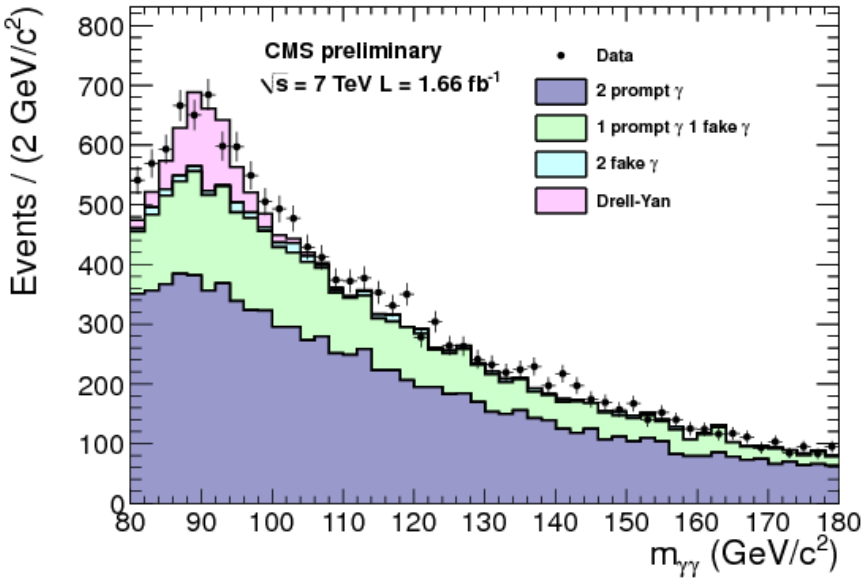
More than 3 $\mathrm{fb}^{-1}$ still to be analysed

Large number of sub-channels analysed. CMS working hard to add more

# H→γγ analysis

- **Signal signatures:**
  **two isolated photons**
  **excellent mass resolution (FWHM/$m_H$)**
  **of order of 2.4% for the best, and**
  **6.5% for worst category di-photons**
- **Main backgrounds:**
  **di-photon production**
  **photon+jet (mis id. as second photon)**



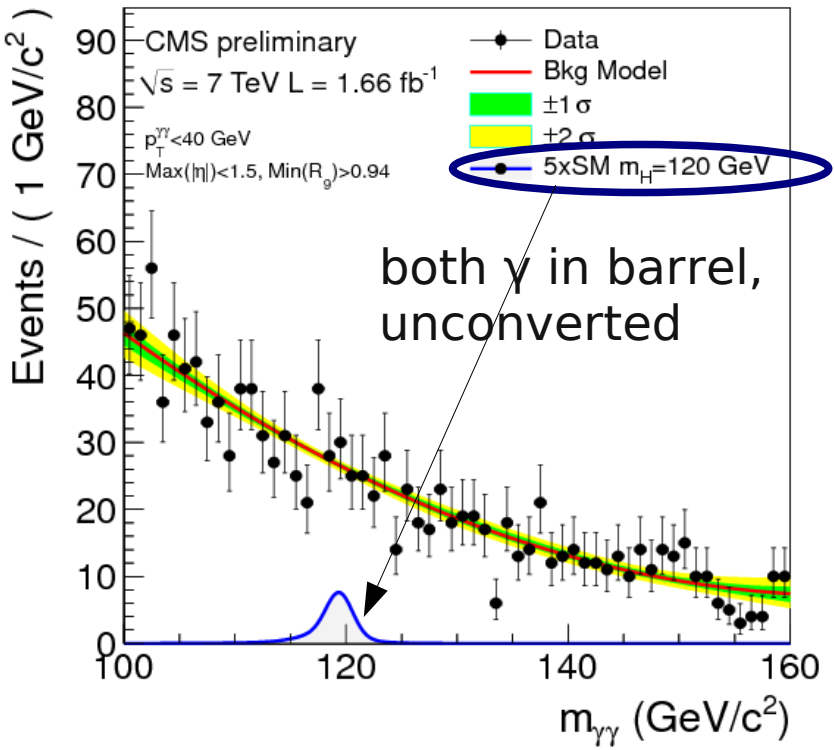
# H→γγ analysis

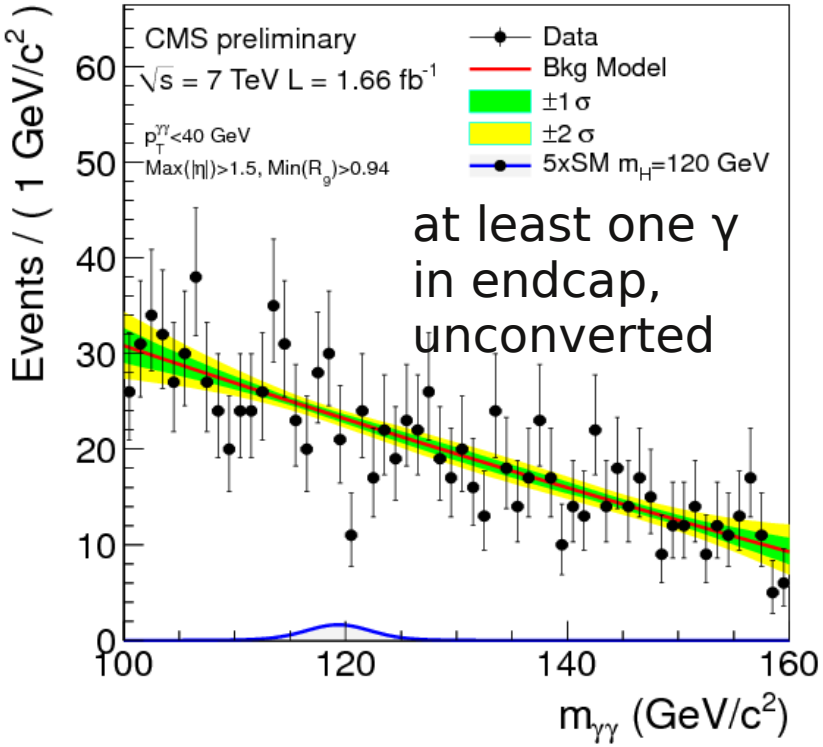
- Data is split into 8 di-photon quality categories based on:

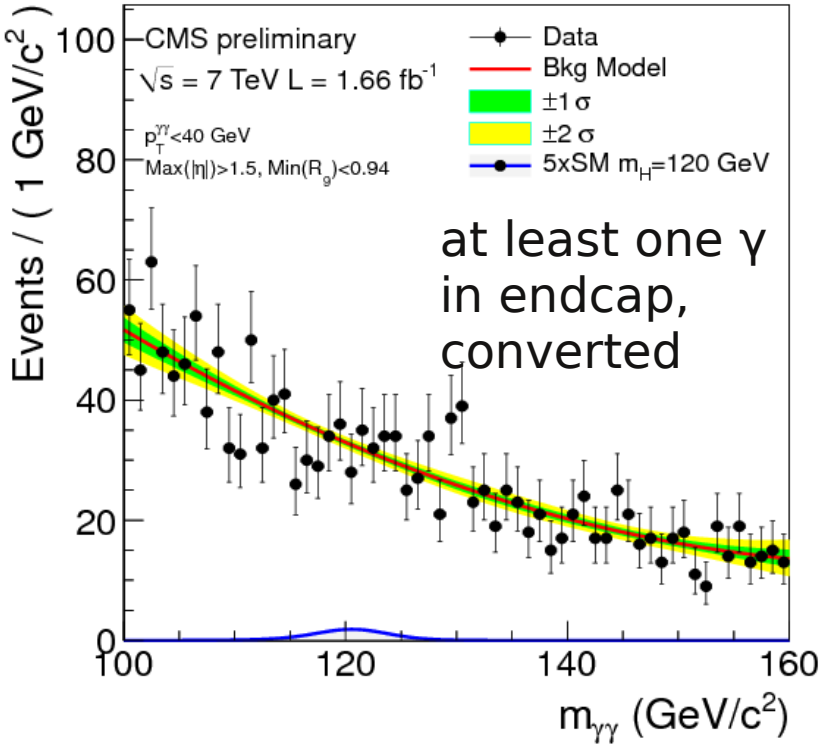
**$p_T^{\text{di-photon}}$ > or < 40 GeV,**

**number of photons in barrel detector,**

**width of the photon shower in ECAL to reject converted γ**



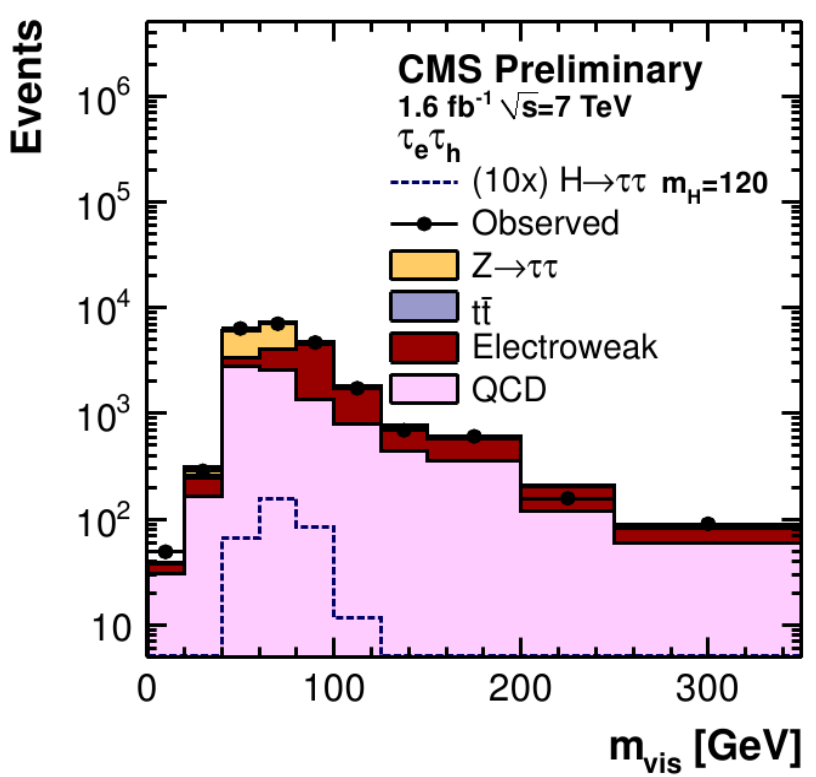



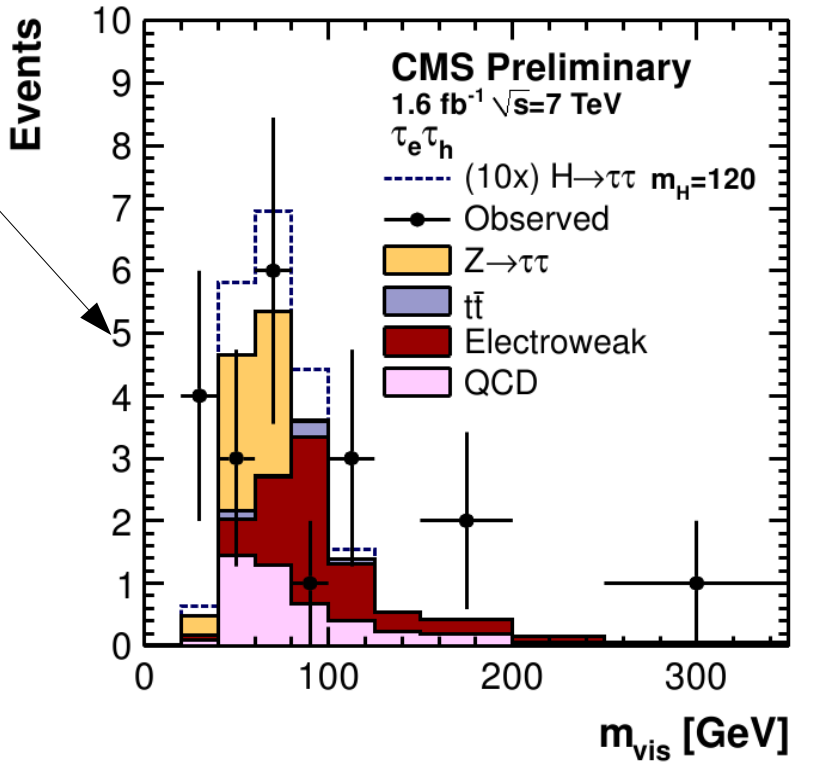



# Searches in ττ

- **Signal signatures:**
  **CMS analysed e+$\tau_{had}$, μ+$\tau_{had}$ and e+μ final states, each divided into categories: without and with VBF-like jets**
- **VBF selections:**
  **2 additional jets, $E_T$>30 GeV, $m_{jj}$>350 GeV, $|\Delta\eta_{jj}|$>3.5, $\eta_1^* \eta_2$<0**

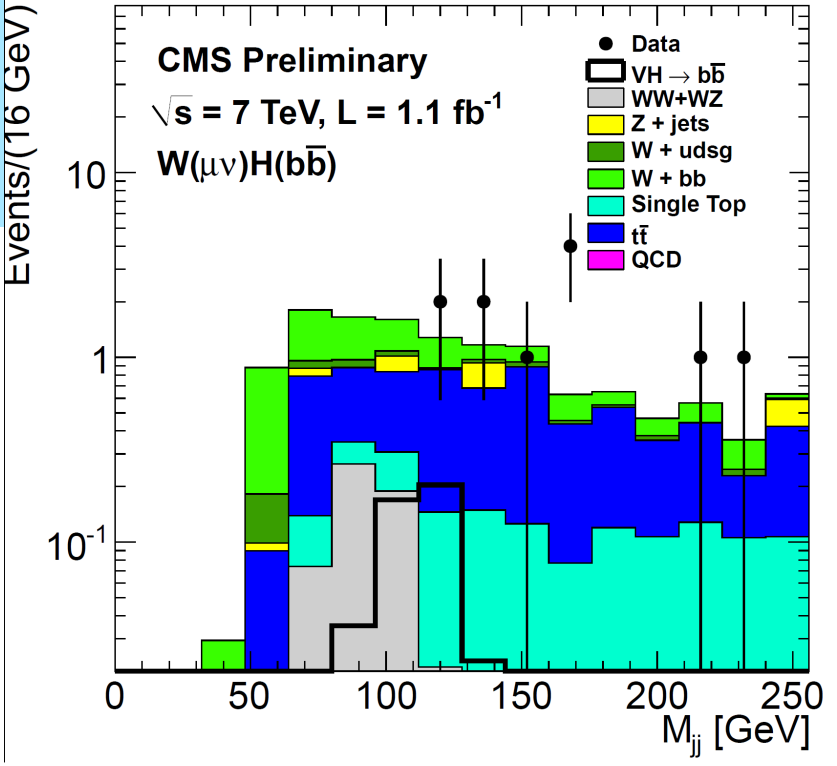
  **Very clean signature, but requires high integrated luminosity**
- **Neutrinos present in final state:** **invariant mass of visible products used ($m_{vis}$)**
- **Main backgrounds:** **Z→ττ, QCD, tt, W+jets,(Z→ee/μμ)+jets**

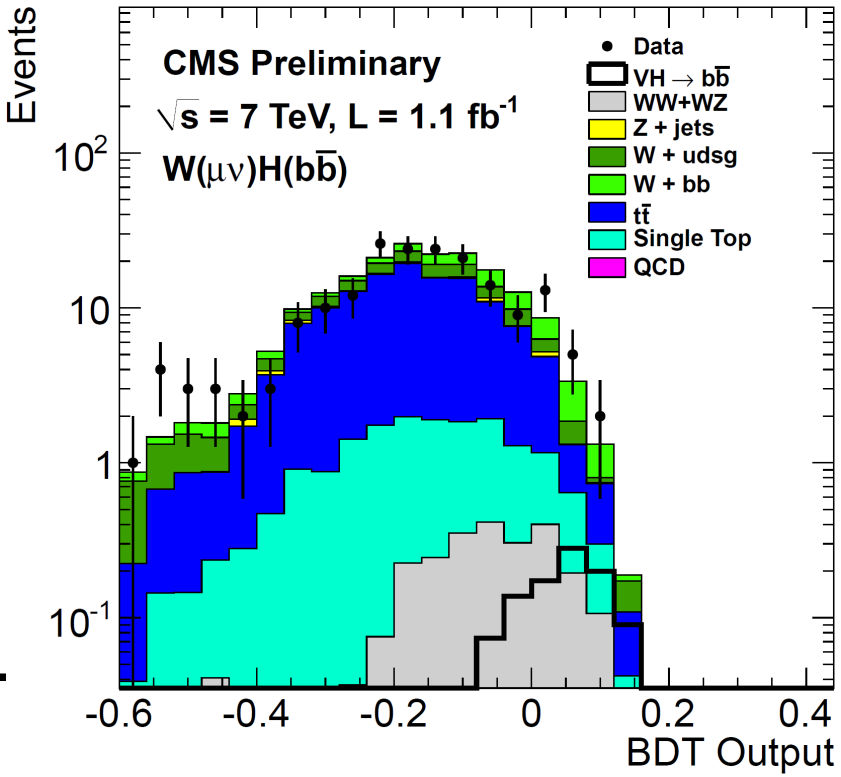


# Searches in bb

- **Signal signatures:**
  **bb decay is dominant, but requires additional handle to suppress huge QCD background, VH production mode is used with Z→ee/μμ/νν and W→eν/μν**
- **Event selections**
  **VH azimuthal separation: ΔΦ(V,H)>2.9**
  **$p_T^V$>160 (Z→νν)/100 (Z→ll)/150 (W→lν)**
  **tight b-tag and MET quality**
- **Boosted Decision Tree analysis made in parallel**
- **Main backgrounds:**
  **V+jets, VV, tt**



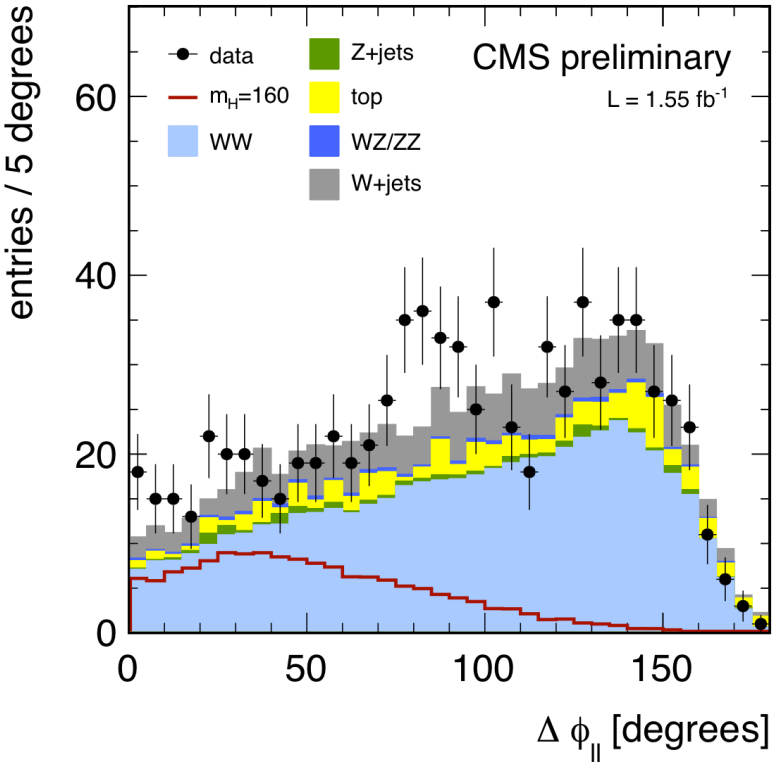



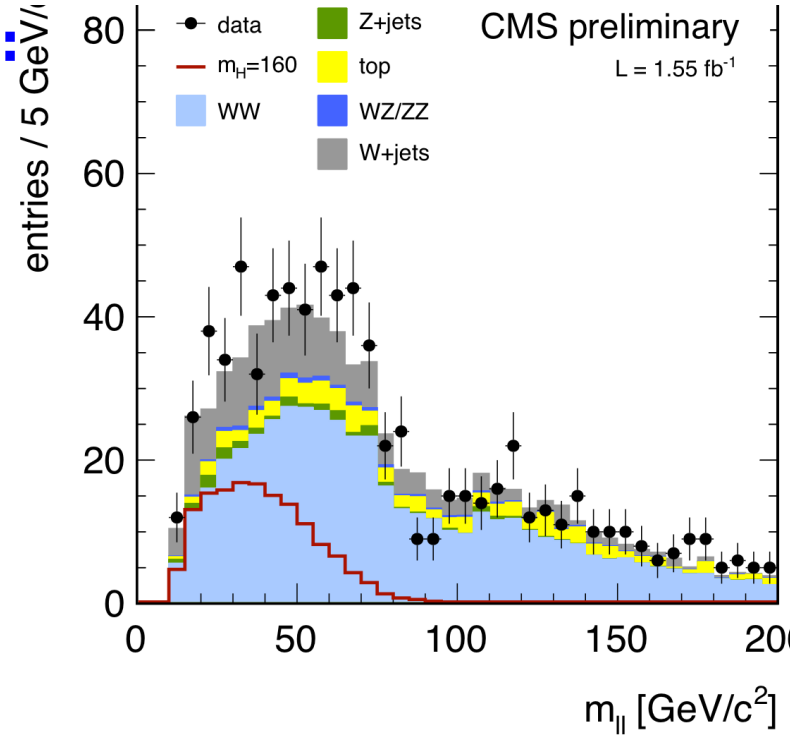
# Searches in H→WW→2l2ν

- **Signal signatures:**
  **two isolated leptons,**
  **large missing $E_{T,}$**
  **lepton azimuthal angle correlations**

- **Event selections:**
  **lepton $p_T$>10 GeV, tight ID, isolation,**
  **veto events with additional soft leptons or with b-tagged jets,**
  **split events in jet multiplicity categories: 0,1 and 2 jets,**
  **for 2 jets cat. apply VBF-like selections,**
  **cut on di-lepton mass,**
  **cut on di-lepton azimuthal separation,**
  **cut on transverse mass of (MET,ll) system**

- **Main backgrounds:** WW, tt,
  W+jets,Drell-Yan, WZ, ZZ



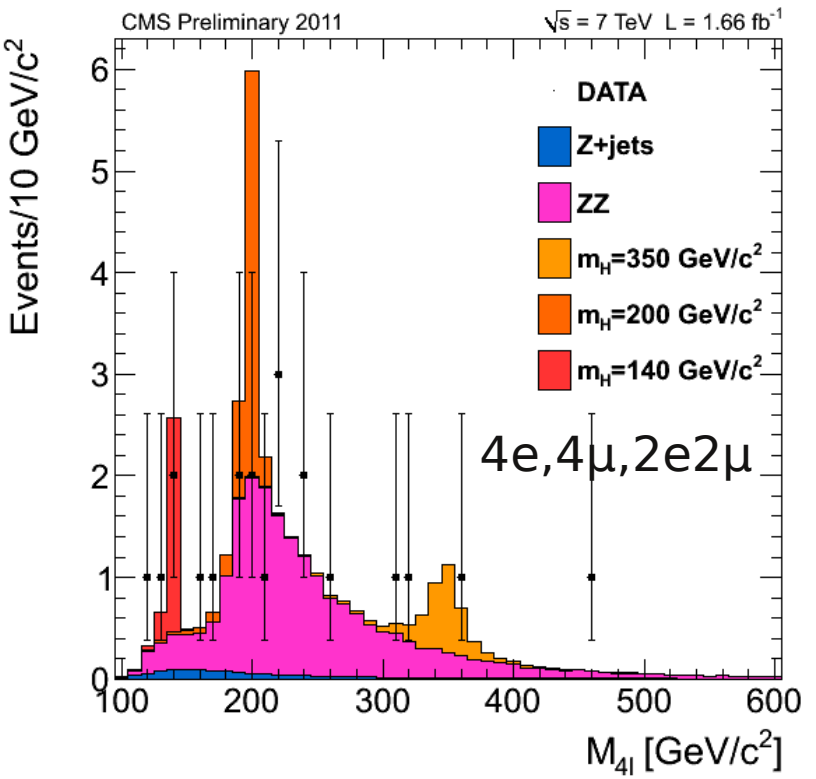
# $H \rightarrow ZZ^{(*)} \rightarrow 4l$

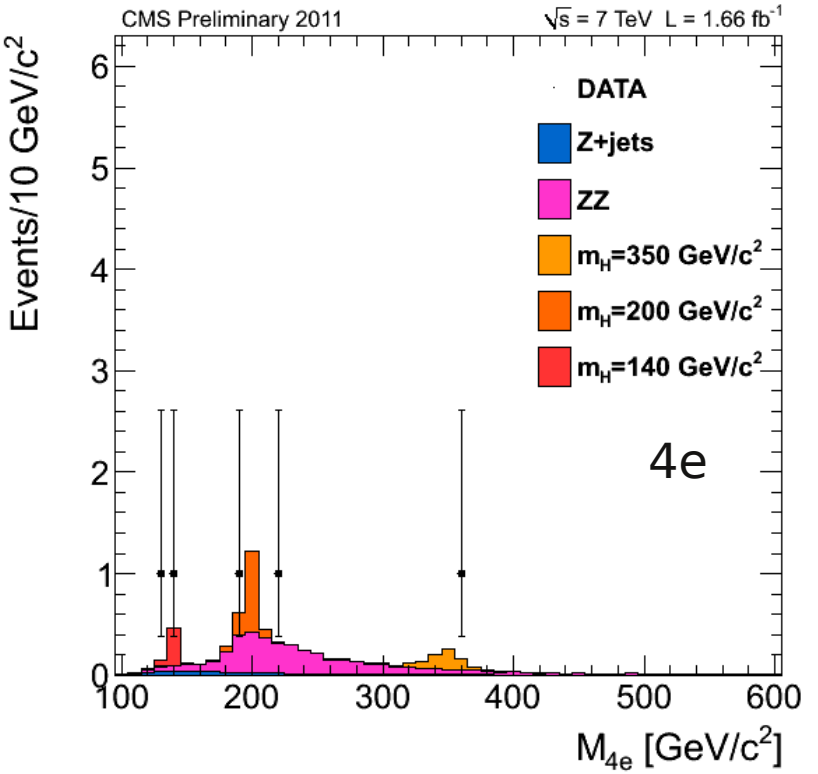
- **Signal signatures:**
  **two isolated leptons,**
  **Z mass constraint for one ll pair,**
  **full H mass reconstruction with**
  **2-4 GeV resolution**

- **Event Selections:**
  **leptons: $p_T^{electron}>7$ GeV, $p_T^{muon}>5$ GeV,**
  **$Z_1$: $p_T^{l1}>20$, $p_T^{l2}>10$, $60<m_{ll}<120$,**
  **$Z_2$: $20<m_{ll}<120$, $m_{4l}>100$**

- **Main backgrounds:**
  **ZZ, Zbb, Z+jets, WZ,tt**

- **The ZZ continuum estimation:** **normalised with Z yield in data and theoretical prediction of σ(ZZ)/σ(Z)**

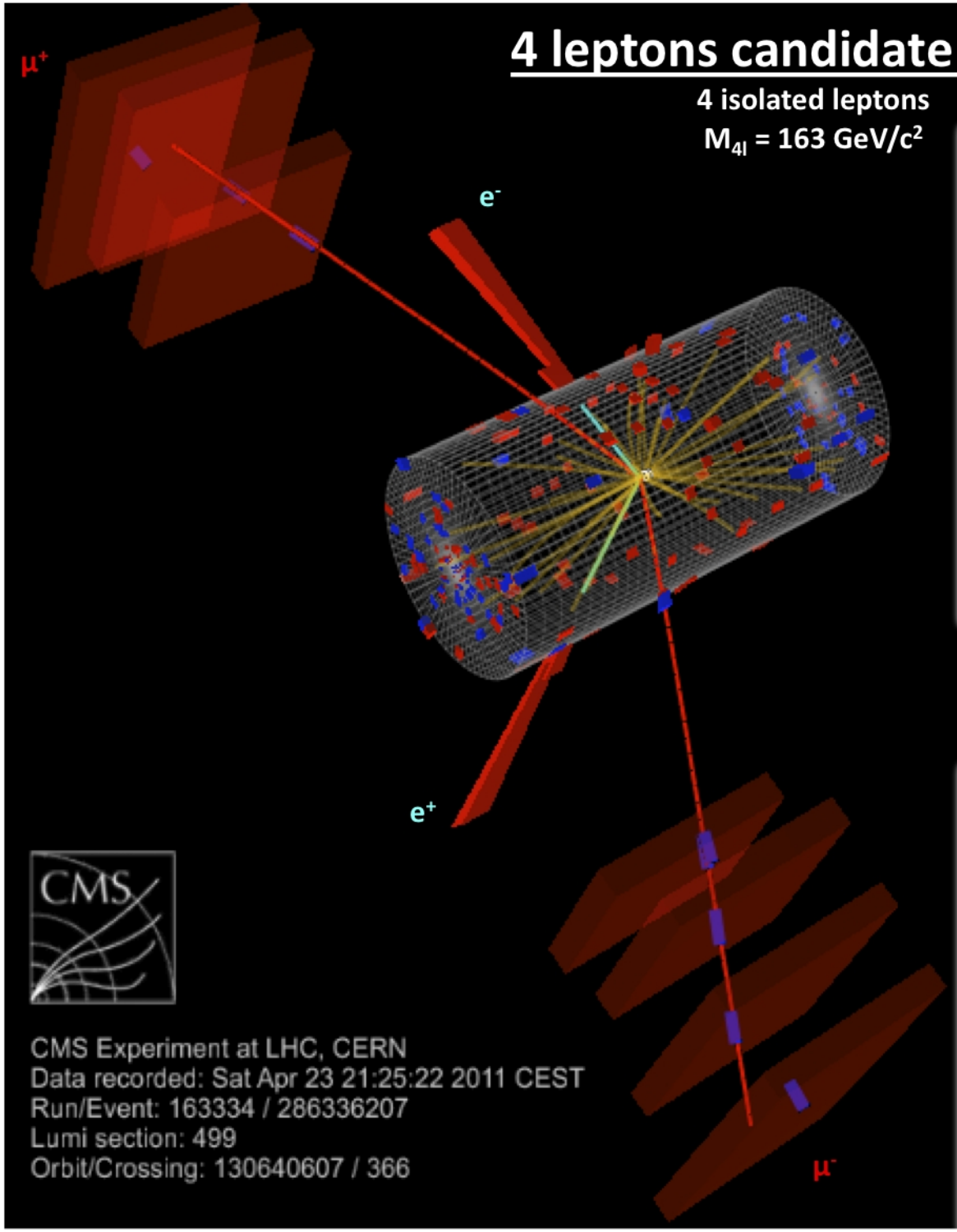


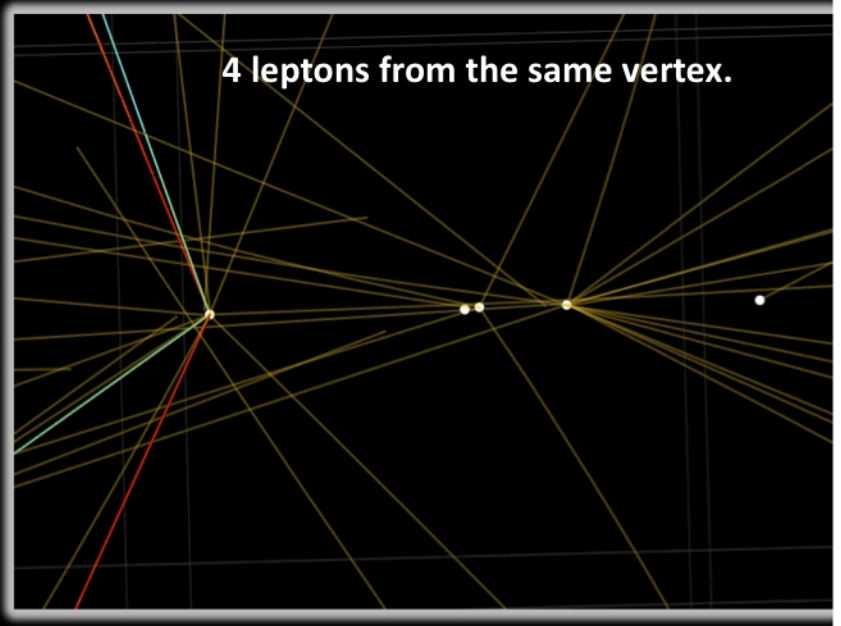



# 4 leptons candidate : 2e2μ

4 isolated leptons

$M_{4l}$ = 163 GeV/$c^2$

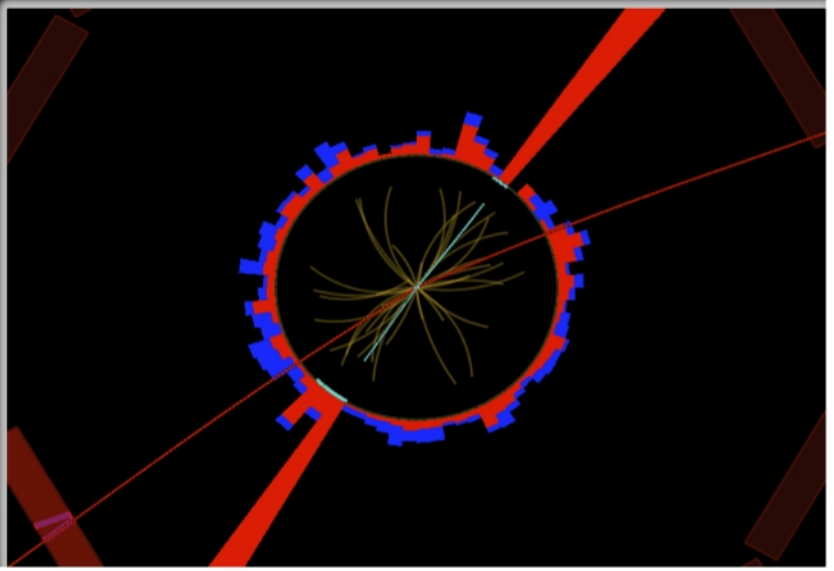



2 leptons pairs

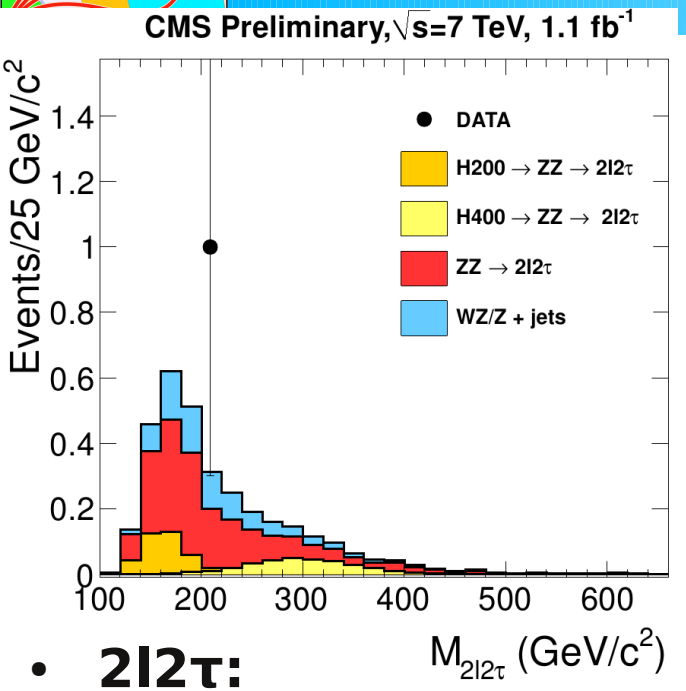
Z (μ+μ-) : m = 94 GeV/$c^2$

Z*(e+e-) : m = 65 GeV/$c^2$

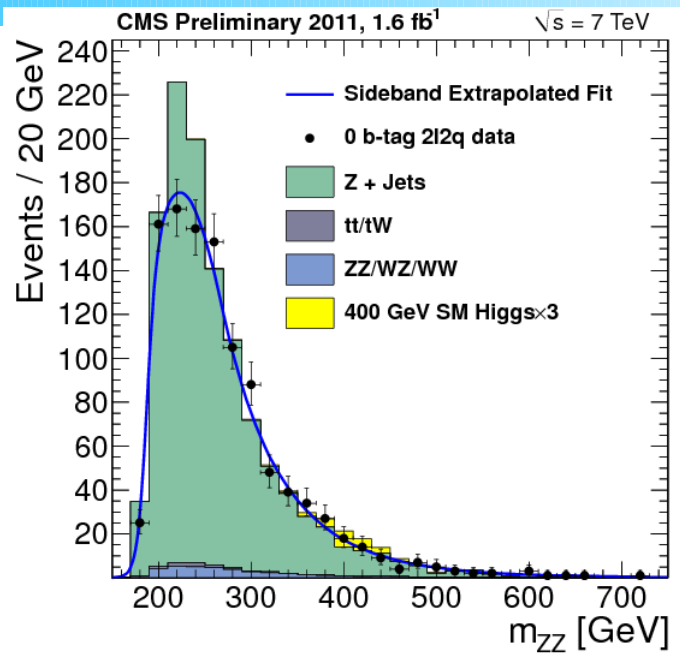


CMS Experiment at LHC, CERN
Data recorded: Sat Apr 23 21:25:22 2011 CEST
Run/Event: 163334 / 286336207
Lumi section: 499
Orbit/Crossing: 130640607 / 366

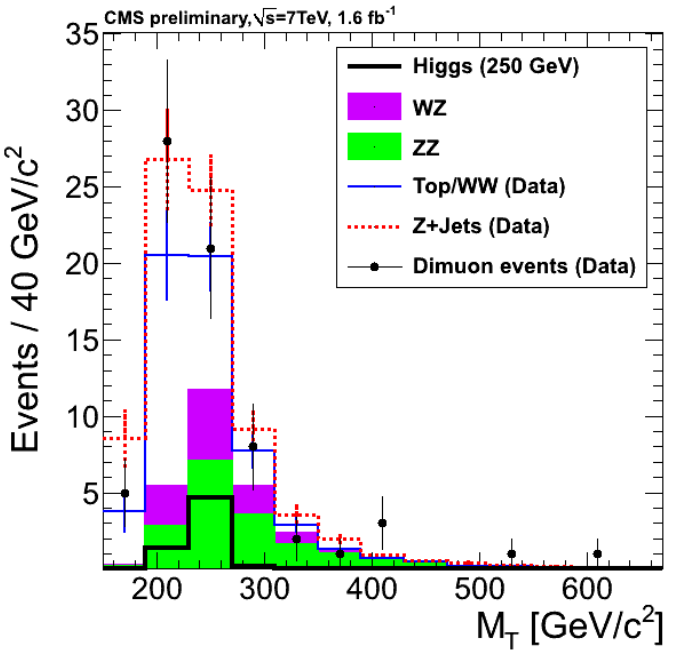
# $H \to ZZ^{(*)} \to 2l2\tau/2l2q/2l2\upsilon$




- **2l2τ:**
- **Selection: "leading" Z: 2e/2μ decay, $p_T^l$>20/10, "subleading" Z: $\mu\tau_{had}$, $e\tau_{had}$, $\mu e$, $\tau_{had}\tau_{had}$**
- **Main backgrounds: ZZ,Z+jets, WZ+jets, tt**



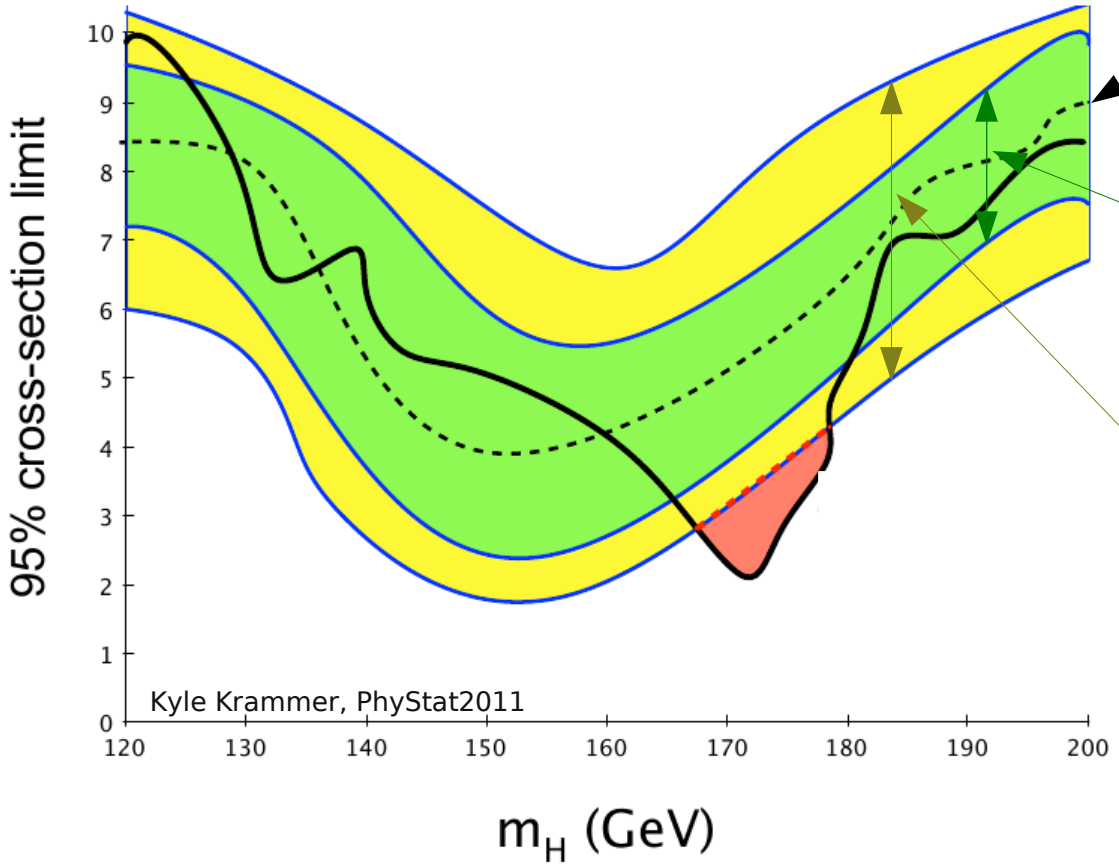

- **2l2q: highest rate among ZZ, events categorised by 0,1,2 b-jets,**
- **Selection: $75<m_{jj}<105$, $70<m_{ll}<110$, use lepton angles in likelihood**




- **2l2υ**
- **Selection: $76<m_{ll}<106$, MET and $M_T$ cut depend on mass hypothesis anti b-tag, $M_T$**
- **Main backgrounds: ZZ,Z+jets, tt, WZ**

# The expectation contours

- to compute exclusion expectation for exclusion limits **background only toy Monte Carlo is used**
- ±1σ, ±2σ bands are plotted to show range of **possible statistical fluctuation of the actual result wrt. expectation**




Median, i.e we expect 50% chance that a real experiment will get better (=less background events), or worse (=more background events) exclusion

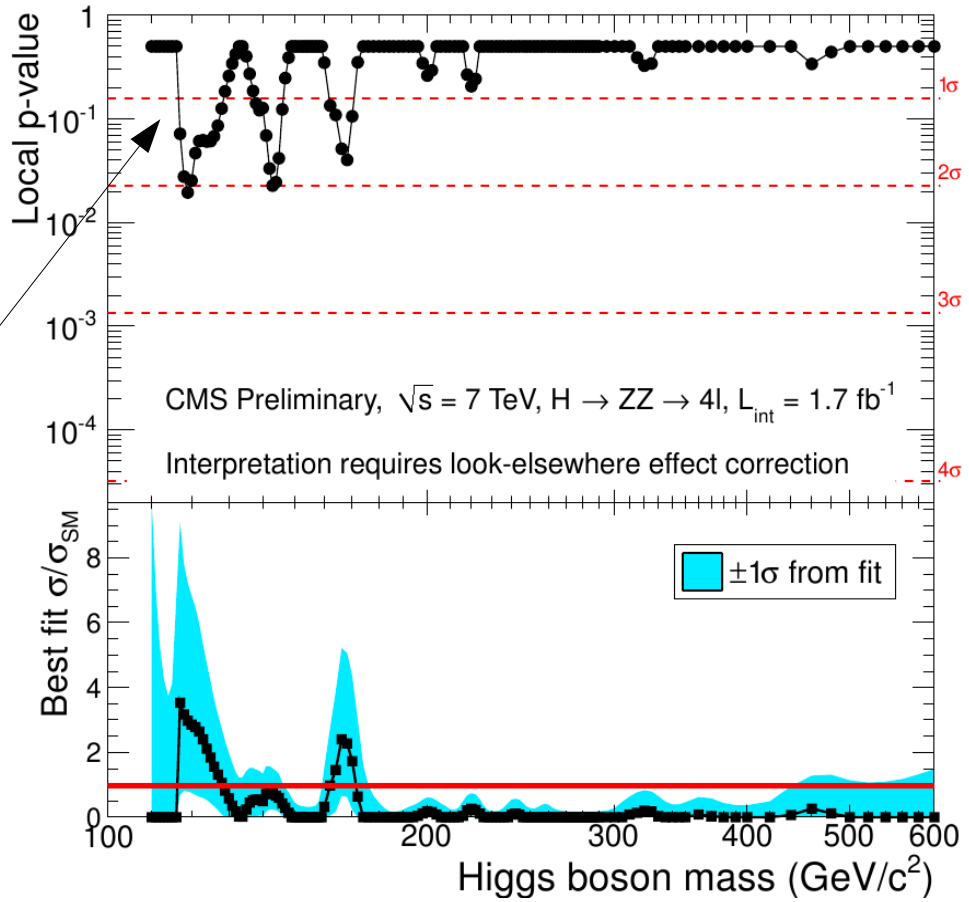
±1σ – 68% toy MC experiments around median gave result within this range, ie. chance that a real experiment will see result within this band is 68%

±2σ – 95% toy MC experiments around median, ie. chance that a real experiment will see result within this band is 95%

# Word of caution: LEE

- we are looking at wide mass range divided in many bins
- probability of upward fluctuation in each bin can be small
- **but given many bins, global probability of observing upward fluctuation can be significant**
- the effect is called “look elsewhere effect”, or “trial factor”

- for H→ZZ→4l CMS estimates the trial factor of order of 35
- **local probability for background-only upward fluctuation should be multiplied by a factor of order 35**
- For local p~0.01, $Z_{max}$~2.3 with LEE we get globally p~0.4, $Z_{global}$~0.25



# G fitter limits on $m_H$

Slide from M.Schott, Higgs Hunting 2011 (arXiv:1107.0975v1 )

- $\Delta\chi^2$ estimator for the standard and complete fits versus $M_H$

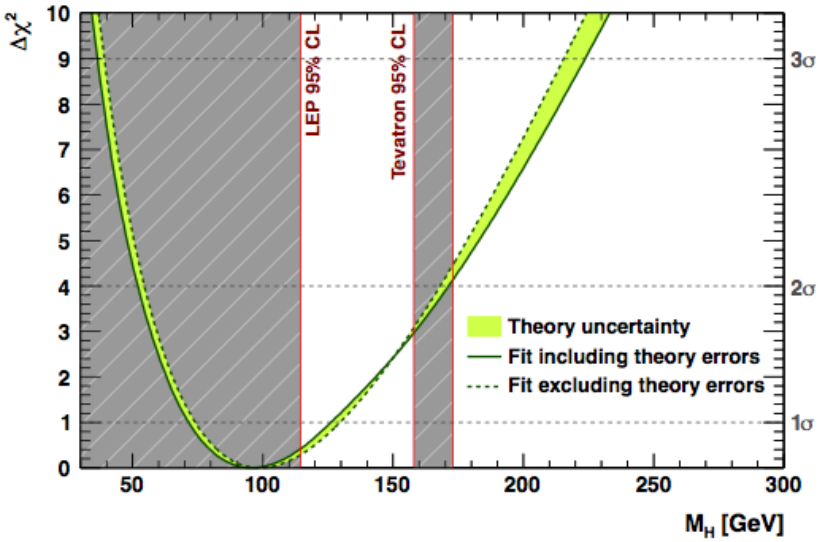
$$M_H = \begin{cases} 96\,^{+31}_{-24}\ \text{GeV} & \text{(standard fit)} \\ 120\,^{+12}_{-5}\ \text{GeV} & \text{(complete fit)} \end{cases}$$

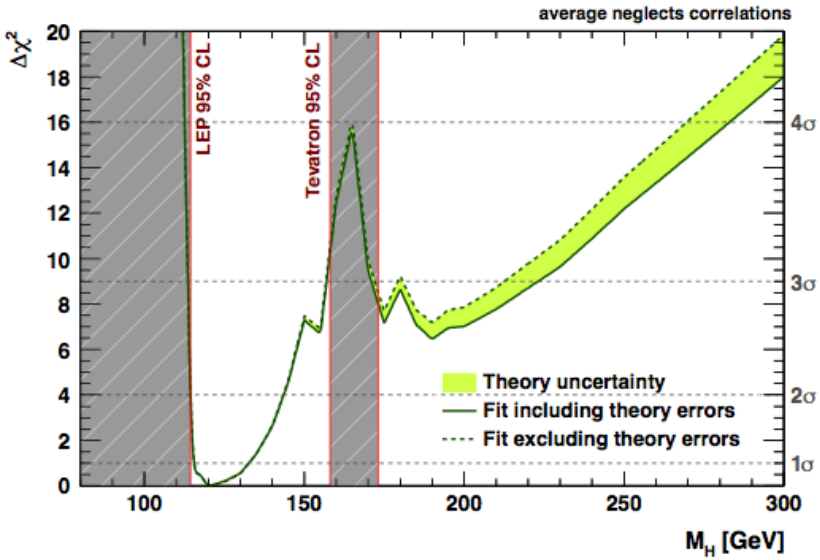
- with the 95% (99%) upper bounds of
  - 169GeV (200 GeV) for the standard fit
  - 143GeV (149 GeV) for the complete fit

- The errors and limits include the various theory uncertainties that taken together amount to approximately 8 GeV on $M_H$ .

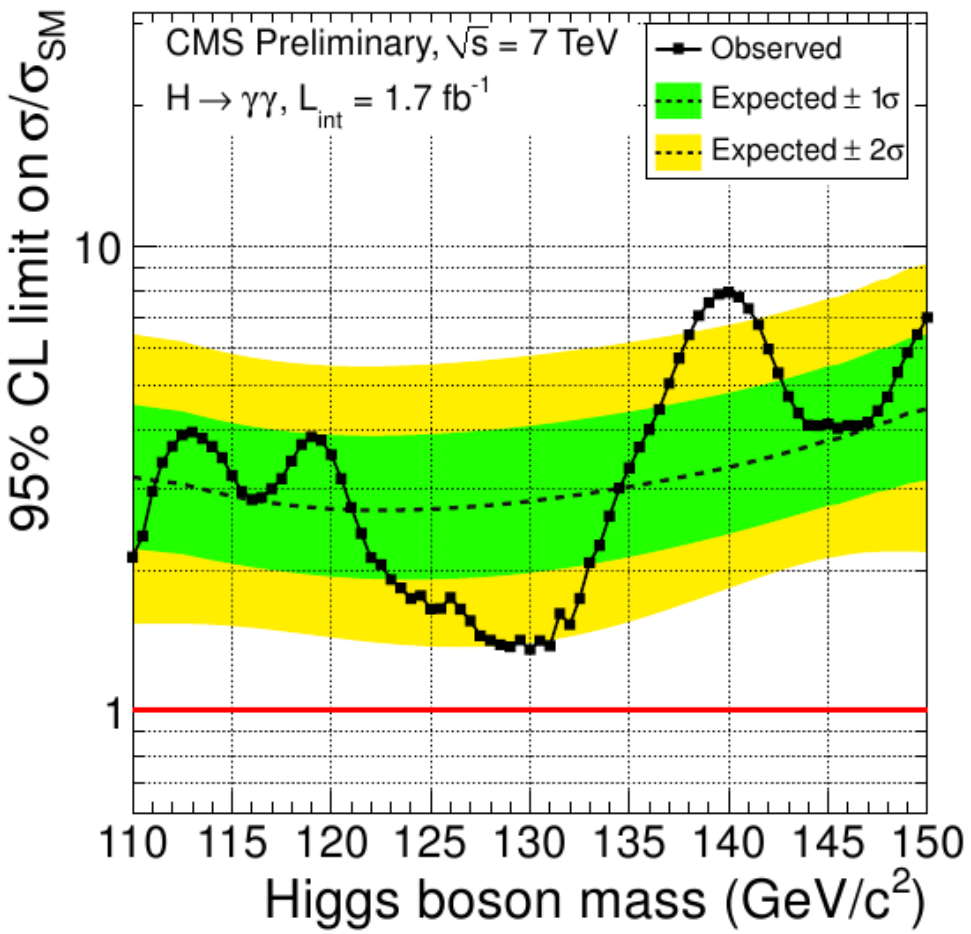
- The standard fit value for MH has moved by +12 GeV as a consequence of the new $\Delta\alpha^{(5)}_{had}(M_Z^2)$
- Using the preliminary result $\Delta\alpha^{(5)}_{had}(M_Z^2)$ of K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, 1105.3149, we find

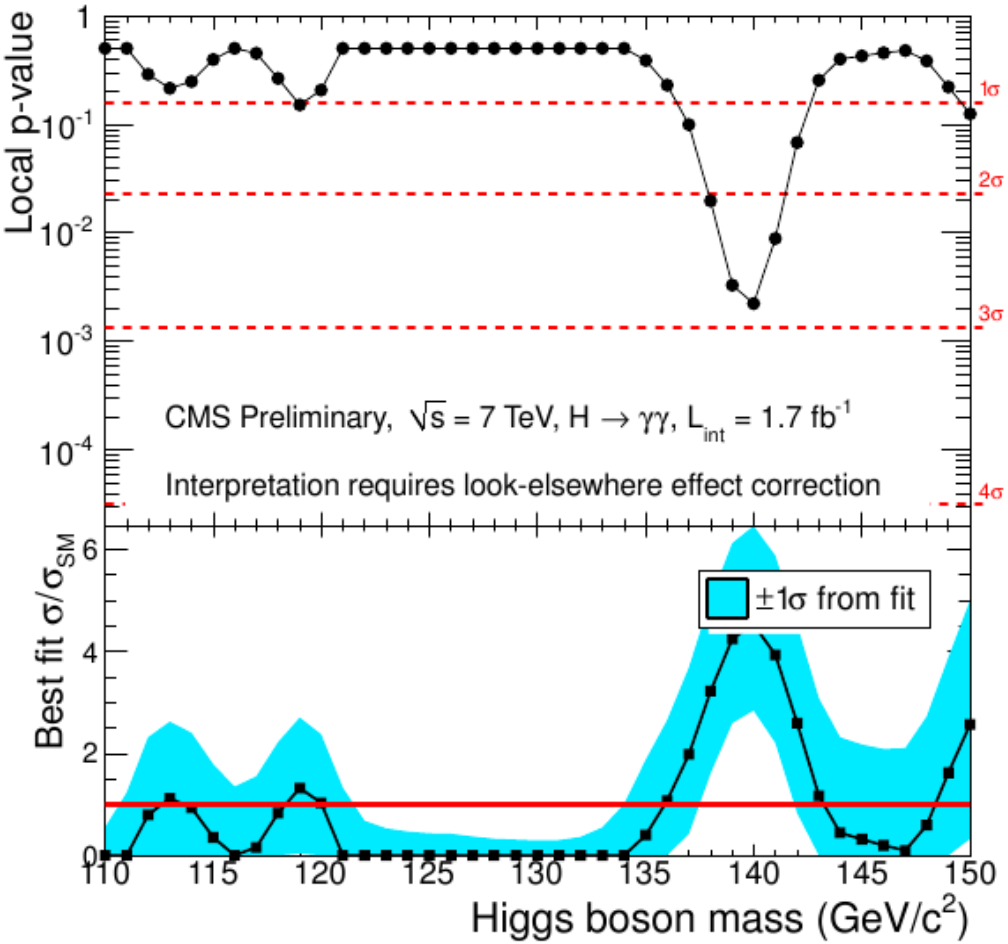
$$M_H = 88\,^{+29}_{-23}\ \text{GeV}$$



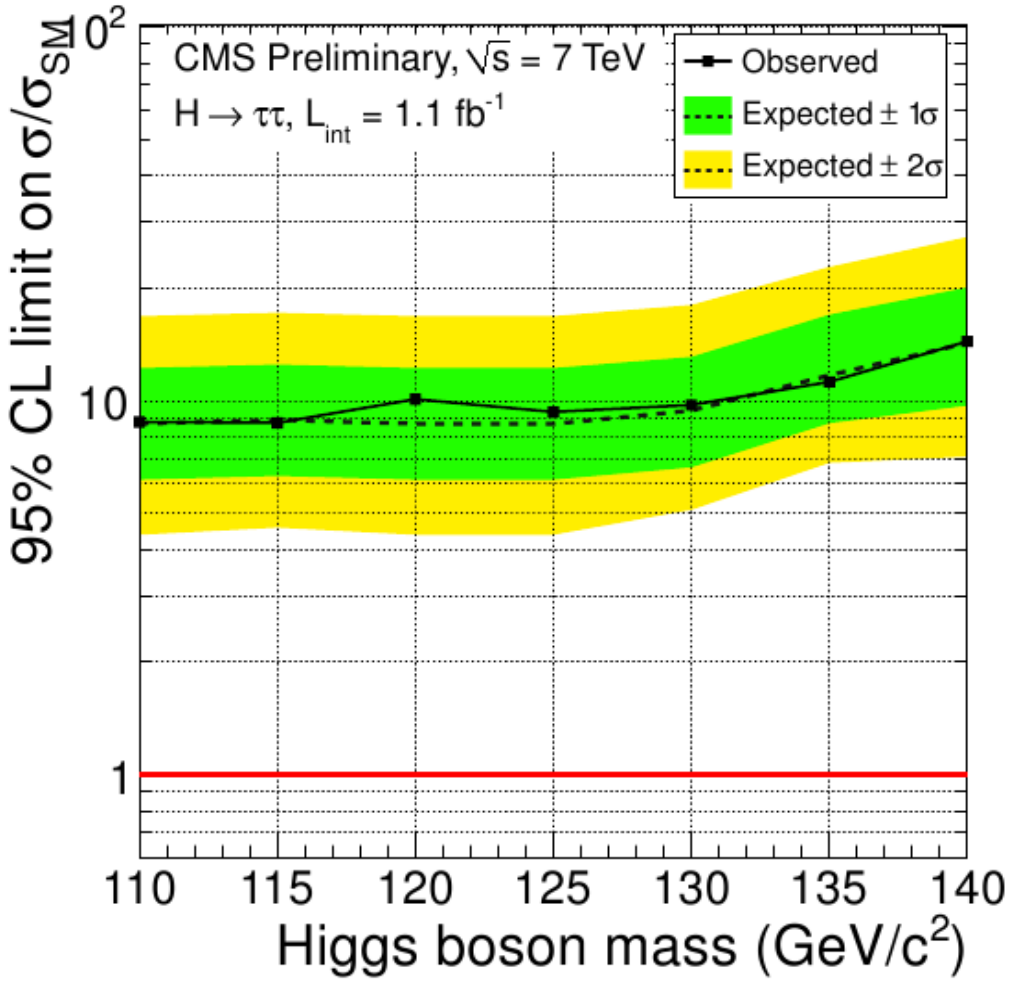
# Results in H→γγ

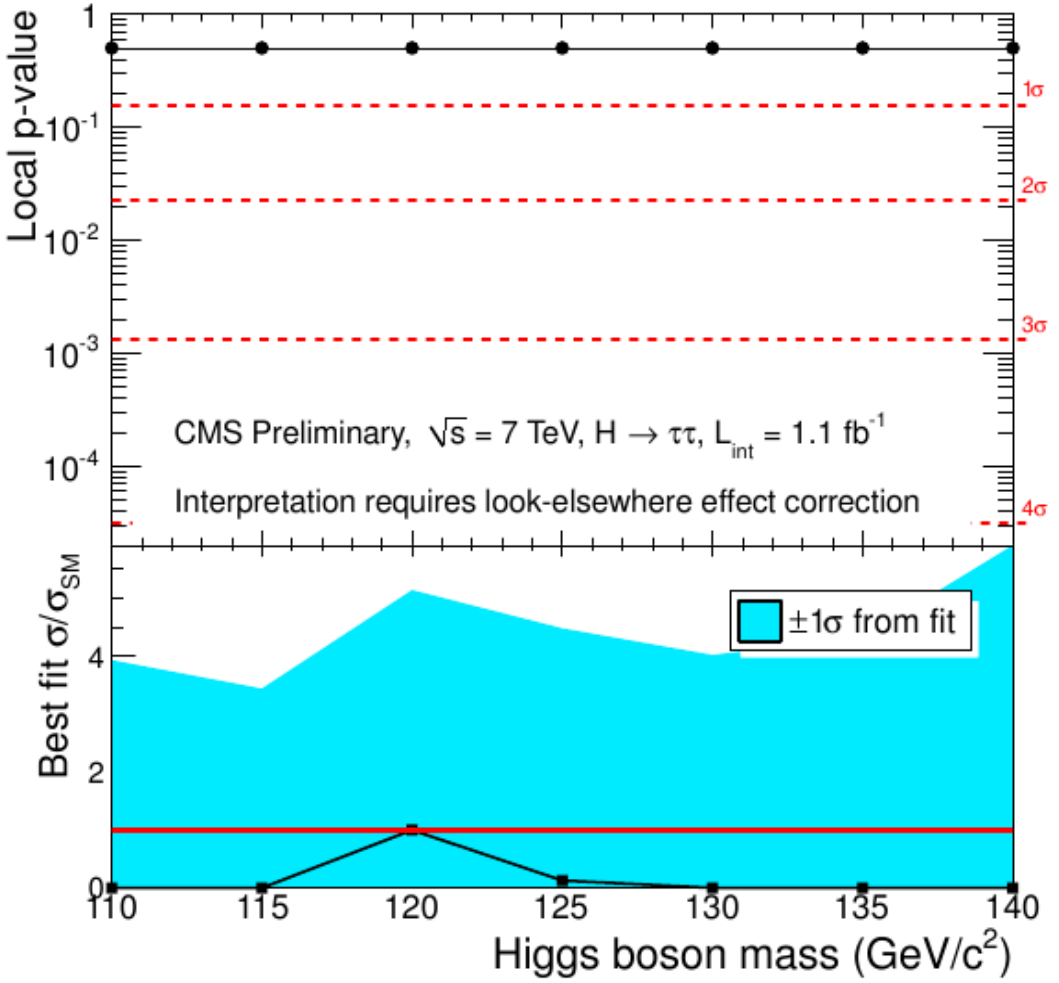



- With 1.7 fb$^{-1}$ exclusion limit in this channel is on the level of 2-4·$\sigma_{SM}$
- Local data excess near 140 GeV of 2.8σ is reduced to 1.7σ with LEE correction

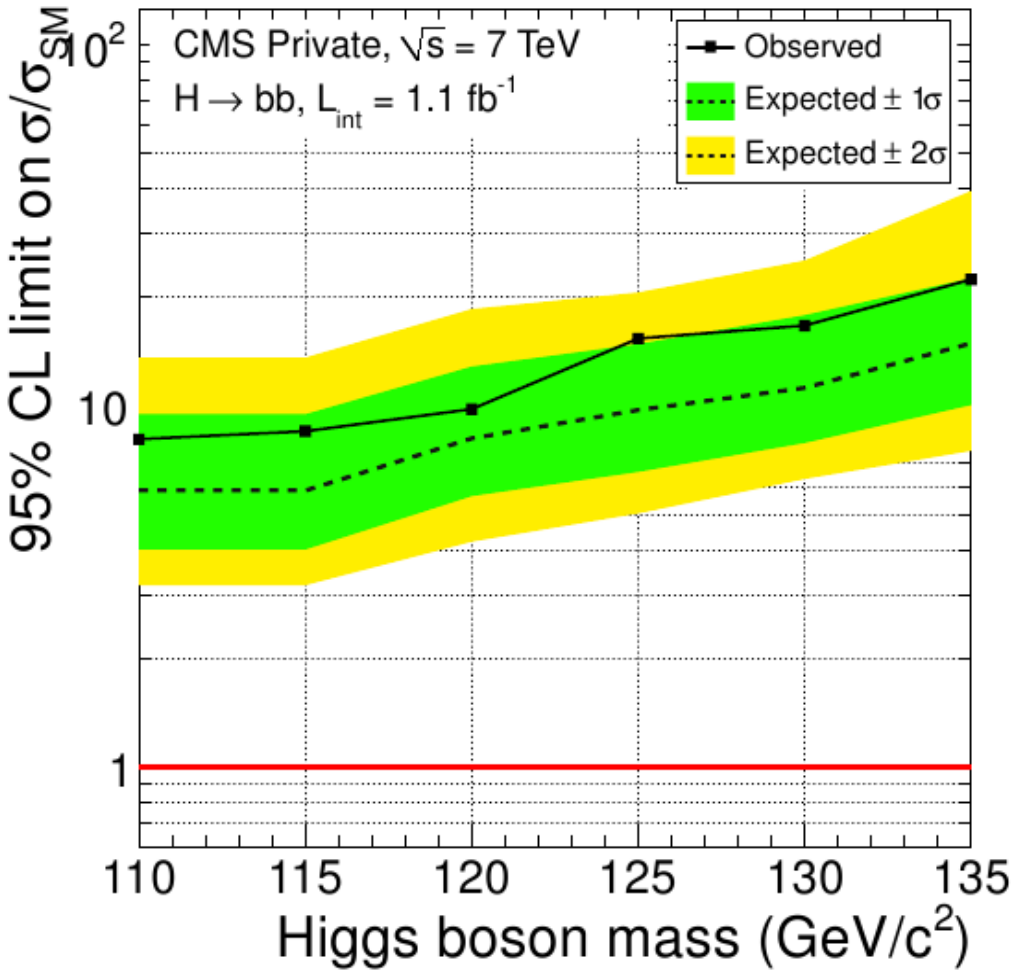
# Results in H→ττ

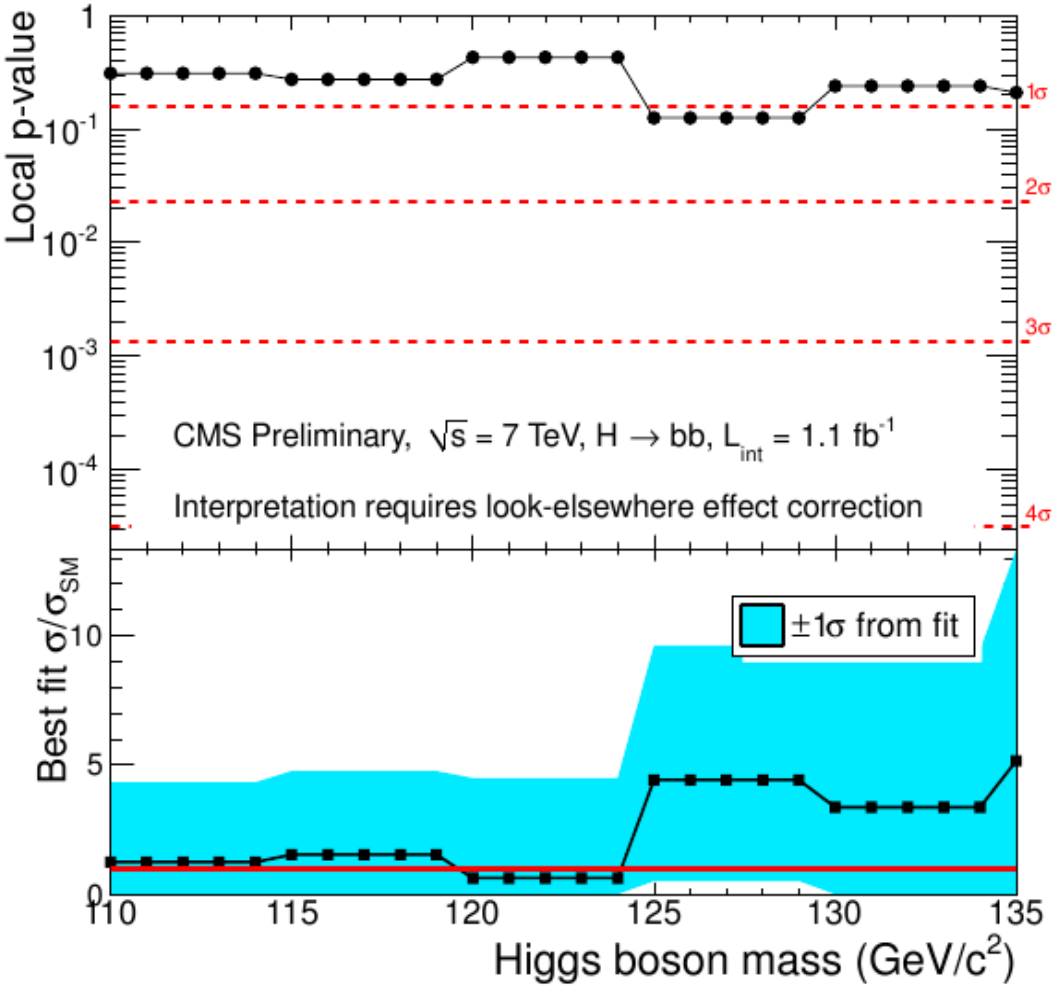



- With 1.1 $fb^{-1}$ exclusion limit in this channel is on the level of $10 \cdot \sigma_{SM}$
- No data excess above expected background is observed

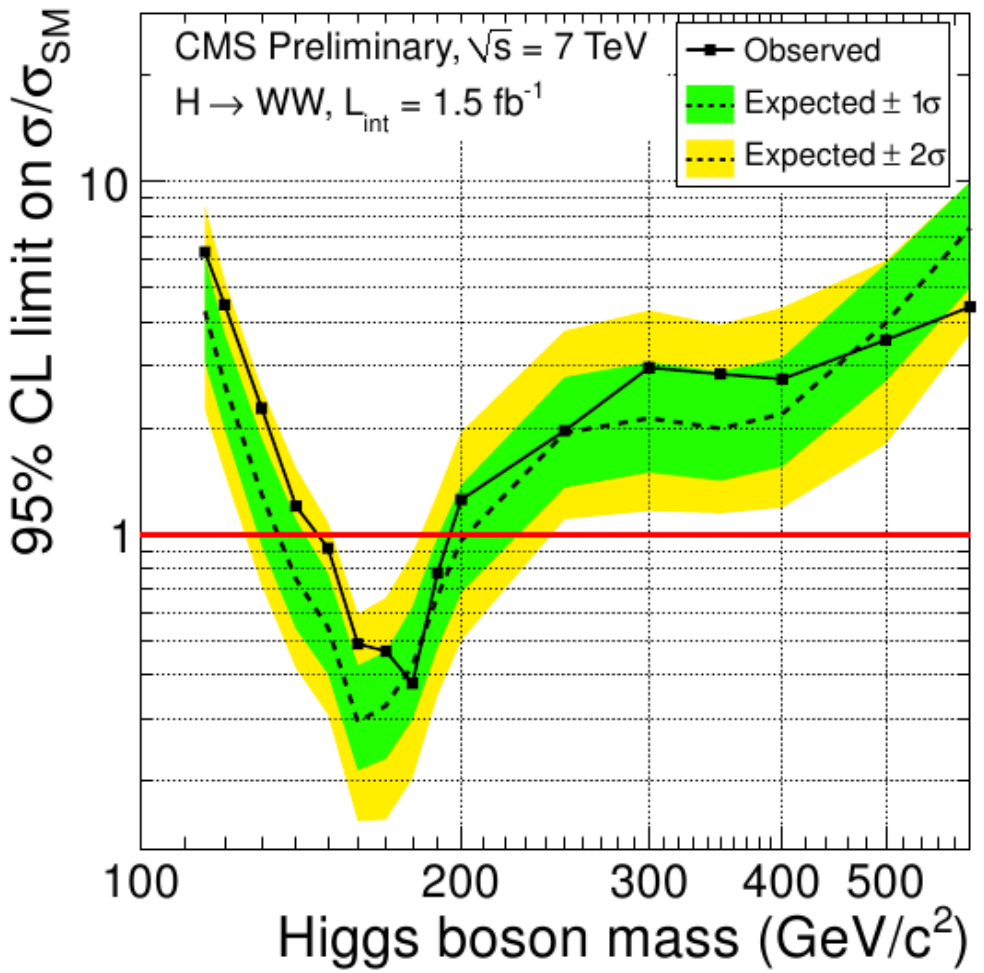
# Results in H→bb

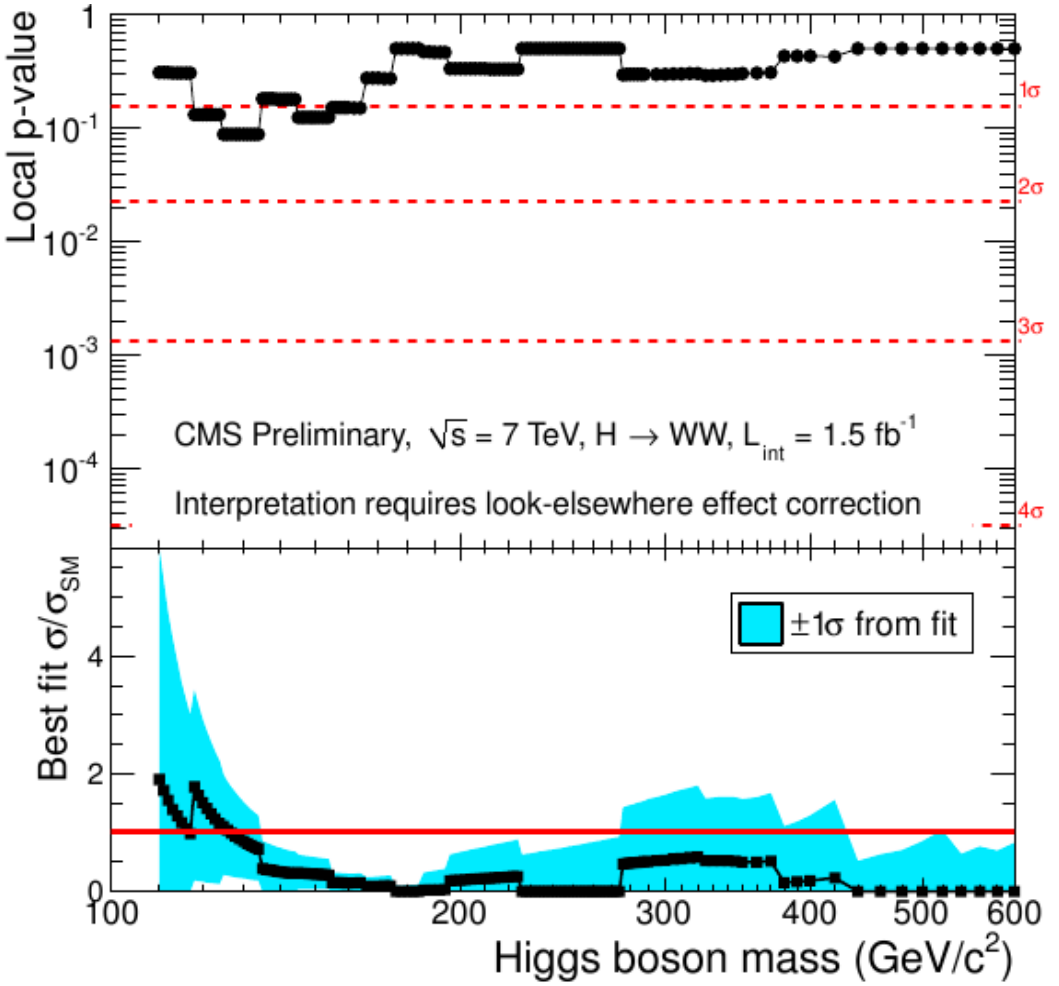



- With 1.1 fb$^{-1}$ exclusion limit in this channel is on the level of 10-20·$\sigma_{SM}$
- No significant data excess above expected background is observed

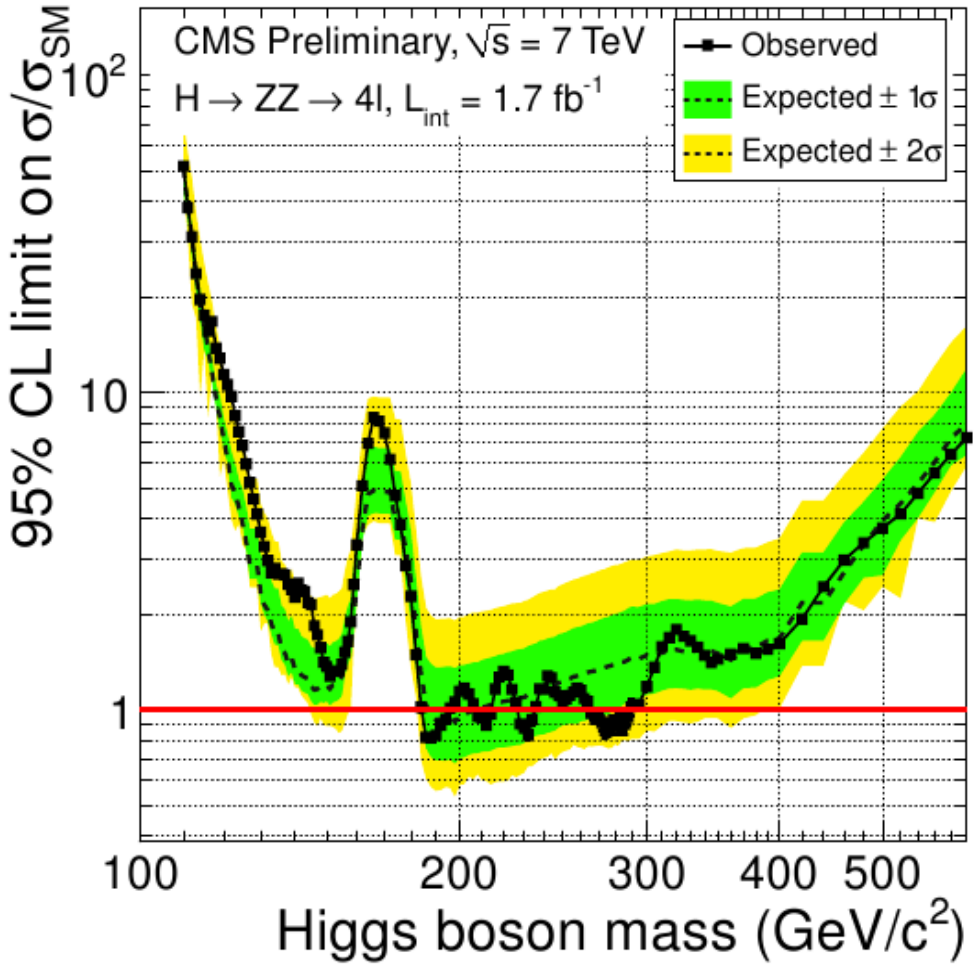
# Results in H→WW→2l2ν

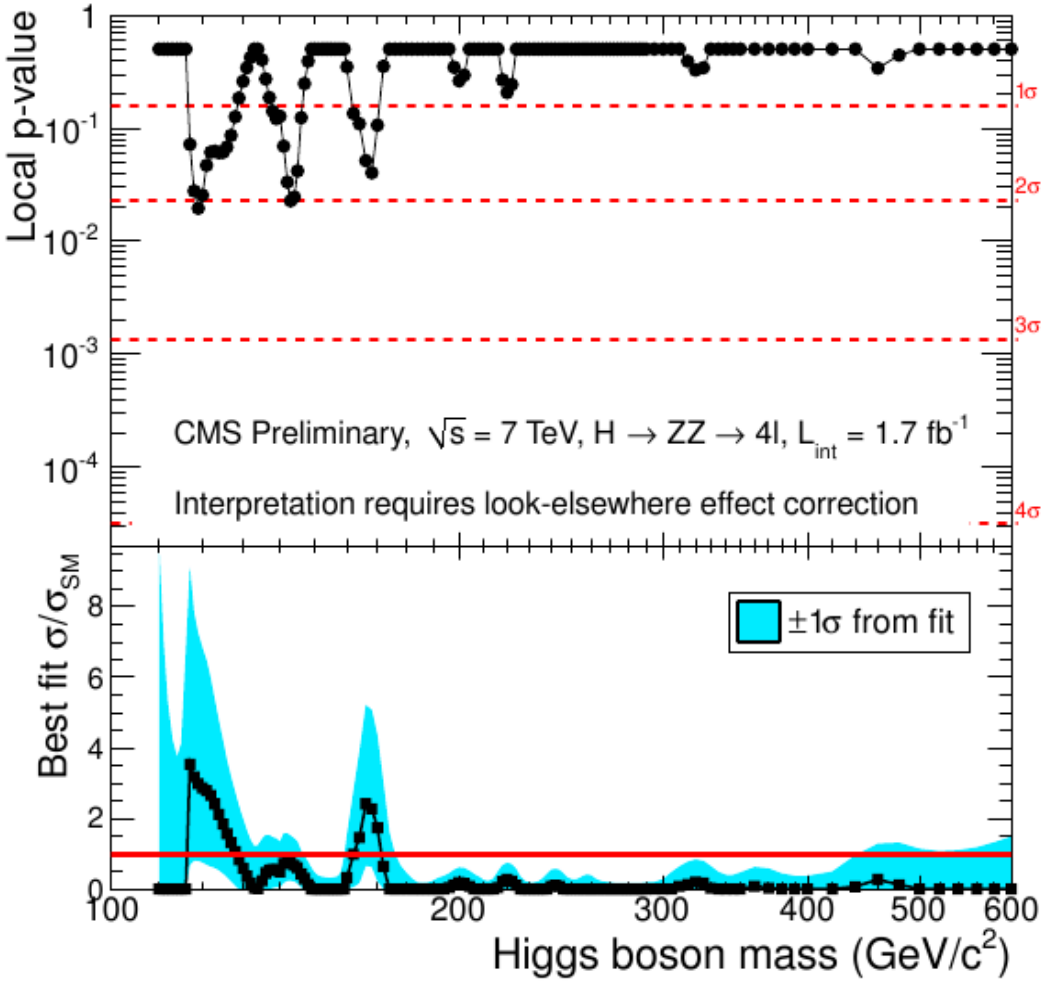



- With 1.5 $fb^{-1}$ exclusion limit in this channel is on the level of 0.8-8·$\sigma_{SM}$
- No significant data excess above expected background is observed

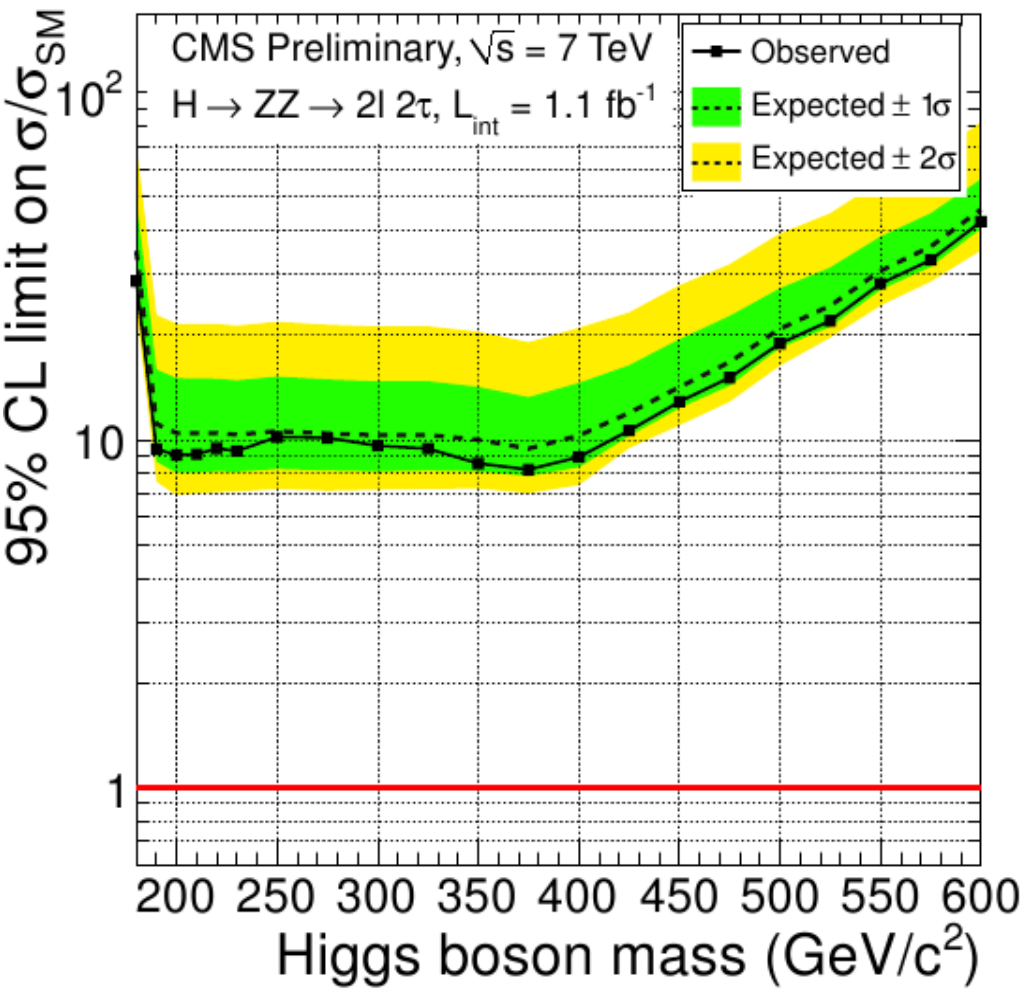
# Results in H→ZZ(*)→4l

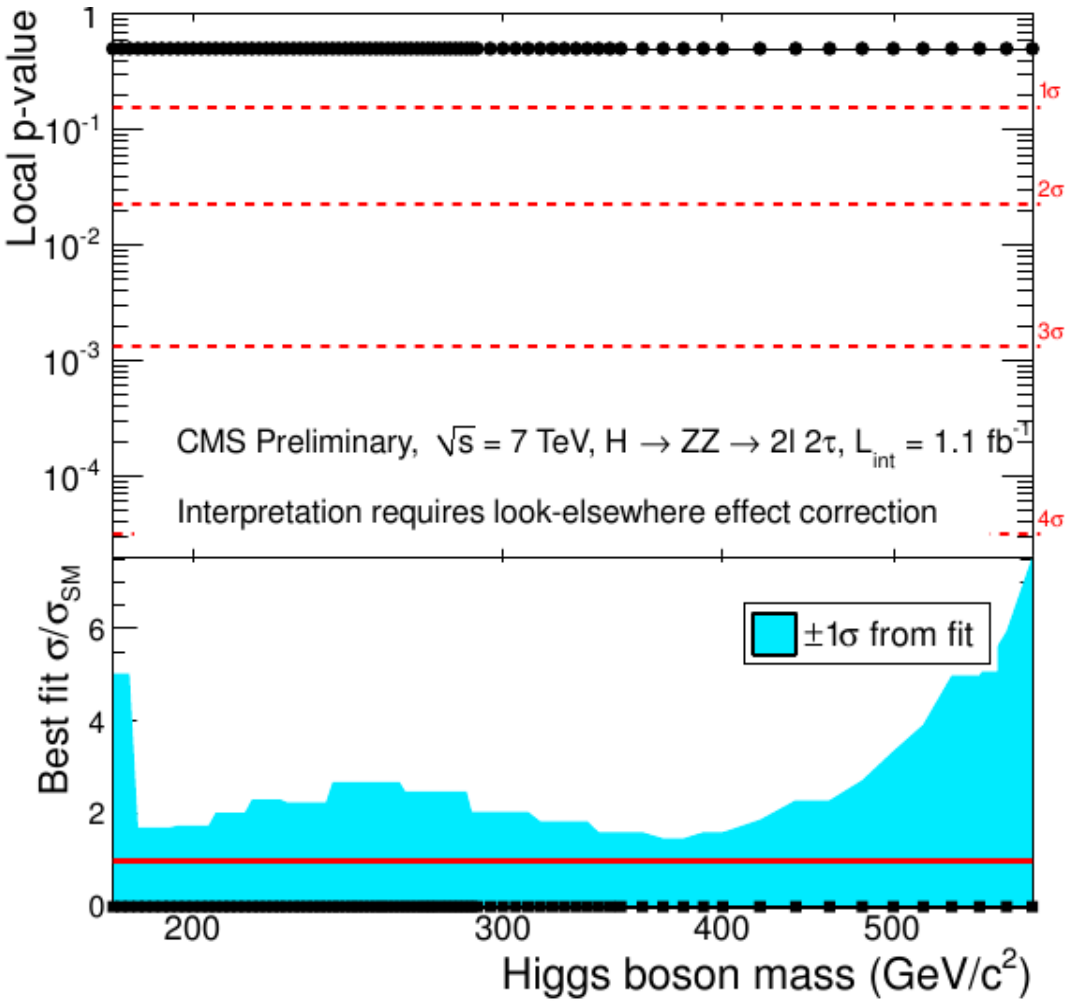



- With 1.7 fb$^{-1}$ exclusion limit in this channel is on the level of 0.9-10·$\sigma_{SM}$
- Local data excesses of order ~2σ are reduced to ~0.25σ (p=0.4) with LEE correction

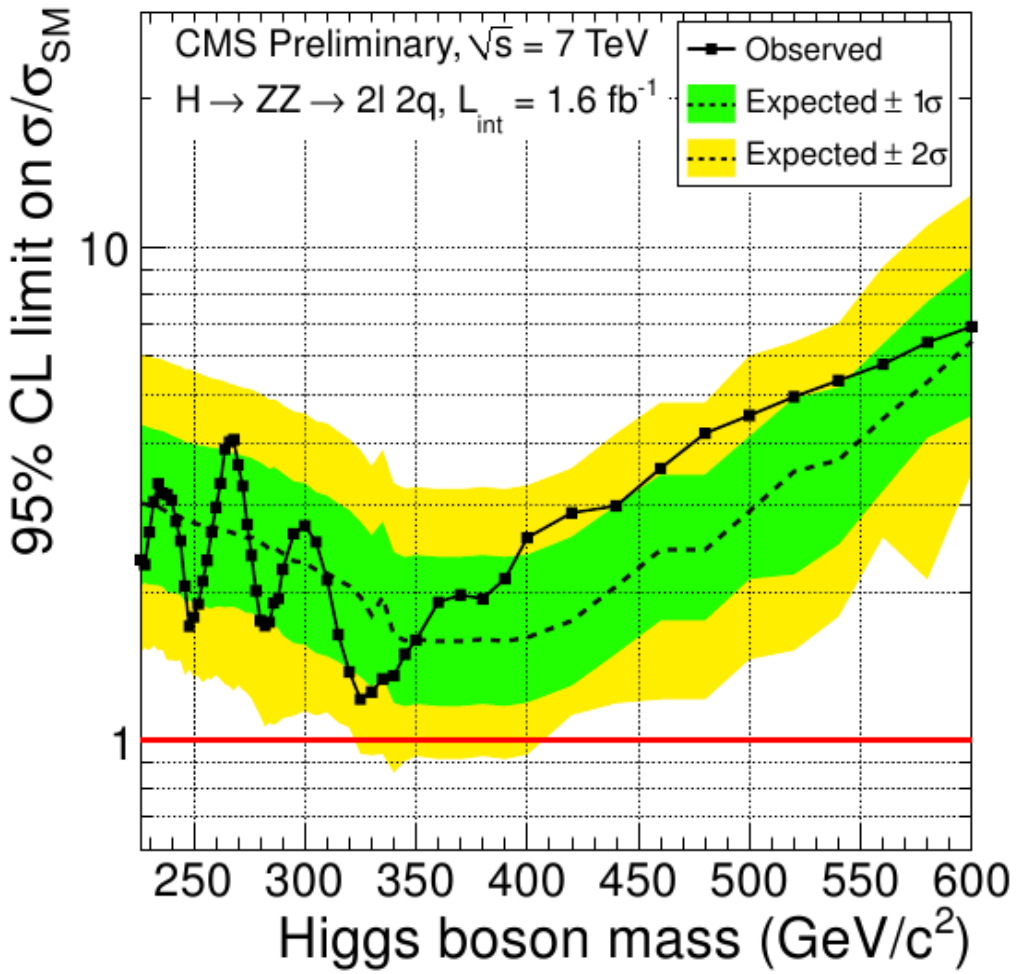
# Results in H→ZZ(*)→2l2τ

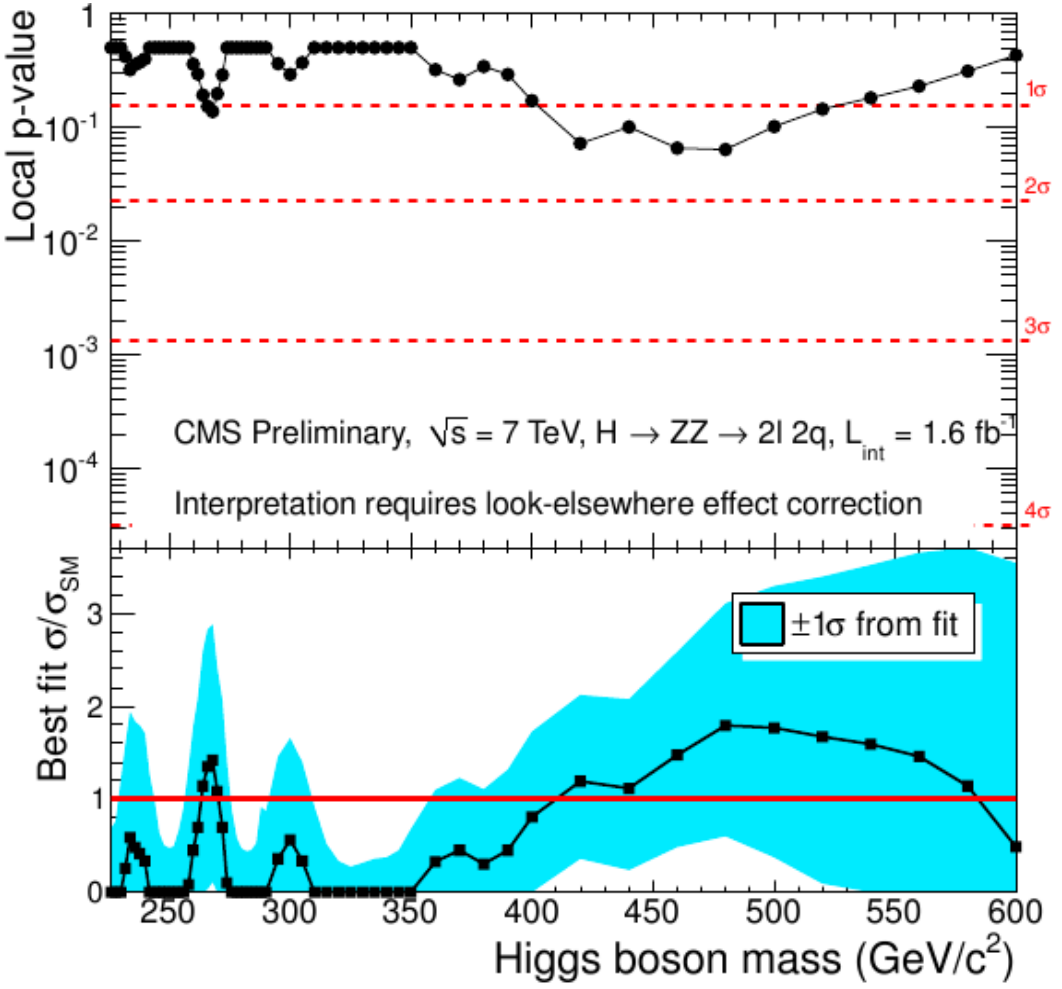



- With 1.1 fb$^{-1}$ exclusion limit in this channel is on the level of 10-20·$\sigma_{SM}$
- No data excess above expected background is observed

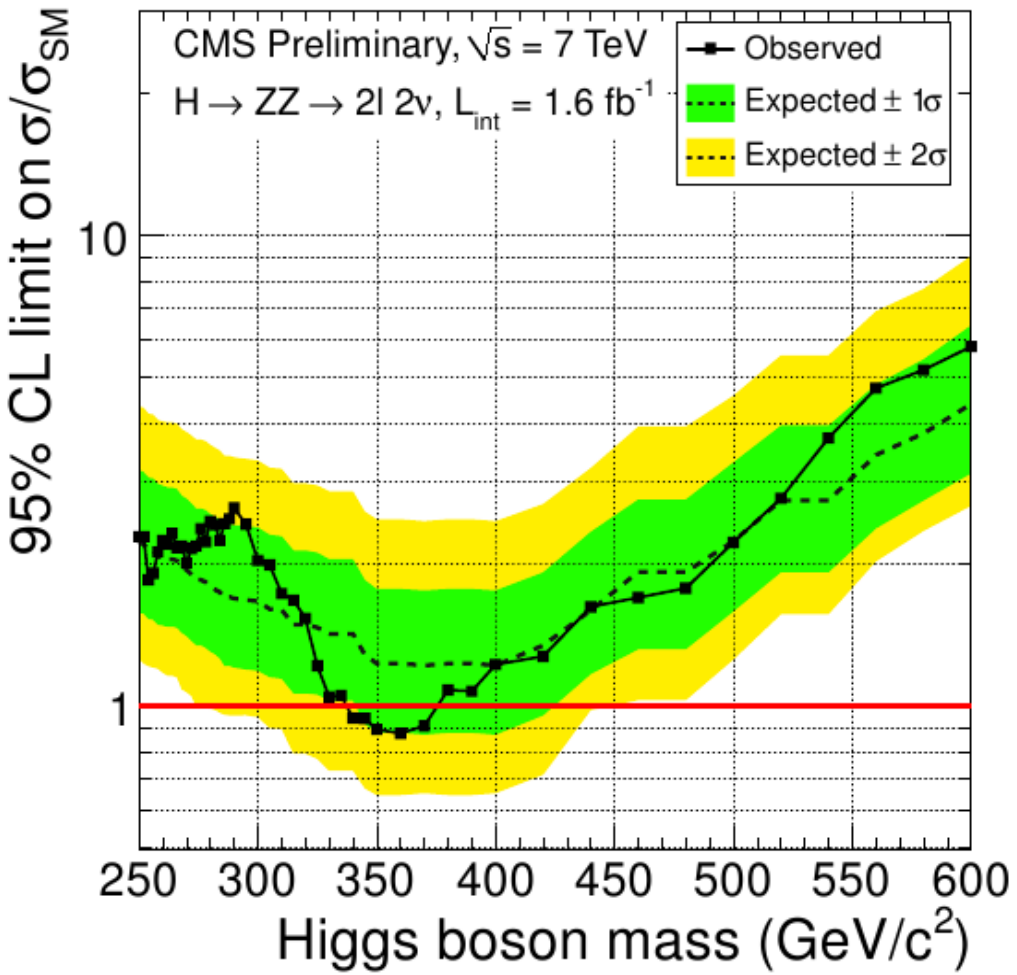
# H→ZZ(*)→2l2q

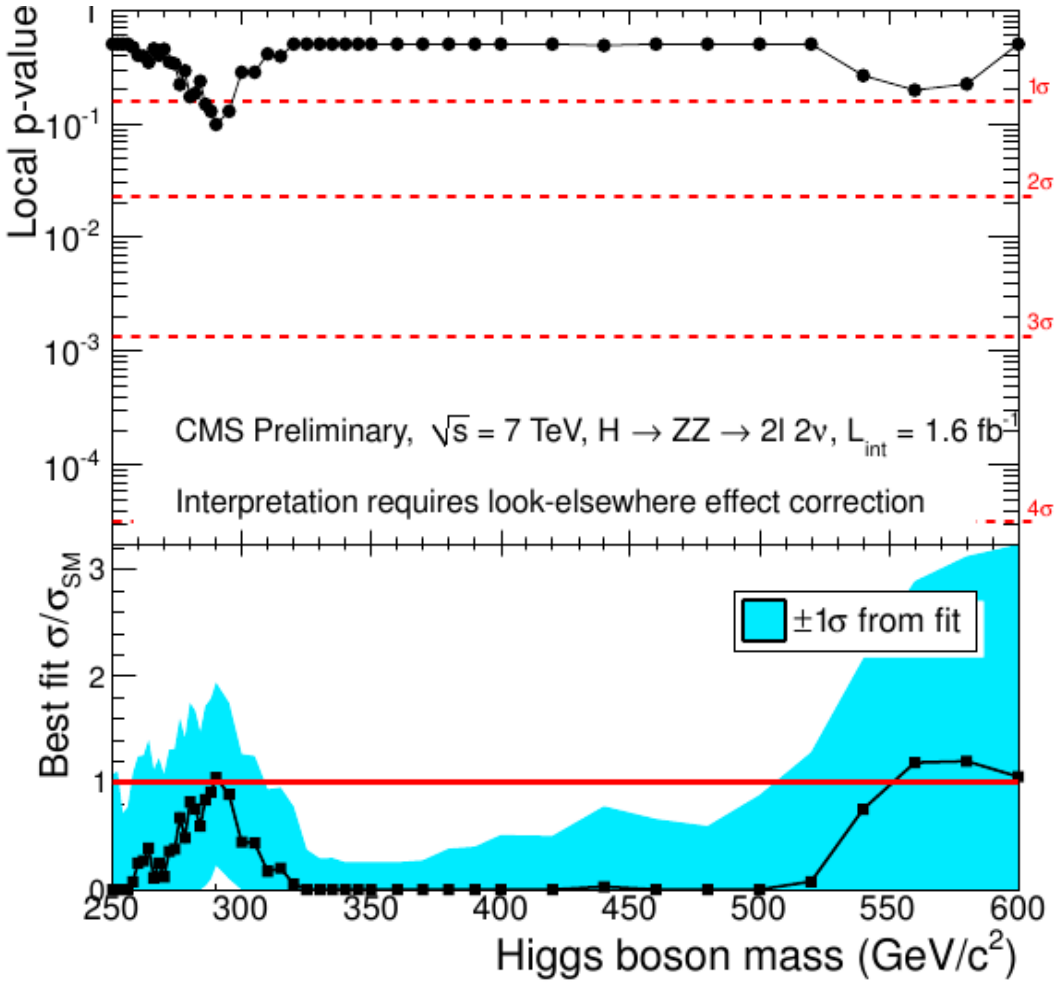



- With 1.6 fb$^{-1}$ exclusion limit in this channel is on the level of 2-8·$\sigma_{SM}$
- No significant data excess above expected background is observed

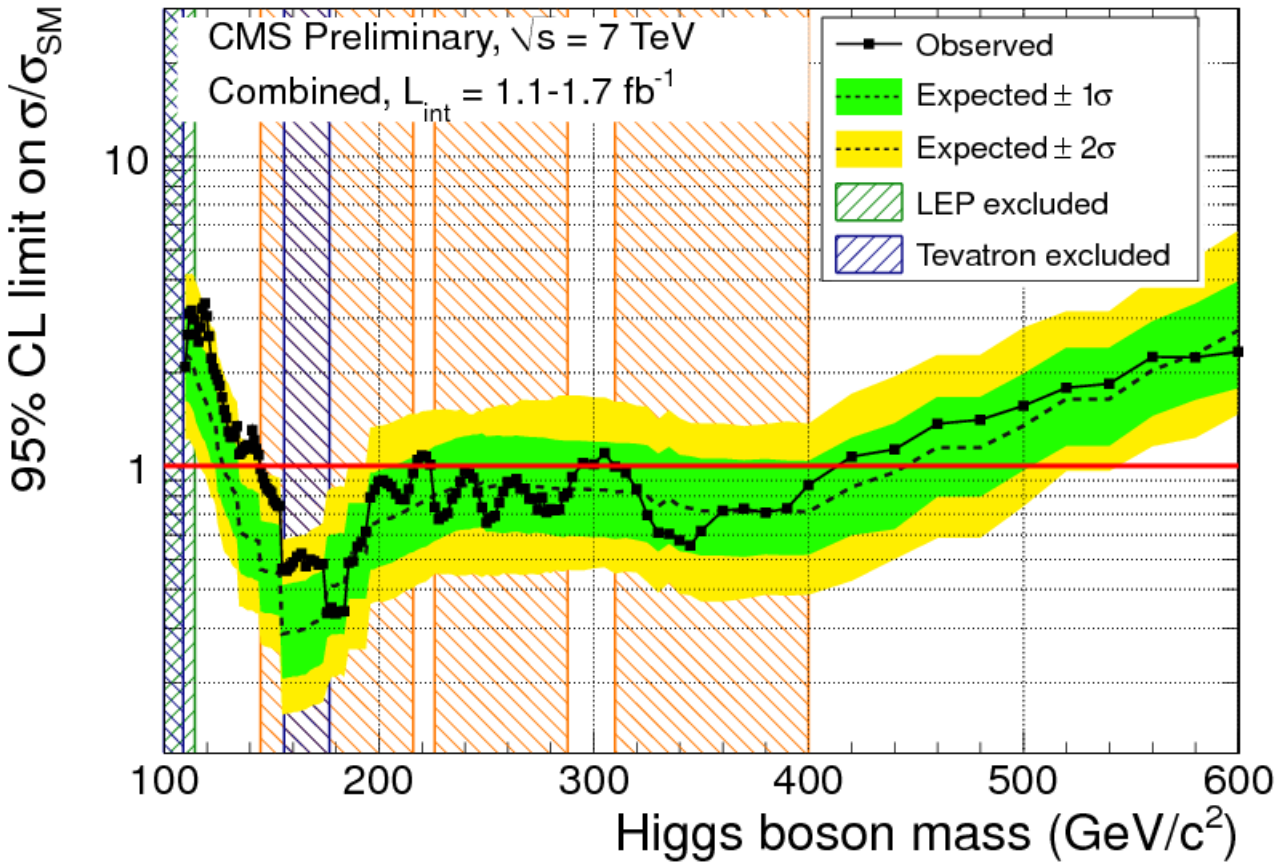
# H→ZZ(*)→2l2υ



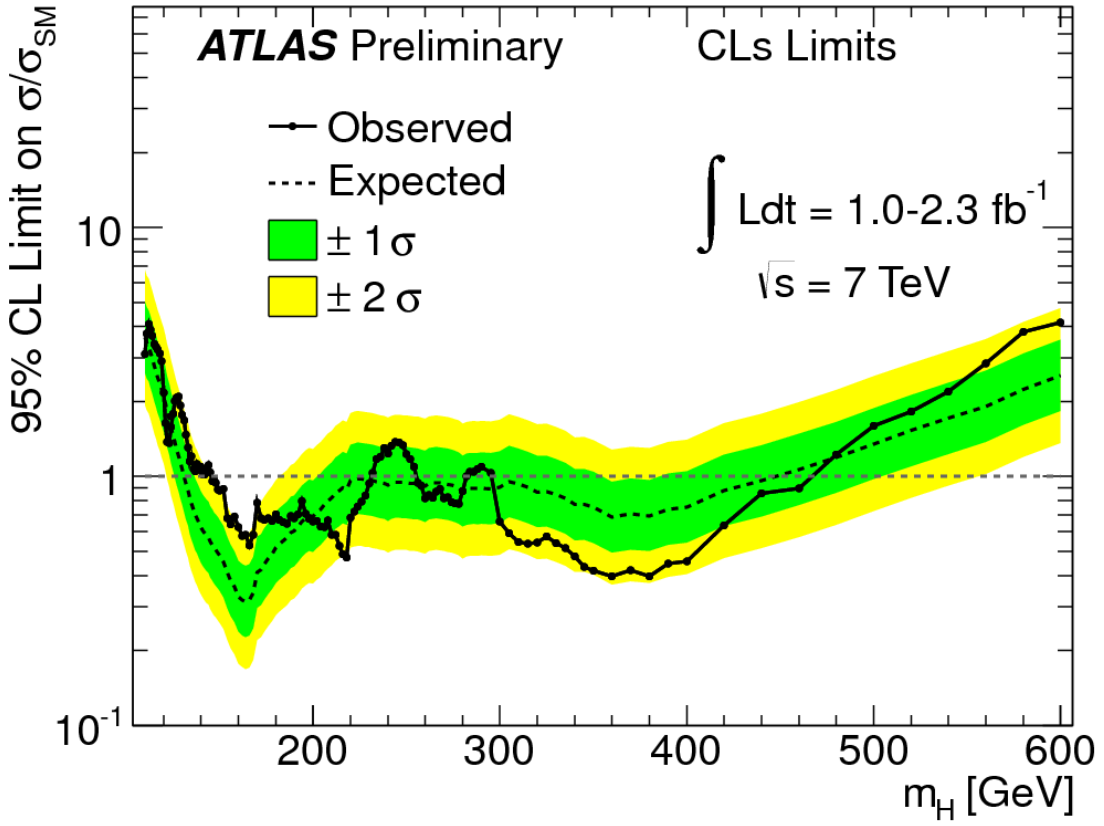

- With 1.6 fb$^{-1}$ exclusion limit in this channel is on the level of 0.9-9·$\sigma_{SM}$
- No significant data excess above expected background is observed

# SM Higgs exclusion limits



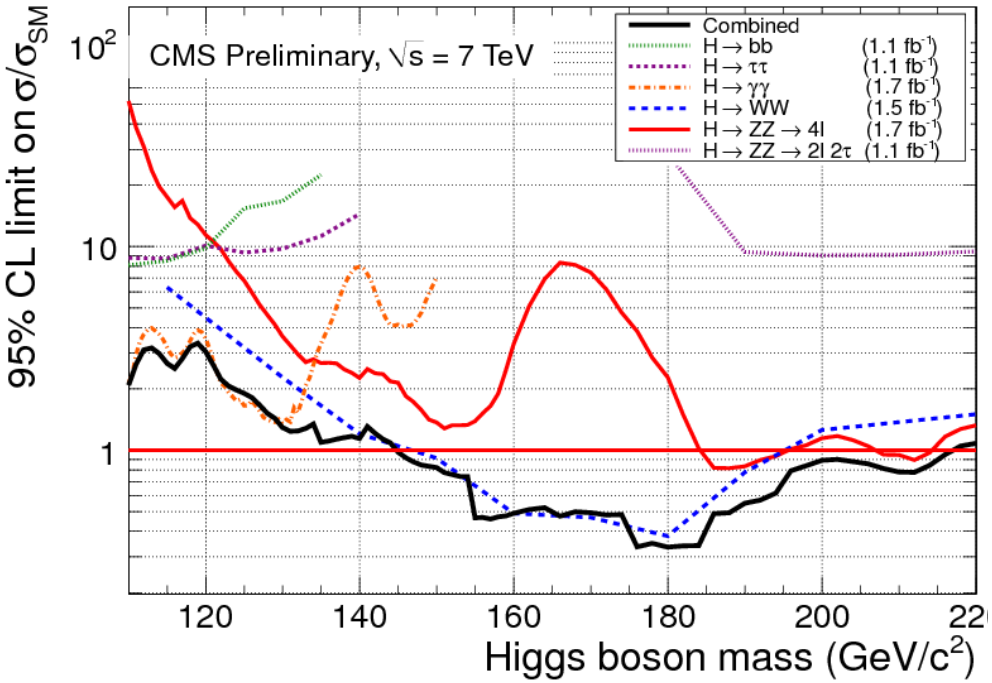

•95% CL exclusion range:**145 – 216, 226 – 288 and 310 – 400 GeV/c²**

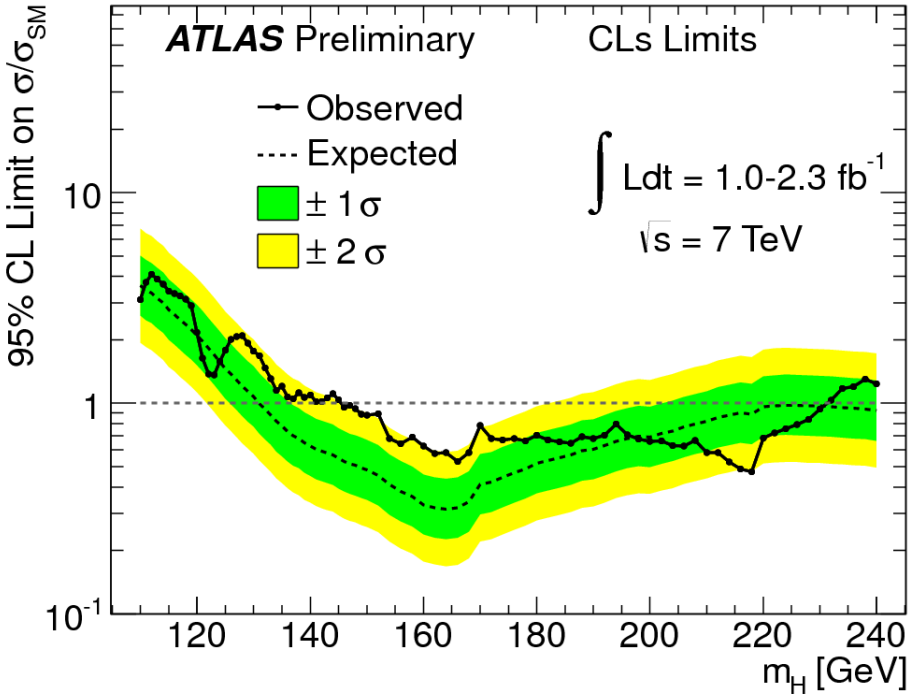
# SM Higgs exclusion limits




•95% CL exclusion range:**146 – 230, 256 – 282 and 296 – 459 GeV/c²**

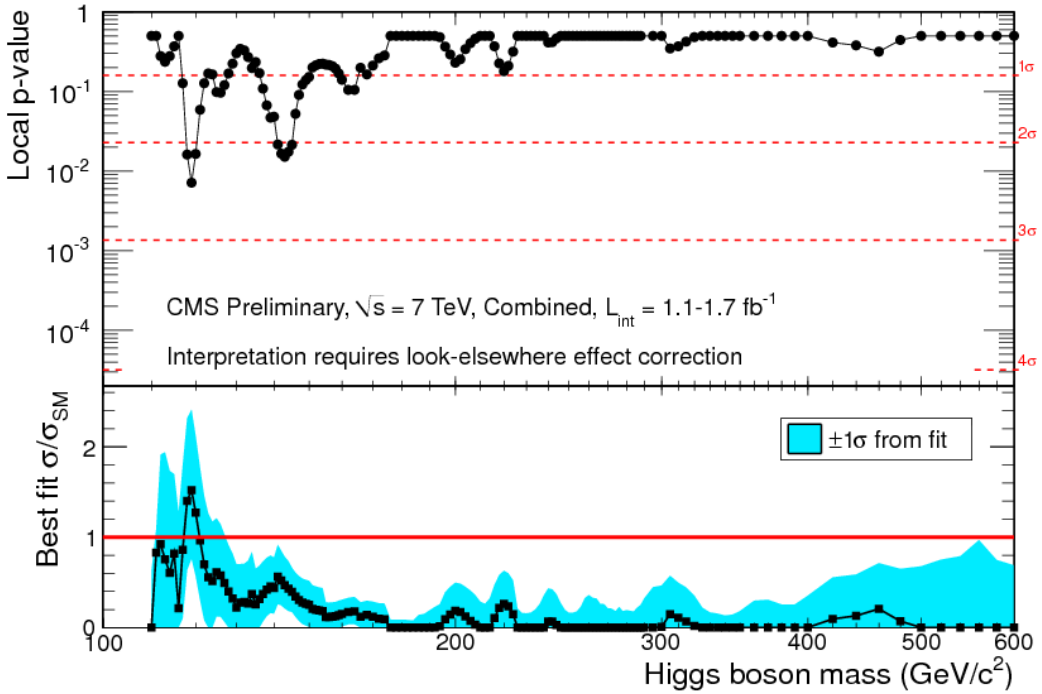
# The low mass region

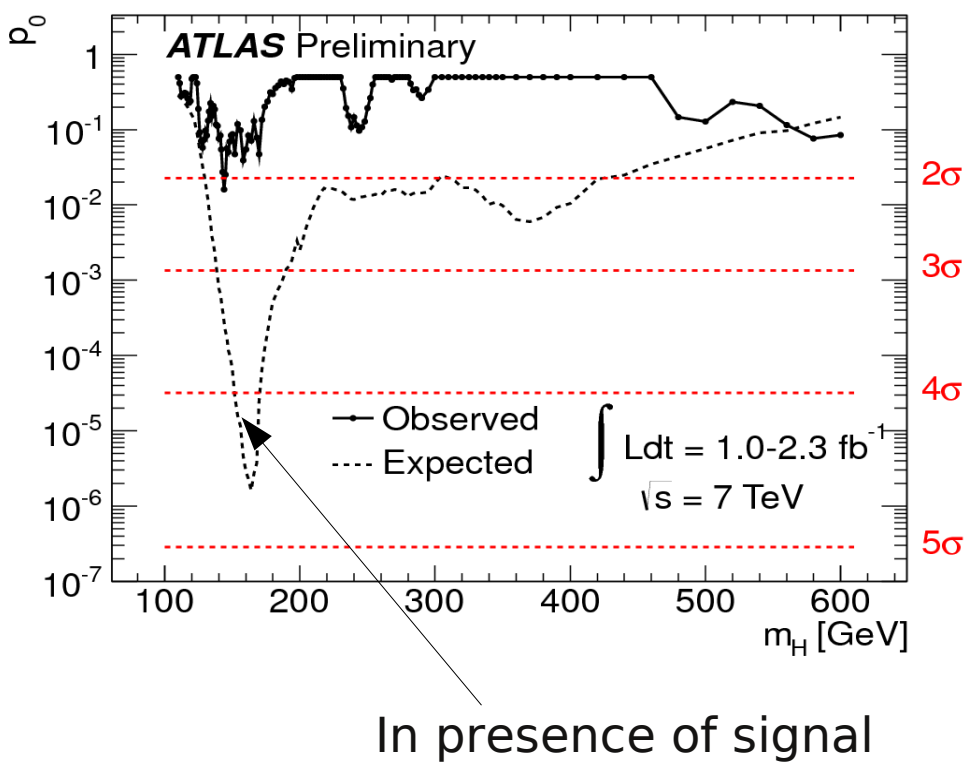



- In low mass region main contribution comes from H→γγ,
- Then H→WW→2l2υ,H→ττ, H→bb,and H→ZZ→4l
- There are many improvements in analyses – at the end of 2011 we can expect better result than what we could get from more data analysed

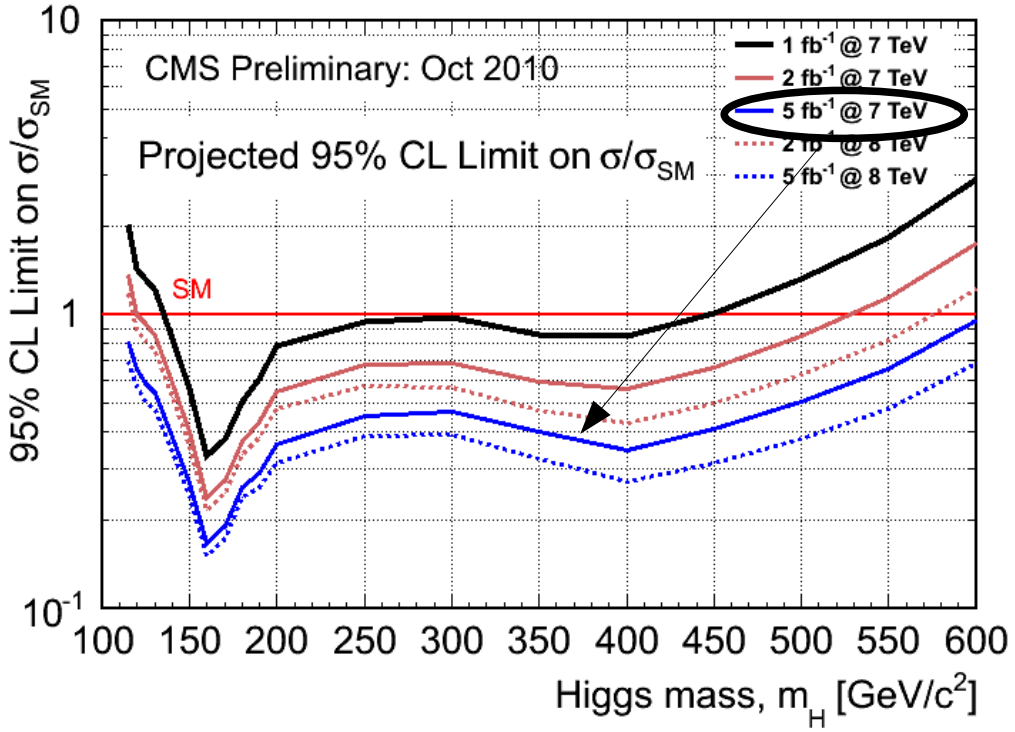
# Excess analysis

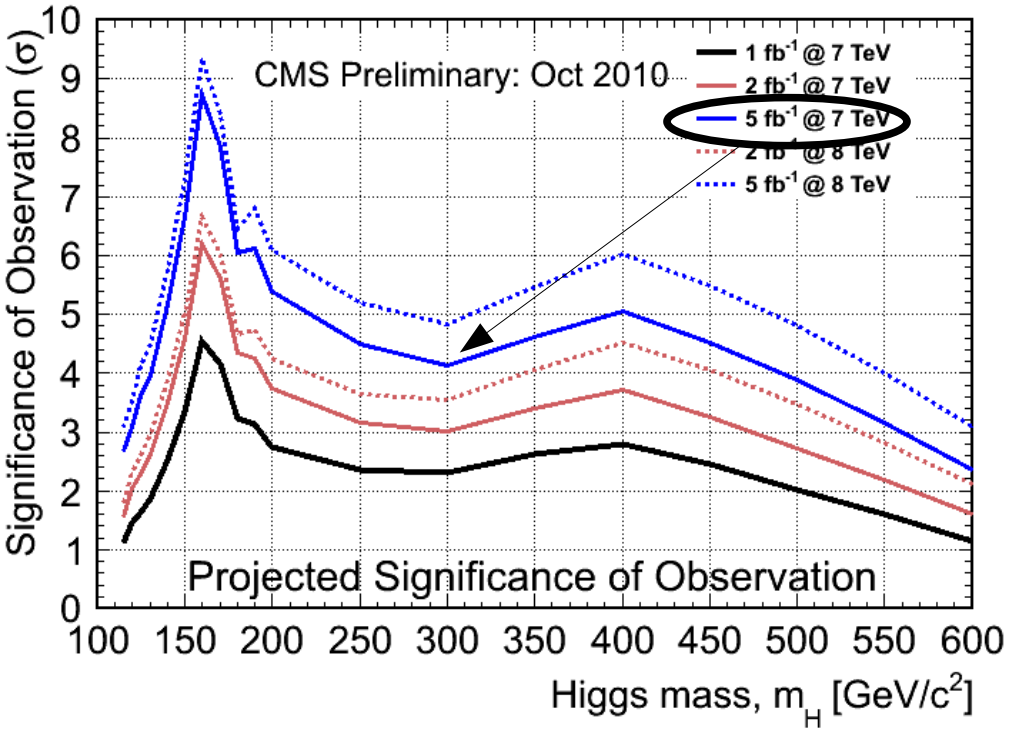



- When looking at such plots always remember about the LEE:
  **2.3σ visible on the plot is reduced to 0.25σ with LEE**
  (trial factor for CMS combination is O(40))
- Both experiments observe some “bumps” at low masses, **but those are not statistically significant yet.**

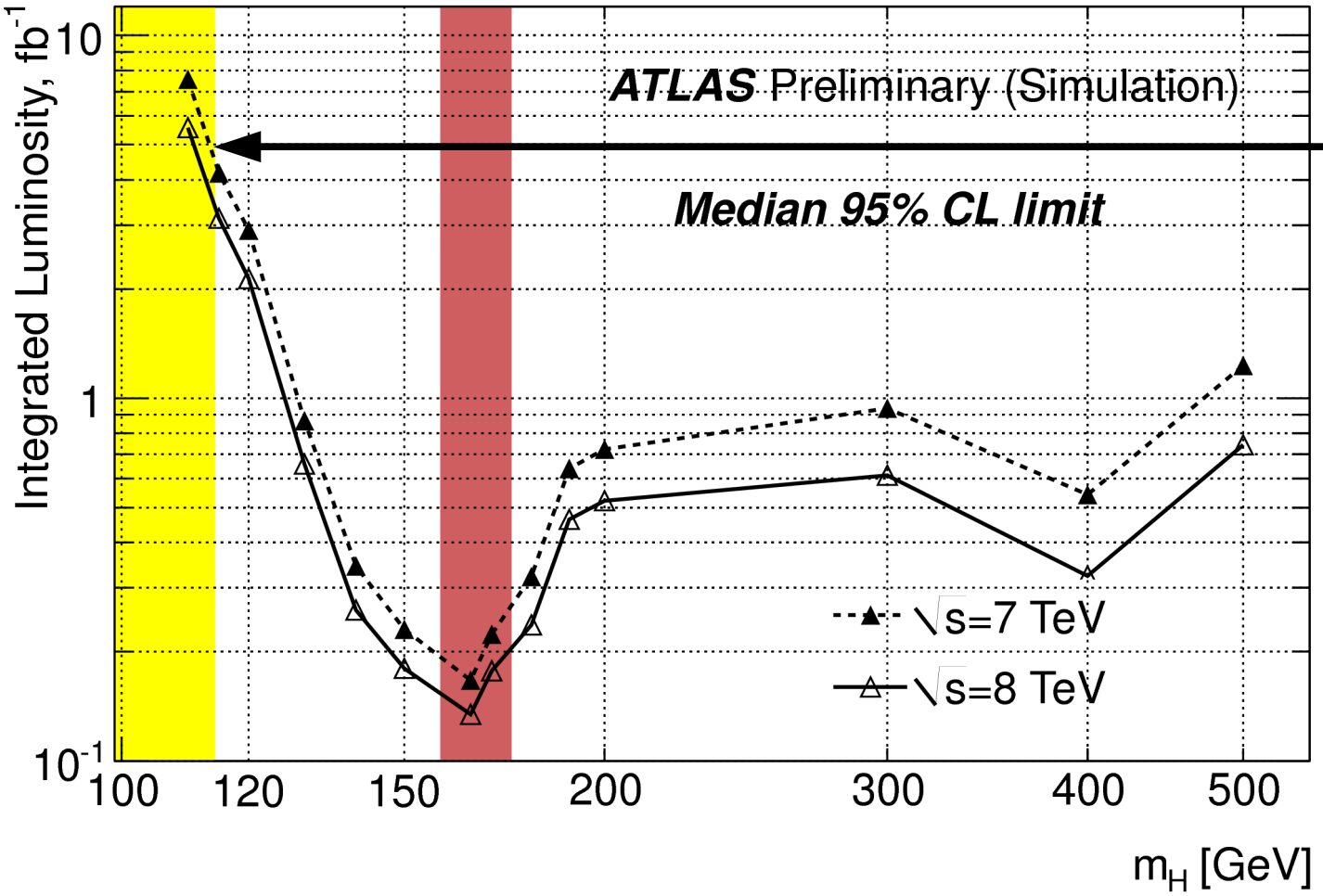
# Prospects with the whole 2011 data




- In October 2010 CMS produced expectations for exclusion power bases on Monte Carlo studies from 2006
- For 1 fb$^{-1}$ the projected exclusion range was **$145<m_H<300$ GeV/c$^2$**, with improved analysis methods in 2011 we estimated it to be **$127<m_H<420$ GeV/c$^2$**
- with 5 fb$^{-1}$ exclusion is expected in range **$114<m_H<600$ GeV/c$^2$**
- with 5 fb$^{-1}$ discovery is expected in range **$145<m_H<230$ GeV/c$^2$**

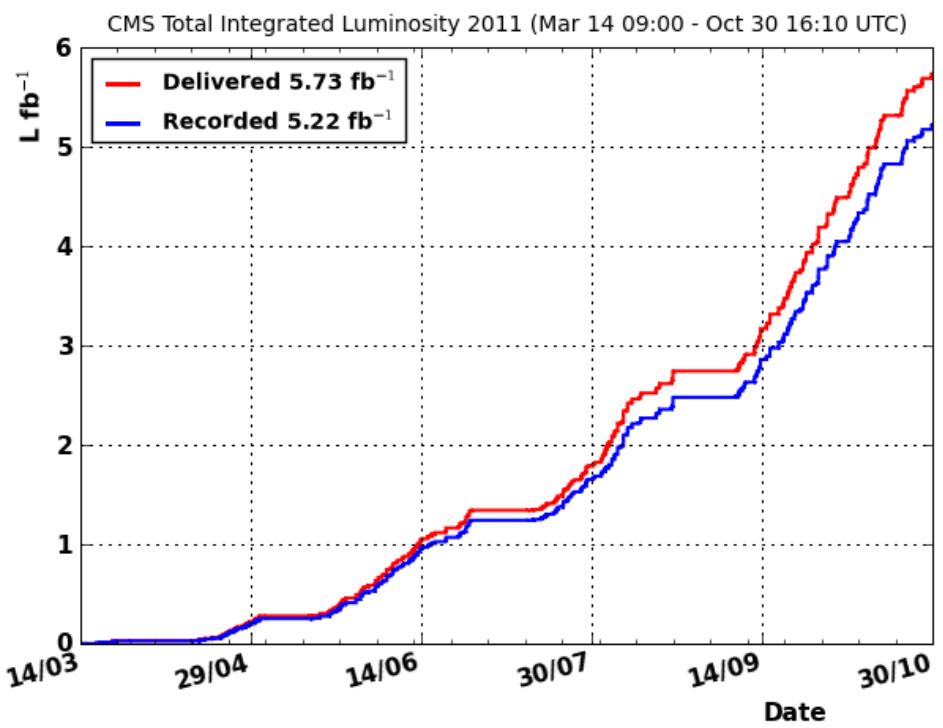
# How long do we have to wait

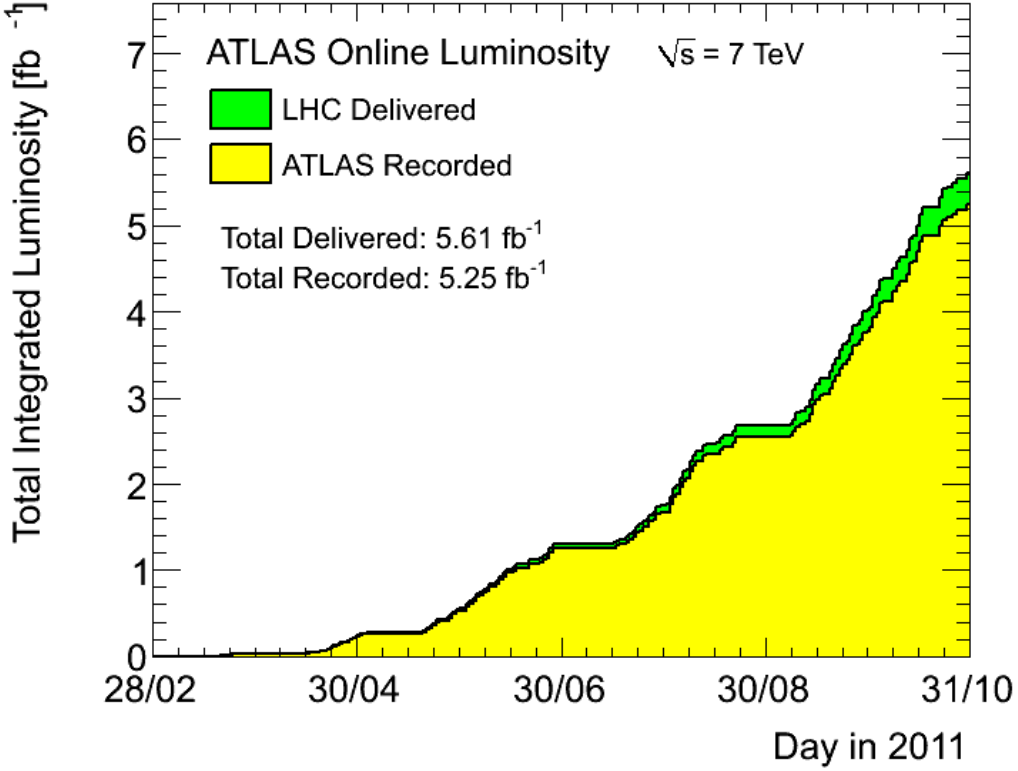



5 fb$^{-1}$

- The luminosity required, as a function of $m_H$, to give a median exclusion significance of 95% CL for a SM Higgs at = 7 or 8 TeV.

# Luminosity status




- LHC proton run in 2011 is over now, the machine has delivered over 5 fb$^{-1}$ of data

# Conclusions

- **The CMS experiment conducted Higgs boson searches in number of channels with upto 1.7 $fb^{-1}$ of data**
- **No signal was observed in any of those, providing 95% CL exclusion limits in ranges: 145-216, 226-288 and 310-340 GeV**
- **In 2011 LHC has delivered 5 $fb^{-1}$ of data**
- **With 5 $fb^{-1}$, and a bit of luck we could be able to exclude the SM-like Higgs boson in the interesting mass range**

# References

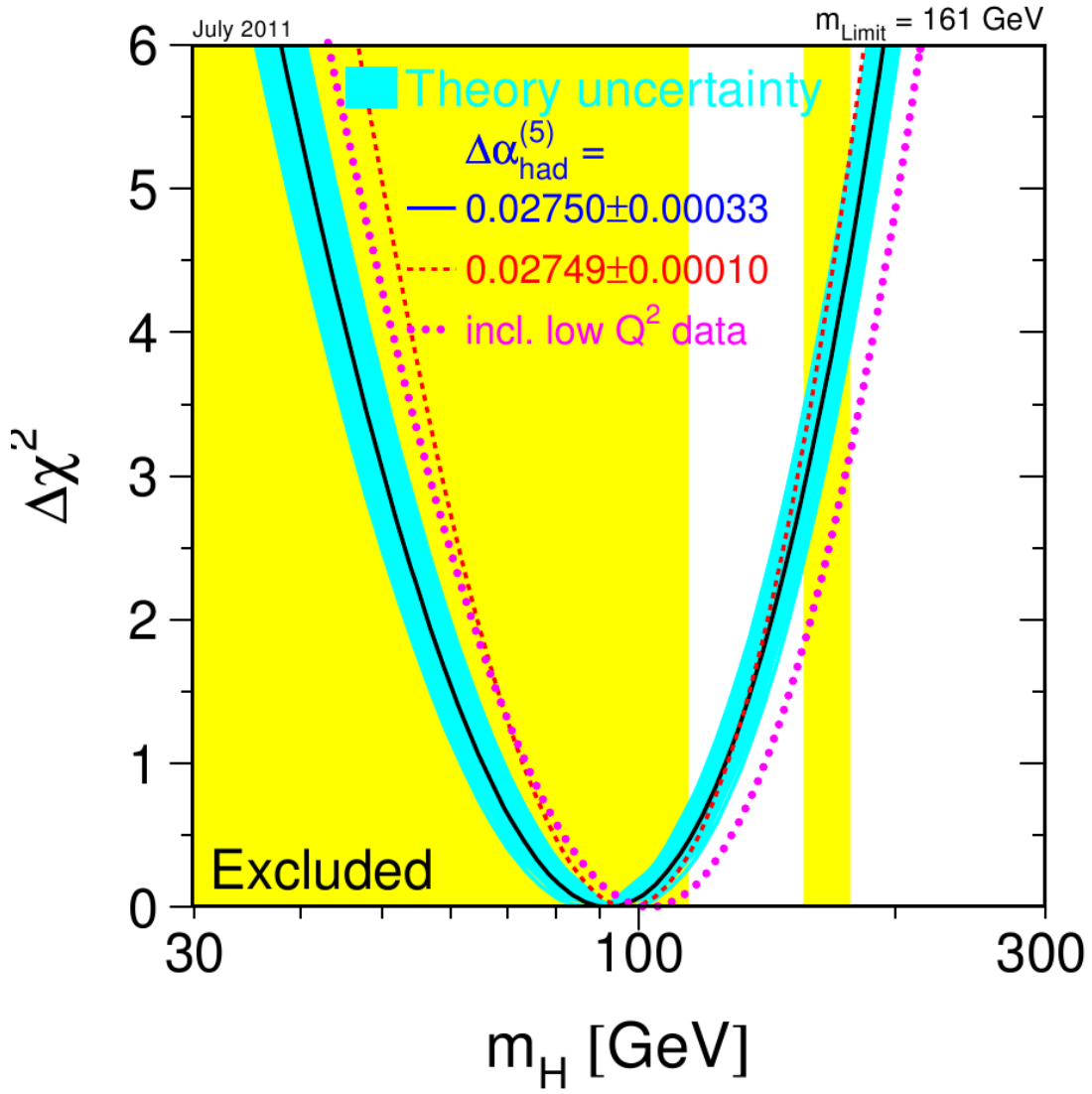
- 14 TeV results: CMS Physics Technical Design Report:
  http://cdsweb.cern.ch/record/942733
- 7 TeV Projections: CMS NOTE-2010/008:
  http://cdsweb.cern.ch/record/1264099
- Higgs cross section for LHC:
  LHC Higgs Cross Section Working Group
- CMS Combination of Higgs Searches:
  http://cdsweb.cern.ch/record/1376643?ln=en
- ATLAS Combination of Higgs Searches:
  http://cdsweb.cern.ch/record/1383838
- CMS Web page with details on Higgs searches:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
- ATLAS Web page with details on Higgs searches:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/AtlasResultsEPS2011

# References

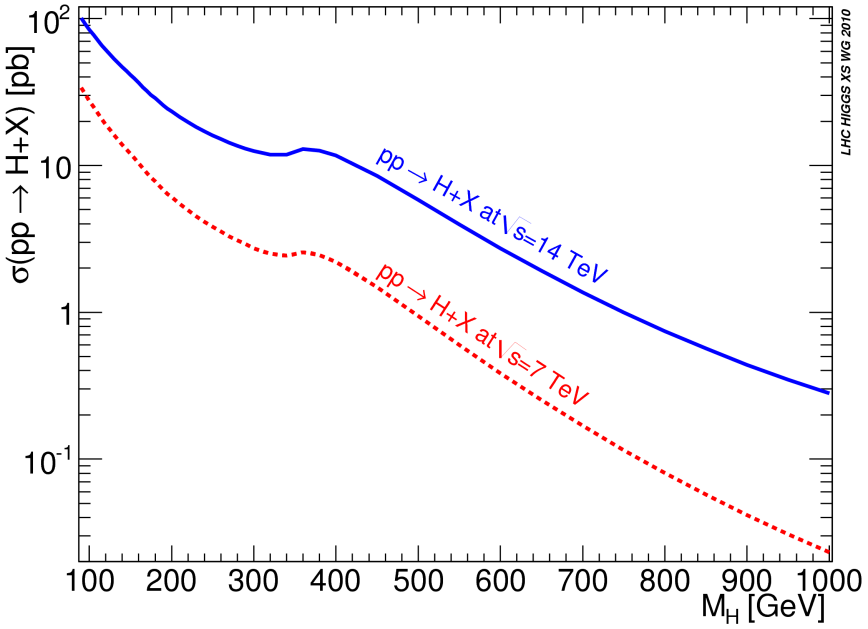

- CMS detector: JINST 3:S08004,2008
  http://iopscience.iop.org/1748-0221/3/08/S08004
- ATLAS detector: JINST 3:S08004,2008
  http://iopscience.iop.org/1748-0221/3/08/S08003

# BACKUP SLIDES

# The blue band plot



# LHC: 7 TeV vs 14 TeV




- LHC was planned to have 14 TeV collisions energy
- In 2010/2011 we run at 7 TeV
- For $m_H$=120 GeV/$c^2$ we loose a factor of

  **53.5/16.63 = 3.2 in gg→H**
- We can not expect 14 TeV before the long LHC shutdown planned for 2013