Standard Model Higgs combination from CMS

Michał Bluj

LLR-École Polytechnique CNRS/IN2P3

on leave from NCBJ, Warsaw

for the CMS Collaboration

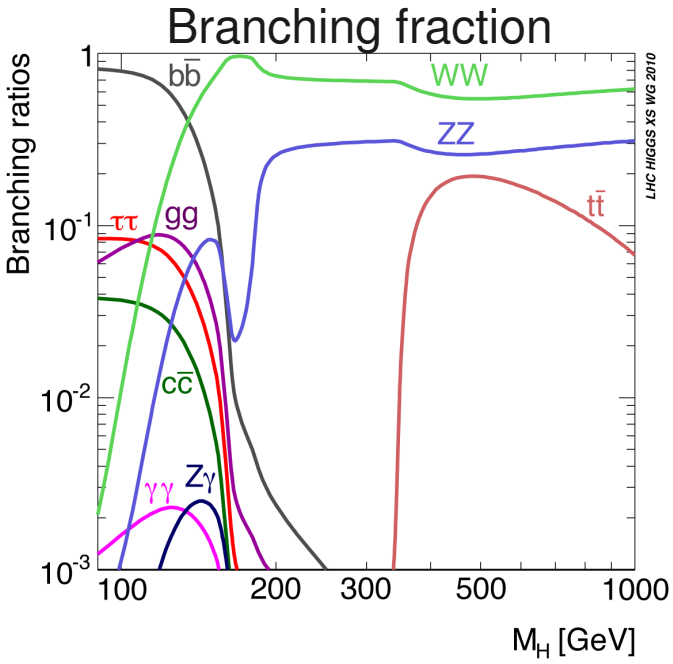
Documentation: HIG-11-022

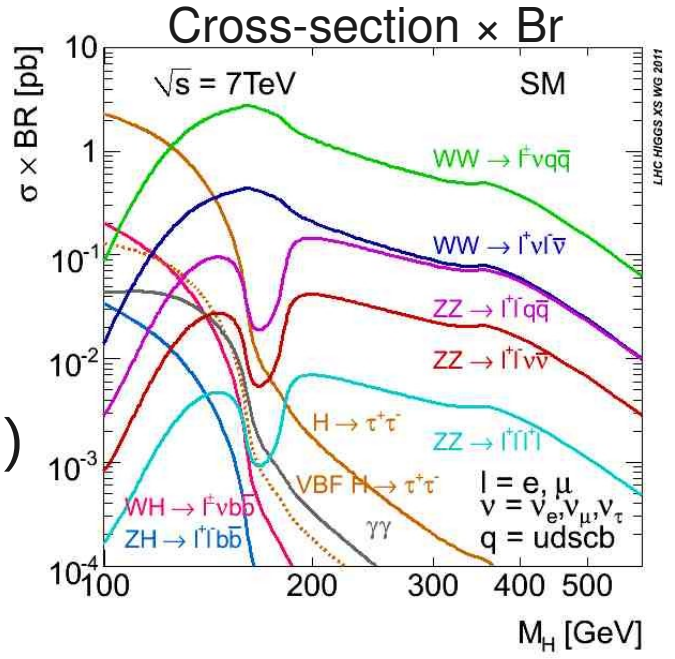
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

→ Higgs Physics → Physics Analyses Summaries

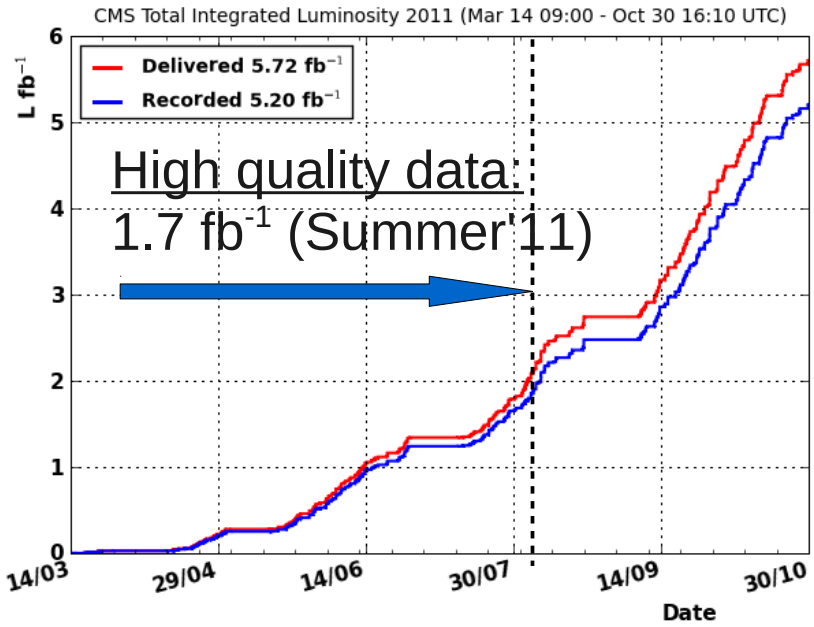
Higgs at LHC

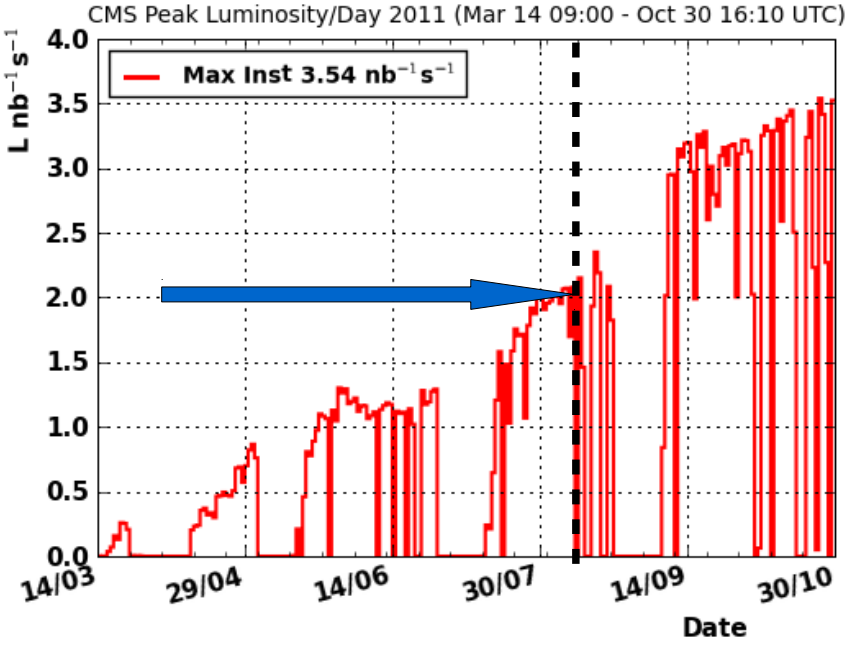
- Decay modes considered in search for Higgs boson determined by σ×Br and S/B
  - S/B disfavours fully-hadronic channels like inclusive $H \rightarrow bb$
  - Final states with leptons and providing good mass resolution preferred (e.g. $H \rightarrow \gamma\gamma$/$H \rightarrow 4l$)
  - Low mass range ($m_H < 2 \times m_W \sim 140$ GeV/c^2) more difficult that high mass one
- Full mass range (m_H = 115-600 GeV/c^2)
  - The powerful: **$H \rightarrow WW^* \rightarrow 2l2\nu$**
  - The golden plated: **$H \rightarrow ZZ^* \rightarrow 4l$**
- Low mass range ($m_H < 2 \times m_W \sim 140$ GeV/c^2)
  - The flagship: **$H \rightarrow \gamma\gamma$**
  - The robust: **$H \rightarrow \tau\tau$** (both ggF and VBF)
  - The difficult: **$VH \rightarrow bb$**
- High mass range ($m_H > 2 \times m_Z$; m_Z constraint used)
  - **$H \rightarrow ZZ \rightarrow 2l2\tau$ / $2l2\nu$ / $2l2j$**





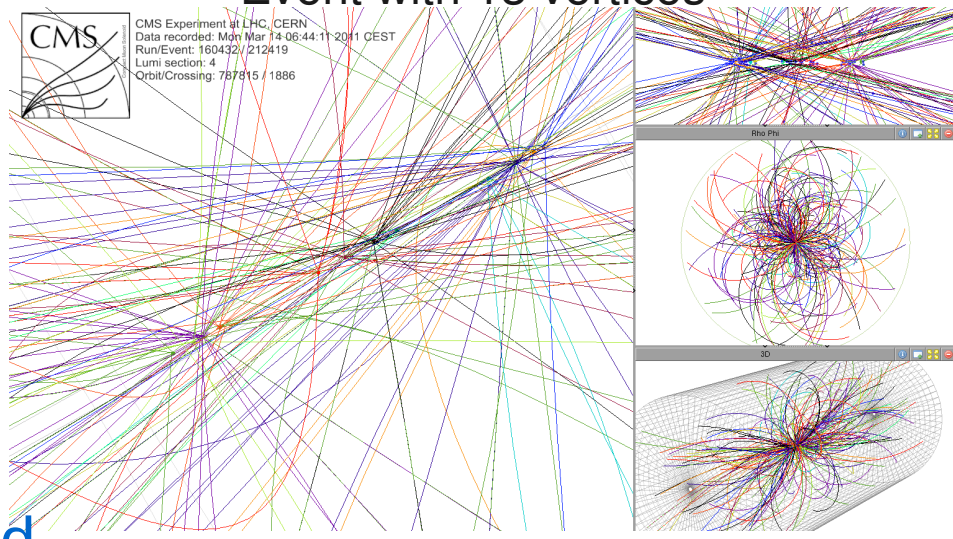
Luminosity





- Results discussed here obtained with data collected between mid of Match and mid of August'11
  - L = 1.7 fb^{-1} of high quality data
- Extreme increase of inst. luminosity
  - 2×10^{32} ⇨ 2×10^{33} cm^{-2}s^{-1}
  - Challenging for trigger system
  - Important pile-up (up to ~15)
- Now, additional 3 fb^{-1} is being analysed

Event with 13 vertices



Statistical methods

Limits

CMS uses the CL_s method to set limits on $\mu = \sigma/\sigma_{SM}$

- Frequentist approach including systematic error evaluation

Likelihood function:

$$\mathcal{L}(data \mid \mu, \theta) = \text{Poisson}\big(\underbrace{data \mid \mu \cdot s(\theta) + b(\theta)}_{\text{Expected S+B}}\big) \cdot \overbrace{p(\tilde{\theta}|\theta)}^{\text{Systematics}}$$

(Observed: $data$)

Test statistics:

$$q_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}$$

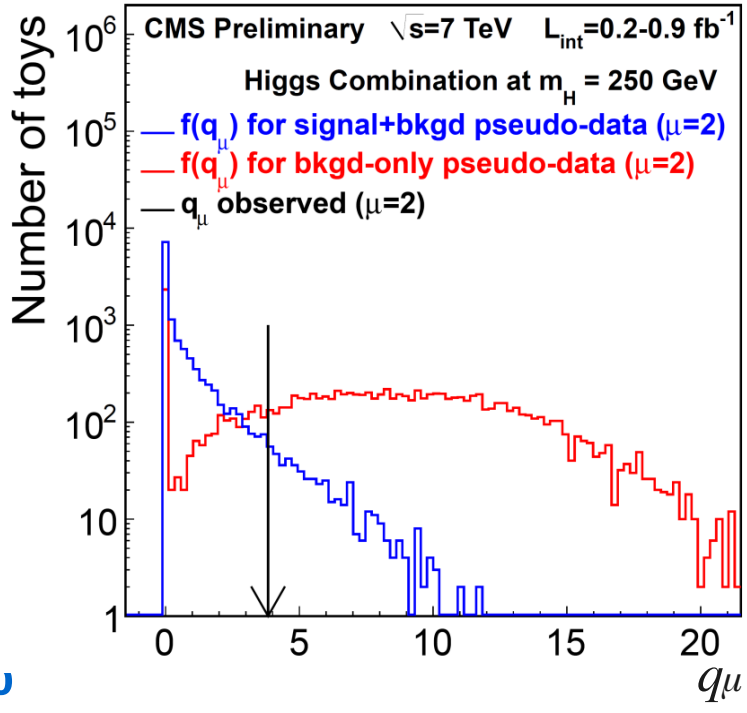
$\leftarrow$ fix μ, vary $\hat{\theta}_\mu$

$\leftarrow$ vary $\hat{\mu}$ and $\hat{\theta}$

$0 \le \hat{\mu} \le \mu$

Finally, calculate CL_s (toy MC):

$$CL_s = \frac{P\left(q_\mu \ge q_\mu^{obs} \mid \mu s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs})\right)}{P\left(q_\mu \ge q_\mu^{obs} \mid b(\hat{\theta}_0^{obs})\right)}$$



95% C.L. is on μ value giving CL_s = 1 - 95%

Significance

To quantify observed excess (above background only hypothesis)

- Same machinery as on previous slide but to test probability of the null hypothesis

Approximate p-value (probability of the null hypothesis)**:**

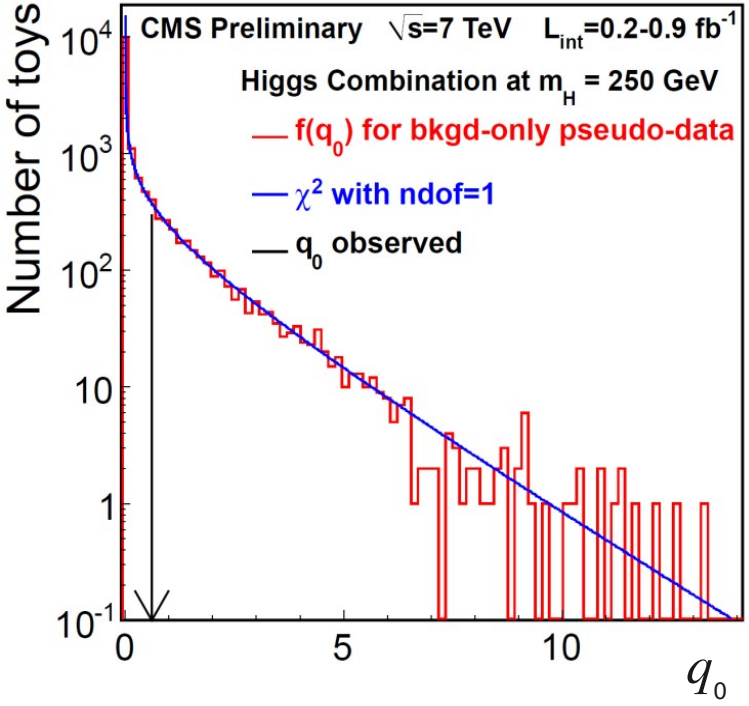
$$\tilde{p} = \frac{1}{2}\left[1 - \mathrm{erf}\left(\sqrt{q_0^{\mathrm{obs}}/2}\right)\right]$$

where q_0^{obs} is the observed q_μ value for the null hypothesis (μ = 0)

Significance (Z) corresponding to p-value

$$p = \int_Z^\infty \frac{1}{\sqrt{2\pi}} \exp(-x^2/2)\, dx$$

Probability expressed in σ's of one-sided normal distribution.



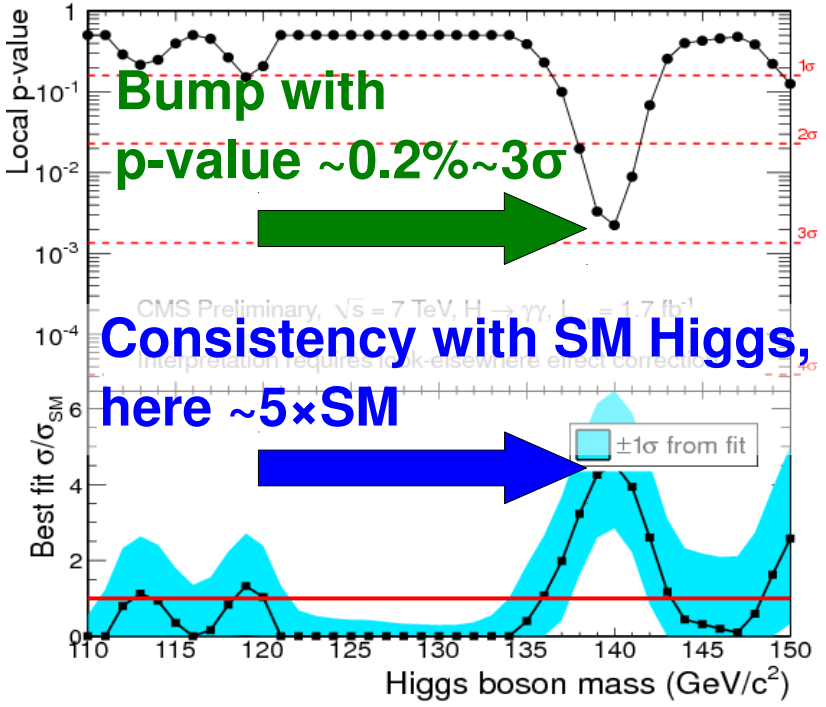
Bumps & LEE

The look-elsewhere effect (LEE) is significant in Higgs searches

- Higgs mass is unknown a priori
- Each channel represents many effective measurements (⇨ trial factor)
- If errors are correctly estimated, ~2% of measurements will fluctuate up by 2σ or more ⇨ bumps are expected!

Resolution is the key parameter

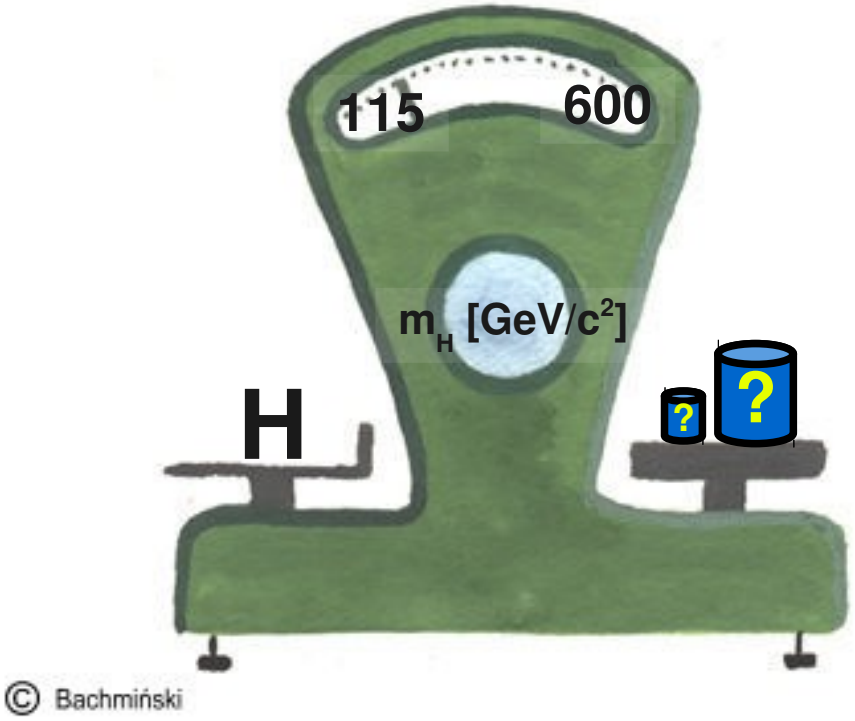
- For a given search window: higher resolution ⇨ larger LEE
- Local p-value plot will show features with frequency driven by resolution
- LEE for channels with high resolution O(10-100)



- LEE: $p^{global} \sim p^{min} + N_0 \exp(-Z^2_{max}/2)$

where N_0 – no. of crossing of $q_0^{obs}(m_H)$ over low threshold line: $q_0(m_H) = 0$

H → WW*/ZZ*

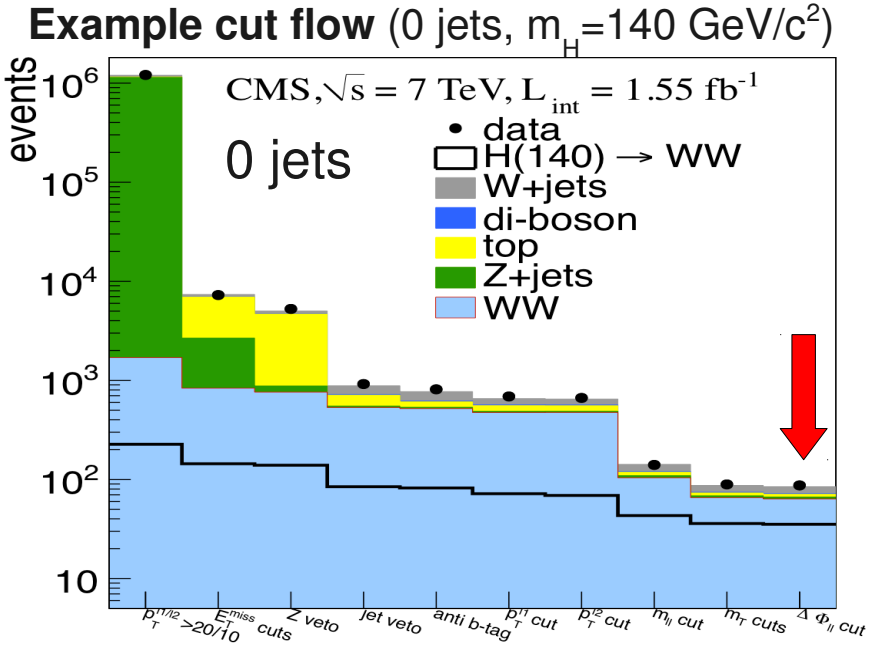


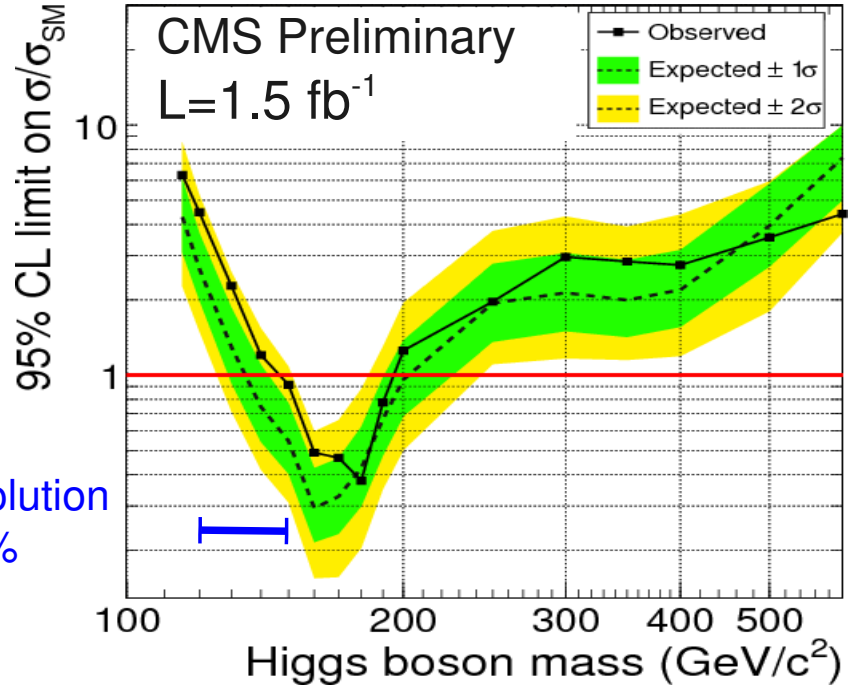
$m_H \in 115 – 600\ GeV/c^2$

- H → WW* → 2l2ν
- H → ZZ* → 4l

Details in Giuseppe's talk this morning

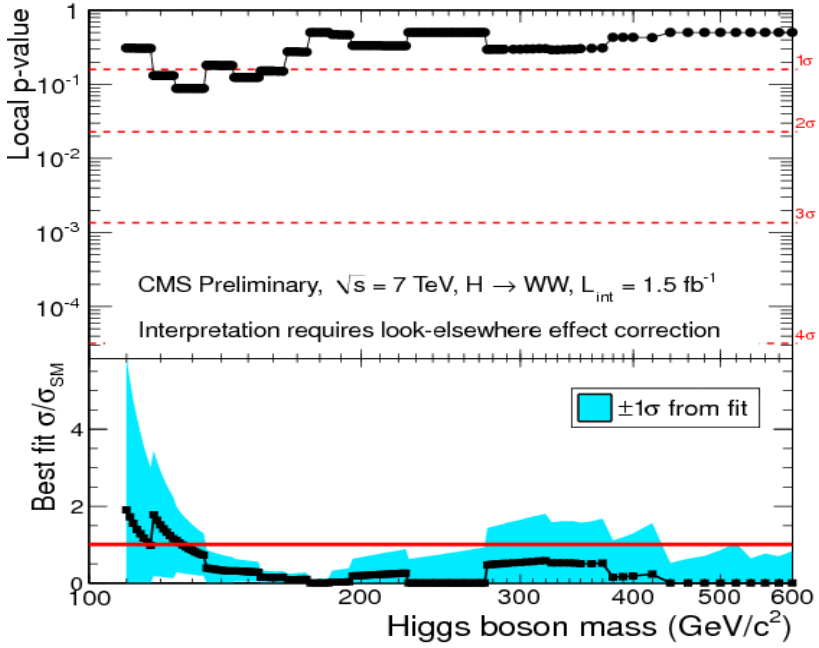
$H \rightarrow WW^* \rightarrow 2l2\nu$





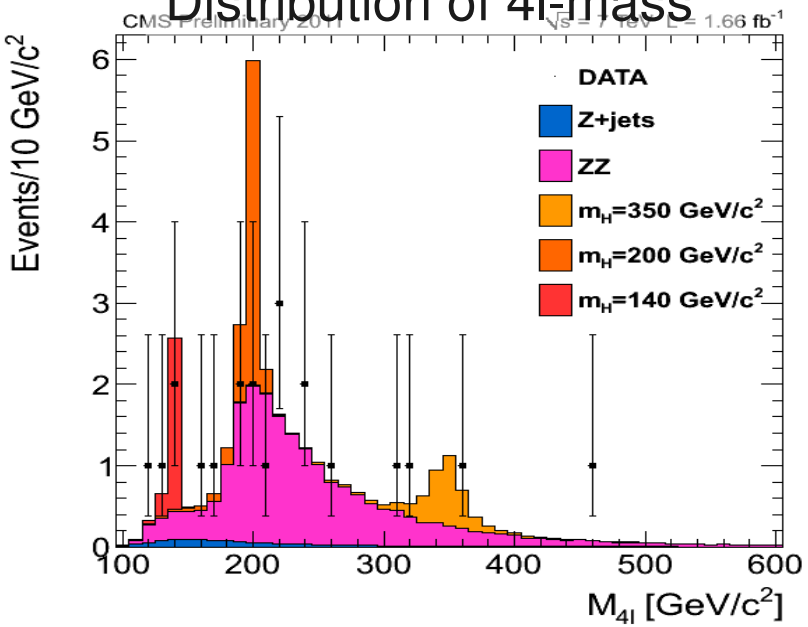
Resolution ~20%

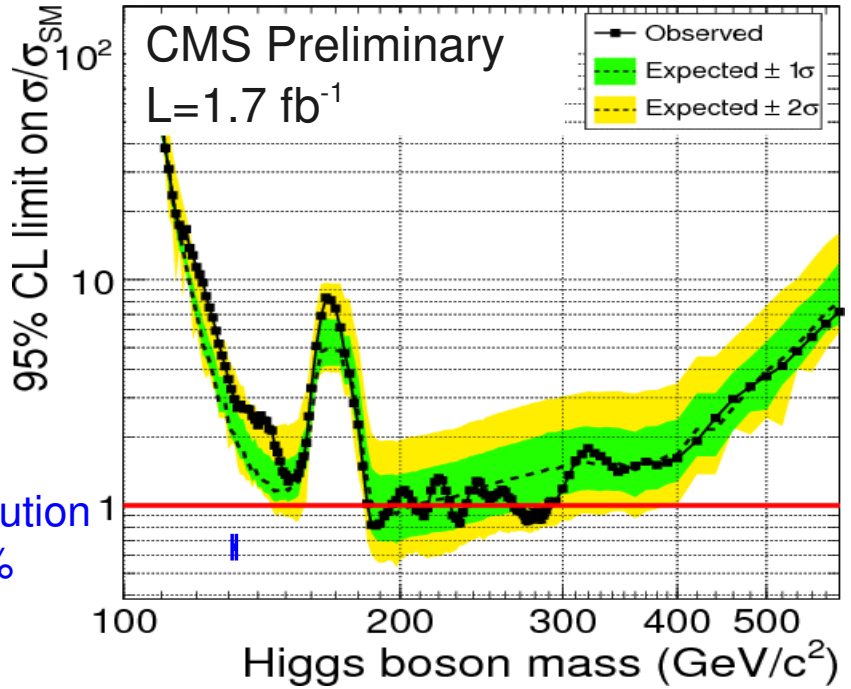
- The most sensitive in intermediate mass range (130–200 GeV/c^2)
  - No mass reconstruction → counting experiment (low resolution)
- **SM Higgs boson with $m_H \in 147 – 194$ GeV/c^2 ruled out at 95% CL**
- Expected sensitivity 136–200 GeV/c^2
  - Broad ~1σ excess 110 – 160 GeV/c^2



$H \rightarrow ZZ^* \rightarrow 4l$

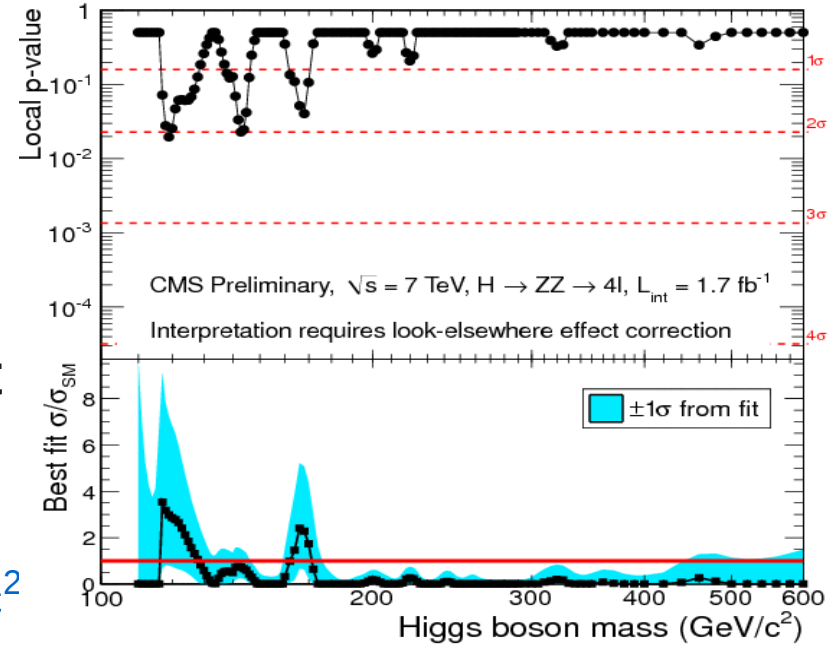
Distribution of 4l-mass



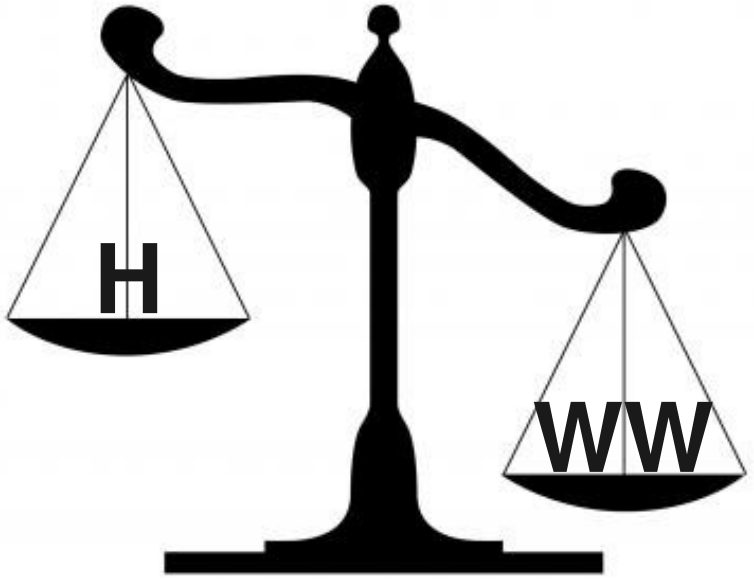


Resolution ~1-2%

- Full mass, resolution ~1-2%
- **21 observed / 21.2 ± 0.8 expected**
- **Three pairs of events** (bumps):
  - m_{4l} = 122, 142, 165 GeV/c^2
  - High resolution → trial factor ~35
  - **Only pair m_{4l} = 142 GeV/c^2 consistent with SM Higgs expectation**
- **Limits very close to the SM Higgs** (small intervals excluded for m_H: 180 – 300 GeV/c^2



Light Higgs searches

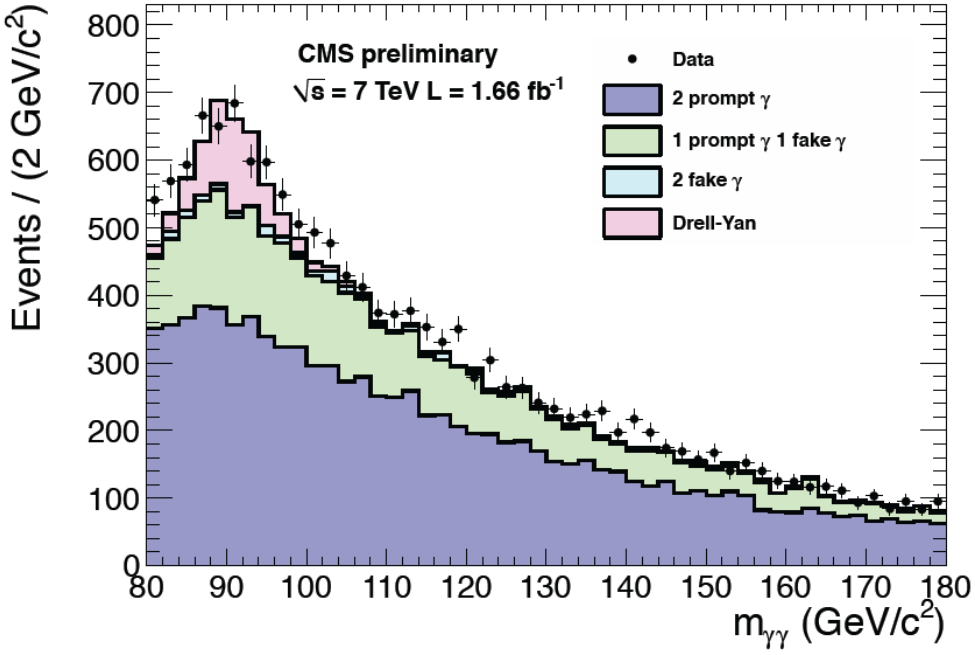


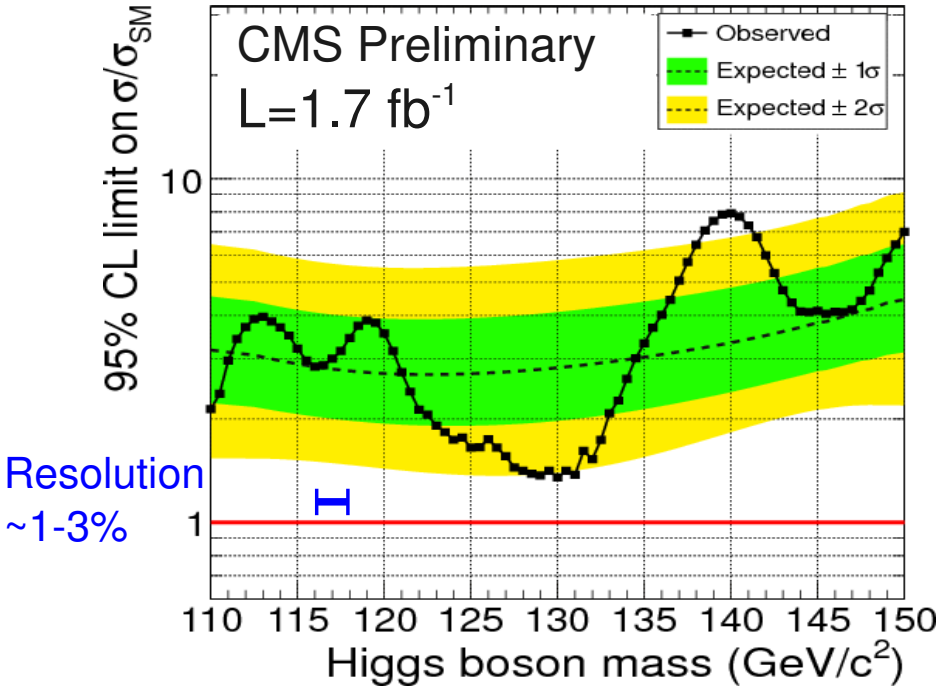
$m_H < 2 \times m_W$ (~140 GeV/c^2)

- H → γγ
- H → ττ (VBF and ggF)
- VH → bb

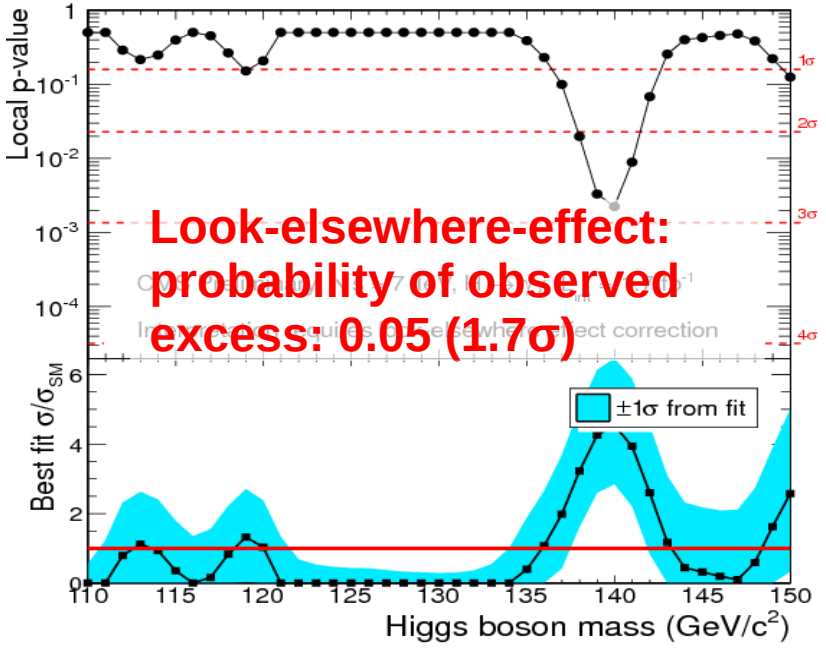
Details in Vladimir's talk this morning

H → γγ



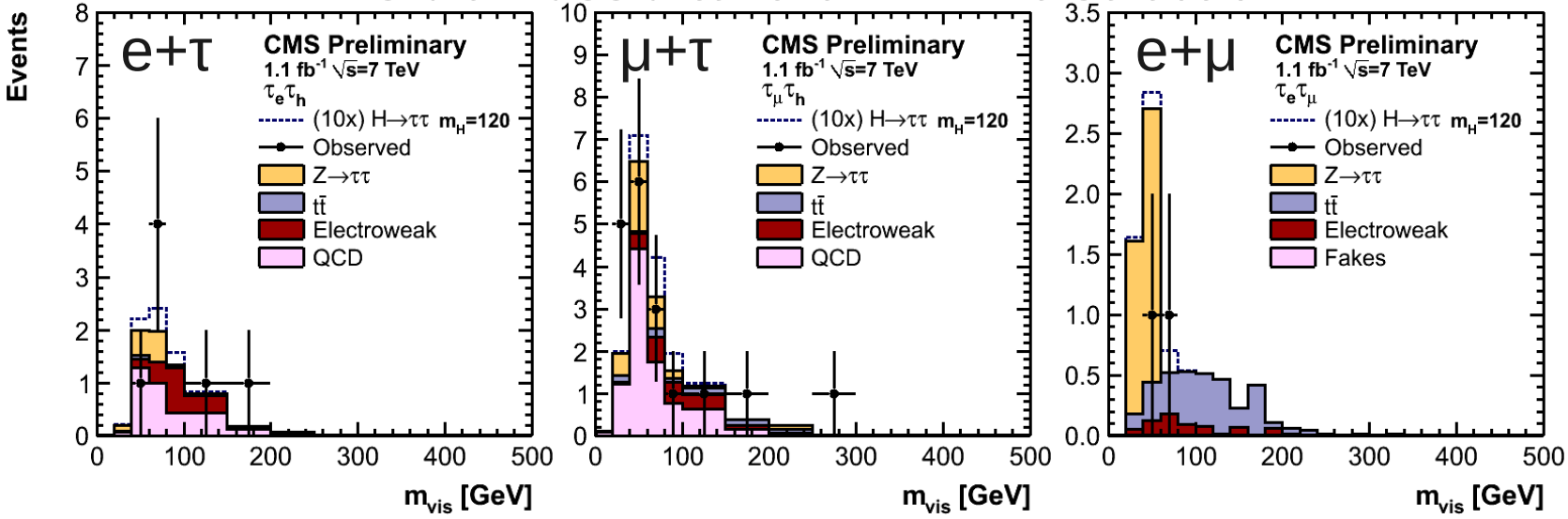


- **The most sensitive channel at low masses despite a small branching fraction** (1-2×10^{-3})
  - Signature: narrow peak in di-photon mass
  - **Discovery potential**
- **No significant excess is found** (L = 1.7 fb^{-1})
  - **Observed exclusion: 1.5 – 8×SM**

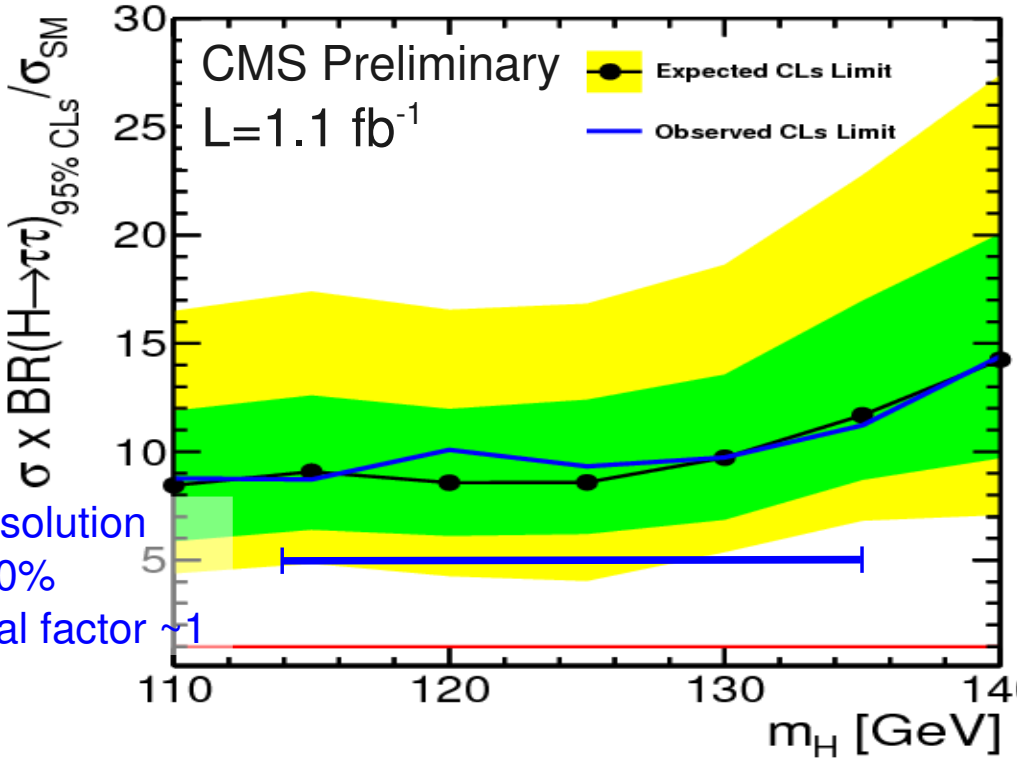


$H \rightarrow \tau\tau$

Visible mass after the VBF-like selection

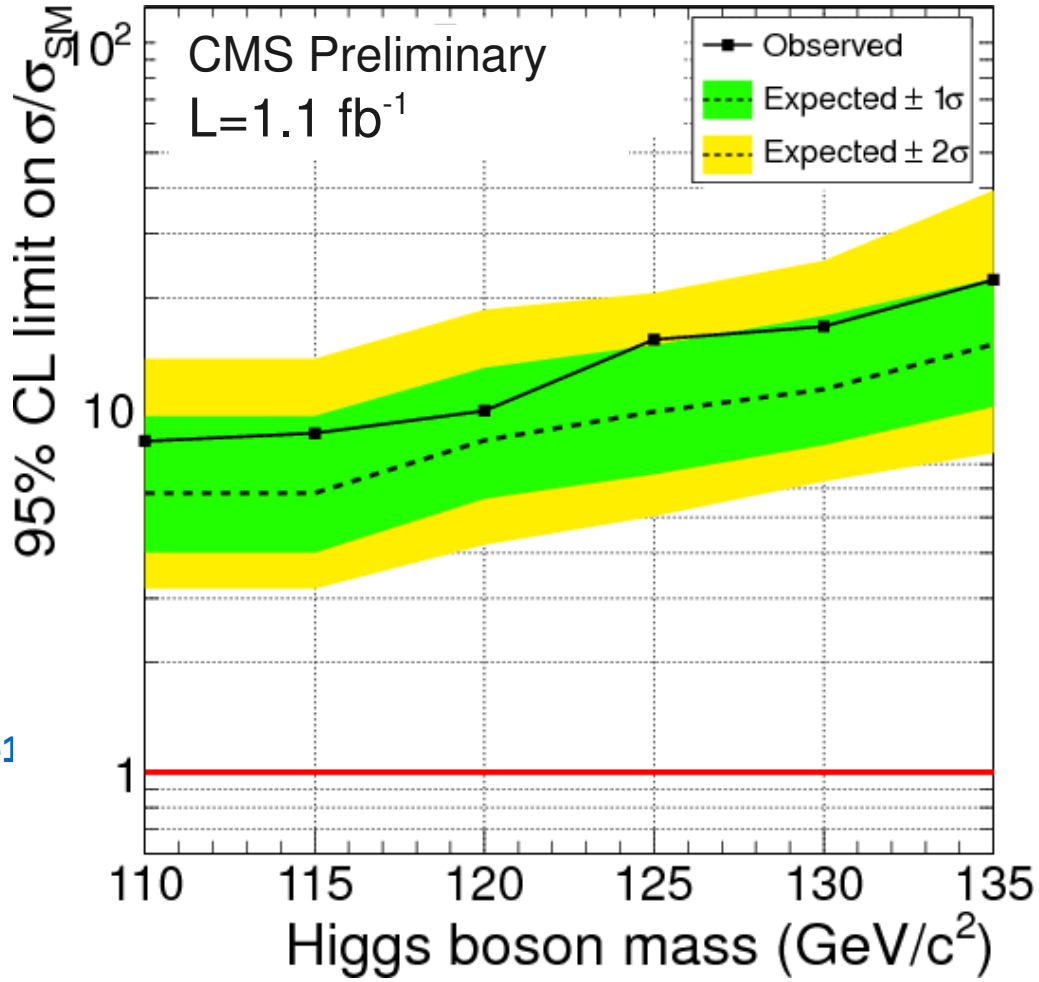


- Sensitivity 8-14×SM with 1.1 fb^{-1}
  - Lead by VBF-like selection
  - **No excess observed**
  - Improves (almost) linearly with data
    - Background systematics lead by statistics
    - Improvement of reconstruction techniques

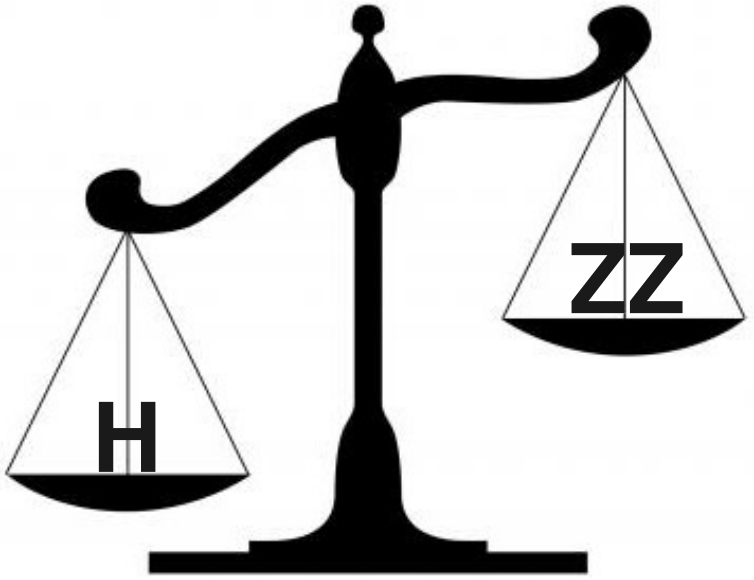


$H \rightarrow bb$

- Dominant production modes ($gg \rightarrow H$, VBF) overwhelmed by QCD multi-jet background
  ⇨ **use $qq \rightarrow V(H \rightarrow bb)$ process**
  - Decays of V provides handles to cope with background
  - MVA discriminant
  - Counting experiment
- Background estimated with control data
- **Sensitivity 10-20×SM with 1.1 fb^{-1}**



Heavy Higgs searches



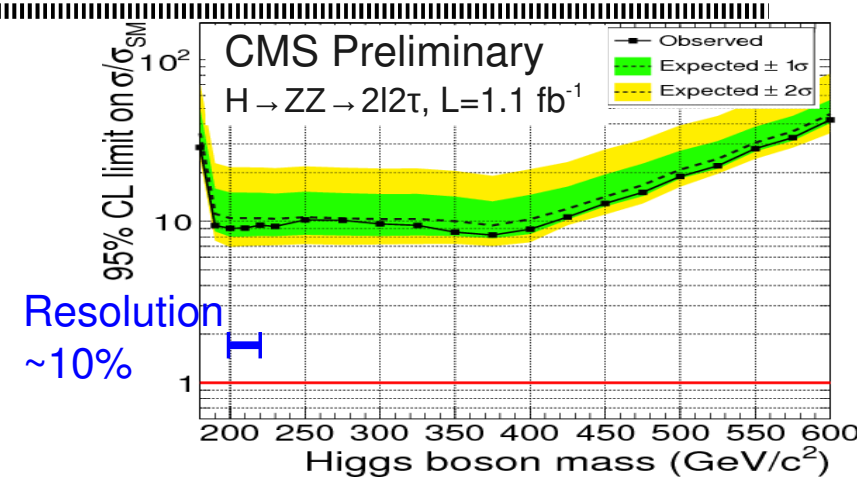
$m_H > 2 \times m_z$ (~180 GeV/c^2)

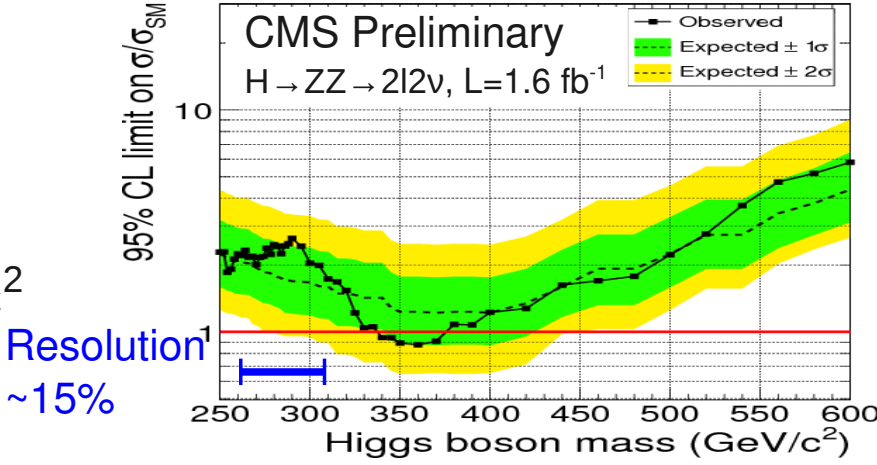
- H → ZZ → 2l2ν
- H → ZZ → 2l2j
- H → ZZ → 2l2τ

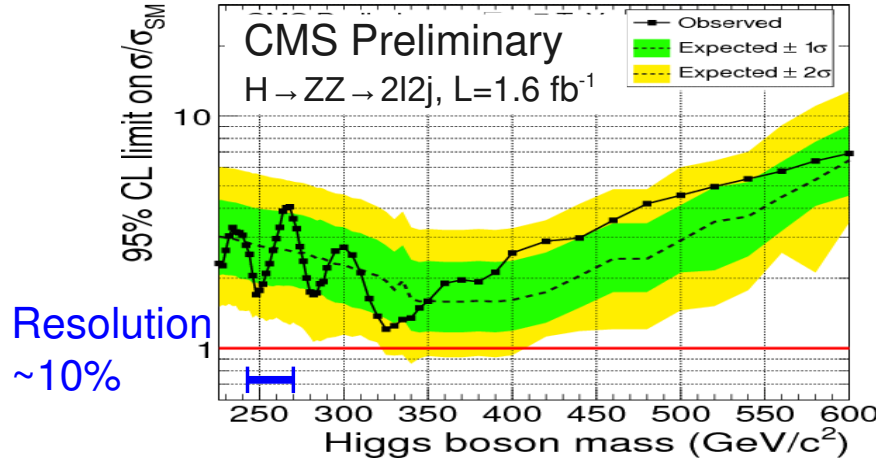
Details in Giuseppe's talk this morning

Heavy Higgs searches

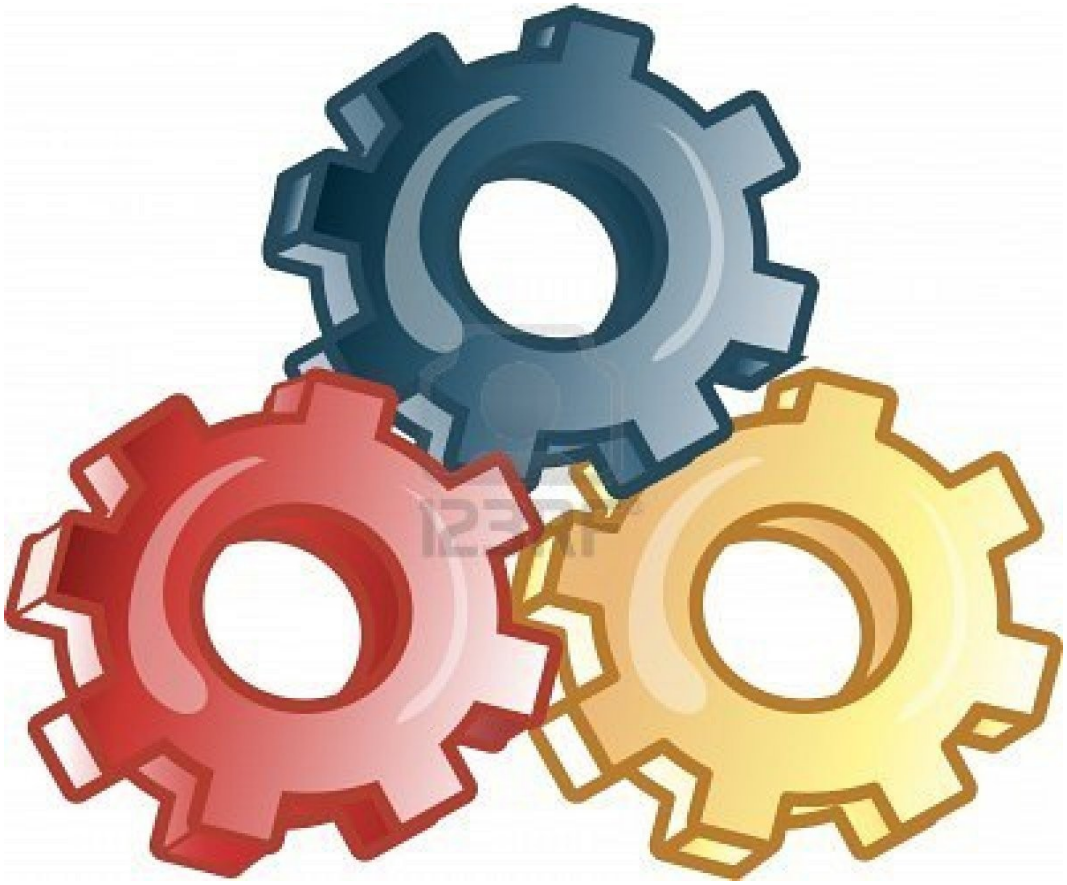
- **Three channels considered**
  - $H \to ZZ \to 2l2\nu$
  - $H \to ZZ \to 2l2j$
  - $H \to ZZ \to 2l2\tau$
- Improve sensitivity for high mass range, where $H \to WW \to 2l2\nu$ less sensitive
- **Exclusions**
  - $H \to ZZ \to 2l2\nu$ (1.6 fb^{-1}): excluded small region for m_H: 340 – 375 GeV/c^2
  - $H \to ZZ \to 2l2j$ (1.6 fb^{-1}): ~1.5–7×SM
  - $H \to ZZ \to 2l2\tau$ (1.1 fb^{-1}): ~10×SM for m_H: 190 – 400 GeV/c^2







Putting it all together: combination



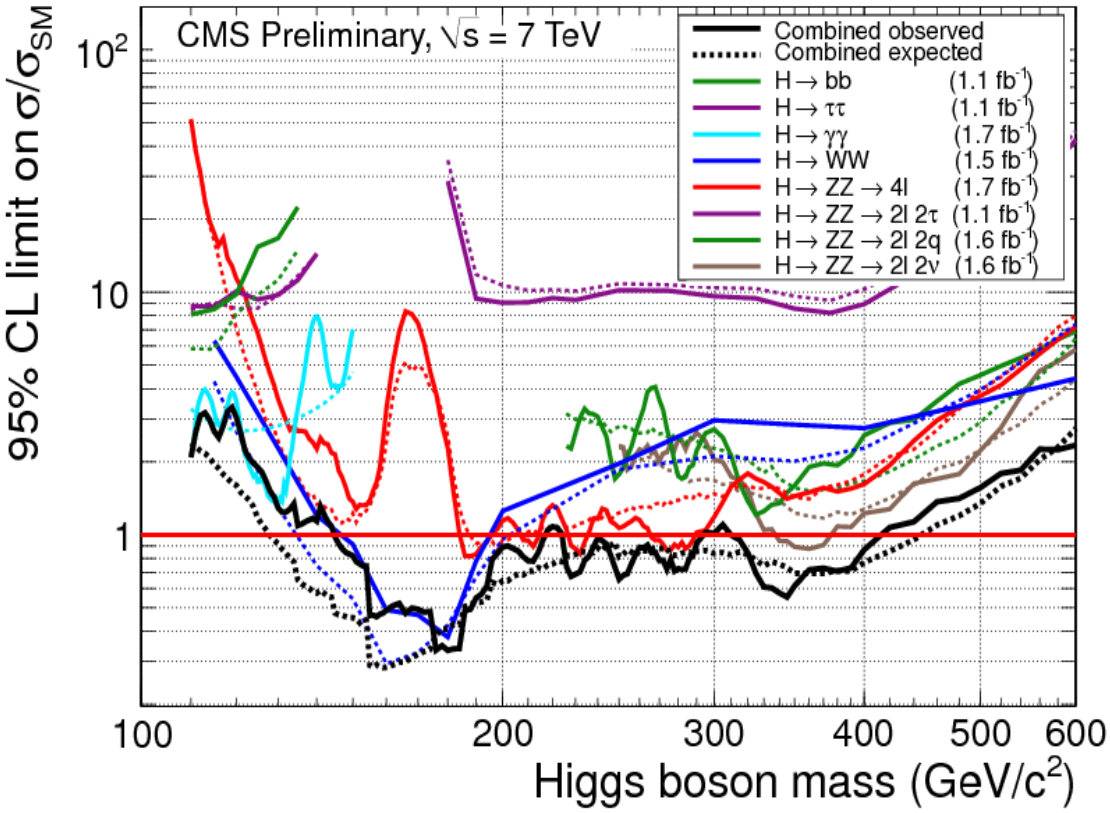
Combined limit

All channels together

- Combination for low mass Higgs (m_H < 130 GeV/c^2) **guided by H → γγ** and **H → WW → 2l2ν**
- Exclusion in intermediate mass range (130 < m_H < 200 GeV/c^2) dominated by **H → WW → 2l2ν** with **sub-leading H → ZZ → 4l**
- In high mass region exclusion by **H → ZZ → 4l** with significant contributions of **H → WW → 2l2ν** and **H → ZZ → 2l+2ν/2j**

All channels together (L = 1.1 – 1.7 fb^{-1})

• Solid – observed; dashed – expected



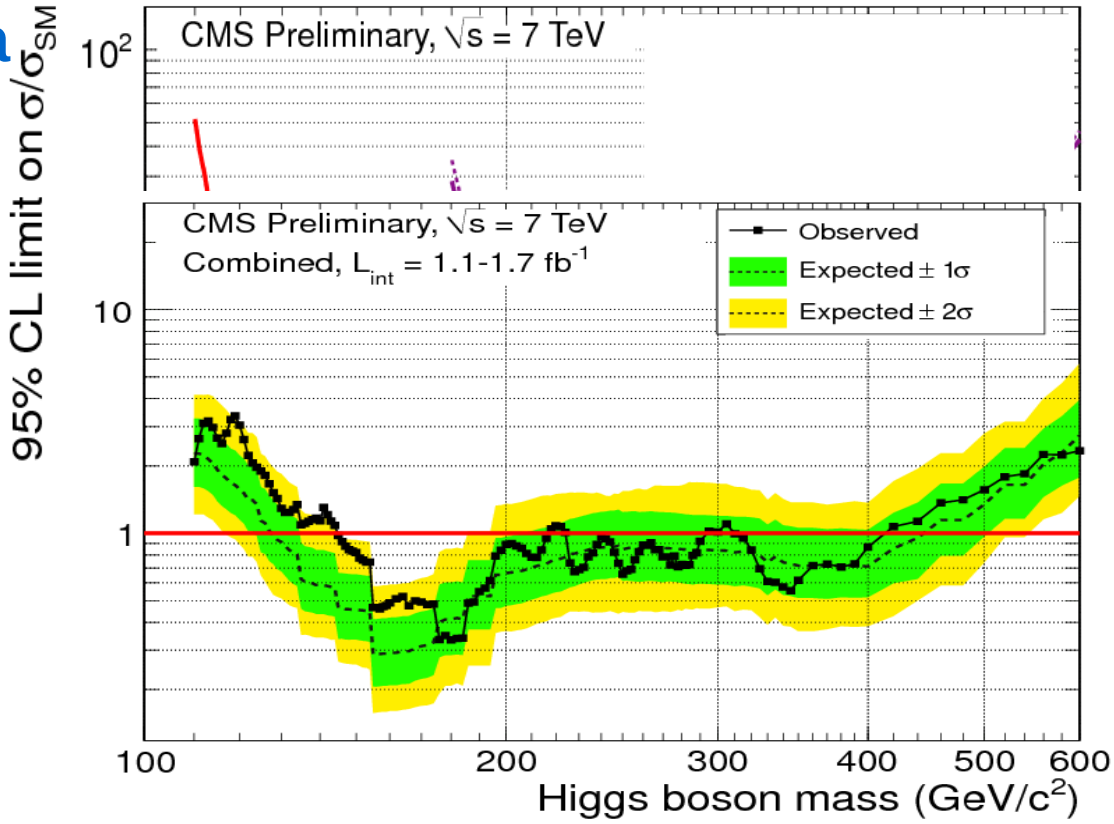
Combined limit

Combined limit (L=1.1–1.7fb^{-1})

- There is **not any evidence for a SM Higgs**, but some fluctuations are observed
  - mostly at low mass due to $H \rightarrow WW \rightarrow 2l2\nu$

Combined limit (L = 1.1 – 1.7 fb^{-1})

- Solid – observed; dashed – expected



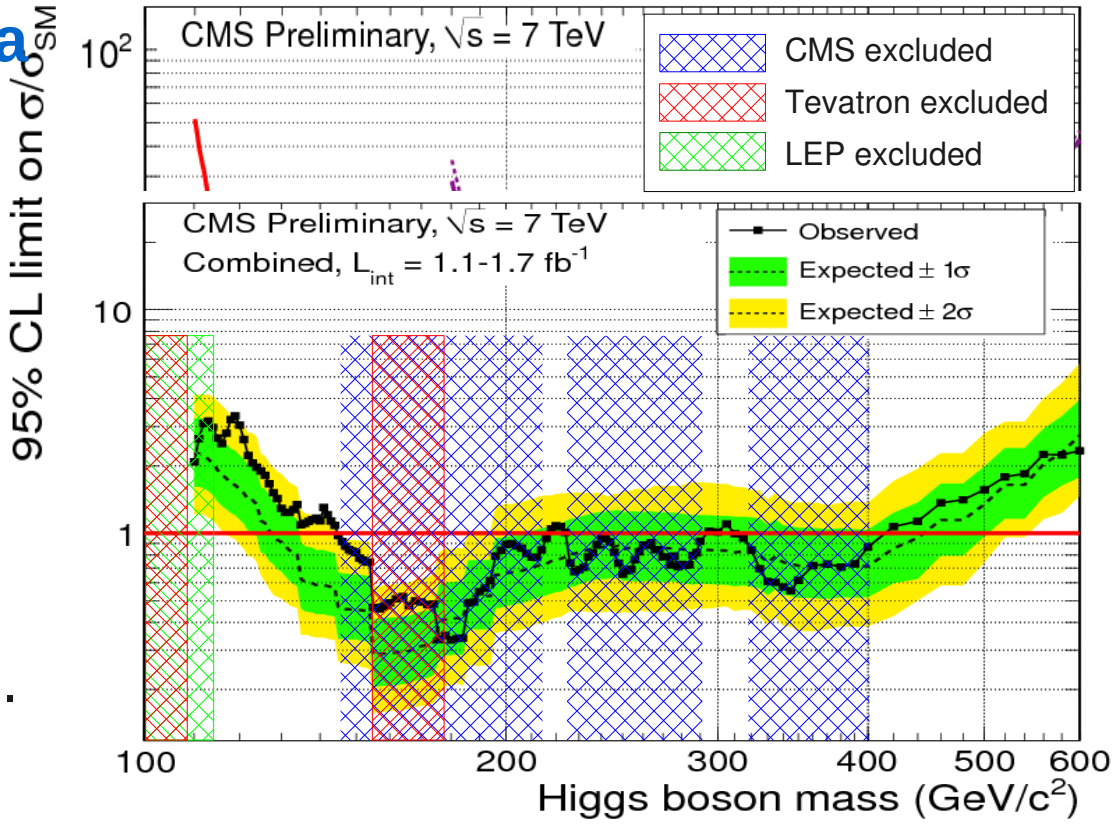
Combined limit

Combined limit (L=1.1–1.7fb^{-1})

- There is **not any evidence for a SM Higgs**, but some fluctuations are observed
  - mostly at low mass due to $H \rightarrow WW \rightarrow 2l2\nu$
- **Excluded mass range (95% C.L.):**
  - **145-216, 226-288, 310-400 GeV/c^2**
  - Small gaps excluded at 90% C.L. (144-440 GeV/c^2)
- Expected exclusion (95% CL):
  - 130-440 GeV/c^2

Combined limit (L = 1.1 – 1.7 fb^{-1})

• Solid – observed; dashed – expected

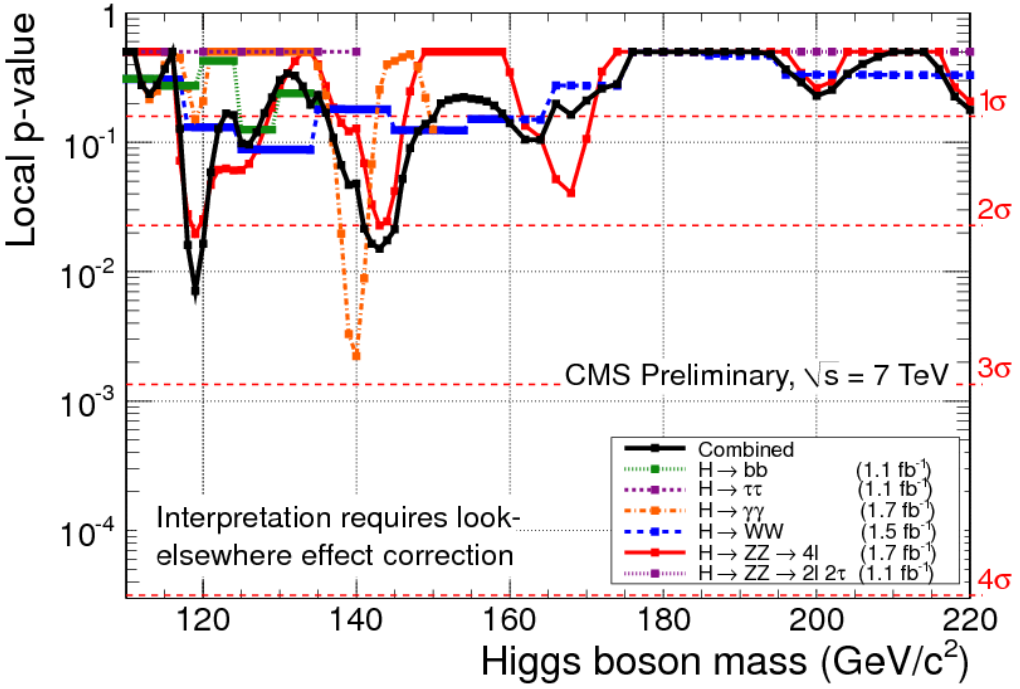


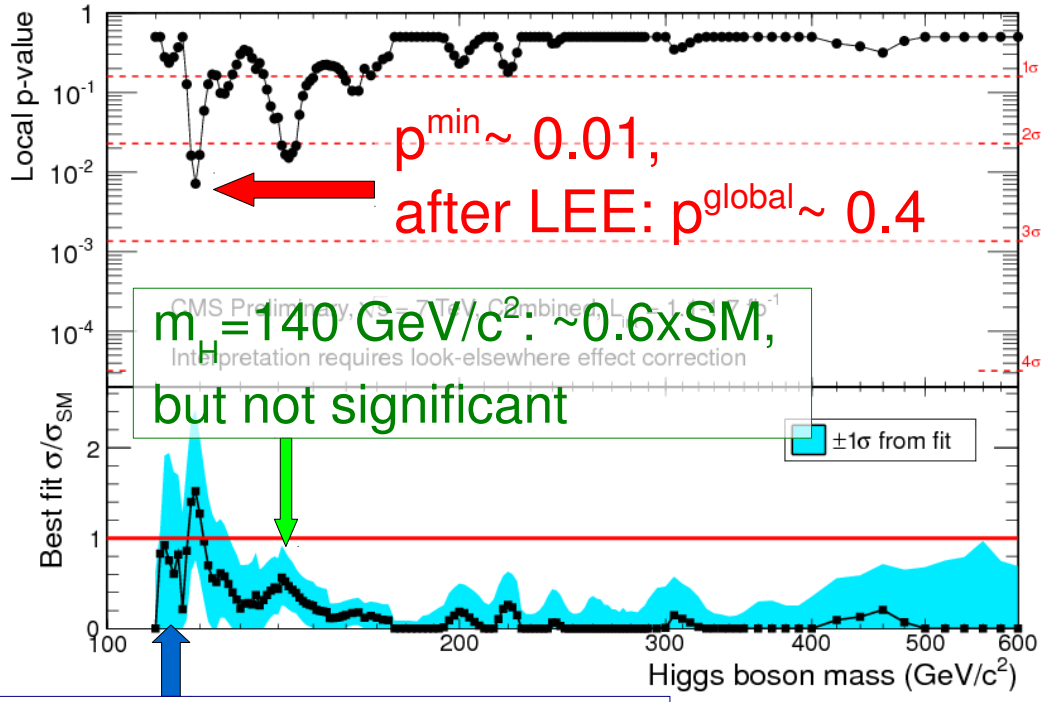
Area when a SM Higgs can reside importantly reduced:

- There is a place of either light (< 140 GeV/c^2) or heavy (> 400 GeV/c^2) Higgs ⇨ both possibilities can be tested soon (by end of 2012)

Local p-values and best fit

- **P-value:** an estimate of probability of upward background fluctuation as high or higher than the excesses observed in data.
  - Interpretation of meaning a local p-value requires correction for look-elsewhere effect.
- **"Best fit":** a cross-section of a "signal" process preferred by fit S+B model to data.





m_H=117-120 GeV/c²: ~1xSM,
but not significant

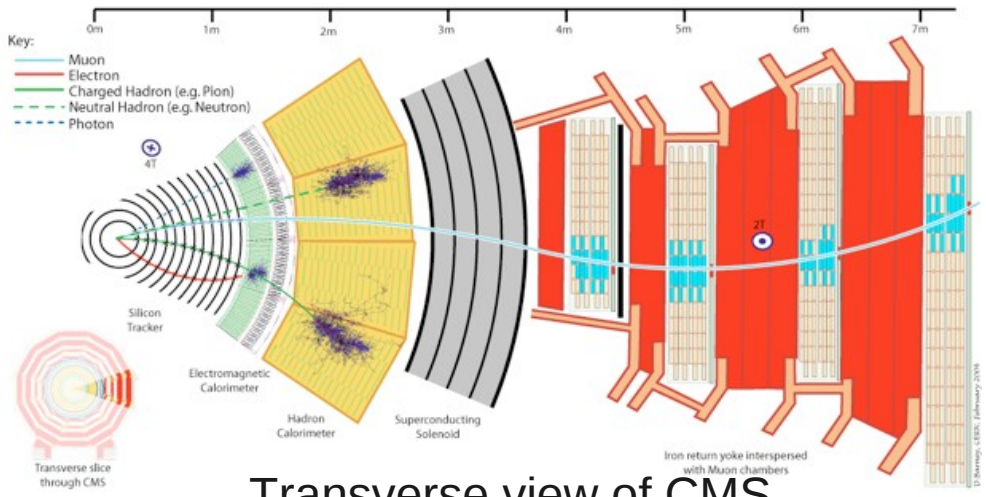
Conclusions

- Search for SM Higgs boson with 1.1 – 1.7 fb^{-1} data collected by the CMS detector was shown
- Several decay modes were used in the search...
  - Full mass range: **$H \to WW \to 2l2\nu$, $H \to ZZ \to 4l$**
  - Low mass: **$H \to \gamma\gamma$, $H \to \tau\tau$** (both ggF and VBF)**, $VB \to bb$**
  - High mass: **$H \to ZZ \to 2l+2\nu/2j/2\tau$**
- **and combined together**
- **No Higgs signal compatible excess was observed**
- **Exclusion limits were set, excluding (95% CL) mass range between 140 – 400 GeV/c^2** (with small gaps excluded at 90% CL)
- Not full potential of CMS explored
  - Existing analysis are being improved
- Full recorded luminosity is ~5 fb^{-1}
  - Analyses are ongoing
- Combination of ATLAS and CMS using Summer'11 data, soon

BACKUP

CMS detector

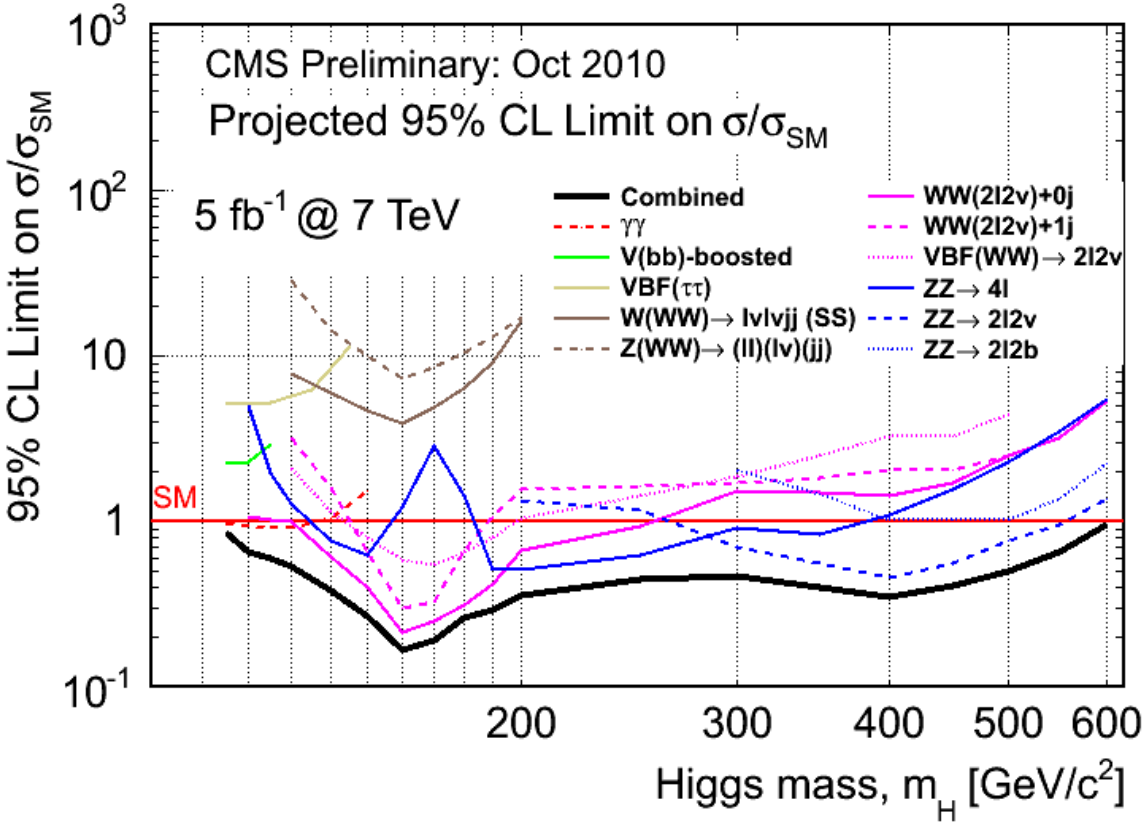
- Silicon tracker $|\eta| < 2.5$, B = 3.8T
  - High quality tracking for lepton track and isolation; b-tagging; tau-Id and vertexing (anti-PU)
  - $\sigma/p_T \approx 1.5 \cdot 10^{-4} p_T \oplus 0.005$
- Calorimetry $|\eta|_{ECAL} < 3$, $|\eta|_{HCAL} < 5$
  - ECAL: High resolution crucial for M(yy) reconstruction and electron-Id, tau-Id
  - ECAL: homogeneous $PbWO_4$ crystals, $\sigma/E \approx 2.8\%/\sqrt{E} \oplus 12\%/E \oplus 0.3\%$
  - HCAL: $\sigma/E \approx 100\%/\sqrt{E} \oplus 0.05$
- Muon Spectrometer $|\eta| < 2.4$
  - Solenoid return yoke instrumented, B = 2T (DT/RPC + CSC/RPC)
  - Muon reconstructed by combination of tracks in muon system and tracker
- Particle Flow reconstruction technique
  - Combines informations from all sub-systems of CMS in an optimal way
  - Significant improvement of resolution of Jets, MET and great Tau-Id
  - Used extensively in CMS analyses



Transverse view of CMS

Projections: exclusions

- Projection obtained by simulation (2010)
  - Over-optimistic, but it tells with some precision (~10-15%?) what will be a result of full 2011 dataset analysis → very close to exclude SM Higgs at 95% C.L.



Projections: significance

- Projection obtained by simulation (2010)
  - Over-optimistic, but it tells with some precision (~10-15%?) what will be a result of full 2011 dataset analysis → some bumps 3-4sigma in regions which are still allowed (< 140 or > 400 GeV/c^2)