Searches for the Higgs Boson with the CMS Detector

Marat Gataullin (Caltech)
on behalf of the CMS Collaboration

Meeting of the Division of Particles and Fields of the American Physical Society
August 9-13, Providence (RI)

Higgs Searches at CMS

- Three search-regions as f(m_H)

a) Low mass (m_H < 140 GeV)

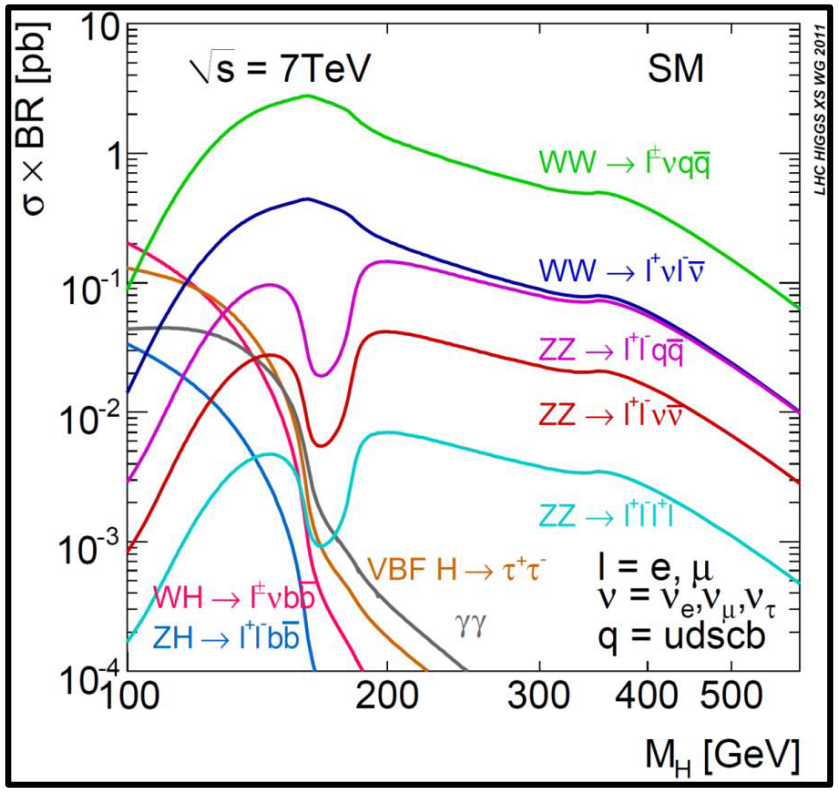
H → γγ, ττ, WW(2ℓ2ν), ZZ(4ℓ)

b) Medium mass (140-200 GeV)

H → WW(2ℓ2ν)

c) High mass (m_H > 140 GeV)

H → ZZ(4ℓ),ZZ(2ℓ2ν),ZZ(2ℓ2j),WW(2ℓ2ν)



- **Plethora of CMS contributions**

H → γγ (C. Palmer talk [178])

H → WW(2ℓ2ν) (K. Sung [171])

H → ZZ(4ℓ) (M. Pelliccioni [170])

H → ZZ(2ℓ2ν) (D. Trocino [173])

H → ZZ(2ℓ2j) (A. Kumar [174])

- **But also BSM Higgs Searches**

$H^{++} \rightarrow \ell^+\ell^+$ (M. Chertok [175])

MSSM H → ττ (L. Antonelli [176])

(tomorrow morning)

Combination Across SM Channels

- Each SM Higgs search channel is characterized by its
  - Signal strength
  - Expected Higgs mass resolution
  - Signal-to-background
- And then we combine the six SM Higgs search channels

(143 m_H-points in the 110 – 600 GeV mass range)

channel	mass range (GeV/c^2)	luminosity (fb^{-1})	number of sub-channels	type of analysis
$H \to \gamma\gamma$	110-140	1.1	8	mass shape (unbinned)
$H \to \tau\tau$	110-140	1.1	6	mass shape (binned)
$H \to WW \to 2\ell 2\nu$	110-600	1.1	5	MVA (binned); cut&count
$H \to ZZ \to 4\ell$	110-600	1.1	3	cut&count
$H \to ZZ \to 2\ell 2\nu$	250-600	1.1	2	mass shape (unbinned)
$H \to ZZ \to 2\ell 2q$	226-600	1.0	6	mass shape (unbinned)
TOTAL (6)	**110-600**	**1.0-1.1**	**30**	

Statistical Tools: Limits

Pursue both frequentist and Bayesian methods, providing us with a test of robustness of results.

Main parameter $\mu=\sigma/\sigma_{SM}$ (signal strength)

1) The CLs method (agreed with ATLAS):

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

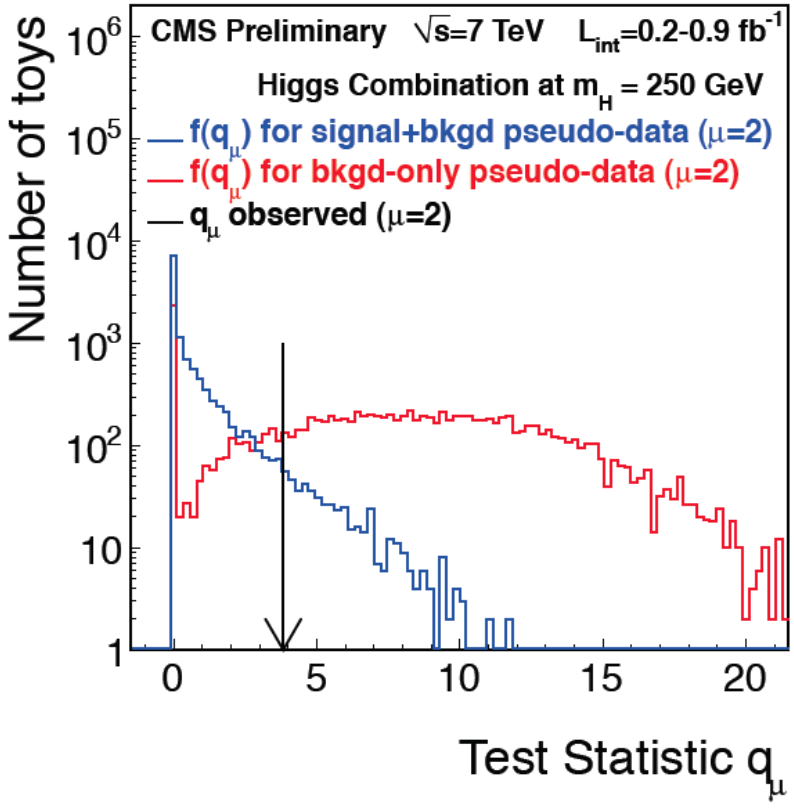
The 95% C.L. is μ such that CLs = 0.05.

Derived by performing toy experiments.

Systematic uncertainties and their correlations taken into account.

2) Bayesian (with flat prior)

$$\int_0^{\mu_{95\%CL}} p(\mu \mid \text{data})\, d\mu = 0.95$$



Statistical Tools: Quantifying Excess

Our Test statistic – profile likelihood

$$q_0 = -2\ln\frac{\mathcal{L}(\text{data}|0,\hat{\theta}_0)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})} \quad \text{and } \hat{\mu} \geq 0$$

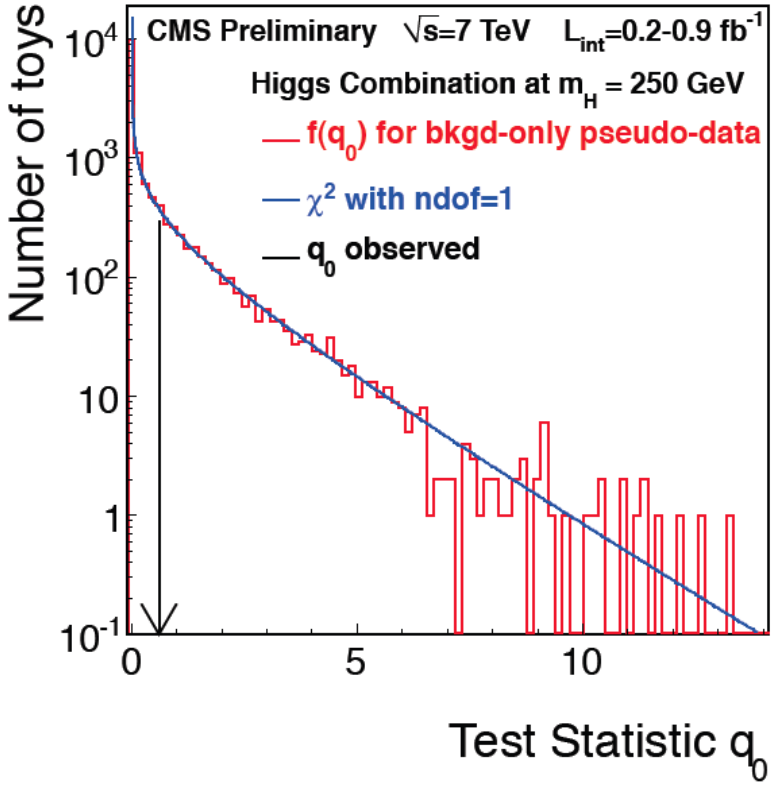
Approximate "Local" p-value

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

Significance Z from p-value

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

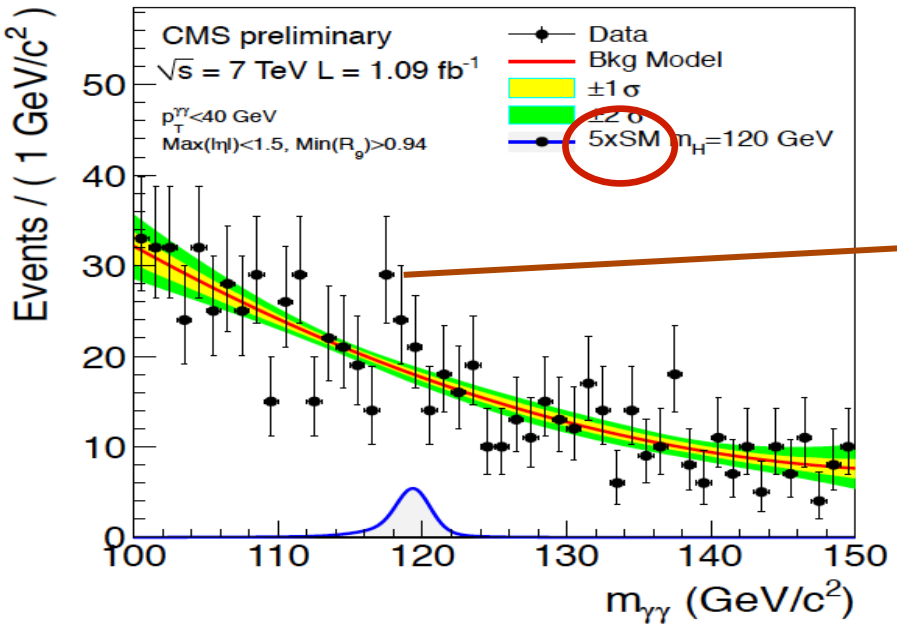
e.g. p=2% would give Z~2σ

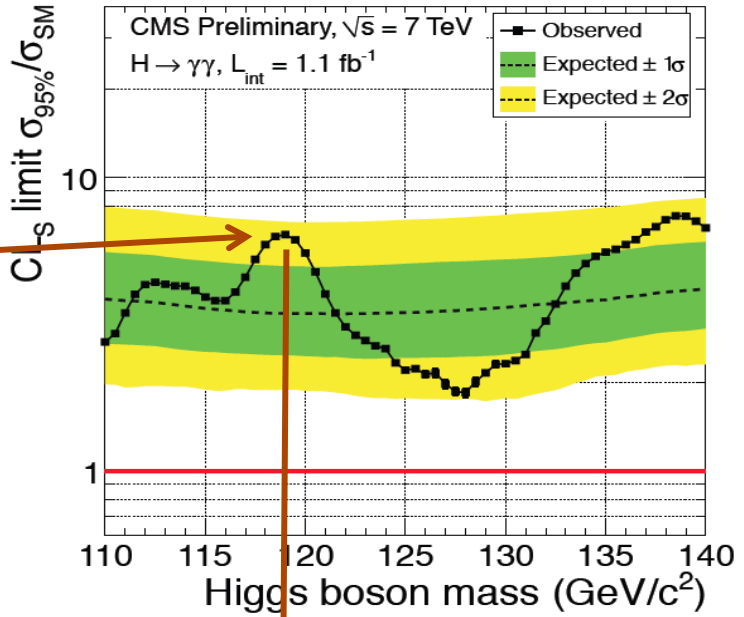


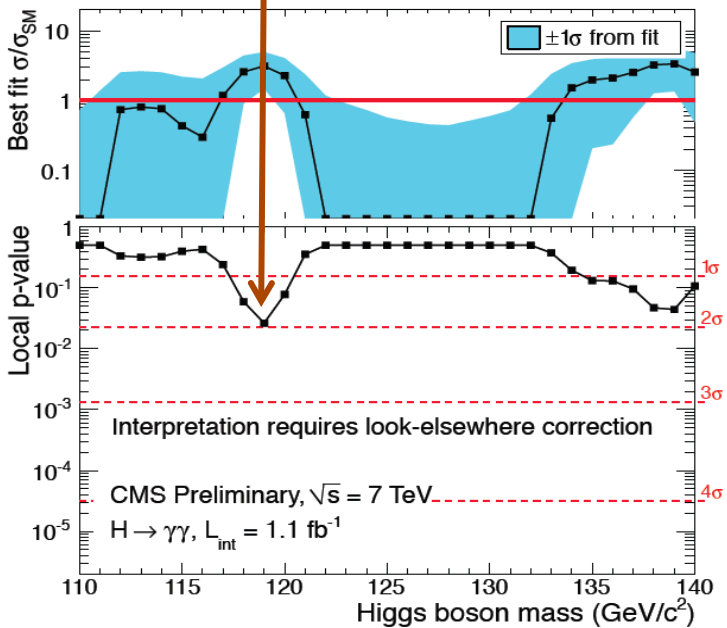
Disclaimer:

- Small "local" p-value means one has a local excess w.r.t. expectations
- It does not tell us whether the excess is due to a signal (or consistent with it)
- Moreover, we must be aware of a potentially large look-elsewhere effect (LEE) that can considerably reduce the "significance" of the minimal p-value found in a search involving scans over the a broad phase space with a good "local" (mass) resolution.

H→γγ (Low Mass 110-140 GeV)



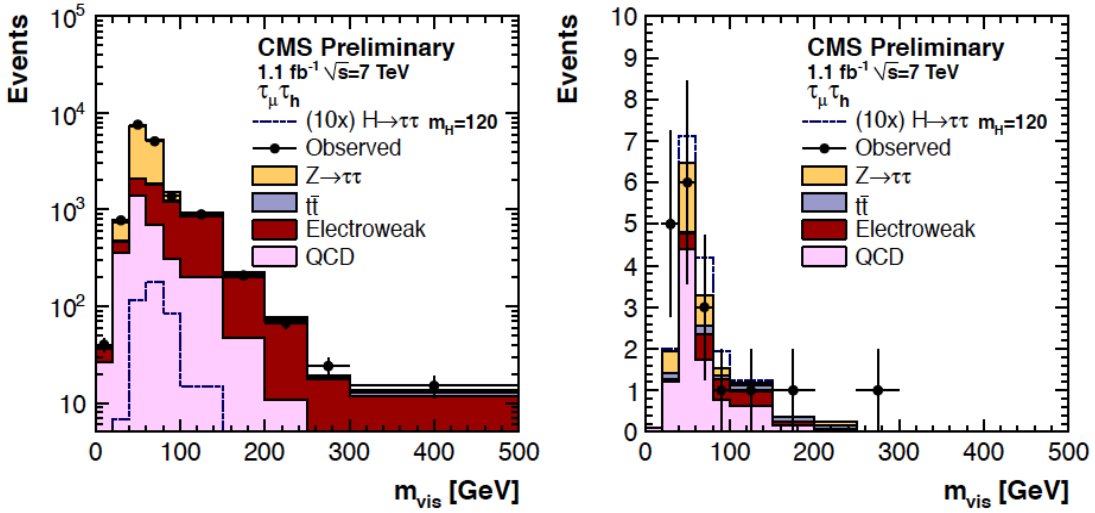


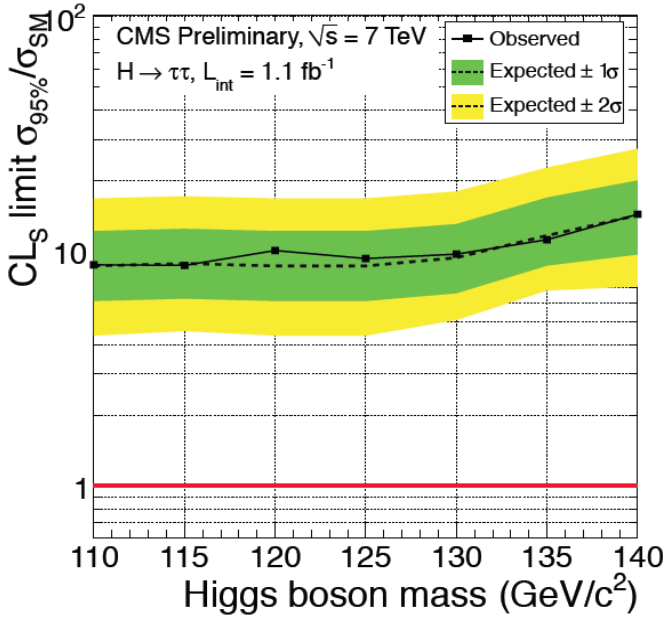


- Candidates divided in 8 classes based on photon shower shape, rapidity and $P_T(H)$
- Unbinned fit to the obtained m_H spectra (background shape derived from the fit)
- Observed exclusion 2-7 σ_{SM}.
- Mass resolution 1-2%: **high LEE trial factor of 20. Probability to see same of higher excess is about 60%.**

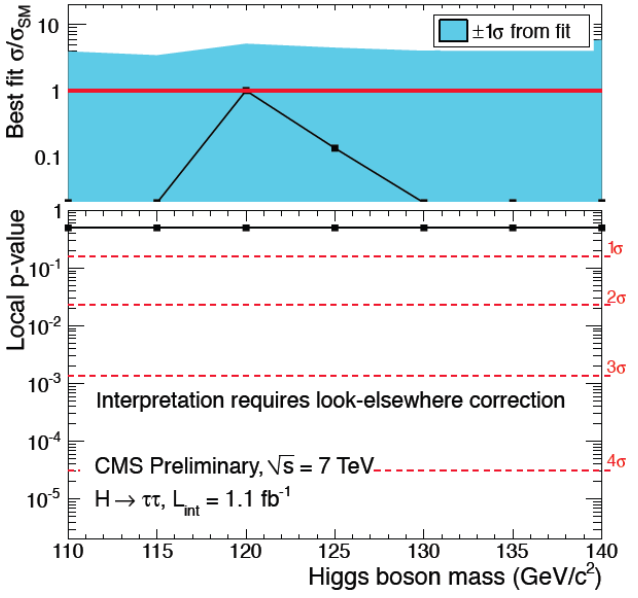
H→ττ (Low Mass 110-140 GeV)

$H\rightarrow\tau_\mu+\tau_{had}$ (non-VBF and VBF)

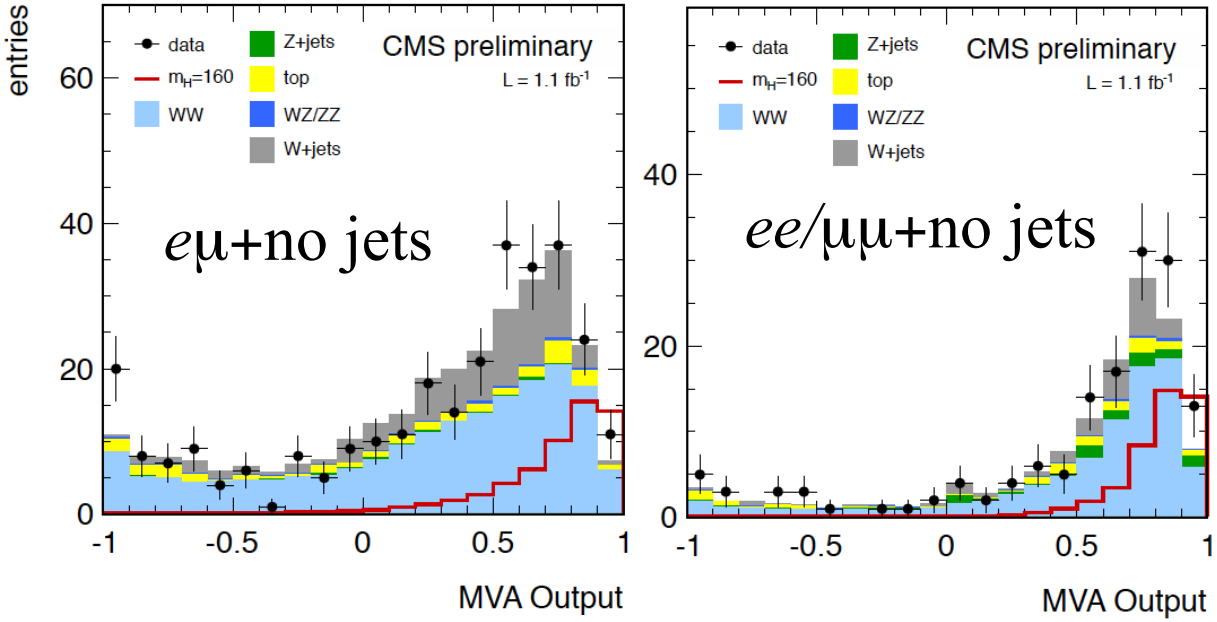


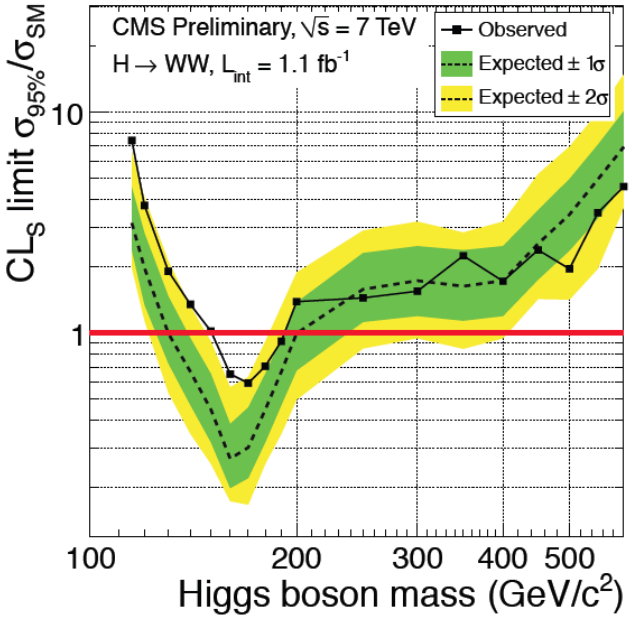


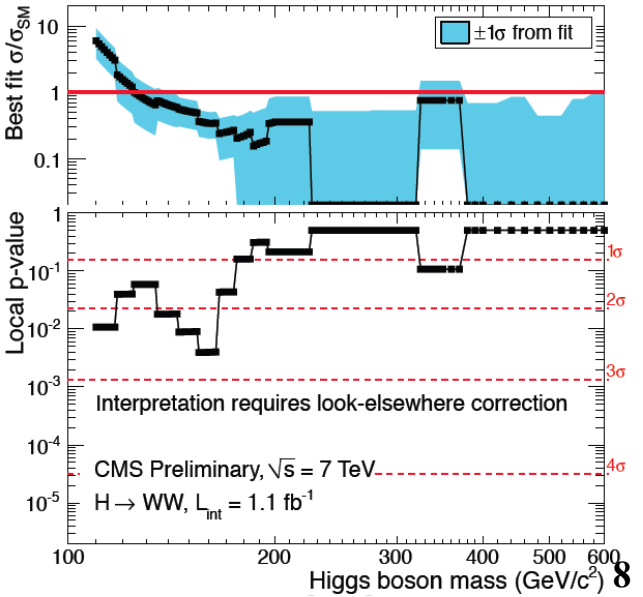
- Binned fit to m_{vis} distributions in 6 exclusive final states ($\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_\mu$) x 2 (VBF + non-VBF)
- No significant excess.
  Observed exclusion ~10 σ_{SM}.
- LEE trial factor of 1.



H→WW→2ℓ2ν: Entire Mass Range

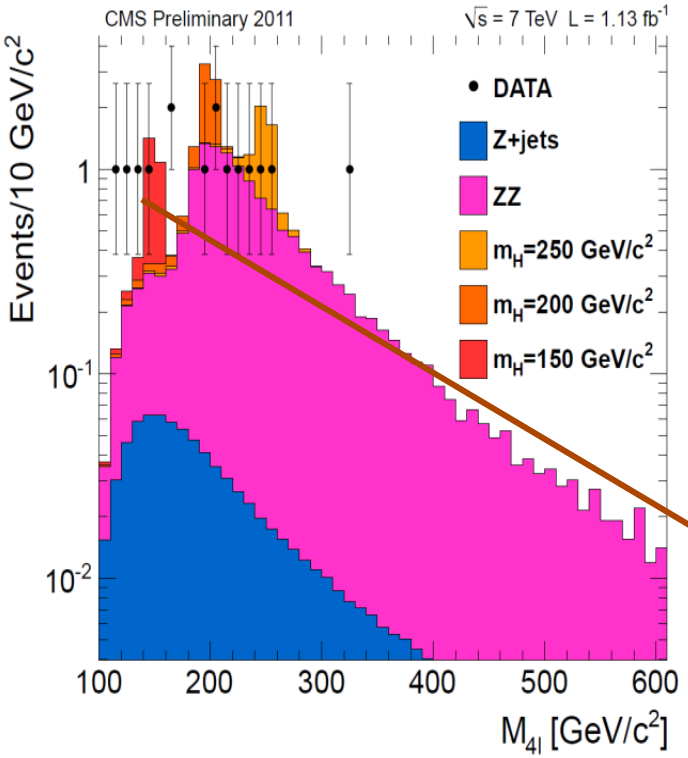




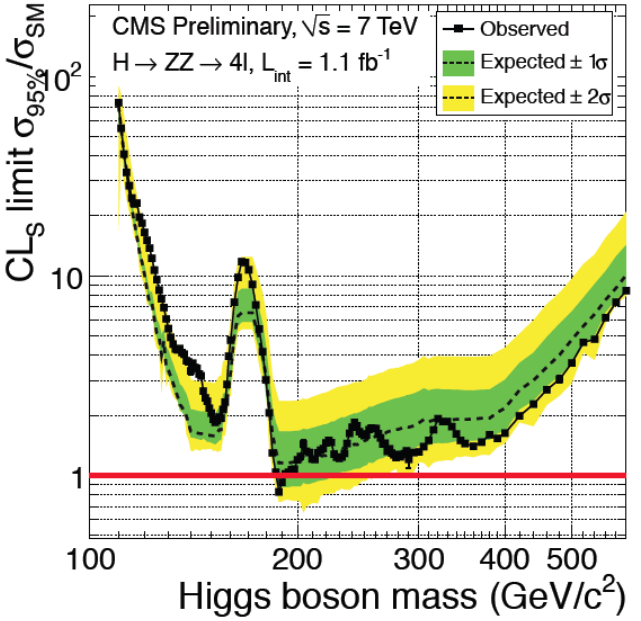


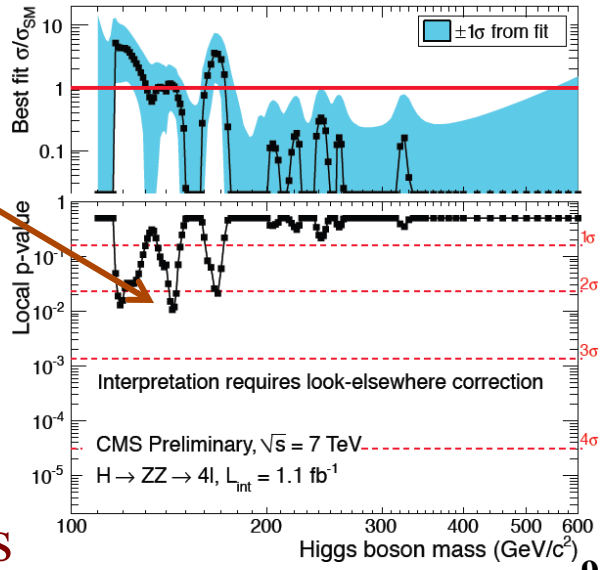
- Binned MVA-output shape analysis (+0/1 jets) + cut-and-count for the +2jets category
- Observed exclusion for m_H=150-193 GeV
- Some excess of events observed at low masses: roughly +2σ deviation in 110-160 GeV
- Equivalent mass resolution is low with the LEE factor estimated to be ~3
- Inconsistent with the SM Higgs <120 or > 150 GeV.

H→ZZ→4ℓ: Low/High Masses



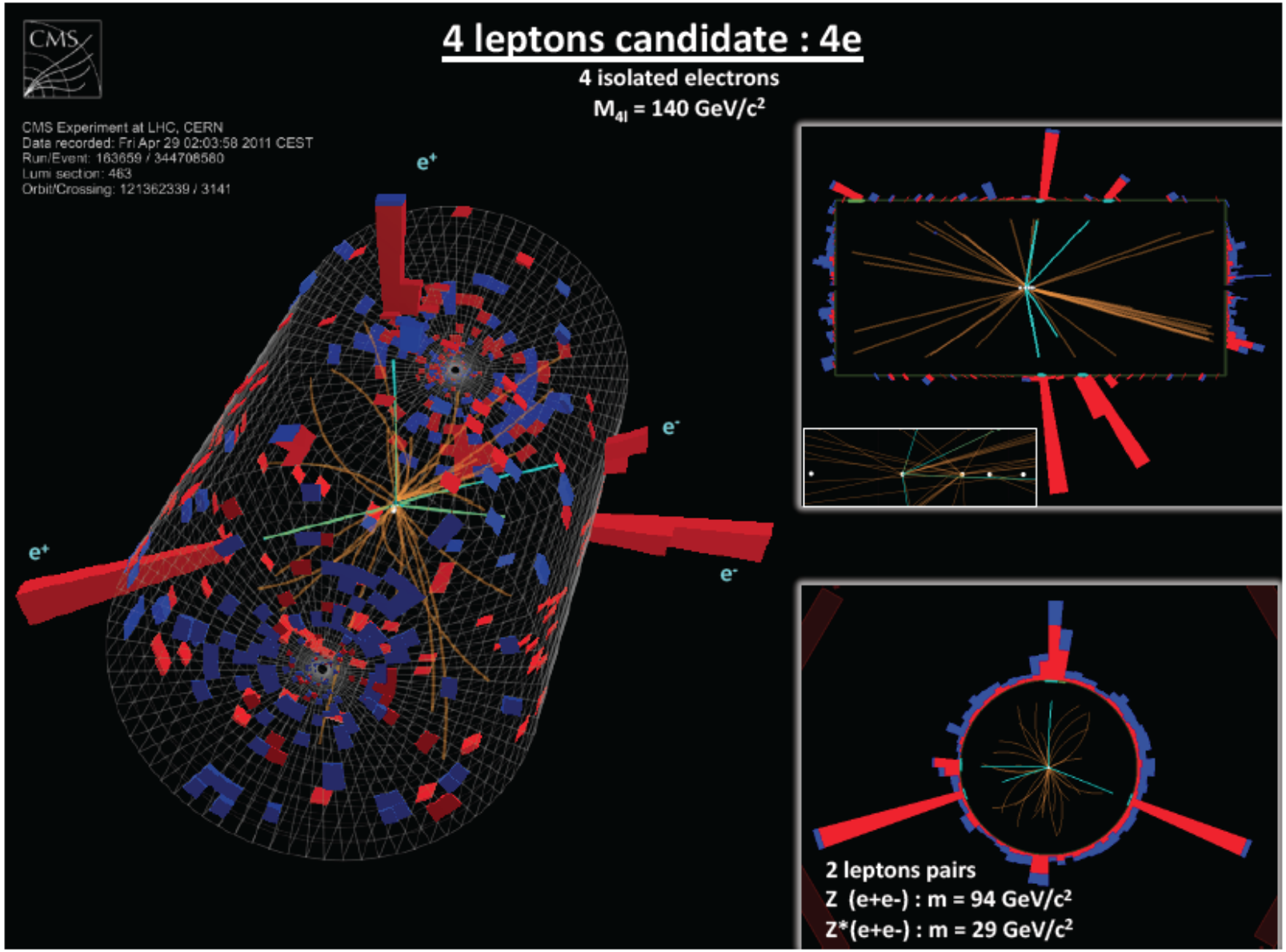
- 15 events in data, 14.4+-0.6 expected
- But for $M_H<2M_Z$ 6 events in data with 1.9+-0.1 expected
  3 event pairs ~120,140,160 GeV



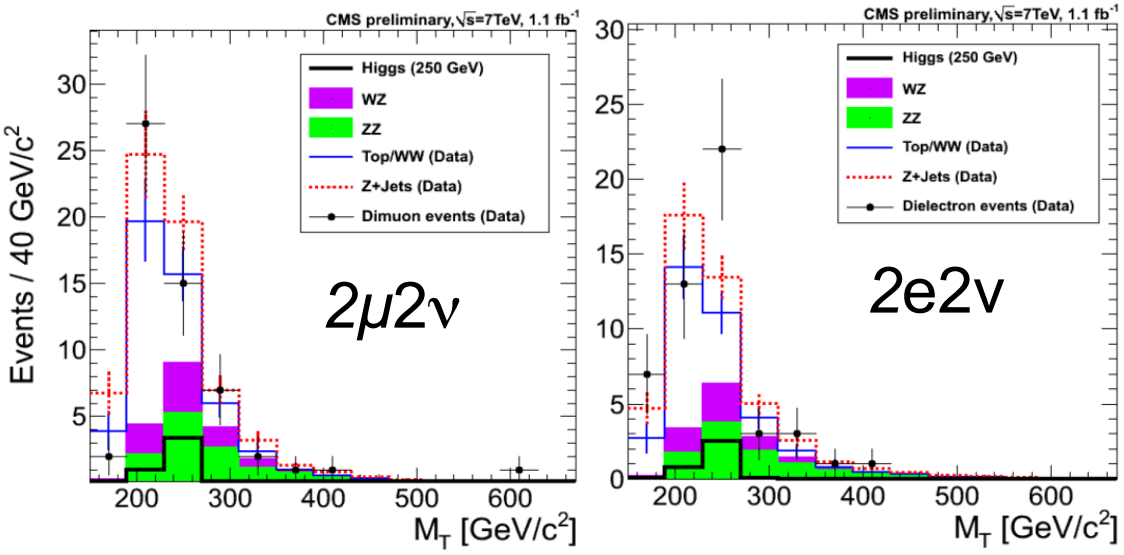


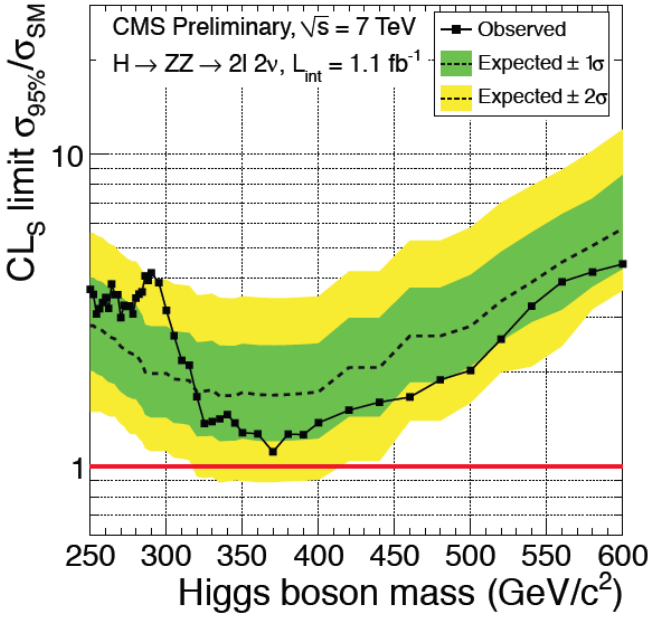
- Unbinned M(4ℓ) analysis in three event categories (4e, 4μ, 2e2μ)
- Observed exclusion 1-100 σ_{SM}
- Mass resolution 1-2%: **high LEE trial factor of ~100.**
- Only the m_H~140 GeV would work for SM Higgs

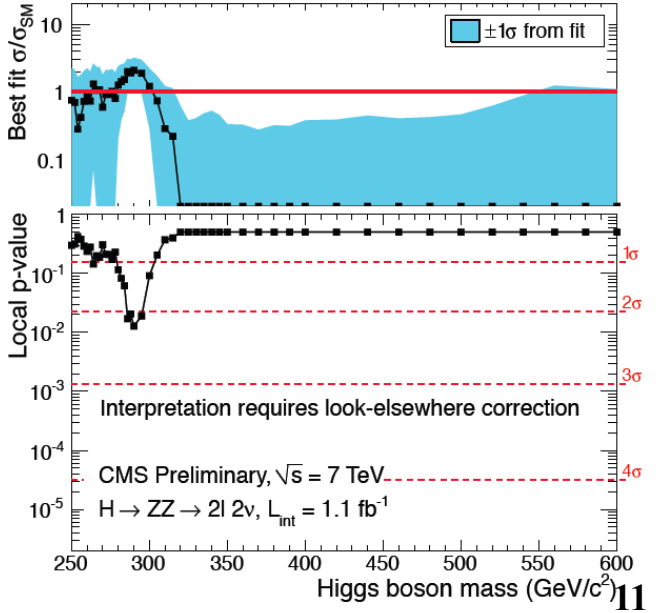
H→ZZ→4e: an Event



H→ZZ→2ℓ2ν: High Mass (>250 GeV)

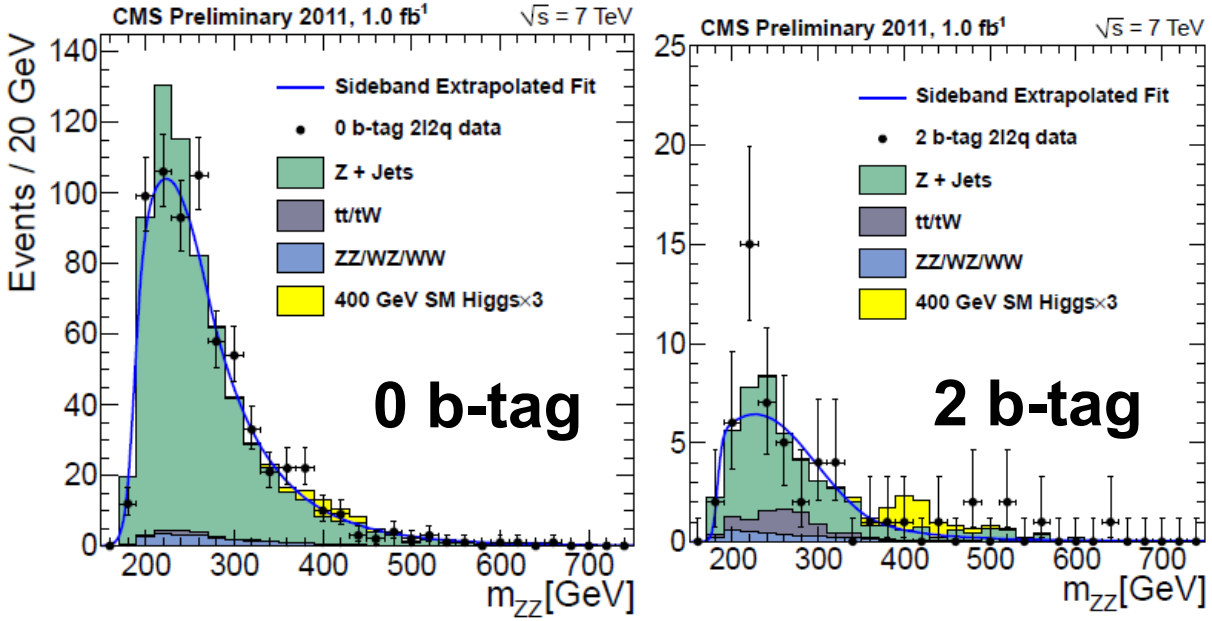


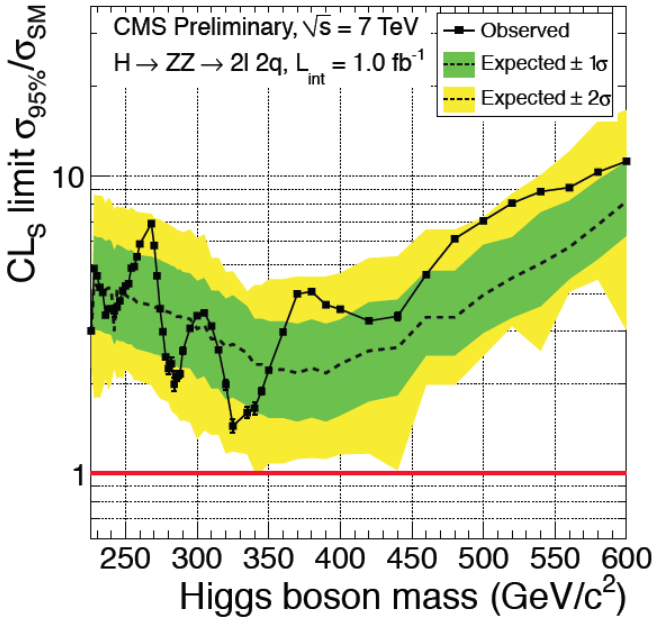




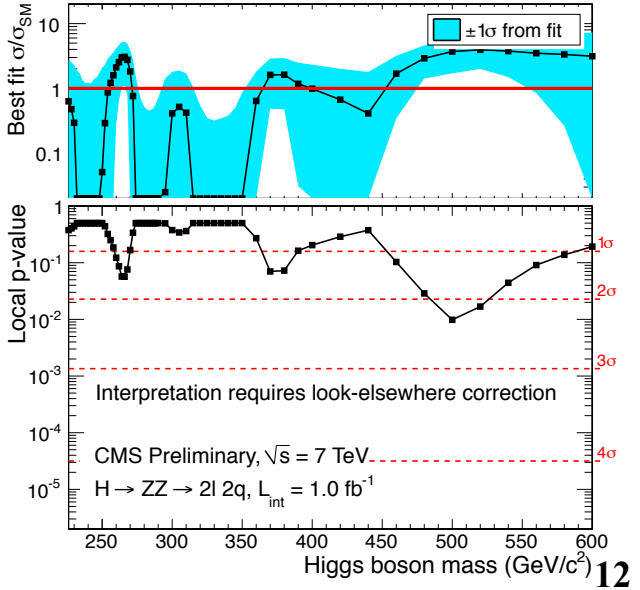
- Cuts-and-count in two categories, with sliding cuts as function of m_H
- Observed exclusion 1-4 σ_{SM}
- Mass resolution ~15%: moderate LEE
- One ~2σ excursion near m_H=290 GeV; would require ~2σ_{SM} cross section, if real.

H→ZZ→2ℓ2j: High Mass (>250 GeV)

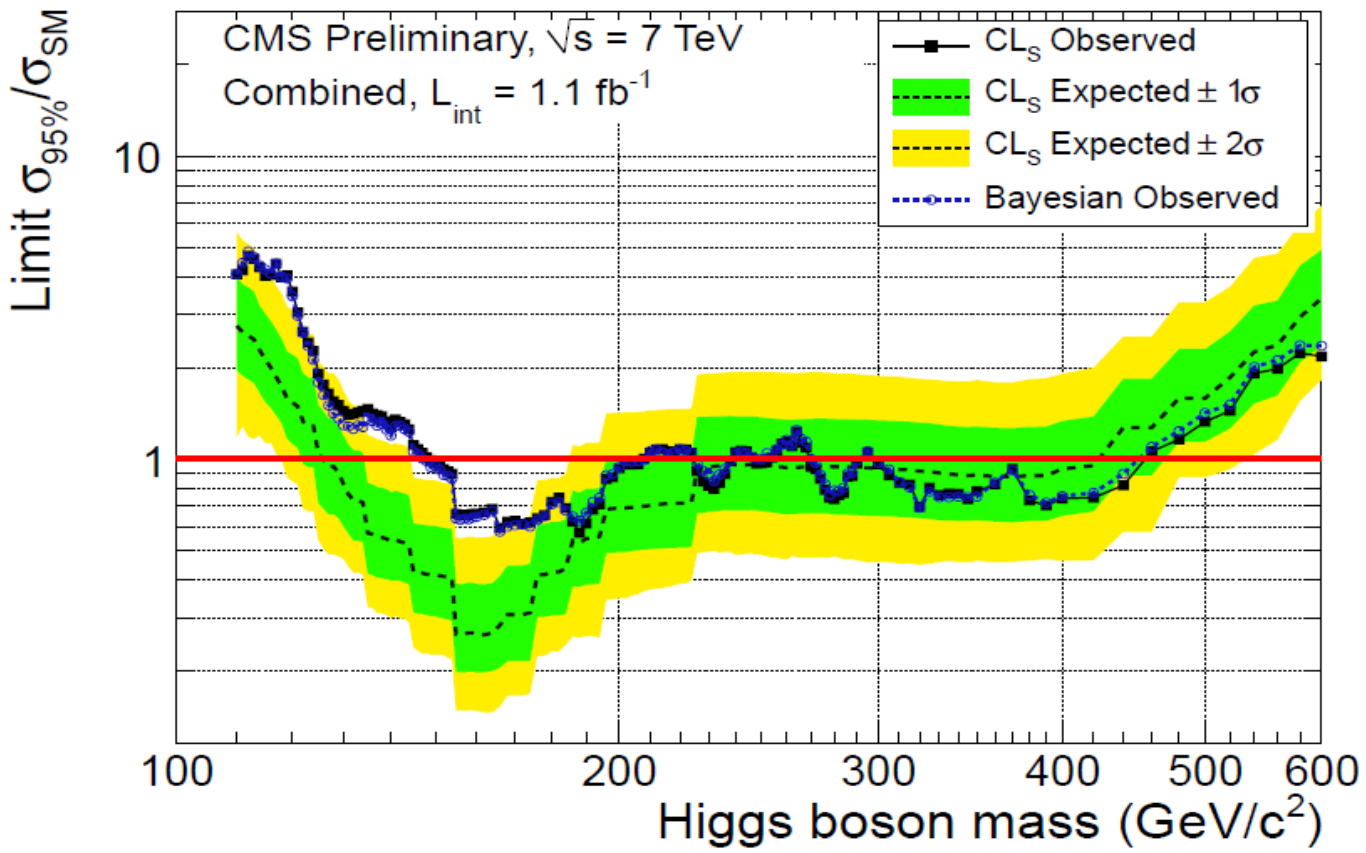




- Unbinned M(2ℓ2j) analysis in six event categories: (2e2j,2μ2j) x (0,1,2 b-tag)
- Observed exclusion 2-10 σ_{SM}
- Mass resolution ~10%: moderate LEE
- One ~2σ excursion near m_H=500 GeV; would require ~3σ_{SM} cross section, if real.

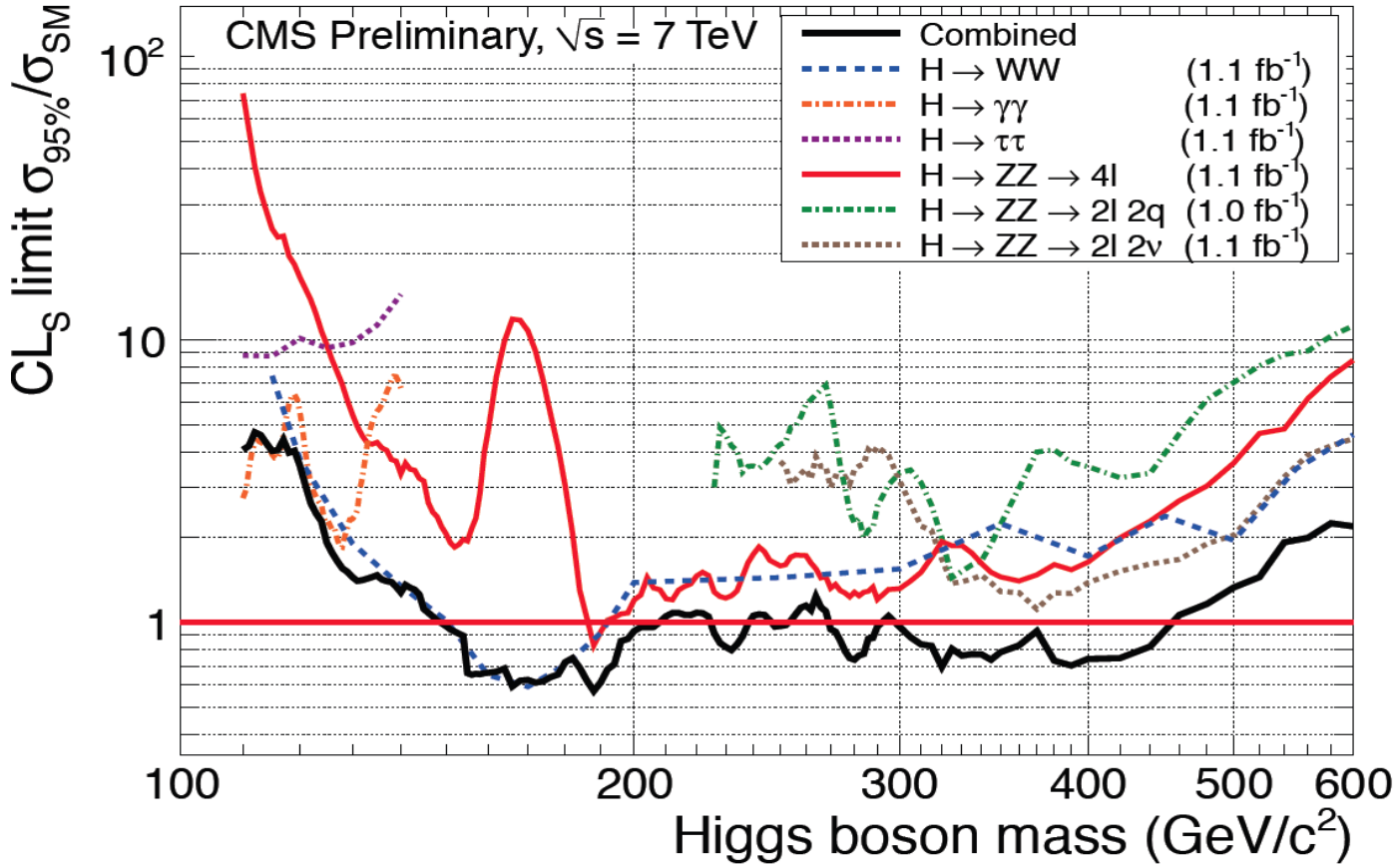


Combined 95% CL Limit on σ/σ_{SM}



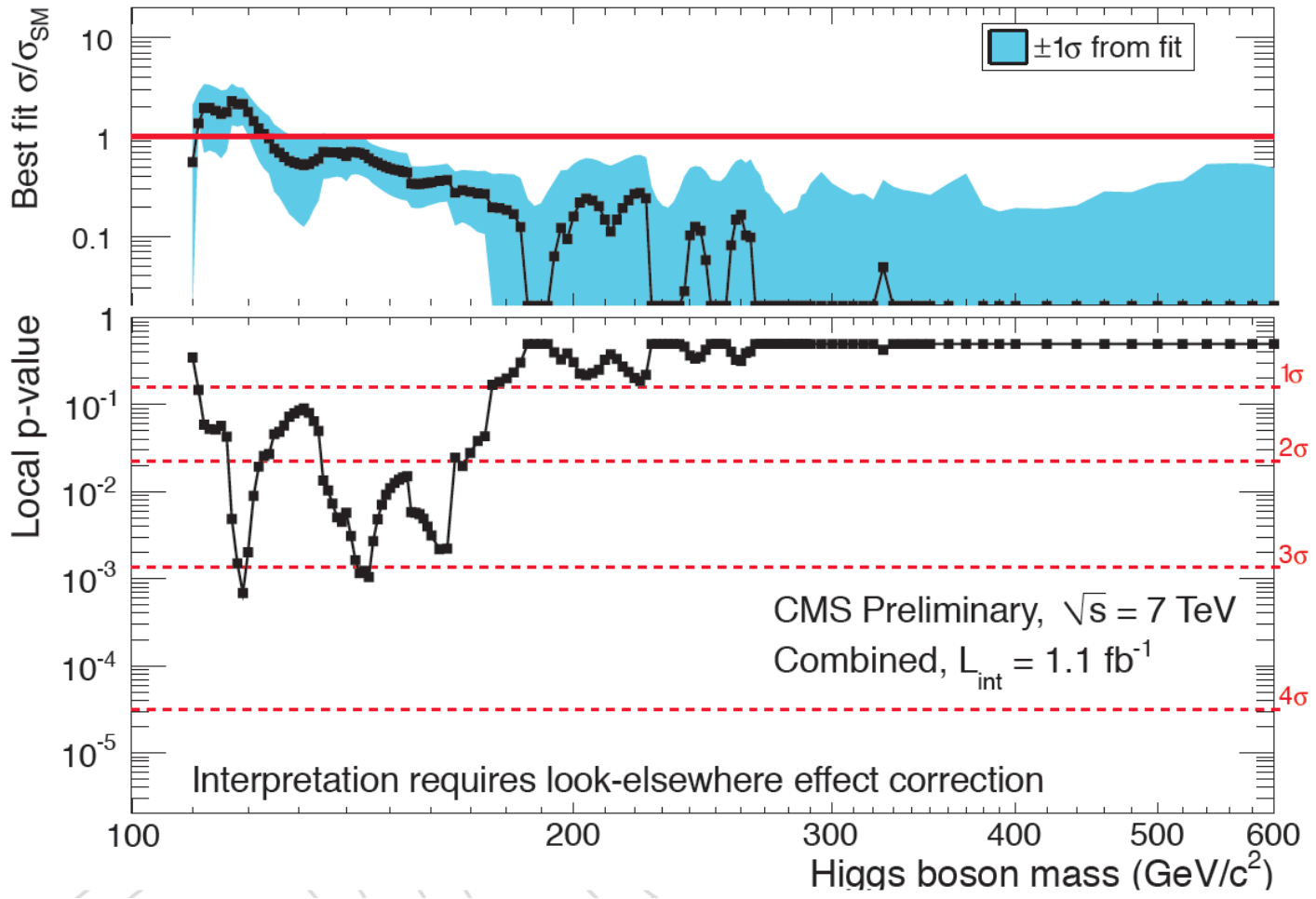
- Observed exclusion regions: **149-206 and 300-440 GeV** (and three short segments in between); Expected exclusion region **127-420 GeV**
- Remarkable agreement between the CLs and Bayesian: **0.3+-4.6%**
- Excess at low m_H due to H→WW with a little help from H→ZZ→4ℓ

Interplay of the Six Channels



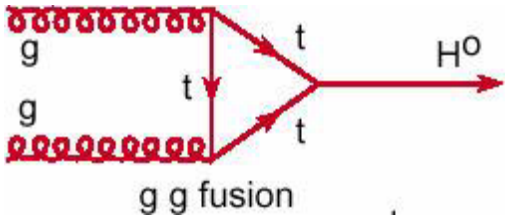
- At high masses, the combination gives a large gain in the observed limit over all individual analyses.
- At low masses, the excess in the H→WW channel dominates the observed limit, making it equal or event more conservative than the limit produced by the H→γγ search alone.

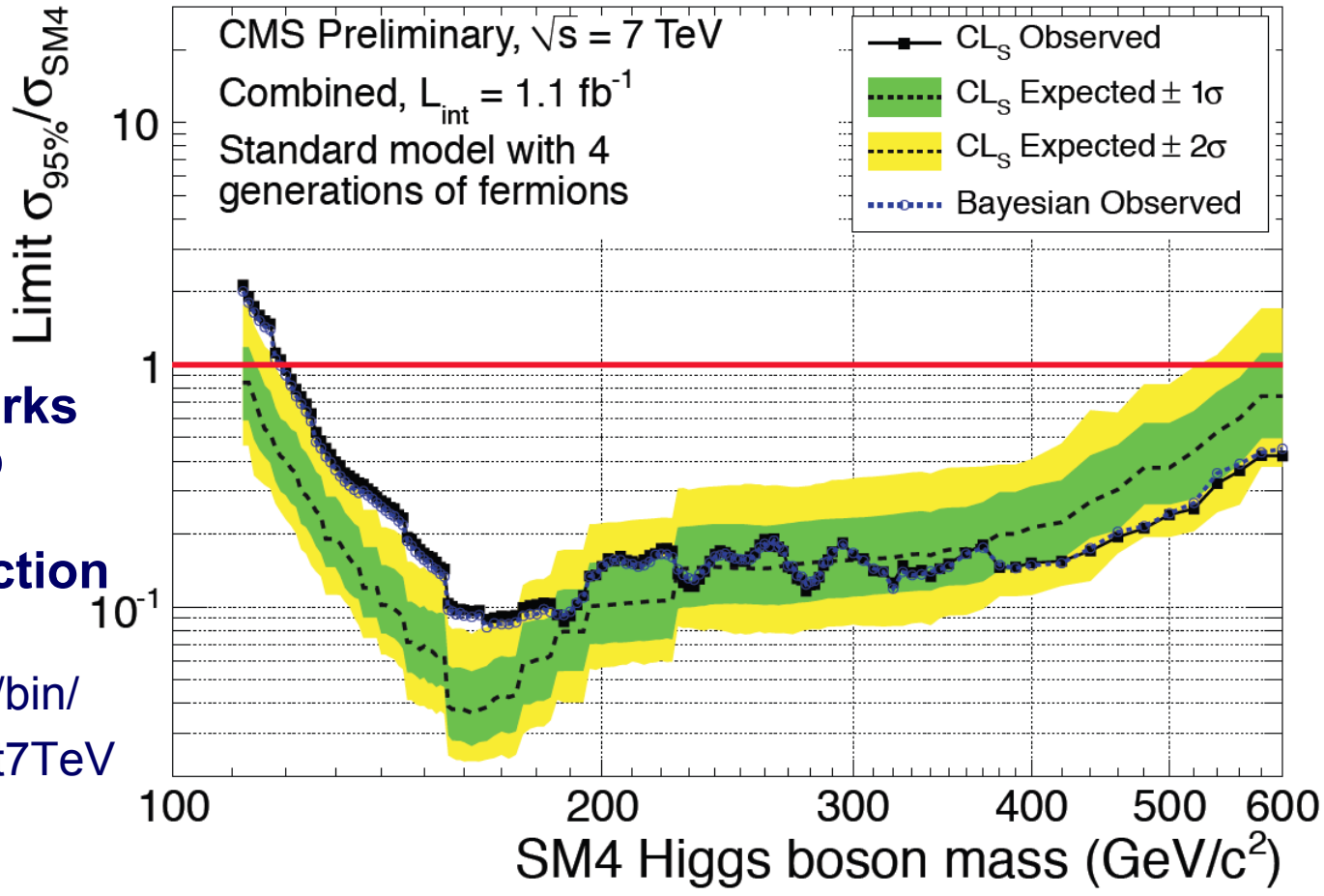
Local p-values and σ/σ_{SM}



- **Recall: small local p-value means an excess, not a proof of signal.**
- **LEE effect for the combination is not yet determined; individual channels entering the combination have LEE from O(1) to O(100).**

Case of a Heavy 4th Generation





Two extra heavy quarks in the gg-fusion loop would enhance the production cross section by O(10)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SM4At7TeV

Assuming a 4th heavy fermion generation, such SM4 Higgs boson is excluded in the range of m_H=120-600 GeV (95% CL)

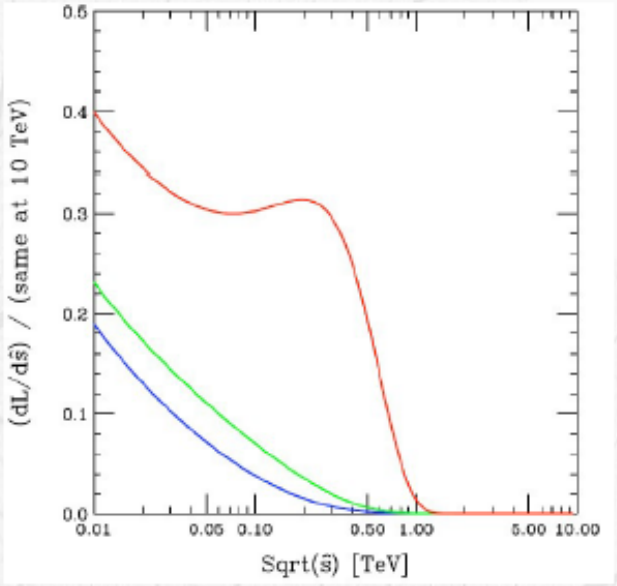
SM Higgs Search Summary

- SM Higgs boson, searched over the mass range of 110-600 GeV. No (very) significant excesses observed.
  - ➡ Excluded at 95% C.L. in two regions 149-206 GeV and 300-440 GeV, and a few segments in between
  - ➡ Excluded at 90% C.L. in the region 145-480 GeV
- SM4 Higgs boson
  - ➡ Excluded at 95% C.L. from 120-600 GeV

- Disentangling the source(s) of some event excesses in the low mass analyses will require more data, which is rapidly coming in this stellar year of the LHC
- Update with ~50% more integrated luminosity will be shown at the Lepton-Photon conference in two weeks!

DPF 2009,What we expected: 10TeV?

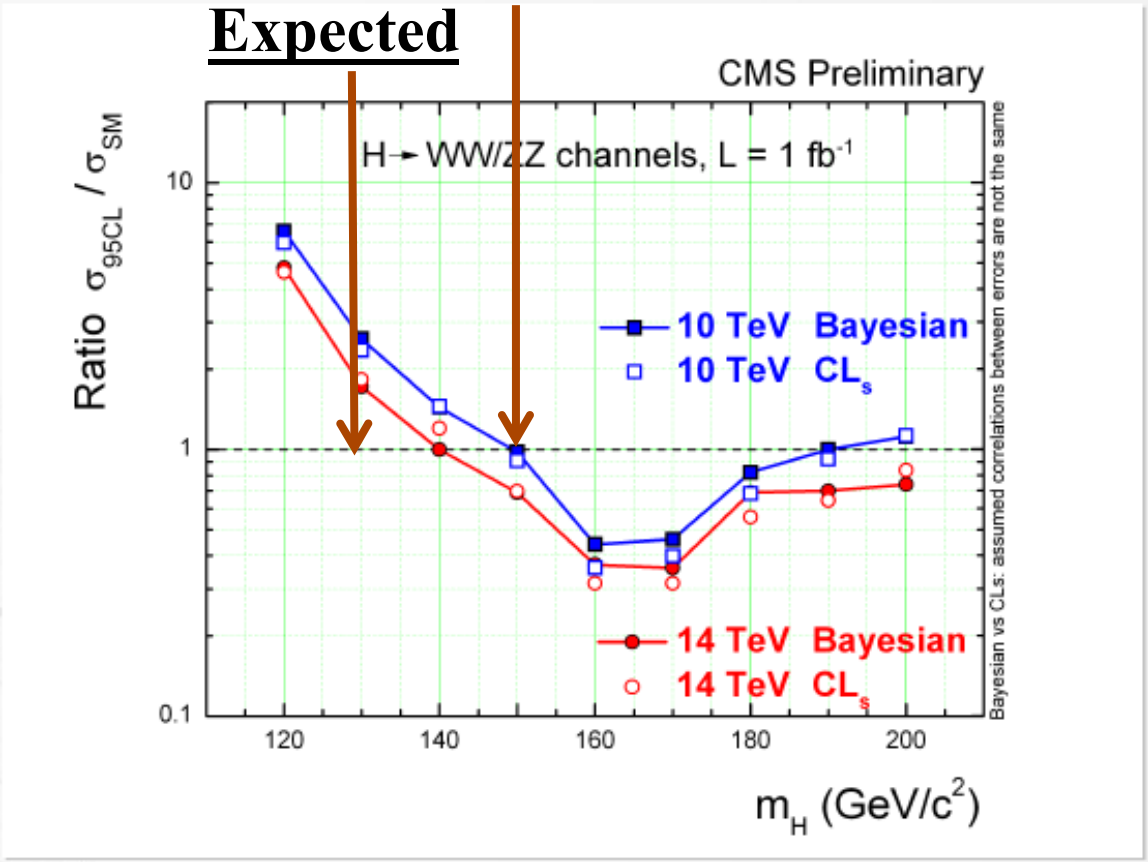
- At Chamonix'09 workshop on LHC it was decided to start with 10TeV
  - Cross sections go down with decreased energy. And for signal they go down faster (gluon fusion) then for backgrounds (qq in initial state).



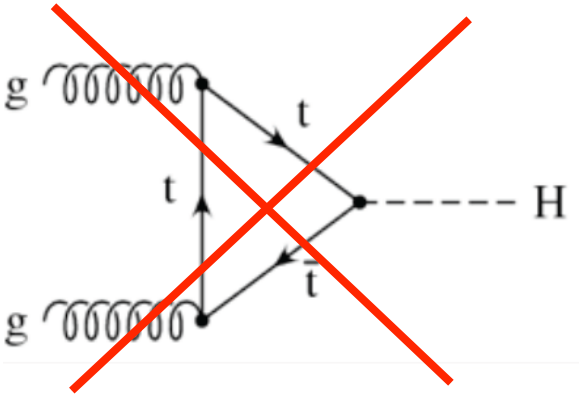
From Joey Huston's talk (for CTEQ collaboration) at CMS Higgs PAG meeting from March 27

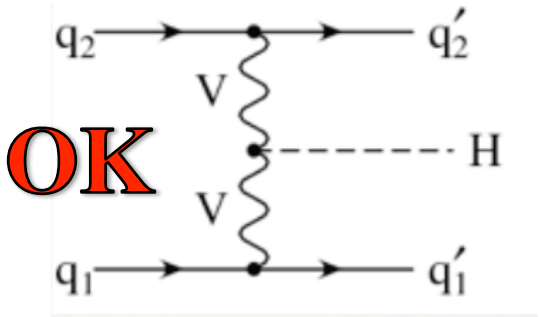
1fb^{-1} at 7 TeV Observed

Expected



Fermiophobic Higgs Scenario





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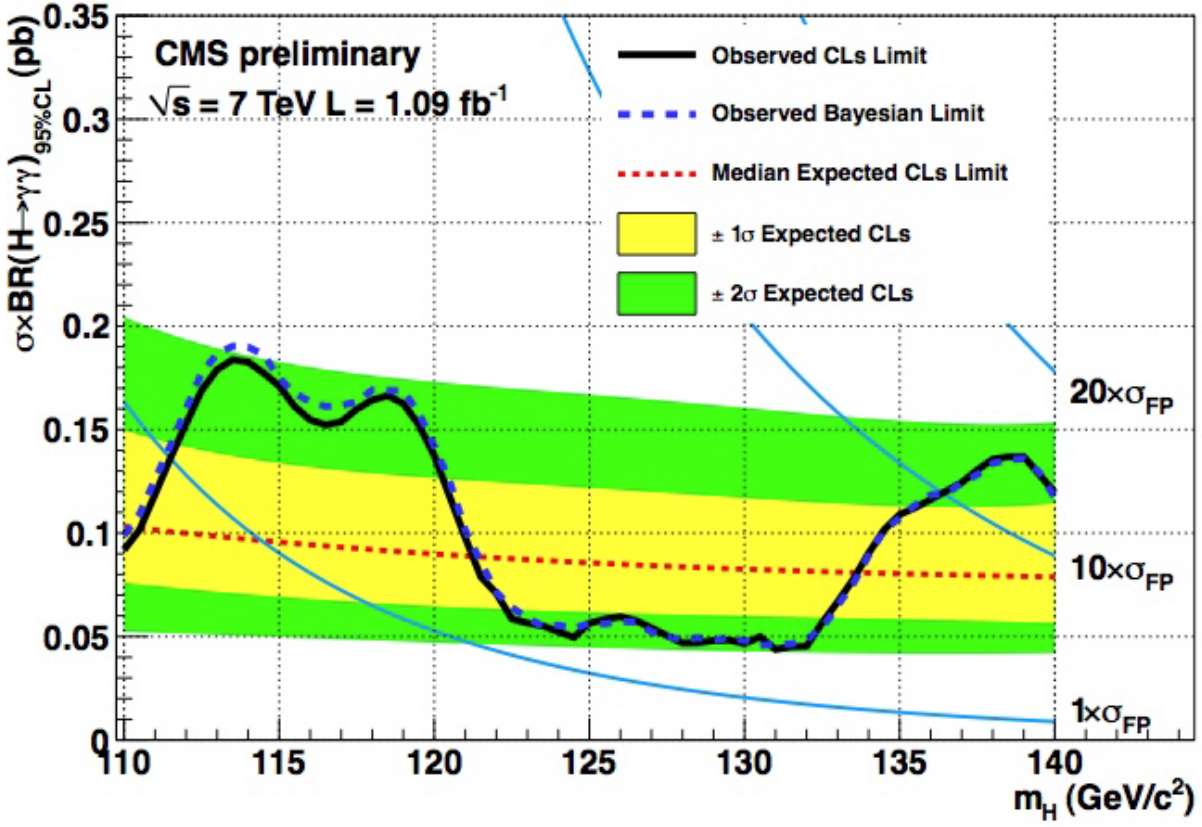

- Coupling to fermions is forbidden: <u>BR(H→γγ) is enhanced</u>
- Observed mass limit is m_H>111 GeV
- Within 2σ of the expectation (see CMS PAS HIG-11-010)
  http://cdsweb.cern.ch/record/1369553?ln=en

Conclusion

- **Detailed descriptions of the combination and searches in individual channels can be found at**

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

  In particular, please see the CMS Physics Analysis Summaries at

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

  starting with the CMS PAS HIG-11-011 "SM Higgs Combination"

  http://cdsweb.cern.ch/record/1370076?ln=en

  and continue to PASes for each subchannel and BSM search.

- **It is a great honor to present these exciting results on behalf of the CMS Collaboration**

SM Higgs Search Summary (déjà vu)

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