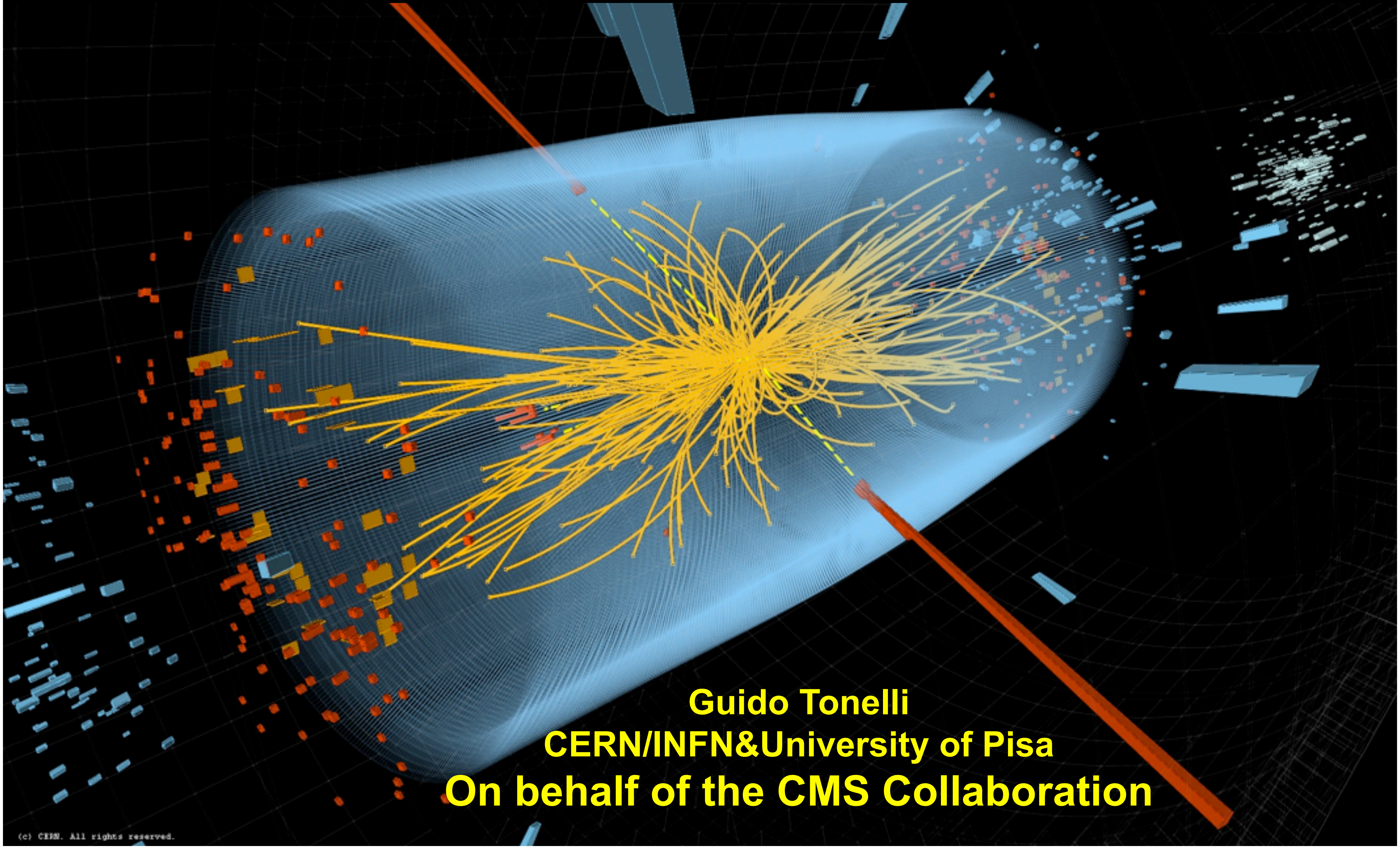
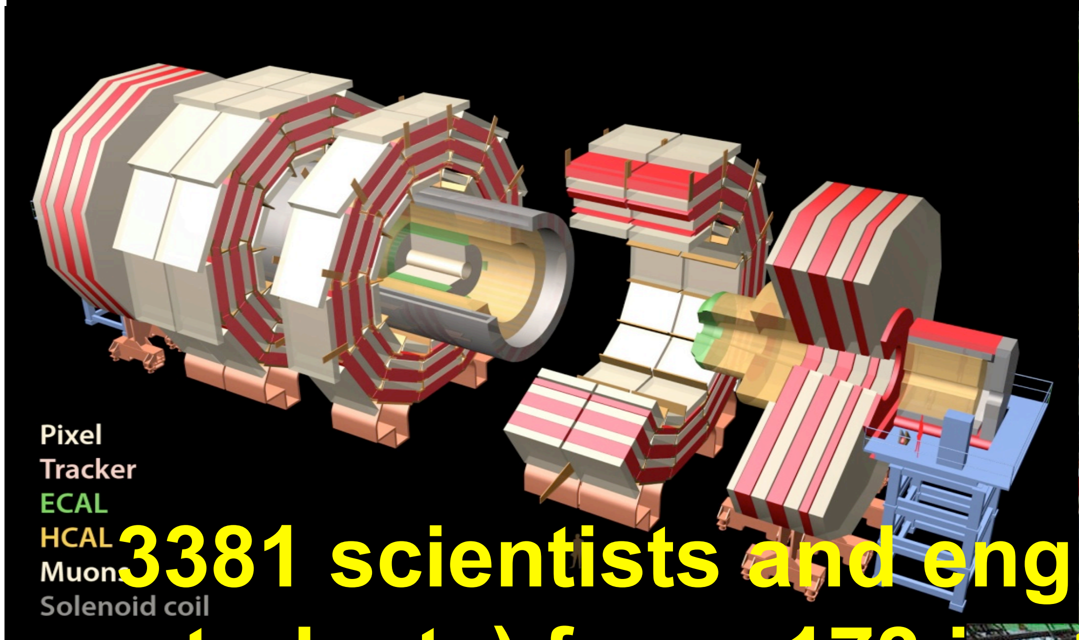
Update on the SM Higgs Search with CMS

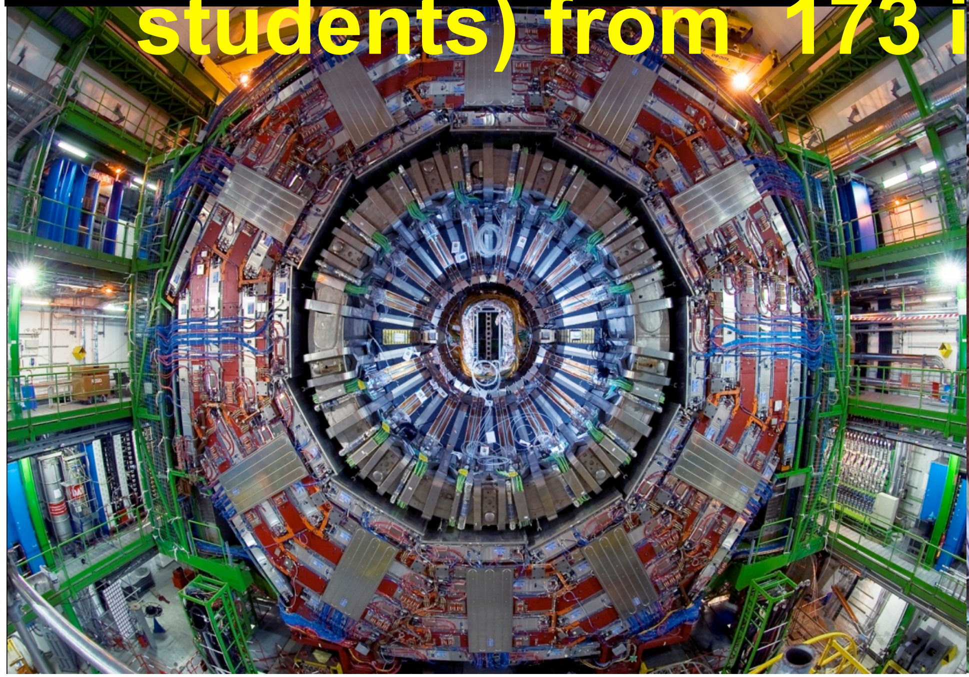


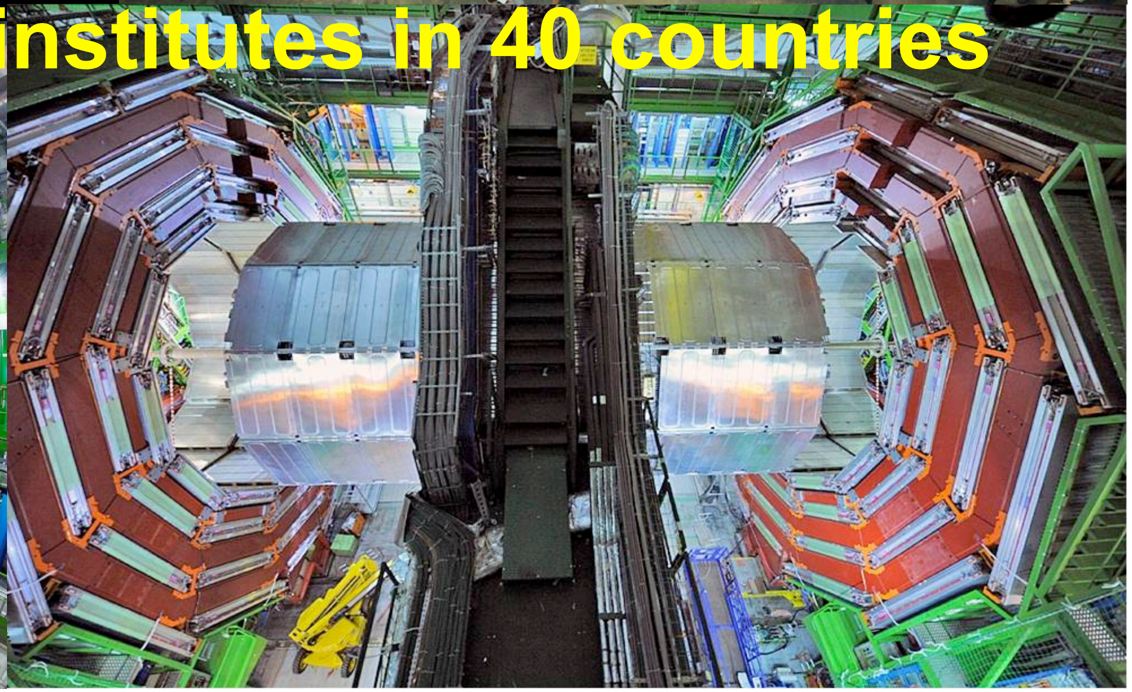
Guido Tonelli
CERN/INFN&University of Pisa
On behalf of the CMS Collaboration

The CMS Collaboration



3381 scientists and engineers (including ~840 students) from 173 institutes in 40 countries





Outline of the talk

- Short introduction.
- Search for a SM Higgs boson in the high mass region.
- Search for a SM Higgs boson in the low mass region.
- Combination of the searches and new exclusion limits.
- Conclusion.

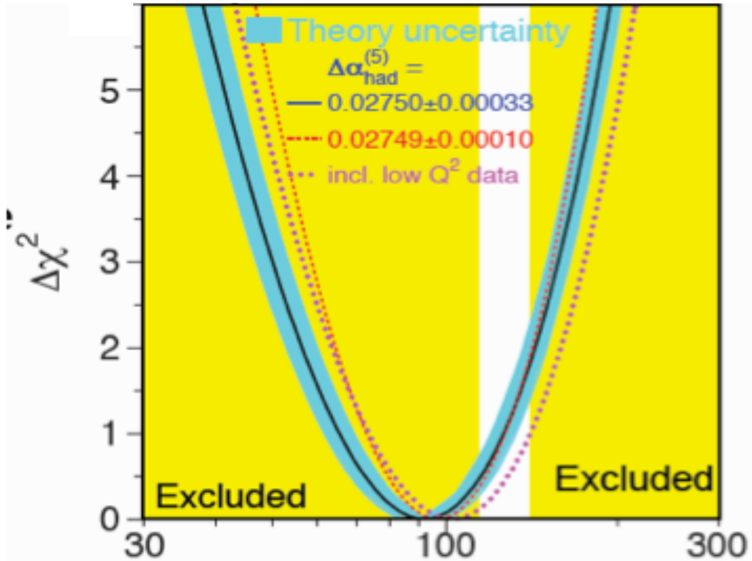
The SM Higgs boson

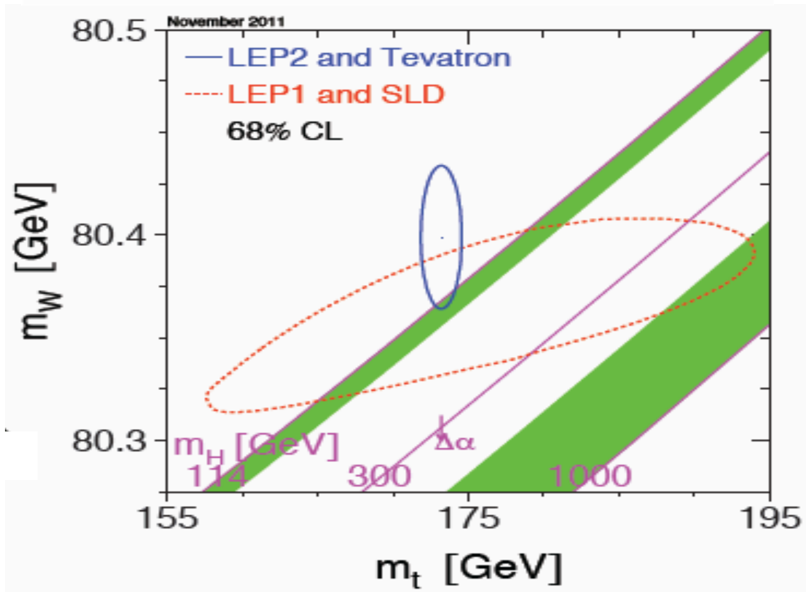
SM Higgs could be an excellent candidate to understand the ElectroWeak Symmetry Breaking mechanism.

Constraints from EWK precision measurements favour a light Higgs with Standard Model like couplings (WW, ZZ).

Recent exclusion limits based on the ATLAS+CMS Combination using 1.1-2.3fb^{-1} of data have costrained significantly the search.

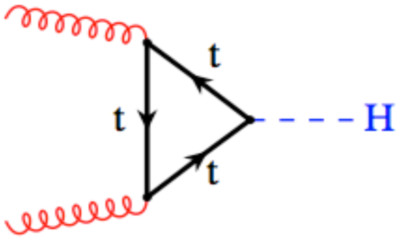
I'll present preliminary results of our exploration in mass up to 600GeV but a special attention will be dedicated to the search of the SM Higgs Boson in the low mass region.



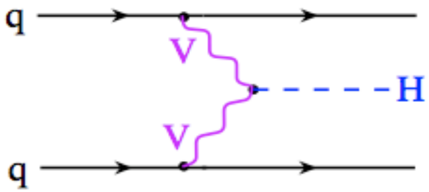


SM Higgs production at LHC

- Gluon fusion

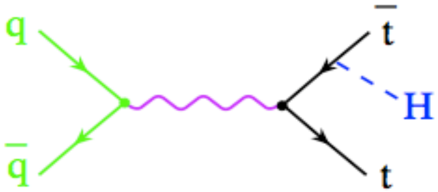


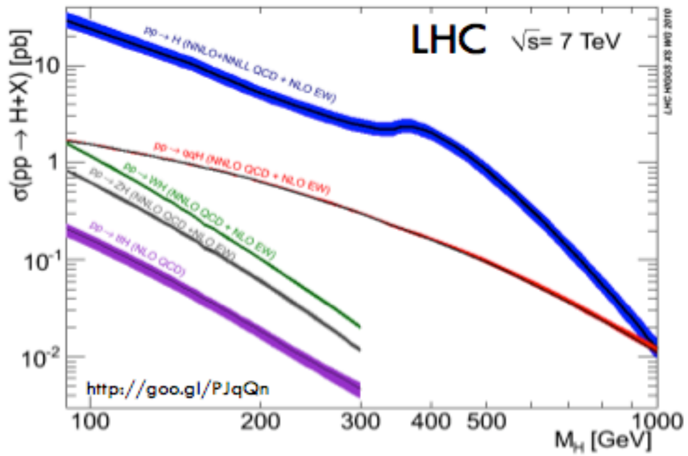
- VBF

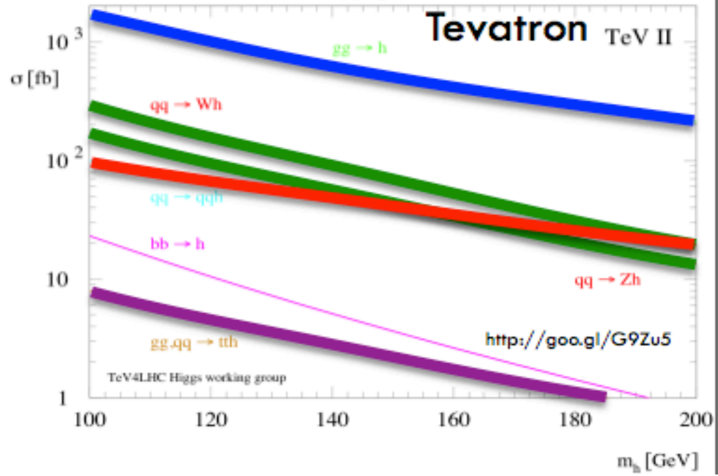


- VH

- ttH



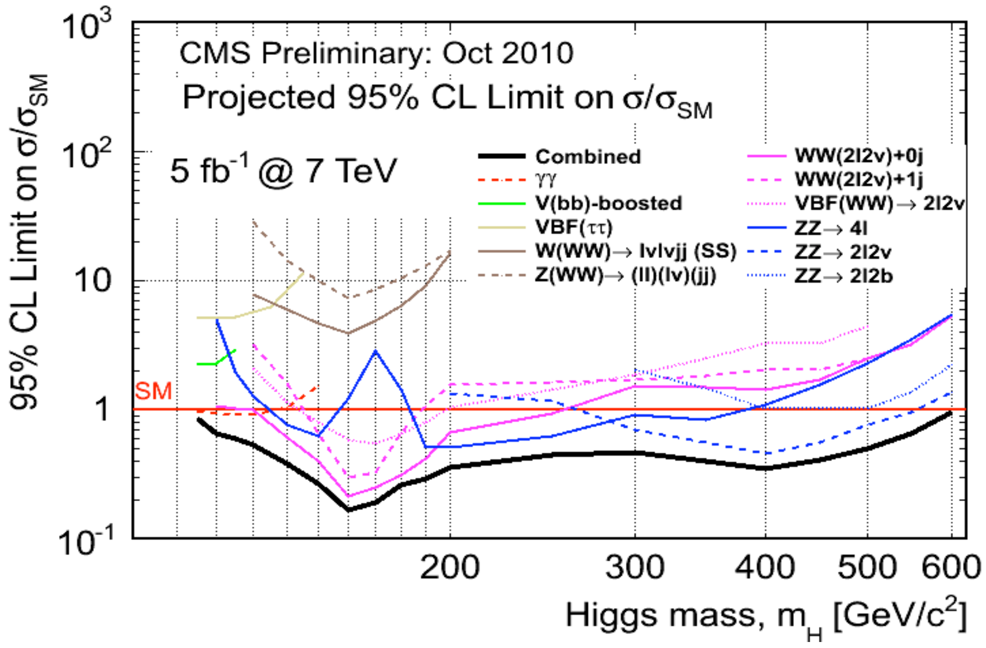




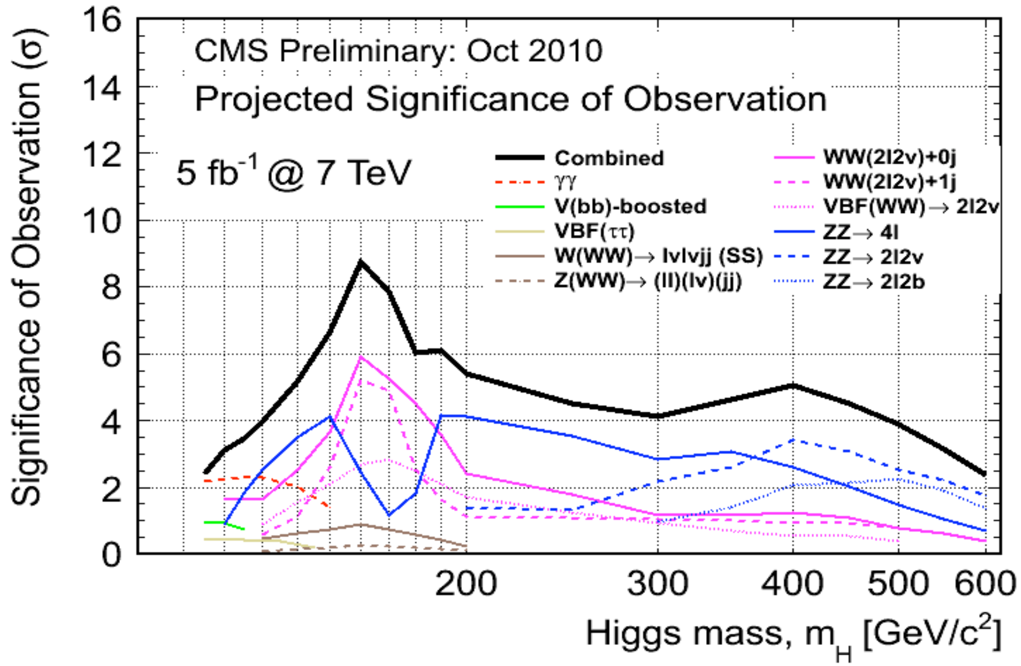
Gluon fusion (gg→ H) is the dominant production mechanism at LHC.
Irreducible backgrounds in H → WW, ZZ, γγ are from qq annihilation. Signal to Noise better than at Tevatron except in VH. **VBF and VH also very useful at LHC**

The challenge

CMS Projected Sensitivity @5fb^{-1}



CMS Projected Significance @5fb^{-1}



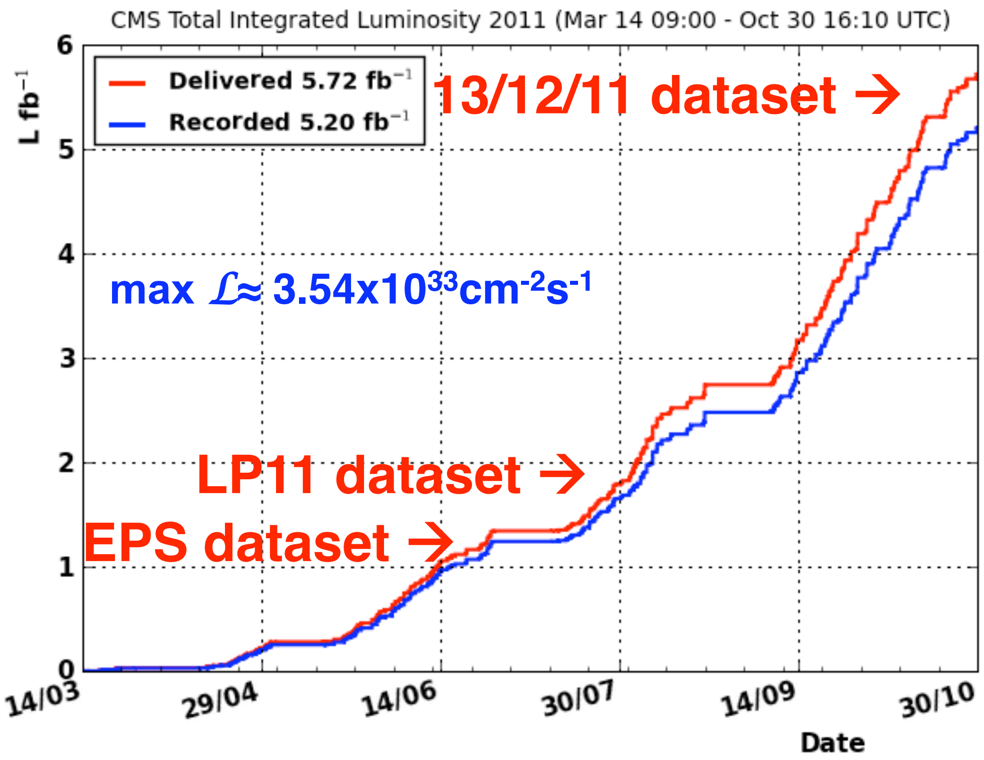
October 2010: with 5fb^{-1} delivered by LHC we could reach a sensitivity below 1xSM in the full mass range.

If the SM Higgs boson would be hidden in the low mass region we could start seeing excesses with a significance of 2-3 sigma.

Every single channel, particularly in the low mass region, brings very important information.

LHC/CMS operations pp@√s=7TeV 2011

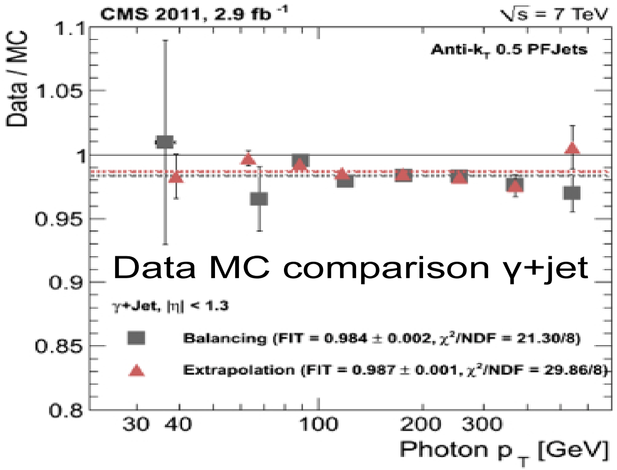
5.72fb^{-1} delivered by LHC and **5.2fb^{-1}** recorded by CMS. Overall data taking efficiency **~91%. Average fraction of operational channels per subsystem >98.5%**



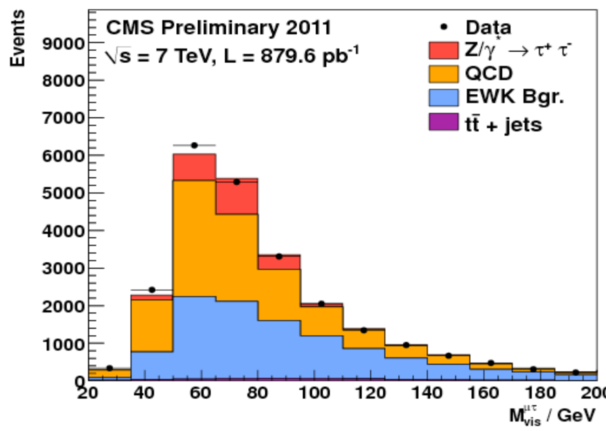
RPC	98.5
CSC	98.3
DT	99.4
HF	99.9
HE	100.0
HB	99.9
ES	95.9
EE	98.6
EB	99.1
STRIP	97.8
PIXEL	96.9

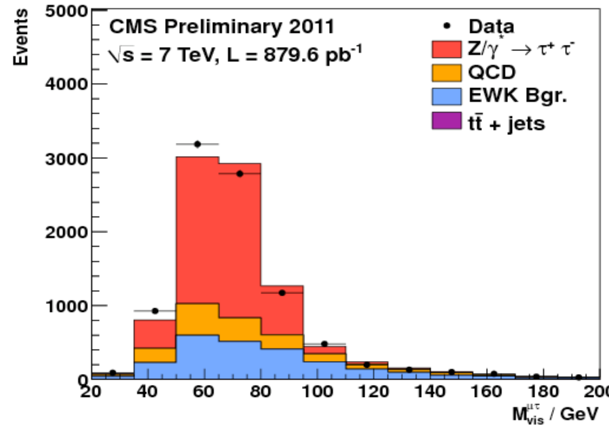
Results shown at this seminar use a large fraction of the full dataset.
Certified data for physics: **Golden 4745pb^{-1} (91.2%), Muon 4965pb^{-1} (~96%)**.
Uncertainty on the luminosity determination **4.5%**.

Excellent understanding of the physics “objects”

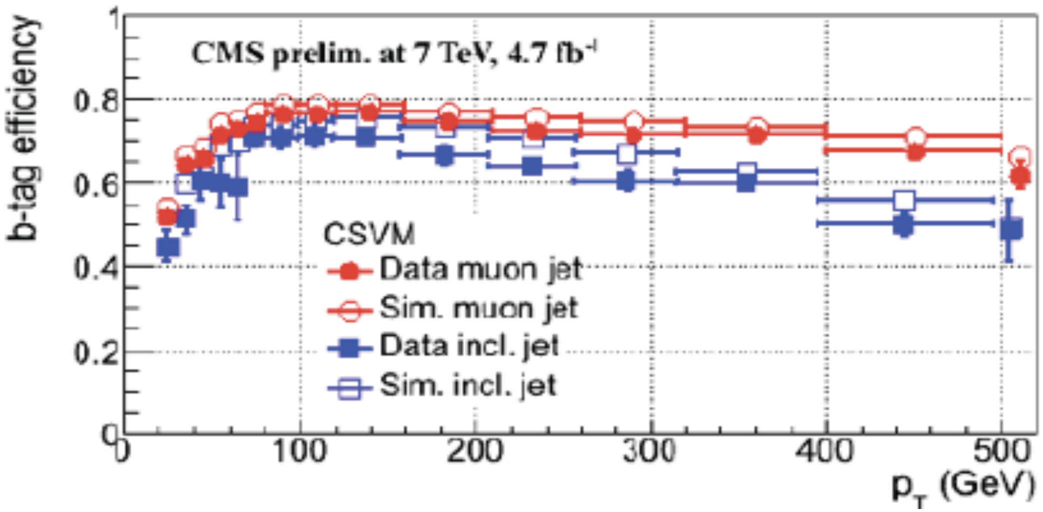


Jet Calibration with pileup

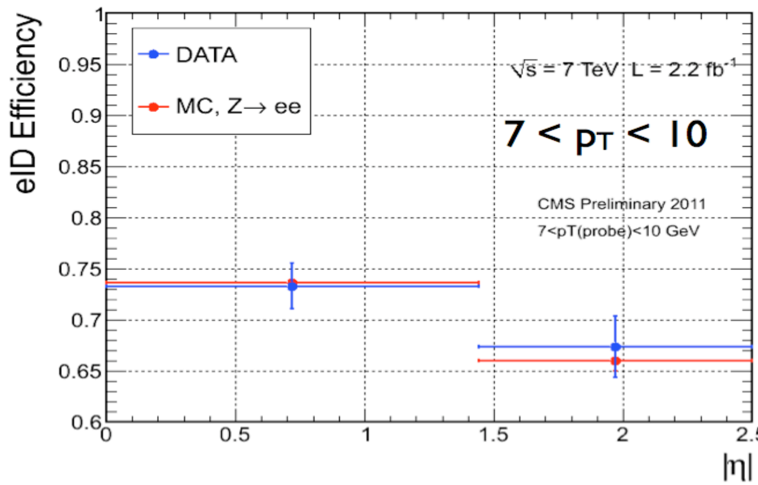




Tau efficiency with T&P on the Z measured to 6%

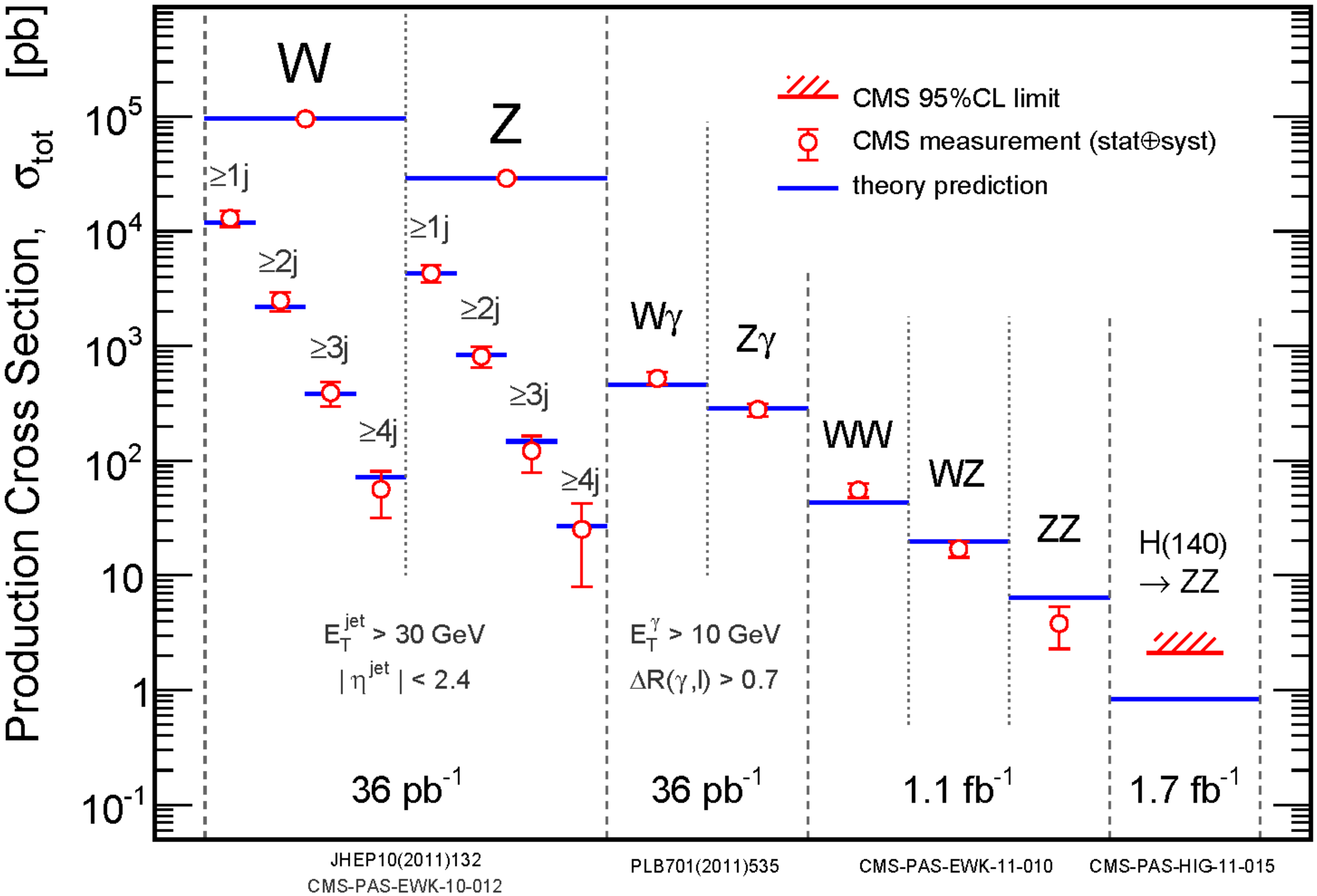


B- tagging efficiency measured to 10% up to 500 GeV

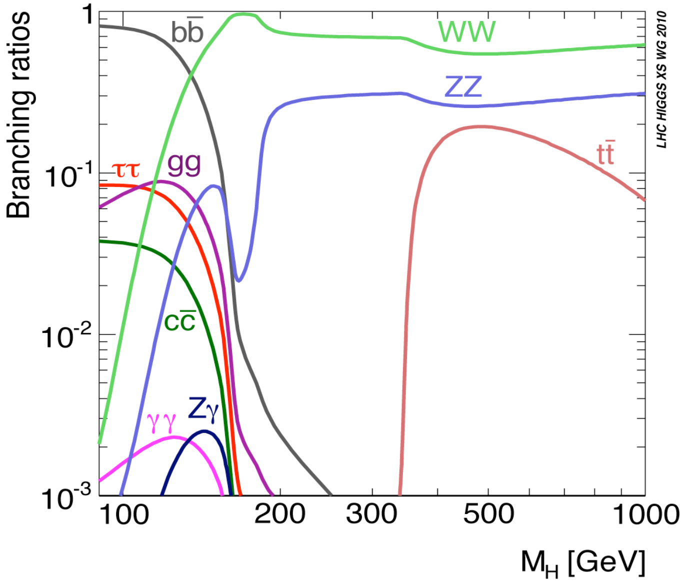


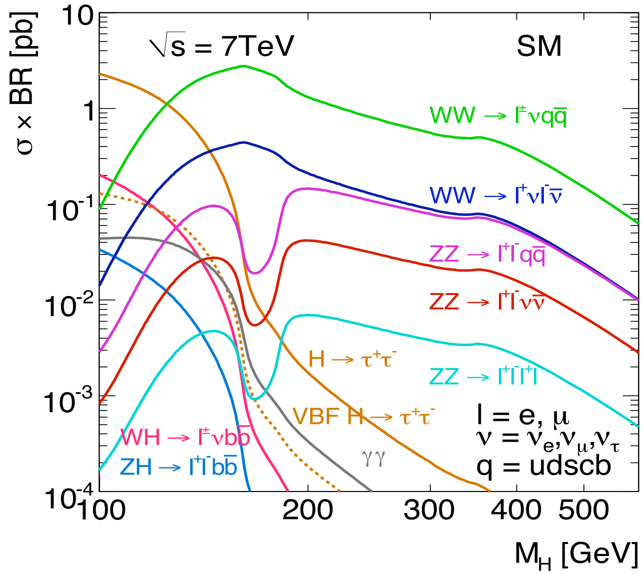
Electron efficiency with T&P on the Z measured down to 7 GeV

Some of the key SM background



SM Higgs Decay Modes Vs Mass





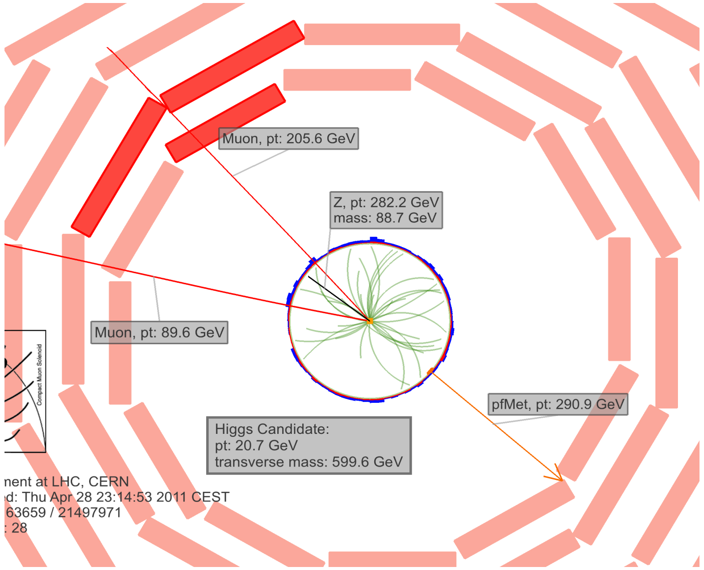
Mode	Mass Range	Data Used (fb^{-1})	CMS Document
H → γγ	110-150	4.7	HIG-11-030
H → bb	110-135	4.7	HIG-11-031
H → ττ	110-145	4.6	HIG-11-029
H →WW →2l 2ν	110-600	4.6	HIG-11-024
H → ZZ →4l	110-600	4.7	HIG-11-025
H → ZZ →2l2τ	190-600	4.7	HIG-11-028
H → ZZ →2l2j	130-165/200-600	4.6	HIG-11-027
H → ZZ →2l2ν	250-600	4.6	HIG-11-026

Analyses presented here

Channel	m_H range (GeV/c^2)	Lumi (fb^{-1})	sub-channels	m_H resolution
$H \to \gamma\gamma$	110 – 150	4.7	4	1–3%
$H \to \tau\tau$	110 – 145	4.6	9	20%
$H \to bb$	110 – 135	4.7	5	10%
$H \to WW \to \ell\nu\ell\nu$	110 – 600	4.6	5	20%
$H \to ZZ \to 4\ell$	110 – 600	4.7	3	1–2%
$H \to ZZ \to 2\ell 2\tau$	190 – 600	4.7	8	10–15%
$H \to ZZ \to 2\ell 2\nu$	250 – 600	4.6	2	7%
$H \to ZZ \to 2\ell 2q$	130 – 164 200 – 600	4.6	6	3%

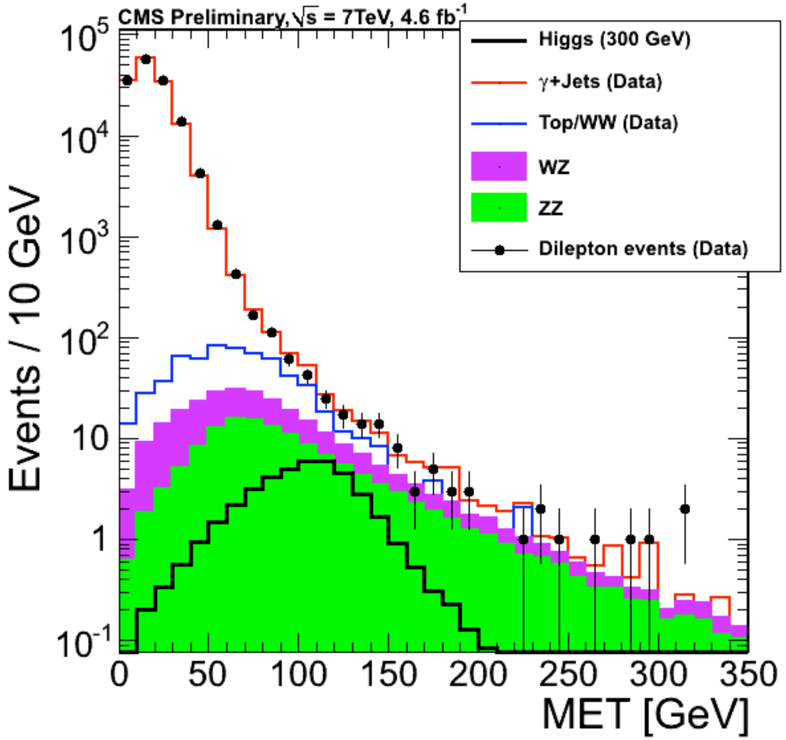
All 8 analyses yielded a preliminary result to be shown today, and contributed to the CMS combination documented in HIG-011-32.

High Mass Higgs: H → ZZ → 2l2ν



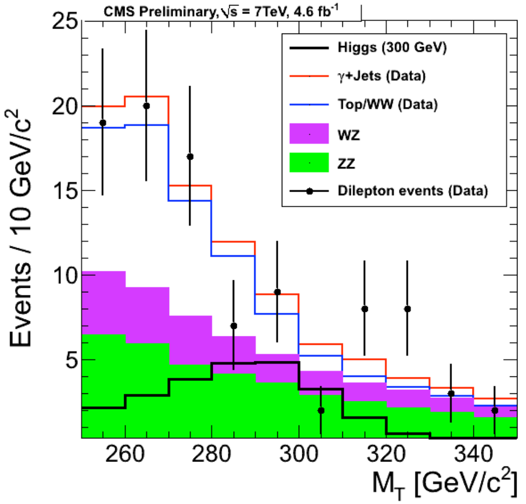
High sensitivity analysis for the high mass;

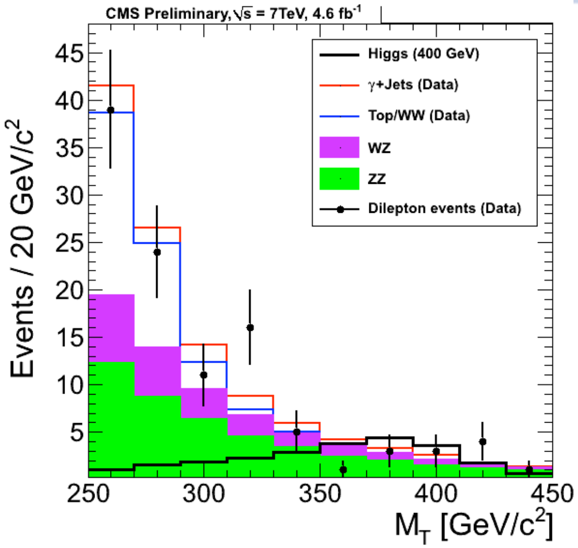
- **Z+jets background estimated from data**
- **M_T shape** analysis introduced
  - 10% improvement compared to cut-based analysis shown in LP



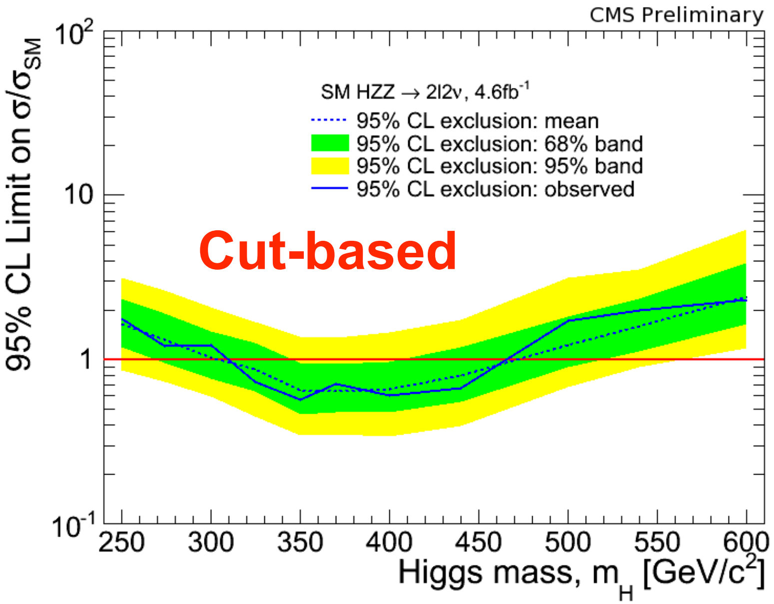
- $M_Z \pm 15$ GeV; P_T (ll) >55 GeV
- Use $M_T{}^2 = (\sqrt{P_{TZ}{}^2 + M_Z{}^2} + \sqrt{MET^2 + M_Z{}^2})^2 - (\vec{P_{TZ}} + \vec{MET})^2$
- Major backgrounds: Z+Jets, ttbar & WW
  - ME_T requirement to suppress Z + jets by x10^5
  - Anti b-tag to suppress ttbar
- Backgrounds estimated from data
  - Z+jets (using γ + jets) ; eμ sample (for ttbar ++WW, single-top/W+jets/Ztautau)
- ZZ, WZ background estimate from MC

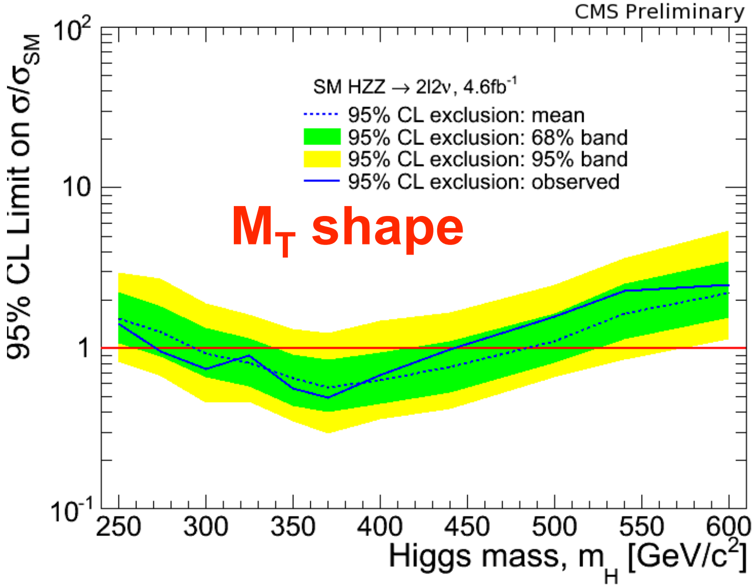
Results and Limits: H → ZZ→ 2l2ν



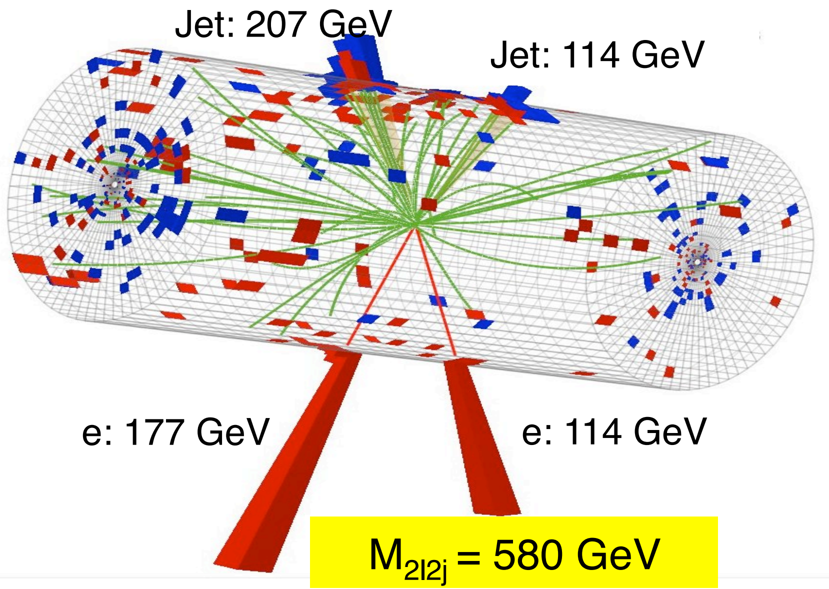


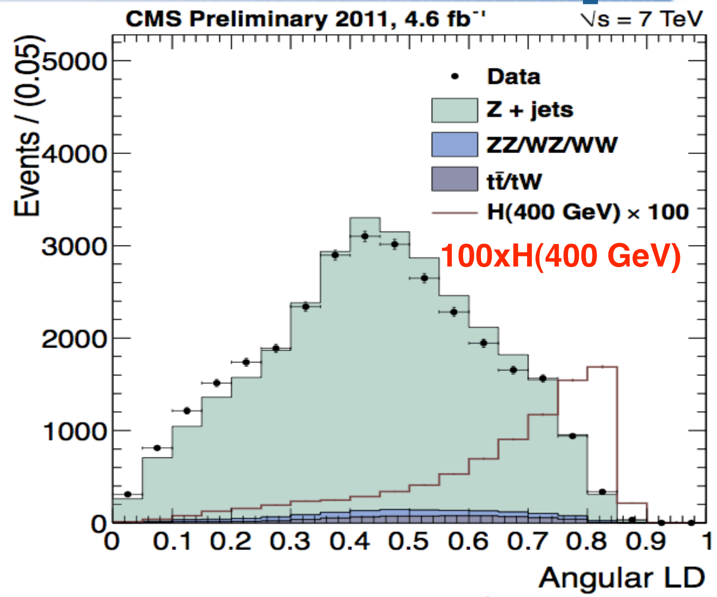
95%CL exclusion limits for a SM Higgs boson in the range 270-440 GeV (M_T shape based analysis)

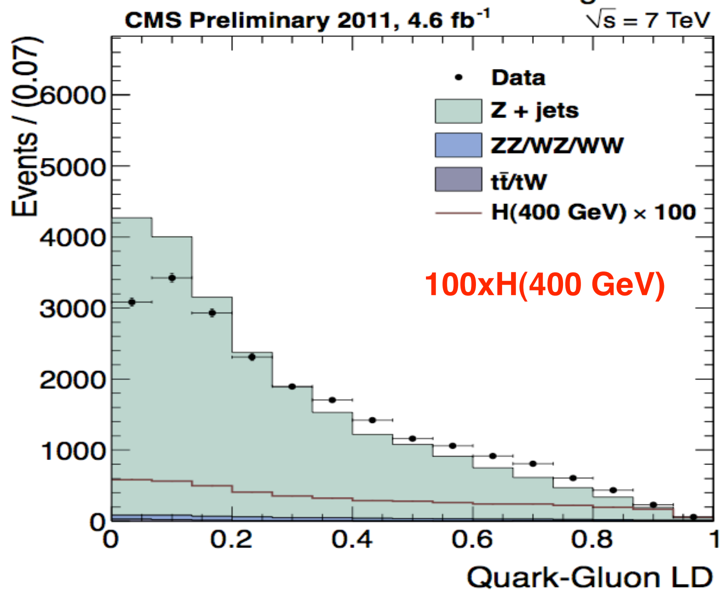




High Mass Higgs: H→ZZ→2l 2q

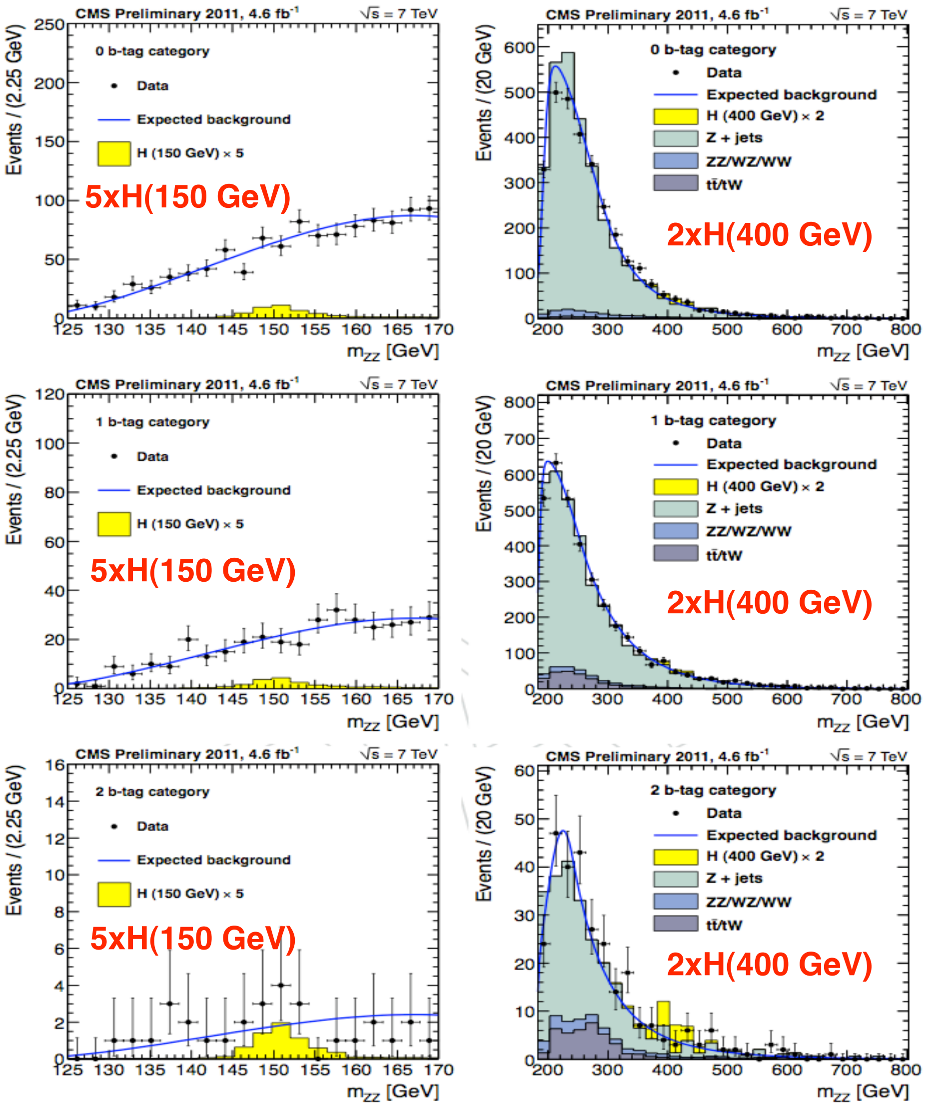


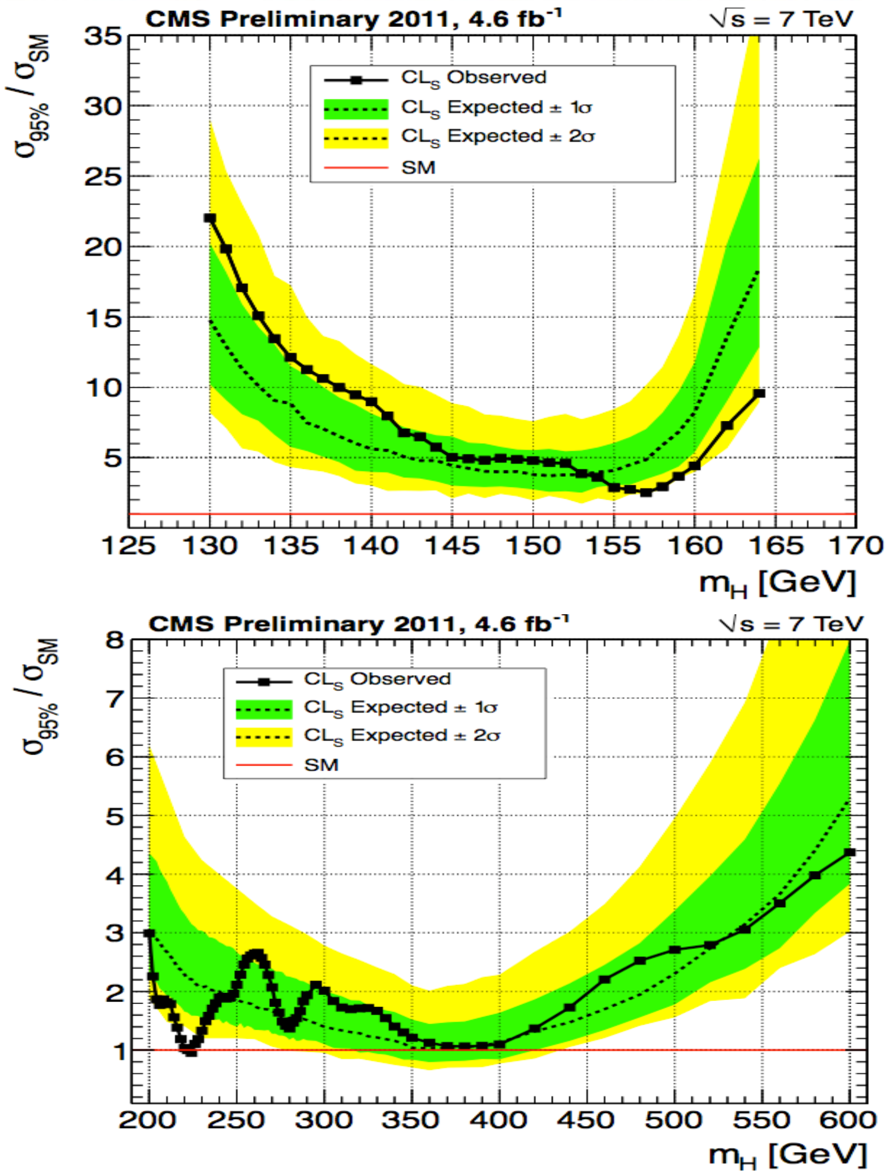




- **Since LP: Added low mass** in M_{2l2j} distribution
- Events categorized by presence of 0, 1, 2 b-jets
- Major background: Z+jets ; ttbar suppressed by ME_T significance requirement
- Use 5 angles of scalar H → ZZ → 2l 2q in an angular likelihood discriminant
- Quark-gluon discriminant to reject Z +jets
- Background shape, normalization ← data sideband

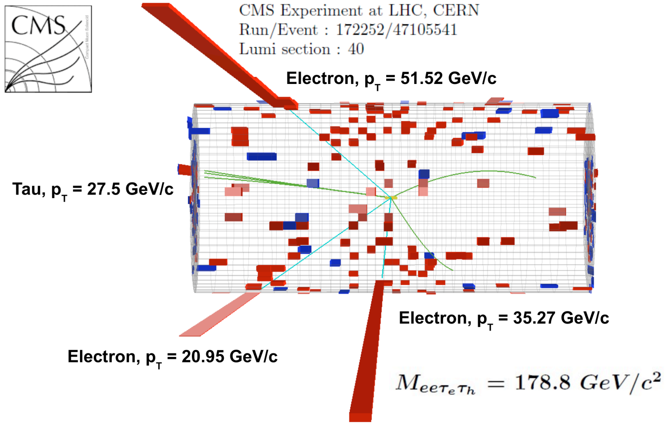
H →ZZ→2l 2q: data and limits

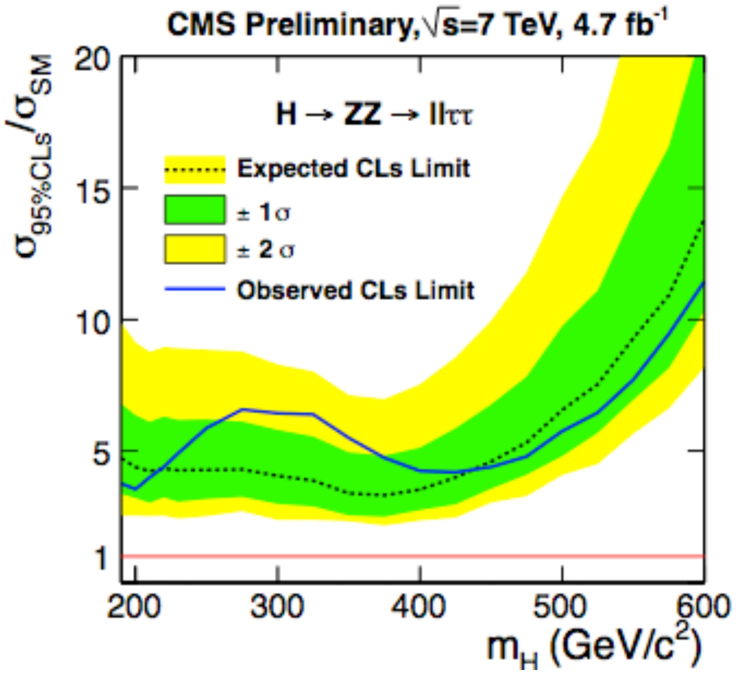




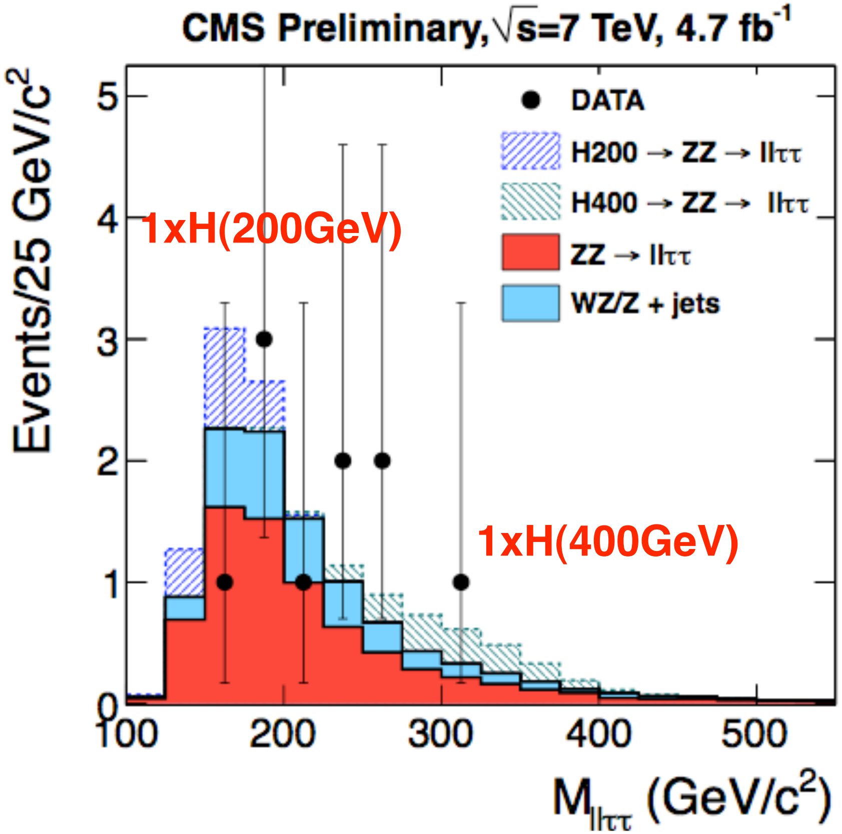
High Mass Higgs: H →ZZ→2l 2τ

eeeτ candidate



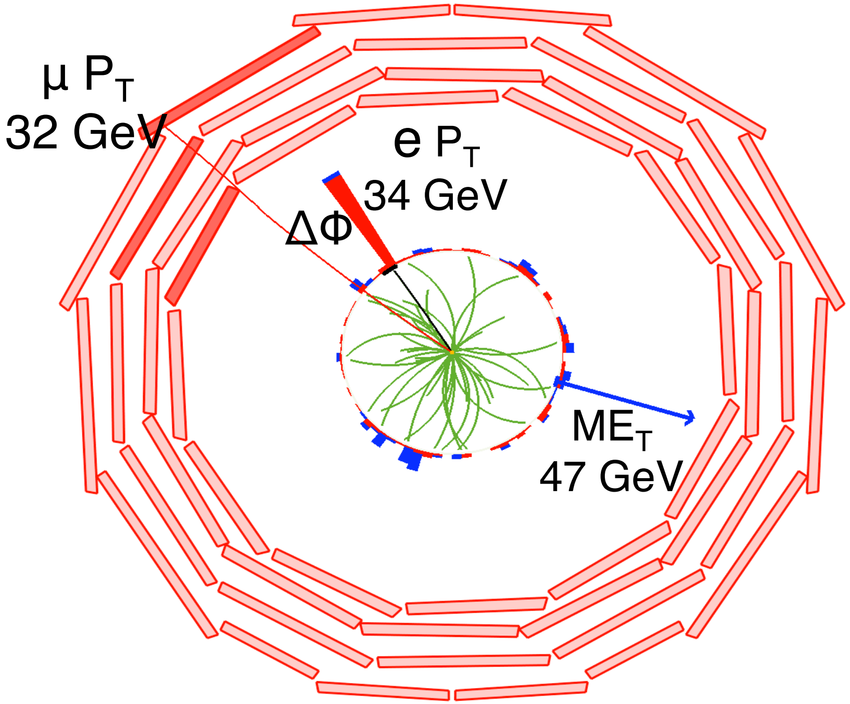


No major change w.r.t LP'11

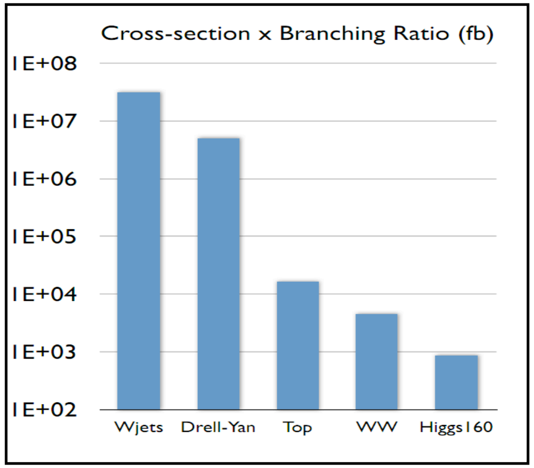


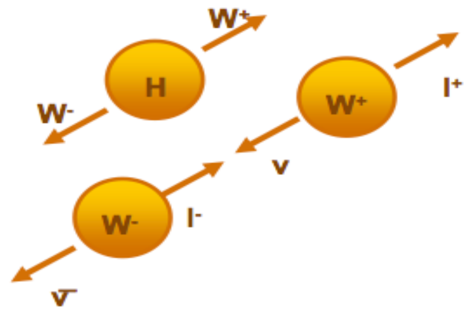
10 observed events, 10.2 expected background
Background shapes are taken from MC simulation and normalized to the values obtained using data-driven techniques.

H→ WW → 2l 2ν



- No signal mass peak (missing νν) ➔ Counting expt.
- Challenge is to remove & control large backgrounds





- Signal characteristics:
  - **Only 2 opposite sign, isolated leptons**
  - **significant ME_T➔ No mass peak**
  - **No b-jets, no additional low P_T μ**
  - **With additional 0, 1 or 2 jets (VBF)**
  - **Small ΔΦ (l^+l^-) ← Higgs scalarity**

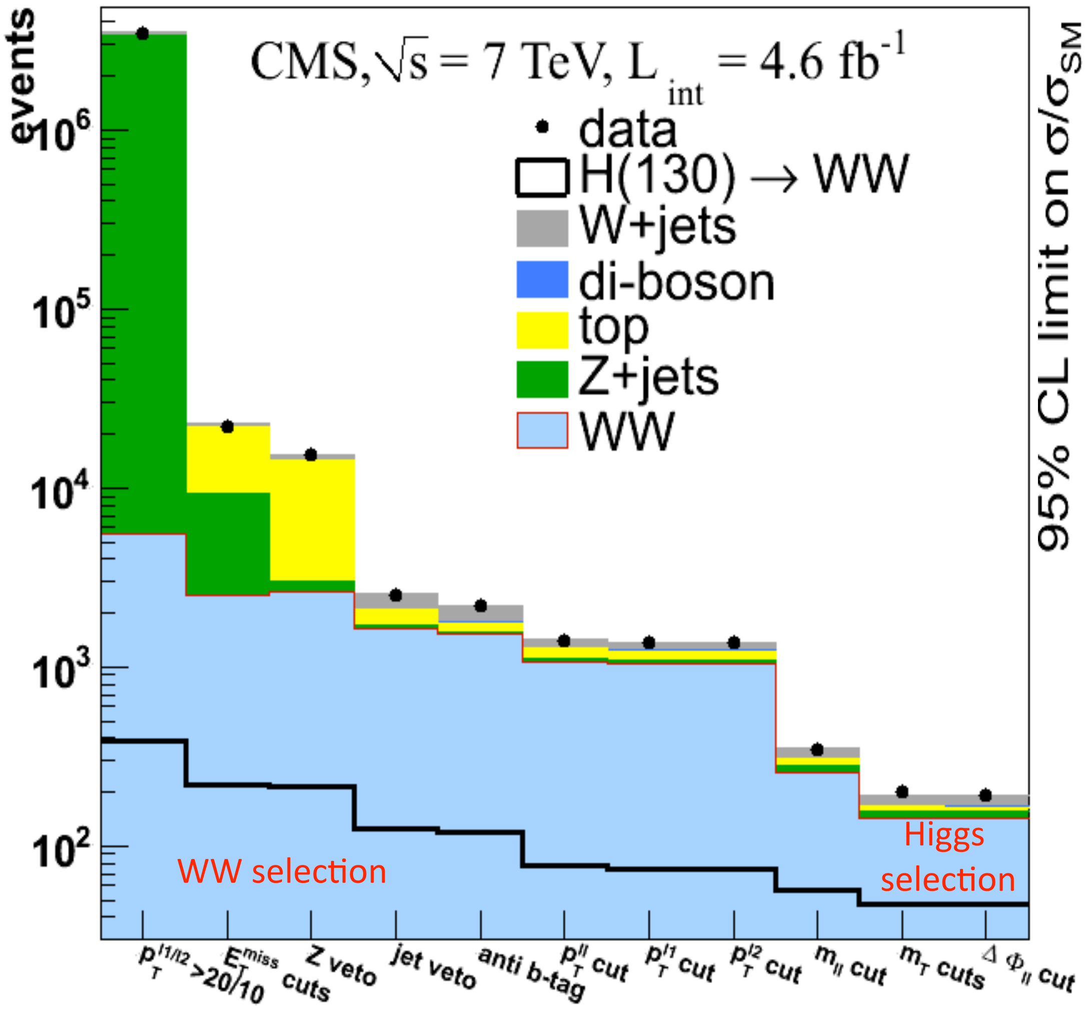
Major requirements:

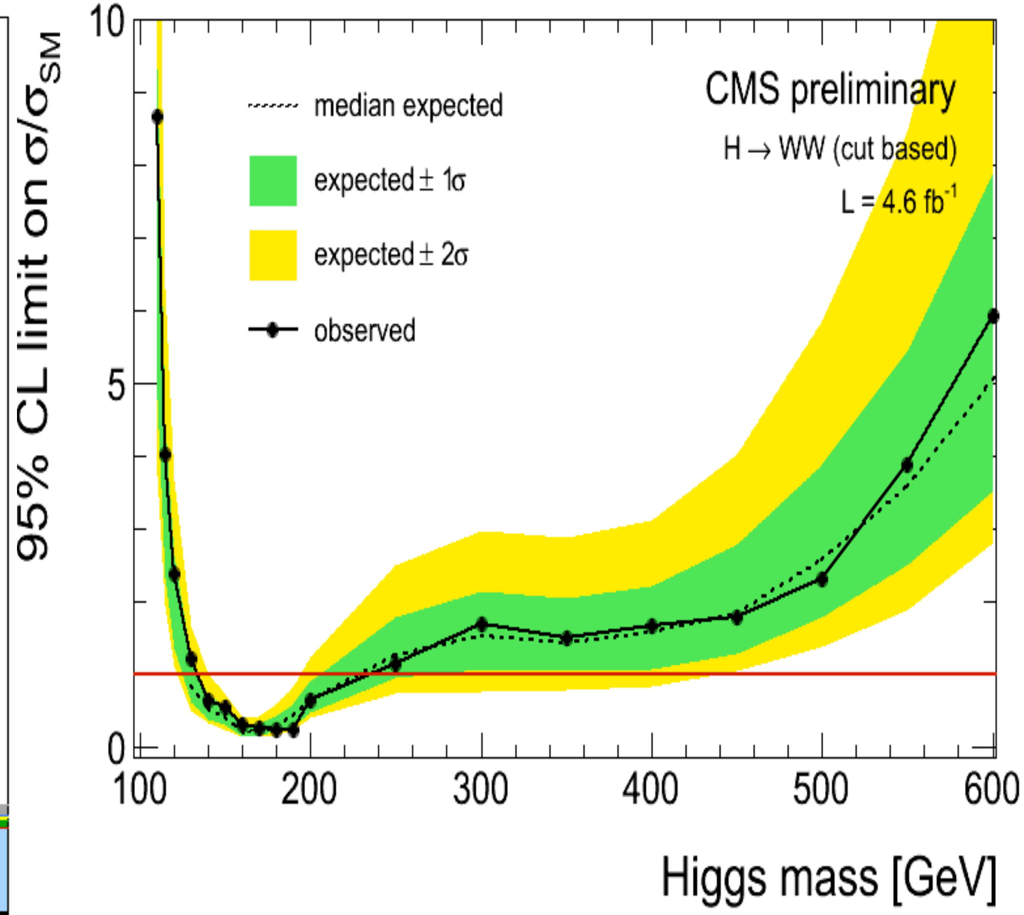
- Lepton P_t > 15 GeV, tight ID & Isolation
  - removes QCD & W+jets contamination
- Large ME_T & Z → μμ, ee veto
  - removes Drell-Yan contamination
- Classification by # of jets (P_T > 30 GeV) & b-jet veto
  - removes Top contamination
- Kinematic discriminants: M_{ll} & ΔΦ (l^+l^-)
  - mitigates pp → WW background
- M_H–dependent cut optimization

H→ WW → 2l 2ν: improvements

- Objects Identification:
  - MVA-based electron identification (fakes reduced by 50%, same signal efficiency)
- Selections:
  - Pileup dependent MET cut
  - Minimum dilepton mass cut from 12→20 GeV for same-flavor events
  - Refined the top tagging procedure (less sensitive to PU)
  - Trailing lepton p_T from 10 to 15 GeV for SF and dilepton p_T cut at 45 GeV (suppressing Drell-Yan and W+jets)
- Backgrounds:
  - Refined DY and top estimation
  - Data driven normalization of DY→ττ and Wγ*
- **Major effort in understanding BDT Shape based analysis:**
  - **Shape variation for systematic uncertainty evaluation**
  - **Additional cross-checks: single variable shape analyses; matrix element analysis**

Data and limits in cut and count analysis

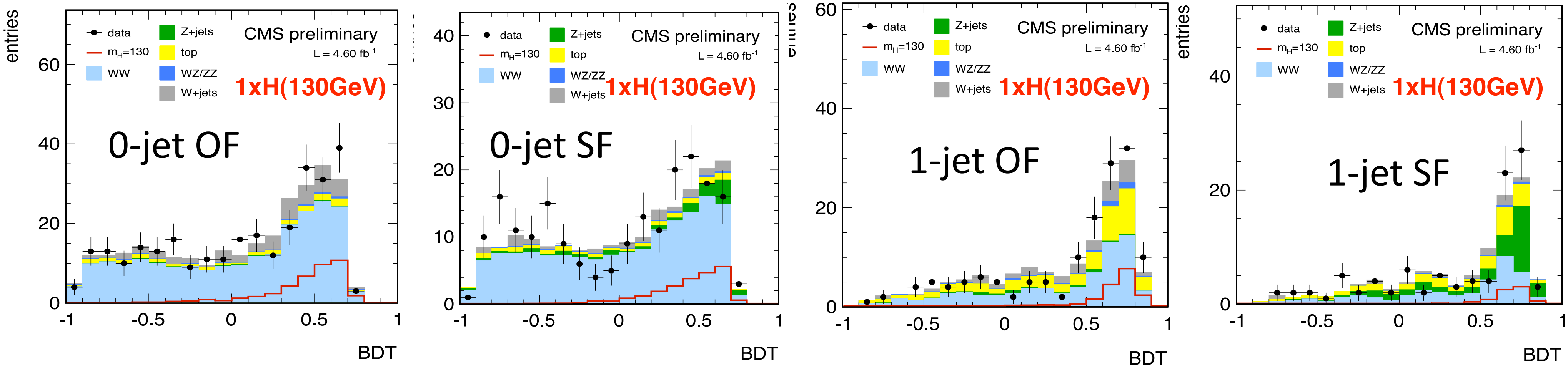


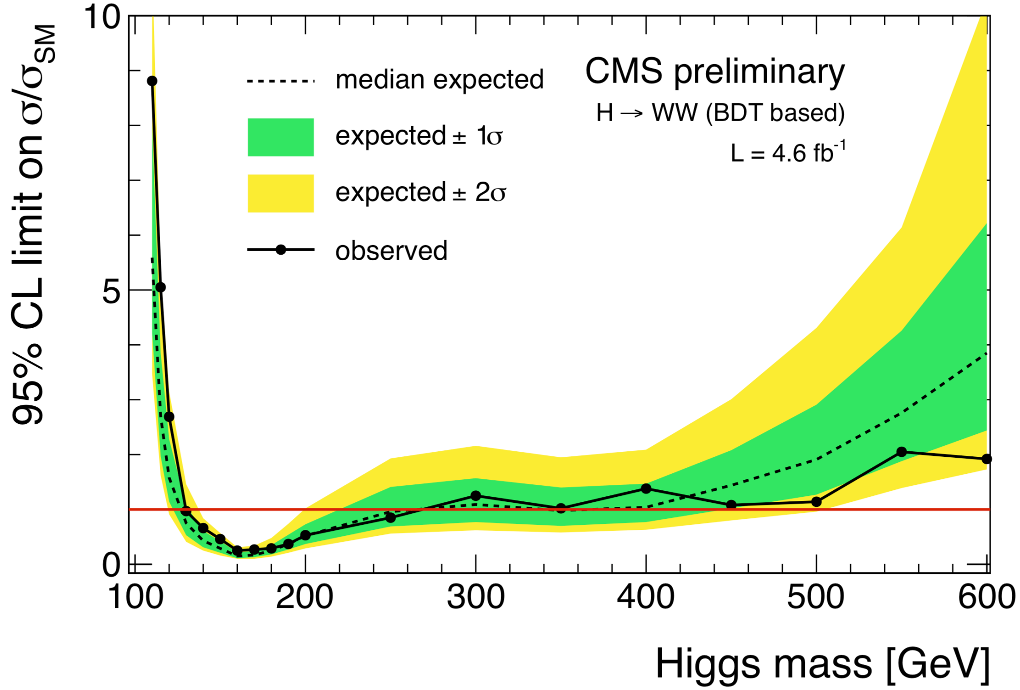


Expected range: 129 < M_H < 236 GeV
Observed range: 132< M_H < 238 GeV

Data describes predicted background well.

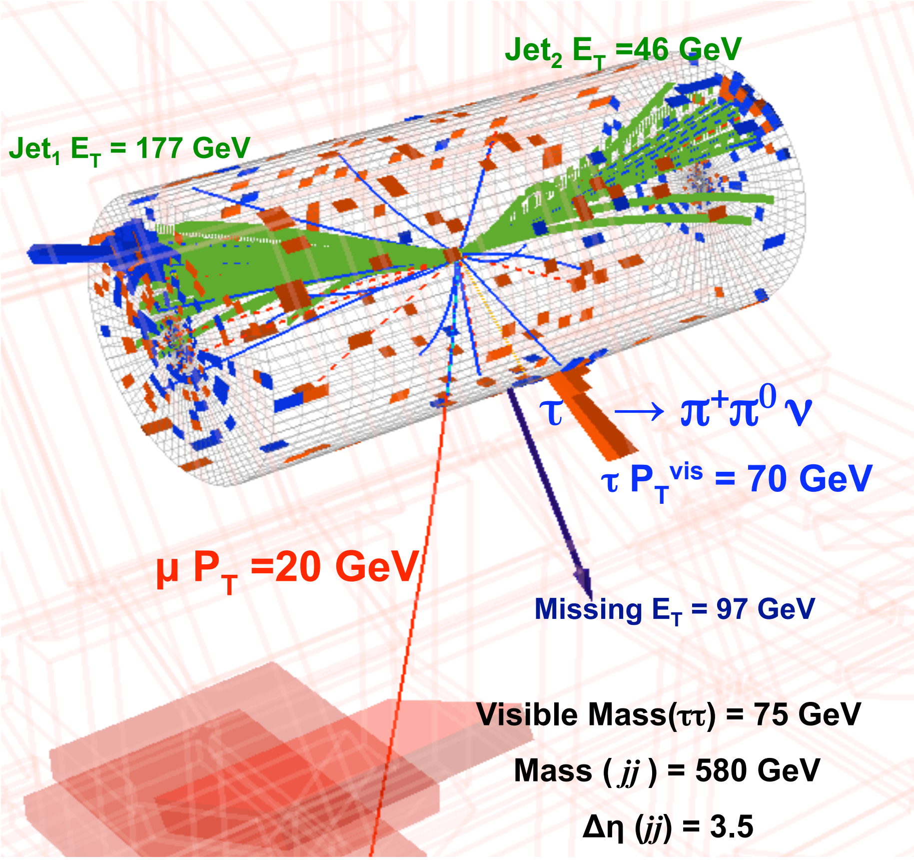
BDT Shape Comparison

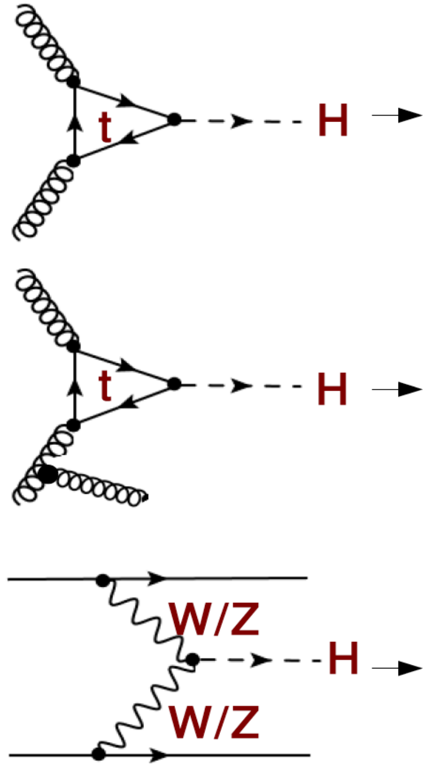




Expected range: $127 < M_H < 270$ GeV
Observed range: $129 < M_H < 270$ GeV

Low Mass Higgs Search : H→ ττ





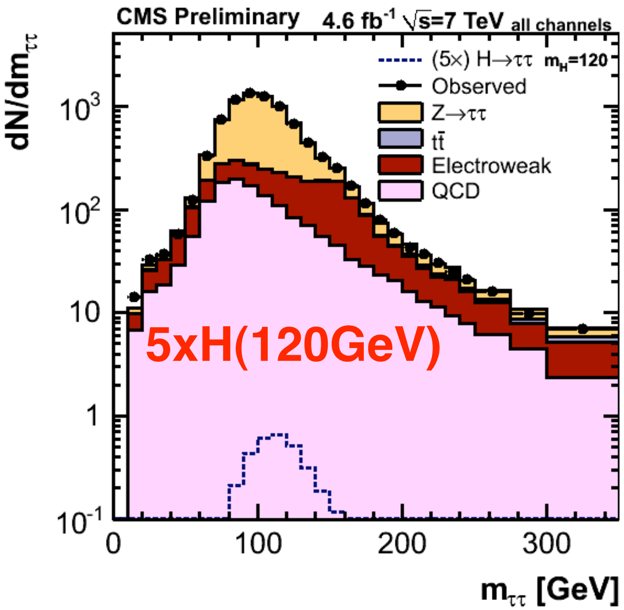
0 or 1 JET
0 jets>30GeV or 1jet<150GeV

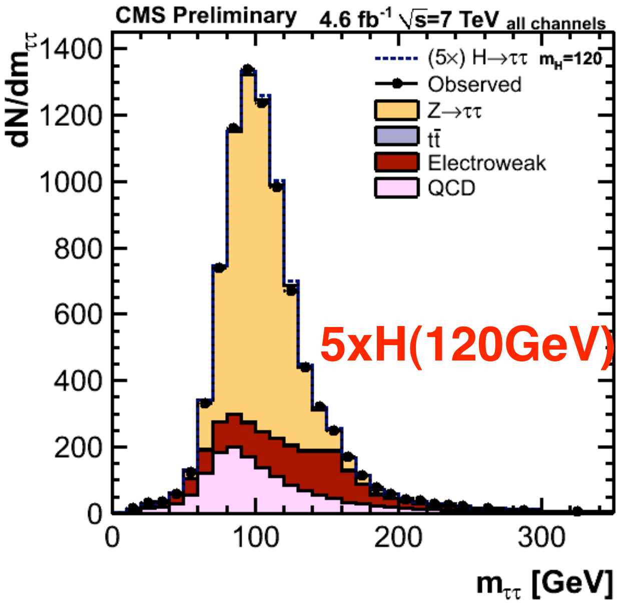
BOOSTED
One jet P_T>150GeV

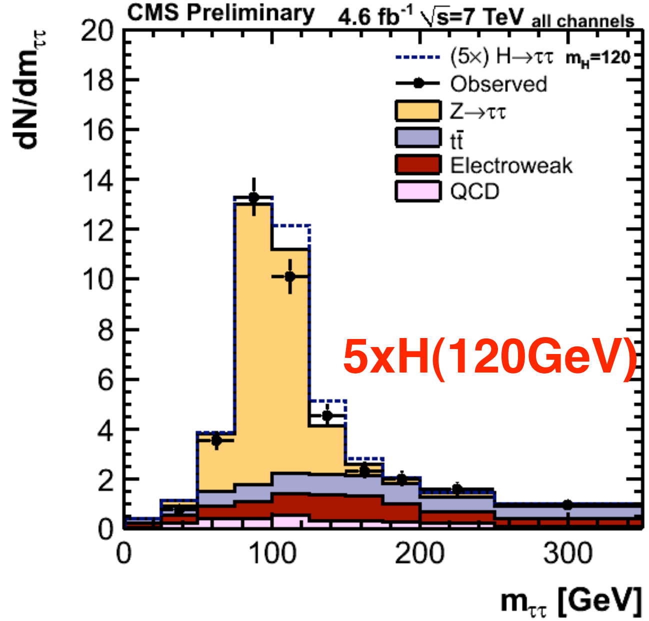
VBF
>= 2jets >30GeV
Δη>4, M_{jj}>400GeV
No additional jets with P_T>30GeV
In the rapidity gap

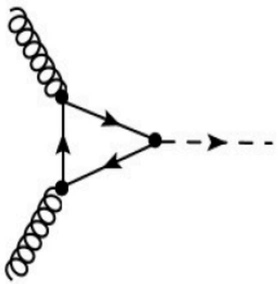
- ττ selection: μ+τ_{had} , μ+τ_{had} , μ+e
- **SM-Boosted mode added**
- **VBF mode cleanest, most sensitive**

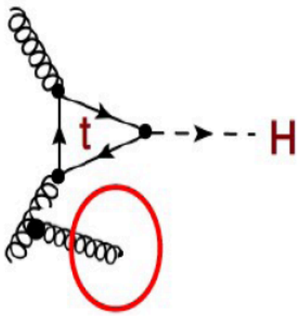
H→ ττ : Mass Spectrum By Categories

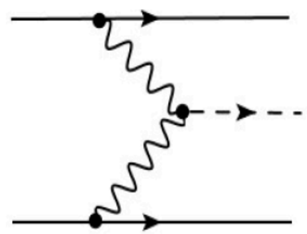




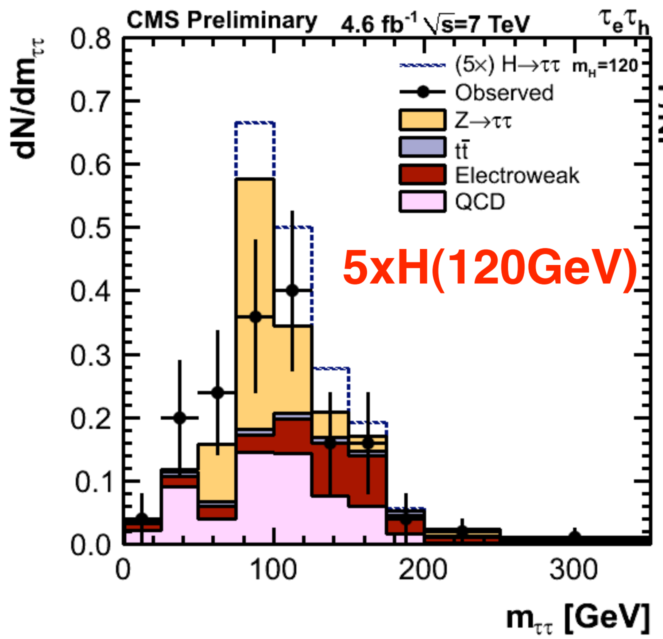


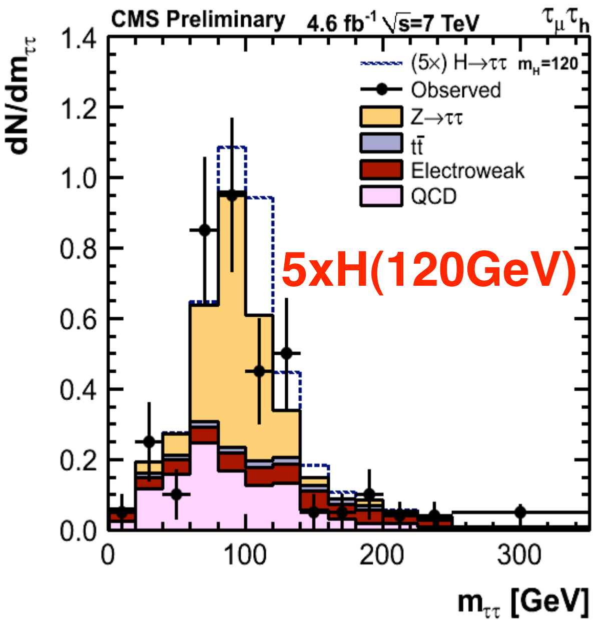


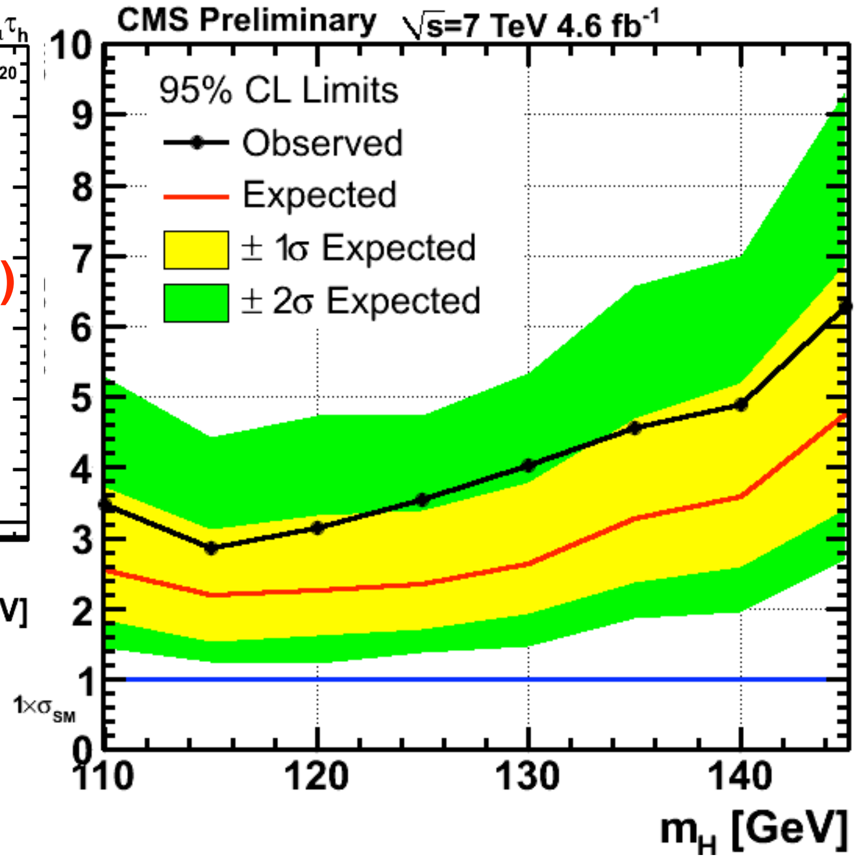




H→ ττ : data and limits





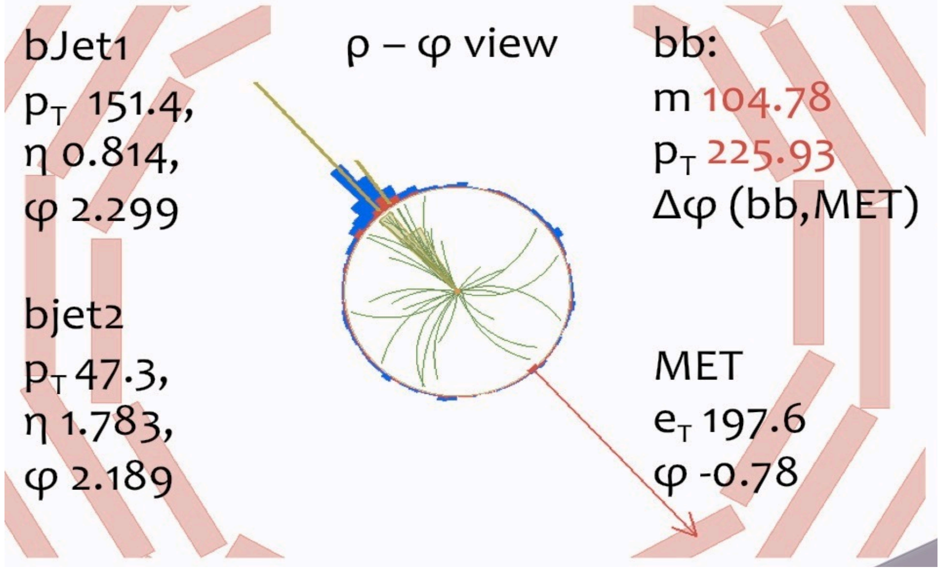


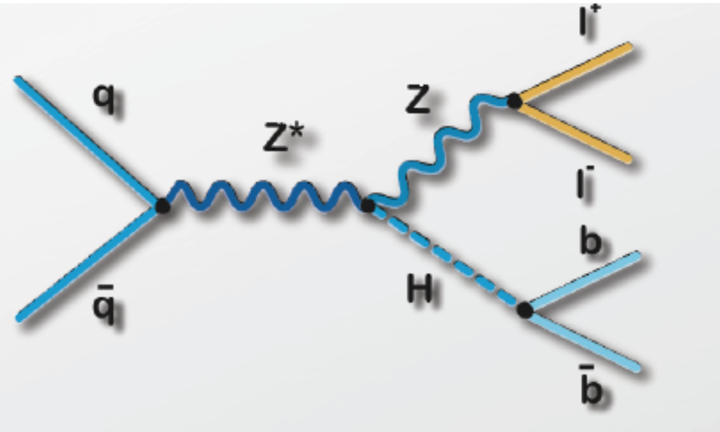
Examples of data in VBF Channels

Significant improvement in sensitivity since LP'11

Low Mass Higgs Search : H→ bb

- gg→ H→ bb and VBF are dominant production modes but overwhelmed by enormous QCD di-jet background
- Best option: qq→ VH; H → bb
  - Major backgrounds are V+jets, VV, ttbar
- Use
  - **VH topology : ΔΦ(V,H) > 3**
  - **P_T(V)> 100-160 GeV (boosted W/Z)**
  - Tight b-tagging & MET quality
  - **Backgrounds estimated from control data**



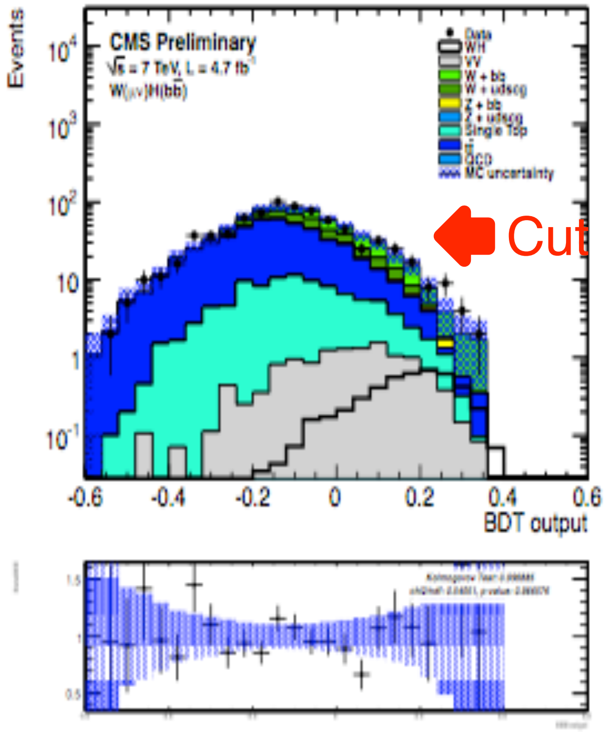


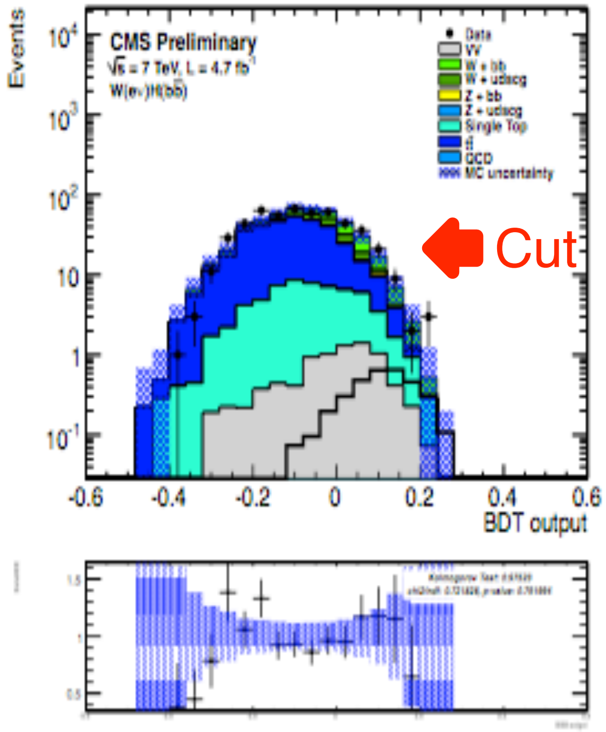
5 sub channels

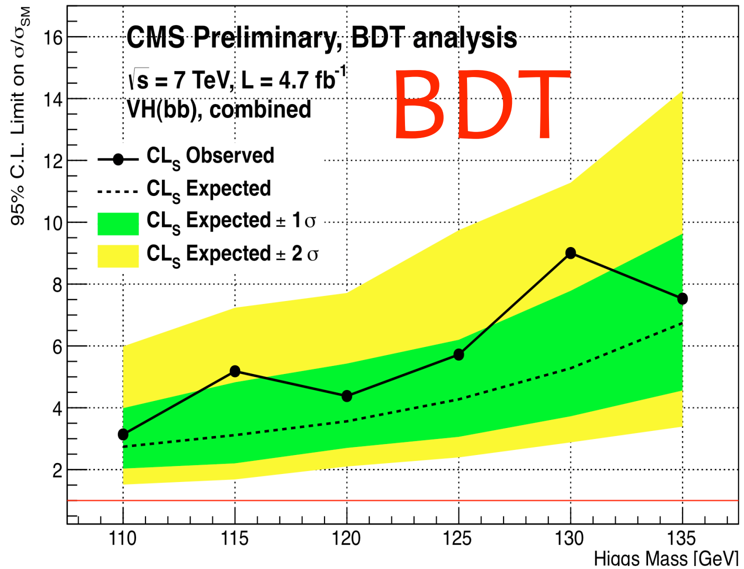
Z(→*ll*); H→bb, *l* = μ, e
W(→lν) ; H→bb, *l* = μ, e
Z(→νν); H→bb

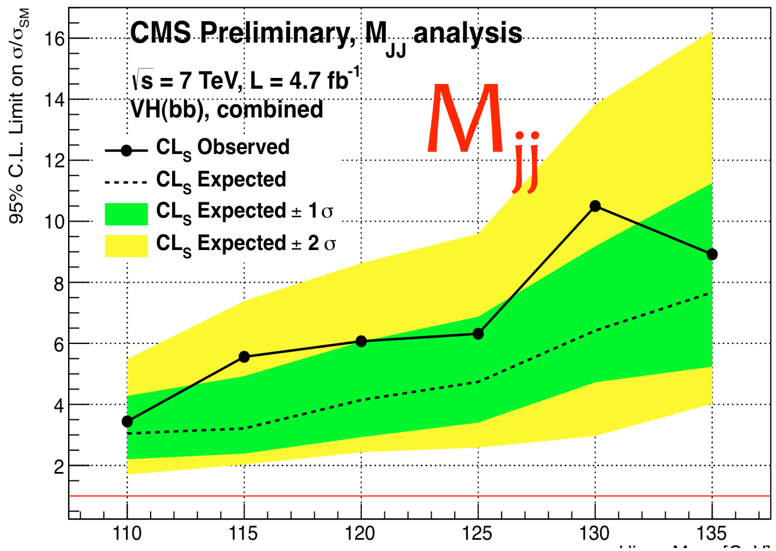
Analysis method largely unchanged w.r.t LP'11
Extensive use of data driven methods to control the backgrounds.

H→ bb: data and limits

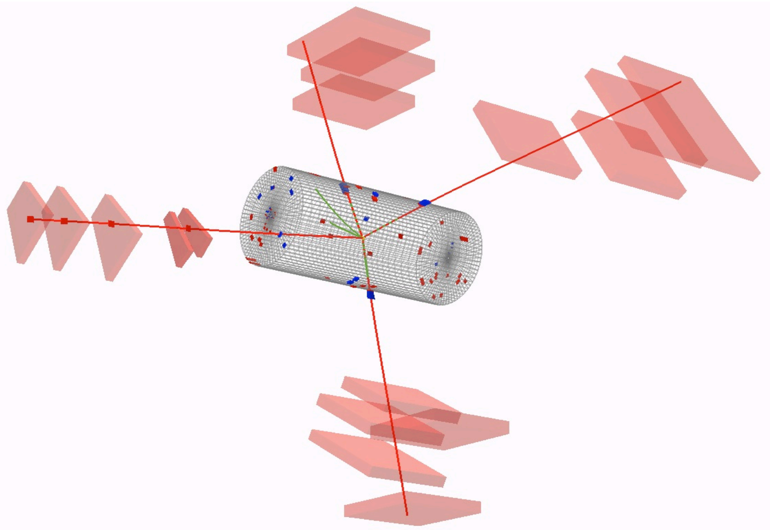


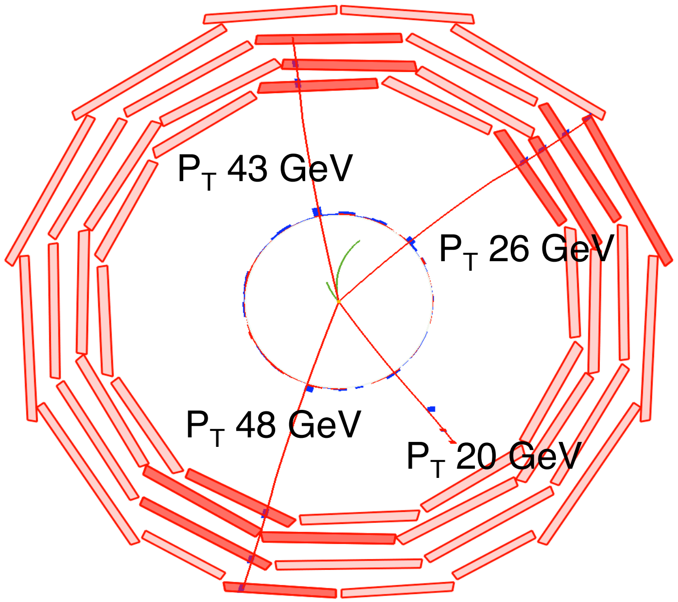






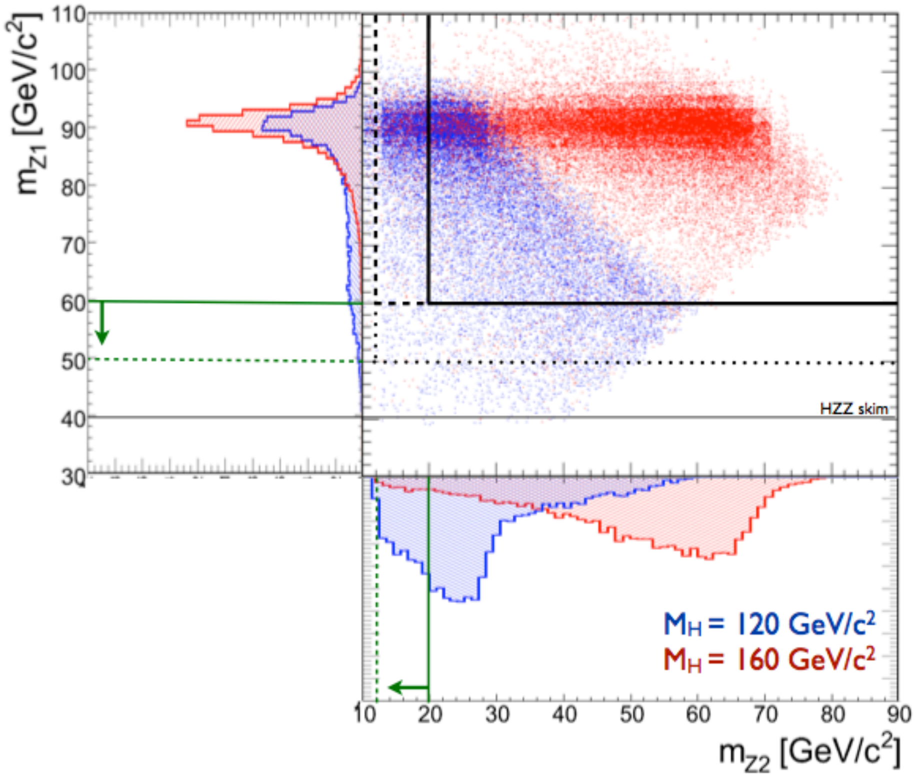
H → ZZ →4e, 4μ, 2e2μ: The Golden Channel





Improved sensitivity at low Higgs masses

- Reduce MZ_1 cut from 60 → 50GeV
- Reduce MZ_2 cut from 20 → 12GeV

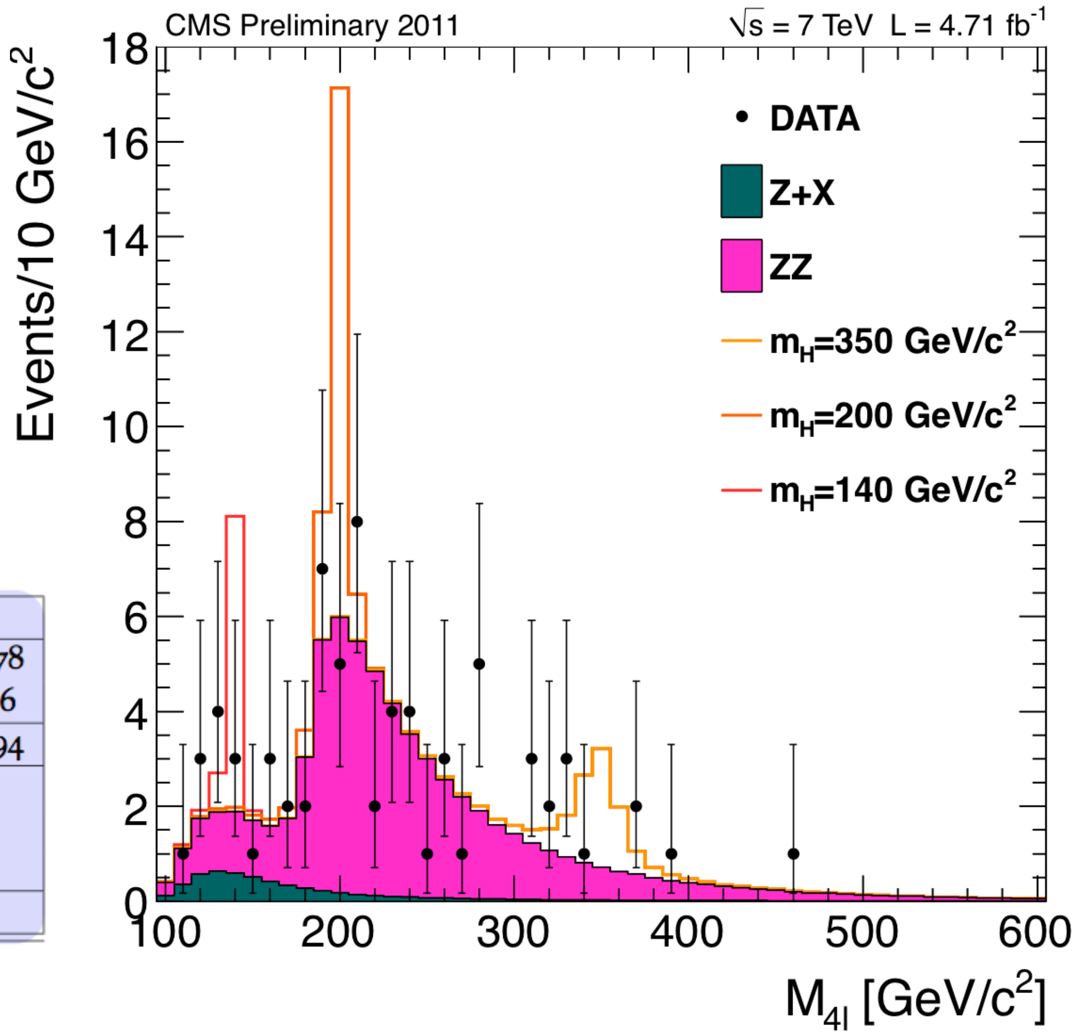


H→ZZ→4l: Baseline Selection

50< m_{Z1} < 120 GeV
12< m_{Z2} < 120 GeV

m_{4l} >100 GeV/c²
Observed events: 72
Expected events: 67.1 ± 6.0

Baseline	$4e$	4μ	$2e2\mu$
ZZ	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
$m_H = 120$ GeV$/c^2$	0.25	0.62	0.68
$m_H = 140$ GeV$/c^2$	1.32	2.48	3.37
$m_H = 350$ GeV$/c^2$	1.95	2.61	4.64
Observed	12	23	37

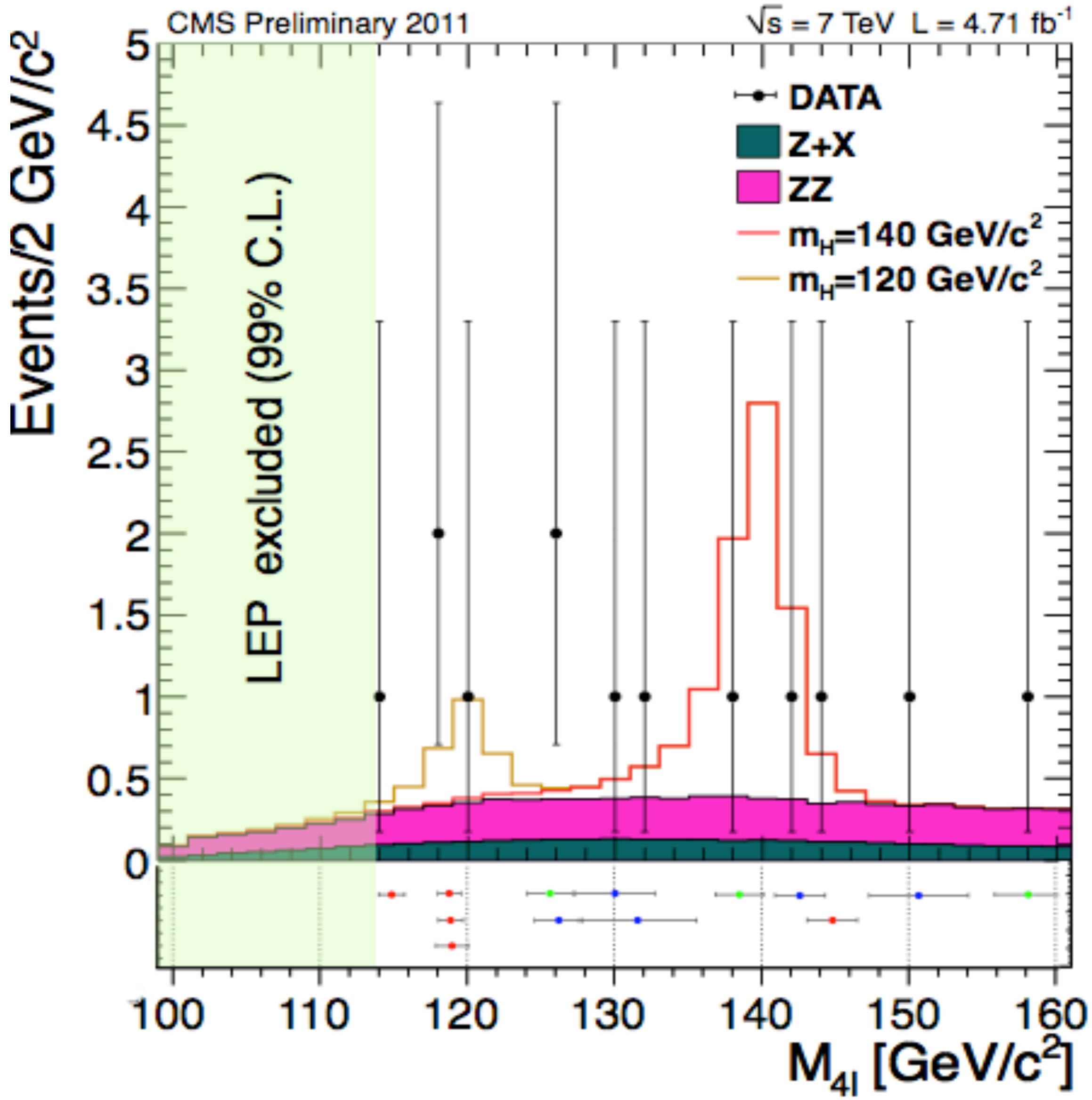


Zoom in the low mass

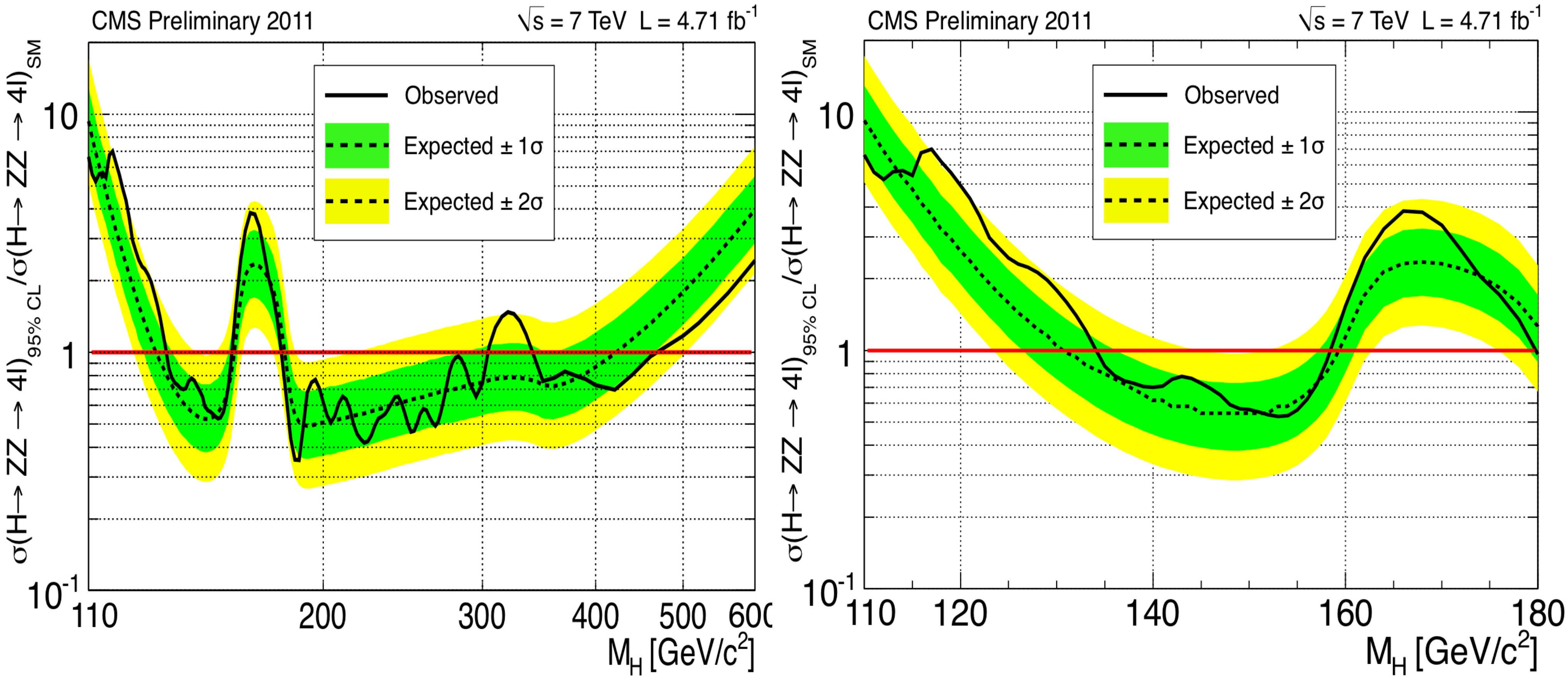
50 *< m_{Z1} < 120 GeV*
12 *< m_{Z2} < 120 GeV*

100 < m_{4l} < 160 GeV/c^2
Observed events: 13
Expected events: 9.5 ± 1.3

Final state:	4e	4μ	2e2μ
Obs. events:	3	5	5
Exp. events:	1.7	3.3	4.5



H→ZZ→4l: 95%CL Excl. Limits

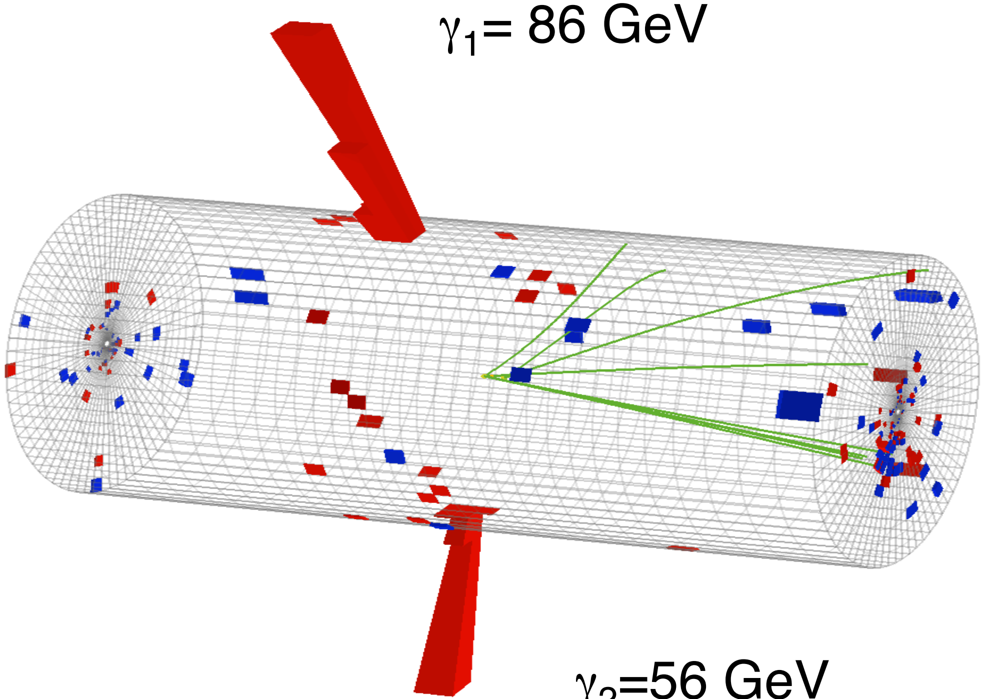


Expected range: $130 < M_H < 160$ GeV; $182 < M_H < 420$ GeV
Observed range: $134 < M_H < 158$ GeV; $180 < M_H < 305$ GeV; $340 < M_H < 460$ GeV

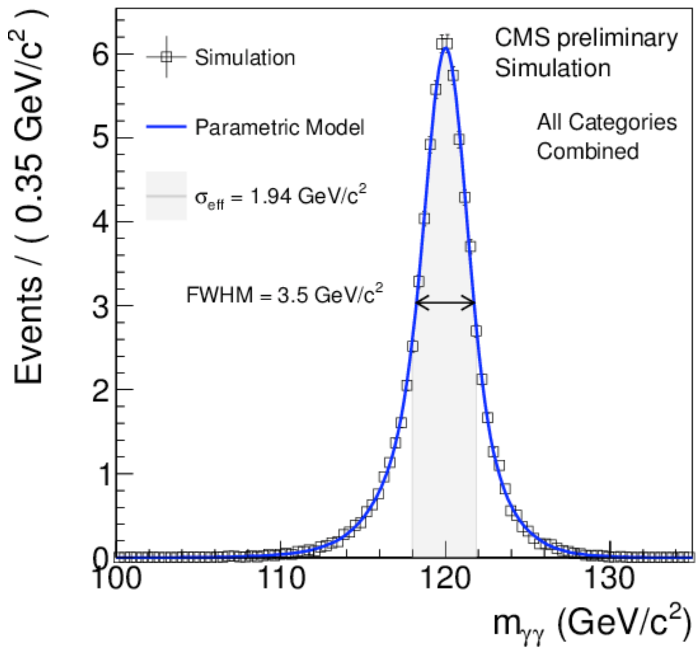
Low Mass Higgs Search : $H \rightarrow \gamma\gamma$

Signal: 2 energetic, isolated γ.
Search for a narrow mass excess over a smoothly falling background.

Challenges: vertexing with PU, calibrations and transparency corrections for the crystals.



Calibration constants derived from Z→ee data



Background: Large and mostly irreducible QCD di-photons. Measured from $M_{\gamma\gamma}$ sidebands in data

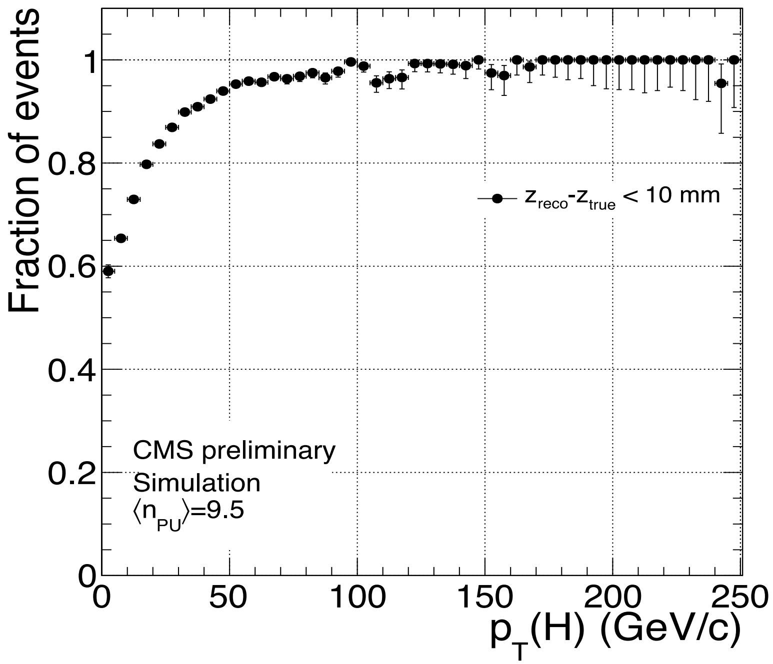
Improvements in the H→ γγ analysis

- Vertex ID uses BDT
  - **Improved vertex identification (gain → 3%)**
- Progressive ("sliding") cuts on photon p_T
  - $p_T^1 > m_{\gamma\gamma}/3$, $p_T^2 > m_{\gamma\gamma}/4$
- **Cluster energy corrections + new intercalibrations+new transparency corrections**
- **using the lasers.**
  - **Improved energy resolution**
- $p_T^{\gamma\gamma}$ event classification dropped for SM analysis
  - Remove threshold shaping of mass spectrum

- **In order to take advantage of**
  - **The better signal over background ratio in the central part of the detector**
  - **The better resolution for central/unconverted photons**
- **The analysis is performed simultaneously in 4 categories (R9 is a metric of the shower transverse**
- **size: $R9 = E_{3x3\ array} / E_{super\text{-}cluster}$. It discriminates unconverted from converted photons)**
  - Both photons in the Barrel, min(R9) > 0.94
  - Both photons in the Barrel, min(R9) < 0.94
  - At least one photon in Endcap, min(R9) > 0.94
  - At least one photon in Endcap, min(R9) < 0.94
- **Better parameterization of background shape.**

Improvements in Vertex finding Efficiency

- Training BDT using input variables computed from
  - Track momenta
  - Photon kinematics
- BDT improves correct vertex selection efficiency by 3% with respect to ranking algorithm used in EPS/LP analyses.
- 'Correct vertex' is defined as being within 10mm of true vertex z position
- Vertex finding efficiency
  - From Z → $\mu\mu$ and γ+ jets
  - Photon Selection efficiency
  - From Z → ee

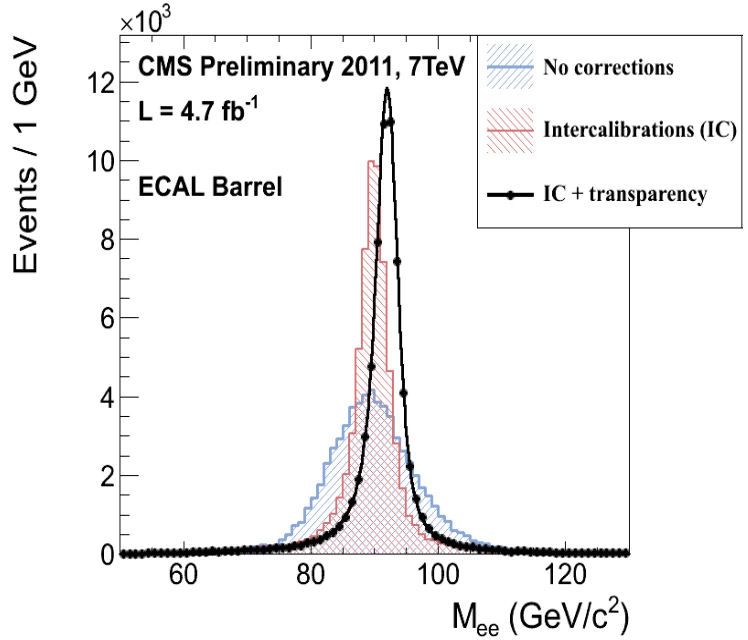


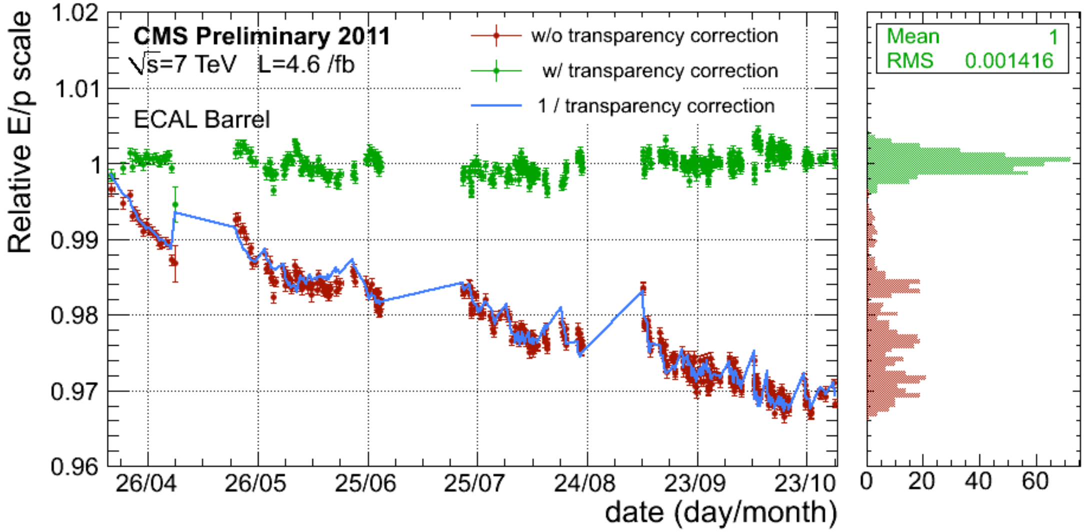
2011A	2011B	2011
$86.3\% \pm 0.2\% \pm 0.4\%$	$79.8\% \pm 0.2\% \pm 0.5\%$	$83.0\% \pm 0.2\% \pm 0.4\%$

Improvemens in Photon Energy Resolution

- **Comprehensive energy resolution studies made with Z →ee, W →eν and E/p, π⁰ intercalibrations and laser signals for transparency corrections**

Effect of new laser corrections and intercalibration on barrel-barrel Z→ee
Resolution in data improves typically by 10%, EB, |η|>1, R9>0.94
Instrumental contribution to the mass resolution in the best EB category is 0.99 ±0.01 GeV

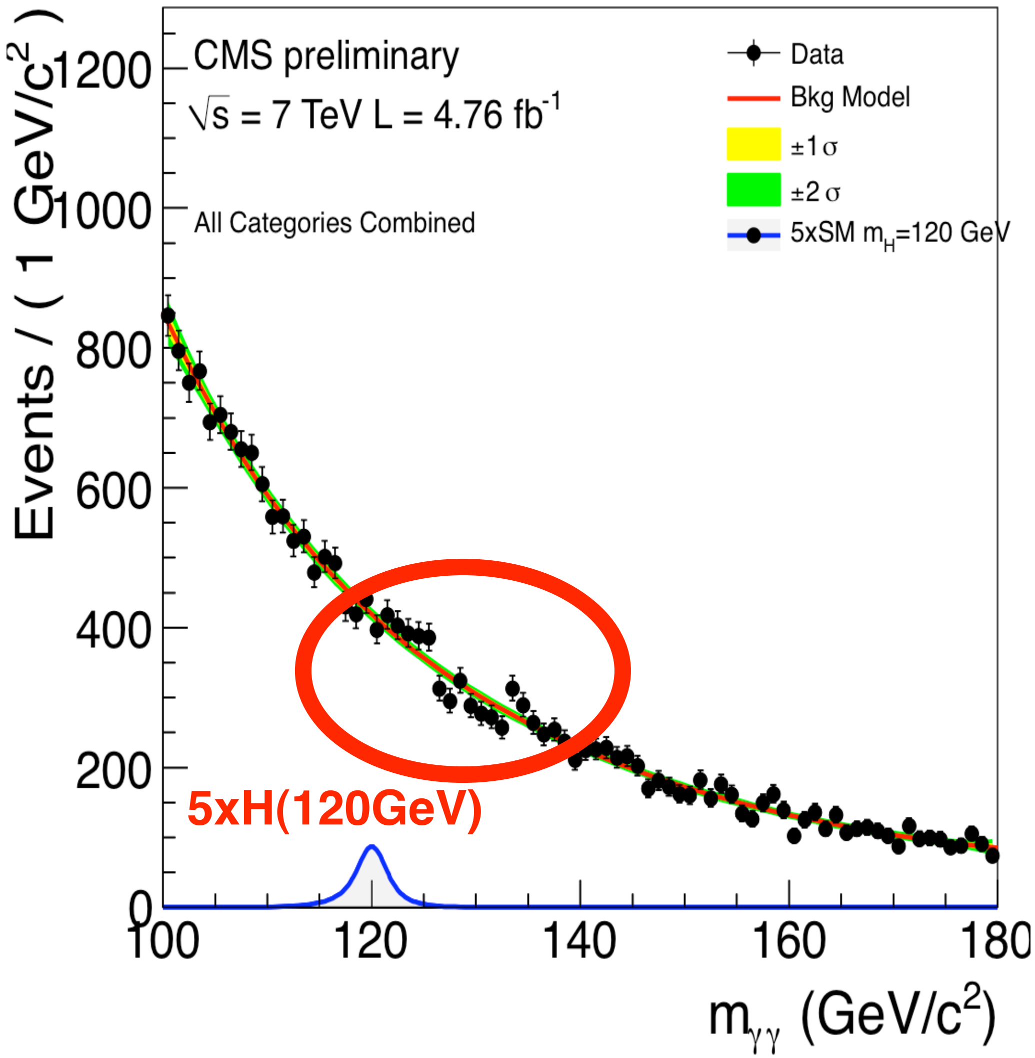


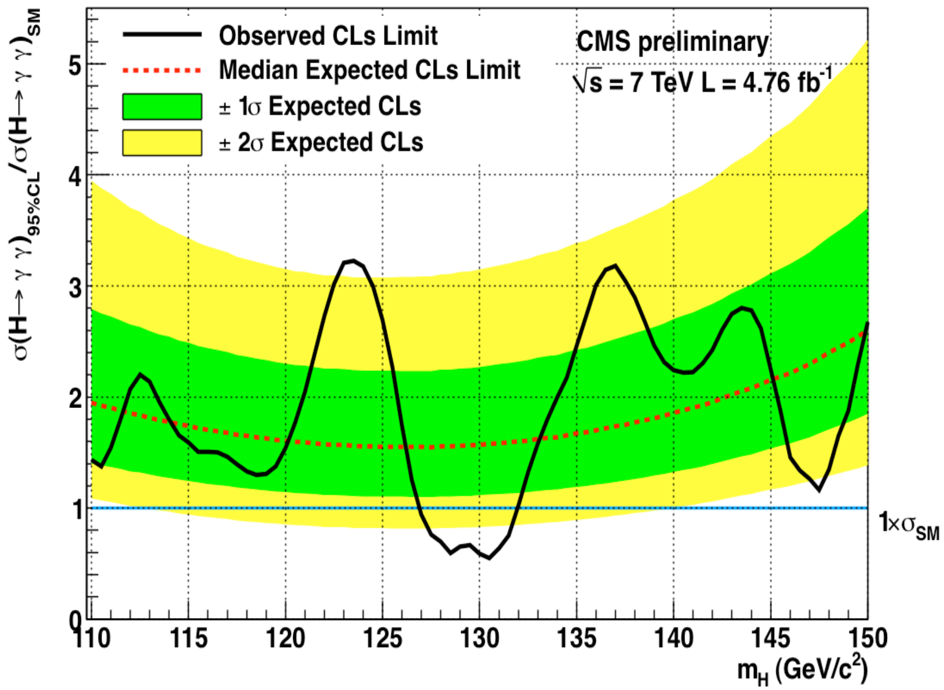


Energy scale for W→eν and Z→ee stable throughout 2011 at the level of 0.1 GeV.

EB inter-calibration and transparency correction fully understood for EB for the entire 2011 data set.

H→ γγ: data and exclusion limits

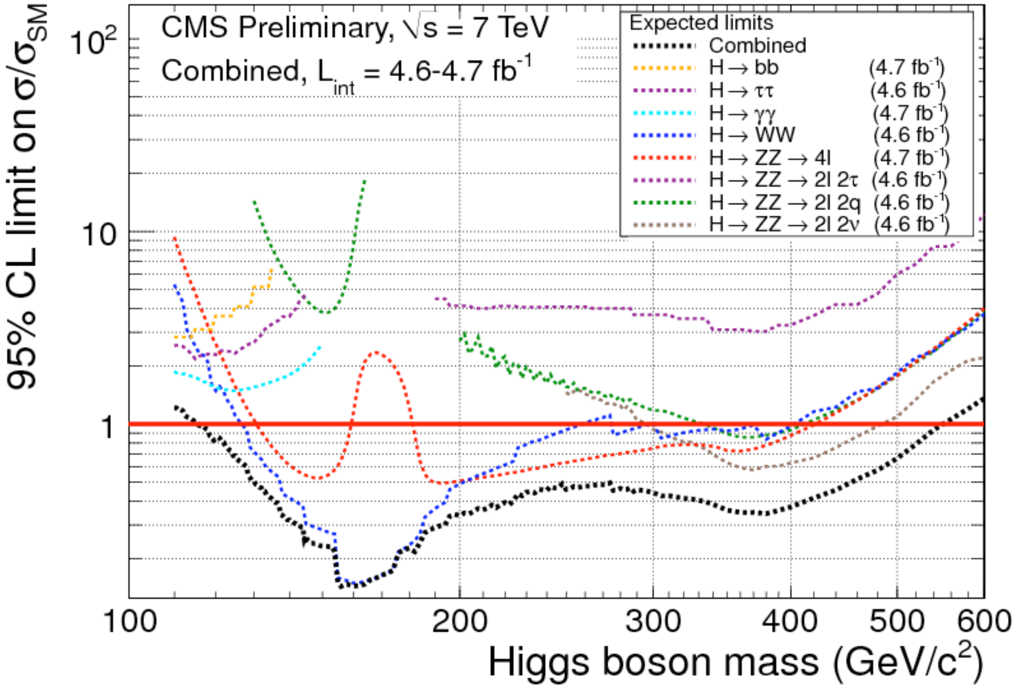


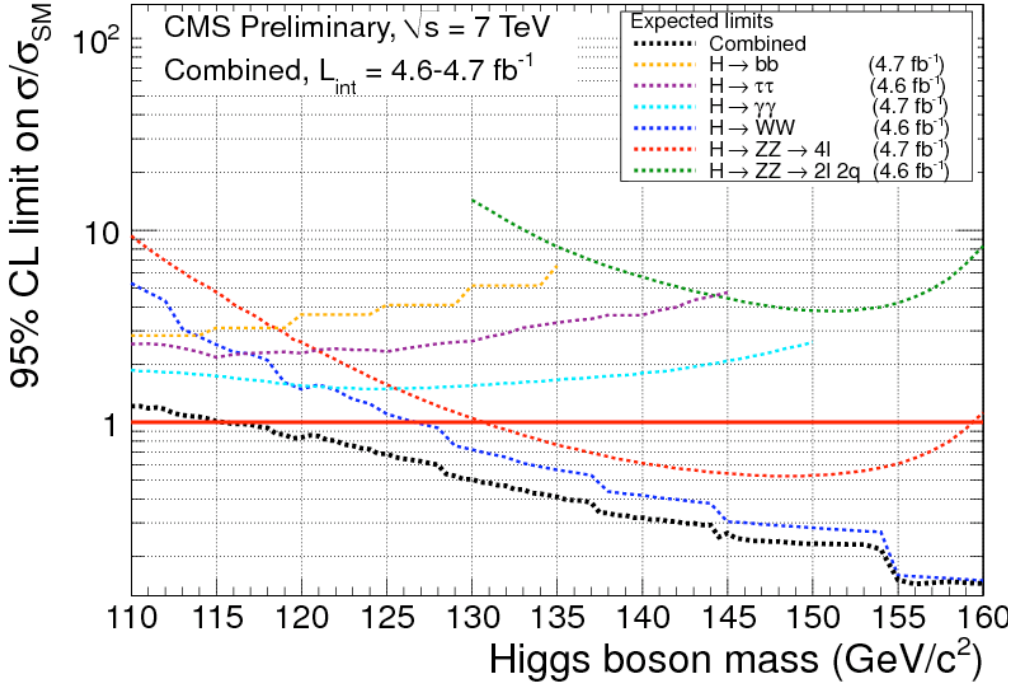


A lot of studies on the background fit model. Is the structure/shape of the observed limit due to the chosen background model? No – this has been shown to not be the case.

Using 5th order polynomial fit to background: some loss in sensitivity but negligible bias.

CMS expected sensitivity @4.7fb^{-1}

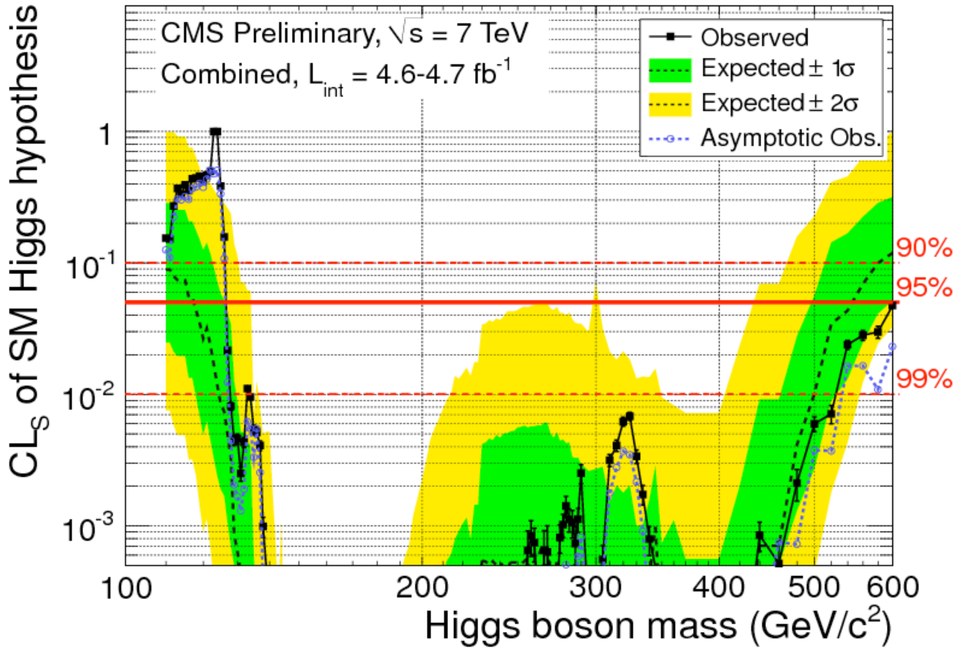


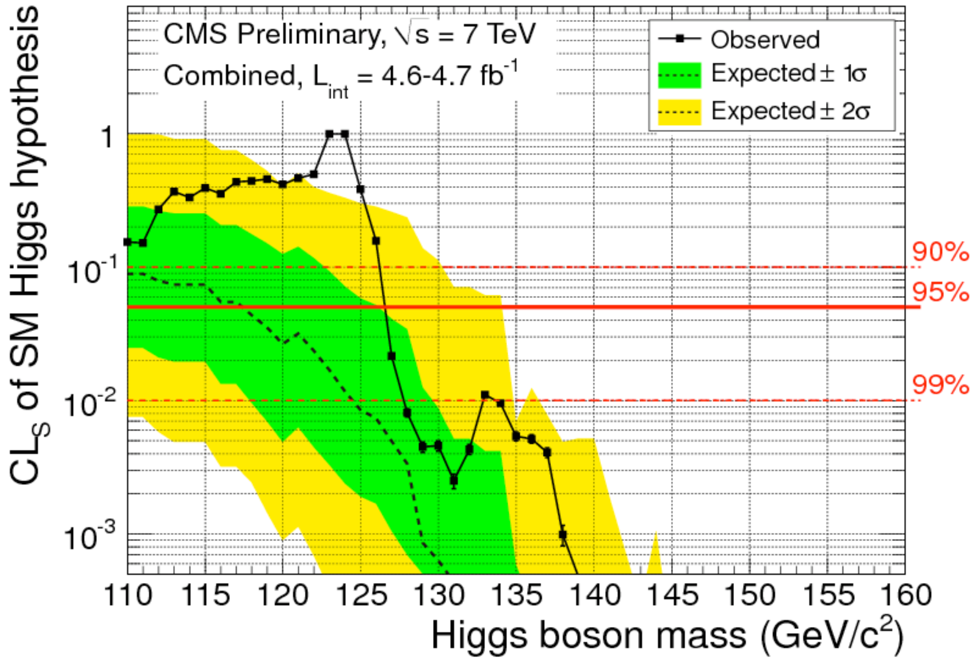


Very close or better than 1xSM in the full mass range.
Optimization of some analyses still ongoing.
Additional sub-channels under study.

Met the expectations set at the end of 2010.

CLs for SM Higgs

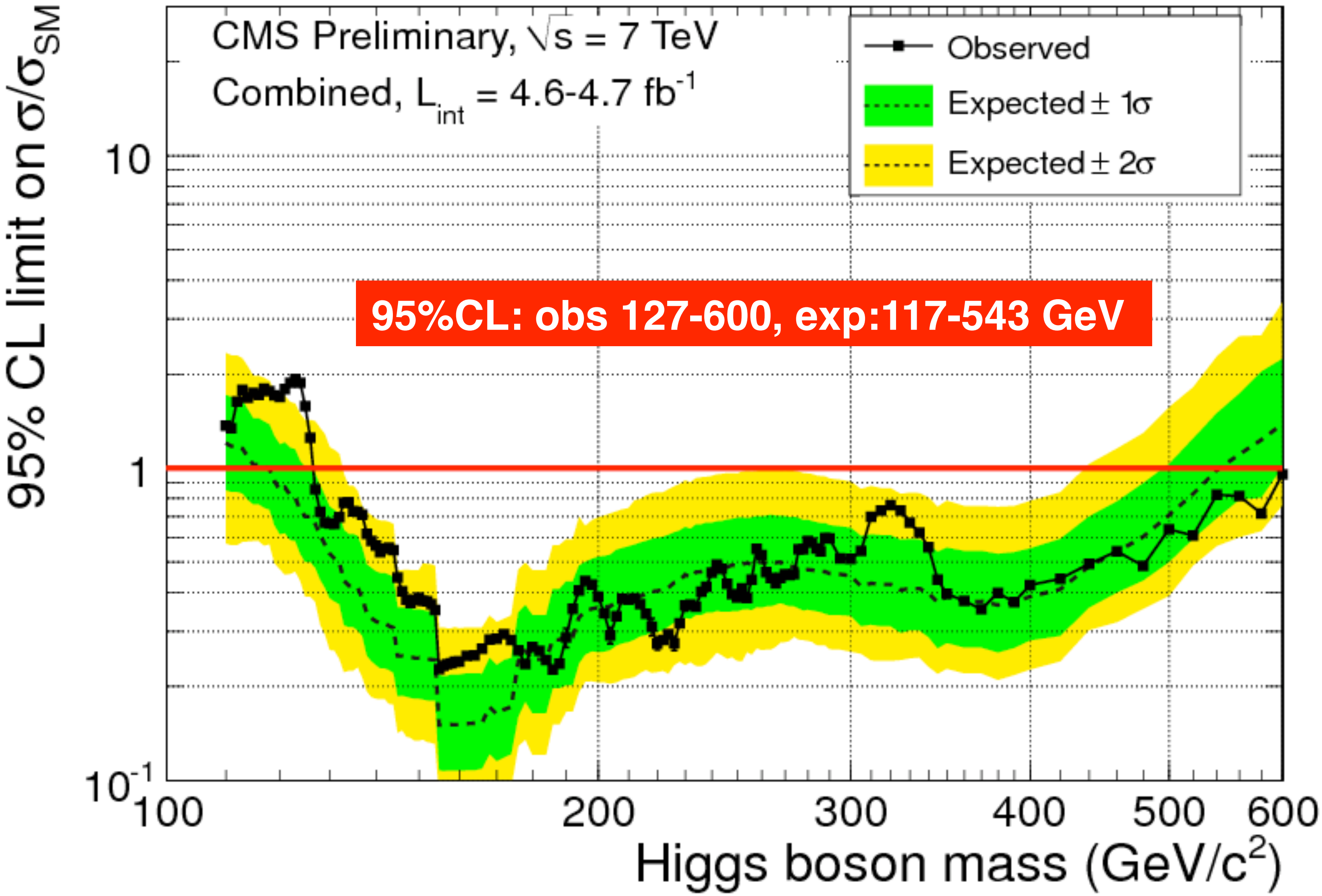




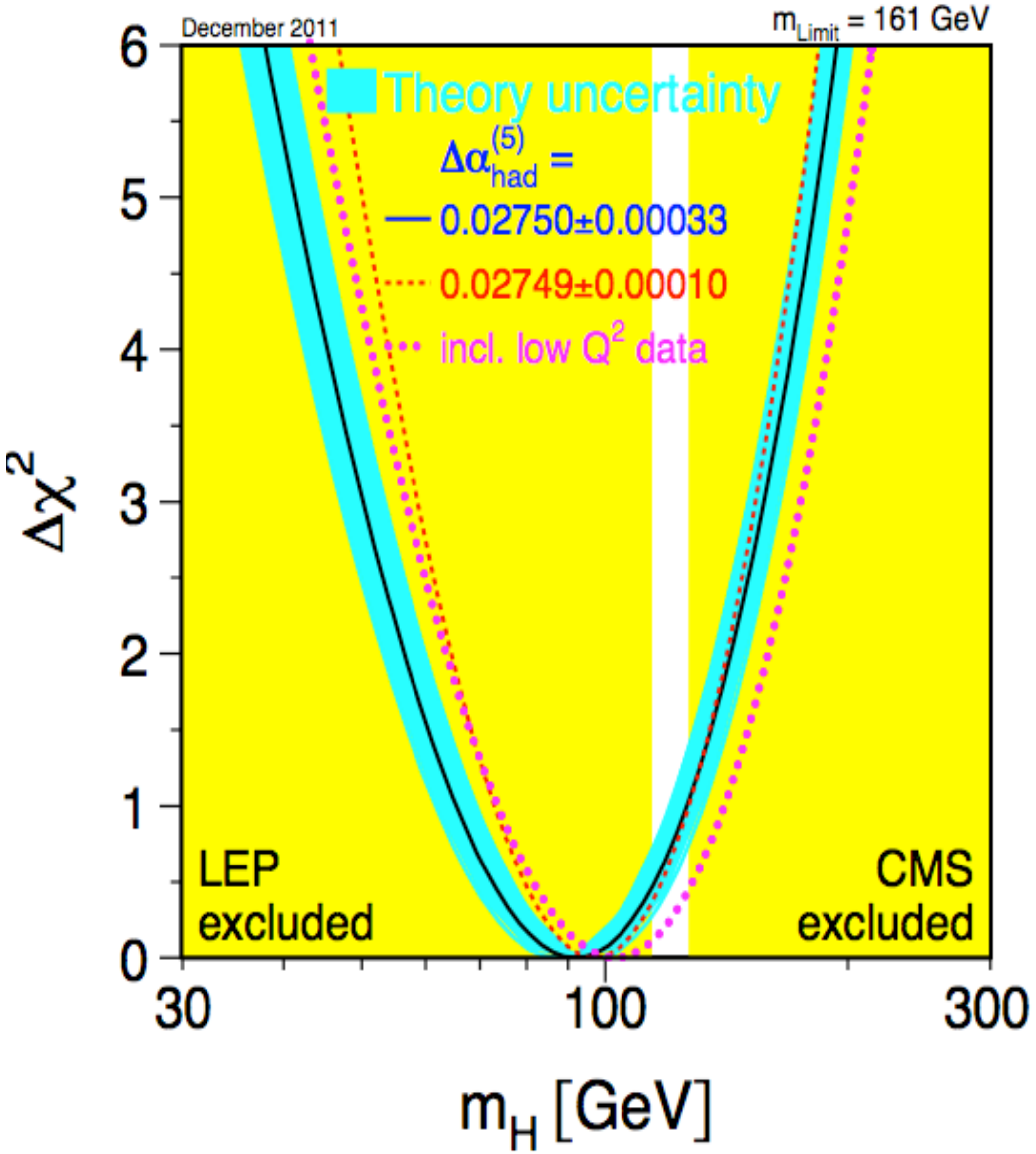
Preliminary 95 and 99%CL exclusion limits

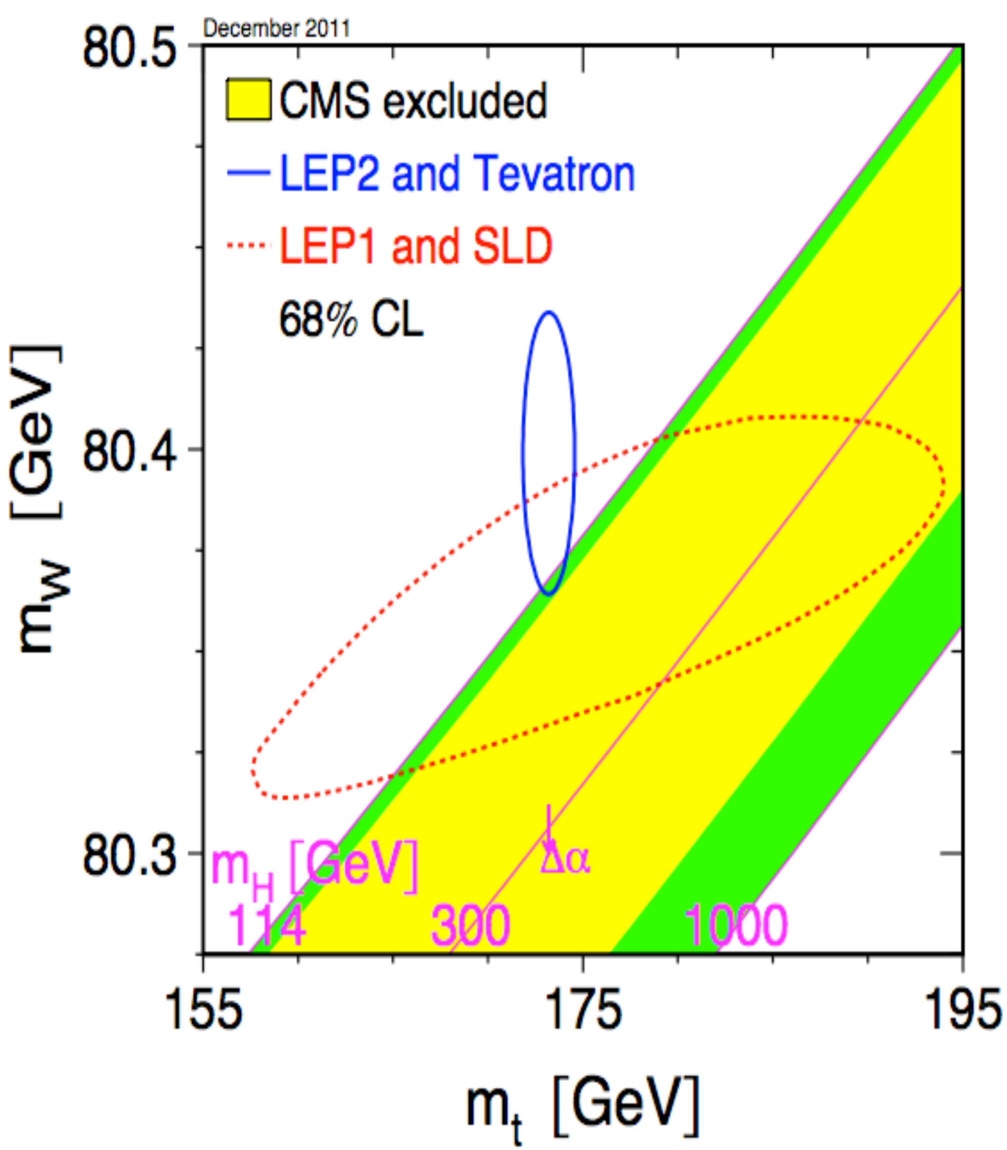
95% CL:	**obs 127-600,**	**exp:117-543**
99% CL:	**obs 128-525,**	**exp:125-500**

Limits on σ/σ_{sm} (CLs method)



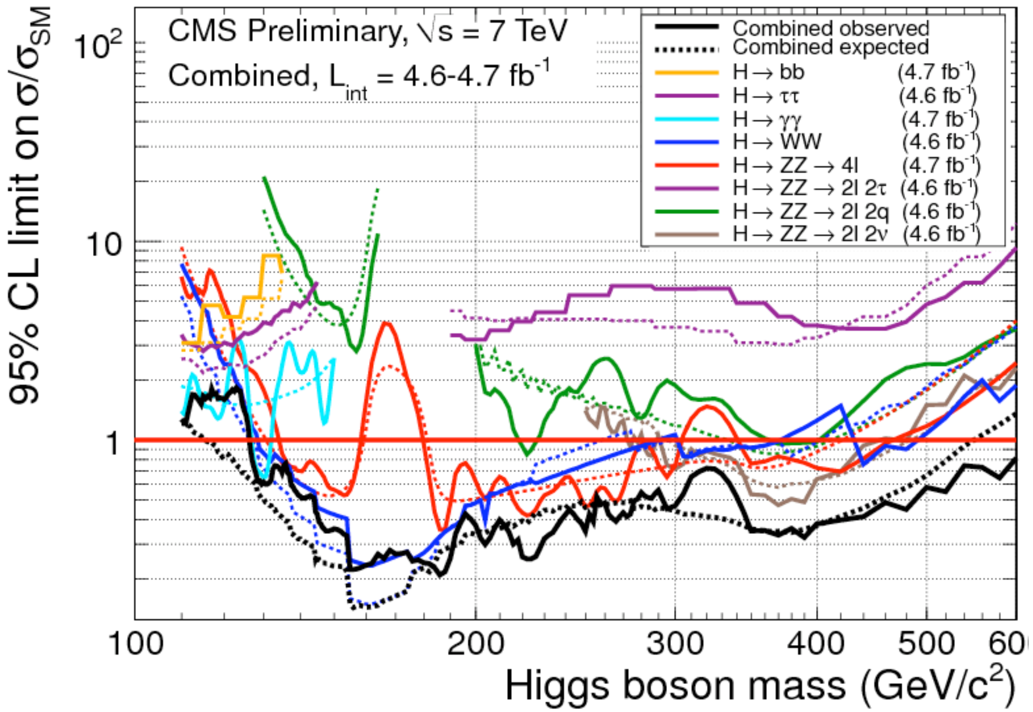
Freshly squeezed EWK plots

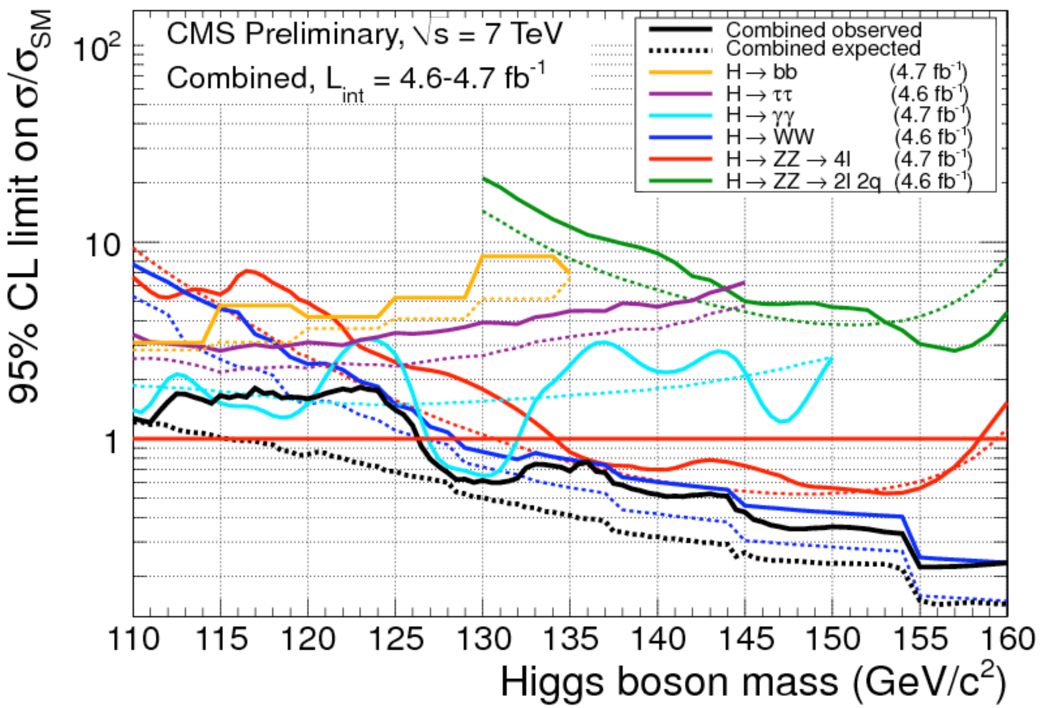




Limits by channel

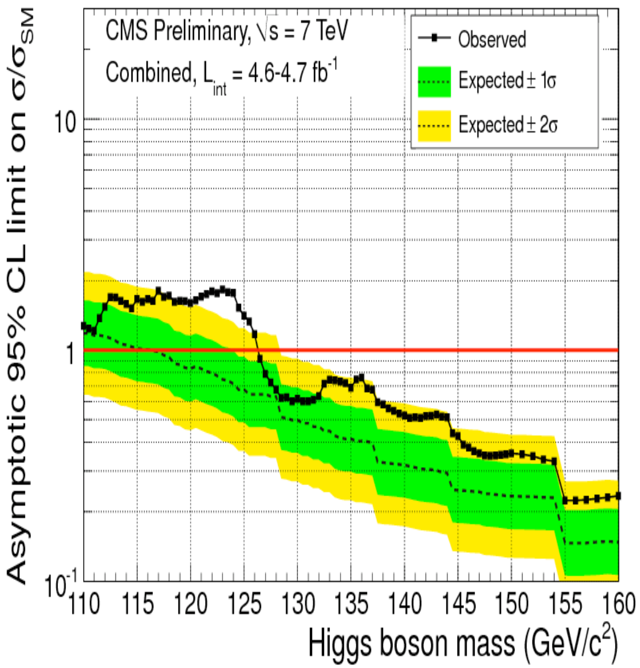
Solid line = Observed limit ; Dashed line = Median Expected

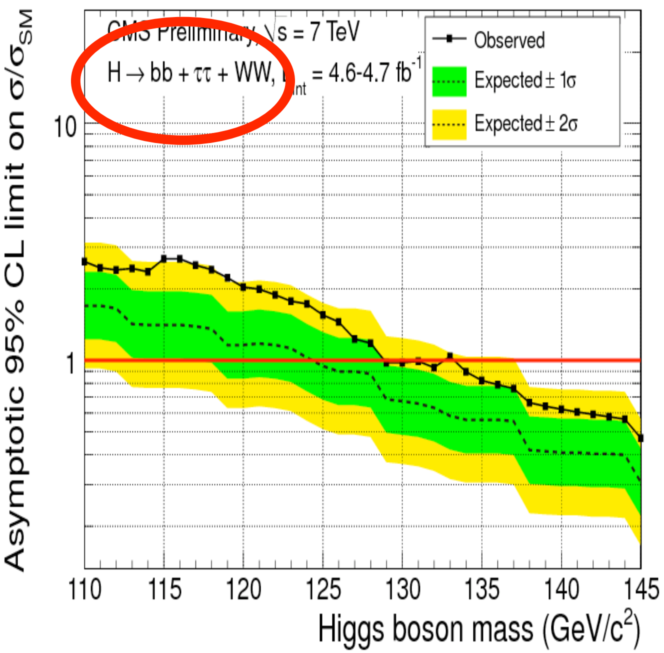


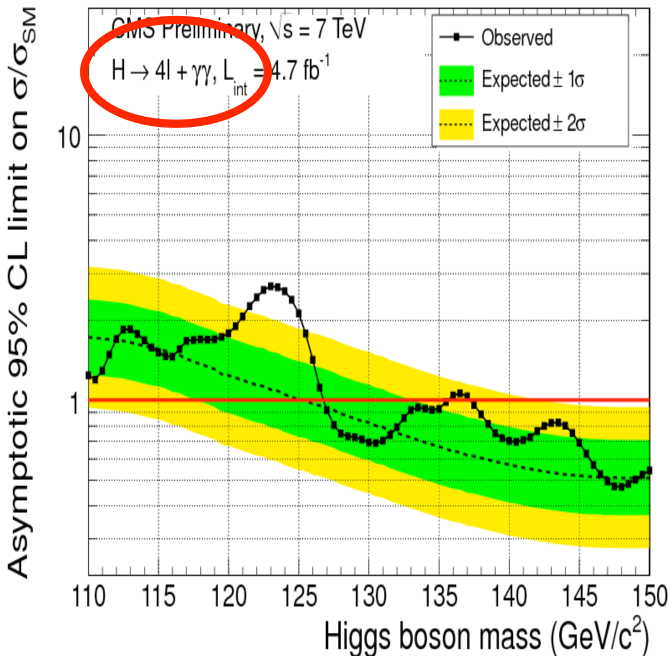


(Asymptotic CLs only)

Zoom in the low mass region



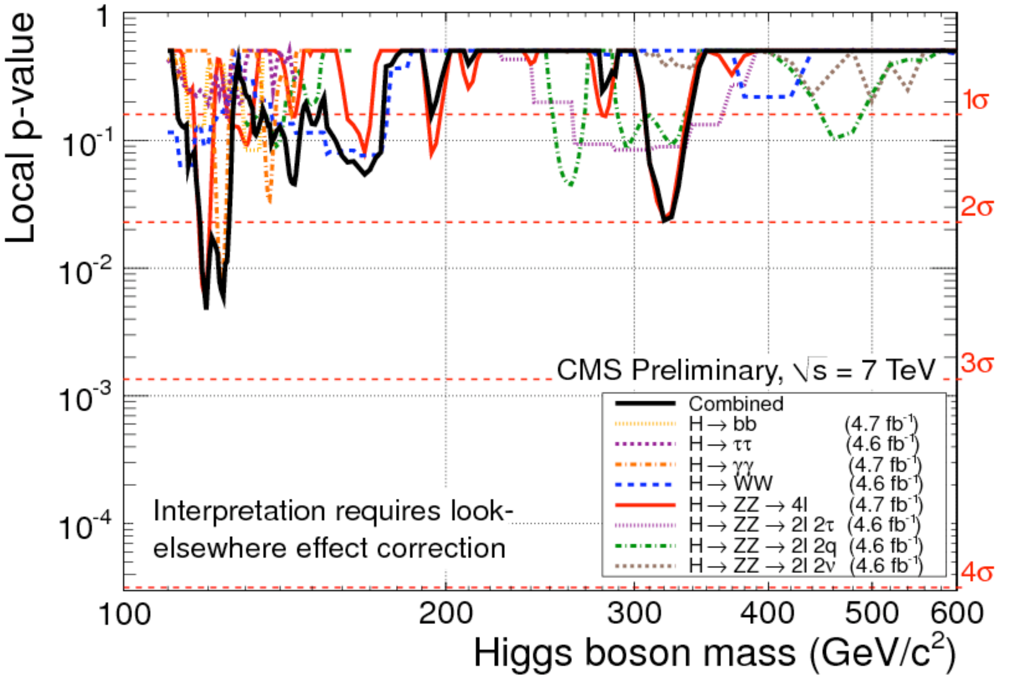


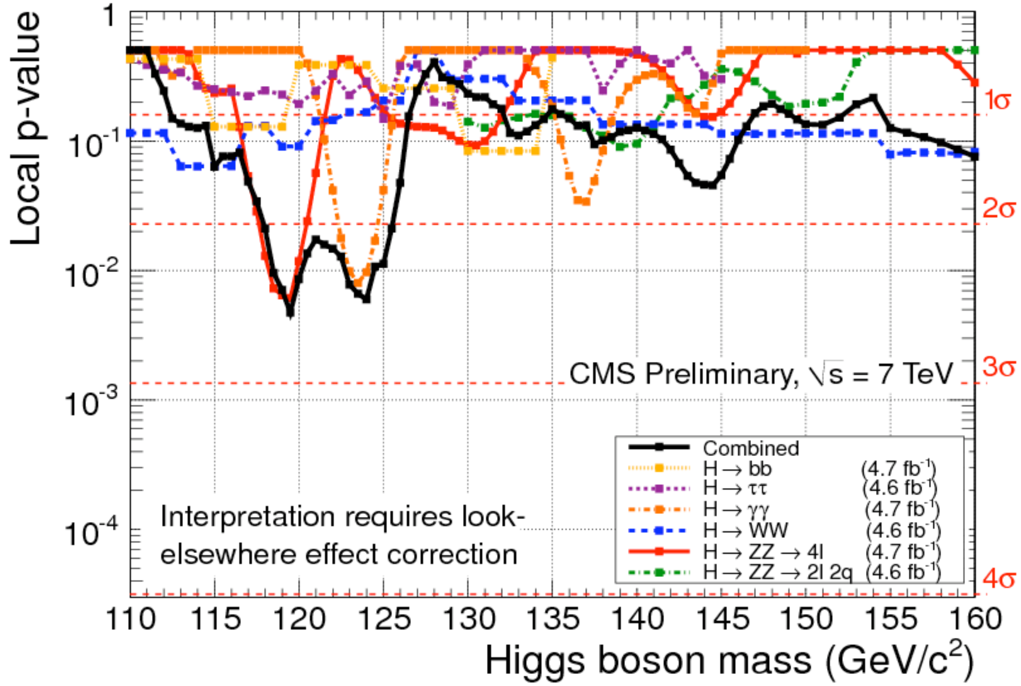


We cannot exclude the presence of the SM Higgs boson below 127GeV because of a modest excess of events in the region between 115 and 127GeV.

The excess at low mass is produced by a broad excess driven by the low resolution channels (H2TT, H2WW, H2BB, center), modulated by the localized excesses seen by the high resolution channels (H2GG and H2ZZ, right).

Anatomy of an excess: local and global p-values





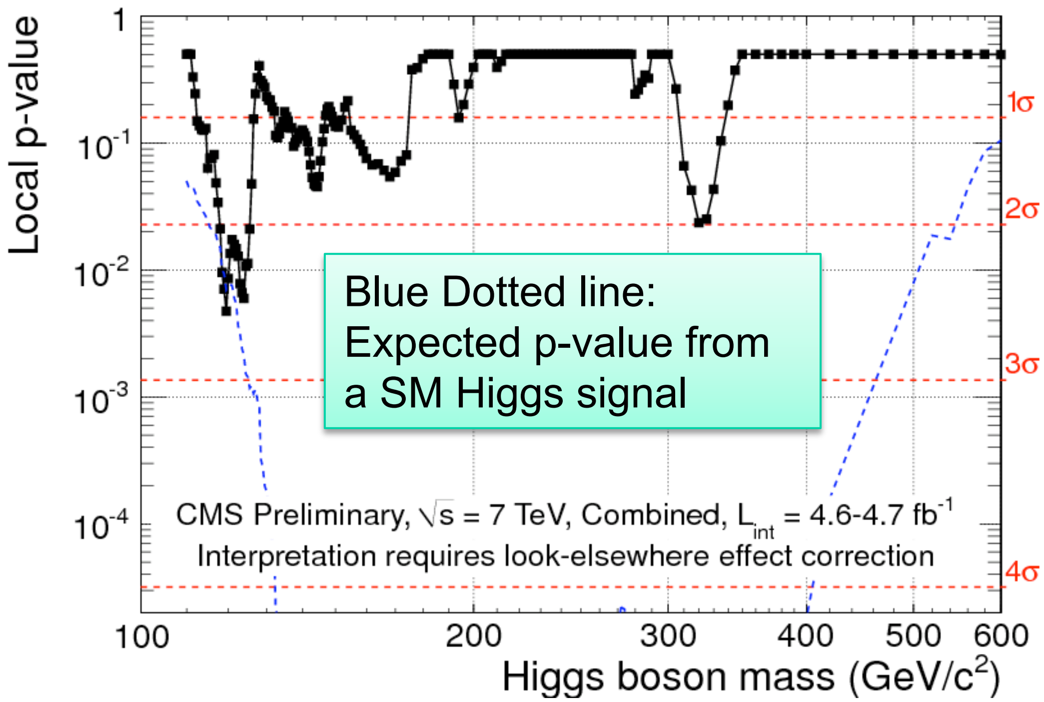
Maximum local significance **2.6σ.**

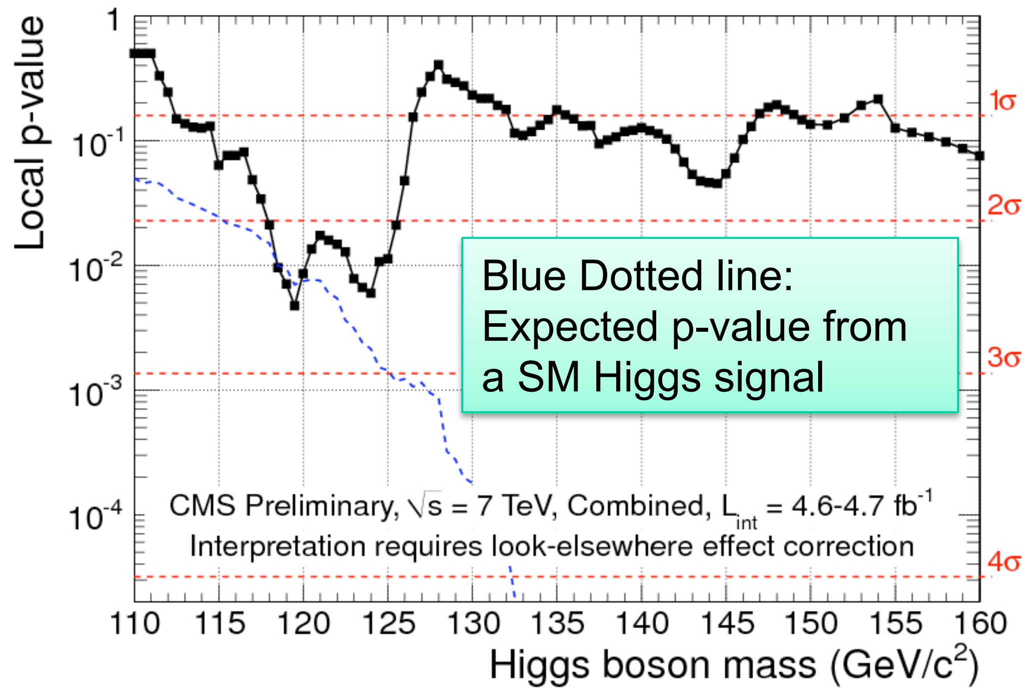
LEE-corrected significance (full mass range: 110-600GeV)= **0.6σ**

LEE-corrected significance (low mass range: 110-145GeV)= **1.9σ**

The excess we see in the low mass region has a modest statistical significance and could be reasonably a fluctuation of the background.

Anatomy of an excess: Observed and Expected

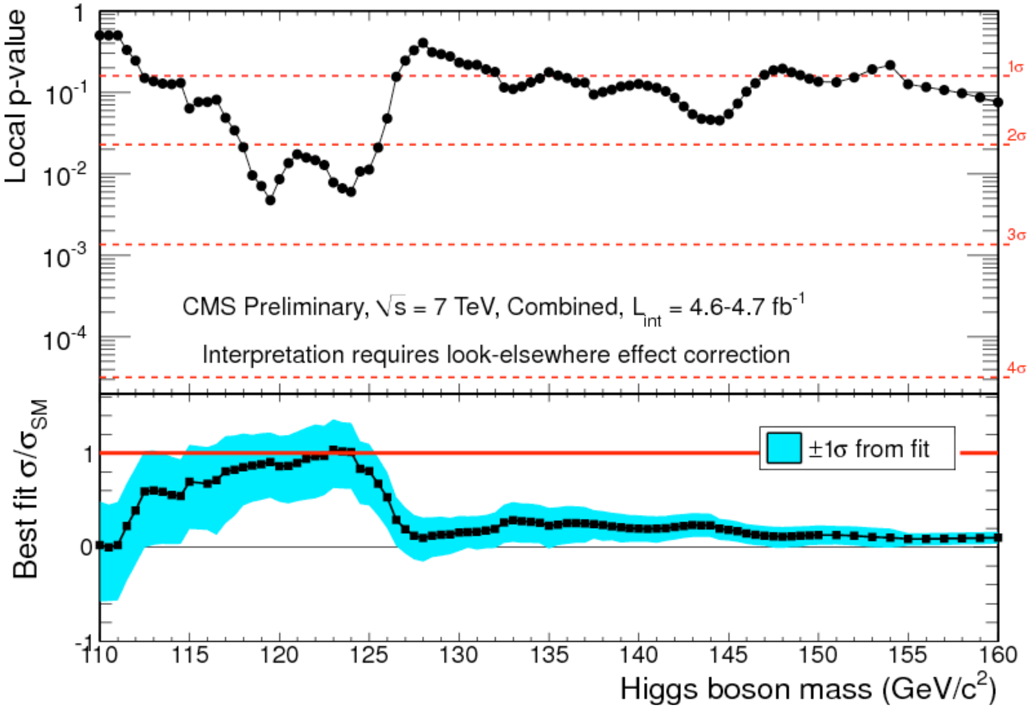


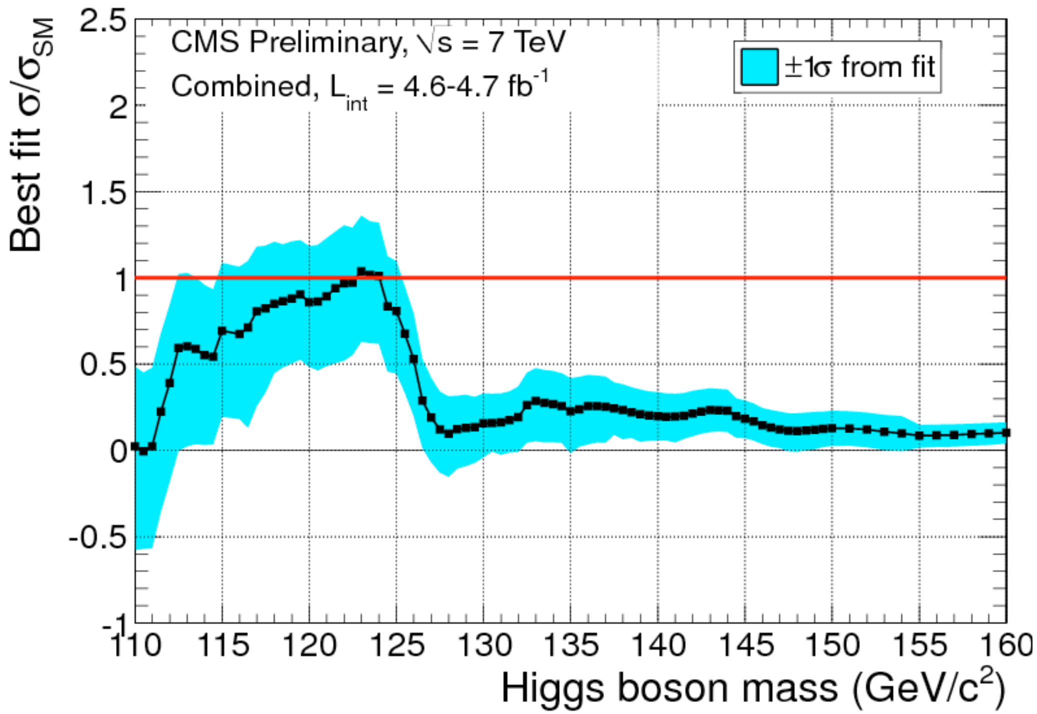


The only region where the observed p-value seems to be compatible with the expected p-value from a SM Higgs is the low mass region.

In this region a SM Higgs boson is expected to yield a modest p-value **(2-3σ median value in the range 115-127GeV)**

Anatomy of an excess: best fit σ/σ_{sm}

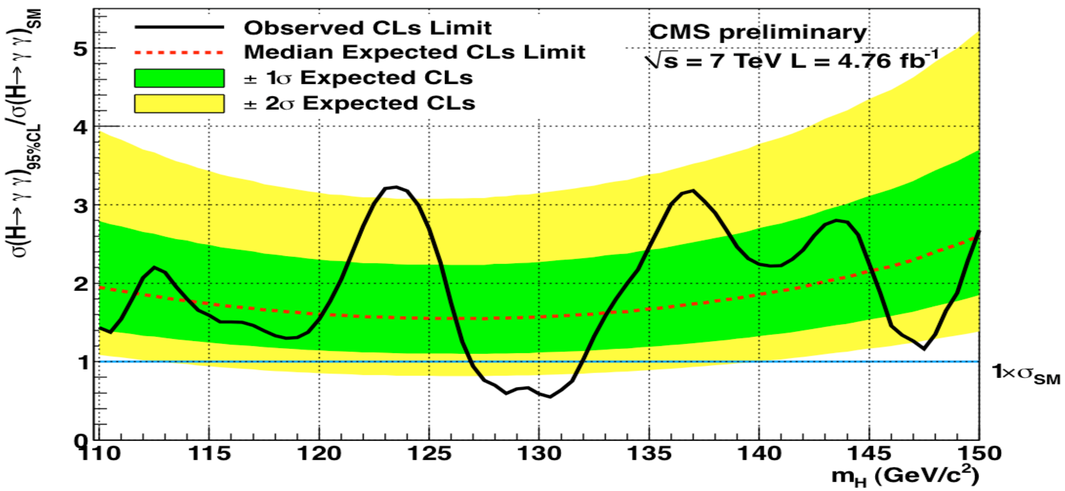


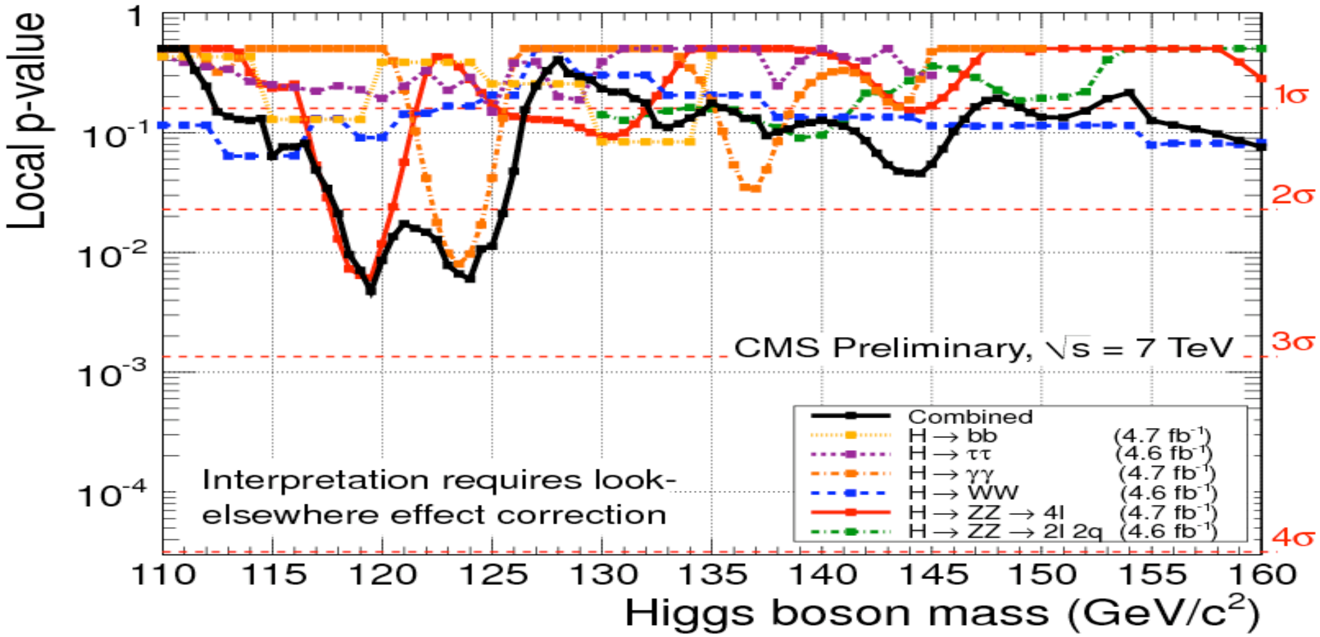


Fitted σ/σ_{SM} compatible with 1 in the full low mass range.
Median value touching 1 at a mass of 124 GeV and below.

Anatomy of an excess: the high resolution channels

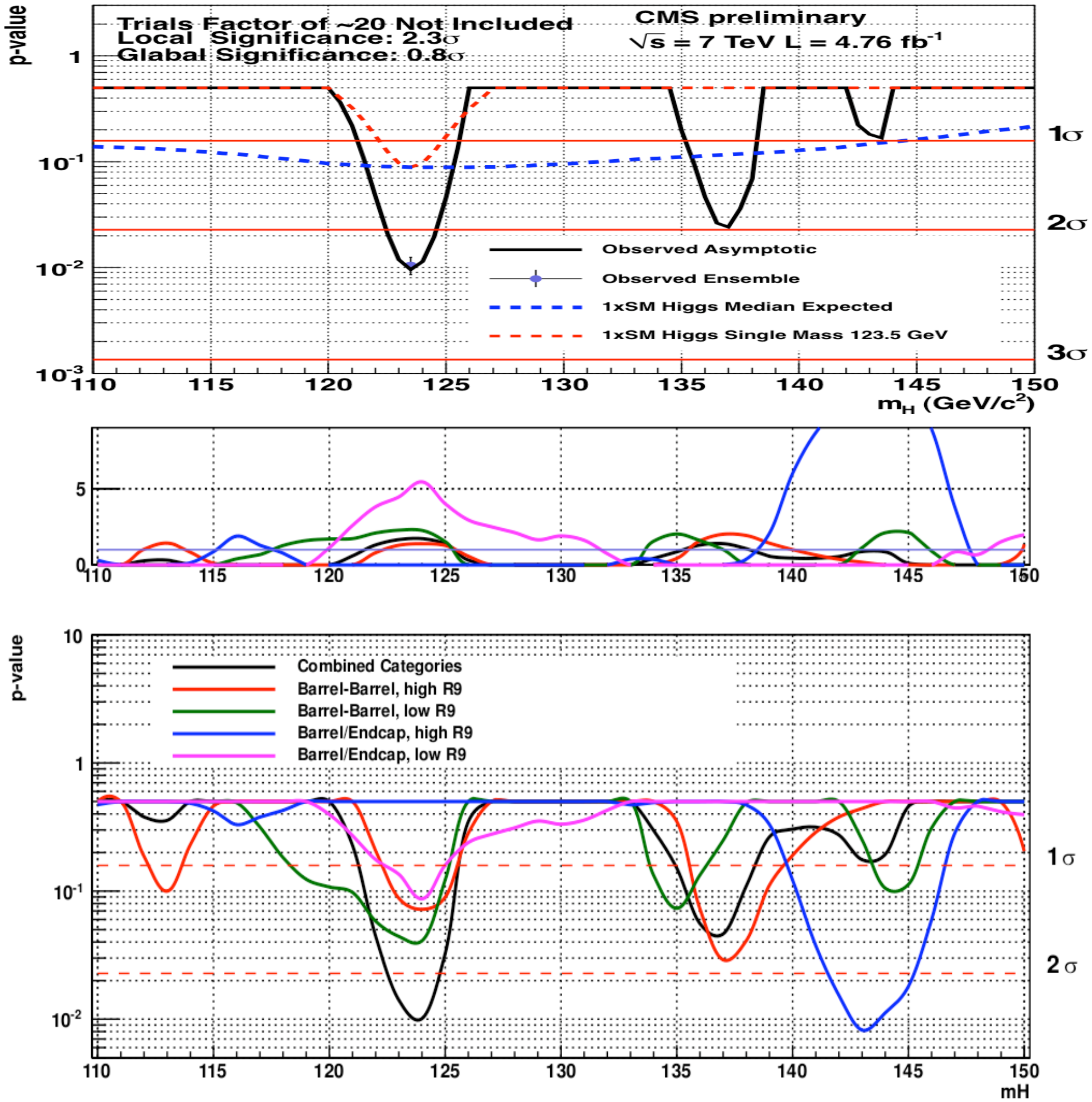
$H \rightarrow \gamma\gamma$





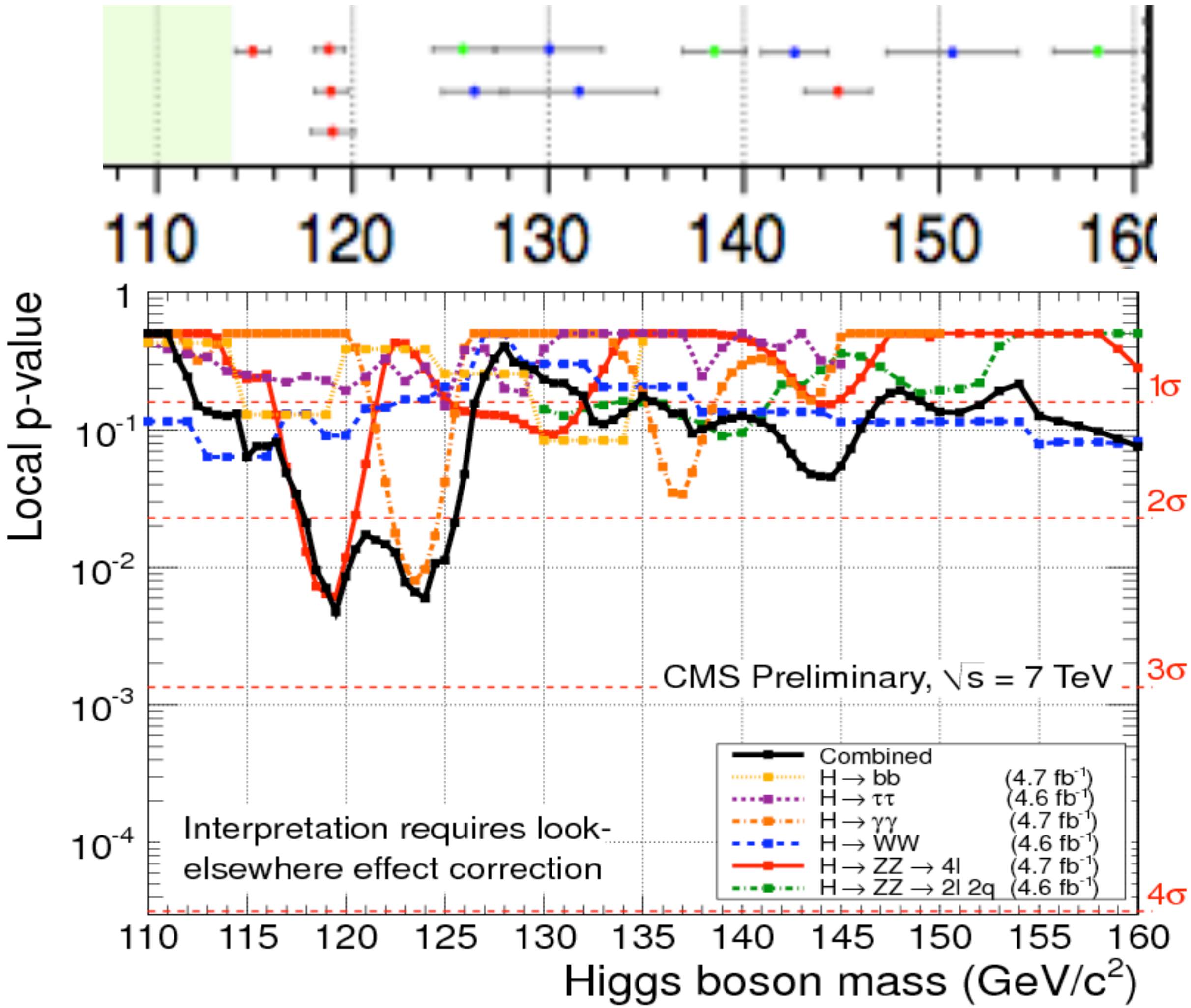
Anatomy of an excess: the high resolution channels

$H \rightarrow \gamma\gamma$



Anatomy of an excess: the high resolution channels

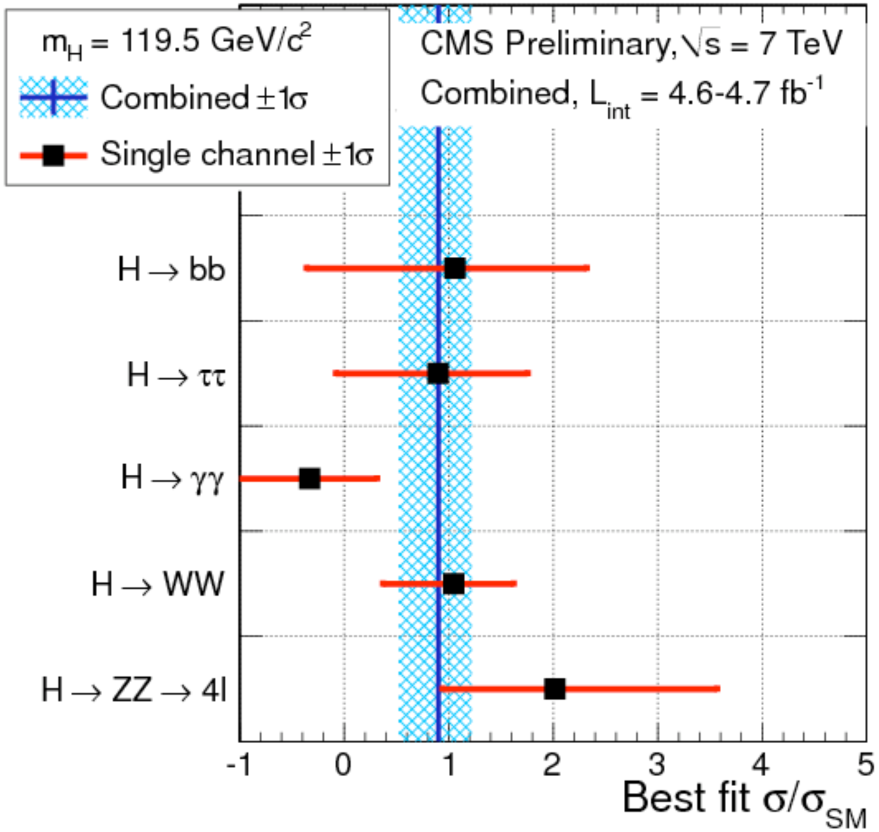
H → ZZ→ 4l: 4e, 4μ, 2e2μ

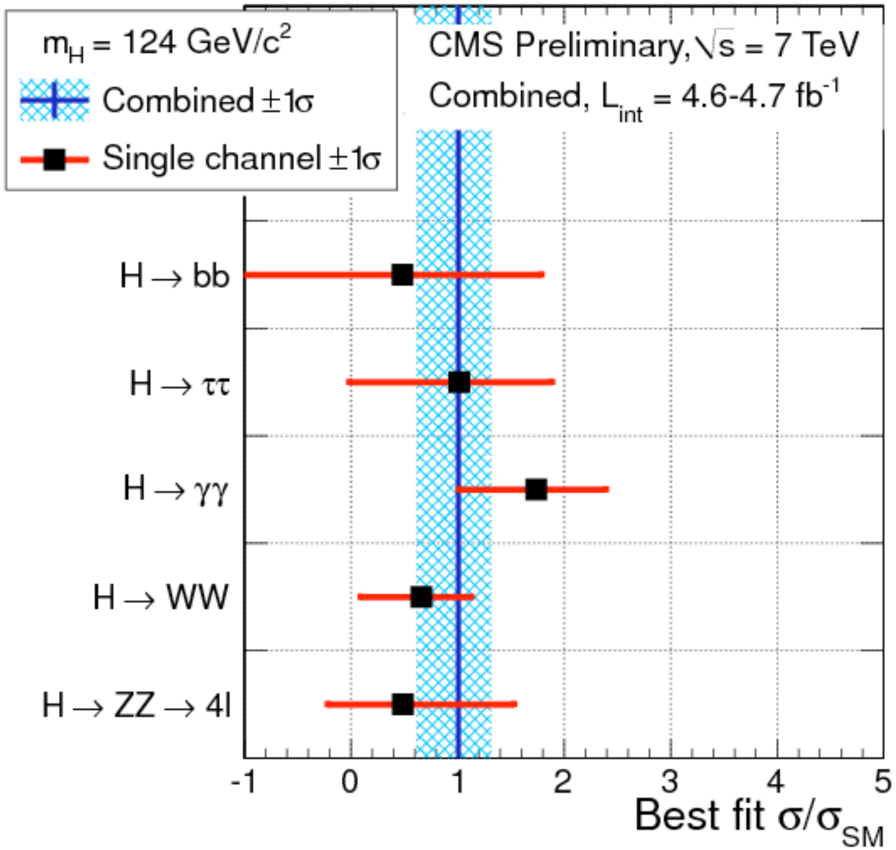


Anatomy of the excess

Best fit σ/σ_{sm} of the various channels

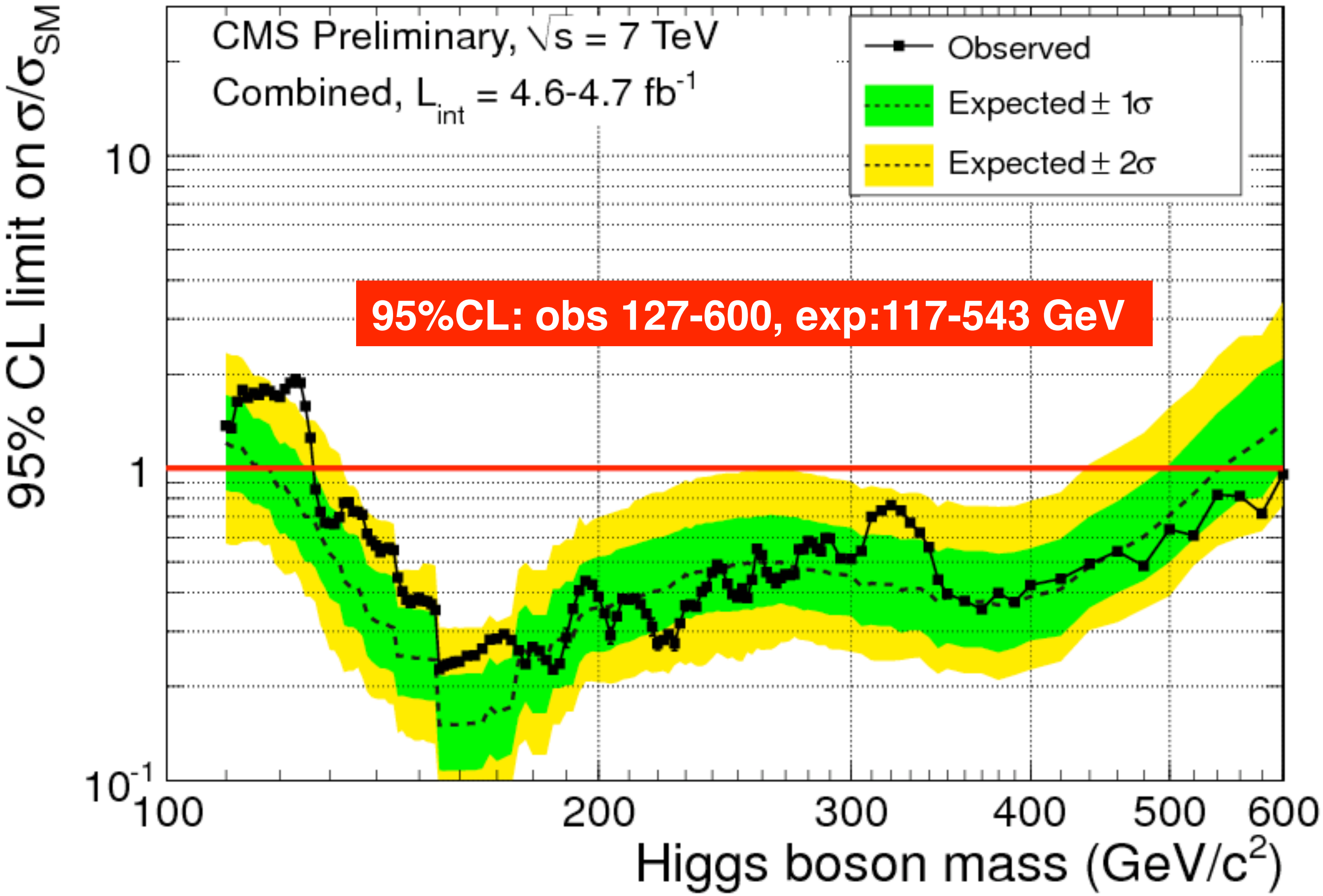
119.5 GeV **124 GeV**





Excess quite consistently seen in all individual channels ±1σ in the low mass region.

Limits on σ/σ_{sm} (CLs method)



Summary.

- We have been able to analyse very quickly the full data set collected in 2011 and to present here a comprehensive set of preliminary results.
- Final results and submission of papers are expected around the end of January (new additional channels, refined analyses).
- **We have reached the expected sensitivity (around or better than 1xSM) in the full mass range of our current exploration (115GeV-600 GeV).**
- We have established **new 95% CL exclusion limits: 127GeV-600GeV.**
- We are not able to exclude the presence of the SM Higgs below 127GeV since we observe in our data **a modest excess of events between 115 and 127GeV that appears, quite consistenly, in five independent channels.**
- **The excess is most compatible with a SM Higgs hypothesis in the vicinity of 124 GeV and below, but the statistical significance (2.6σ local and 1.9σ global after correcting for the LEE in the low mass region) is not large enough to say anything conclusive.**
- As of today what we see is consistent either with a background fluctuation or with the presence of the SM Higgs boson.
- Refined analyses and additional data in 2012 will definitely give an answer.

Conclusion

- **Many thanks** to the thousand of people that contributed to the success of the CMS experiment, from the conceptual design throughout the construction, commissioning and operation of our magnificent detector.

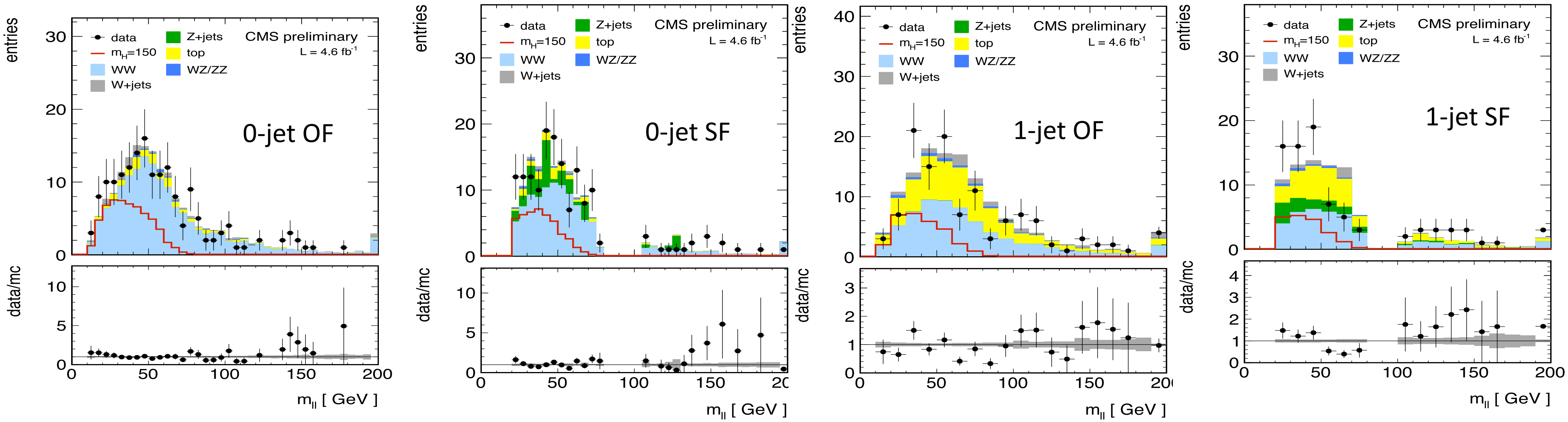
- **Many thanks** to the hundreds of analysers, software and computing experts that worked so hard to produce these complete set of results just a few weeks after the end of 2011 data taking.

- **Many thanks** to Steve Myers and the whole LHC team for having delivered to the experiments an integrated luminosity exceeding our most optimistic expectations.

Lastly, a personal note.

to my father
Giuliano Tonelli,
passed away on Sunday December 11, 2011.

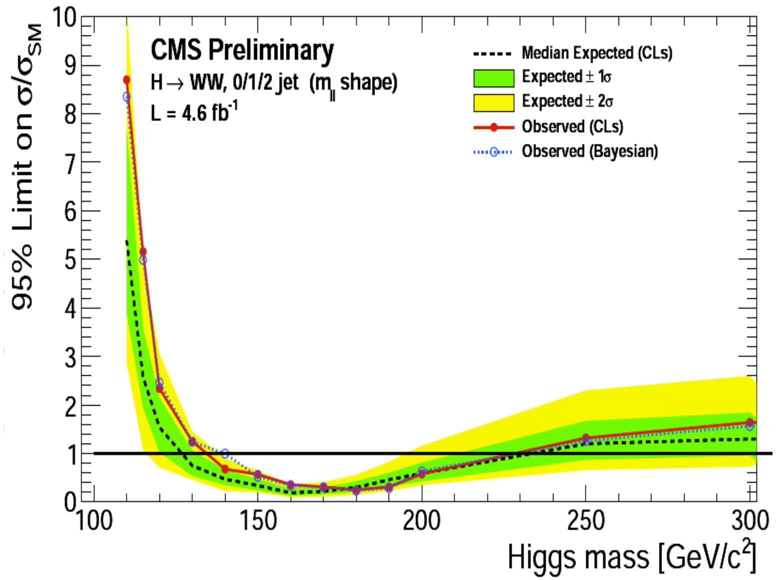
Cross Check : Single Variable Shape Analysis



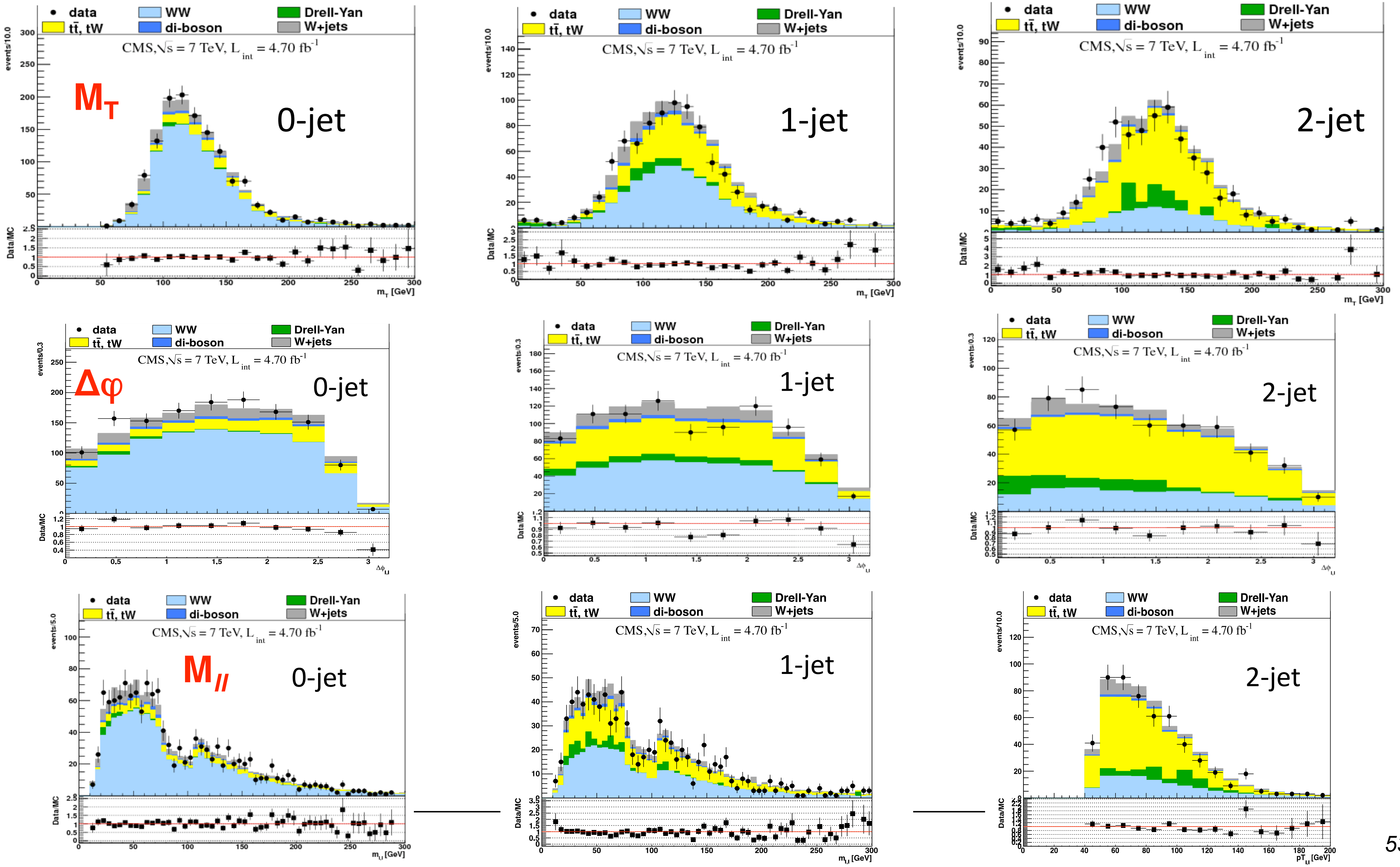
Use the shape of m_{ll} at the Cut Based Higgs selection level but the m_{ll} cut:

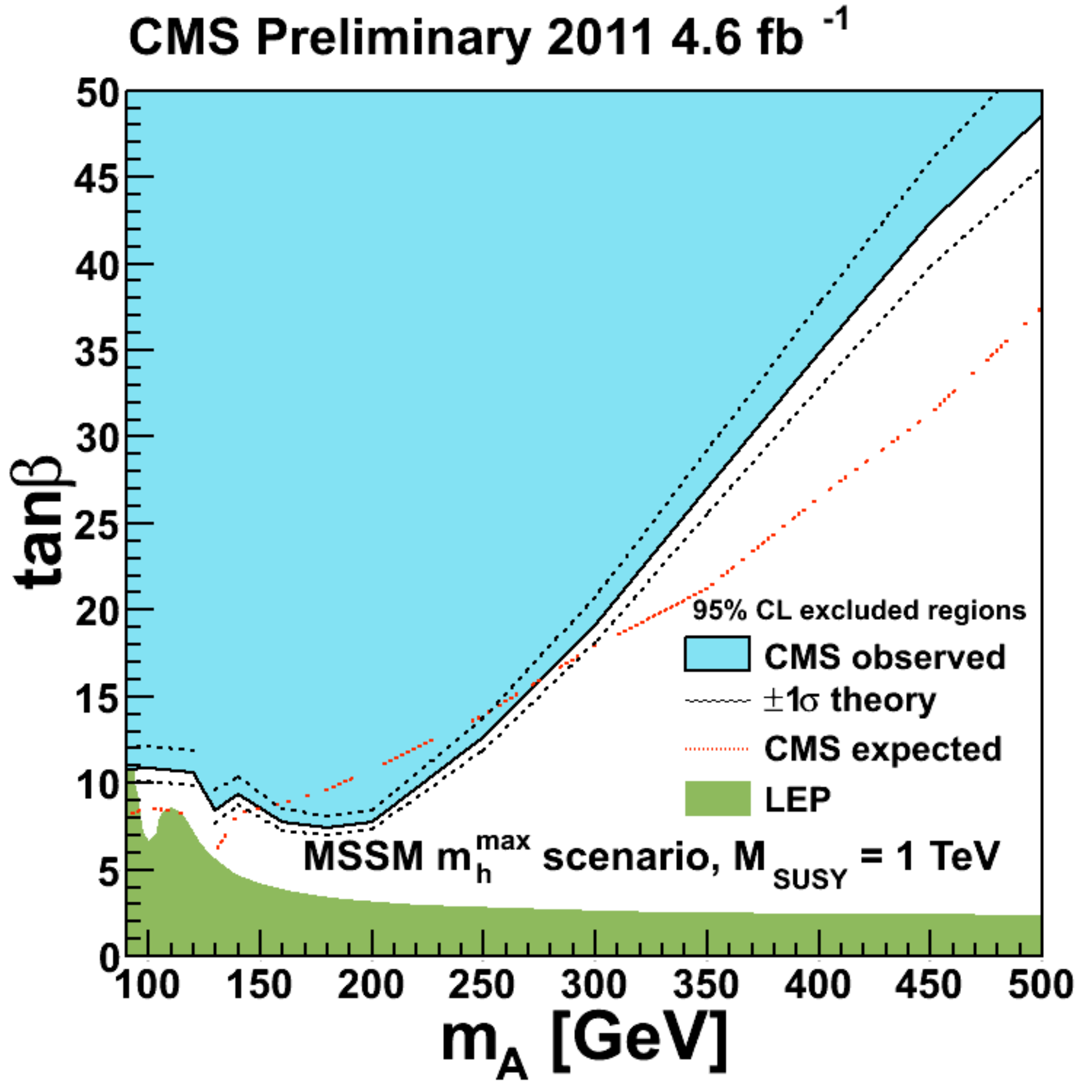
Expected range: 126 < M_H < 230 GeV
Observed range: 132 < M_H < 238 GeV

Result consistent with BDT



Distributions at WW Selection level

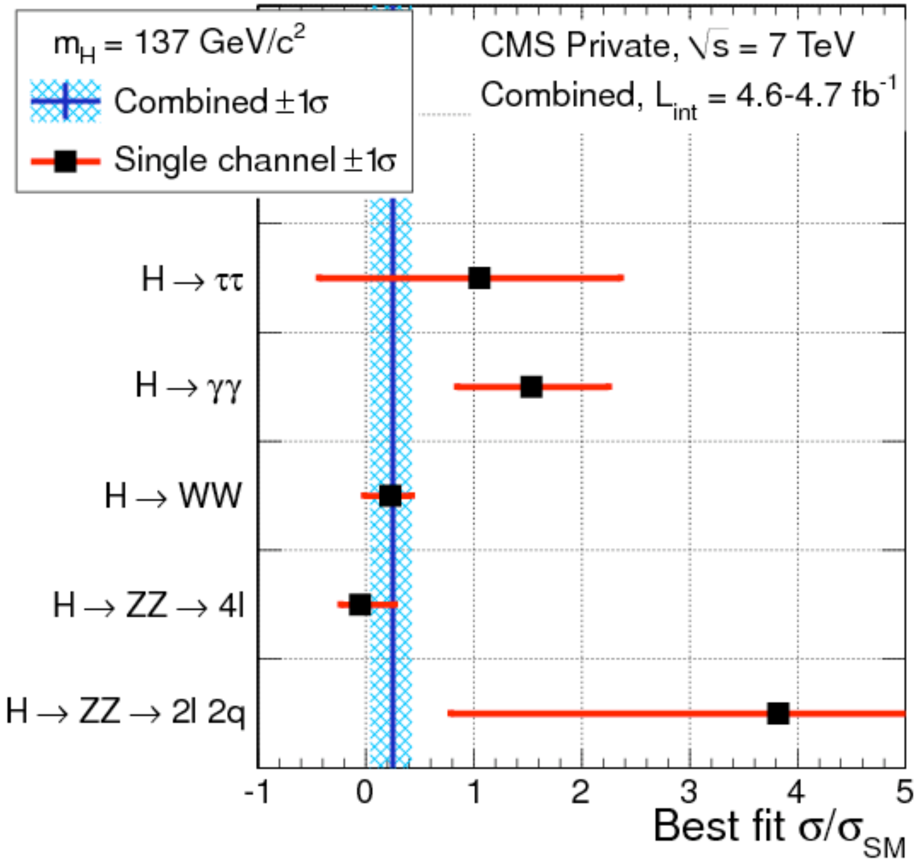



CMS Preliminary 2011 4.6 fb -1
tanβ
m_A [GeV]
95% CL excluded regions
CMS observed
±1σ theory
CMS expected
LEP
MSSM m_h^max scenario, M_SUSY = 1 TeV
0
5
10
15
20
25
30
35
40
45
50
100
150
200
250
300
350
400
450
500

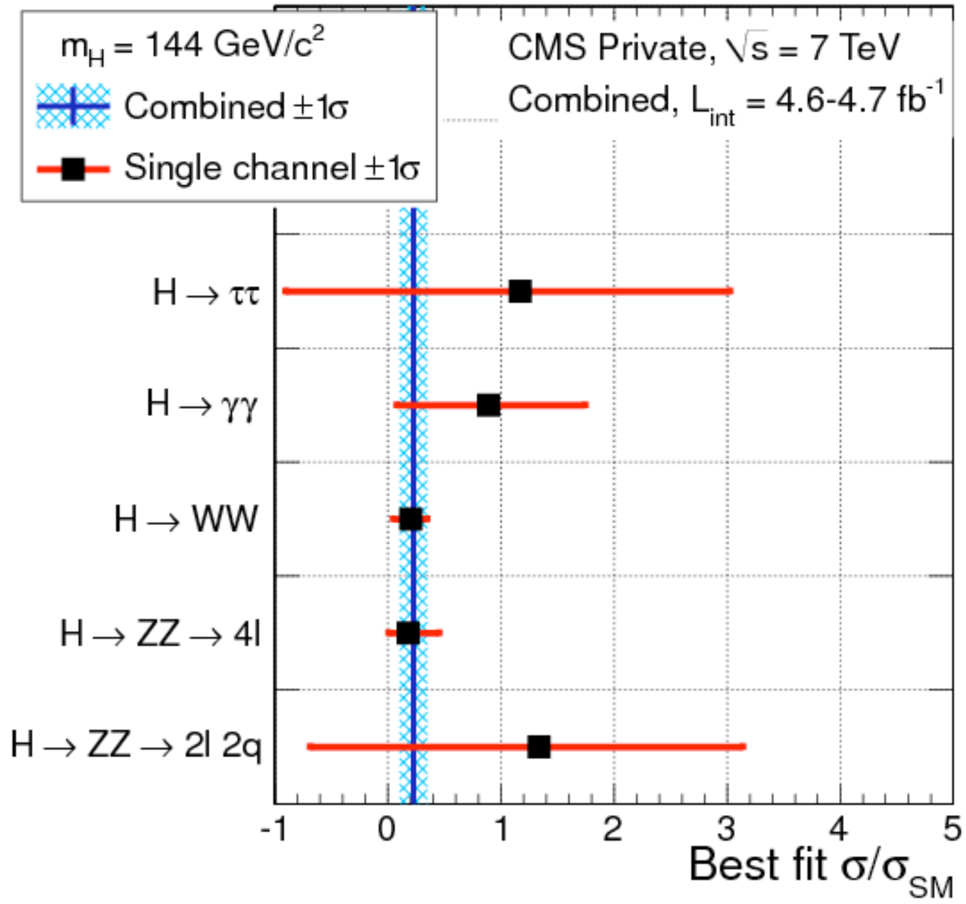
Anatomy of the excess

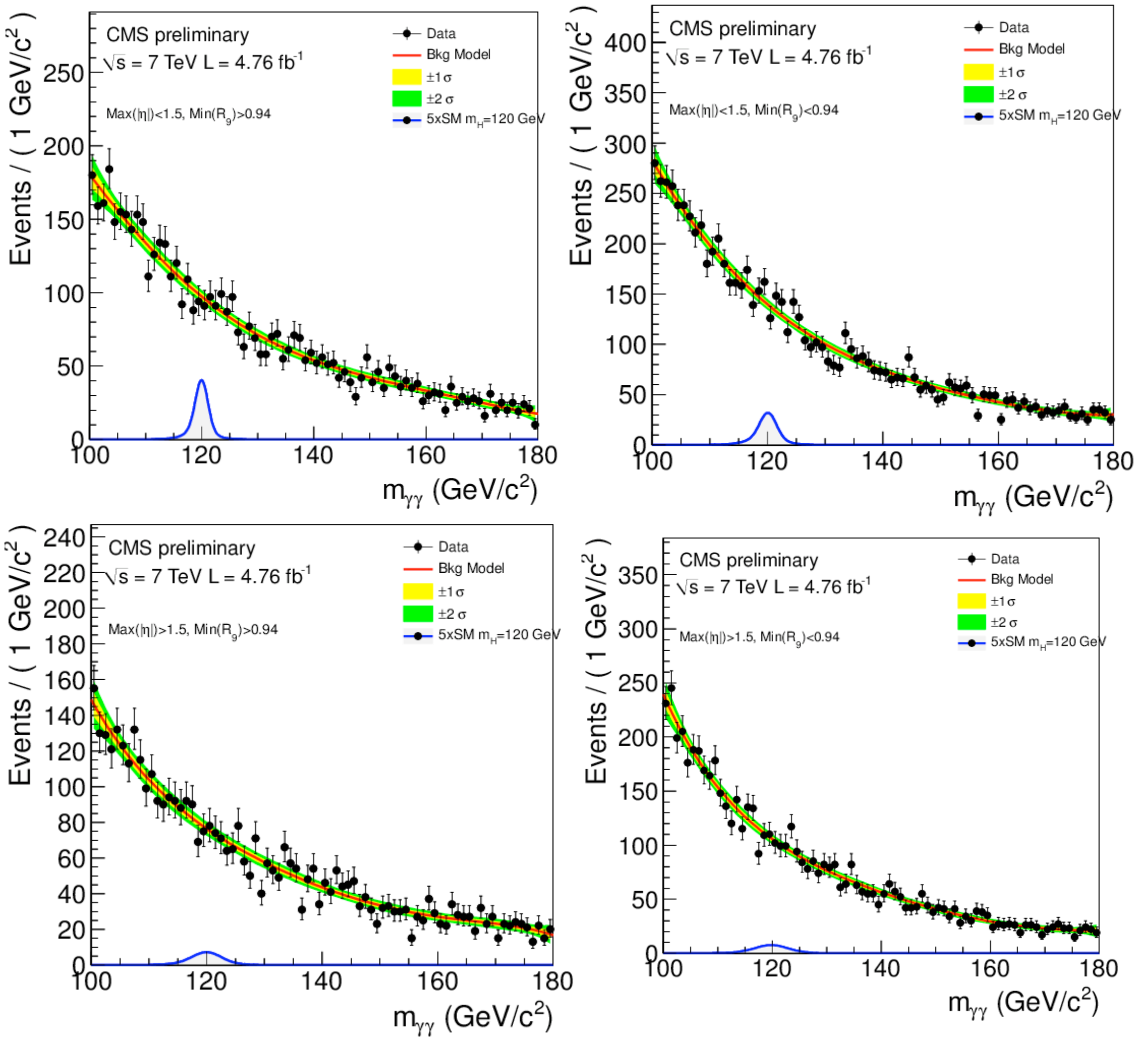
Best fit σ/σ_{sm} of the various channels

137 GeV



144 GeV




CMS preliminary
$\sqrt{s}$ = 7 TeV L = 4.76 fb^{-1}
Max(|η|)<1.5, Min(R$_9$)>0.94
Data
Bkg Model
±1 σ
±2 σ
5xSM m$_H$=120 GeV
Events / (1 GeV/c^2)
m$_{\gamma\gamma}$ (GeV/c^2)
CMS preliminary
$\sqrt{s}$ = 7 TeV L = 4.76 fb^{-1}
Max(|η|)<1.5, Min(R$_9$)<0.94
Data
Bkg Model
±1 σ
±2 σ
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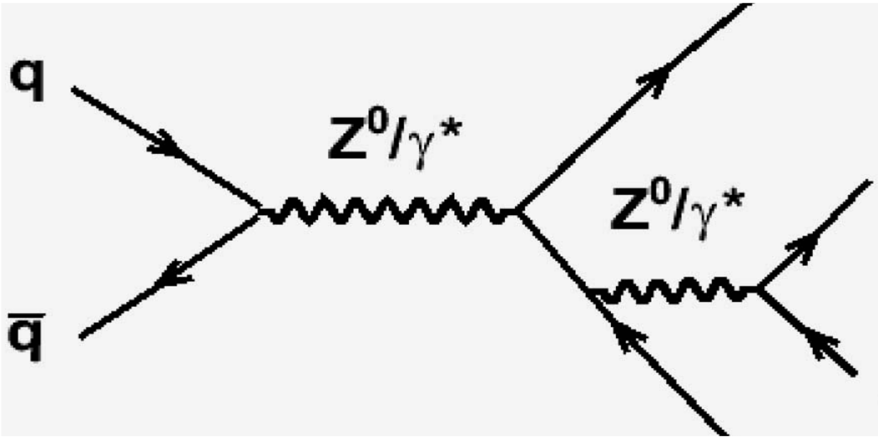
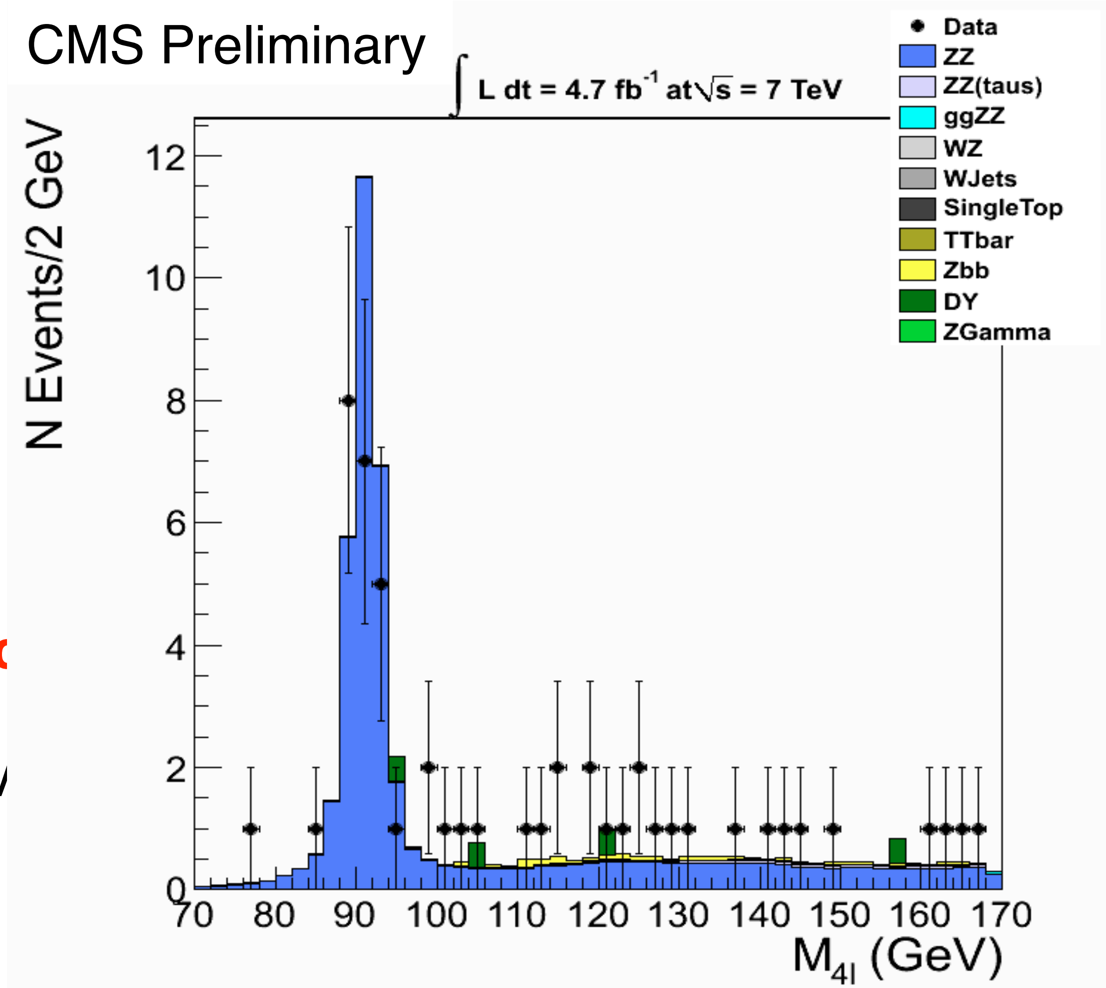
±1 σ
±2 σ
5xSM m$_H$=120 GeV
Events / (1 GeV/c^2)
m$_{\gamma\gamma}$ (GeV/c^2)

Observation of single-resonant qqbar→ Z → 4l



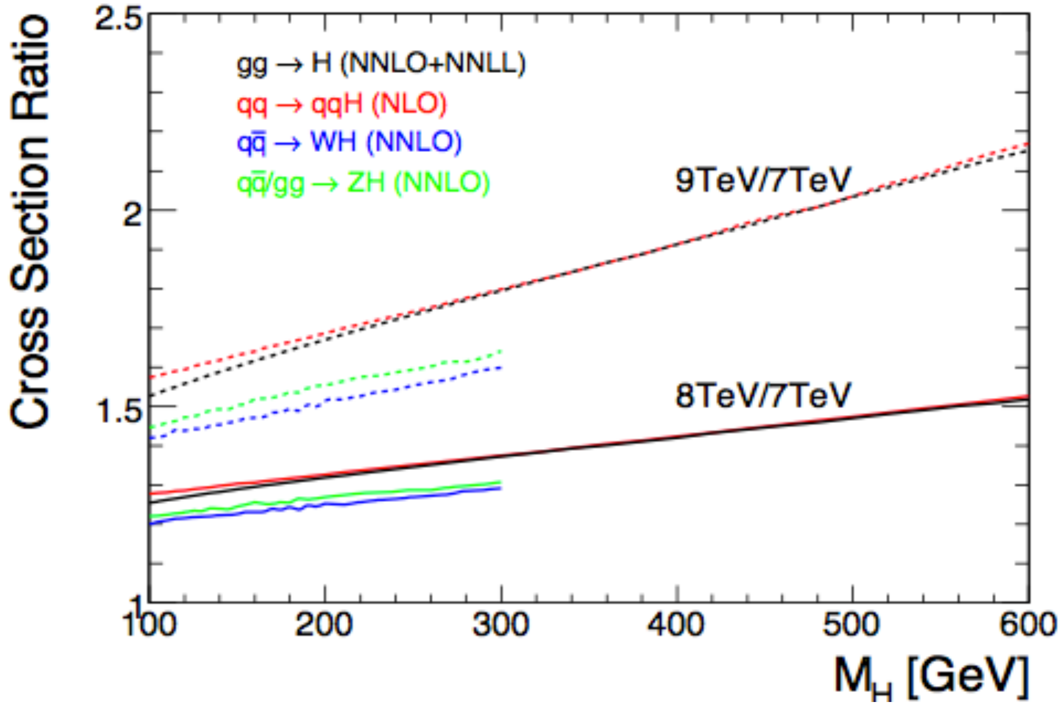


Standard candle for H->ZZ->4l searc

Di-lepton mass cut is relaxed to 4 GeV

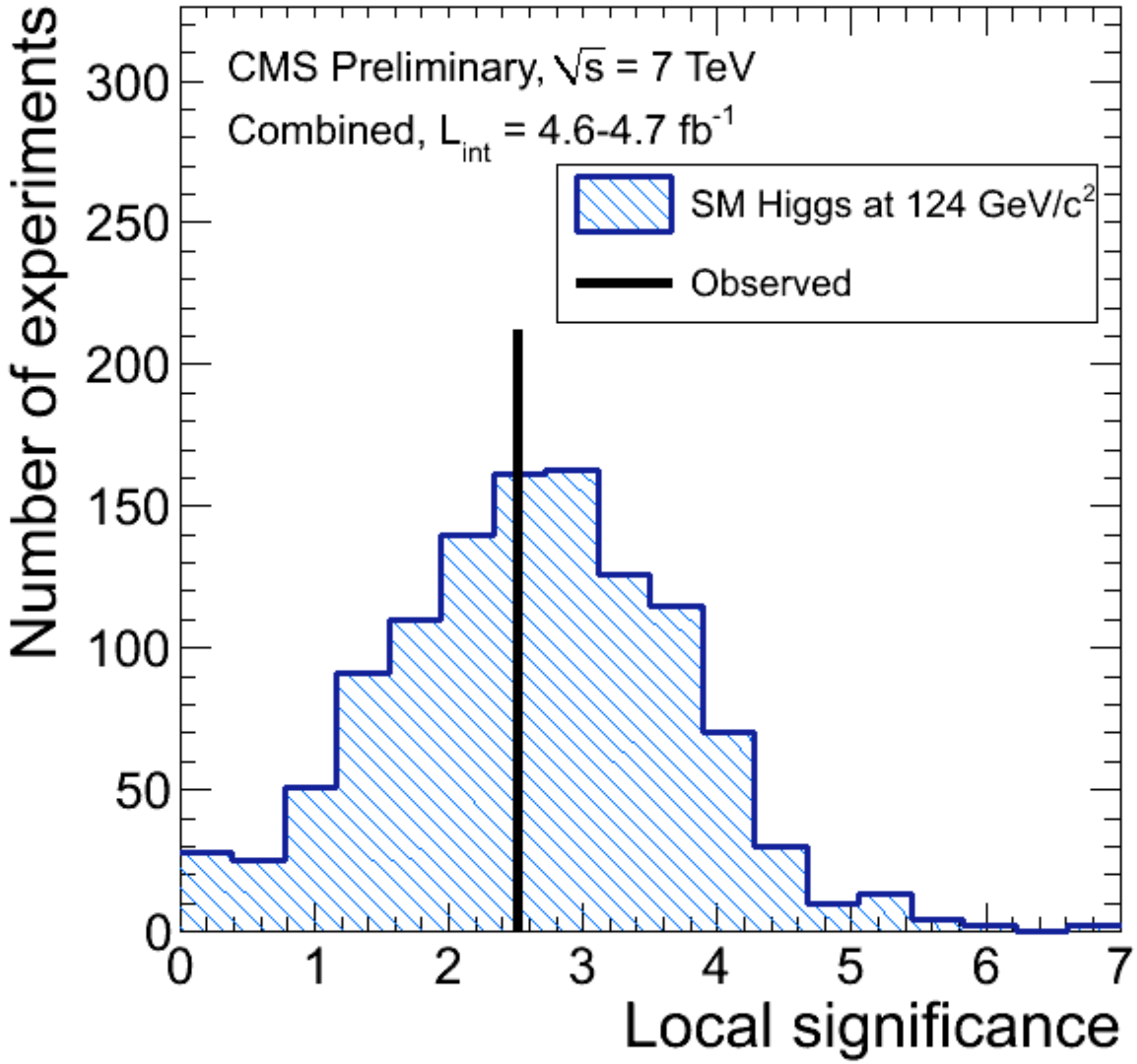
8 TeV means more useful luminosity

- $\sqrt{s}$ = 8 TeV has a big impact
  - γ-factor 14% higher
- Higgs gains everywhere
  - Even low mass higgs benefits
    ~30% increase (gg fusion) at 125 GeV
- SUSY
  - Moves key searches into much higher probability PDF regions
    - x2 to x4 increase in SUSY right in the key mass ranges to look now!
- Could trade for lower pileup
  - 30 p/u at 7 TeV gives same reach for low mass Higgs as 23 PU at 8 TeV
  - And you still get most of the big benefits for SUSY and high mass searches



- Extending mass limits

Model	$\sqrt{s}$=7 TeV	$\sqrt{s}$=8 TeV
Z'_{SSM}	2450 (GeV)	2750 (GeV)
Z'_{Ψ}	2150	2350
G_{KK} (k=0.1)	2250	2550


CMS Preliminary, $\sqrt{s}$ = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
SM Higgs at 124 GeV/c^2
Observed
Number of experiments
Local significance
0
50
100
150
200
250
300
0
1
2
3
4
5
6
7