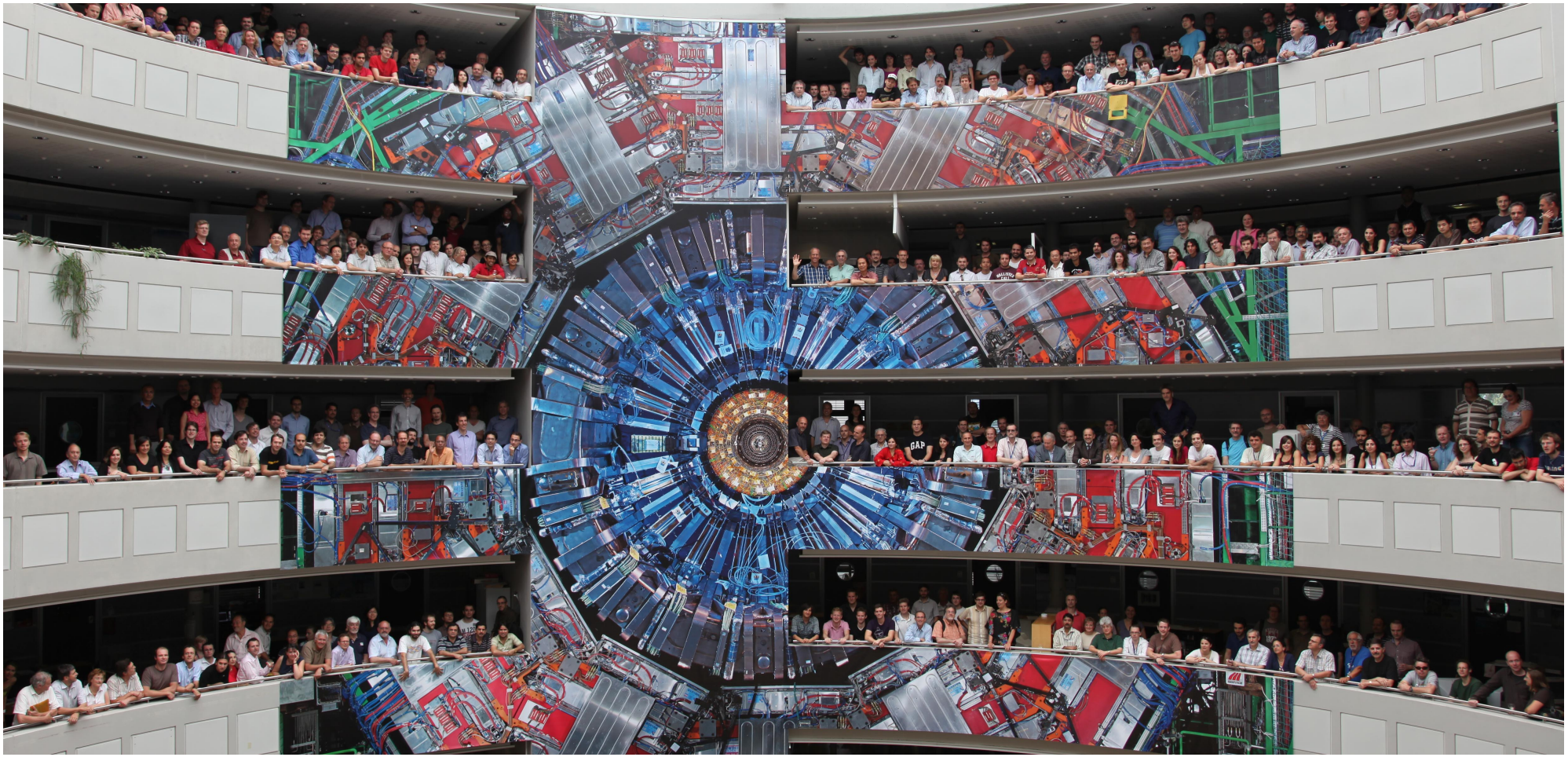


Higgs searches with the CMS detector at LHC

Guenakh Mitselmakher
University of Florida

Outline

- **Preamble:**
  - **LHC and CMS performance**
  - **Statistics definitions**
- **SM Higgs searches (published results):**
  - **H → bb**
  - **H → ττ**
  - **H → γγ**
  - **H → WW**
  - **H → ZZ**

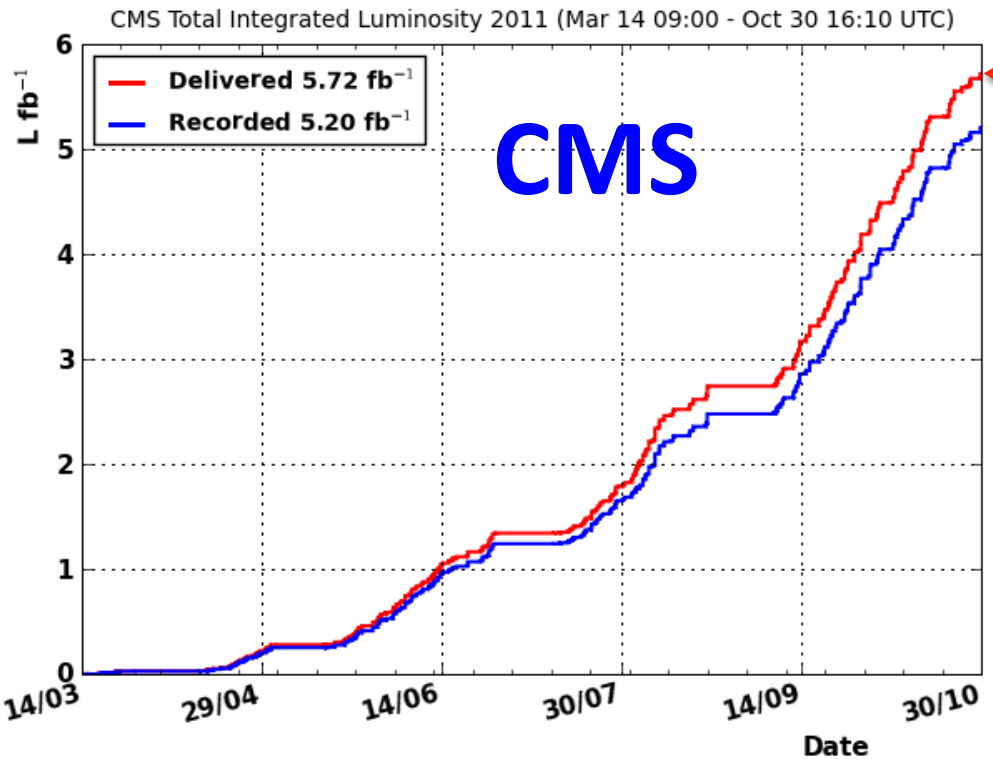
    - observation of the Z→4l decay in pp-collisions:

    a standard candle for the H→4l decay
  - **CMS SM Higgs Combination**
- **Additional results reported at Moriond -2012**
- **Outlook**

Preamble 1

LHC and CMS performance

LHC performance in 2011 (7 TeV)



>5 fb^{-1}delivered.
LHC target for this year was 1 fb^{-1} per exp.

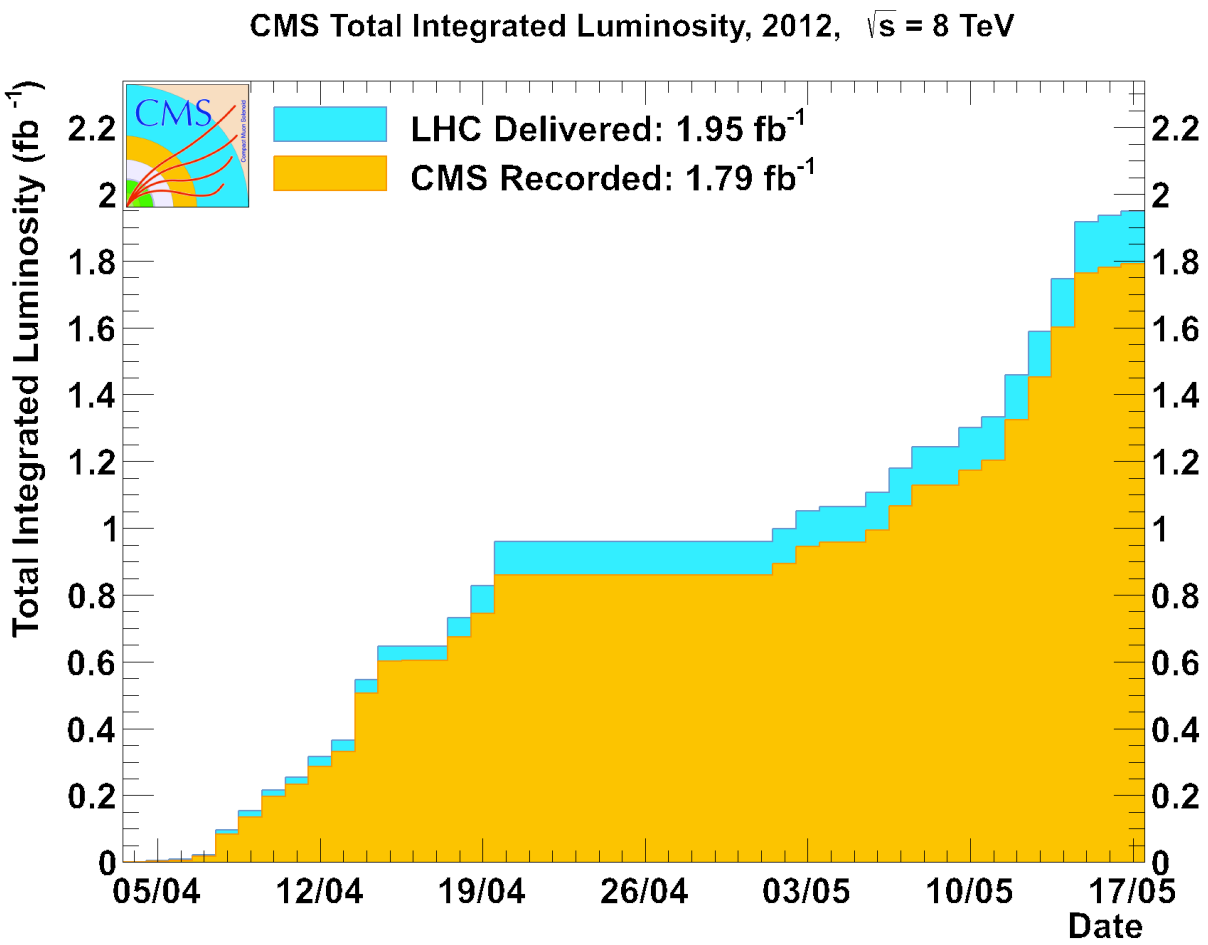
Max luminosity
$L = 3.5 \times 10^{33}\ cm^{-2}\ s^{-1}$

Rapid increase in instantaneous luminosity:

April ($L=2\times10^{32}\ cm^{-2}s^{-1}$) – October ($3.5\times10^{33}$)

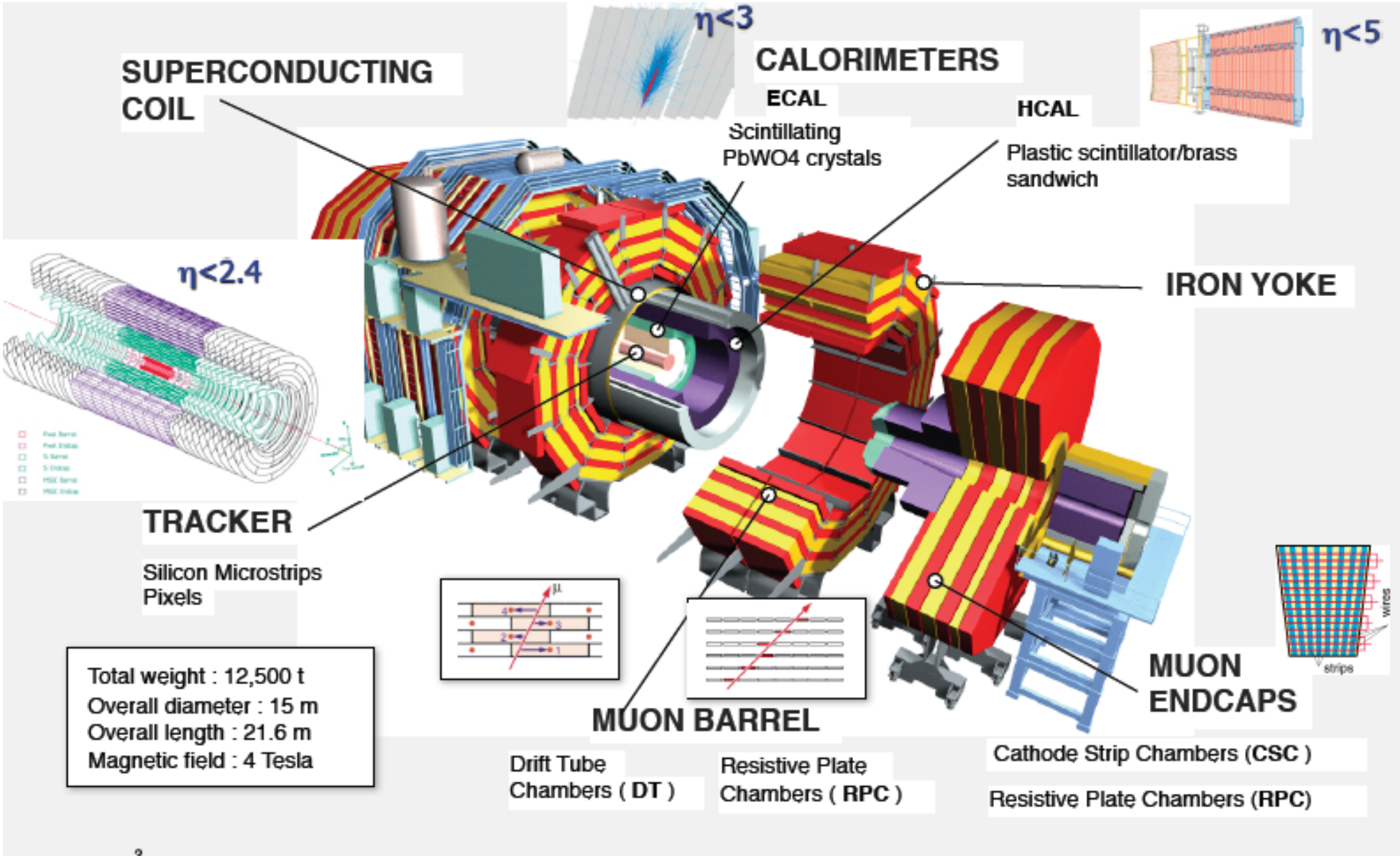
1 day in October 2011= more data than 4 x (entire 2010 run)

LHC performance 2012 (8 TeV)

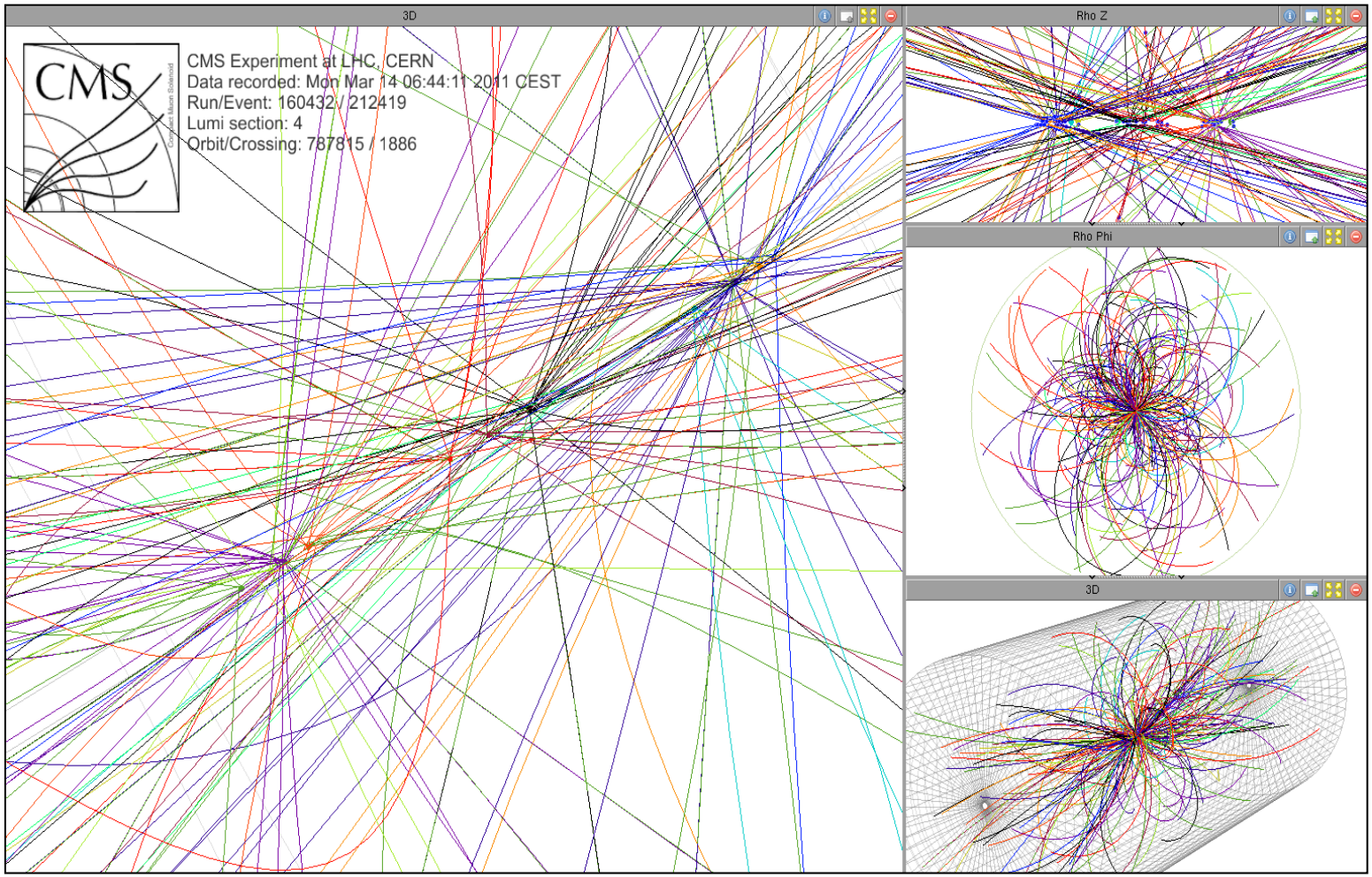


> 20 fb-1 next year?

The Compact Muon Solenoid



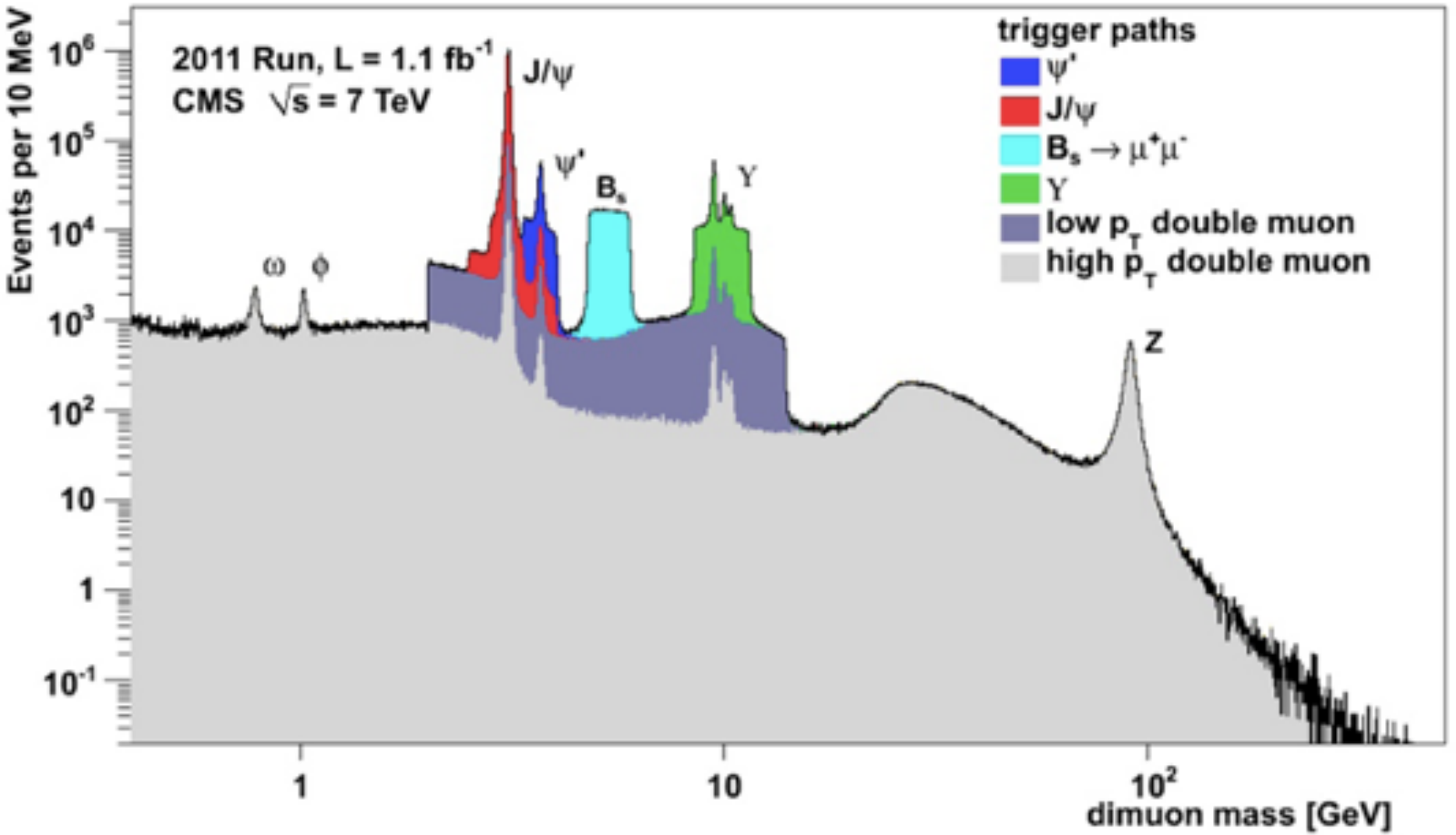
Reconstruction of pile-up in CMS



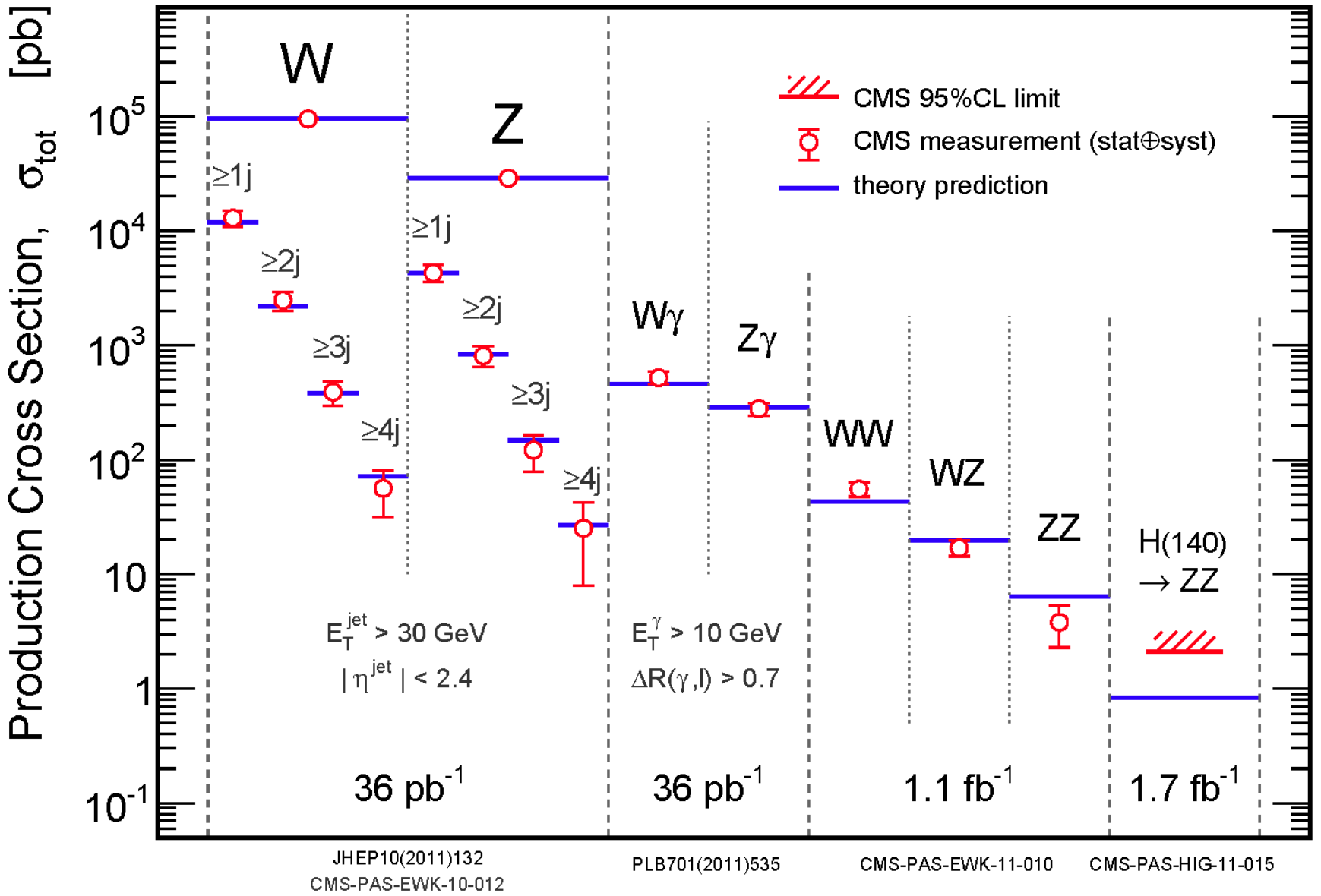
On average, 2011 data have 6 pile-up events per BX

Event shown above has 13 reconstructed vertices

CMS rediscovery of Standard Model (1)



CMS Rediscovery of Standard Model (2)



Four slides on statistics

What is μ ?
(SM Higgs cross-section modifier)

SM Higgs boson cross section: σ_{SM}

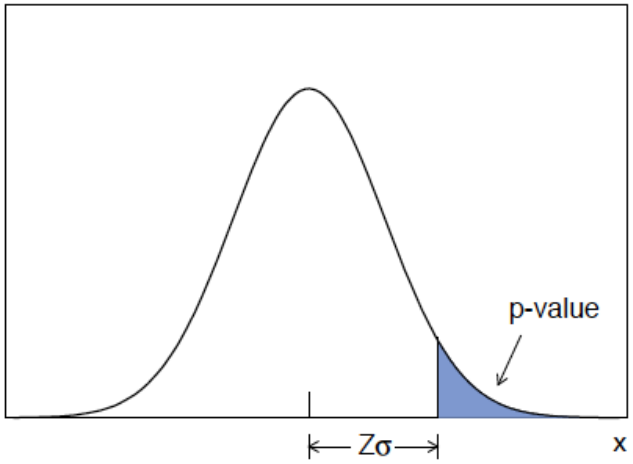
Hypothetical Higgs boson cross section: $\sigma = \mu\ \sigma_{SM}$

Excesses

- ***p-value*:** chance of background fluctuating higher than what has been observed in data

$$p = \mathrm{P}(\, n \geq n_{\mathrm{obs}} \mid \mathrm{b}\,)$$

- ***significance Z*** is related to *p-value* via the tail probability of the normal distribution

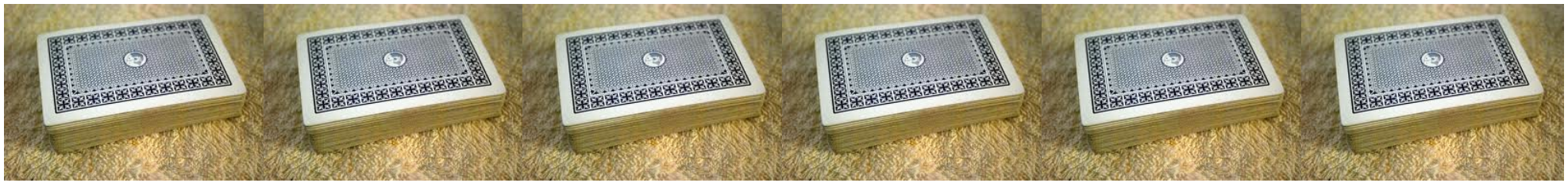


- *p-value* does not tell us whether the excess is consistent with the SM Higgs boson CS.

Look-elsewhere effect (LEE)

What is the chance that the top card in a deck is Queen of Hearts?

Local *p-value*



What is the chance that the top card in at least one of N decks is Queen of Hearts?

Global *p-value*

The fact that the two answers are not the same is known under a name **Look-Elsewhere Effect.** The ratio of the two probabilities = **trials factor.**

Limits

- **CL_s method:** "know your odds"

$$CL_S = \frac{P(n \le n_{obs} \mid b + s_{SM})}{P(n \le n_{obs} \mid b)}$$

There are other methods available.
ATLAS and CMS agreed on CL_s,
or, more accurately,
on one particular flavor of it.

- **Confidence Level:**

$CL_s < \alpha$ ==> "SM signal is excluded with 1-α Confidence Level".

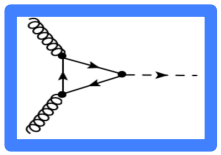
95% C.L. ($\alpha < 0.05$) is a popular convention for an exclusion…

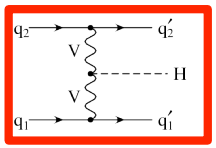
SM Higgs searches

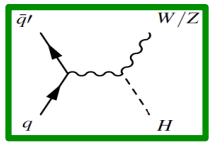
In CMS, nearly all analyses have crosschecks done with alternative techniques.

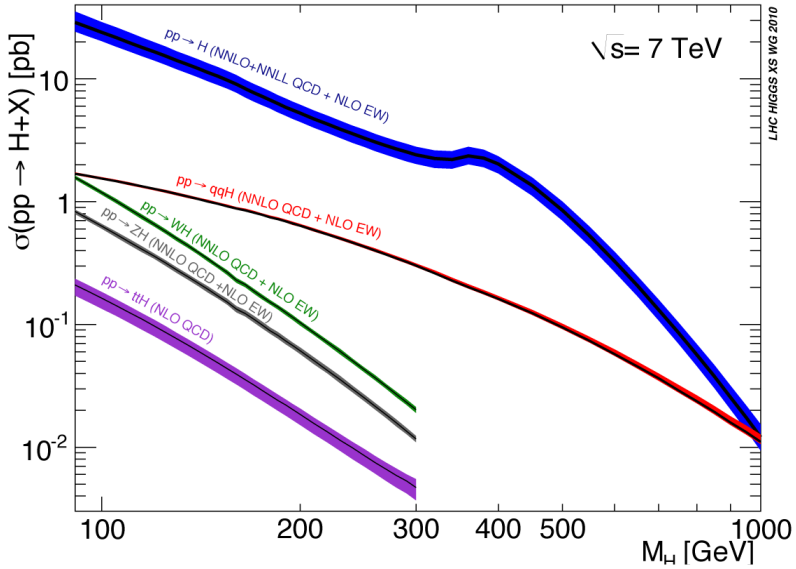
Also, majority of analyses are executed by at least two independent groups

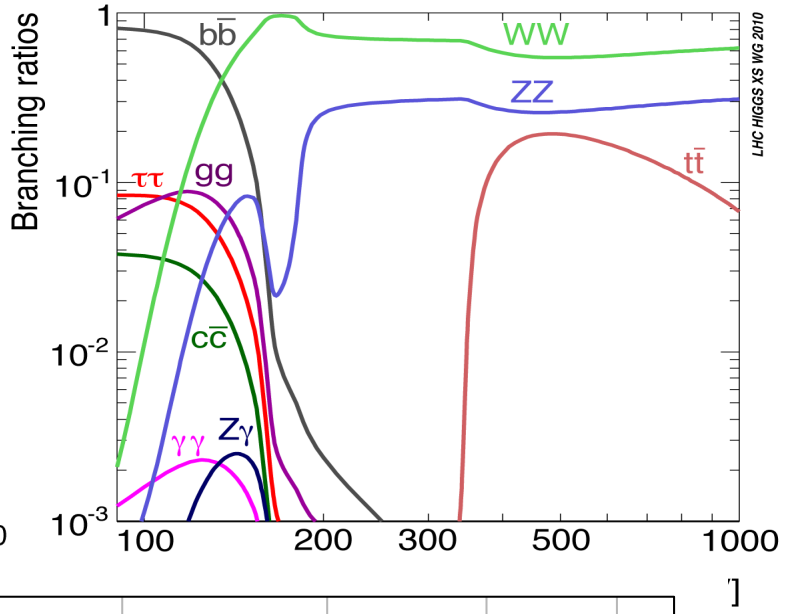
SM Higgs: production, decays, searches

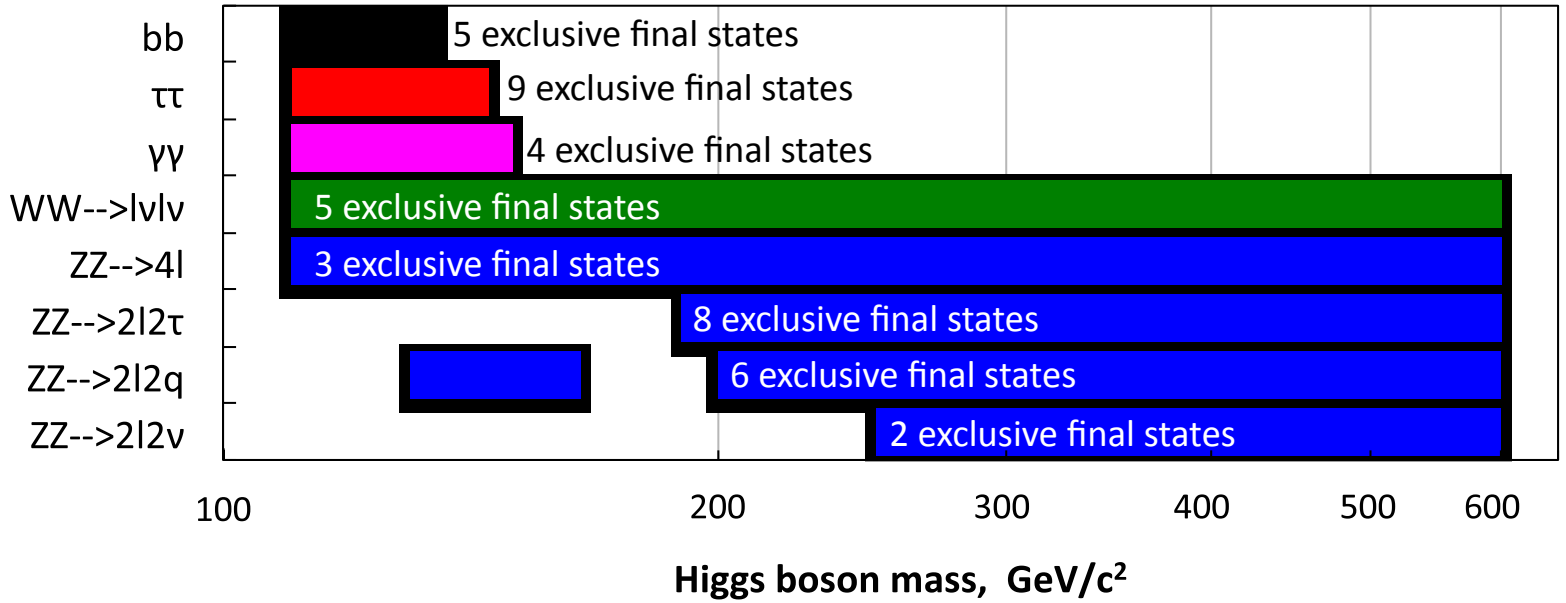






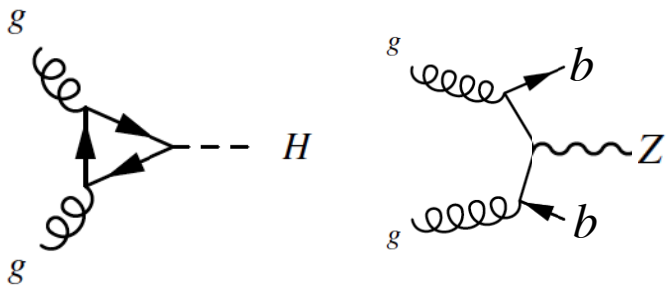




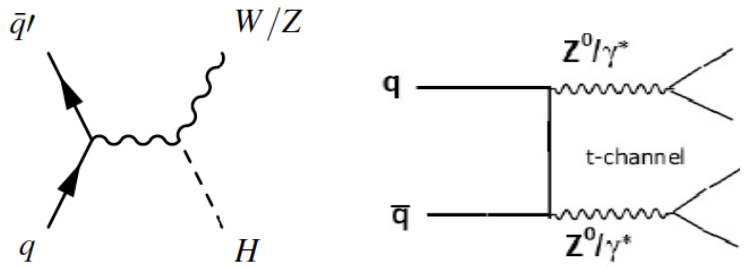


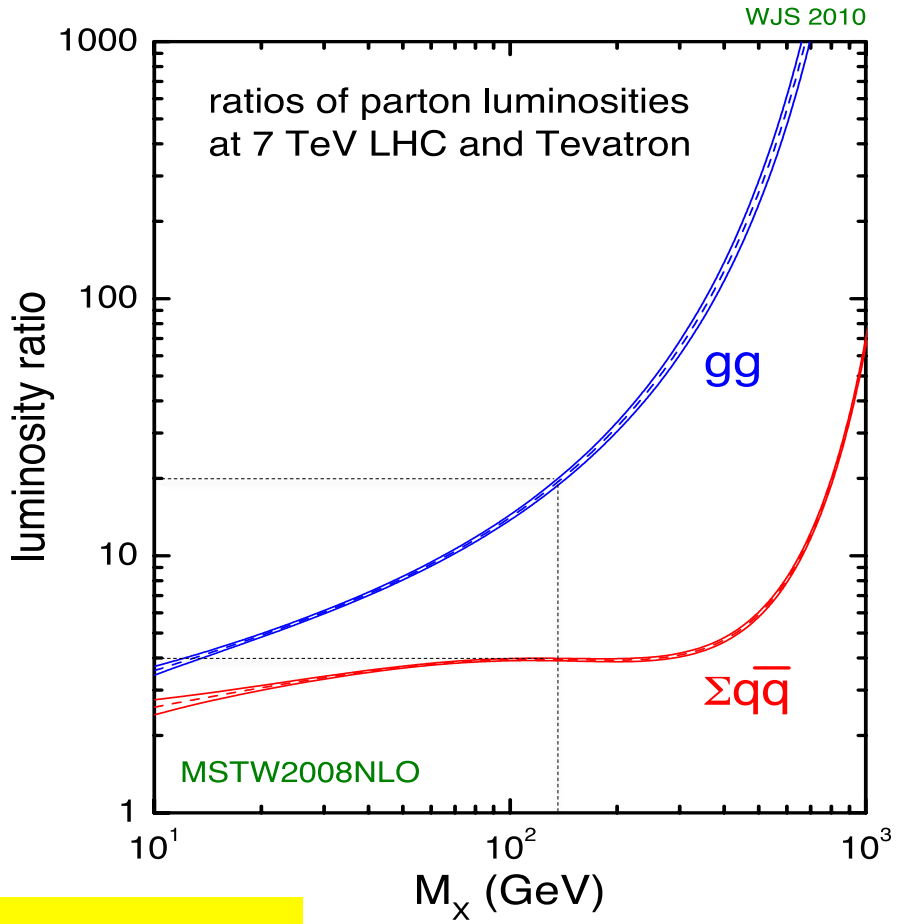
LHC vs Tevatron

gg-production: x 20



qqbar production: x 4

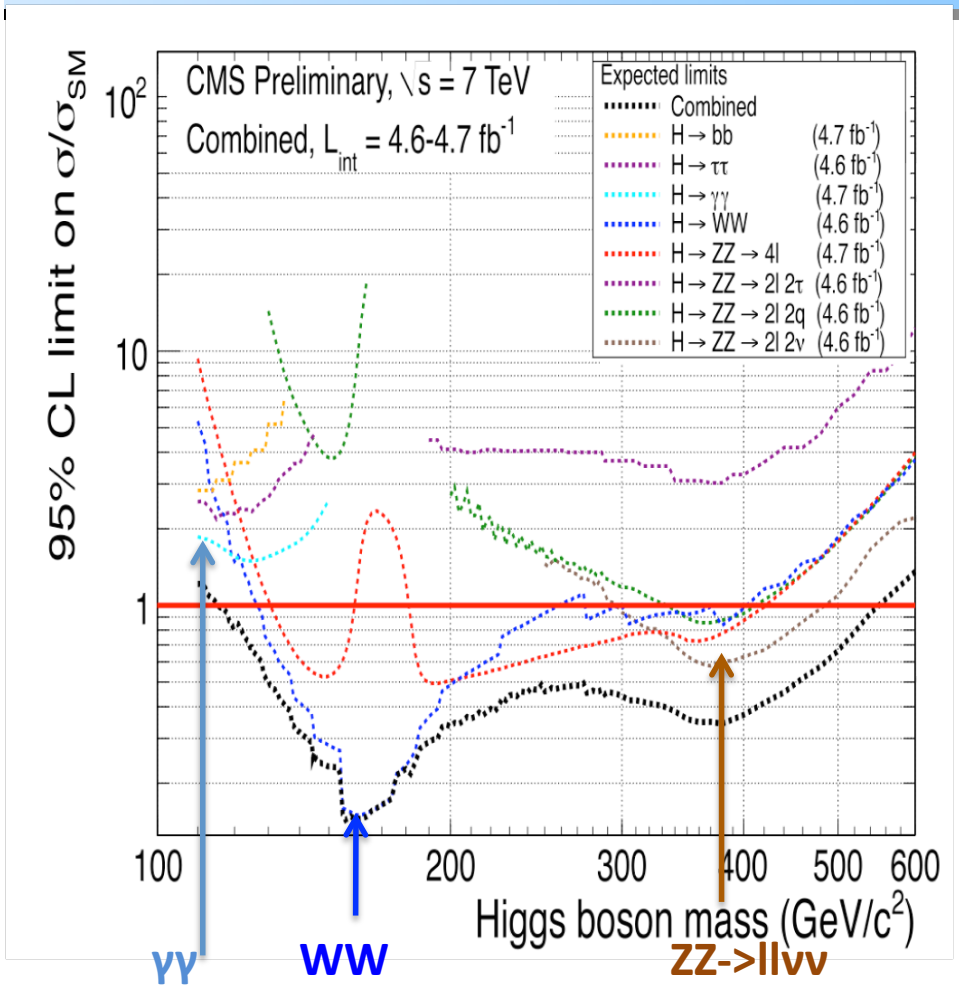


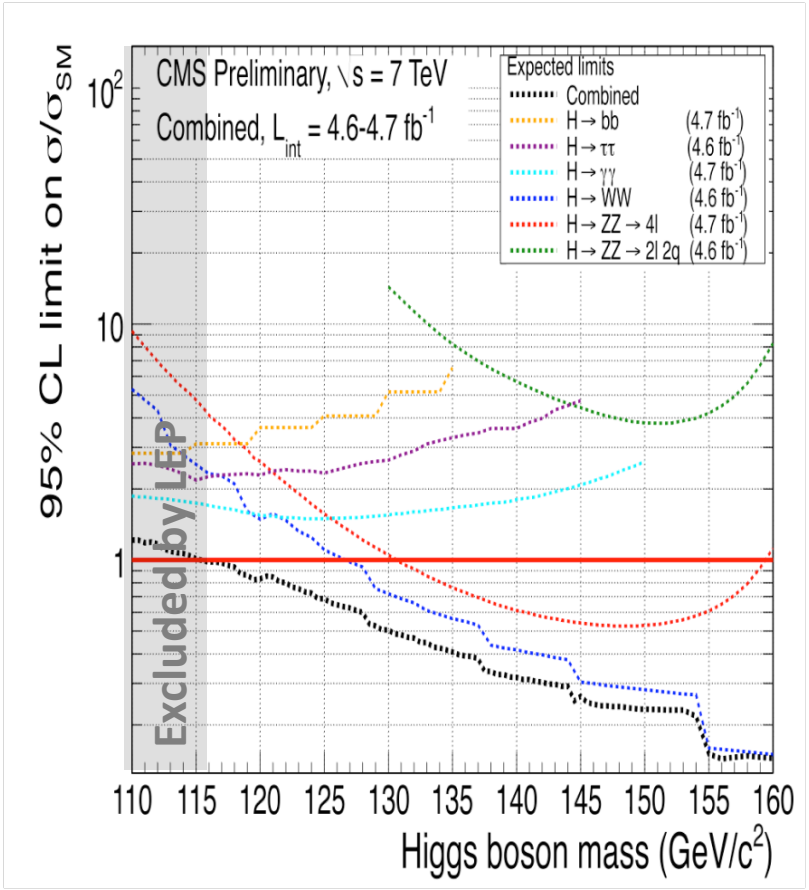


Signal-to-Background ratio:

- **VH(bb): S/B is worse at LHC**
- **γγ/WW/ZZ: S/B is better at LHC**
- **VBF ττ: S/B is about the same**

Expected sensitivity





Note: only two channels give narrow mass peak: γγ and ZZ->4l

95% CL expected sensitivity: 117—543 GeV

“Golden” channel

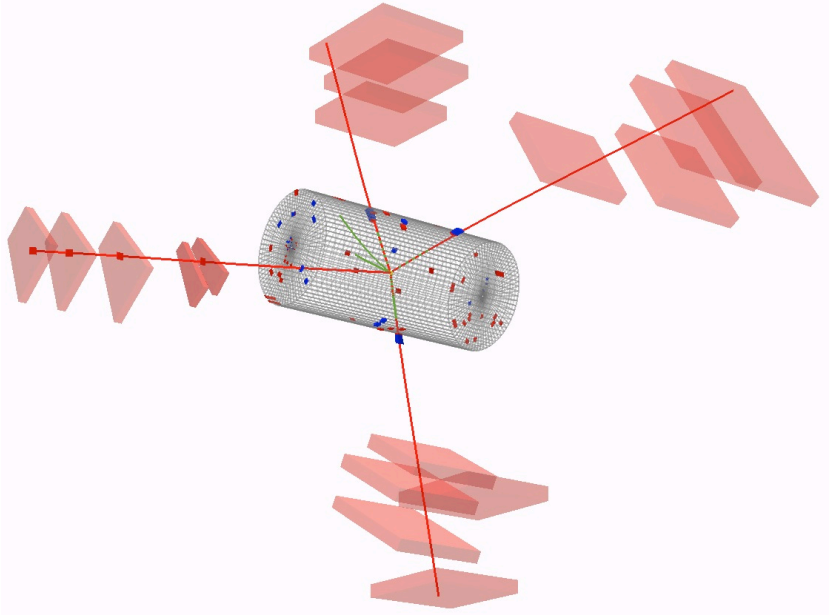
H -> ZZ -> 4l , or:

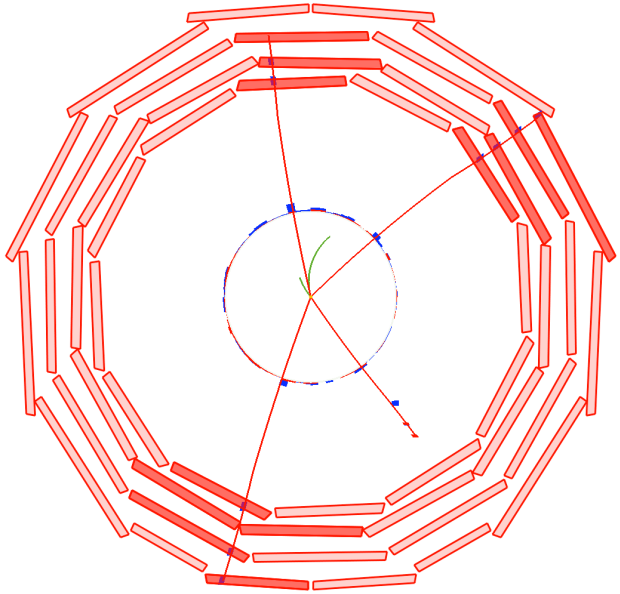
$H \to \mu^+ \mu^- \mu^+ \mu^-$

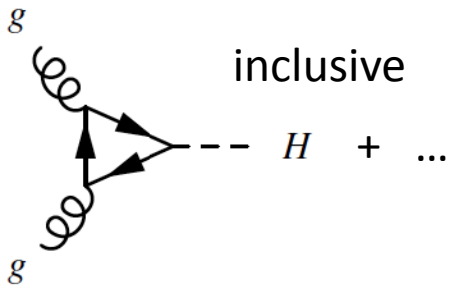
$H \to e^+ e^- e^+ e^-$

$H \to \mu^+ \mu^- e^+ e^-$

H->ZZ->4l signature







Selection:

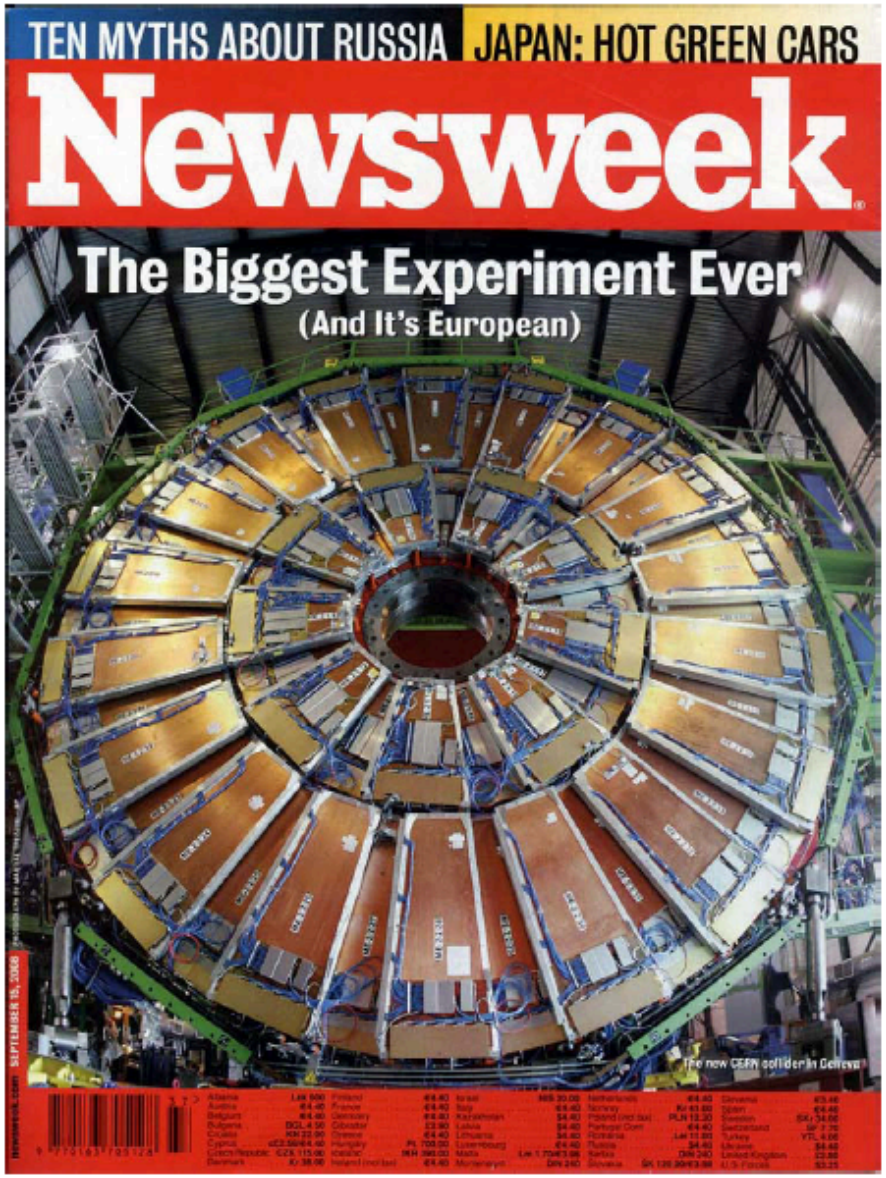
- **4 isolated leptons: 4e, 4μ, 2e2μ**
- **no impact parameter**
- **Final discriminant: m(4l) mass distribution**

Mass resolution: 1%

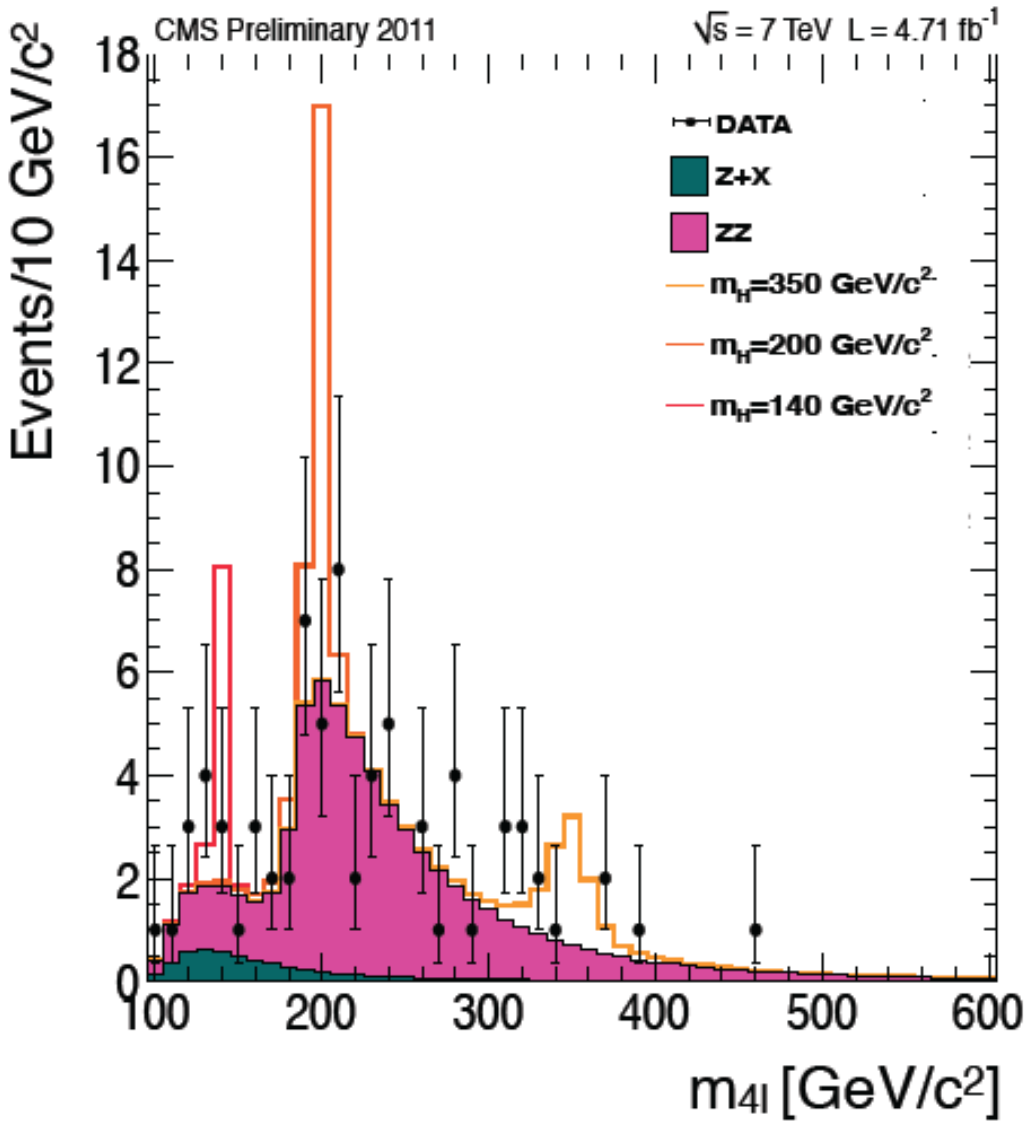
Main backgrounds:

- **ZZ: from MC ZZ/Z and measured Z**
- **tt and Z+jets: from data (4l with loose leptons), shape and extrapolation from MC**

CMS Endcap Muon system (Cathode Strip Chambers)



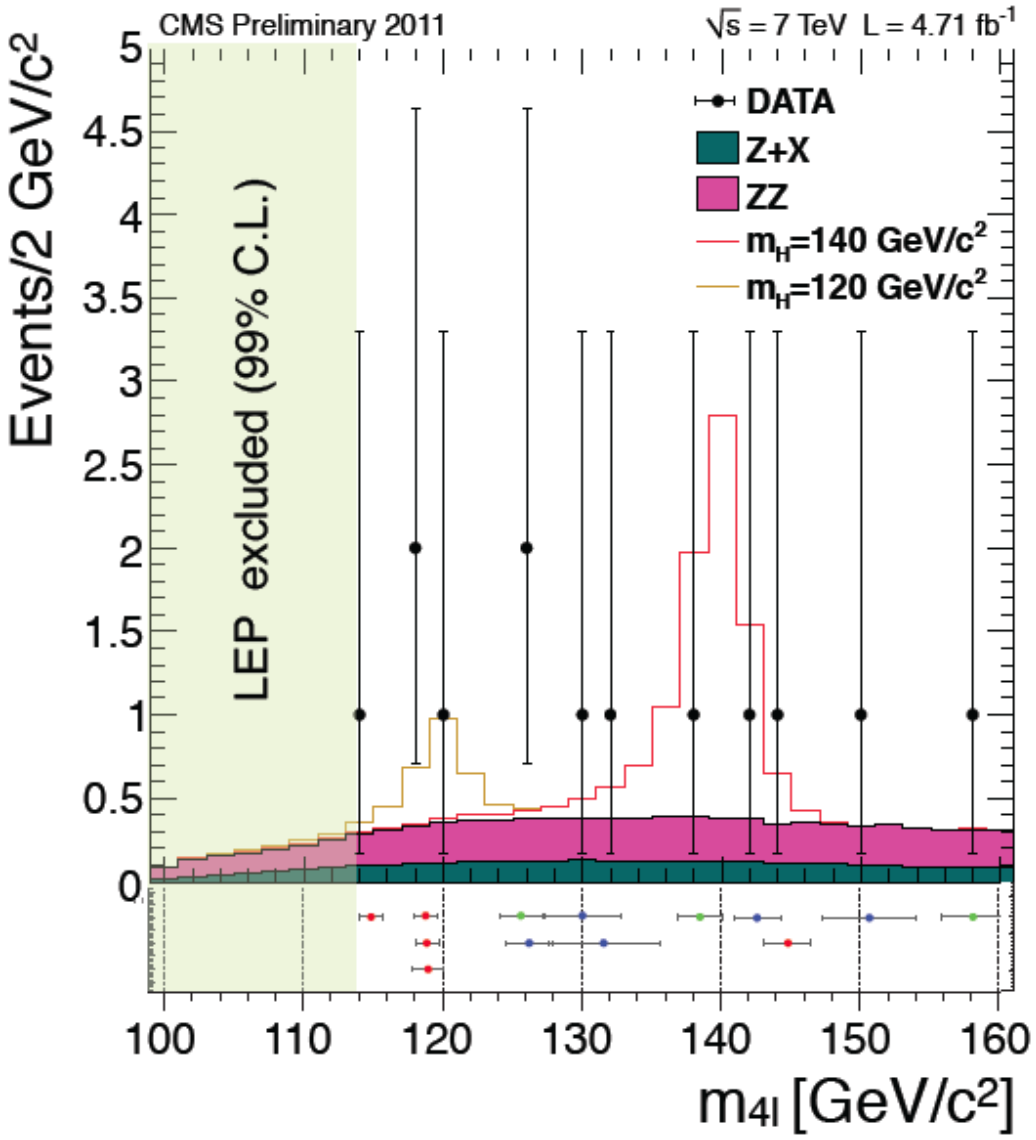
H->ZZ->4l: mass distributions



m_{4l}>100 GeV

- **Observed 72 events**
- **Expected 67.1 ± 6.0**

H->ZZ->4l: mass distributions

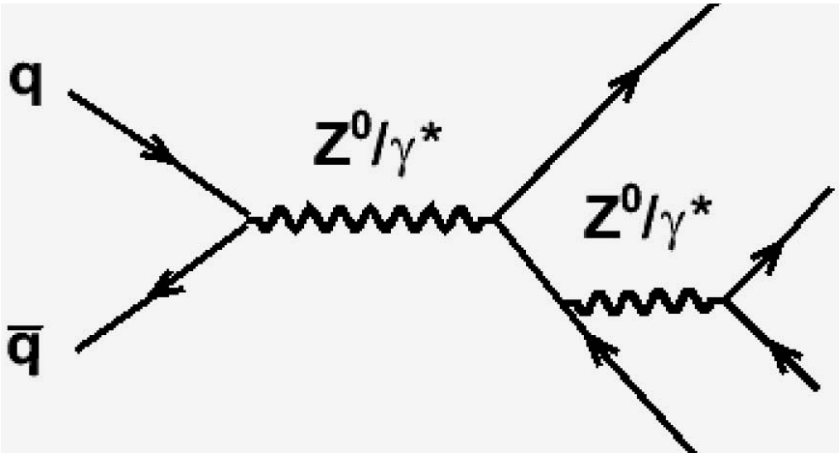


100<m_{4l}<160 GeV

- **Observed 13 events**
- **Expected 9.5 ± 1.3**

Note:
- unbinned events in the bottom panel
- **4e**, **4μ**, **2e2μ**
- Event-by-event mass errors (bars)

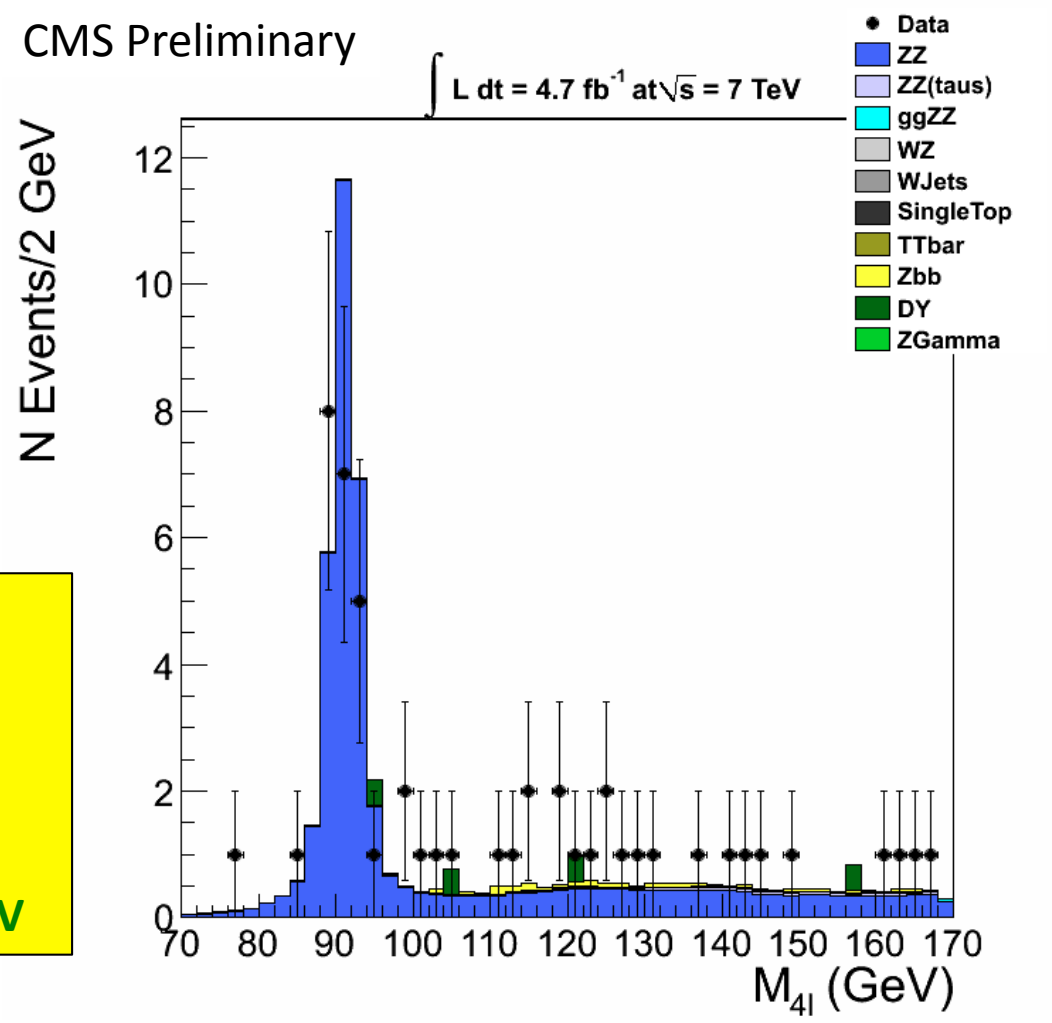
Observation of Z->4l



Standard candle for H->ZZ->4l search:

- **direct calibration of m4l scale**
- **direct measure of m4l resolution**
- **validation of efficiencies**

- **With current lumi: m=91.3±0.6 GeV**



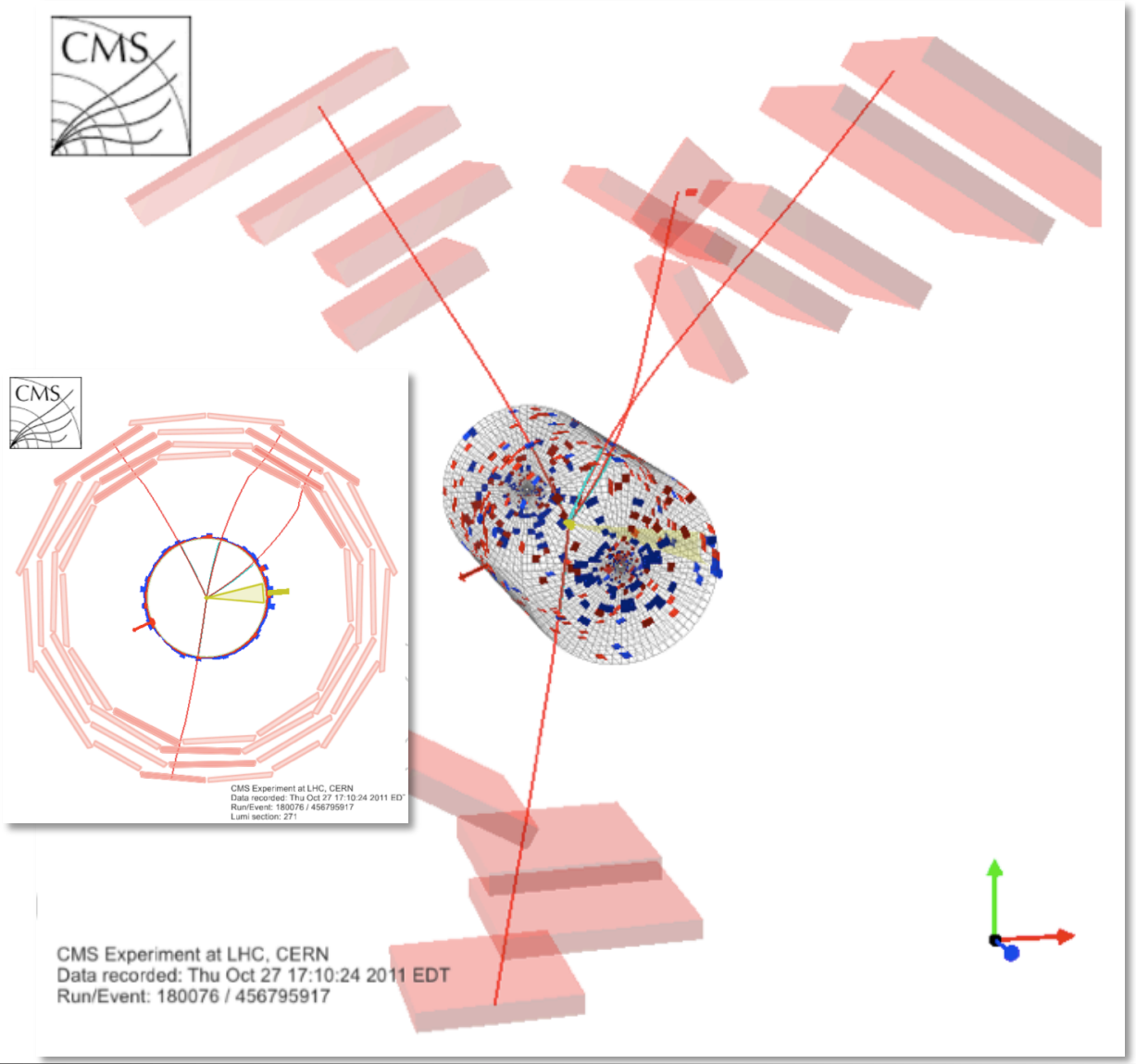
Di-lepton mass cut is relaxed to 4 GeV

Z→ 4l Event Display

- Run 180076, Lumi 271, Event 456795917

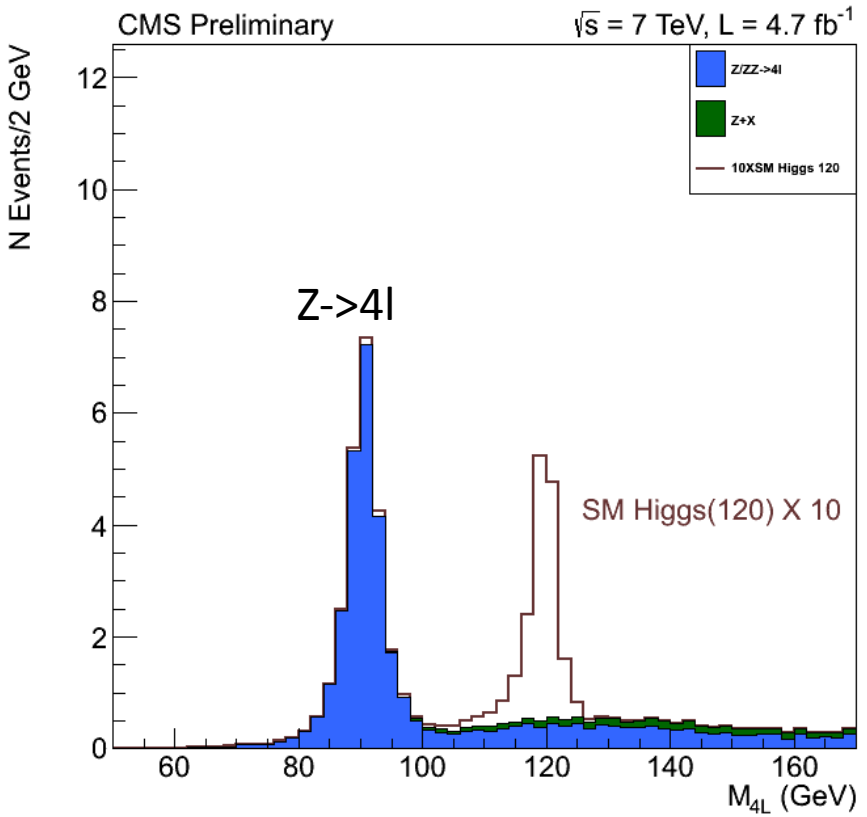
- Reconstructed objects:
  - 4 muons
  - 1 jet with p_T > 20 GeV/c
  - missing E_T (PF): 22.9 GeV
  - 9 vertices
  - 0 photons

- Z → 4l system:
  - 3lepton against 1lepton transverse plane
  - m_{4l} = 91.18 GeV
  - m_{Z1} = 62.53 GeV
  - m_{Z2} = 17.24 GeV

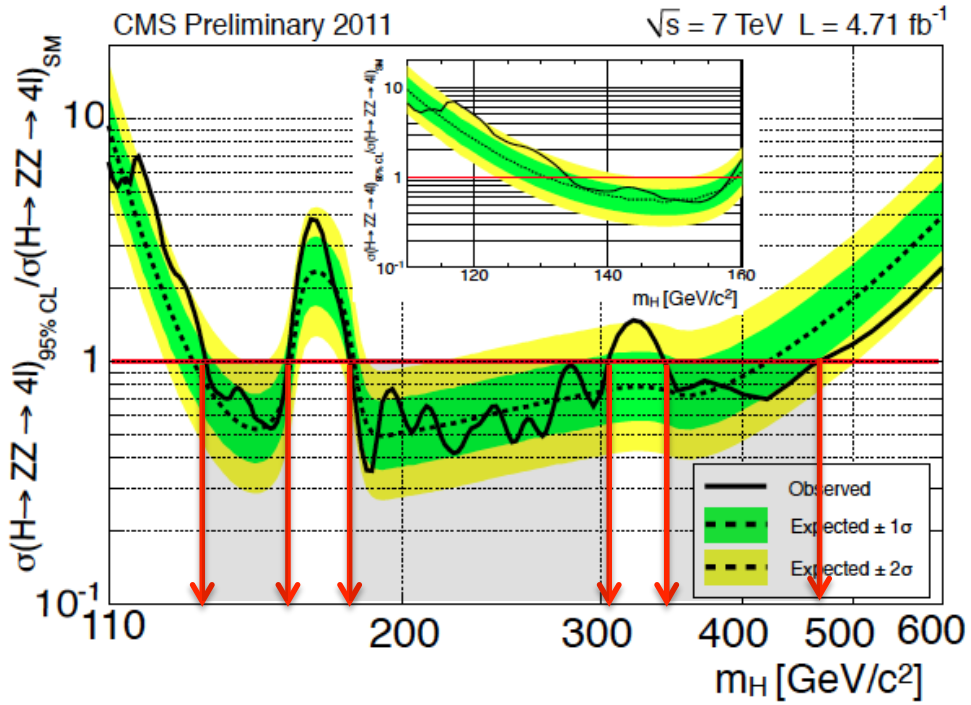


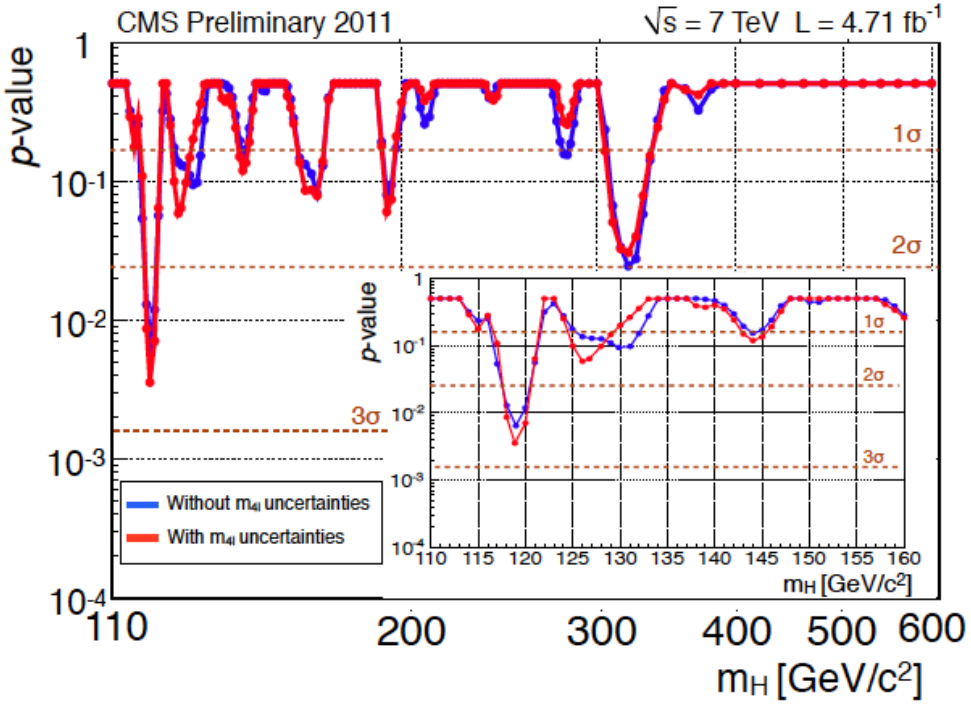
Z→4l decay as a Standard Candle for H->ZZ->4L

- Z-> 4l Decay width comparable with experimental resolution
  → calibration of m4l resolution
- Well known position of Z-> 4l four-lepton mass peak
  → calibration of m_{4l} scale
- Much higher expected event yield in Z-> 4l than in H → 4l
  → calibration of reconstruction efficiencies



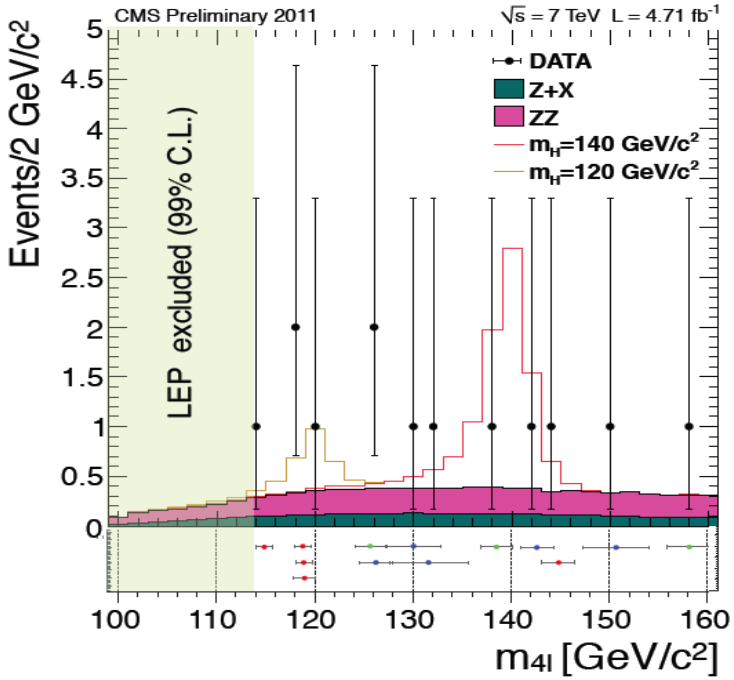
H->ZZ->4l results

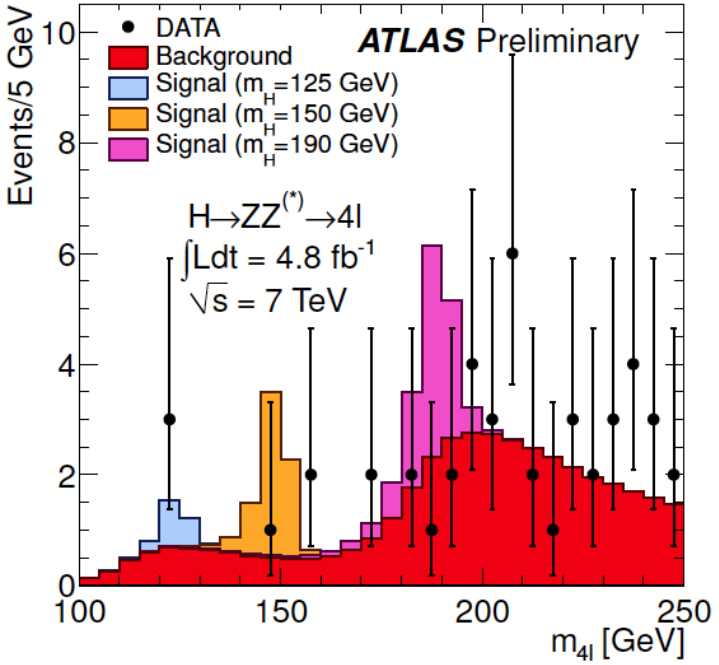




LEE trials factor ≈40 for the full mass range.
Hence, 2σ deviations are not very significant.

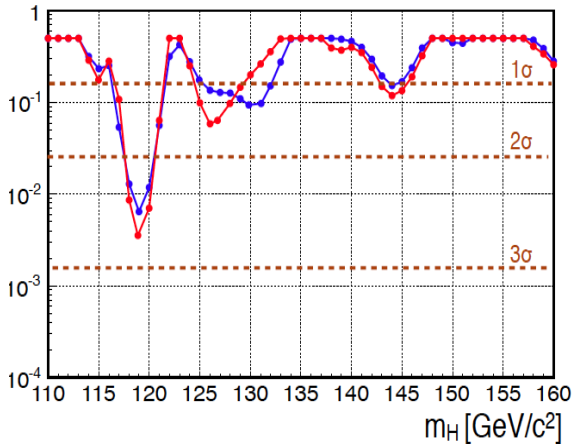
H→ZZ→4l, CMS vs ATLAS: p-values

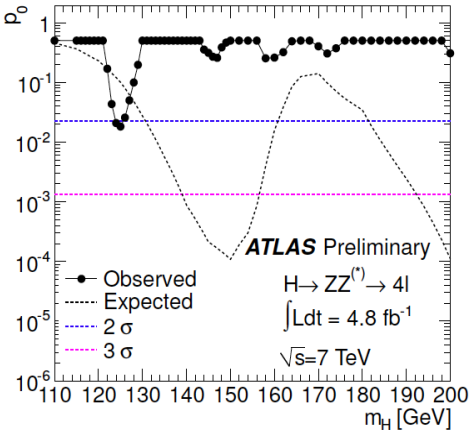




m=118.8 (4μ)
m=118.9 (4μ)
m=119.0 (4μ)

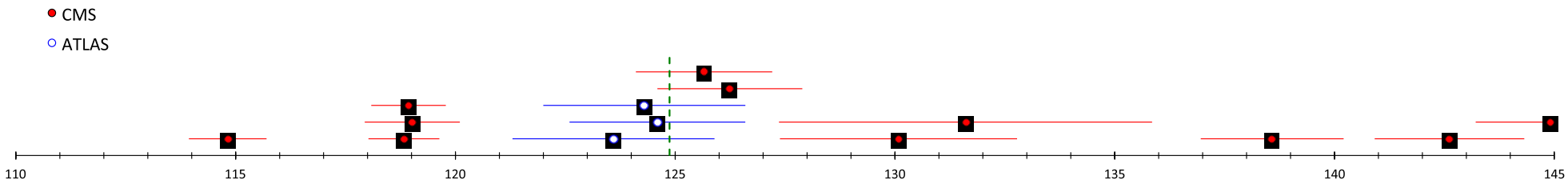
m=125.7 (4e)
m=126.2 (2e2μ)





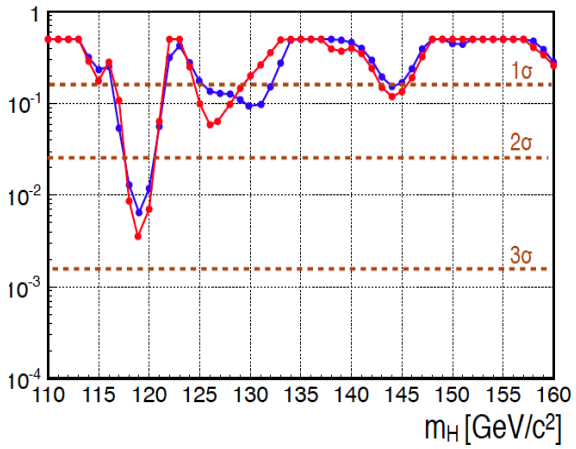
m=123.6 (2μ2e)
m=124.3 (2e2μ)
m=124.6 (4μ)

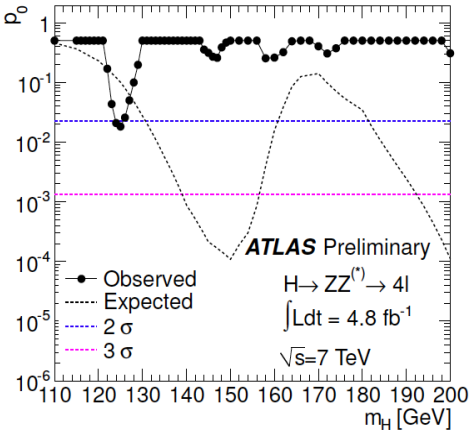
H→ZZ→4l: CMS vs ATLAS



m=118.8 (4μ)
m=118.9 (4μ)
m=119.0 (4μ)

m=125.7 (4e)
m=126.2 (2e2μ)

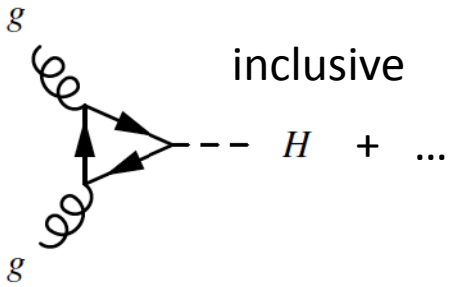


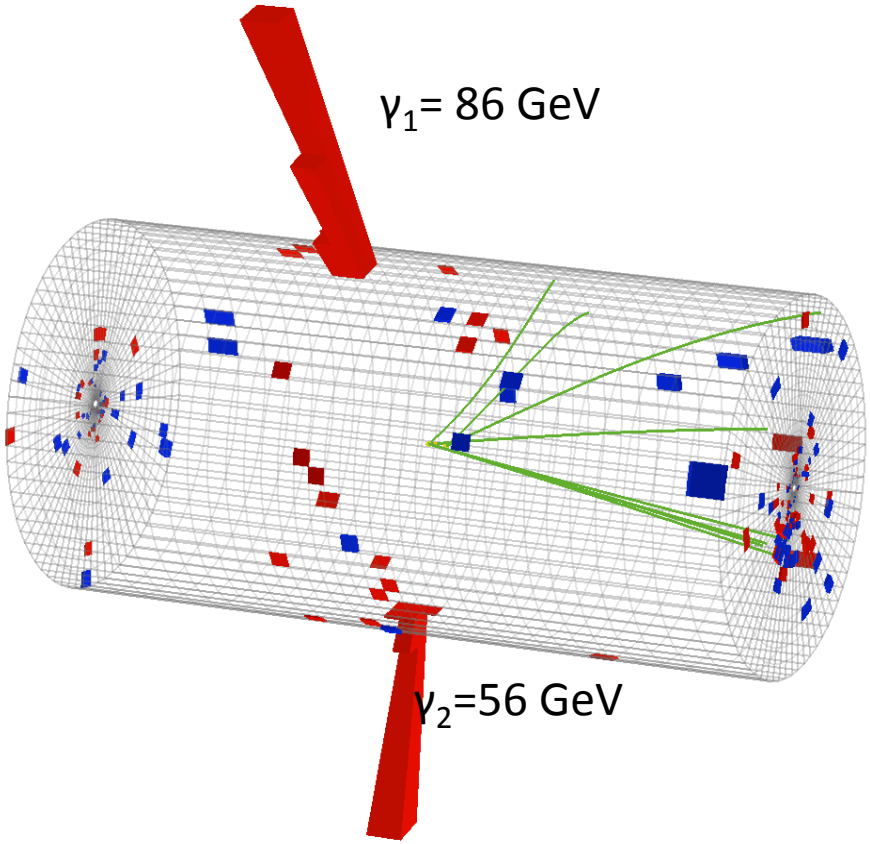


m=123.6 (2μ2e)
m=124.3 (2e2μ)
m=124.6 (4μ)

H -> γγ

H->γγ signature



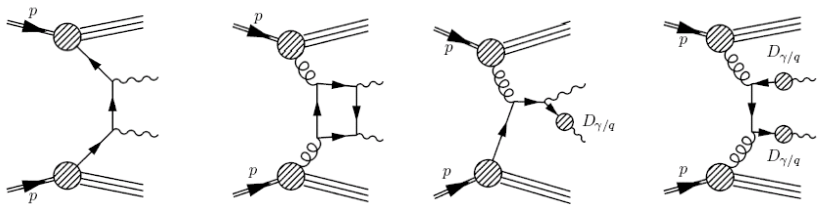


Selection:

- inclusive production
- two isolated photons
- 4 event categories based on quality of photons and, hence, expected $m_{\gamma\gamma}$ resolution
- Events are NOT split based on $p_T(\gamma\gamma)$
- Final discriminant: γγ-mass distributions

Best category $m_{\gamma\gamma}$ resolution: ~1%

Main backgrounds: from sidebands



H->γγ categories

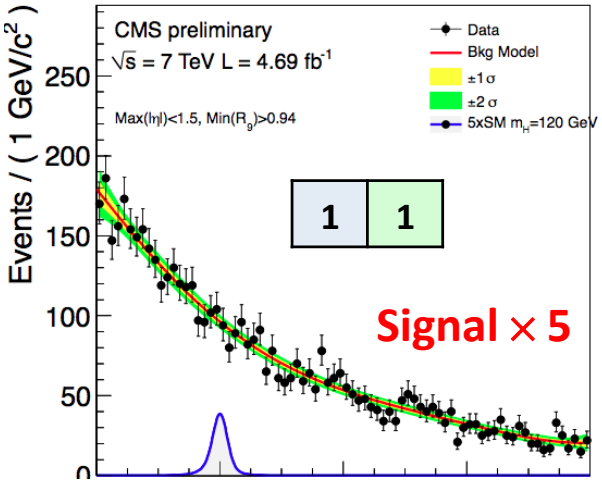
Both photons of high quality?

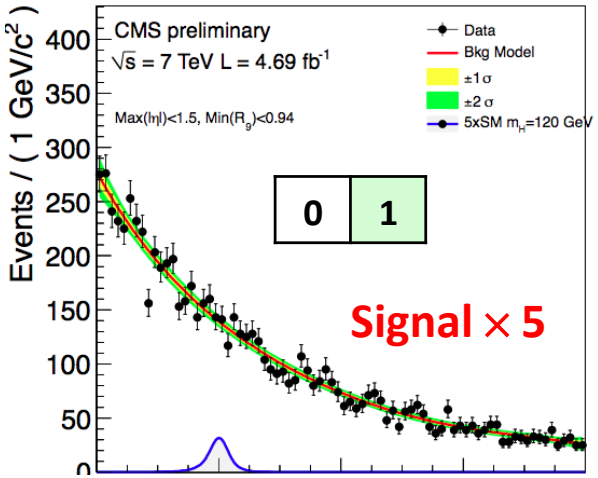
Both photons in barrel?

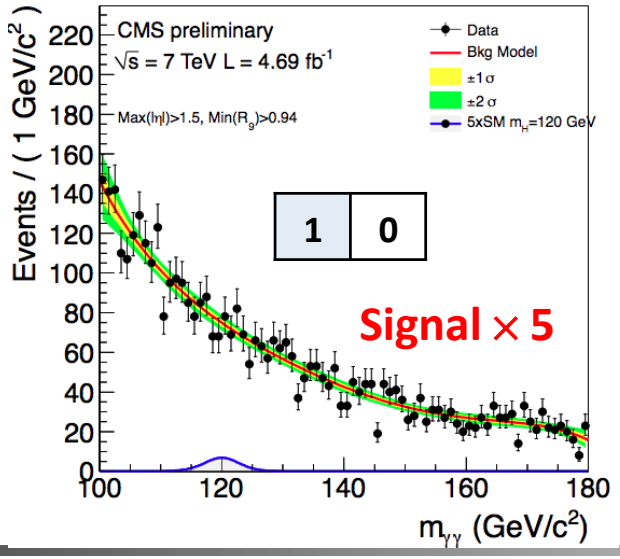
1	1

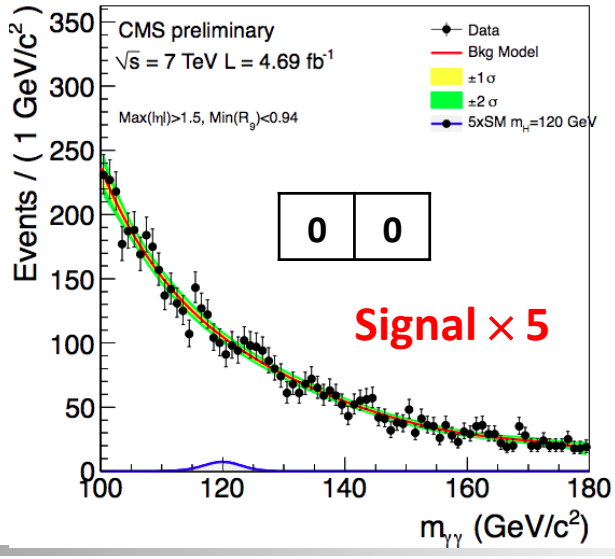
NOTE:
- $m_{\gamma\gamma}$ resolutions
- S/B ratios

Classification helps with both

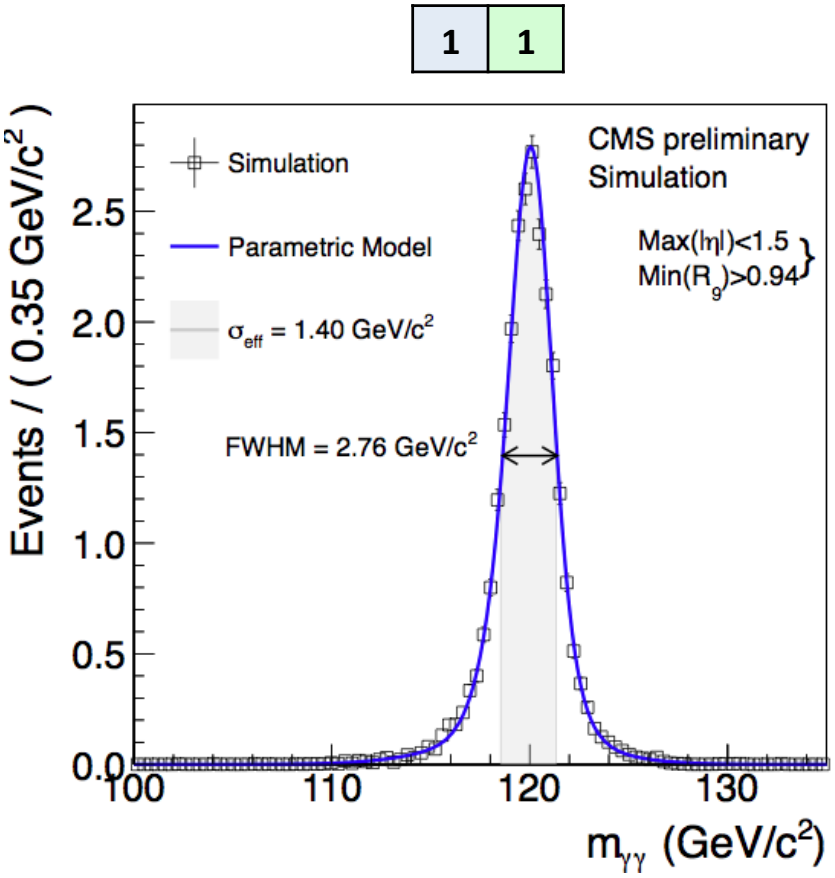


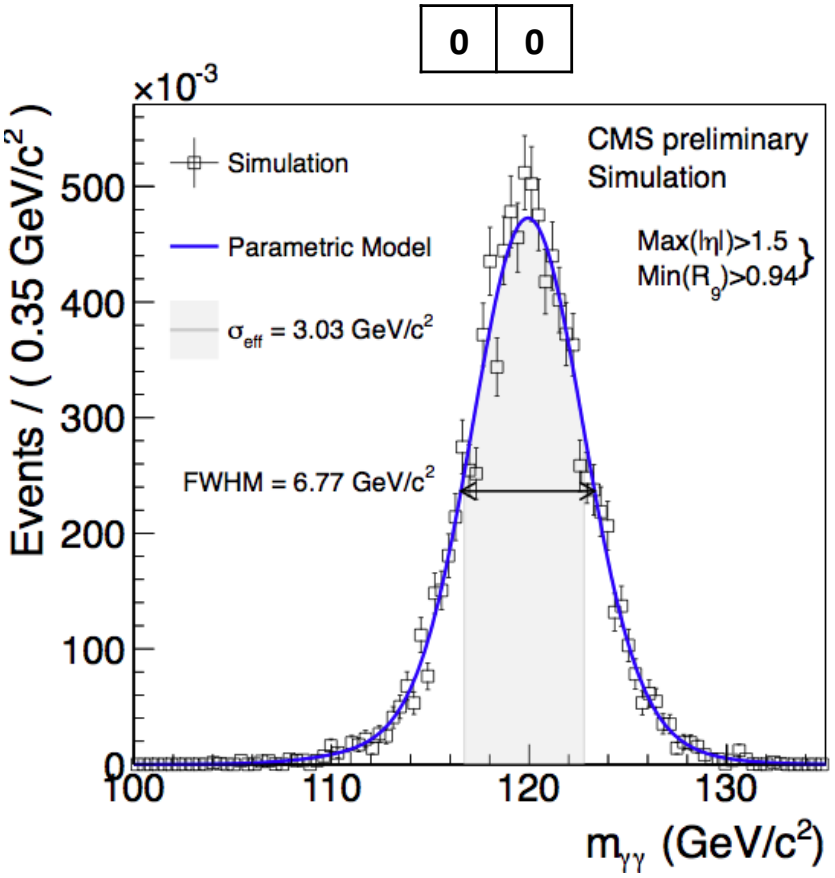




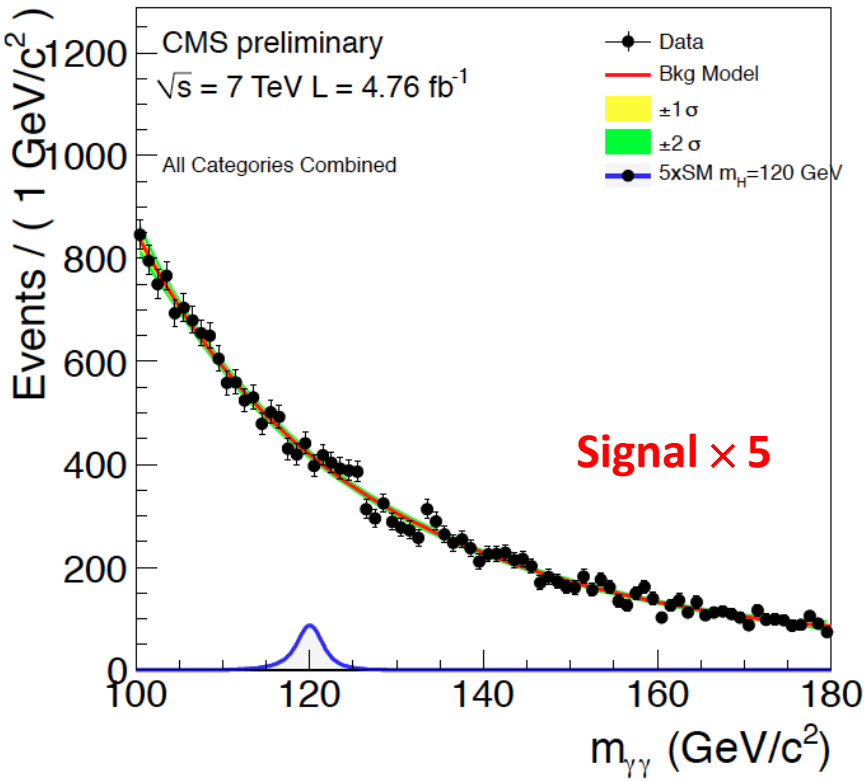


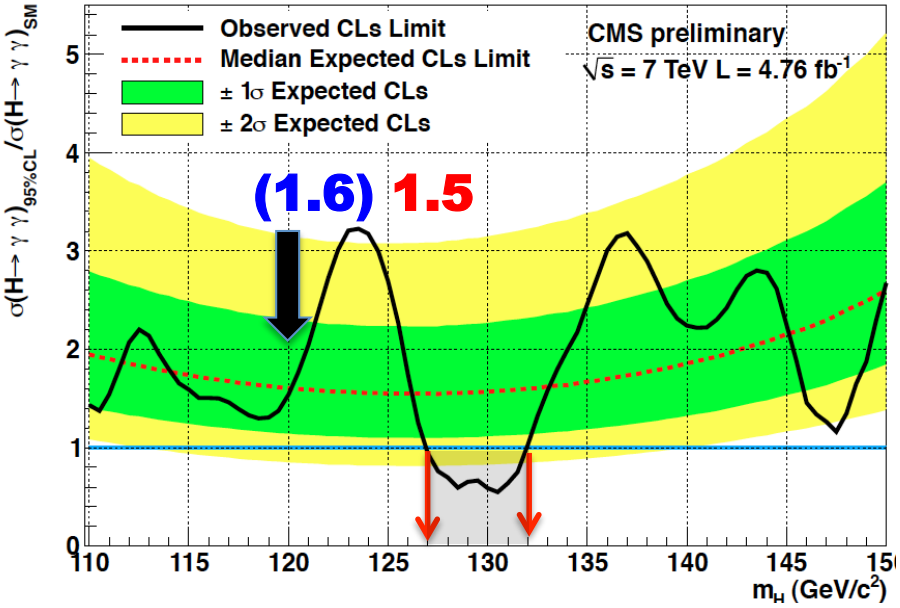
H->γγ mass resolutions

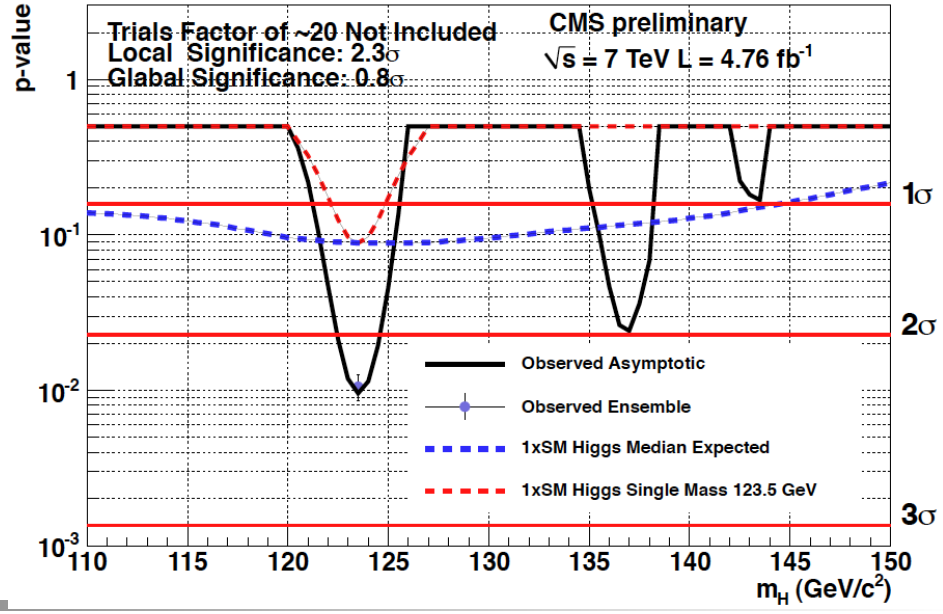




H->γγ results: CMS, 2011 data, CL and p-values

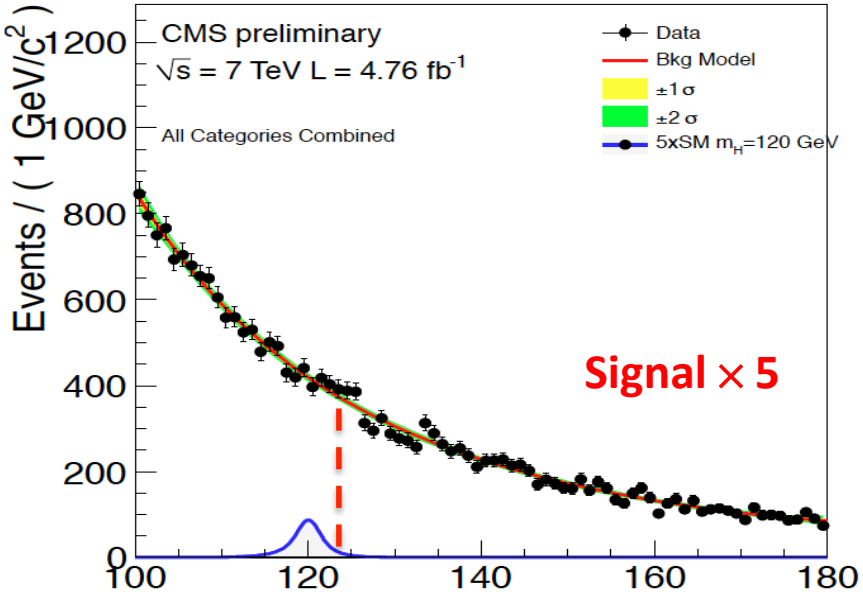


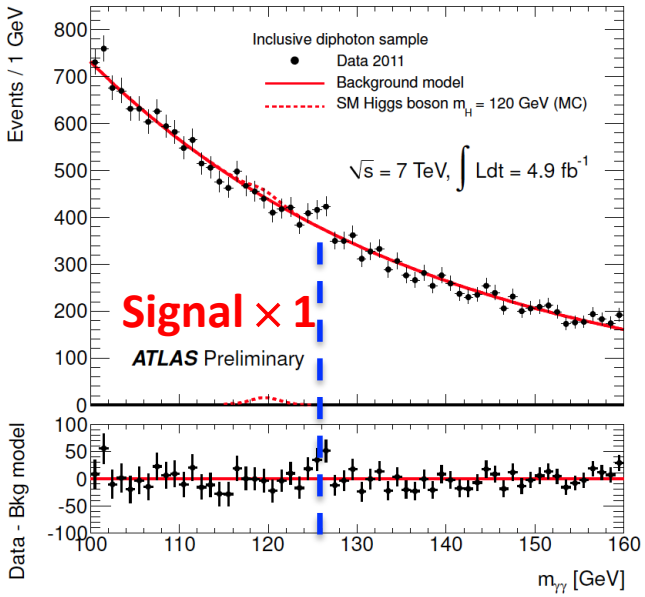


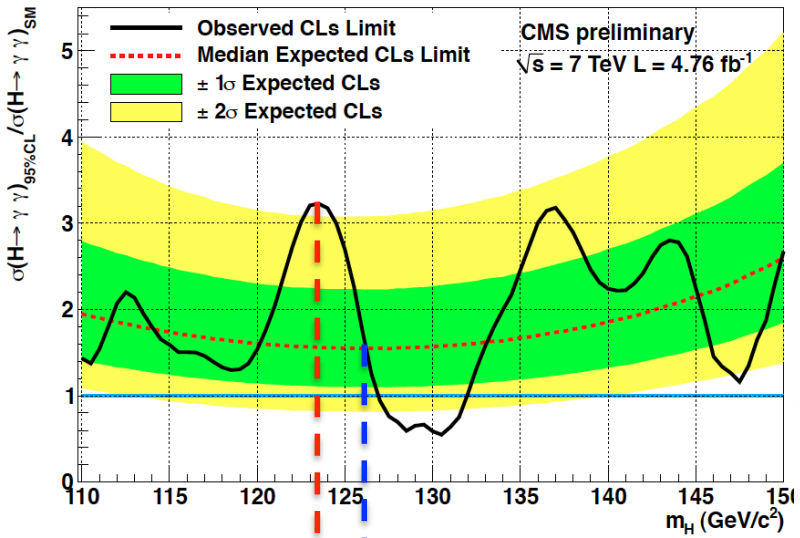


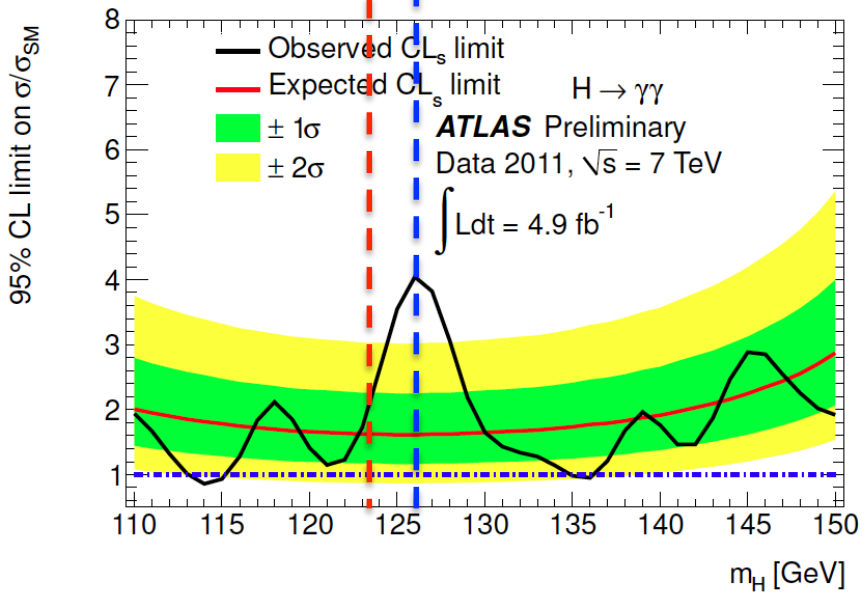
- **Bkgd MC predictions are not used in the analysis**
- **Mass distributions analyzed in 4 event categories**

H→γγ results: CMS vs ATLAS, 2011 data,CL

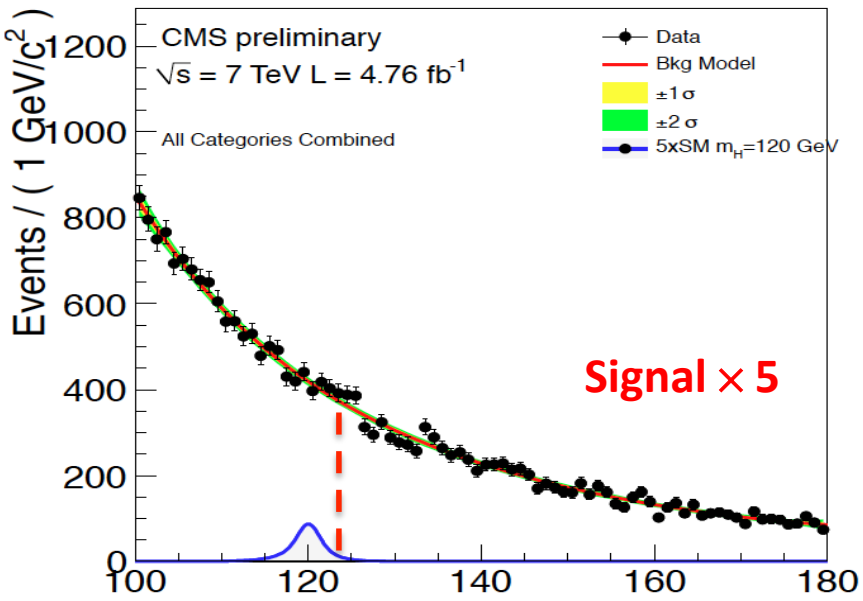


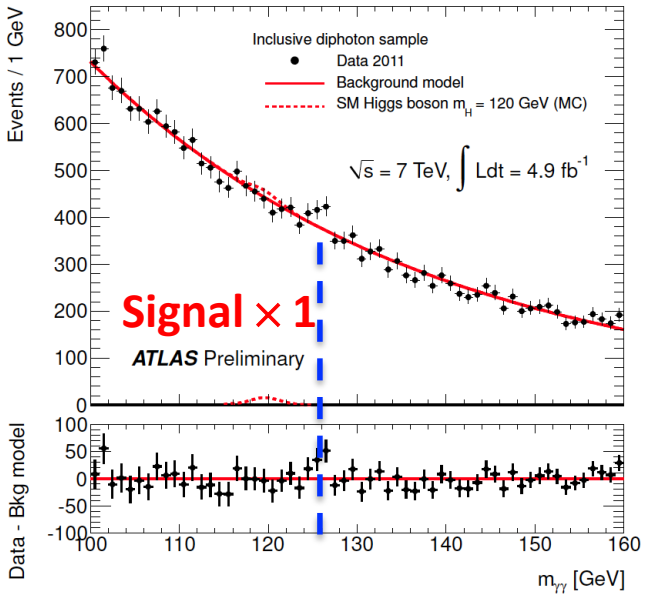


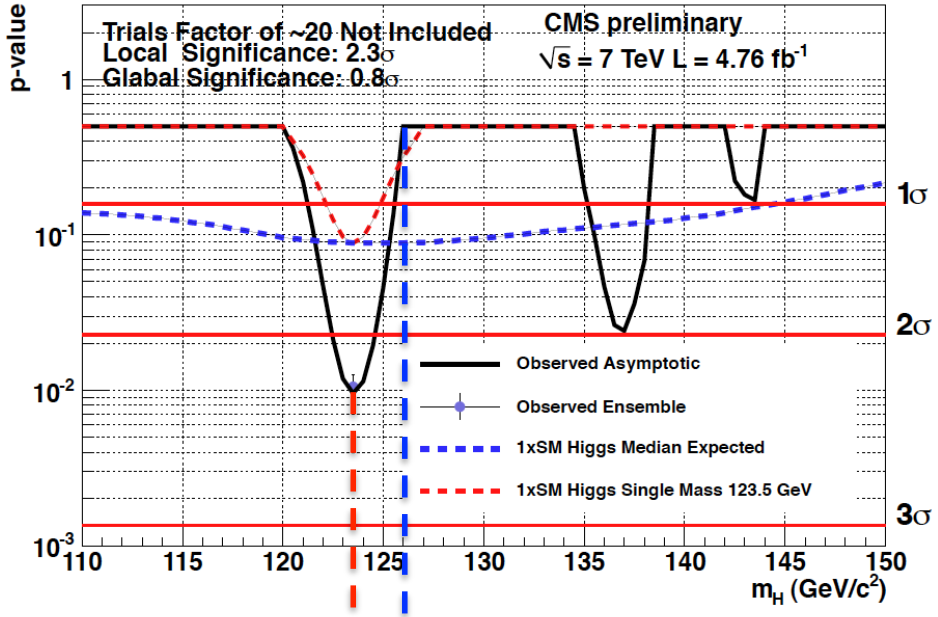


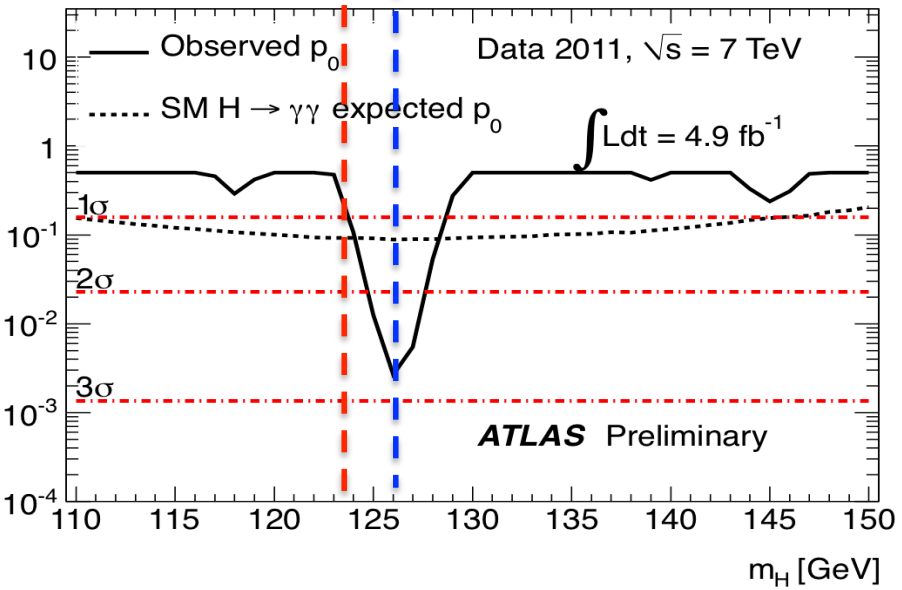


H→γγ results:CMS vs ATLAS, p-values



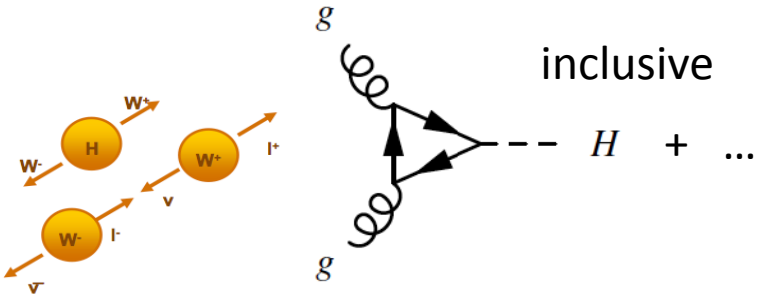


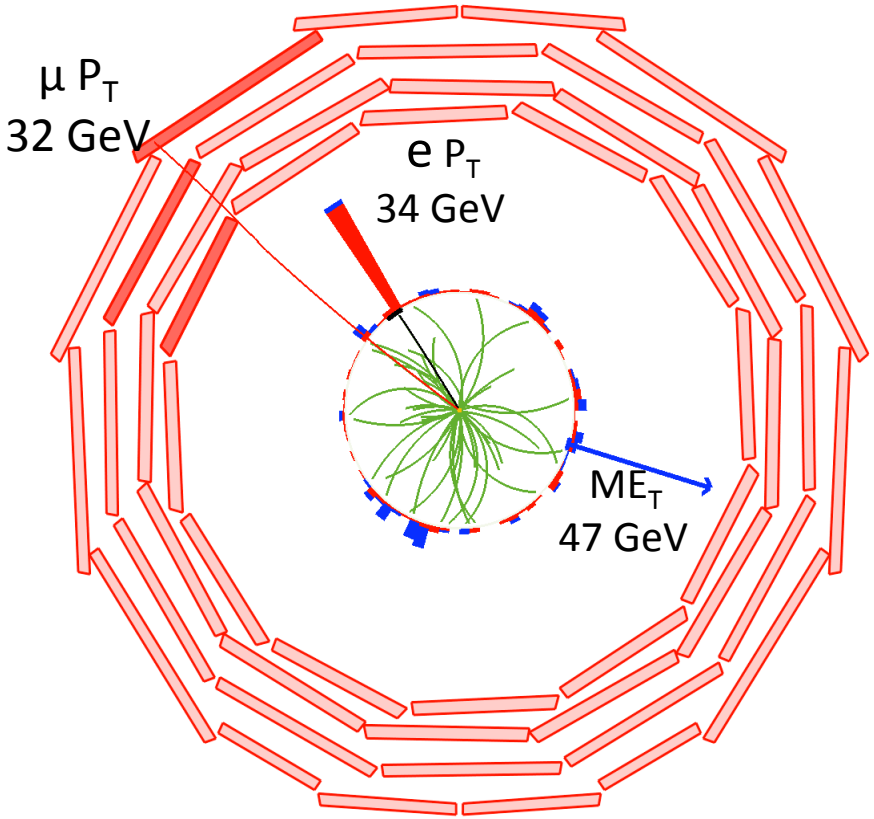




H -> WW

H->WW->lvlv signature





Selection:

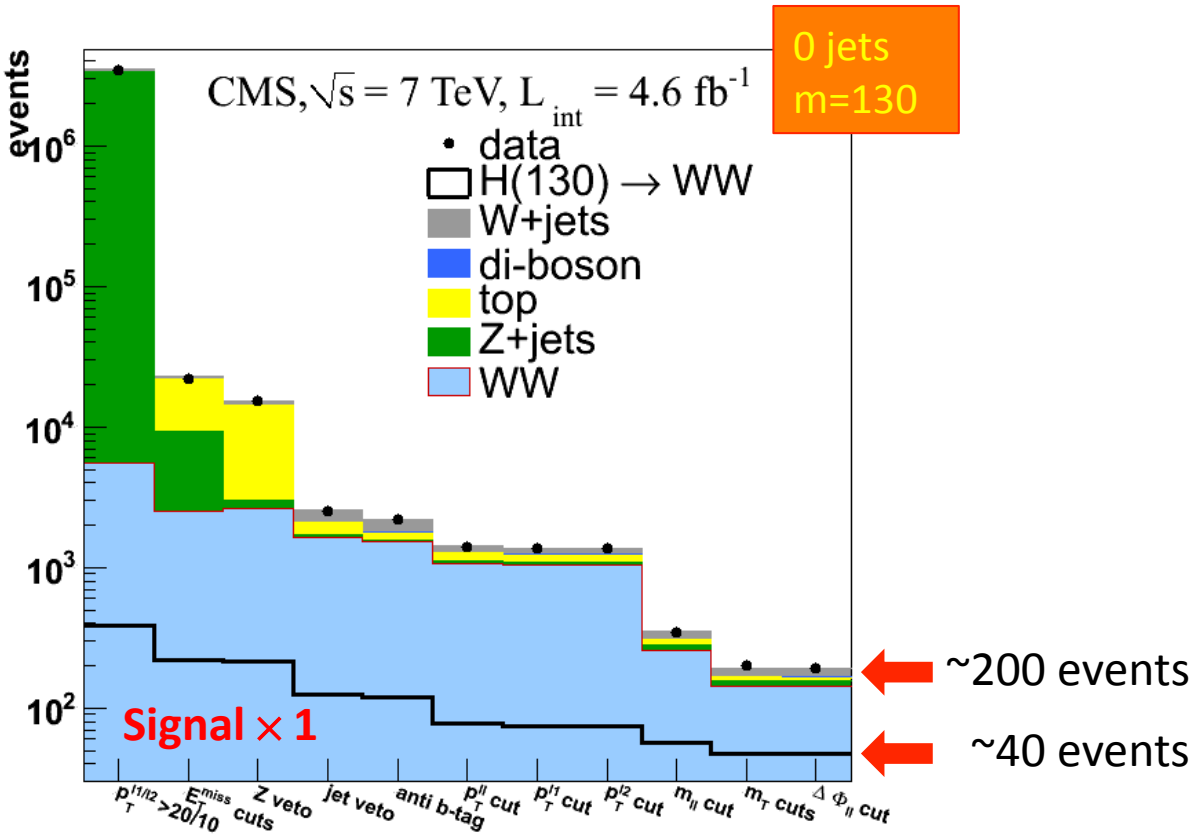
- **two isolated leptons, small Δϕ, small m_{ll}**
- **MET**
- **Transverse mass m_T**
- **Final discriminants: MVA output shape**
  - Same-Flavor di-leptons + 0 jets
  - Opposite-Flavor di-leptons + 0 jets
  - Same-Flavor di-leptons + 1 jet
  - Opposite-Flavor di-leptons + 1 jet
- **and cut-and-count:** SF/OF di-leptons + 2 VBF jets

Mass resolution: 20%

Main backgrounds:

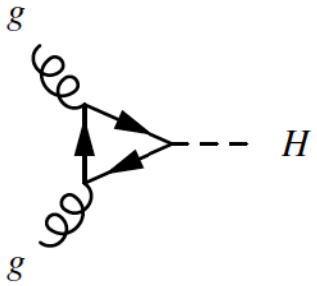
- **WW(m_H<200): from data (large di-lepton mass)**
- **WW(m_H>200): from MC**
- **tt: from data (inverted b-tag)**
- **W: from data (tight-to-loose fake rate)**
- **Drell-Yan: from data (on-shell Z)**
- **WZ, ZZ: from MC**

H->WW->lvlv: cut flow

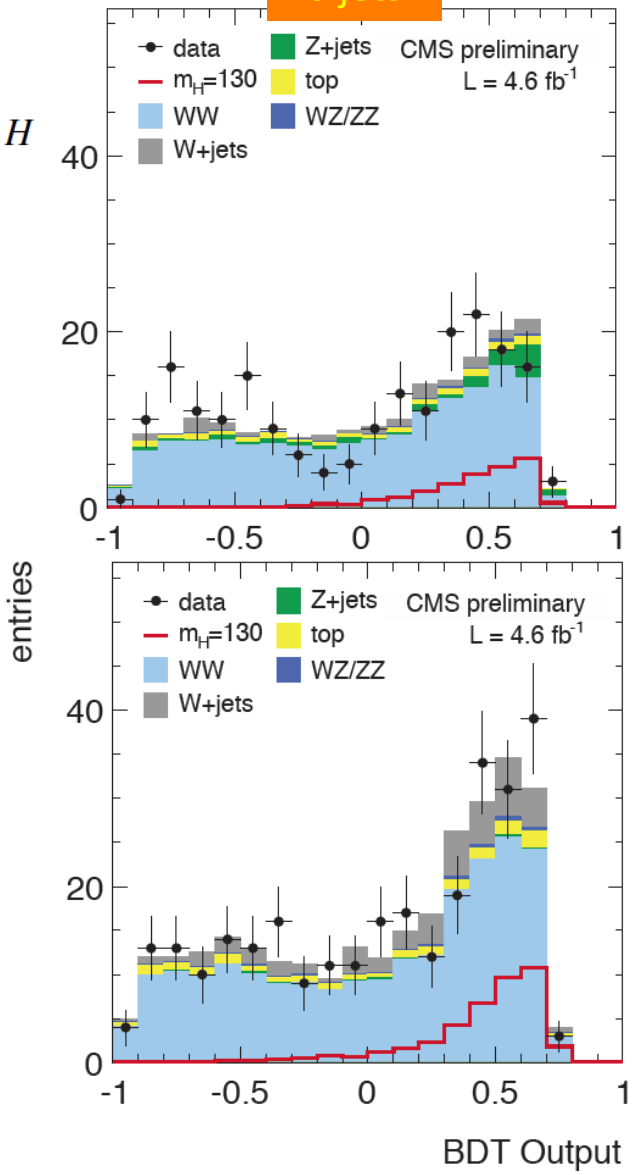


- **Observations:**
  - **remarkable agreement of data and bkgd predictions cut by cut**
  - **we should be close to excluding Higgs boson with m_H=130**

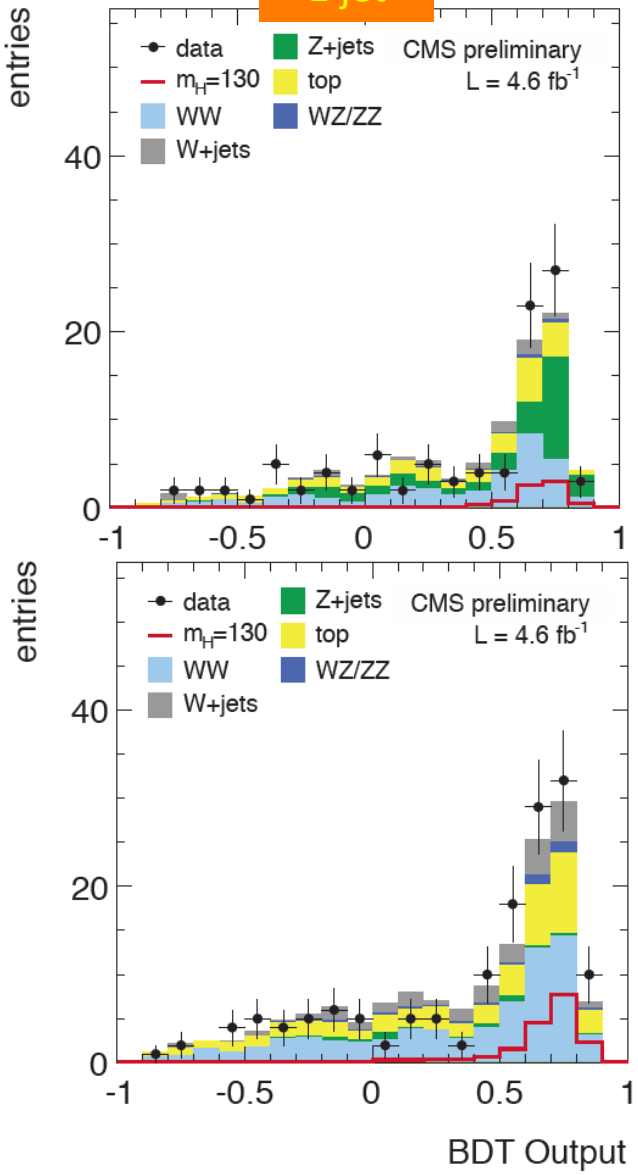
H->WW->lvlv distributions



0 jets



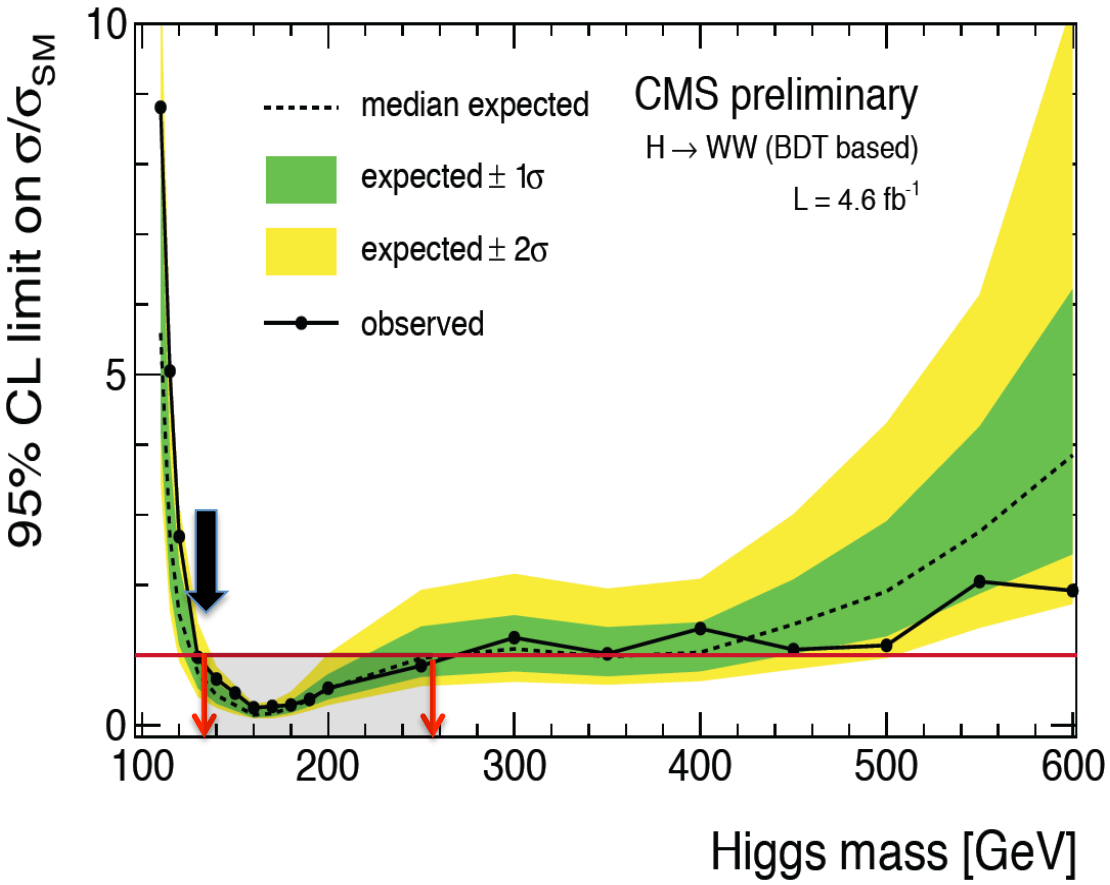
1 jet



ee + μμ

eμ

H->WW->lvlv results: CL

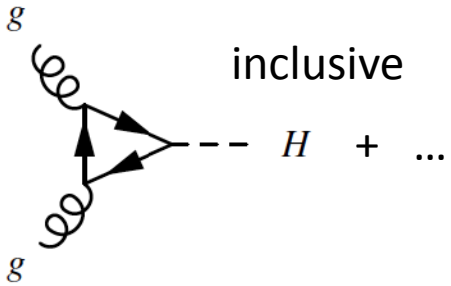


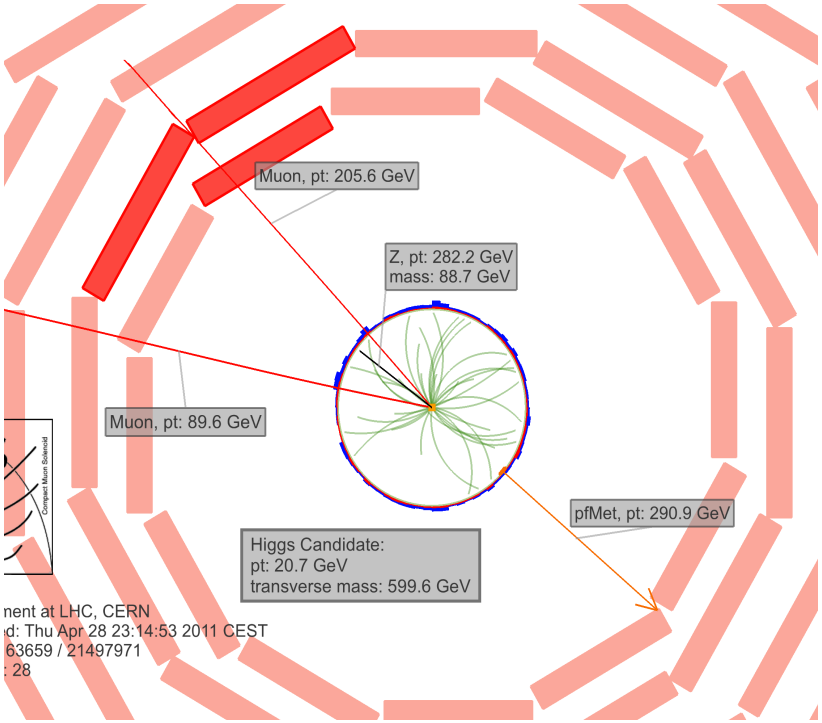
- **SM Higgs boson with mass 129 < M_H < 270 GeV ruled out at 95% CL**
- **SM Higgs boson expected sensitivity 127 < M_H < 270 GeV**

H -> ZZ

(not counting “golden” channel H ->4l)

H->ZZ->2l2ν signature





Selection:

- 2 channels: 2 isolated leptons: Z(2e), Z(2μ)
- no impact parameter
- large p_T(ll)
- large MET, not aligned with jets or leptons
- Final discriminant: m_T shape

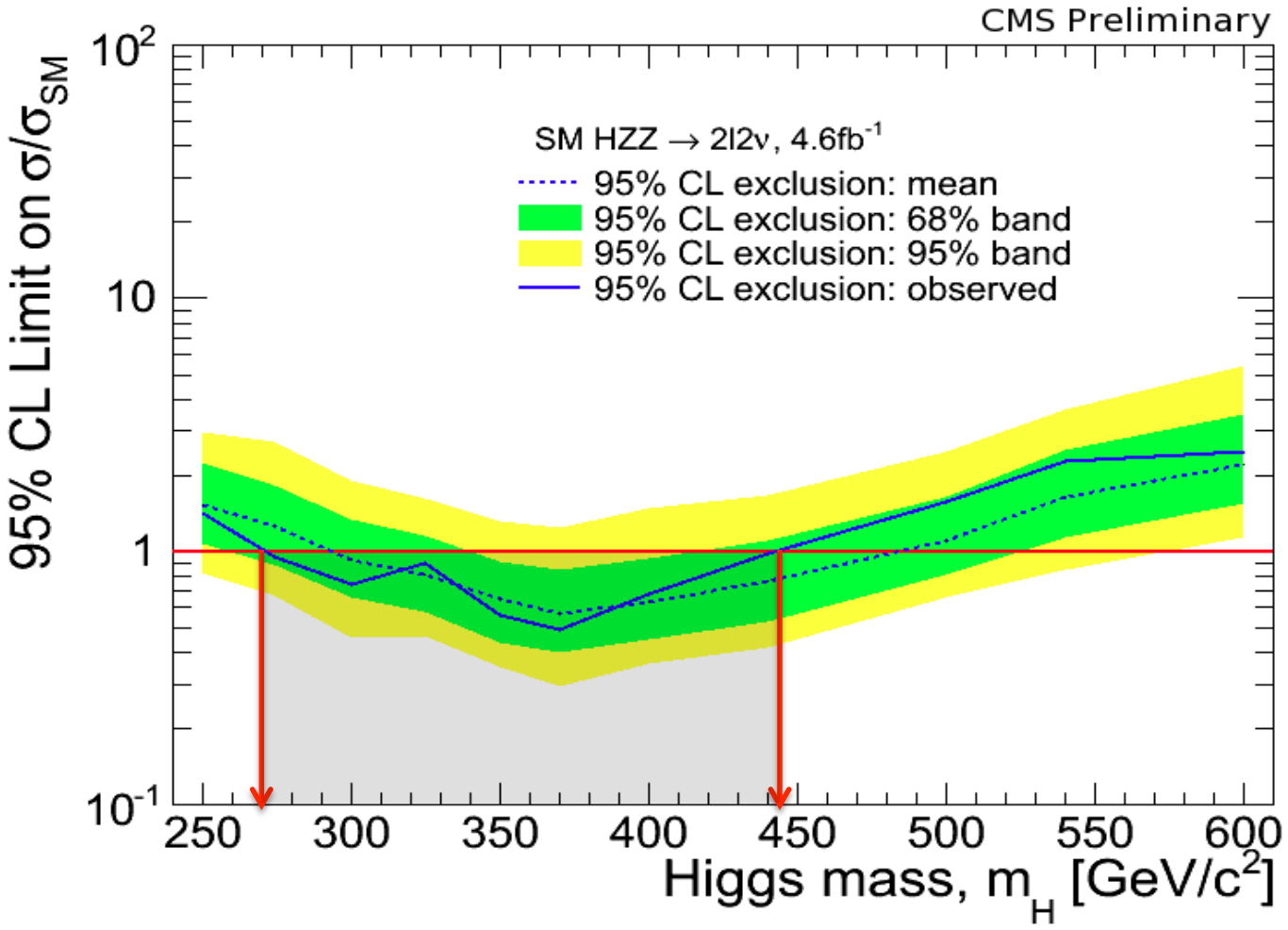
Mass resolution: 7%

Main backgrounds:

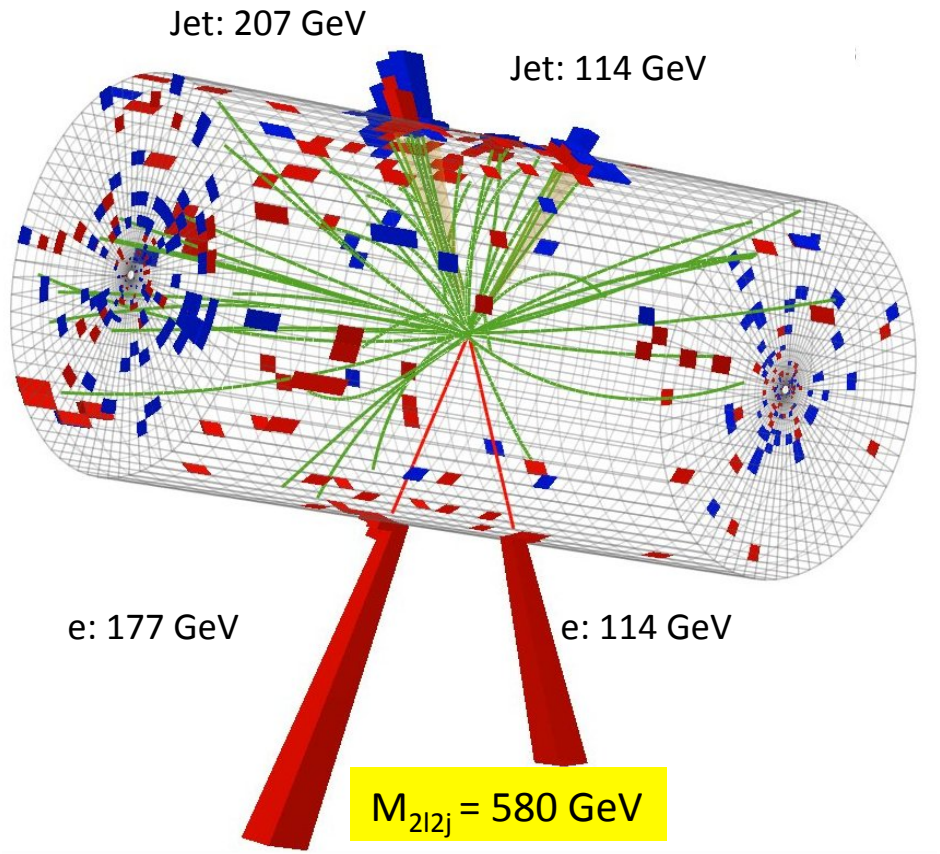
- Z+jets (sig:bkgd = 1:10^5): from data (γ+jets)
- tt, WW, Wjets: from data (off Z-peak)
- ZZ, WZ: from MC

H->ZZ->2l2v results: CL

Note: most sensitive channel for high mass Higgs boson



H->ZZ->2l2q signature



Selection:

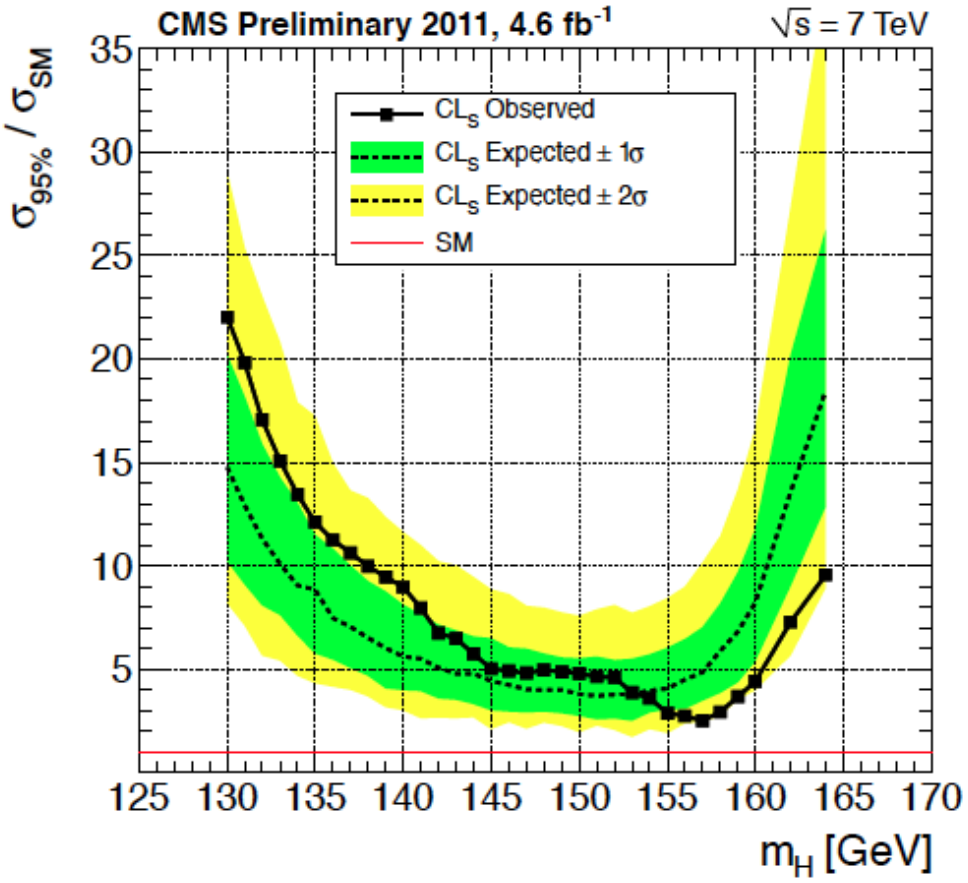
- 2 isolated leptons, Z(2e), Z(2μ), with no impact parameter
- two jets: Z(jj) with 0, 1, 2 b-tags
- most of sensitivity from 2 b-tag category
- no MET
- cut on angular topology (ME-based)
- Final discriminant: m_{lljj} mass distribution

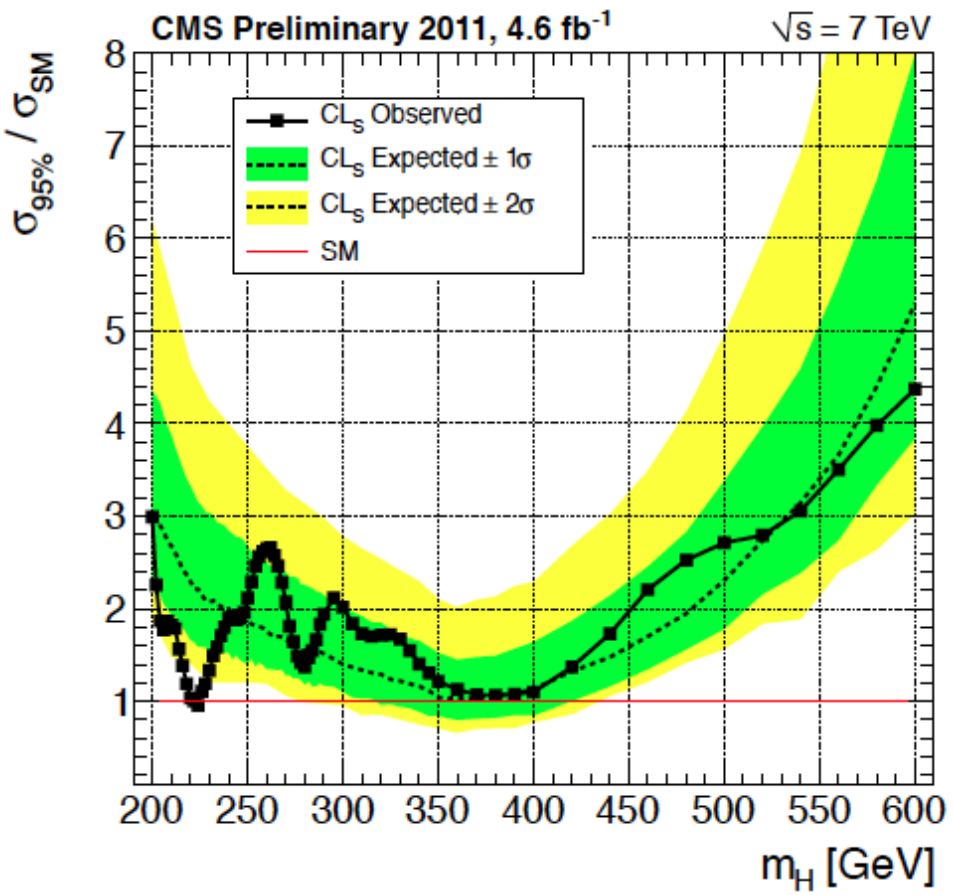
Mass resolution: 3%

Main backgrounds: from sidebands

- Z+jets (including heavy flavor jets)
- WZ, ZZ
- tt, WW

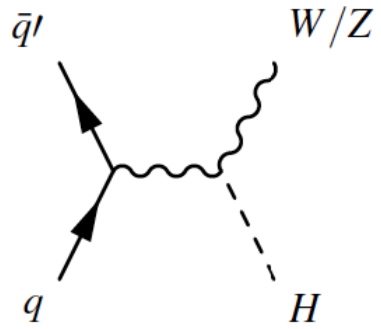
H->ZZ->2l2q results: CL

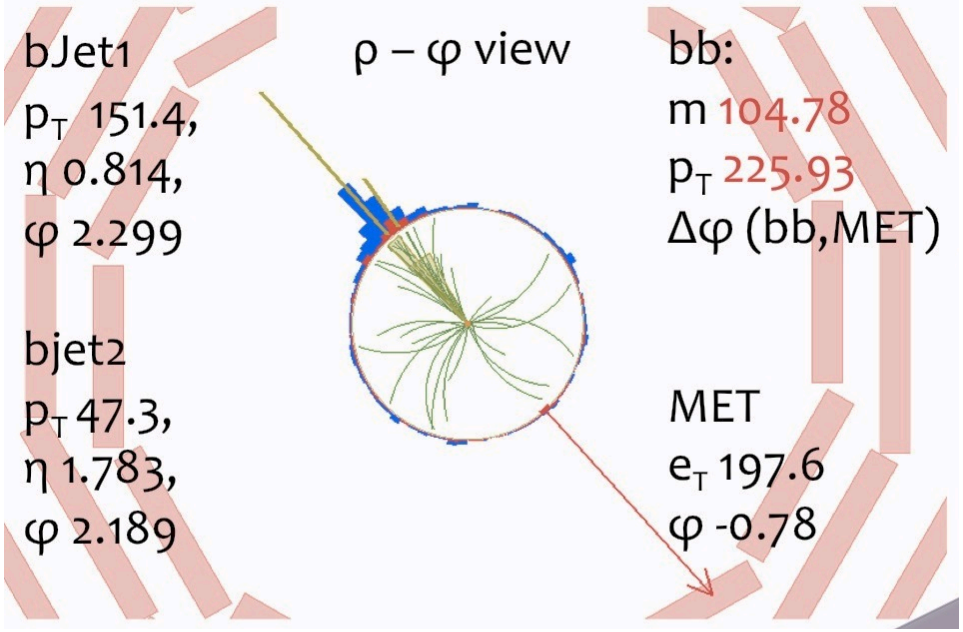




H -> bb

V+H(bb) signature





Selection:

- 5 channels: W→lν, Z→ll, Z→νν
- high MET quality for W(lν) and Z(νν)
- two jets with tight b-tags
- V+H(bb) topology: back-to-back, Δφ(V,H) > 3
- p_T(bb)> 100-160 GeV (*but not super boosted*)
- Final discriminant: MVA output shape

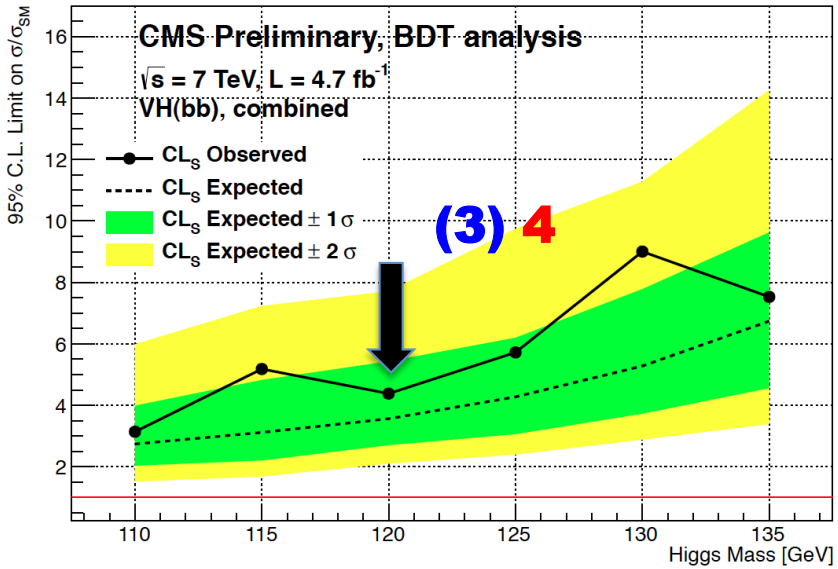
bb mass resolution: 10%
(aided by the bb-system boost)

Main backgrounds:

- Vbb: from data (invert p_T(bb) boost)
- V+jets: from data (invert b-tag)
- tt: from data (require extra jet)
- QCD: from data (require small Δφ(MET,jet), …)
- W+Z(bb) and Z+Z(bb): from MC

H->bb results

CMS



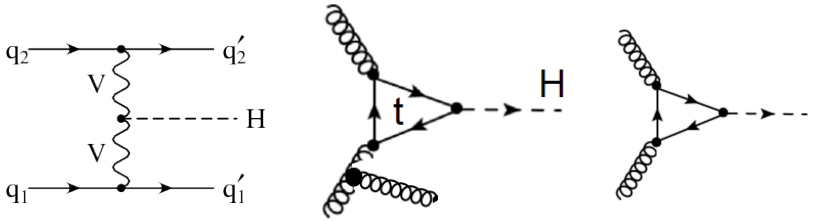
BDT shape analysis

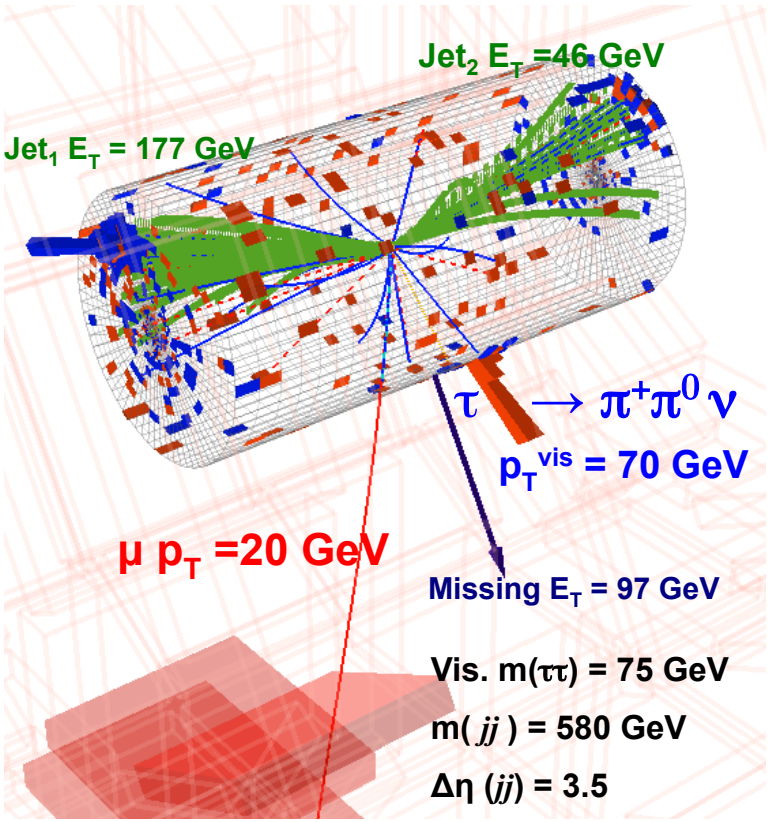
m_H=120 GeV

- **Sensitivity 3**
- **Observed 4**

H -> ττ

H->ττ signature





Selection:

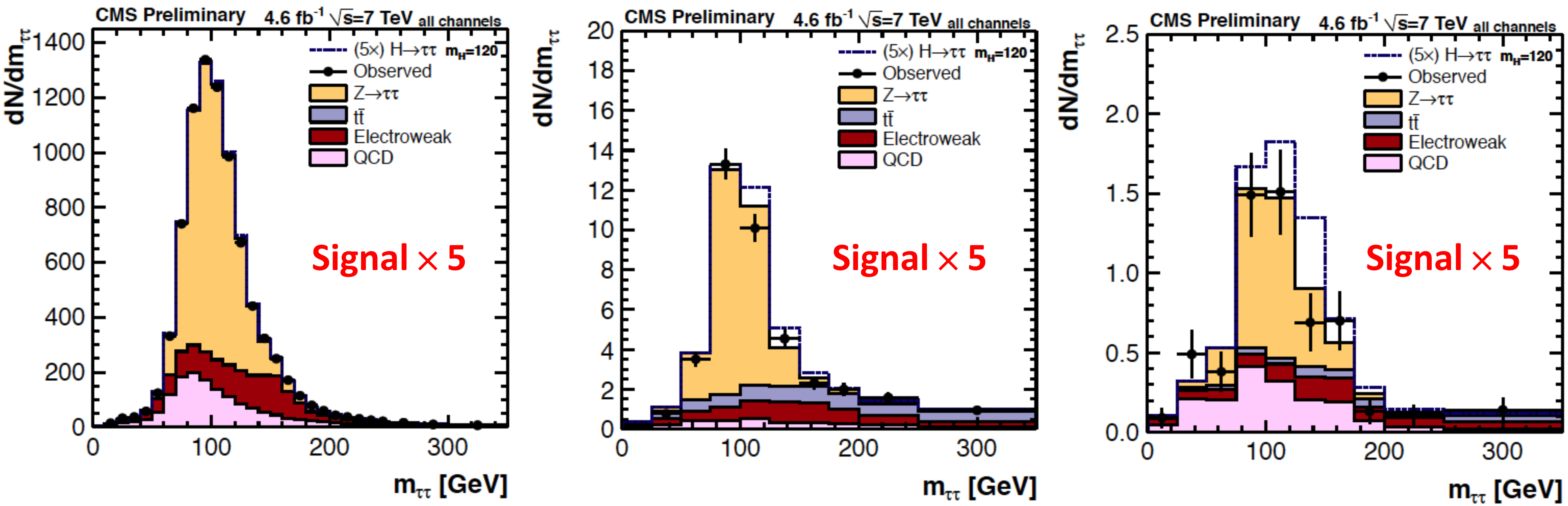
- 9 channels: $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_e\tau_\mu$ (VBF, 1-jet, the rest)
- main sensitivity from VBF production: two forward jets with no jets in between
- isolated leptons
- CDF topological cut (p_{T1}, p_{T2}, MET)
- final discriminant: ττ-mass distribution

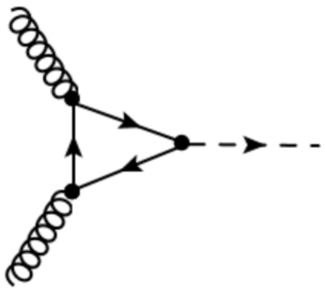
ττ mass resolution: 20%

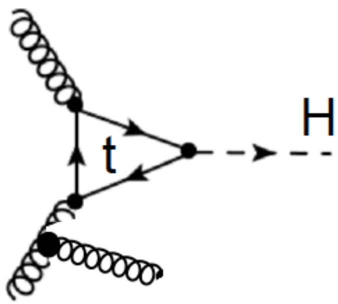
Main backgrounds:

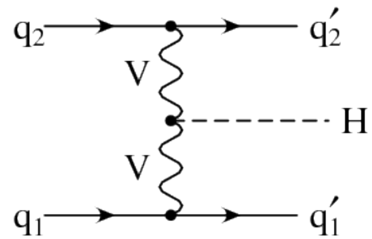
- Z→ττ: from data (mass distr. fit with MC shape)
- W+jets: from data (invert topological cut)
- QCD: from data (same sign ττ)
- tt, di-bosons (e faking τ): from data (ll events)

H->ττ distributions (m_H=120 GeV)

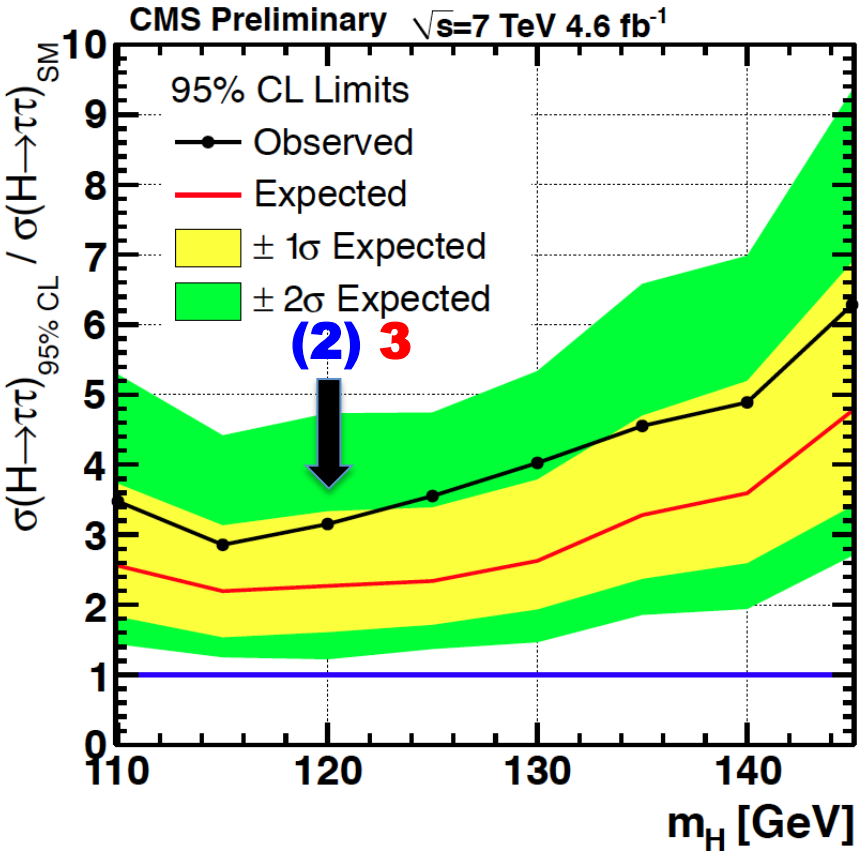








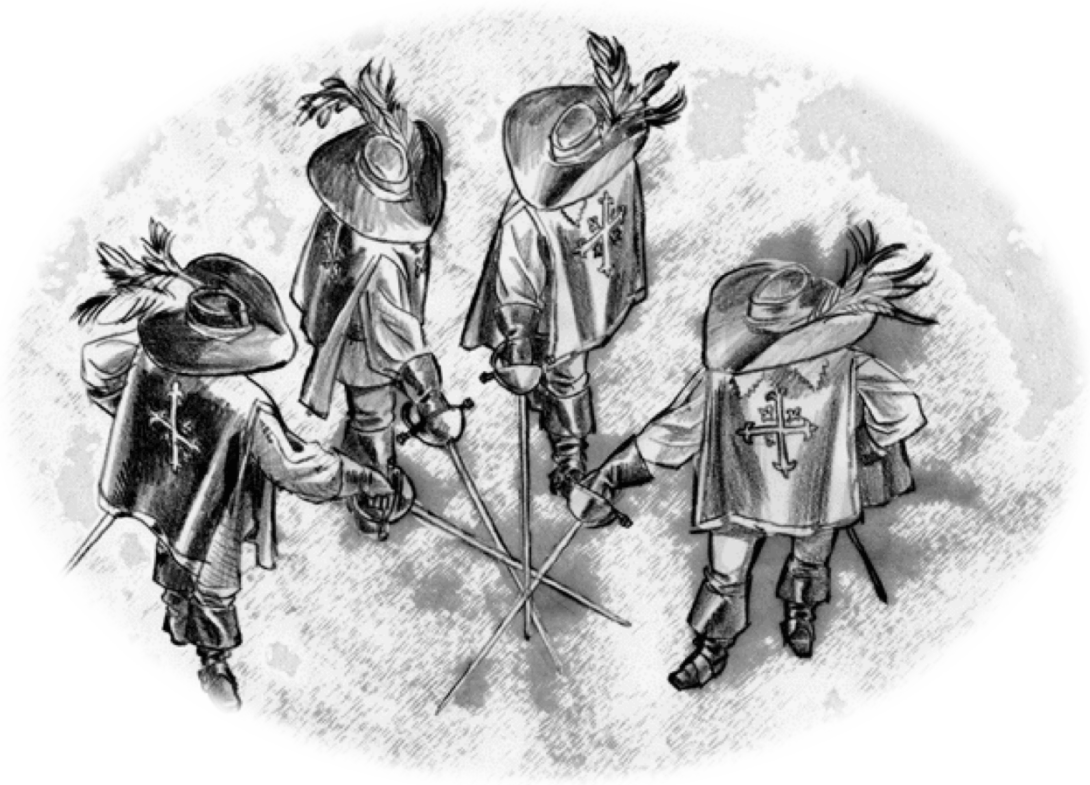
H->ττ results



m_H=120 GeV

- **Sensitivity 2.3**
- **Observed 3.2**

Combination of searches



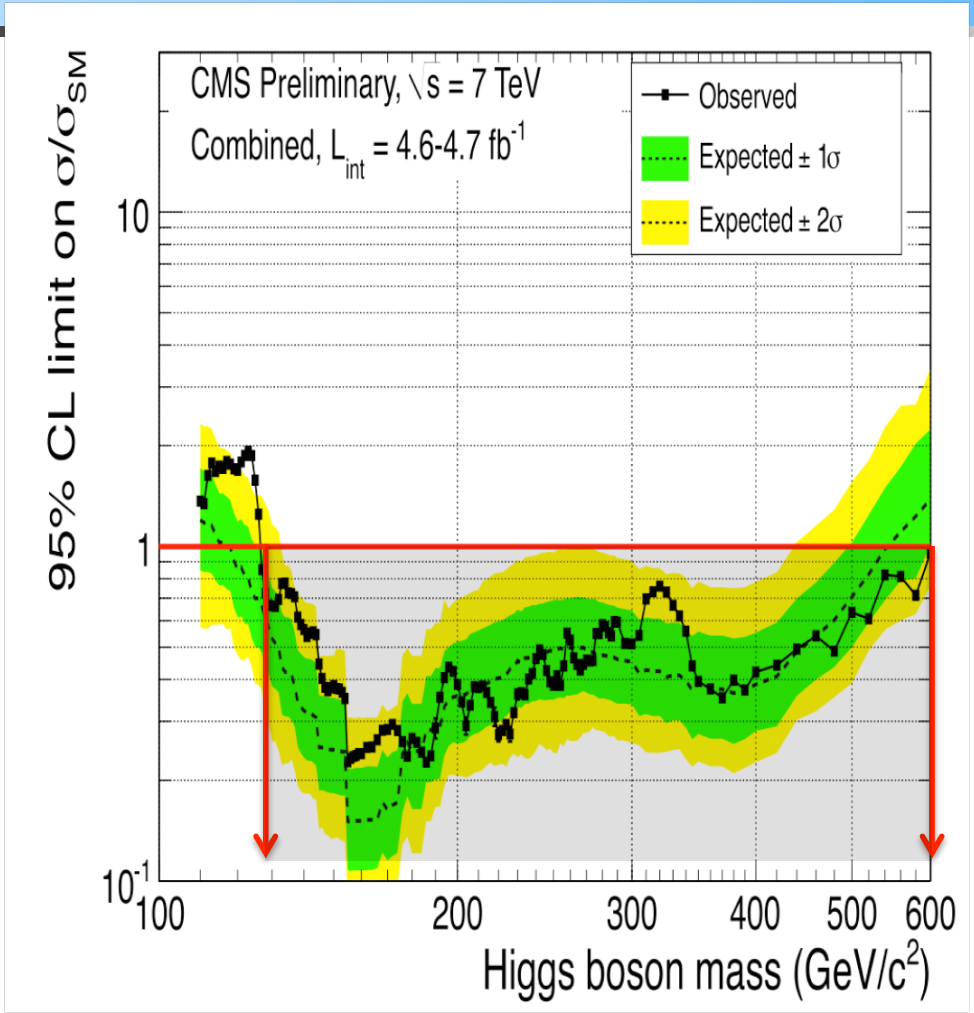
Combination scope

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%

- **42 exclusive final states**
- **about 200 nuisance parameters (systematic errors)**

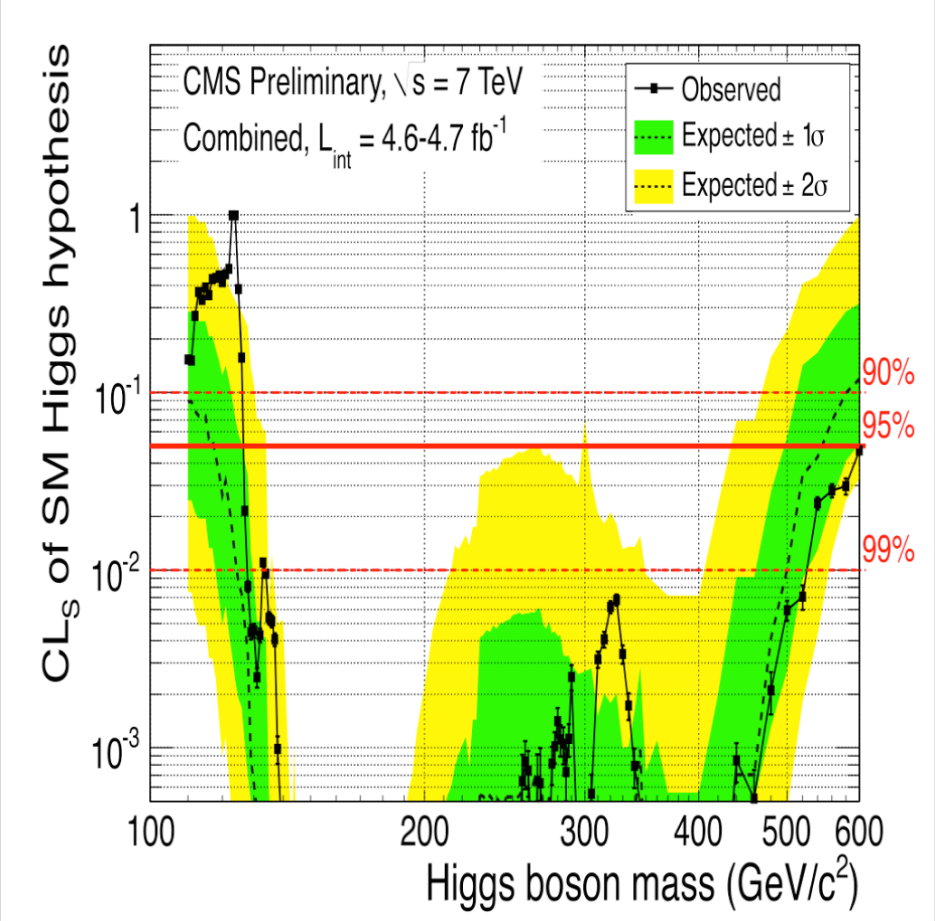
LIMITS

Exclusion limits on SM Higgs



- **95% CL expected sensitivity: 117—543 GeV**
- **95% CL observed limits: 127 – 600 GeV**

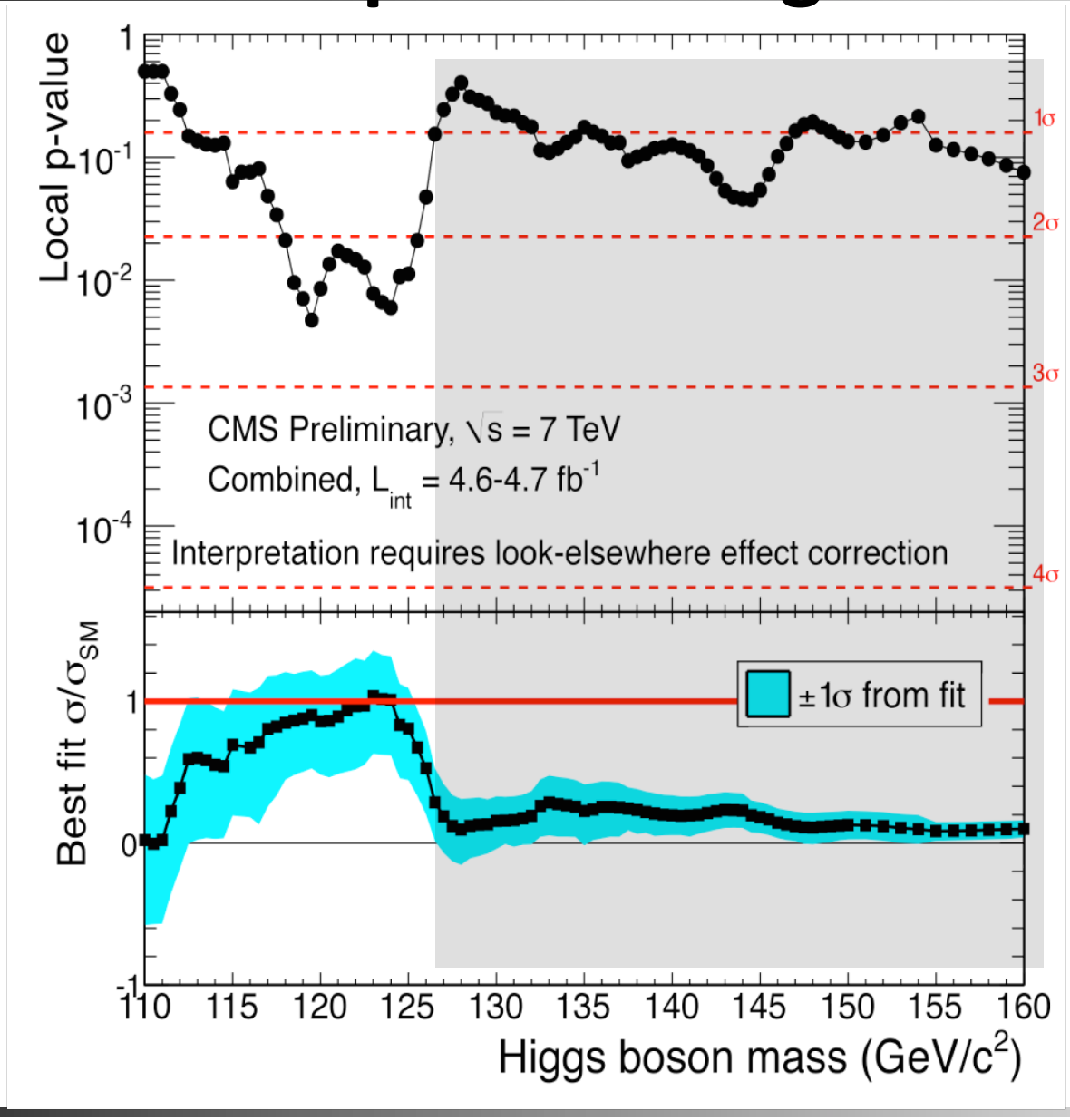
Exclusion CL for SM Higgs: 95% vs 99%



- **95% CL observed limits: 127—600 GeV**
- **99% CL observed limits: 128 – 525 GeV**

LOW MASS EXCESS

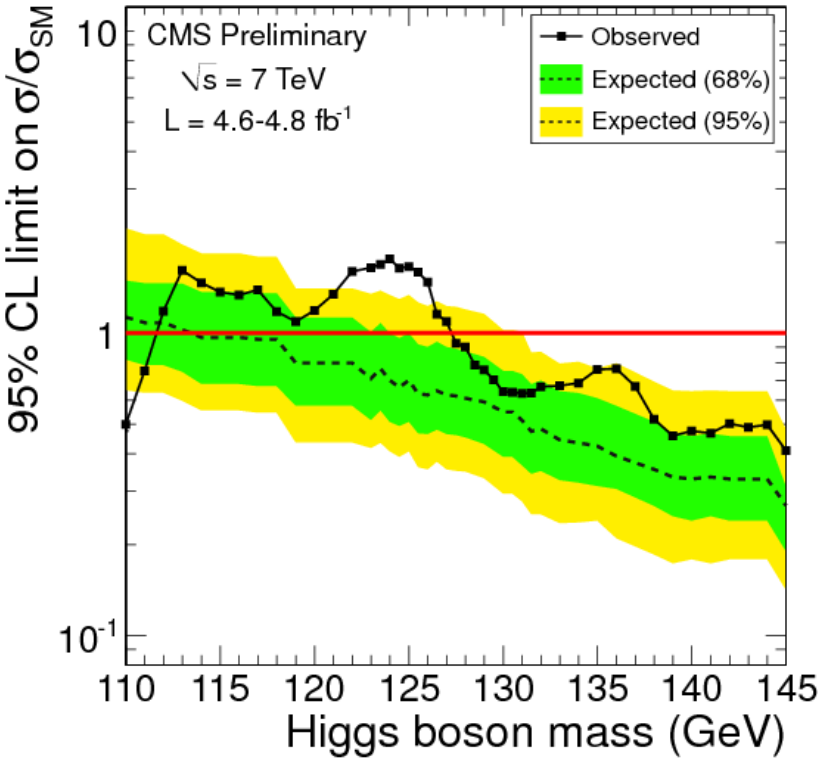
Excess compatible with SM Higgs (but also with possible bkgd fluctuations)

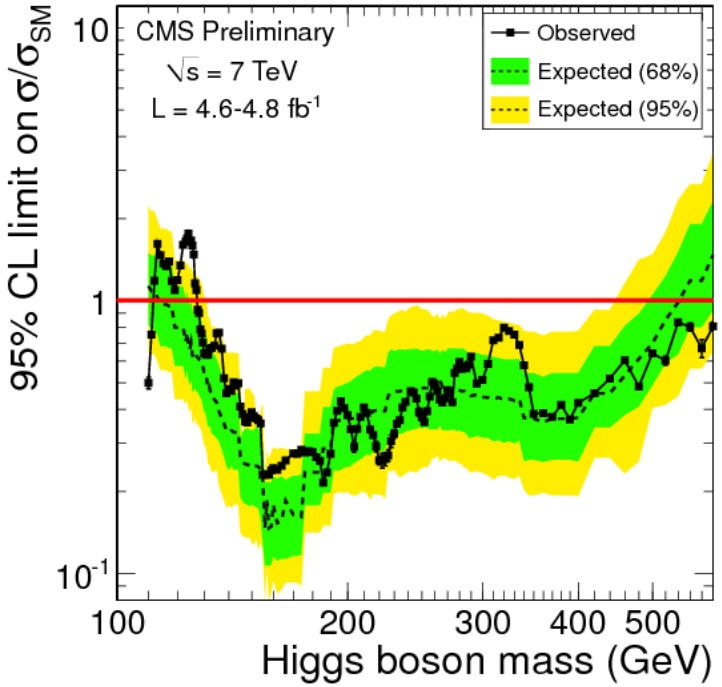


Latest changes (for Moriond, March 2012)

- **CMS:**
  - 1) include H → γγ VBF (published)
  - 2) change H → γγ from cut based to MVA-based
  - 3) WH→W(WW)→3l3ν (does not contribute much)
  - 4) WH→W(tautau)→2l + tau (does not contribute much)
- **ATLAS:**
  - December: at full luminosity: only H → γγ and H → 4l
  - Since December: updated all other channels for the full luminosity
  - WW channel has mu=0.2 (pulls significance down)
- **Tevatron:**
  - new combination: 2sigma excess (improved btag in CDF)

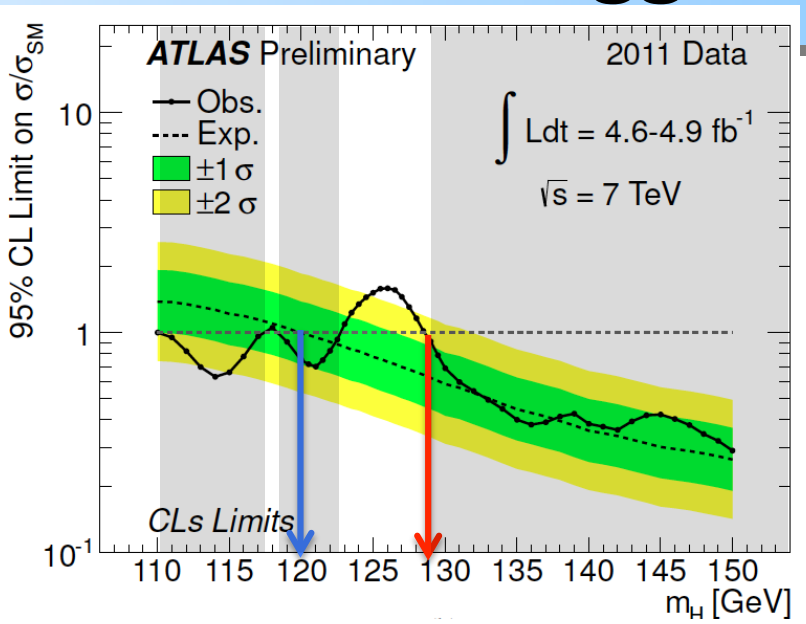
CMS Moriond combination

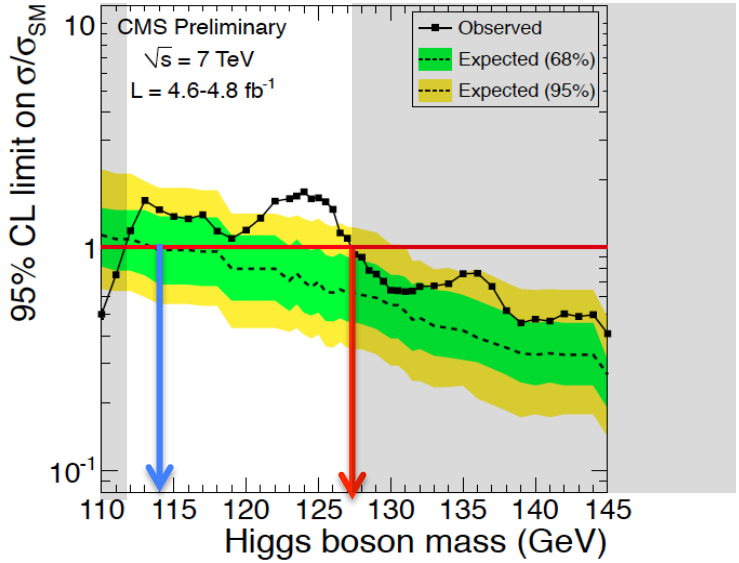




Moriond: CMS limits in low/full mass ranges

Low mass Higgs exclusion (ATLAS and CMS)





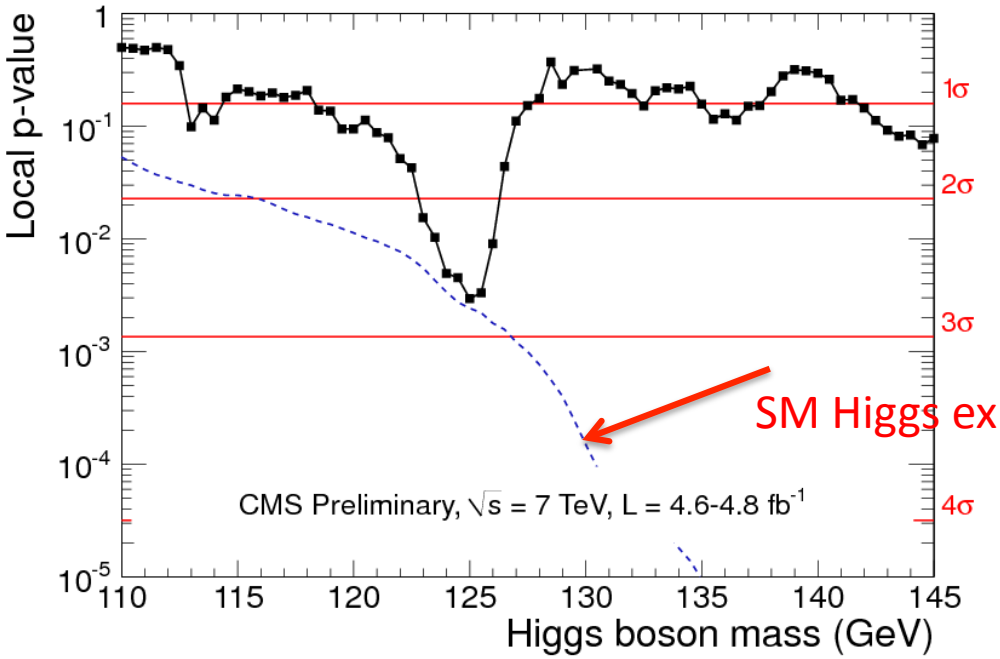
ATLAS SM Higgs exclusion:

- expected: 120–… GeV,
- observed: 110.0–117.5 GeV
  118.5–122.5 GeV
  129.0–… GeV

CMS SM Higgs exclusion:

- expected: 114.5–… GeV
- observed: 127.5–… GeV

CMS: Moriond Higgs significance

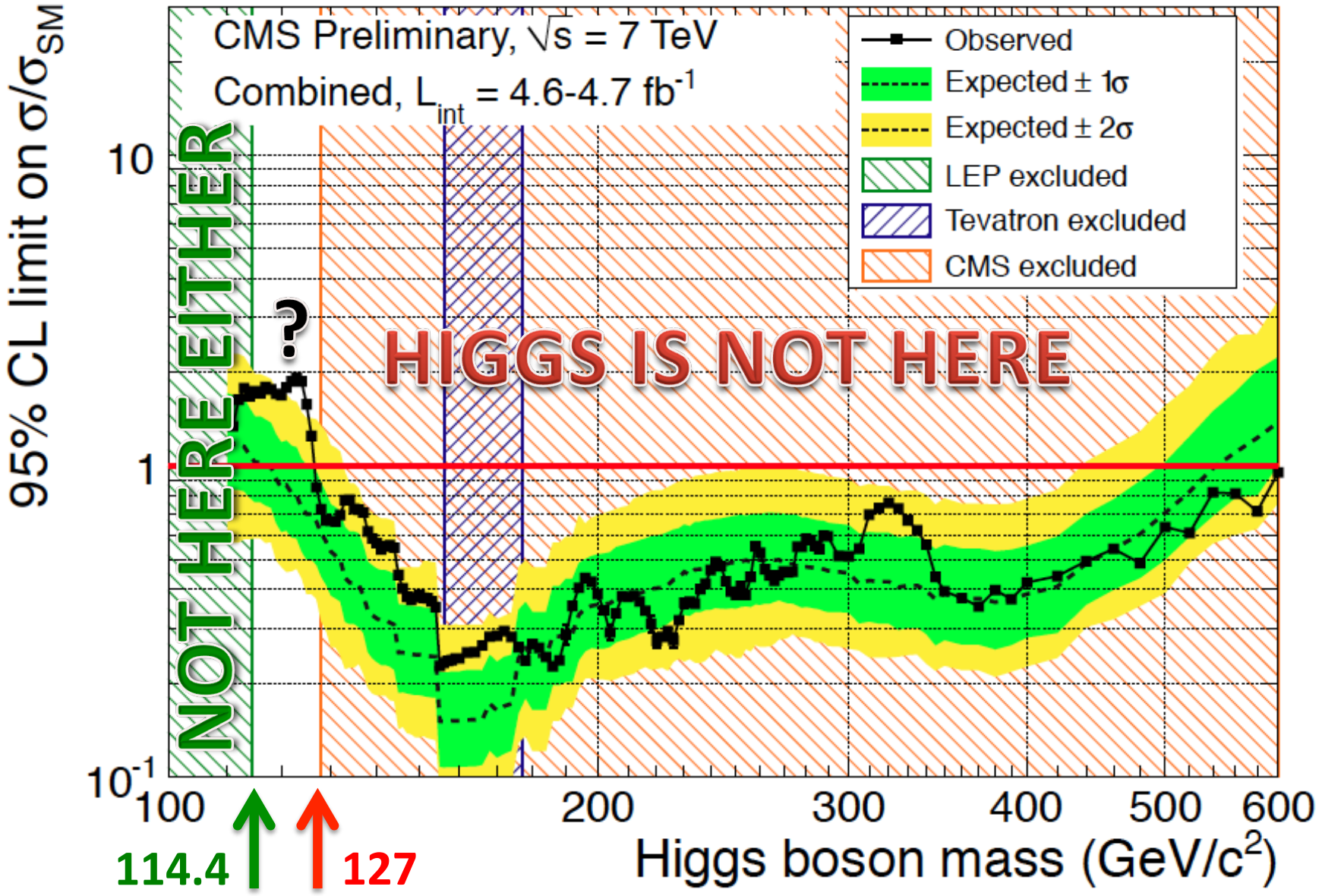


SM Higgs expectation for different Higgs masses

Moriond'12: Combined significance (right scale)

– excess at 124 GeV close to SM Higgs expectation

CMS one-plot summary

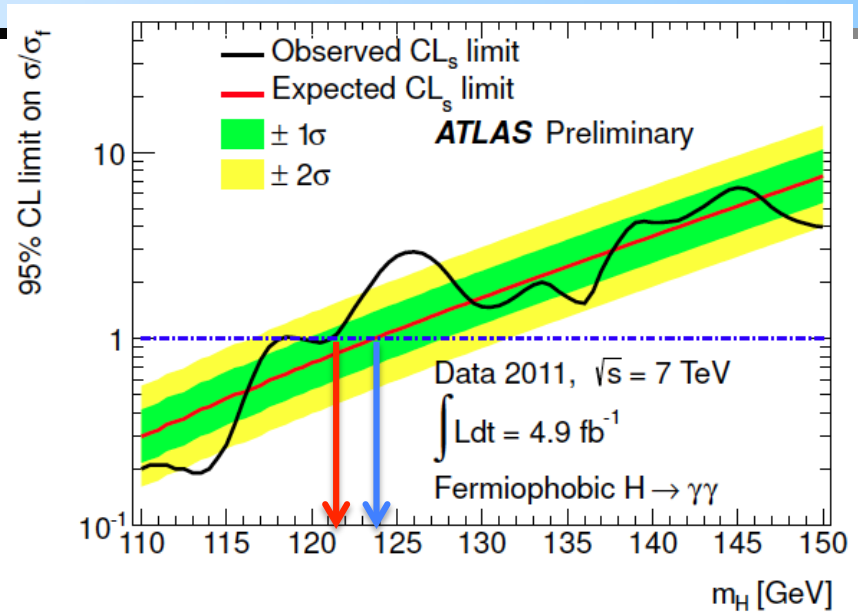


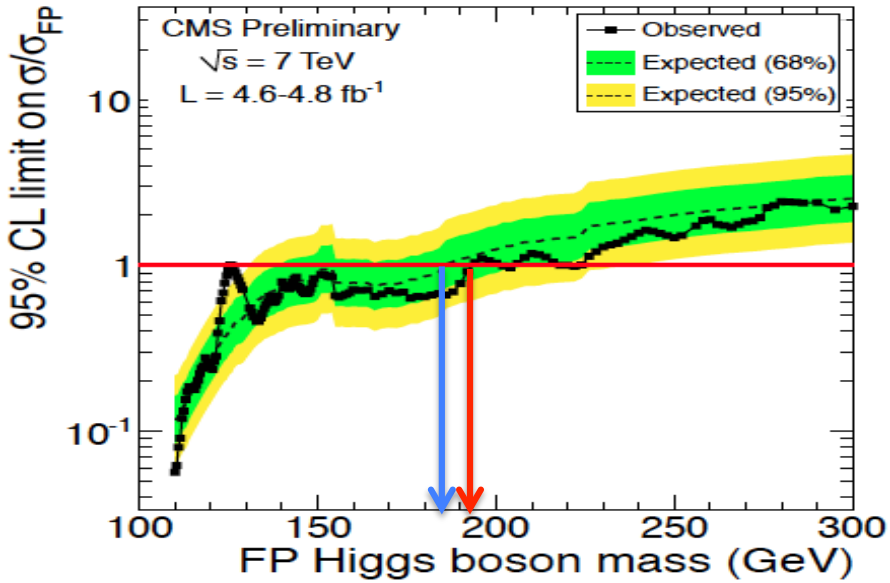
Guido Altarelli at Moriond 2012:

- A narrow window for SM Higgs: 122.5-127.5 GeV
- An indication for mH ~ 125 GeV (to be checked in '12)
- No evidence of new physics in searches other than Higgs, although a big chunk of new territory has been explored
- mH ~ 125 GeV is a bit too light for SM (metastability)
- mH ~ 125 GeV is a bit too heavy for CMSSM, mSUGRA, NUHM..

OK for pMSSM, NMSSM, λ-SUSY

Exclusion of Fermiophobic Higgs





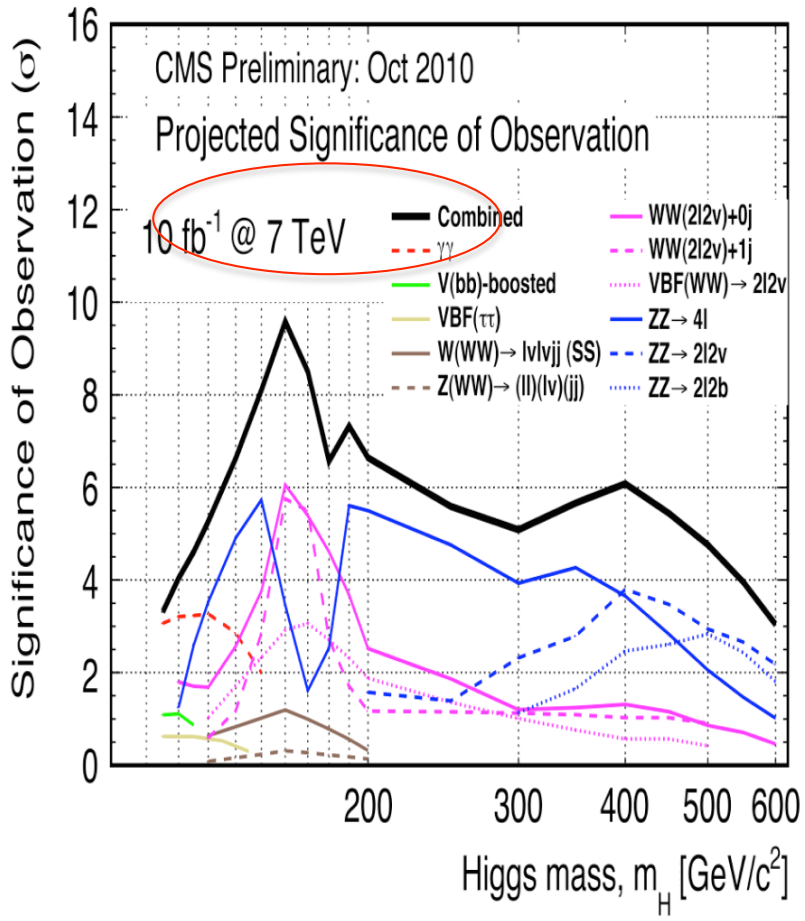
ATLAS:

- **Expected exclusion: 110-124**
- **Observed exclusion: 110-121**
- **γγ only**

CMS:

- **Expected exclusion: 110-186**
- **Observed exclusion: 110-192**
- **γγ + WW + W(WW) + ZZ**
- **γγ alone is somewhat better in CMS**

Outlook: prospects for 2012



2012 integrated lumi being discussed: ~ 20 fb^{-1}

If SM Higgs is there, discovery is very likely next year

Summary

- **CMS reached SM Higgs exclusion sensitivity in the full mass range**

- **SM Higgs excluded by CMS at 95% CL for m_H = 127–600 GeV**
  at 99% CL for m_H = 128–525 GeV
  ATLAS+CMS results leave only narrow window for SM Higgs: 122.5-127.5 GeV
- **The excess at low masses remains.**
  It is consistent with SM Higgs, but it may well be bkgd fluctuation
  To ascertain the origin of the excess, more data are required.

- **2012: with > 20 fb^{-1} per experiment next year, we expect to reach discovery sensitivity in the full mass range**