# *Recent Higgs Search Results with the CMS Detector*

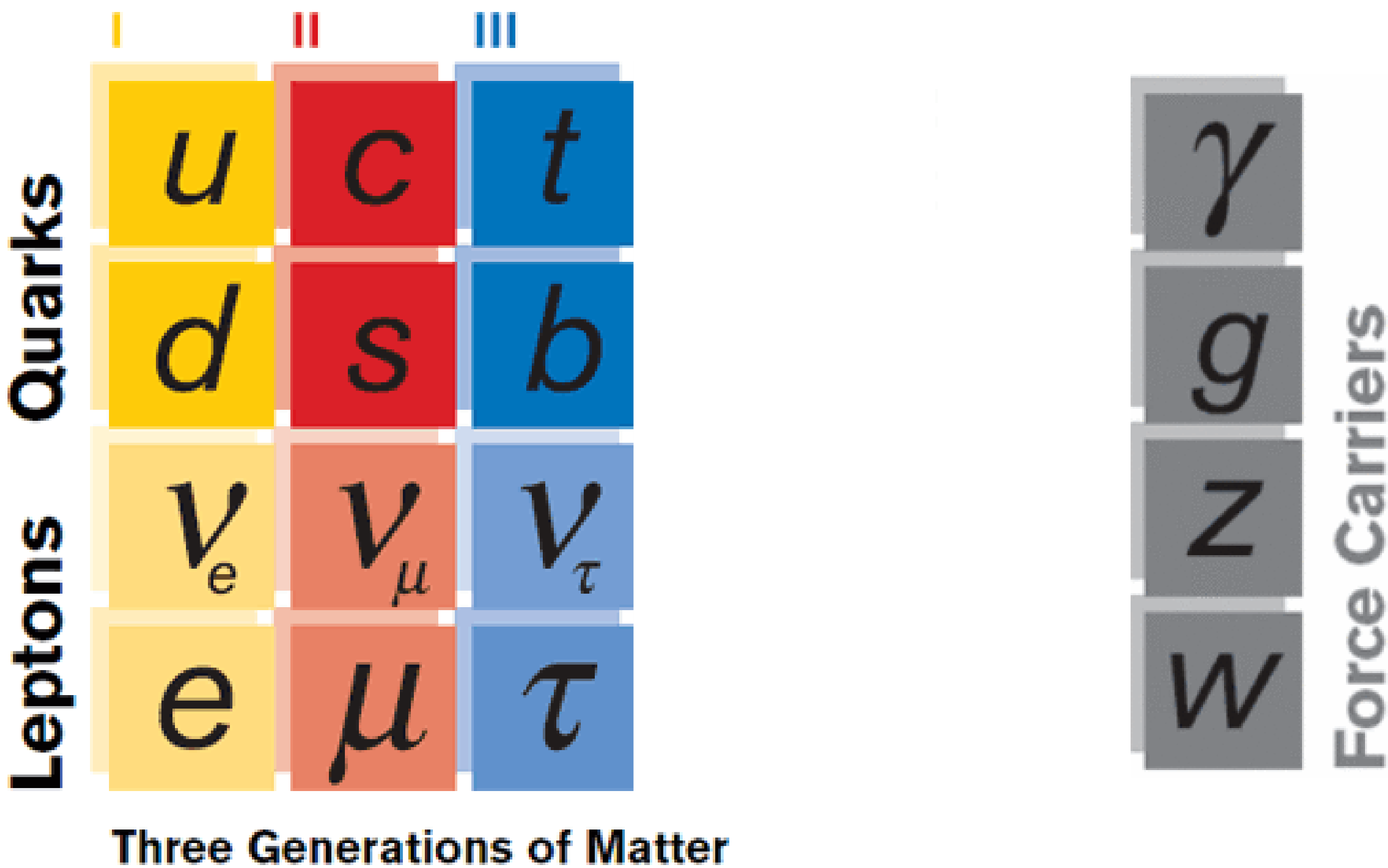
Christoph Paus, MIT

The Zurich Phenomenology Workshop (Zürich)

*January 09, 2012*

# *The Standard Model* *of Particle Physics*

Building blocks: matter (fermions), forces (bosons)




Simple Lagrangian formalism describes this very well but only for massless particles....

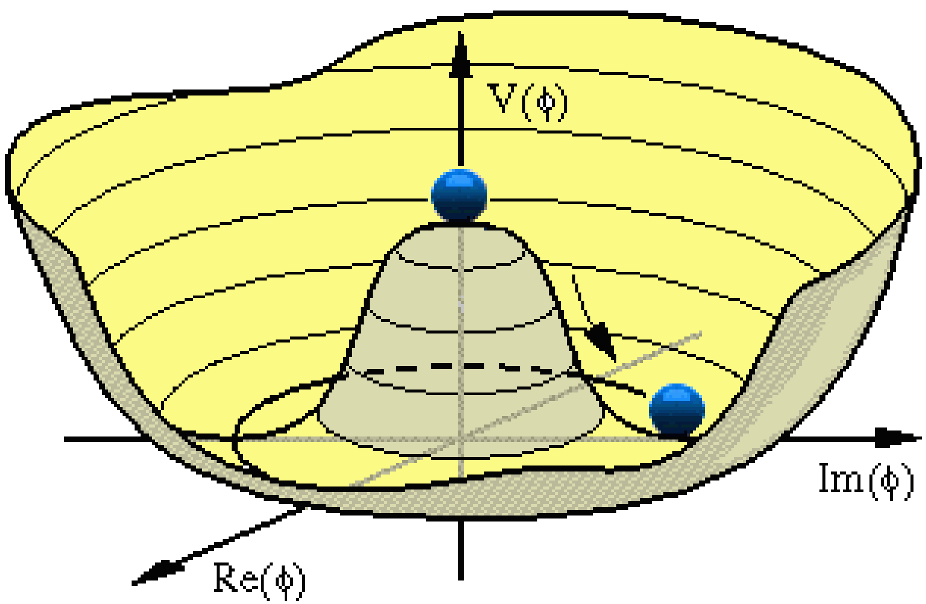
# *The Standard Model* *of Particle Physics*

## How do particles acquire their masses?

- hand inserted mass terms destroy gauge invariance (local)
- need gauge invariant mechanism to generate mass terms
- Higgs mechanism is the simplest way to do it

## The Higgs mechanism

- introduce additional scalar field (a new scalar particle)
- modifies derivatives
- additional terms with mass appear
- vacuum expectation value ≠ 0
- particles move through field which gives them mass
- no experimental evidence, yet



# *Higgs Particle: Pros and Cons*

## The mystery of mass

- can be resolved with one scalar Higgs boson

## What is good about it?

- resolves fundamental problem of mass
- nature tends to be economic: few particles
- model makes very precise predictions: decay kinematics (scalar), couplings, cross section, cross section ratios ....
  - only one parameter to vary: $m_H$
  - search can be very well targeted
  - similar mechanisms for example SUSY, partially covered

## What is not good about it?

- no physics beyond Standard Model, we like new things
- fundamental problems of Standard Model remain

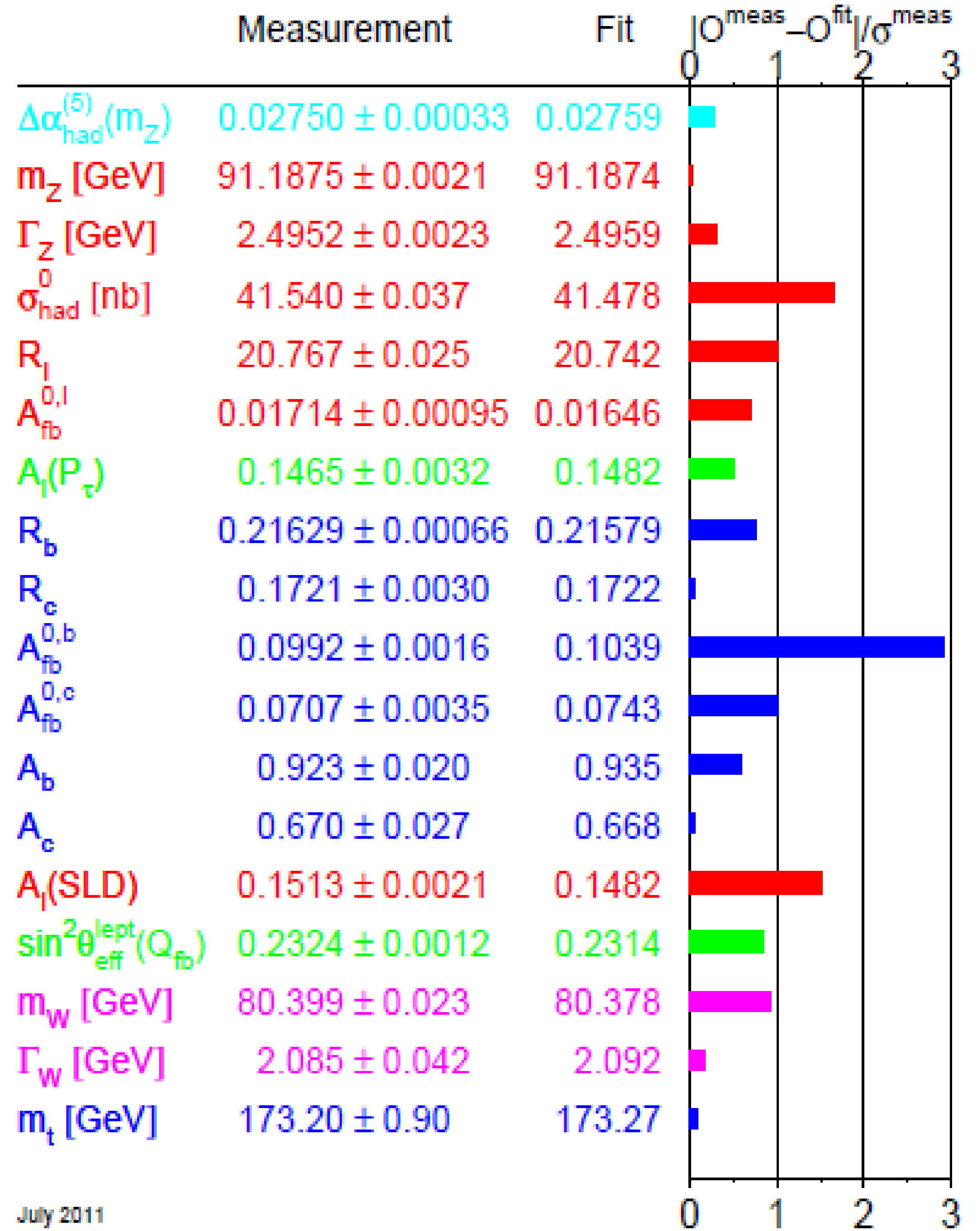
# *The Standard Model: Measurements*

## Experimental data

- LEP, SLC
- Tevatron
- Neutrino experiments
- ....

## Measurements

- over a thousand individual measurements combined
- very different accelerator and detector setups
- decent agreement with SM



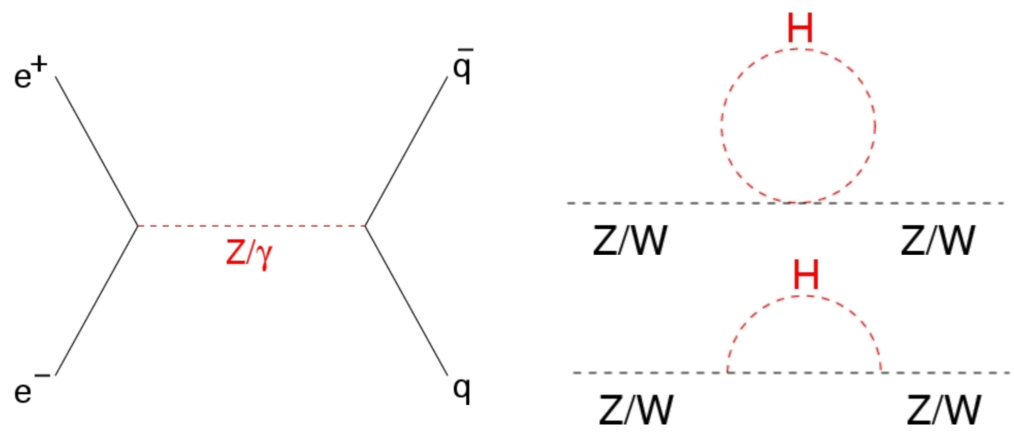
# The Standard Model: Higgs Constraints

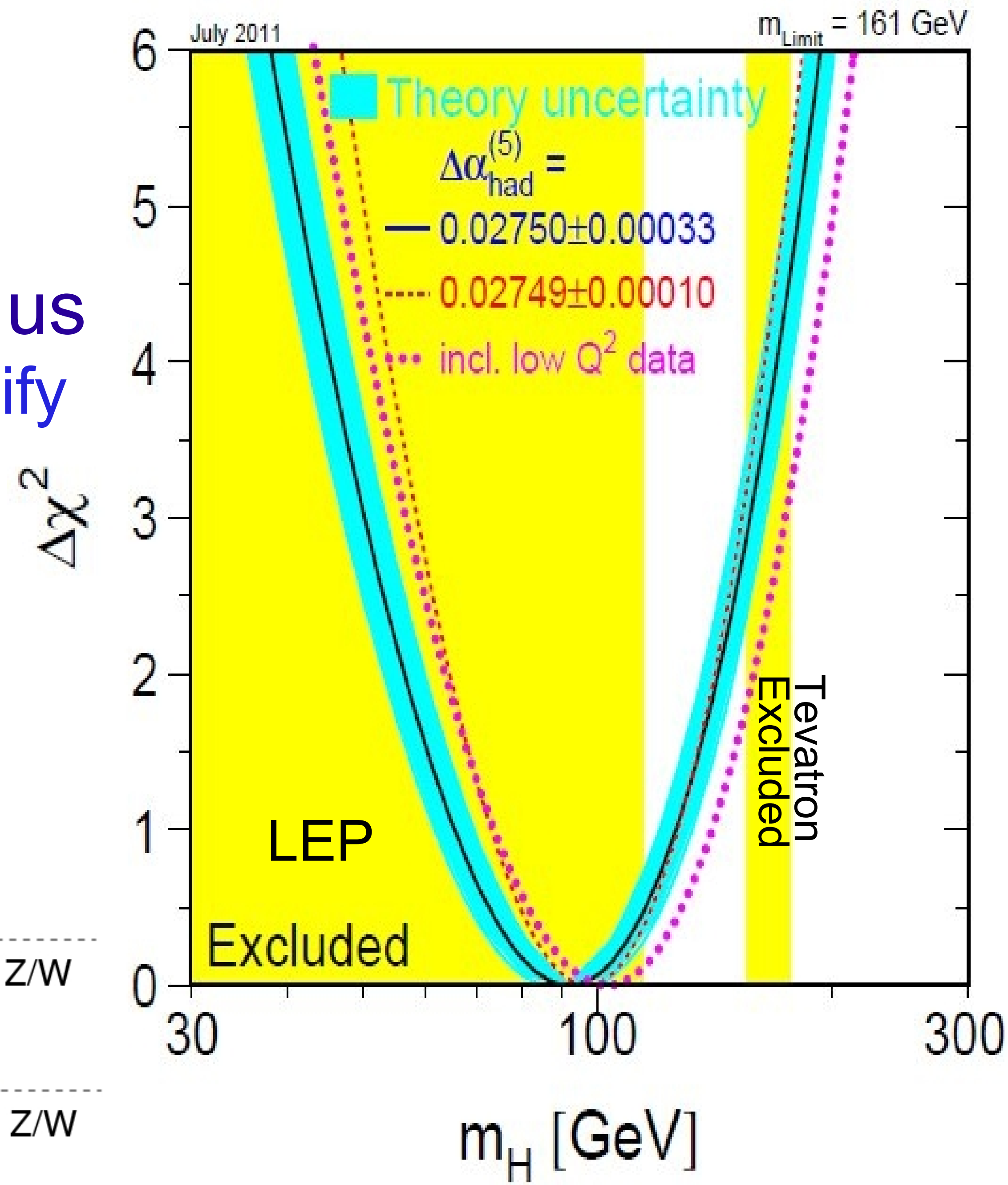
## Direct searches

- nothing found
- Higgs boson too heavy

## What precision data tell us

- radiative corrections modify lowest order processes
- Higgs present in virtual loops
- modifies observables

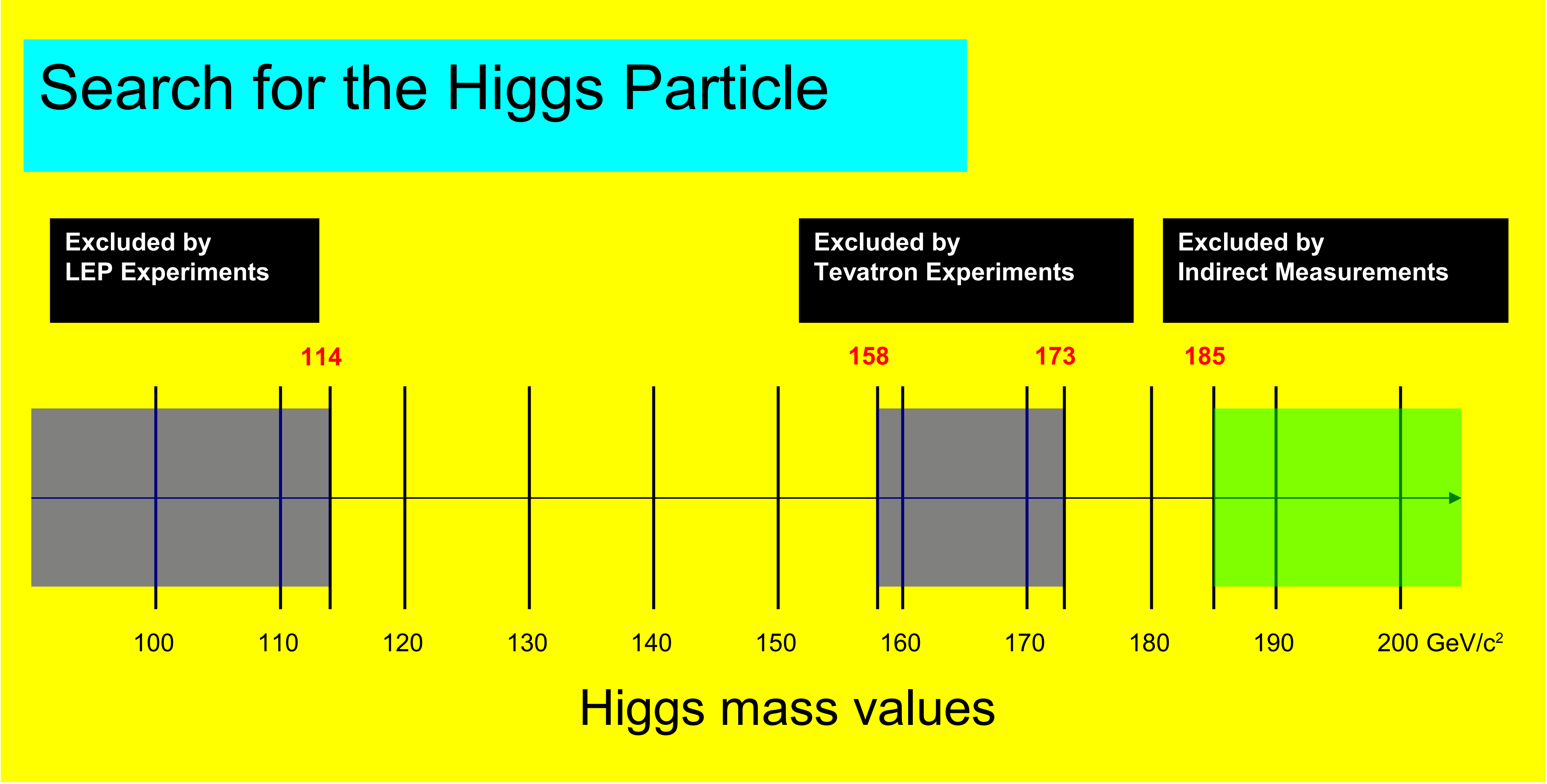


# *Higgs Landscape Before LHC*

## Fundamental limitations

- center of mass energy (Tevatron 2 TeV, LEP 210 GeV)
- searches limited to low mass region (plots stop at 200 GeV)



# The CMS Conclusion

Quantum leap in Higgs search in 2011: ~5/fb data

- excluded region : 127 GeV < $m_H$ < 600 GeV
- expected : 117 GeV < $m_H$ < 543 GeV
- small window left: **114.4 GeV < $m_H$ < 127 GeV**

Looking beyond 95% CL → 99% CL

- 99% CL exclusion: 128 GeV < $m_H$ < 525 GeV
- search will not stop at 95% CL exclusion

Comments on low mass region

- excluded less than expected
- small excess, but inconclusive at this point
- **need more data to come to a conclusion (this year, 2012)**

# Higgs Hunting Basics

Needle in the hay stack problem

- need high energy
- need lots of data

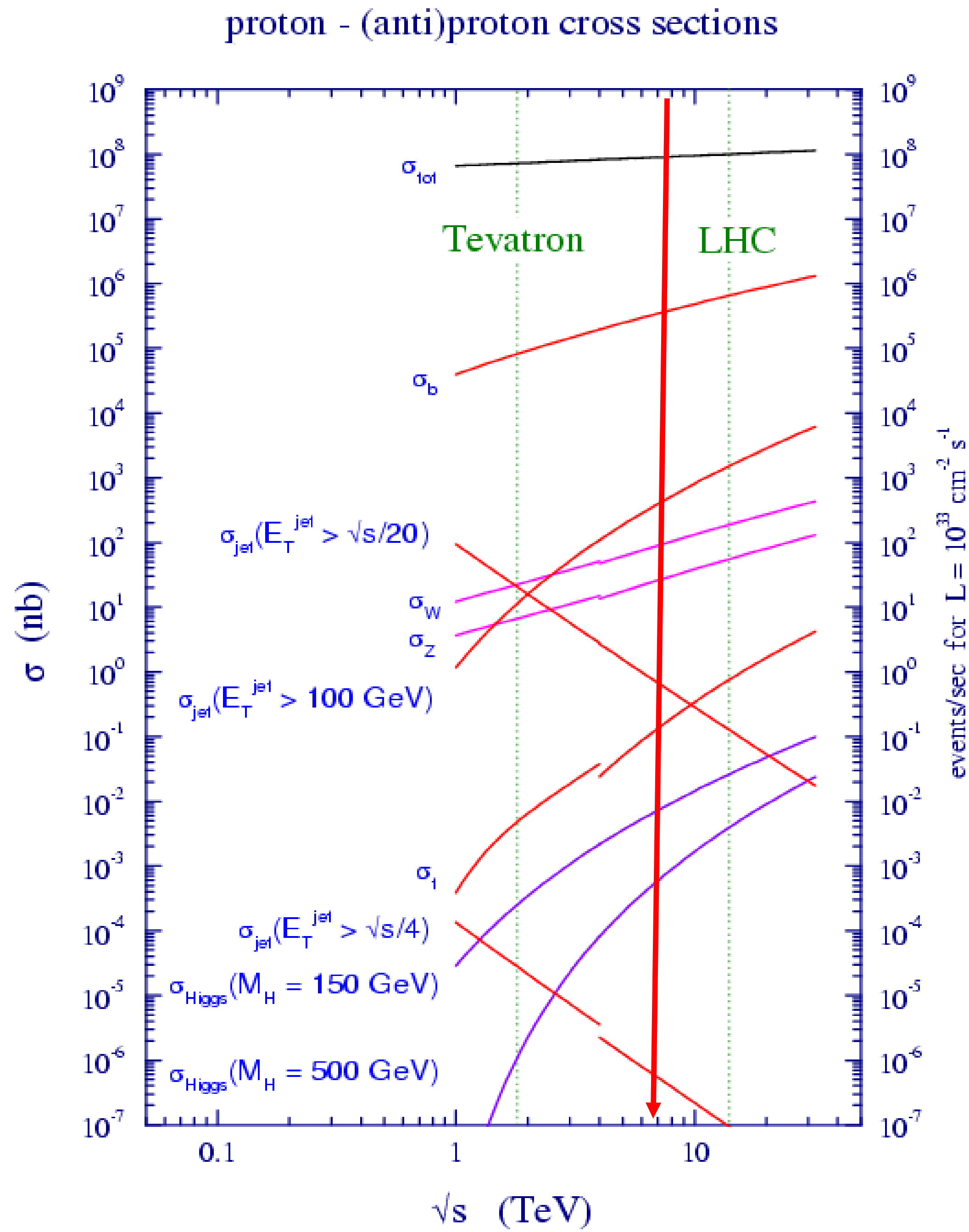
# Higgs Hunting Basics

## Physics processes

- production relative to $\sigma_{tot}$:
  - *bb* at $10^{-3}$,
  - $W\rightarrow \ell\nu$ at $10^{-6}$ and
  - *Higgs* (*m*=110 GeV) at ~$10^{-11}$
- 32 MHz beam crossing, only about 300 Hz tape writing: $1/10^{5}$
- fast and sophisticated selection process essential: trigger

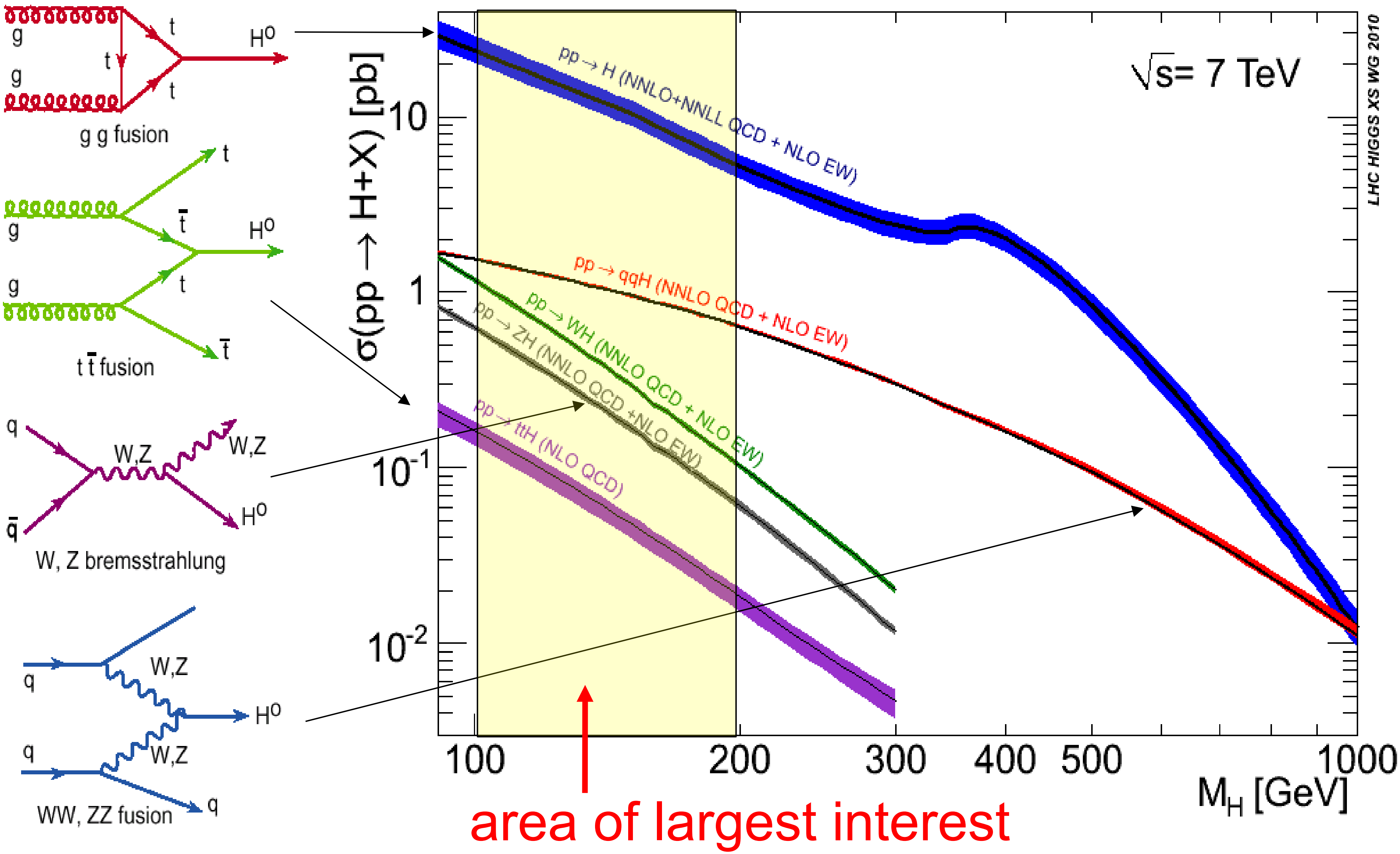
## Trigger

- trigger has to work: otherwise no useful data registered
- already in first data taking: rate enormous and trigger important
- core trigger organization: use electron, muon, jet and energy signatures

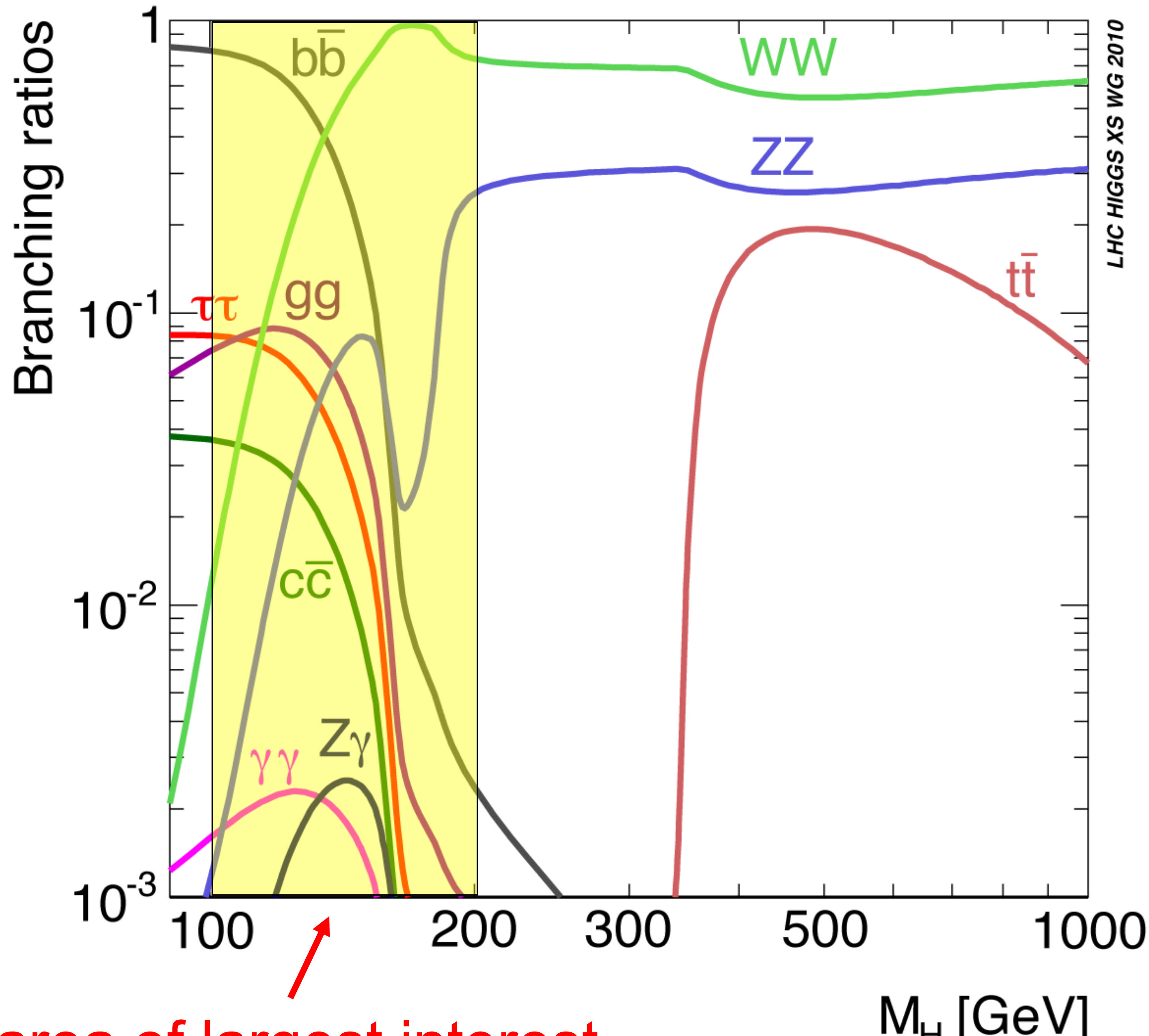


# Higgs Production at the LHC

## Higgs production in proton-proton collisions



# *Higgs Decays (Tevatron/LHC)*



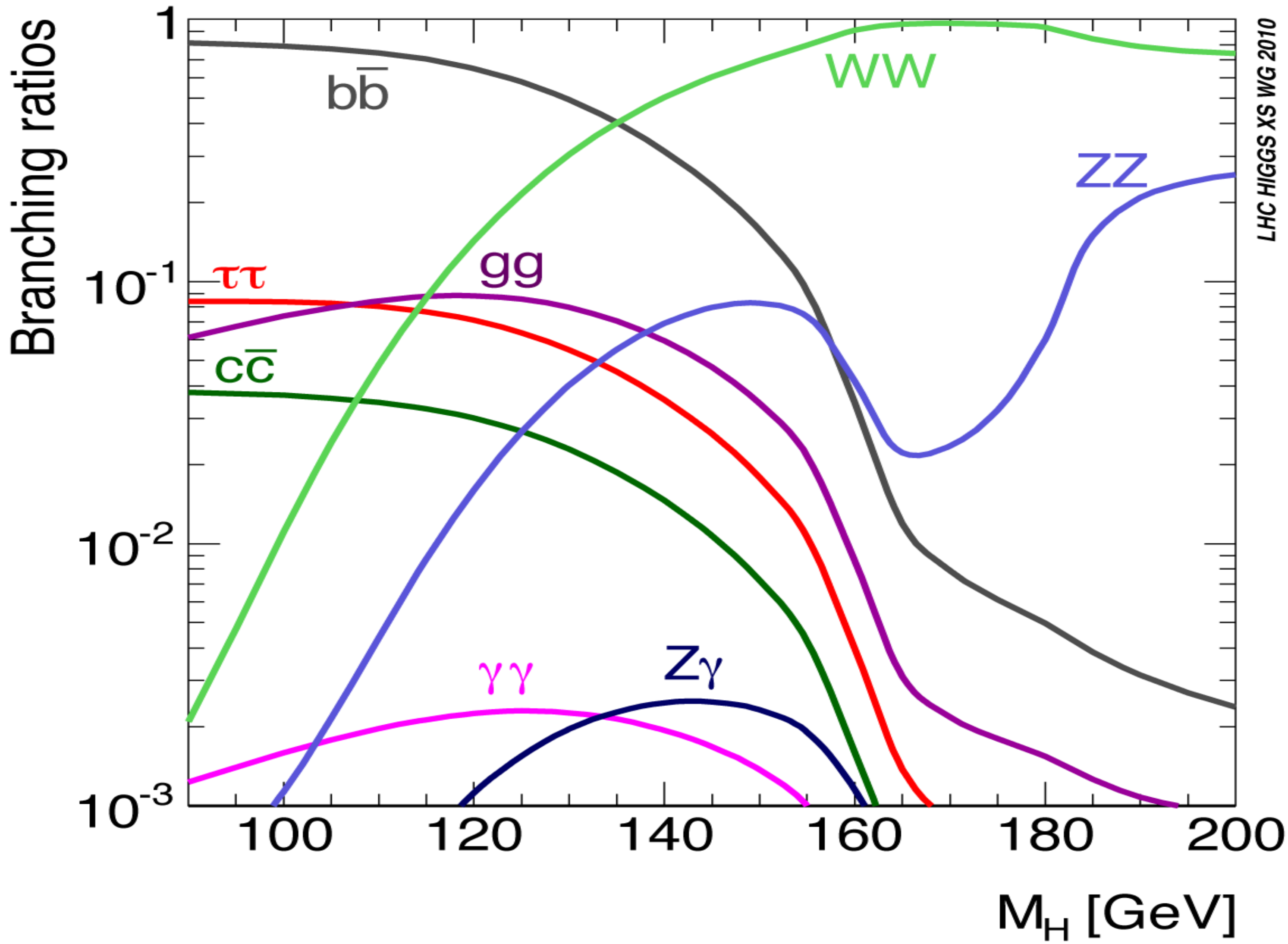

area of largest interest

Higgs couples to mass

$$\Gamma_{Hff} \sim m_f^2$$

$$\Gamma_{HVV} \sim m_V^4$$

# Higgs Decays (Tevatron/LHC)




Higgs boson couples to mass

$\Gamma_{Hff} \sim m_f^2$

$\Gamma_{HVV} \sim m_V^4$

Messy: many channels, many subsequent decays *etc. etc.*

– common: leptons/photons essential for any search

# *LHC Location*

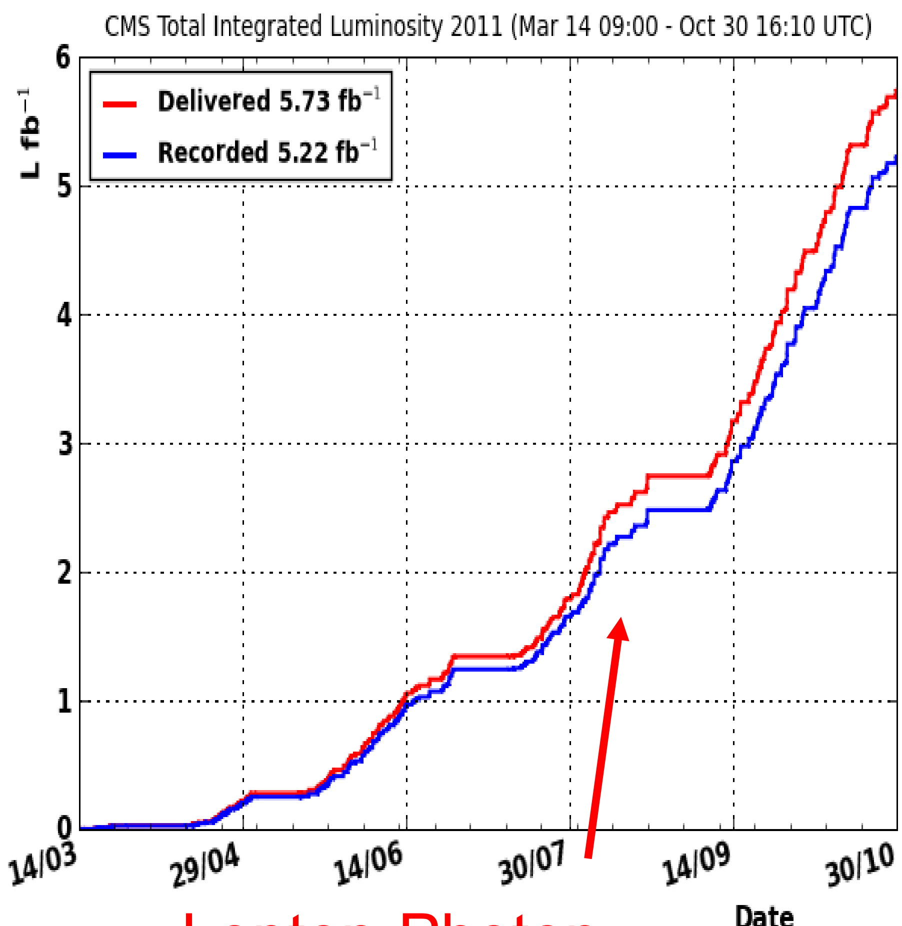
Proton-proton collisions at 7 TeV (up to 14 TeV)

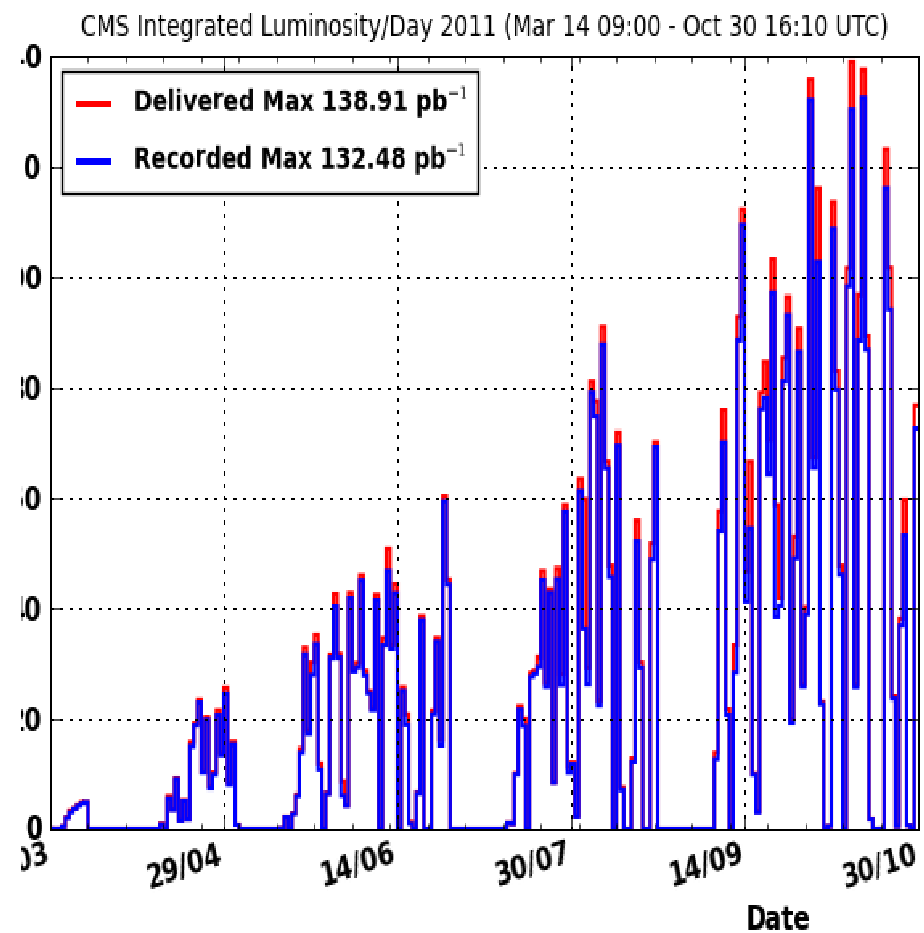
# *LHC Status*

Super short summary

- proceeding with caution
- no show stoppers so far
- nom. bunch intensity reached
- bunch trains commissioned easily
- no beam related quenches
- very clean beams
- machine parameters better then expected
- all goals reached
- 2011 smooth running
- 2012: 8 TeV? 25 ns or 50 ns?

# Delivered and Recorded Collisions



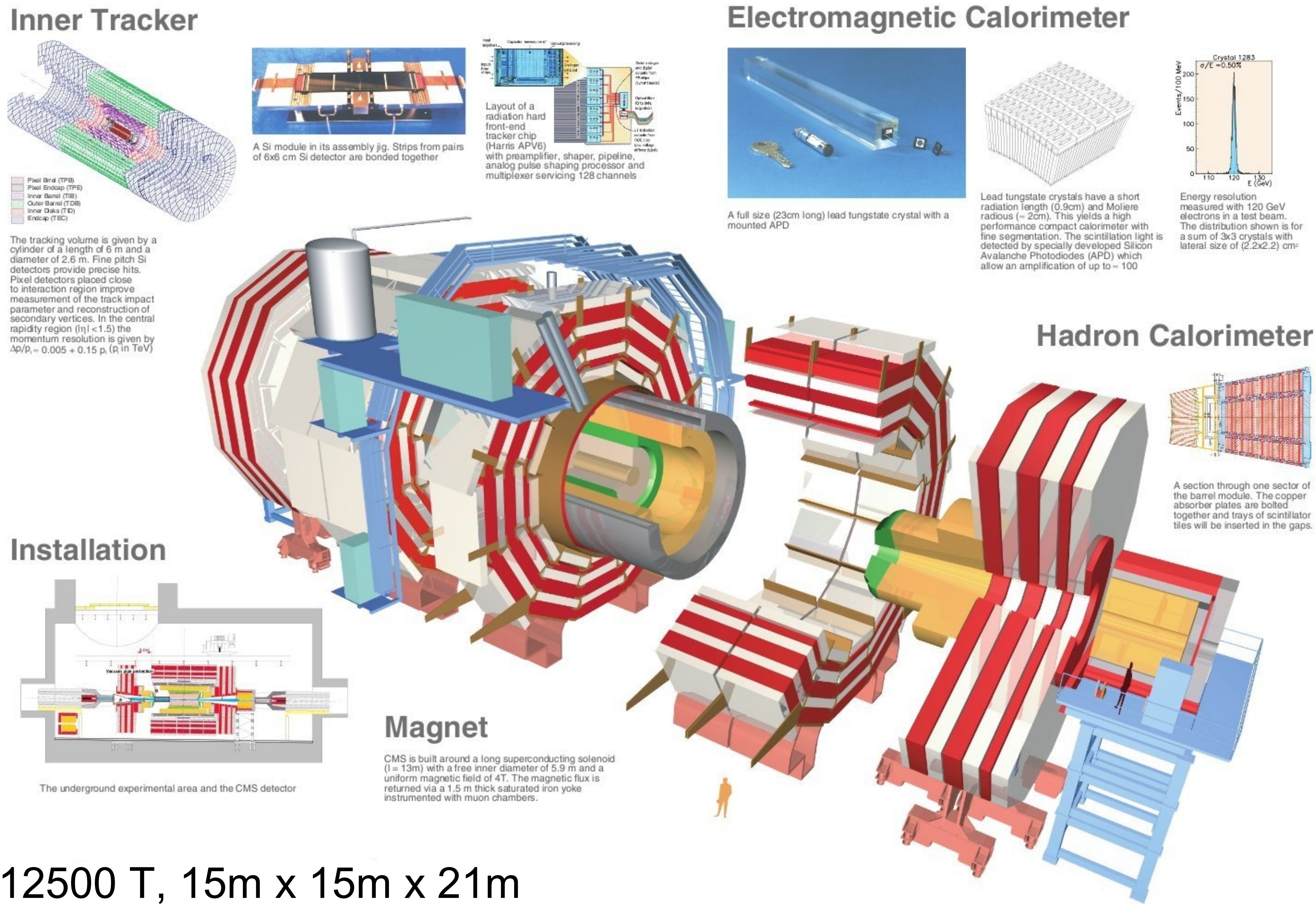




Lepton-Photon

LHC performs better than expected

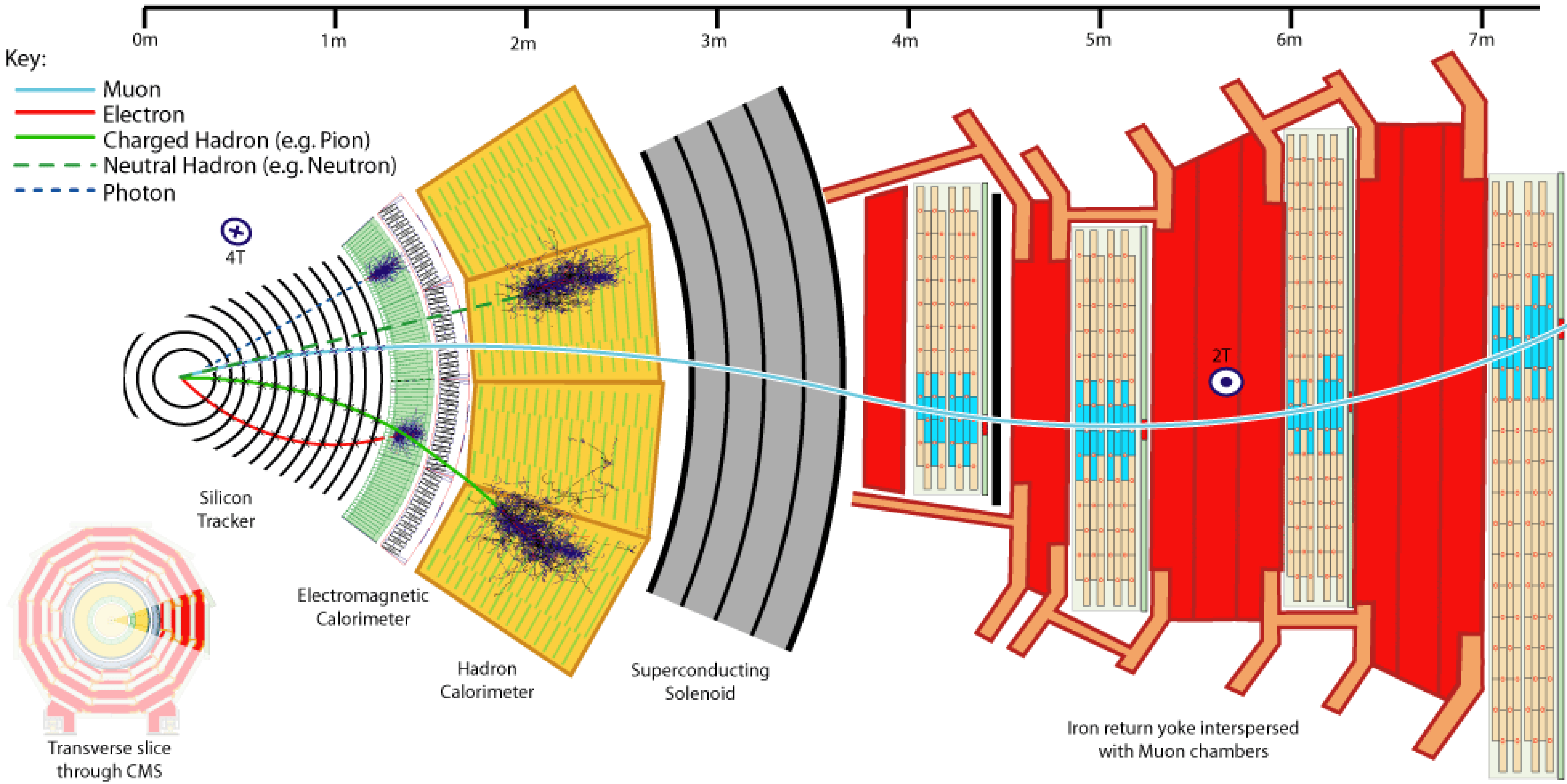
- summer conference based on 1.66/fb (for Lepton-Photon)
- 2011: 5.73/fb delivered of 5.22/fb recorded (91%)

# CMS Overview

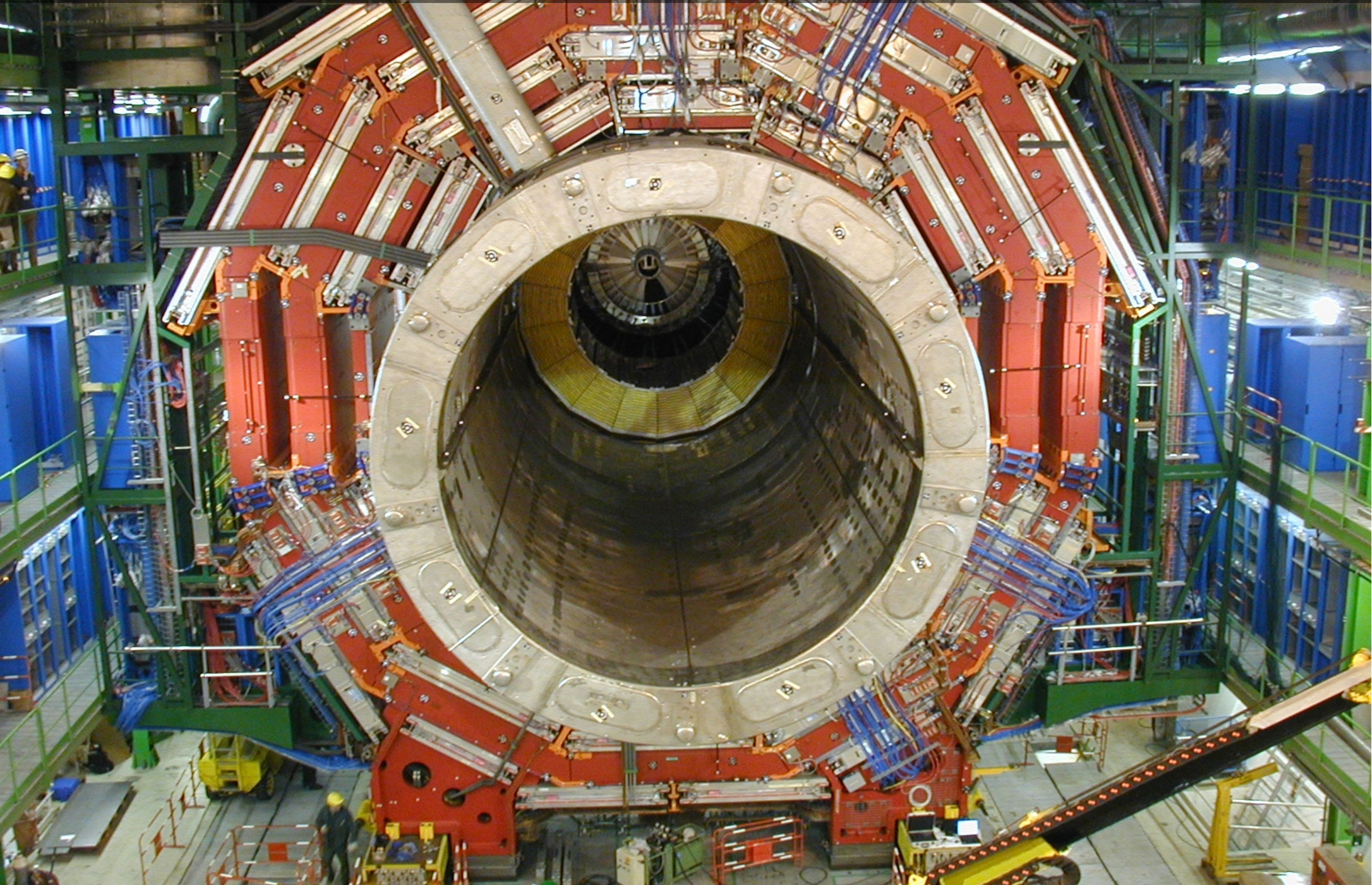



12500 T, 15m x 15m x 21m

# CMS Overview



# CMS Detector in the Cavern



*So far CMS*

*does not see the Higgs but ....*

*…. we could have seen it in some mass interval and thus we exclude those regions.*

*Let’s see what we have so far.*

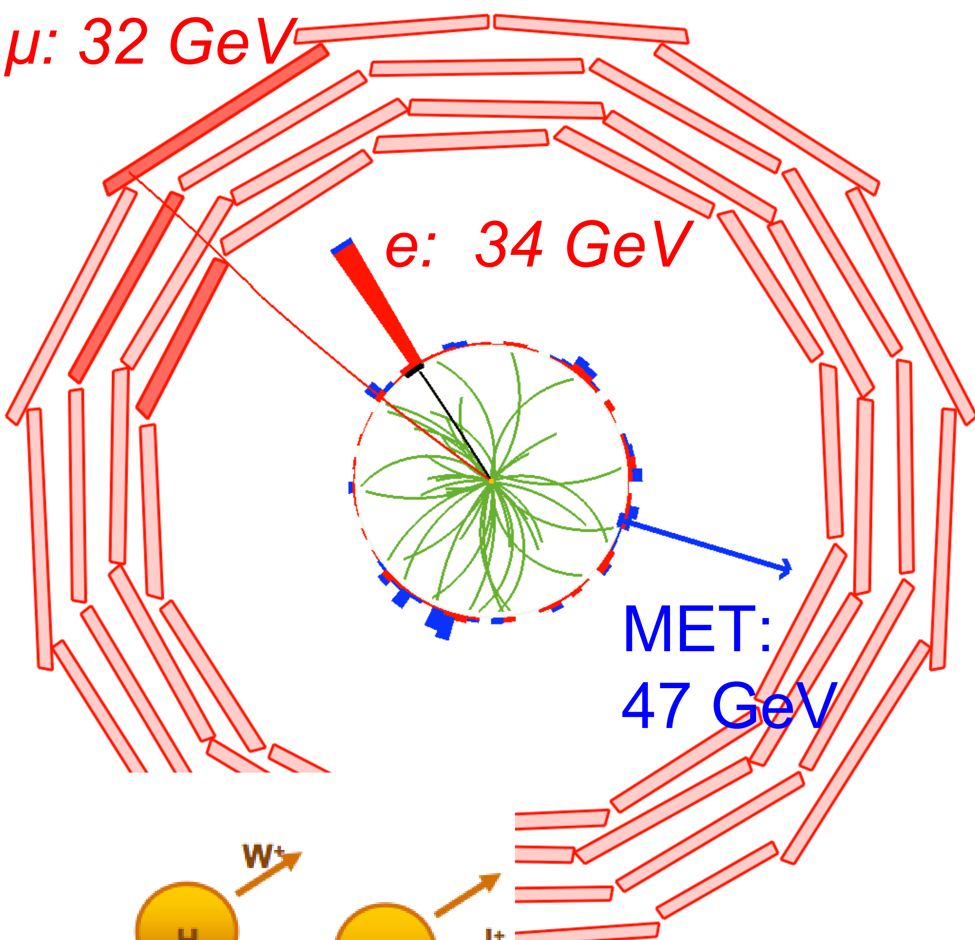
# *CMS Analysis on Full 2011 Data*

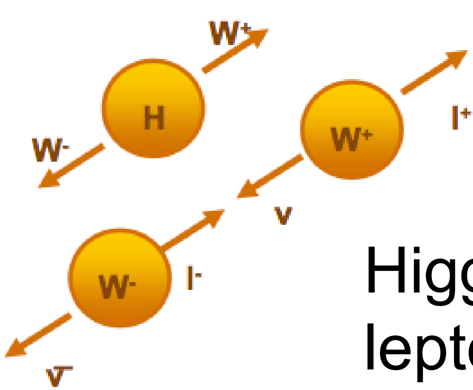
| Channel | Physics Analysis Summary | $m_H$ range ($GeV/c^2$) | Luminosity ($fb^{-1}$) | sub-channel | $m_H$ resolution |
|---|---|---|---|---|---|
| $H \to \gamma\gamma$ | HIG-11-030 | 110-150 | 4.7 | 4 | 1-3% |
| $H \to tt$ | HIG-11-029 | 110-145 | 4.6 | 9 | 15% |
| $H \to bb$ | HIG-11-031 | 110-135 | 4.7 | 5 | 10% |
| $H \to WW \to lnln$ | HIG-11-024 | 110-600 | 4.6 | 5 | 20% |
| $H \to ZZ \to 4l$ | HIG-11-025 | 110-600 | 4.7 | 3 | 1-2% |
| $H \to ZZ \to 2l2t$ | HIG-11-028 | 190-600 | 4.7 | 8 | 10-15% |
| $H \to ZZ \to 2l2\nu$ | HIG-11-026 | 250-600 | 4.6 | 2 | 7% |
| $H \to ZZ \to 2l2q$ | HIG-11-027 | 130-165, 200-600 | 4.6 | 6 | 3% |
| Combination | HIG-11-032 | | | | |

## The approximate main regions

- low mass region 110 GeV – 140 GeV
- intermediate mass region 140 GeV – 200 GeV
- high mass region 200 GeV – 600 GeV

# The Main Channel: $H \rightarrow WW \rightarrow 2l\ 2nu$




Higgs is scalar
leptons are close

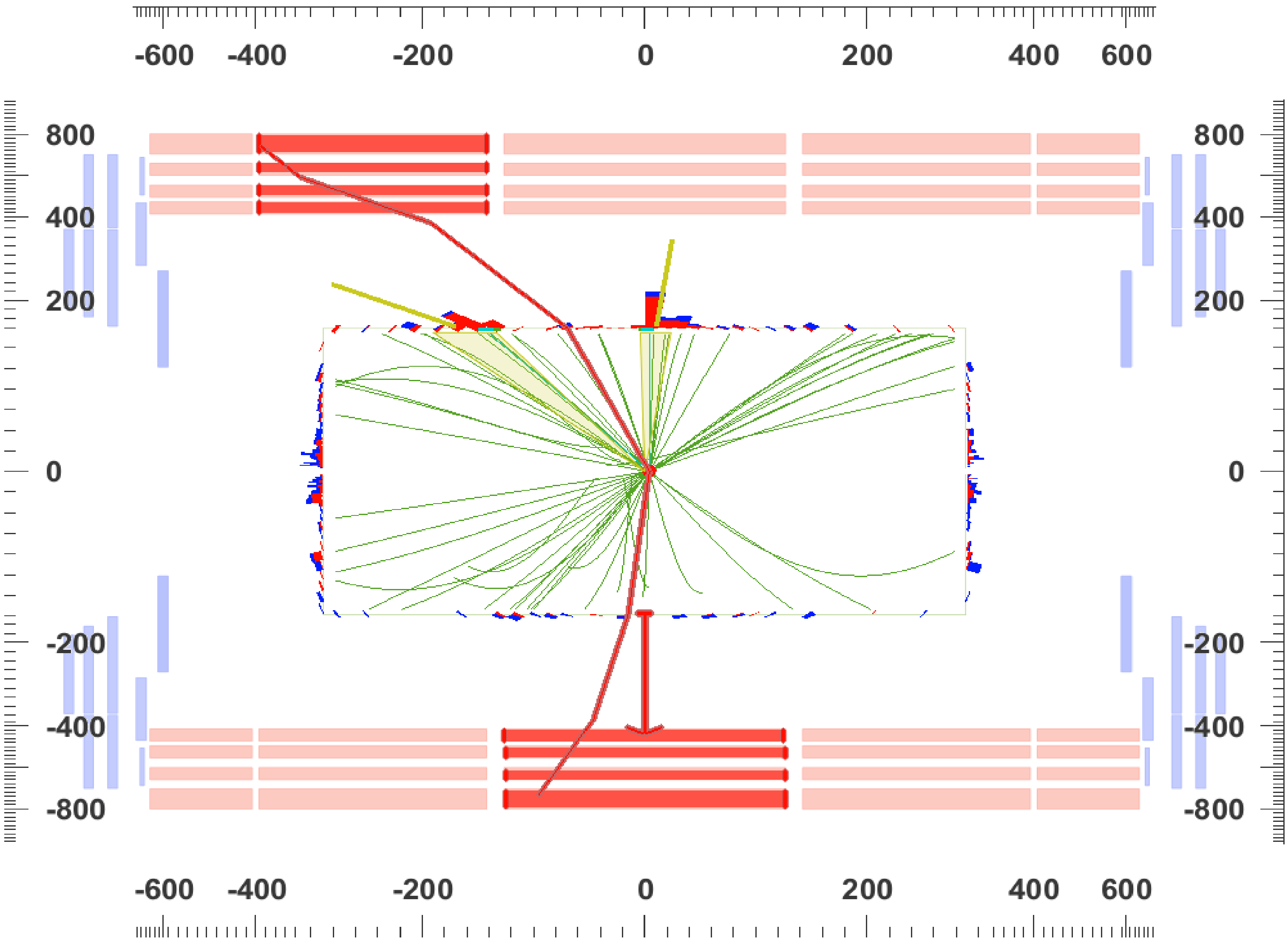
## Signature

- 2 opposite charged leptons (leptons only *e, μ)*
- 2 neutrinos == missing transverse energy (MET)
- no Higgs mass peak
- basically a counting analysis
- enhance sensitivity by subdividing into + (0,1,2) jets

## Analysis challenges

- understand backgrounds
- normalize to control regions
- backgrounds: WW, W+jets, top, DY

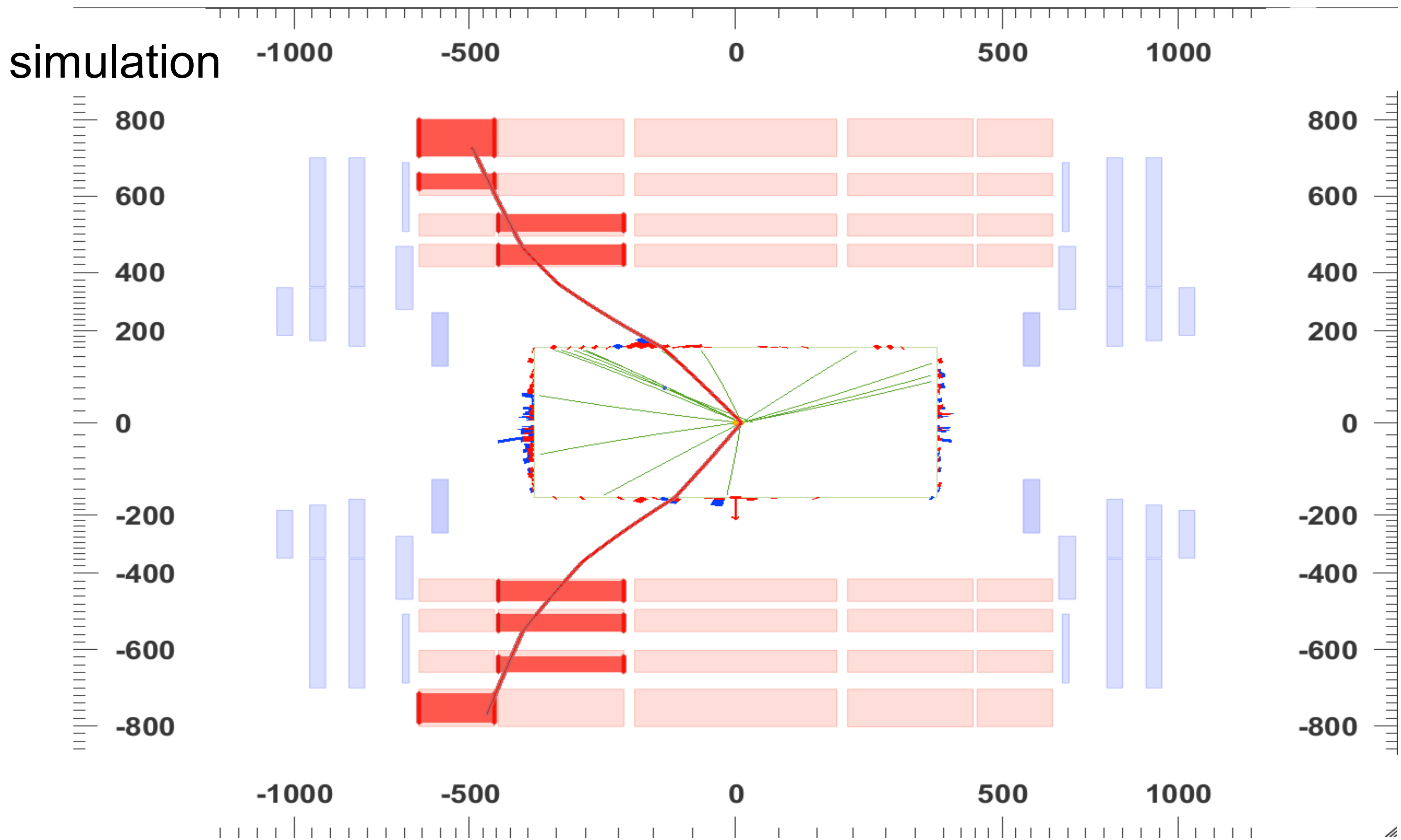
# Top Background to H → WW → 2l 2nu




## Signature and rejection strategy

- jets and jets from *b*-quarks: remove events with jets and veto *b*-jets

# *Drell-Yan Background to H → WW → 2l 2nu*




## Signature and rejection strategy

- small MET: remove events with small MET

# *Non Resonant WW Background to H → WW → 2l 2nu*

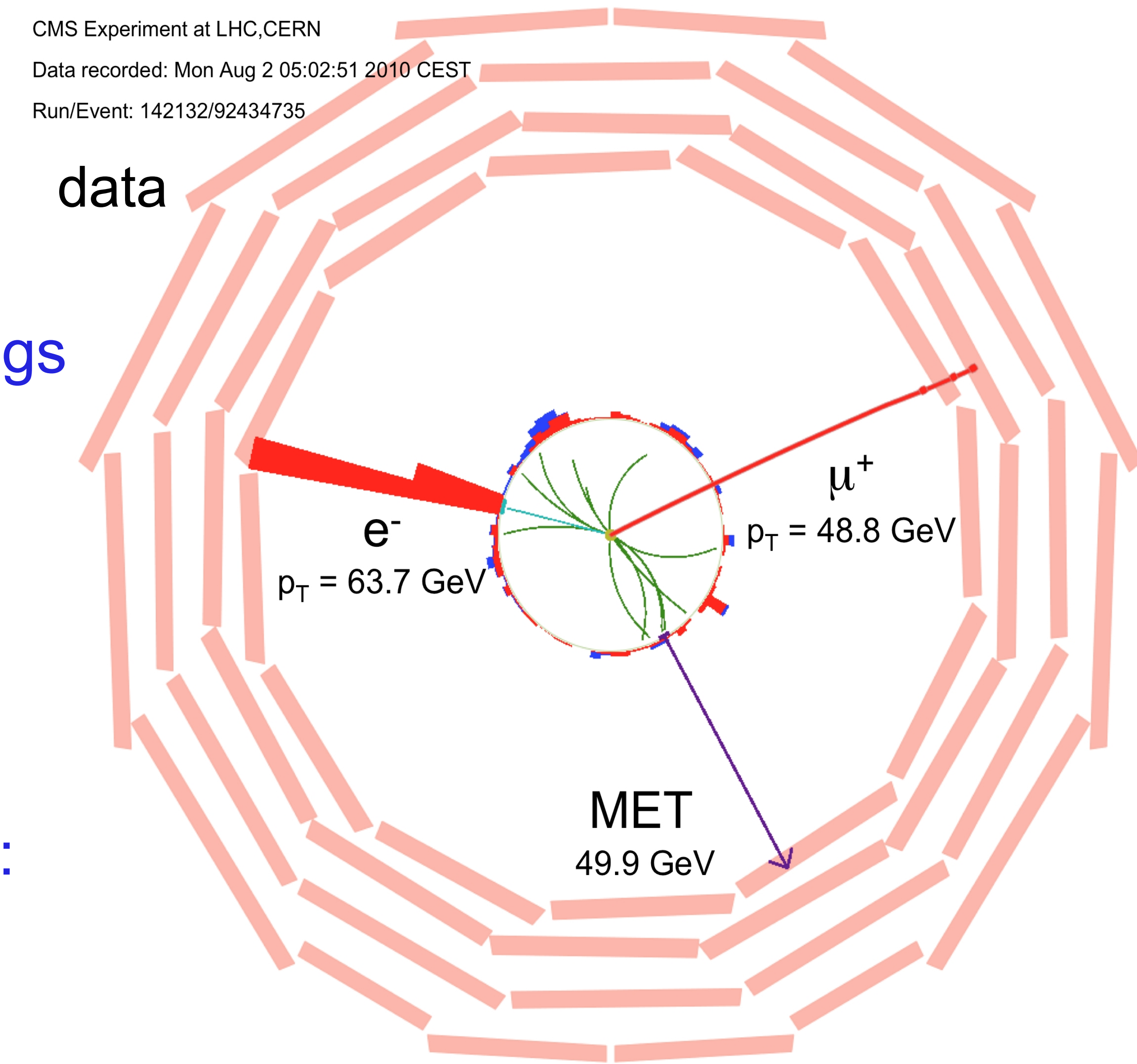
## Signature

- irreducible
- slightly different kinematics than Higgs decay

## Strategy

- use kinematics depending on the Higgs mass value
- variables of interest:

$\Delta\Phi_{ll}$ and $m_{ll}$



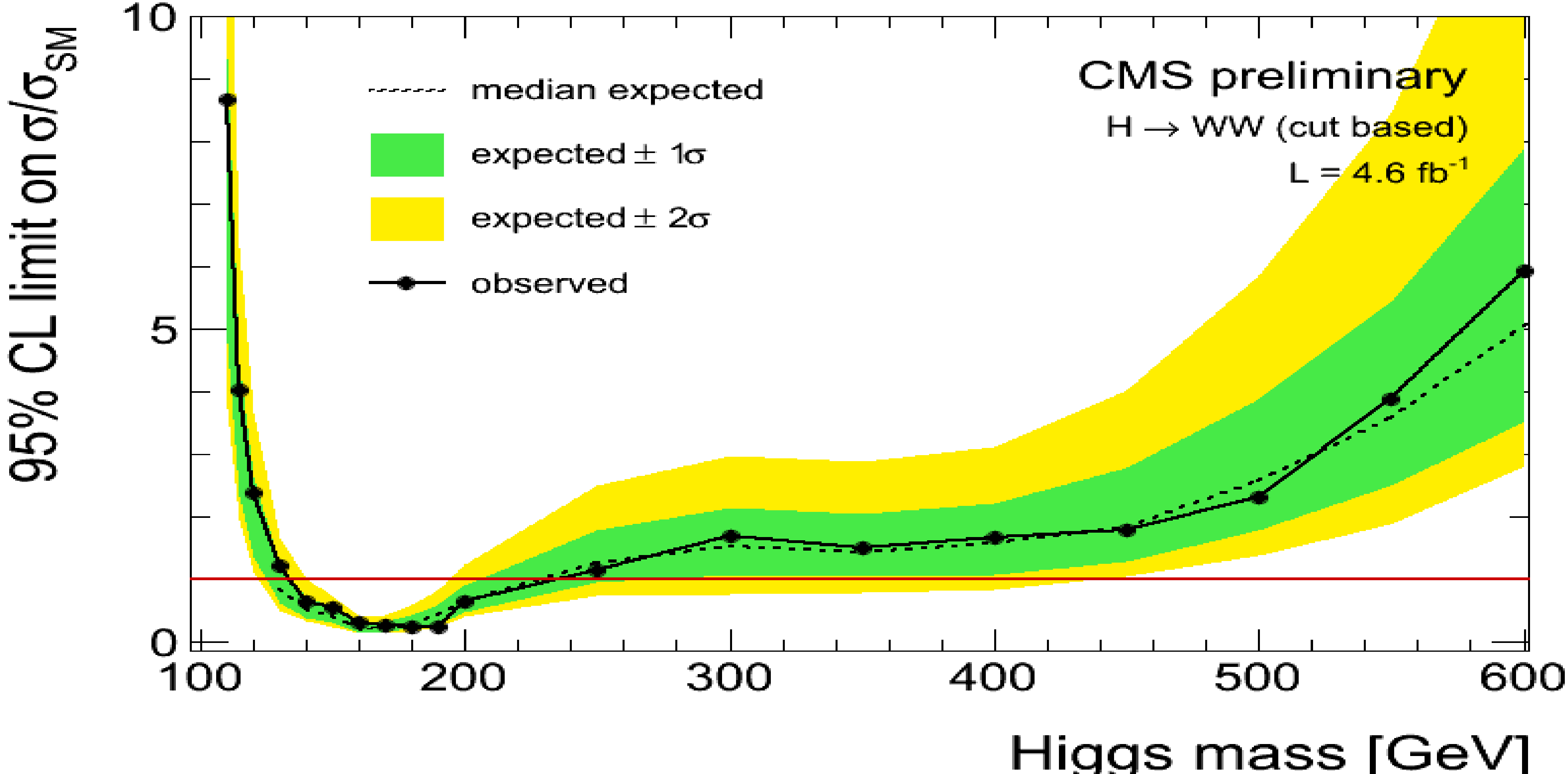
# Counting Analysis .... Numbers

| mH | DY→ll | ttbar+tW | W+jets | WZ+ZZ+Wγ | WW | all BG | H→WW | data |
|---|---|---|---|---|---|---|---|---|
| 120 | 8.8±9.2 | 6.7±1.0 | 14.7±4.7 | 6.1±1.5 | 100.3±7.2 | 136.7±12.7 | 15.7±0.8 | 136 |
| 130 | 13.7±7.8 | 10.6±1.6 | 17.6±5.5 | 7.4±1.6 | 142.2±10.0 | 191.5±14.0 | 45.2±2.1 | 193 |
| 160 | 3.4±3.4 | 10.5±1.4 | 3.0±1.5 | 2.2±0.4 | 82.6±5.4 | 101.7±6.8 | 122.9±5.6 | 111 |
| 200 | 2.7±3.7 | 23.3±3.1 | 3.4±1.5 | 3.2±0.3 | 108.2±4.5 | 140.8±6.8 | 48.8±2.2 | 159 |
| 250 | 0.3±0.6 | 36.2±4.8 | 6.7±2.1 | 5.7±0.7 | 101.8±4.5 | 150.8±6.9 | 23.5±1.1 | 152 |
| 300 | 0.7±1.9 | 41.6±5.4 | 6.5±2.1 | 7.0±0.7 | 87.5±3.9 | 143.3±7.2 | 20.2±0.9 | 147 |
| 400 | 0.2±0.2 | 35.9±4.7 | 5.5±1.8 | 9.3±1.1 | 59.8±2.7 | 110.8±5.8 | 17.5±0.8 | 109 |

## Considerations

- key columns here
- large systematic uncertainties on various backgrounds require 're-tuning' of analysis for optimal result: DY background, W+jets ....
- need to be careful in the process to avoid biases

# Conservative Cut and Count Analysis

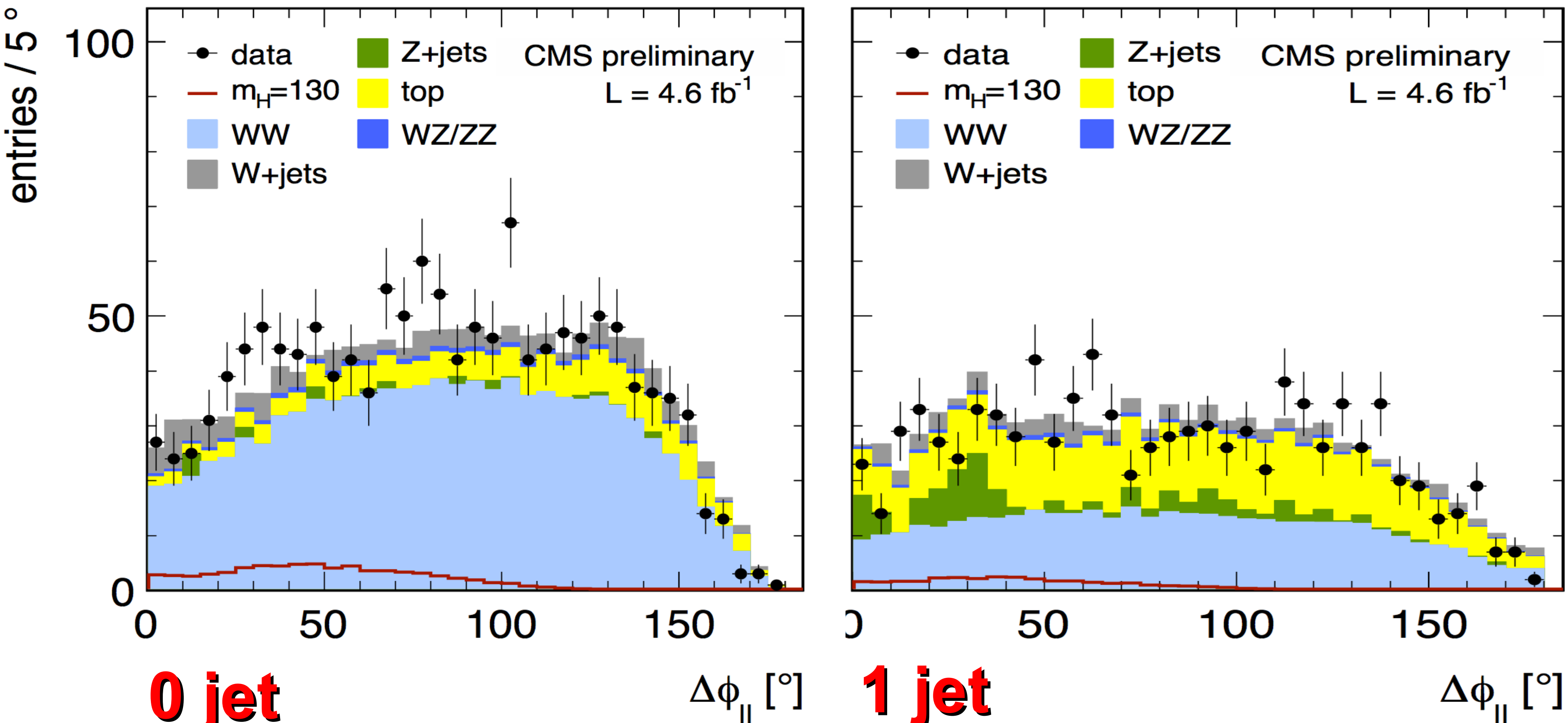



## Observations

exclude Higgs masses from 132 GeV < $m_H$ < 238 GeV

expected exclusion 129 GeV < $m_H$ < 236 GeV

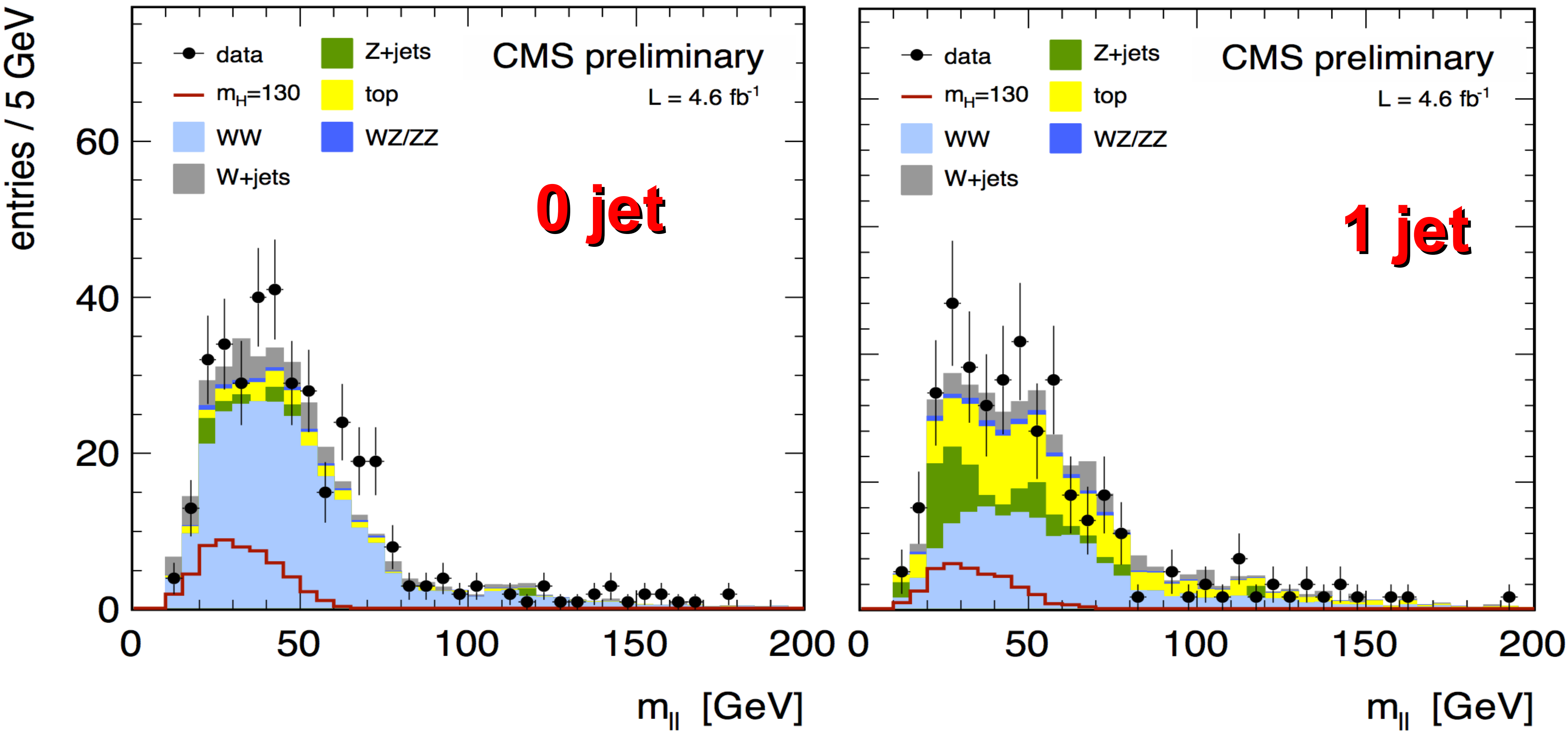
# Kinematic Variables: $\Delta\Phi_{ll}$




## Higgs at 130 GeV: signature

- small opening angle between leptons in 0 and 1 jet selection

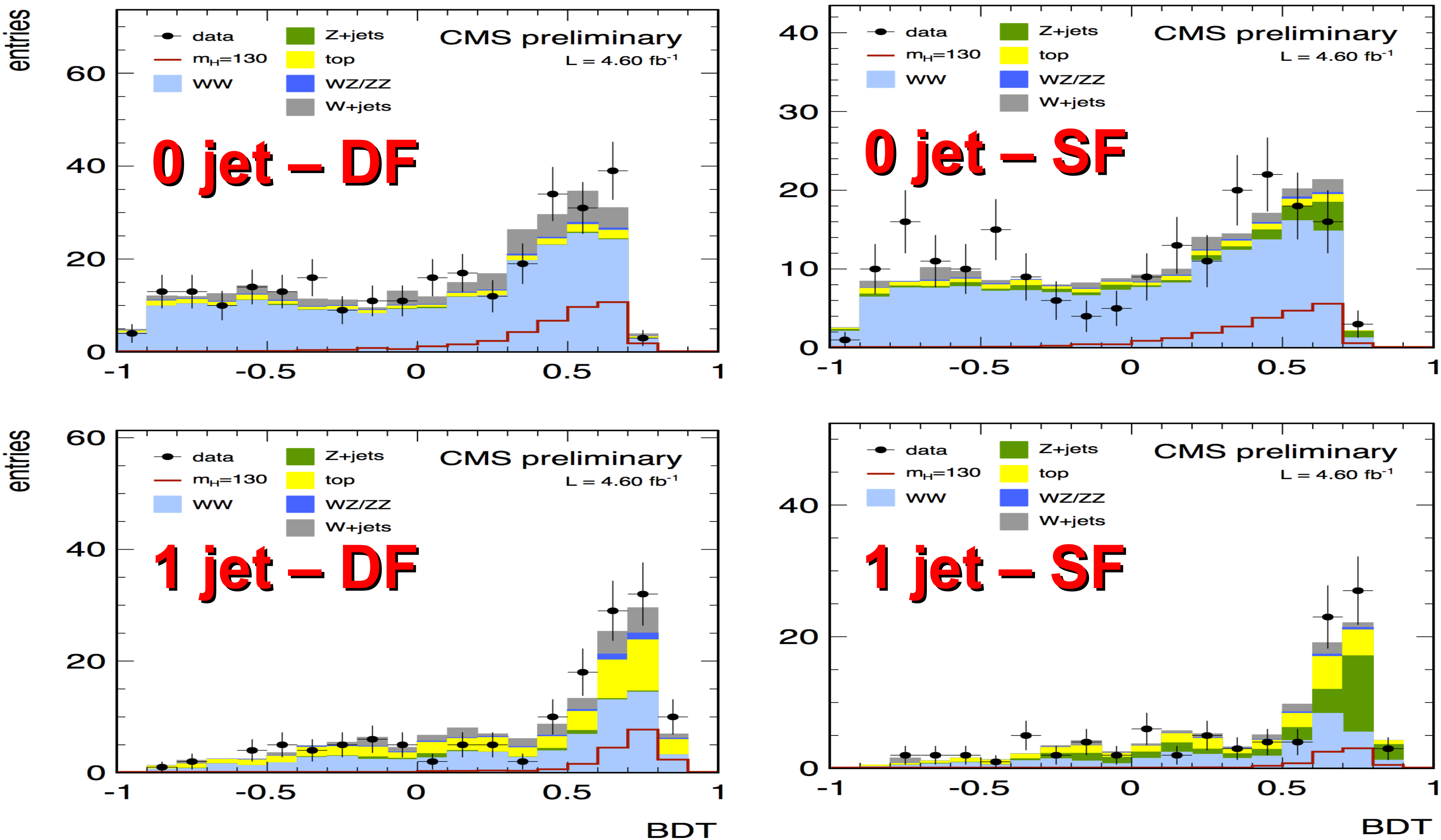
# *Kinematic Variables: $m_{ll}$*




## Higgs at 130 GeV: signature

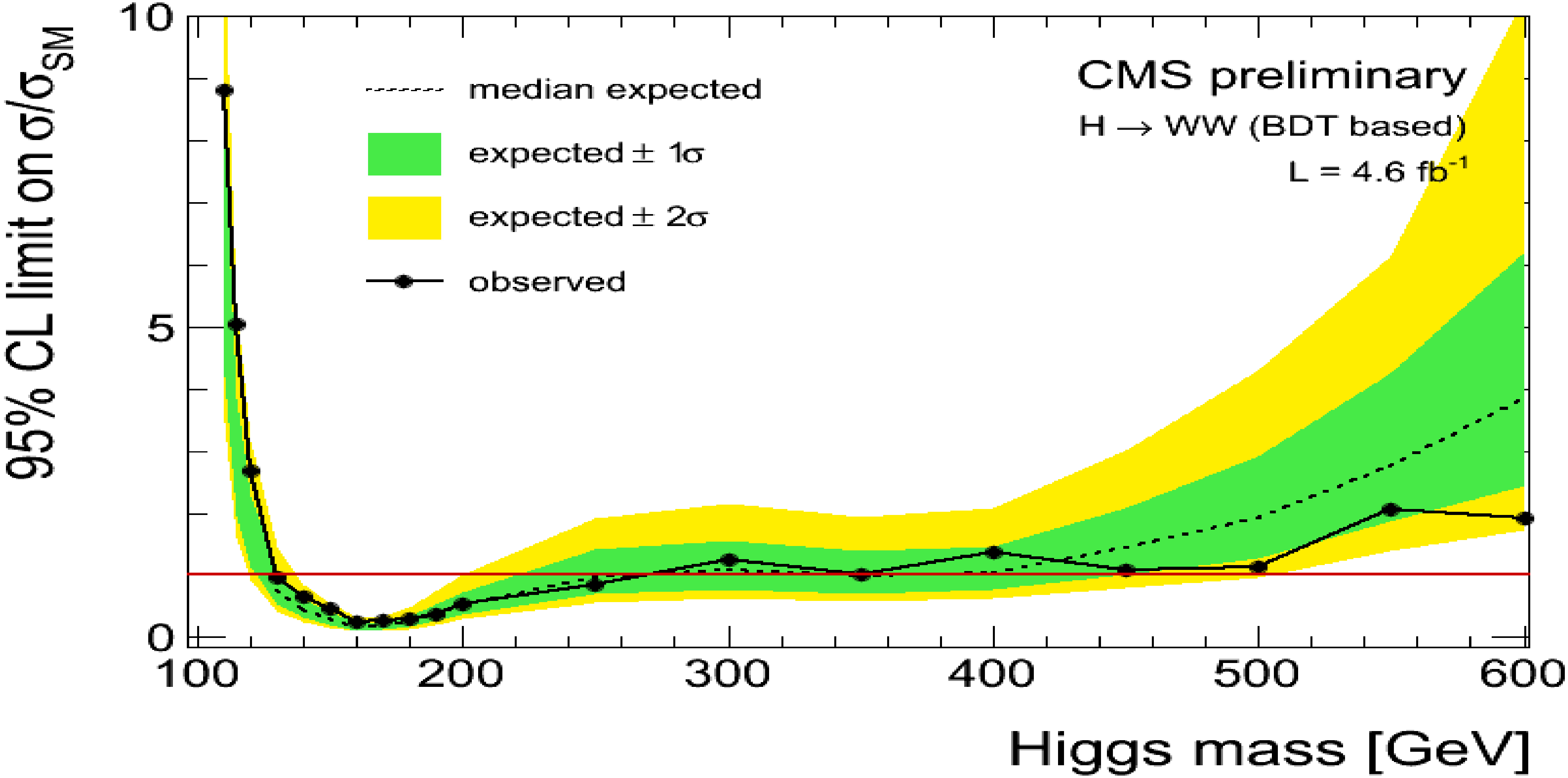
- small dilepton mass in 0 and 1 jet selection

# *Multi Variate Analysis Output (BDT)*




Monte Carlo prediction agrees with data

# *Full MVA Shape Analysis*

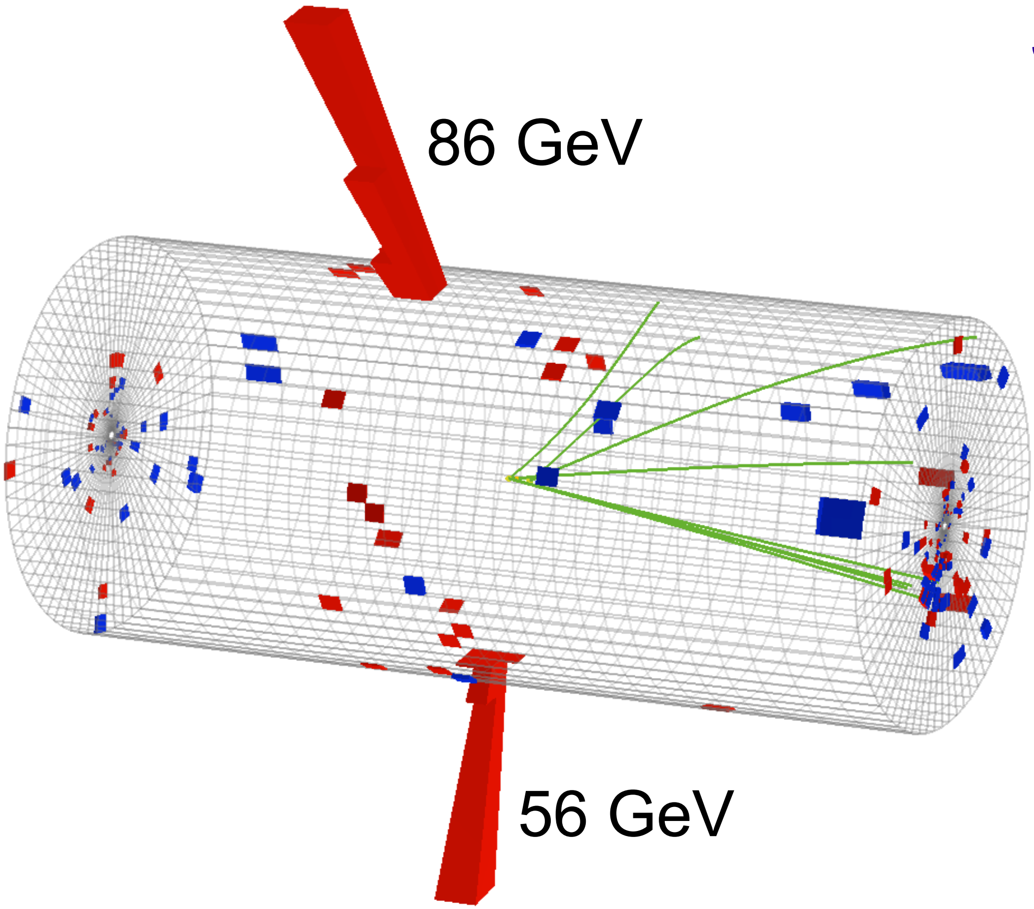



## Observations

exclude Higgs masses from 129 GeV < $m_H$ < 270 GeV

expected exclusion 127 GeV < $m_H$ < 270 GeV

# *Low Mass Specialist:* $H \rightarrow \gamma\gamma$



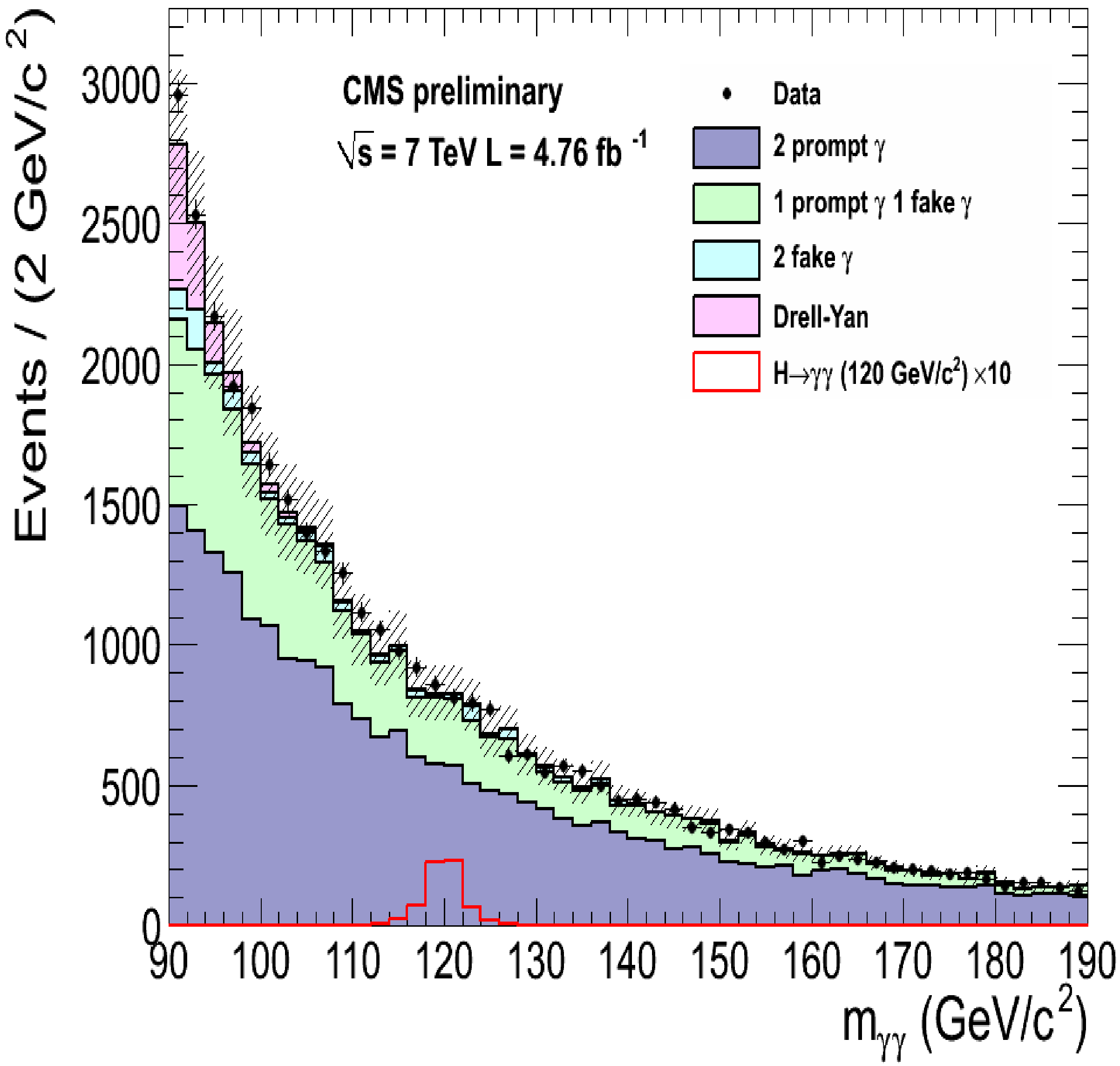

## Signature and background

- two high momentum photons
- low mass Higgs narrow
- two photon resolution excellent
- looking for narrow peak
- large irreducible background from direct two photons
- smaller fake photon background

## Key analysis features

- energy resolution is almost everything: calibrate and optimize
- rejection of fake photons and optimized use of kinematics

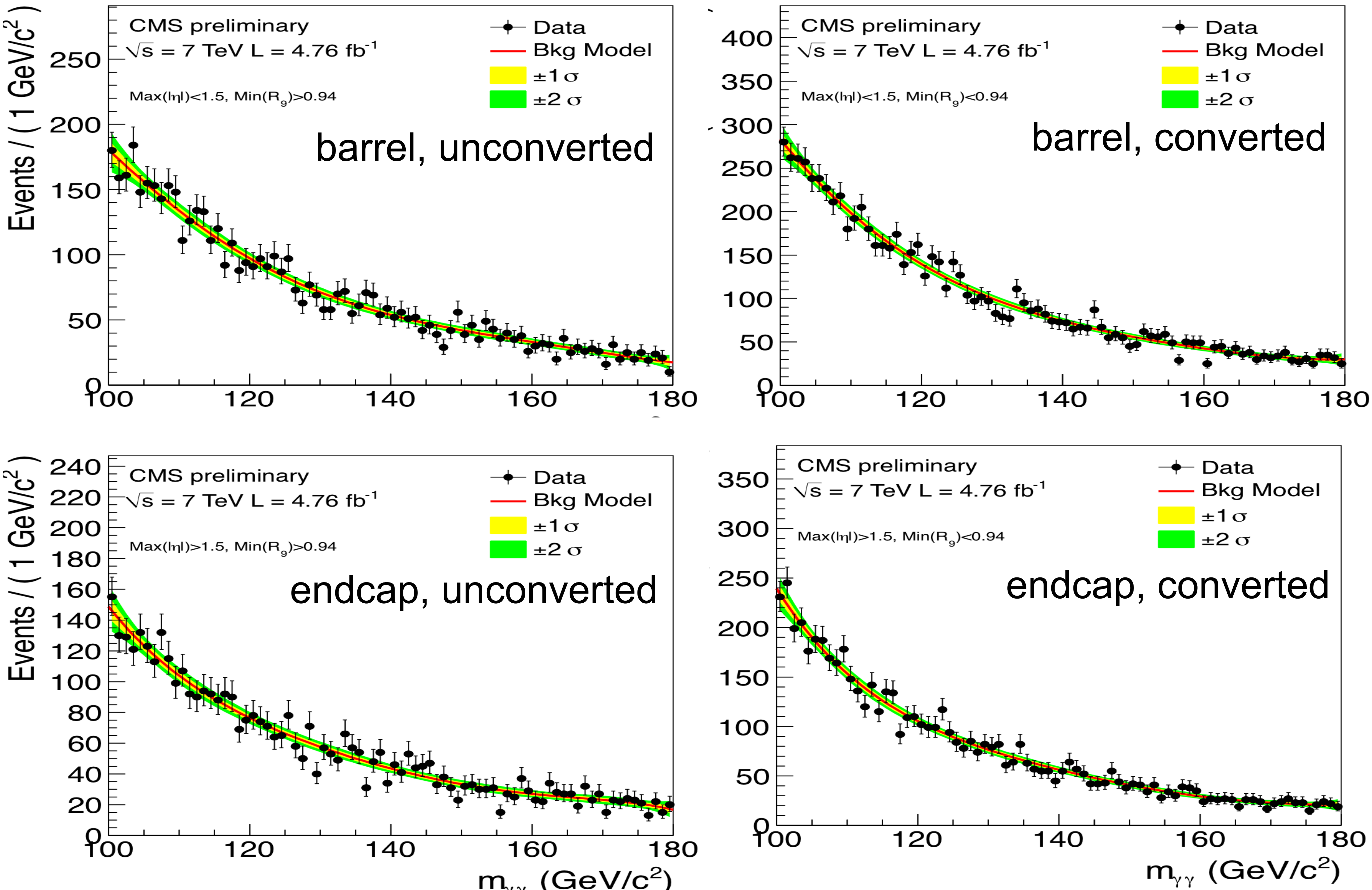
# Low Mass Specialist: $H \rightarrow \gamma\gamma$



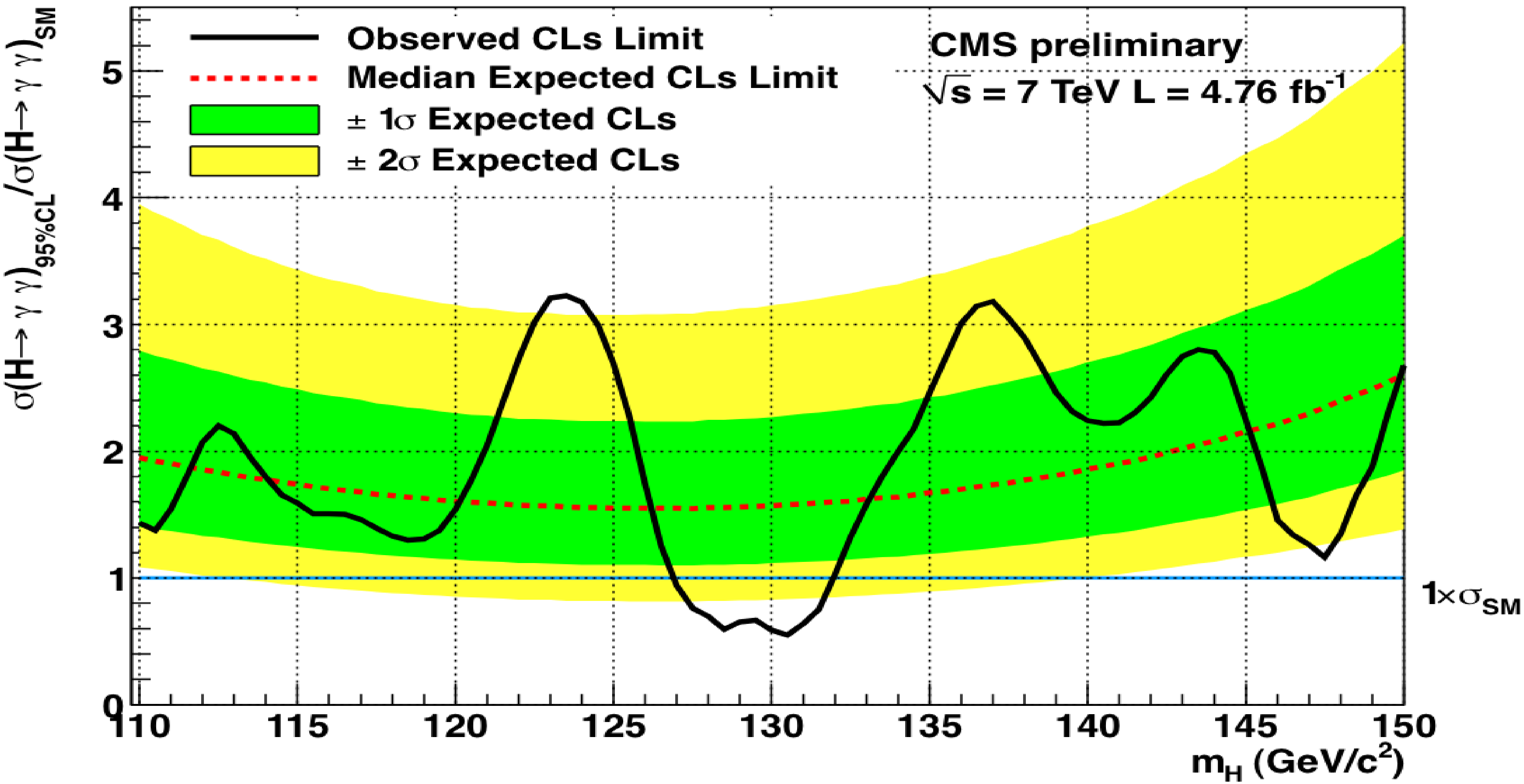

## Data MC comparison

- only used for illustration
- general agreement
- fake/real photons about: 30%/70%
- perform analysis in optimized 4 categories
- idea: separate well measured from less well measured photons
- assume smooth background shape: no MC needed for mass fit

# Low Mass Specialist: $H \rightarrow \gamma\gamma$

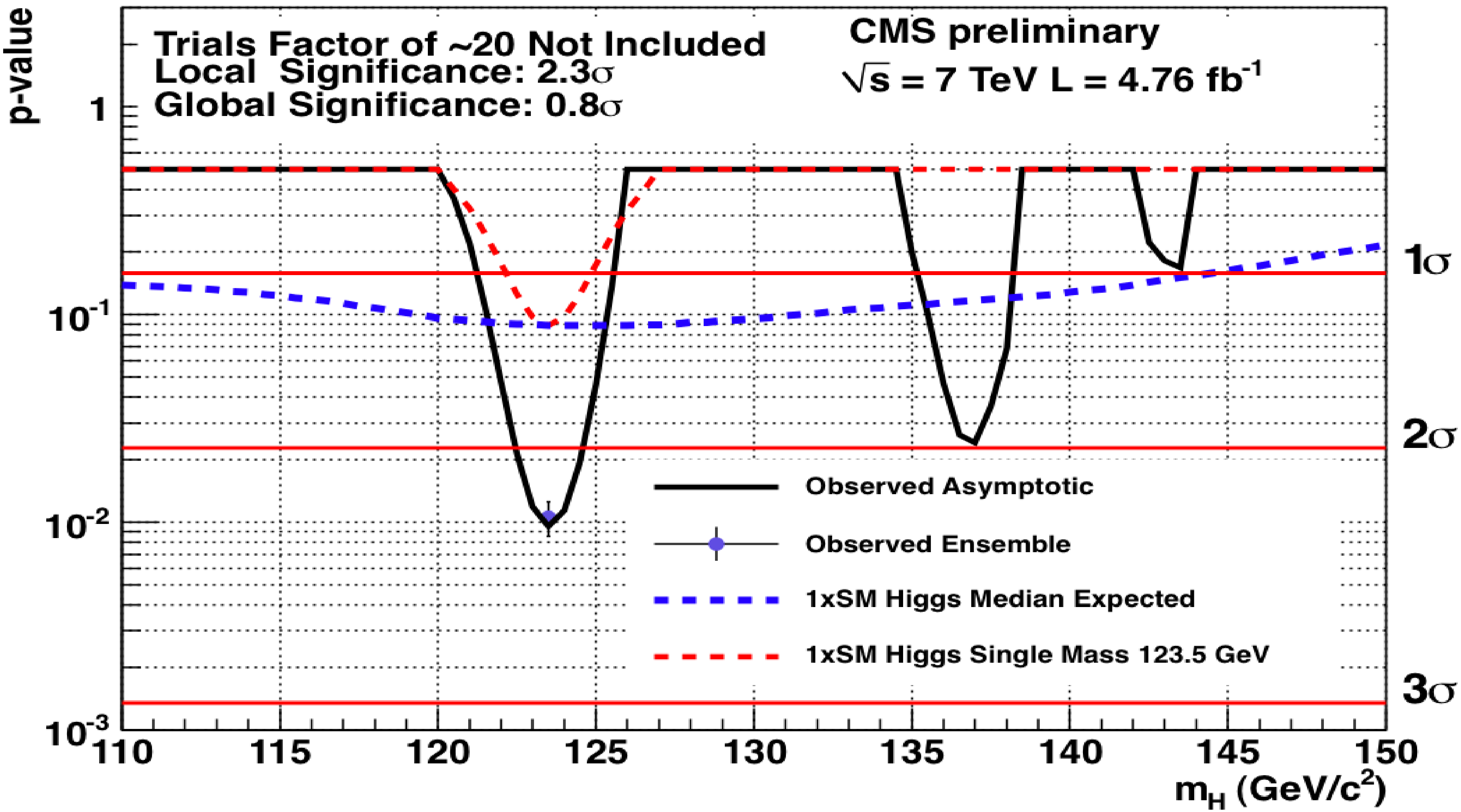


# *Low Mass Specialist:* $H \to \gamma\gamma$



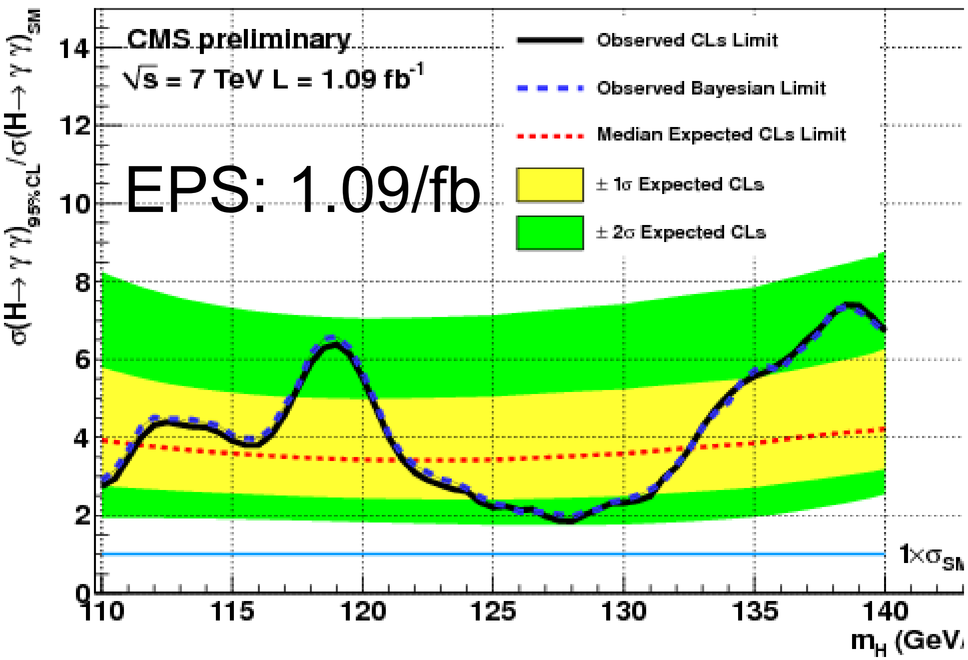

- most sensitive channel below 120 GeV, exclusion below 2
- no significant excess: structure at 125 GeV ~ 2.3 std (local)
- including LEE over full mass range *p*-value ~ 0.8 std

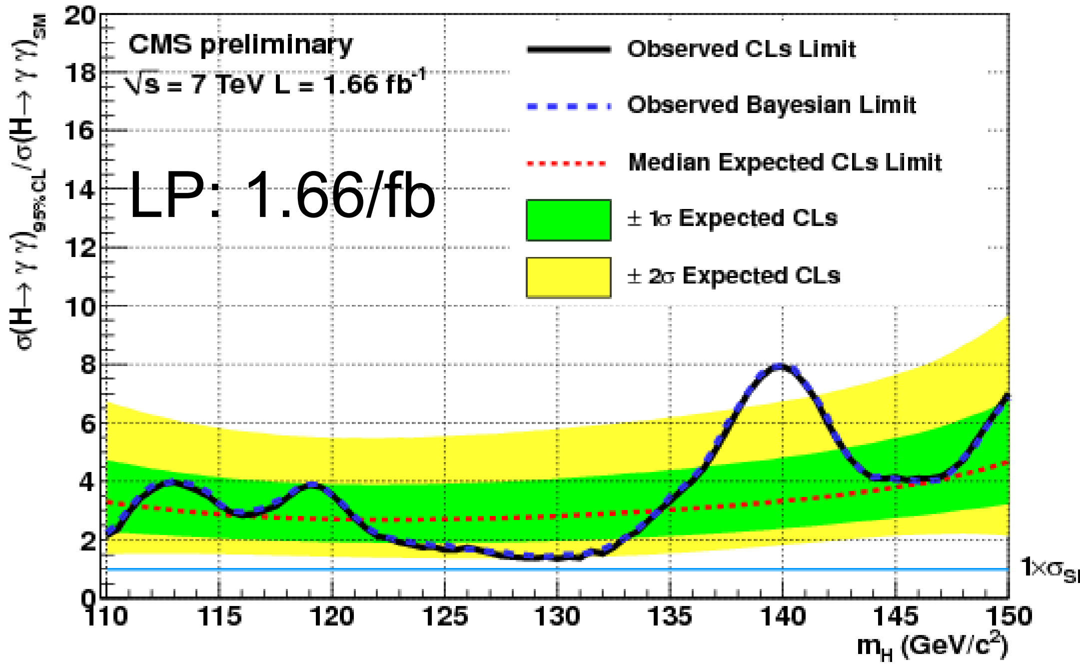
# *Low Mass Specialist: H → γγ*



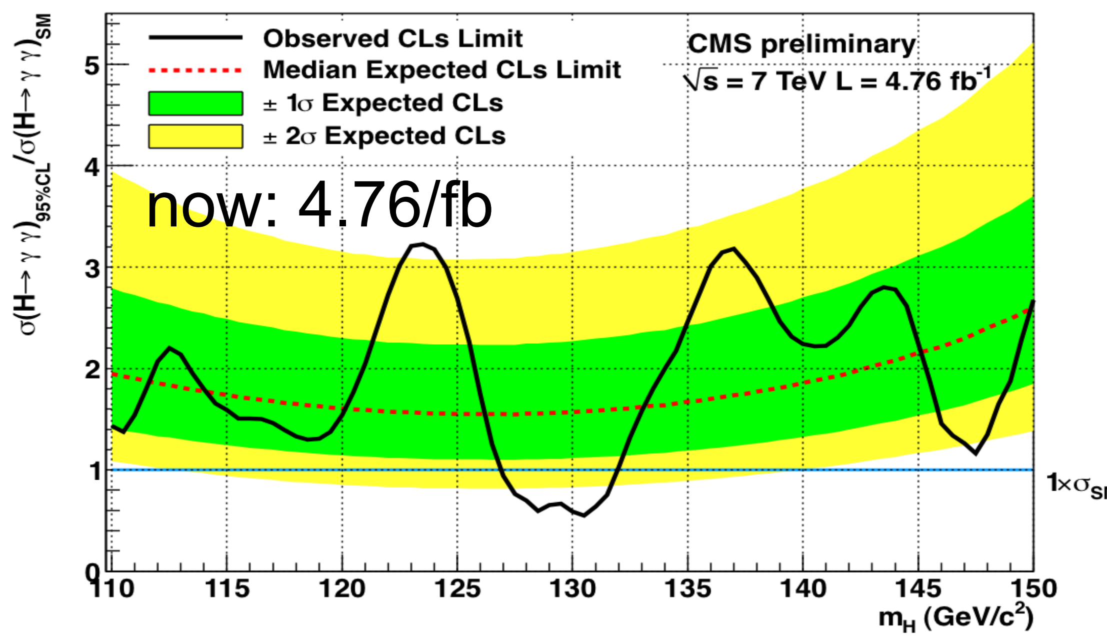

- signal strength is about consistent with the SM – a little large – as we are starting to become sensitive to it

# CMS History: $H \rightarrow \gamma\gamma$

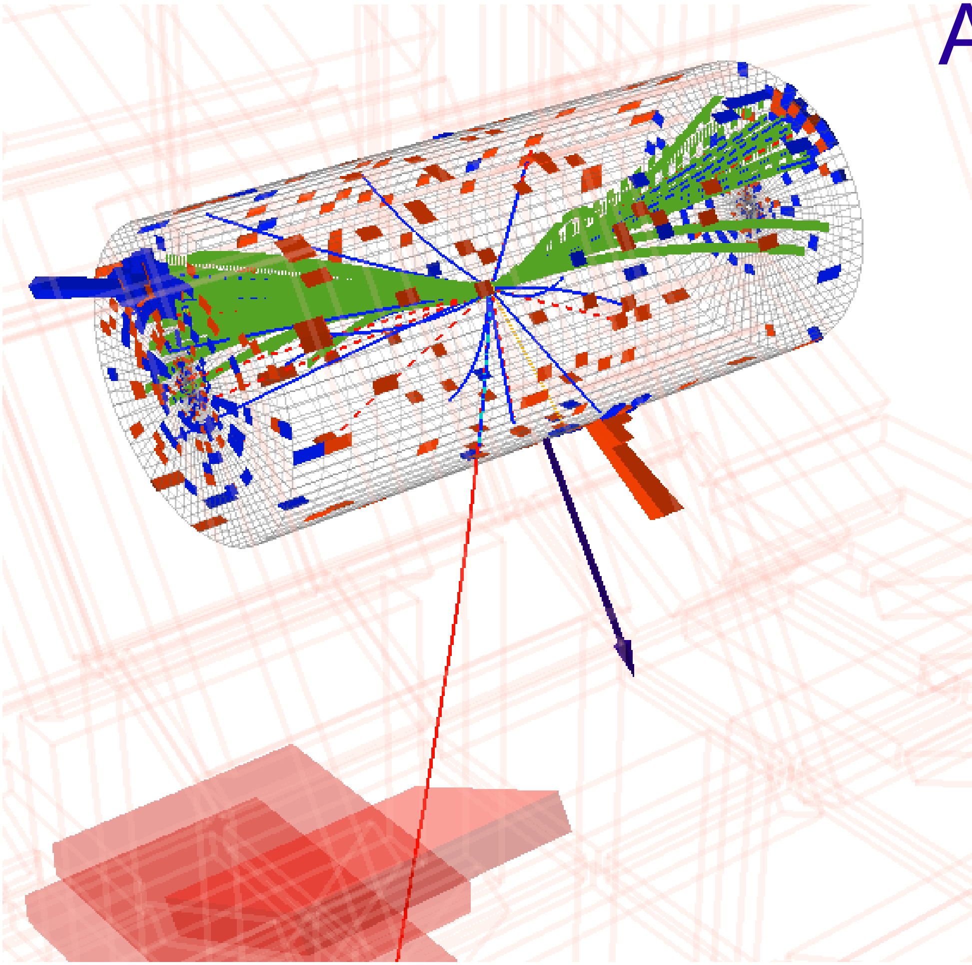



- EPS (1.09/fb) LP (1.66/fb) Dec 19 (4.76/fb)
- ‘peaks’ come and go
- of course now we are getting into interesting territory

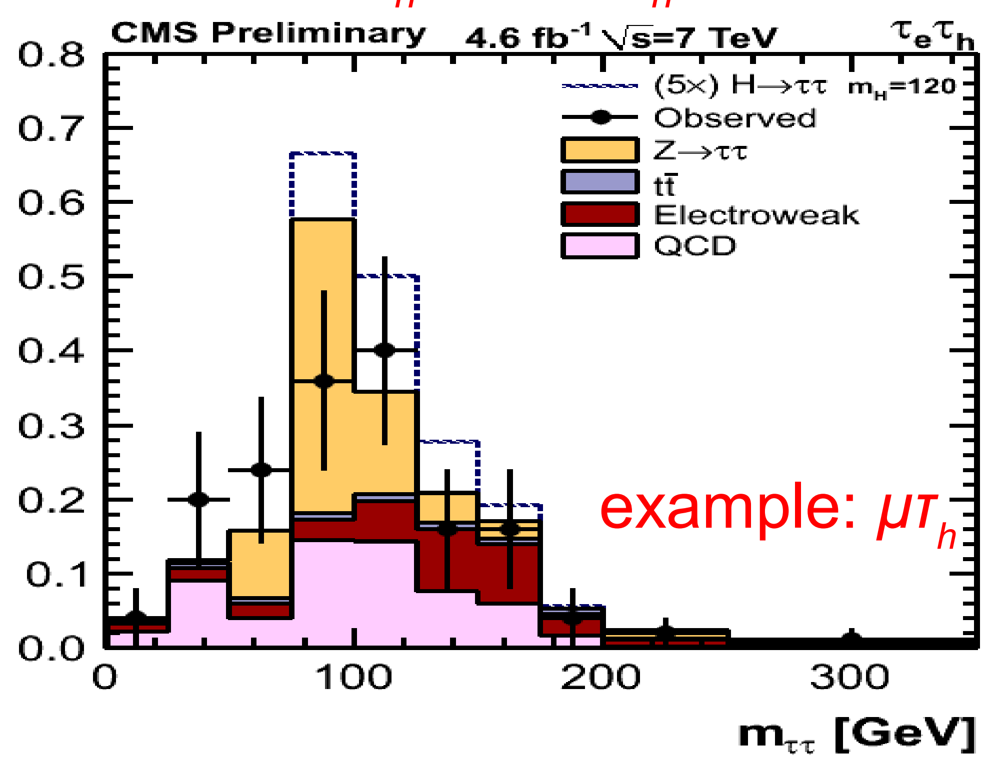


# *Low Mass Special: H → ττ*



## Analysis telegram

- 3 categories: incl. / VBF / boosted
- VBF style most sensitive
- require 2 taus (at least one decaying leptonically)
  - *e-μ, μ-$\tau_h$* and *e-$\tau_h$*

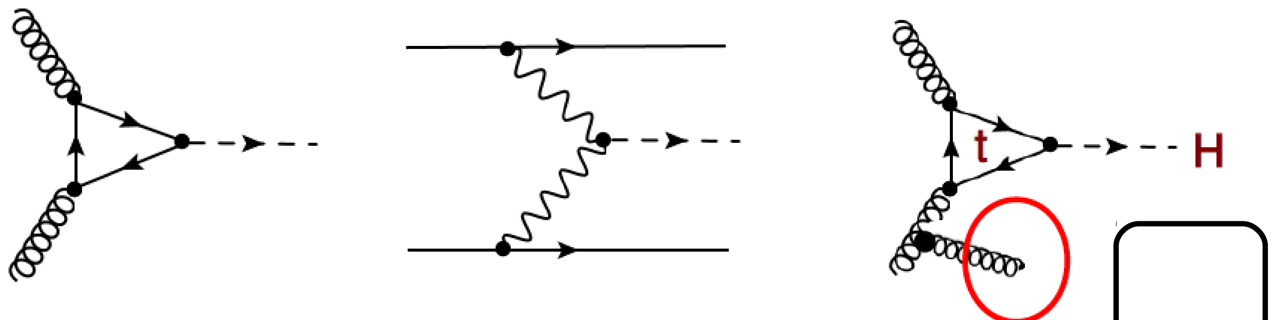



## Backgrounds

- top, EWK, DY (irreducible)

# *Search Modes in Pictures: H → ττ*

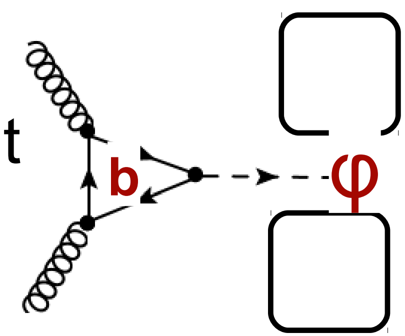
## Standard Model



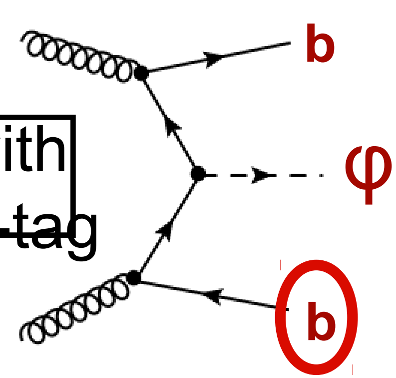

Inclusive VBF Boosted

## Minimal SuperSymmetric Model

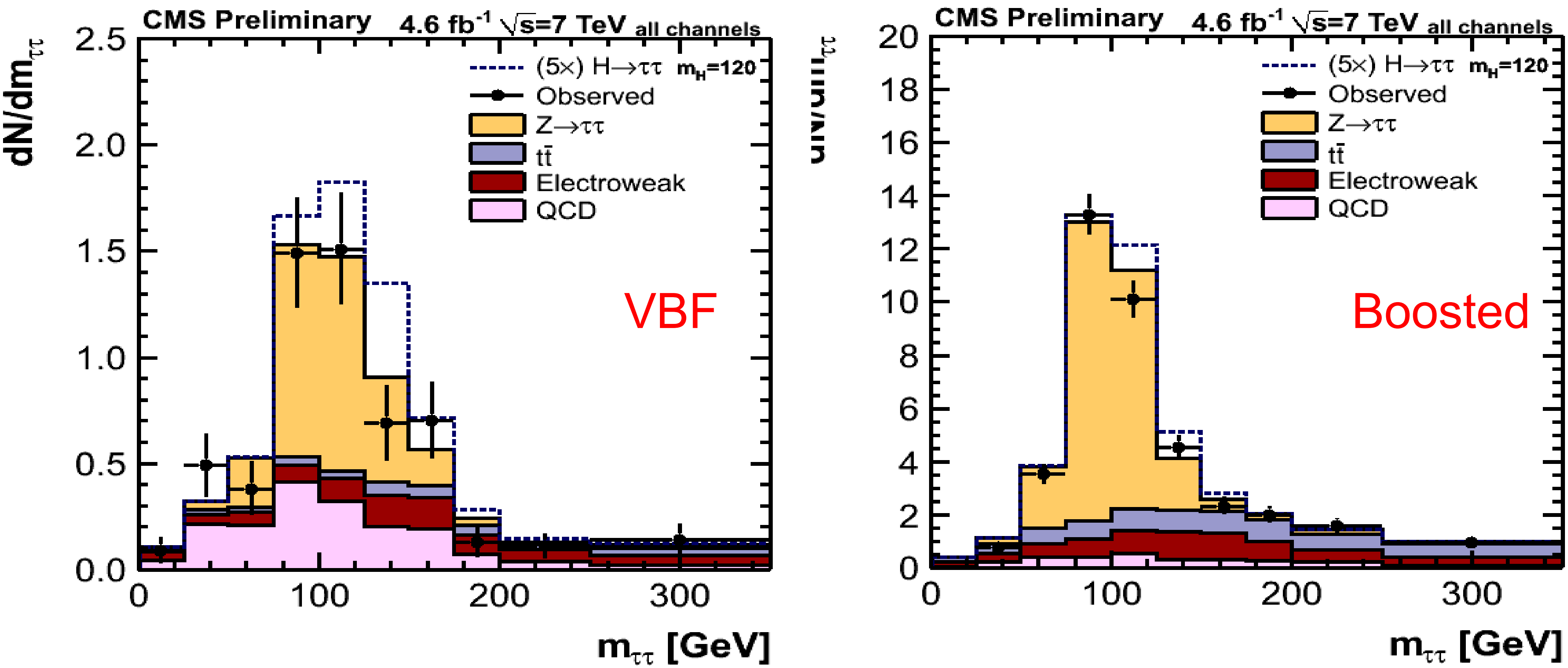
without b-tag




with b-tag



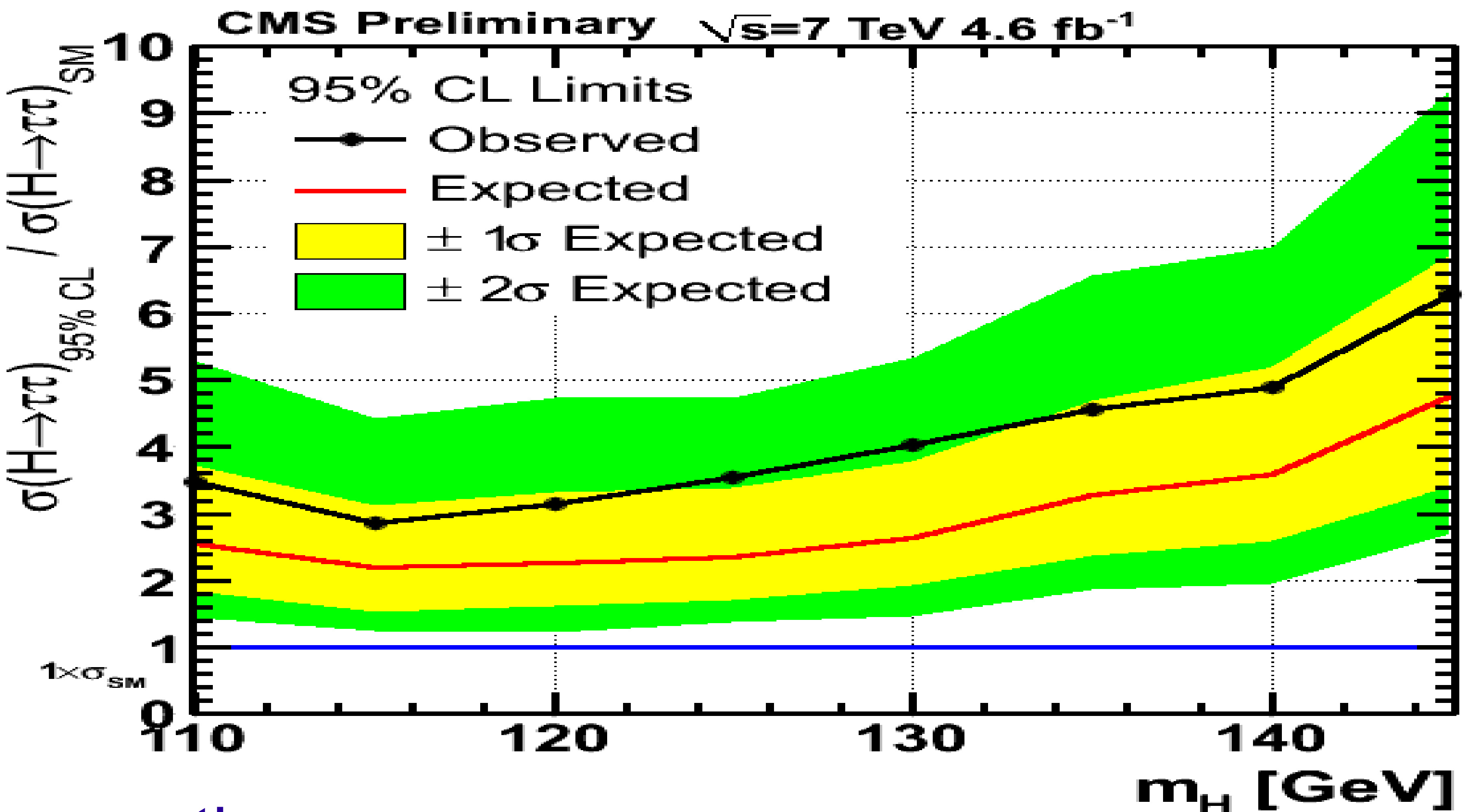
# Low Mass Special: $H \to \tau\tau$




## Full mass spectra

- inclusive not shown (no sensitivity)
- VBF / boosted substantially reduce the background
- harder $p_T$ also improves resolution

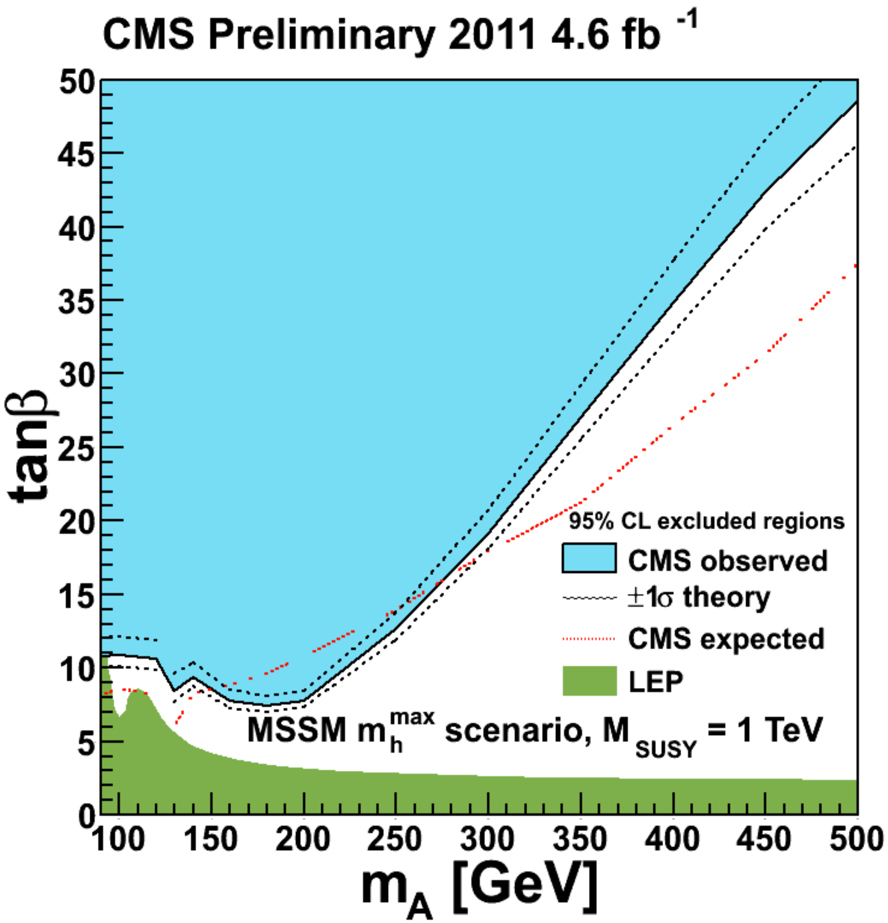
# *Low Mass Special: H → ττ*

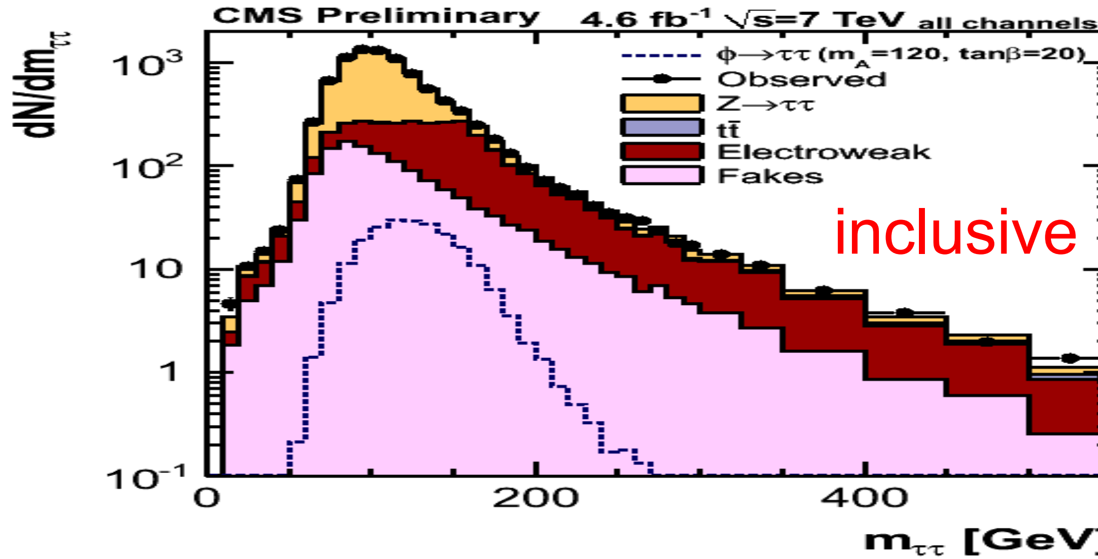


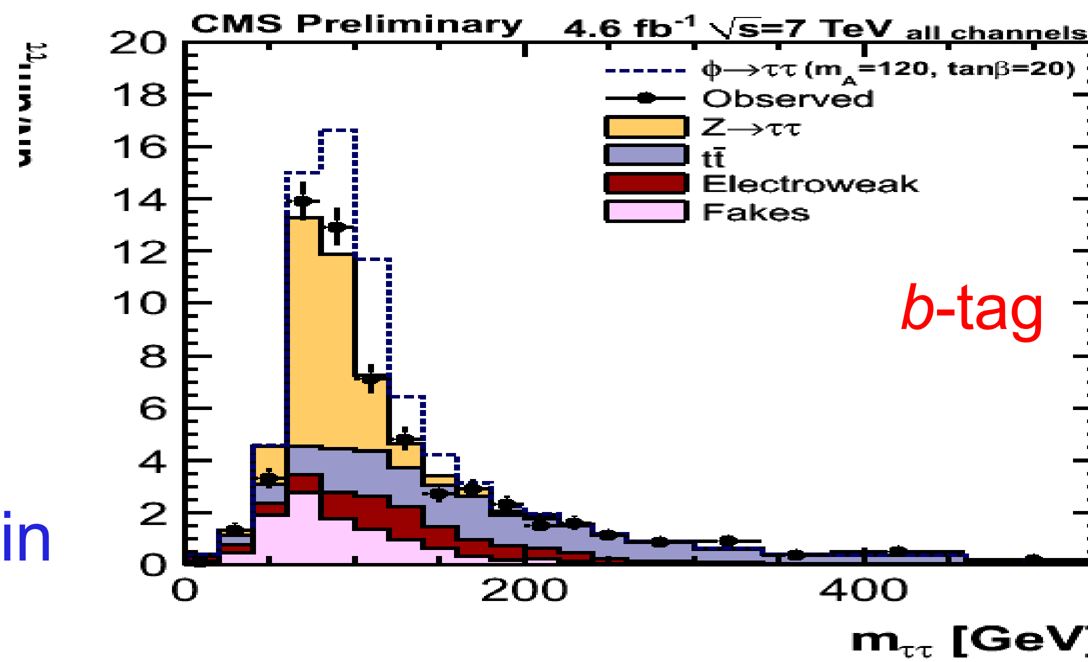

## Observations

- observed tracks expected sensitivity
- limit around 3 at low mass, further improvements possible

# MSSM: $\Phi \to \tau\tau$



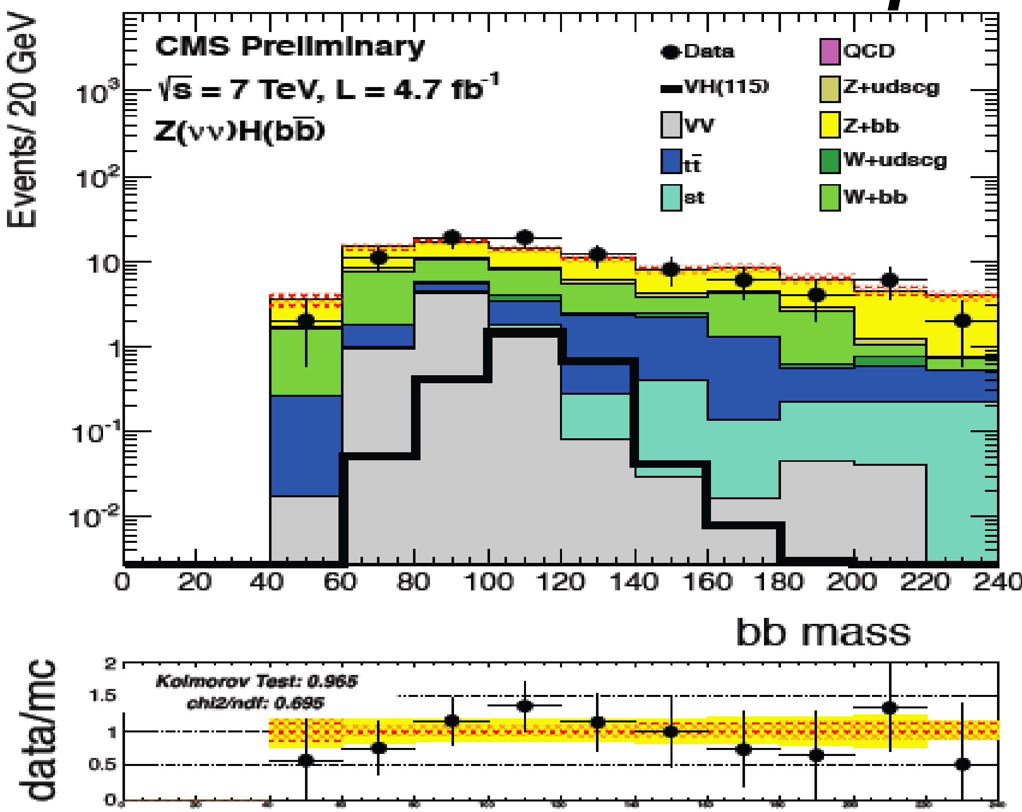




## Observations

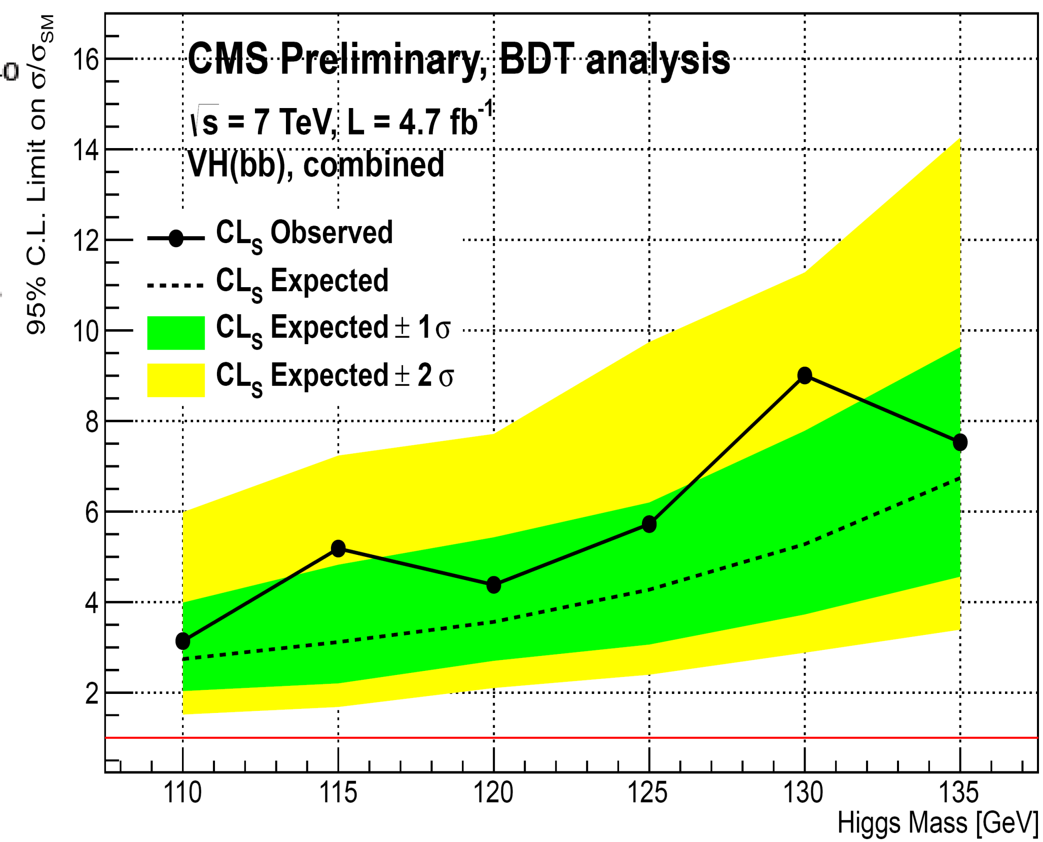
- b-tags removes main DY
- impressive improvements in exclusion plane

# *Low Mass Special: VH → Vbb*




## Analysis telegram

- enormous background in $H \to bb$
- use *VH* with leptonic *V* decays
- also require high momentum: 'boosted' analysis



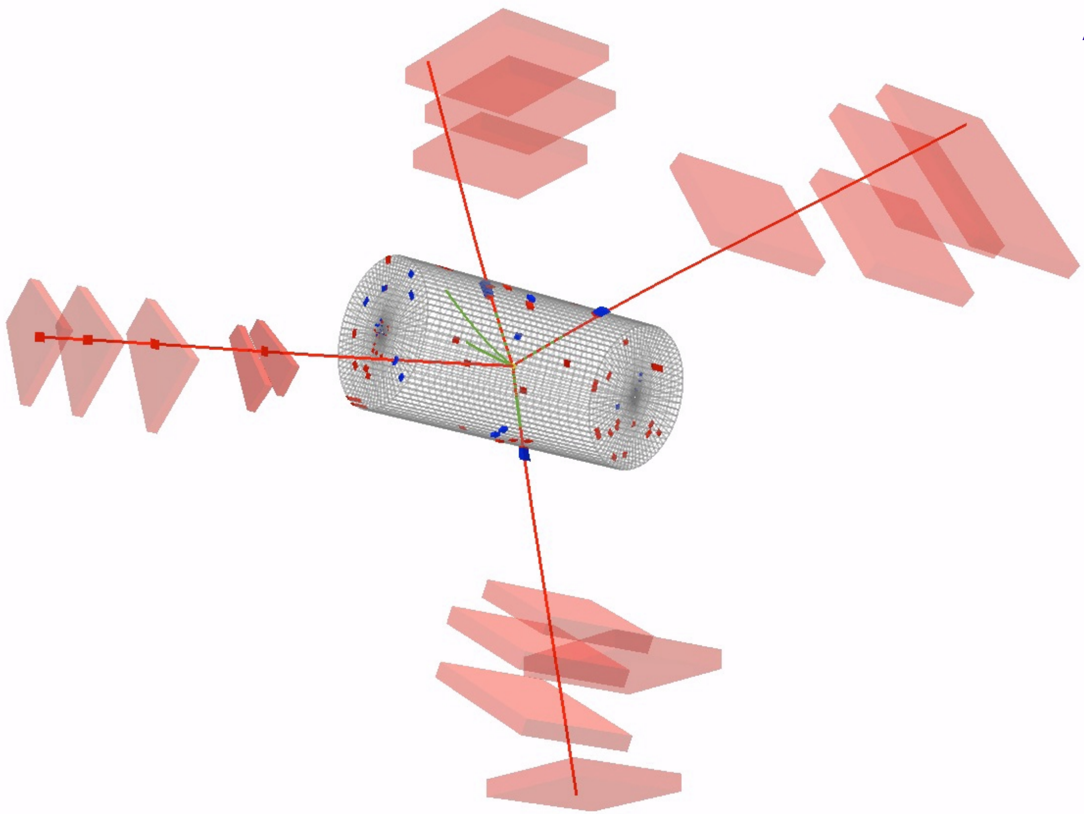

## Backgrounds

- *V+jets (Wbb, Wcc), VV, top*

## Result

- limit is around 3 at low mass
- further improvements possible

# The *Golden* Mode: $H \rightarrow ZZ \rightarrow 4l$



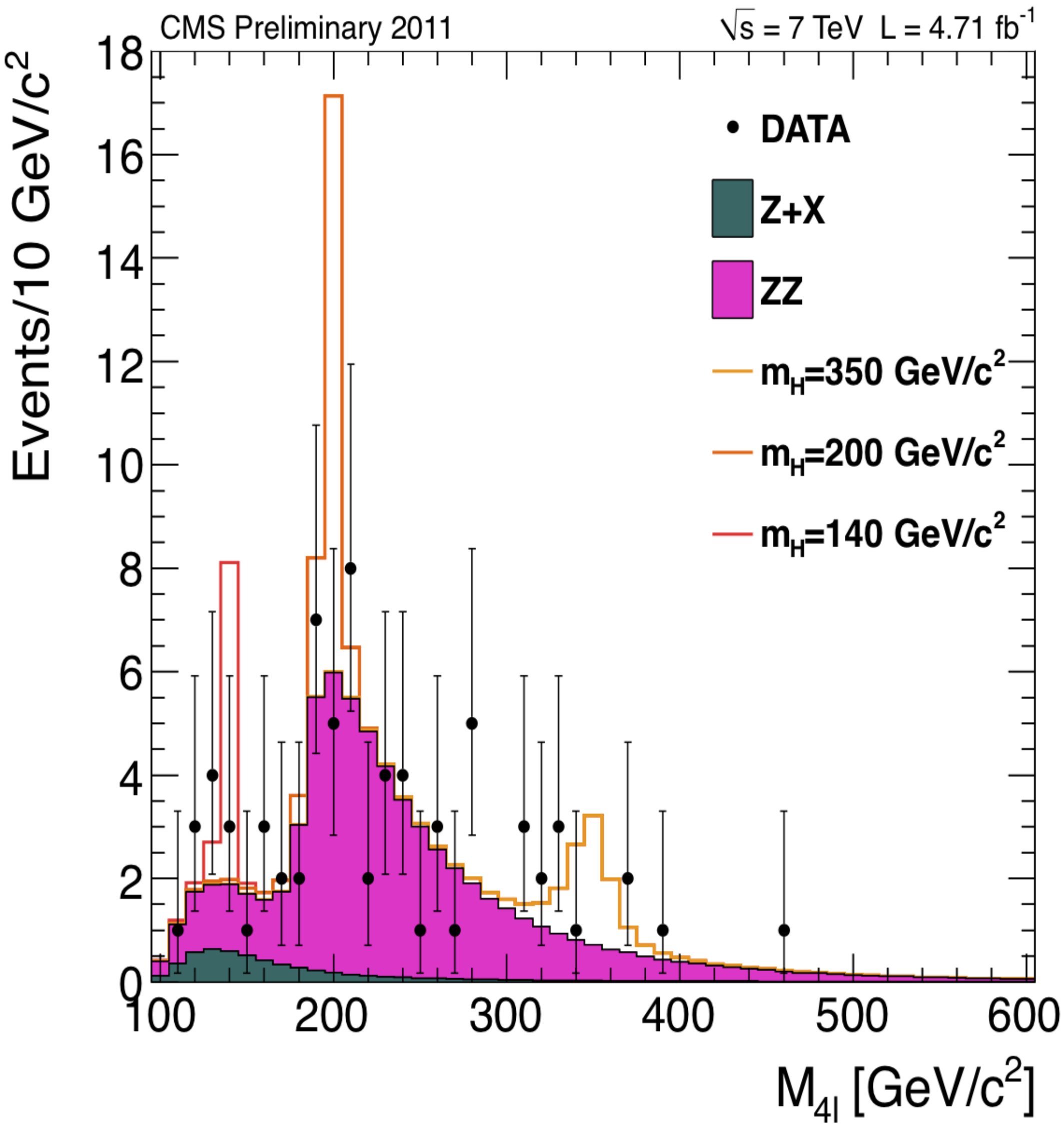
## Analysis telegram

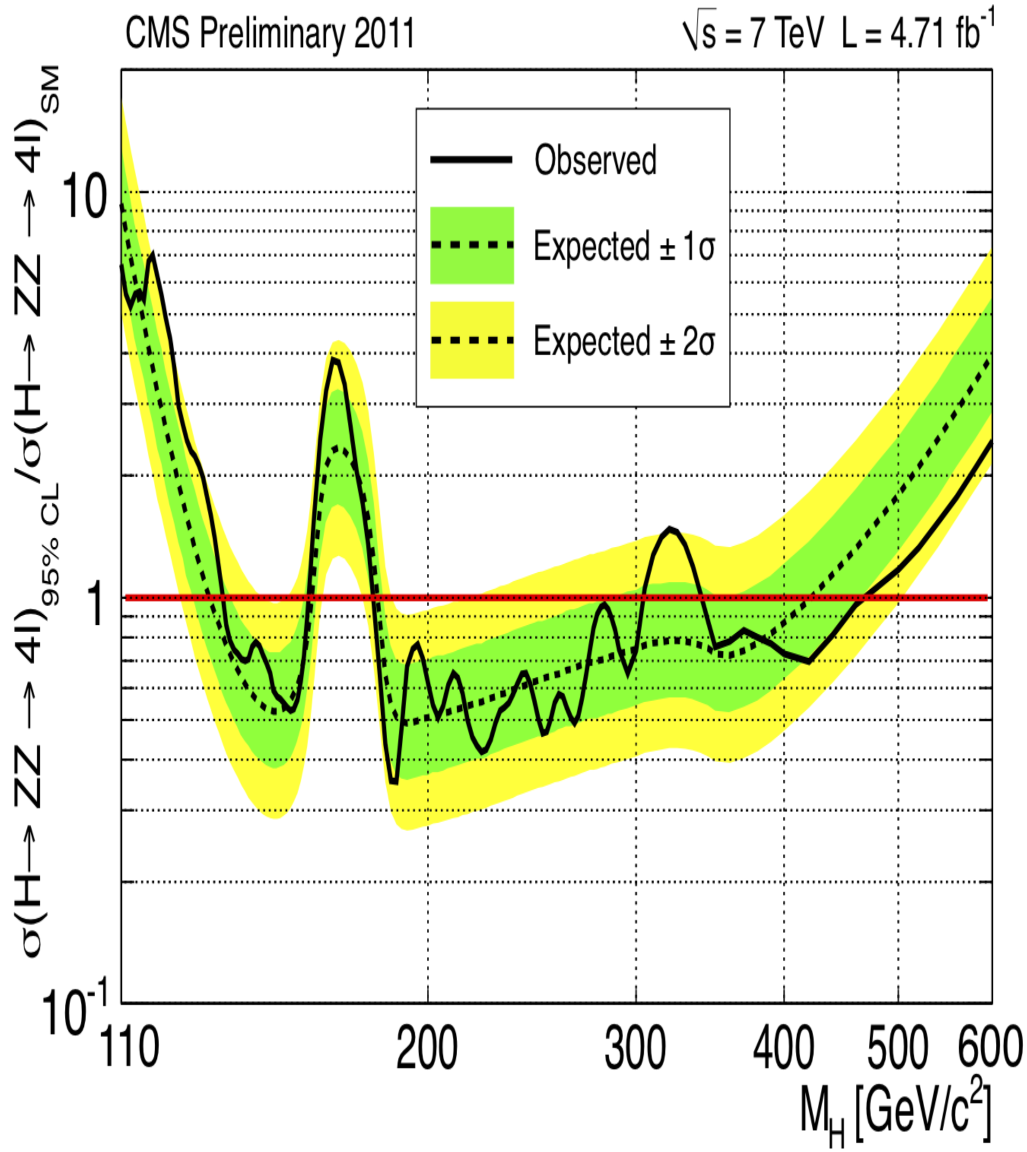
- 4 isolated high $p_T$ leptons
- consistent with *Z* decays
- from same vertex
- fit mass peak with resolution: 2-4 GeV
- little background, main comes from non-resonant *ZZ* production, irreducible
- also *Zbb* and top (*2l2nu2b*)

## Background removal

- leptons from *b*-decays are non-isolated and displaced
- require isolation and small impact parameter

# The Golden Mode: $H \rightarrow ZZ \rightarrow 4l$

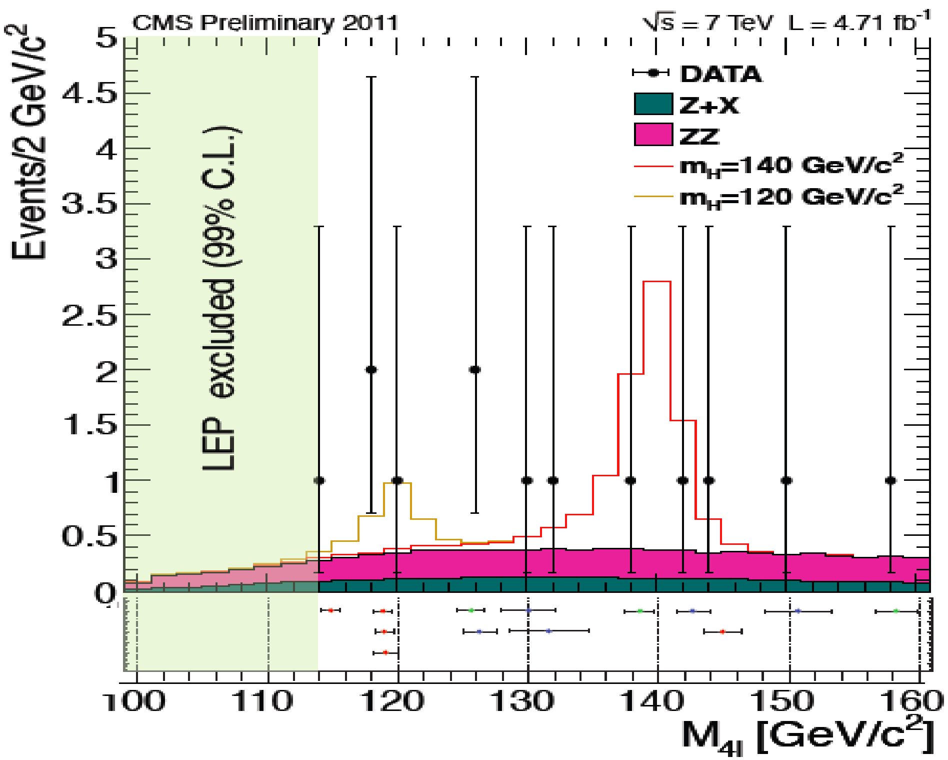


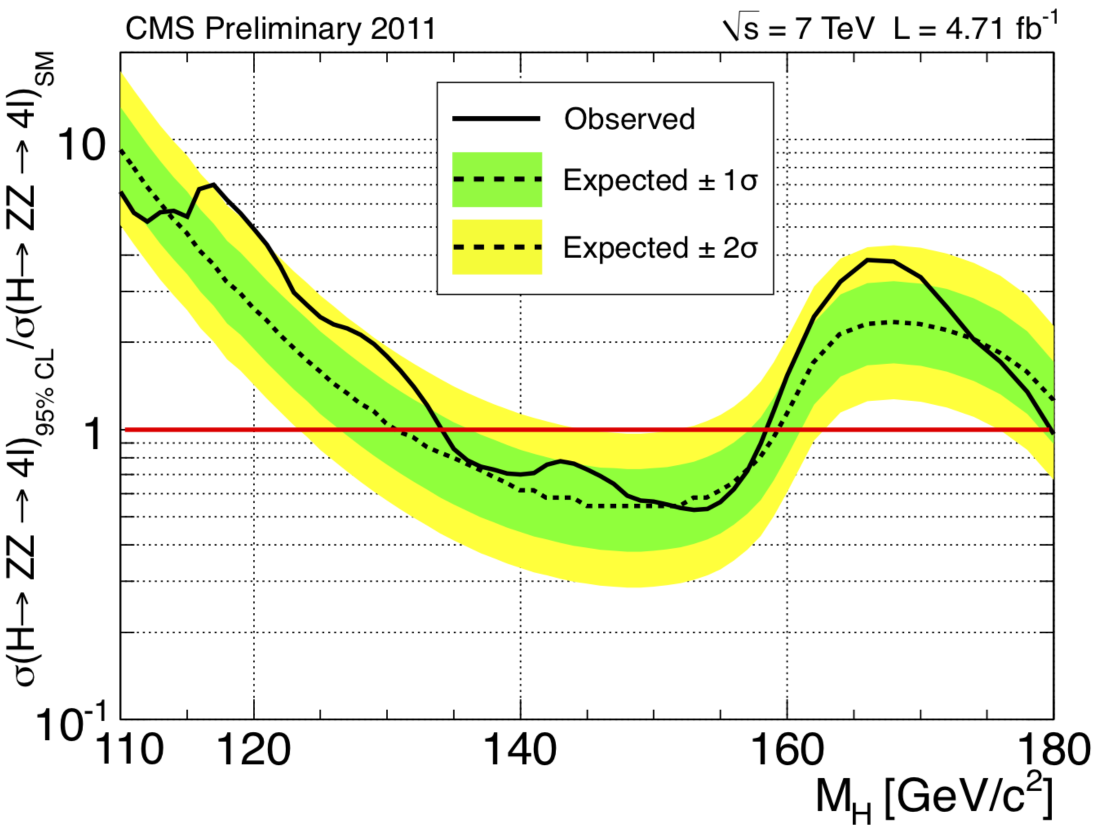




Observed events overall consistent with expectations

- 72 observed, expected 67.1 ± 6, mild excess

# *Low Mass: H → ZZ → 4l*

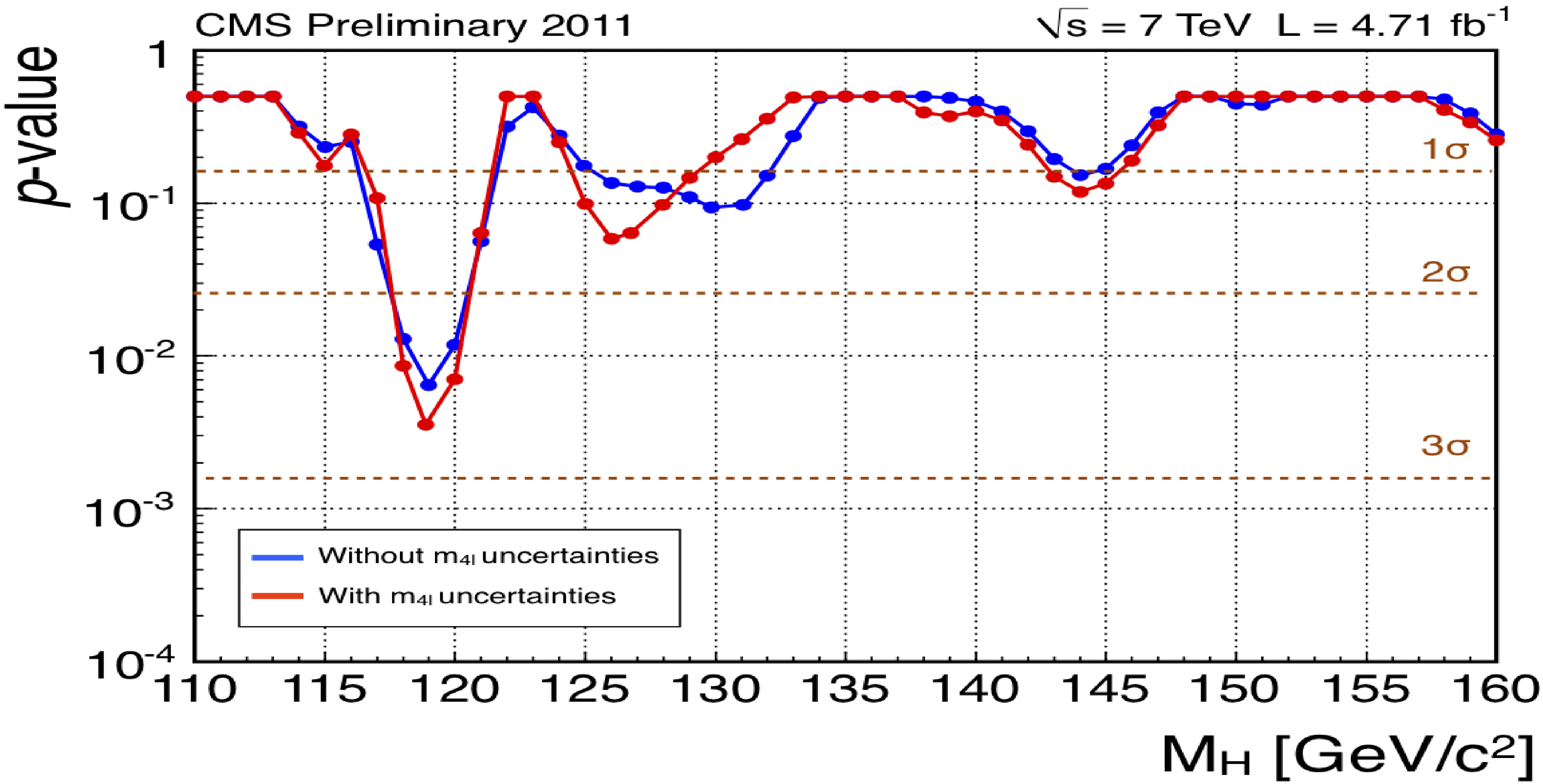



## Observed events overall consistent with expectations

- 13 observed, expected 9.5 ± 1.3, excess
- some clustering around ~119 GeV and ~125 GeV

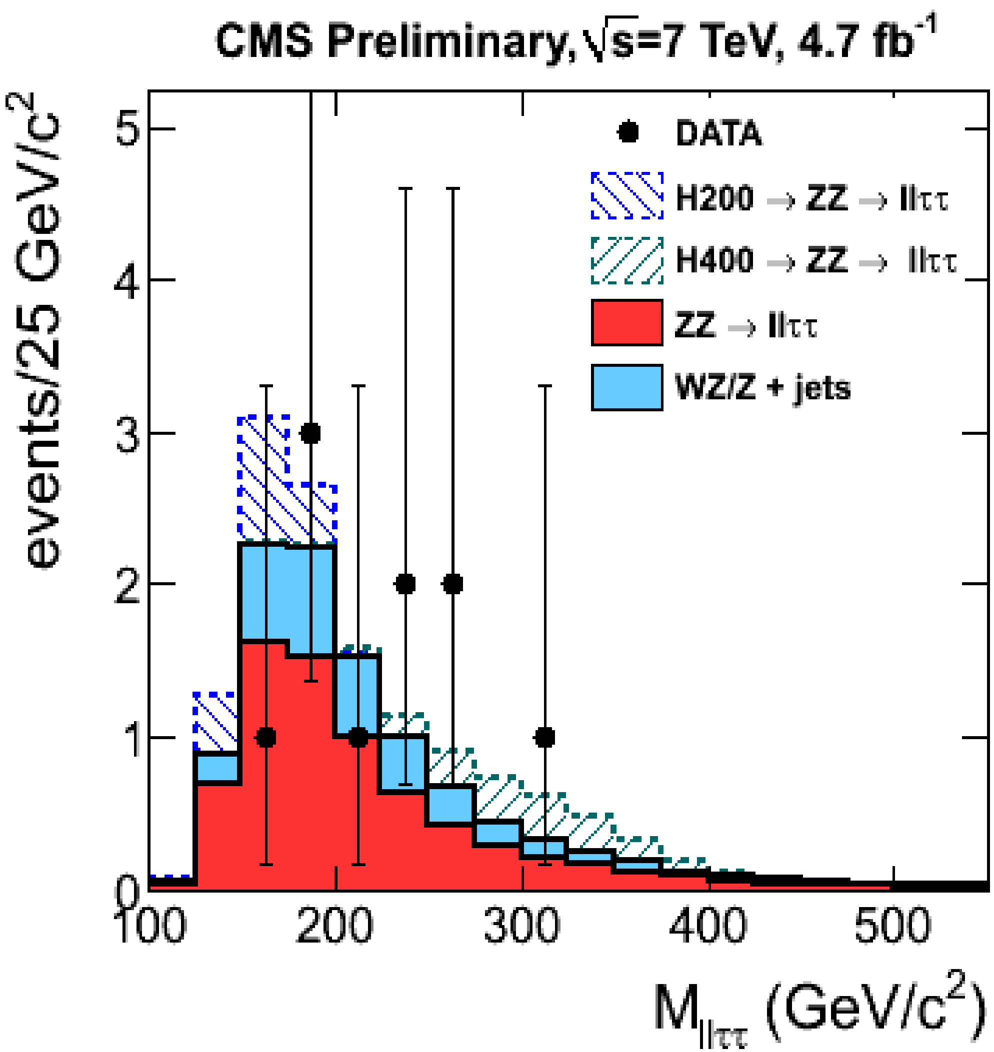
# *Low Mass: H → ZZ → 4l*

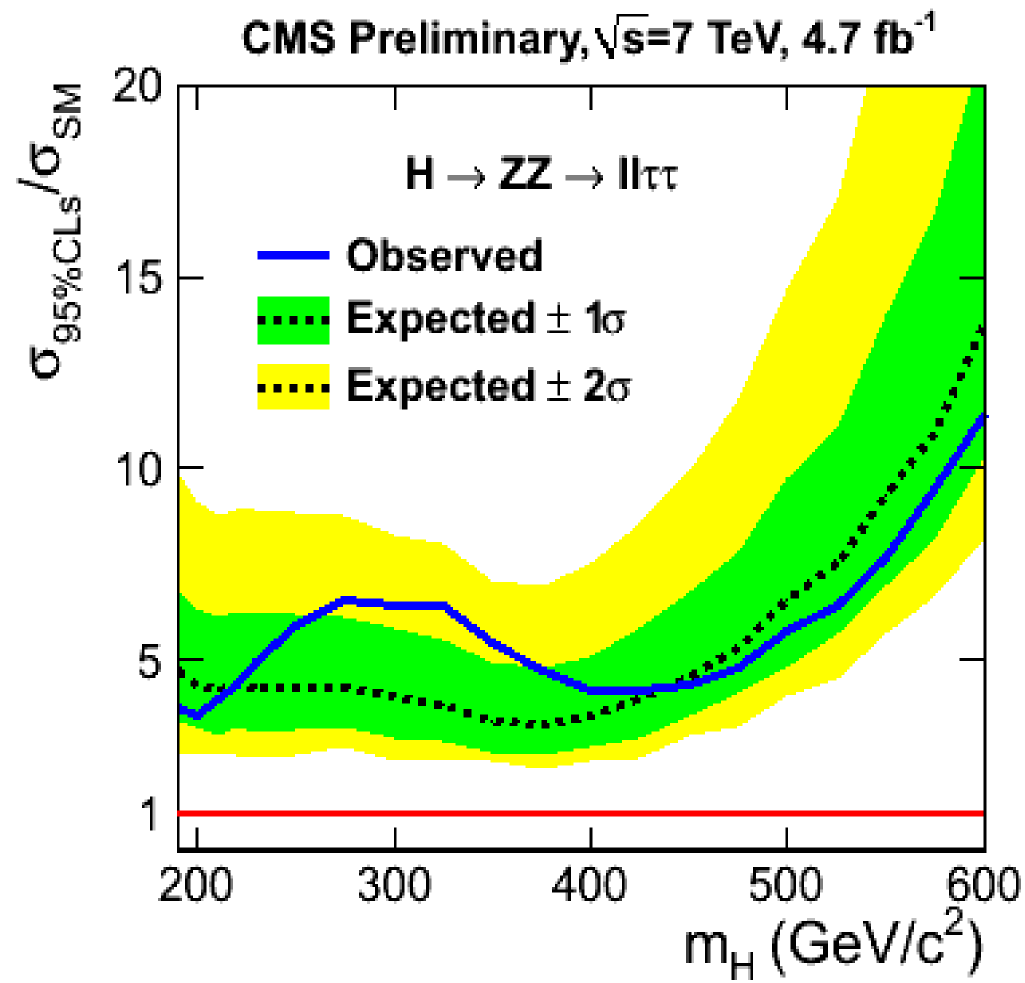



## *p*-values (at 119 GeV)

- local significance is 2.5 (2.9) reduced to 1.1 (1.3) after LEE
- signal strength is about 2 ± 1 times the SM

# High Mass Special: $H \rightarrow ZZ \rightarrow 2l2\tau$

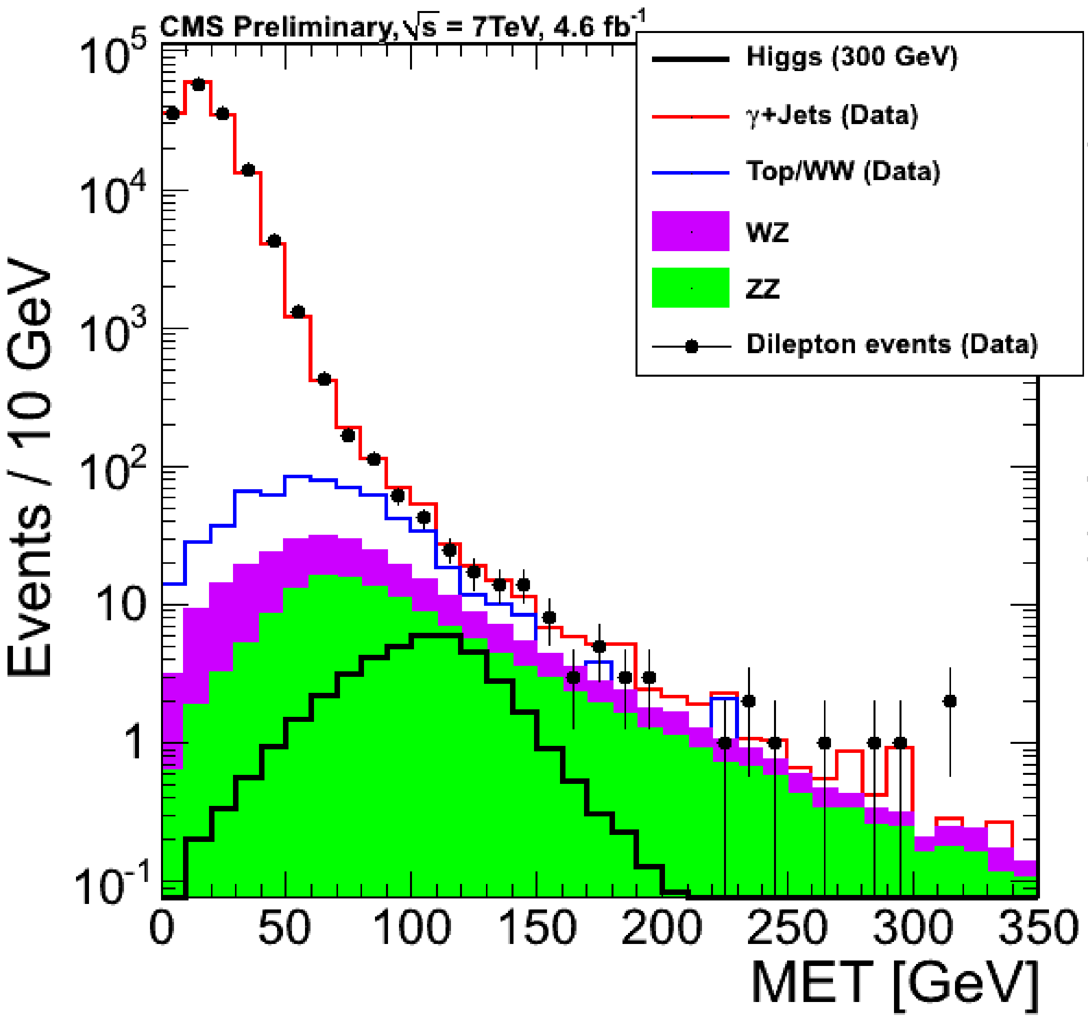


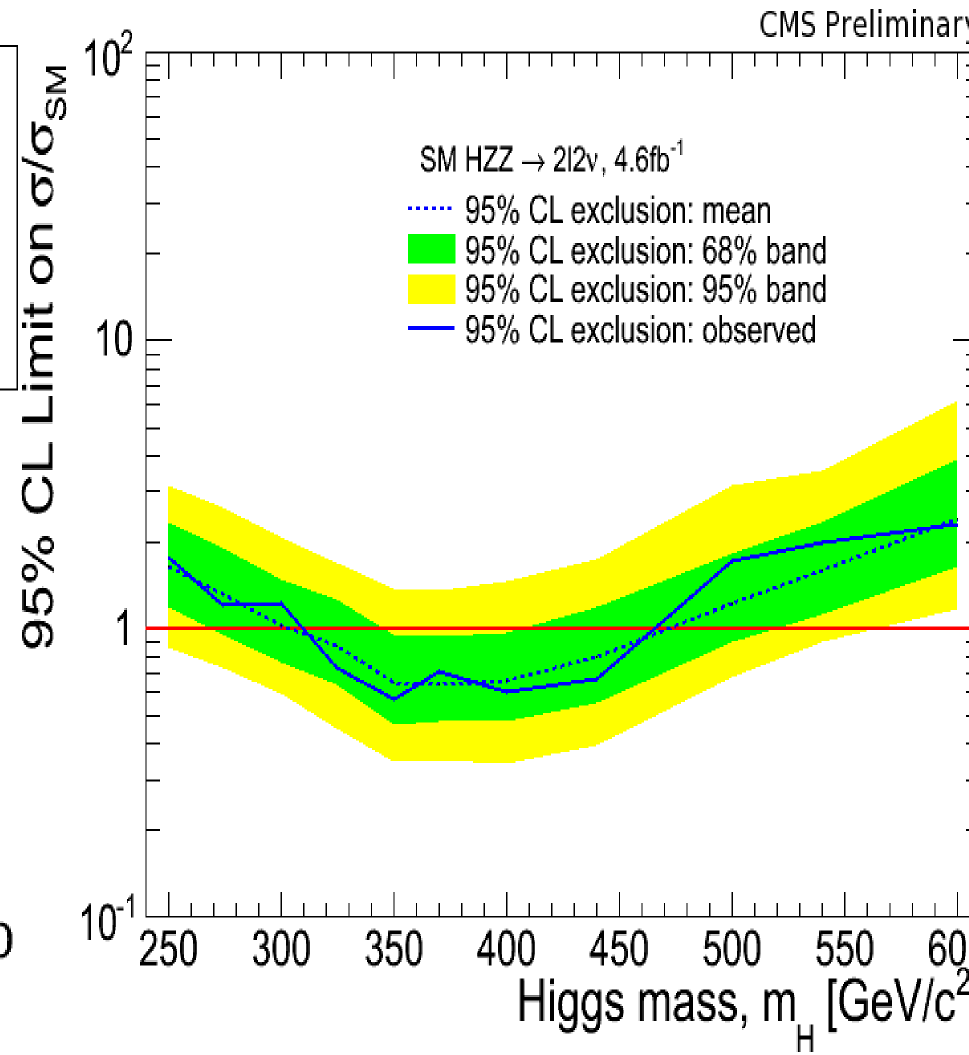




## Improved $2l\ 2\tau$ analysis

– replace *ee* or *μμ*, with *ττ*, analysis sensitivity at 200 GeV at ~4

# High Mass Special: H → ZZ → 2l2nu

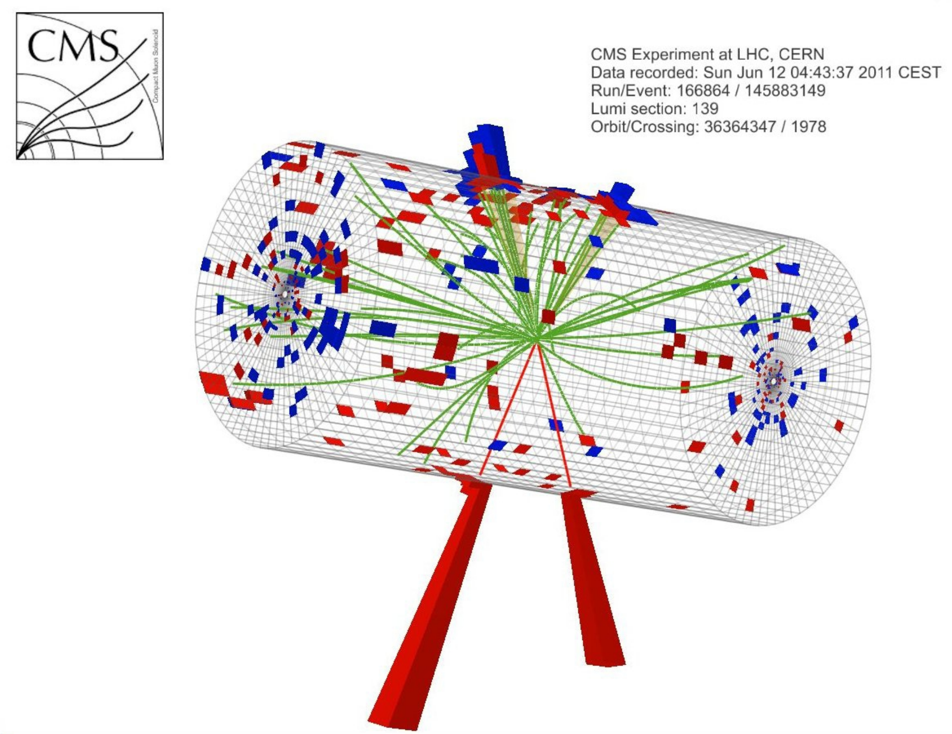


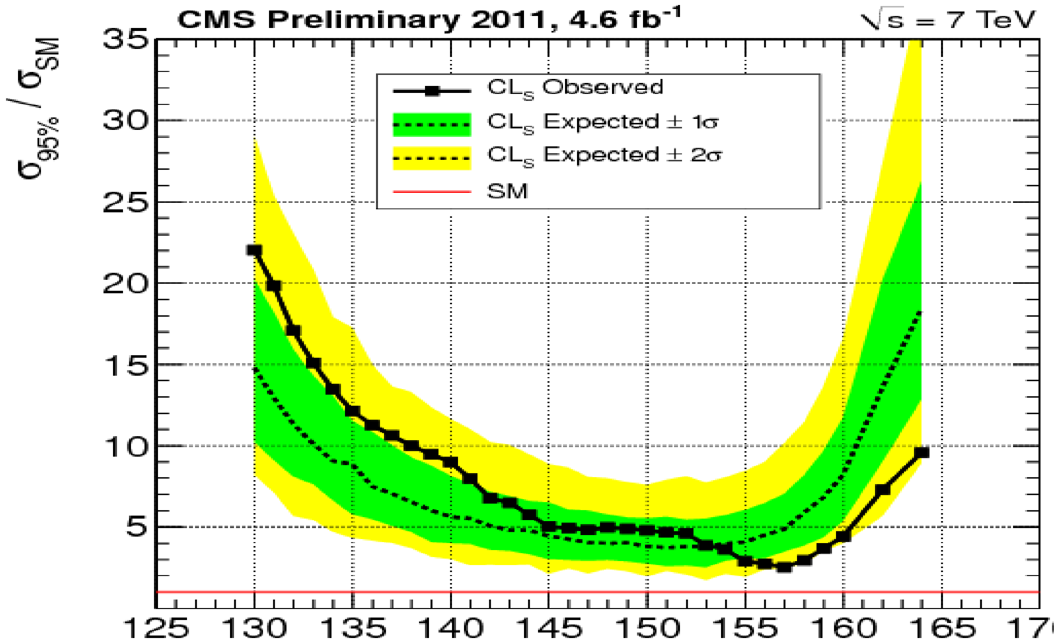



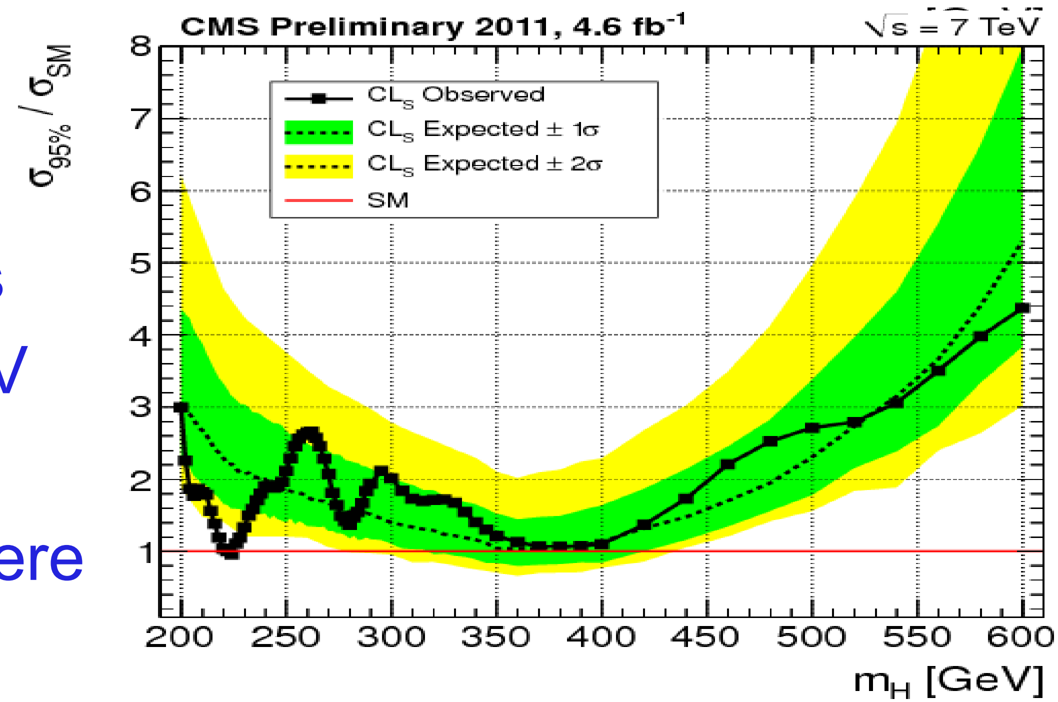

## Analysis telegram

- same final state as our H→WW, smaller production fraction
- similar issues: starts to have sensitivity at about $m_H$ = 350 GeV

# *High Mass: H → ZZ → 2l 2jets (or 2b-jets)*




## Analysis telegram

- highest rate of H→ZZ analyses
- search peak: detector ~ 10 GeV
- full scale angular analysis
- not yet excluding but getting there

# CMS Higgs Result Combination

***H -> WW -> 2l2nu***

***H -> $\gamma\gamma$***

***H -> $\tau\tau$***

***H -> bb***

***H -> ZZ -> 4l***

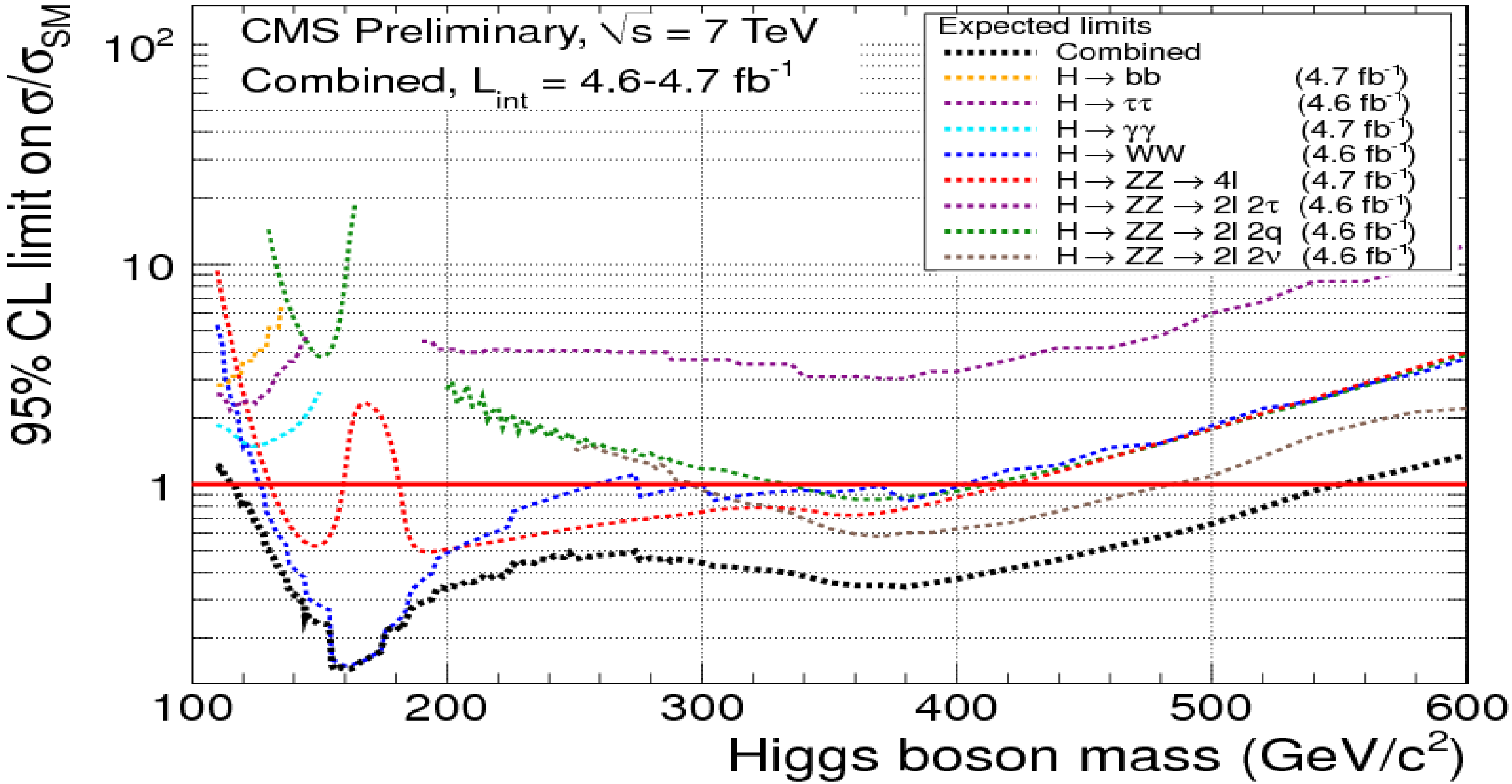
***H -> ZZ -> 2l2$\tau$***

***H -> ZZ -> 2l 2nu***

***H -> ZZ -> 2l 2jets***


ATLAS and CMS use consistent, solid, statistical methods: CLs

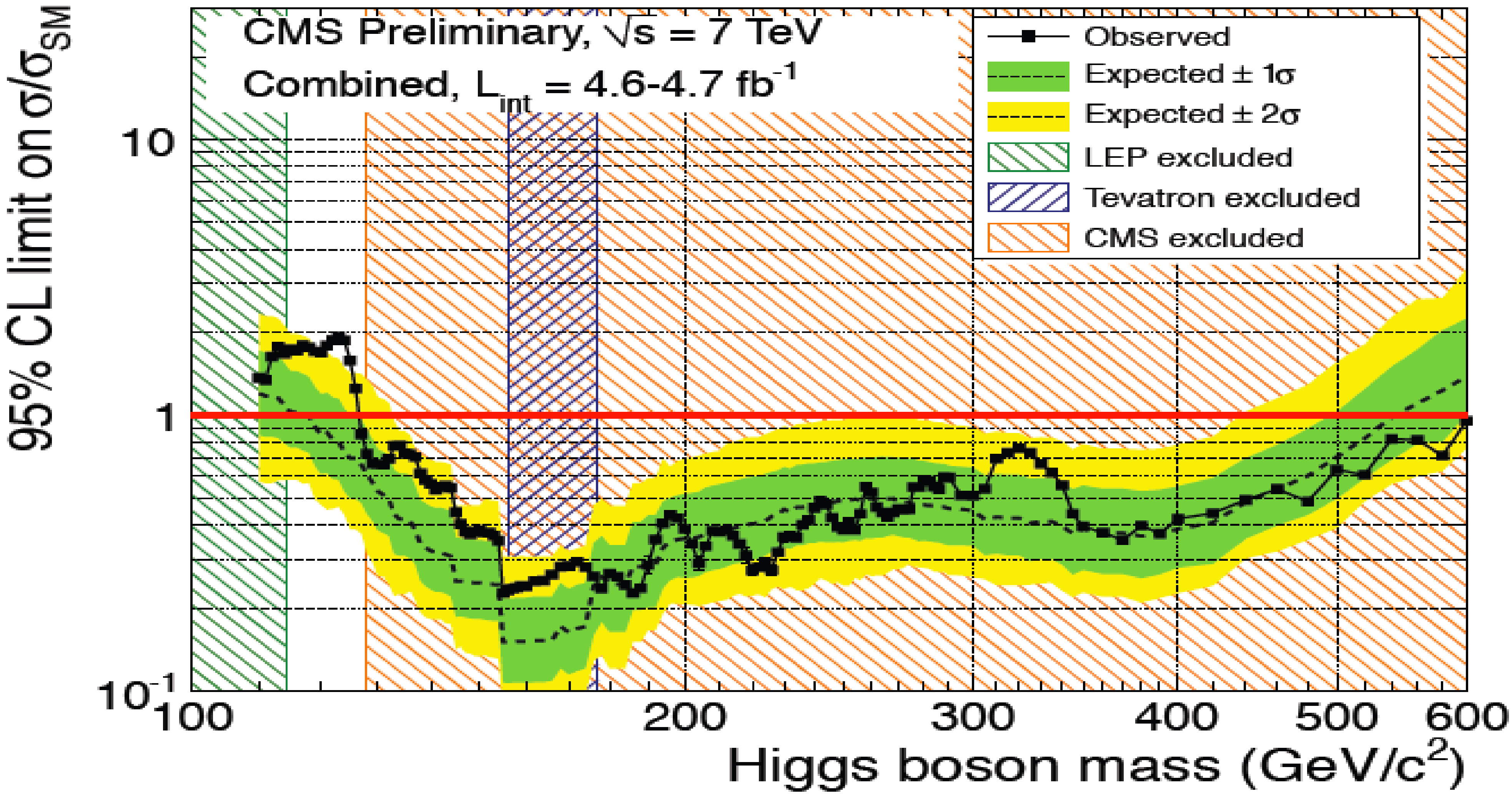
# CMS SM Higgs Combination




## Dominant channels

- 110-120 GeV ***H -> γγ*** 120-200 GeV ***H -> WW -> 2l 2nu***
- 200-330 GeV ***H -> ZZ -> 4l*** 330-600 GeV ***H -> ZZ -> 2l 2nu***

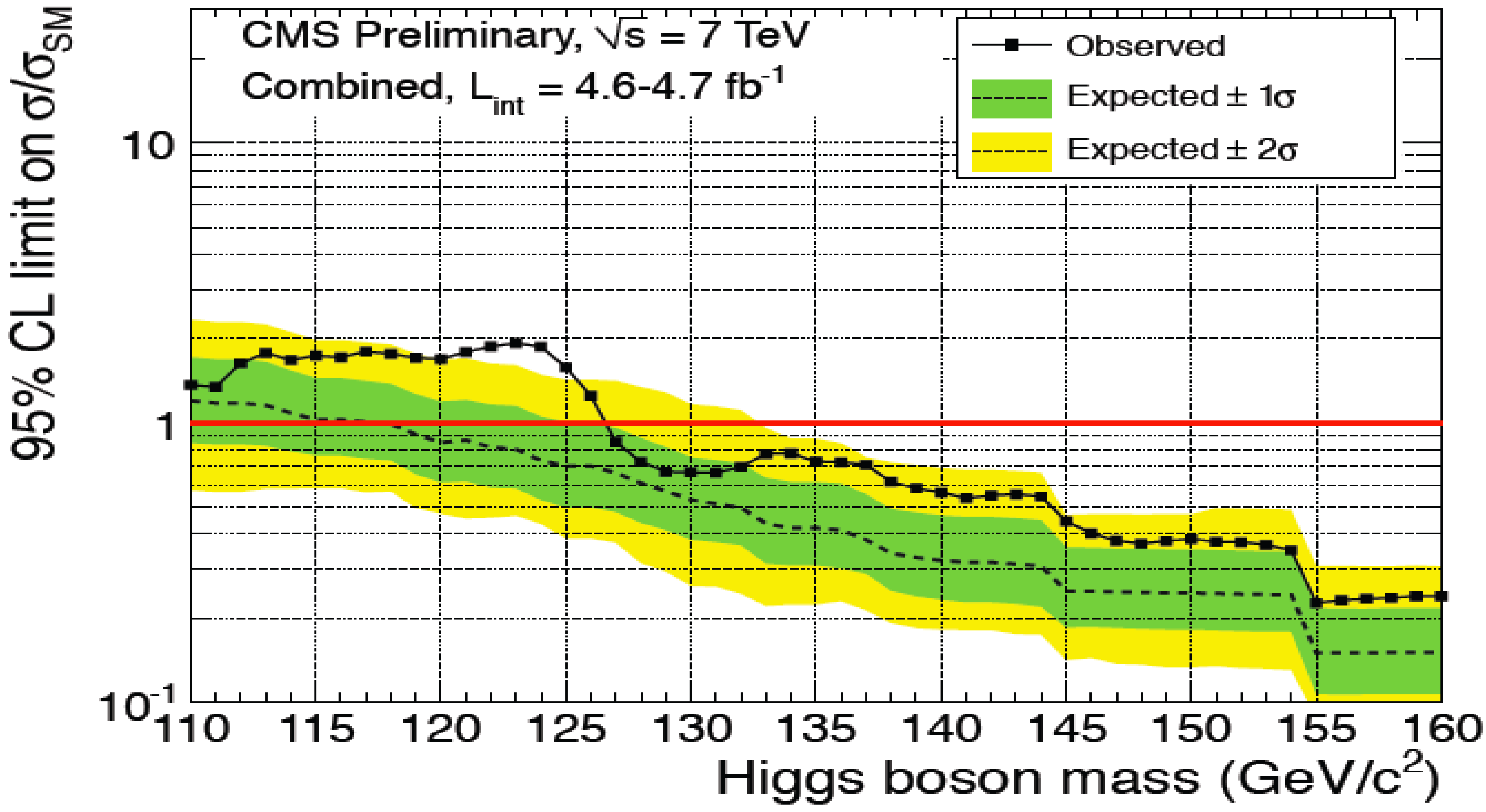
# CMS SM Higgs Combination




## Observations

- exclude (95%): 127-600 GeV (exp. 117-583 GeV)
- exclude (99%): 129-525 GeV (exp. 128-500 GeV)

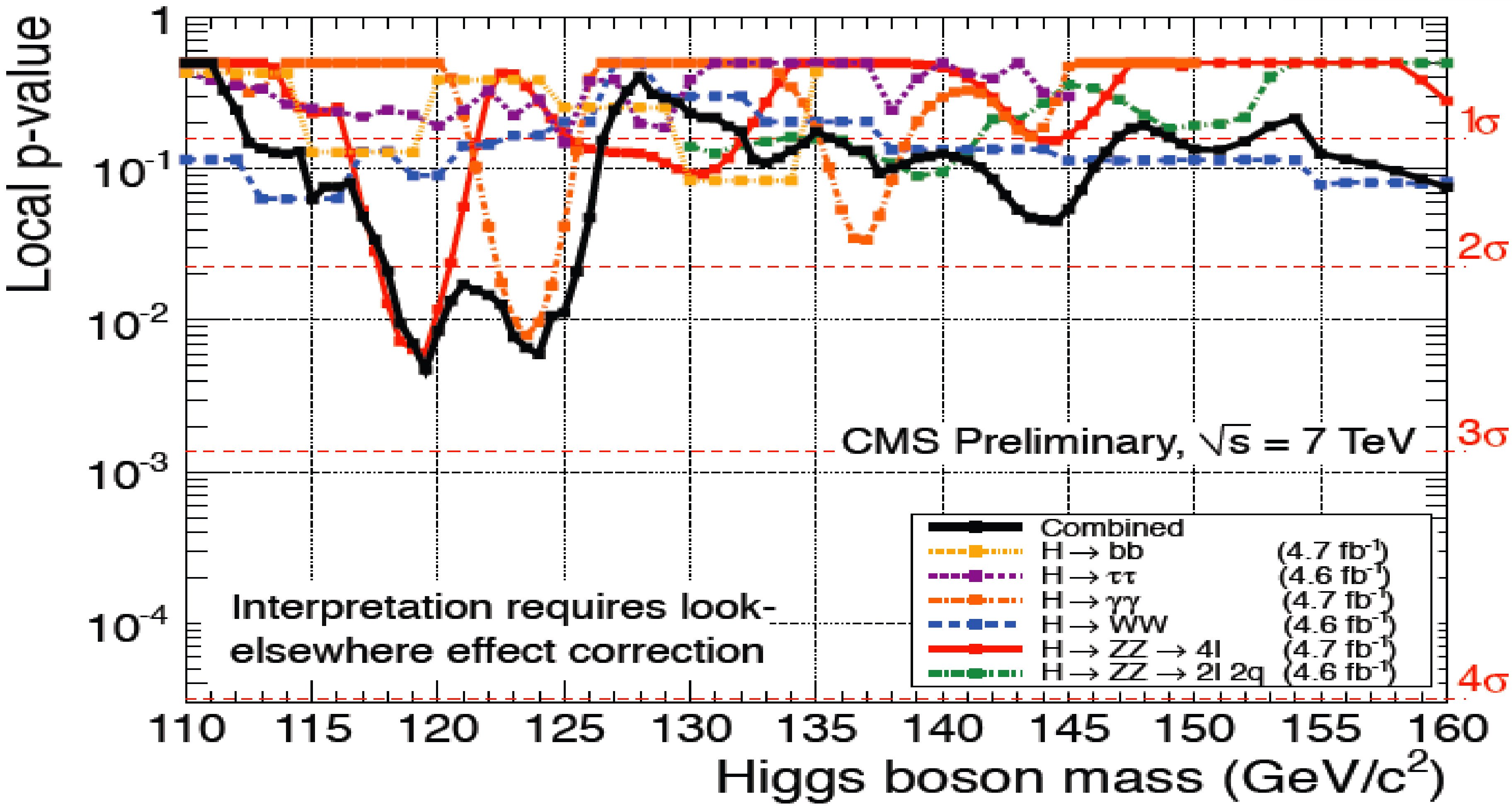
# CMS SM Higgs Combination




## Comment

- some excess around ~124 GeV

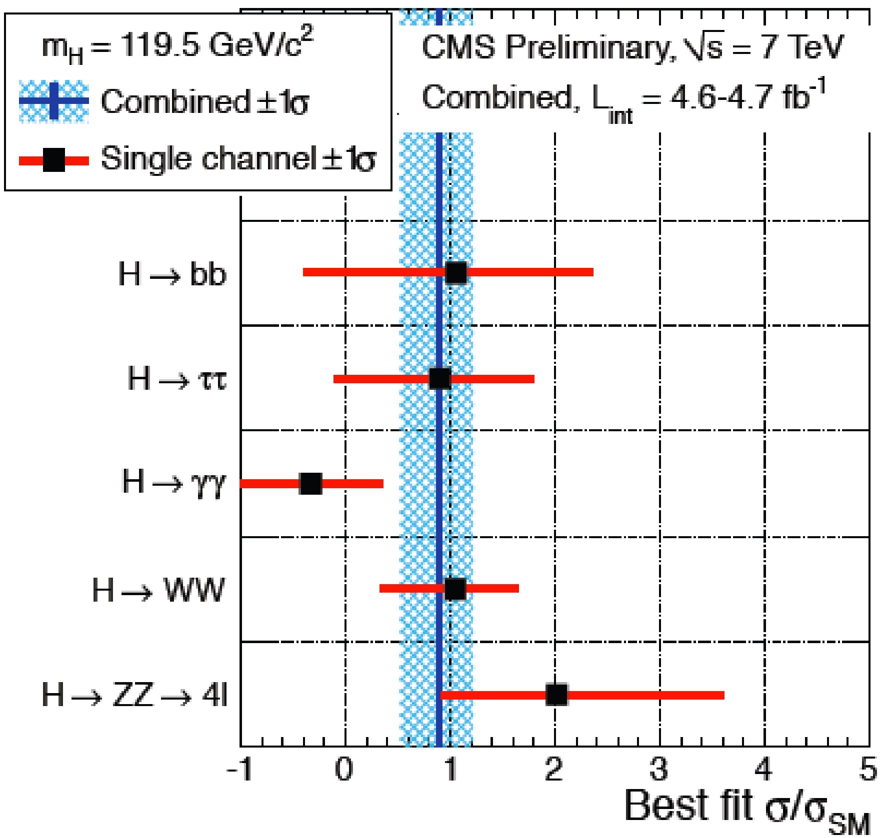
# Combined p-Value

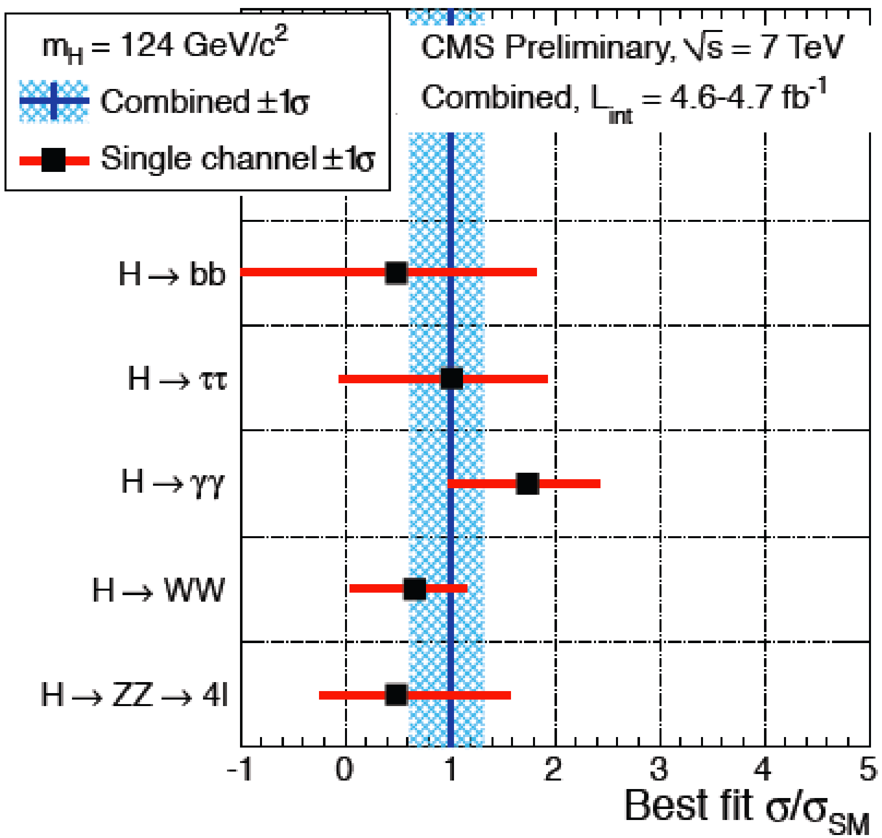



## Comments

- smallest p-value at 119 GeV: local significance 2.6 std
- global: 0.6 std in 110-600 GeV or 1.9 in 110 -145 GeV

# Compare Channel by Channel




Comments

- consistent values for the cross section
- excess drivers: 119.5 GeV by 4l, 124 GeV by γγ

# *Conclusion*

## Quantum leap in Higgs search in 2011: ~5/fb data

- excluded region : 127 GeV < $m_H$ < 600 GeV
- expected : 117 GeV < $m_H$ < 543 GeV
- small window left: **114.4 GeV < $m_H$ < 127 GeV**

## Looking beyond 95% CL → 99% CL

- 99% CL exclusion: 129 GeV < $m_H$ < 525 GeV
- search will not stop at 95% CL exclusion

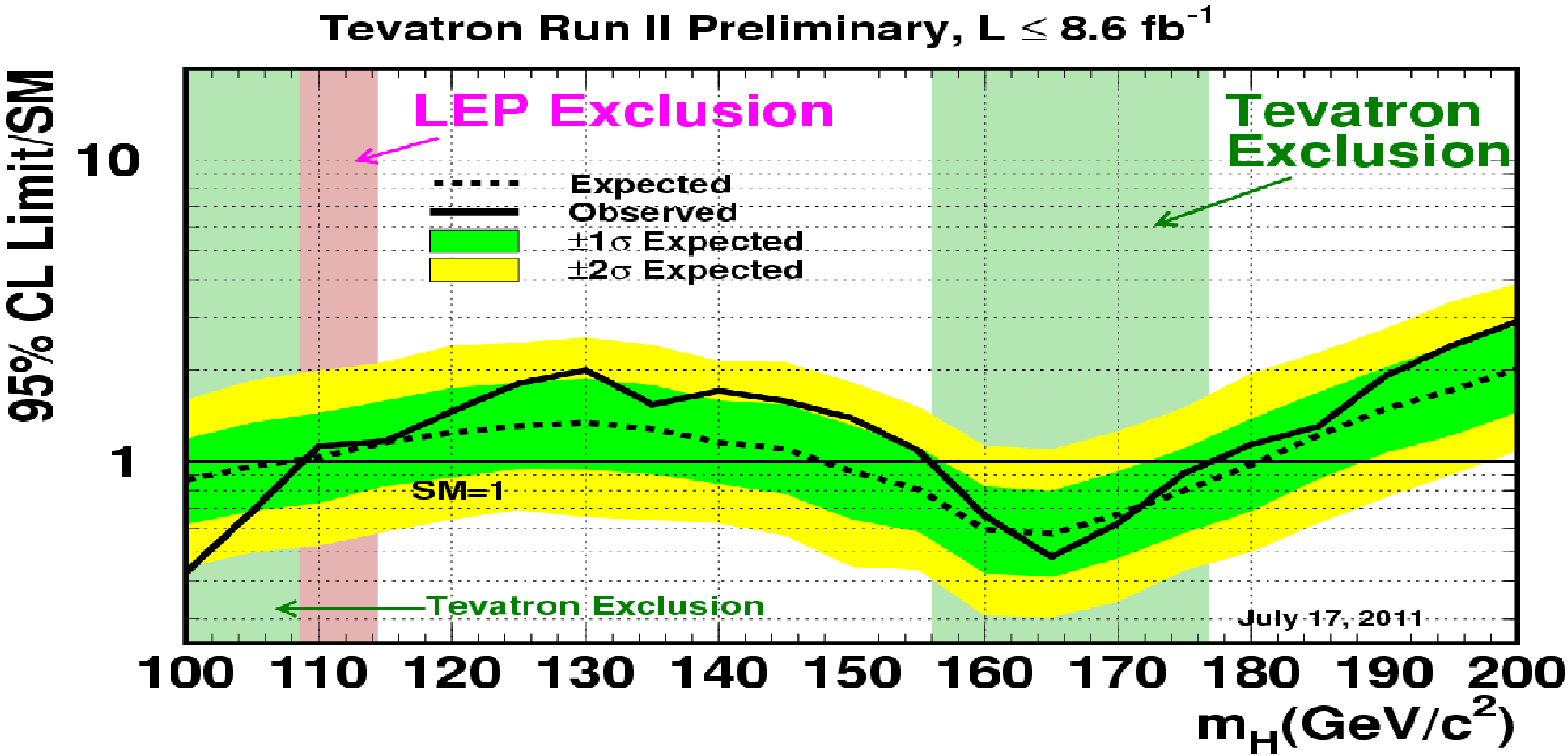
## Comments on low mass region

- excluded less than expected
- small excess, but inconclusive at this point
- **need more data to come to a conclusion**
- **this year, 2012 will be the decisive one !**

# *Tevatron*

proton-antiproton collisions at 2 TeV

# *Tevatron Higgs Exclusion*

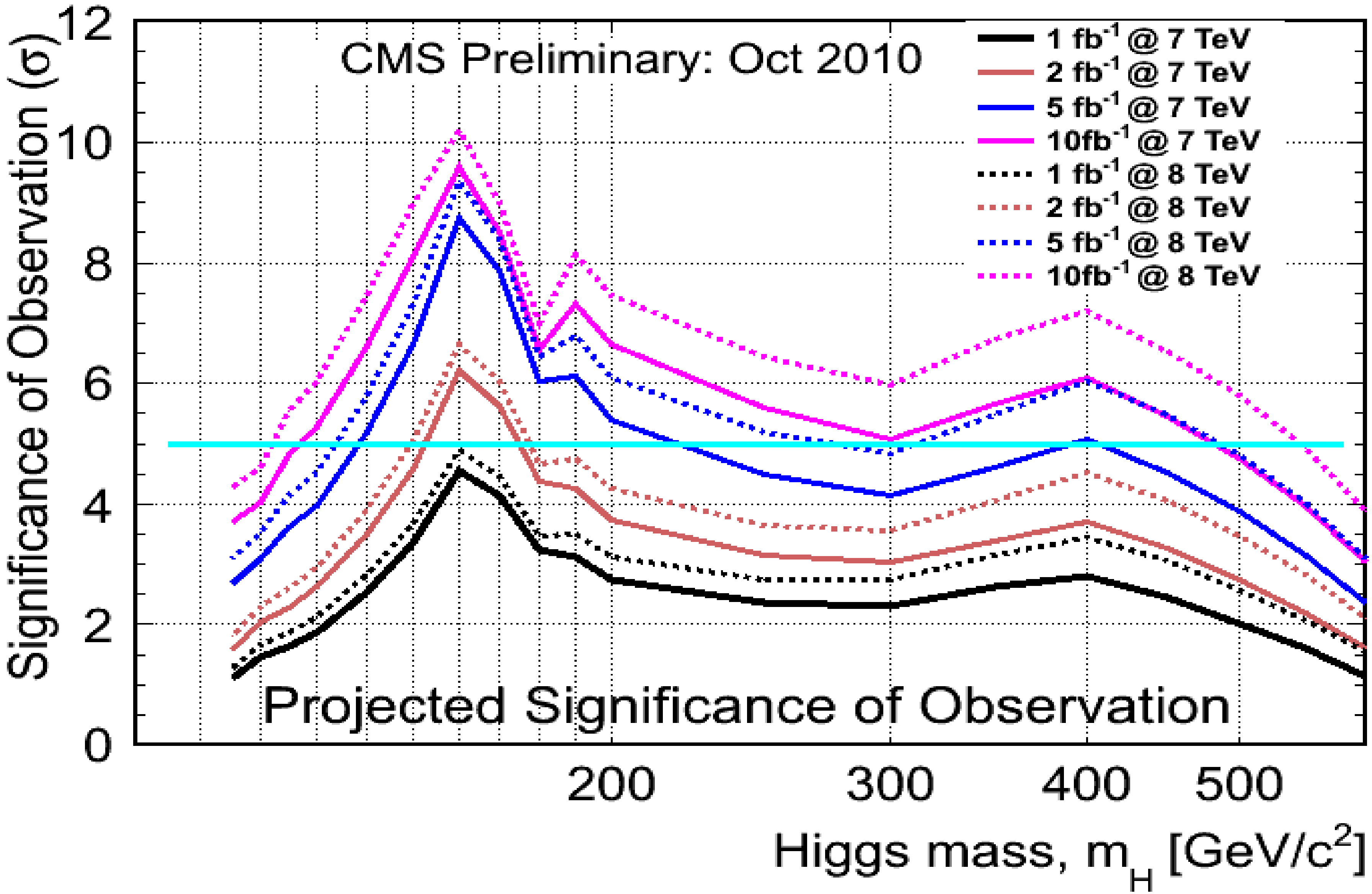



## Recent update from Tevatron (Jul 17)

- new limit at 95% CL: 156 GeV – 177 GeV excluded
- mildly worse than last summer but expected limits now much more consistent with observed limit
- 'no channel left' behind policy implemented

*More Details*

# *Prospects Discovery – Example CMS*




Indeed: the Higgs is in reach!

# *Sensitivity Prospects – Summary*

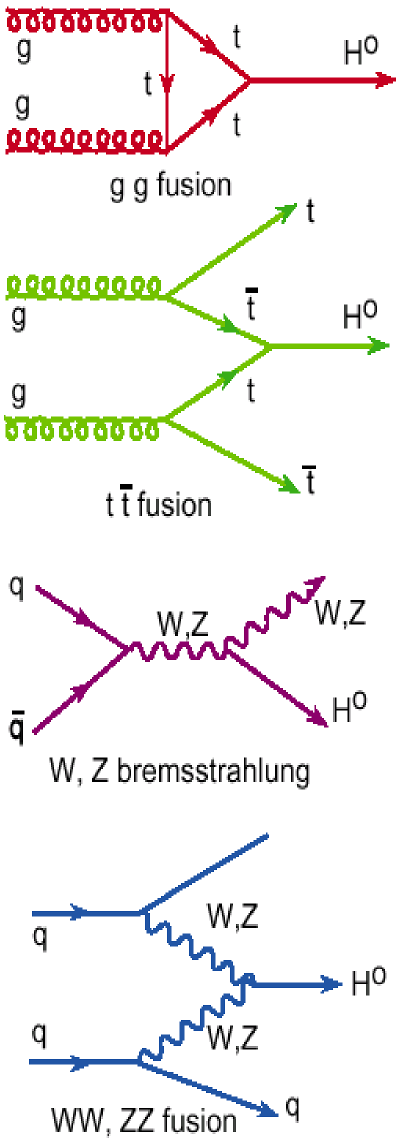
| ATLAS + CMS ≈ 2 x CMS | 95% CL exclusion | $3\sigma$ sensitivity | $5\sigma$ sensitivity |
|---|---|---|---|
| 1 $fb^{-1}$ | 120 - 530 | 135 - 475 | 152 - 175 |
| 2 $fb^{-1}$ | 114 - 585 | 120 - 545 | 140 - 200 |
| 5 $fb^{-1}$ | 114 - 600 | 114 - 600 | 128 - 482 |
| 10 $fb^{-1}$ | 114 - 600 | 114 - 600 | 117 - 535 |

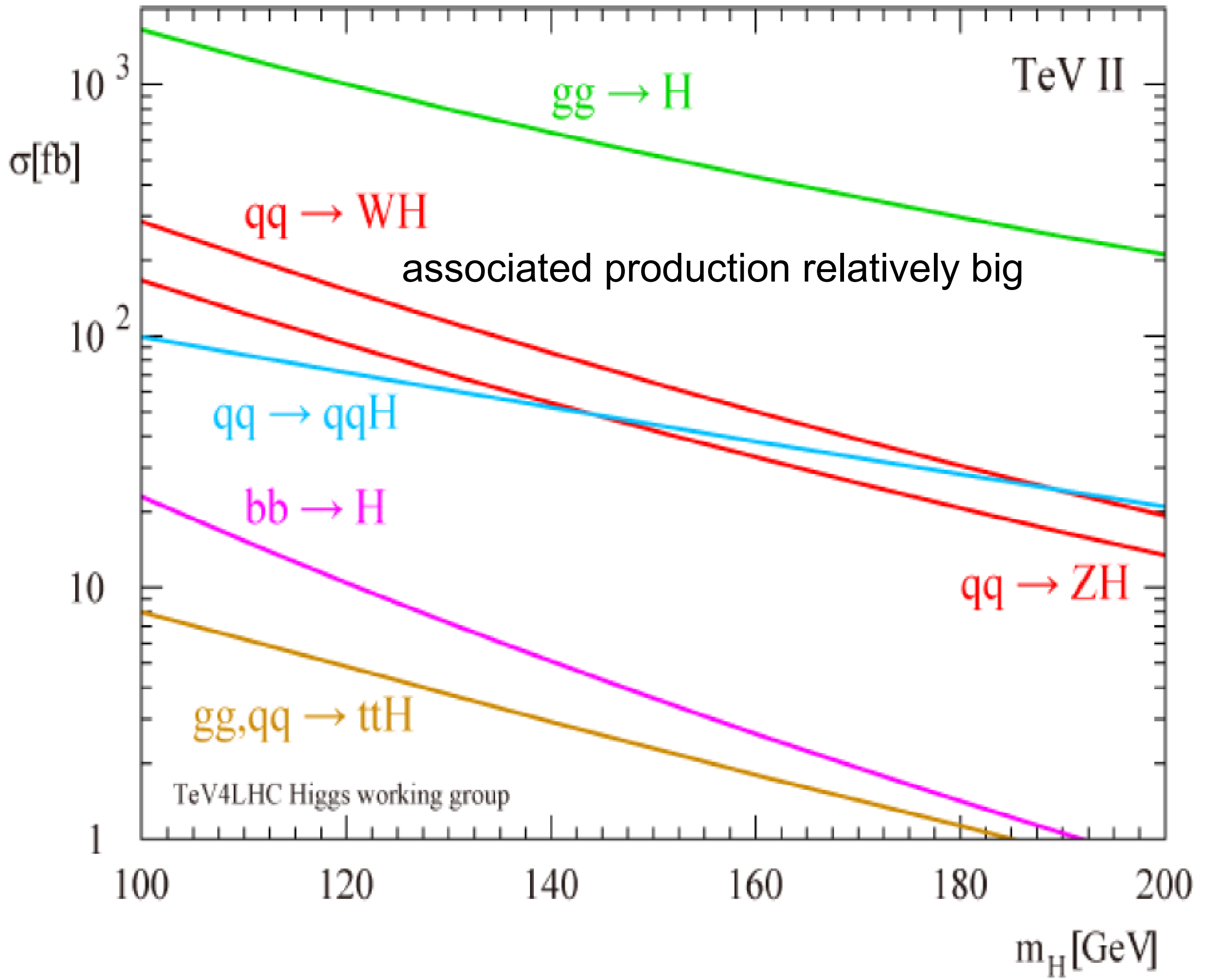
# Think about this

– how likely is it that we will see a 3 standard deviation evidence by the summer?

# *Higgs Production at the Tevatron*

## Higgs production in proton-antiproton collisions

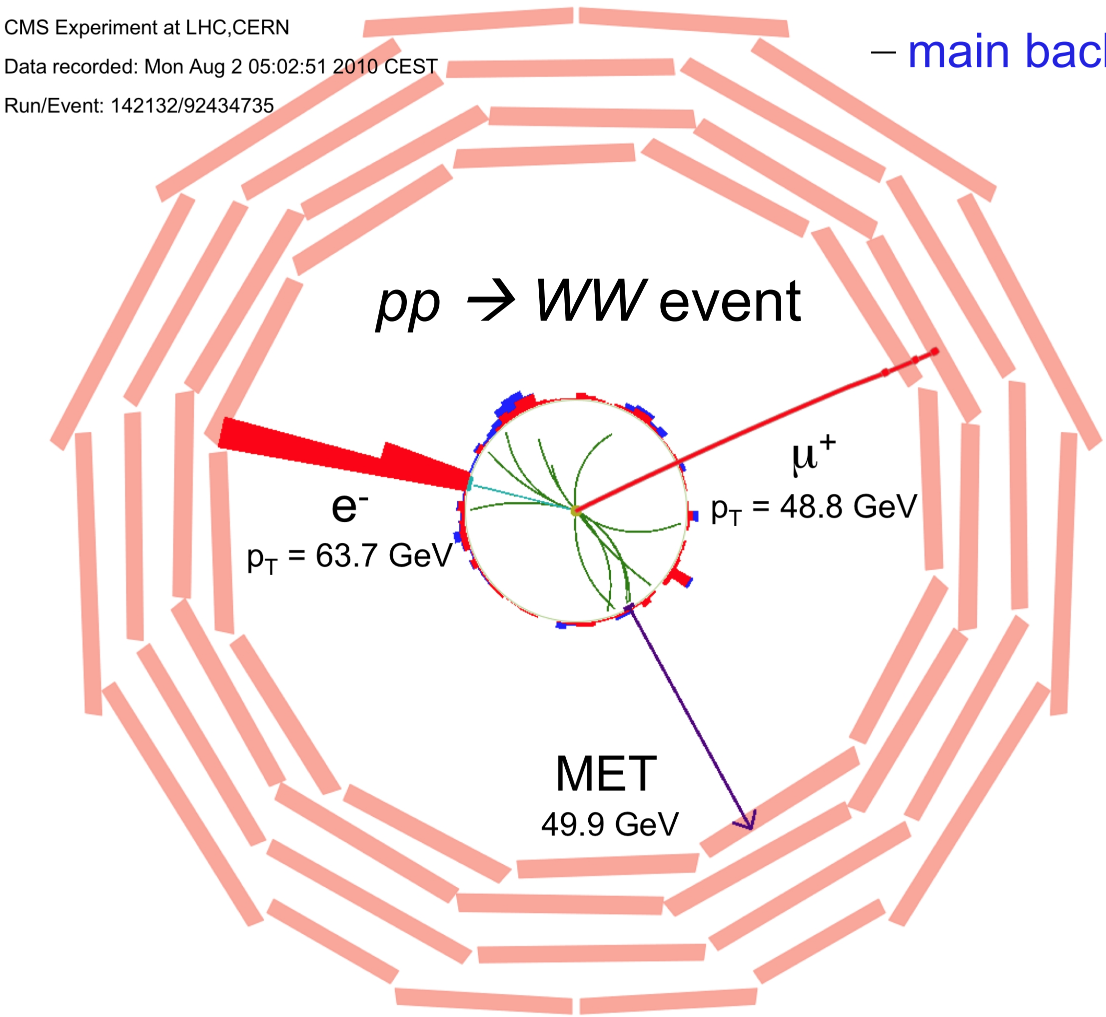


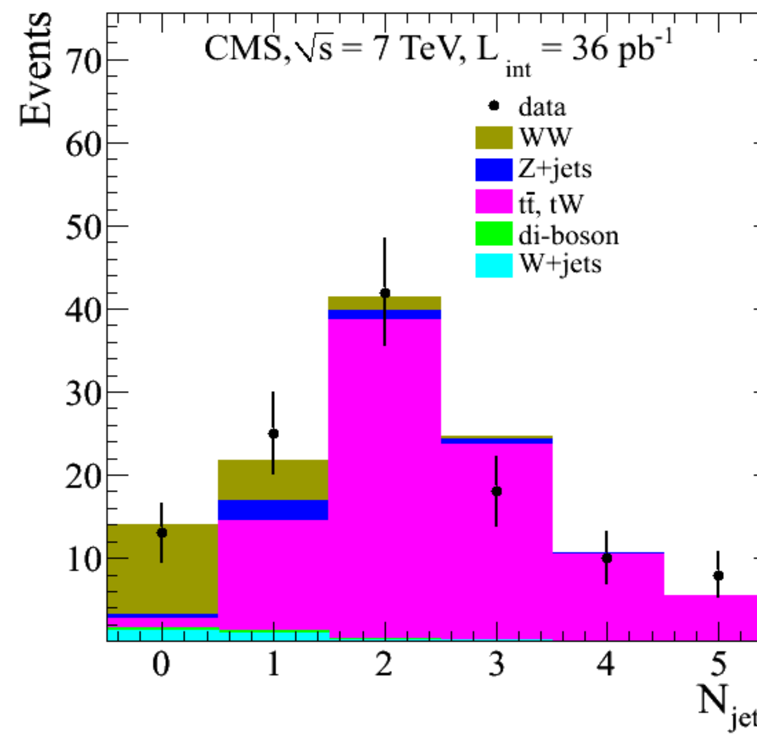
# Final State: $WW \rightarrow 2l2\nu$

Observe 13 candidate *pp* → *WW* events

- measure cross section
- $\sigma(pp \rightarrow WW) = (41.1 \pm 15.3 \pm 5.8 \pm 4.5(L))$ pb
- main background for Higgs to *WW*



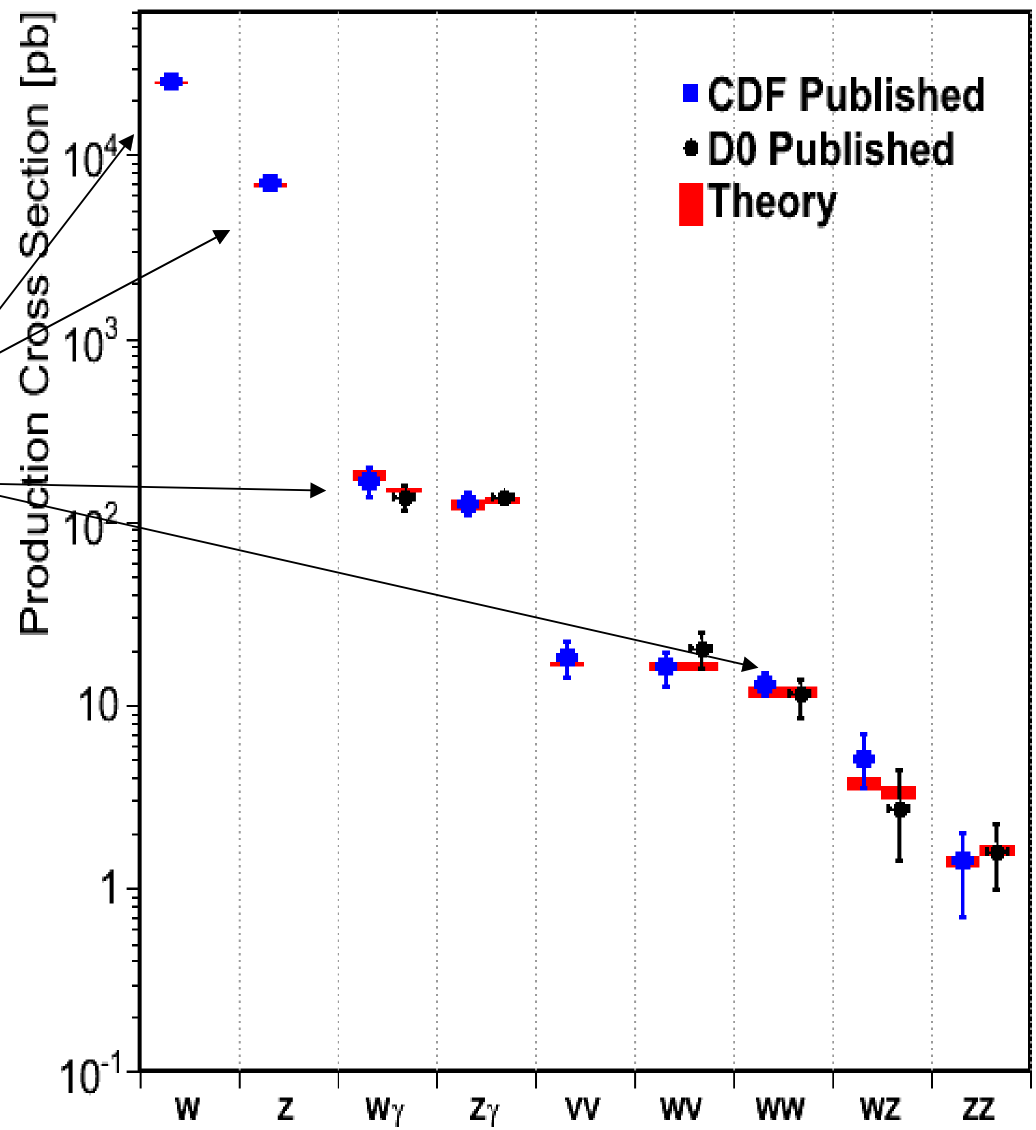

*http://arxiv.org/abs/1102.5429*



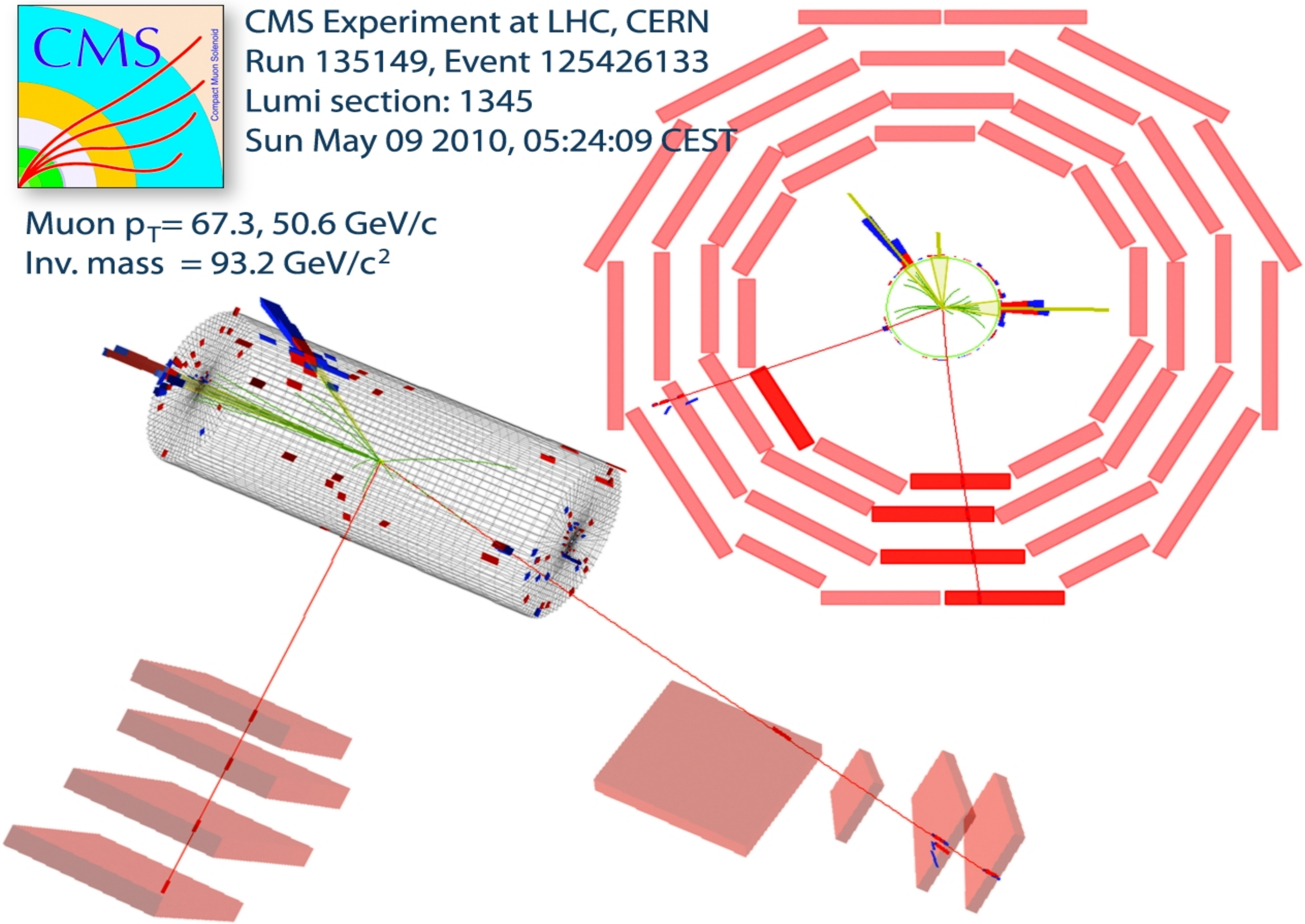
# *Experiment Status*

## Detectors work very well

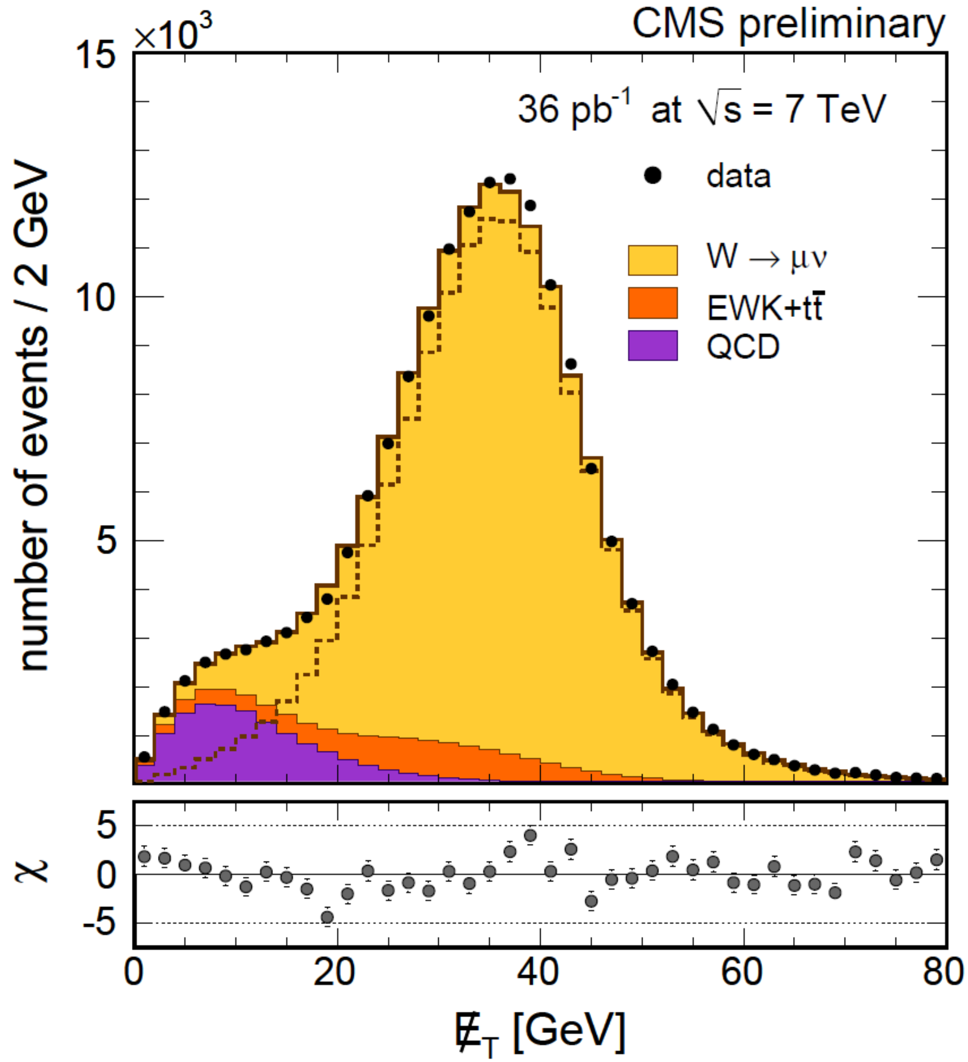
- no show stoppers
- excellent understanding
- first measurements out
- *W*, *Z* as example
- $W\gamma$, $Z\gamma$, *WW* also out
- ways to go, but lumi is rolling in
- others dibosons will follow very soon
- should be ready to do Higgs searches
- all di-bosons by summer

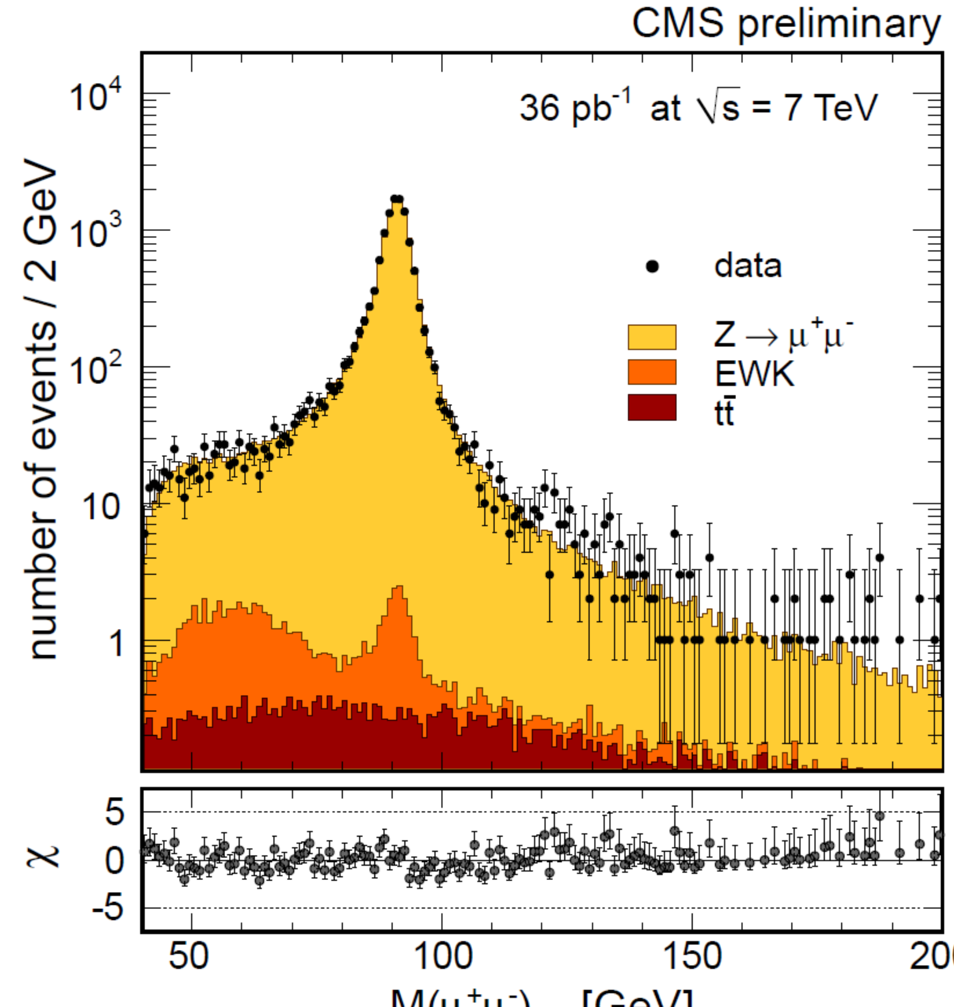


# A Dimuon Event, CMS



# *Muons, CMS*

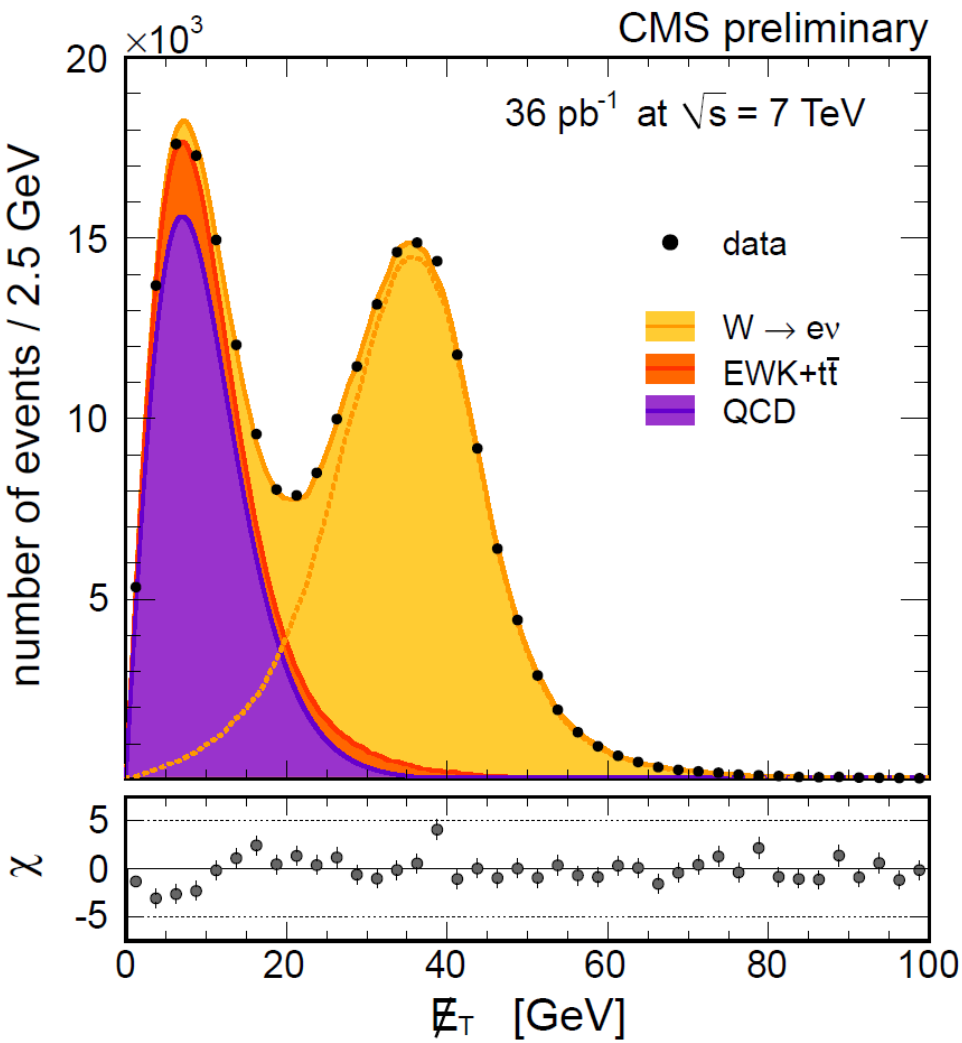


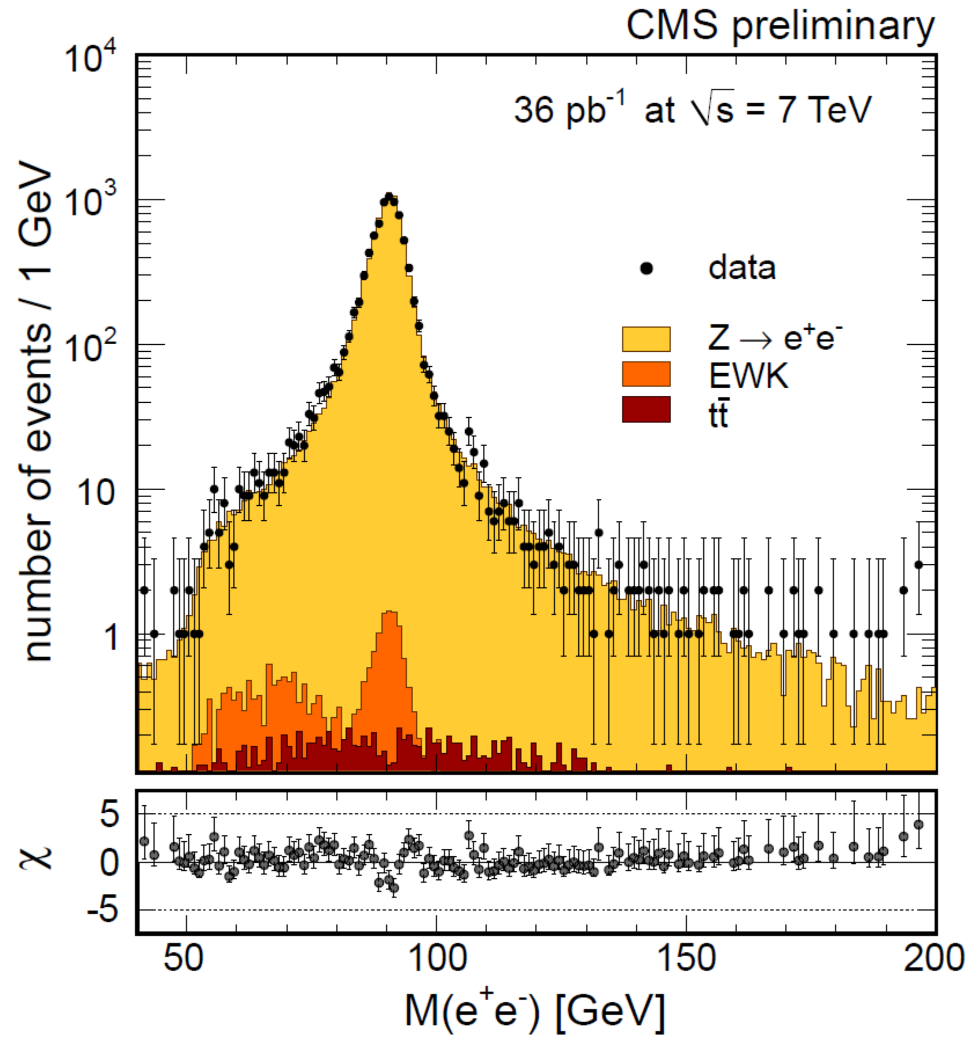




## Muons in CMS

– W/Z cross section in 36 pb$^{-1}$, extremely clean dimuons

# Electrons, CMS




## Electrons in CMS

– W/Z cross section in 36 $pb^{-1}$, extremely clean dielectrons