Unveiling the Mystery of Mass

the newest from CMS and prospects

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Physics: Understanding World Around Us

What is the world around us made of?

- try to bring order to the apparent chaos

Aristotle

- earth, water, air and fire (classical 4 elements)

Democritus

- atomic theory: discrete indivisible pieces make up matter
- early 19 hundreds: first observations 'indivisible atom'

Rutherford (it is the 100th anniversary)

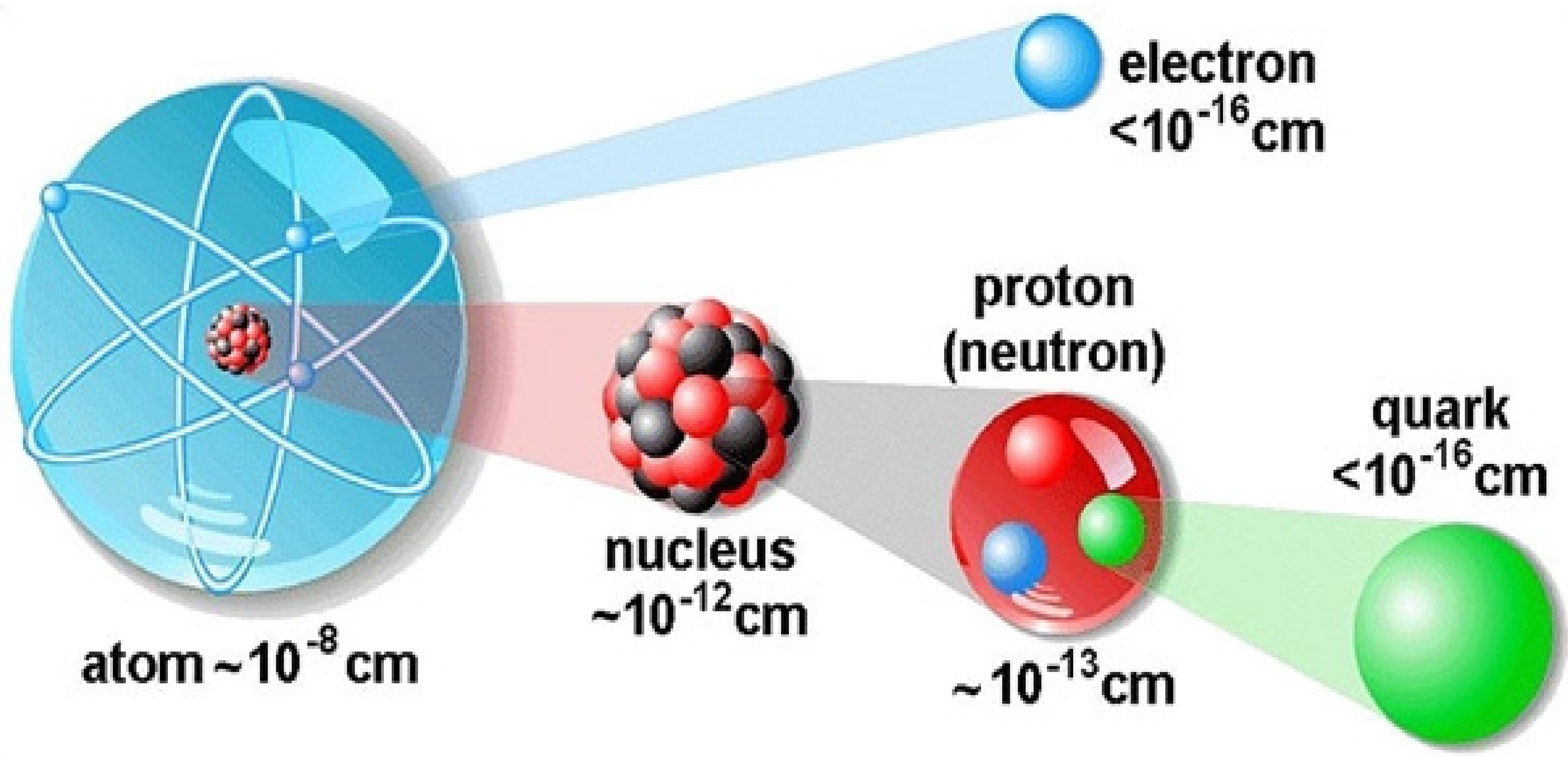
- atom has structure: nucleus and electron cloud around

Friedman, Kendall & Taylor

- the proton and the neutron are made of quarks

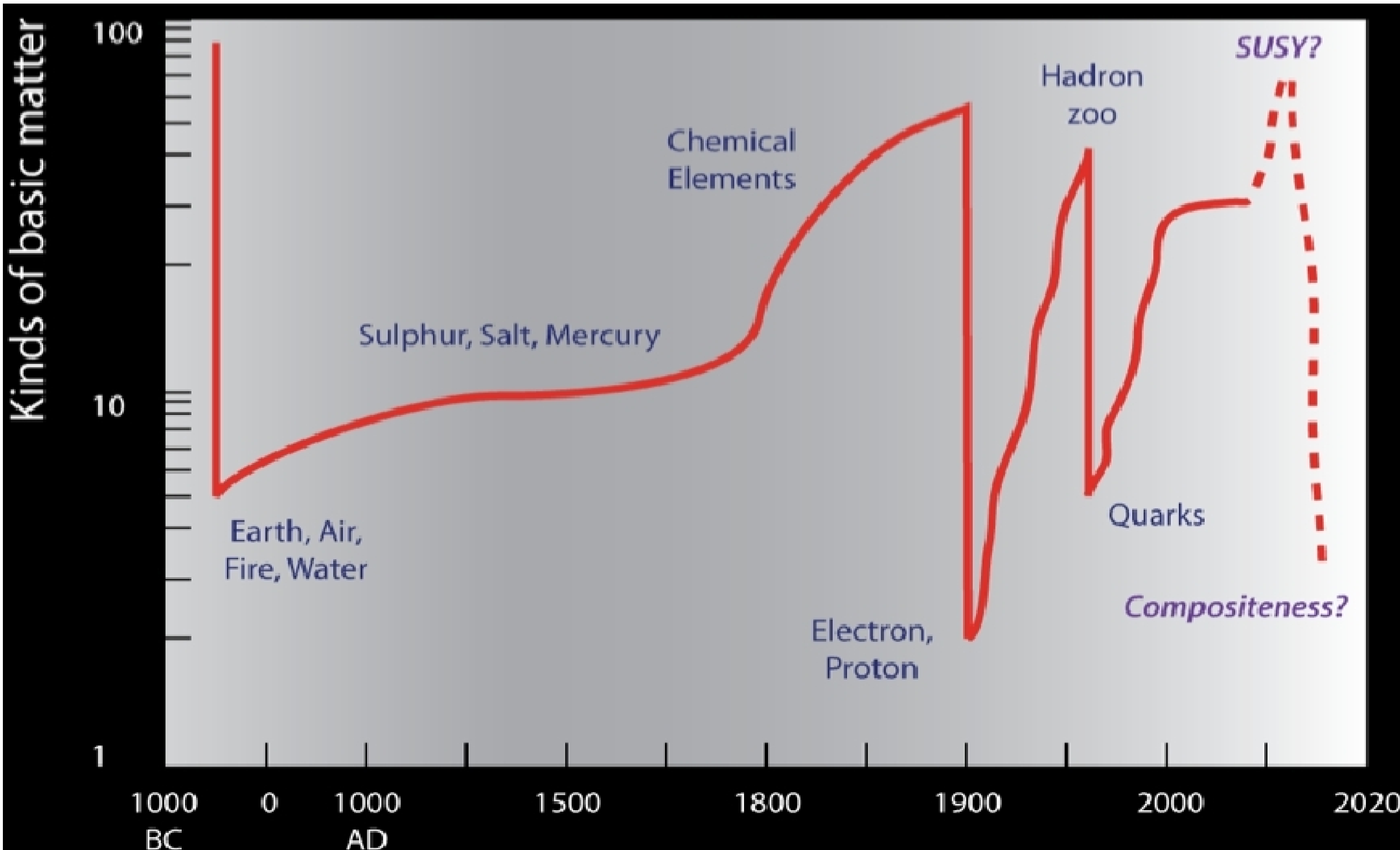
Physics is about Understanding!

Pealing the onion



Physics is about Understanding!

Putting order into the Chaos of appearances....



Interesting Transition

Initial key concept

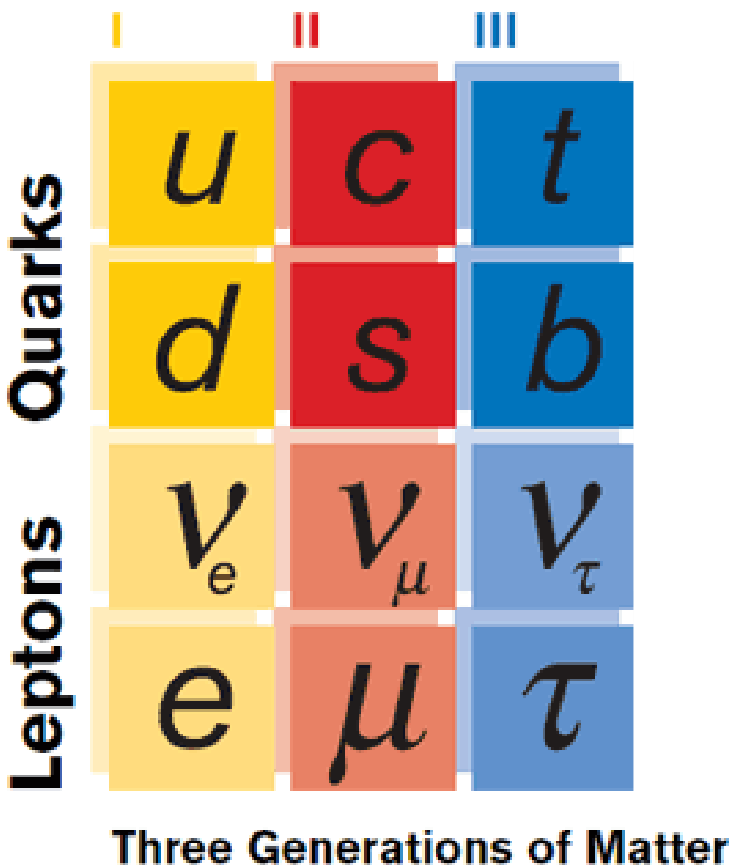
- dissect existing matter (~ nuclear physics)
- electron and proton and neutrons are the main components

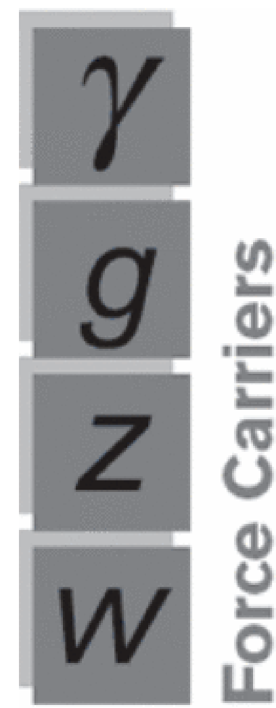
Todays concept

- provide energy and let particles form respecting $E = m\,c^2$ (~ particle physics or high energy physics)
- particle form on statistical basis (non-deterministic)
- the higher the mass the smaller the probability for their creation

The Standard Model of Particle Physics

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





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

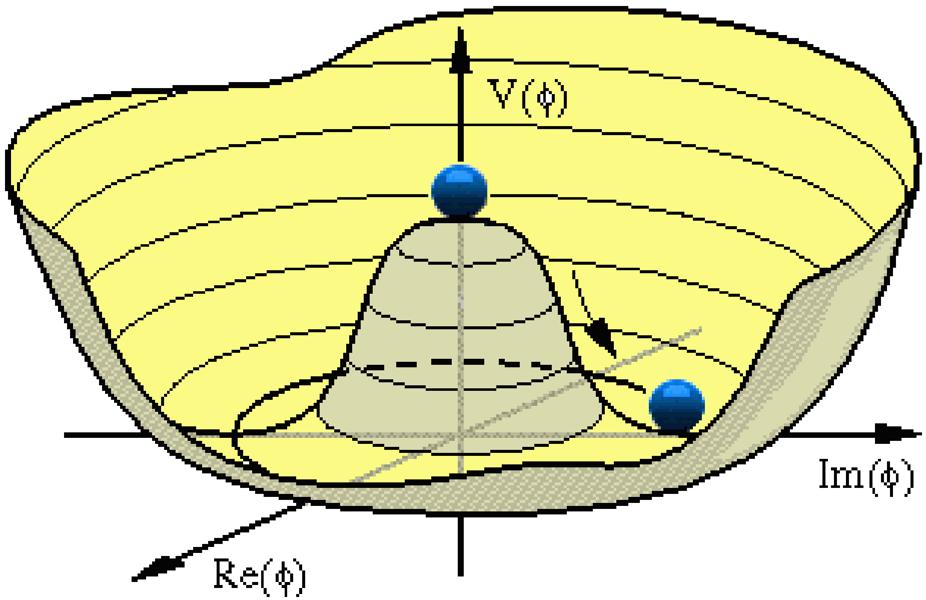
The Standard Model of Particle Physics

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 $\neq 0$
- particles move through field which gives them mass
- no experimental evidence, yet

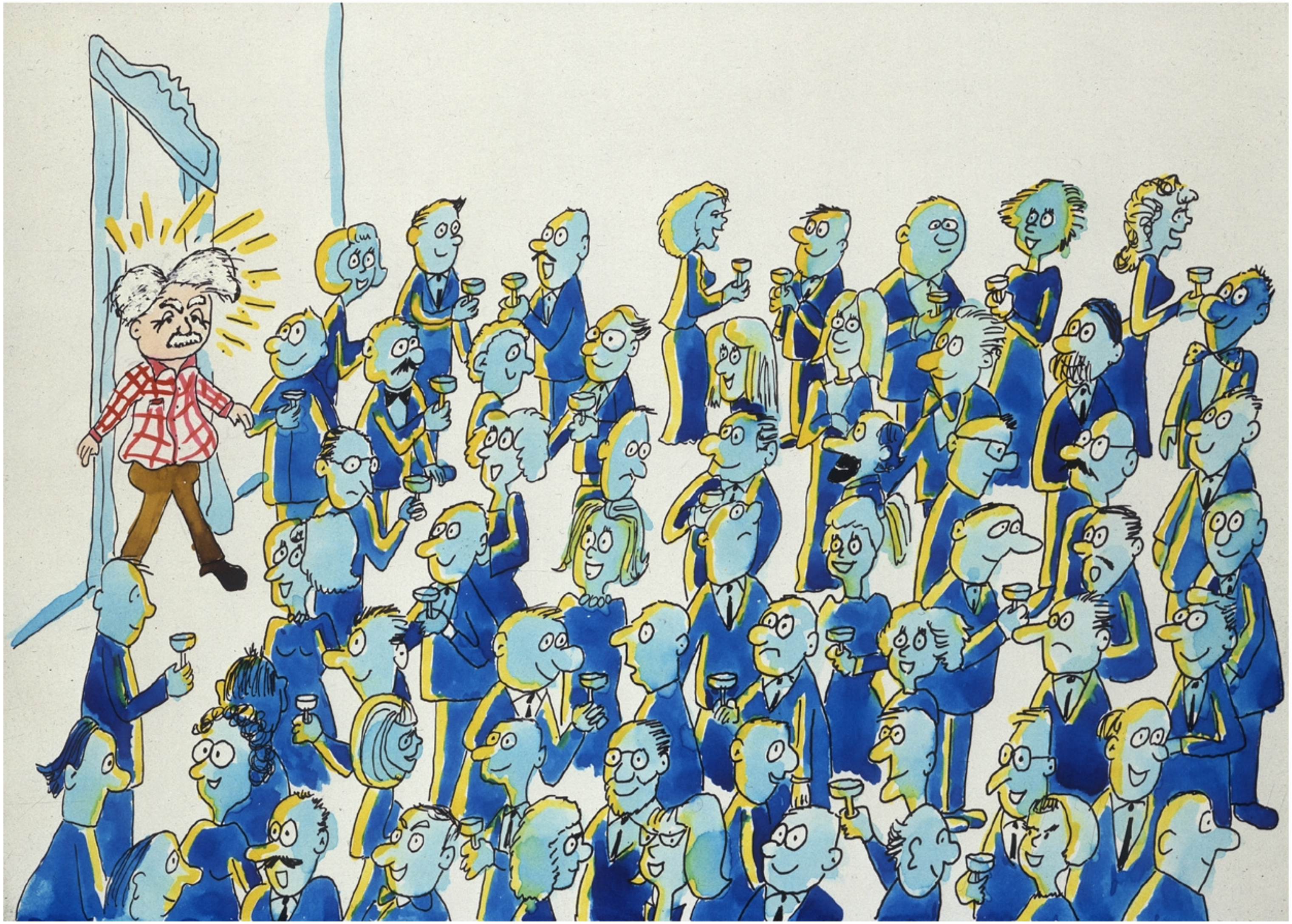


Higgs Mechanism – For Politicians

The Higgs field – Maggy Thatcher put out a bottle of champagne for anybody who could explain the Higgs mechanism. The solution of the winner follows.

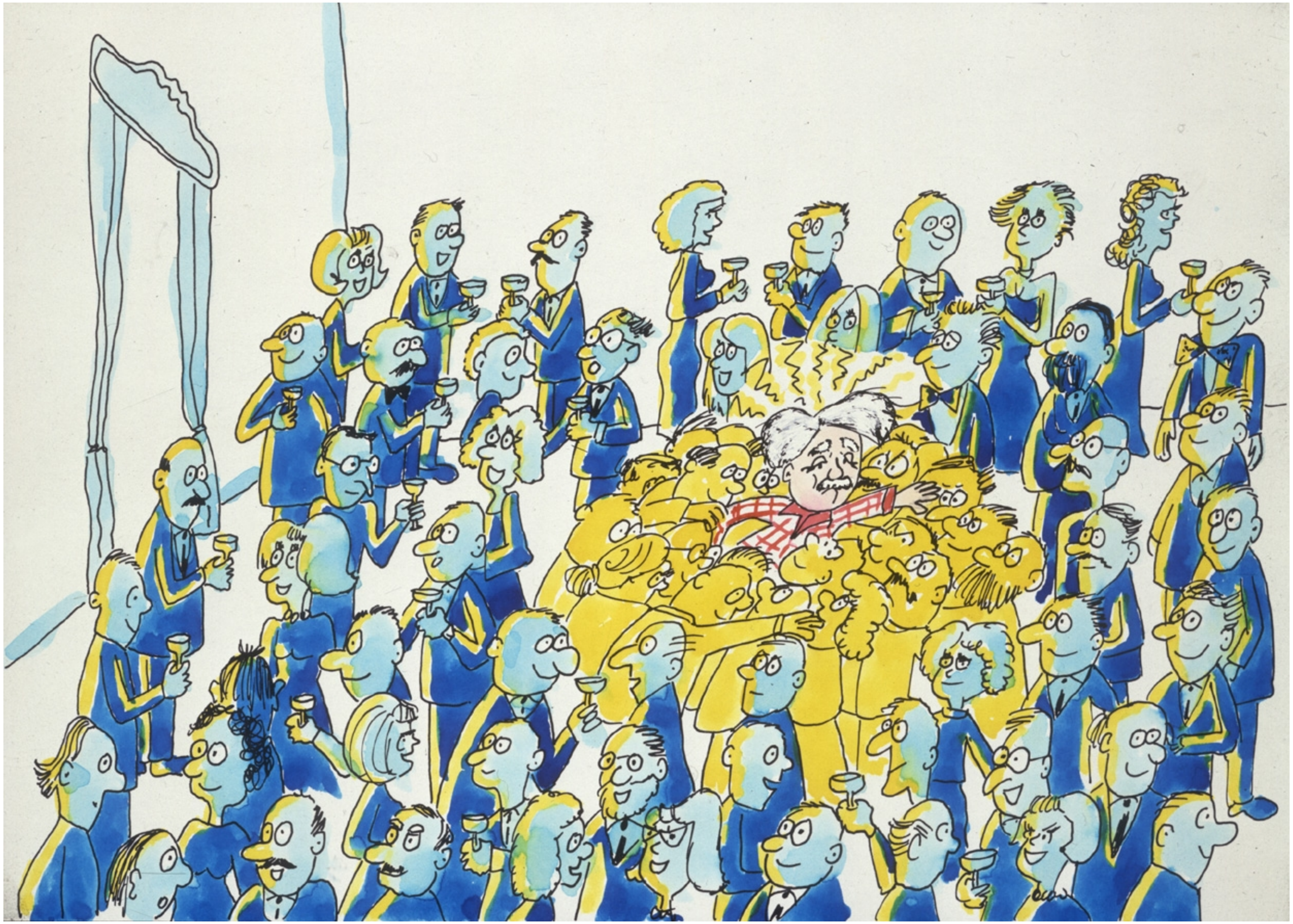
Higgs Mechanism – For Politicians

- The Higgs field with a particle entering



Higgs Mechanism – For Politicians

The Higgs field with a particle having acquired mass



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

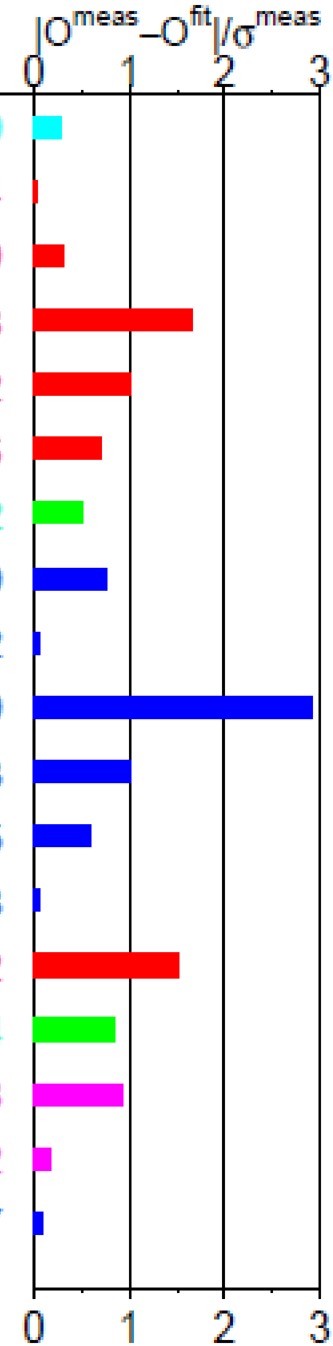
Experimental data

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

Measurements

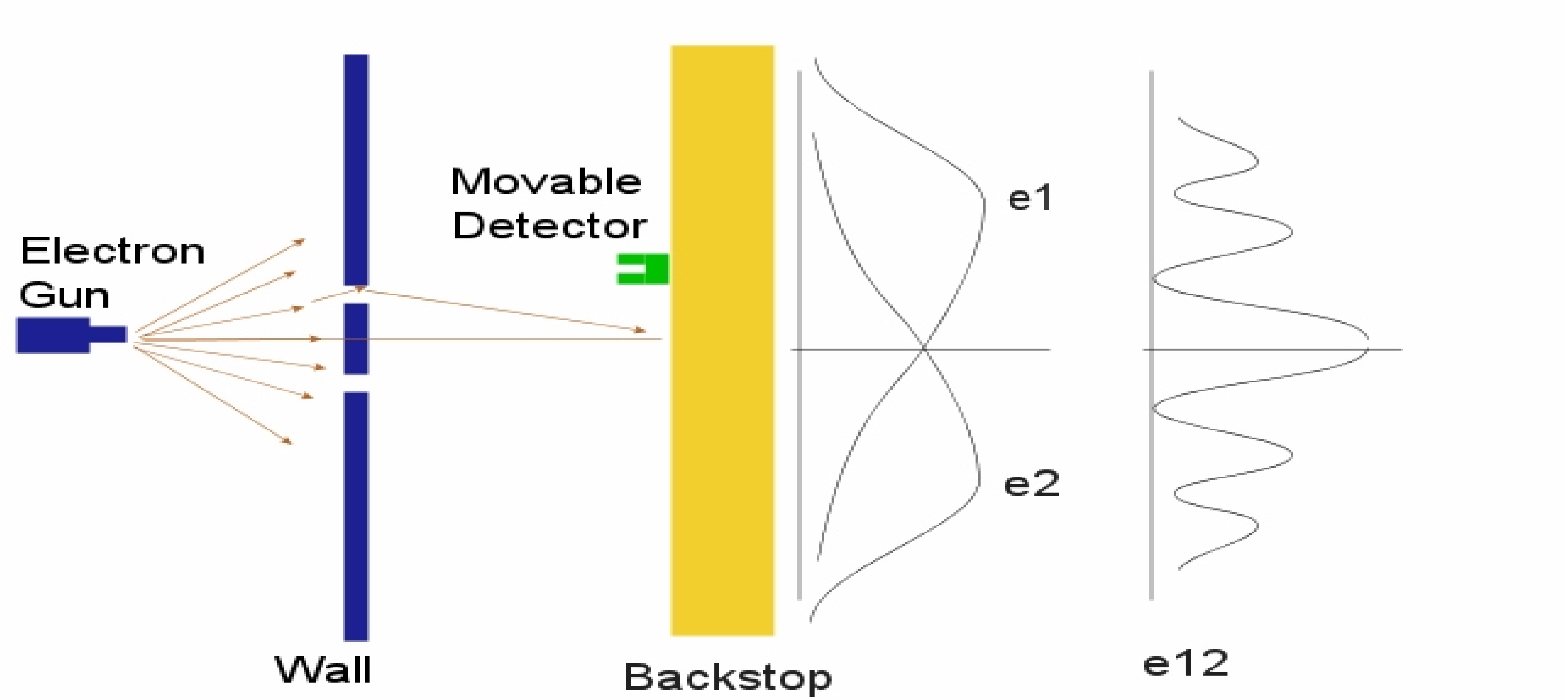
- over a thousand individual measurements combined
- very different accelerator and detector setups
- decent agreement with SM

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



July 2011

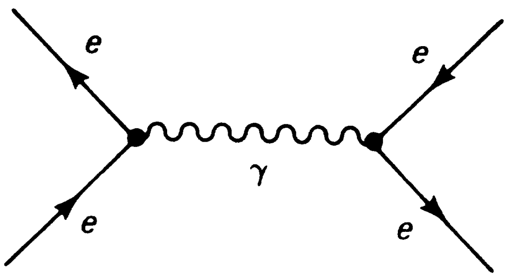
Double Slit Experiment

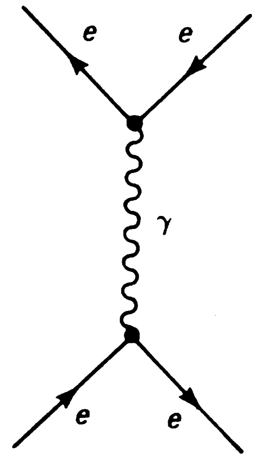


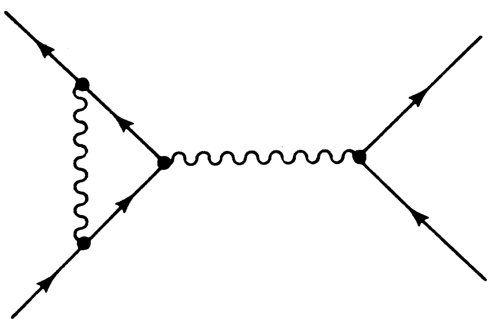
A simple example: double slit experiment

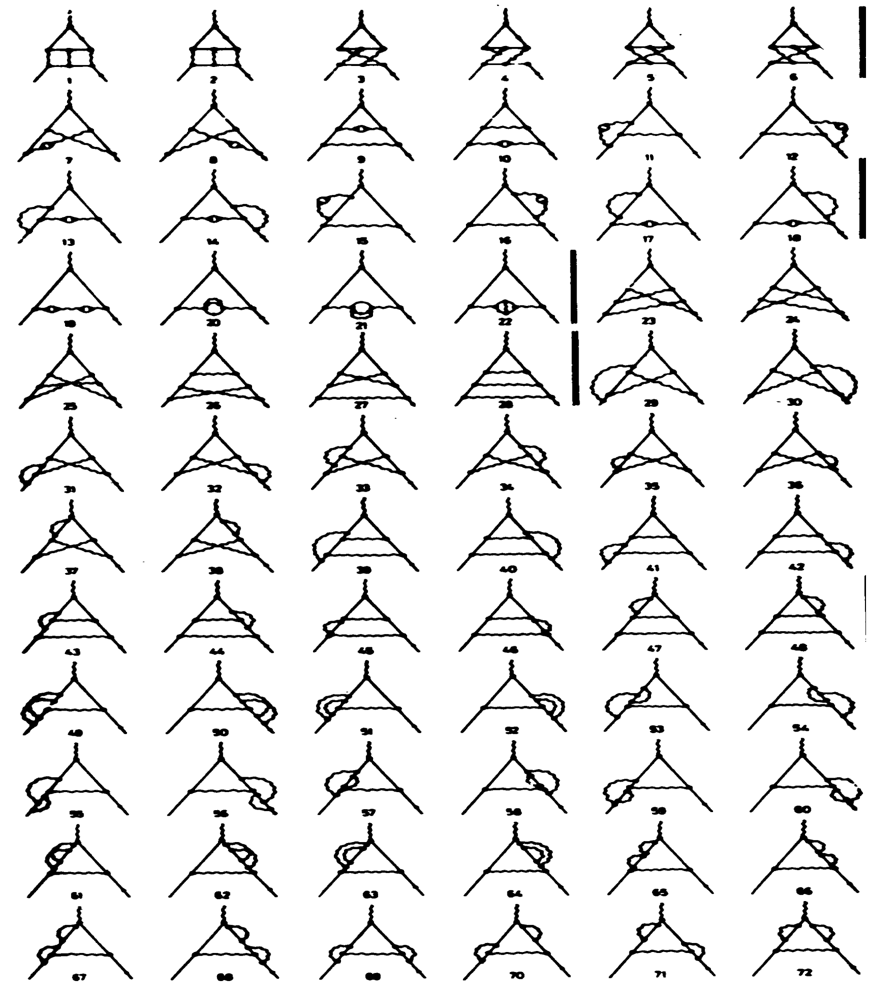
- even a single electron does not go through slit 1 or 2
- every electron goes through both slits at the same time
- an electron is not a simple particle but a distribution

Double Slit → Feynman Diagrams









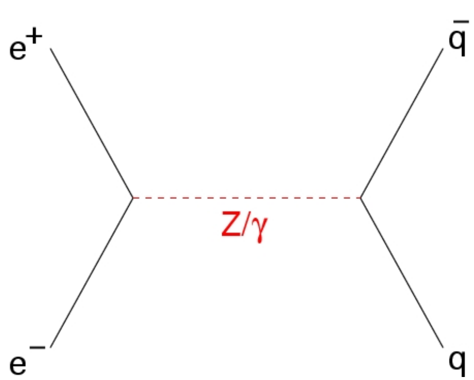
Initial and final state are given

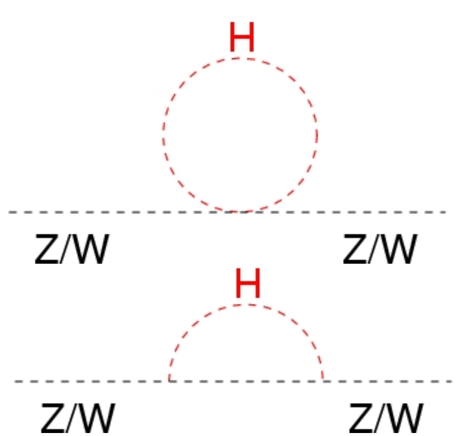
- simplest diagram carries most weight
- picture only correct if every possible path is implemented
- virtual particles do not have to be on-shell.....

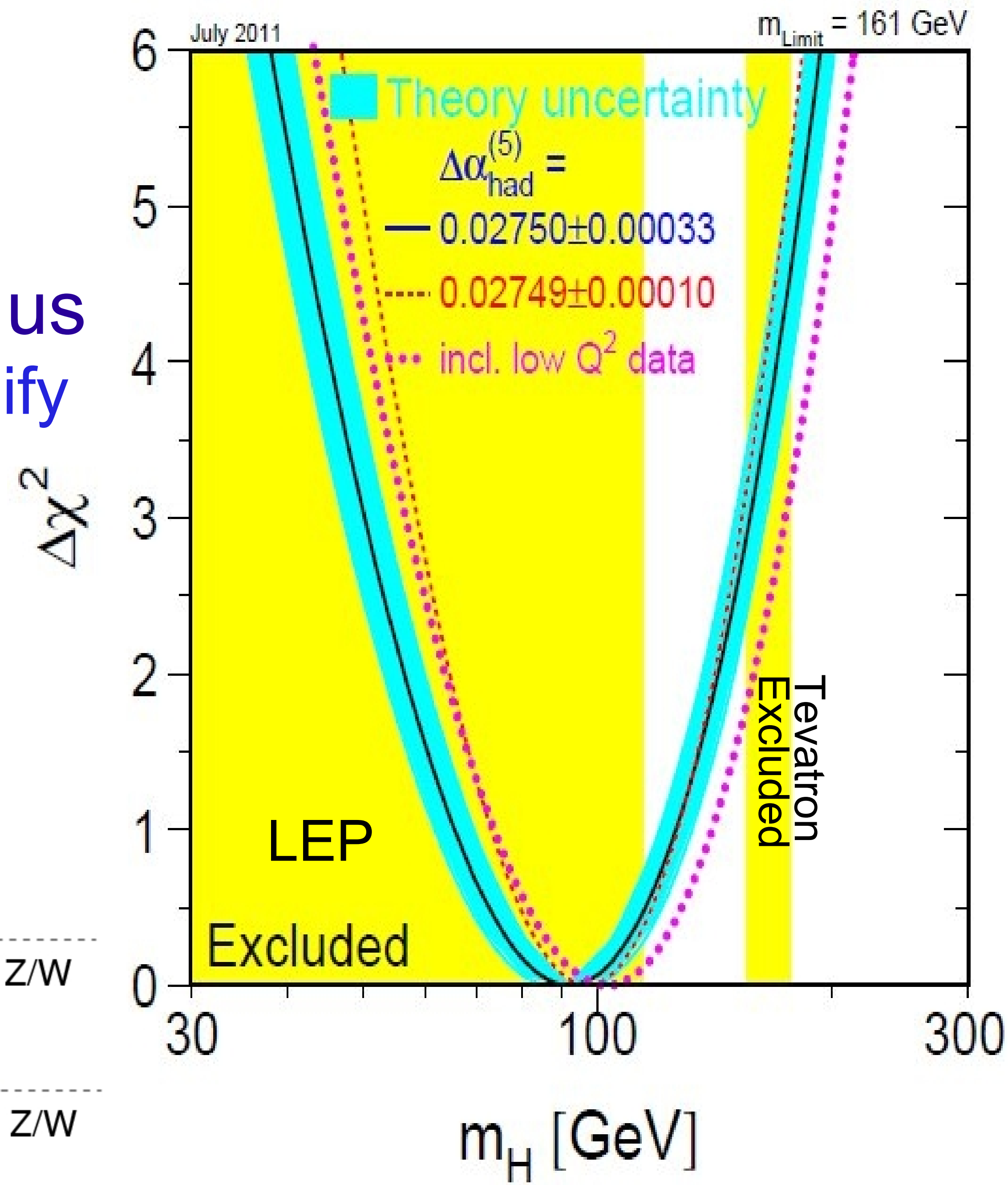
The Standard Model: Higgs Constraints

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







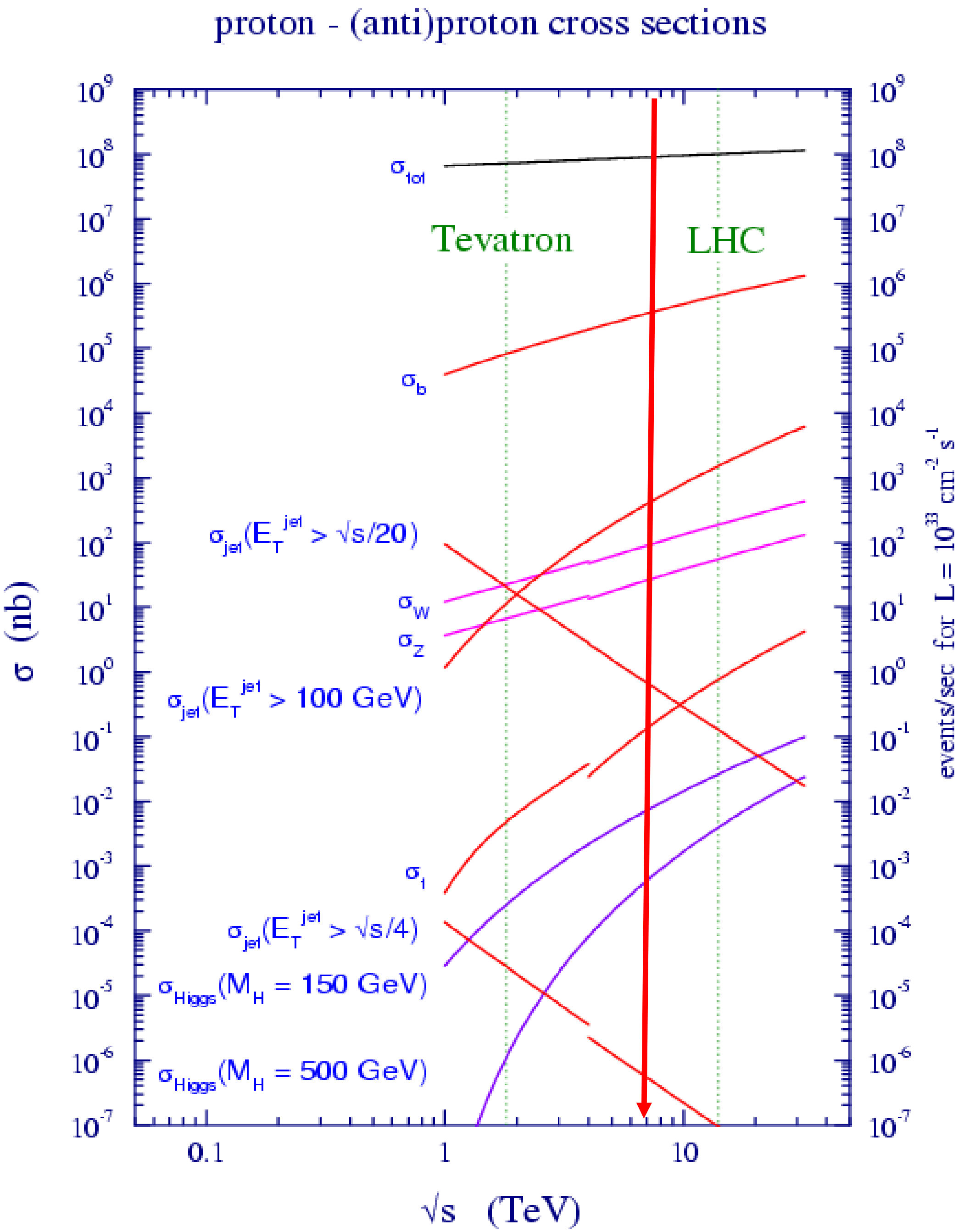
Higgs Hunting Basics

Physics processes

- production relative to σ_{tot}:
  - *bb* at 10^{-3},
  - $W \to \ell\nu$ at 10^{-6} and
  - *Higgs* (*m*=100 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



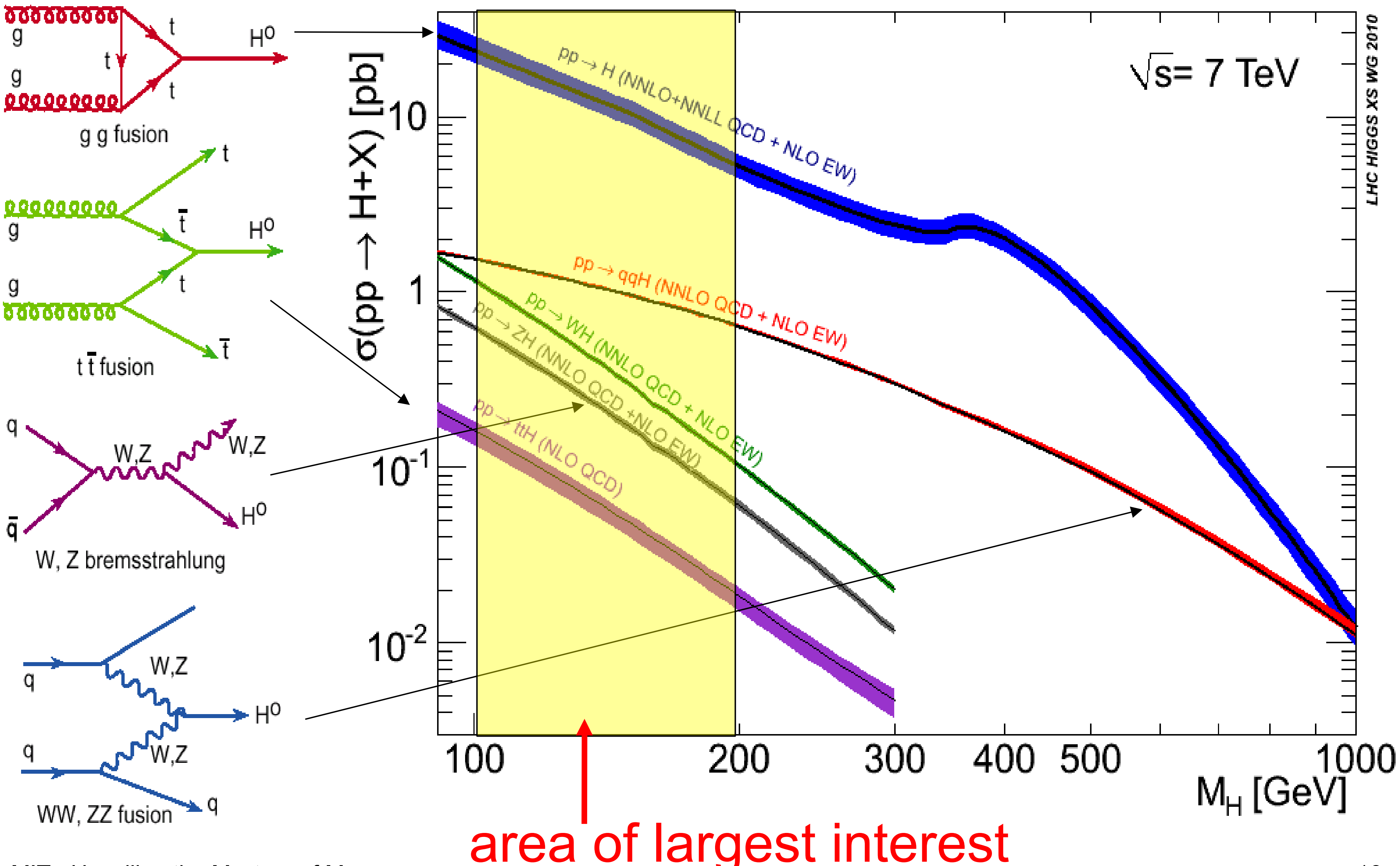
Higgs Hunting Basics

Needle in the hay stack problem

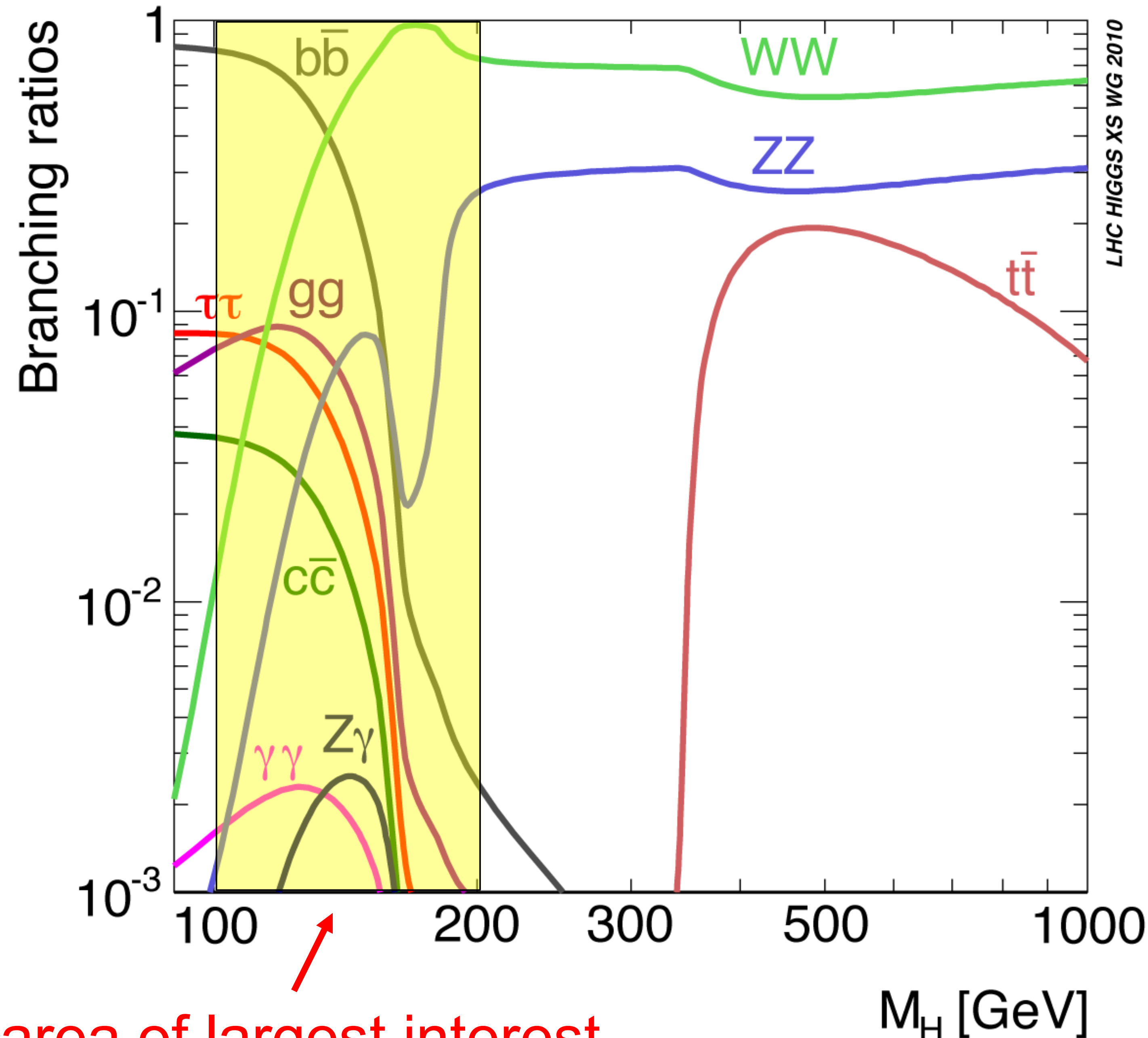
- need high energy
- need lots of data

Higgs Production at the LHC

Higgs production in proton-proton collisions



Higgs Decays (Tevatron/LHC)



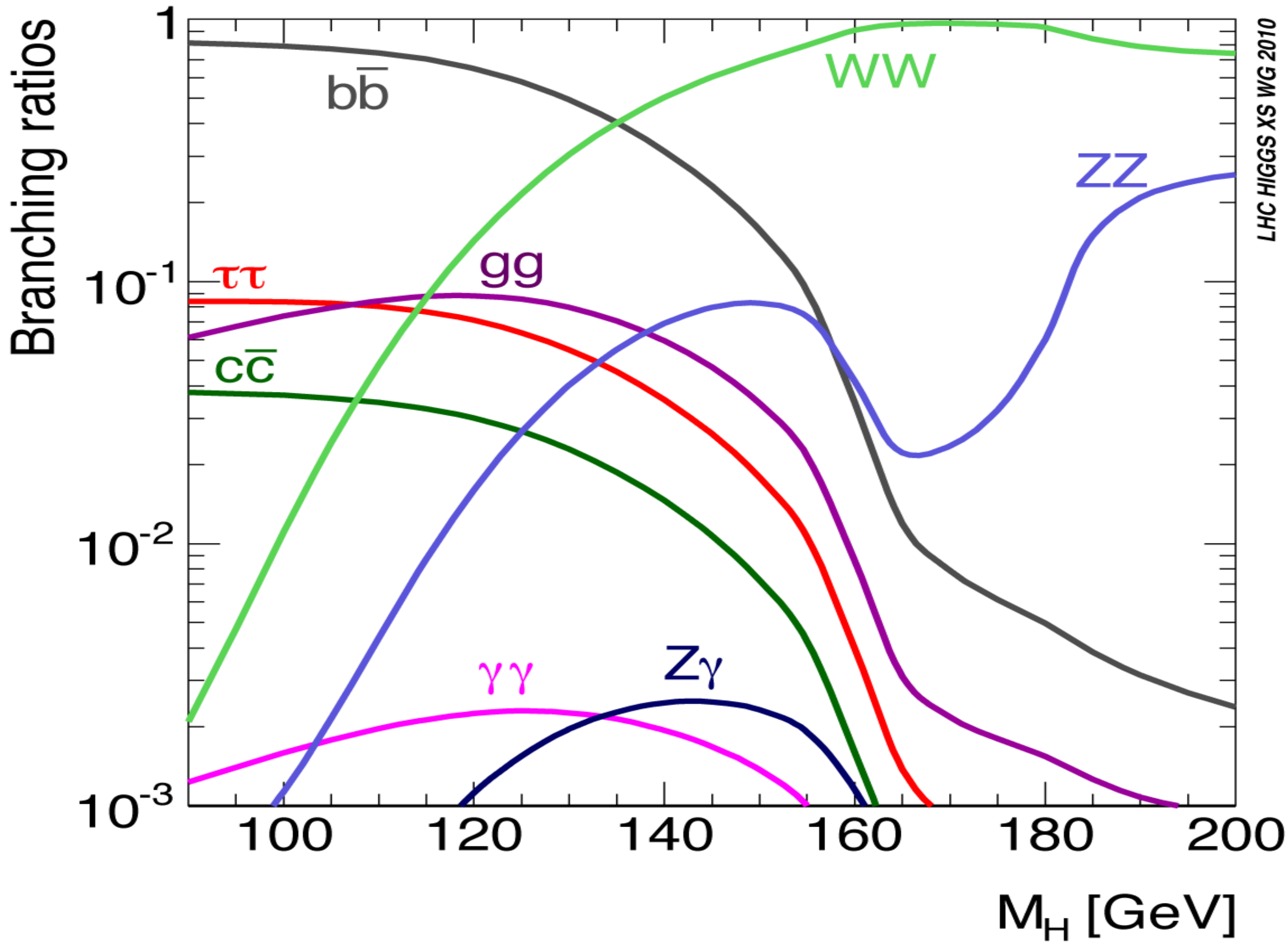
area of largest interest

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

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

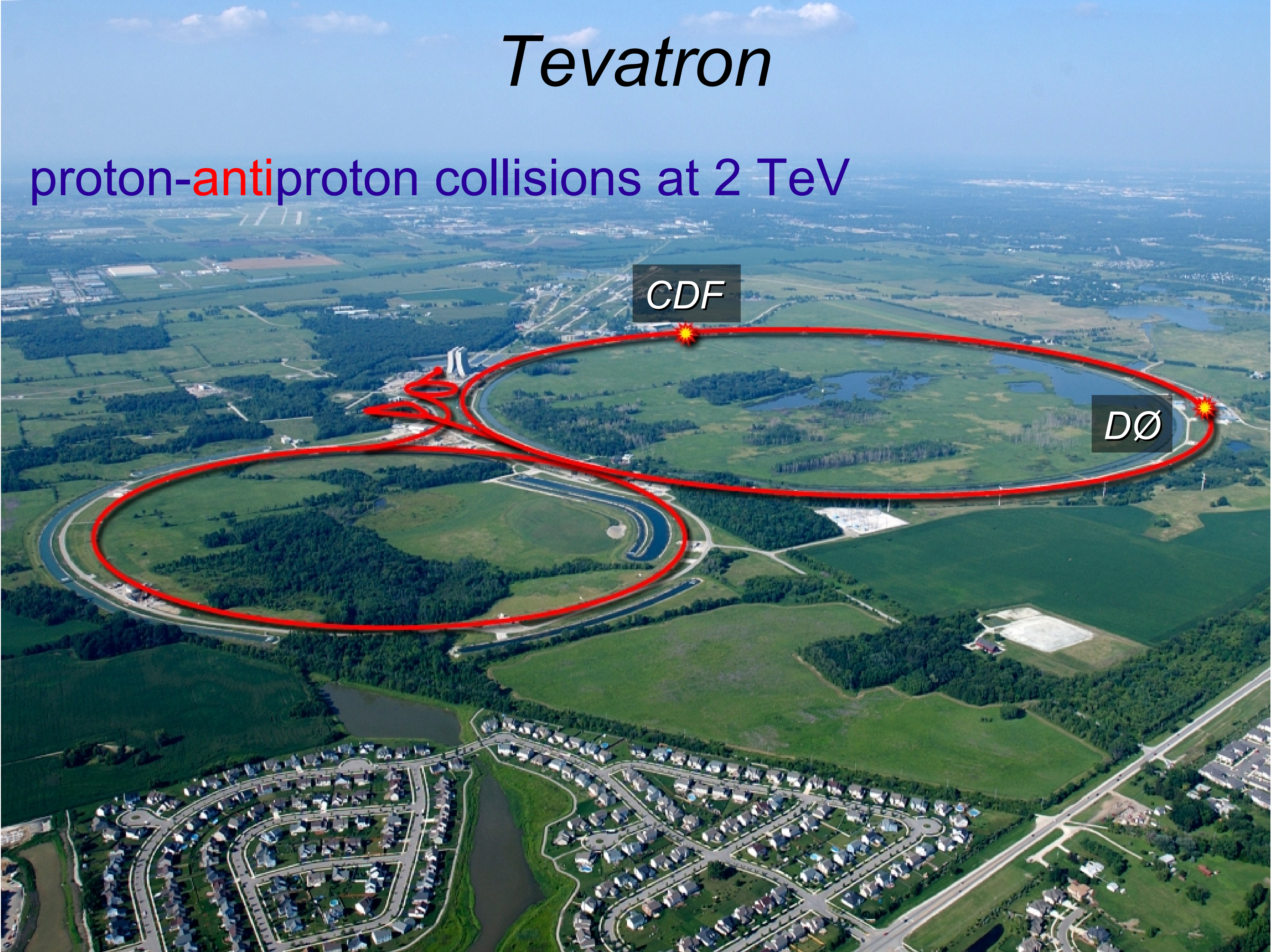
$$\Gamma_{HVV} \sim m_V^4$$

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

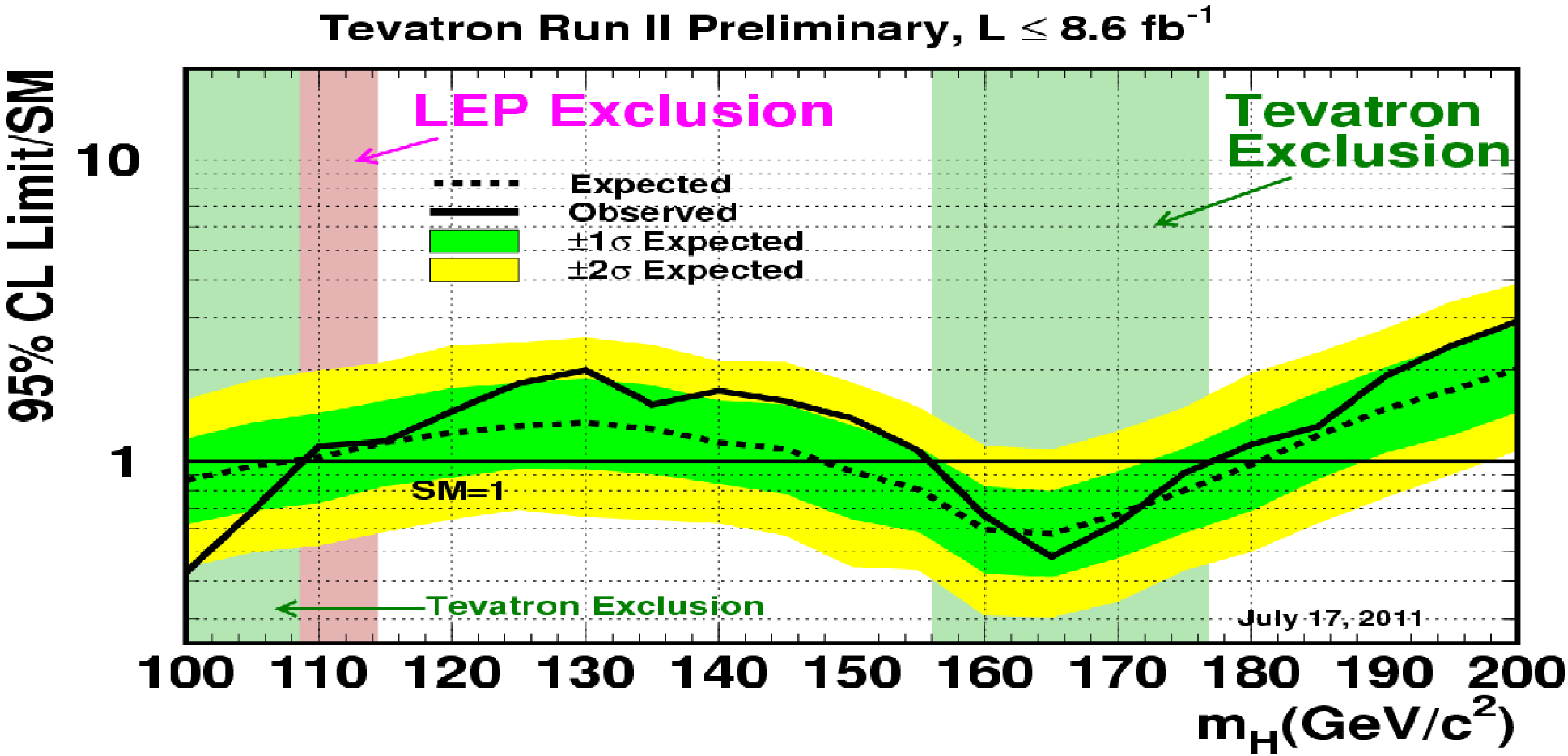
– common: leptons/photons essential for any search

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

LHC Location

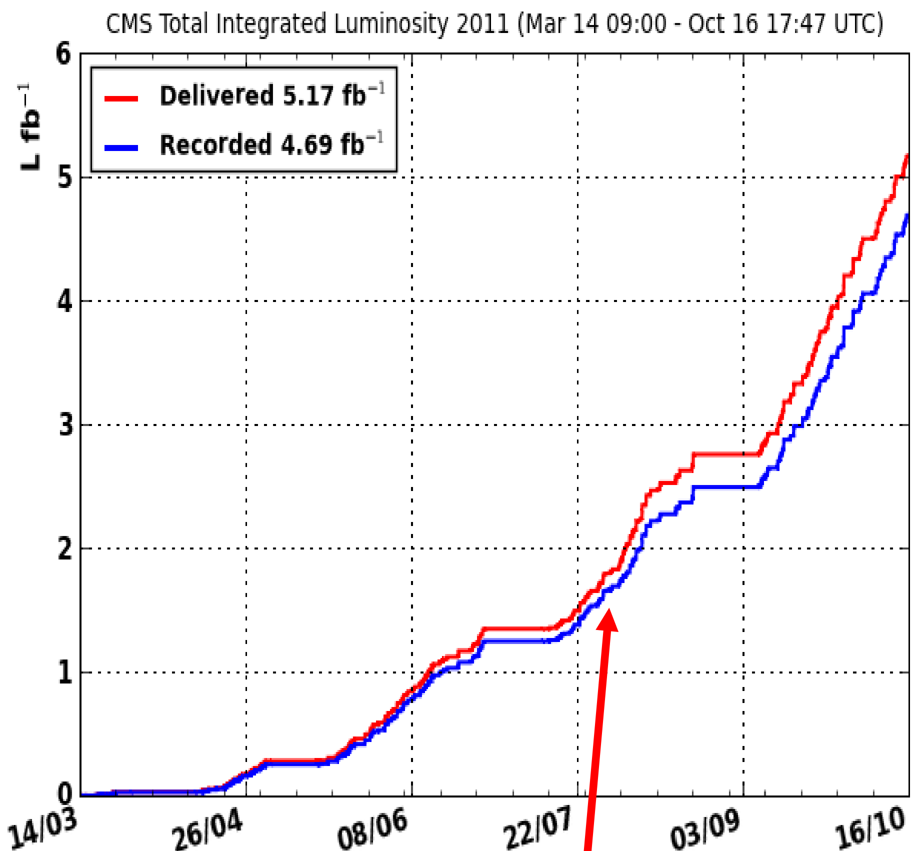
Proton-proton collisions at 7 TeV (up to 14 TeV)

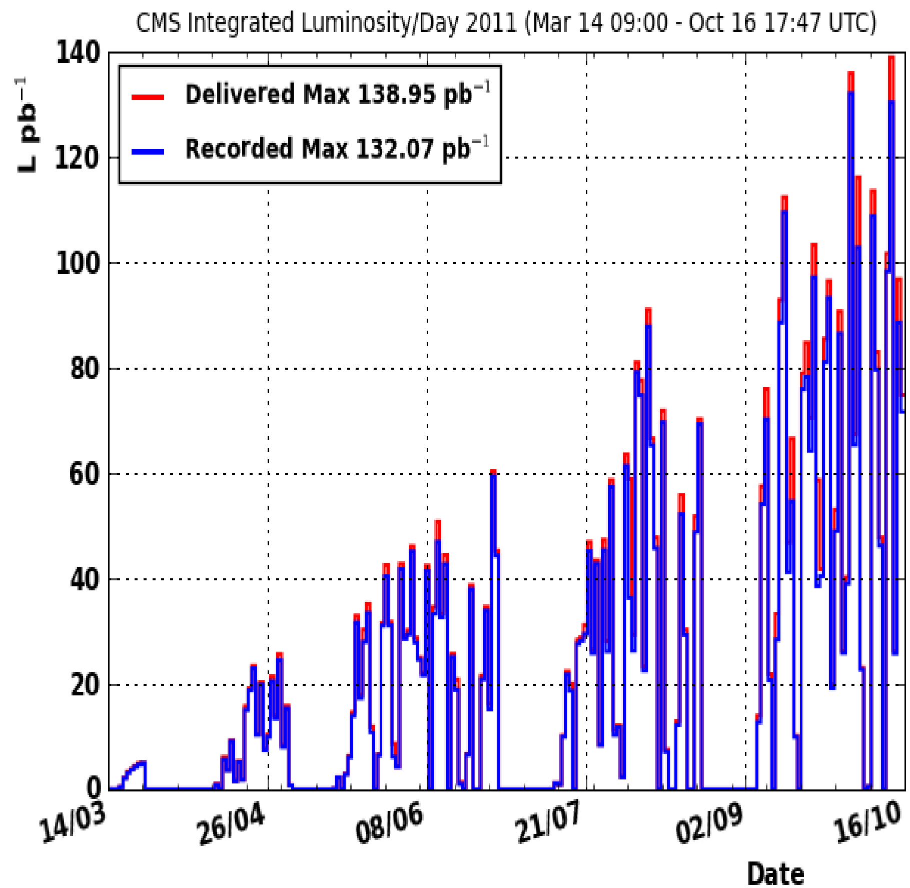
LHC Status

Super short summary

- proceeding with extreme caution
- no show stoppers so far
- nom. bunch intensity reached
- bunch trains commissioned easily
- no beam related quench (yet)
- very clean beams
- machine parameters better then expected
- all goals reached
- 2011 smooth running

Delivered and Recorded Collisions



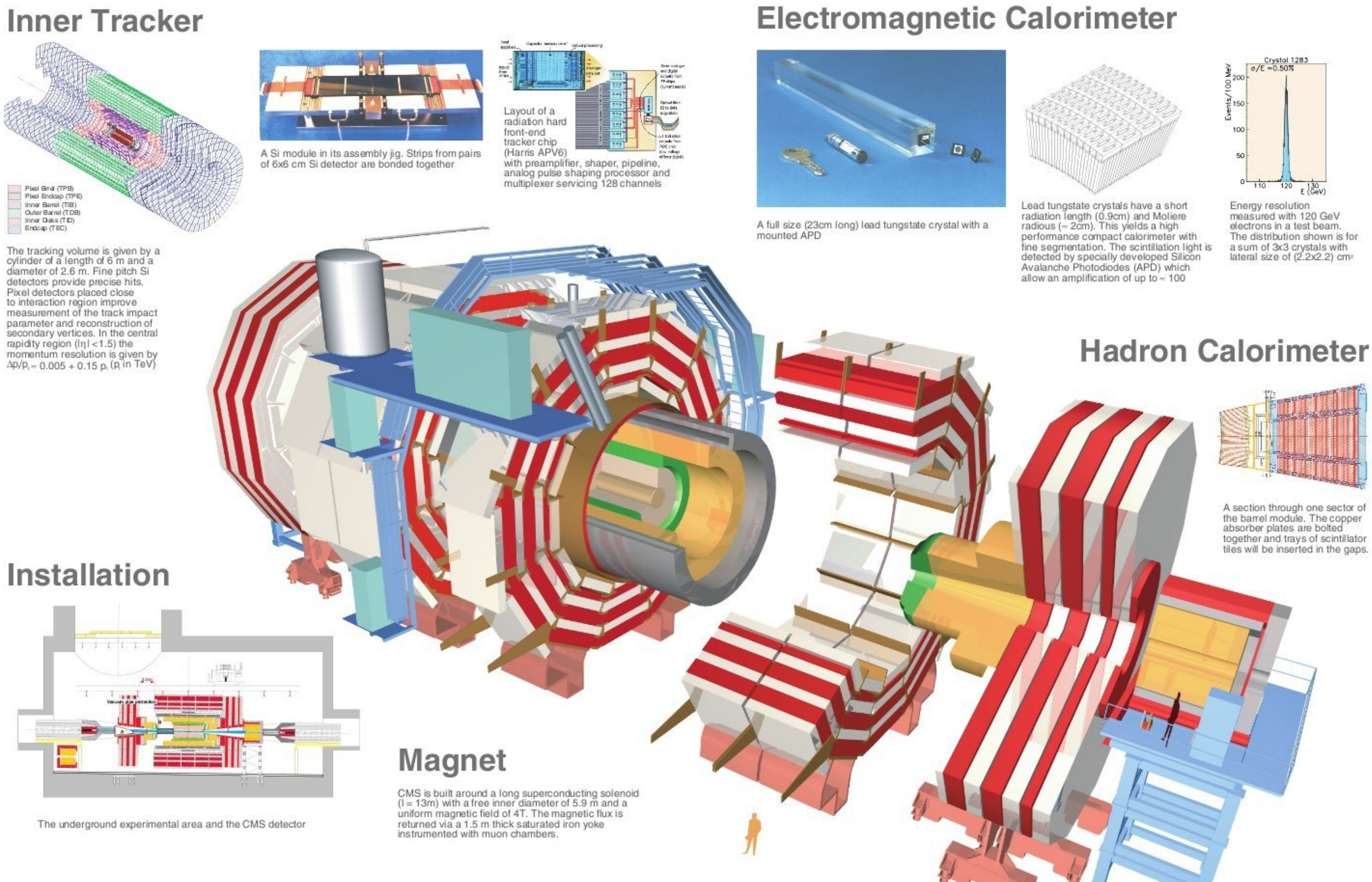


Lepton-Photon

LHC performs better than expected

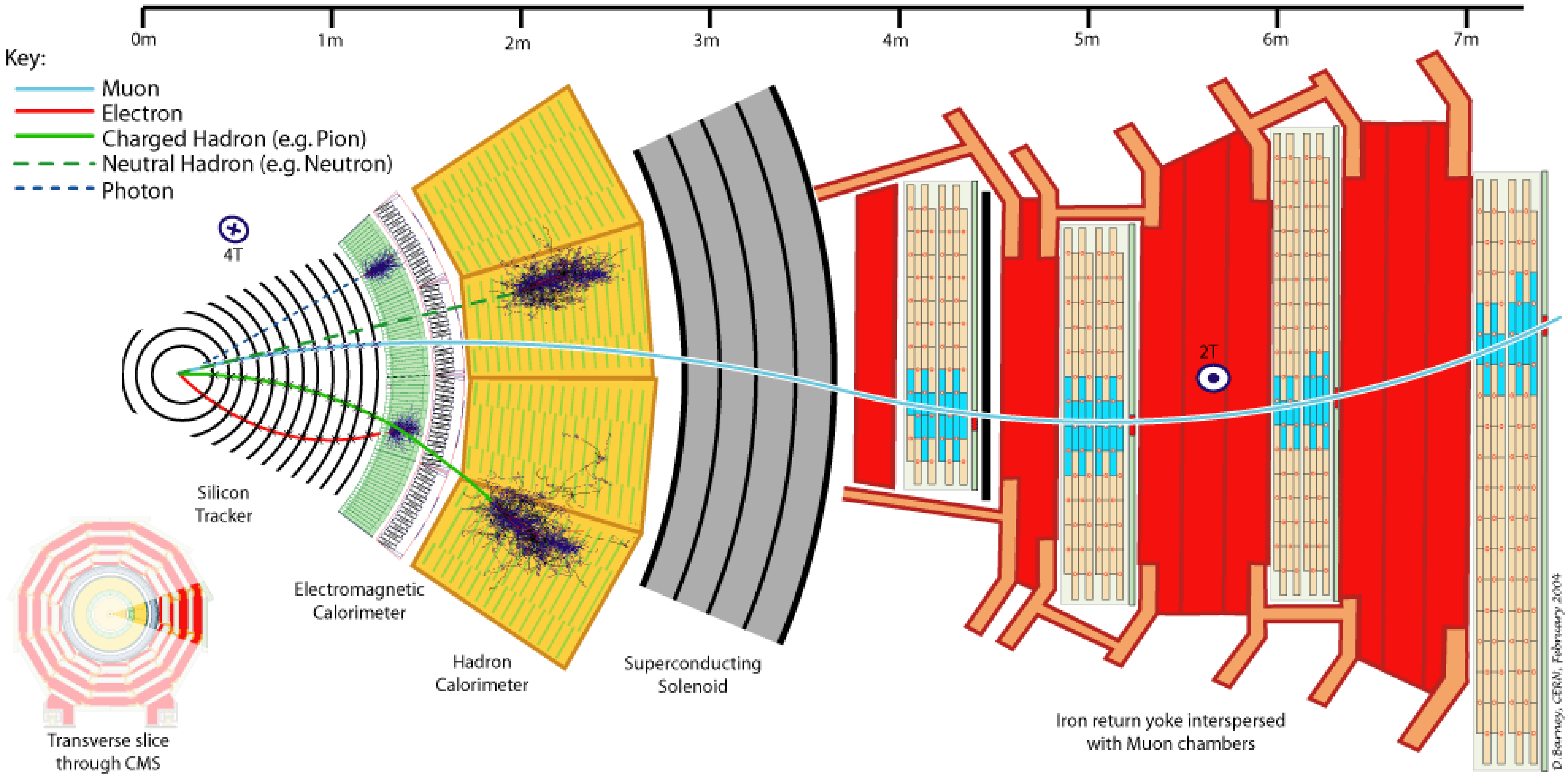
- summer conference based on 1.66/fb (for Lepton-Photon)
- already 4.5/fb recorded, expect ~5/fb (factor larger than 3)

CMS Overview



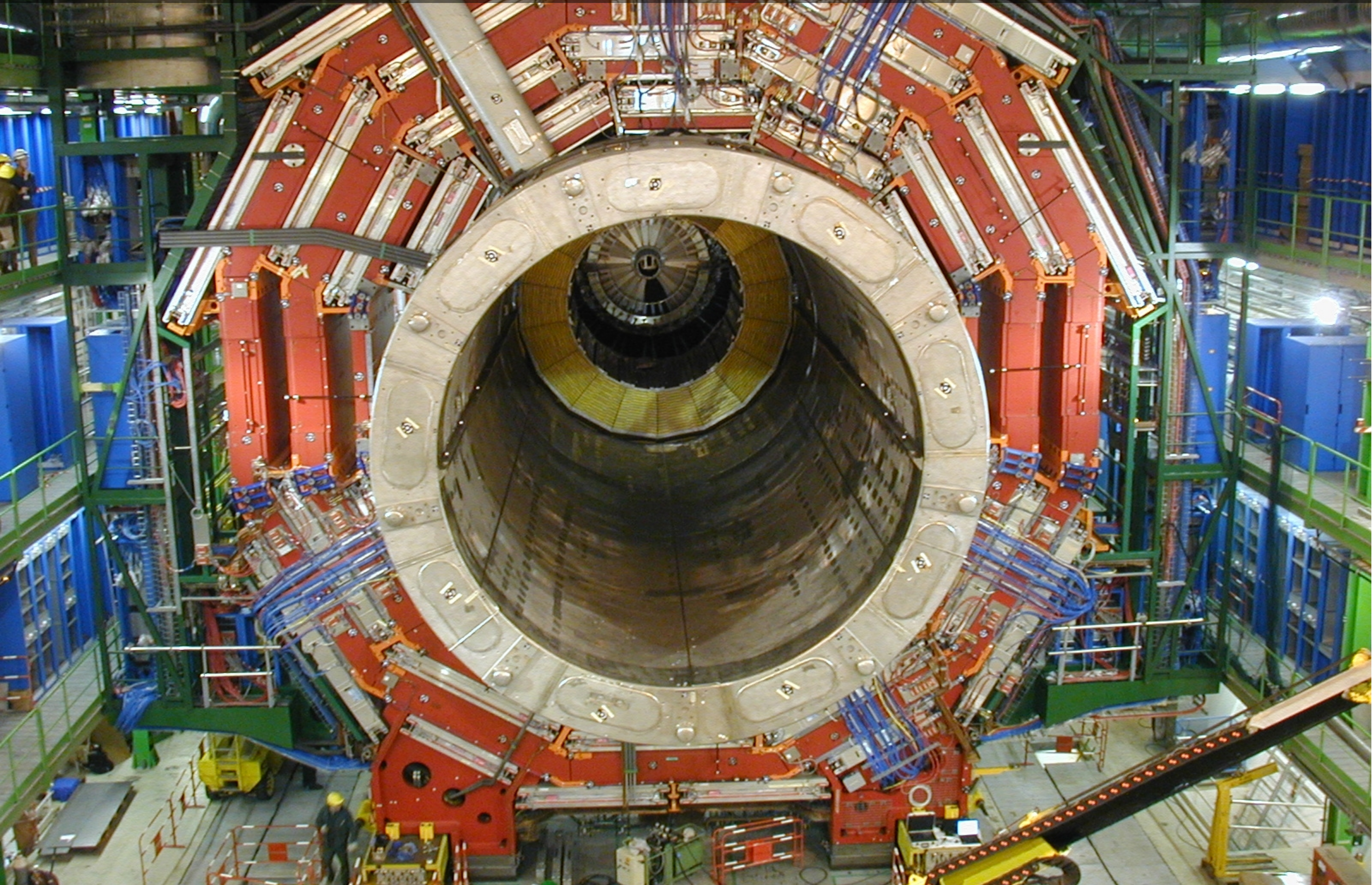
12500 T, 15m x 15m x 21m

CMS Overview



CMS Empty Cavern

CMS Detector in the Cavern



First 'Touching' Protons, CMS

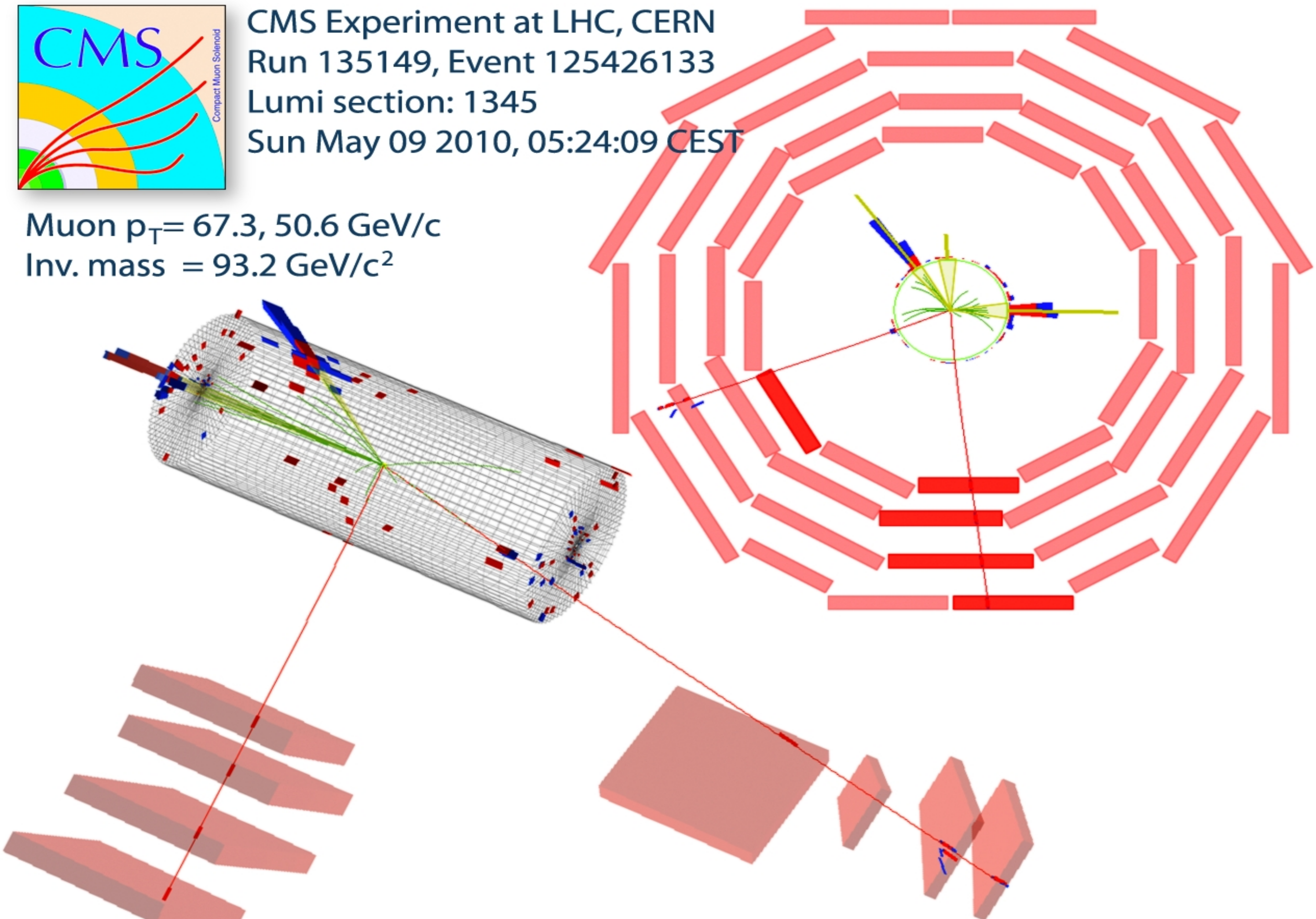
Jim (Spokesperson) sees it coming!

First beams (Nov 20, 2009), ATLAS

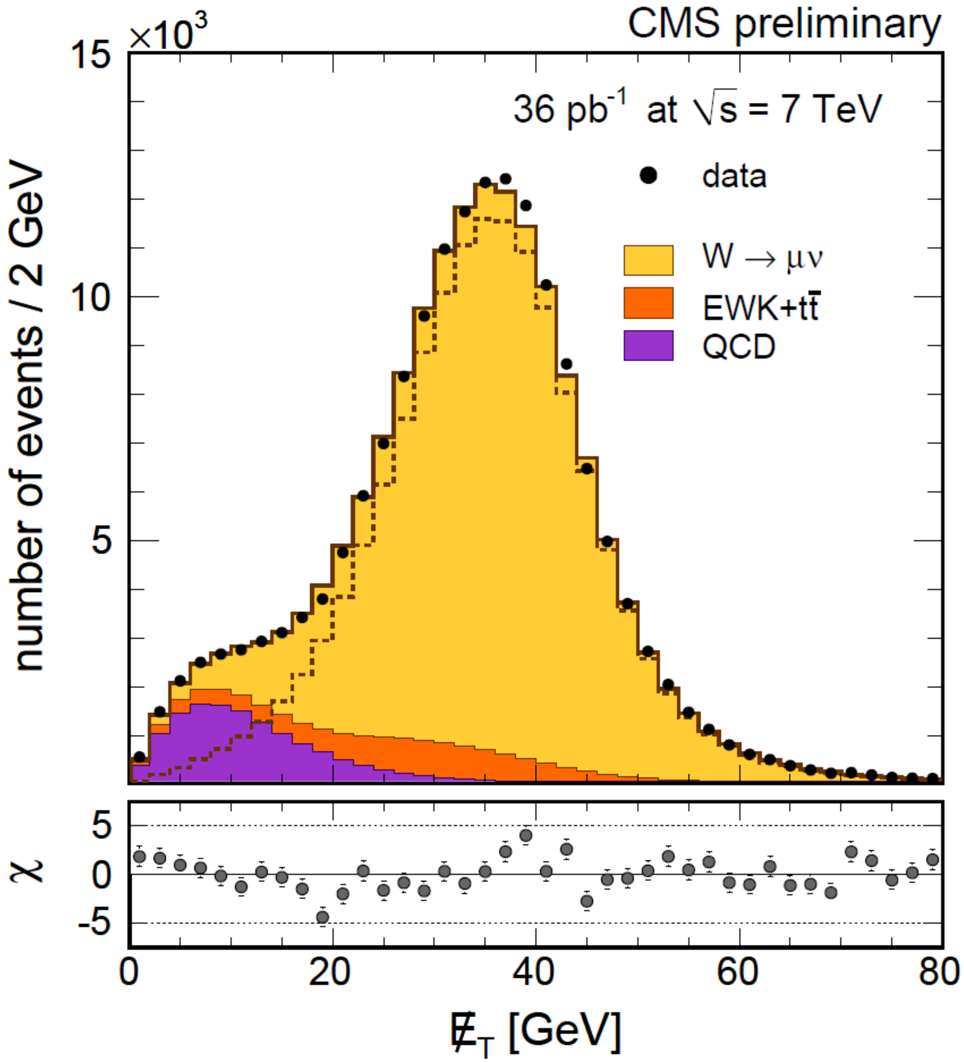
Of Course there was Champagne

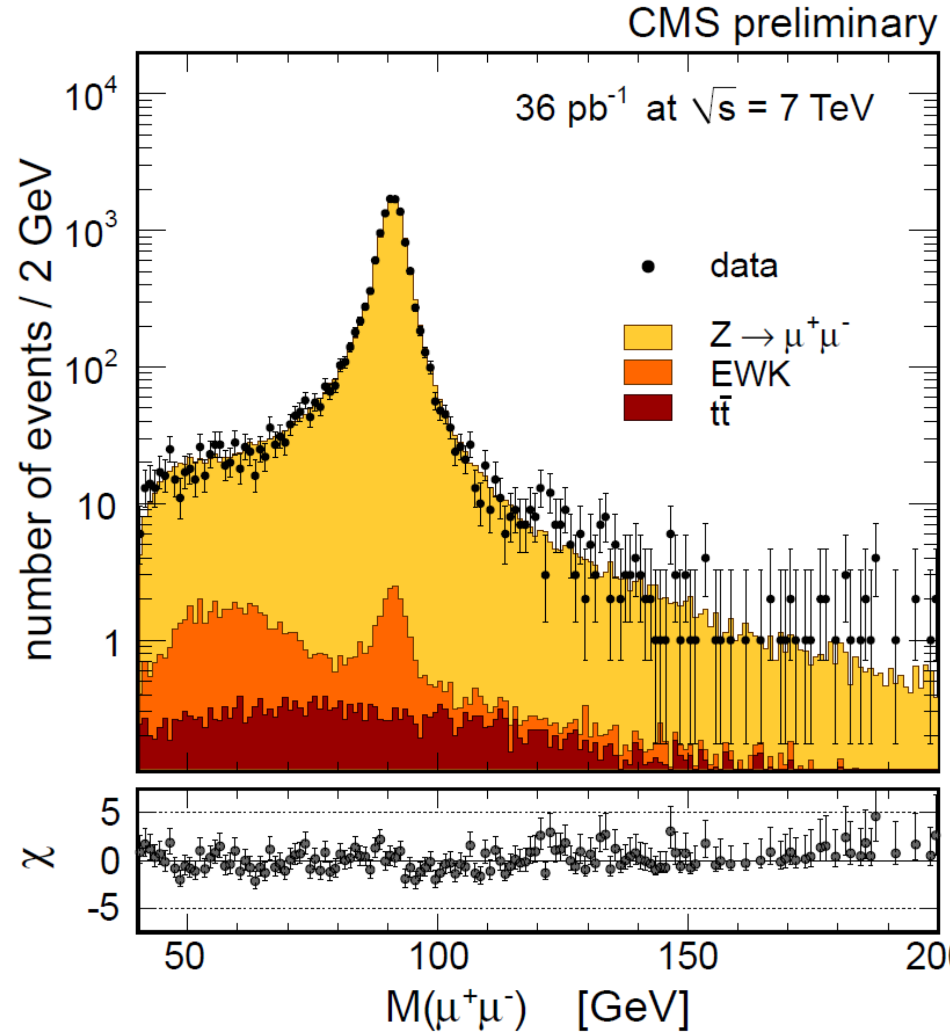
… remember CMS is on the French side

A Dimuon Event, CMS



Muons, CMS

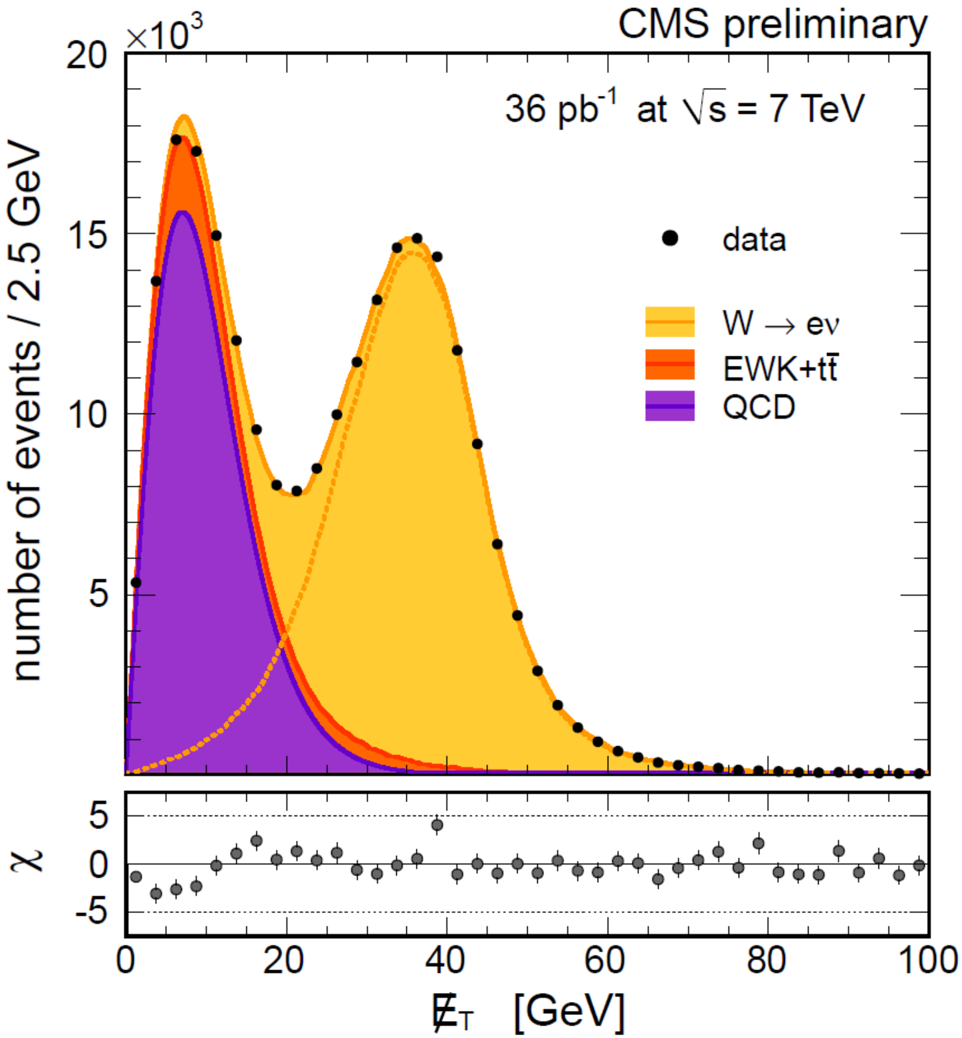


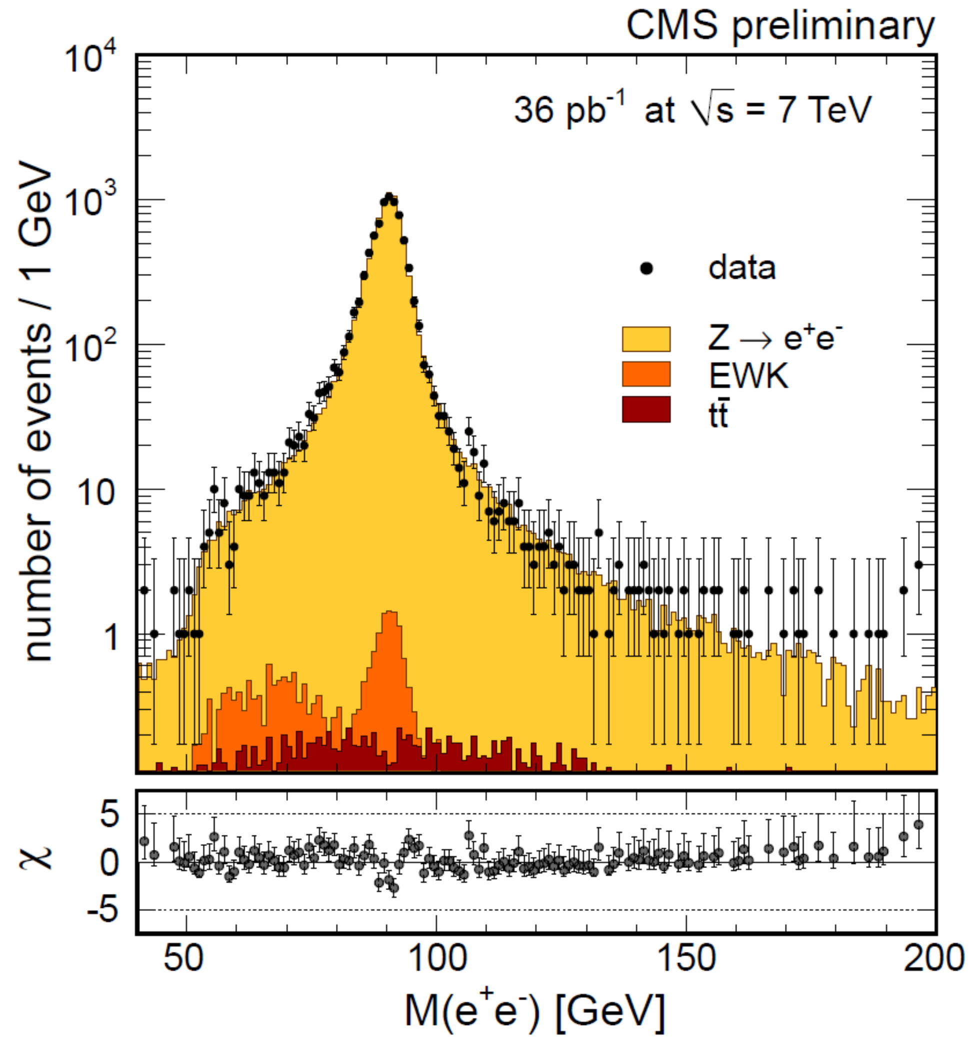


Muons in CMS

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

Electrons, CMS





Electrons in CMS

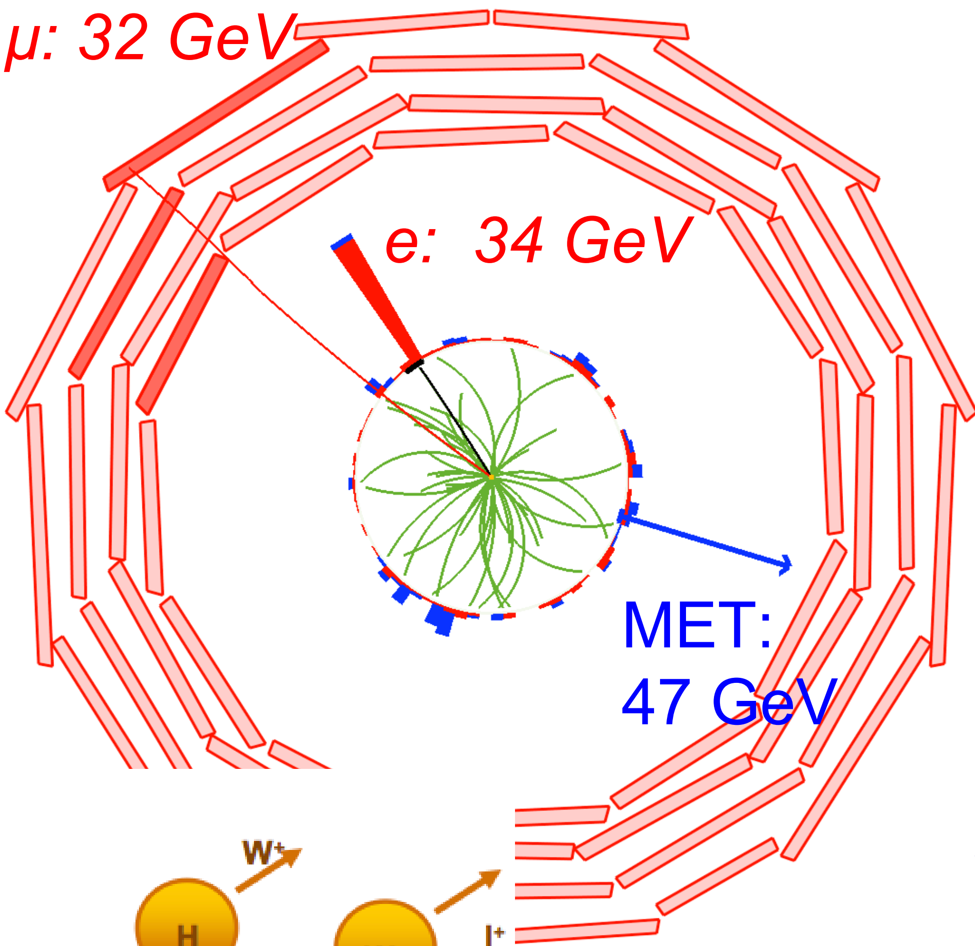
– W/Z cross section in 36 pb^{-1}, extremely clean dielectrons

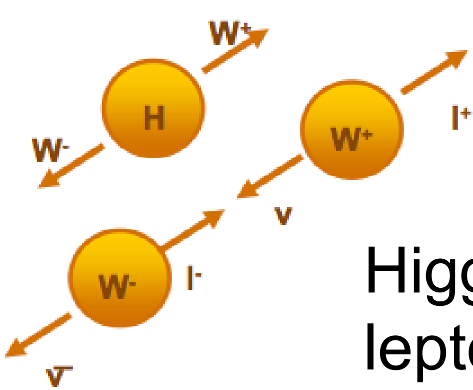
*So far CMS and ATLAS do **not** see the Higgs **but** ....*

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

Let’s see what we have so far.

The Main Channel: H -> WW -> 2l 2nu





Higgs is scalar
leptons are close

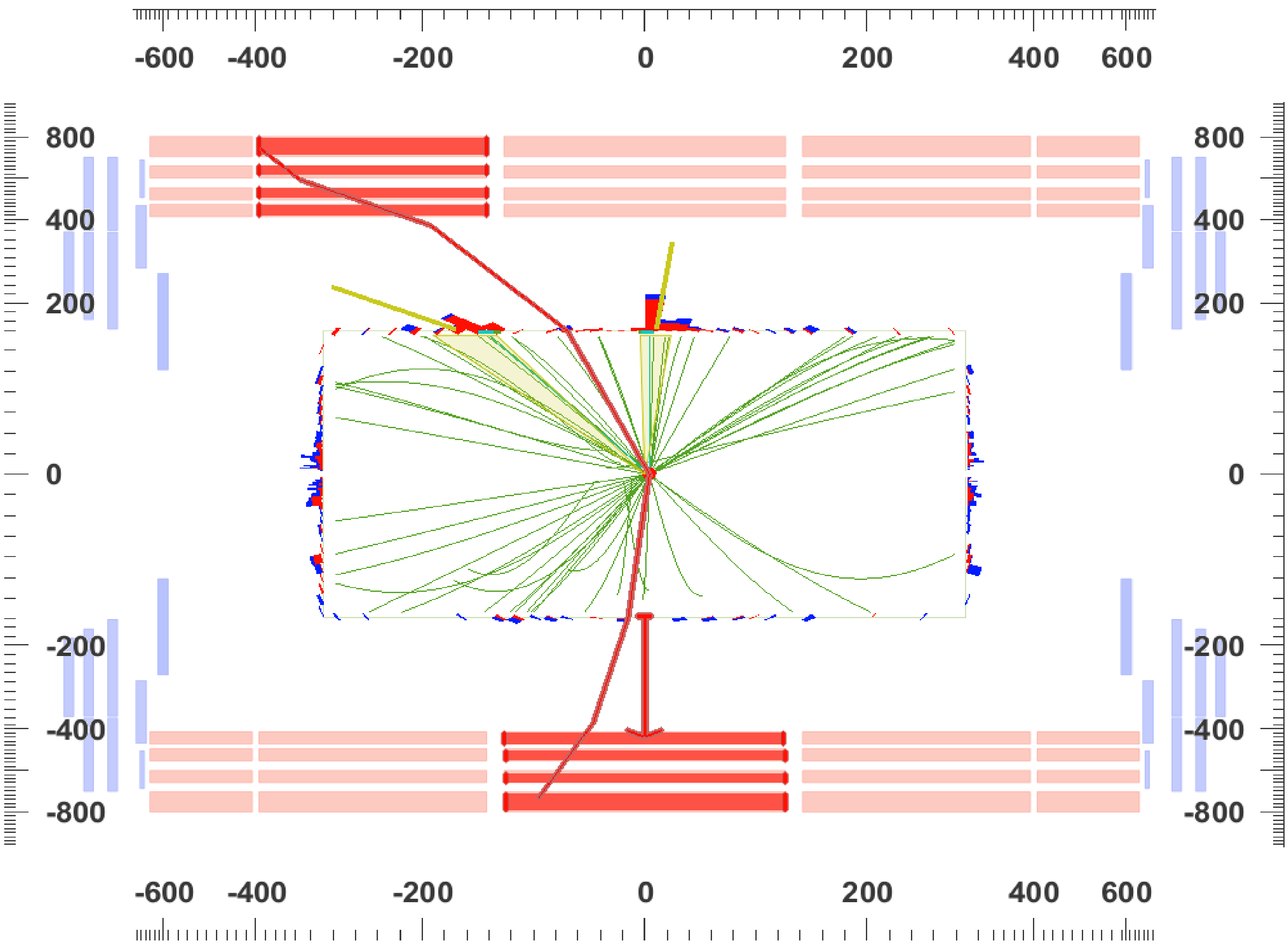
Signature

- 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

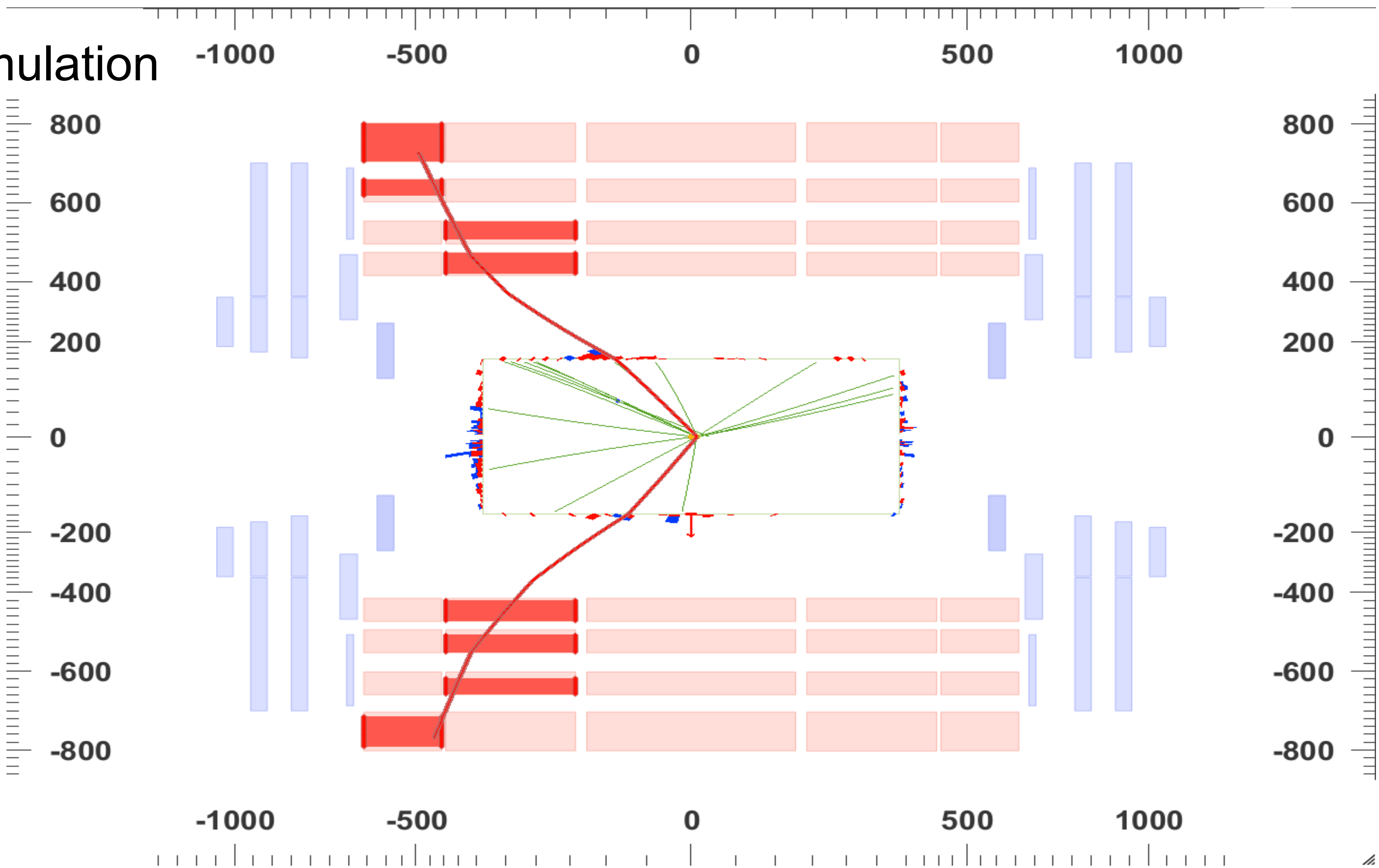


Signature and rejection strategy

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

Drell-Yan Background to H -> WW -> 2l 2nu

simulation



Signature and rejection strategy

- small MET: remove events with small MET

Non Resonant WW Background to H -> WW -> 2l 2nu

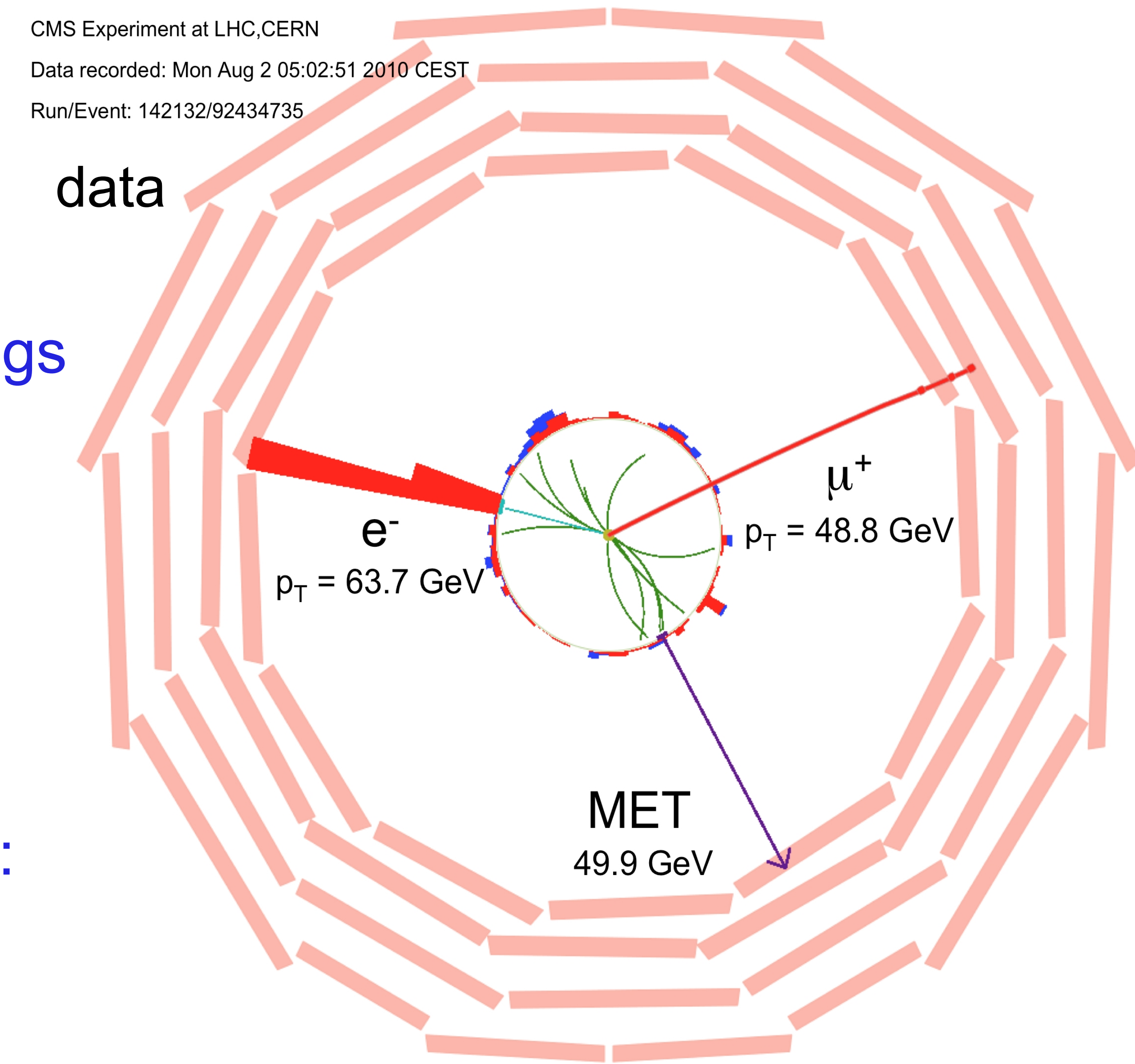
Signature

- irreducible
- slightly different kinematics than Higgs decay

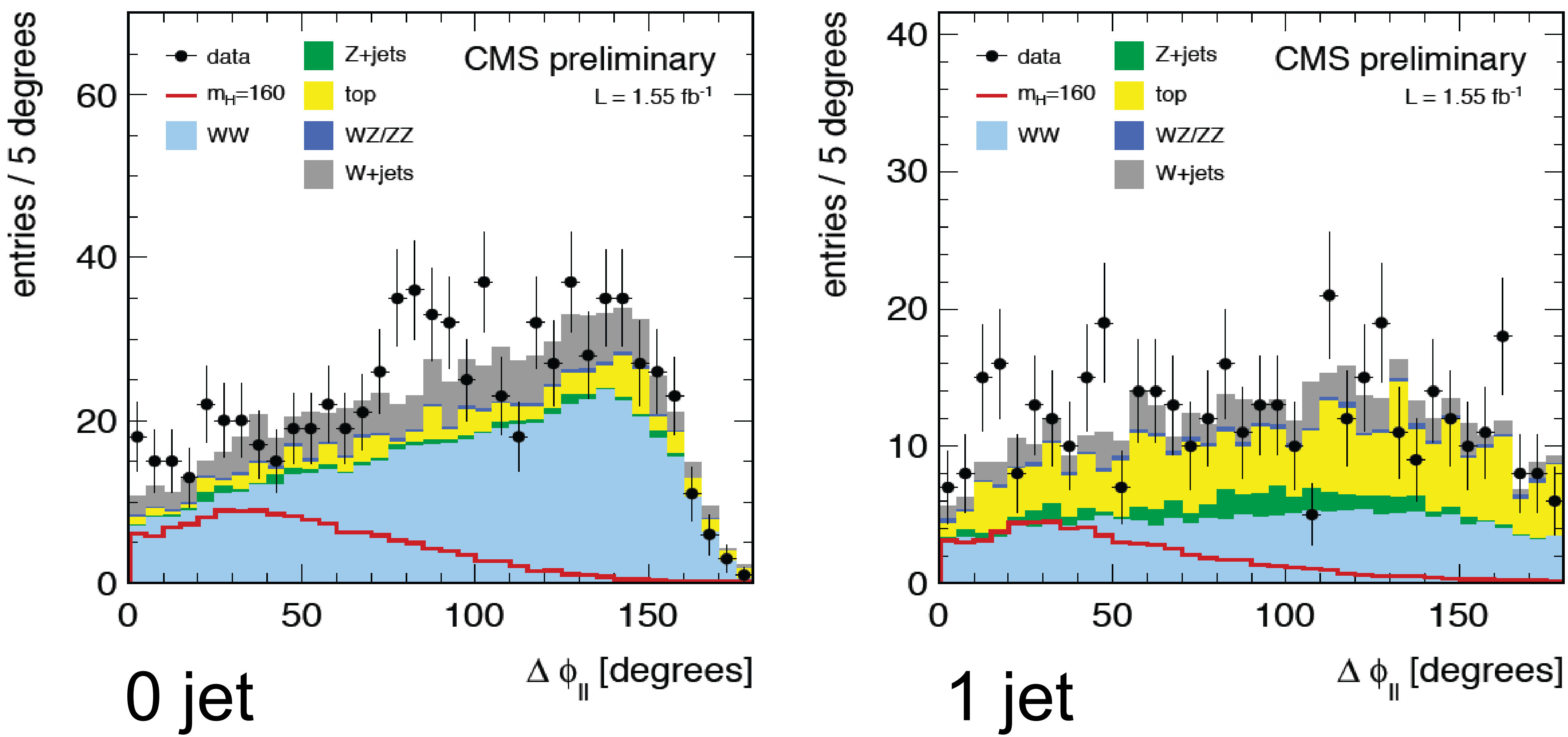
Strategy

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

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



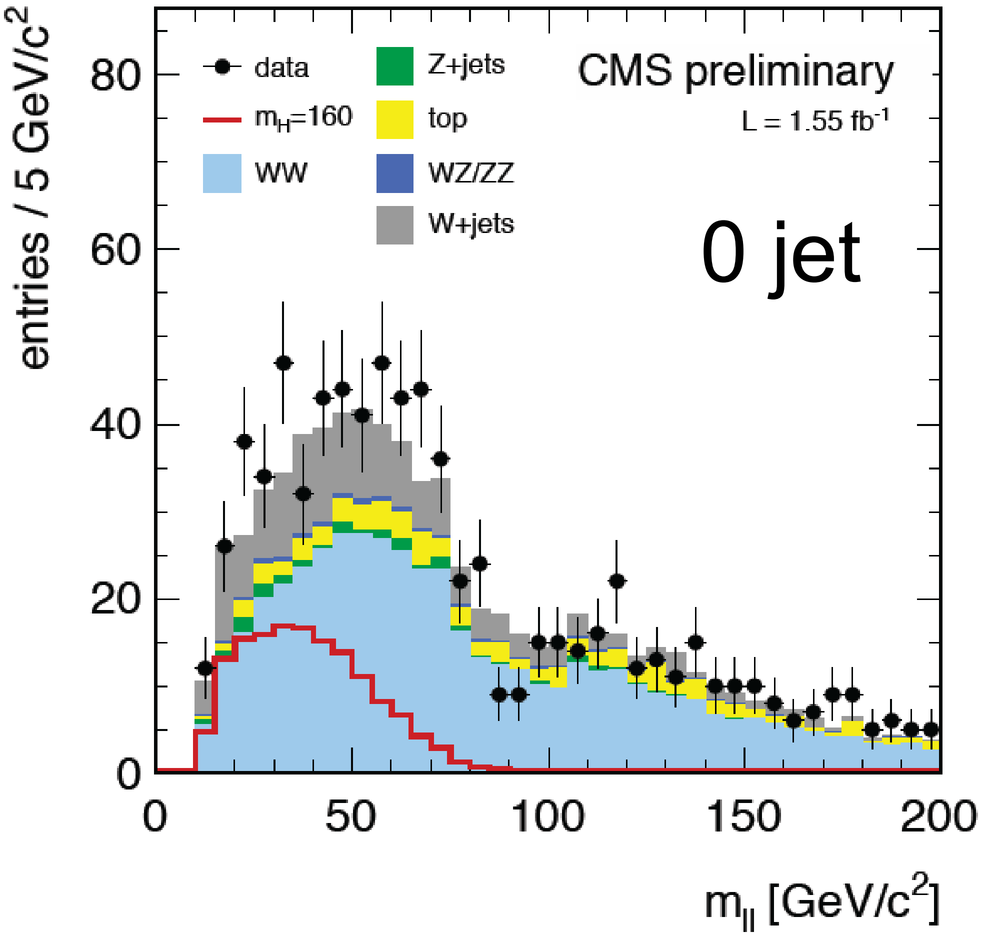
Kinematic Variables: $\Delta\Phi_{ll}$

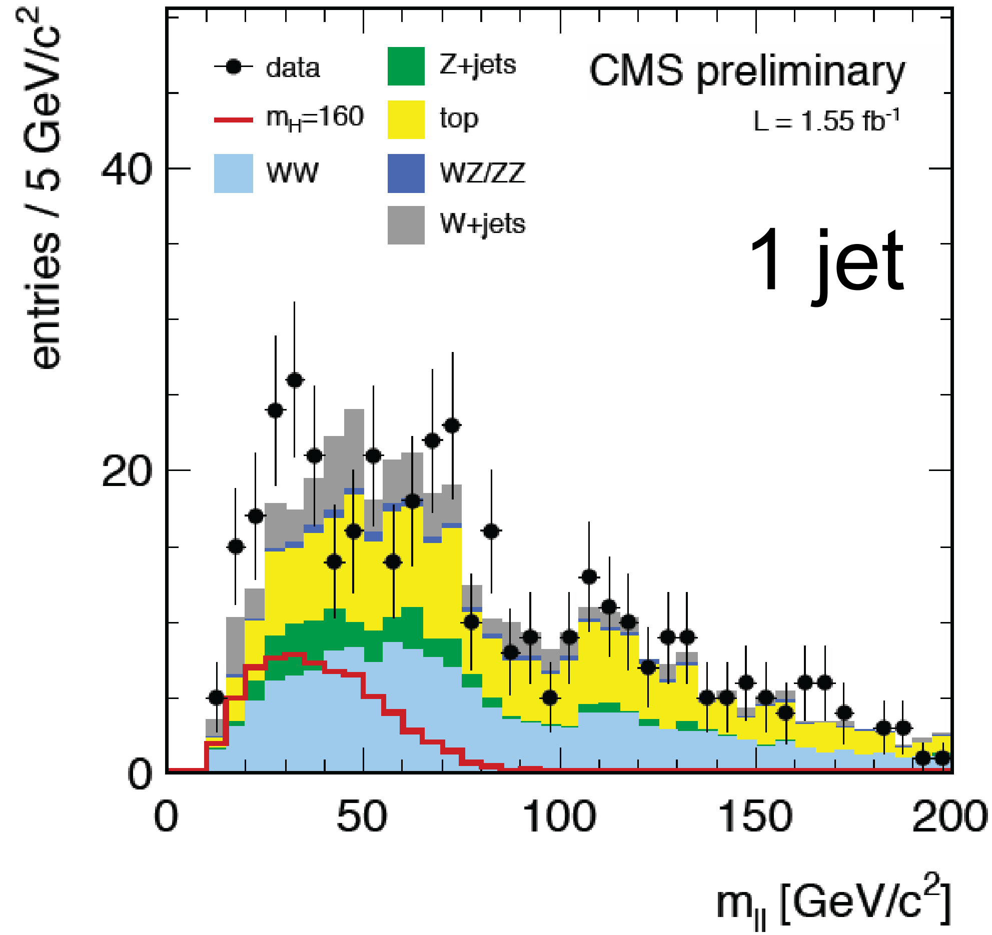


Higgs at 160 GeV: signature

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

Kinematic Variables: m_{ll}

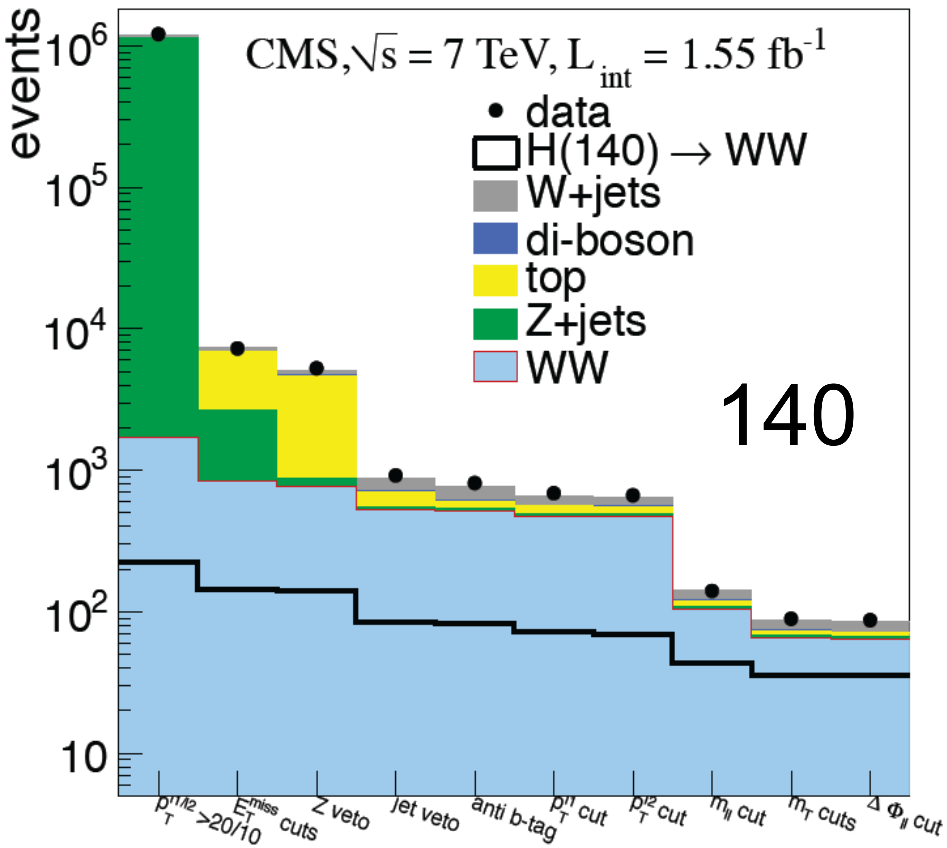


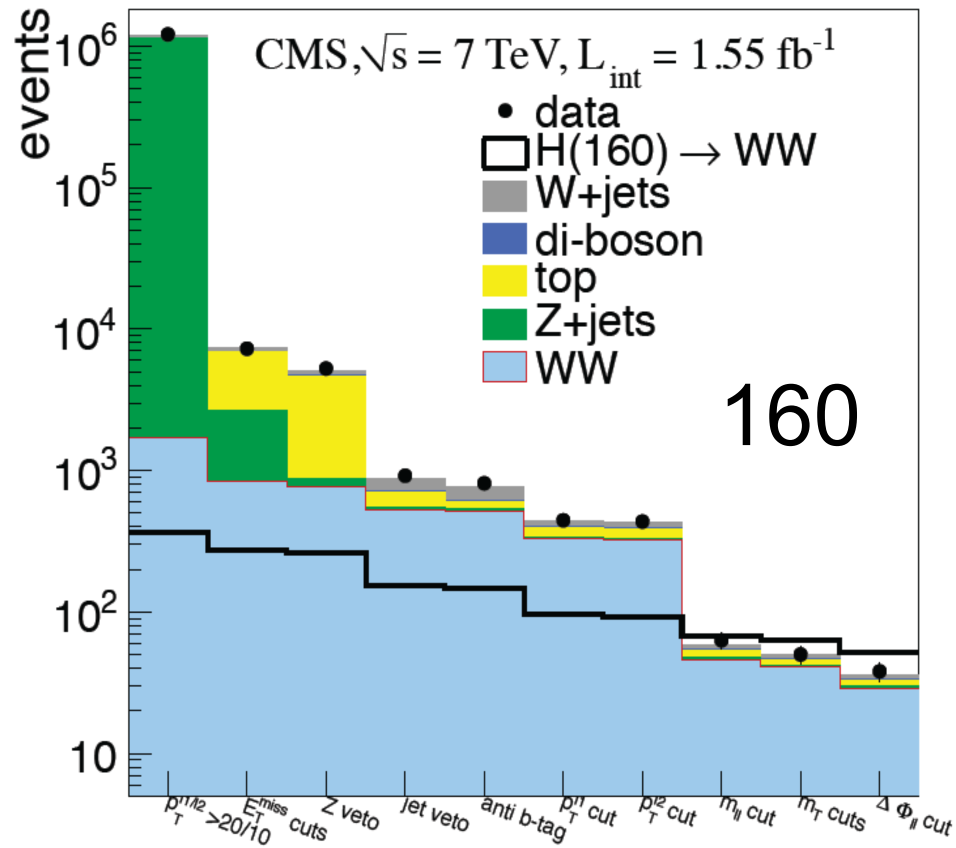


Higgs at 160 GeV: signature

- small dilepton mass in 0 and 1 jet selection

Sequence of Selection





Background predictions follows data closely

- normalization for background derived by normalizing to data in carefully designed unbiased calibration regions

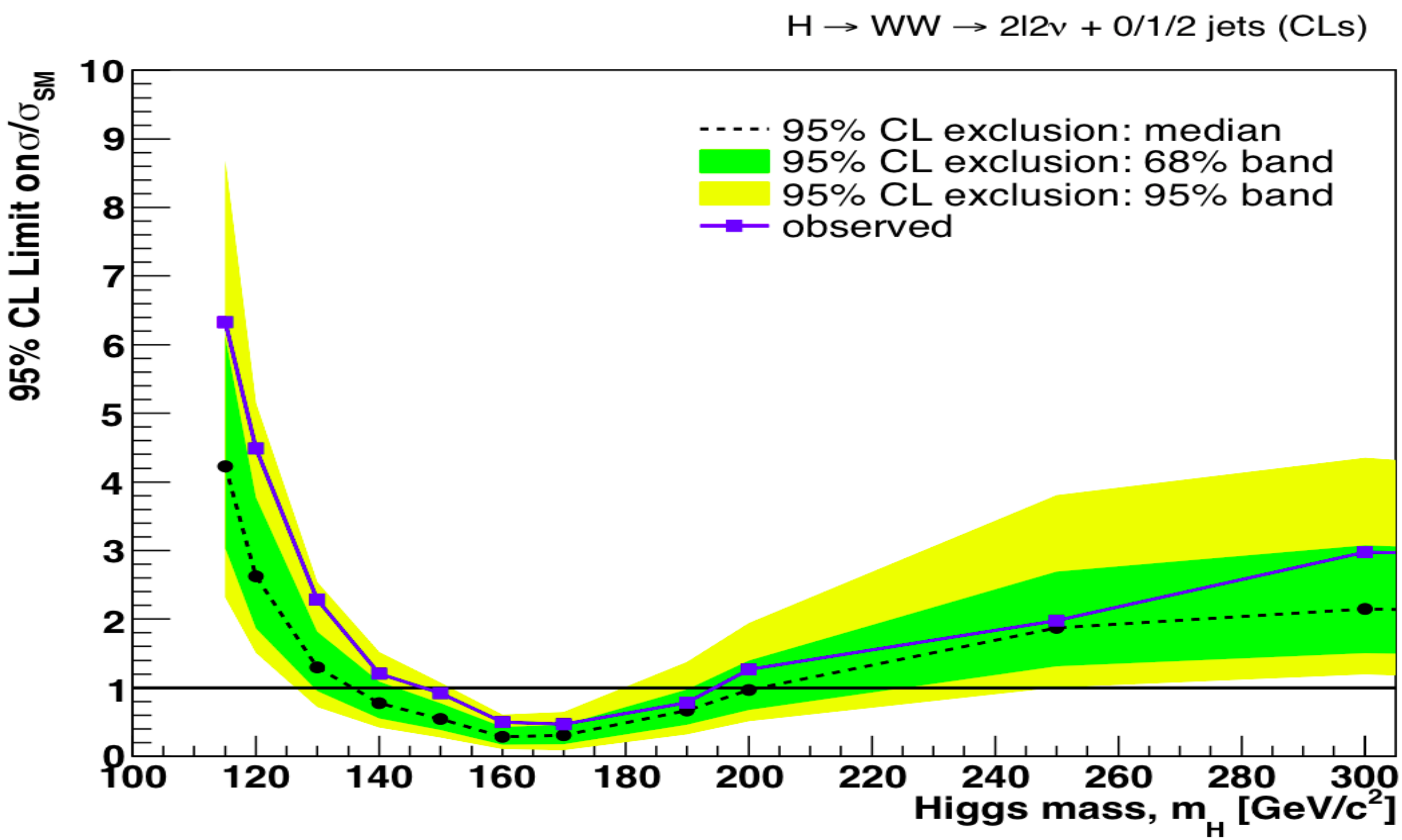
Counting Results for m_H=140 GeV

Process	0-j OF	0-j SF	1-j OF	1-j SF	2-j
qqWW	31.5 ± 5.5	29.1 ± 5.1	8.3 ± 3.1	5.8 ± 2.2	0.6 ± 0.2
ggWW	1.5 ± 0.8	1.3 ± 0.7	0.5 ± 0.3	0.3 ± 0.2	0.1 ± 0.1
VV	0.8 ± 0.1	0.5 ± 0.1	0.5 ± 0.1	0.3 ± 0.1	0.0 ± 0.0
Top	3.1 ± 1.1	1.4 ± 0.5	5.6 ± 1.2	3.2 ± 0.8	2.6 ± 1.5
Zjets	0.1 ± 0.0	3.1 ± 4.2	0.2 ± 0.1	1.2 ± 2.7	0.8 ± 0.6
Wjets	5.6 ± 2.3	5.3 ± 2.2	2.4 ± 1.1	1.5 ± 0.9	1.0 ± 0.6
$W\gamma$	1.5 ± 0.7	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.2	0.0 ± 0.0
$Z\tau\tau$	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.2	0.0 ± 0.0	0.2 ± 0.2
Tot. Bkg.	44.0 ± 6.2	40.6 ± 7.0	17.8 ± 3.5	12.6 ± 3.7	5.3 ± 1.7
Higgs	19.1 ± 4.3	16.1 ± 3.6	7.7 ± 2.6	5.3 ± 1.8	2.5 ± 0.3
Data	46	41	23	23	7

Background predictions follows data closely

- compare total background to data (Higgs signal does not fit)
- OF means *e+μ,* while SF means *μ+μ* or *e+e*
- main result from 0 and 1 jet selections

Derive Limits from the Numbers

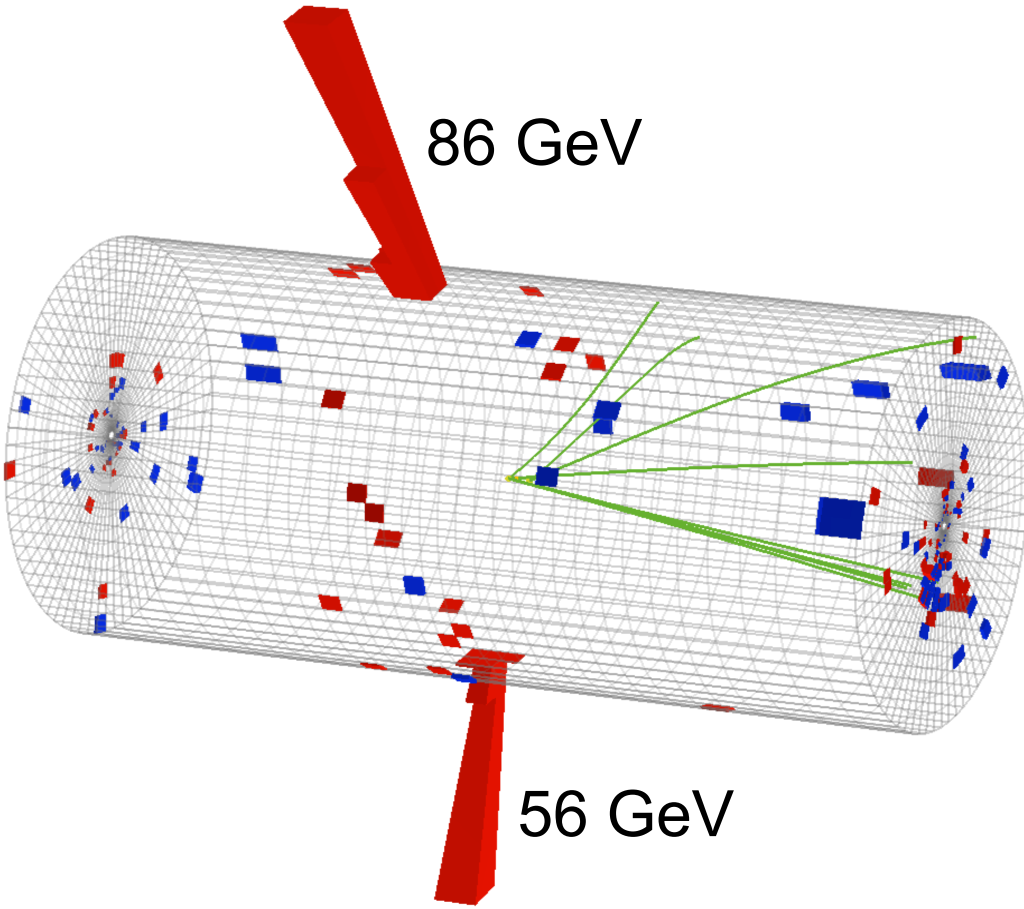


Observations

exclude Higgs masses from 147 GeV < m_H < 194 GeV

expected exclusion 136 GeV < m_H < 200 GeV

Low Mass Specialist: H -> $\gamma\gamma$



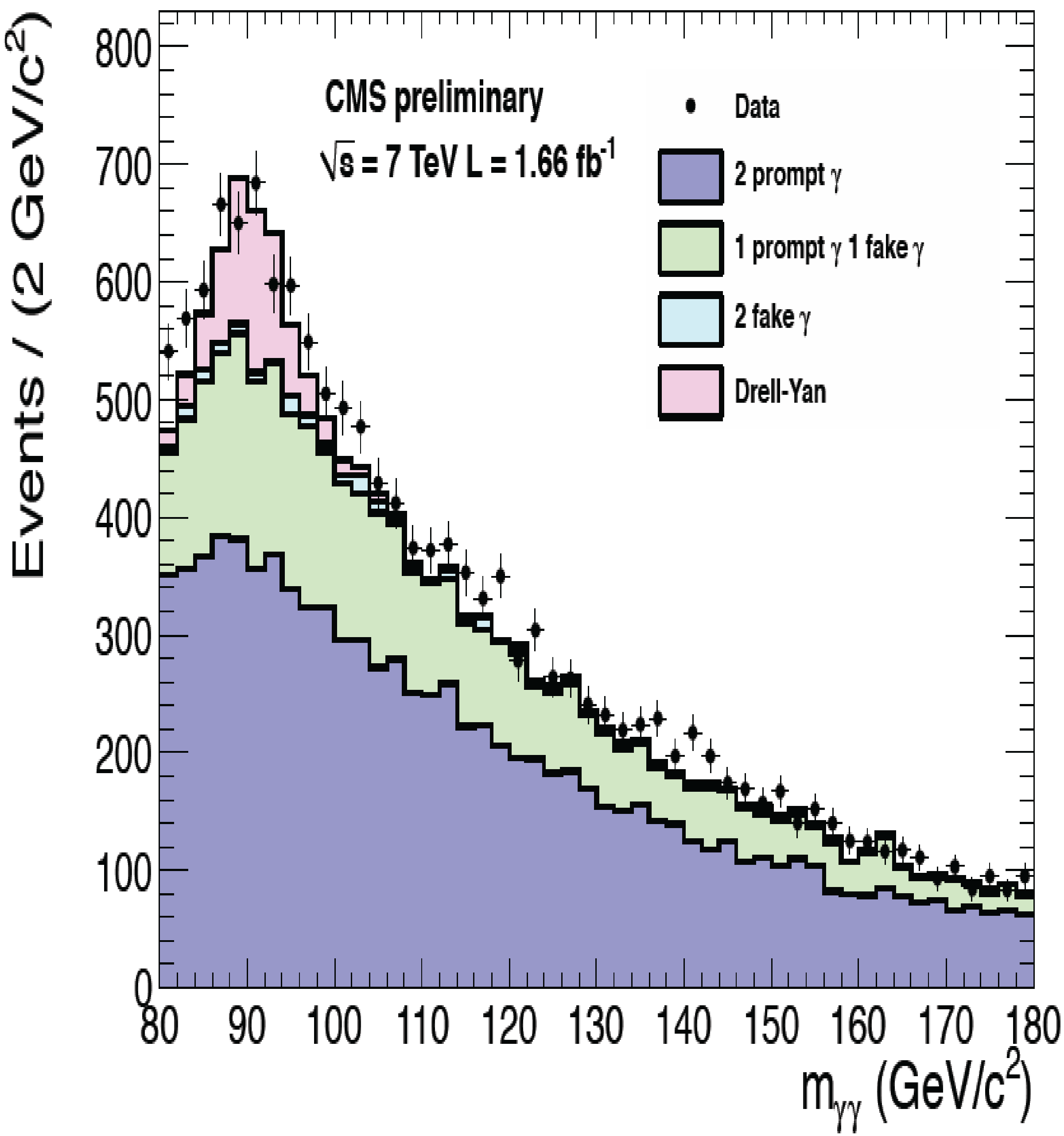
Signature and background

- 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

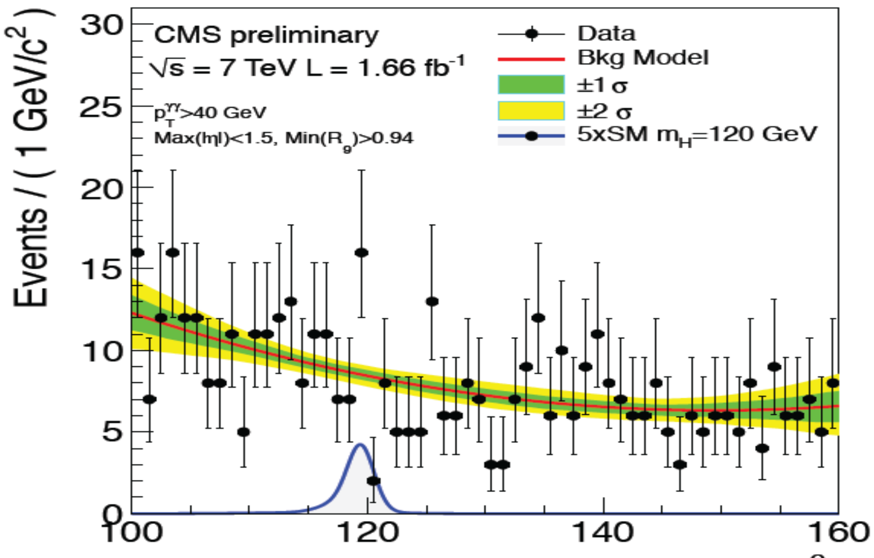
Low Mass Specialist: H -> $\gamma\gamma$



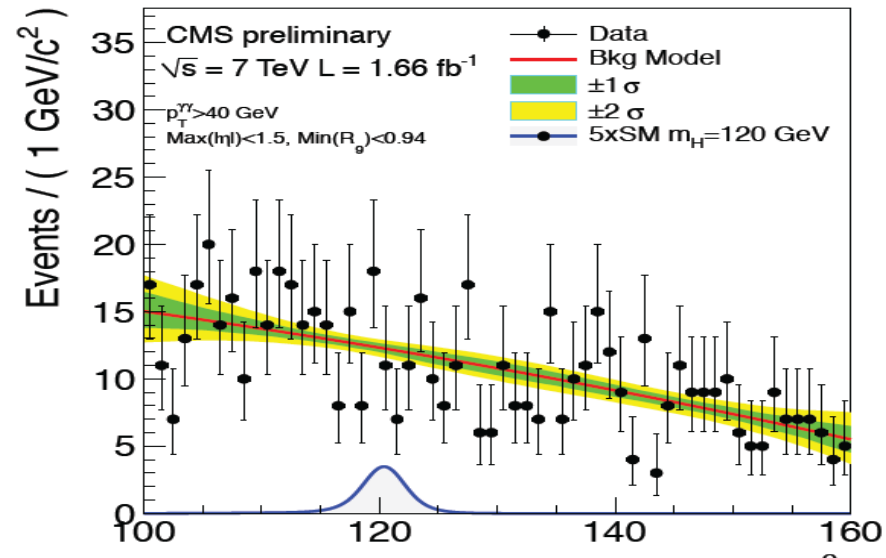
Data MC comparison

- only used for illustration
- general agreement
- fake/real photons about: 30%/70%
- perform analysis in optimized 8 categories
- idea: separate well measured from less well measured photons
- assume smooth background shape: no MC needed for mass fit

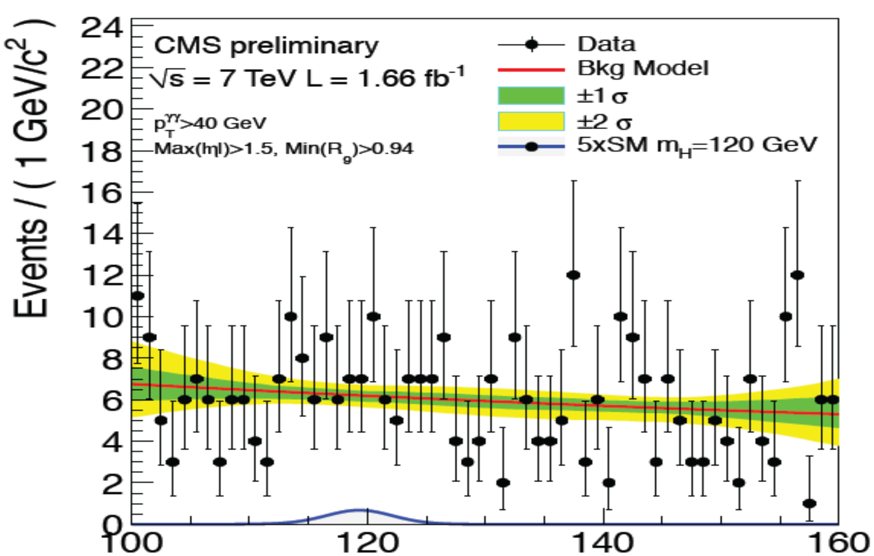
Low Mass Specialist: H -> $\gamma\gamma$



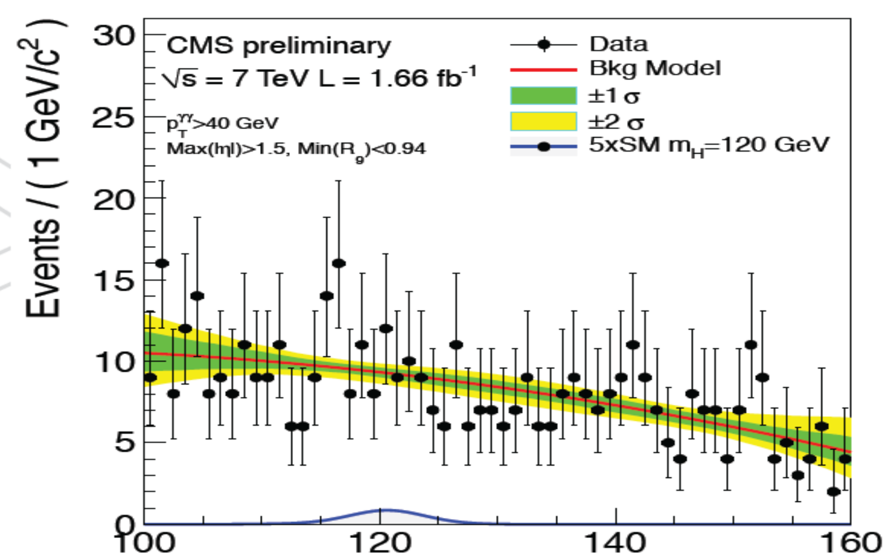
barrel, unconverted



barrel, converted

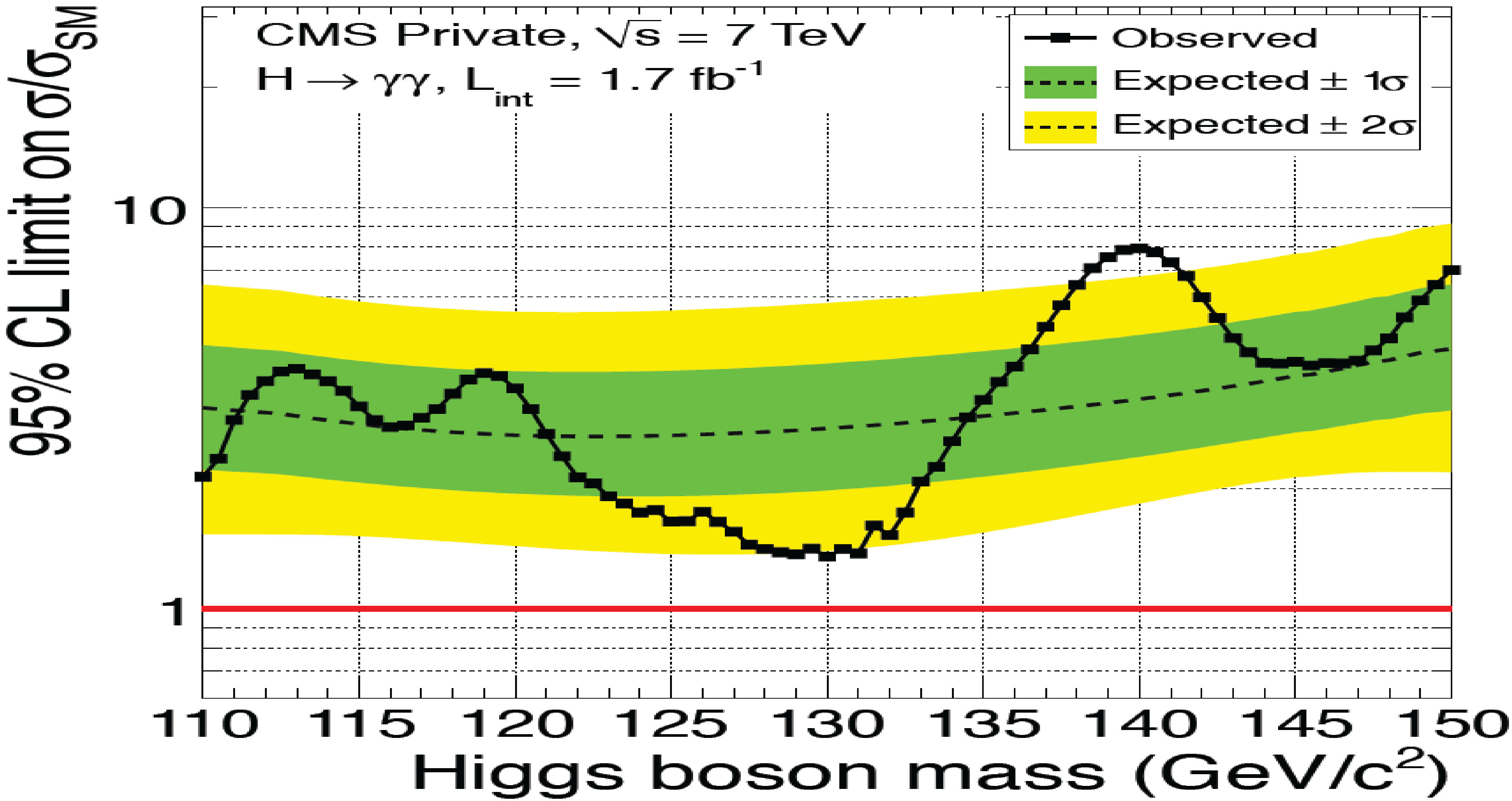


endcap, unconverted



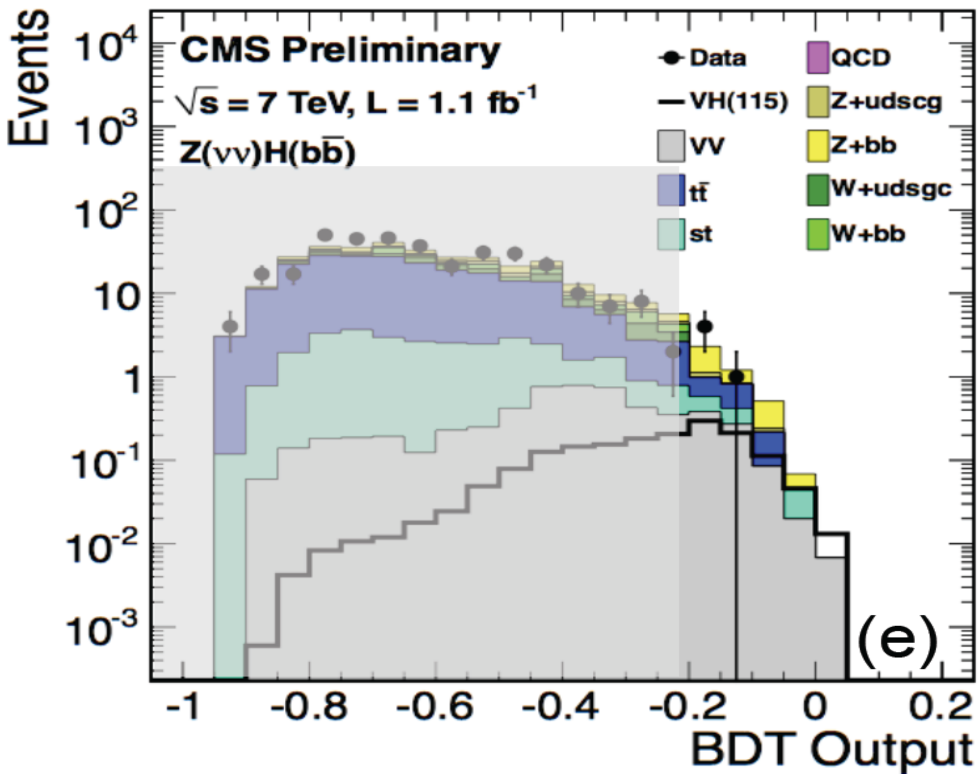
endcap, converted

Low Mass Specialist: H -> $\gamma\gamma$



- most sensitive channel below 140 GeV, exclusion around 2
- no significant excess: bump at 140 GeV ~ 1.6 std

Low Mass Special: VH -> Vbbbar



Analysis telegram

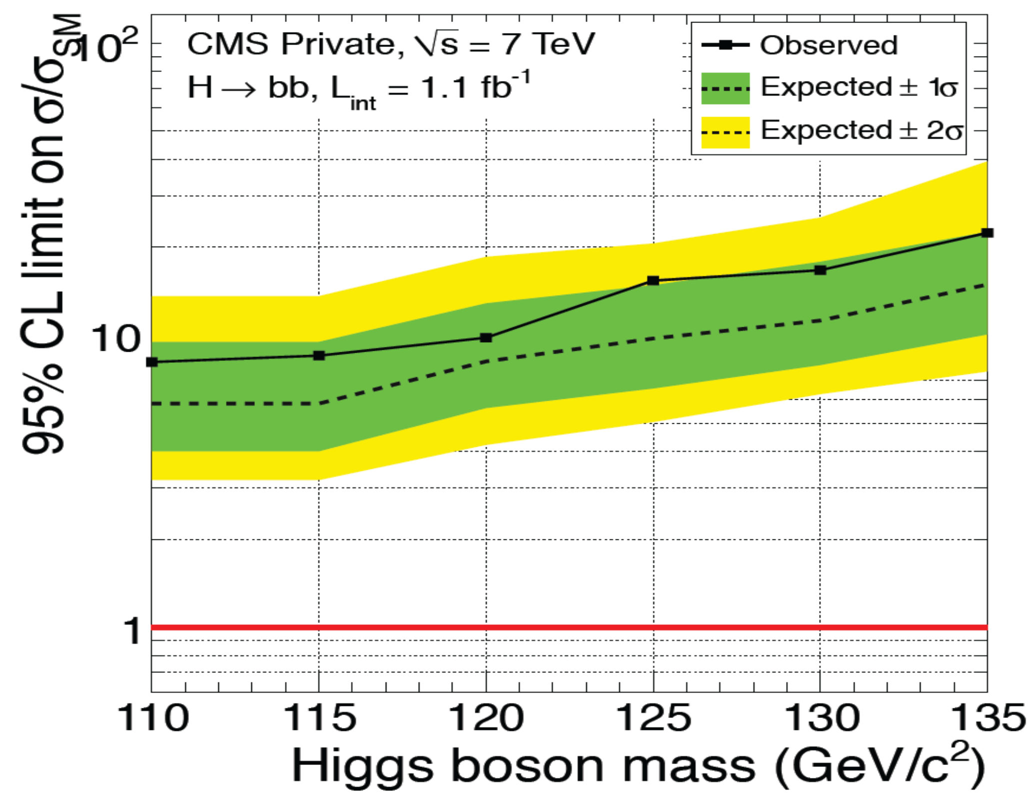
- enormous background in *H->bb*
- use *VH* with leptonic *V* decays
- also require high momentum: ‘boosted’ analysis

Backgrounds

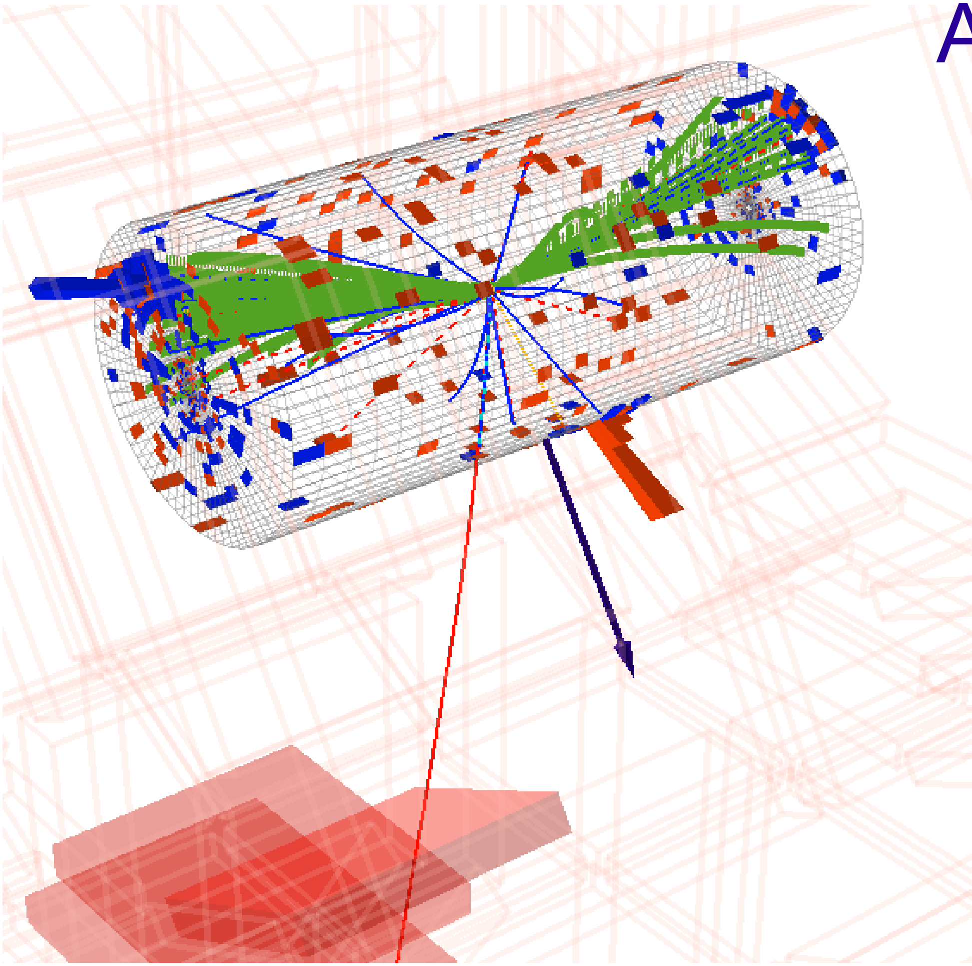
- *V+jets, VV, top*

Result

- limit is around 8 at low mass
- lots of improvements possible

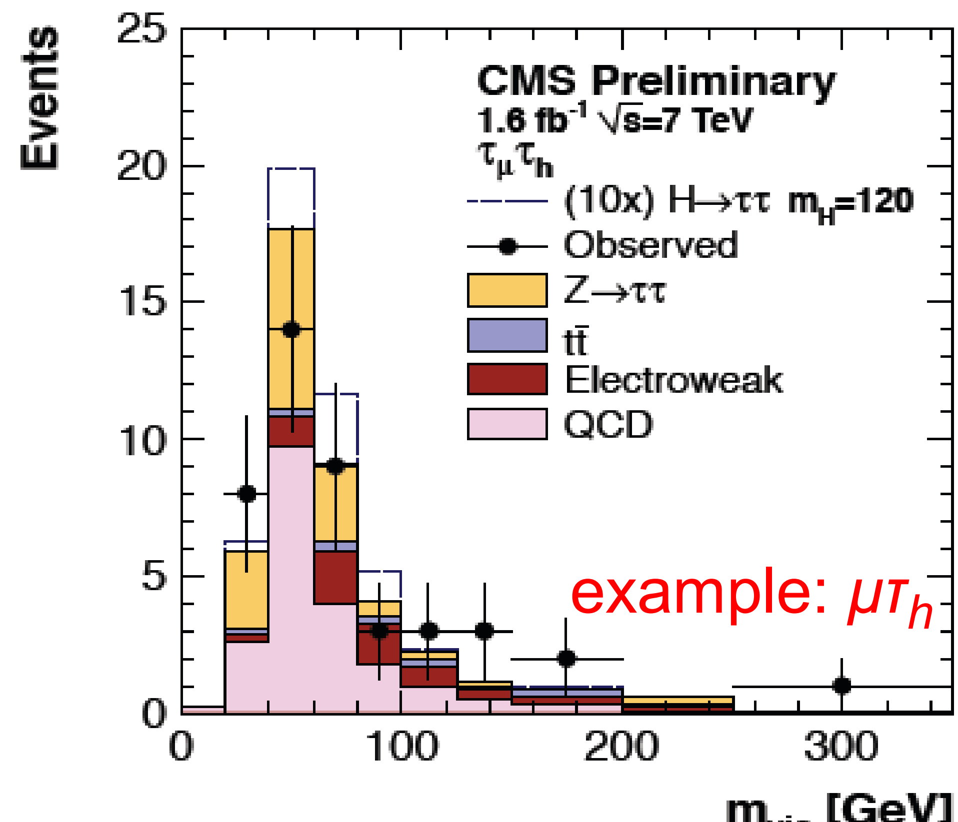


Low Mass Special: H -> ττ



Analysis telegram

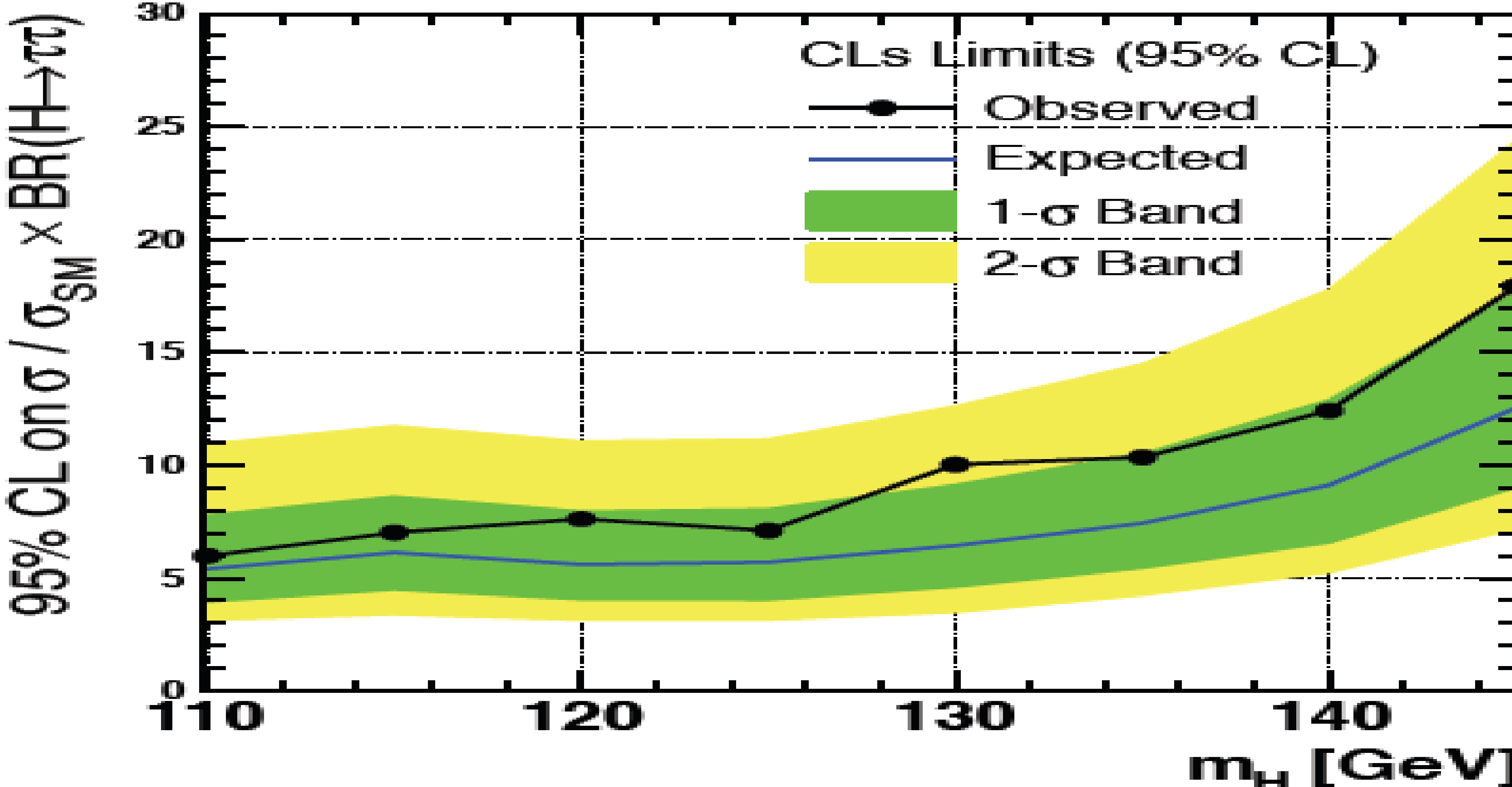
- VBF style most sensitive
- require 2 taus (at least one decaying leptonically)
- *e-μ, μ-τ_h* and *e-τ_h*



Backgrounds

- top, EWK, DY (irreducible)

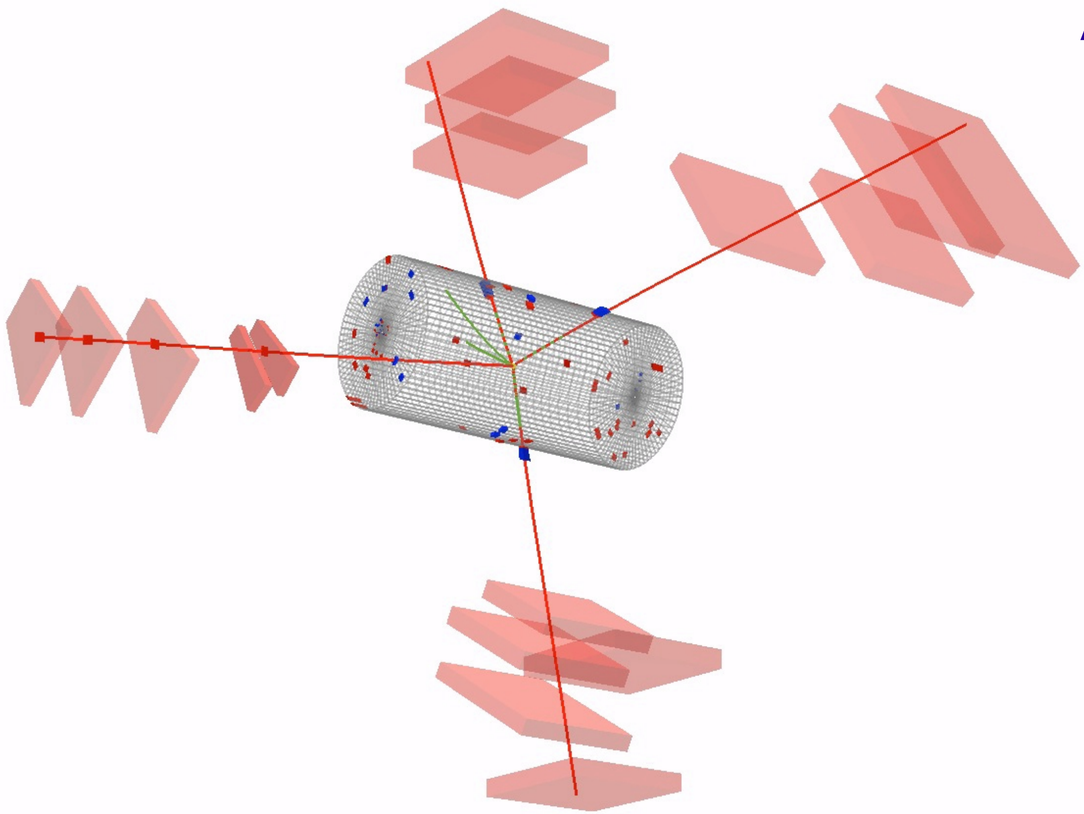
Low Mass Special: H -> ττ



Observations

- observed and expected sensitivity track each other well
- limit around 6 at low mass, many handles to improve analysis

The Golden Mode: H -> ZZ -> 4l



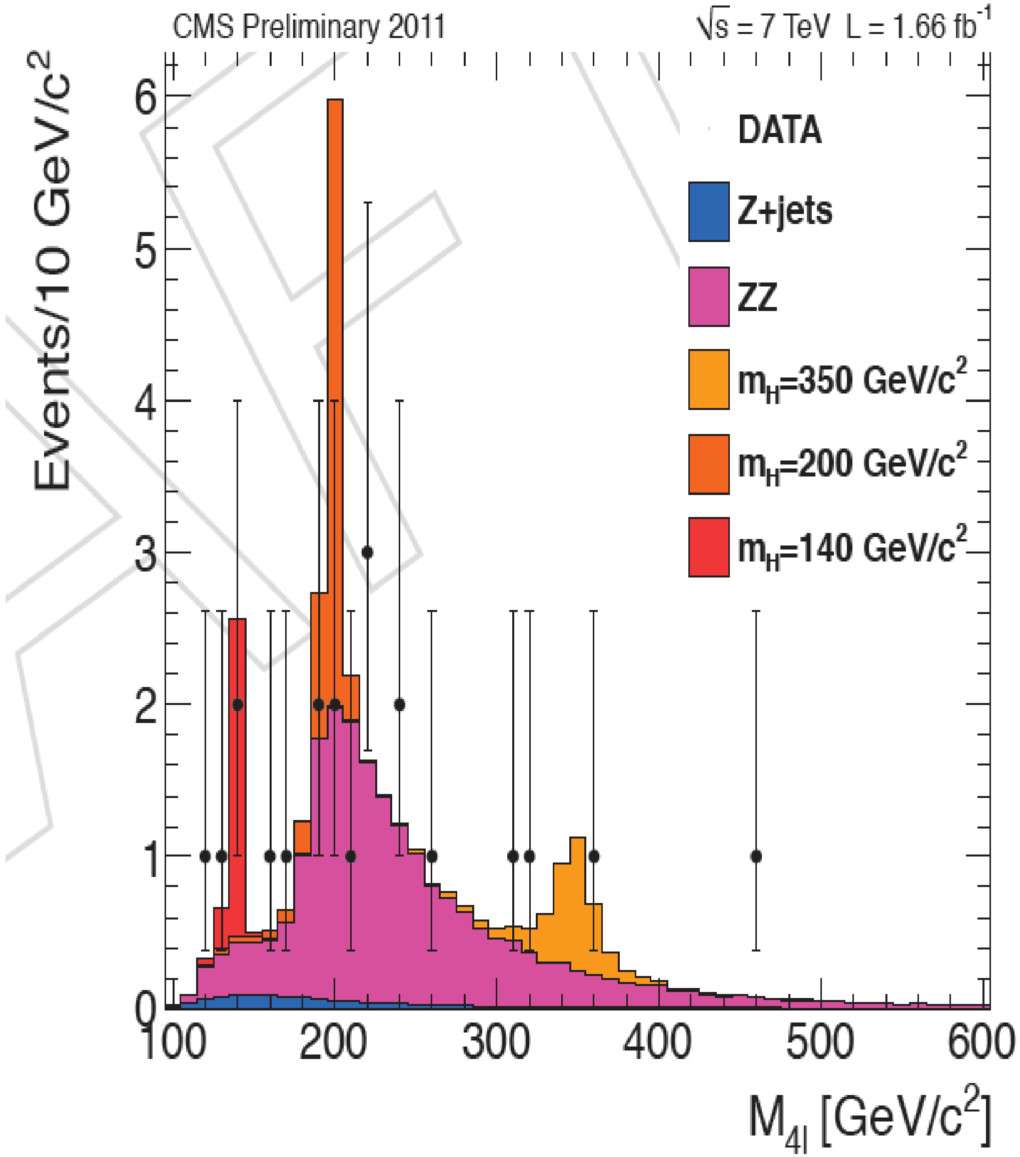
Analysis telegram

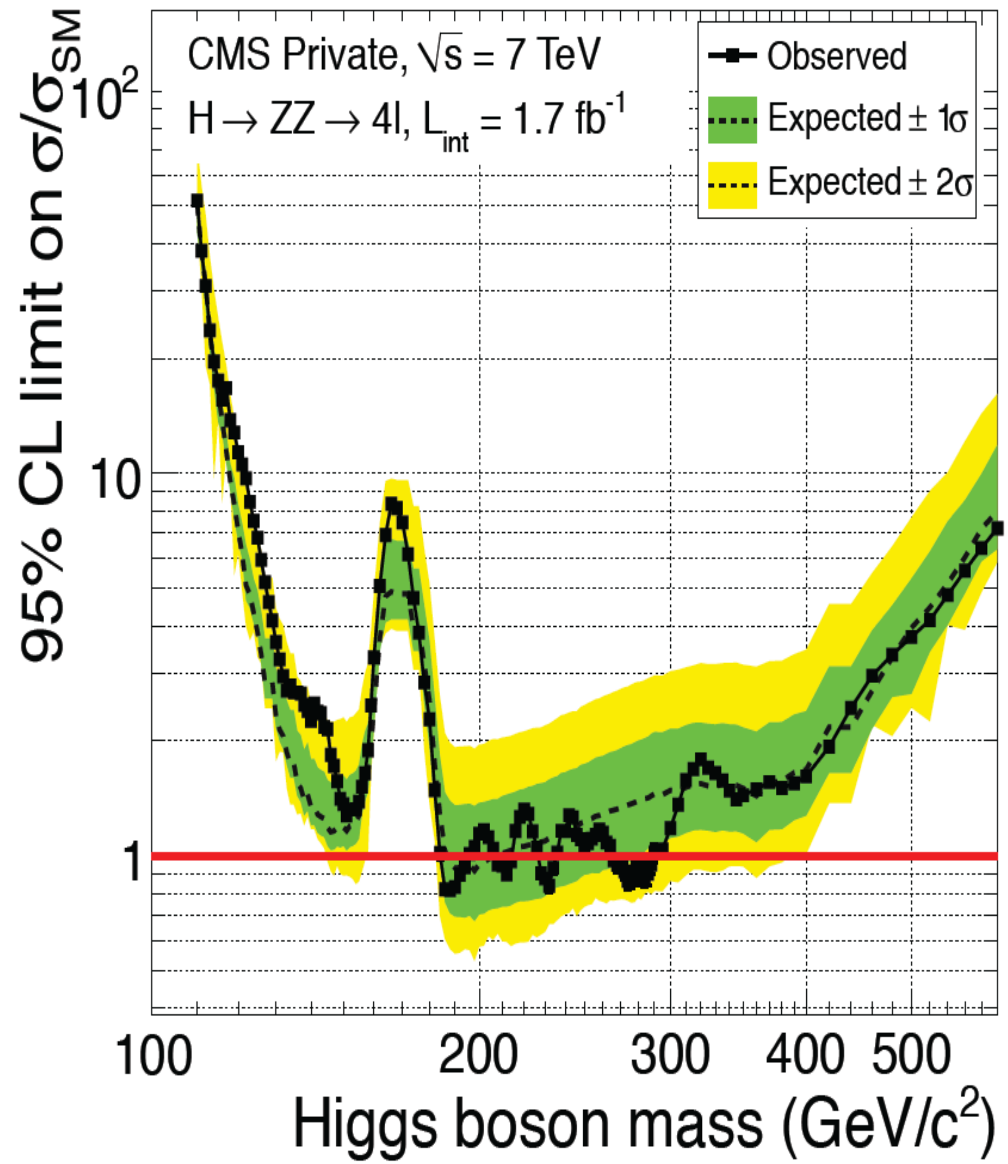
- 4 isolated high p_T leptons
- consistent with *Z* decays
- from same vertex
- fit mass peak with resolution: 2-4 GeV
- little background, main comes from non-resonant *ZZ* production, irreducible
- also *Zbb* and top (*2l2nu2b*)

Background removal

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

The Golden Mode: H -> ZZ -> 4l

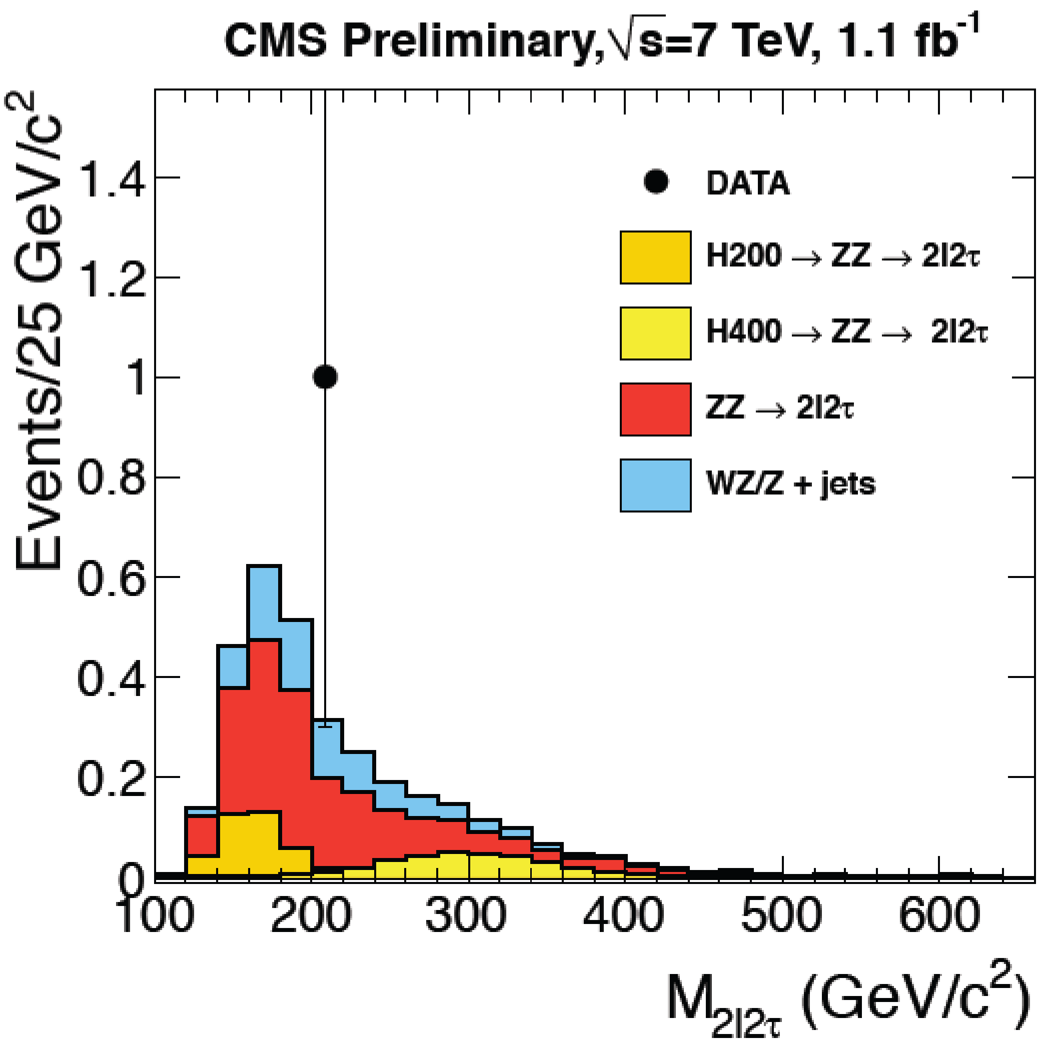


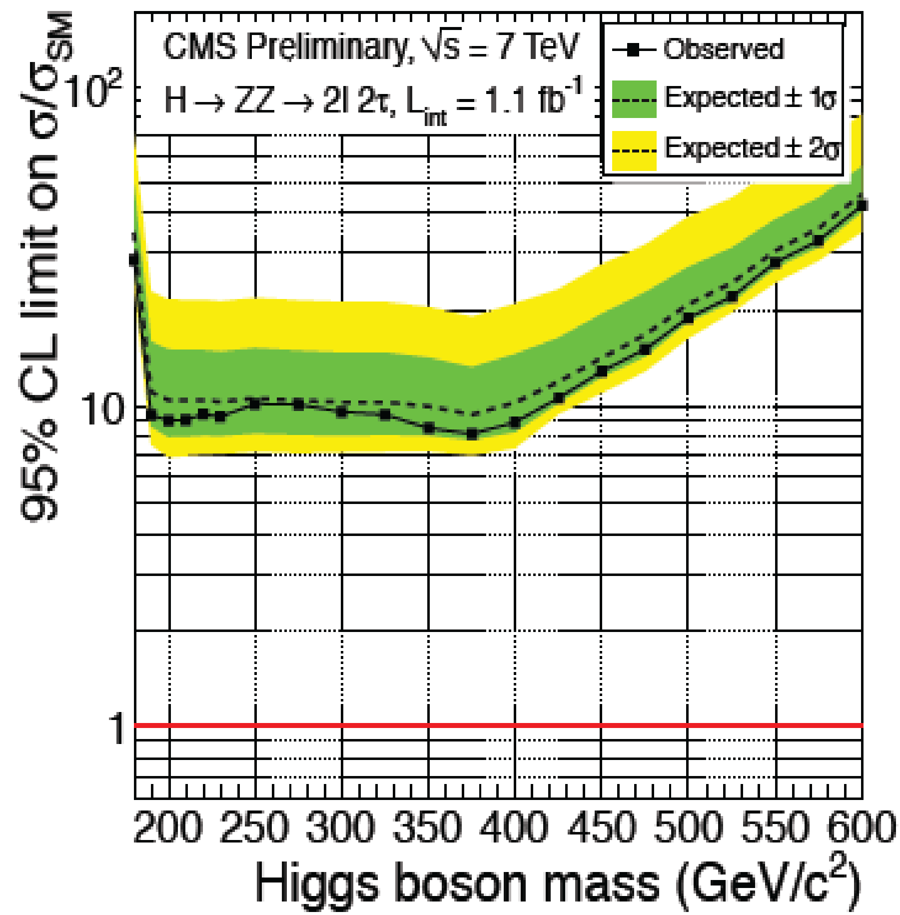


Observed events overall consistent with expectations

- some exclusion beyond m_H = 190 GeV

High Mass Special: H -> ZZ -> 2l2τ

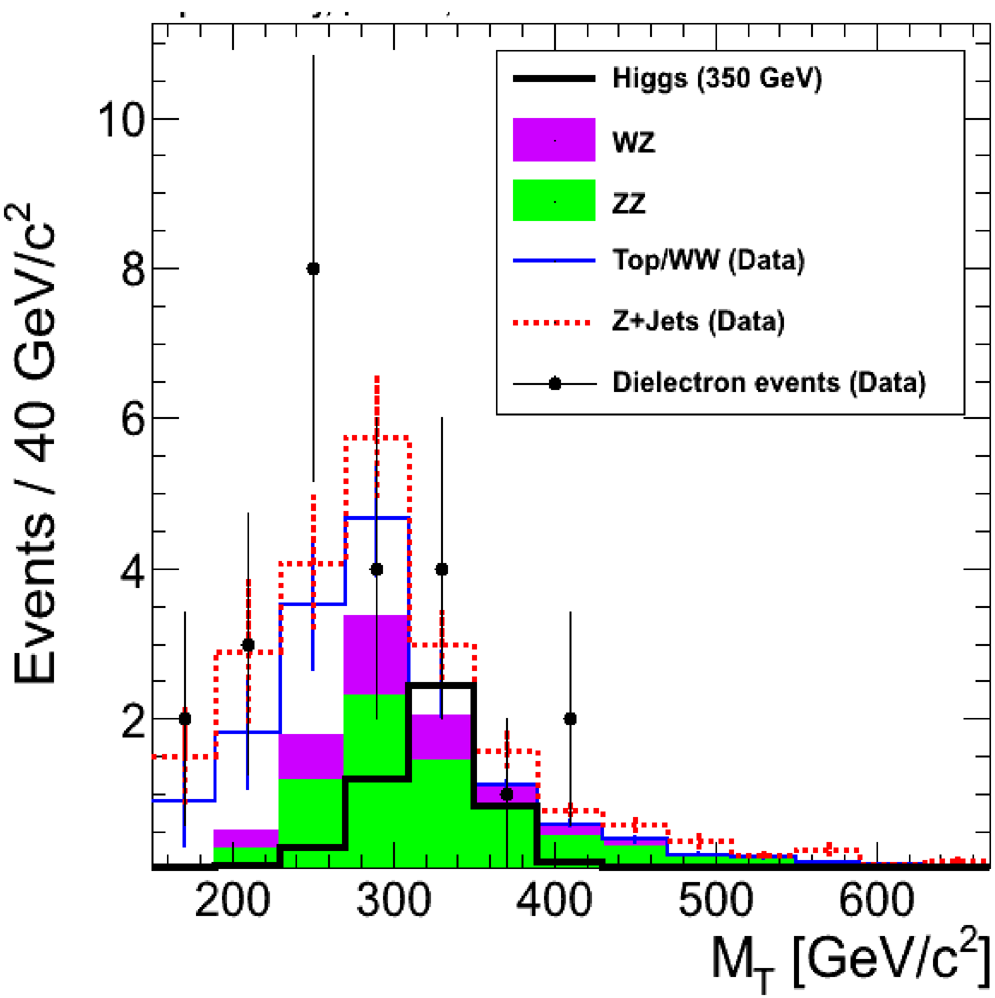


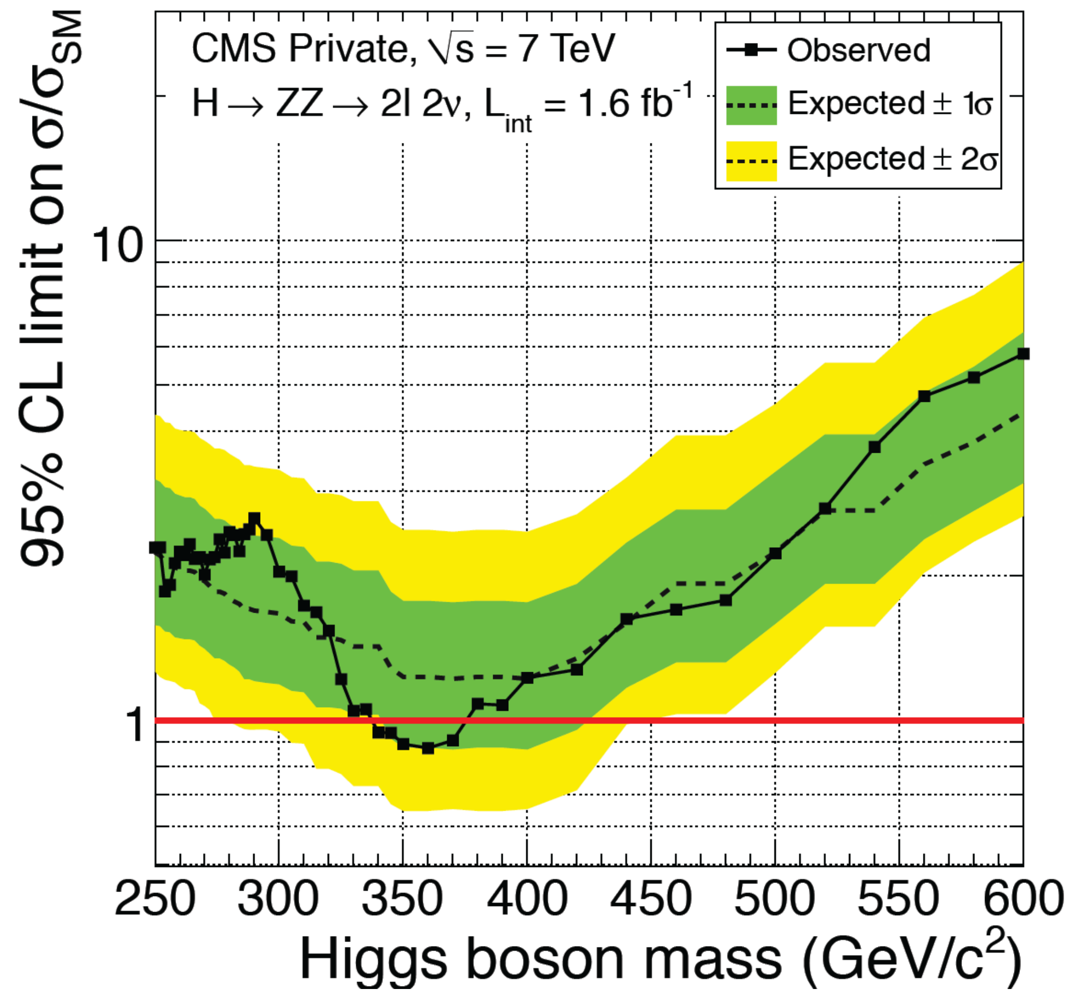


New analysis for Lepton Photon

– replace *ee* or *μμ*, with *ττ*, limited sensitivity (~9)

High Mass Special: H -> ZZ -> 2l2nu

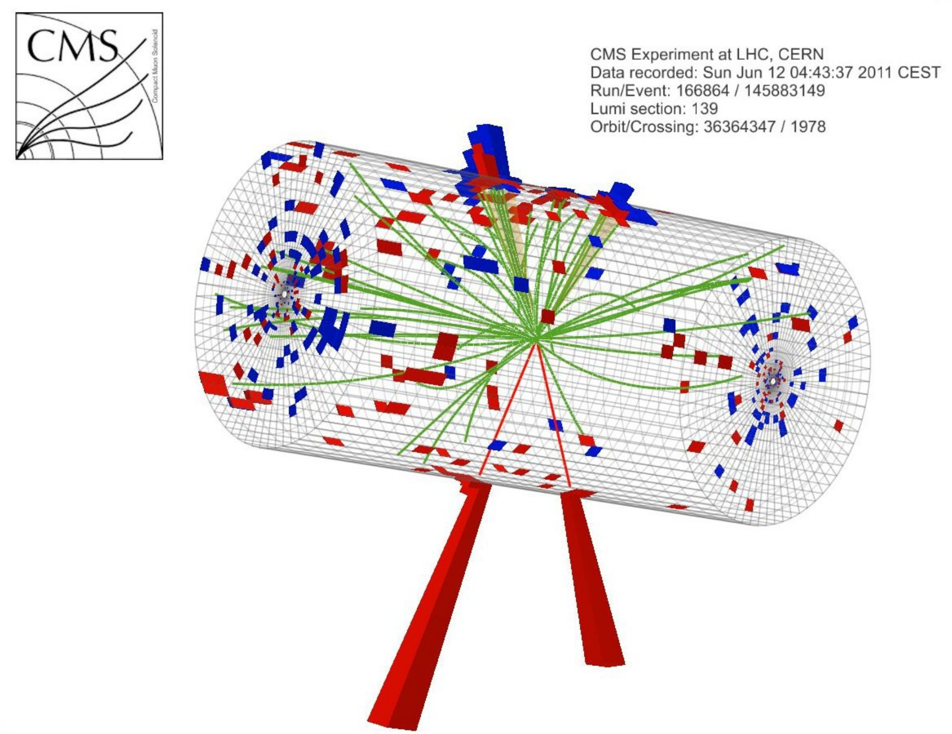


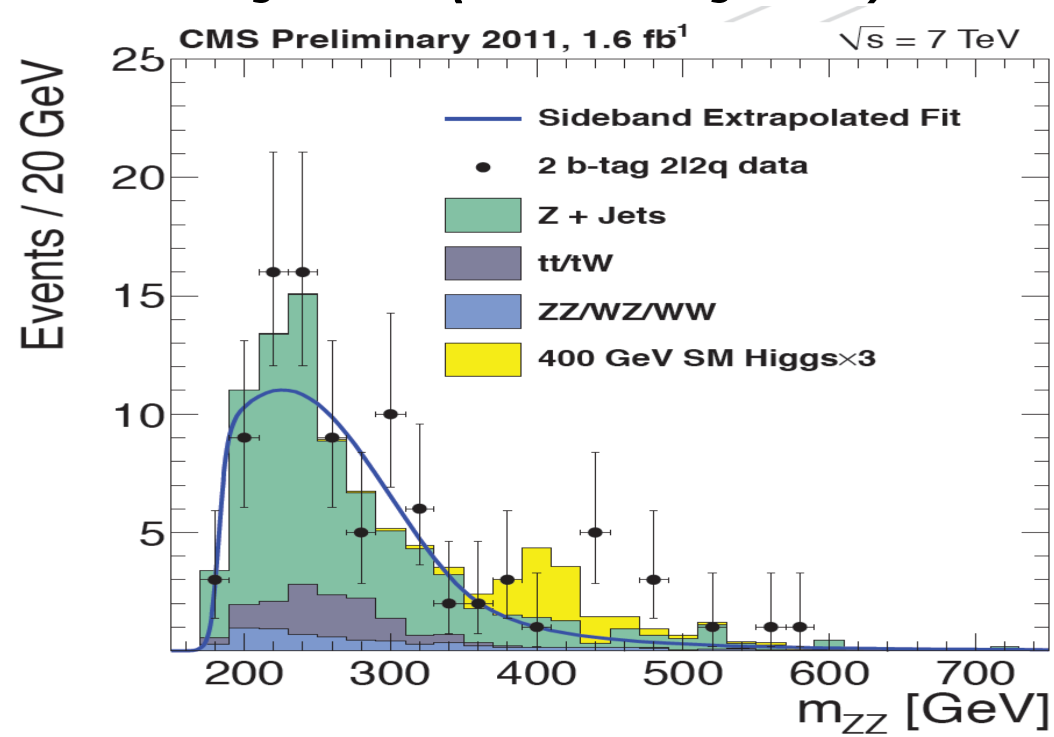


Analysis telegram

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

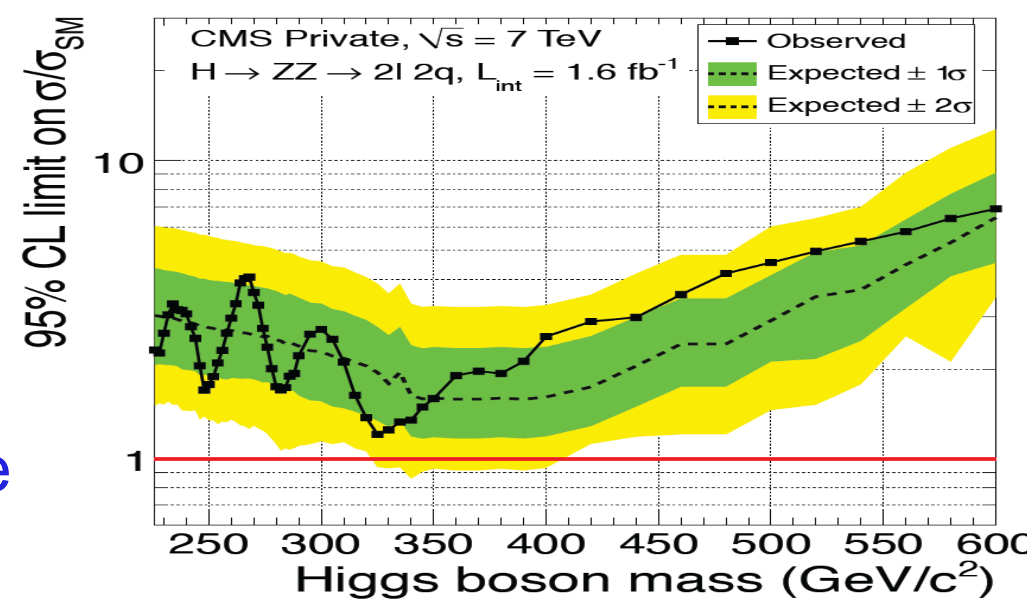
High Mass: H -> ZZ -> 2l 2jets (or 2b-jets)





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

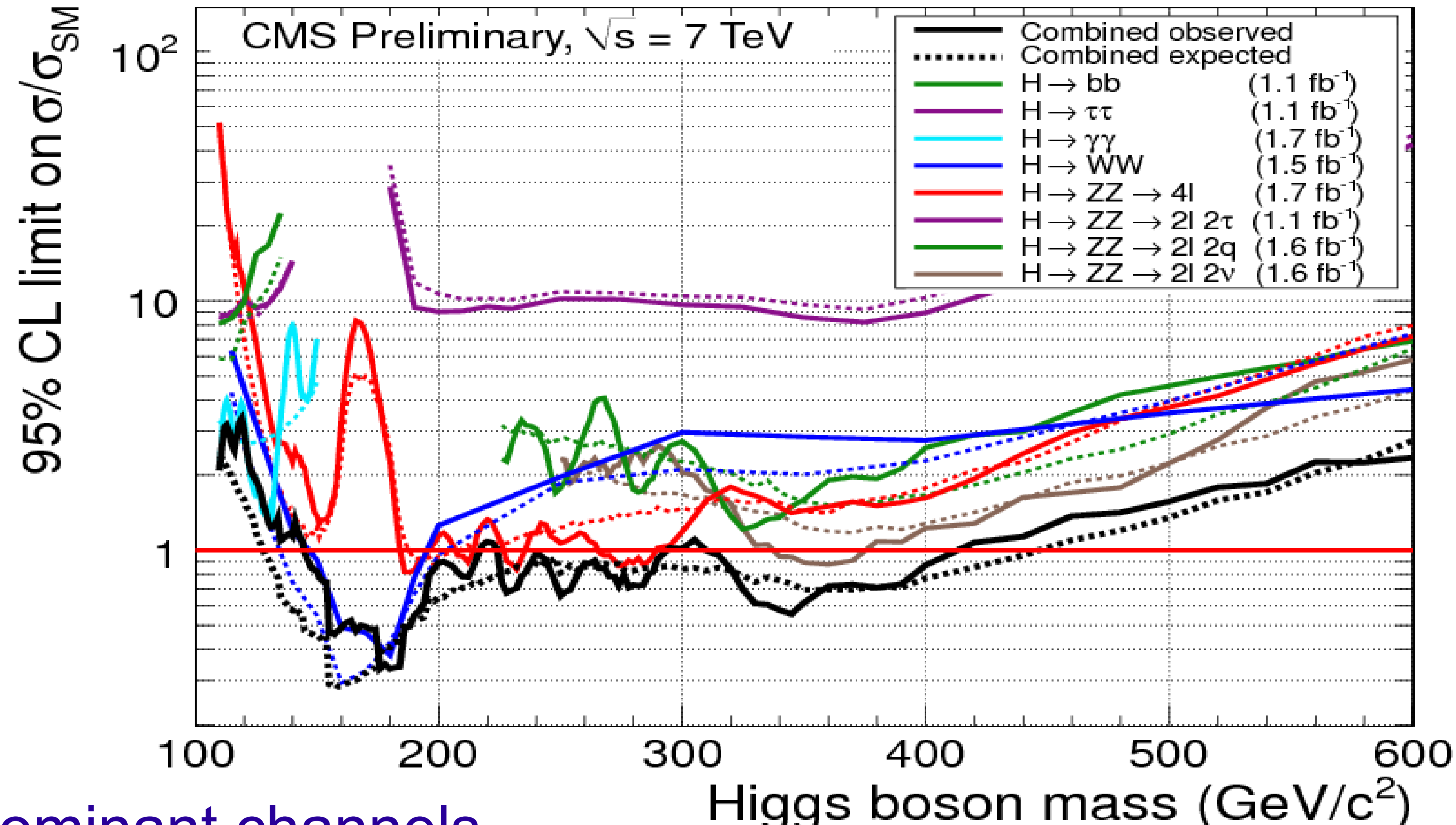
H -> ZZ -> 4l

H -> ZZ -> 2l2τ

H -> ZZ -> 2l 2nu

H -> ZZ -> 2l 2jets

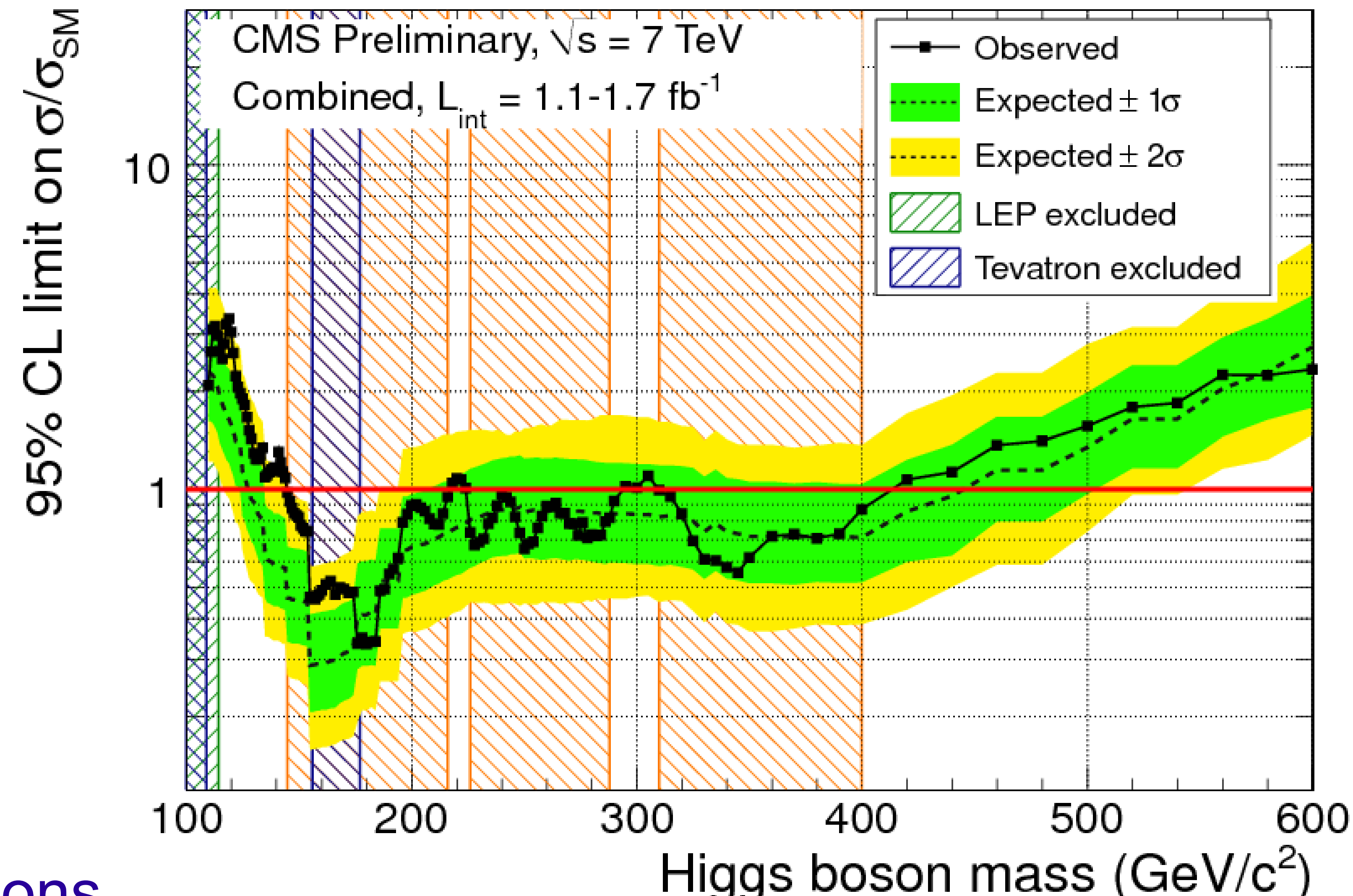
CMS SM Higgs Combination



Dominant channels

- 110-140 GeV ***H -> γγ*** 140-200 GeV ***H -> WW -> 2l 2nu***
- 200-320 GeV ***H -> ZZ -> 4l*** 320-600 GeV ***H -> ZZ -> 2l 2nu***

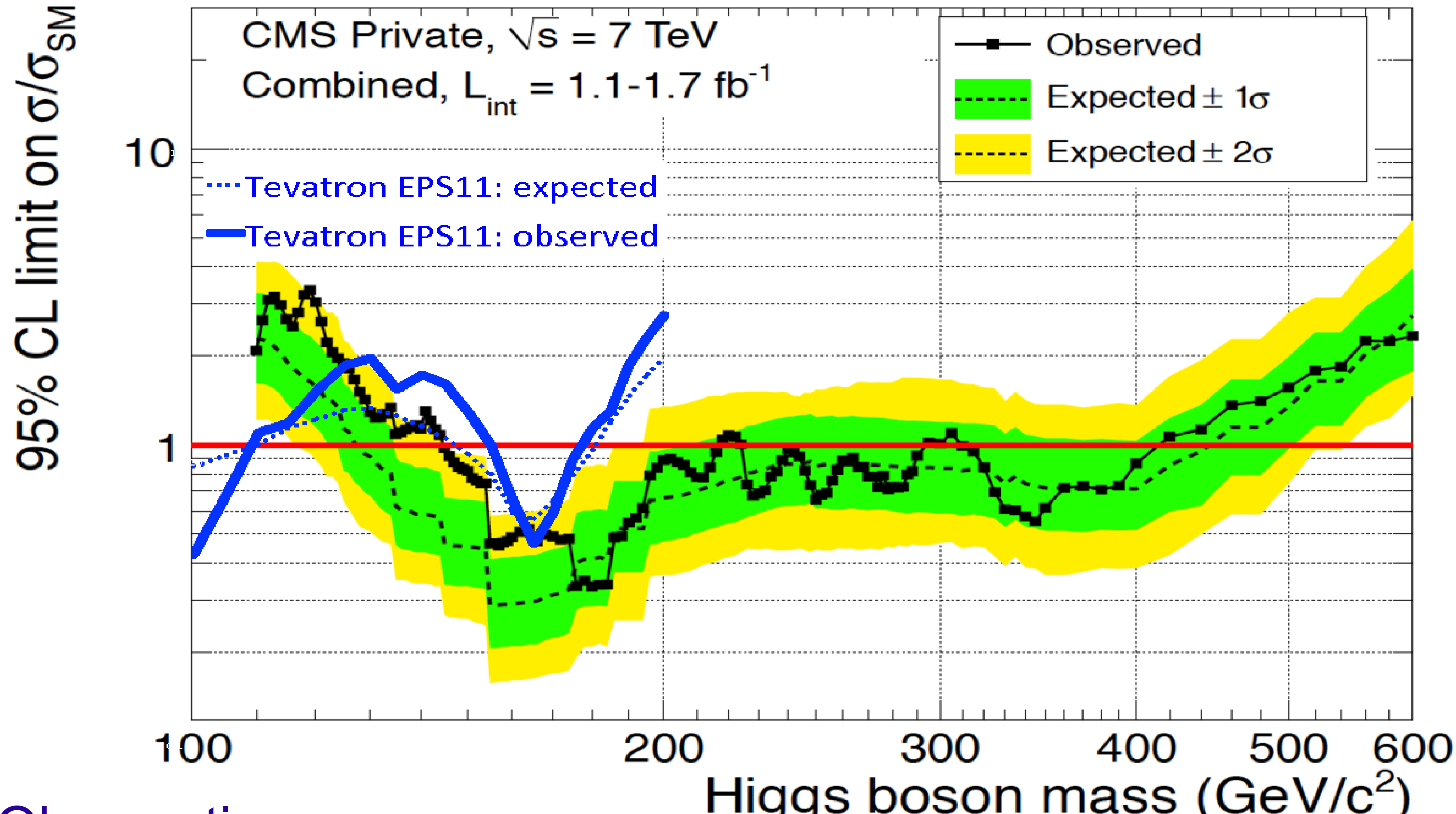
CMS SM Higgs Combination



Observations

- expected and observed track each other reasonably
- expect exclusion down to 130 GeV, only get to 145 GeV

CMS SM Higgs Combination



Observations

– Tevatron still better at low mass, but not for long ....

Conclusion

The Standard Model of particle physics

- beautifully describes all existing measurements
- but... we have no experimental evidence for what is responsible for particle masses

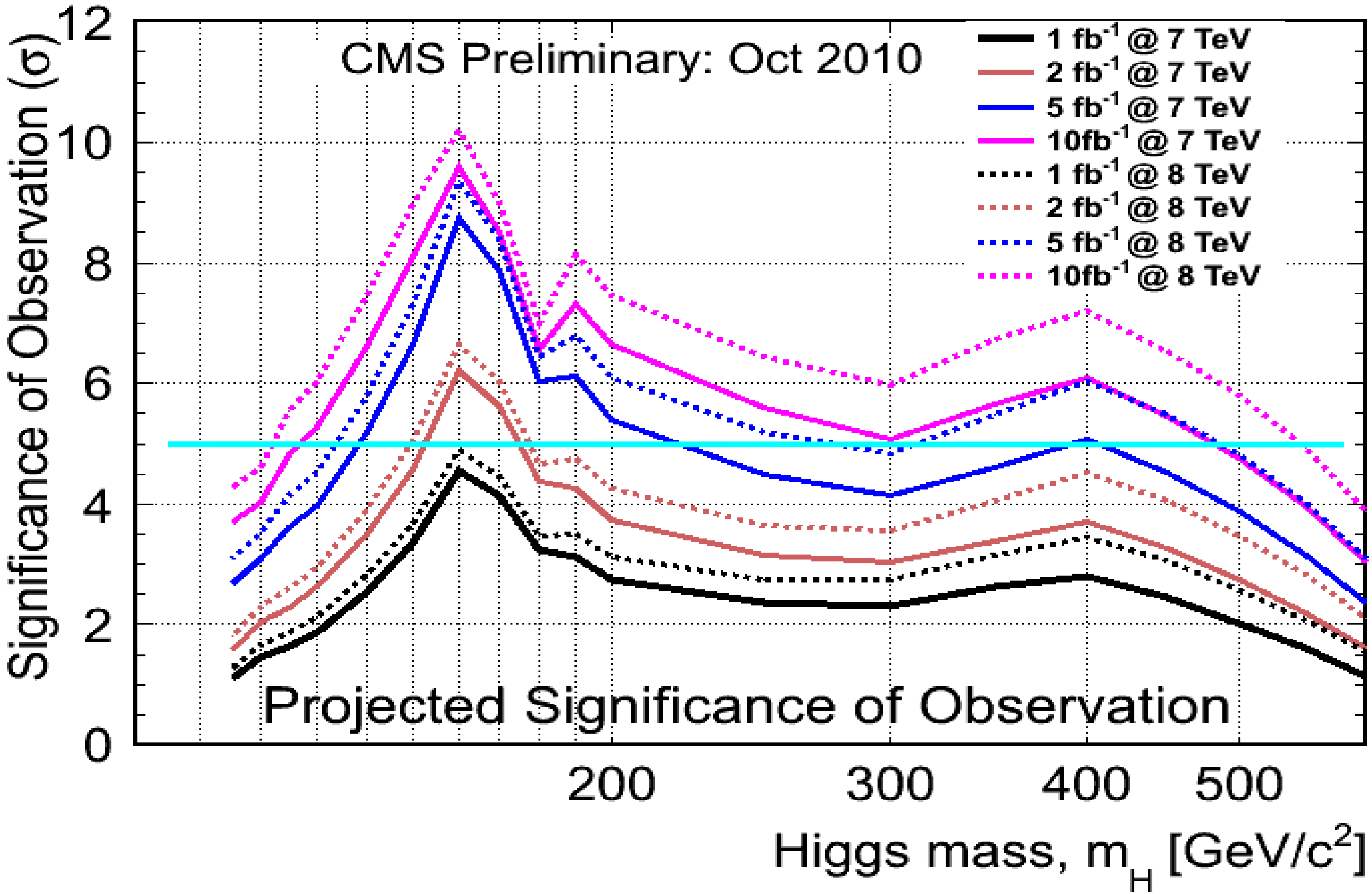
The LHC and CMS

- taking data and doing better than expected by a lot
- all major Higgs decays channels have been analyzed
- summer 2011 analyses have not found a signal
- derived limits erase interesting m_H parameter space
- prospects for 2011: exclude Higgs in full mass range at 95% CL or something starts to build up

Very exciting times (2 years) are upon us:
Find or exclude the Higgs – Goal since SM exists

More Details

Prospects Discovery – Example CMS



Indeed: the Higgs is in reach!

Sensitivity Prospects – Summary

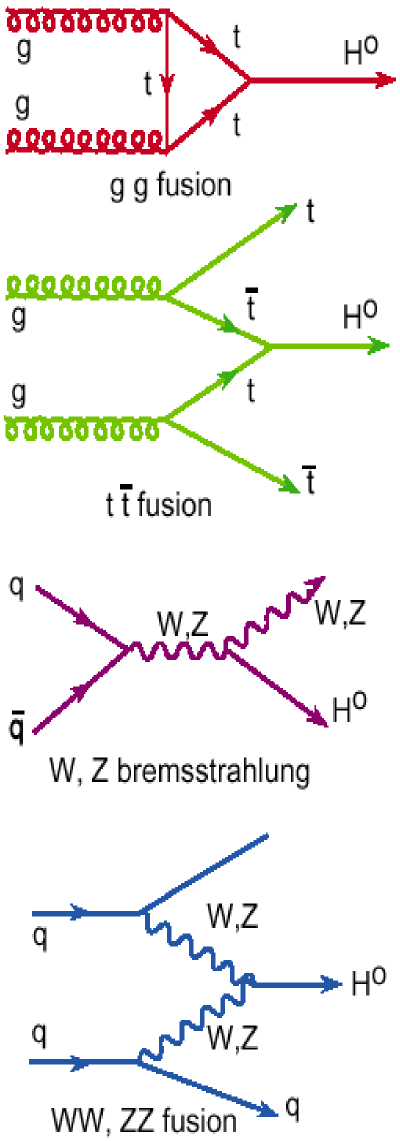
ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

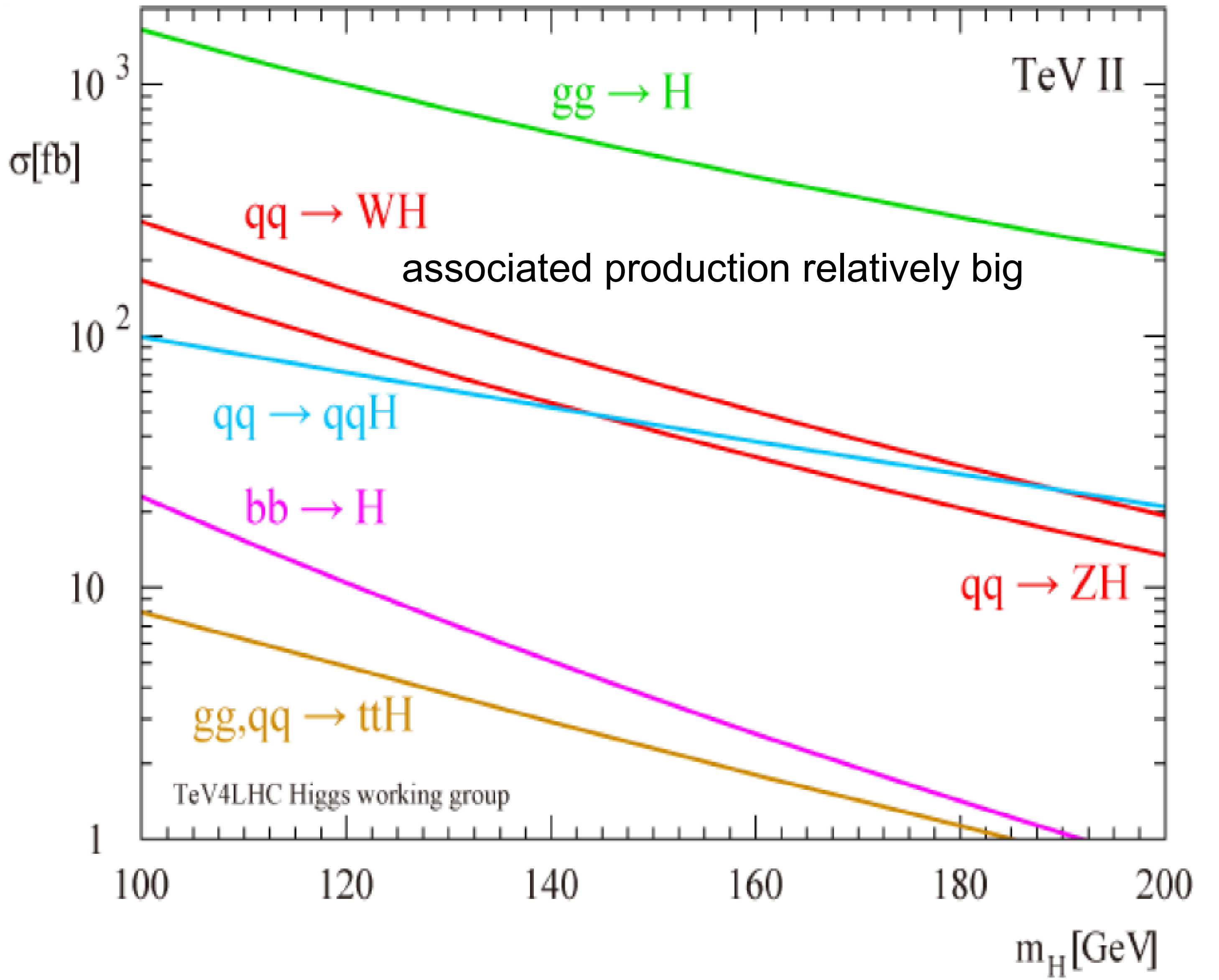
Think about this

– 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

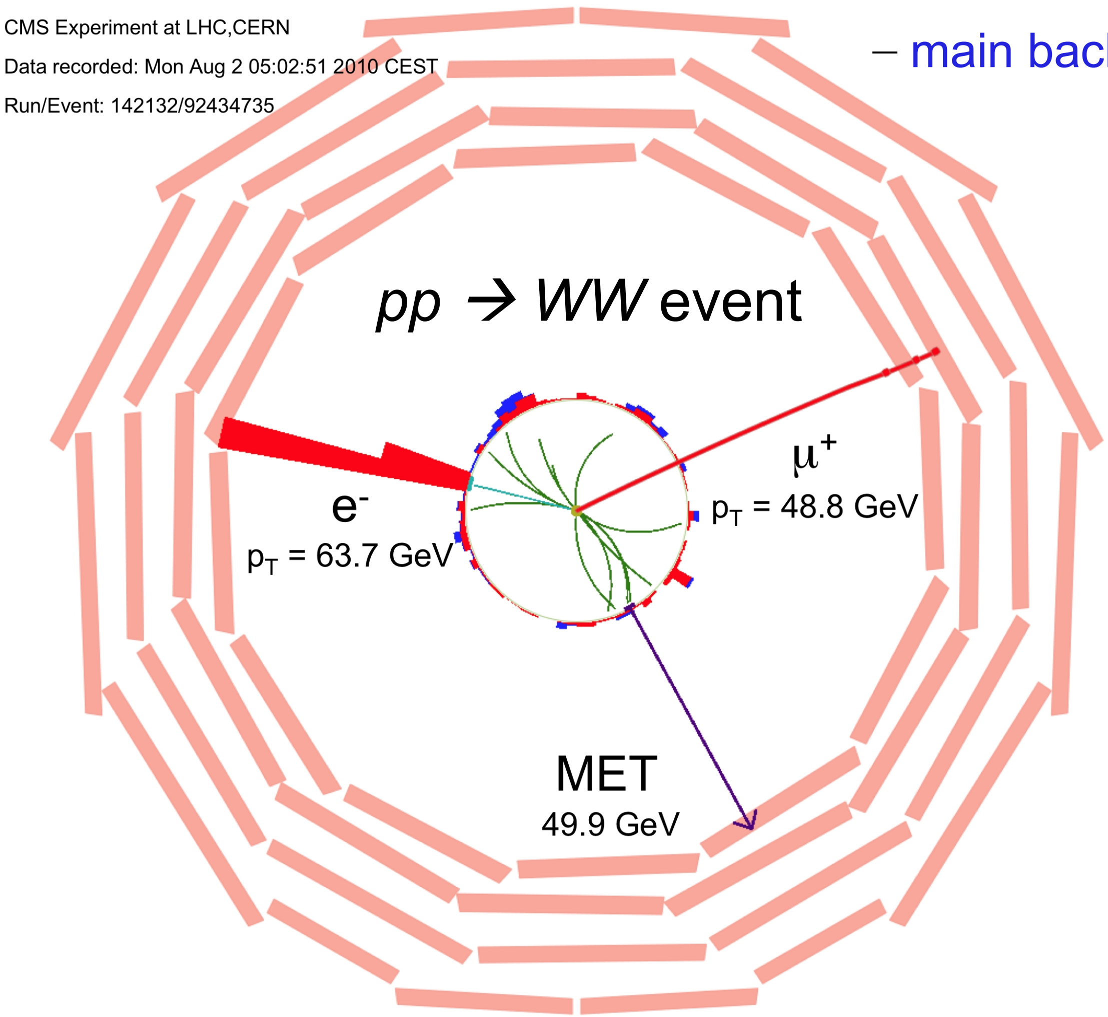




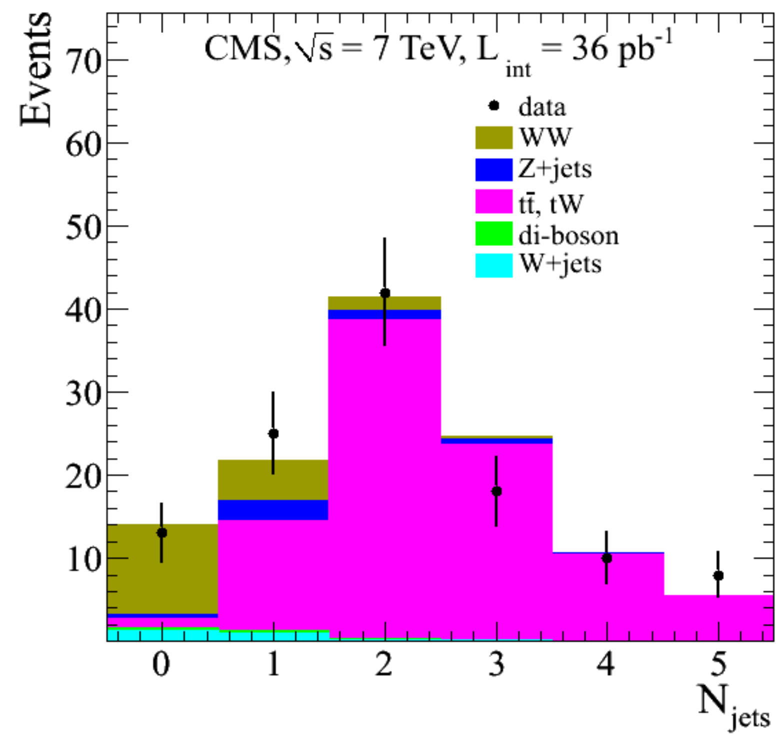
Final State: $WW \rightarrow 2l2\nu$

Observe 13 candidate *pp* → *WW* events

- measure cross section
- σ(*pp* → *WW*) = (41.1 ± 15.3 ± 5.8 ± 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