Resultados da pesquisa do bosão de Higgs no LHC

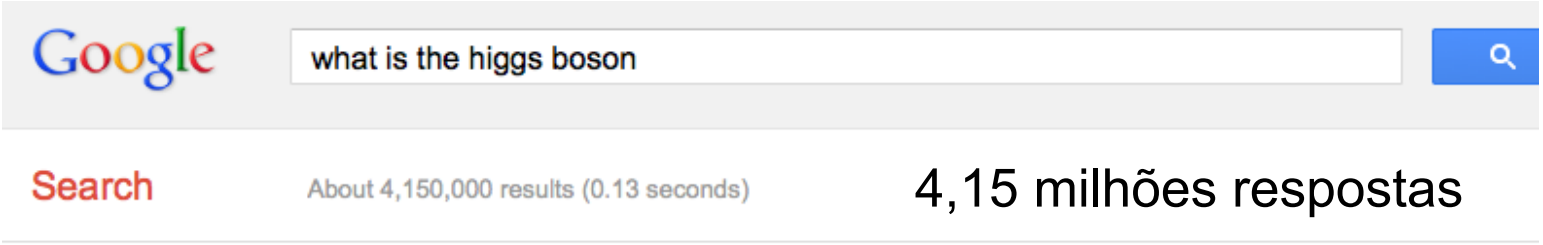
Observação de uma nova partícula com uma massa de 125 GeV

João Varela

Professor do IST e Investigador no LIP
Vice-director da Colaboração CMS

Why to search for the Higgs boson?

What is the Higgs boson?



4,15 milhões respostas

Wikipedia:

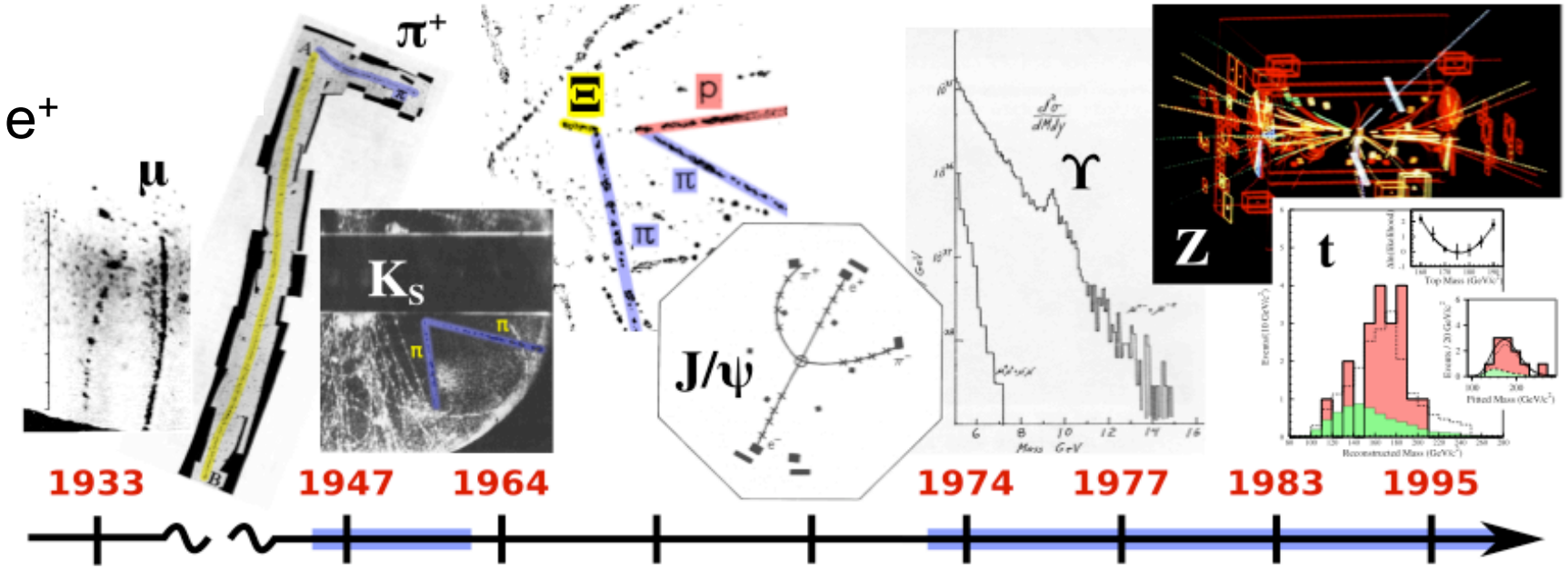
The Higgs boson is a hypothetical elementary particle predicted by the Standard Model (SM) of particle physics.

It belongs to a class of **particles** known as **bosons**, characterized by an integer value of their **spin quantum number**.

The **Higgs field** is a **quantum field** with a non-zero value that fills all of space, and explains why fundamental particles such as **quarks** and **electrons** have **mass**.

XXth century: The Standard Model of Particles

From X-rays and radioactivity to the Higgs boson



Cosmic rays — **Accelerators**

Quantum Field Theory

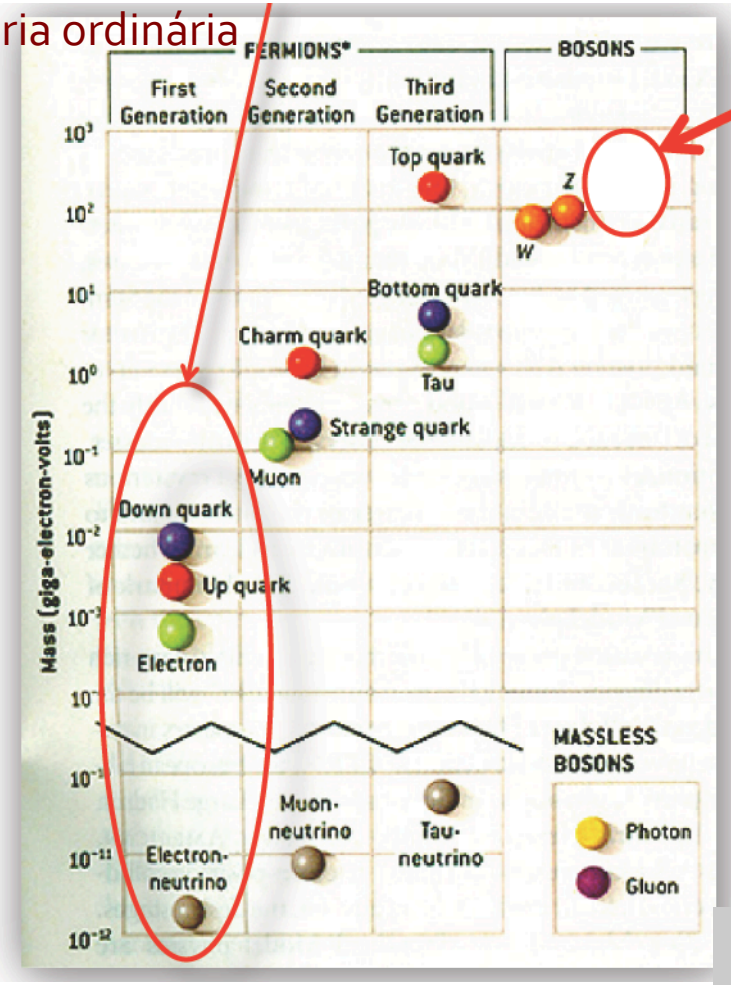
The Quark Model

Electroweak Theory

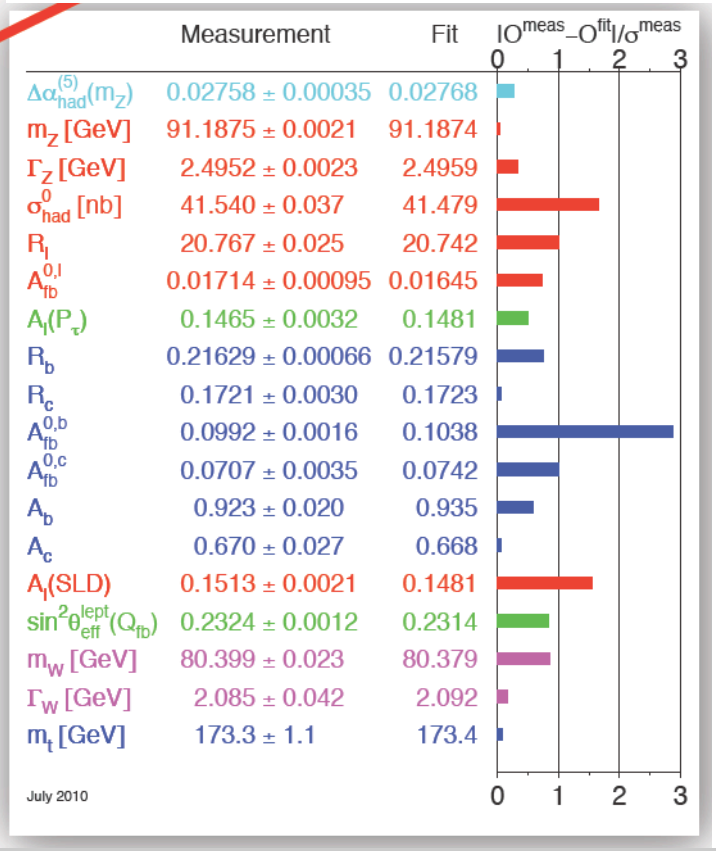
The Standard Model

Teoria que descreve as partículas fundamentais e as suas interacções
Acordo extraordinário com todos os resultados experimentais conhecidos

Matéria ordinária



1 Elemento em falta: Higgs



Confirmado com precisão melhor que 1%

Fermions and Bosons

Fermions:

- spin is semi-integer
- only one fermion can occupy a particular quantum state at any given time
- particles of matter

- **Examples:** electron, muons, quark, neutrino **(spin ½)**

Bosons:

- spin integer
- more than one boson can occupy the same quantum state
- mediators of forces

- **Examples:** photon, W boson, Z boson , gluon **(spin 1)**

Higgs boson has spin 0

Higgs: Partícula ou Campo?

Princípio básico da teoria quântica:
A cada partícula está associado um campo

Prémio Nobel de Einstein:

Ondas de luz consistem em corpúsculos de energia (quanta) designados por fotões

Em geral, o campo electromagnético (ondas rádio, micro-ondas, luz, raios-X) consiste em fotões.

Partícula de Higgs ←→ Campo de Higgs

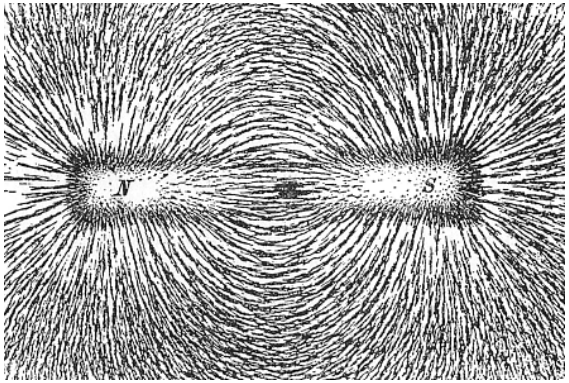
Campo electromagnético

Campos de forças eléctricas ou magnéticas são manifestações diferentes de um único **campo de forças electromagnéticas**

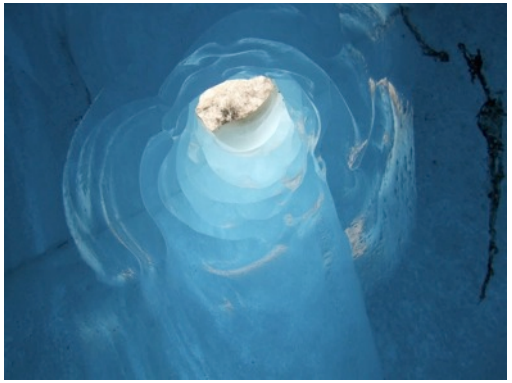
Equações de Maxwell, século XIX

Ondas rádio

Forças magnéticas



Luz



O que é a massa?

A massa é uma propriedade básica dos constituintes elementares da matéria (partículas)

Sem massa não haveria átomos, planetas, galáxias, Universo

Einstein: partículas sem massa (m=0) deslocam-se à velocidade da luz

GeV

Caso de partícula ao repouso:

$E=mc^2$: massa = energia (c = velocidade da luz)

No caso geral:

$E^2 = (mc^2)^2 + (pc)^2$ energia de massa + energia cinética

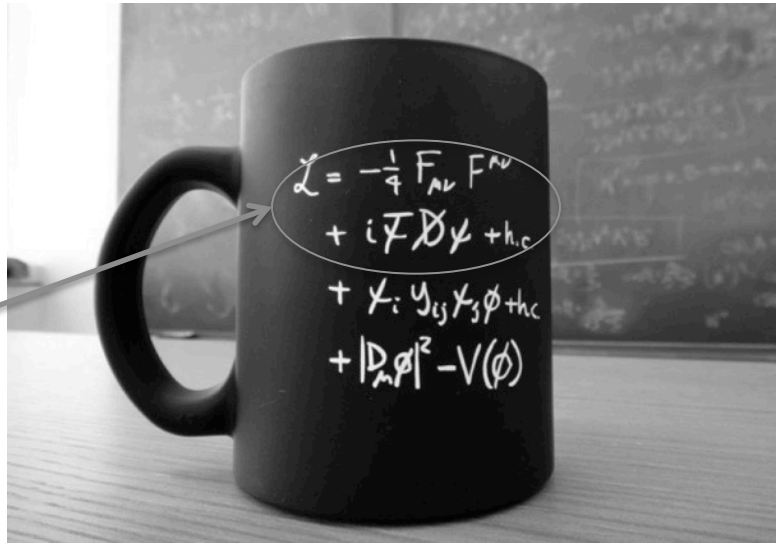
Fotões e outras partículas sem massa: $E=pc$

Electroweak unification

Weak forces: radioactivity, neutrinos, Sun

Electromagnetic and **weak forces** have the same origin

The **electroweak theory** is based in a **underlying symmetry** between the two interactions



Electromagnetic interaction:

Photon **m=0**

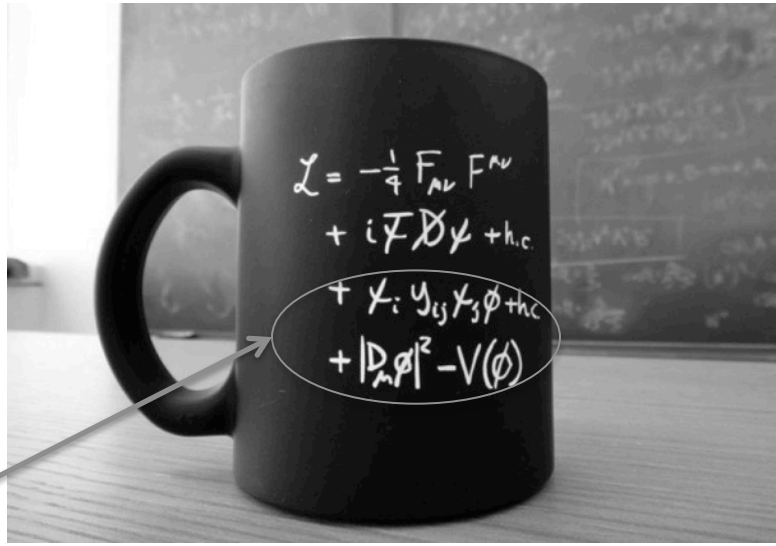
Weak interaction:

Bosões W e Z **m~80-90 GeV**

Different masses of γ, W and Z breaks the symmetry

O Higgs e a origem da massa

As equações da teoria inicial só faziam sentido se todas as partículas tivessem massa nula e se deslocassem à velocidade da luz

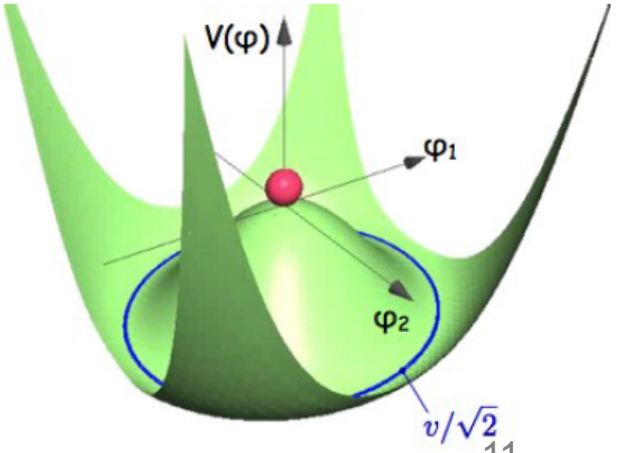


Mecanismo de quebra espontânea de simetria

Englert-Brout
Higgs
Guralnik-Hagen-Kibble

Campo de Higgs nas equações:

- Quebra espontânea da simetria no mínimo de energia
- O campo de Higgs existe em todo o espaço
- As partículas W, Z adquirem massa através da interacção com o campo de Higgs.

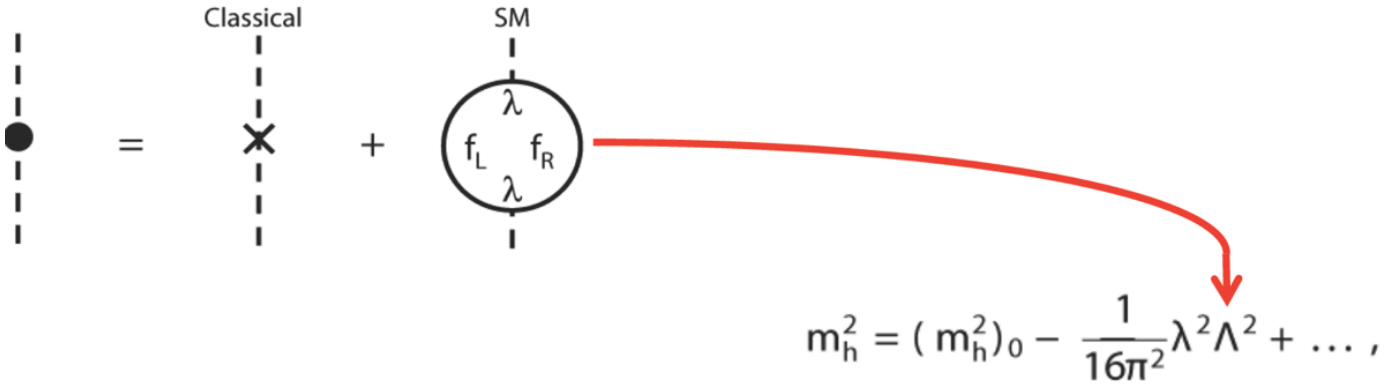


Beyond the Higgs

Higgs mass is a huge problem:

- Virtual SM particles in quantum loops contribute to the Higgs mass
- Contributions grow with Λ (upper scale of validity of the SM)
- Λ could be huge – e.g. the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass < 1 TeV

This is known as the gauge hierarchy problem



Beyond the Higgs:

New physics beyond the Standard Model is very likely
Supersymmetry, hidden dimensions of space-time, ...

How to search for the Higgs boson?

A escala de energia do LHC

Modelo Standard não funciona a alta energia sem a partícula de Higgs ou sem outra "nova física"

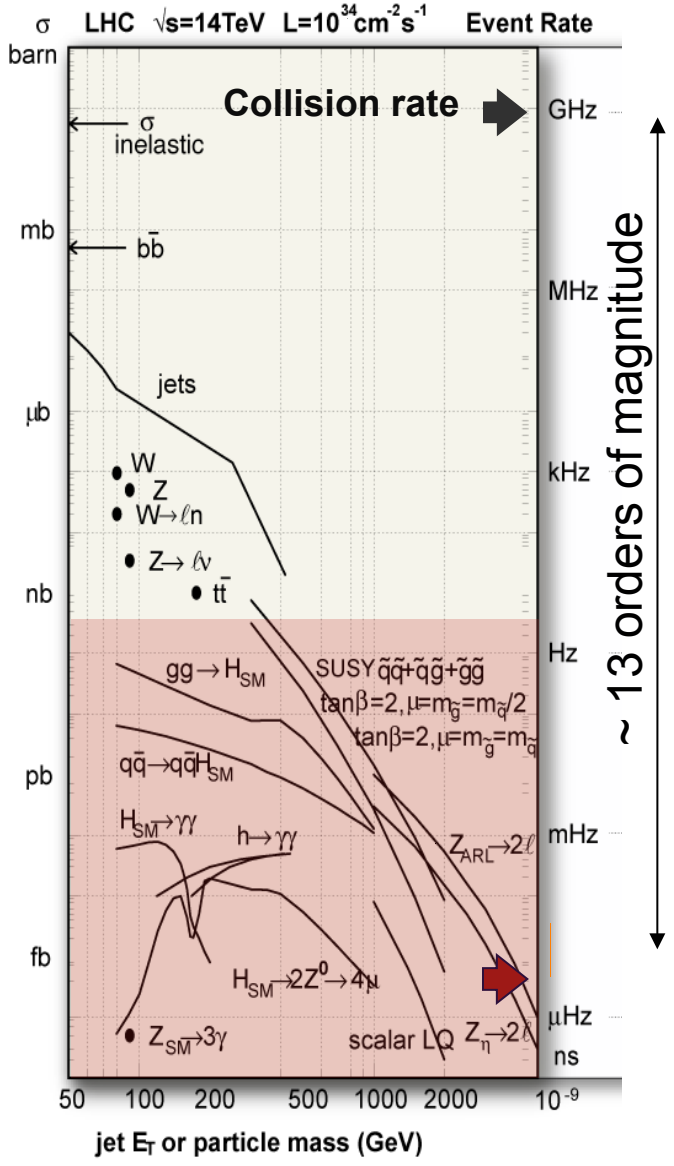
Com base na compreensão presente da teoria e das observações experimentais, esperamos que a "nova física" se manifeste a uma energia inferior a

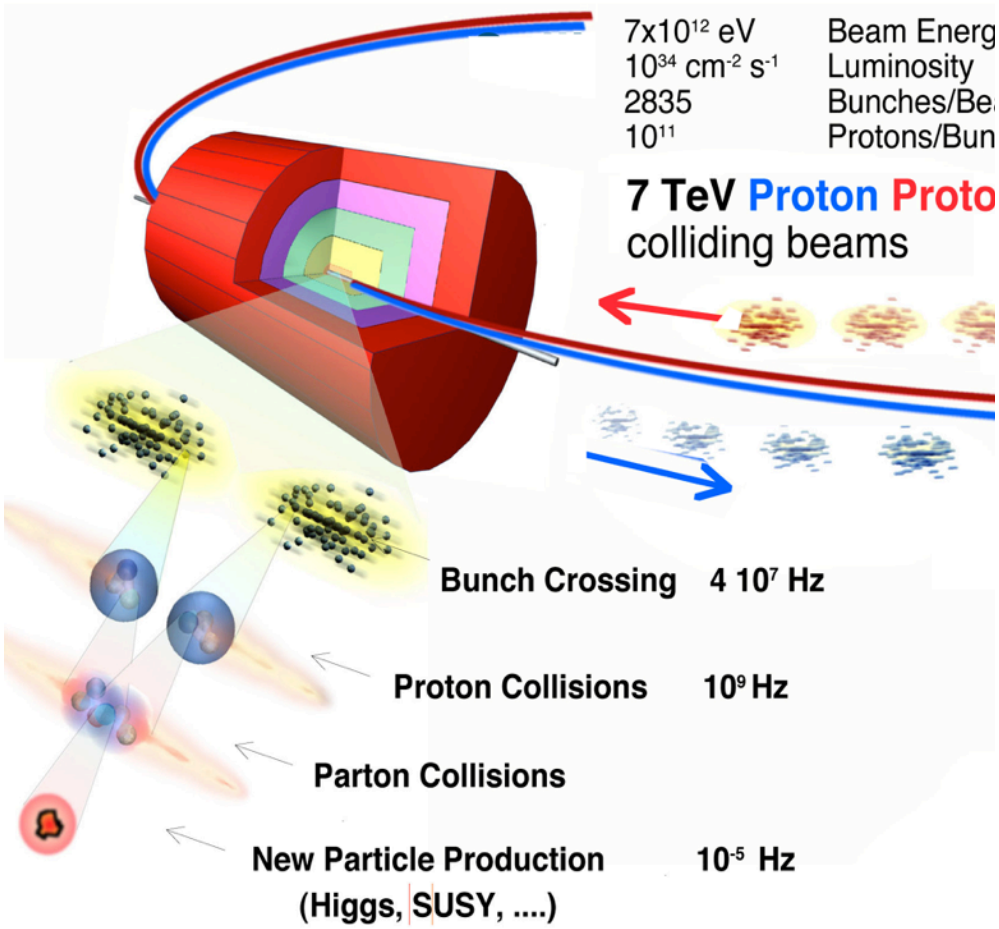
1 Tera-electronVolt (TeV) = 10^{12} electronVolt

acessível no LHC pela primeira vez.

A massa do Higgs deve ser inferior a 1TeV

Proton collisions at LHC





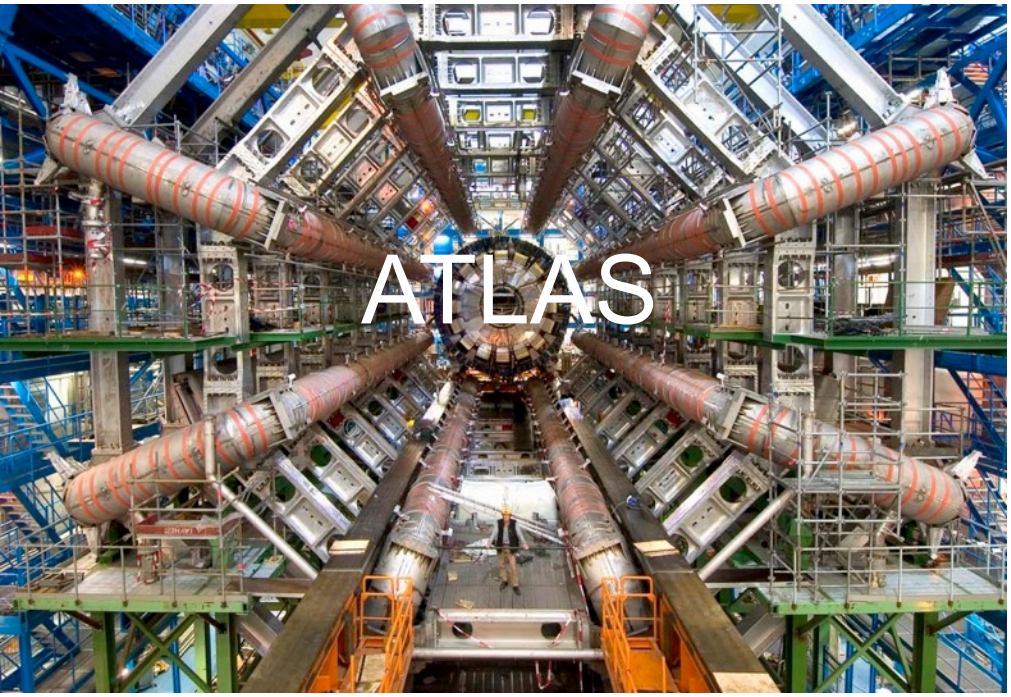
LHC 2010-12:

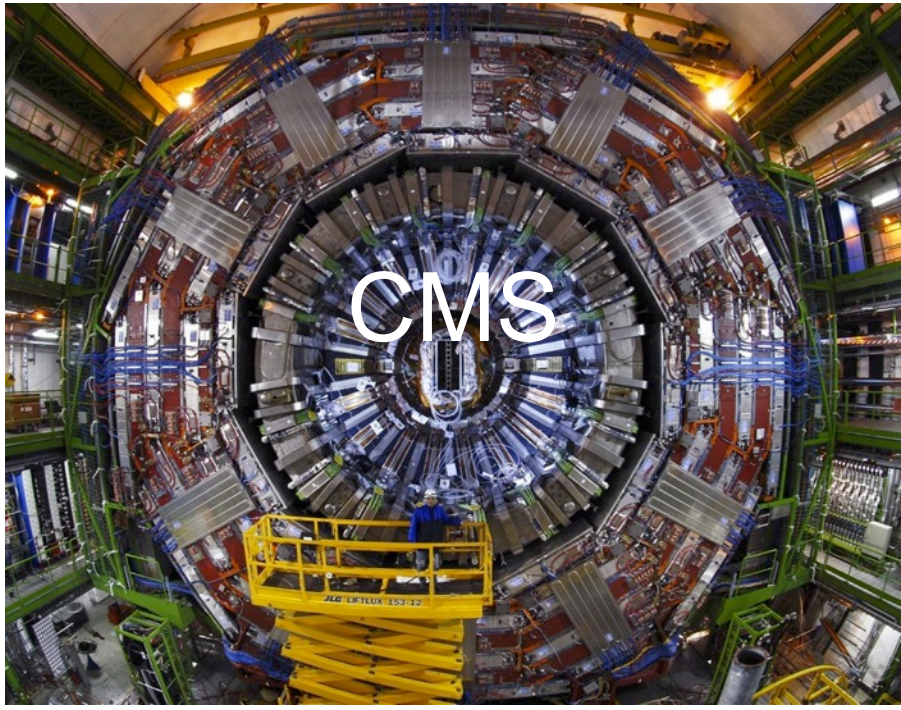
Collision Energy 7 TeV

Luminosity $10^{32\text{-}34}$ cm^{-2}s^{-1}

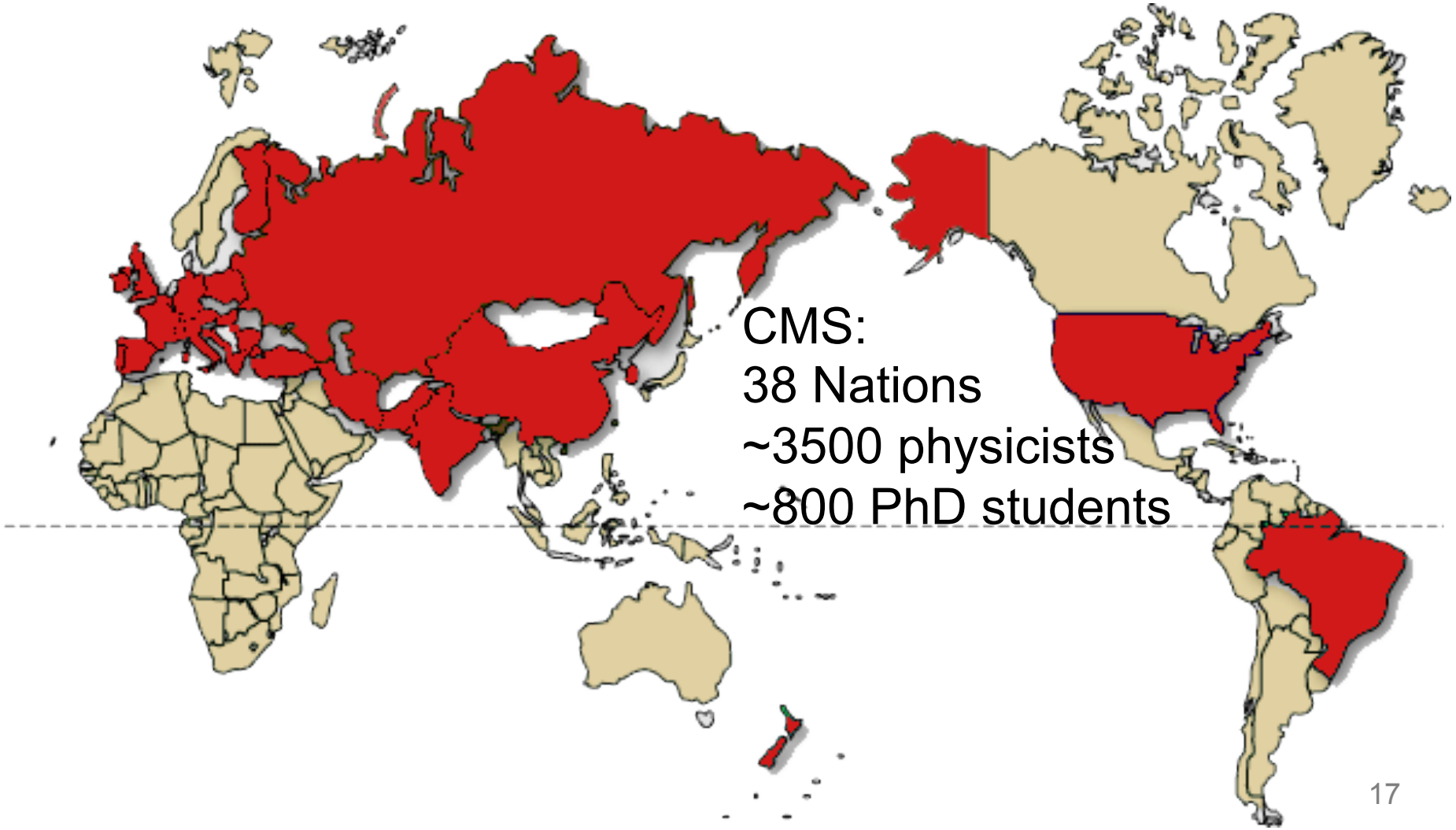
LHC accelerator

LHC Detectors





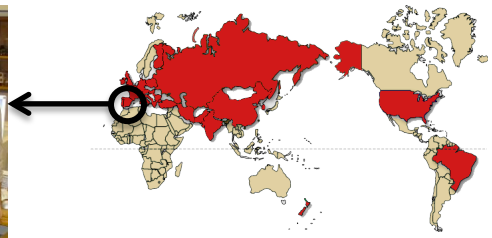
World-wide collaborations

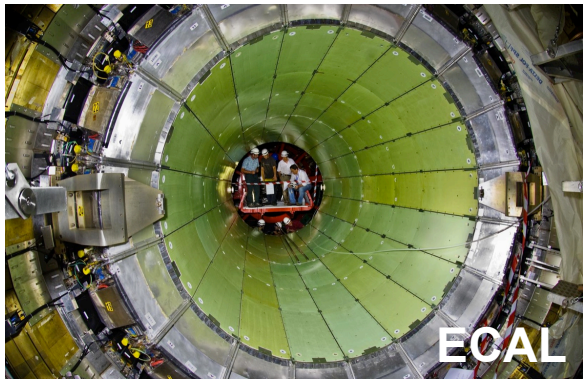


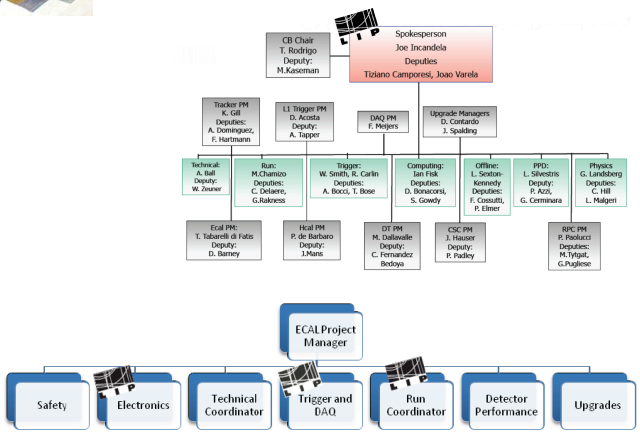
CMS Collaboration

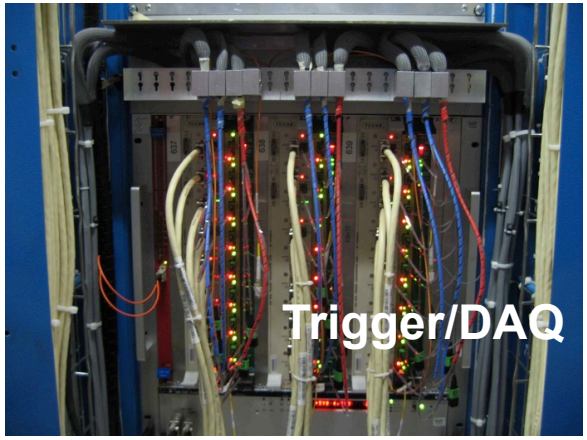
The LIP/CMS group

www.lip.pt

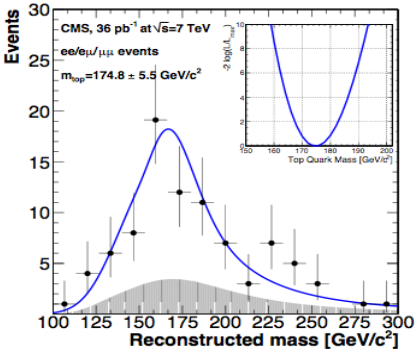




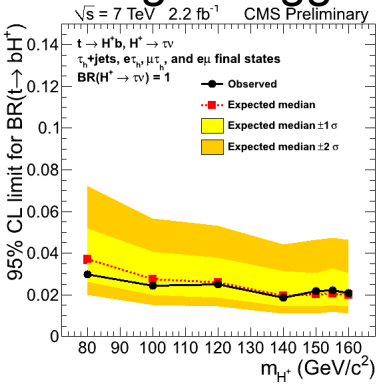




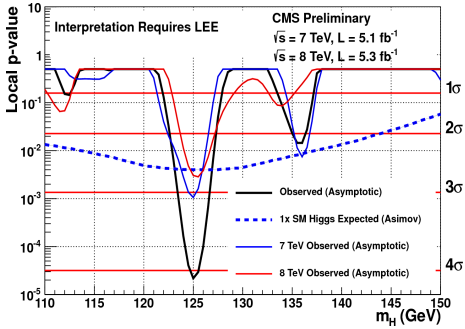
Top quark mass



Charged Higgs



SM Higgs



It’s collaborative!

Bloomberg BusinessWeek

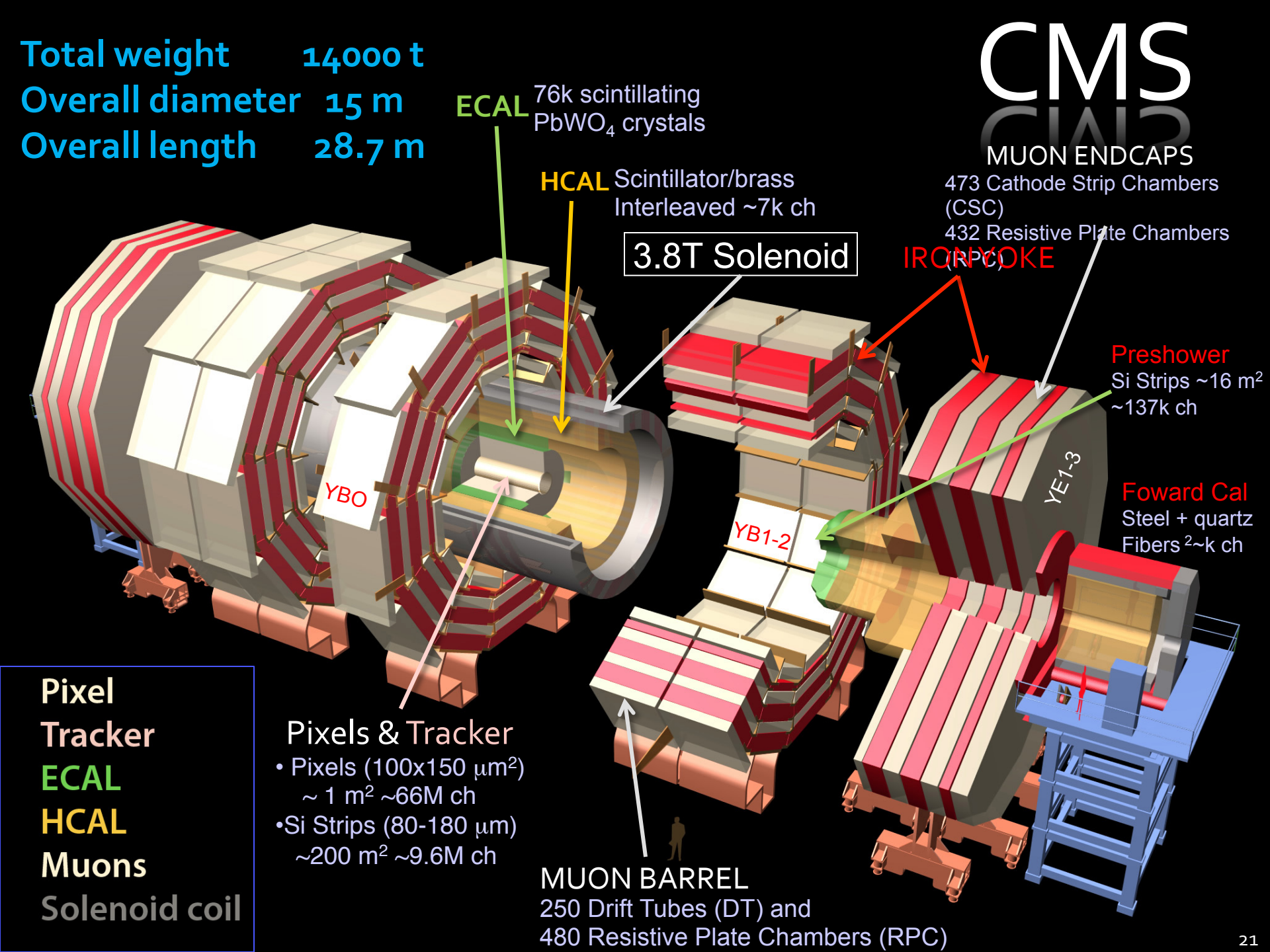
VIEWPOINT May 20, 2009, 11:57AM EST

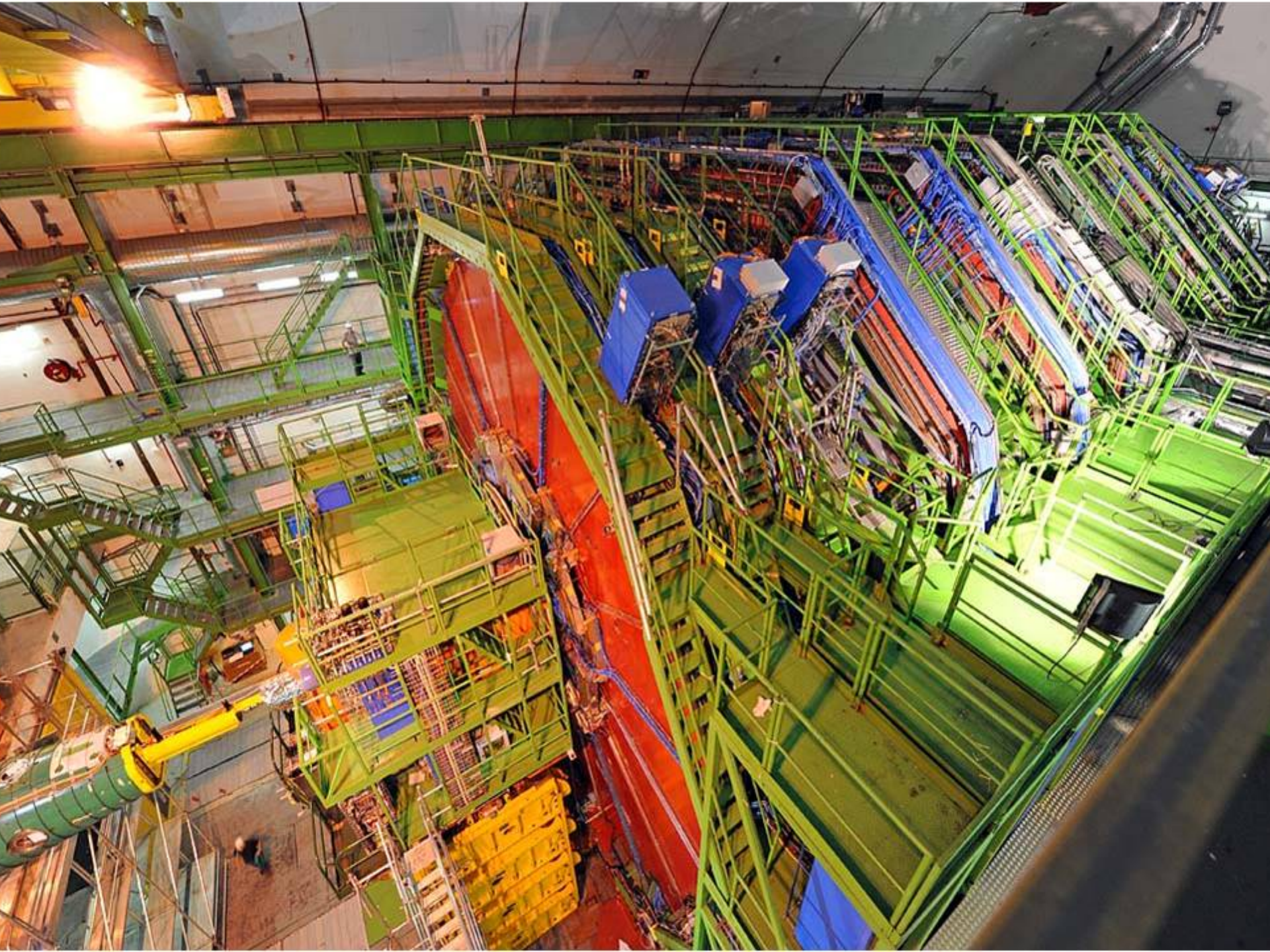
CERN's Collaborative Management Model

Business leaders could learn valuable leadership lessons from the collaborative management style at the Large Hadron Collider at CERN

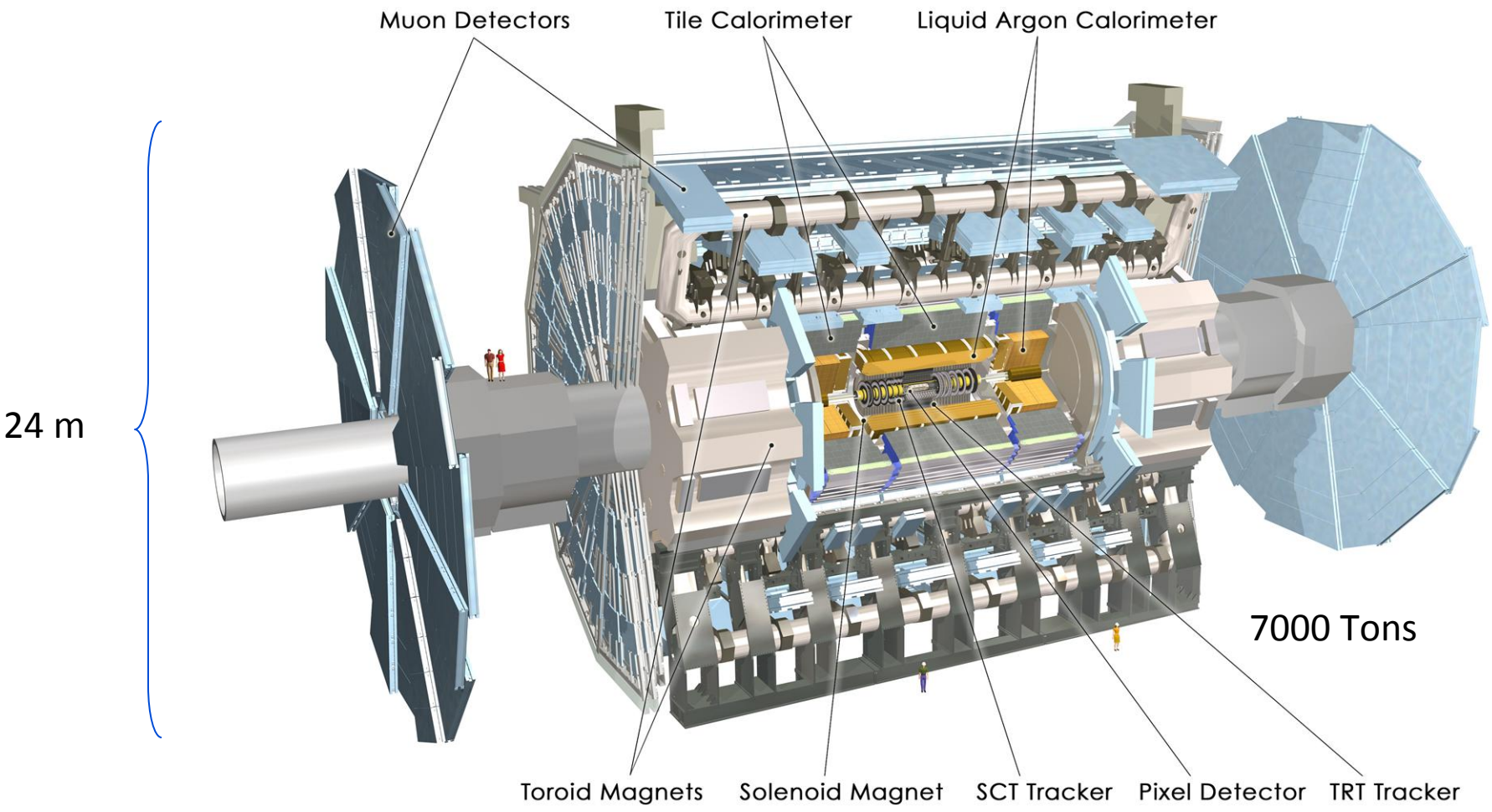
By Krisztina Holly

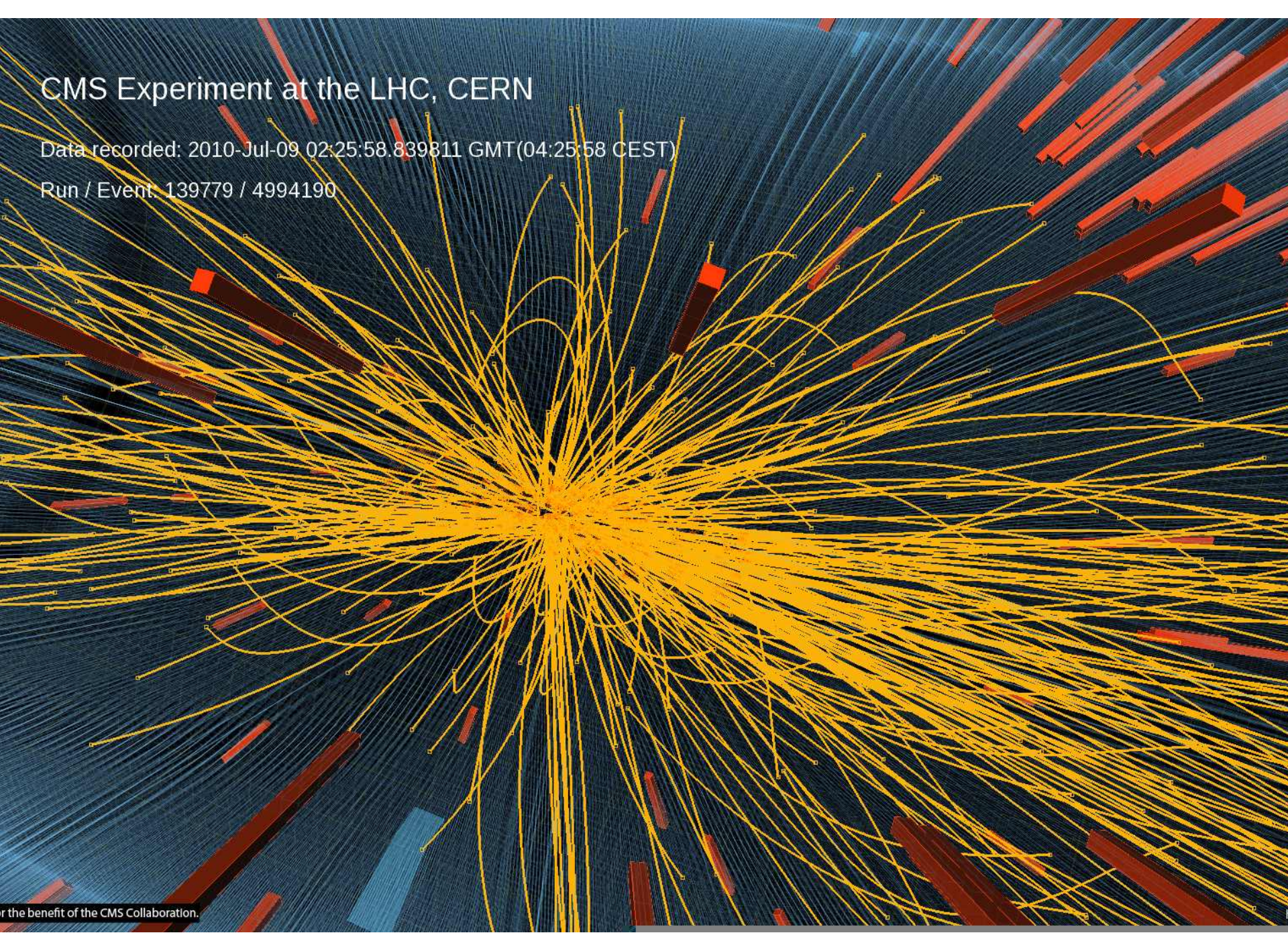
As a business leader, imagine trying to manage more than 7,000 scientists from 85 countries around the world—with their own languages, cultures, and expertise—on a 20-year collaboration to create the most complex system ever built.


Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
IRON YOKE
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
Preshower
Si Strips ~16 m²
~137k ch
Foward Cal
Steel + quartz Fibers ²~k ch
YBO
YB1-2
YE1-3
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²) ~ 1 m² ~66M ch
•Si Strips (80-180 μm) ~200 m² ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

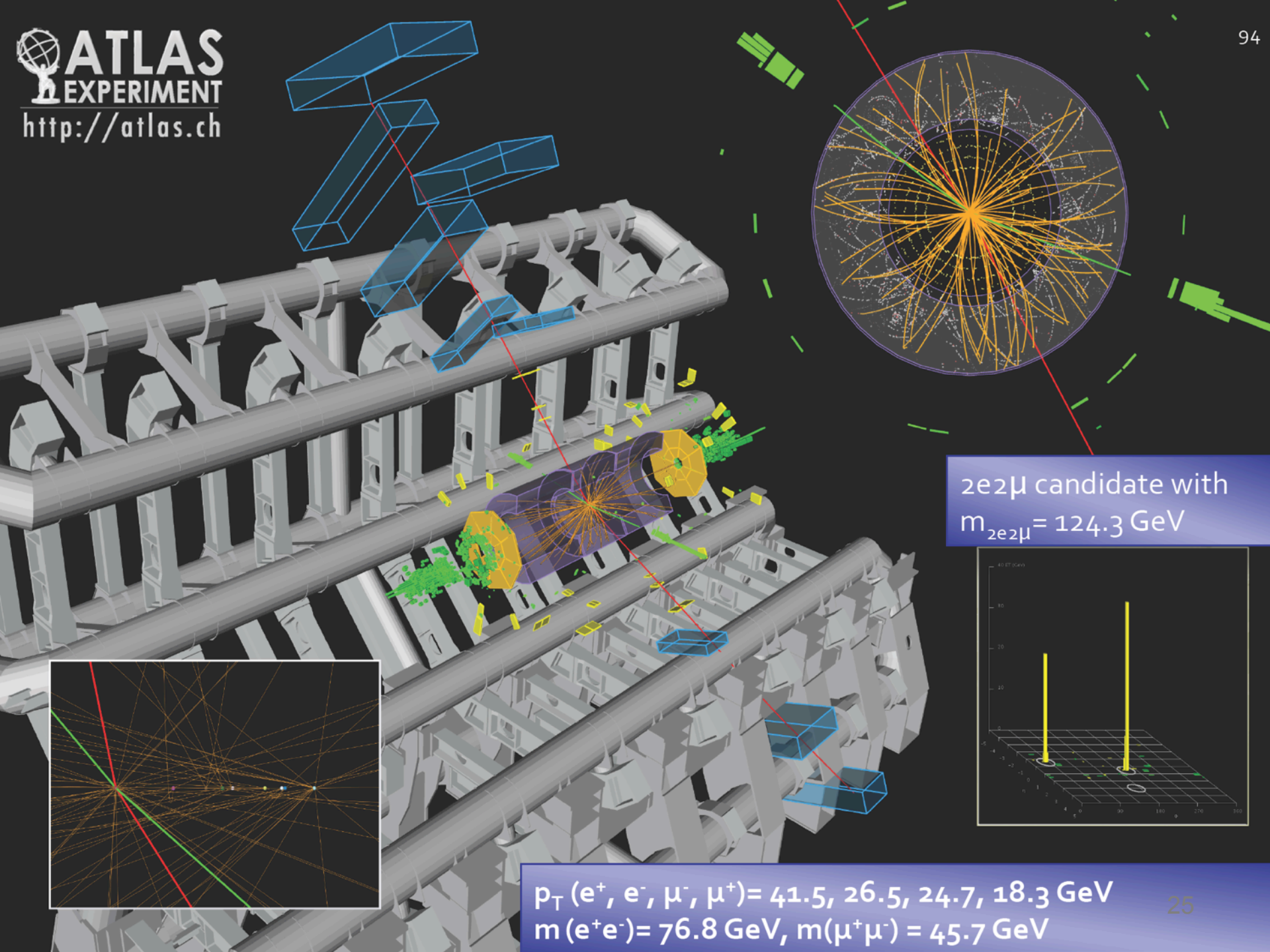


ATLAS detectors



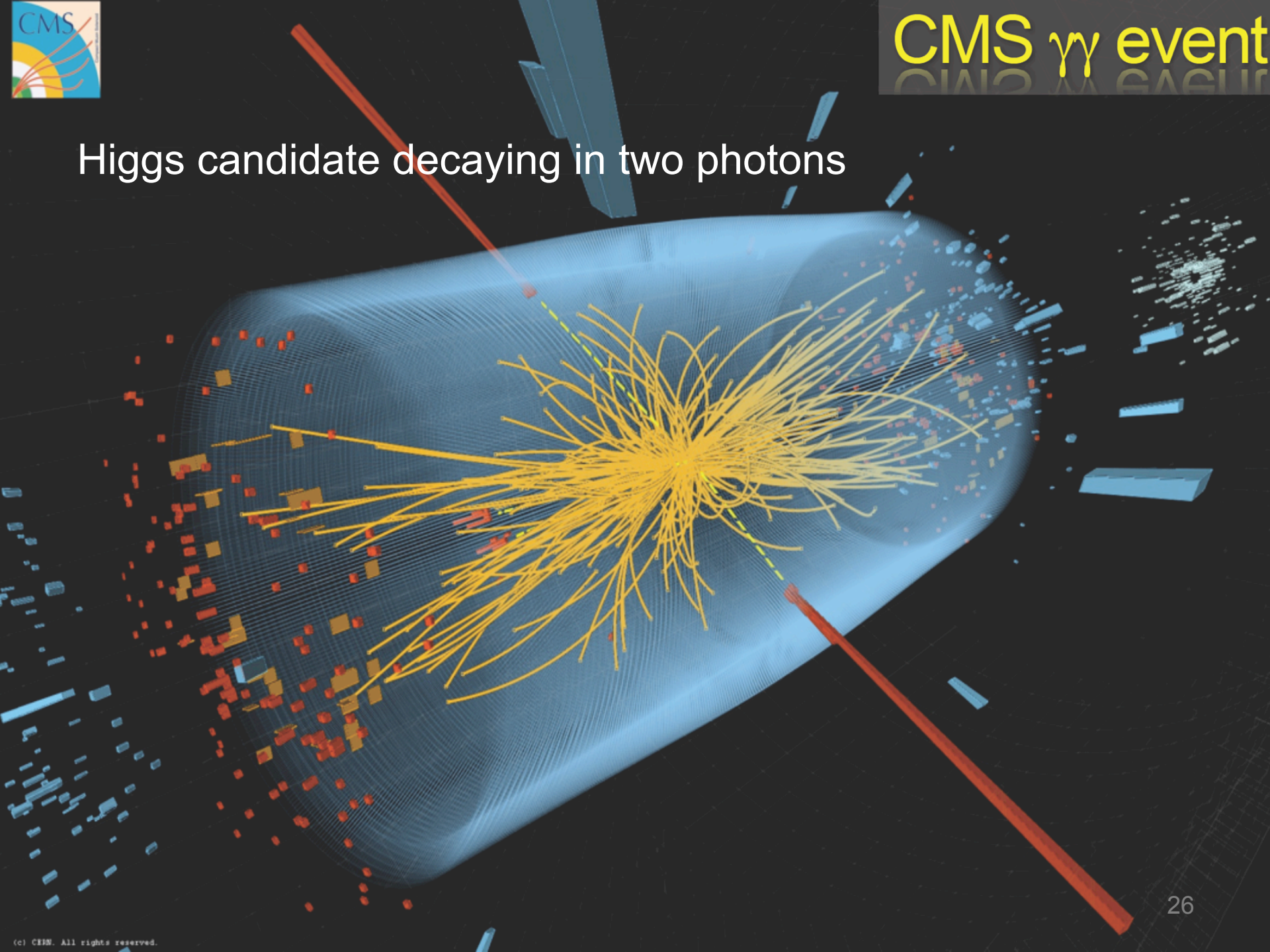

CMS Experiment at the LHC, CERN
Data recorded: 2010-Jul-09 02:25:58.839811 GMT(04:25:58 CEST)
Run / Event: 139779 / 4994190
r the benefit of the CMS Collaboration.

ATLAS EXPERIMENT
http://atlas.ch



2e2μ candidate with
$m_{2e2\mu}$ = 124.3 GeV

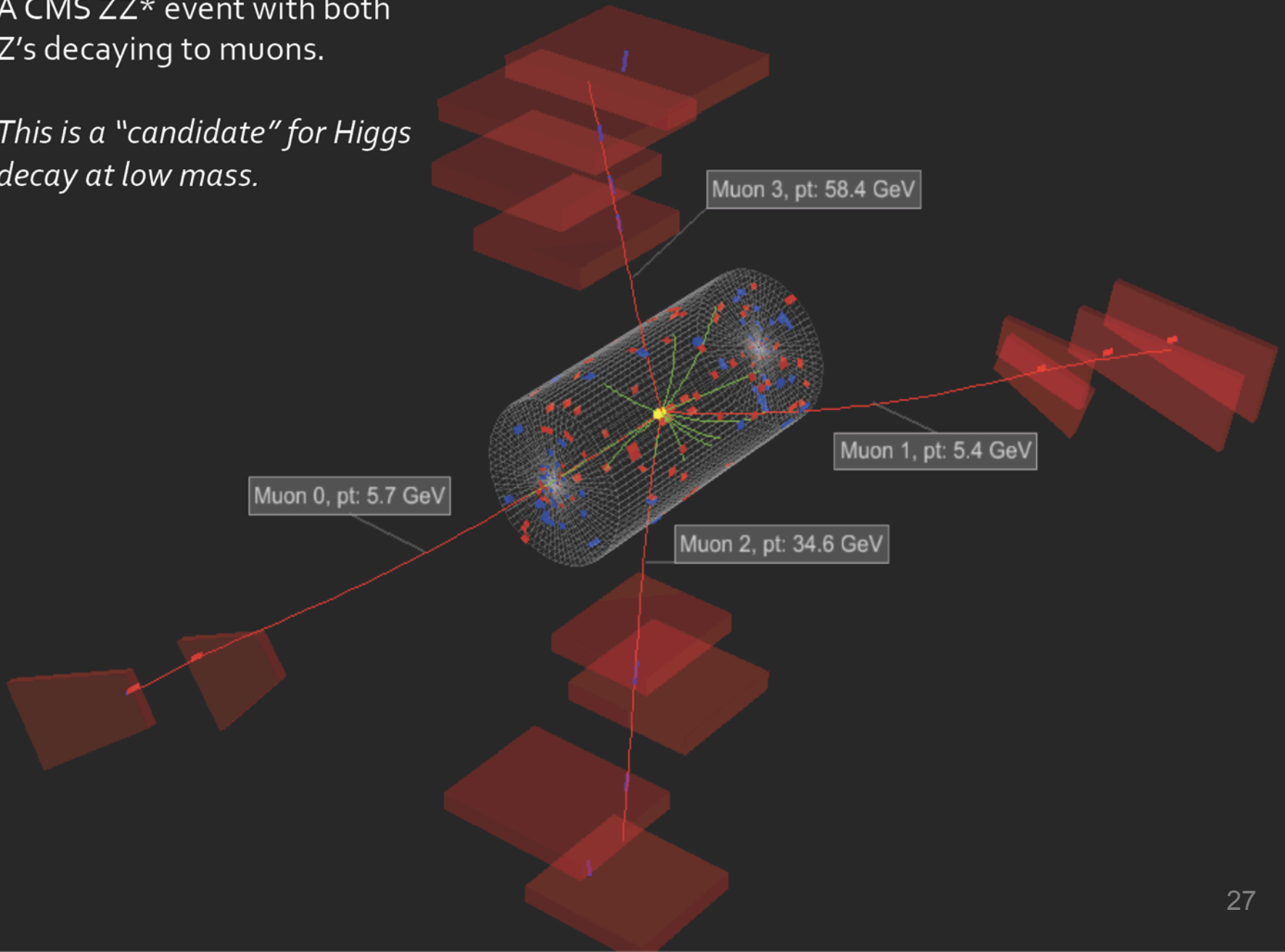
p_T (e^+, e^-, μ^-, μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m (e^+e^-)= 76.8 GeV, m($\mu^+\mu^-$) = 45.7 GeV



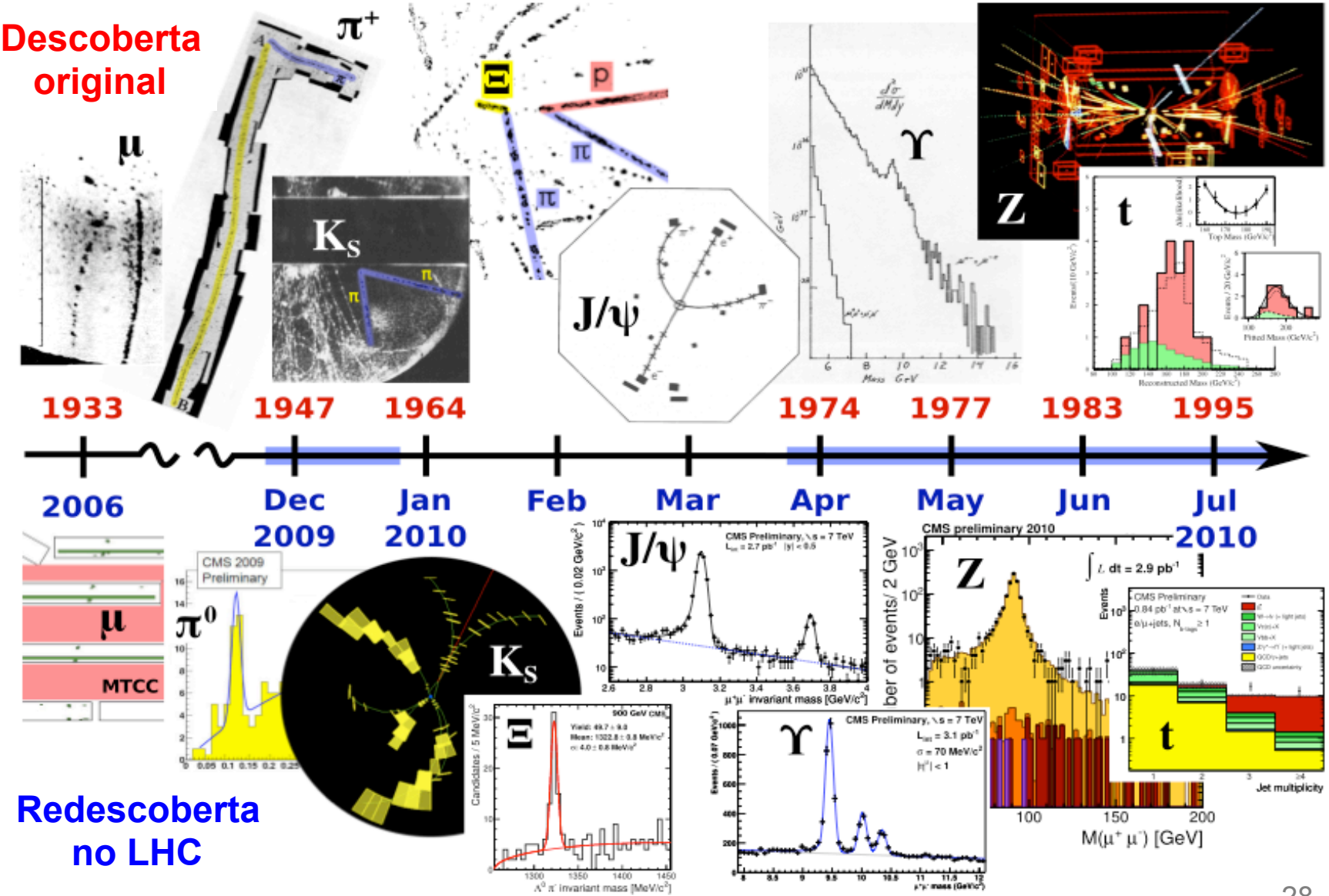
Higgs candidate decaying in two photons

A CMS ZZ* event with both Z's decaying to muons.

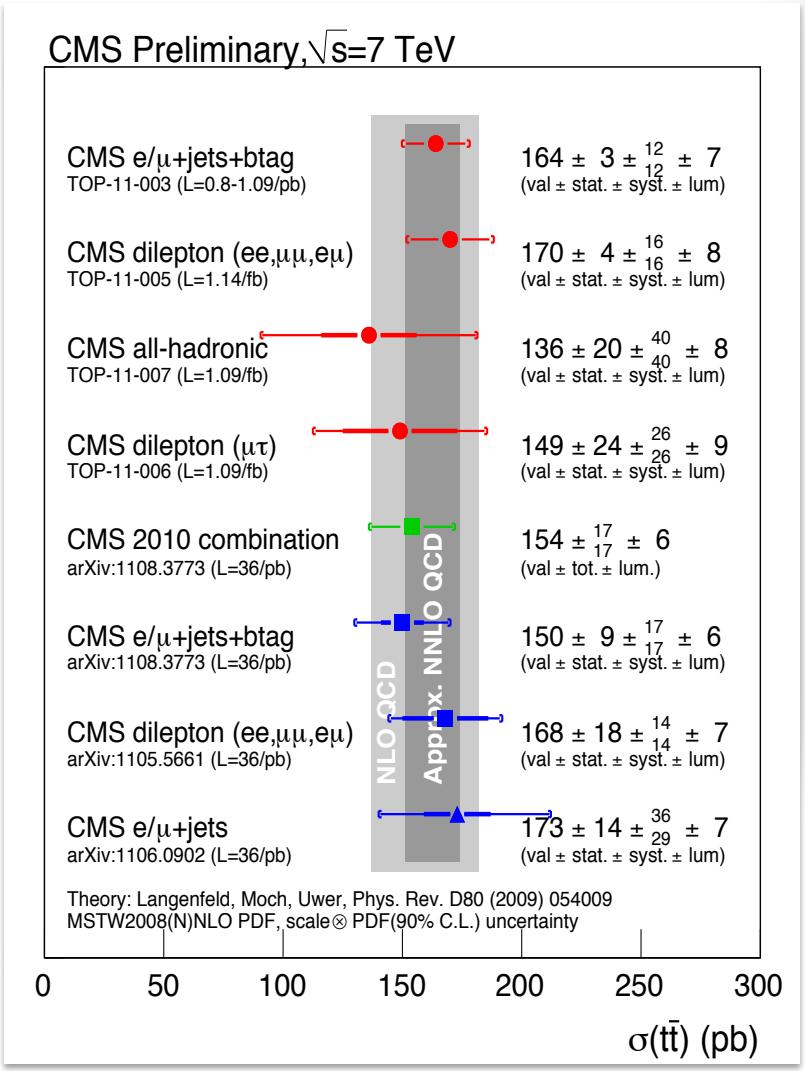
This is a "candidate" for Higgs decay at low mass.

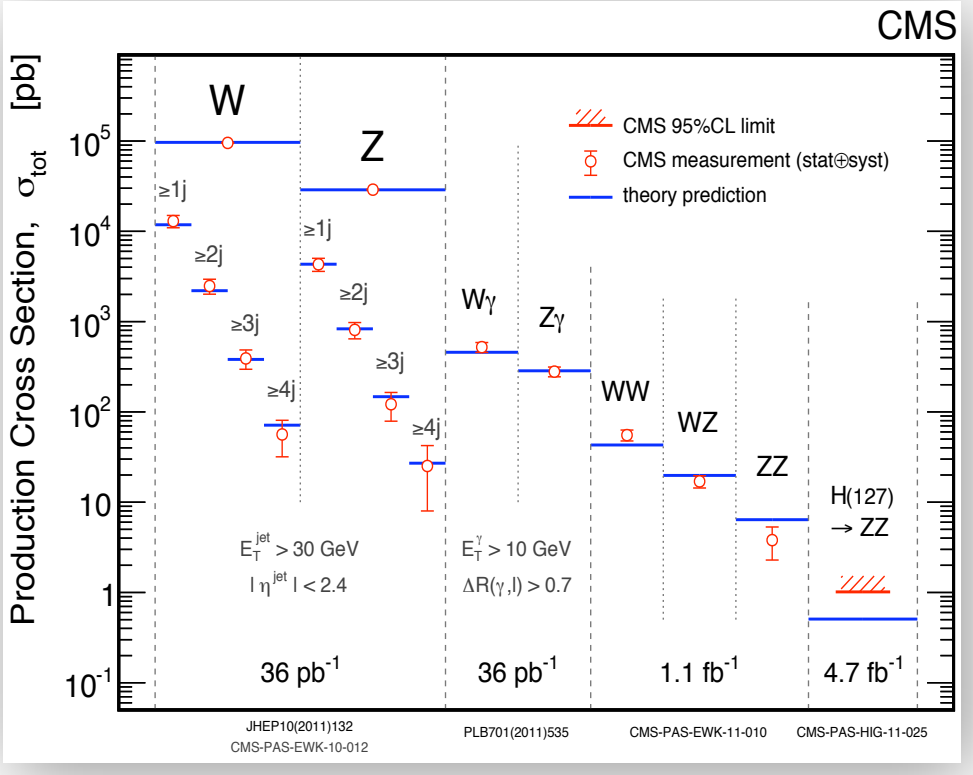


Redescoberta do modelo standard no LHC



Standard Model at 7 TeV 2010-2011



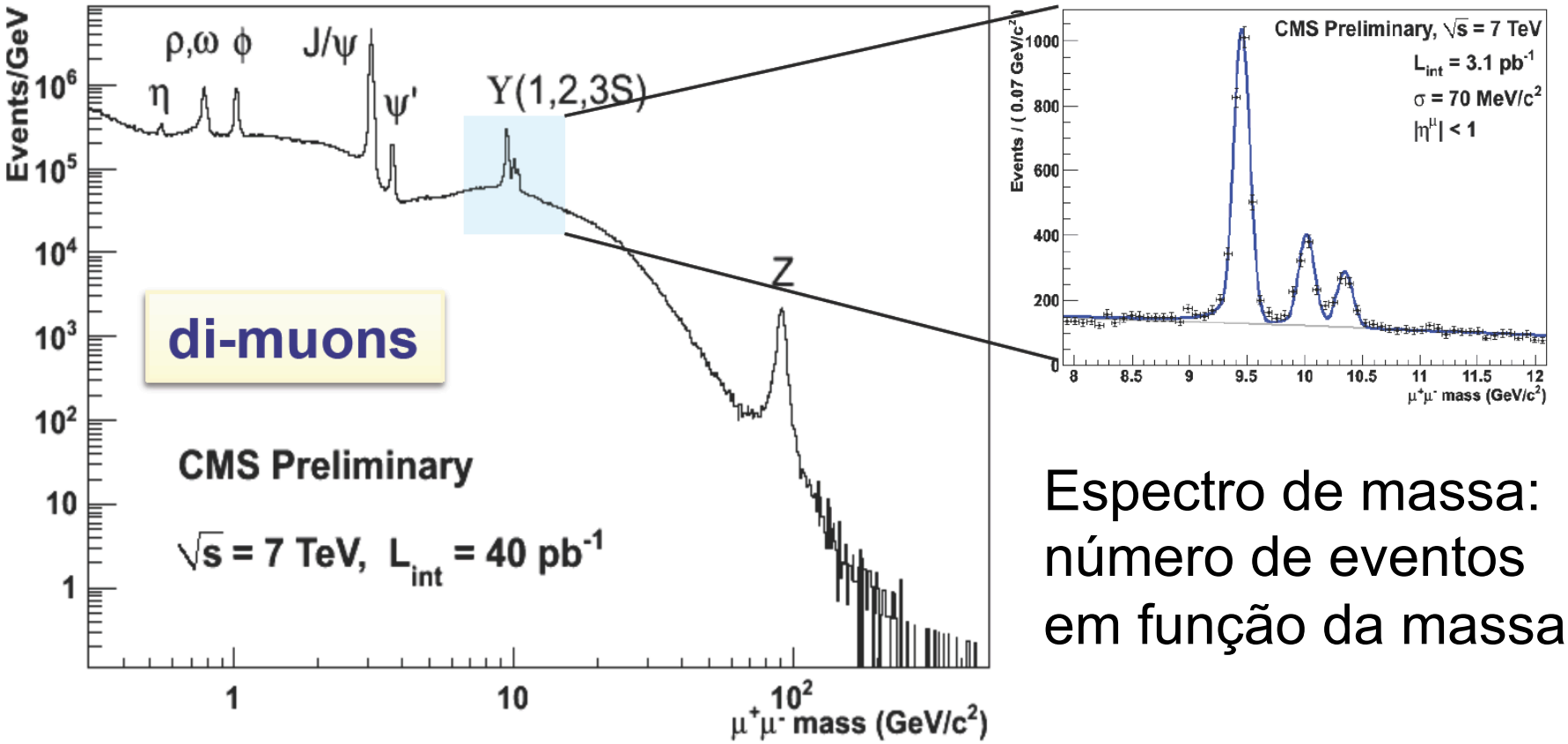


- Fabulous agreement
- Lots of data

… on to the Higgs…

Espectro de massa de pares de muões

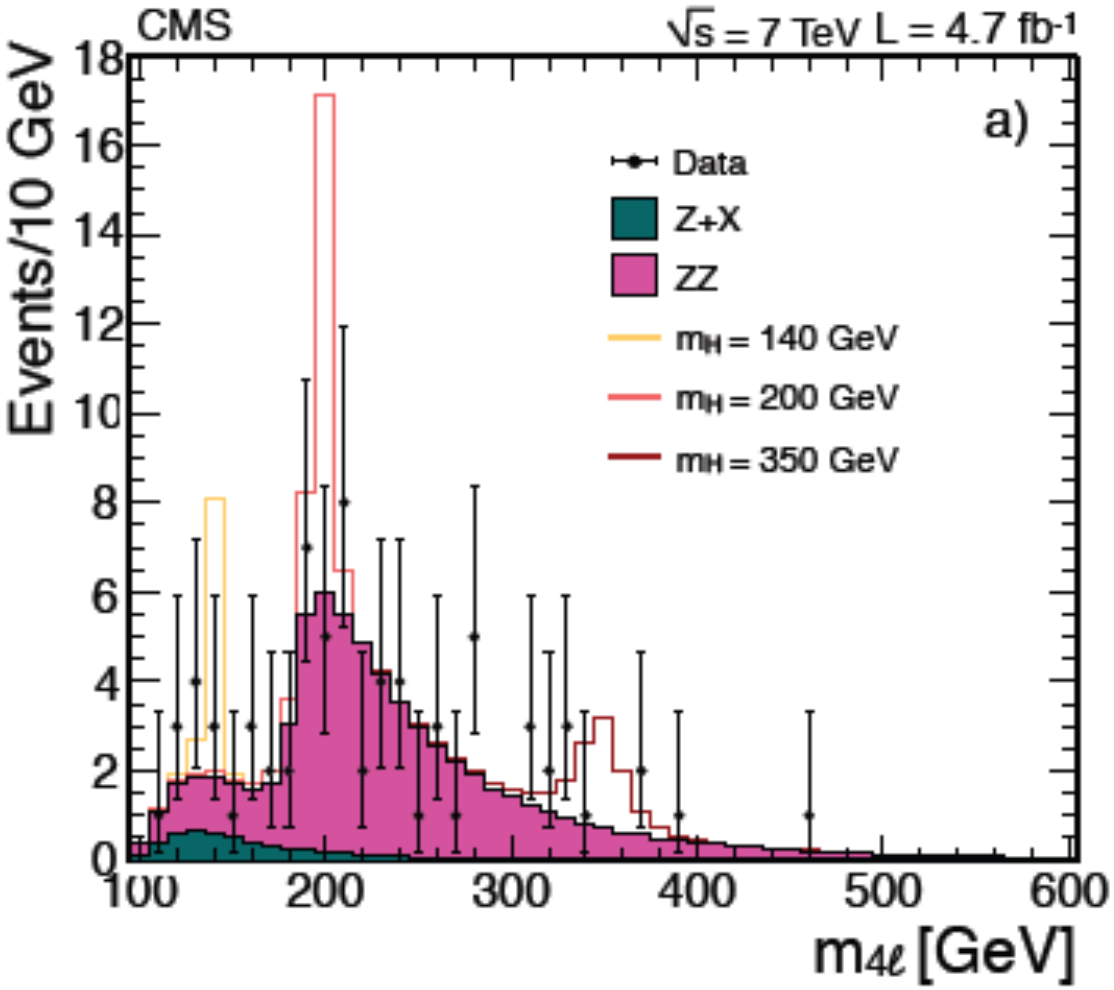
- Eventos com dois muões
- Pesquisa de partículas X que decaem em dois muões:
  Calcula-se m(X) a partir da energia-momento dos muões



Espectro de massa: número de eventos em função da massa

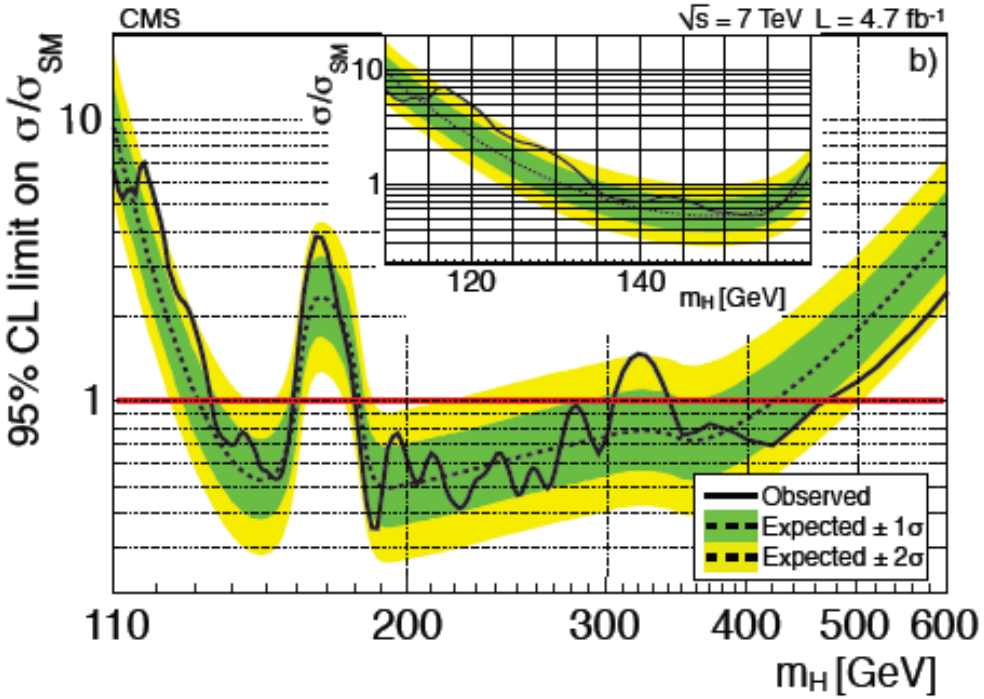
H → ZZ → 4 leptões

Espectro de massa de 4 leptões



Limites experimentais

Limites na secção eficaz (probabilidade) de produção do Higgs no canal H → ZZ → 4 leptões



Secção eficaz medida, relativa à secção eficaz prevista no MS

= 1, a secção eficaz é com 95% de confiança igual ou inferior ao MS

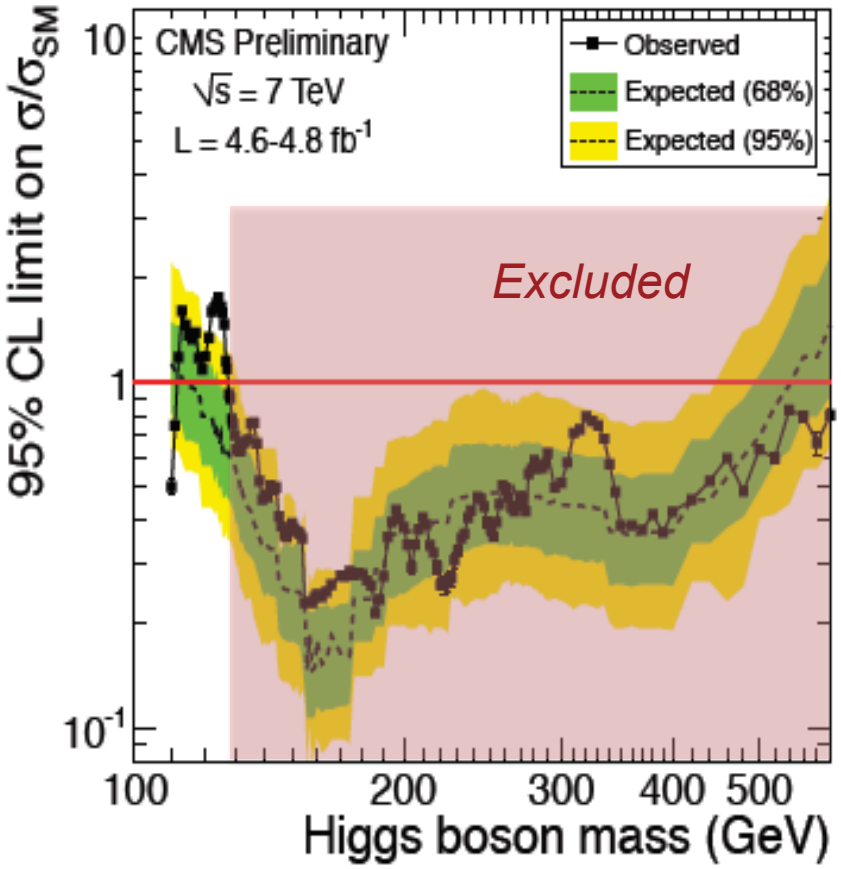
——————— limite medido experimentalmente

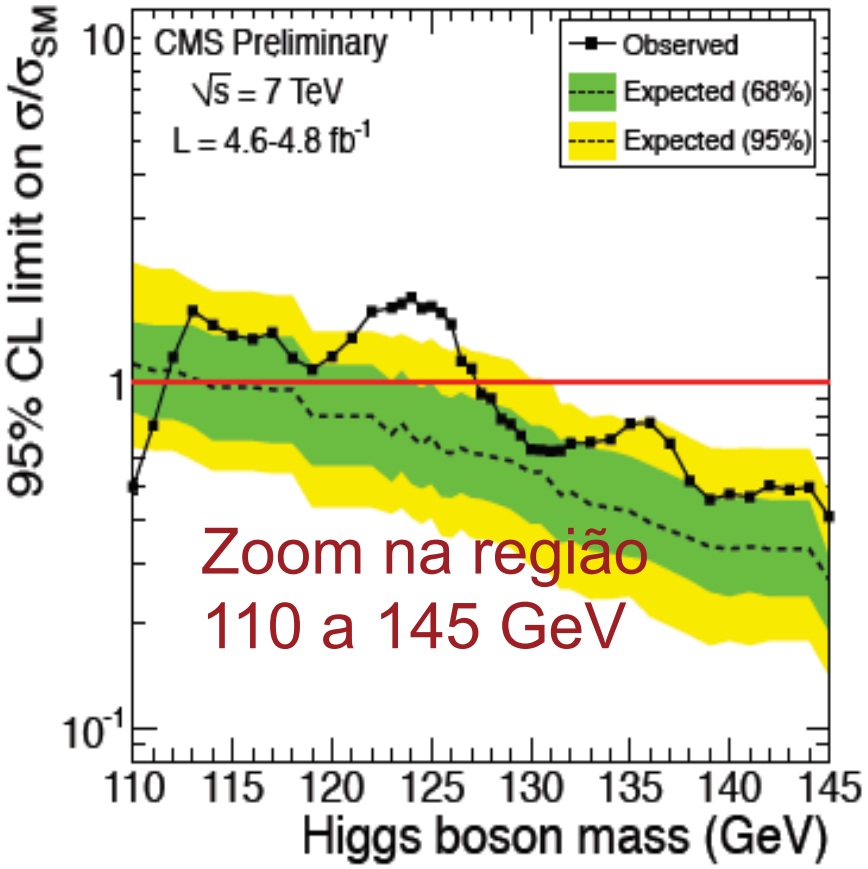
---------- limite esperado, obtido por simulação

bandas de incerteza no limite esperado (1 e 2 desvios padrão)

Higgs limits in 2011

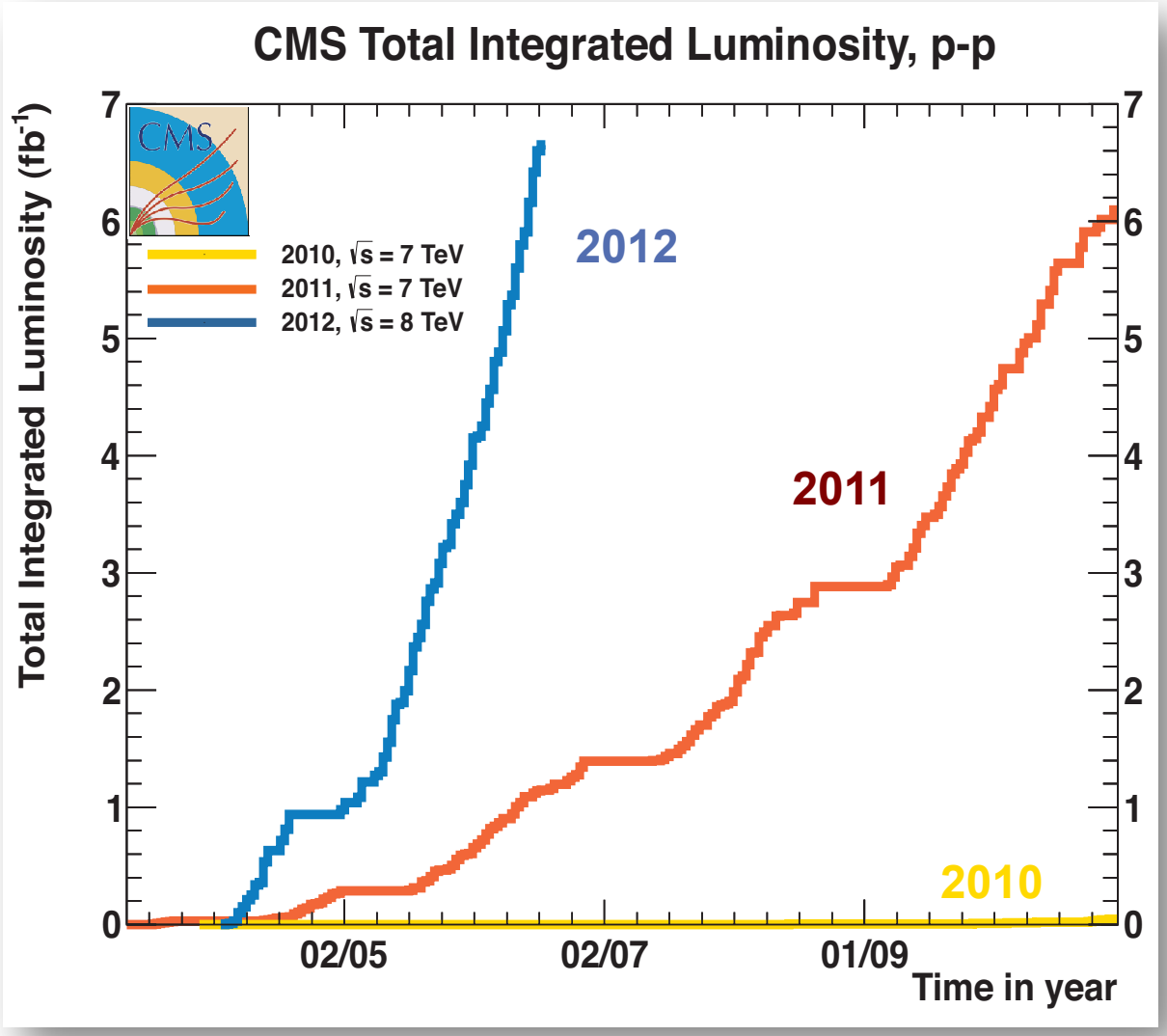
Todos os canais combinados





Bosão de Higgs excluído 127.5 - 600 GeV

LHC performance: 2010-2011-2012



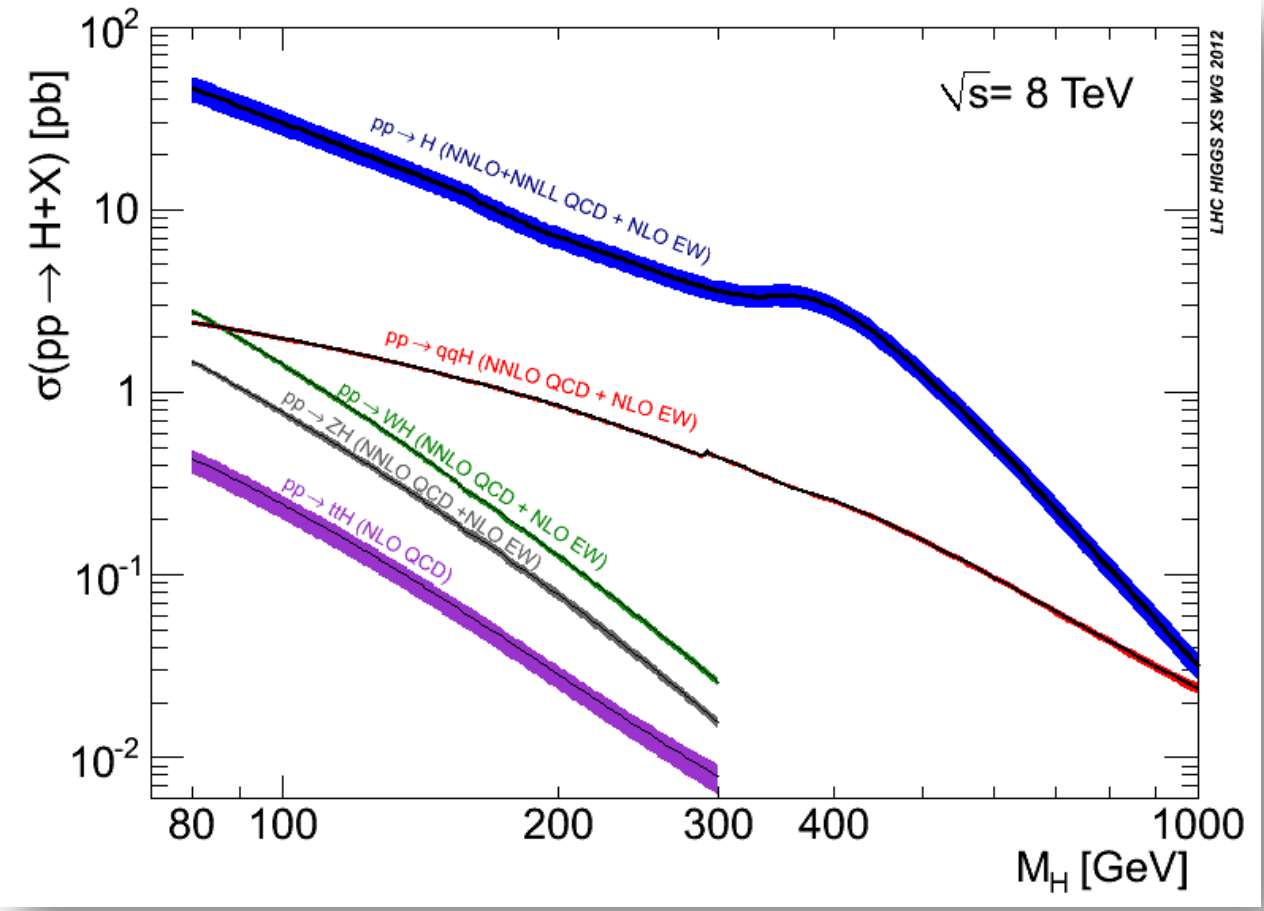
Stellar performance of the LHC enables all experiments to produce significant physics results

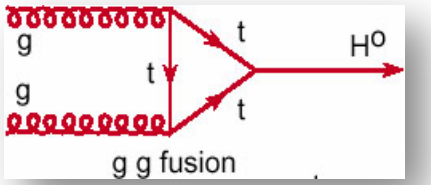
Many thanks to the LHC teams and the many others who made this possible!

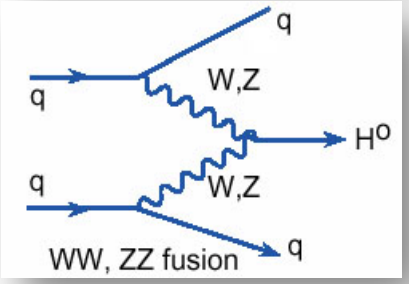
Search for the Higgs boson in 2012

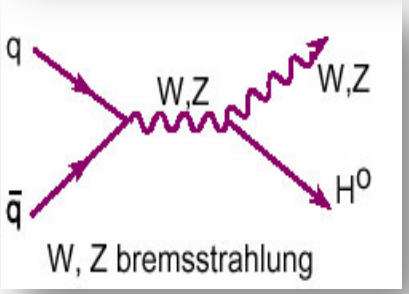
Higgs boson production

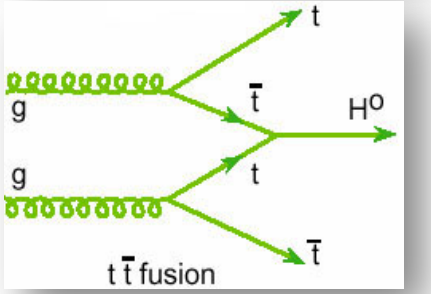
Higgs production rates (cross-sections) are predicted by the Standard Model as a function of the Higgs mass





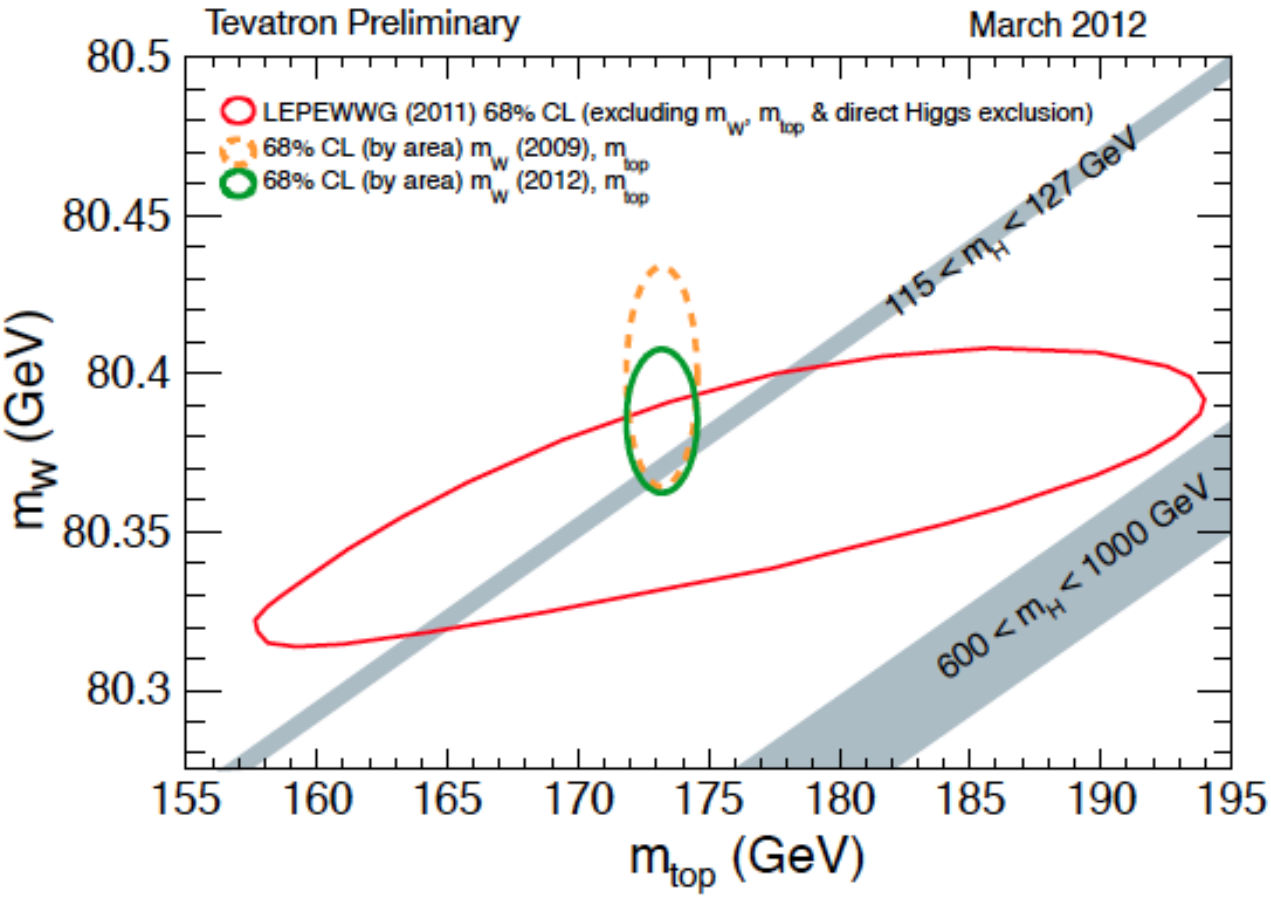






Massas do Higgs, top e W

As massas do Higgs, quark top e bosão W são interdependentes no MS
As medidas das massas do top e do W permite prever a massa do Higgs

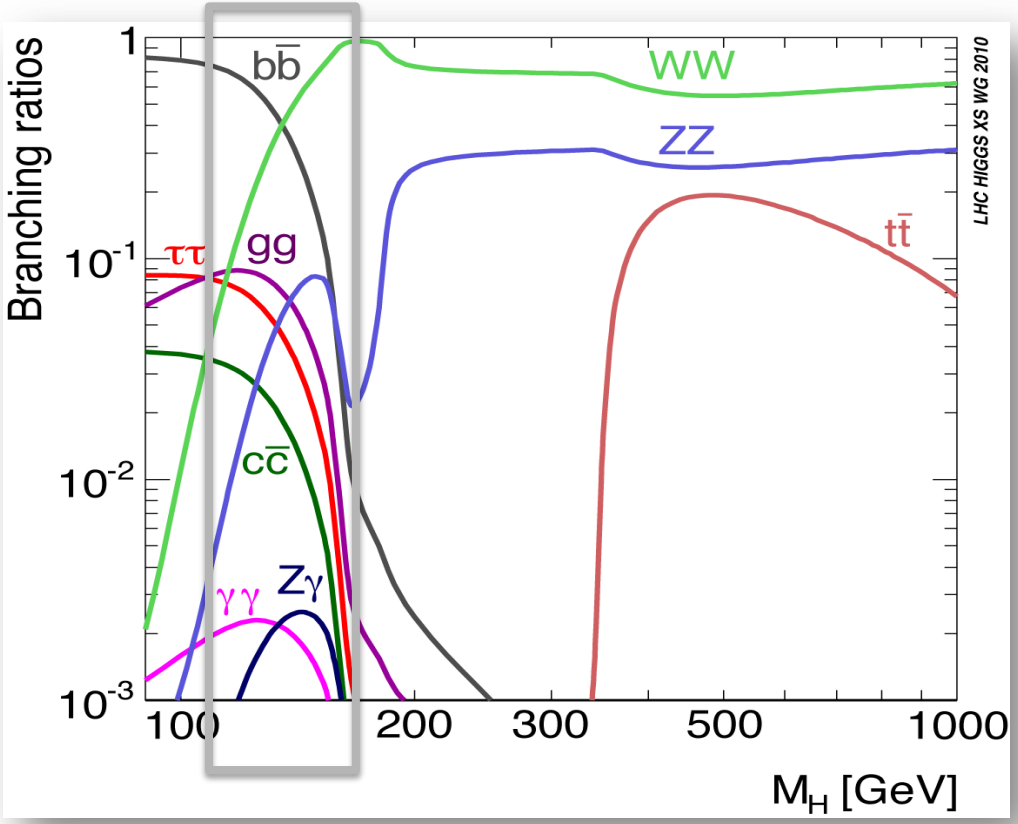


Higgs boson decays

5 decay modes exploited

Low mass region is very rich but also very challenging:

- High sensitivity, high resolution: ZZ, γγ
- High sensitivity, low resolution: WW
- Low sensitivity, Low resolution: bb, ττ

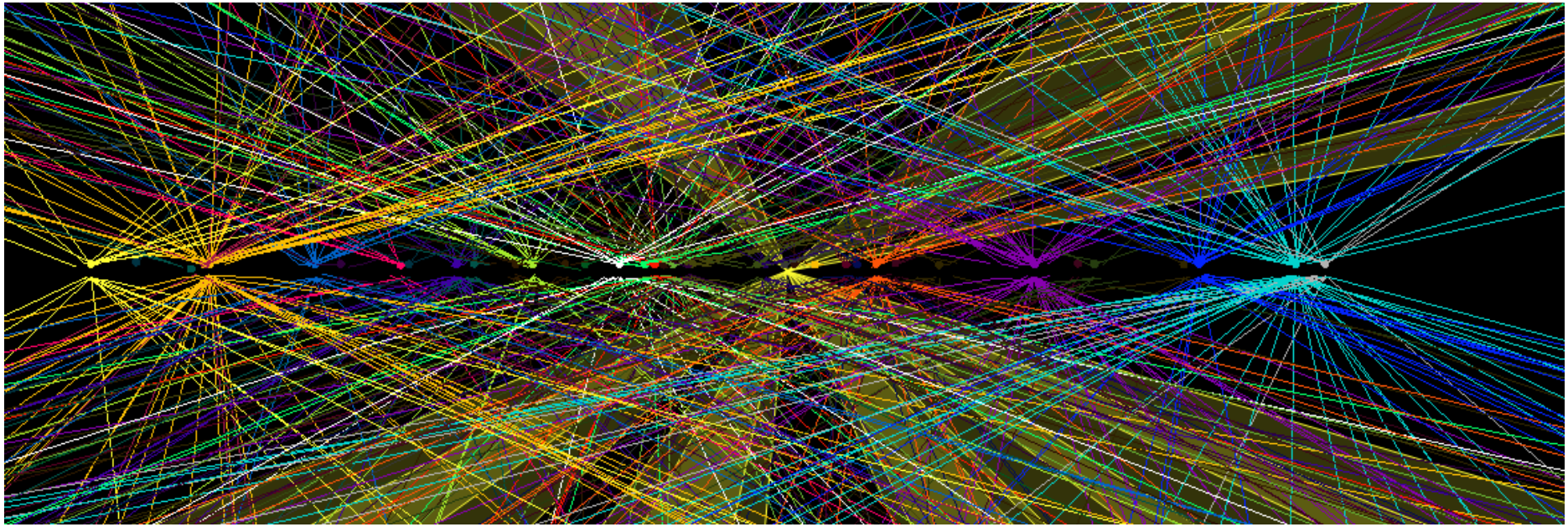


Collisions pileup

LHC luminosity in 2012: $6.5\ 10^{33}\ cm^{-2}s^{-1}$

Average number of proton-proton collisions per bunch crossing ~ 30

Challenging experimental conditions

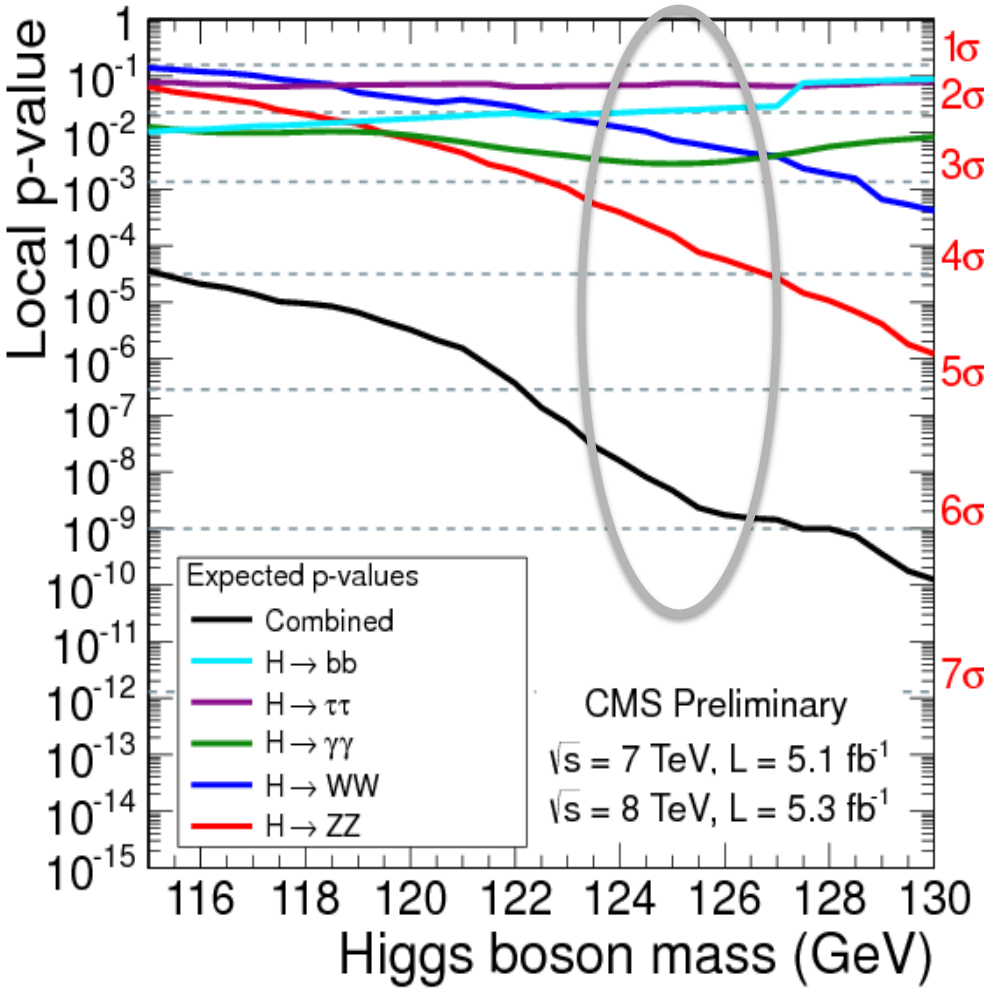


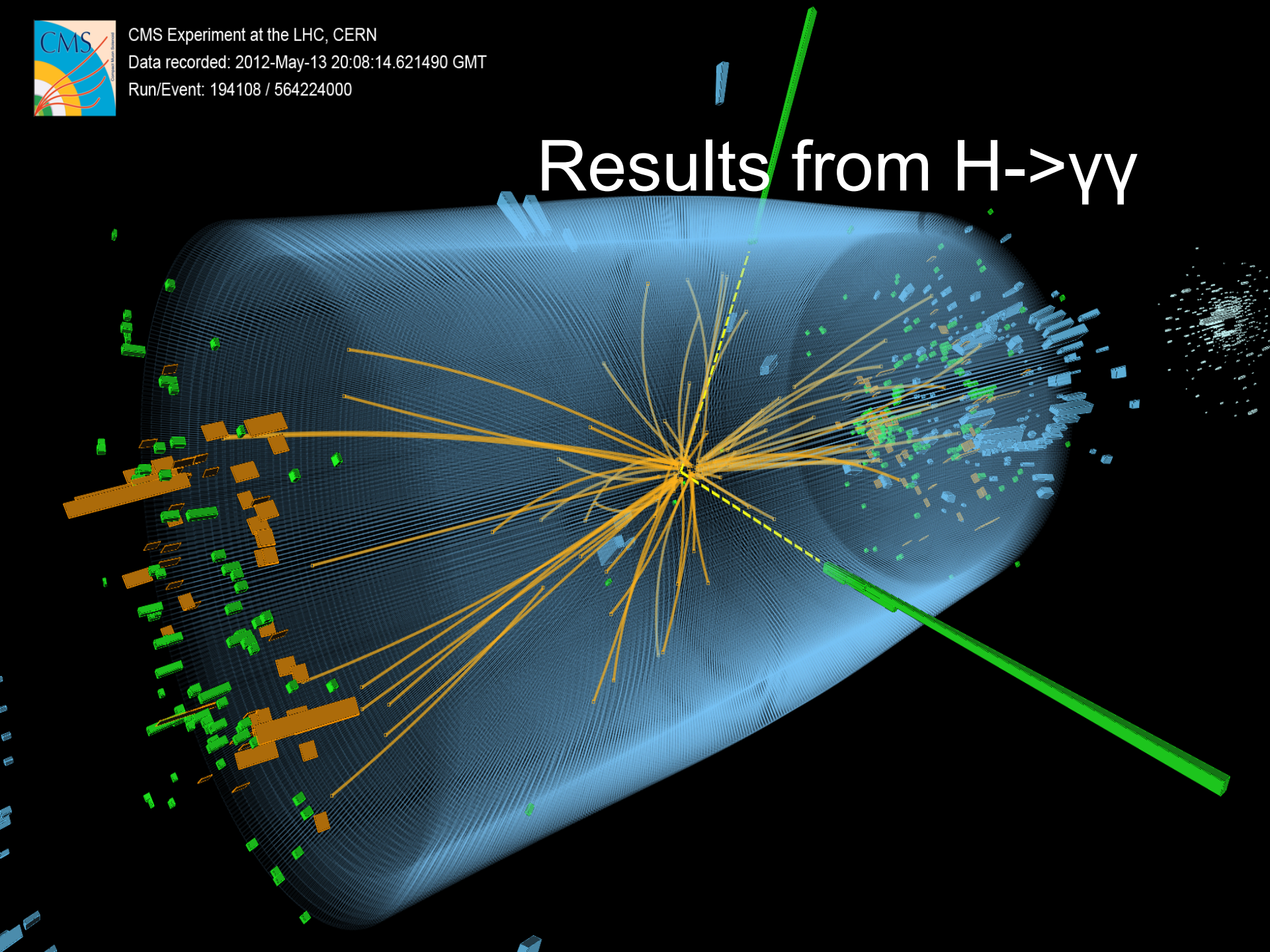
CMS discovery potential

p-values

- Probability that background fluctuates to give an excess as large as the signal size expected for a SM Higgs.

- **5 σ (sigma) = probability of one in 3 million**



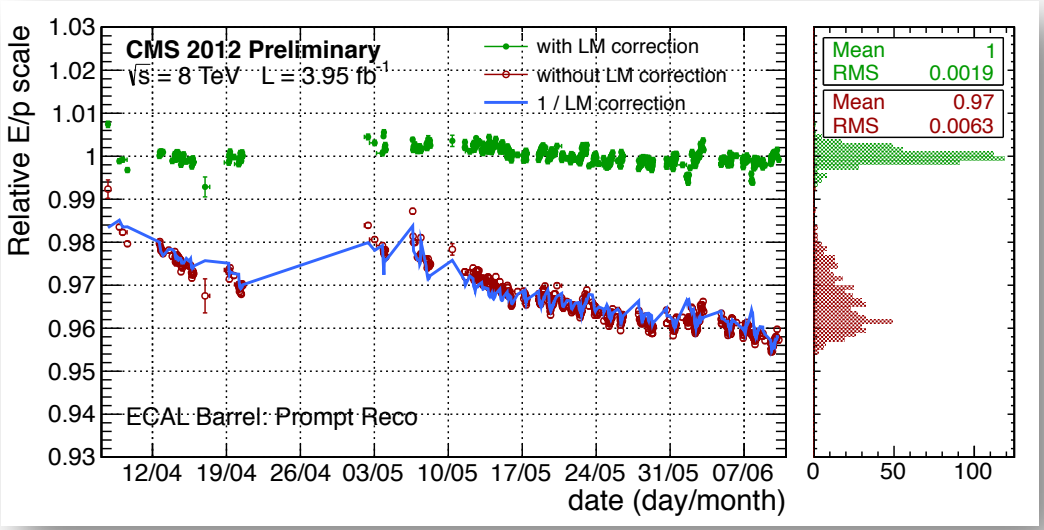


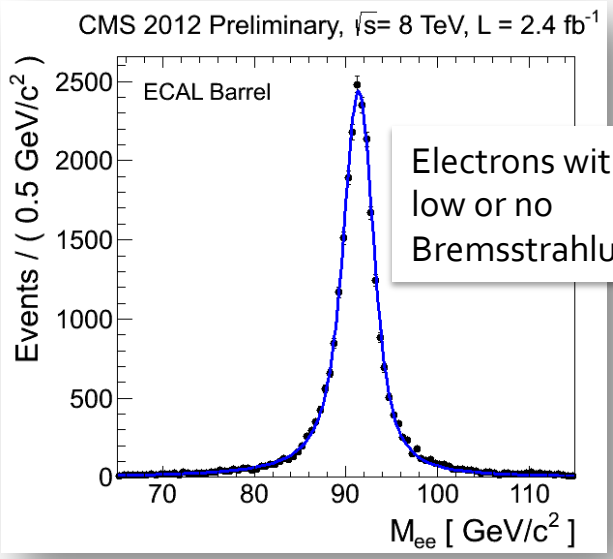
Results from H->γγ

ECAL calibration, 2012 data

Single electron energy scale (E/p) stability in barrel measured with W →ev events

Z→ee invariant mass distribution for electrons measured in the barrel



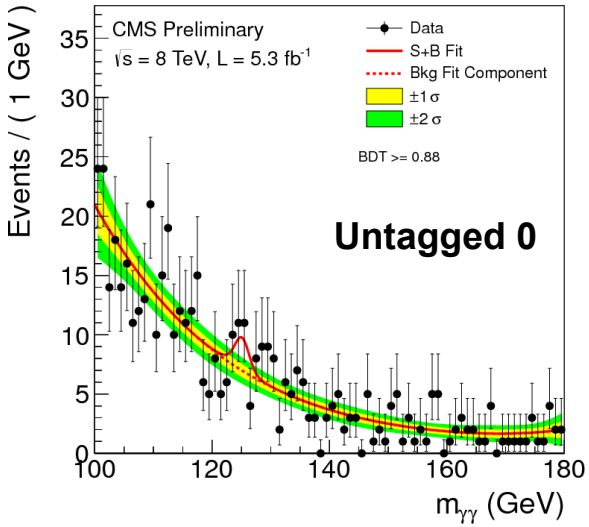


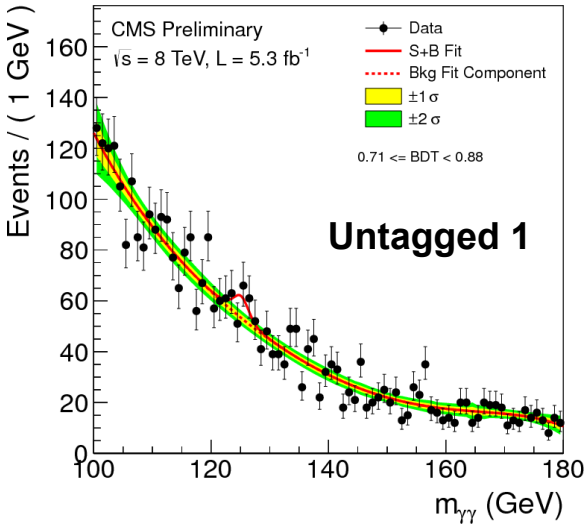
- **W→ev E/p:** Stable E scale during 2012 run after light monitoring corrections:
  - ECAL Barrel (EB): RMS stability after corrections 0.19%
- **Z→ee:** Good resolution with preliminary energy calibration for 2012:
  - Instrumental resolution: 1.0 GeV in ECAL Barrel (~1%)

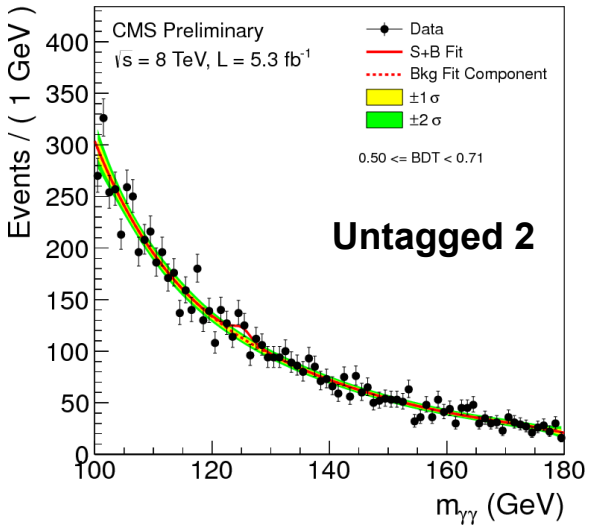
Di-photon Mass Distribution in Categories

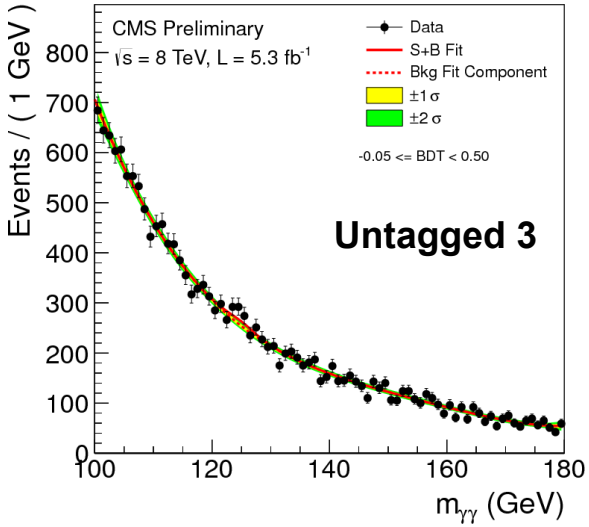
Combined fit of signal and background to all 11 categories

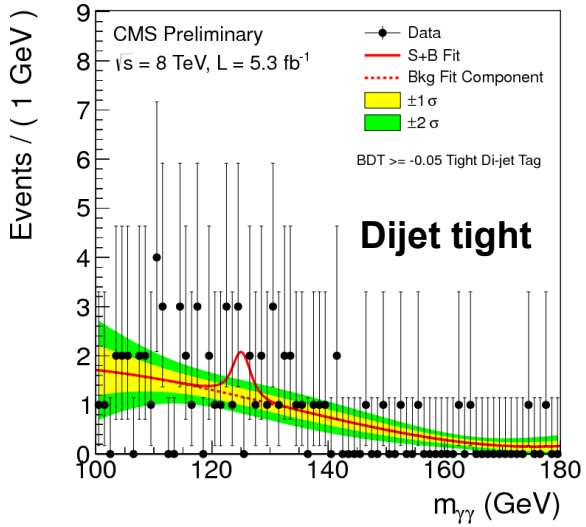
8 TeV data

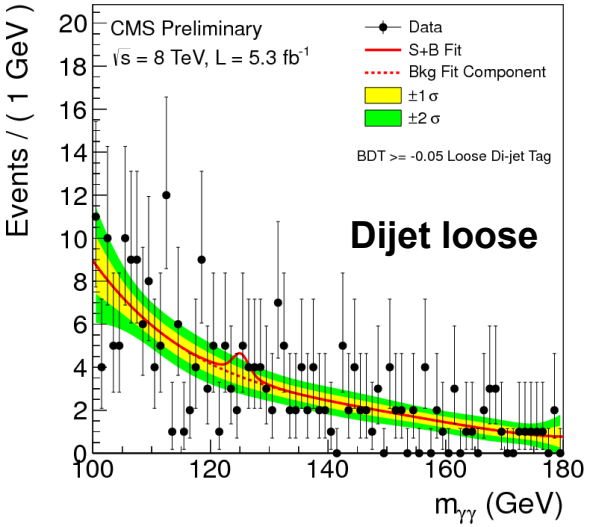








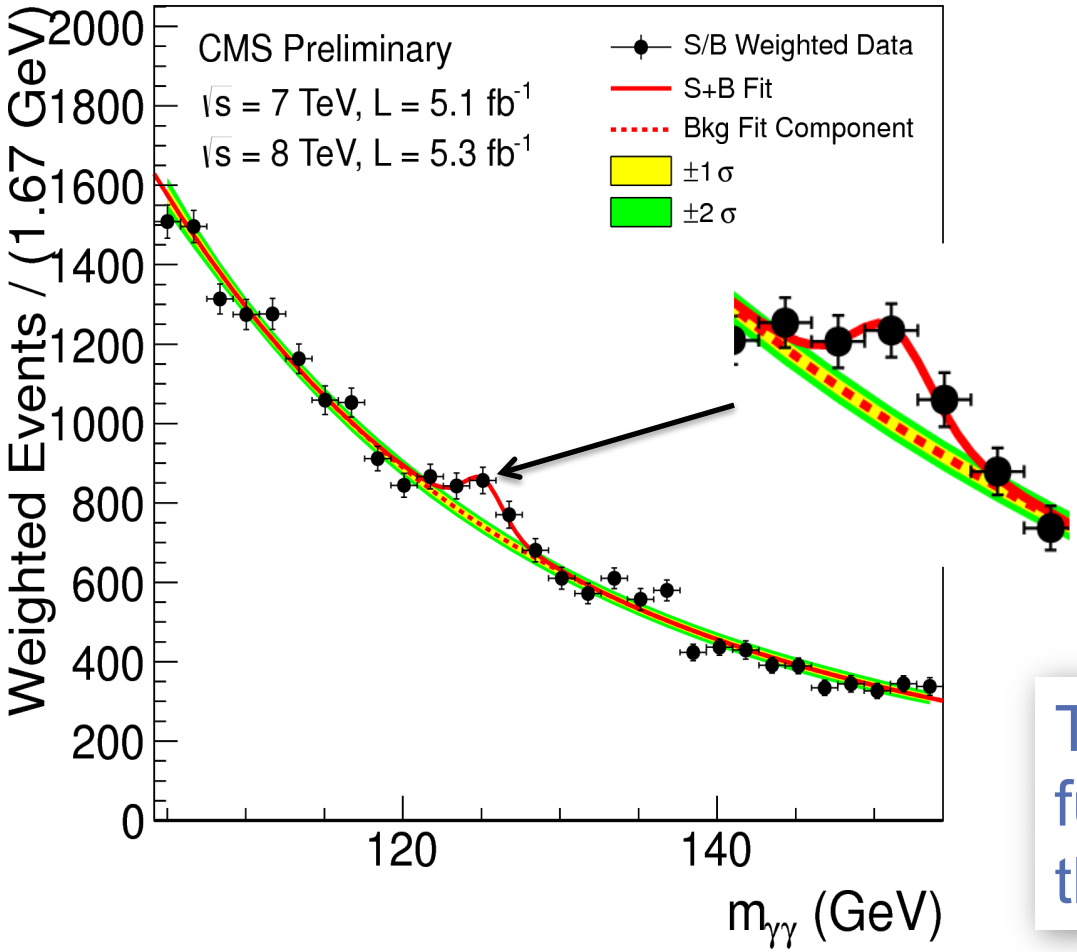




Results from H->γγ:

Di-photon mass distribution

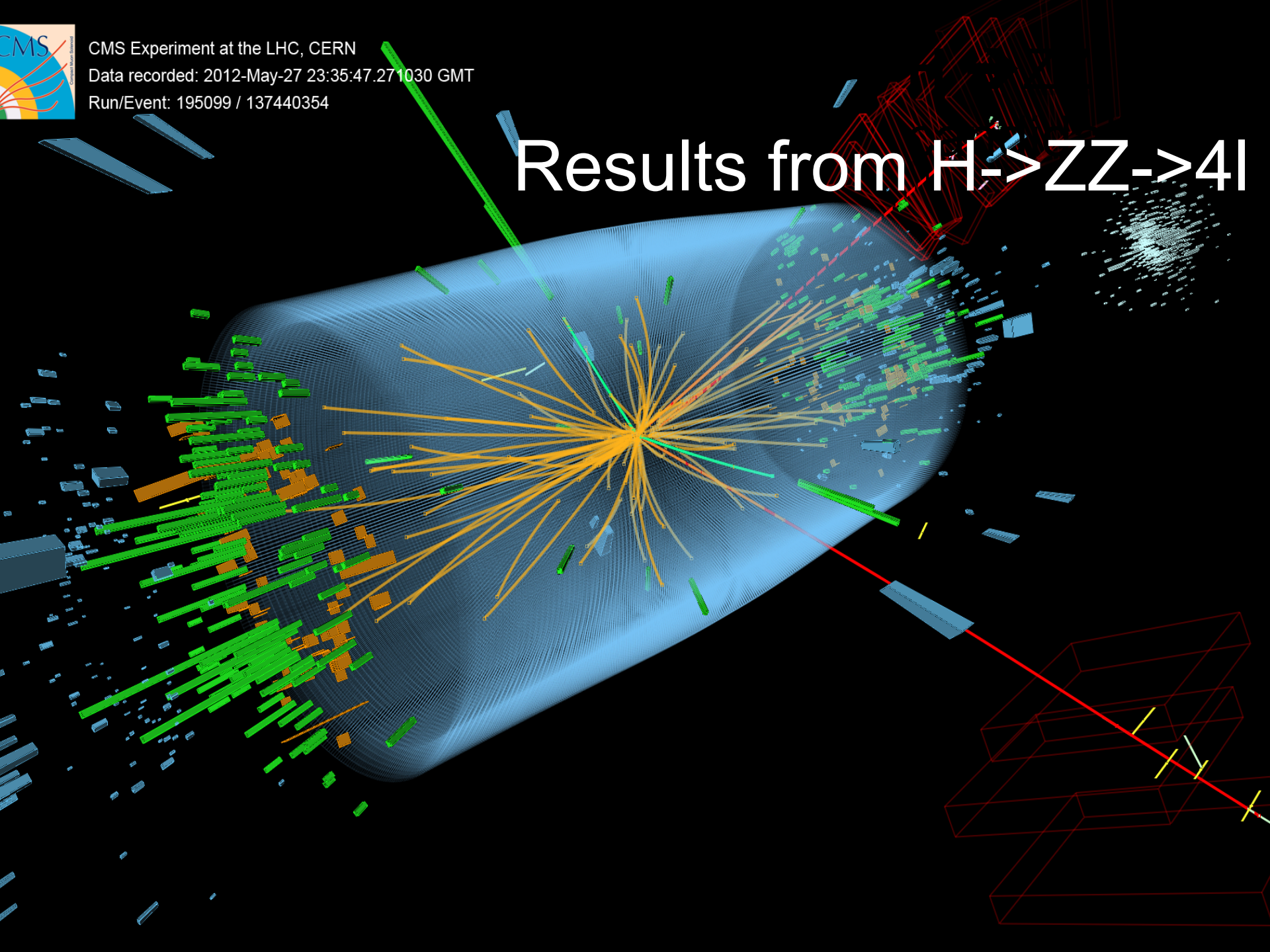
Sum of mass distributions for each event class, weighted by S/B



In the γγ mass distribution there is an excess of events above background, at a mass near 125 GeV.

The observation of the two-photon final state implies that the **new particle is a boson**, not a fermion, and that **it cannot be a "spin 1" particle.**

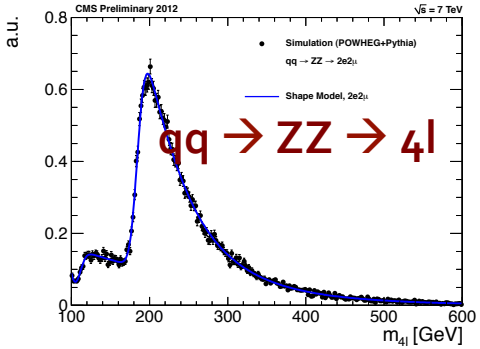
There is no other fundamental particle with these properties

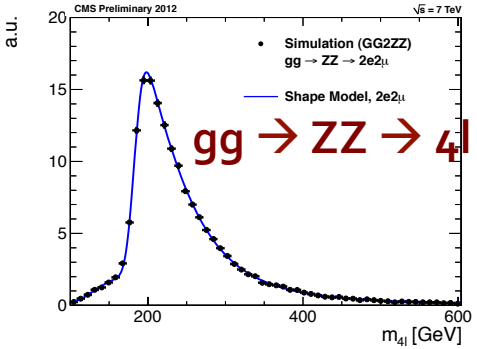


Results from H->ZZ->4l

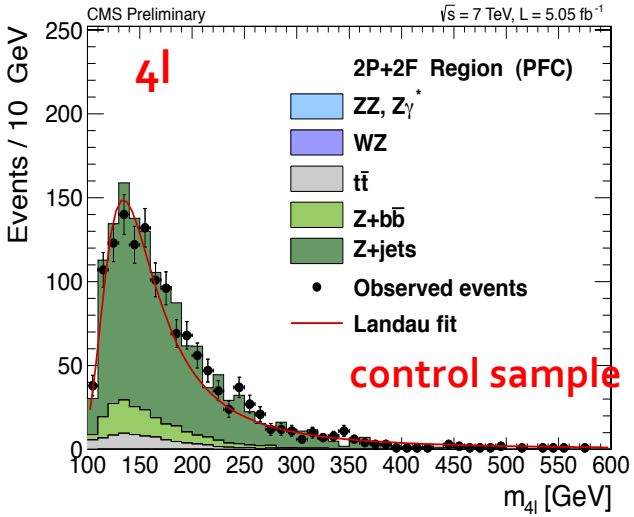
Background models

- **Irreducible background ZZ → 4l**
  - Estimated **using simulation**
  - Phenomenological shape models
  - Corrected for data/simulation scale

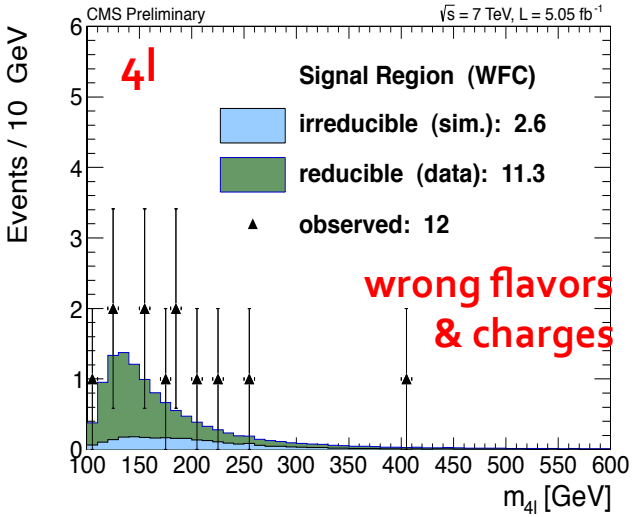




- **Reducible backgrounds estimated from data**
  - Extrapolation from control samples enriched with misidentified leptons
  - Total uncertainty ~50%

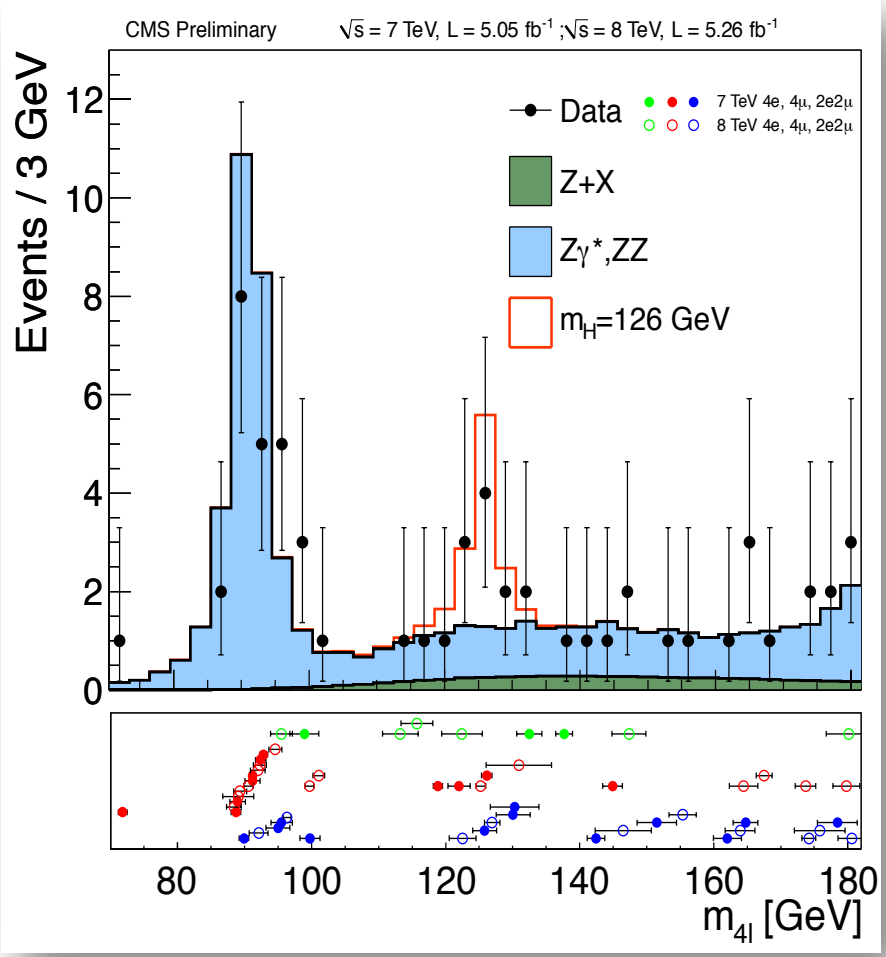


Validation in **data**



Results from H decaying to ZZ*

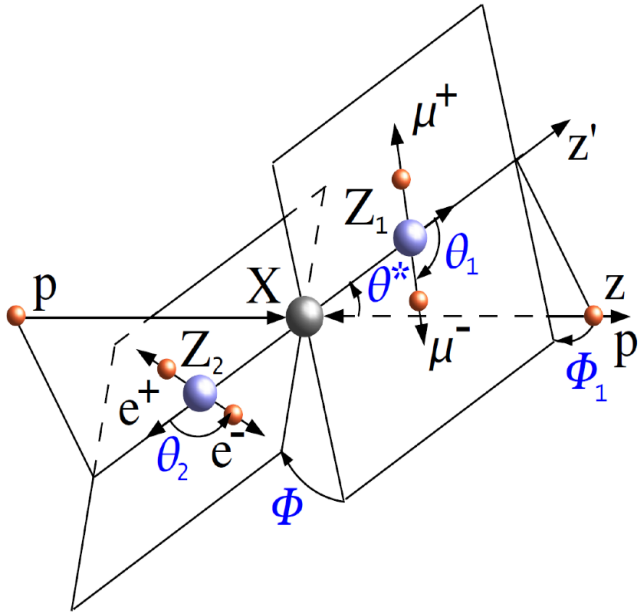
4 lepton mass distribution



Mass distribution for the four leptons (two pairs of electrons, or two pairs of muons, or the pair of electrons and the pair of muons).

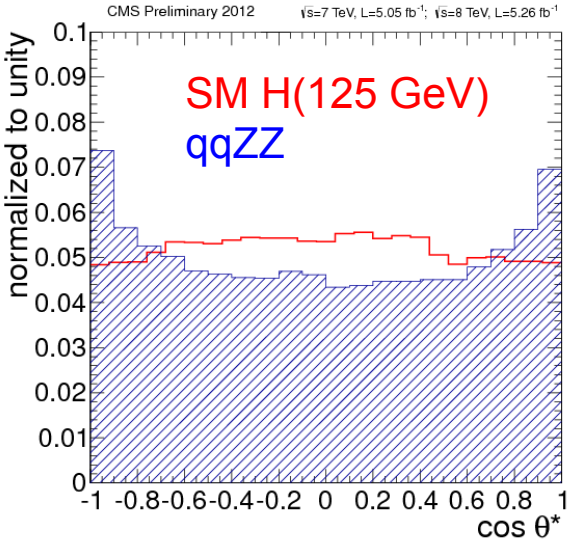
Accounting also for the decay angle characteristics, it yields an **excess of 3.1 sigma above background at a mass of 125.6 GeV.**

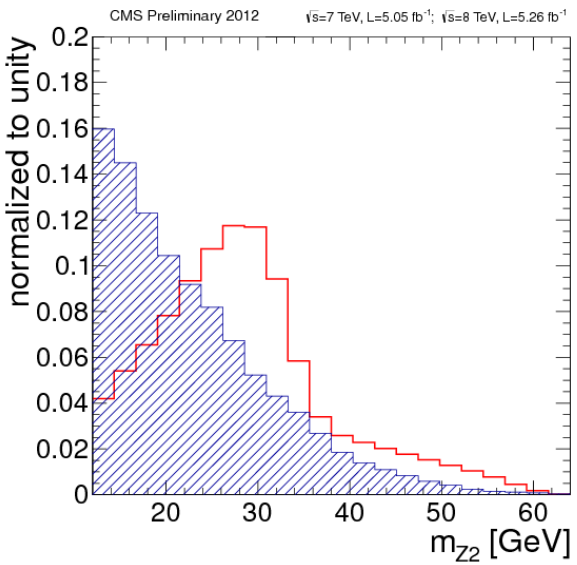
Matrix Element Likelihood Analysis

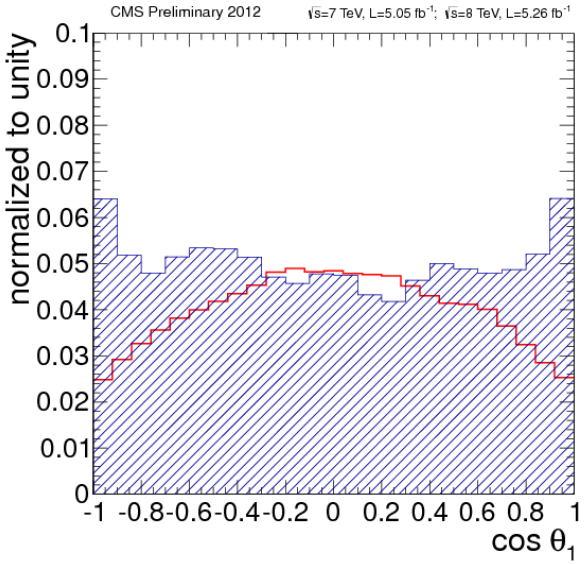


Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



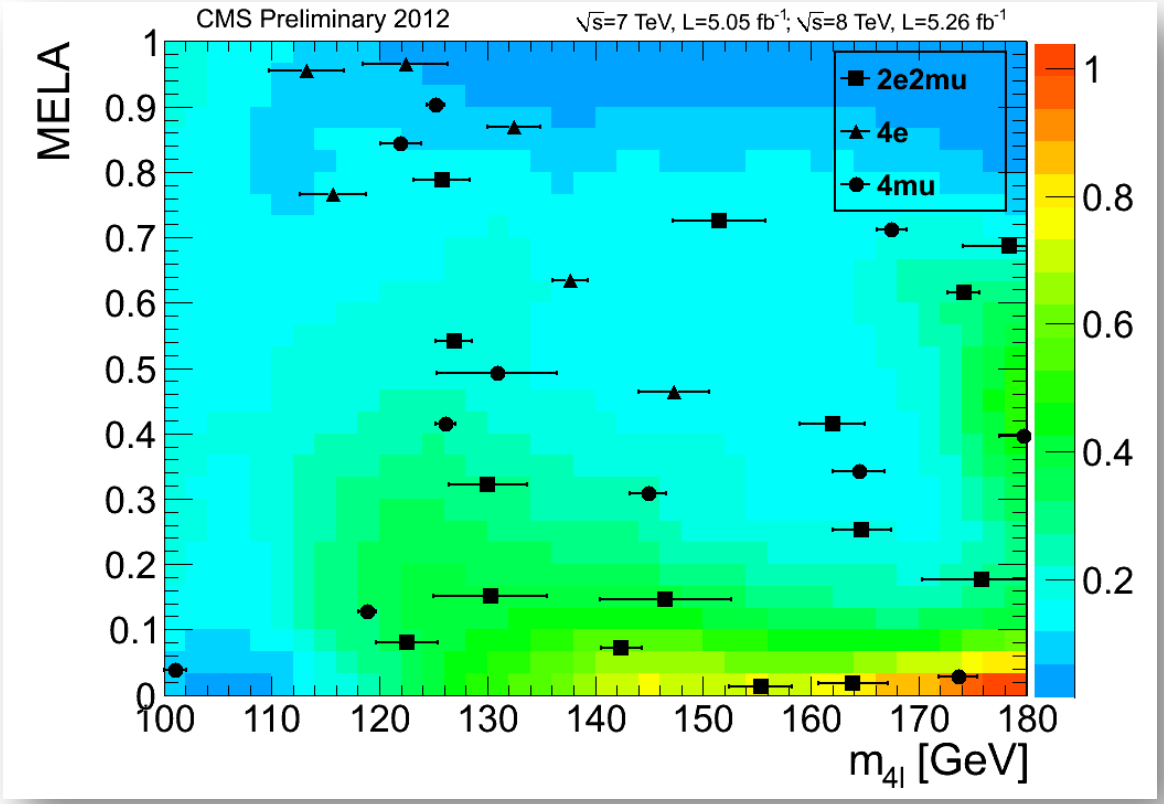




Results: 2D plots

Perform 2D fit

- MELA discriminant versus m_{4l}
  - Data points shown with per-event mass uncertainties

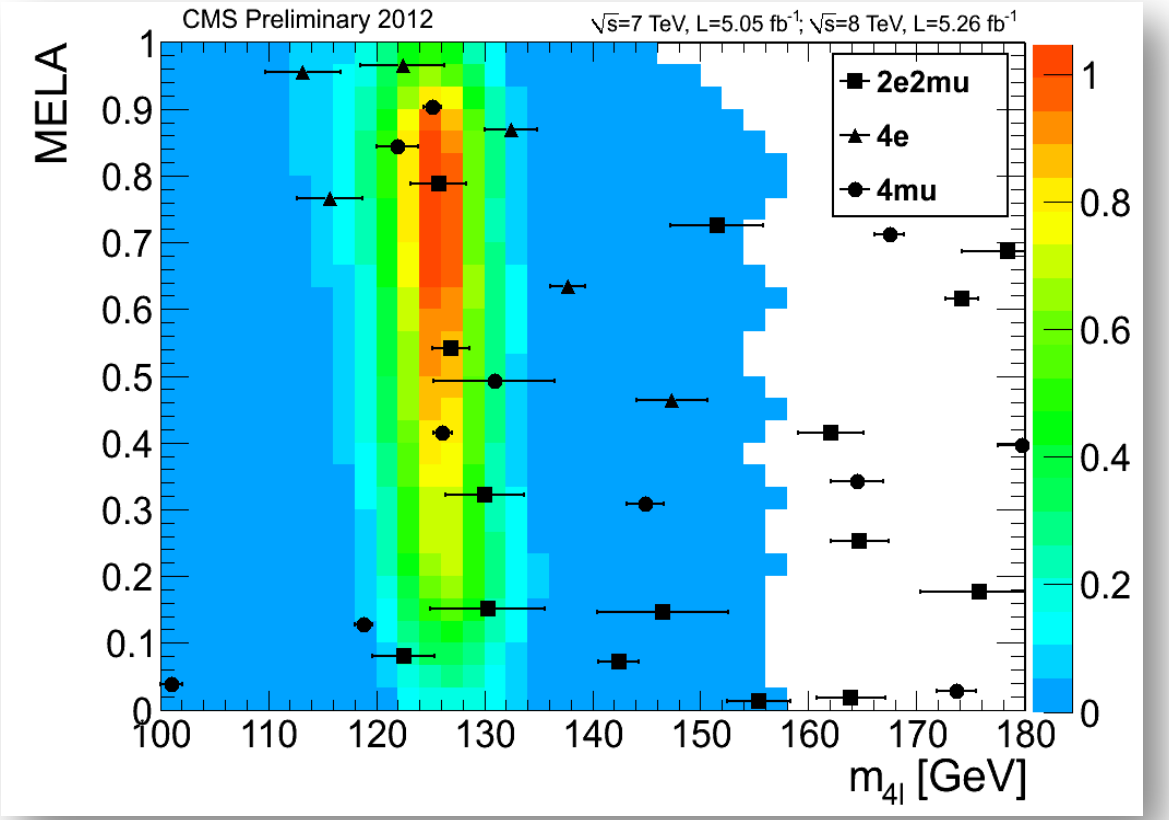


Data w.r.t. background expectation

Results: 2D plots

Perform 2D fit

- MELA discriminant versus m_{4l}
  - Data points shown with per-event mass uncertainties

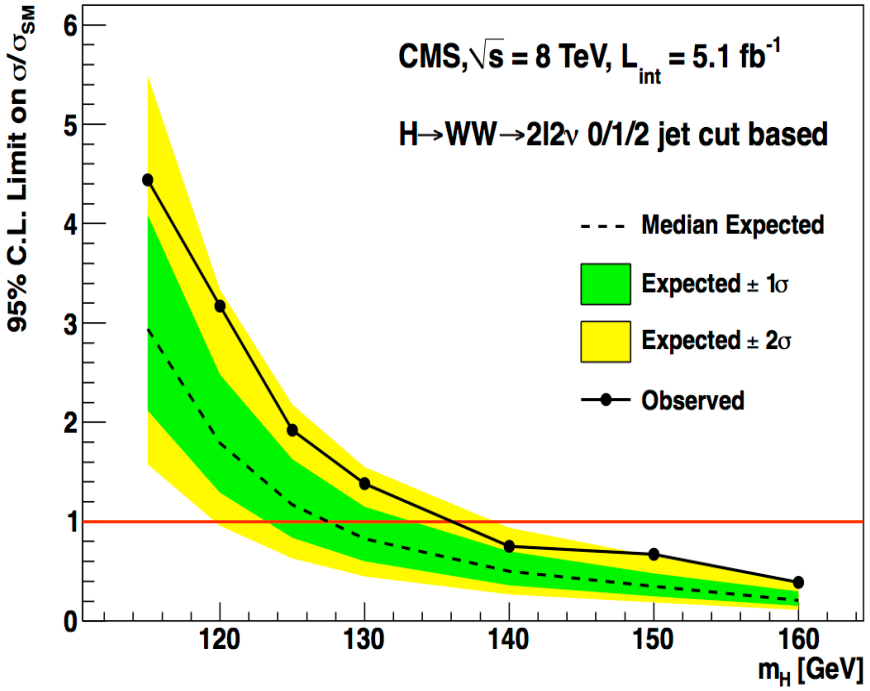


Data w.r.t 126 GeV Higgs Expectation

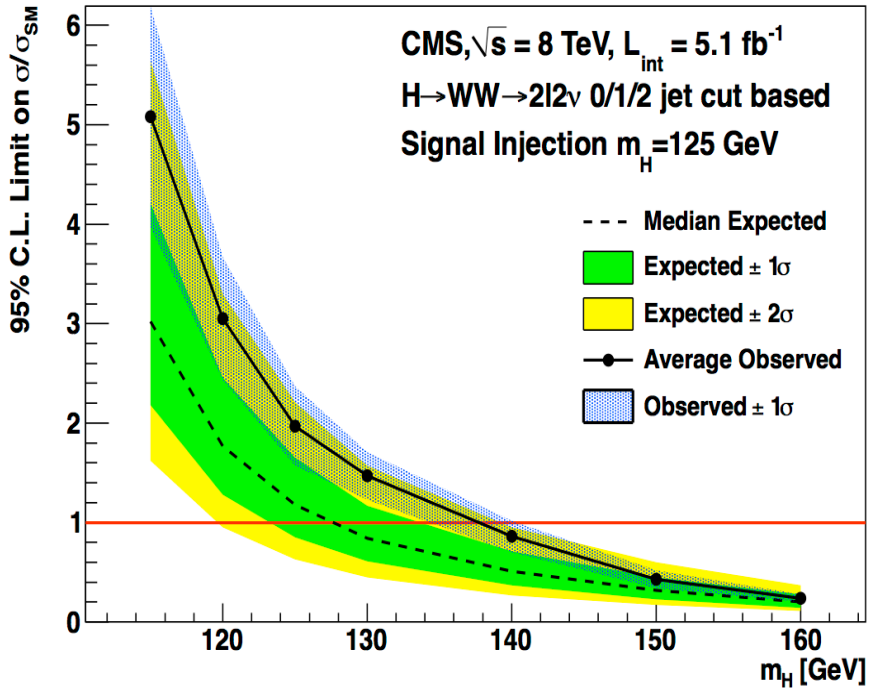
Results from H->WW

WW->llvv channel: a broad excess in the mass distribution of 1.5 sigma is observed.

Data

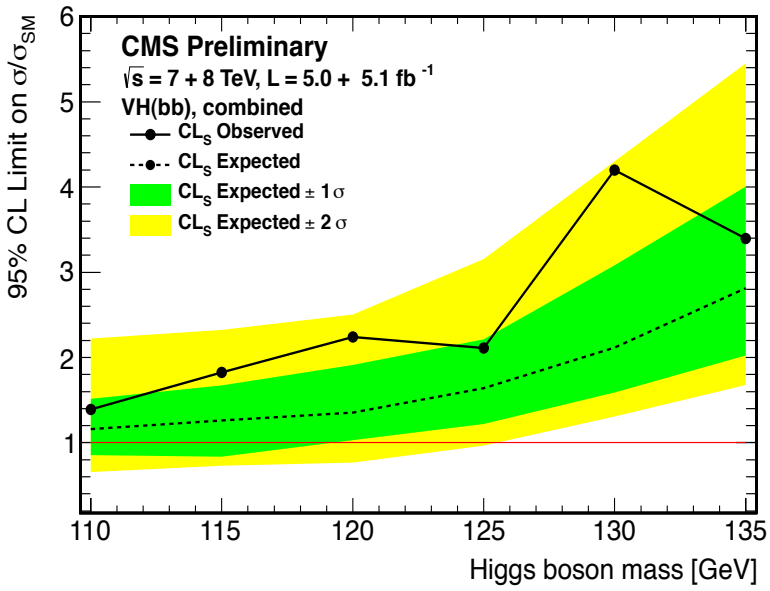


SM Higgs simulation



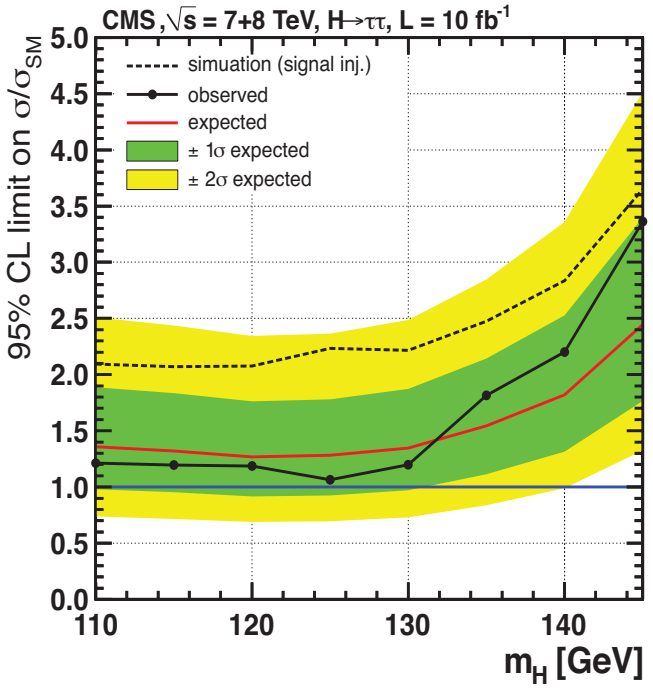
Results from low-sensitivity channels

VH->Vbb



Compatible with either background or signal from a 125 GeV Higgs

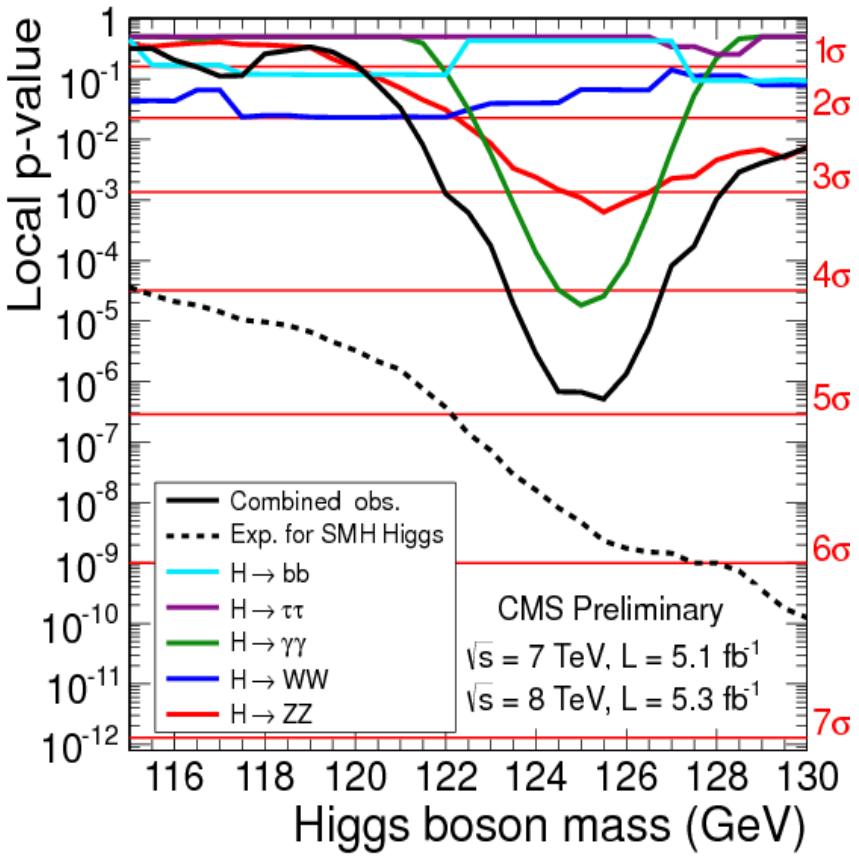
H->π



No significant departure from SM background-only expectation

Characterization of excess near 125 GeV

Probability that background fluctuates to give the excess



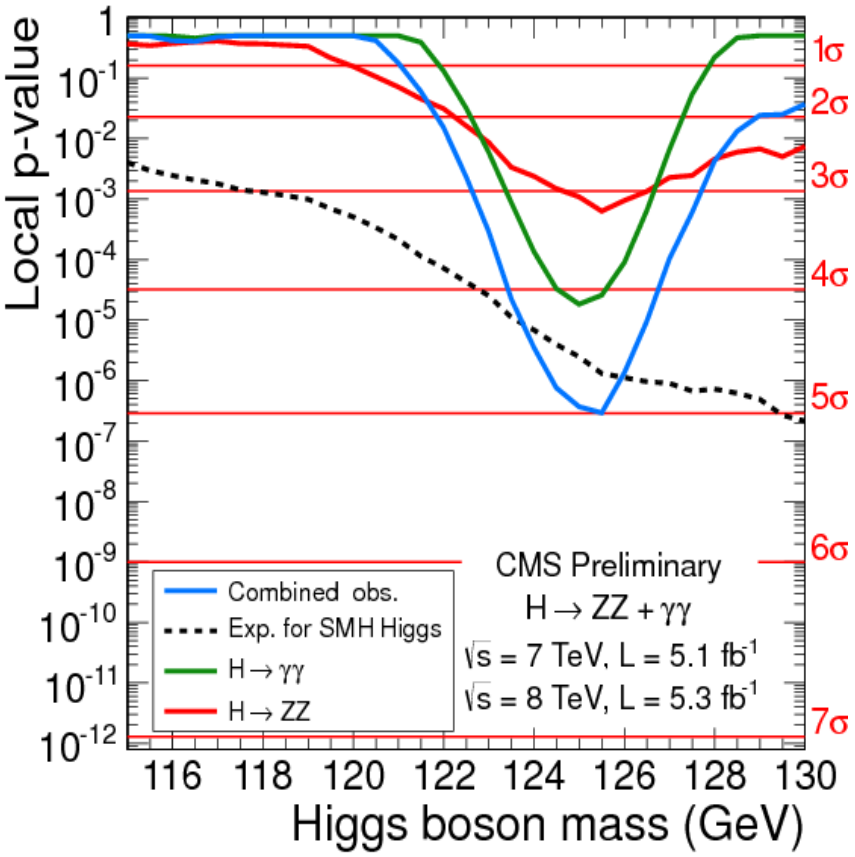
- **all channels together: comb. significance:**

4.9 σ

- **expected significance for SM Higgs: 5.9 σ**

Characterization of excess near 125 GeV

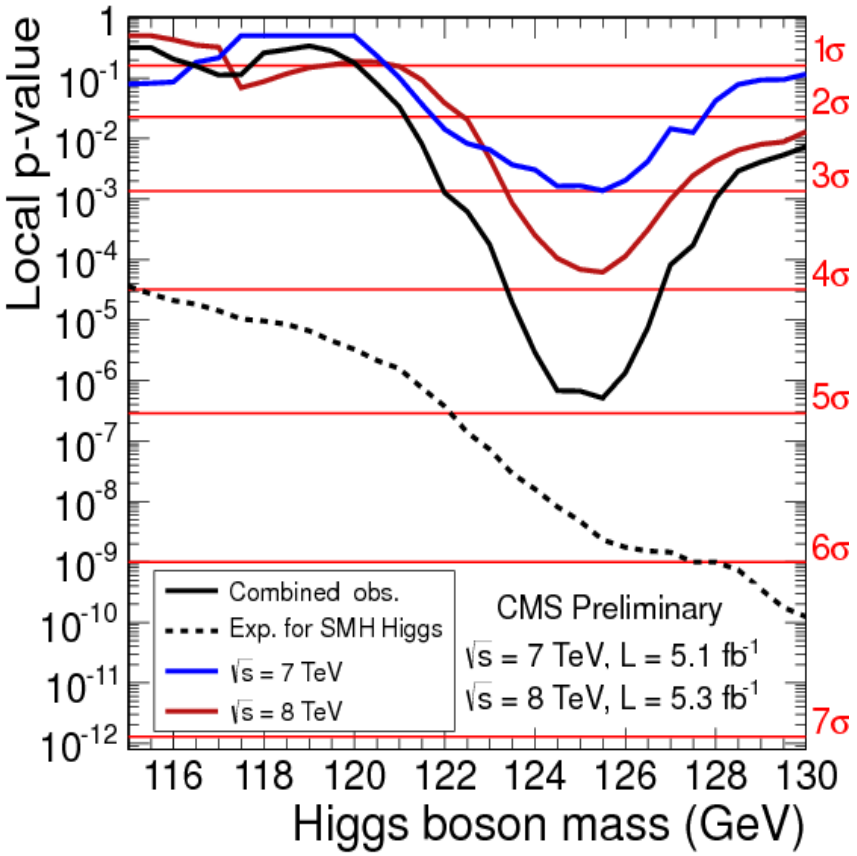
Probability that background fluctuates to give the excess



- **high sensitivity, high mass resolution channels: γγ+4l**
- **comb. significance: 5.0 σ**
- **expected significance for SM Higgs: 4.7 σ**

Characterization of excess near 125 GeV

Probability that background fluctuates to give the excess



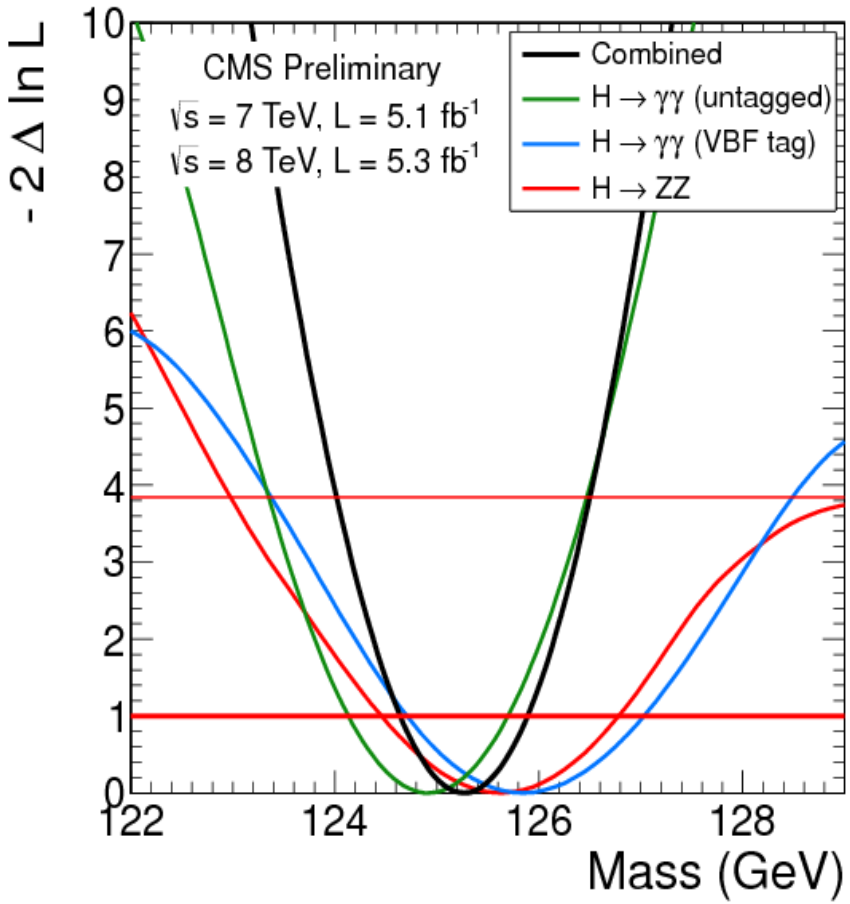
- **Observed significance:**

4.9 σ

- **Excess seen in both**
  - **7 TeV data (3.0 σ)**
  - **8 TeV data (3.8 σ)**
  - **near the same mass 125 GeV**

Mass of the new resonance

Likelihood fit to the new resonance

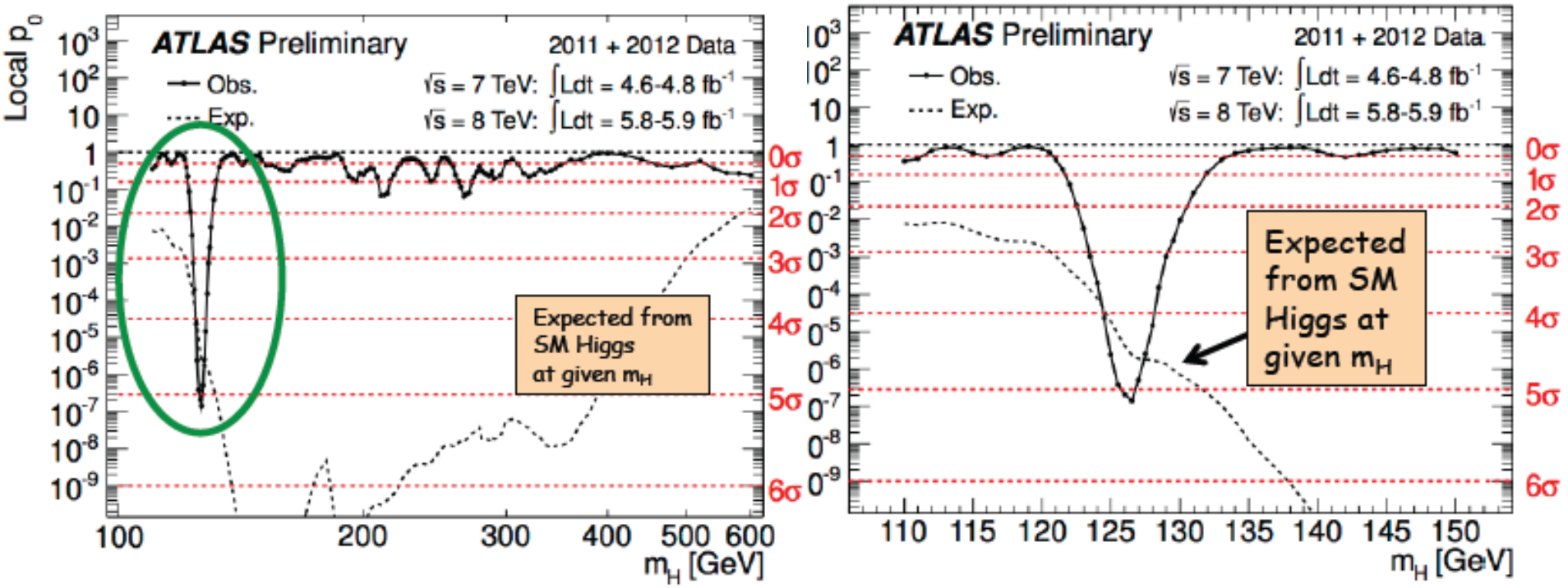


Mass measurement from the two high-resolution channels:

$m_X = 125.3 \pm 0.6$ GeV

ATLAS results

Combination of γγ and ZZ channels in 2012 + all channels in 2011



Significance 5 sigma at m= 126.5 GeV

In summary

Both LHC experiments have observed a new boson with a mass around **125 GeV** at **5 σ** significance !

Acknowledgements

I would like to thank everyone in Portugal that made possible our participation in this adventure:

- the Portuguese scientific community
- those in leadership positions that allowed the boom of science in Portugal seen in the past 20 years
- FCT that consistently funded the participation in the LHC
- LIP and IST, his people and his directors
- our colleagues and friends from LIP/ATLAS
- the members of the LIP/CMS group