A Discovery in the Hunt for the Elusive Higgs Boson

Andrei Gritsan

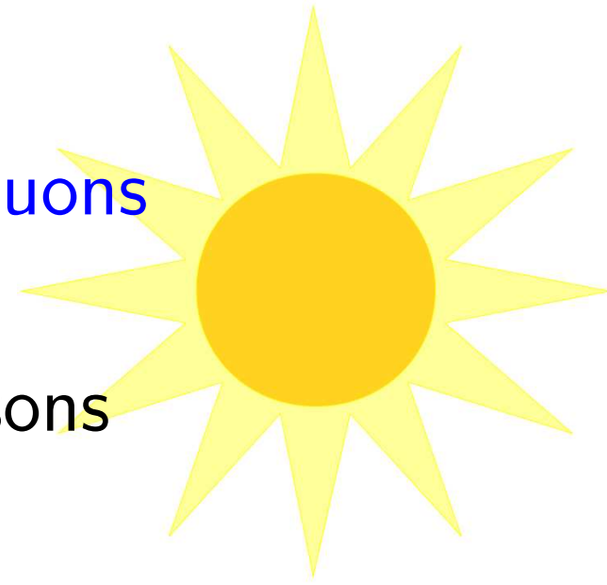
Johns Hopkins University

30 July 2012

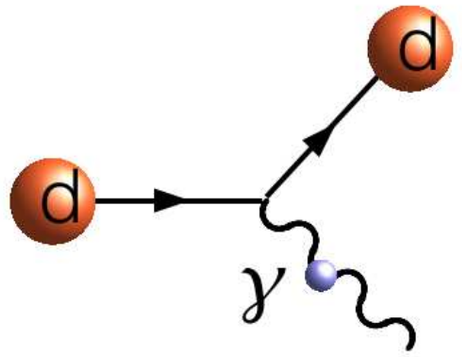
Johns Hopkins University

Physics and Astronomy Seminar

What is a Boson?



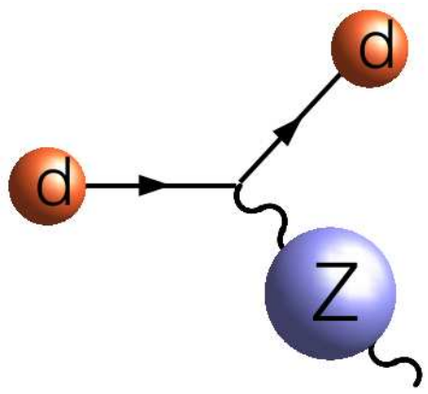
- We know 12 bosons: photon, Z^0, W^+, W^-, 8 gluons
- Photons (γ) are massless vector (spin$=\hbar=1$) bosons
- Z^0 and $W^{\pm}$ are heavy $\longrightarrow$ weak force



- Gauge bosons in unified electro-weak theory after spontaneous symmetry breaking

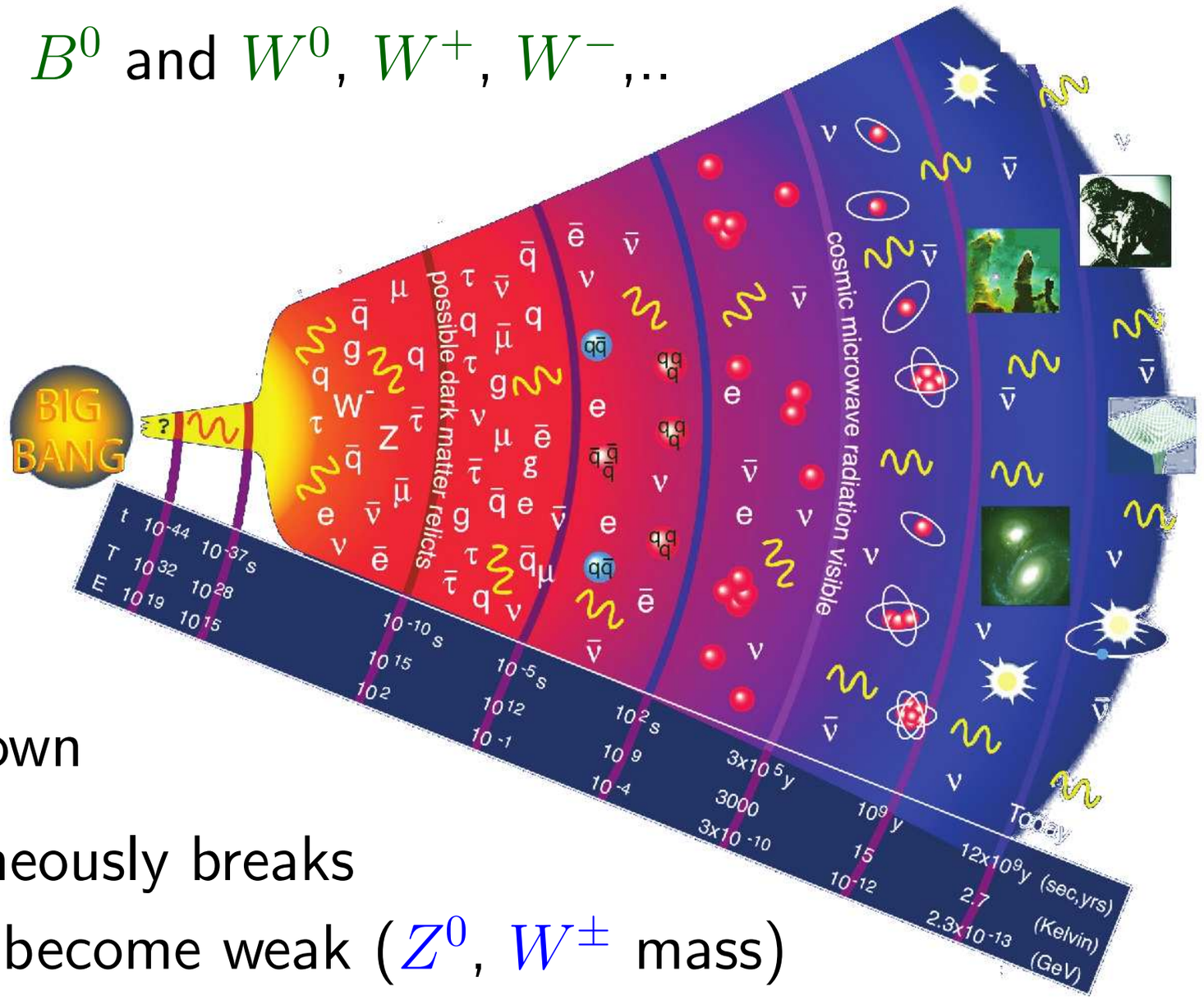
$$|\gamma\rangle = \cos\theta_W |B^0\rangle + \sin\theta_W |W^0\rangle \quad \text{light (massless)}$$
$$|Z^0\rangle = \sin\theta_W |B^0\rangle + \cos\theta_W |W^0\rangle \quad \text{heavy}$$

θ_W - Weak mixing (Weinberg) angle



Path from Light to Heavy

- Early moments of the Universe
  - massless particles: B^0 and W^0, W^+, W^-,..
  - all forces unify

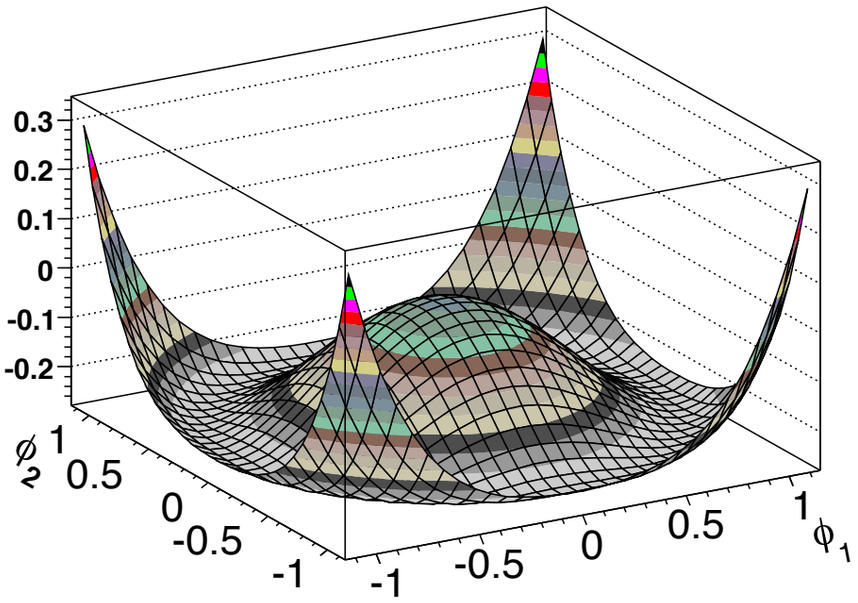


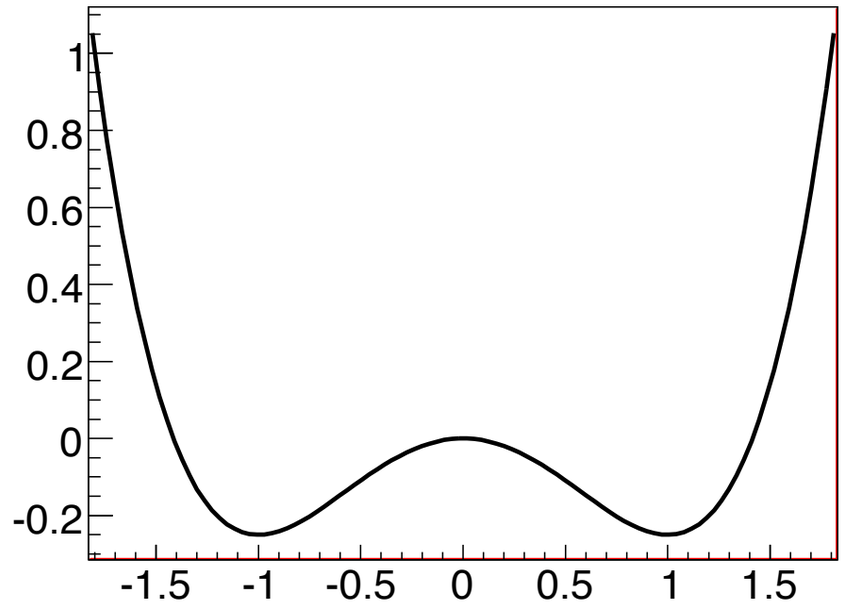
- As Universe cools down
  - symmetry spontaneously breaks
  - weak interactions become weak (Z^0, $W^\pm$ mass)
  - Higgs field – possible mechanism

The Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism

- Symmetry spontaneously breaks near minimum (vacuum) energy of Higgs field $(\phi_1, \phi_2, \phi_3, \phi_4)$

$$V(\phi_1, \phi_2, \phi_3, \phi_4) = \frac{1}{4}\lambda \left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]^2 - \frac{1}{2}|\mu|^2 \left[\ldots\right]$$





- Higgs particle described by one component of the Higgs field

$$h = \phi_1 - v$$

- The other Higgs field components ϕ_2, ϕ_3, ϕ_4 couple to Weak bosons Z^0, W^-, W^+ and generate mass, longitudinal polarization (not γ)

Idea - the Higgs Field

- Empty space filled with invisible "force" – the Higgs field

Idea - the Higgs Field

- The Higgs field clusters around the particle – gives mass

Idea - the Higgs Field

- Pass energy into the Higgs field (no particle)

Idea - the Higgs Field

- The Higgs particle cluster created from the Higgs field

Vacuum

- As far as we can tell vacuum (empty space)

  is not exactly empty

- like a bank account balance:

when you take all your money out

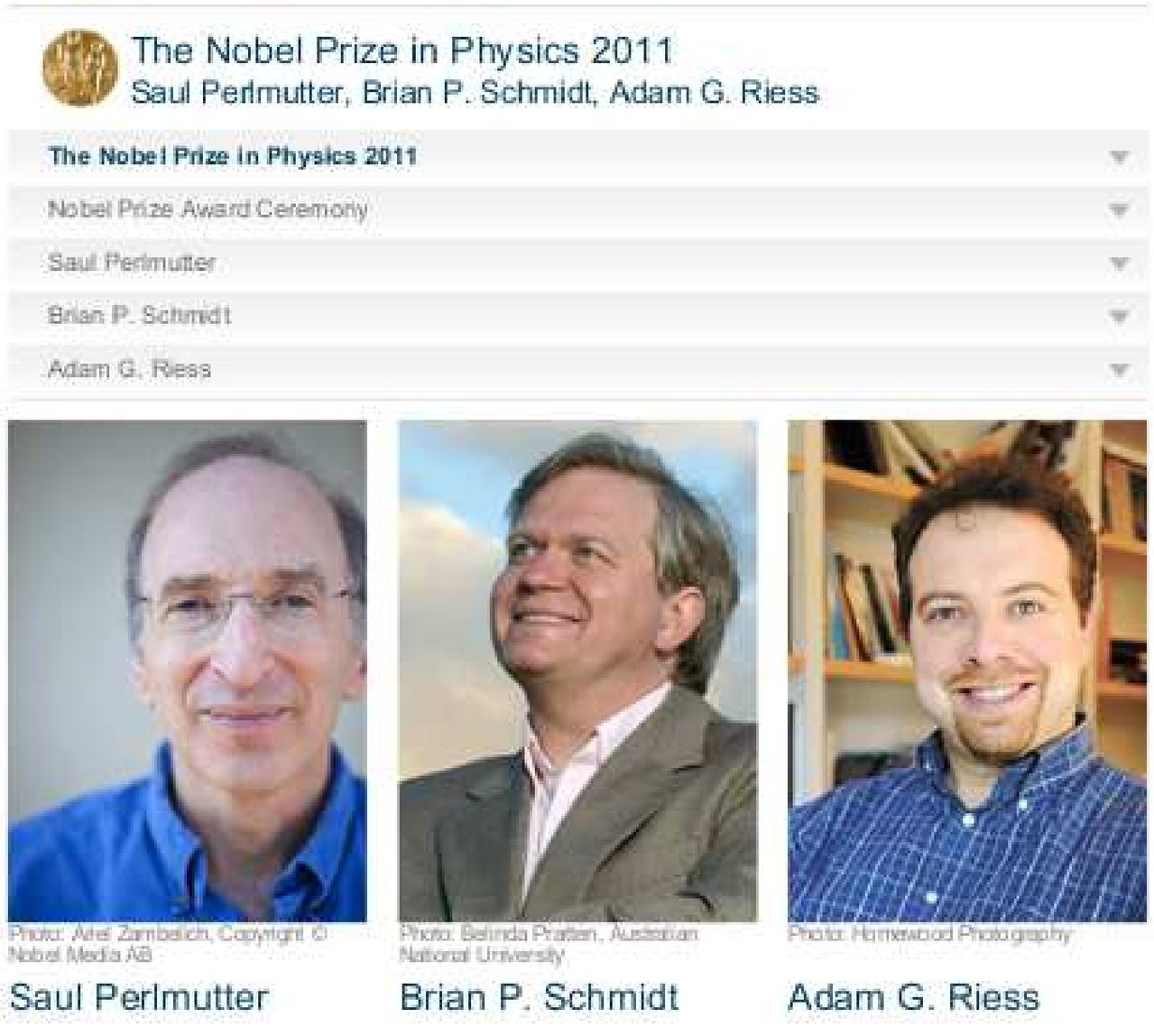
there is a minimum balance left

- Invisible "force" present
  - dark energy
  - Higgs field

2011 Nobel Prize in Physics

- Accelerating expansion of the Universe

  requires some kind of "dark energy" through empty space



Puzzles of the Universe

- Dark energy (∼70%)
  - do not know what it is; explain accelerated expansion

- Dark matter (∼25%)
  - does not emit light, but seen with gravity

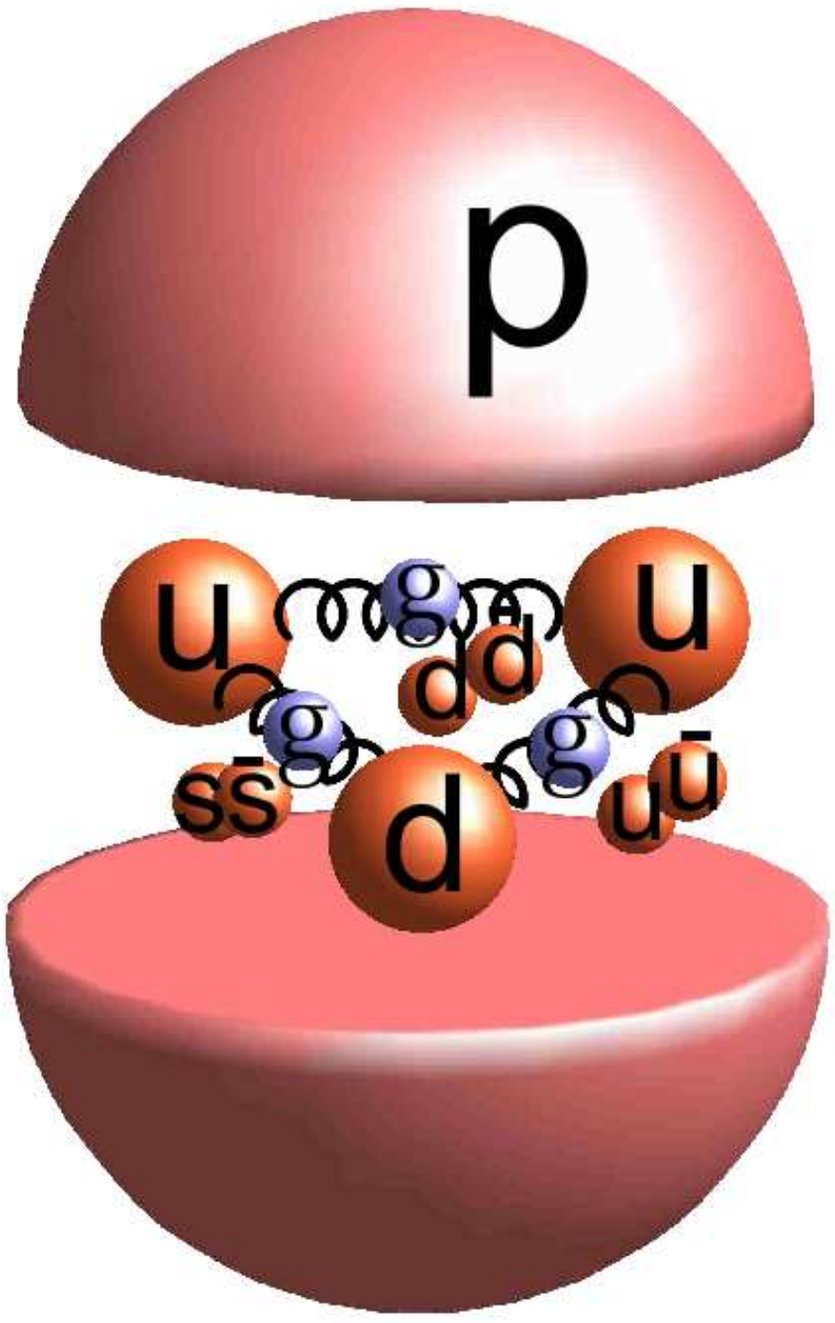
- Ordinary matter (∼5%)
  - the only thing we knew until recently: from Hydrogen to Uranium

- Ordinary antimatter (∼0%)
  - equal amount of matter and antimatter in the Big Bang

- Origin of mass
  - everything created equal and massless in the Big Bang

Mass of Matter

- Most of our mass is in protons and neutrons in atoms



Majority from quark-glue soup

$m_p c^2 = 938$ MeV

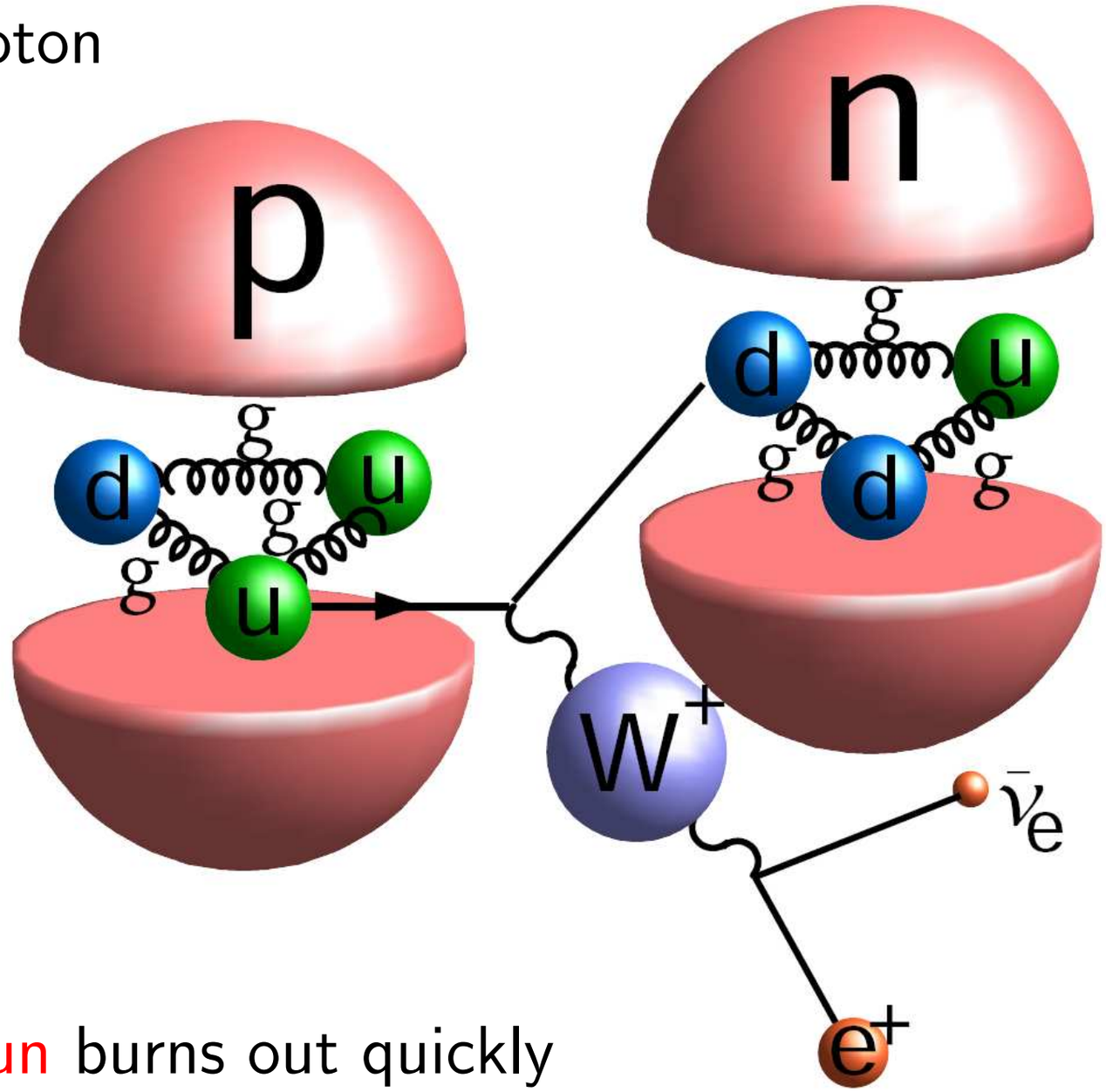
Some from the Higgs field

$m_q c^2 \sim$ few MeV

but Higgs field is very important

Higgs Field in our Life

- Remove the Higgs field:
  - catastrophic decay of a proton
  - no water (hydrogen)



- Origin of Sun light

  Weak (slow) fusion pp

Remove the Higgs field – Sun burns out quickly

Mass of Matter

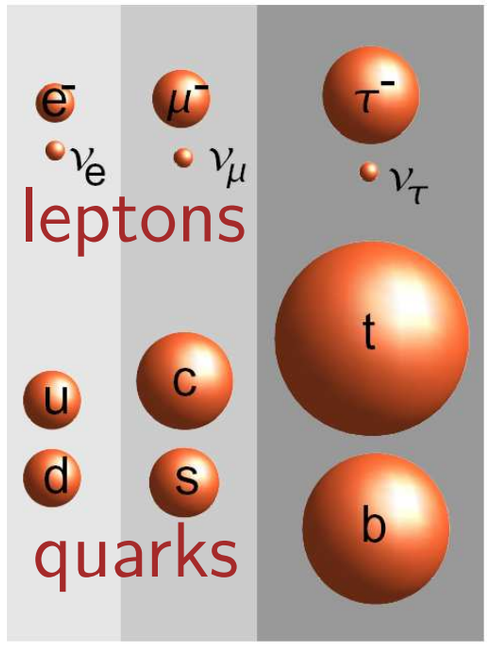
- Higgs mechanism works with fermions (ad hoc)

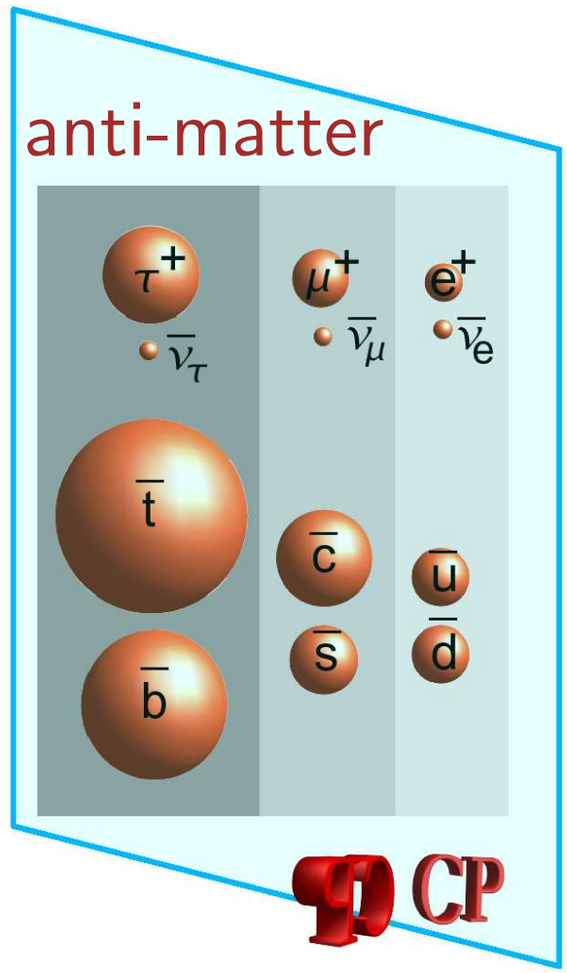
  fermions ($S = \frac{\hbar}{2}$) occupy space $\Rightarrow$ matter

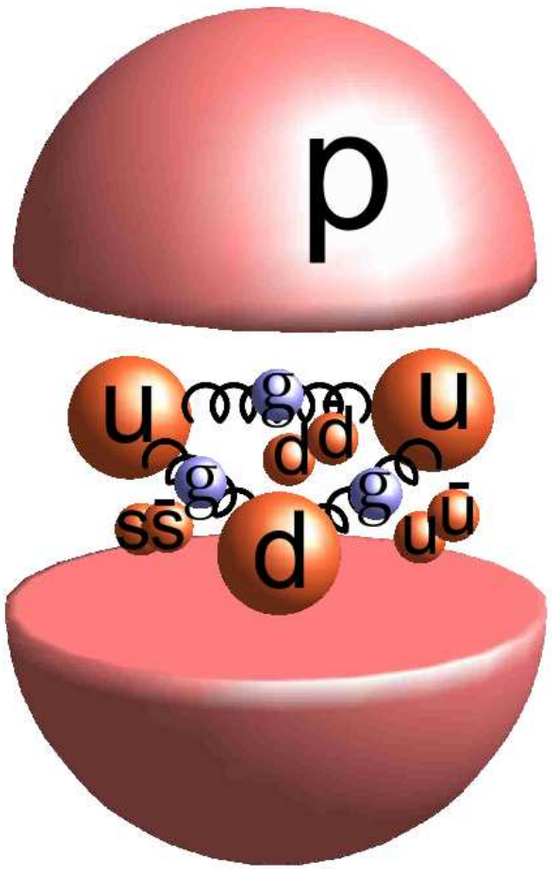
- Proton mass $m_p c^2 = E$(sea)

  not from Higgs field

  energy of gluons & quarks







$m_p = 938$ MeV

$m_u \sim 2.5$ MeV, $m_d \sim 4.9$ MeV

$\sim 50\%$ gluon, $\sim 50\%$ $q\bar{q}$ sea energy

u, u, d set quantum numbers and interactions

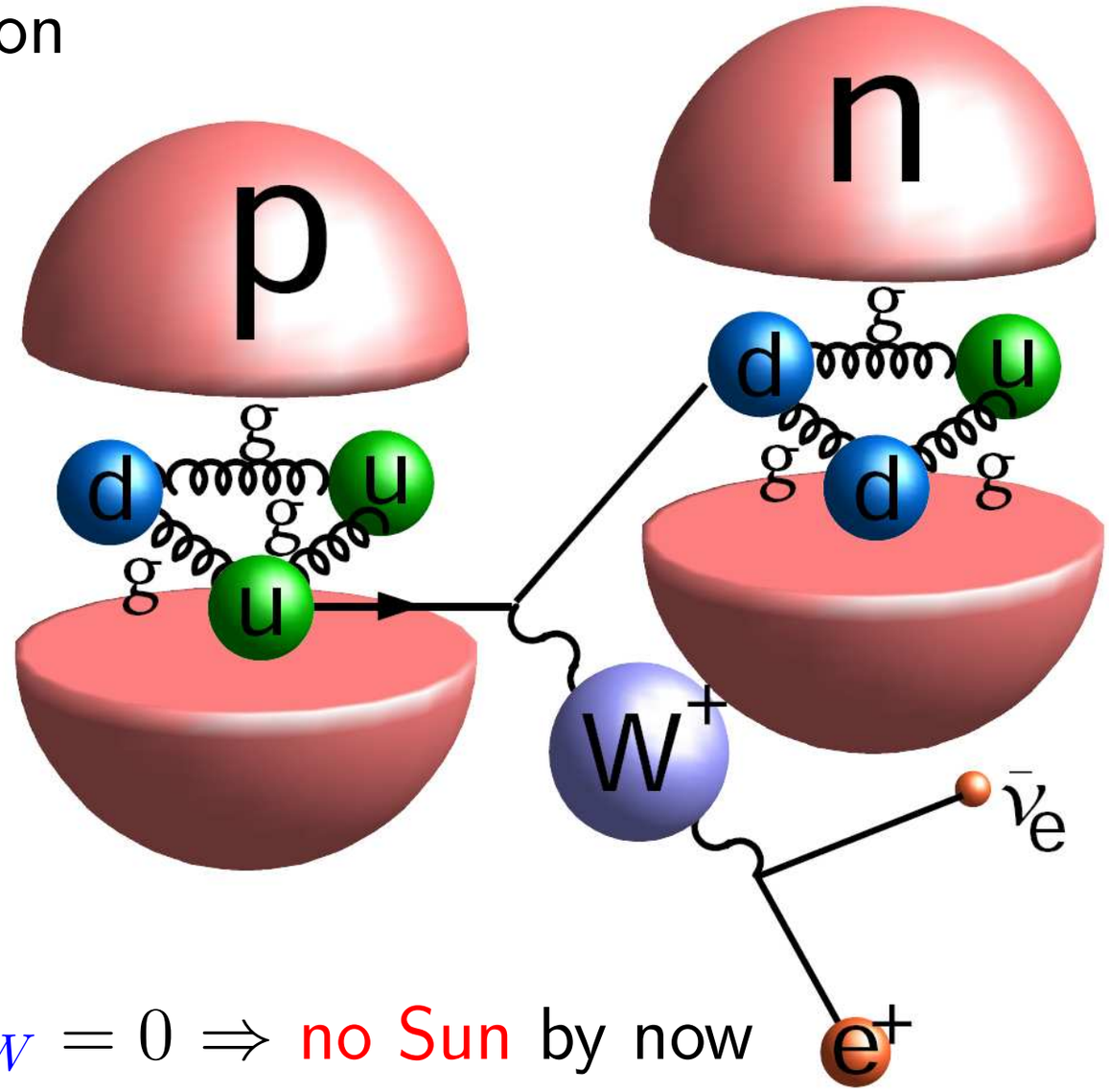
Higgs Mechanism in our Life

- Without a Higgs-like mechanism: $m_u = m_d \;\Rightarrow\; m_p > m_n$

  $\Rightarrow$ catastrophic decay of a proton

  $\Rightarrow$ no H_2O (water), no life

  but safe from $m_u < m_d$



- Origin of Sun light

  starts from Weak fusion

  $p + p \longrightarrow d(pn) + e^+ + \nu_e$

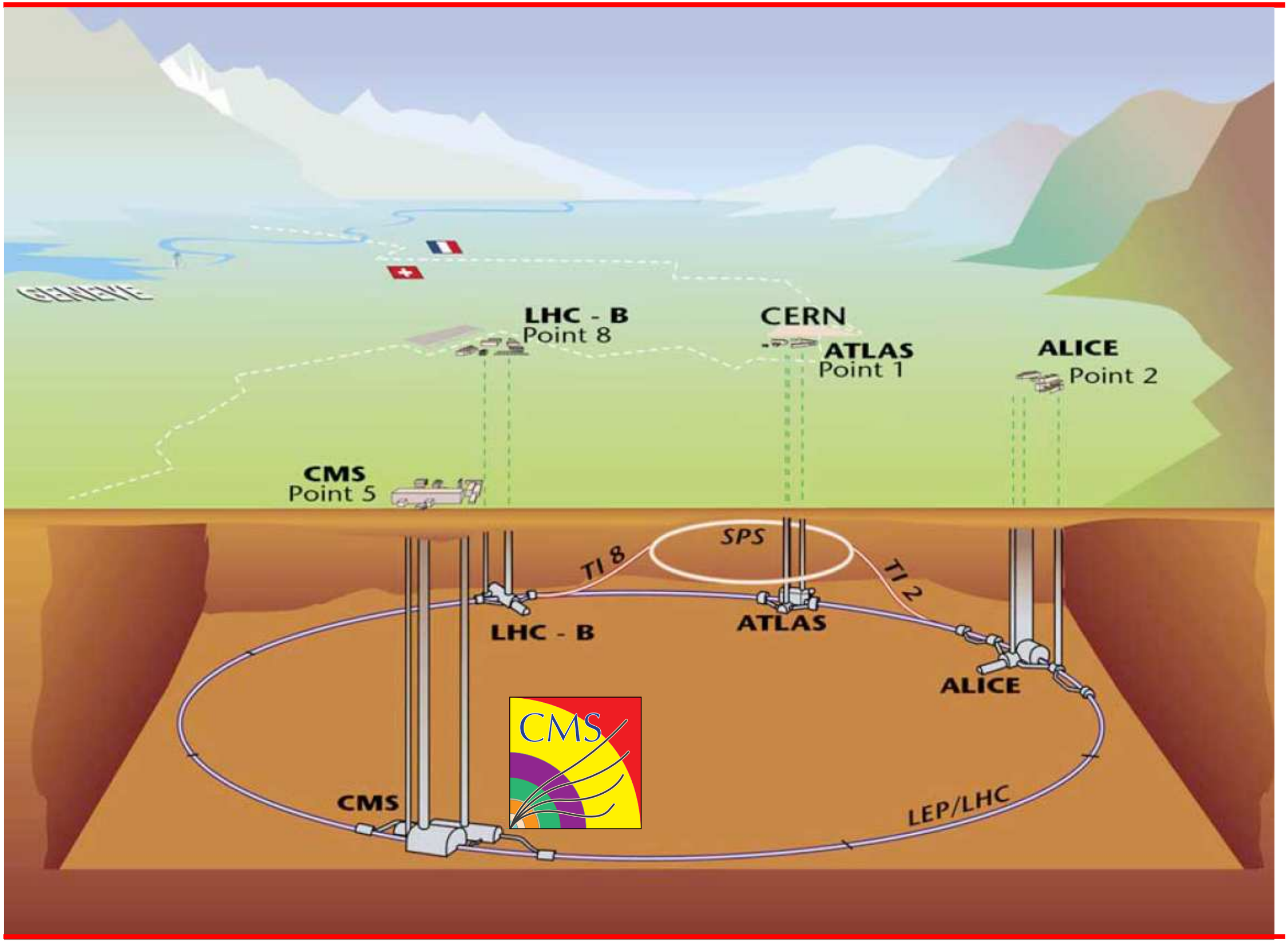
  slow burning due to heavy W^+

  no Higgs-like mechanism $\Rightarrow m_W = 0 \Rightarrow$ no Sun by now

  hot in the Sun core ($\sim 10^7$ K), not as hot as at LHC ($\sim 10^{16}$ K)

The Large Hadron Collider

The Large Hadron Collider



The Large Hadron Collider

- What has changed? $\times 10$ data since Summer 2011

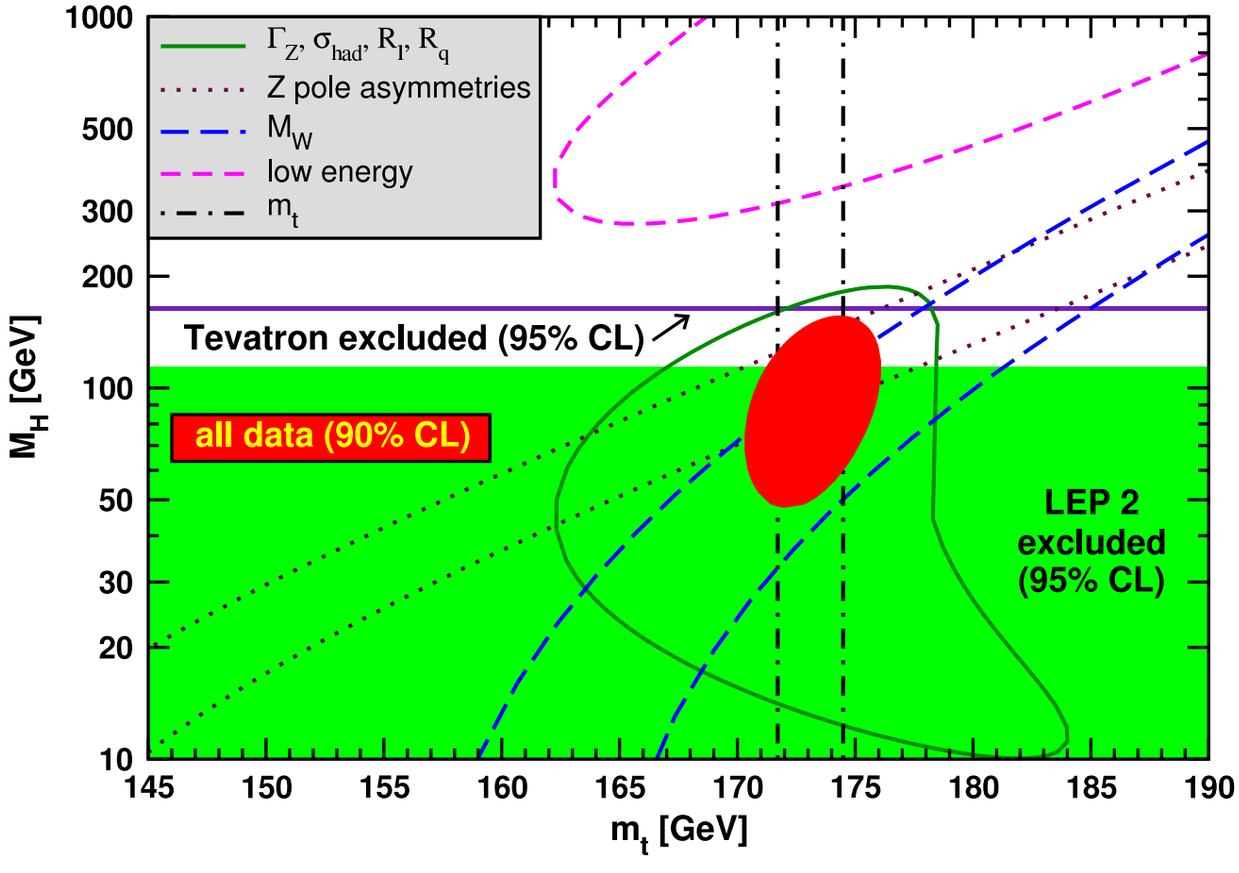
  > 1000 trillion proton-proton collisions in 2011-2012

  > 10 billion events recorded, $\sim$0.6 Mbyte each ($\sim$Petabyte)

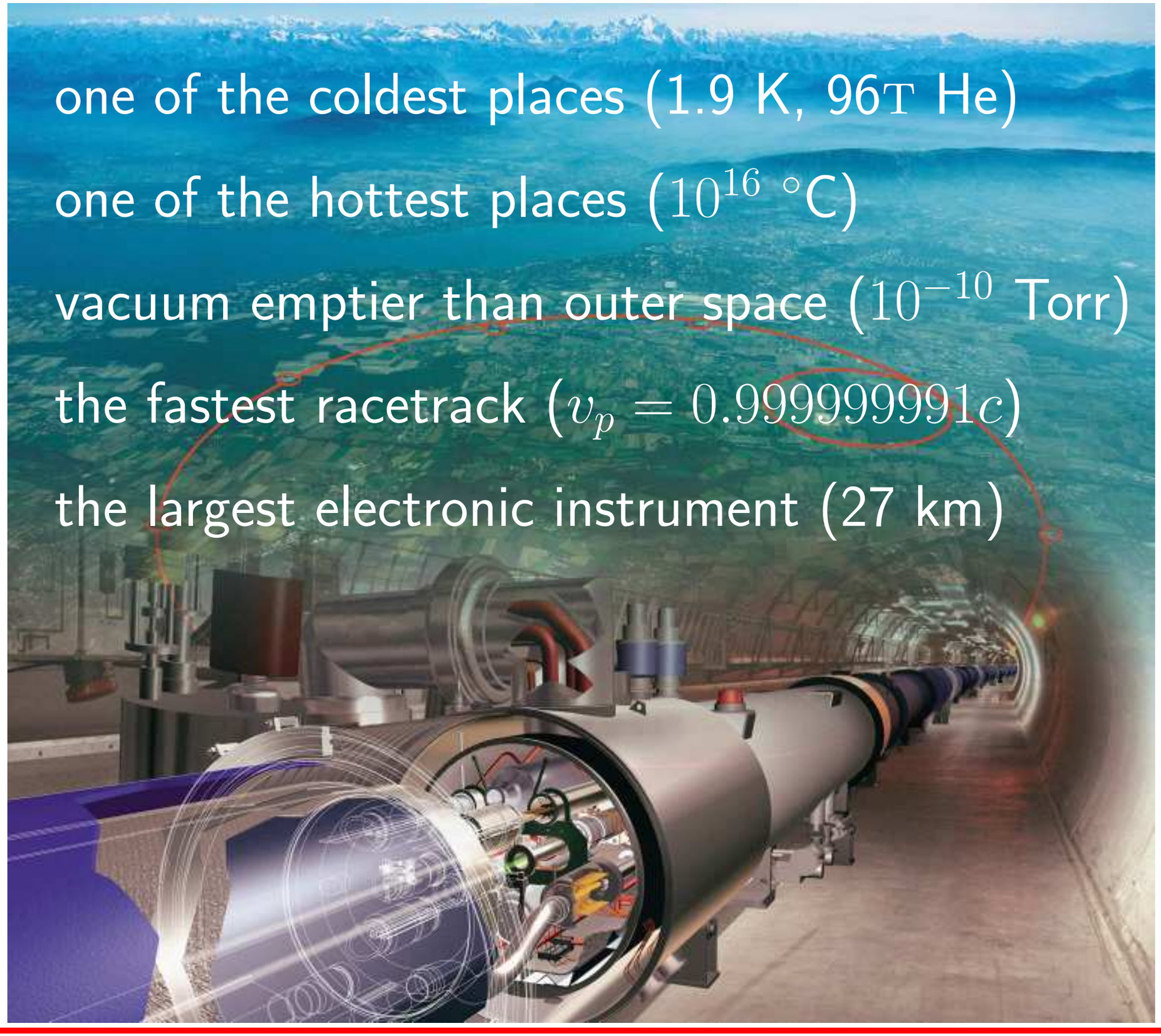
  > 100 million Z^0 bosons

  > 100 thousand Higgs bosons produced – if it exists

- Before LHC:



The Large Hadron Collider



Global Effort at the Large Hadron Collider

- 1991: first World Wide Web (http://www...) server at CERN

- 20 years later: LHC Computing Grid
  - distributed across >34 countries
  - 200,000 computer cores
  - 150 Petabytes of disk space

  Petabyte = Million Gigabytes

  1 Gigabyte $\simeq$ 1 CD

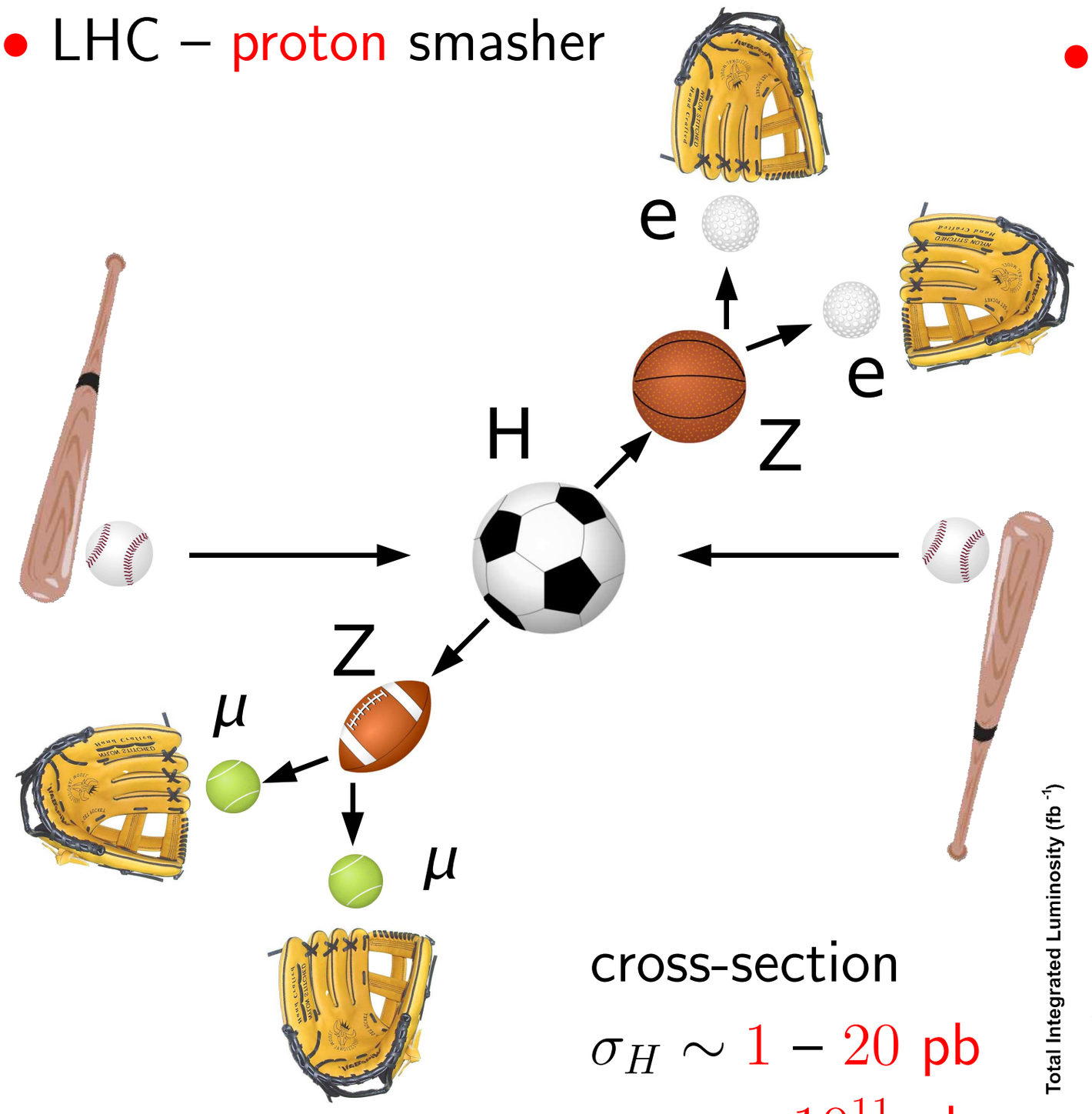
- Flow of data from one experiment alone (CMS):

  > 300 trillion proton-proton collisions in 2011

  > 3 billion "events" recorded on disk in 2011

The Large Hadron Collider

- LHC – proton smasher



- ATLAS & CMS

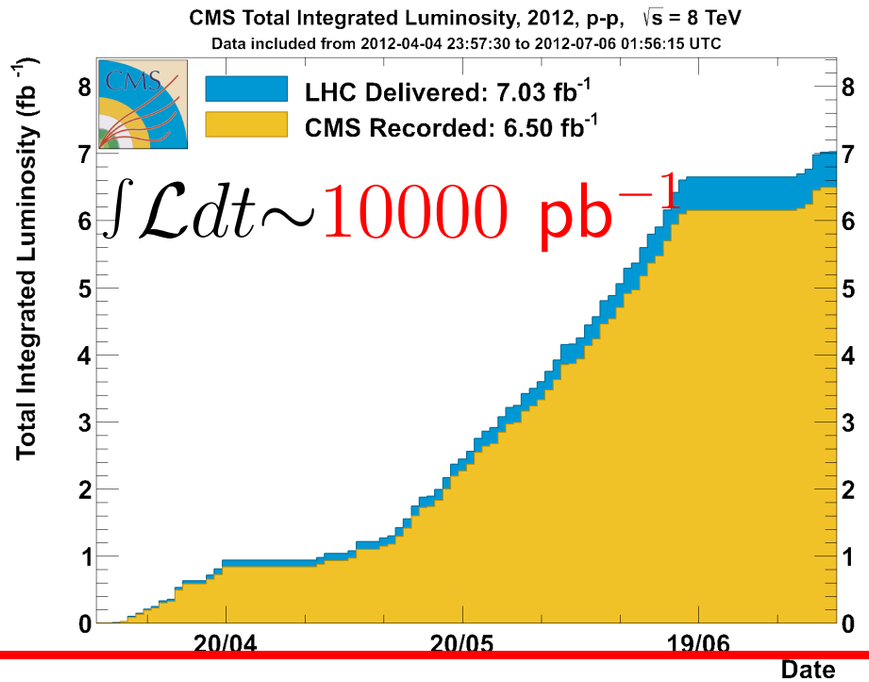
  detectors sort it out

cross-section

$\sigma_H \sim 1 - 20$ pb

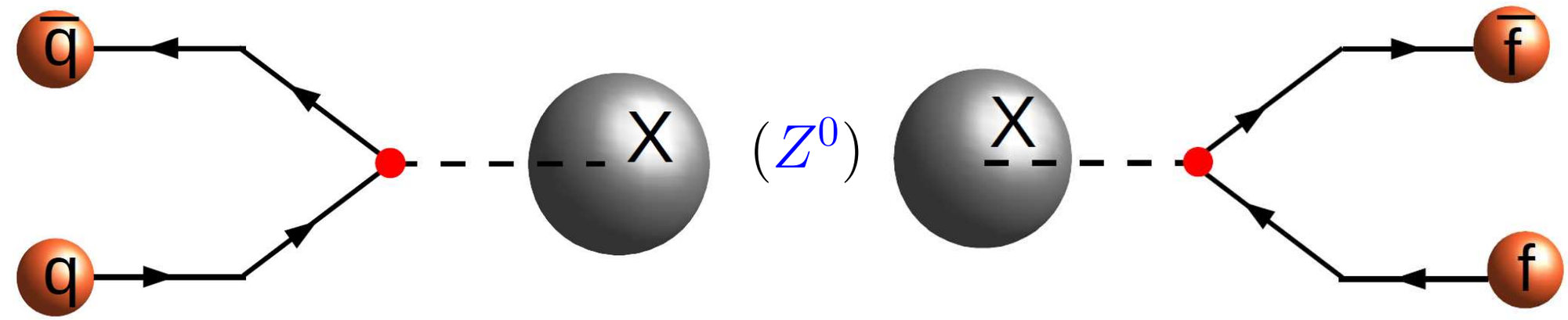
$\sigma_{\text{total}} \sim 10^{11}$ pb

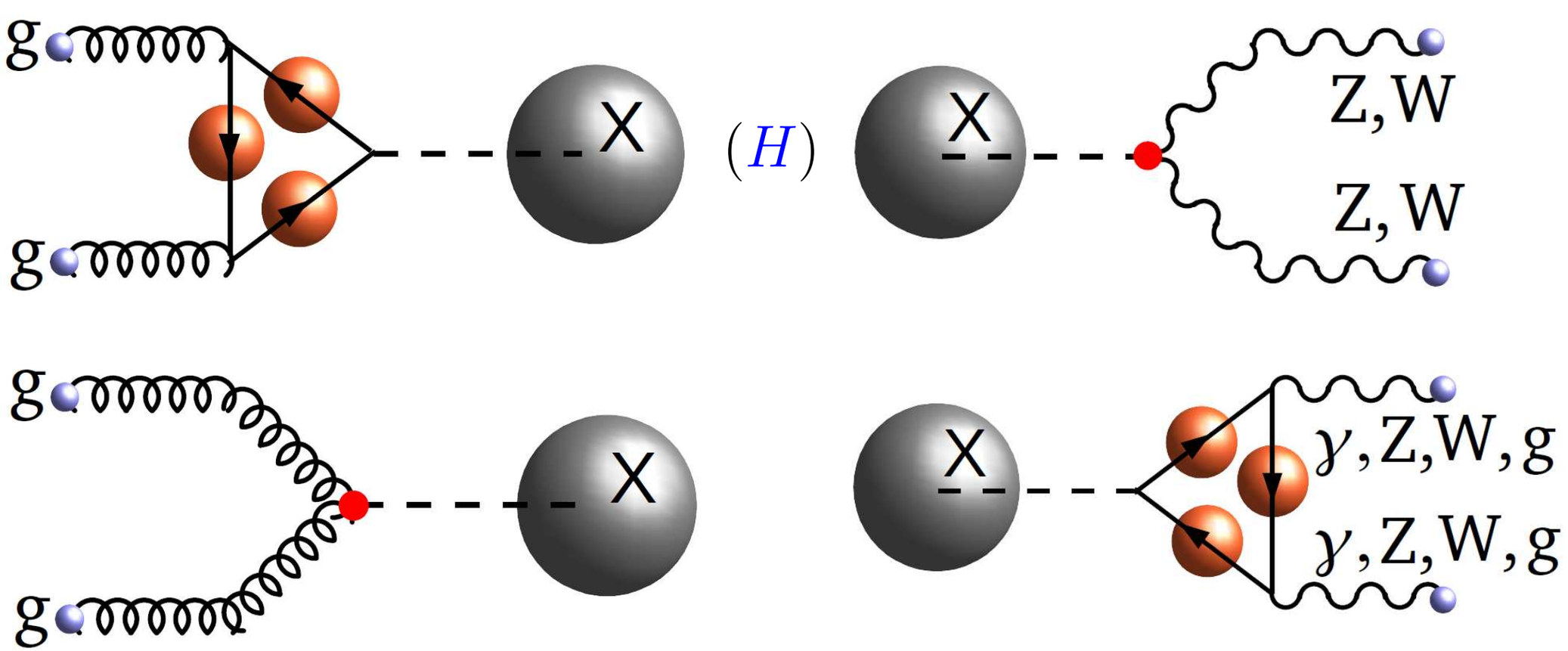
luminosity



Production of New Particles at LHC

- Particles are produced and decay: $X = Z^0$, Higgs, RS Graviton, ...

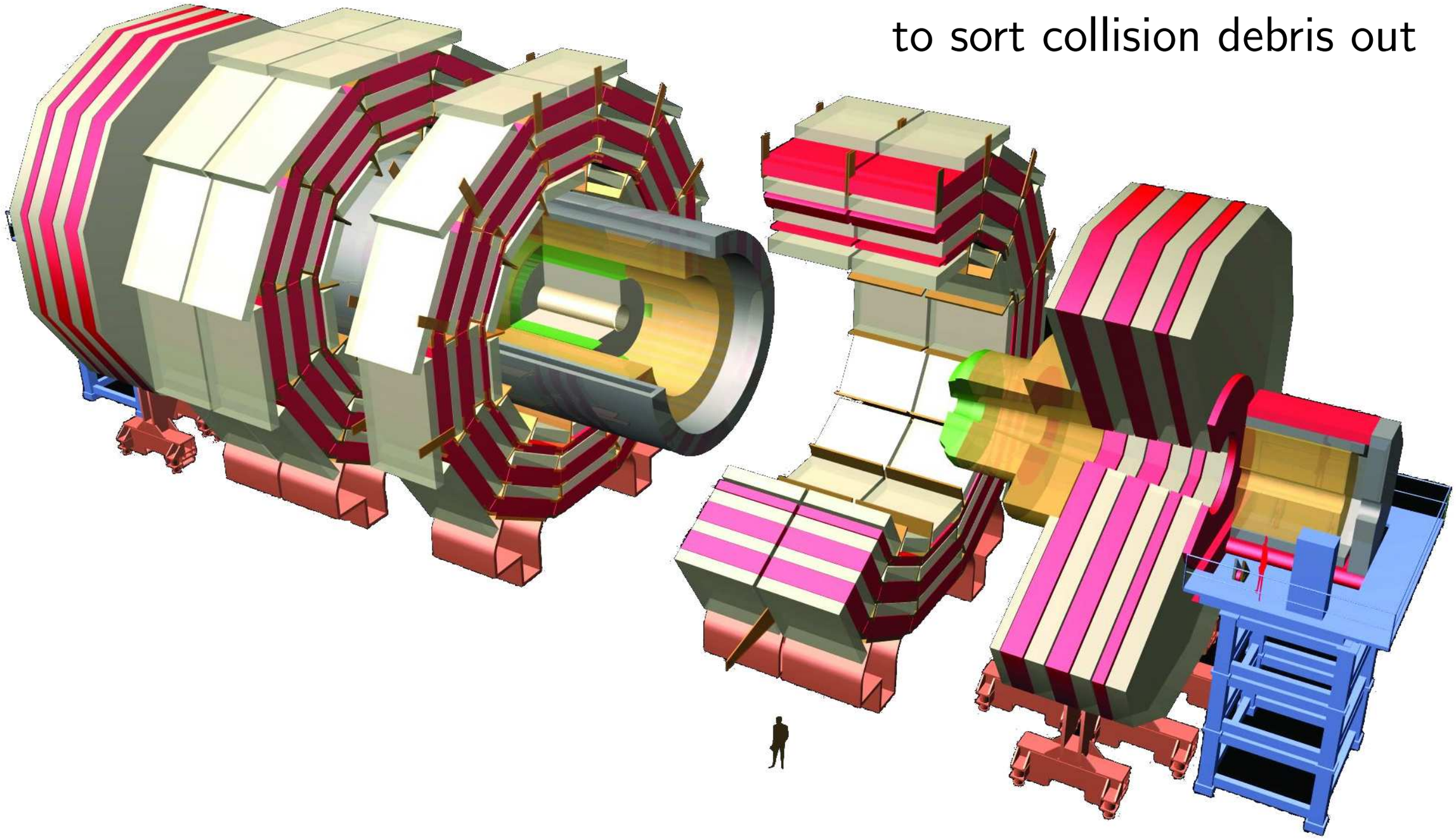




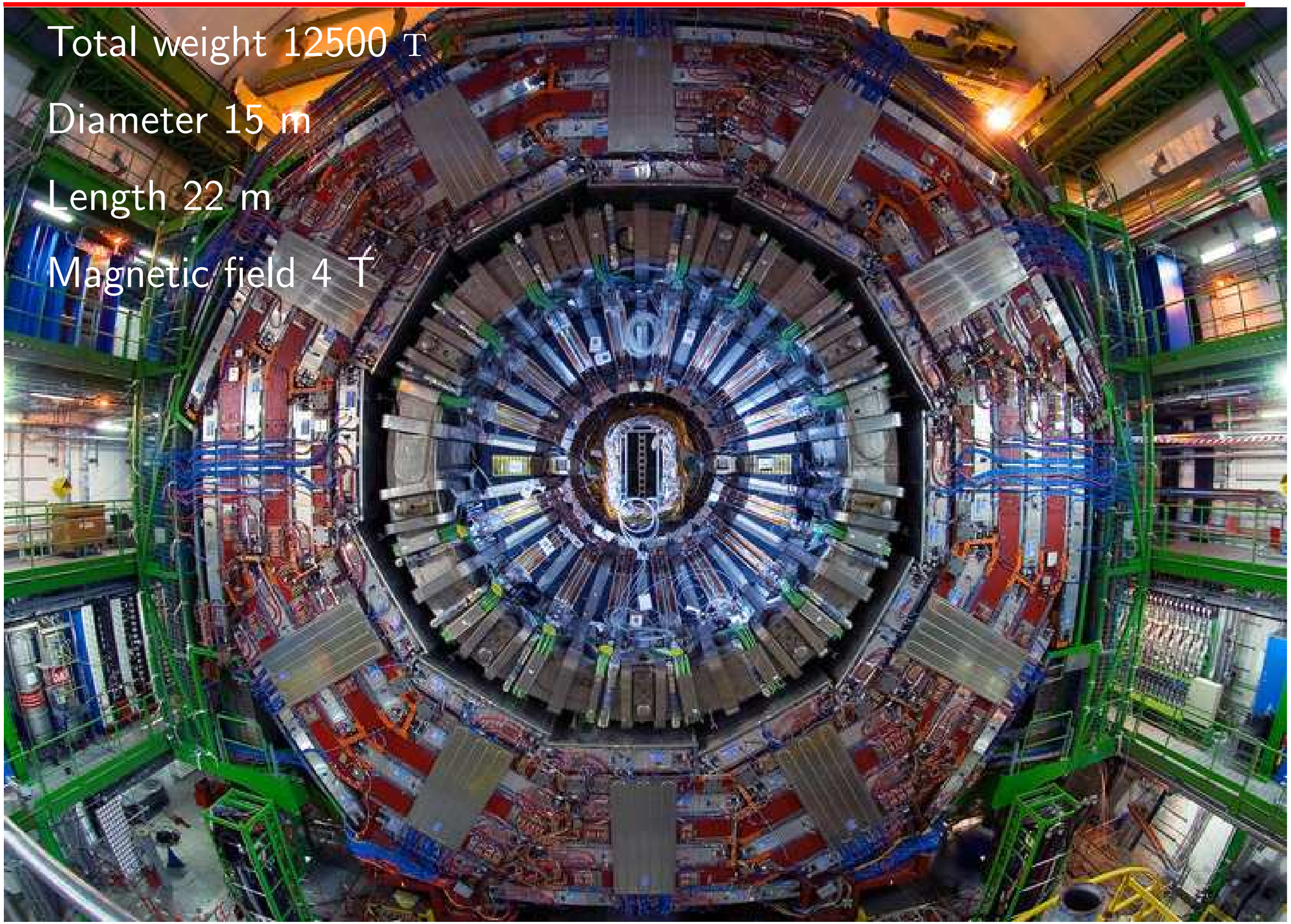
The CMS Detector

- Complex detector

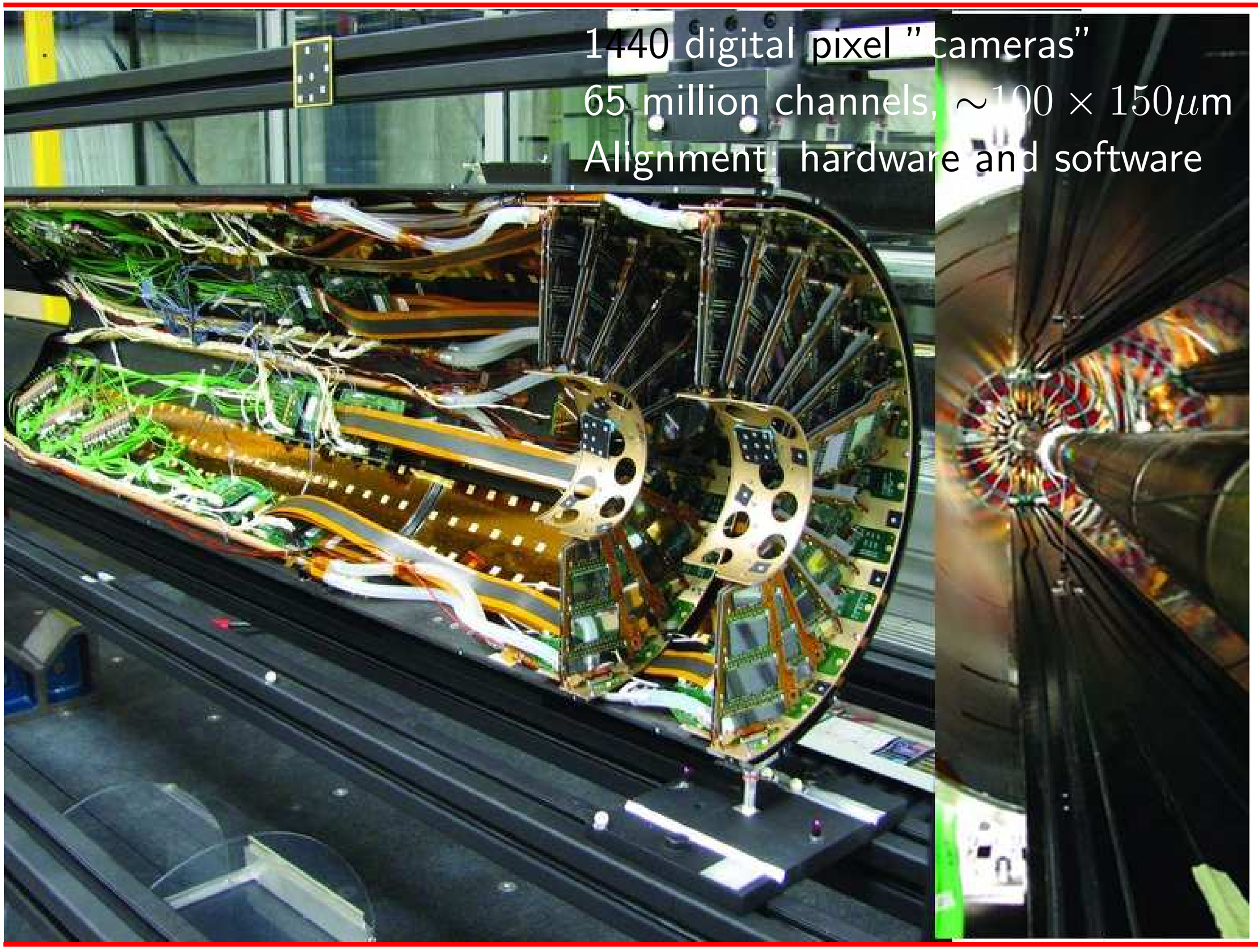
  to sort collision debris out



The CMS Detector



The Silicon Pixel Detector



1440 digital pixel "cameras"

65 million channels, $\sim 100 \times 150 \mu$m

Alignment: hardware and software

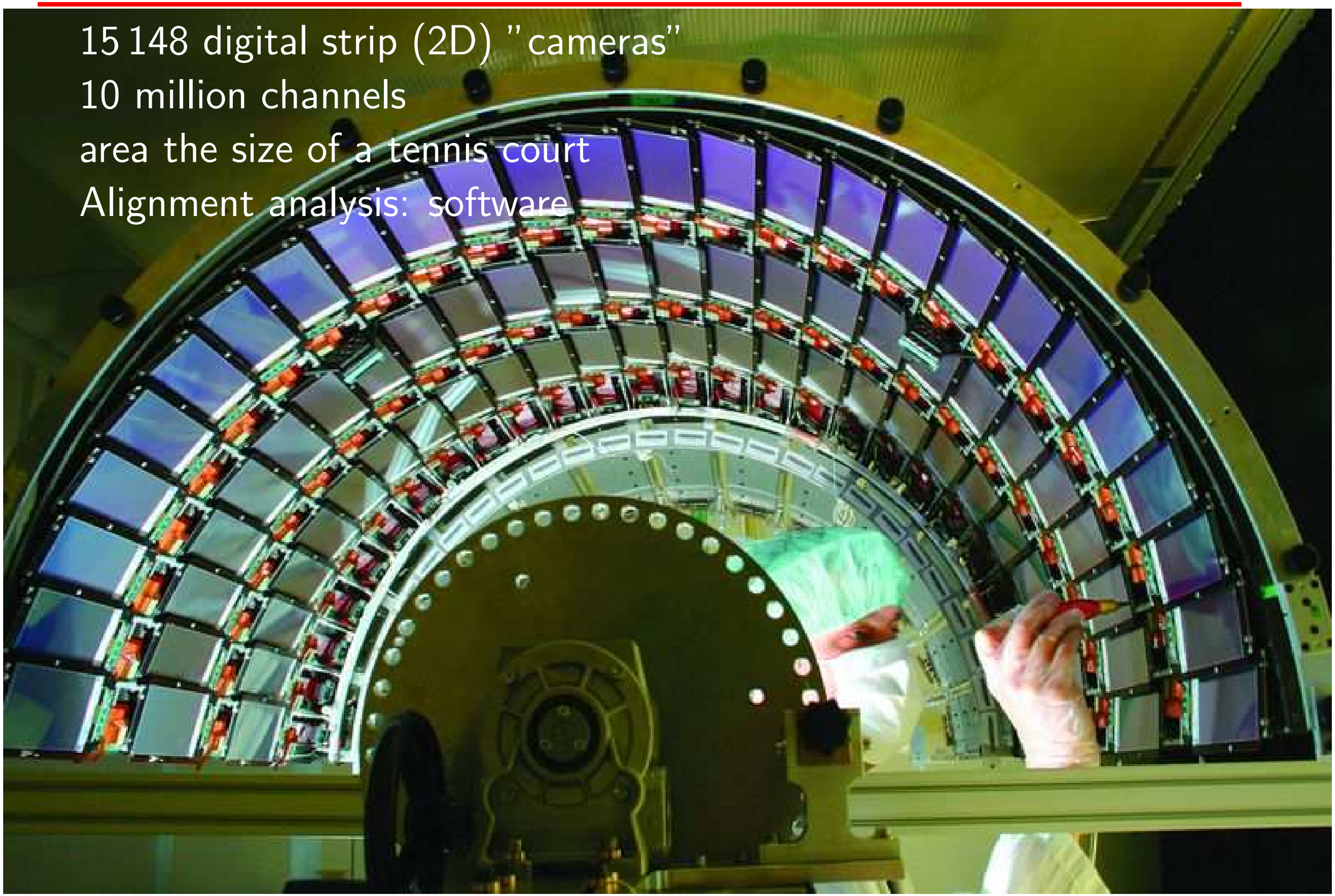
The Silicon Strip Detector

15 148 digital strip (2D) "cameras"

10 million channels

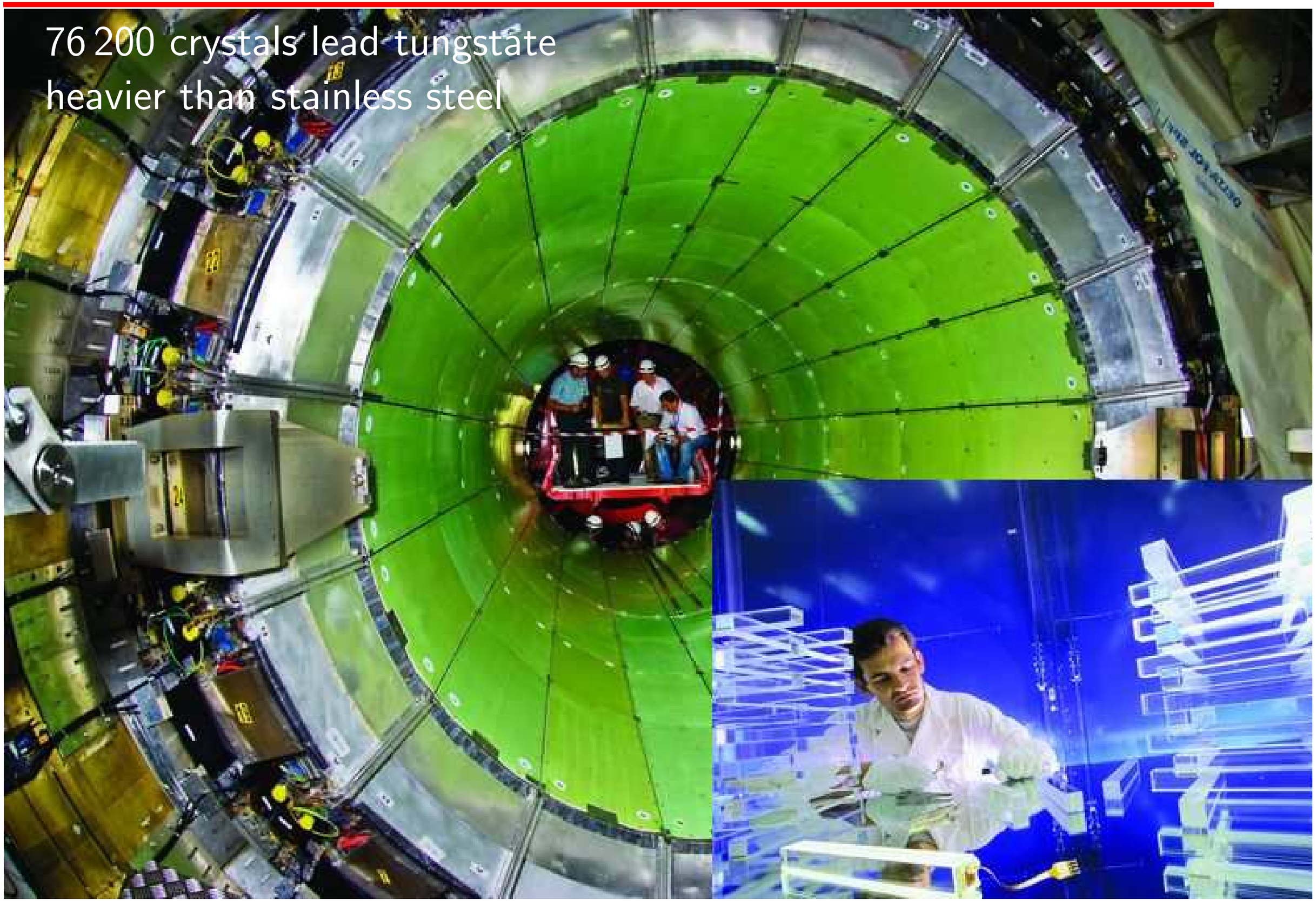
area the size of a tennis court

Alignment analysis: software



Electromagnetic Calorimeter

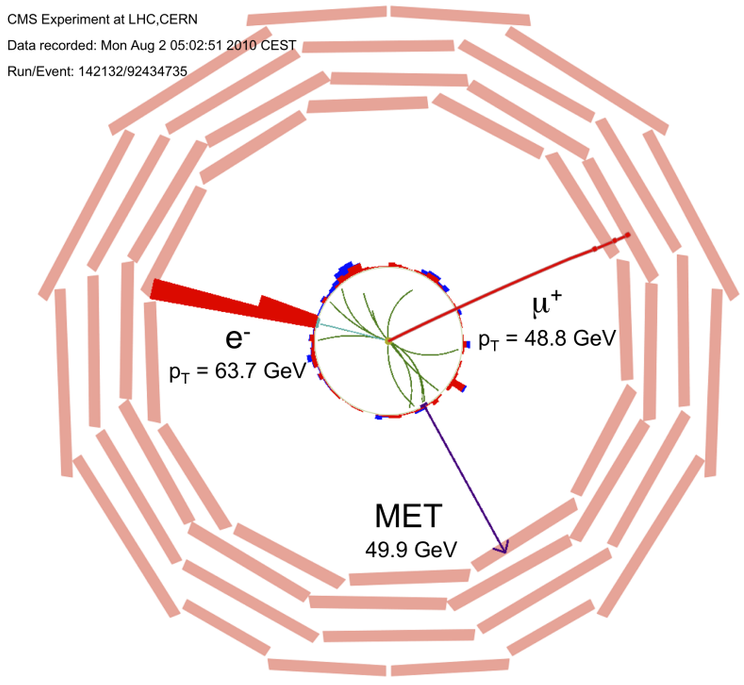
76 200 crystals lead tungstate
heavier than stainless steel

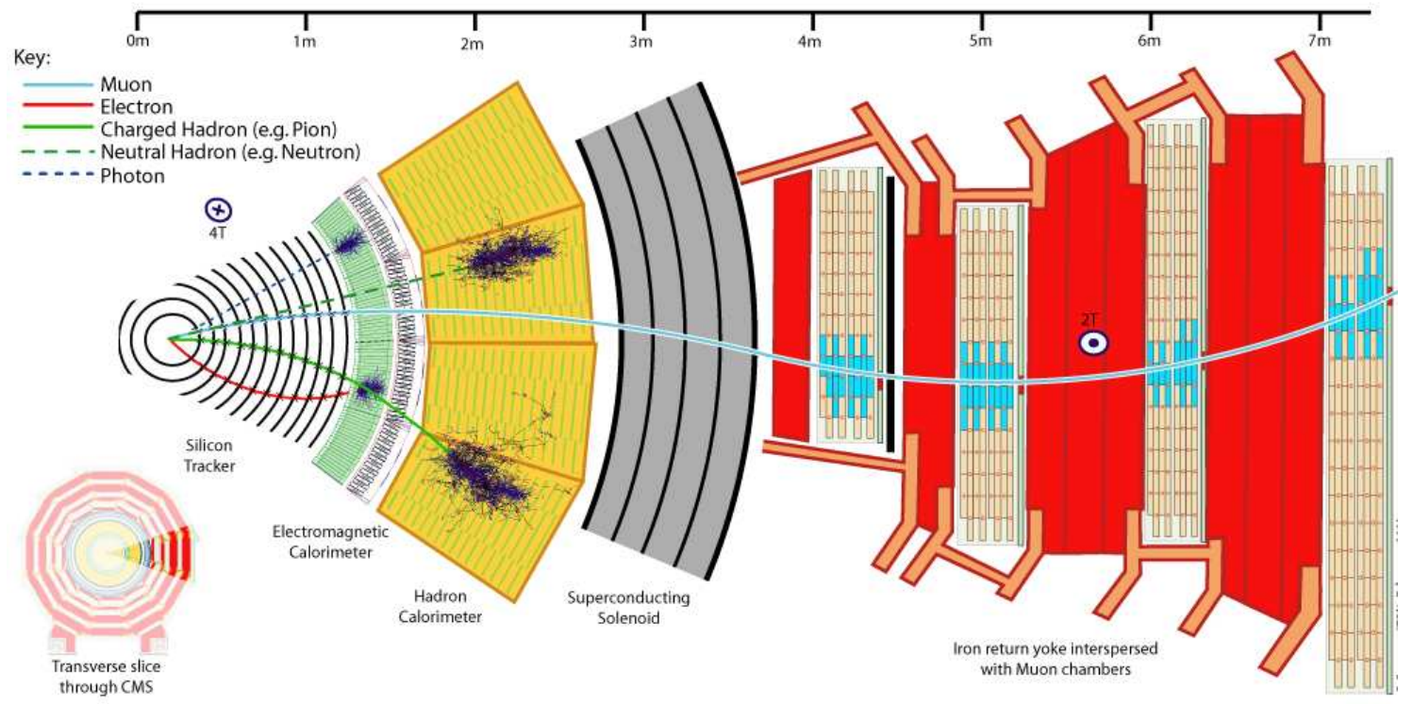


Hadronic Calorimeter and Muon System

Detection of Major Objects

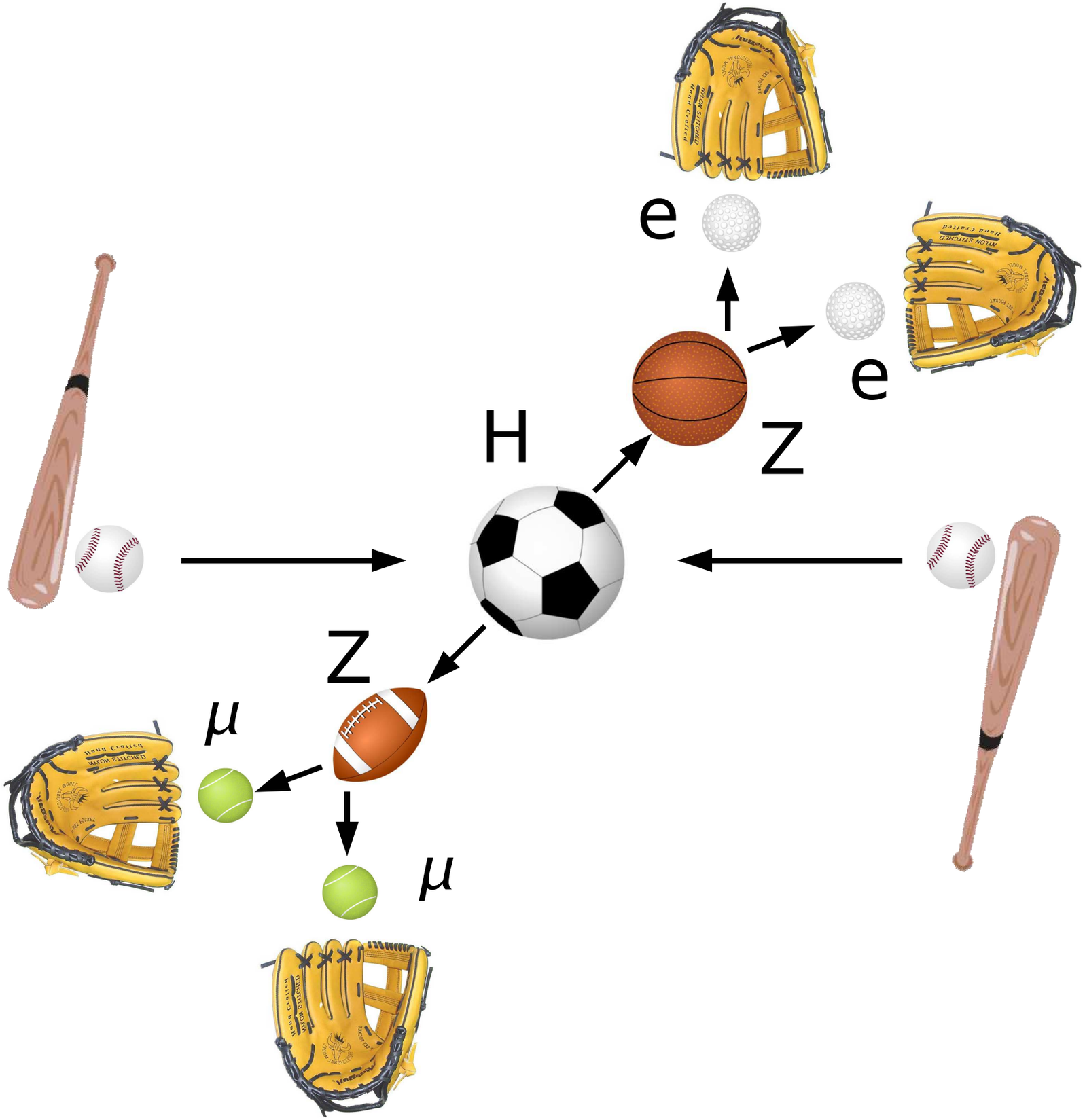
- Leptons: $\ell^{\pm}$ in Si Tracker: $e^{\pm}$ (EM Calorimeter), $\mu^{\pm}$ (Muon System)
- Photons: γ (EM Calorimeter)
- Quark q & gluon g jets $\longrightarrow$ "Particle Flow" thru Hadronic Calorimer
- Neutrinos $\nu \Rightarrow$ missing energy ("MET")



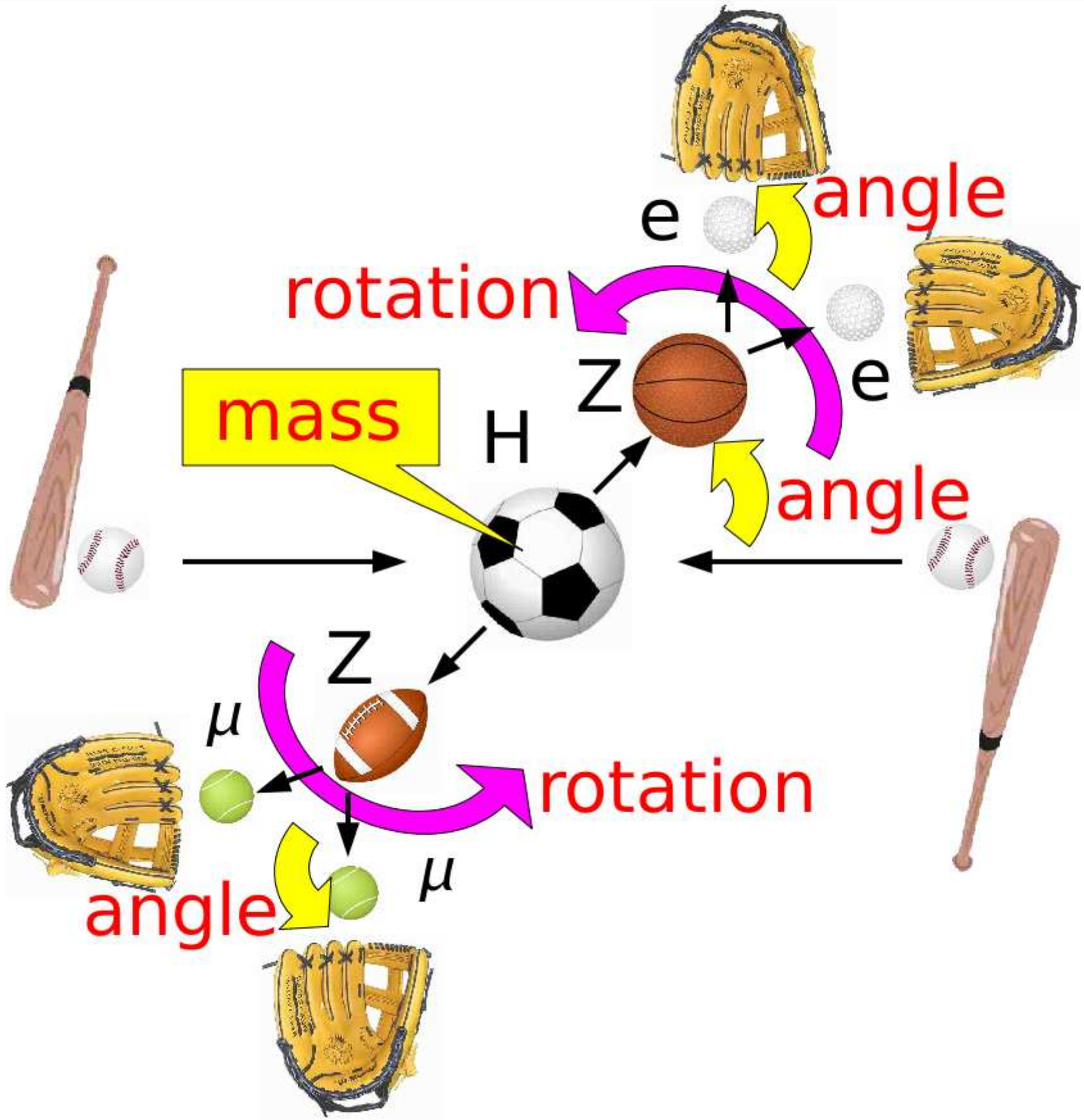


$$WW \longrightarrow (e^{-}\bar{\nu})(\mu^{+}\nu)$$

An Experiment

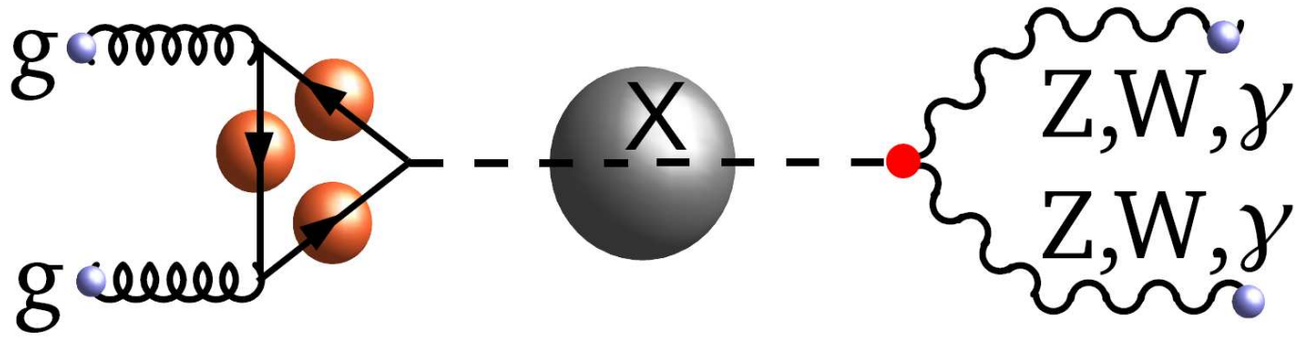


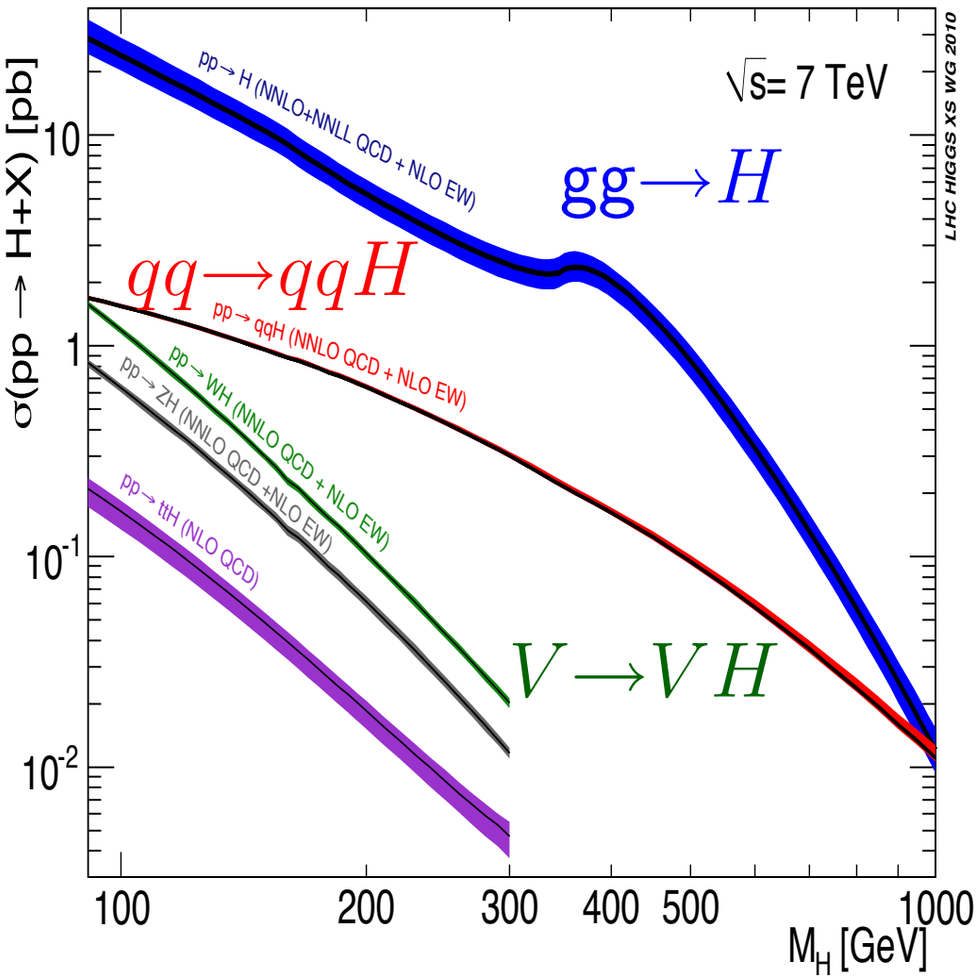
Kinematics in the Experiment

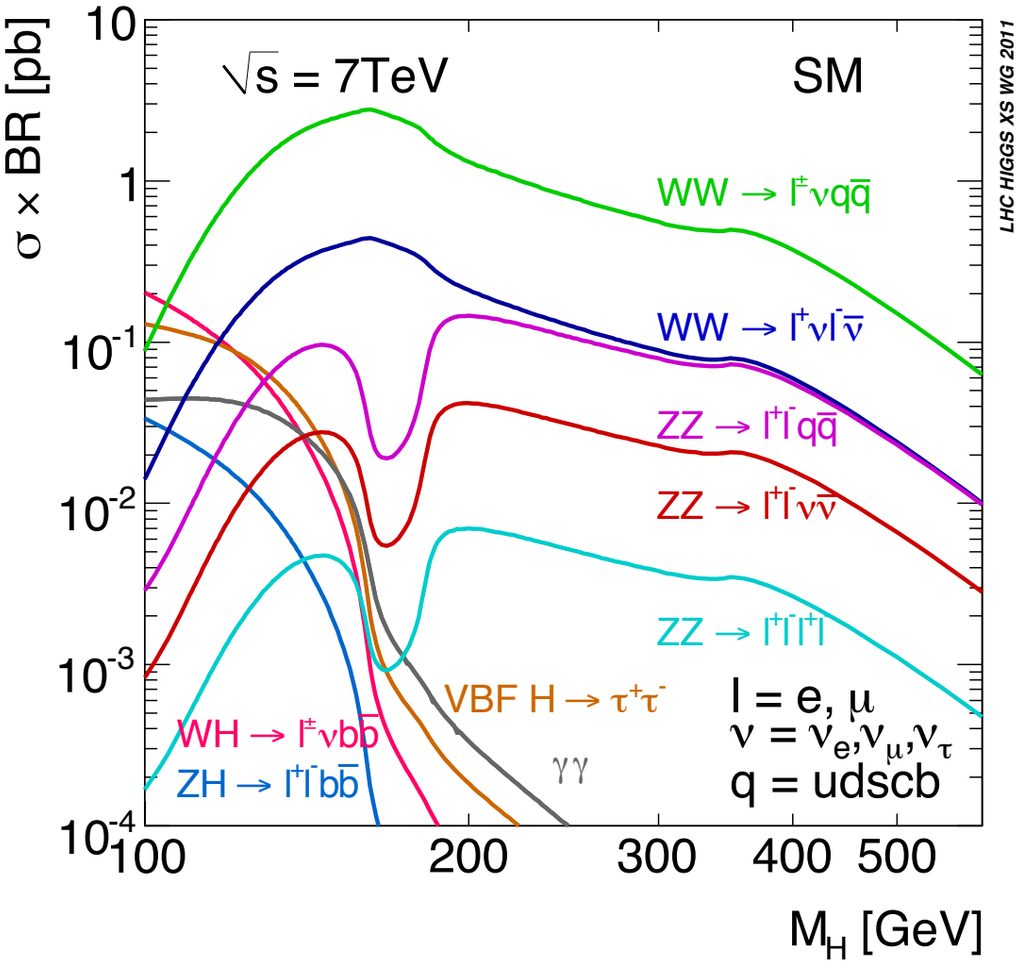


The Standard Model Higgs

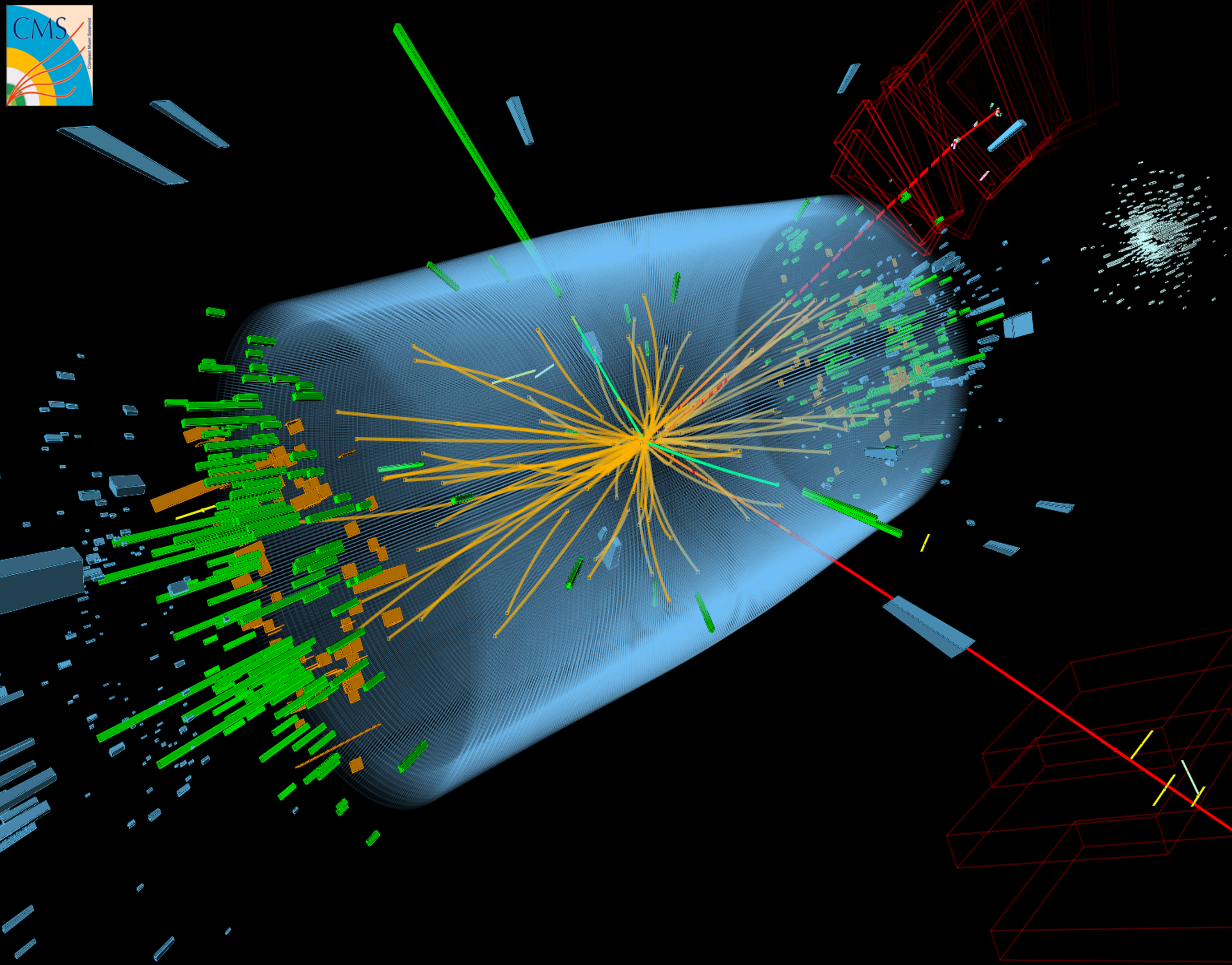
$$\mathrm{gg} \longrightarrow H \longrightarrow \gamma\gamma,\ ZZ^{(*)},\ W^+W^-,..$$



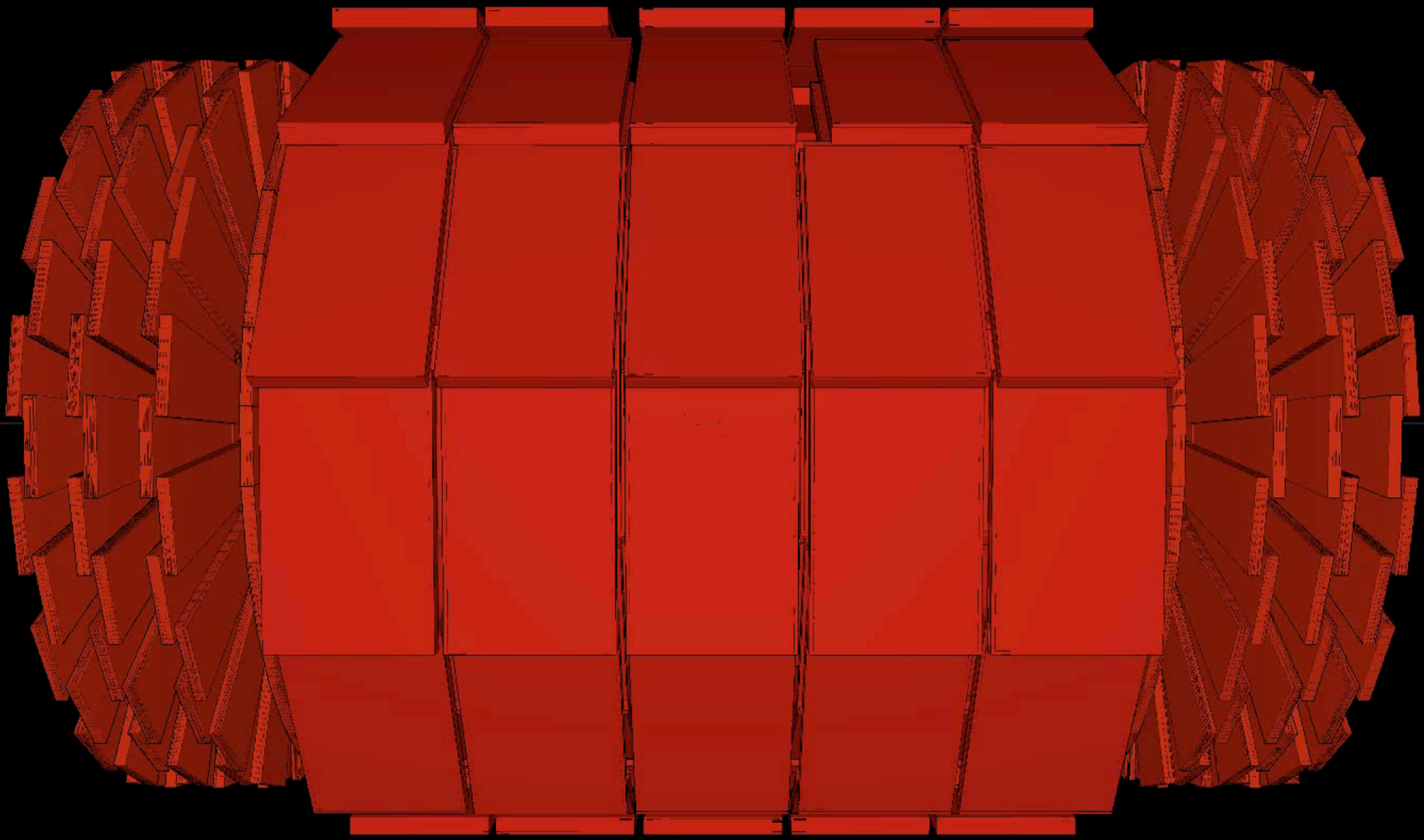




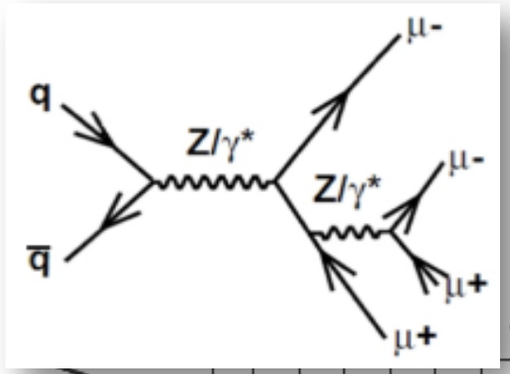
CMS: H → ZZ*



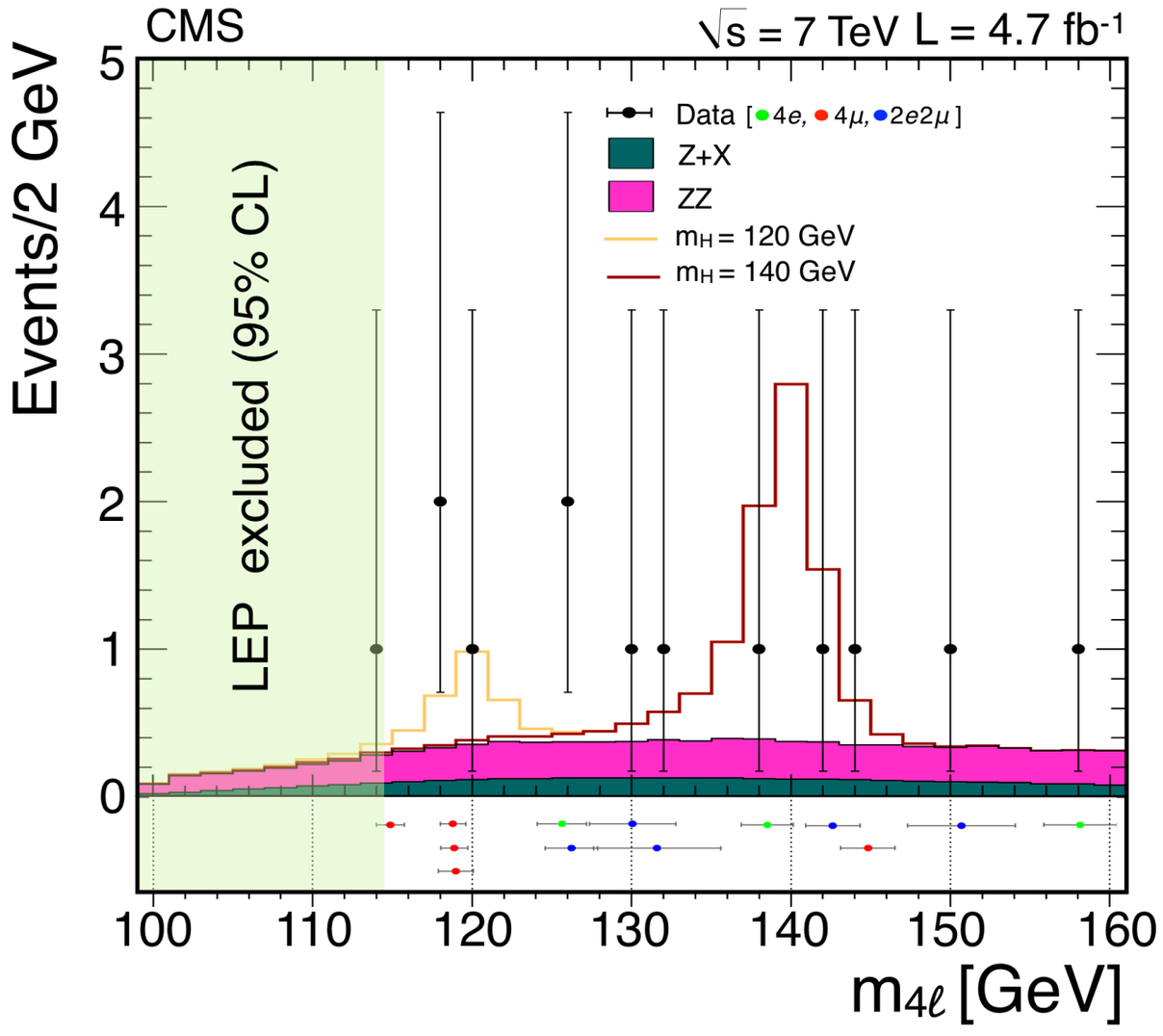
CMS Experiment at the LH
Fri 2010–Sep–24 02:2
Run 146511 Event 5
C.O.M. Energ



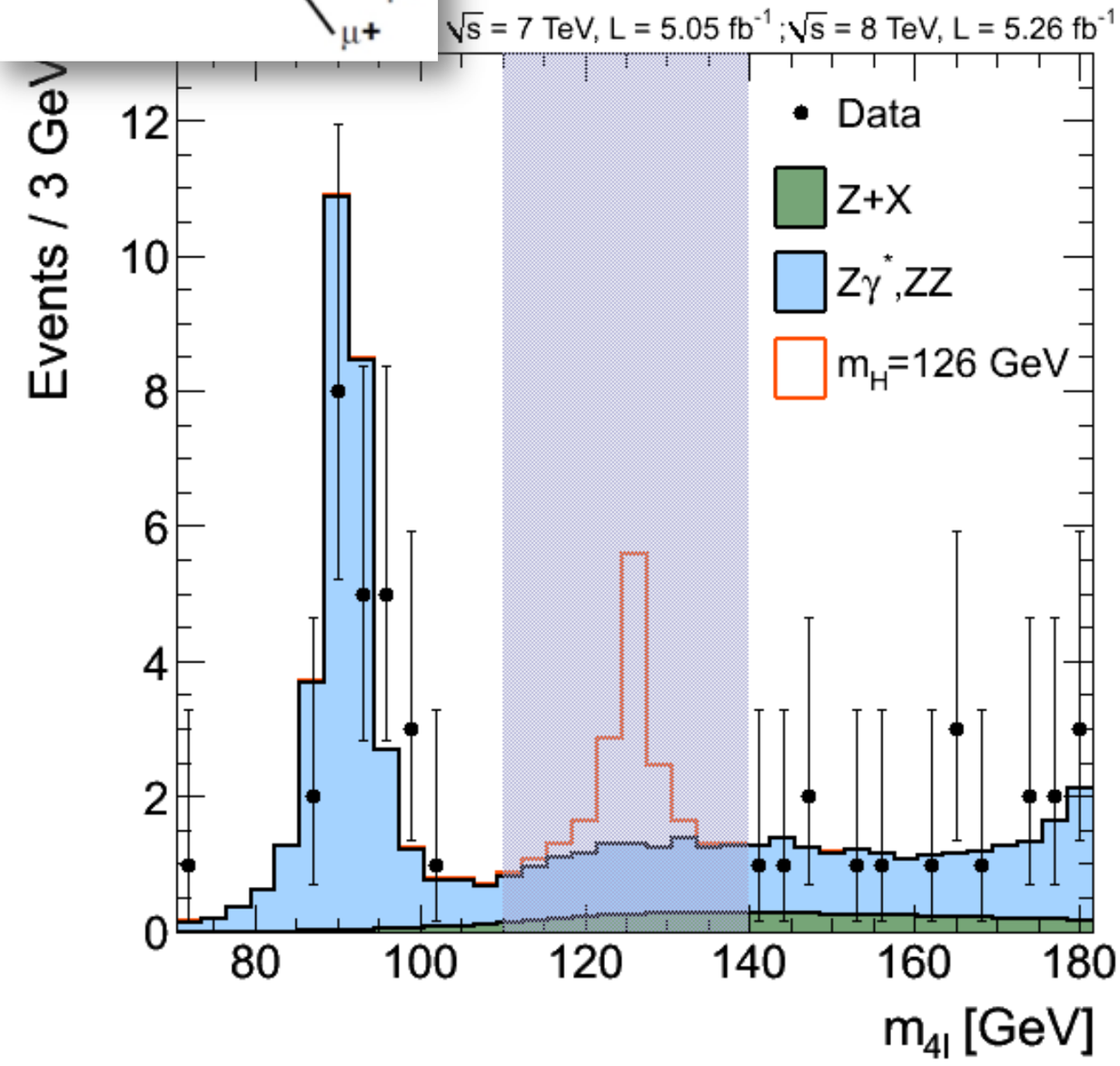
Analysis performed “blind”



Last year



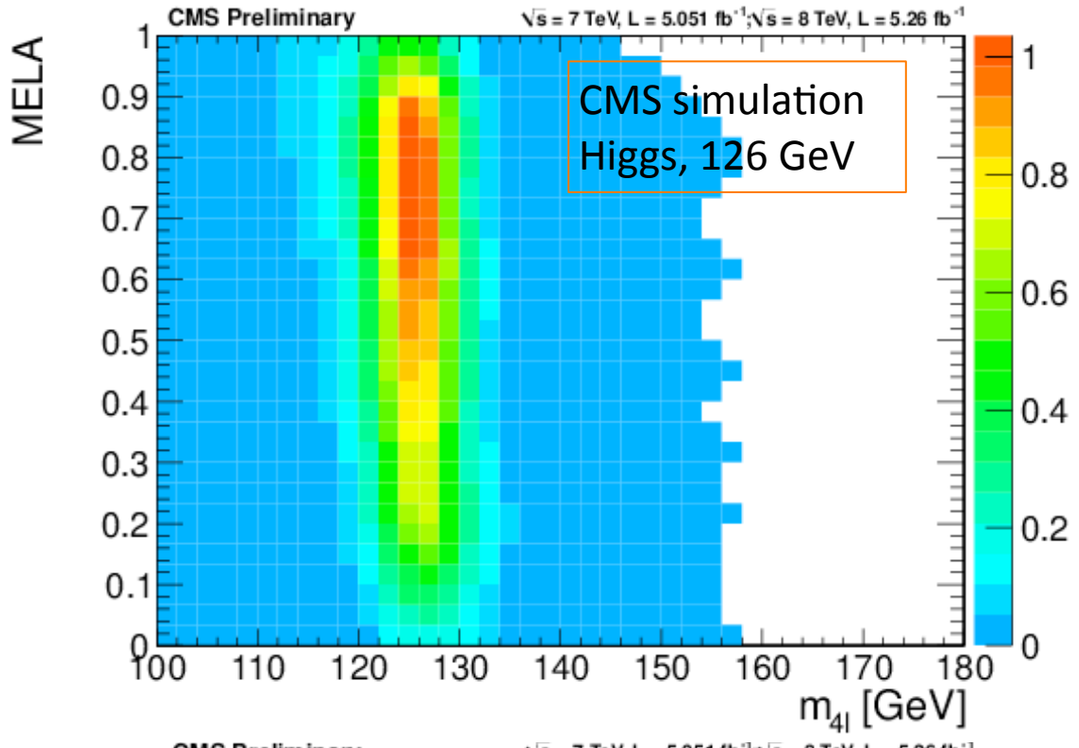
This year



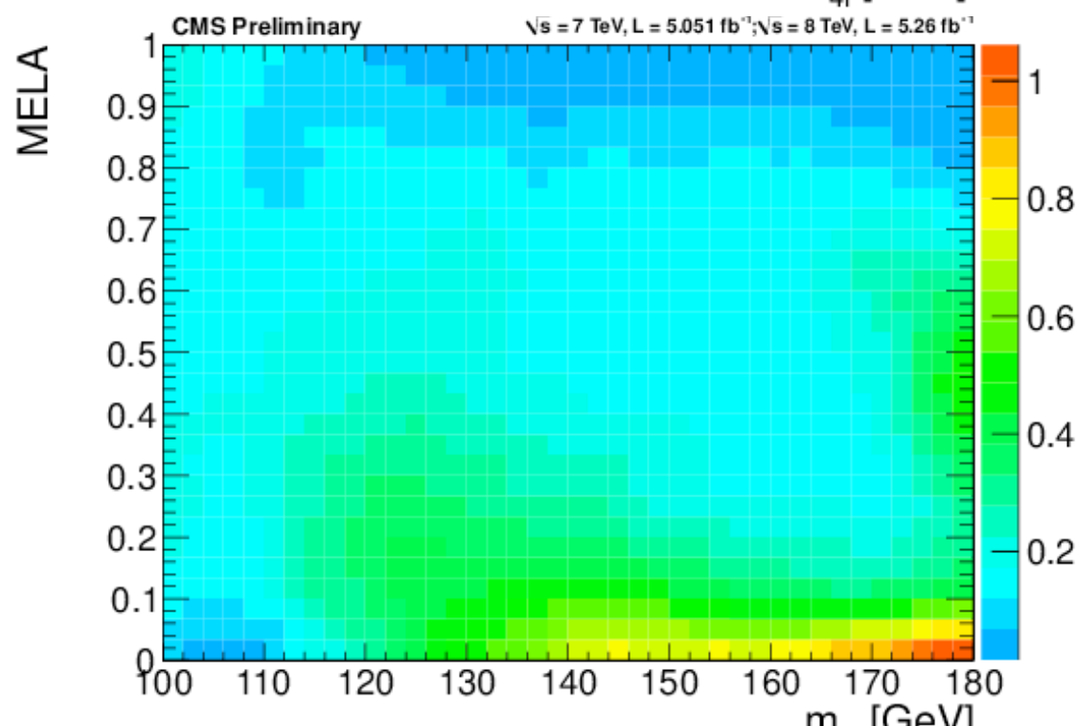
More information in data analysis

2D analysis using $\{m_{4l}, MELA\}$

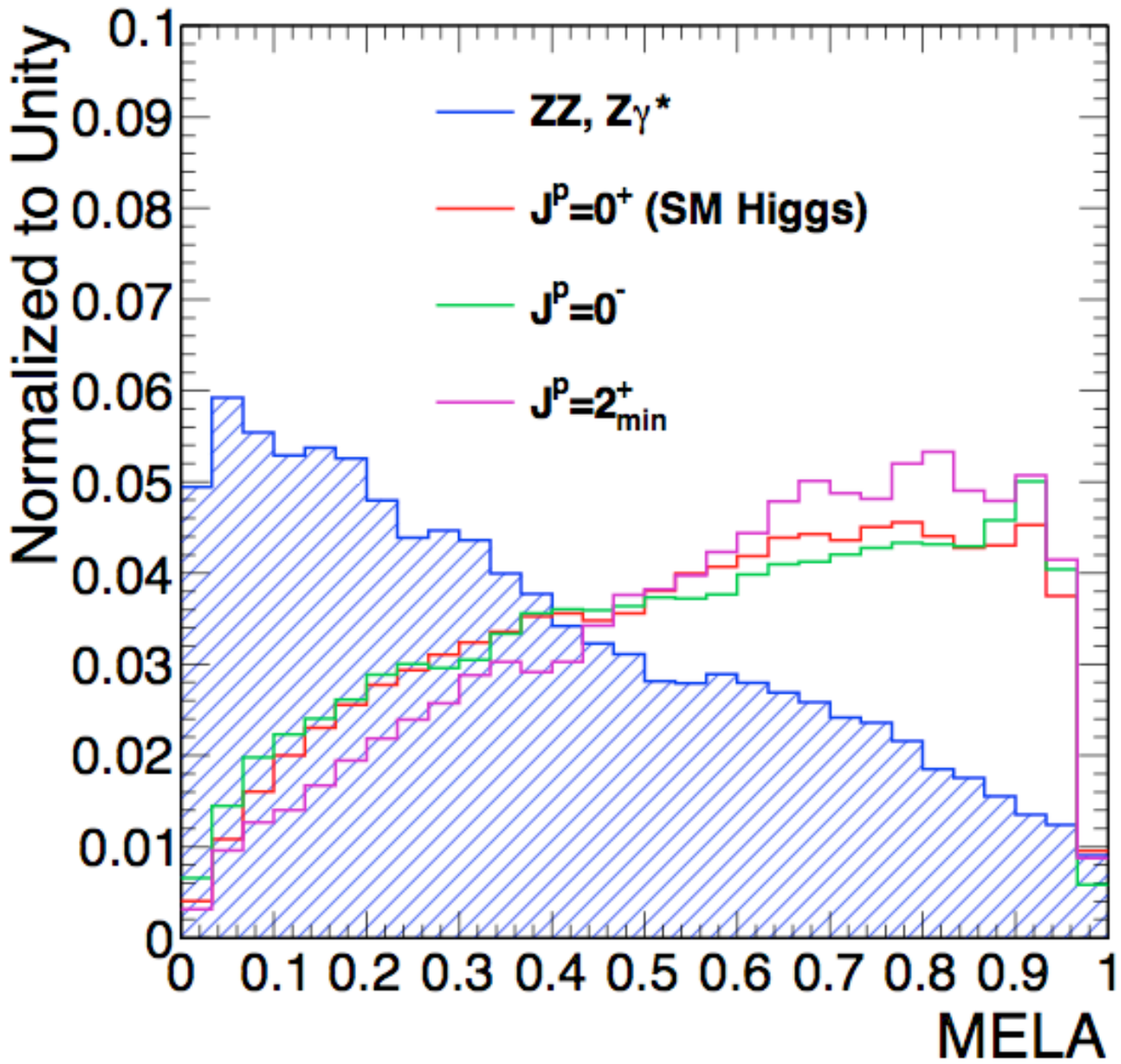
signal



background



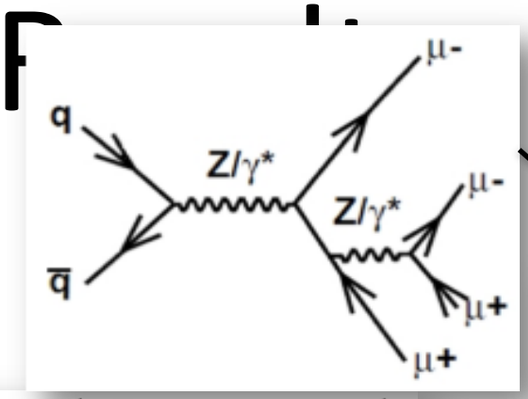
MELA offers powerful discrimination of background

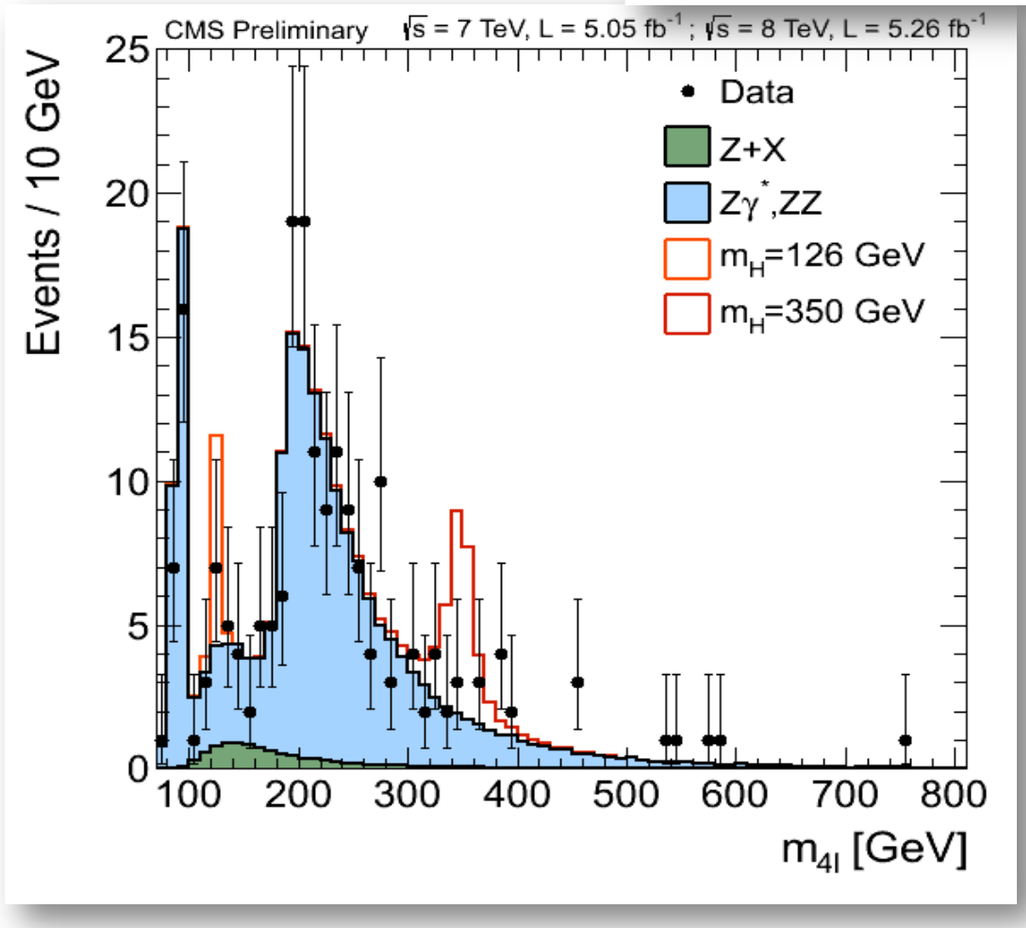


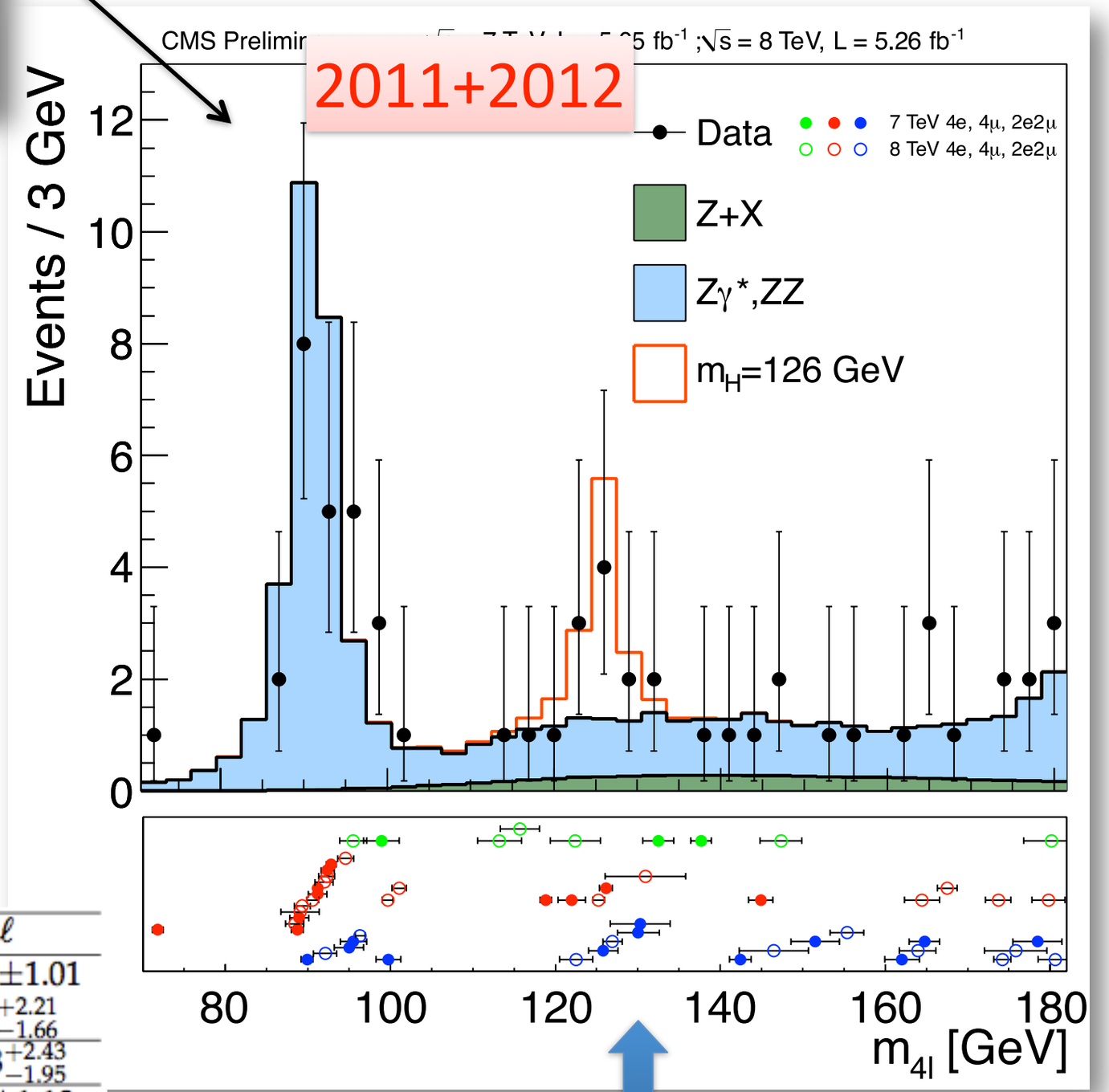
technique applicable for signal hypothesis testing

Blind until Thursday June 14

R…m(4l) spectrum







Yields for m(4l)=110..160 GeV

Channel	4e	4μ	2e2μ	4ℓ
ZZ background	2.65 ±0.31	5.65 ±0.59	7.17 ±0.76	15.48 ±1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ±0.48	2.99 ±0.60	3.81 ±0.89	8.31 ±1.18

164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

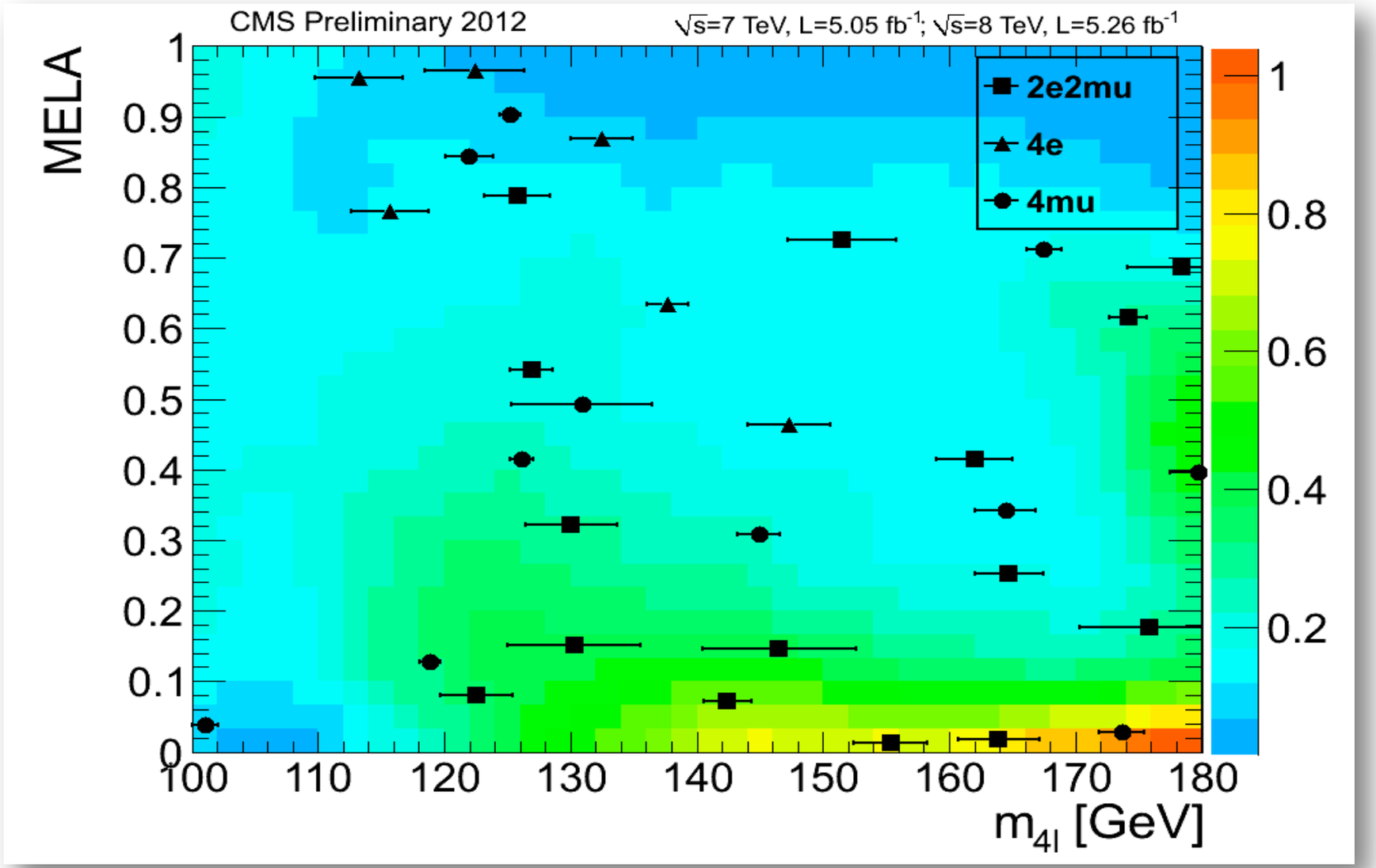
Event-by-event errors

Results: MELA 2D plots

Perform 2D fit

– MELA discriminant versus m_{4l}

- Data points shown with per-event mass uncertainties



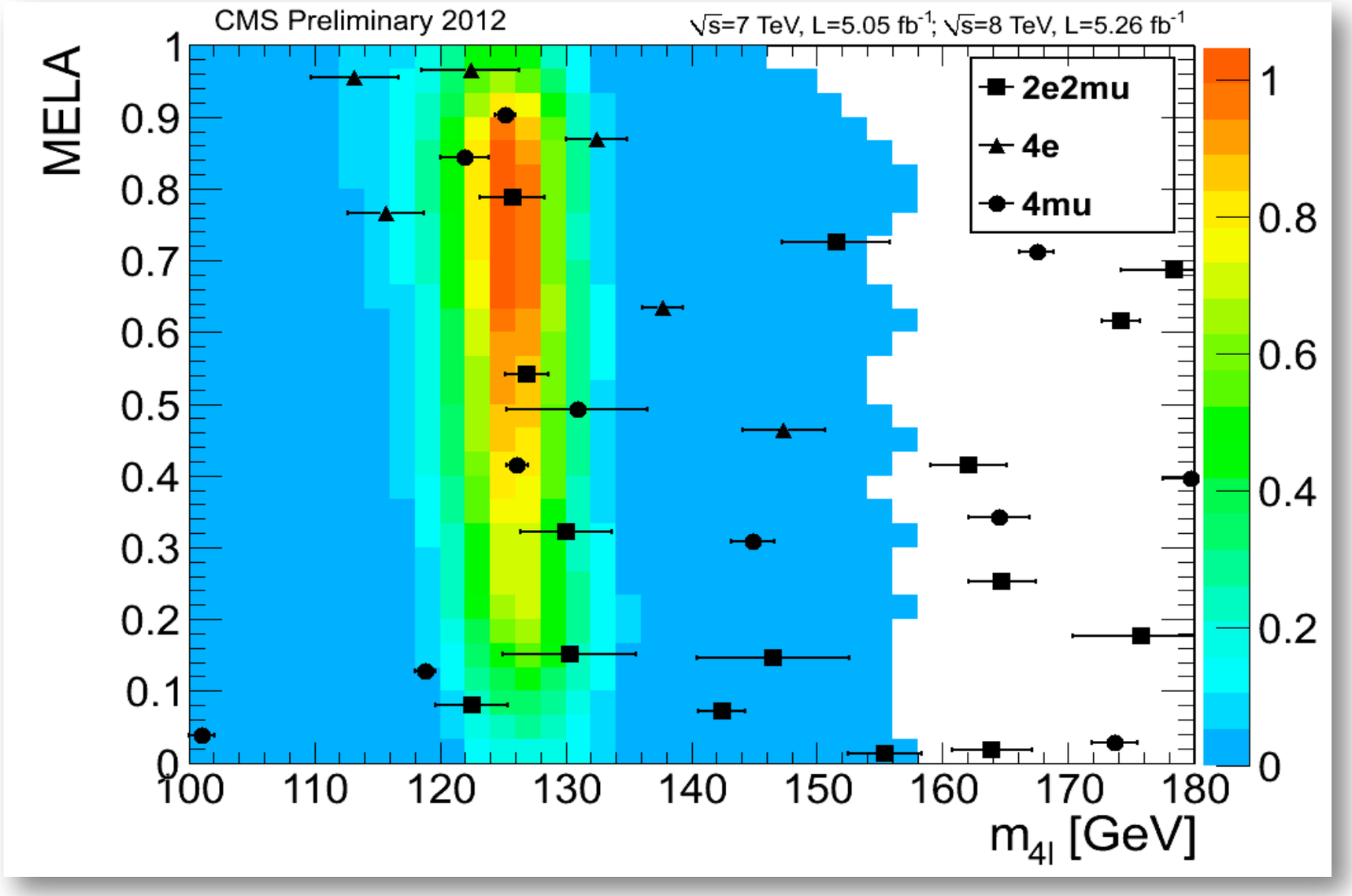
Data w.r.t. background expectation

Results: MELA 2D plots

Perform 2D fit

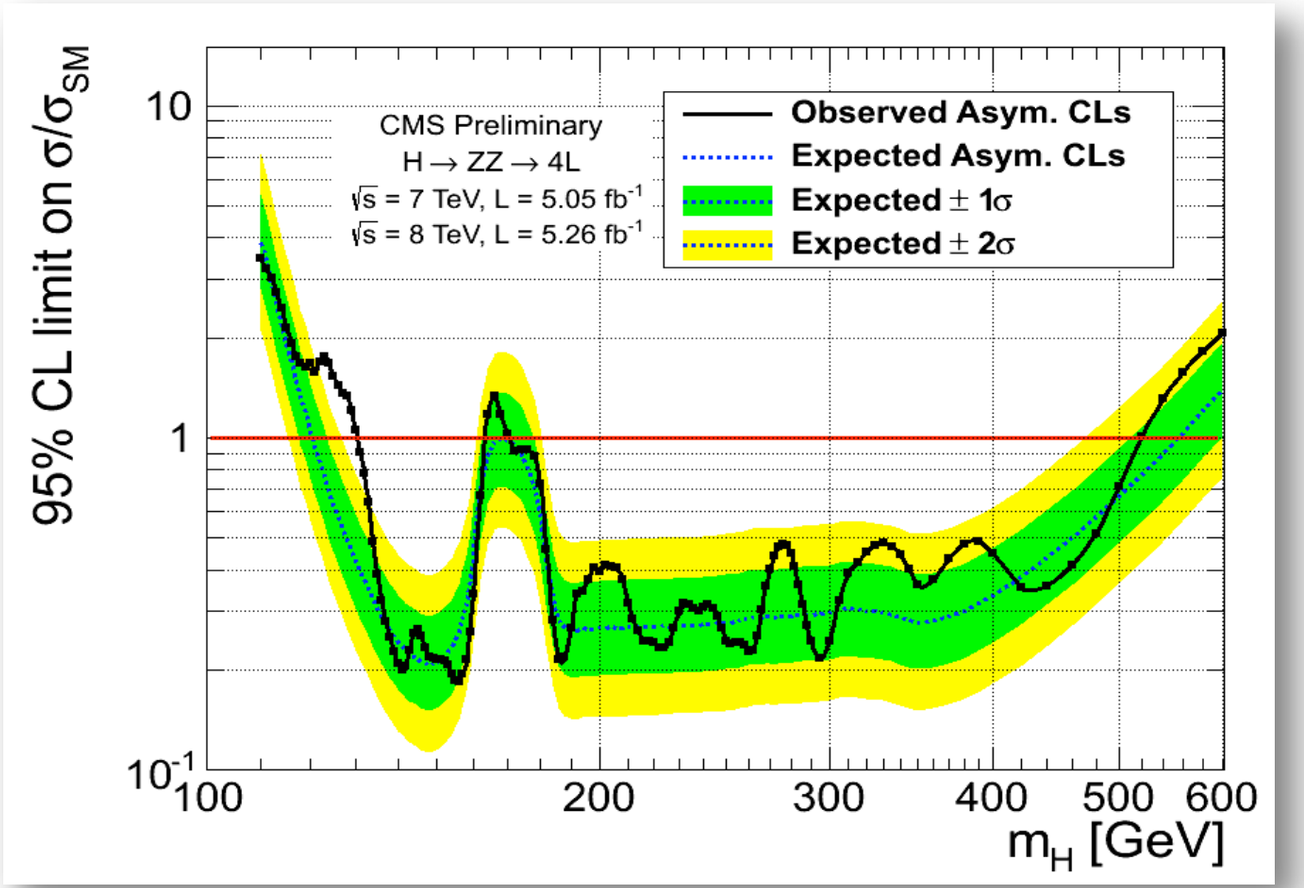
– MELA discriminant versus m_{4l}

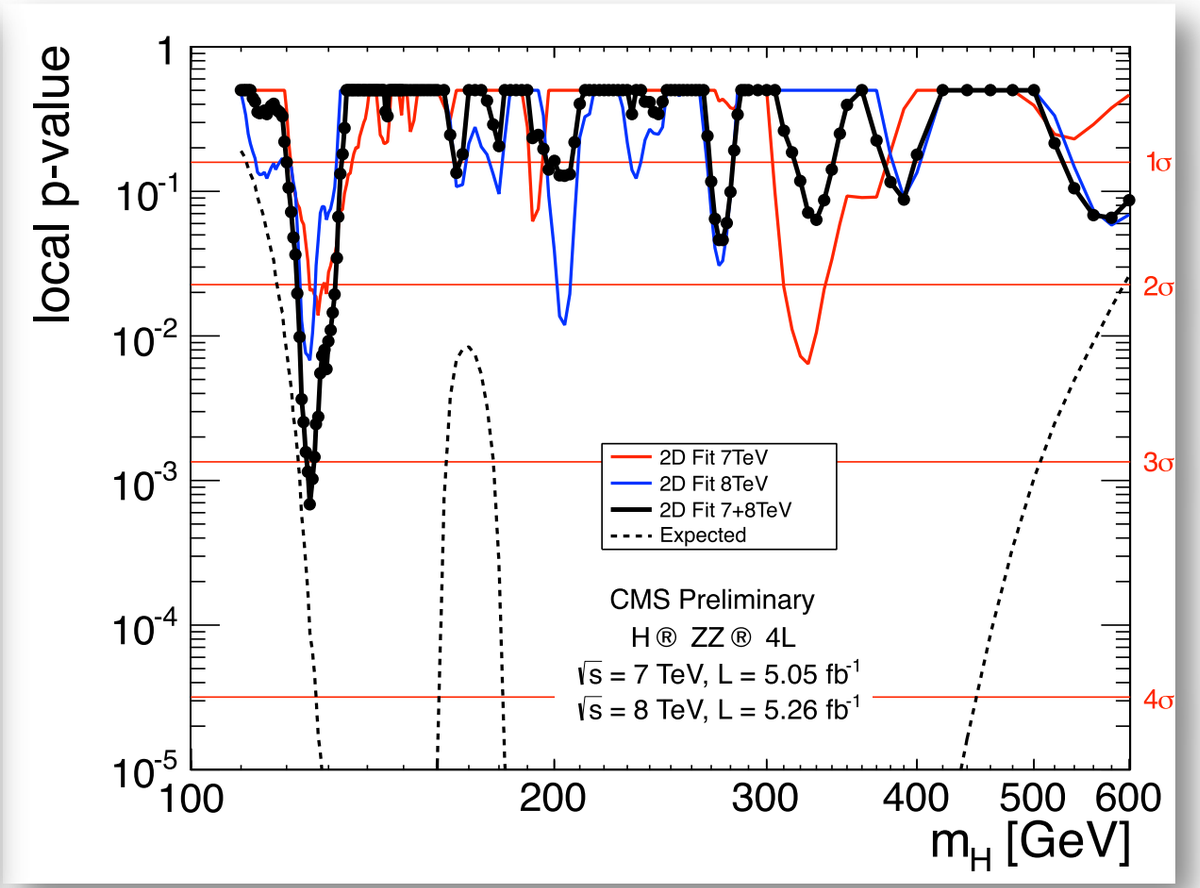
• Data points shown with per-event mass uncertainties



Data w.r.t 126 GeV Higgs Expectation

Limits and p-values





Expected exclusion at 95% CL :

121-550 GeV

Observed exclusion at 95% CL :

131-162 GeV and 172-530 GeV

Expected significance at 125.5 GeV :

3.8 σ

Observed significance at 125.5 GeV:

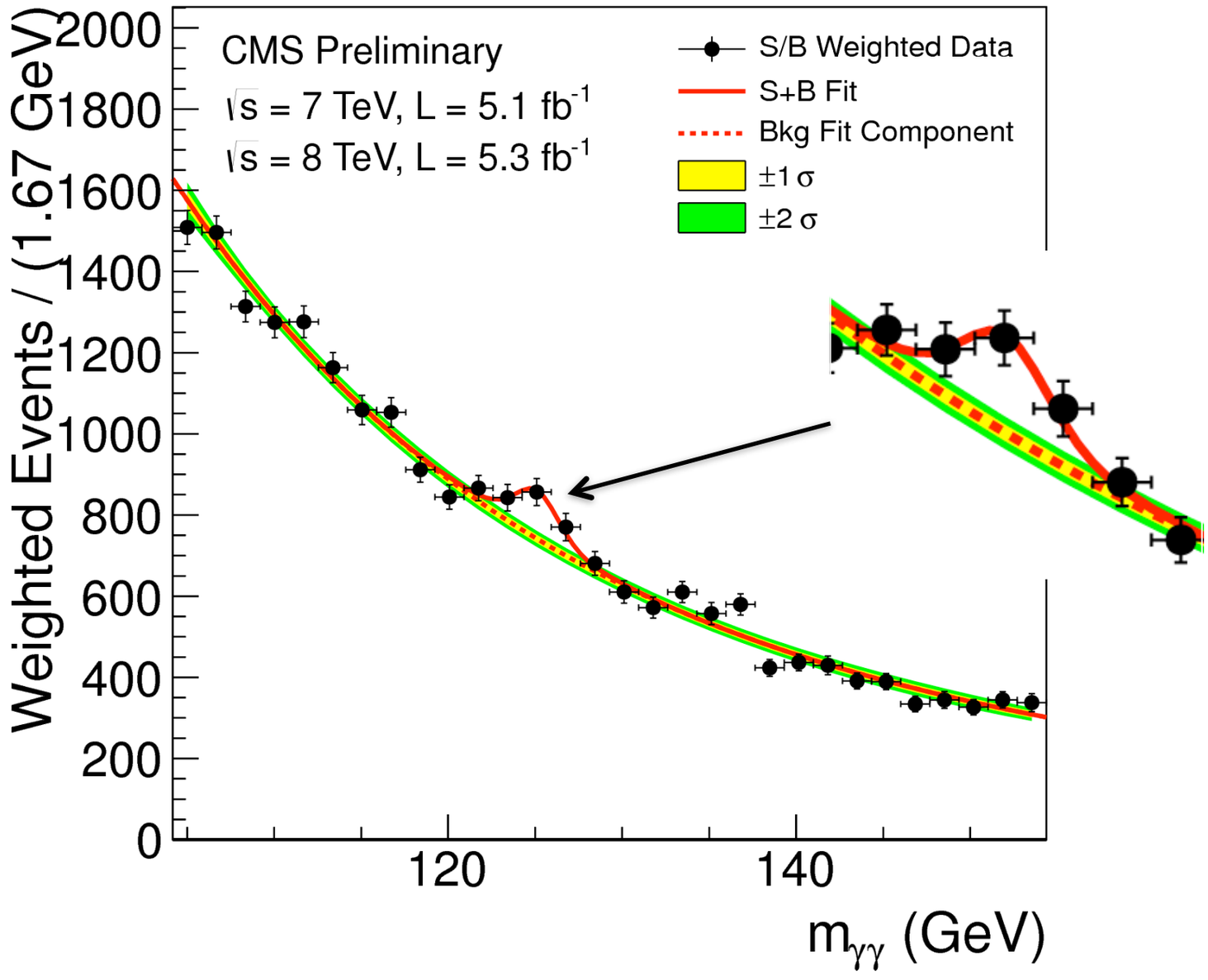
3.2 σ

CMS: H ➔ γγ

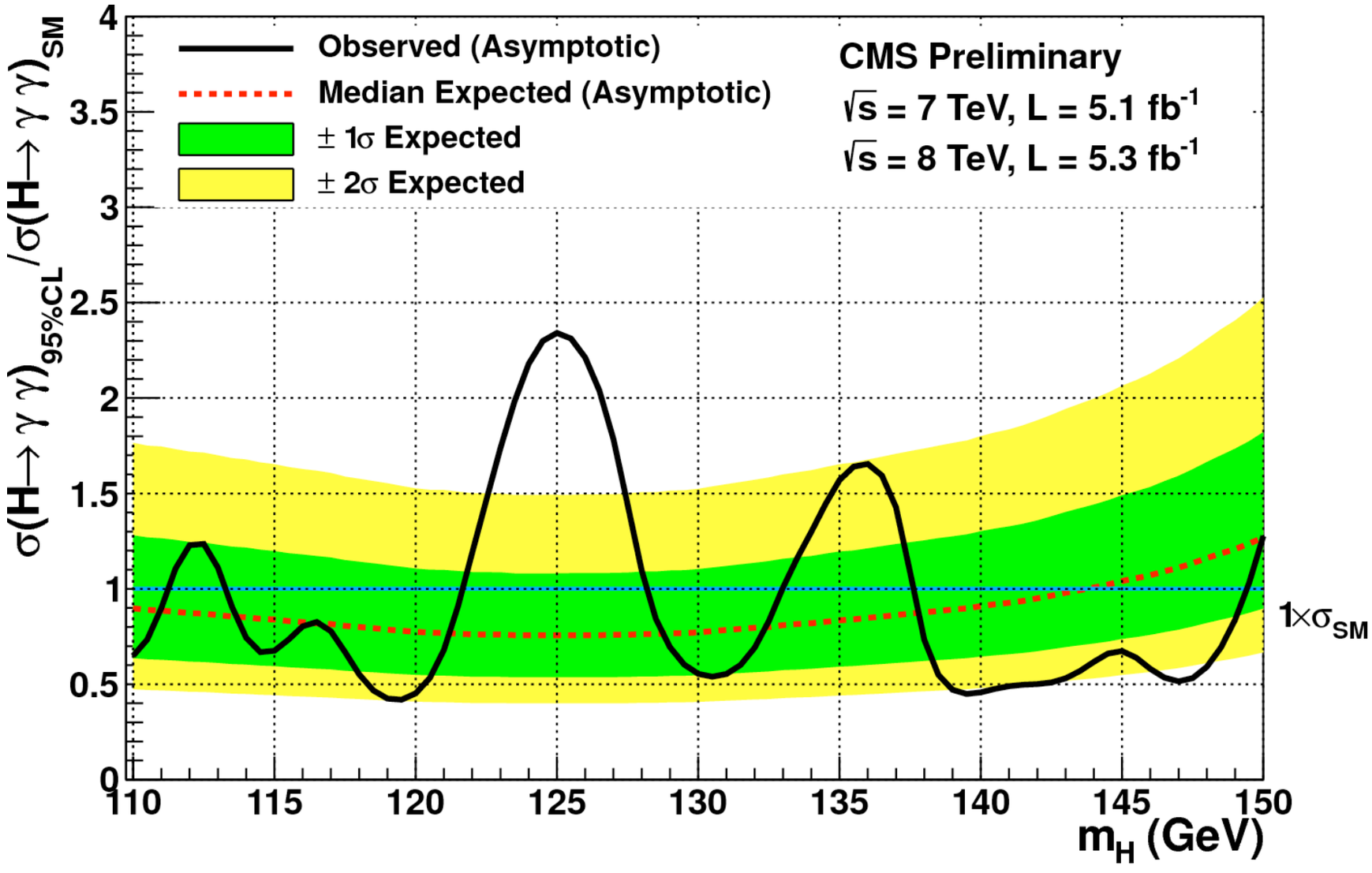
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval

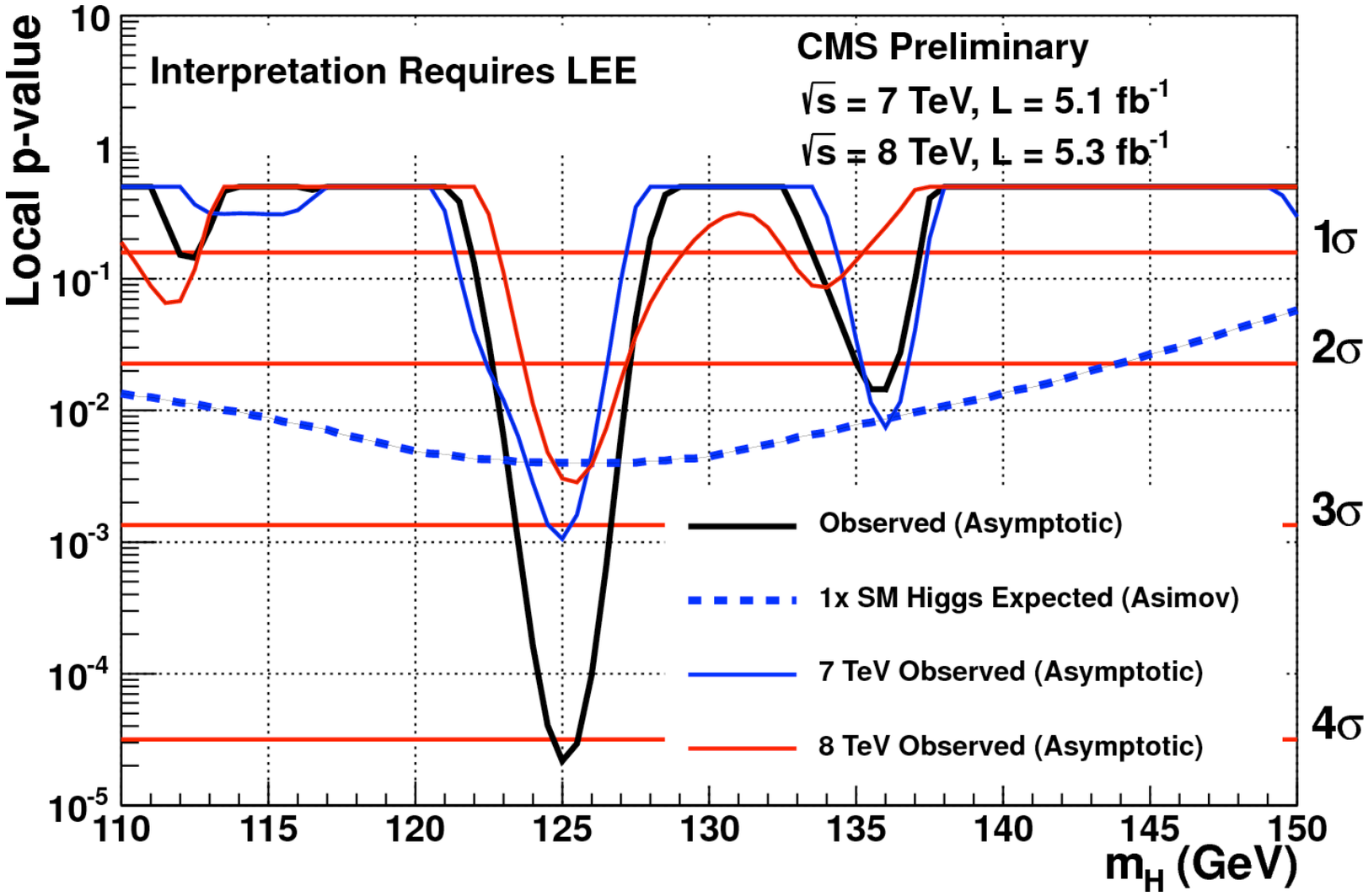


95% CL Exclusion for SM Higgs



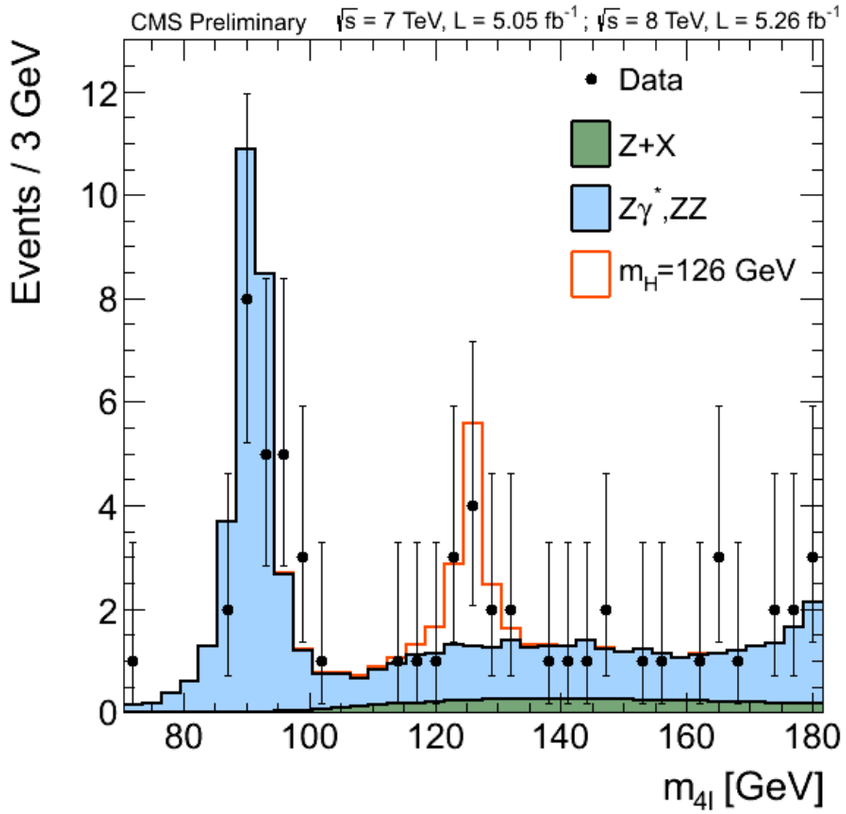
- Expected 95% CL exclusion 0.76 times SM at 125 GeV
- Large range with expected excusion below σ_{SM}
- Largest excess at 125 GeV

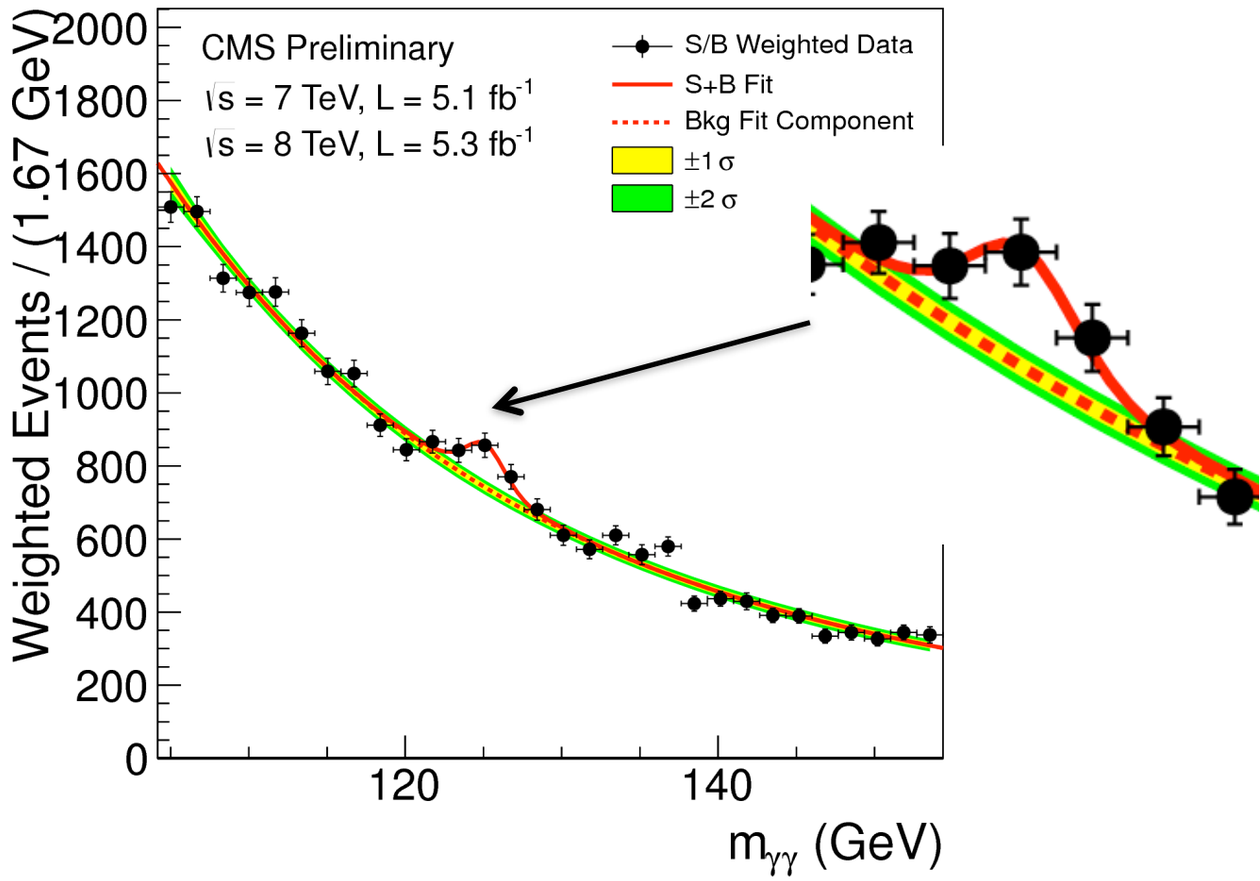
P-Values



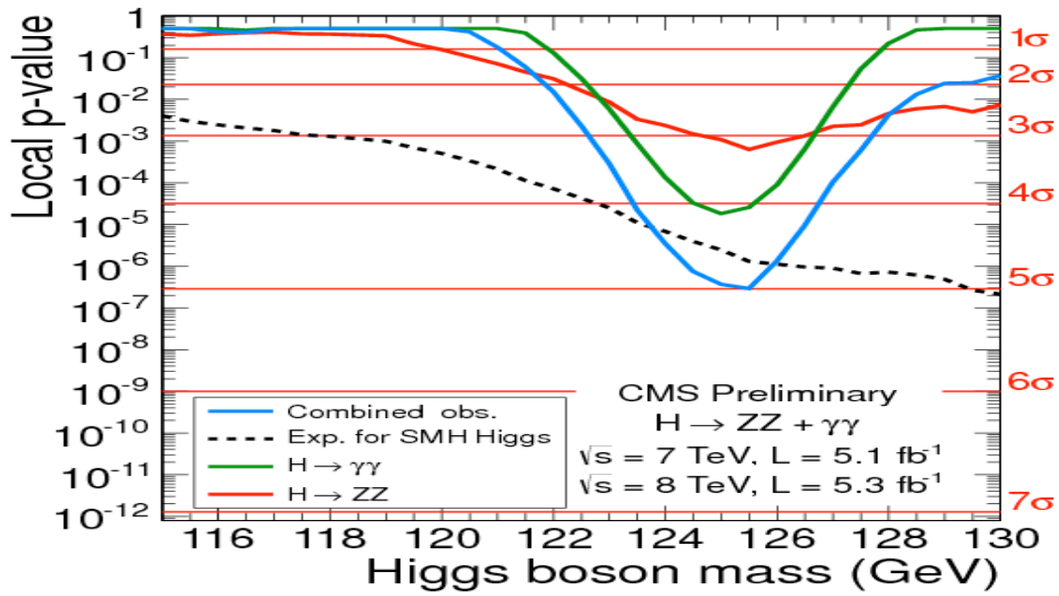
- Minimum local p-value at 125 GeV with a local significance of 4.1 σ
- Global significance in the full search range (110-150 GeV) 3.2 σ

Two channels ZZ and 2gamma combined

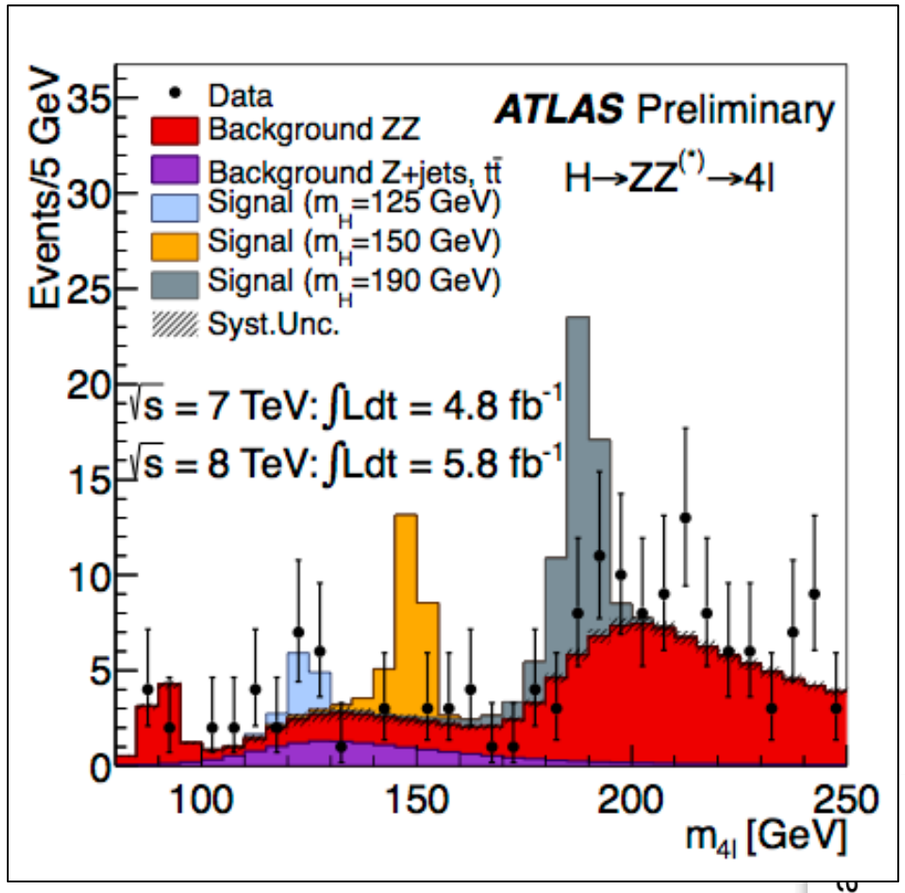


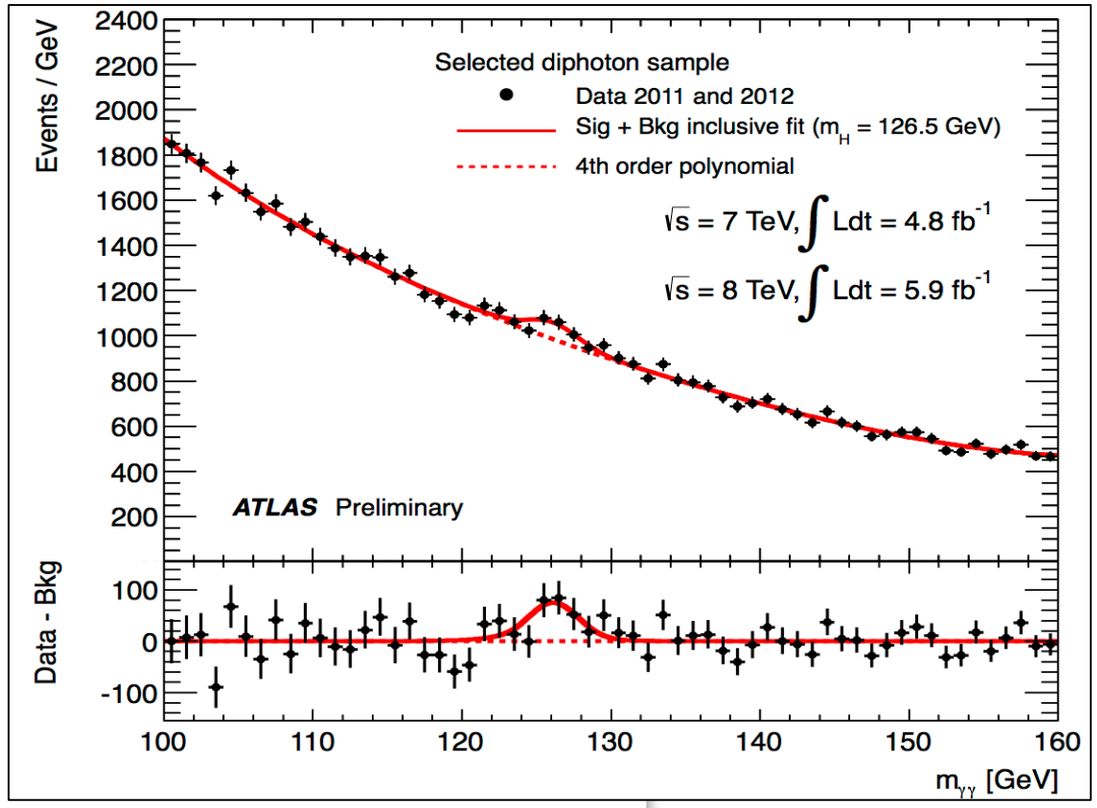


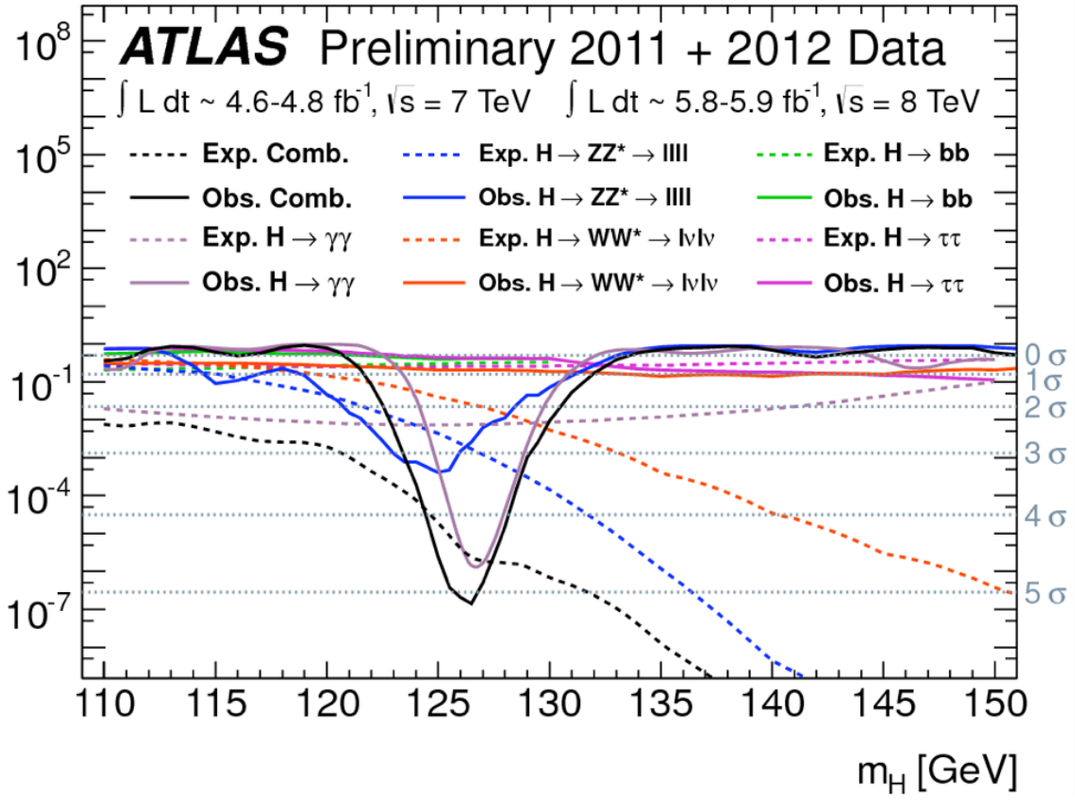
- **comb. significance: 5.0 σ**
- **Expected 4.7 σ**



The ATLAS experiment has it too







"All the News That's Fit to Print"

The New York Times

Late Edition
Today, sunny to partly cloudy, rather hot, high 92. Tonight, mostly clear, low 72. Tomorrow, mostly sunny, hot and humid, high 90. Weather map appears on Page B16.

VOL. CLXI . . No. 55,823

NEW YORK, THURSDAY, JULY 5, 2012

$2.50

Oil Backed Up, Iranians Put It On Idled Ships

Subterfuge at Tankers as Embargo Tightens

By THOMAS ERDBRINK and CLIFFORD KRAUSS

BANDAR ABBAS, Iran — The hulking tanker Neptune was floating aimlessly this week in the warm waters of the Persian Gulf, a fresh coat of black paint barely concealing its true identity as an Iranian ship loaded with hundreds of thousands of barrels of oil that no one is willing to buy.

The ship's real name was Iran Astaneh, and it was part of a fleet of about 65 Iranian tankers serving as floating storage facilities for Iranian oil, each one given a nautical makeover to conceal its origin and make a buyer easier to find. The Neptune had been floating there for a month, and local fishermen said there were two even larger tankers anchored nearby.

Iran, faced with increasingly stringent economic sanctions imposed by the international community to force it to abandon any ambitions to develop nuclear weapons, has been reluctant to reduce its oil production, fearing that doing so could damage its wells. But Iran has insufficient space to store the crude it cannot sell. So while it furiously works to build storage capacity on shore, it has turned to mothballing at sea.

"We have never seen so many just waiting around," said Rostam, a fisherman and smuggler

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

By JEREMY W. PETERS

WOLFEBORO, N.H. — Mitt Romney declared on Wednesday that President Obama's health care mandate was in fact a tax, shifting his campaign's characterization of the law and aligning himself with the conservative voices in his party.

Mr. Romney's remarks, made in a hastily arranged interview with CBS News on a national holiday, prompted renewed criticisms that he was willing to adjust his views for political expediency. Two days earlier, his chief spokesman and senior strategist had said that Mr. Romney did not believe the mandate should be called a tax.

Mr. Romney was already in the uncomfortable position of standing at odds with the dominant Republican Party message on health care: that President Obama was imposing a burdensome new tax on the middle class by requiring health insurance. His latest statement, while carrying the short-term risk of allowing his opponent to brand him a flip-

Physicists Find Elusive Particle Seen as Key to Universe

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

Date Night at the Zoo, if Rare Species Play Along

By LESLIE KAUFMAN

FRONT ROYAL, Va. — After cautiously sniffing the grass, three male cheetahs at the animal-breeding center here suddenly began running in frenzied circles. It was a sign that a female cheetah that normally lives in the yard was in heat.

Then one of the males let out a

THE ANIMAL LIFEBOAT
Barriers to Breeding

fore they mate. It turns out that familiarity can be a turnoff for cheetahs, too.

Finally, it was time to bring in the female. She seemed mystified by the male cheetah's eagerness and failed to assume a mating po-

thing but.

Eighty-three percent of those species in North American zoos are not meeting the targets set for maintaining their genetic diversity, the Association of Zoos and Aquariums reports. In the case of cheetahs, fewer than 20 percent of those in North American zoos have been able to reproduce.

Zoos must figure out how to

'I Think We Have It' Is Cheer of Day at Home of Search

By DENNIS OVERBYE

ASPEN, Colo. — Signaling a likely end to one of the longest, most expensive searches in the history of science, physicists said Wednesday that they had discovered a new subatomic particle

Seminar at CERN on July 4, 2012

CMS collaboration

What is Next

Discovery of a New Boson

- Major Discovery of the decade(s)
  new form of matter / energy (!)
- Still need to solve

  (1) dark matter
  e.g. lightest $\tilde{\chi}_1^0$

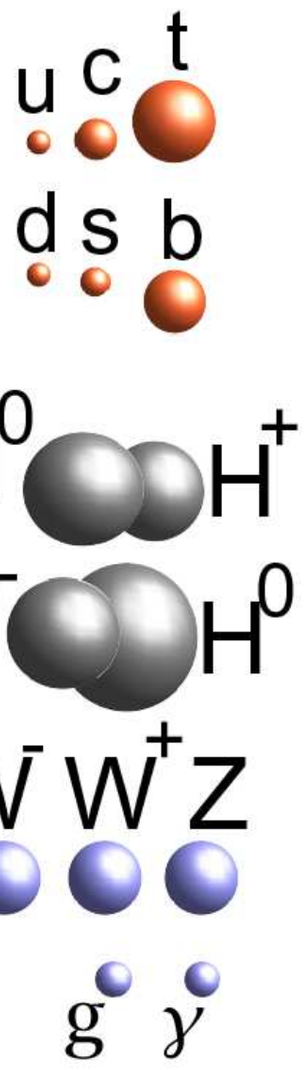
  (2) large CP phases (matter)
  and baryon violation

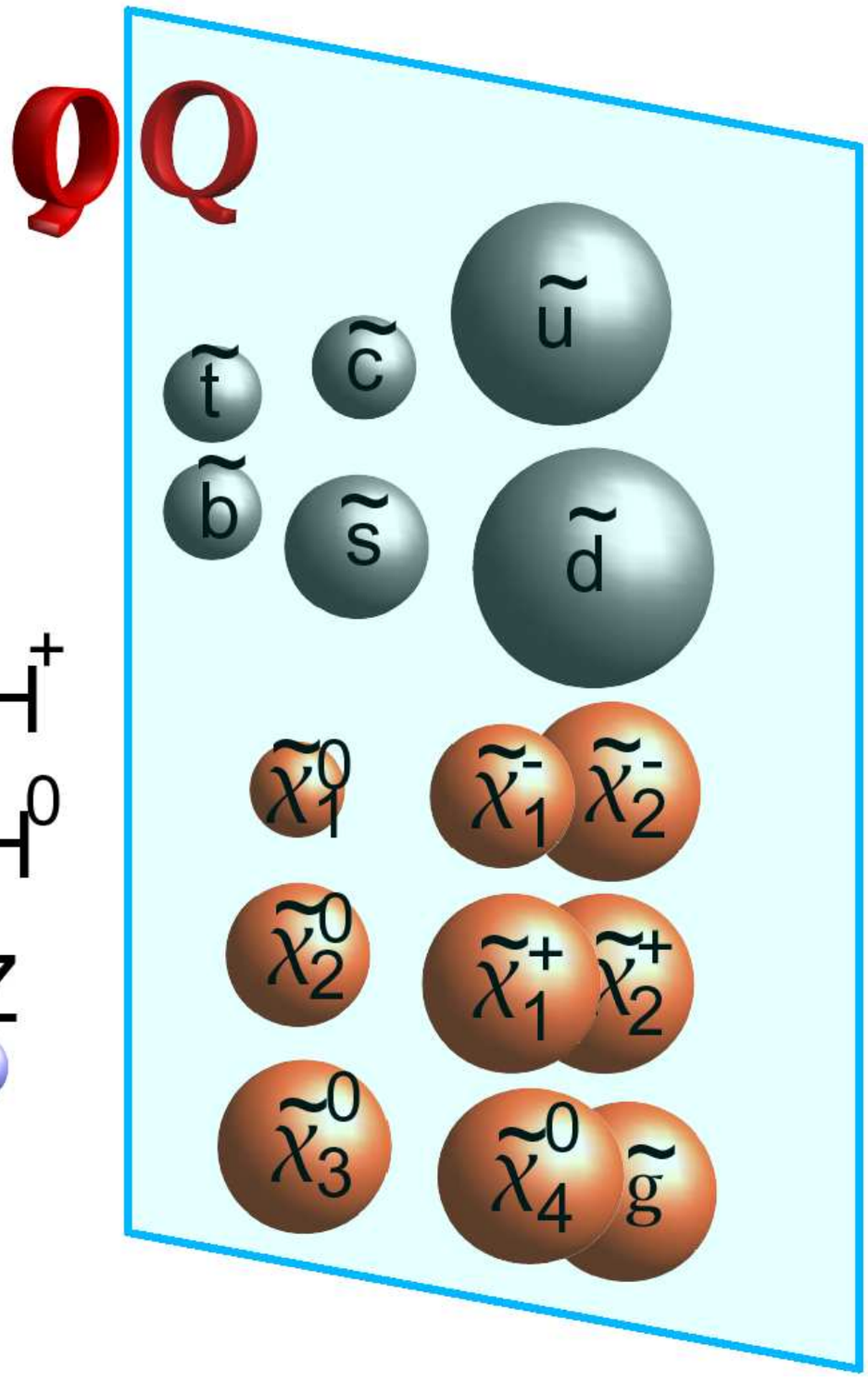
  (3) unification of forces ...

- Higgs may be beyond SM

  e.g. Supersymmetry:

  $Q|\text{fermion}\rangle = |\text{boson}\rangle$
  $Q|\text{boson}\rangle = |\text{fermion}\rangle$



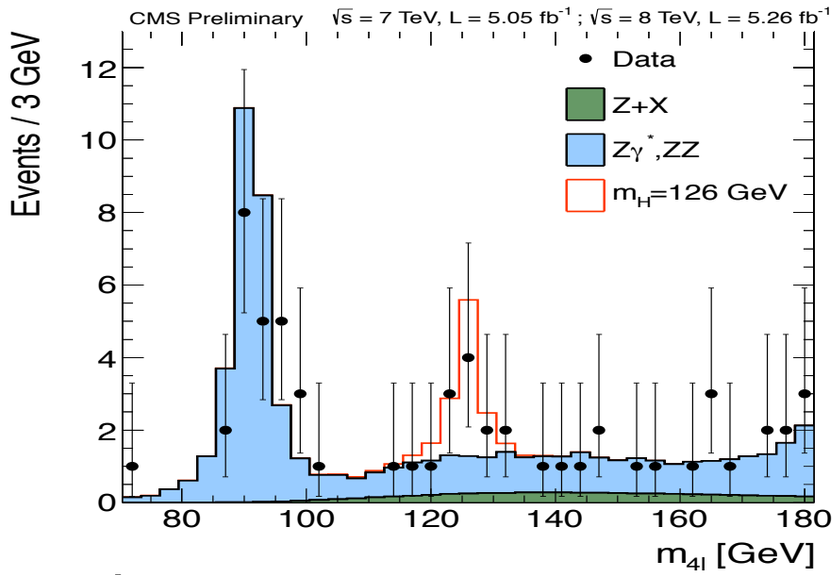


- Study properties of Higgs ! (angular analysis: J^P, couplings,..)

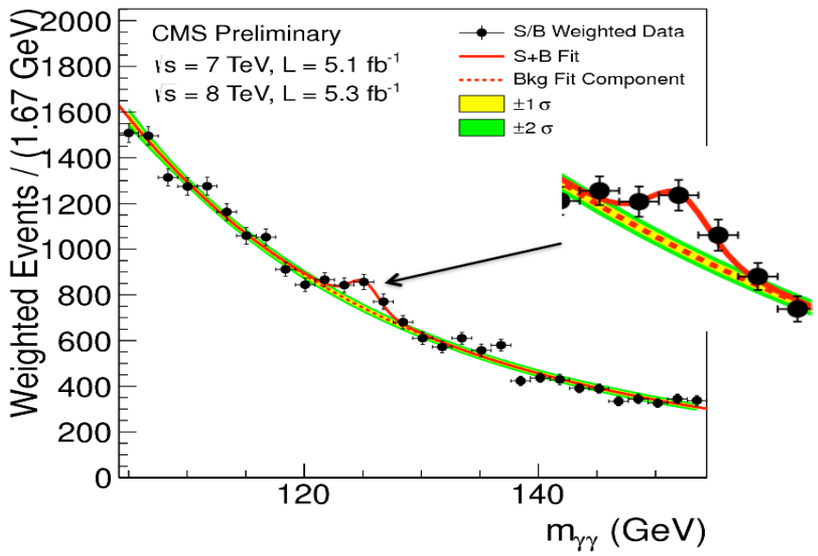
Discovery of a New Boson "X"

- Major Discovery of the decade(s), CMS example here:

$X \to Z^{(*)}Z^{(*)}$



$X \to \gamma\gamma$



- What we know:
  - it is a boson, spin$\neq$1 $\Rightarrow$ spin $=$ 0 or 2... (nothing like this before)
  - it couples to vector bosons (spin-1)
- What we do not know:
  - if it is the Higgs boson
  - if it couples to Fermions (matter)
  - if it is a tip of an Iceberg of new exciting states of matter / energy