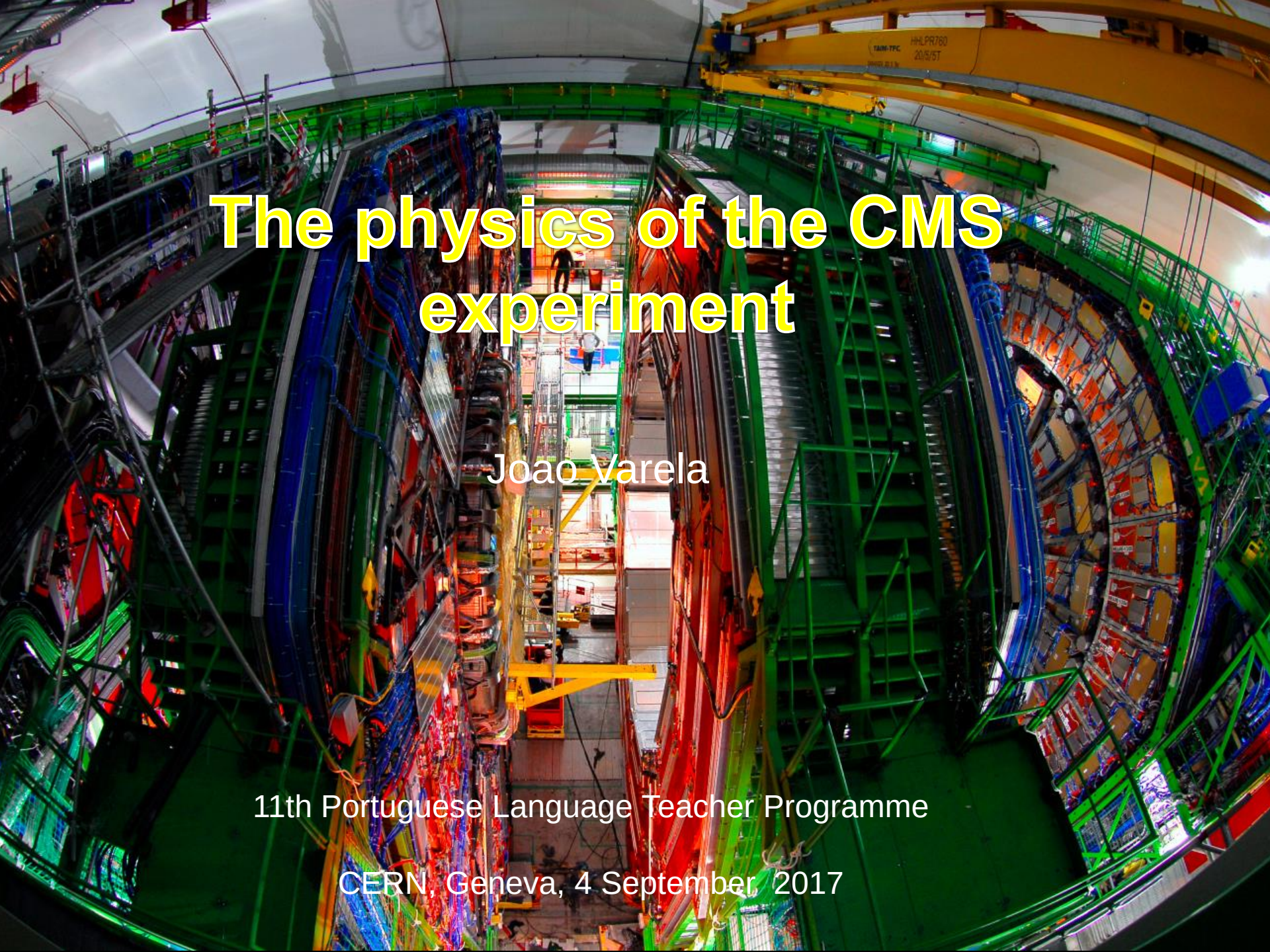


The physics of the CMS experiment

Joao Varela

11th Portuguese Language Teacher Programme

CERN, Geneva, 4 September 2017

Outline of the lecture

The LHC physics case

The CMS experiment

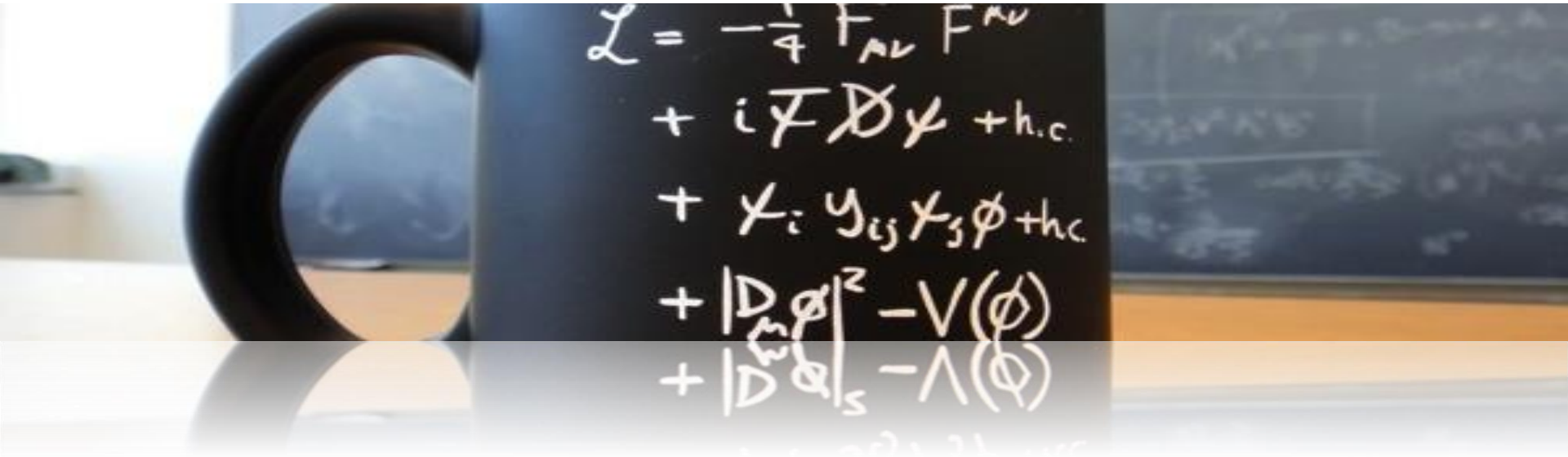
Experimental challenges

The Higgs discovery

Unsolved mysteries

The future

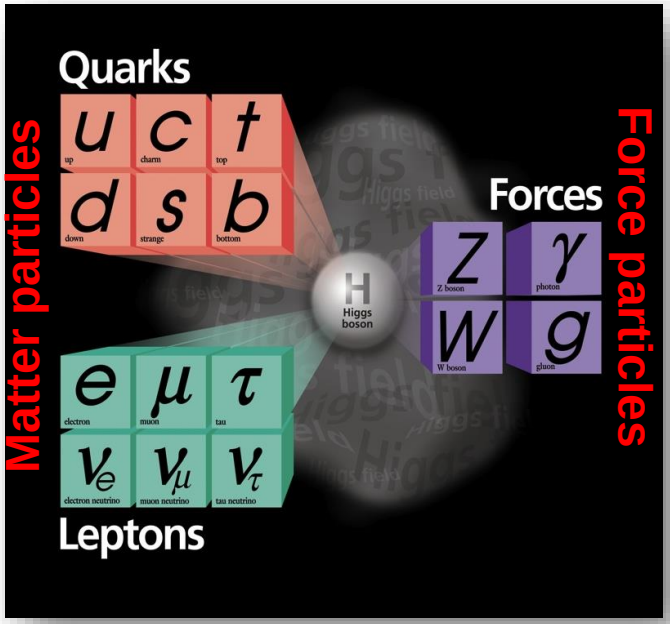
The LHC physics case



The Standard Model

Over the last ~100 years: The combination of Quantum Field Theory and discovery of many particles has led to

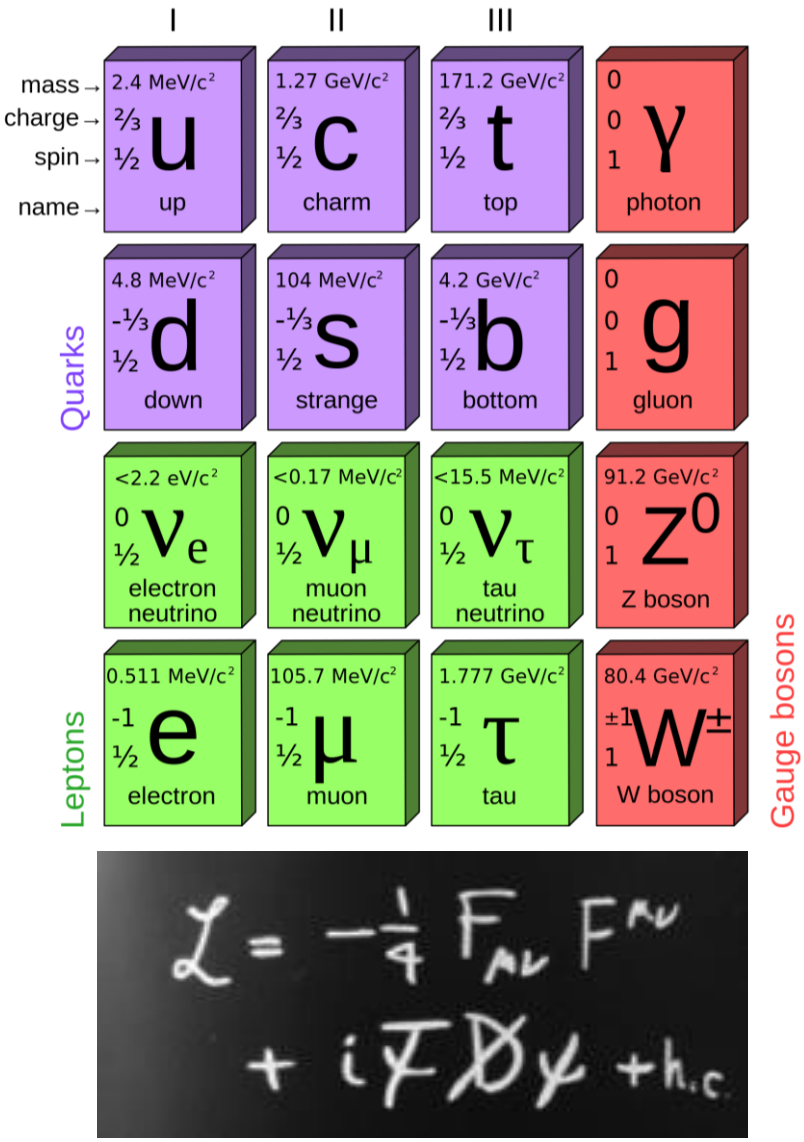
- The Standard Model of Particle Physics
  - With a new "Periodic Table" of fundamental elements



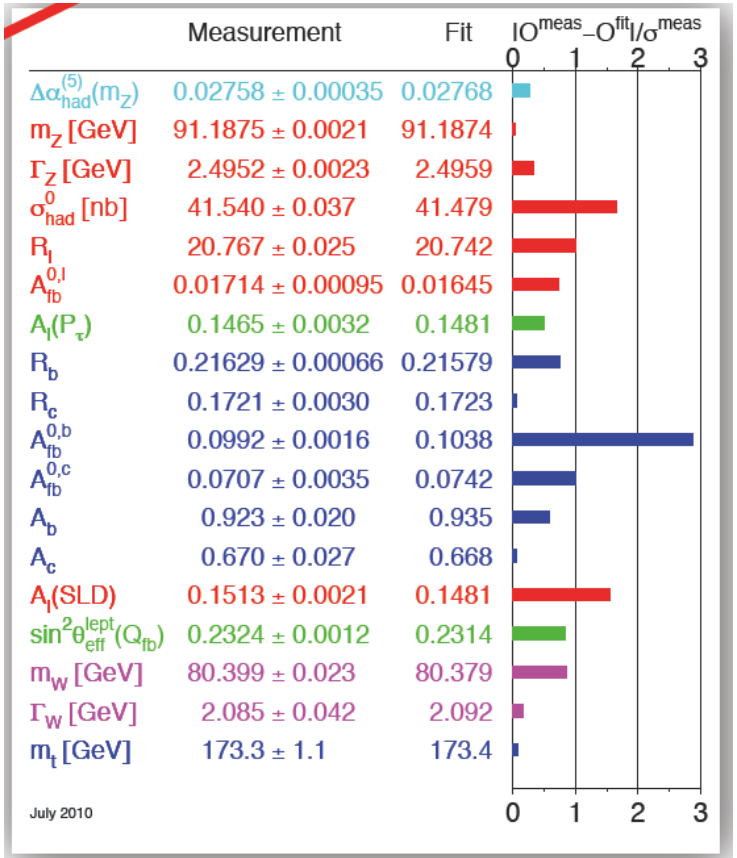
One of the greatest achievements of 20th Century Science

$$L_H = \frac{1}{2}(\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4}H^4 + \frac{g^2}{4}(W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) + \sum_{l,q,q'}(\frac{m_l}{\lambda}\bar{l}l + \frac{m_q}{\lambda}\bar{q}q + \frac{m_{q'}}{\lambda}\bar{q}'q')H$$

SM confirmed by data



STANDARD MODEL OF ELEMENTARY PARTICLES

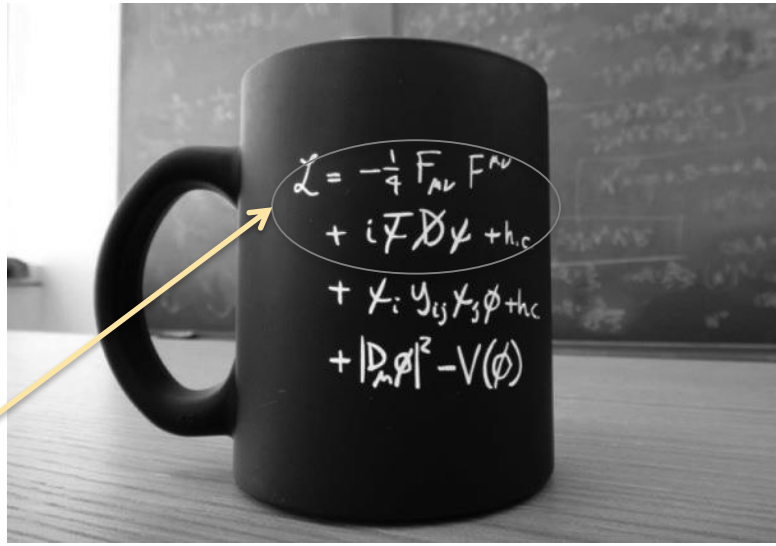


Confirmed at sub 1% level!

Electroweak unification

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

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



The equations of this model would imply that **all particles have zero mass**

In reality:

Electromagnetic interaction:

Photon (γ) m=0

Weak interaction:

Bosons W e Z m~80-90 GeV

Different masses of γ, W and Z **break the symmetry**

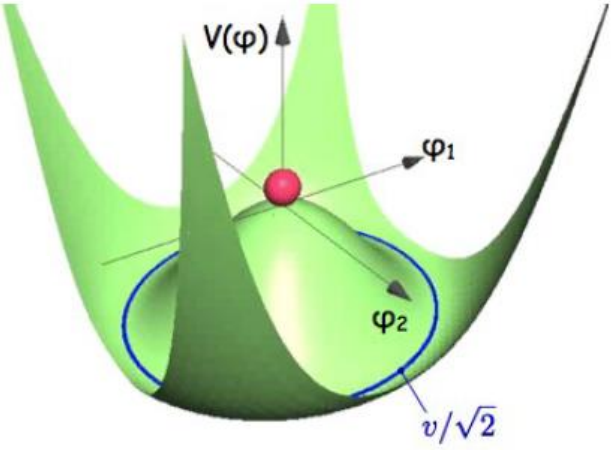
What's missing?

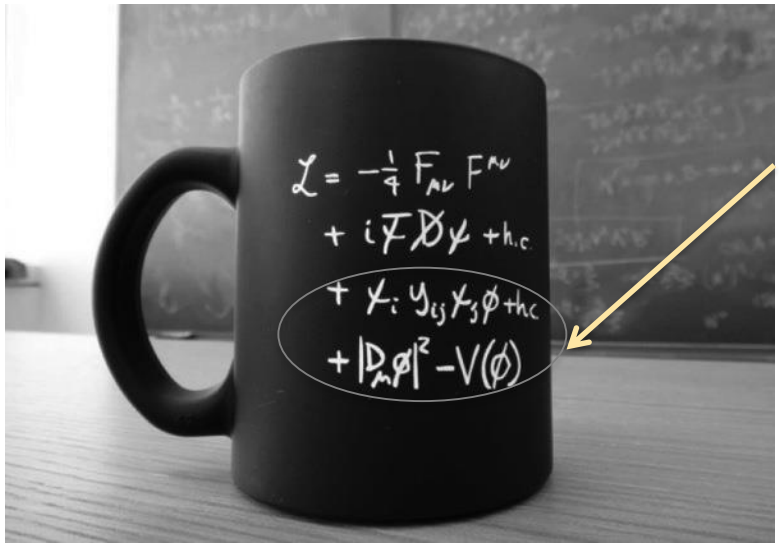
A "funny" thing happened on the way to the modern theory of quarks, leptons, force fields, and their quanta:

The equations only made sense if all the bosons, and all the quarks and leptons, had no mass and moved at the speed of light!

The Higgs mechanism

Breakthrough ideas to allow non-zero masses, known as the **"Higgs mechanism"**, came from many directions in the 1960's:
Englert-Brout, Higgs
Guralnik-Hagen-Kibble





Higgs field in the equations:

- The Higgs field permeates the space of the whole Universe;
- The field has a non-zero value in the energy minimum;
- Particles get mass through the interaction with the Higgs field.

The Higgs field breaks the symmetry

Mass of W and Z results from the interactions with the Higgs field

The symmetry between the electromagnetic and the week interactions is broken:

- Photon do not have mass
- W, Z do have a mass ~ 80-90 GeV

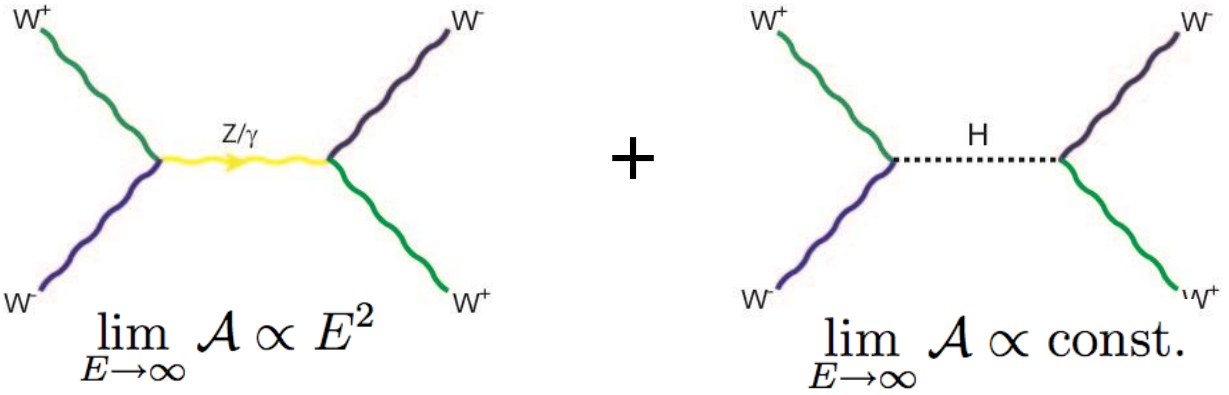
Non-zero average value of the Higgs field can also give masses to the quarks, electrons and muons – to all point-like particles.

Promise of new physics at 1 TeV

Old theoretical problem affecting the quantum theory of the weak force :

the probability of two W's interacting becomes larger than 1 at high energies (> 1 TeV).

This is solved by the Higgs field!



The Terascale and the LHC

The Standard Model would fail at high energy without the Higgs particle or other ‘new physics’.

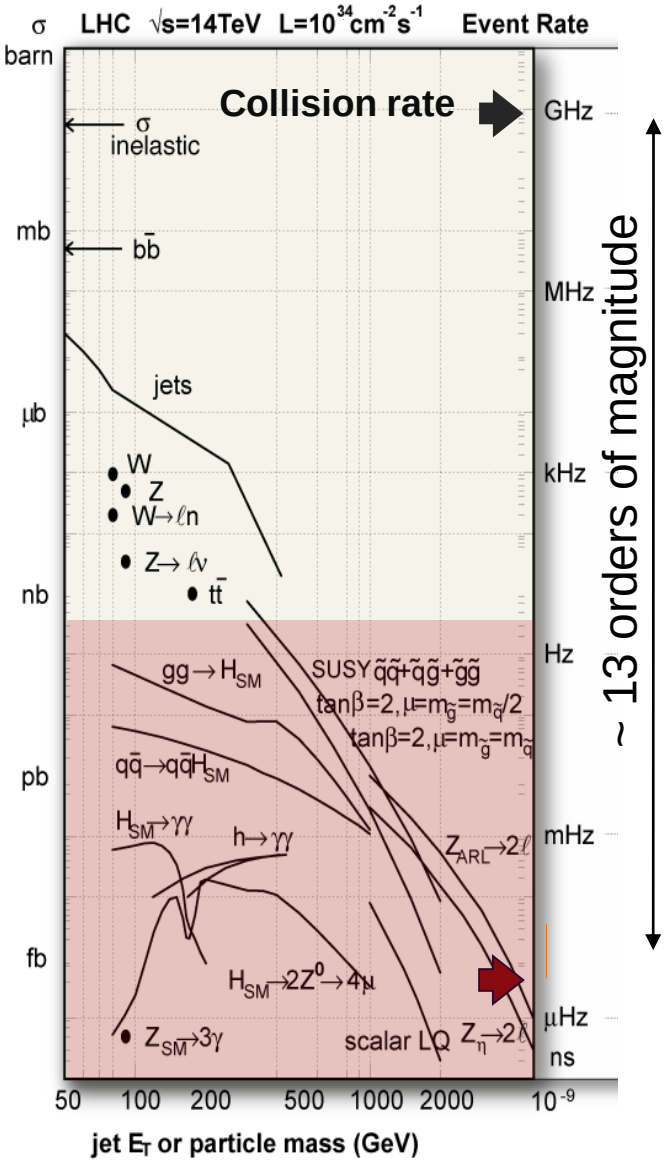
It was expected that the **‘new physics’** would manifest at an energy around

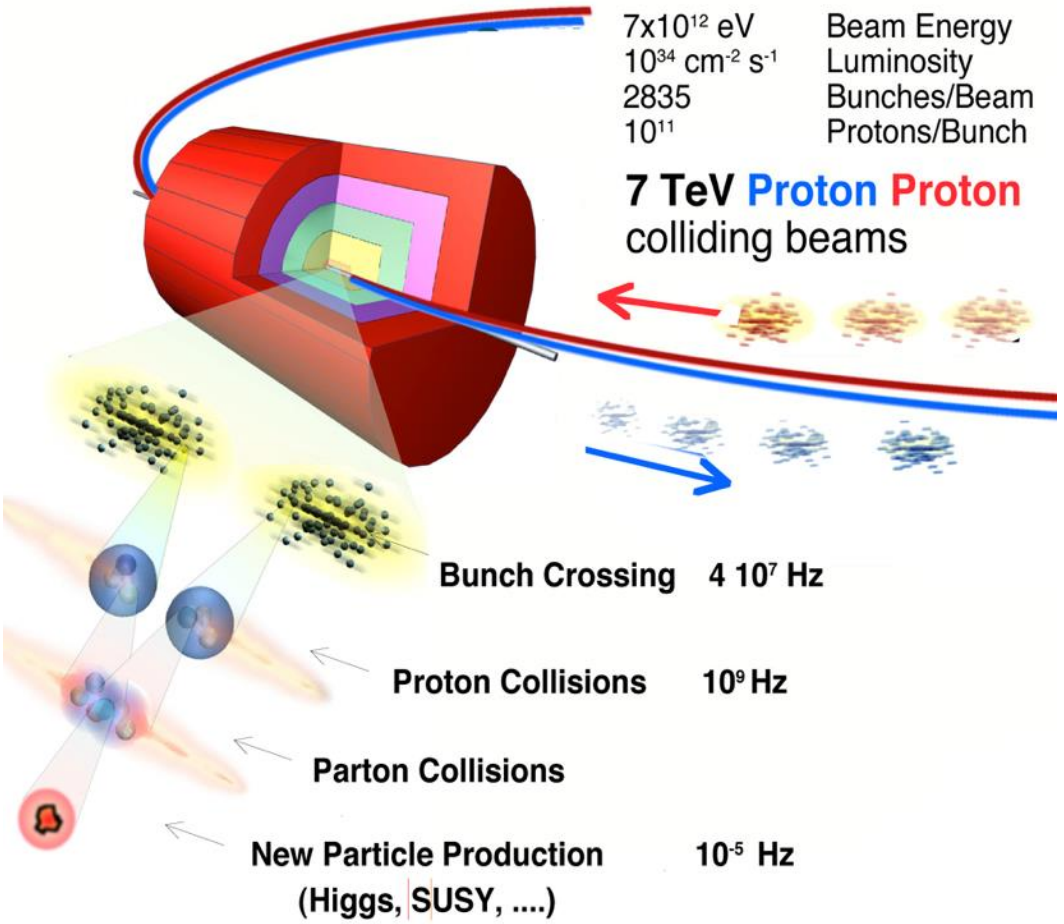
1 Tera-electronVolt (TeV) = 10^{12} electronVolt (eV)

accessible at the LHC for the first time.

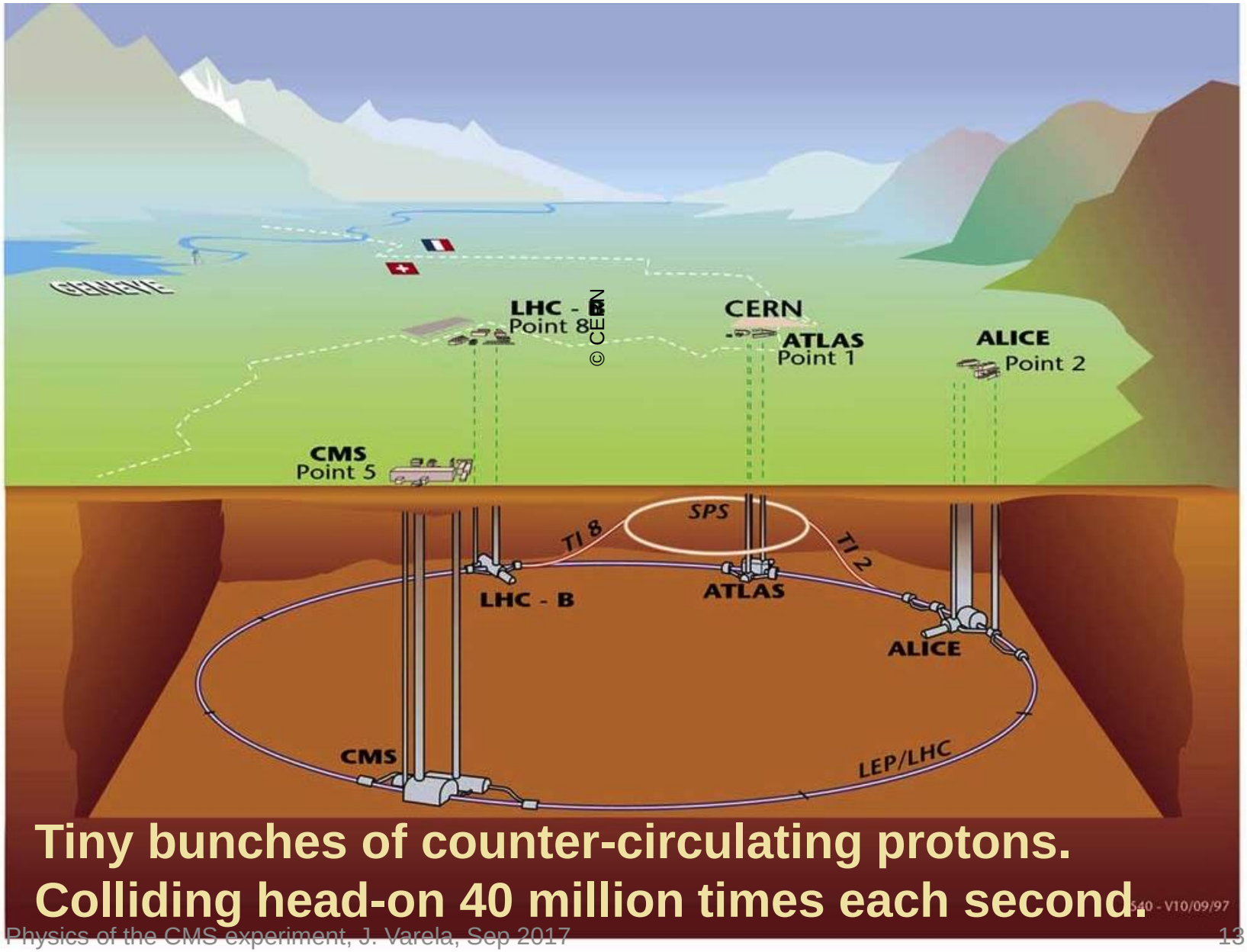
The SM does not predict the Higgs mass, but the model would also fail if $m_H > 1$ TeV.

Proton collisions at LHC

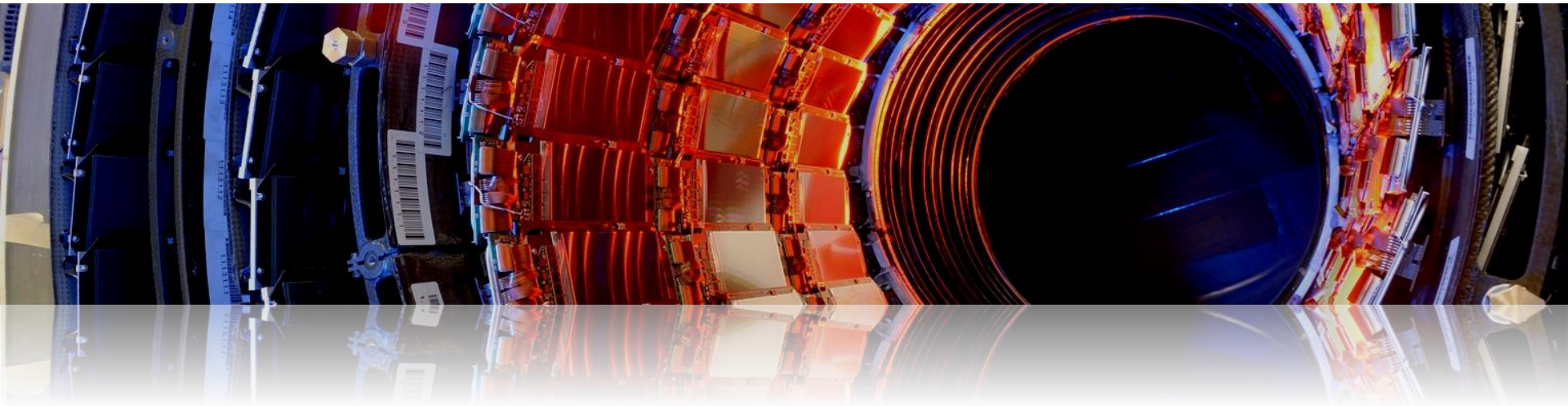


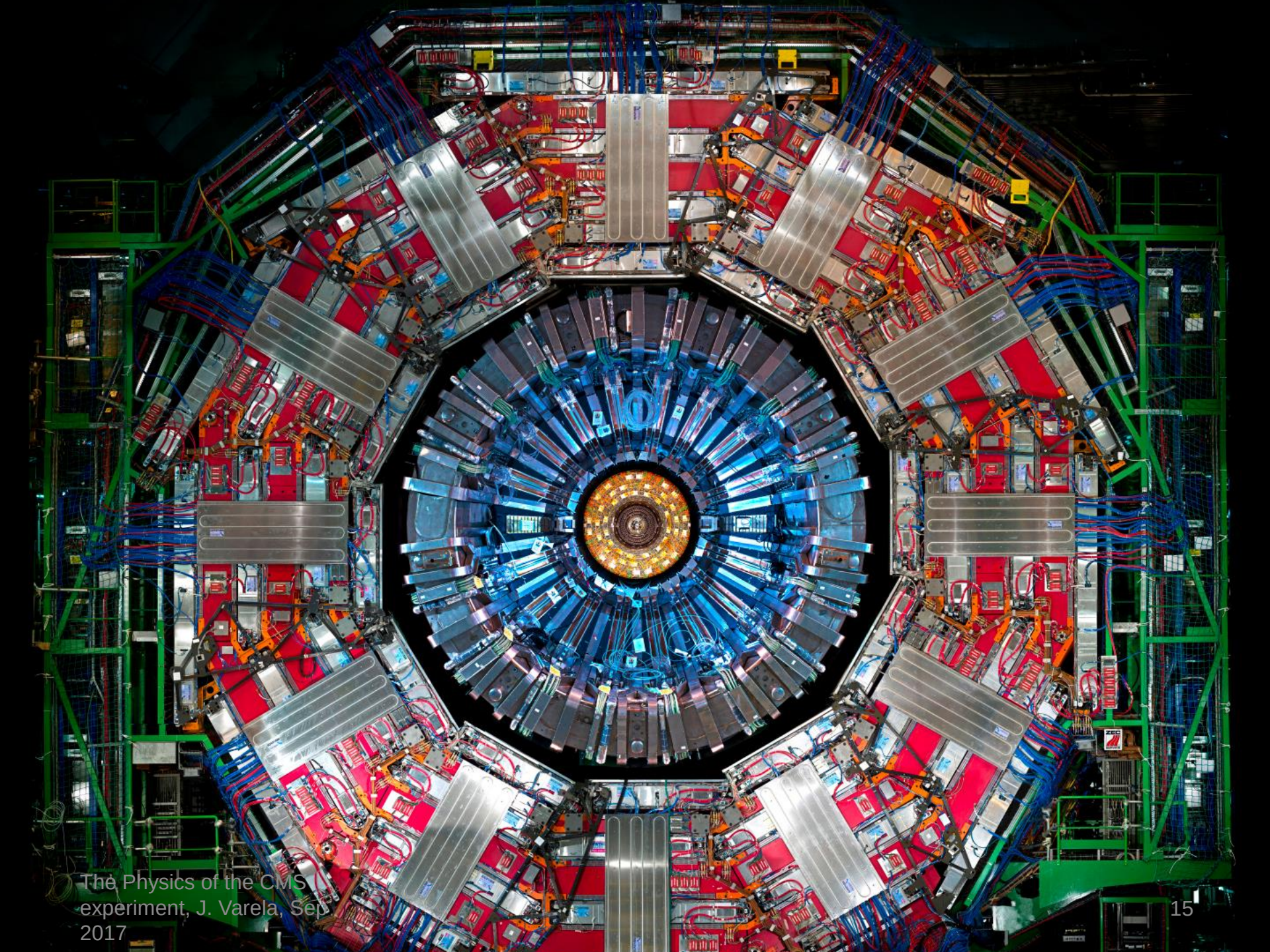


Accelerator and experiments layout



The CMS Experiment

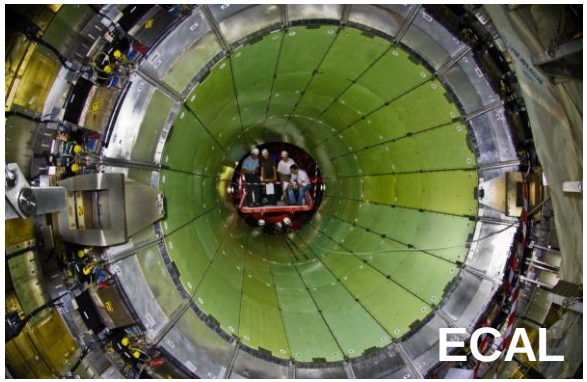


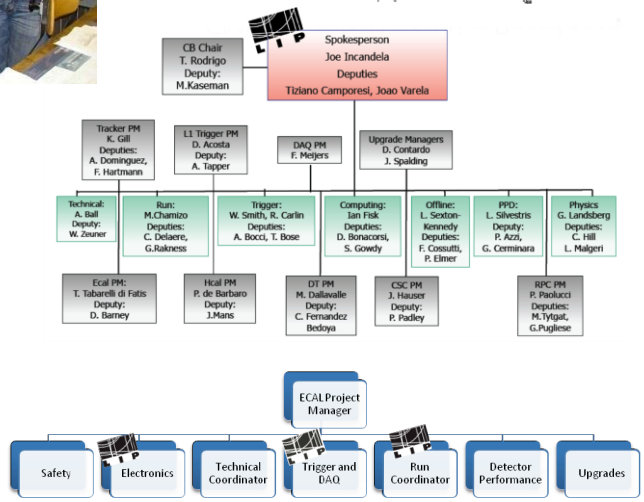


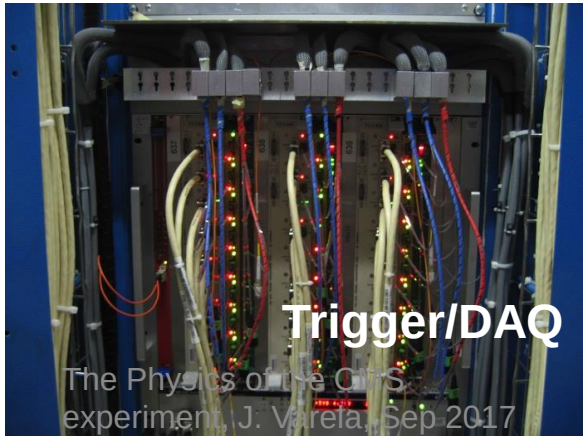
Art @ CMS

A collective endeavor

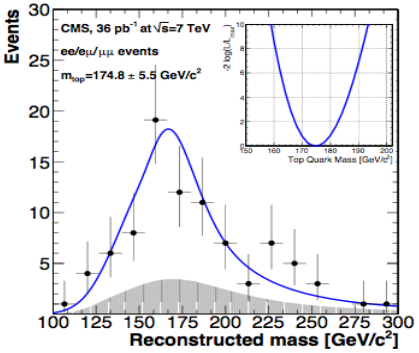
The LIP/CMS group



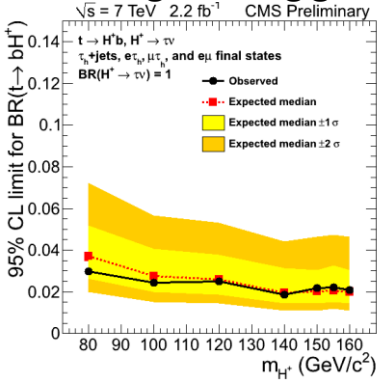




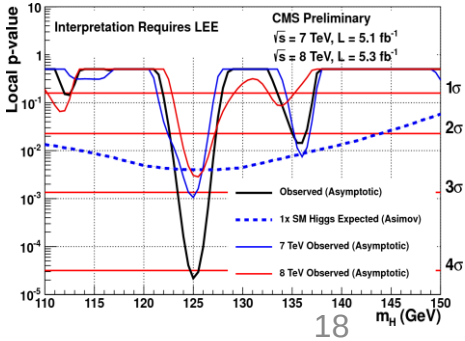
Top quark mass



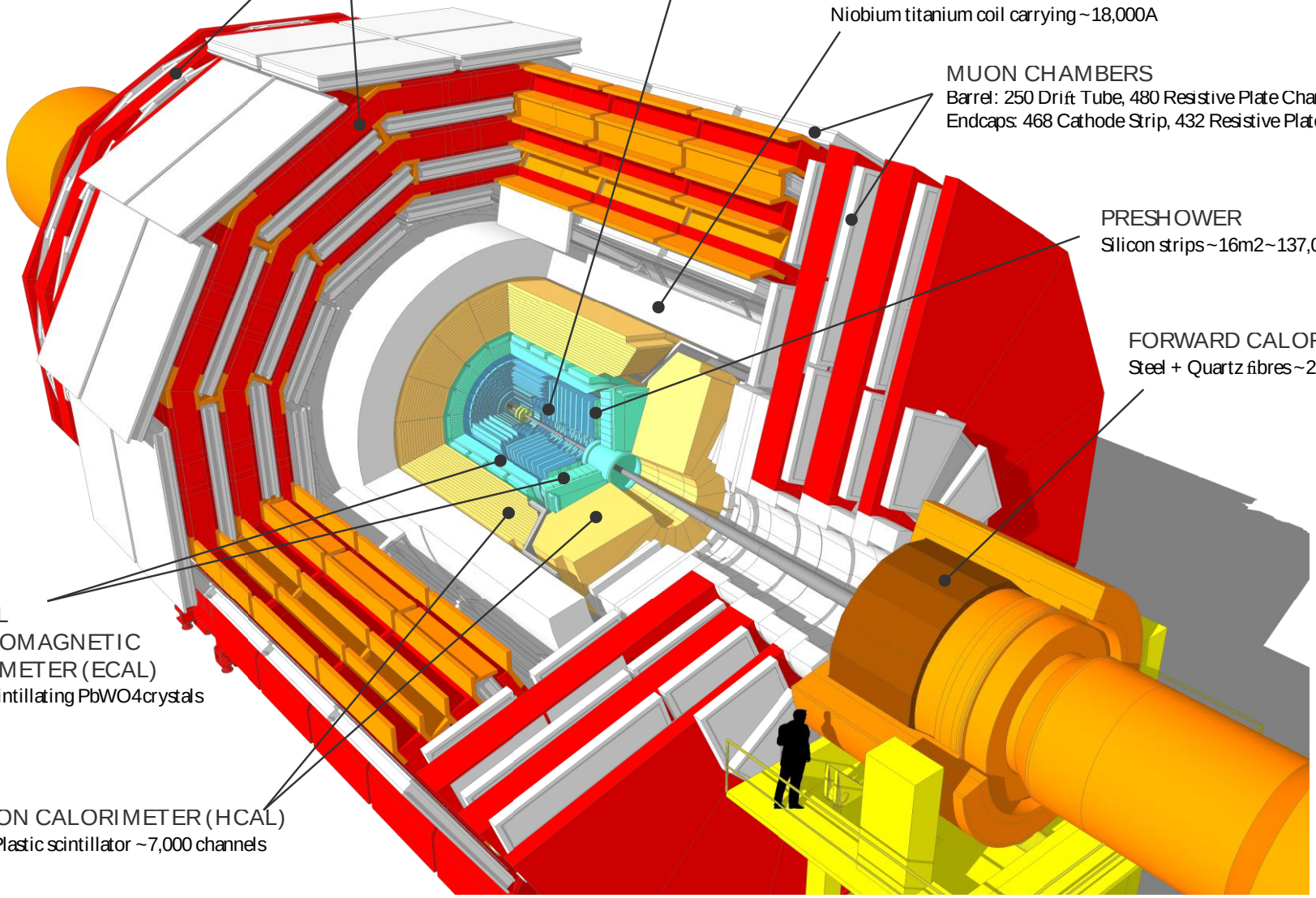
Charged Higgs



SM Higgs in γγ

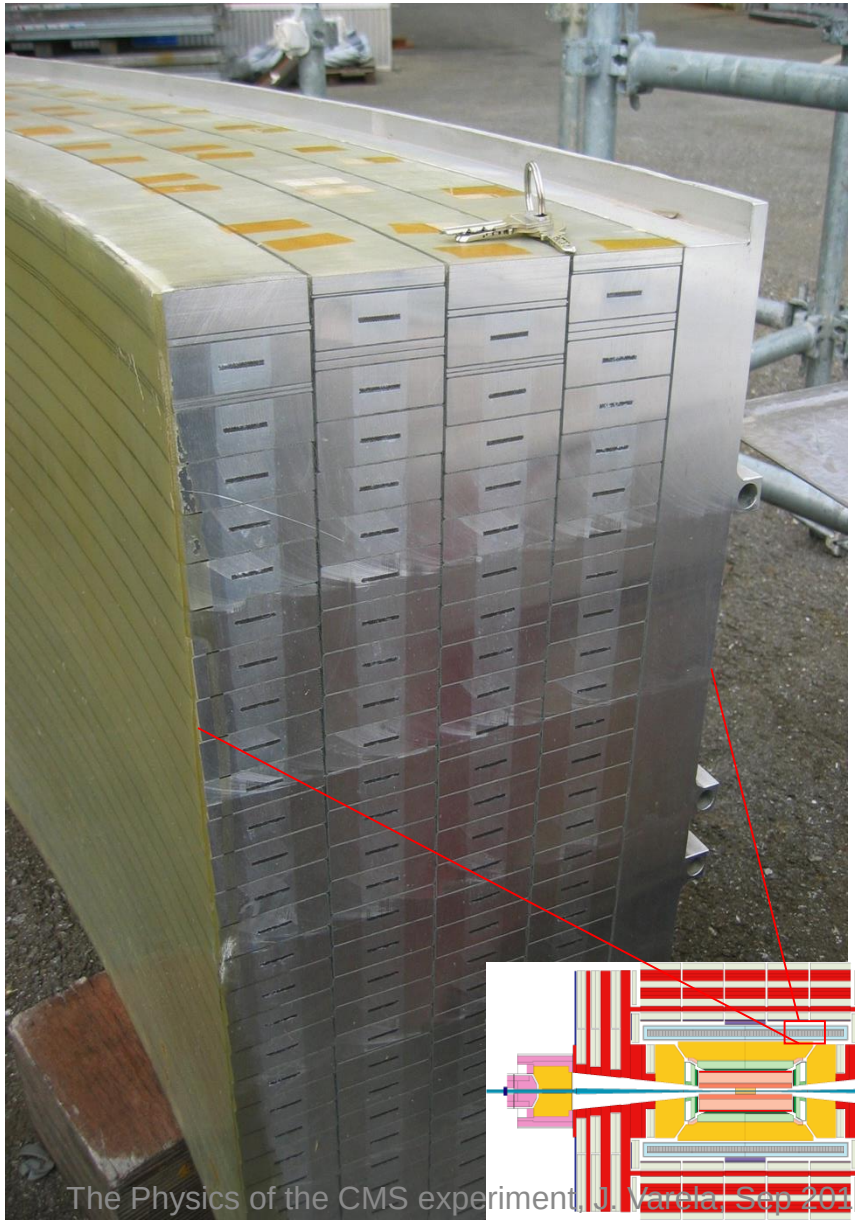


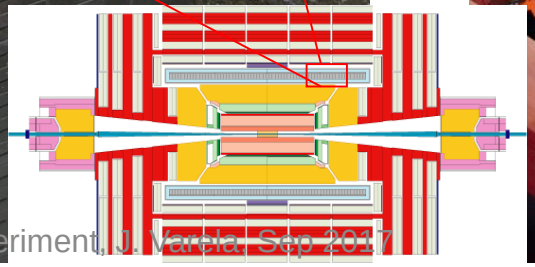
CMS Detector

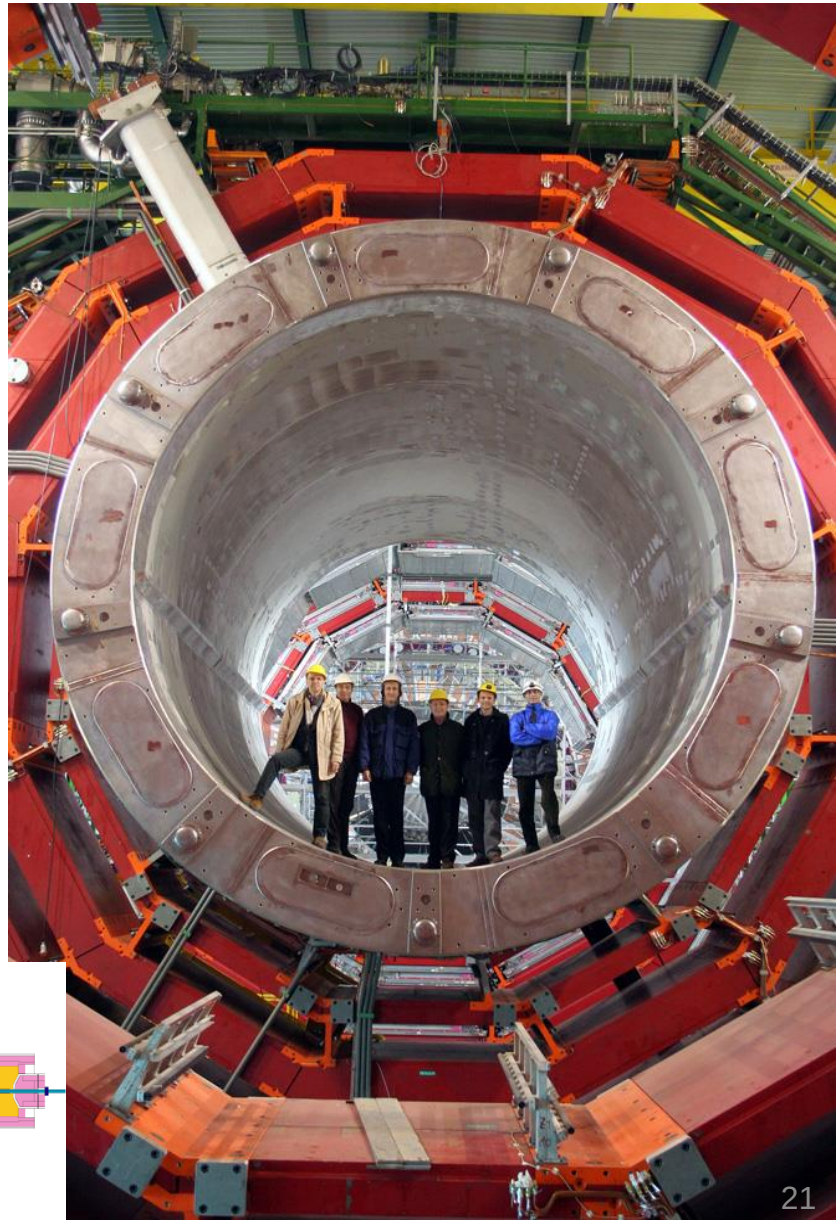


1993-2008: detector R&D and construction

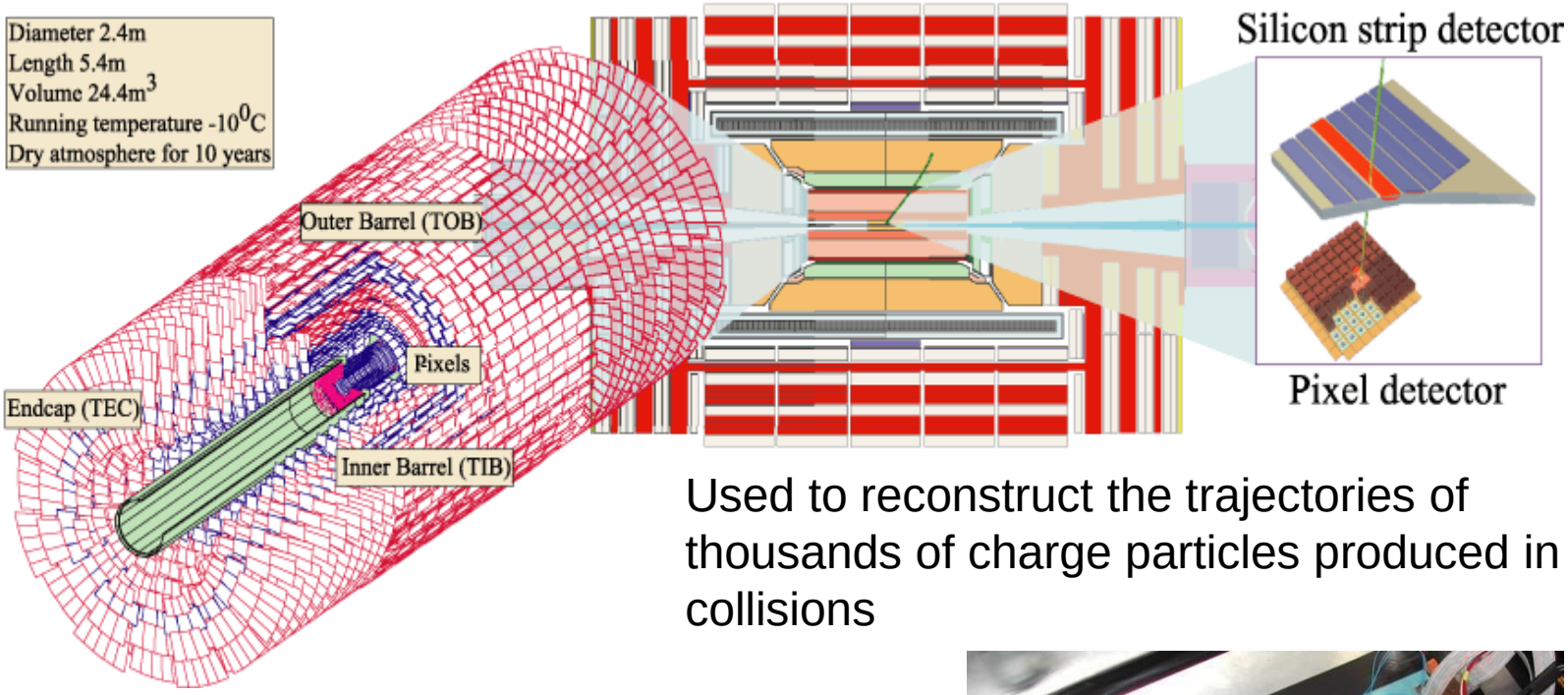
Superconductor solenoid at 3.8 Tesla





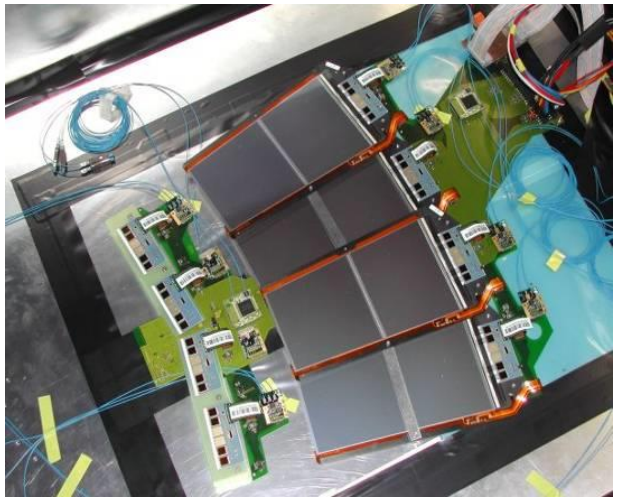


Silicon Tracker

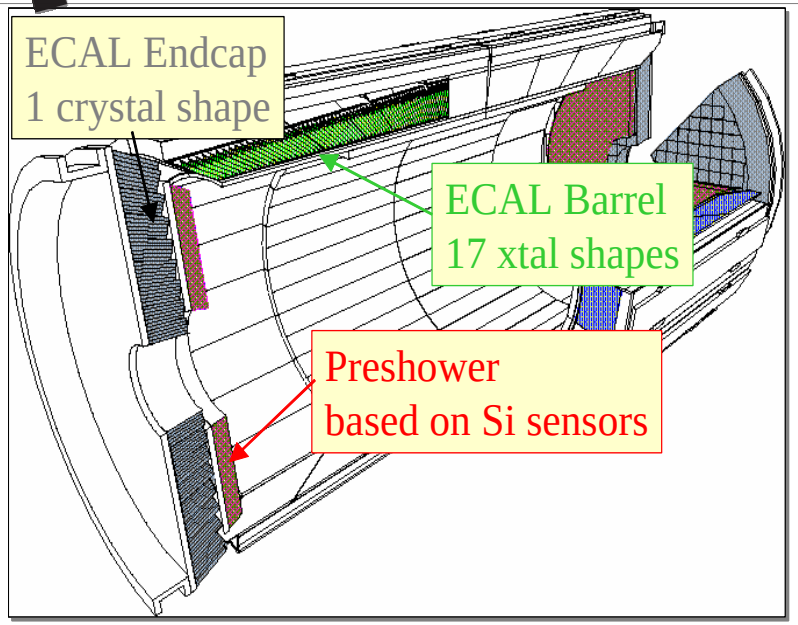


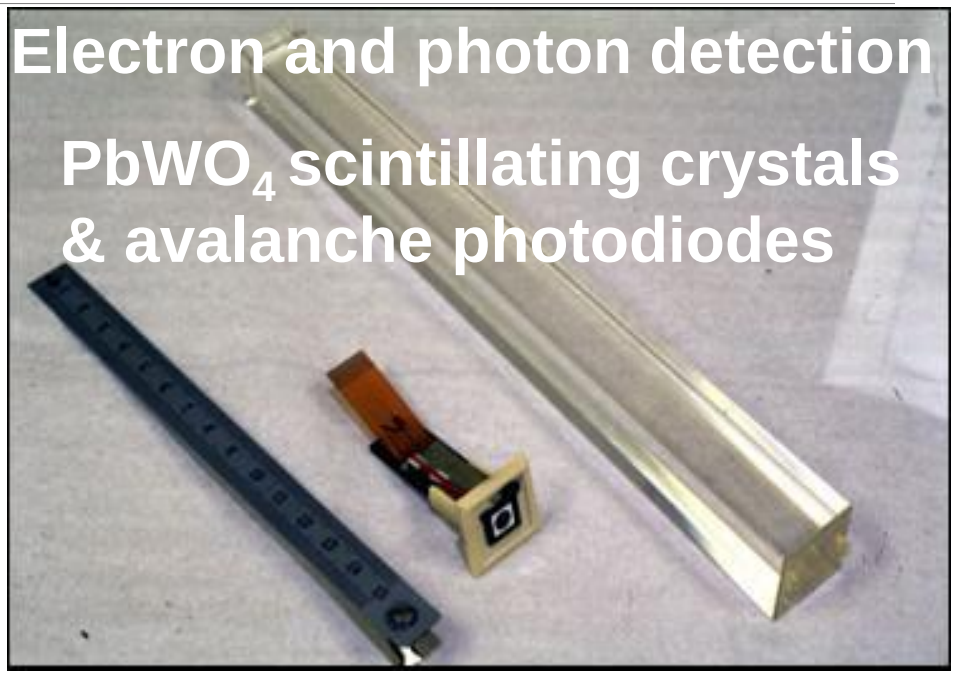
Used to reconstruct the trajectories of thousands of charge particles produced in the collisions

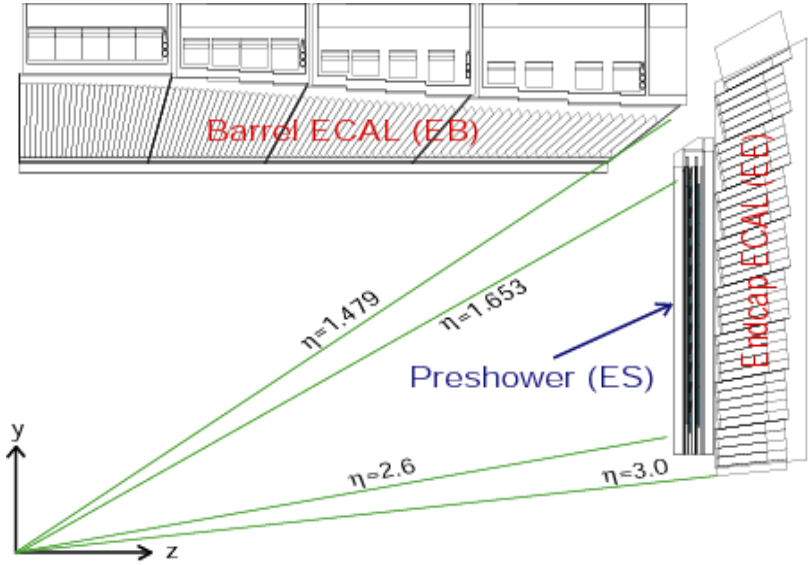
214m² silicon sensors
11.4 million silicon strips
65.9 million silicon pixels



ECAL Electromagnetic Calorimeter







Design Goal: Measure the energies of photons from a decay of the Higgs boson **to precision of ≤ 0.5%**

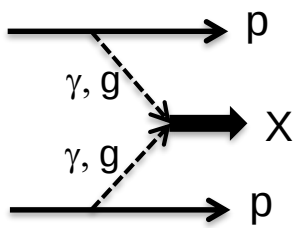
Parameter	Barrel	Endcaps
# of crystals	**61200**	**14648**
Volume	**8.14m^3**	**2.7m^3**
Xtal mass (t)	**67.4**	**22.0**

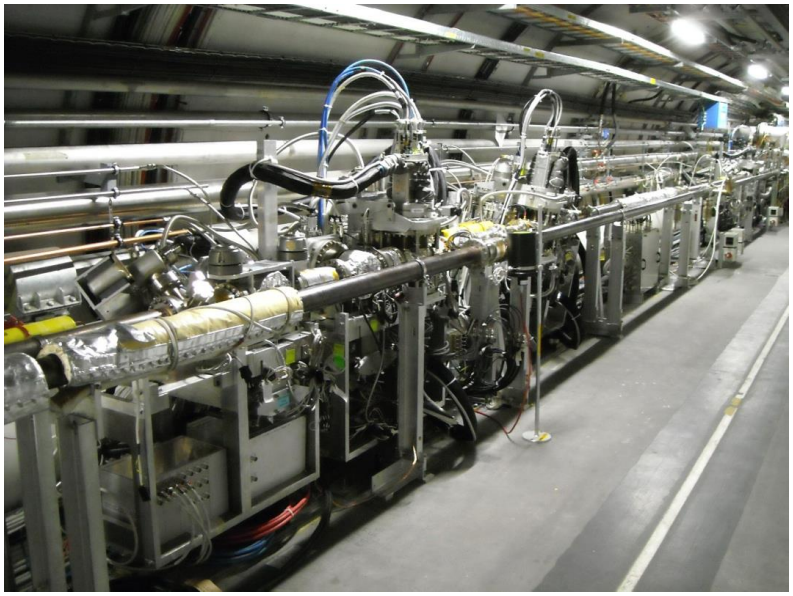
CTPPS Proton Spectrometer

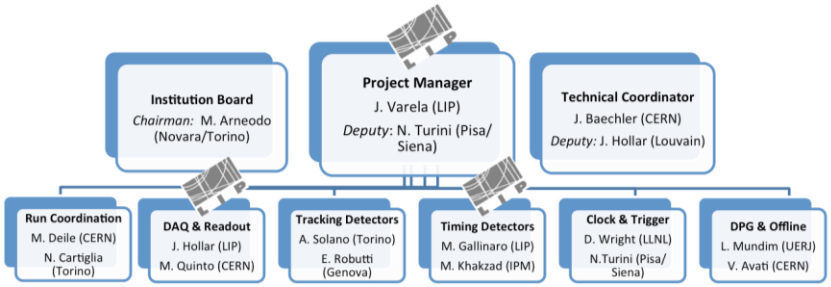
The LHC as a photon collider

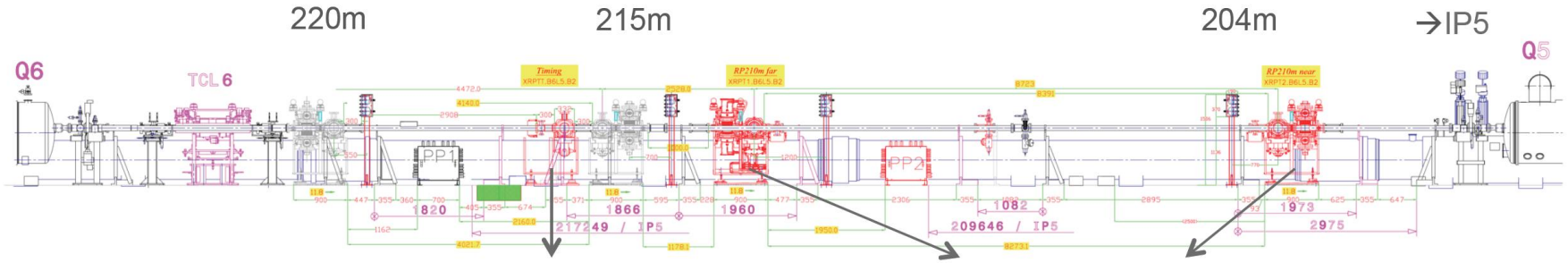
Proton tagging of central exclusive production

- **photon or gluon fusion**





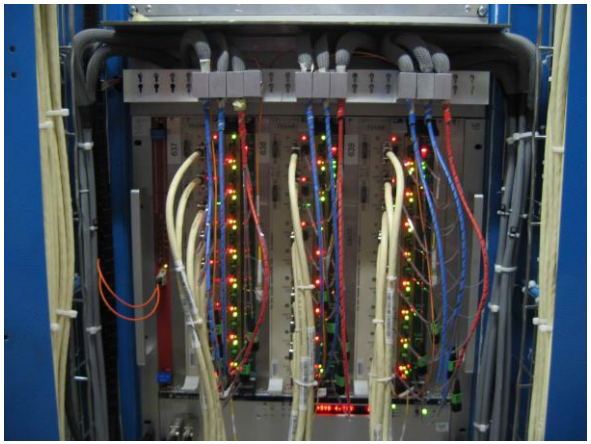


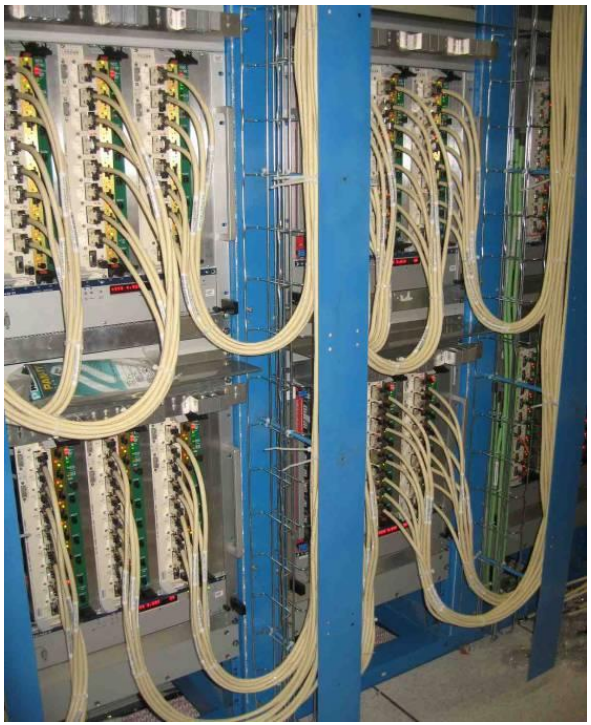


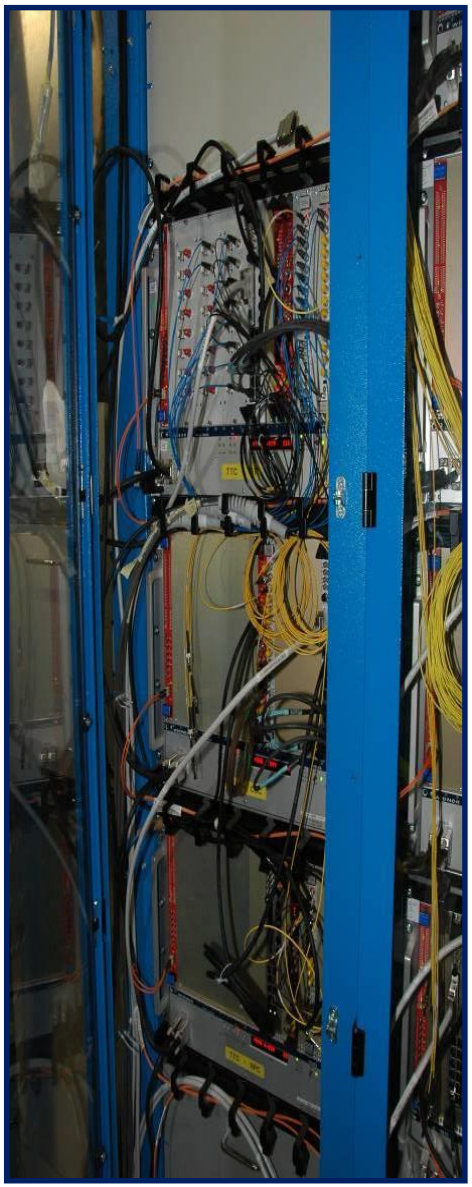
2 new horizontal cylindrical RPs (1 in LS1)

2 horizontal box-shaped RPs

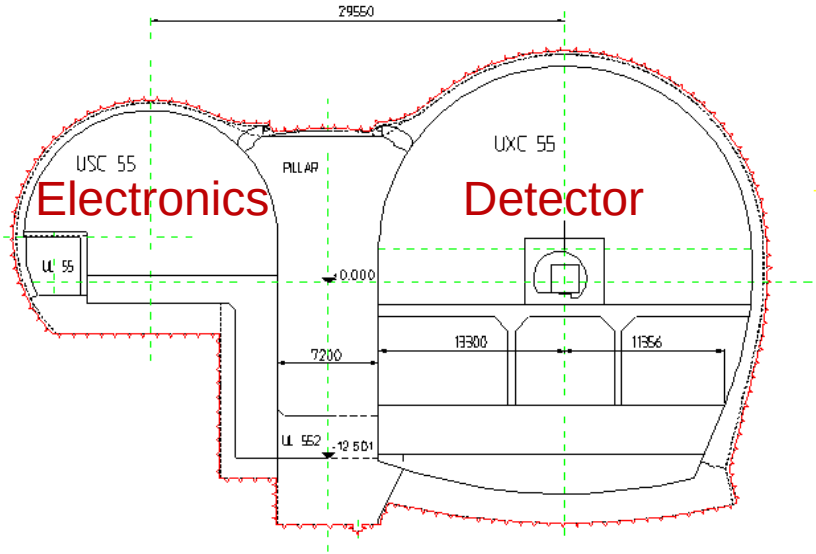
Trigger and readout electronics





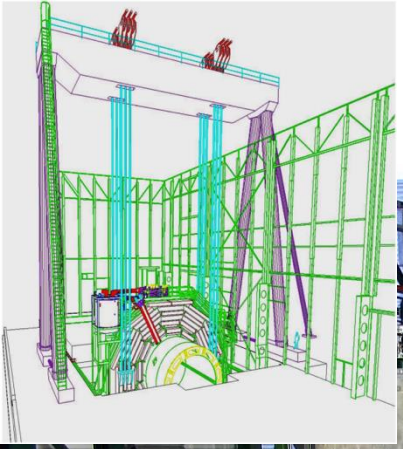


Underground caverns



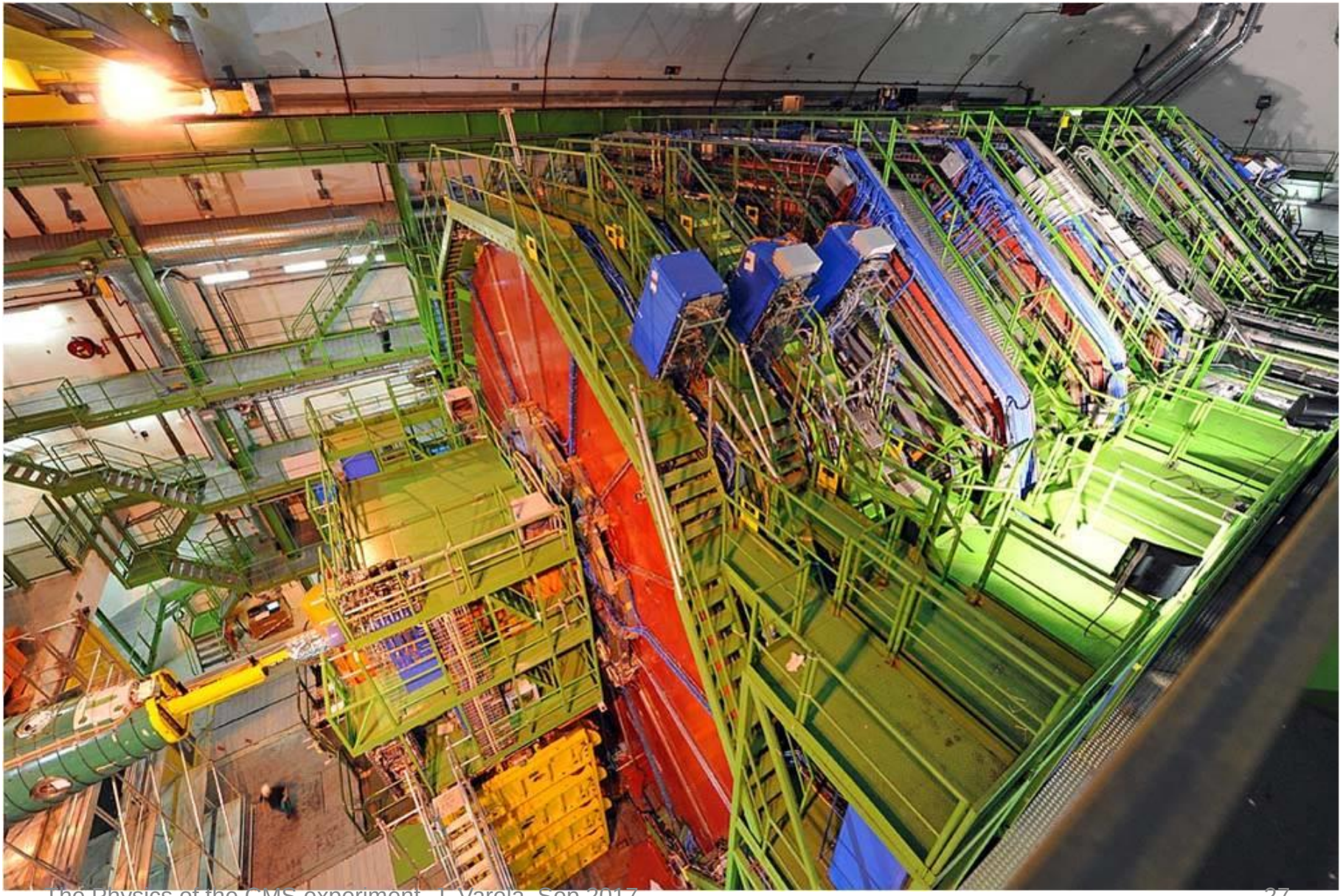
Electronics systems in the Service Cavern.
About 150 racks occupy two floors.
Most electronics was designed and built specifically for the experiment

Feb 2007:lowering central “wheel”

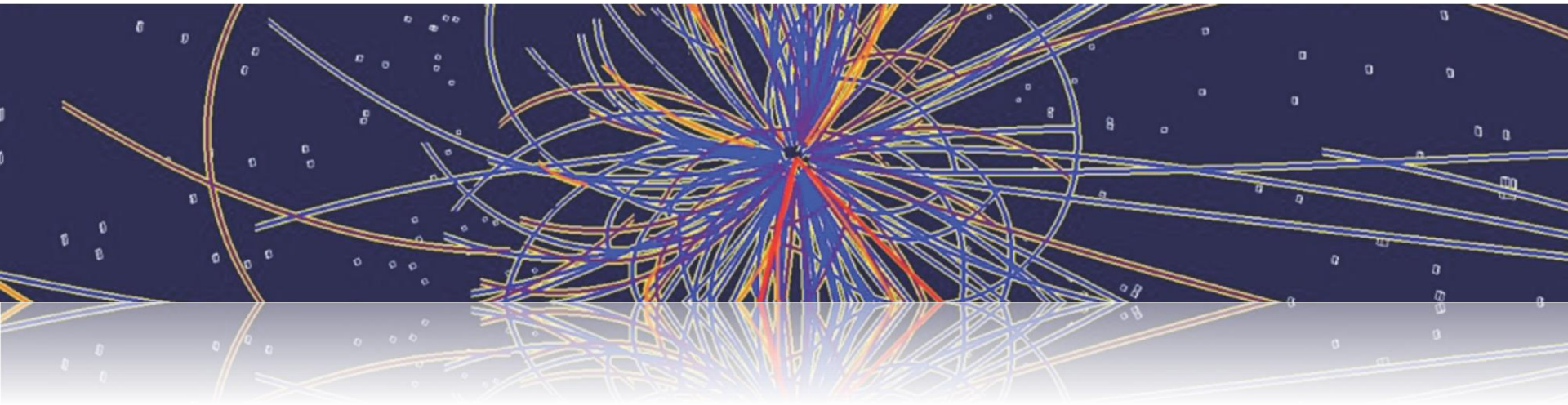


Started the travel at 6 am….

Sep 2008: CMS detector ready for beams

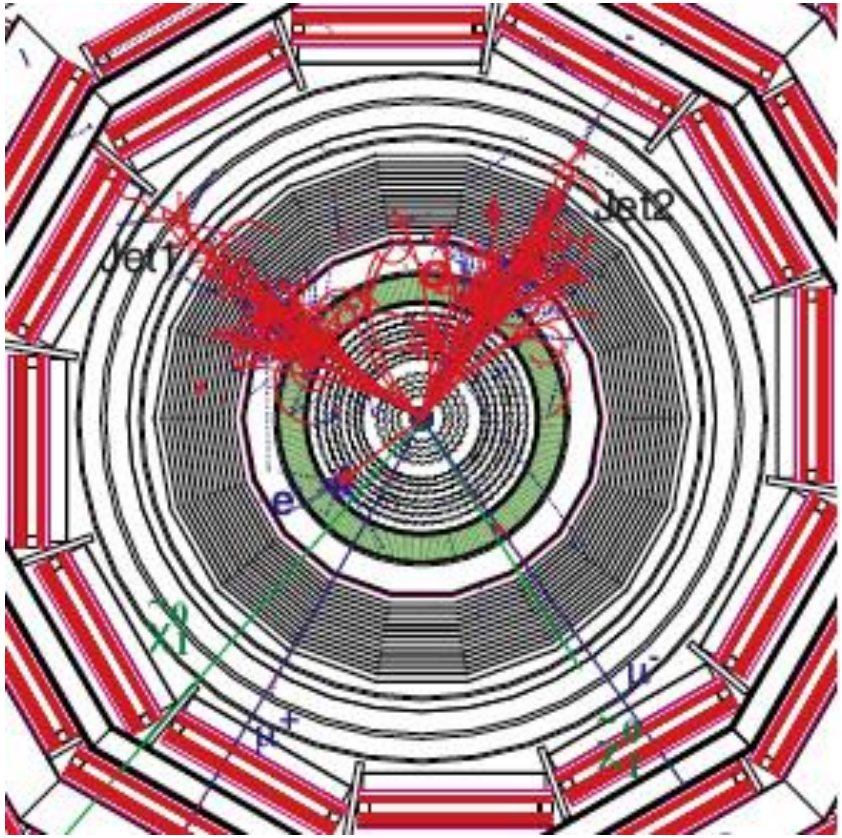


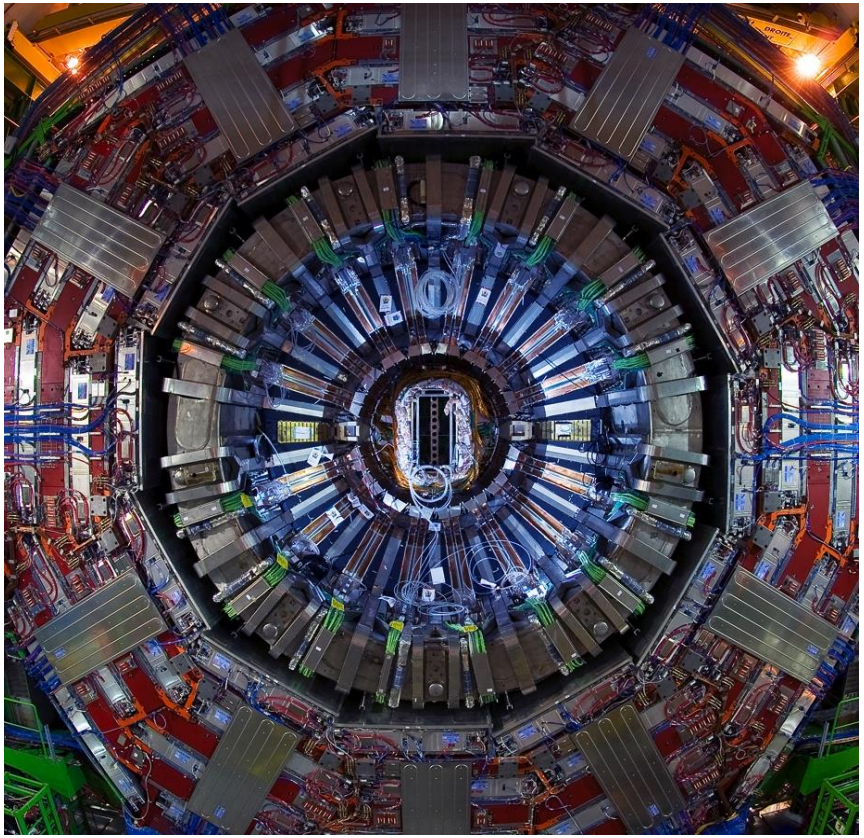
Physics and detector simulation



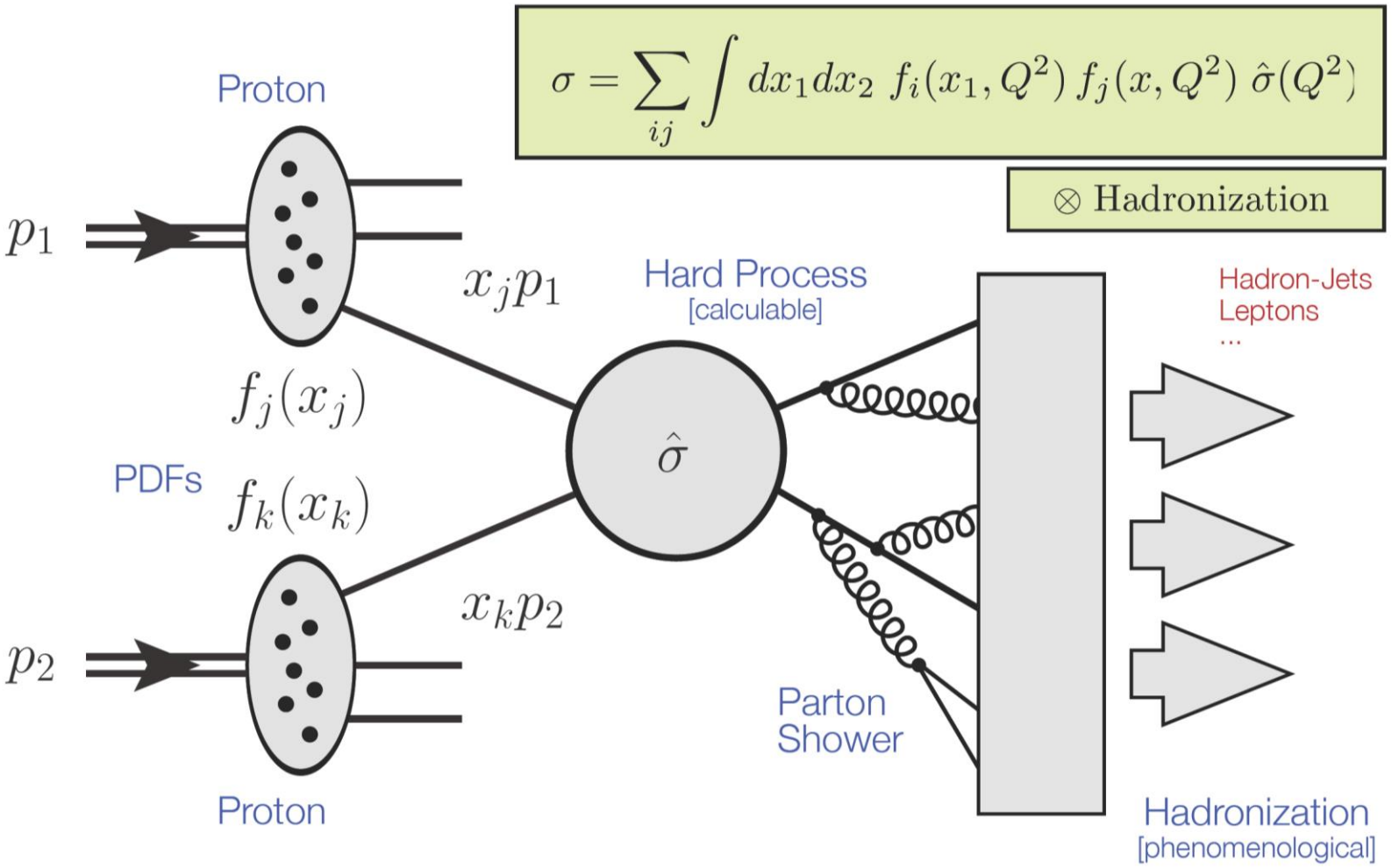
How did we prepare for discoveries?

Simulation of proton-proton collision
making two dark matter particles





Proton-Proton Scattering



From Partons to Jets

From partons to
color neutral hadrons:

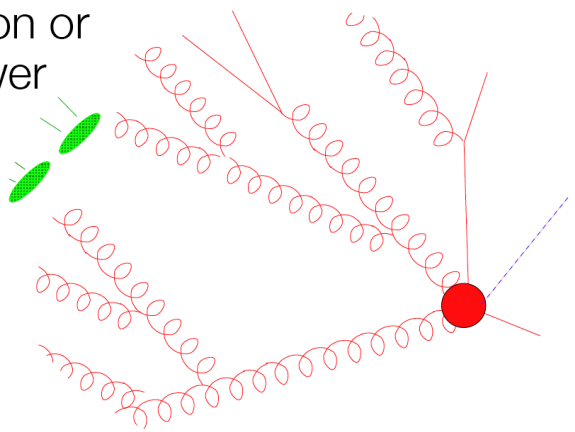
Fragmentation:

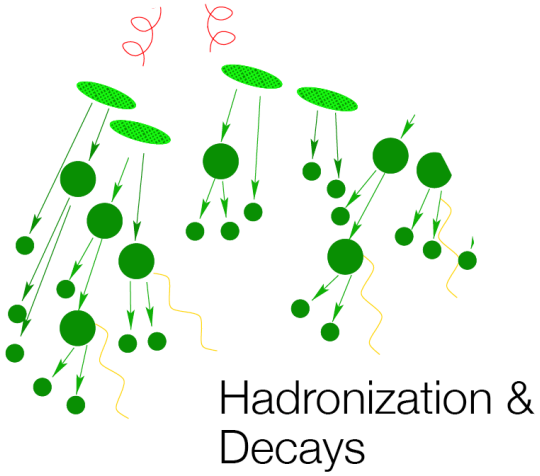
Parton splitting into other partons
[QCD: re-summation of leading-logs]
[“Parton shower”]

Hadronization:

Parton shower forms hadrons
[non-perturbative, only models]

Decay of unstable hadrons
[perturbative QCD, electroweak theory]





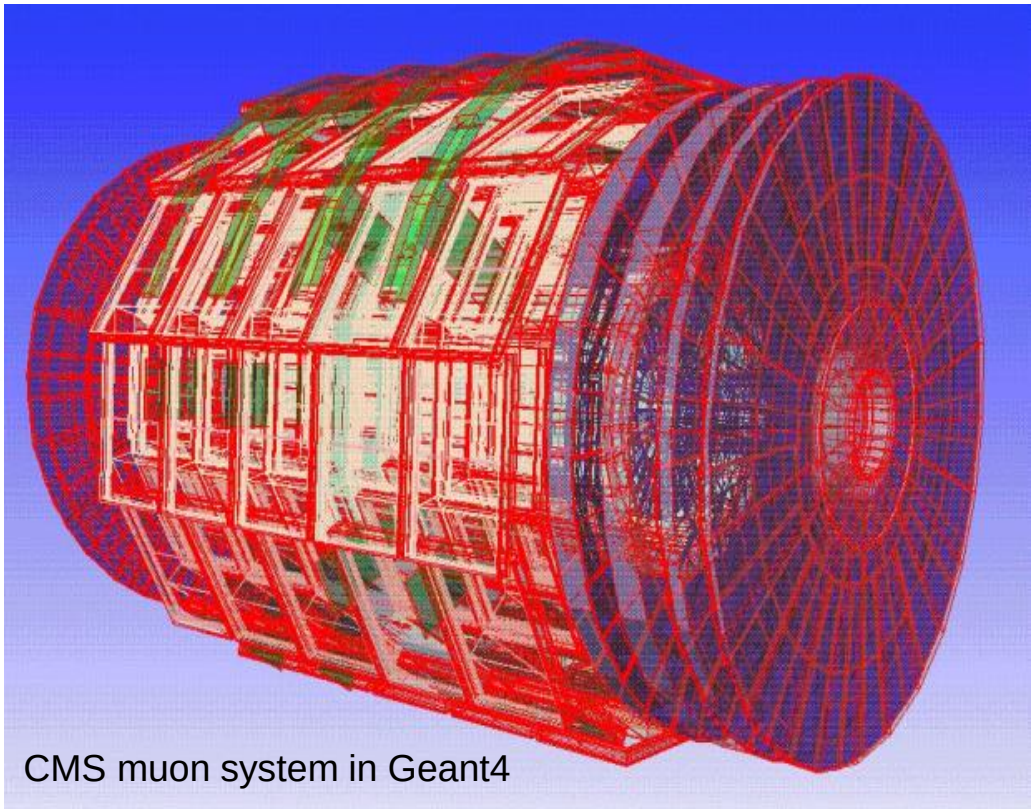
Detector simulation

GEANT
Geometry And Tracking

Detailed description of detector geometry
[sensitive & insensitive volumes]

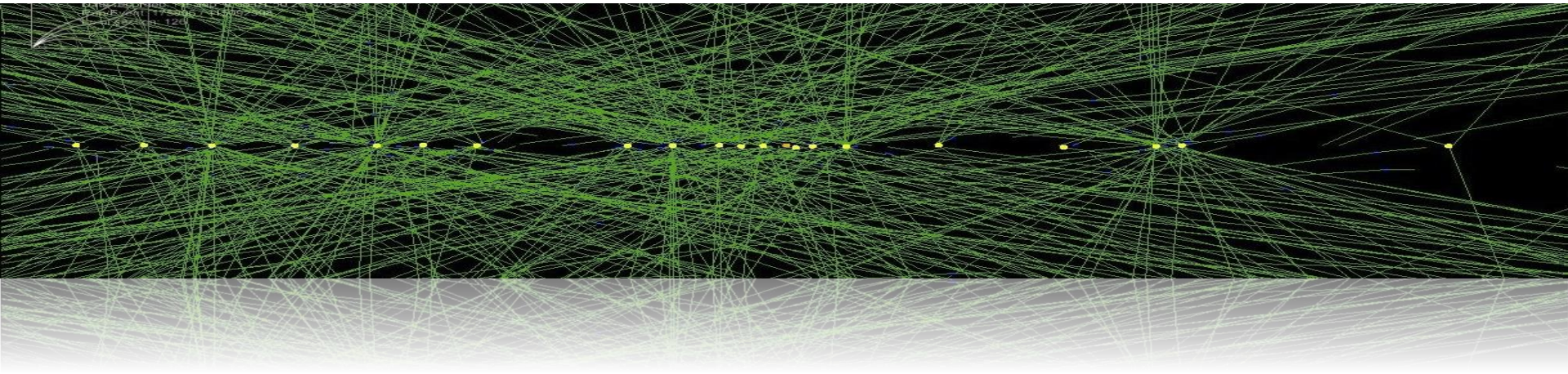
Tracking of all particles through detector material ...

➔ Detector response


CMS muon system in Geant4

Developed at CERN since 1974 (FORTRAN)
[Today: Geant4; programmed in C++]

Experimental challenges



High collision rate

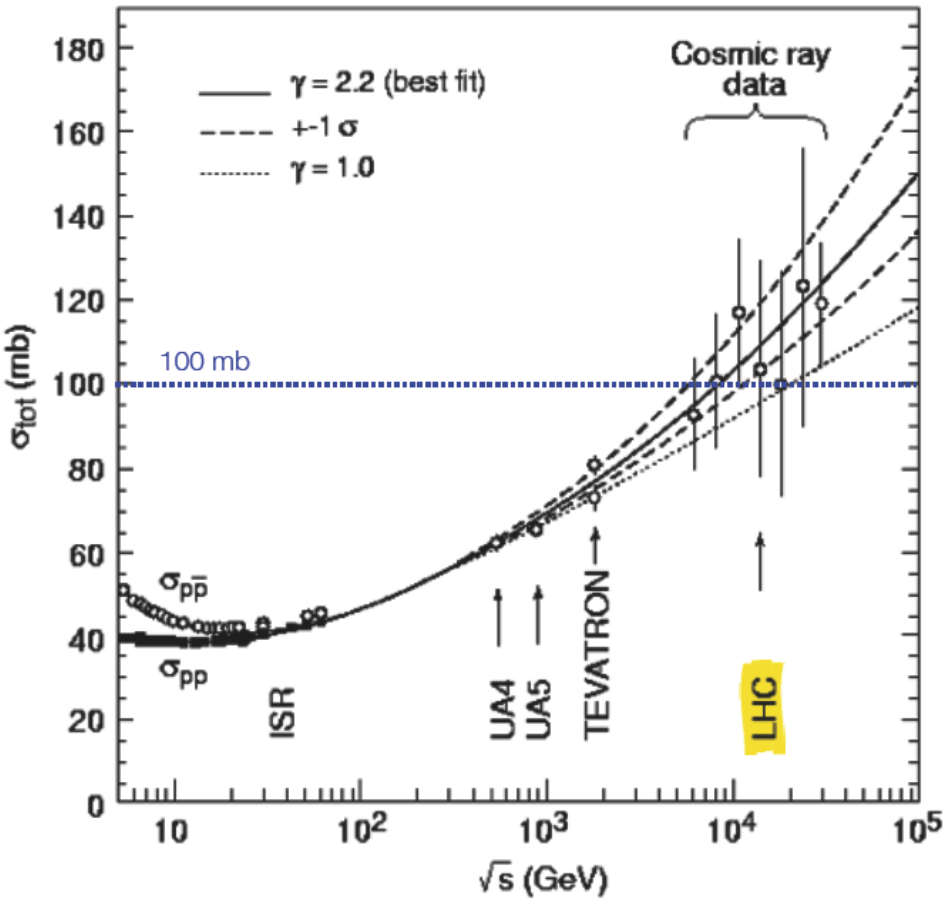
Luminosity:

$L = 10^{34}\ cm^{-2}s^{-1}$
$= 10^{7}\ Hz/mb$

Cross section:

$\sigma \approx 100\ mb$

➥ $N = L\sigma \approx 1\ GHz$

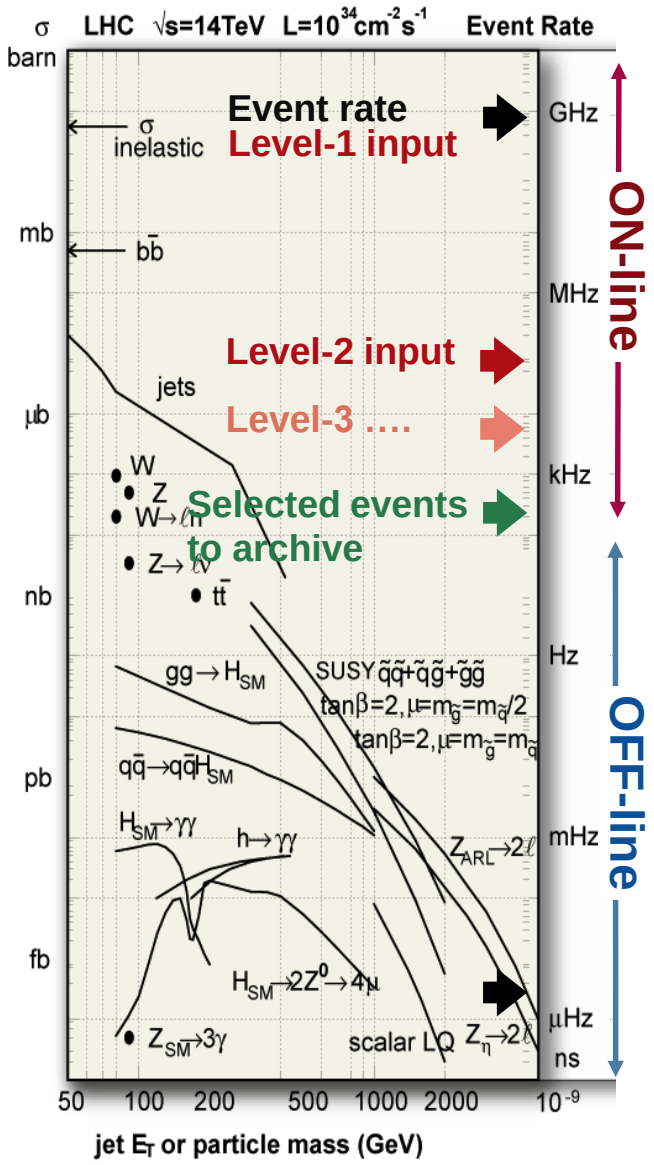


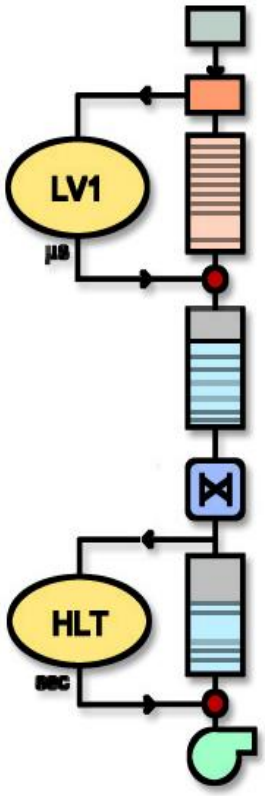
However:

Bunch crossing rate: 40 MHz
∴ Interactions/crossing ~ 25

This is a real challenge !

Two-level trigger





Trigger system decide if the event is interesting to be recorded

Two-step process:
- Level 1: dedicated hardware processors

- High level: computer farm

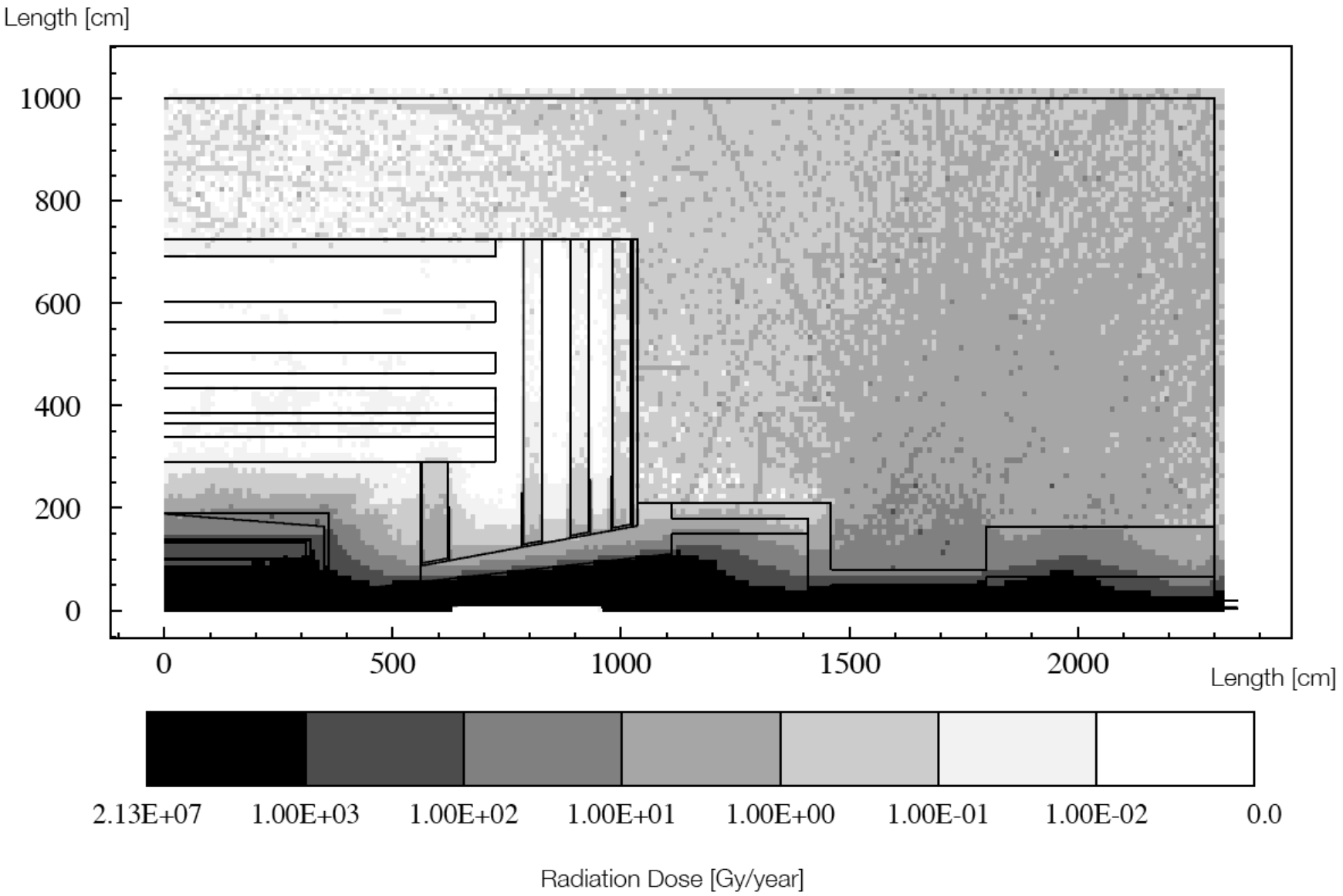
The LHC Computing Grid

The Grid unites computing resources of particle physics institutions around the world

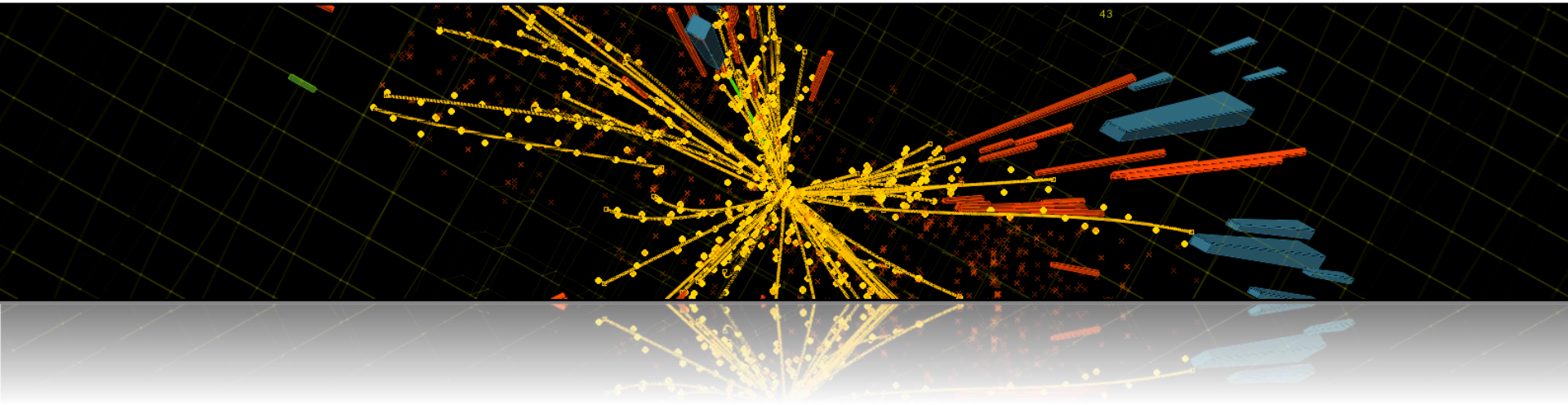
The **World Wide Web** (invented at CERN) provides seamless access to information that is stored in many millions of different geographical locations

The **Grid** is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe

High radiation levels



Commissioning of the CMS detector

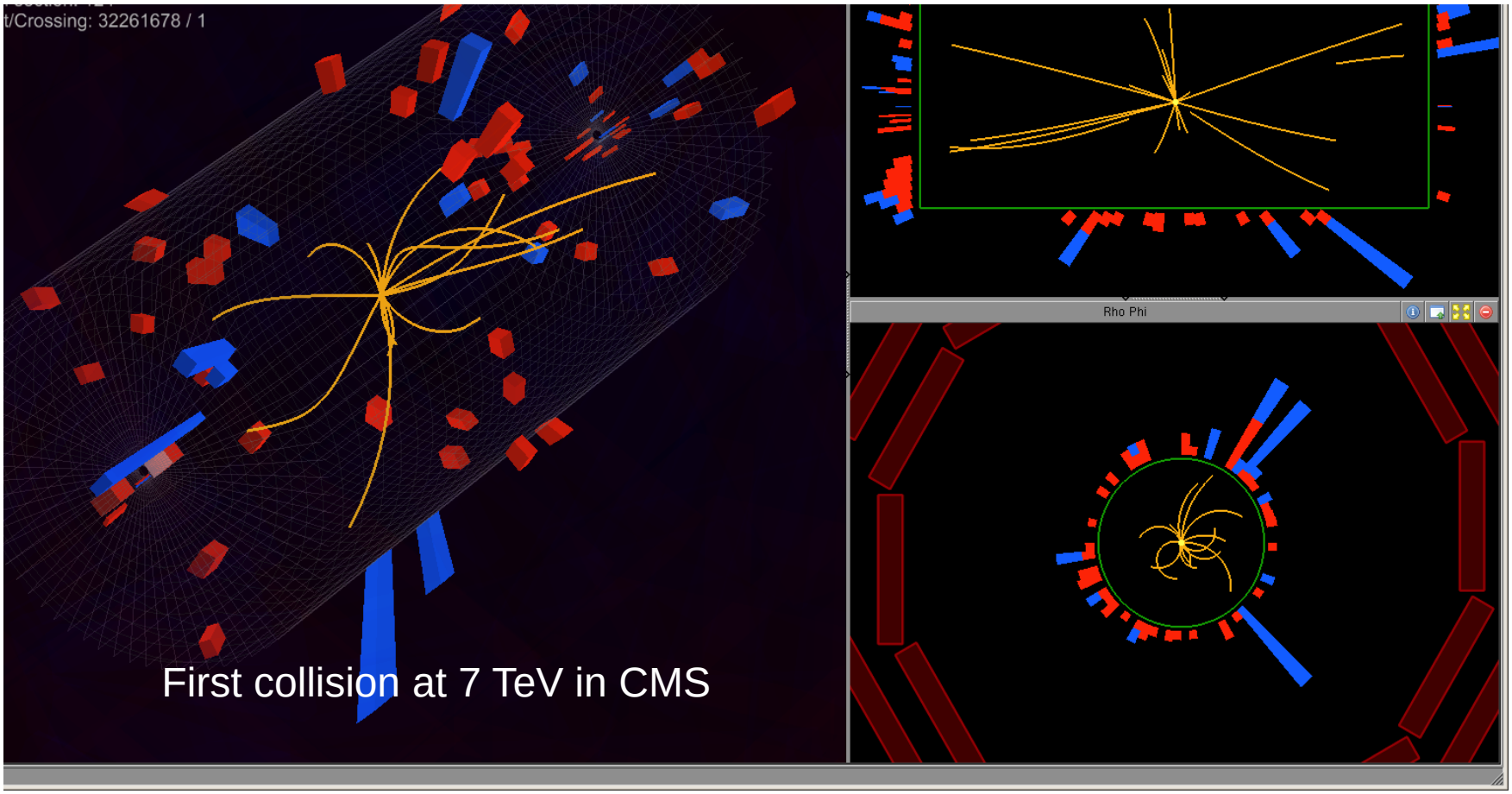


2009: First p-p collisions at LHC

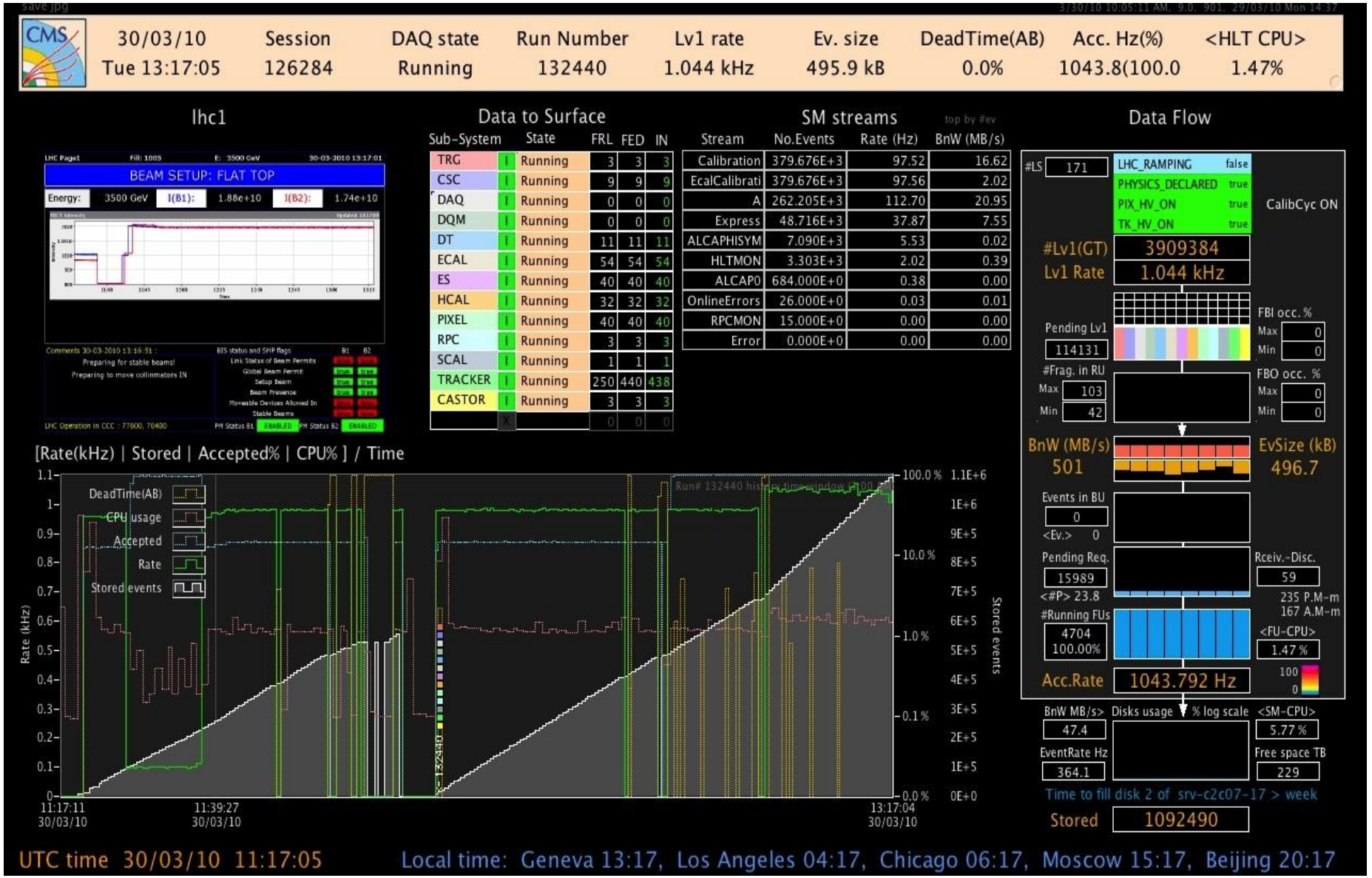
November 23, 2009
First collisions at 900 GeV

December 14, 2009
First collisions at 2.36 TeV

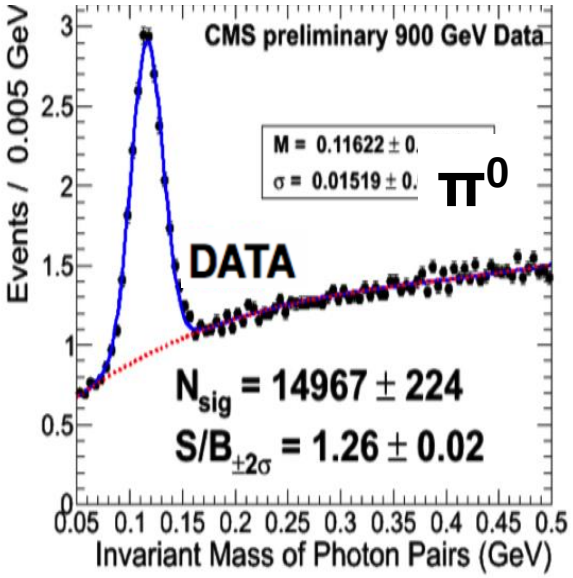
March 30, 2010
First collisions at 7 TeV

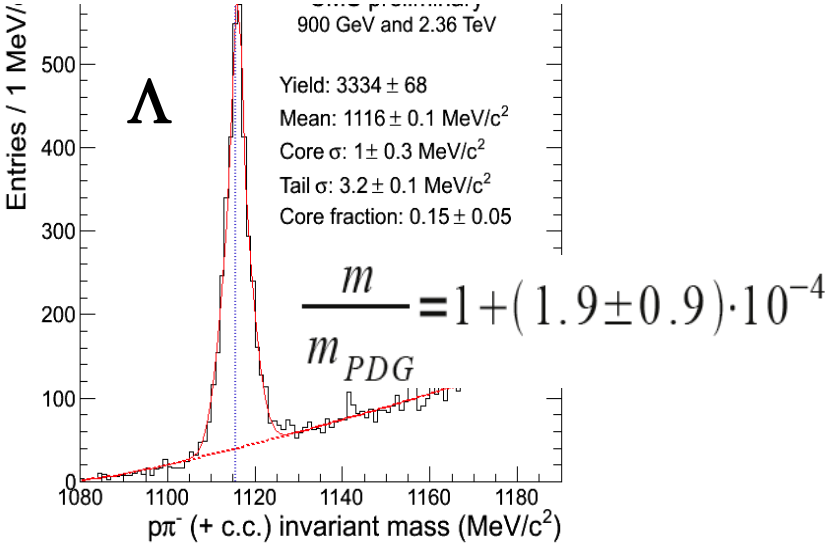


March 30, 2010: CMS Page 1

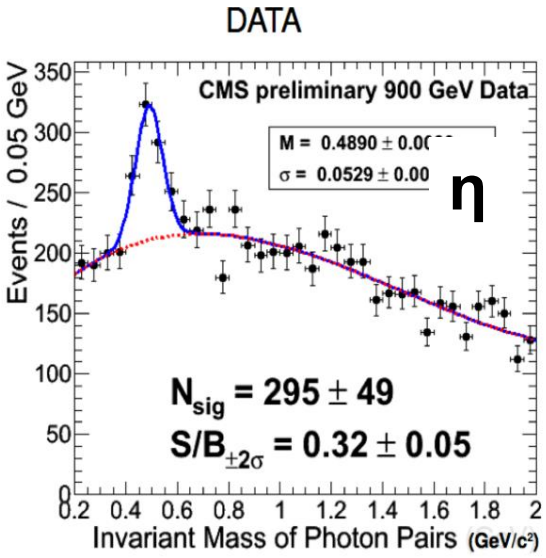


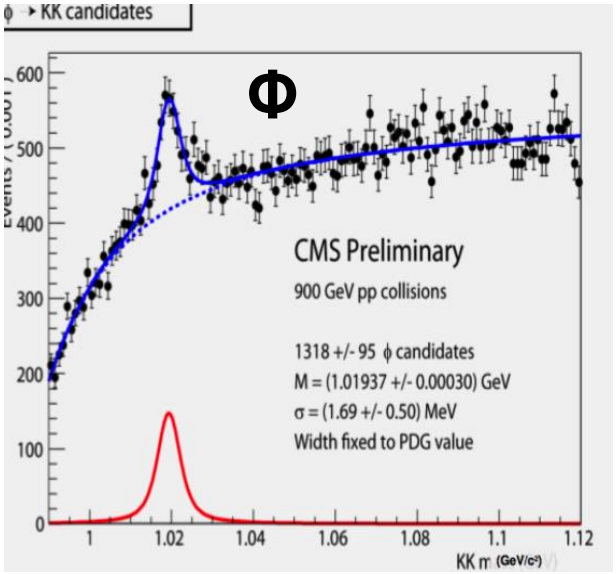
Rediscovery of unstable hadrons

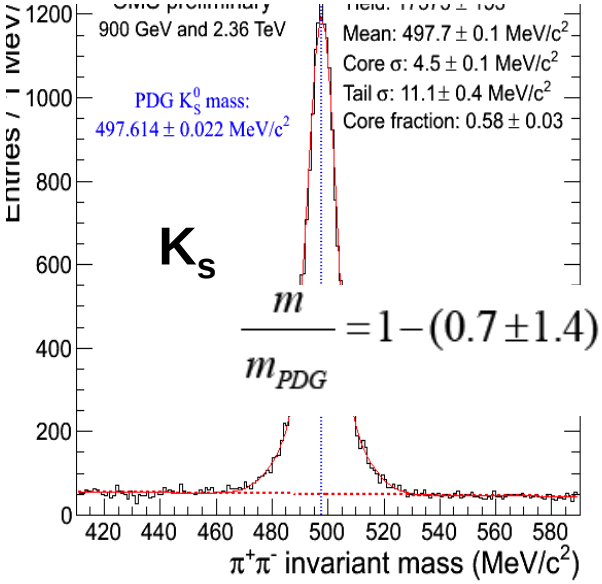




$$\frac{m}{m_{PDG}} = 1 + (1.9 \pm 0.9) \cdot 10^{-4}$$







$$\frac{m}{m_{PDG}} = 1 - (0.7 \pm 1.4) \cdot 10^{-4}$$

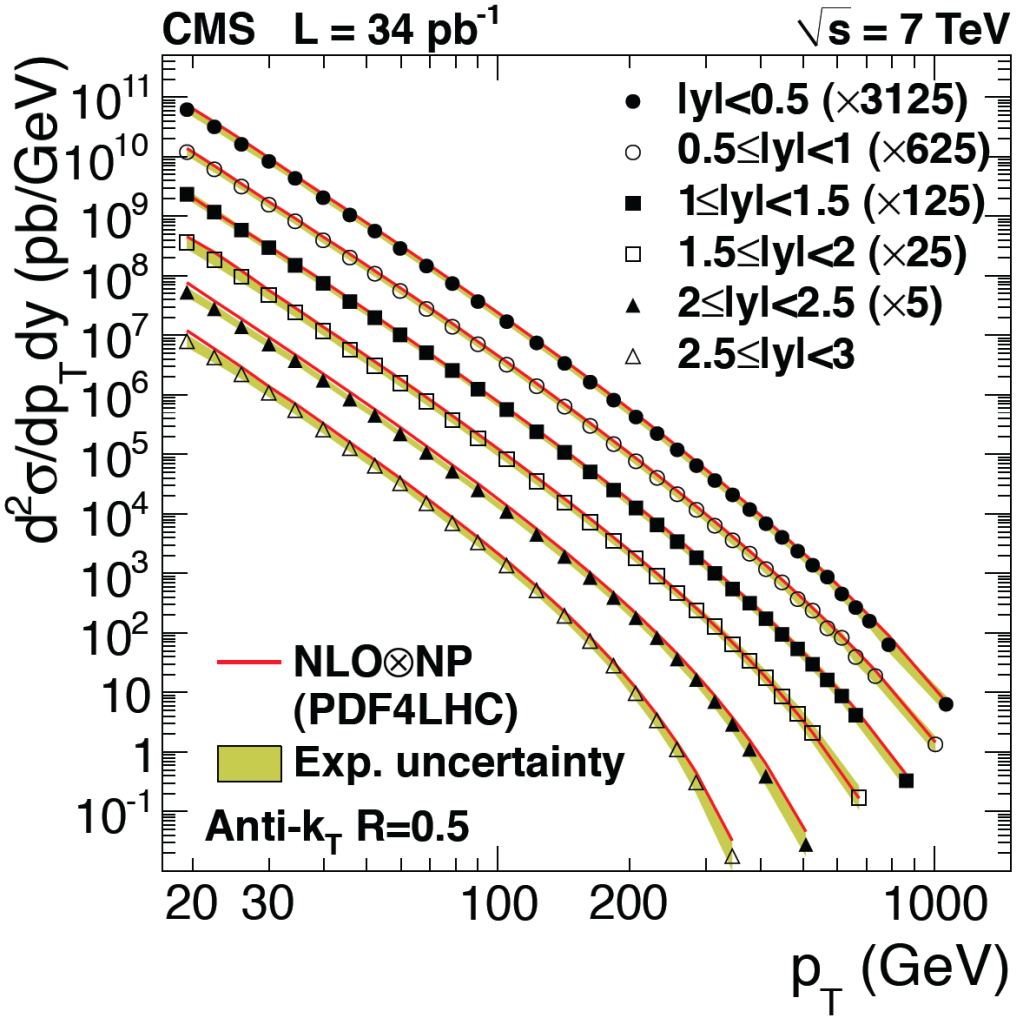
Inclusive jet cross-section

Cross section is huge
(~ Tevatron x 100)

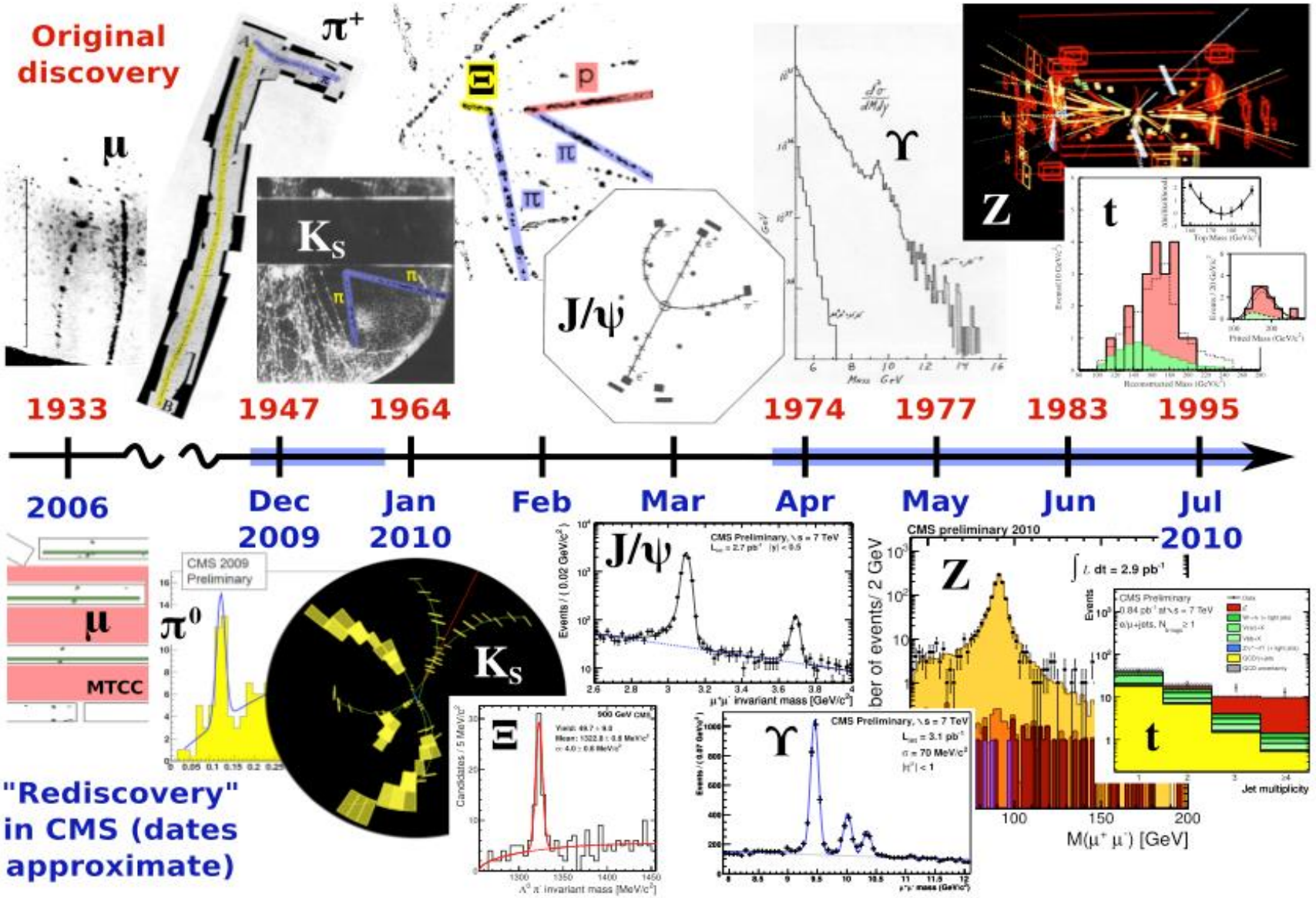
Very good agreement with NLO QCD over nine orders of magnitude

PT extending from 20 to 500 GeV

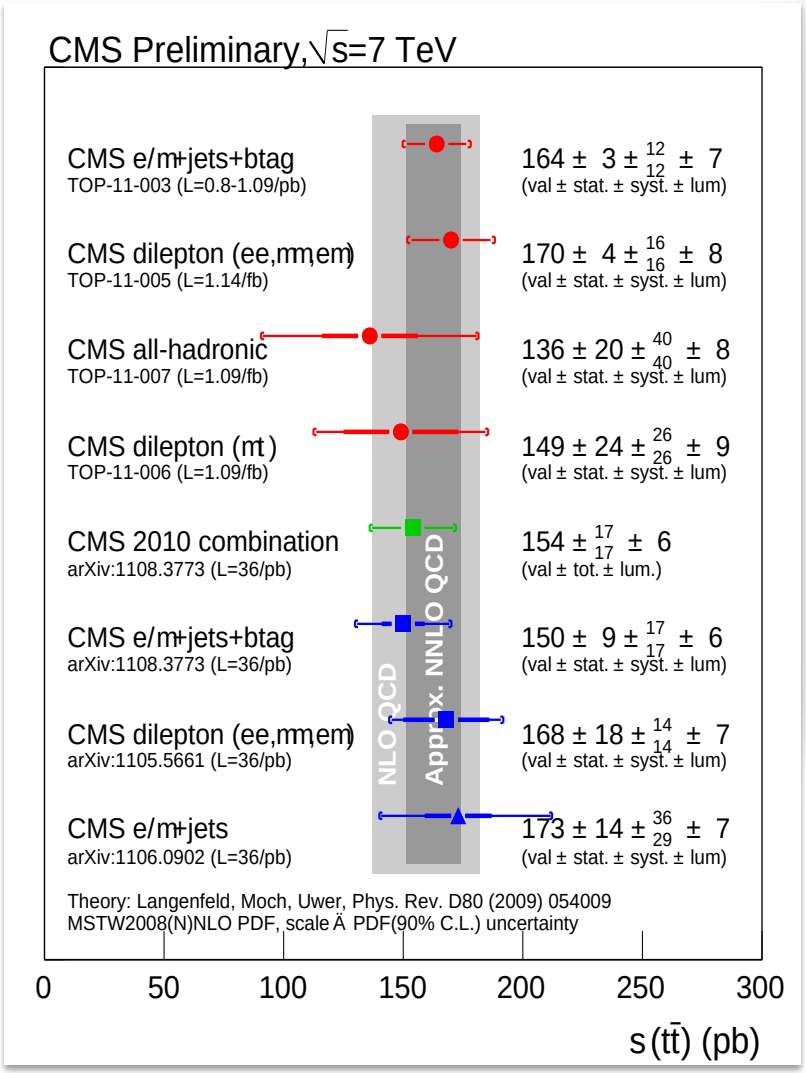
Main uncertainty:
Jet Energy Scale (3-4%)

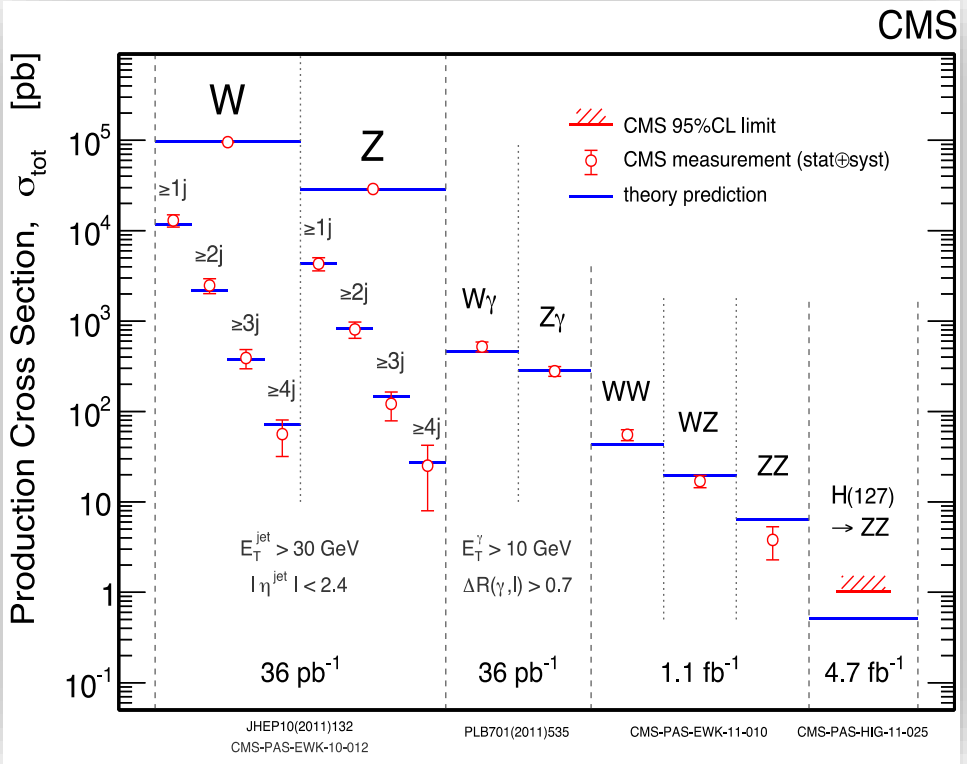


Rediscovery of the Standard Model in CMS



Standard Model at 7 TeV (2010-2011)

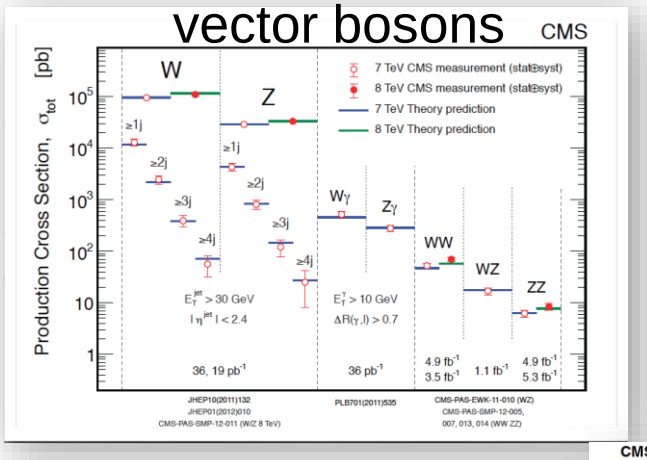


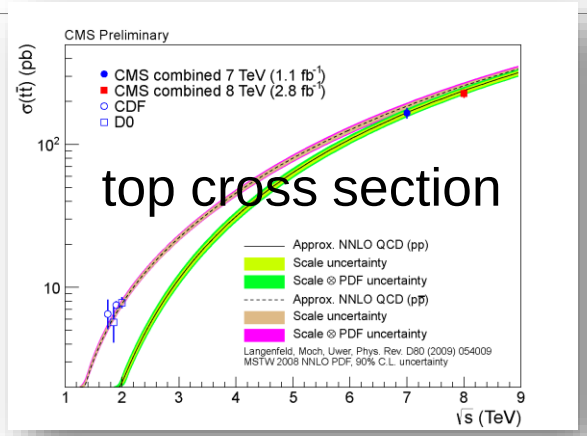


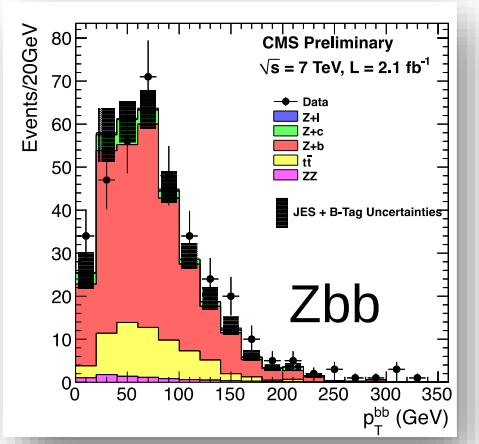
- **Fabulous agreement**
- **Lots of data**

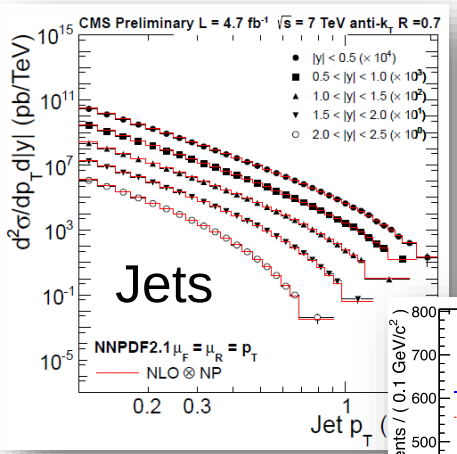
… on to the Higgs…

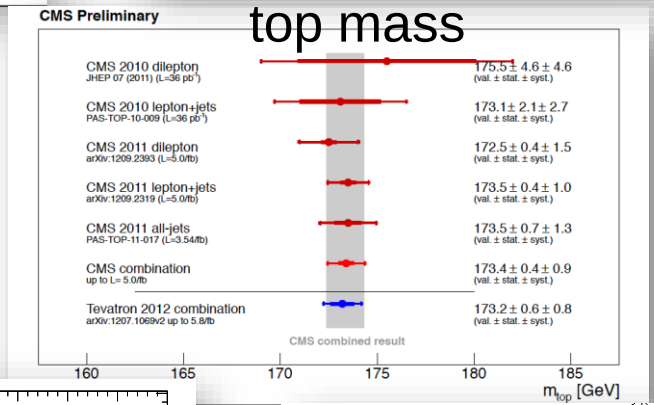
…and many more physics results

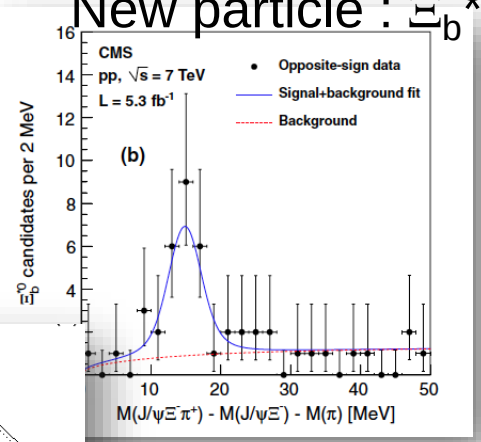


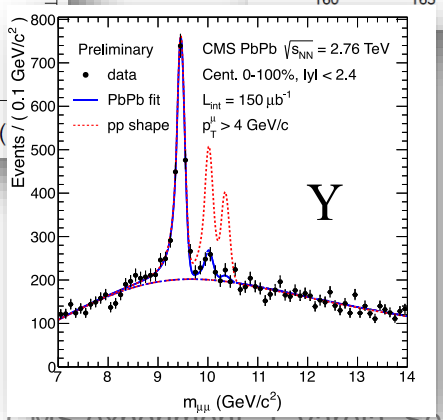


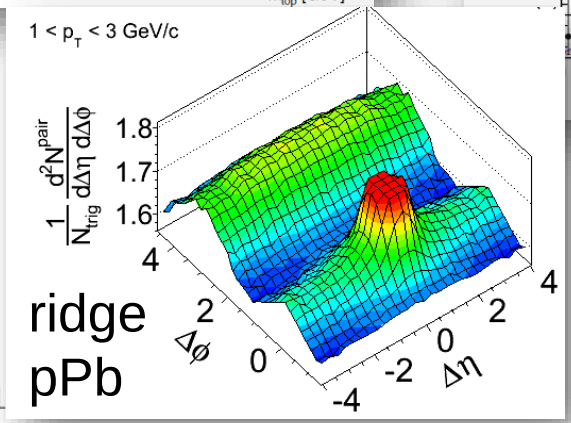






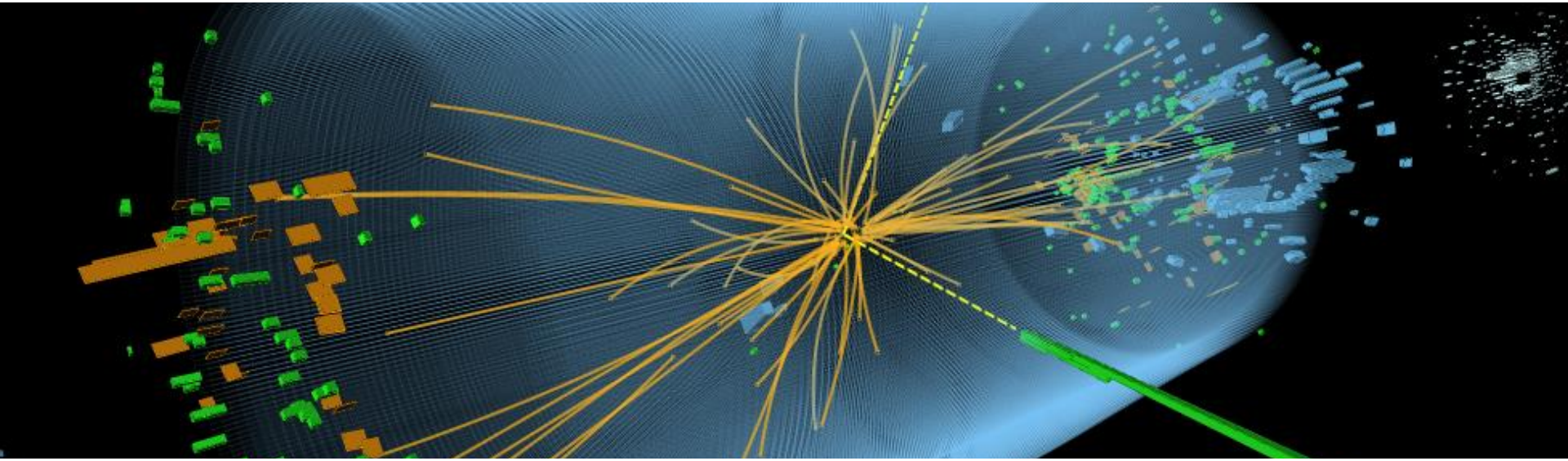






More than 600 papers from CMS

The Higgs discovery

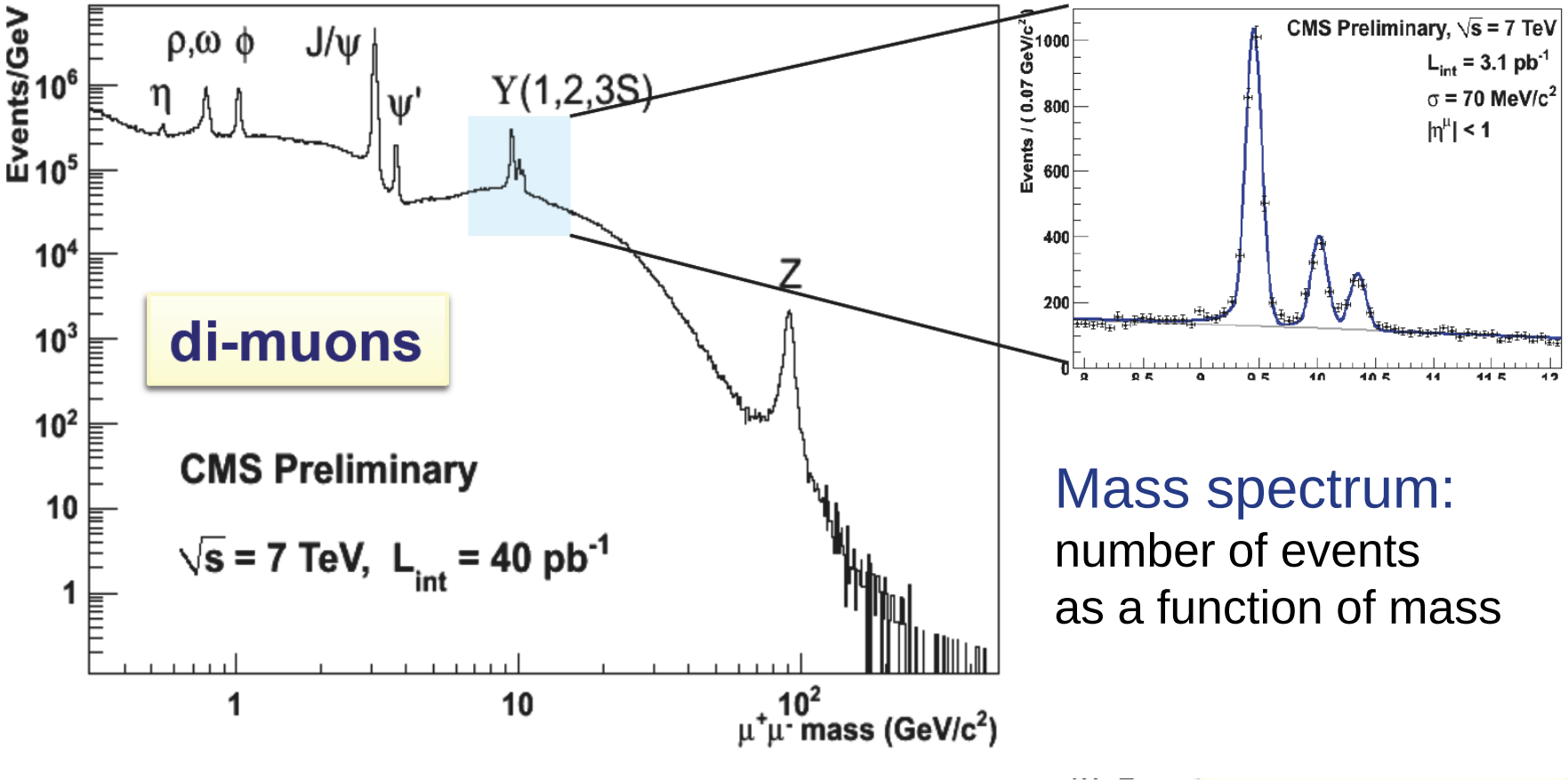


Data analysis example: mass spectrum of muon pairs

Events with two muons

Search for particles X decaying in two muons

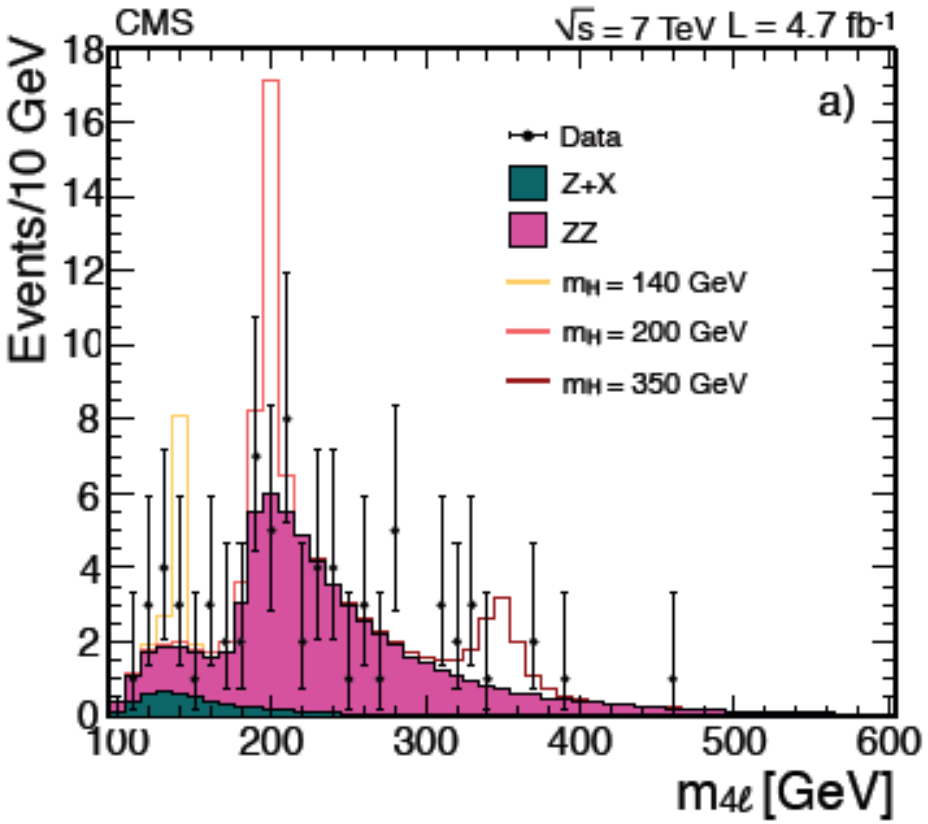
Compute mass m(X) from the energy-momentum of the two muons



Mass spectrum:
number of events
as a function of mass

H → ZZ → 4 leptons

Mass spectrum of 4 leptons

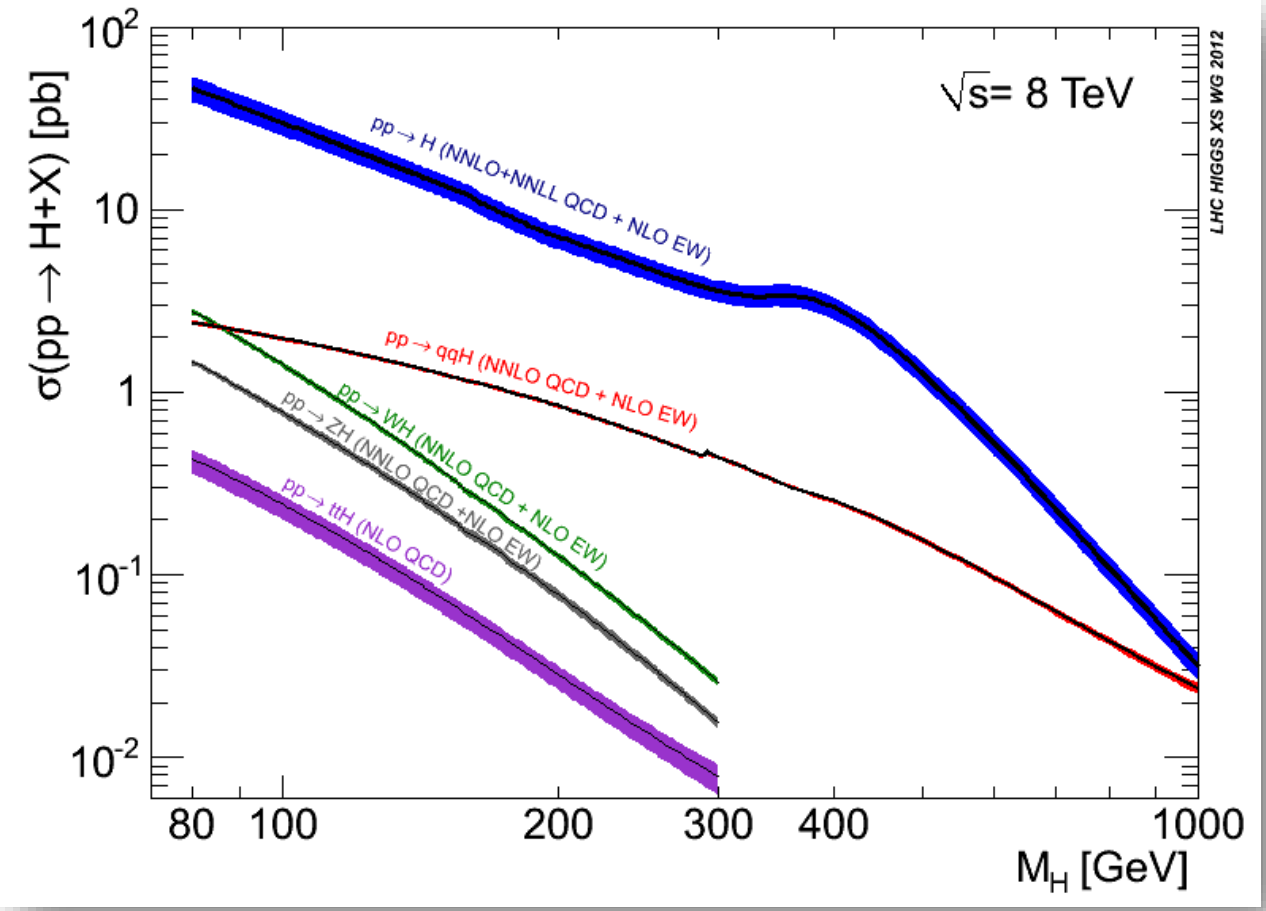


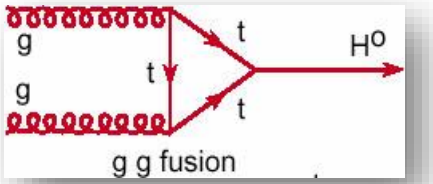
Rare process with low statistics

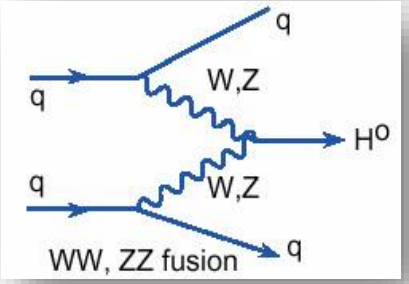
Requires sophisticated methods to isolate signal from background

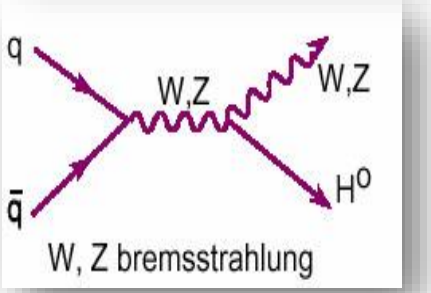
Higgs boson production

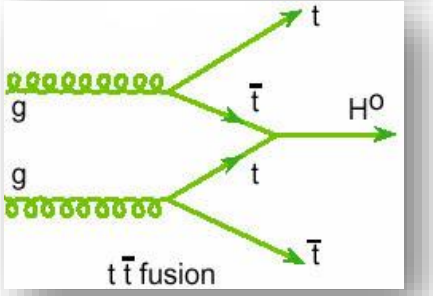
Higgs production rates are predicted by the Standard Model as a function of the Higgs mass









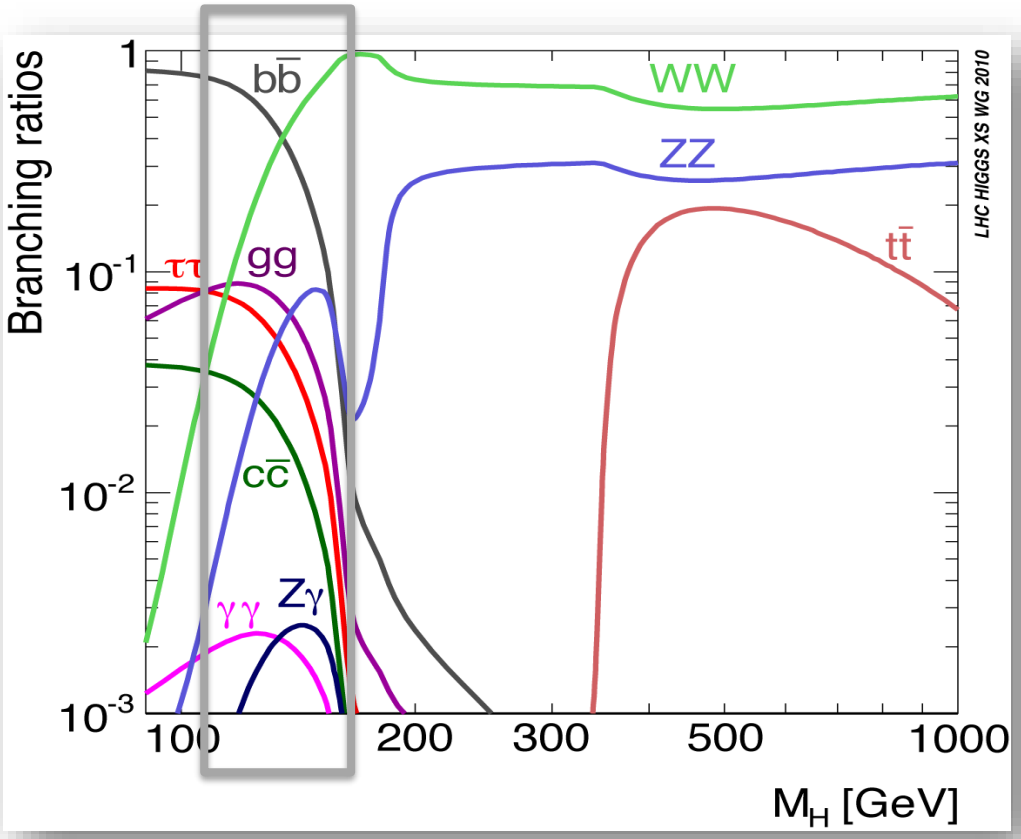


Higgs boson decays

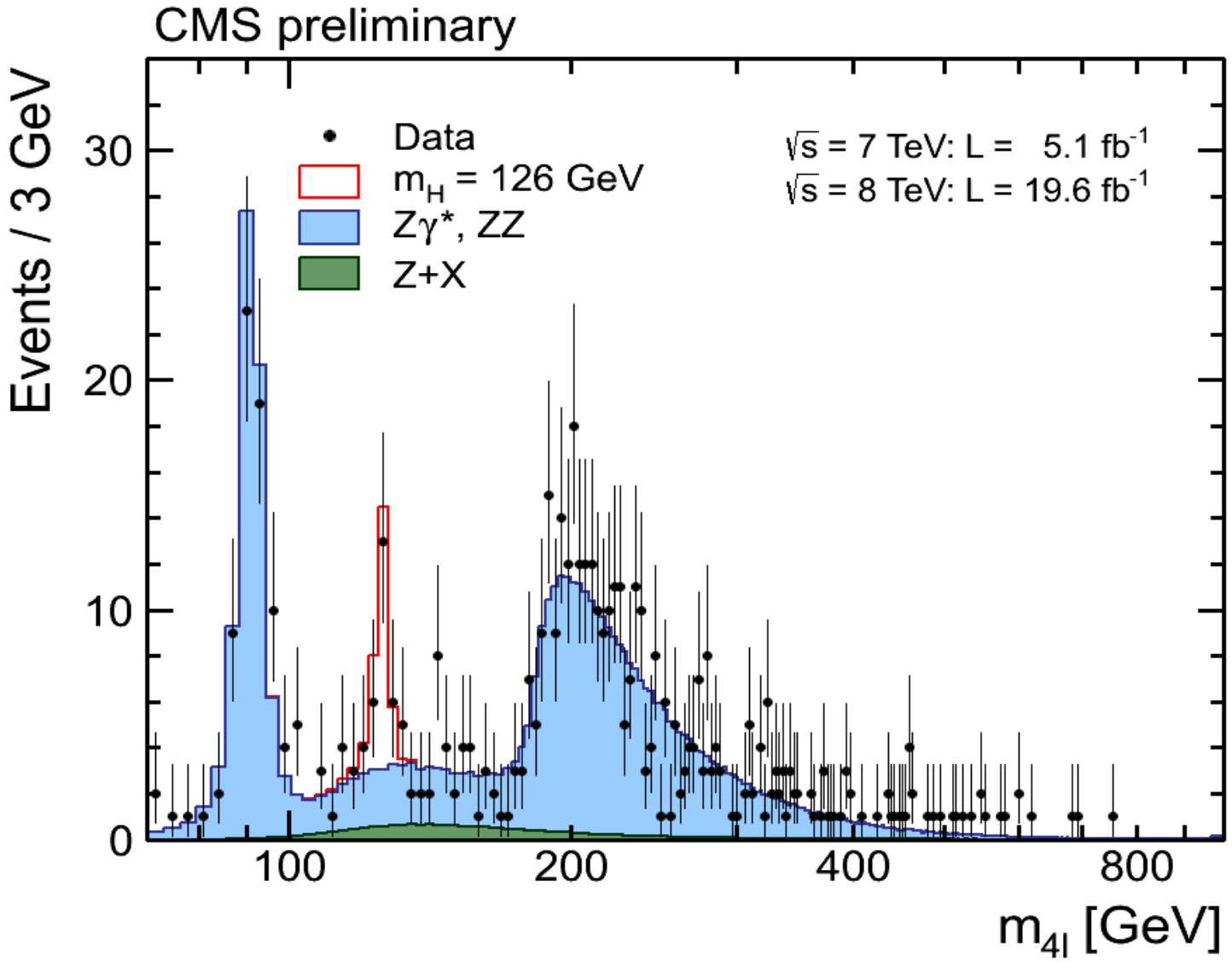
Five Higgs decay modes were exploited

Low mass region is very rich but also very challenging:

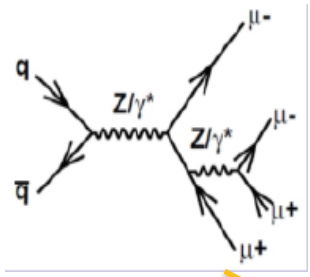
- High sensitivity, high resolution: ZZ, $\gamma\gamma$
- High sensitivity, low resolution: WW
- Low sensitivity, low resolution: bb, $\tau\tau$

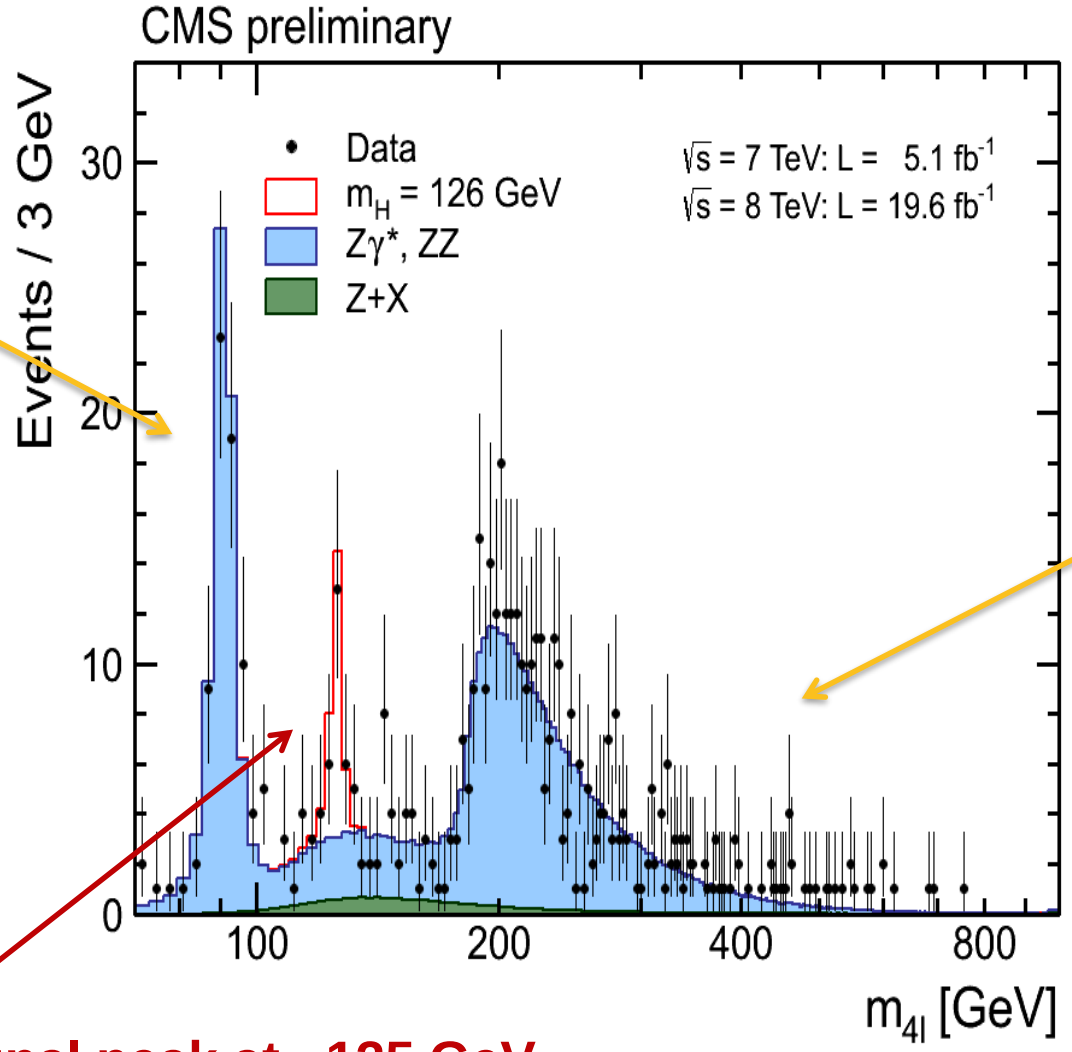


A beautiful peak



Four lepton mass spectrum



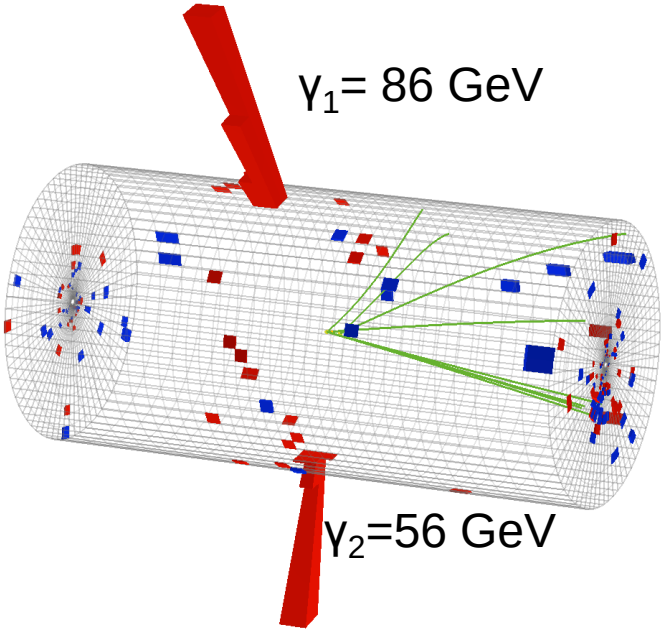


Very good control of the dominant ZZ background

M(4l)>160 GeV
Data 380
MC 364.5

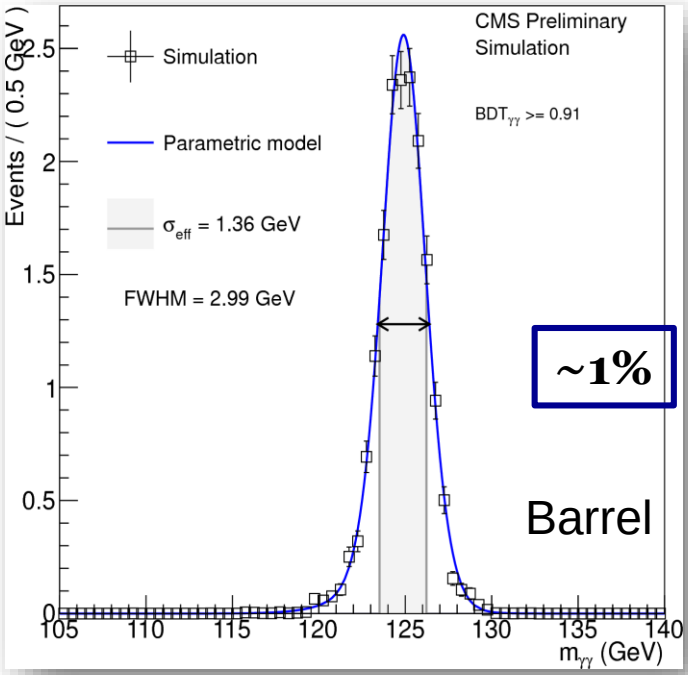
Clean signal peak at ~125 GeV

H → diphoton



Signature:

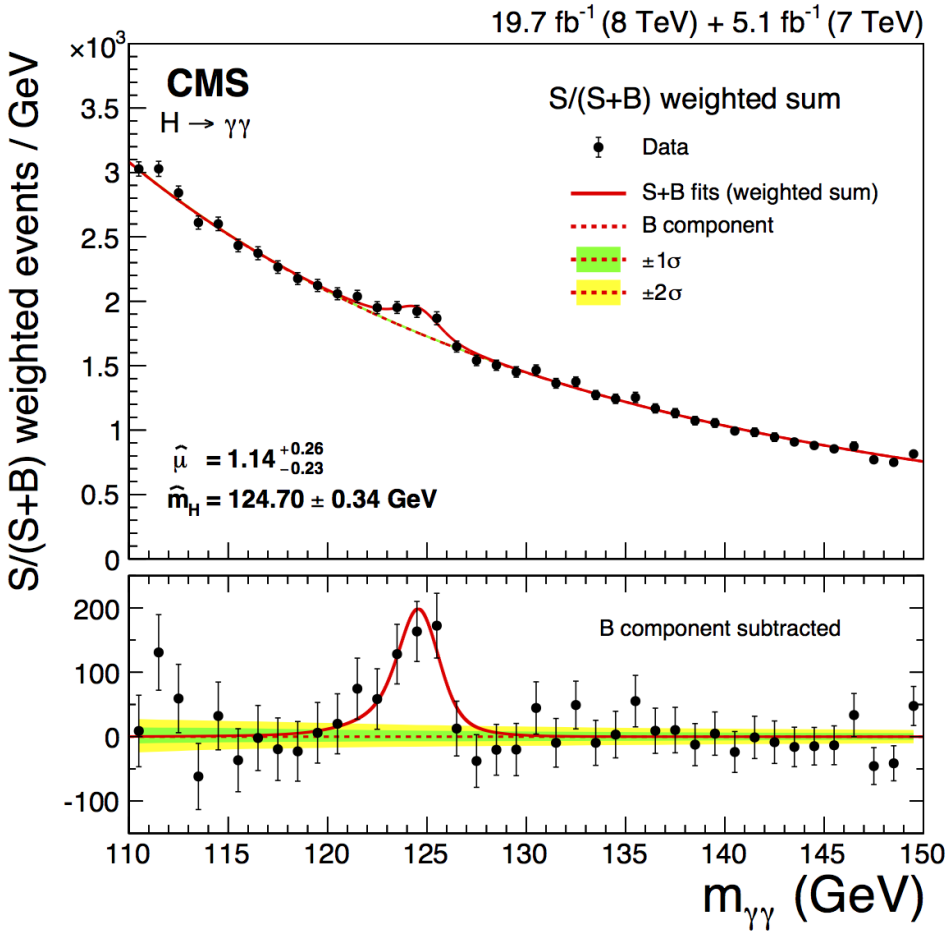
- Two energetic and isolated photons
- Narrow mass peak on top of a large steeply falling background

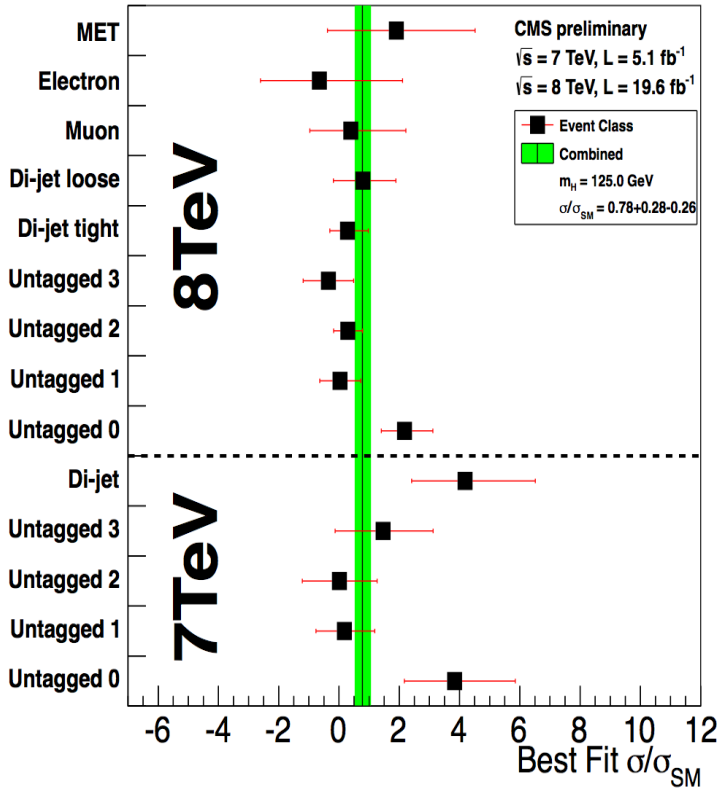


Relevant aspects:

- Photon identification/ background rejection
- Di-photon mass resolution
- Background estimation
- Primary vertex determination (pile-up!)

H→diphoton results

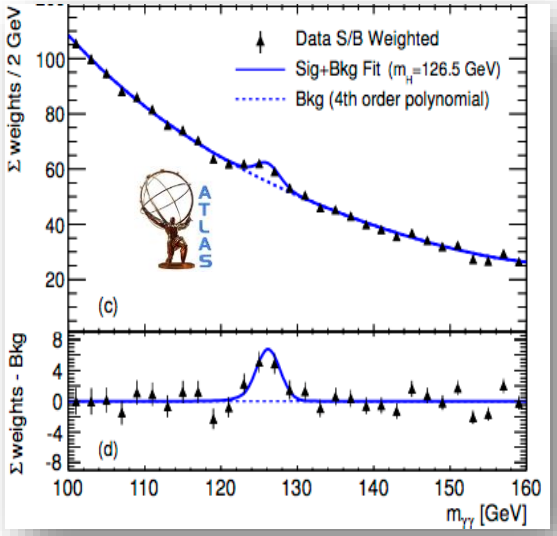


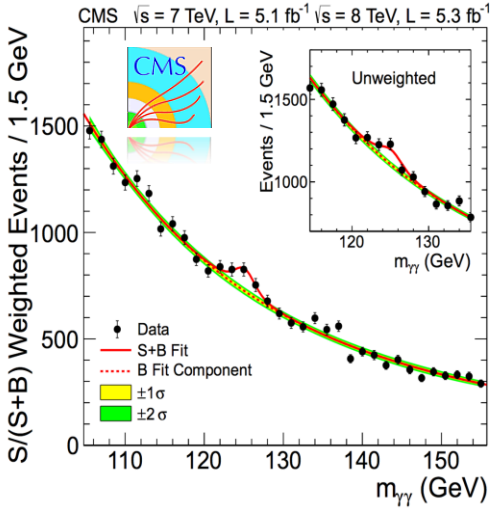


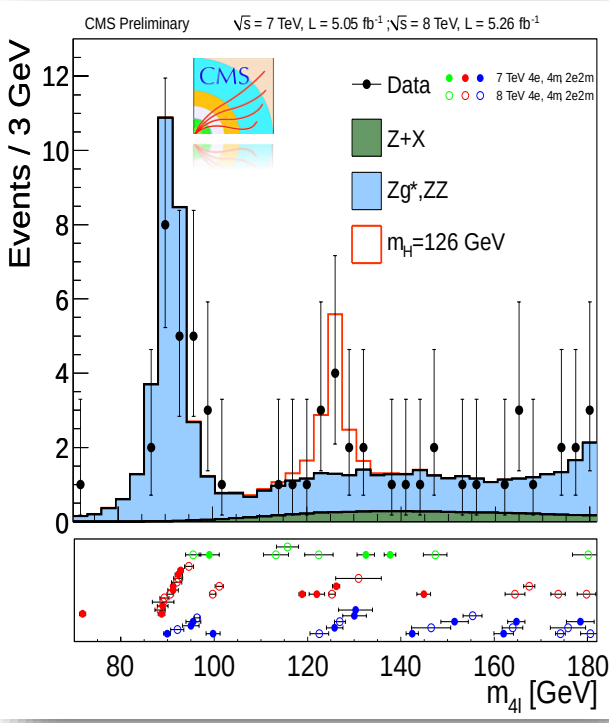
7+8 TeV:

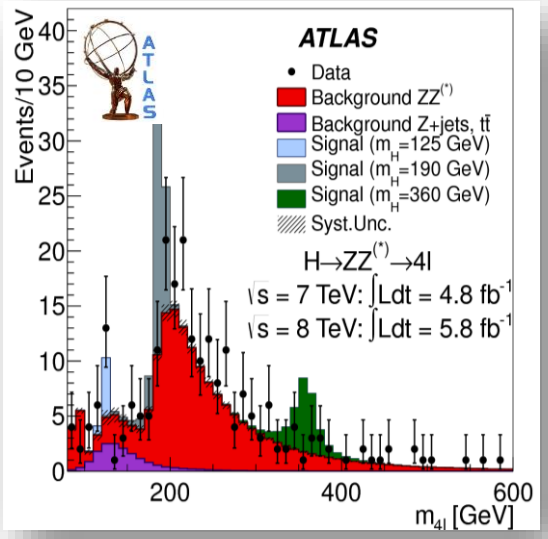
σ/σ_{SM} at 125.0 GeV = $\mathbf{0.78\ ^{+0.28}_{-0.26}}$

July 4th 2012









A major discovery in physics

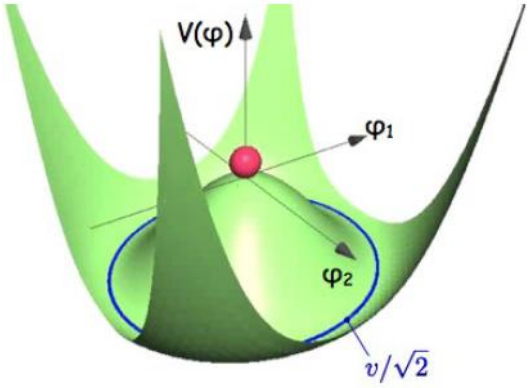
The **new boson** is a Higgs boson.

The **H boson** is not just … “yet another particle”.

The **space is filled with a Higgs field** since the origin of the Universe.

A new framework to understand the Universe. Cosmological models become more plausible:

- The Universe inflation after the big-bang
- Energy of a Higgs-like field as the source of all matter in the Universe



Unsolved mysteries

Beyond the standard model

The Standard Model answers many of the questions about the structure of matter.

But the Standard Model is not complete: there are still many unanswered questions.

Three generations

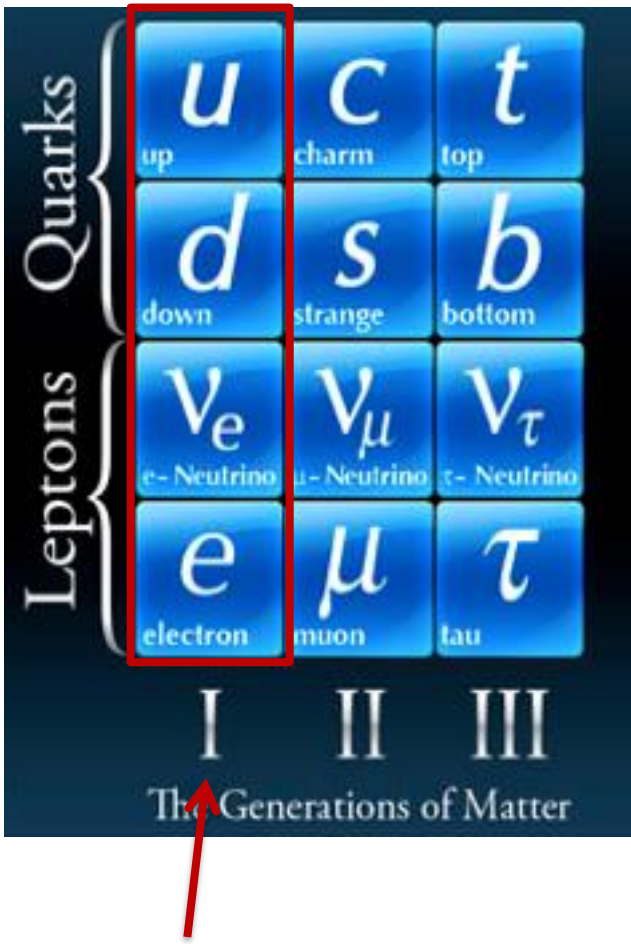
There are three "sets" of quark pairs and lepton pairs, called generations.

The generations increase in mass.

Higher generation particles decay into lower generation particles.

We do not know why there are three generations.

We do not have an explanation for the observed mass pattern



Every-day world

What happened to the antimatter?

Experiments tell us that for every fundamental particle there exists an antiparticle.

The big bang almost certainly produced particles and antiparticles in equal numbers.

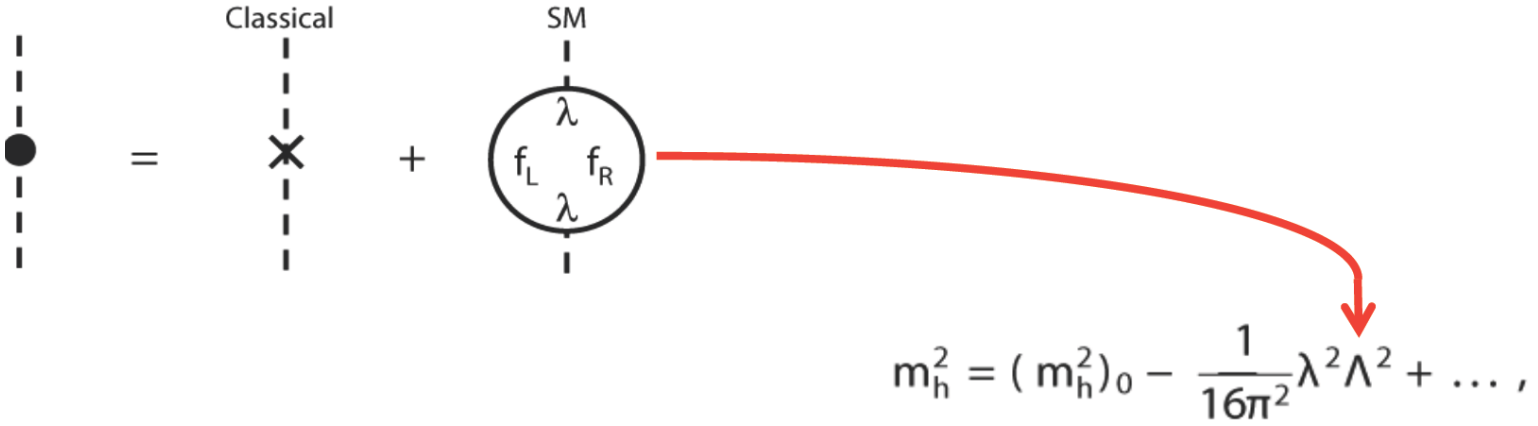
However our observations indicate that we live in a universe of matter, not antimatter.

What happened to the antimatter?

Higgs and hierarchy problem

In the SM the Higgs mass is a huge problem:

- The calculation of the Higgs mass results in a sum of many terms
- Each term can be as large as the Plank scale (10^{19} GeV)
- Miraculous cancelations are needed to keep the Higgs mass ~ 125 GeV

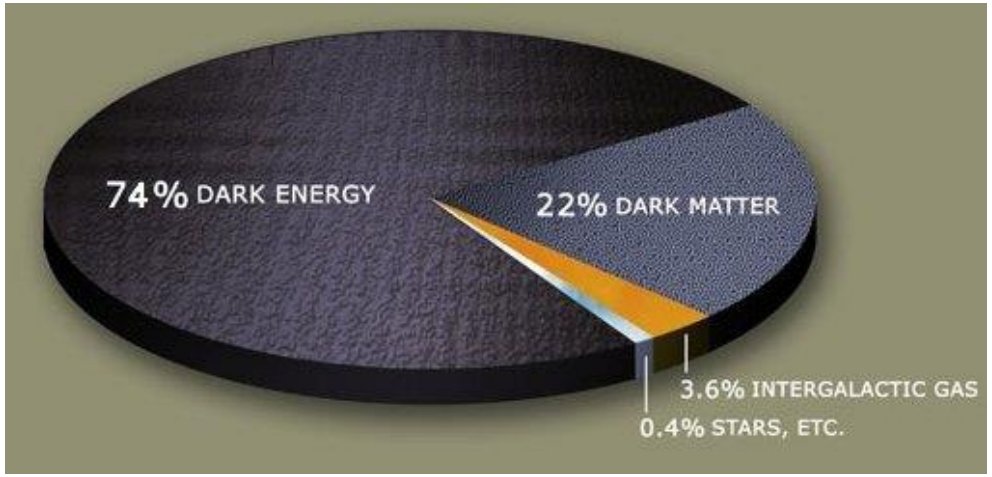


This is known as the hierarchy problem

The dark side of the Universe

Long standing problem:

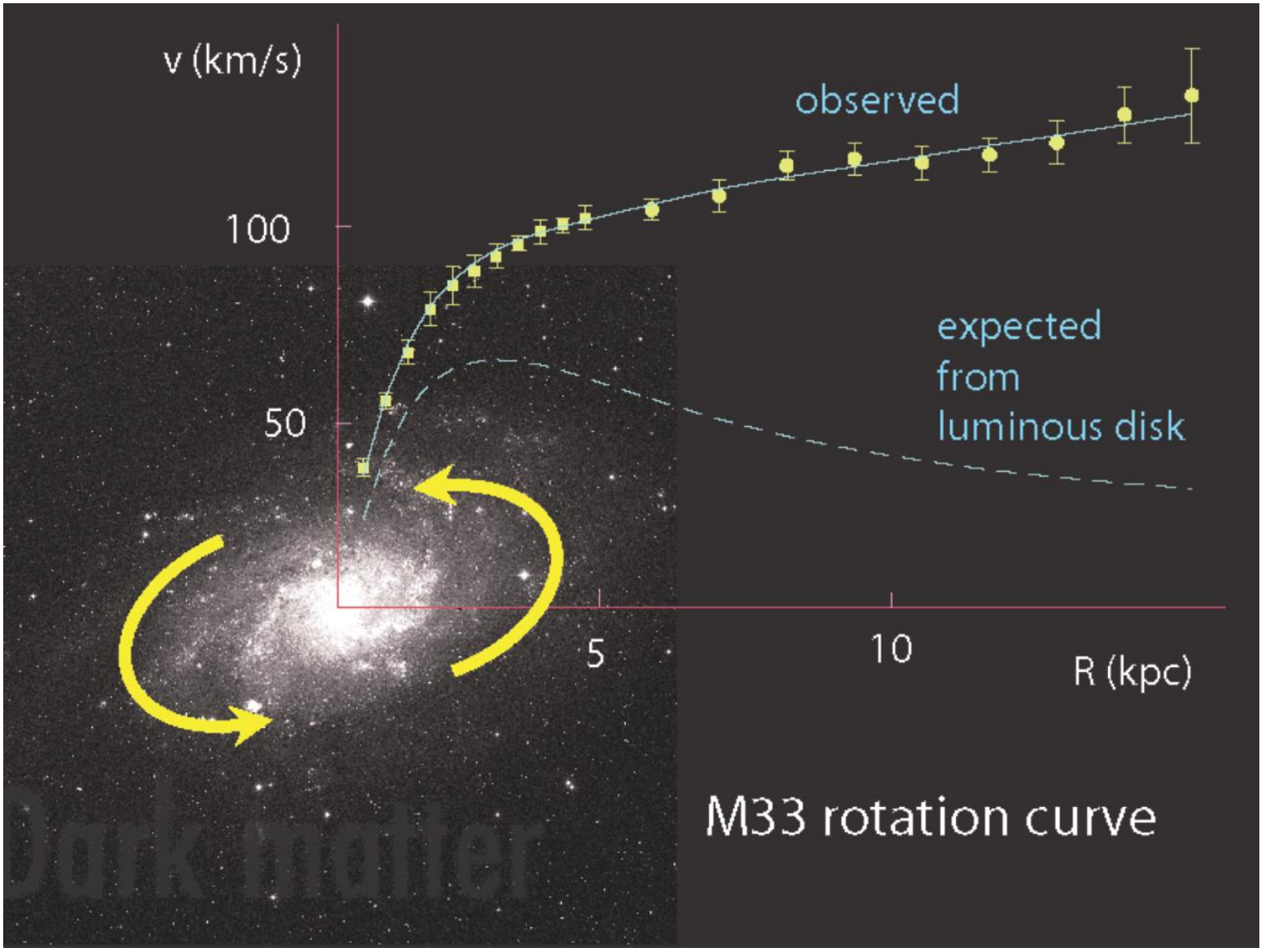
We know that ordinary matter is only ~4% of the matter-energy in the Universe.



What is the dark stuff which accounts for 96% of the matter-energy of the Universe? Nobody knows.

It is one of the greatest mysteries of science

The dark matter problem



What is the dark matter?

Must be invisible matter (“dark matter”) to account for these observations.

What in the world (out of this world?) is that?

After 40 years, answer still unknown.

“Ordinary matter” makes up only about 1/6 of the matter in the universe.

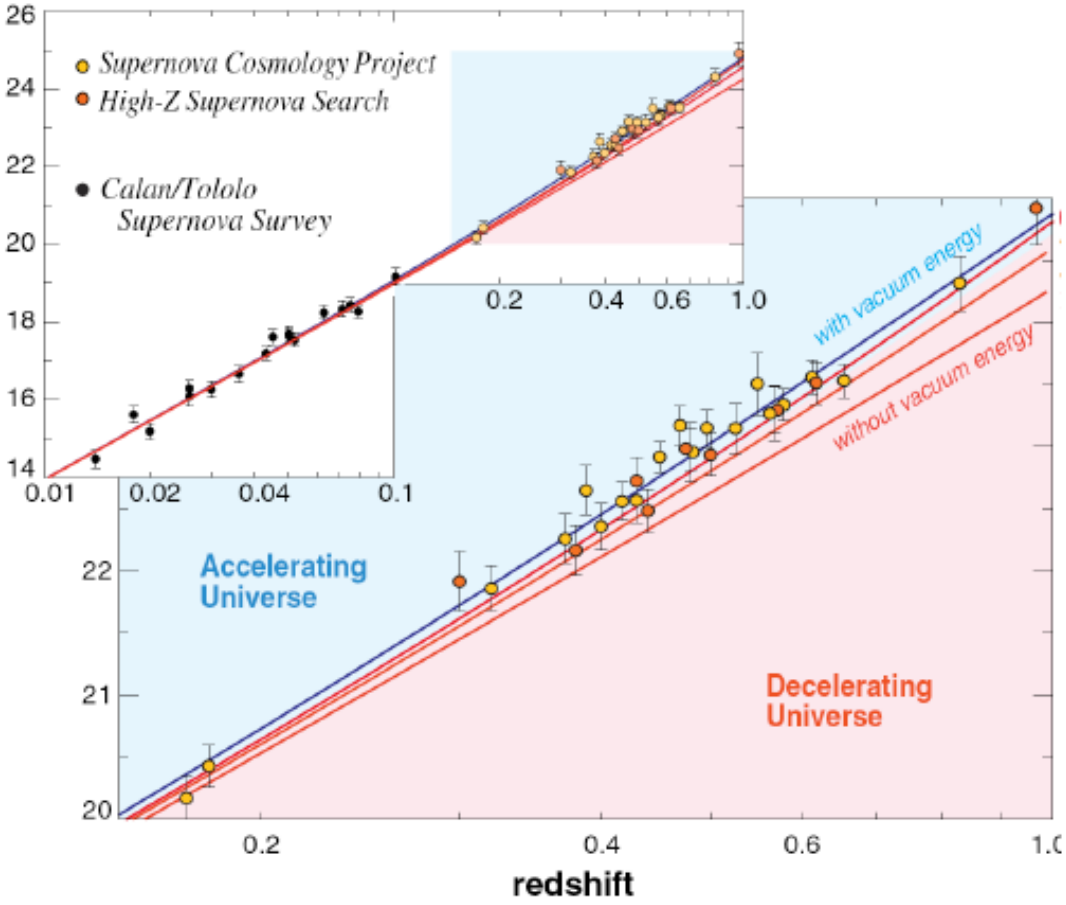
The rest is something else!

The Universe expansion is accelerating

In 1998, two groups used distant Supernovae to measure the expansion rate of the universe.
(Supernova Cosmology Project and High-z Supernova Team)

They got the same result:
The Universe expansion is accelerating

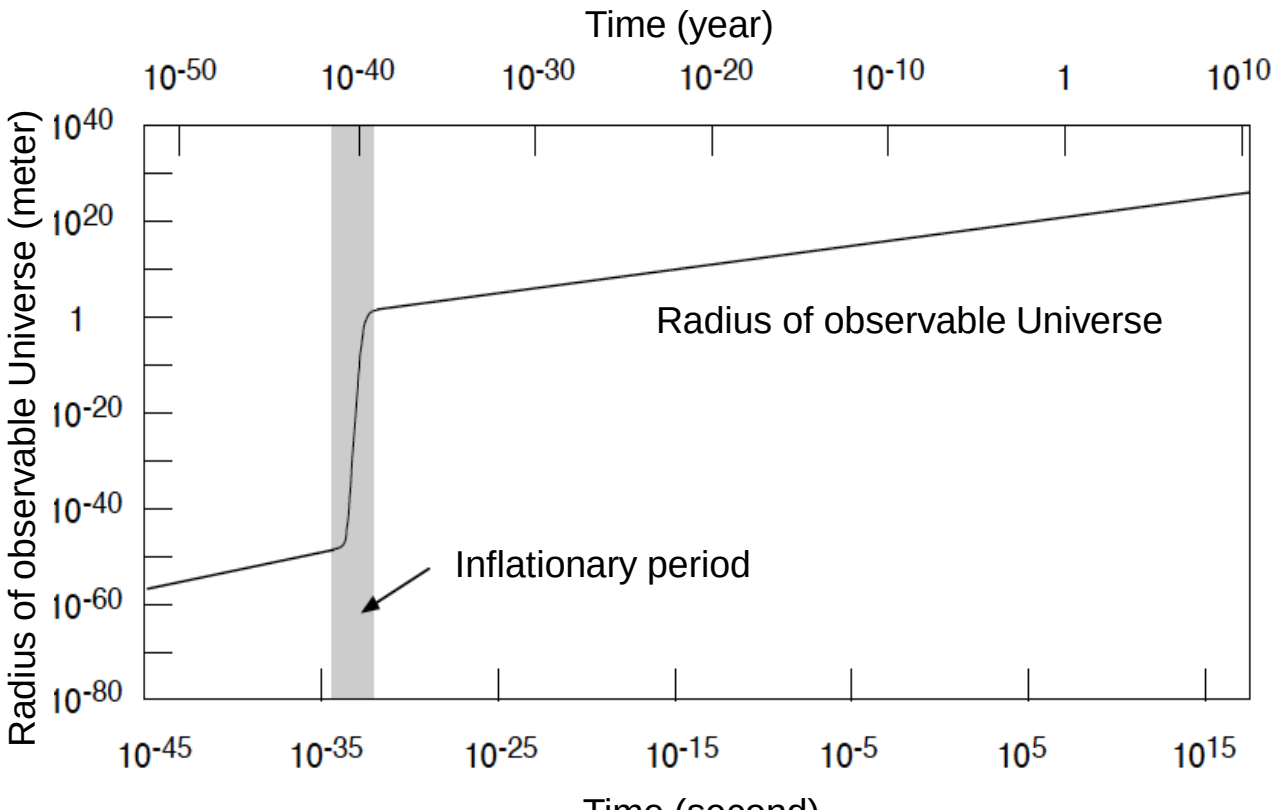
General Relativity requires that some form of energy fills space (cosmological constant) to justify accelerated expansion



Cosmological inflation

In the very early universe space undergoes a dramatic exponential expansion.

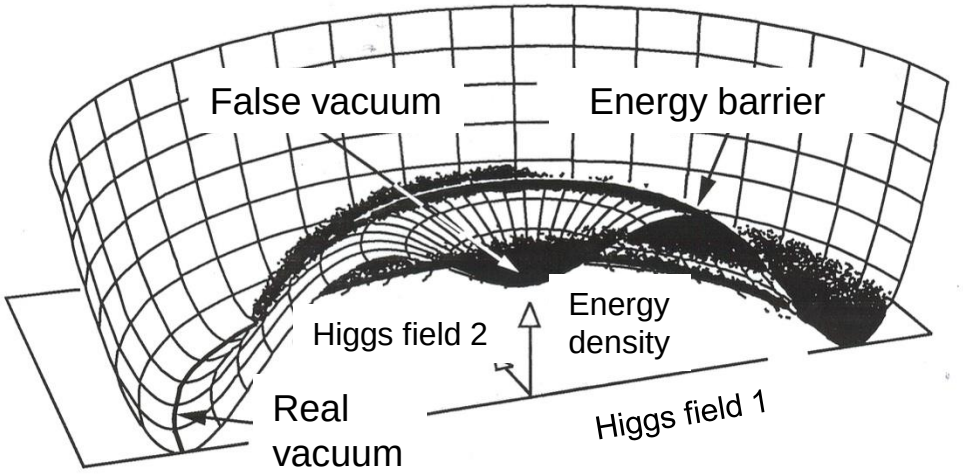
Explains why the Universe has a uniform Temperature (3 K) and why space-time has a flat geometry



The inflation theory was developed independently in the late 1970's by Alan Guth, Alexey Starobinsky, and others

Higgs like field and inflation

At the origin of the Universe, the energy density of a Higgs-like field is positive.



While the energy density of the Higgs field is positive, the Universe expands at accelerated rate (inflation)

Inflation stops when the Higgs field decays to the real vacuum.

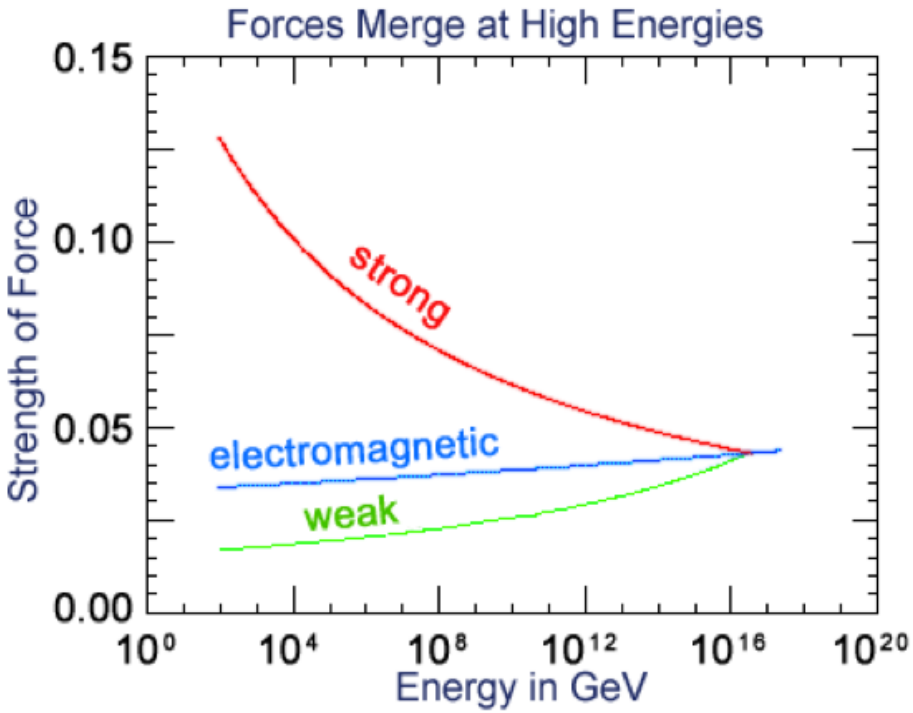
The energy released by the Higgs field is converted into matter particles.

Beyond the Standard Model

Forces and the Grand Unified Theory

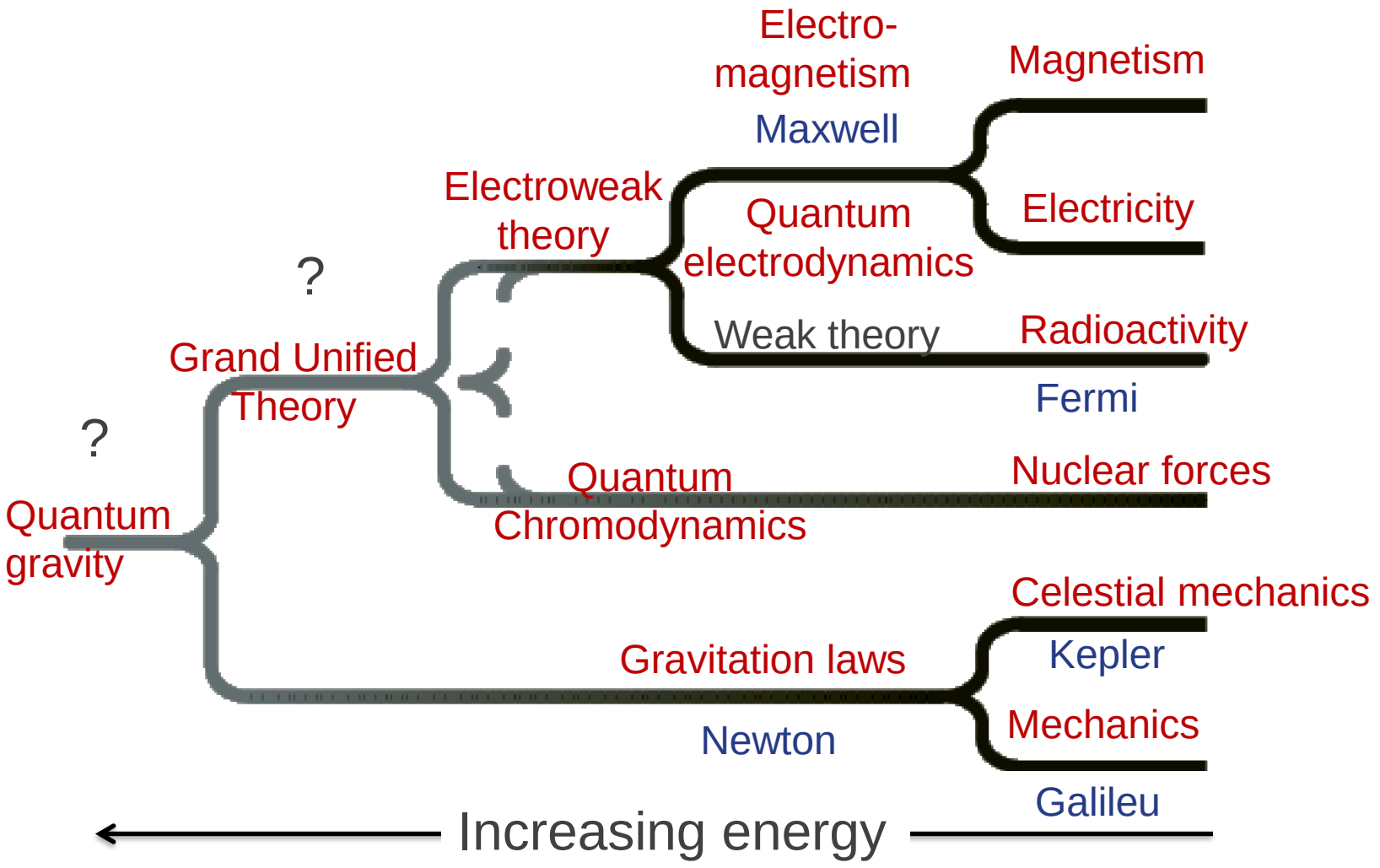
Physicists hope that a Grand Unified Theory will unify the strong, weak, and electromagnetic interactions.

However, how can this be the case if strong and weak and electromagnetic interactions are so different in strength and effect?



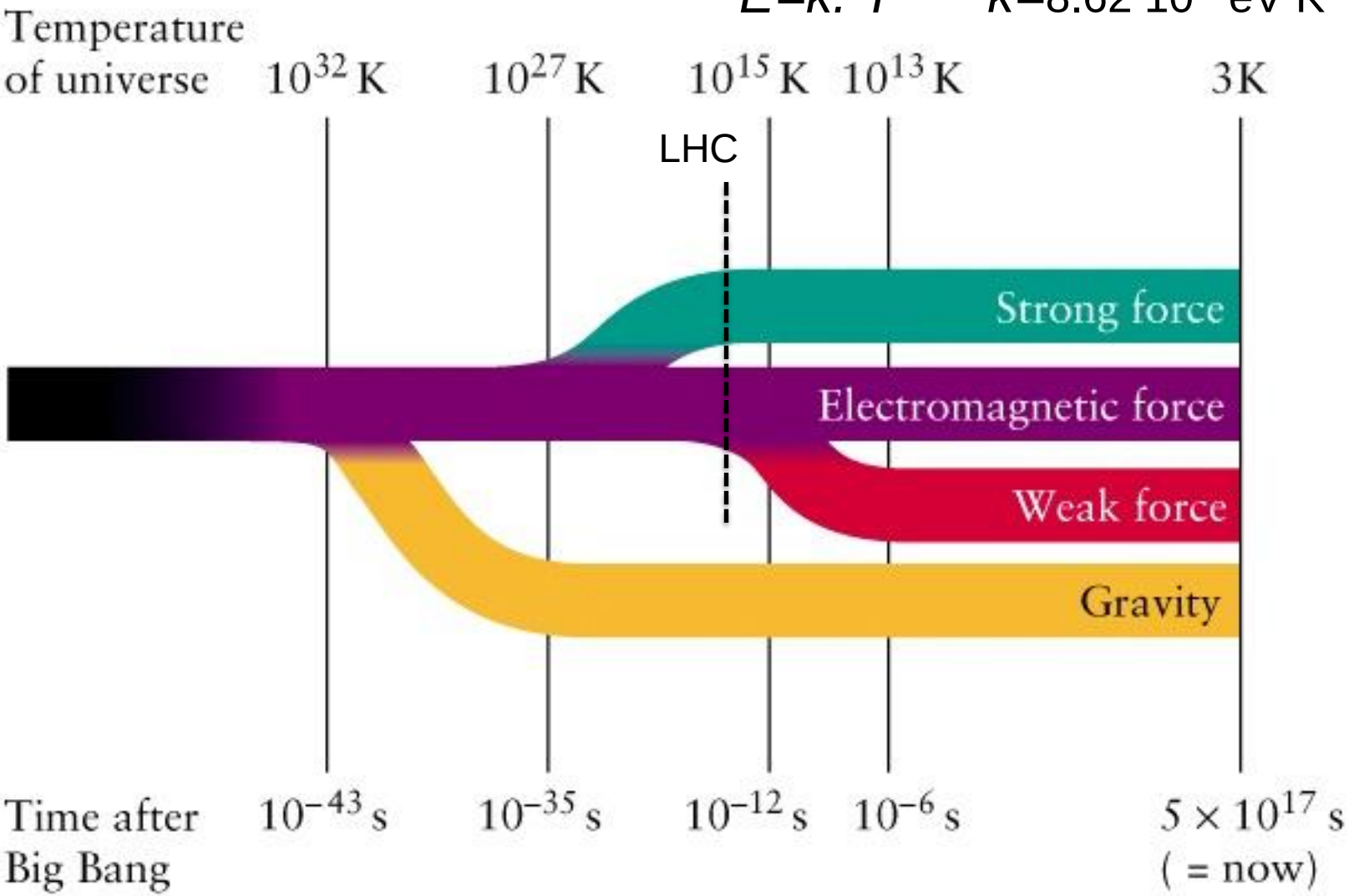
Strangely enough, current data and theory suggests that these varied forces merge into one force when the particles being affected are at a high enough energy.

Unification of the Forces



Forces and expansion of the Universe

$E = k.\ T$ $k = 8.62\ 10^{-5}\ \text{eV K}^{-1}$



Supersymmetry

Some physicists have proposed a new fundamental symmetry:

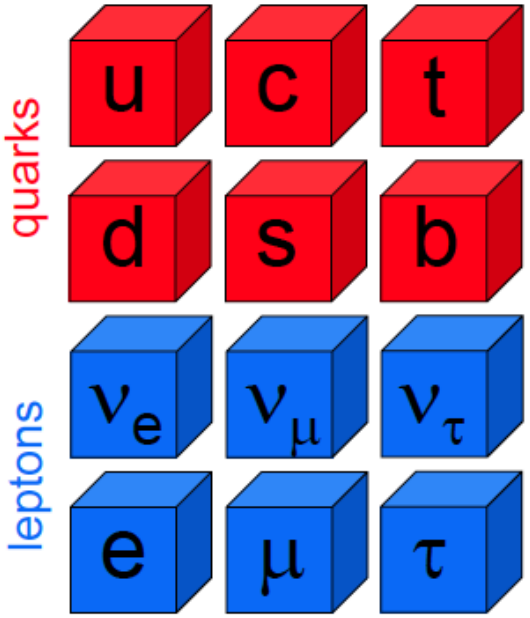
- Every fundamental matter particle should have a massive force particle partner
- Every force particle should have a massive matter particle partner

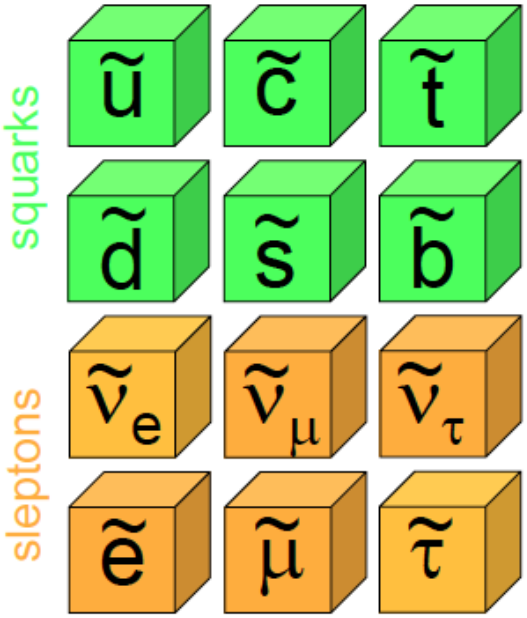
This relationship between matter particles and force carriers is called supersymmetry (**SUSY**)

No supersymmetric particle has yet been found, but experiments are underway at CERN to detect supersymmetric partner particles.

Supersymmetry

Double the whole table with a new type of matter?





Heavy versions of every quark and lepton
Supersymmetry is broken

The Lightest Susy Particle (LSP) is a candidate to explain Dark Matter.

Could DM be SUSY particles?

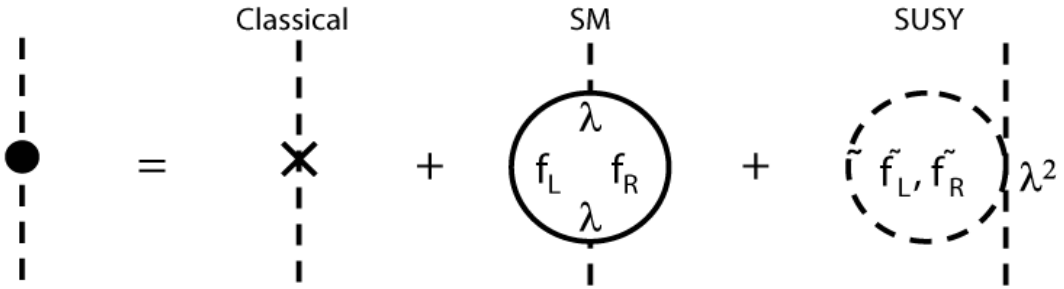
For every “normal” force quanta (boson), there are supersymmetric partners:

photon	photino
W, Z bosons	Wino, Zino
gluon	gluino
Higgs boson	higgsino

These “…inos” are prime suspects to be the galactic dark matter!

Relics from the Big Bang!

SUSY and the Higgs mass



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

Natural cancellation

Higgs mass:

- correction has quadratic divergence!
  - Λ a cut-off scale – e.g. Planck scale

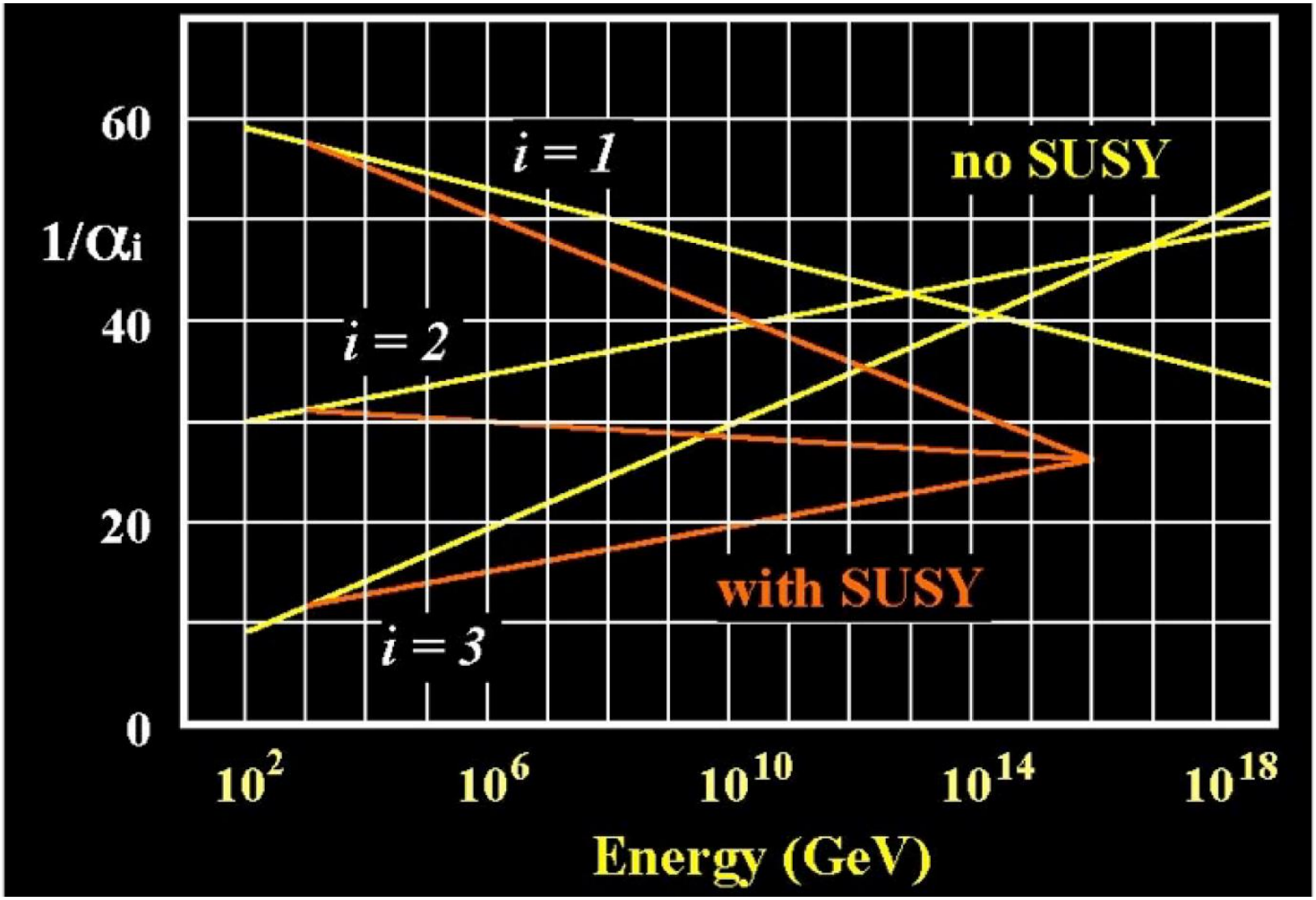
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots$$

$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}}) ,$$

Superpartners fix this:

- Need superpartners at mass ~1-2 TeV
  - Otherwise the logarithmic term becomes too large, which would require more fine-tuning.

The temptation unification



Extra dimensions

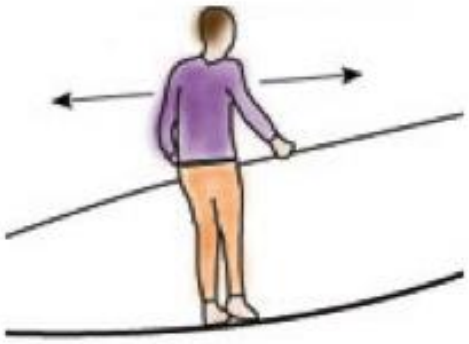
Space-time could have more than three space dimensions. The extra dimensions could be very small and undetected until now.

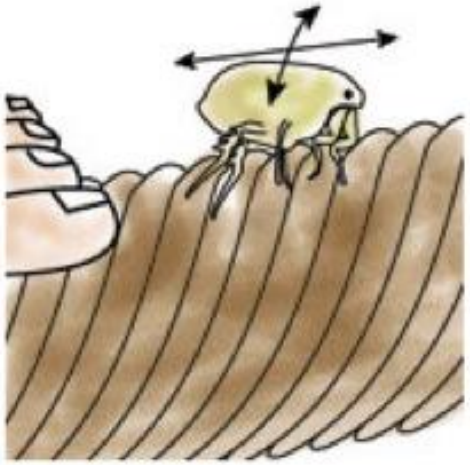
How can there be extra, smaller dimensions?

The acrobat can move forward and backward along the rope: **one dimension**

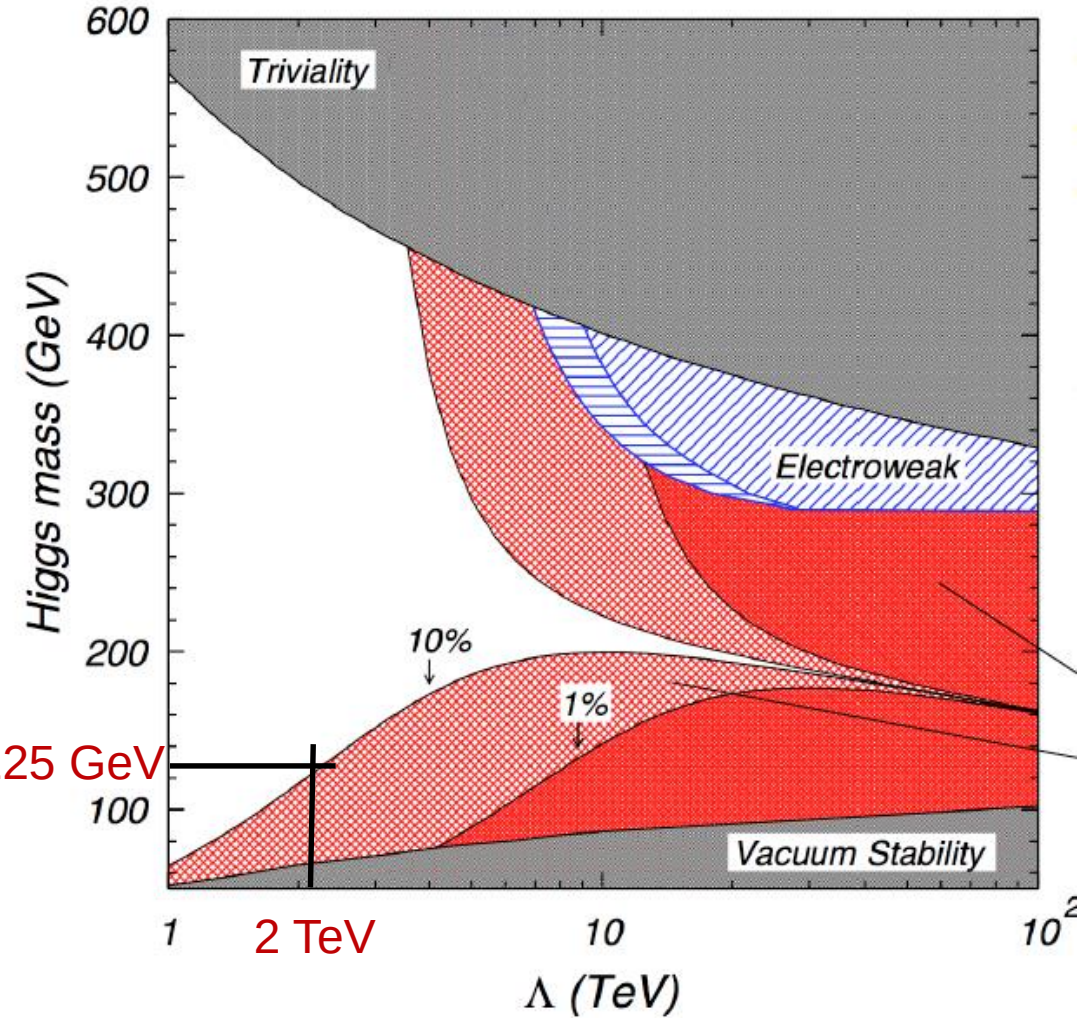
The flea can move forward and backward as well as side to side: **two dimensions**

But one of these dimensions is a small closed loop.





New physics at a few TeV?



Λ □ Scale of New Physics

Naturalness implies Supersymmetry or another 'New Physics' below ~ 2 TeV

There are a large number of models which predict new physics at the TeV scale accessible at the LHC

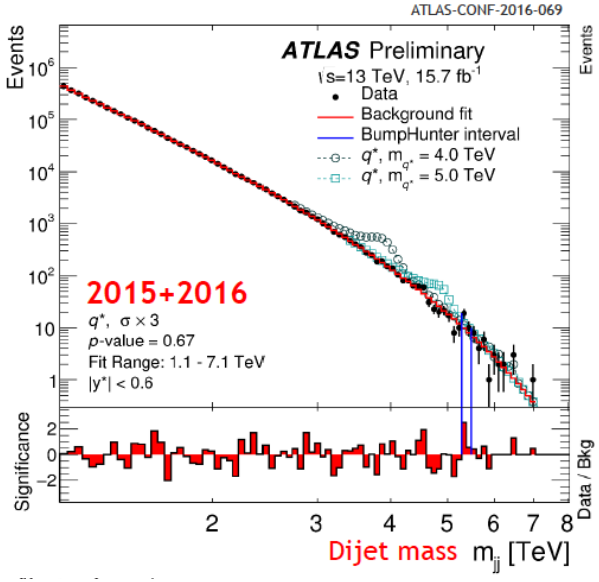
Still no sign of new physics at LHC…

No new bumps…

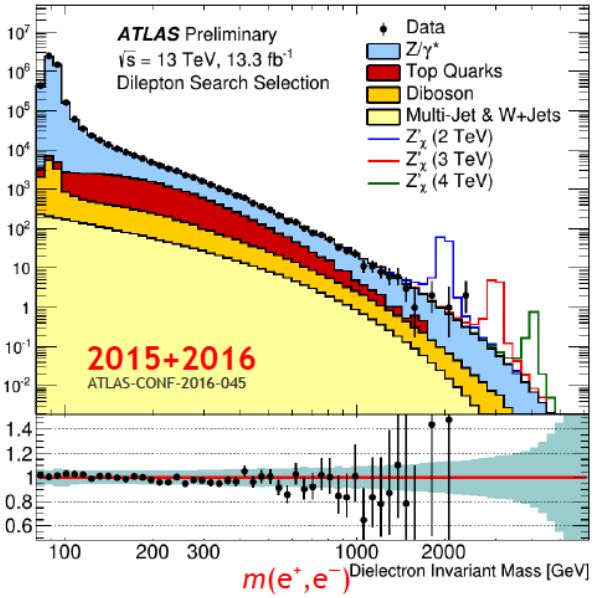
New particles could decay in pairs of quarks (jets), leptons or photons, among others.

The new particle would be revealed by peaks appearing in the mass distribution of the pair.

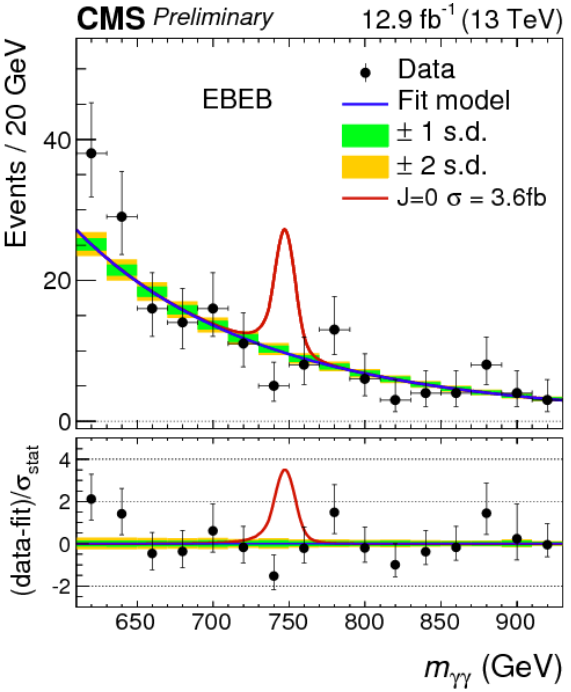
Di-jets



Di-leptons



Di-photons



The future

Particle physics is big science

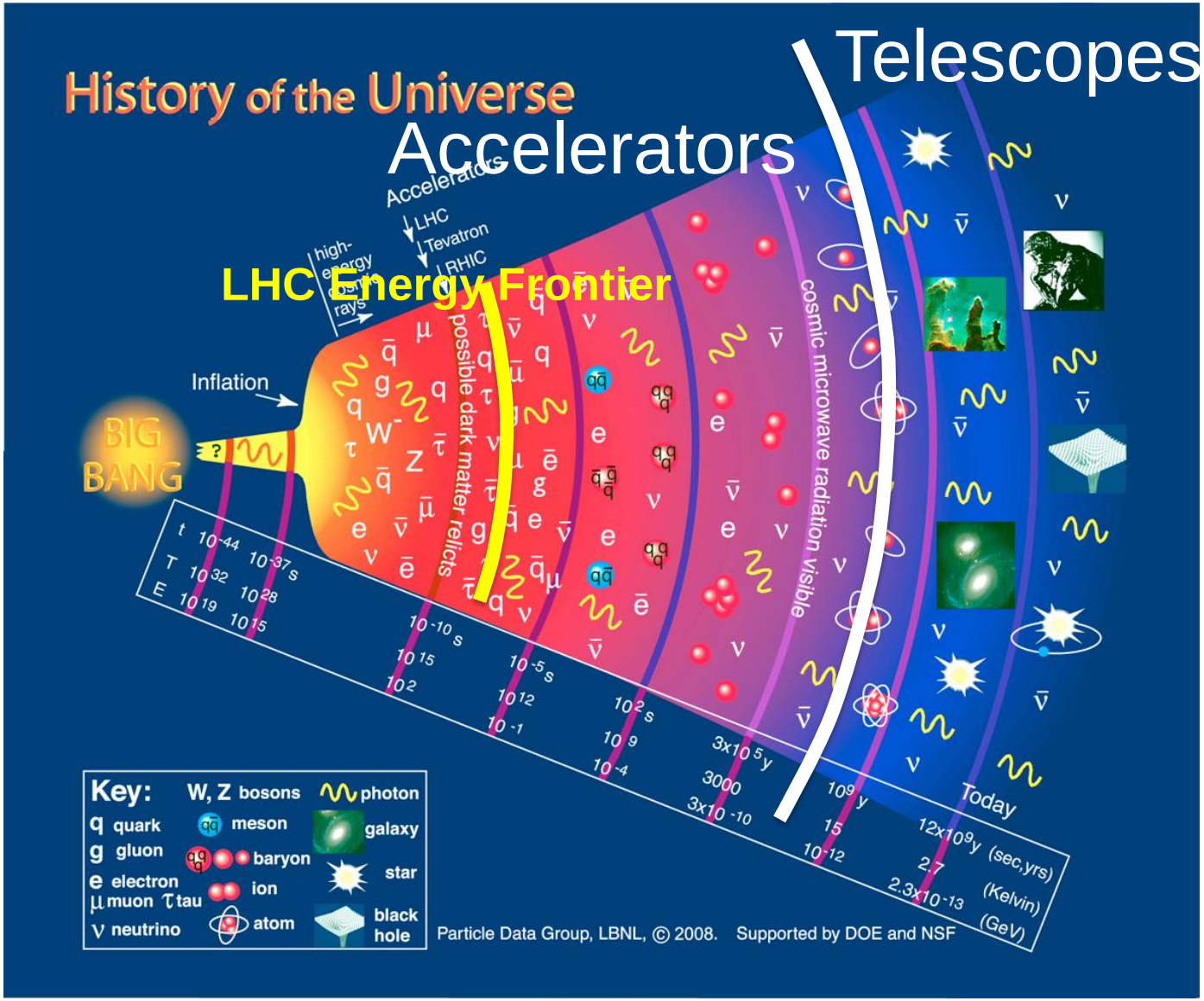
Can't we do this research without increasingly more powerful accelerators?

Aren't there subtler ways to unveil the mysteries of Nature?

Unfortunately, to the best of our knowledge the answer to both questions is NO.

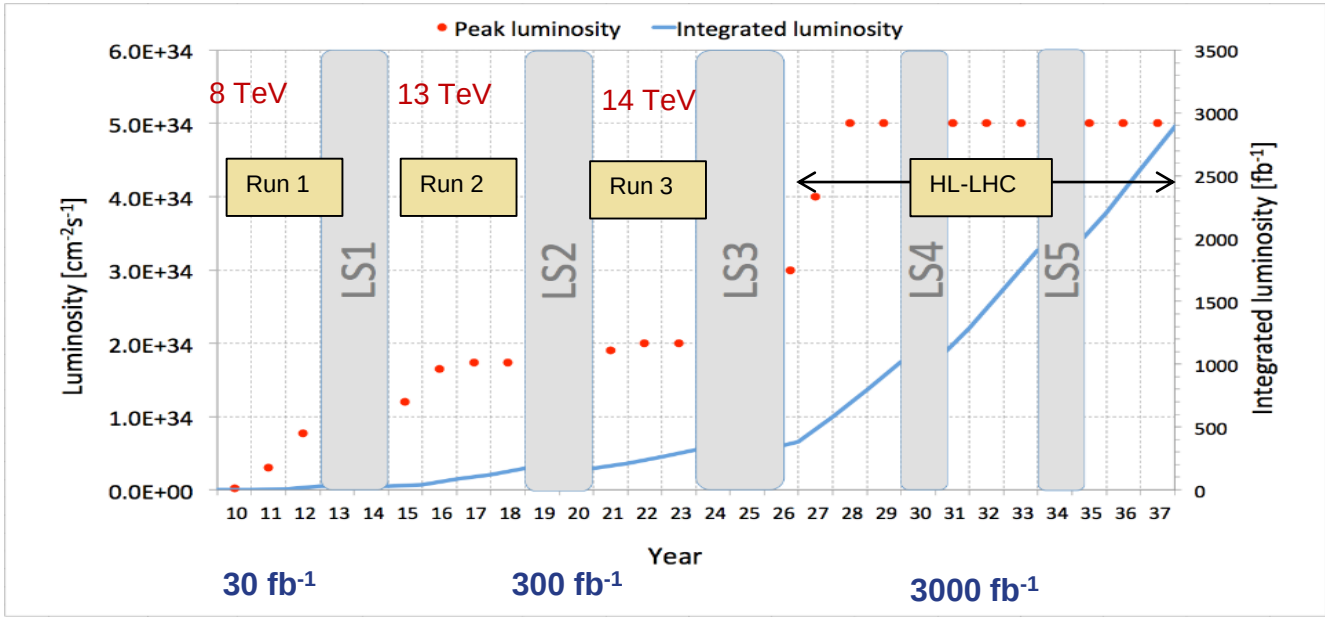
Before some unexpected breakthrough(s) happens, this tendency will remain.

Tools to understand the Universe



High Luminosity LHC

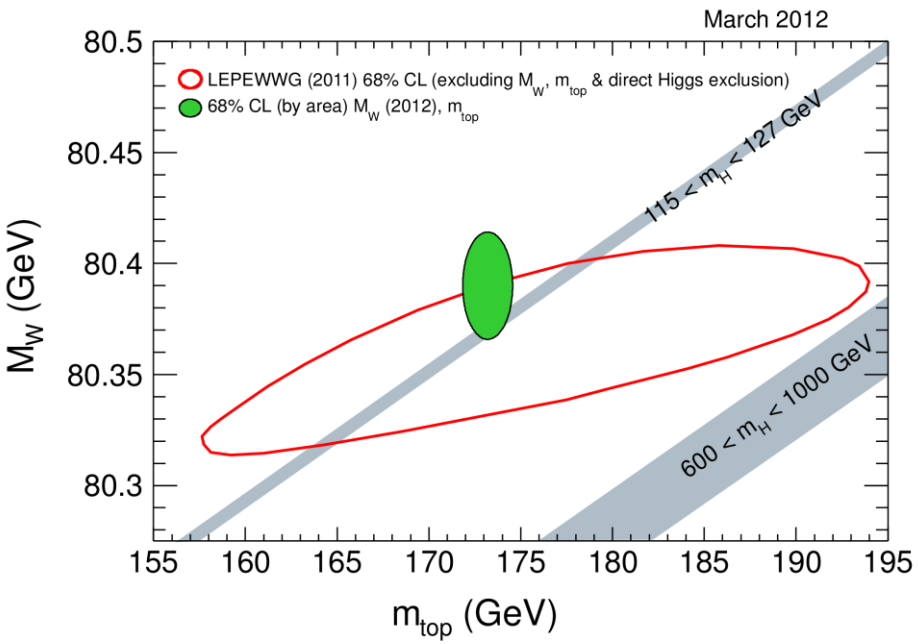
1. Search for direct evidence of new physics
2. Measure the Standard Model with very high precision
3. Deviations relative to the SM may point the direction to New Physics



The power of precision measurements

The SM establishes a precise relation between the masses of the Higgs, the Top quark and the W boson.

Even before the Higgs discovery, the precision measurements of W and Z bosons done in e+e- collisions at LEP and of top quark at the Tevatron had pointed towards a light Higgs.



Measuring deviations of Higgs properties relative to the prediction of the SM provides powerful guidance towards Physics Beyond the SM.

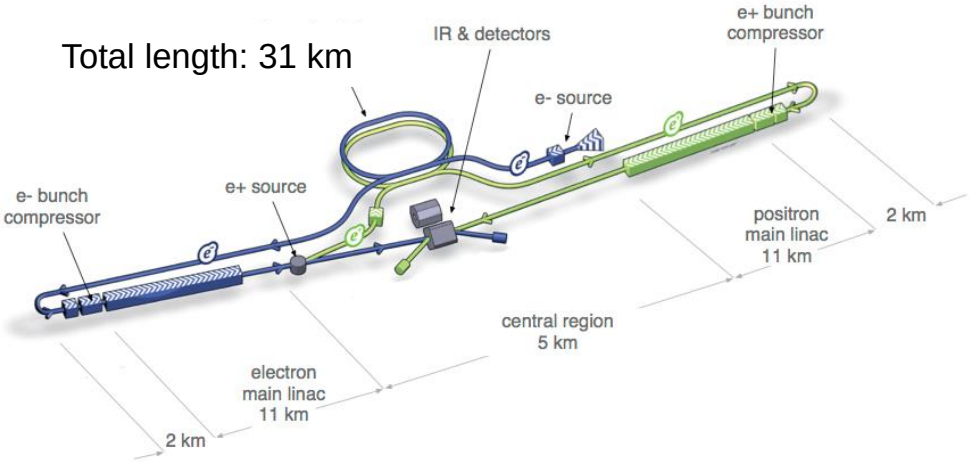
A precision of the order of 0.1-1% will be needed! High luminosity will be needed.

Linear e+e- colliders

Precise measurements of the Higgs boson

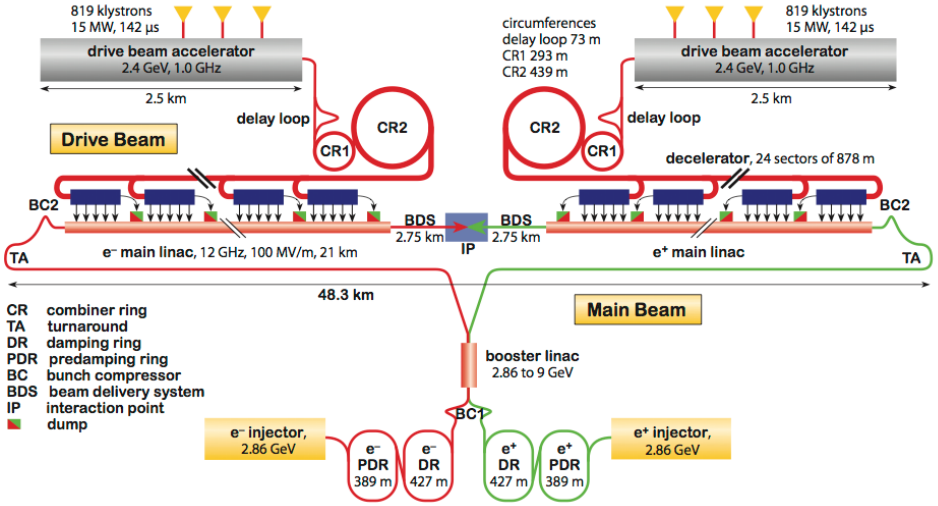
International Linear Collider (ILC)

- 0.5 TeV machine
- Construction duration ~10 years
  → physics could start ~2030



Compact Linear Collider (CLIC)

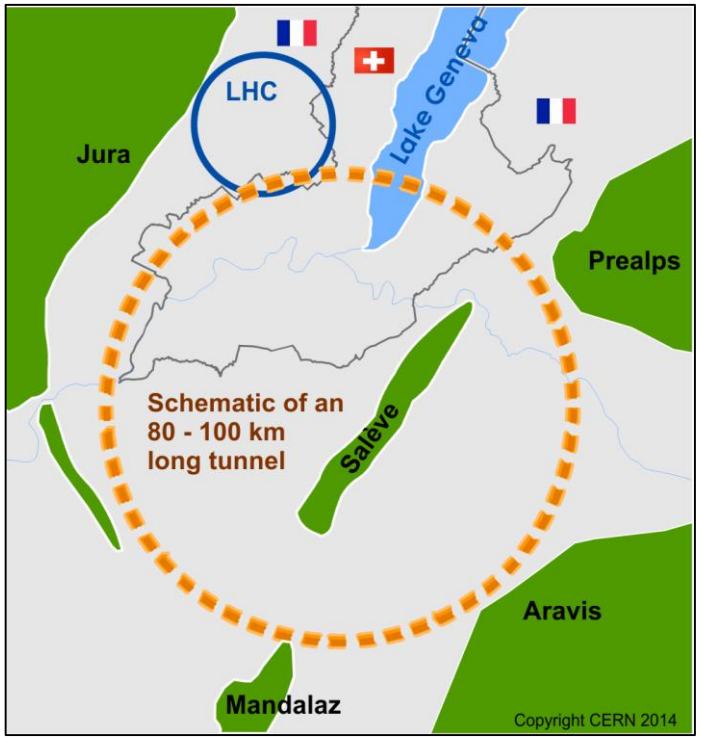
- 3 TeV collider - 50 km



The FCC project at CERN

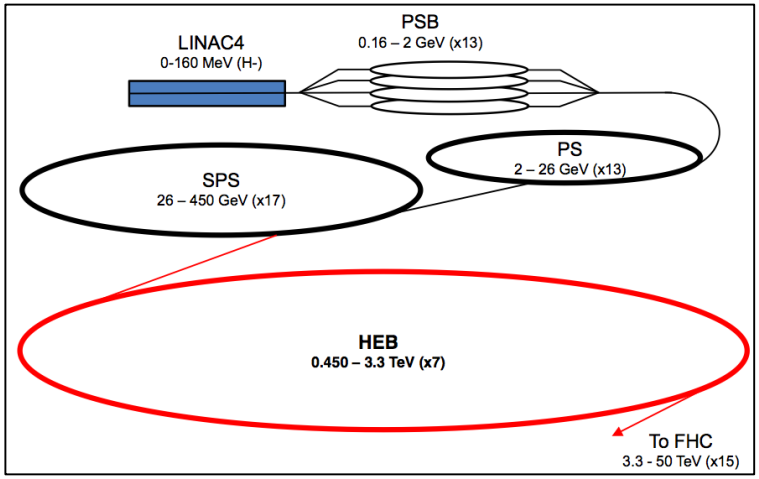
Future Circular Collider in a ~100 km ring:

- e+e- collider 350 GeV and high luminosity
- proton collider, E = 100 TeV



90-100 km ring fits geology in Geneva area

FCC injector chain would be based on existing accelerator complex



Many big technological challenges:

- technology of bending dipoles
- synchrotron radiation
- stored beam energy

Final comments

- The discovery of the Higgs boson opens new paths of exploration and a very broad and challenging experimental program
- New physics: hiding well, needs more data or is beyond present LHC reach ?
- Hadron colliders permit direct exploration of the “energy frontier”
- Precision measurements at High-Luminosity LHC and at future e+e- colliders have great potential to uncover physics beyond the SM
- The full exploitation of the LHC, as well as future high-energy and high intensity colliders, are necessary to advance our knowledge of fundamental physics

Thank you