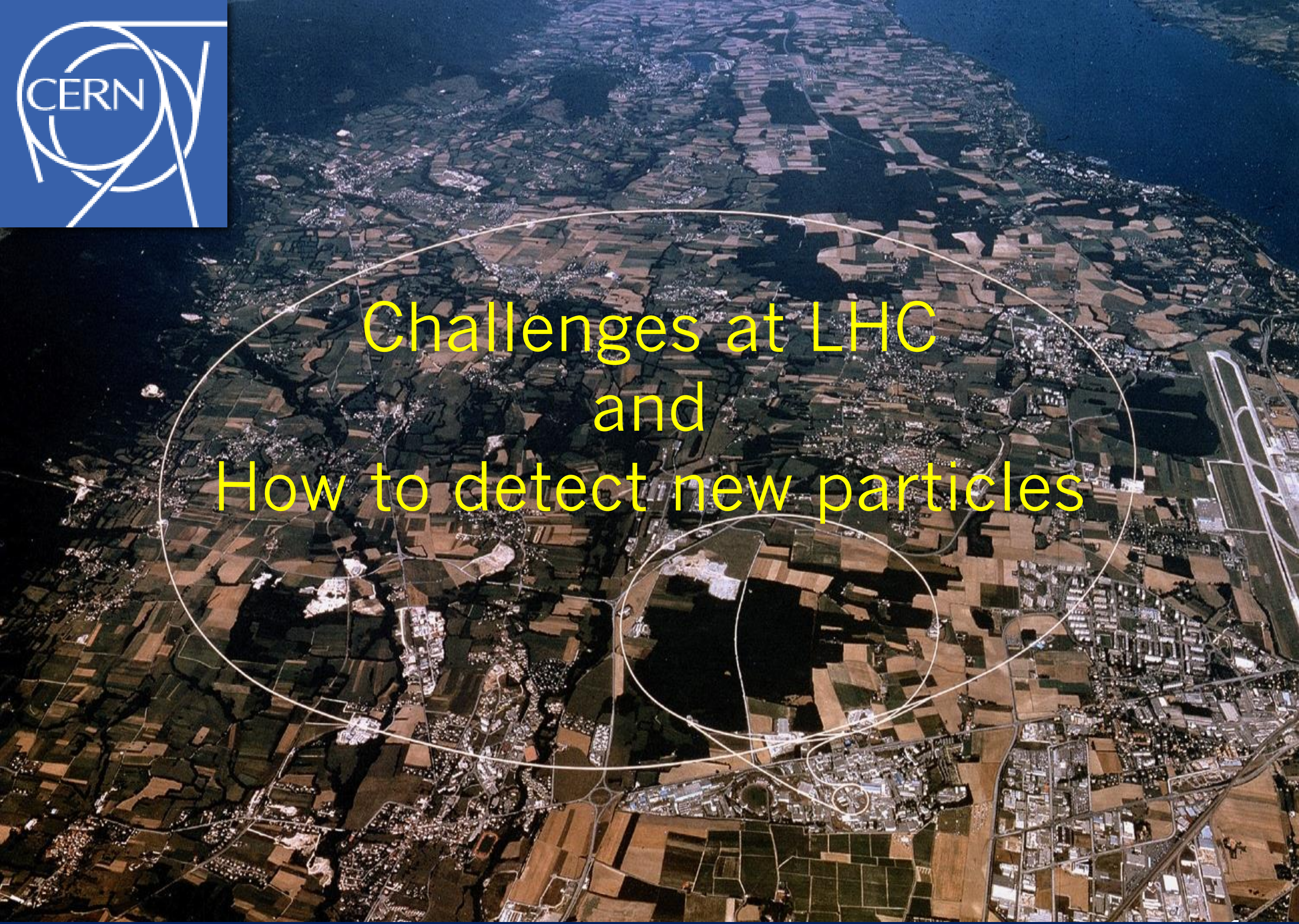
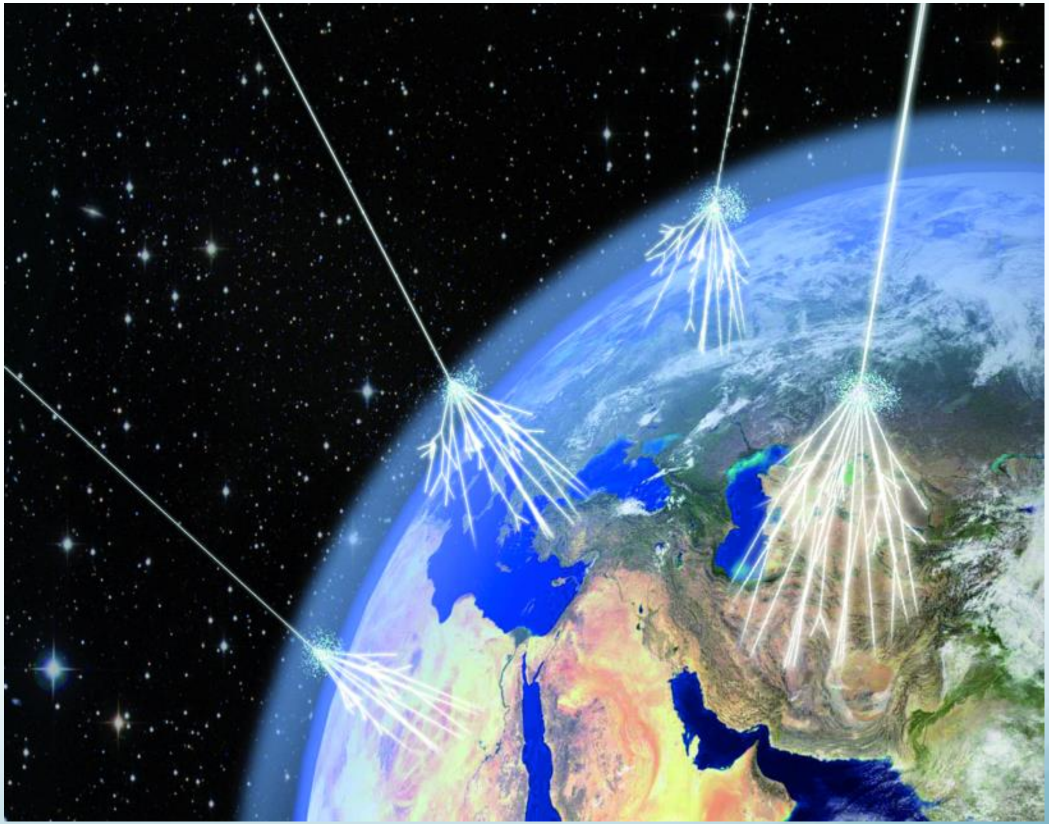


Challenges at LHC and How to detect new particles

H. Danielsson, CERN 28/10/2022

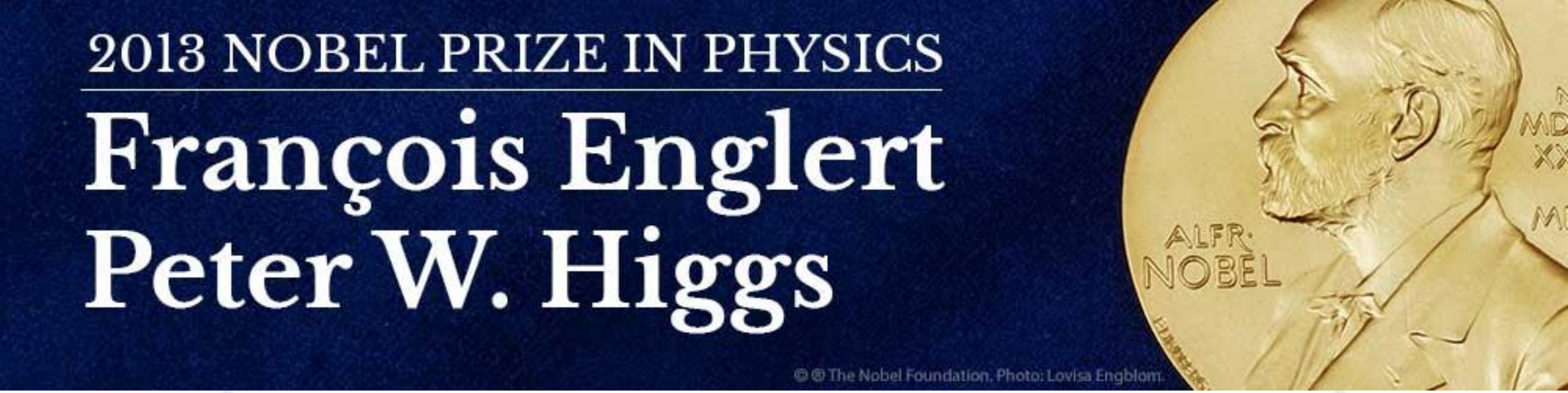
Cosmic rays are used to study the performance of the detector. Free of charge! 💻

Hess received the Nobel Prize in Physics in 1936 for his discovery (1912)



2017: AMS

- **AMS-02** is a particle-physics detector that looks for dark matter, antimatter and missing matter from a module attached to the outside of the **International Space Station (ISS)**. It also performs precision measurements of cosmic rays.



8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

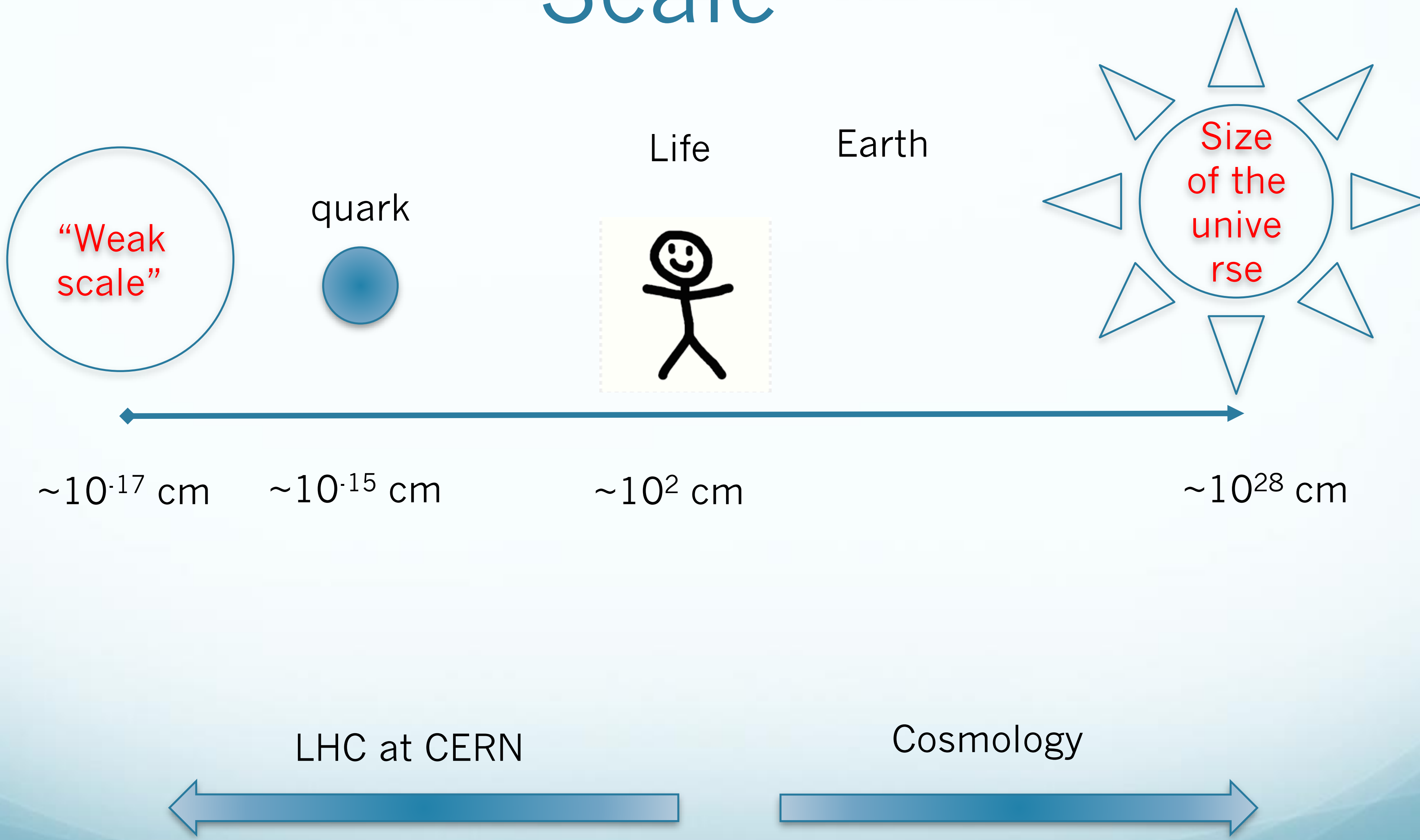
François Englert and Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Outline

- Introduction
    - SM
- CERN and the Large Hadron Collider (LHC)
    - The accelerator
    - How detectors work and examples
- The Higgs discovery
- What’s next?

Scale


"Weak scale"
quark
Life
Earth
Size of the unive rse
~10-17 cm
~10-15 cm
~102 cm
~1028 cm
LHC at CERN
Cosmology

A few examples from last century:

- The theory has a problem/make predictions and the search can start:
  - In 1928, Paul Dirac published a paper proposing that electrons can have both a positive and negative charge.
    - Carl David Anderson discovered the positron on 2 August 1932,[25] for which he won the Nobel Prize for Physics in 1936
  - The quarks:
    - At the time of the quark theory's inception, the "particle zoo" included a multitude of hadrons, among other particles. Gell-Mann and Zweig posited that they were not elementary particles, but were instead composed of combinations of quarks and antiquarks.
  - The neutrino:
    - The neutrino[a] was postulated first by Wolfgang Pauli in 1930 to explain how beta decay could conserve energy, momentum, and angular momentum (spin).

$$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$$

  - The Higgs Boson
    - Higgs, Brout, Englert . Problem : without the Higgs mechanism the bosons (force carriers) have no mass which is clearely not the case for Z and W.

The Standard Model

- Is a very successful theory and describes the world around us
- The Standard Model is a discovery in itself
- However, it explains only a fraction of the universe (~5%)
  - 95% is dark energy and dark matter. What is made of? The search is ongoing for particles(?)...
  - Or do we have an issue with our understanding of gravity?
- And, the gravity is not part of the standard model !

Unification

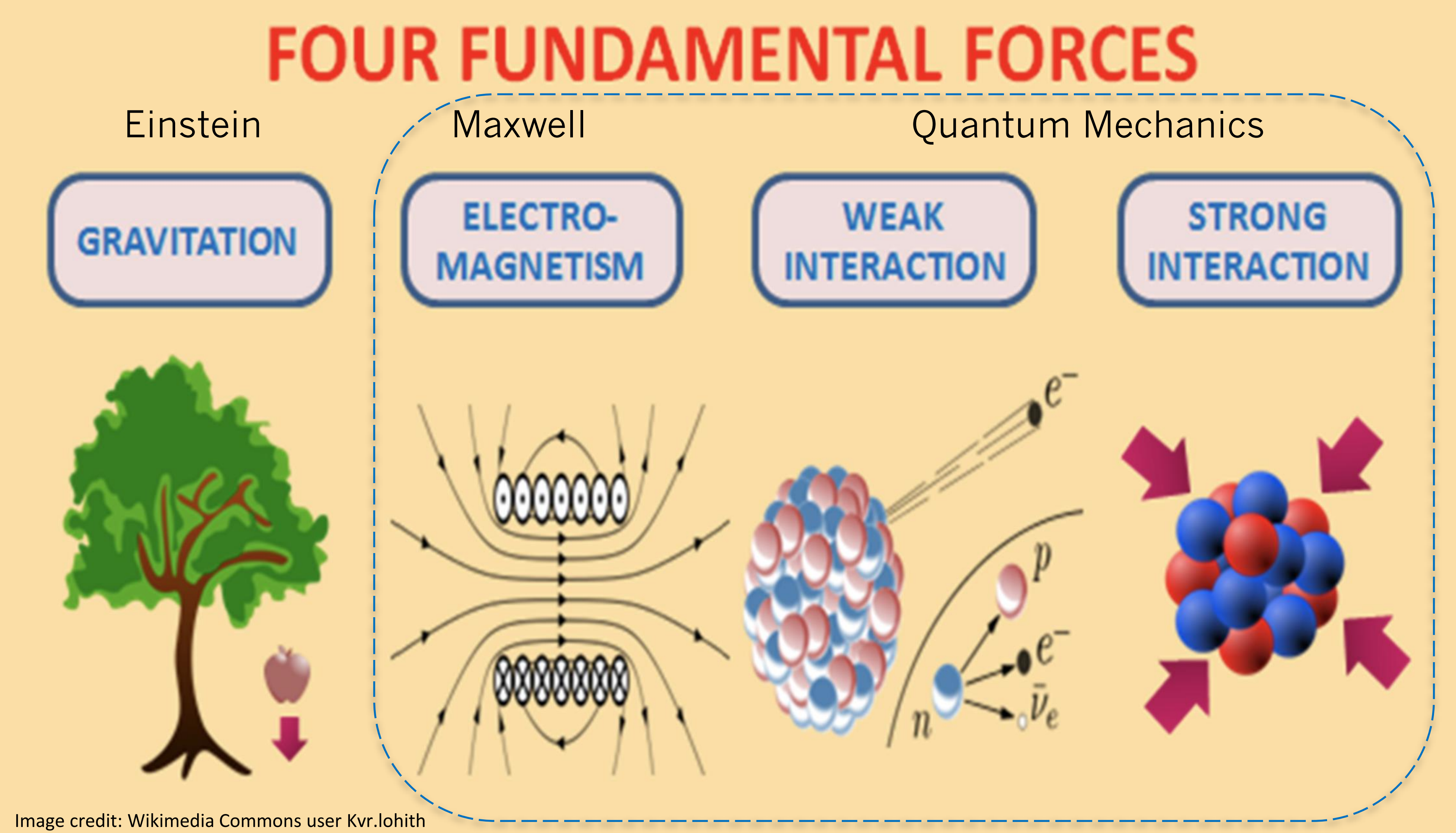
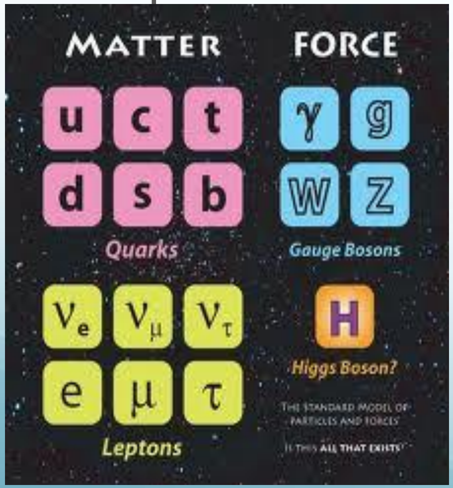


Image credit: Wikimedia Commons user Kvr.lohith

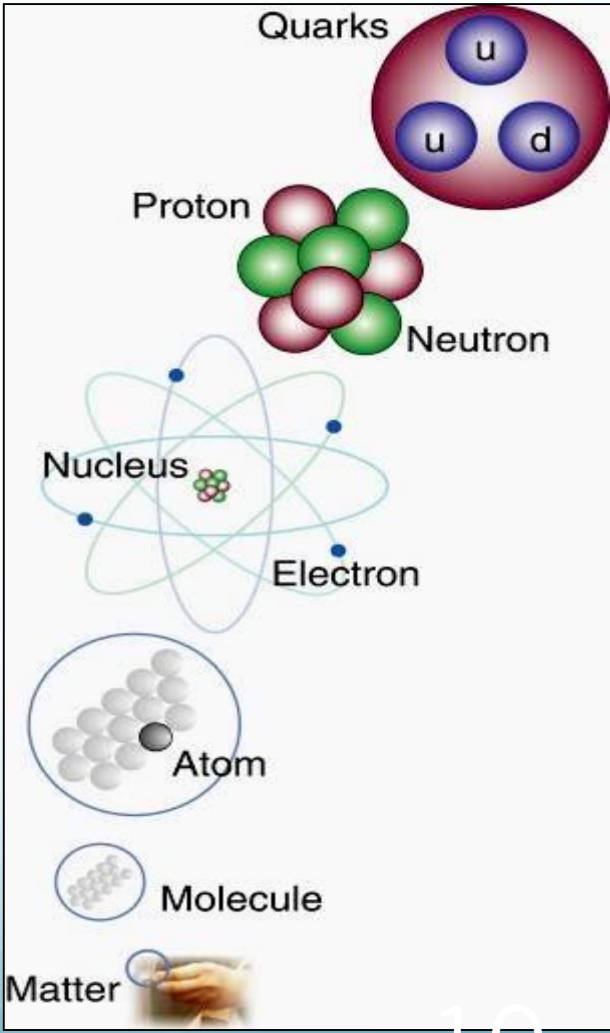
The Standard Model (1970-90s)

- Matter particles: fermions (1/2 integer spin)
- 'Force' particles: bosons (integer spin)
- Higgs field causes electro weak symmetry breaking and gives particles their masses



→ Nucleon level (partons) : binding energy ~98% of the mass

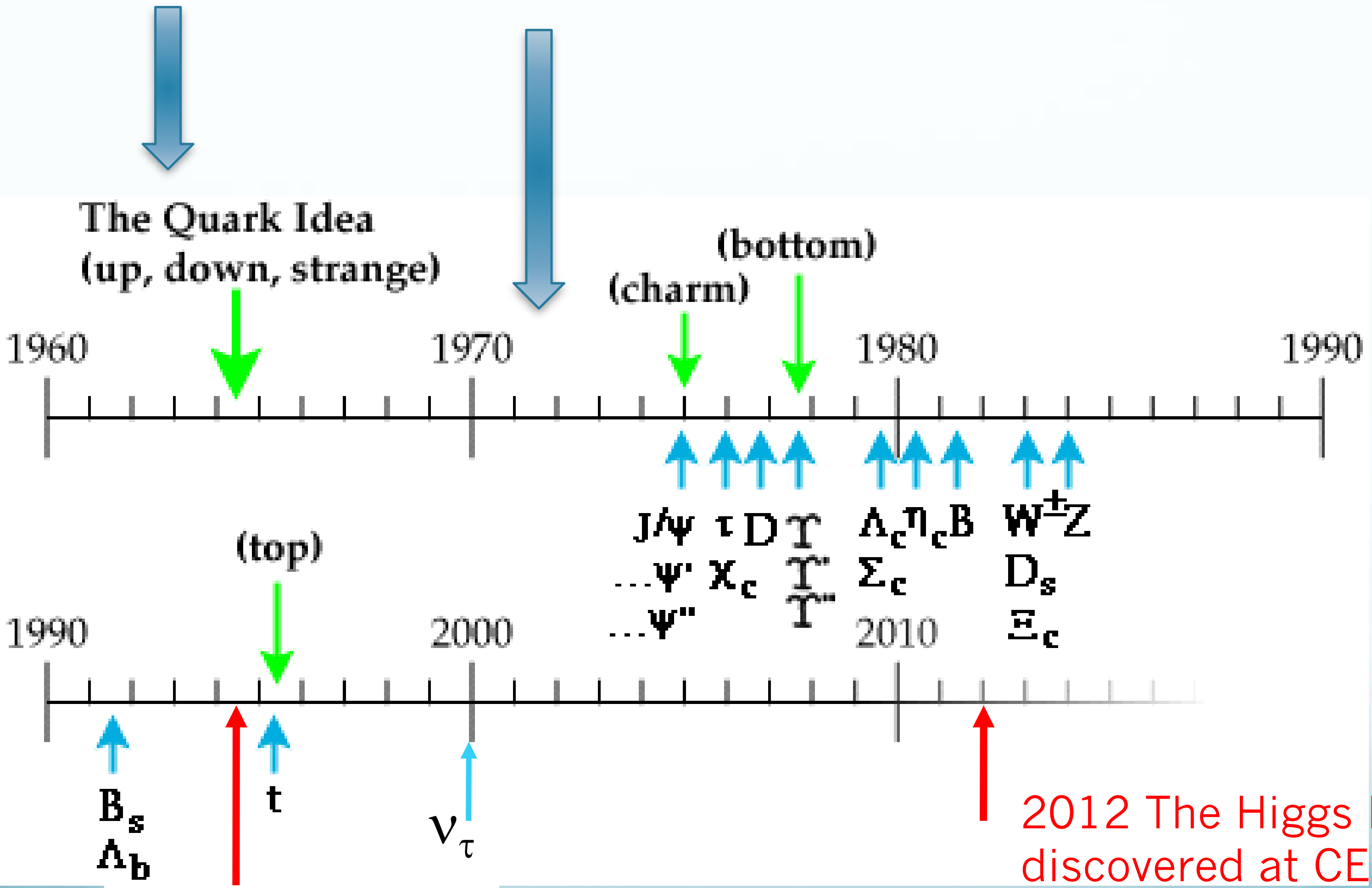
→ Most of the (luminous) mass in the universe comes from QCD confinement energy. $E=mc^2$



A bit of history

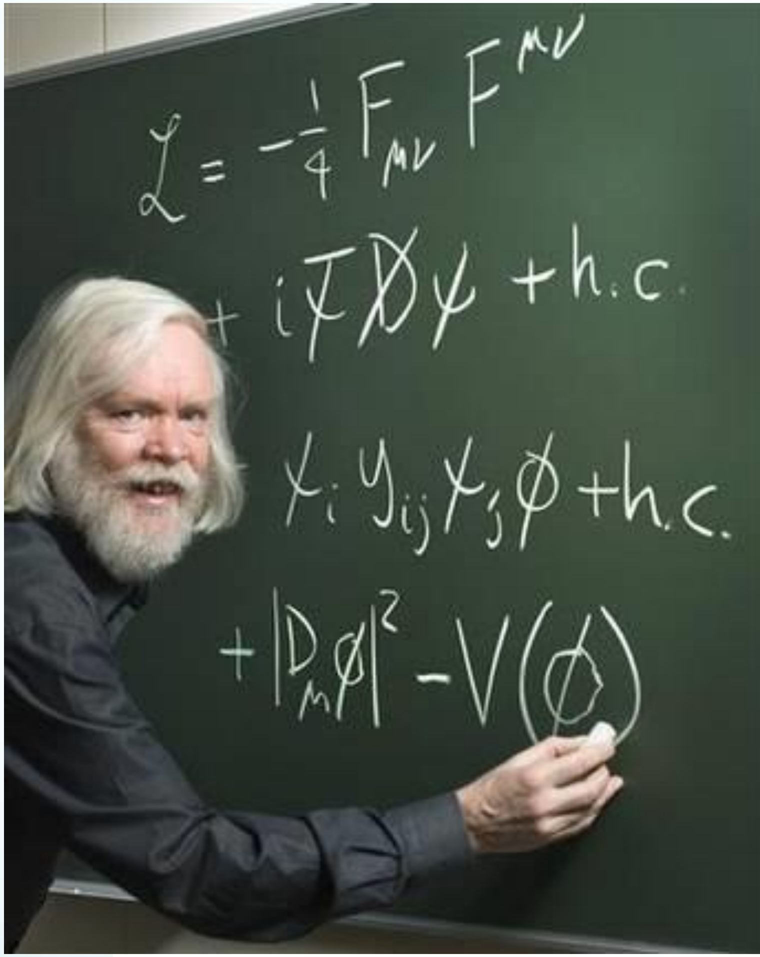
1964 The BEH mechanism

The Standard Model completed



LHC approved on 16 December 1994

2012 The Higgs boson discovered at CERN



In 1976:

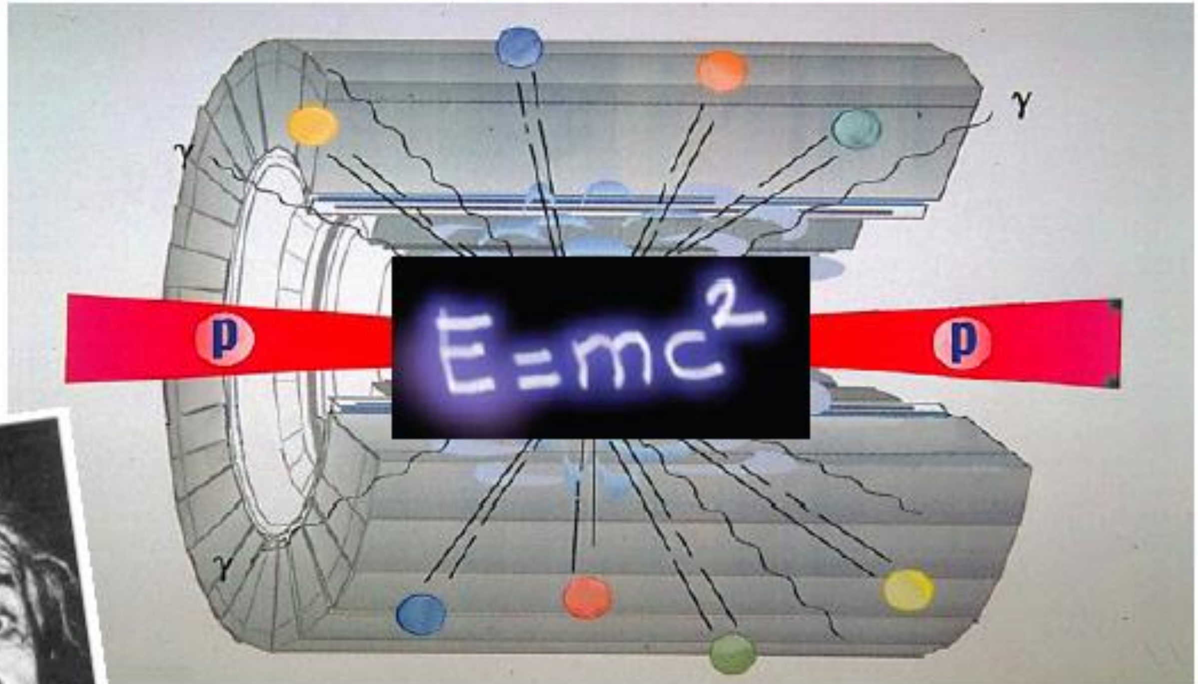
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard [*)] and D.V. Nanopoulos [+)]
CERN -- Geneva

The Roadmap:

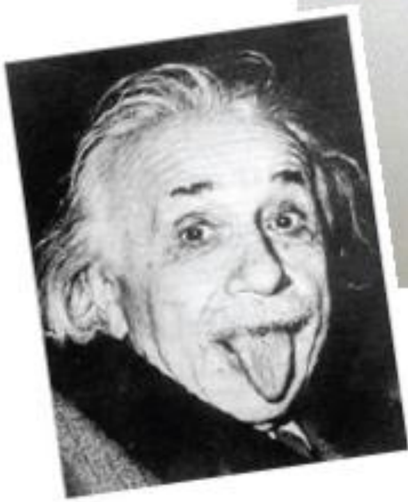
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

How ?



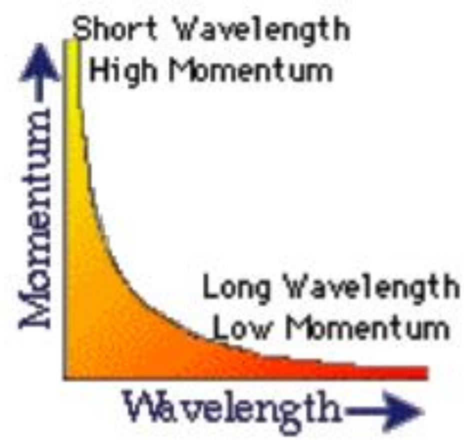
E=3.5TeV ❾
V=99.999996% of c

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$



Energy = Matter

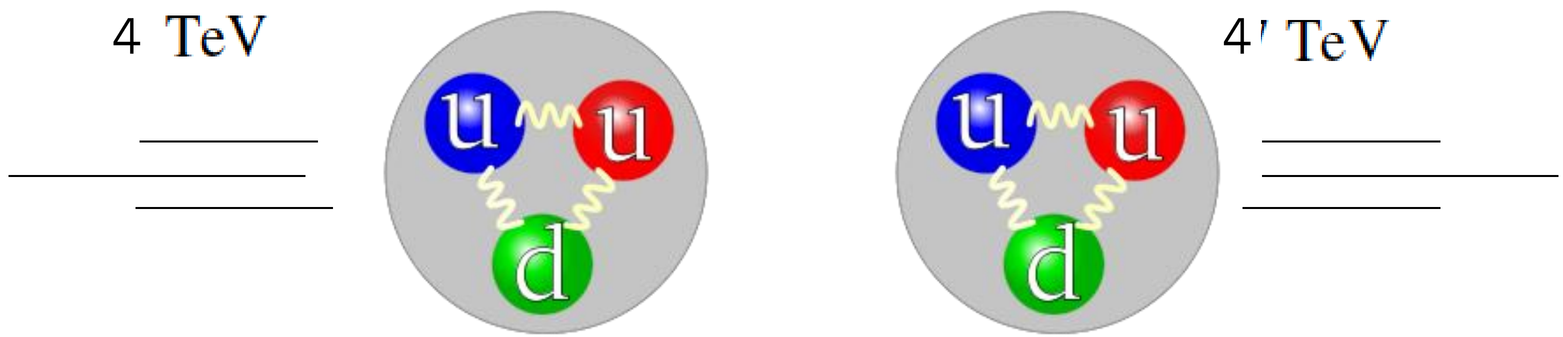
$E^2 = (m_0c^2)^2 + (pc)^2$

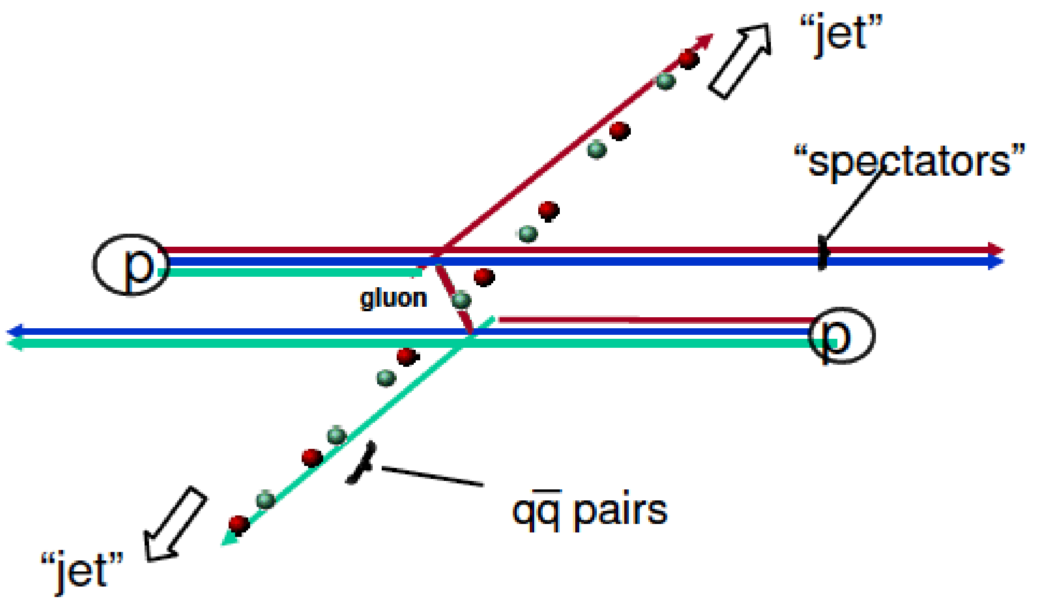


Experimental High Energy Physics – detecting particles

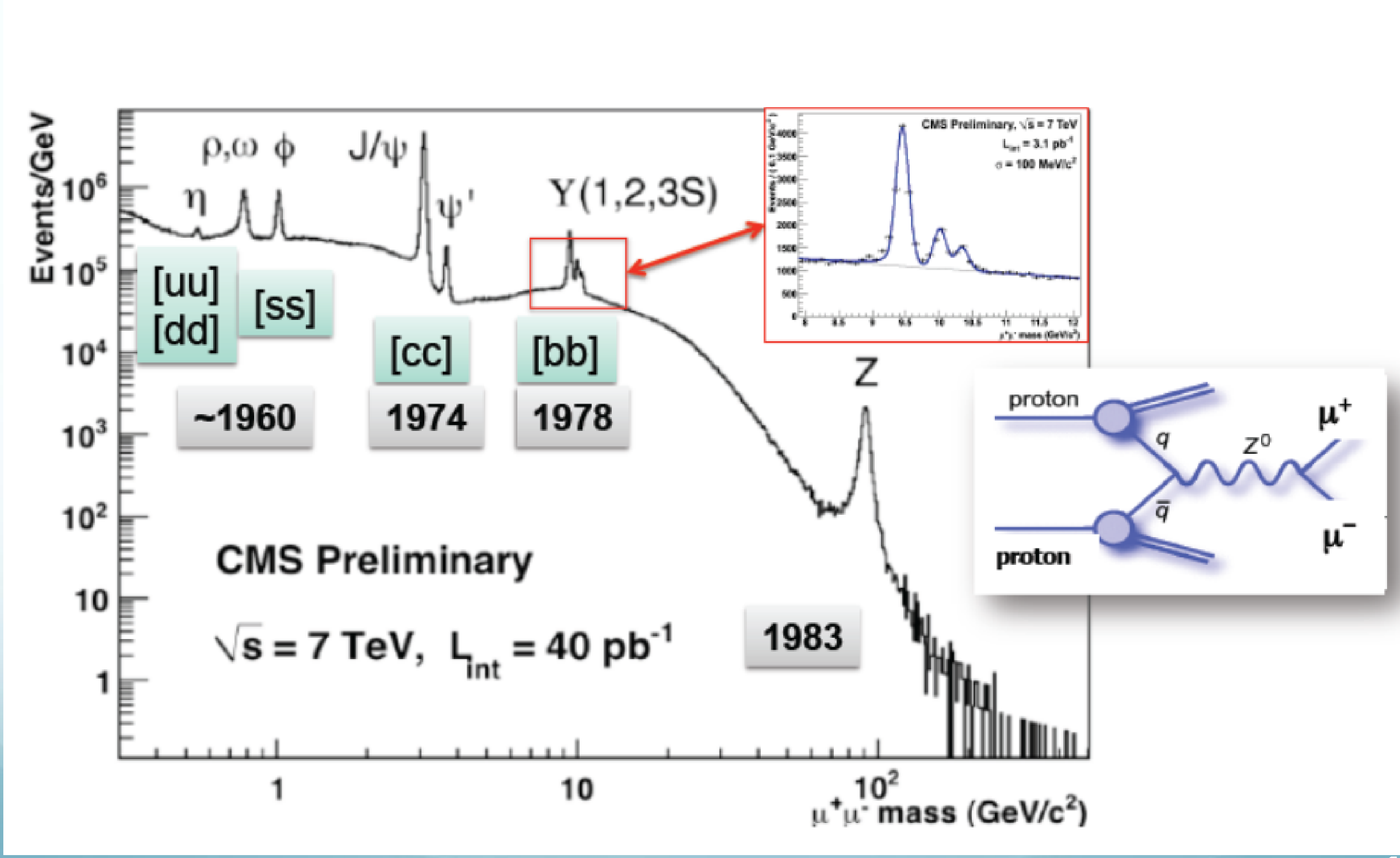
Two Protons collide at high energy

Large Hadron Collider (LHC) at CERN



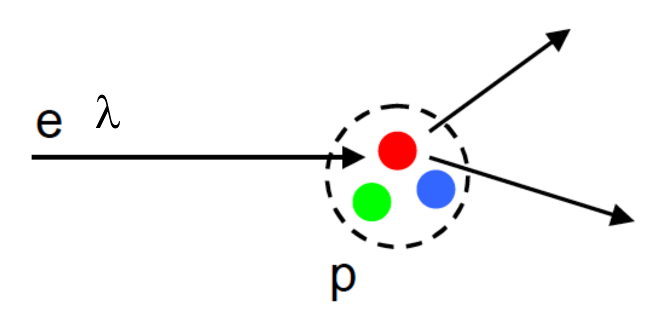


After 10 min of LHC running: full history of SM



On example: the discovery of the quarks at SLAC in 1968

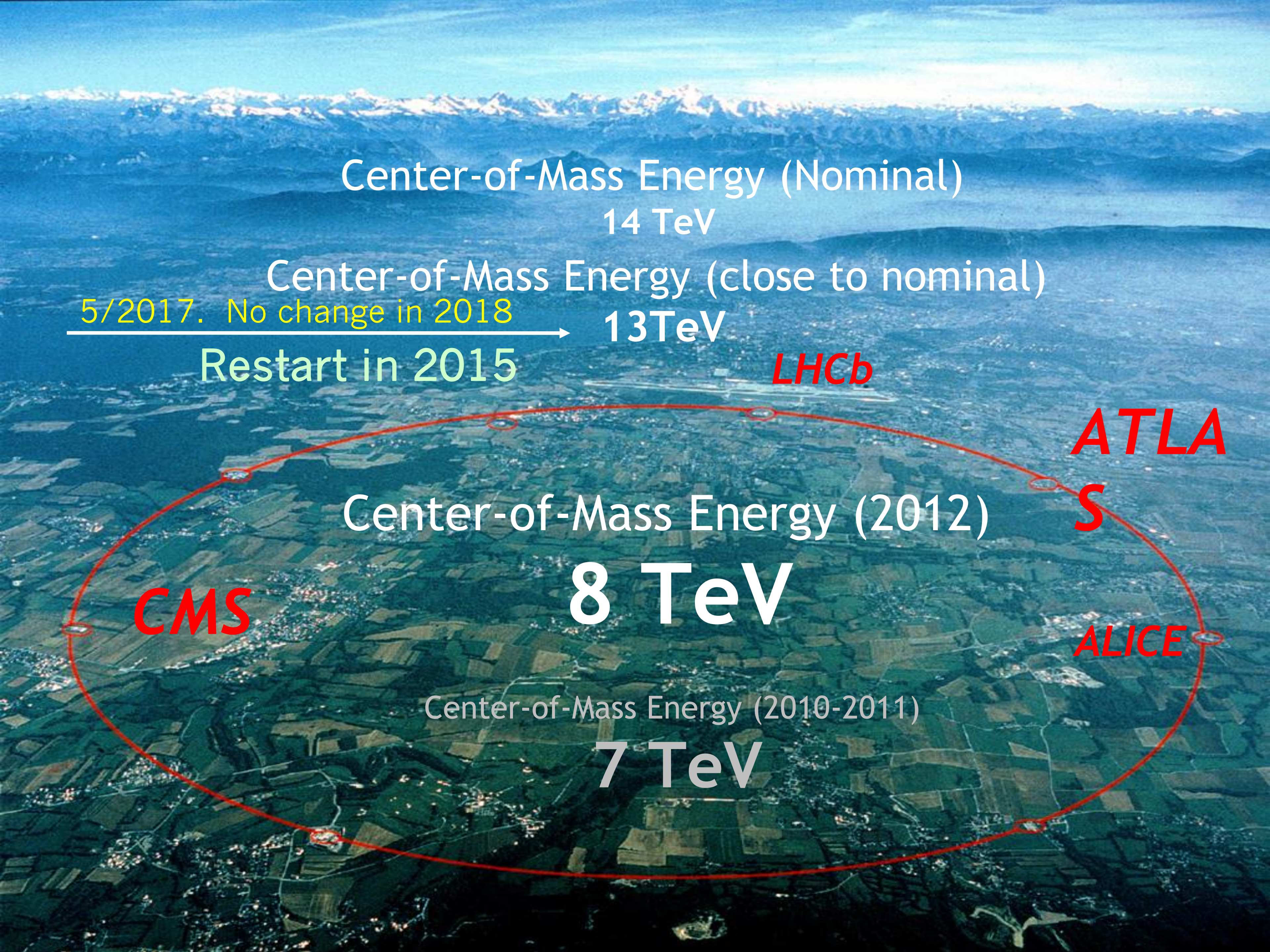
$$\lambda = \frac{h}{p}, P = 20\,GeV \Rightarrow \lambda \approx 10^{-17}\,m$$



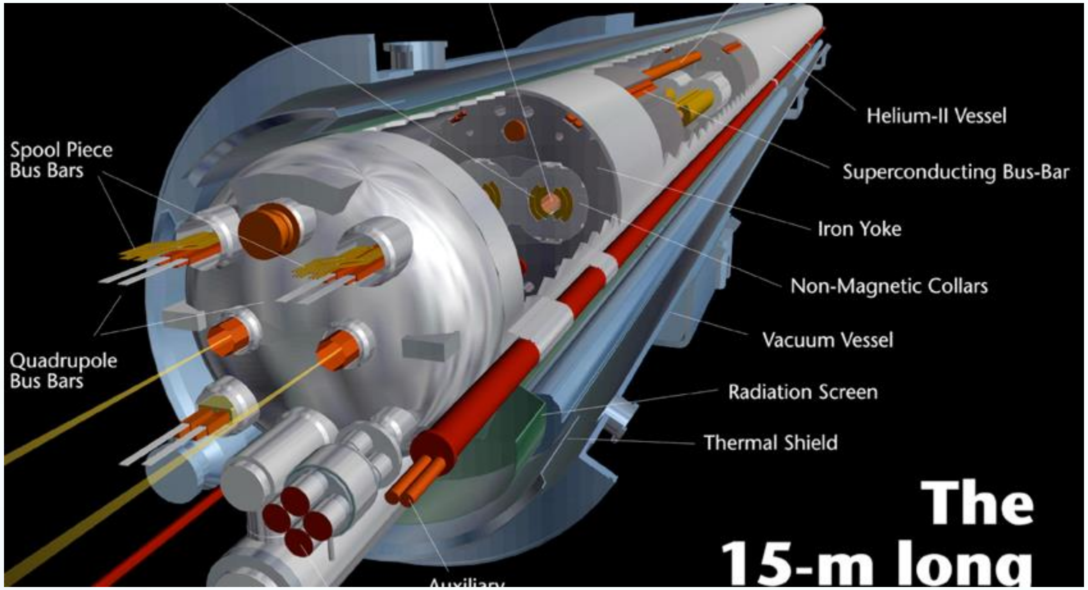
- The quark model was independently proposed by physicists Murray Gell-Mann and George Zweig in 1964.
- Gell-Mann found the quarks in:

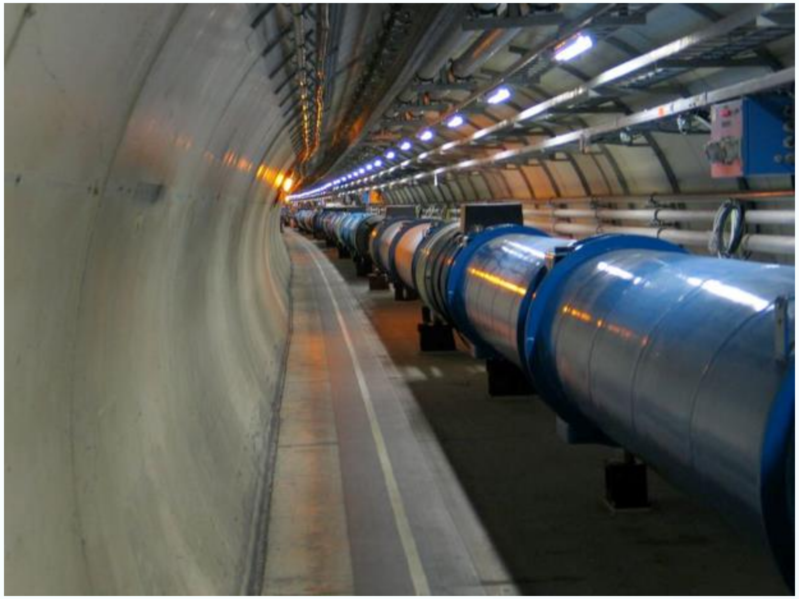
"Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark."

—James Joyce, *Finnegans Wake*

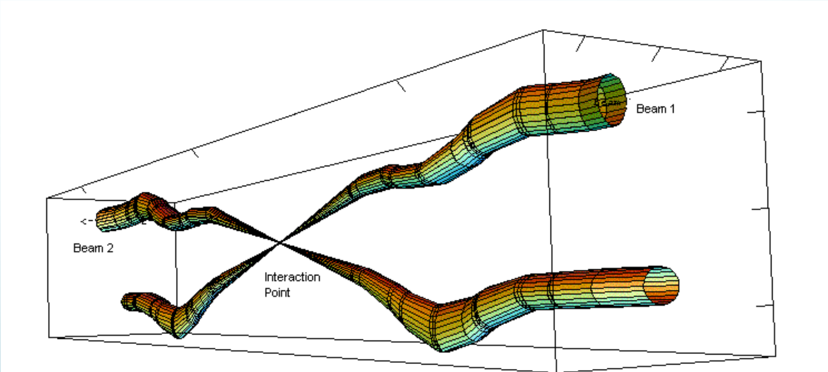

Center-of-Mass Energy (Nominal)
14 TeV
Center-of-Mass Energy (close to nominal)
5/2017. No change in 2018
13TeV
Restart in 2015
LHCb
ATLA
S
Center-of-Mass Energy (2012)
8 TeV
CMS
ALICE
Center-of-Mass Energy (2010-2011)
7 TeV

Large Hadron Collider (LHC)





- The Accelerator
  - 100 - 150 m below surface at 1.9 Kelvin in a tunnel 27 km long.
  - The protons circulate at a speed of ~ 11000 turns/sec
  - There are 2808 bunches
  - Collisions at 40 MHz (every 25 ns)
  - **600 000 000 collisions per second !**

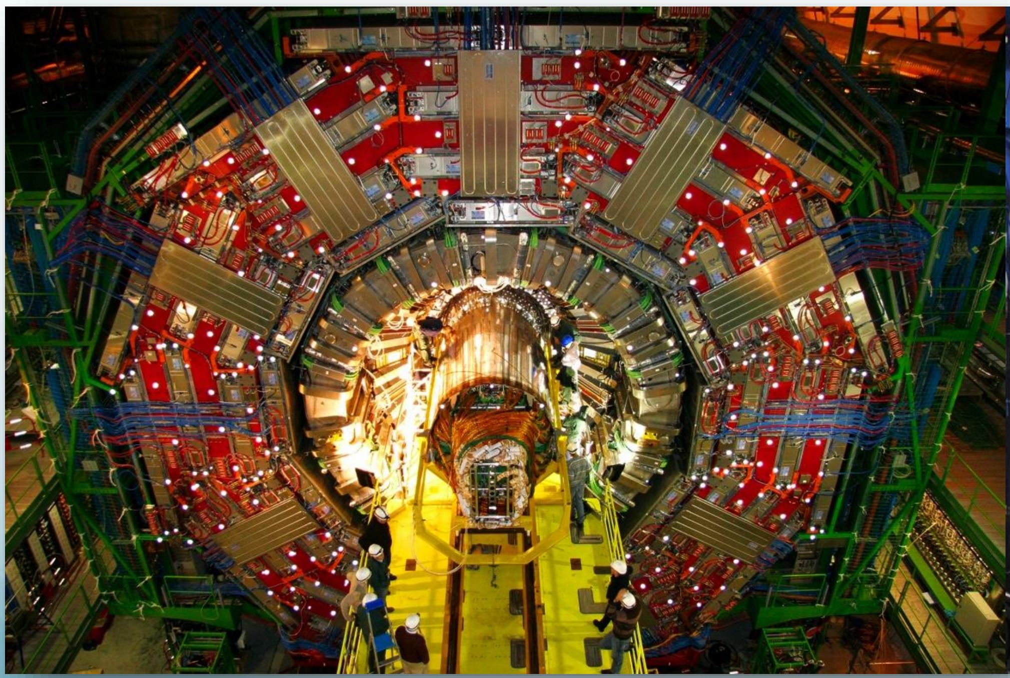


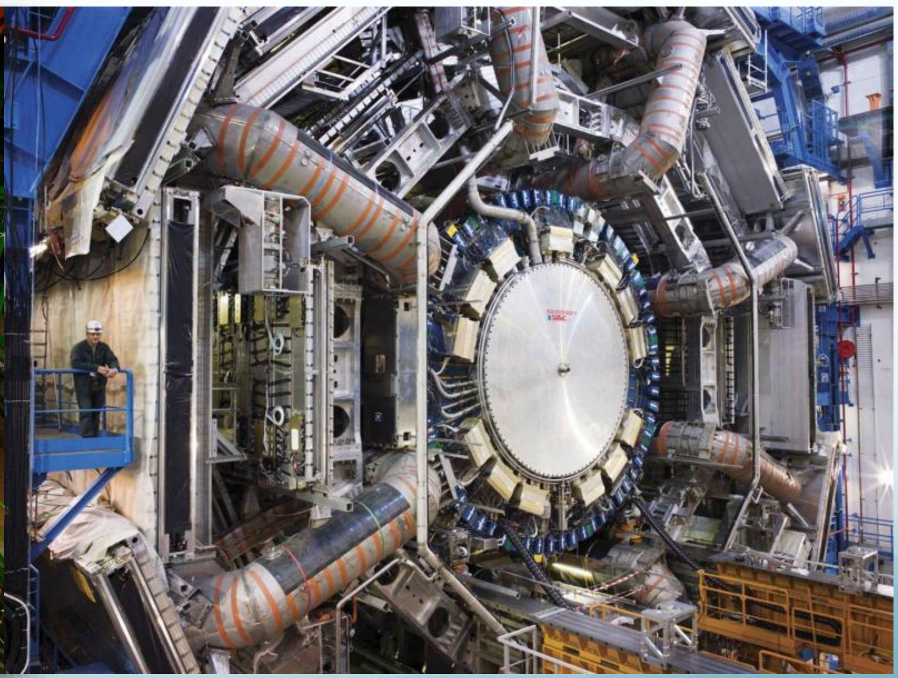
Relative beam sizes around IP1 (Atlas) in collision

The experiments

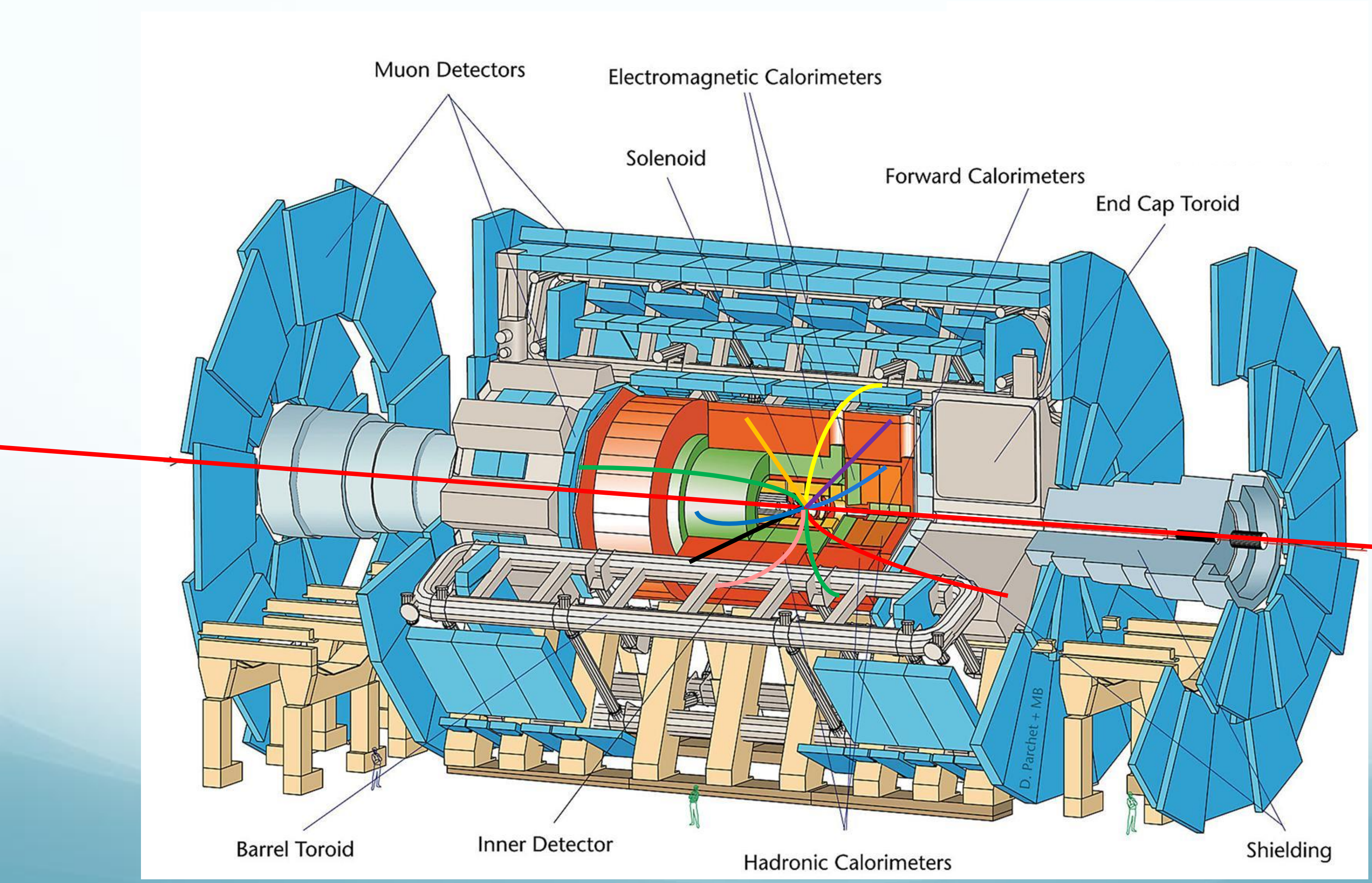
CMS: heavier than the Eiffel Tower

ATLAS: as big as a 5 storey building





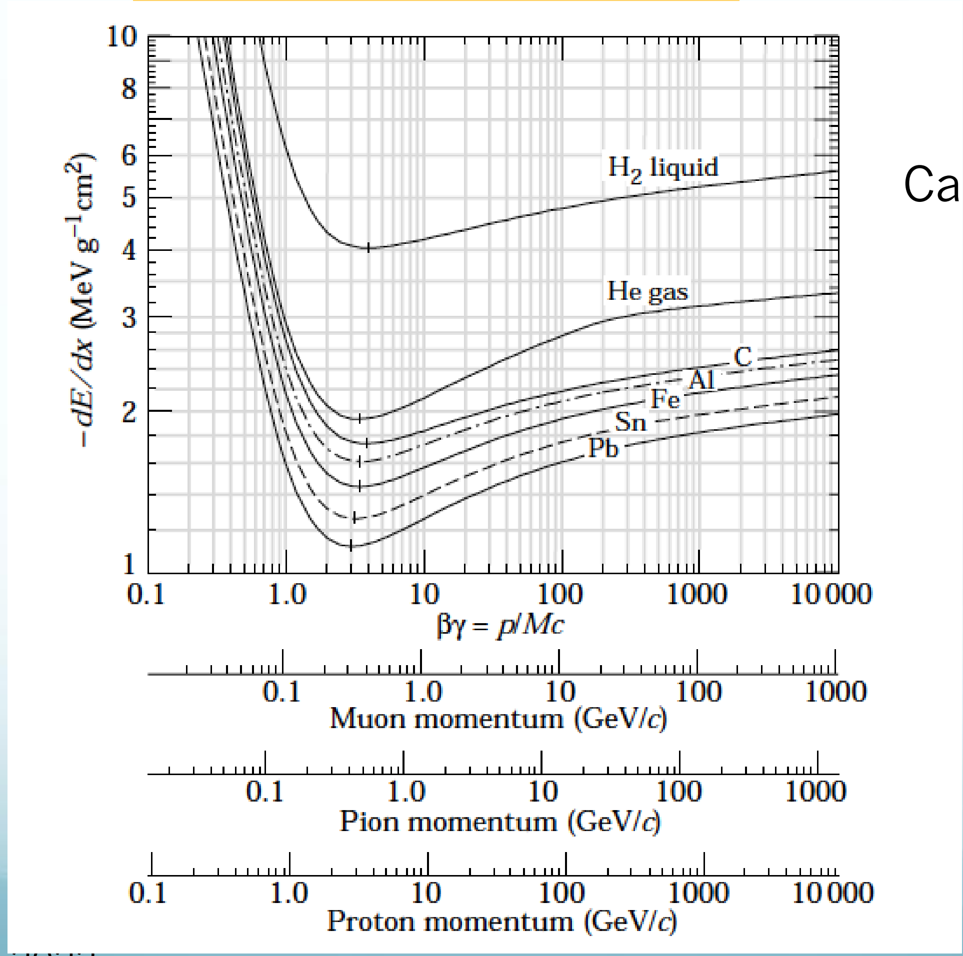
Största och mest sofistikerade detektorer



Bethe-Bloch Energy Loss

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2\right]$$

PDG plots: http://pdg.lbl.gov/index.html

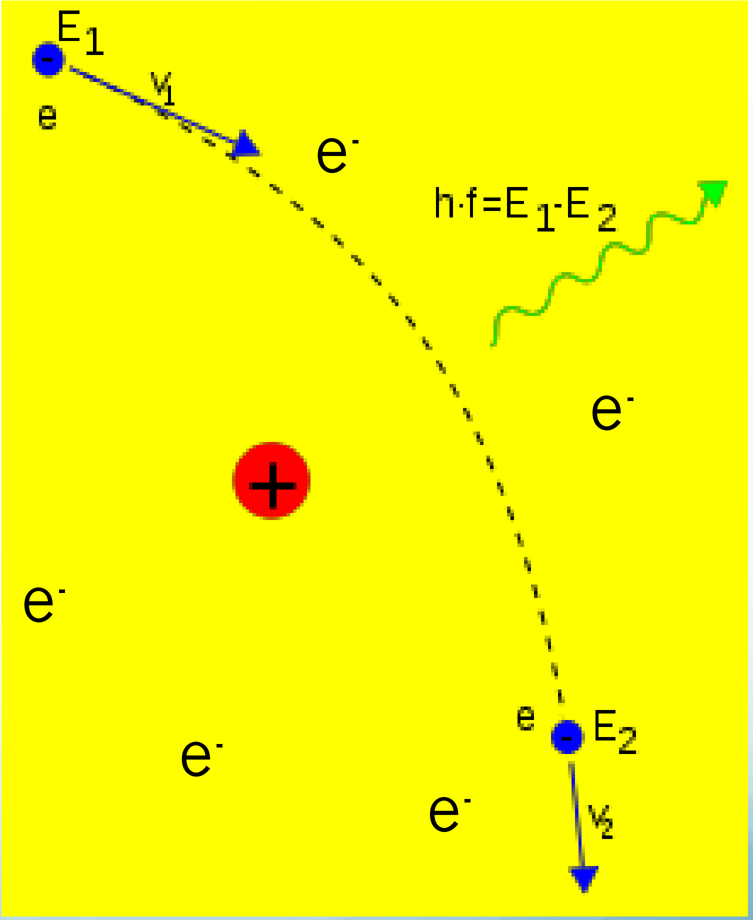


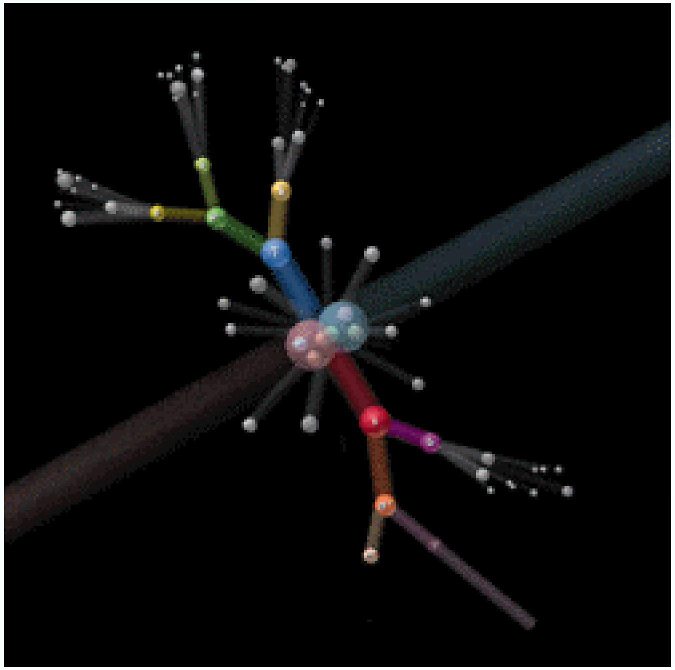
Calculated

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

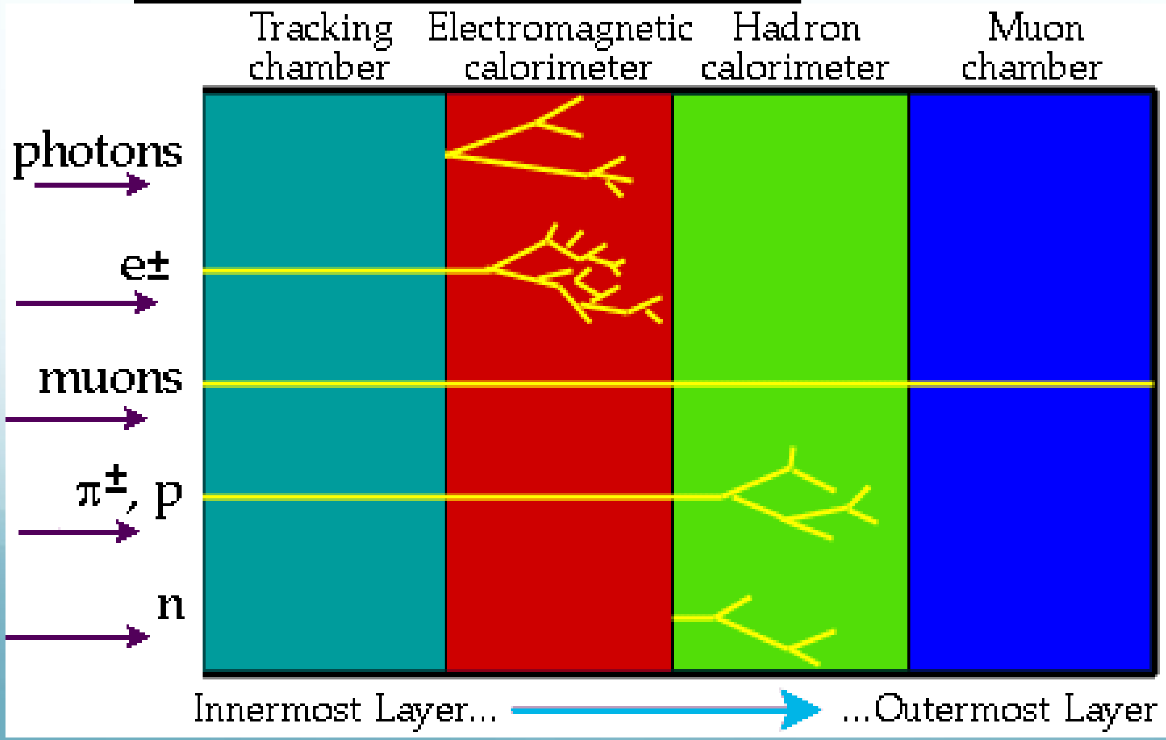
Bremsstrahlung (braking radiation)

- A fast moving particle is decelerated in the electrical field of the nuclei.
- Above a few tens MeV, bremsstrahlung is the most dominated process for **electrons and positrons**
- It becomes important to muons (and pions) at a few hundred GeV
- What about the atomic electrons? Yes, the electron cloud gives and *additional contribution* to the bremsstrahlung
- *Let's see how this is used in the detector layout later*





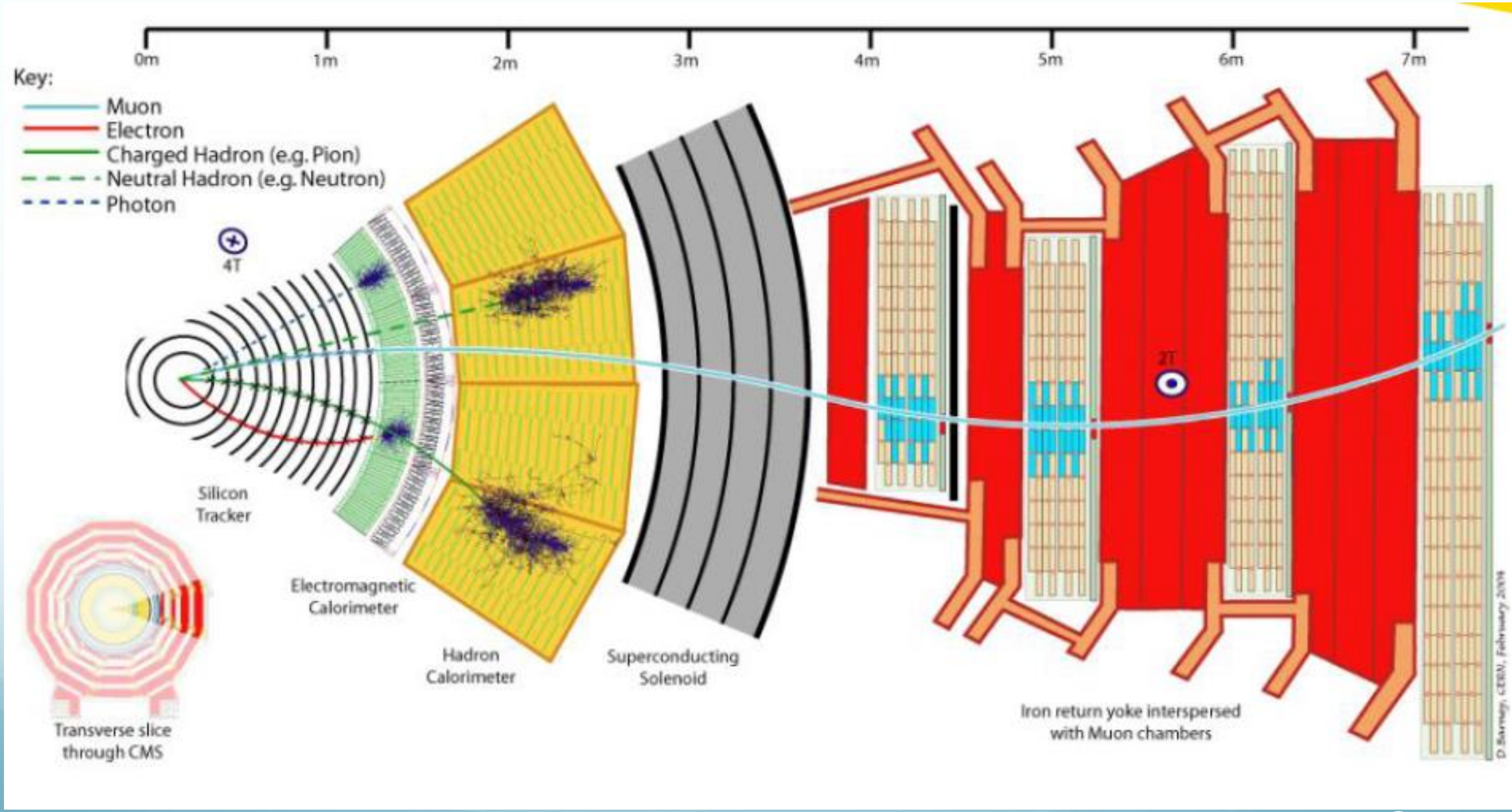
Principles of Detection



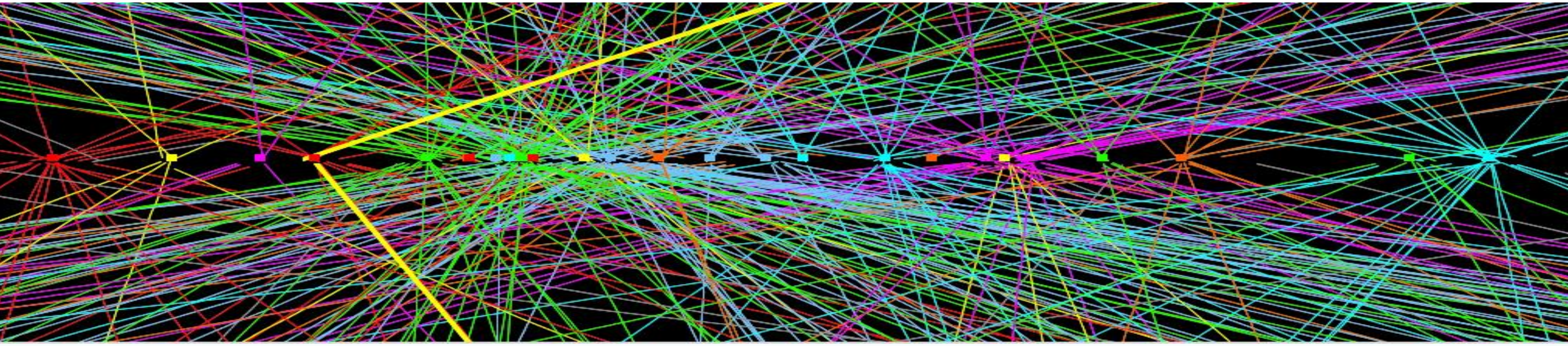
The collision energy condenses into particles (e, p, π, μ,γ K…)

Detectors surrounding the collision point (or *after* in case of fixed target) are sensitive to the passage of energetic particles.

Partikeldetektorer



Detector Challenges (Highlights)



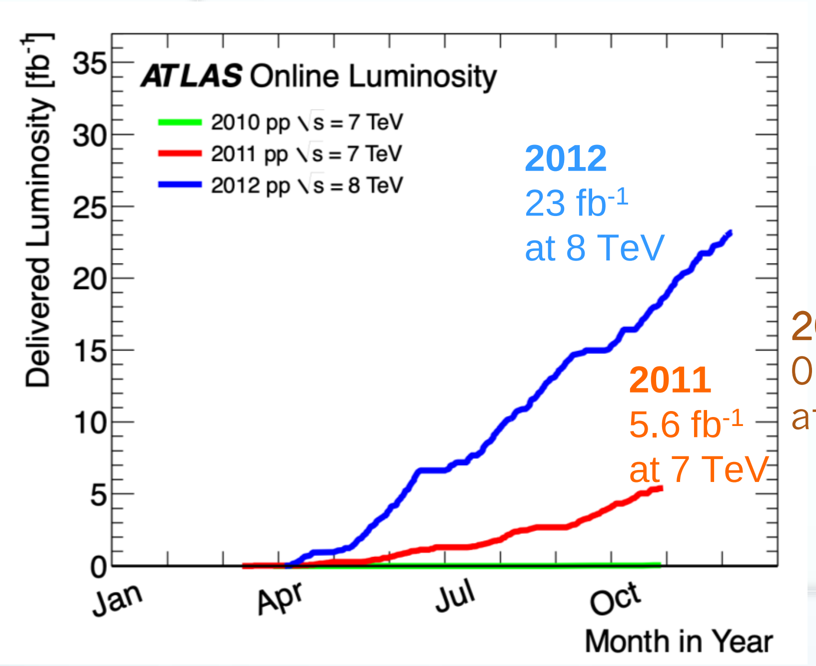
10 cm

- Trigger Challenge : How to select 400 out of $20x10^6$ events per second while keeping the interesting (including unknown) physics

- Computing Challenge : How to reconstruct, store and distribute 400 increasingly complex events per second (over 100 Petabite per experiment)

The first LHC run

Event rate = luminosity x cross-sections

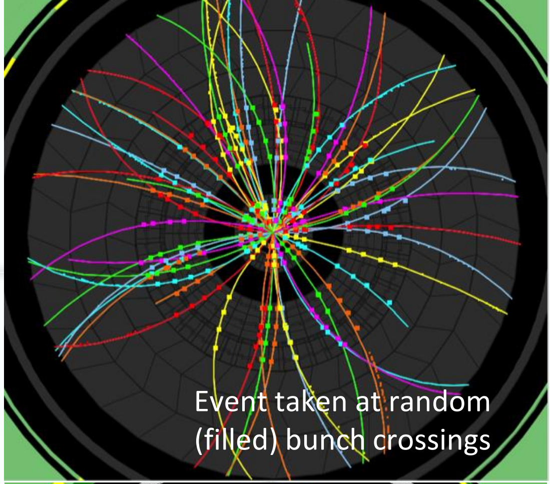


2010
0.05 fb^{-1}
at 7 TeV

2010

O(2) Pile-up events

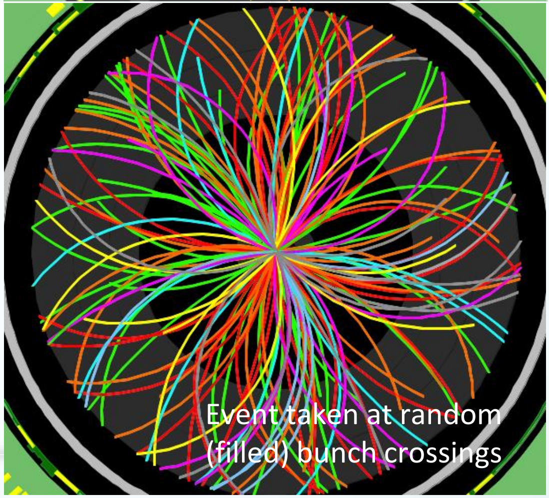
150 ns inter-bunch spacing



2011

O(10) Pile-up events

50 ns inter-bunch spacing



Design value (expected to be reached at $L=10^{34}$!)

2012

O(20) Pile-up events

50 ns inter-bunch spacing

The detection of the Higgs boson

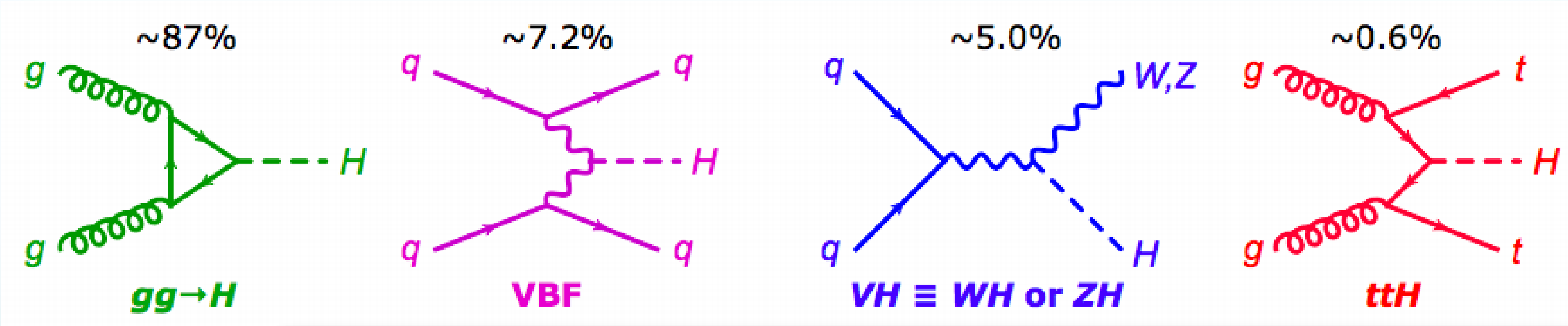
Higgs production

Vector boson fusion
VBF

Top-antitop fusion
ttH

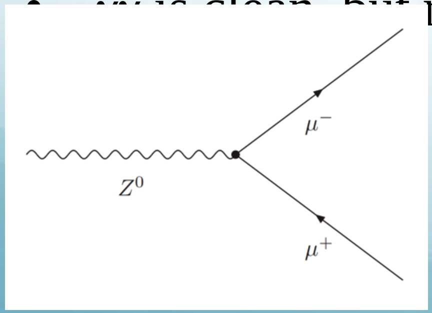
Higgs strahlung
VH

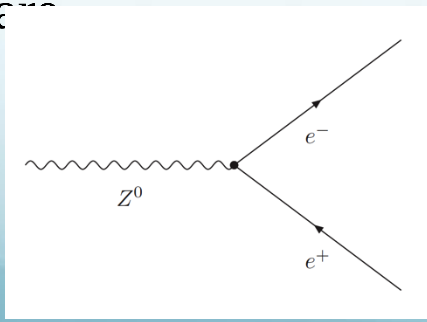
Gluon-gluon fusion
gg→H

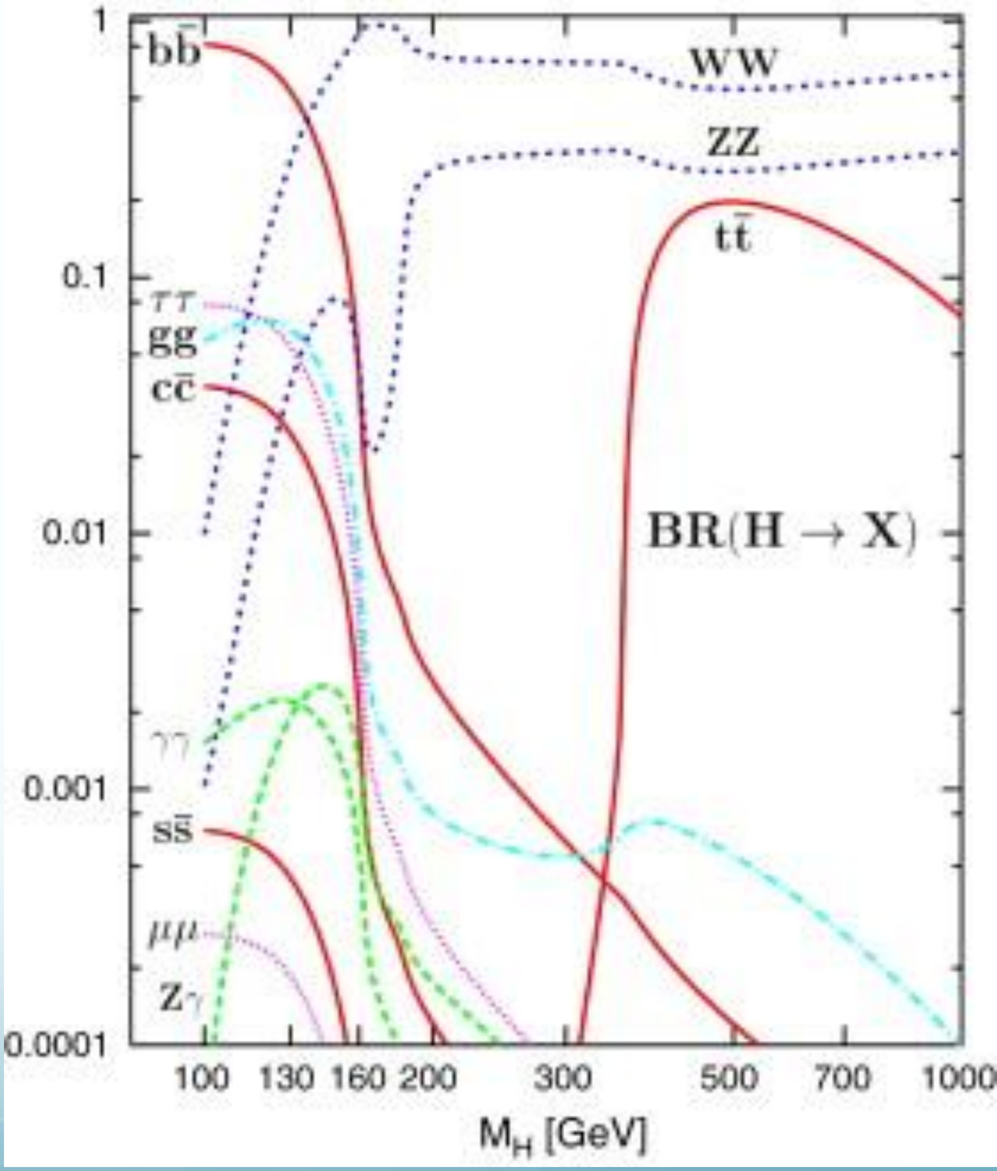


Detect Higgs by decay products

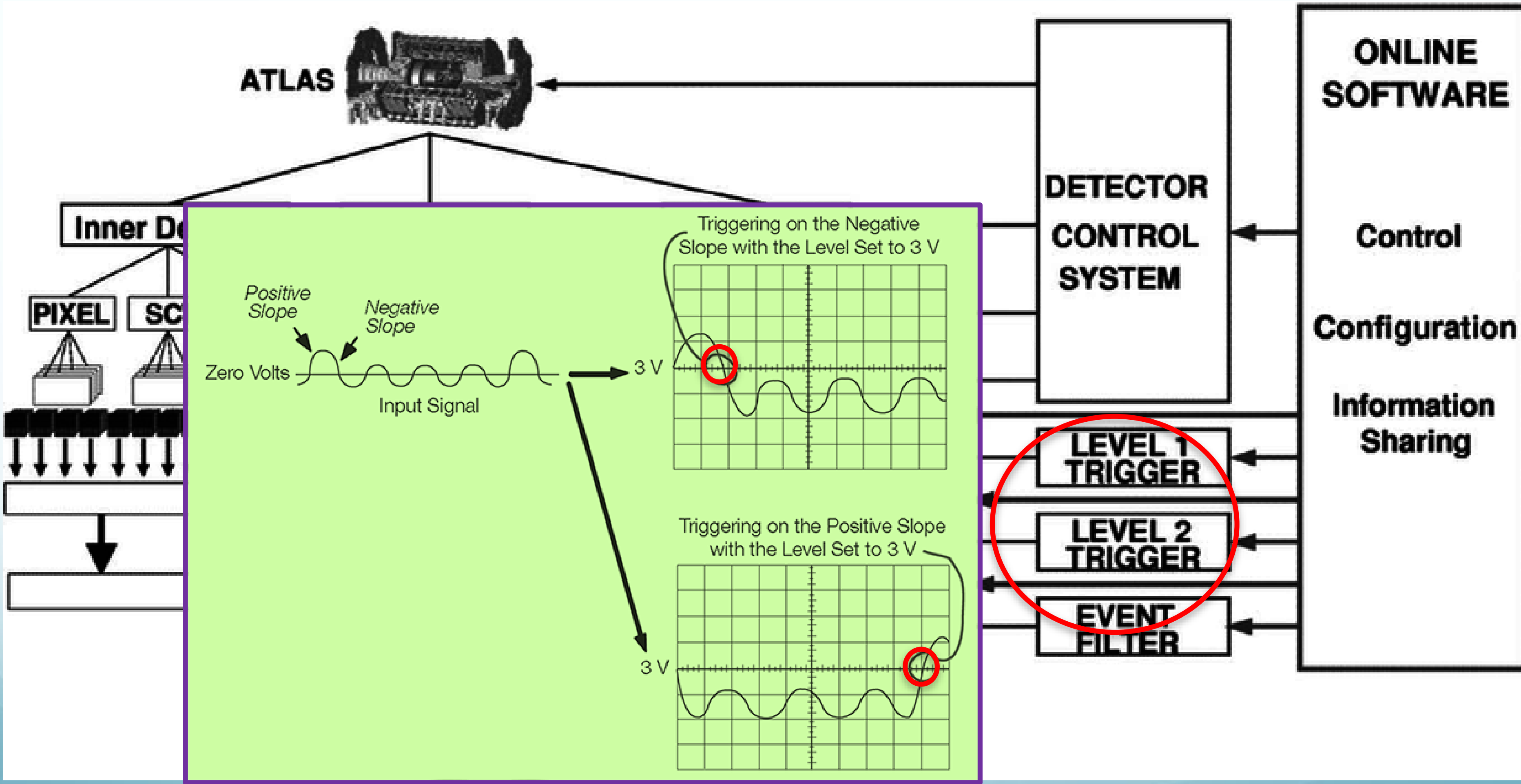
- Variety of decay channels
- Massive particles more likely
- Difficult to detect from background
- Life time is 1.56×10−22 s (!)
(predicted in the Standard Model)
- γγ is clean, but rare





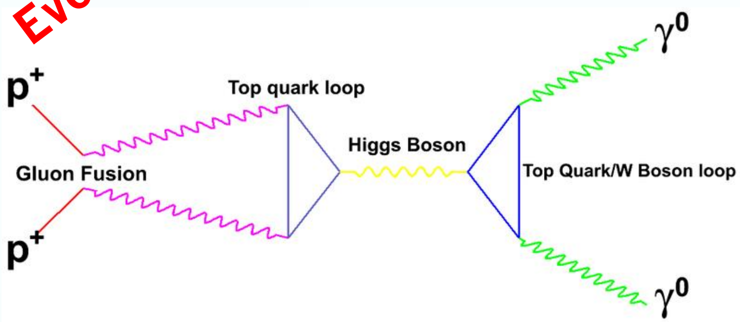


Online, Offline Trigger

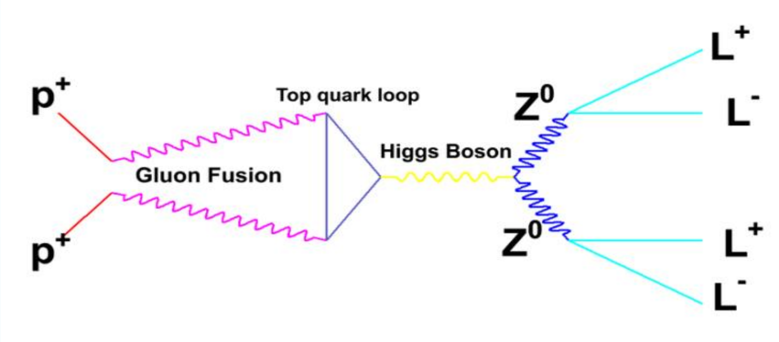


ONLINE
Event visualization

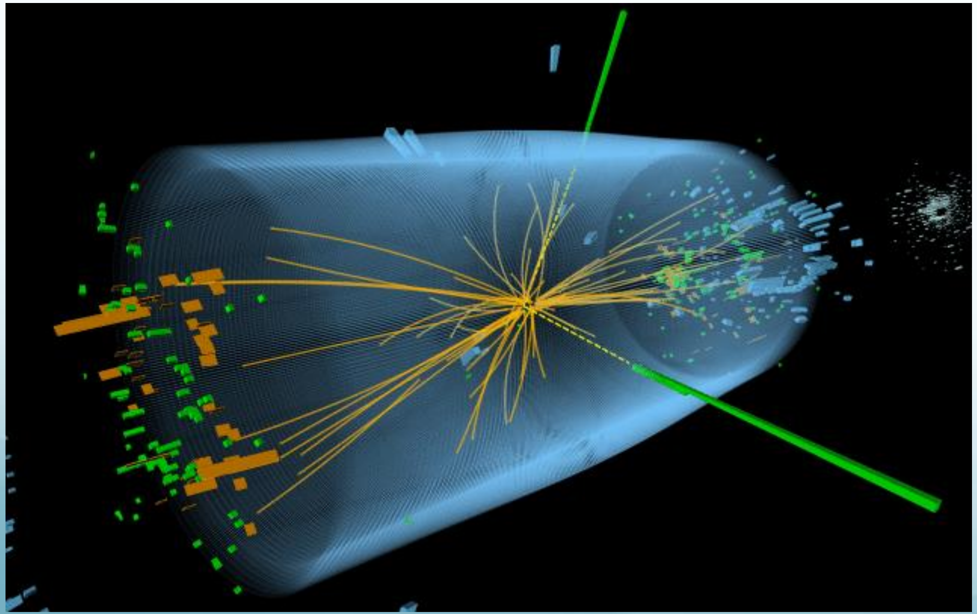
April-July 2012: *8 TeV*, *5.8* fb^{-1}

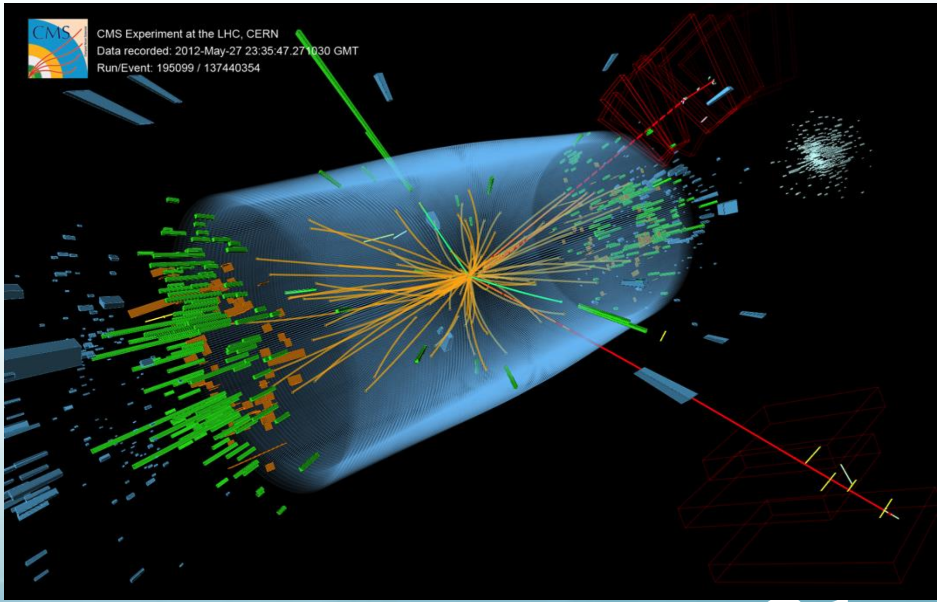


Measure energy of <u>photons</u> emitted



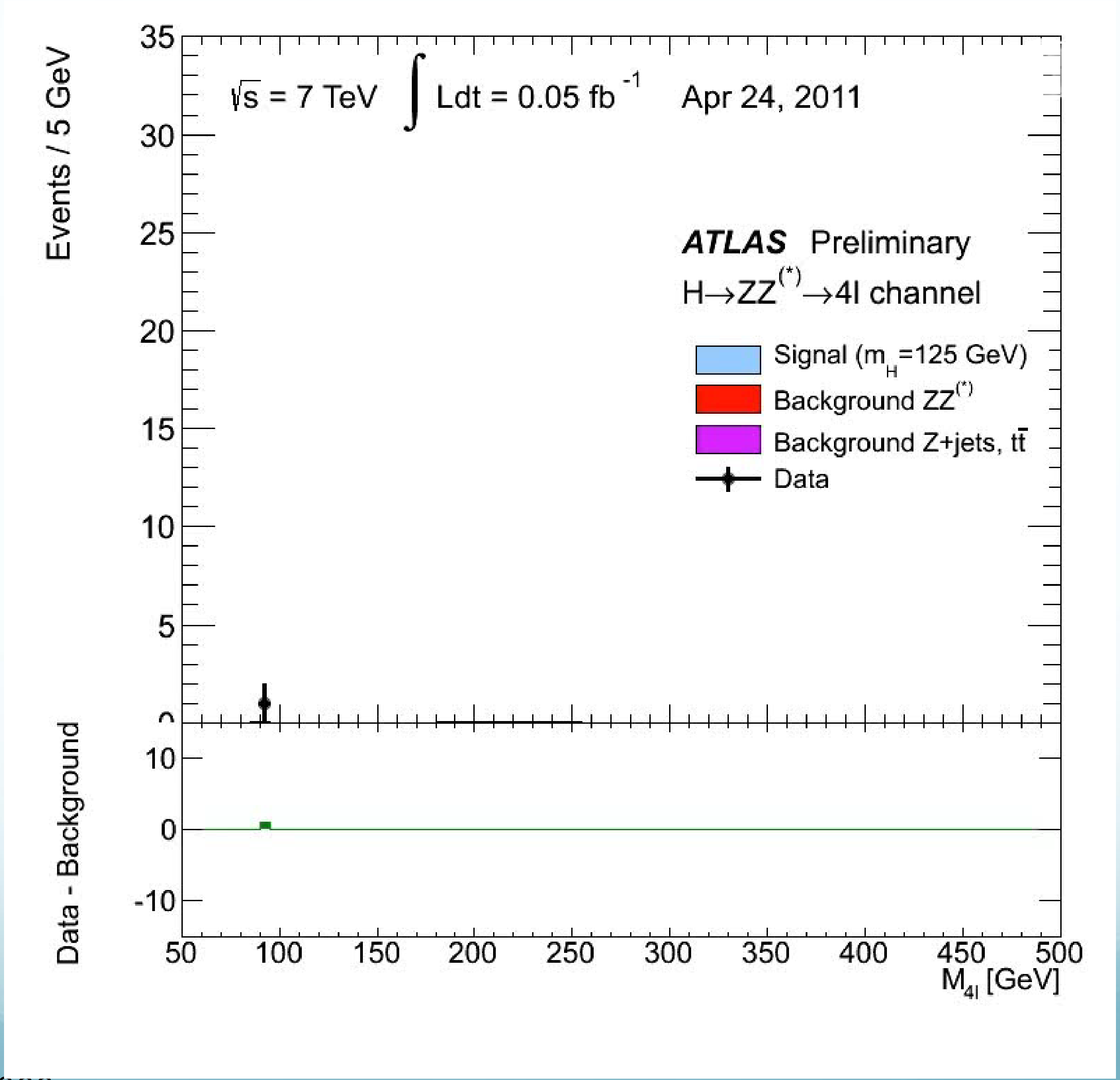
Measure decay products of <u>Z bosons</u>



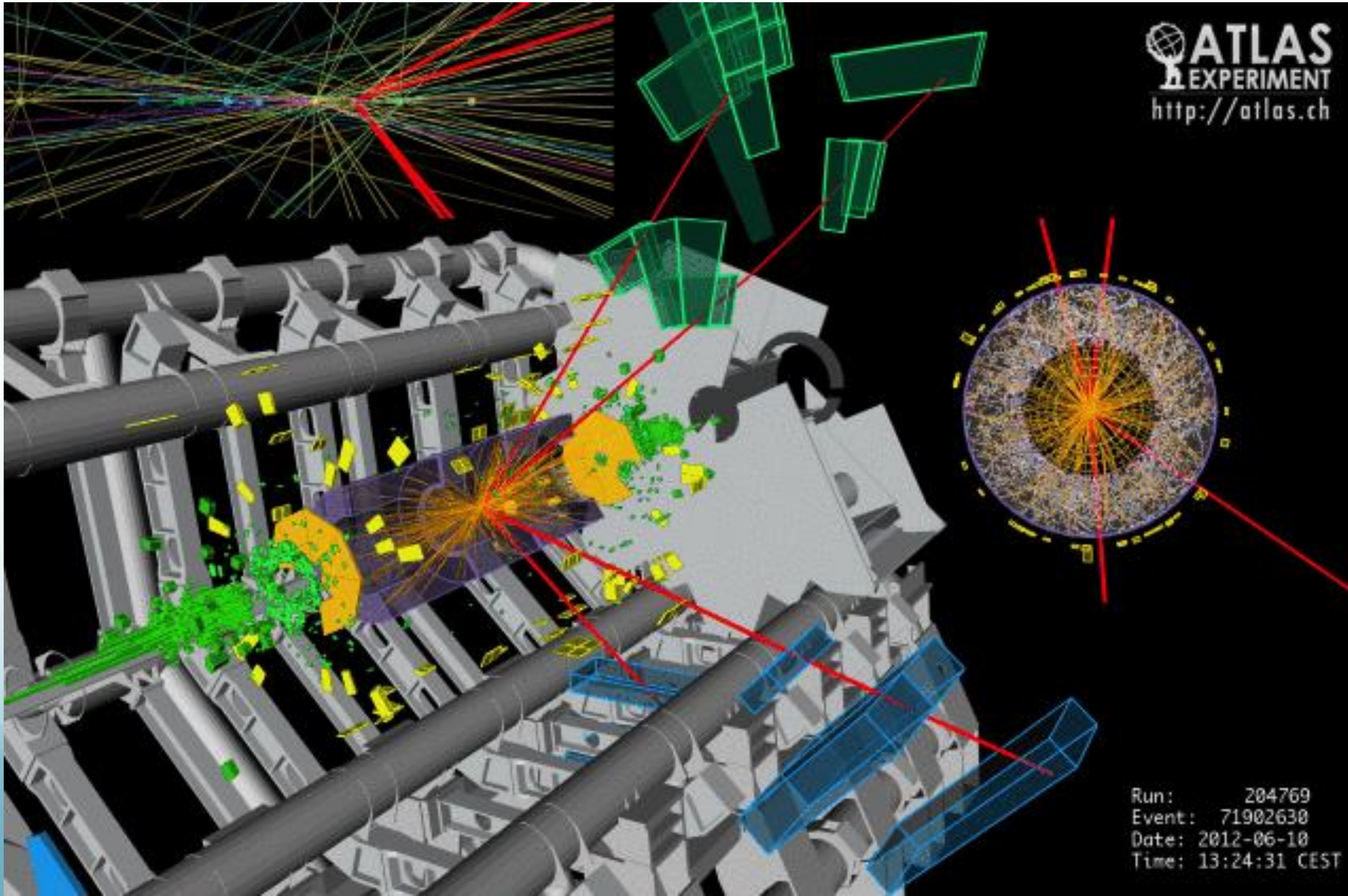


H→ 4 leptons

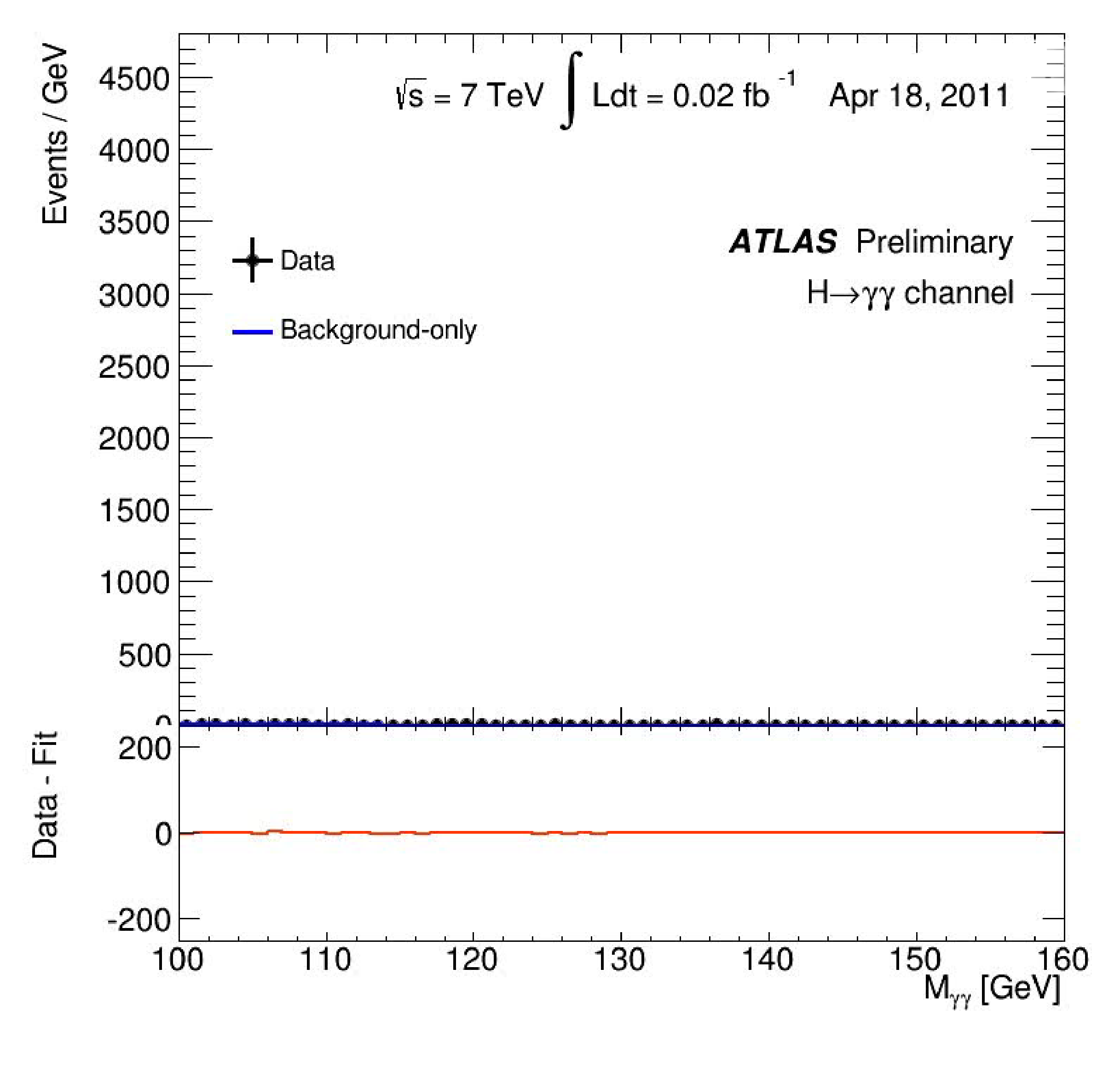
OFFLINE
Full analysis



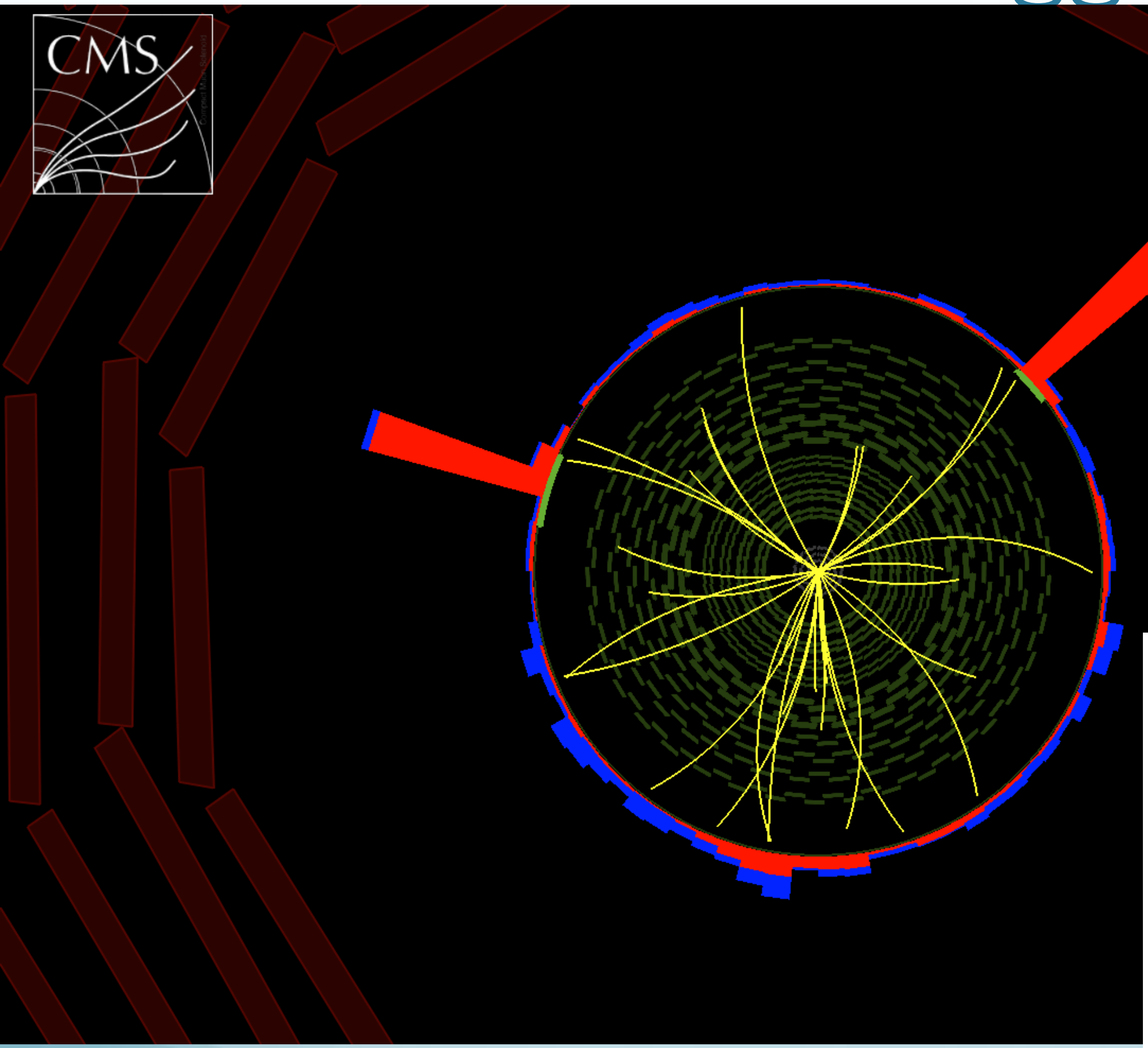
Higgs events H→4l (muons)

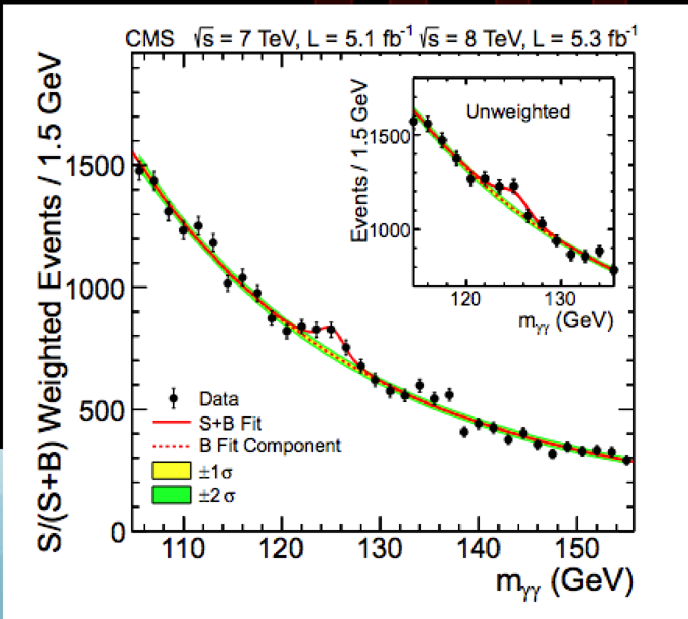


H → γγ


√s = 7 TeV ∫ Ldt = 0.02 fb⁻¹ Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

From CMS Higgs→γγ

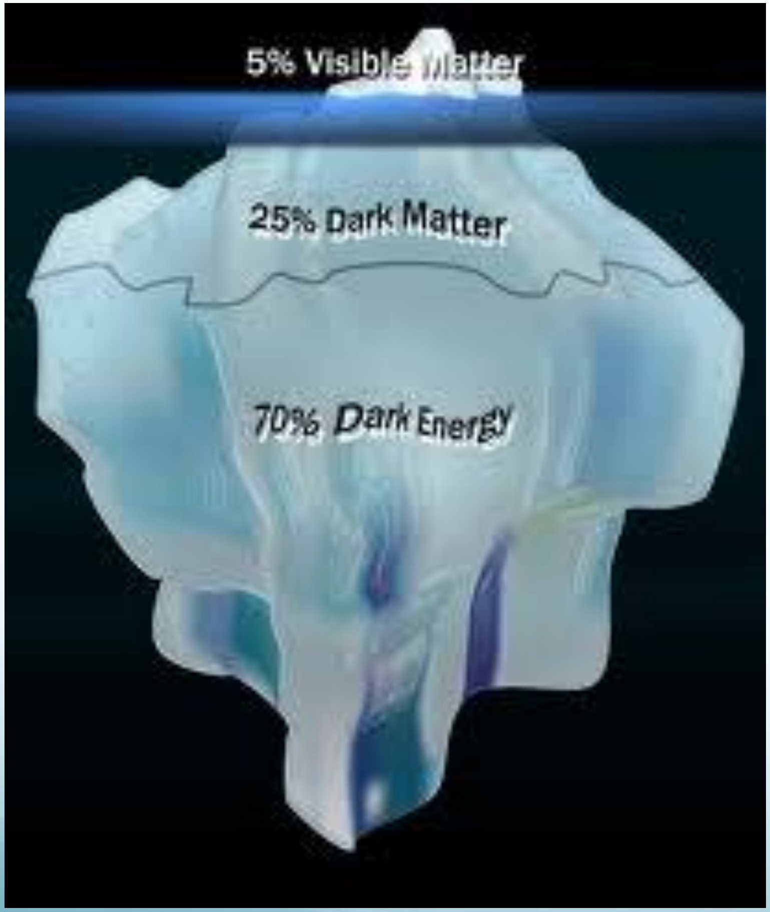




But

- There is a problem (at least).......

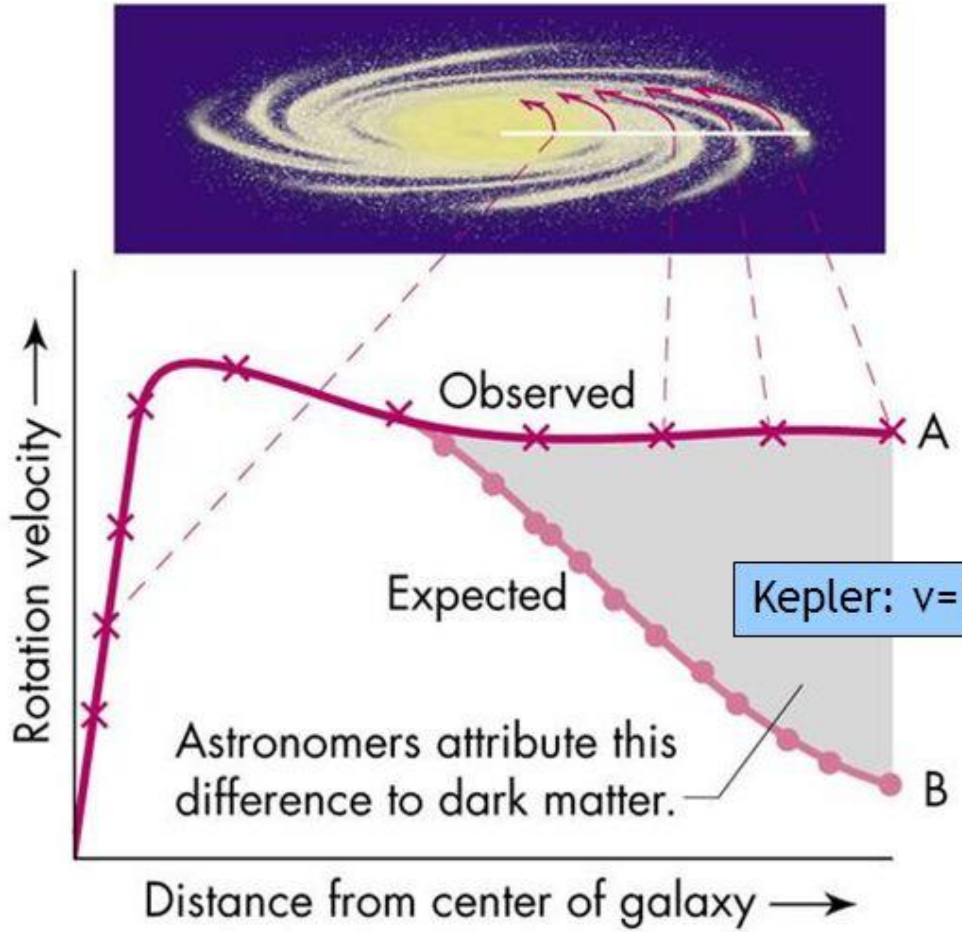
Dark Matter? Dark Energy?



- **Dark Matter** is invisible matter, it does not emit light. Its evidence comes from the study of the motion of galaxies and groups of galaxies
- **Dark Energy** is the term introduced to justify the acceleration of the Universe expansion (is it equivalent to Einstein's cosmological constant)

Potential Wells are much deeper than can be explained with visible matter

We have measured this for many years on galactic scales



Kepler: $v=[GM/R]^{1/2}$

But Where Is Everybody?

Nima Arkani-Hamed

What about future experiments ?

- **SHiP** and the associated SPS Beam Dump Facility is a new general-purpose experiment proposed at the SPS to search for "hidden" particles as predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe. The experiment is design to search for any type of very weakly interacting long-lived particles, among which are found e.g. heavy neutral leptons, dark photons , dark scalars, axion-like particles, and light supersymmetric particles - sgoldstinos, etc, as well as different types of Light Dark Matter.

- **Hike (future of NA62)** Measure branching ratios of rare Kaon decays for direct comparison with standard model predictions

Modified Newtonian Dynamics (MOND) as an alternative to dark matter !

Who is right ?

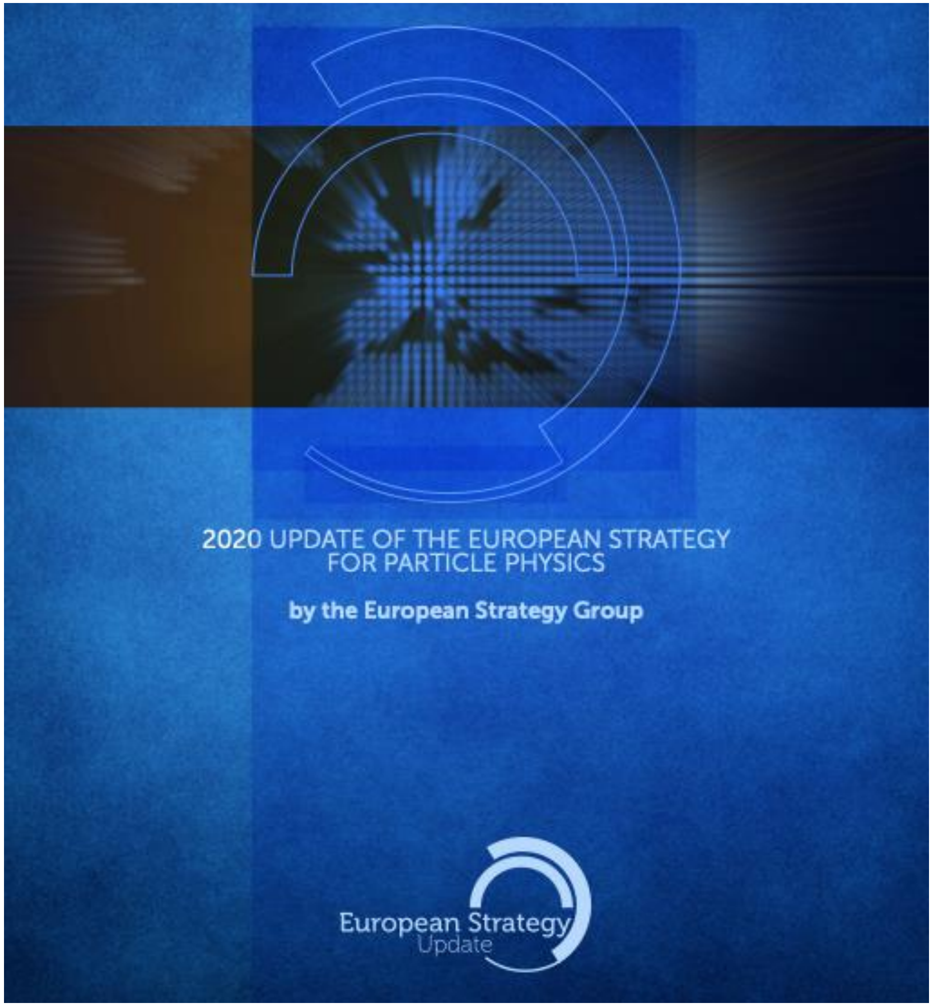
>A new theory of gravity

>Experiments:

- In space or on the ground
- Accelerators (CERN)

An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy

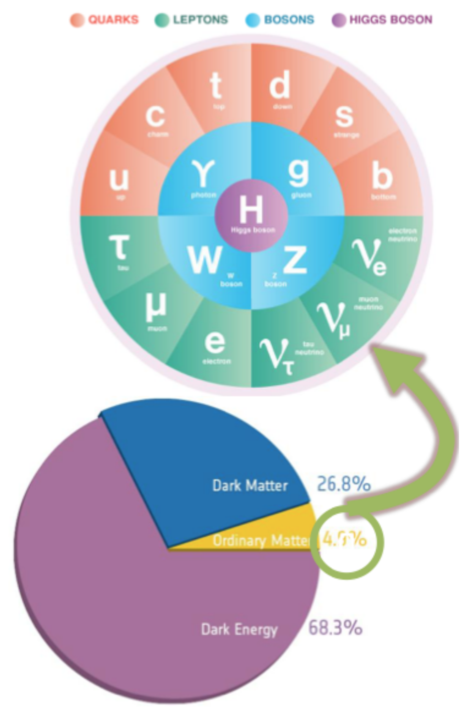
Large-scale data-intensive software and computing infrastructures are an essential ingredient to particle physics research programmes



The High Energy Physics Program Mission

…is to understand how the universe works at its most fundamental level:

- **Discover** the most elementary constituents of **matter and energy**
- **Probe** the **interactions** between them
- **Explore** the basic nature of **space and time**



The Next Big Discovery in Particle Physics

The DOE HEP mission is to understand how the universe works at its most fundamental level:

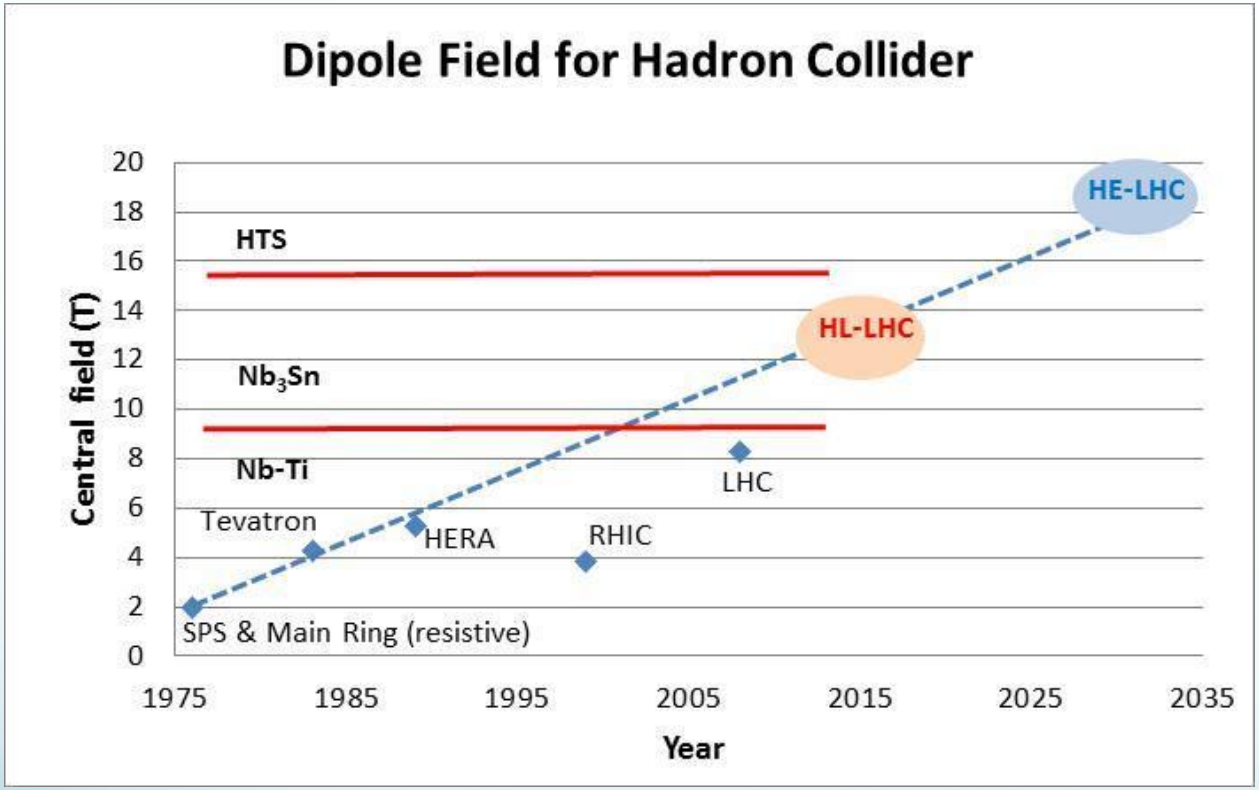
- **Discover** the most elementary constituents of matter and energy
- **Probe** the interactions between them
- **Explore** the basic nature of space and time

Science priorities guided by the five intertwined science drivers presented by P5:

- **Use the Higgs boson as a new tool for discovery** **2013*
- **Pursue the physics associated with neutrino mass** **2015*
- **Identify the new physics of dark matter**
- **Understand cosmic acceleration: dark energy and inflation** **2011*
- **Explore the unknown: new particles, interactions, and physical principles**

** Since 2011, three of the five science drivers have been lines of inquiry recognized with Nobel Prizes*

HL-LHC and HE- LHC

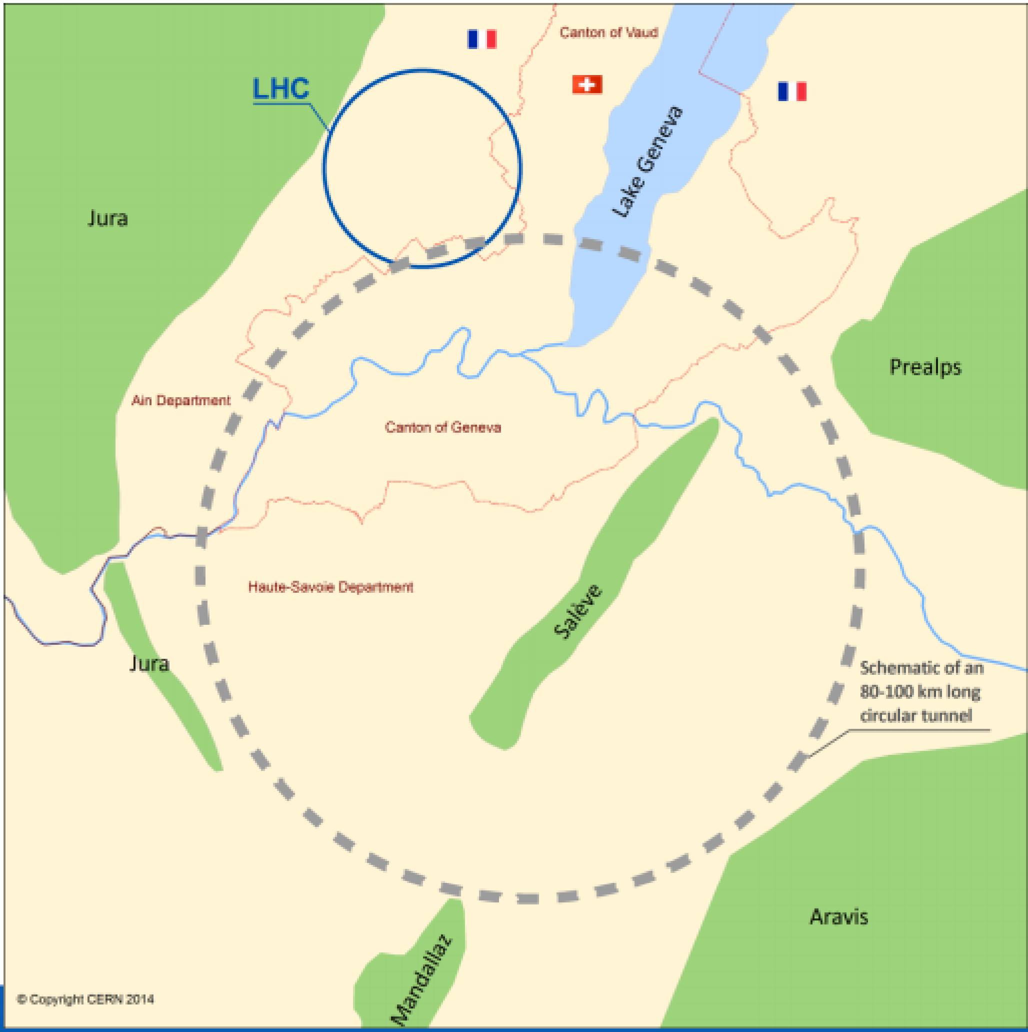


- Development of high field superconducting magnets
- High-Energy LHC with 10-13 T magnets
- HE-LHC with ~30 TeV center-of-mass energy for proton collisions and 16-20 T magnets

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh) with possibility of e+-e- (FCC-ee) and p-e (FCC-he)

FCC (Future Circular Colliders) CDR and cost review for the next ESU *(2018)* (including injectors)

16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km



Literature

- CERN Academic Training
  http://indico.cern.ch/conferenceDisplay.py?confId=266737

- CERN ATLAS
  http://atlas.cern/resources

- European Strategy (2019):
  - https://europeanstrategy.cern/european-strategy-for-particle-physics
  - https://indico.cern.ch/event/808335/timetable/ -20190513.detailed

No one in physics dares say so, but the race to invent new particles is pointless

Sabine Hossenfelder

In private, many physicists admit they do not believe the particles they are paid to search for exist – they do it because their colleagues are doing it

'The Large Hadron Collider (LHC) hasn't seen any of the particles theoretical physicists have hypothesised, even though many were confident it would.' A technician works on the LHC, near Geneva, Switzerland. Photograph: Laurent Gilliéron/AP

What are these theories she talks about

- SUSY
  - In particle physics, a supersymmetric extension of the Standard Model is a possible candidate for undiscovered particle physics, and seen by some physicists as an elegant solution to many current problems in particle physics if confirmed correct, which could resolve various areas where current theories are believed to be incomplete and where limitations of current theories are well established.
- GUT: A Grand Unified Theory (GUT) is a model in particle physics in which, at high energies, the three gauge interactions of the Standard Model comprising the electromagnetic, weak, and strong forces are merged into a single force.
- Dark matter:
  - To solve the problem of rotating galaxies and other problems in the universe
- Hierarchy problem

Spares

Question: Higgs production?

Ref (link) : *Higgs production*

- *Gluon fusion*. If the collided particles are hadrons such as the proton or antiproton – as is the case in the LHC and Tevatron – then it is most likely that two of the gluons binding the hadron together collide. The easiest way to produce a Higgs particle is if the two gluons combine to form a loop of virtual quarks. Since the coupling of particles to the Higgs boson is proportional to their mass, this process is more likely for heavy particles. In practice it is enough to consider the contributions of virtual top and bottom quarks (the heaviest quarks). This process is the dominant contribution at the LHC and Tevatron being about ten times more likely than any of the other processes.[86][159]

- *Higgs Strahlung*. If an elementary fermion collides with an anti-fermion – e.g., a quark with an anti-quark or an electron with a positron – the two can merge to form a virtual W or Z boson which, if it carries sufficient energy, can then emit a Higgs boson. This process was the dominant production mode at the LEP, where an electron and a positron collided to form a virtual Z boson, and it was the second largest contribution for Higgs production at the Tevatron. At the LHC this process is only the third largest, because the LHC collides protons with protons, making a quark-antiquark collision less likely than at the Tevatron. Higgs Strahlung is also known as *associated production*.[86][159][160]

- *Weak boson fusion*. Another possibility when two (anti-)fermions collide is that the two exchange a virtual W or Z boson, which emits a Higgs boson. The colliding fermions do not need to be the same type. So, for example, an up quark may exchange a Z boson with an anti-down quark. This process is the second most important for the production of Higgs particle at the LHC and LEP.[86][160]

- *Top fusion*. The final process that is commonly considered is by far the least likely (by two orders of magnitude). This process involves two colliding gluons, which each decay into a heavy quark–antiquark pair. A quark and antiquark from each pair can then combine to form a Higgs particle.[86][159]

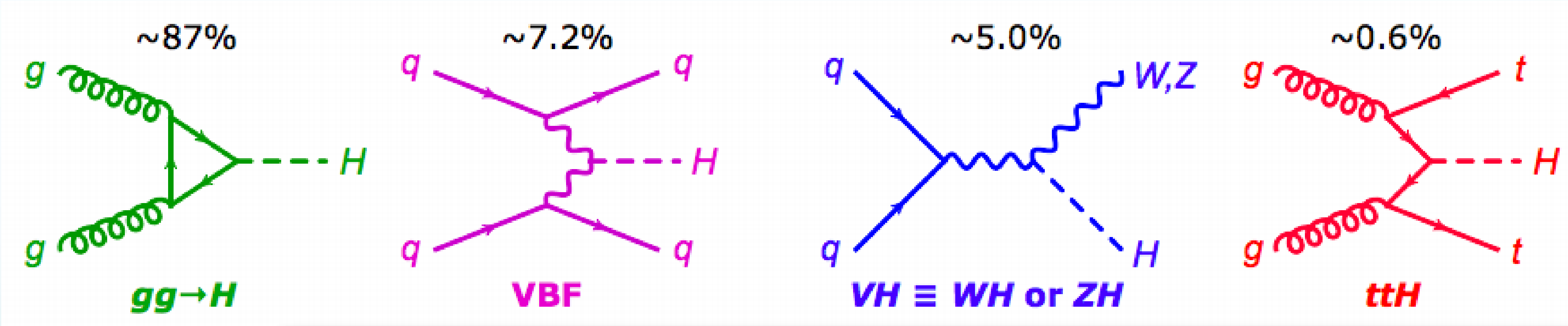
Higgs production

Vector boson fusion
VBF

Top-antitop fusion
ttH

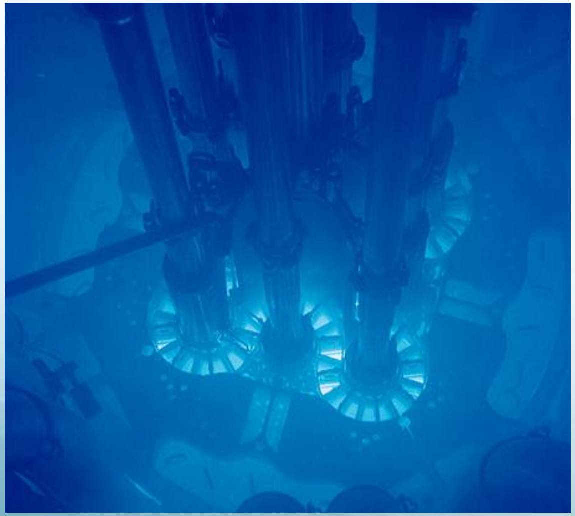
Higgs strahlung
VH

Gluon-gluon fusion
gg→H



Cherenkov light

- Named after the Russian scientist P. Cherenkov who was the first to study the effect in depth (he won the Nobel Prize for it in 1958)
- From Relativity, nothing can go faster than the speed of light *c* (in vacuum)
- However, due to the refractive index *n* of a material, a particle *can* go faster than the *local* speed of light in the medium $c_p = c/n$
- Fast electrons in a reactor emitting blue light (Cherenkov radiation)
- This is analogous to the bow wave of a boat travelling over water
  or the sonic boom of an aeroplane travelling faster than the speed of sound



Cherenkov radiation

The left corner of the triangle represents the location of the superluminal particle at some initial moment (t=0). The right corner of the triangle is the location of the particle at some later time t. In the given time t, the particle travels the distance

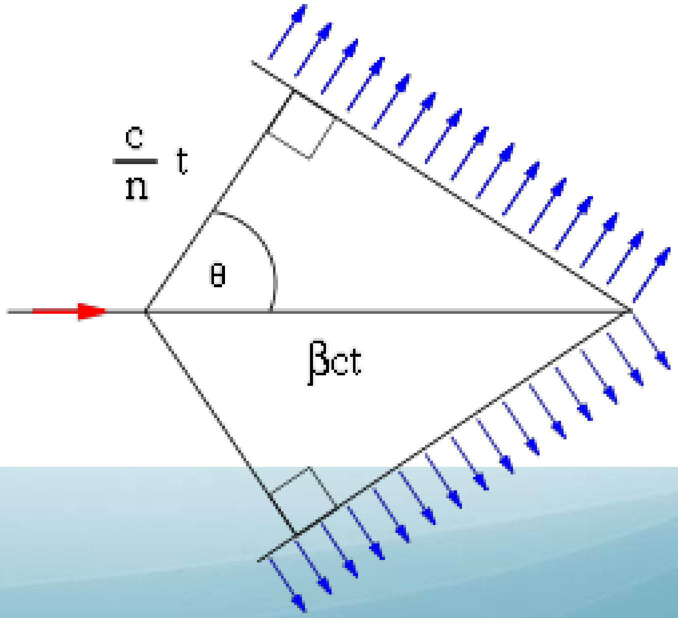
$$x_p = v_p t = \beta\, ct$$

whereas the emitted electromagnetic waves are constricted to travel the distance

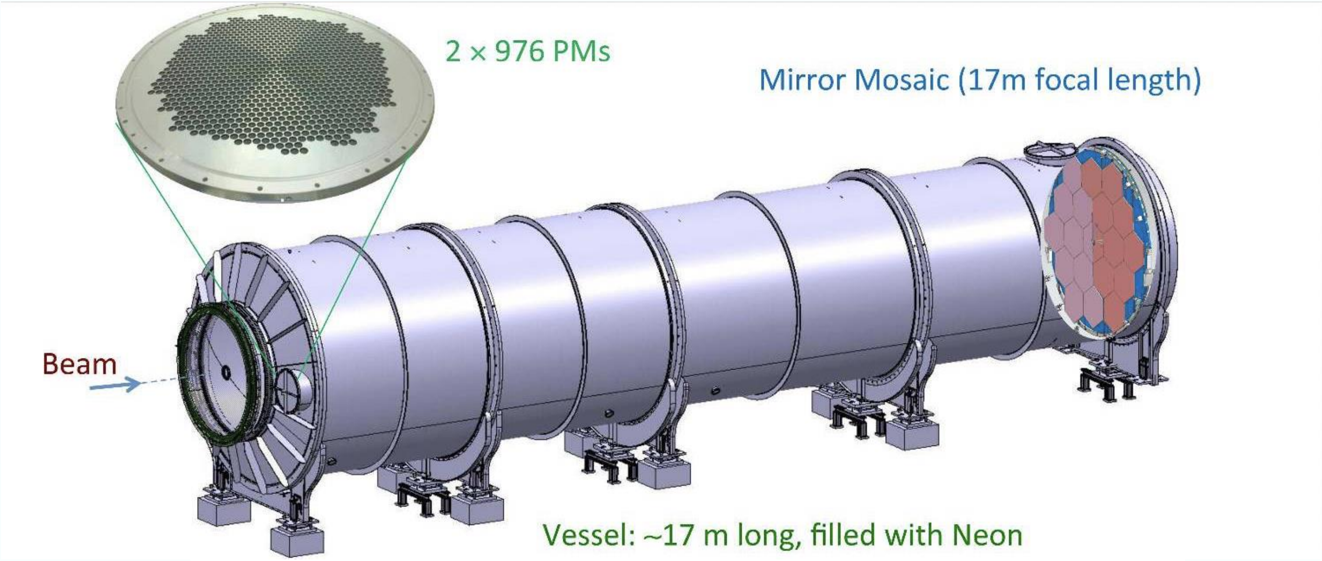
$$x_{em} = v_{em} t = \frac{c}{n} t$$

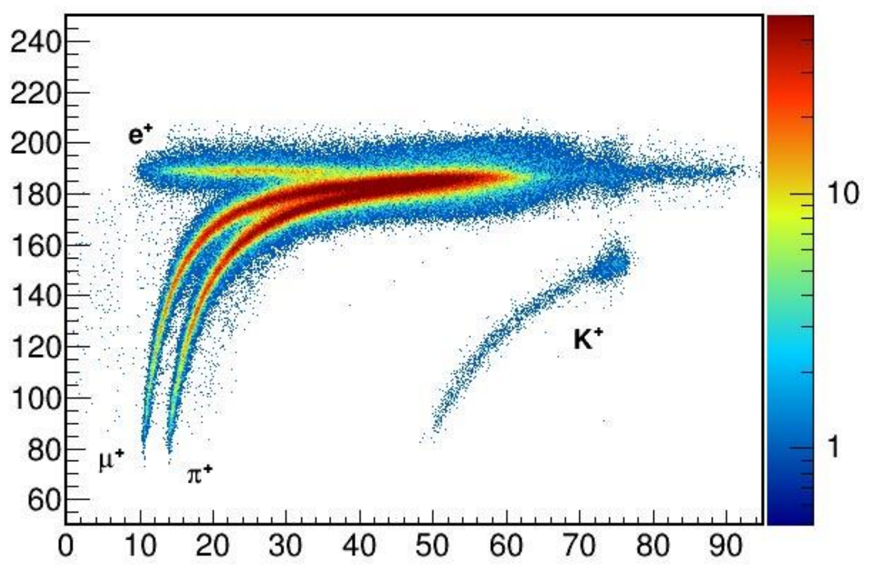
So:

$$\cos\theta = \frac{1}{n\beta}. = \frac{v_{em}}{v_p}$$



Cherenkov Detector NA62





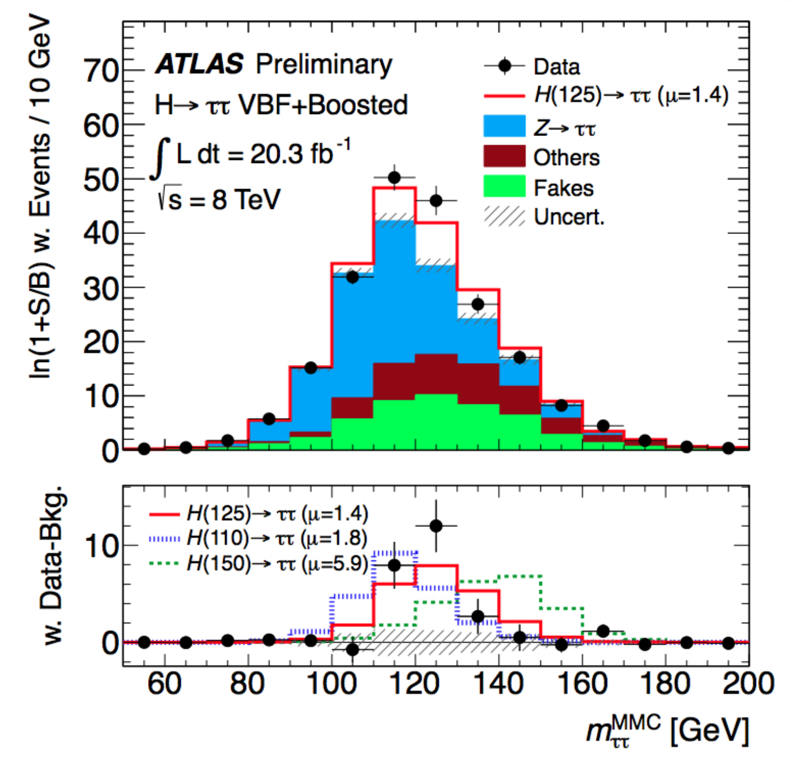
Higgs to Fermions

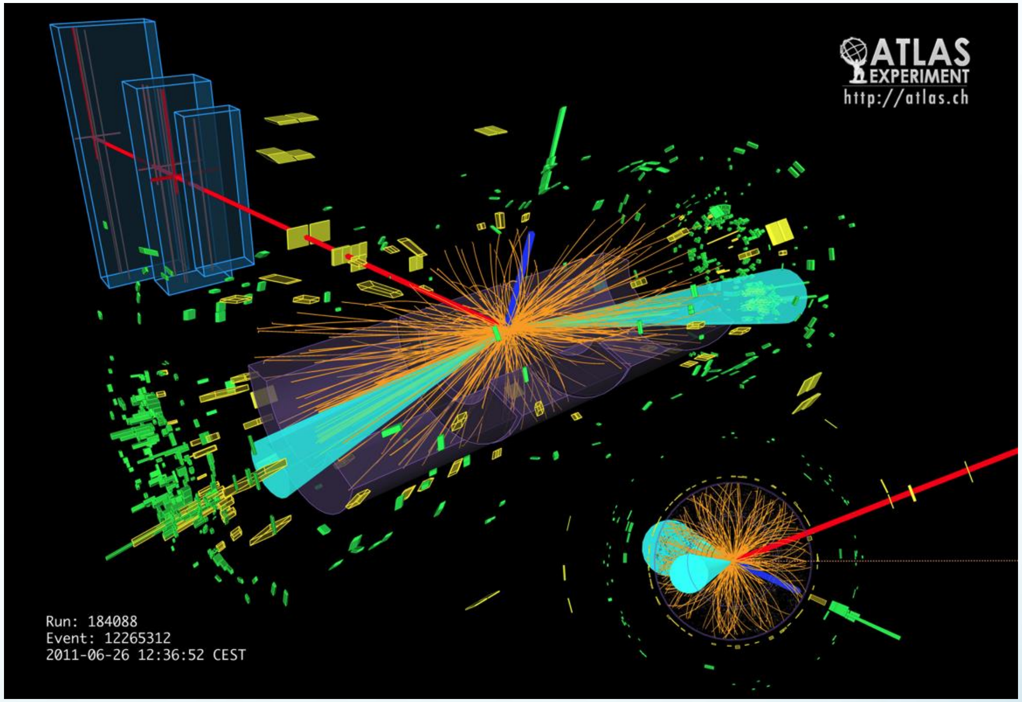
- Recent analysis shows evidence of Higgs boson decaying to fermions (leptons or quarks). Not previously observed!
- It is important to measure this decay but no surprise is expected
- Difficult due to high background

  BR related to mass. High mass fermions preferred (τ,b)

- Both ATLAS and CMS has “evidence” in the channel H→ $\tau\tau$ ....but not yet the famous “5 σ” needed to claim discovery

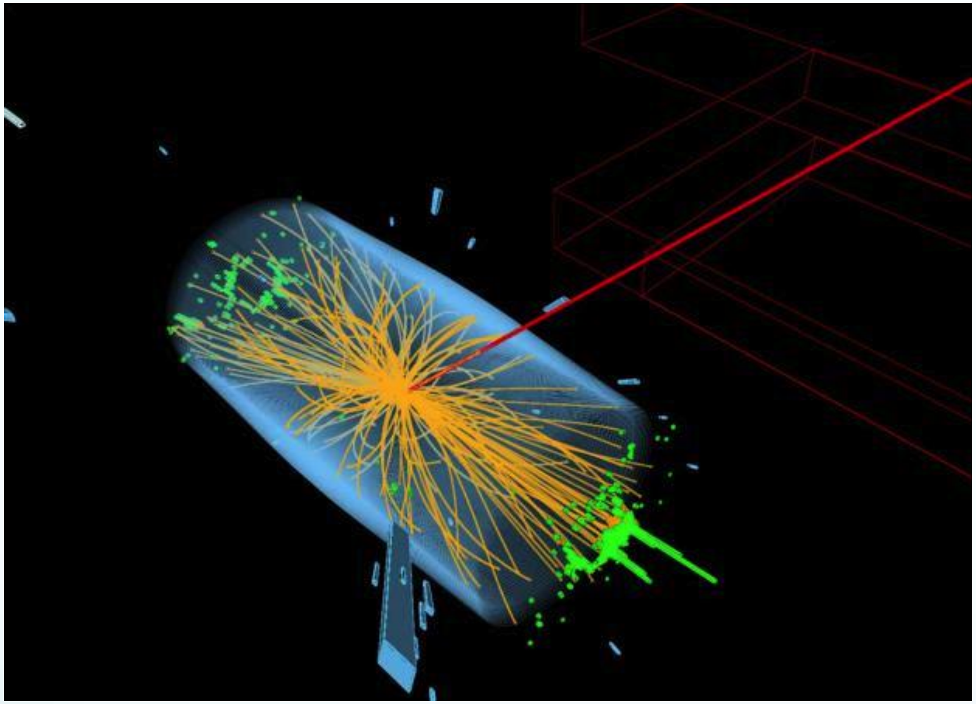
Higgs decays to fermions (ττ) in ATLAS (26 Nov 2013)



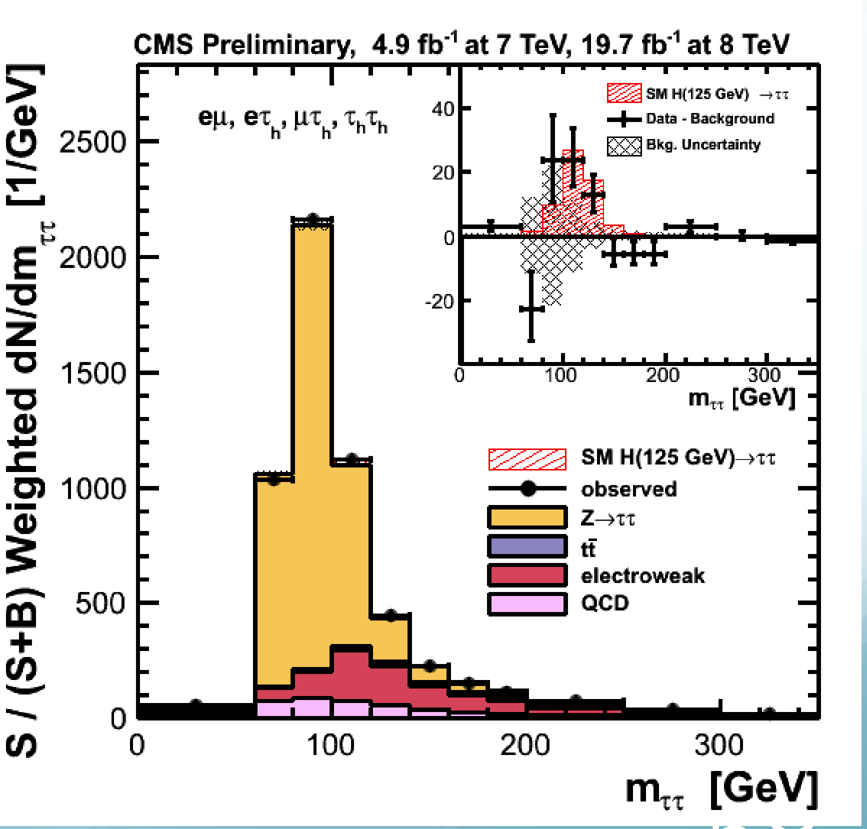


The taus decay into an electron (blue line) and a muon (red line)

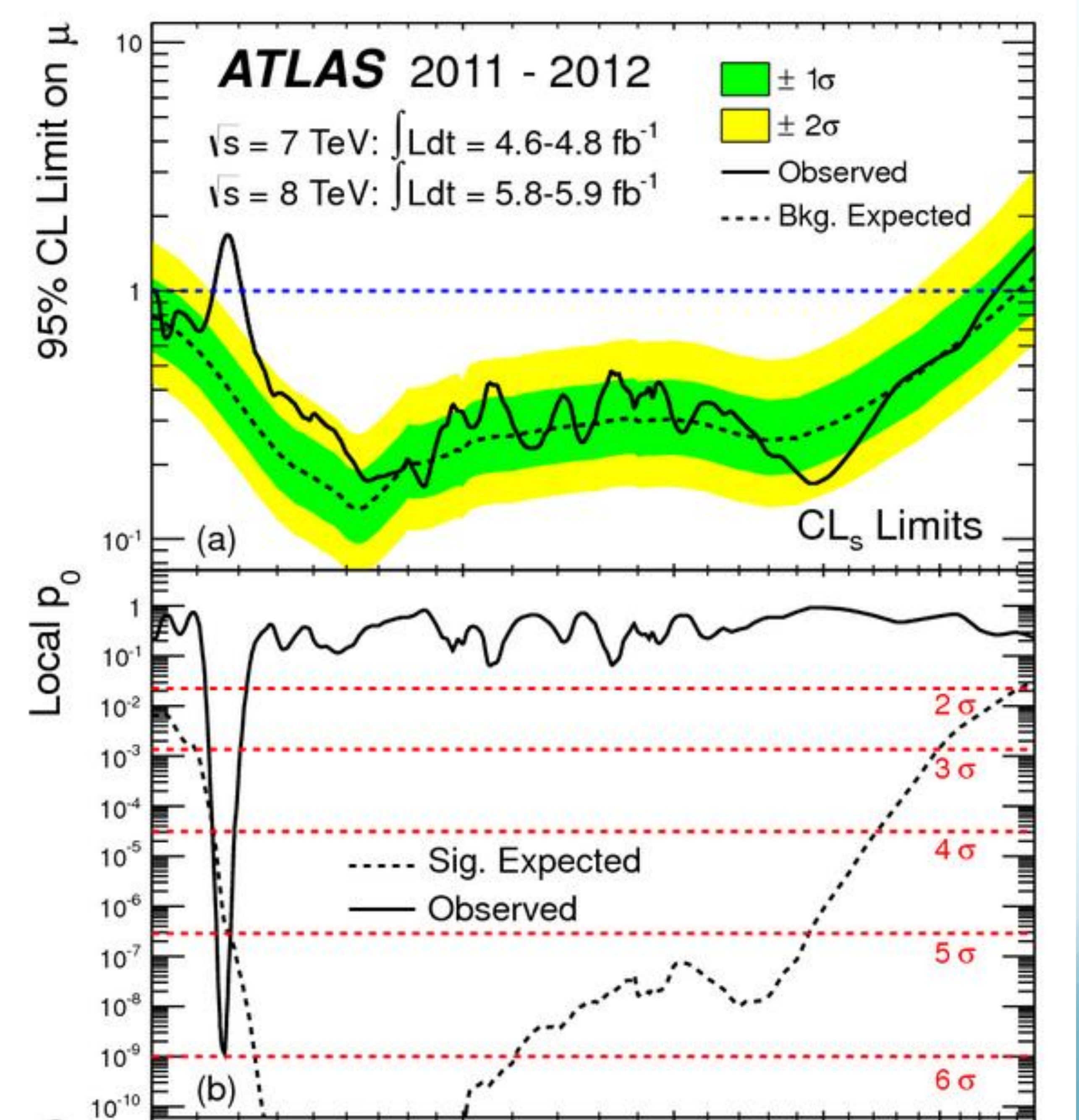
Higgs decays to fermions ($\tau\tau$) in CMS (3 Dec. 2013)



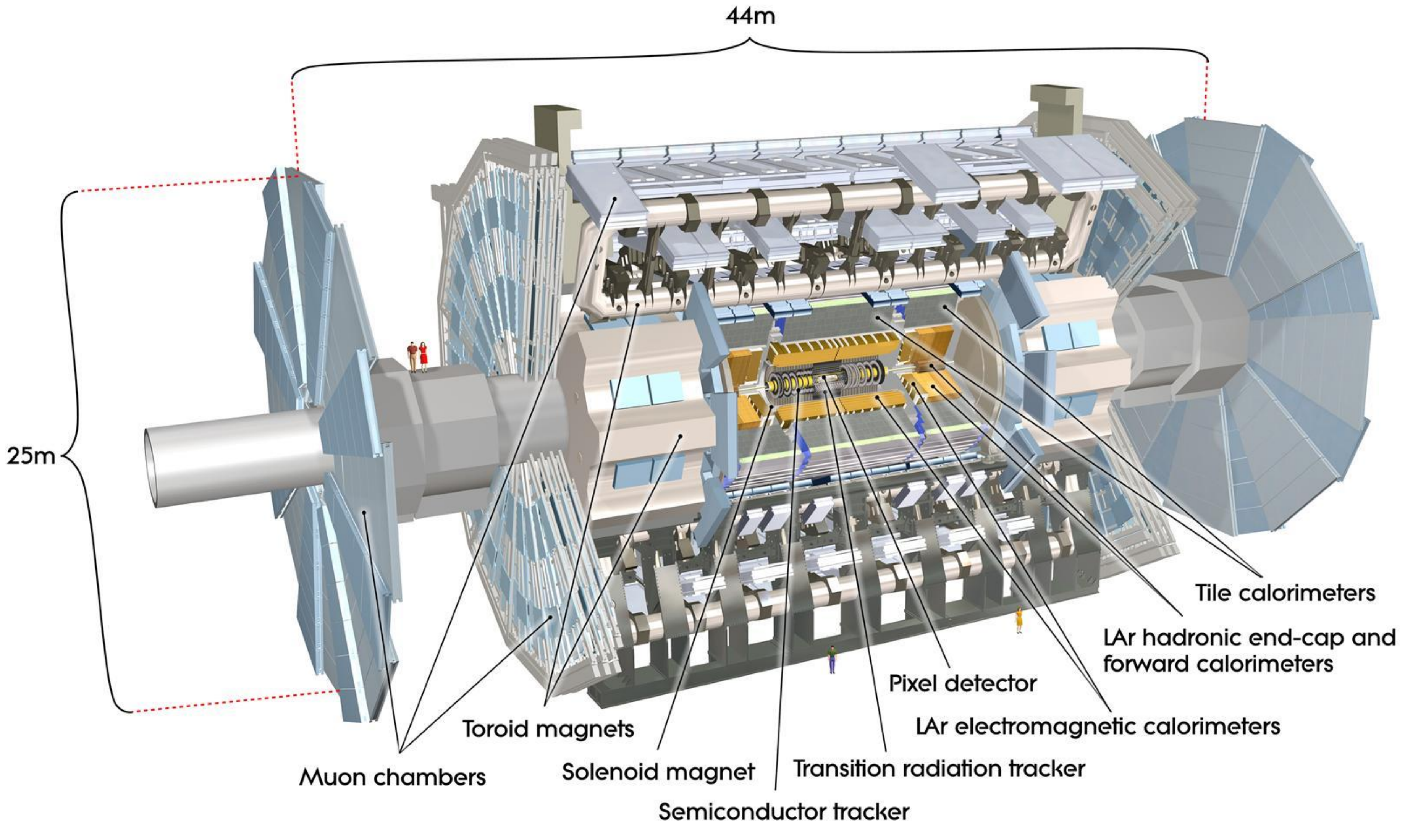
One tau decays to neutrinos and a muon (red lines on the right), while the other decays into a charged hadron (blue towers) and a neutrino



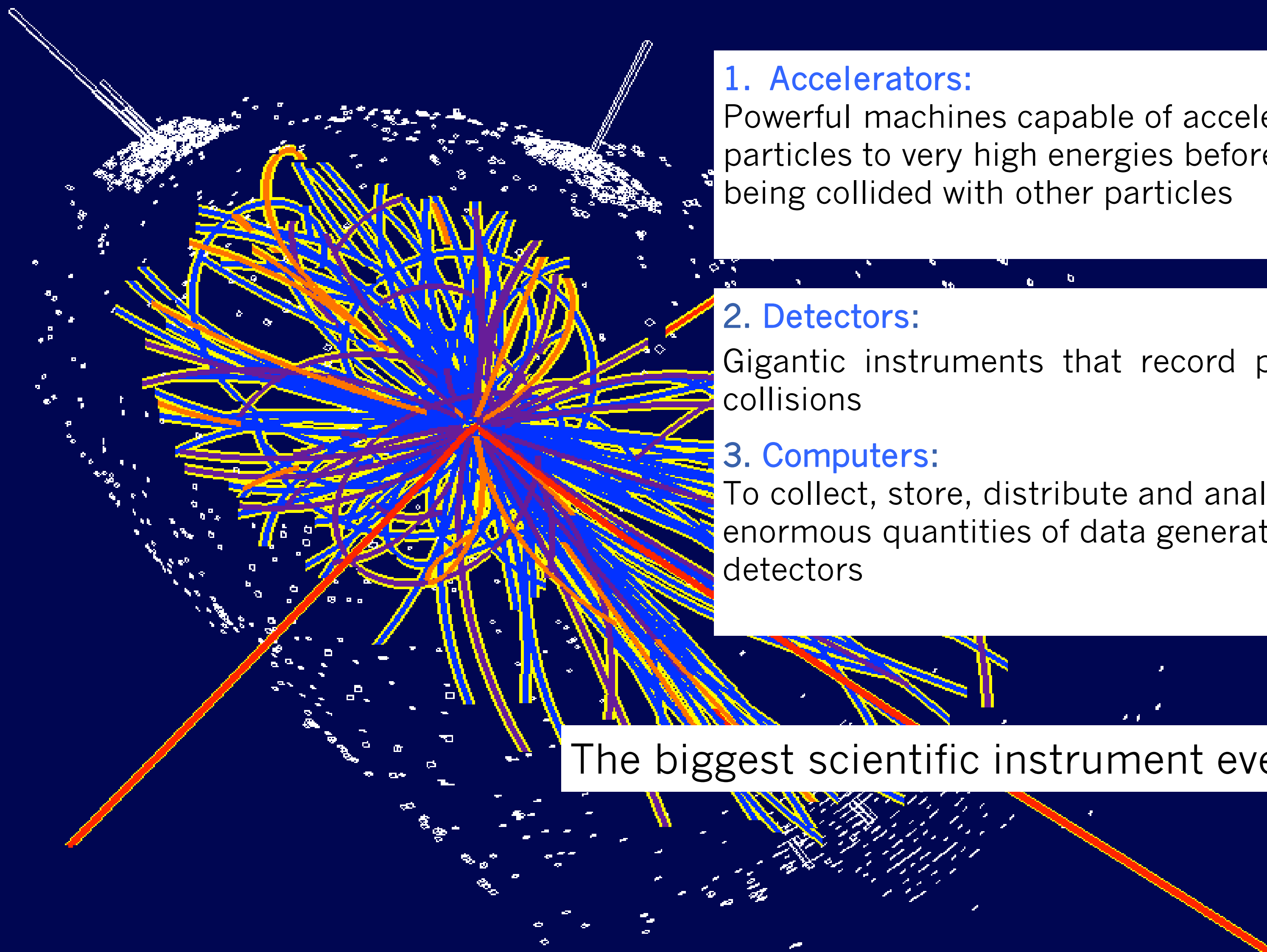
Higgs
“exclusion
plots”



The ATLAS experiment



LHC
20 Years, projecting, constructing and Simulating...



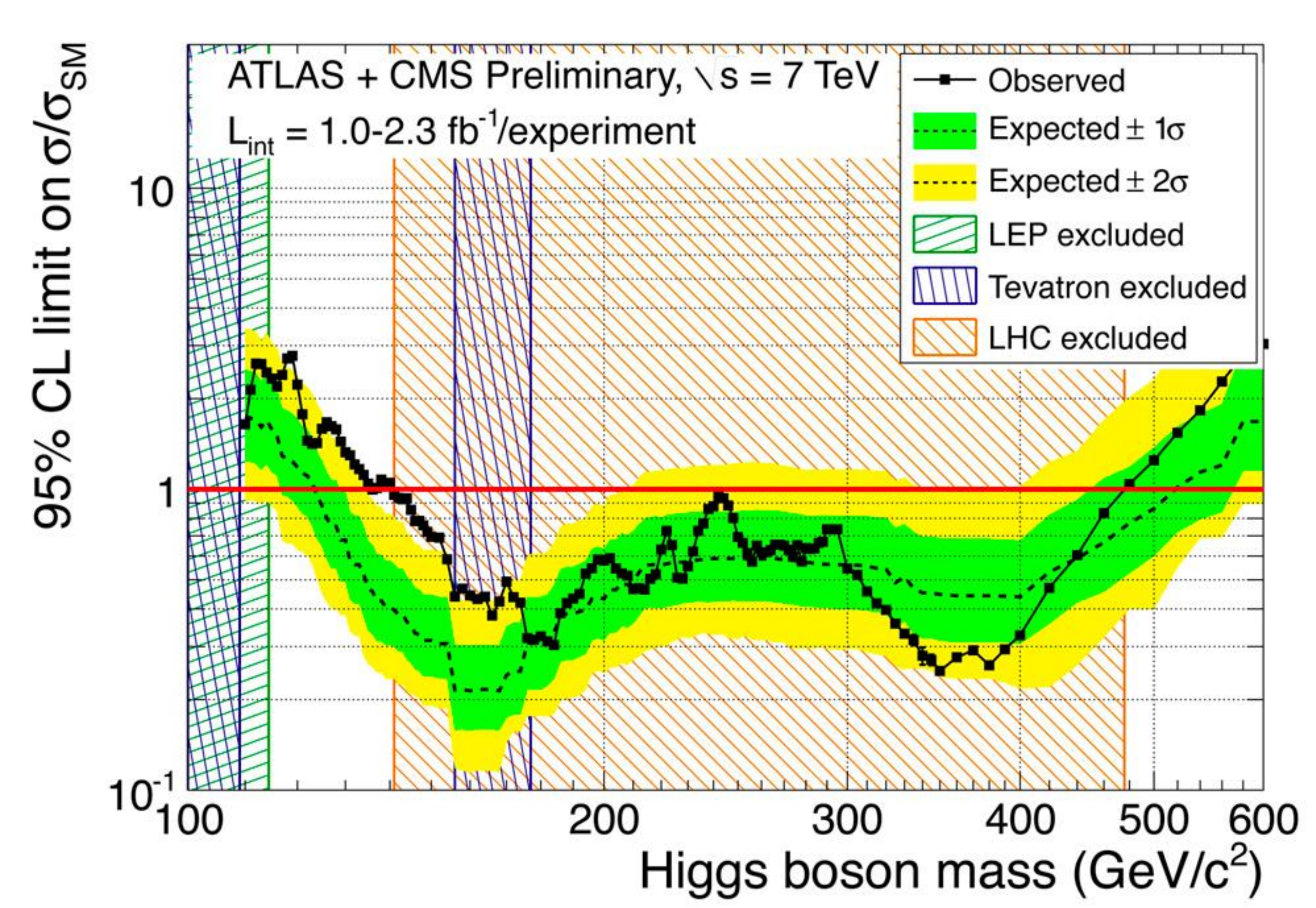
1. **Accelerators:**
Powerful machines capable of accelerating particles to very high energies before being collided with other particles

2. **Detectors:**
Gigantic instruments that record particle collisions

3. **Computers:**
To collect, store, distribute and analyze enormous quantities of data generated by detectors

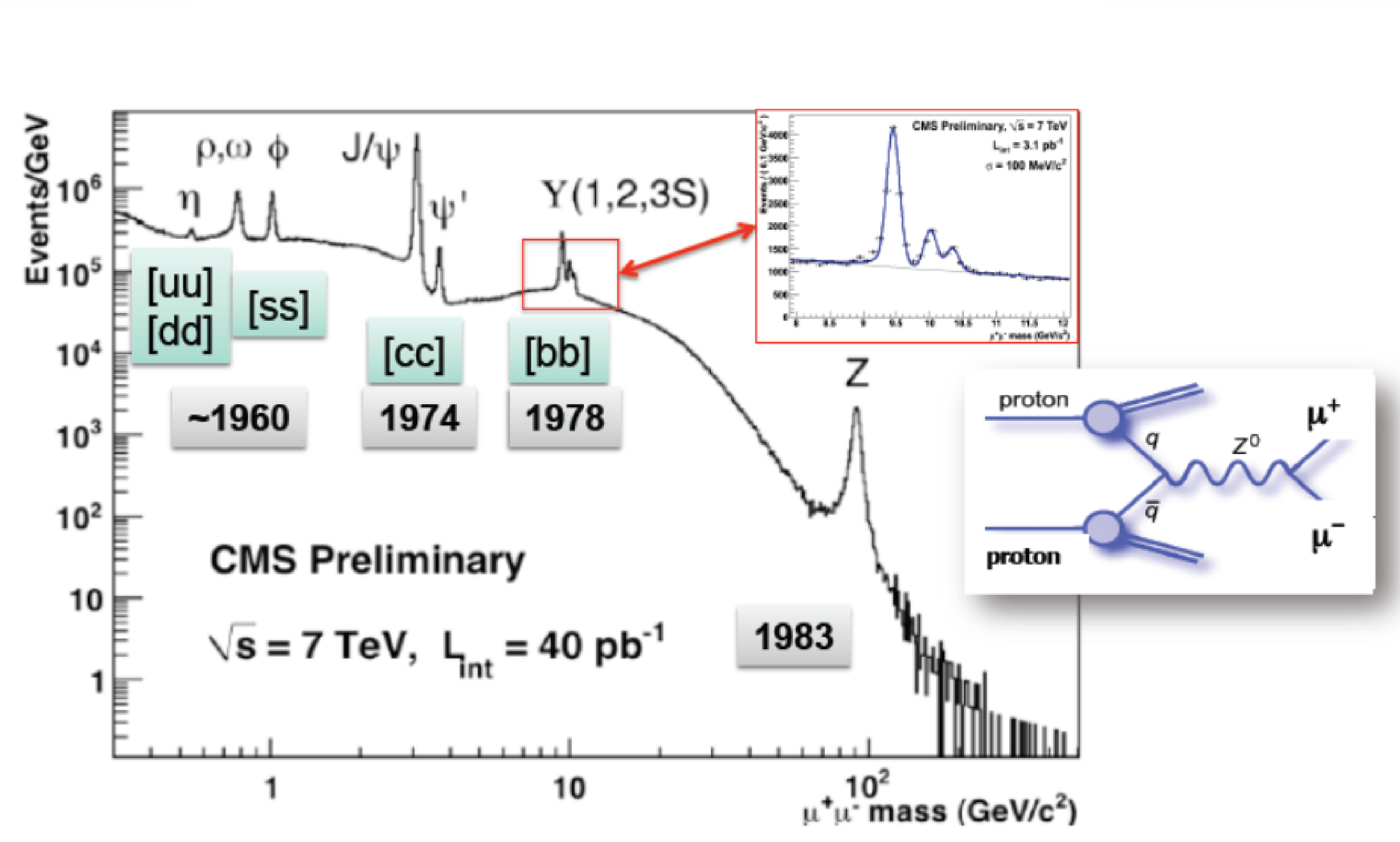
The biggest scientific instrument ever built

The Higgs search as of 18/11/2011



To be continued........

After 10 min of LHC running: full history of SM



What LEP (CERN) and Tevatron (Fermilab)

Until year 2000

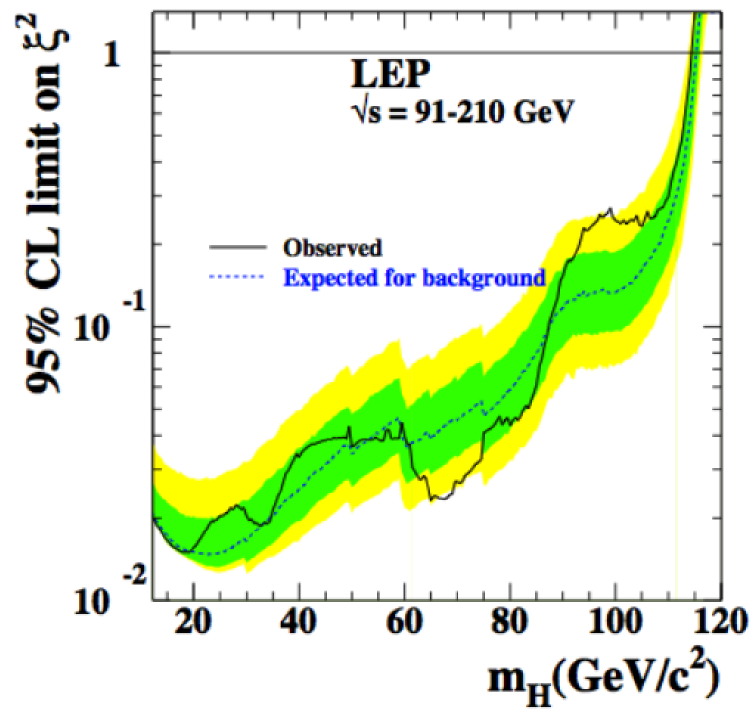


Figure 2.10: Higgs exclusion range from LEP experiments.

Until year 2011

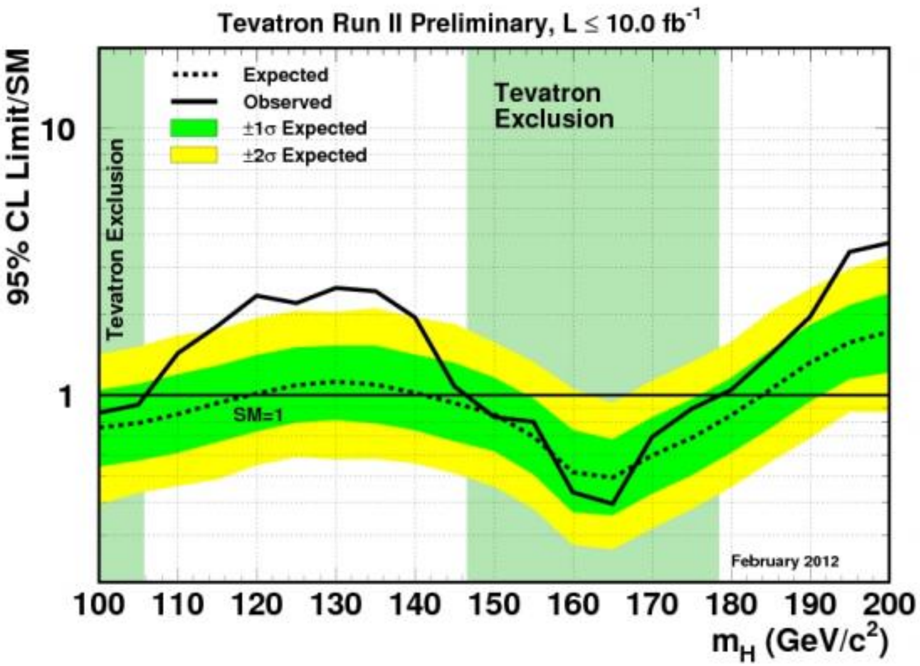
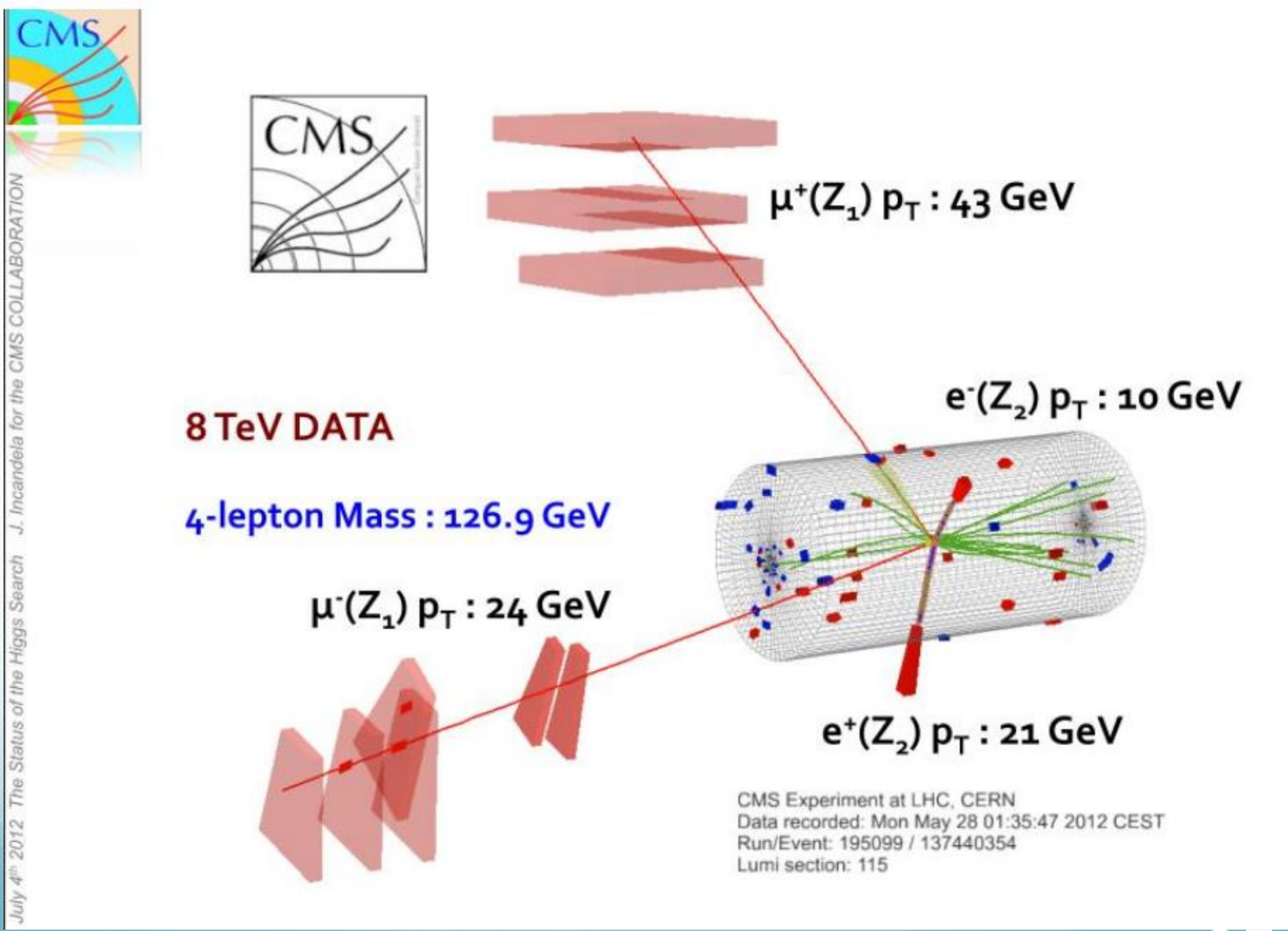


Figure 2.11: Combined Run II Higgs limits from the Tevatron experiments.


CMS
CMS
$\mu^+(Z_1)$ p_T : 43 GeV
$e^-(Z_2)$ p_T : 10 GeV
8 TeV DATA
4-lepton Mass : 126.9 GeV
$\mu^-(Z_1)$ p_T : 24 GeV
$e^+(Z_2)$ p_T : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION

Interaction of Particles with Matter

In order to detect a particle it must interact with matter!

The most important interaction processes are electromagnetic:

Charged Particles:

- Energy loss due to ionization (e.g. charged track in straw detector) heavy particles (*not* electrons/positrons!)
- Energy loss due to photon emission (electrons, positrons) bremsstrahlung

Photons:

Interaction of photons with matter (e.g. EM calorimetry)

Photoelectric effect

Compton effect

Pair production

Other important electromagnetic processes:

Multiple Scattering (Coulomb scattering)

scintillation light (e.g. TOF systems)

Cherenkov radiation

Transition Radiation (e.g. particle id normally electrons)

Can calculate the above effects with a combo of classical E&M and QED.
In most cases calculate approximate results, exact calculations very difficult.

Bethe-Bloch Formula for Energy Loss

Average energy loss for **heavy charged particles**
Energy loss due to ionization and excitation
Valid for energies <100's GeV and $\beta \gg z\alpha$ ($\approx z/137$)

heavy= $m_{incident} \gg m_e$
proton, k, π, μ

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2\right]$$

$2\pi N_a r_e^2 m_e c^2$ =0.1535MeV-cm^2/g

Fundamental constants
r_e=classical radius of electron
m_e=mass of electron
N_a=Avogadro's number
c=speed of light

Absorber medium
I=mean ionization potential
Z= atomic number of absorber
A=atomic weight of absorber
ρ=density of absorber
δ=density correction
C=shell correction

Incident particle
z=charge of incident particle
β=v/c of incident particle
$\gamma=(1-\beta^2)^{-1/2}$
W_{max}=max. energy transfer in one collision

$$W_{max} = \frac{2m_e(c\beta\gamma)^2}{1 + m_e/M\sqrt{1+(\beta\gamma)^2} + (m_e/M)^2} \approx 2m_e(c\beta\gamma)^2$$

Note: the classical dE/dx formula contains many of the same features as the QM version: $(z/\beta)^2$, & ln[]

$$-dE/dx = \frac{4\pi z^2 r_e^2 m_e c^2 N_e}{\beta^2}\ln\frac{b_{max}}{b_{min}}$$

Multiple Scattering

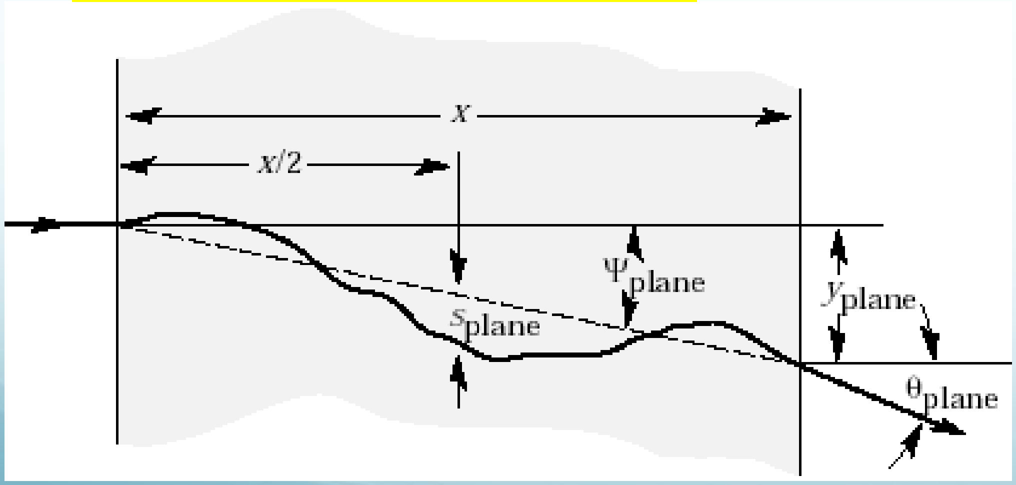
A charged particle traversing a medium is deflected by many small angle scatterings.
These scattering are due to the **coulomb field of atoms** and are **assumed to be elastic**.
In each scattering the energy of **the particle is constant but the particle direction changes**.

In the simplest model of multiple scattering we ignore large angle scatters.
In this approximation, the distribution of scattering angle θ_{plane} after traveling a distance x through a material with radiation length $=L_r$ is approximately gaussian:

$$\frac{dP(\theta_{plane})}{d\theta_{plane}} = \frac{1}{\theta_0\sqrt{2\pi}}\exp\left[-\frac{\theta_{plane}^2}{2\theta_0^2}\right] \quad \text{with} \quad \theta_0 = \frac{13.6\,\mathbf{MeV}}{\beta pc} z\sqrt{x/L_r}\left(1+0.038\ln\{x/L_r\}\right)$$

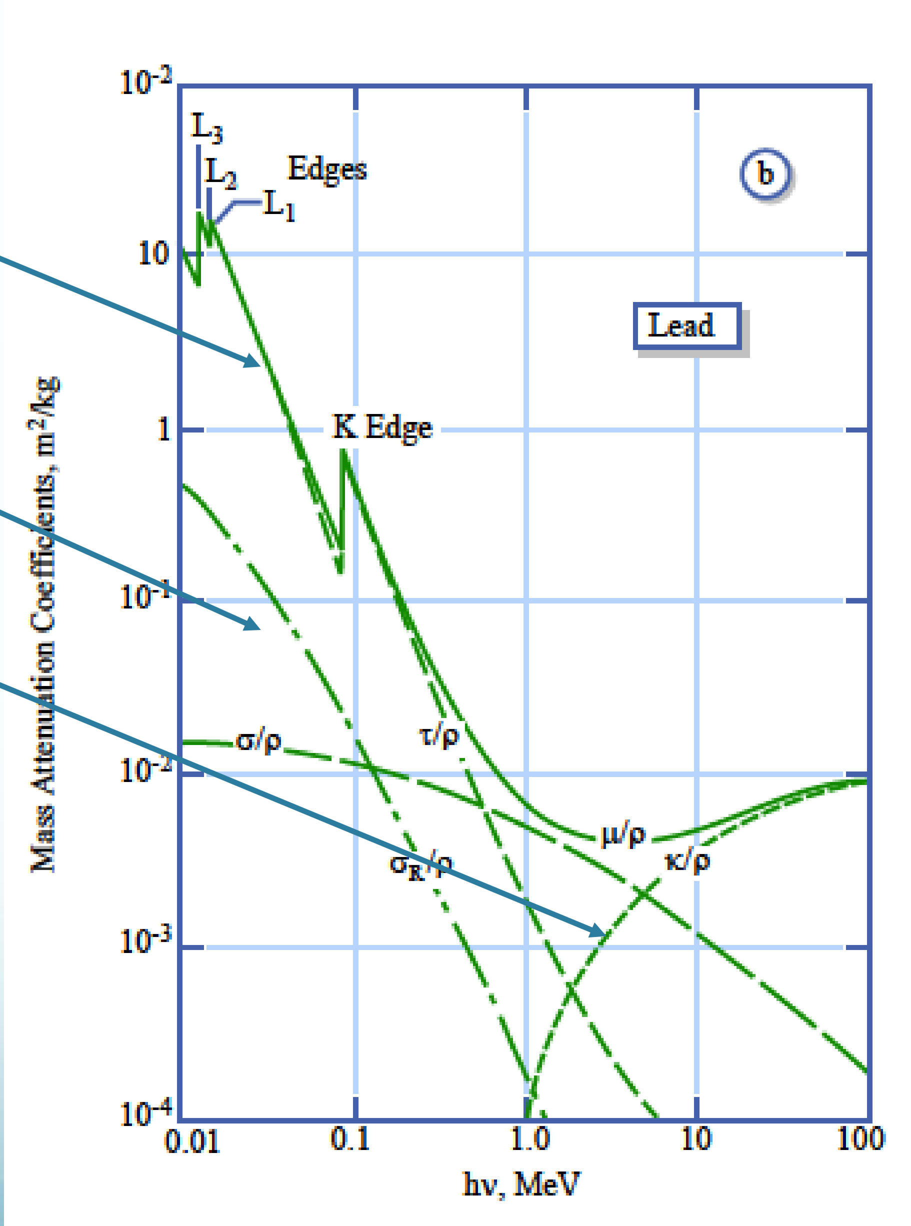
In the above equation $\beta=v/c$, and p=momentum of incident particle

This is not good for tracking!

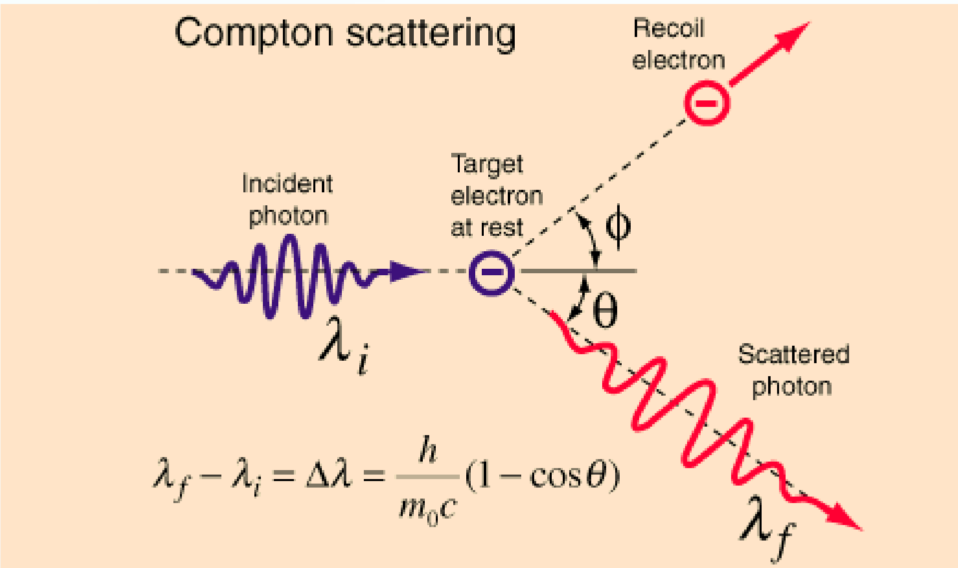


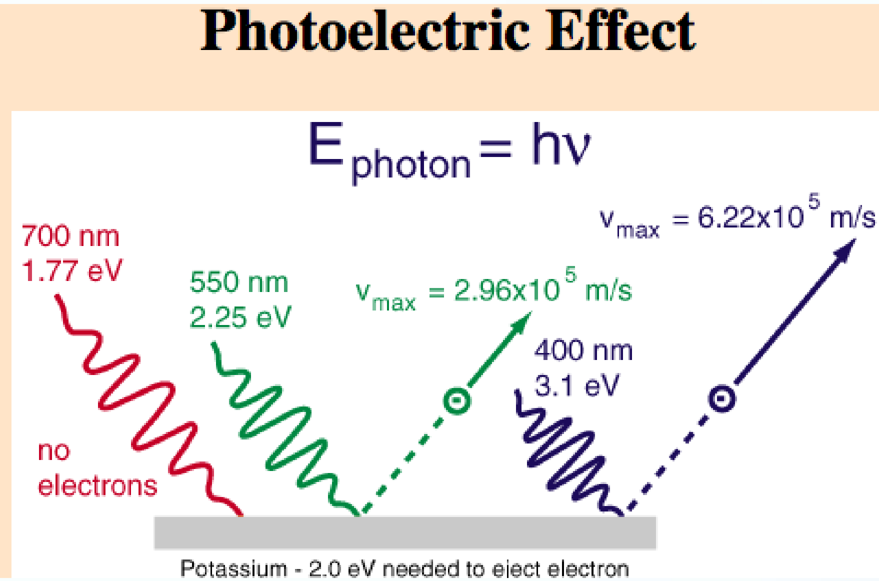
Photons interacting with matter

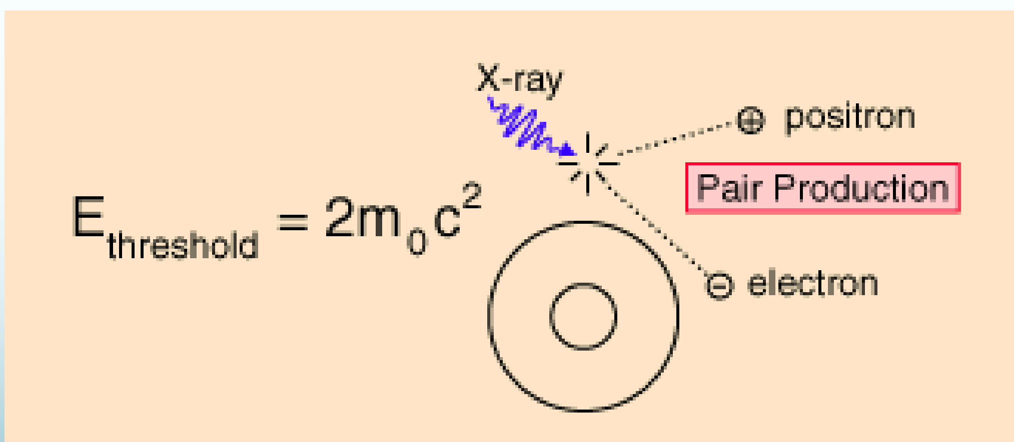
- Photoelectric effect
- Compton scattering
- Pair production
- *Mass Attenuation Coefficient* = Interaction probability/density



Photons - 3 interactions







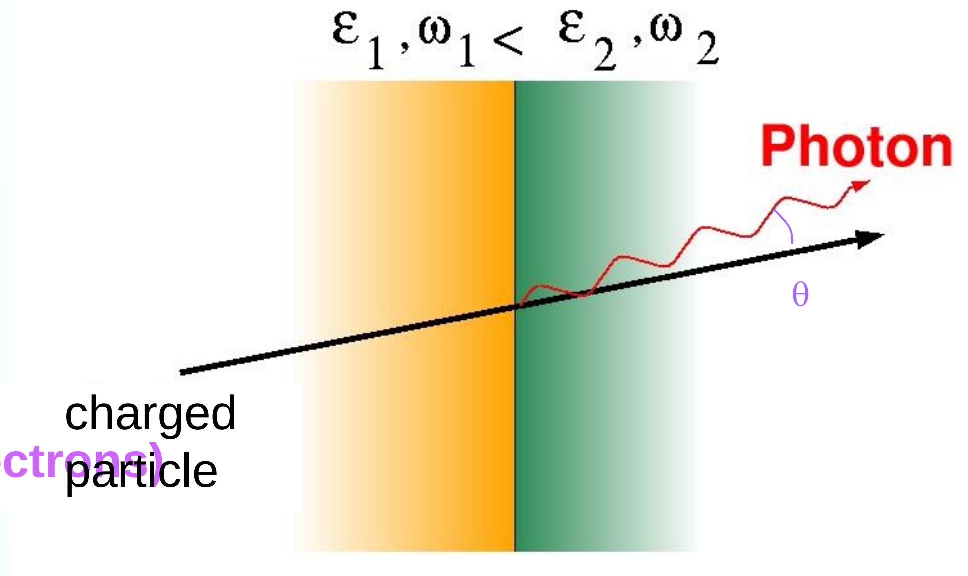
Transition Radiation (Particle ID)

- **Transition Radiation: photon emitted by a charged particle when traversing the boundary between materials with different dielectrical constants ($\varepsilon_1 \varepsilon_2$)**

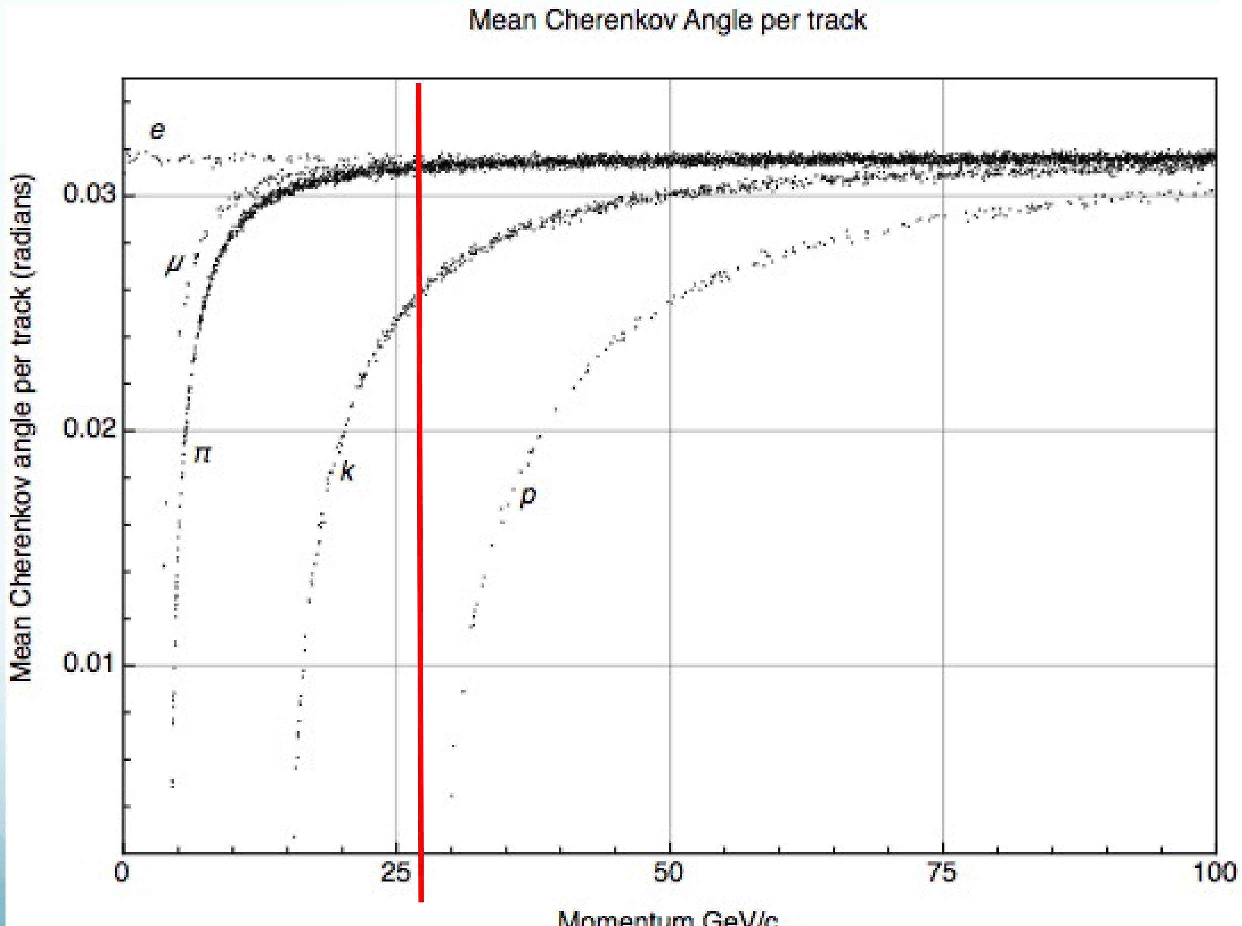
- **γ > 1000**

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

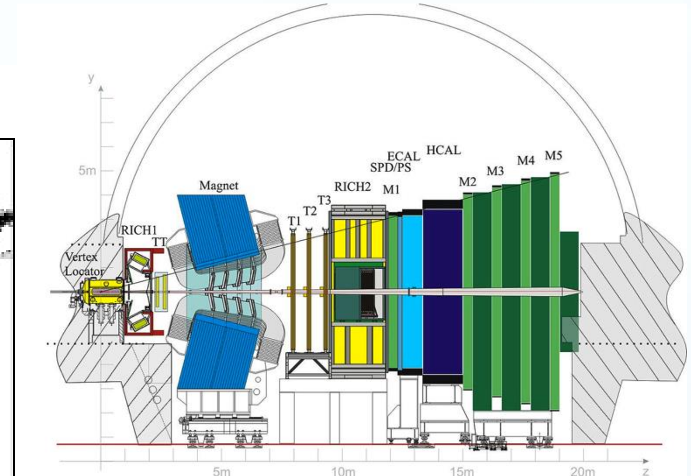
- **Intensity: I ~ γ = E/m,**
  - $\rightarrow$ Identification of transition radiation photons used for **particle identification (mostly electrons)** of particles with momenta between 1 and few 100 GeV



Cherenkov Detector



LHCb



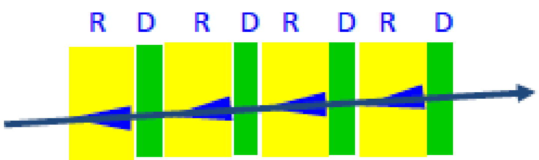
AMS

Transition radiation
(particle identification)

→ Number of emitted photons per boundary $N_{ph} \approx \frac{W}{\hbar\omega_p} \propto \alpha$ is very small.
→ Need many transitions to produce a sizable signal.

TR Radiators:

- stacks of thin foils made out of CH_2 (polyethylene), $C_5H_4O_2$ (Mylar)
- hydrocarbon foam and fiber materials. Low Z material preferred to keep re-absorption small ($\propto Z^5$)

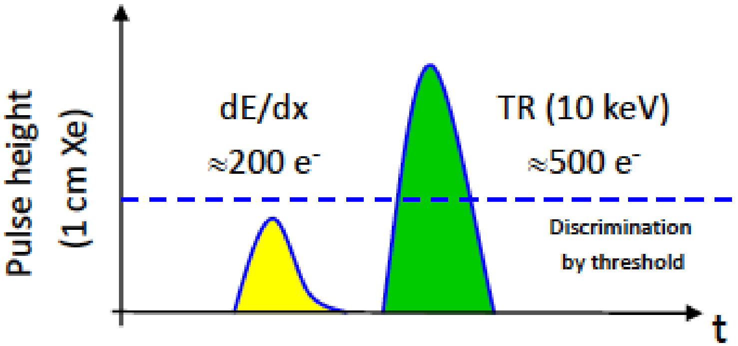


alternating arrangement of radiators stacks and detectors
→ minimizes re-absorption

TR X-ray detectors:

- Detector should be sensitive for $3 \leq E_\gamma \leq 30$ keV.
- Mainly used: Gas detectors: MWPC, drift chamber, straw tubes...
- Detector gas: $\sigma_{\text{photo effect}} \propto Z^5$

→ gas with high Z required, e.g. Xenon (Z=54)



TRT (ATLAS): 3 straws and radiators