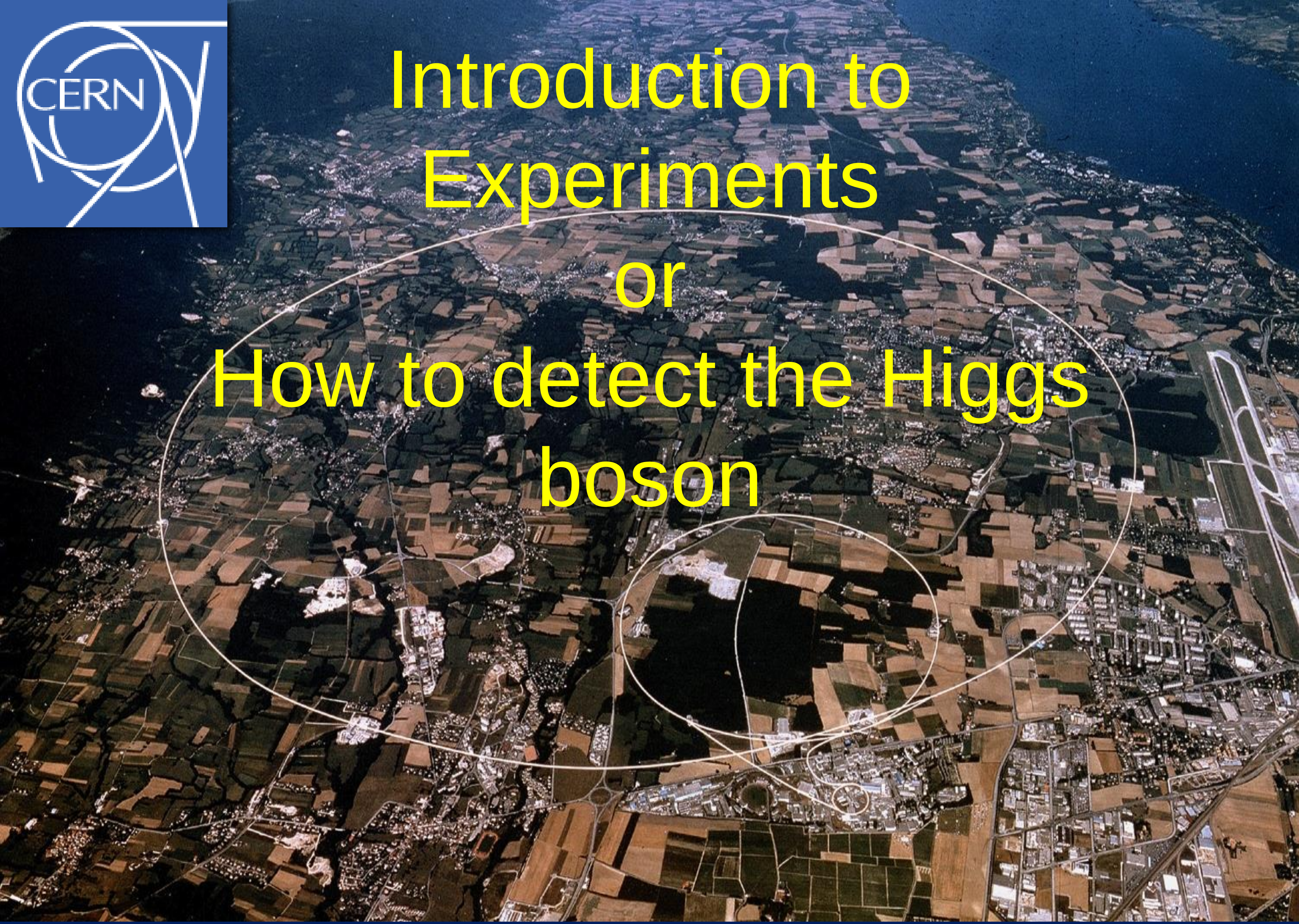
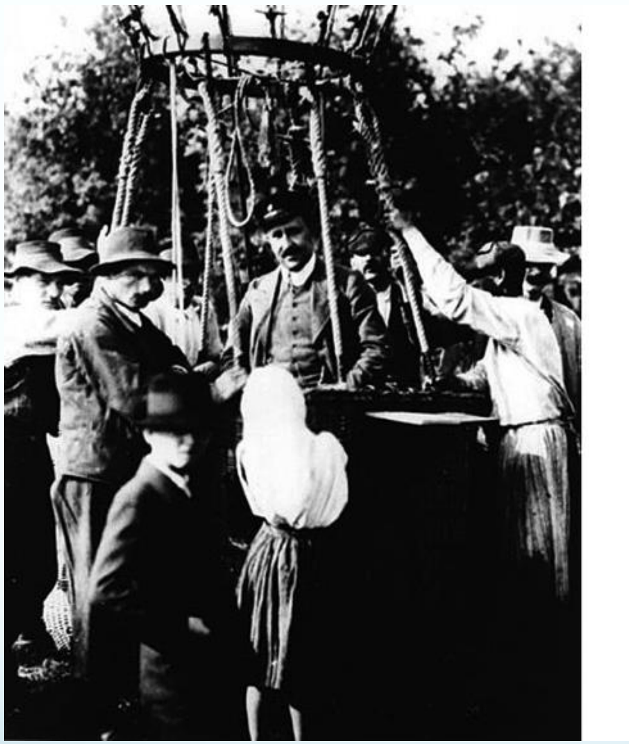
# Introduction to Experiments or How to detect the Higgs boson



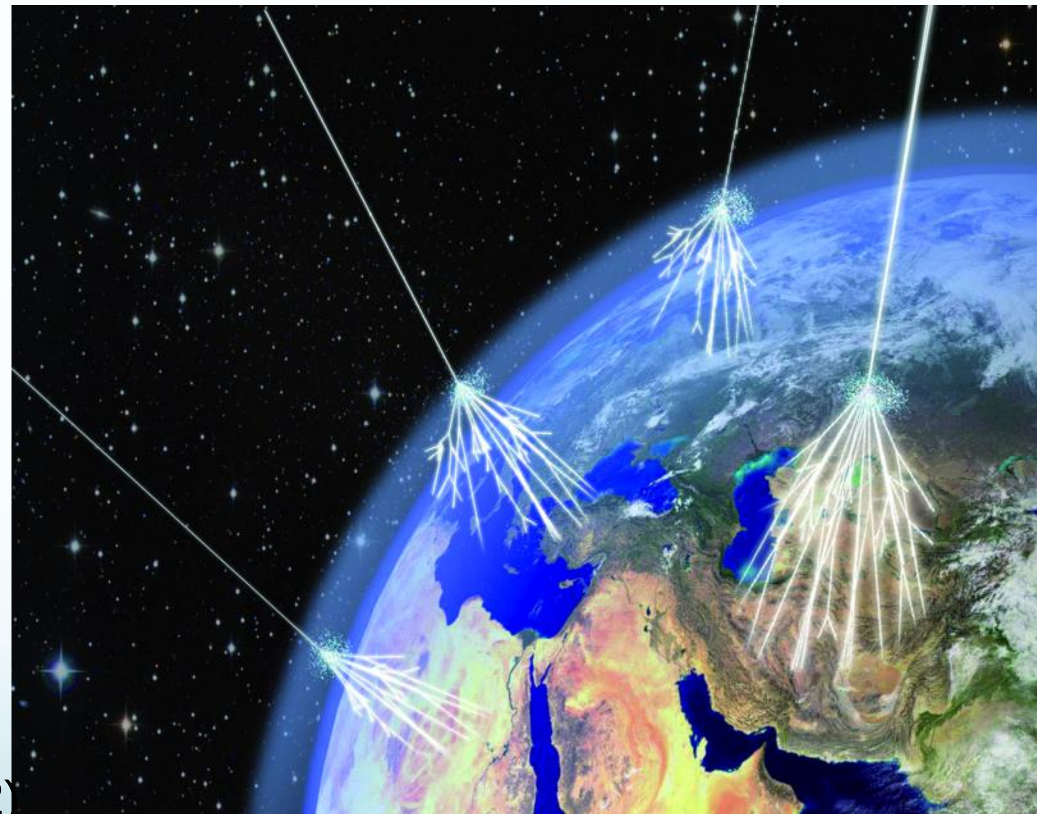
H. Danielsson, CERN

30/10/2017

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

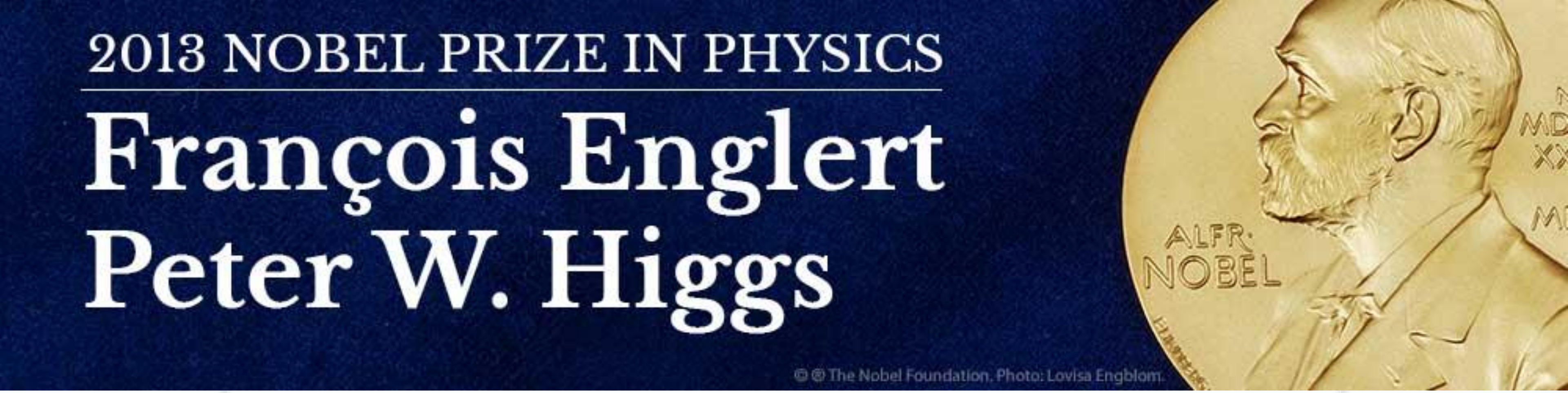


Hess received the Nobel Prize in Physics in 1936 for his discovery (1912)



# 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

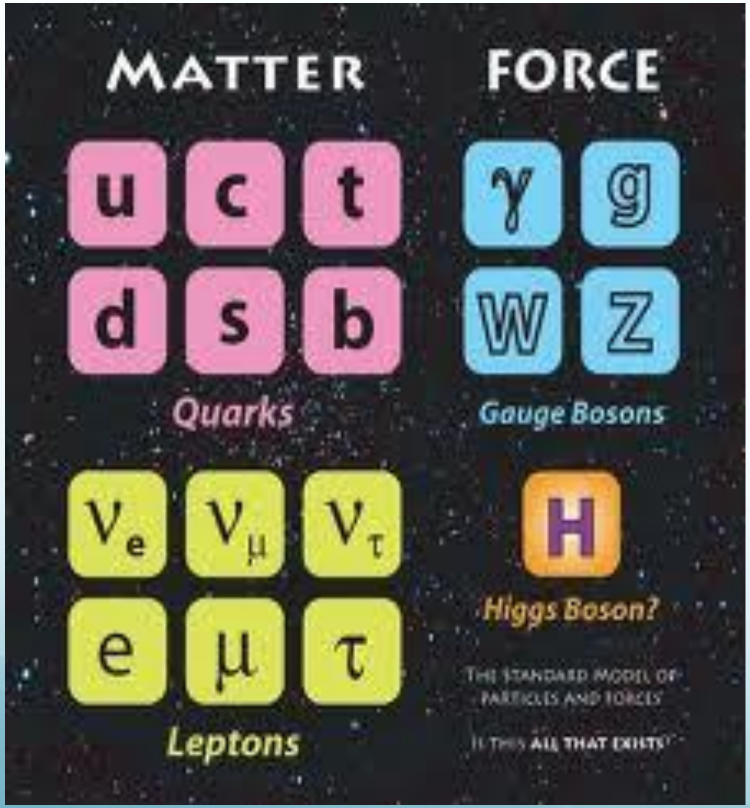
- Introduction
- CERN and the Large Hadron Collider (LHC)
  - The accelerator
  - How detectors work and examples
- The Higgs discovery

# 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…
  - What about super symmetry  (SUSY)

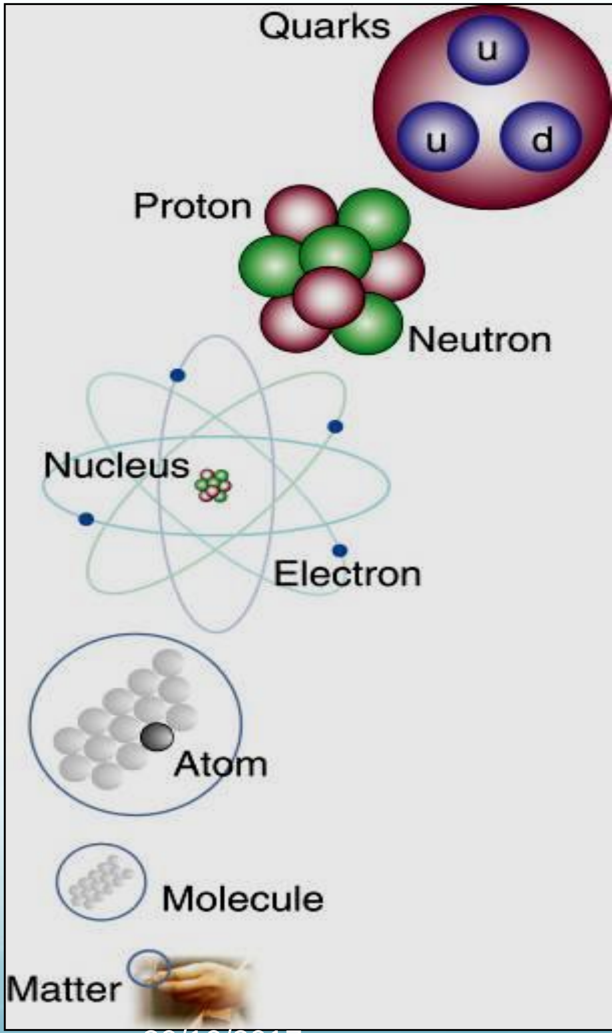
# The Standard Model (1970-90s)

- 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

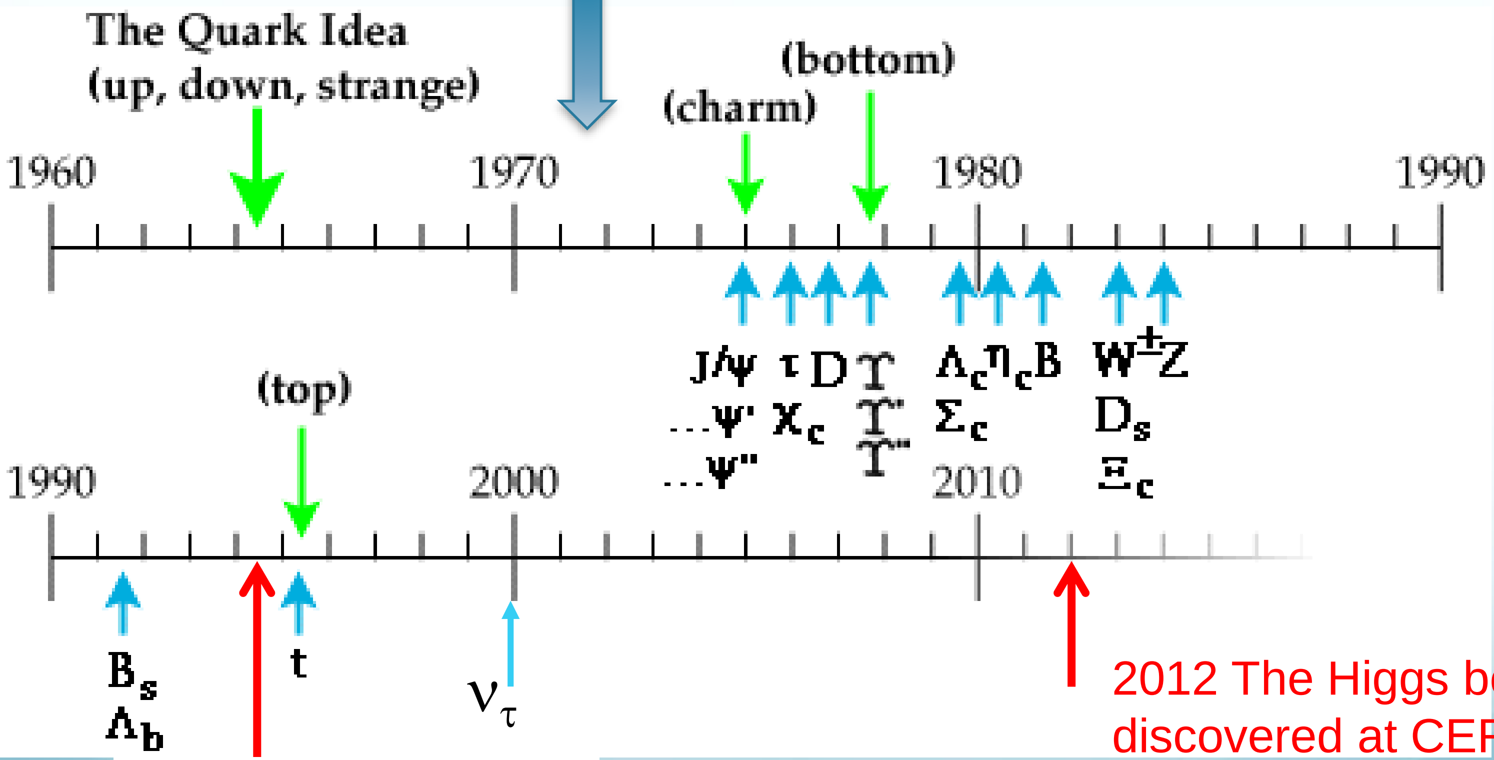
→ Most of the (luminous) mass in the universe comes from <u>QCD confinement energy</u>



# A bit of history

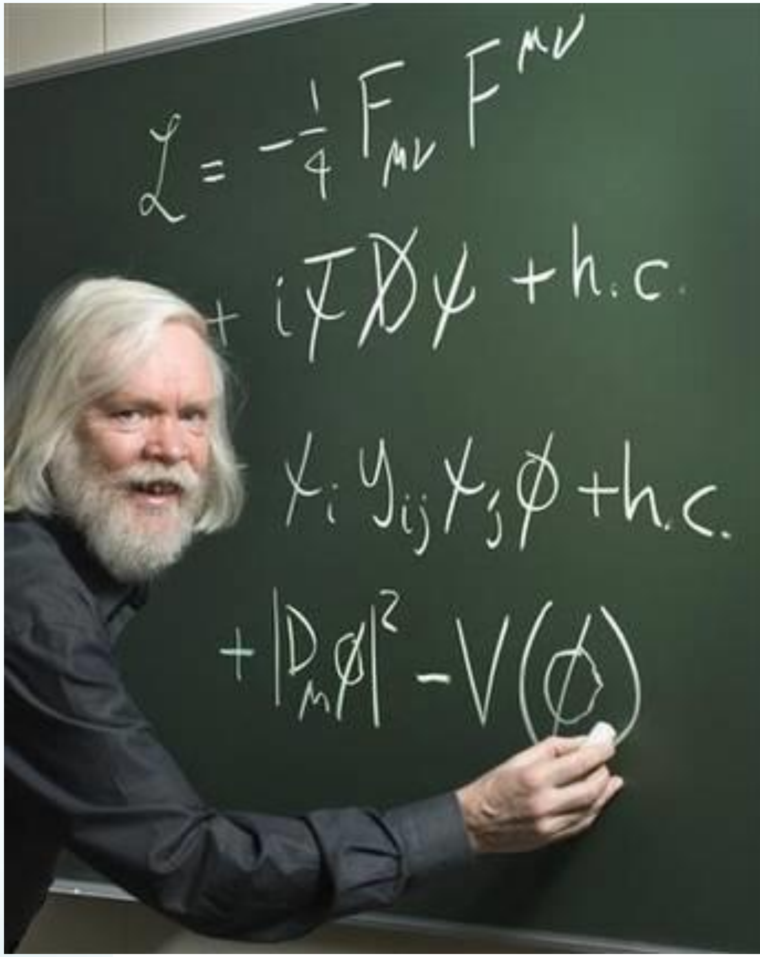
1964 The BEH mechanism

The Standard Model completed




2012 The Higgs boson discovered at CERN

LHC approved on 16 December 1994




# In 1976:

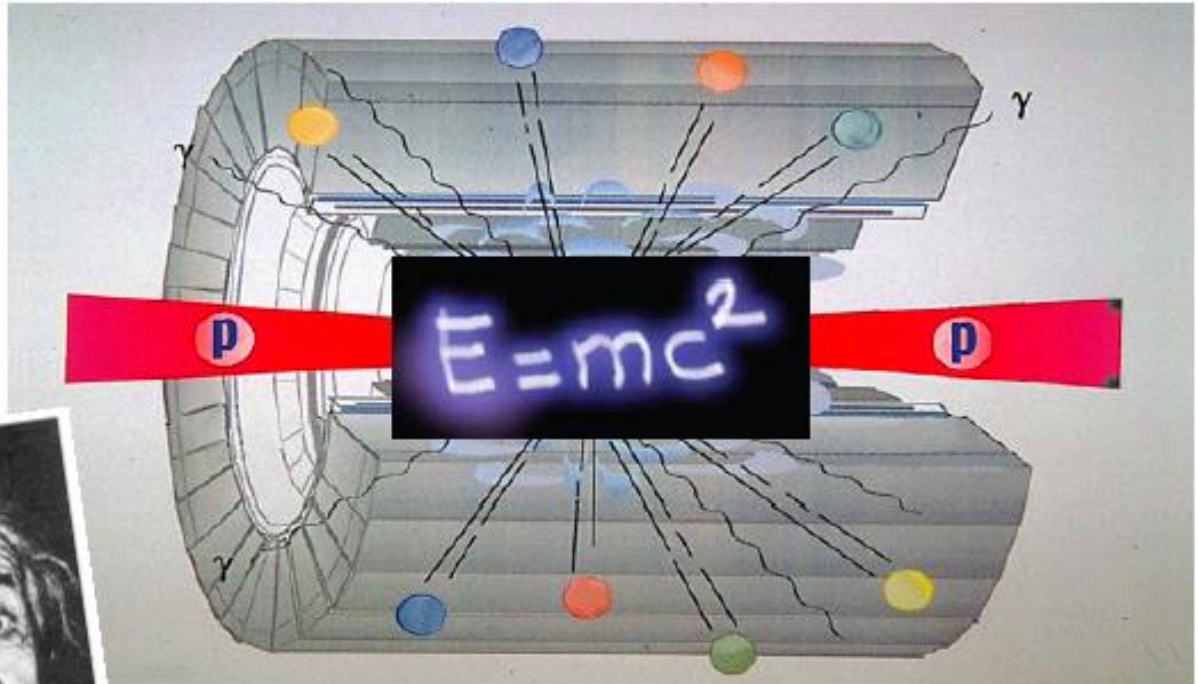
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

*The Roadmap:*

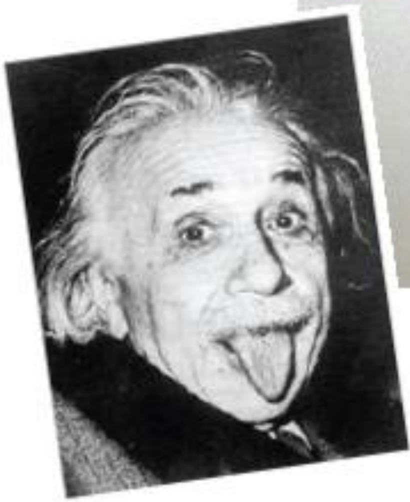
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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 ?



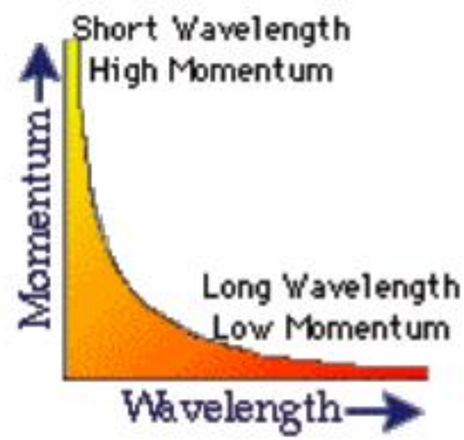

E=3.5TeV ➔ V=99.999996% of c

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



## Energy = Matter

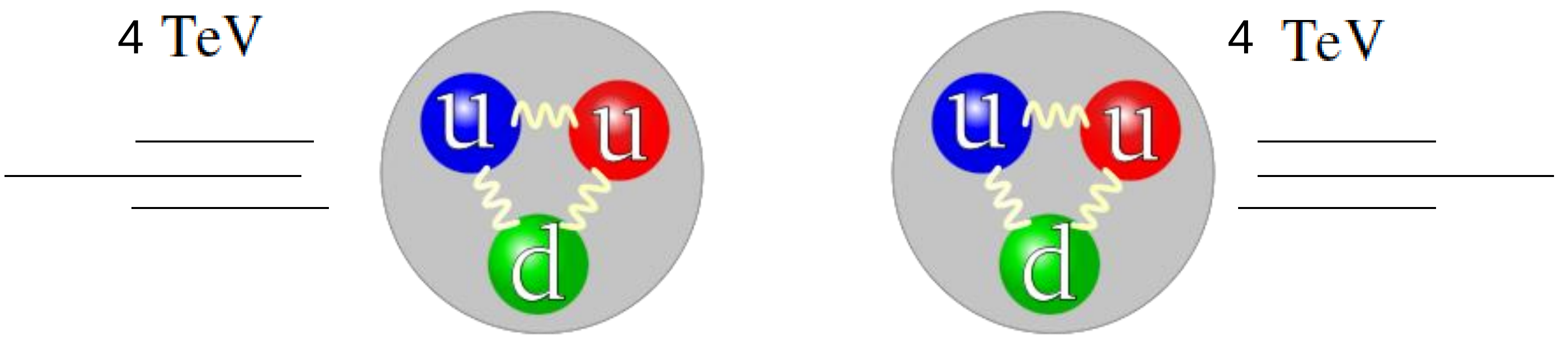
$E^2 = (m_0c^2)^2 + (pc)^2$

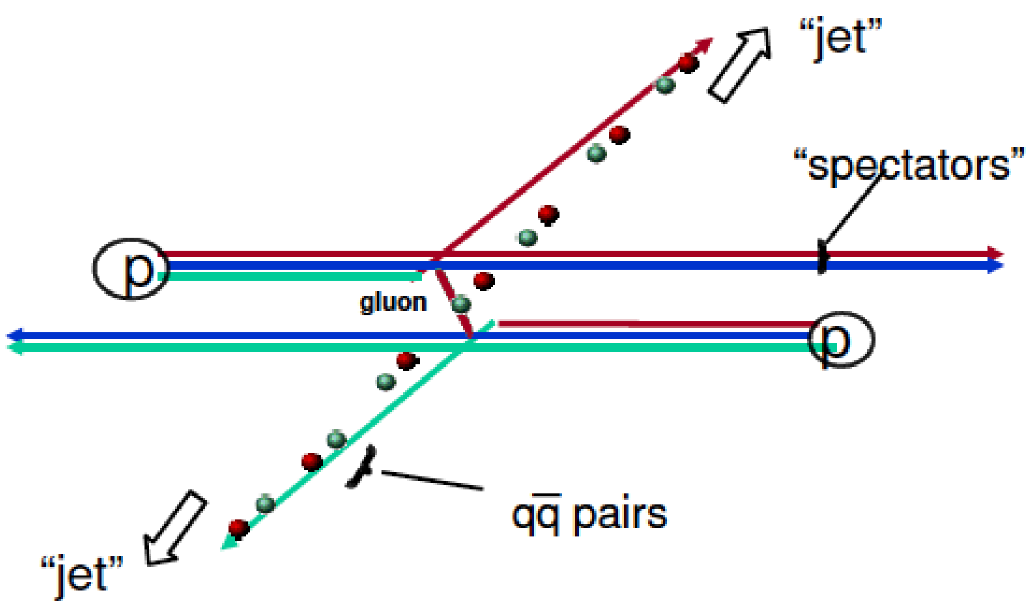


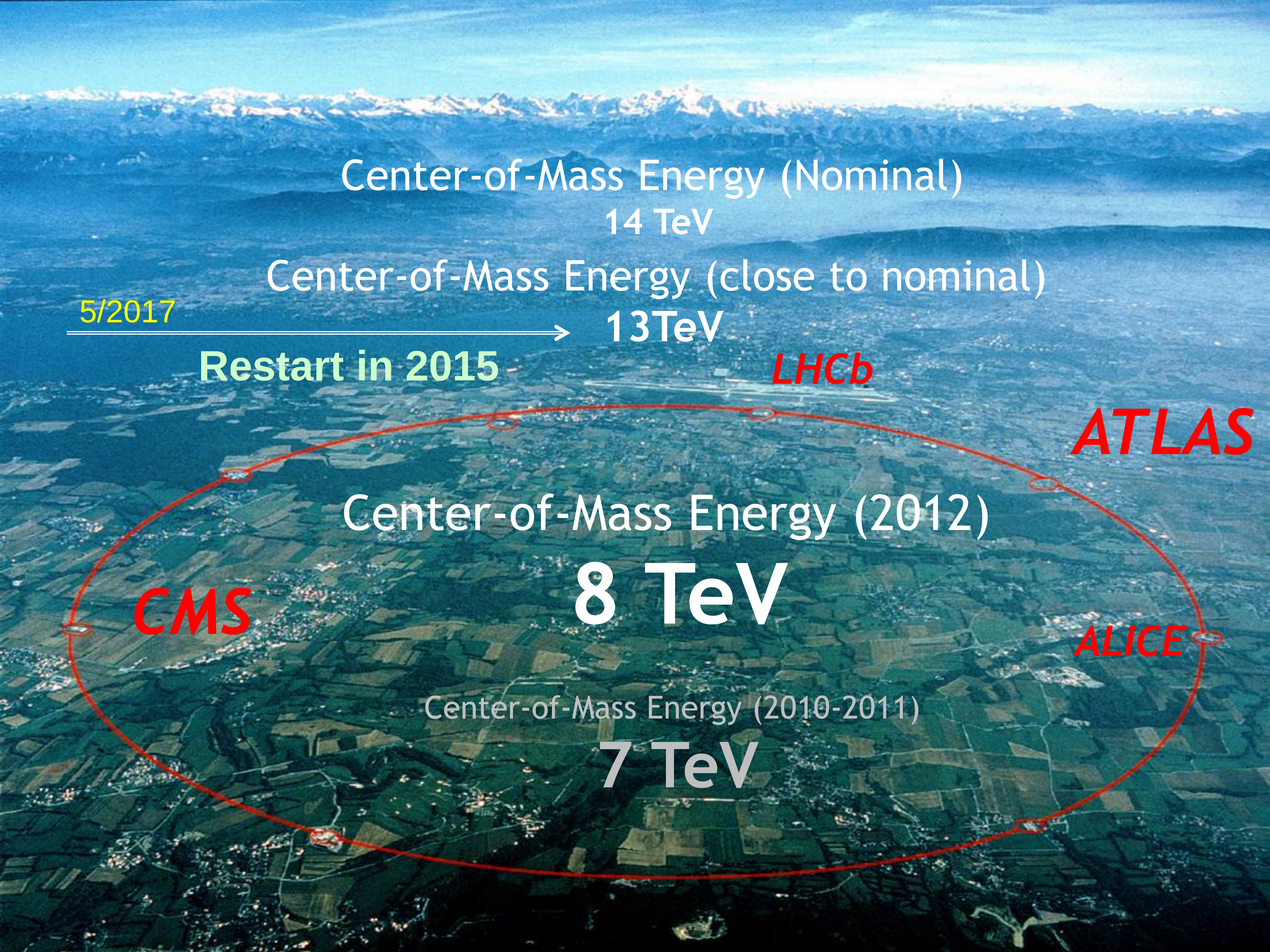
# Experimental High Energy Physics – detecting particles

## Two Protons collide at high energy

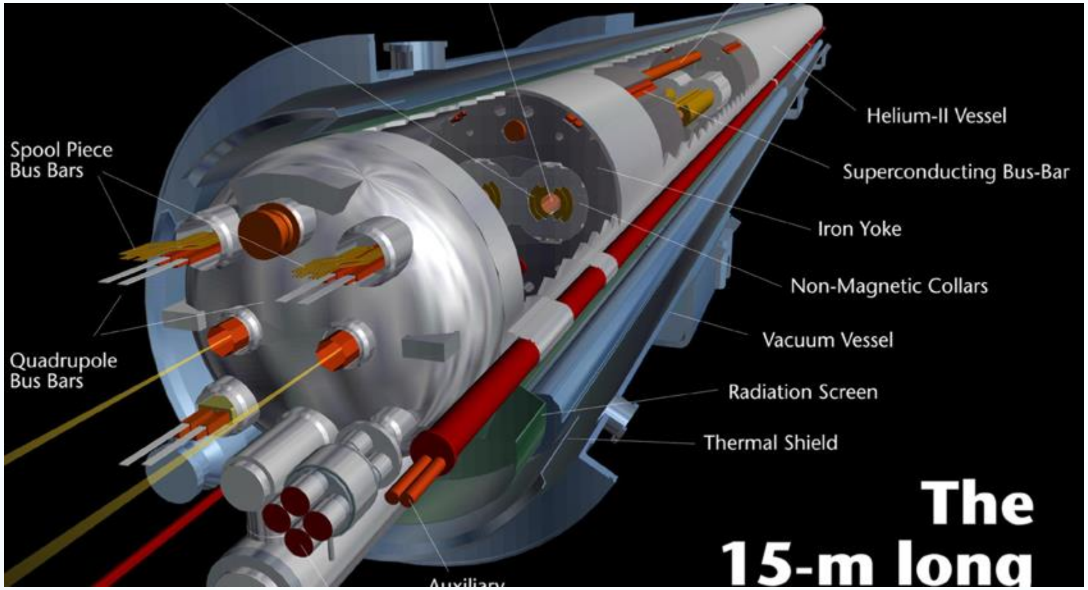
## Large Hadron Collider (LHC) at CERN

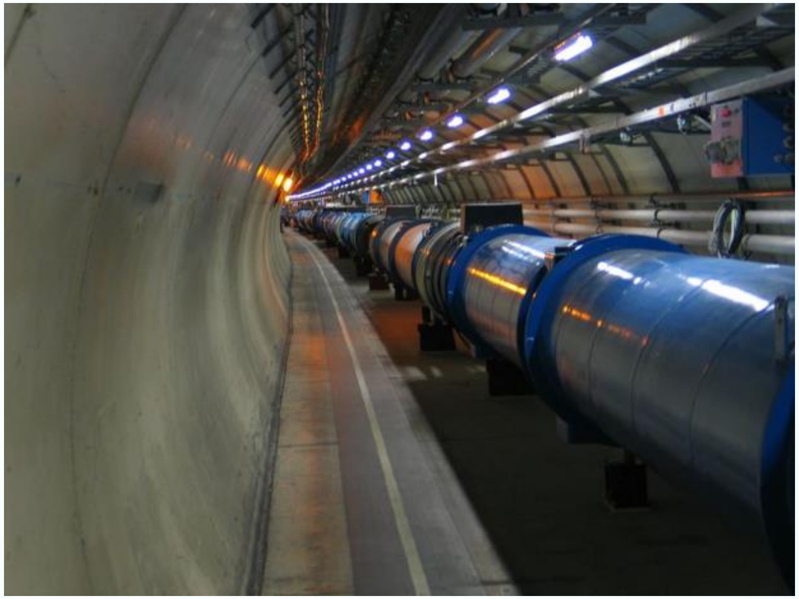


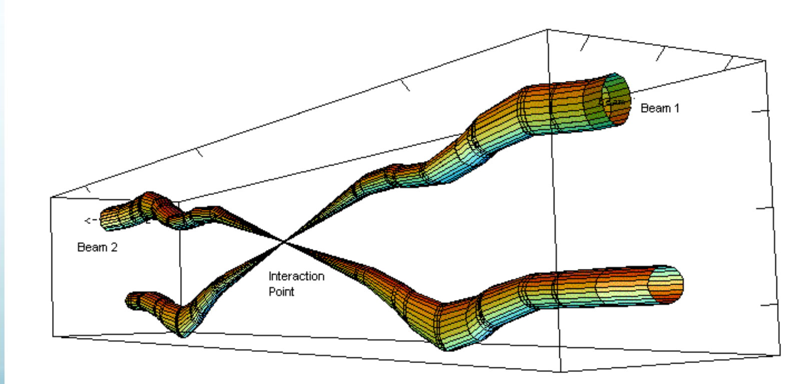

Center-of-Mass Energy (Nominal)
14 TeV
Center-of-Mass Energy (close to nominal)
5/2017
13TeV
Restart in 2015
LHCb
ATLAS
Center-of-Mass Energy (2012)
8 TeV
CMS
ALICE
Center-of-Mass Energy (2010-2011)
7 TeV

# 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 !**

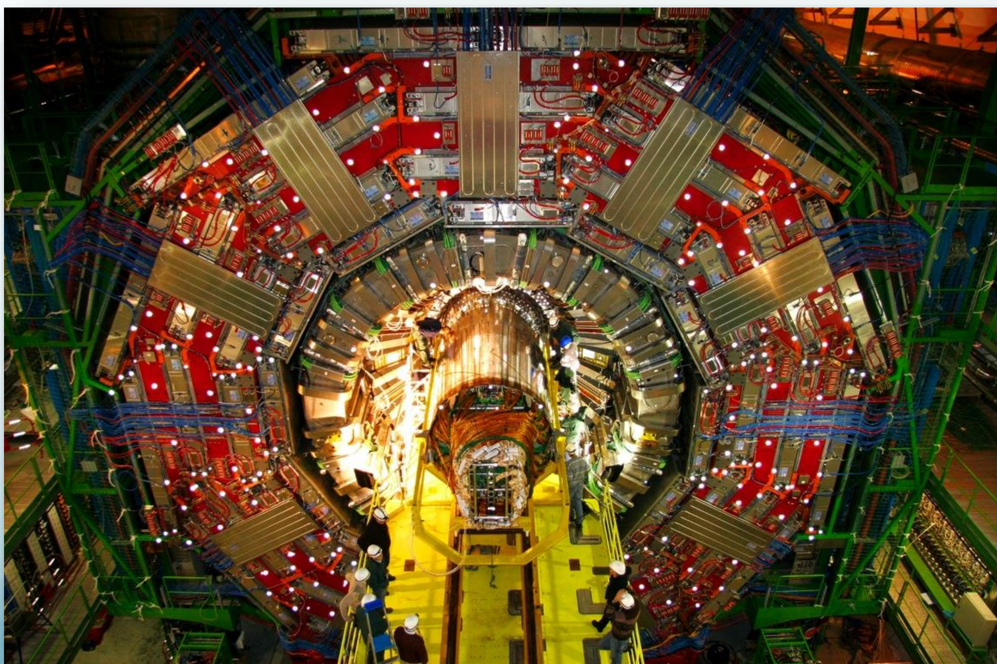


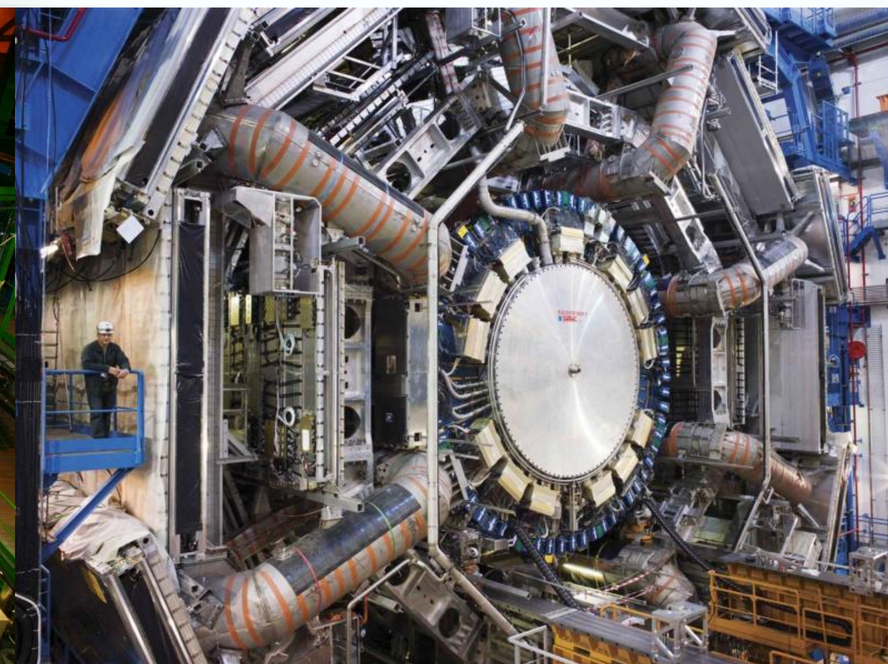

Relative beam sizes around IP1 (Atlas) in collision

# The experiments

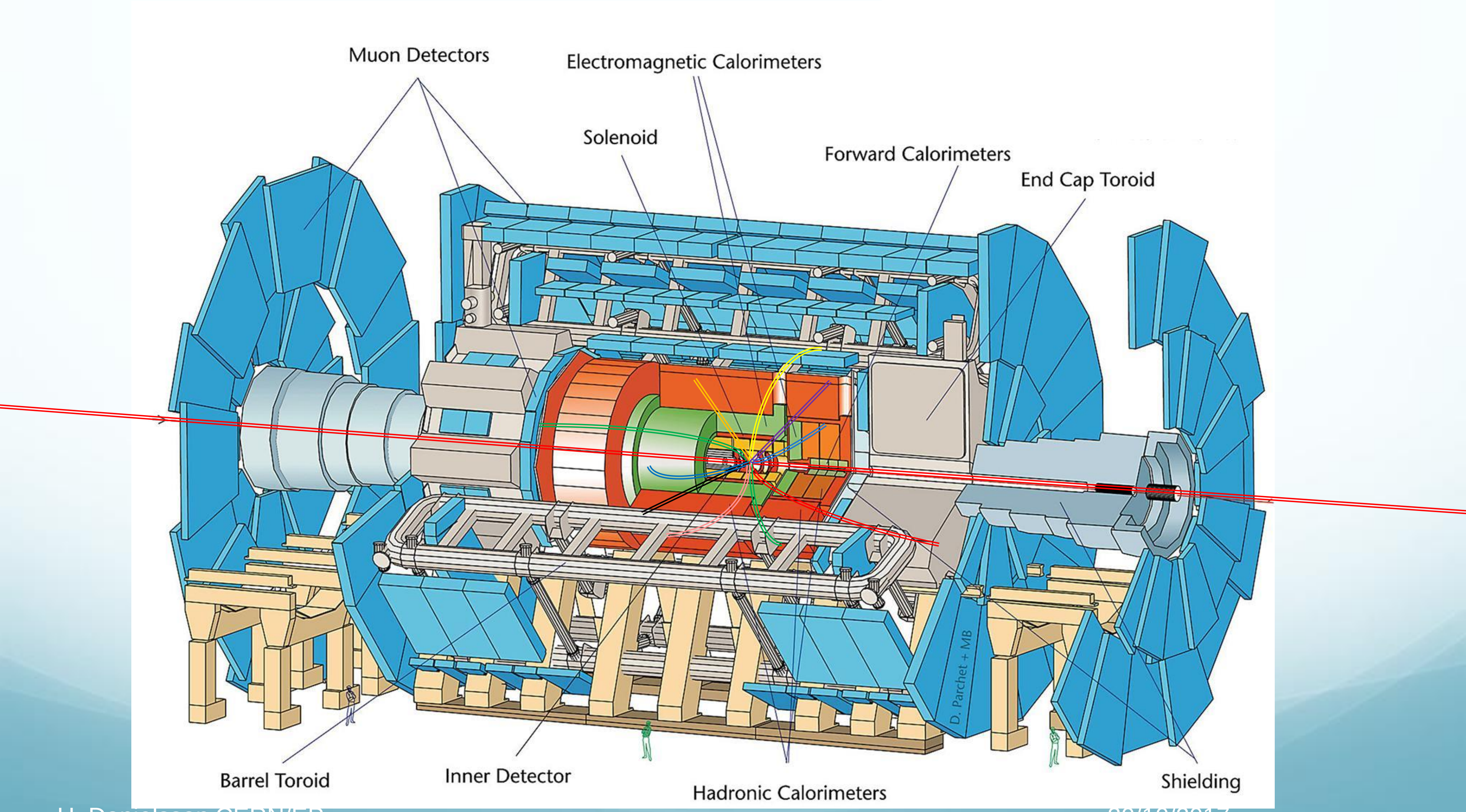
***CMS: heavier than the Eiffel Tower***

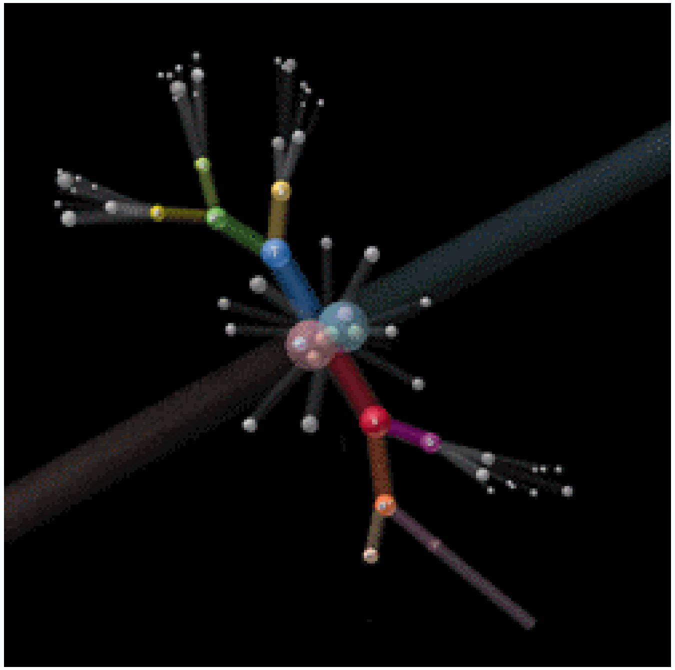
***ATLAS: as big as a 5 storey building***



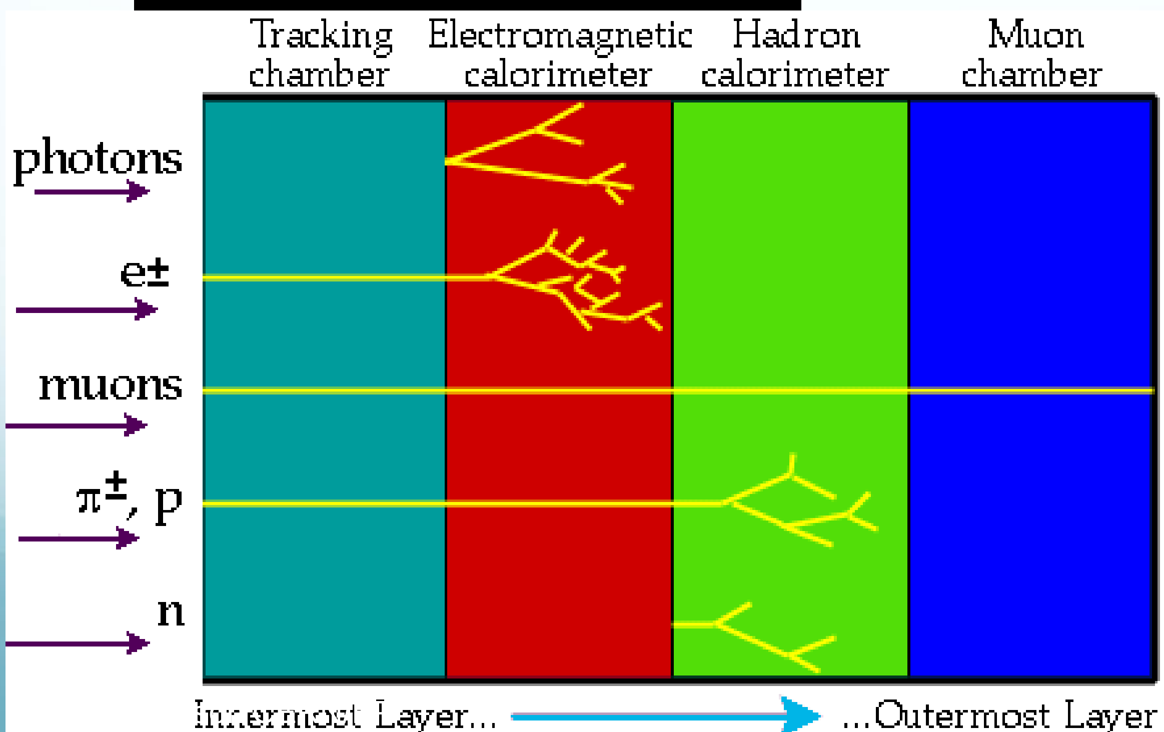


# Största och mest sofistikerade detektorer





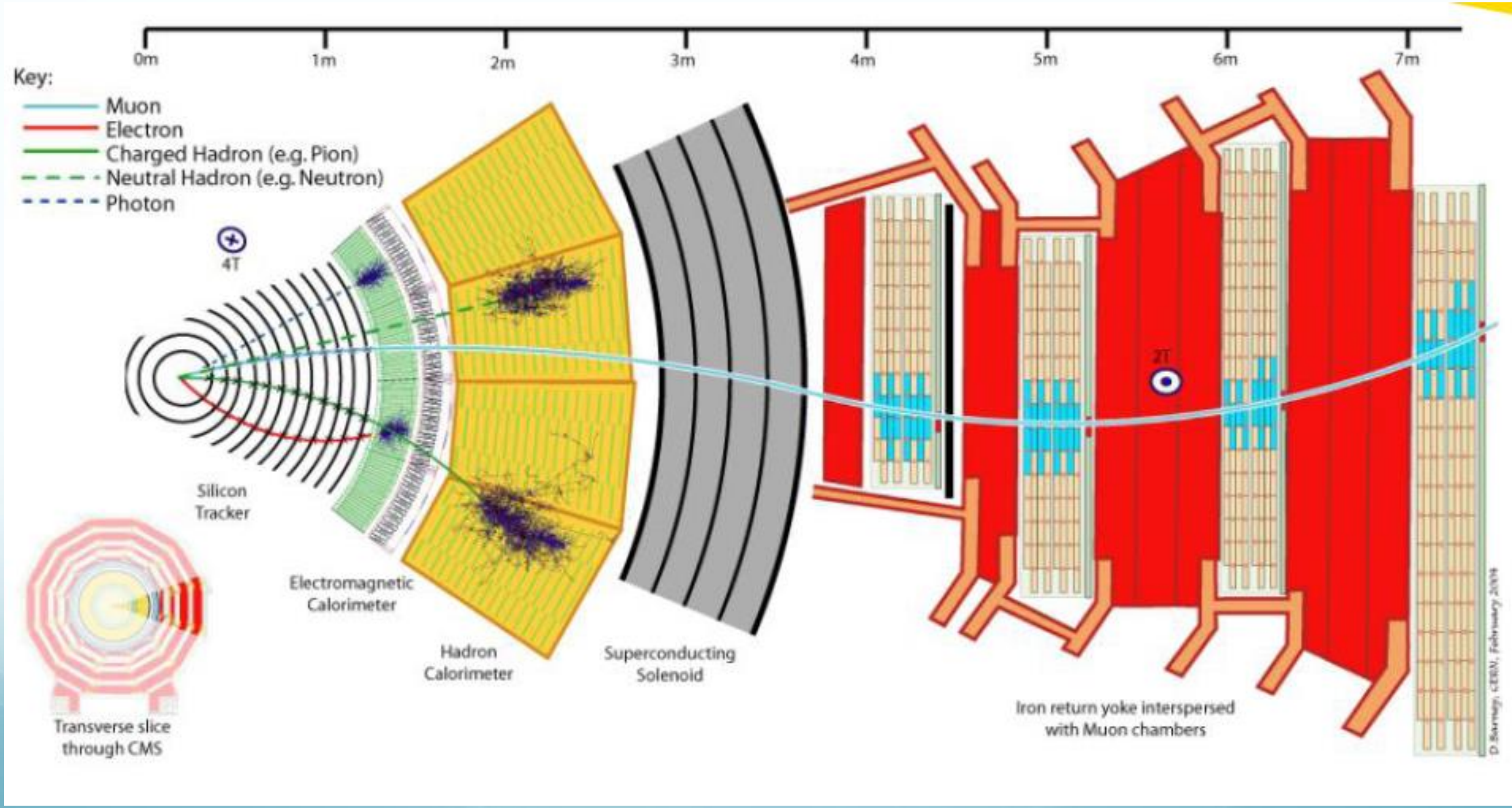
# Principles of Detection




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



# 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, $\pi$, $\mu$

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

$=0.1535\,\text{MeV-cm}^2/\text{g}$

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

$\rho$=density of absorber

$\delta$=density correction

C=shell correction

Incident particle

z=charge of incident particle

$\beta$=v/c of incident particle

$\gamma=(1-\beta^2)^{-1/2}$

$W_{max}$=max. energy transfer in one collision

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

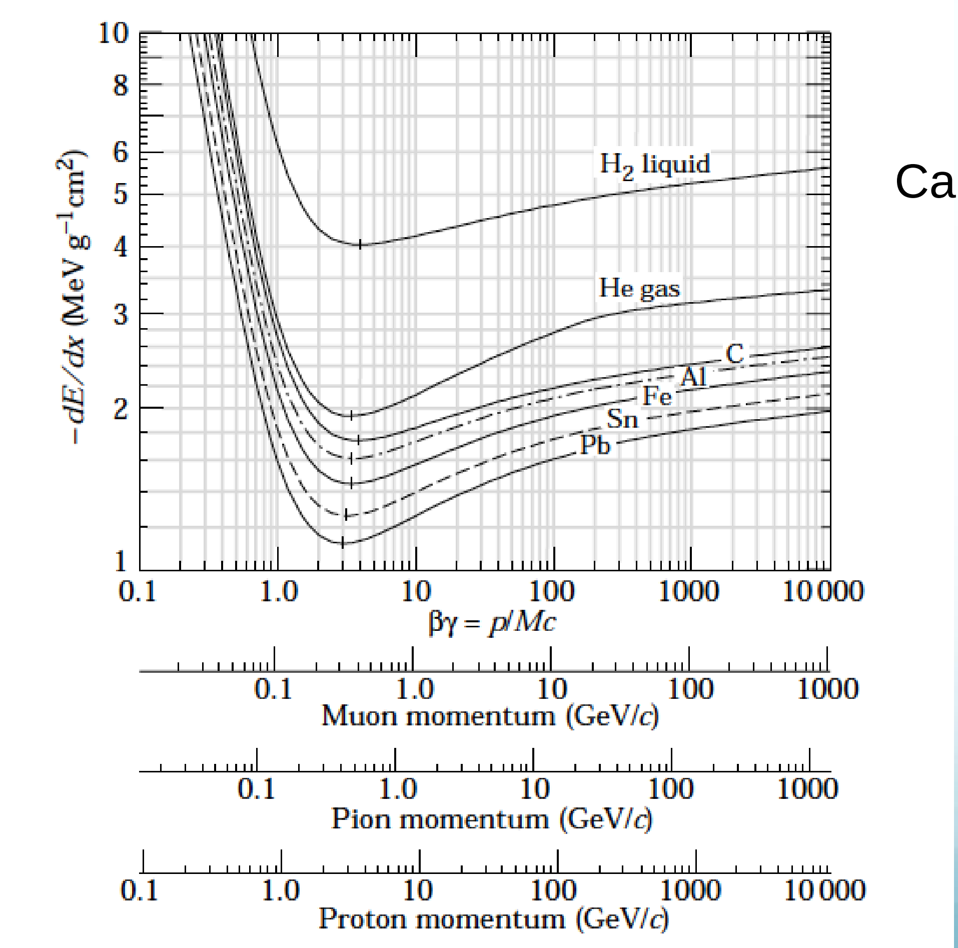
Note: the classical dE/dx formula contains many of the same features as the QM version: $(z/\beta)^2$, & ln[]

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

# Bethe-Bloch Energy Loss

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

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




Calculated

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

# Multiple Scattering

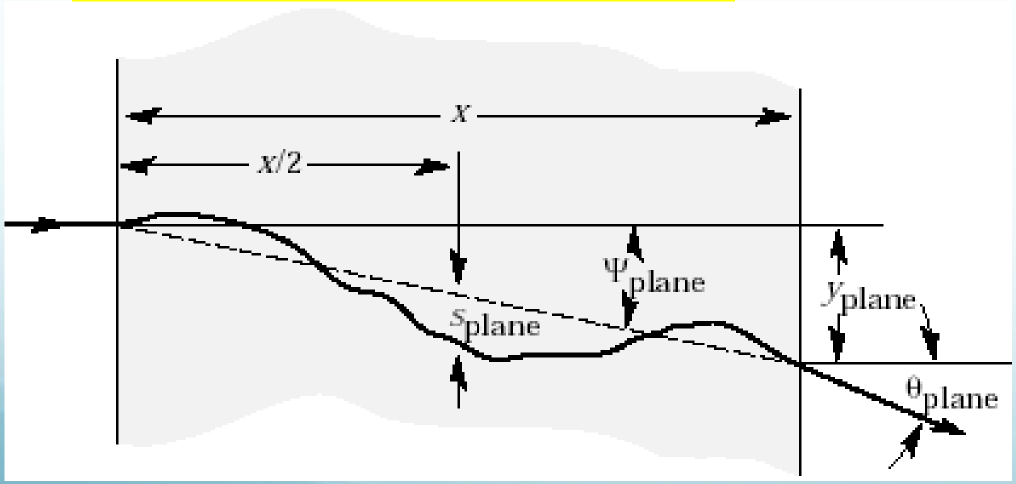
A charged particle traversing a medium is deflected by many small angle scatterings.
These scattering are due to the **coulomb field of atoms** and are **assumed to be elastic**.
In each scattering the energy of **the particle is constant but the particle direction changes**.

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

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

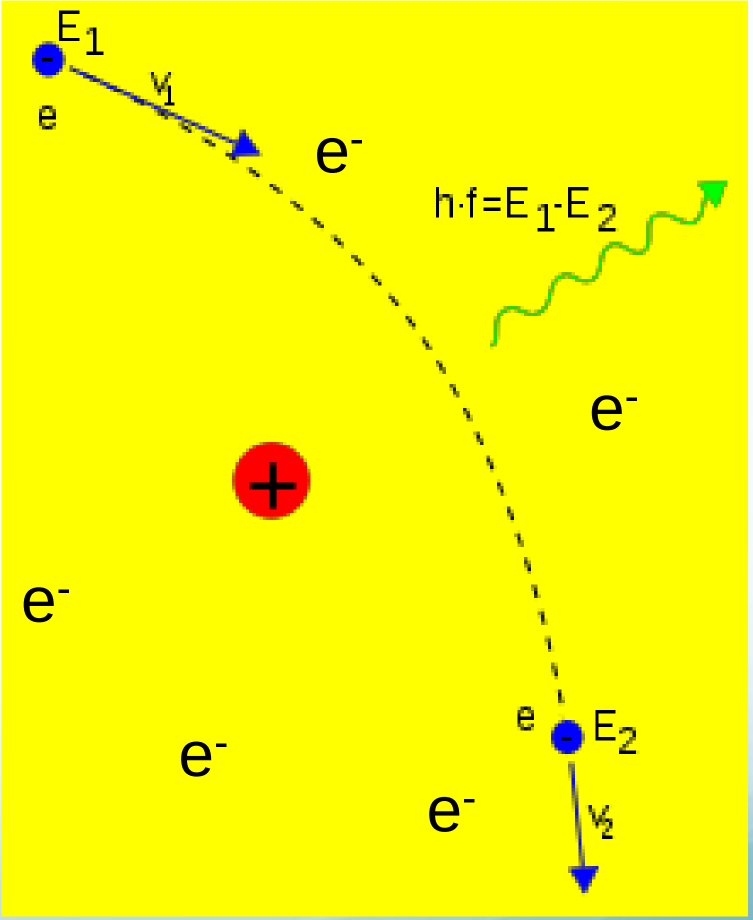
In the above equation $\beta=v/c$, and p=momentum of incident particle

*This is not good for tracking!*



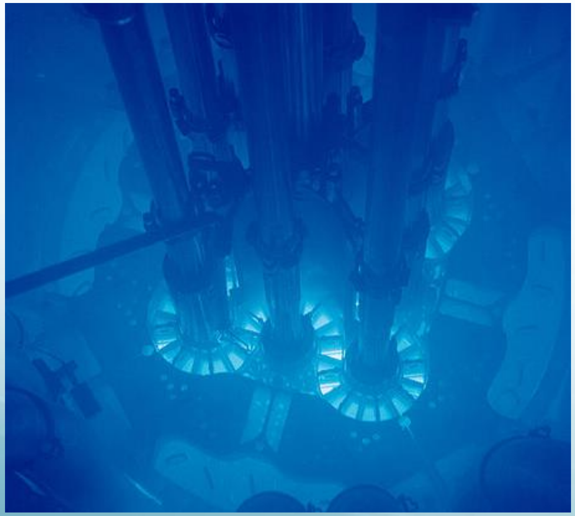

# Bremsstrahlung (braking radiation)

- 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*



# 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

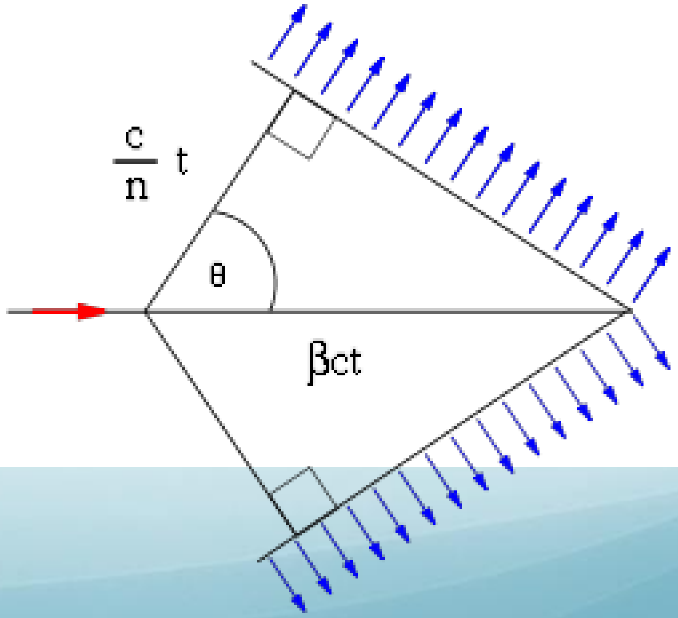
$$x_p = v_p t = \beta\, ct$$

whereas the emitted electromagnetic waves are constricted to travel the distance

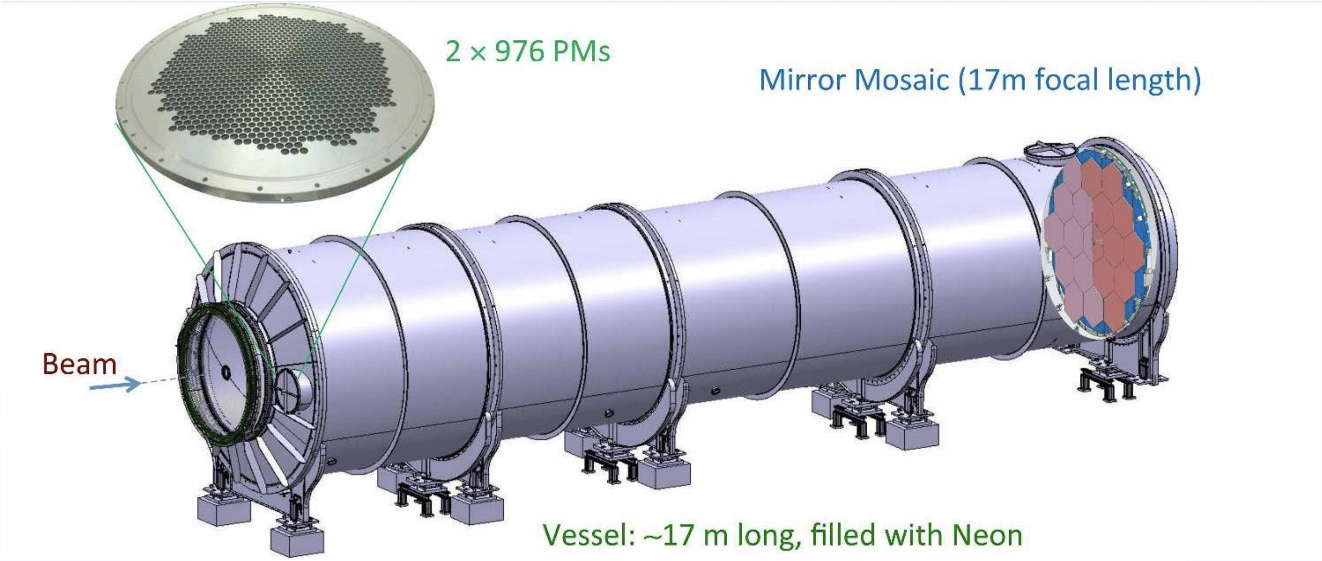
$$x_{em} = v_{em} t = \frac{c}{n} t$$

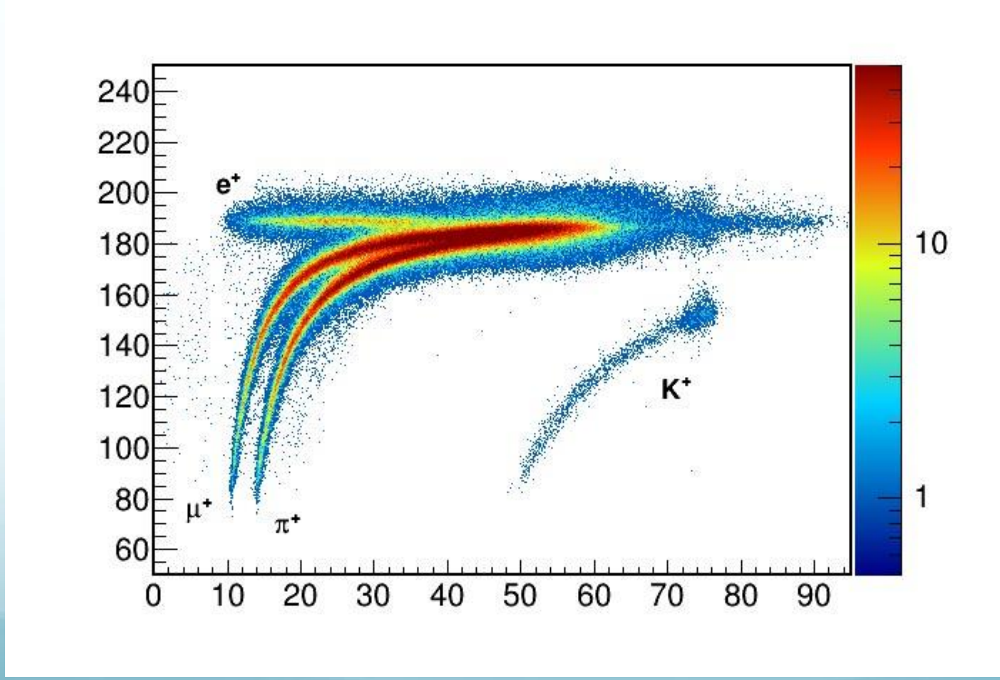
So:

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



# Cherenkov Detector NA62



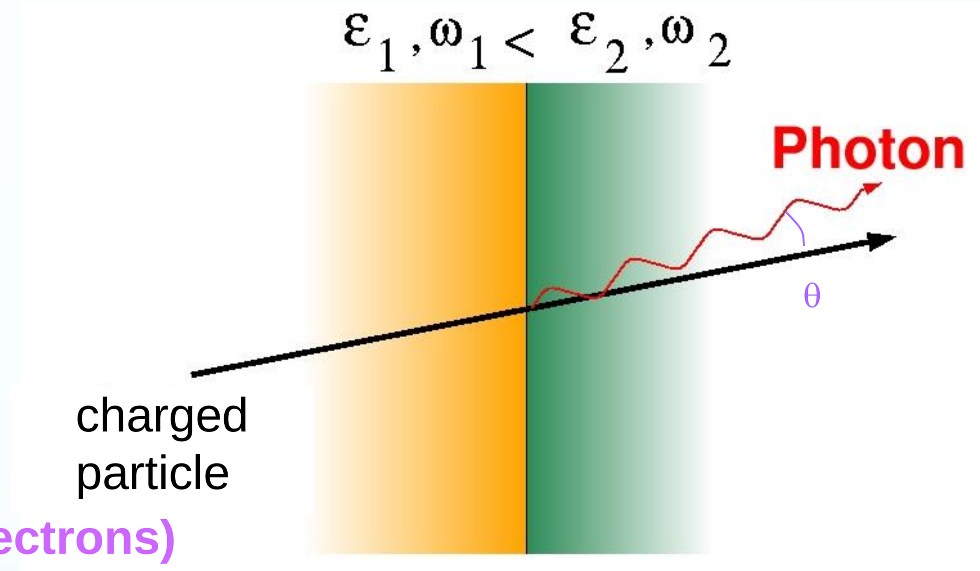
# Transition Radiation (Particle ID)

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

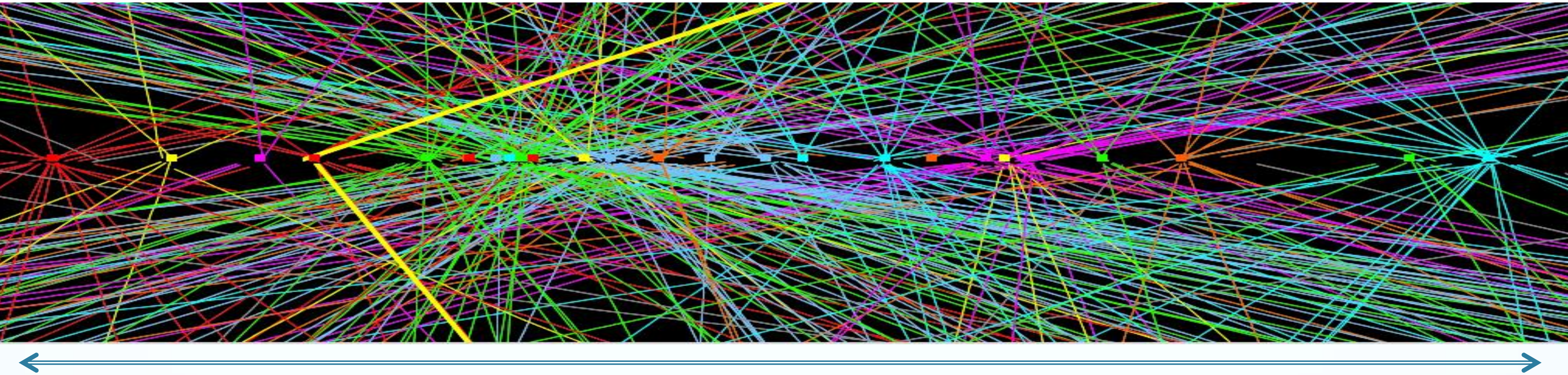
- **$\gamma$ > 1000**

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

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



# Detector Challenges (Highlights)



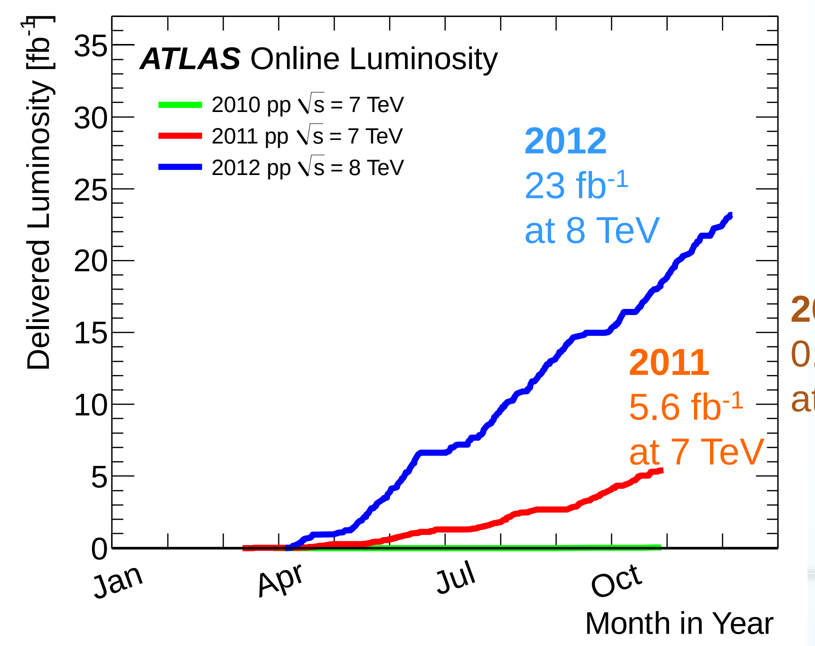
10 cm

- 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

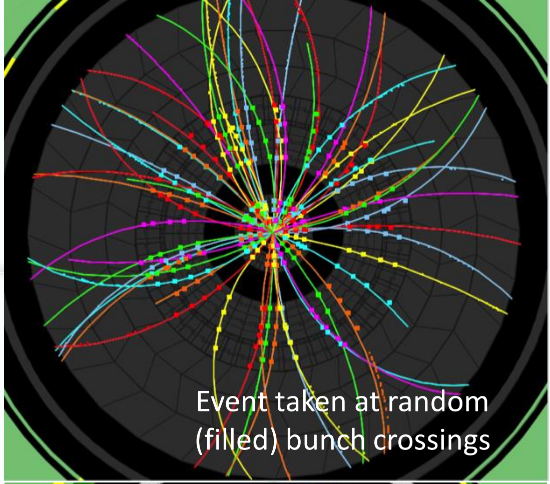
Event rate = luminosity x cross-sections




*2010*

O(2) Pile-up events

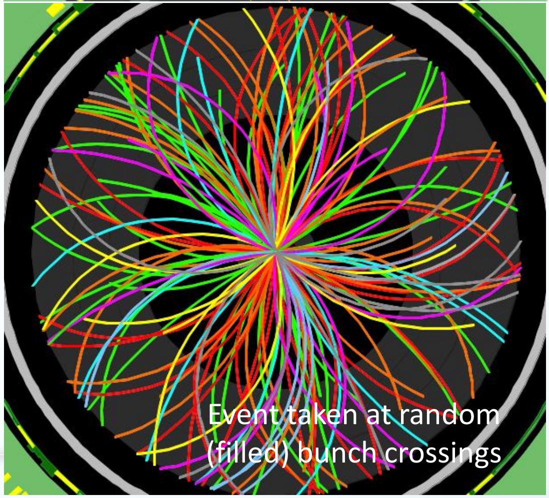
150 ns inter-bunch spacing




*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

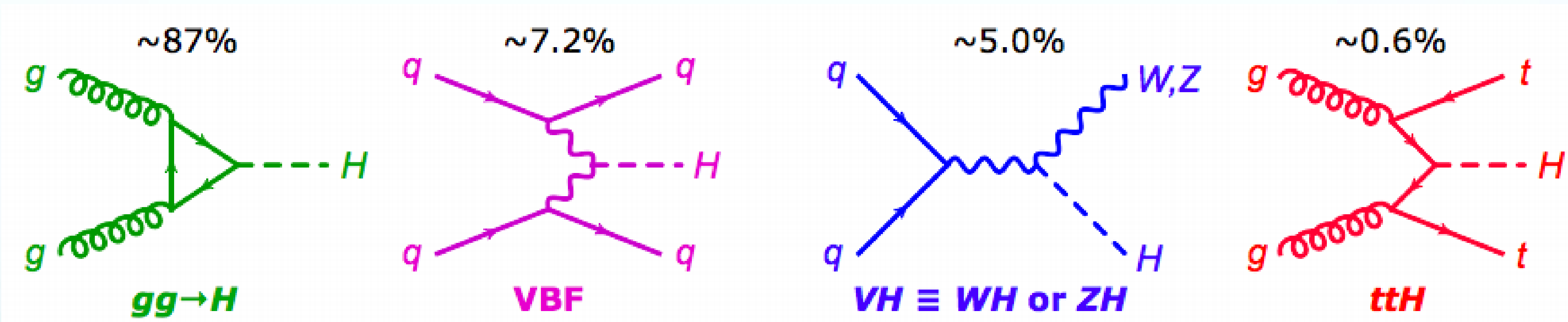
# Higgs production

Vector boson fusion
VBF

Top-antitop fusion
ttH

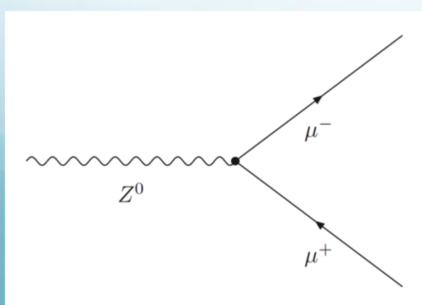
Higgs strahlung
VH

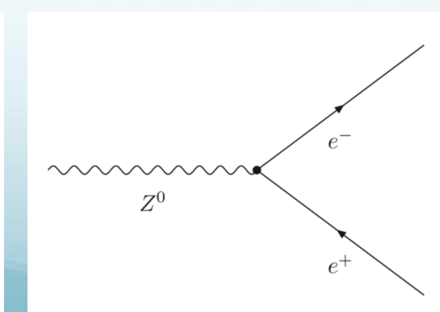
Gluon-gluon fusion
gg→H

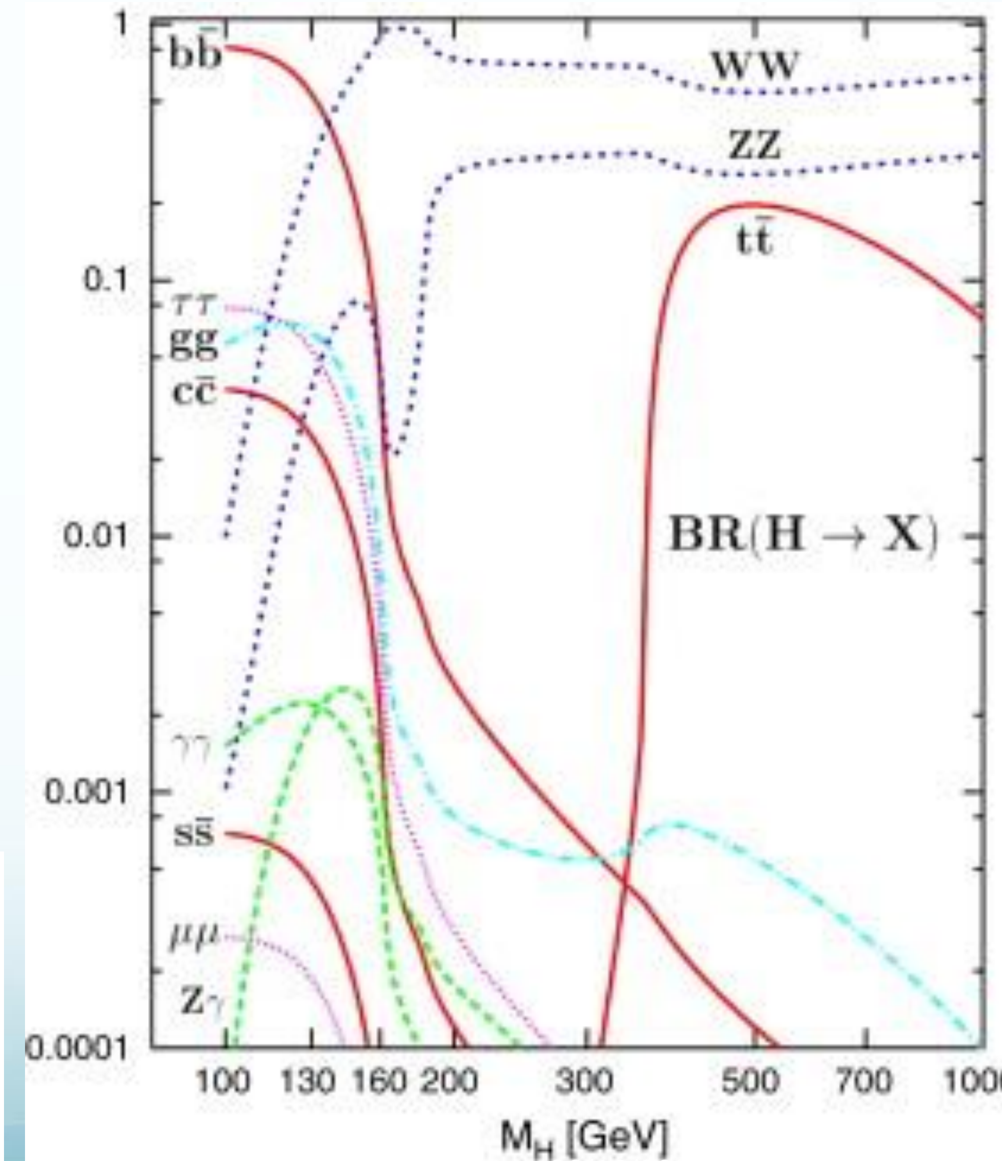


# Detect Higgs by decay products

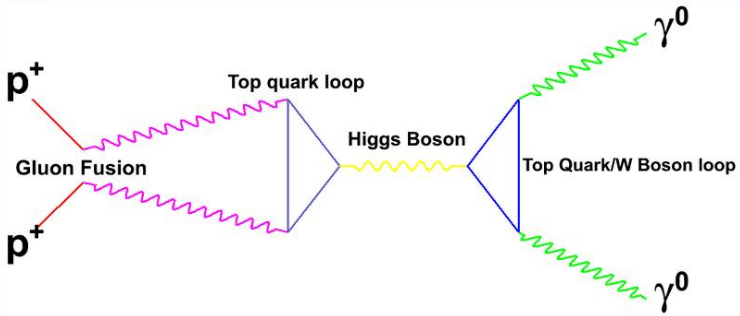
- <u>Variety of decay channels</u>
- Massive particles more likely
- Difficult to detect from background
- Life time is 1.56 × 10−22 s (!) (predicted in the Standard Model)
- $\gamma\gamma$ is clean, but rare



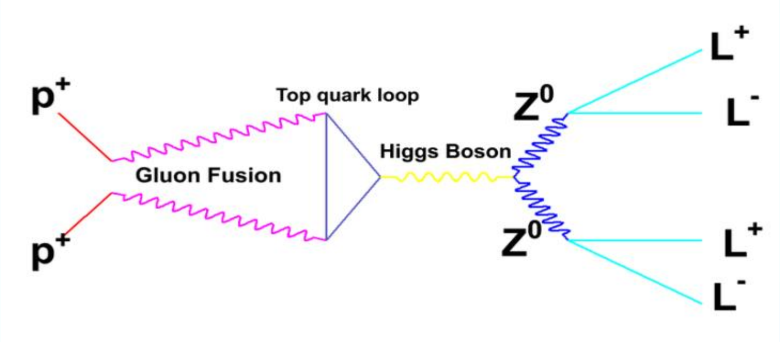



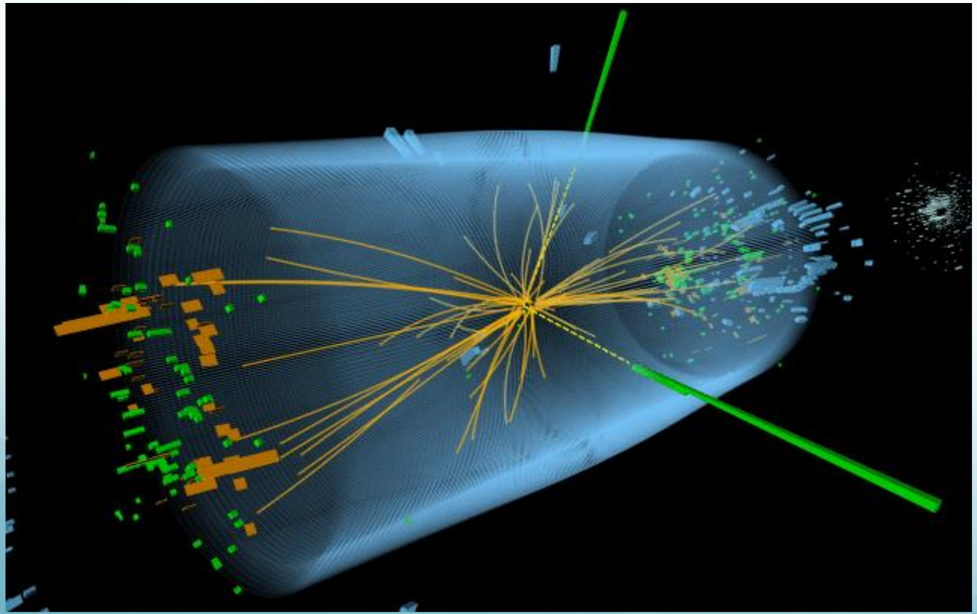
# April-July 2012: *8 TeV*, *5.8* $fb^{-1}$

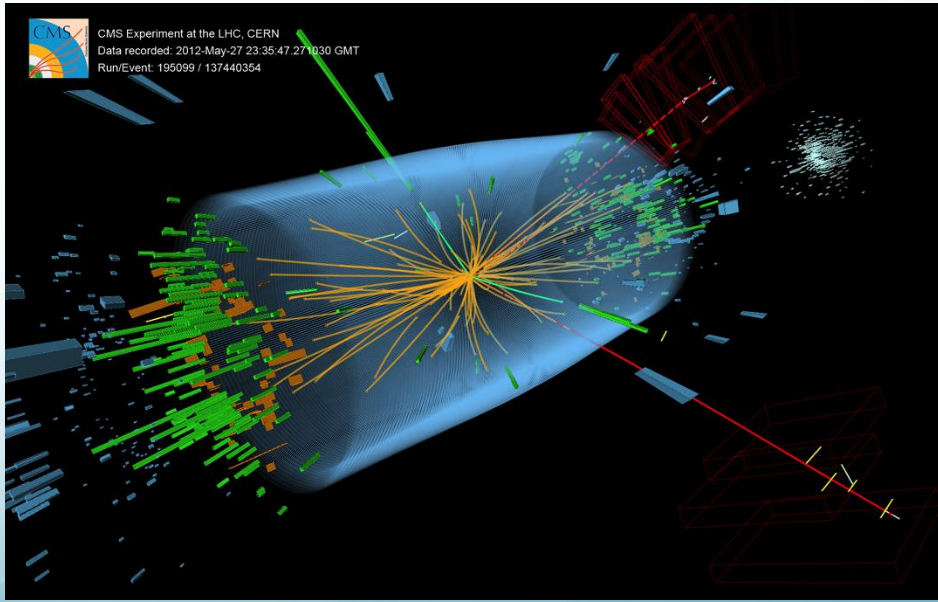



*Measure energy of photons emitted*

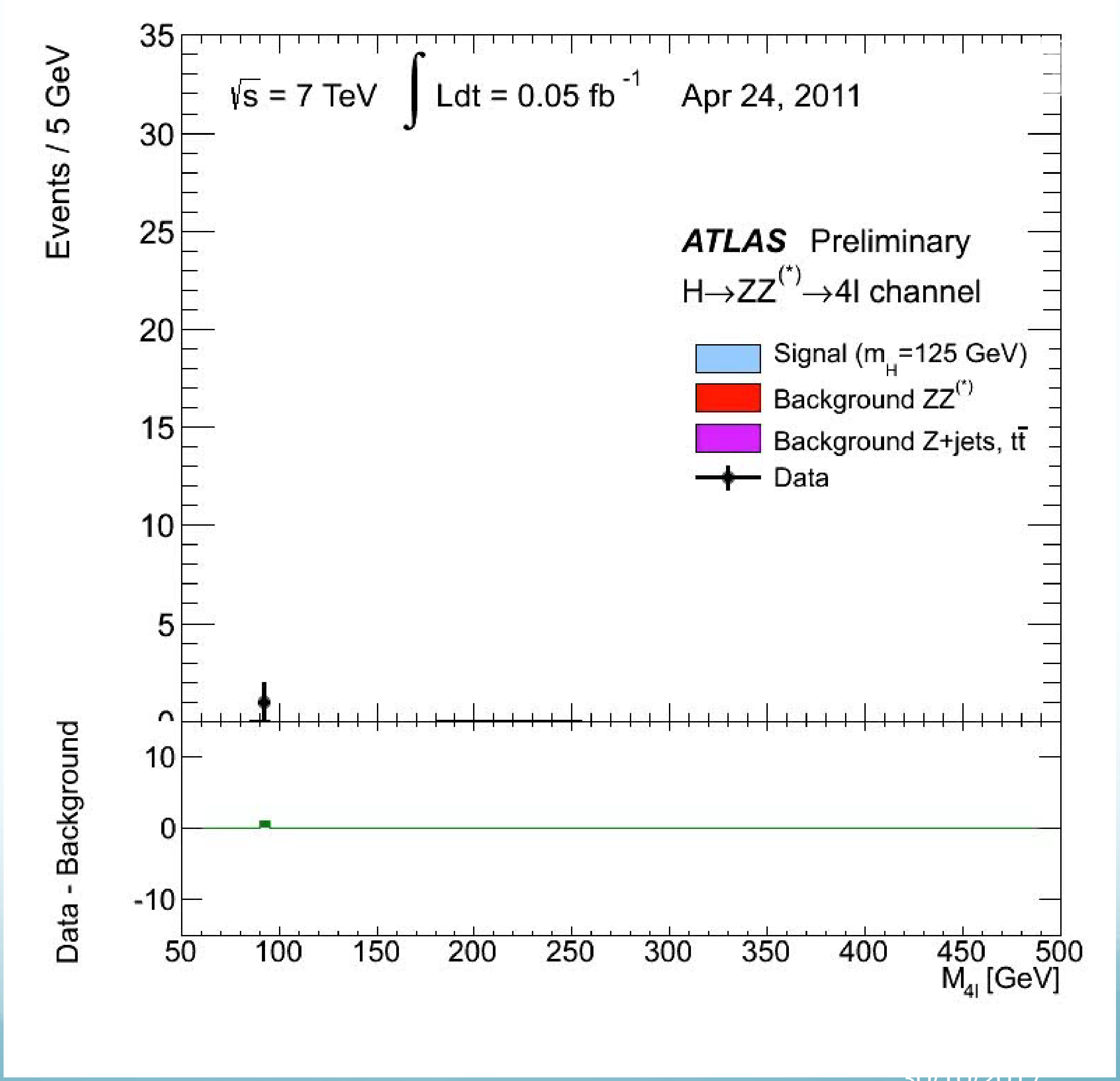



*Measure decay products of Z bosons*

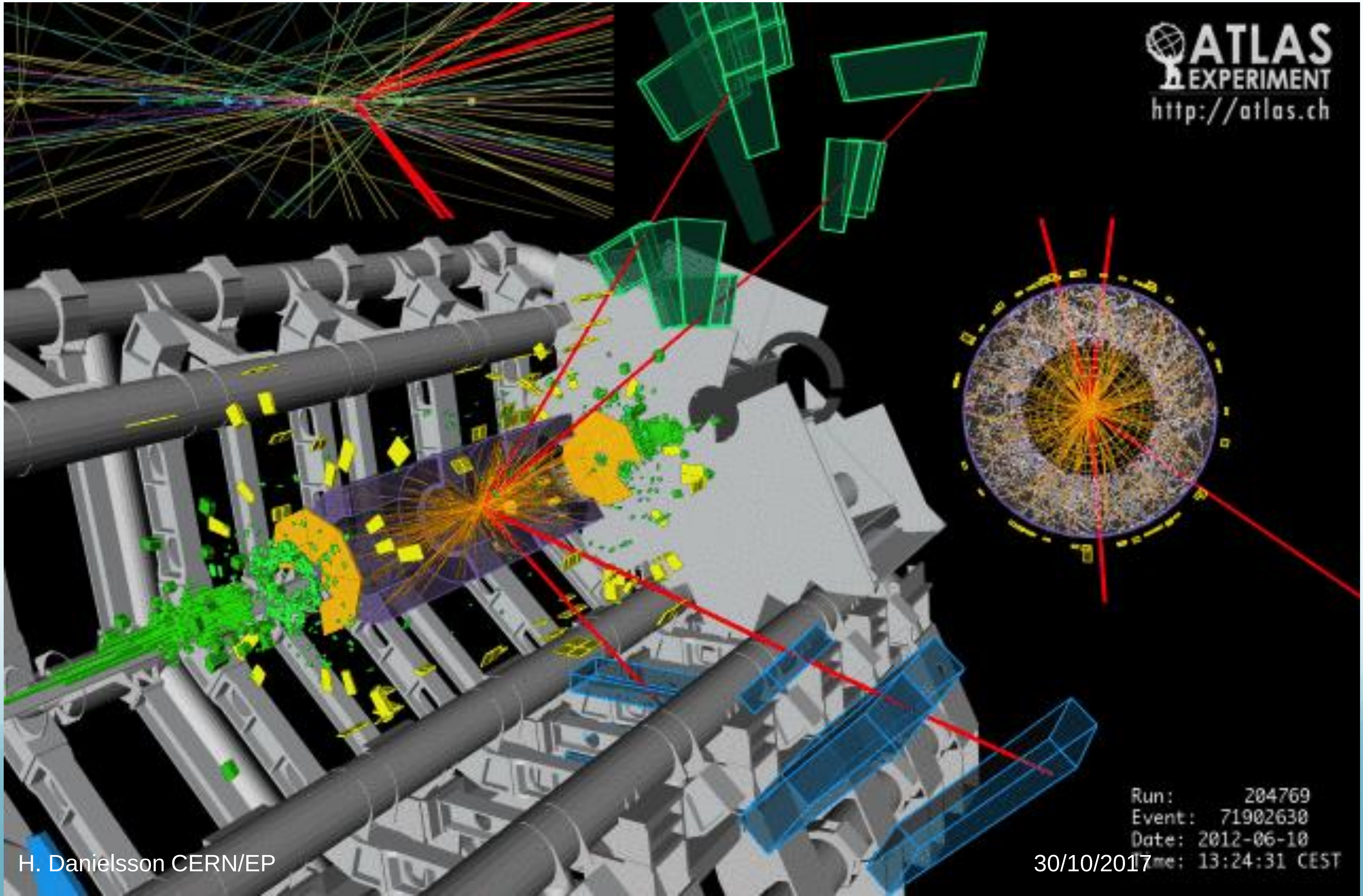




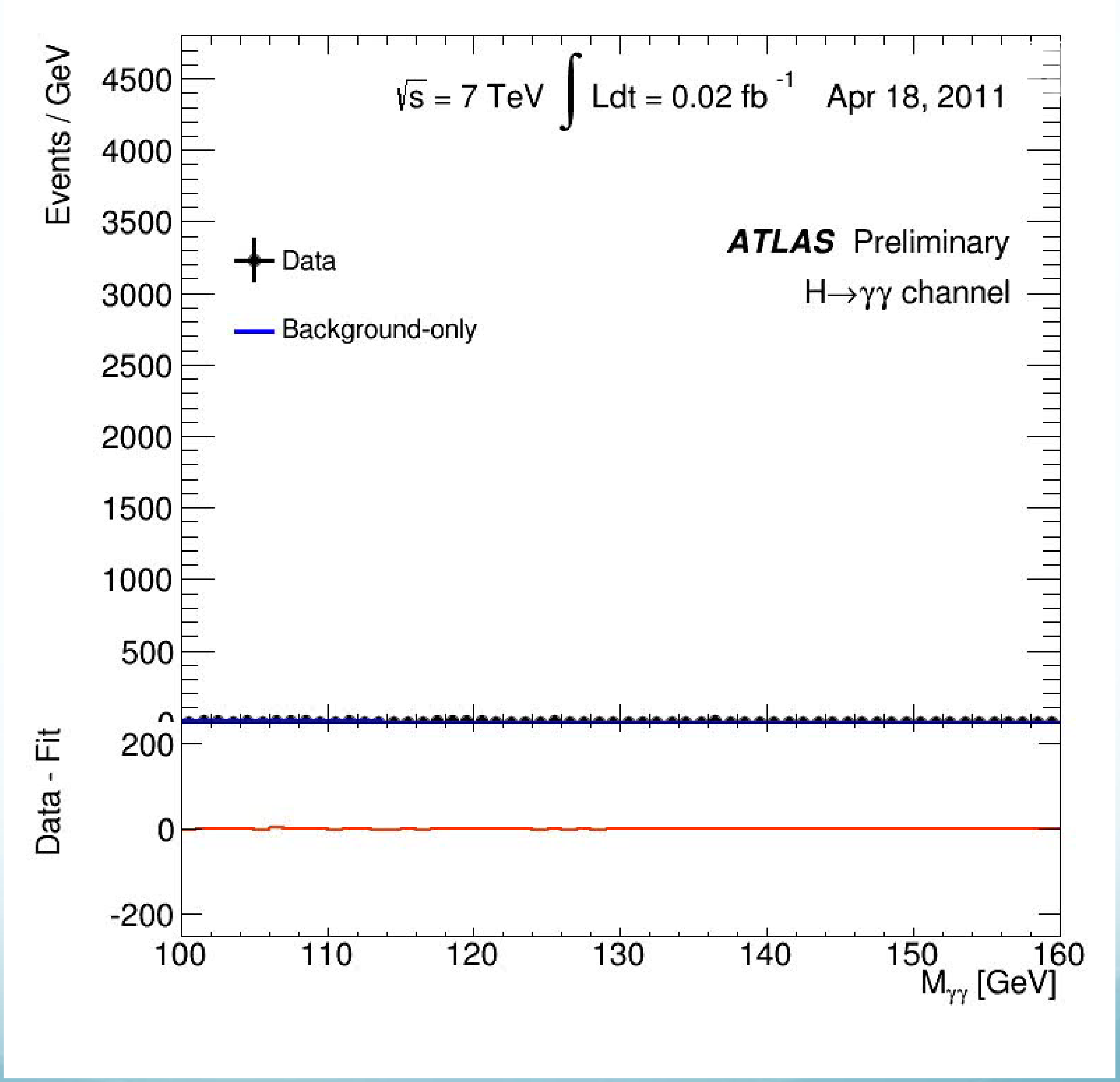
# H→ 4l


√s = 7 TeV
∫ Ldt = 0.05 fb^-1
Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (m_H=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M_4l [GeV]
35
30
25
20
15
10
5
0
10
0
-10
50
100
150
200
250
300
350
400
450
500

# Higgs events H→4l (muons)

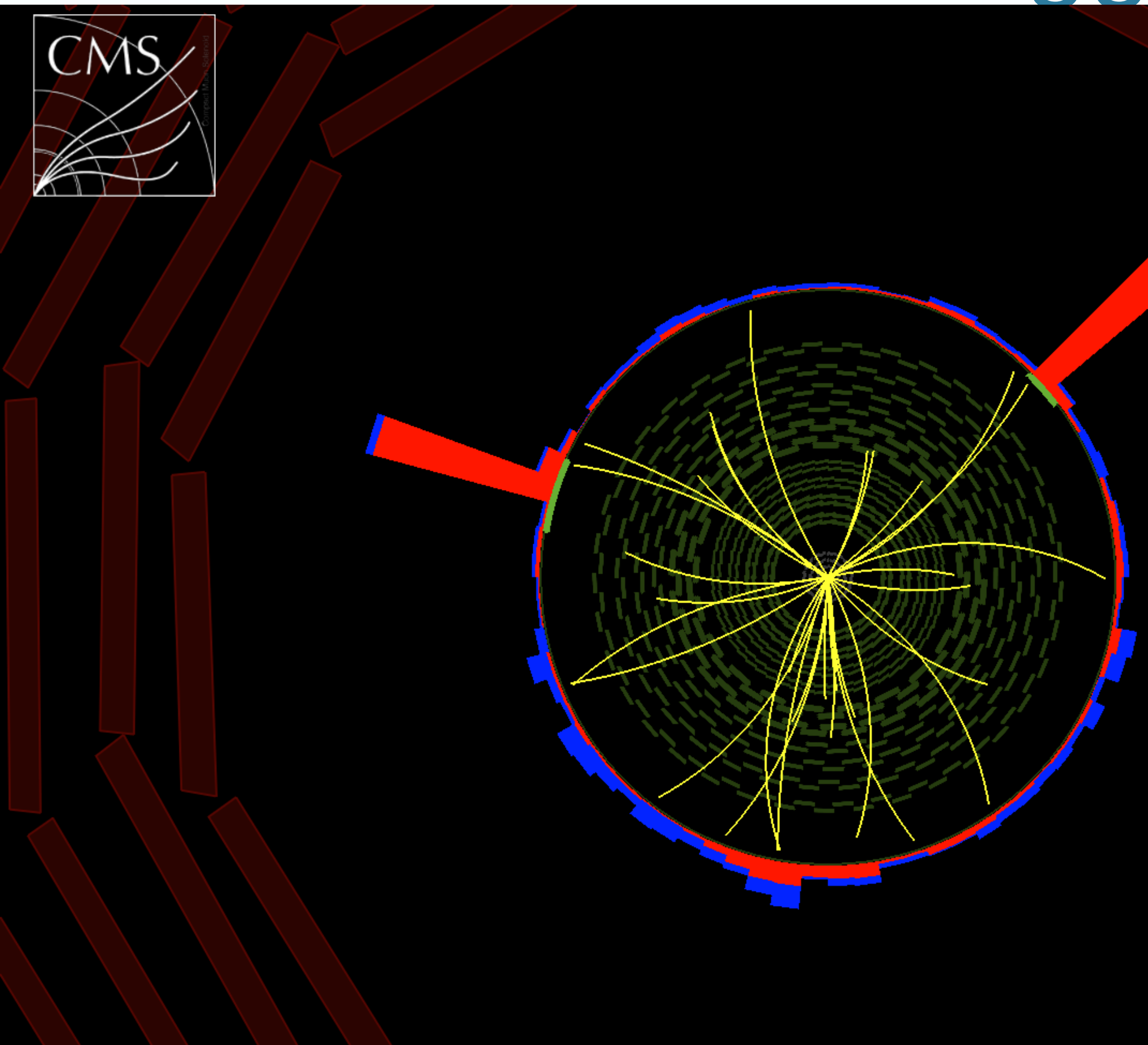


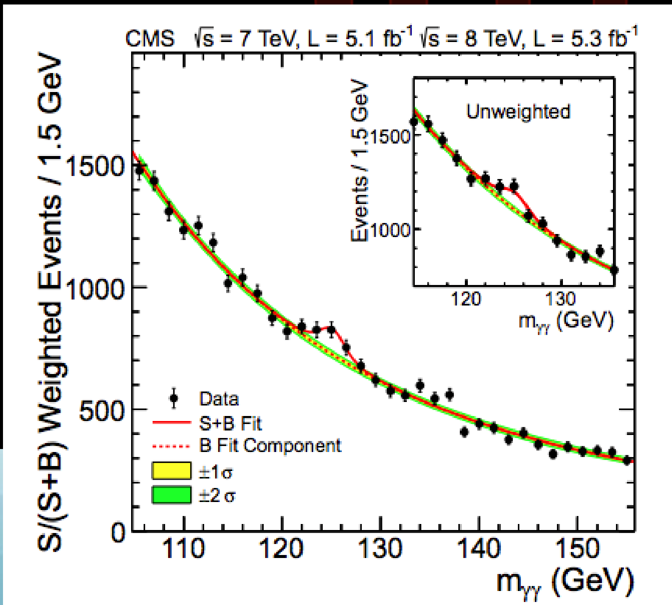
# H → γγ



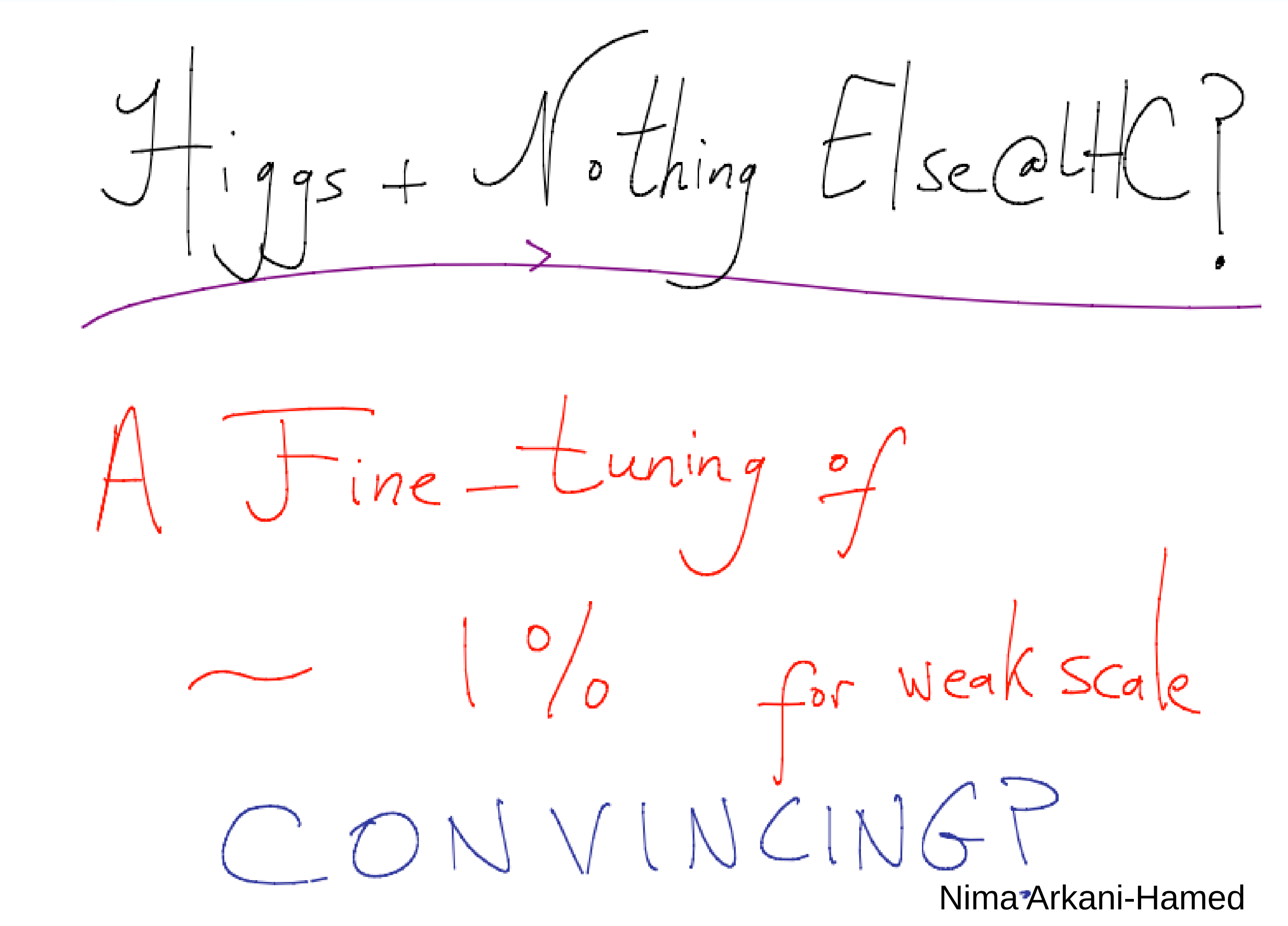
√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

# From CMS Higgs→$\gamma\gamma$



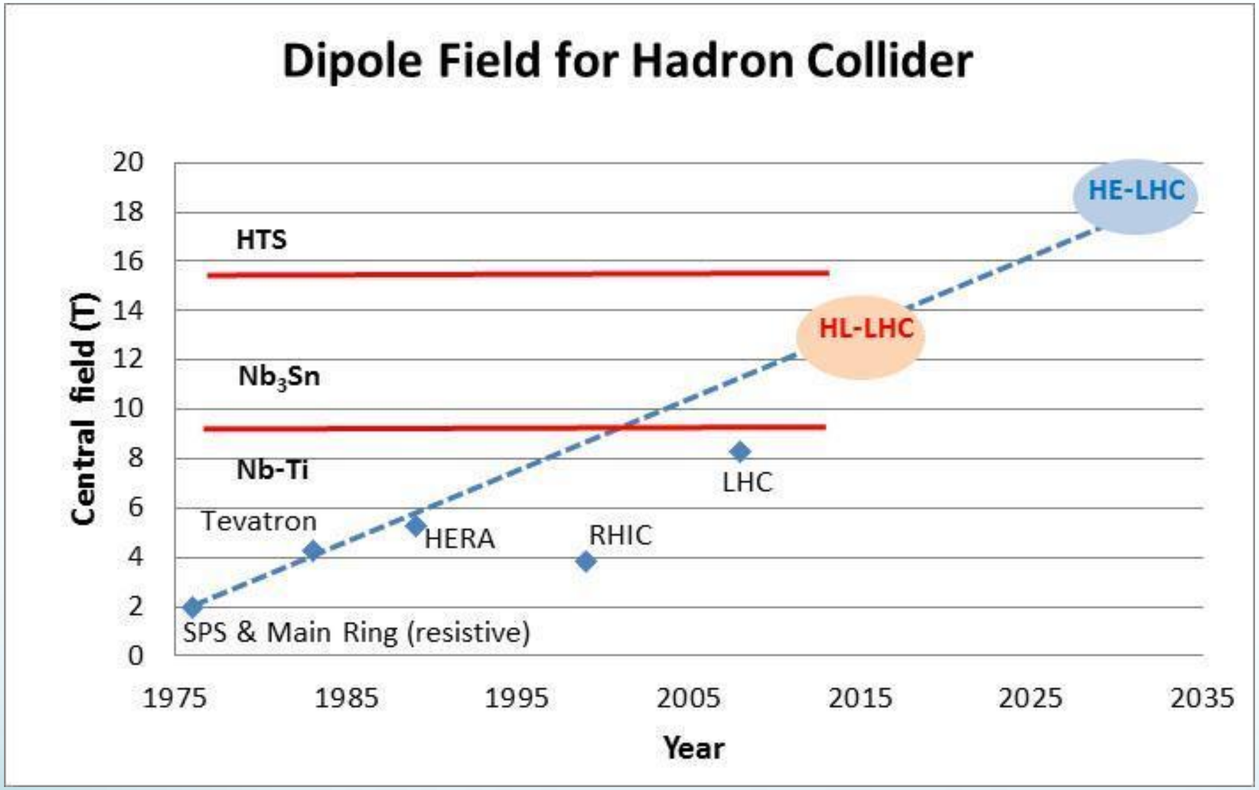


# Future (after LHC): FCC?




http://indico.cern.ch/event/282344/contributions/1630763/attachments/519399/716598/FCCtalk.pdf

# HL-LHC and HE- LHC

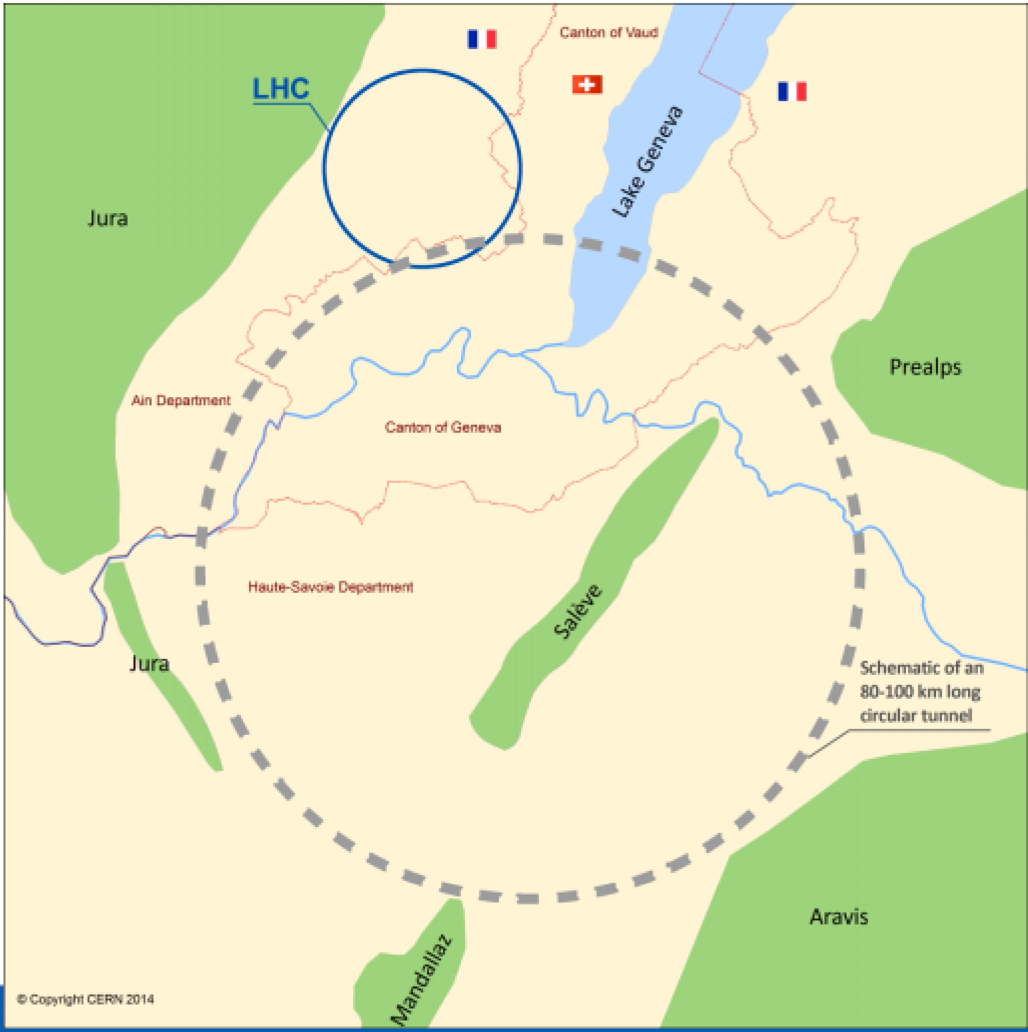



- Development of high field superconducting magnets
- High-Energy LHC with 10-13 T magnets
- HE-LHC with ~30 TeV center-of-mass energy for proton collisions and 16-20 T magnets

# 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://www.atlas.ch/HiggsResources/

# Spares

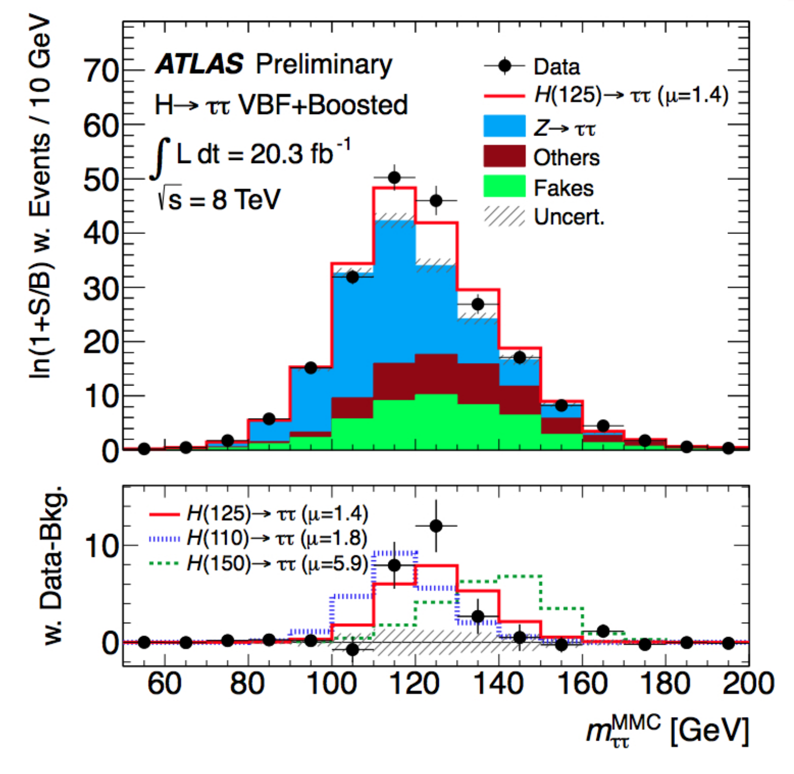
# Higgs to Fermions

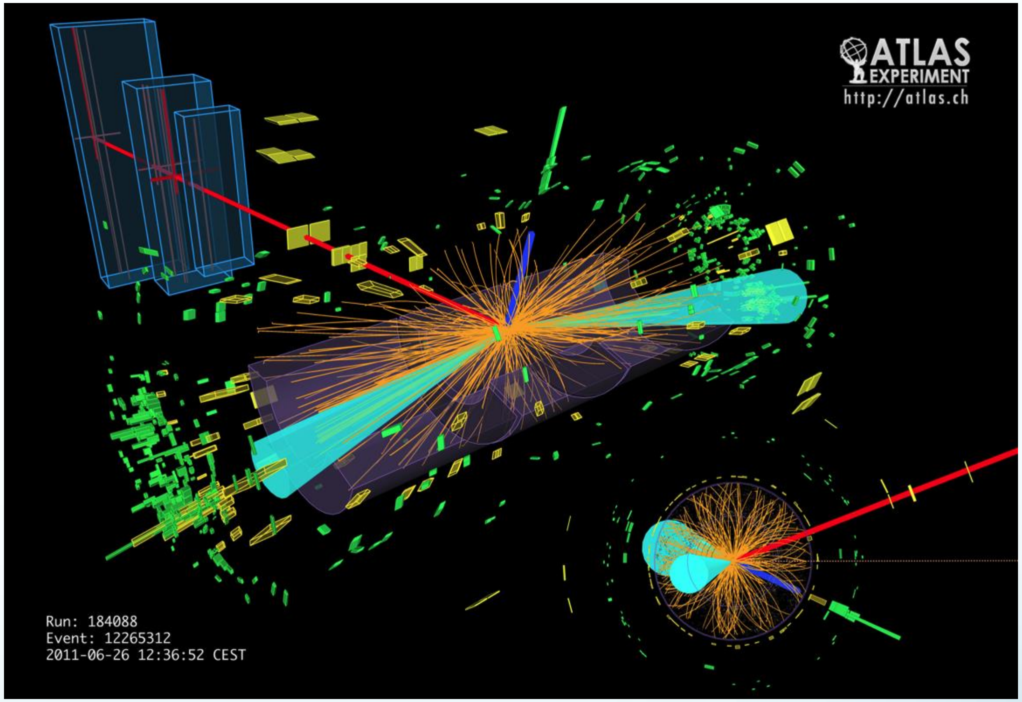
- Recent analysis shows evidence of Higgs boson decaying to fermions (leptons or quarks). Not previously observed!
- It is important to measure this decay but no surprise is expected
- Difficult due to high background

  BR related to mass. High mass fermions preferred ($\tau$,b)

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

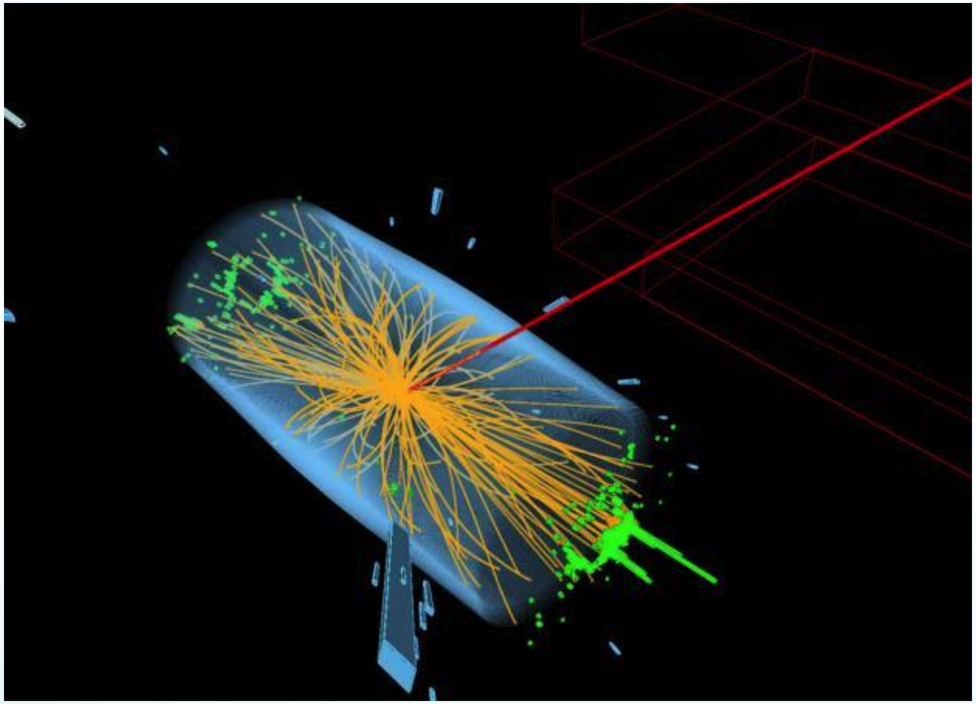
# Higgs decays to fermions (ττ) in ATLAS (26 Nov 2013)

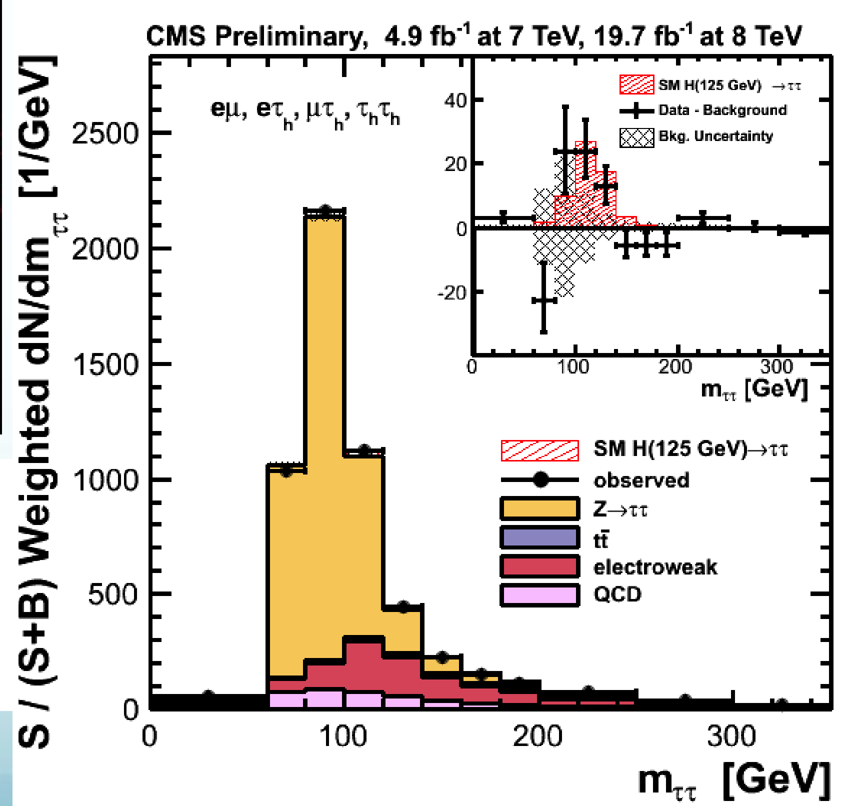



The taus decay into an electron (blue line) and a muon (red line)

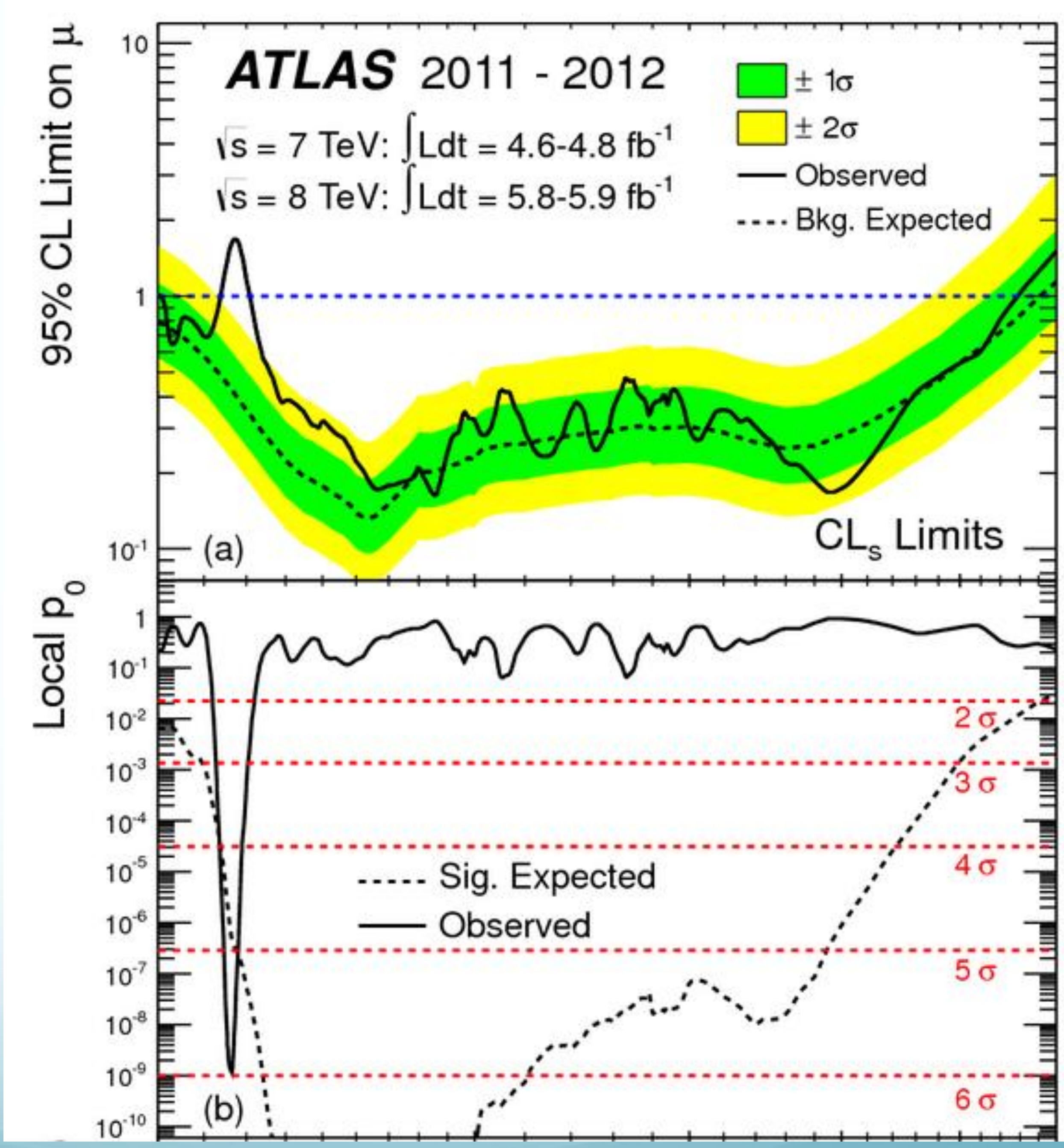
# Higgs decays to fermions ($\tau\tau$) in CMS (3 Dec. 2013)



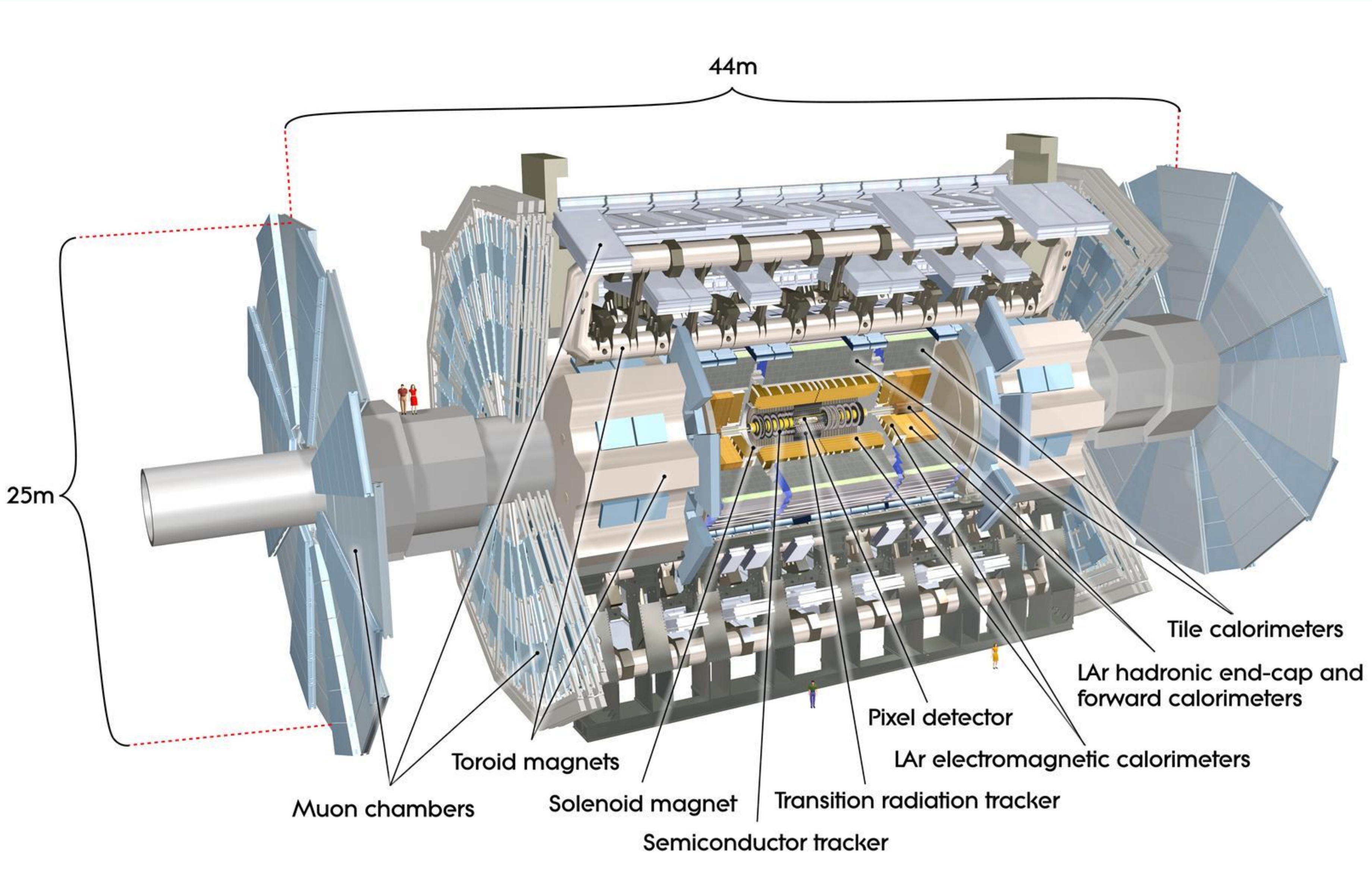



One tau decays to neutrinos and a muon (red lines on the right), while the other decays into a charged hadron (blue towers) and a neutrino

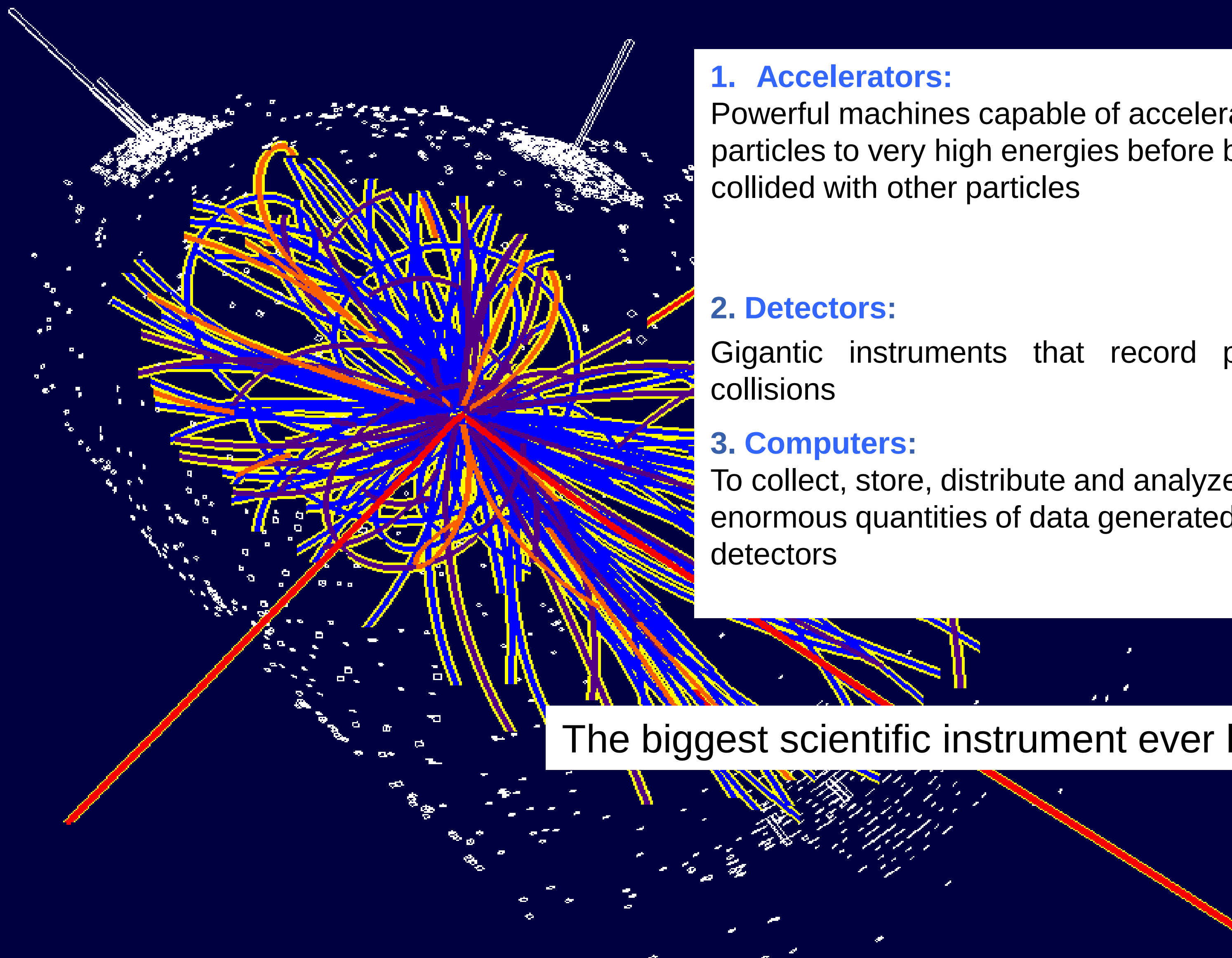
# Higgs "exclusion plots"



# The ATLAS experiment



# *LHC*
# *20 Years, projecting, constructing and Simulating…*



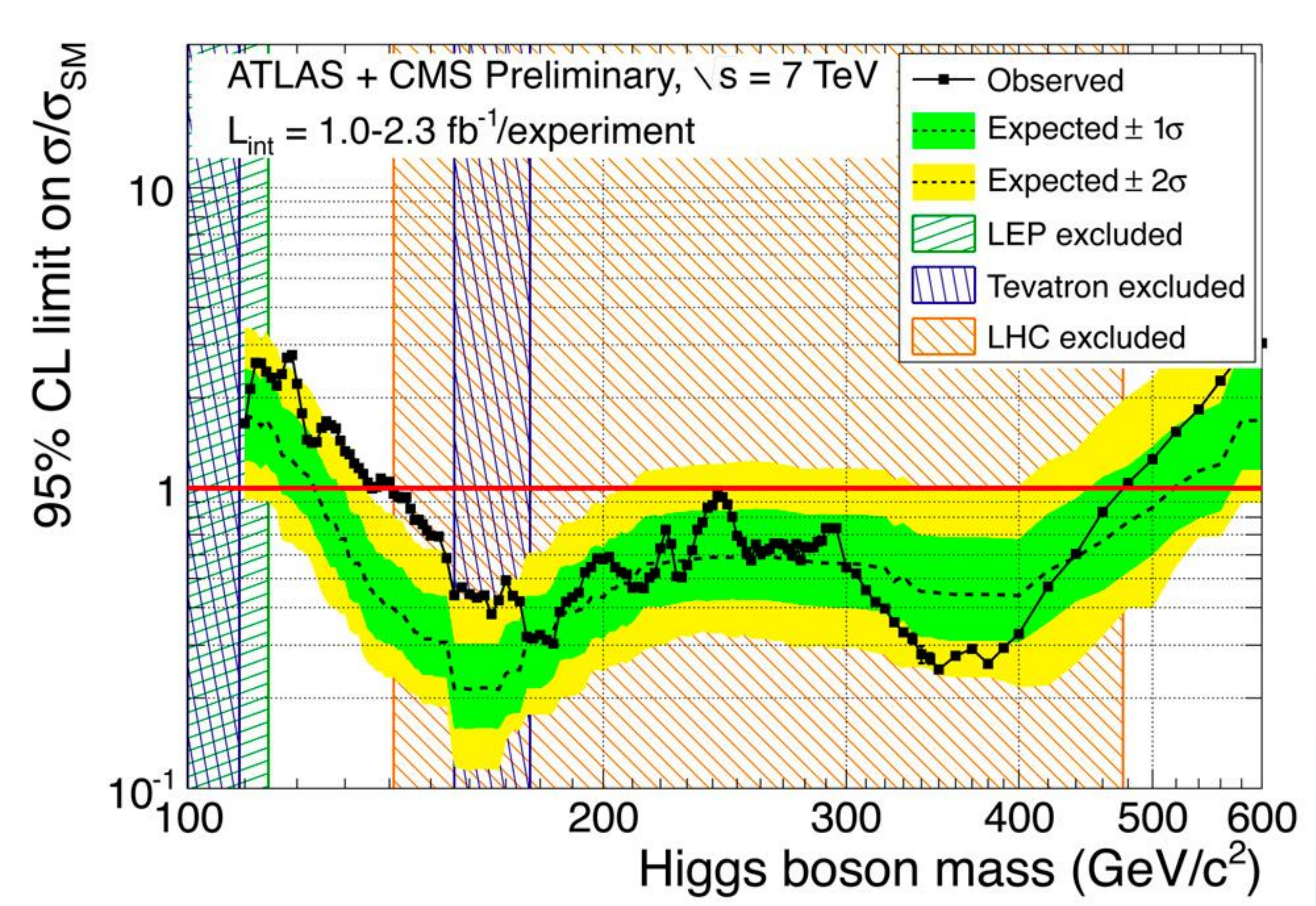
1. **Accelerators:**
Powerful machines capable of accelerating particles to very high energies before being collided with other particles

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

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

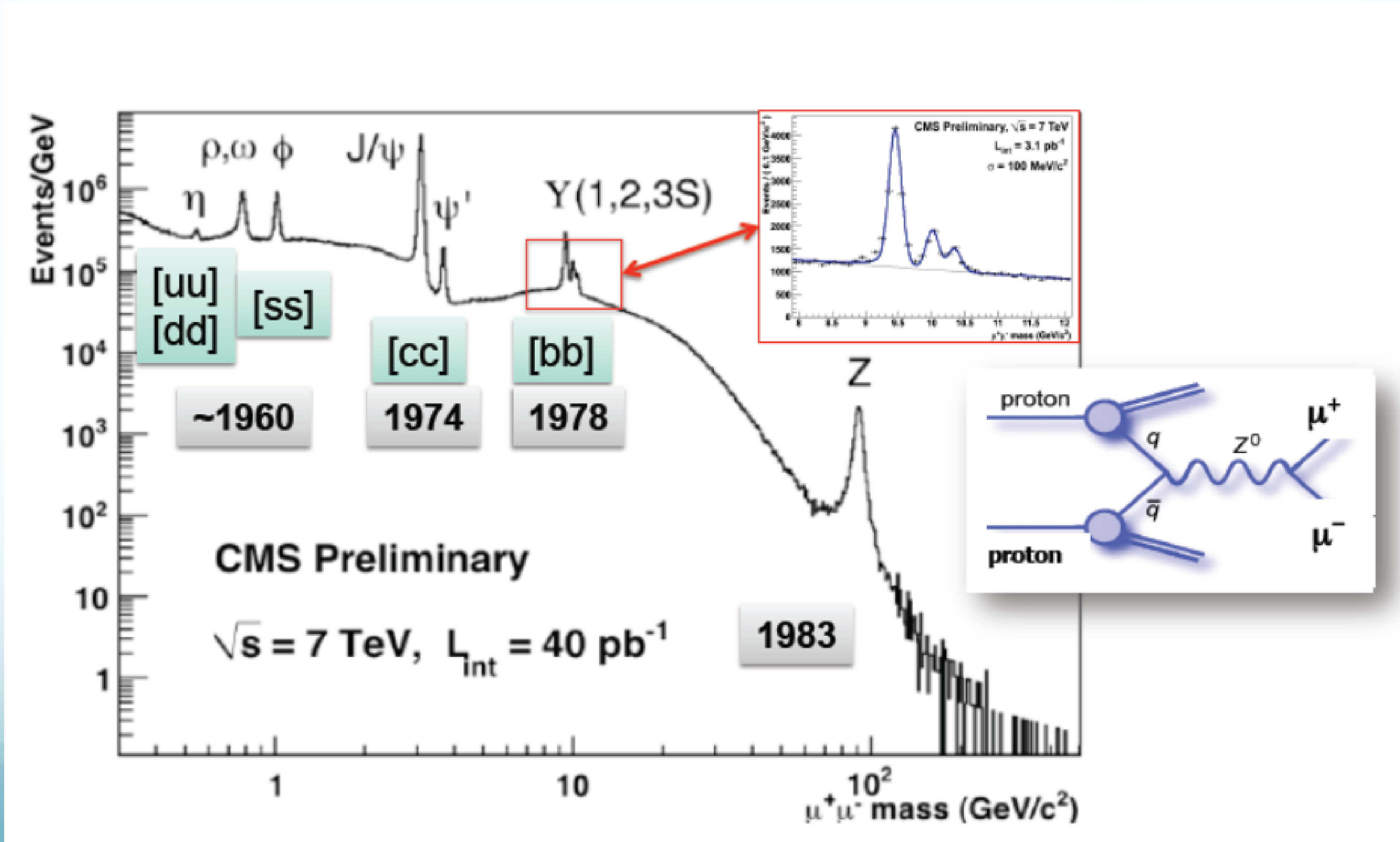
The biggest scientific instrument ever built

# 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

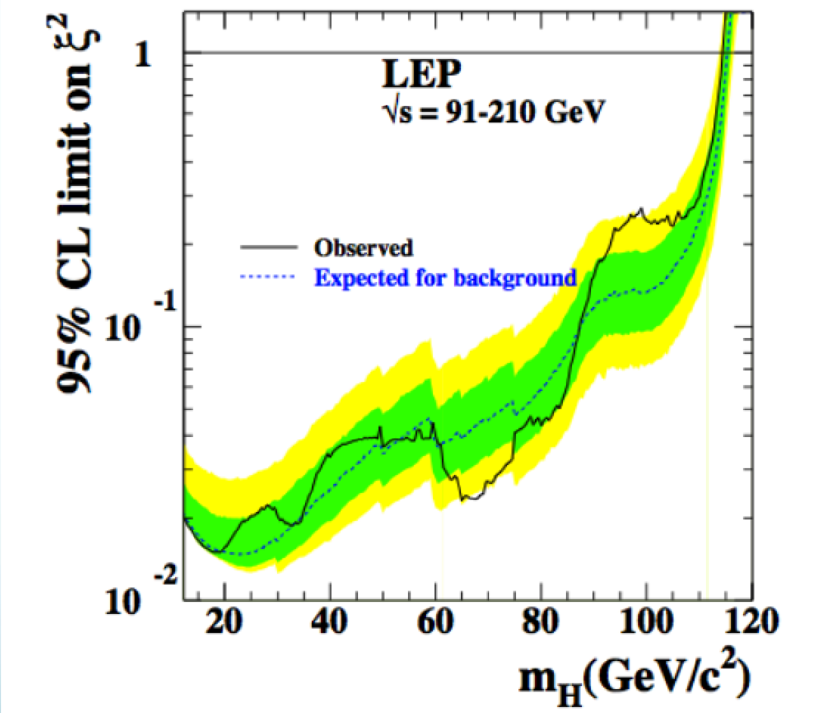



Figure 2.10: Higgs exclusion range from LEP experiments.

Until year 2011

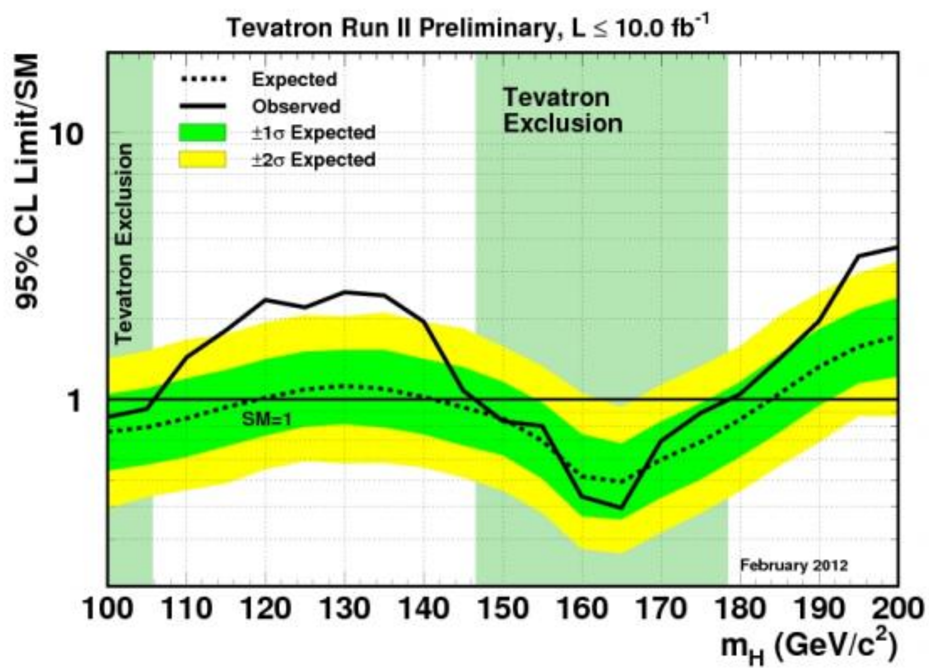
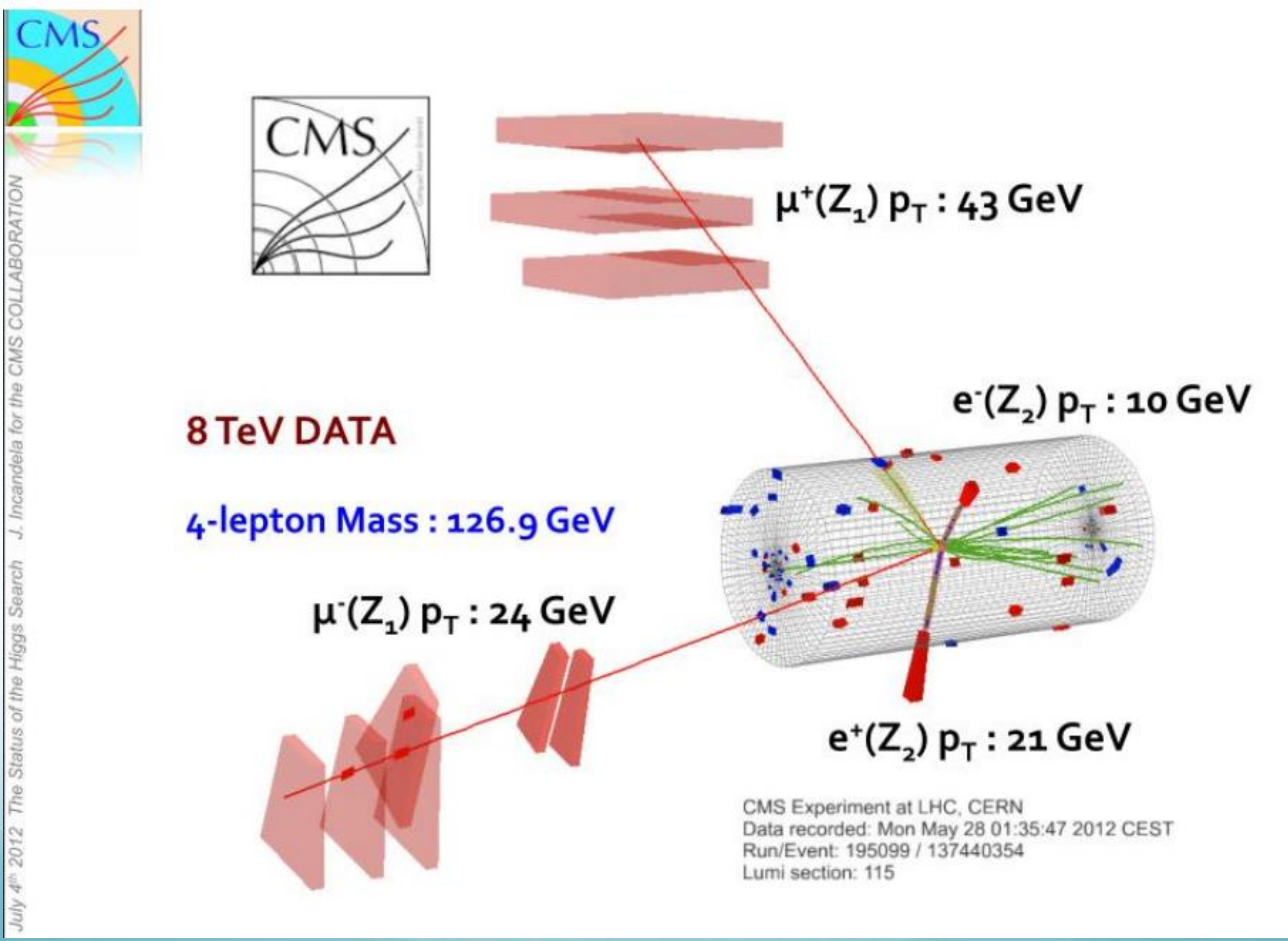


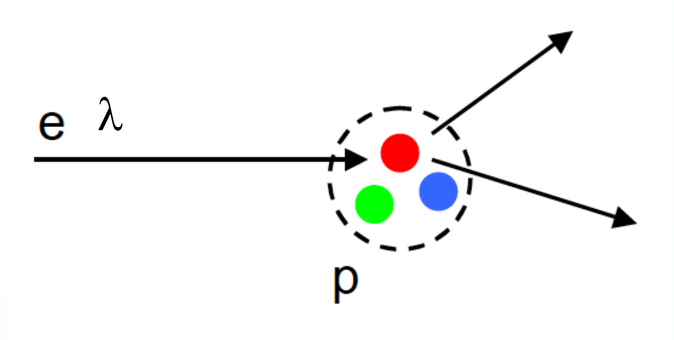

Figure 2.11: Combined Run II Higgs limits from the Tevatron experiments.



July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION
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

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

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



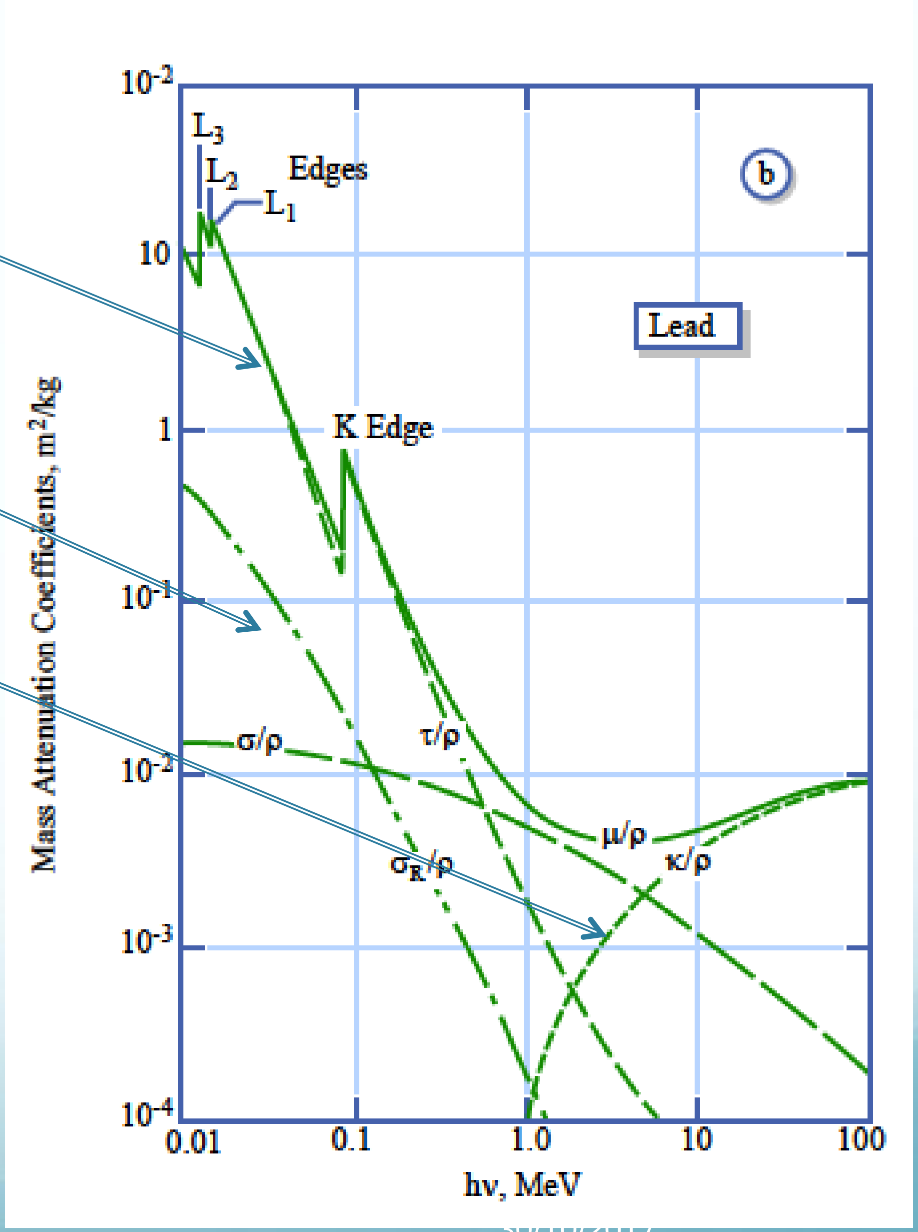

- The quark model was independently proposed by physicists Murray Gell-Mann and George Zweig in 1964.
- Gell-Mann found the quarks in:

"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."

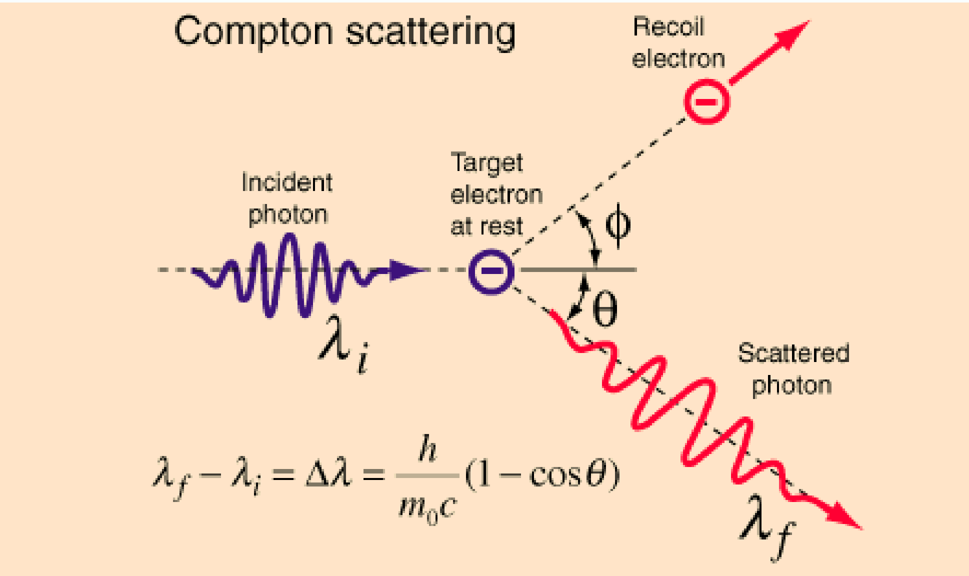
—James Joyce, *Finnegans Wake*

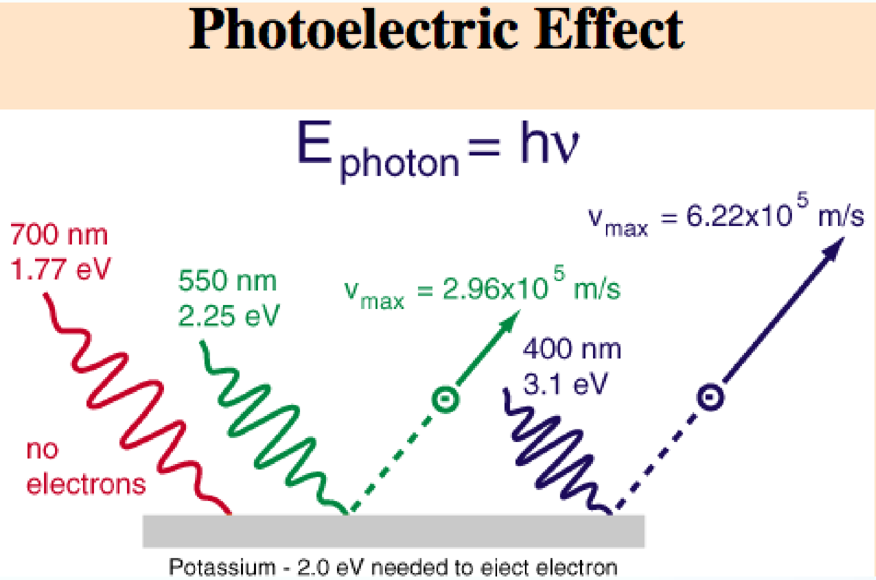
# Photons interacting with matter

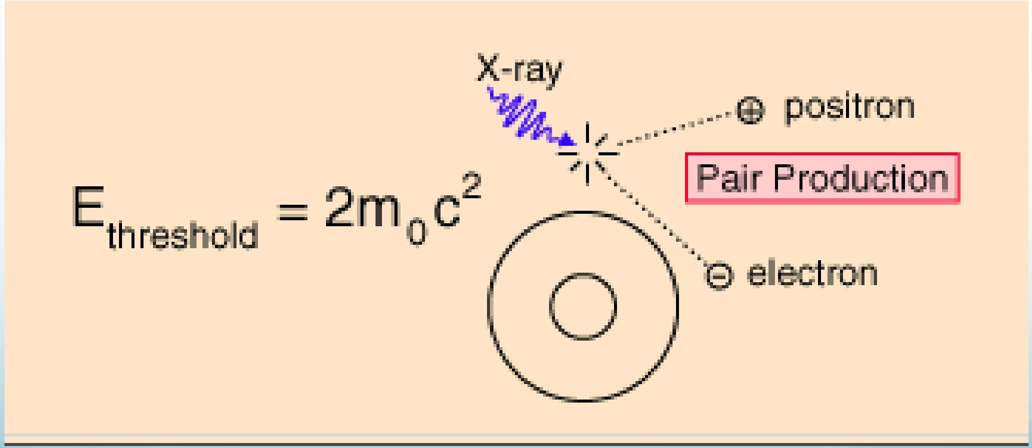
- Photoelectric effect
- Compton scattering
- Pair production
- *Mass Attenuation Coefficient* = Interaction probability/density



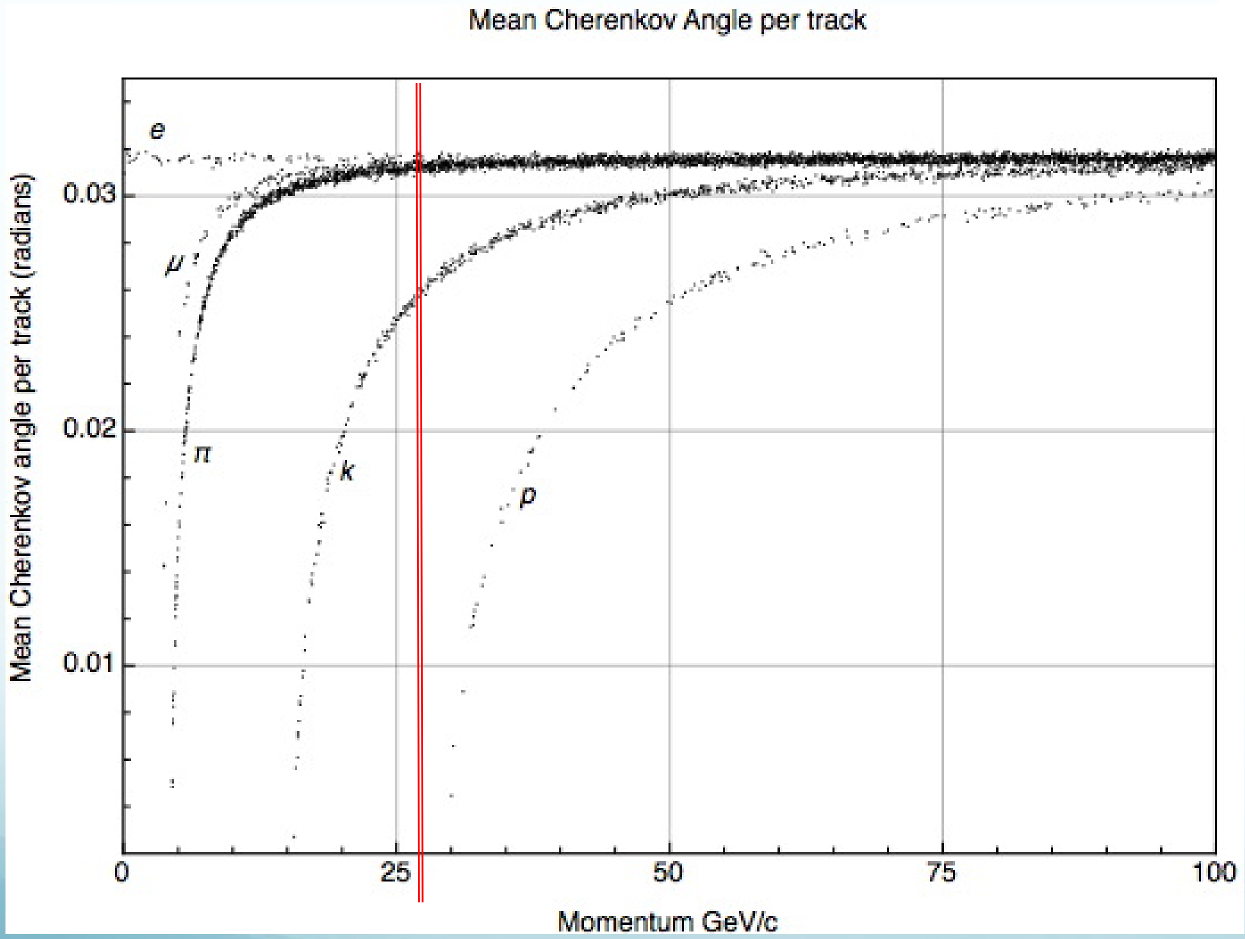
# Photons - 3 interactions



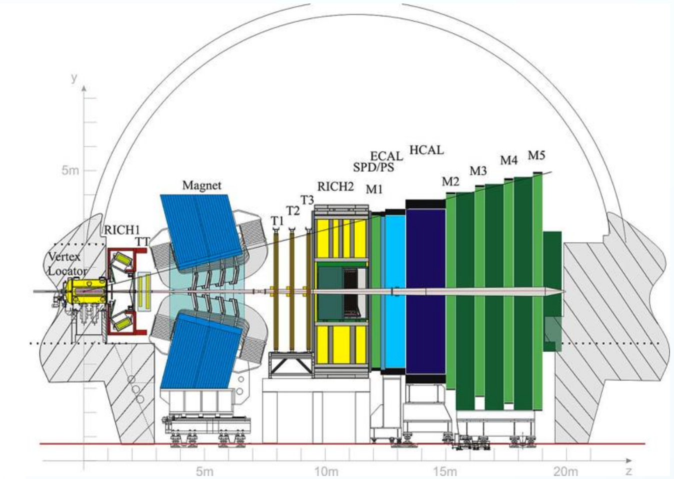



# Cherenkov Detector




LHCb

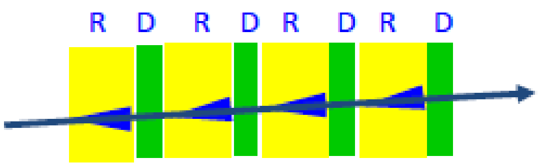



AMS

# 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.

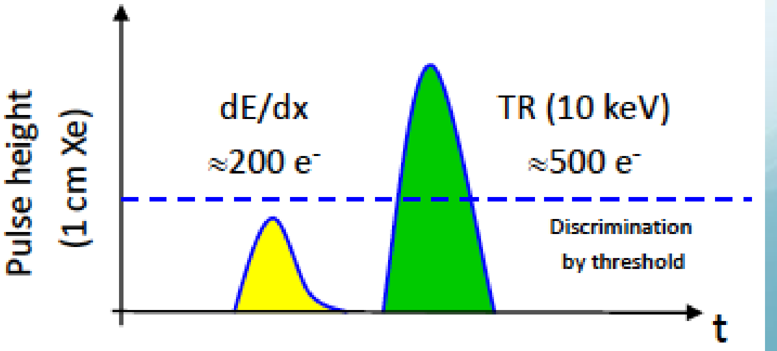
- **TR Radiators:**
  - stacks of thin foils made out of $CH_2$ (polyethylene), $C_5H_4O_2$ (Mylar)
  - hydrocarbon foam and fiber materials. Low Z material preferred to keep re-absorption small ($\propto Z^5$)




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