LHC physics
(experimental side)
part 1

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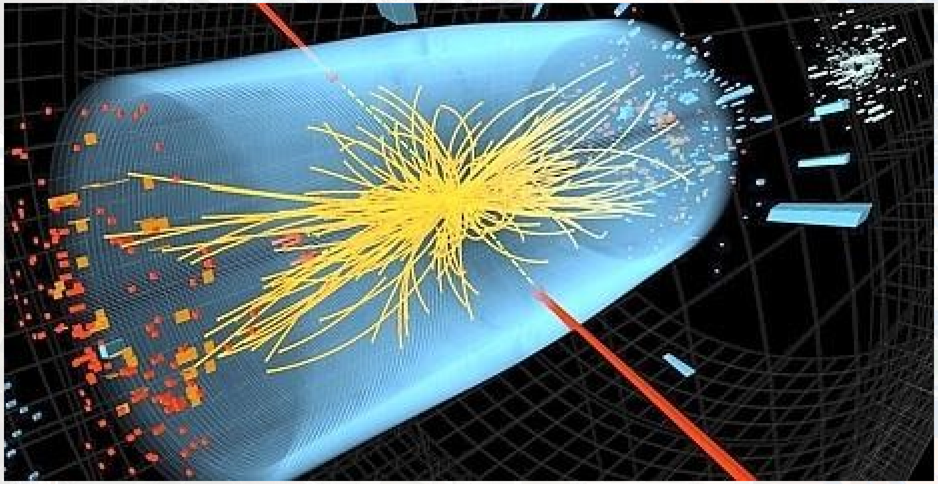
Introduction

- From here:

$$
\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
\frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
\frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
g M W^+_\mu W^-_\mu H - \frac{1}{2} g \frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \\
\phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + \\
i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\frac{1}{4} g^2 \frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + \\
m_d^\lambda) d^\lambda_j + i g s_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j \gamma u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j \gamma d^\lambda_j)] + \frac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \\
\gamma^5)\nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\frac{4}{3} s_w^2 - 1 - \gamma^5) u^\lambda_j) + \\
(\bar{d}^\lambda_j \gamma^\mu (1 - \frac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \frac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1 + \\
\gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \frac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa} \gamma^\mu (1 + \gamma^5) u^\lambda_j)] + \\
\frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H (\bar{e}^\lambda e^\lambda) + \\
i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \\
\gamma^5) d^\kappa_j] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \gamma^5) u^\kappa_j] - \\
\frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \\
\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + \\
i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + \\
i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + \\
i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \\
\frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
\bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \\
\bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{gathered}
$$

- To here:



Outline of first lesson

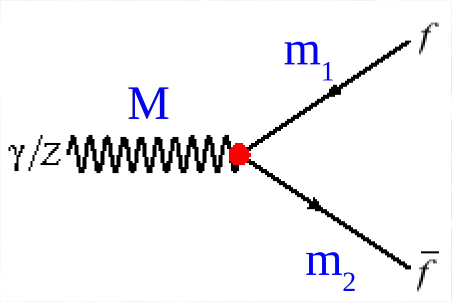
- Accelerating particles = create new particles
- Detectors = see those particles
- How to reconstruct an event

Basic formula

- Energy unit: electron-volt
  - 1 eV = $1.6.10^{-19}$ J
  - $m_{electron}$ = 511 keV
  - m_{proton} ~ 1 GeV

- Energy in special relativity: $E^2 = \vec{p}^2 c^2 + m_0^2 c^4$
  - invariant under relativist change
  - in HEP, c = 1

- Invariant mass:
  - conservation of four vector $(E, \vec{p})$
  - $M^2 = m_1^2 + m_2^2 + 2*(E_1 E_2 - \vec{p}_1 . \vec{p}_2)$



Physics with colliders

- To produce particles, need energy

- Fixed target experiment:
  - $E_{CM} = \sqrt{2 * E_{beam} + m^2_{target}}$
  - examples:
    - Rutherford experiment
    - hadron-therapy

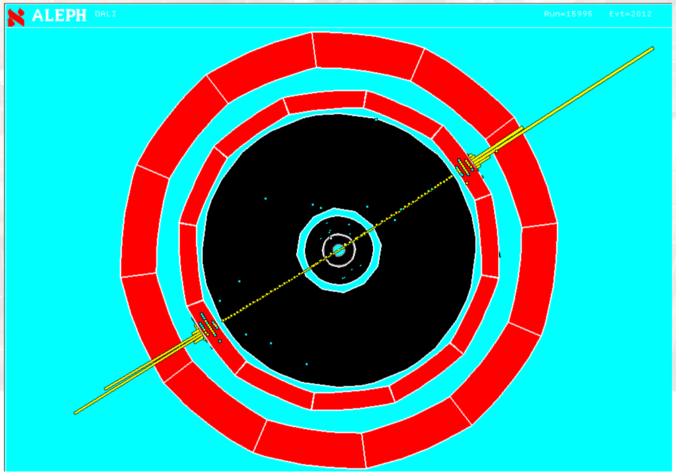
- Collider:
  - $E_{CM} \propto 2 * E_{beam}$
  - examples:
    - SPS, LEP, Tevatron, LHC

http://pdg.web.cern.ch

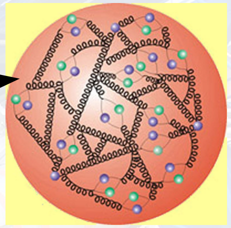
Leptonic vs hadronic colliders

Electron-positron collider

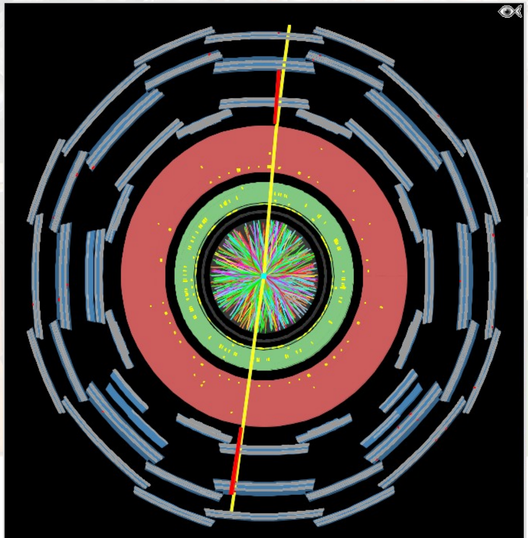
- no internal structure
- $E_{collision} = 2*E_{beam}$
- Pros:
  - probe precise mass
    ⇒ precision measurements
  - clean
- Cons:
  - only one $E_{collision}$ at a time
  - limited by synchrotron radiation at high energy



Hadronic collider (pp or $p\bar{p}$)

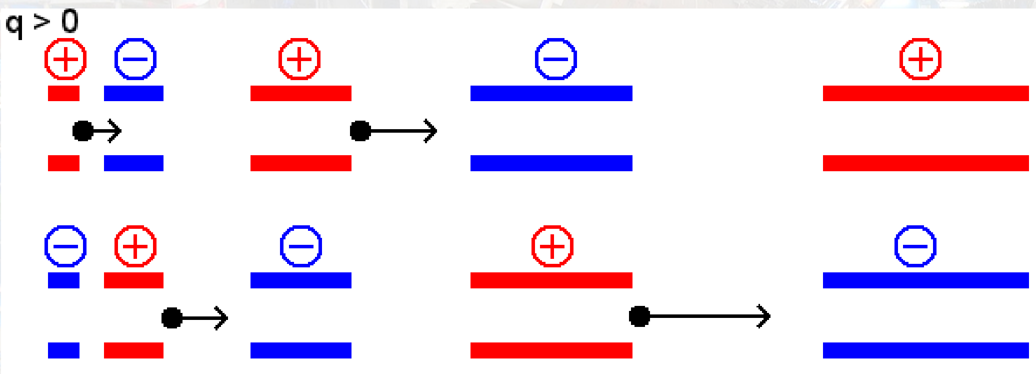


- quarks + gluons
- $E_{collision} < 2*E_{beam}$
- Pros:
  - scan different masses
    ⇒ discovery machine
- Cons:
  - $E_{collision}$ not known
  - several collisions on top of interesting one



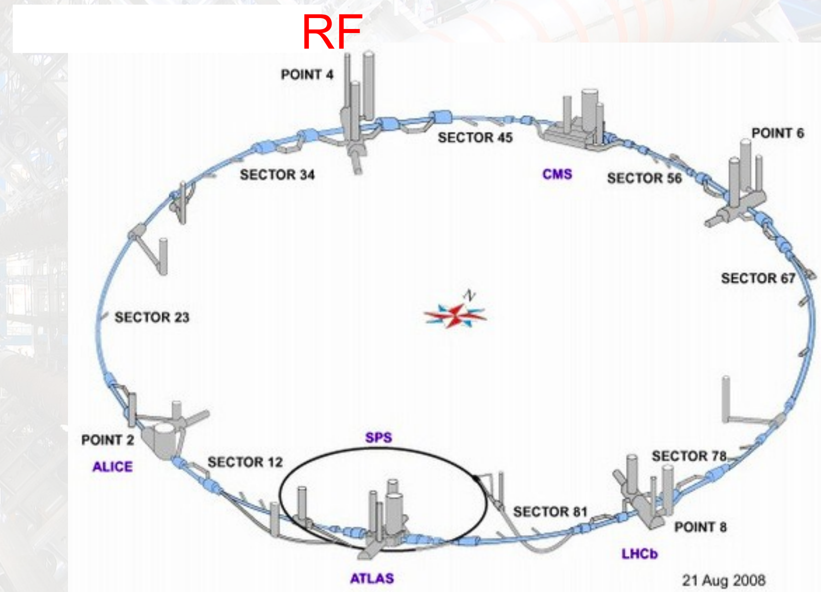
Synchrotrons

- Acceleration with electric fields
  - $\Delta E = q\Delta V$
- Radiofrequency (RF) cavities
  - alternating potential (~100 MHz)



- LAPP round-about = LEP cavity

- Closed path = goes several times through the accelerating part

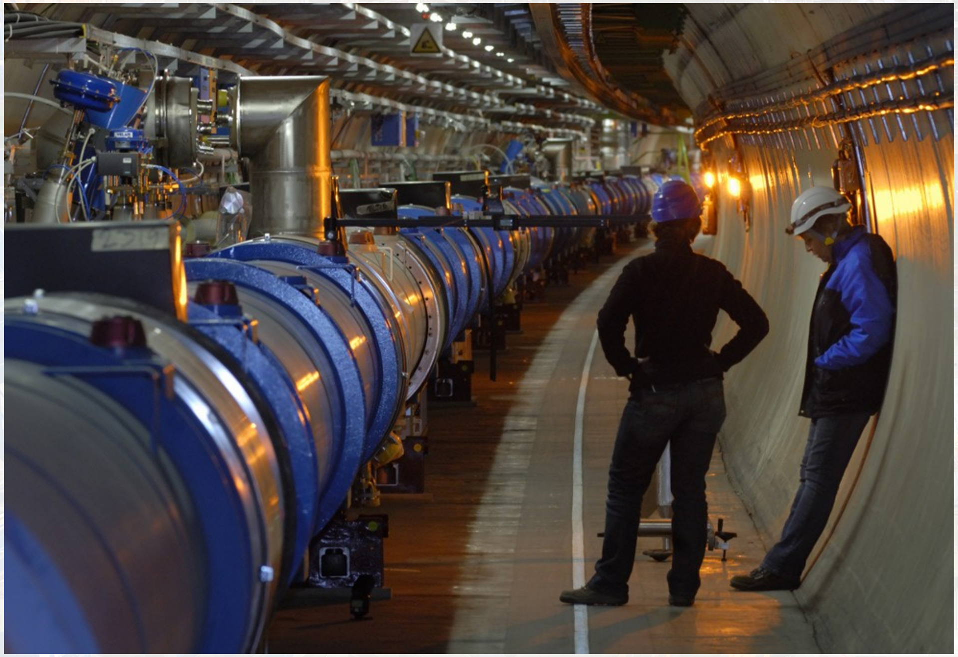


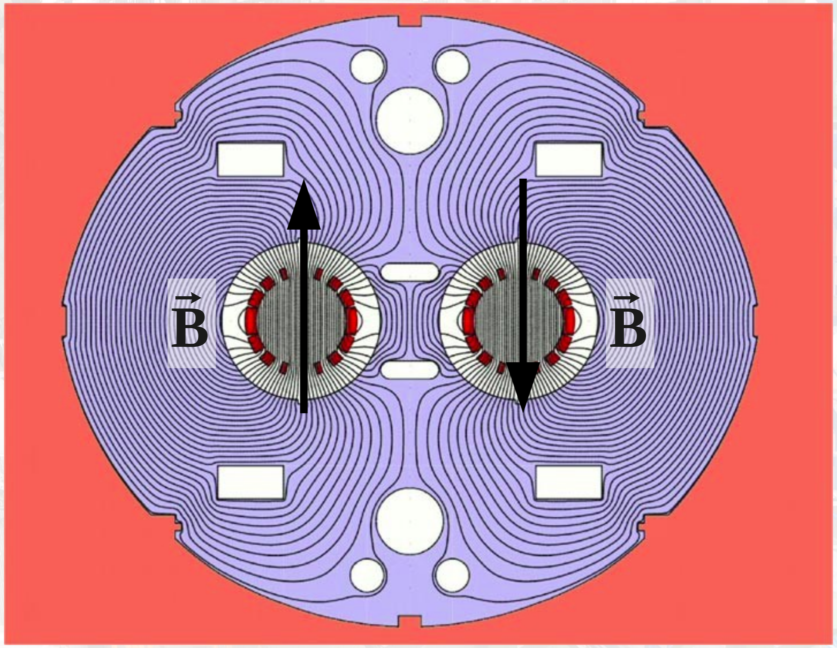
- Particles guided by magnetic field

The LHC (1)

- p-p collider
- ~9000 superconducting magnets
- ~1000 bunches of 100 billions of protons

- Protons accelerated to (7) 8 TeV centre-of-mass energy
  - ~ train at 100 km/h concentrated in a few tens of μm

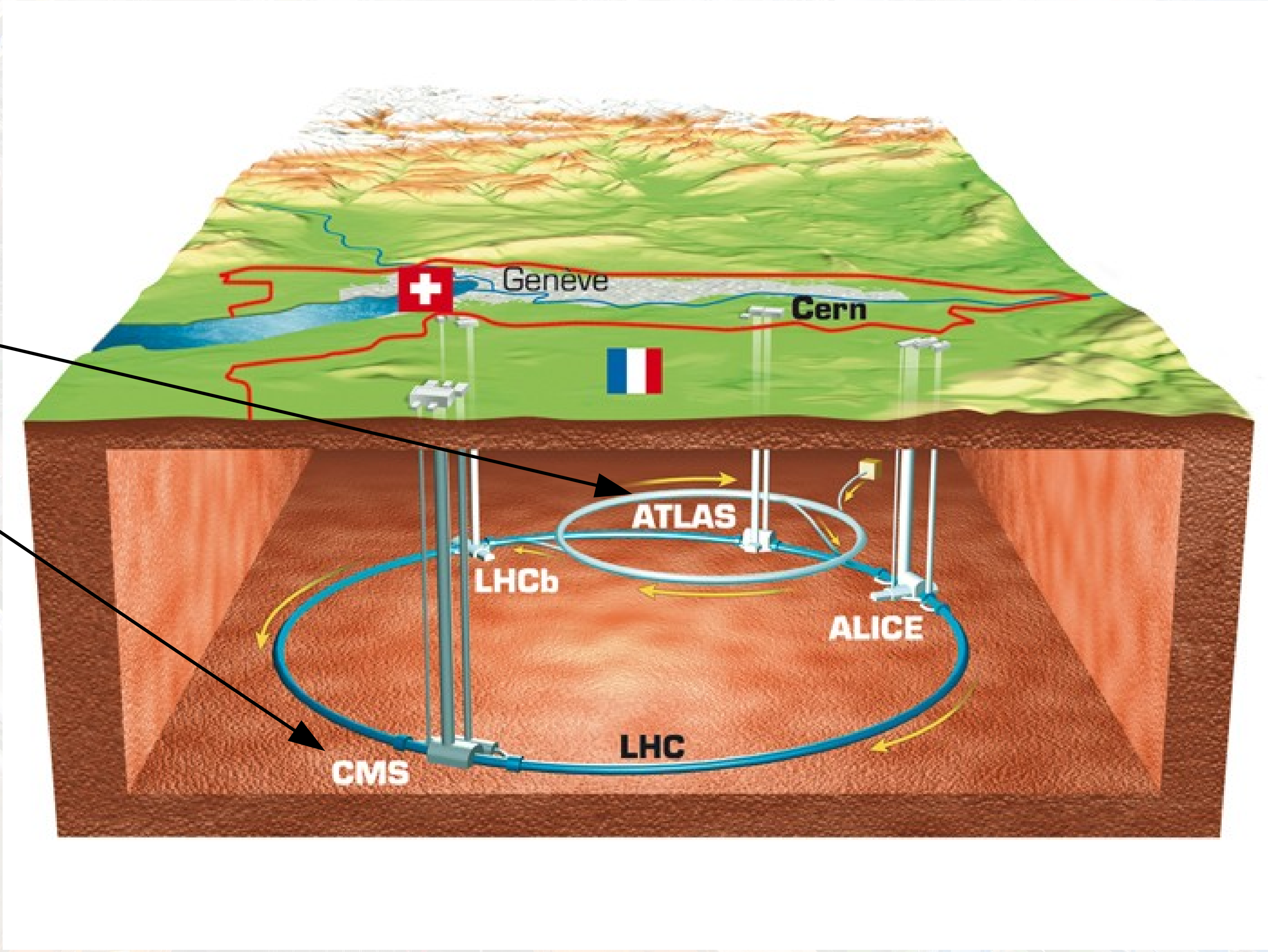




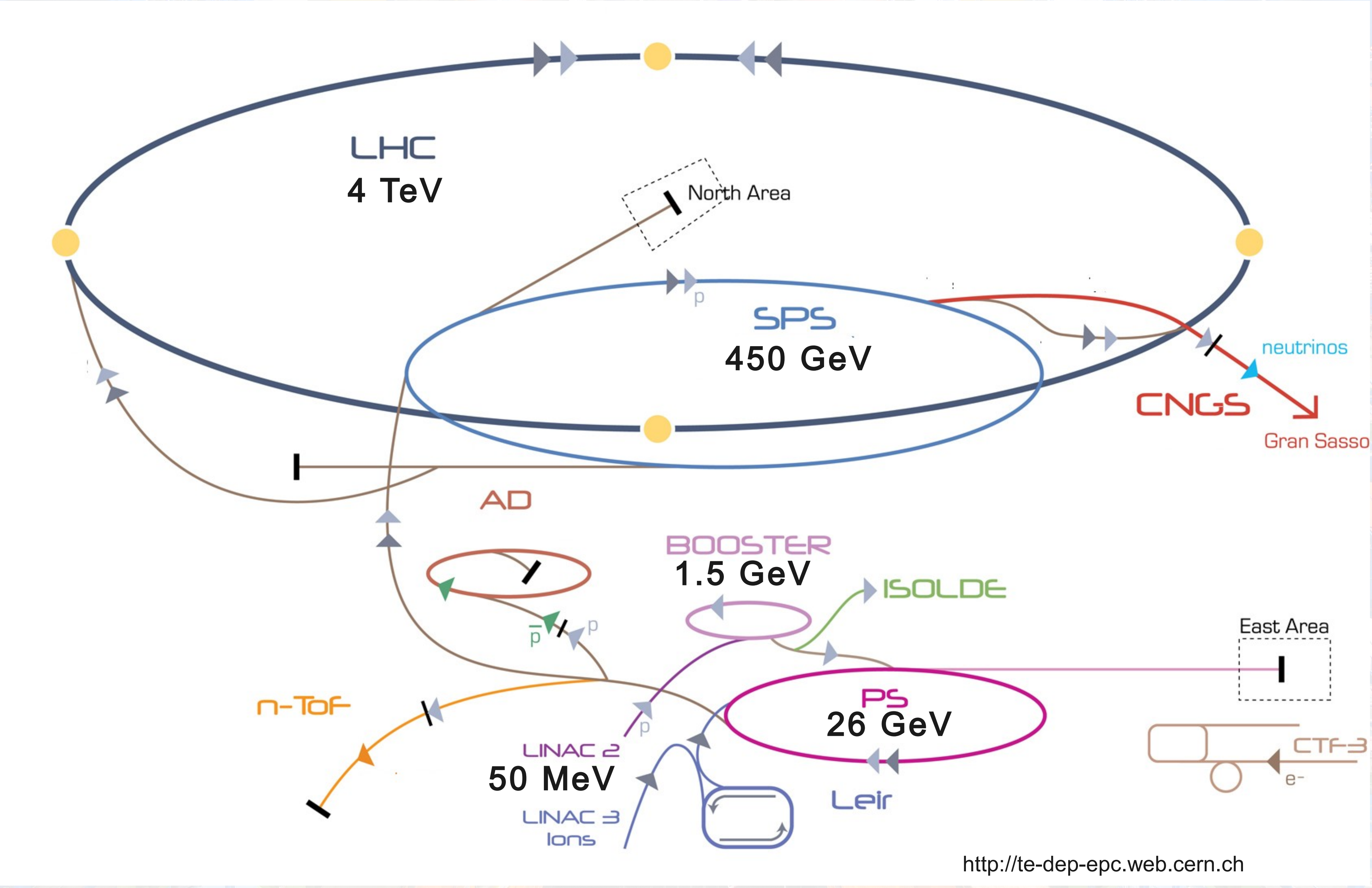
The LHC (2)

- 27 km long
- 4 main experiments
  - ATLAS
  - CMS
  - LHCb
  - ALICE

see course by P.Ghez



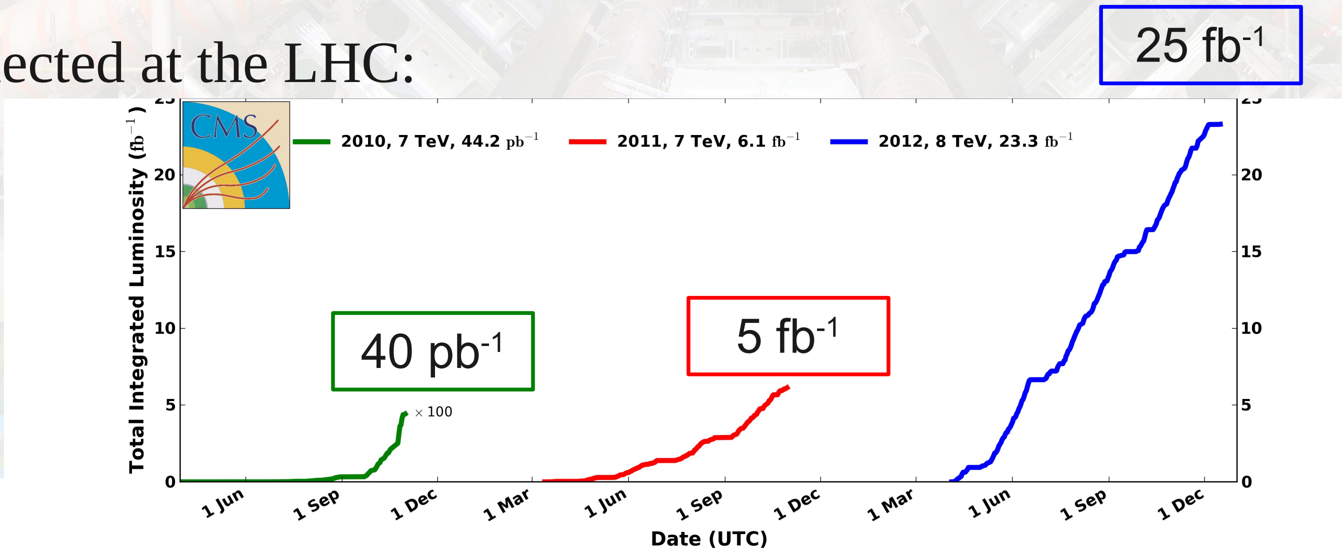
CERN accelerator complex



Luminosity

- Instantaneous luminosity: $L_{inst} = \frac{f.N^2}{4\pi\sigma_x\sigma_y}$
  - N = number of particules/beam ($\sim 10^{11}$)
  - f = frequency revolution (11 kHz)
  - σ_x, σ_y: transverse width of the beam (~60 µm)
  - unit: $cm^{-2}.s^{-1}$
- Total luminosity: $L_{tot} = \int L_{inst}\, dt$
  - unit: cm^{-2} or $barn^{-1}$
  - $1\ b = 10^{-24}\ cm^2$
- Collected at the LHC:

T	tera	10^{12}	1000000000000
G	giga	10^{9}	1000000000
M	mega	10^{6}	1000000
k	kilo	10^{3}	1000
		1	1
m	milli	10^{-3}	0.001
µ	micro	10^{-6}	0.000001
n	nano	10^{-9}	0.000000001
p	pico	10^{-12}	0.000000000001
f	femto	10^{-15}	0.000000000000001



Cross section

- Production cross section σ = probability of a particle to be produced
  - unit: cm^2 or barn
- Number of producted particle: $N = \sigma . L$
- At the LHC, total luminosity = ~30 fb^{-1}

  ⇒ number of produced particles:

	mass (GeV)	cross section	Events (millions)
2 quarks/gluons		500 μb	100000000
$W \rightarrow l\nu$	80.4	10 nb	300
$Z \rightarrow ll$	91.2	0.9 nb	30
$t\bar{t}$	173.1	165 pb	5
Higgs	125	22 pb	0.7

Lifetime and decay

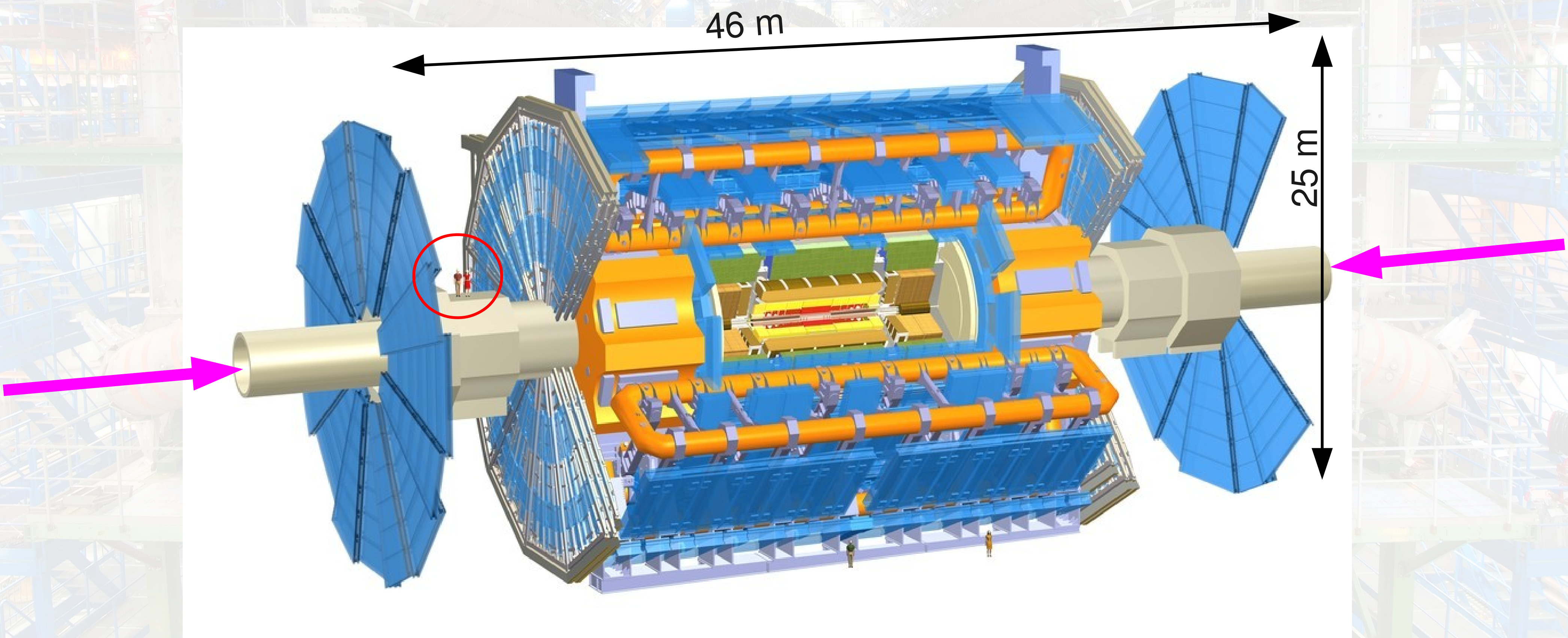
- Most of the particles produced at the LHC are instable
  - decay through electroweak force or strong force
- A few examples:

	lifetime (s)	decay products	Branching ratio
W boson	10^{-25}	$e\nu$	11%
		$\mu\nu$	11%
		2 quarks	68%
Z boson	10^{-25}	ee	3%
		$\mu\mu$	3%
		$\nu\nu$	20%
top quark	5.10^{-25}	Wb	100%
Higgs boson	$1.5.10^{-22}$	$b\bar{b}$	56%
		WW	23%

- Conclusion: need to find the decay products

ATLAS and CMS experiments

- Giant experiments
  - 46x25m for ATLAS
  - 13800 t for CMS (= 1.3*)



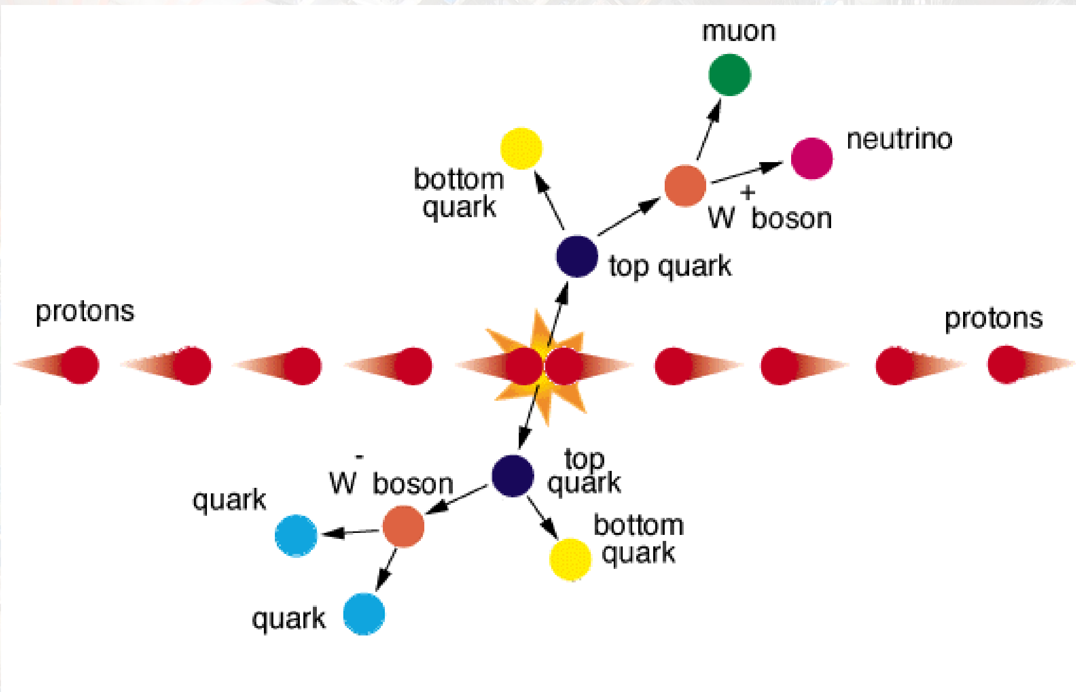
ATLAS and CMS collaborations

- > 3000 physicists /collaboration
- > 200 institutes

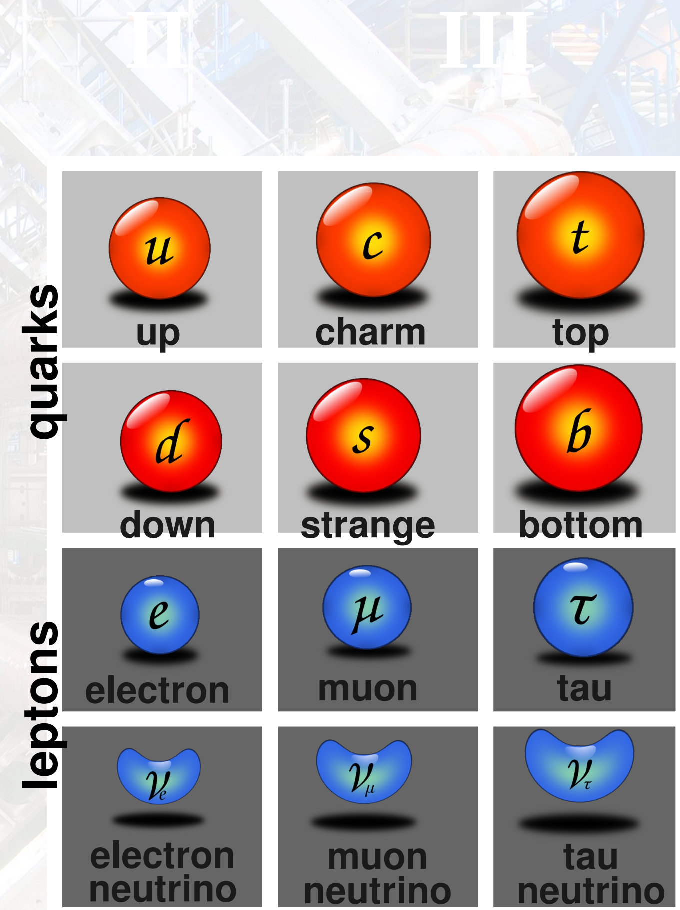
- "The ~~empire~~ collaborations on which the sun never sets"

Detecting particles (1)

- Example for top-antitop production and decay:



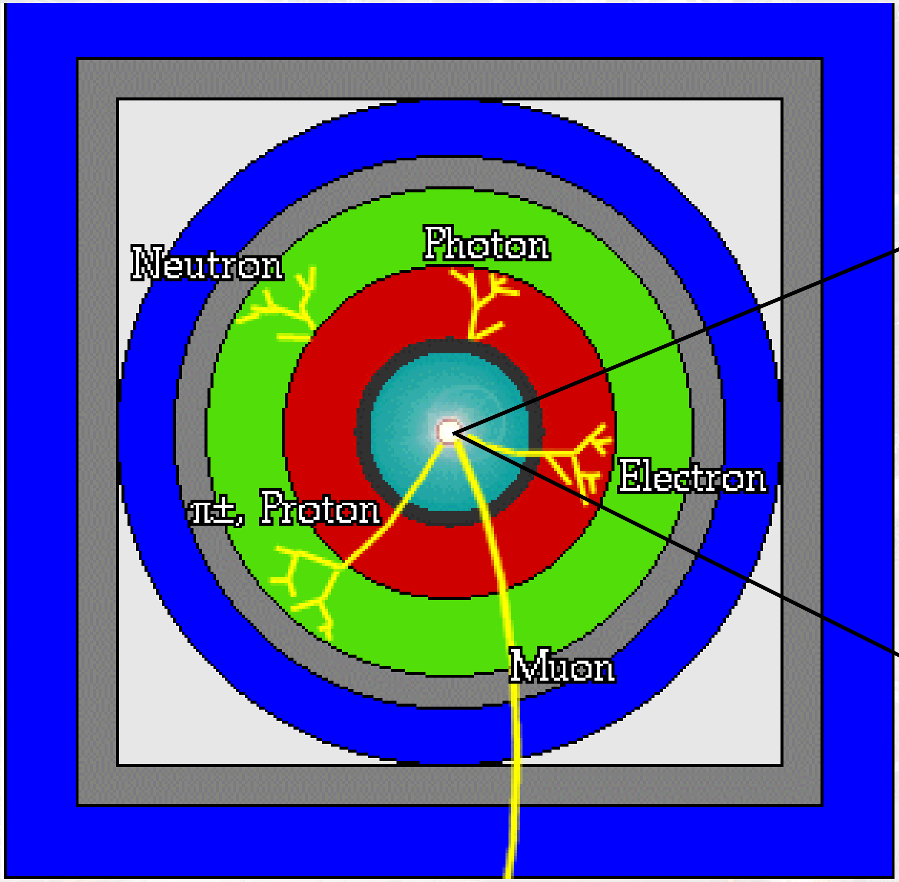
adapted from http://www.physics.rutgers.edu/ugrad/labs/particles.html

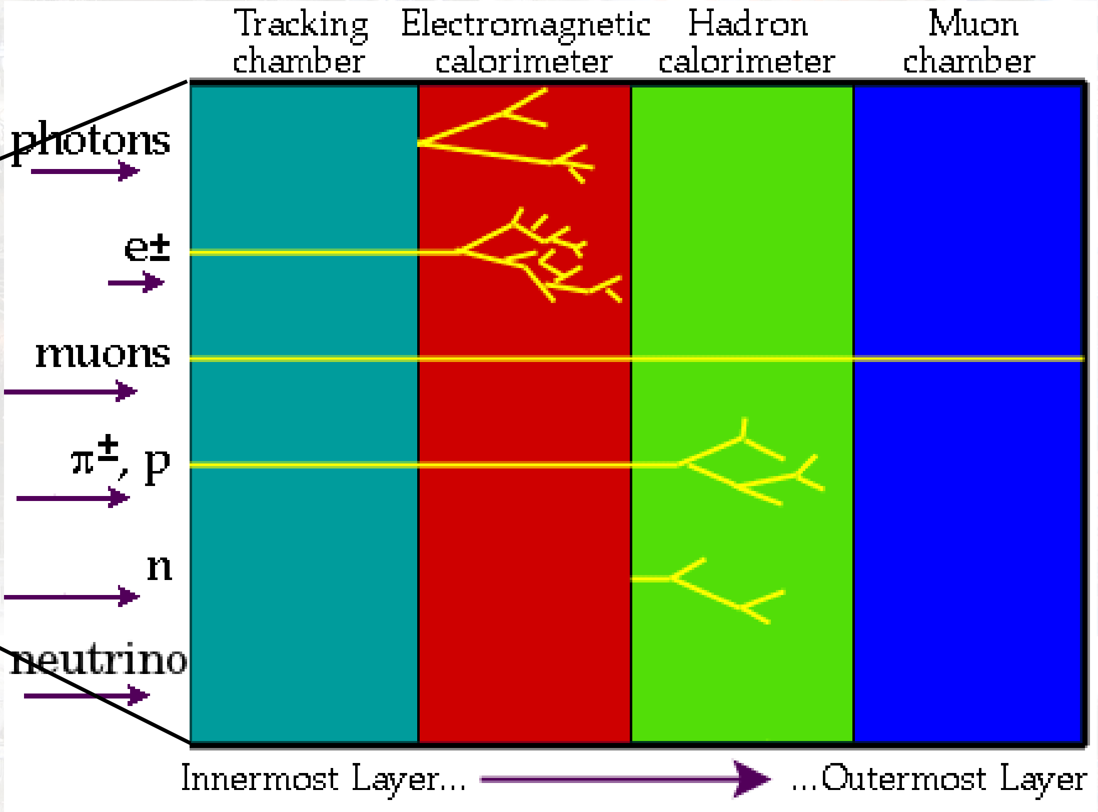


- In order to reconstruct this event, need to detect many particles: here, electron, muon, quarks, neutrinos

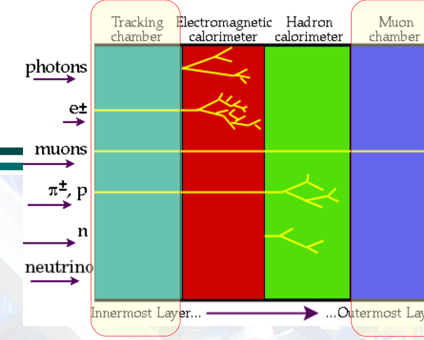
Detecting particles (2)

- Detectors surrounding the collision point

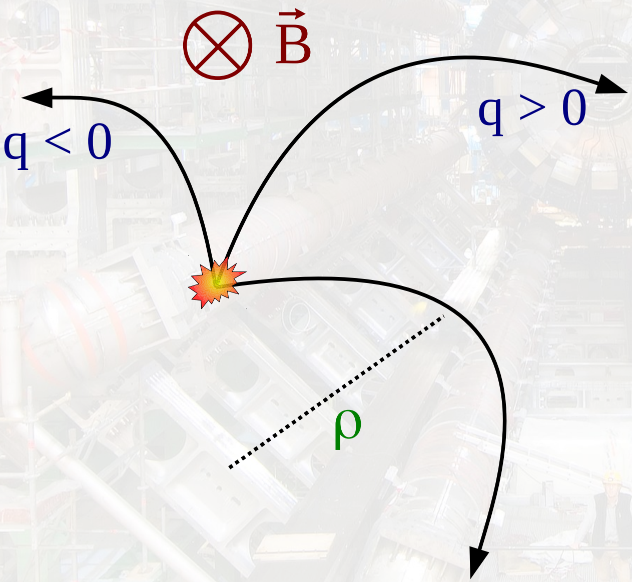




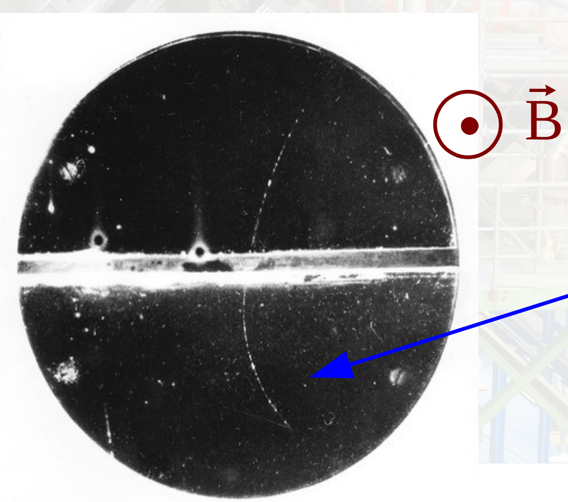
Tracking (1)



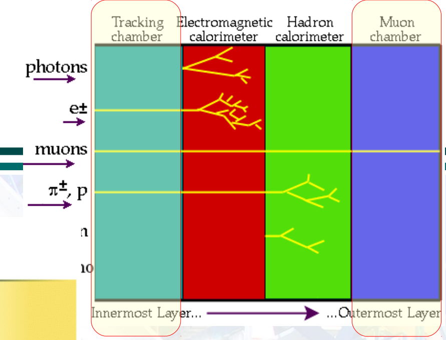
- Aim: measure momentum and charge of charged particles
- Principle: deviate particles in magnetic field:
  - $p = q.B.\rho$

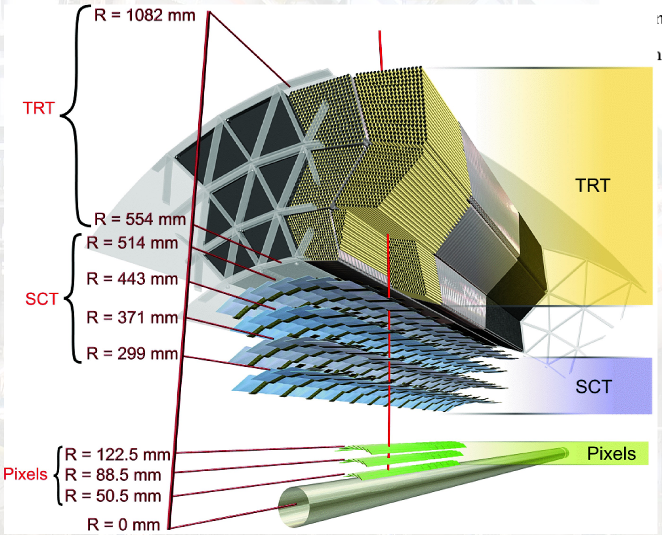


- Used to discover antimatter (1932):

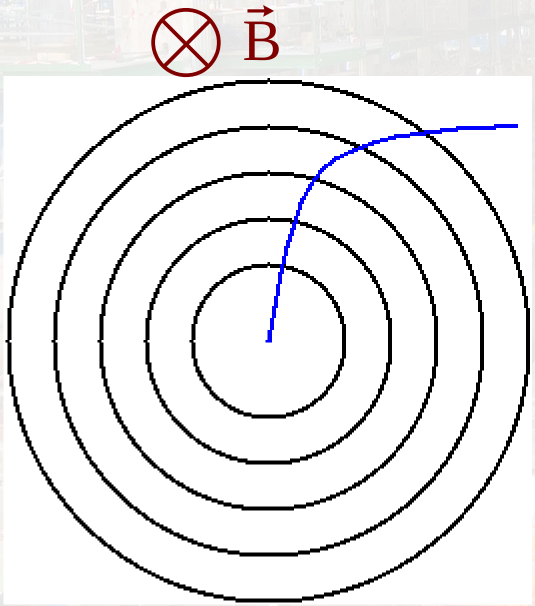


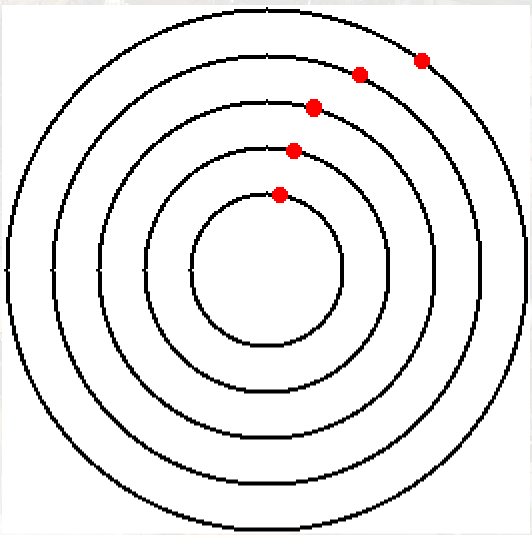
Tracking (2)





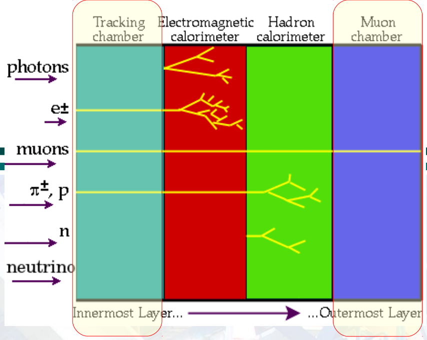
- ♦ Layers of finely segmented detectors with which the particles interact



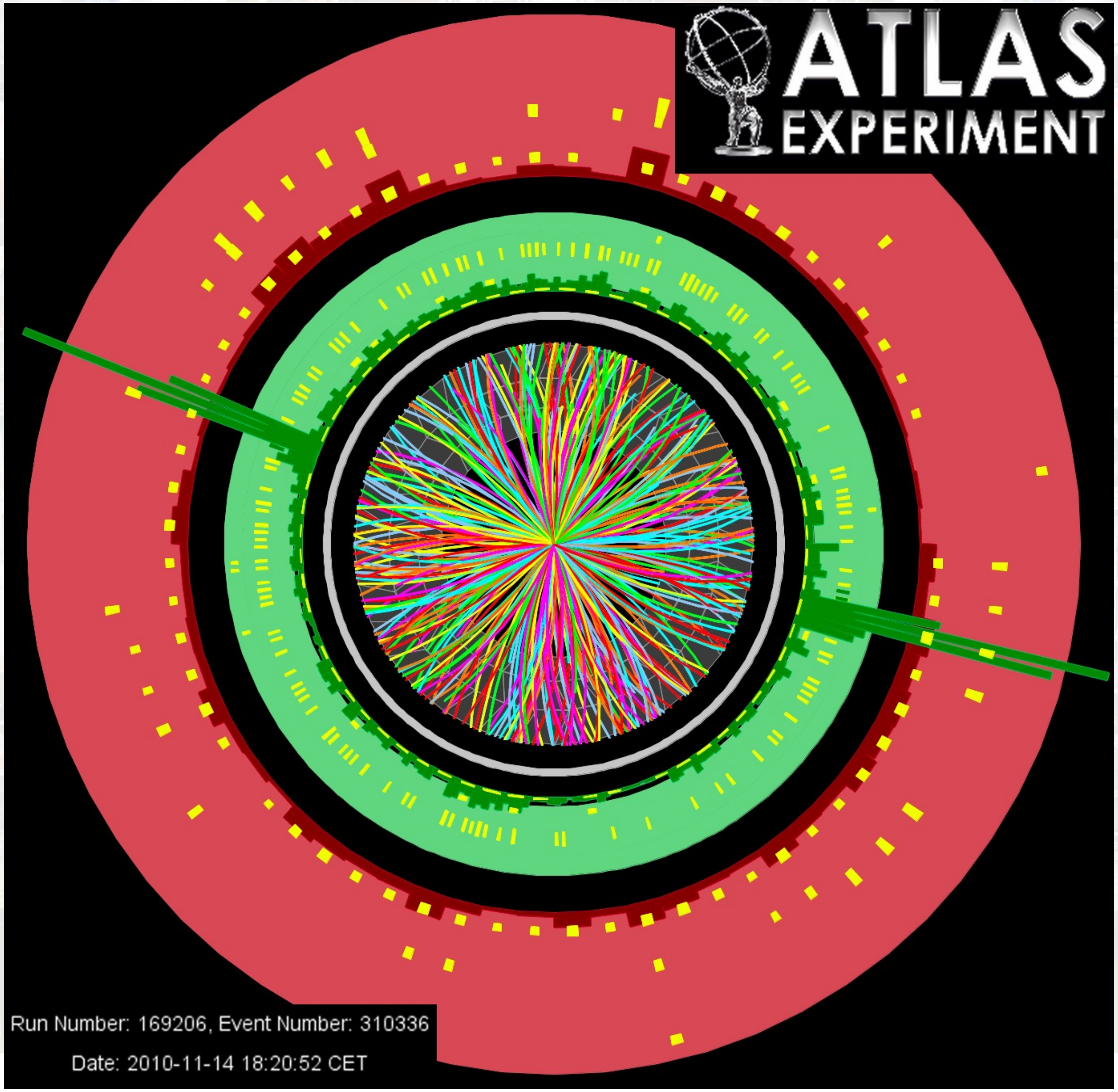


- ♦ Algorithms to reconstruct tracks from hits in the tracker layers

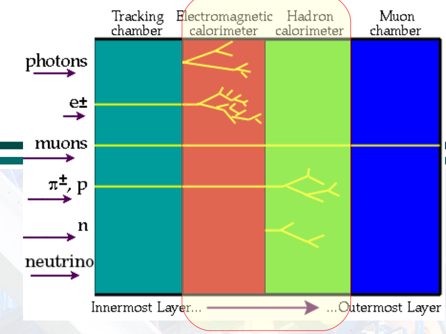
Tracking (3)



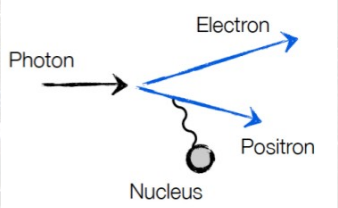
- Quite complicated when hundreds of tracks!

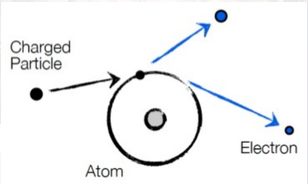


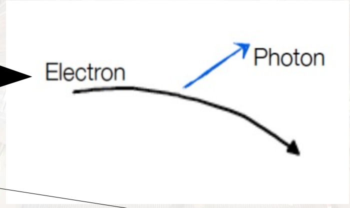
Calorimetry (1)

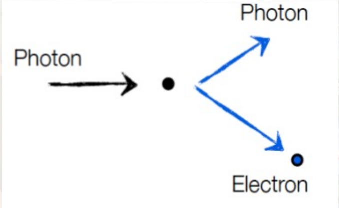


- <u>Aim</u>: measure energy of
  - electrons and photons (electromagnetic calorimeter)
  - quarks, gluons (hadronic calorimeter)
- <u>Principle</u>:
  - very dense material to stop particle completely *(absorber)*
  - measure energy lost by the particle *(active material)*
- Energy loss (= shower) by:
  - pair production
  - ionisation
  - bremsstrahlung
  - Compton scattering
  - nuclear interaction
  - ...



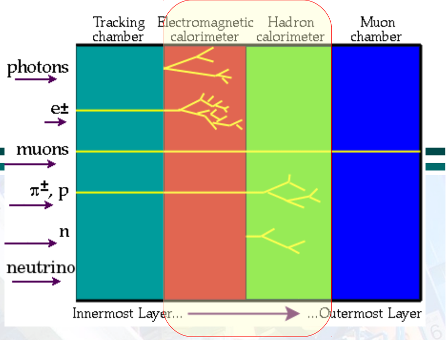




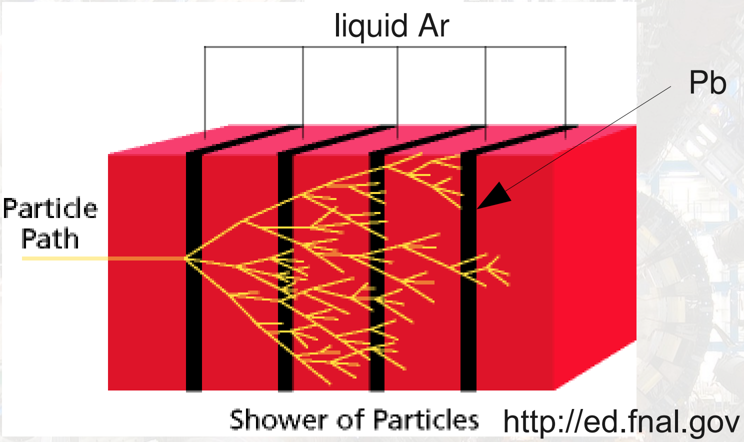


Pictures from D. Bortoletto

Calorimetry (2)

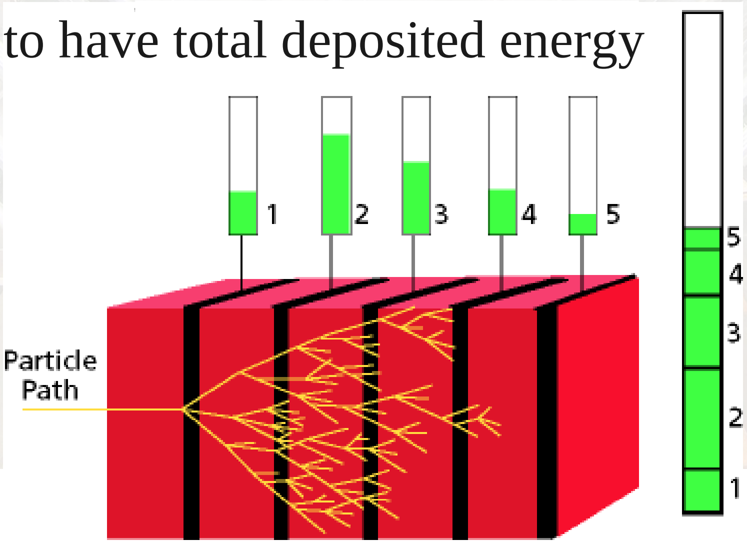


- Example: ATLAS electromagnetic calorimeter
  - sandwich of lead (*absorber*) and liquid Argon (*active material*)

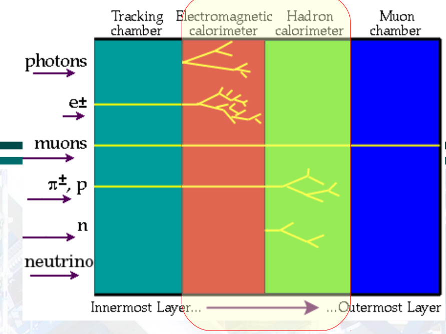


http://ed.fnal.gov

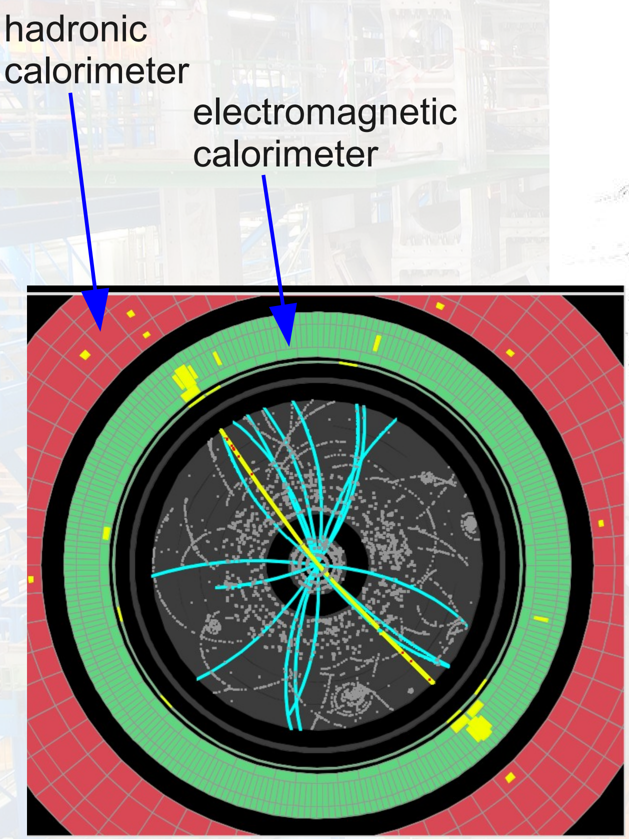
  - liquid Ar ionised and electrons derivate towards electrode ⇒ electrical signal
  - signals summed to have total deposited energy

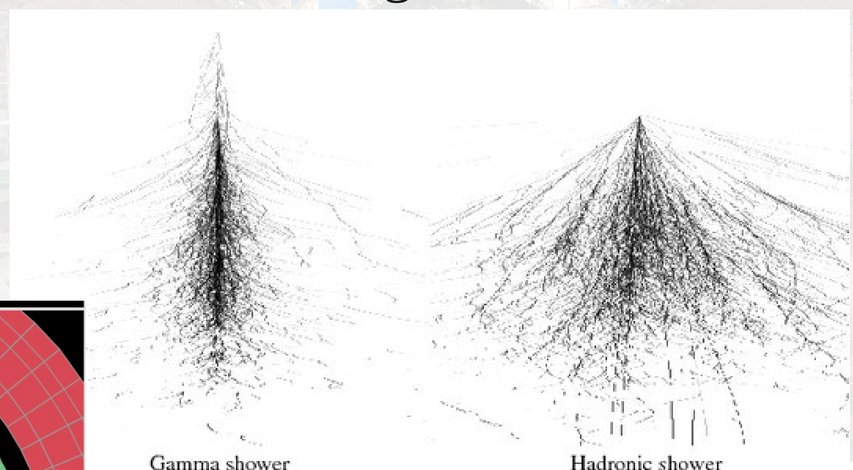


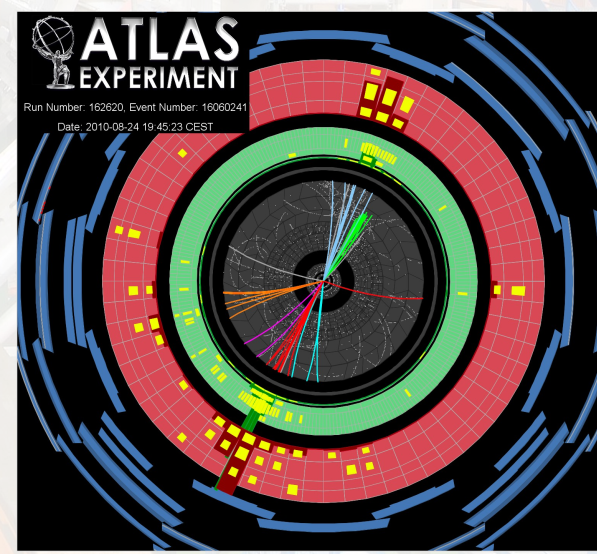
Particle identification



- Example: showers from quarks/gluons can fake showers from electrons/photons
  - orders of magnitude more quarks/gluons than electrons/photons
- Use shape of the shower to distinguish between both:







Computer processing (1)

- Before the 70's:

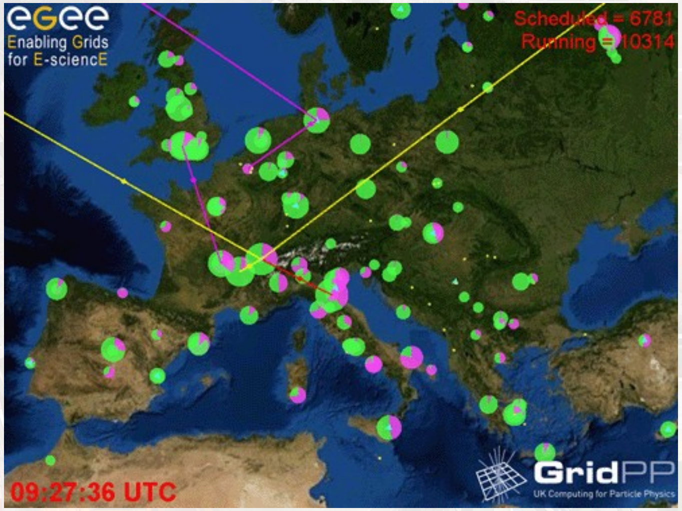
- Now: each event is processed and reconstructed by complex algorithms
  - 1 collision = 1 MB
  - 1 collision every 25 ns
    - 200 events/s stored
  - ~ 20 PB / year
  - to be stored and analysed

http://www.lhc-france.fr

Computer processing (2)

- 1989: web invented at CERN
  - to exchange information between physicists all around the world
  - http protocol, html, first web browser, ...

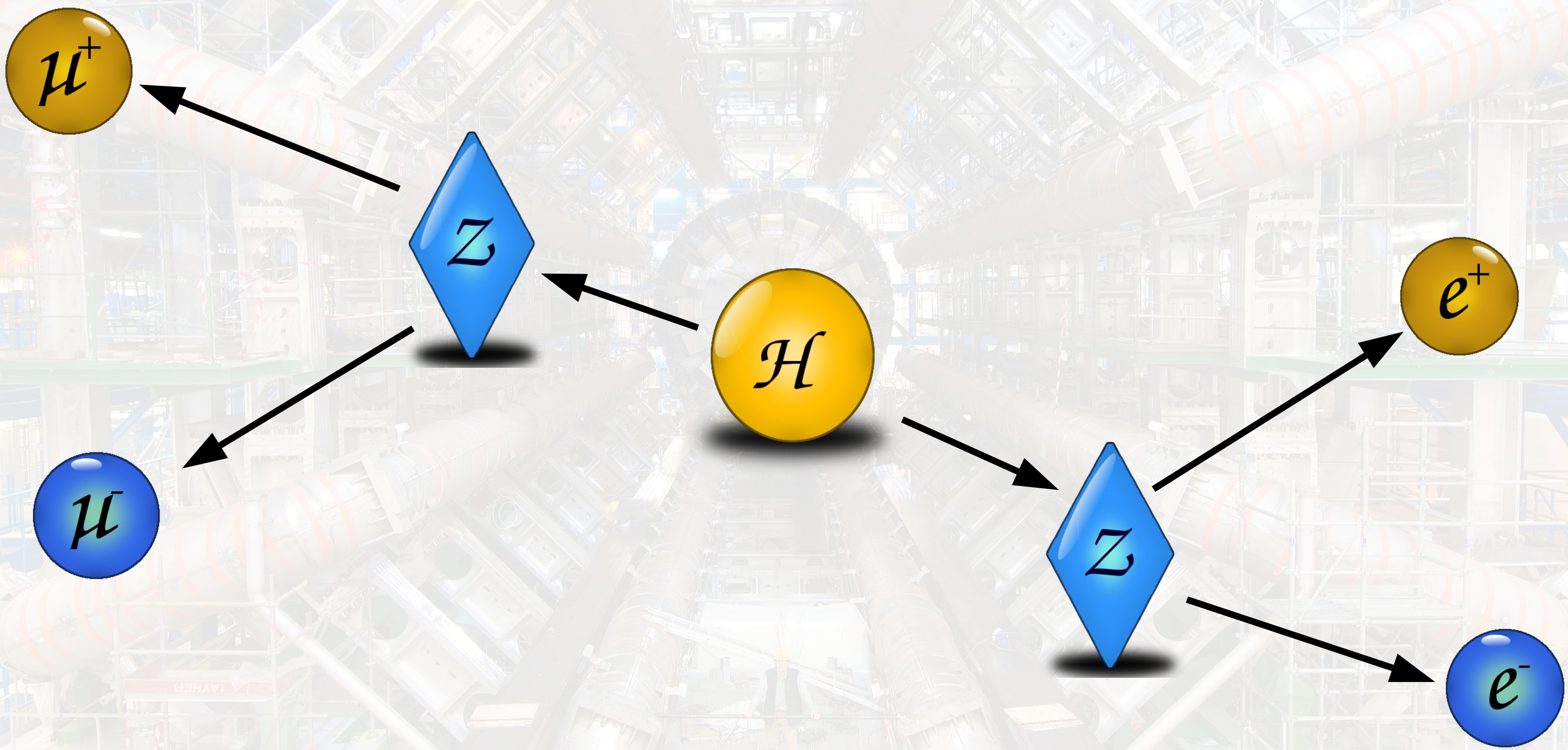
http://info.cern.ch/



- Now: Grid technology
  - data stored in many sites
  - analysis jobs sent to computers where the data is
  - output sent back to analyser
  - real time monitor: http://rtm.hep.ph.ic.ac.uk/webstart.php

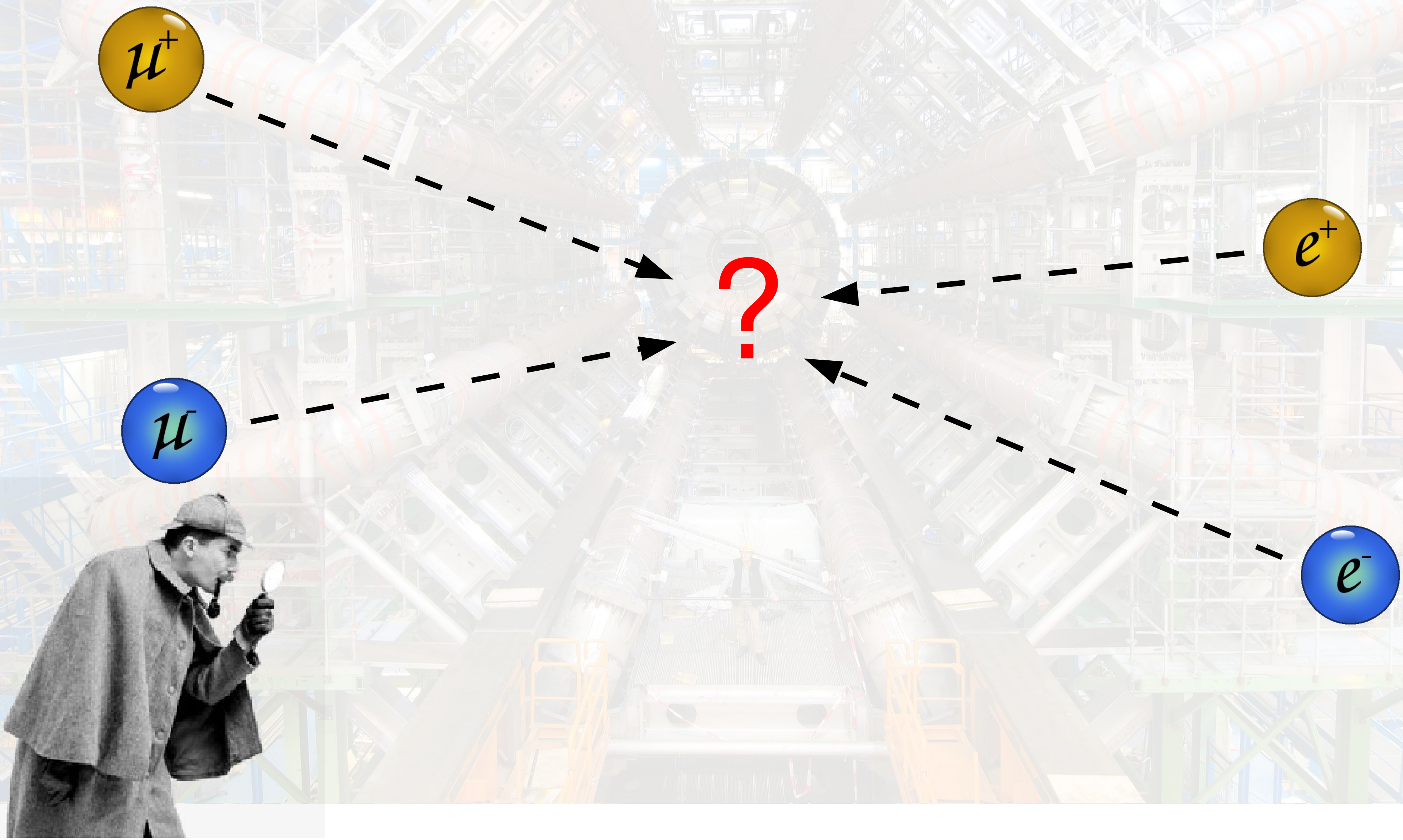
A LHC event (1)

- Example of $H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$ decay:



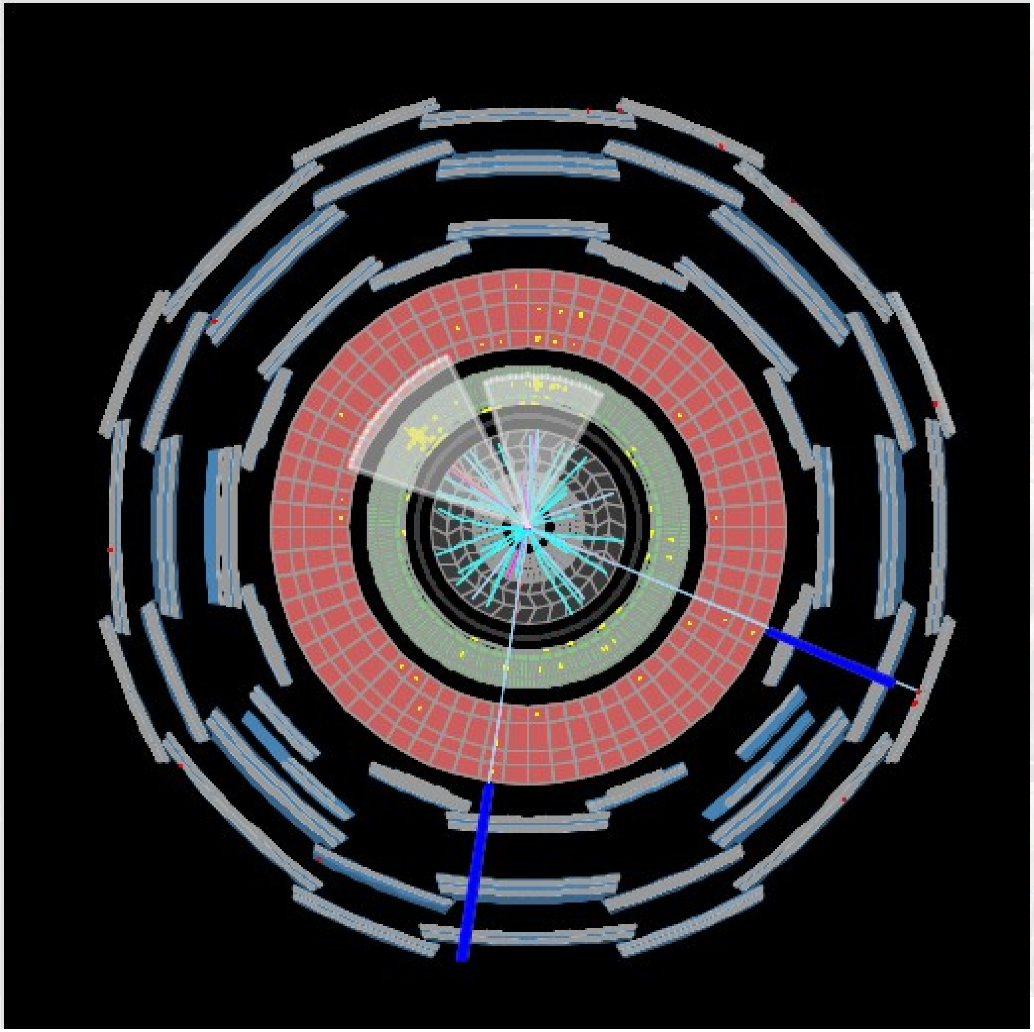
A LHC event (2)

- What we see in the detector:



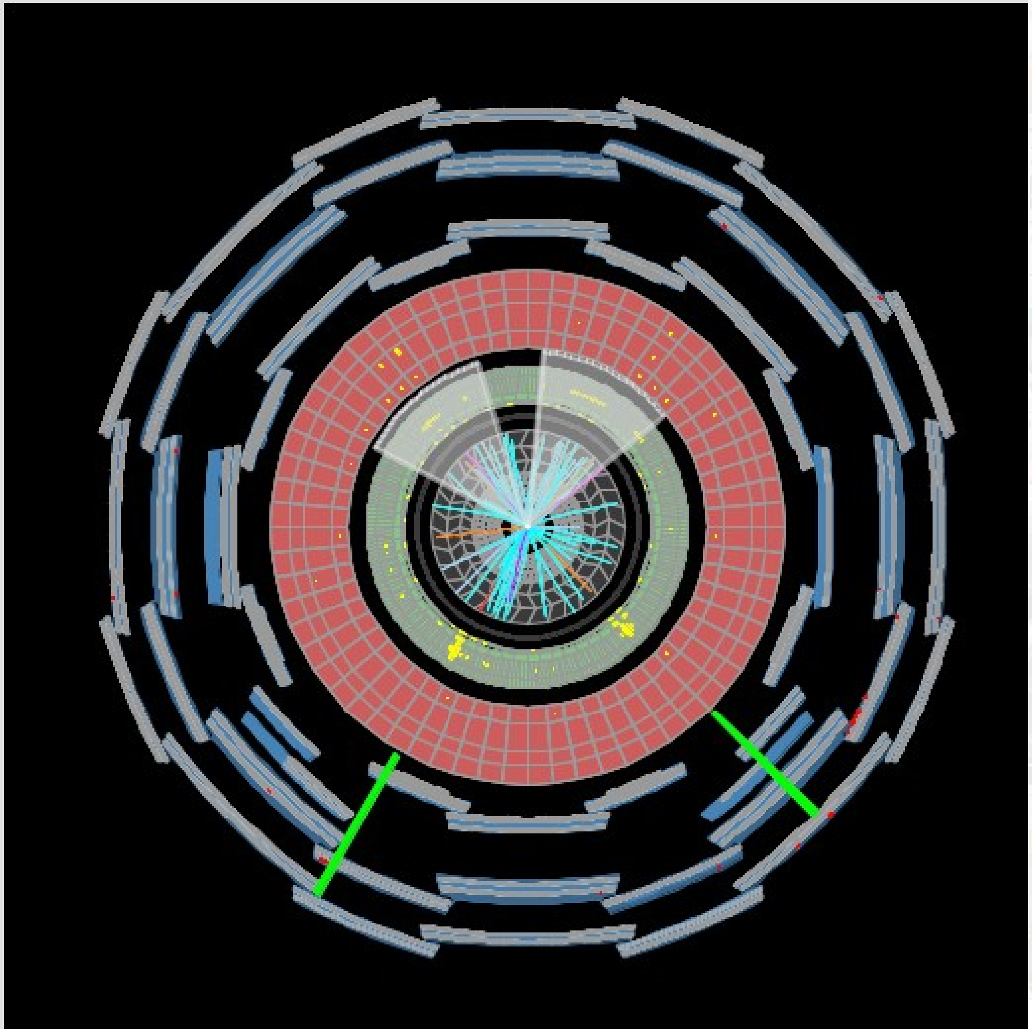
Step 1: Find interesting events

- We are looking for $e^+e^-\mu^+\mu^-$
- Is this event OK?



Step 1: Find interesting events

- We are looking for $e^+e^-\mu^+\mu^-$
- Or this one?



Step 1: Find interesting events

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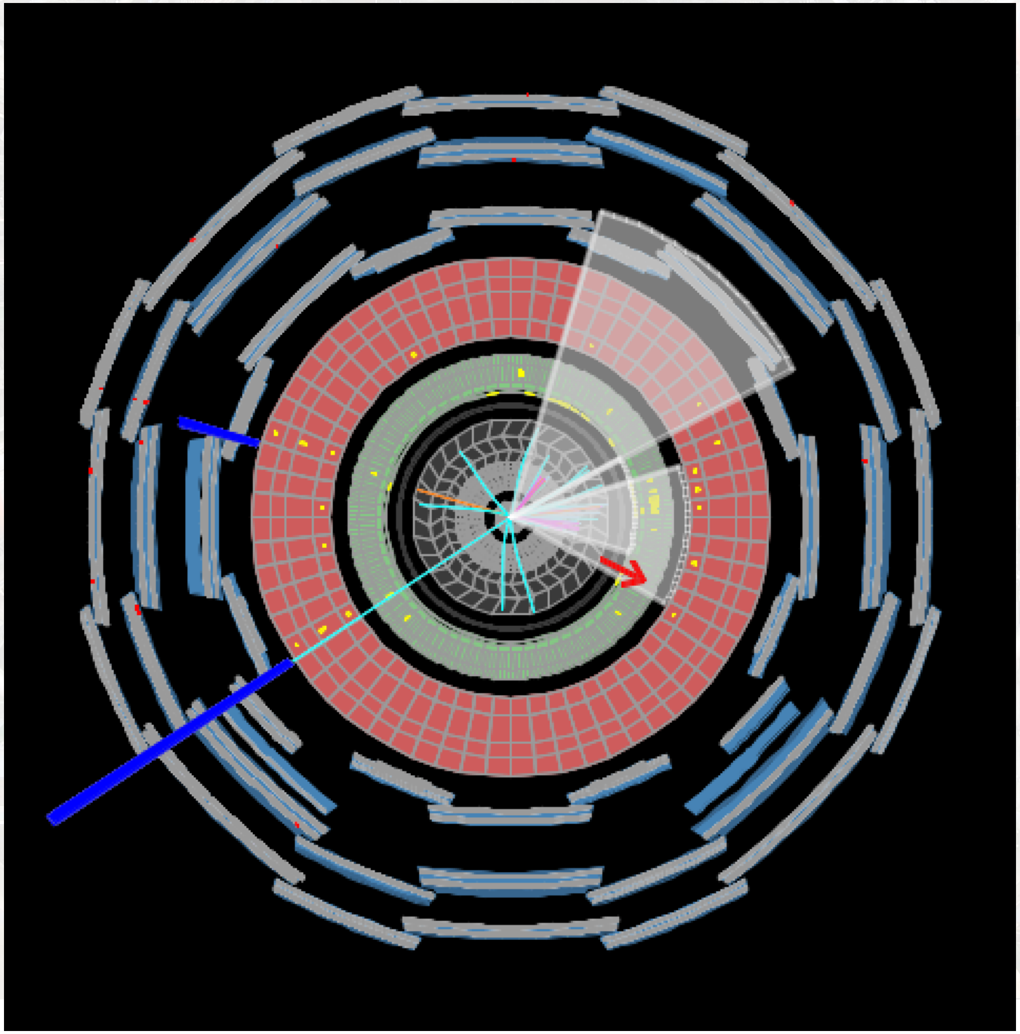
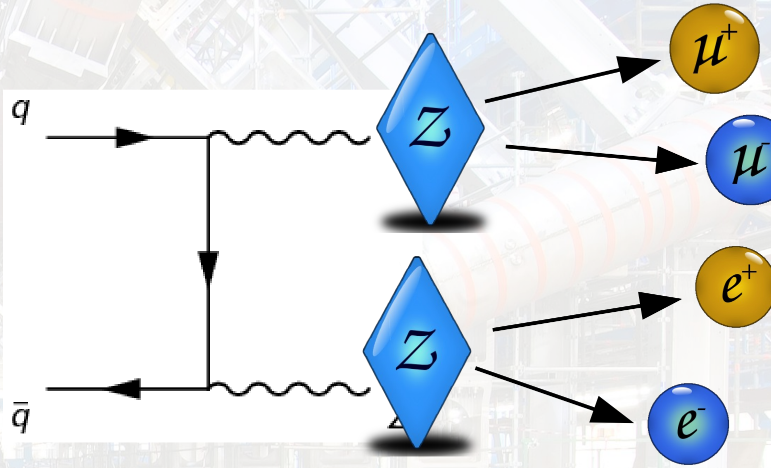


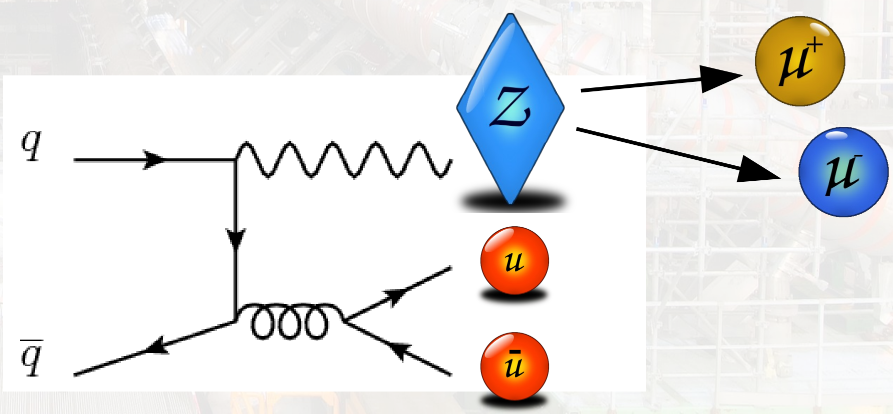
Signal and background

- Signal: $H \rightarrow ZZ \rightarrow e^{+}e^{-}\mu^{+}\mu^{-}$



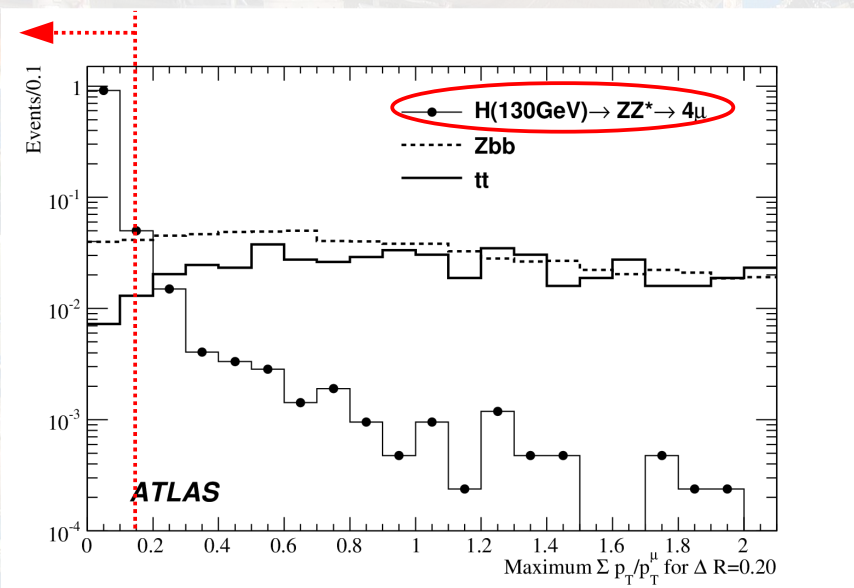
- Irreducible background:
  - exactly the same final state
  - ex.: ZZ not coming from Higgs

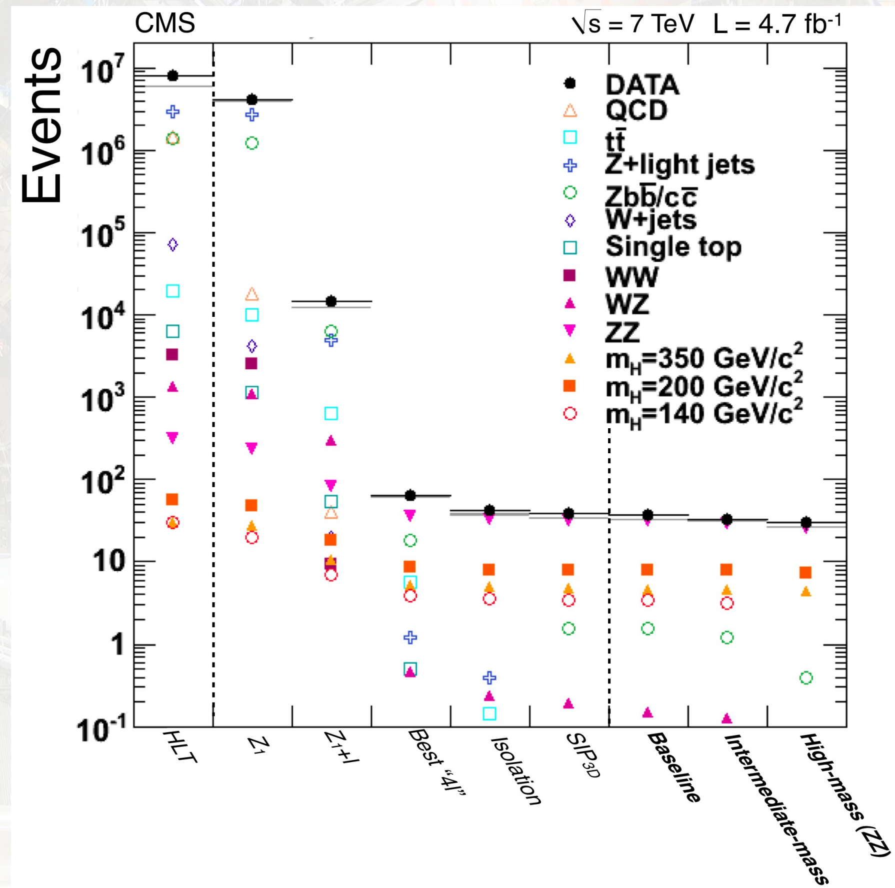
- Reducible background:
  - final state mimicking the signal
  - ex.: Z+2 quarks, $t\bar{t}$, etc



Selection cuts

- Cut on particle kinematics, event shape, etc, to distinguish signal from background
- Example:



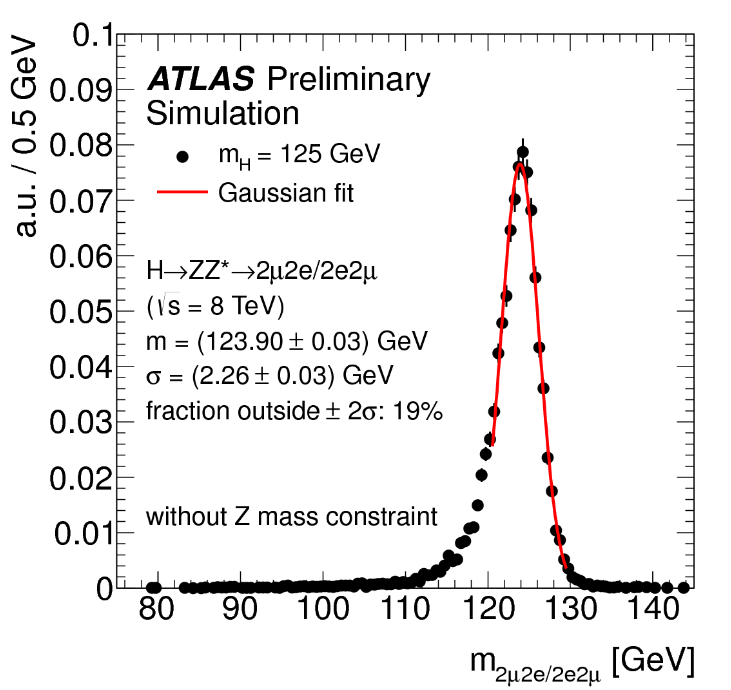


- Try to keep signal while removing background (ie increase S/B)

Step 2: Reconstruct initial particle

- We have 4 particles with their energy (calorimeters), charge and momentum (tracker)
- Use pairs of opposite sign e^+e^- and $\mu^+\mu^-$
- Reconstruct invariant mass from the 4 particles:

$$M^2 = (E_1 + E_2 + E_3 + E_4)^2 - \|\vec{p}_1 + \vec{p}_2 + \vec{p}_3 + \vec{p}_4\|^2$$



That's all for today!