LHC at CERN laboratory

CERN: the world's largest particle physics laboratory
- international organisation created in 1953/1954, initial membership: 12 countries
- Poland is a member starting from year 1991
- About 10 000 active physicists, computing scientists, engineers

situated between
Jura mountains and Geneva
(France/Swiss)

http://public.web.cern.ch

The full LHC accelerator complex

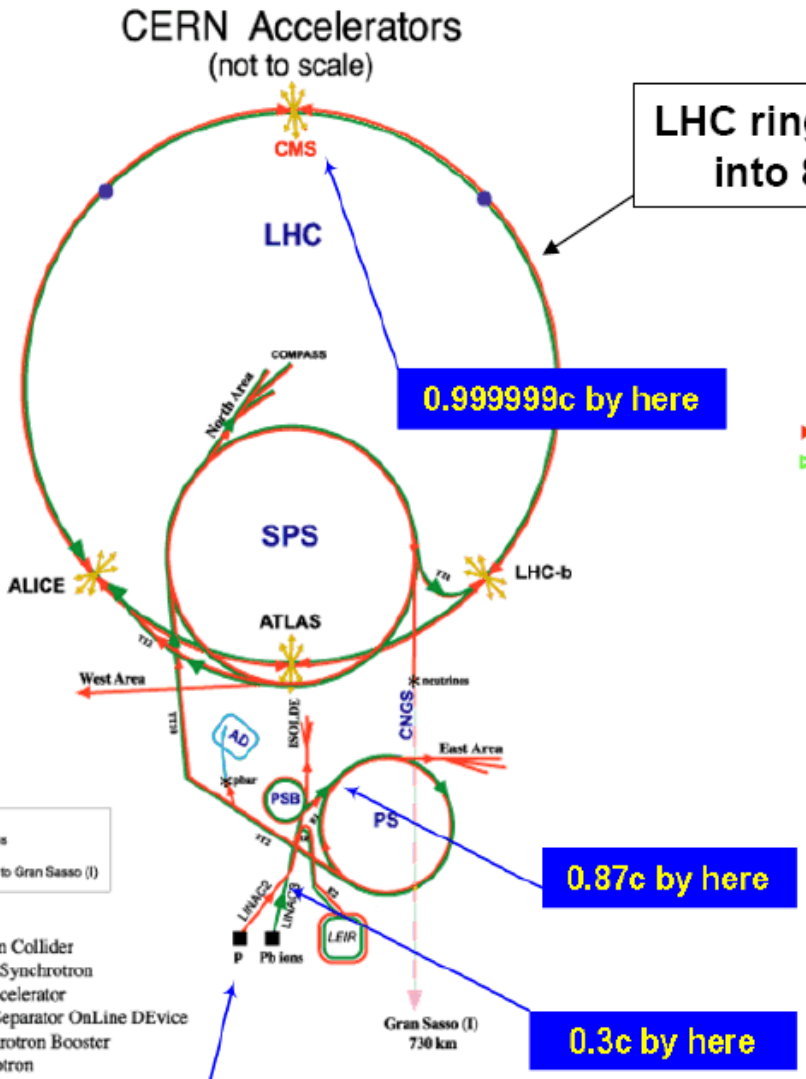
Linac

Booster

PS

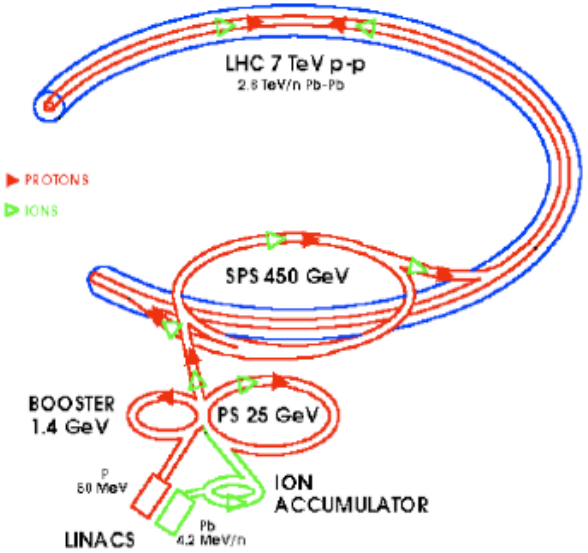
SPS

LHC



LHC ring is divided into 8 sectors

0.999999c by here



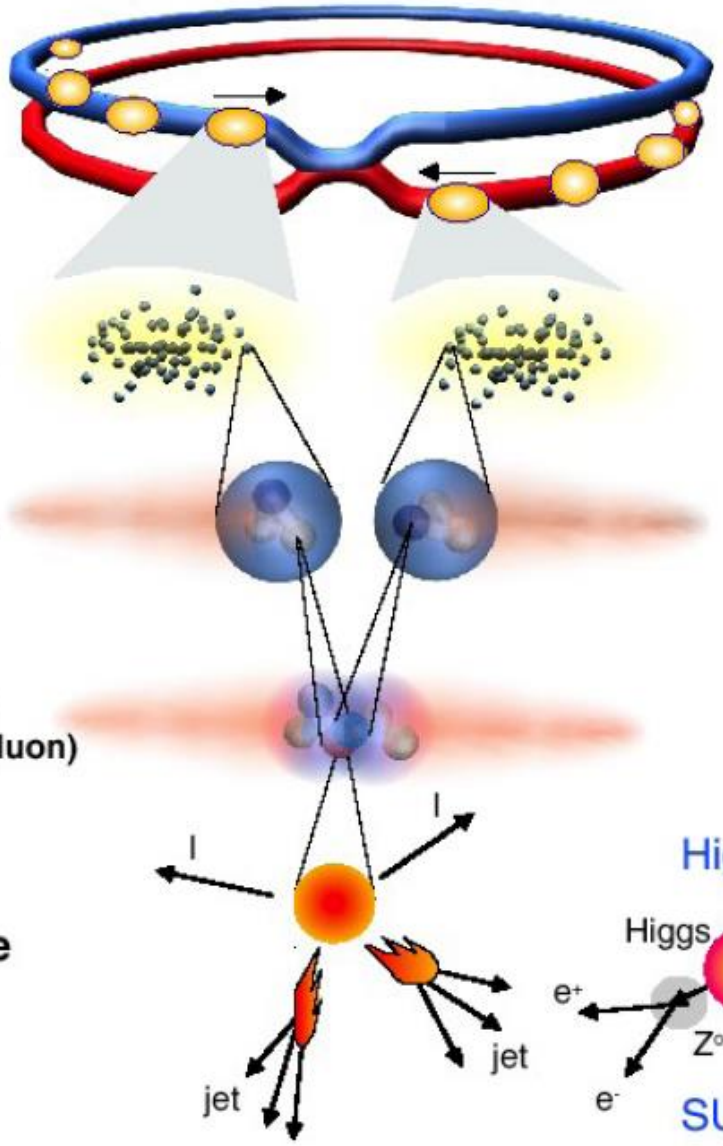
0.87c by here

0.3c by here

Start the protons out here

> 50 years of CERN history still alive and operational

Collisions at LHC

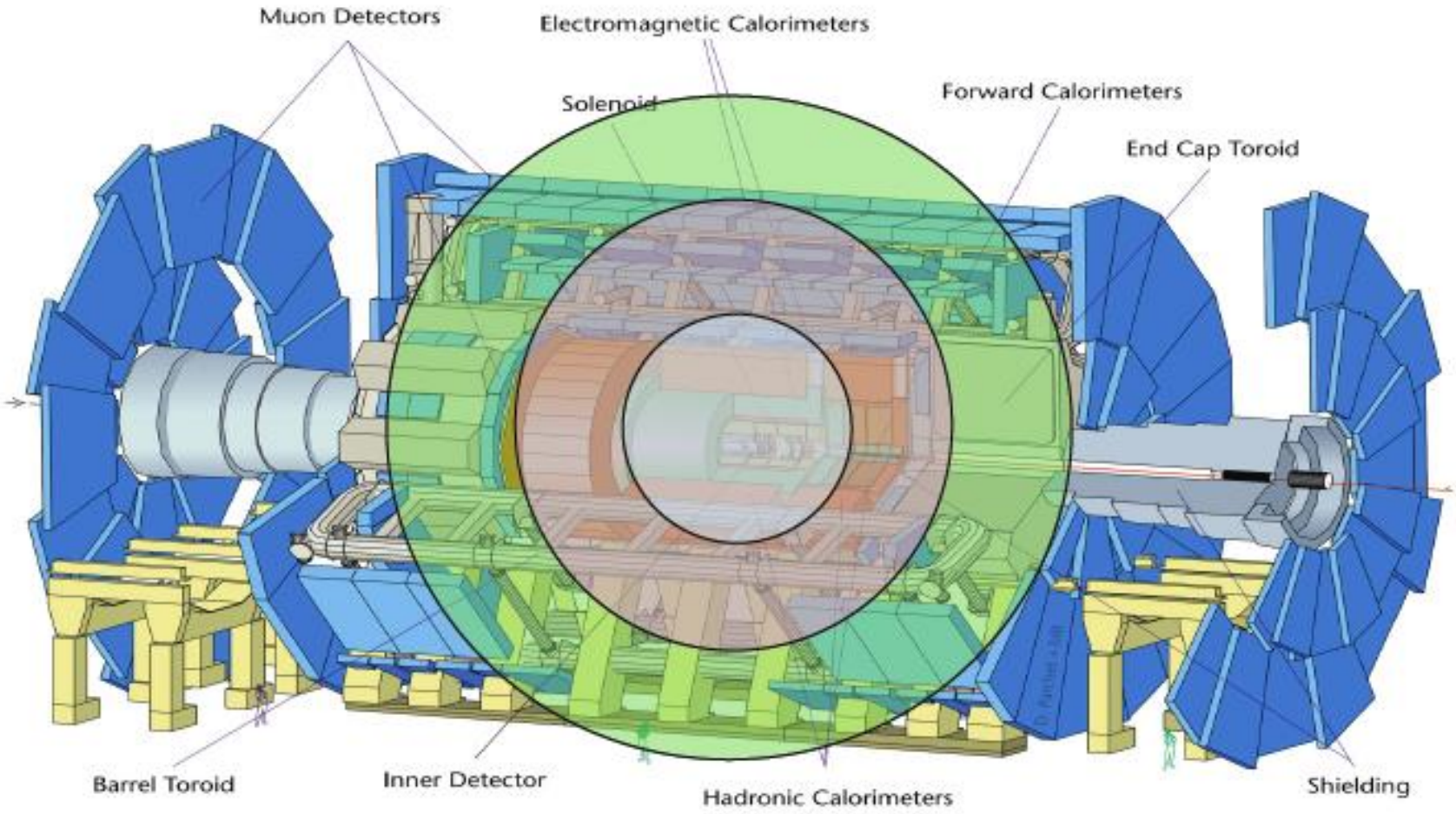


Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

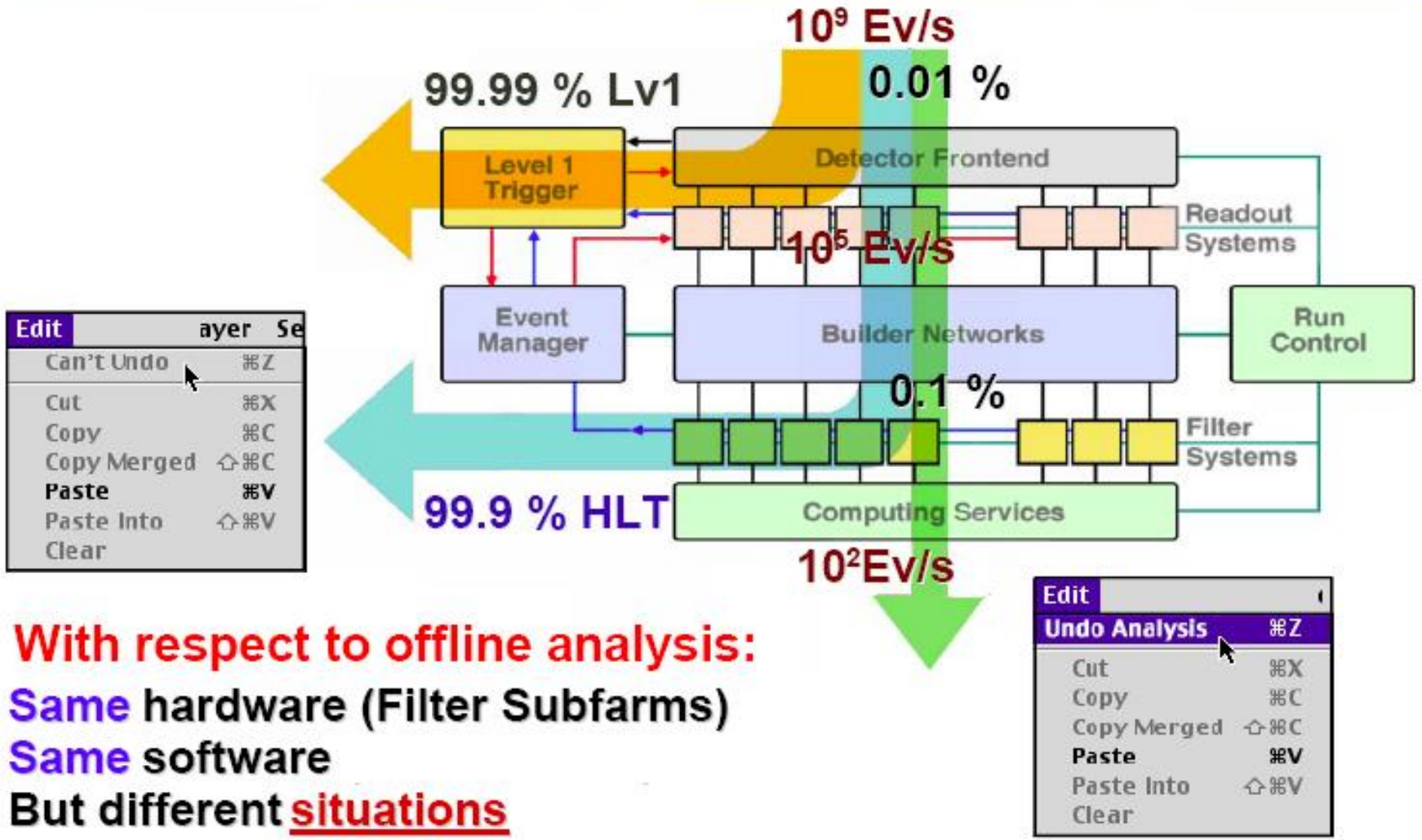
Selection of 1 in
10,000,000,000,000

Time of Flight

c=30cm/ns; in 25ns, s=7.5m



Trigger



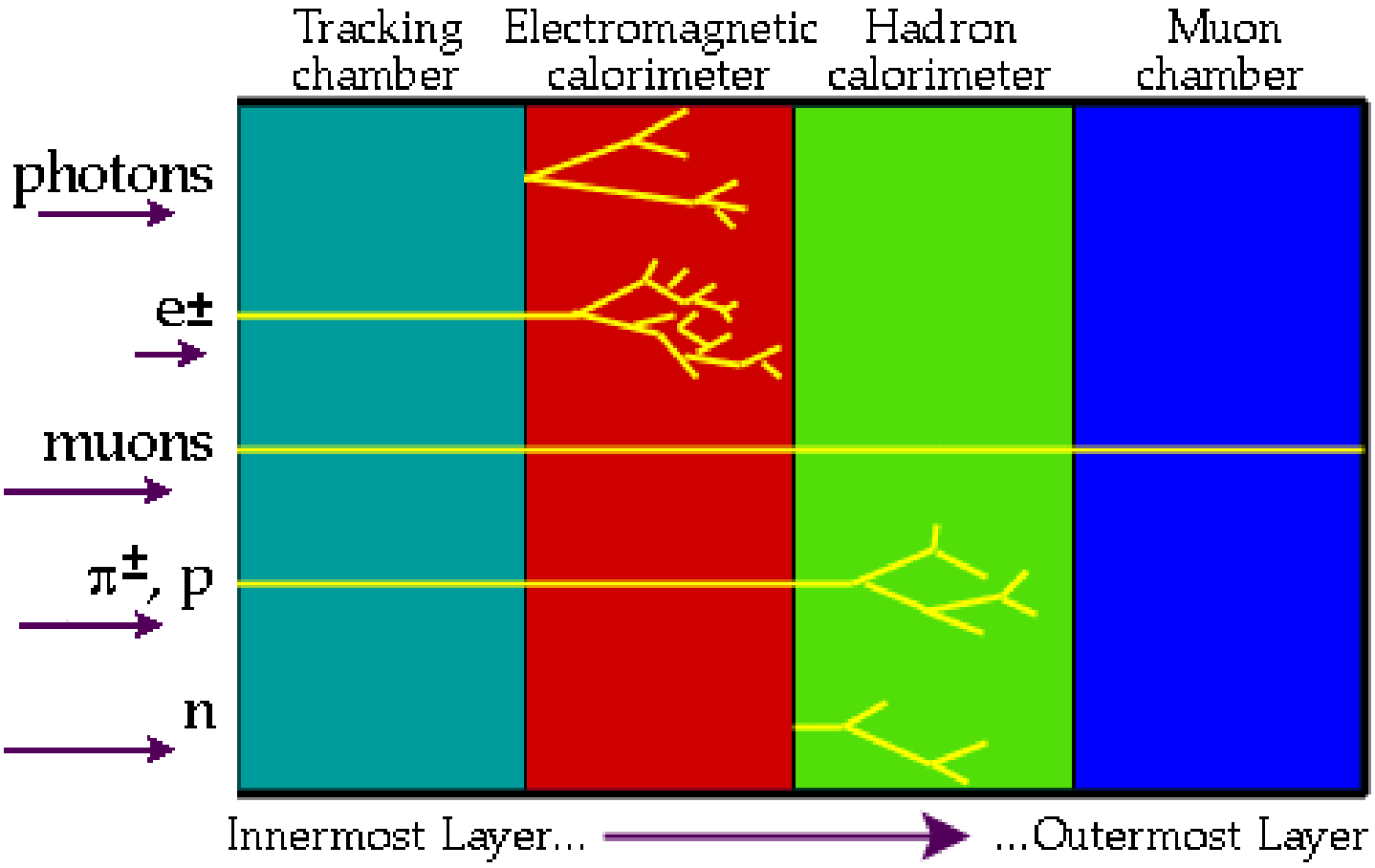
With respect to offline analysis:

Same hardware (Filter Subfarms)

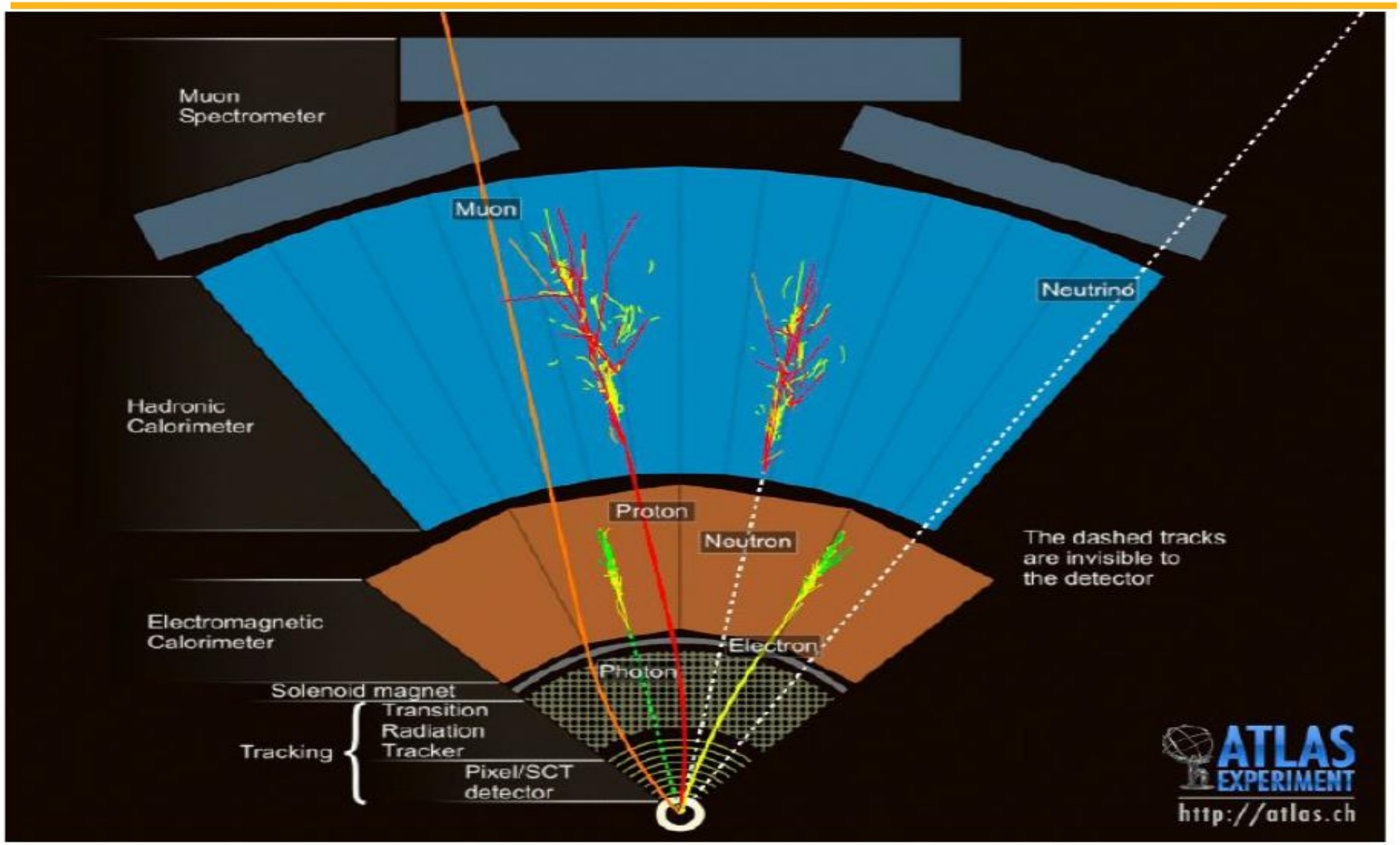
Same software

But different **situations**

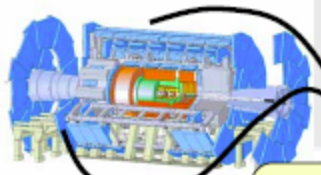
General purpose detectors



Particle identication



Data Flow for Physics Analysis



detector

event filter (selection & reconstruction)

reconstruction

event data

processed data

100%

raw data

10%

batch physics analysis

event reprocessing

analysis

1%

analysis objects (extracted by physics topic)

event simulation

simulation

interactive physics analysis

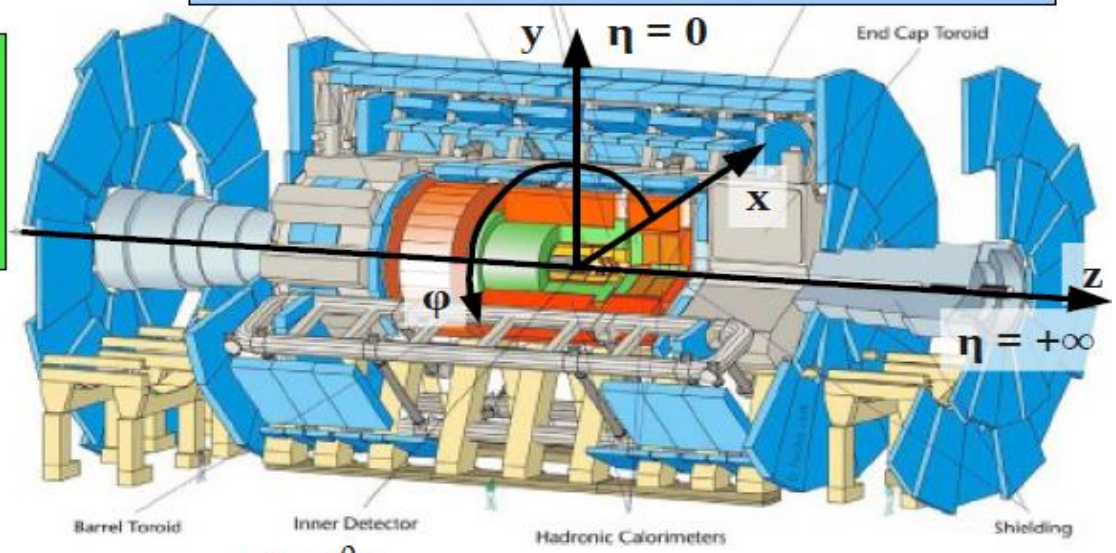
ATLAS Detector

Inner detector (2 T)
$|\eta| < 2.5$
Si Pixel et SCT, TRT
tracks, vertex
$\sigma/p_T \sim 0.05\% \; p_T \text{ (GeV)} \oplus 1\%$

Electromagnetic calorimeter
$|\eta| < 3.2$
Pb + LAr
electrons, photons, trigger
$\sigma/E \sim 10\%/\sqrt{E} \text{ (GeV)} \oplus 0.7\%$

Hadronic calorimeter
$|\eta| < 4.9$
Fe/Tile (central)
Cu/W + LAr (forward)
jets, E_T^{miss}, trigger
$\sigma/E \sim 50\%/\sqrt{E} \text{ (GeV)} \oplus 3\%$

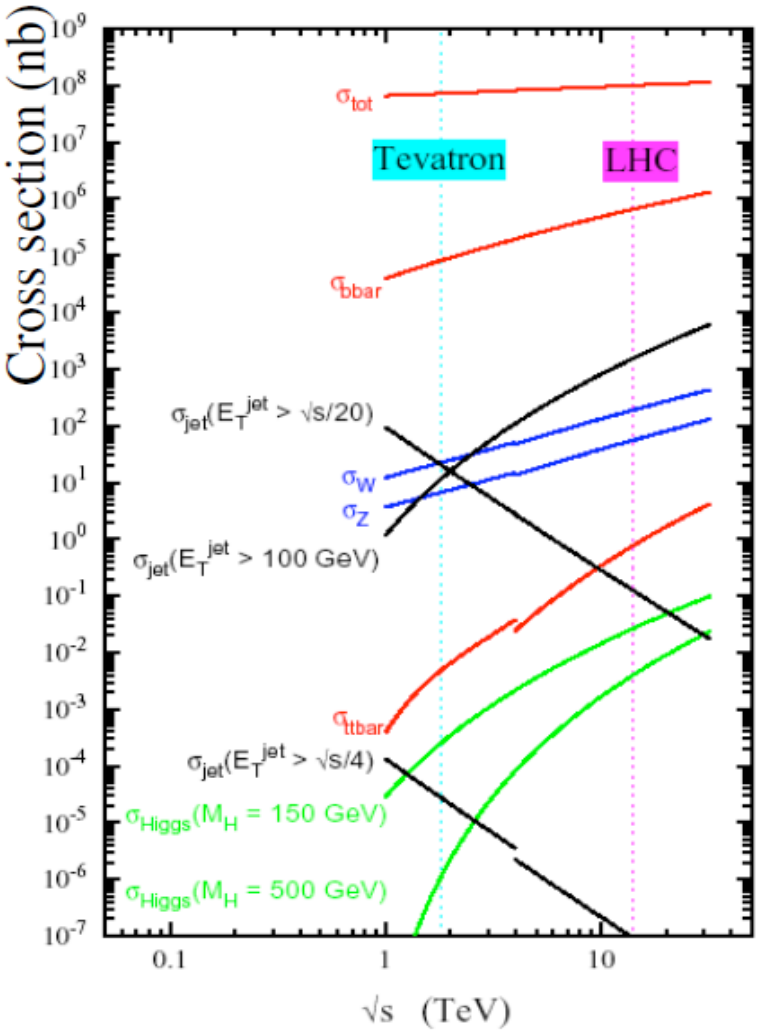
Muon spectrometer (0.5 T)
$|\eta| < 2.7$
gas chamber in toroidal magnetic field
tracks, trigger
$\sigma/p_T < 10\%$ up to 1 TeV



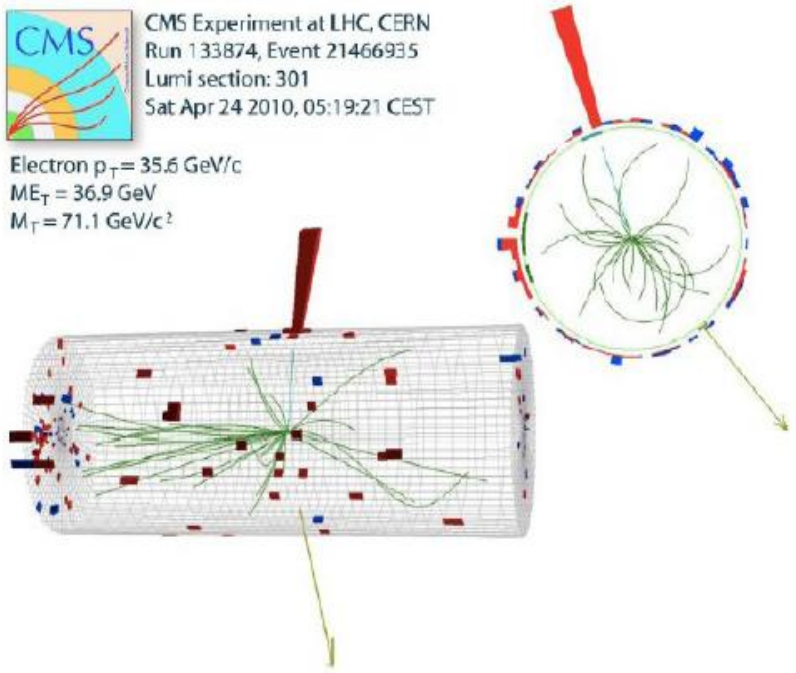
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Cross-sections at LHC

- A lot more “uninteresting” than “interesting” processes at design luminosity (L = $10^{34}cm^{-2}s^{-1}$)
  - Any event: 10^9/sec
  - W boson: 150/sec
  - Top quark: 8/sec
  - Higgs (125GeV): 0.2/sec
- Interesting events gets selected:
  I. trigger (decision!)
  II. physics analysis (selection)

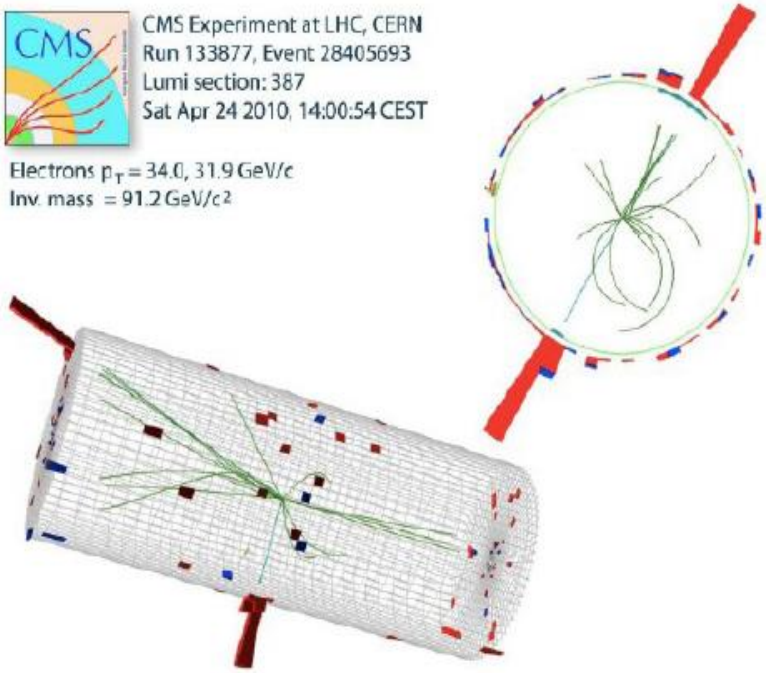


Electron channel W and Z events



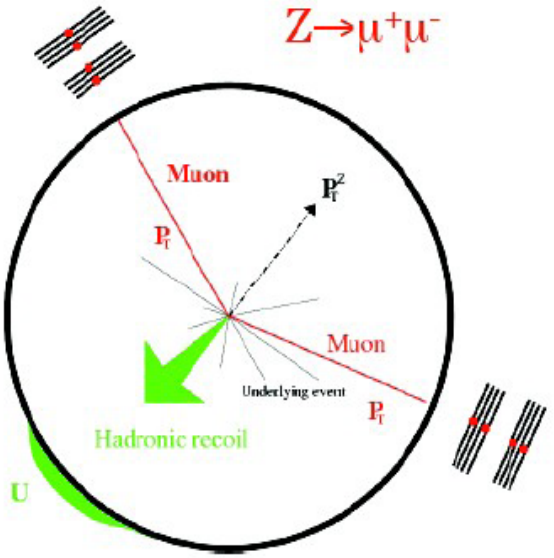
$W \rightarrow e\nu$

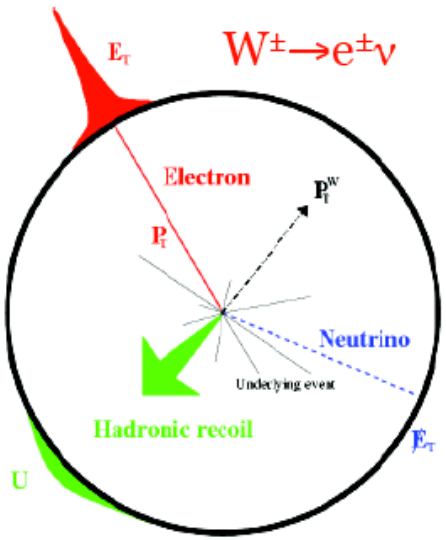
$Z \rightarrow ee$



Detecting W and Z

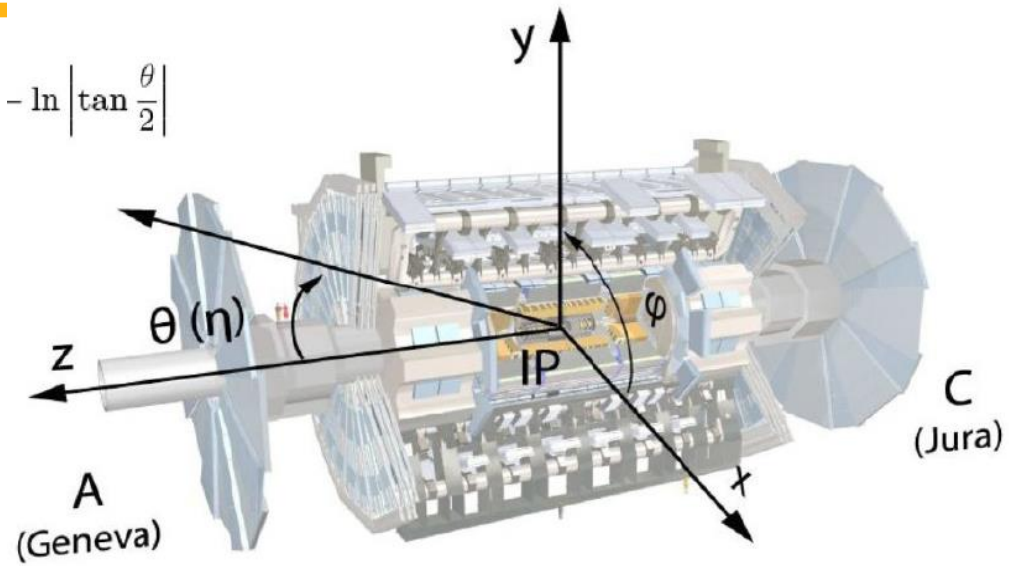
- $Z \rightarrow l^+l^-$
  - **Signature:** pair of charged leptons with opposite sign charge
    - Leptons are high p_T and isolated
  - Peak in l^+l^- invariant mass





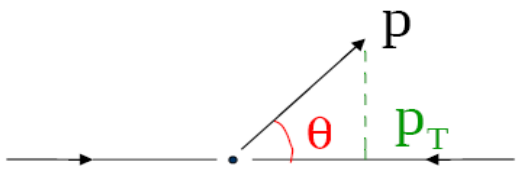
- $W \rightarrow l^{\pm}\nu^{\pm}$
  - **Signature:** single charged lepton and missing transverse energy (MET)
    - Leptons are high p_T and isolated
    - MET from neutrino
      - $p_T\nu$ is inferred
  - Peak in transverse invariant mass

ATLAS Detector



THE ATLAS DETECTOR IS REALLY BIG!

- Length : ~ 46 m
- Radius : ~ 12 m
- Weight : ~ 7000 tons
- ~ 10^8 electronic channels
- 3000 km of cables



Transverse momentum

(in the plane perpendicular to the beam)

$p_T = p \sin\theta$

Rapidity: $\eta = -\log(\mathrm{tg}\,\frac{\theta}{2})$

$\theta = 90^\circ \rightarrow \eta = 0$

$\theta = 10^\circ \rightarrow \eta \cong 2.4$

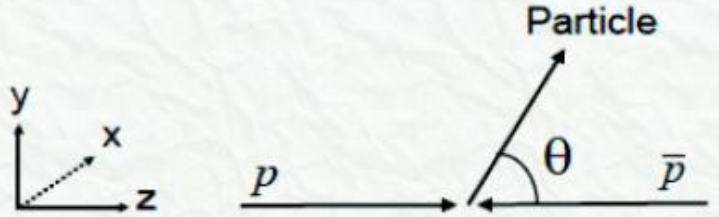
$\theta = 170^\circ \rightarrow \eta \cong -2.4$

Some kinematic distributions

Rapidity (y) and Pseudo-rapidity (η)

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

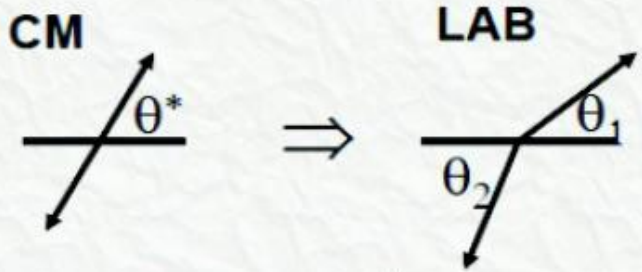
$$\beta\cos\theta = \tanh y \quad \text{where} \quad \beta = p/E$$



In the limit $\beta \to 1$ (or $m << p_T$) then

$$\eta \equiv y\big|_{m=0} = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

LAB System ≠ parton-parton CM system



Δη and p_T are invariant under longitudinal boosts

Some kinematic definitions

Transverse Energy/Momentum

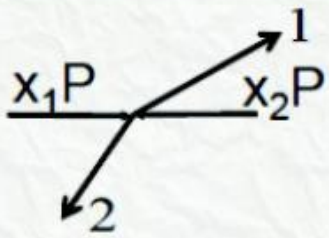
$$E_T^2 \equiv p_x^2 + p_y^2 + m^2 = p_T^2 + m^2 = E^2 - p_z^2$$

$$p_z = E \tanh y$$
$$E = E_T \cosh y$$
$$p_z = E_T \sinh y$$

$$p_T \equiv p \sin\theta \xrightarrow[m \to 0]{} E_T$$

Invariant Mass

$$M_{12}^2 \equiv (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu})$$
$$= m_1^2 + m_2^2 + 2(E_1 E_2 - \boldsymbol{p}_1 \cdot \boldsymbol{p}_2)$$
$$\xrightarrow[m_1, m_2 \to 0]{} 2E_{T1}E_{T2}(\cosh\Delta\eta - \cos\Delta\phi)$$



Partonic Momentum Fractions

$$x_1 = \left(e^{\eta_1} + e^{\eta_2}\right) E_T / \sqrt{s}$$
$$x_2 = \left(e^{-\eta_1} + e^{-\eta_2}\right) E_T / \sqrt{s}$$

$$x_T \equiv 2E_T / \sqrt{s} = x_{1,2}(\eta_{1,2} = 0)$$

Parton CM $(\text{energy})^2 \rightarrow \hat{s} = x_a x_b s$

$$0 < x_1, x_2 < 1$$
$$x_T^2 < x_1 x_2 < 1$$

Energy and momentum resolution

Calorimetry:

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

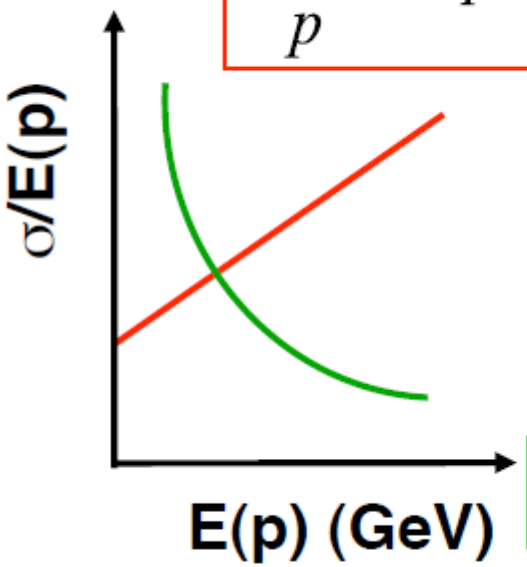
a the stochastic term accounts for Poisson-like fluctuations
- naturally small for homogeneous calorimeters
- takes into account sampling fluctuations for sampling calorimeters

b the noise term (hits at low energy)
- mainly the energy equivalent of the electronics noise
- at LHC in particular: includes fluctuation from non primary interaction (pile-up noise)

c the constant term (hits at high energy)
- Essentially detector non homogeneities like intrinsic geometry, calibration but also energy leakage

Tracking

$$\frac{\sigma(p)}{p} = ap \oplus b$$



$$\frac{\sigma(E)}{E} \approx \frac{a}{\sqrt{E}}$$

Calorimetry