LHC at CERN laboratory

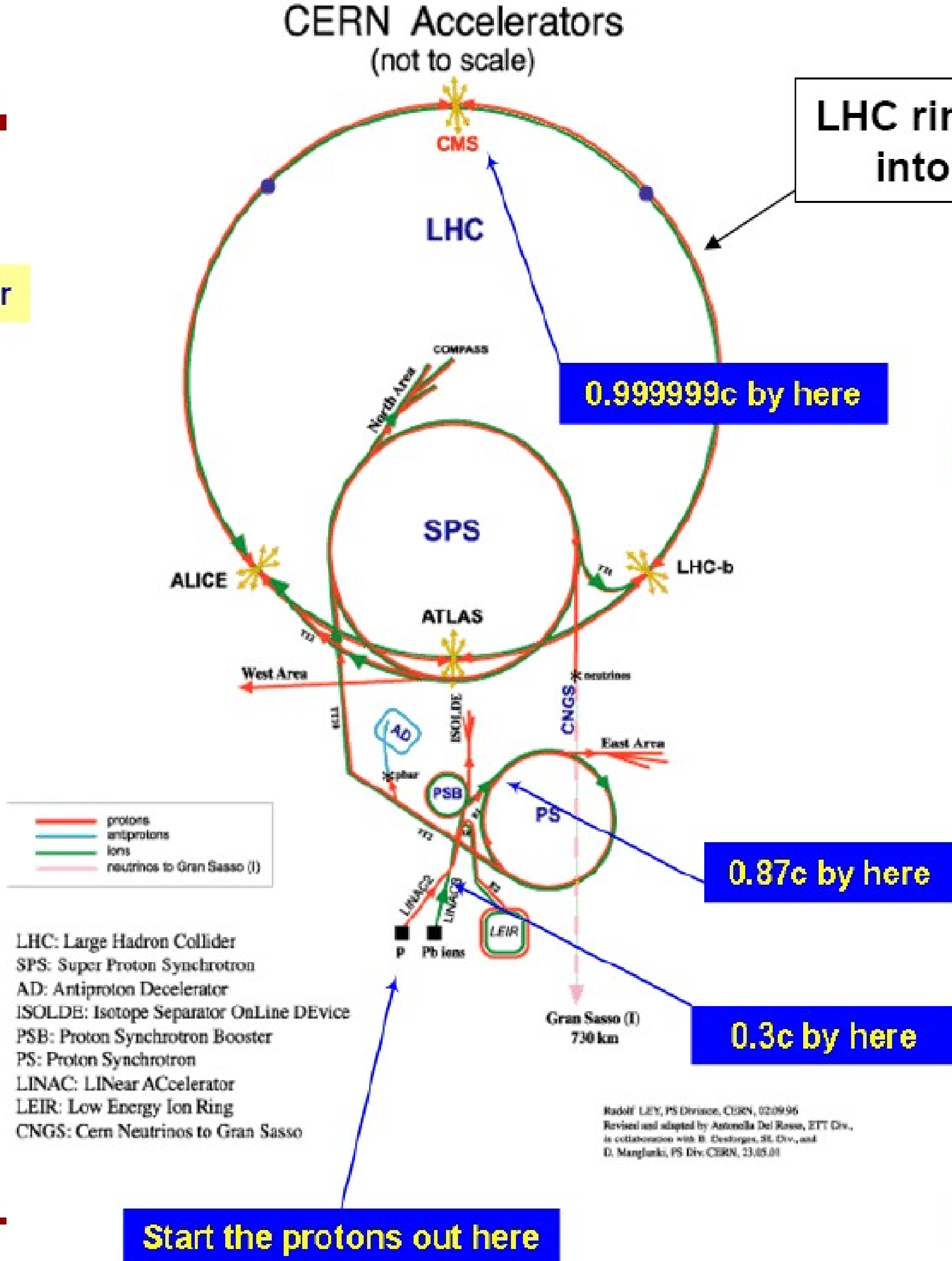
CERN: the world's largest particle physics laboratory
- international organisation created in 1953/1954, initial membership: 12 countries
- Poland is a member starting from year 1991
- About 10 000 active physicists, computing scientists, engineers

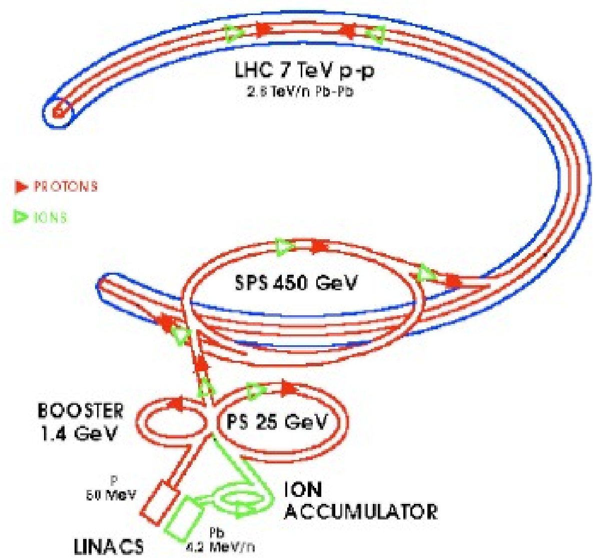
situated between
Jura mountains and Geneva
(France/Swiss)

http://public.web.cern.ch

The full LHC accelerator complex

Linac
↓
Booster
↓
PS
↓
SPS
↓
LHC

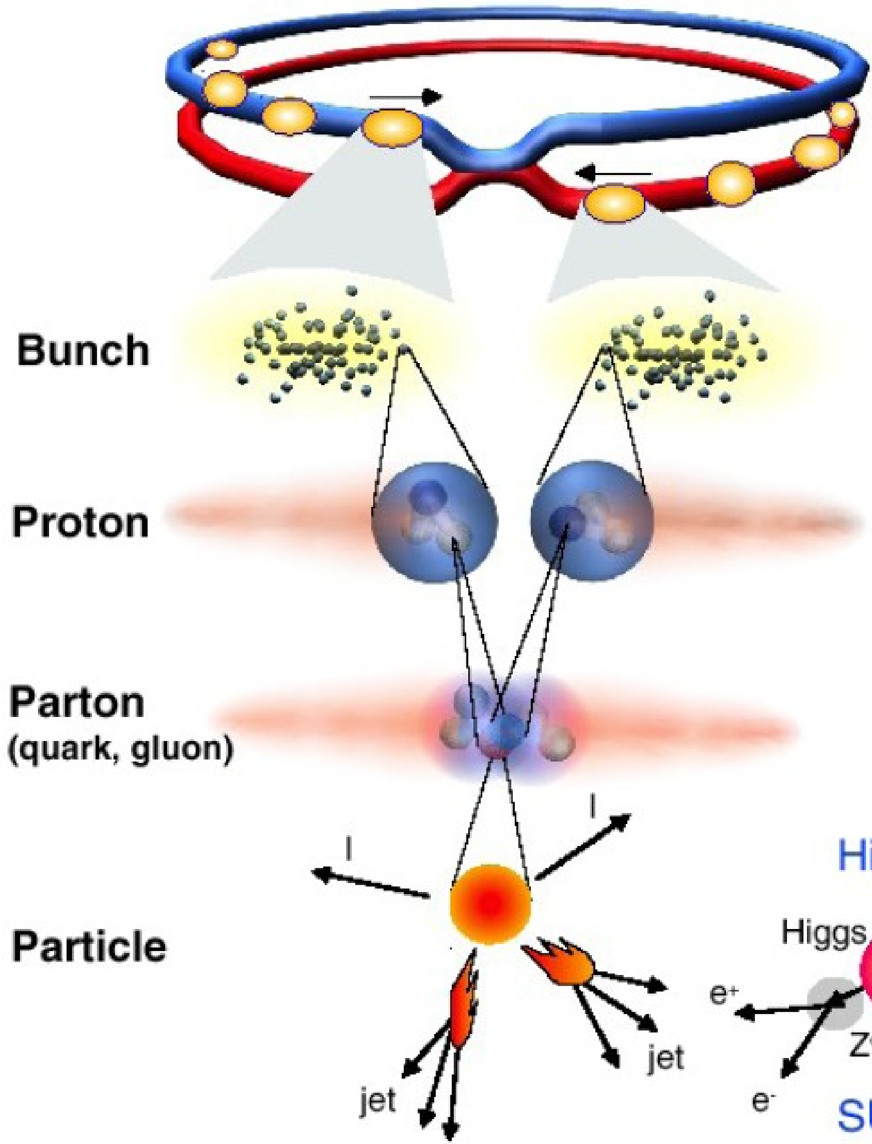


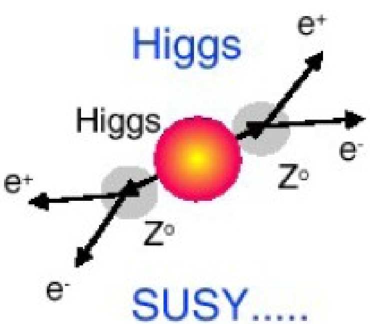


> 50 years of CERN history still alive and operational

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

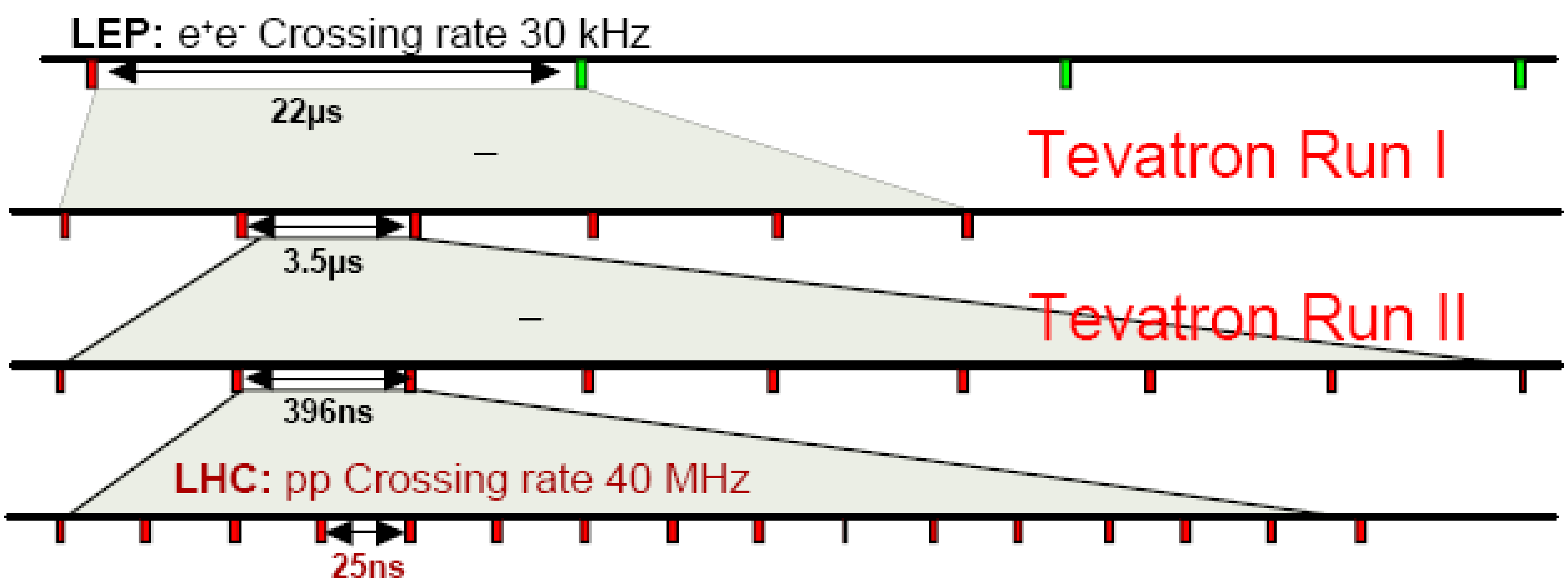




Selection of 1 in 10,000,000,000,000

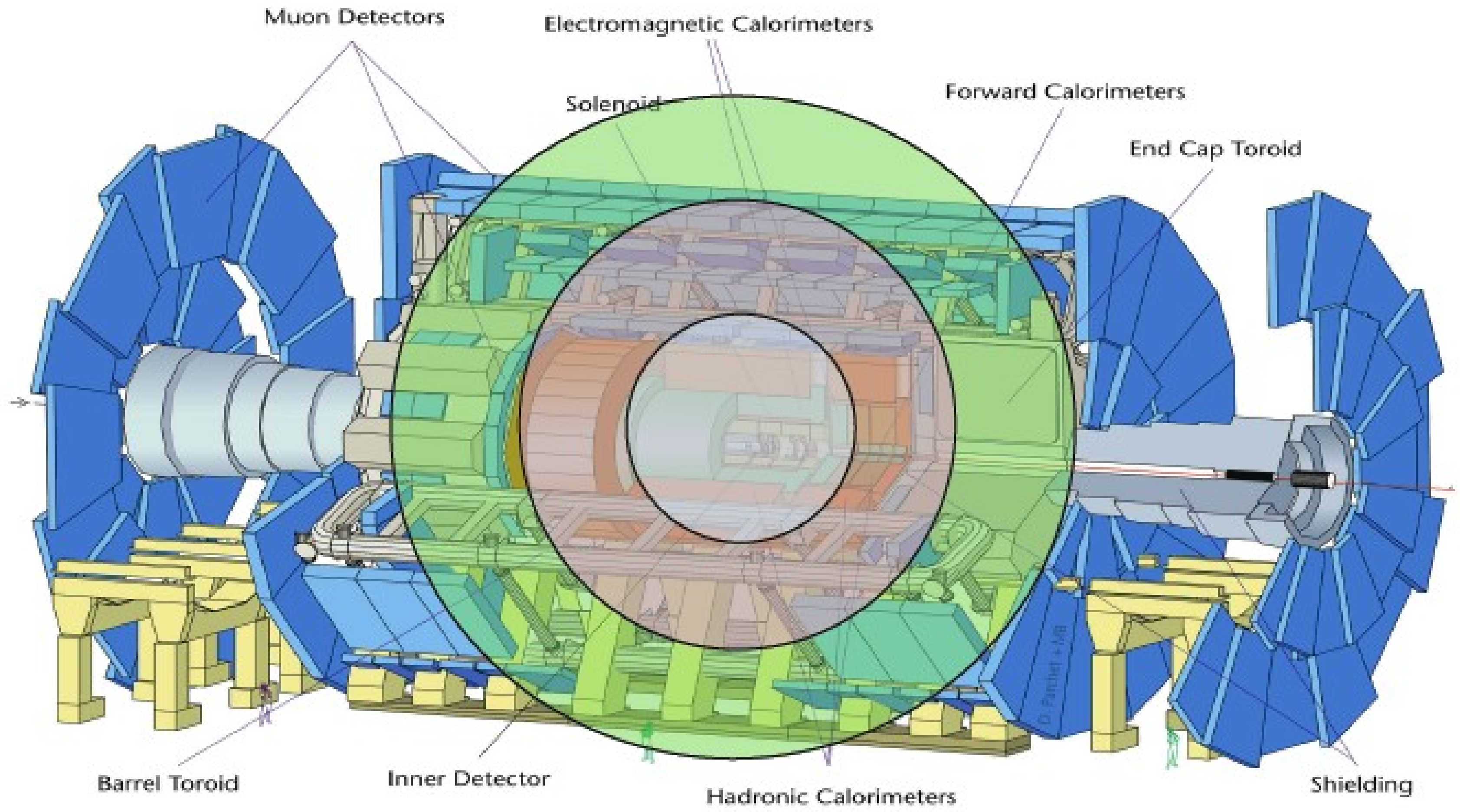
Beam crossings: LEP, Tevatron and LHC

- **LHC will have ~3600 bunches**
  - And same length as LEP (27 km)
  - Distance between bunches: 27km/3600=7.5m
  - Distance between bunches in time: 7.5m/c=25ns

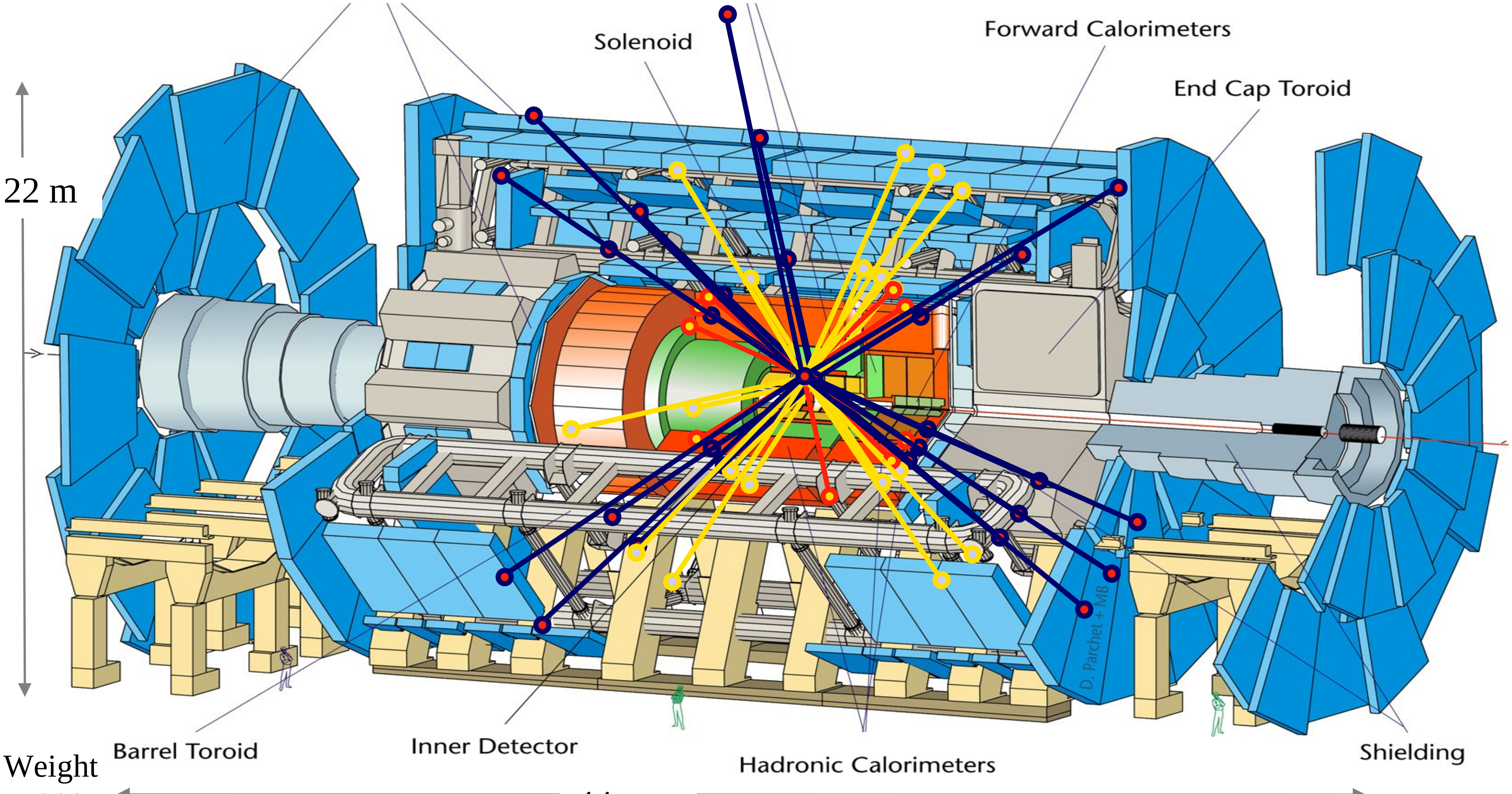


Time of Flight

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



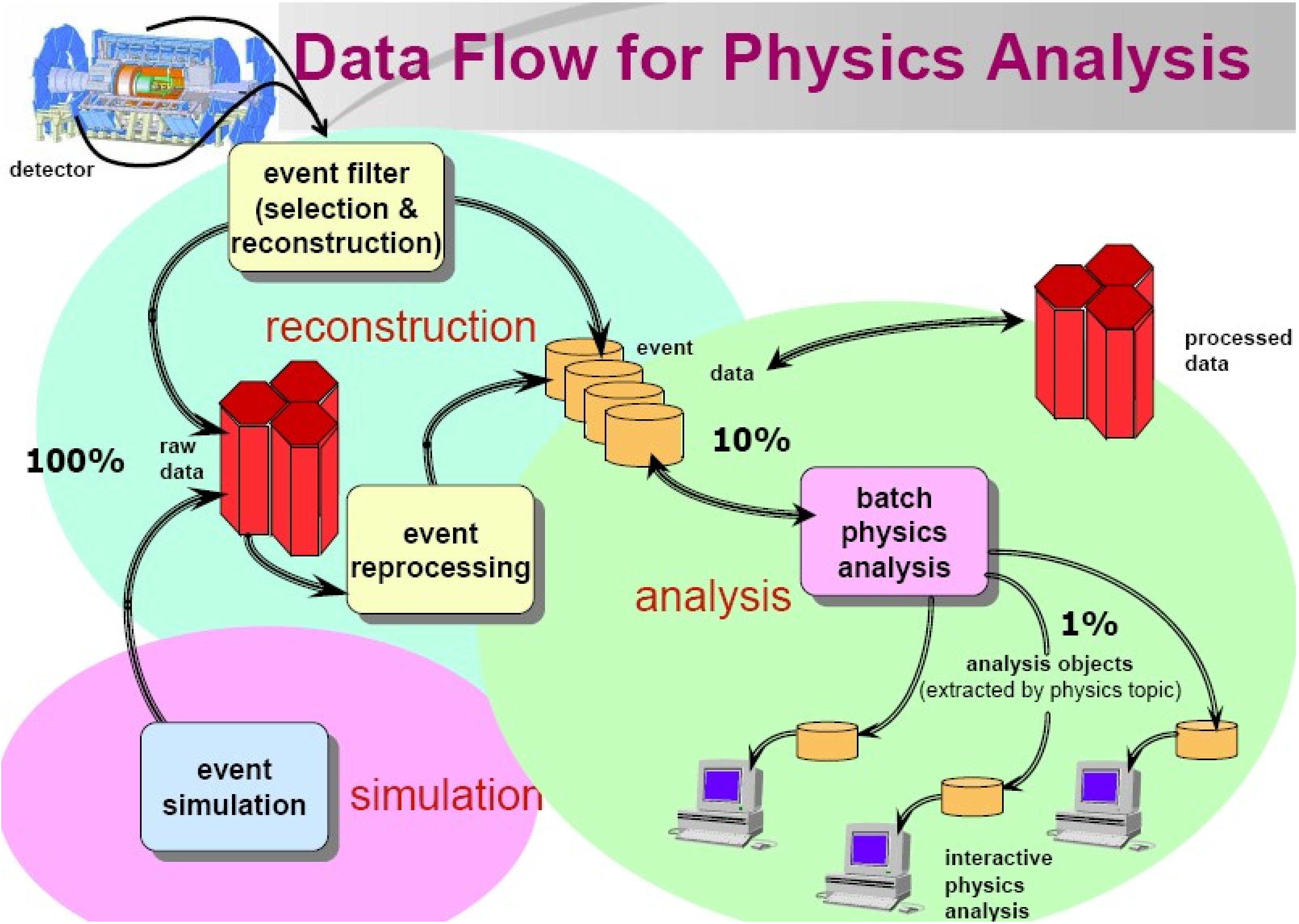
- **Interactions every 25 ns …**
  - **In 25 ns particles travel 7.5 m**



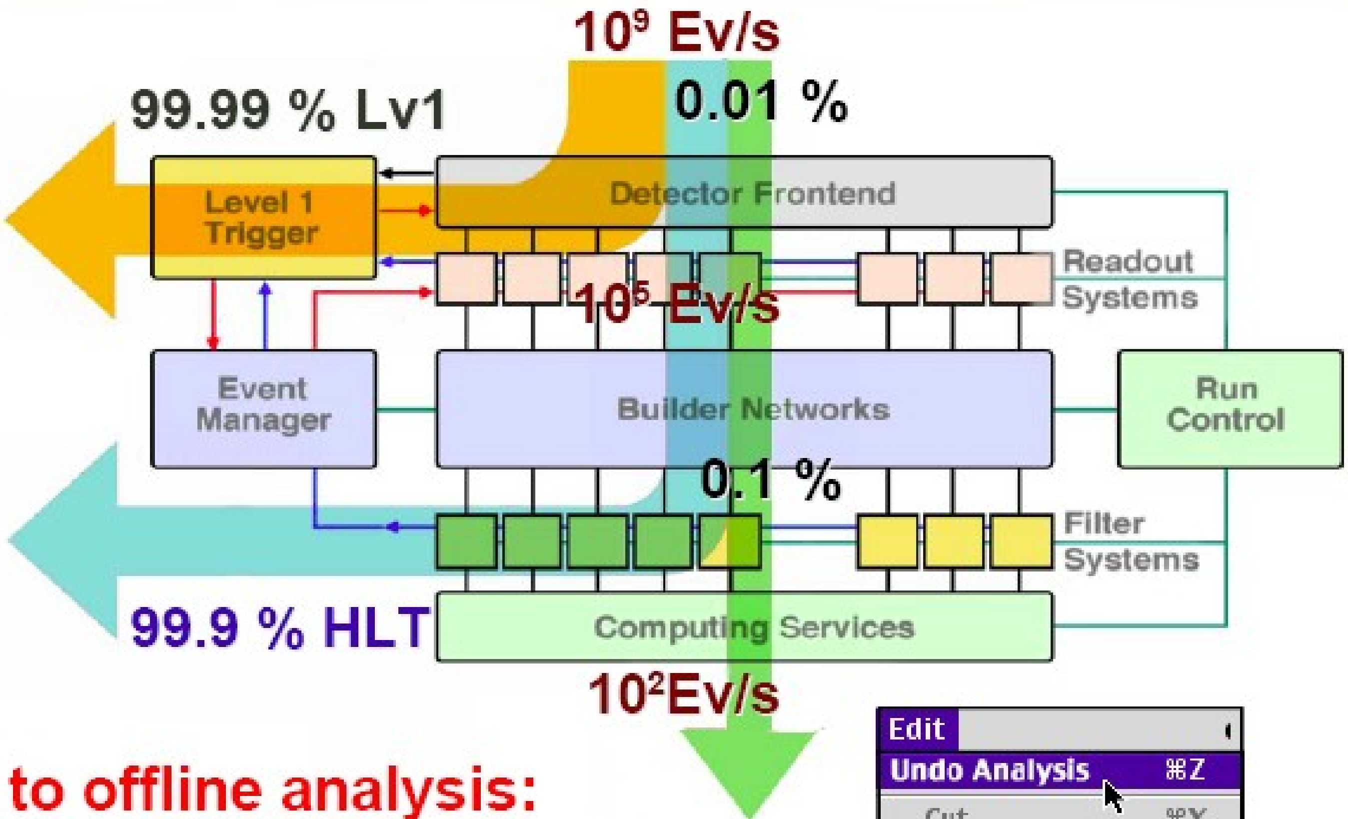
Weight : 7000 t

- **Cable length ~100 meters …**
  - **In 25 ns signals travel 5 m**

Data Flow for Physics Analysis



Trigger

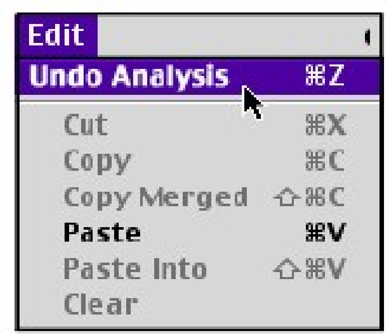


With respect to offline analysis:

Same hardware (Filter Subfarms)

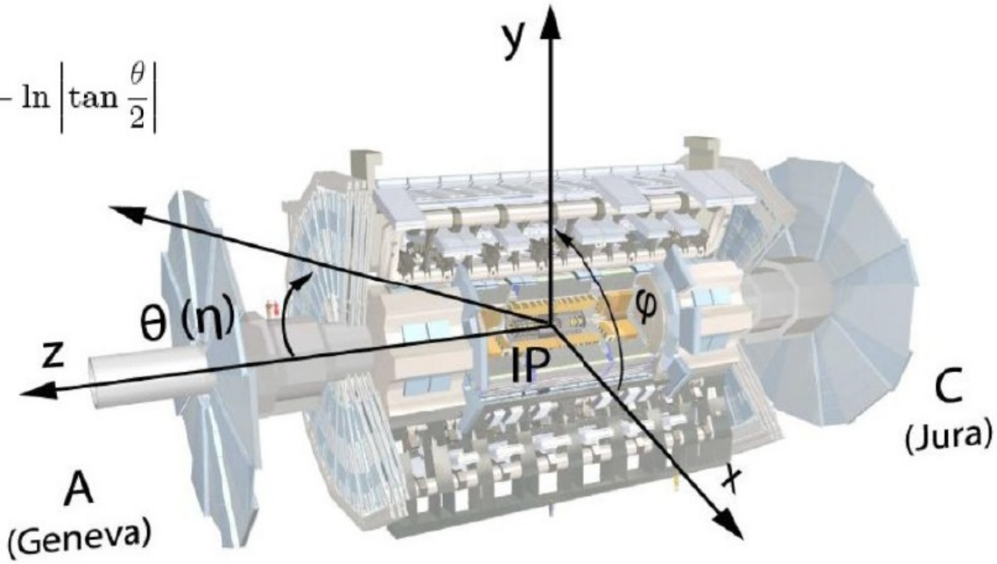
Same software

But different <u>situations</u>



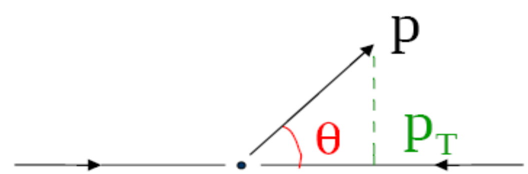
ATLAS Detector

$$-\ln\left|\tan\frac{\theta}{2}\right|$$



THE ATLAS DETECTOR IS REALLY BIG!

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



Transverse momentum

(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

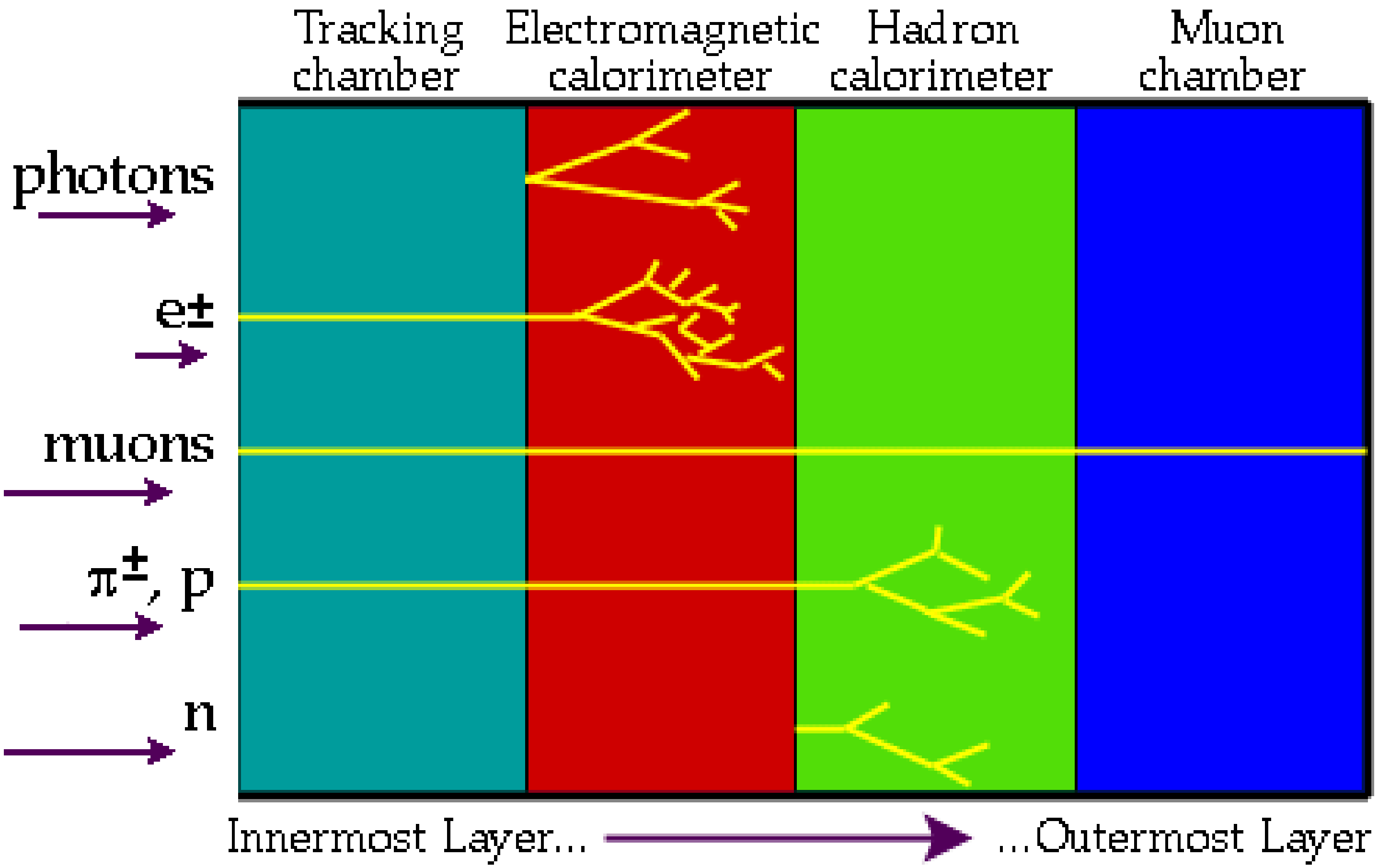
Rapidity: $\eta = -\log\left(\mathrm{tg}\,\frac{\theta}{2}\right)$

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

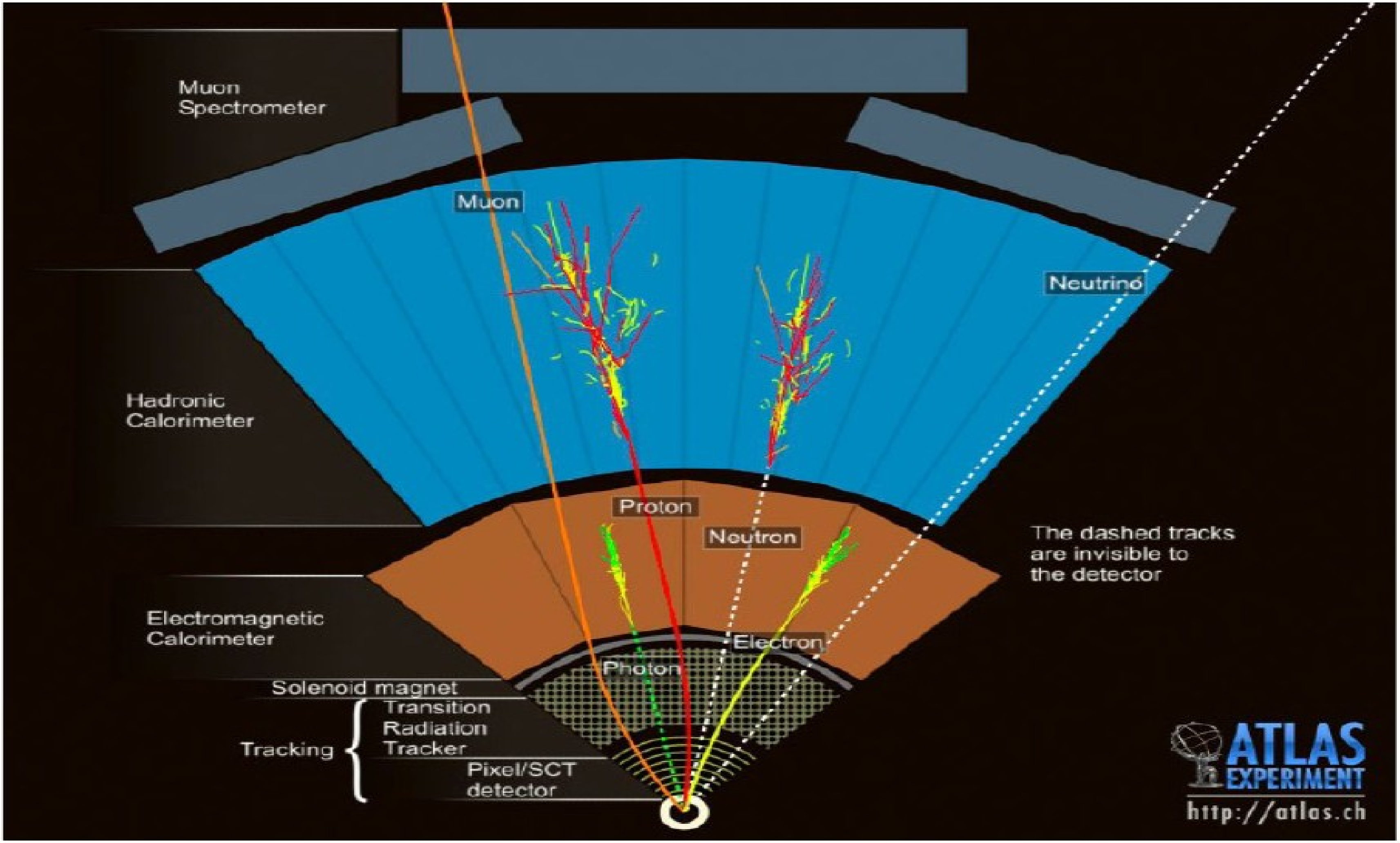
$\theta = 10^\circ \rightarrow \eta \cong 2.4$

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

General purpose detectors



Particle identication



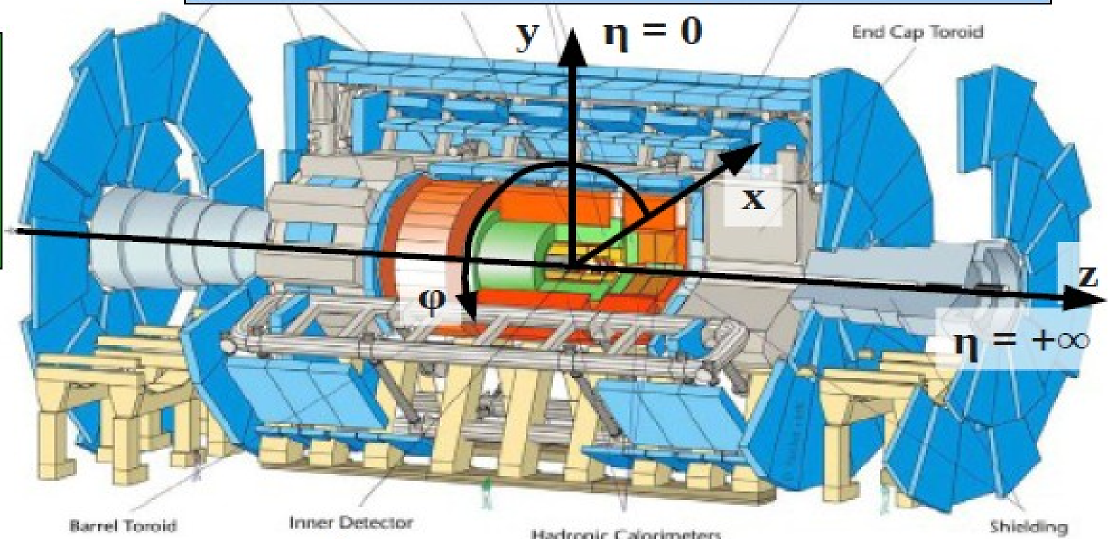
ATLAS Detector

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

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

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

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



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

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

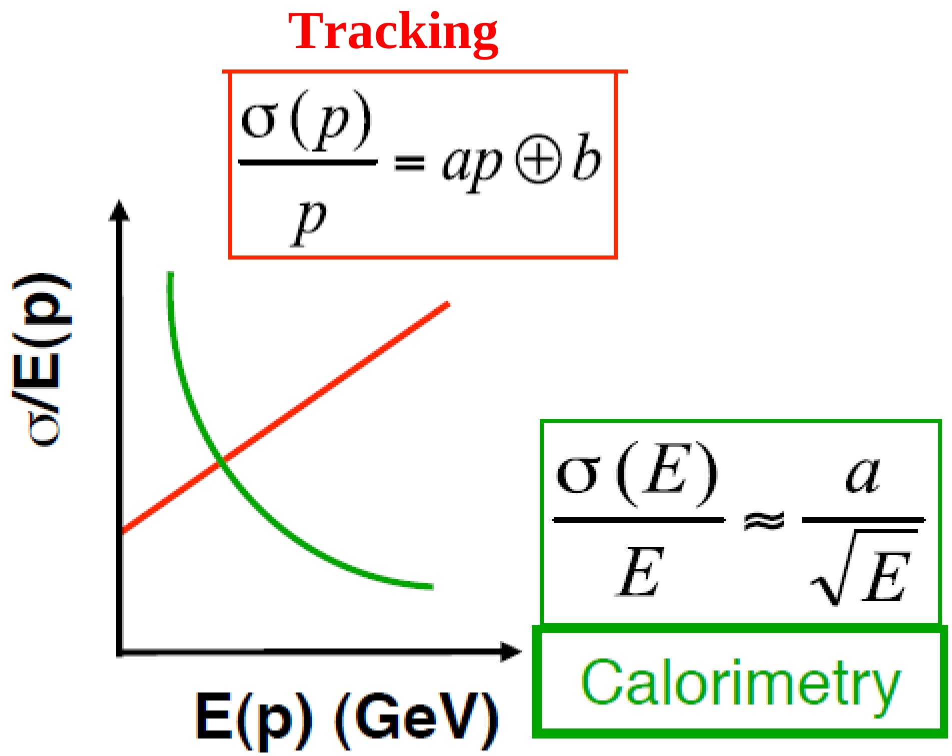
b the noise term (hits at low energy)

mainly the energy equivalent of the electronics noise

at LHC in particular: includes fluctuation from non primary interaction (pile-up noise)

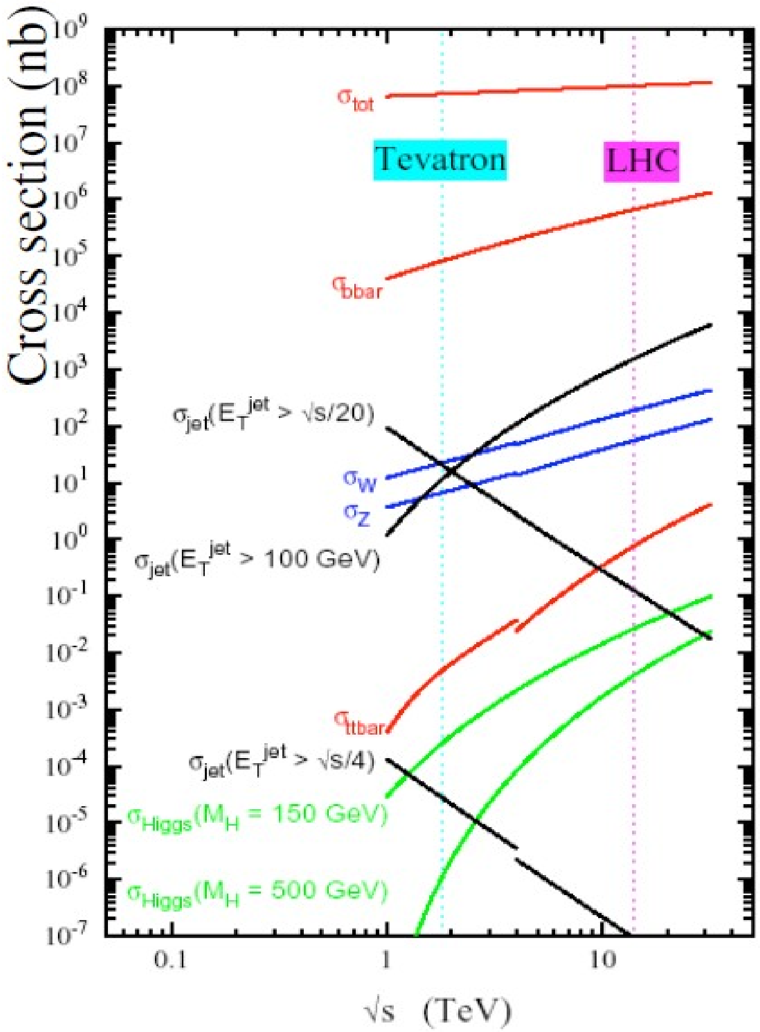
c the constant term (hits at high energy)

Essentially detector non homogeneities like intrinsic geometry, calibration but also energy leakage



Cross-sections at LHC

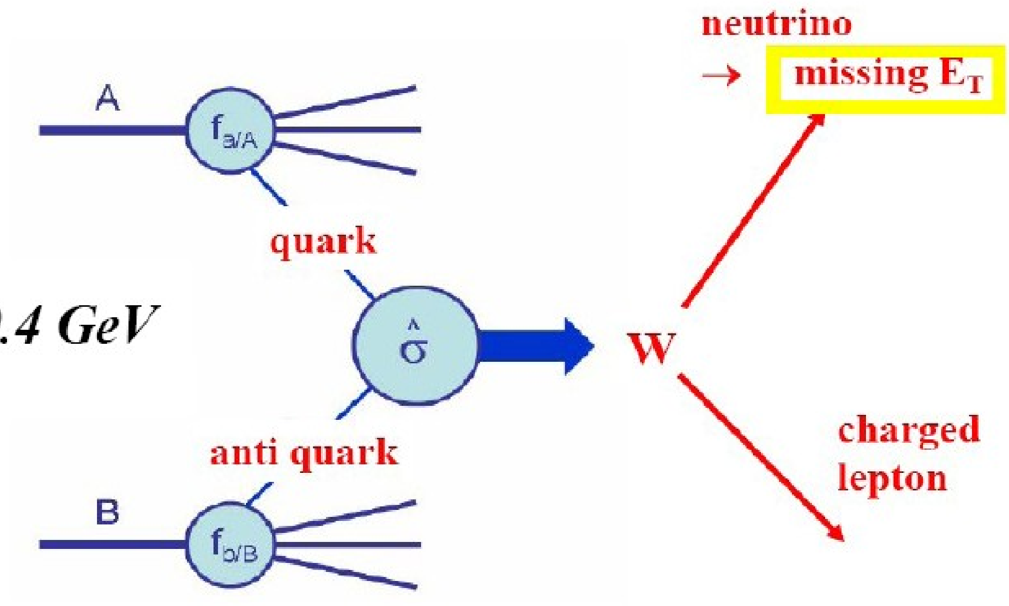
- A lot more “uninteresting” than “interesting” processes at design luminosity (L = 10^{34}cm^{-2}s^{-1})
  - Any event: 10^9/sec
  - W boson: 150/sec
  - Top quark: 8/sec
  - Higgs (125GeV): 0.2/sec
- Interesting events gets selected:
  I. trigger (decision!)
  II. physics analysis (selection)



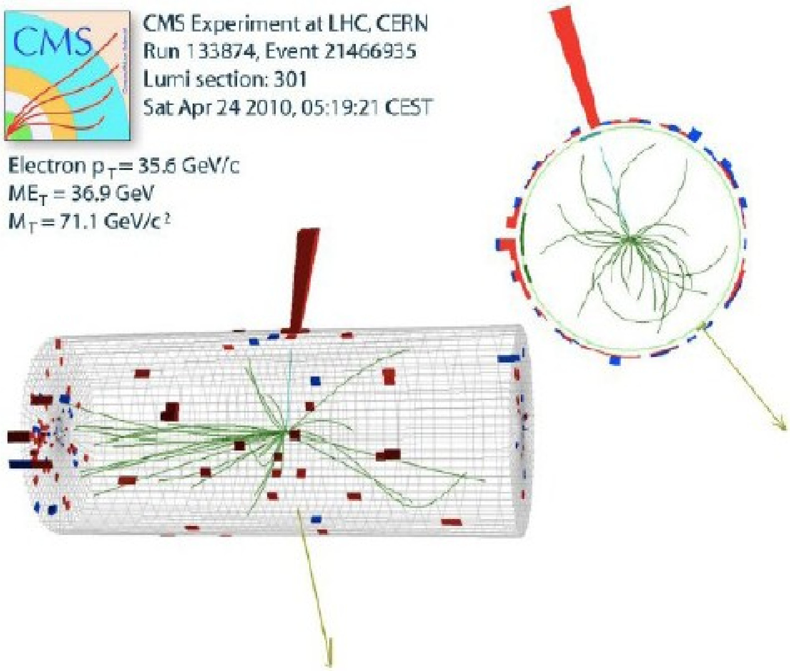
Measurement: $W \rightarrow l\,\nu$

- Signature:
  - Single charged lepton and missing transverse energy (MET)
  - Leptons are high p_T and isolated
  - MET from neutrino
  - Peaking at transverse invariant mass

M(W) ~ 80.4 GeV

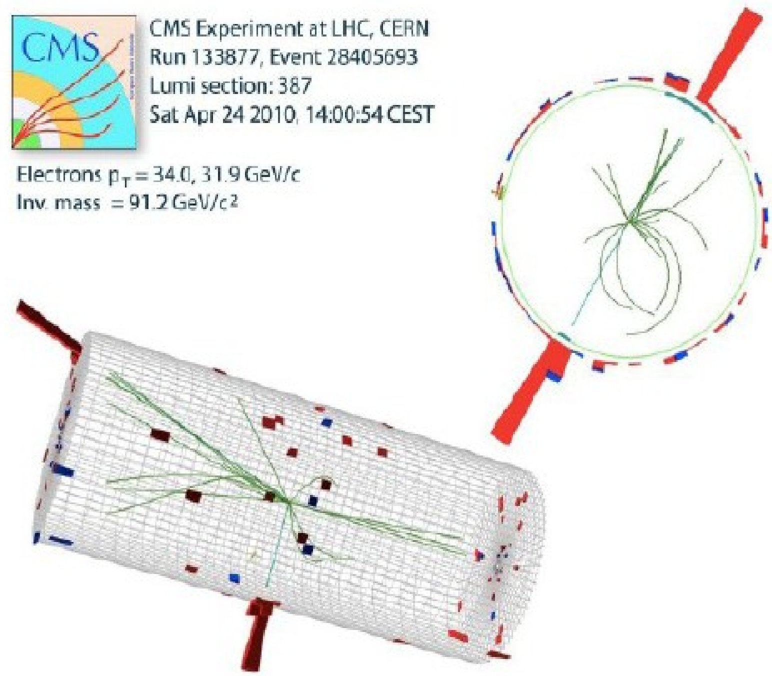


Electron channel W and Z events



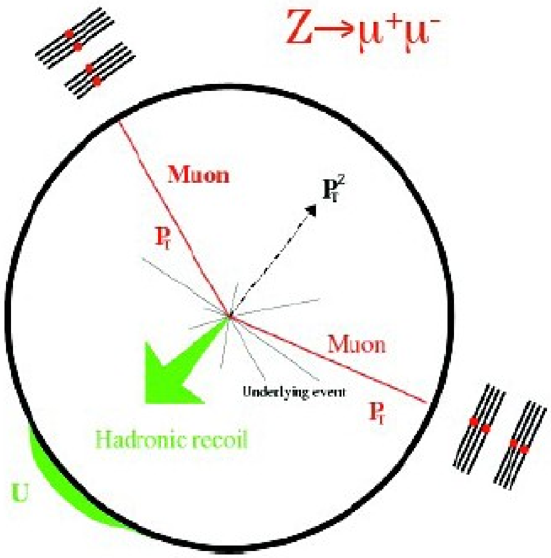
$W \rightarrow e\nu$

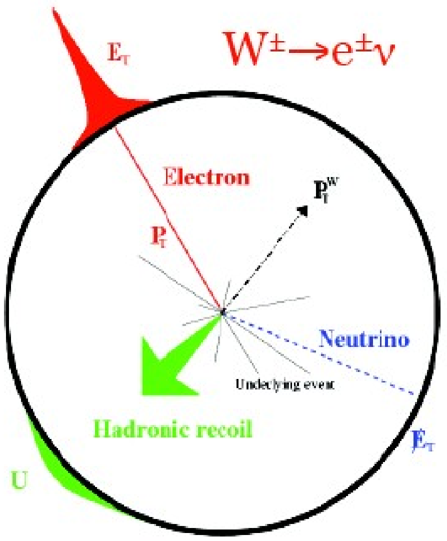
$Z \rightarrow ee$



Detecting W and Z

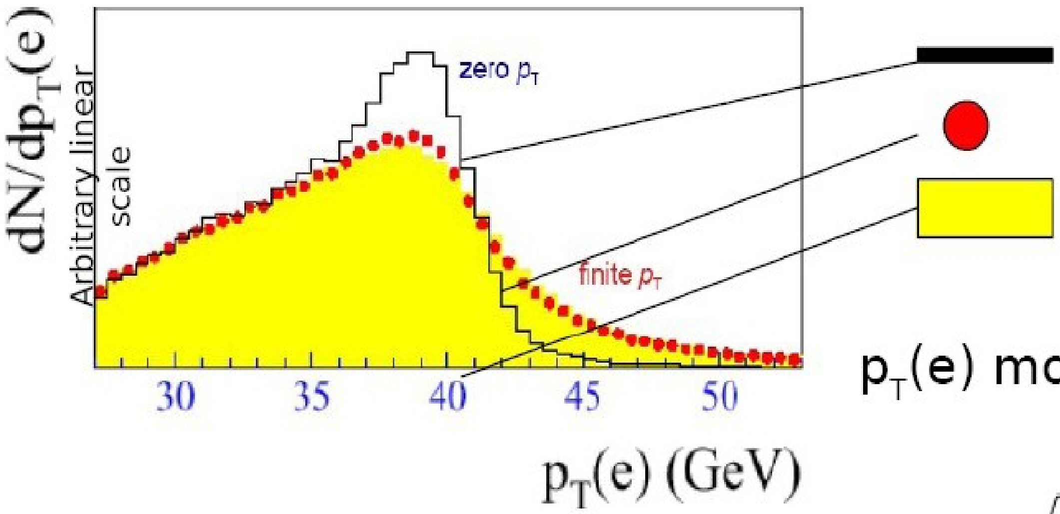
- $Z \rightarrow l^+l^-$
  - **Signature:** pair of charged leptons with opposite sign charge
    - Leptons are high p_T and isolated
  - Peak in l^+l^- invariant mass





- $W \rightarrow l^{\pm}\nu^{\pm}$
  - **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

Experimental observables

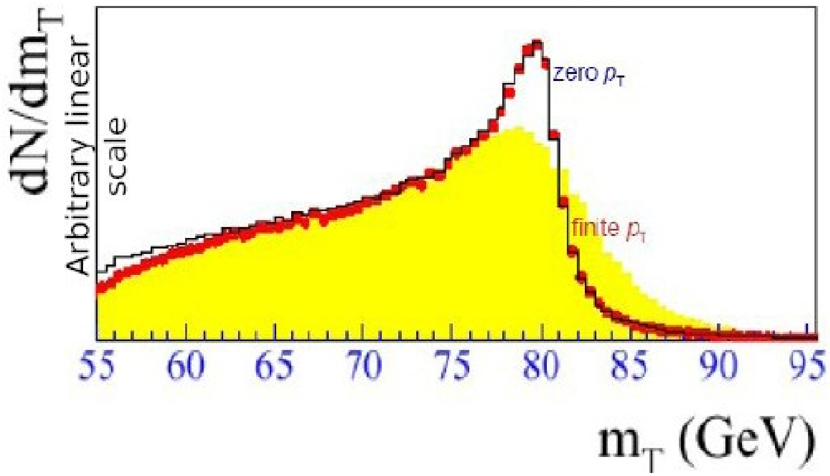


No $P_T(W)$

$P_T(W)$ included

Detector Effects added

$p_T(e)$ most affected by $p_T(W)$



$$m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos \Delta\phi)}$$

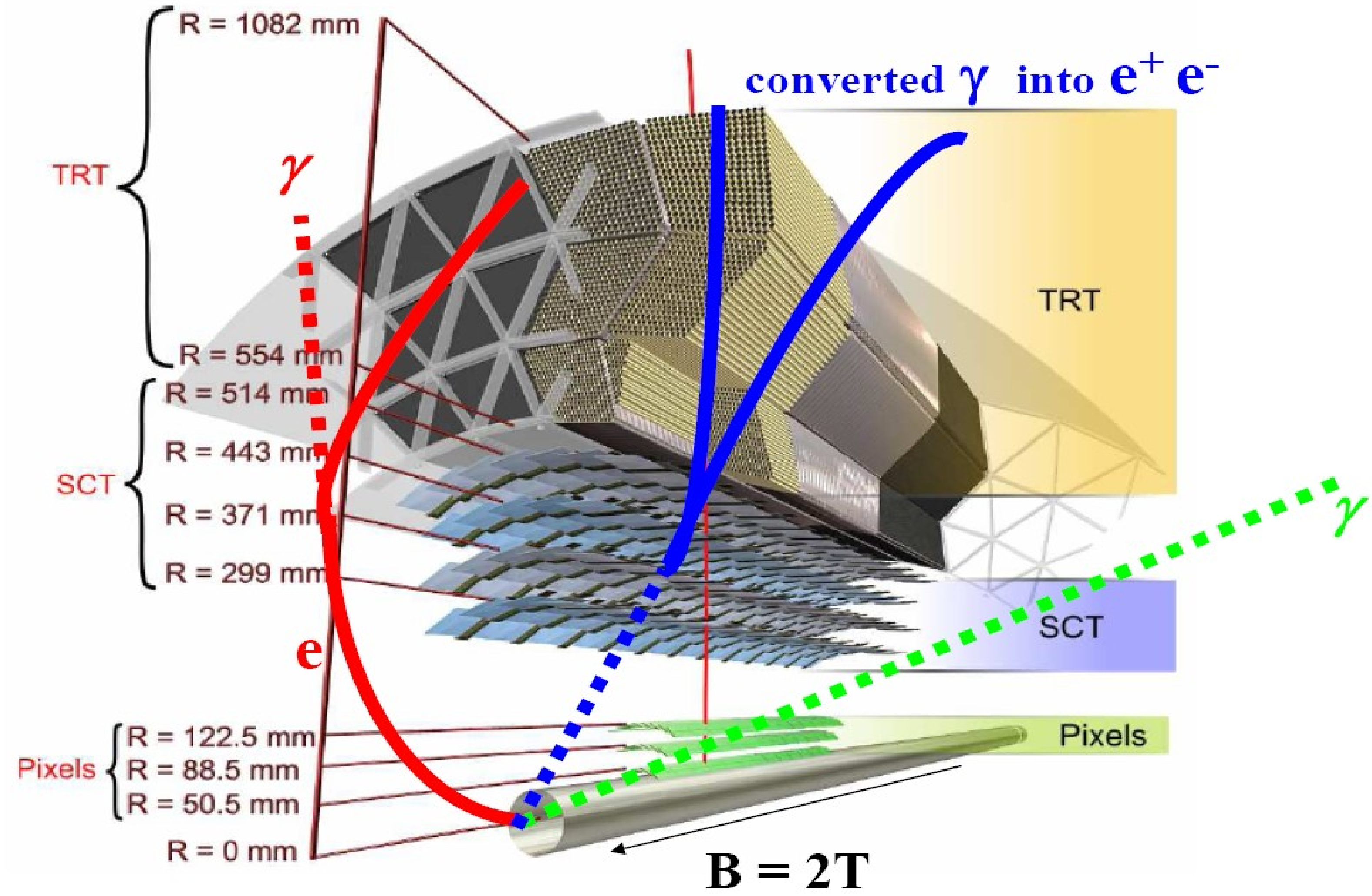
m_T most affected by measurement of MET

Off-line selection

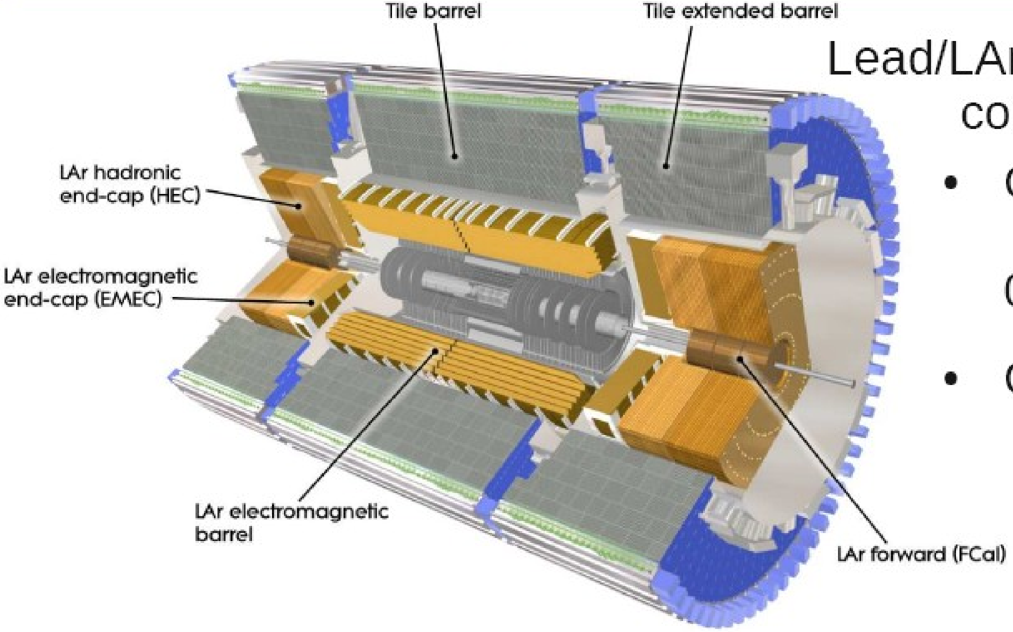
Analysis selection

- **Trigger:**
  - EF_e13_etcut_xs60_noMu
  - EF_xs60_noMu_L1EM10XS45
- **Electron:**
  - el_cl_Et > 25000 (MeV)
- **Missing energy:**
  - DetphiMinIsol > 0.70
  - MassTransv > 40000 (MeV)
  - Etmiss > 25000 (MeV)

The ATLAS Inner Detector

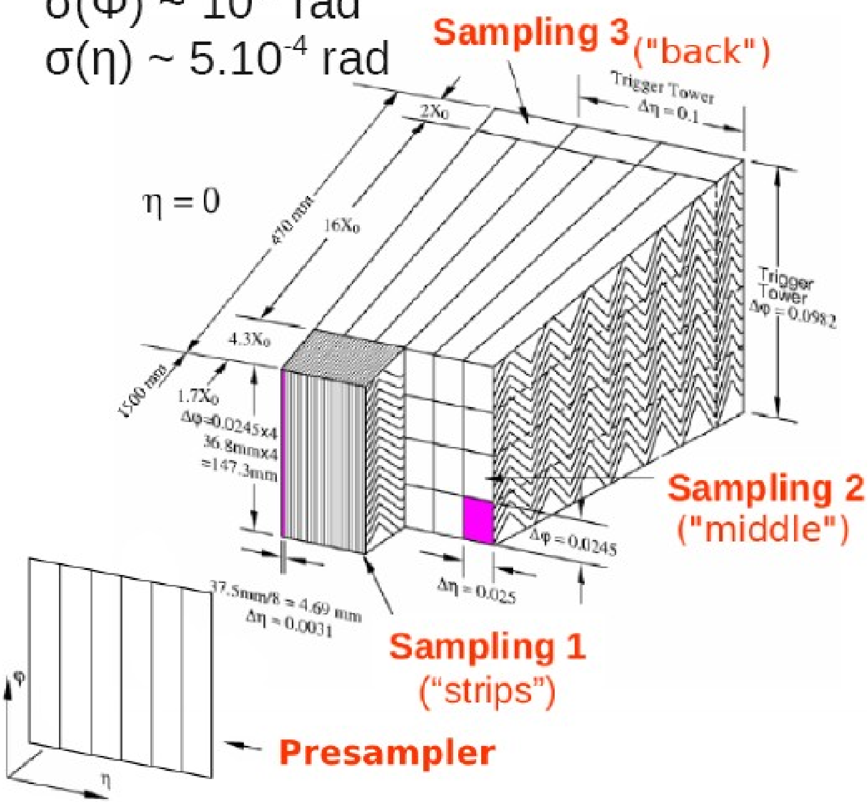


The ATLAS electromagnetic calorimeter



Lead/LAr EM calorimeter divided in 3 longitudinal compartments + Pre-sampler in front

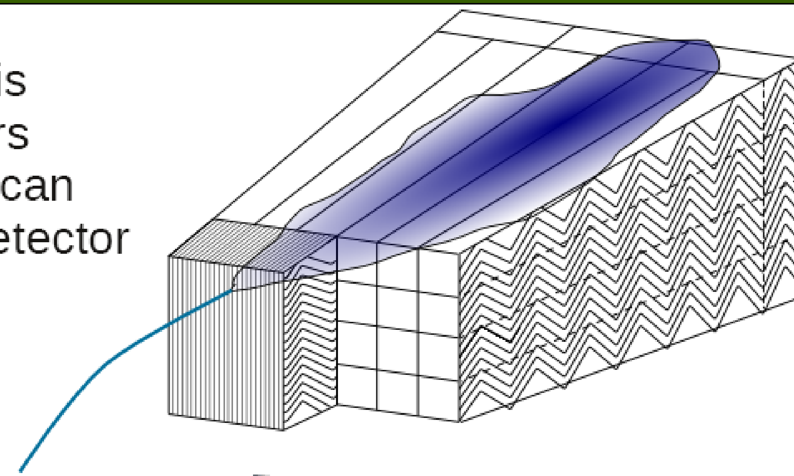
- Good energy resolution :
  $\sigma(E)/E = a/E \oplus b/\sqrt{E} \oplus c$ (with a ~ 0.3 GeV, b ~ 10%, c ~ 0.7%)
- Good angular resolution :
  $\sigma(\Phi) \sim 10^{-3}$ rad
  $\sigma(\eta) \sim 5.10^{-4}$ rad



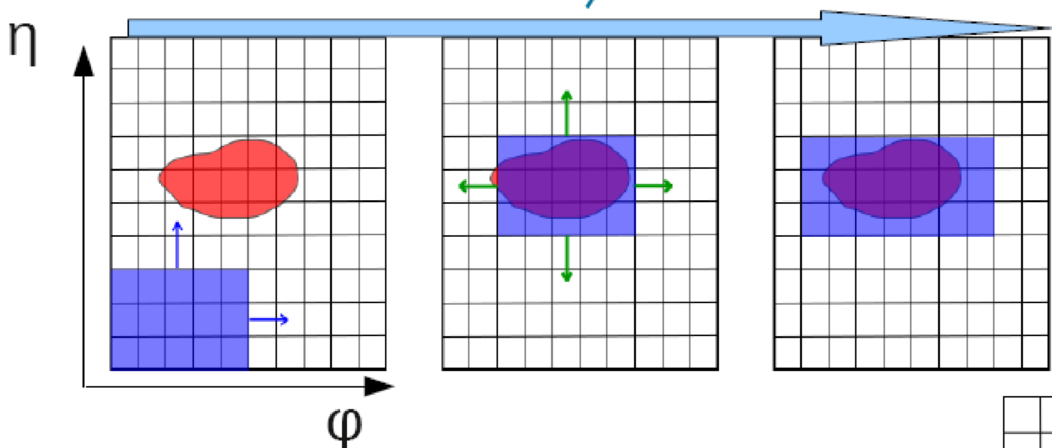
Layer	Granularity Δη x Δφ	Radiation length
Pre-sampler	0.025 x 0.1	
Strips	0.003 x 0.1	$4.3\ X_0$
Middle	0.025 x 0.025	$16\ X_0$
Back	0.05 x 0.025	$2\ X_0$

Electromagnetic objects in ATLAS

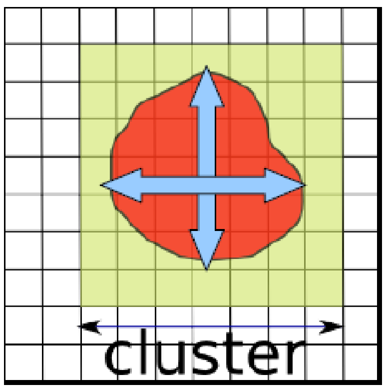
- In ATLAS an electron or a photon candidate is defined as a cluster of cells in the calorimeters representing the energy deposit to which we can associate tracks reconstructed in the inner detector



- Sliding window algorithm to reconstruct the energy deposits :



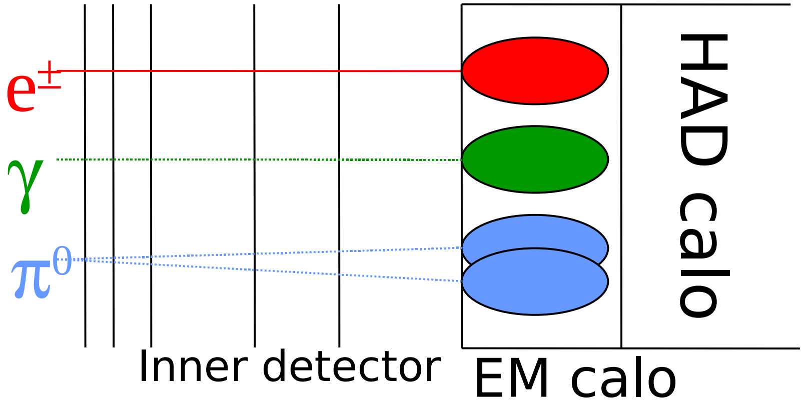
- The identification of such objects is then based on :
  - The shower shape in the calorimeter
  - Track quality (number of hits, direction wrt the cluster,...)
  - Transition radiation (TRT “high threshold hits”)
  - E/p



Electron identification

- Calorimetric variables
  - Float_t el_f1;
  - Float_t el_f3;
  - Float_t el_etas1;
  - Float_t el_etas2;
  - Float_t el_weta2;
  - Float_t el_Emax2;
  - Float_t el_emaxs1;
  - Float_t el_wstot;
  - Float_t el_Ethad;
  - Float_t el_Ethad1;
  - Float_t el_reta;
  - Float_t el_rphi;

- Tracking variables
  - Int_t el_nBLHits;
  - Int_t el_nPixHits;
  - Int_t el_nSCTHits;
  - Int_t el_nTRTHits;
  - Int_t el_nTRTHighTHits;
  - Int_t el_nSiHits;
  - Float_t el_TRTHighTHitsRatio;
  - Float_t el_trackd0;



Electron identification

- float eratio = (el_emaxs1 - el_Emax2)/(el_emaxs1 +el_Emax2) ;
- float Rhad = el_Ethad/(el_cl_E * cosh(el_etas2));
- float HadLeak = el_Ethad1/(el_cl_E * cosh(el_etas2));

Electron identification

- Calorimetric & tracking variables
  - Float_t   el_deltaeta1;
  - Float_t   el_deltaeta2;
  - Float_t   el_deltaphi2;
  - Int_t   el_isConv;

LOOSE identification

Hadronic leakage	⋆ Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| < 0.8$ and $\|\eta\| > 1.37$) ⋆ Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| > 0.8$ and $\|\eta\| < 1.37$)	R_{had1} R_{had}
Second layer of EM calorimeter	⋆ Ratio in η of cell energies in 3×7 versus 7×7 cells. ⋆ Lateral width of the shower.	R_η $w_{\eta 2}$

MEDIUM identification

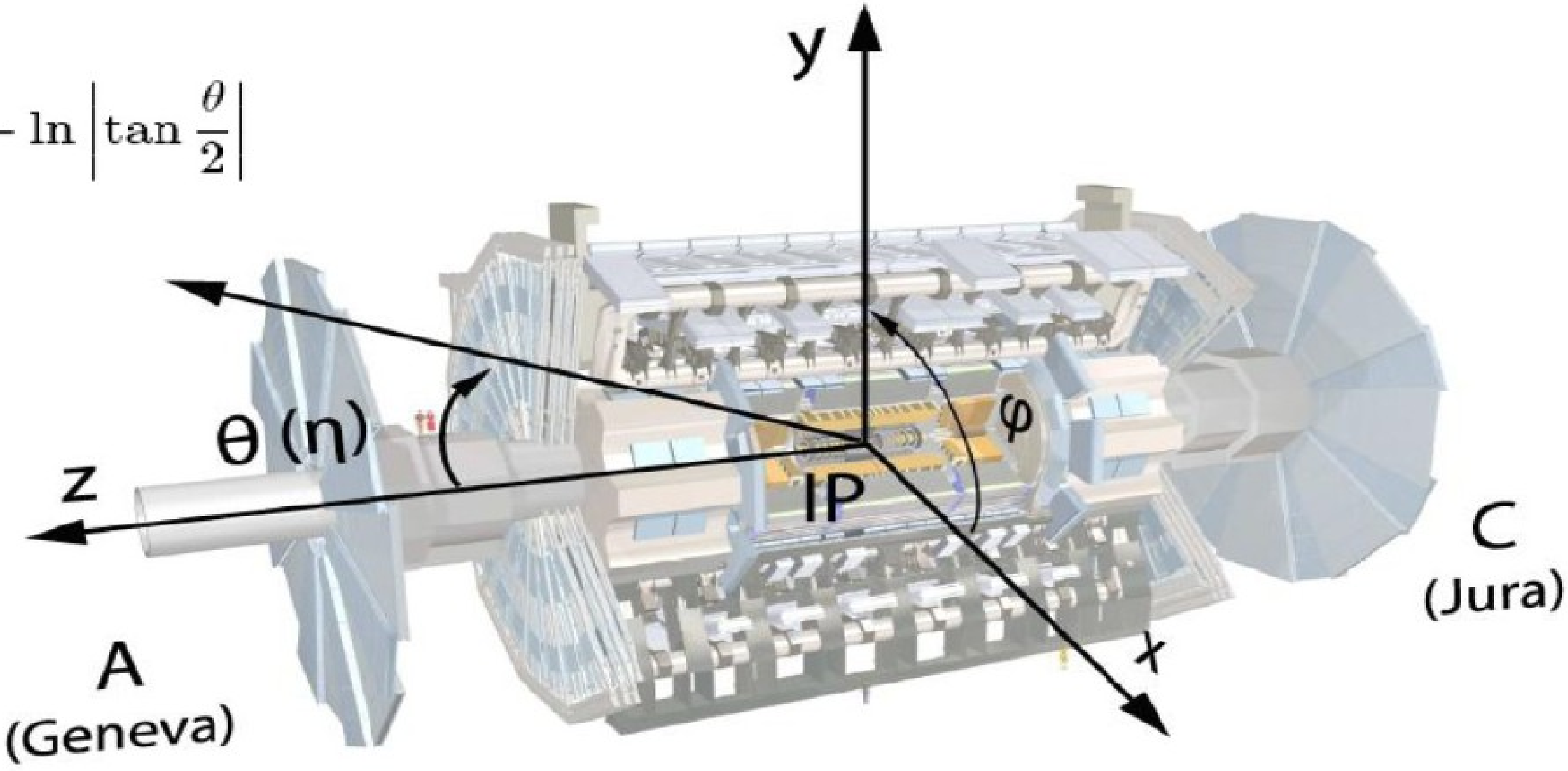
Medium cuts (includes Loose)		
First layer of EM calorimeter.	⋆ Total shower width. ⋆ Ratio of the energy difference associated with the largest and second largest energy deposit over the sum of these energies	w_{stot} E_{ratio}
Track quality	⋆ Number of hits in the pixel detector (≥ 1). ⋆ Number of hits in the pixels and SCT (≥ 7). ⋆ Transverse impact parameter (<5 mm).	d_0
Track matching	⋆ $\Delta\eta$ between the cluster and the track (< 0.01).	$\Delta\eta_1$

TIGHT identification

Tight cuts (includes Medium)		
b-layer	⋆ Number of hits in the b-layer (≥ 1).	
Track matching	⋆ $\Delta\phi$ between the cluster and the track (< 0.02). ⋆ Ratio of the cluster energy to the track momentum ⋆ Tighter $\Delta\eta$ cut (< 0.005)	$\Delta\phi_2$ E/p $\Delta\eta_1$
Track quality	⋆ Tighter transverse impact parameter cut (<1 mm).	d_0
TRT	⋆ Total number of hits in the TRT. ⋆ Ratio of the number of high-threshold hits to the total number of hits in the TRT.	
Conversions	⋆ Electron candidates matching to reconstructed photon conversions are rejected	

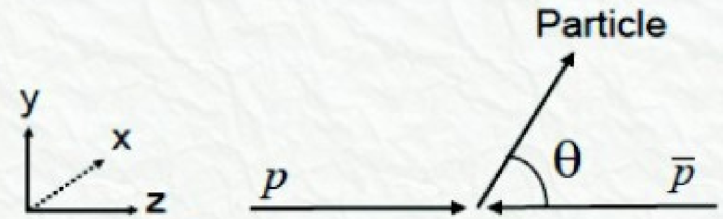
Kinematics

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



Some kinematic distributions

Rapidity (y) and Pseudo-rapidity (η)



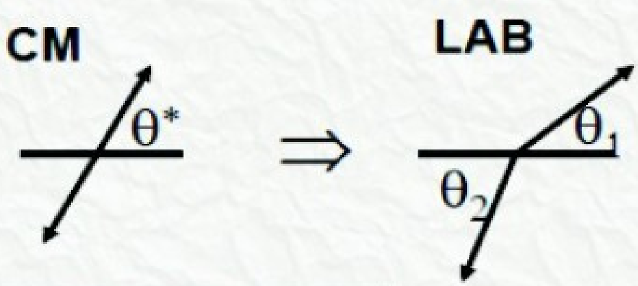
$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

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

In the limit $\beta \rightarrow 1$ (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

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

$$p_z = E \tanh y$$

$$E = E_T \cosh y$$

$$p_z = E_T \sinh y$$

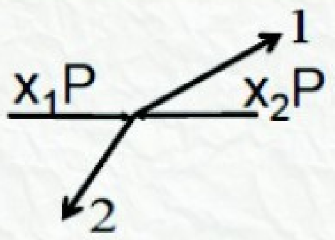
$$p_T \equiv p \sin\theta \xrightarrow[m \to 0]{} E_T$$

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

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

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

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

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

$$0 < x_1, x_2 < 1$$

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