FYST17 LECTURE 4 DETECTING AND IDENTIFYING PARTICLES

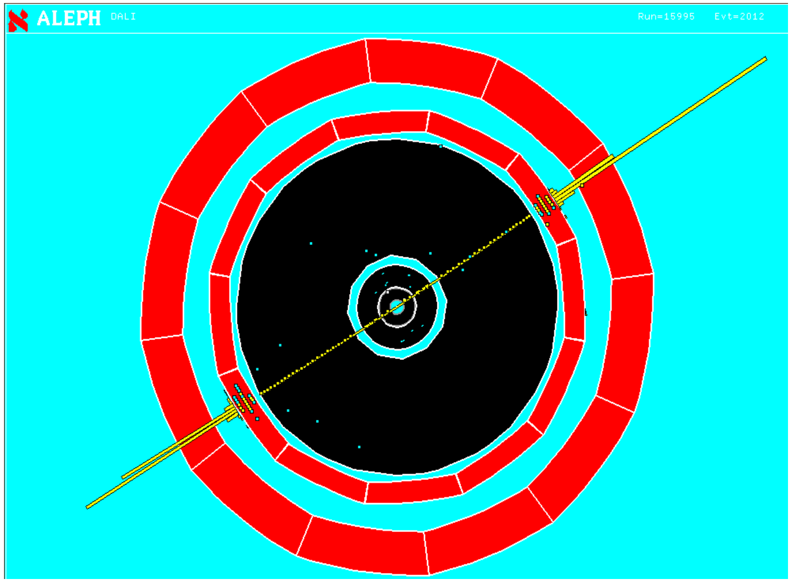
Thanks to D. Bortoletto, M. Wielers, and P. Hobson

Today & tomorrow:

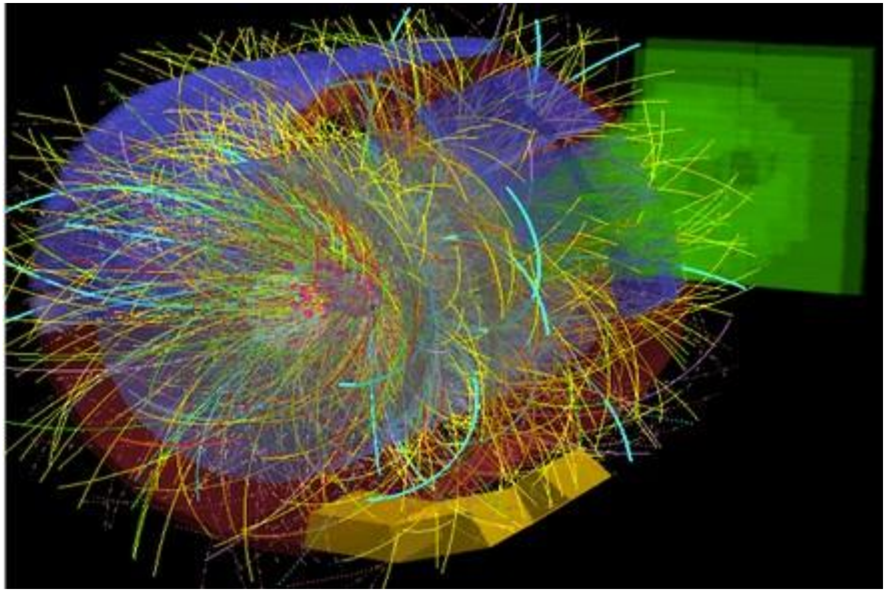
- Reminders
  - Cross section
  - Rapidity \ pseudo-rapidity
  - Bethe-Bloch ionization
- More about tracking and trackers
  - Types, resolution
- More about calorimeters
  - Types, resolution
- Some particle identification strategies
- Triggers

Detecting particles

- Measurements depends on the available physics (given by the cross section) and our ability to identify it
- “Every effect of particles or radiation can be used as a working principle for a particle detector” *Claus Grupen*
- Goal of experiments: identifying (as many) particles (as possible) and measure their 4-momentum

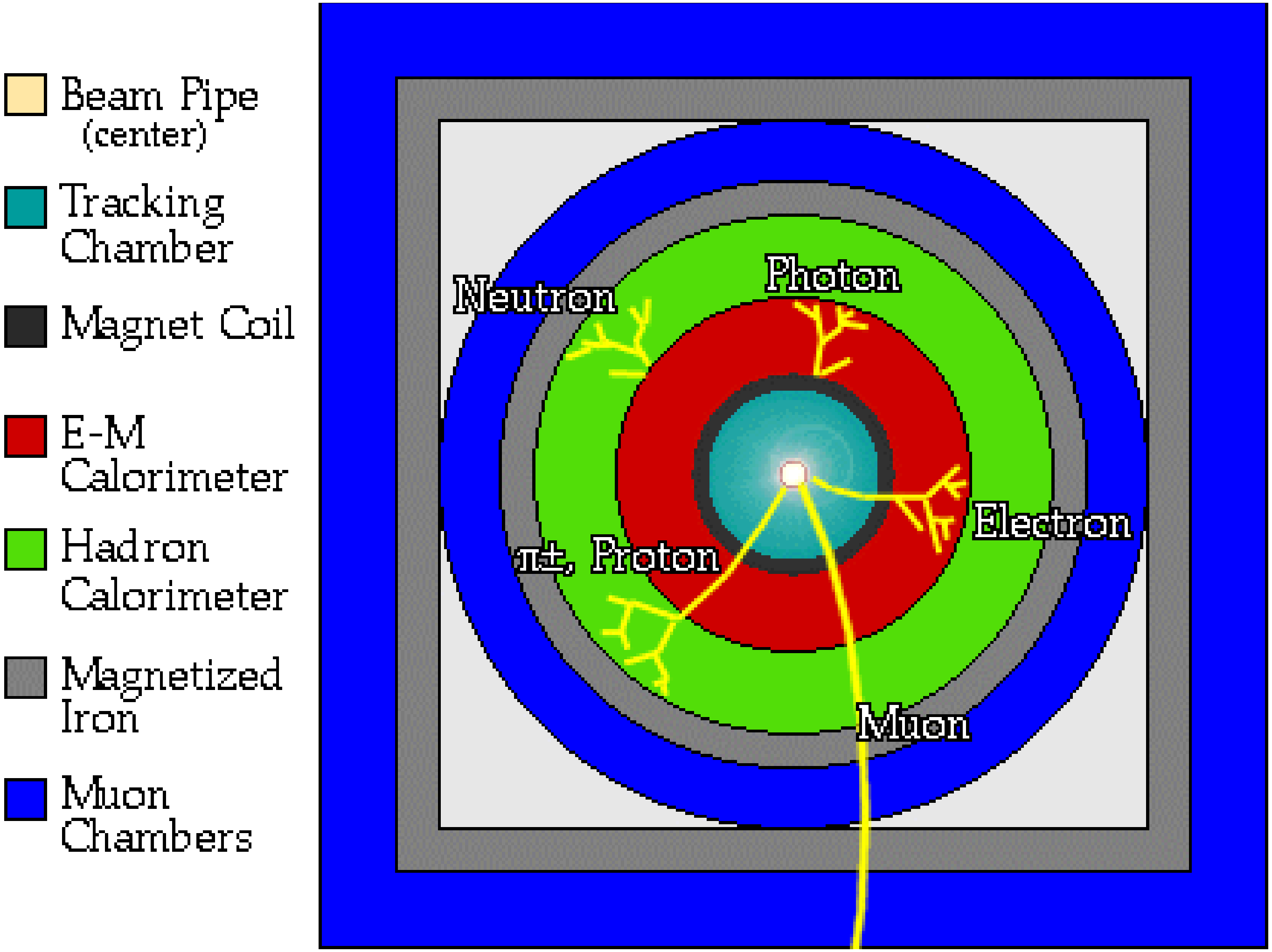


Z → e+e-



ALICE heavy-ion collision

A Detector cross section



Reminder: Cross section

$$\sigma = \frac{\text{no of interactions per unit time per target}}{\text{incident flux}}$$

Flux = number of incident particles/ unit area/unit time

- The "cross section", σ, can be thought of as the <u>effective</u> cross-sectional area of the target particles for the interaction to occur.
- In general this has nothing to do with the physical size of the target although there are exceptions, e.g. neutron absorption

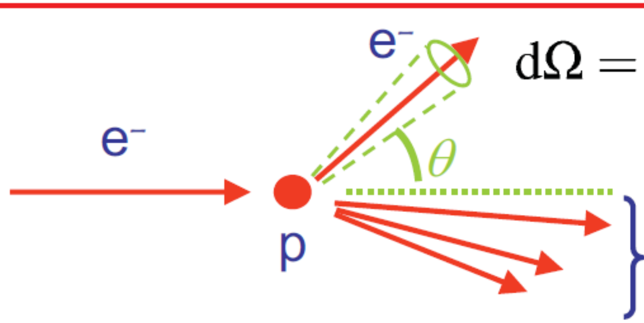
here σ is the projective area of nucleus

Differential Cross section

$$\frac{d\sigma}{d\Omega} = \frac{\text{no of particles per sec/per target into } d\Omega}{\text{incident flux}}$$

or generally

$$\frac{d\sigma}{d\ldots}$$



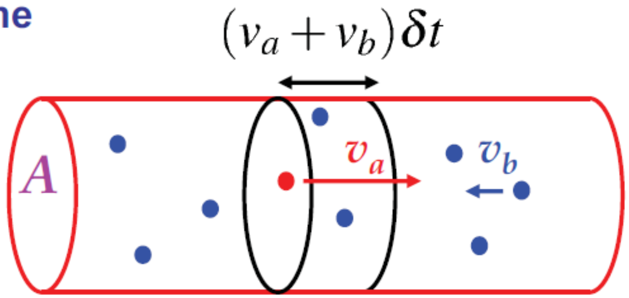
$$d\Omega = d(\cos\theta)d\phi$$

integrate over all other particles

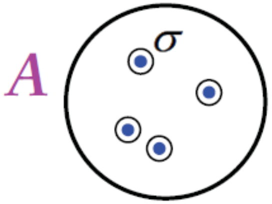
with $\sigma = \int \frac{d\sigma}{d\Omega} d\Omega$

Reminder: Cross section

- Consider a single particle of type a with velocity, v_a, traversing a region of area A containing n_b particles of type b per unit volume



In time δt a particle of type a traverses region containing $n_b(v_a + v_b)A\delta t$ particles of type b



★ Interaction probability obtained from effective cross-sectional area occupied by the $n_b(v_a + v_b)A\delta t$ particles of type b

- Interaction Probability = $\dfrac{n_b(v_a + v_b)A\delta t\sigma}{A} = n_b v \delta t \sigma$ $\quad [v = v_a + v_b]$

➡ **Rate per particle of type a = $n_b v \sigma$**

- Consider volume V, total reaction rate = $(n_b v \sigma).(n_a V) = (n_b V)(n_a v)\sigma$
  = $N_b \phi_a \sigma$

- As anticipated: **Rate = Flux x Number of targets x cross section**

Rapidity

Rapidity y defined as:

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{(E+p_z)^2}{(E+p_z)(E-p_z)} = \frac{1}{2}\ln\frac{(E+p_z)^2}{m^2+p_\perp^2}$$

$$= \ln\frac{E+p_z}{m_\perp} = \ln\frac{m_\perp}{E-p_z}$$

Simple for calculations, Δy' = Δy for simple boost along z-axis

BUT ***need to know m.*** Experimentally often unknown, instead use pseudo-rapidity η

$$y = \frac{1}{2}\ln\frac{\sqrt{m^2+\mathbf{p}^2}+p_z}{\sqrt{m^2+\mathbf{p}^2}-p_z} \Rightarrow \eta = \frac{1}{2}\ln\frac{|\mathbf{p}|+p_z}{|\mathbf{p}|-p_z} = \ln\frac{|\mathbf{p}|+p_z}{p_\perp}$$

or

$$\eta = \frac{1}{2}\ln\frac{\underline{p}+\underline{p}\cos\theta}{\underline{p}-\underline{p}\cos\theta} = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta}$$

$$= \frac{1}{2}\ln\frac{2\cos^2\theta/2}{2\sin^2\theta/2} = \ln\frac{\cos\theta/2}{\sin\theta/2} = -\ln\tan\frac{\theta}{2}$$

Only depends on the polar angle!

Not so simple, Δη' ≠ Δη !

Example of use of η

Align beam direction with z axis

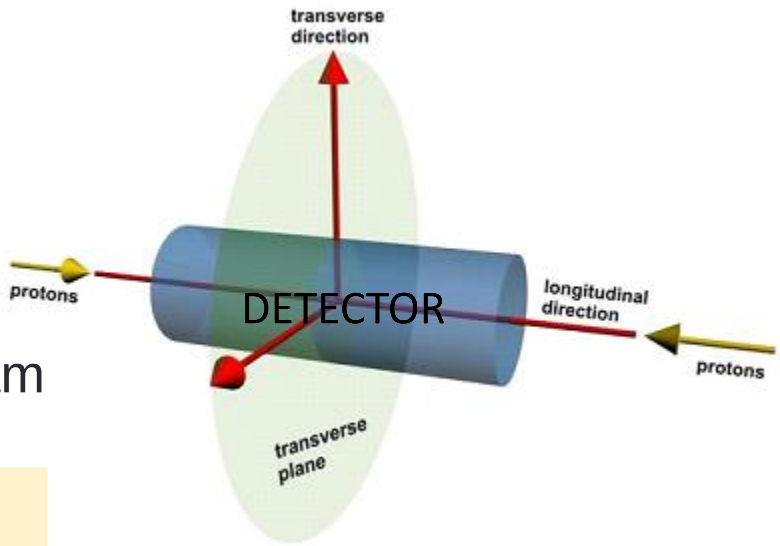
The x-y plane is then transverse to the beam

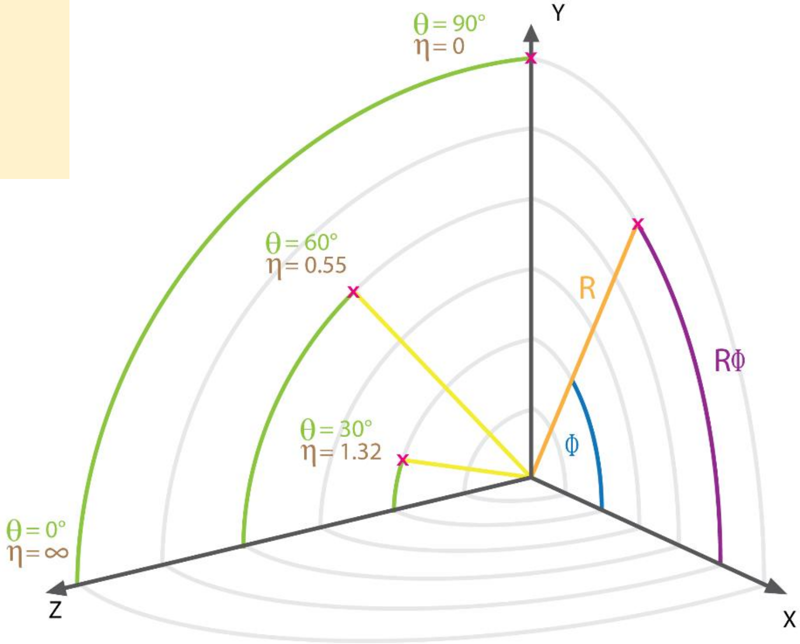
i.e. :

η (and y) → 0 when particle travels transverse to beam ;

η (and y) → ∞ when moving along beam axis

Important for accelerator physics:
y Lorentz invariant along beam axis!





The pseudo-rapidity gap

One can calculate that

$$\frac{d\eta}{dy} = \frac{d\eta/dp_z}{dy/dp_z} = \frac{E}{p} > 1$$

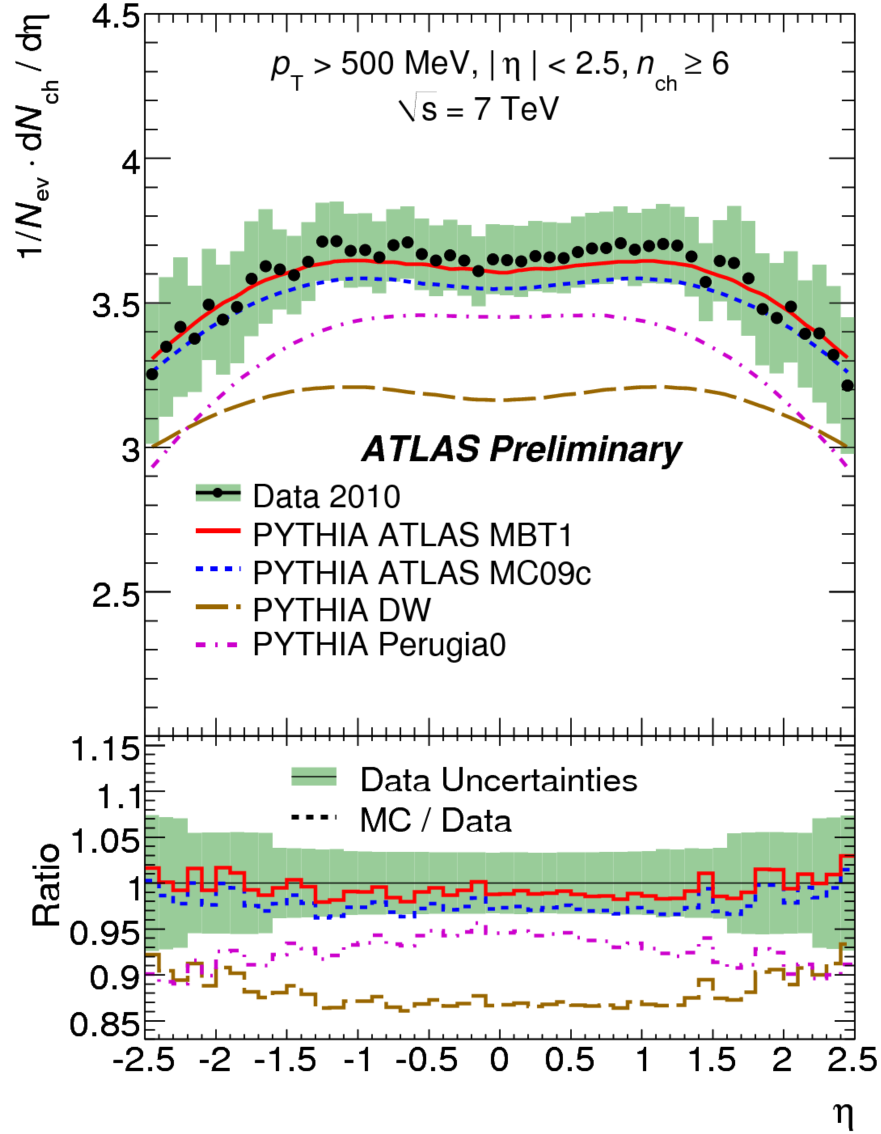
With the limits

$$\frac{\mathrm{d}\eta}{\mathrm{d}y} \rightarrow \frac{m_\perp}{p_\perp} \text{ for } p_z \rightarrow 0$$

$$\frac{\mathrm{d}\eta}{\mathrm{d}y} \rightarrow 1 \text{ for } p_z \rightarrow \pm\infty$$

So if the incremental flux dn/dy is flat for y≅0 then dn/dη has a dip.

Referred to as the ***rapidity gap***, very visible when tuning simulation to data



Bethe-Bloch formula for energy loss by ionization

Valid for heavy charged particles ($m_{incident} >> m_e$), e.g. proton, k, π, μ

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

$2\pi N_a r_e^2 m_e c^2$ =0.1535 MeV cm²/g

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln\left(a\beta^2\gamma^2\right)$$

Fundamental constants

r_e=classical radius of electron

m_e=mass of electron

N_a=Avogadro's number

c =speed of light

$$r_e = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{m_e c^2}$$

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

γ = $(1-\beta^2)^{-1/2}$

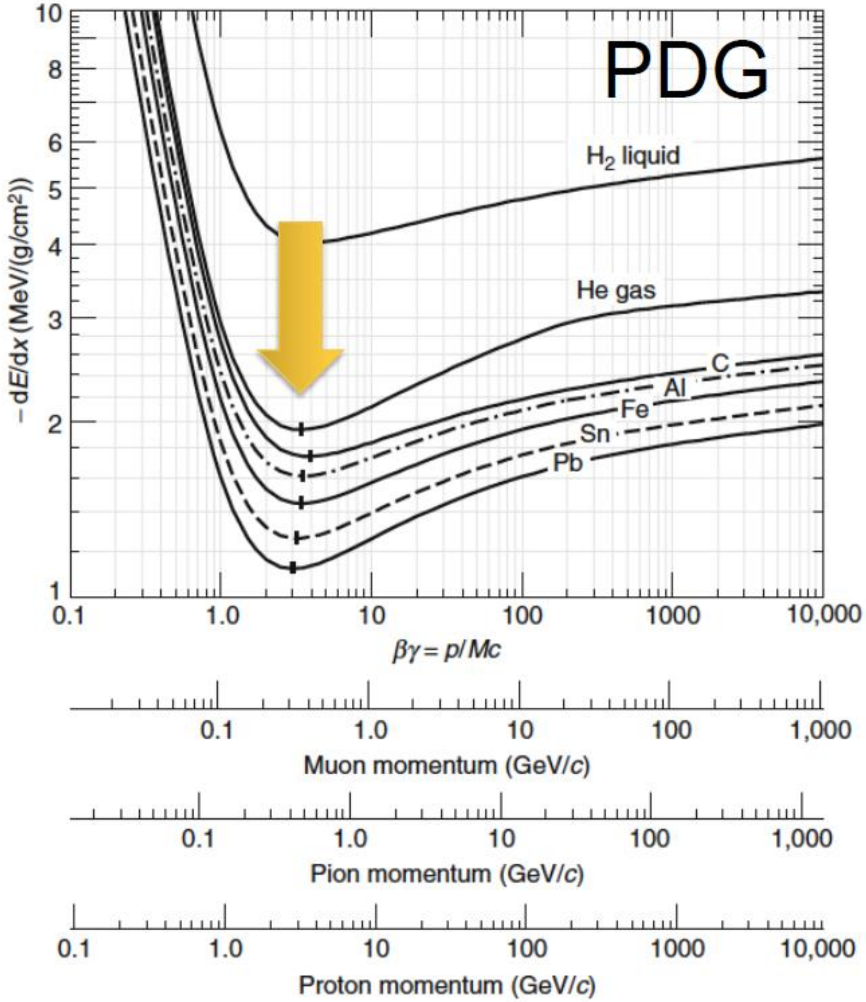
W_{max}= max. energy transfer in one collision

Bethe-Bloch formula

Low momentum: energy loss decreases as ~ $^1/_{\beta^2}$
(slow particles feel the EM pull of atomic electrons)
Reaches minimum
Then relativistic rise as $\beta\gamma>4$ to plateau (Transv E field increases. Density effects due to increased polarization/ shielding in medium)

A particle with dE/dx near the minimum is called a minimum ionizing particle – MIP

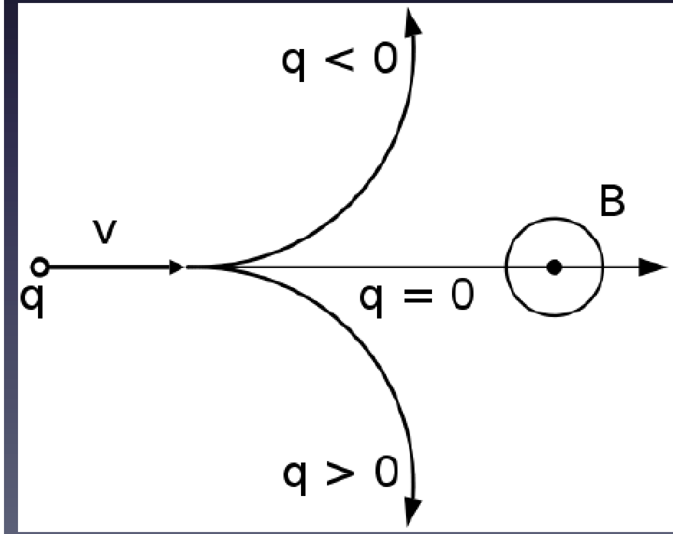
Notice that dE/dx in combination with momentum measurement can be used for particle ID!



Tracking

- Particle detection has many aspects:
  - Particle counting
  - Particle Identification = measurement of mass and charge of the particle
  - Tracking
- Charged particles are deflected by B fields:

$$\vec{F} = q\vec{v} \times \vec{B}$$

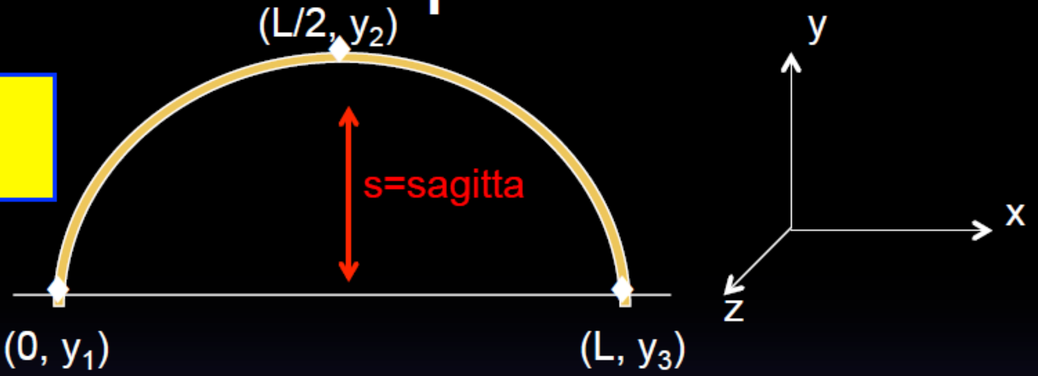


$$\rho = \frac{p_T}{q|B|} = \frac{\gamma m_0 \beta c}{q|B|}$$

- By measuring the radius of curvature we can determine the momentum of a particle
- If we can measure also β independently we can determine the particle mass.

Momentum and position resolution

Trajectory of charged particle



Assume: we measure y at 3 points in (x, y) plane (z=0) with precision σ_y and a constant B field in z direction so $p_\perp$=0.3Br.

$$s = y_2 - \frac{y_1 + y_3}{2} \approx \frac{L^2}{8r} = \frac{L^2}{8p_\perp/(0.3B)} = \frac{0.3BL^2}{8p_\perp}$$

The exact expression is

$$s = r - \sqrt{r^2 - \frac{L^2}{4}}$$

The error on the sagitta, σ_s, due to measurement error is (using propagation of errors):

$$\sigma_s = \sqrt{3/2}\,\sigma_y$$

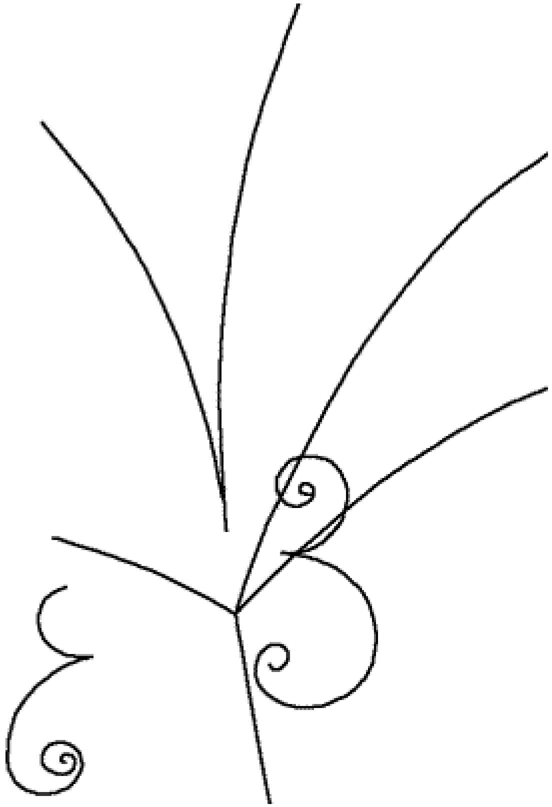
Thus the momentum ($\perp$ to B) resolution due to position measurement error is:

$$\frac{\sigma_{p_\perp}}{p_\perp} = \frac{\sigma_s}{s} = \frac{\sqrt{3/2}\,\sigma_y}{(0.3L^2B)/(8p_\perp)} = \frac{8p_\perp\sqrt{3/2}\,\sigma_y}{0.3L^2B} = 32.6\frac{p_\perp\sigma_y}{L^2B}\ \textbf{(m, GeV/c, T)}$$

Tracking detectors

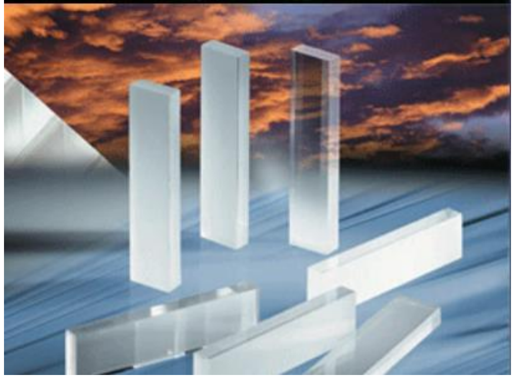
Many different implementations:

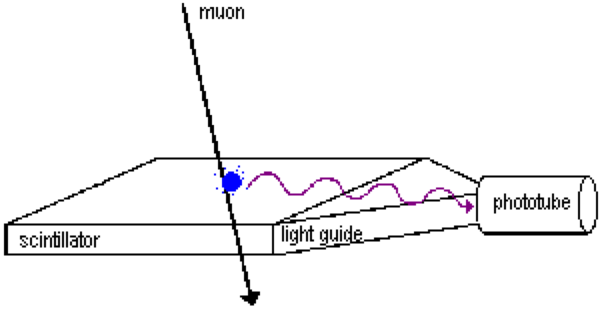
- Scintillators
  - Organic/inorganic crystals, plastic scintillator,
  - noble gases …
- Photo detectors
  - PMTs
- Gaseous detectors
  - Wire chambers , drift chambers, time projection chambers
- Semiconductors
  - Silicon ,strips or pixels



Scintillator trackers

- dE/dx converted into light that is then detected with photo-detectors
- Main features:
  - Sensitivity to energy
  - Fast time response
  - Pulse shape discrimination
- Requirements:
  - High efficiency for the conversion of excitation energy into fluorescent radiation
  - Transparency to this radiation
  - Emission of light in a frequency range detectable for photo-detectors
  - Short decay time for fast response





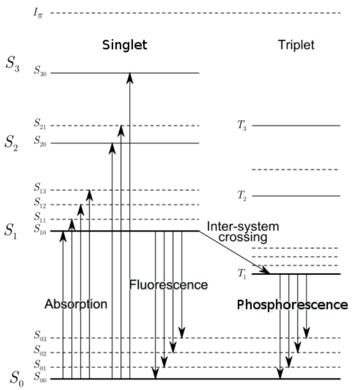
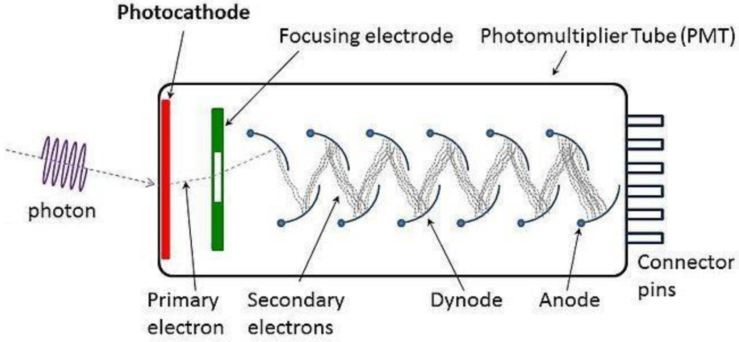
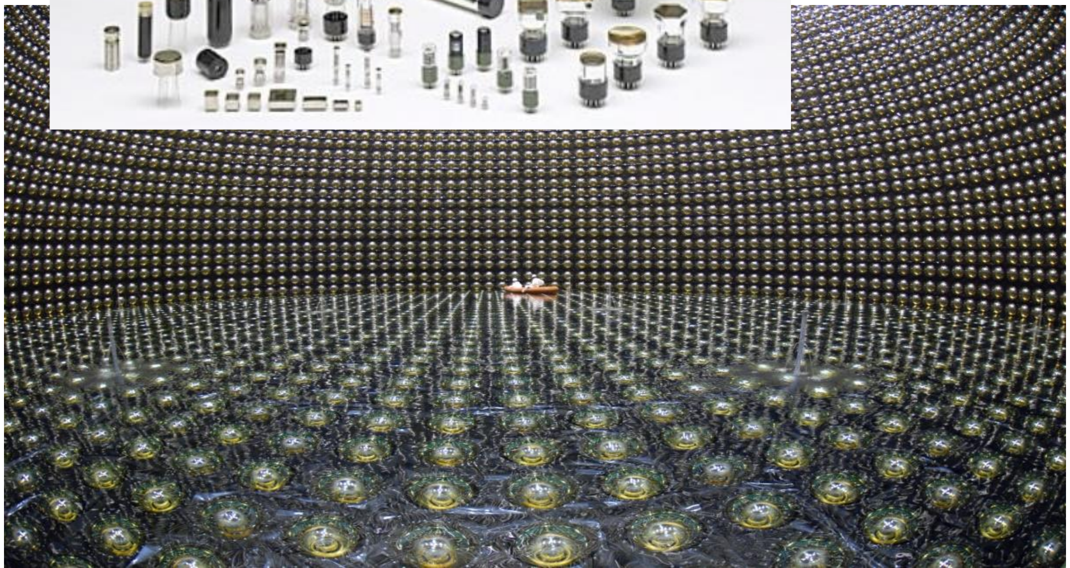


Photo-detectors

Convert light into an electronic signal using photo-electric effect (convert photons into photo-electrons

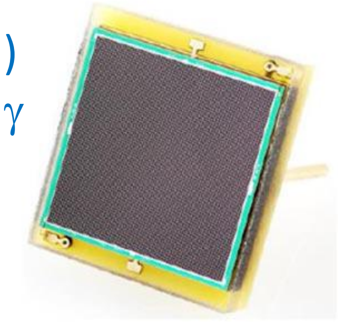
Need high-efficiency photon-detection!





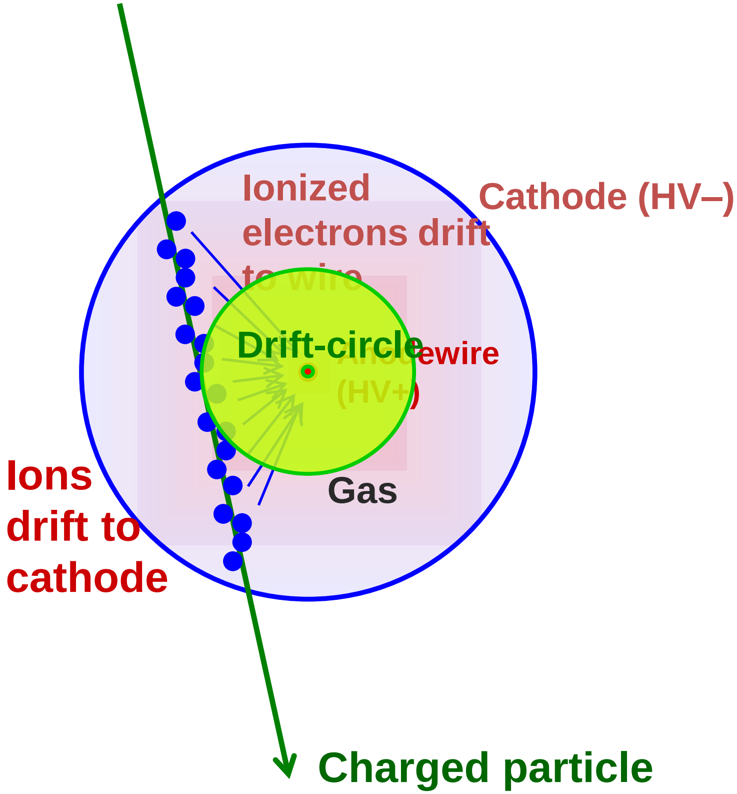
Photomultiplier tubes PMTs

Also SiPM, Silicon photomultipliers
Compact (few mm)
Sensitive to single γ

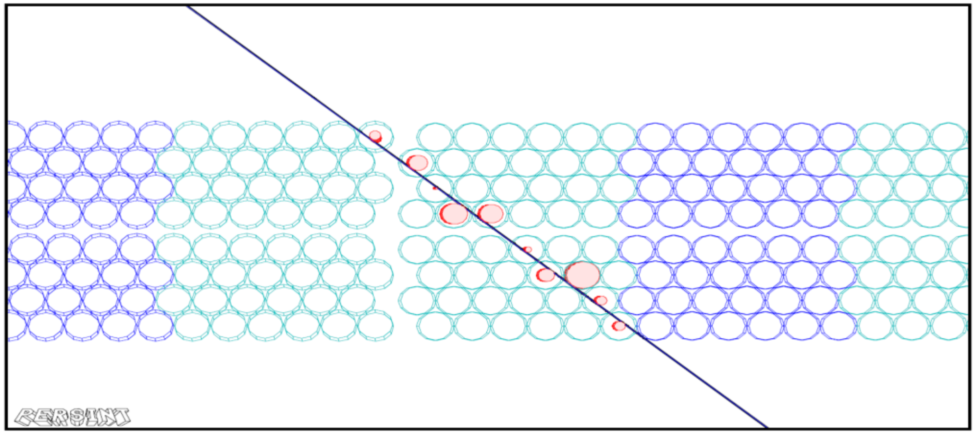


Drift tubes

Classical detection tecnique for charged particles based on ionization of gas and measurement of the drift-time

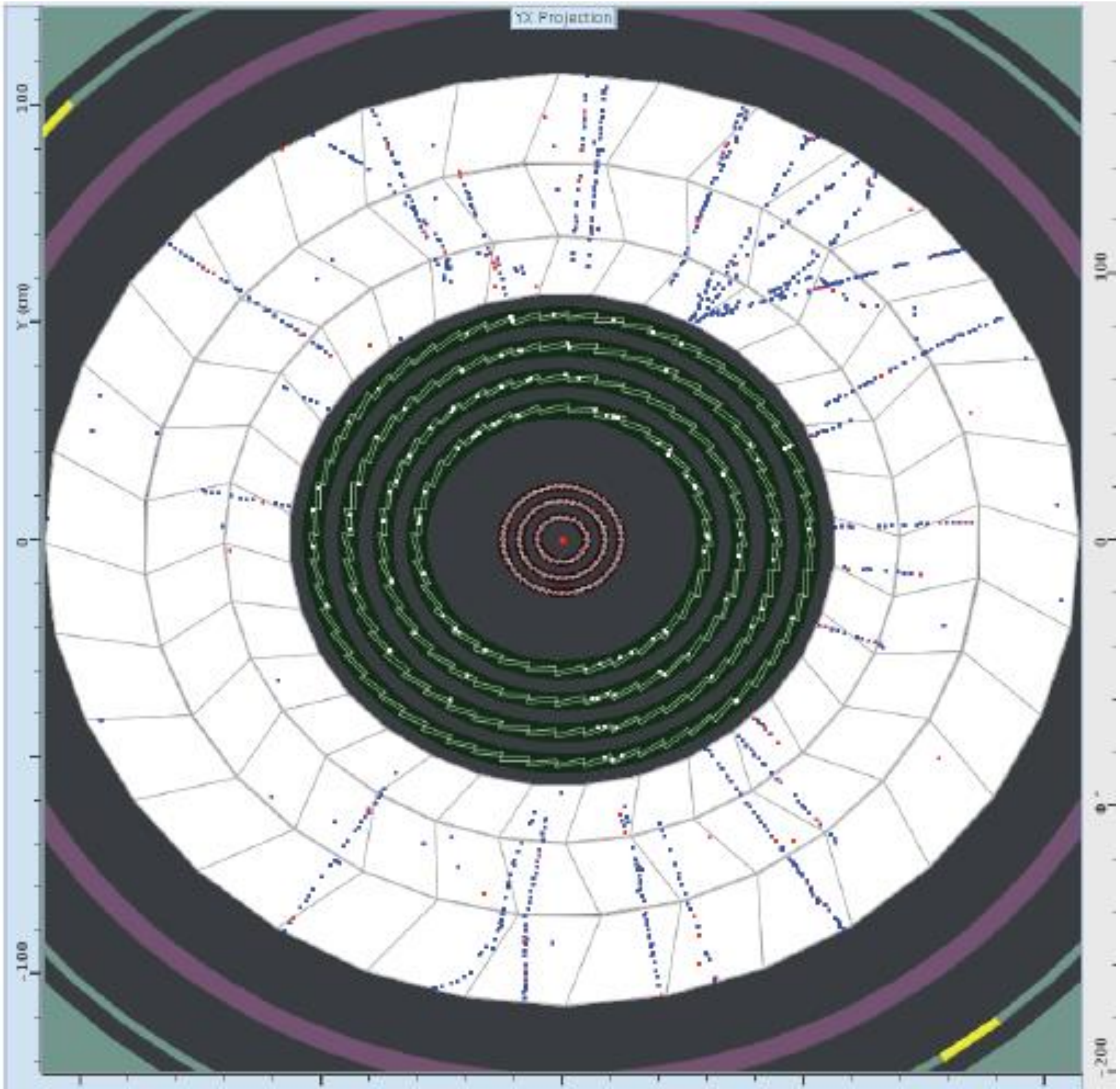


Example: muon passing muon drift tubes

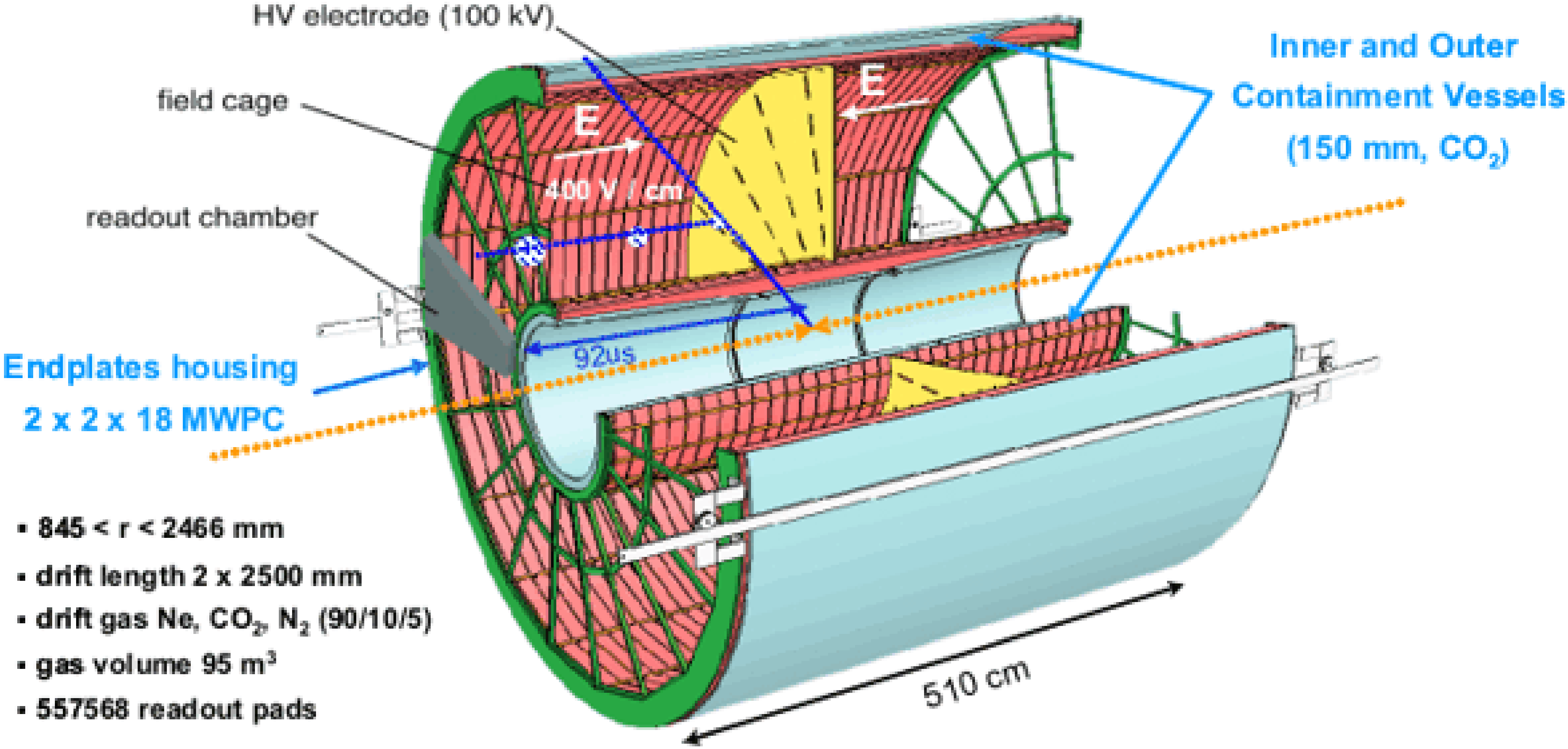


TRT: Kapton tube, ∅ = 4 mm
MDT: Aluminium tube, ∅ = 30 mm

Example drift tube chamber: the ATLAS tracker



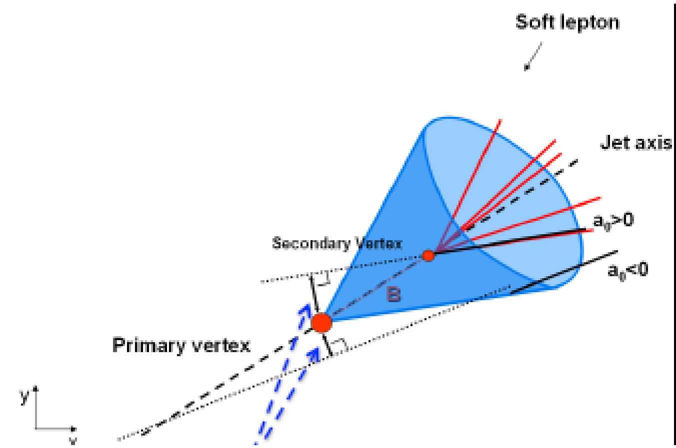
The ALICE TPC



- 845 < r < 2466 mm
- drift length 2 x 2500 mm
- drift gas Ne, CO_2, N_2 (90/10/5)
- gas volume 95 m^3
- 557568 readout pads

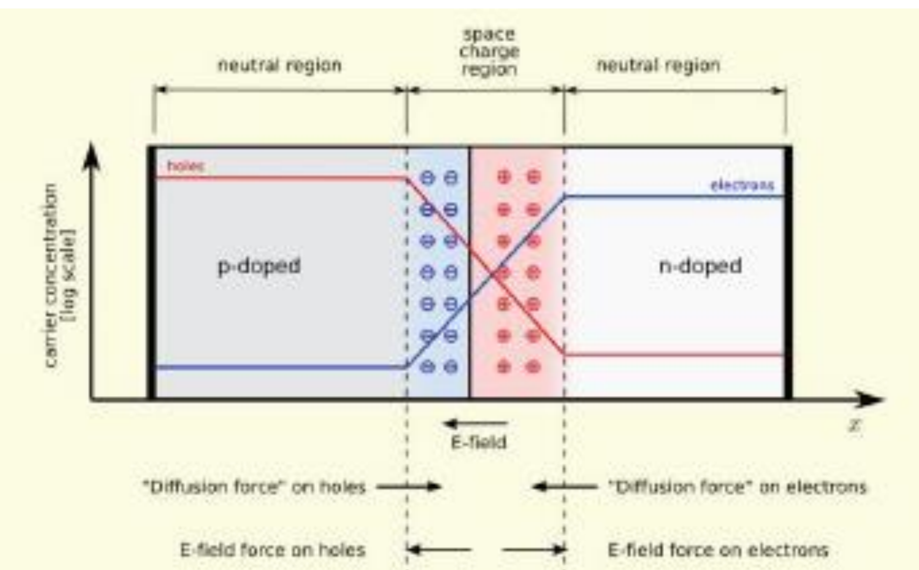
Silicon detectors

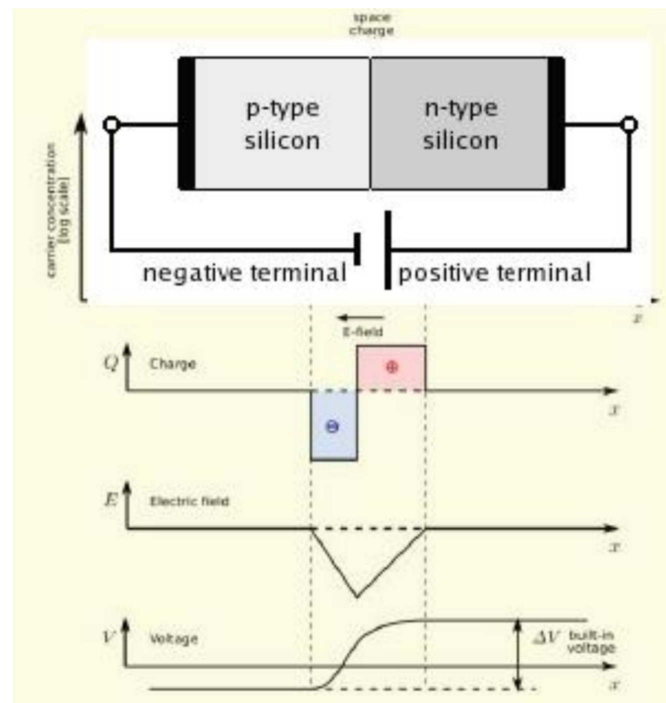
Ionization detector for greater precision & vertexing



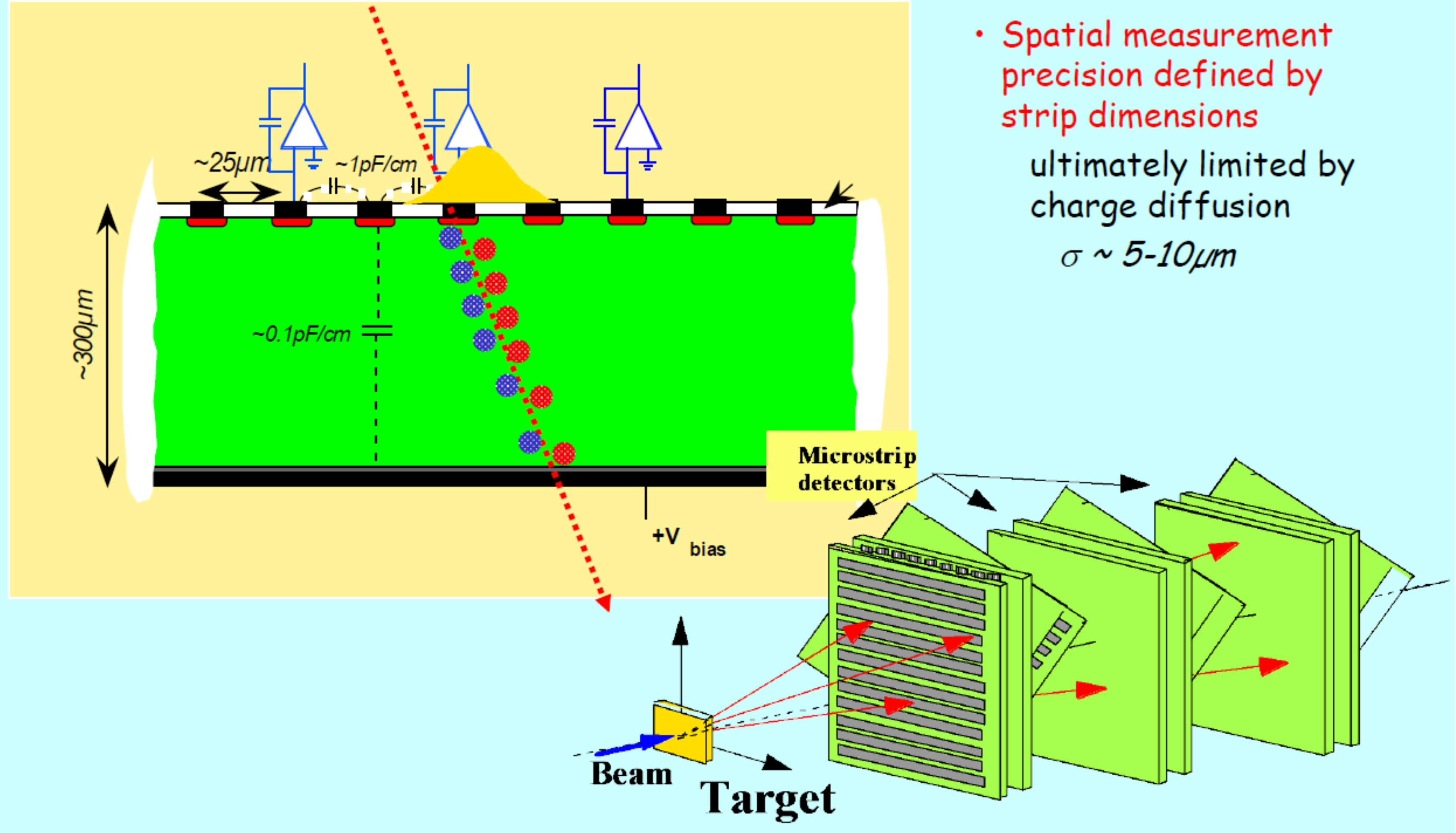
Impact parameter

p-n junction w/o external voltage:
limited sensitive region (depletion zone)





Silicon diodes as position detectors

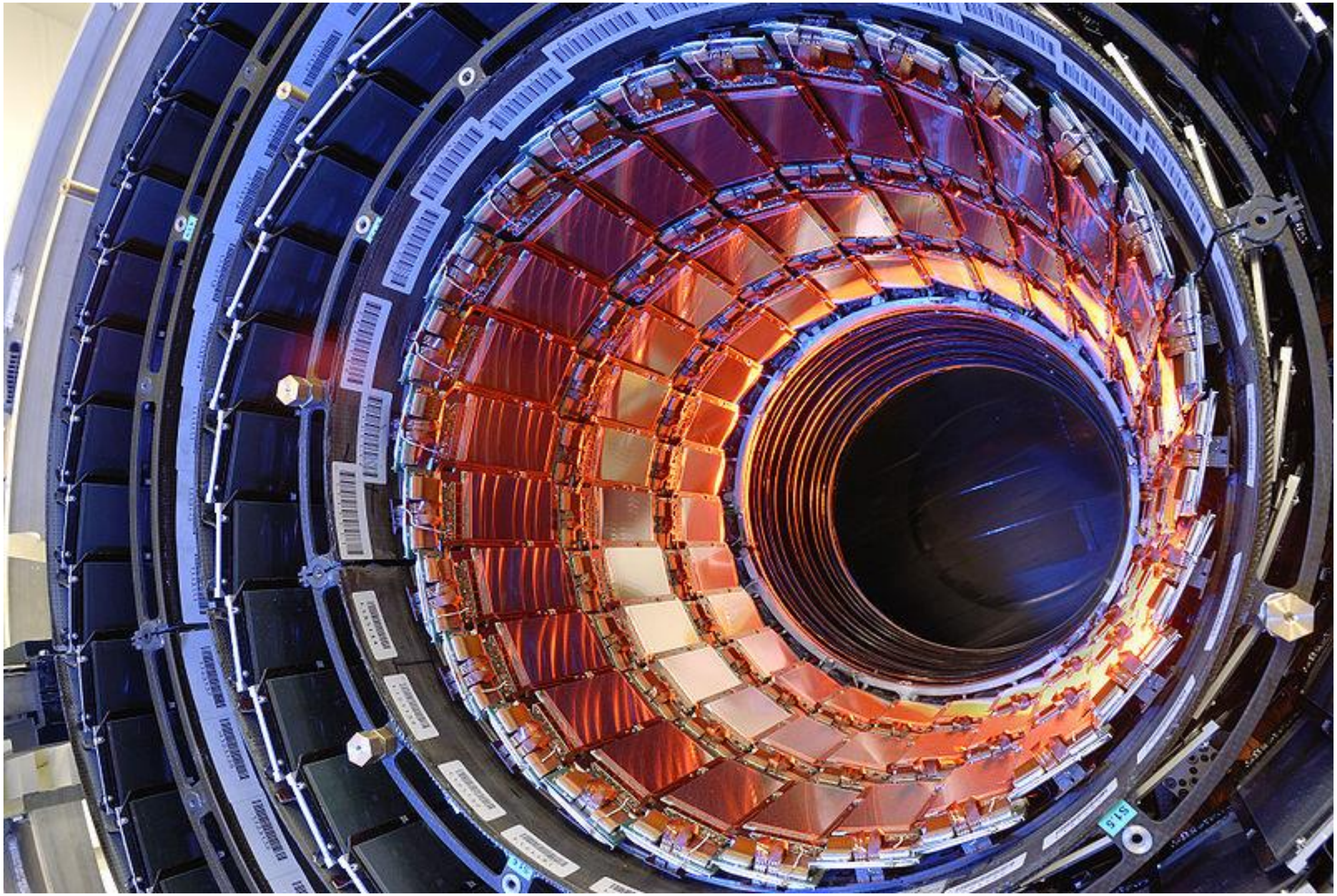


- Spatial measurement precision defined by strip dimensions

  ultimately limited by charge diffusion

  $\sigma \sim 5\text{-}10\mu m$

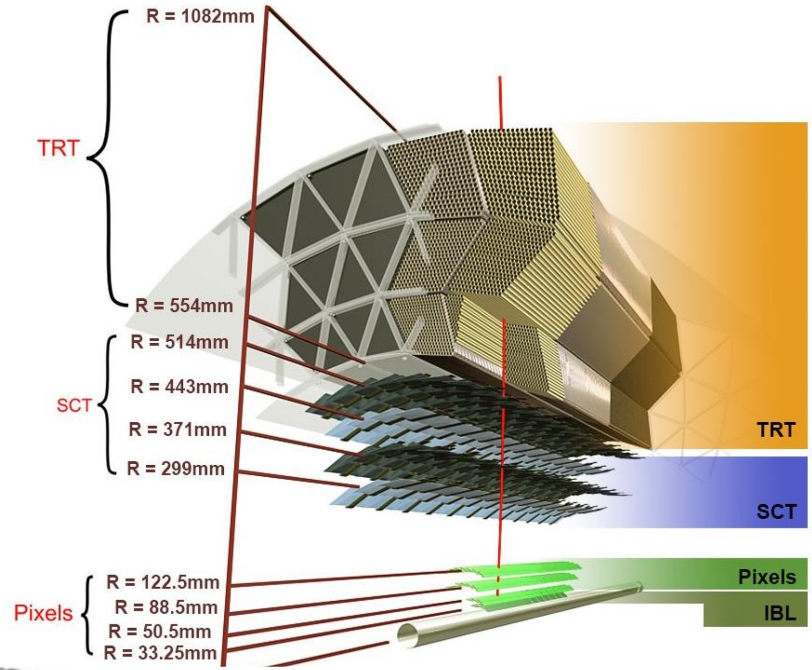
CMS Si detector

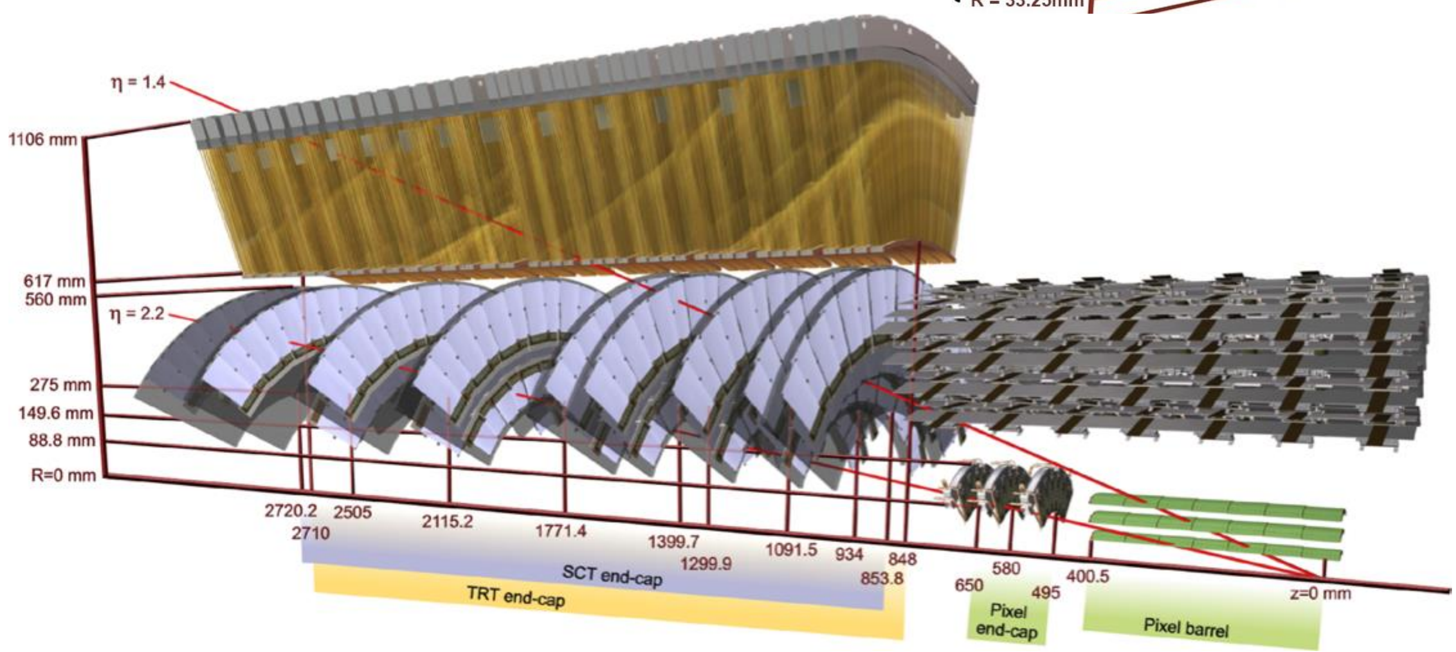


Tracking in ATLAS

	Pixel	SCT	TRT
barrel layers	3	4	72
end-cap layers	2*3	2*9	2*160
∅ hits / track	3	8	~30
element size [µm]	50x400	80	4 mm
resolution [µm]	10x115	17x580	130
channels	8*10e7	6.3*10e6	3.5*10e5

5 track parameters: d_0, z_0, ϕ_0, θ, q/p





For good tracking, needs:

- p resolution $\frac{\sigma(p_T)}{p_T} \sim p_T \frac{\sigma_{meas}}{B.L^2 \sqrt{N_{pts}}}$

  large B and L

- high precision space points

  detector with small intrinsic σ_{meas}

- well separated particles

  good time resolution

  low occupancy => many channels

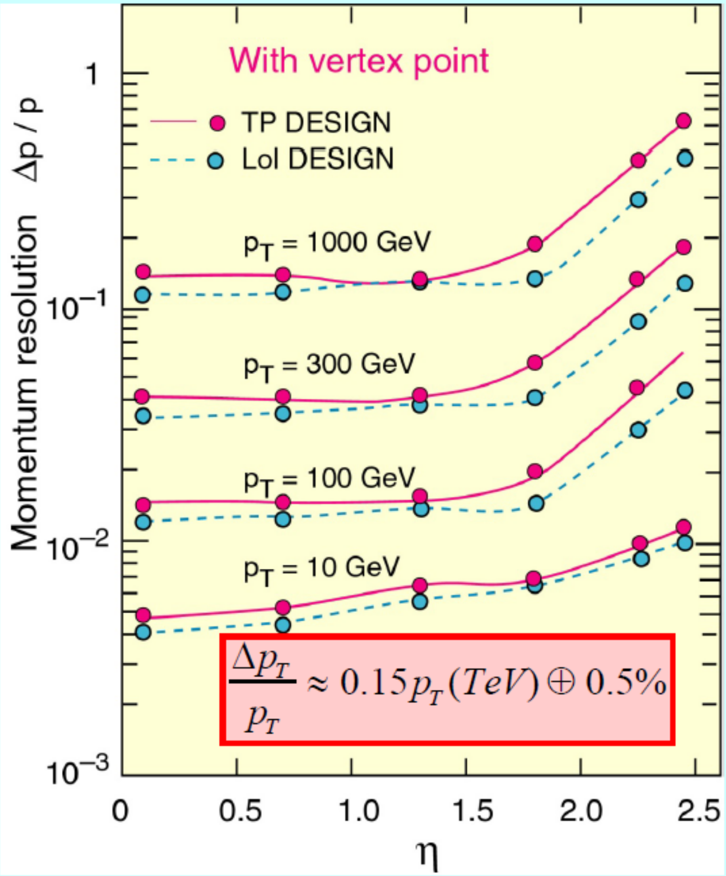
  good pattern recognition

- minimise multiple scattering
- minimal bremsstrahlung, photon conversions

  material in tracker

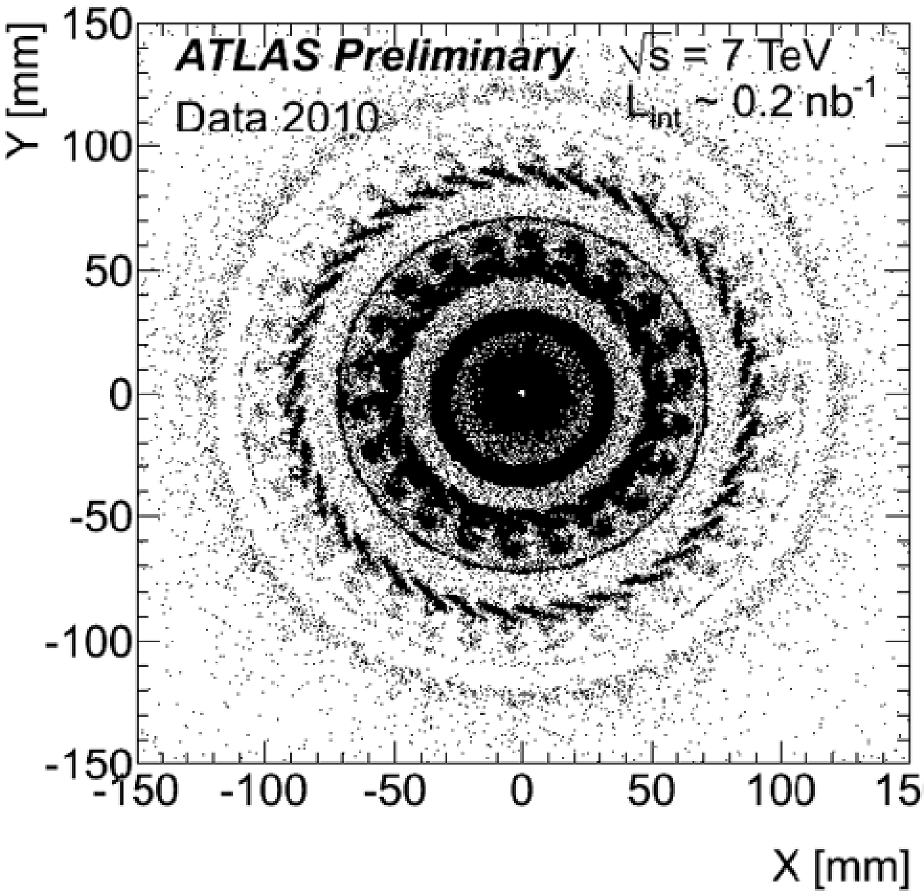
  most precise points close to beam

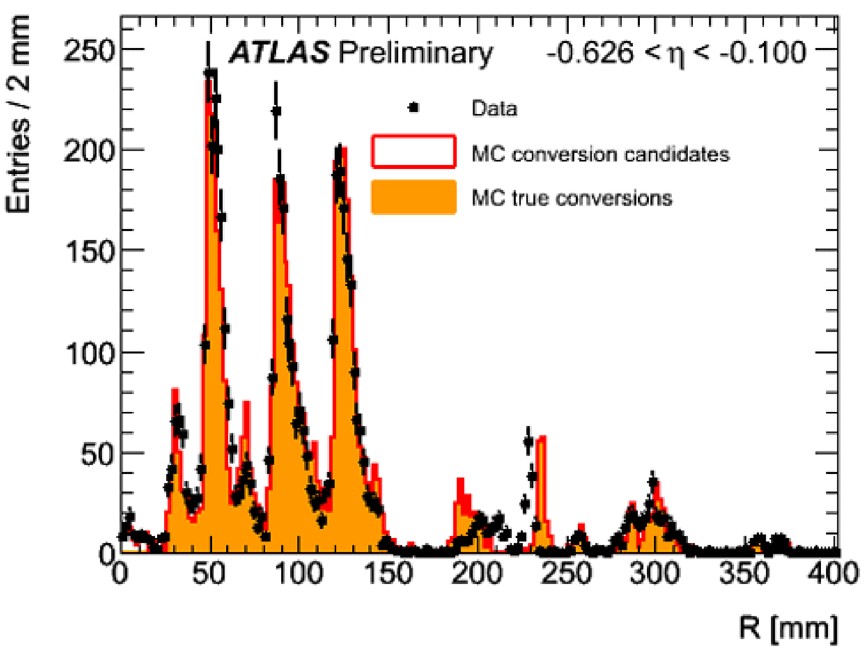
CMS example



The ATLAS tracker as seen by photon conversions

Reconstructed photon conversions show clearly the location of (Si) tracking modules!





(Preliminary) Summary

- ✓Reminders of often-used variables
- ✓Need several different techniques to uncover particles identities
- ✓Today discussed possibilities for detecting charged particles
  - ✓Si trackers and drift chambers are the most frequently used
- ✓Good performance requires optimization in several parameters
- ✓More tomorrow …

Today & tomorrow:

- Reminders
  - Cross section
  - Rapidity \ pseudo-rapidity
  - Bethe-Bloch ionization
- More about tracking and trackers
  - Types, resolution
- More about calorimeters
  - Types, resolution
- Some particle identification strategies

- Triggers

Accelerating particles

Lorentz force law

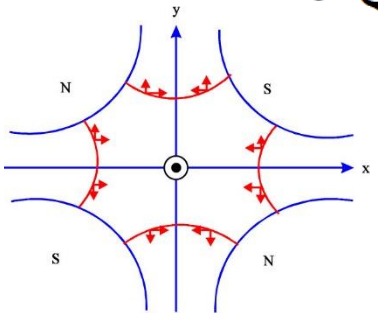
$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

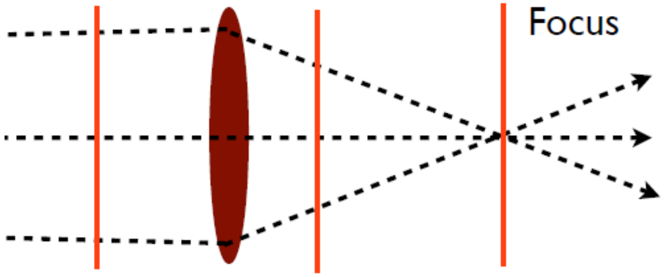
Electric field Velocity Magnetic field

Energy change

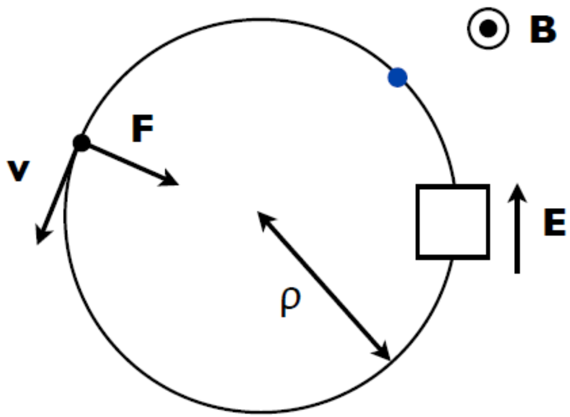
$$\Delta E = \int_{\mathbf{r}_1}^{\mathbf{r}_2} \mathbf{F} \cdot d\mathbf{r}$$

- 2nd year electromagnetism
  - Electric field (either static, or more commonly, time varying) to accelerate, or more appropriately, increase energy of beam
  - Magnetic part of Lorentz force used to guide and focus
    - Dipole magnets : to bend
    - Quadrupole : to focus or defocus





The synchrotron



Velocity

$$qBv = \frac{m_0 v^2}{\rho}$$

Magnetic field

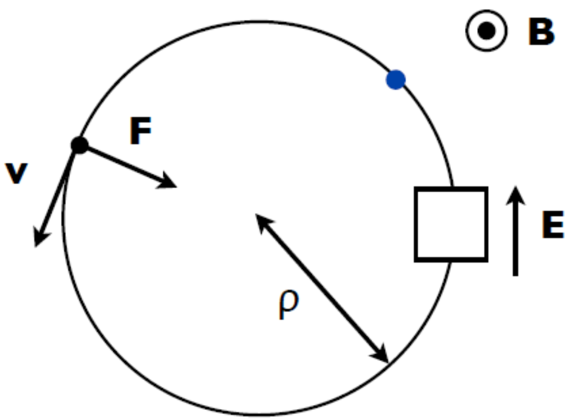
Bending radius

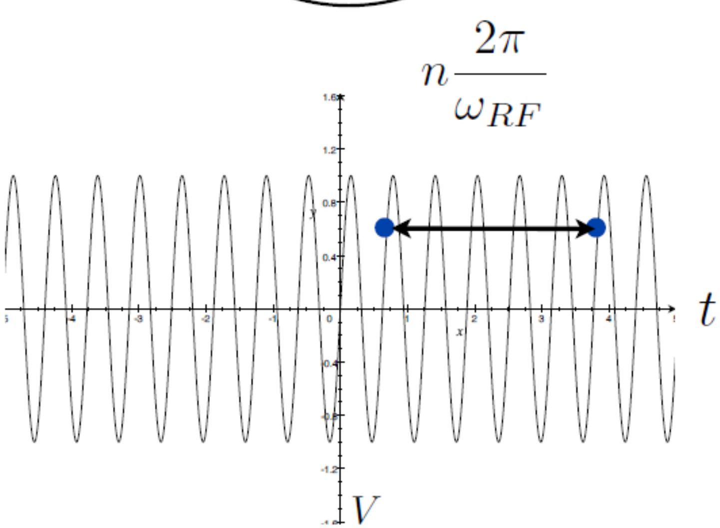
$$B\rho = p/q$$

Momentum

- Work horse of modern particle physics
  - Huge legacy of discovery
    - W/Z, Gluon, Higgs, SUSY?
  - Increase energy whilst synchronously increasing bending magnet strength
  - Stable storage of high beam current/power
- Magnetic field proportional to momentum

The synchrotron





- Time varying electric field:

$$V(t) = V_0 \sin(\omega_{RF} t + \phi)$$

Angular frequency of accelerating field

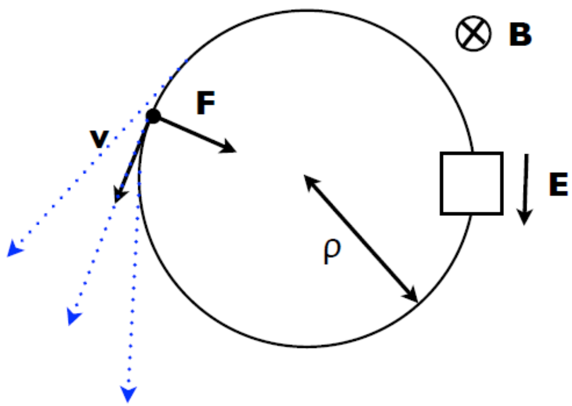
- Particle gets a kick every revolution

$$\frac{1}{f_{\text{ref}}} = n \frac{2\pi}{\omega_{\text{RF}}}$$

Revolution frequency

Integer

- As you know, circular colliders have the problem of synchrotron radiation



Power

$$P = \frac{1}{4\pi\epsilon_0}\frac{e^2 v^4}{c^3\rho^2}\gamma^4$$

Energy loss per turn

Beam energy

$$W = 8.85 \times 10^{-5} E^4/\rho$$

Magnetic radius

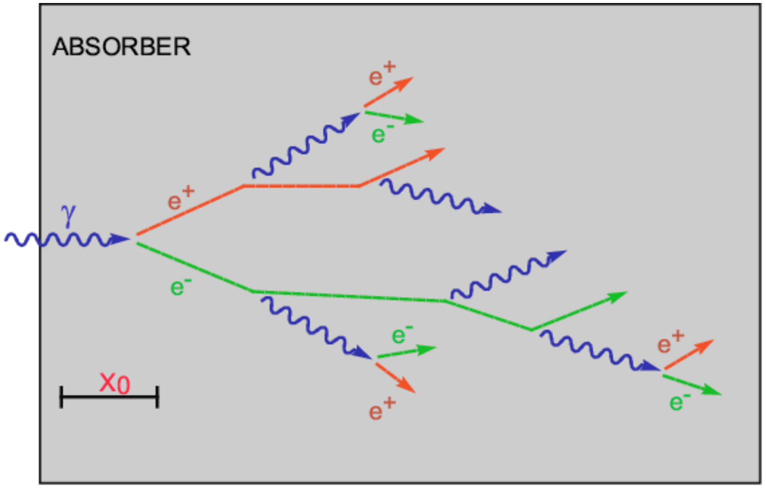
Goes as $1/m^4$ so not a problem for the LHC but practical limit for e+e- reached already

Linear colliders do not have this problem
But other practical problems (such as sheer size, loss of beam particles after collisions, steep accelerating gradient etc)

Calorimeters

Measures th energy of ***both*** charged and neutral particles!

Measured via secondary cascades



The relative energy resolution

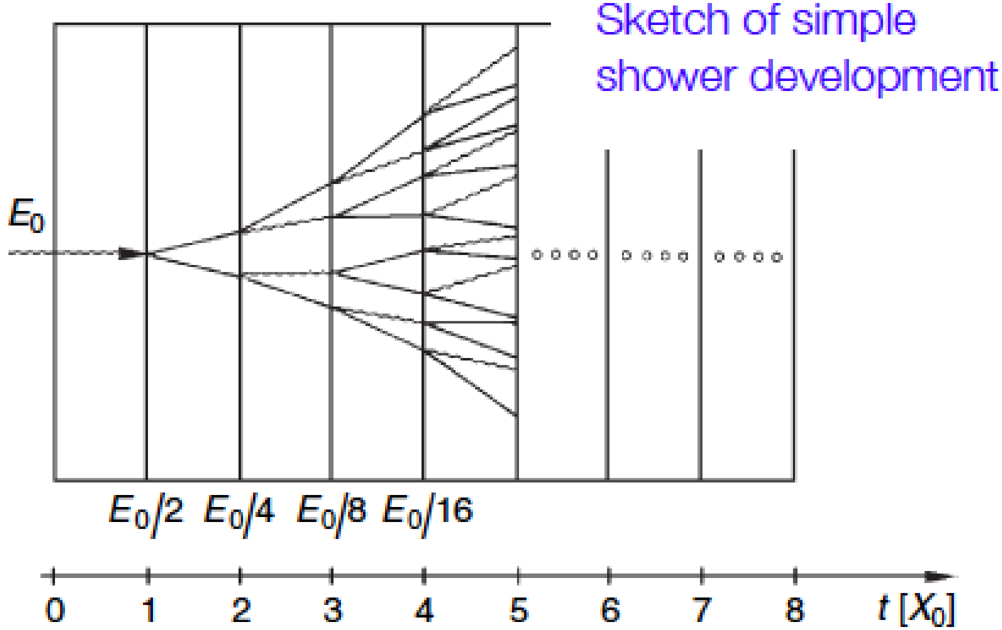
improves with E:

$$\frac{\sigma}{E} \propto \frac{1}{\sqrt{n}} \propto \frac{1}{\sqrt{E}}$$

(n = #secondary cascade particles)

In contrast to momentum resolution

Analytic shower model



Location of stop

$$t_{\max} = \frac{\ln(E / Ec)}{\ln 2} \propto \ln\left(\frac{E}{E_c}\right)$$

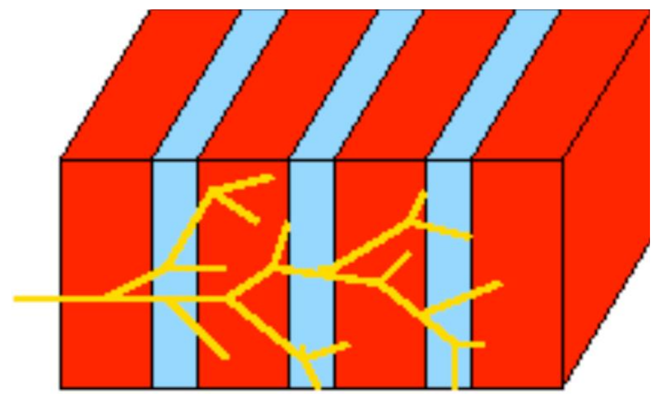
Initial energy

$$N_{\max} = 2^{t_{\max}} = \frac{E_0}{E_C}$$

Types of calorimeters

- Homogeneous calorimeter:
  - Simpler geometry, simpler corrections
- Sampling calorimeter:
  - *Pro:* Depth and spatial segmentation
  - *Con*: only sampling a fraction of the shower, less precise, fluctuations
- Both need multiple corrections for non-uniformities etc

Pb crystal



$$f_{sampling} = \frac{E_{visible}}{E_{deposited}}$$

Energy resolution

- For EM calorimeters we can parameterise the resolution as

$$\left(\frac{\Delta E}{E}\right)^2 = \left(\frac{a_0}{E}\right)^2 + \left(\frac{a_1}{\sqrt{E}}\right)^2 + b^2$$

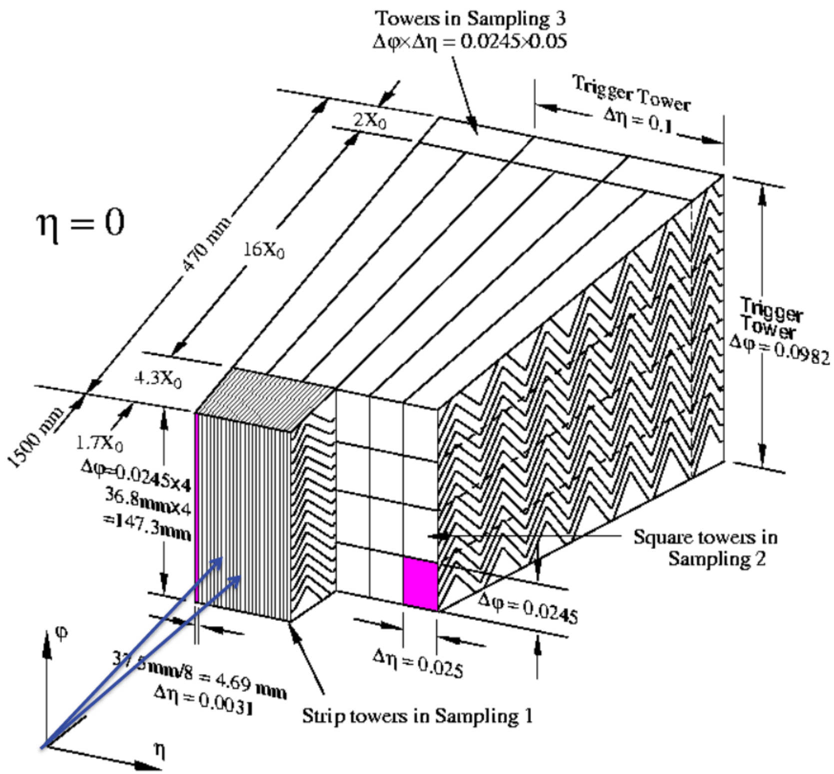
Systematic (or "constant") term

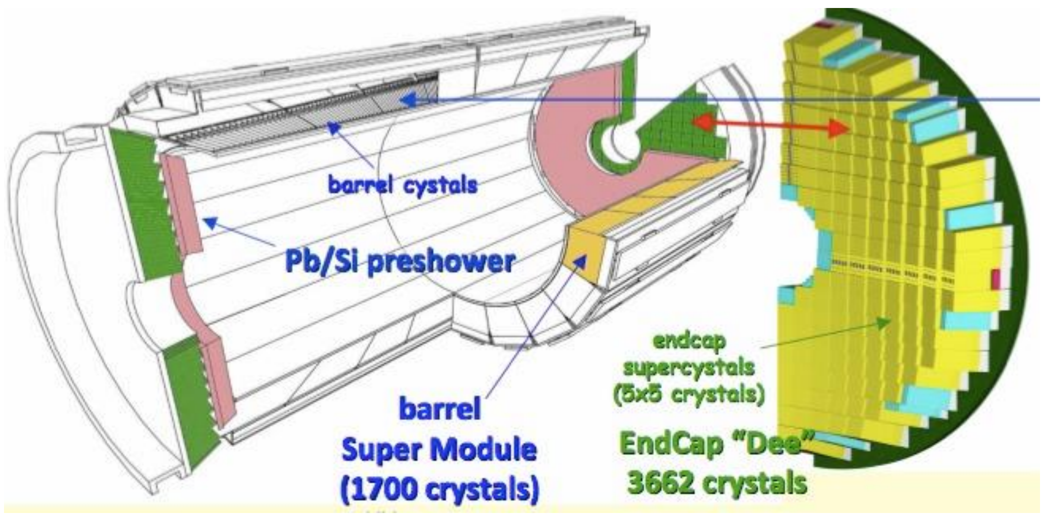
Electronic noise summed over a few channels (3x3 or 5x5 typically)

Photoelectron statistics (Poisson)

For sampling calorimeters also additional effects : since only a fraction of the total energy is sampled

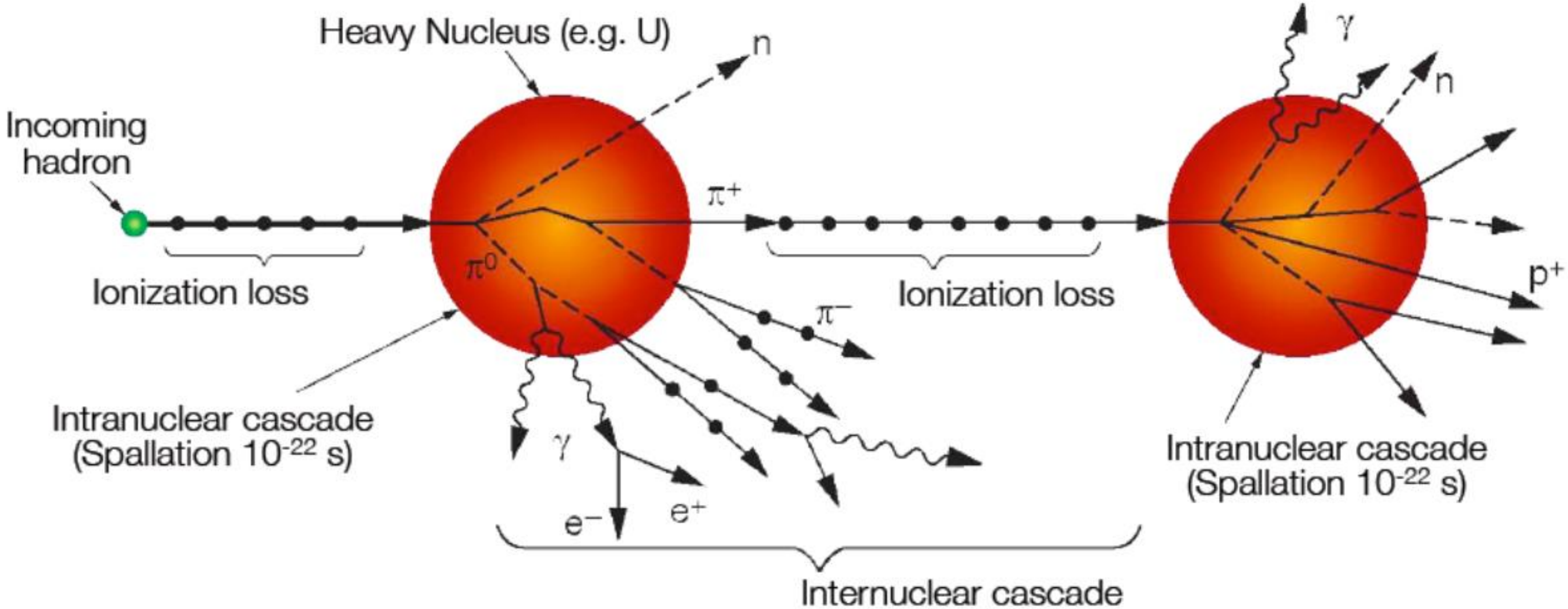
Pictures of ATLAS and CMS calorimeters





3x difference in sampling terms – other resolution terms similar

Hadron calorimeters



Both strong and EM deposits + large fraction undetected

Effect on resolution:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b\left(\frac{E}{E_0}\right)$$

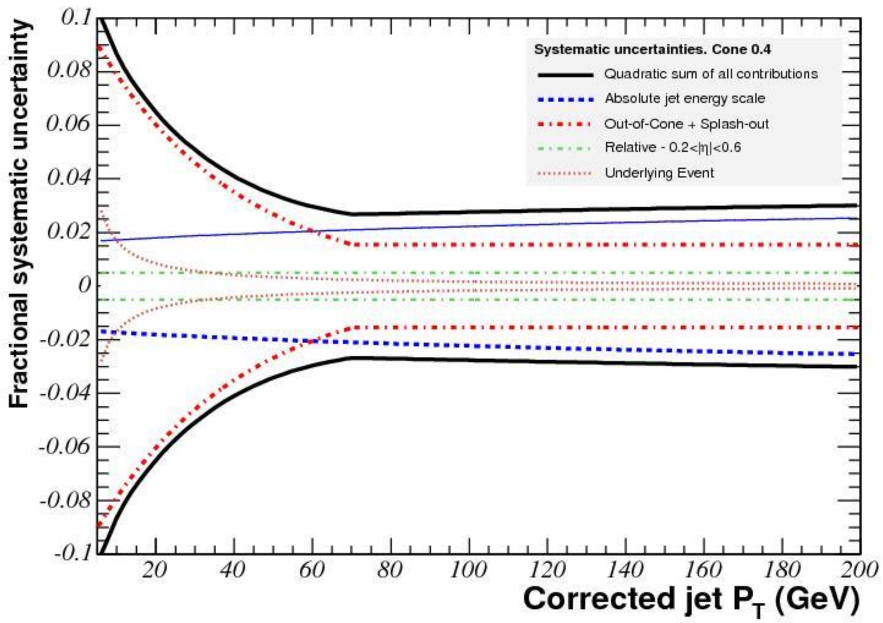
What we actually use

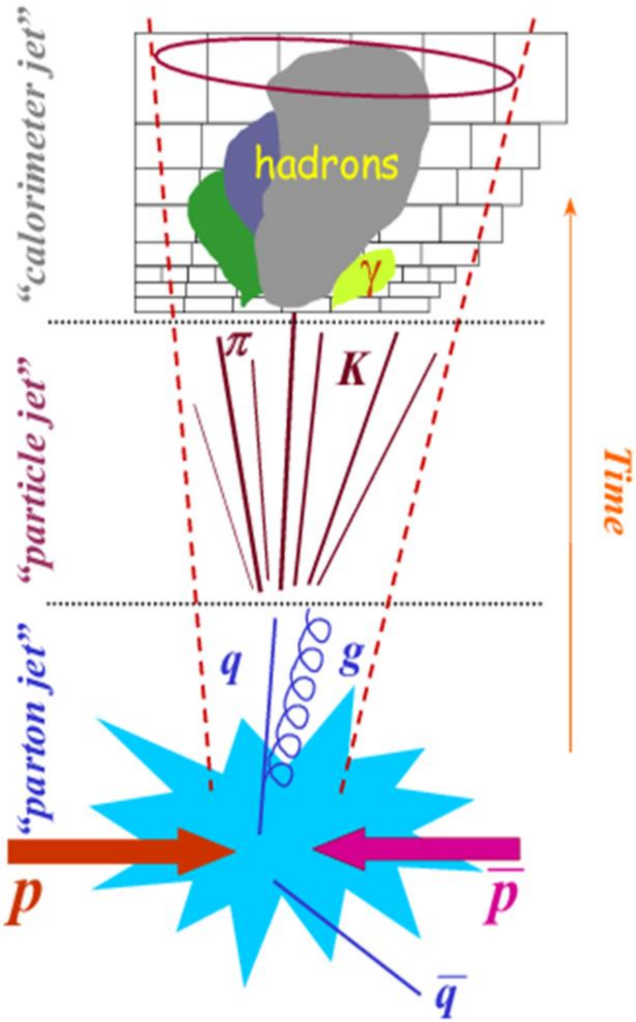
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b$$

Corrections: Jet energy scale

Select dijet events to study corrections:

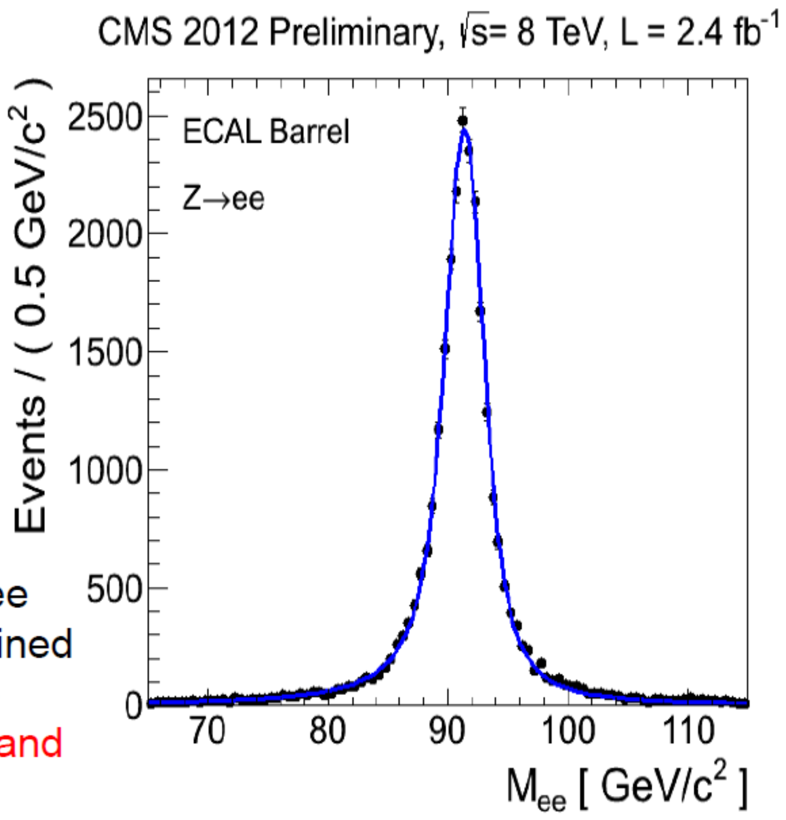
- EM vs hadron behavior
- Non-uniformity in response
- Pile-up
- Underlying event
- ”out-of-cone” corrections





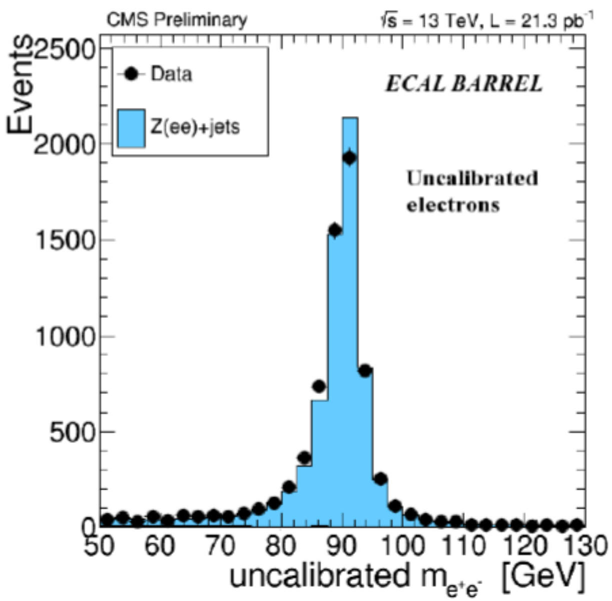
CMS: Effect of corrections electrons

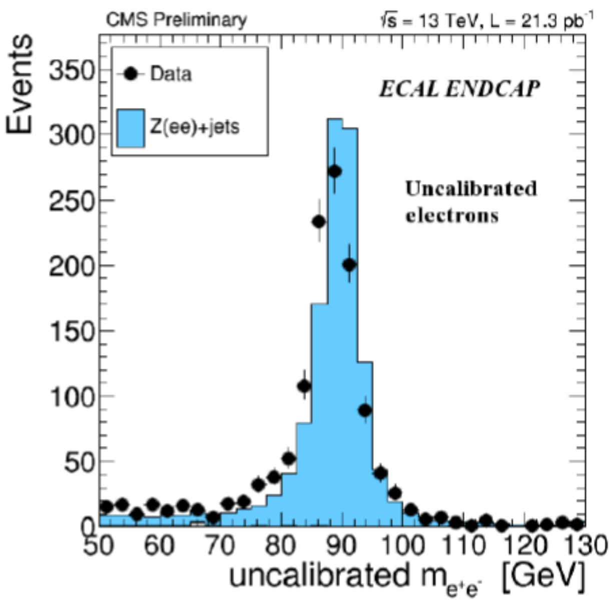
Instrumental resolution in barrel is 1 GeV at the Z peak



The plot shows the improvements in Z->ee energy scale and resolution that are obtained from applying energy scale corrections to account for the intrinsic spread in crystal and photo-detector response, and time-dependent corrections to compensate for crystal transparency loss

Same experiment, first (not fully corrected) 13 TeV results

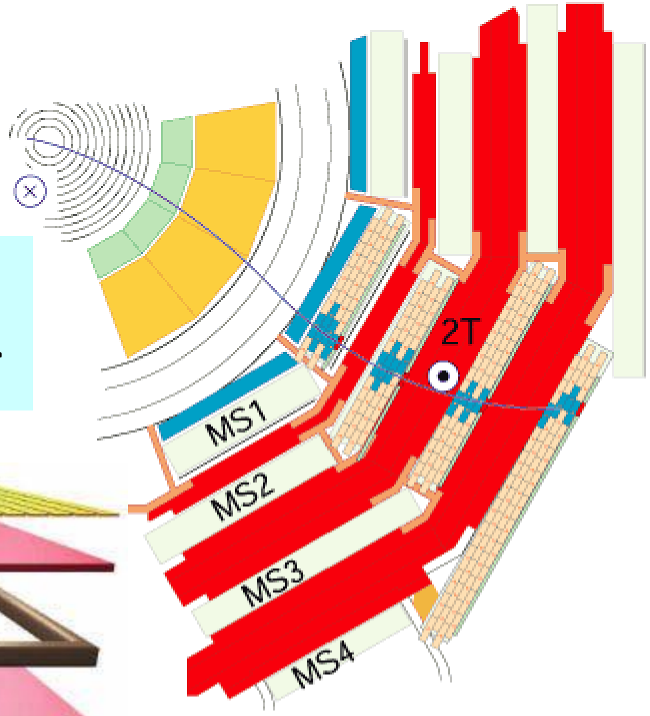


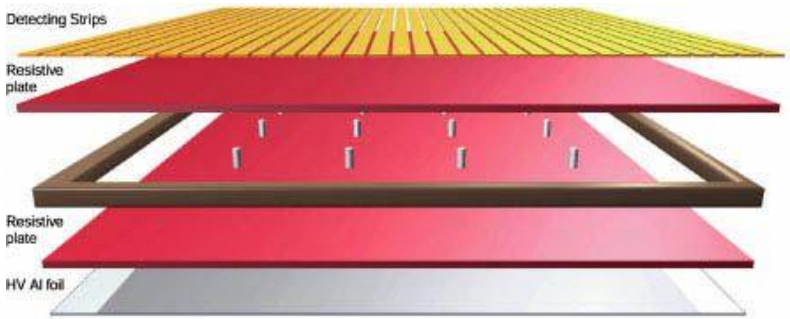


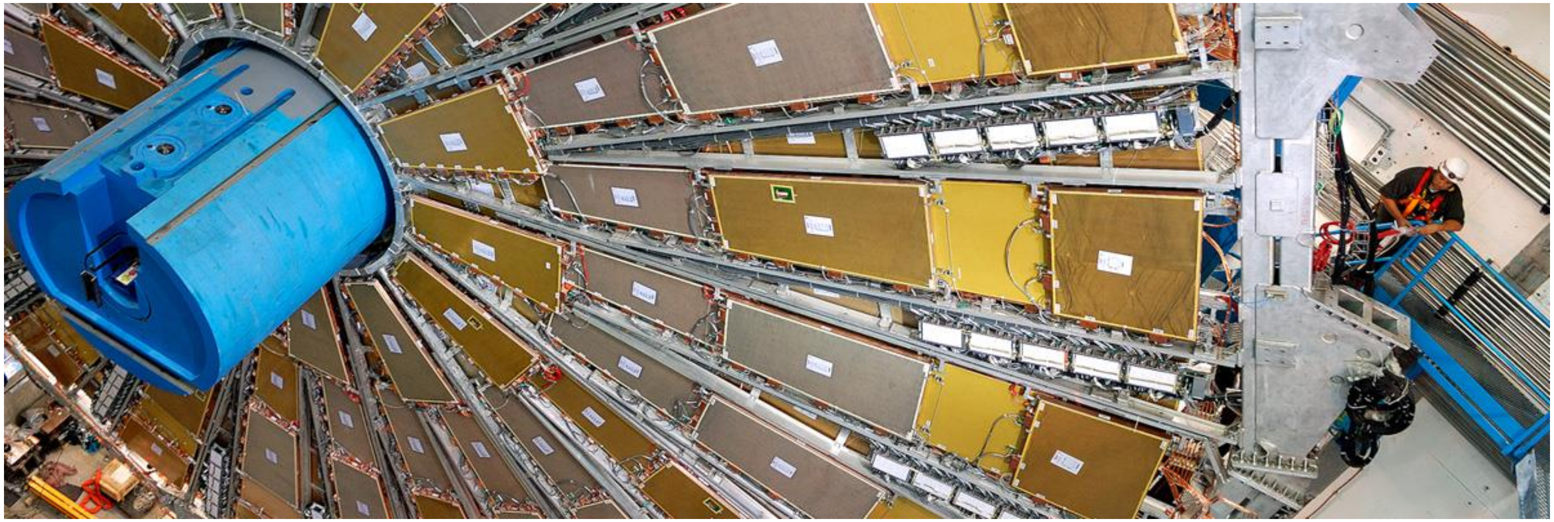
Non-optimised data (shown at EPS conference) from early Run 2 data in 2015. MC number is normalised to data and calibration is based on an extrapolation from Run 1 constants.

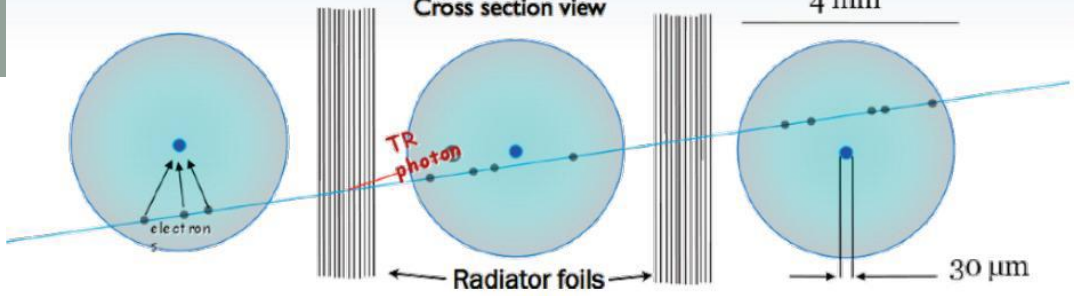
Muon chambers

Muon tracking
(much) Larger scales than for inner detector







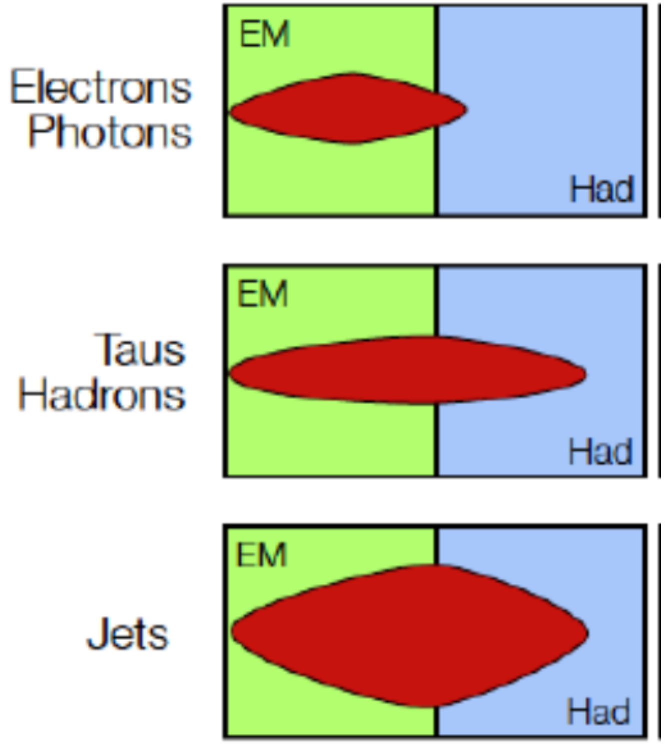


Particle ID

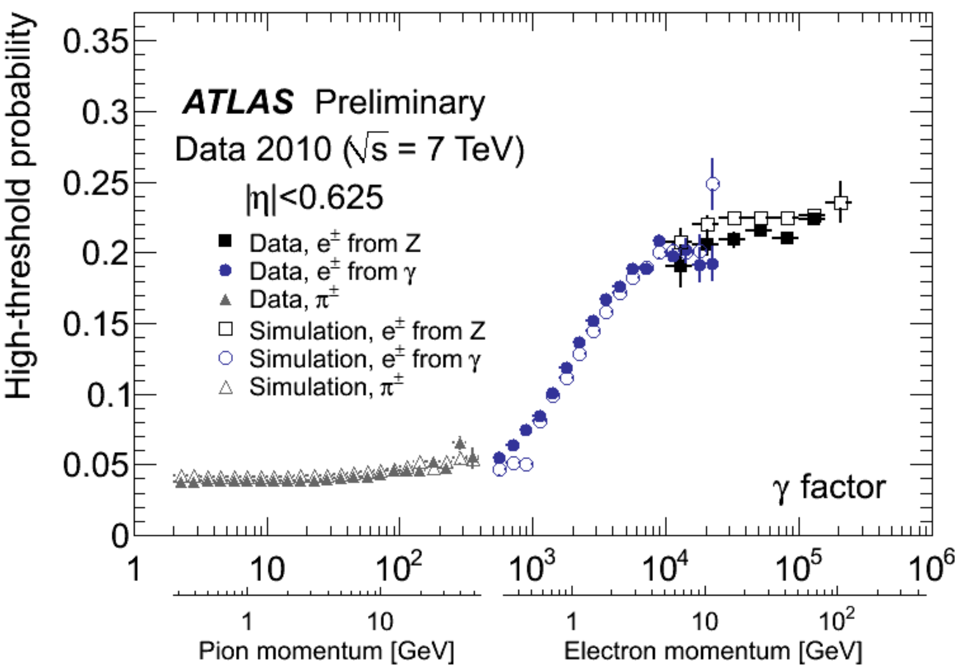
We use the combination of information to identify particles

For instance:

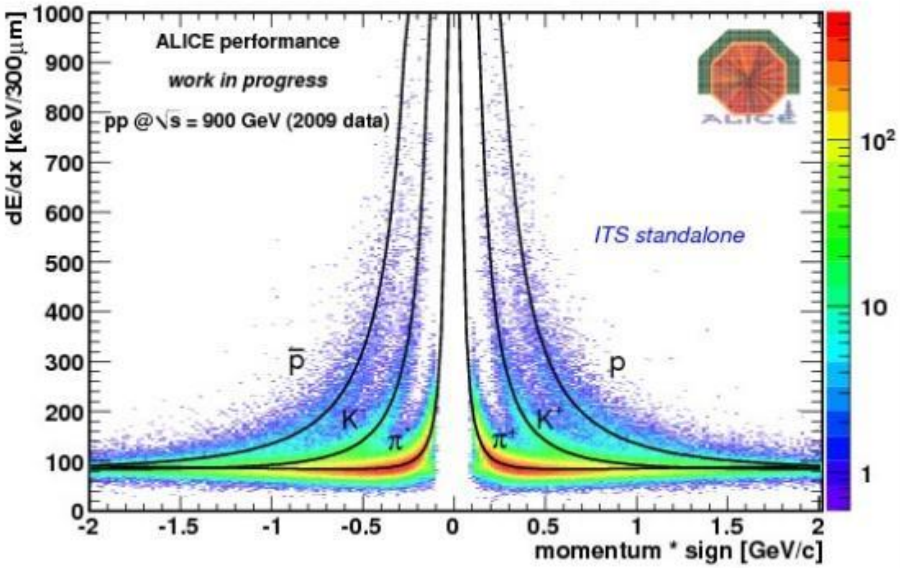
Shower shapes:

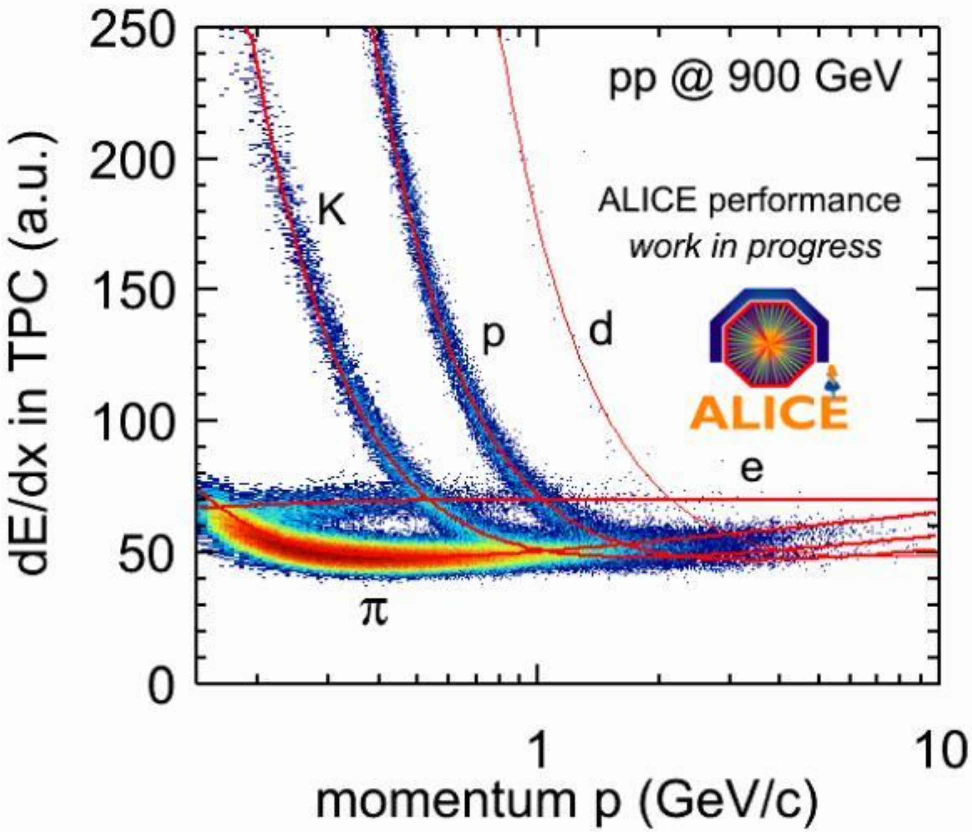


Transition radiation:



Particle ID from ALICE



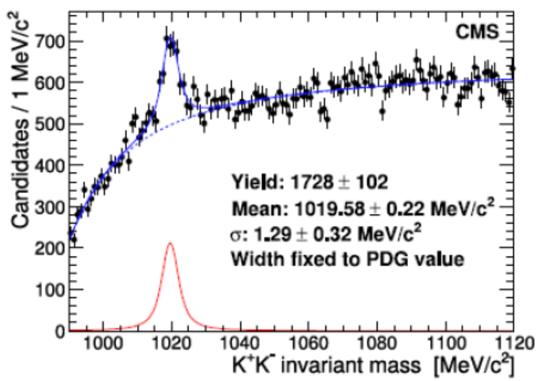


Slide from CMS

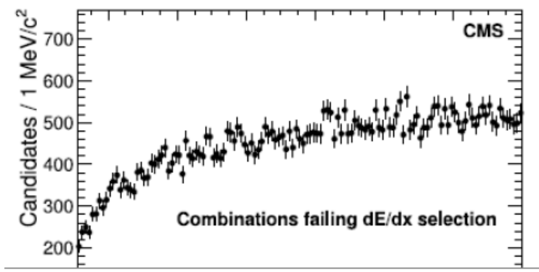
dE/dx

- Using dE/dx data to fit the KK invariant mass distribution to detect the ϕ(1020).

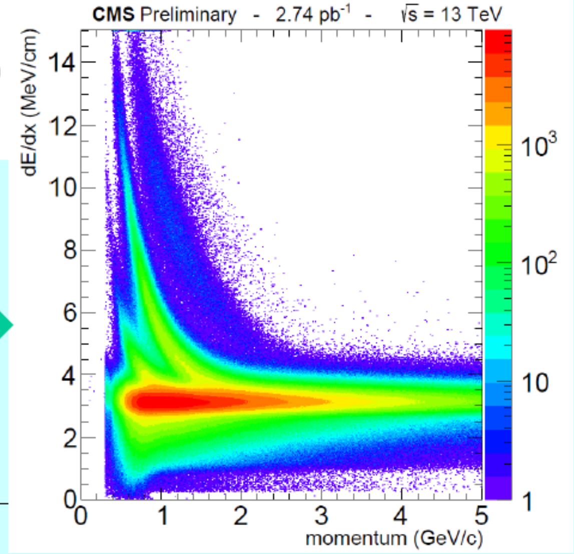
Fig. 15 K^+K^- invariant mass distribution, with (**a**) both kaons satisfying the dE/dx requirement and with (**b**) at least one particle failing that requirement. In (**a**) a fit to the $\phi(1020)$ hypothesis is shown



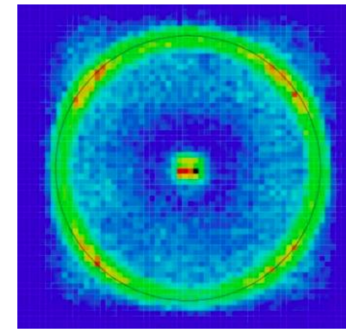
(a)



13 TeV data



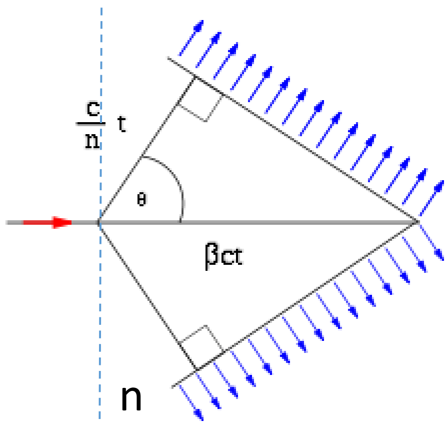
Particle ID with Cherenkov detectors

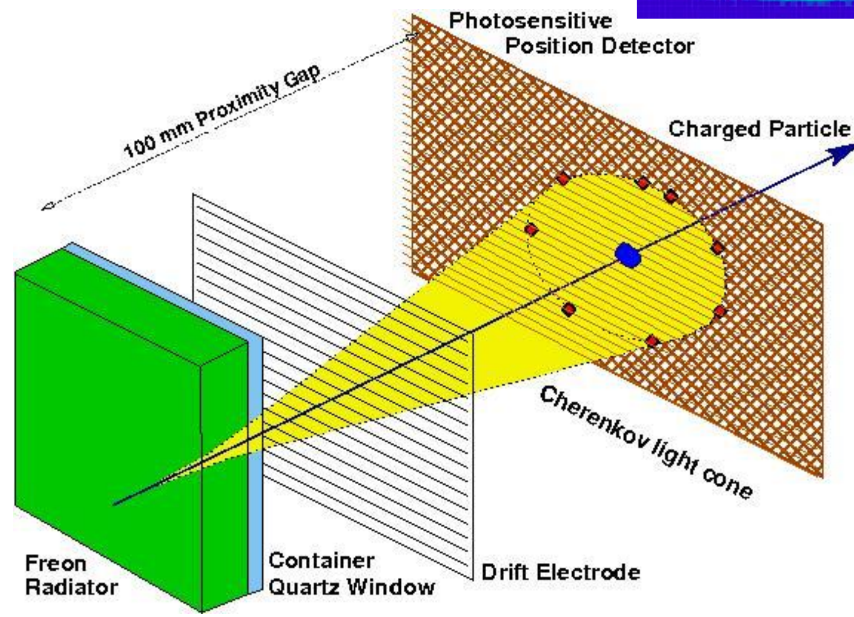


Charged, relativistic particles in dielectric

Polarization effect, Cherenkov photons emitted only if

$v_p > \frac{c}{n(\lambda)}$, where n(λ) is the refractive index





Simple geometric derivation gives the Cherenkov angle

$$cos\theta_c = \frac{1}{n(\lambda)\beta}$$

Detector examples: Super-K , IceCube

Cherenkov - applications

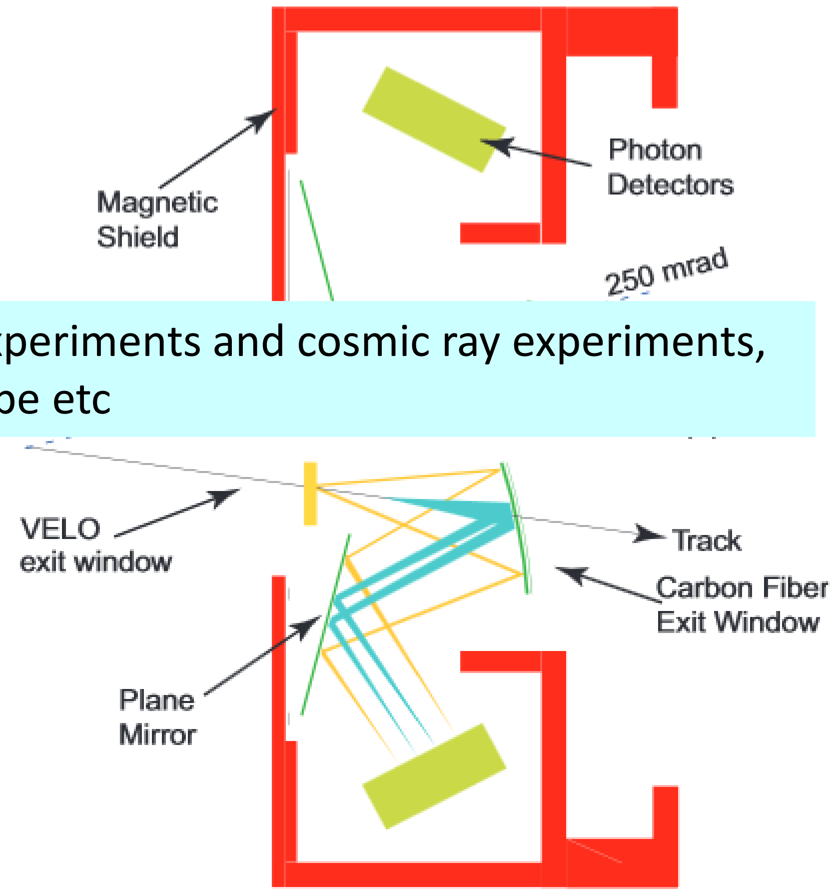
LHCb RICH

Measurement of Cherenkov angle:
Use medium with known refractive index n ➔ β

Principle of:

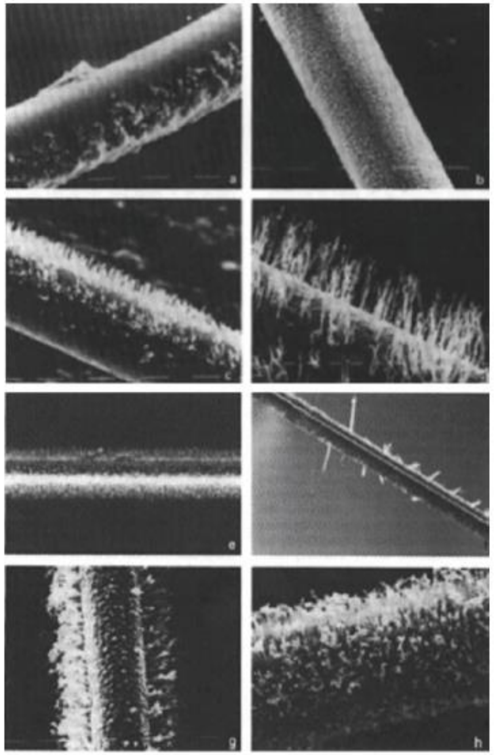
RICH (Ring Imaging Cherenkov Counter)
DIRC (Detection of Internally Reflected Cherenkov Light)

Cherenkov detection widely used in both collider experiments and cosmic ray experiments,
For instance ALICE, AMS, the Air Cherenkov Telescope etc



Particles pass through radiator and radiated photons focused and detected by photo detector
Velocity determined by measuring radius of ring

Anode wires with deposits



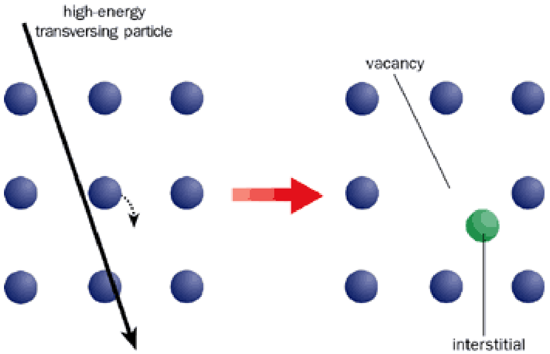
Radiation damage

The high particle flux accelerates the aging process

This affects both the performance of the electronics as well as detection quality.

For instance

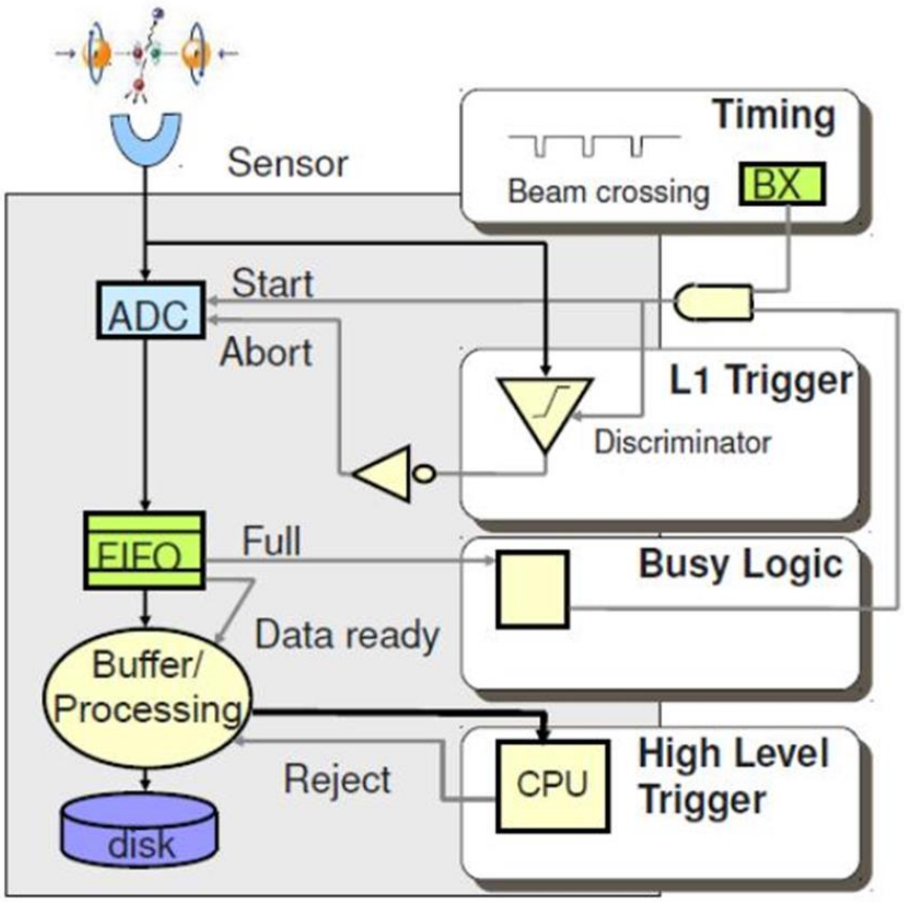
- discoloration of scintillator material
- anode wires in wire chamber can get deposits of polymers and free radicals



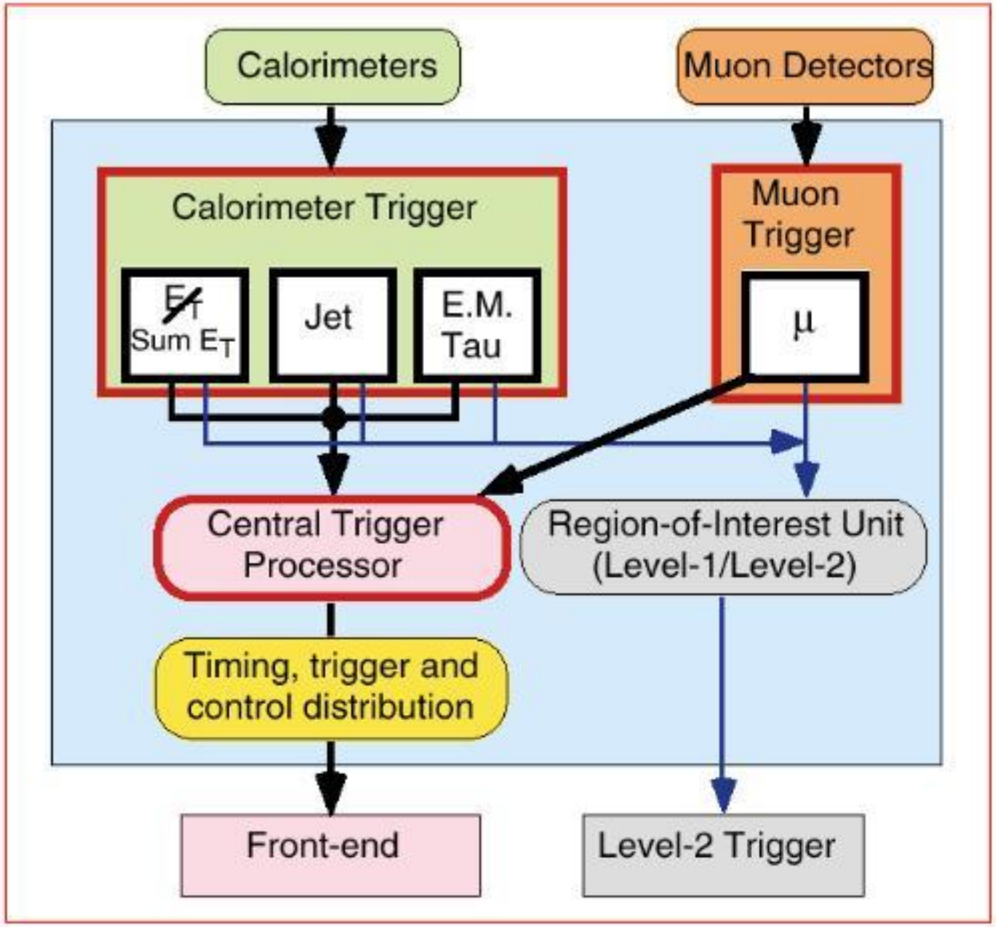
Silicon detectors: When a high-energy particle traverses a silicon detector, lattice defects are produced. These take the form of lattice vacancies and atoms at interstitial sites. They move around and combine with bulk impurities to create energy levels in the normally "forbidden" bandgap. (@CERN Courier)

Triggers

- *Purpose: Reject events!*
- When storage and processing power insufficient
- Careful what you reject – cannot be recovered
- Multilayer structure to improve rejection factor and minimize mistakes



Trigger input ATLAS example



Decision times from μs to s

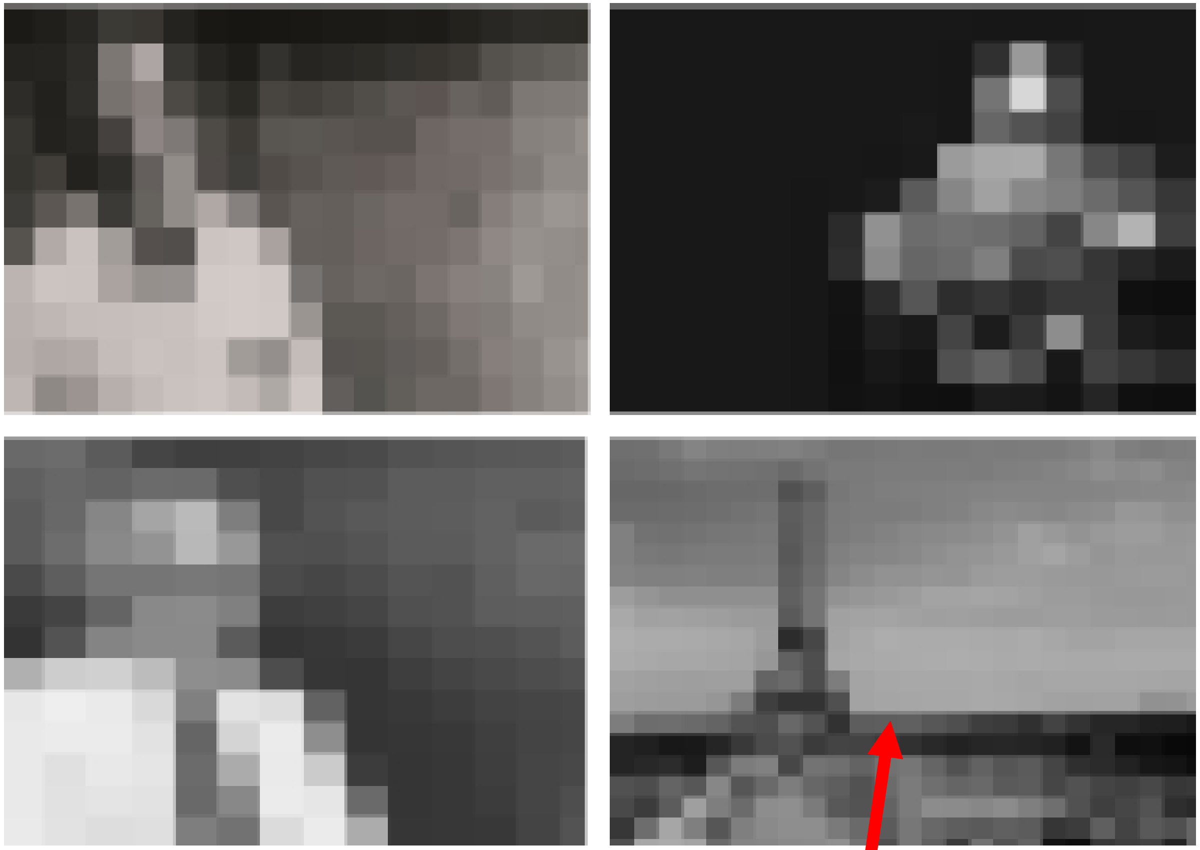
Only limited-granulariy information available for the first trigger levels

- ”the trigger does not determine which physics model is right, only which physics model is left” A. Bocci

Example: Higgs

- L1

  Coarse granularity

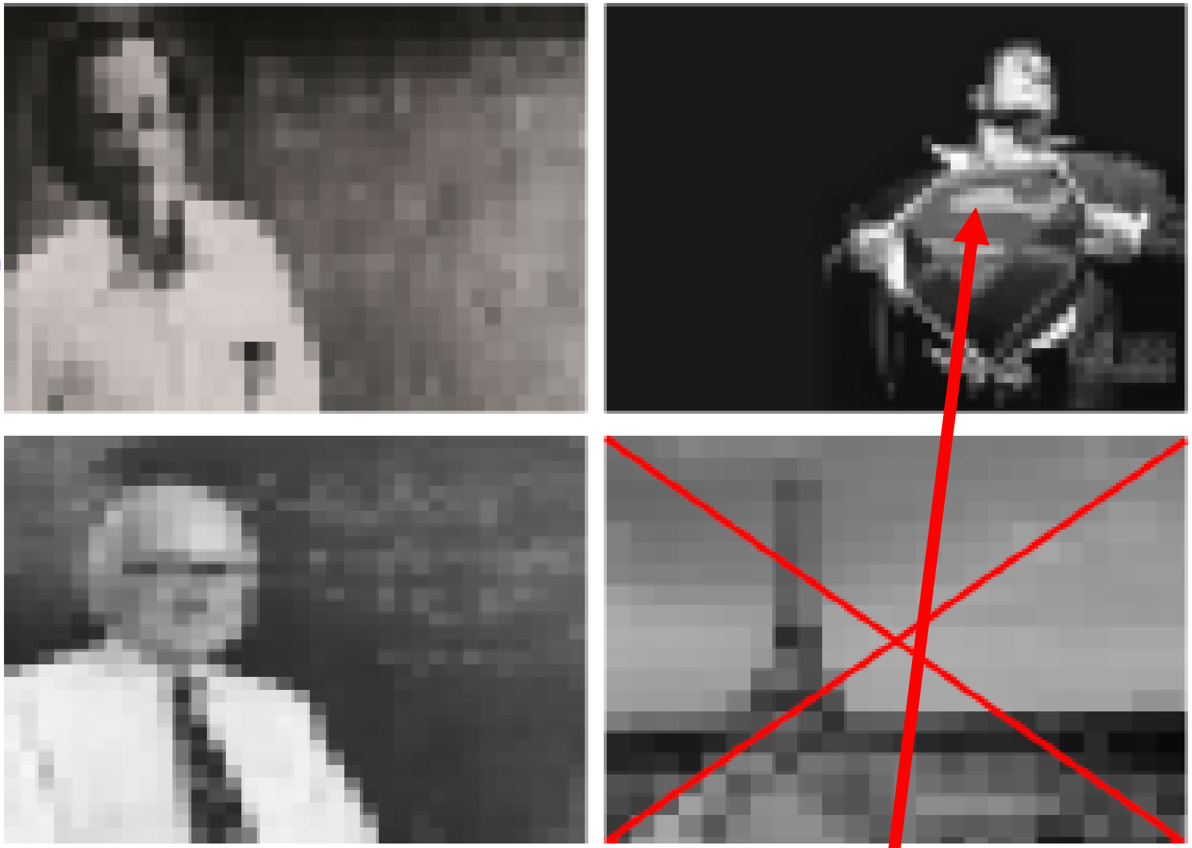


L1: This is not Higgs

Example: Higgs

- L2

  Improved reconstruction, improved ability to reject events

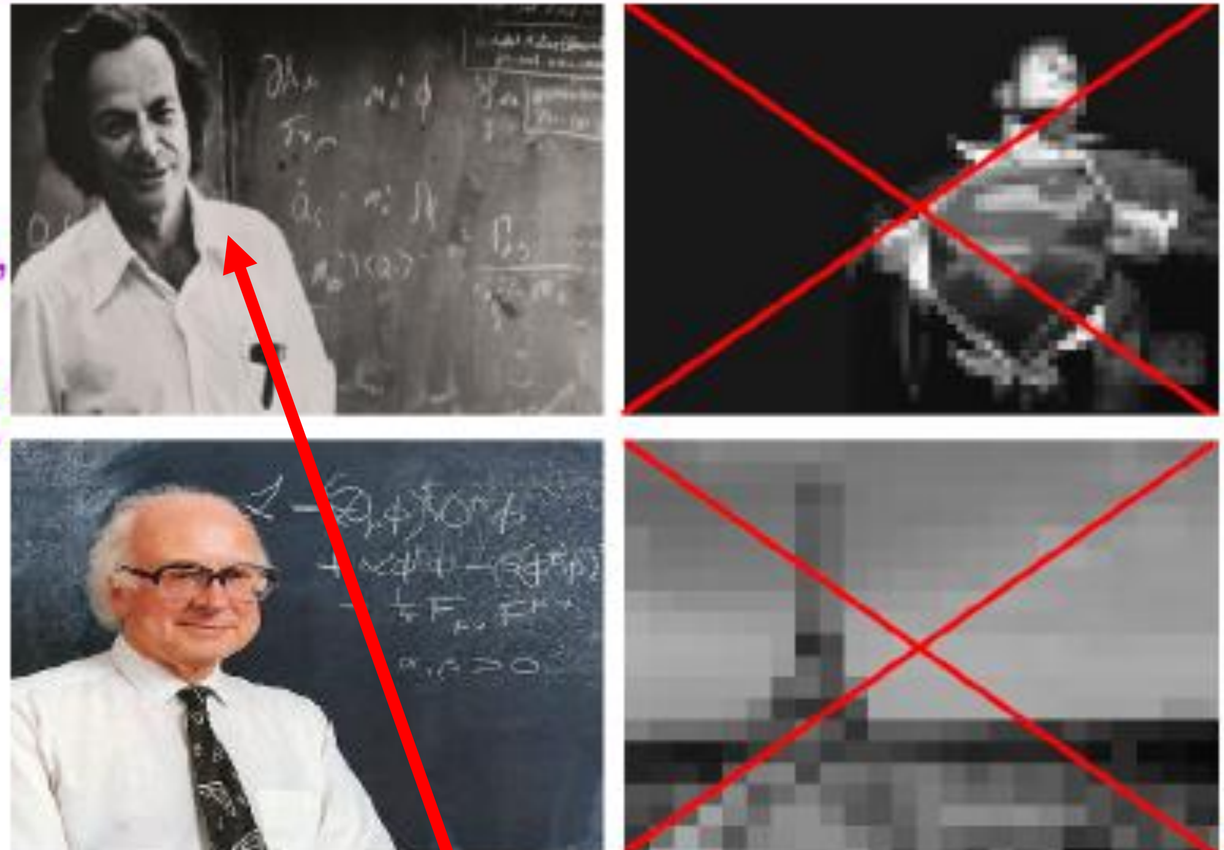


L2: This is not Higgs

Example: Higgs

- EF

  high quality reconstruction, improved ability to reject events



L3/EF: This is not Higgs

Trigger efficiency

Enters in calculation of cross section:

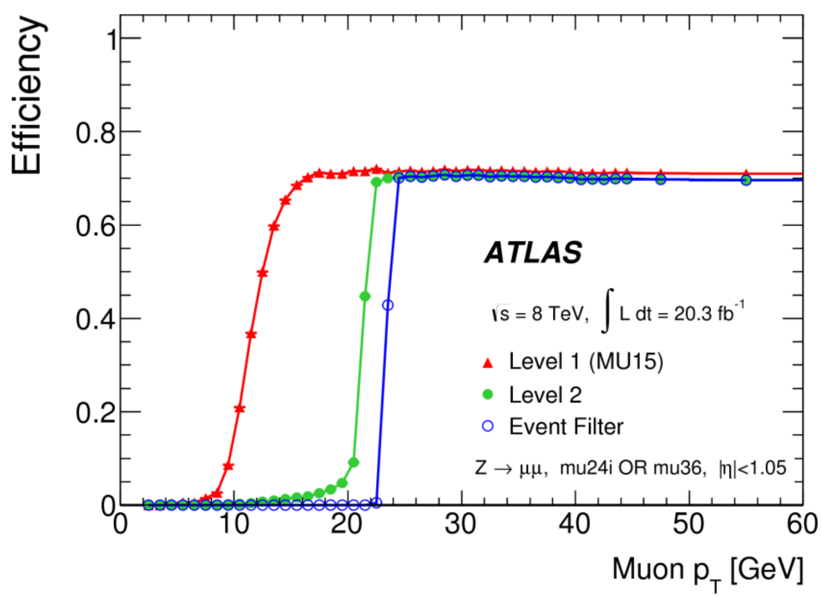
$$\sigma = \frac{N}{A \cdot \varepsilon \cdot \int L\, dt}$$

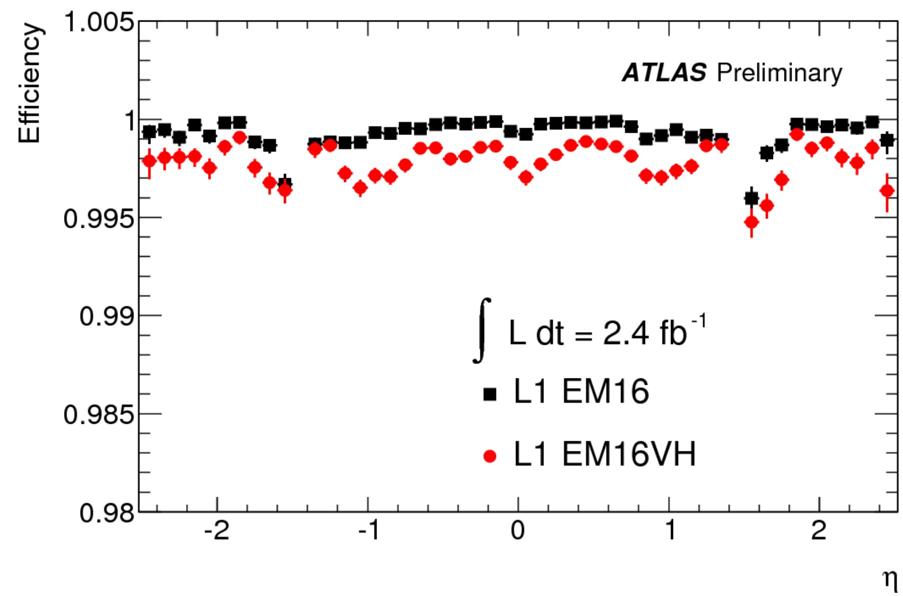
Acceptance

Efficiency

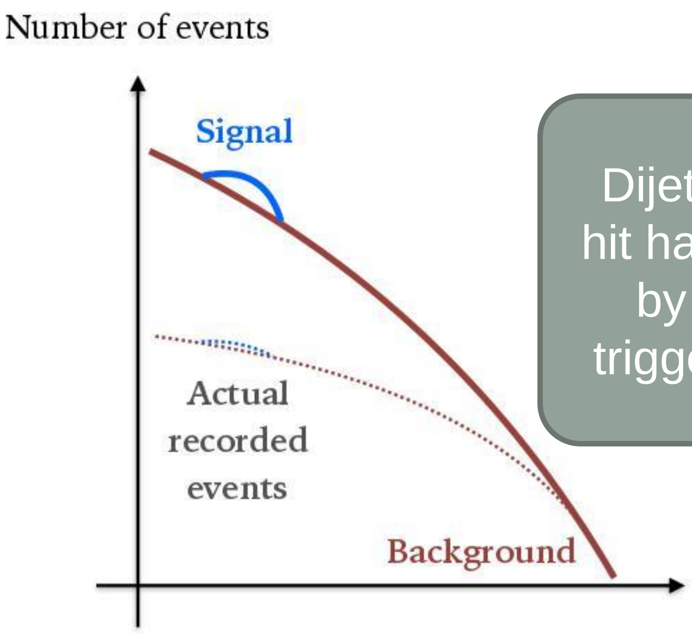
Integrated luminosity

Examples: ATLAS trigger:





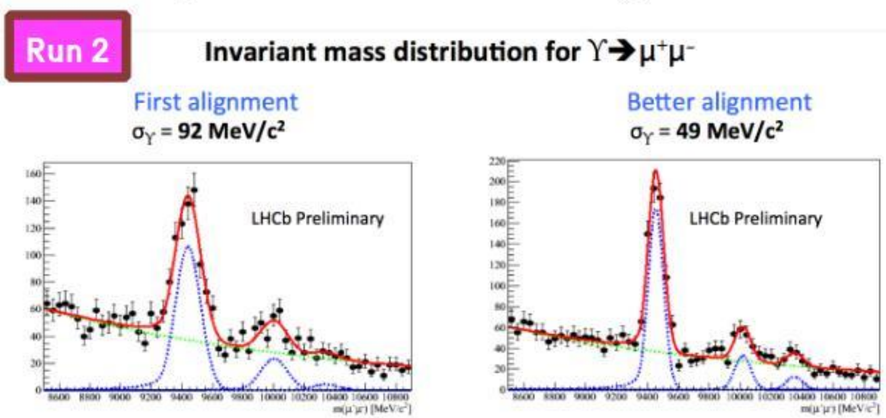
Online analysis: by-passing the trigger?



Dijets hit hard by trigger

If we relax storage requirement
Analysis can be done directly on first level trigger output

Detector performance/ resolution degraded
-but not always a show stopper



First attempts on-going at the LHC experiments

Raw data still not stored …

B. Storaci, CERN Seminar

Summary/outlook

- Success often spells many different techniques
- Detector choice depends on conditions – almost always a compromise, signal vs background vs costs
- Triggers part of current detector technology
  - Events not triggered not stored $\rightarrow$ online analysis only
- Several challenges
  - Calibration always necessary
  - Radiation hardness – detectors affected by particle flux