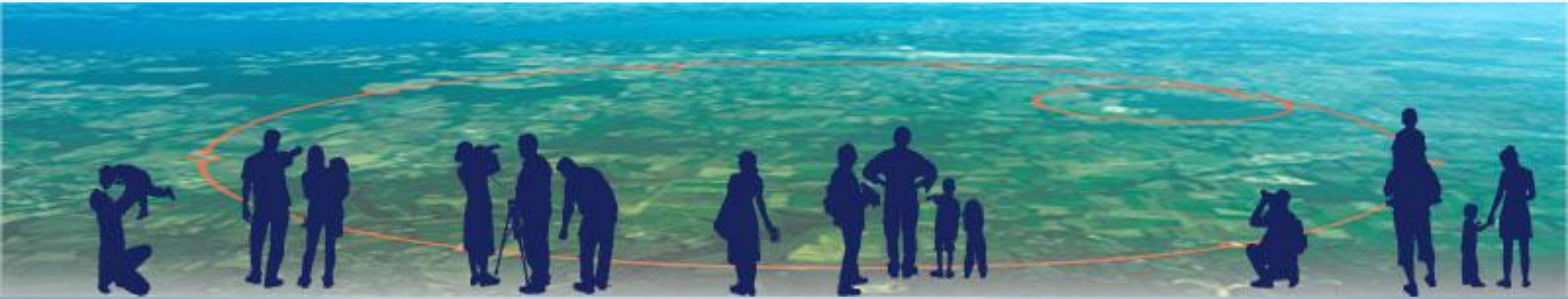
Introduction to Experiments

How do you detect particles?



Content

- Particle interaction with matter
- Principles of detection
- How does it work

    Some detector examples

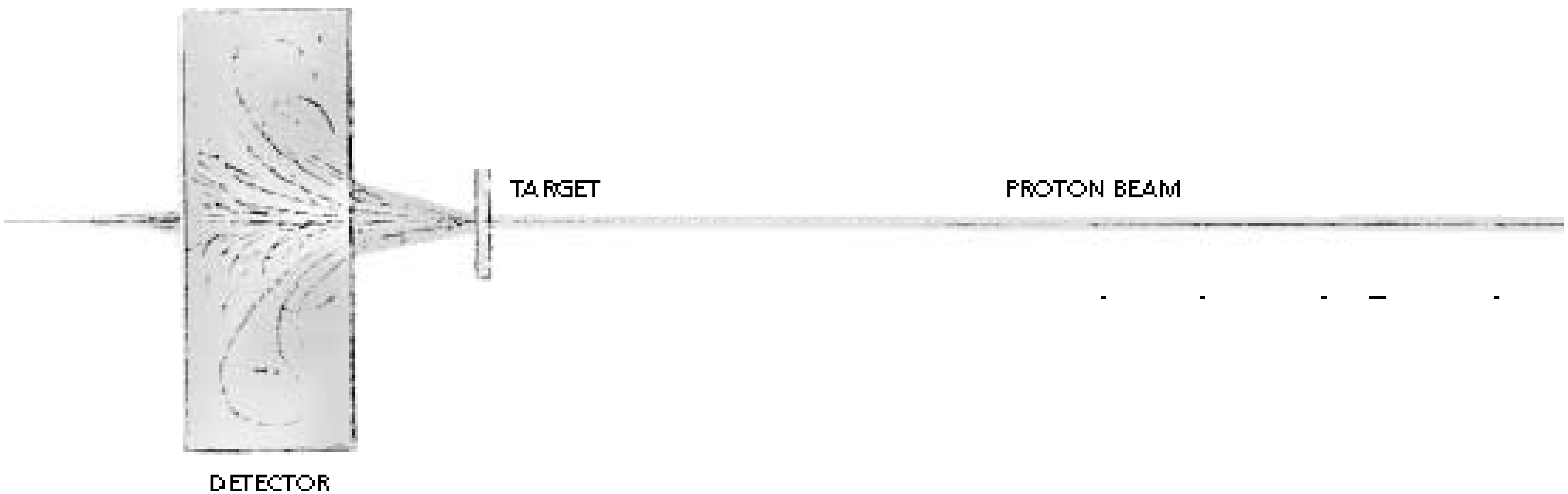
Fixed Target ↔ Collider

W = Energy available in center-of-mass for making new particles

Collider

Fixed Target

For fixed target :



❑ Cost is lower

Particle interaction with matter

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, π, μ

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

$2\pi N_a r_e^2 m_e c^2$ =0.1535MeV-cm^2/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

ρ=density of absorber

δ=density correction

C=shell correction

Incident particle

z=charge of incident particle

β=v/c of incident particle

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

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

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

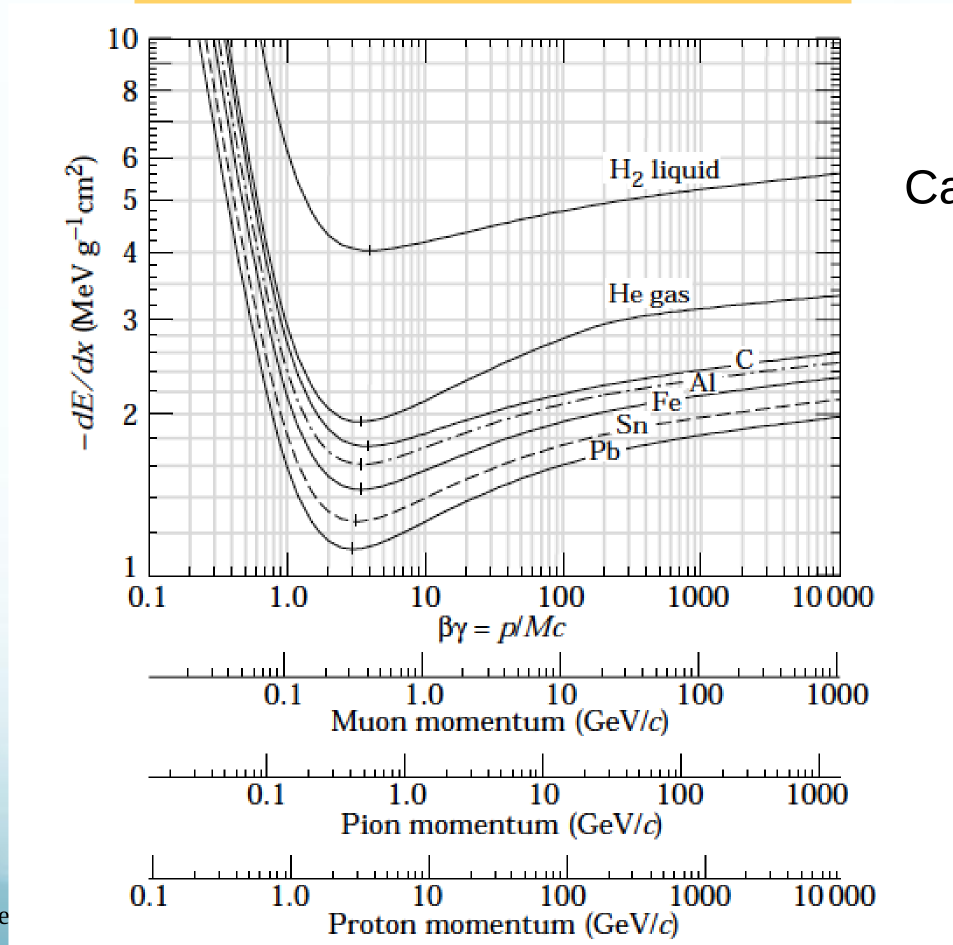
Note: the classical dE/dx formula contains many of the same features as the QM version: $(z/\beta)^2$, & ln[]

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

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

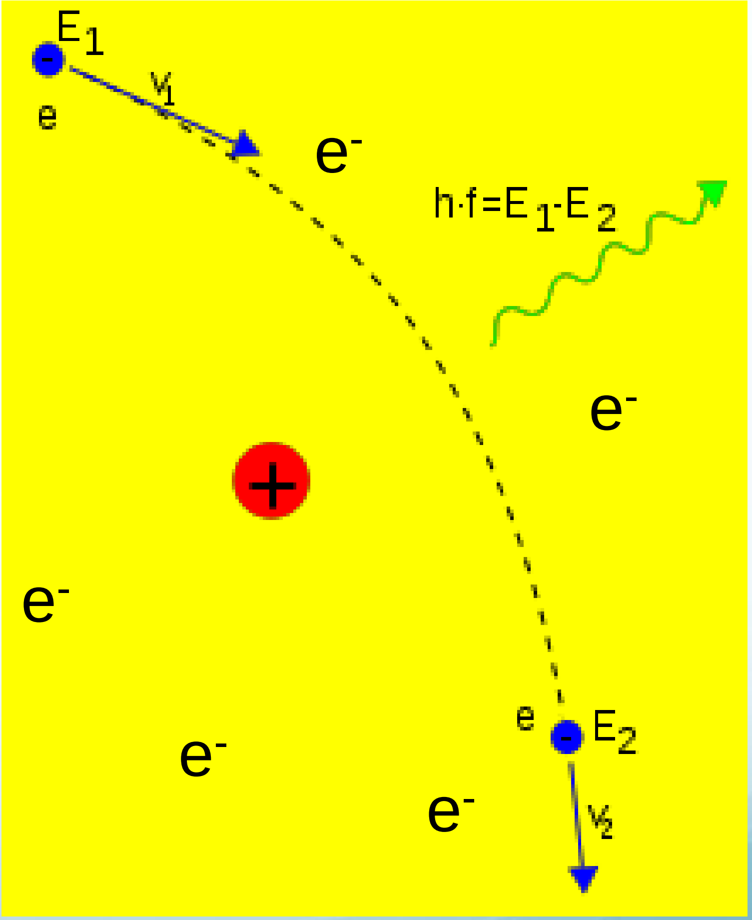


Calculated

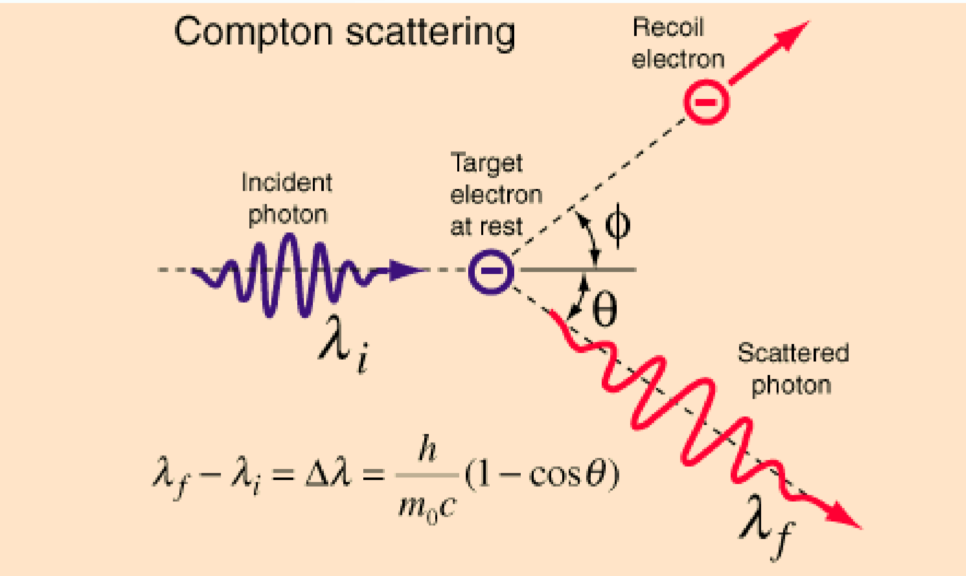
$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

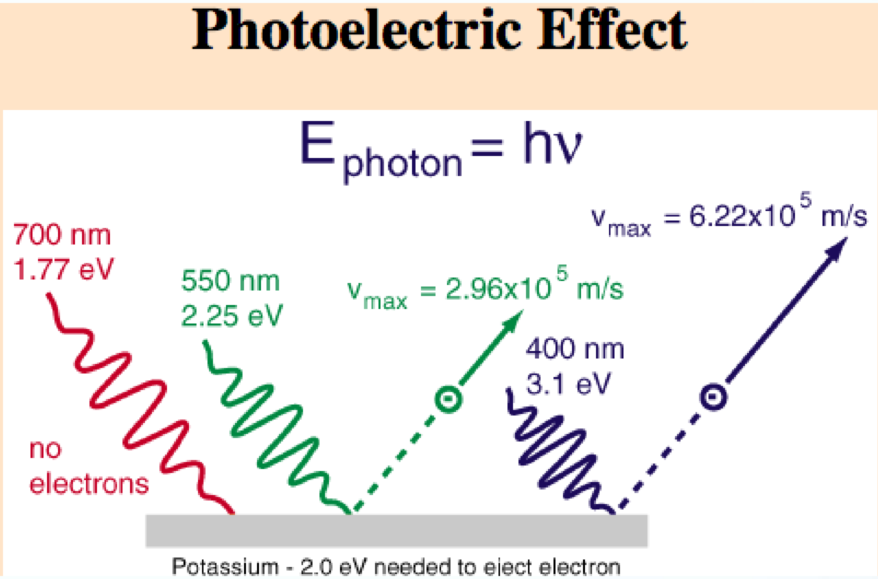
Bremsstrahlung (braking radiation)

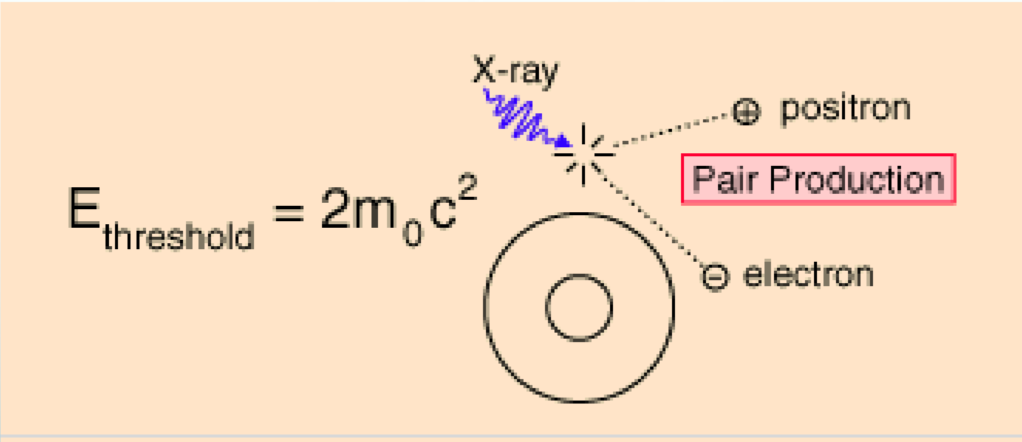
- A fast moving particle is decelerated in the electrical field of the nuclei.
- Above a few tens MeV, bremsstrahlung is the most dominated process for **electrons and positrons**
- It becomes important to muons (and pions) at a few hundred GeV
- What about the atomic electrons? Yes, the electron cloud gives and *additional contribution* to the bremsstrahlung
- *Let's see how this is used in the detector layout later*



Photons - 3 interactions

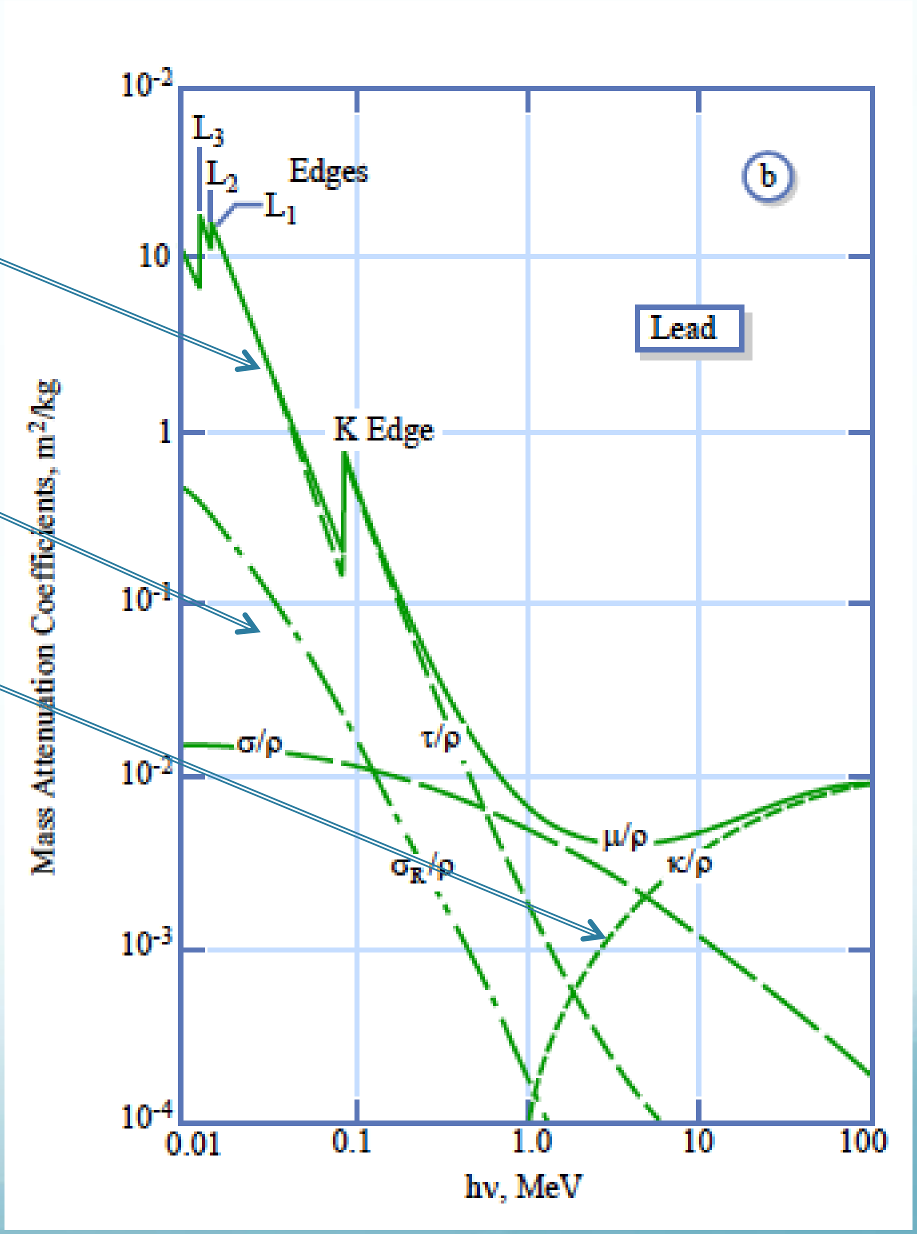






Photons interacting with matter

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



Multiple Scattering

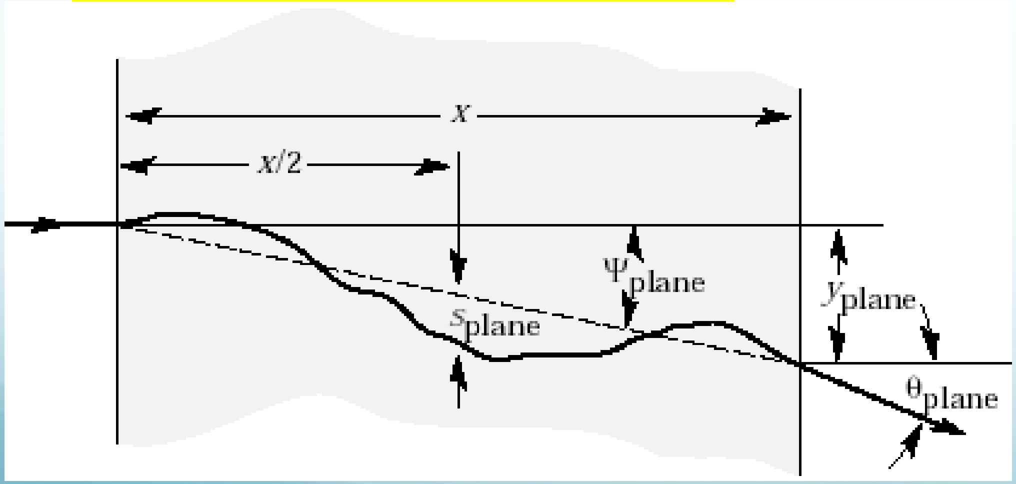
A charged particle traversing a medium is deflected by many small angle scatterings.
These scattering are due to the **coulomb field of atoms** and are **assumed to be elastic**.
In each scattering the energy of **the particle is constant but the particle direction changes**.

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

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

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

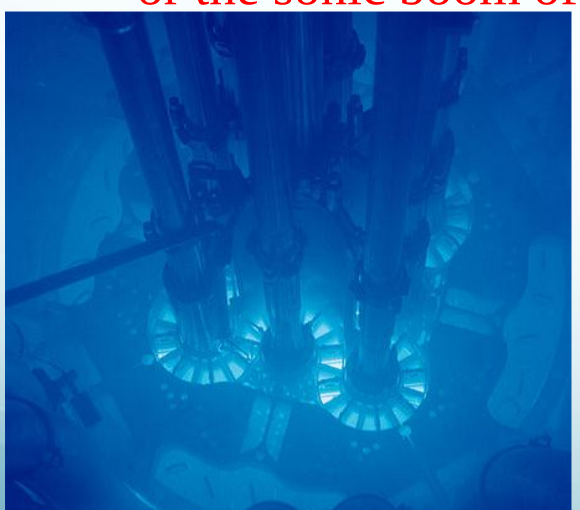
This is not good for tracking!



H. Danielsson, Swedish Teachers Program

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



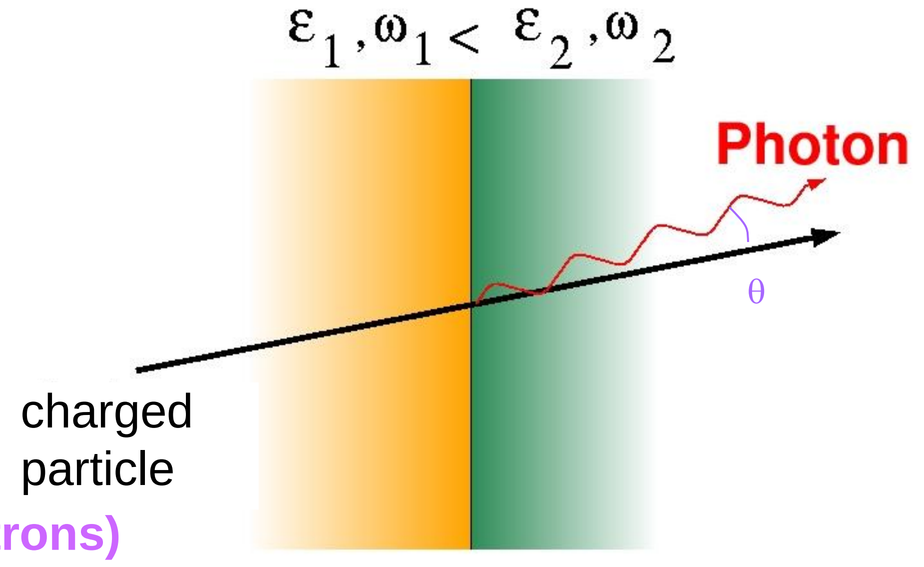
Transition Radiation (Particle ID)

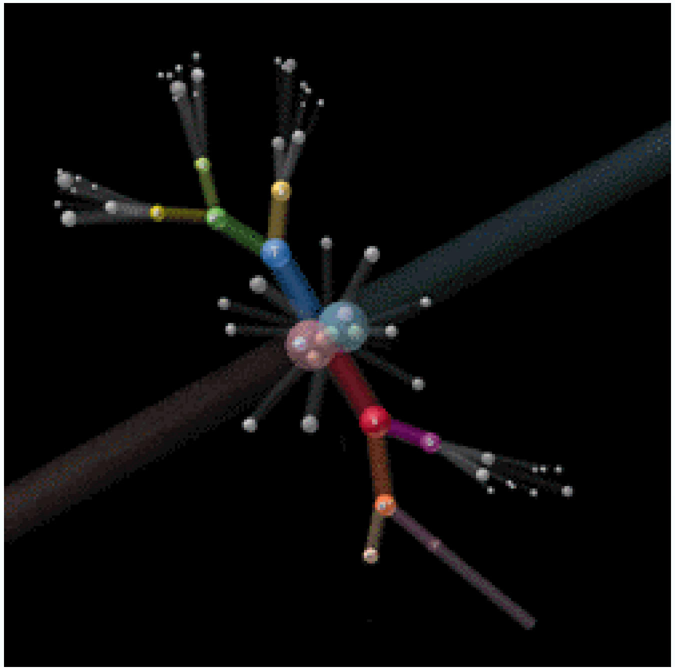
- **Transition Radiation: photon emitted by a charged particle when traversing the boundary between materials with different dielectrical constants ($\varepsilon_1 \varepsilon_2$)**

- **γ > 1000**

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

- **Intensity: I ~ γ = 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

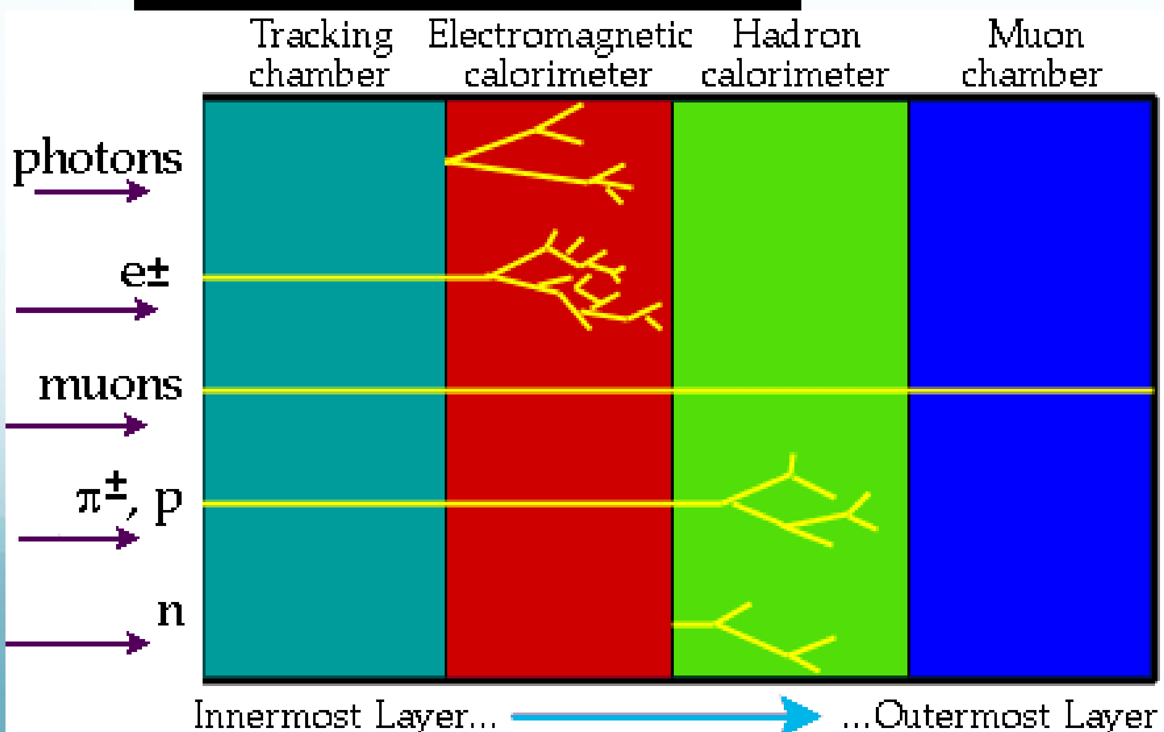




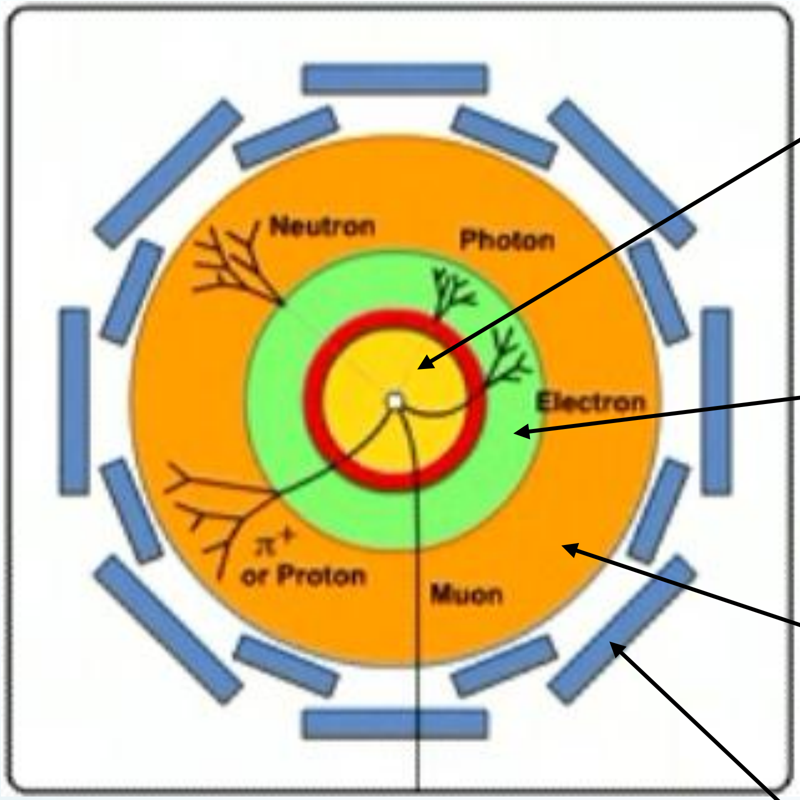
Principles of Detection

The collision energy condenses into particles (e^-, p, π…)

Detectors surrounding the collision point (or *after* in case of fixed target) are sensitive to the passage of energetic particles.



How to detect particles in a detector



Tracking detector

−Measure charge and momentum of charged particles in magnetic field

Electro-magnetic calorimeter

−Measure energy of electrons, positrons and photons

Hadronic calorimeter

−Measure energy of hadrons (particles containing quarks), such as protons, neutrons, pions, etc.

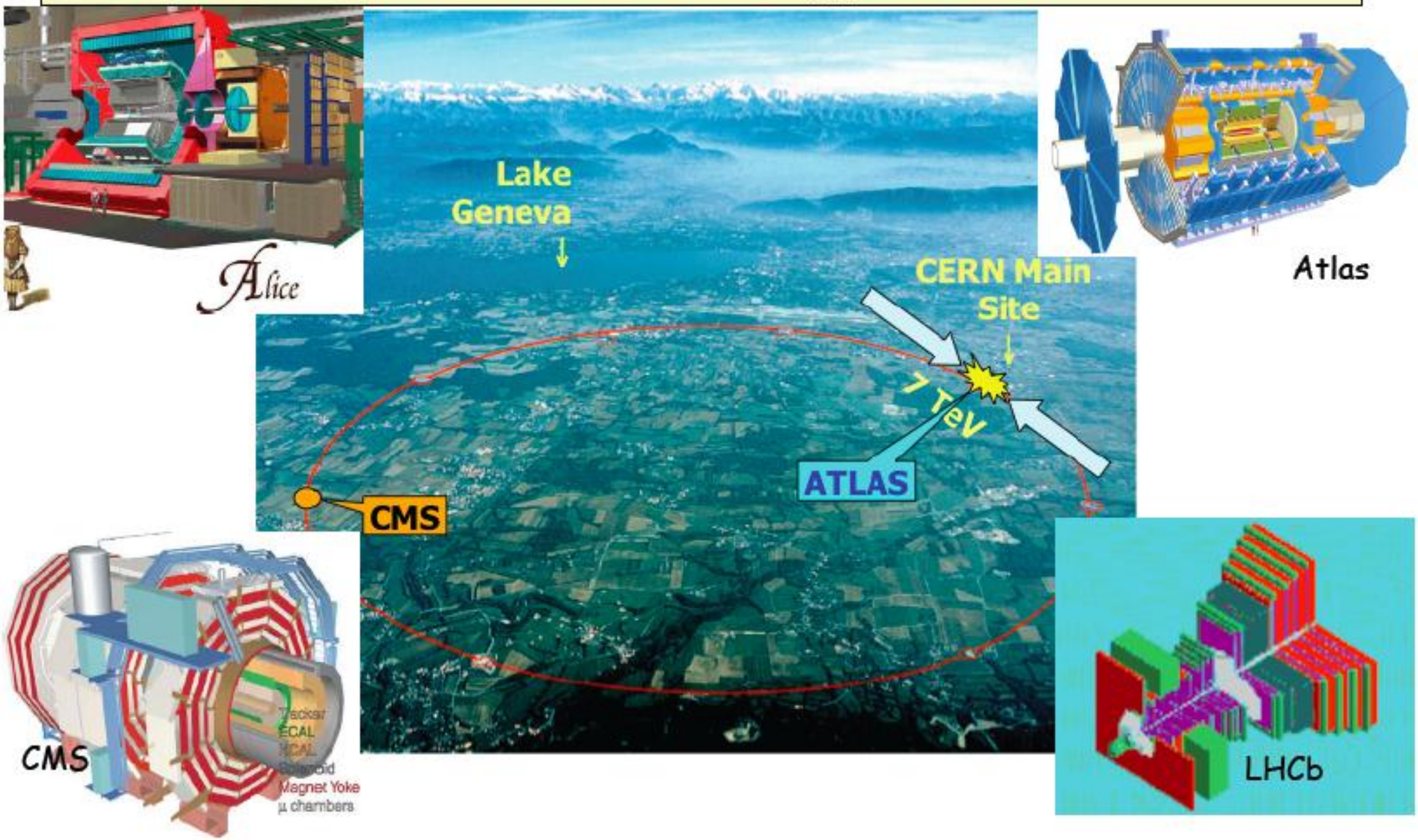
Muon detector

−Measure charge and momentum of muons

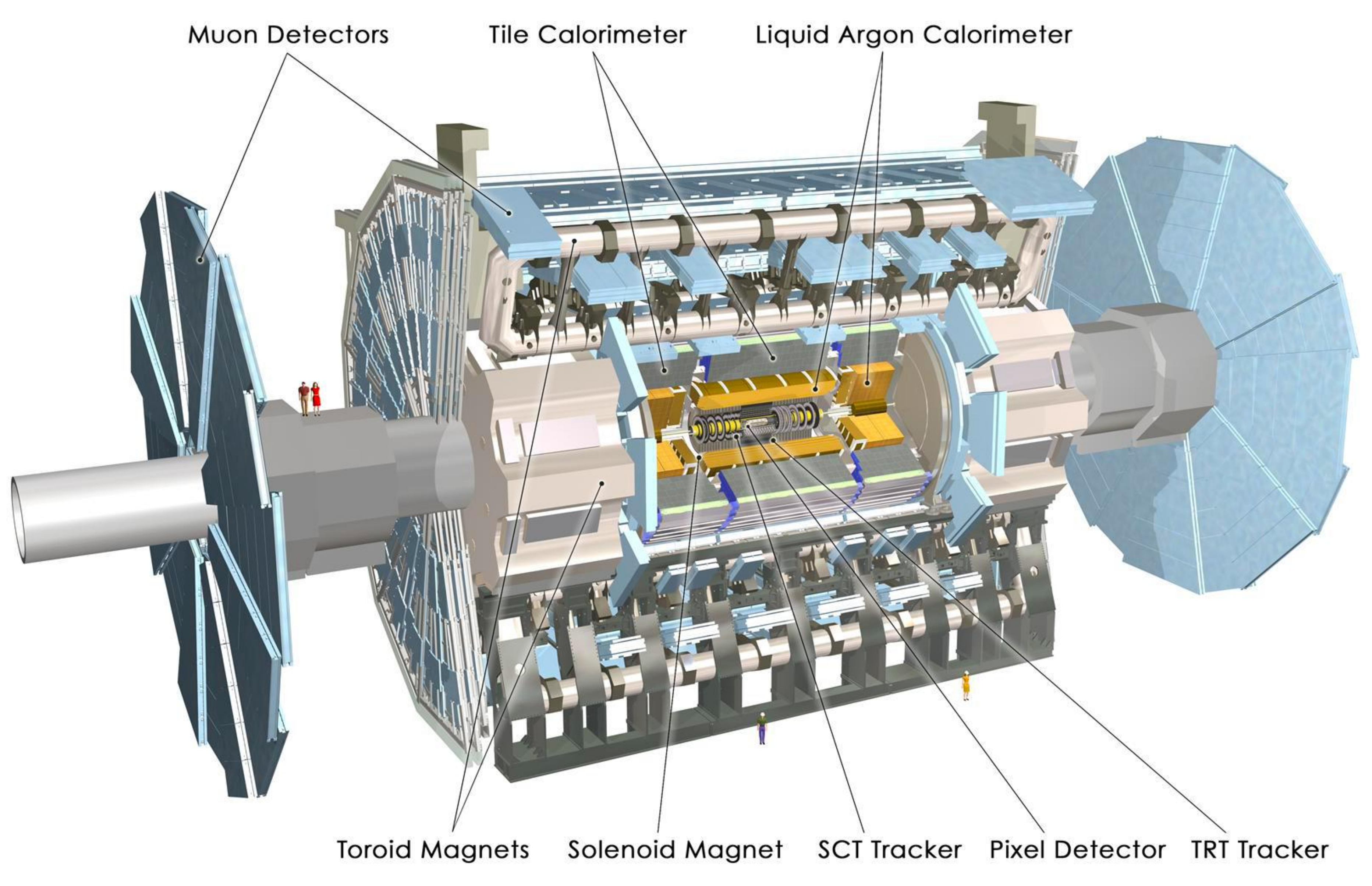
Neutrinos are only detected indirectly via ‘missing energy’ not recorded in the calorimeters

LHC at CERN

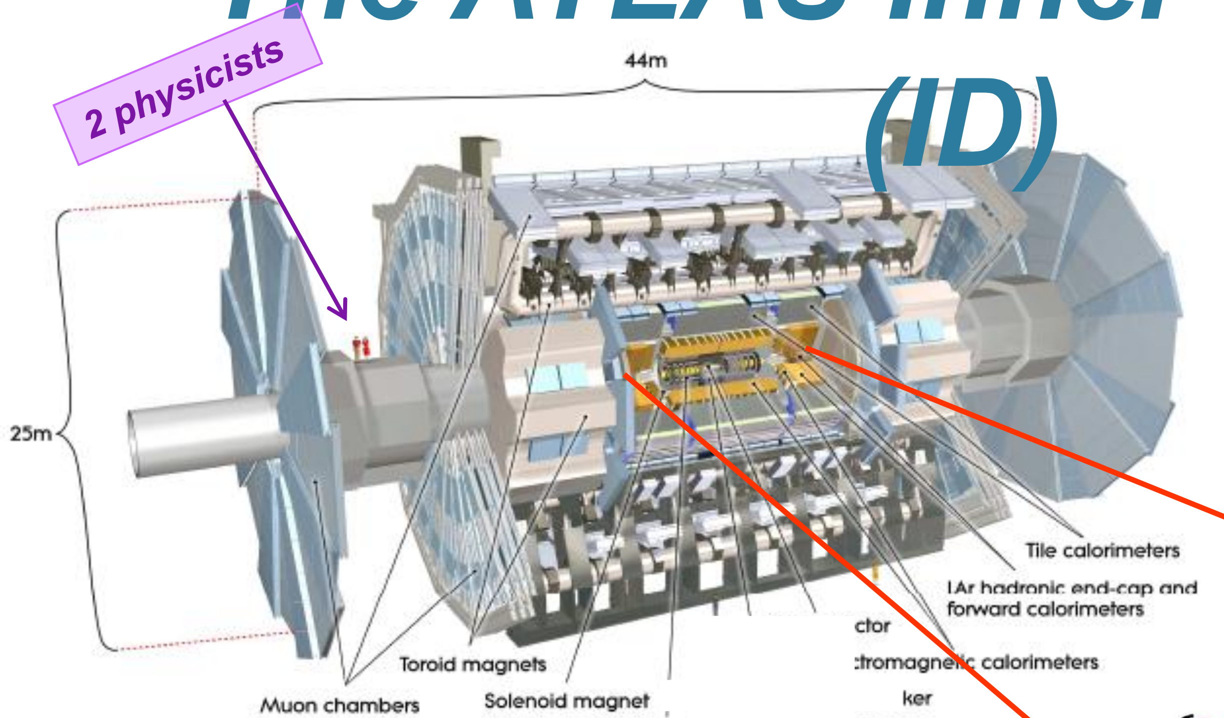
Operating since Fall 2009
Currently with p-p collisions at $\sqrt{s}$=7 TeV as mostly of 2010
Will Collide Pb ion beams in Nov 2011 at $\sqrt{s_{NN}}$=2.78TeV (same in 2010)



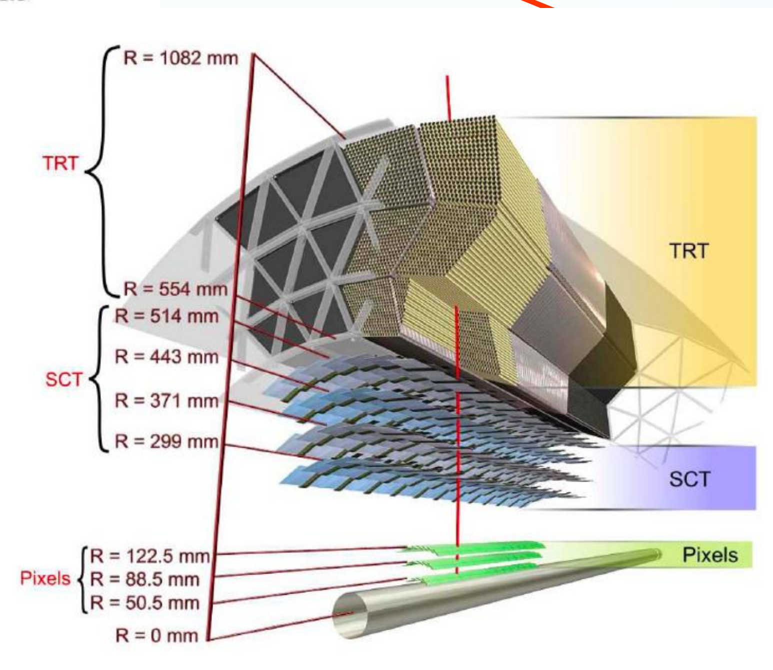
Example: ATLAS



The ATLAS Inner Detector (ID)



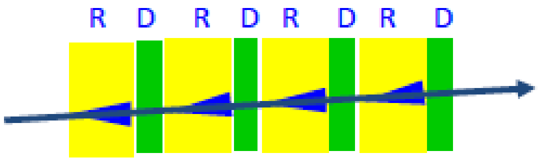
- Provides charged particle tracking for particles above 0.5GeV, |η| < 2.5
- Electron identification for particles with |η|<2 and 0.5 < p_T < 150 GeV
- Surrounded by solenoid B = 2T
- Consists of Pixel detectors, Semiconductor Tracker and Transition Radiation Detector (TRT)



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.

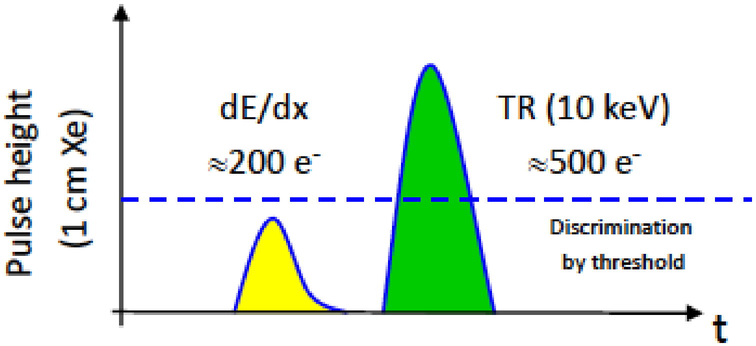
- **TR Radiators:**
  - stacks of thin foils made out of CH_2 (polyethylene), $C_5H_4O_2$ (Mylar)
  - hydrocarbon foam and fiber materials. Low Z material preferred to keep re-absorption small ($\propto Z^5$)



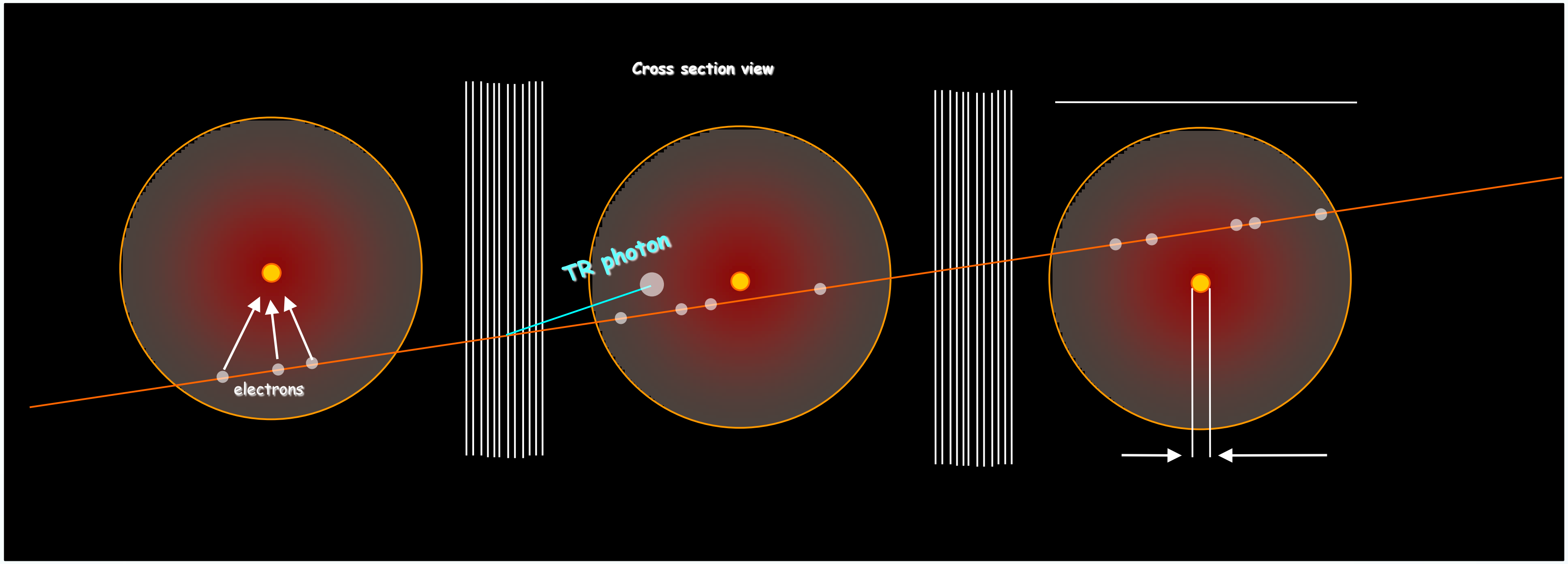
alternating arrangement of radiators stacks and detectors
→ minimizes re-absorption

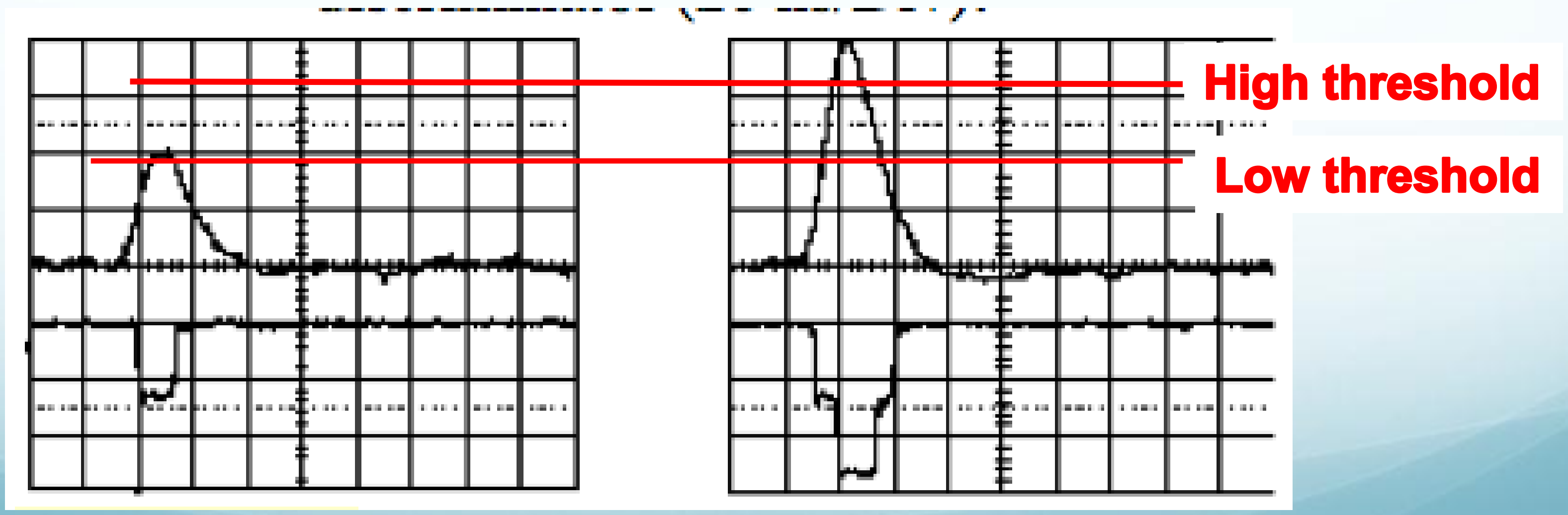
- **TR X-ray detectors:**
  - Detector should be sensitive for $3 \leq E_\gamma \leq 30$ keV.
  - Mainly used: Gas detectors: MWPC, drift chamber, straw tubes...
  - Detector gas: $\sigma_{\text{photo effect}} \propto Z^5$

  → gas with high Z required, e.g. Xenon (Z=54)

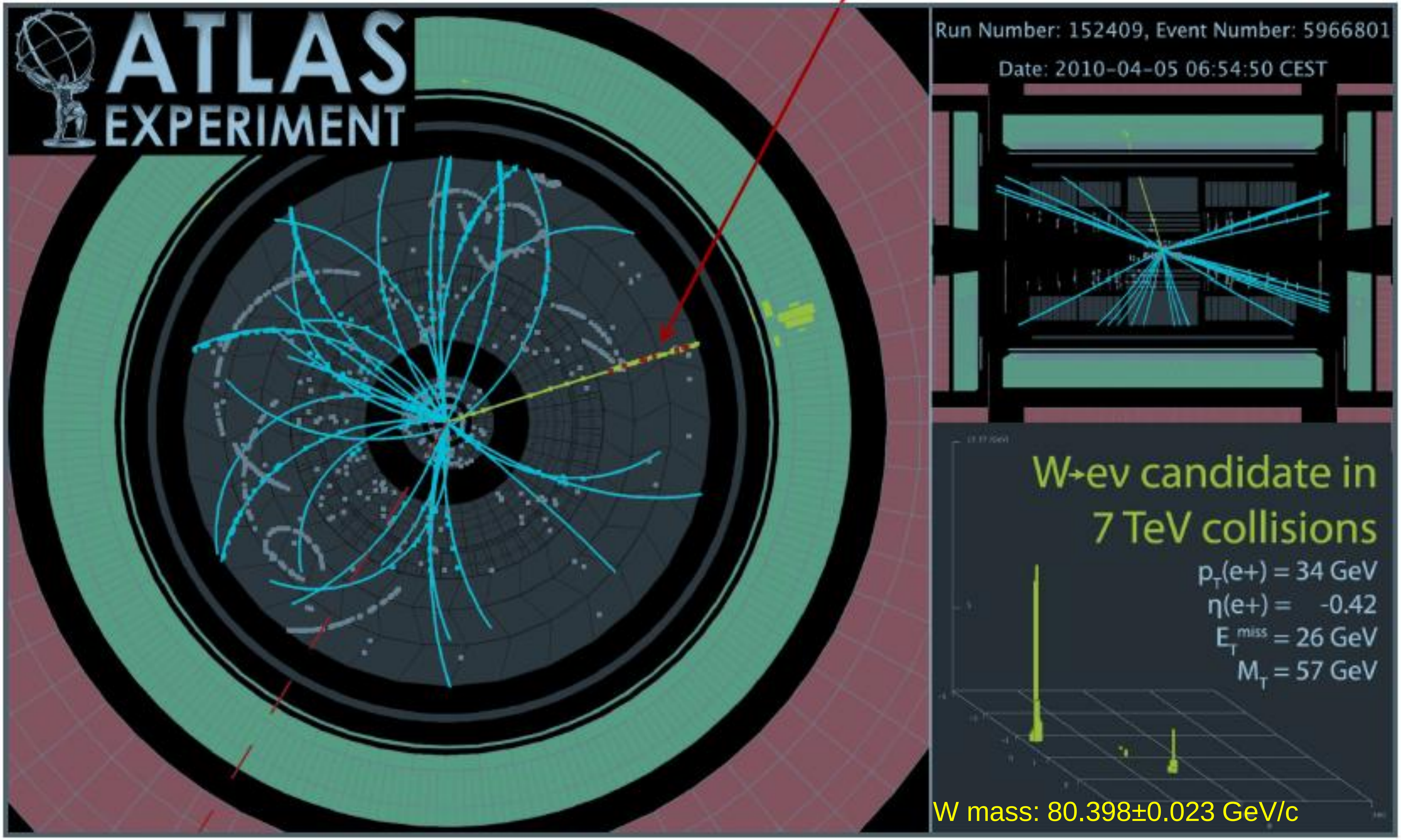


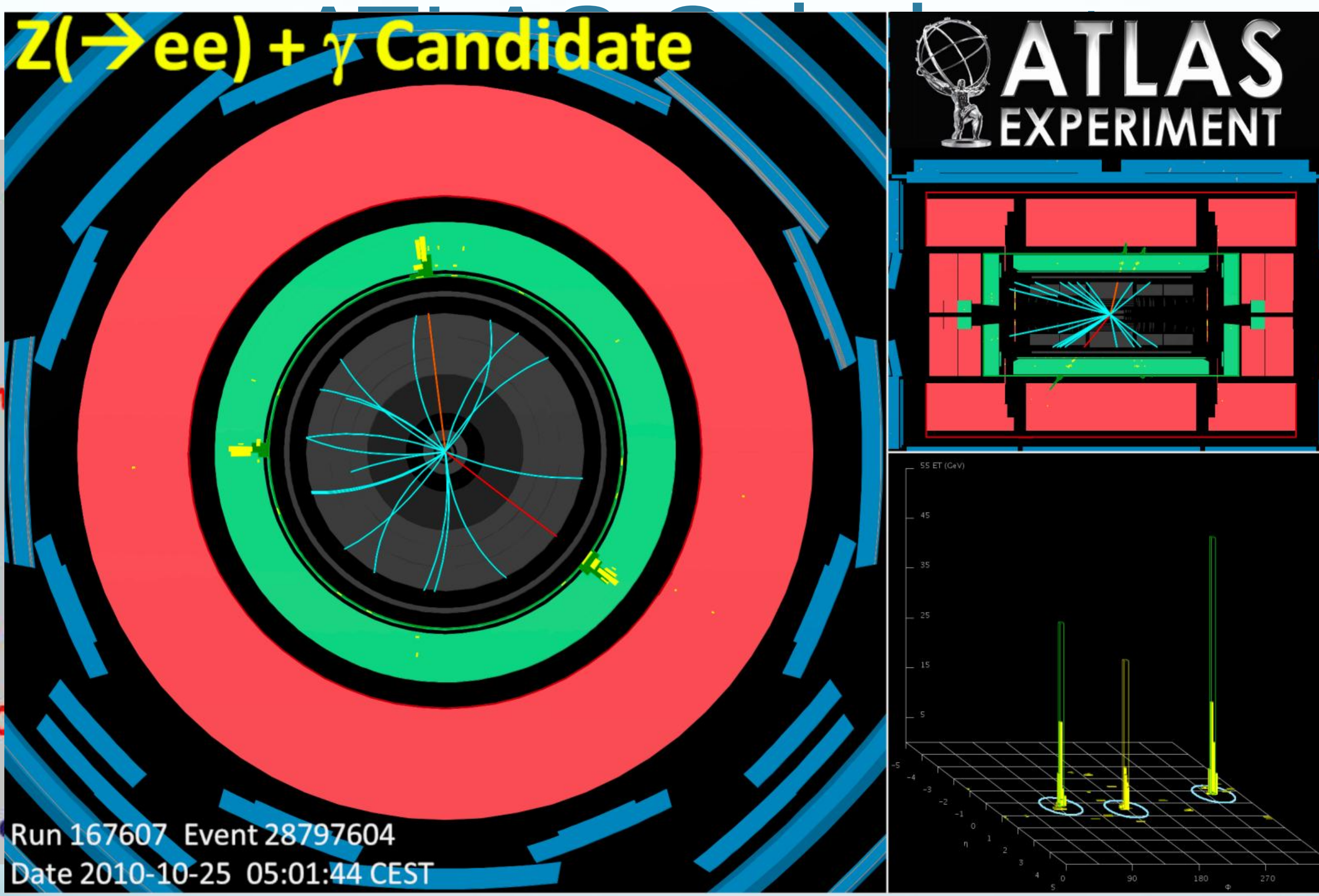
TRT (ATLAS): 3 straws and radiators





Red dots indicates High threshold hits





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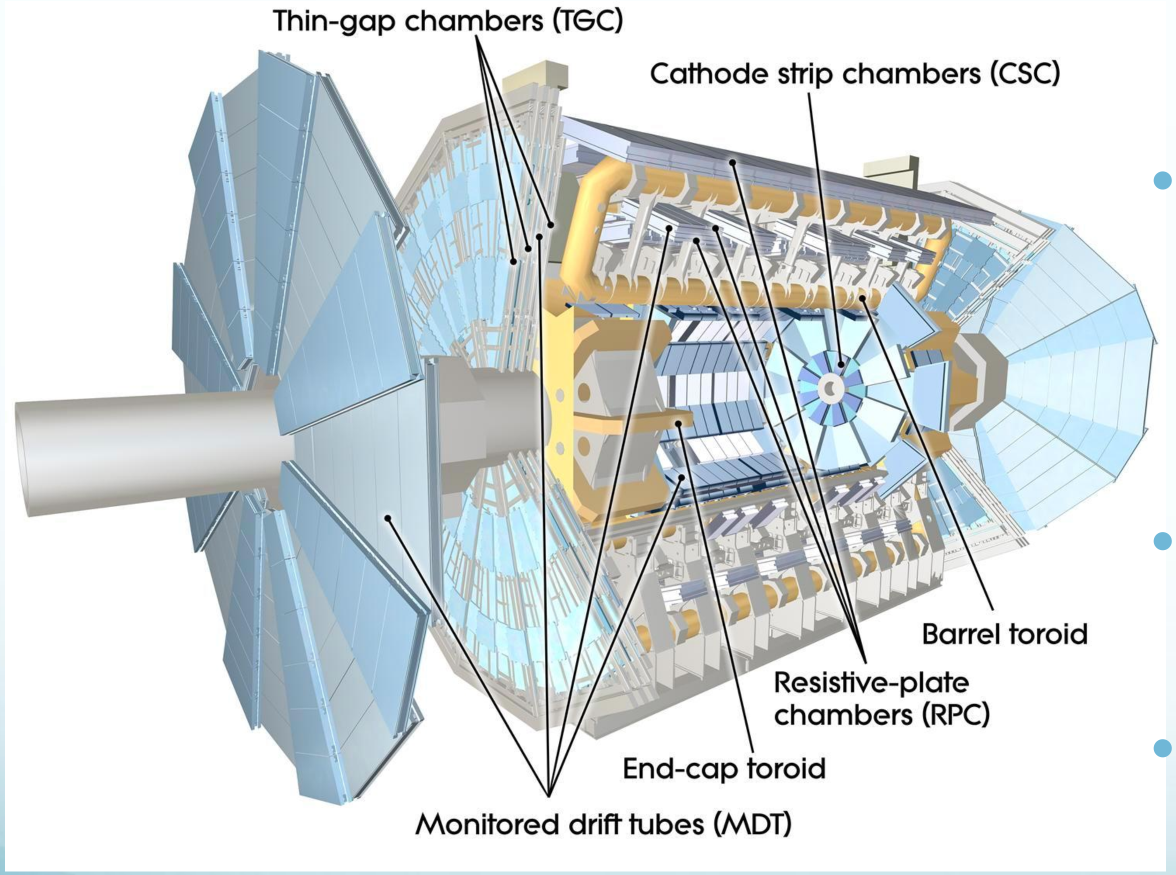
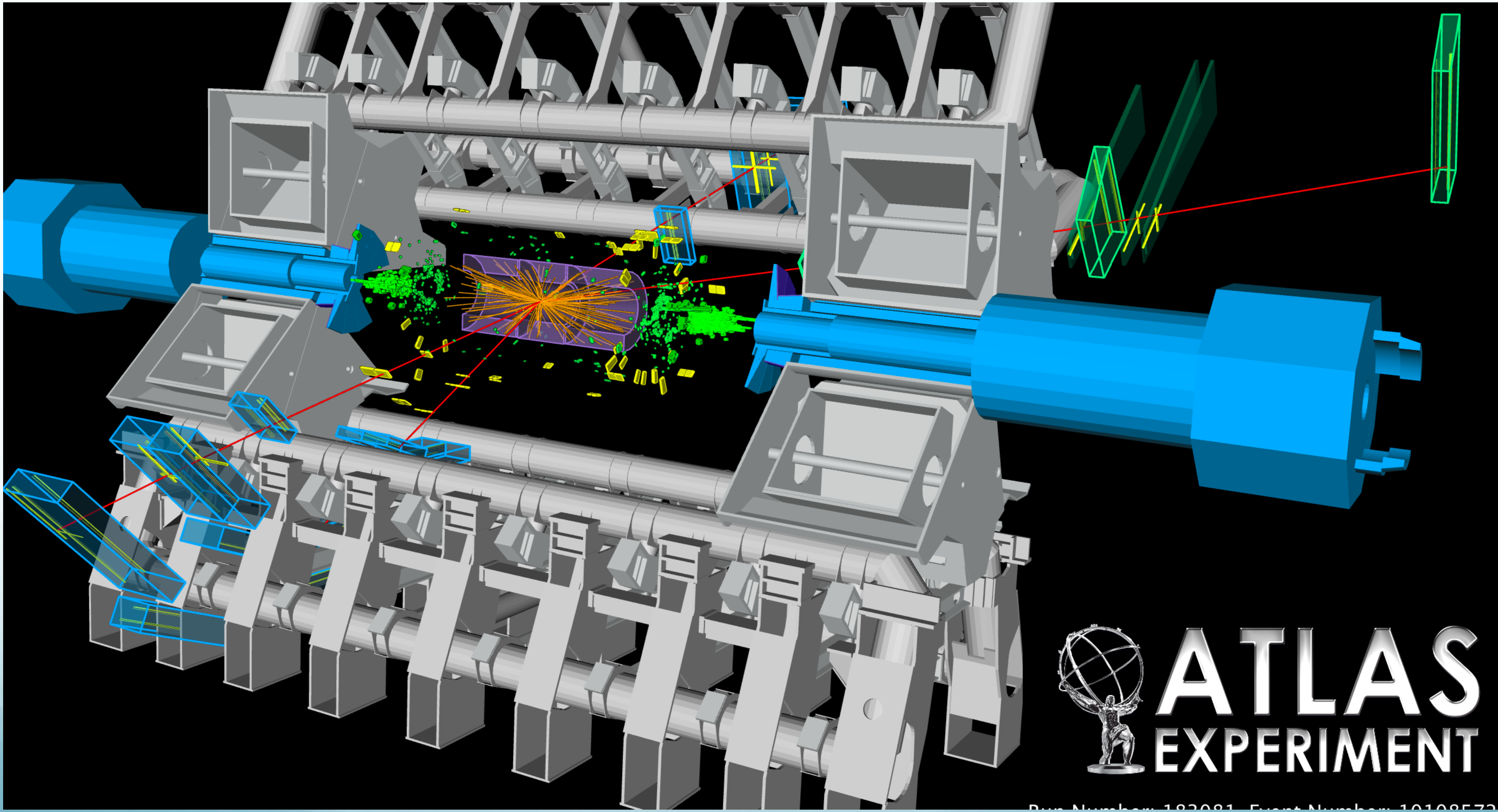
ATLAS Muon Spectrometer



- Muons act like heavier versions of the electron, with mass 105.7 MeV
- Distance they travel (on average) before decay: $d = \beta\gamma c\tau_\mu$
  where *velocity* $\beta = v/c$
  boost $\gamma = E/m = 1/\sqrt{(1-\beta^2)}$
- So a 10 GeV muon flies ~ 60 km before decay >> detector size $\rightarrow$ effectively stable
- Since mass is large, Bremsstrahlung radiation is small, and as a lepton it does not feel the strong interaction

Z→ 4 muons



Particle identification detector

- **Cherenkov radiation:** this is light emitted when a charged particle travels faster than the speed of light through a given medium. Combined with a measurement of the momentum of the particle the velocity can be used to determine the mass and hence to identify the particle.
- **Transition radiation:** this radiation is produced by a fast charged particle as it crosses the boundary between two electrical insulators with different resistances to electric currents.
- **TOF (Time of Flight)** detector is a particle detector which can discriminate between a lighter and a heavier elementary particle of same momentum using their time of flight between two scintillators. The first of the scintillators activates a clock upon being hit while the other stops the clock upon being hit.

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

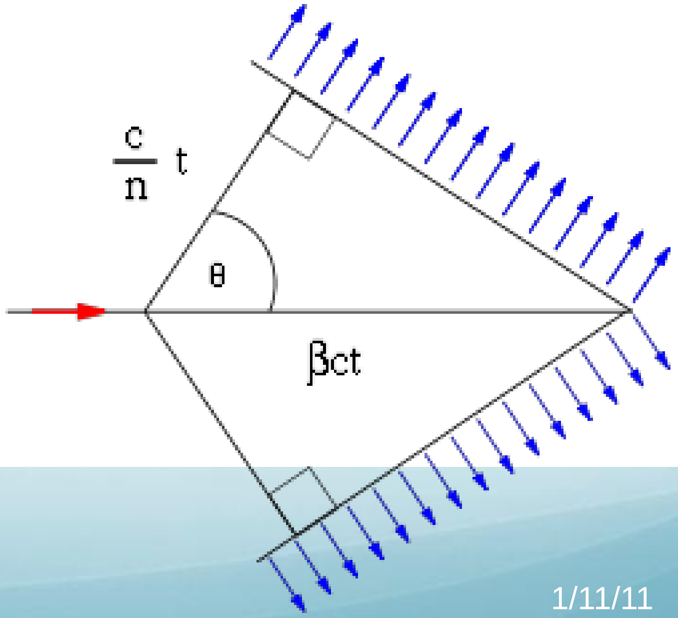
$$x_p = v_p t = \beta\, ct$$

whereas the emitted electromagnetic waves are constricted to travel the distance

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

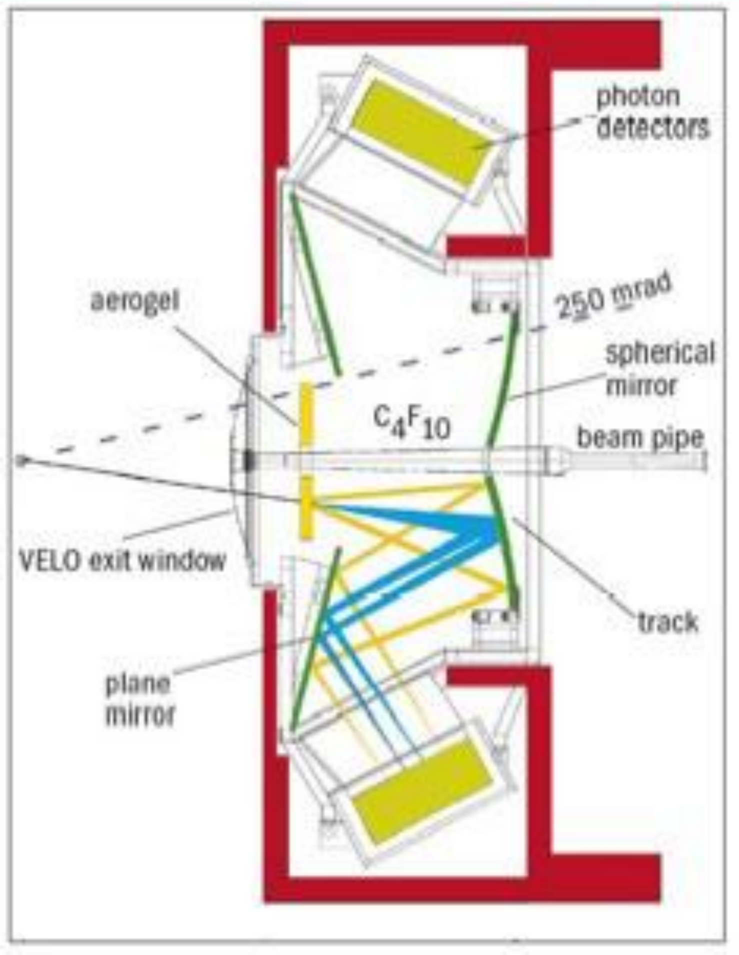
So:

$$\cos\theta = \frac{1}{n\beta}. = \frac{v_1}{v_p}$$

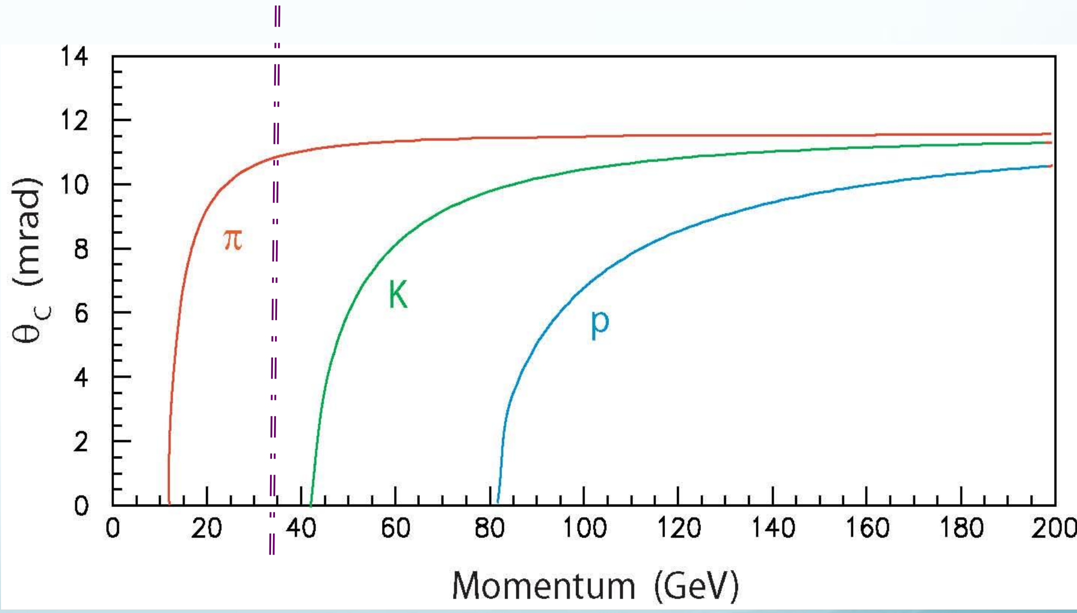


Cherenkov Detector

Ring Imaging Cherenkov detector (RICH detector) of LHCb



The LHCb RICH system has the task of identifying charged particles over the momentum range 1-150 GeV/c, within an angular acceptance of 10-300 milliradians (mrad)



Time Of Flight

- Si
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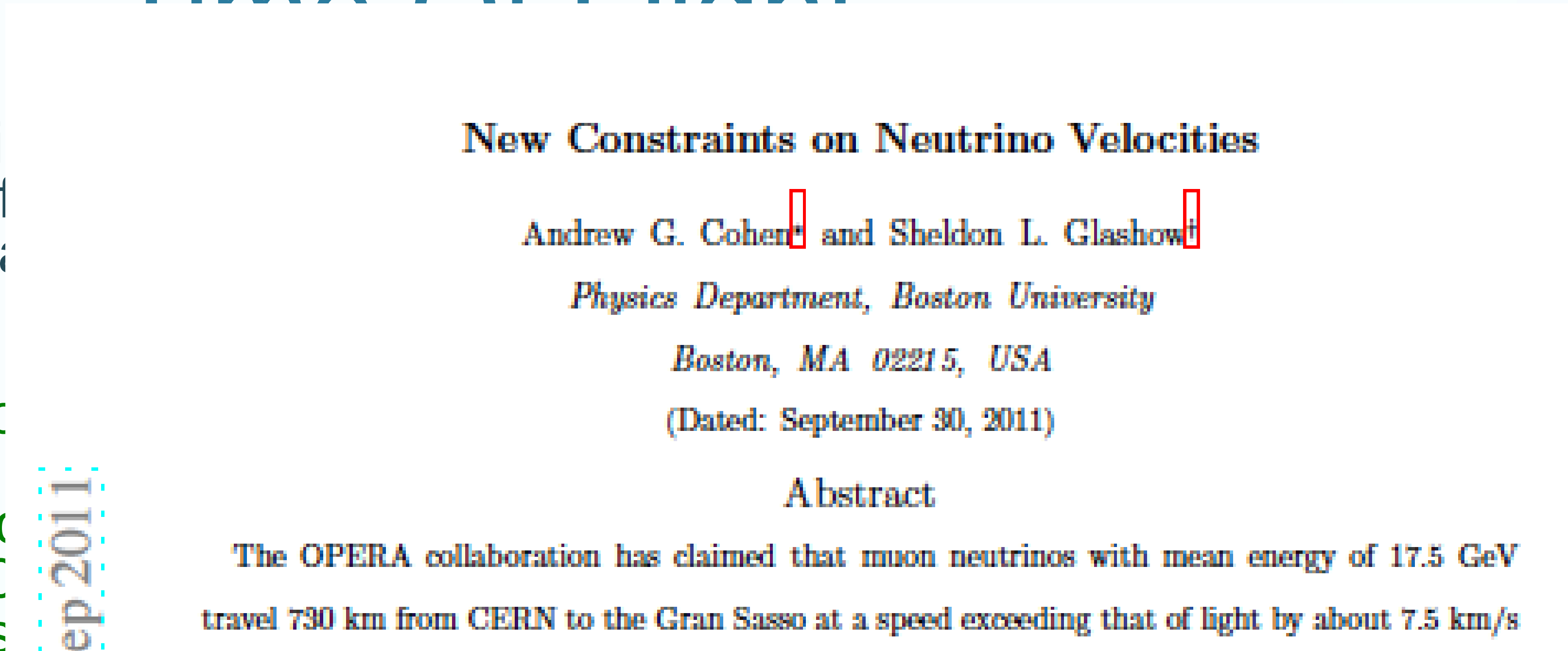


New Constraints on Neutrino Velocities

Andrew G. Cohen[*] and Sheldon L. Glashow[†]

Physics Department, Boston University

Boston, MA 02215, USA

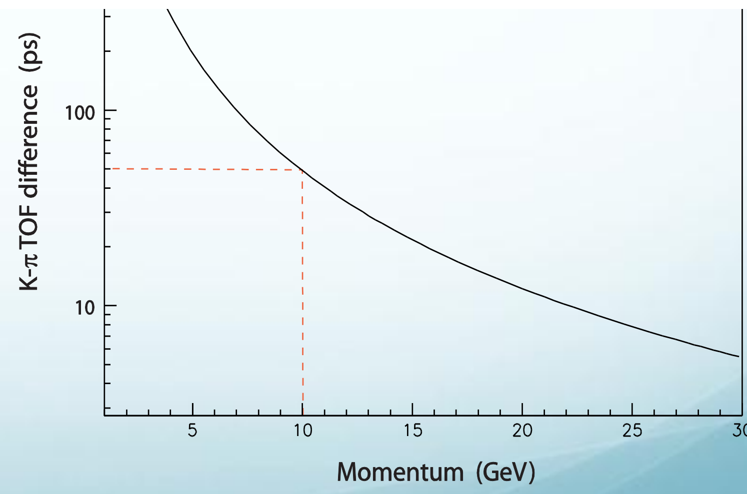
(Dated: September 30, 2011)

ep 2011

Abstract

The OPERA collaboration has claimed that muon neutrinos with mean energy of 17.5 GeV travel 730 km from CERN to the Gran Sasso at a speed exceeding that of light by about 7.5 km/s

- Modern detectors + readout electronics
  have resolution σ_t ~ 10 ns, fast enough
  for the LHC (bunch crossings 25 ns apart)
  but need σ_t < 1 ns to do useful TOF

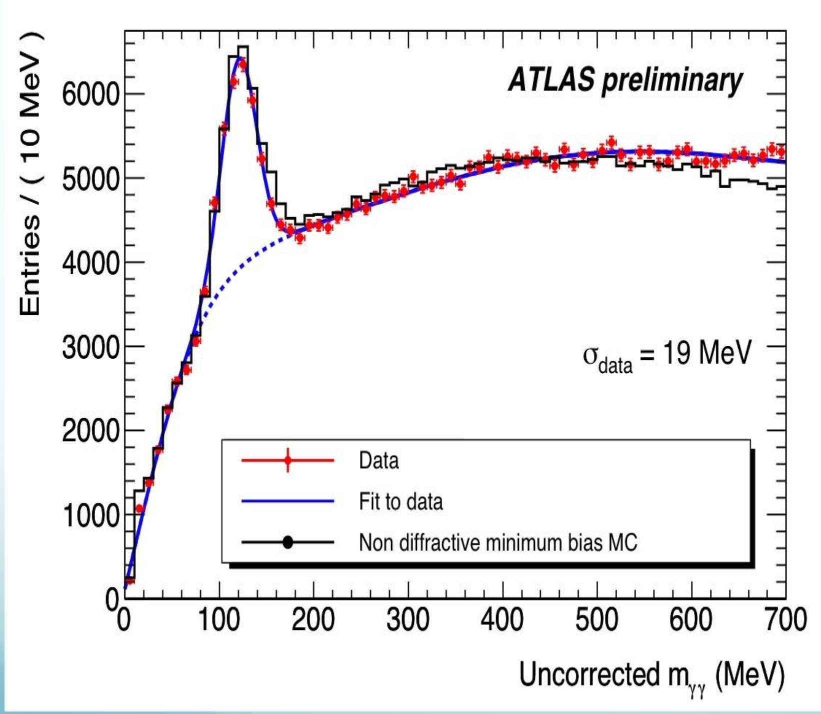


How does it work?
Some examples

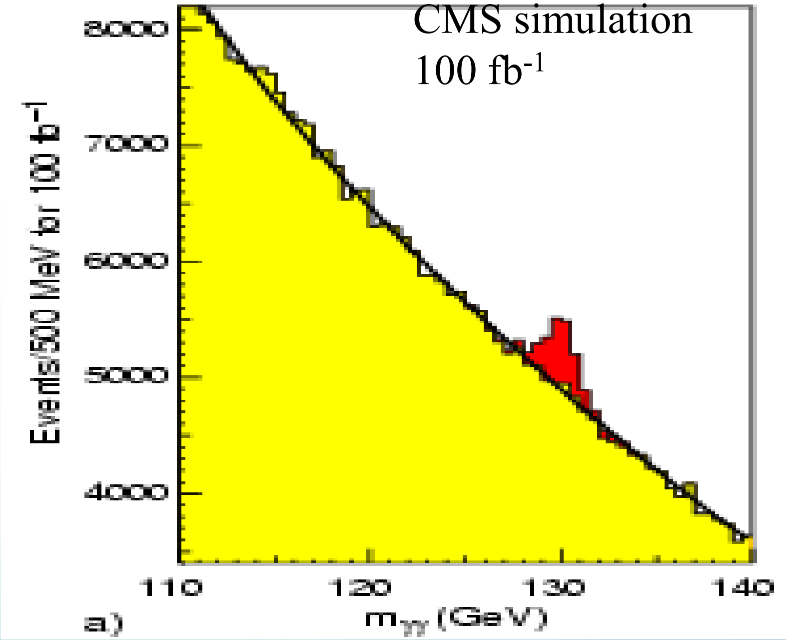
Mass reconstruction

- Typical example of reconstruction of a particle decay: $\pi^0 \rightarrow \gamma\gamma$
  one of the first composite particles reconstructed in the LHC experiments
- This technique an also be used to search for more exciting signals:

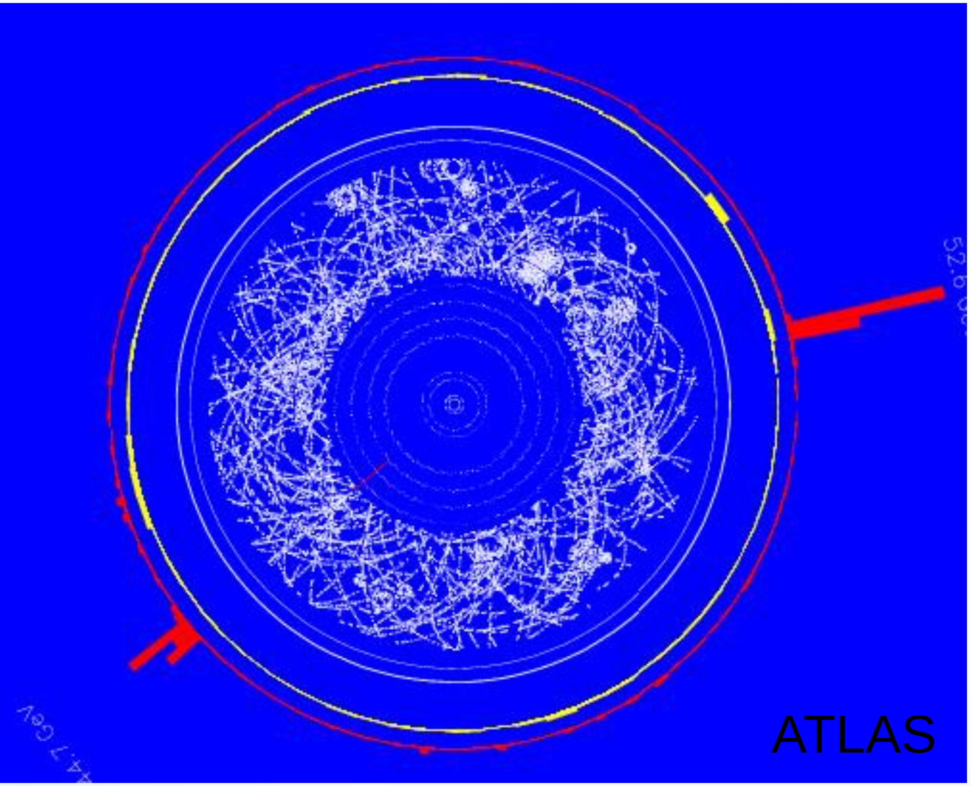
$m(\pi^0) = 135$ MeV



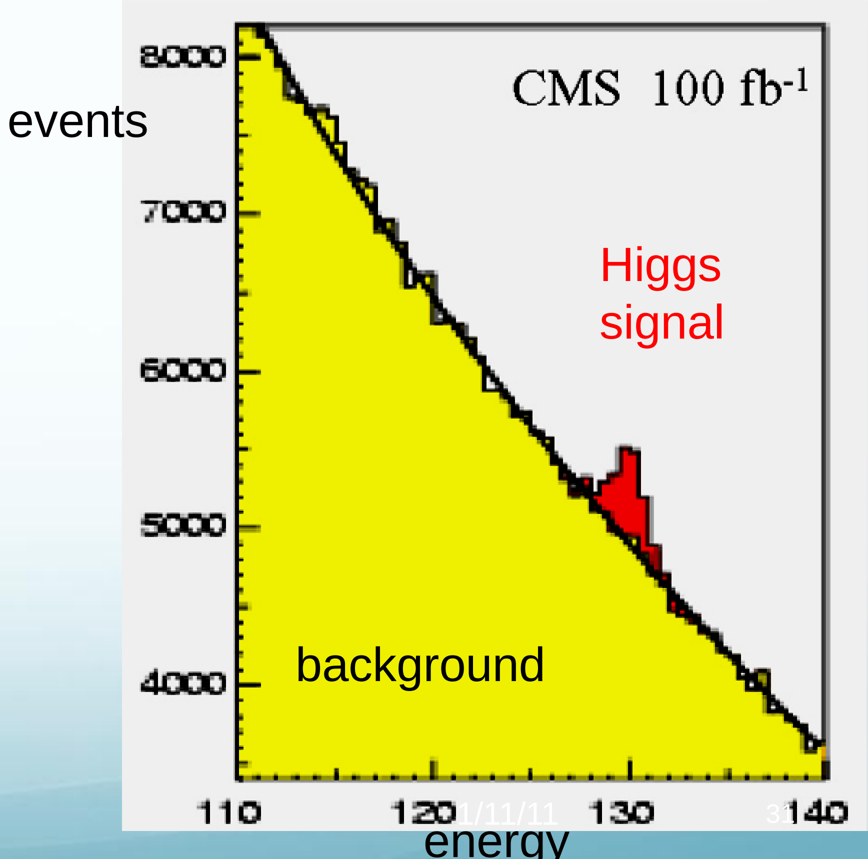
$H \rightarrow \gamma\gamma$



Higgs Detection: H -> $\gamma\gamma$

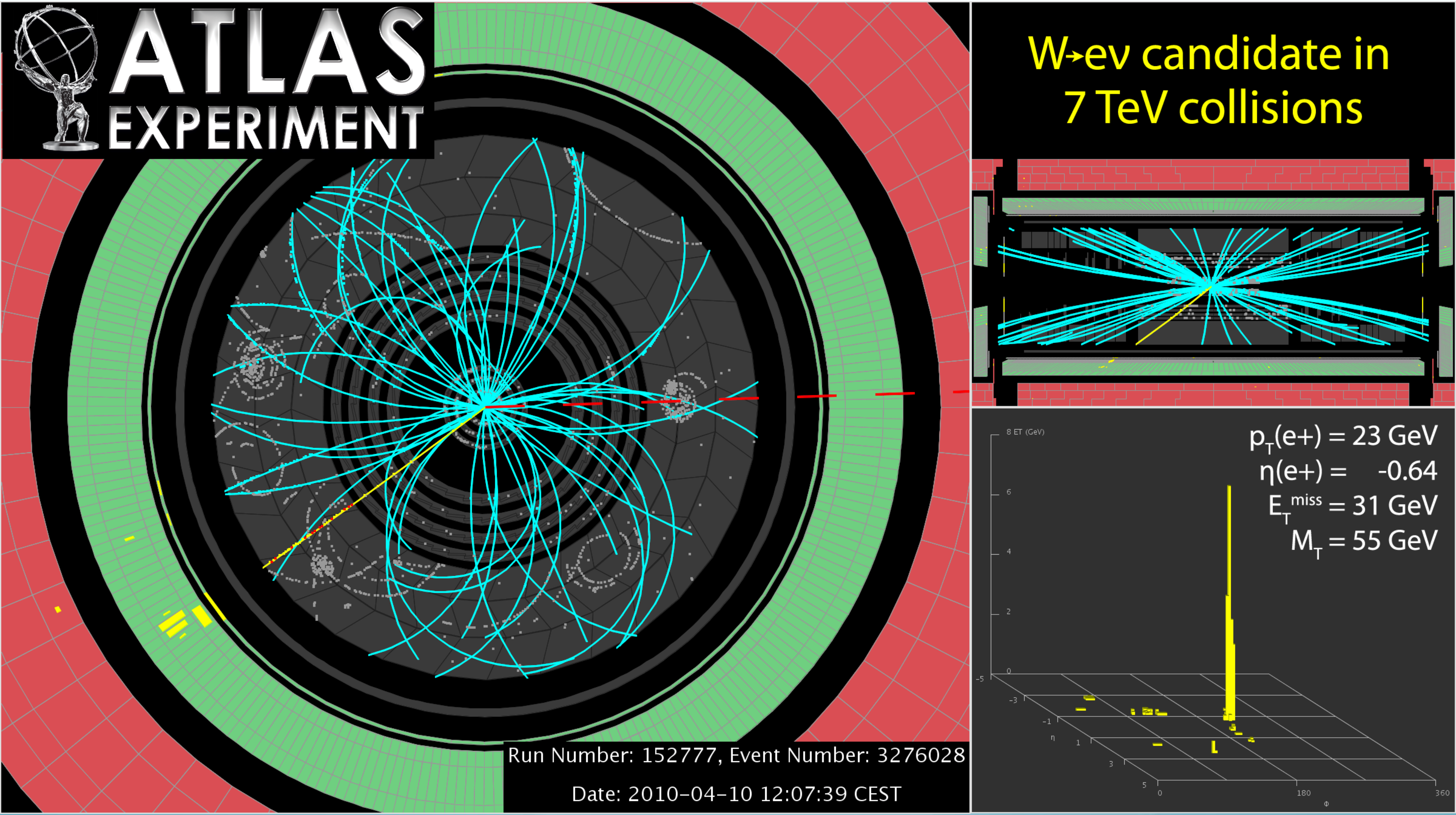


A Higgs decaying to 2 energetic photons would be a striking event in the LHC detectors.

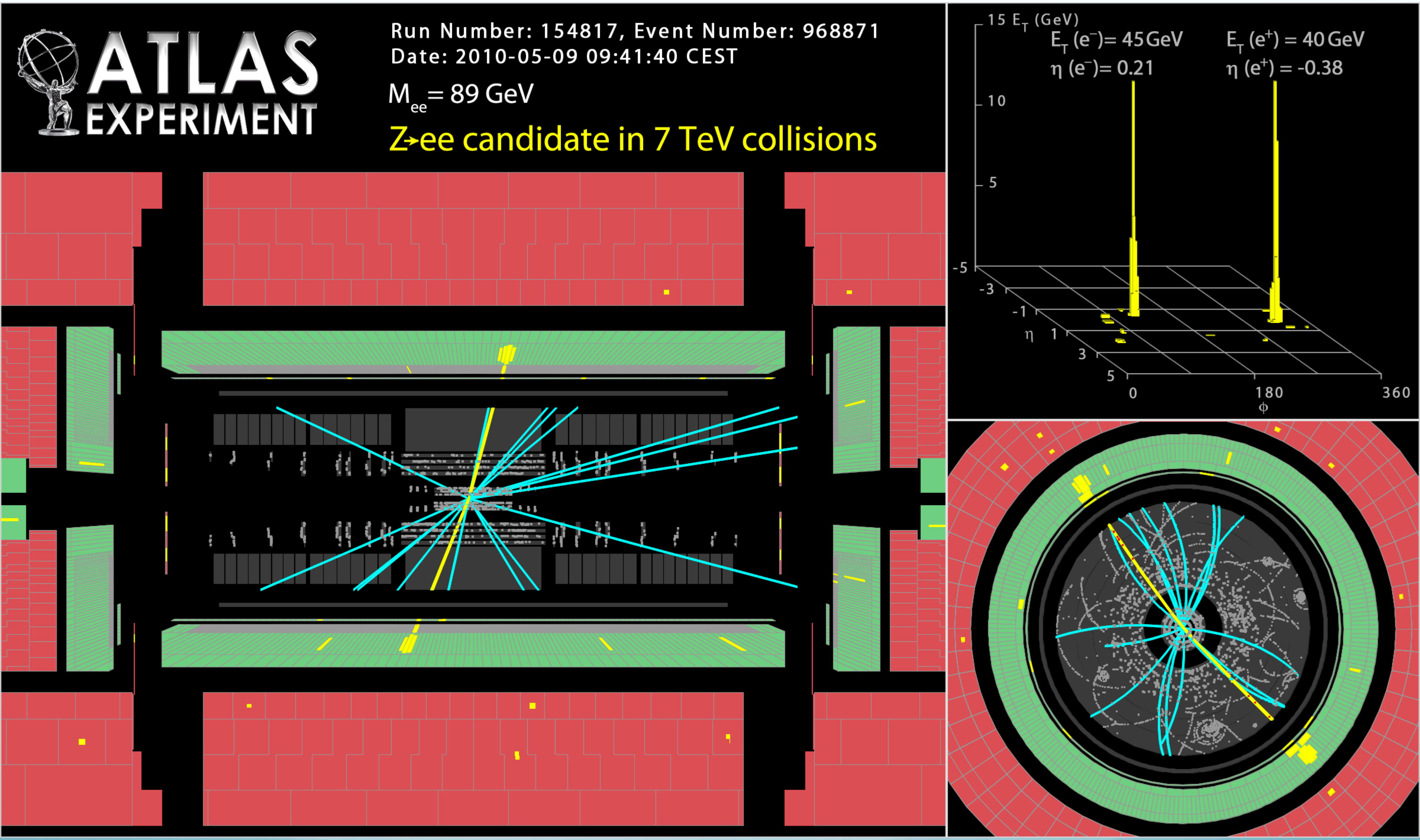


The combined energies of the signal photons would cluster at the mass of the Higgs boson. In contrast, background events include photon pairs with a variety of energies.

ATLAS example



ATLAS


ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_{ee} = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
E_T (e⁻)= 45 GeV
η (e⁻)= 0.21
E_T (e⁺) = 40 GeV
η (e⁺) = -0.38
10
5
-5
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η
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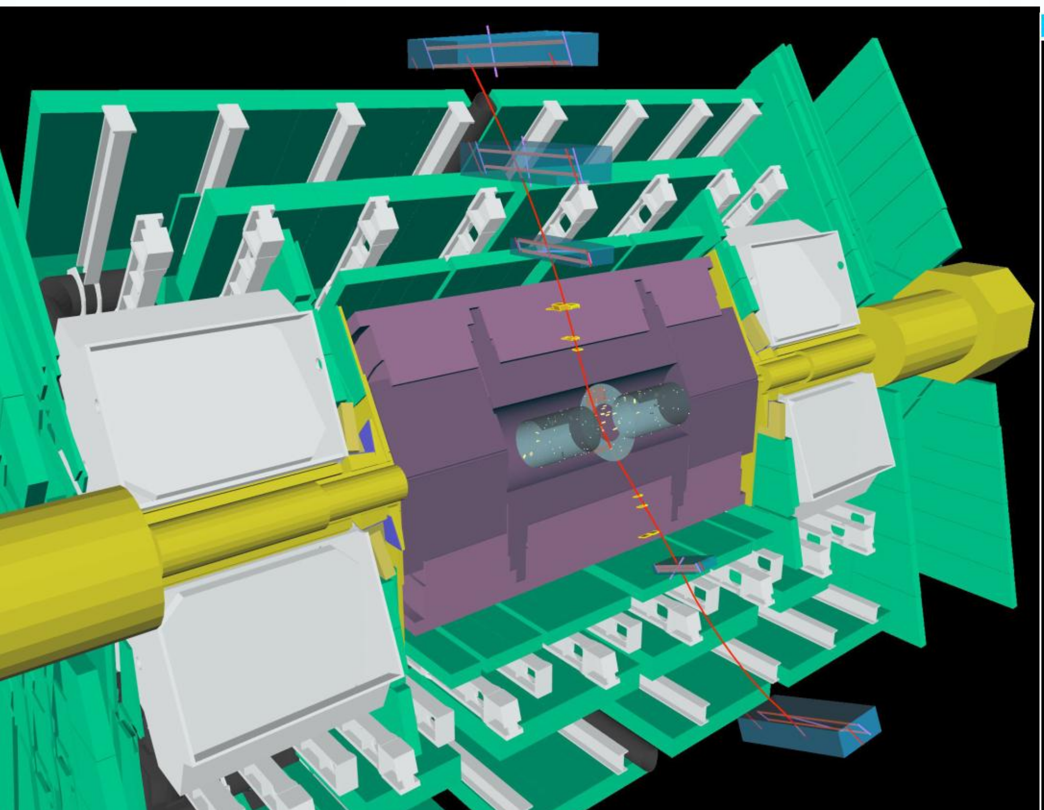
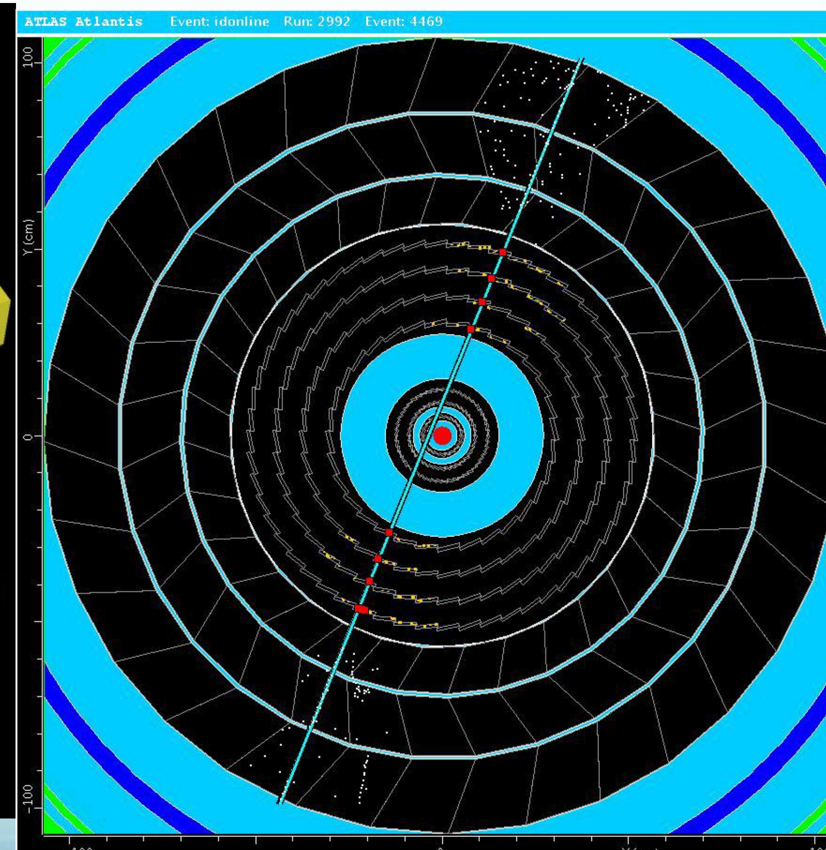
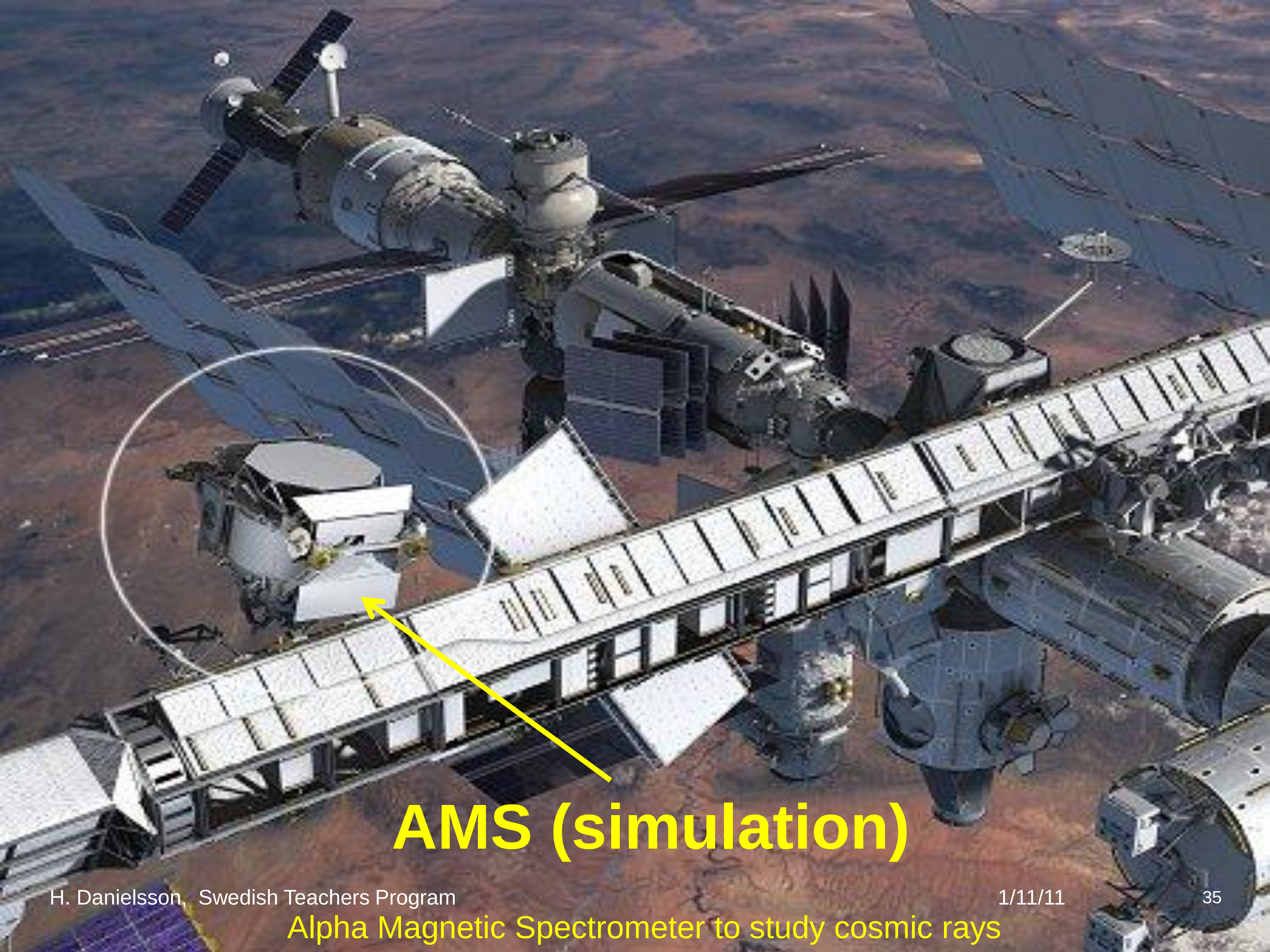
What is this???

(From ATLAS)







AMS (simulation)

Alpha Magnetic Spectrometer to study cosmic rays

References

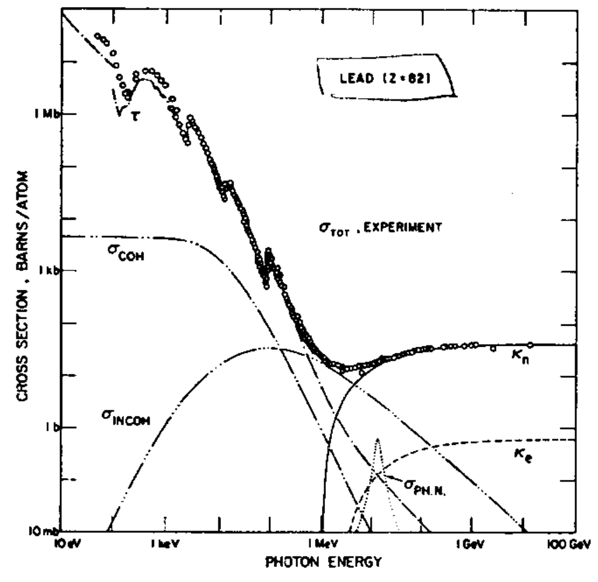
- Richard Kass, 880.P20 Winter 2006
- Roger Forty, ICFA Instrumentation School, Bariloche, 19-20 January 2010.
- Ana Henriques, on behalf of the ATLAS collaboration, ICATPP11 Como, 3-7October 2011

Spares

Interaction of Photons (γ' s) with Matter

There are three main contributions to photon interactions:

- Photoelectric effect ($E\gamma <$ few MeV)
- Compton scattering
- Pair production (dominates at energies > few MeV)



Contributions to photon interaction cross section for lead including photoelectric effect (τ), rayleigh scattering (σ_{coh}), Compton scattering (σ_{incoh}), photonuclear absorbtion ($\sigma_{ph,n}$), pair production off nucleus (K_n), and pair production off electrons (K_e).

Rayleigh scattering (σ_{coh}) is the classical physics process where γ' s are scattered by an atom as a whole. All electrons in the atom contribute in a coherent fashion. The γ' s energy remains the same before and after the scattering.

A beam of γ' s with initial intensity N_0 passing through a medium is attenuated in number (but not energy) according to:

$$dN=-\mu N dx \text{ or } N(x)=N_0 e^{-\mu x}$$

With μ= linear attenuation coefficient which depends on the total interaction cross section ($\sigma_{total}= \sigma_{coh}+ \sigma_{incoh} + +$).

Photoelectric effect

The photoelectric effect is an interaction where the incoming photon (energy E_γ=hv) is absorbed by an atom and an electron (energy=E_e) is ejected from the material:

$$E_e = E_\gamma - BE$$

Here BE is the binding energy of the material (typically a few eV).

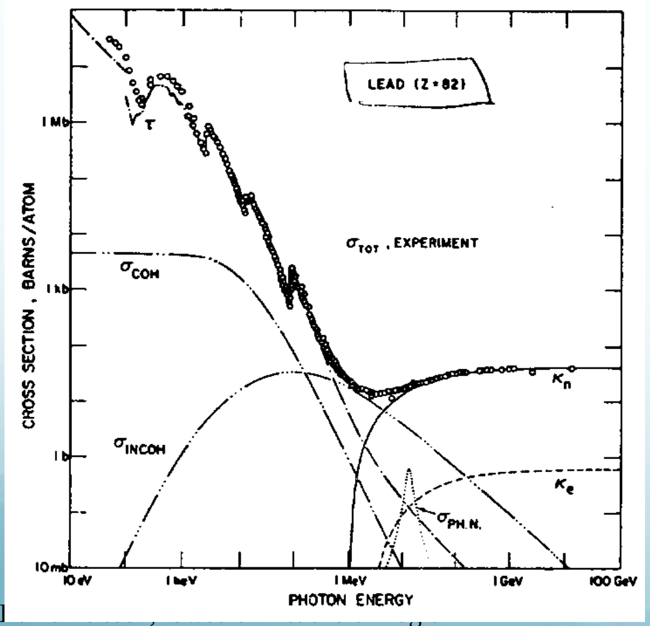
Discontinuities in photoelectric cross section due to discrete binding energies of atomic electrons (L-edge, K-edge, etc).

Photoelectric effect dominates at low γ energies (< MeV) and hence gives low energy e's.

Exact cross section calculations are difficult due to atomic effects.

Cross section falls like $E_\gamma^{-7/2}$

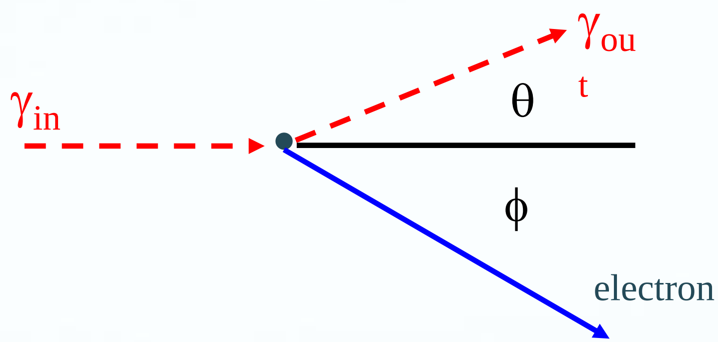
Cross section grows like Z^4 or Z^5 for E_γ> few MeV



Einstein wins Nobel prize in 1921 for his work on explaining the photoelectric effect. Energy of emitted electron depends on energy of γ and NOT intensity of γ beam.

Compton Scattering

Compton scattering is the interaction of a real γ with an atomic electron.



Solve for energies and angles using conservation of energy and momentum

$$\cos\theta = 1 - \frac{m_e c^2}{E_{\gamma,in} E_{\gamma,out}} (E_{\gamma,in} - E_{\gamma,out})$$

The result of the scattering is a "new" γ with less energy and a different direction.

$$E_{\gamma,out} = \frac{E_{\gamma,in}}{1+\gamma(1-\cos\theta)} \quad \textit{with} \;\; \gamma \equiv E_{\gamma,in} / m_e c^2$$

Not the usual γ!

$$\text{Kinetic Energy of Electron} = T = E_{\gamma,in} - E_{\gamma,out} = E_{\gamma,in} \frac{\gamma(1-\cos\theta)}{1+\gamma(1-\cos\theta)}$$

The Compton scattering cross section was one of the first (1929!) scattering cross sections to be calculated using QED. The result is known as the Klein-Nishima cross section.

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2[1+\gamma(1-\cos\theta]^2} \left(1+\cos^2\theta + \frac{\gamma^2(1-\cos\theta)^2}{1+\gamma(1-\cos\theta)}\right) = \frac{r_e^2}{2} \left(\frac{E_{\gamma,out}}{E_{\gamma,in}}\right)^2 \left(\frac{E_{\gamma,out}}{E_{\gamma,in}} + \frac{E_{\gamma,in}}{E_{\gamma,out}} - \sin^2\theta\right)$$

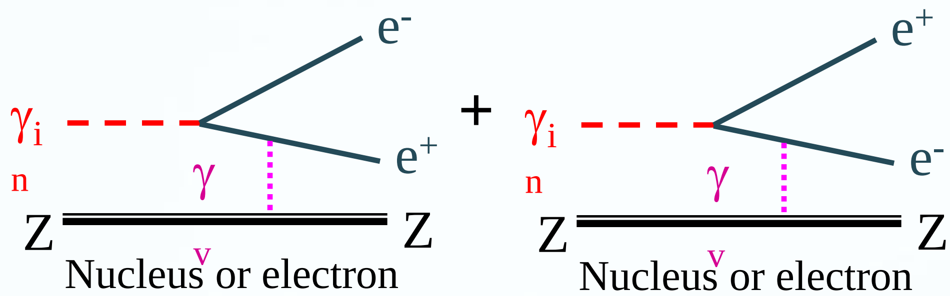
At high energies, γ>>1, photons are scattered mostly in the forward direction (θ=0)

At very low energies, γ≈0, K-N reduces to the classical result: $\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}(1+\cos^2\theta)$

Pair Production ($\gamma \rightarrow e^+e^-$)

This is a pure QED process.

A way of producing anti-matter (positrons).



Threshold energy for pair production in field of nucleus is $2m_ec^2$, in field of electron $4m_ec^2$.

First calculations done by Bethe and Heitler using Born approximation (1934).

At high energies ($E_\gamma >> 137 m_ec^2Z^{-1/3}$) the pair production cross sections is ≈ constant.

$$\sigma_{pair} = 4Z^2\alpha r_e^2[7/9\{\ln(183Z^{-1/3}) - f(Z)\} - 1/54]$$

Neglecting some small correction terms (like 1/54, 1/18) we find:

$$\sigma_{pair} = (7/9)\sigma_{brem}$$

The mean free path for pair production (λ_{pair}) is related to the radiation length (L_r):

$$\lambda_{pair} = (9/7)\, L_r$$

Consider again a mono-energetic beam of γ's with initial intensity N_0 passing through a medium. The number of photons in the beam decreases as:

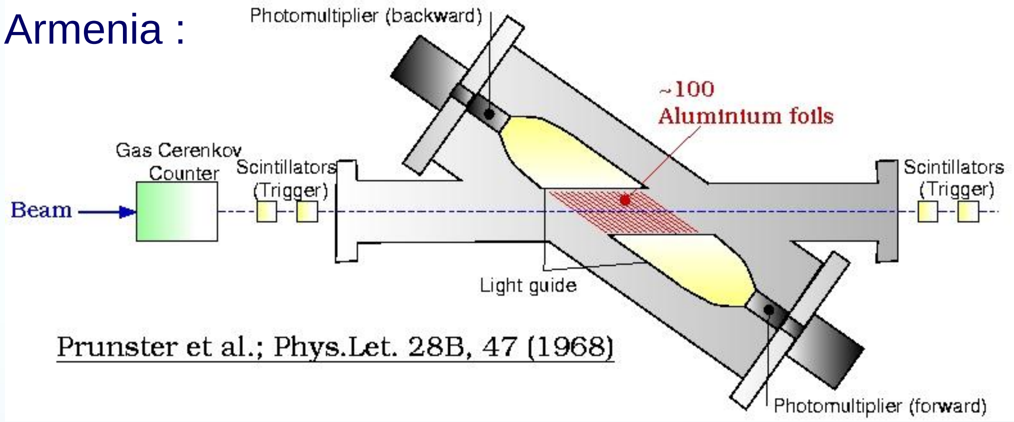
$$N(x) = N_0 e^{-\mu x}$$

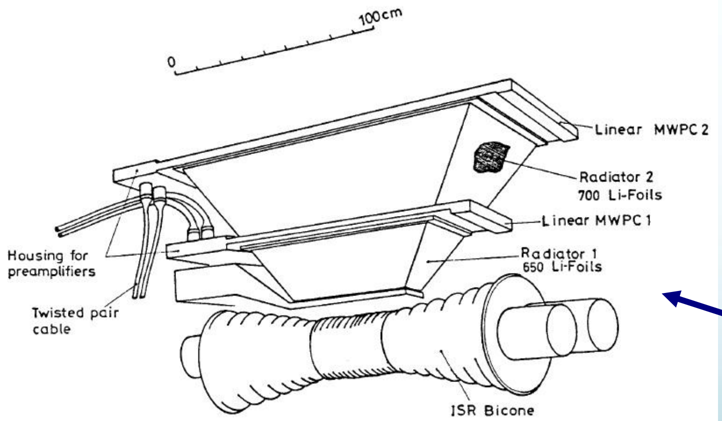
The linear attenuation coefficient (μ) is given by: $\mu = (N_a\rho/A)(\sigma_{photo} + \sigma_{comp} + \sigma_{pair})$.

For compound mixtures, μ is given by Bragg's rule: $(\mu/\rho) = w_1(\mu_1/\rho_1) + \ldots + w_n(\mu_n/\rho_n)$ with w_i the weight fraction of each element in the compound.

A bit of history

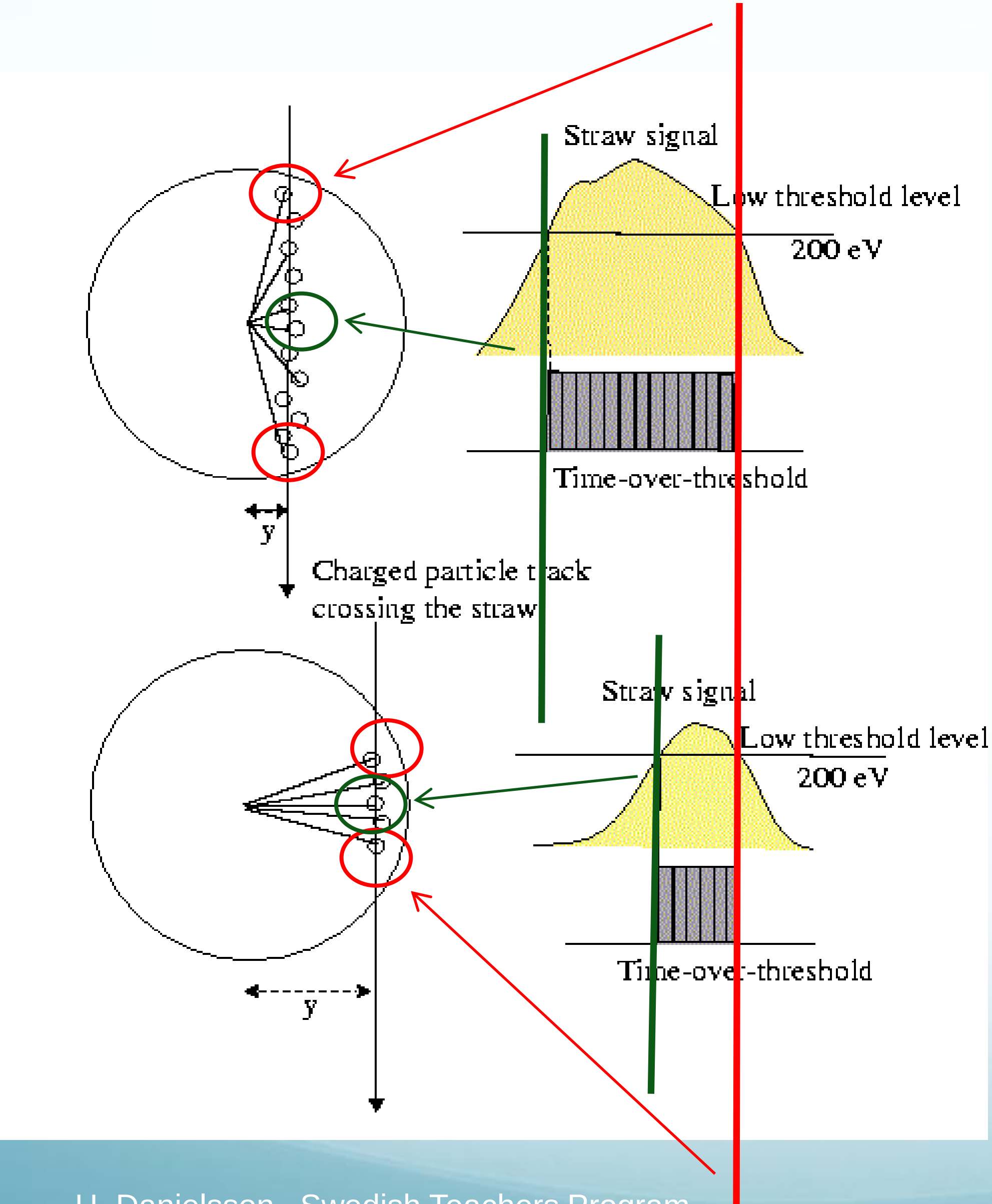
- 1919: J.E. Lilienfeld observes that surfaces emit light when hit by electron beam
  - → **"Es ist Dunkeladaption des Auges notwendig um einen Leuchtfleck, erzeugt von einem Elektronenstrahl mit 5keV Energie und 20µA Strahlstrom wahrzunehmen" Physikalische Zeitschrift 1919 20, 280)**
- 1946: W. Ginzburg and G. Frank publish their theory of transition radiation
- >1960: experiments observe transition radiation,
  A.I.Alikhanian and his collaborators from Armenia :
  first XTR observations and investigations





- 1975: First TRD for electron ID in balloon flight
- 1976: First TRD in HEP experiment for electron ID R806 @ ISR (CERN)

A bit more on the signal…



Tailing edge of the signal:

→ Independent of distance of track to wire

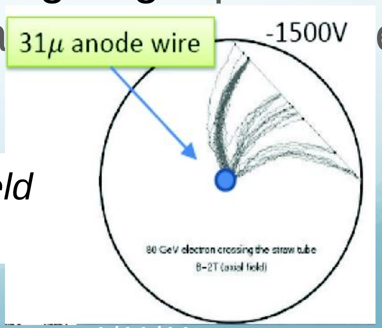
→ "late" ionisations always originate from R=2mm

Leading edge of the signal:

→ Depends on distance of ionisation which happens closest to the wire

→ "early" leading edge: particle crossed stra… e

N.b.: drift is B-field dependent



Scattering

gold foil. Alpha particles produce a tiny, but visible flash of light when they strike a fluorescent screen. Surprisingly, alpha particles were found at large deflection angles and some were even found to be back-scattered.