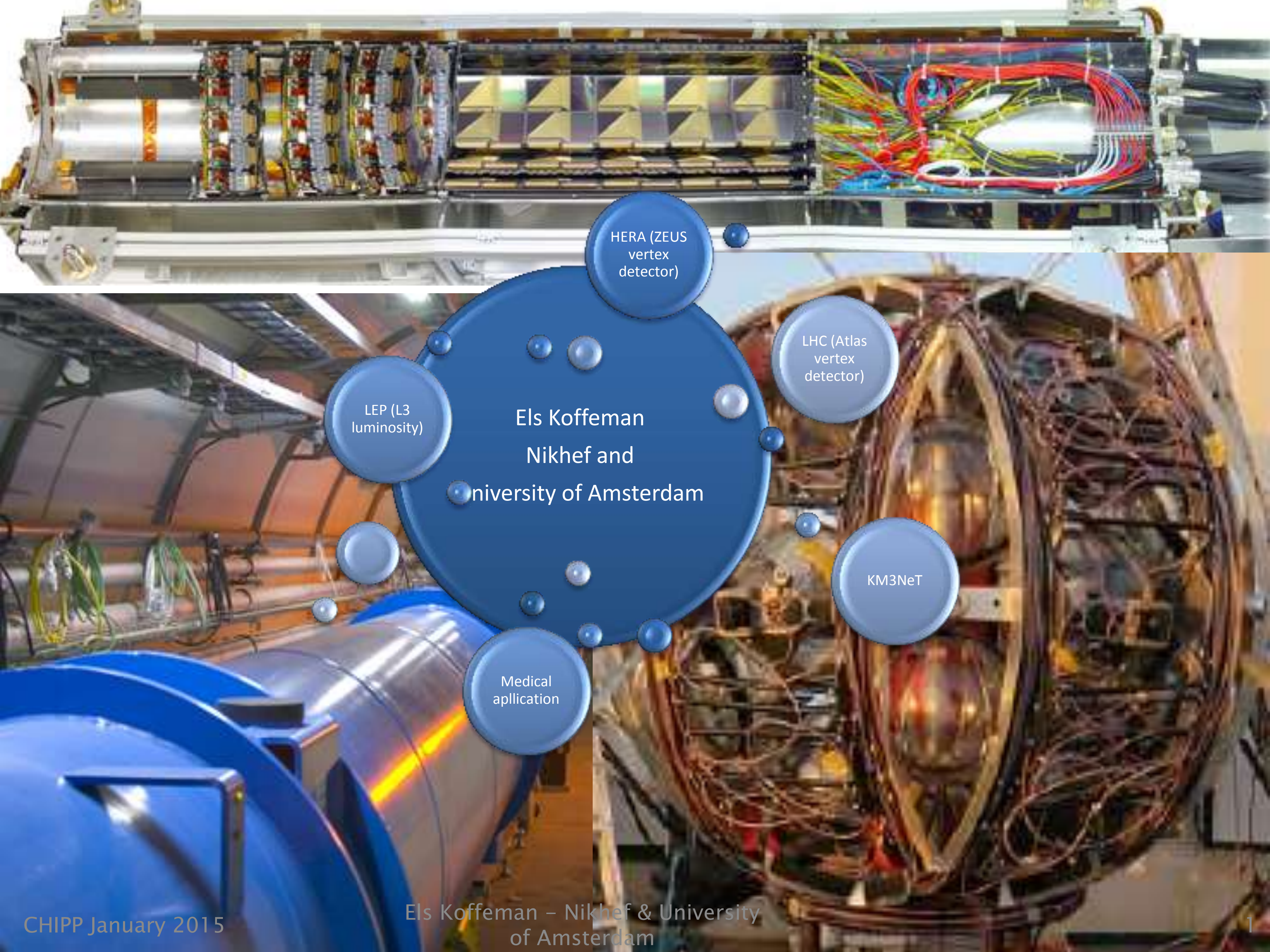

Els Koffeman
Nikhef and
University of Amsterdam
HERA (ZEUS vertex detector)
LHC (Atlas vertex detector)
LEP (L3 luminosity)
KM3NeT
Medical apllication

I: Observables
II: Particle Interactions
III: Tracking
IV: Medical applications

Els Koffeman
koffeman@nikhef.nl

Photon attenuation

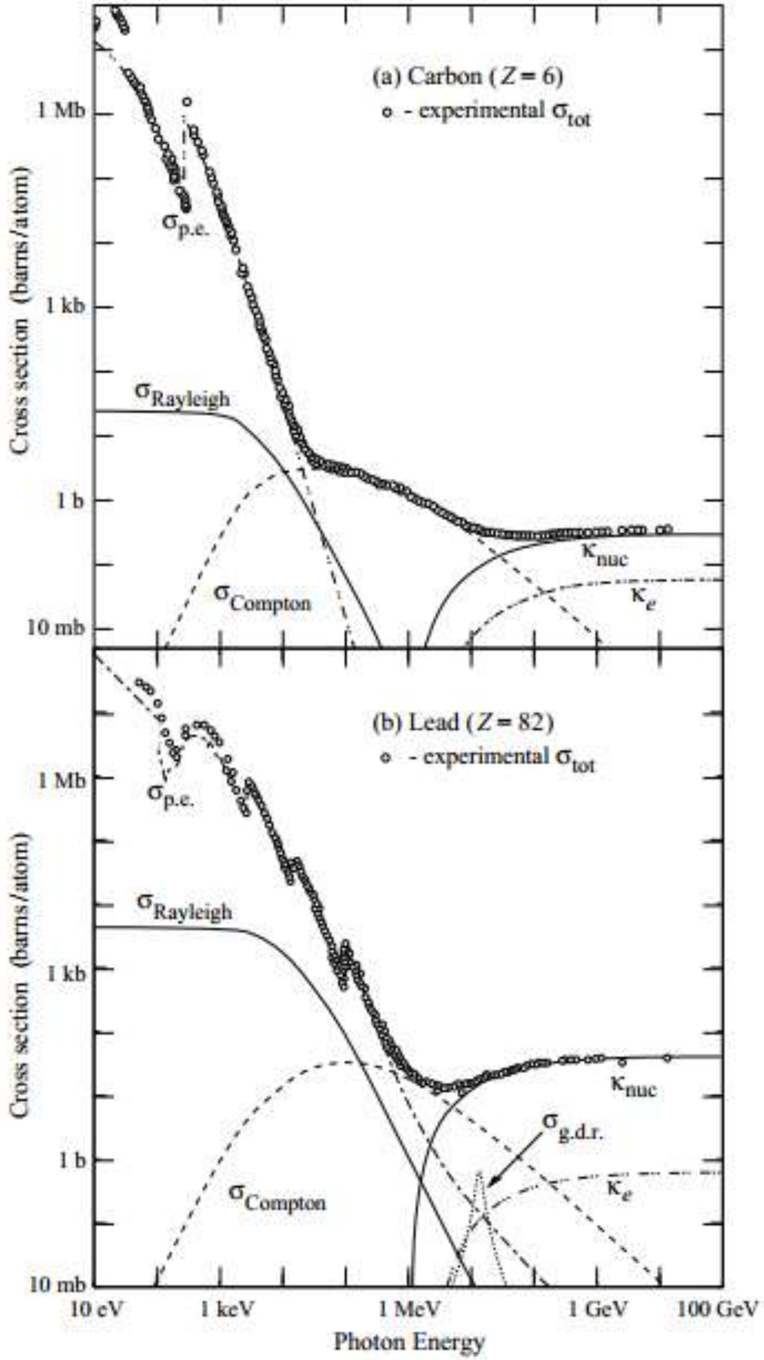
- Photo electric effect (cross section like Z^4/E^3)
- Pair creation
- Compton scattering

$$\frac{dI}{dx} = -\mu I$$

$$I(t) = I_0 e^{(-\mu x)}$$

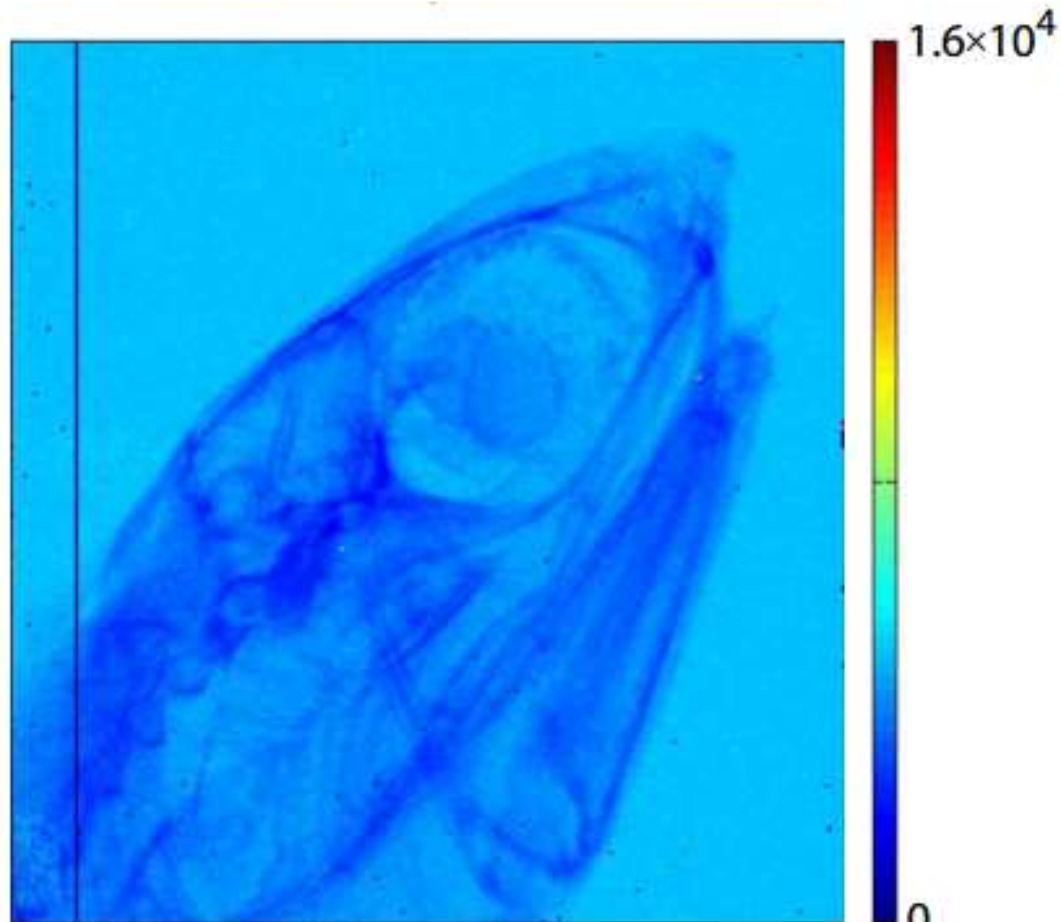
$$\mu = \mu_{foto} + \mu_{compton} + \mu_{pair}$$

$$\frac{\mu}{\rho} = \sum_i w_i \left(\frac{\mu_i}{\rho_i} \right)$$



Imaging

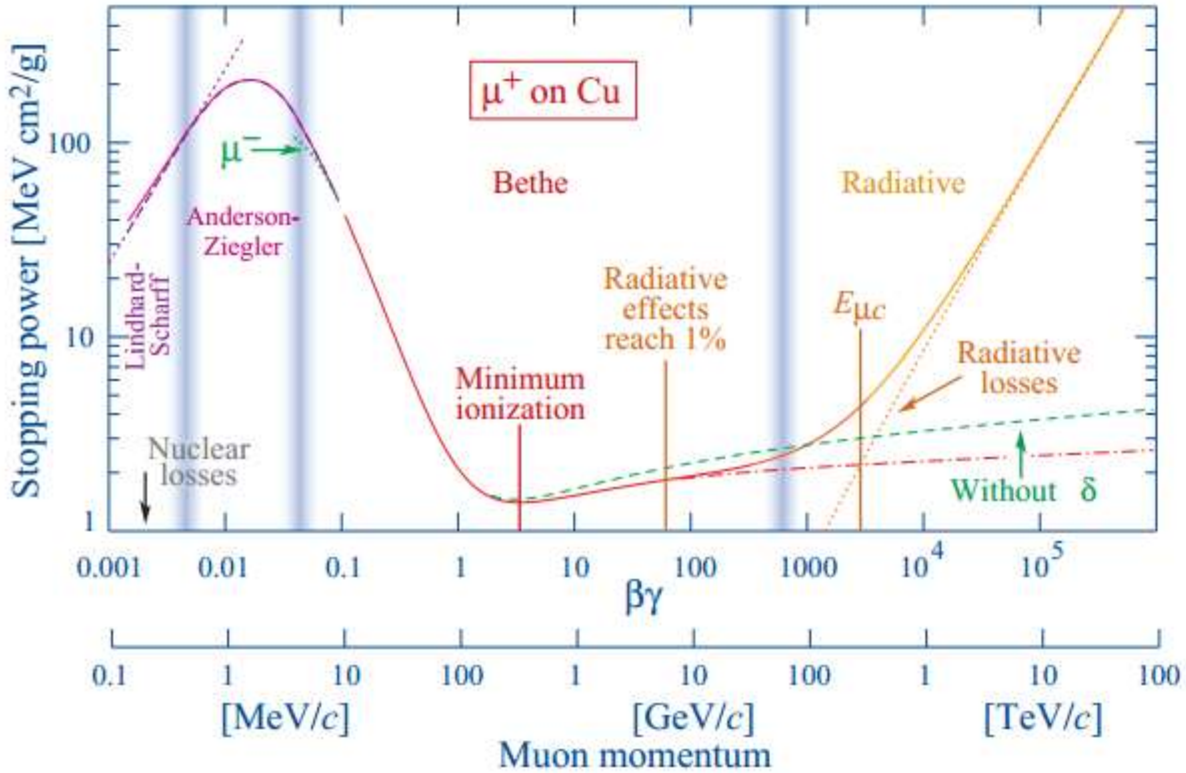
- Count number of photons
  - Conventional Xray
  - TFT film
  - Phosphorous screen with CCD
  - (particle physics) pixel chip



Corrected

Charged particles

- Energy loss to atomic electron dominates

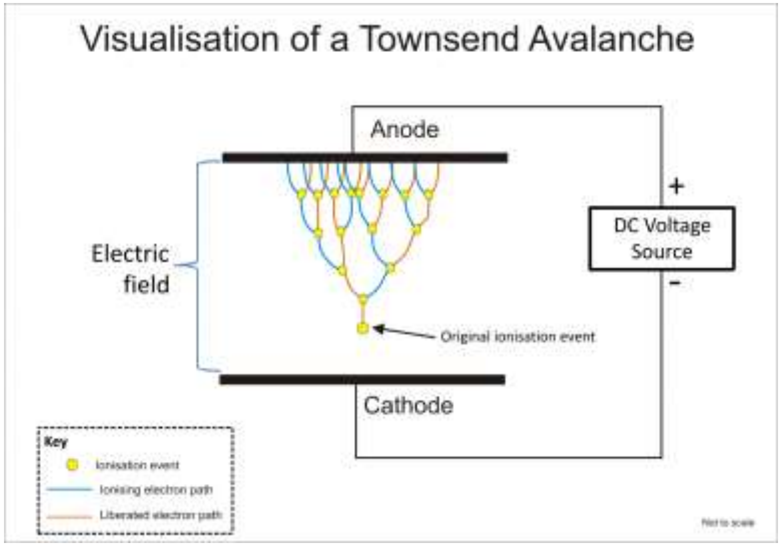


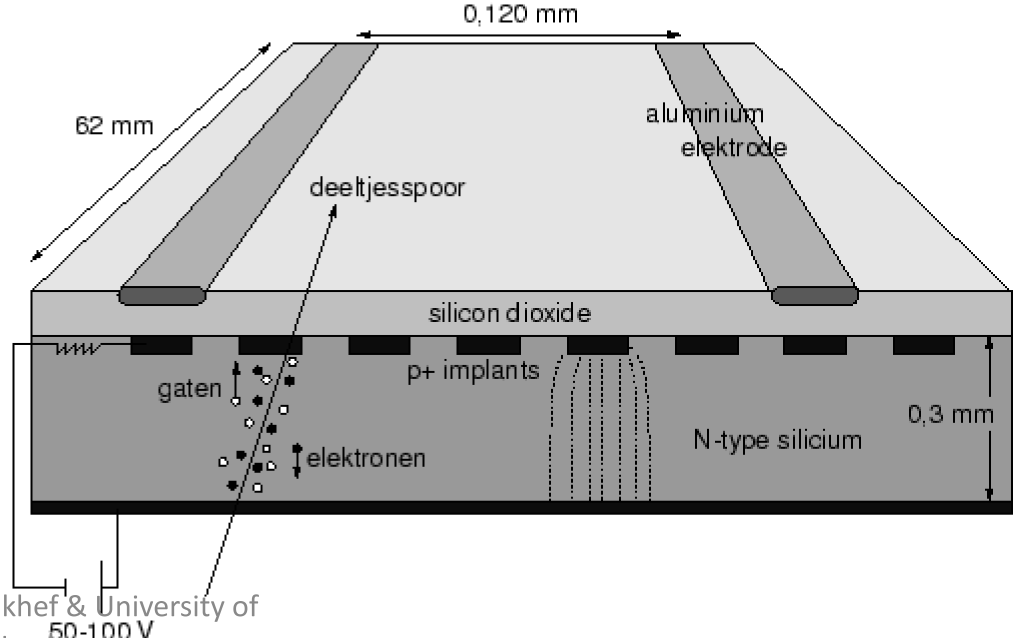
Interactions creating (visible) light

- Scintillation
  - Crystals or plastics with small admixtures of large molecules allow low energy excitations
  - secondary emission leads to emission(visible) light
- Cerenkov radiation
  - particle speed exceeds the velocity of light in medium
- Chemical reactions
  - photographic emulsion reducing silver grains
- Transition radiation
  - Medium emits x-rays when permittivity changes

Interaction creates charge

- Production of free ions and electrons
  - Gas with low density little disturbance of a particle track but need gas amplification
  - Liquid can be flushed and may increase radiation hardness
- Creation of eh pairs
  - solid state highly efficient and precise but can be expensive to process
  - Material may cause defections of particles path





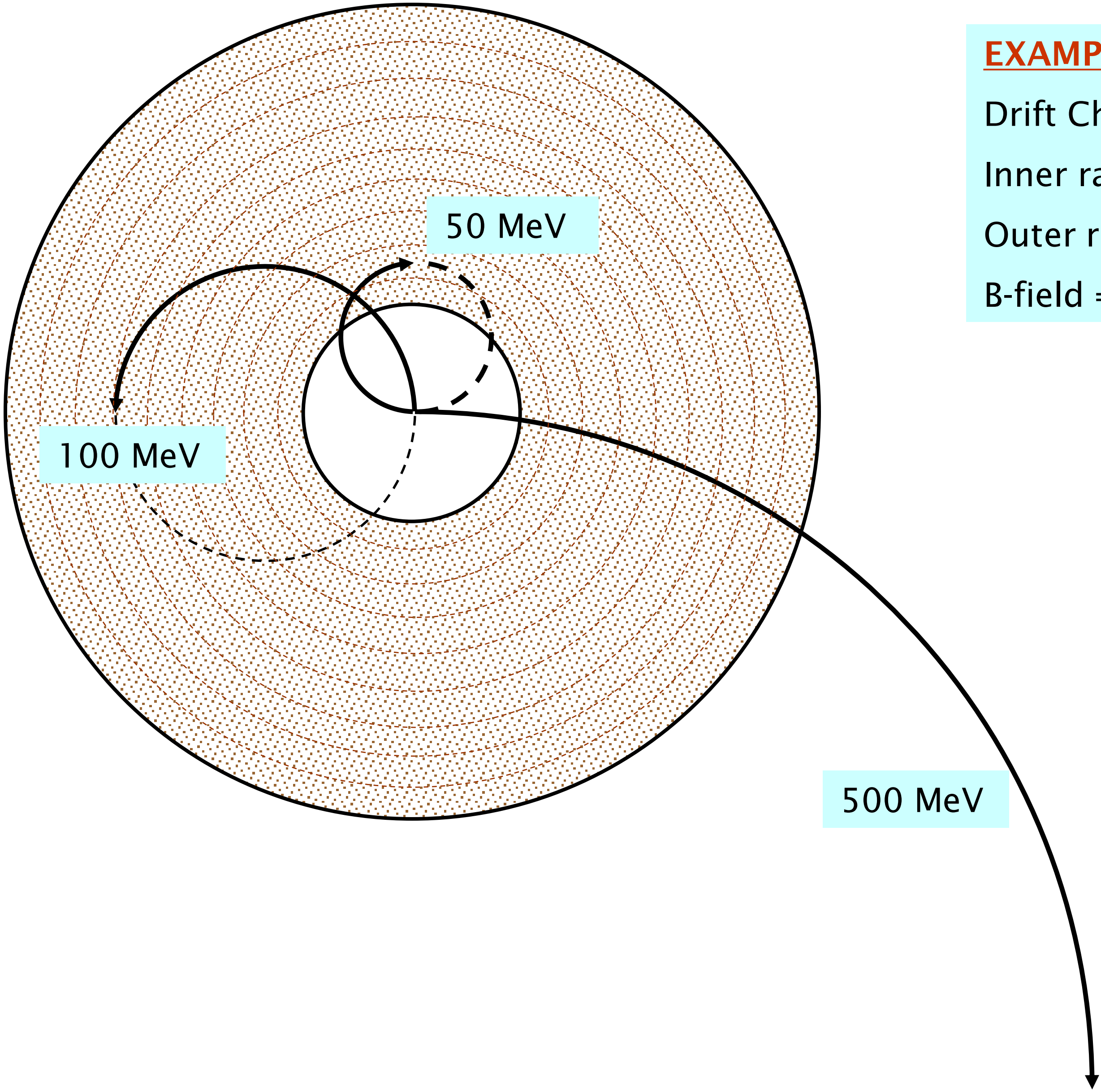
Momentum Measurement

$$\mathrm{m}\frac{\mathrm{d}\vec{\mathrm{v}}}{\mathrm{dt}} = q\vec{E} + q\vec{\mathrm{v}} \times \vec{B}$$

- Particle in a magnetic field follows a ‘helix shape’ track

$$F_{Lorentz} = q(\vec{v} \times \vec{B})$$

- Toroidal or solonoidal fields
  - CMS large field in a ‘smal’ volume
  - ATLAS two perpendicular fields (inner detector and muon spectrometer)



EXAMPLE: ZEUS

Drift Chamber

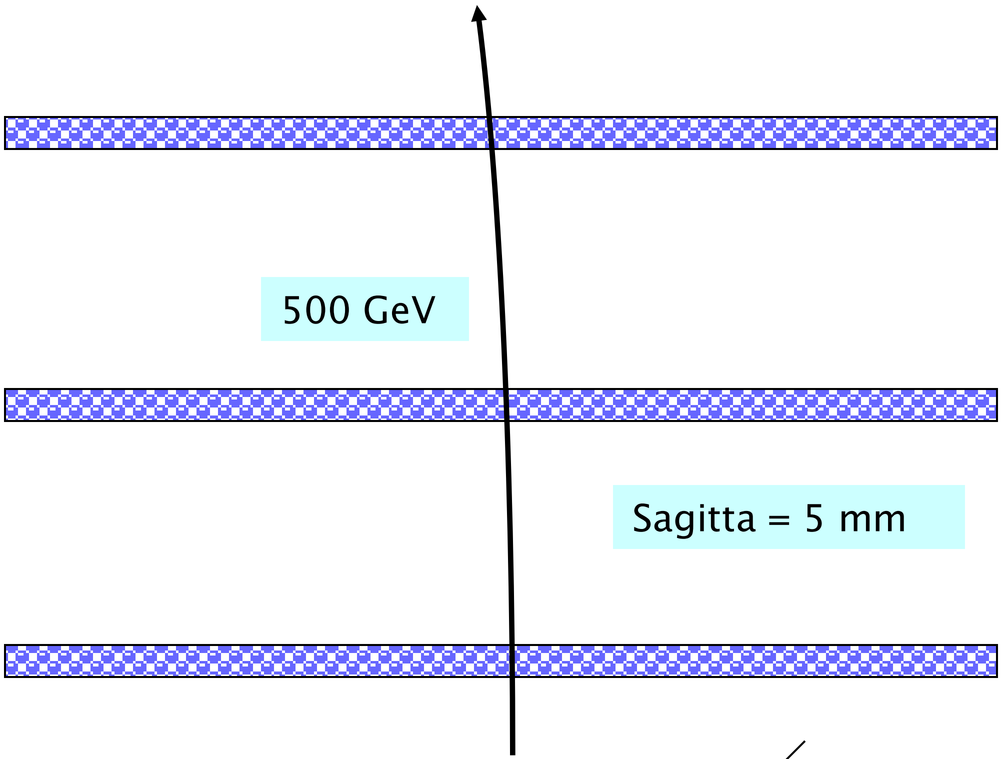
Inner radius 16 cm

Outer radius 85 cm

B-field = 1.5 Tesla

$$\text{radius} = \frac{1}{\rho}$$

$$\rho = \frac{0.3\,B}{p \cdot \sin\theta}$$



EXAMPLE: ATLAS

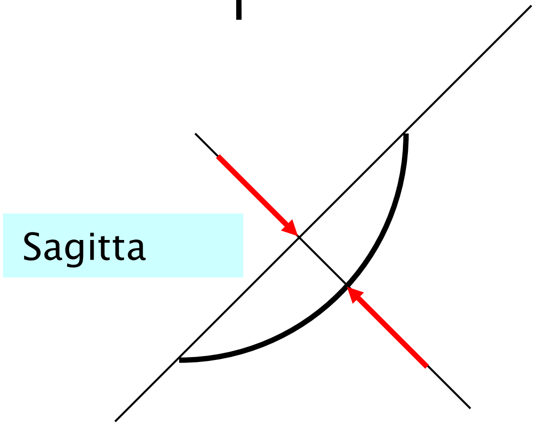
Drift tubes

Inner radius 5 m

Middle radius 10 m

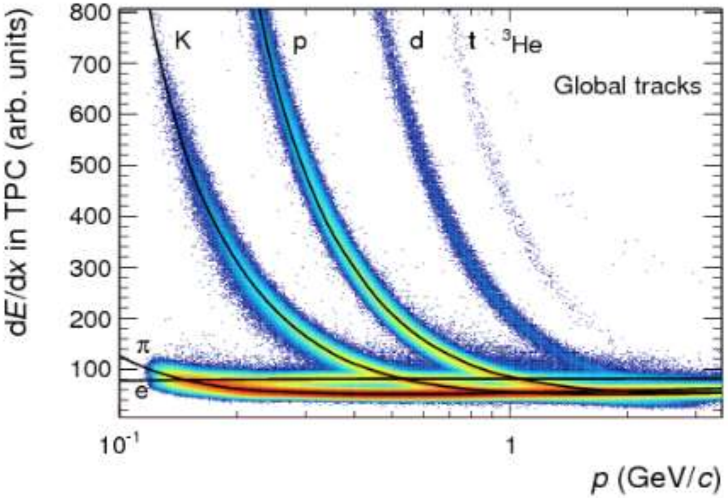
Outer radius 15 m

B-field = 0.6 Tesla

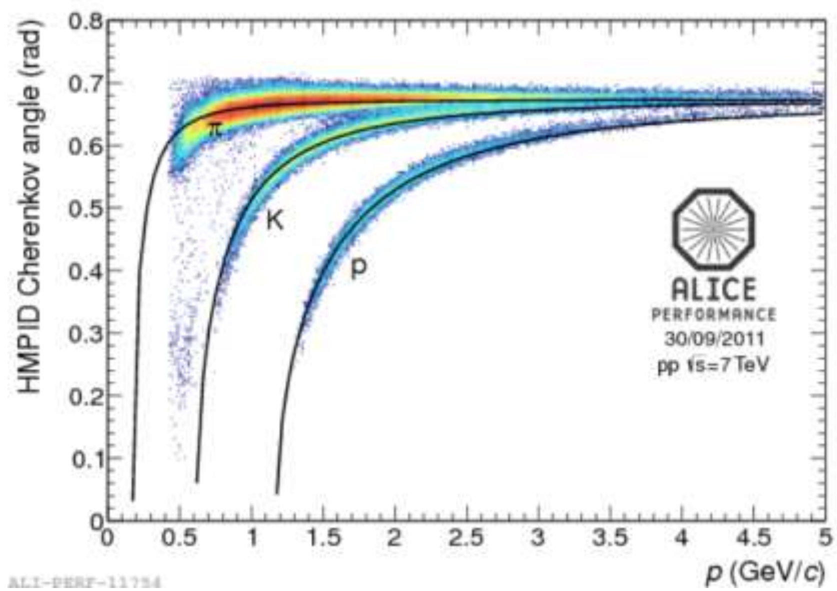


$$\text{radius} = \frac{1}{\rho}$$

$$\text{Sagitta} = \frac{L^2}{8\rho}$$



Energy loss dE/dx in the ITS (top-left) and in the TPC (top-right). The continuous curves represent the Bethe-Bloch parametrization. (bottom-left) particle velocity β measured with TOF as a function of momentum. (bottom-right) Cherenkov angle measured in the HMPID as a function of the track momentum.



Velocity Measurements

- Time of Flight
- Specific Energy loss (Bethe Bloch)

$$\frac{\mathrm{dE}}{\mathrm{dx}} = f(\beta)$$

- Cerenkov effect

$$\cos\vartheta = \frac{1}{\beta \mathrm{n}}$$

- Transition radiation

$$\vartheta_{mp} = \sqrt{\frac{1}{\gamma^2} + \Upsilon_2^2}$$

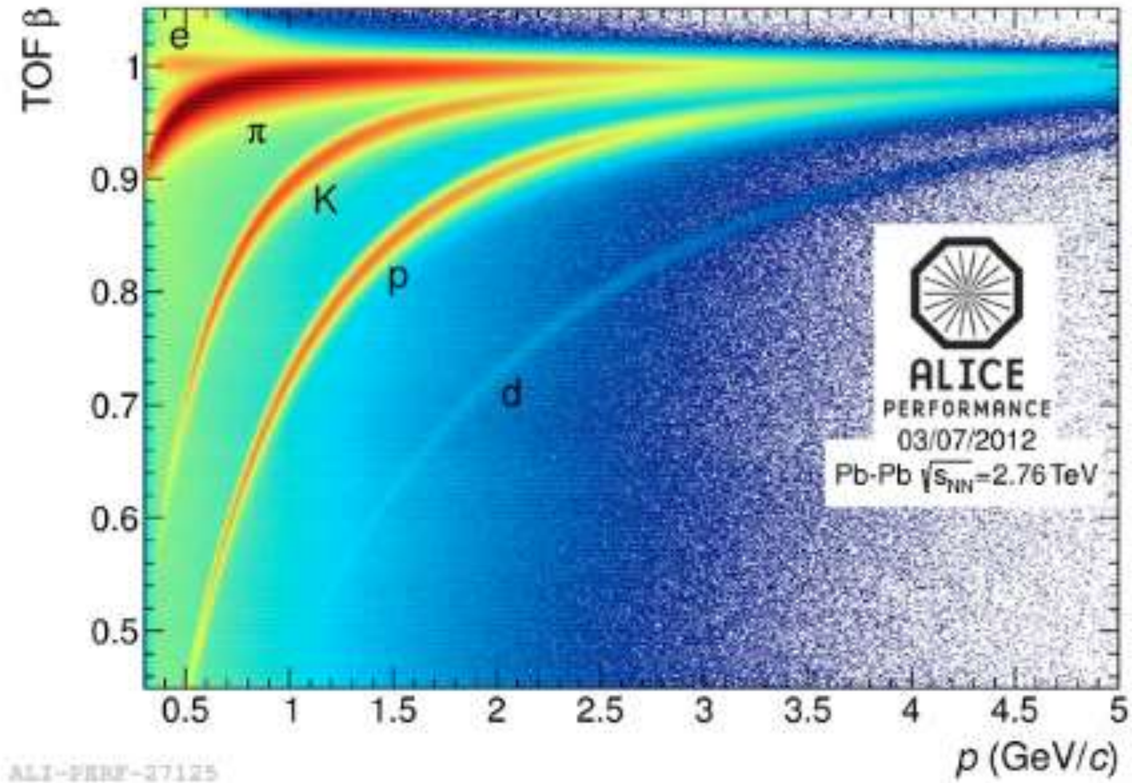


Figure 4: Particle velocity beta = v/c as measured with the ALICE TOF detector as a function of the particle momentum p for a data sample taken with heavy-ion collisions provided by the LHC in the year 2011. The bands for electrons, pions, kaons, protons and deuterons are clearly visible. Particles outside those bands are tracks wrongly associated with a TOF signal. No data is available for momenta smaller than about 300 MeV/c, since these particles do not reach the detector due to the curvature of their tracks in the magnetic field.

Faster than the wave velocity

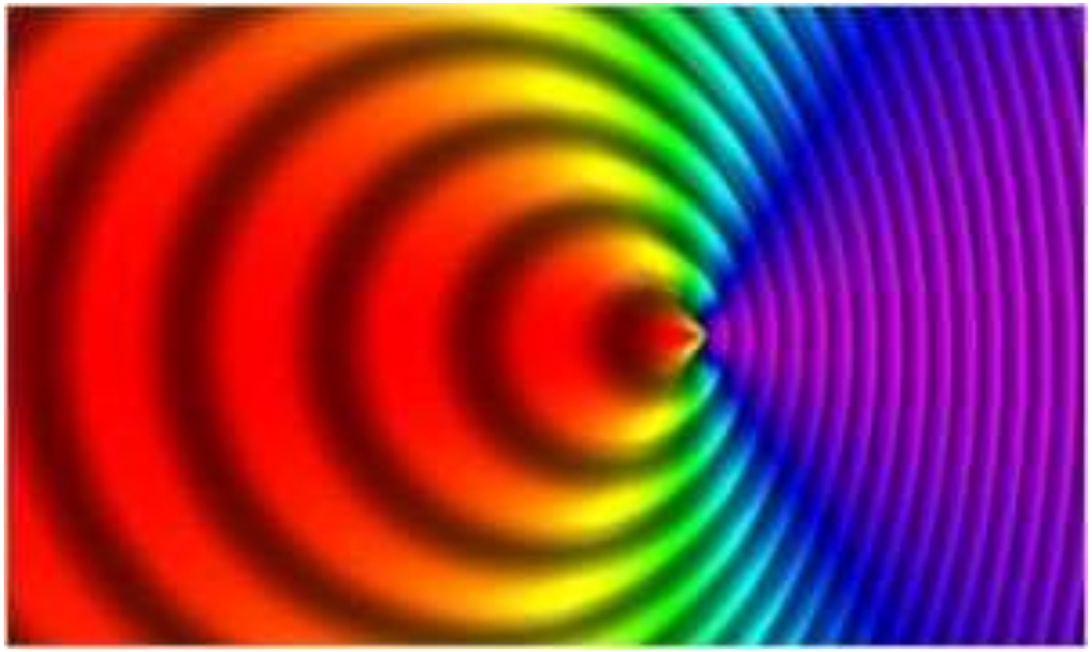
- wave speed = 1 m/s
- See the interference pattern
  - the lines are the result of non linear addition of wavefronts (shockwave)

Breaking the sound barrier

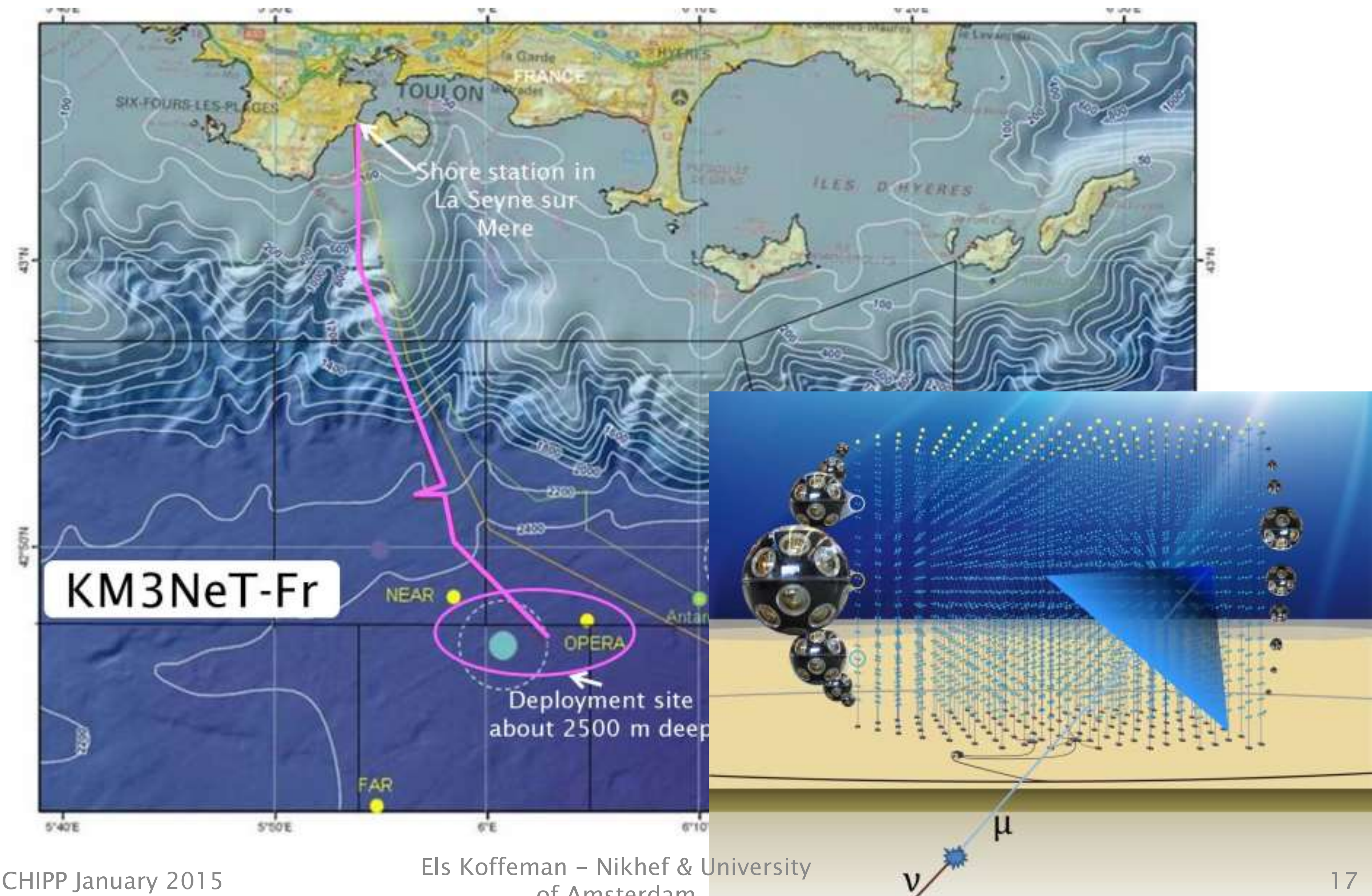
- Vsound = 343 m/s
- object emits sound waves and you hear sound
- sonic boom is the result of the object overtaking its own wave fronts (non lineair shockwave)

Cerenkov light

- particle travels
  - $x_{particle} = ct$
- wave travels
  - $X_{wave} = ct/n$



Cerenkov light



Particle Identification

- If the momentum is measured the energy loss gives information on the mass of the particle
- From the curvature also the charge of the particle is known.
- Mass and charge give particle identification

Energy measurement

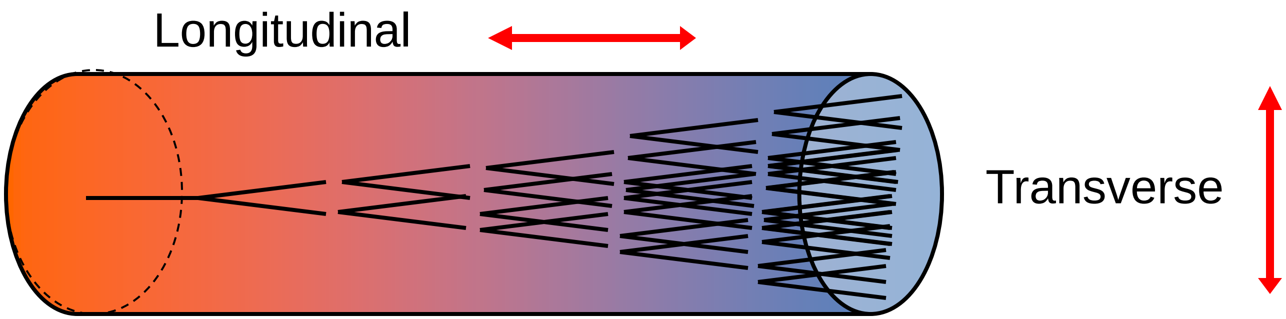
- Electrons (or positrons) and photons
  - Electromagnetic shower
  - Electrons (positrons) and photons lose energy due to Bremsstrahlung and pair creation
- Hadrons
  - Hadronic shower
  - Charged and neutral hadrons undergo nuclear and subsequent electromagnetic interactions
- Muons
  - No or almost no showering, mainly minimum ionising (but: high energy muons may generate Bremsstrahlung, resulting in an electromagnetic shower)
- Jets
  - In particle physics calorimeters often measure the energy of a jet, a mix (hadrons, photons and electrons) of many particles coming from one point in a small cone.

Calorimeters

- Shower development
  - Energy loss mechanisms
  - Electromagnetic showers
  - Hadronic showers
- Detector types
  - Homogenous absorbers like crystals
  - Sampling detectors
    - EM sampling calorimeters
    - Hadron sampling calorimetrs
    - Compensating Calorimeters
    - Examples

Simple EM-shower model

- Bremsstrahlung and pair production
  - Each step the nr of particles in the shower doubles
  - The energy per particle reduces with factor of two
  - The emission angles are small and a narrow shower develops
- When the energy falls below the critical energy
  - Ionisation becomes equally important in the energy loss
  - Showers stops over a relatively short distance



Electromagnetic Shower

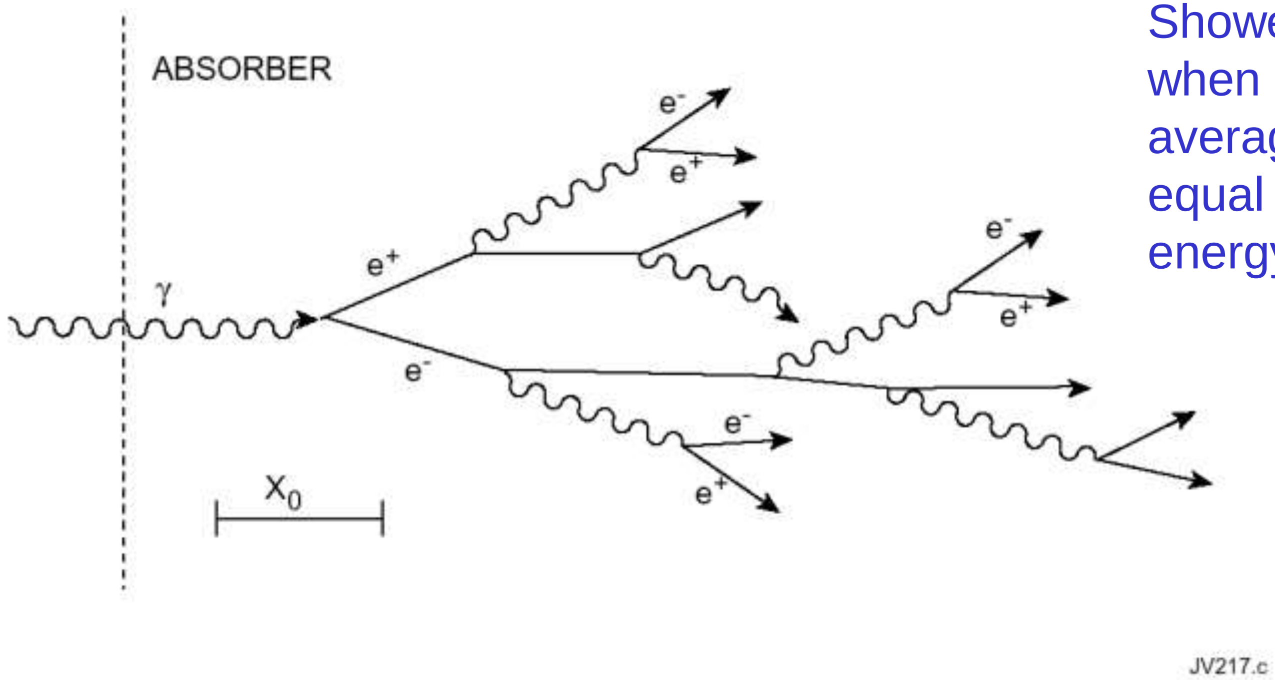
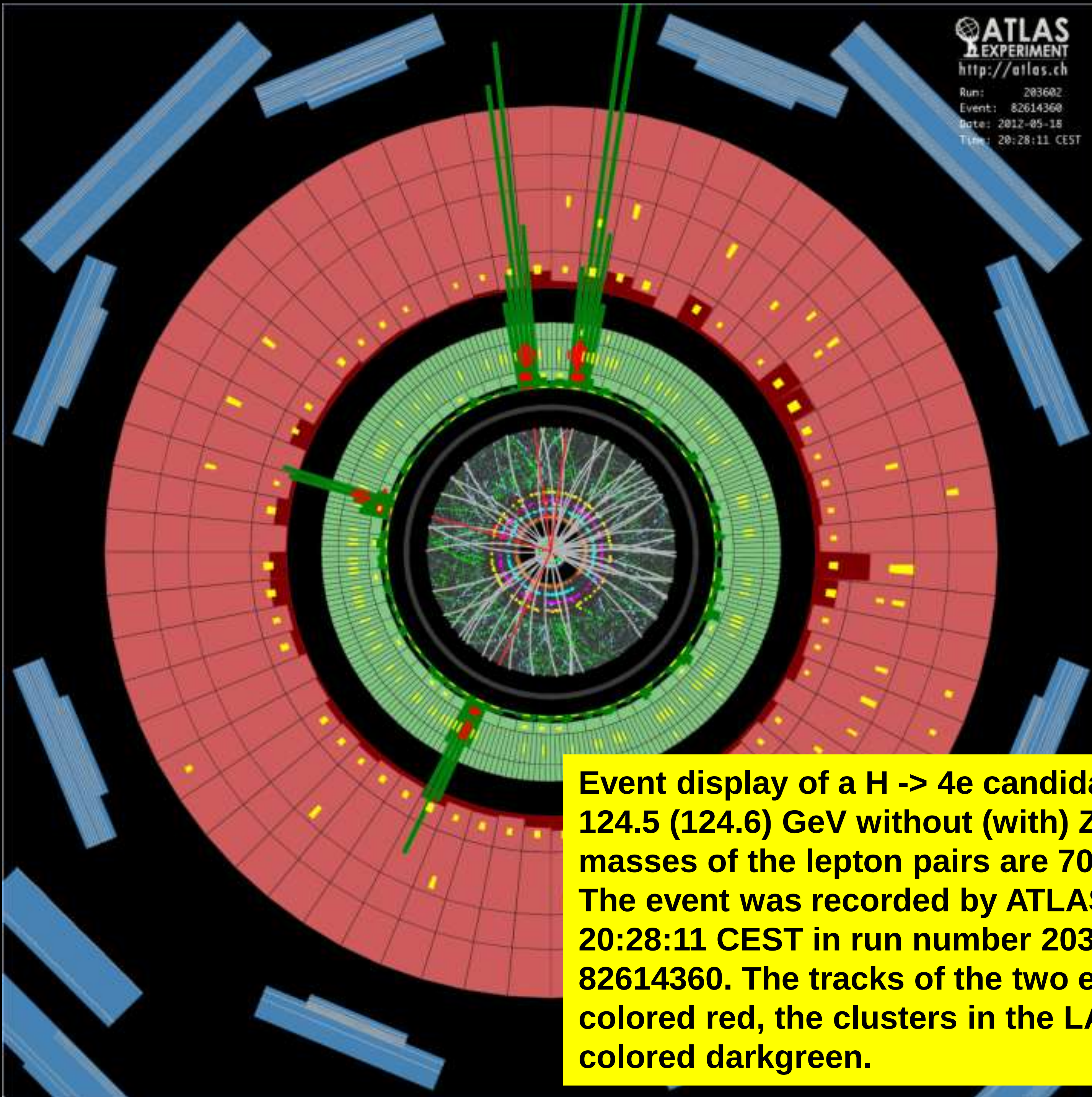


Figure 5: Schematic development of an electromagnetic shower.

Shower maximum occurs when shower particles on average have an energy equal to the critical energy

T.S.Virdee, Proc. of the 1998 European School of High-Energy Physics, CERN 99-0



Event display of a H -> 4e candidate event with m(4l) = 124.5 (124.6) GeV without (with) Z mass constraint. The masses of the lepton pairs are 70.6 GeV and 44.7 GeV. The event was recorded by ATLAS on 18-May-2012, 20:28:11 CEST in run number 203602 as event number 82614360. The tracks of the two electron pairs are colored red, the clusters in the LAr calorimeter are colored darkgreen.

Electromagnetic showers

- Radiation length (lose all but 1/e of the energy)
  - Lead $X_0 = 0.5$ cm
  - Silicon $X_0 = 10$ cm

$$X_0 = 180 \frac{A}{Z^2} \quad \left(\mathrm{g\,cm^{-2}}\right)$$

- The critical energy is defined as
  - The energy at with the energy loss due bremsstrahlung equals the energy loss due to ionisation.
  - Assume the critical energy is 100 MeV, then a layer of 10 times the radiation length would stop a 100 GeV photon.
  - $E_{critical}$ (MeV) = 800/(Z+1.2)

Electromagnetic showers

- Shower development
  - A particle with energy E_0 traverses a layer with thickness *t*, generating a cascade with *N* particles, each with energy *E*.

$$N(t) = 2^t \quad , \quad E(t) = \frac{E_0}{2^t}$$

  - The *shower maximum* is defined as the position where the number of particles in the cascade is at its maximum, this is at the point where *E* reaches the *critical energy*

$$t_{showermax} = \frac{\ln(E_0 / E_{critical})}{\ln 2}$$

$$\frac{\sigma(E)}{E} \propto \frac{\sigma(N_{showermax})}{N_{showermax}} = \frac{1}{\sqrt{N}} \propto \frac{1}{E}$$

Energy loss

- The measured signal is related to the number of charged particles, more specifically the overall track length of all charged particles in the shower

$$N_{tracks} \cdot tracklength = L = \int_0^{t_{max}} N(t)dt \cong \frac{E_0}{E_c}$$

- The intrinsic uncertainty in the energy determination scales with the fluctuatiuon in the number of particles

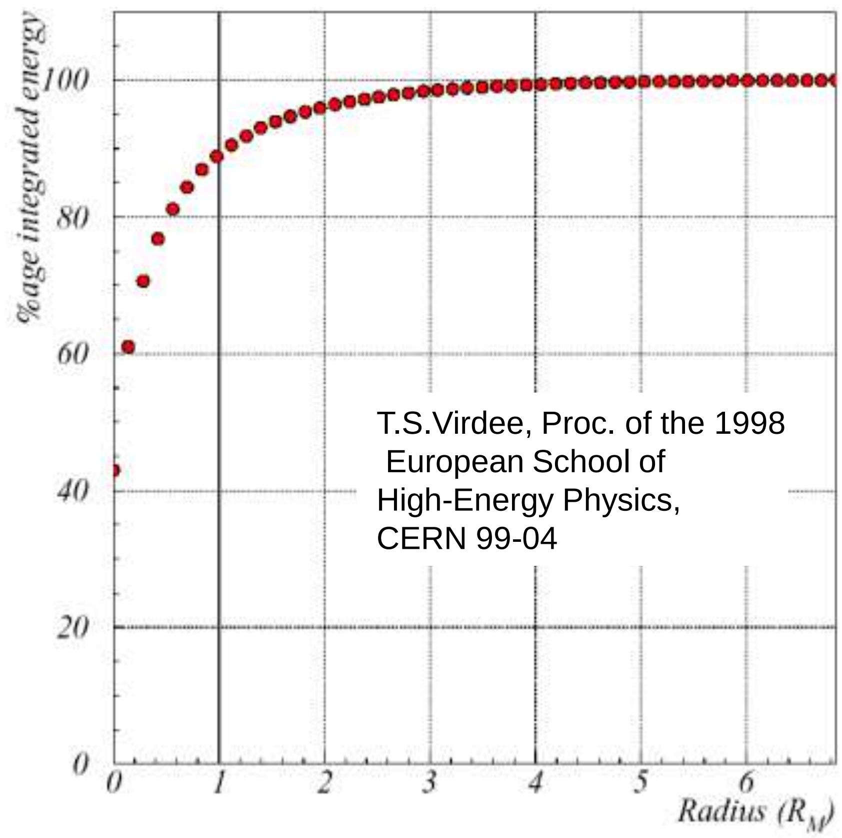
$$\frac{\sigma(E_0)}{E_0} \propto \frac{\sigma(N_{showermax})}{N_{showermax}} = \frac{1}{\sqrt{N}}$$

Electromagnetic showers

- Transverse shower development
  - Before the shower maximum the transverse size fits in a cylinder with a radius close to one radiation length
  - After that point most of the energy is contained in a cylinder with a radius equal to two times the Moliere Radius

$$\rho_M = 7\frac{A}{Z} \quad \left(\mathrm{g\,cm^{-2}}\right)$$

  - Lead $\rho = 1.6$ cm
  - Silicon $\rho = 6$ cm



Hadron showers

- Hadron interaction
  - A hadron loses energy by nuclear reactions, the probability or cross section for this process is low but the energy loss is high. The main energy loss is caused by
    - Protons losing energy by ionisation
    - π^0 decaying into two photons starting EM showers
    - Breaking up nuclei (binding energy is transferred)
    - Neutrino production
  - The processes are complex and a simple calculation is not possible. Monte Carlo based simulations yield empirical relation for the longitudinal and transverse shower development

Hadronic showers

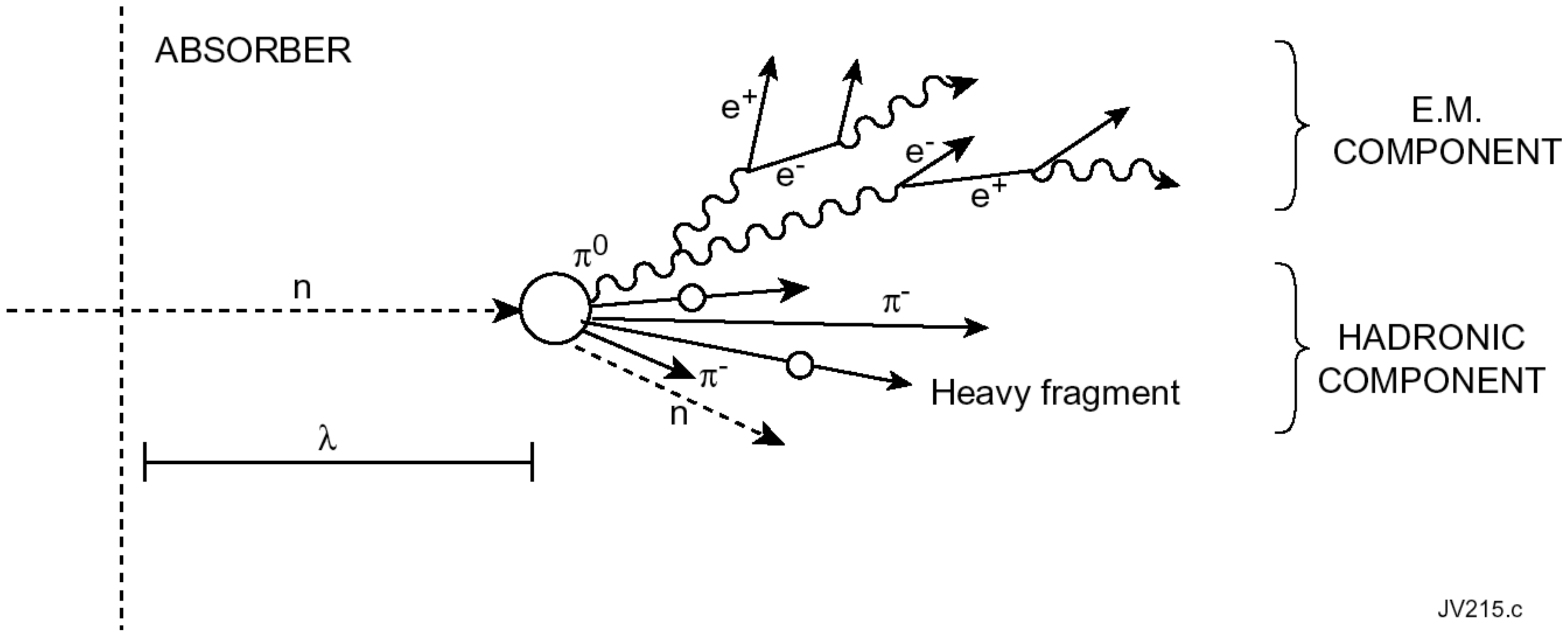


Figure 12: Schematic of development of hadronic showers.

T.S.Virdee, Proc. of the 1998 European School of High-Energy Physics, CERN 99-0

Hadron showers

- Hadron interaction
  - The longitudinal shower development is expressed in terms of the interaction length:

$$\lambda = \frac{A}{\sigma_{abs} N_A}$$

$$\lambda_{max} = 0.9 + 0.36 \ln E$$

  - $\sigma_{absorbtion}$ is proportional to $\sigma_0 A^{2/3}$, where the cross section, σ_0, depends on the incoming particle.

$$\lambda_{lead}^{proton} = 50cm$$

Hadron shower

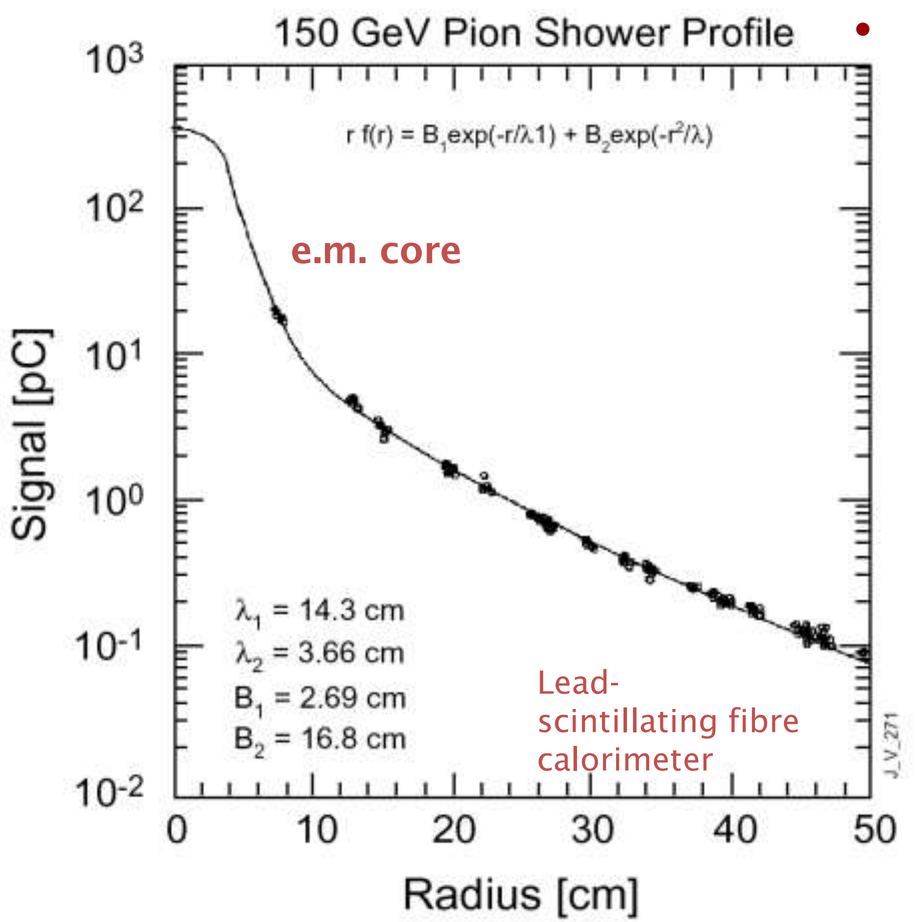


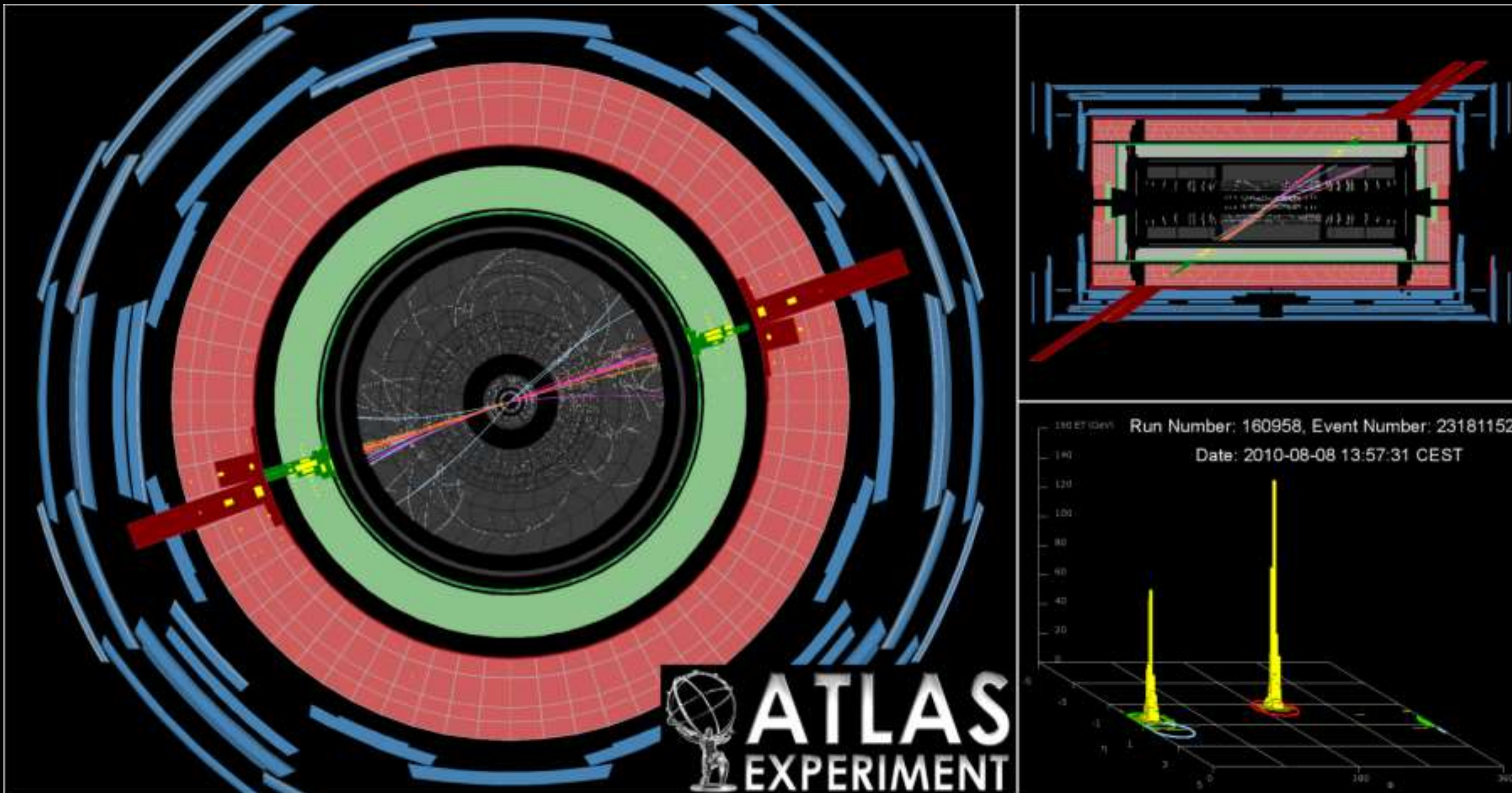
Figure 15: The lateral profile of energy deposition of pion showers.

- Transverse shower development
  - The secundaries have significant transverse momenta and produce a wide shower (compared with EM showers)

$$\text{Width} = -17.3 + 14.3 \ln E \quad (\text{cm})$$

  - Part of the shower gets an electromagnetic nature (i.e. The decay of the π^0 produced in the interaction) and does remain inside a narrow cylinder (two times the Moliere radius)

T.S.Virdee, Proc. of the 1998 European School of High-Energy Physics, CERN 99-04



A high mass dijet event: two high-p_T jets with invariant mass 2.8 TeV. A track p_T cut of 2.5 GeV has been applied for the display.1st jet (ordered by p_T): p_T = 310 GeV, y = -2.0, φ = -0.2
2nd jet: p_T = 280 GeV, y = 2.5, φ = 2.9
3rd jet: p_T = 14 GeV, y = -0.9, φ = -1.0
Jet momenta are calibrated according to the "EM+JES" scheme. Event collected on 5 August 2010.

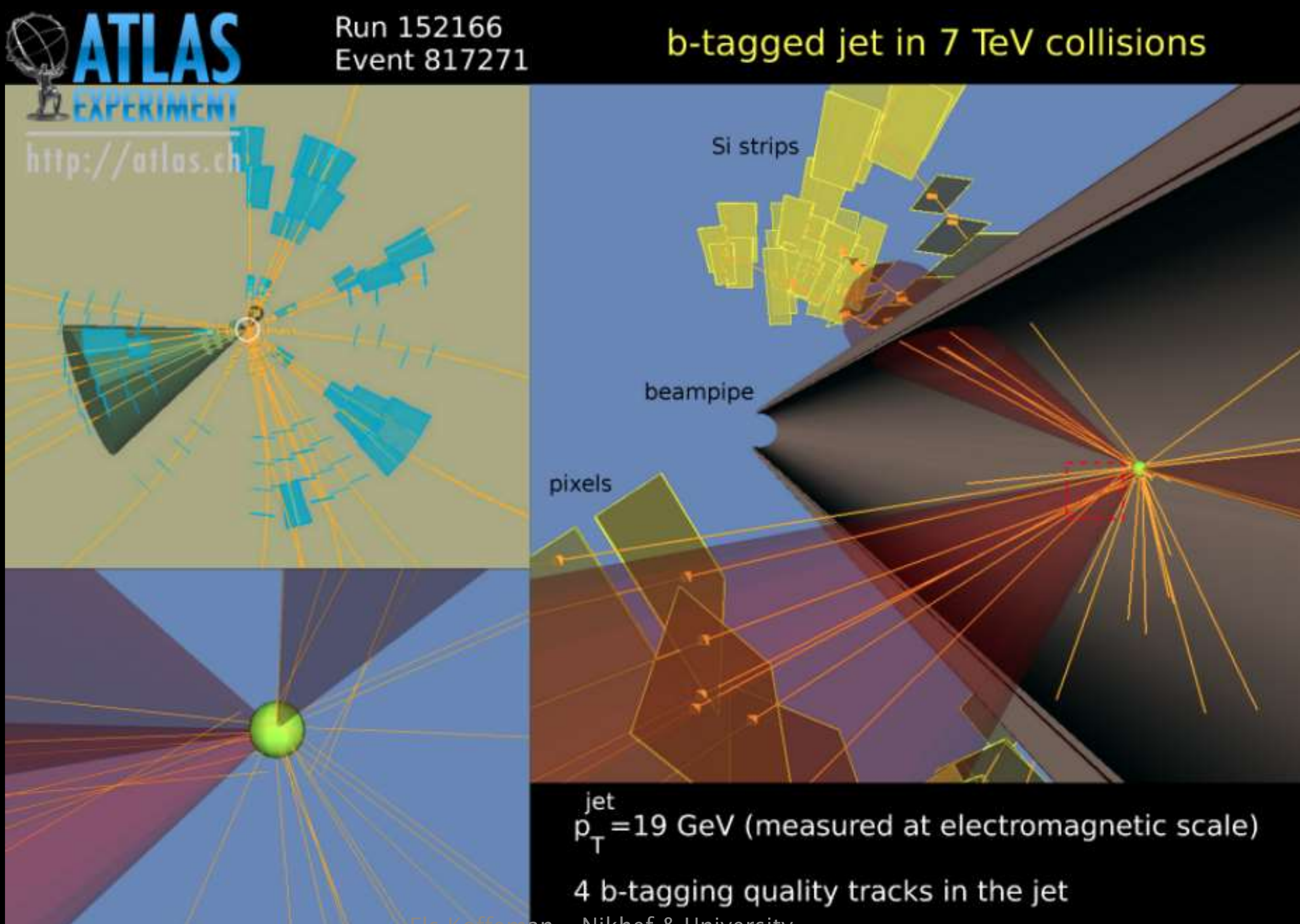
Summary

- Energy loss mechanisms
  - Carefully distinguish electrons and photons
  - Charged particles (mass > mass_electron)

- Determination
  - Momentum
  - Velocity
  - Energy

Calorimeters

- Absorber and detector in one
  - Scintillating crystal (NaI(Tl) of BGO)
  - Good energy resolution
  - Interaction depth limited (cost)
- Absorber and detector separated: sampling
  - Absorber:Tungsten, uranium, iron...
  - Detector :
    - Proportional counter
    - scintillator (fiber, gas or liquid)
    - semiconductor
  - Longitudinal segmentation straightforward
  - Interaction depth is (almost) umlimited



p_T^{jet}=19 GeV (measured at electromagnetic scale)

4 b-tagging quality tracks in the jet

Multiple Scattering

- Small angle scattering off the nucleus

$$\theta_{min} \approx \alpha Z_2^{1/3} \frac{m_e c}{p} \qquad \theta_{max} \approx \frac{2 m_e c}{\alpha p A^{1/3}}$$

$$\left\langle \Theta^2_{MS,proj} \right\rangle = \frac{1}{2} n_a l \int \theta^2 \frac{d\sigma}{d\Omega} d\Omega = \frac{1}{2} n_a l \int_{\theta_{min}}^{\theta_{max}} 2\pi \left(\frac{2 Z_1 Z_2 e^2}{p v_1} \right)^2 \frac{d\theta}{\theta} = 4\pi n_a l Z_1^2 Z_2^2 r_e^2 \left(\frac{m_e c}{p\beta} \right)^2 \left(\ln \frac{2}{\alpha^2 A^{1/3} Z_2^{1/3}} \right)$$

n_a = number of atoms per unit of volume

l = length traversed

A ≈ 2Z the logarithm becomes: 2 ln($173 Z_2^{-1/3}$), which is similar to the logarithm found for the radiation length:

$$L_R^{-1} = 4 n_a \alpha Z_2^2 r_e^2 \left(\ln \frac{183}{Z_2^{1/3}} + 1/18 \right)$$

Due to multiple scattering after traversing a thickness of material
a lateral displacement will occur:

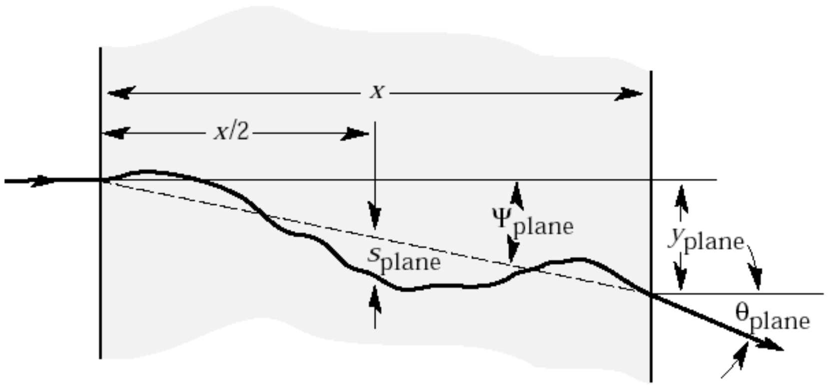


Figure 26.8: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

Angle

$$\psi^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta_0 \ ,$$

$$y^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,x\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,x\,\theta_0 \ ,$$

$$s^{\rm rms}_{\rm plane} = \frac{1}{4\sqrt{3}}\,x\,\theta^{\rm rms}_{\rm plane} = \frac{1}{4\sqrt{3}}\,x\,\theta_0 \ .$$

Multiple scattering

- Using: $2 \ln(173 Z_2^{-1/3}) \approx 1/(2 n_a \alpha Z_2^2 r_e^2 L_R)$
- average of the square of the projected scattering angle can be expressed in the radiation length:

$$\left\langle \Theta^2_{\mathrm{MS,proj}} \right\rangle \approx 4\pi n_a l Z_1^2 Z_2^2 r_e^2 \left(\frac{m_e c}{p\beta} \right)^2 \frac{1}{2 n_a \alpha Z_2^2 r_e^2 L_R} = \frac{2\pi}{\alpha} Z_1^2 \left(\frac{m_e c}{p\beta} \right)^2 \frac{l}{L_R}$$

$$\sqrt{\left\langle \Theta^2_{\mathrm{MS,proj}} \right\rangle} \approx \frac{13.6\,\mathrm{MeV}}{\beta c p} Z_1 \sqrt{\frac{l}{L_R}} \left[1 + 0.038 \ln(l/L_R) \right]$$