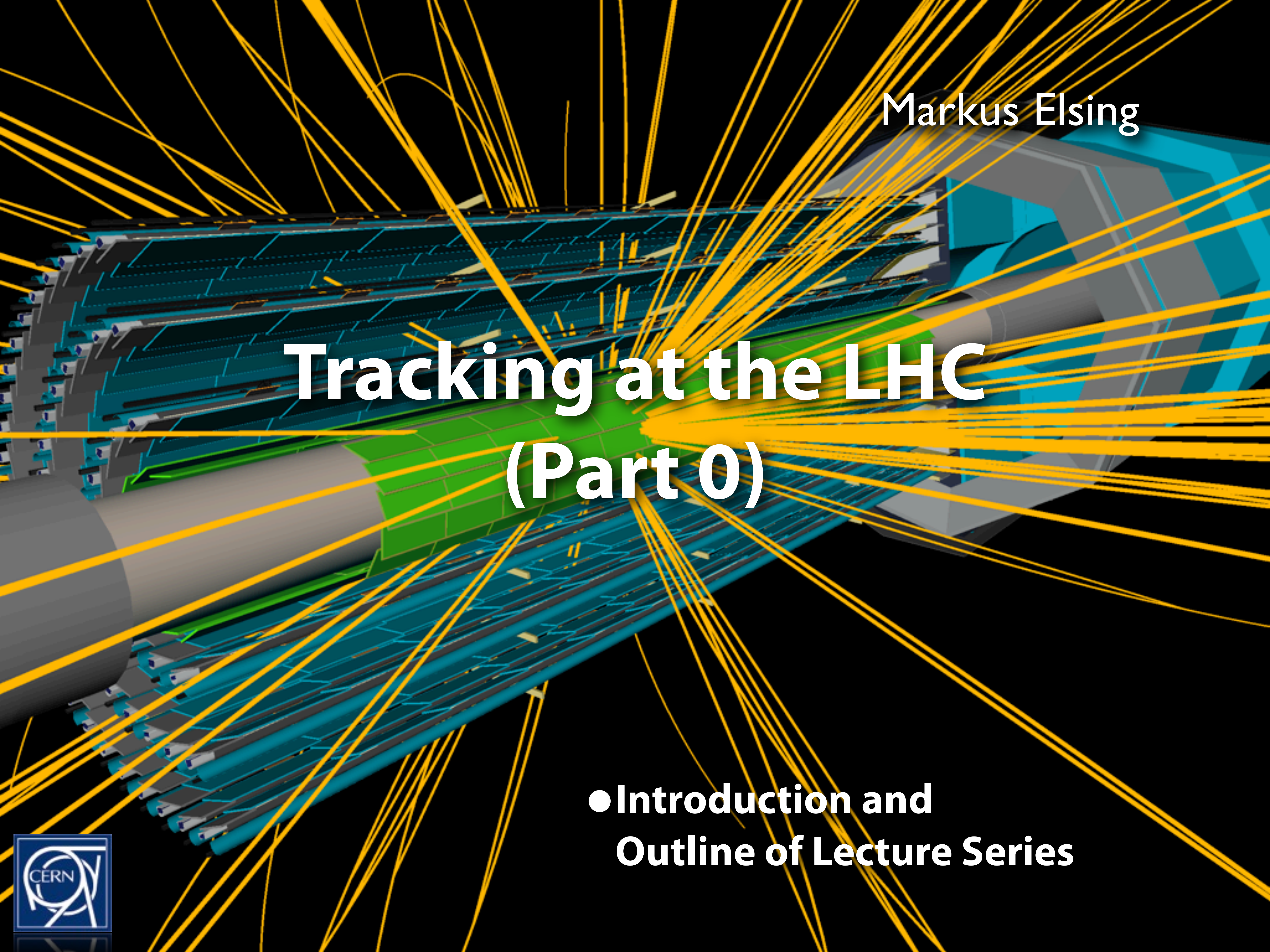


Markus Elsing

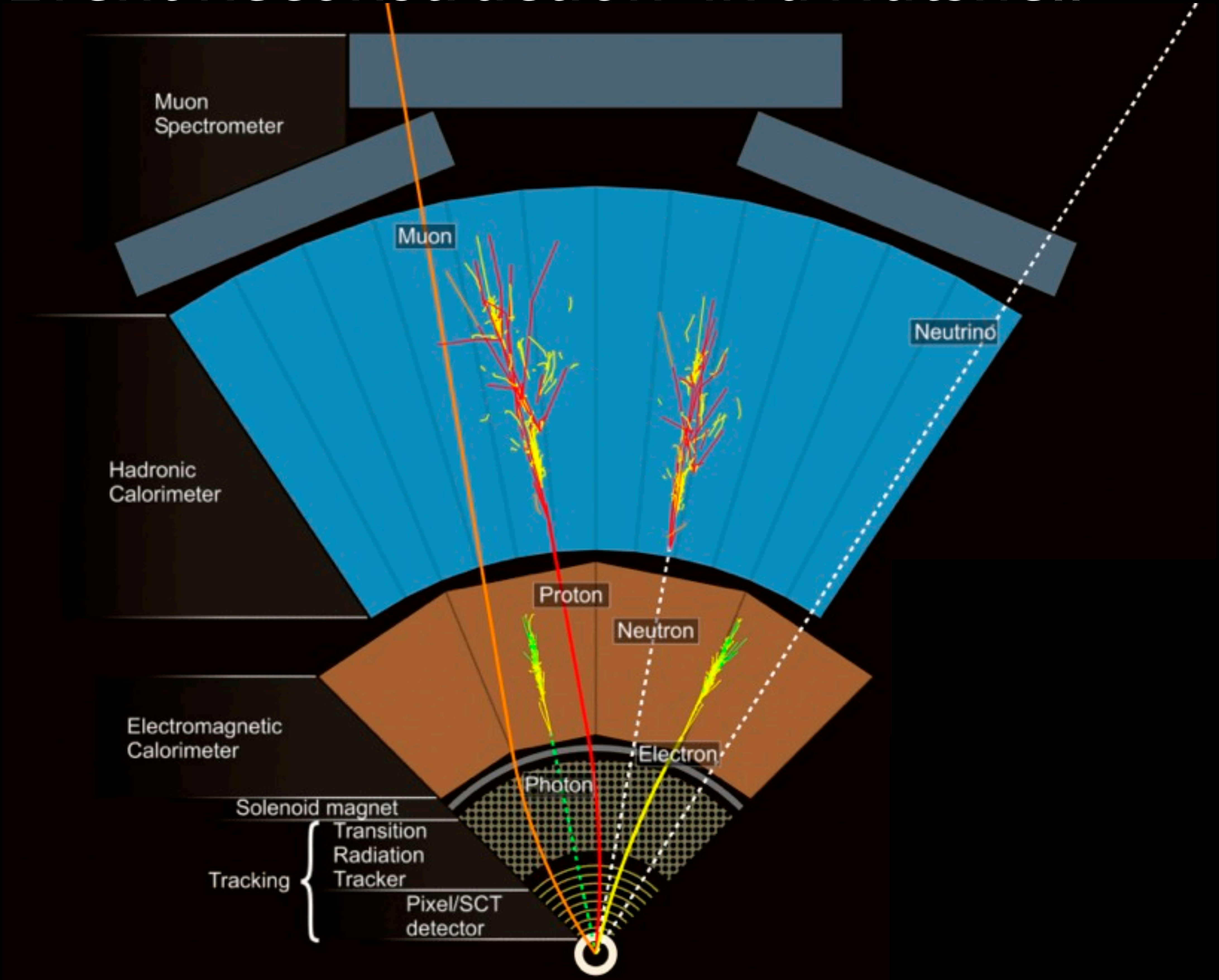
Tracking at the LHC
(Part 0)

- **Introduction and Outline of Lecture Series**

Introduction

- broad **physics program** covered by **LHC** experiments
  - ➡ 2 general purpose pp experiments (ATLAS and CMS) cover: SM QCD/W/Z/top, Higgs, SUSY, Exotics, (b-physics) ...
  - ➡ LHCb as dedicated b-physics experiment (forward physics)
  - ➡ ALICE as a heavy ion experiment
- **detectors** designed to optimize physics performance
  - ➡ at design luminosities (10^{34} $cm^{-2}s^{-1}$) and pileup (~23 min.bias events)
  - ➡ b-physics trigger (LHCb)
  - ➡ heavy ion "central" event multiplicities (ALICE)
- task of **event reconstruction** is to identify objects
  - ➡ $e/\mu/\tau$ leptons, photons, (b) jets, missing E_T, exclusive hadronic states...
  - ➡ input to physics analysis of complete event signature

Event Reconstruction “in a Nutshell”



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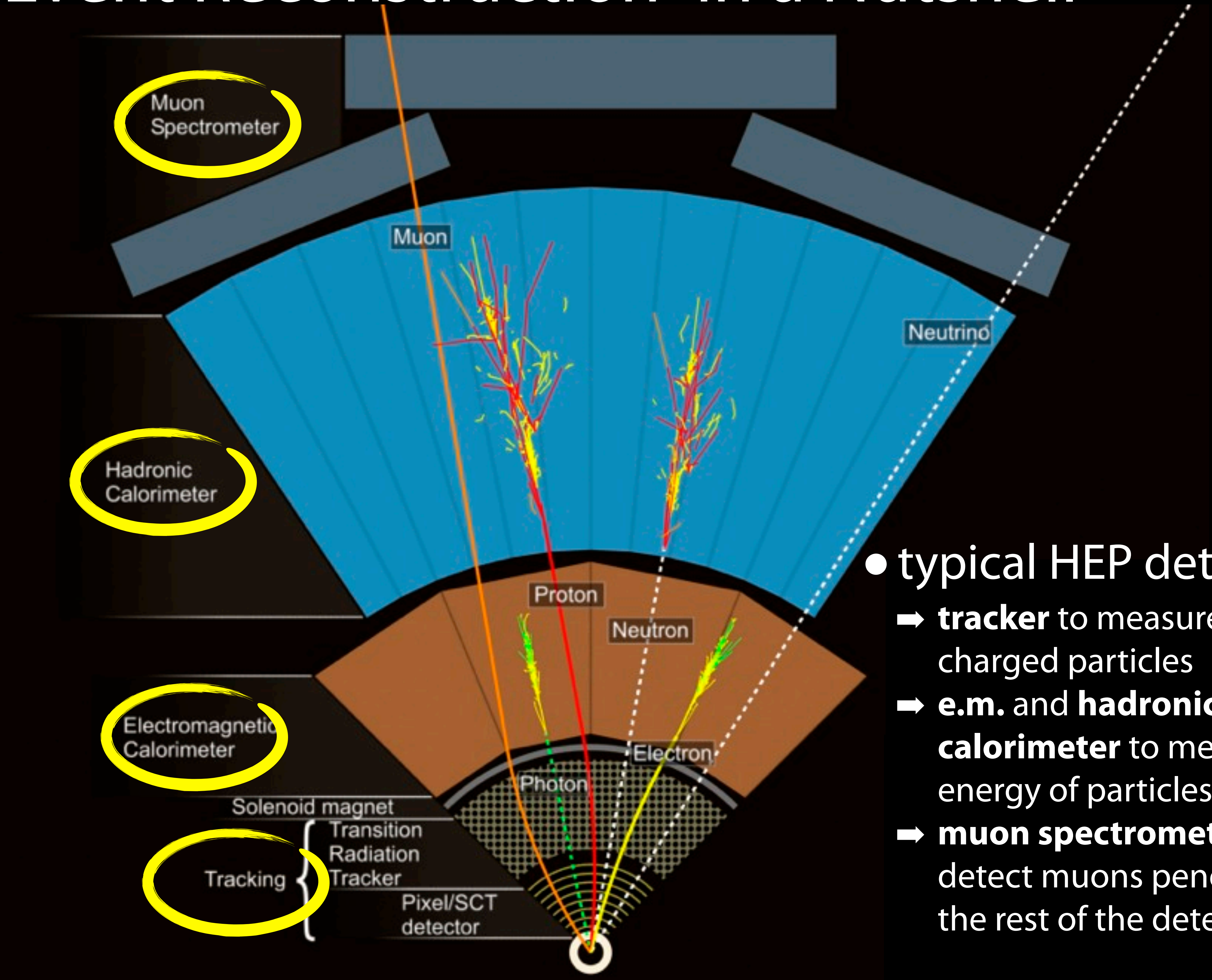
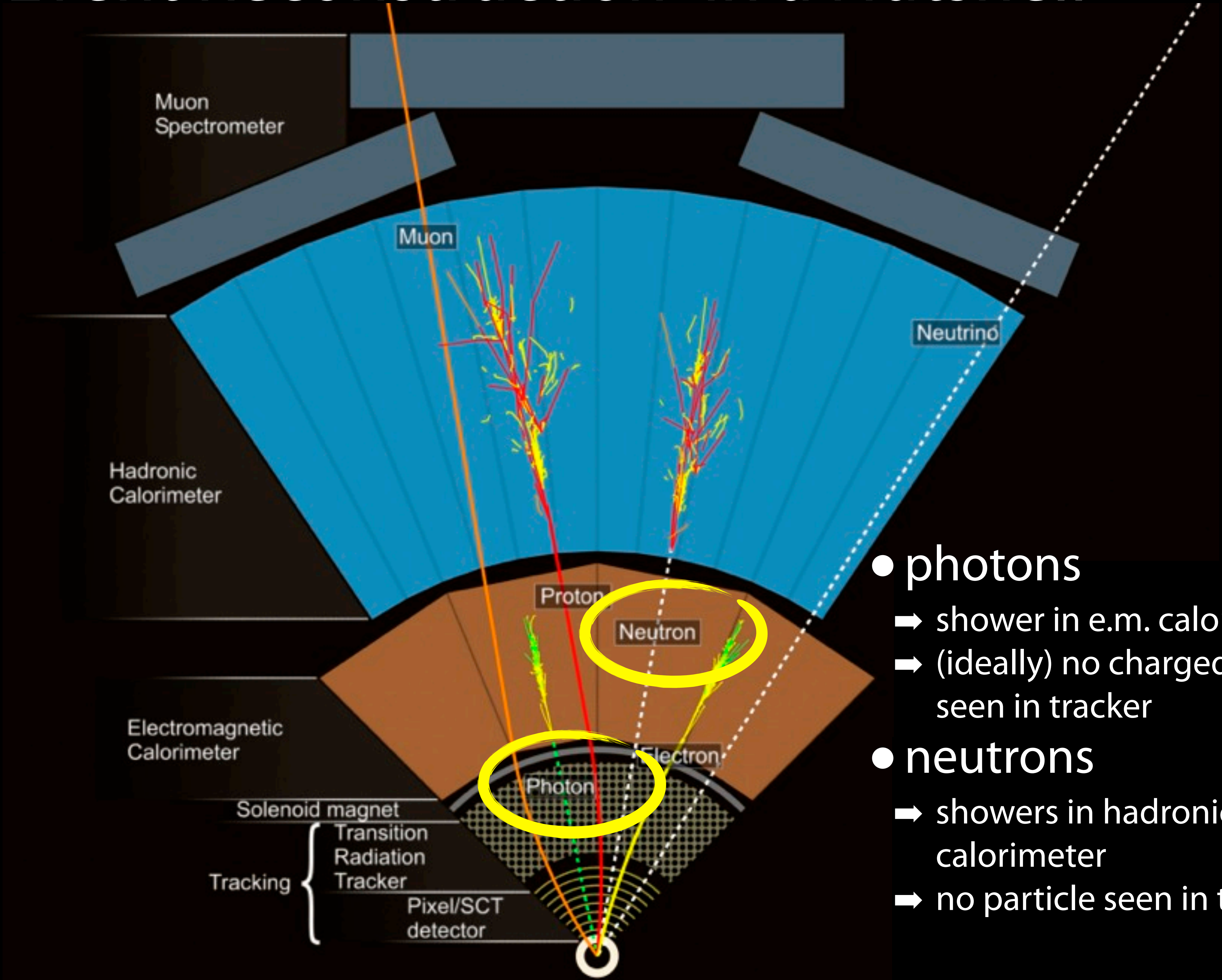


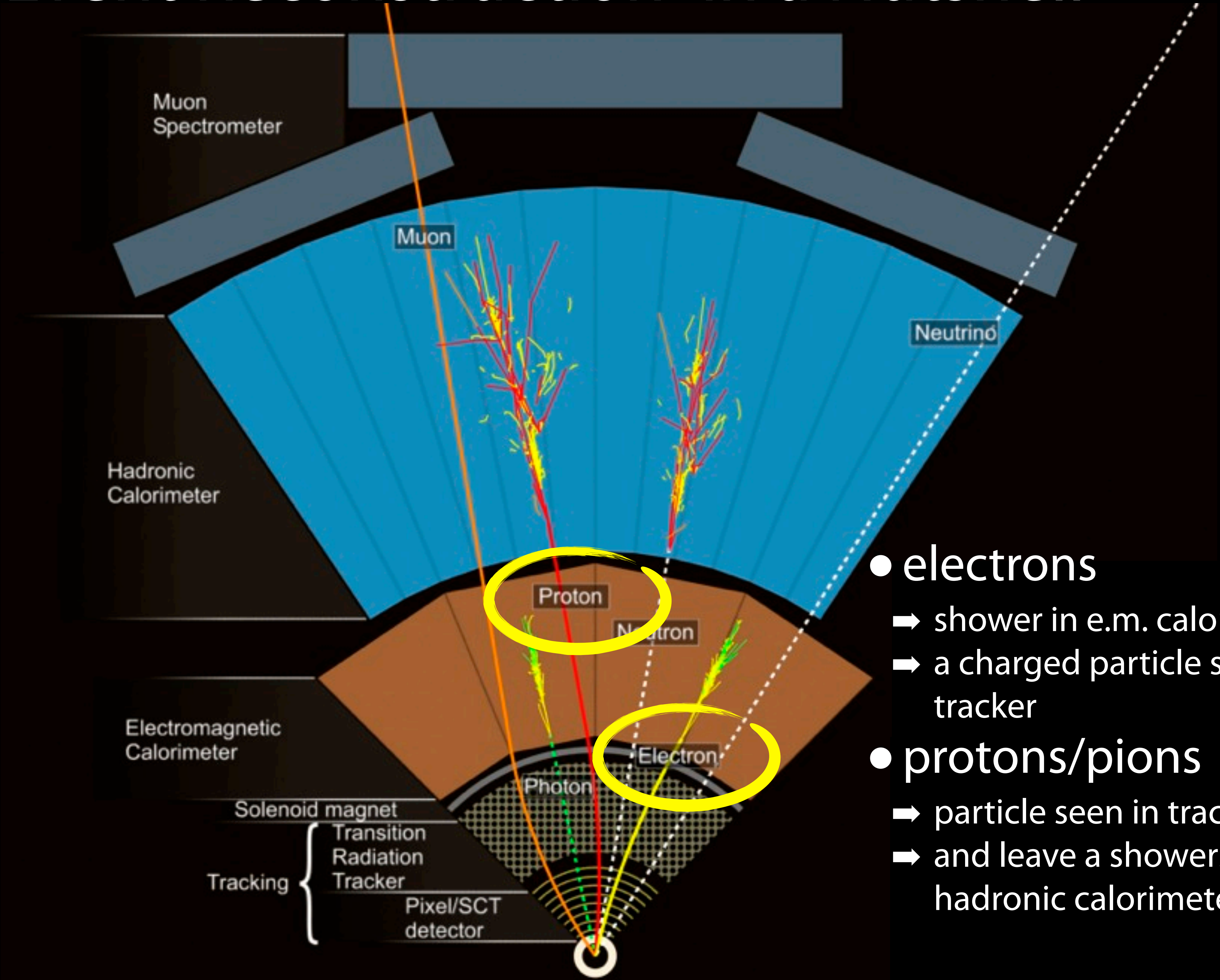
- typical HEP detector
  - ➡ **tracker** to measure charged particles
  - ➡ **e.m.** and **hadronic calorimeter** to measure energy of particles (jets)
  - ➡ **muon spectrometer** to detect muons penetrating the rest of the detector

Event Reconstruction "in a Nutshell"



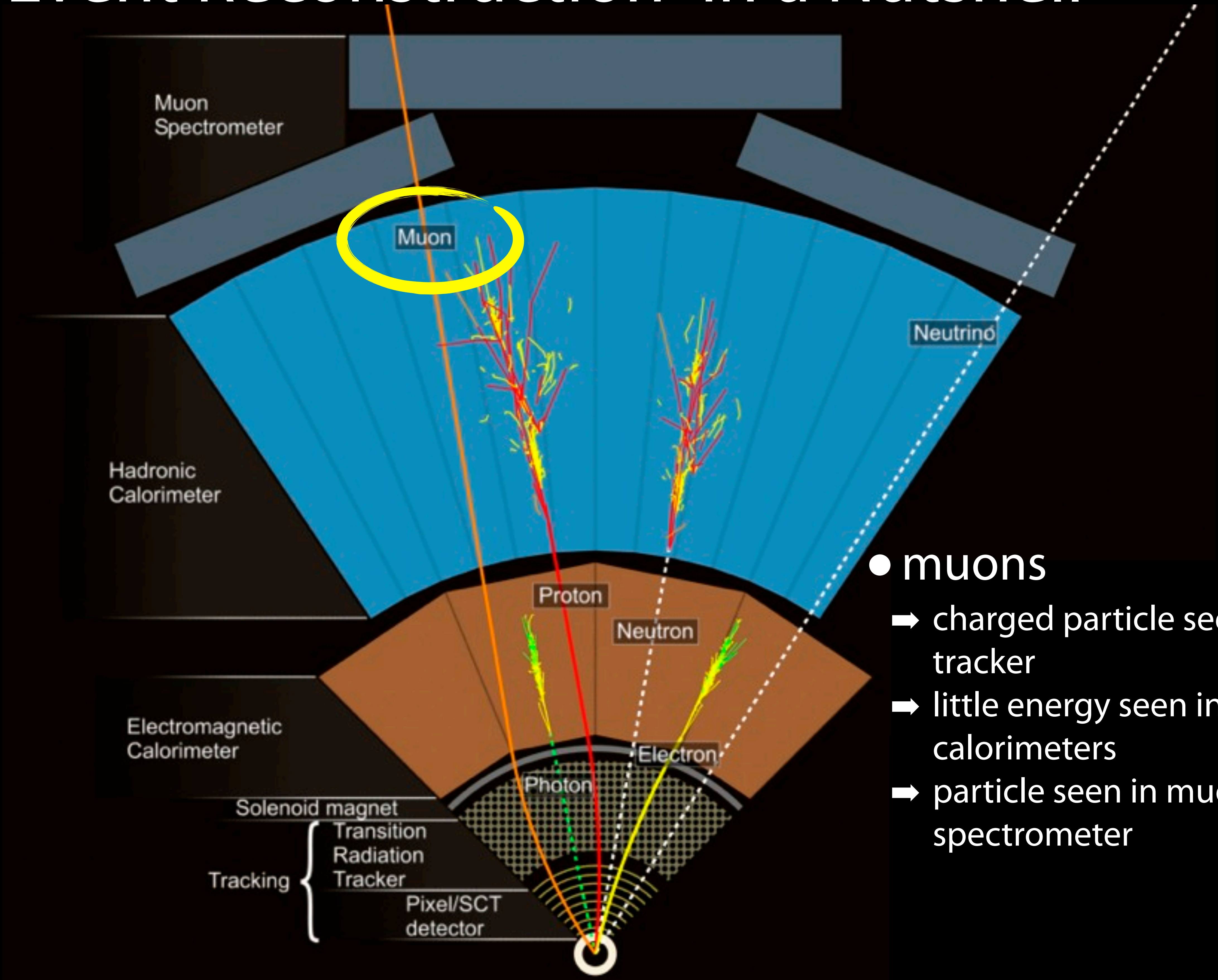
- photons
  - ➡ shower in e.m. calorimeter
  - ➡ (ideally) no charged particle seen in tracker
- neutrons
  - ➡ showers in hadronic calorimeter
  - ➡ no particle seen in tracker

Event Reconstruction "in a Nutshell"



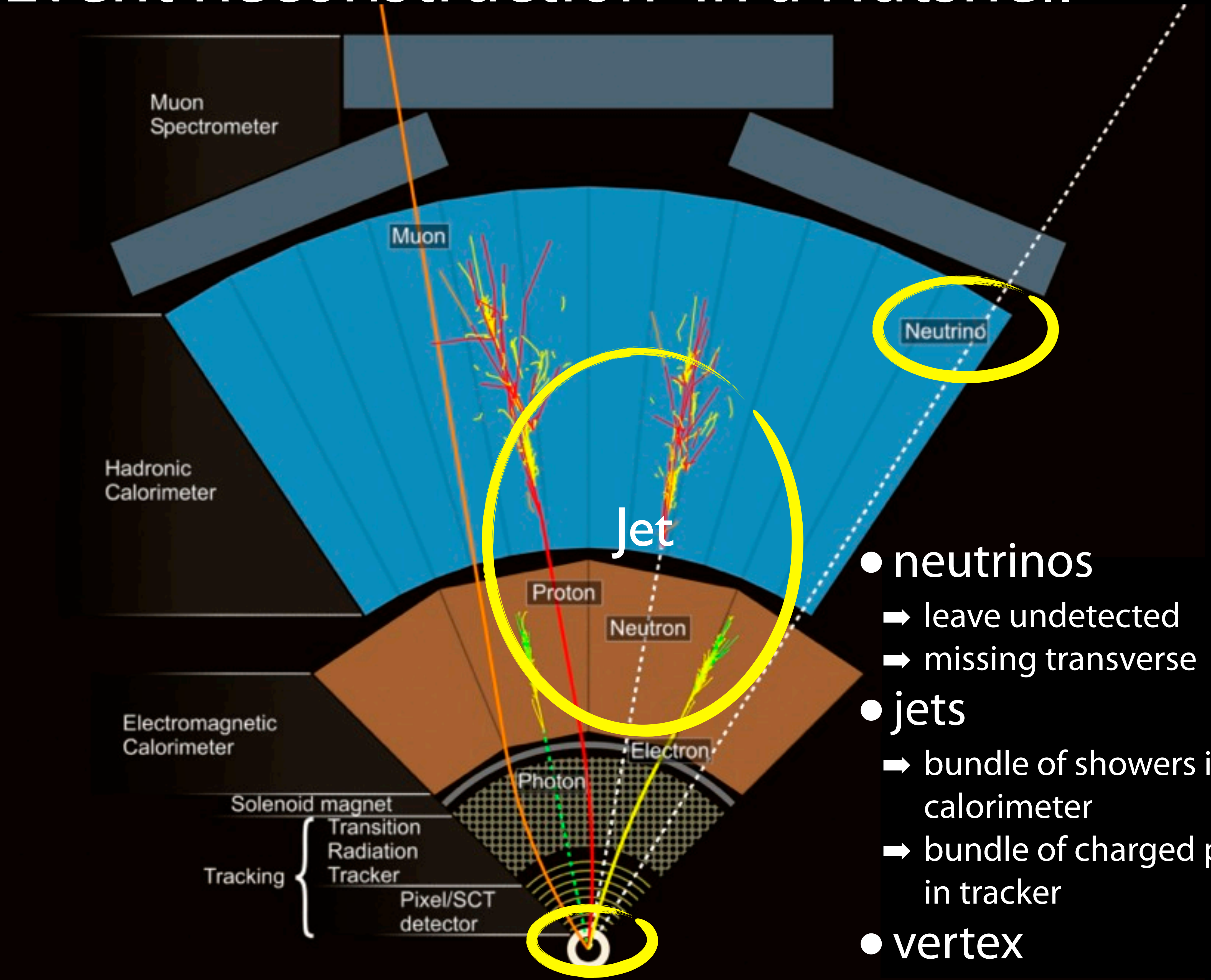
- electrons
  - ➡ shower in e.m. calorimeter
  - ➡ a charged particle seen in tracker
- protons/pions
  - ➡ particle seen in tracker
  - ➡ and leave a showers in hadronic calorimeter

Event Reconstruction “in a Nutshell”



- muons
  - ➡ charged particle seen in tracker
  - ➡ little energy seen in calorimeters
  - ➡ particle seen in muon spectrometer

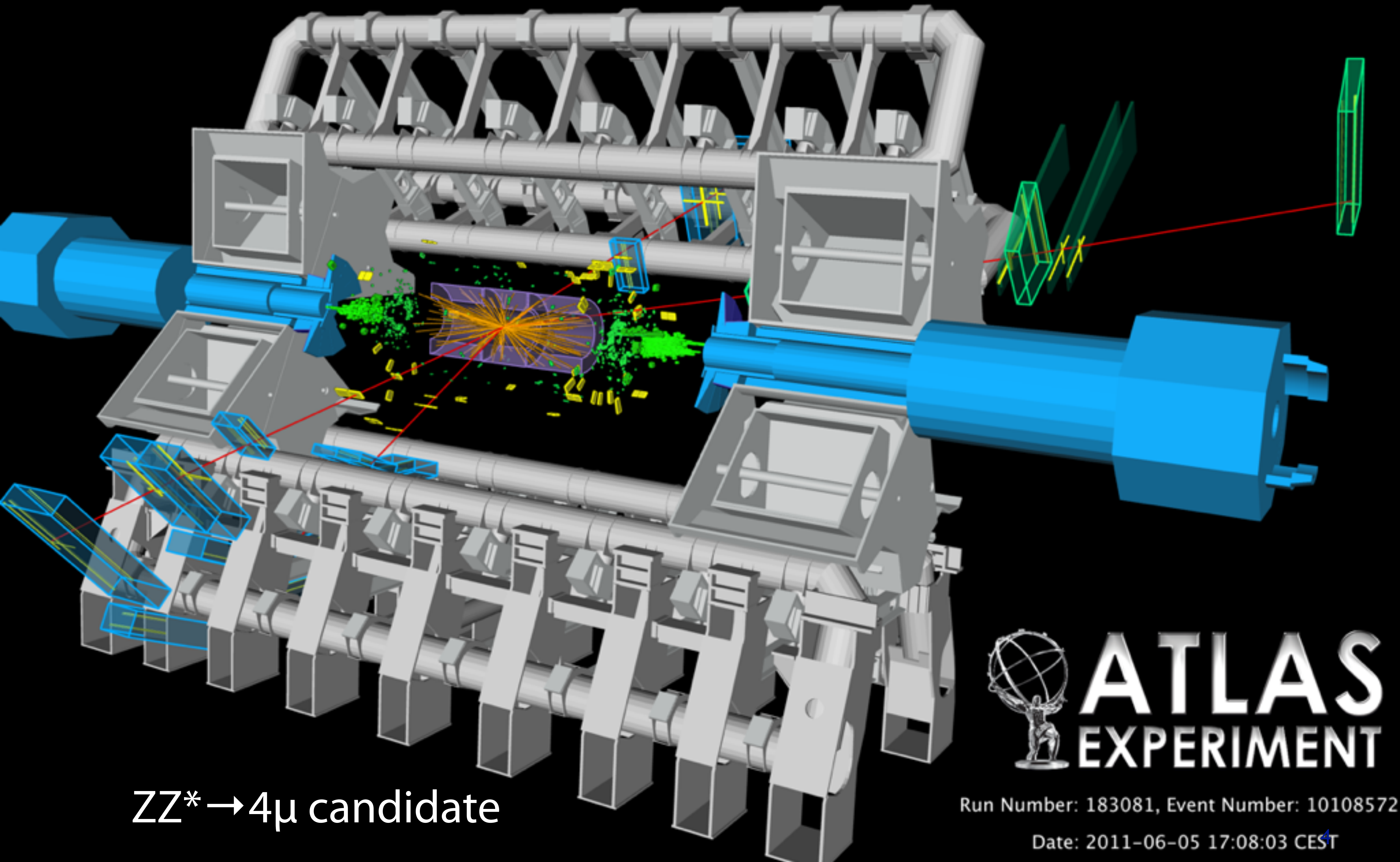
Event Reconstruction “in a Nutshell”



- neutrinos
  - ➡ leave undetected
  - ➡ missing transverse energy
- jets
  - ➡ bundle of showers in calorimeter
  - ➡ bundle of charged particles in tracker
- vertex

In Reality ?

... a bit more complicated



ZZ*→4μ candidate

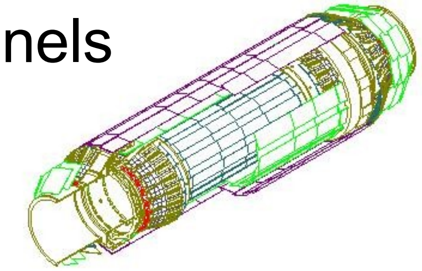
Tracking at the LHC

- object reconstruction to cover LHC physics program
  - ➡ often requires **combining information** from tracking detector with calorimetric and muon spectrometer measurements
  - ➡ **TRACKING** is a central aspect of the event reconstruction and analysis

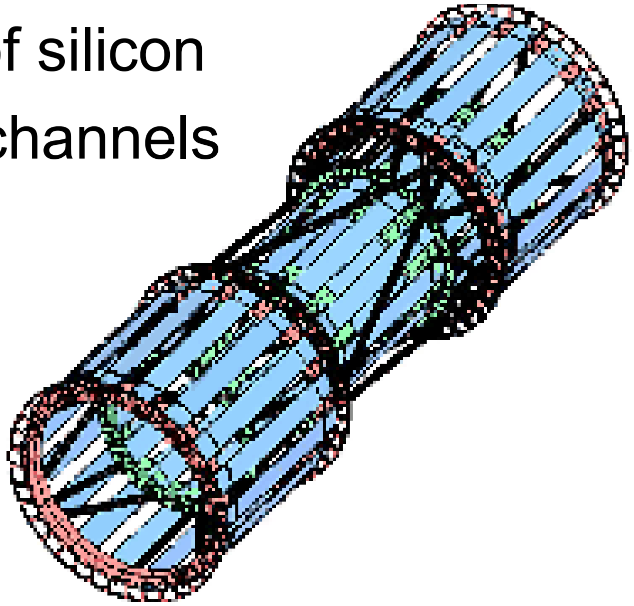
- requirements on tracking detectors
  - ➡ **precision tracking** at LHC luminosities (central heavy ion event multiplicities) with a hermitic detector
  - ➡ usually Pixel/Strip Detector for precise **primary/secondary vertex** reconstruction and to provide excellent **b-tagging in jets**
  - ➡ reconstruction of **electrons** (and converted photons)
  - ➡ tracking of **muons** combined with muon spectrometer, good resolution over the full accessible momentum range
  - ➡ enable (hadronic) **tau**, exclusive **b-** and **c-hadron** reconstruction
  - ➡ provide **particle identification**, e.g.:
    - transition radiation in ATLAS TRT/ALICE TRD for electron identification
    - dE/dx in Pixels/Silicon or ALICE TPC, Cherenkov detectors (LHCb)
  - ➡ not to forget: enable fast tracking for **(high level) trigger**

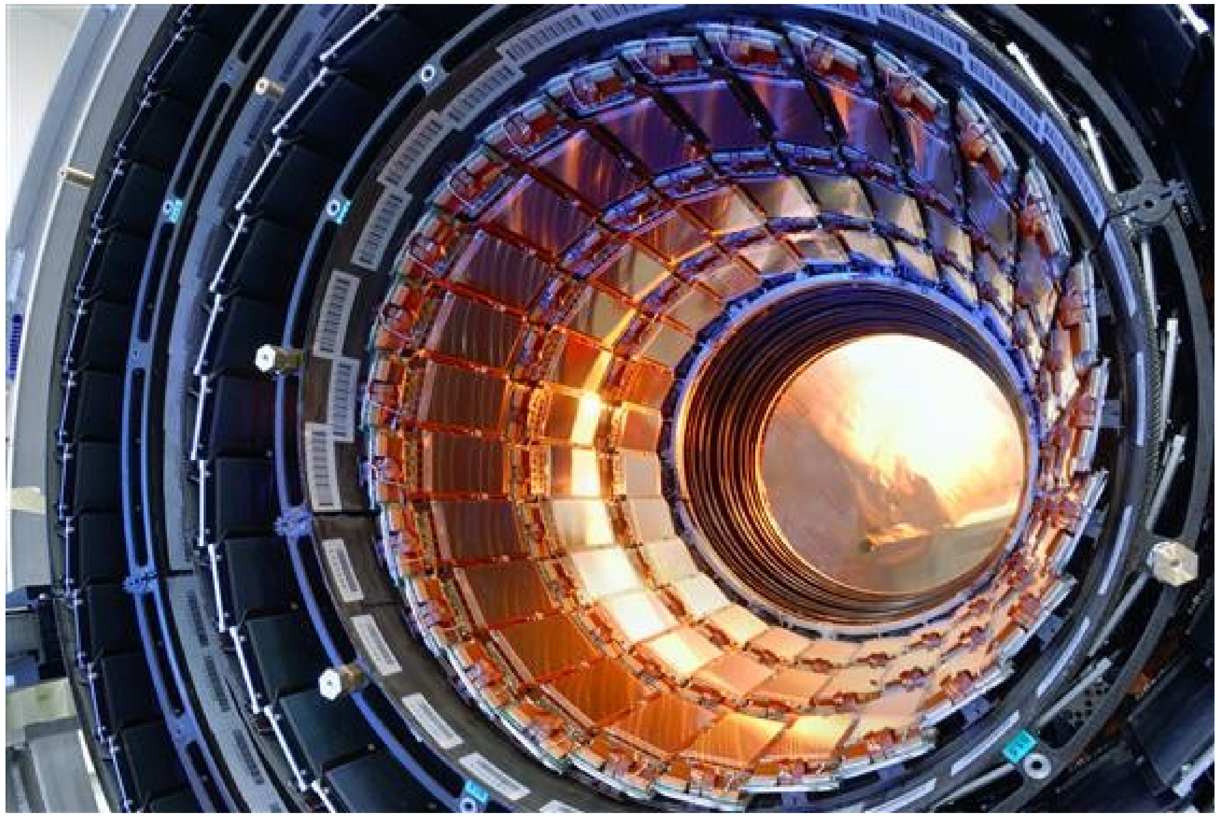
Evolution of (Silicon) Detectors

- LEP eg. DELPHI (1996)
  - 1.8 m^2 of silicon
  - 175k readout channels



- CDF SVX IIa (2001)
  - 6 m^2 of silicon
  - 175k channels





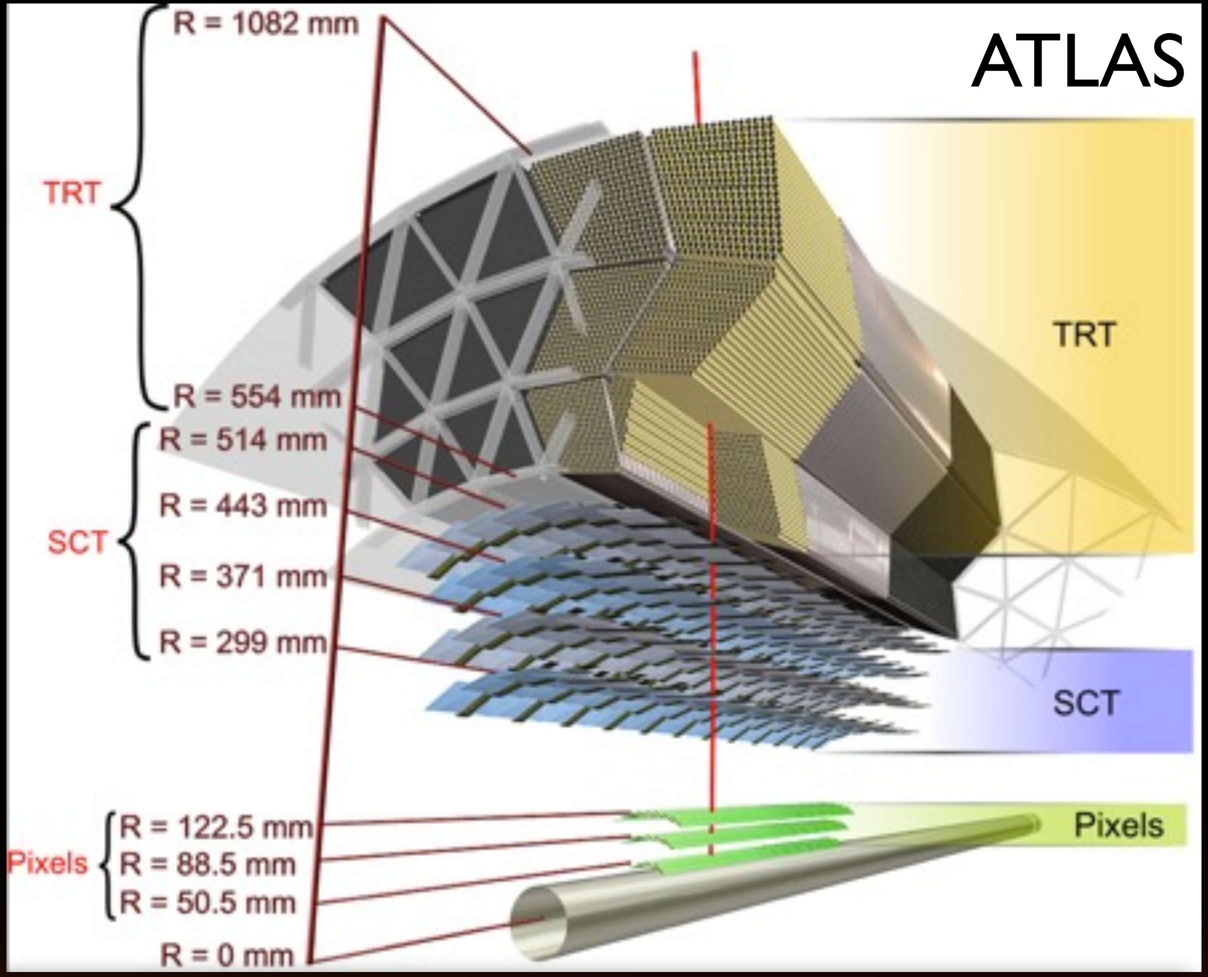
- CMS tracker
  - full silicon tracker
  - 210 m^2 of silicon
  - 10.7 M channels

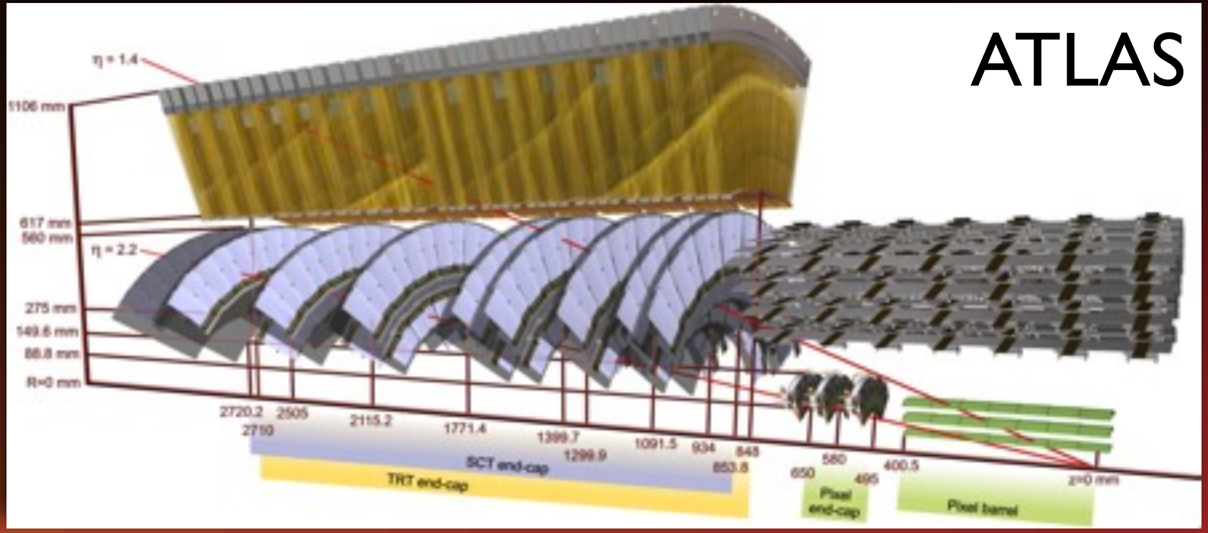
P.Wells

➡ results from huge technology advancements to match requirements of every generation of experiments

Example for an LHC Tracking Detector

- answer of the experiments to match physics requirements
- ATLAS:
  - ➡ 3 layer **Pixel** system, 3 endcap disks
    - 1744 Pixel modules
    - 80.4 million channels
    - pitch 50 µm × 400 µm
    - total of 1.8 m^2
  - ➡ 4 layers of small angle stereo strips, 9 endcap disks each side (**SCT**)
    - 4088 double sided modules
    - 6.3 million channels
    - pitch 80 µm, 40 mrad stereo angle
    - total of 60 m^2
  - ➡ Transition Radiation Tracker (**TRT**)
    - typically 36 hits per track
    - transition radiation to identify electrons
    - total of 370K drift tubes





Outline of Lectures on next 3 Days

- part 1 ~ Passage of Particles through Matter
- part 2 ~ LHC Tracking Detectors
- part 3 ~ Concepts for Track Reconstruction
- part 4 ~ Vertex Reconstruction and its Applications
- part 5 ~ Commissioning, Alignment and Performance
- part 6 ~ High Luminosity and Upgrade

Feedback Welcome !

- first time I give this lecture series
  - ➡ after years in this field I may take things for granted which in reality are technicalities that need to be explained
- will try to give a balanced overview on tracking and vertexing relevant for all LHC experiments
- material presented is probably biased towards ATLAS
  - ➡ easier for me to find the relevant plots, etc.

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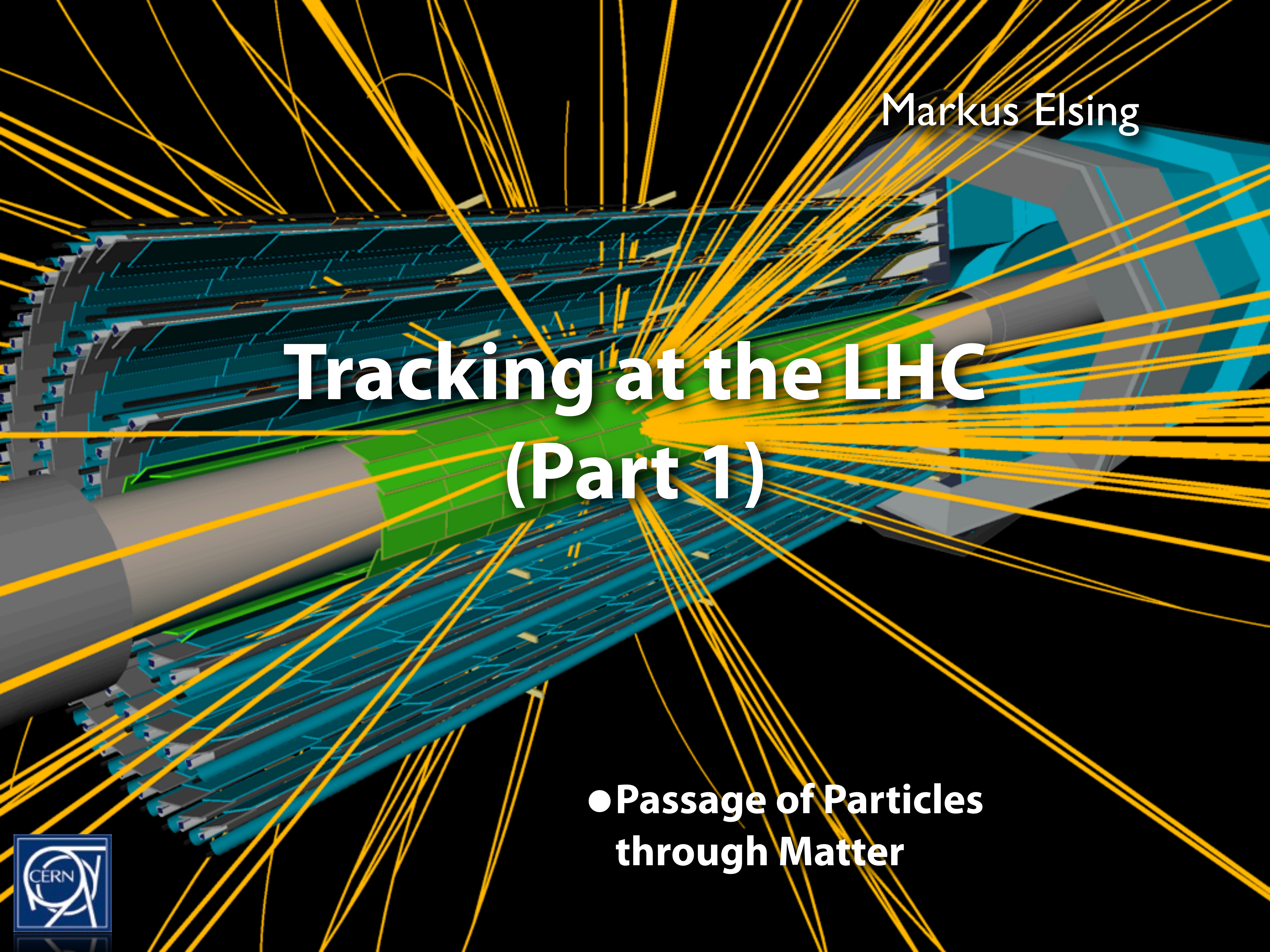
CREDITS: tanks for help and material from...
A.Salzburger, G.Herten, D.Froidevaux, M.Hauschild, P.Wells, W.Riegler, R.Mankel, T.Cornelissen, A.Poppleton, A.Strandli, R.Frühwirth, G.Piacquadio, A.Morley and several others I should mention here



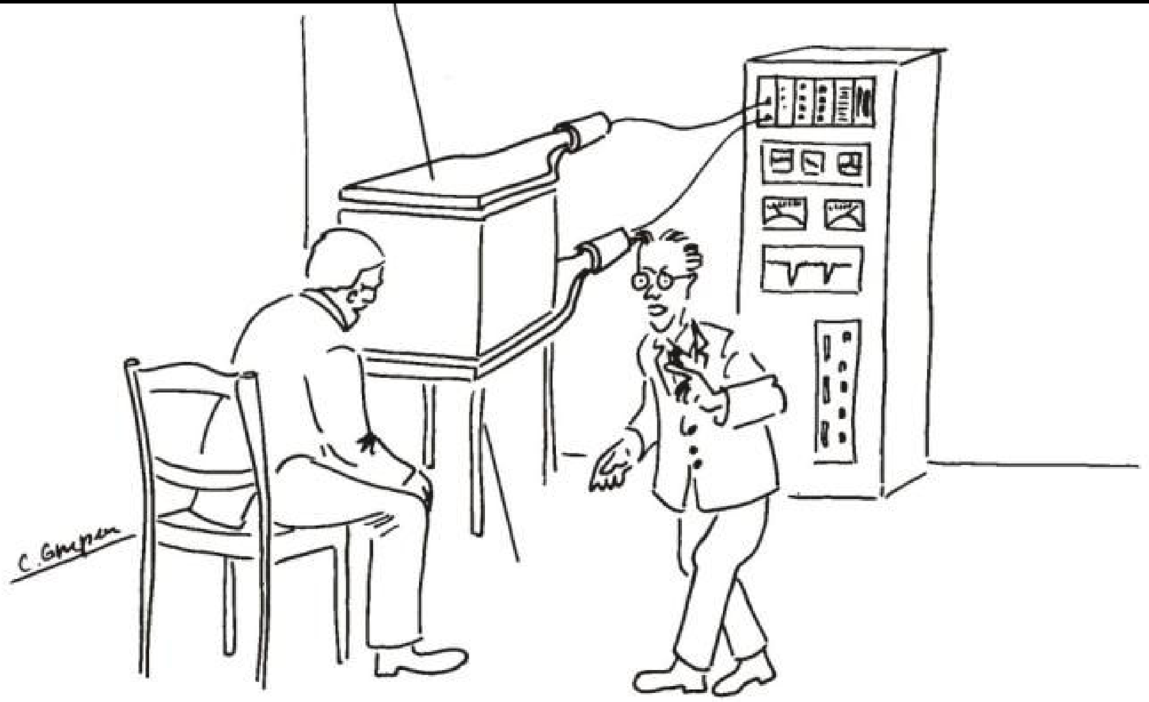
Markus Elsing

Tracking at the LHC
(Part 1)

- Passage of Particles through Matter

Passage of Particles through Matter

- any device that is to detect a particle must interact with it in some way
  - ➡ well, almost...
  - ➡ in many experiments neutrinos are measured by missing transverse momentum



"Did you see it?"
"No nothing."
"Then it was a neutrino!"

Claus Grupen, Particle Detectors, Cambridge University Press, Cambridge 1996 (455 pp. ISBN 0-521-55216-8)

Outline of Part 1

- overview of charged particle interactions with matter
  - ➡ provide not only the means to detect charged particles
- important as well to understand they affect the tracking performance of
  - ➡ energy loss
  - ➡ multiple scattering
  - ➡ Bremsstrahlung
  - ➡ hadronic interactions

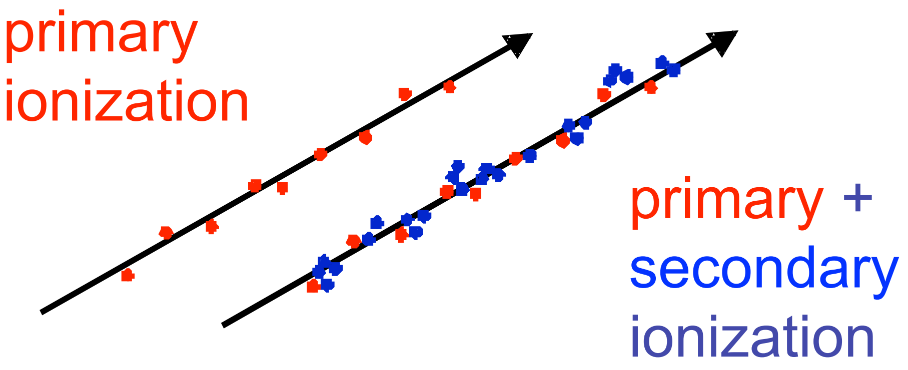
Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials

Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - **energy loss by ionization**

primary ionisation can generate secondary ionisation



typically:
total ionization ≈ 3 x primary ionization
➡ ~ 90 electrons/cm in gas at 1 bar

Charged Particle Interactions with Matter

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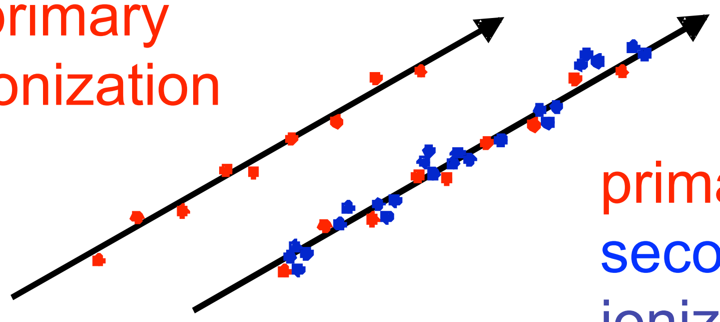
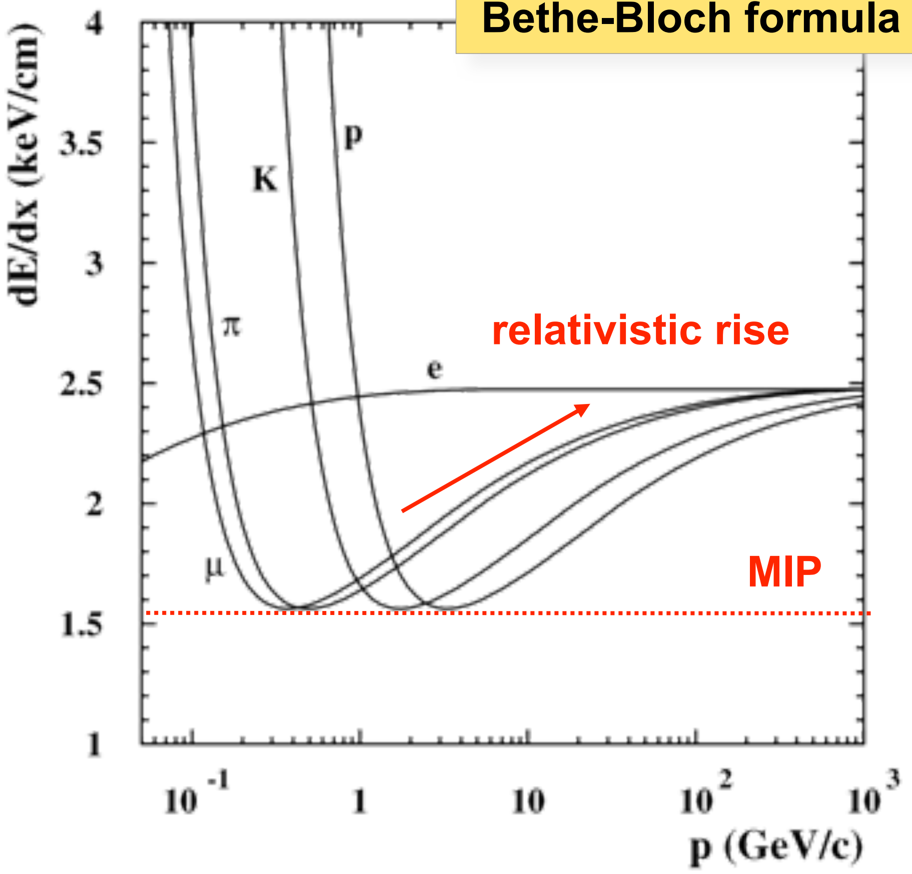


primary ionization

primary + secondary ionization

typically:
total ionization ≈ 3 x primary ionization
➡ ~ 90 electrons/cm in gas at 1 bar

***dE/dx* described by Bethe-Bloch formula**



➡ not directly used for particle identification by ATLAS/CMS

Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - energy loss by ionisation

Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - energy loss by ionisation
  - **Bremsstrahlung**

due to interaction with Coulomb field of nucleus

dominant energy loss mechanism for electrons down to low momenta (~20 MeV)

initiates EM cascades (showers)

Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - Energy loss by ionization
  - Bremsstrahlung

Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - Energy loss by ionization
  - Bremsstrahlung
  - **multiple scattering**

charged particles traversing a medium are deflected by many successive small-angle scatters

angular distribution ~ Gaussian

$$\sigma_{MS} \sim 1/p * (x/X_0)^{1/2}$$

but also large angles from Rutherford scattering $\sim \sin^{-4}(\theta/2)$

➡ complicates track fitting, limits momentum measurement

Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - energy loss by ionization
  - Bremsstrahlung
  - multiple scattering

Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - energy loss by ionization
  - Bremsstrahlung
  - multiple scattering
  - **radiation length**

material thickness in detector is measured in terms of dominant energy loss reactions at high energies:

- Bremsstrahlung for electrons
- pair production for photons

<u>definition</u>:

$\boldsymbol{X_0}$ = length over which an electron loses all but **1/*e*** of its energy by bremsstrahlung

= 7/9 of mean free path length of photon before pair production

describe material thickness in units of X_0

Charged Particle Interactions with Matter

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describe material thickness in units of X_0

material	X_0 **[cm]**
Be	35.3
Carbon-fibre	~ 25
Si	9.4
Fe	1.8
$PbWO_4$	0.9
Pb	0.6

ATLAS LAr absorber

CMS ECAL crystals

Charged Particle Interactions with Matter

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  - multiple scattering
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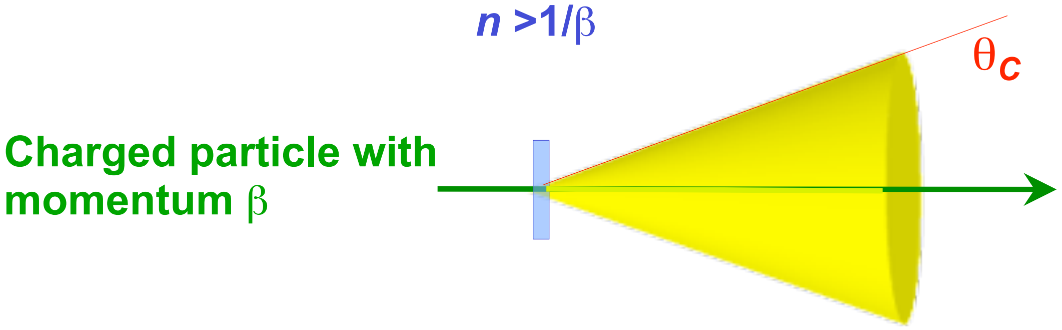
Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - energy loss by ionisation
  - Bremsstrahlung
  - multiple scattering
  - radiation length
  - **Cherenkov radiation**

a relativistic charge particle traversing a dielectric medium with refraction index $n > 1/\beta$ emits Cherenkov radiation in cone with angle θ_C around track: $\cos\theta_C = (n\beta)^{-1}$



light cone emission when passing thin medium

detector types RICH (LHCb), DIRC, Aerogel counters (not employed by ATLAS/CMS))

Charged Particle Interactions with Matter

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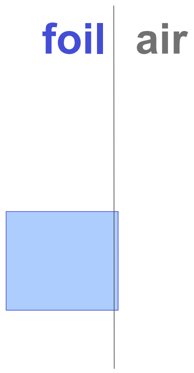
  - radiation length
  - Cherenkov radiation

Charged Particle Interactions with Matter

- particles are detected through their interaction with the active detector materials
  - energy loss by ionization
  - radiation length
  - Bremsstrahlung
  - Cherenkov radiation
  - multiple scattering
  - **transition radiation**

photon radiation when charged ultra-relativistic particles traverse the boundary of two different dielectric media (foil & air)



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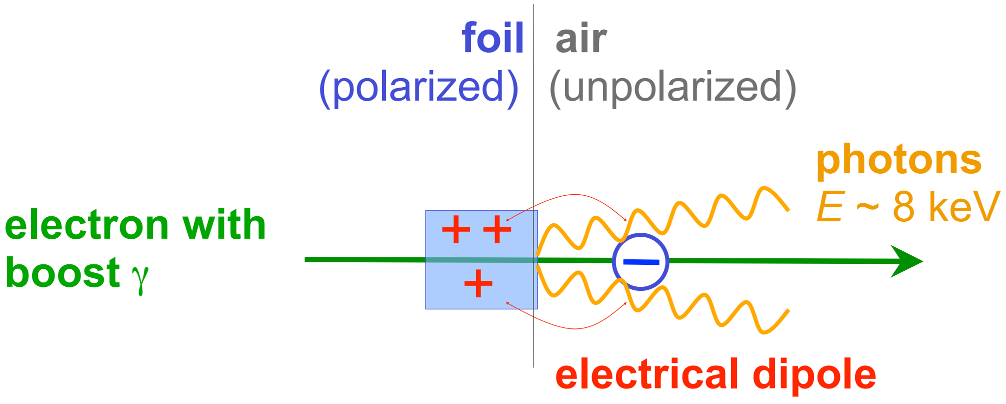

➡ significant radiation for $\gamma > 1000$ and > 100 boundaries

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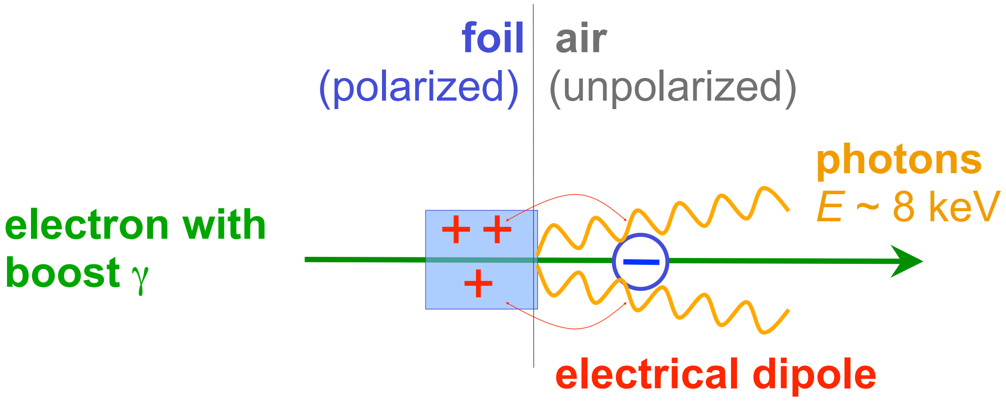

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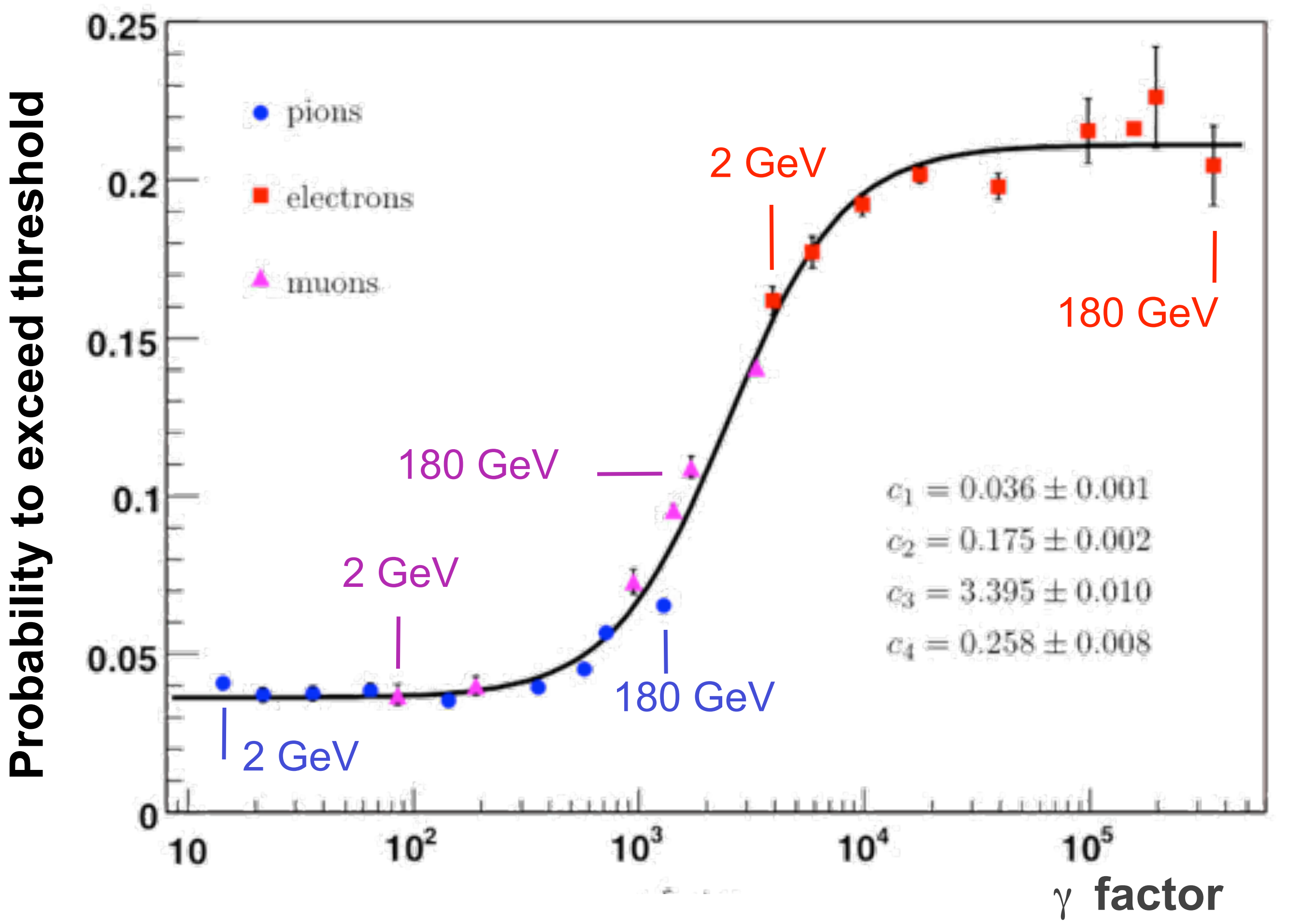
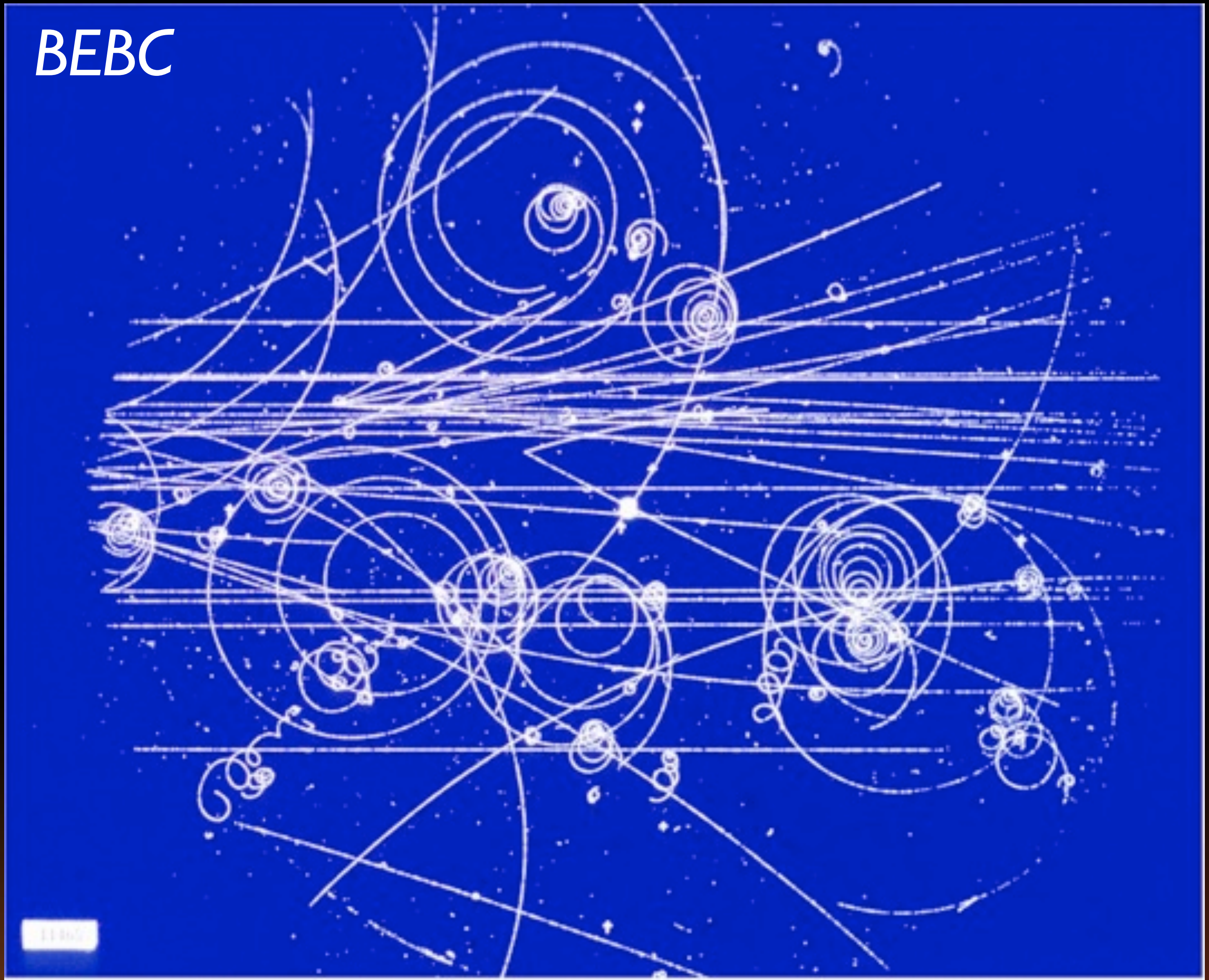
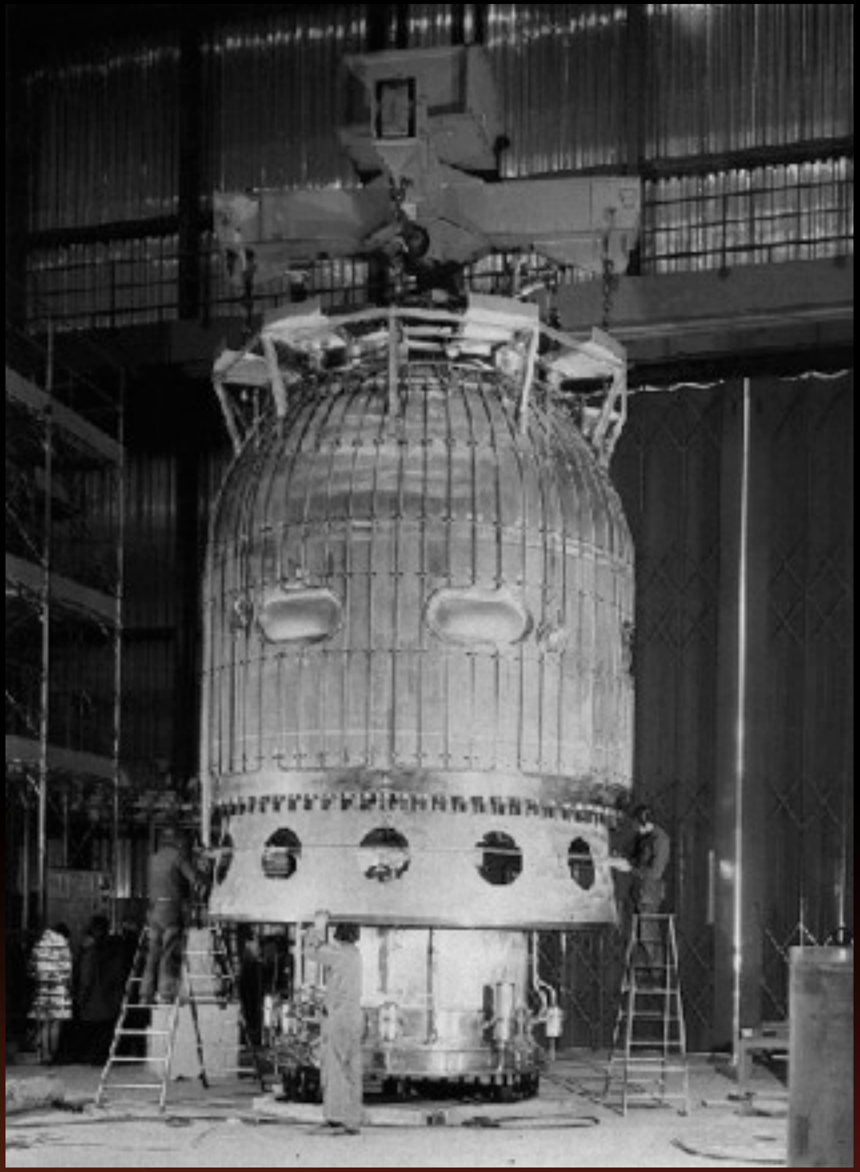


Effects are visible by Eye...

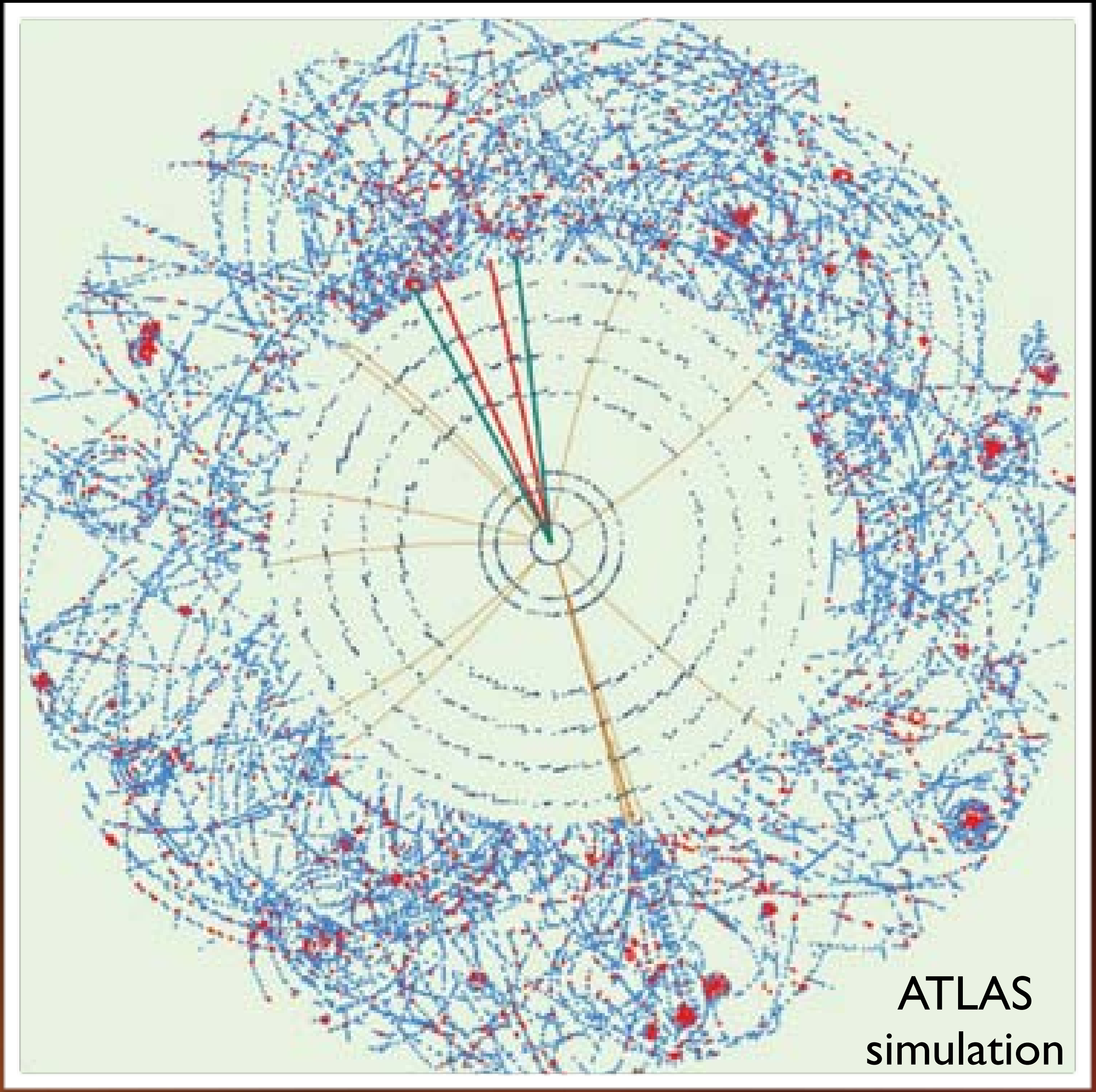




BEBC can be seen outside the Microcosm Exhibition

- give rise to beautiful old bubble-chamber photos
  - ➡ energy loss by ionization, δ-electrons, pair production, ...

… as well in modern Detectors



History of Energy Loss Calculations: dE/dx

1915: **Niels Bohr**, classical formula, Nobel prize 1922.
1930: non-relativistic formula found by **Hans Bethe**
1932: relativistic formula by **Hans Bethe**

Bethe's calculation is leading order in perturbation theory, thus only z^2 terms are included.

additional corrections:

- z^3 corrections calculated by **Barkas+Andersen**
- correction calculated by **Felix Bloch** (Nobel prize 1952,for nuclear magnetic resonance). Although the formula is called Bethe-Bloch formula the z^4 term is usually not included.
- shell corrections: atomic electrons are not stationary
- density corrections: by **Enrico Fermi** (Nobel prize 1938, for discovery of nuclear reaction induced by slow neutrons)

Hans Bethe
1906-2005

Born in Strasbourg,
emigrated to US in 1933.
Professor at Cornell U.
Nobel prize 1967
for theory of nuclear
processes in stars.

The Bethe-Bloch Formula

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

➡ characteristics of the energy loss as a function of the particle velocity ($\beta\gamma$)

➡ with

- z ~ charge of incident particle
- Z ~ atomic number of absorber
- A ~ atomic mass of absorber

$$\frac{K}{A} = 4\pi N_A r_e^2 m_e c^2 / A = 0.307075 \text{ MeV g}^{-1}\text{cm}^2, \text{ for A} = 1\text{g mol}^{-1}$$

- I ~ mean excitation energy of absorber
- T_{max} ~ maximum energy transfer in a single collision

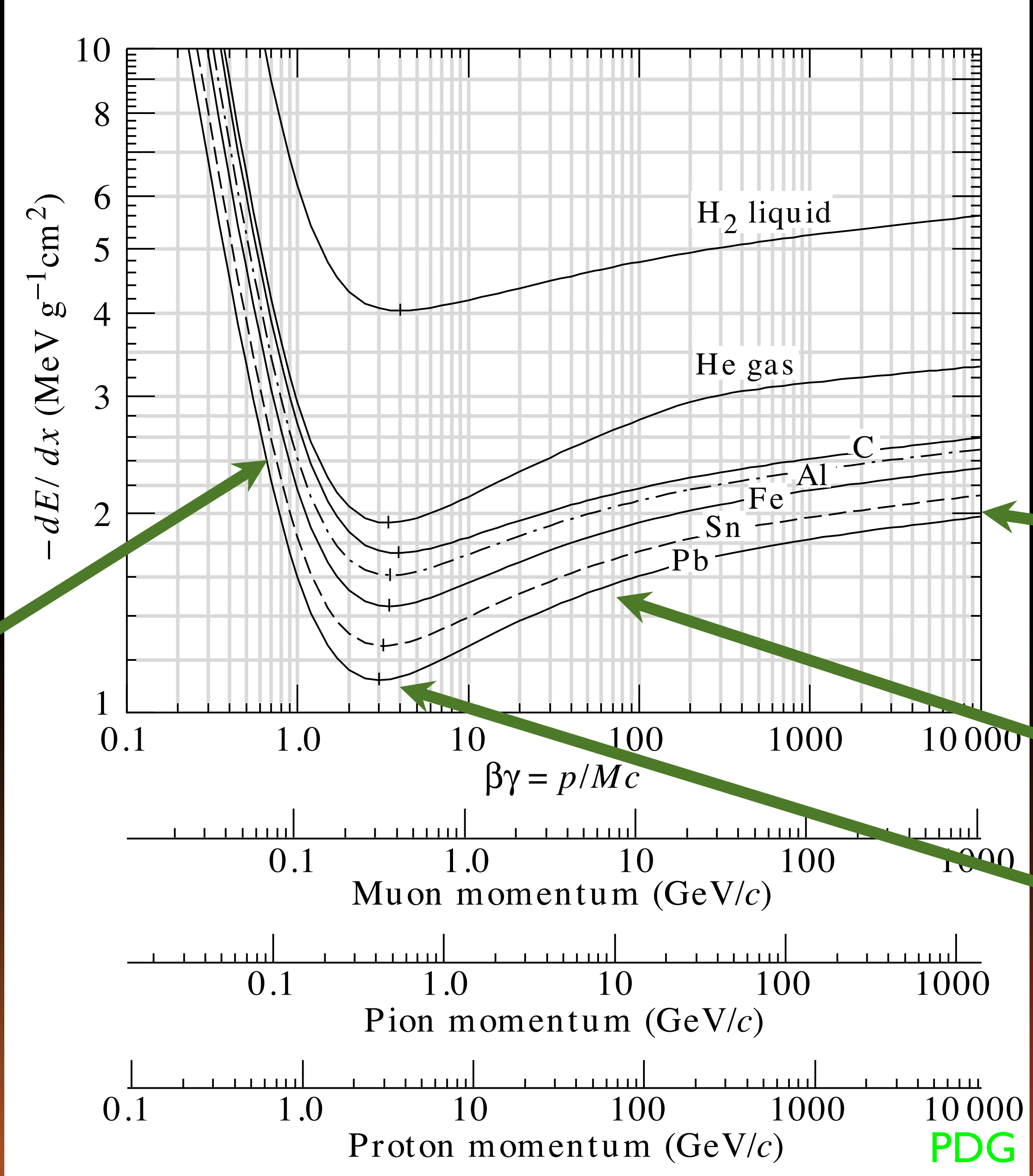
$$T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

- $\delta(\beta\gamma)$ ~ density effect correction to ionization loss

➡ $x = \rho s$ ~ surface density or mass thickness, with unit g/cm^2, **s** is the length

(*dE/dx* has the units *MeV cm^2/g*)

The Bethe-Bloch Formula



Bethe-Bloch formula:

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln f(\beta) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

except in hydrogen, particles of the same velocity have similar energy loss in different materials.

Fermi plateau: density effect, polarization of medium “screens” particle charge

classical $1/\beta^2$ dependency (Rutherford Scattering)

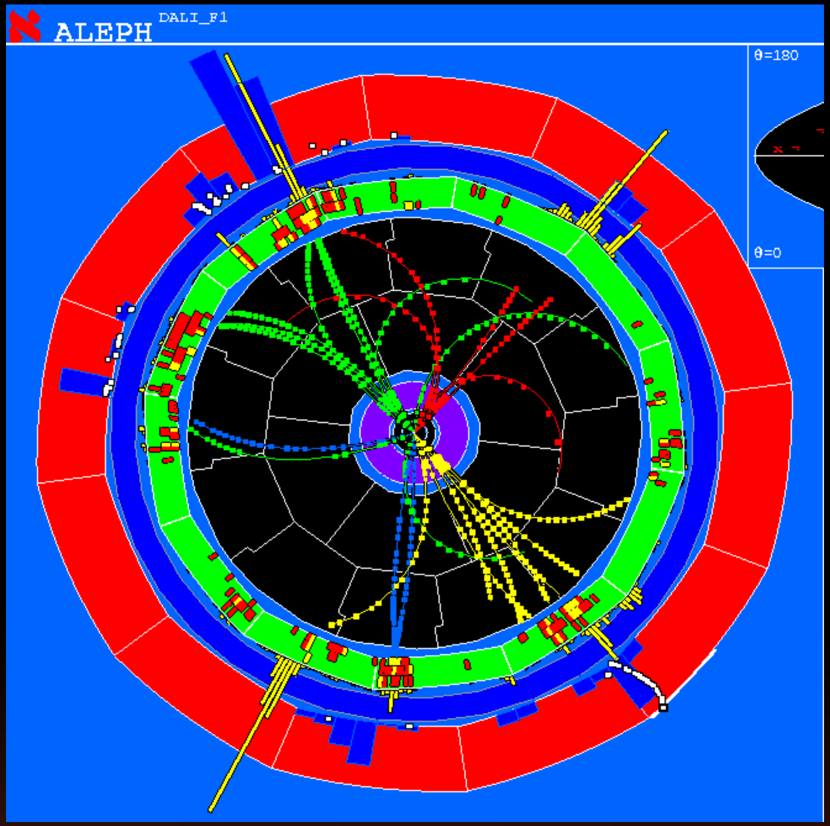
relativistic rise

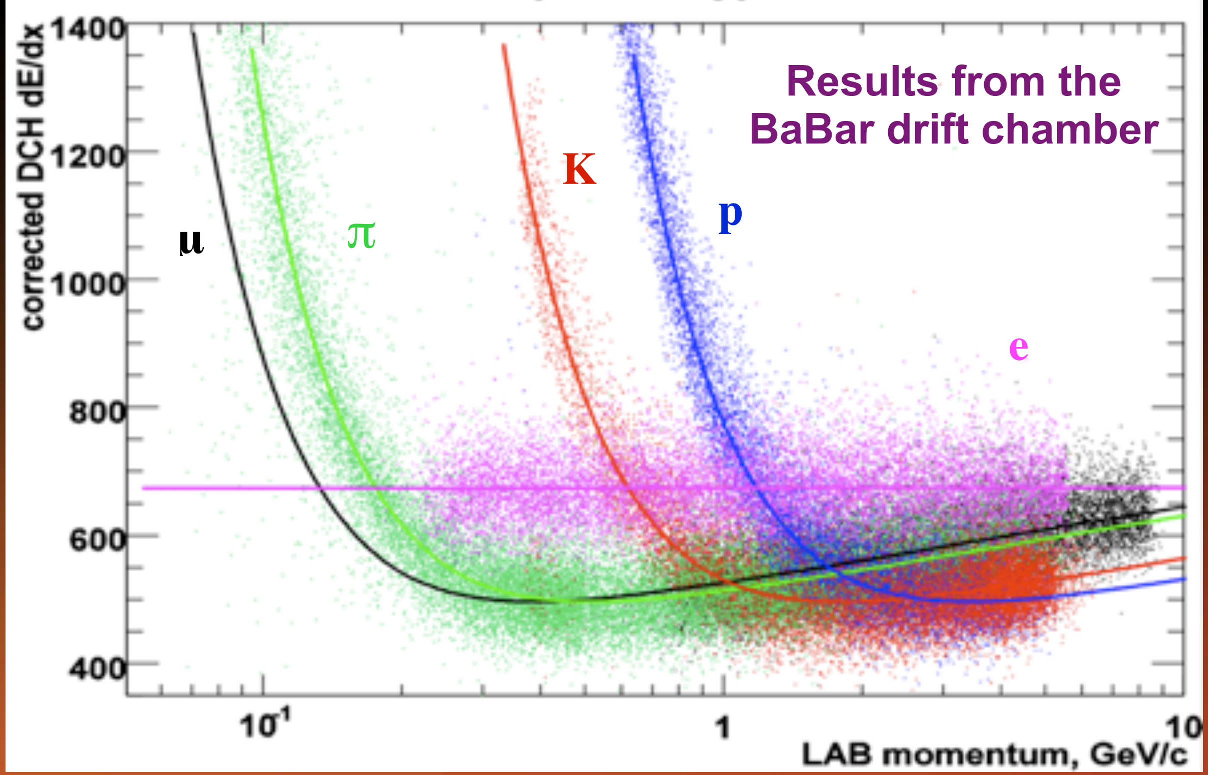
the minimum in ionization occurs at $\beta\gamma$ = 3.0 to 3.5, as Z goes from 7 to 100

Particle Identification using dE/dx

- energy loss depends on particle velocity
  - ➡ ≈ independent of particle mass M
- as a function of particle momentum
  - ➡ **$p = Mc\beta\gamma$** depends on particle mass !

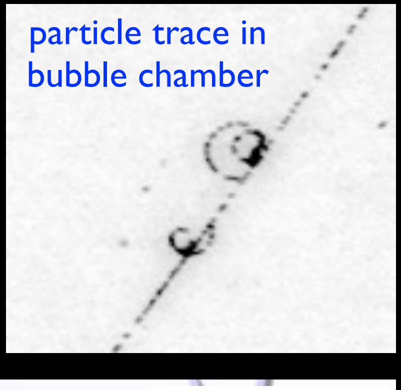
- application in an experiment:
  - ➡ measure momentum from curvature of particle track in magnetic field
  - ➡ measure ionization along the track





Results from the BaBar drift chamber

Fluctuations in Energy Loss


particle trace in bubble chamber

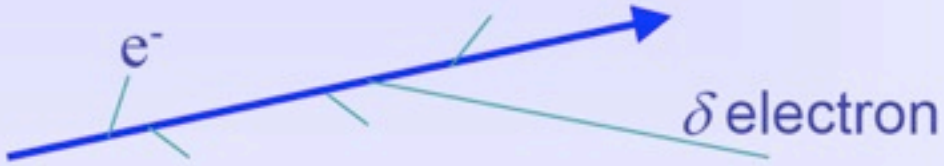
from L. Ropelewski

Real detector (limited granularity) can not measure <*dE/dx*> !

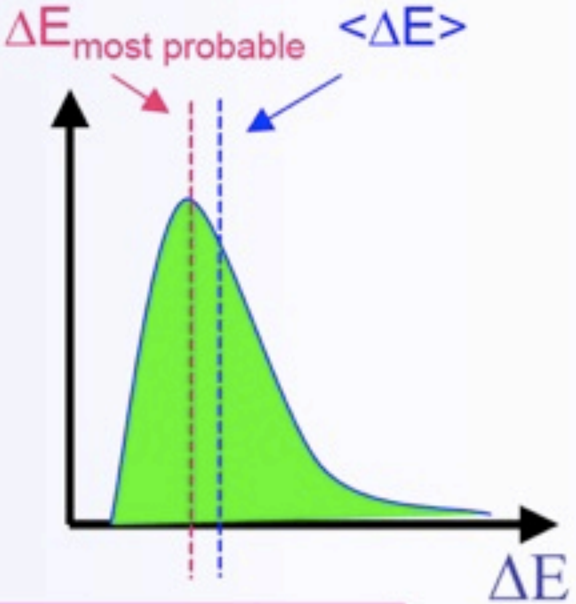
It measures the energy *ΔE* deposited in a layer of finite thickness δx.

For thin layers or low density materials:

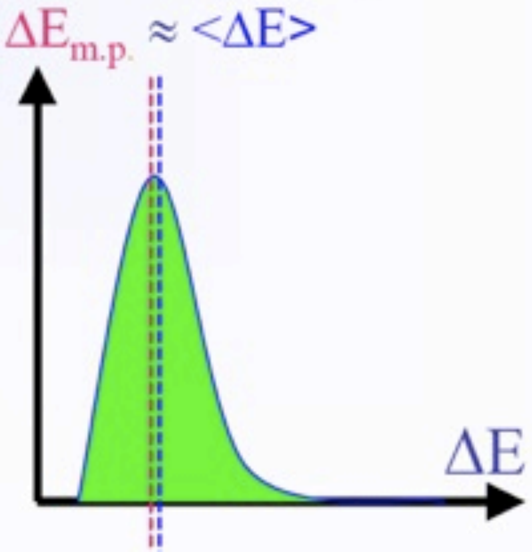
→ Few collisions, some with high energy transfer.



→ Energy loss distributions show large fluctuations towards high losses: "Landau tails"

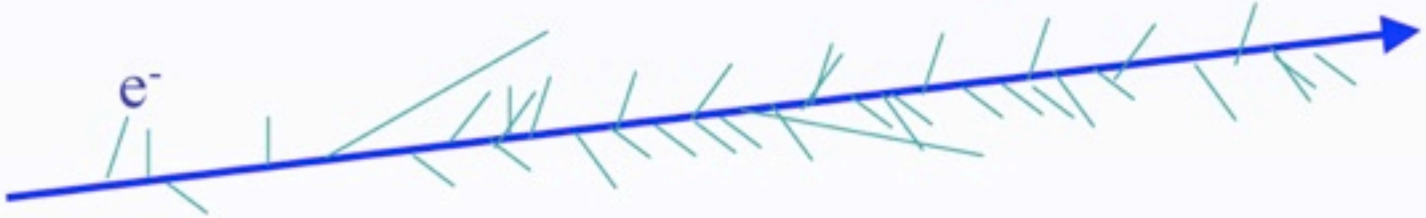


Example: Si sensor: 300 μm thick. $\Delta E_{m.p} \sim 82$ keV $<\Delta E> \sim 115$ keV



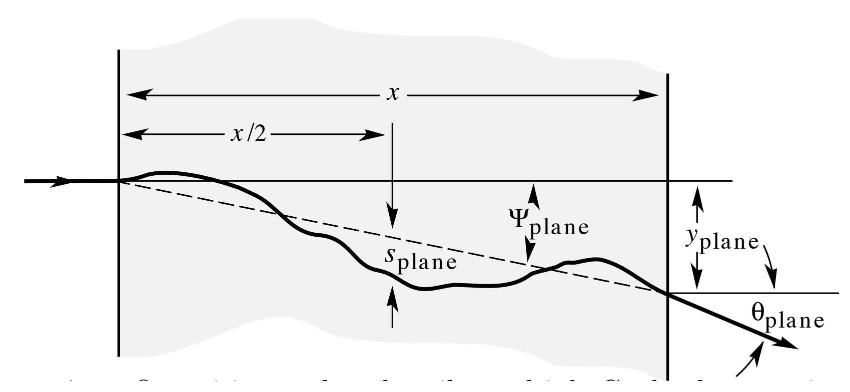
For thick layers and high density materials:

→ Many collisions.
→ Central Limit Theorem → Gaussian shaped distributions.



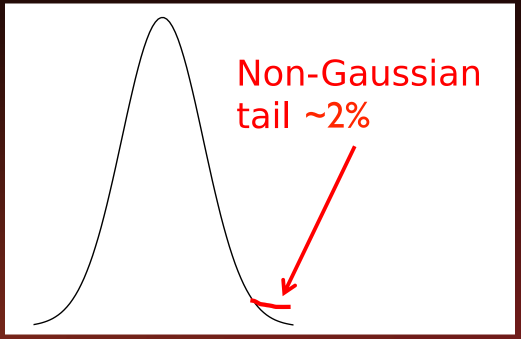
Multiple Scattering

- a particle which traverses a medium is deflected
  - ➡ by small angle **Coulomb scattering** in field of nuclei
  - ➡ for hadronic particles as well the strong interaction contributes



- **angular deflection** after traversing a distance **x**
  - ➡ described by the **Molière theory**
  - ➡ angle has roughly a Gaussian distribution, but with larger tails due to Coulomb scattering
  - ➡ Gaussian approximation

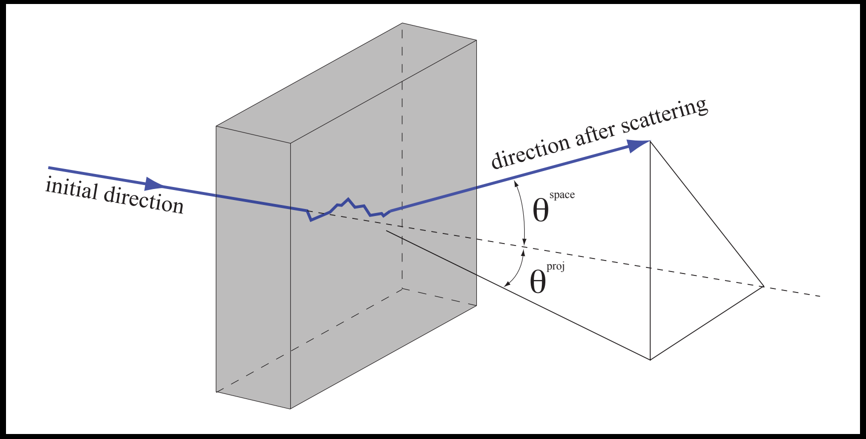
$$\Delta\Theta = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$

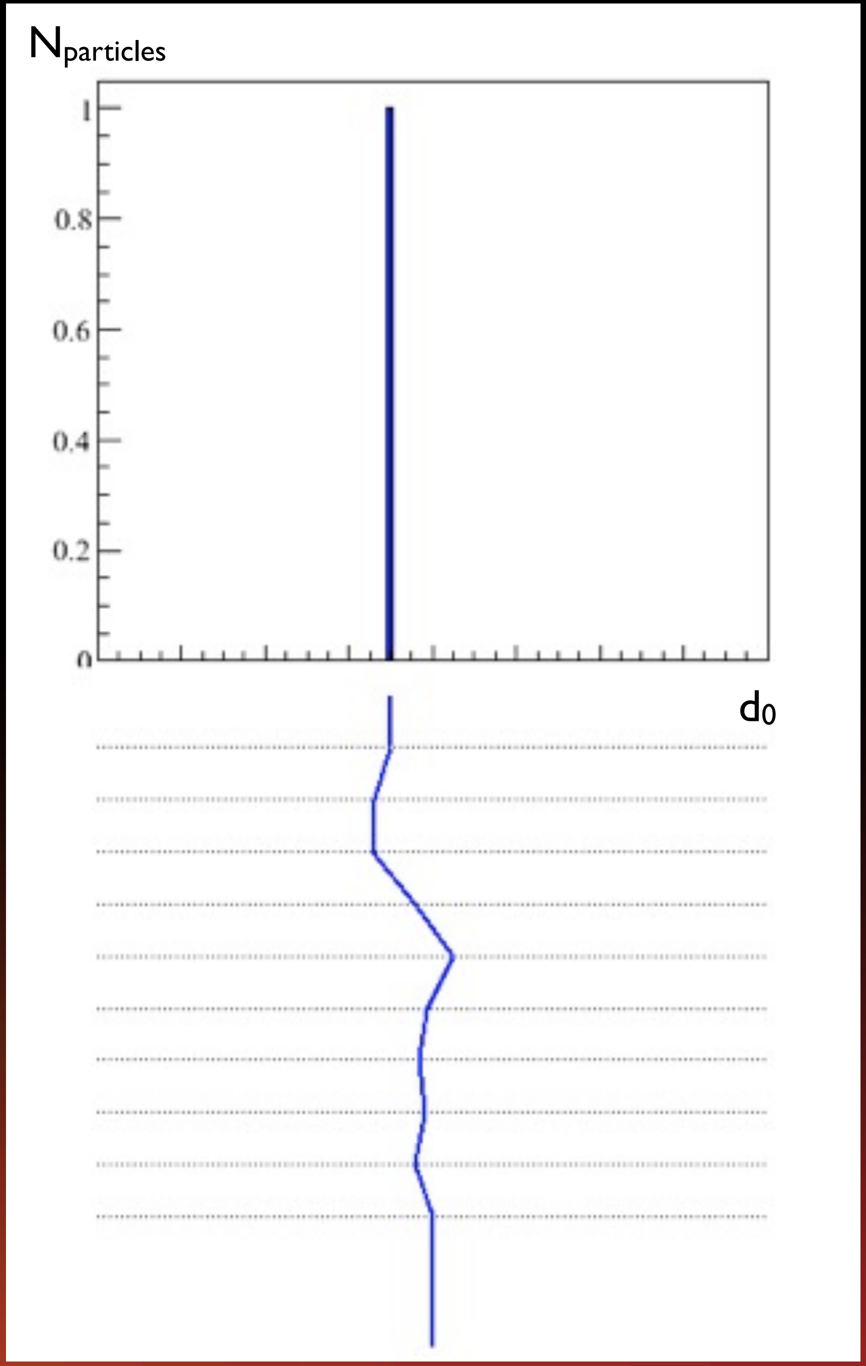


- x/X_0 ~ thickness of material in units of radiation length
- z ~ charge of the particle

Illustration of M.S. Effect

- toy simulation
  - ➡ simulation of single particle traversing a set of individual thin material layers
    - single scattering steps accumulate





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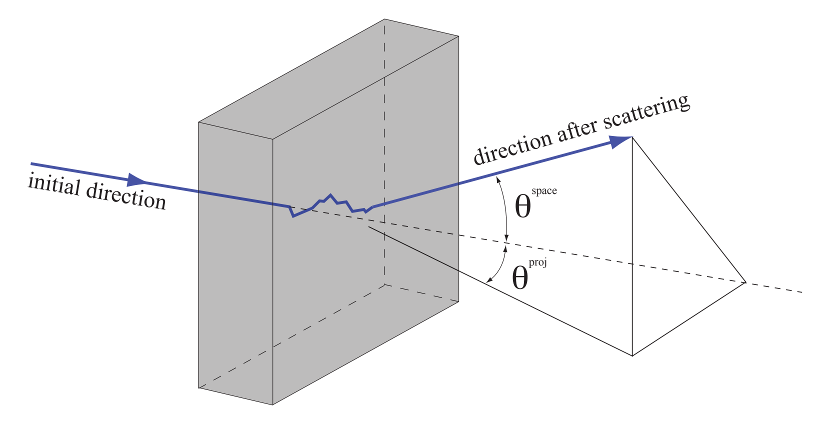
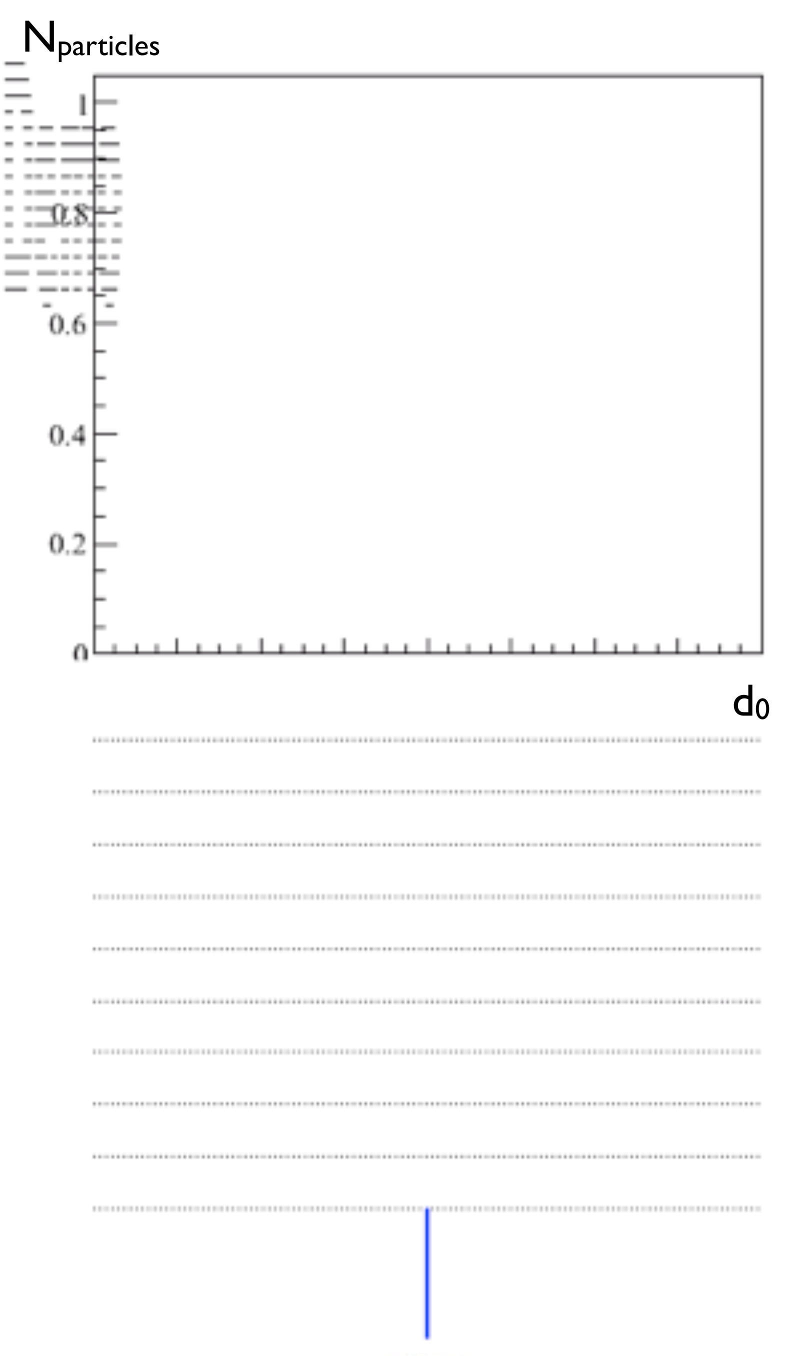
  - ➡ repeat N times:
    - central limit theorem predicts gaussian distribution





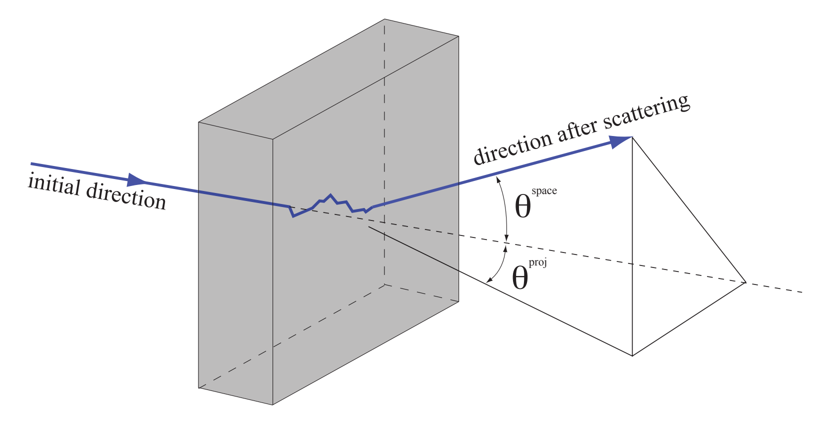
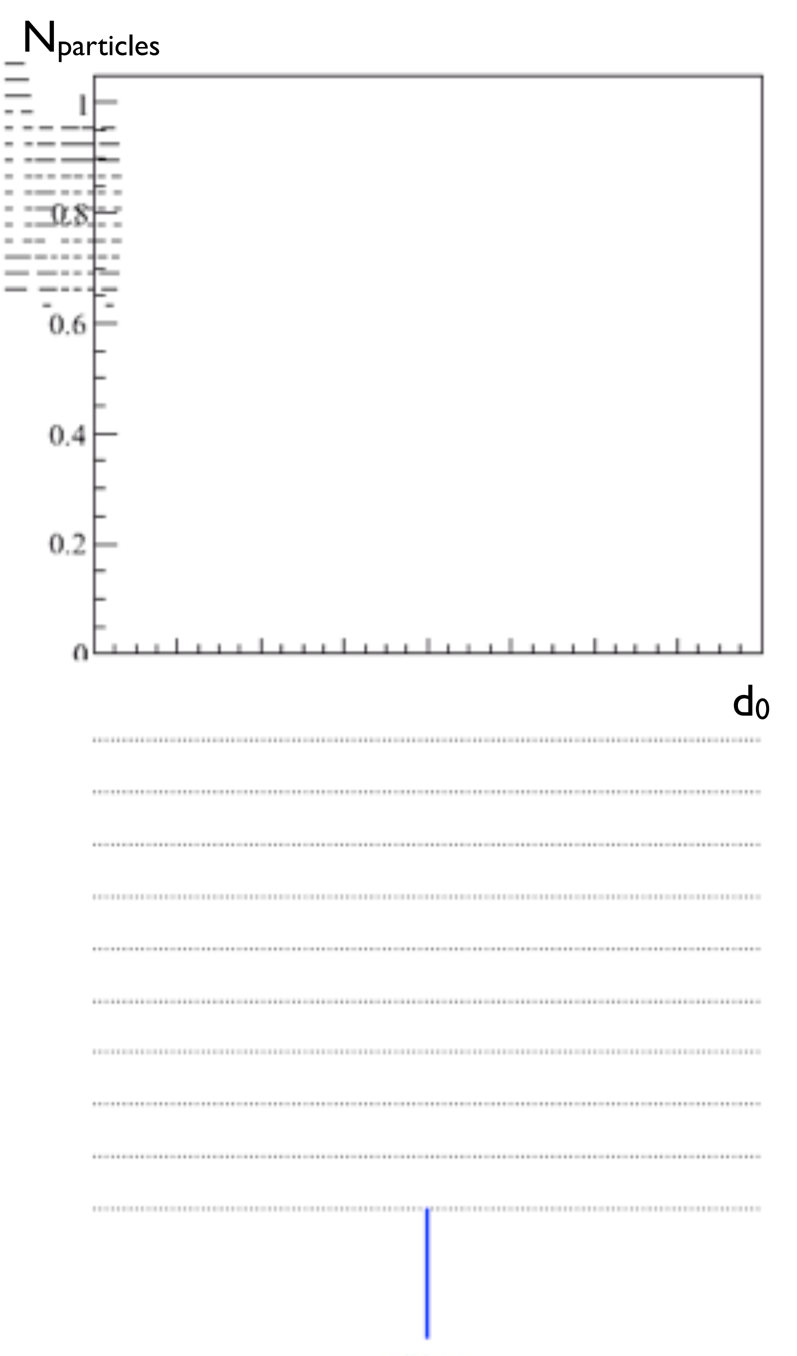
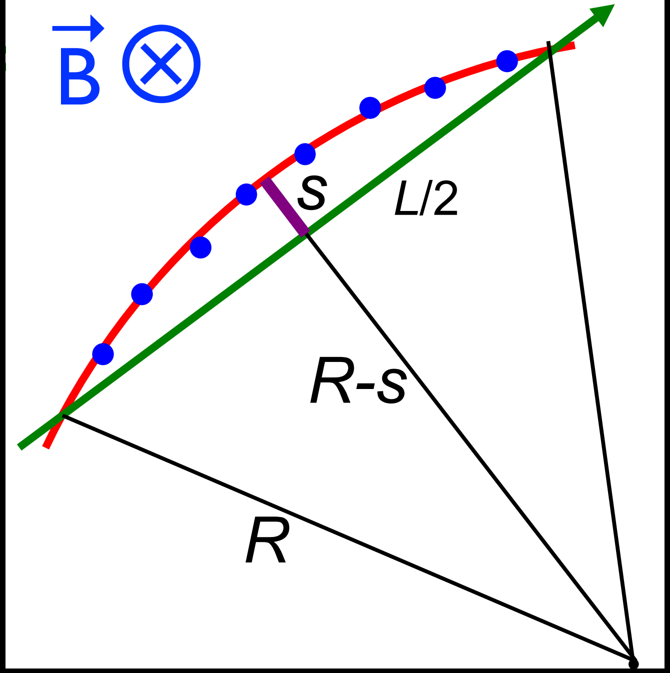


Illustration of M.S. Effect

- toy simulation
  - ➡ simulation of single particle traversing a set of individual thin material layers
    - single scattering steps accumulate
  - ➡ repeat N times:
    - central limit theorem predicts gaussian distribution
- sometimes we experience the effect



Effect on Momentum Resolution



- magnetic spectrometer
  - ➡ charged particle describes a circle in a magnetic field

$$p_T[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

  - ➡ measure sagitta **s** of arc to determine curvature **R**

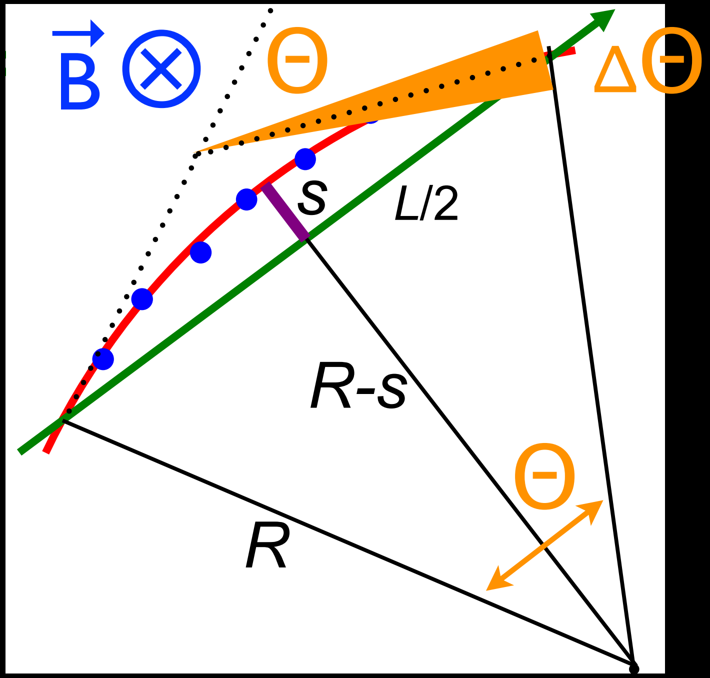
$$R = \frac{L^2}{8s} + \frac{s}{2} \approx \frac{L^2}{8s}$$

- put into upper equation results in $p_T \equiv p_T(s)$
  - ➡ relative error on momentum equals relative error on sagitta

$$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3BL^2}\sigma_s$$

  - ➡ hence relative momentum uncertainty is proportional to momentum $\mathbf{p_T}$ times sagitta uncertainty $\boldsymbol{\sigma_s}$
  - ➡ as well, one wants large field **B** and long path length **L**

Effect on Momentum Resolution



- multiple scattering contribution to momentum uncertainty

$$\frac{\sigma_{PT}}{P_T} = \frac{\Delta\Theta}{\Theta} \cong \frac{0.05}{BL}\sqrt{\frac{x}{X_0}}$$

- putting things together gives

$$\frac{\sigma_{PT}}{P_T} = \frac{8 p_T \sigma_S}{0.3BL^2} \oplus \frac{0.05}{BL}\sqrt{\frac{x}{X_0}} \approx a\, p_T \oplus b$$

➡ **a** ~ resolution term dominating at high p_T
b ~ multiple scattering term limiting at low p_T

➡ sagitta uncertainly from **N** points, each with resolution $\boldsymbol{\sigma_{R\phi}}$

$$\sigma_S = \sqrt{\frac{A_N}{N+4}}\,\frac{\sigma_{R\phi}}{8}$$

Statistical factor $A_N = 720$:
(Gluckstern)

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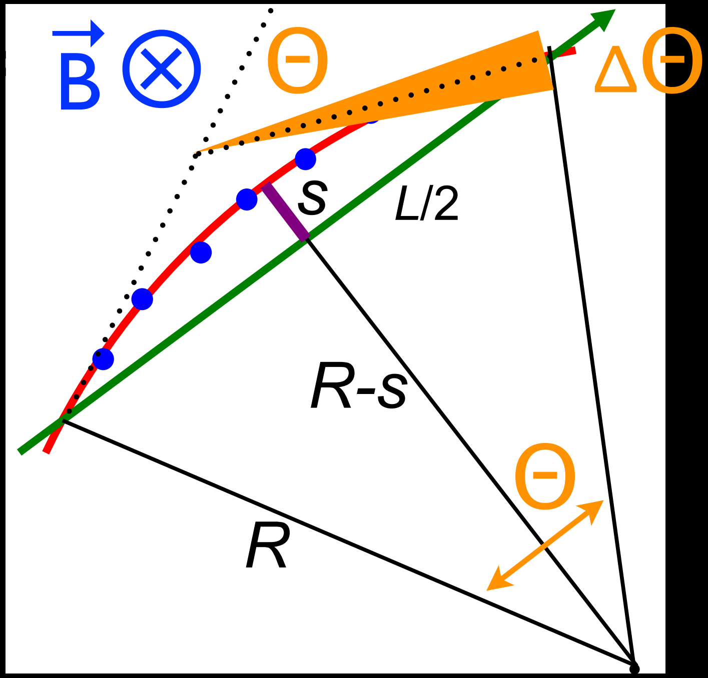

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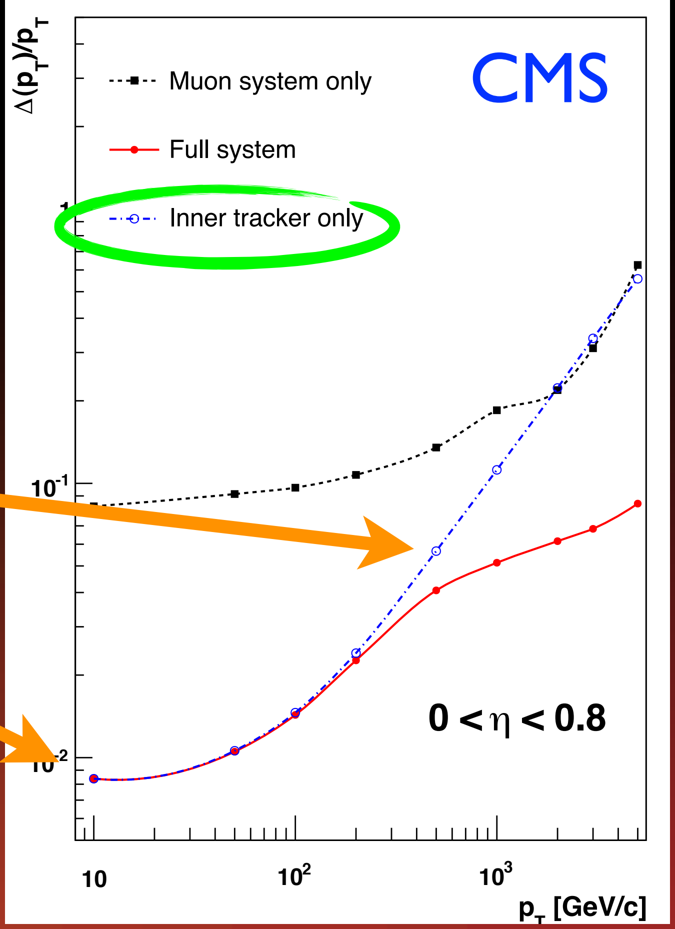
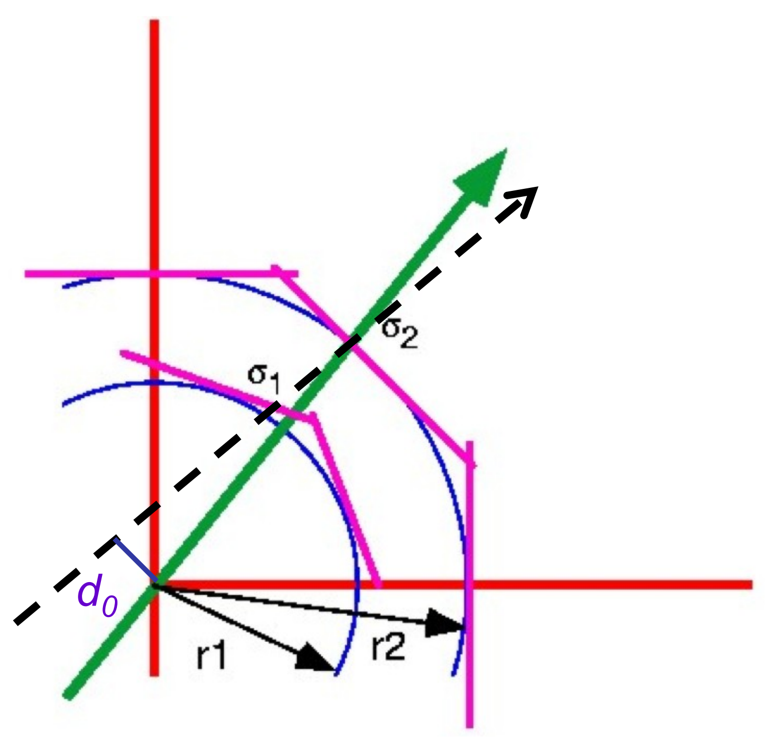


Effect on Impact Parameter Resolution

- uncertainty on the transverse impact parameter **d0**
  - ➡ depends on the radii and space point precision
  - ➡ simplified formula for straight line and just two layers:

$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

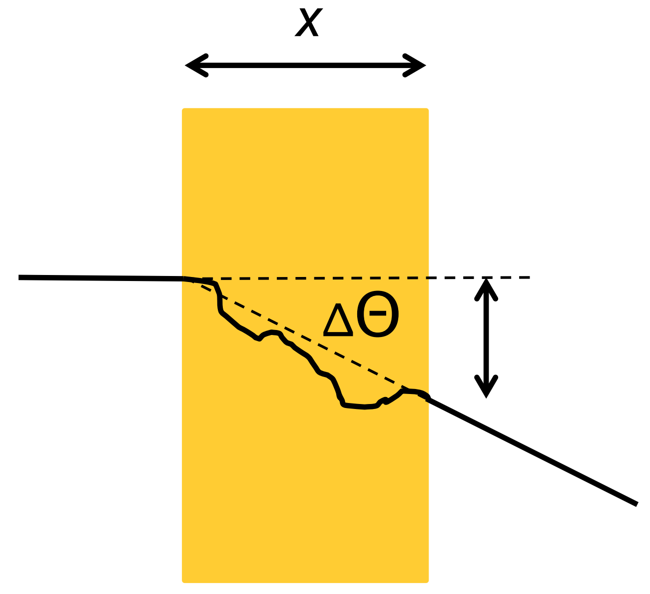
  - ➡ suggests: small r_1, large r_2, small σ_1, σ_2



- precision is degraded by multiple scattering

$$\Delta d_0 = r\tan\Delta\Theta \approx r\,\Delta\Theta = r\,\frac{0.0136}{\beta c p}\sqrt{\frac{x}{X_0}}$$

  - ➡ at low momentum scattering contribution becomes large
  - ➡ best precision if small radius **r** and minimum thickness **x**



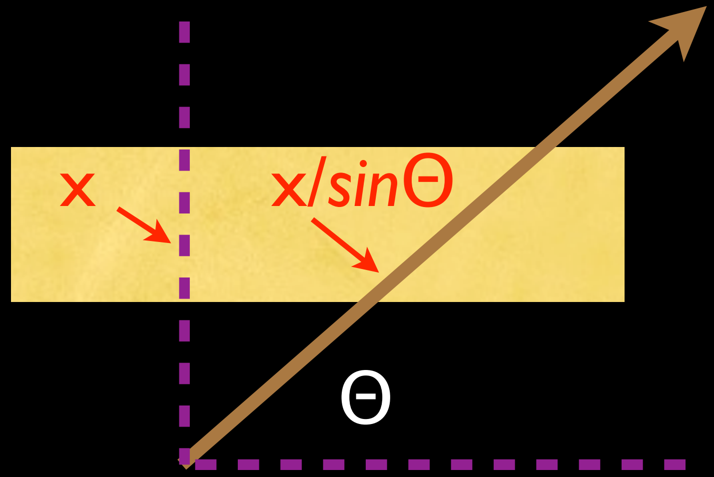
Effect on Impact Parameter Resolution

- for tracks with Θ≠90°: r→r/sinΘ x→x/sinΘ

$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p\sin^{3/2}\theta} 13.6\text{MeV}\sqrt{\frac{x}{X_0}}$$

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T\sin^{1/2}\theta}$$

  - constant term describing resolution
  - multiple scattering term decreasing with pT



- similarly momentum resolution term becomes:

$$\frac{\sigma_{p_T}}{p_T} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$

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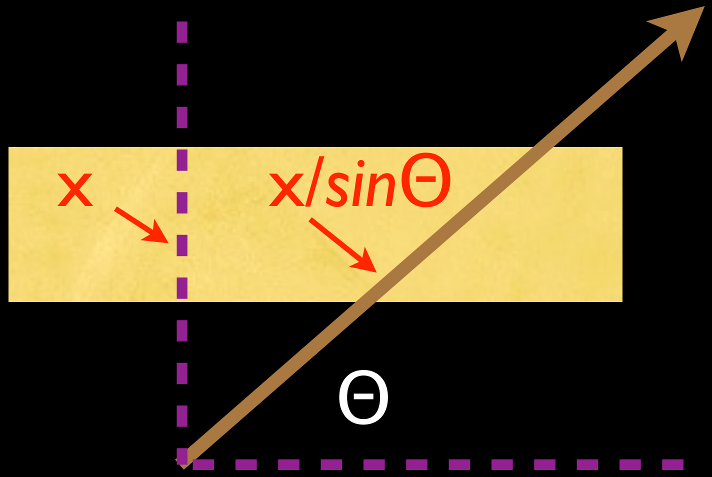

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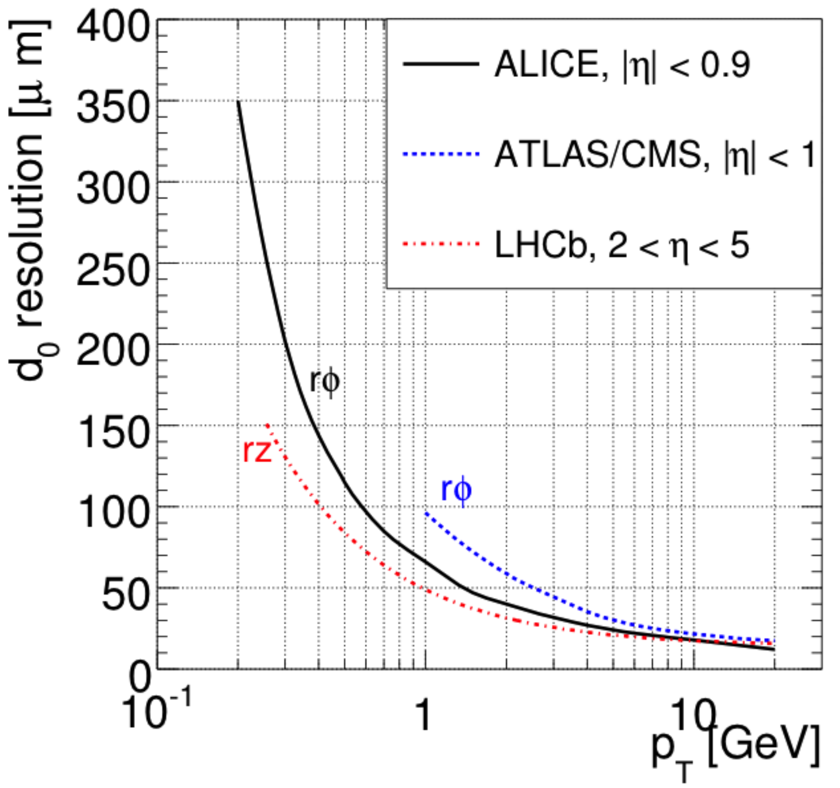
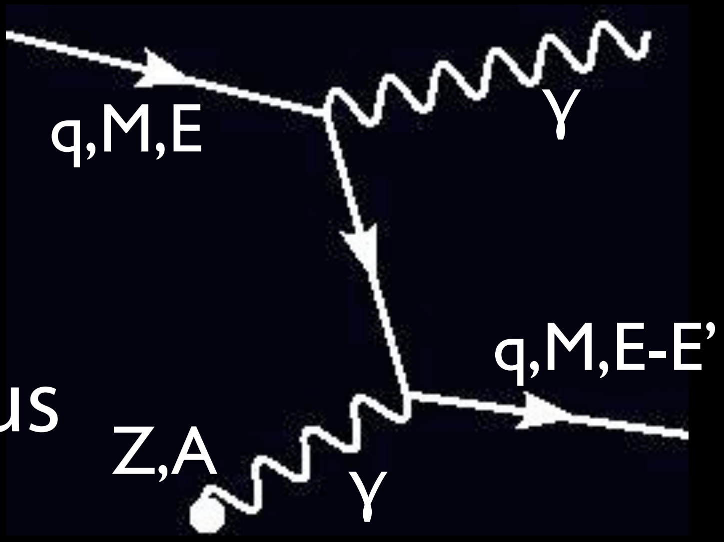
S.Alekhin et al. HERA and the LHC - A workshop on the implications of HERA for LHC physics:Proceedings Part B, arXiv:hep-ph/0601013.

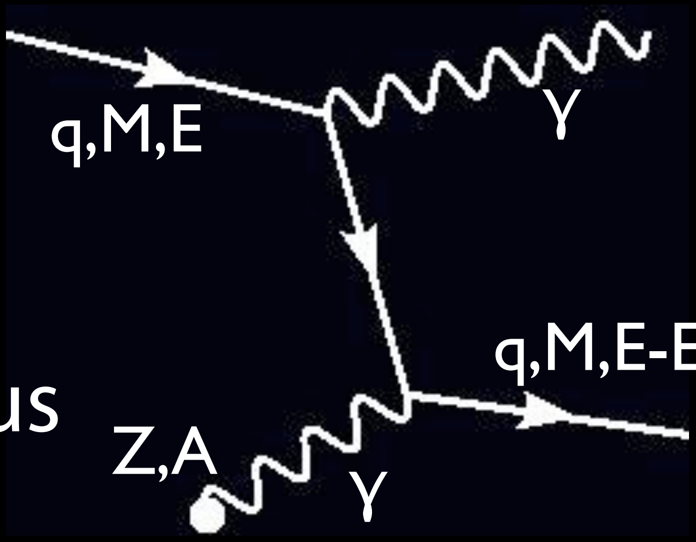


Bremsstrahlung



- charged particle deflected by field of nucleus
  - ➡ deflecting a charged particle means "acceleration"
  - ➡ therefore radiates a photon → **Bremsstrahlung**
  - ➡ effect is strong for light particles (**electrons**), as acceleration is large for given force
  - ➡ for heavier particles (**muons**), bremsstrahlung only important at energies of a few hundred GeV (**important for ATLAS/CMS** at the LHC!)
  - ➡ presence of a nucleus is required to restore energy-momentum conservation

Bremsstrahlung



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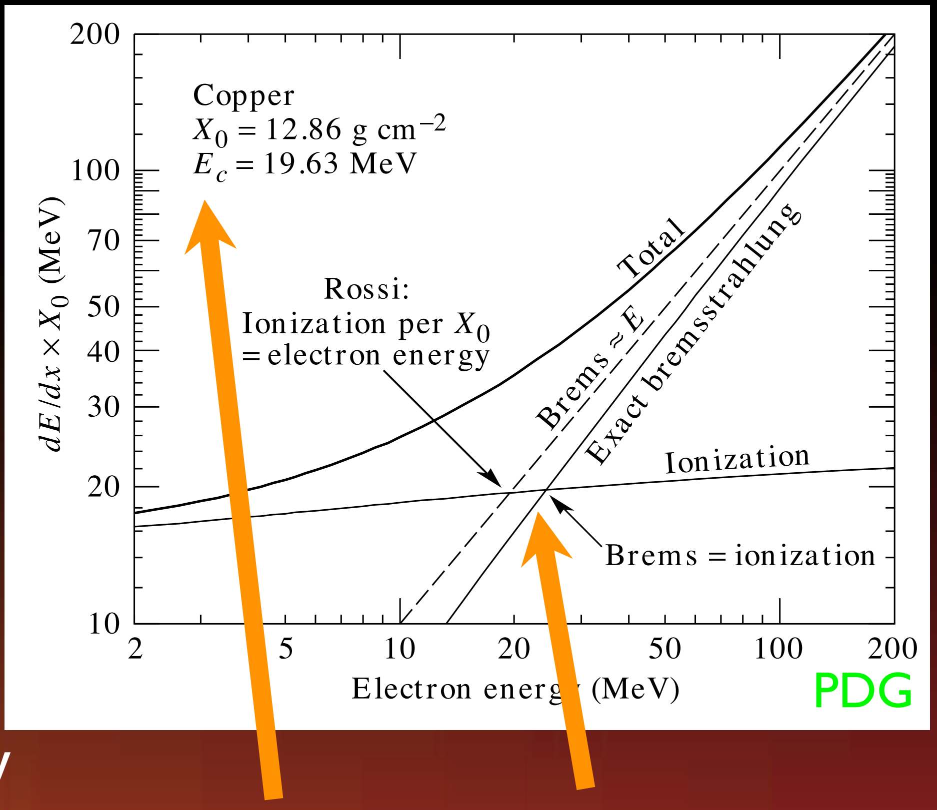
- Bremsstrahlung proportional to
  - Z^2/A and ρ of the material
  - q^4 and $1/M^2$ of incoming particle
  - ➡ energy lost ~ proportional to energy of particle:

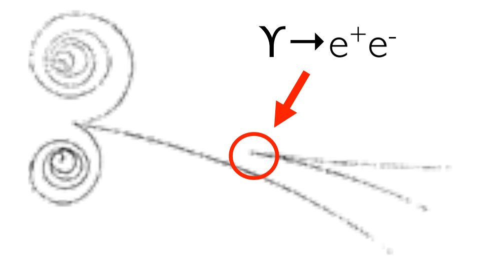
$$E(x) \approx E_0 e^{-x/X_0} \qquad X_0 \propto \frac{M^2 A}{q^4 \rho Z^2}$$

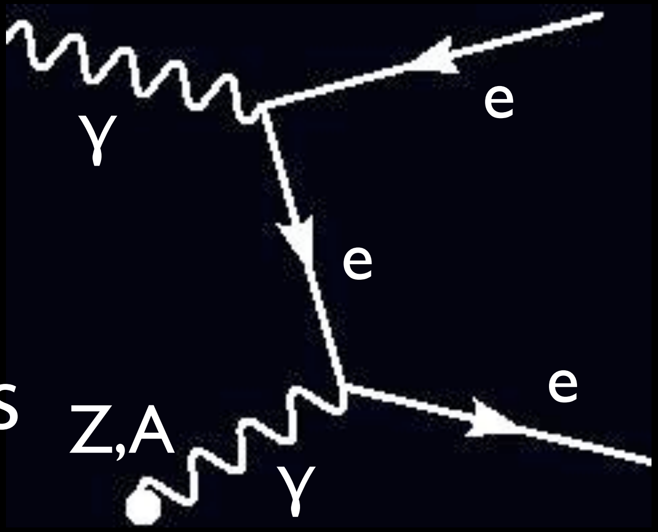
  - **radiation length X_0** ~ characteristic amount of material traversed before it looses 1/e of its energy
  - ➡ Bremsstrahlung of electrons in tracker material is limiting reconstruction efficiency !



important above critical energy E_c

Pair-Production





- γ→e⁺e⁻ conversion process in field of nucleus
  - ➡ described by diagram similar to Bremsstrahlung
  - ➡ conversion probability:

$$P(x) \propto e^{-\frac{7}{9}\frac{x}{X_0}}$$

  - ➡ radiation length X_0 is 7/9 of mean free path for pair production by a high energy photon
  - ➡ pair production in tracker material main source of inefficiency for photons

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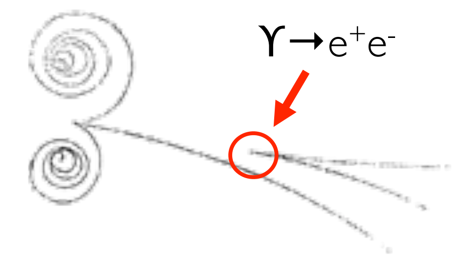

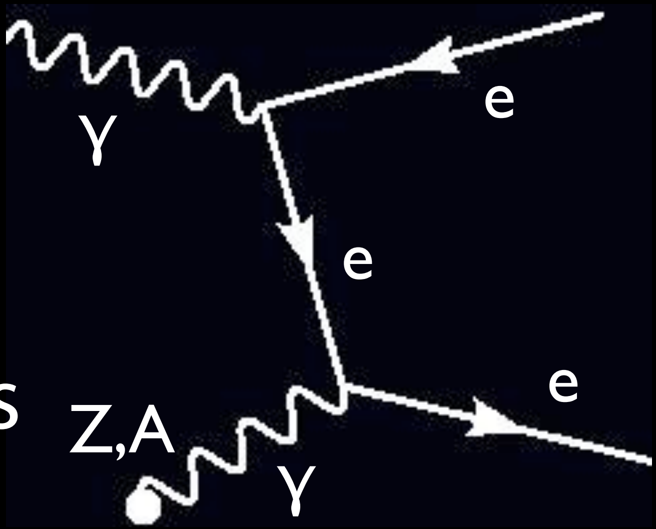

- $\gamma \rightarrow e^+e^-$ conversion process in field of nucleus
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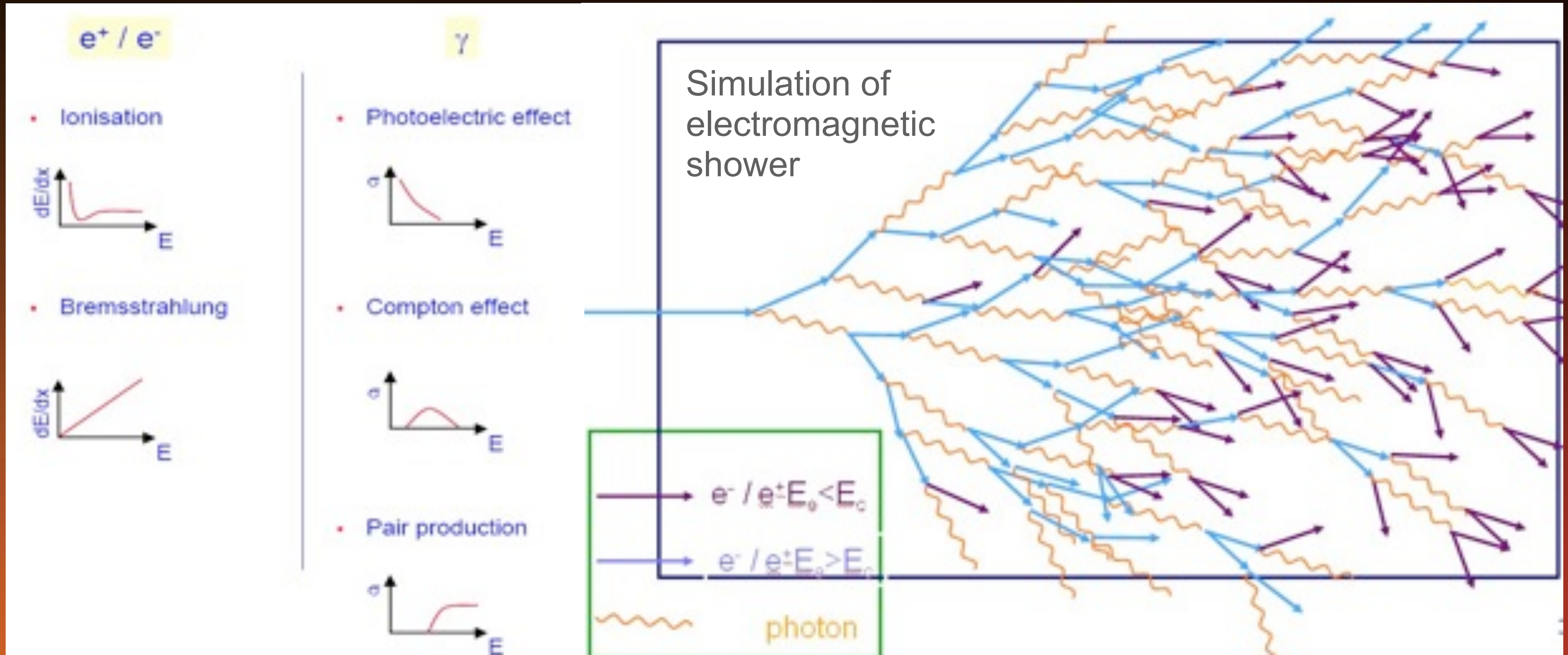
  - ➡ pair production in tracker material main source of inefficiency for photons
- together they give rise to electromagnetic showers
  - ➡ processes contributing to showers, detection in EM calorimeters



Hadronic Interactions

- nuclear interaction length λ : *mean free path of hadrons between strong collisions*

material	**λ [cm]**
Si	45.5
Fe	16.8
Pb	17.1

interactions with nuclei lead to hadronic (HAD) showers

- $\lambda > X[X_0]$, can separate EM (close) from HAD (far) showers
- detection of HAD showers in hadronic calorimeters

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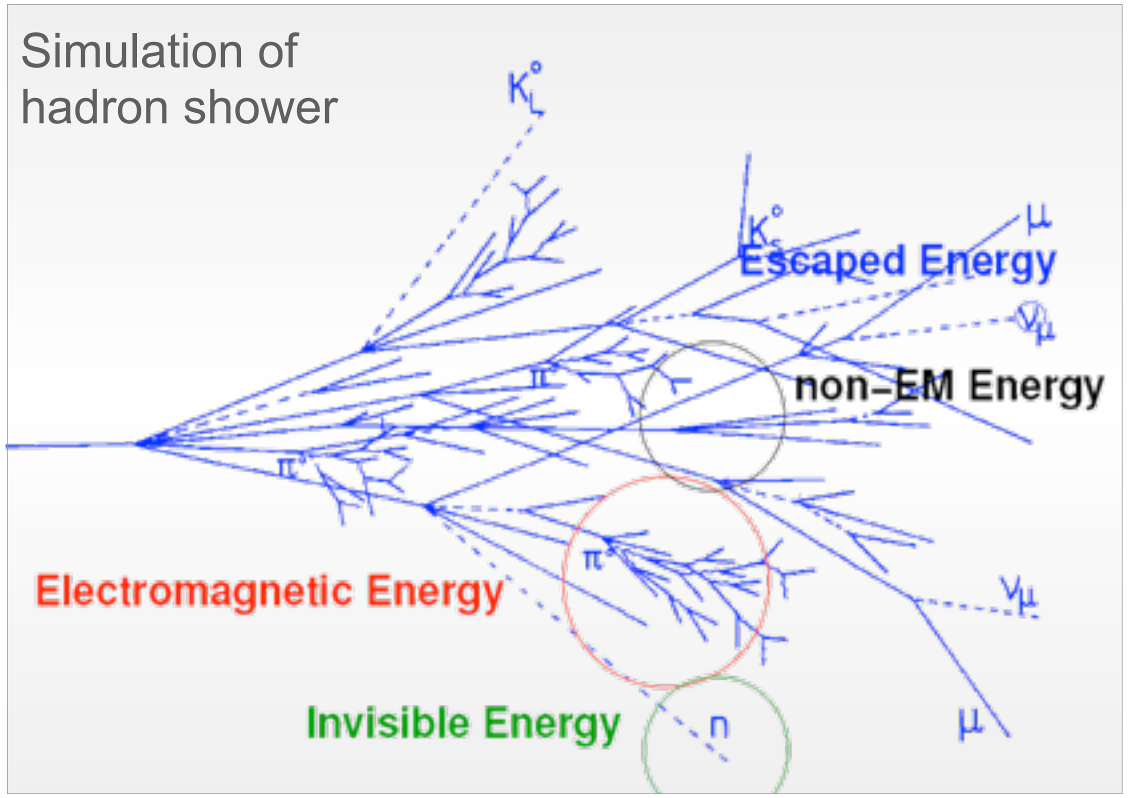


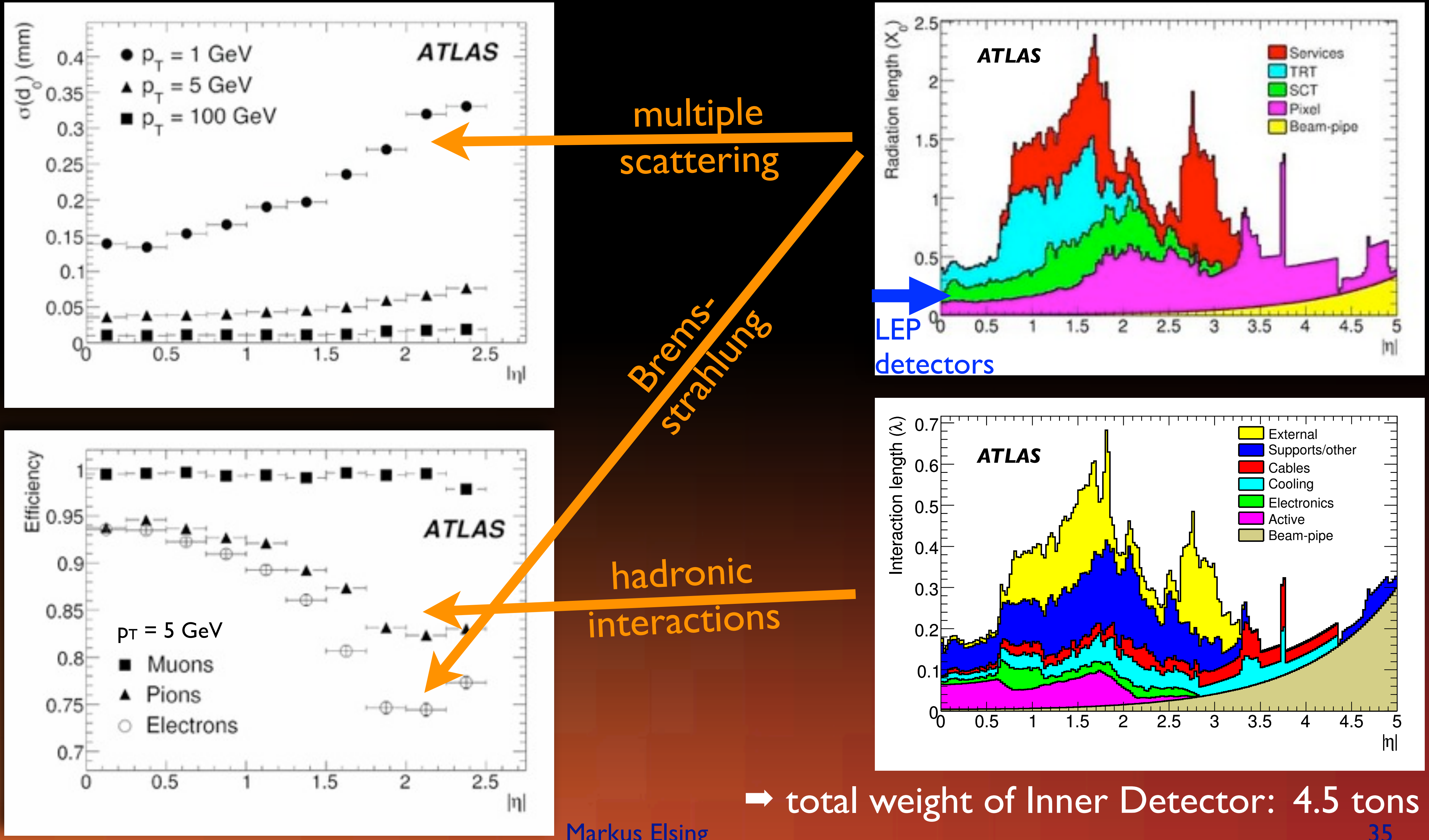
a hadronic shower consists of:

- EM energy (e.g., $\pi^0 \rightarrow \gamma\gamma$) *O*(50%)
- non-EM energy (*e.g.*, *dE*/*dx* from $\pi^\pm,\mu^\pm,K^\pm$) *O*(25%)
- invisible energy
  (nuclear fission/excitation, neutrons) *O*(25%)
- escaped energy (*e.g.* neutrinos) *O*(2%)

hadronic shower in material of tracking detector is main source of inefficiency for pions, kaons and protons !

Effect on Expected Performance

- ATLAS/CMS tracking resolution and efficiency mostly driven by interactions in detector material



multiple scattering

Brems-strahlung

hadronic interactions

LEP detectors

➡ total weight of Inner Detector: 4.5 tons

Let's Summarize...

- discussed the most relevant physics processes for particles passing through (detector) material

- discussed some of the consequences

  ➡ provide the means to detect charged particles and to identify them
    - measuring the ionization of charged particles in a medium (gas, silicon...)
    - detecting transition and Cherenkov radiation

  ➡ as well, limiting factor for the performance of a detector
    - e.g. multiple scattering effects or effects from hadronic interactions...

- next is to talk about LHC tracking detectors