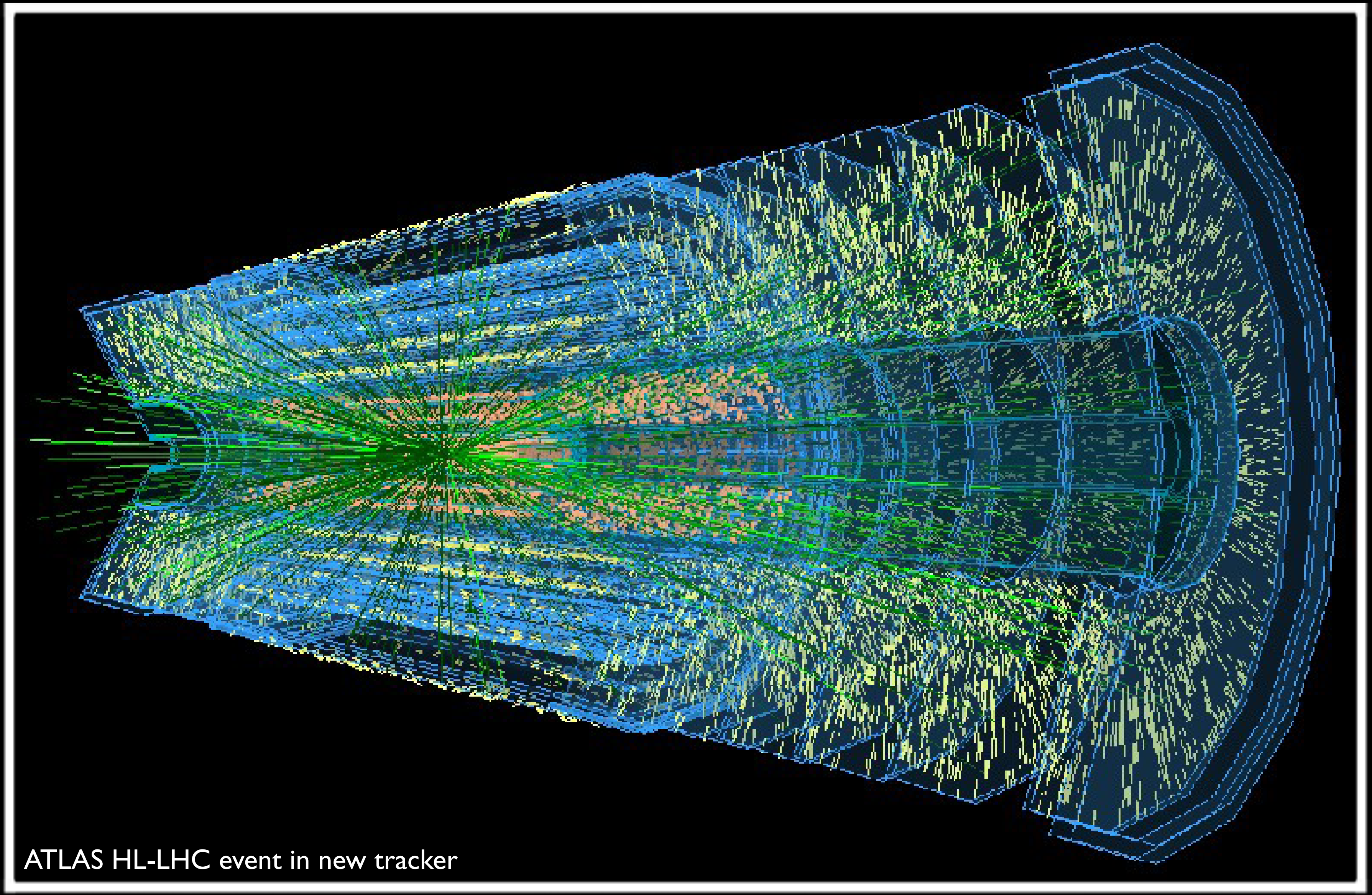
Tracking at the LHC

Lectures given at the University of Freiburg

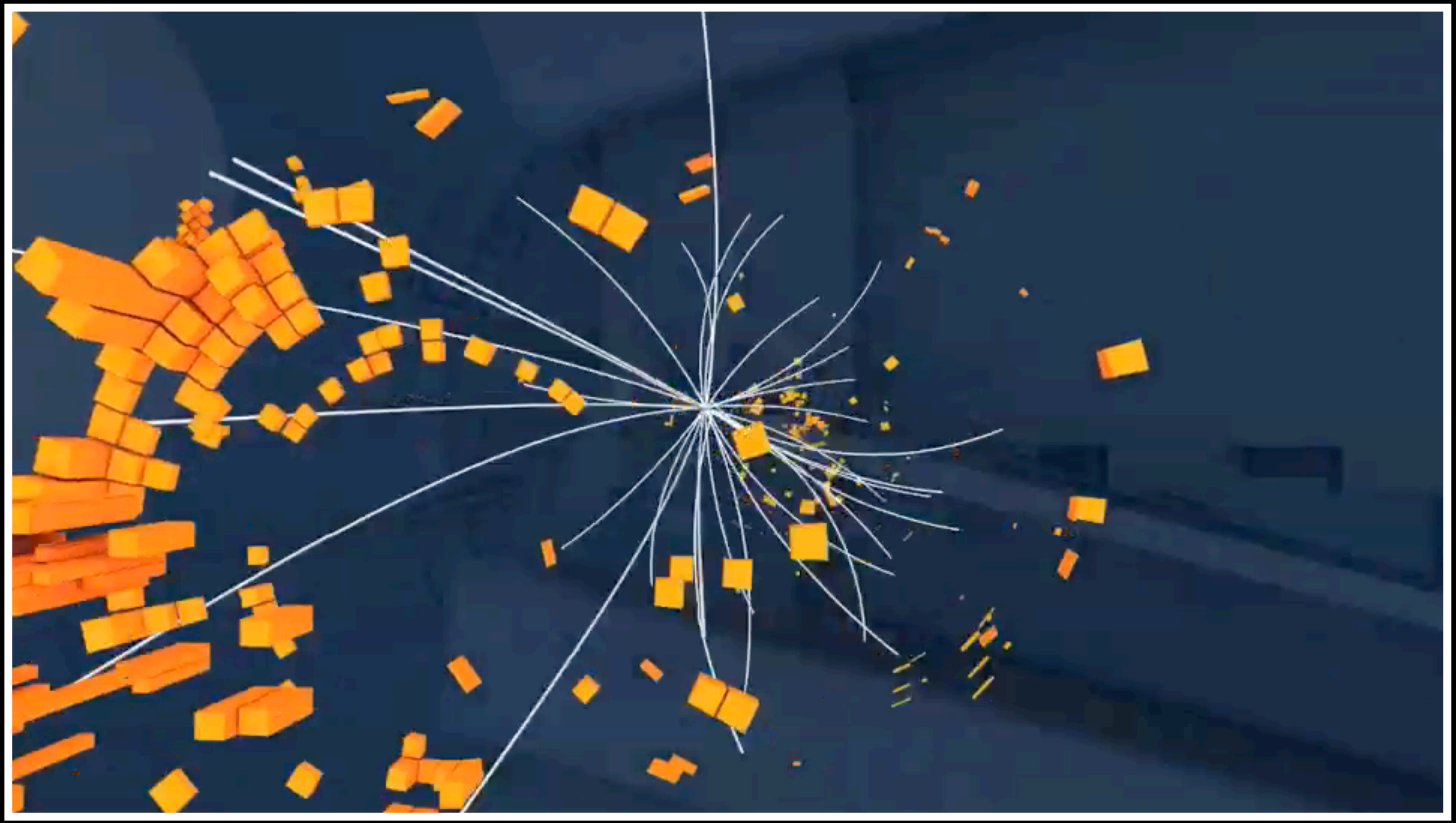
Markus Elsing, 12-13.April 2016



Introduction

- broad physics program covered by LHC experiments
  - ➡ 2 general purpose p-p 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 optimise 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, but as well the others)
- task of event reconstruction is to identify objects
  - ➡ e/μ/τ leptons, photons, (b) jets, missing ET, exclusive hadronic states...
  - ➡ input to physics analysis of complete event signature

Event Reconstruction



- ➡ LHC experiments are giant "cameras" to take "pictures" of p-p collisions
  - taking a picture every 25 nsec (40 MHz) with 100 million channels
- ➡ task of the reconstruction is the interpretation of the picture !
  - answer the question: which particles were produced ?

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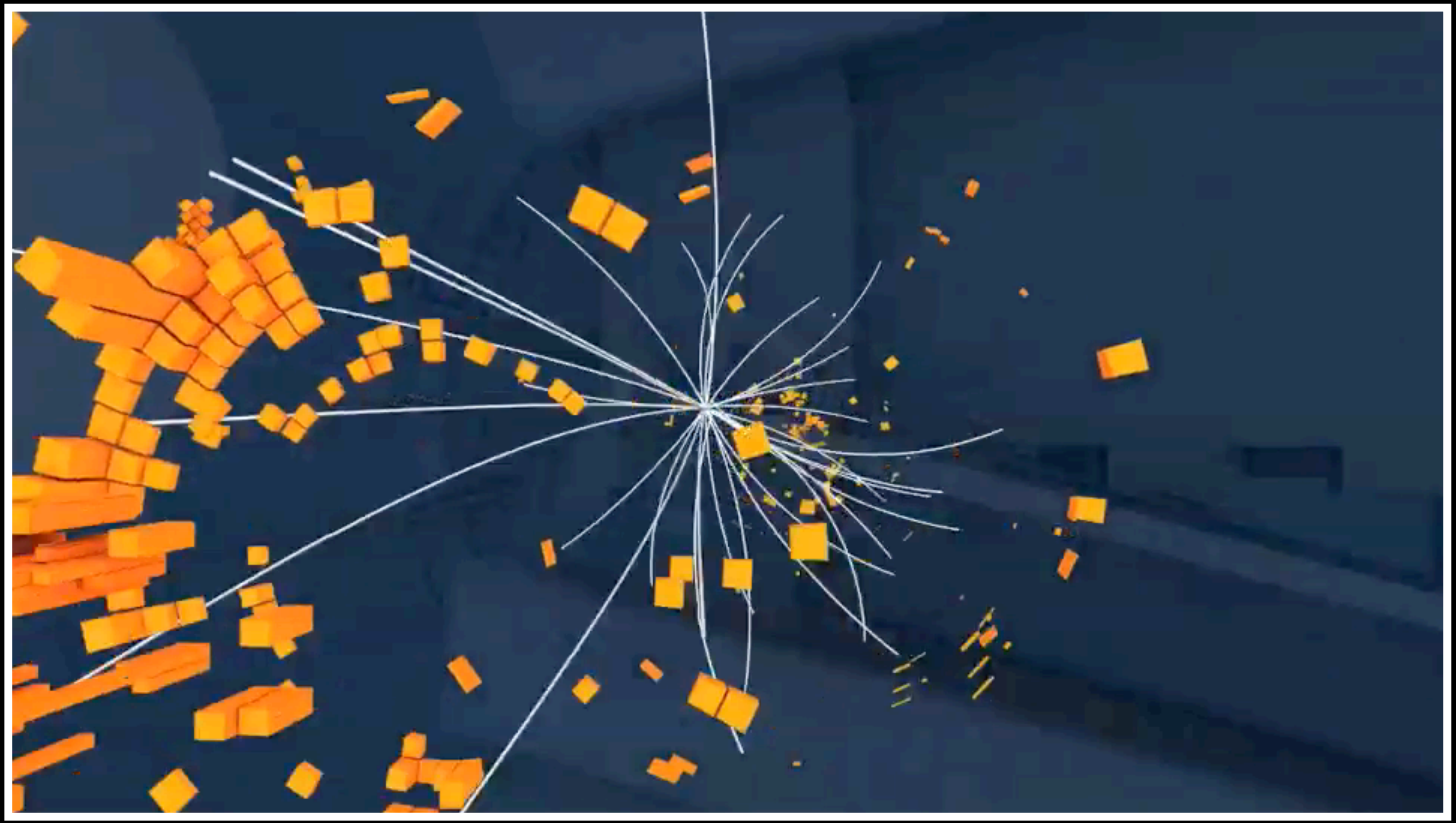

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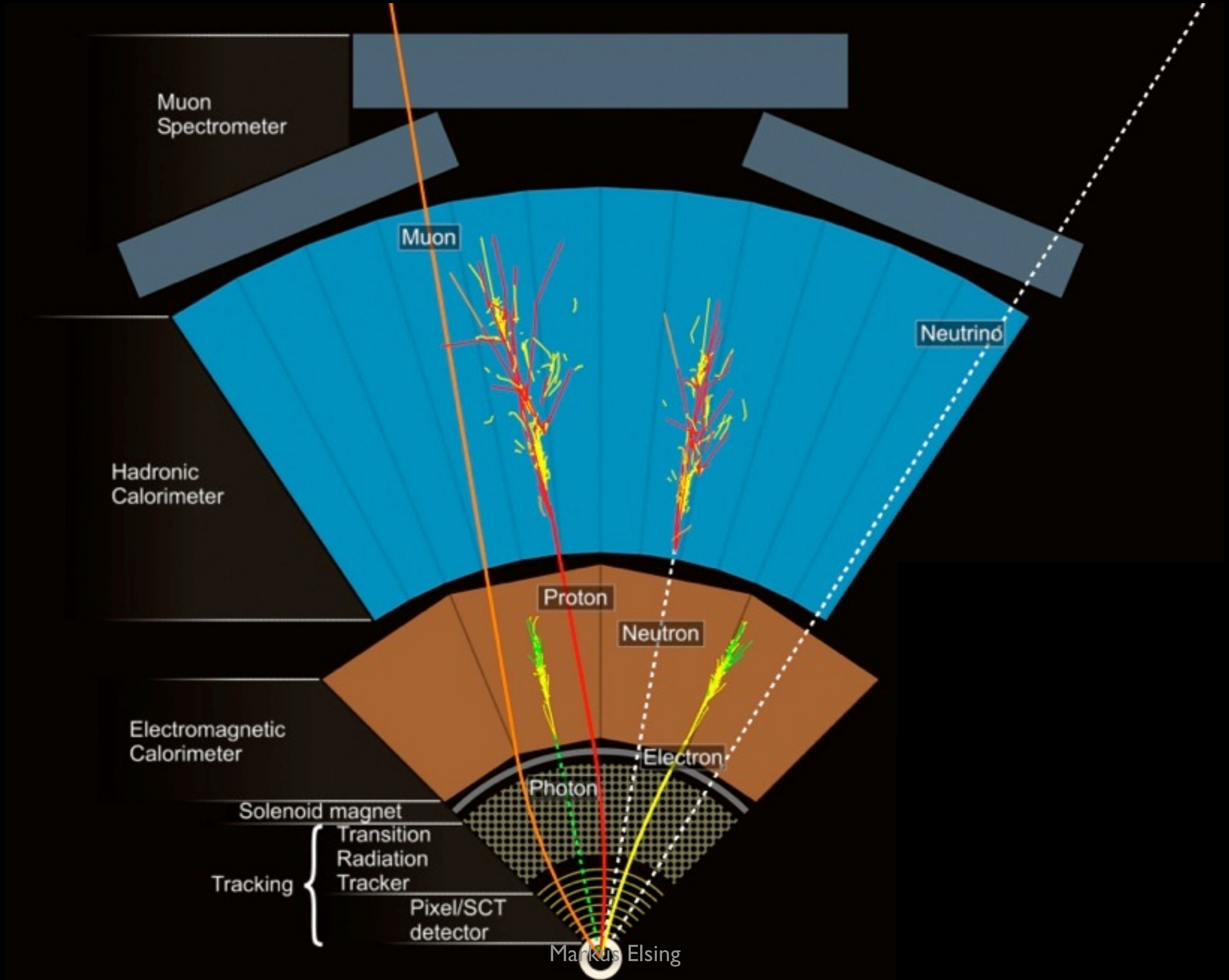
Event Reconstruction "in a Nutshell"



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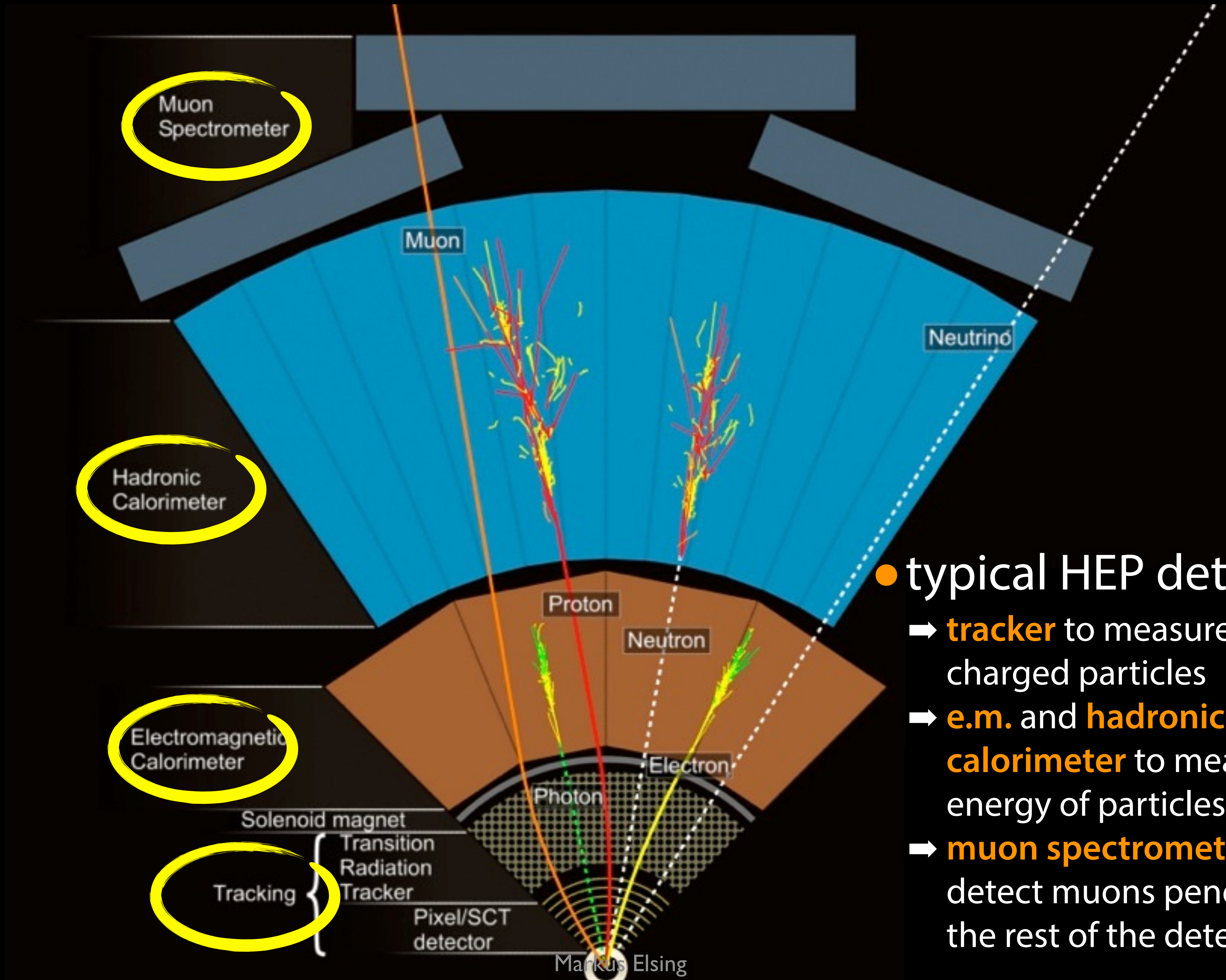

- typical HEP detector
  - ➡ **tracker** to measure charged particles
  - ➡ **e.m.** and **hadronic calorimeter** to measure energy of particles (jets)
  - ➡ **muon spectrometer** to detect muons penetrating the rest of the detector

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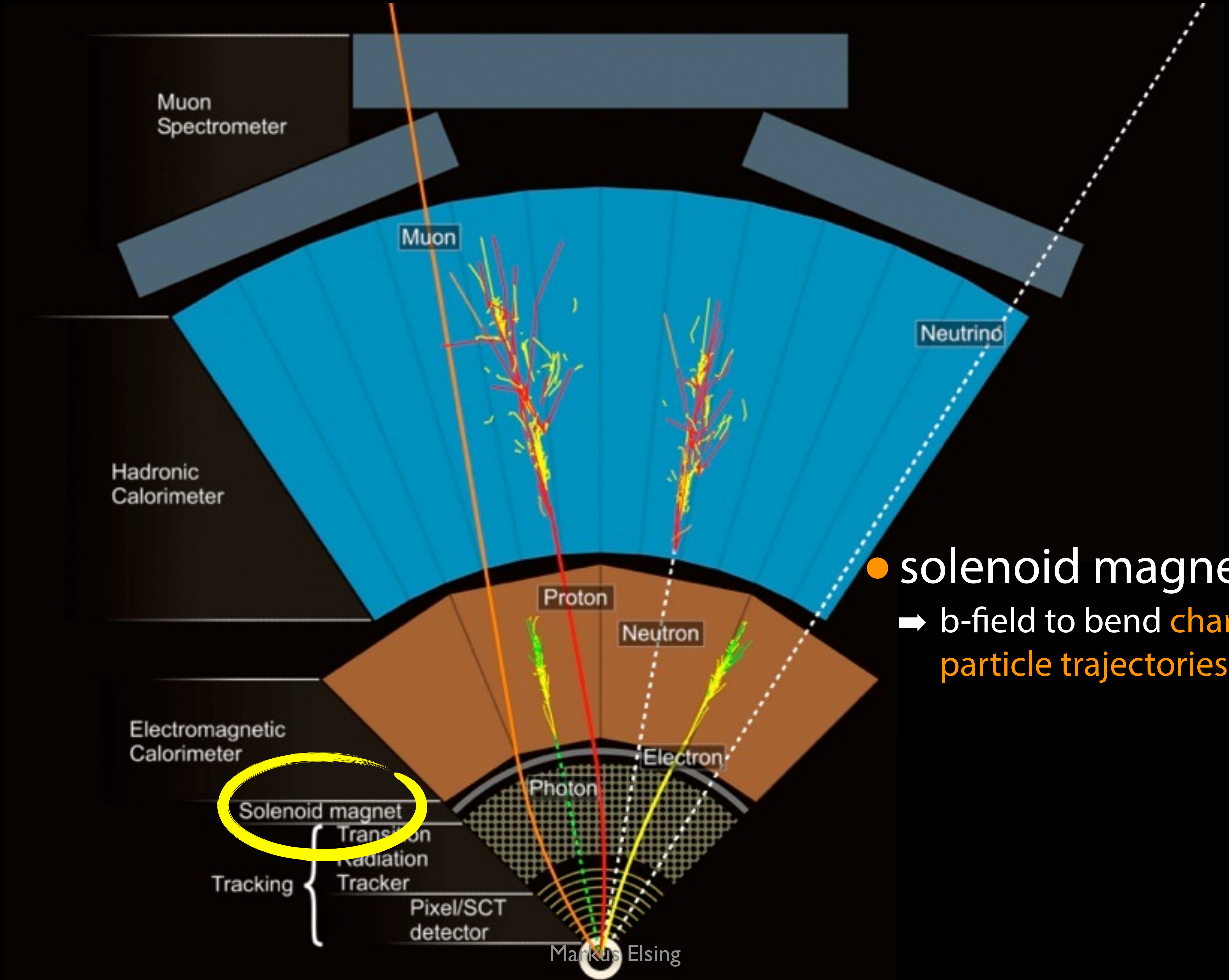

- solenoid magnet
  - ➡ b-field to bend charge particle trajectories

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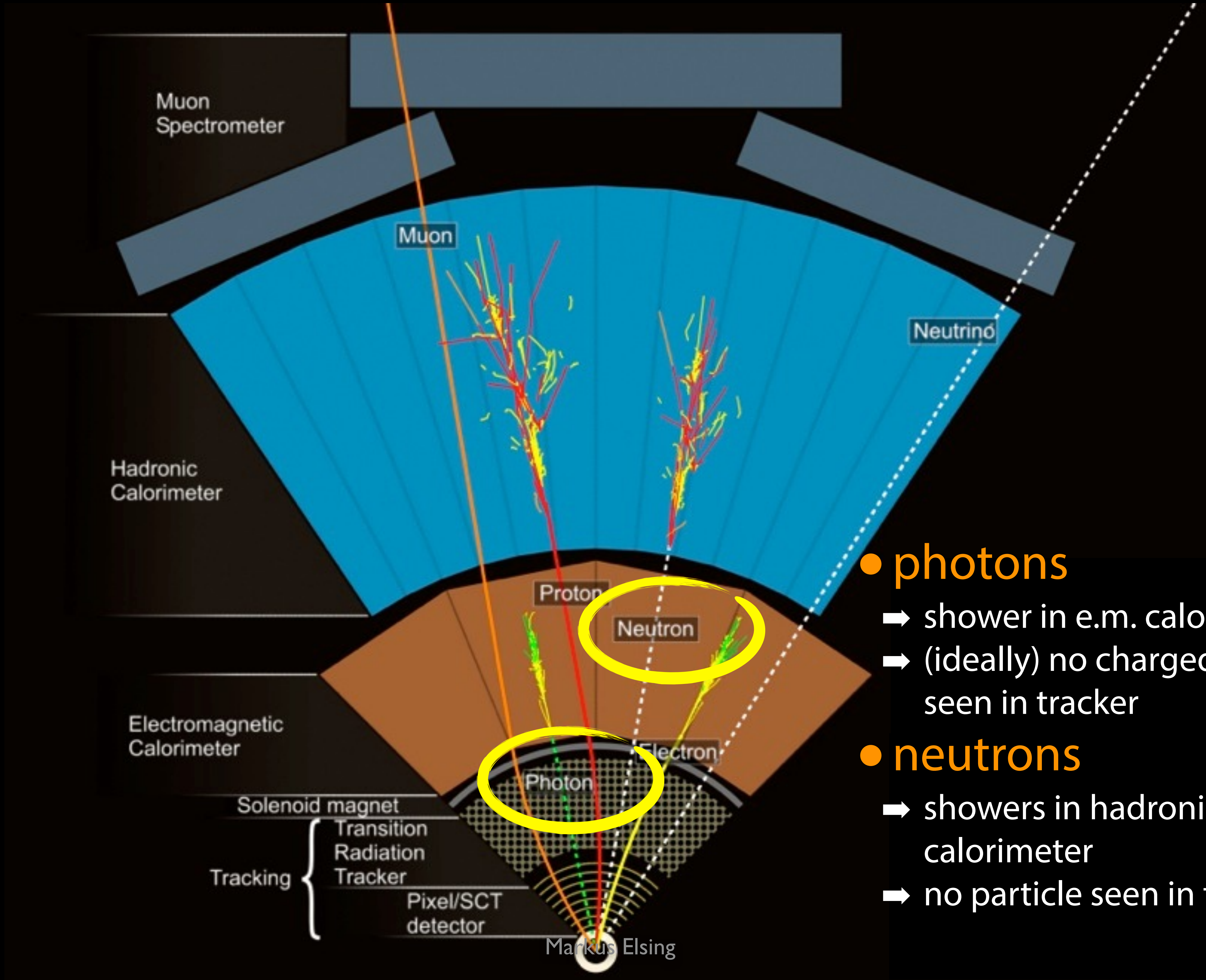
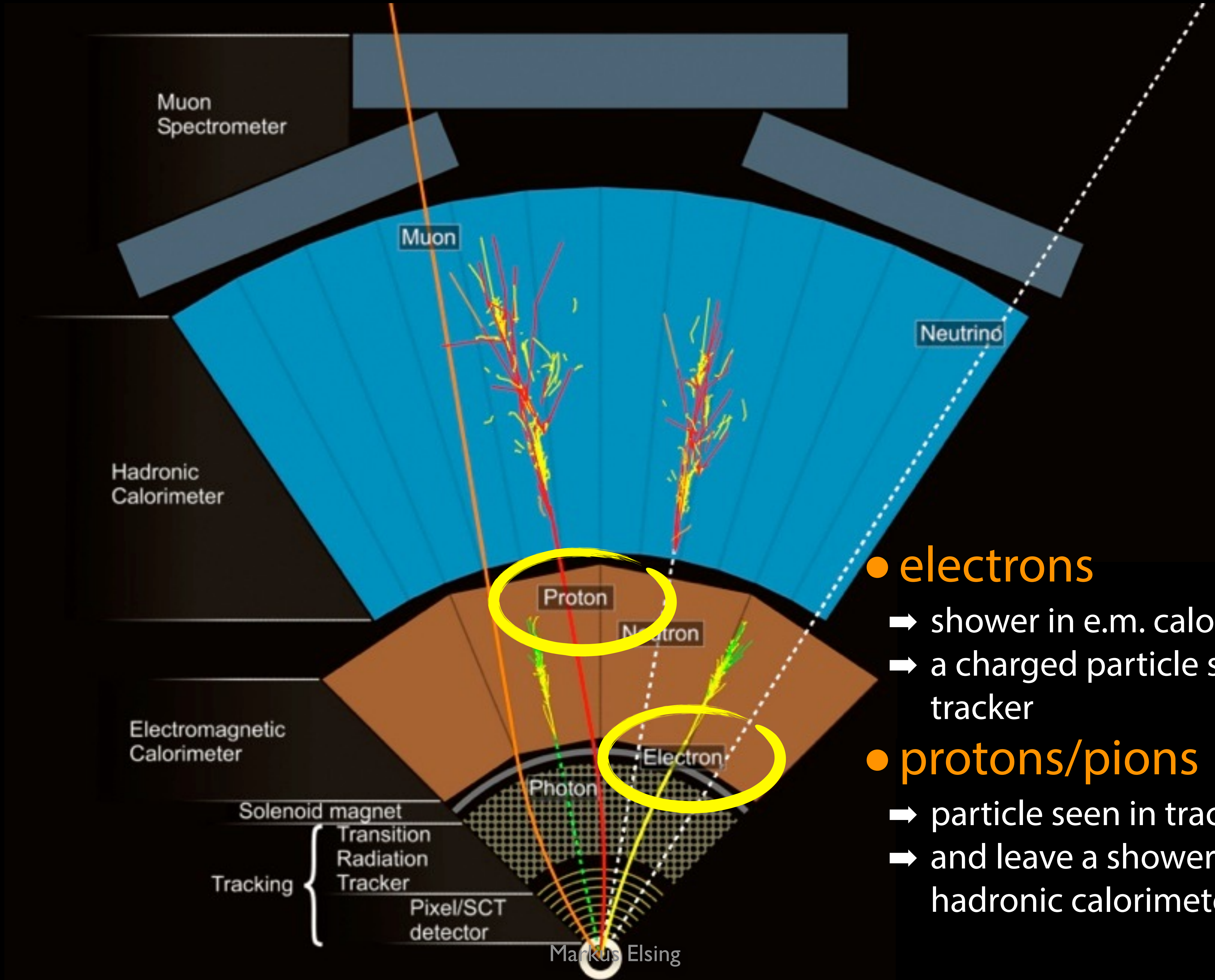


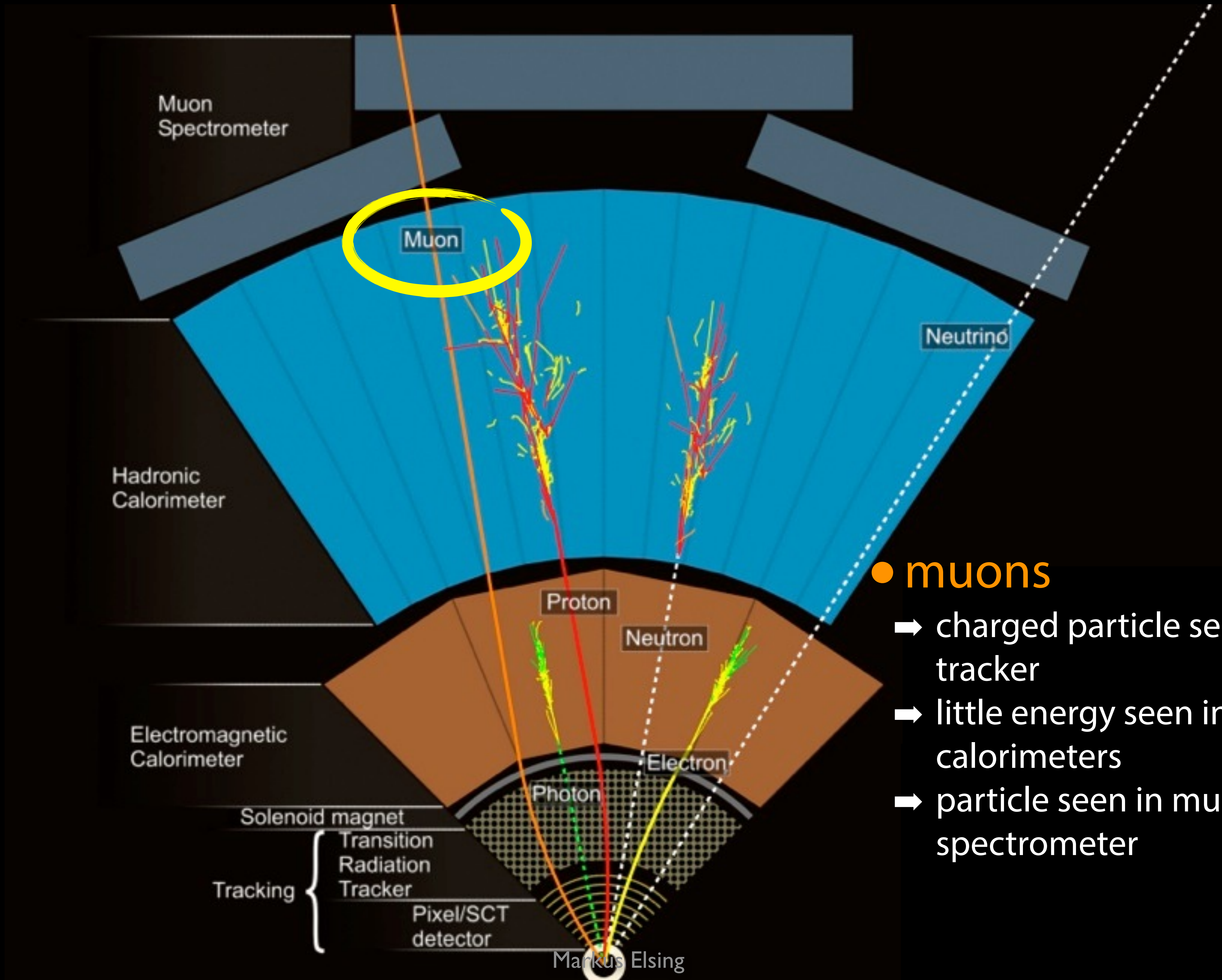
- photons
  - ➡ shower in e.m. calorimeter
  - ➡ (ideally) no charged particle seen in tracker
- neutrons
  - ➡ showers in hadronic calorimeter
  - ➡ no particle seen in tracker

Event Reconstruction “in a Nutshell”



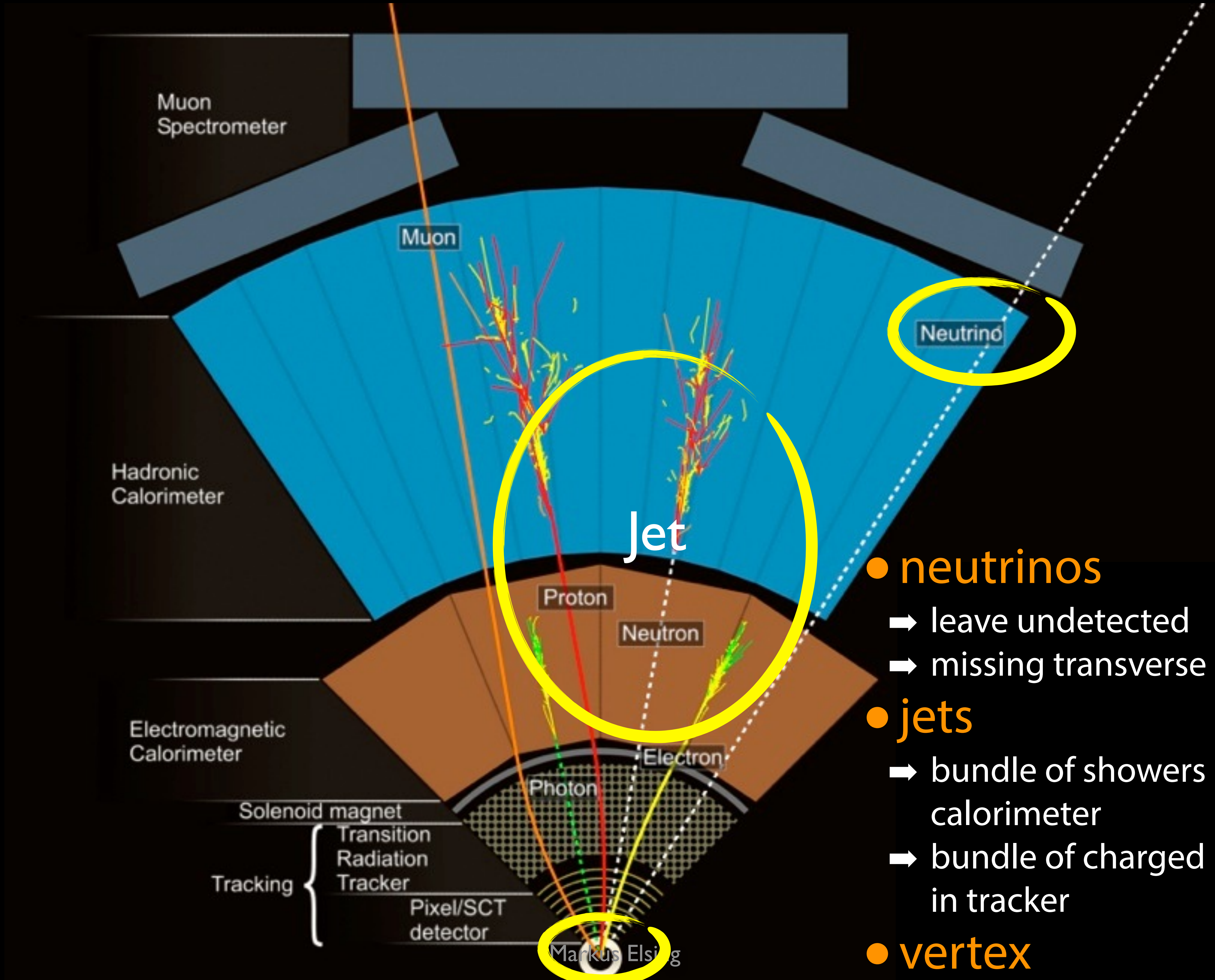
- electrons
  - ➡ shower in e.m. calorimeter
  - ➡ a charged particle seen in tracker
- protons/pions
  - ➡ particle seen in tracker
  - ➡ and leave a showers in hadronic calorimeter

Event Reconstruction "in a Nutshell"



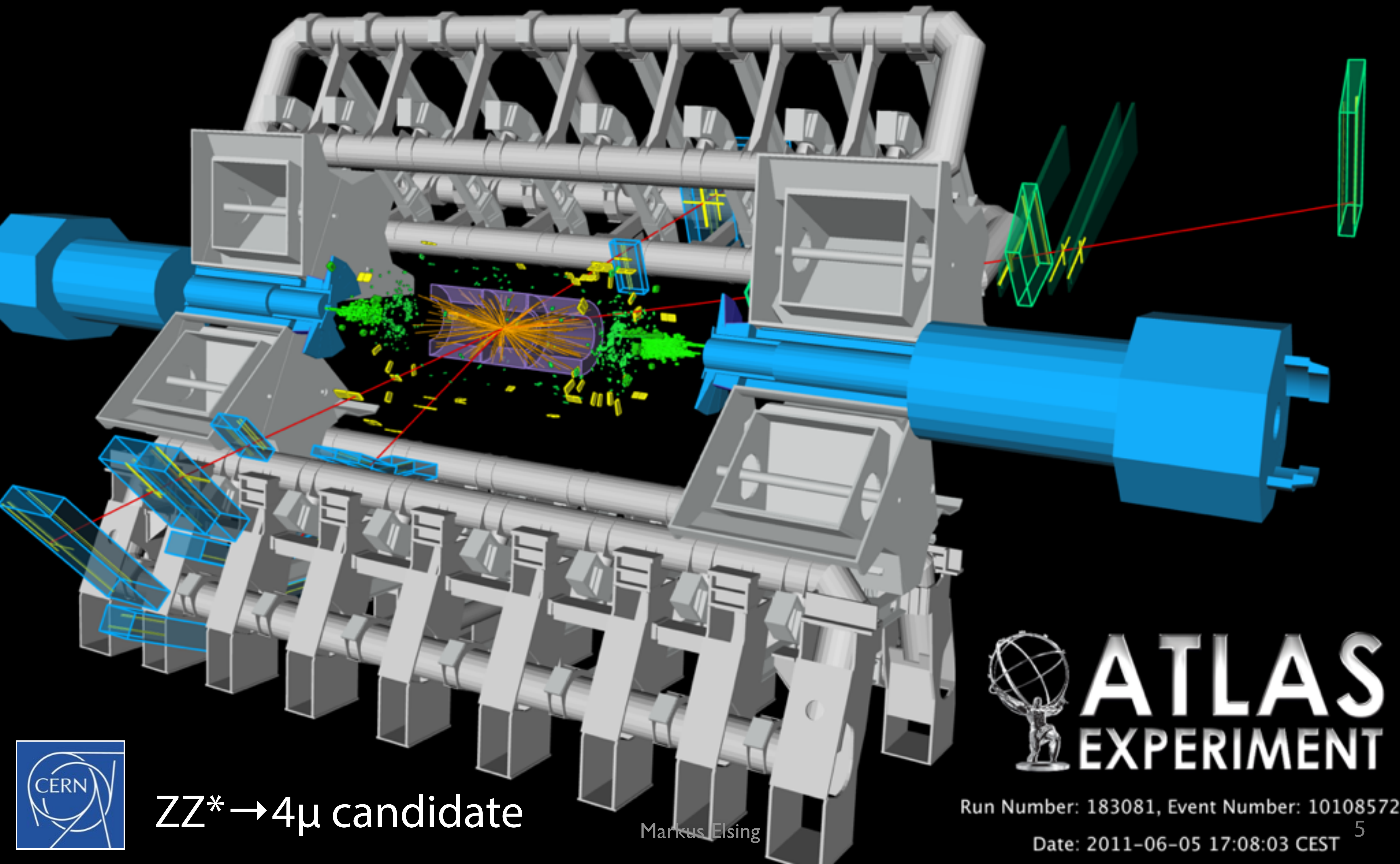
- muons
  - ➡ charged particle seen in tracker
  - ➡ little energy seen in calorimeters
  - ➡ particle seen in muon spectrometer

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

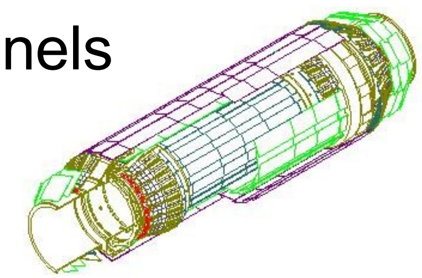
Tracking at the LHC

- 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

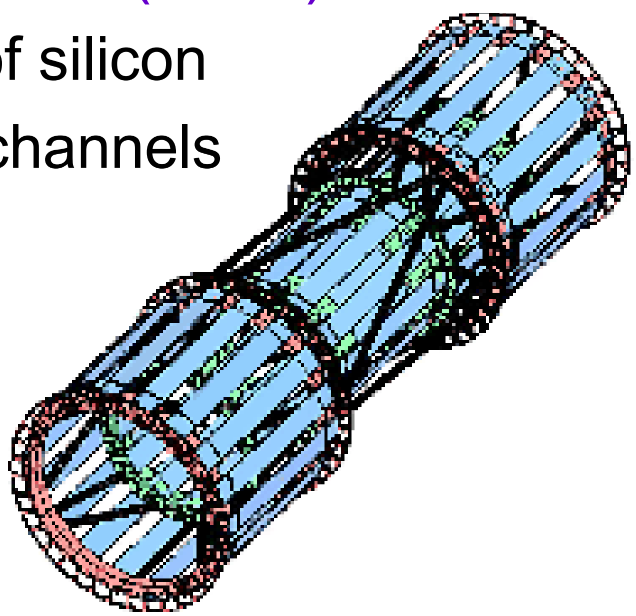
- requirements on tracking detectors
  - ➡ precision tracking at LHC luminosities (central heavy ion event multiplicities) with a hermitic detector
  - ➡ usually Pixel/Strip Detector for precise primary/secondary vertex reconstruction and to provide excellent b-tagging in jets
  - ➡ provide particle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

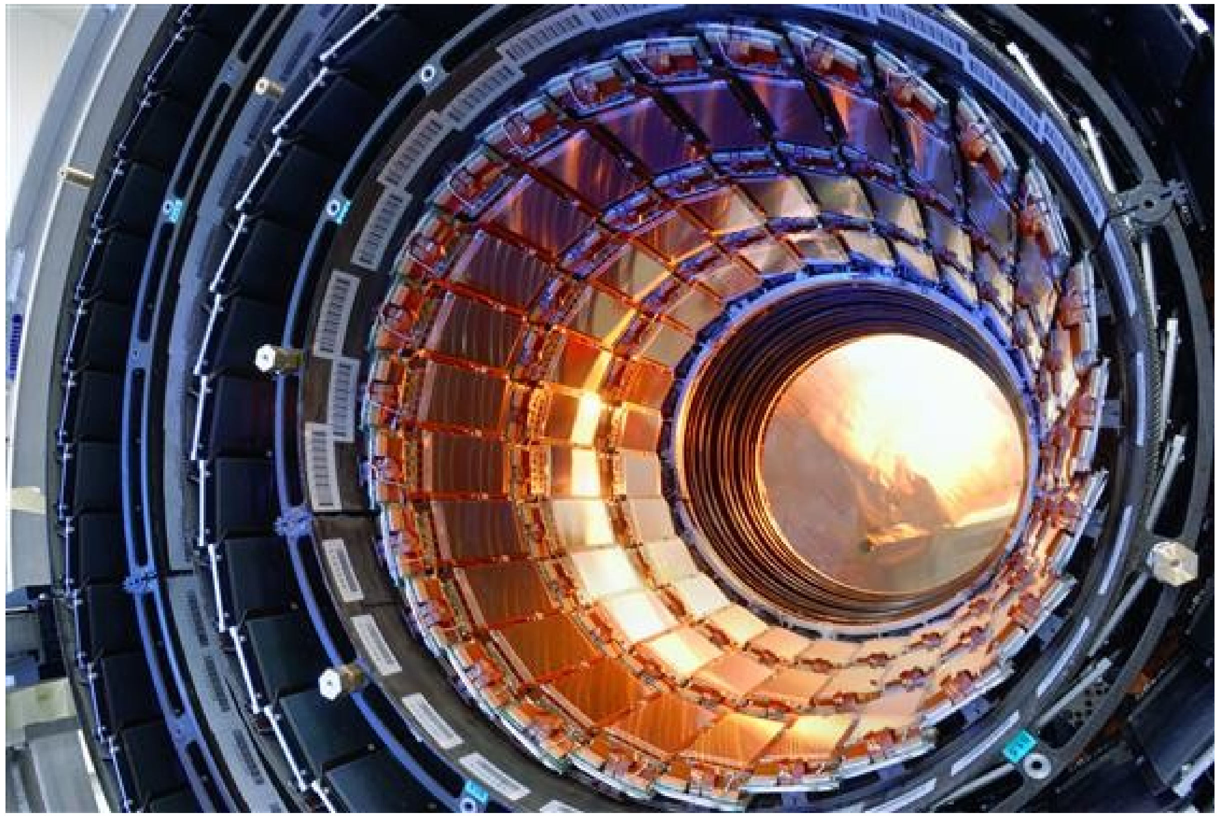
Evolution of (Silicon Strip) Detectors

- 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

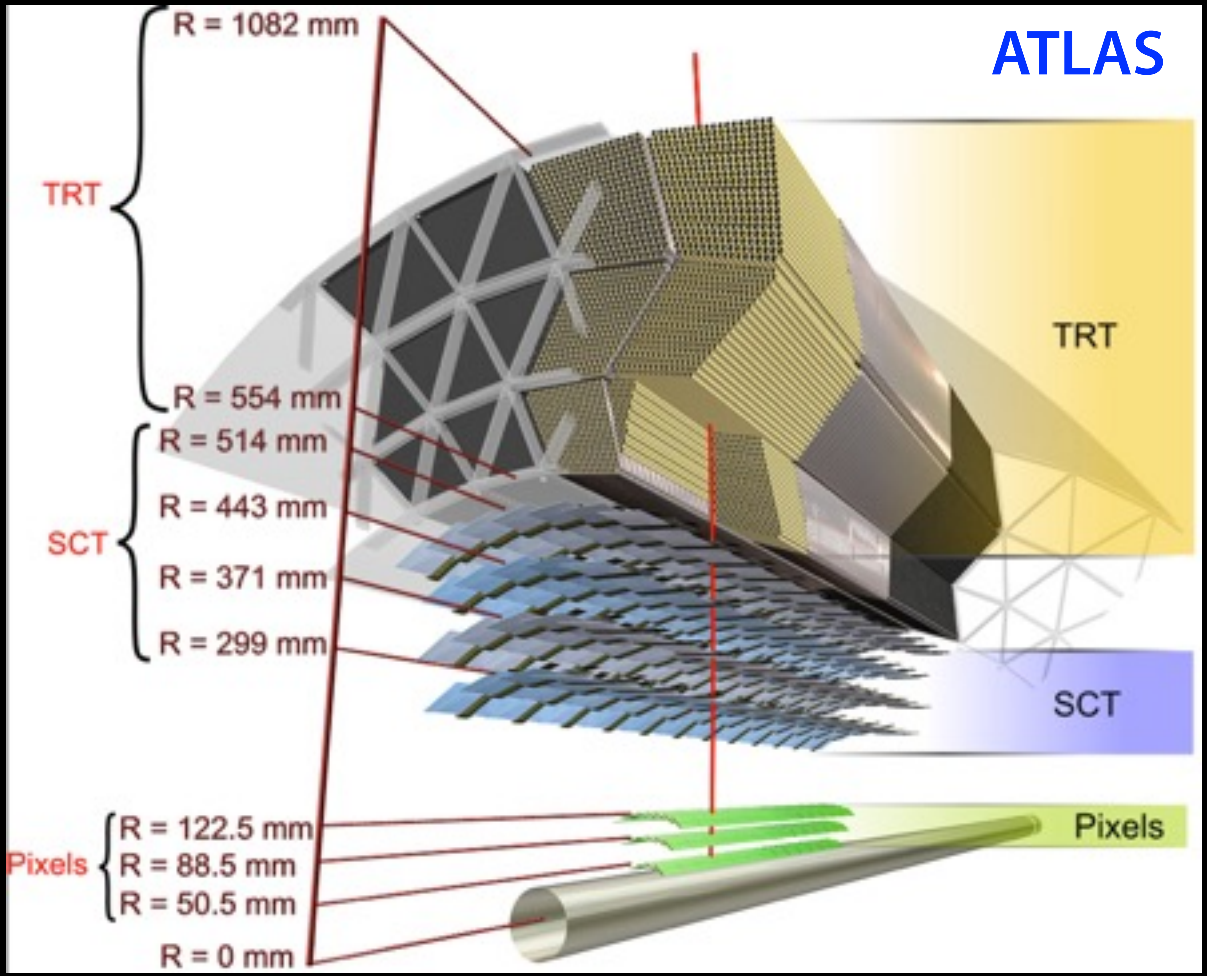
T.Wells

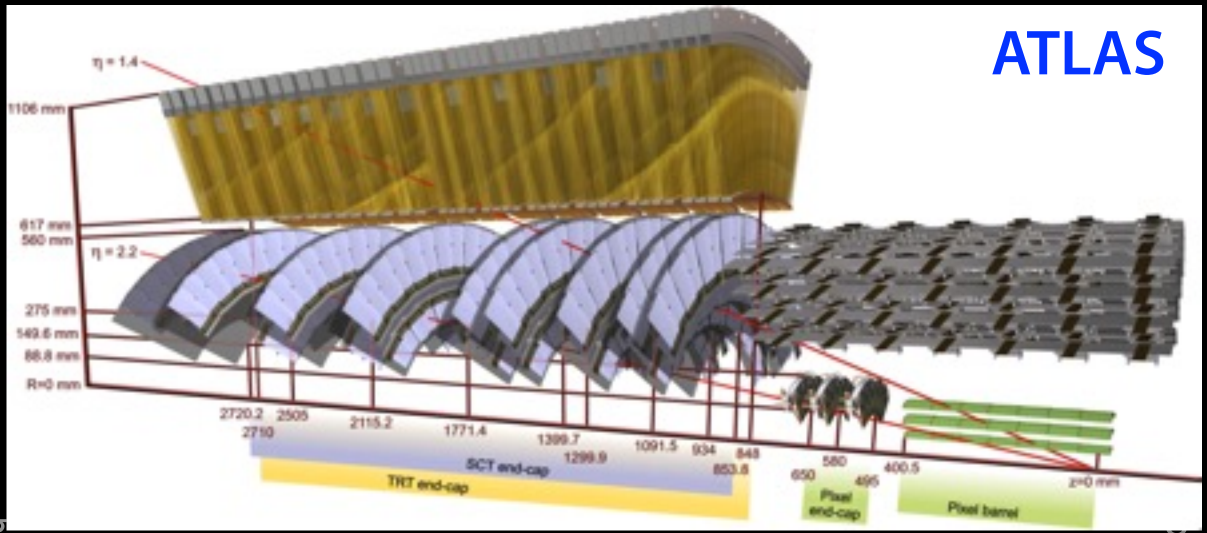
➡ results from huge technology advancements to match requirements of every generation of experiments

Example for a LHC Tracking Detector

- answer of ATLAS collaboration to match physics requirements

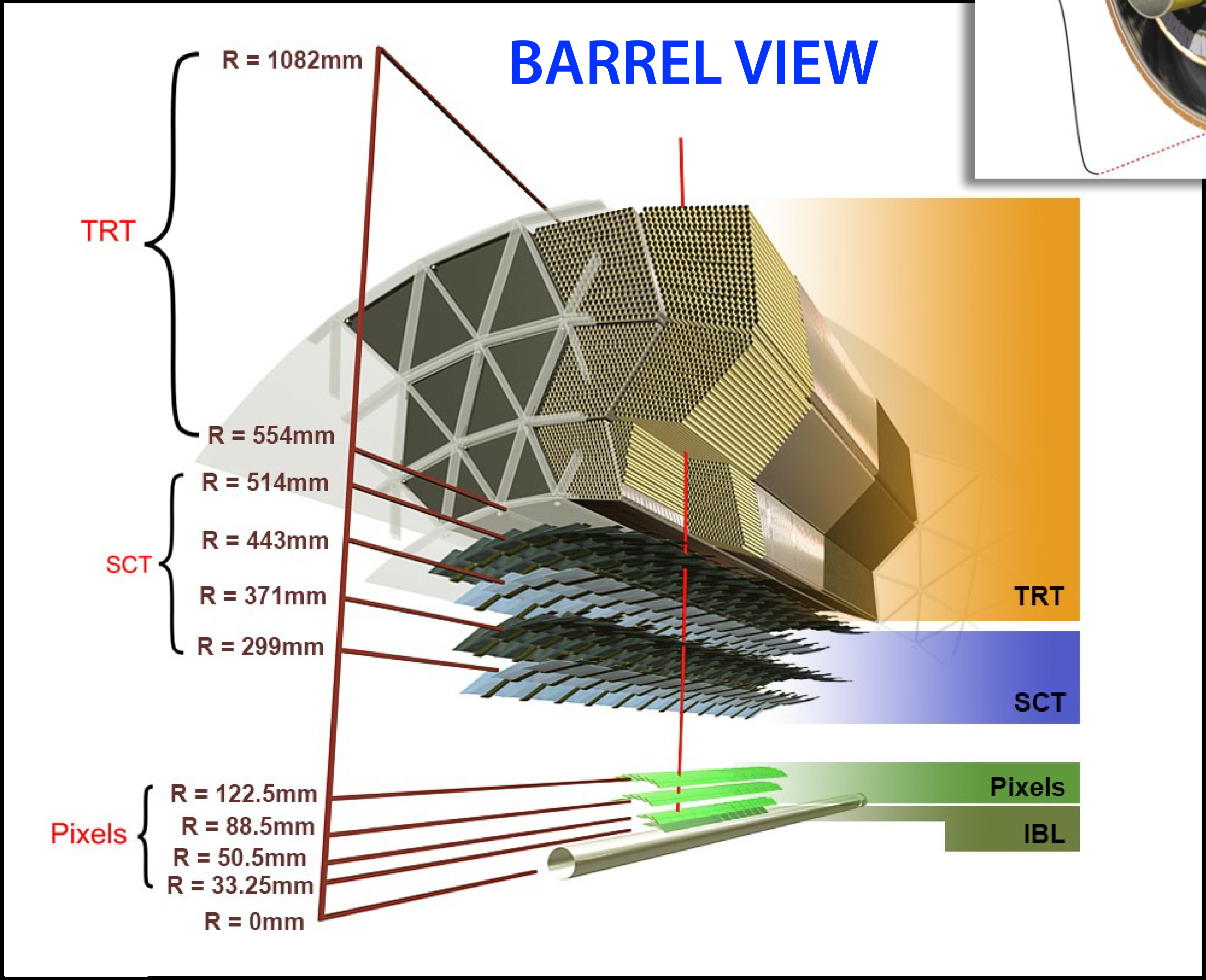
- ATLAS Run-1 Inner Detector:
  - ➡ 3 layer Pixel system, 3 endcap disks
    - 1744 pixel modules
    - 80.4 million channels
    - pitch 50 µm × 400 µm
    - total of 1.8 m²
  - ➡ 4 layers of small angle stereo strips (SCT)
    - 4088 double sided modules
    - 6.3 million channels
    - pitch 80 µm, 40 mrad stereo angle
    - total of 60 m²
  - ➡ transition radiation tracker (TRT)
    - typically 36 hits per track
    - transition radiation to identify electrons
    - total of 370K drift tubes

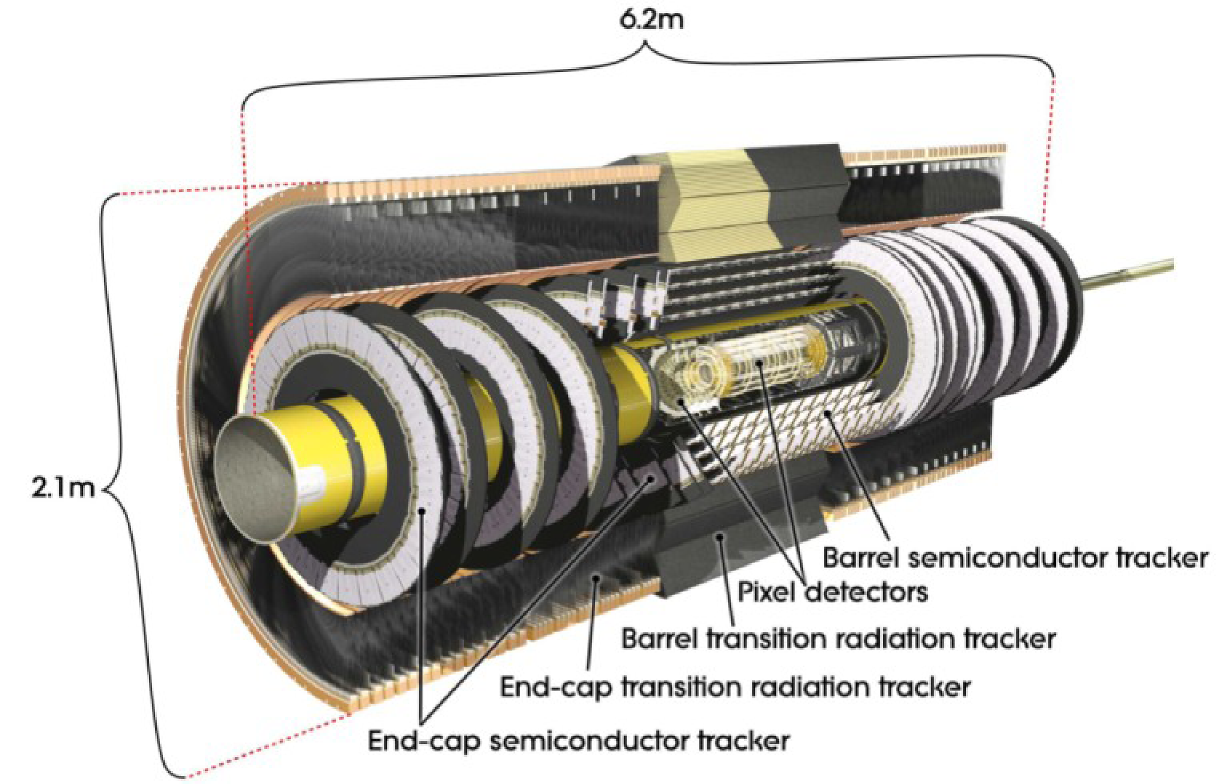




Pixel Upgrade for Run-2

- IBL was installed in 2014
  ➡ inside Run-1 Pixel detector





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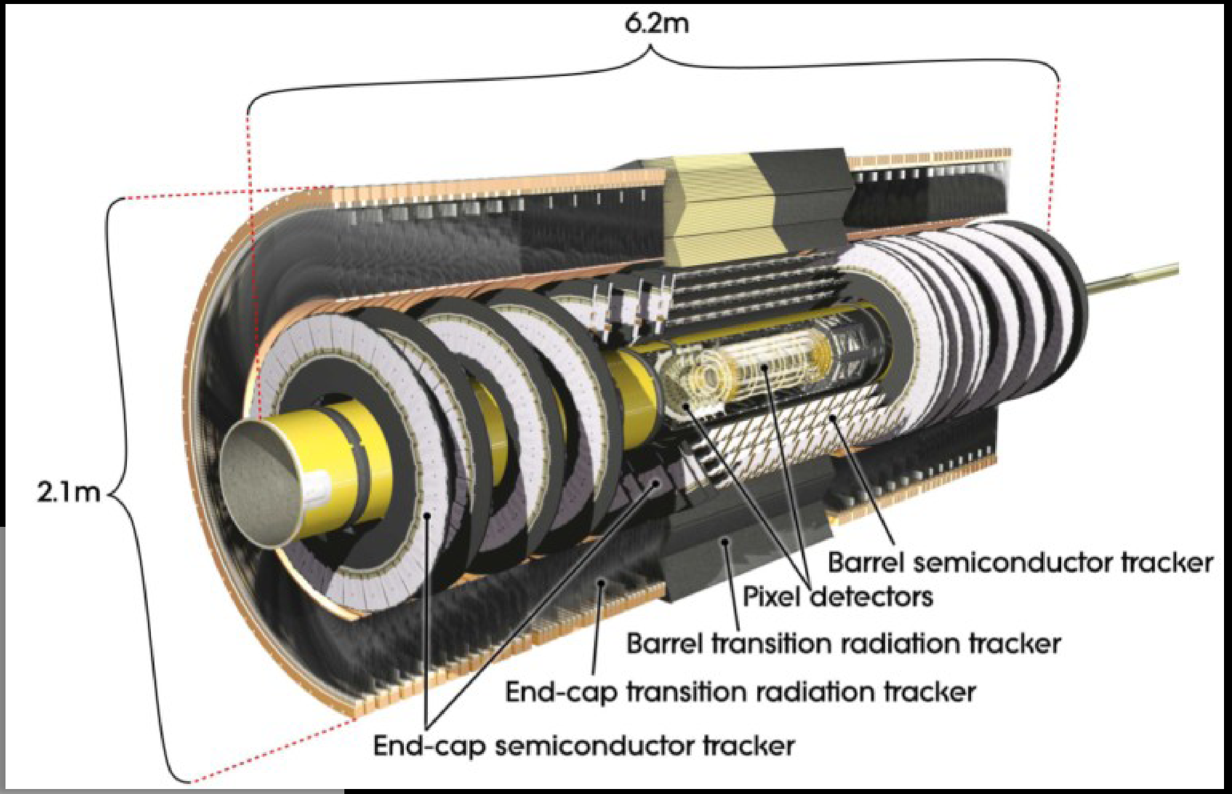

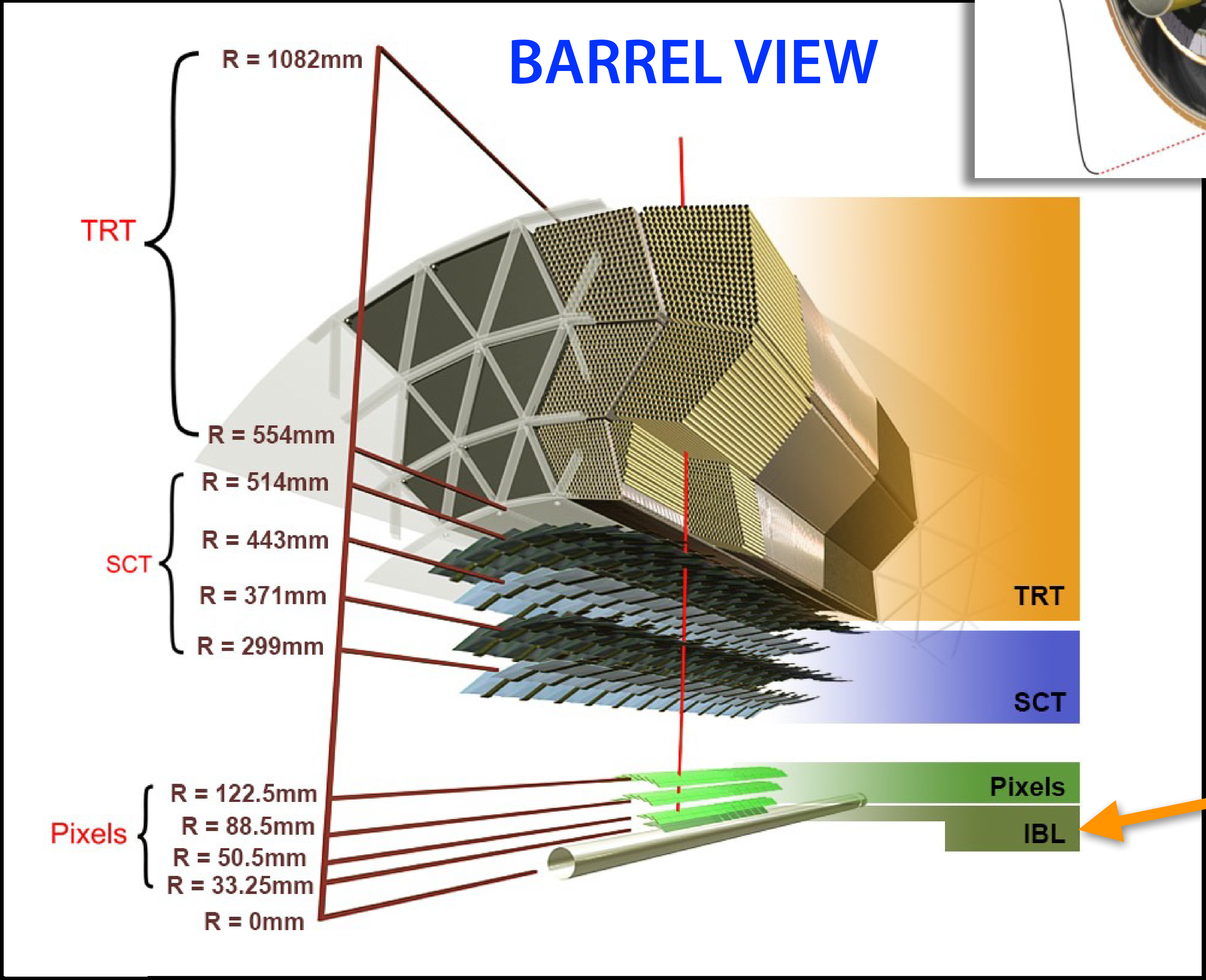

- 4th Pixel layer
  - ➡ new smaller beam-pipe
  - ➡ smaller pitch (50x250 μm)
  - ➡ improves vertexing and b-tagging, ...

Outline of Lectures for the next 2 Days

- part 1 ~ Passage of Particles through Matter
- part 2 ~ Brief Overview of LHC Tracking Detectors
- part 3 ~ Concepts for Track Reconstruction
- part 4 ~ Vertex Reconstruction and its Applications

Feedback welcome !

- after years in this field
  - ➡ may take things for granted that 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
  - ➡ these lectures are written having a general audience of young PhD students in mind
- material is never the less biased towards ATLAS
  - ➡ it's anyway interesting to look outside the box at times...

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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, R.Jansky , V.Innocente and several others I should mention here

Tracking at the LHC (Part 1):
Passage of Particles through Matter

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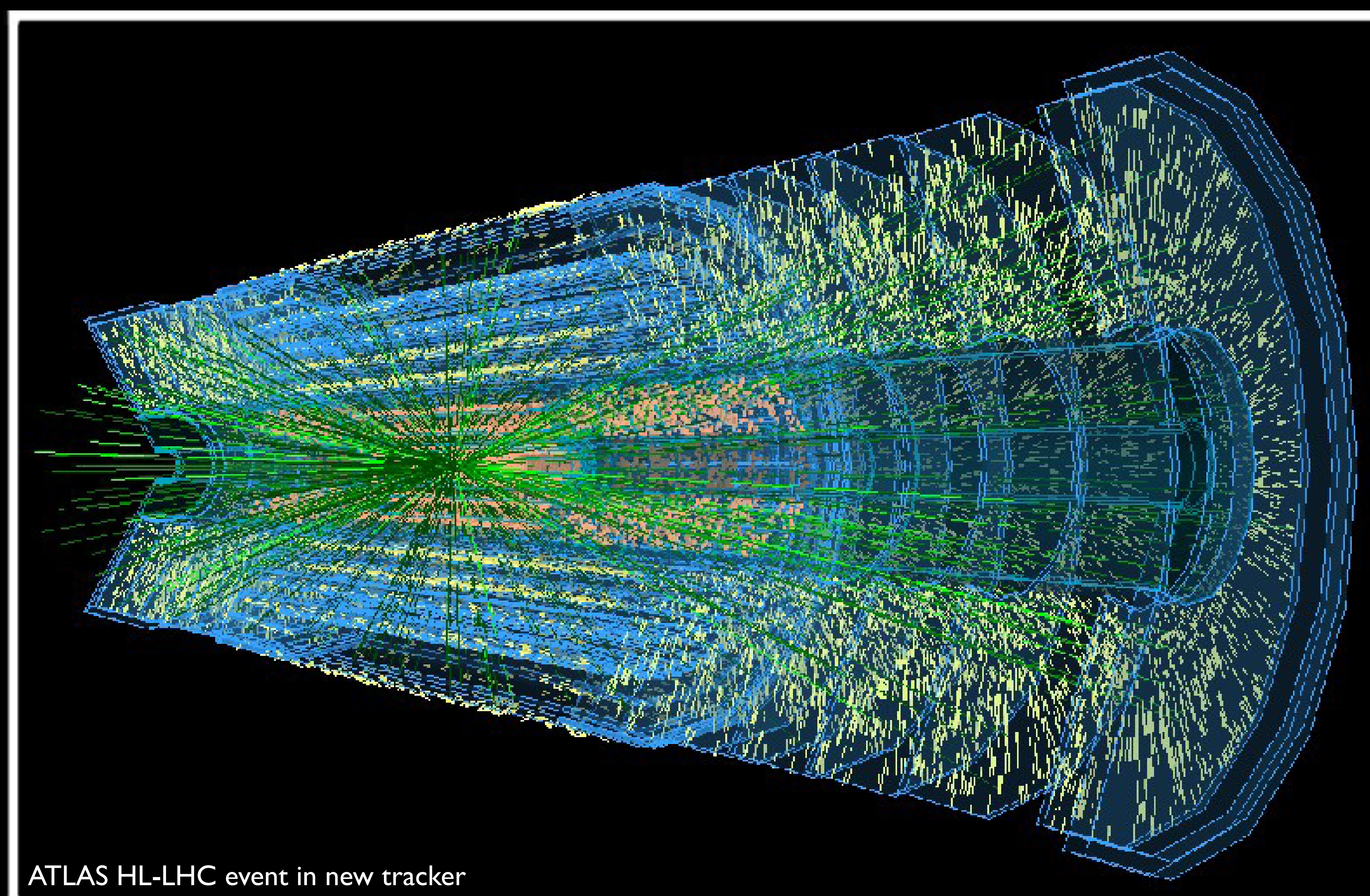
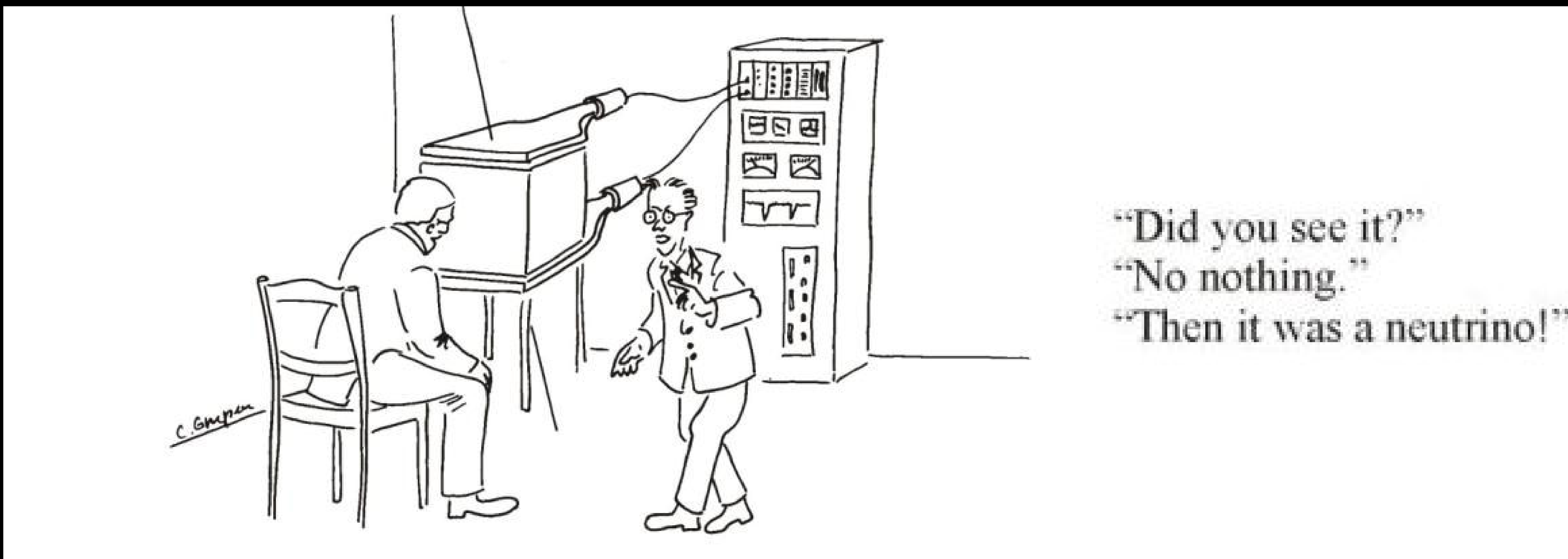


ATLAS HL-LHC event in new tracker

CERN

Passage of Particles through Matter

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



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
- aim to understand how they affect the tracking performance
  - ➡ energy loss
  - ➡ multiple scattering
  - ➡ Bremsstrahlung
  - ➡ hadronic interactions

Charged Particle Interactions with Matter

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

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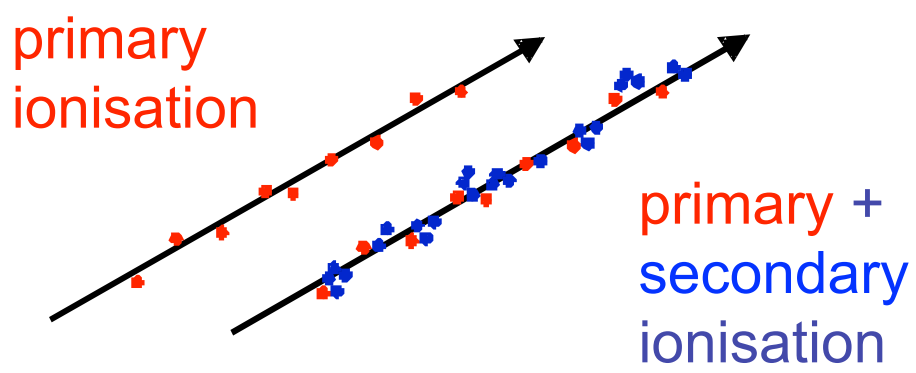
- **energy loss by ionisation**

primary ionisation can generate secondary ionisation



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

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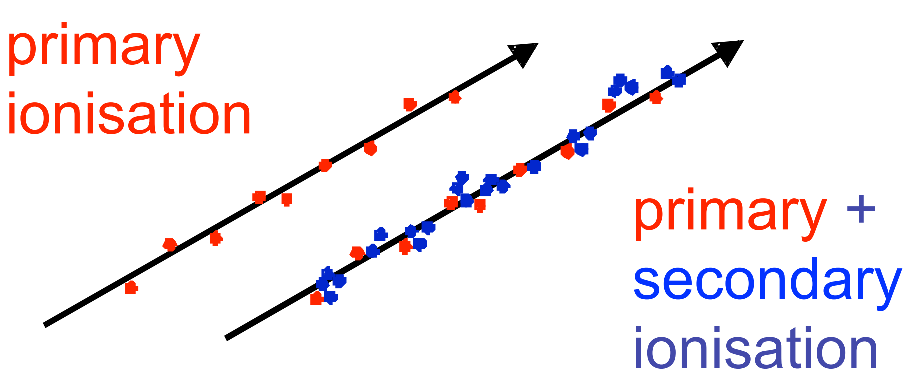

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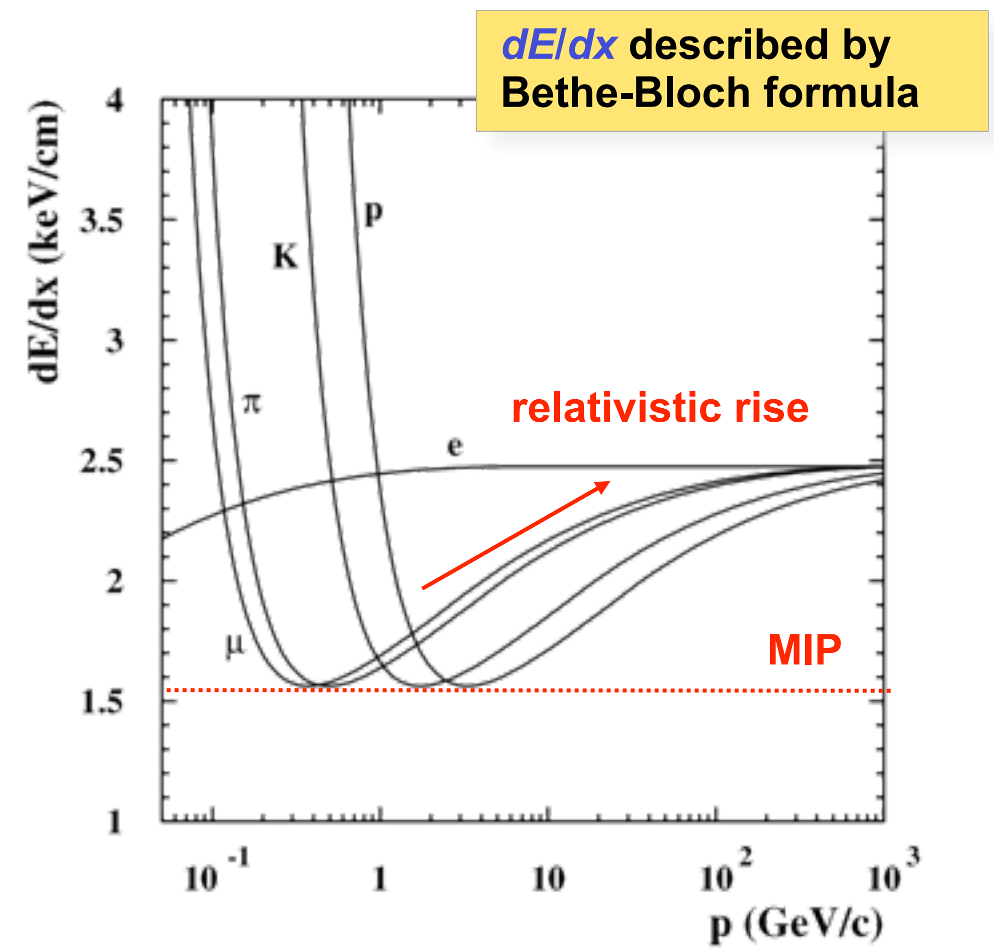

➡ not directly used for particle identification by ATLAS/CMS

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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**

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

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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**

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 ~ $\sin^{-4}(\theta/2)$

➡ complicates track fitting, limits momentum measurement

Charged Particle Interactions with Matter

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- **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

definition:

$\boldsymbol{X_0}$ = 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

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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 (Pb)

CMS ECAL crystals ($PbWO_4$)

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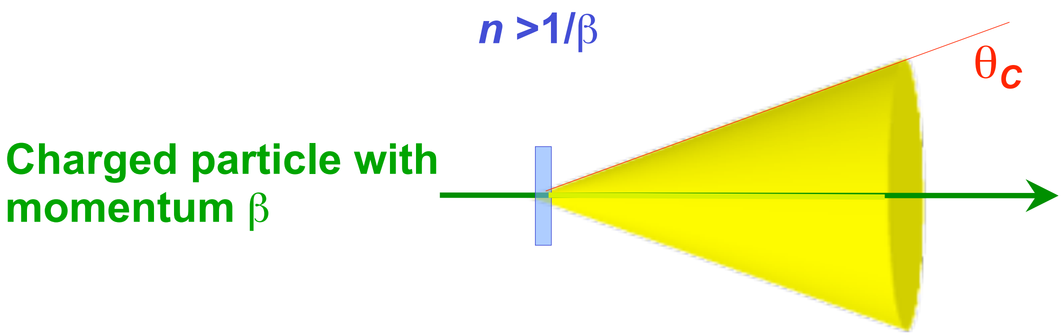
  - radiation length
  - **Cherenkov radiation**

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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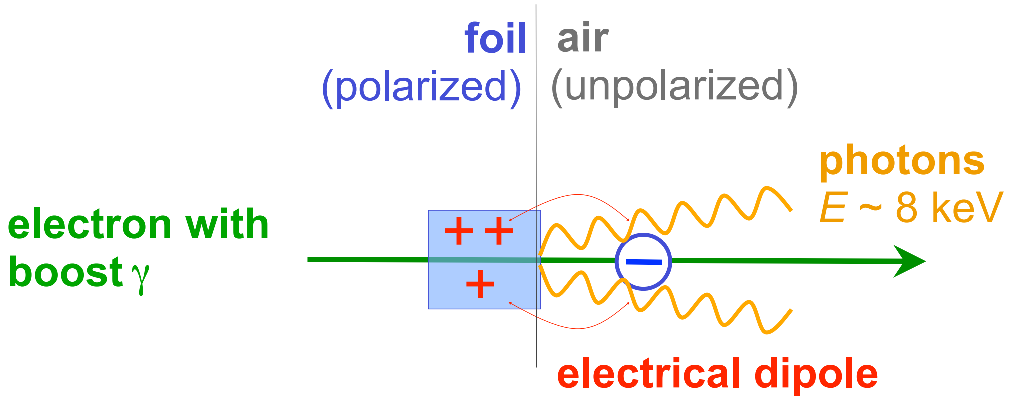
  - Cherenkov radiation
  - **transition radiation**

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



➡ significant radiation for γ > 1000 and > 100 boundaries

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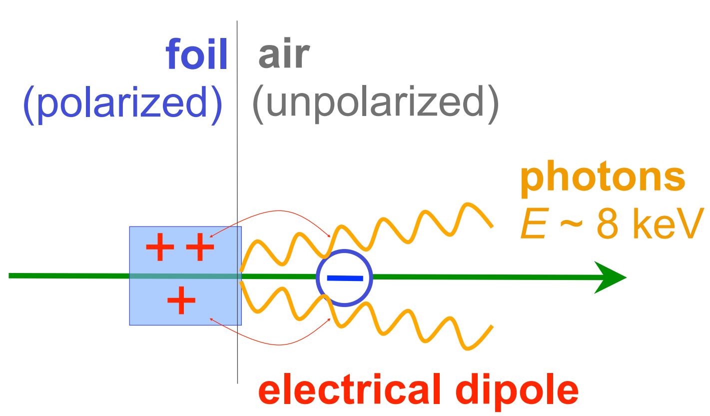

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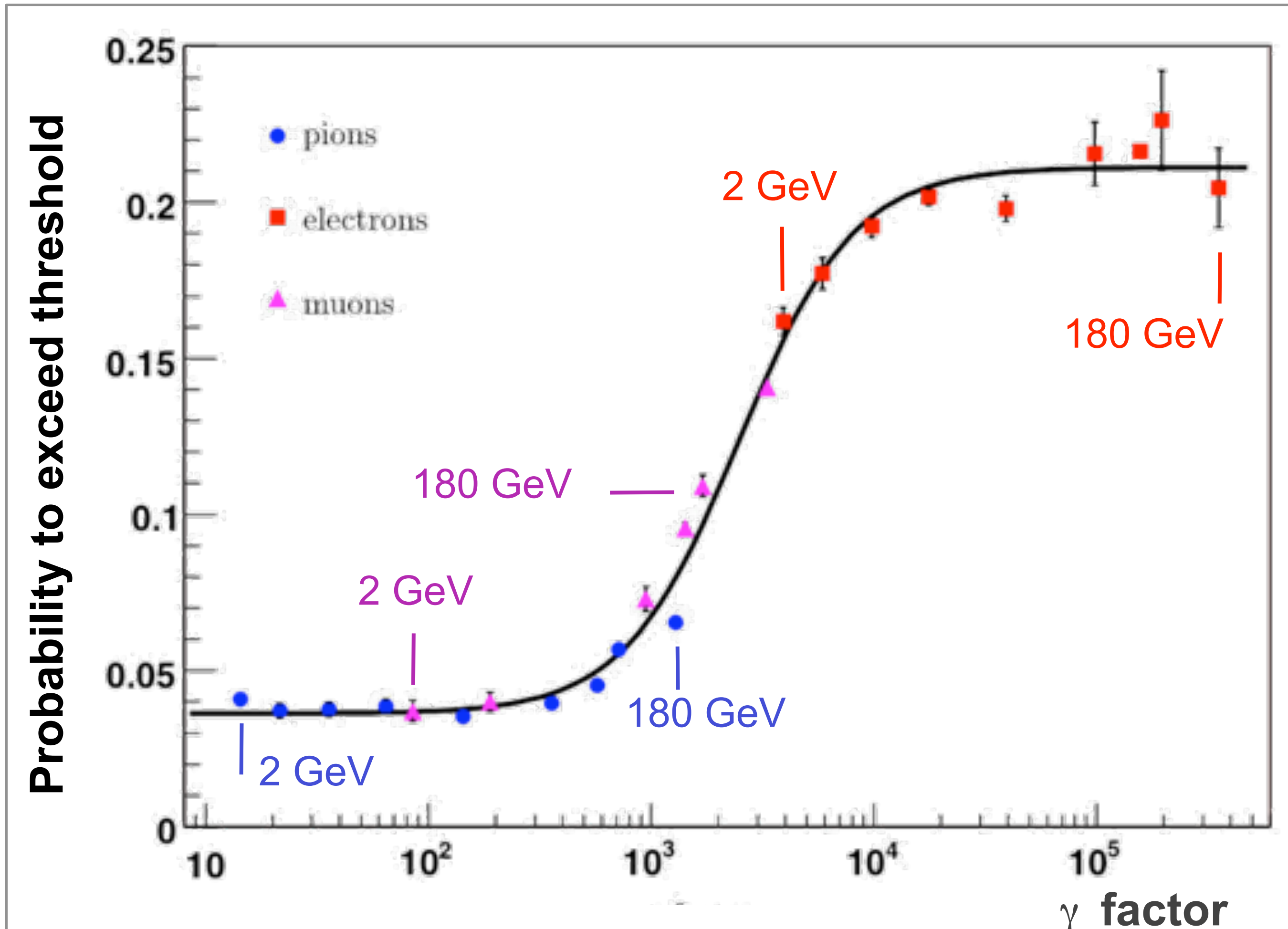
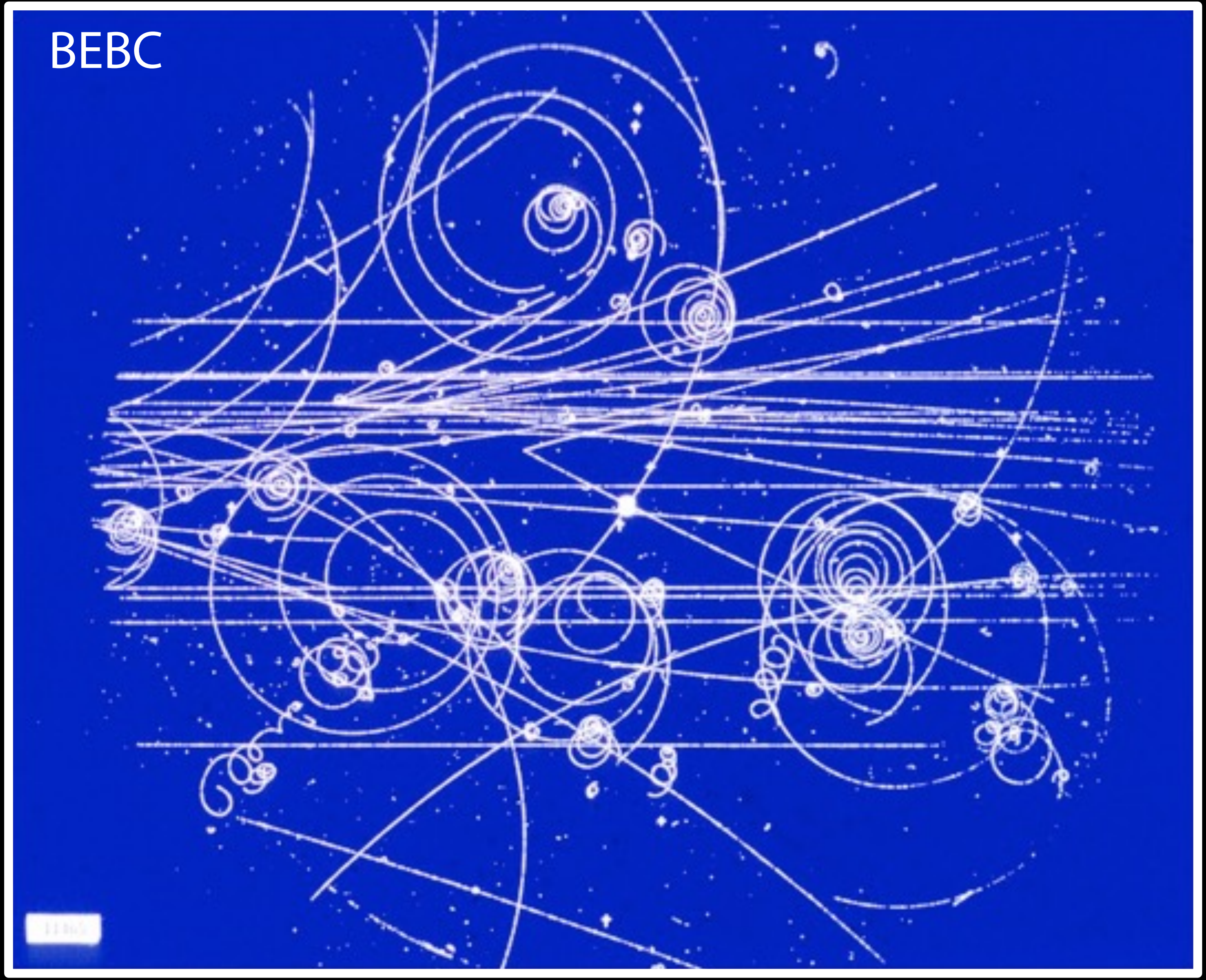
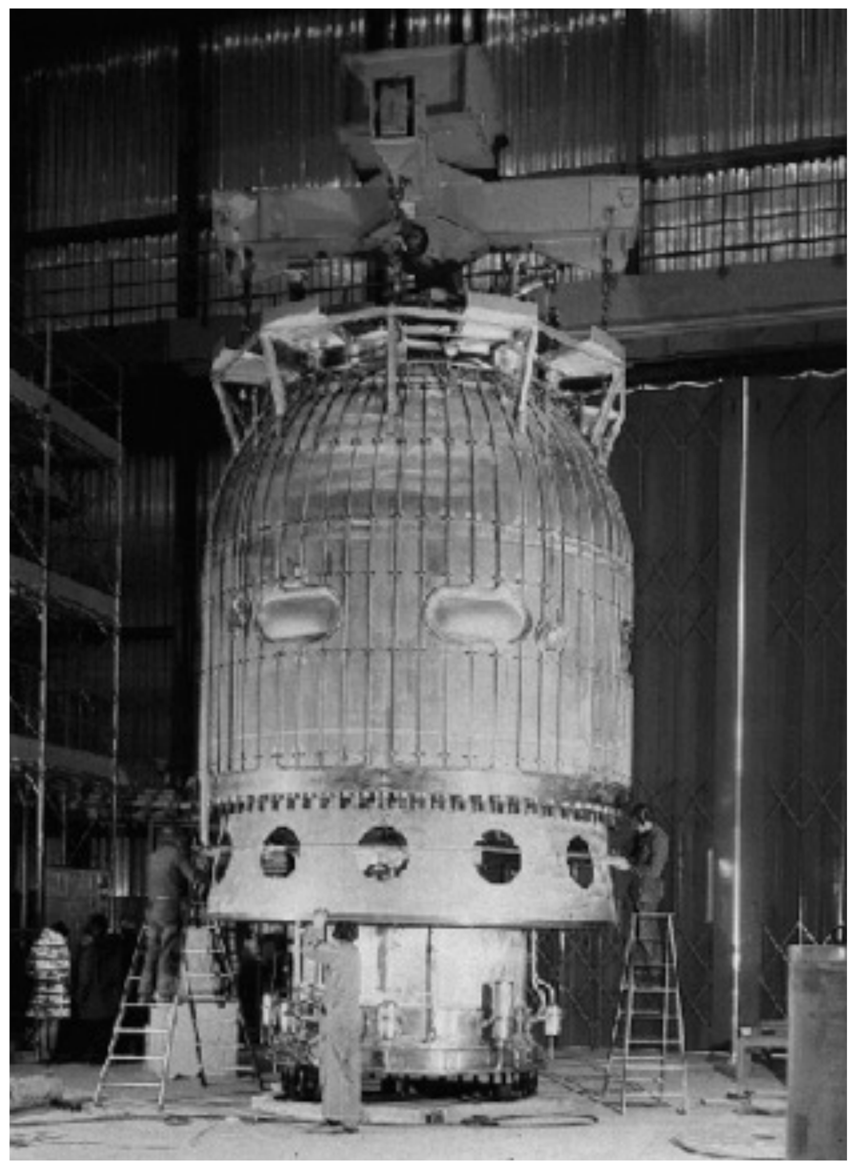


Effects are visible by Eye...

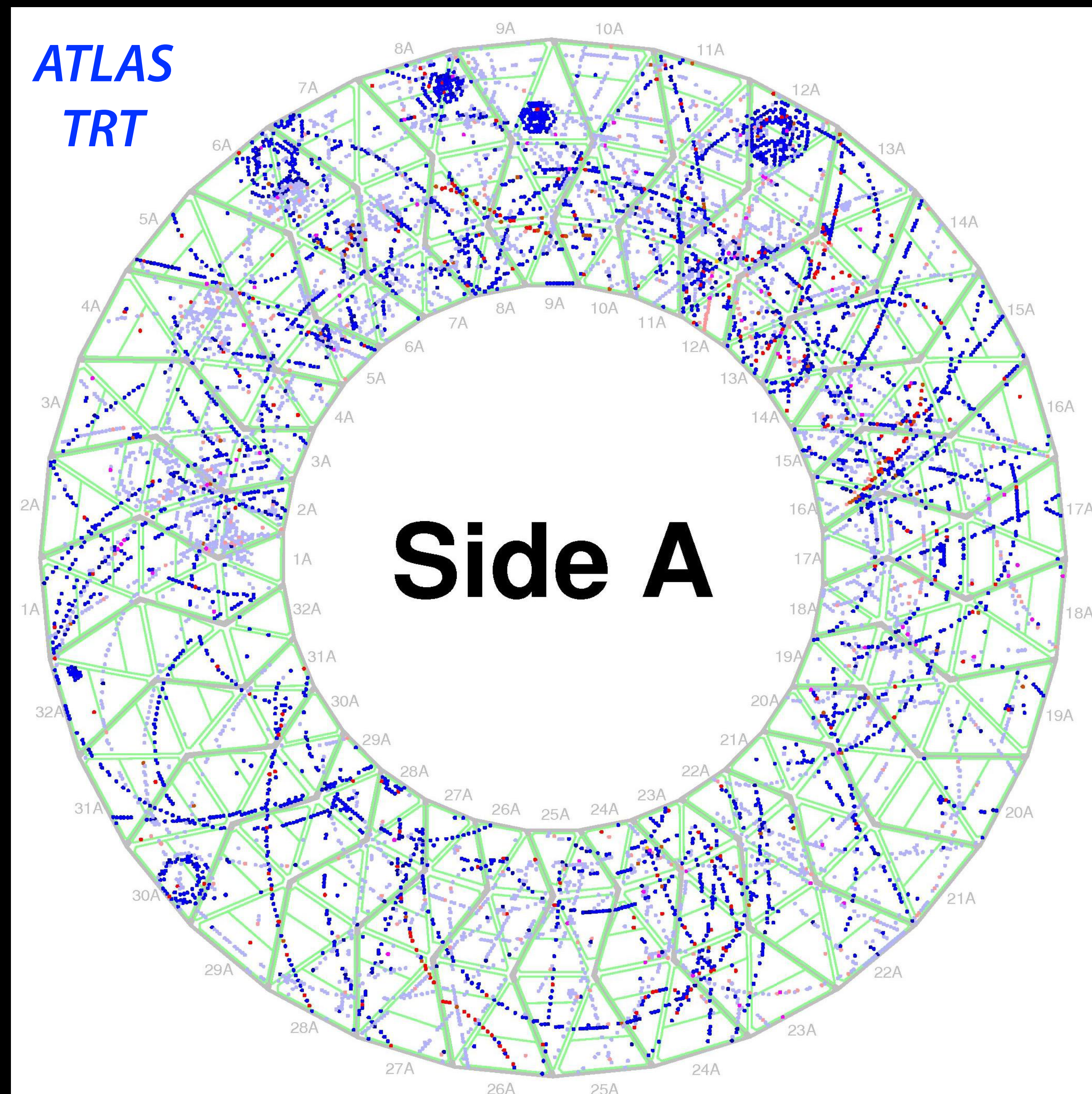




BEBC can be seen outside the Microcosm Exhibition

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

… as well in modern Detectors



early event from 2009 in TLAS TRT

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 (βγ)

➡ with

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

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

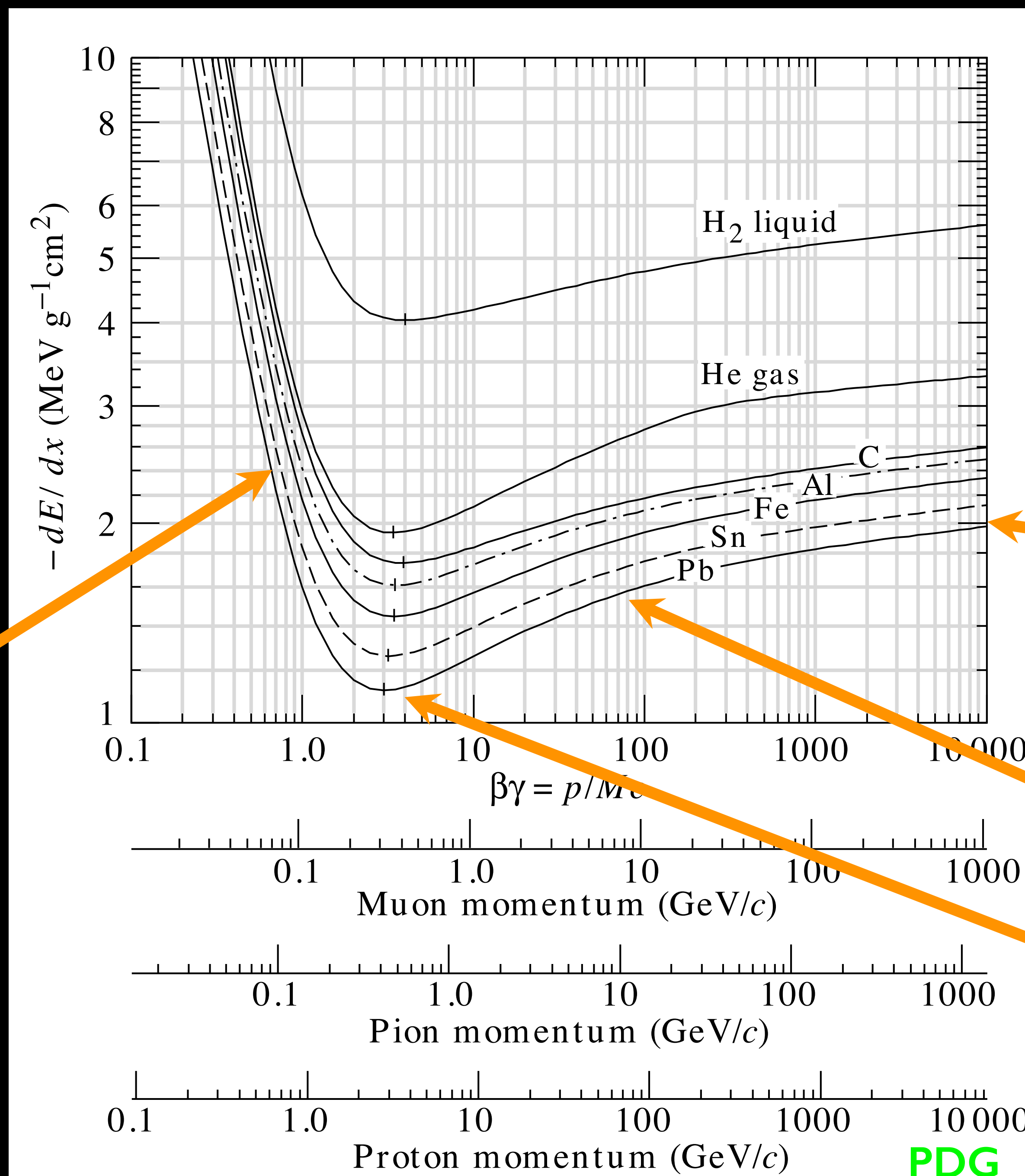
- I ~ mean excitation energy of absorber
- T_{max} ~ maximum energy transfer in a single collision

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

- δ(βγ) ~ density effect correction to ionisation loss

➡ x = ρ 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:

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

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

Fermi plateau: density effect, polarisation of medium "screens" particle charge

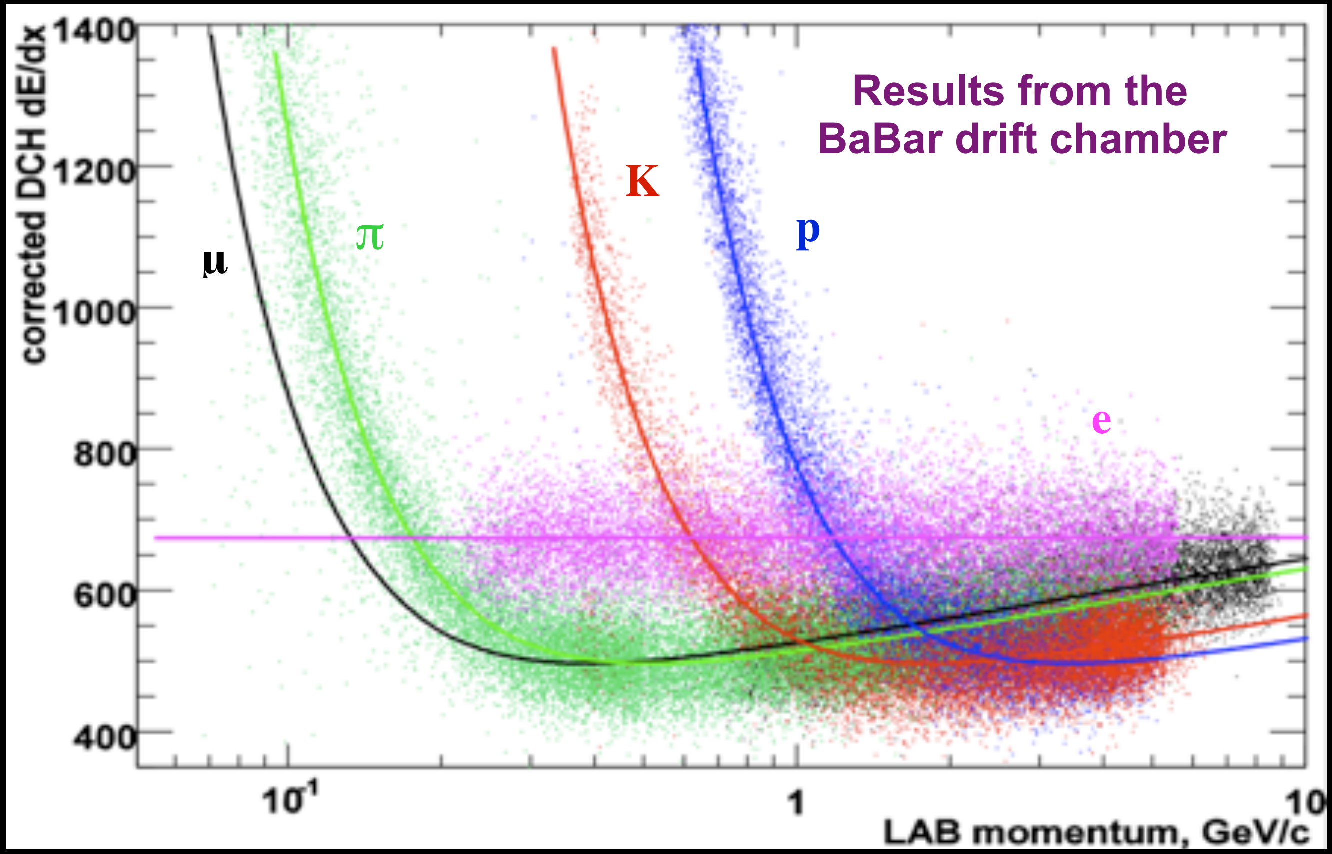
classical $1/\beta^2$ dependency (Rutherford Scattering)

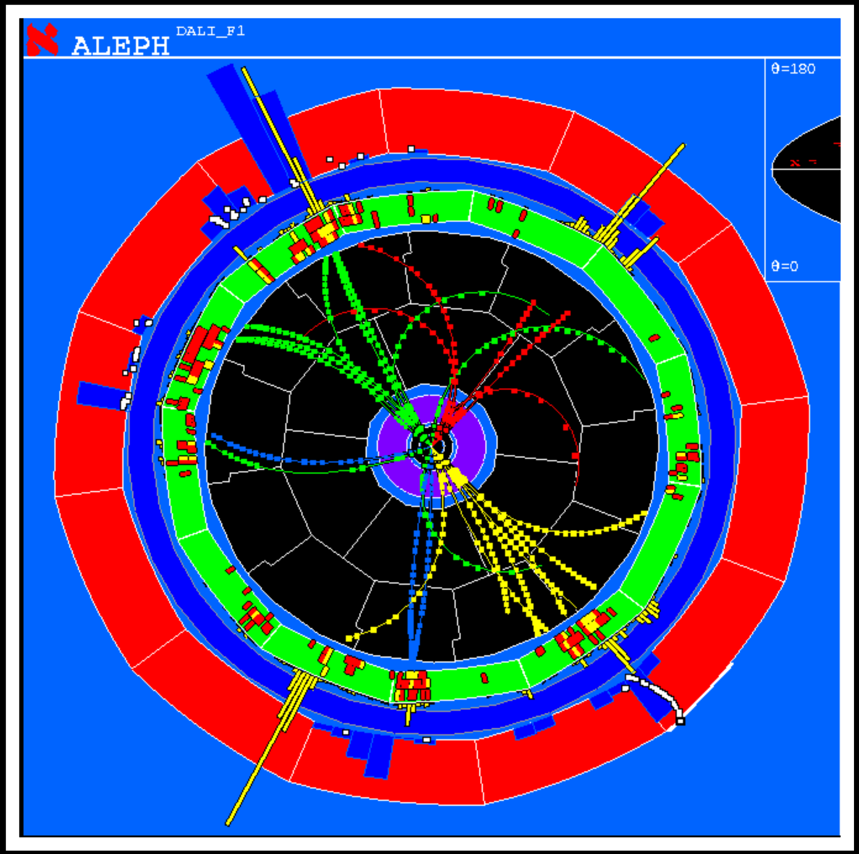
relativistic rise

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

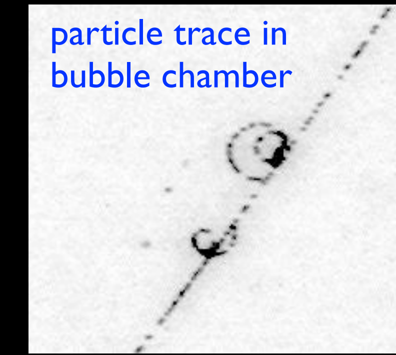
Particle Identification using dE/dx

- 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 ionisation along the track





Fluctuations in Energy Loss



from L. Ropelewski

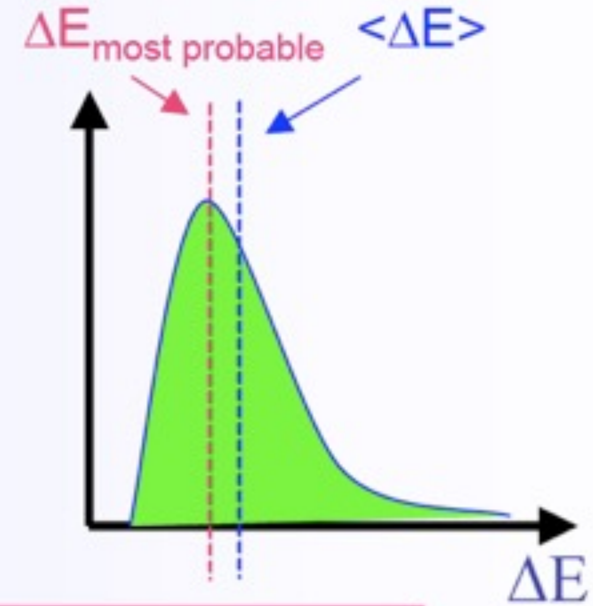
Real detector (limited granularity) can not measure <*dE/dx*> !

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"

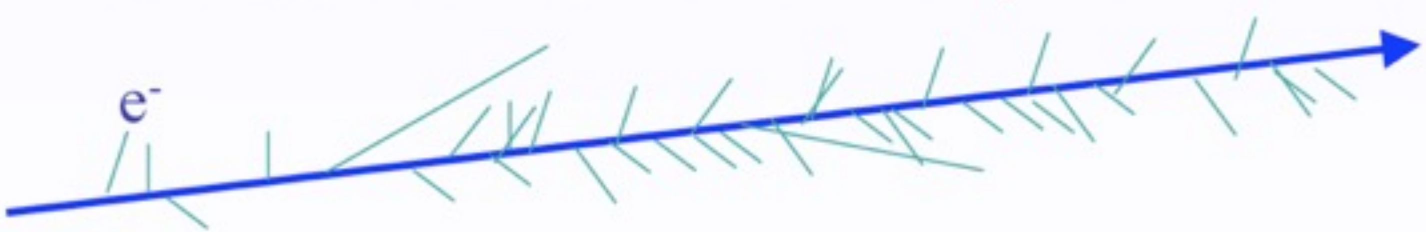


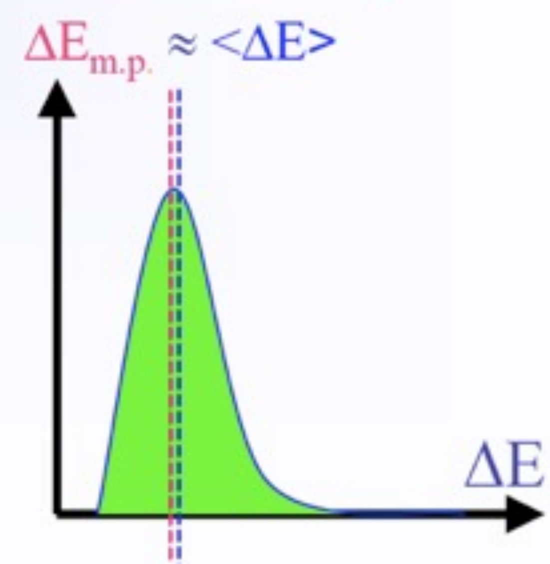
Example: Si sensor: 300 μm thick. $\Delta E_{m.p} \sim 82$ keV $\langle \Delta E \rangle \sim 115$ keV

For thick layers and high density materials:

→ Many collisions.

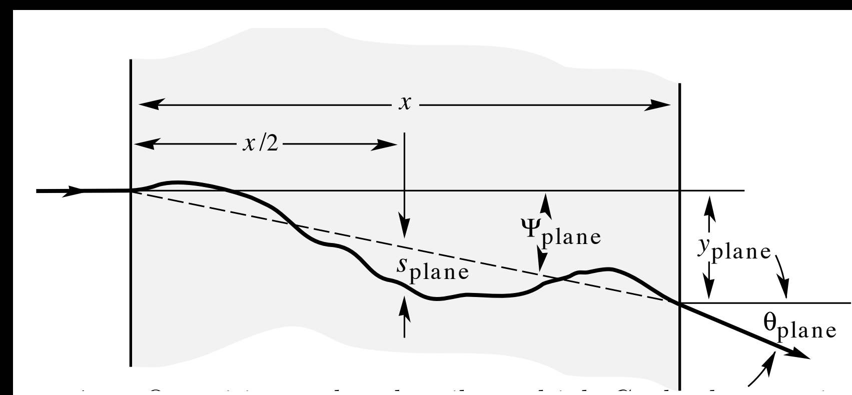
→ Central Limit Theorem → Gaussian shaped distributions.





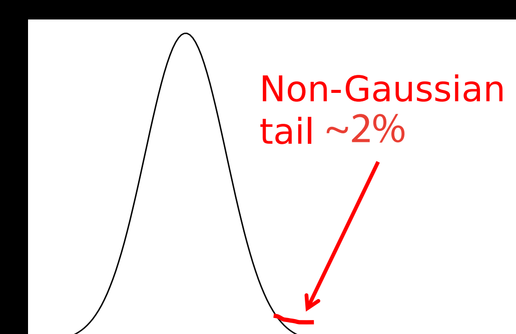
Multiple Scattering

- 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

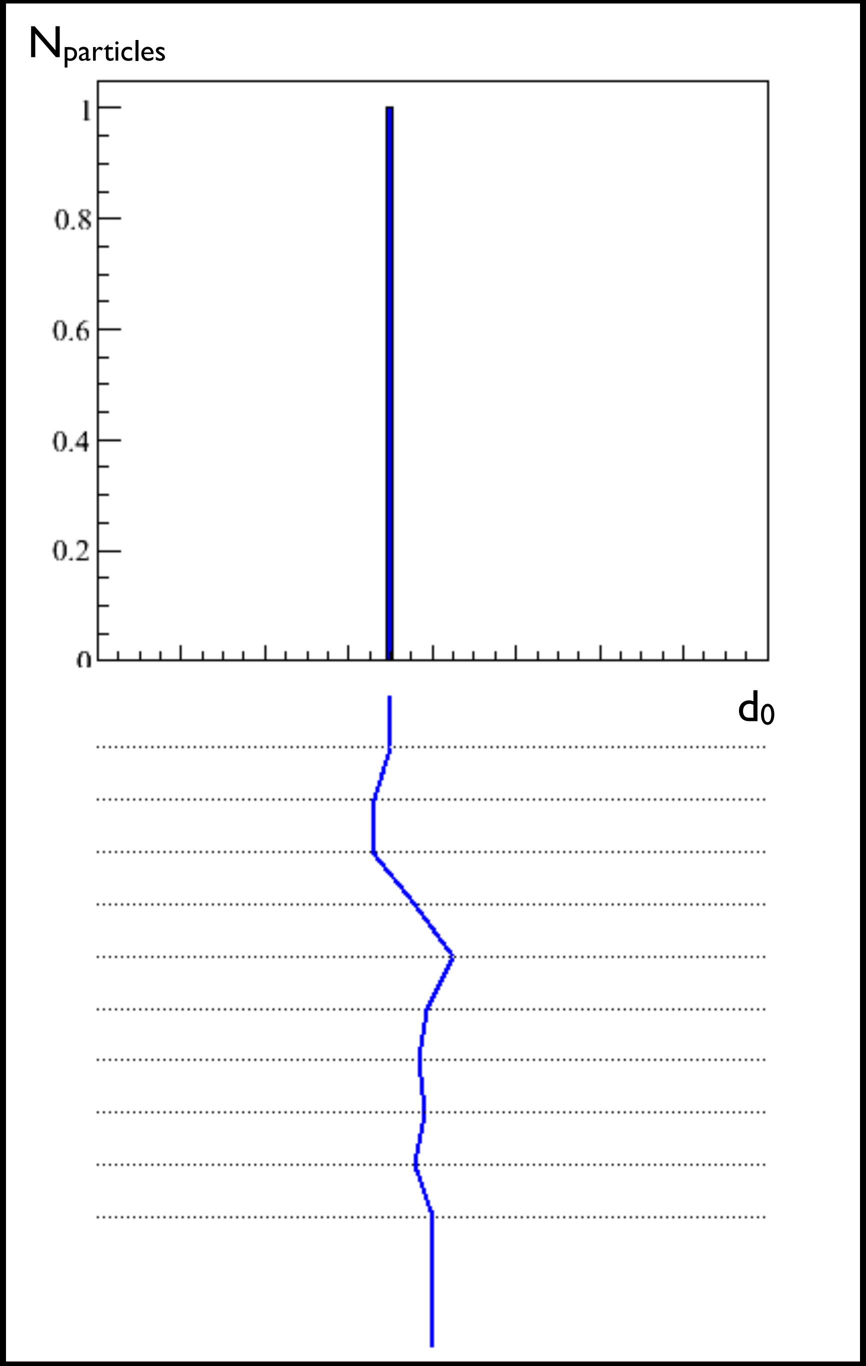
$$\Delta\Theta = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\left[1 + 0.038 \ln(x/X_0)\right]$$



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

Illustration of Multiple Scattering Effect

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



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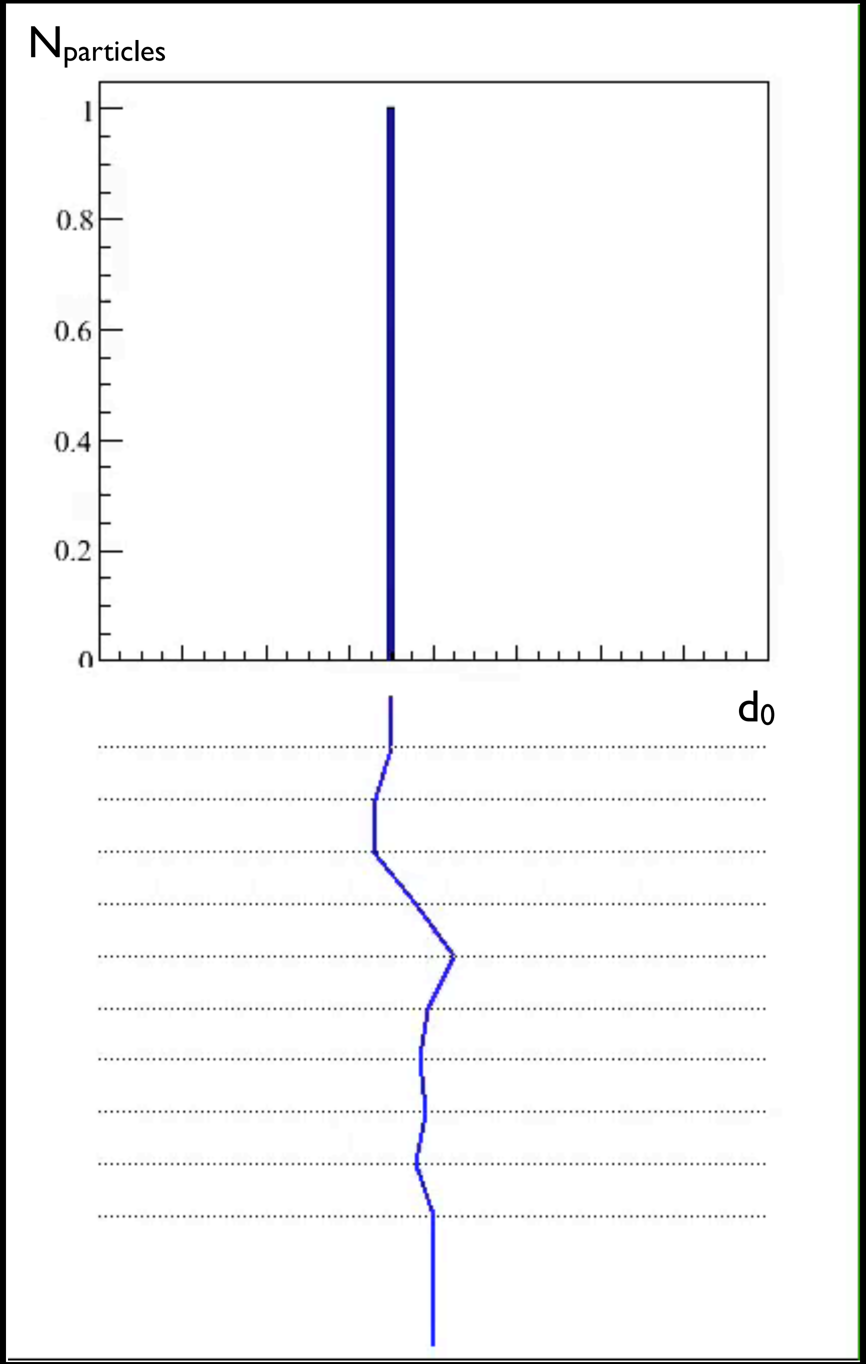
    - central limit theorem predicts gaussian distribution



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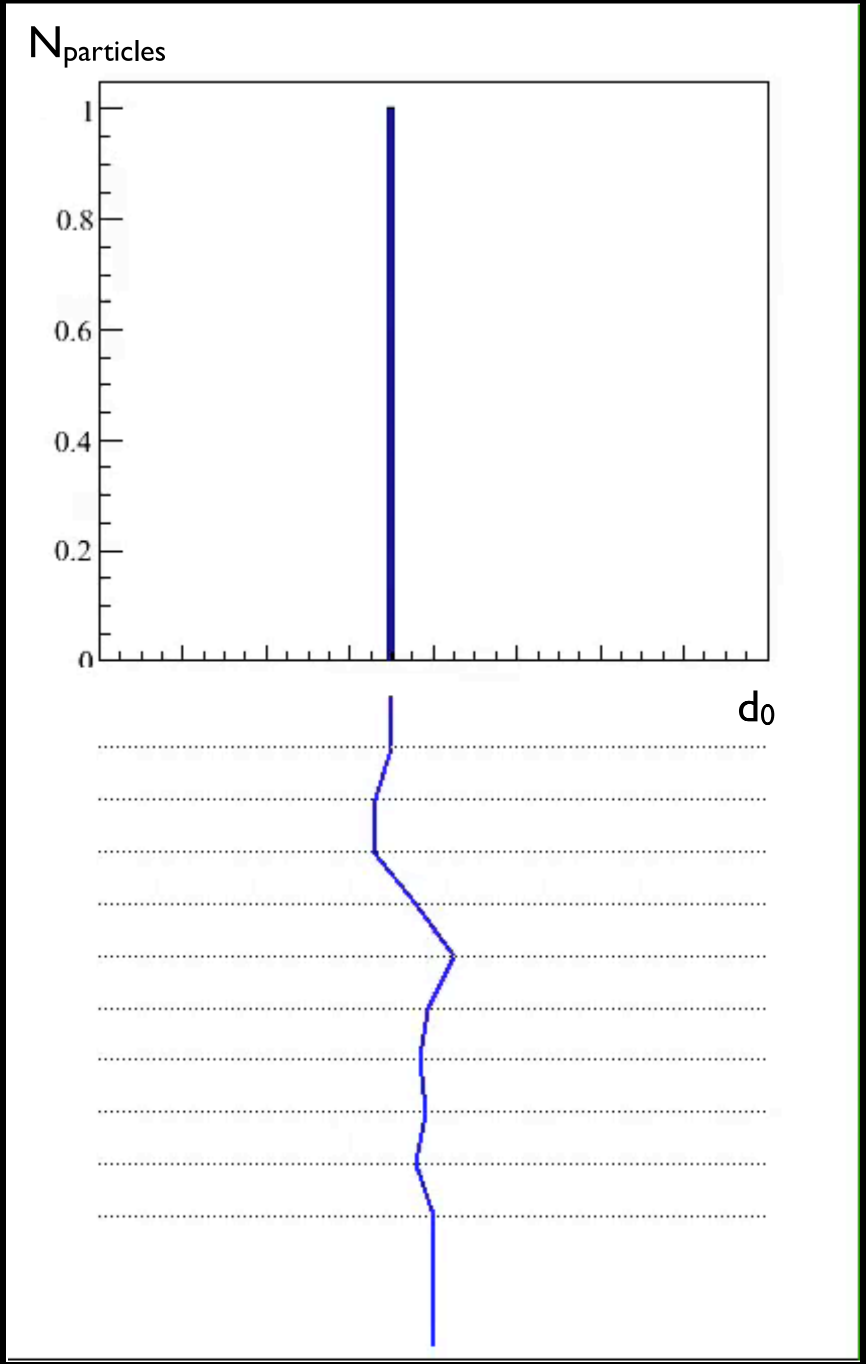


- sometimes we experience the effect

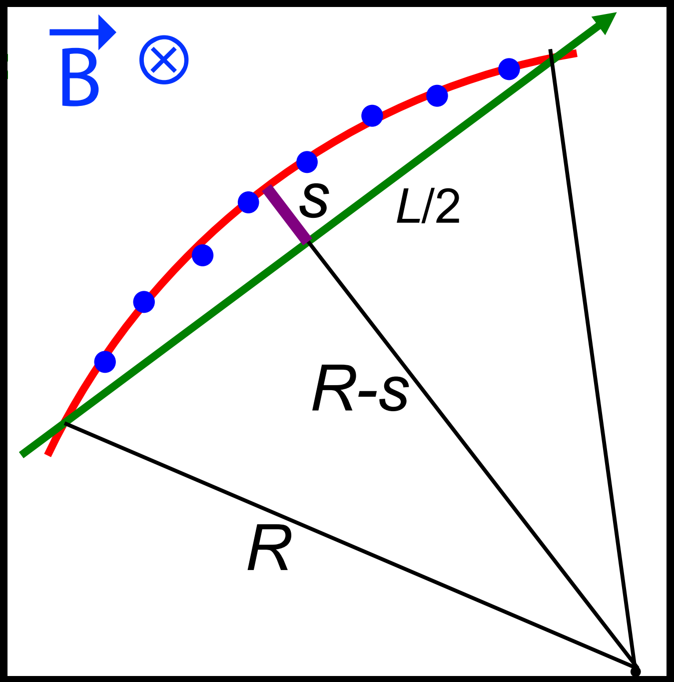
Effect on Momentum Resolution

- 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 R in 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 p_T times sagitta uncertainty σ_s
  - ➡ as well, one wants large B-field and long path length L

Sagitta uncertainly from N points, each with resolution $\sigma_{R\phi}$

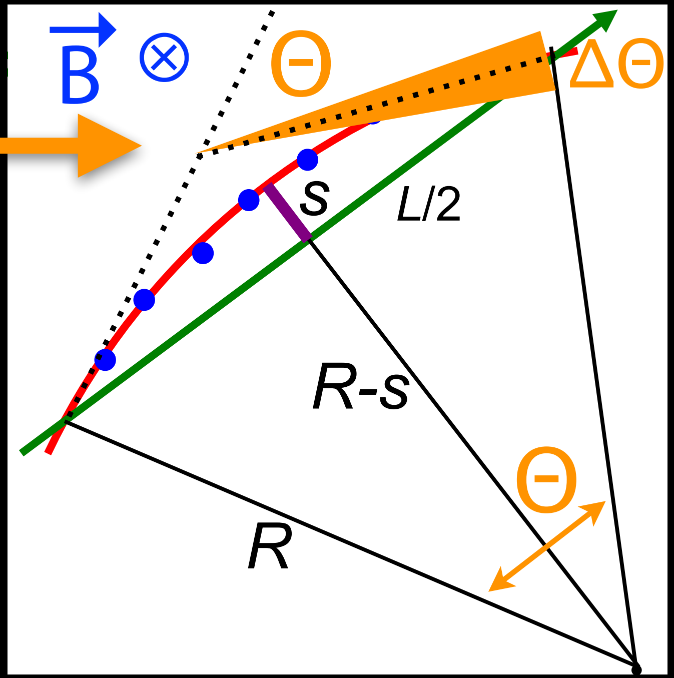
$$\sigma_s = \sqrt{\frac{A_N}{N+4}}\frac{\sigma_{R\phi}}{8}$$

Statistical factor A_N = 720:
(Gluckstern)

Effect on Momentum Resolution

- multiple scattering contribution to momentum uncertainty

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



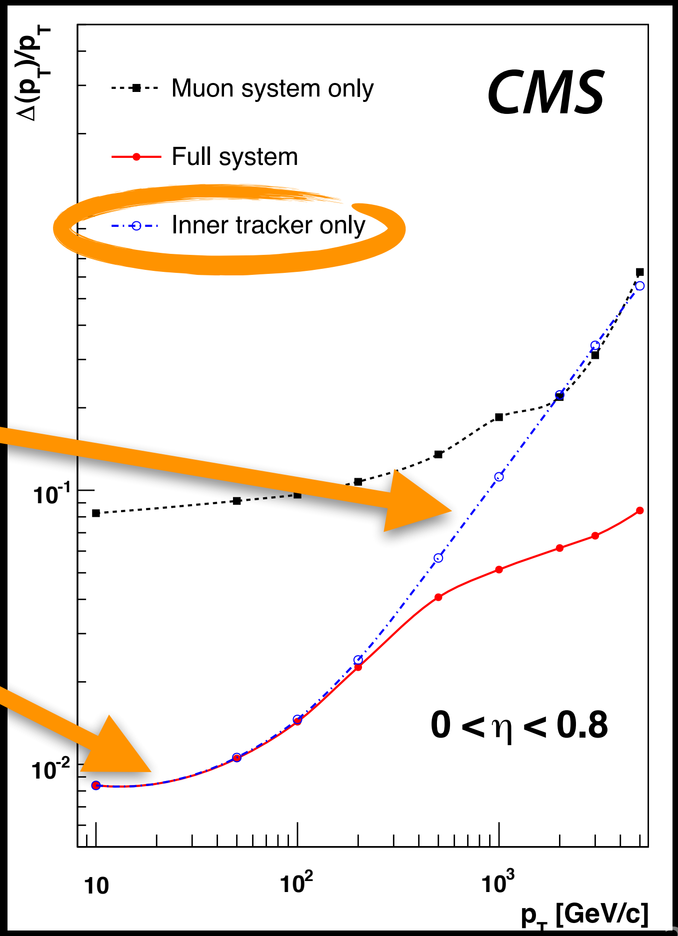
- putting things together gives

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

➡ a ~ resolution term dominating at high p_T

(term is proportional to $1/L^2$ and $\sigma_{R\Phi}$)

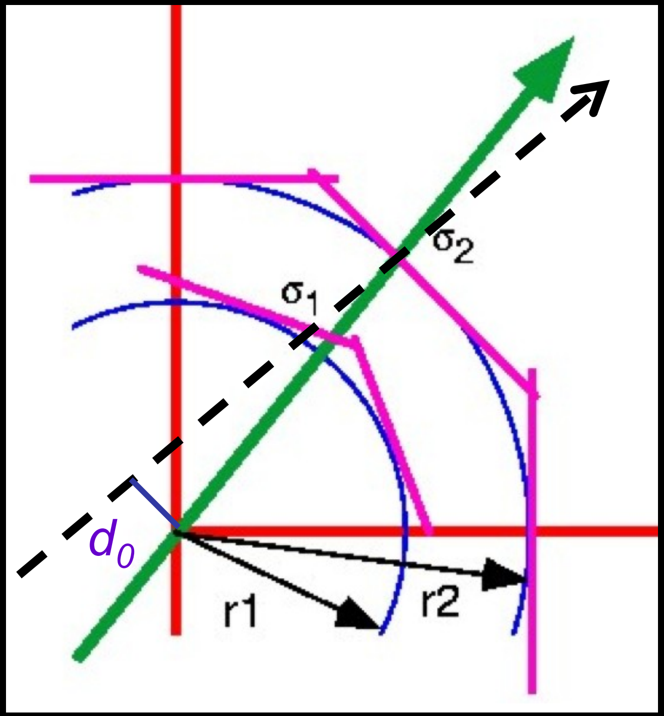
b ~ multiple scattering term limiting at low p_T



Effect on Impact Parameter Resolution

- uncertainty on the transverse impact parameter d_0
  - ➡ depends on the radii and space point precision
  - ➡ simplified formula for straight line and just two layers

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



  - ➡ best performance: small r_1, large r_2, small σ_1 and σ_2

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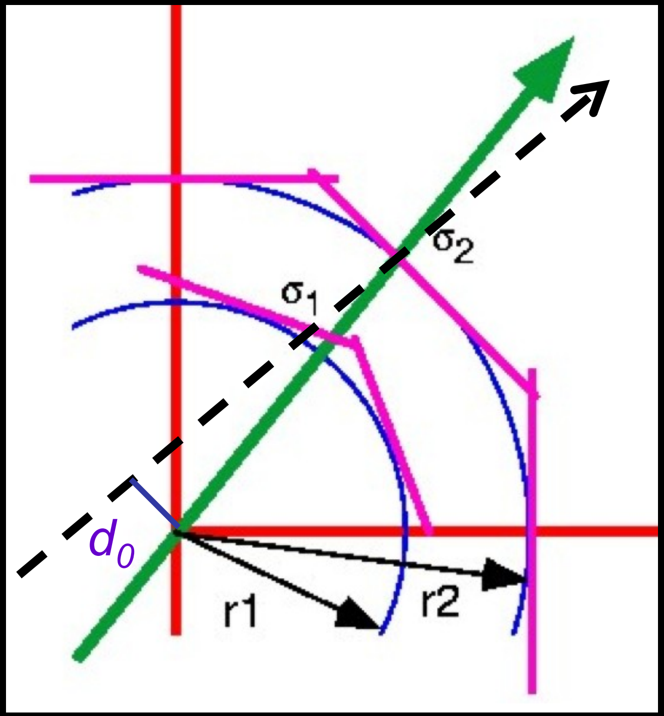
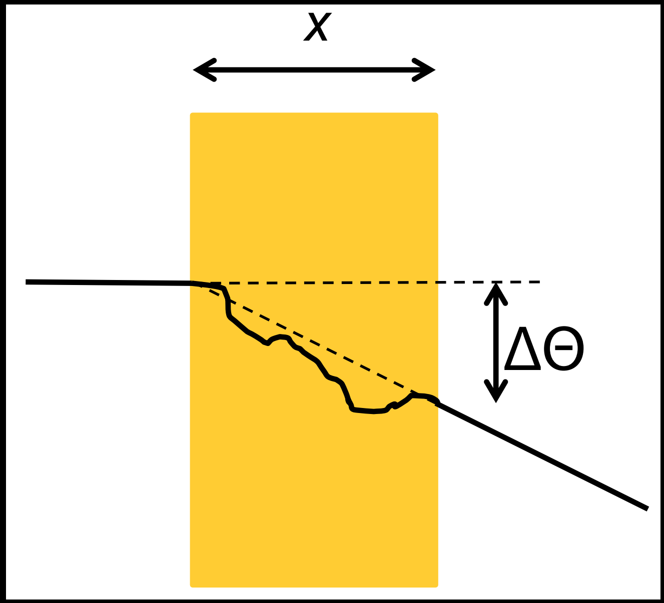


- precision is degraded by multiple scattering

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

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

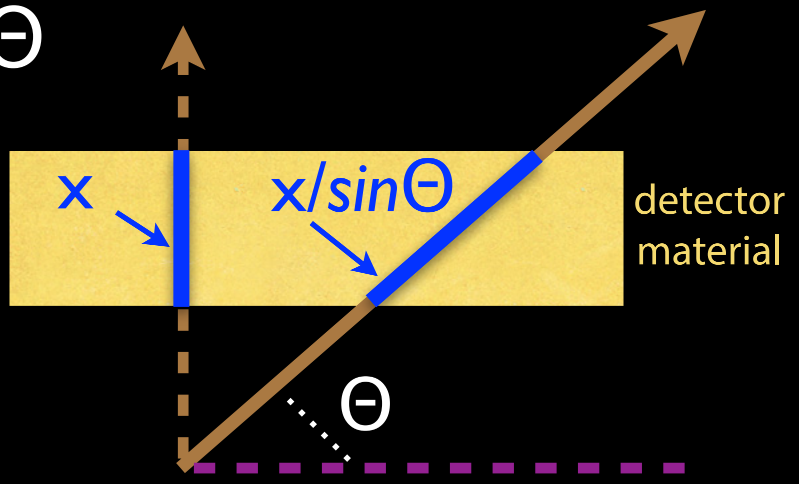


Effect on Impact Parameter Resolution

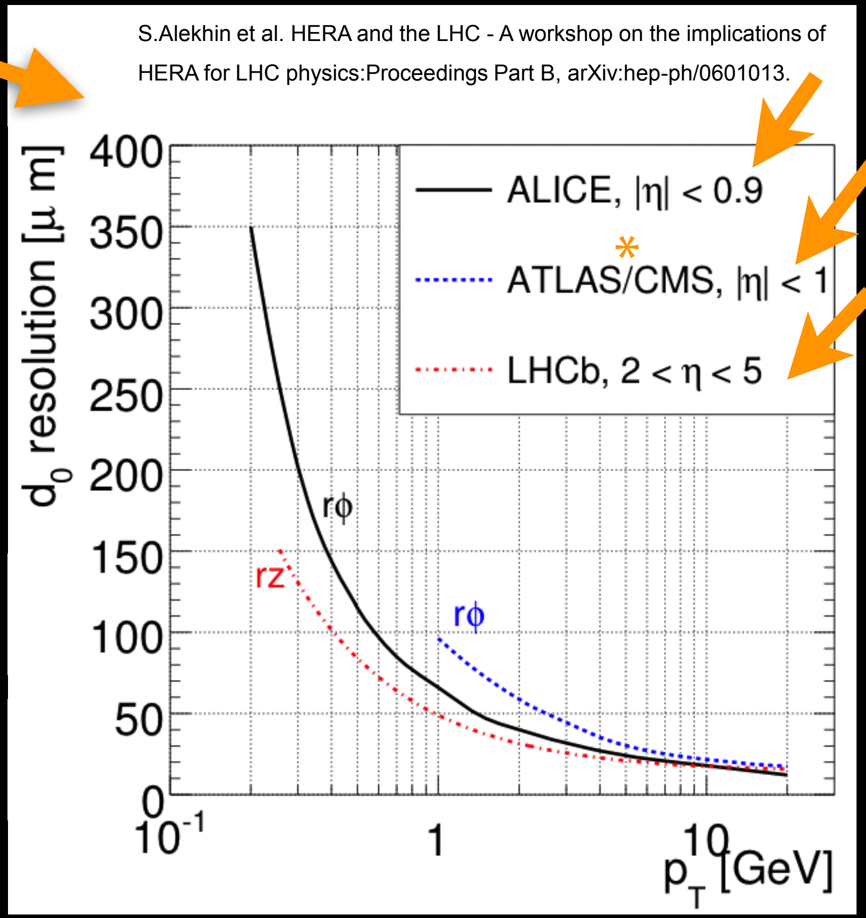
- for tracks with Θ≠90°: r→r/sinΘ   x→x/sinΘ

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

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



➡ constant term describing resolution
➡ multiple scattering term decreasing with p_T



*no IBL

Effect on Impact Parameter Resolution

- for tracks with $\Theta \neq 90°$: $r \rightarrow r/\sin\Theta \quad x \rightarrow x/\sin\Theta$

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

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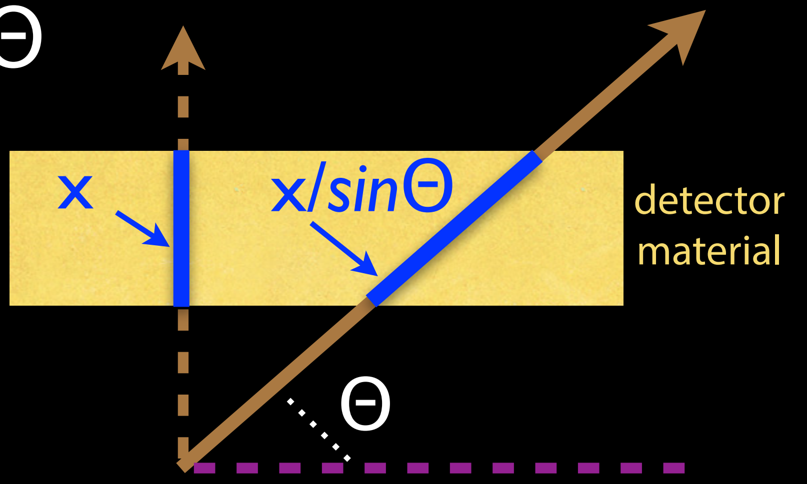
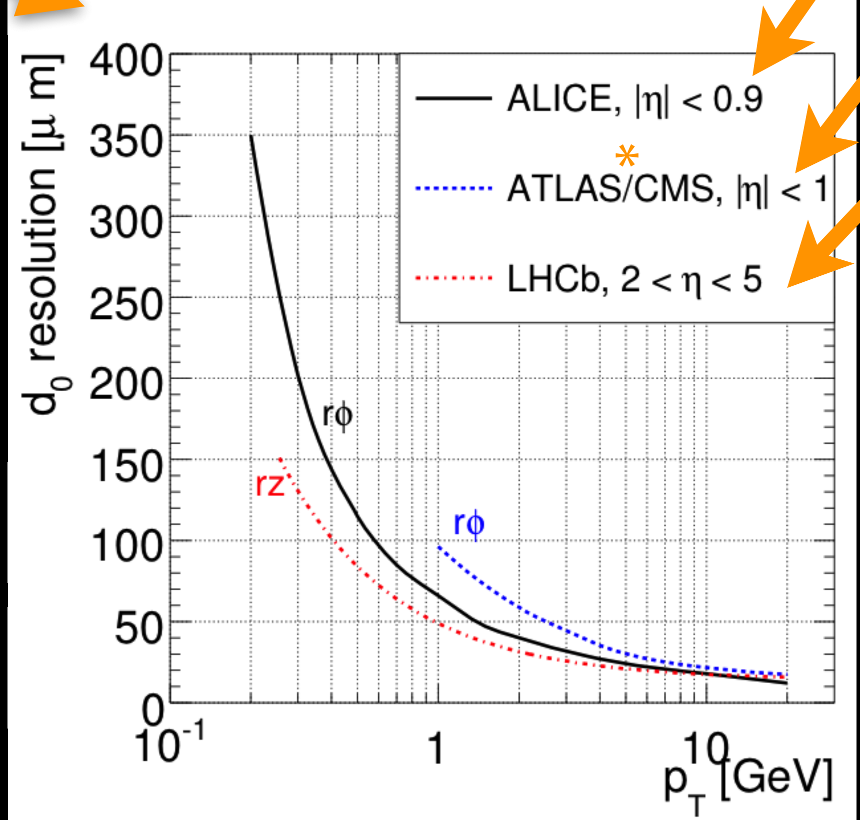


➡ constant term describing resolution
➡ multiple scattering term decreasing with p_T

- similarly **momentum resolution** term becomes:

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

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.



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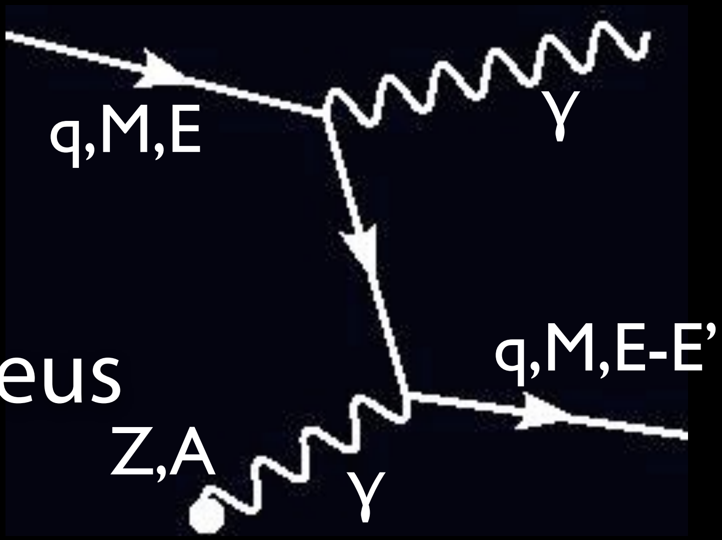
Bremsstrahlung



- charged particle is 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

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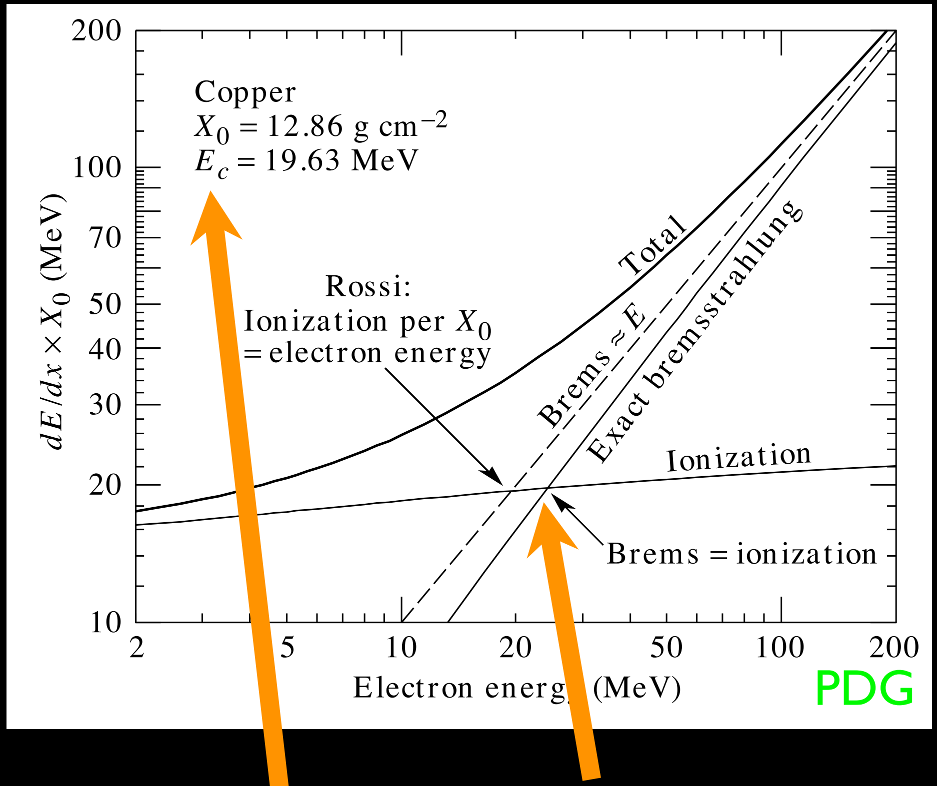
- Bremsstrahlung proportional to
  - Z^2/A and ρ of the material
  - q^4 and $1/M^2$ of incoming particle
  - ➡ energy lost ~ proportional to energy of particle:

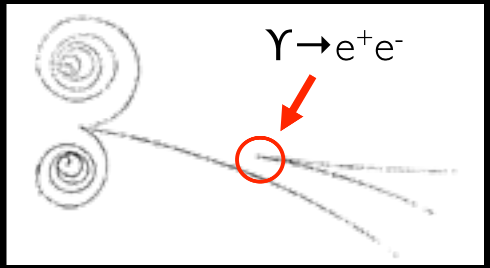
$$E(x) \approx E_0 e^{-x/X_0} \qquad X_0 \propto \frac{M^2 A}{q^4 \rho Z^2}$$

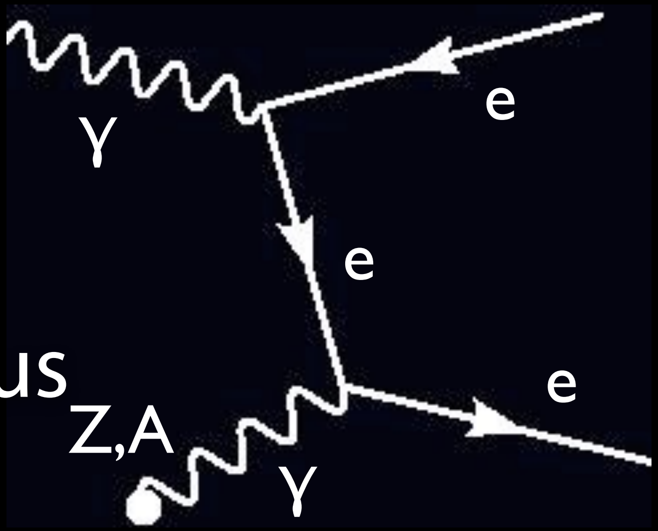
  - **radiation length X_0** ~ characteristic amount of material traversed before it looses 1/e of its energy
  - ➡ Bremsstrahlung of electrons in tracker material is limiting reconstruction efficiency !



important above critical energy E_c

Pair-Production



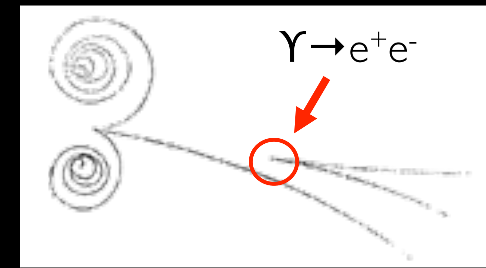


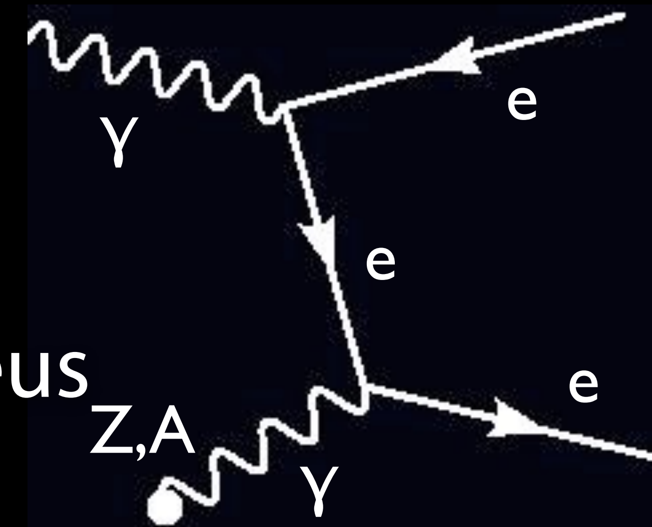
- $\gamma \rightarrow e^+e^-$ conversion process in field of nucleus
  - ➡ described by diagram similar to Bremsstrahlung
  - ➡ conversion probability:

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

  - ➡ 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

Pair-Production





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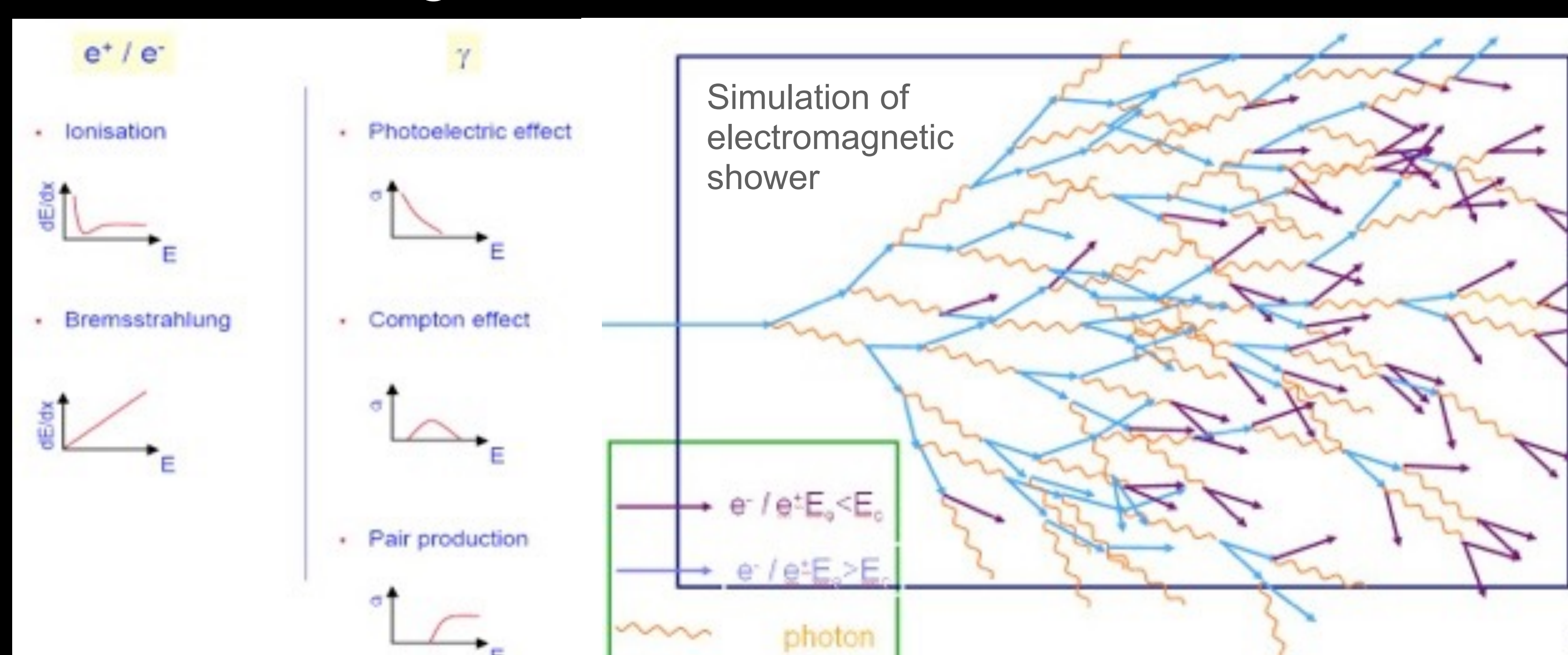
- with Bremsstrahlung gives rise to electromagnetic showers
  - ➡ processes contributing to showers, detection in EM calorimeters



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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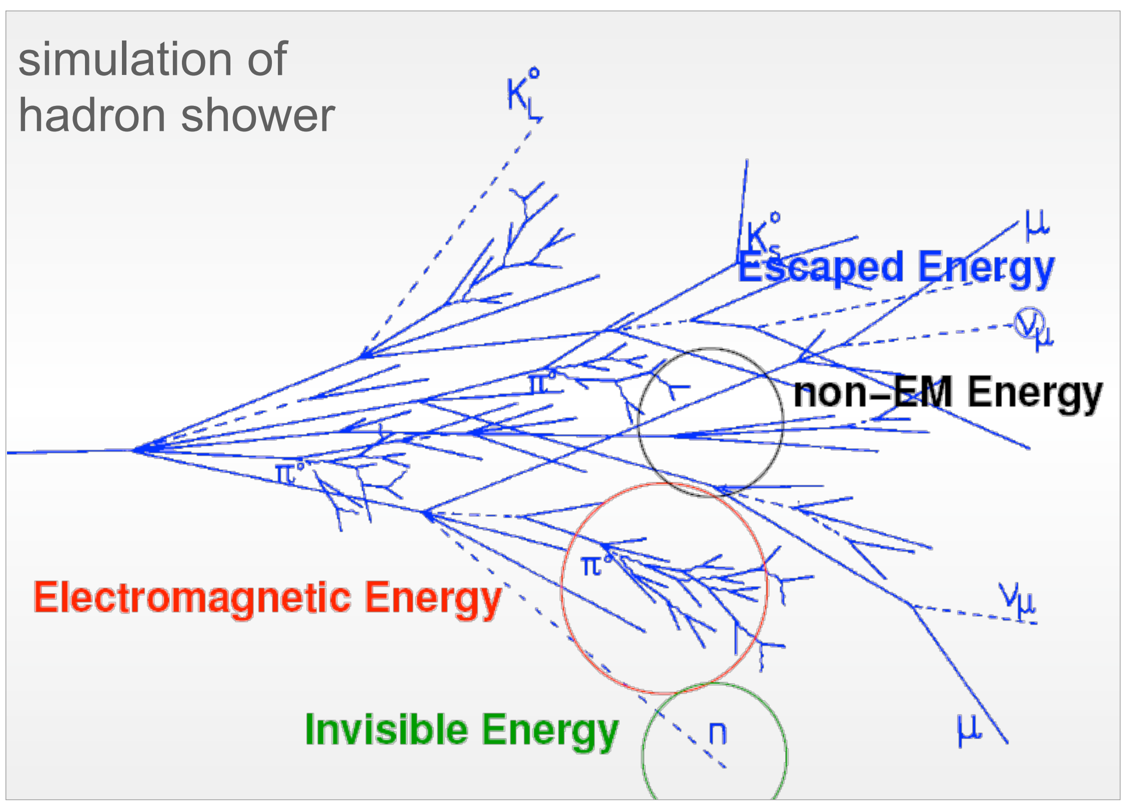


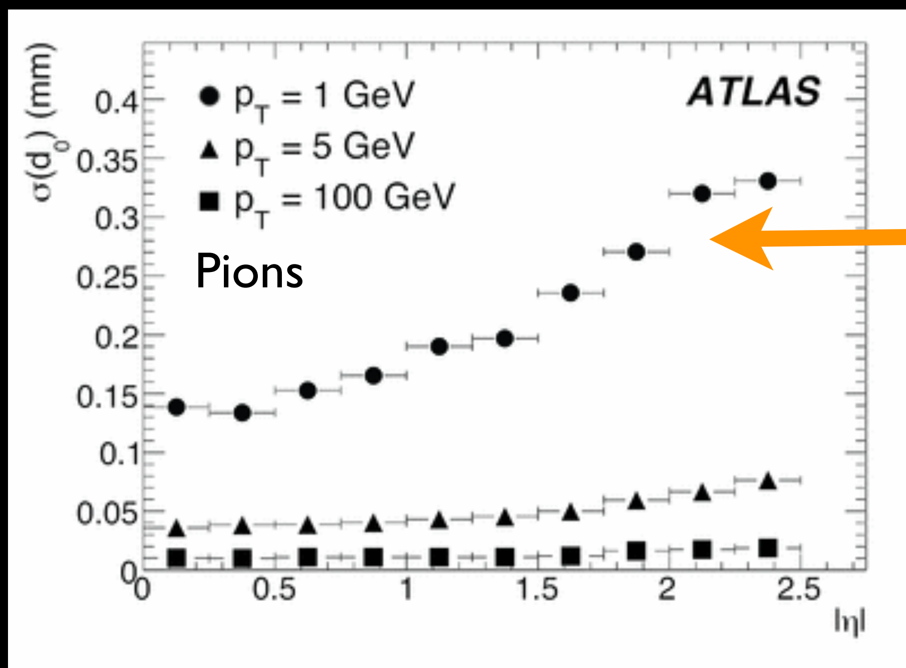
a hadronic shower consists of:

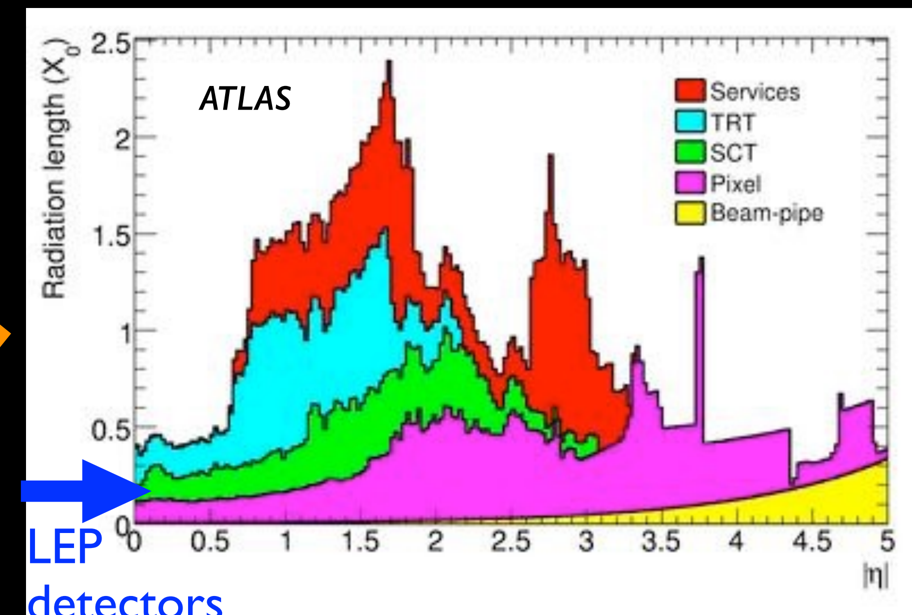
- EM energy (e.g., $\pi^0 \rightarrow \gamma\gamma$) $O(50\%)$
- non-EM energy (*e.g.*, *dE*/*dx* from $\pi^\pm,\mu^\pm,K^\pm$) $O(25\%)$
- invisible energy
  (nuclear fission/excitation, neutrons) $O(25\%)$
- escaped energy (*e.g.* neutrinos) $O(2\%)$

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

Effect on Expected Performance

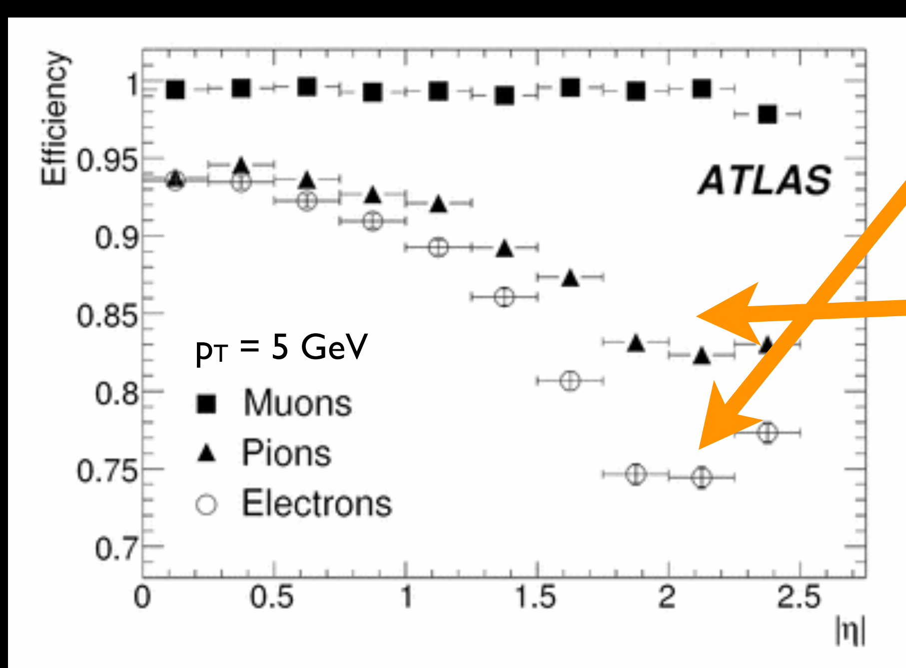
- ATLAS/CMS tracking resolution and efficiency mostly driven by interactions in detector material

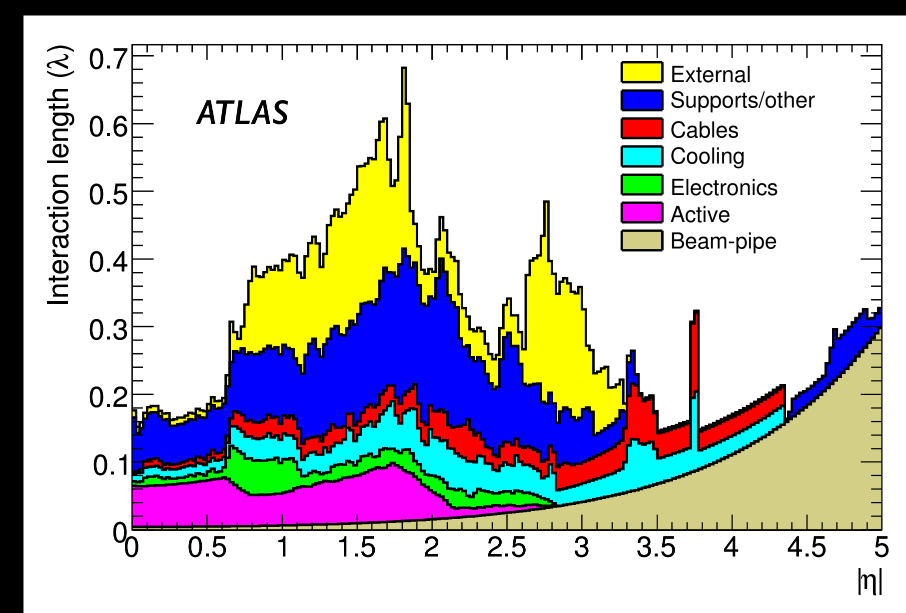




multiple scattering

Bremsstrahlung (without recovery)





hadronic interactions

➡ total weight of Inner Detector: 4.5 tons

Let's Summarise...

- 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 ionisation 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