Detectors and Reconstruction

Nhan Tran, Fermilab

December 5, 2020

VSOP26

PREFACE

The plan:

I will give 2 lectures on detectors and reconstruction at the LHC

Then you will hear from Sezen on analysis techniques and physics results

Caveat 1: my experience is in ATLAS/CMS style reconstruction, so I will focus on that, with a few special topics for heavy ions and b-physics.

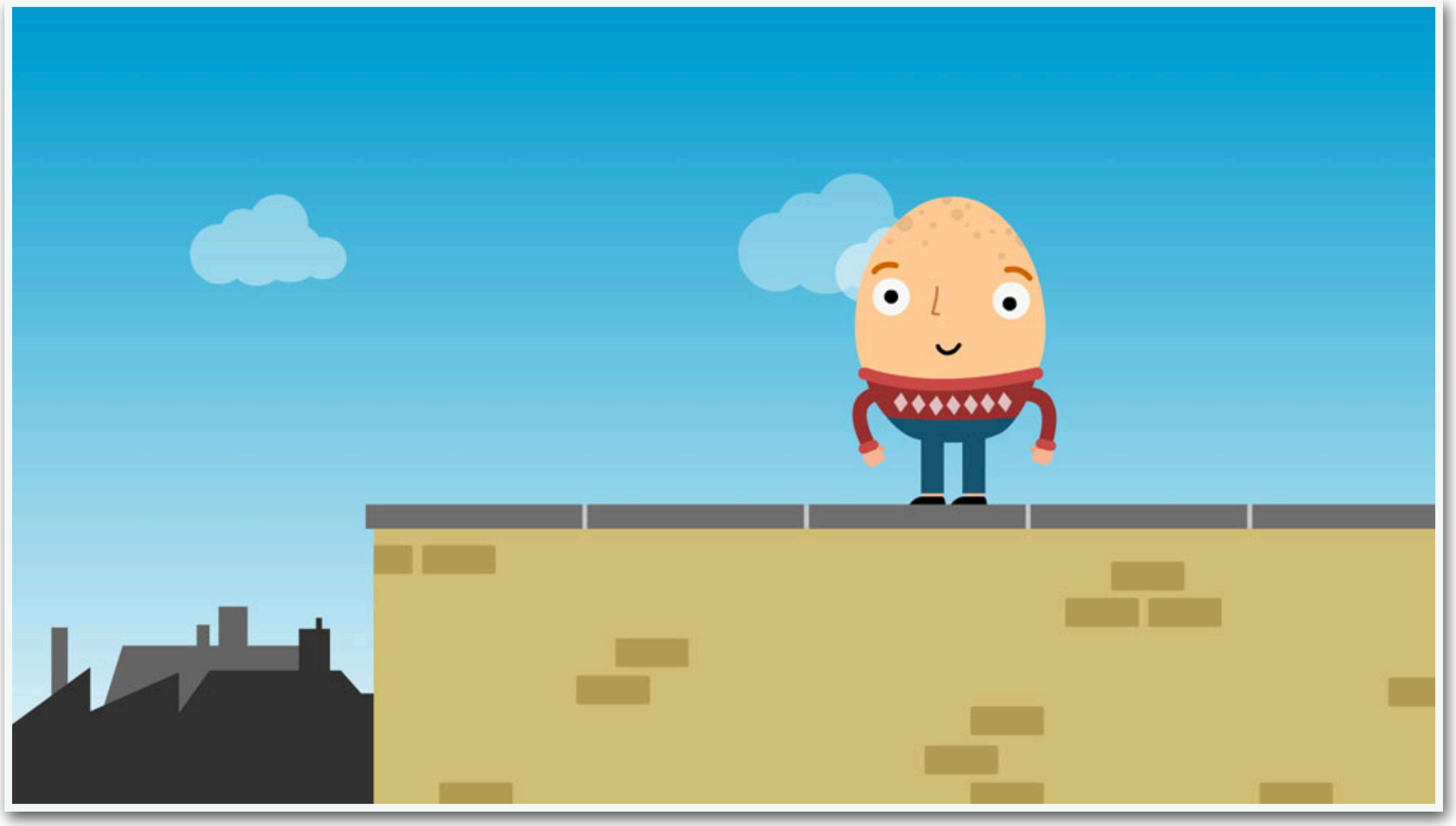
Caveat 2: More CMS results mostly because I know where to find those plots more easily — but most everything I will say will be generic

Table of contents

A LOT OF GROUND TO COVER!
MY STRATEGY: GIVE YOU AN IDEA OF MANY THINGS RATHER THAN FOCUS ON A FEW

I'm drawing a lot from different sources, but great references are lectures from previous HCPSS (Phil Harris and Rick Cavanaugh) and also from lectures by Alex Tapper

INTRODUCTION



Collision

Physics process

Partons

Stable particles

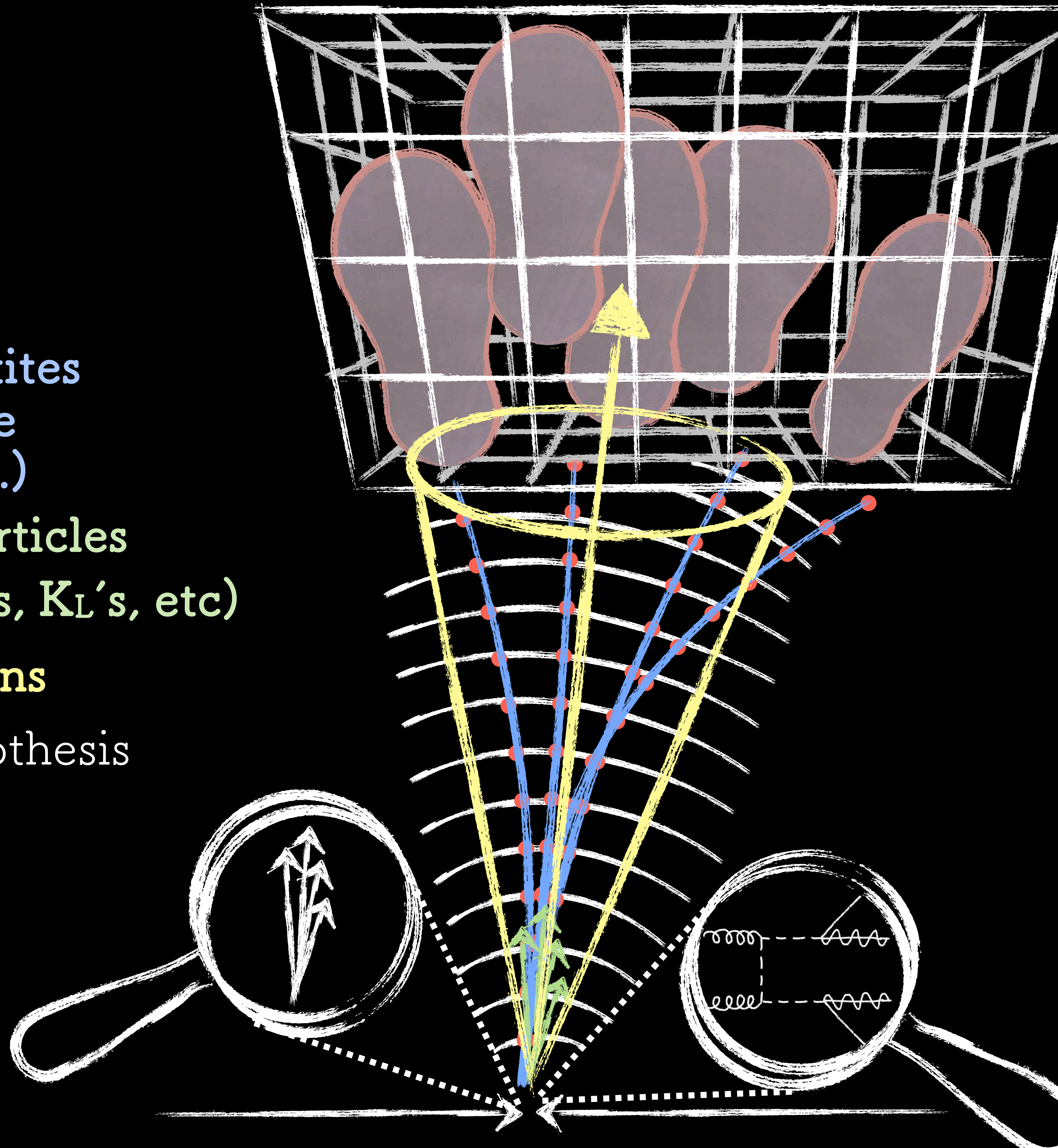
Detector hits

Reconstructed quantites
(momenta, charge
energy, angles, ...)

List of ID'd reco. particles
(e's, μ's, γ's, π's, K_L's, etc)

Reconstructed partons

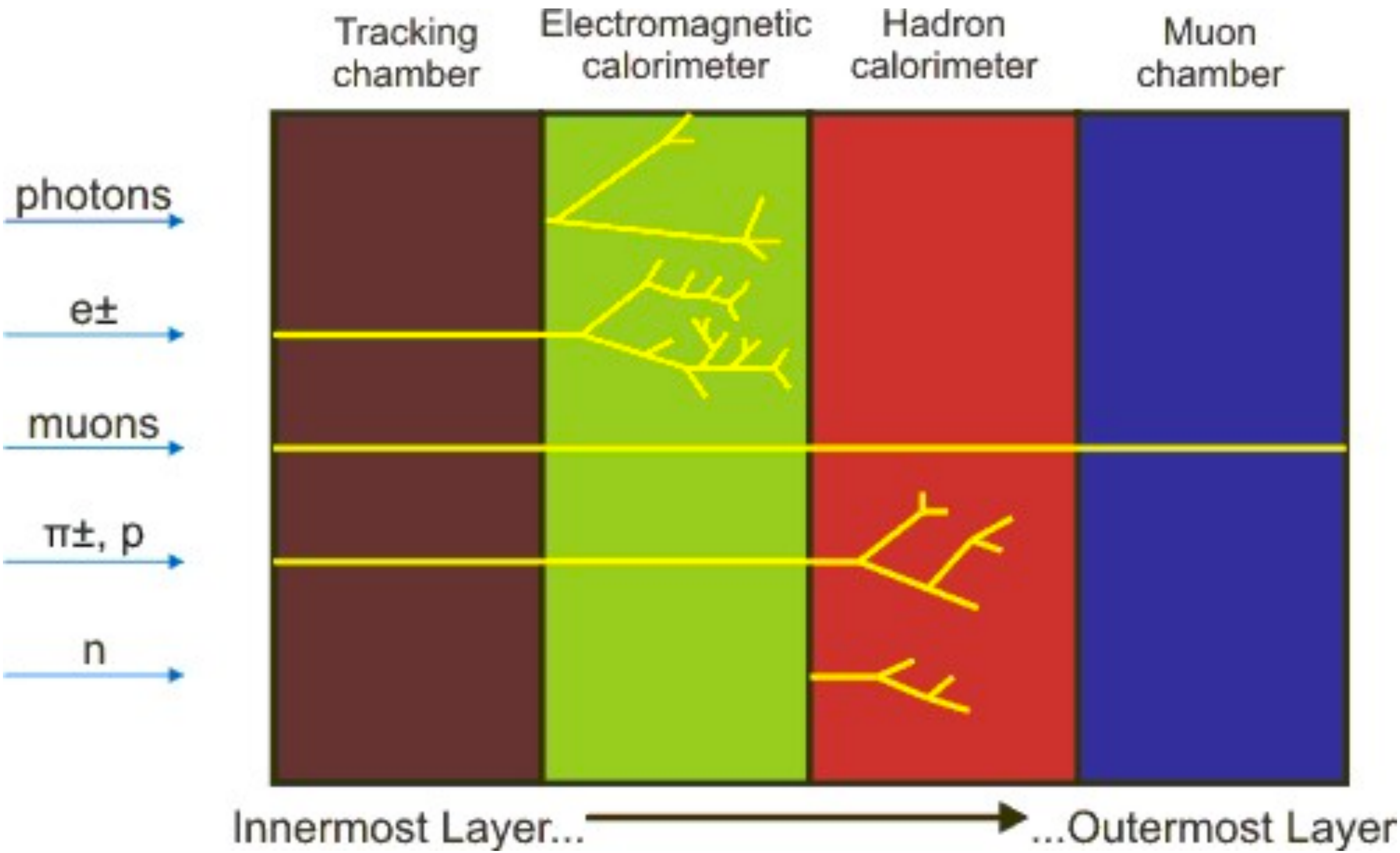
Physics process hypothesis



Particle Physics Detectors

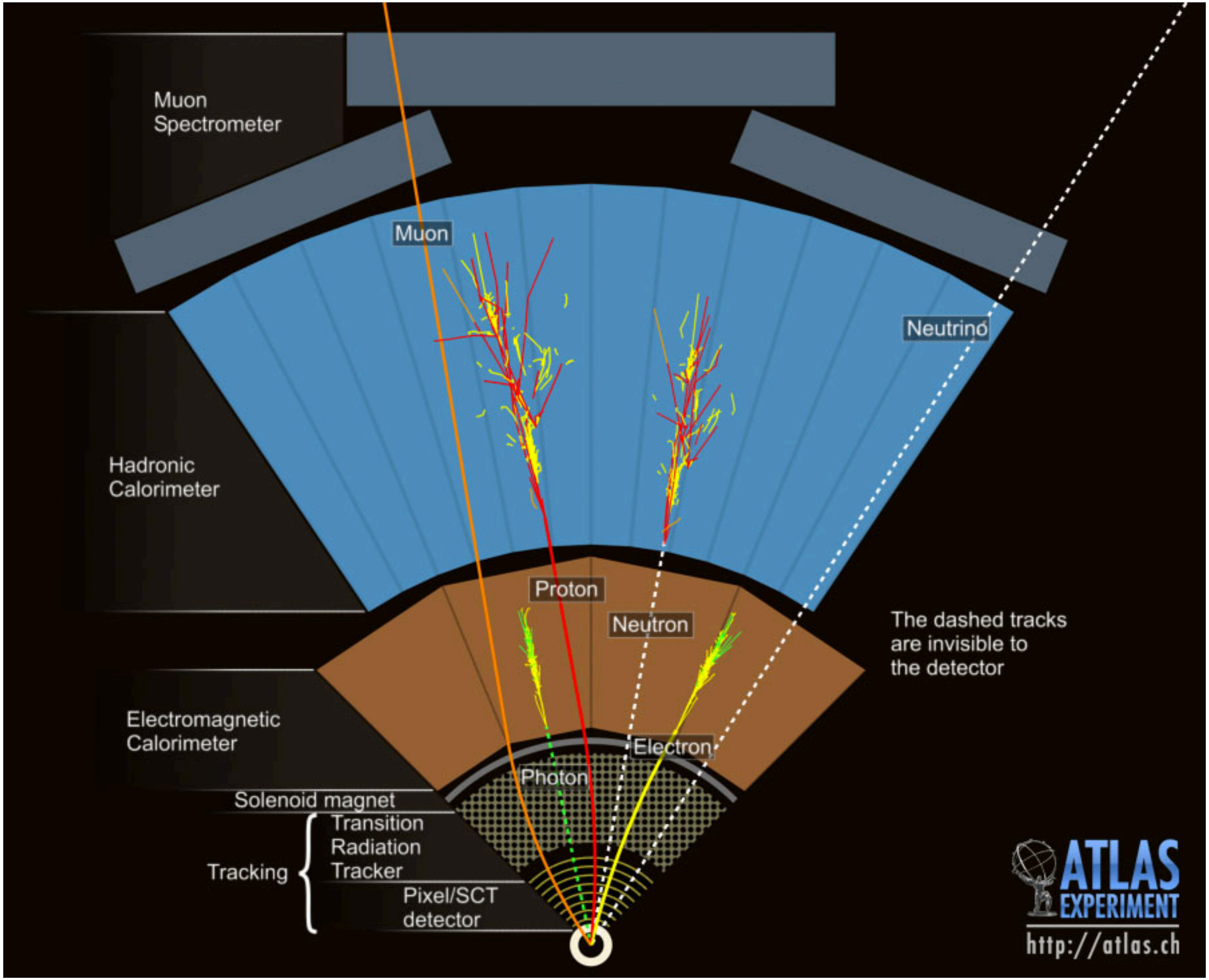
Courtesy: Rick Cavanaugh

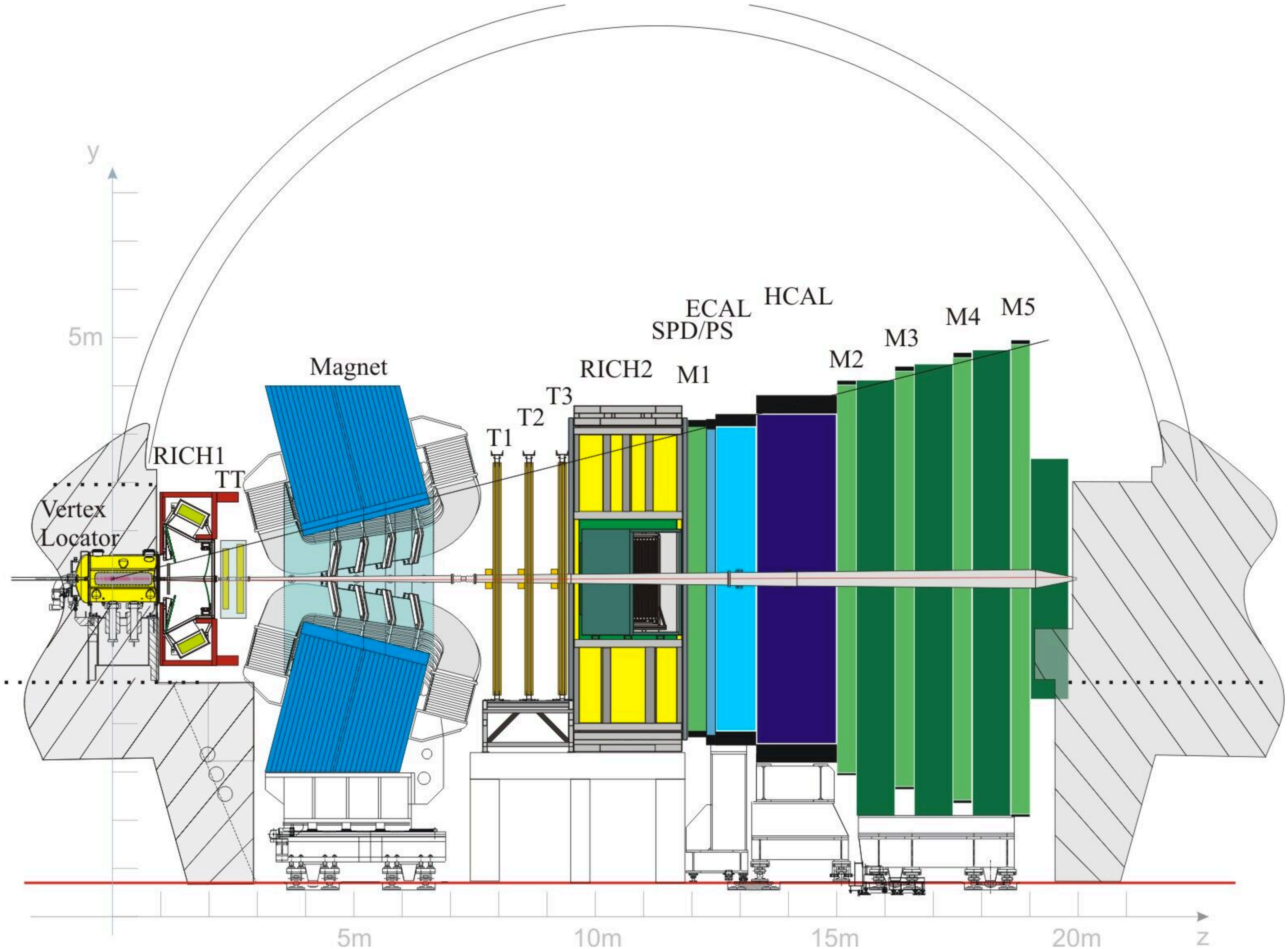
Particle identification



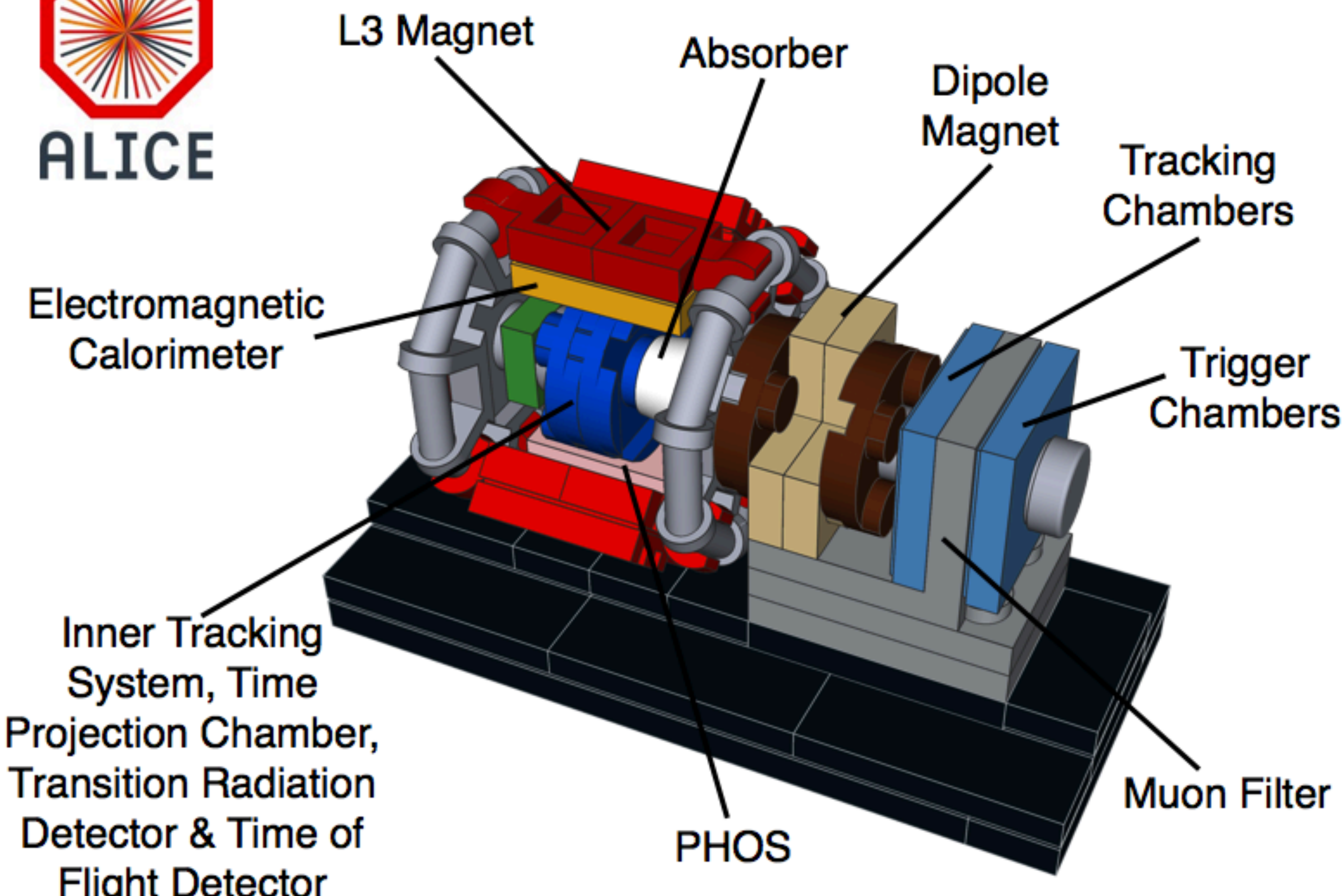
CMS

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004


Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
Muon
Proton
Neutron
Neutrino
Electron
Photon
The dashed tracks
are invisible to
the detector
ATLAS
EXPERIMENT
http://atlas.ch


y
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

ALICE


L3 Magnet
Absorber
Dipole Magnet
Tracking Chambers
Electromagnetic Calorimeter
Trigger Chambers
Inner Tracking System, Time Projection Chamber, Transition Radiation Detector & Time of Flight Detector
PHOS
Muon Filter

Reconstruction Basics

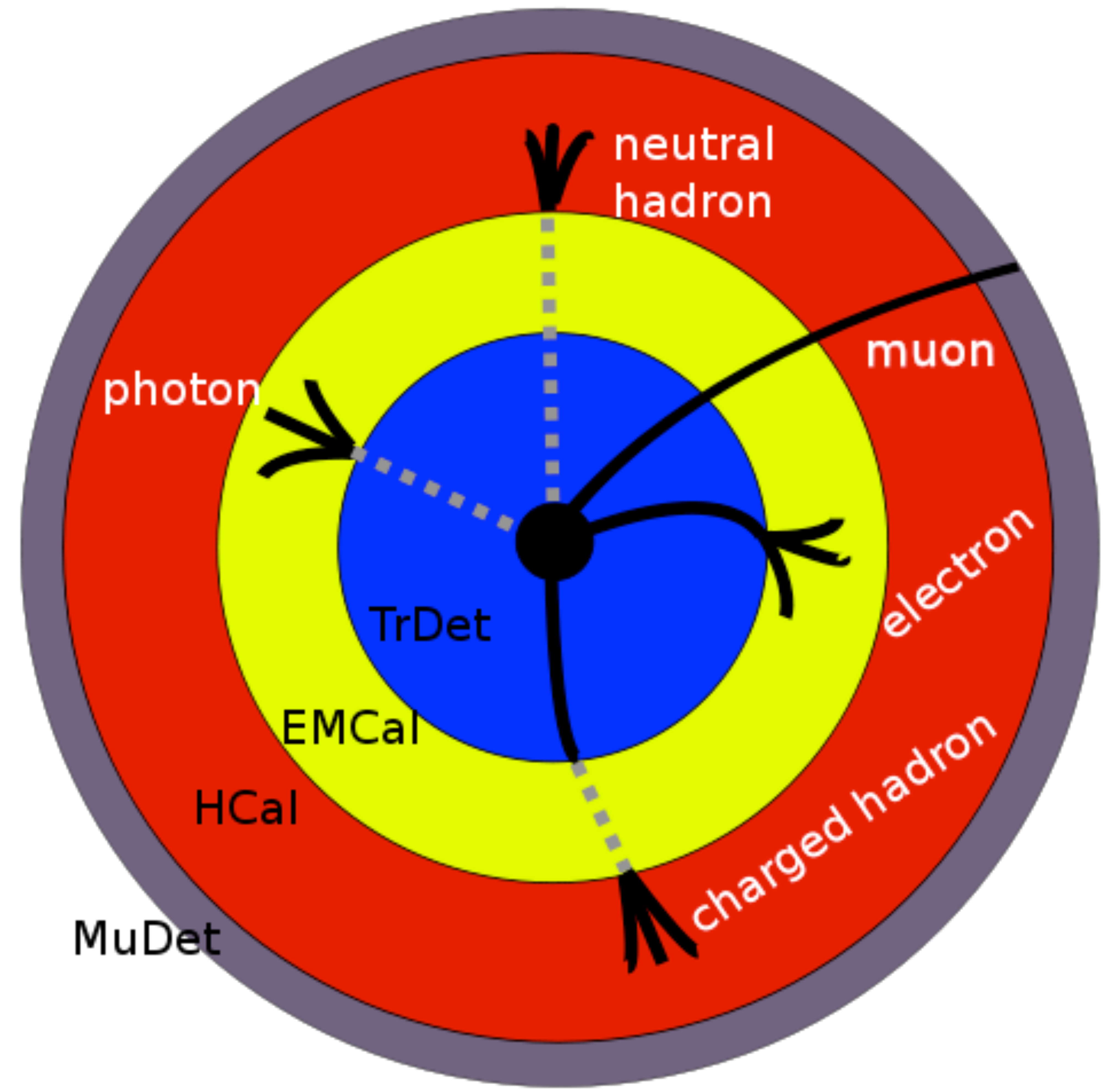
Detectors are built in layers to detect different species of (semi-) stable particles

Goal: determine momentum, energy, charge, mass

Techniques:

- Energy loss (dE/dx)
- Total Energy (E_{dep})
- Velocity (β)
- Curvature ($1/\rho$)

Detectors are like ogres



MuDet: muon detectors
TrDet: trace detector + vertex detector
EMCal: elekcromagnetic calorimeter
HCal: hadron calorimeter

Big picture goals

Introduce the basic way we identify particle types and measure particle properties

- Important: the resolution effects associated with performance of that reconstruction

Next:

- Explore the **complementarity** of those measurements

Build up those objects to get to more complex objects

Goals:

Understand why we have all these different layers of detector and how they complement each other!

Understand reconstruction strategies, from the simplest to the most complex objects, and the physics concepts behind them

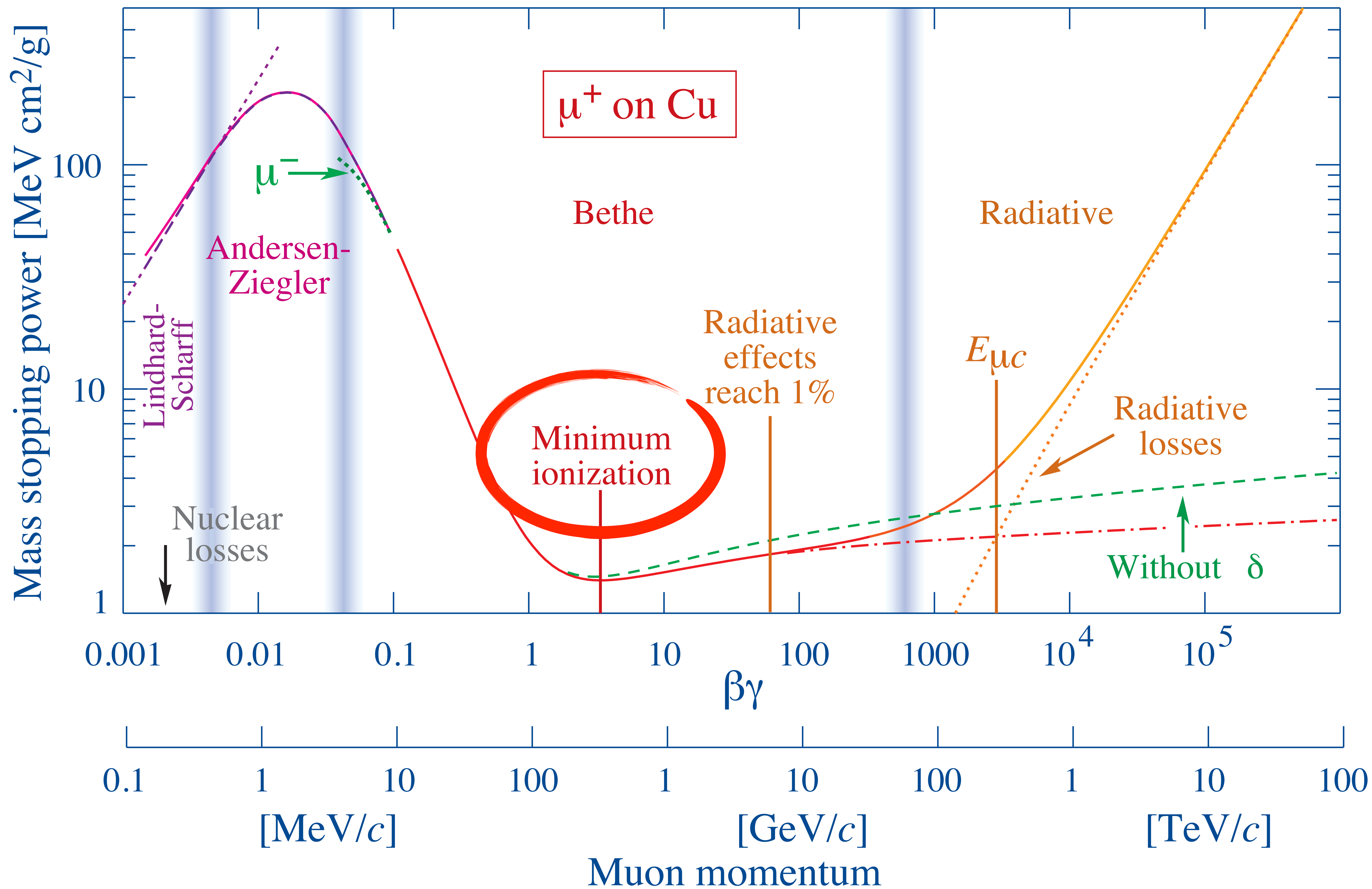
1. BUILDING BLOCKS AND DETECTORS

Tracking, Timing, Calorimetry, Particle ID

Particles in matter

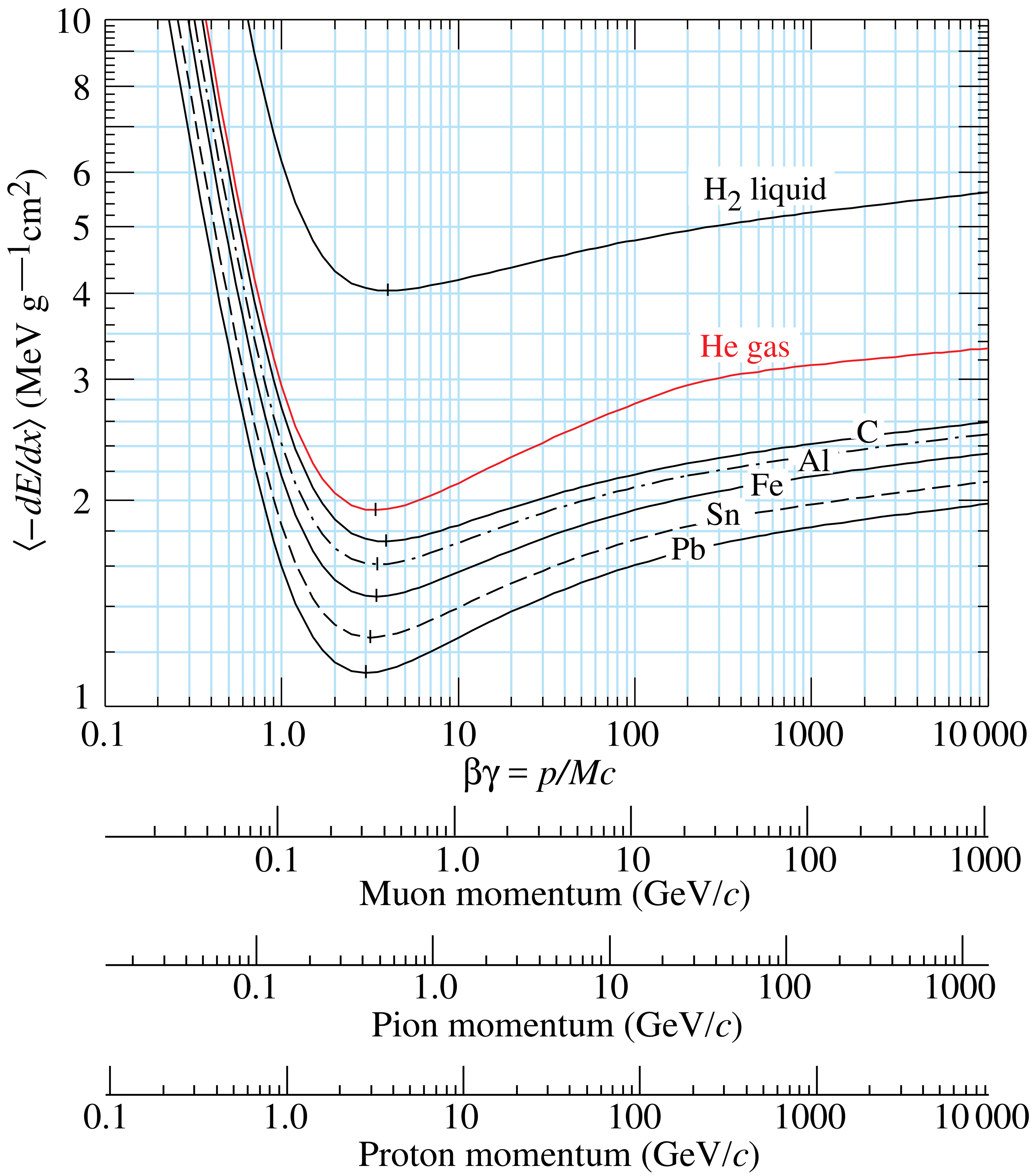
Charged (heavy) particle energy loss in material via ionization (e.g. muon, pion, protons)

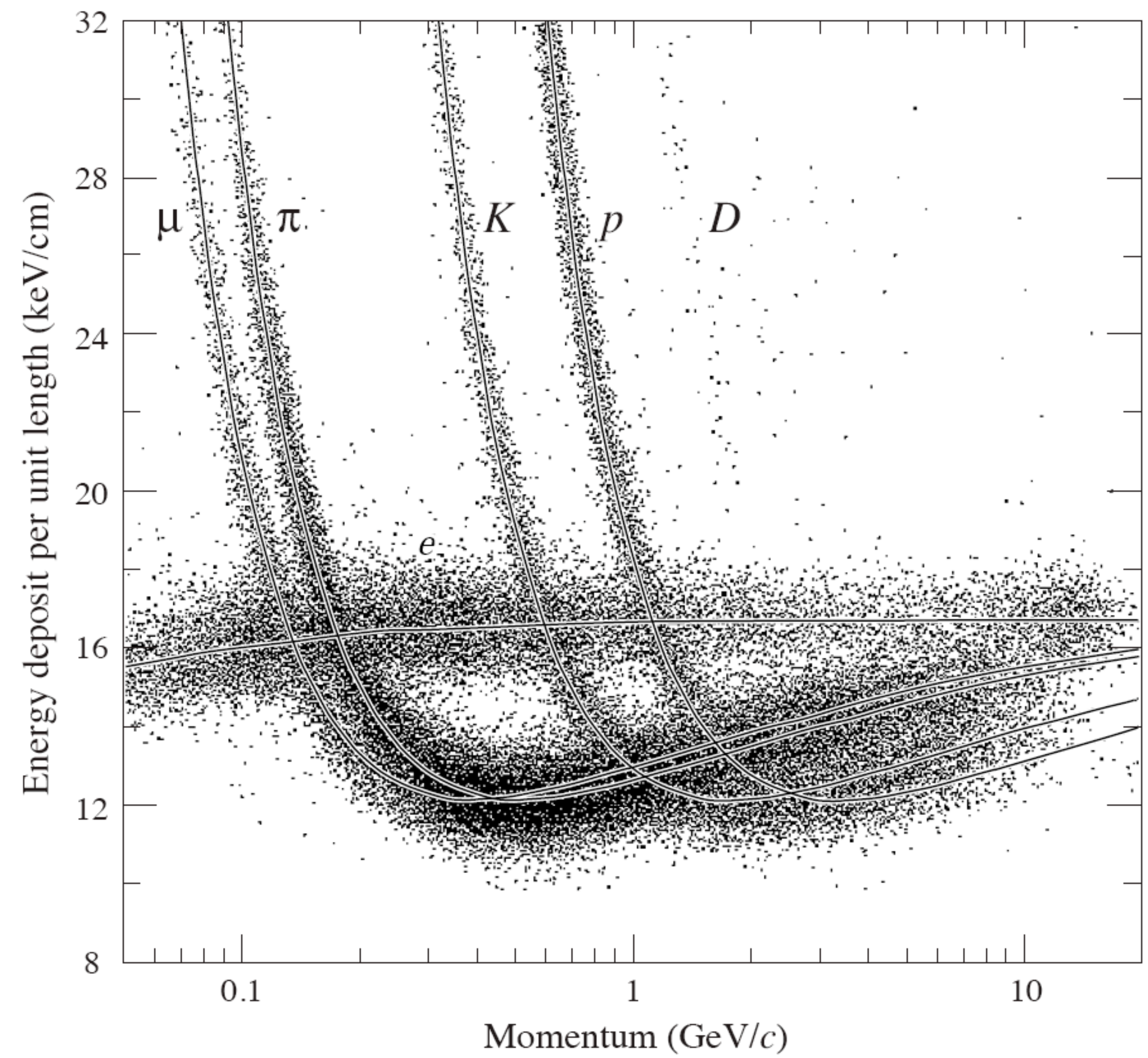
material modeled as a free electron cloud to leading order



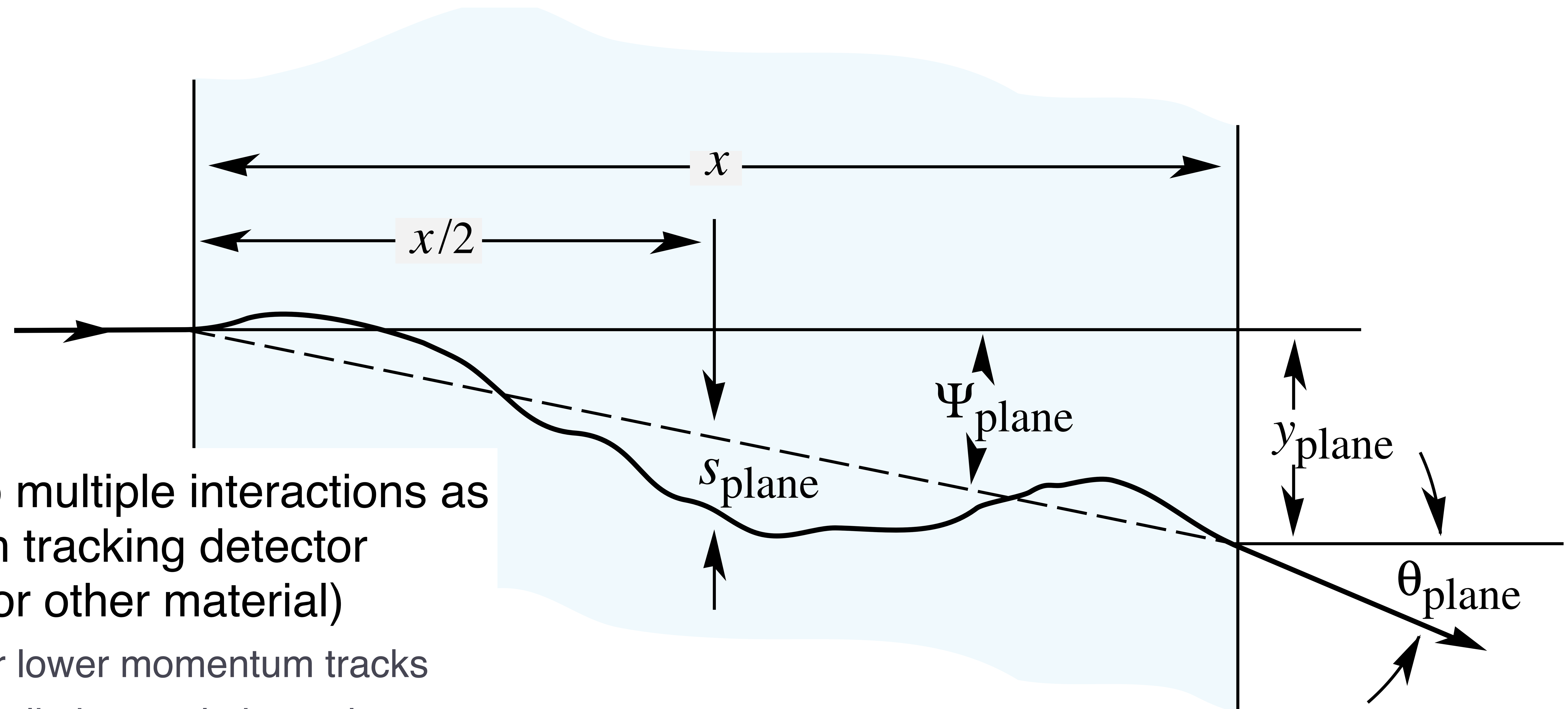
$$\left\langle -\frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

MIPs and particle ID





Multiple scattering

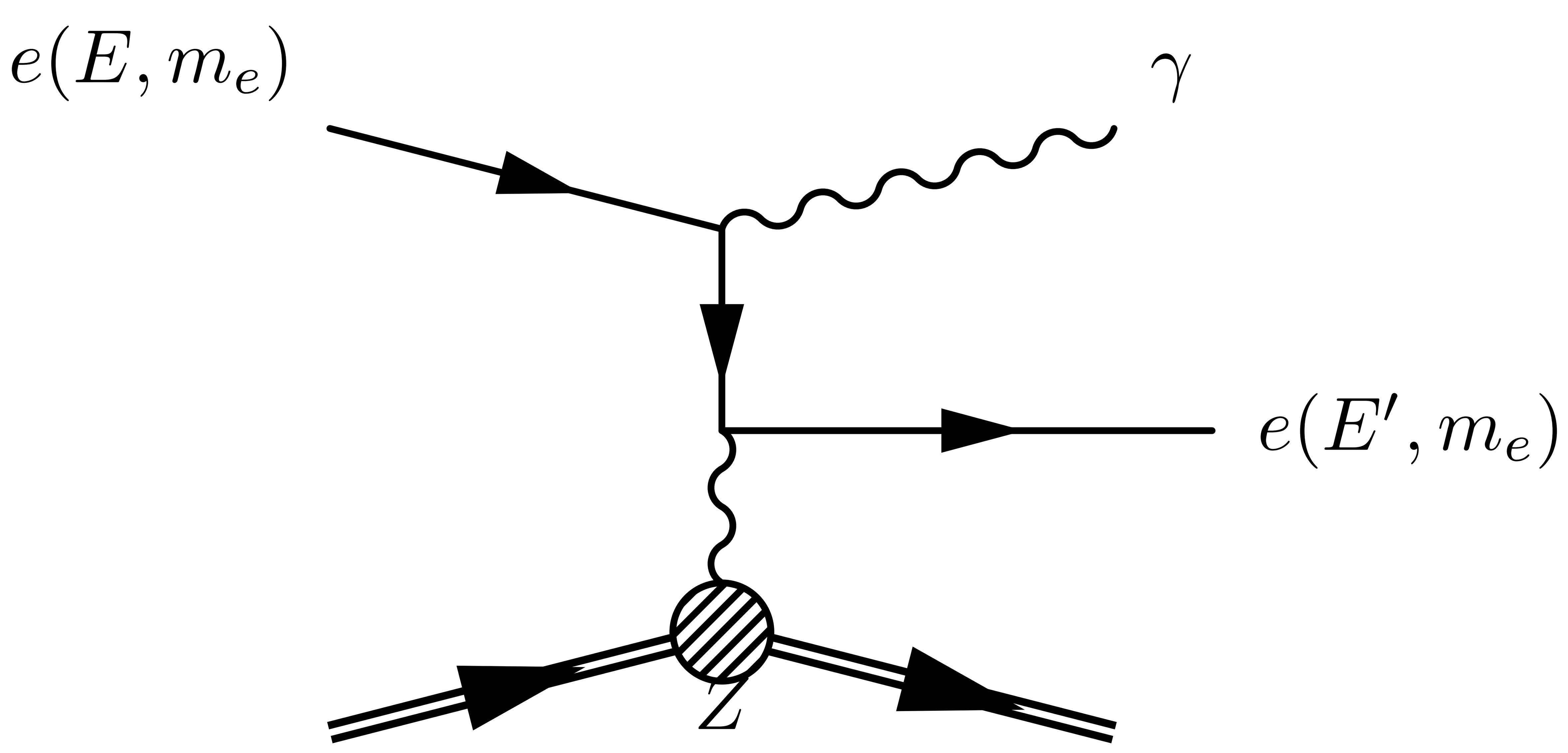


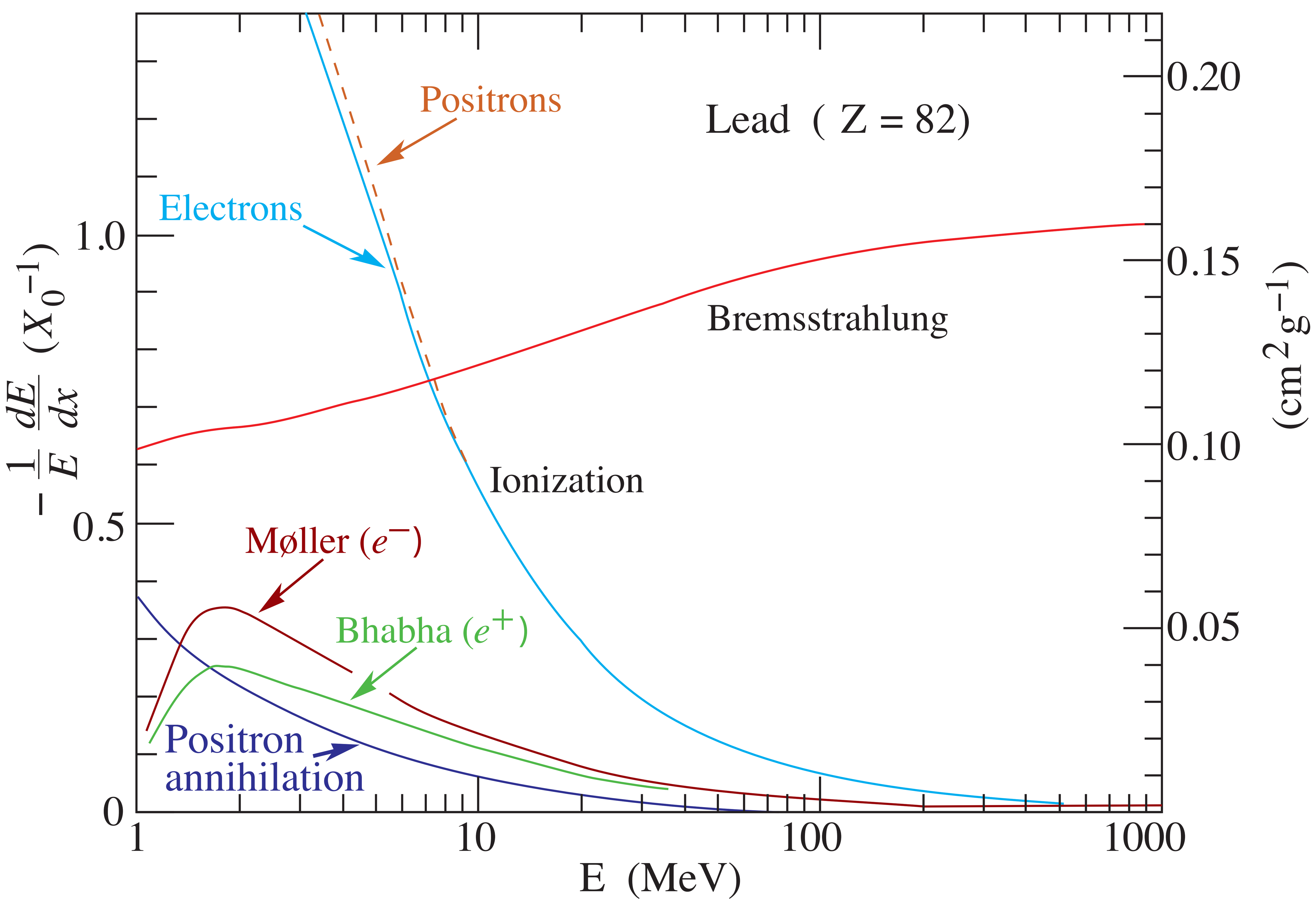
- Particles undergo multiple interactions as they pass through tracking detector material (and air or other material)
  - A bigger effect for lower momentum tracks
  - Multiple scattering limits resolution at low p
  - Tracks no longer follow a Helix
- Probability that after passing through a thickness x of a material with radiation length X_0 a particle is deflected by an angle θ is a gaussian distribution with sigma

$$\Theta_0 = \frac{0.0136}{\beta c p\,[\mathrm{GeV}/c]} Z \sqrt{\frac{x}{X_0}}$$

Bremsstrahlung

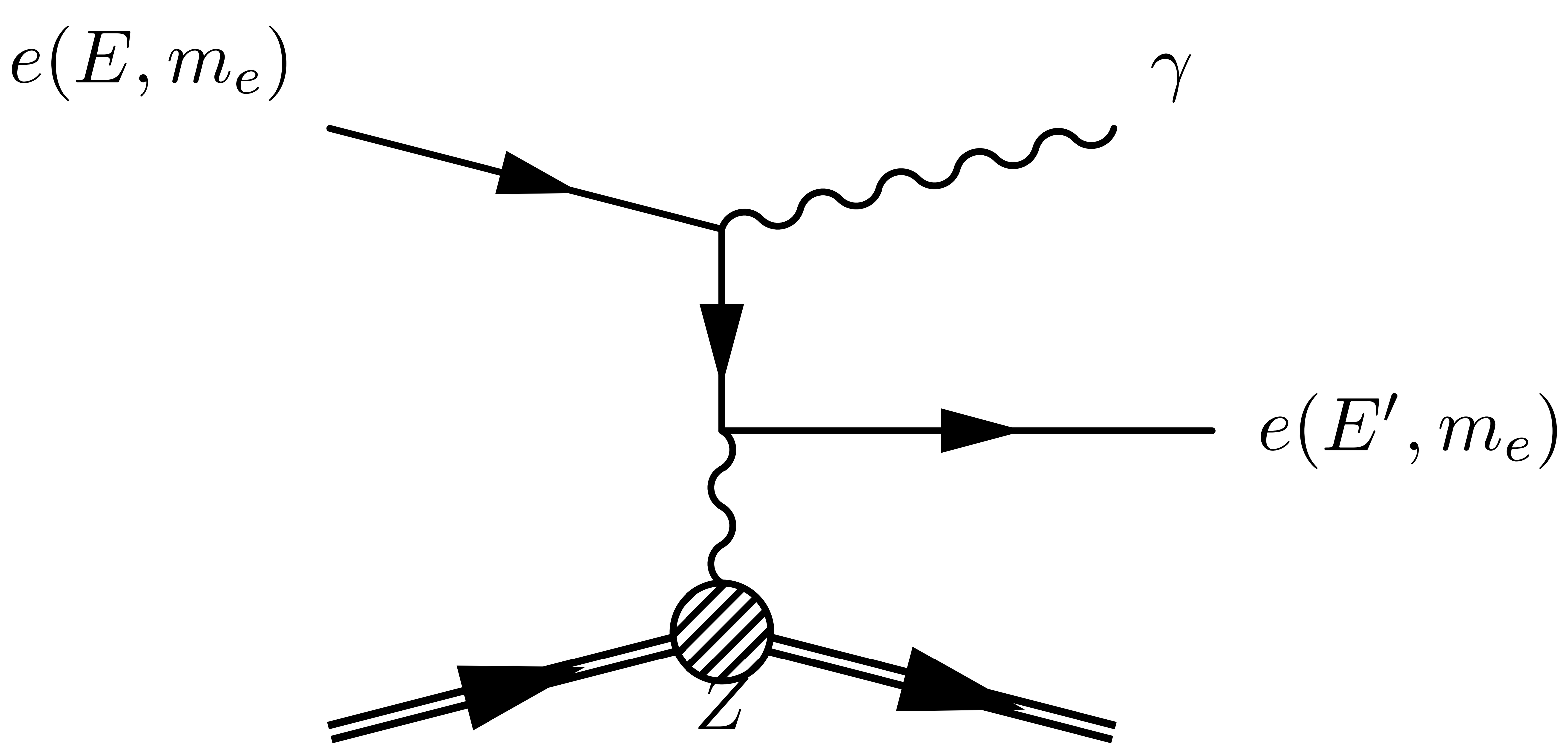
For lighter charged particles (i.e. electrons), bremsstralung (braking radiation) dominates





Bremsstrahlung

For lighter charged particles (i.e. electrons), bremsstralung (braking radiation) dominates



Energy loss is proportional to the energy of the incoming particle

Compare to Ionization which is flat in Energy

Energy loss proportional to 1/m2 of the incoming particle

Muons radiate much less than electrons via Bremsstrahlung

$$|dE/dx|_{\text{brems}} \approx E/X_0$$

$$\frac{1}{X_0} = 4\left(\frac{\hbar}{m_e c}\right)^2 Z(Z+1)\alpha^3 n_a \log\left(\frac{183}{Z^{1/3}}\right)$$

X0 is the Radiation length which is a characteristic of the material

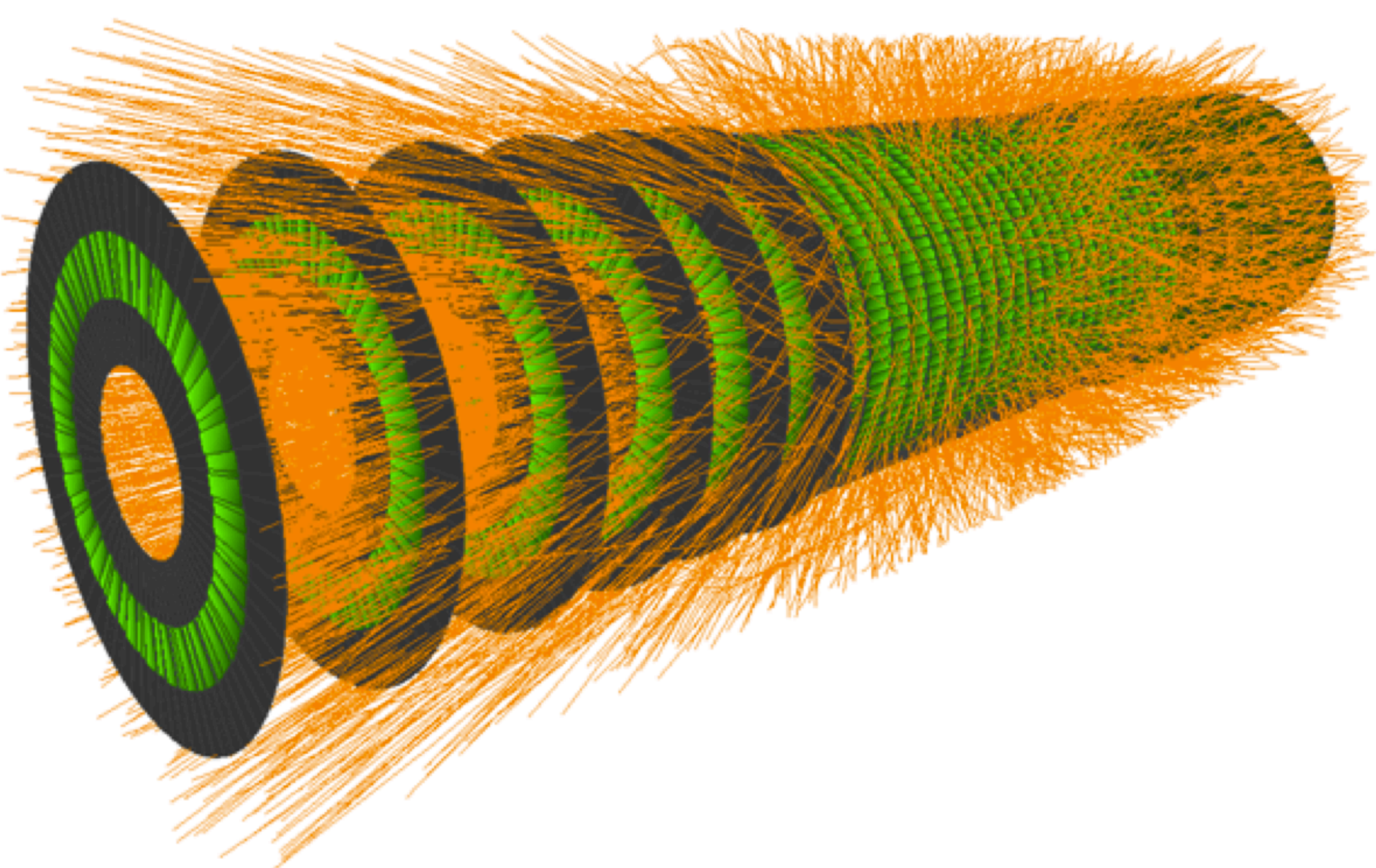
The incoming particle energy will decrease to $E_0 e^{-1}$ after traveling through one X0 of material

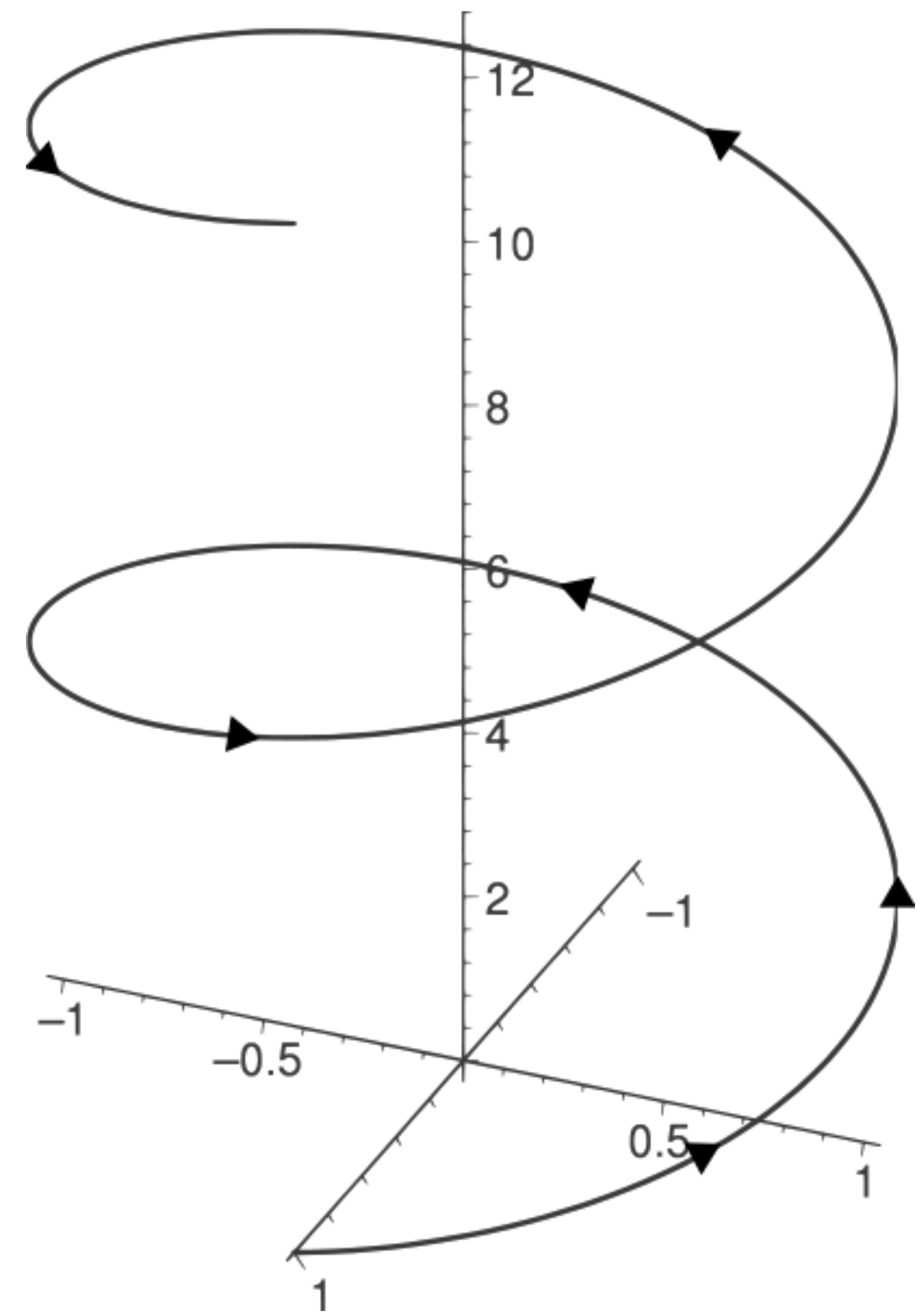
TRACKING

Charged particles in a strong magnetic field follow a helical trajectory with curvature proportional to momentum

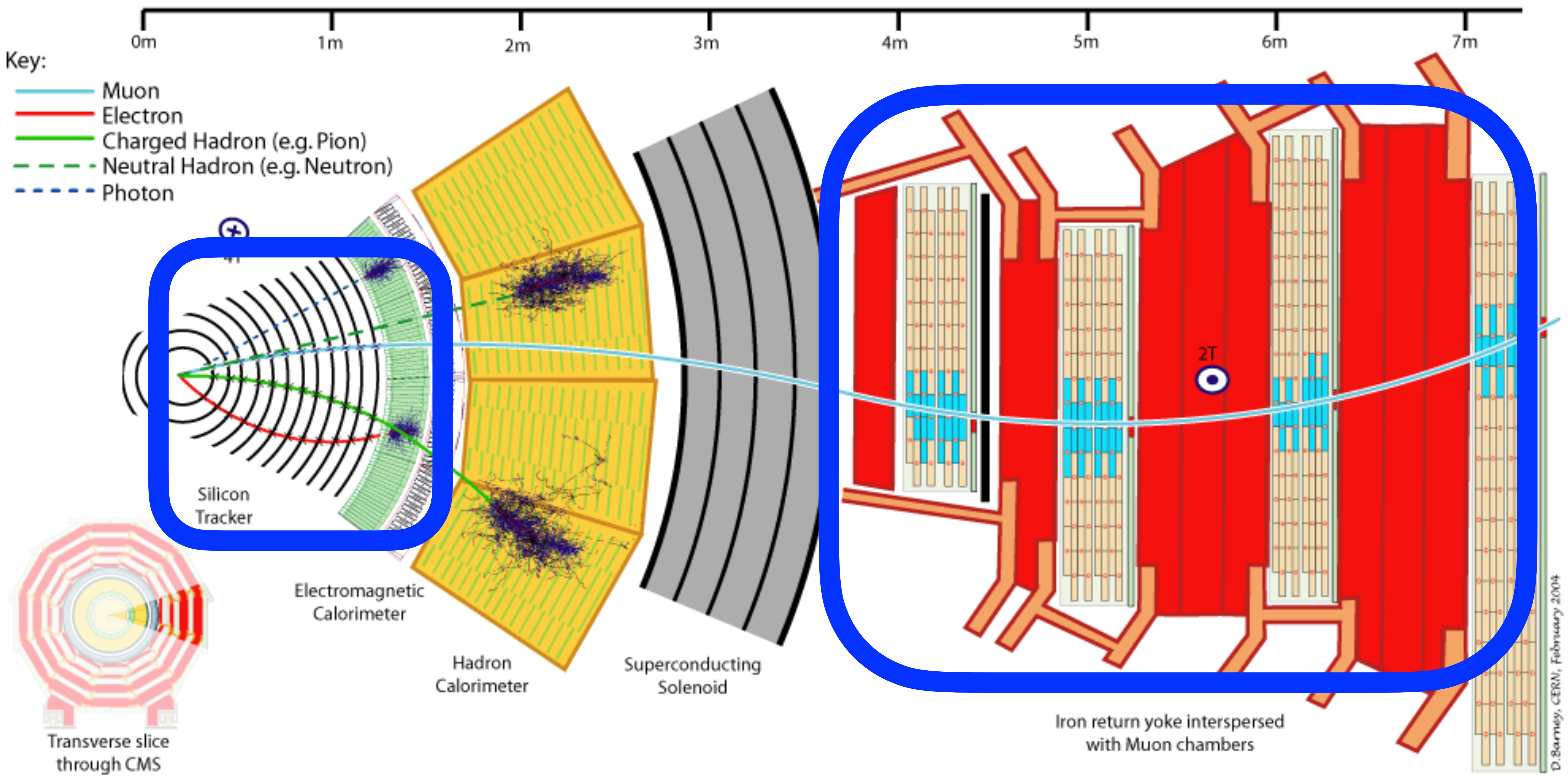
Determine track parameters:

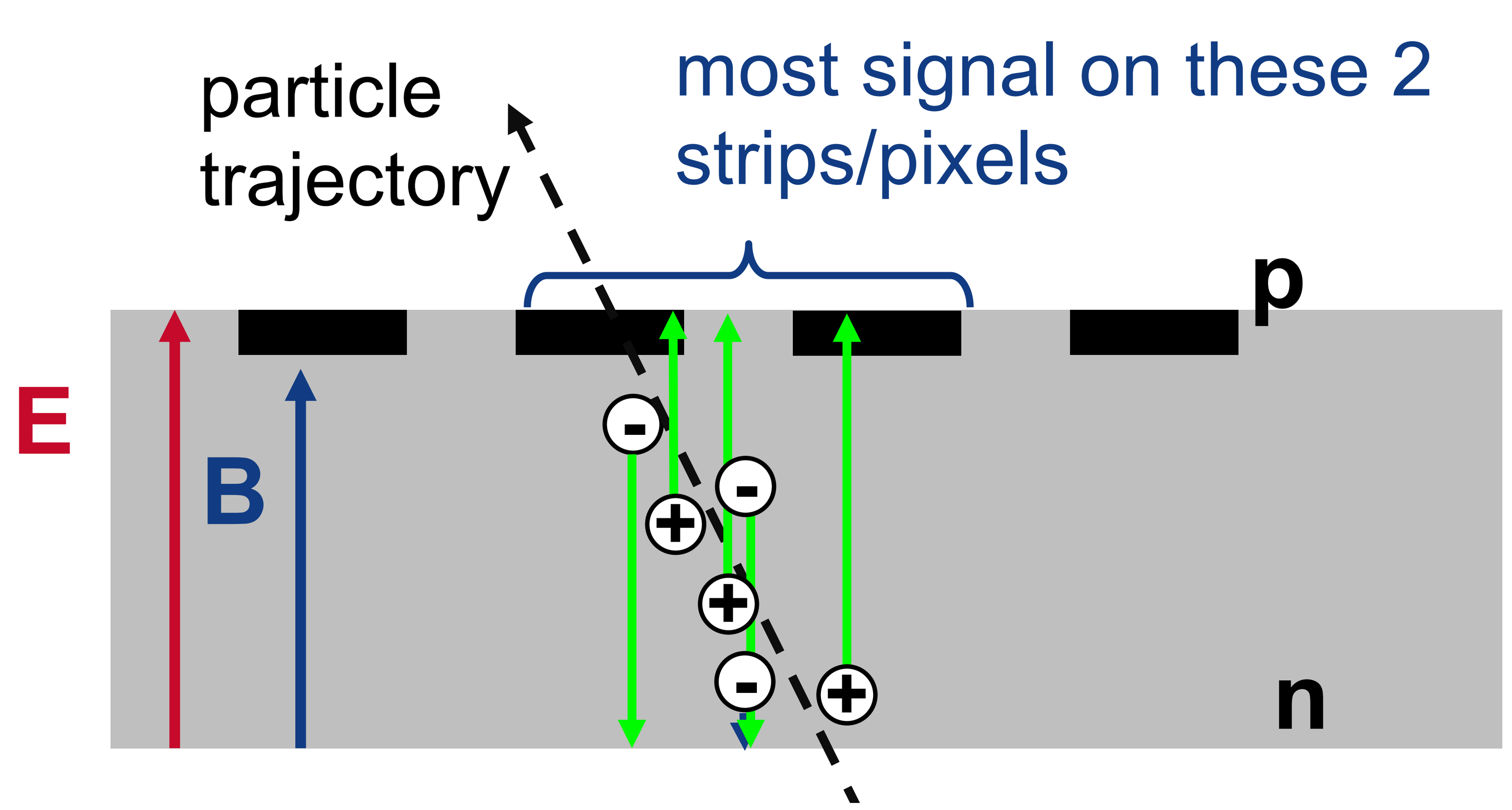
- pT
- theta, phi
- impacts parameters: d0, dz

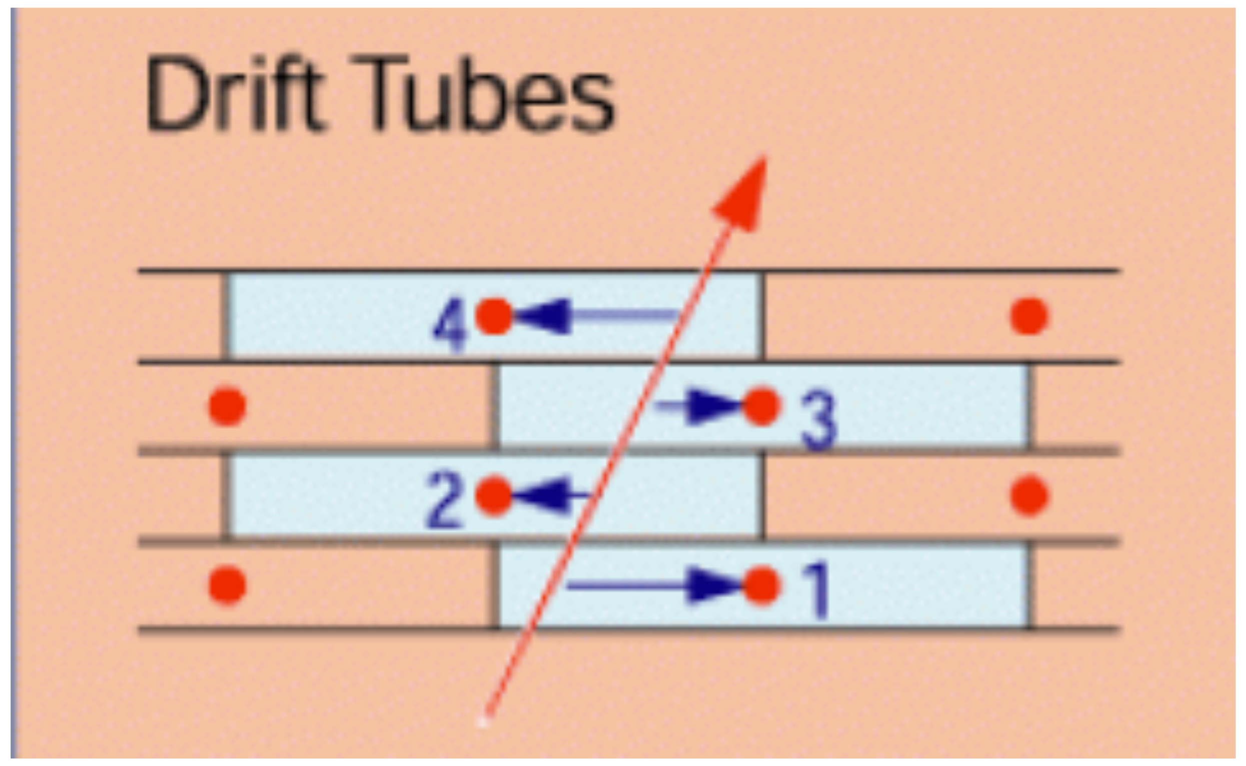




Tracking challenge





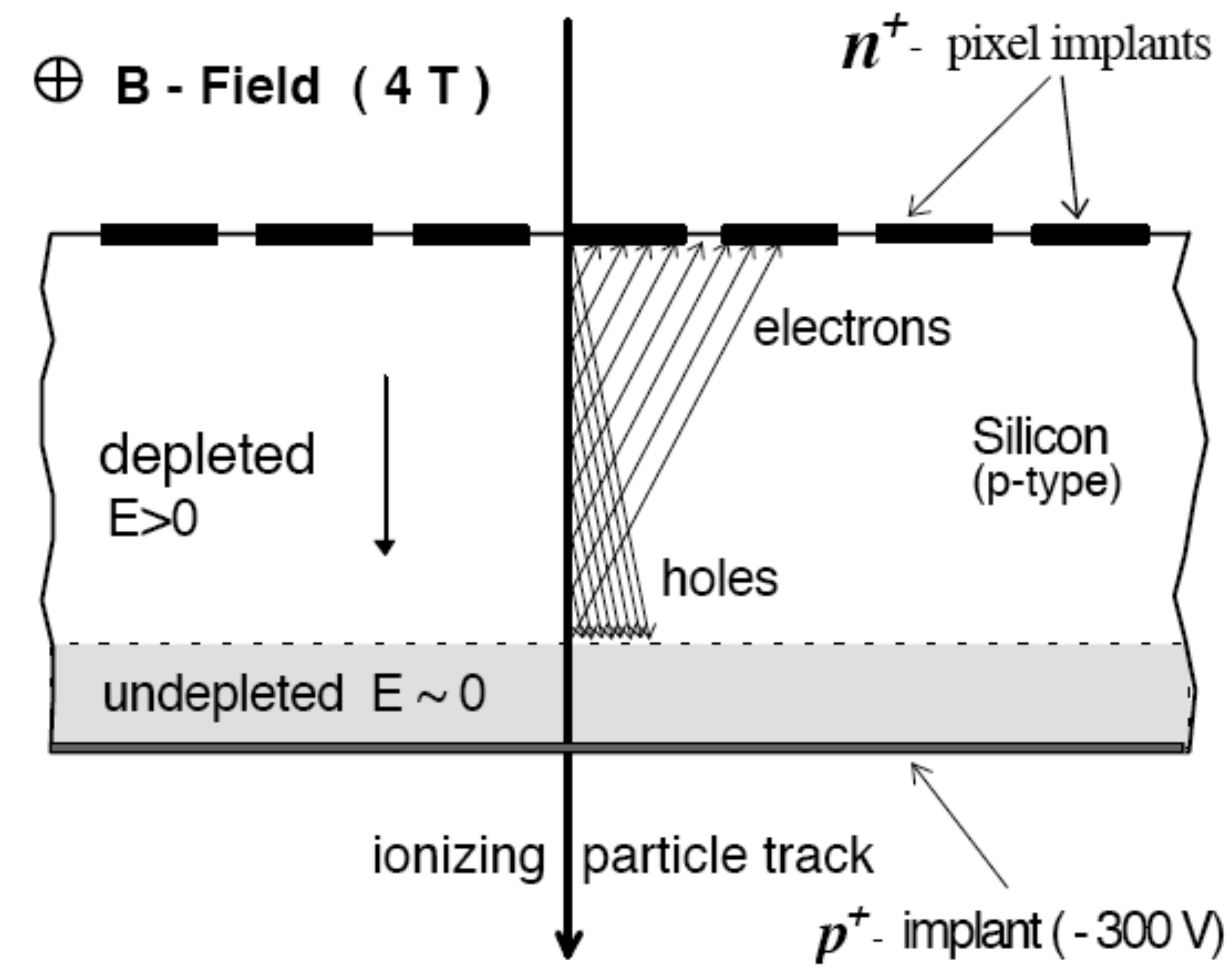


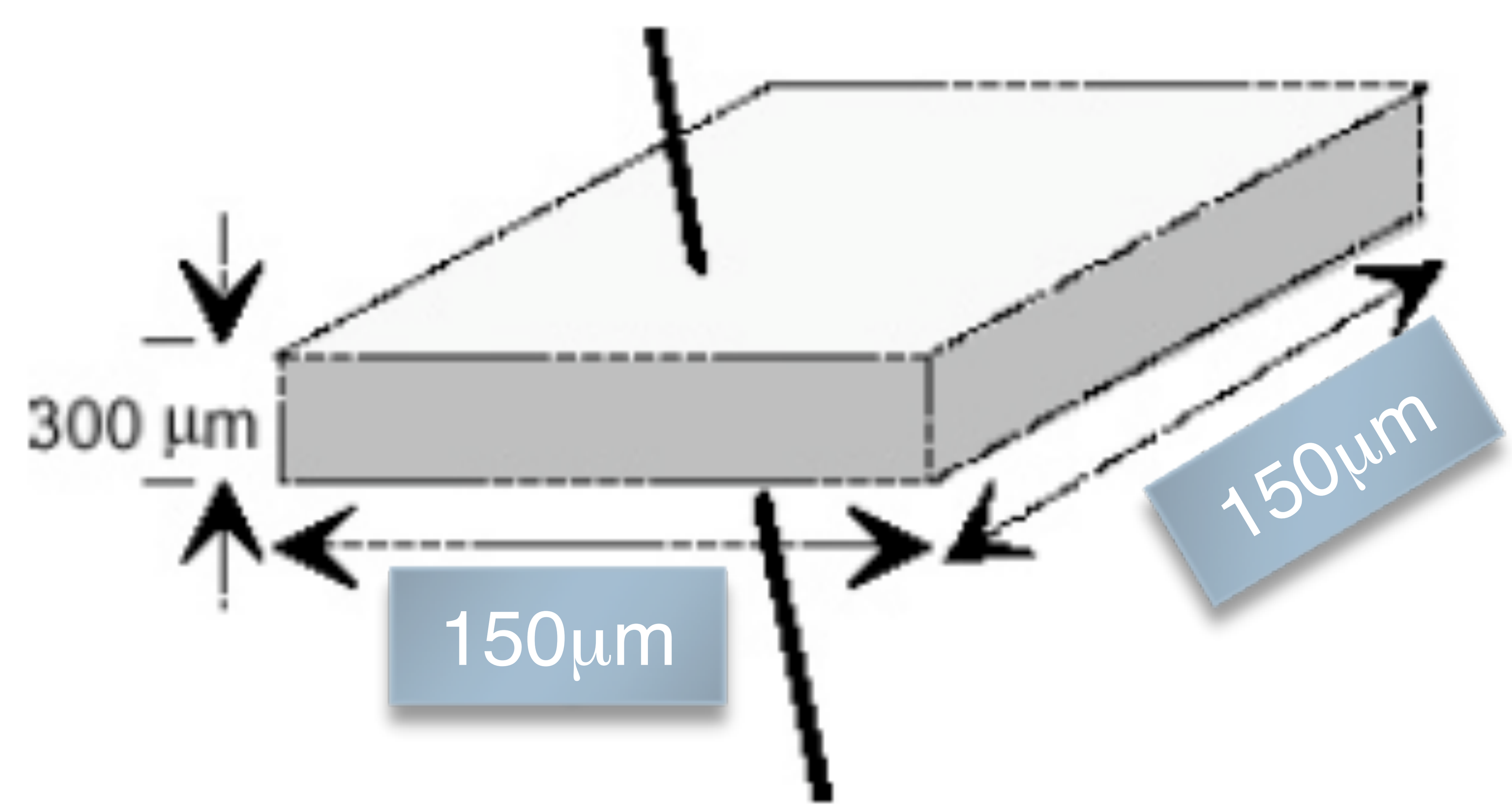
Precise, high-granularity silicon pixel and strip detectors are the workhorse

Muon trackers have to economically cover a lot of ground! Example are gaseous drift tube detectors

SILICON PIXELS

- A reverse bias is applied to the diode which extends the depleted region
- When a charged particle passes through a silicon diode, many electron-hole pairs are created in the depleted region
  - Silicon is dense
    - Energy loss 3.8 Mev/cm
  - The energy to create an e-h pair is much lower than the ionization energy
    - 3.6eV compared to 10's of eV for Ioniztion
  - ~9000 e- created in each 100μm thickness of Silicon
- The electrons drift in the electric field to the end of the detector where they create a signal which can be read out
  - Charge sharing between neighboring pixels or strips allows us to achieve a better single hit position resolution



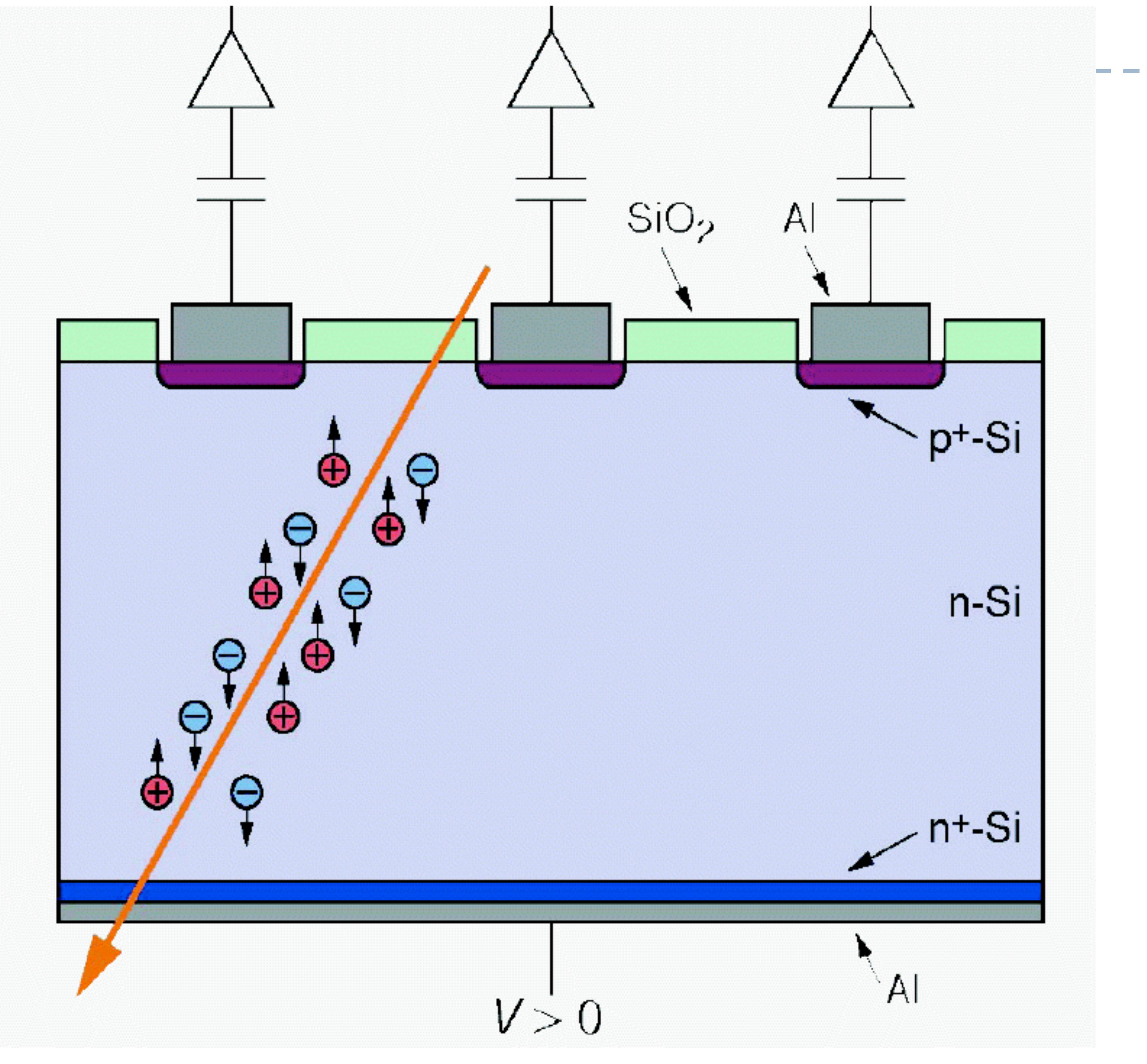


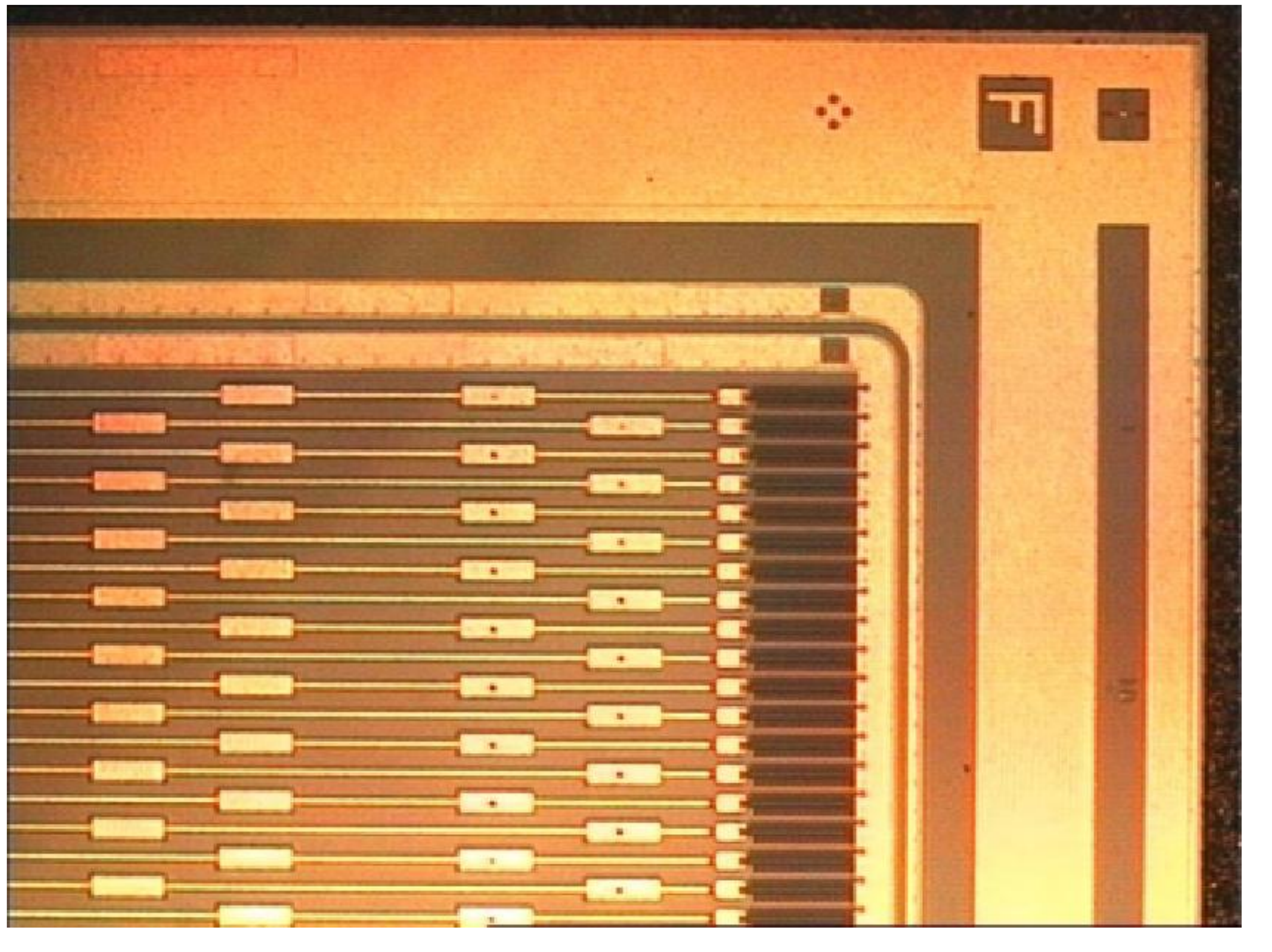
Low mass, radiation hard

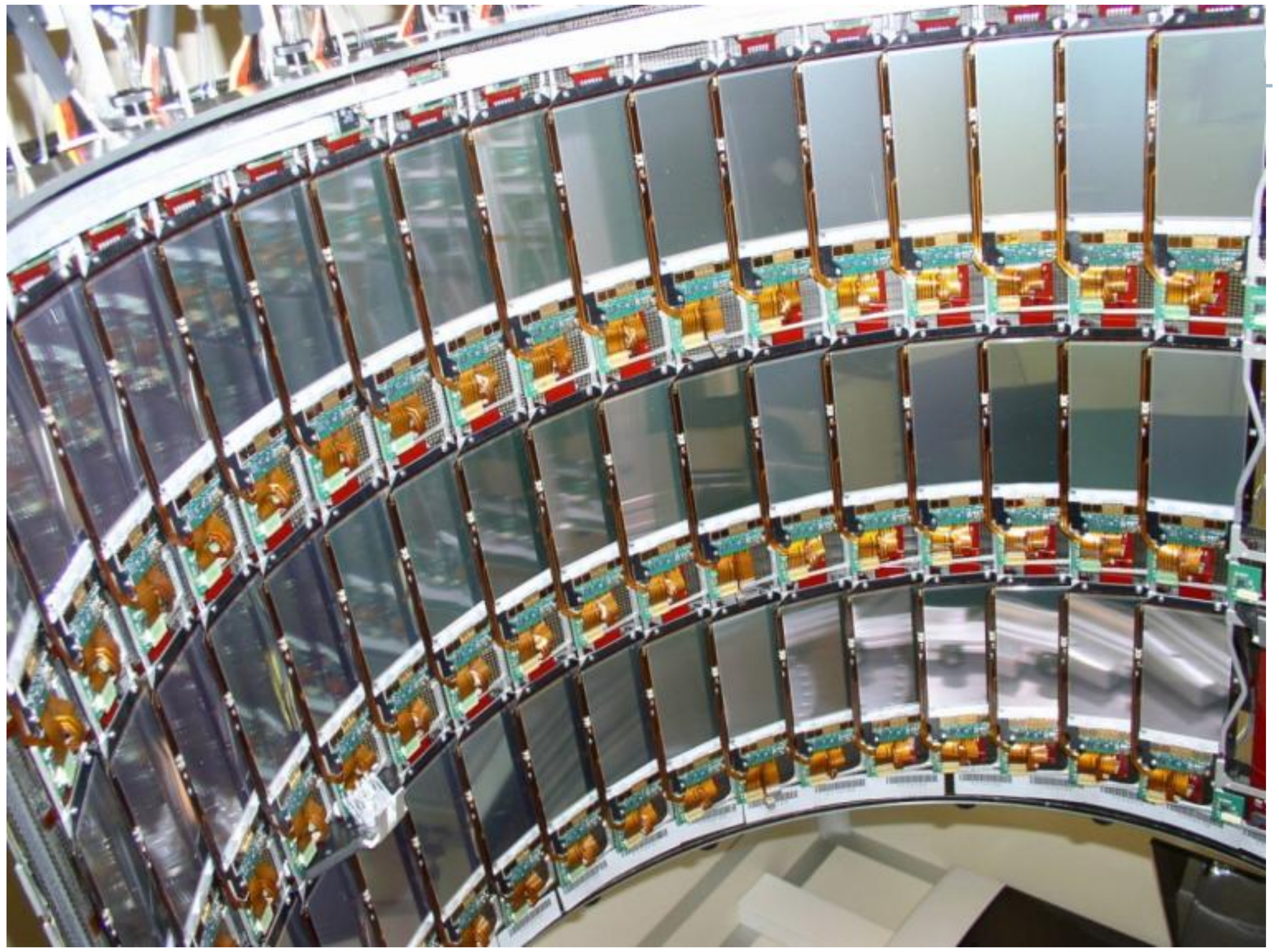
Typical Pixel

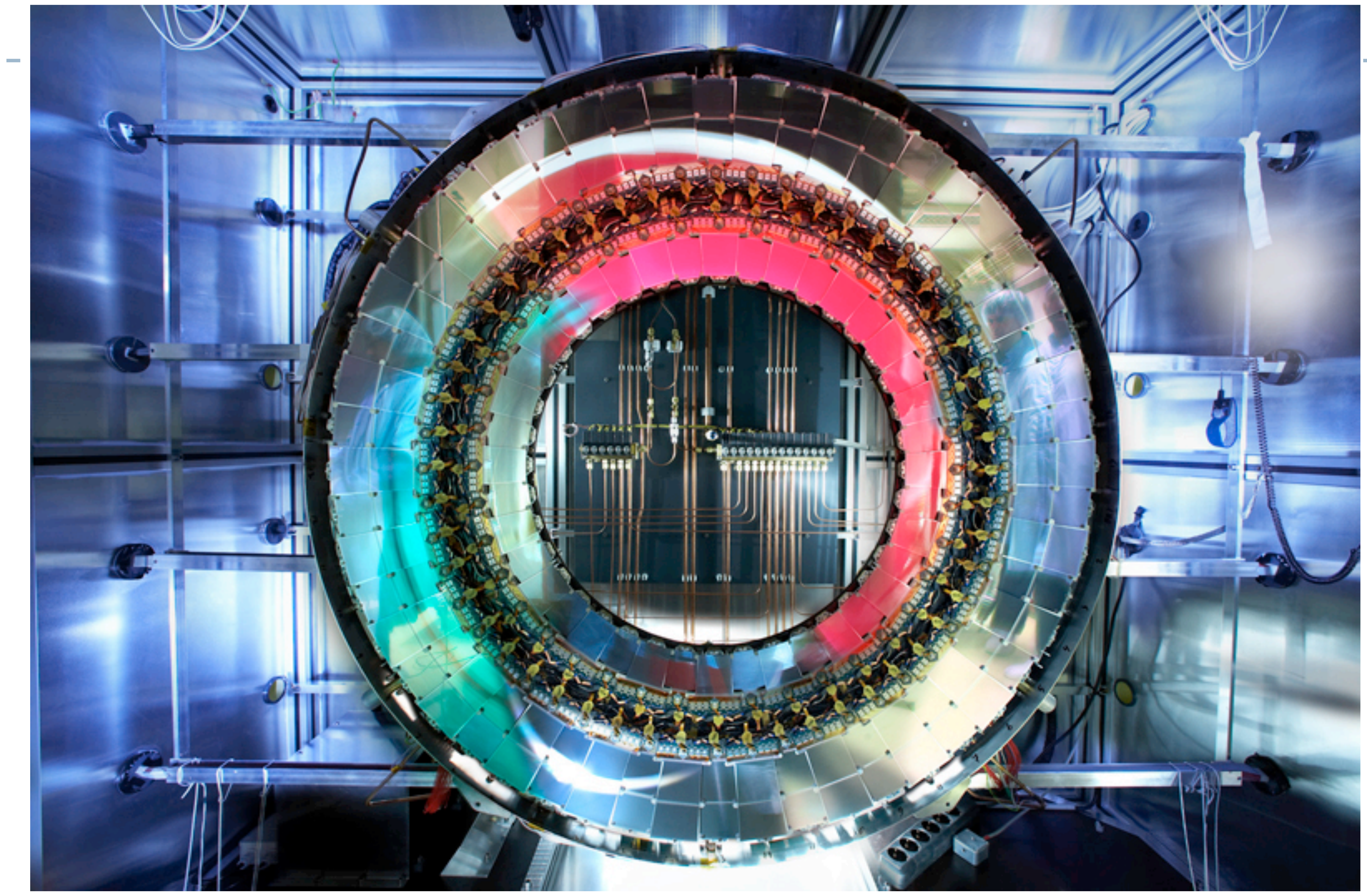
Silicon Strips

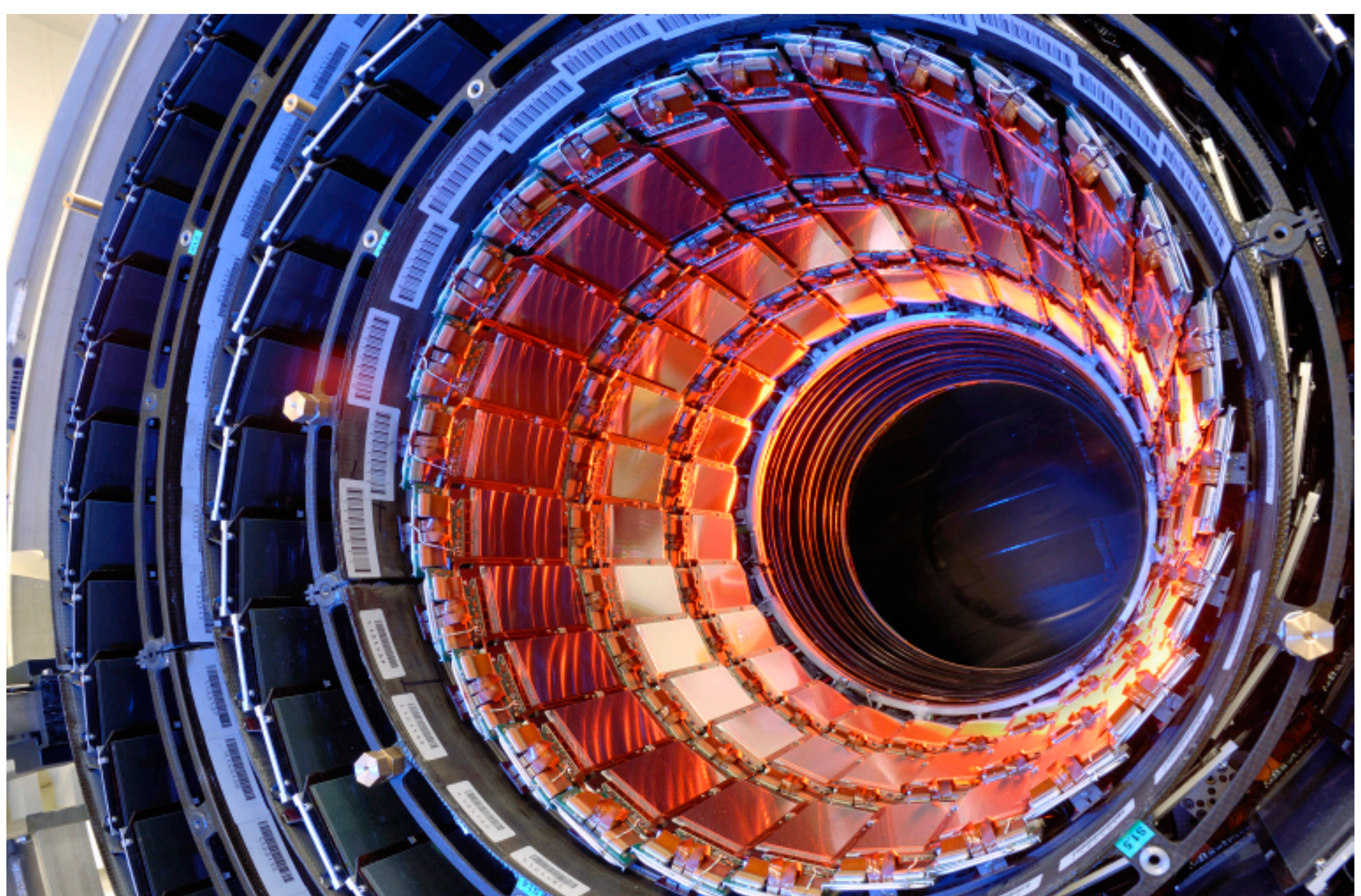
- Can't build an infinitely large pixel detector
  - Too many channels
  - Too expensive!
- Strip detectors can cover a larger area with less readout channels
  - Strips are placed separated by ~100μm
    - Metal of strip ~15μm
  - They are typically around 10cm long
  - Only a 2D resolution possible
    - Some 3D possible with "Stereo" layers

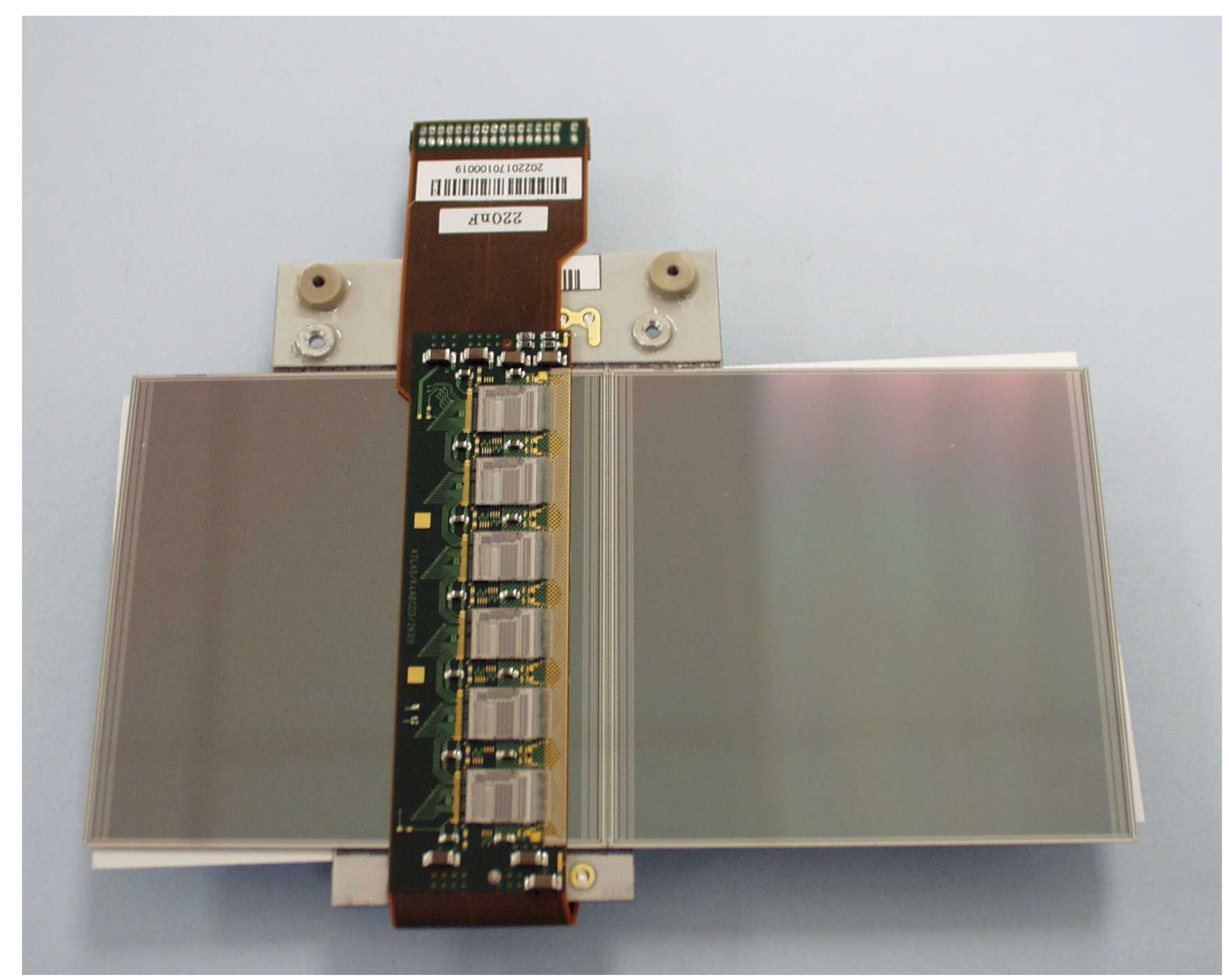






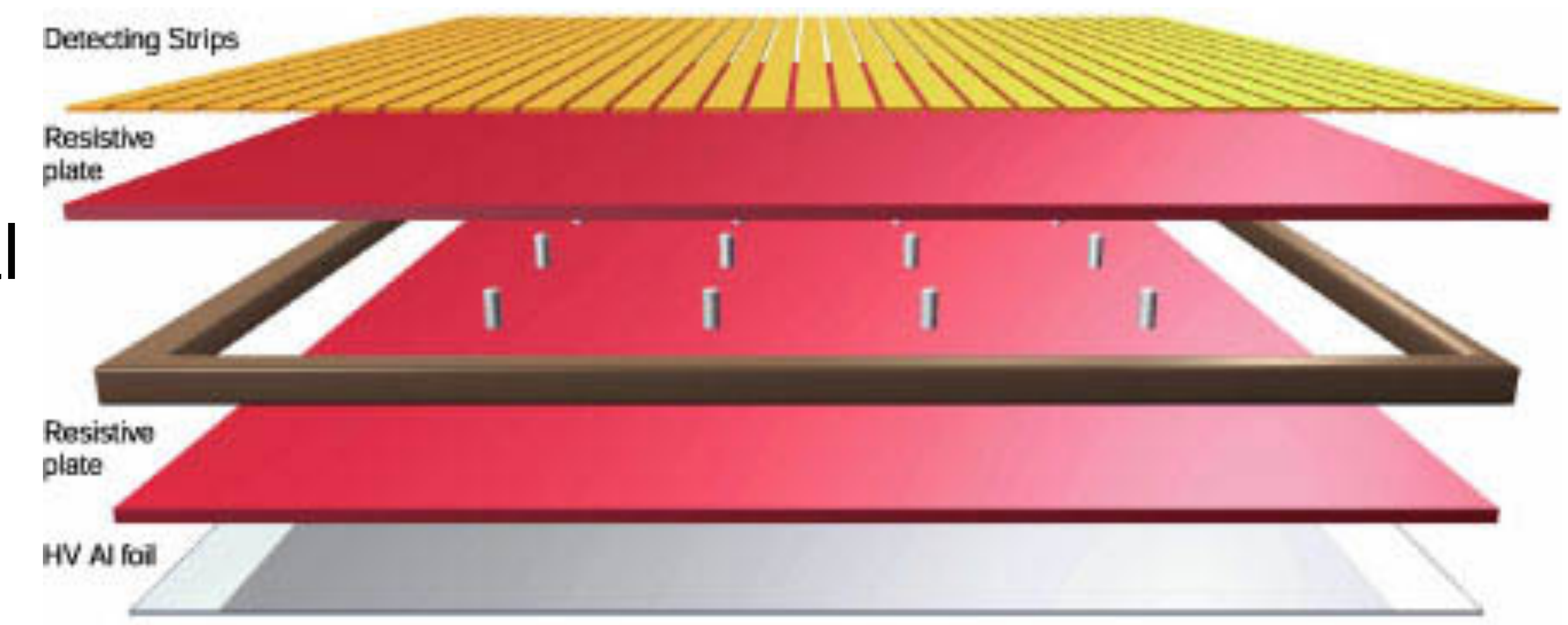


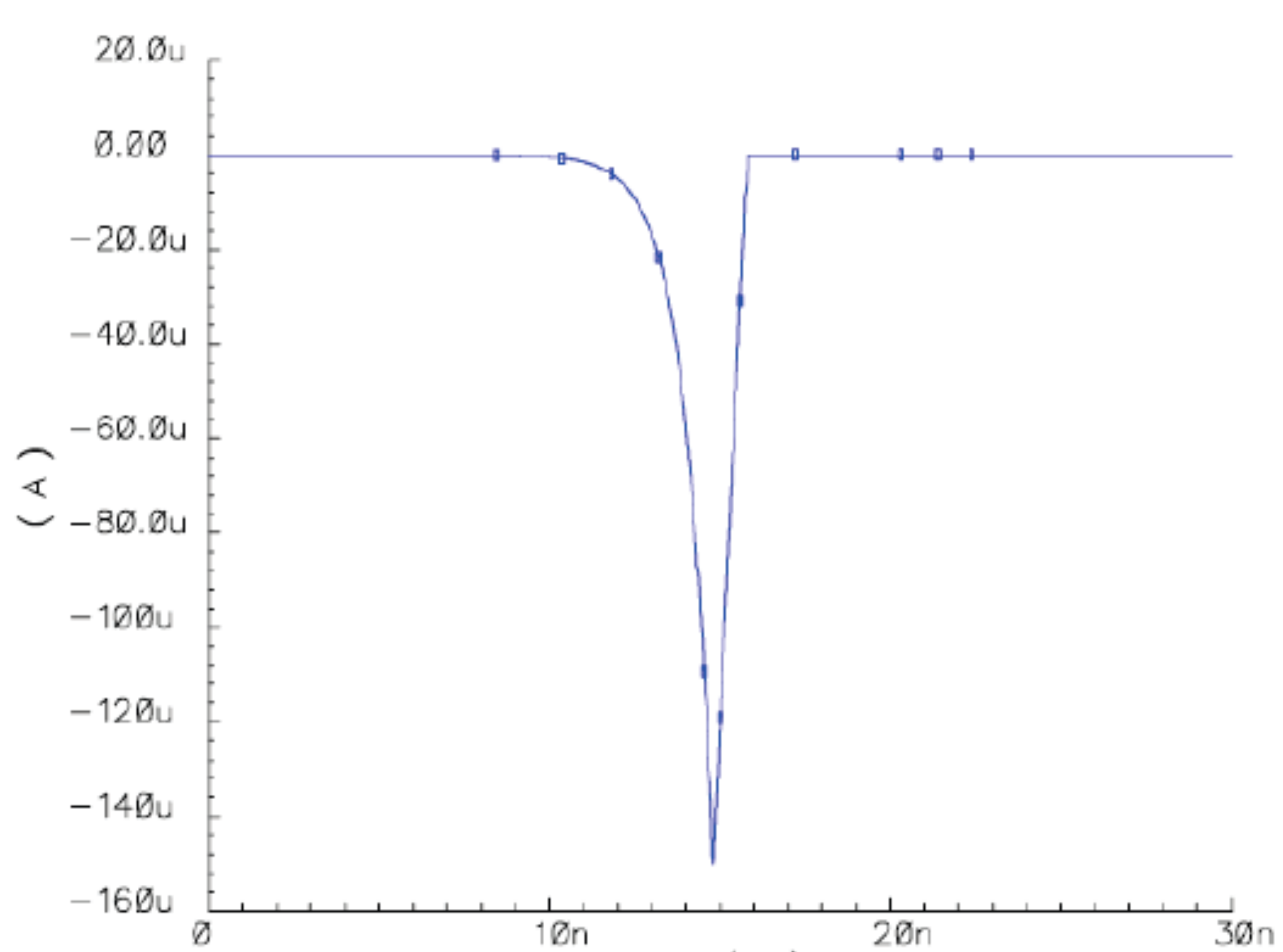


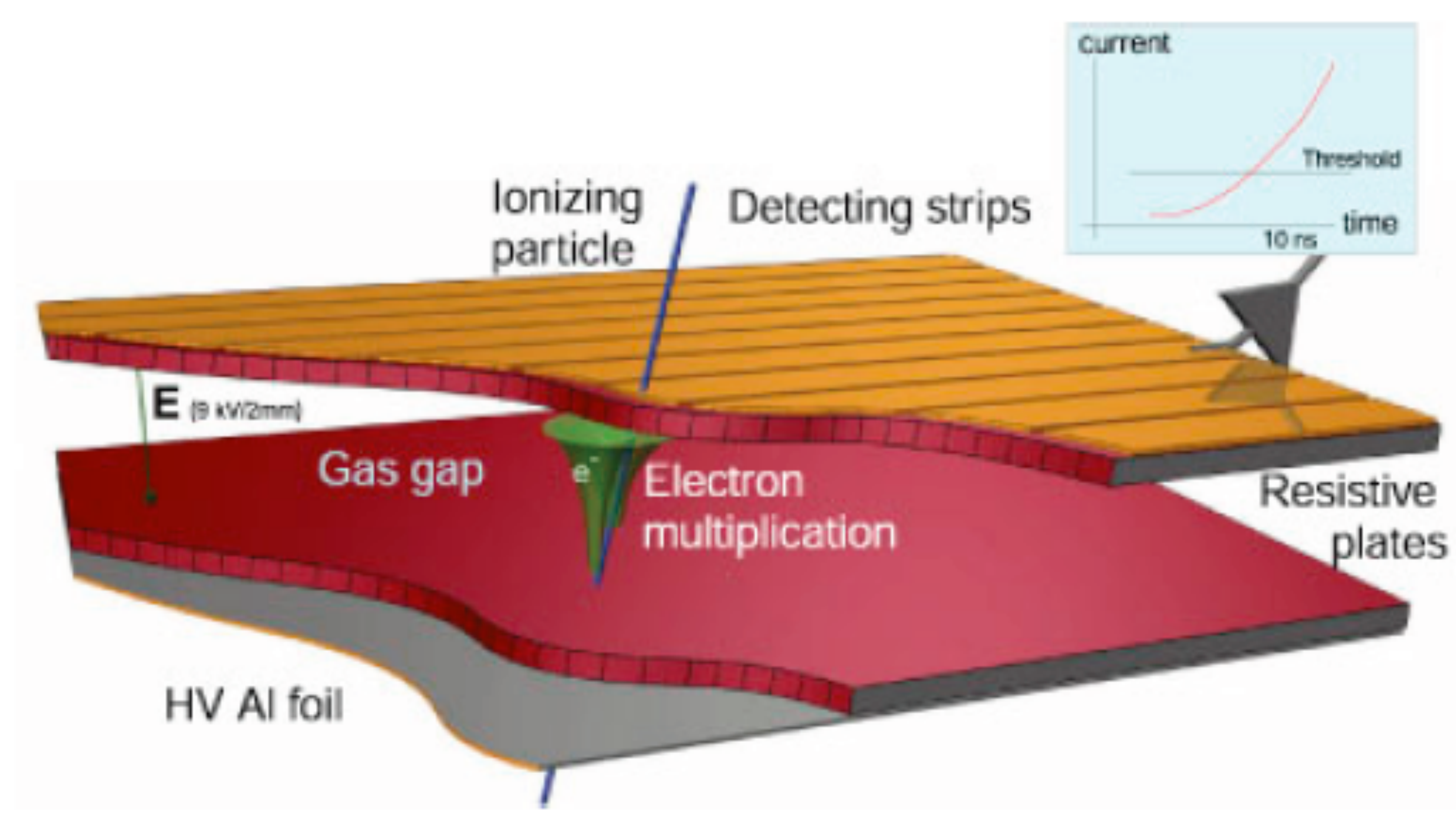


Muon detector example: RPC

- Resistive plate chambers (RPC) fast gaseous detectors
  - Relatively inexpensive to cover a large area
- RPCs consist of two parallel plates
  - a positively-charged anode and a negatively-charged cathode,
- Plates are made of a very high resistivity plastic material and separated by a gas volume.
- Ionizing muons cause an avalanche of electrons
  - very high field means avalanche starts immediately
- The electrodes are transparent to the signal (the electrons), which are instead picked up by external metallic strips after a small but precise time delay.
- RPCs combine a good spatial resolution with a time resolution of just one nanosecond.







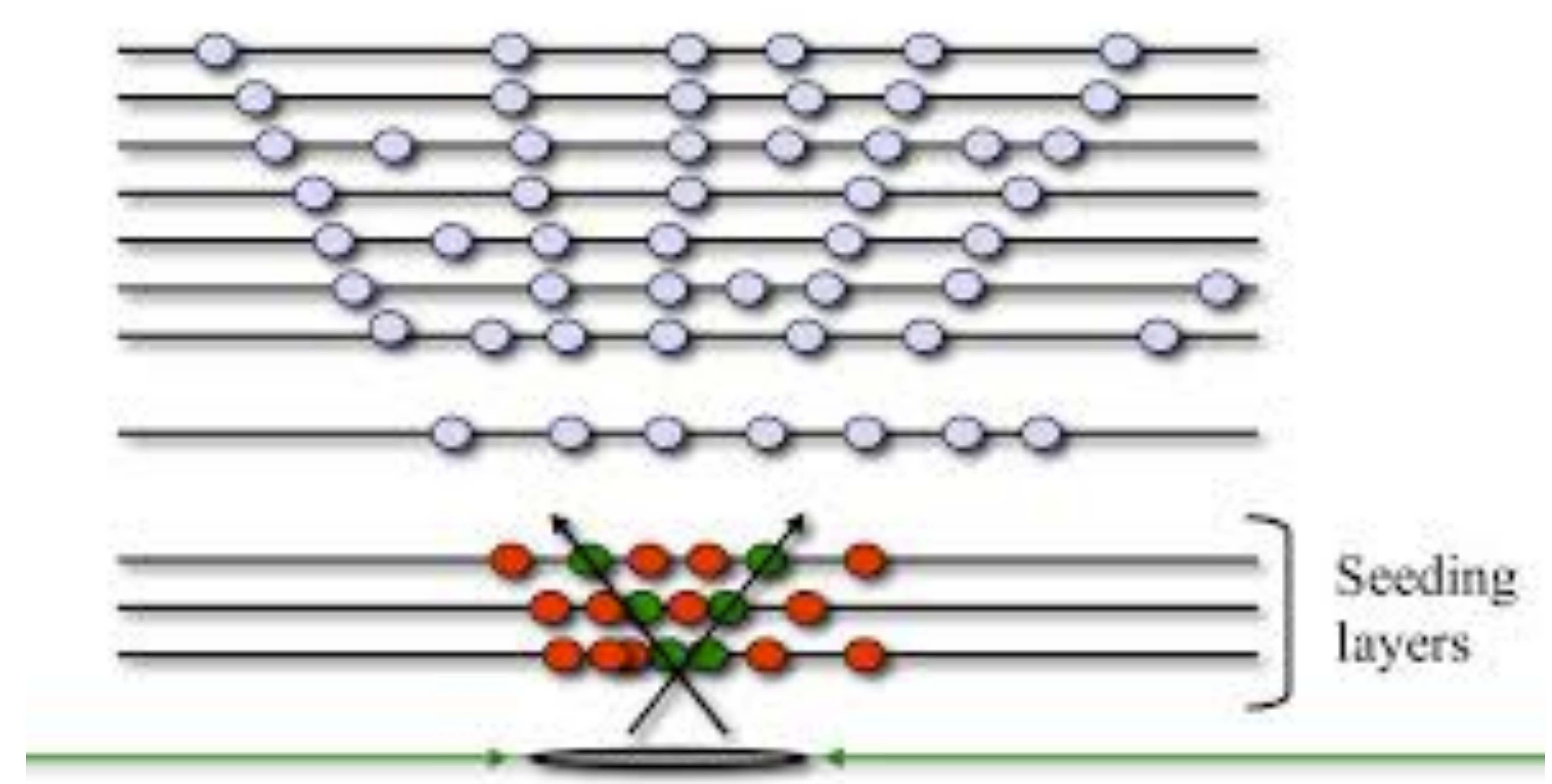
Tracking steps

Tracking in the inner tracking volume is an important and compute intensive task

- A constant challenge and one of the big bottlenecks in the reconstruction chain
- Combinatorics are huge!

4 Basic Steps:

- Seeding: initial candidate from a few hits
- Finding: extrapolating from seeds with Kalman filter
- Fitting: smooth trajectory and fit params
- Selection: apply quality cuts



Cf. Silicon detector lectures from C. Mills

FITTING FOR MOMENTUM

To get the pT of the track, we fit for its curvature

Useful formula:

$$p_T[GeV/c] = 0.3 \times B[T] \times r[m]$$

The full momentum is related by the polar angle

Lorentz Force

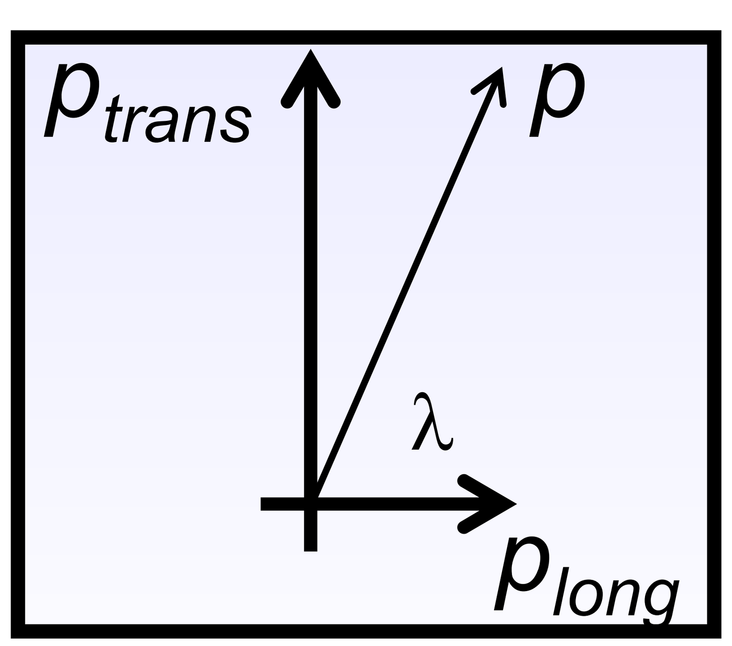
$$\vec{F}_L = q \cdot \vec{v} \times \vec{B}$$

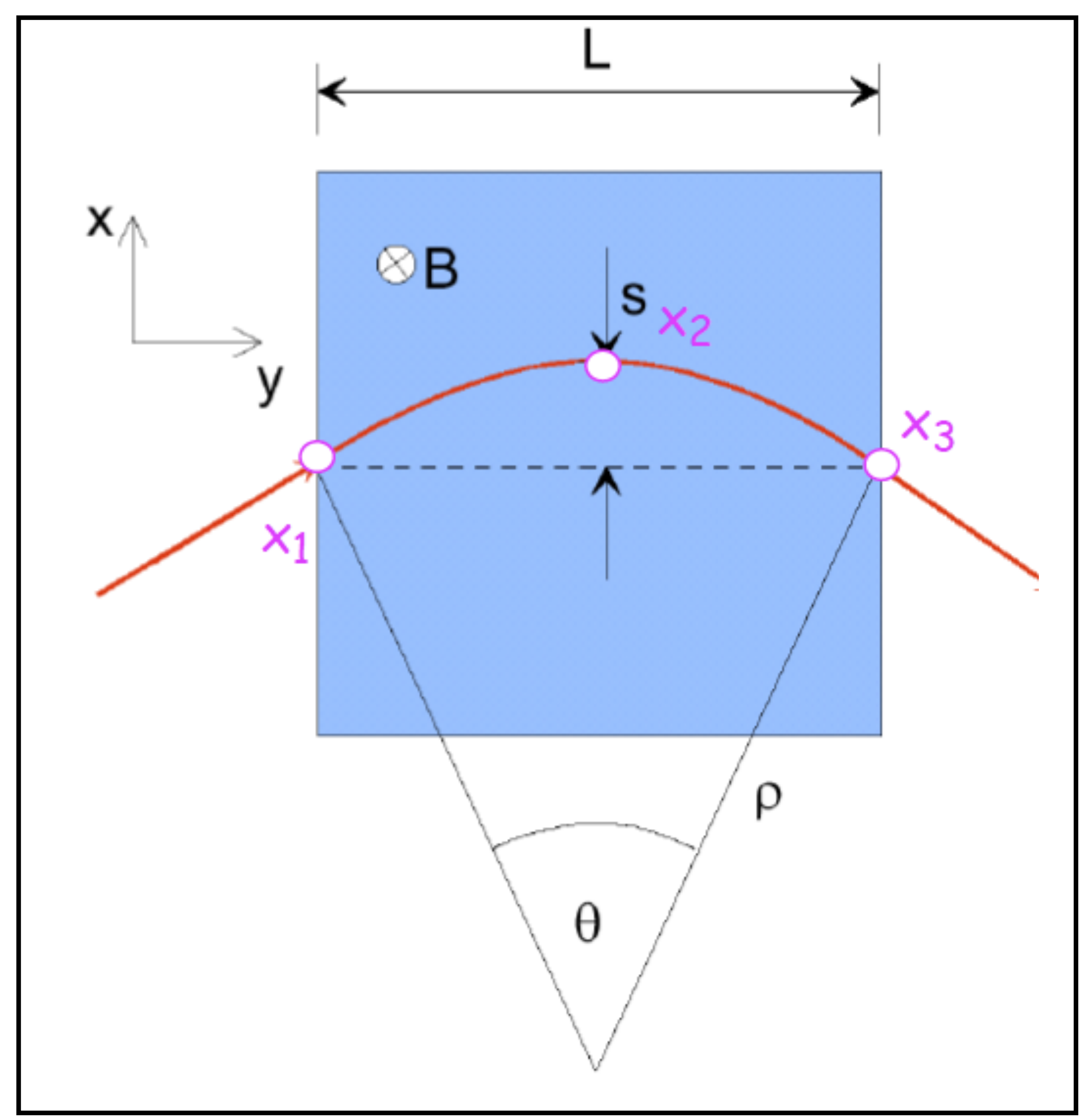
Centripetal Force

$$F_c = m \cdot v^2 / r$$

$$p = q \cdot B \cdot r$$

$$p = \frac{p_T}{sin\lambda}$$





Momentum resolution

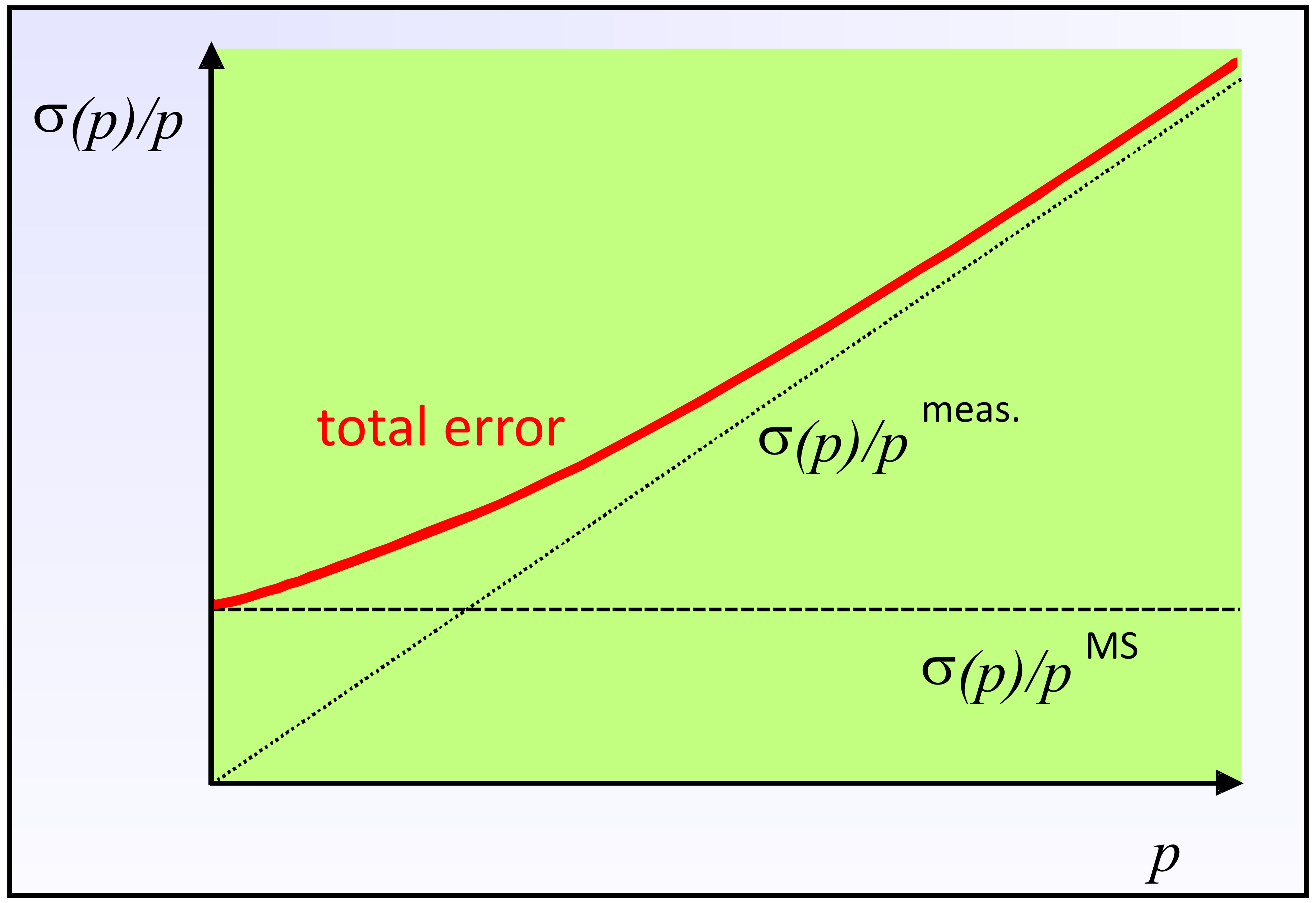
The transverse momentum resolution is driven by:

- Curvature measurement and hit resolution
- Multiple scattering

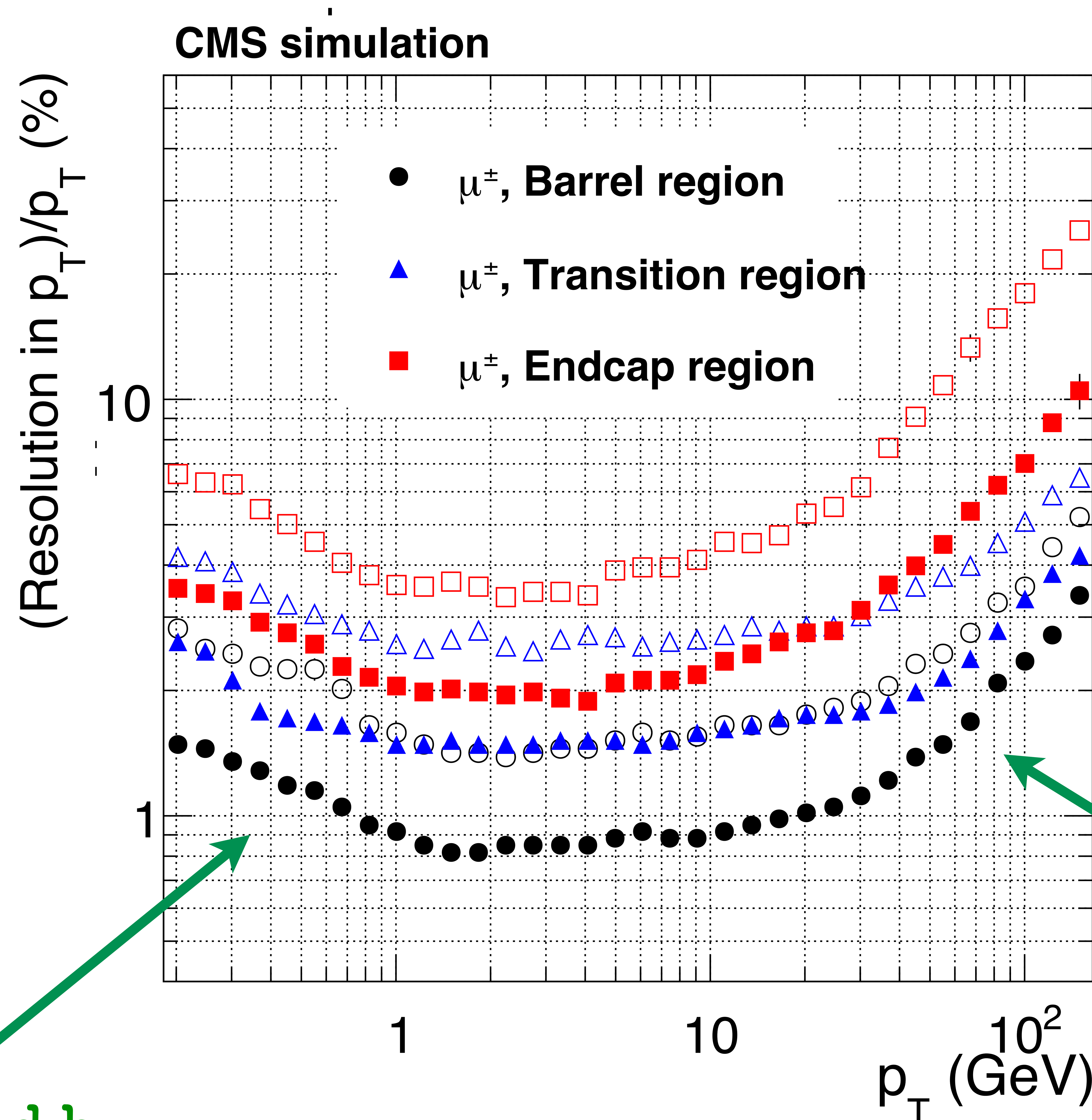
$$\frac{\delta p}{p} \sim \frac{0.0136}{\beta}\sqrt{\frac{X}{X_0}}\frac{1}{0.3BL}\frac{\sqrt{4A_N}}{N}$$

$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 \propto \boxed{c_1 \cdot \left(\frac{p_T}{BL^2}\sqrt{\frac{720}{N+4}}\right)^2} + \boxed{c_2 \cdot \left(\frac{1}{B\sqrt{LX_0}}\right)^2}$$

curvature multiple scattering



Momentum resolution

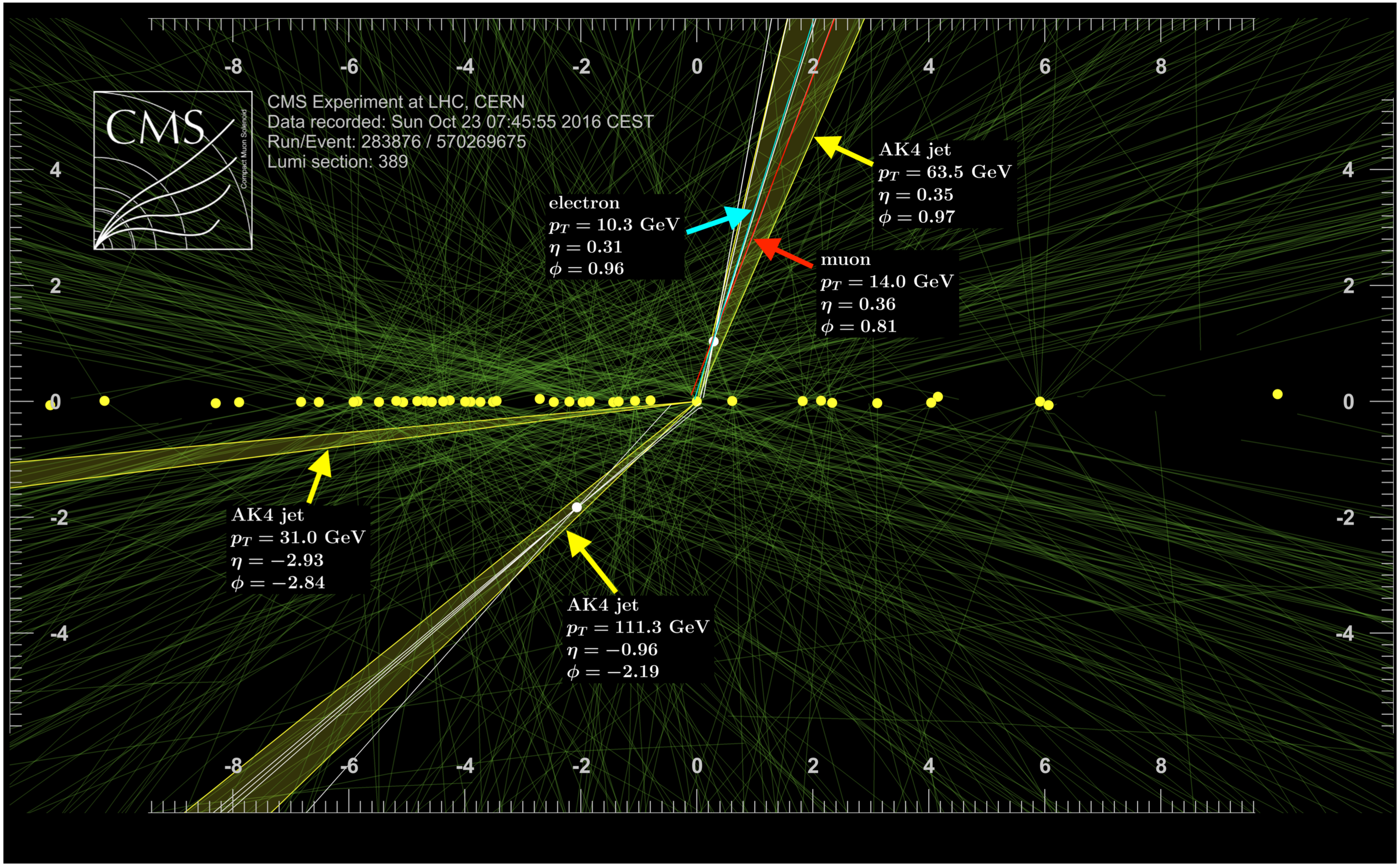


Why is resolution worse in more forward regions?

Dominated by curvature meas.

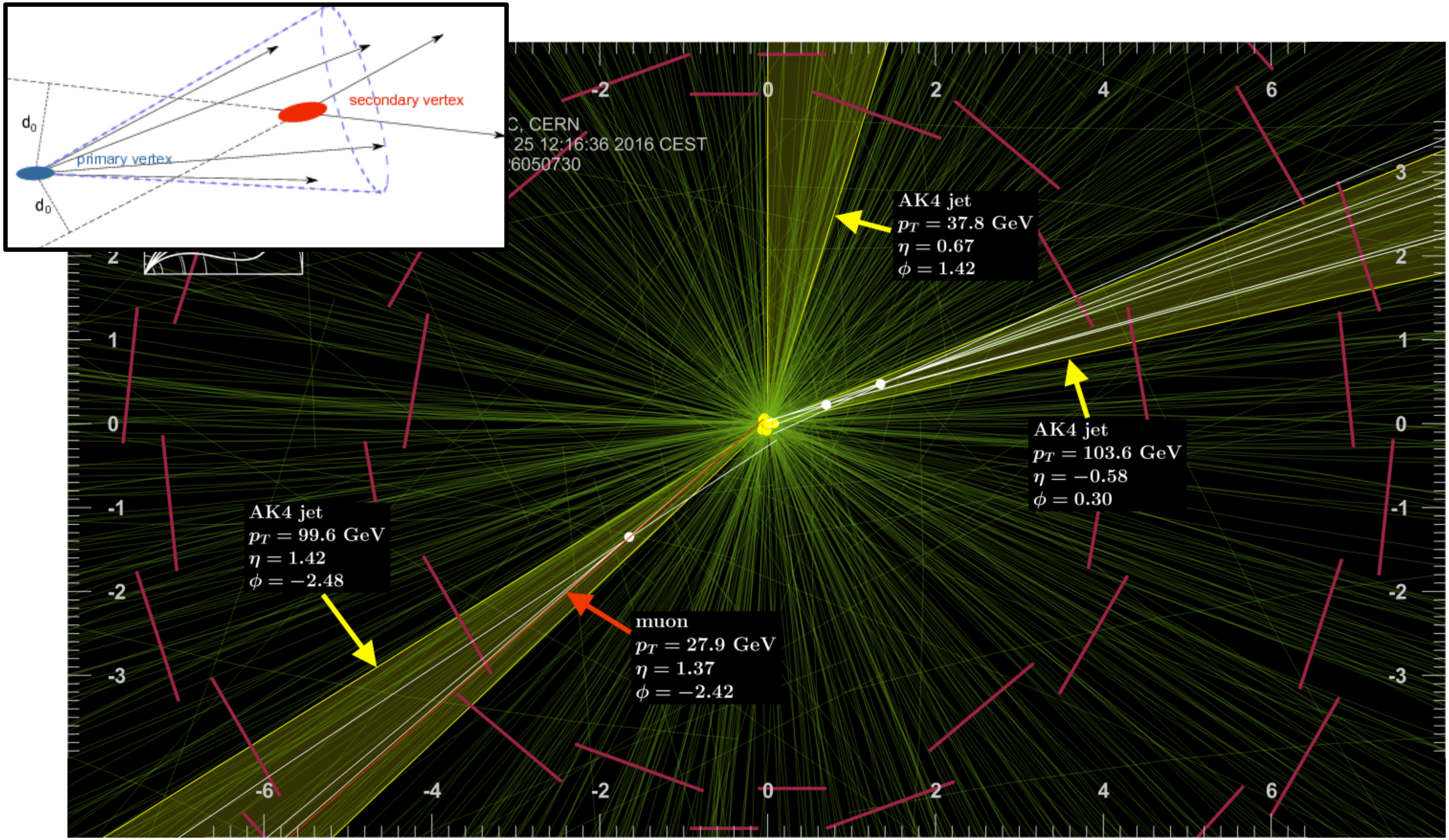
Dominated by multiple scattering

Vertex reconstruction [Z]



Use Z position of the primary vertex to separate pileup
(much more on this later)

Vertex reconstruction [XY]



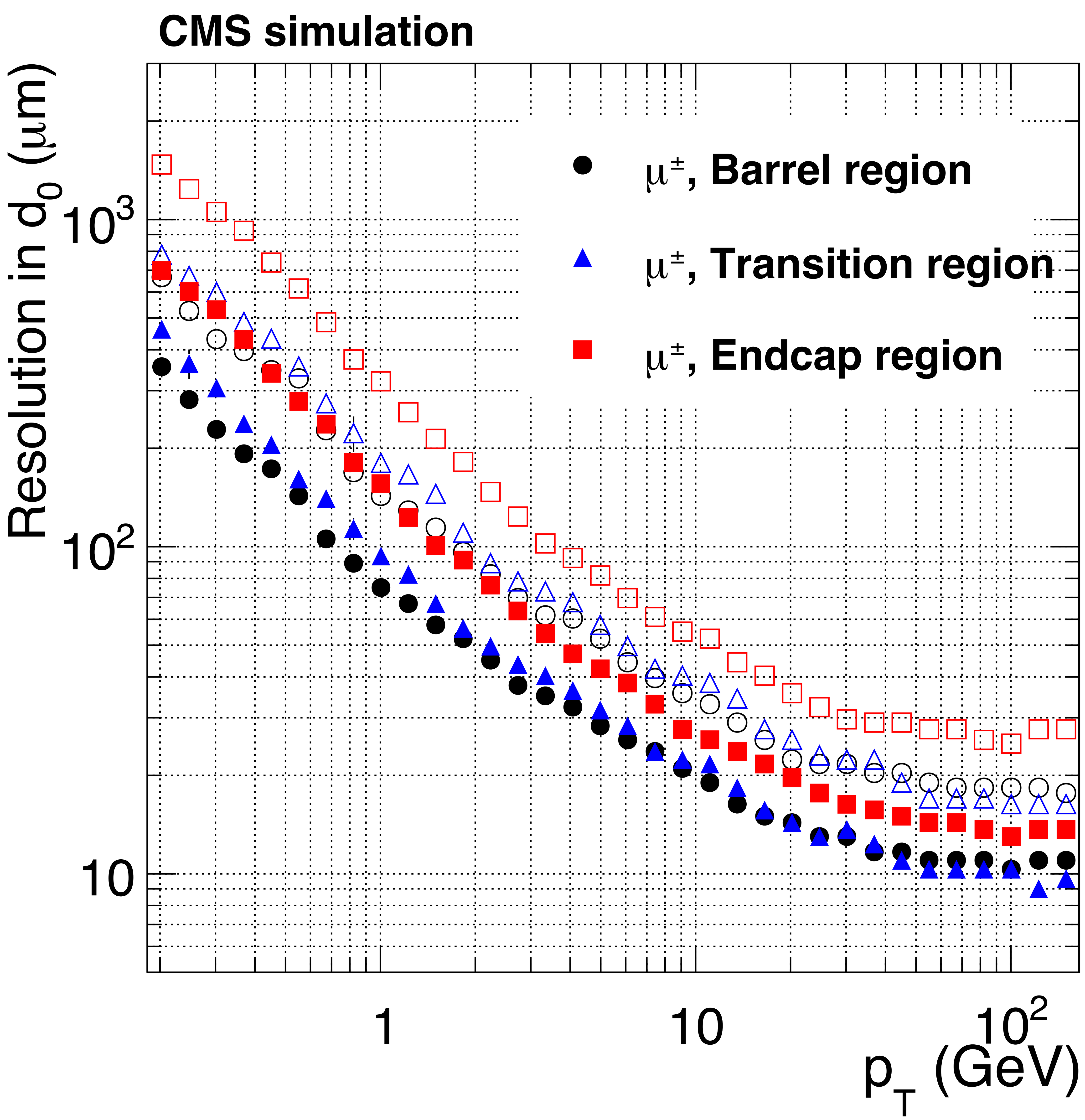
Use impact parameter of the secondary vertex to identify displaced vertices

IMPACT PARAMETER RESOLUTION

The main drivers of the vertex resolution are the position measurement and the lever arm of the measurement (how far are you away from the vertex)

For example:

$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{\left(r^2 - r^1\right)^2} + \sigma_{MS}^2$$

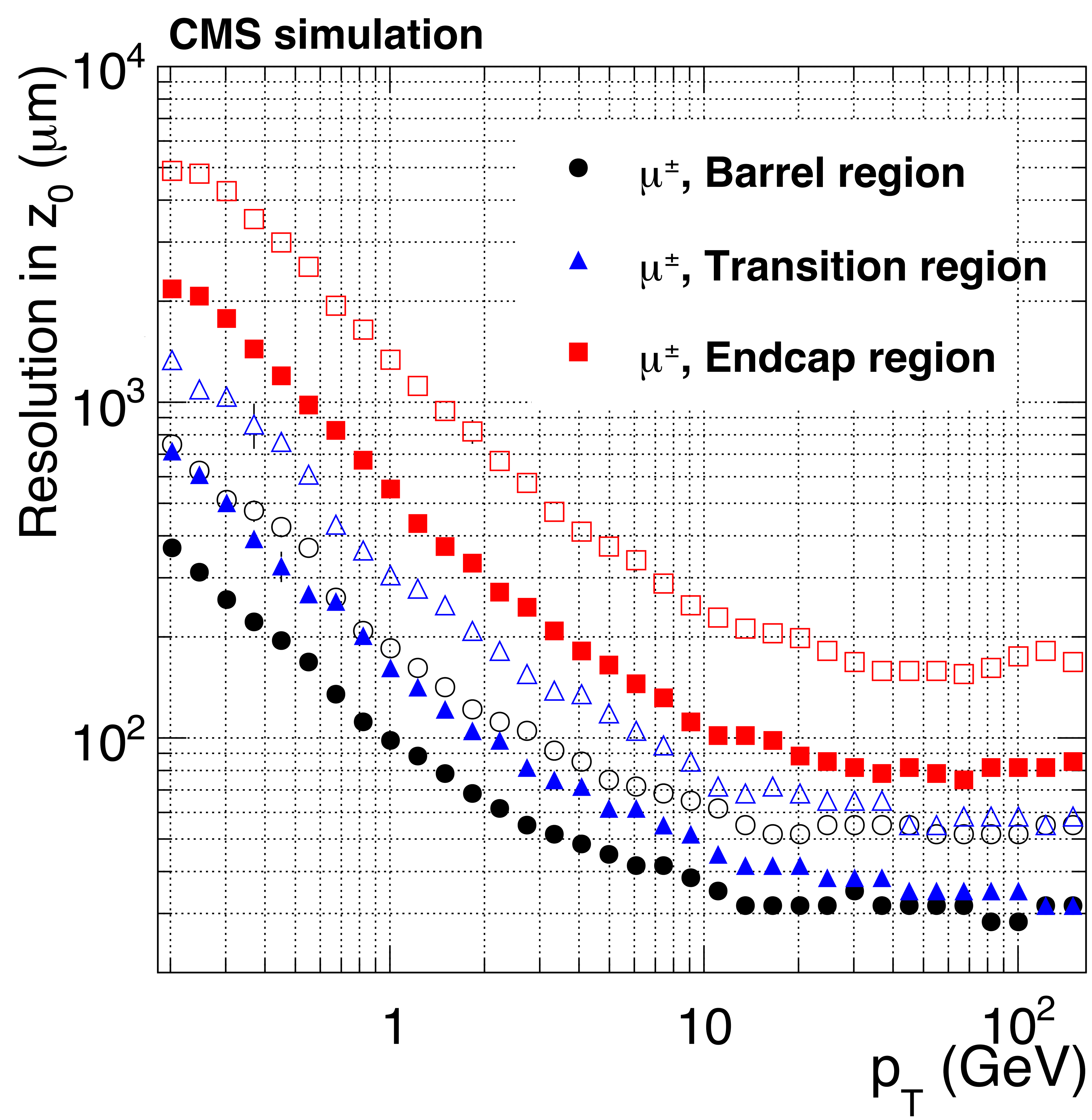


Impact parameter resolution

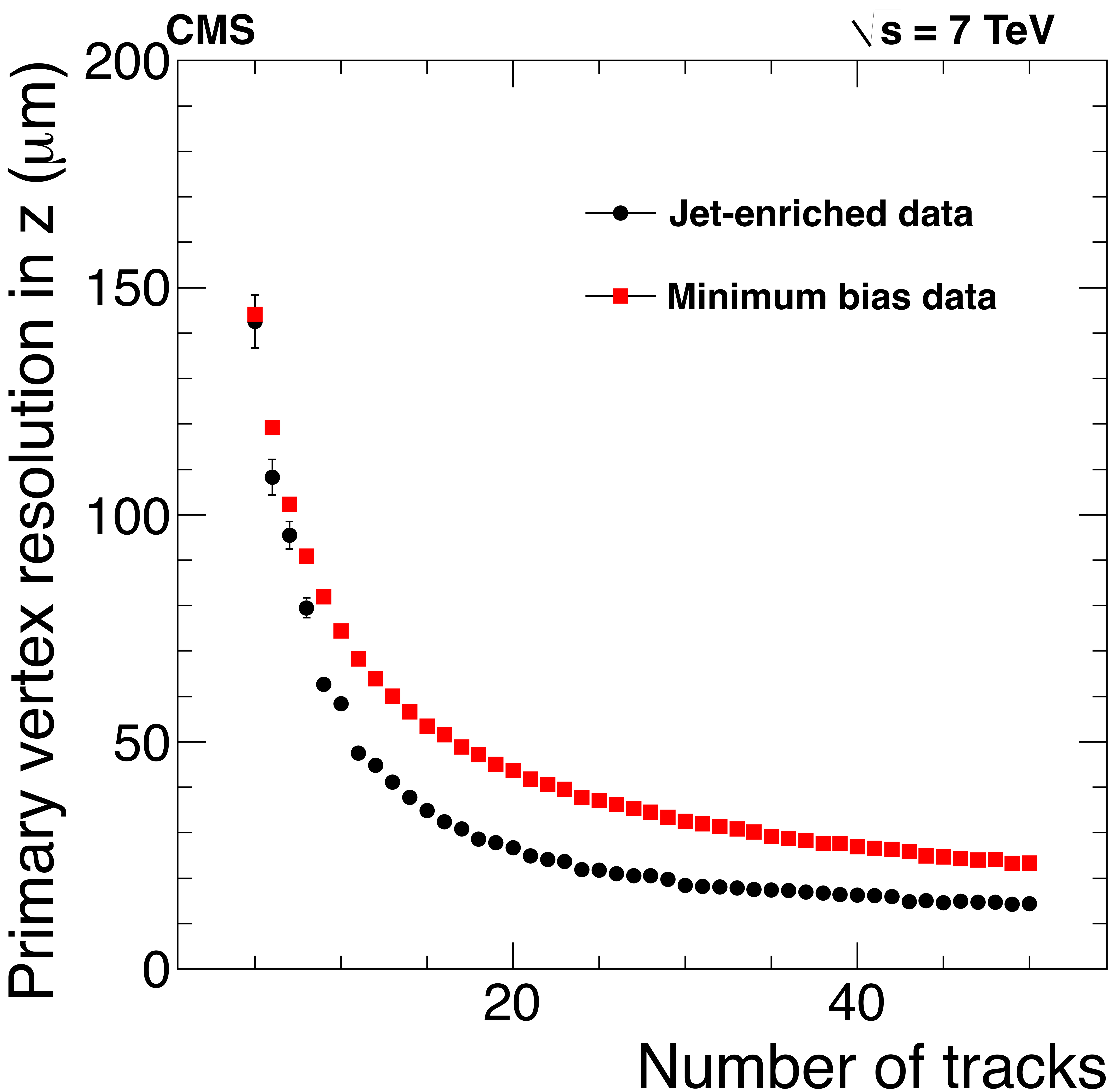
The main drivers of the vertex resolution are the position measurement and the lever arm of the measurement (how far are you away from the vertex)

For example:

$$\sigma_{d_0}^2 = \frac{r_2^2 \sigma_1^2 + r_1^2 \sigma_2^2}{\left(r^2 - r^1\right)^2} + \sigma_{MS}^2$$



Primary vertex resolution

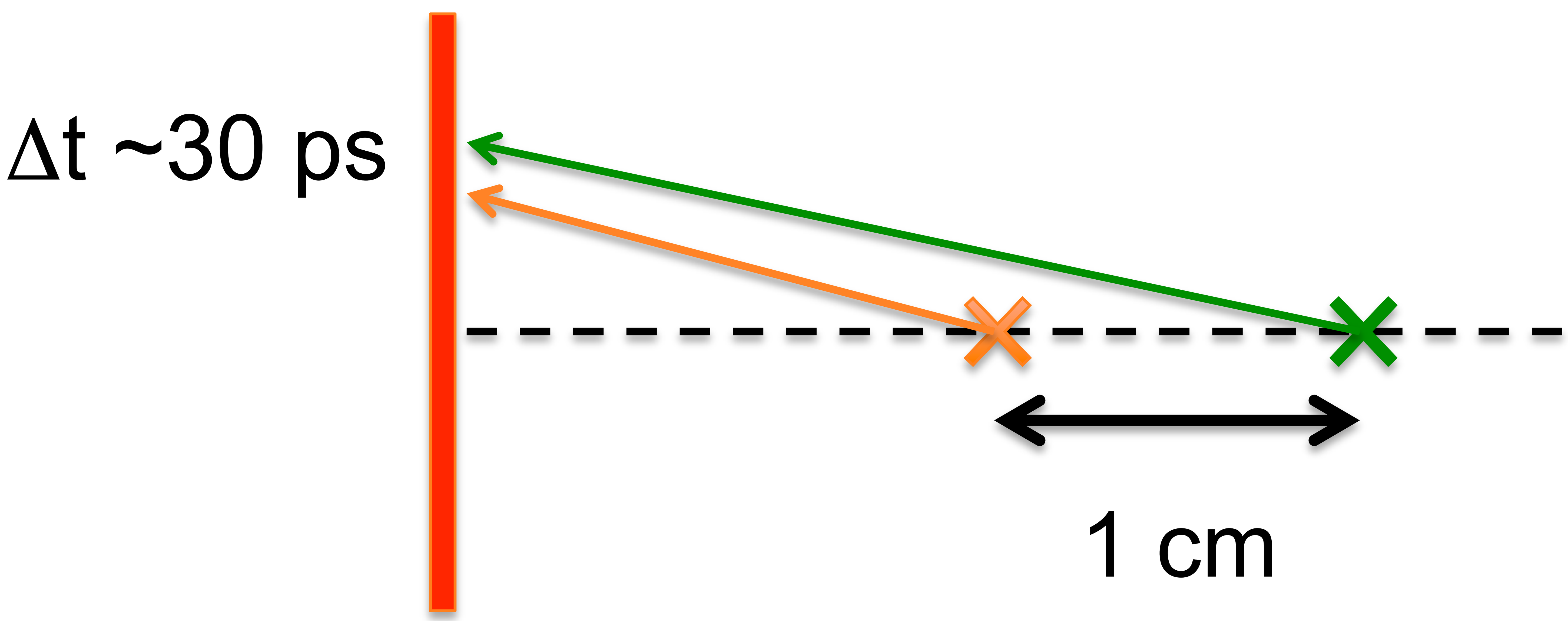


~similar performance of the vertex resolution in x,y too

THE 4TH DIMENSION!

Precision fast timing has promise to be a powerful additional piece of information for reconstruction

- There are plans by ATLAS and CMS to include precision timing detectors for HL-LHC upgrades

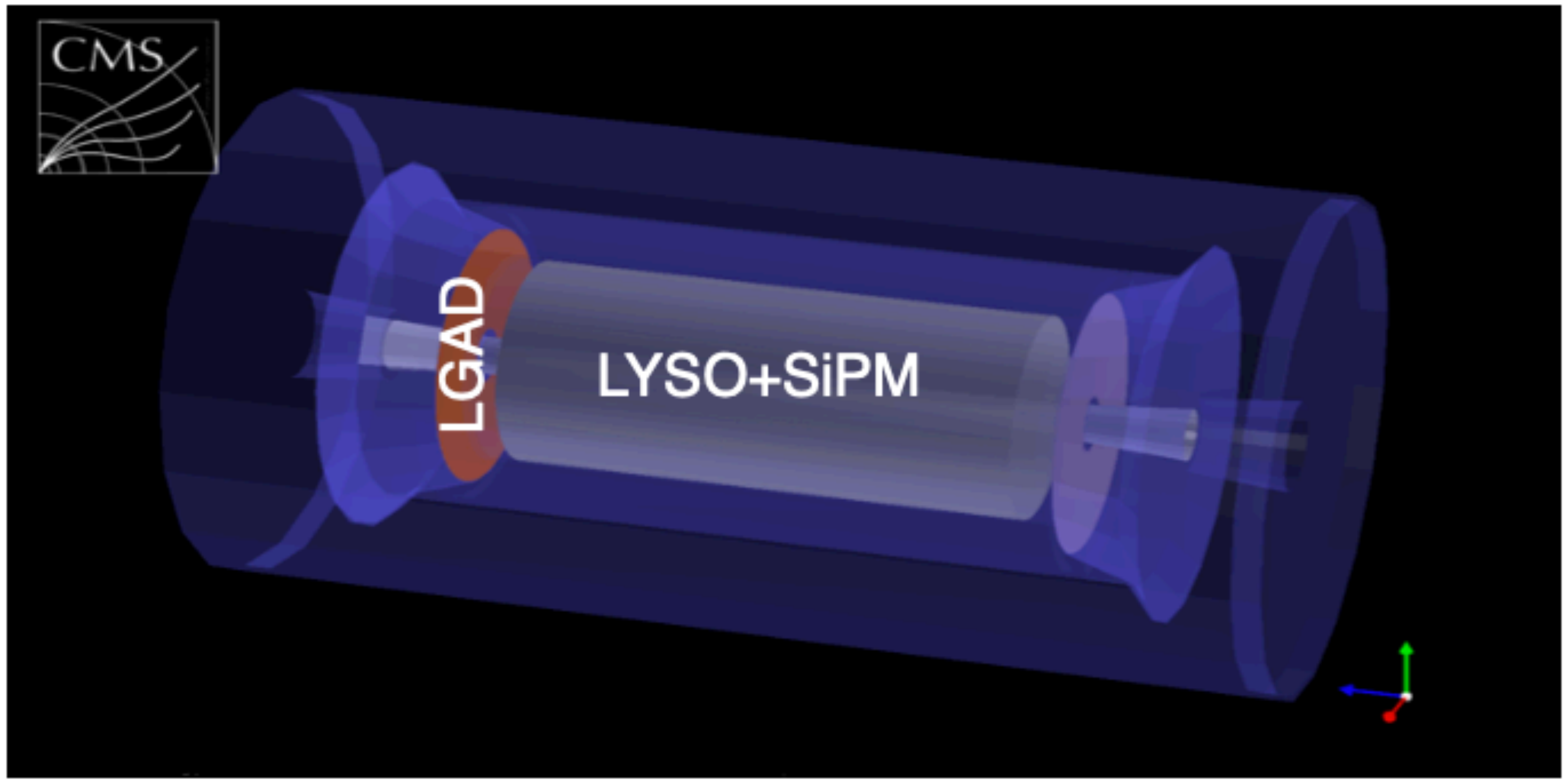


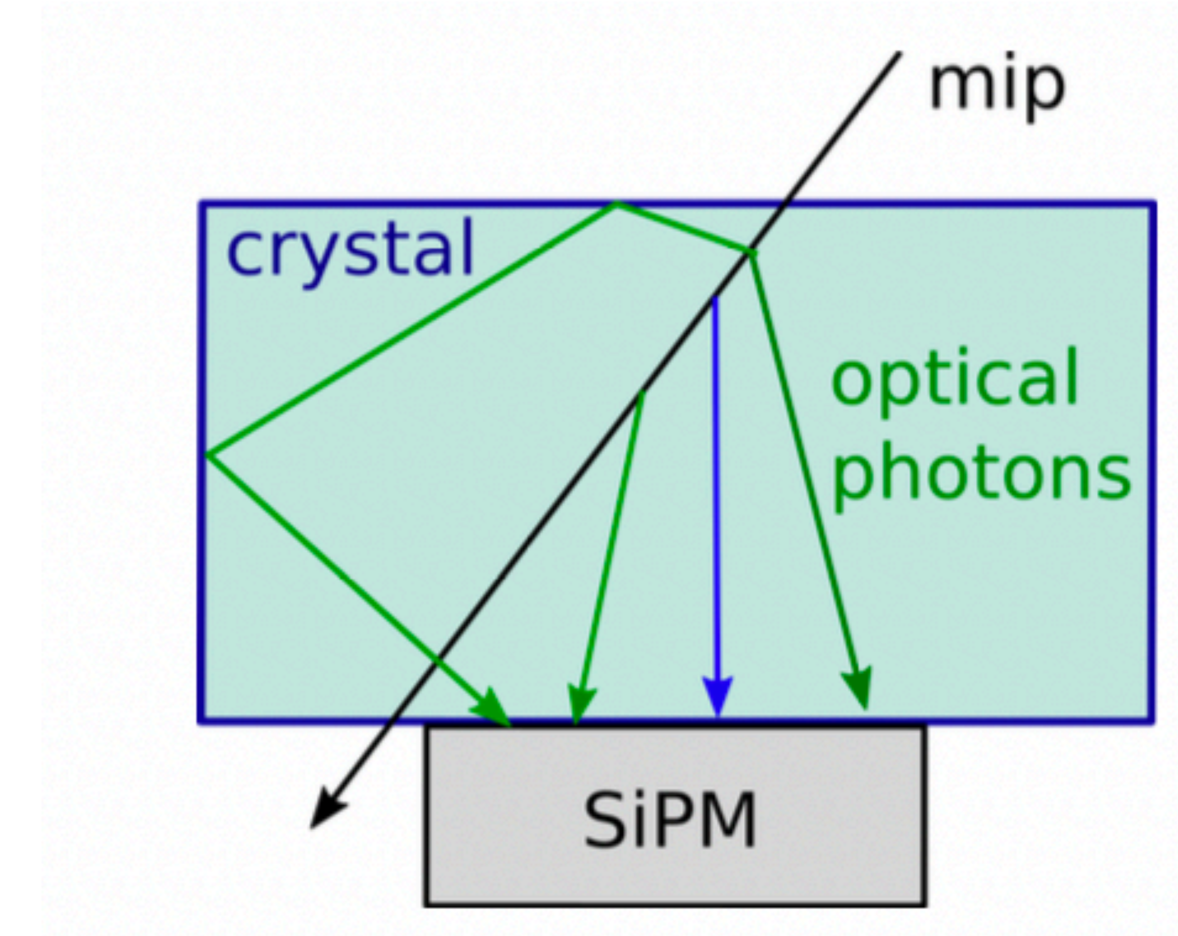
Resolution for charged particles is around ~30 ps.

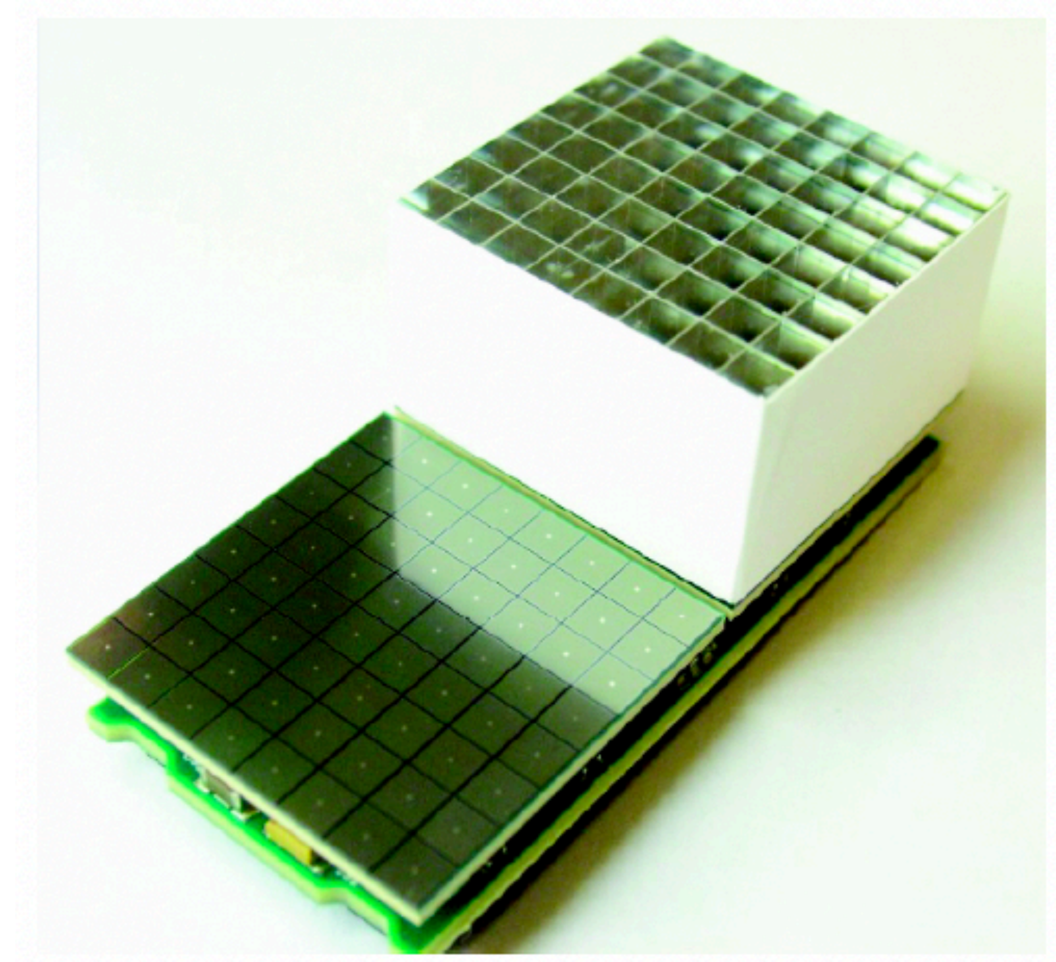
Neutral resolution is energy dependent: ~30-300 ps for 100-few GeV

Time of flight can be used to disentangle the origin of particles as well — particularly useful for neutral particles

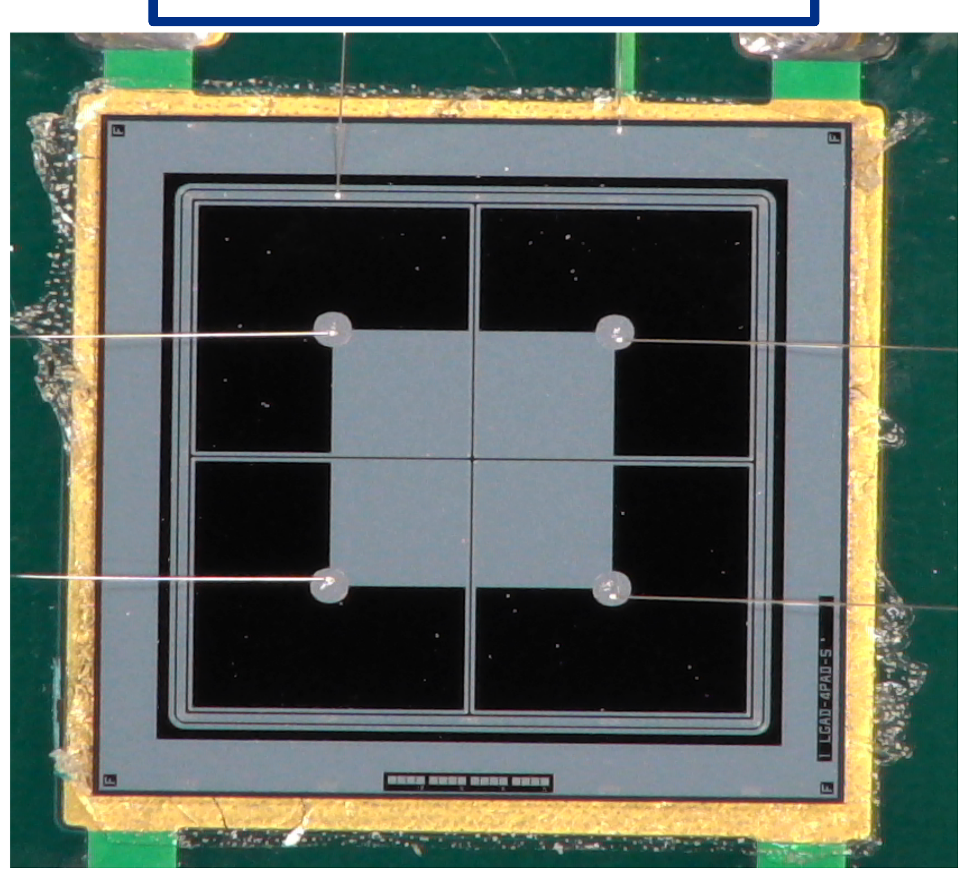
Timing detectors, examples

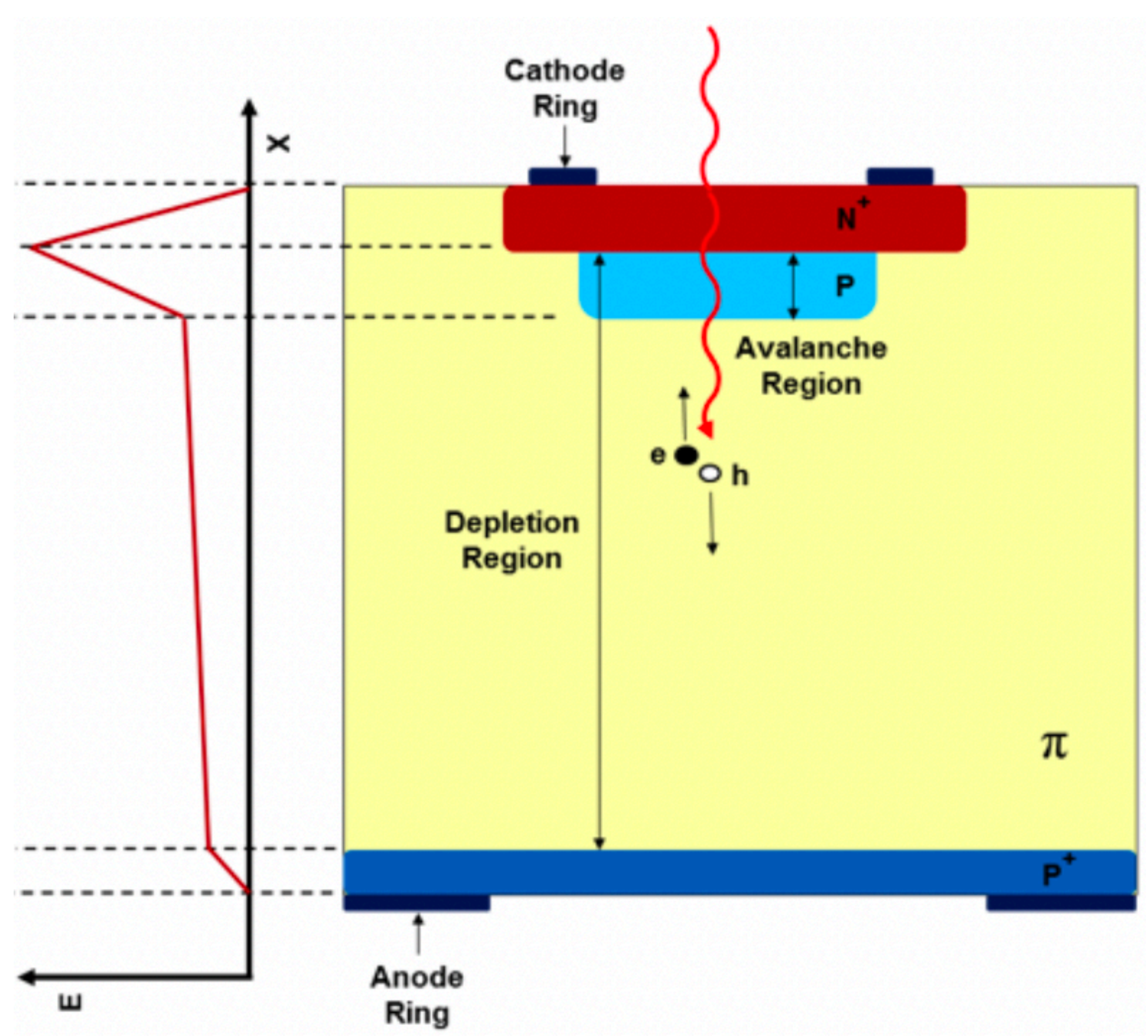






Hamamatsu 2x2 LGAD array3x3 mm^2 pixels





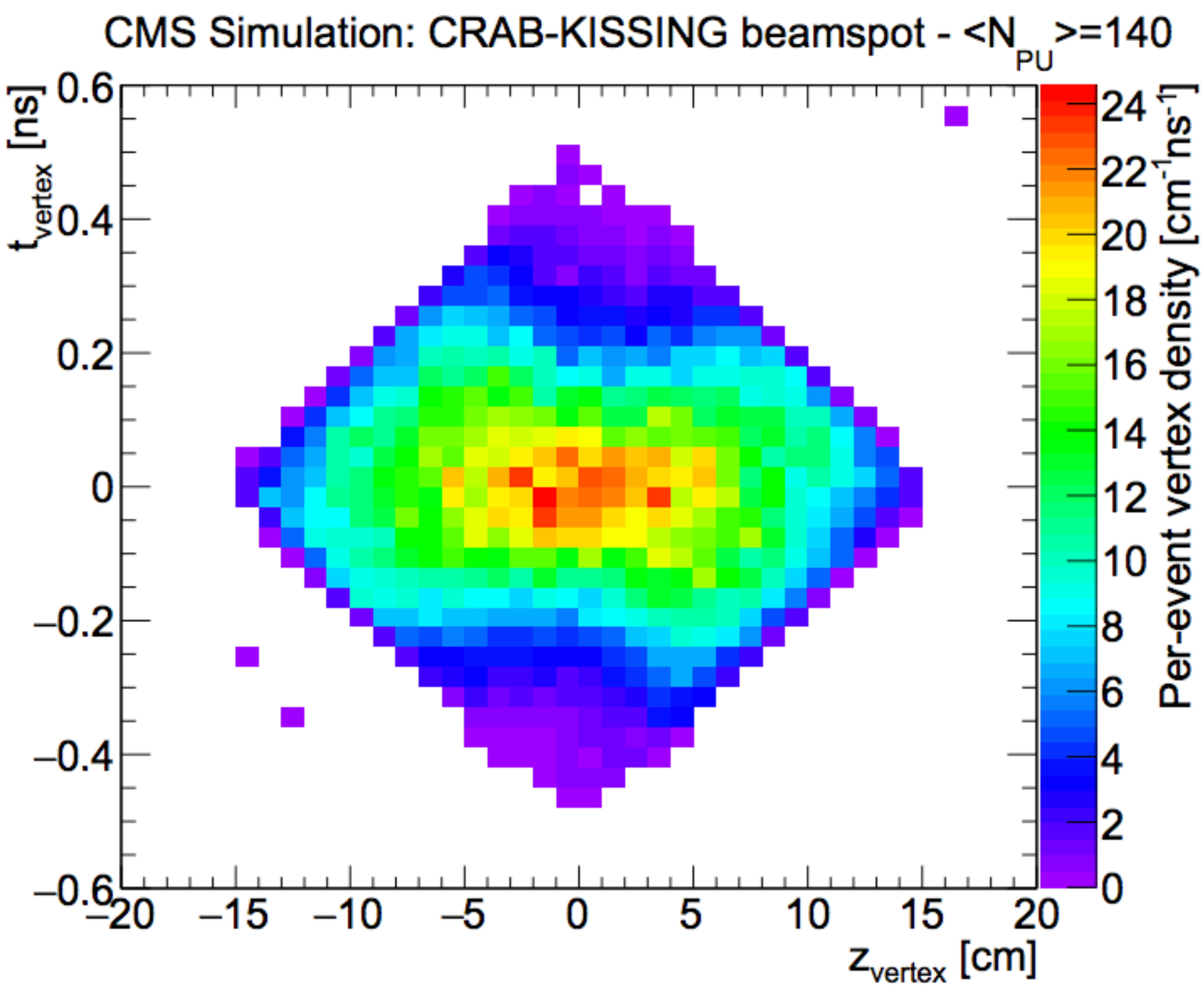
Use LGAD detector (low gain avalanche) for endcap — harsher radiation environment
Silicon sensor with special doped thin region

Few mm thick LYSO, high light yield scintillator

~100% efficient for MIPs with good S/N

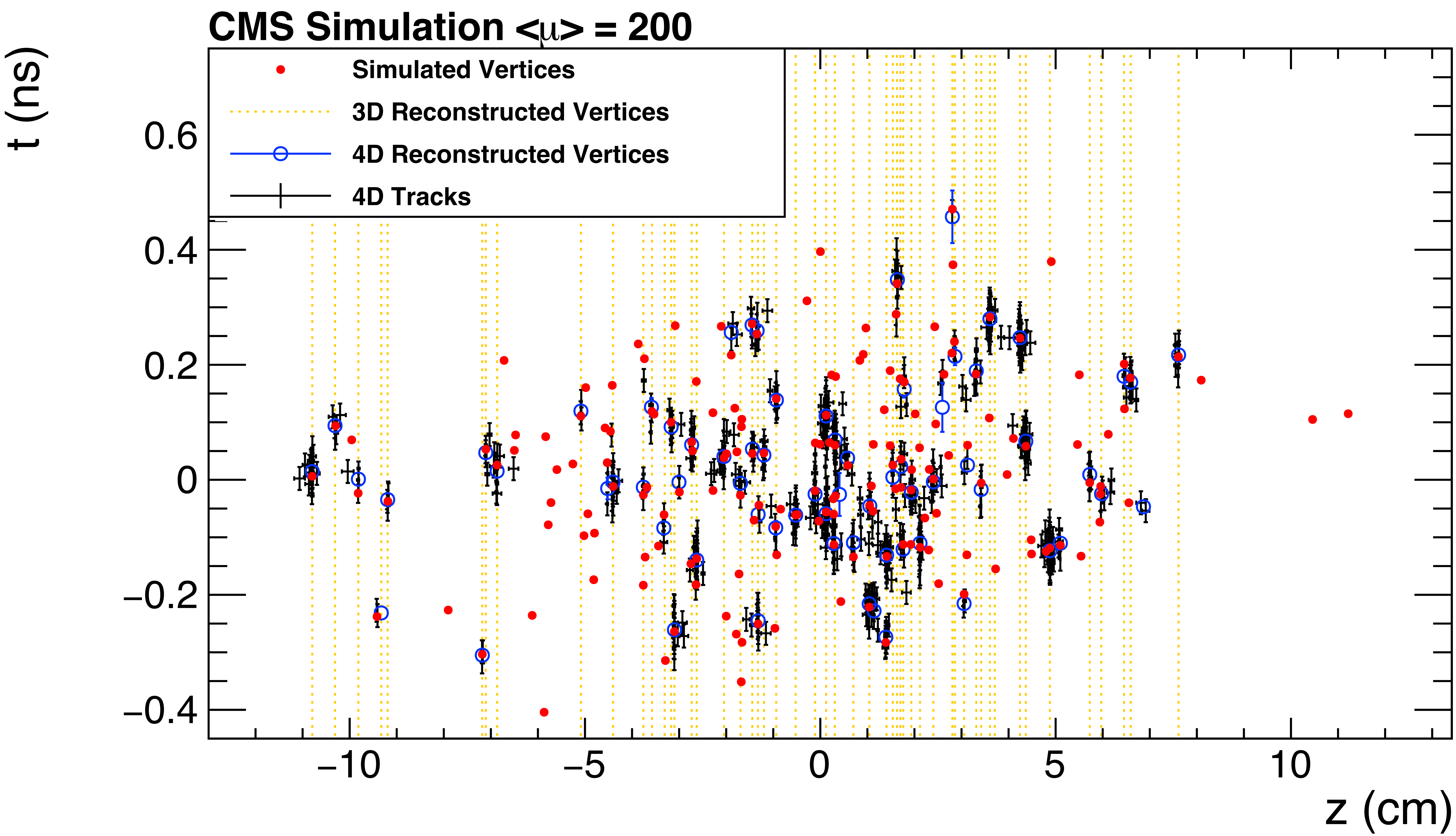
Good radiation tolerance

Vertexing with timing!

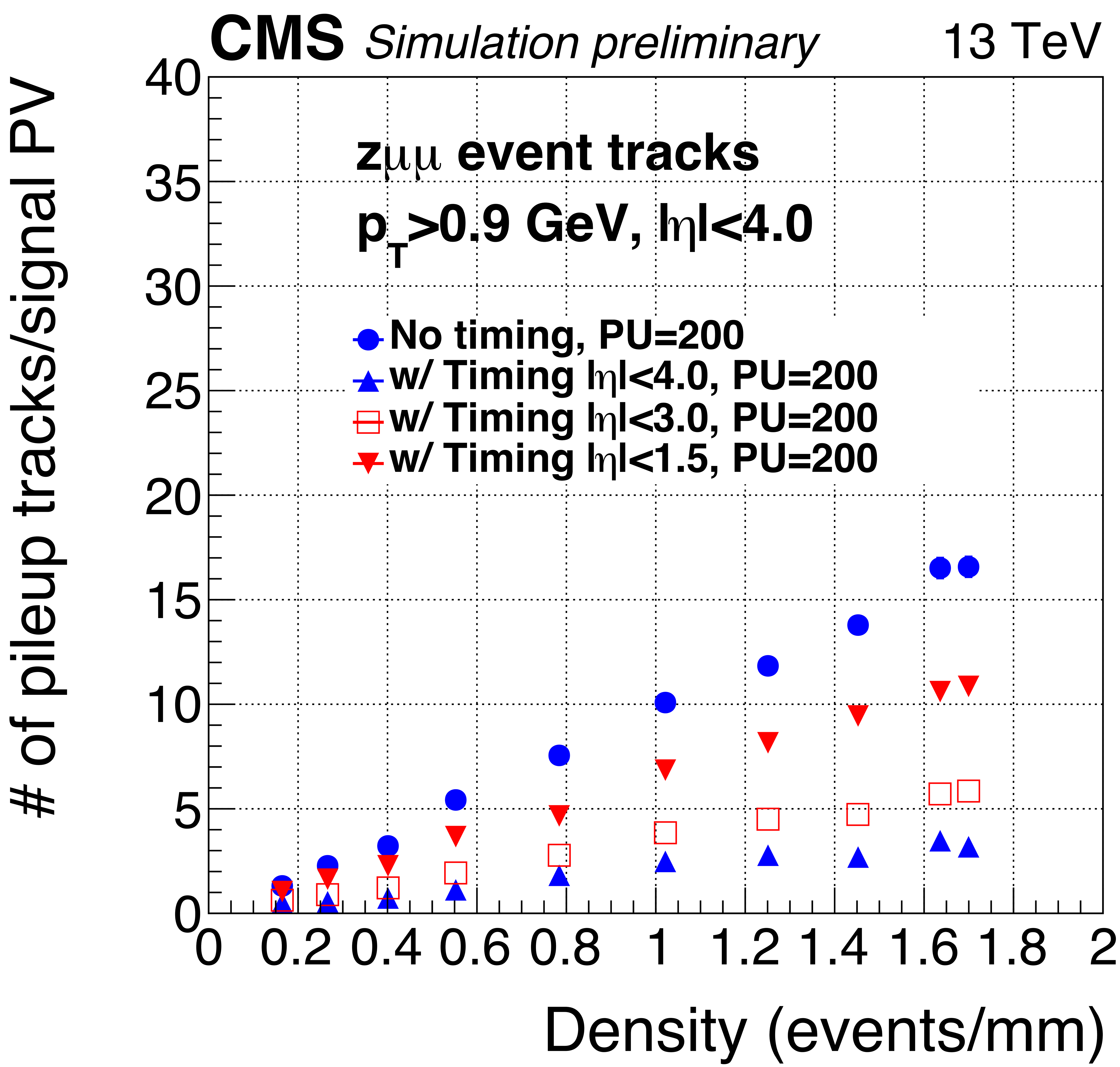


In future conditions of ~200 pileup, timing can be used to disentangle pileup vertices. Proton beam crossing spread out of z and time!

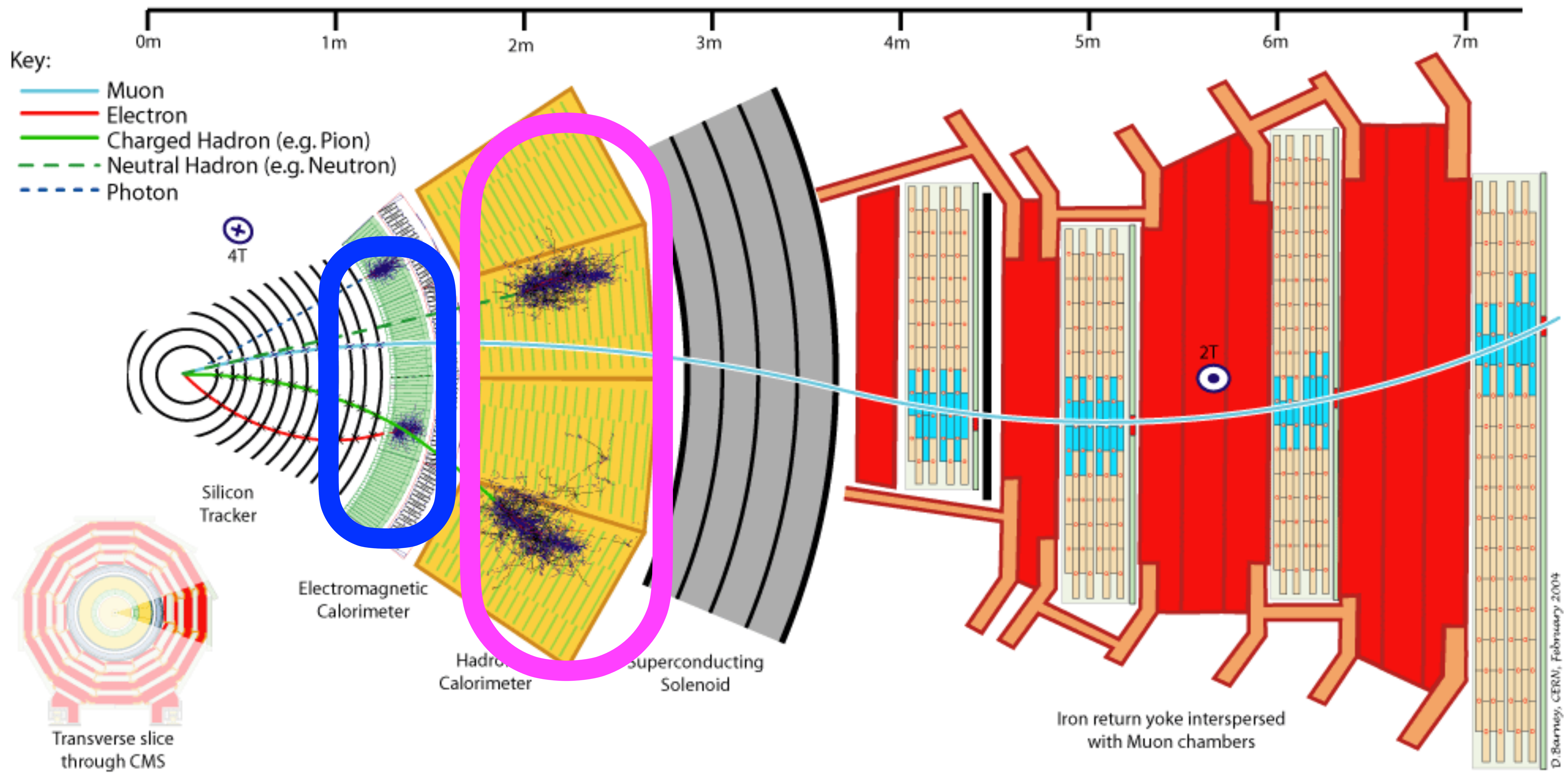
4D RECONSTRUCTION



Timing performance improvements

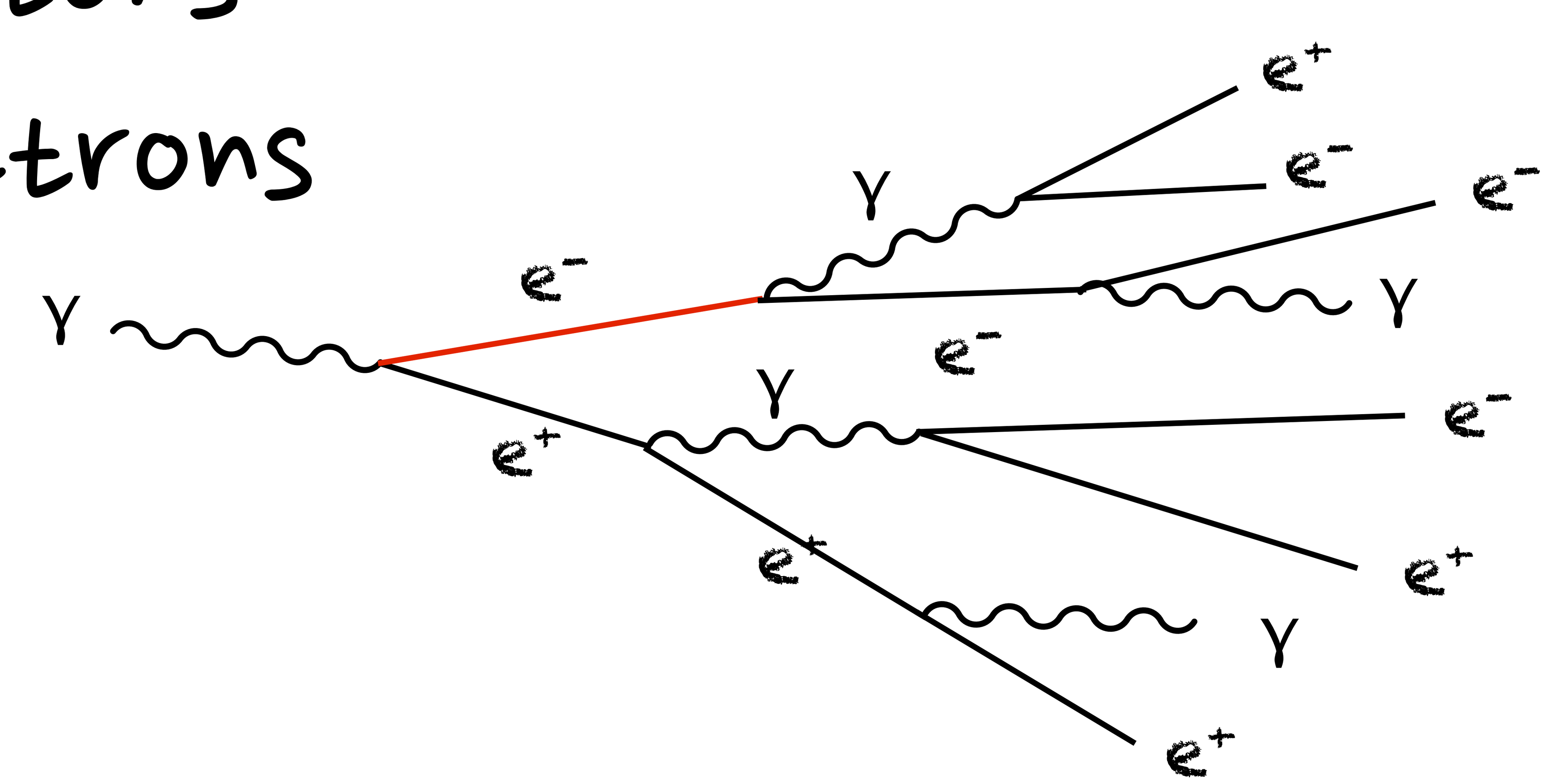


Calorimetry

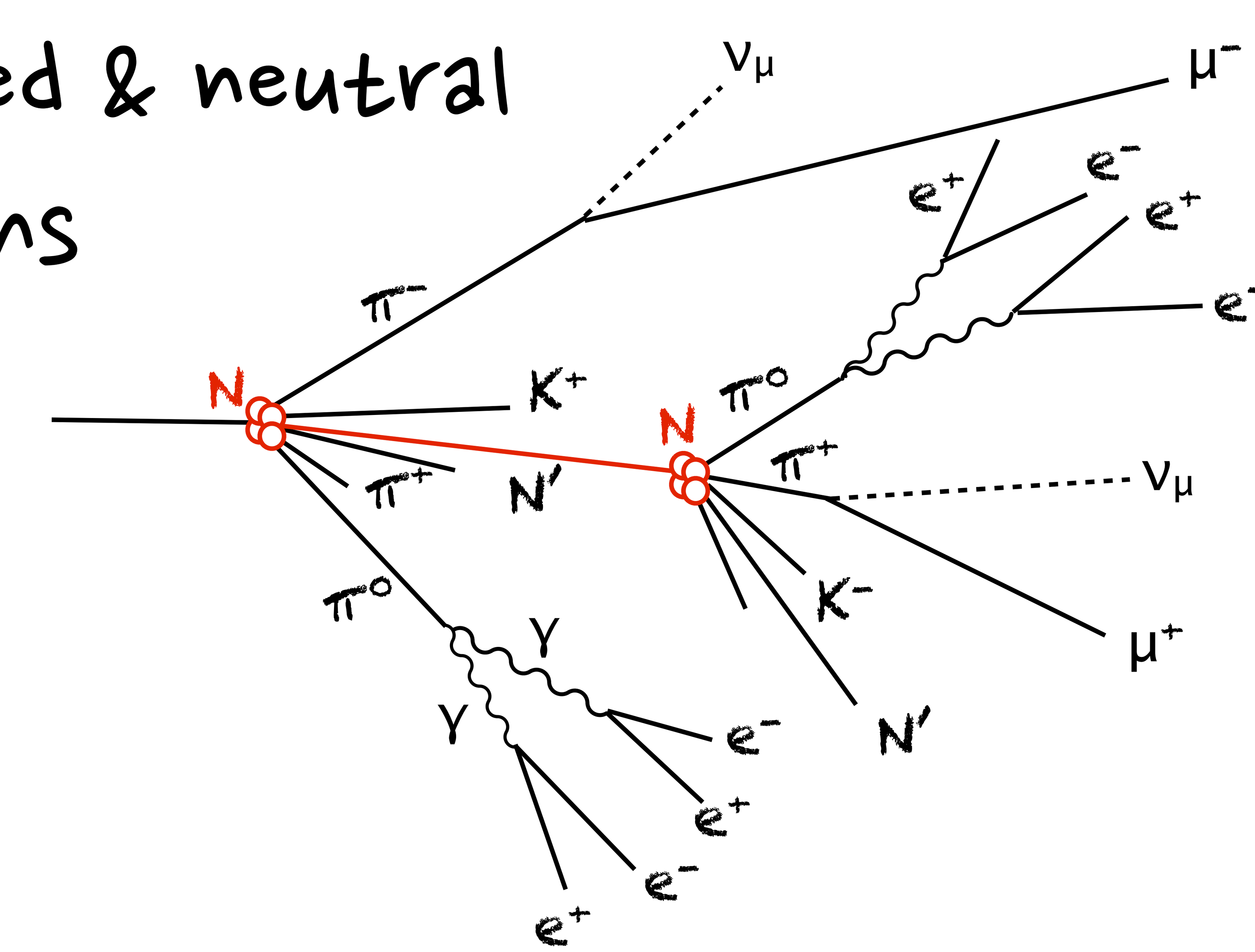


Photons

Electrons

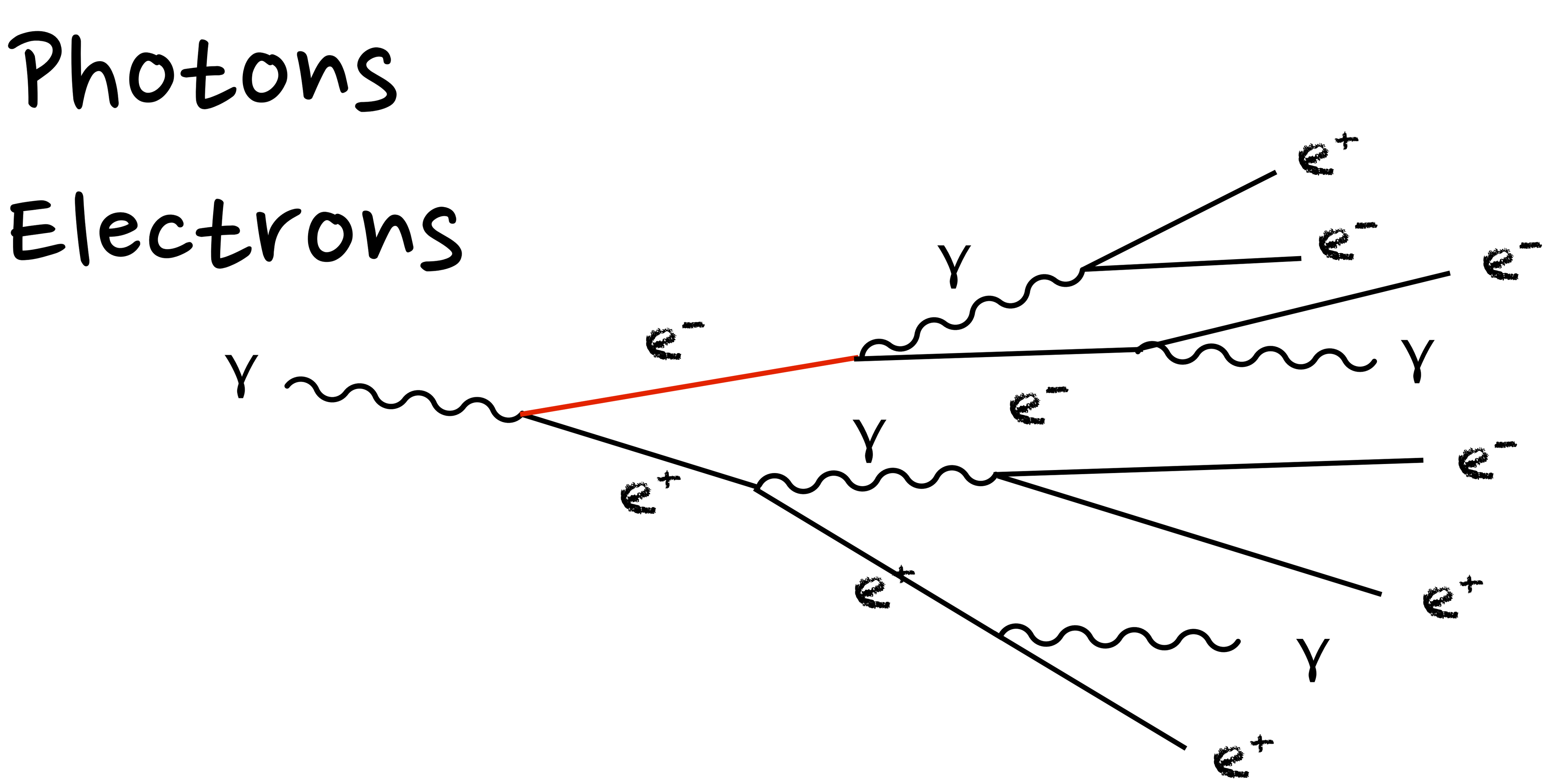


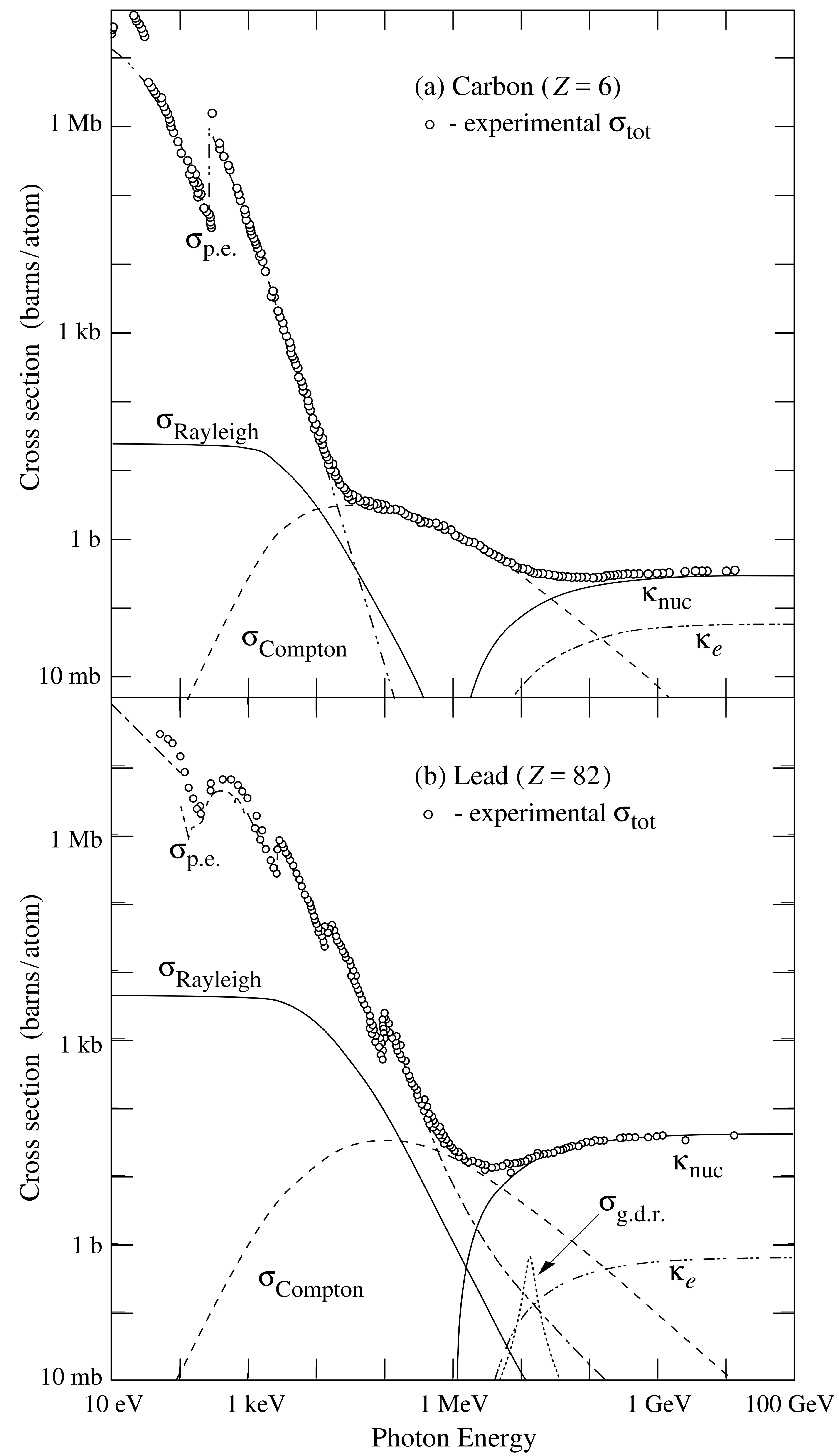
charged & neutral hadrons



PHOTON INTERACTION

Pair production of electron/positron is main interaction mechanism of photon





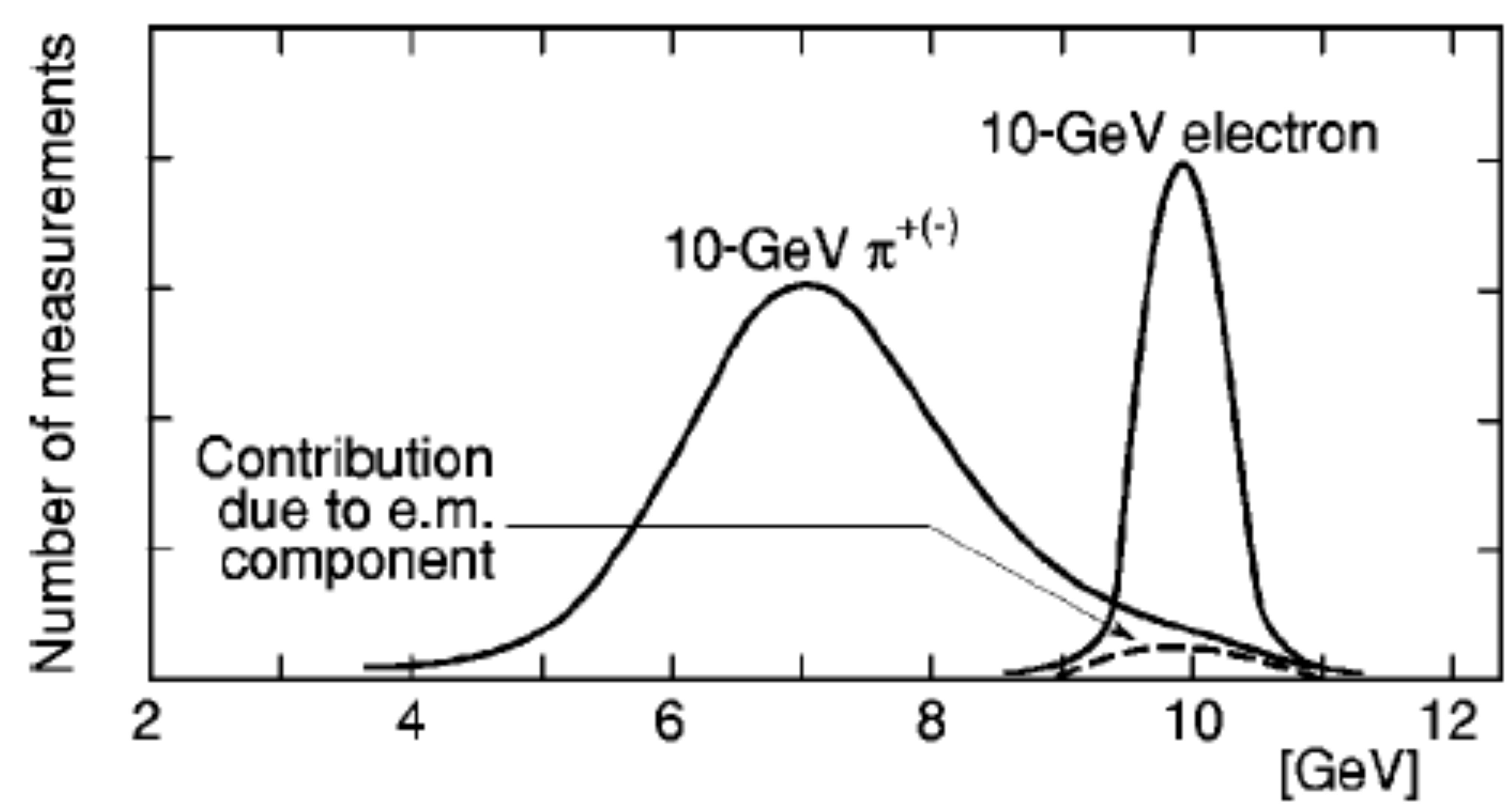
Characteristic scale also X_0

$$\sigma = \frac{7}{9}(A/X_0 N_A).$$

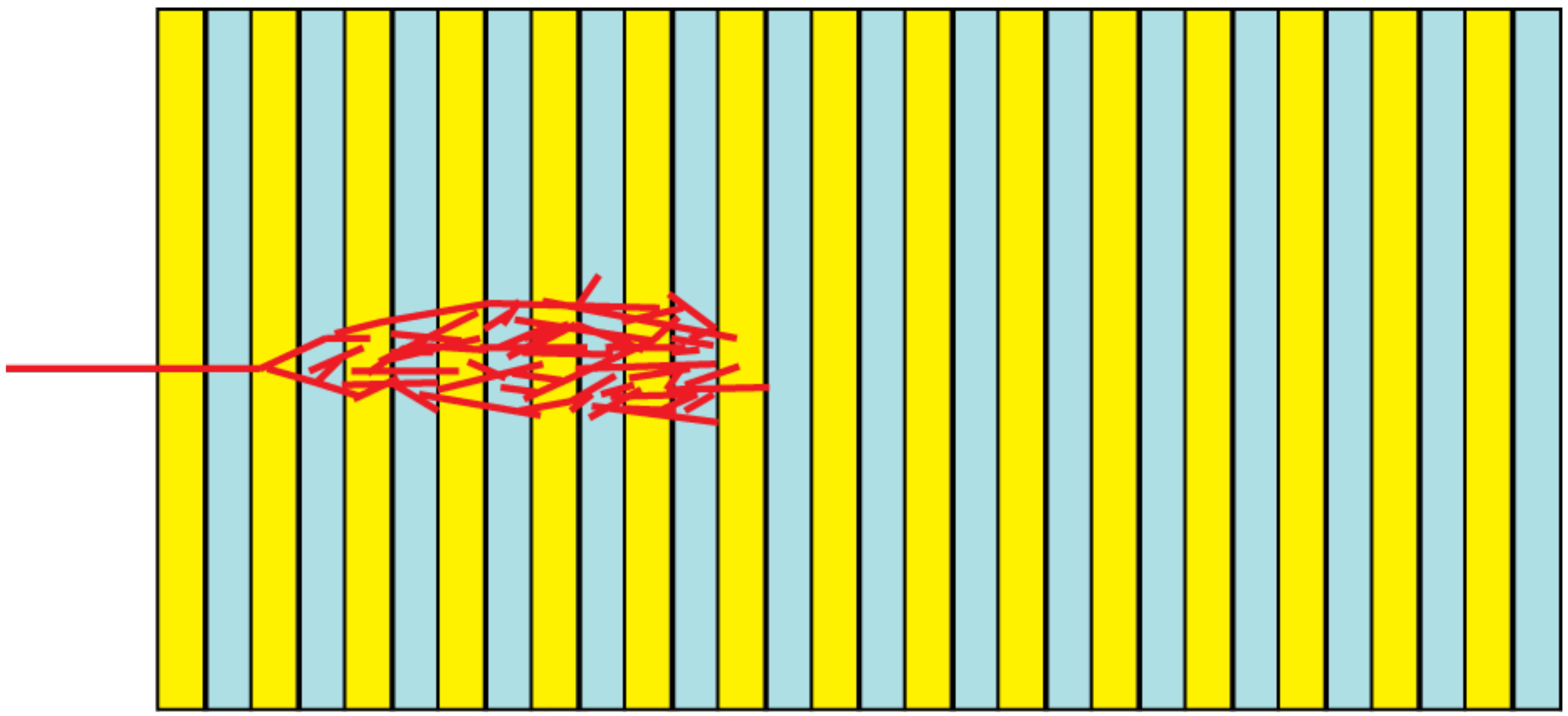
Interaction Length

	Z	ρ g.cm^{-3}	I/Z eV	$(1/\rho)dT/dx$ MeV/g.cm^{-3}	ε MeV	X_0 cm	λ_{int} cm
C	6	2.2	12.3	1.85	103	≈ 19	38.1
Al	13	2.7	12.3	1.63	47	8.9	39.4
Fe	26	7.87	10.7	1.49	24	1.76	16.8
Cu	29	8.96		1.40	≈ 20	1.43	15.1
W	74	19.3		1.14	≈ 8.1	0.35	9.6
Pb	82	11.35	10.0	1.14	6.9	0.56	17.1
U	92	18.7	9.56	1.10	6.2	0.32	10.5

- Characteristic lengthy over which a hadronic interaction will occur is λ similar to the radiation length for EM showers
- Interaction lengths tend to be much longer than radiation length for the same material
- Hadronic showers are much less uniform in their development than electromagnetic showers



Signal (in energy units) obtained for a 10 GeV energy deposit



Calorimetric measurements

Sampling Calorimeters

Mix layers which can detect energy deposited and passive layers which act as absorbers. Not all energy is detected

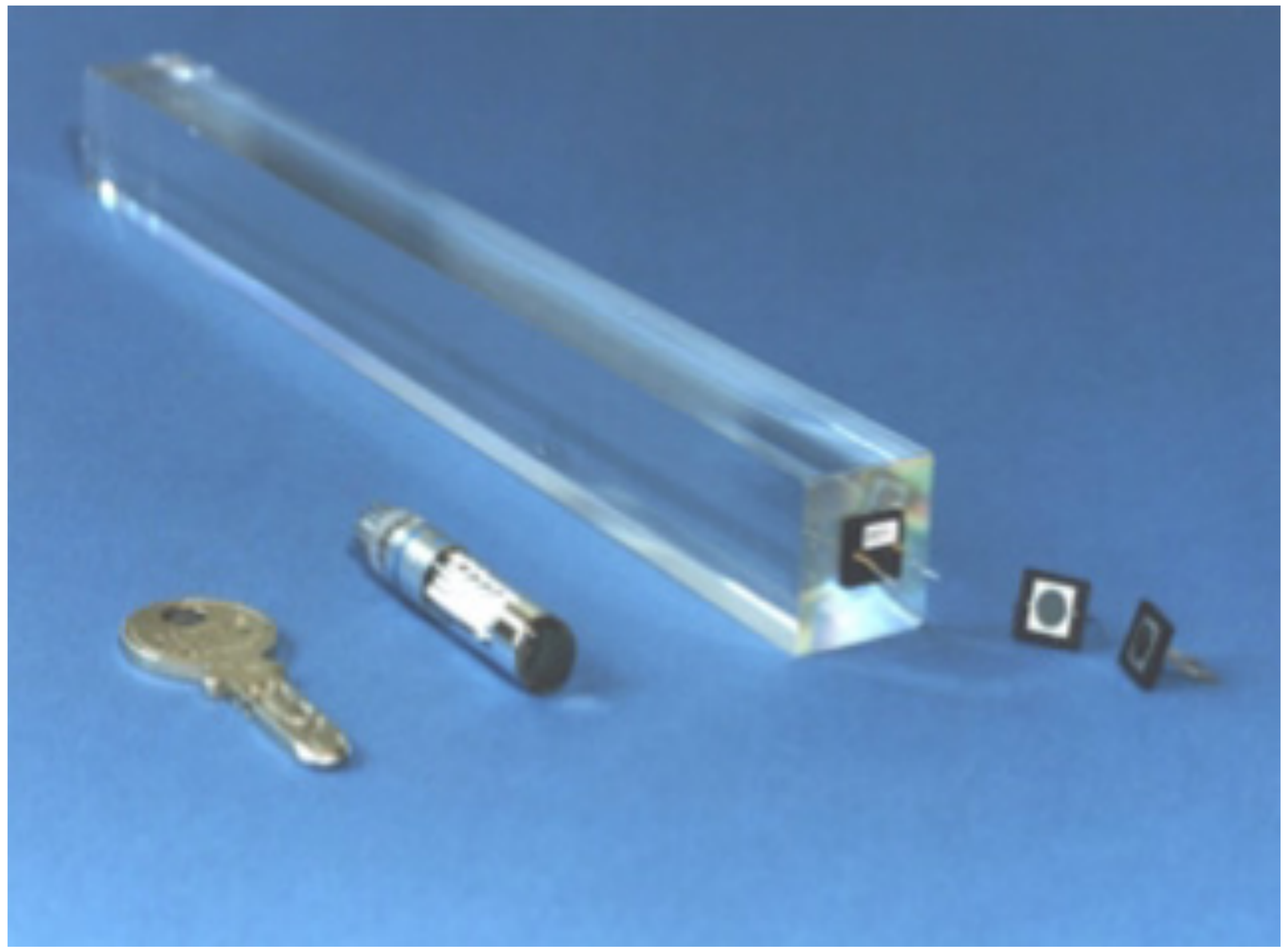
Homogenous Calorimeters

Absorber material is also the detecting material

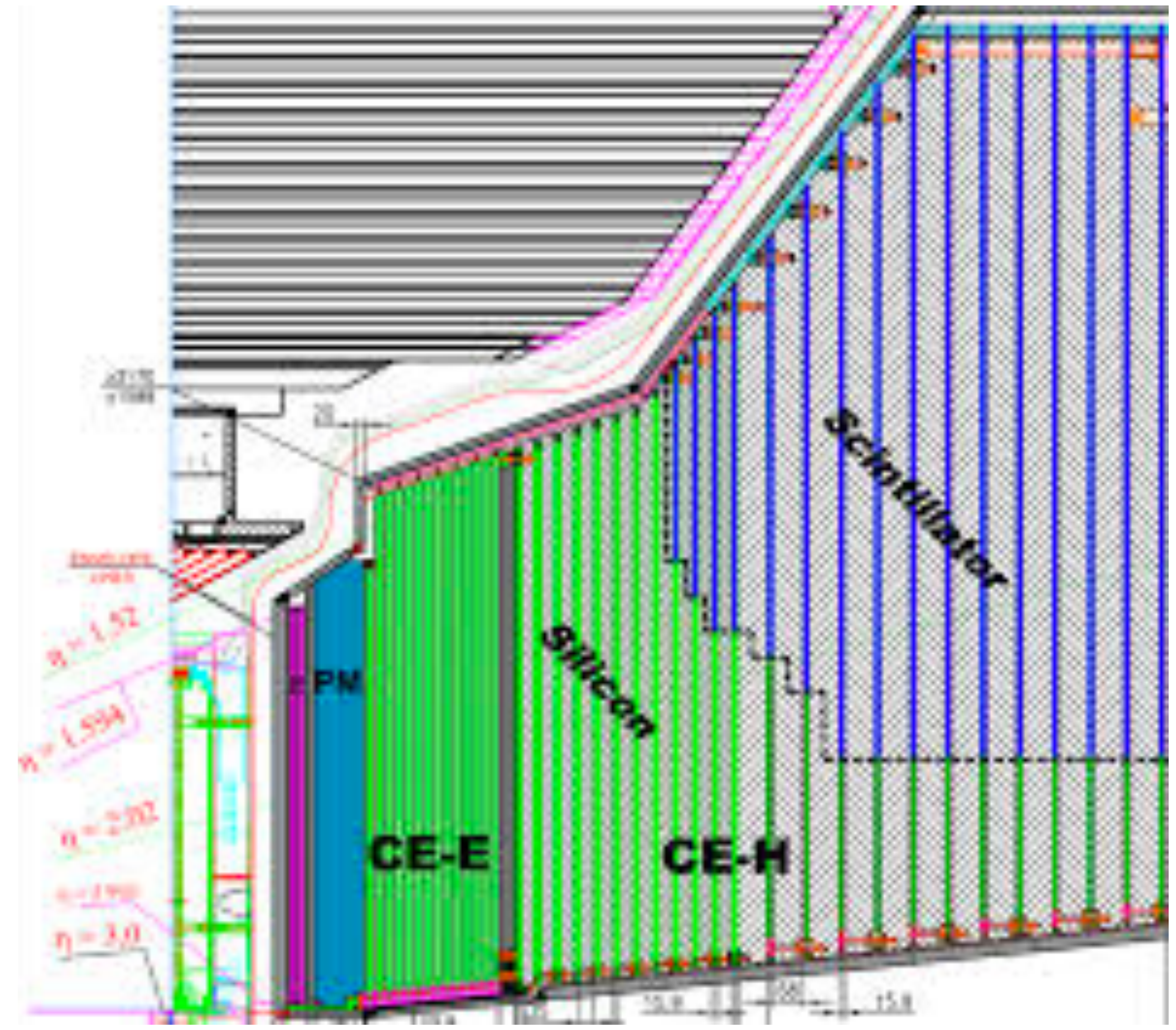
All energy deposited in the calorimeter is detected

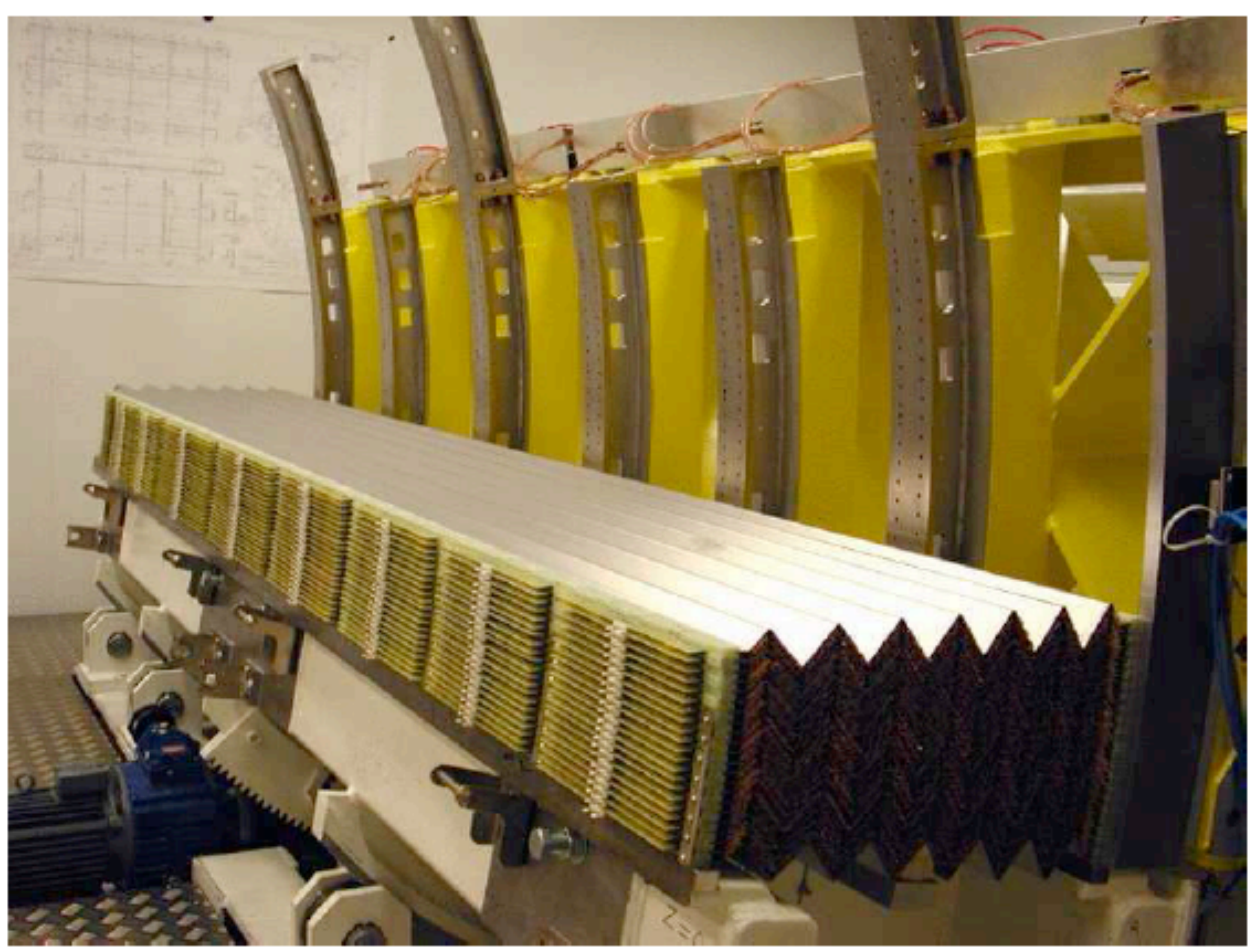
Calorimeters

CMS Crystal Calorimeter



CMS HGCal





ATLAS LAr Sampling Calorimeter

Example:

W-Si sampling calorimeter

Tungsten (W)

X_0 = 0.35cm

Moliere Radius = 0.9cm

Interaction length = 9.9cm

Calorimeter reconstruction

Cf. Calorimetry lectures from R. Wigmans

A reminder of the basics: energy resolution and characteristic size of electromagnetic and hadronic showers

Resolution:

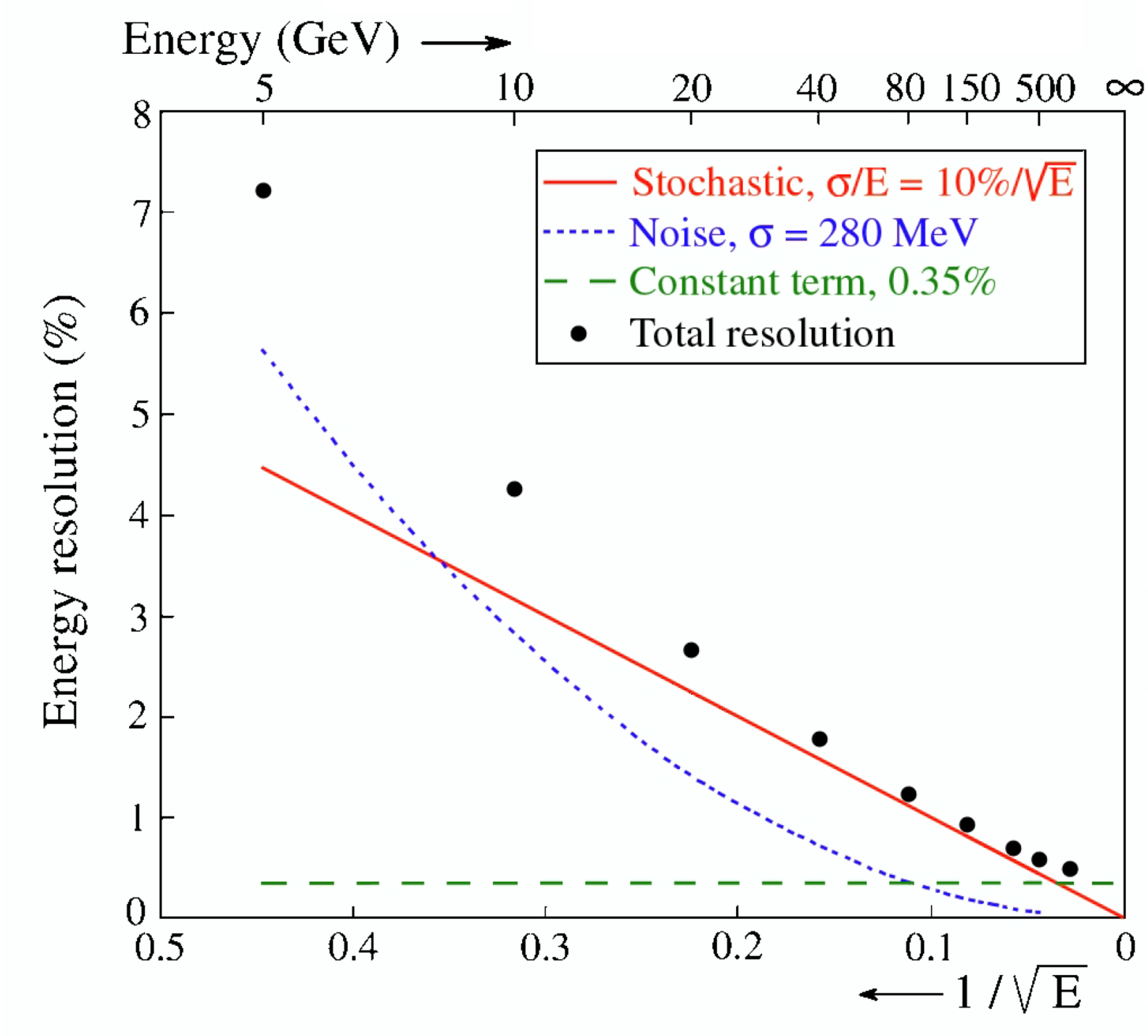
$$\frac{\sigma_E}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

Noise term:
fixed vs. energy
Typically important at low energies

Stochastic term:
Error is ~$E^{-1/2}$, as a counting error

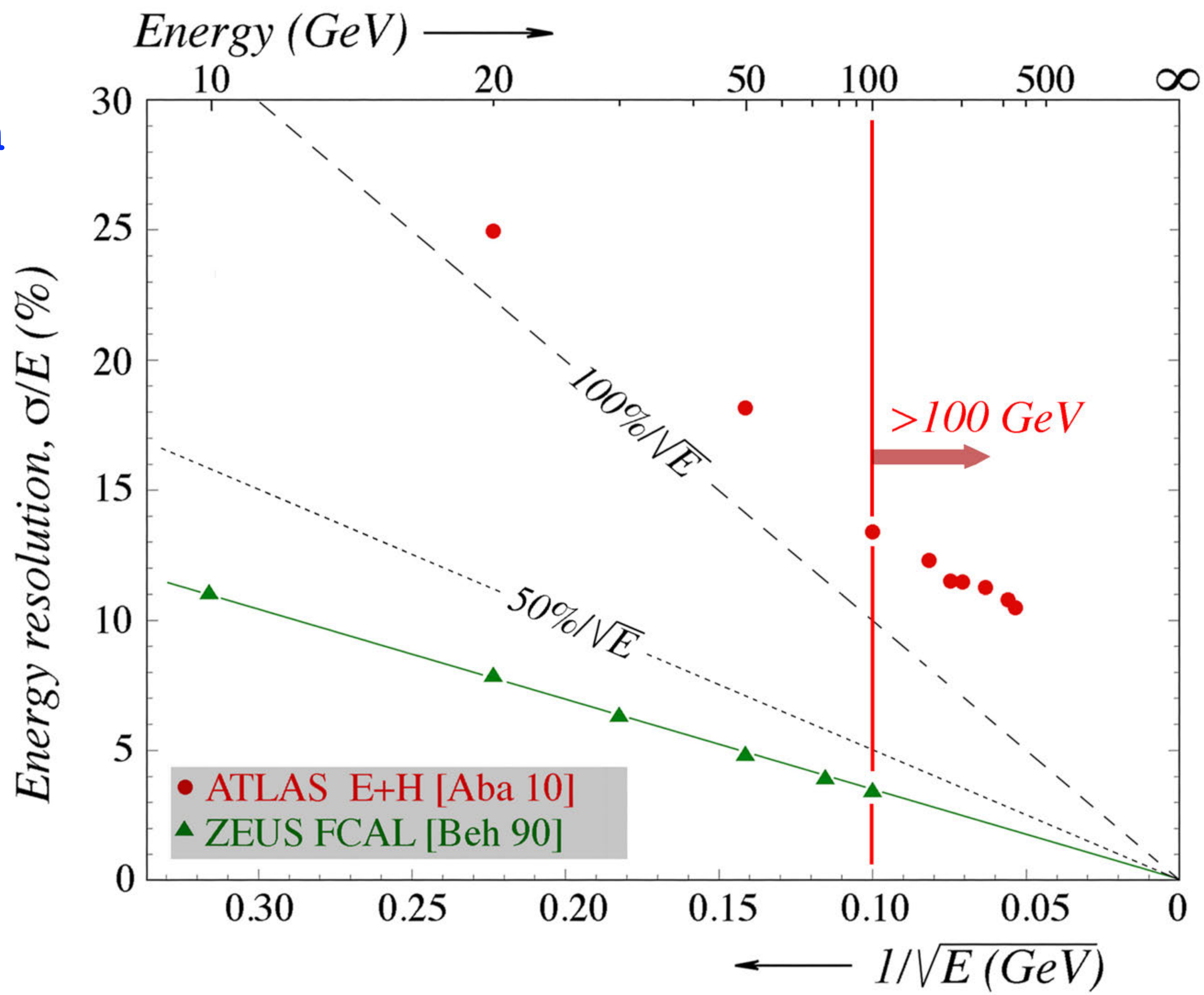
Constant term:
instrumental effect, shower leakage, etc.

Example: ATLAS EM Calorimeter



HADRONIC CALORIMETERS

Note the change in scale!!



Shower size and energy resolution

Another important consideration in reconstruction are the size of the showers

- EM showers are much smaller, uniform
- Hadronic showers are larger, less-uniform

Important concept

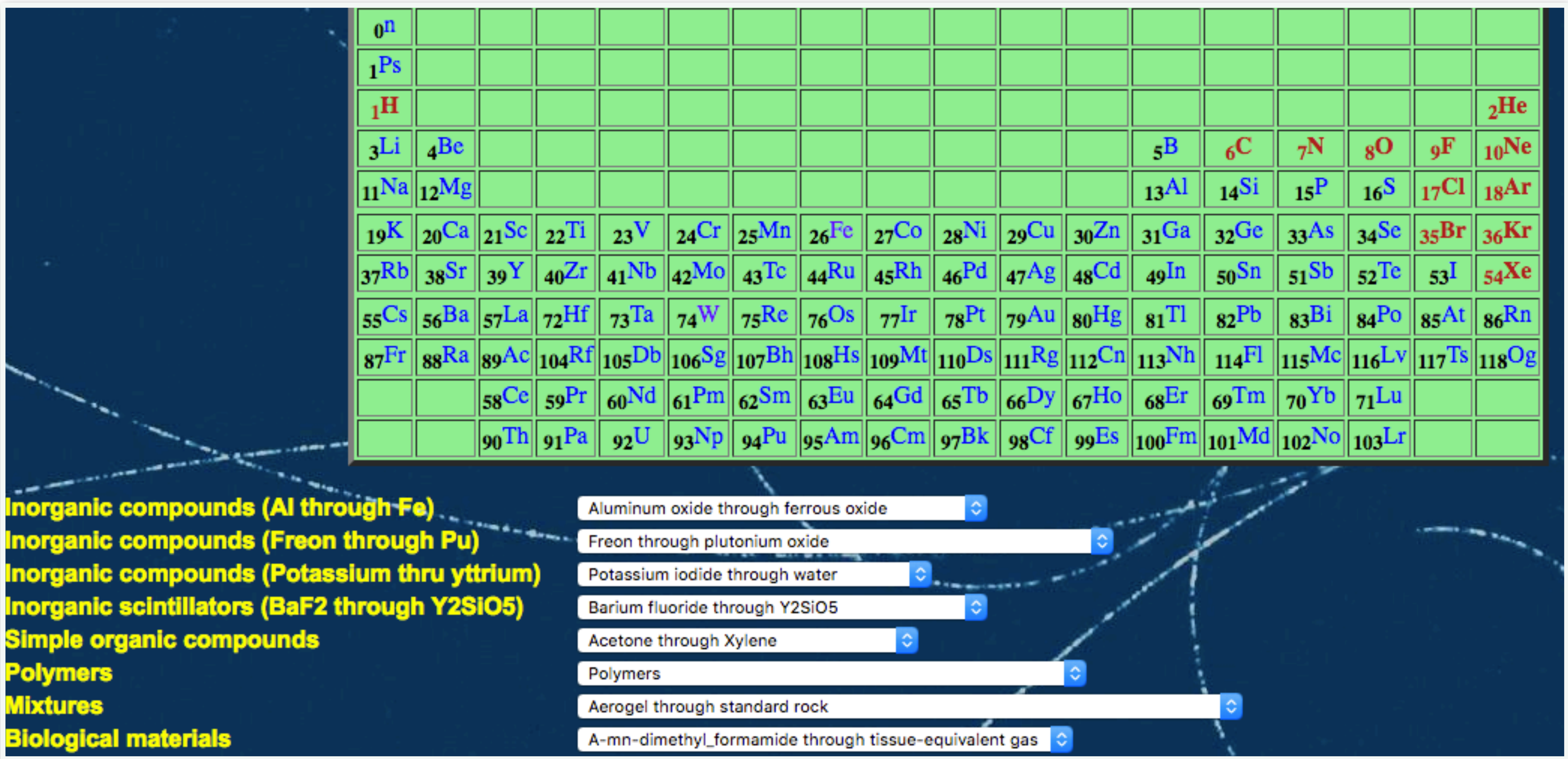
$$X_0 = \frac{716.4\ \mathrm{g\ cm^{-2}}\ A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- **X_0, radiation length**: characteristic length of a energy loss of particles interacting electromagnetically
  - Moliere radius: transverse size of the shower is related to X_0
  - $R_M = 0.0265\ X_0\ (Z + 1.2)$

- **λ, interaction length**: characteristic length of particles interacting with nuclei

NICE RESOURCE

http://pdg.lbl.gov/2017/AtomicNuclearProperties/



Atomic and nuclear properties of iron (Fe)

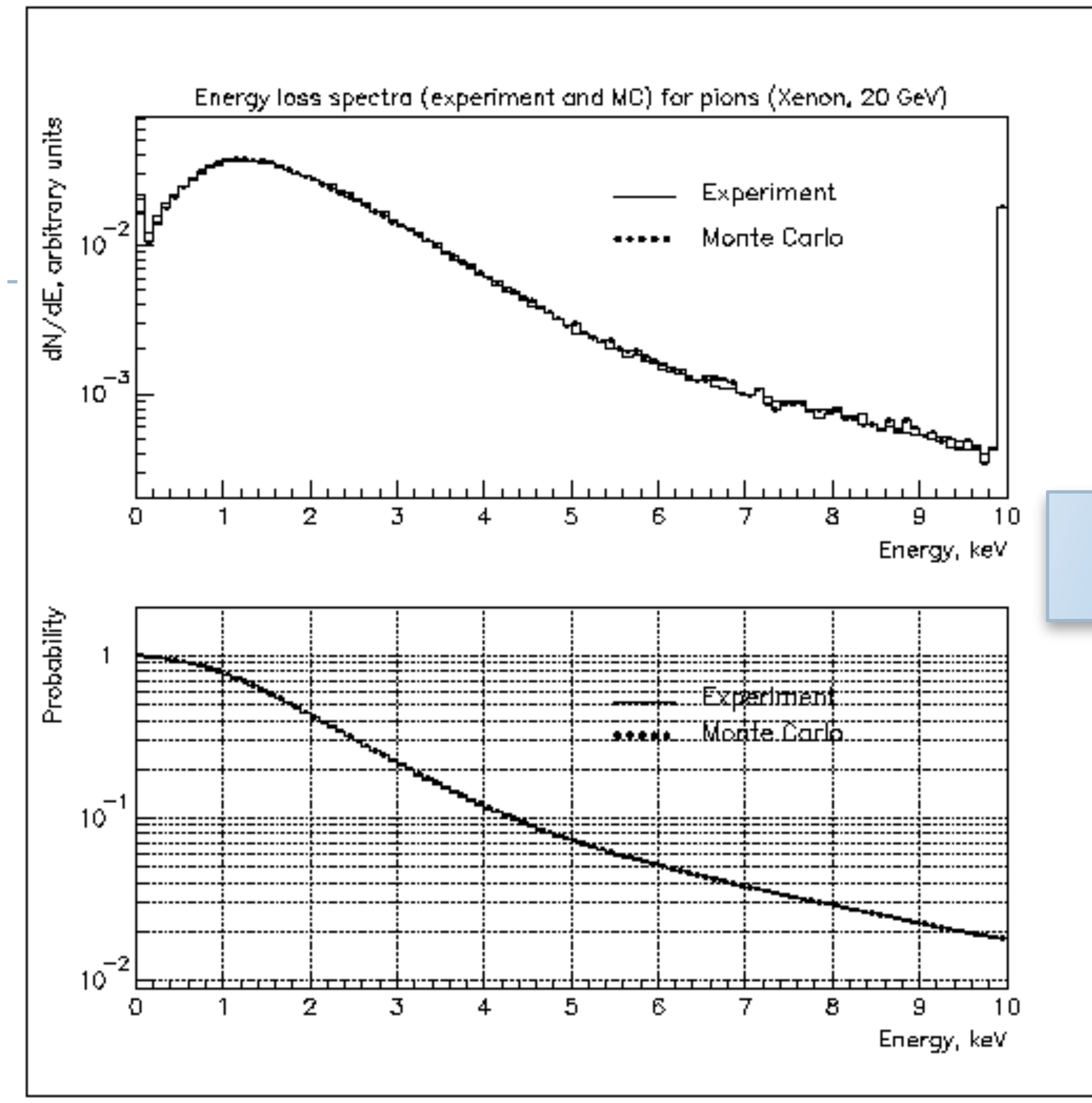
Nuclear collision length	81.7	g cm^{-2}	10.37	cm
Nuclear interaction length	132.1	g cm^{-2}	16.77	cm
Pion collision length	107.0	g cm^{-2}	13.59	cm
Pion interaction length	160.8	g cm^{-2}	20.42	cm
Radiation length	13.84	g cm^{-2}	1.757	cm

For high Z materials

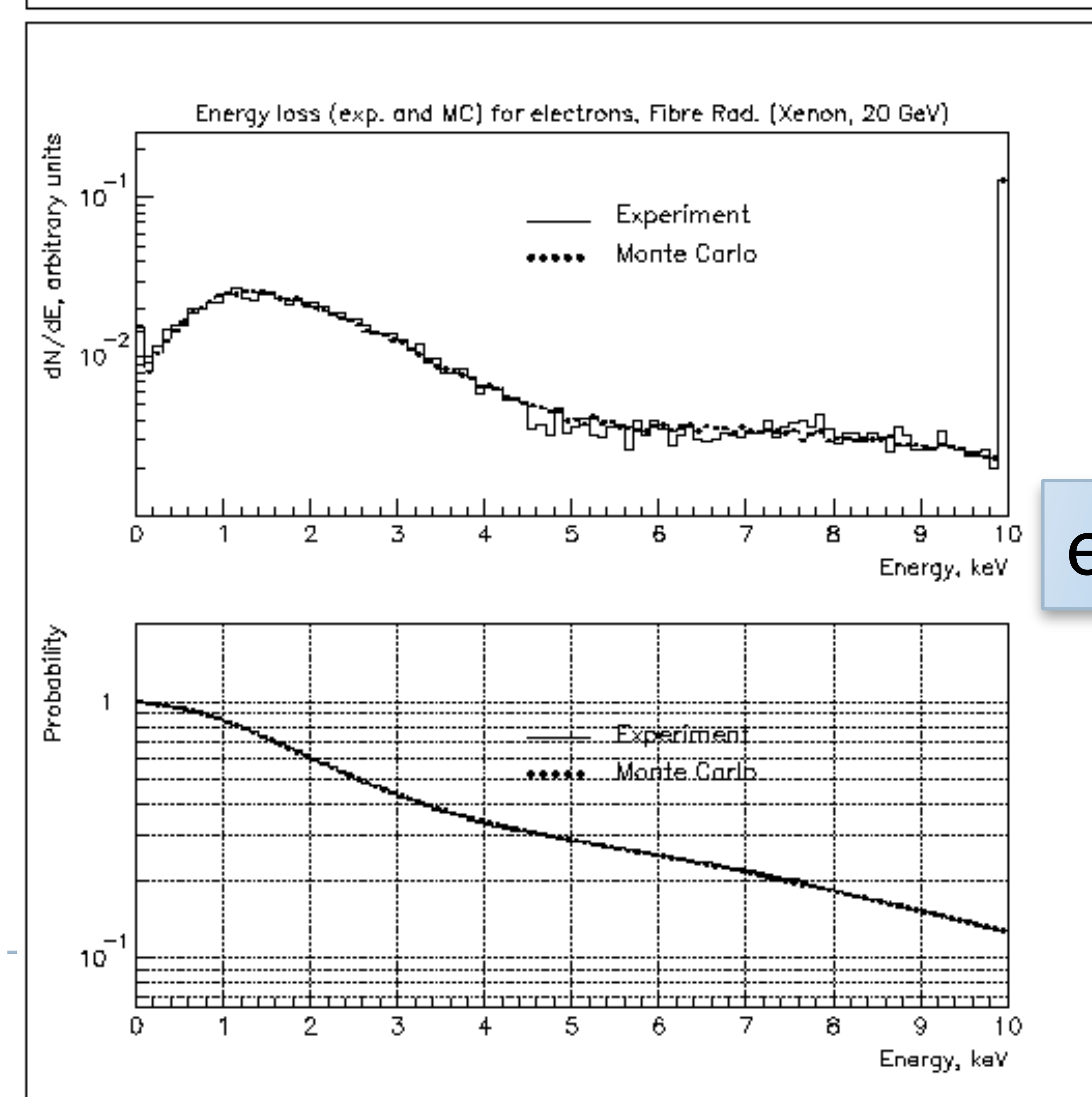
$X_0 << \lambda$

TRD

- When particle pass through a region with a discontinuous refractive index they can emit Transition Radiation
- These are only emitted for particles with a very high β (of order 1000, so really only seen for electrons)
- The photons from transition radiation have an energy of order 10KeV
- In the ATLAS TRT, these photons are absorbed by the gas, and give a larger signal than the minimum ionizing signal.
  - Straws are packed in radiator material
- In each straw, look for larger hits which signal a possible TR hit
- Can provide electron ID



Pions



electrons

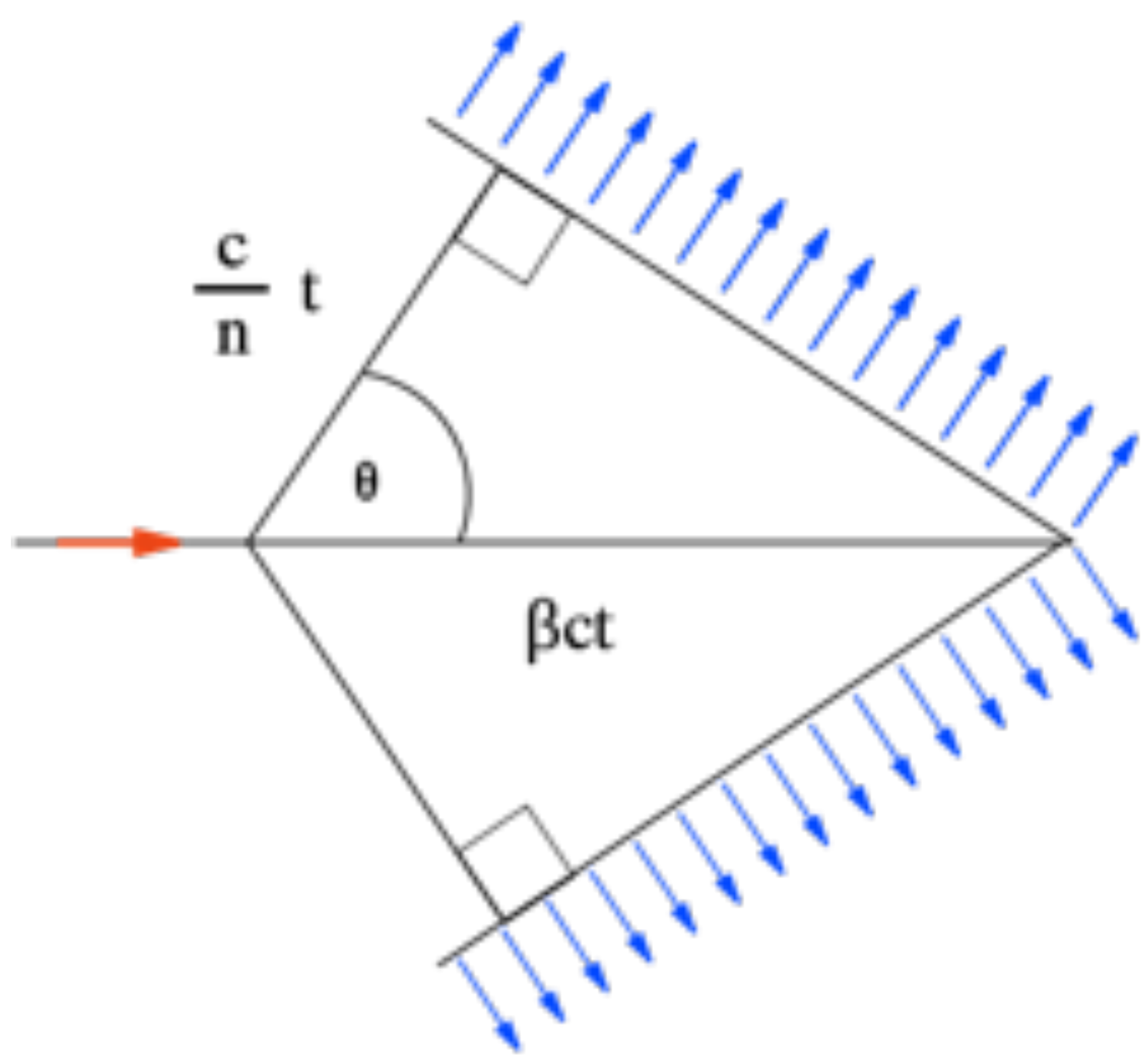
SPECIAL TOPIC: LHCB RICH DETECTOR

Hadron ID is very important, particular in b physics

LHCb has a dedicated detector, RICH, for particle ID

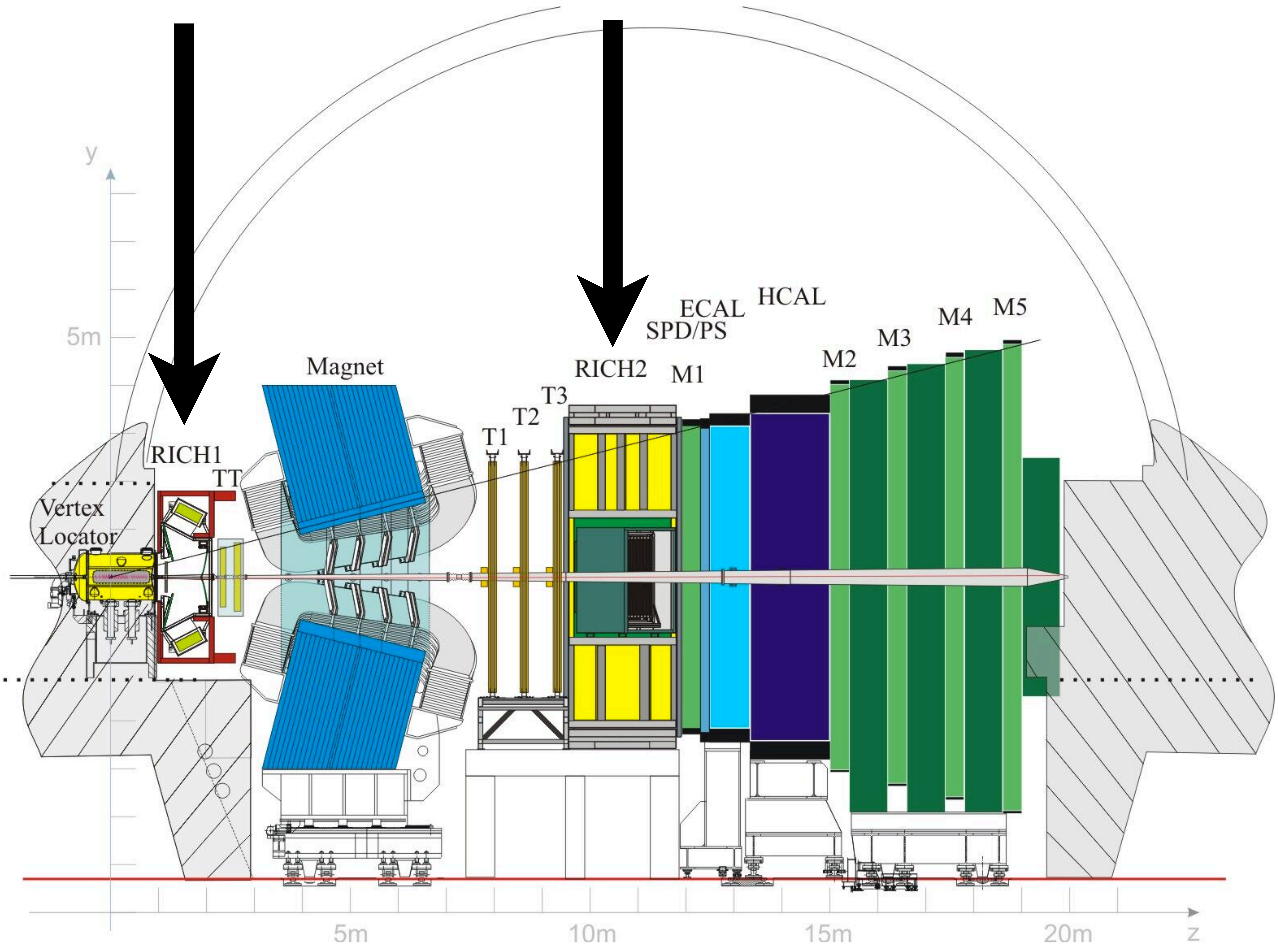
RICH: Ring Imaging Cherenkov Detector

Cherenkov radiation: Particles moving in material with index of refraction greater than 1 travel faster than the speed of light and emit radiation at an angle θ_c

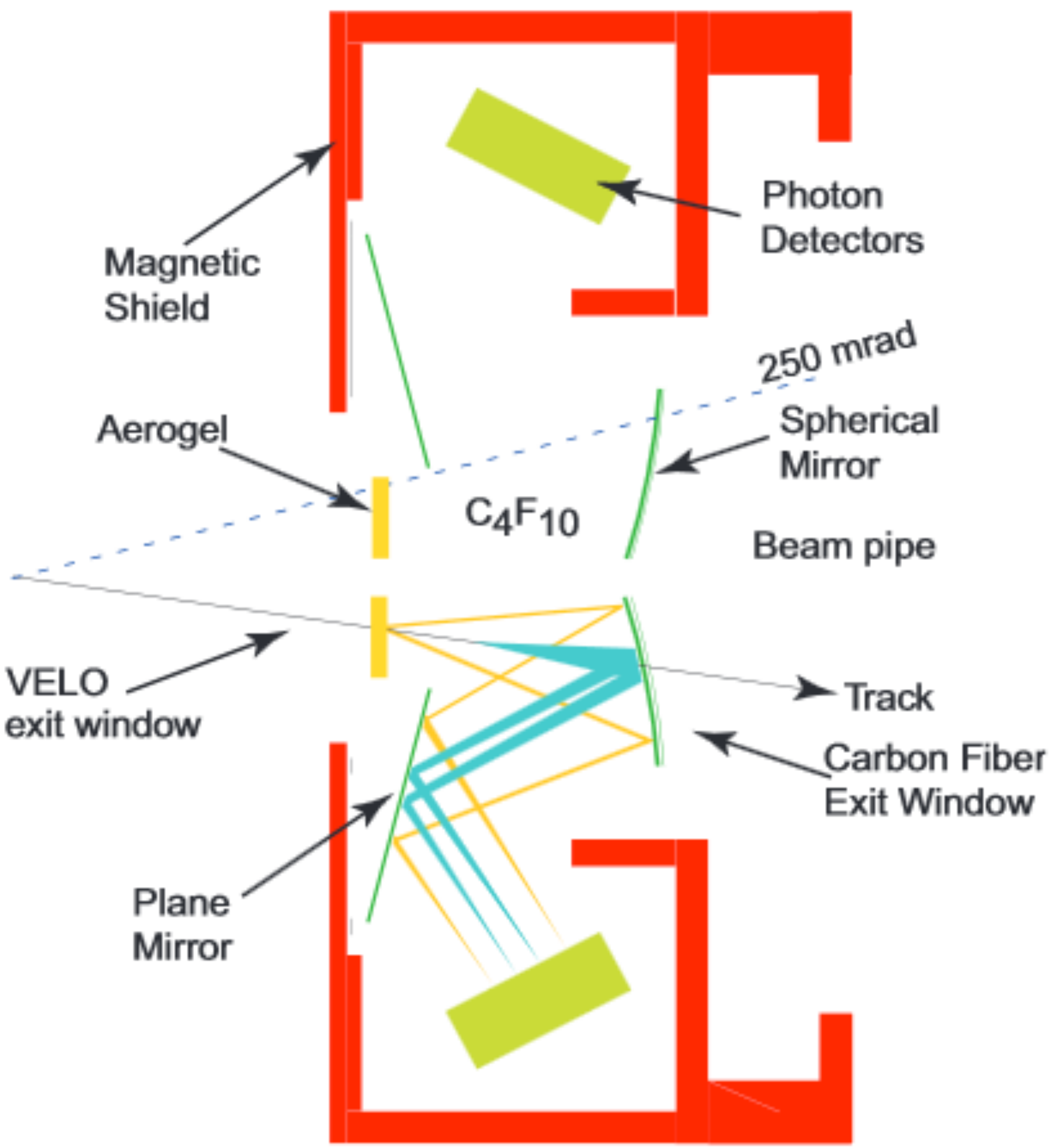


$$\cos\theta_c = \frac{1}{\beta n}$$

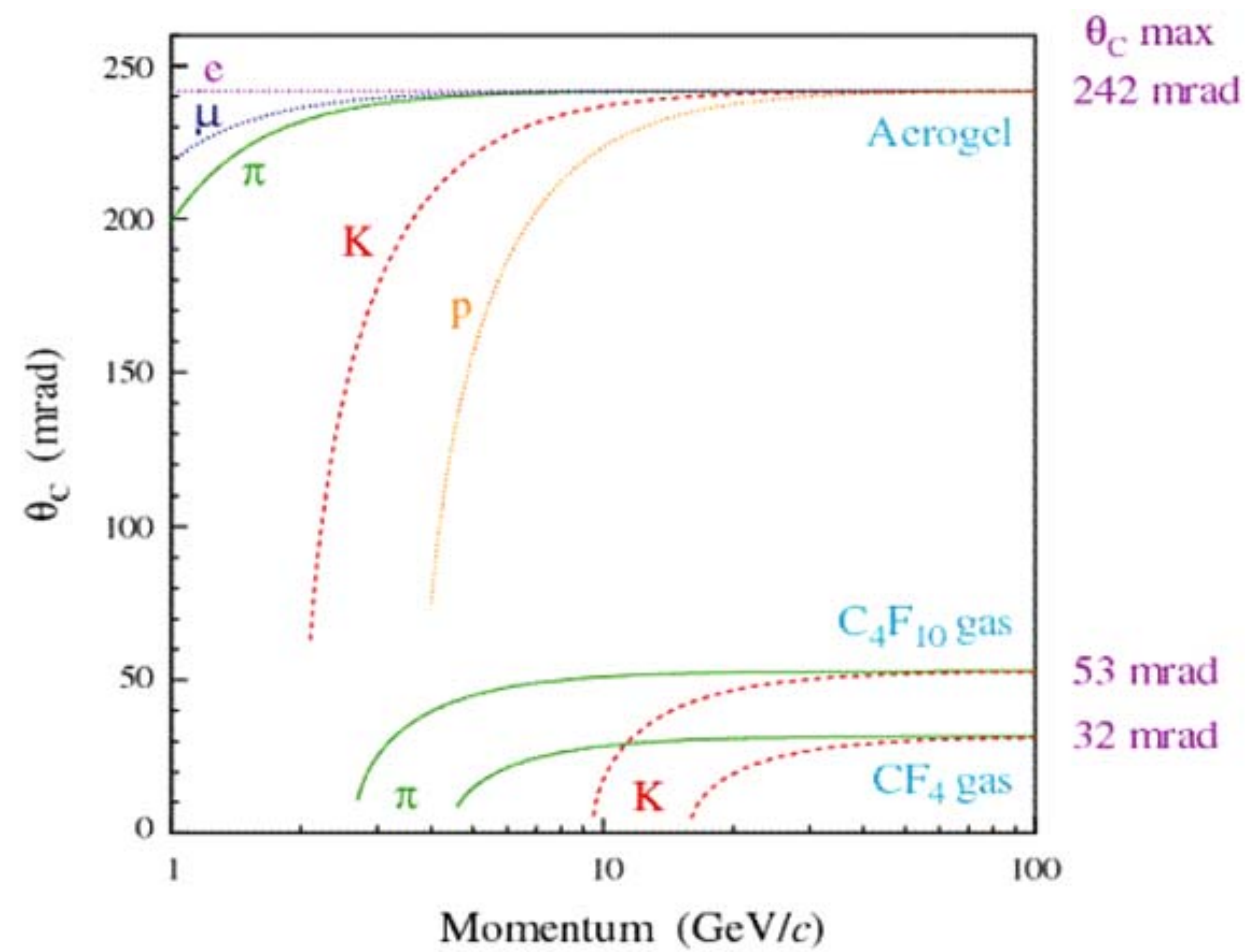
LHCb reminder



Particle ID

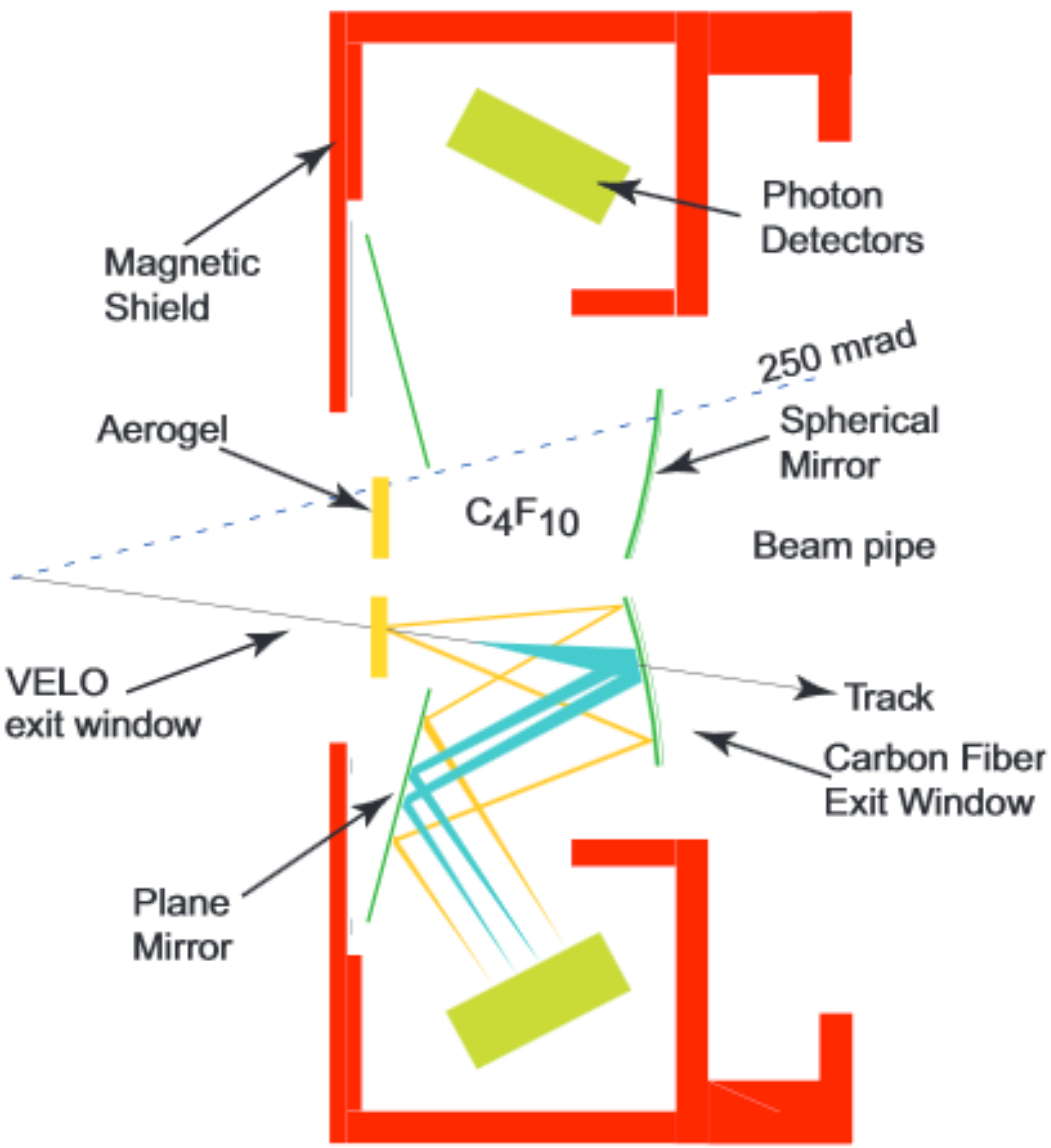


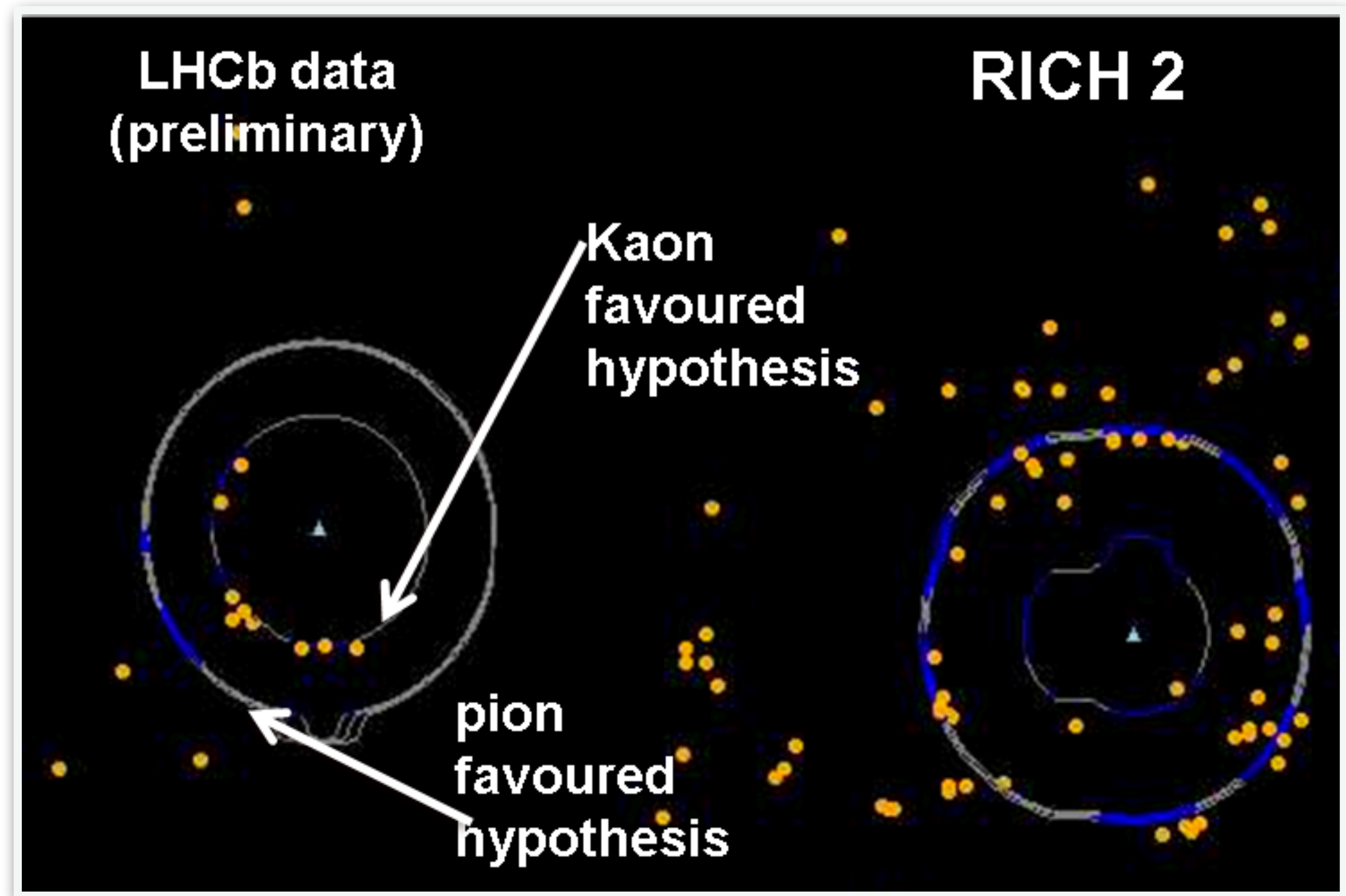
By measuring the track momentum and θ_c, one can identify the particle type



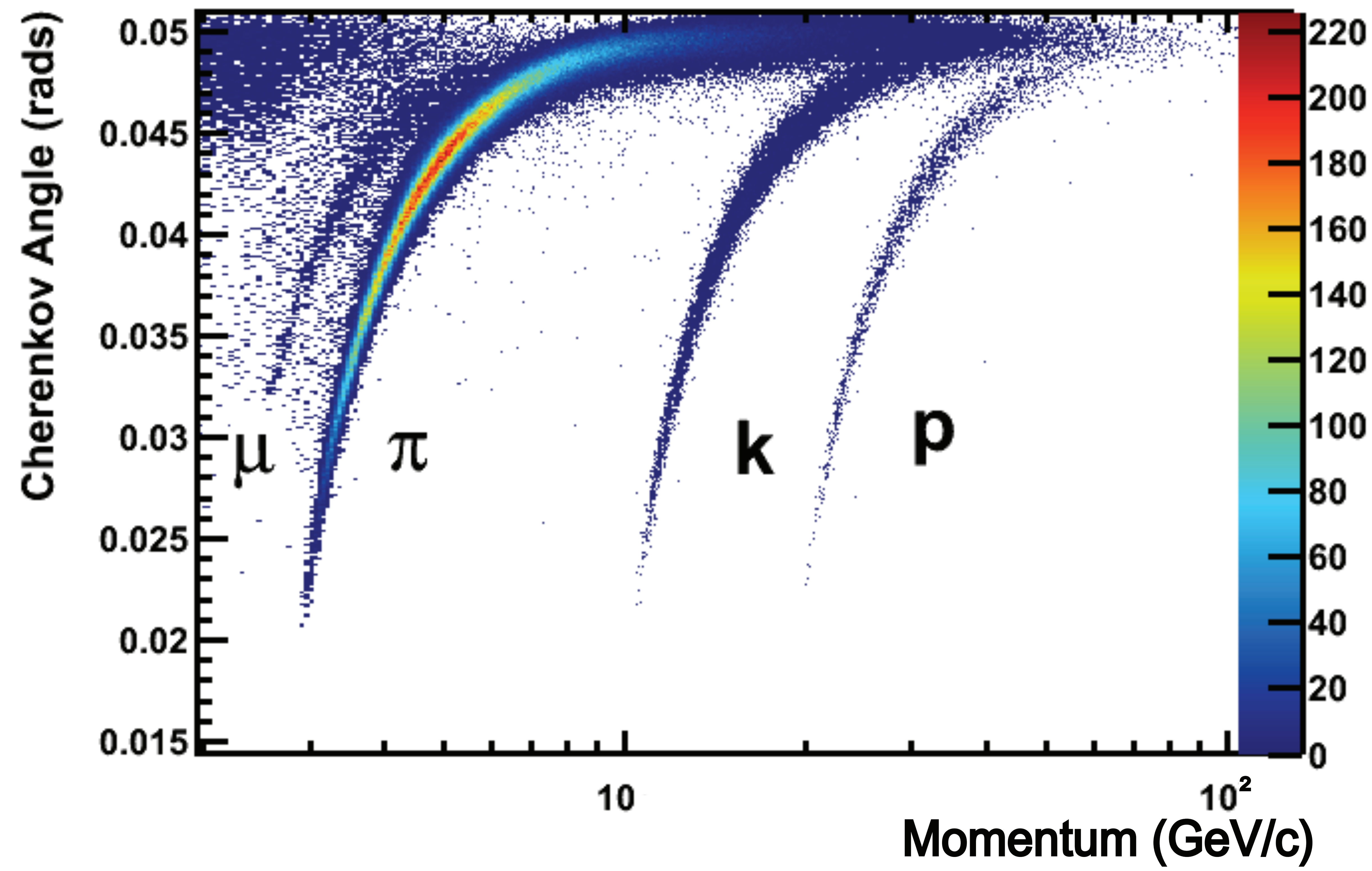
RICH1 = aerogel and C_4F_{10} gas
RICH2 = CF_4 gas

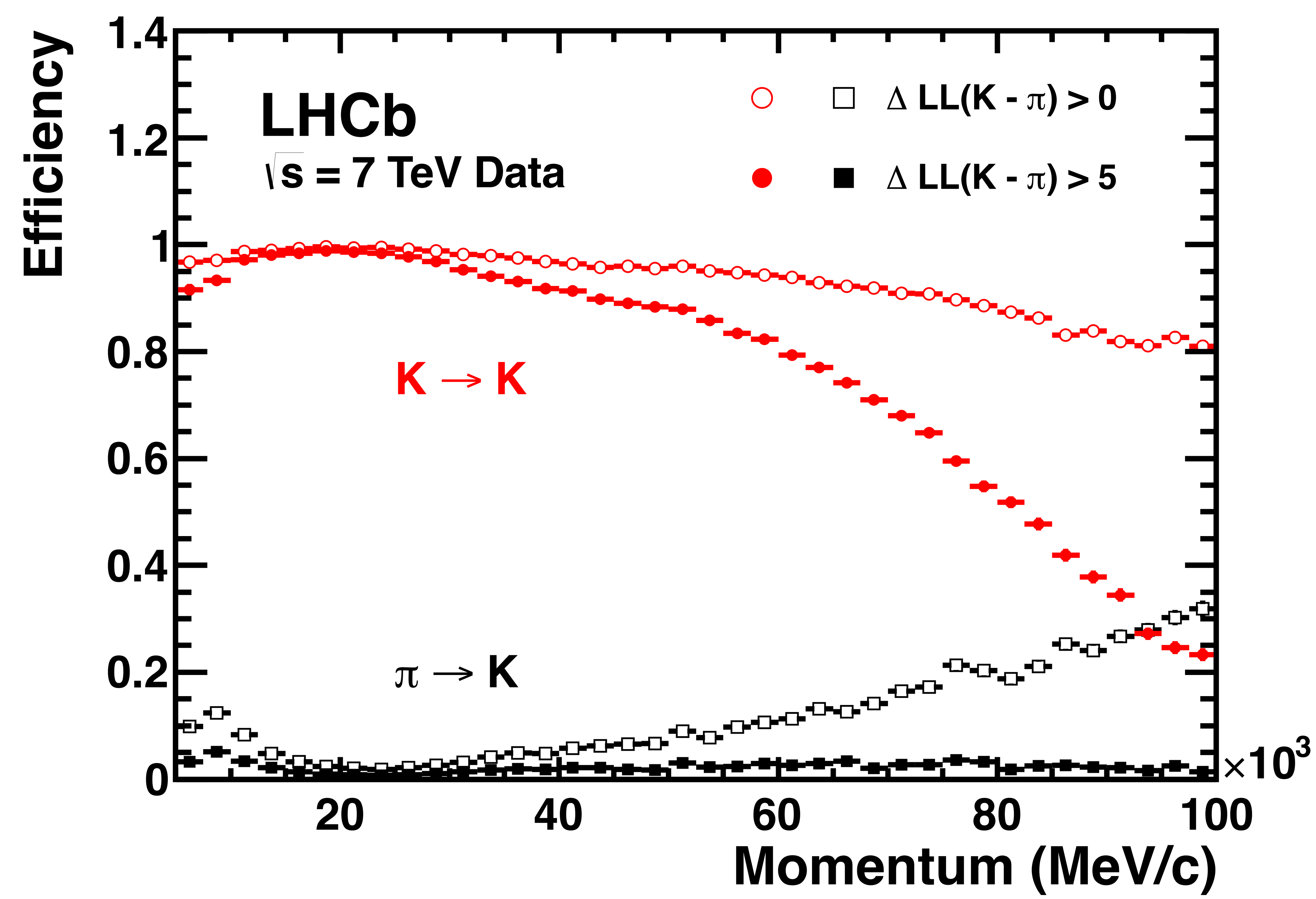
Particle ID


Magnetic Shield
Photon Detectors
250 mrad
Spherical Mirror
Aerogel
C_4F_{10}
Beam pipe
VELO exit window
Track
Carbon Fiber Exit Window
Plane Mirror

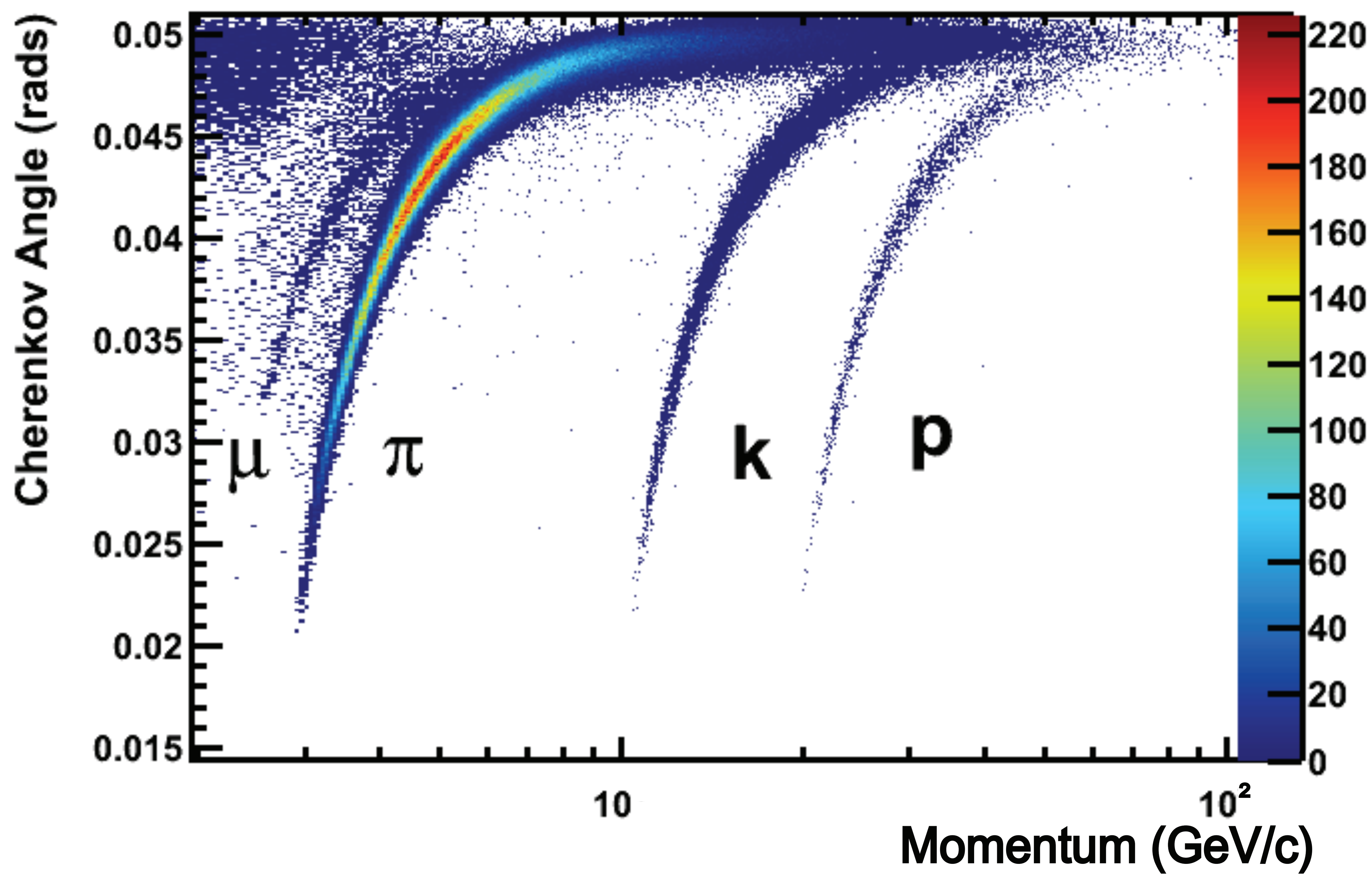

LHCb data (preliminary)
RICH 2
Kaon favoured hypothesis
pion favoured hypothesis

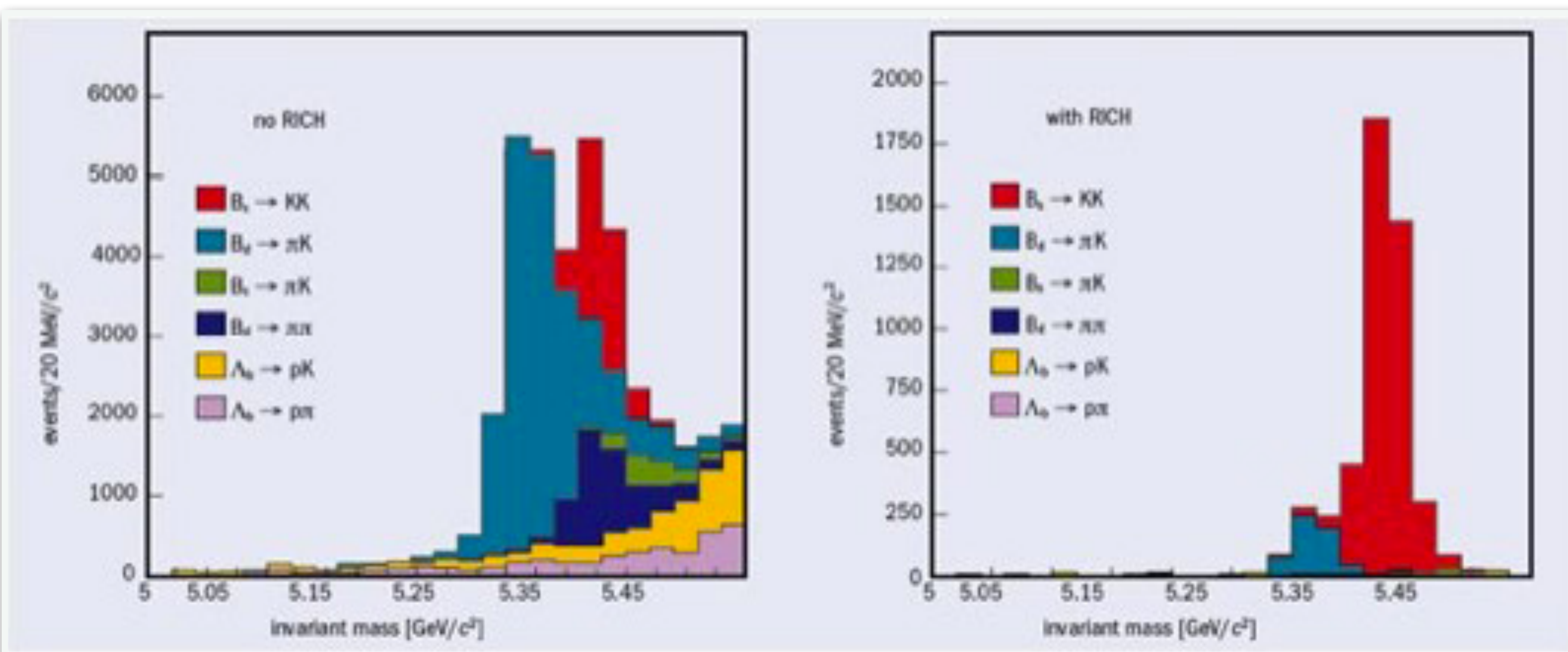
LHCb RICH effect





LHCb RICH effect





Mini-Summary

The different detector technologies and their intrinsic resolution are **complementary**!

- As one starts to get worse, the other starts to get better
- Tracking has the best intrinsic spatial resolution

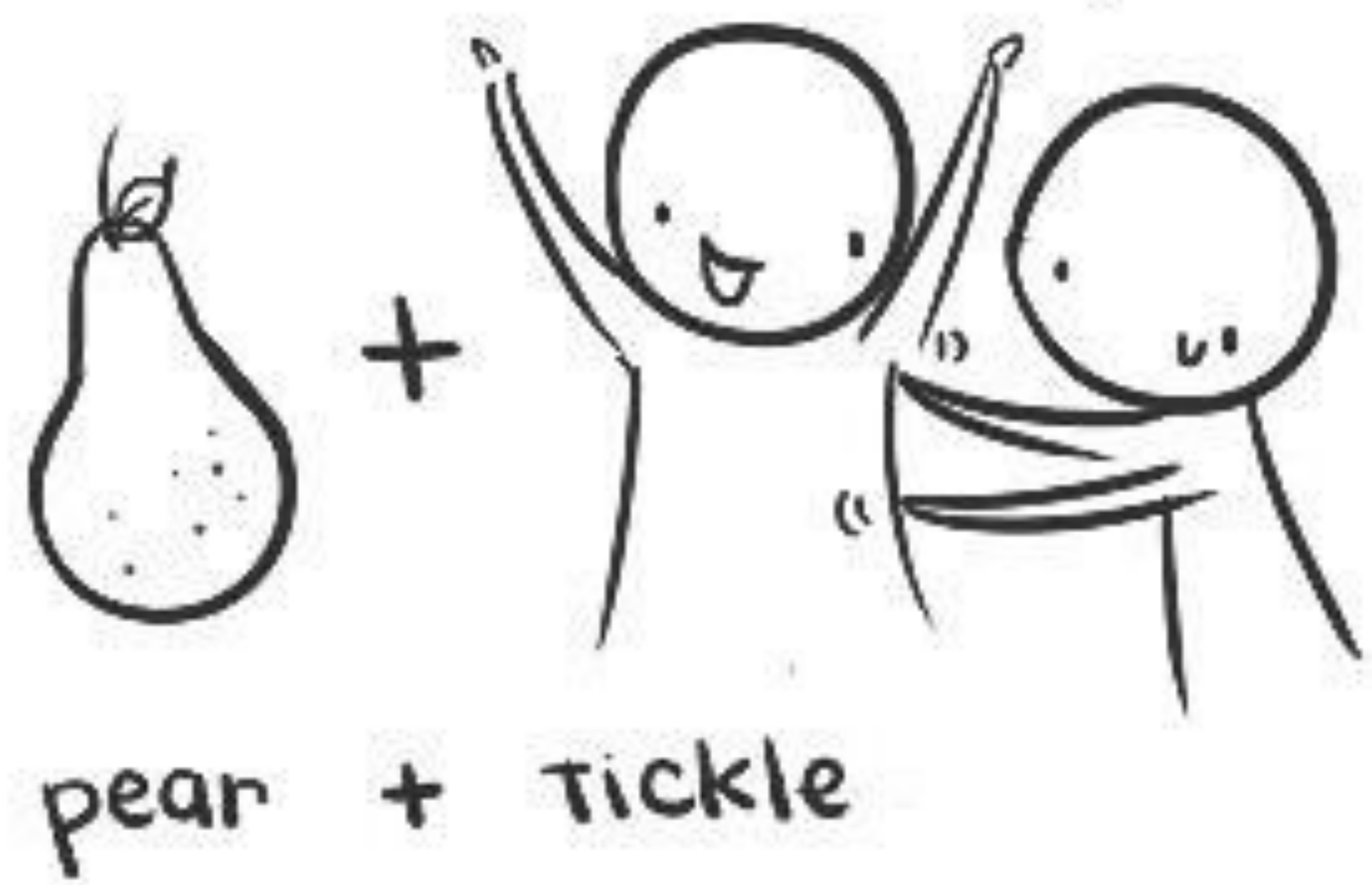
Representative numbers for the CMS case

Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)

Vertexing numbers:

Primary vertex resolution: ~25-100 mm
Timing detector resolution: ~30-300 ps

2. Particle reconstruction



Muon

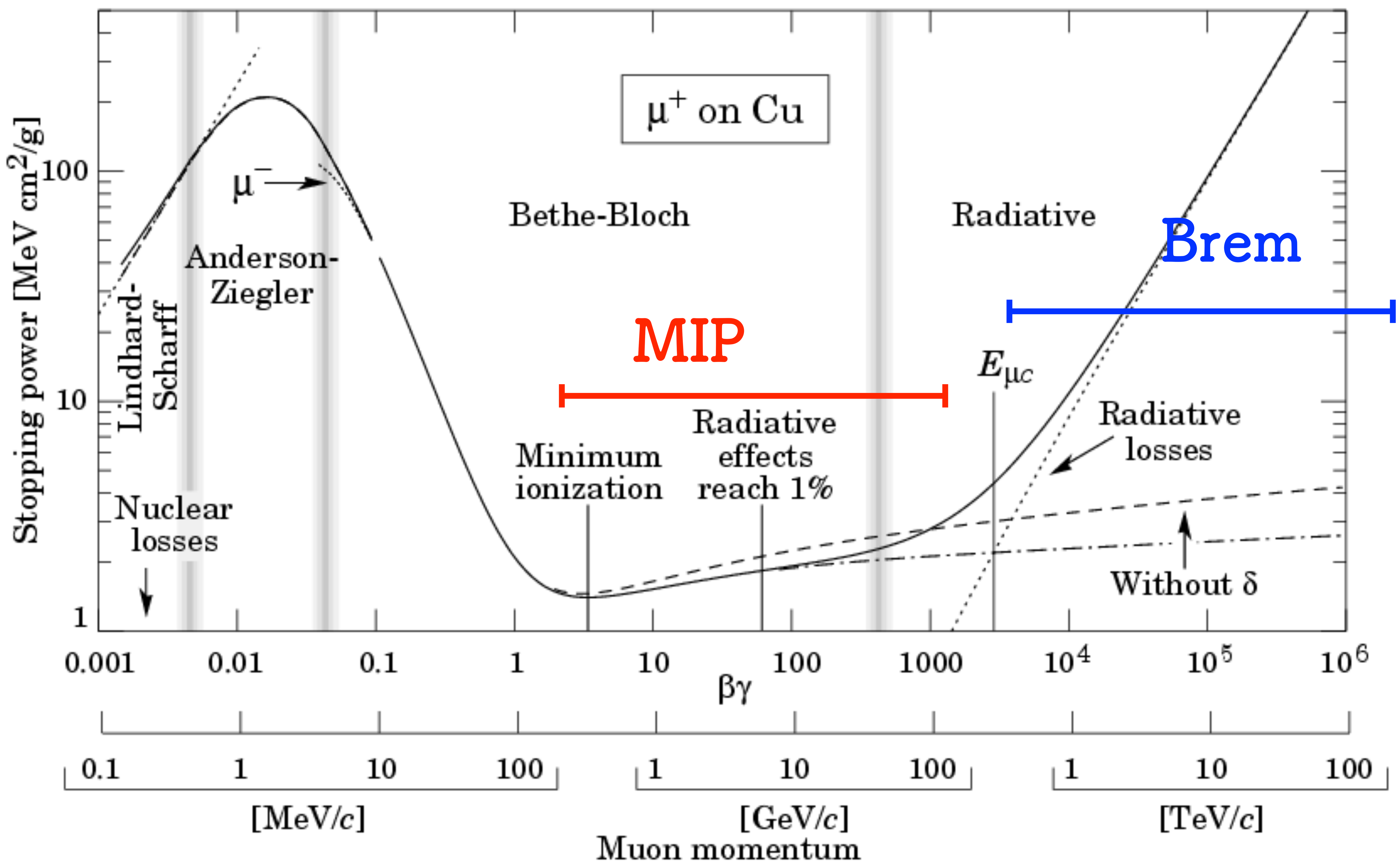

4T
2T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
Iron return yoke interspersed
with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Dave Barney

Muons

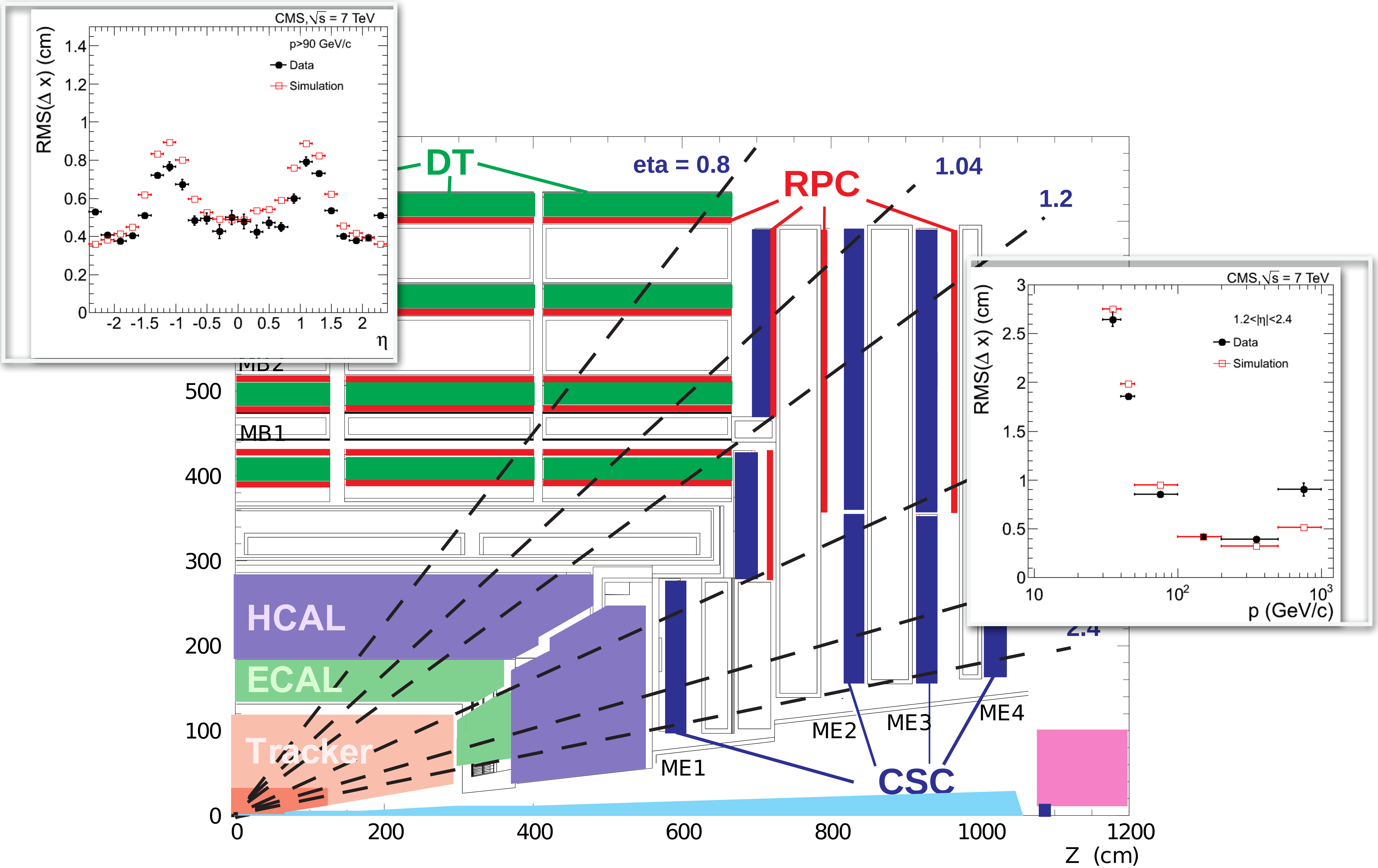
Because of it's long lifetime — the muon is a stable particle for our purposes ($c\tau$ = 700m)

It does not feel the strong interaction, so it's only minimum ionizing particle

... except at high energies where it acts like an electron (> 1 TeV)



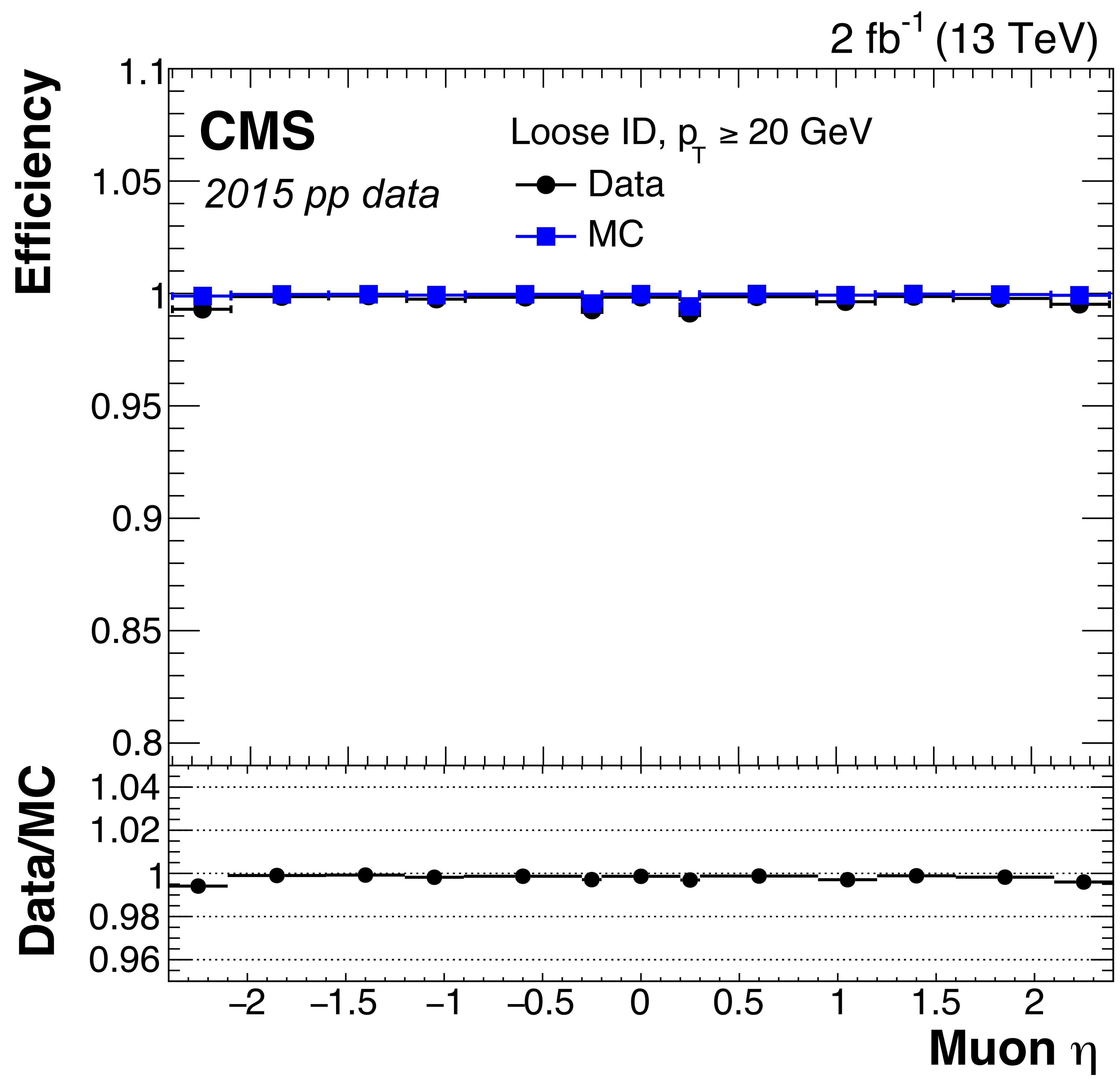
Muon detectors

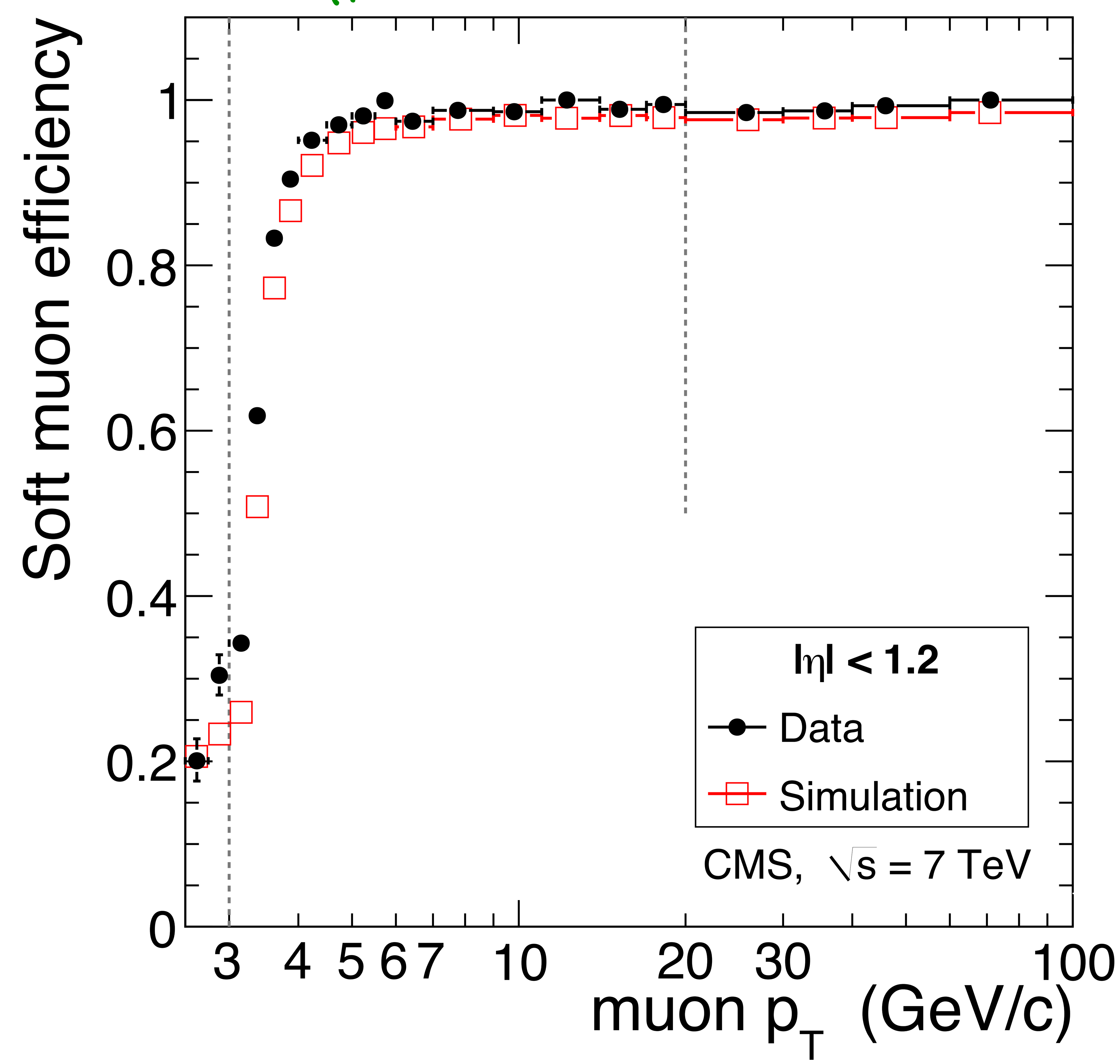


Muons are very penetrating and primarily interacts as a MIP

- Very high ID efficiency!

WHY THE DROPOFF IN PT?

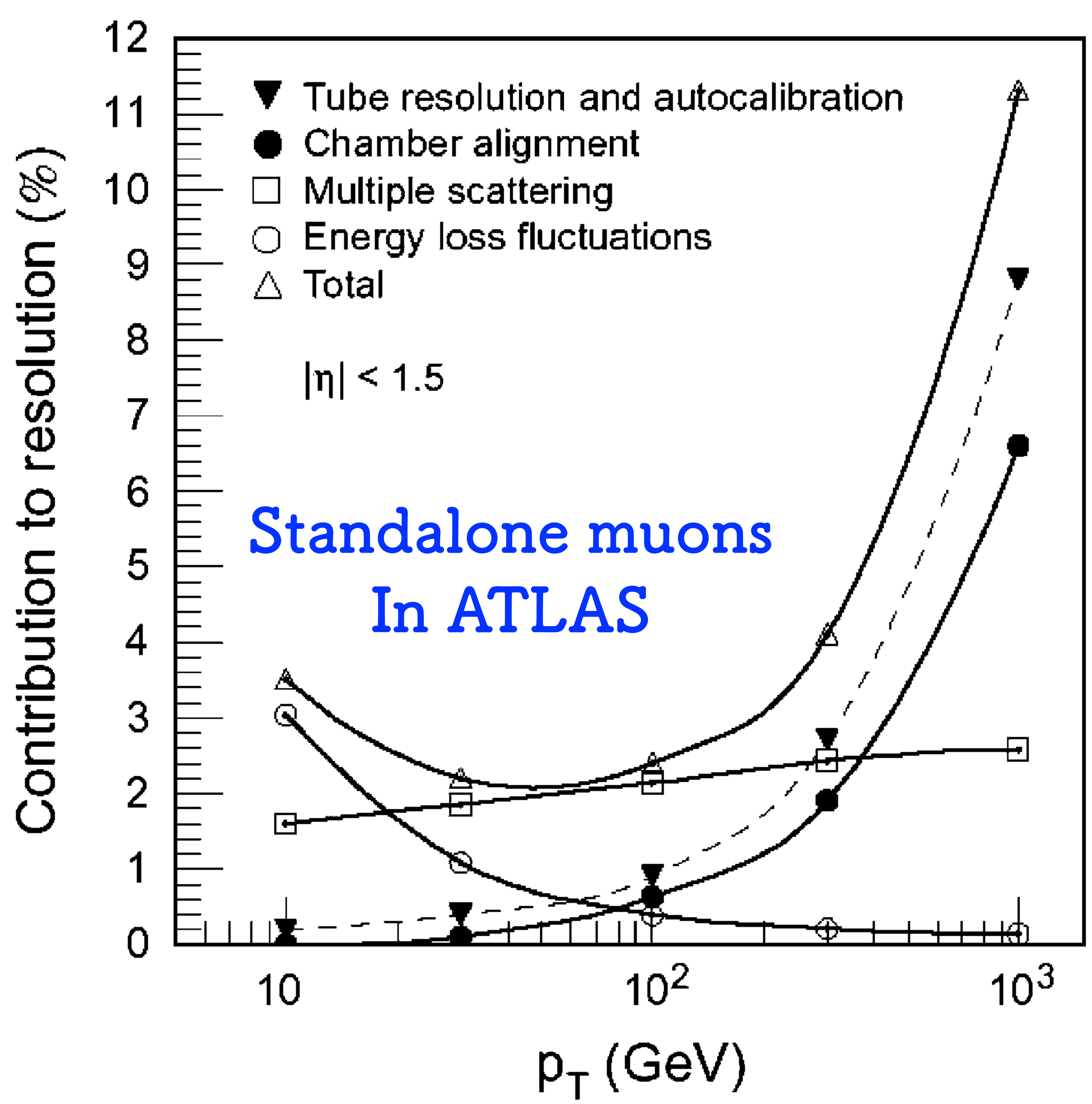


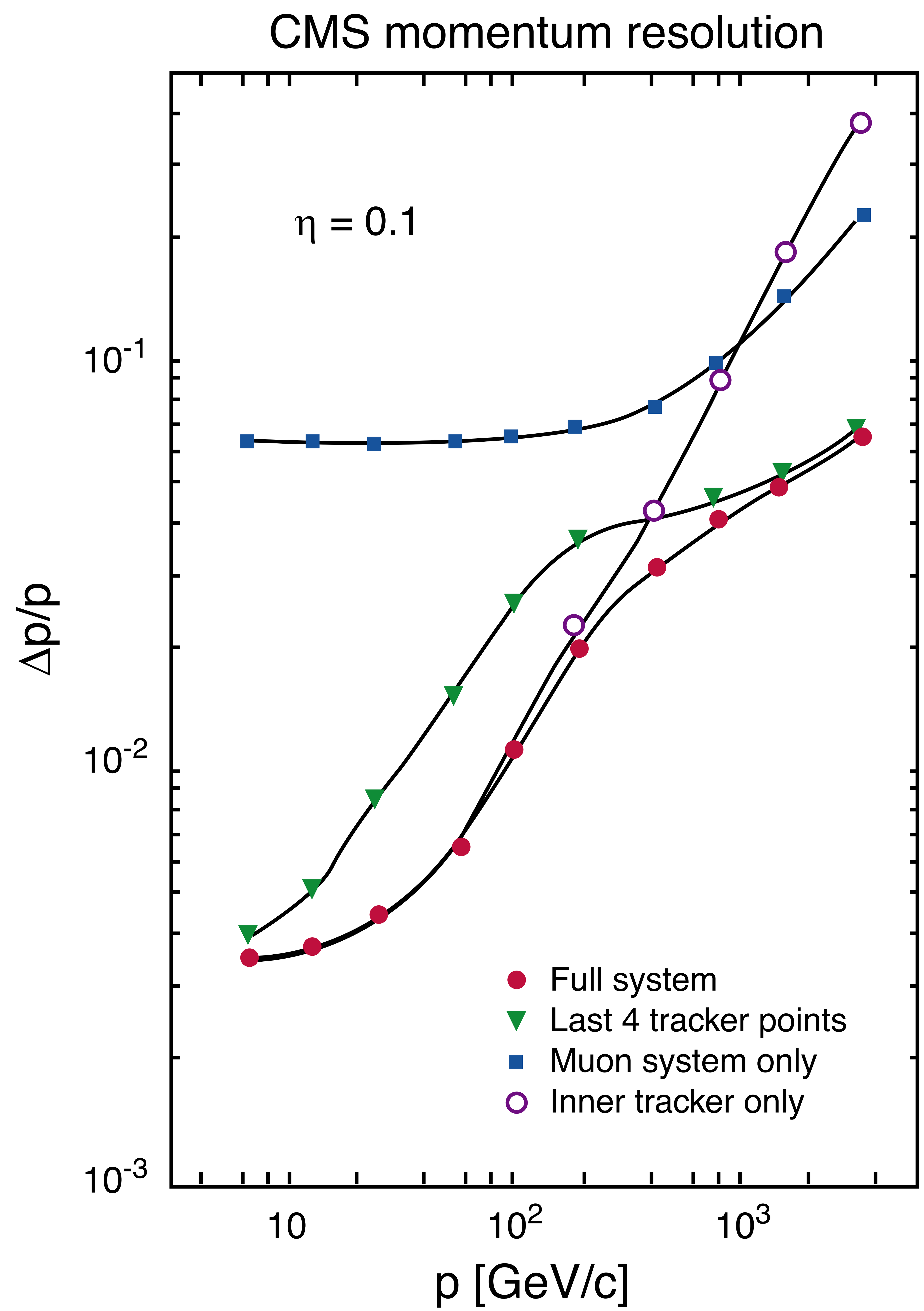


Muon momentum resolution

The muon system should be very efficient for identifying muons

Momentum measurements important at the **trigger level**
And also for **high pT muons**





Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Dave Barney

Electron


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Dave Barney

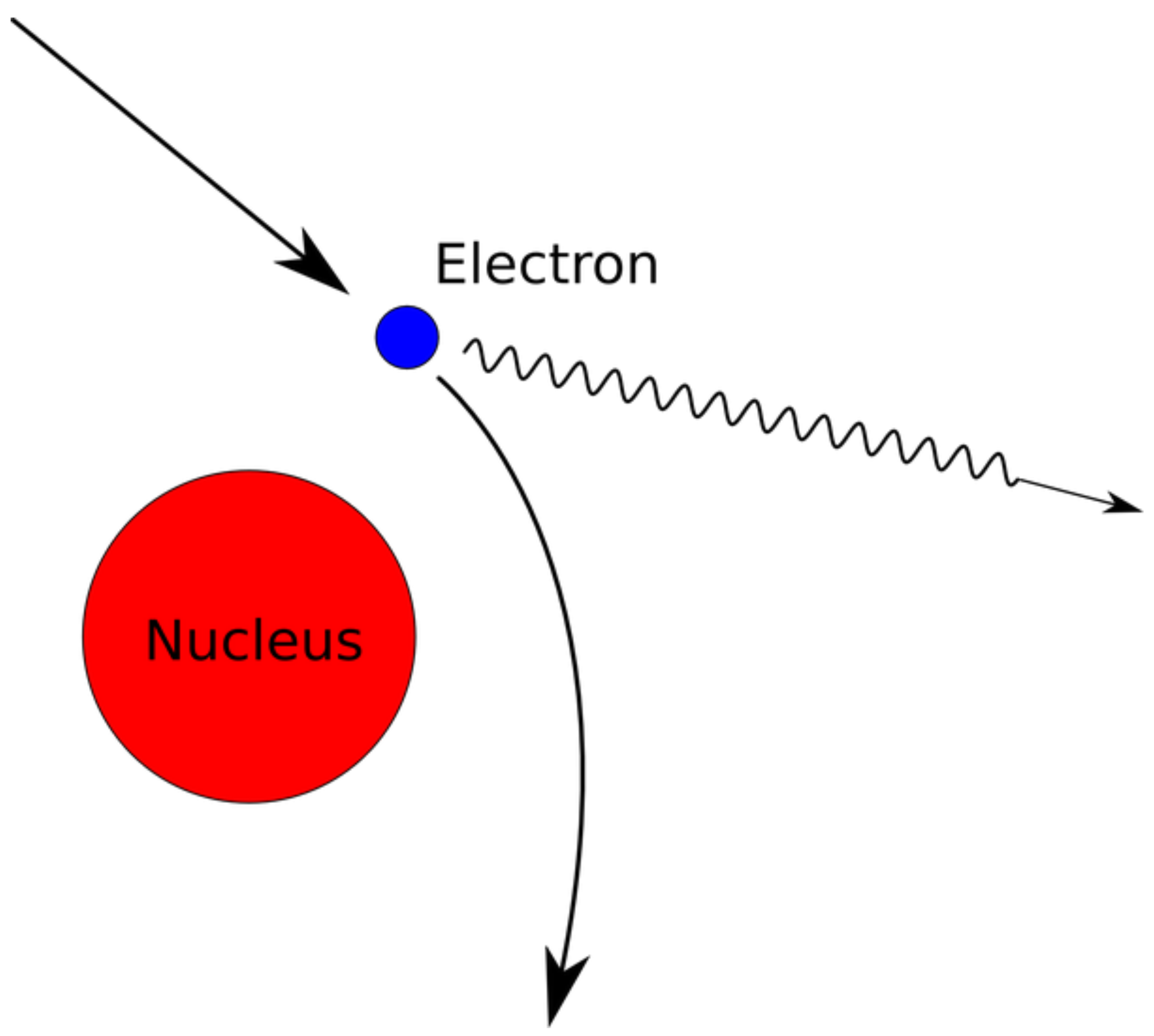
The problem with electrons...

They interact a lot more! Primarily through **bremsstrahlung**

Energy loss from bremsstrahlung:

(energy loss is proportional to energy)

$$-\frac{dE}{dx} = \frac{E}{X_0}$$



Electrons

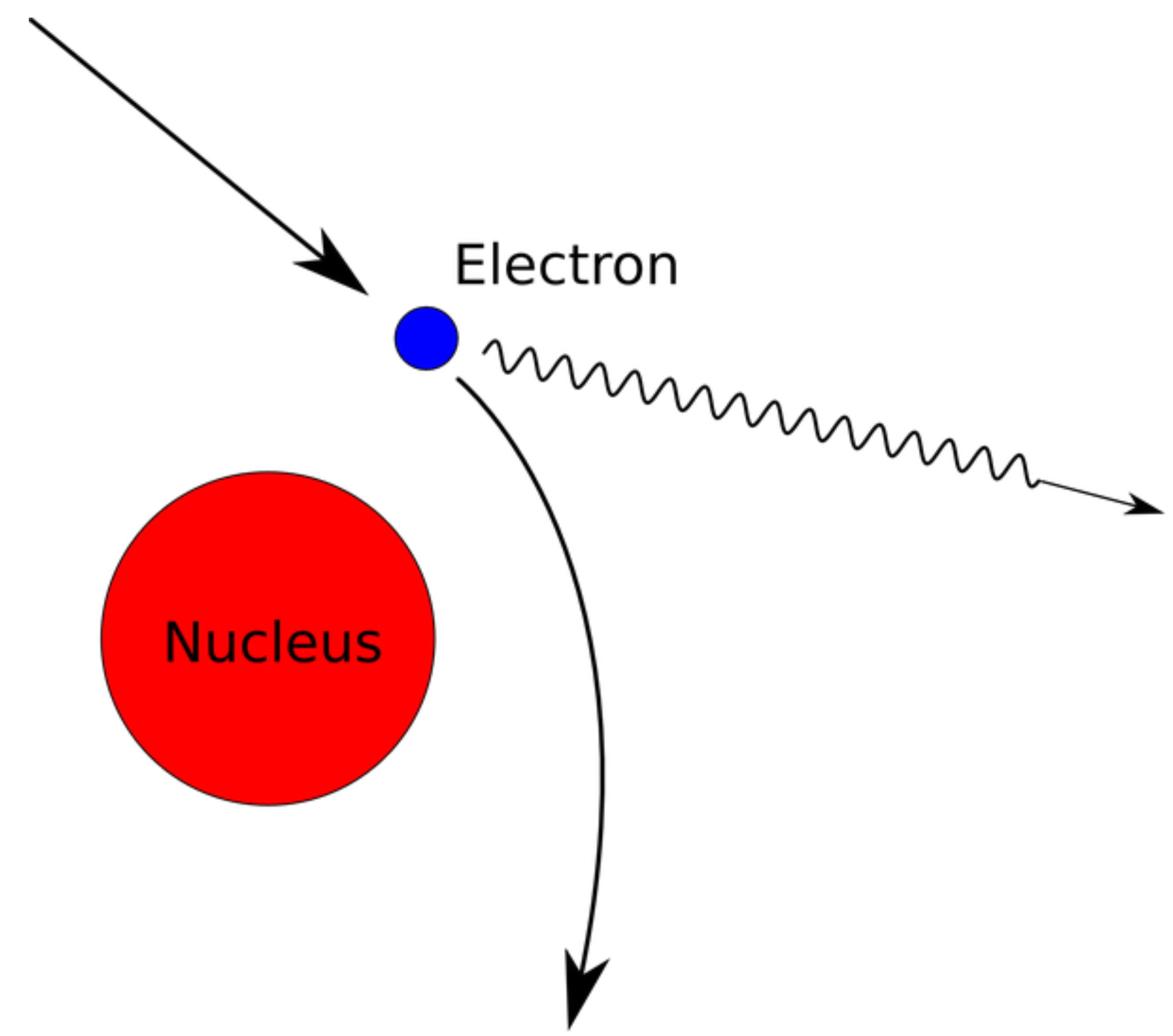
The problem with electrons...

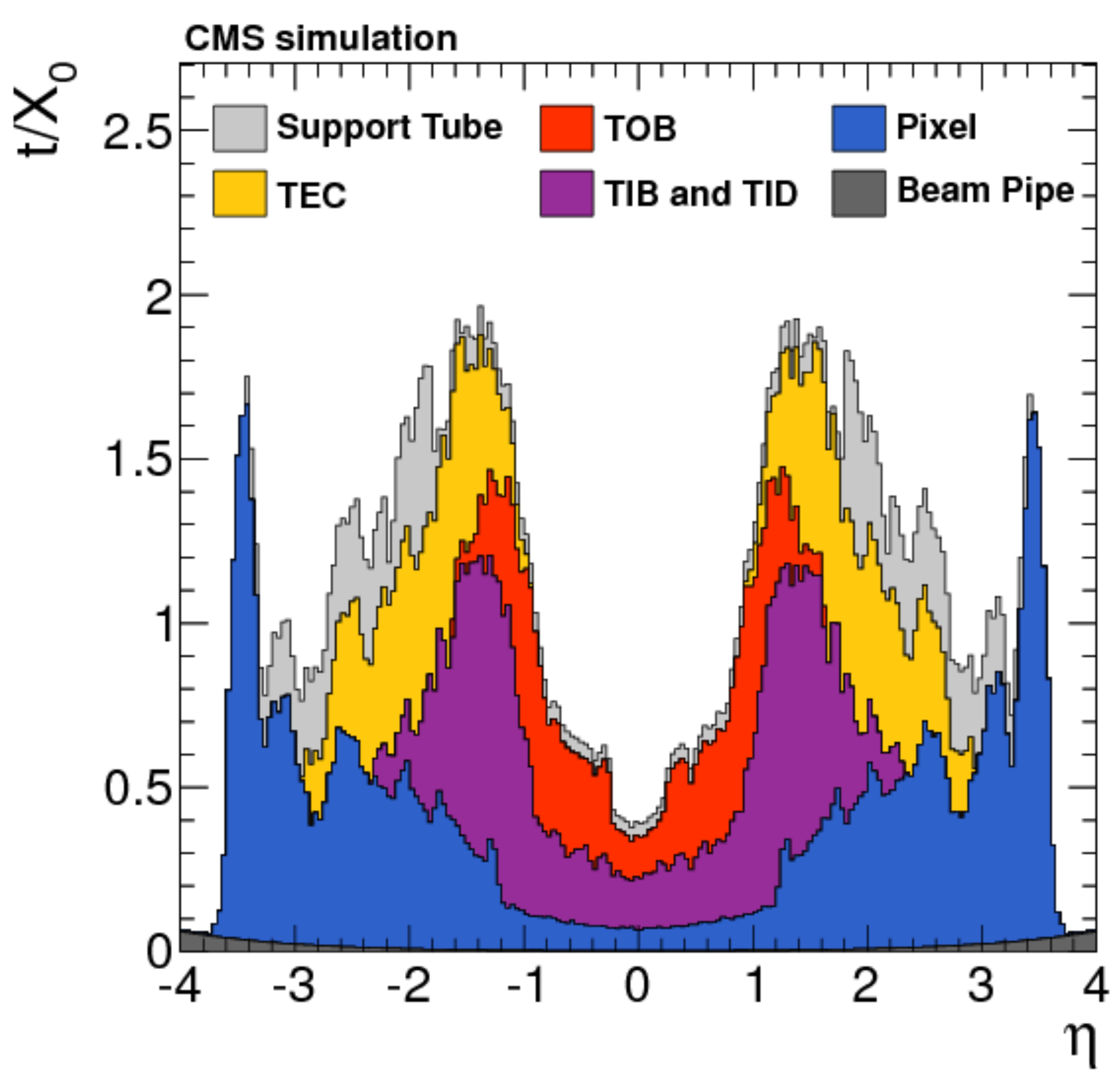
They interact a lot more! Primarily through **bremsstrahlung**

Energy loss from bremsstrahlung:

(energy loss is proportional to energy)

$$-\frac{dE}{dx} = \frac{E}{X_0}$$





Mind your material!

Important to consider the material budget in the tracker detector design

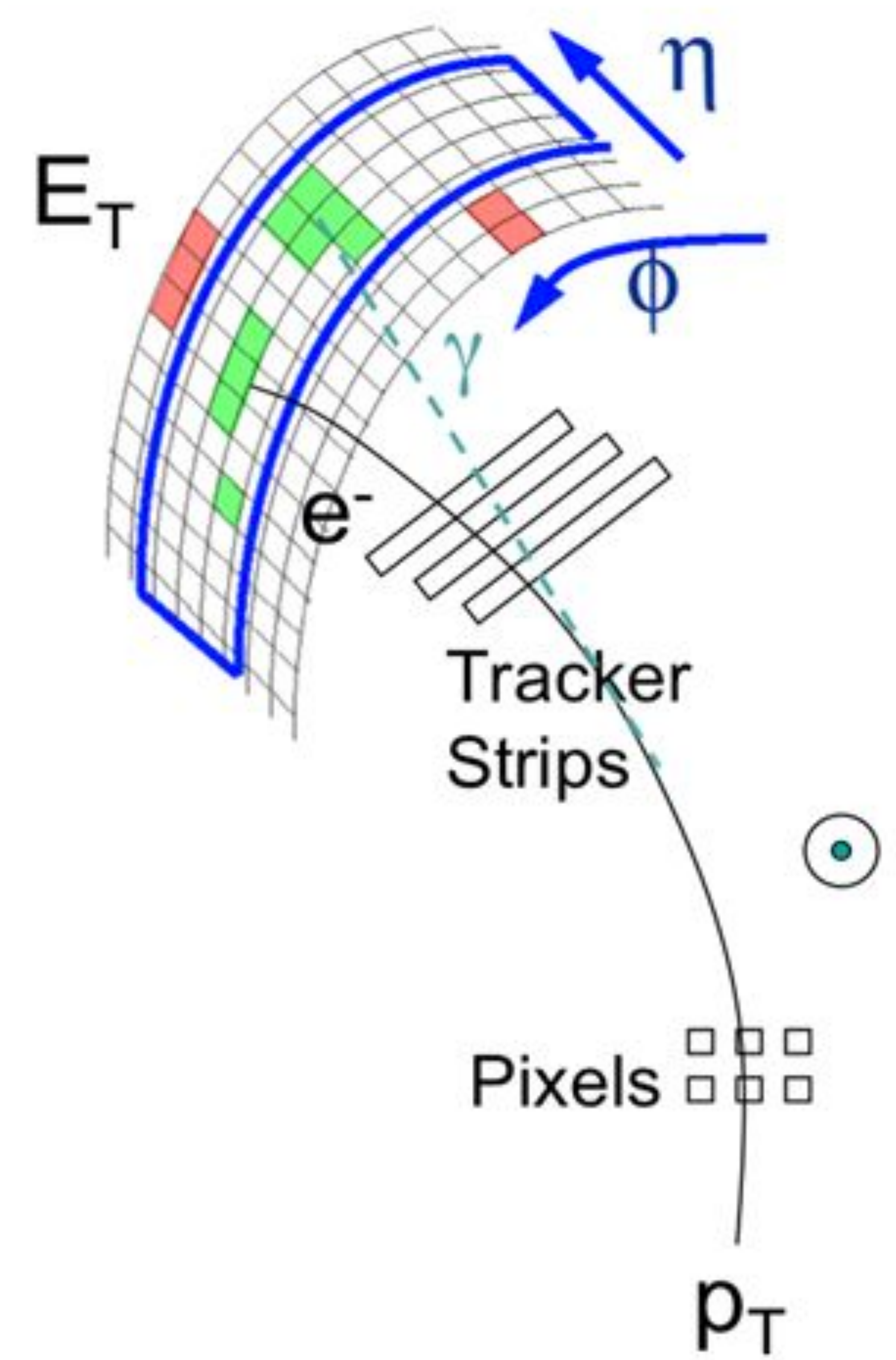
Complications with electrons

The tricky part of electron tracking is accounting for **radiation loss from bremsstrahlung along the track trajectory**

Electron undergoes brem ~70% of the time
Photon converts to e+e- pair 50% of the time

Recover brem particles along the ϕ trajectory of the track because of the magnetic field

Tracking has to account for energy loss
Gaussian Sum Filter tracking = extension of Kalman Filter algorithm with a sum of Gaussians weighted by radiation probability



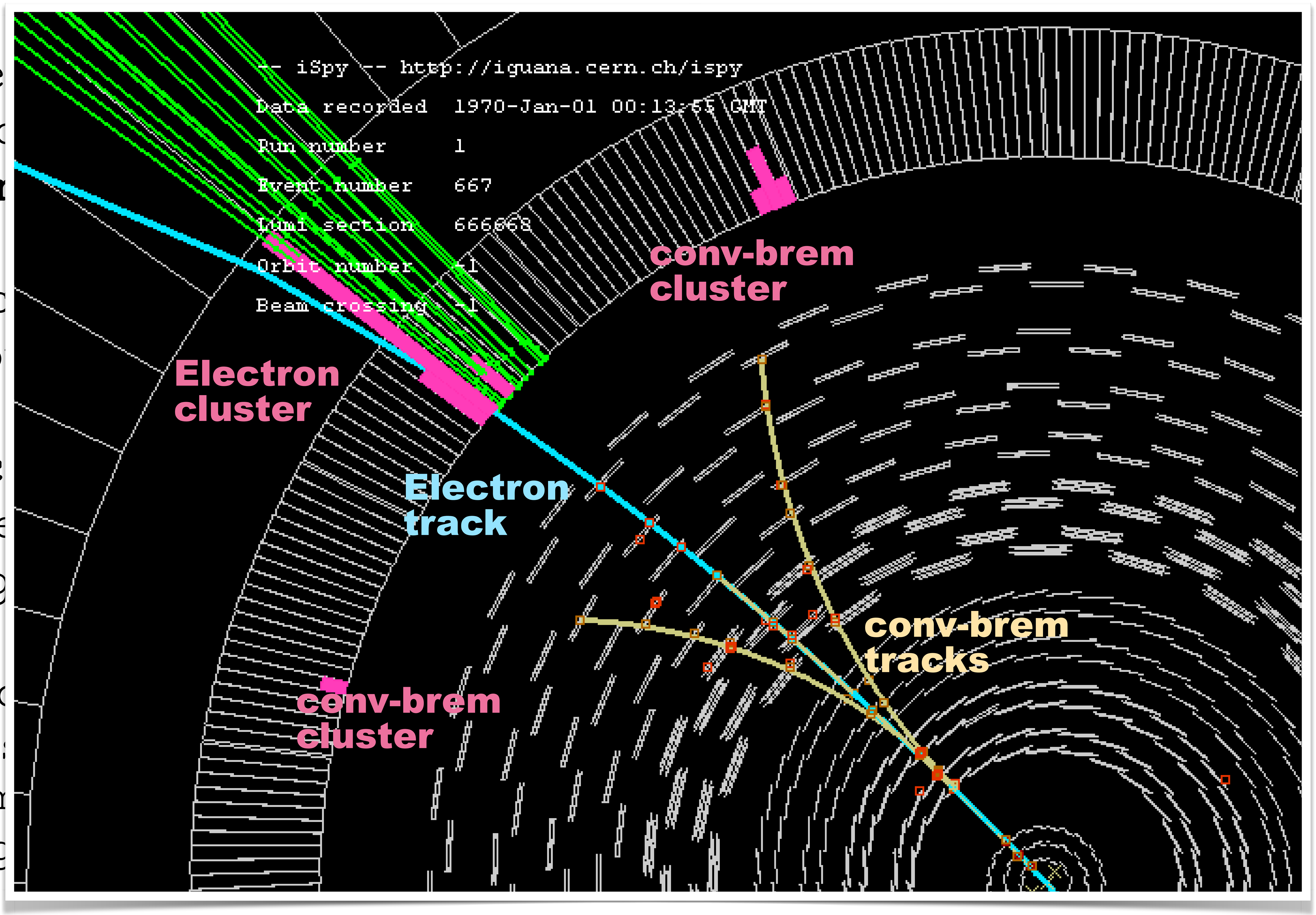
Complications with electrons

The
acc
bre

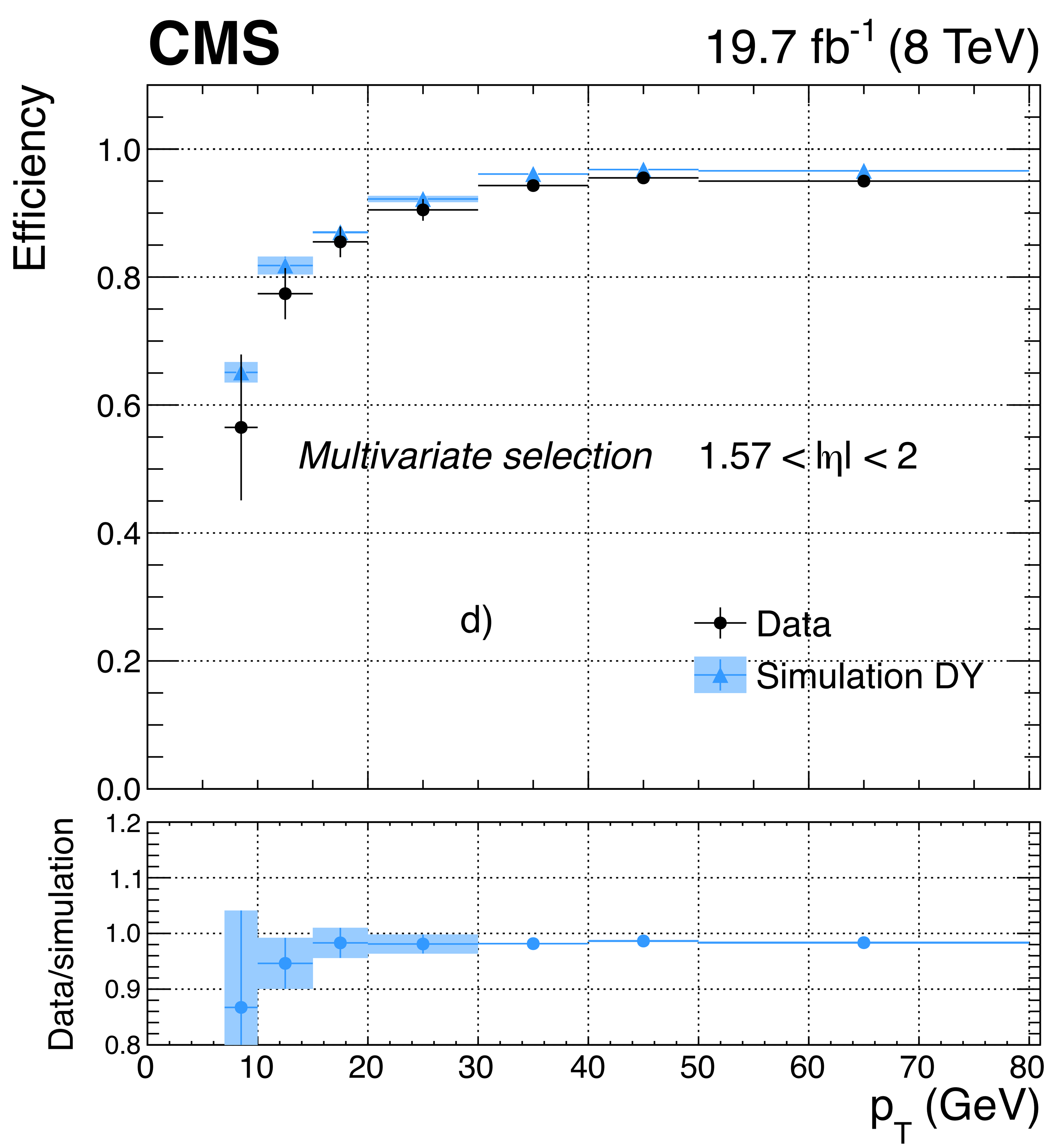
Elec
Pho

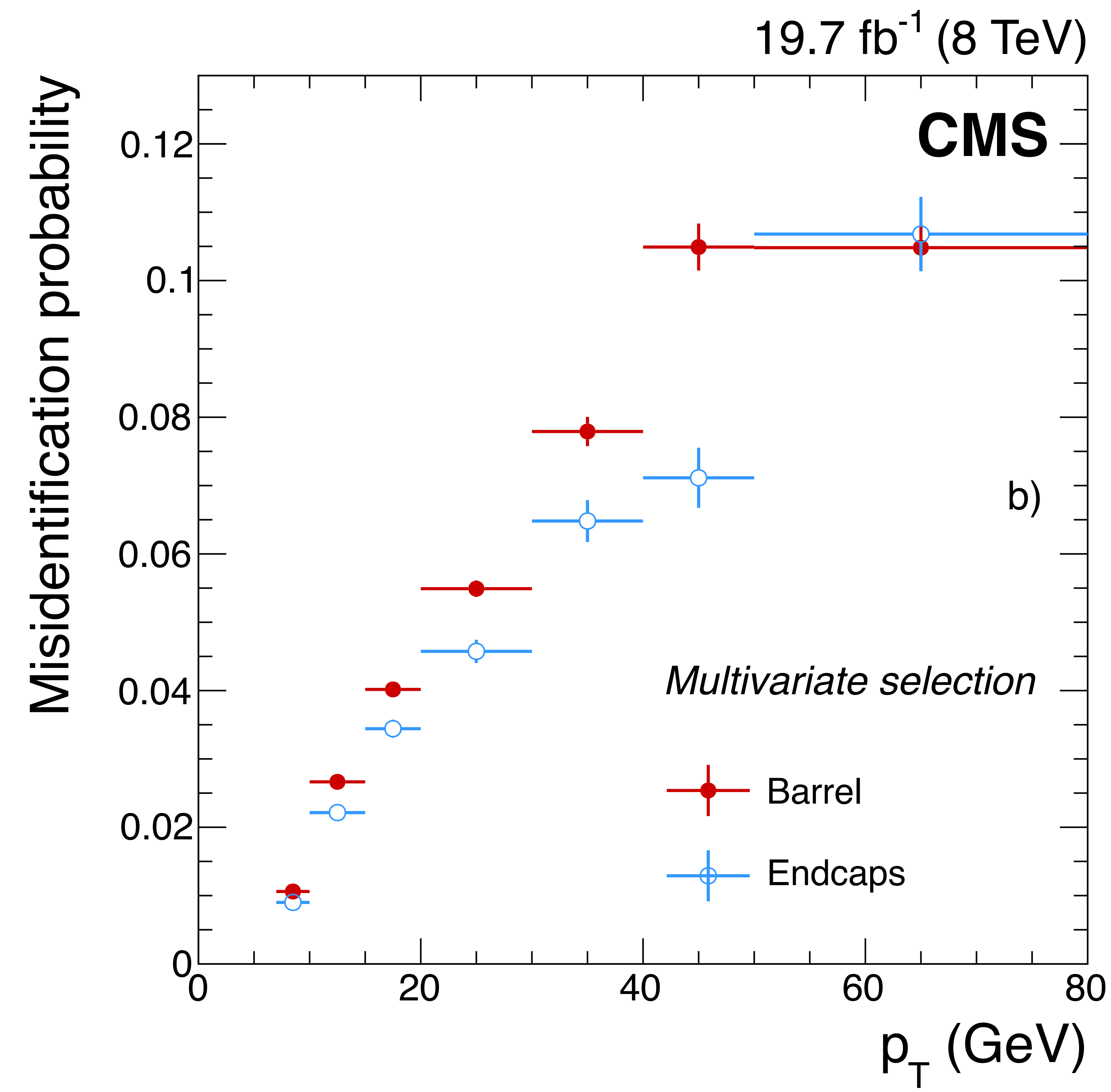
Rec
traje
mag

Trac
Gaus
Kalm
weig



Electron performance





$|\Delta\eta|$
$|\Delta\phi|$
H/E_{SC}
$\sigma_{\eta\eta}$
$|1/E_{SC} - 1/p|$
$\mathrm{Iso_{PF}}$ (ΔR=0.3) / p_T
$|d_0|$
$|d_z|$
Missing hits
Conversion-fit probability

What variables go into the selection?

Photons

Identifying **prompt** and **isolated** photons important

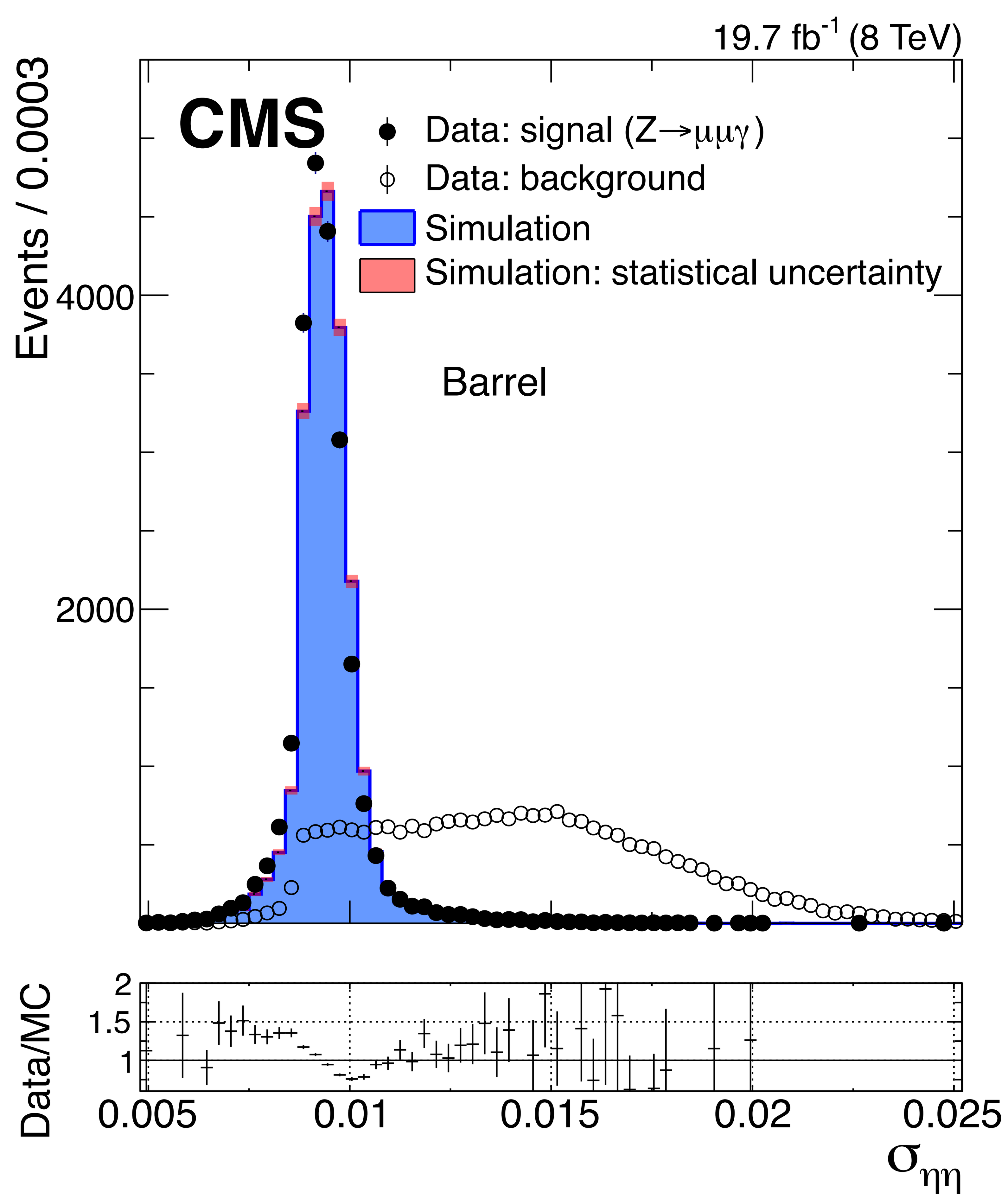
- Particularly for analyses like H(γγ)

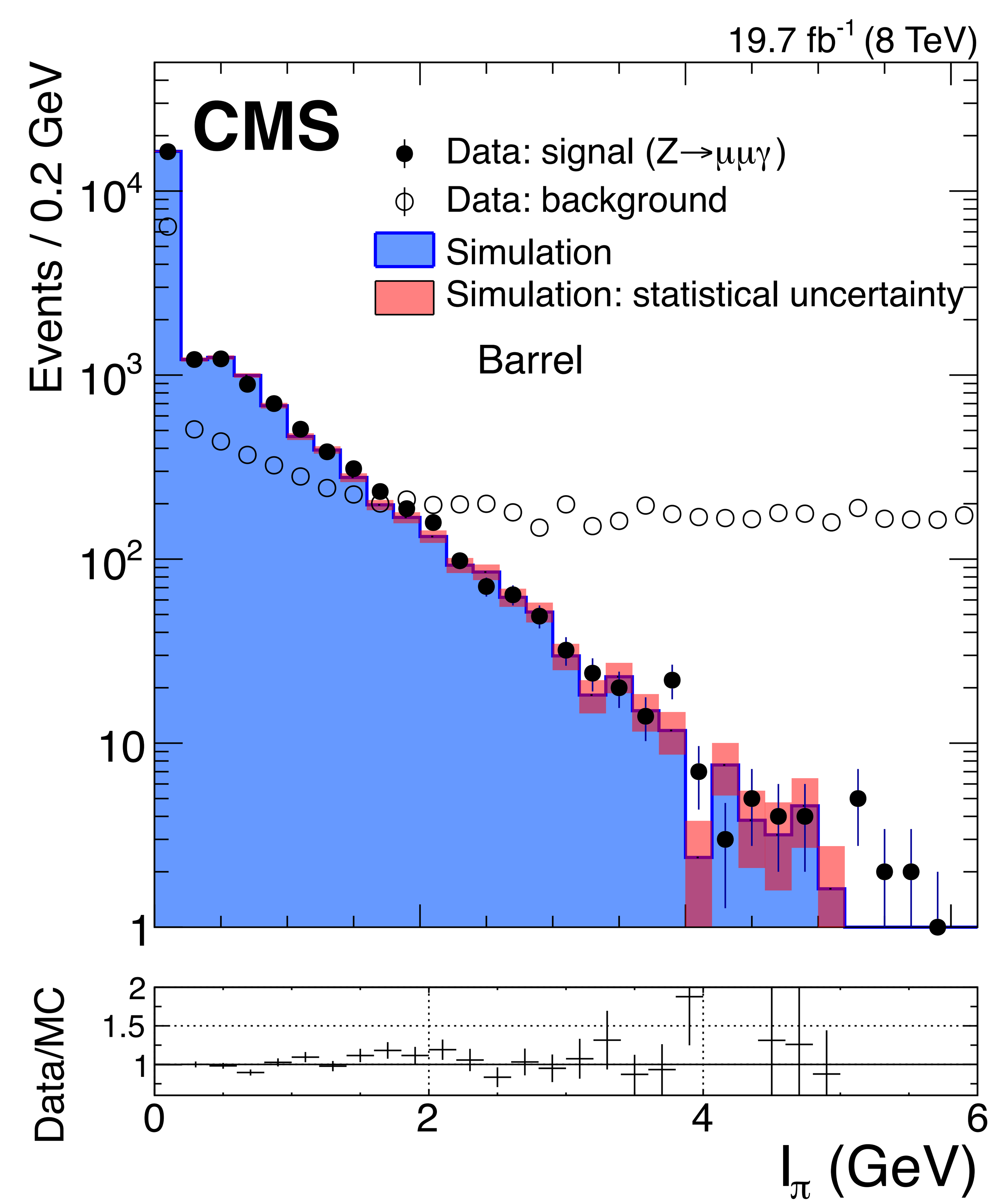
Primary variables for photon identification are shower-shape and isolation (more on this later) variables

- No matched track to separate from electrons

signal
Isolated FSR photons from Zμμ

background
Photons from jets





Charged Hadron

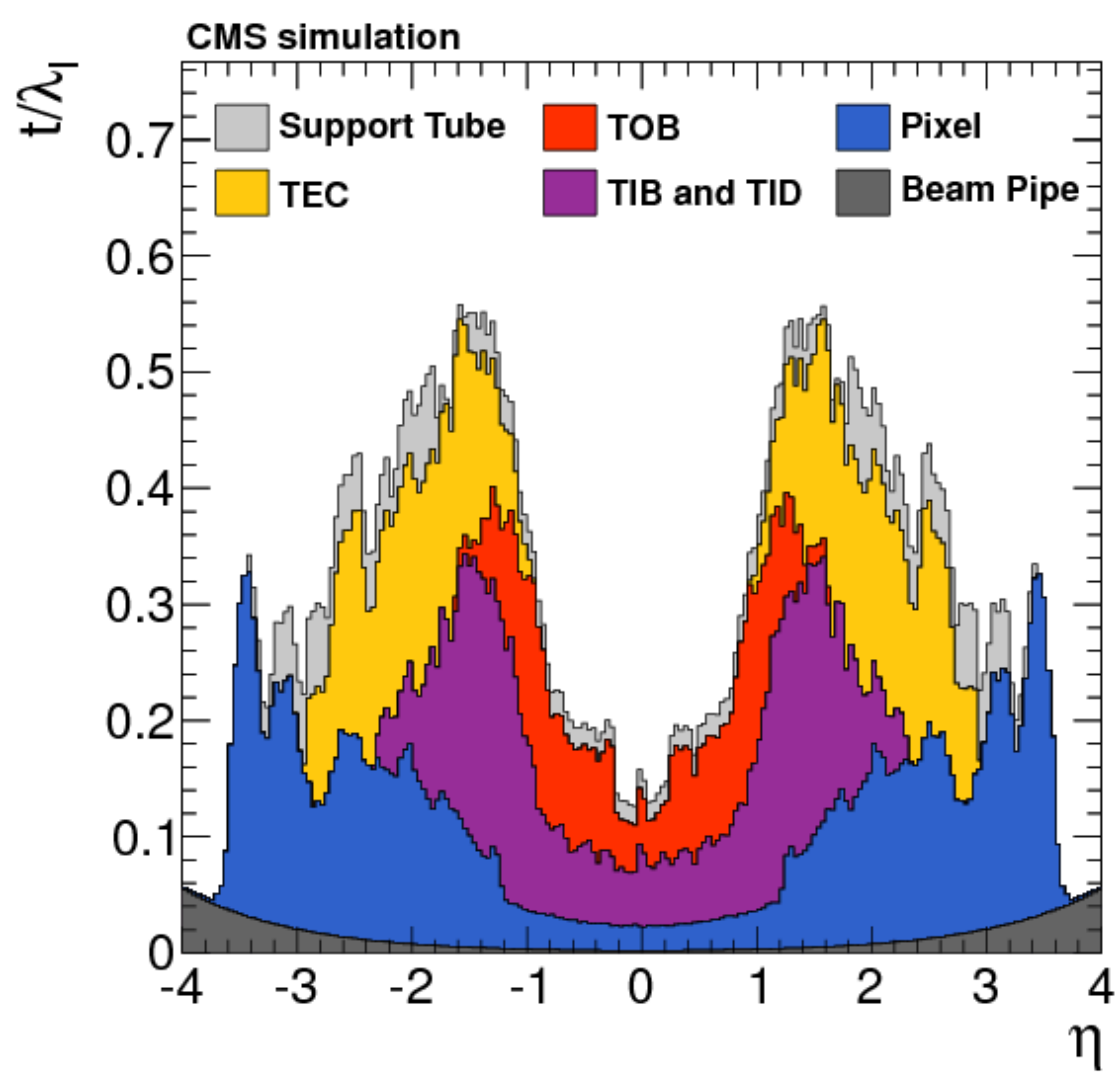

Neutral
Hadron
4T
2T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
Iron return yoke interspersed
with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Dave Barney

[Charged] hadrons

Match tracks to hadronic clusters to form charged hadrons

Again, mind your materials!

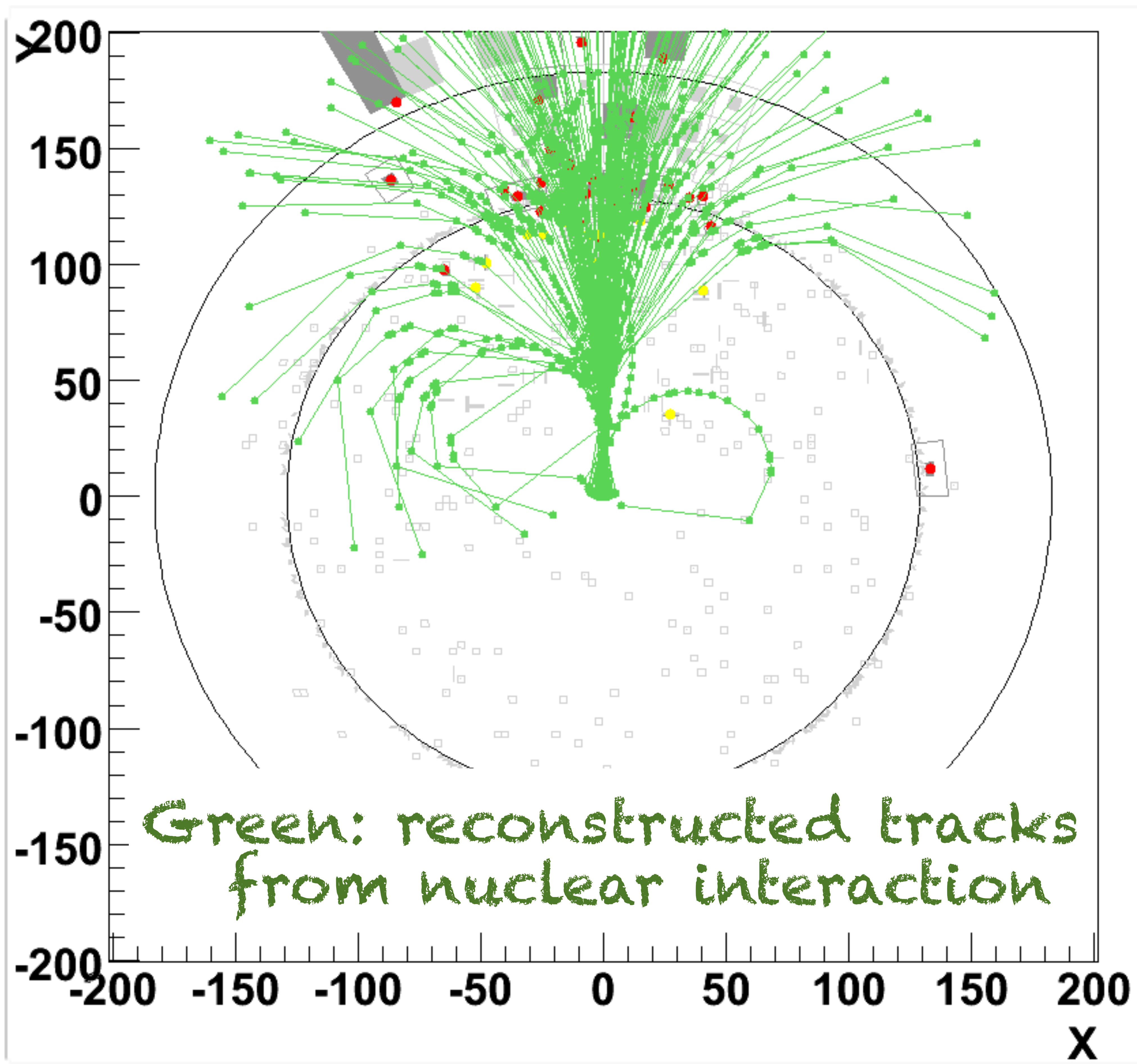
- The tracker material acts as a hadronic preshower
  - (for both charged and neutral hadrons)



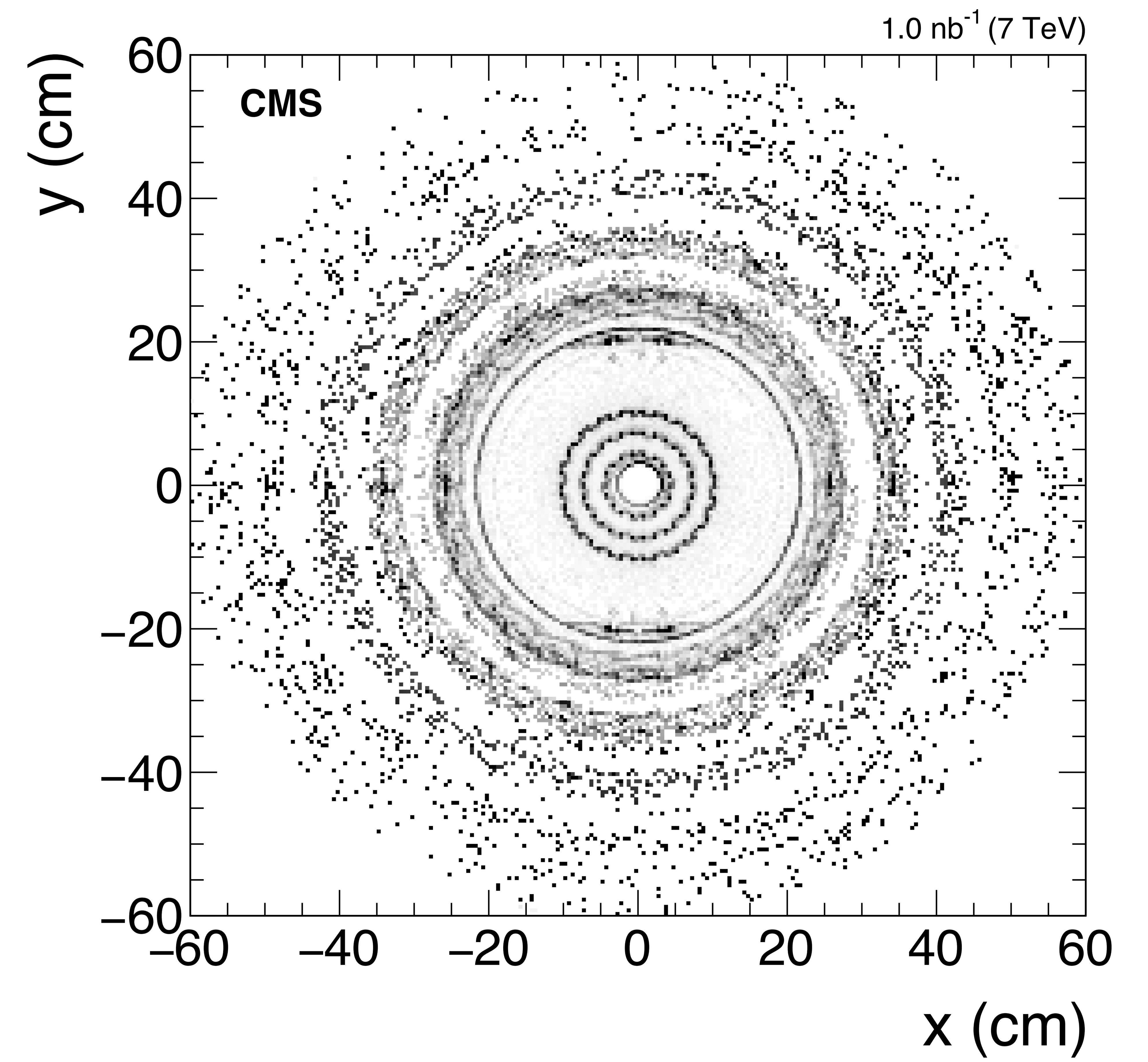
Complications with hadrons

Nuclear interactions often result in kinks in the track or a production of secondary particles

- Can be recovered with displaced track reconstruction



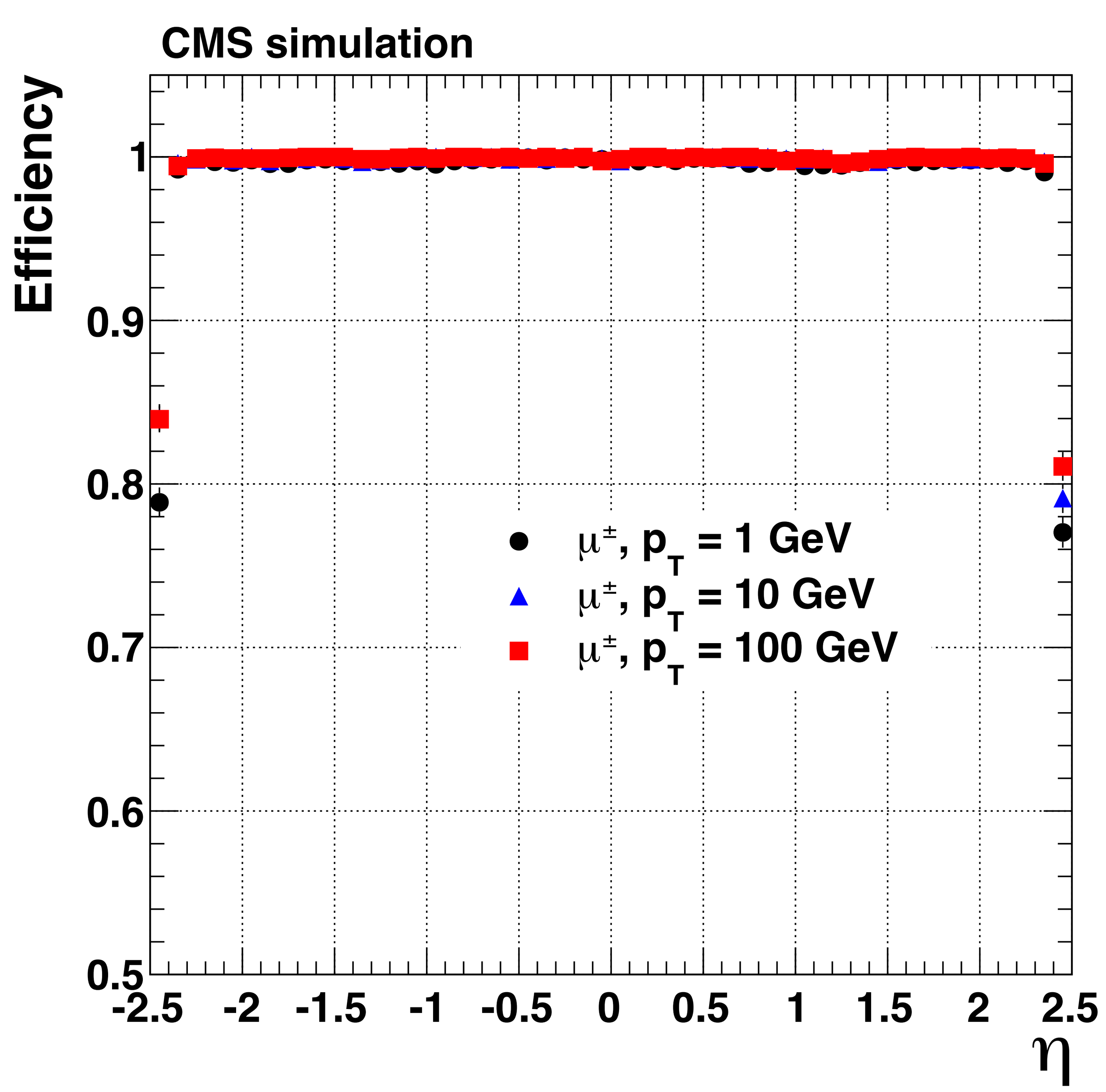
Map of nuclear interactions



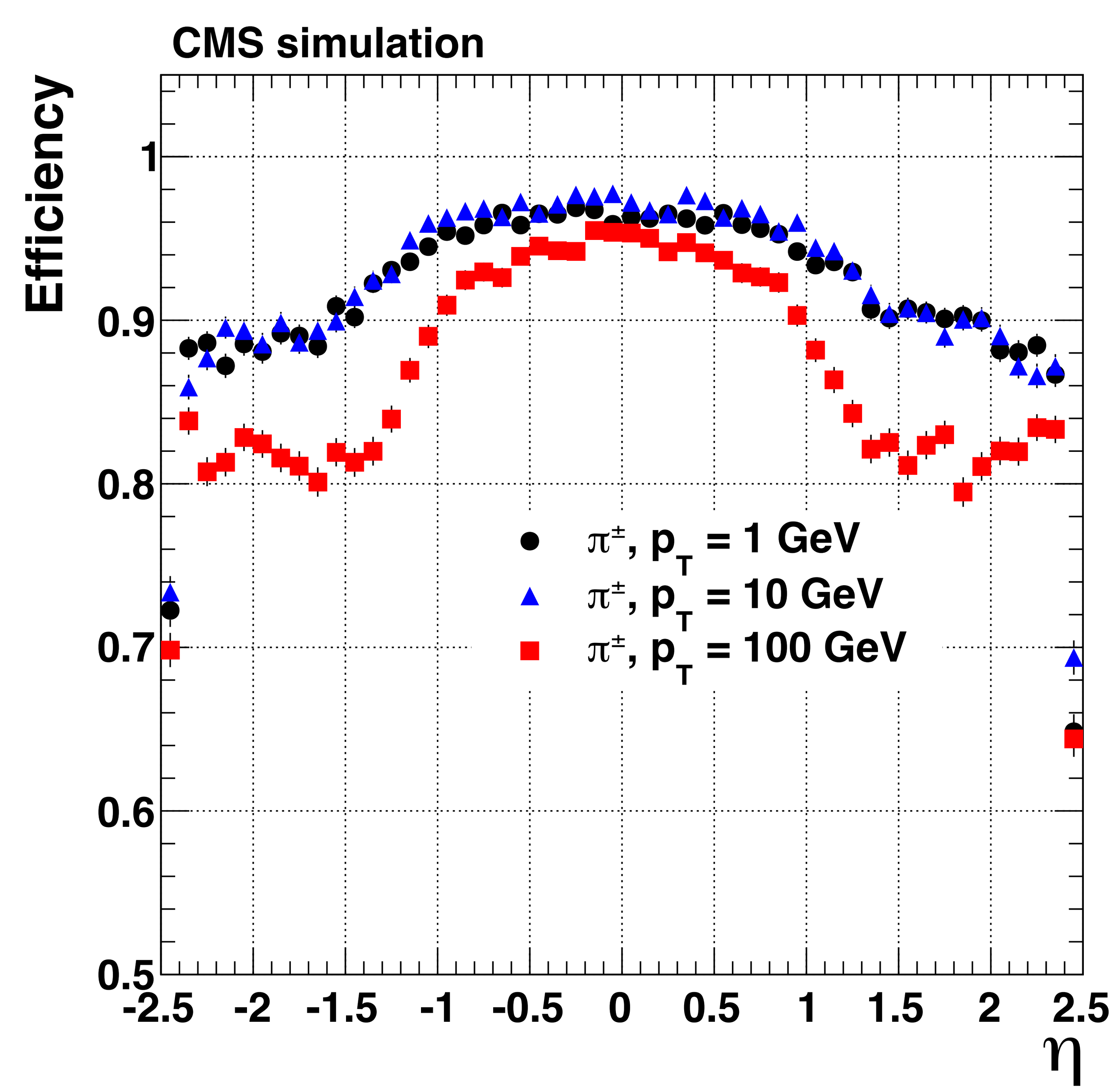
To avoid double counting, nuclear interactions need to be identified and combined into primary particles (part of particle flow, see later)

SUMMARY: CHARGED PARTICLE TRACKING

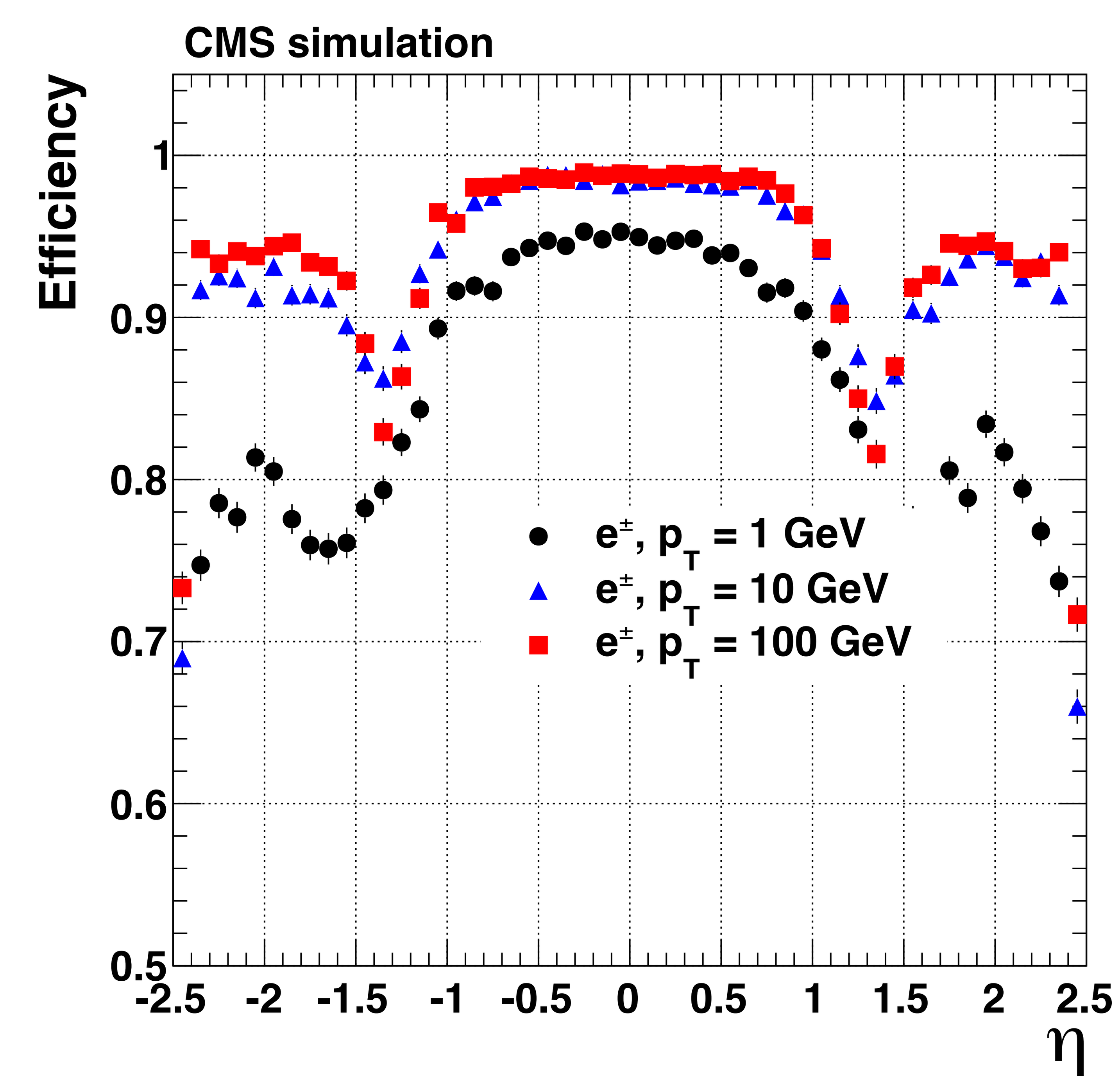
Muons



Pions



Electrons



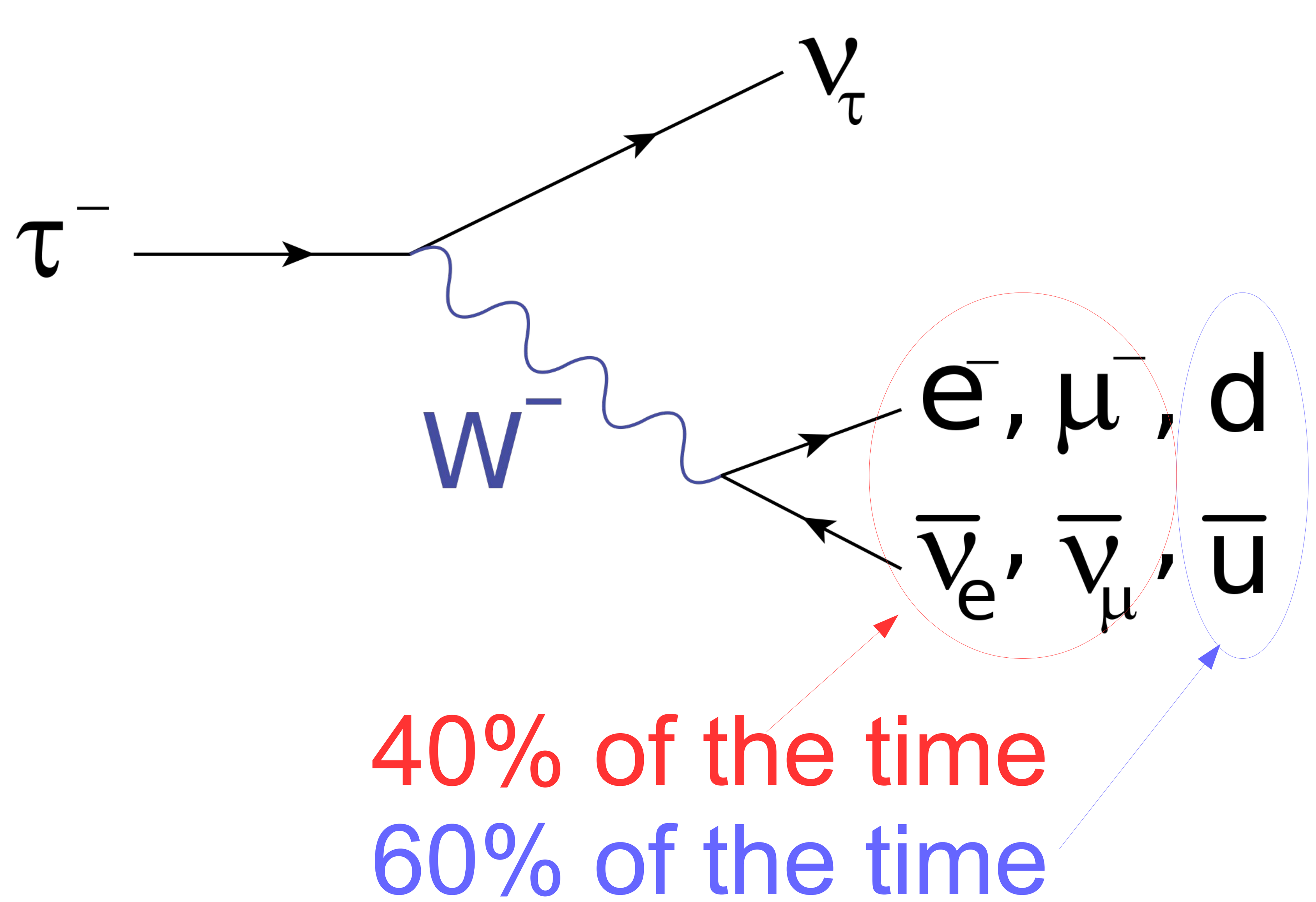
Side-by-side comparison of muon, pion, electron tracking efficiency — this illustrates the challenge of tracker material for charged hadrons and electrons

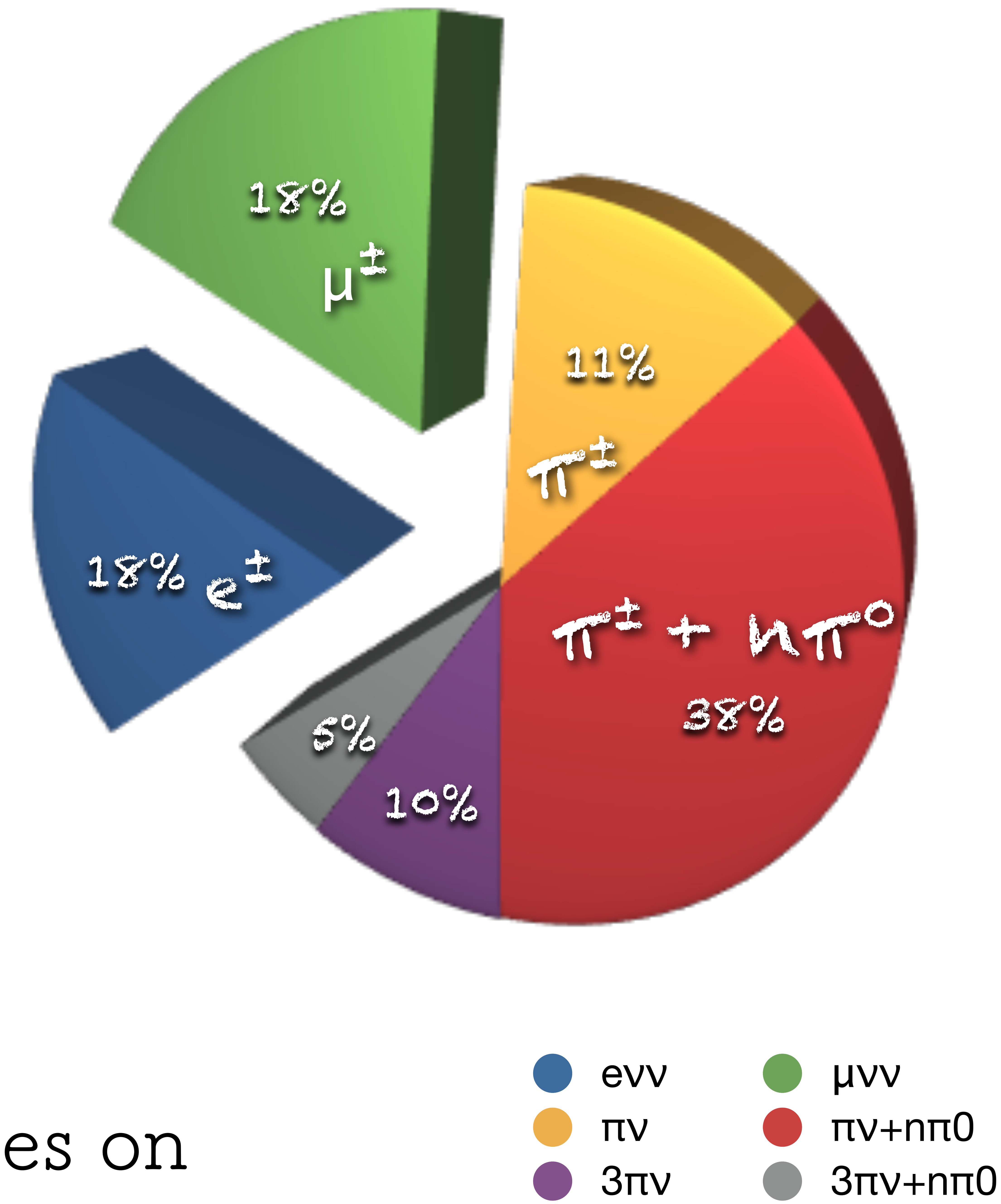
TAUS

Massive and relatively long lived

$m(\tau)$ = 1.7 GeV

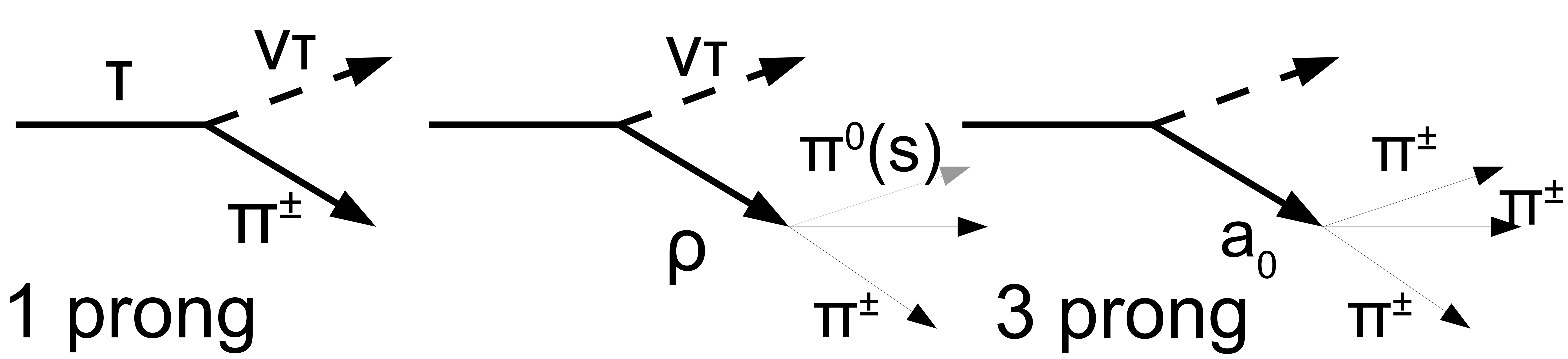
$c\tau$= 87 μm

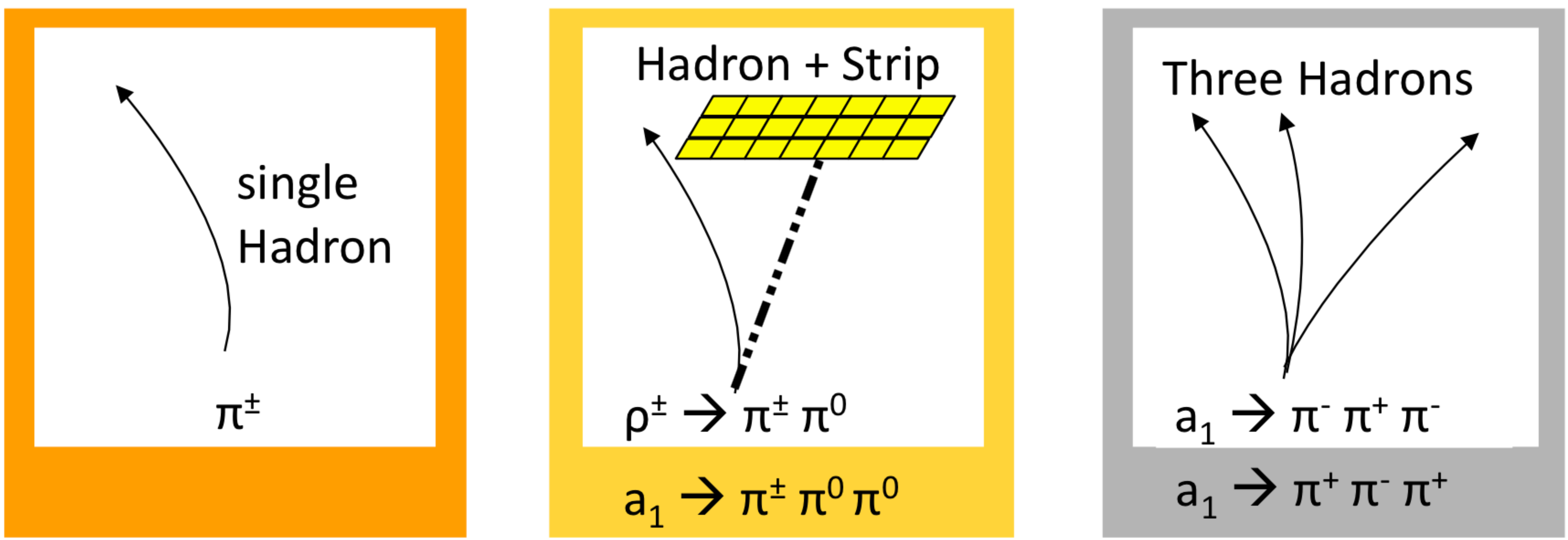




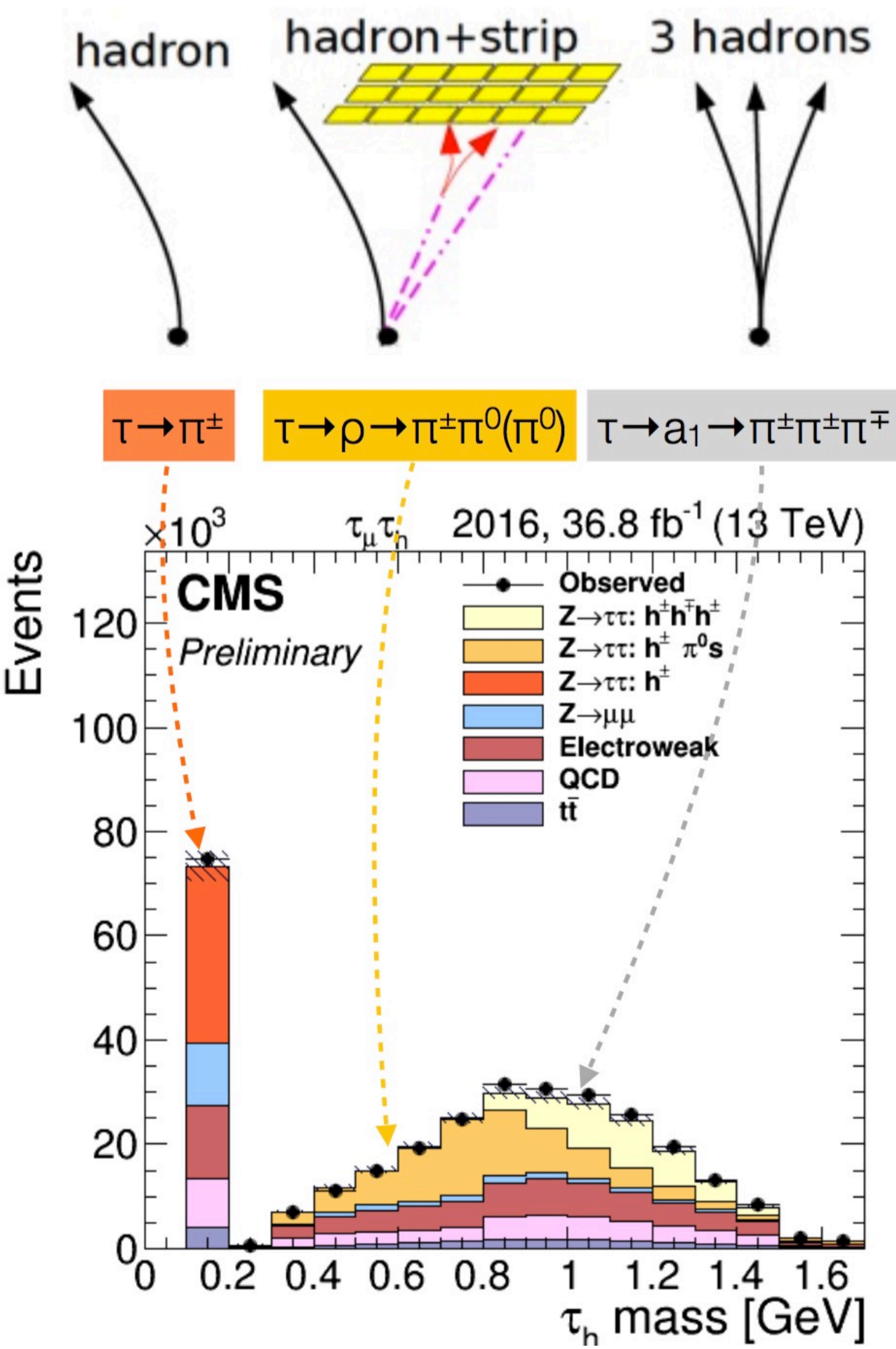
Leptonic tau reconstruction relies on missing energy from the neutrinos

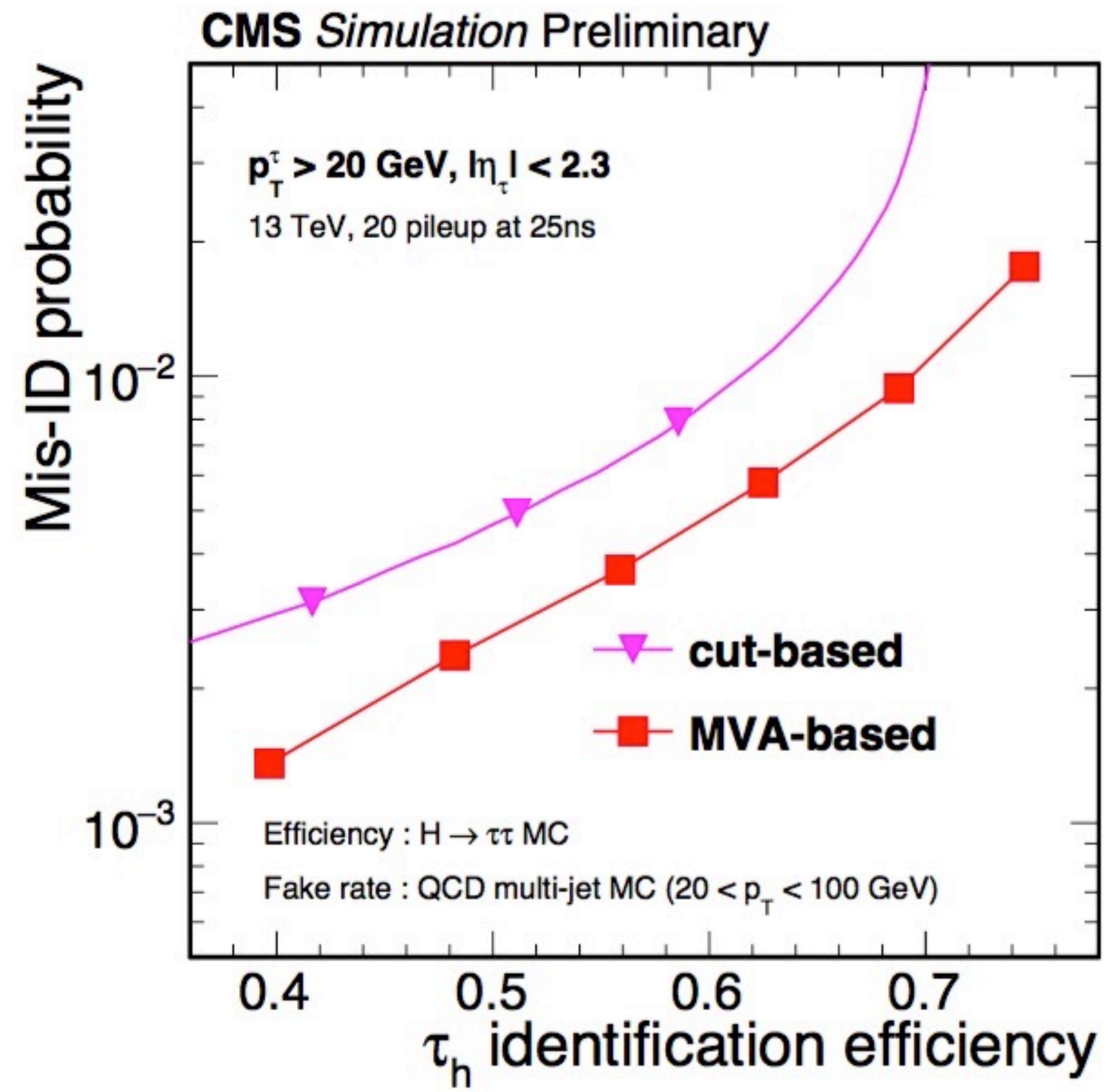
HADRONIC TAUS



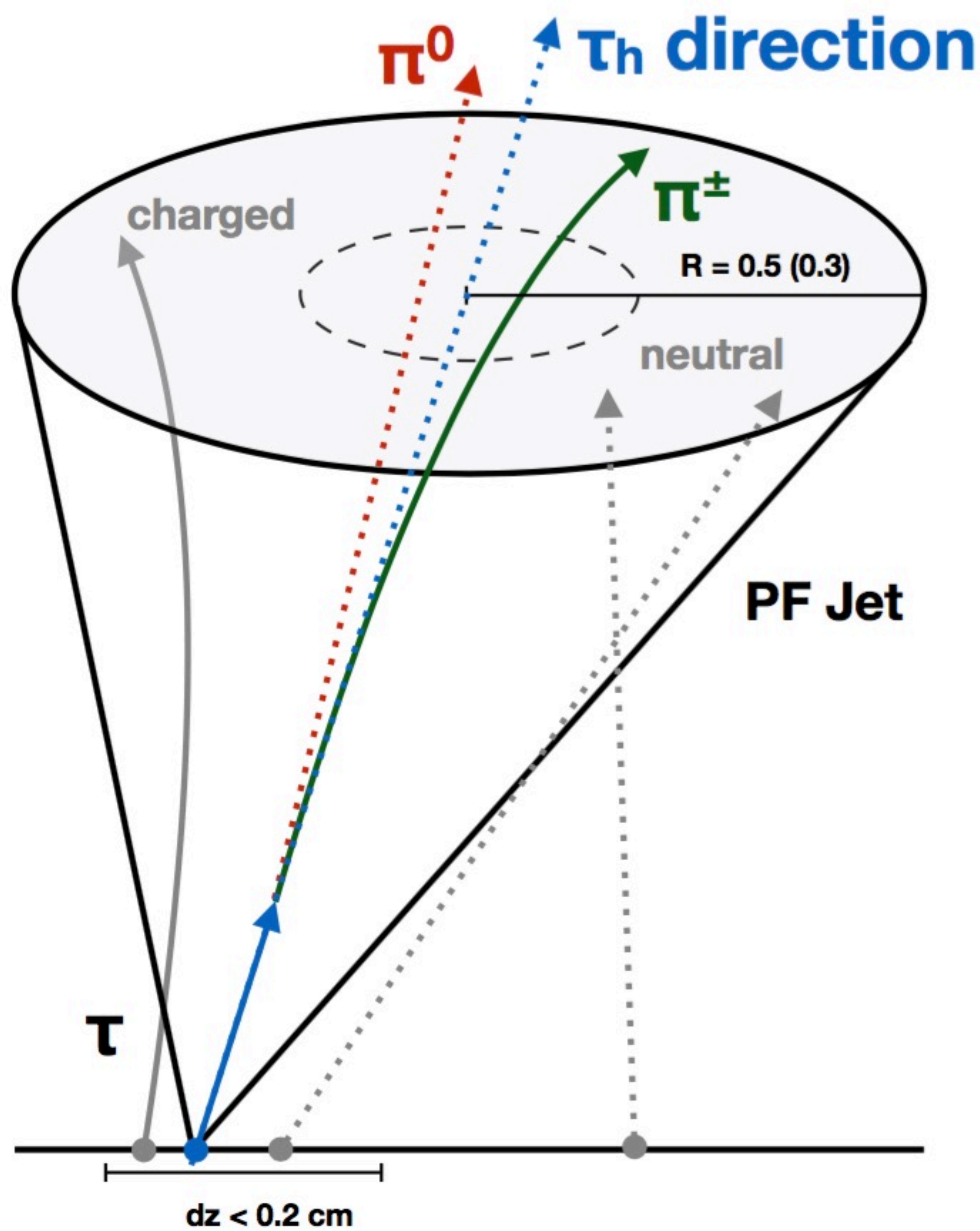


TAU PERFORMANCE





A NOTE ON ISOLATION



So far isolation has been mentioned in many contexts

Isolation very important to identify prompt muon, electron, photon, tau signals

For example:
- Prompt:
  - Hadronic Tau vs. jet
  - Photon vs. jet
  - Muon vs. b jet

Isolation: the extra amount of energy around the object of interest
- **Often <u>relative isolation</u> is the quantity of interest**
- Will come back to this later with pileup discussion

Tomorrow: Let's get ADVANCED

Particle flow
Jets and MET
Jet substructure
Pileup and underlying event in HI
Exotic and beyond