Particle identification

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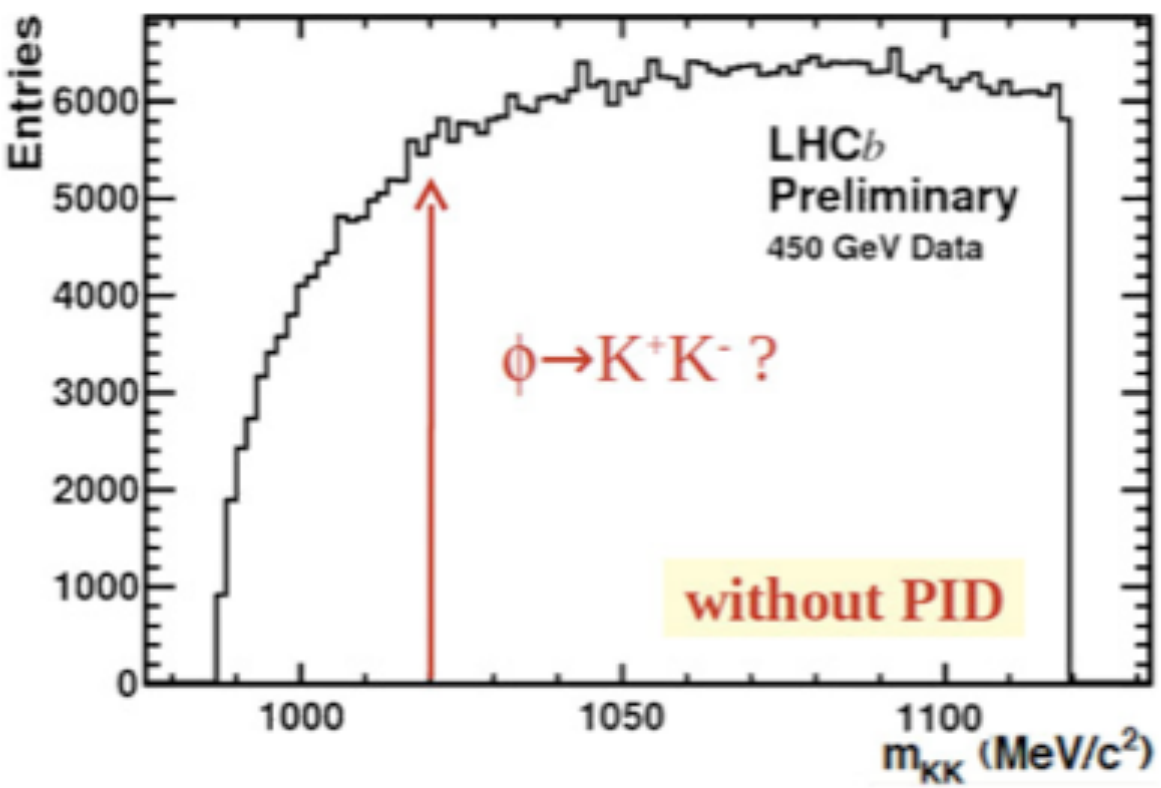
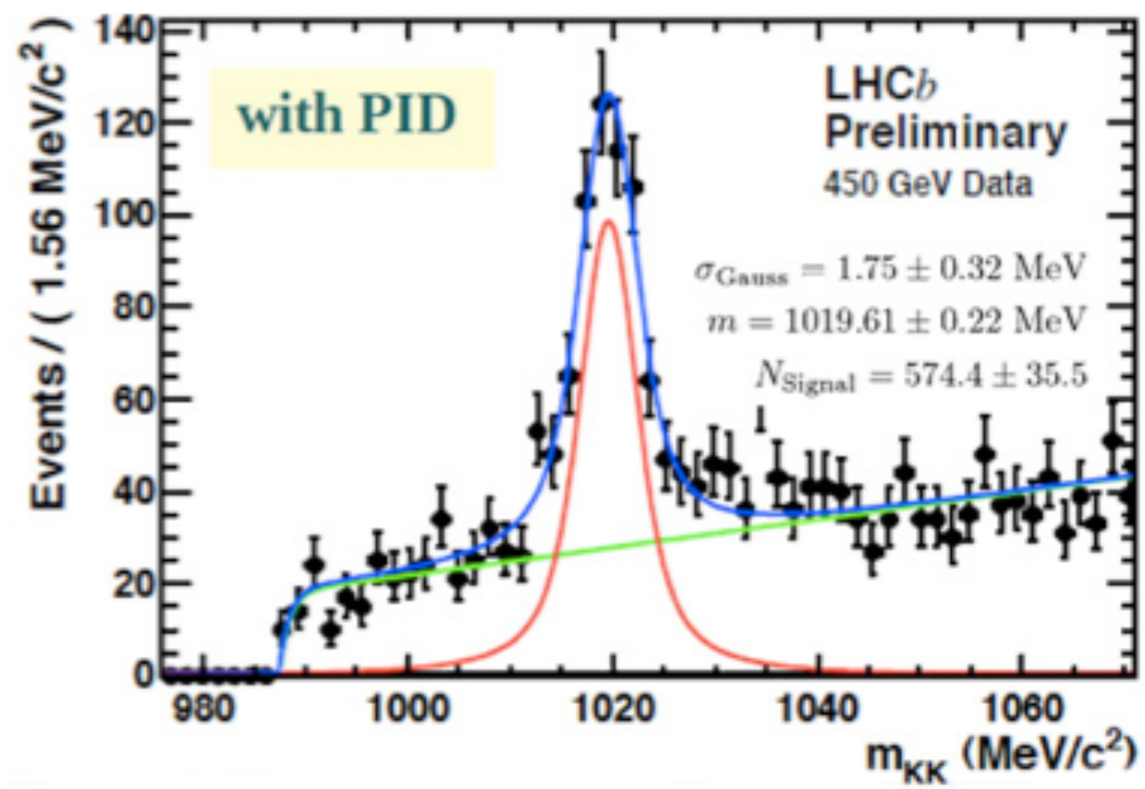
Why particle identification ?

- *Is particle X decaying to electrons or muons ? Which are the corresponding branching ratio ?*
  - Understand properties (couplings) of this particle
- *Use particle Identification to separate signal and backgrounds*
  - To search for H->gamma gamma at LHC identify photons in the final state
- *Use particle Identification to optimize measurement of complicated final state*
  - «particle flow» event reconstruction in collider experiments

Example of particle ID in flavor physics





many more examples where K/pion discrimination is important to study beauty and charm decays

What is a «stable» particle ?

- Only few known particles are stable: photon, electron, proton, neutron(in nuclei), neutrinos
- Everything else decays but sometime are stable «enough» at the scale of the detector
- L = beta.gamma.c.tau
- Can a E=40 GeV muons (mass=105 MeV, tau=2.2 10^{-6}s) in a collider experiment (size ~20m) be considered stable ?
    - *=> gamma =E / M ~ 40/0.105 ~380   and   beta ~1*
    - *=> L beta.gamma.c.tau ~ 380*3.10^{8} * 2.2*10^{-6} ~ 2500.10^{2} m ~ 250 km*

Particle Identification depends on the experimental context and which particles are «directly» detected and which particle are «indirectly» detected (through their decay products)

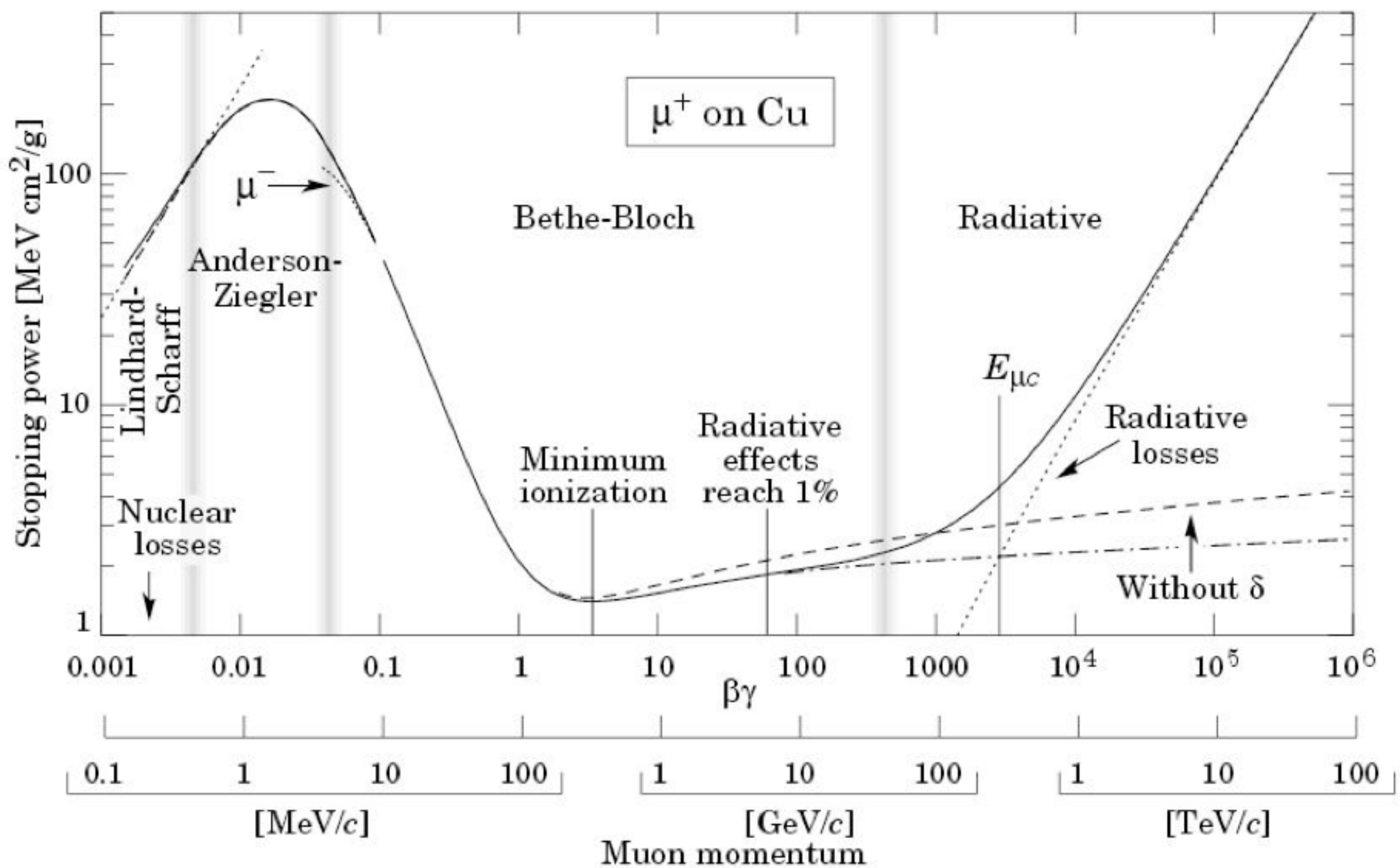
Particle identification covers a wide range of techniques

- Exploit very different interaction of particles with matter (for instance calorimeter)
  - electron/photon/muon/hadron discrimination, neutrinos
- Measure mass of particle
  - Mass and charge enough to identify a particle
  - Once energy or momentum are measured, mass can be measured through measurement of beta (velocity) or gamma
  - mass from beta measurement works better a low energy
- Reconstruct decay of a particle to identify it
  - «identify» H by mass peak in H->gamma gamma
  - identify «long lived» particles by displaced decay vertex reconstruction

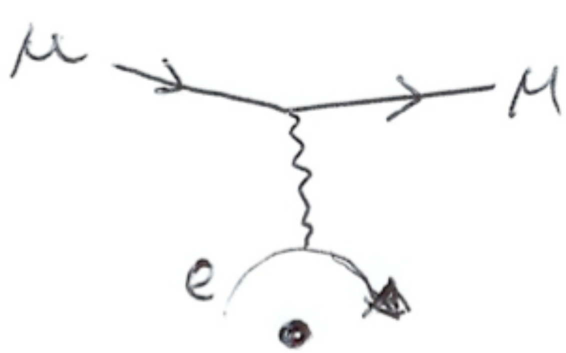
Exploiting different interactions with matter

- Mostly useful for e / muon / «hadron» discrimination
- In collider, high energy hadrons are not isolated but produced in «jets» from high energy quark and gluons
- Neutrinos are a special case

Muon energy loss

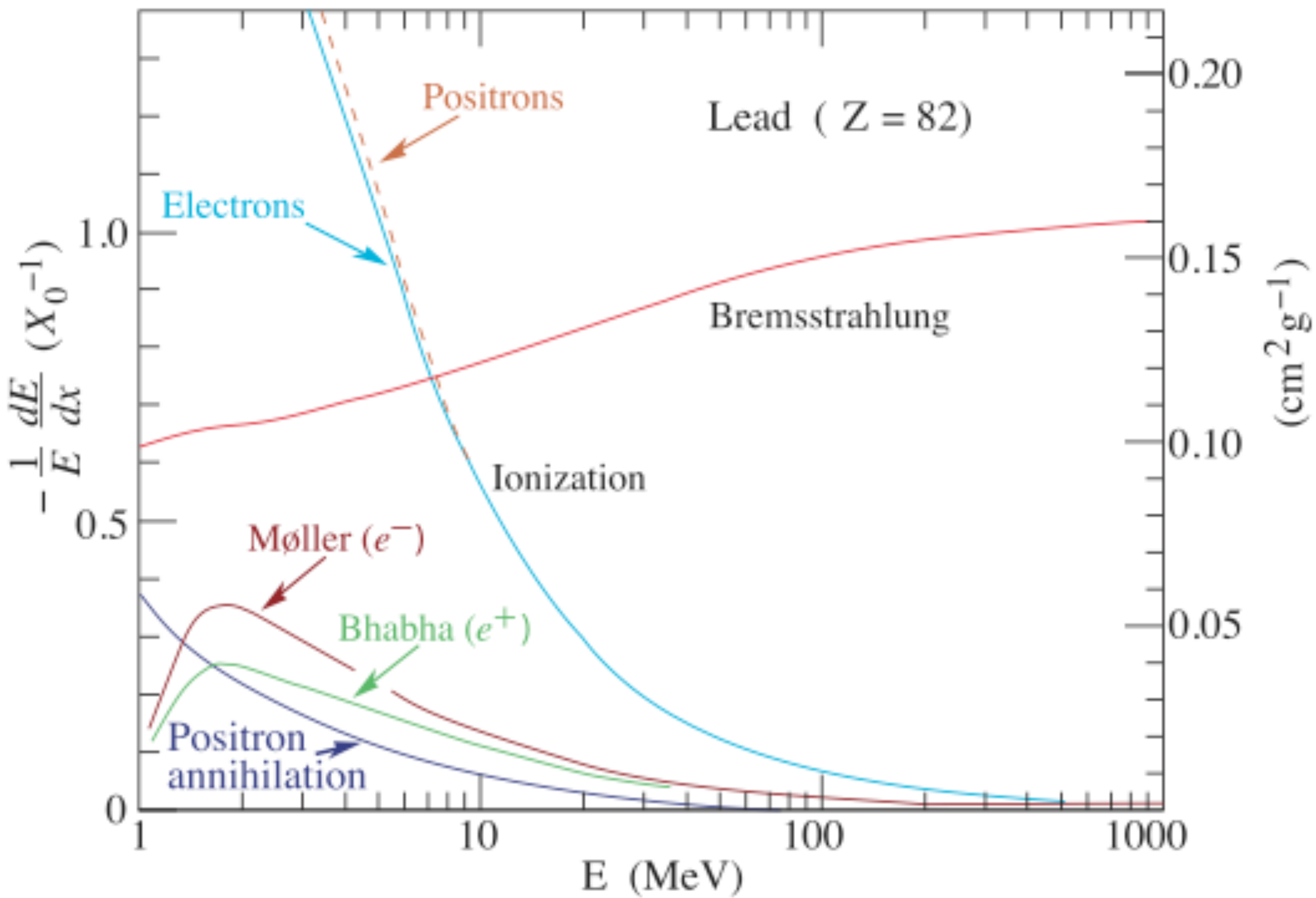


Ionization



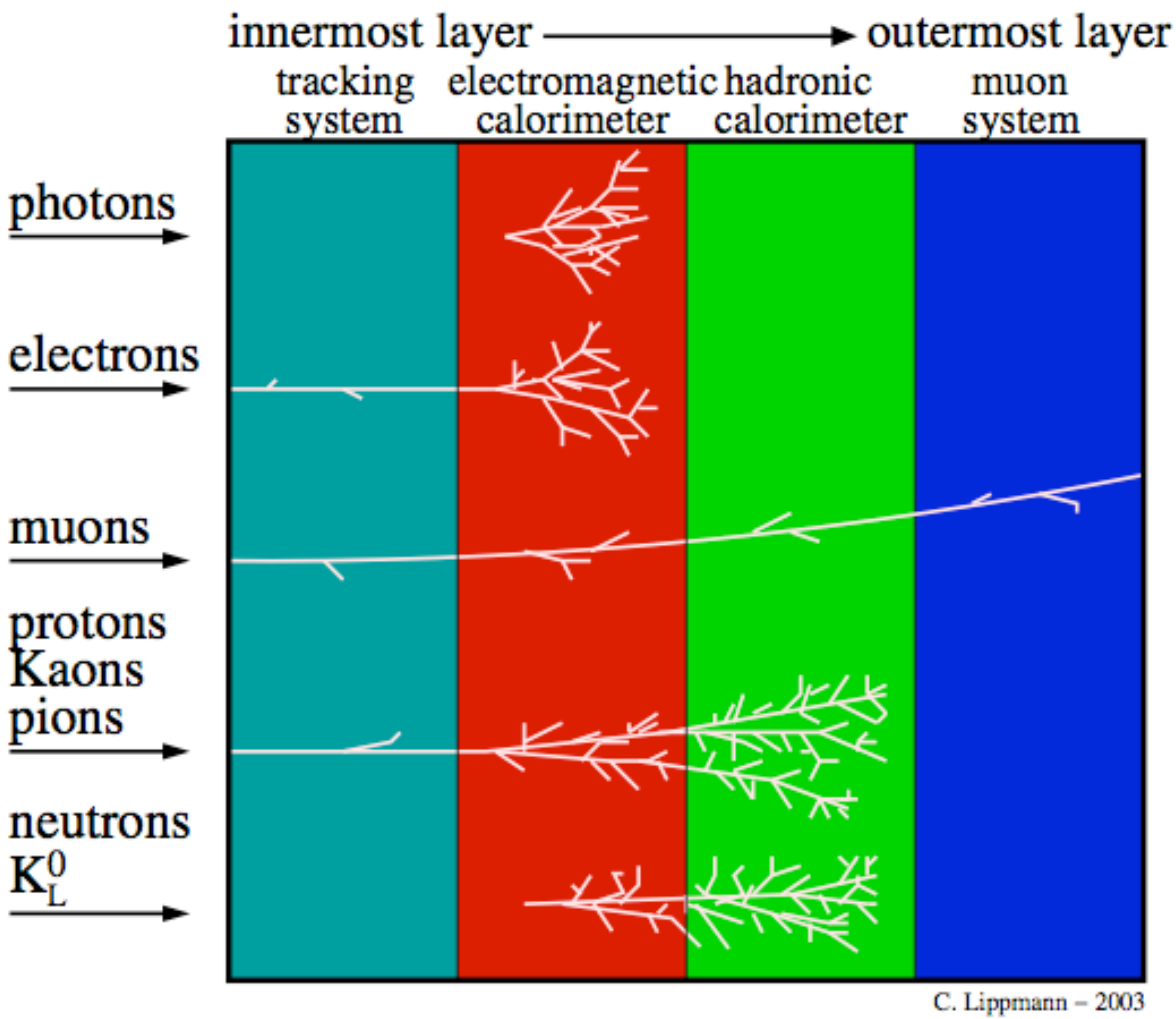
Bremsstrahlung

Electron energy loss



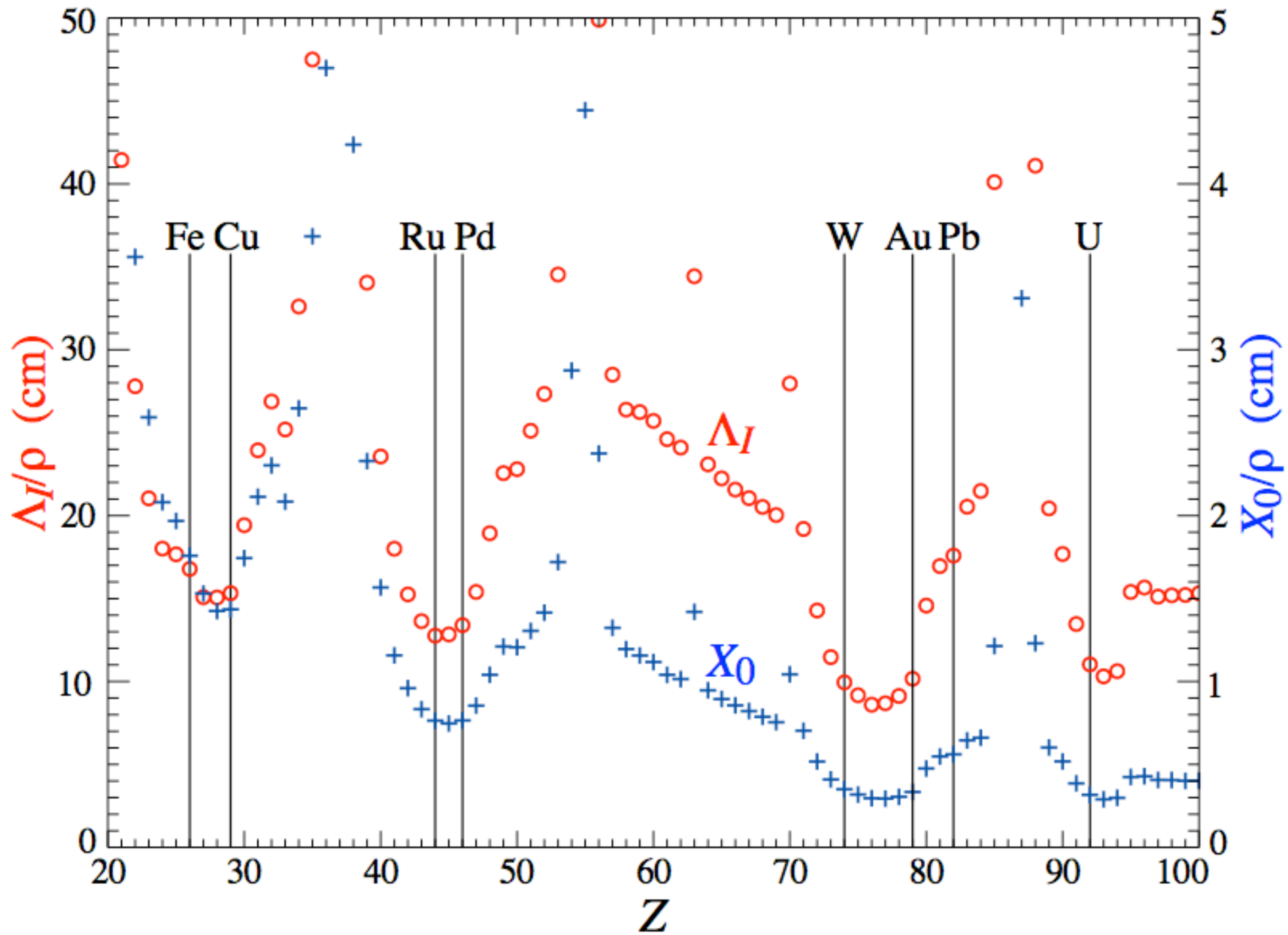
What is the most striking difference compared to the muon case ?
Much higher loss by Bremmsstrahlung

Sketch of particle interactions in detector

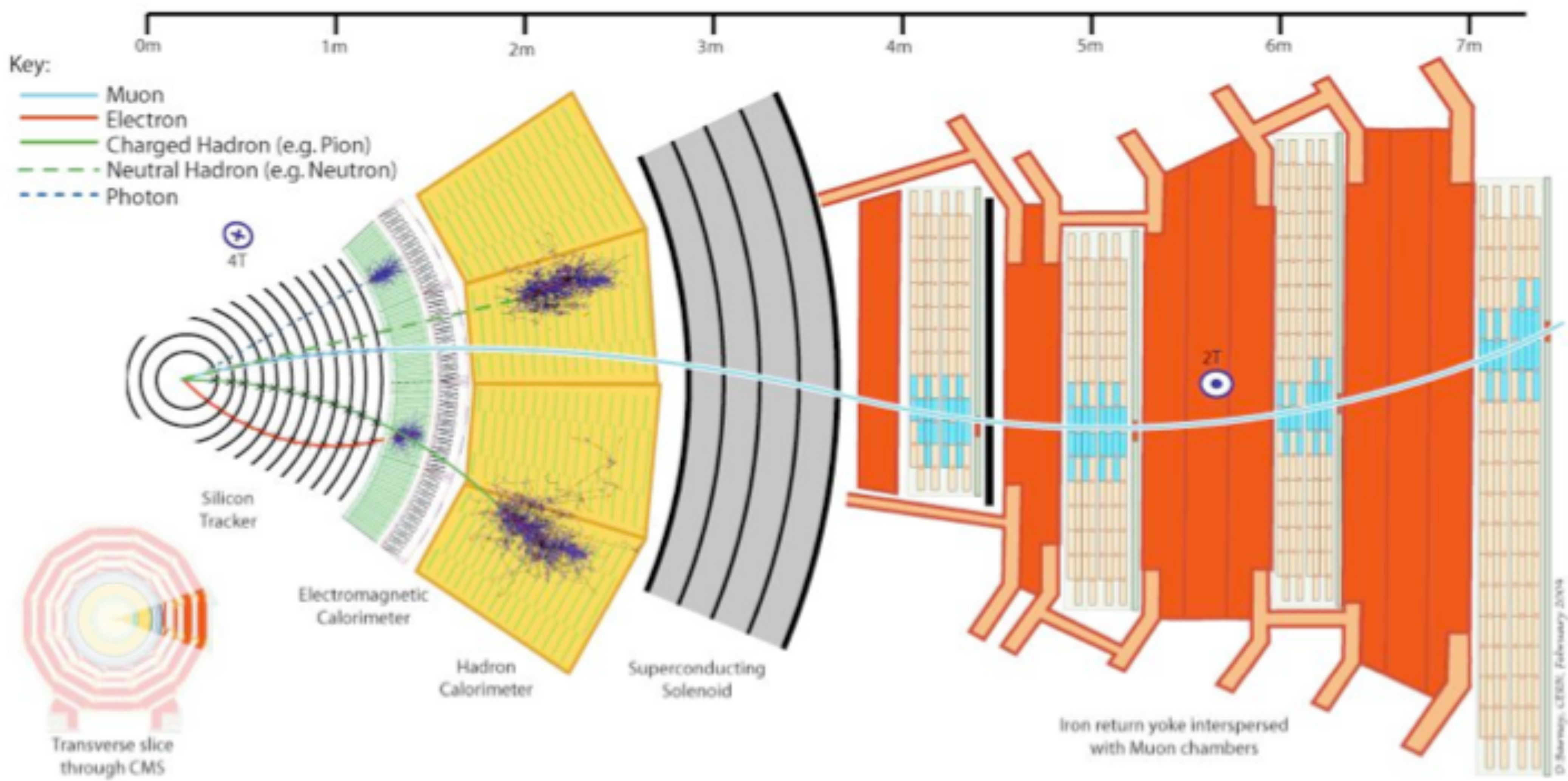


X0 = distance in which electron energy is reduced by 1/e by bremsstrahlung

Lambda_I = interaction length for hadronic interaction



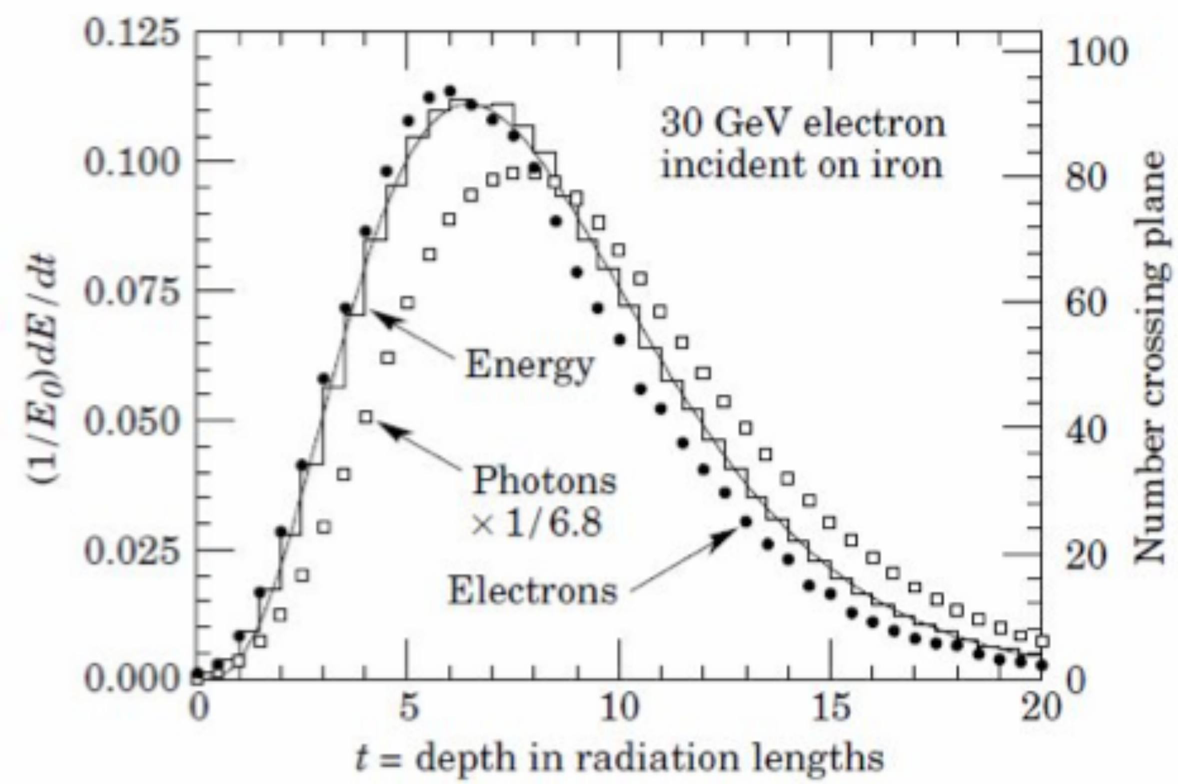
$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\ln\frac{287}{\sqrt{Z}}}\ \mathrm{g \cdot cm^{-2}}$$



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

Calorimeter showers initiated by e / photon

longitudinal



Difference electron-photon ?

Photon has to convert first
P(not convert) ~ exp(-7/9*x/x0)

lateral

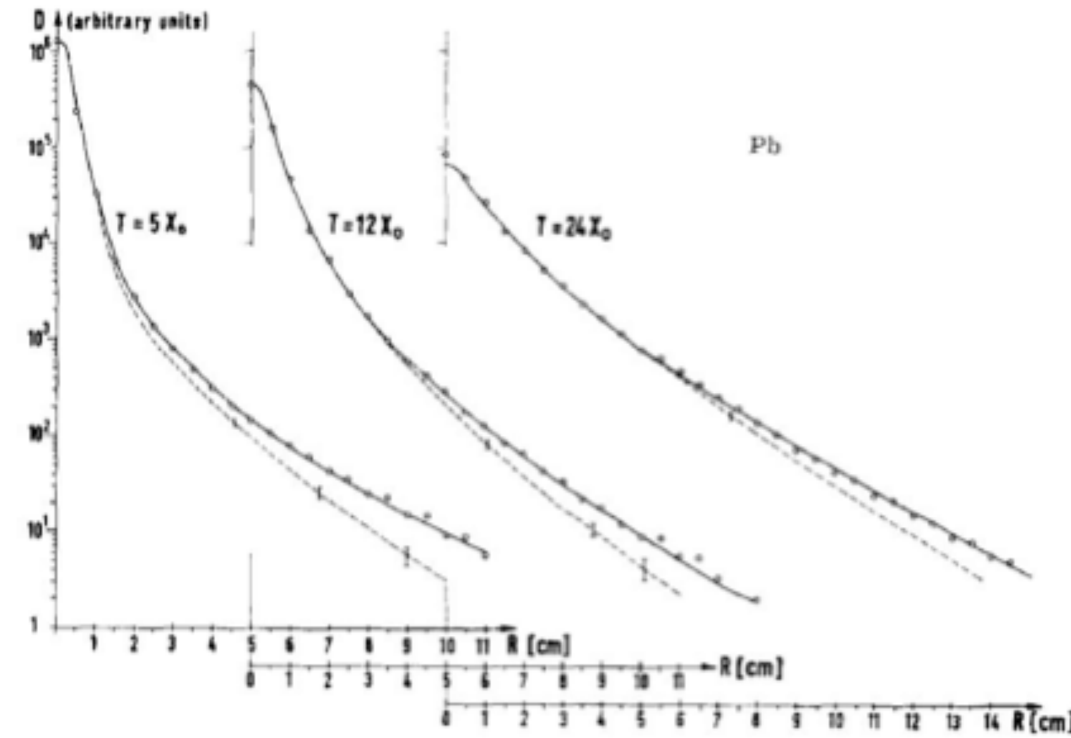


Fig. 4. Measured lateral distribution for lead (circles) in comparison with Monte-Carlo results (dotted line with error bars).

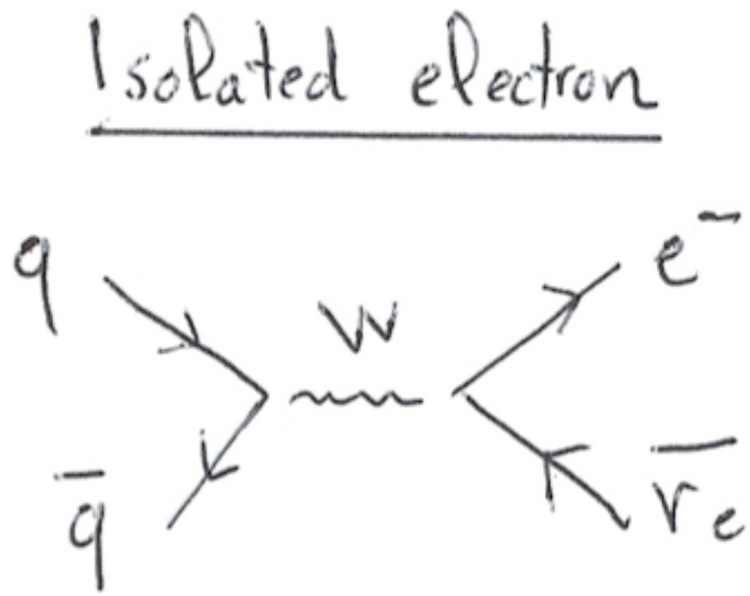
Moliere radius ~X0.(21MeV/Ec)
cylinder of ~2 Rm contains
~ 95% of energy

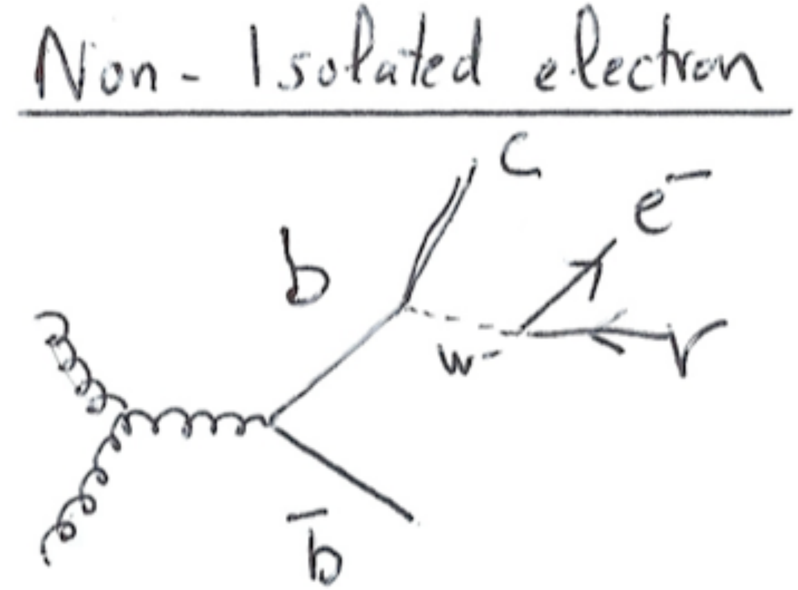
Powerful discriminant to separate e/photon induced showers from hadron showers

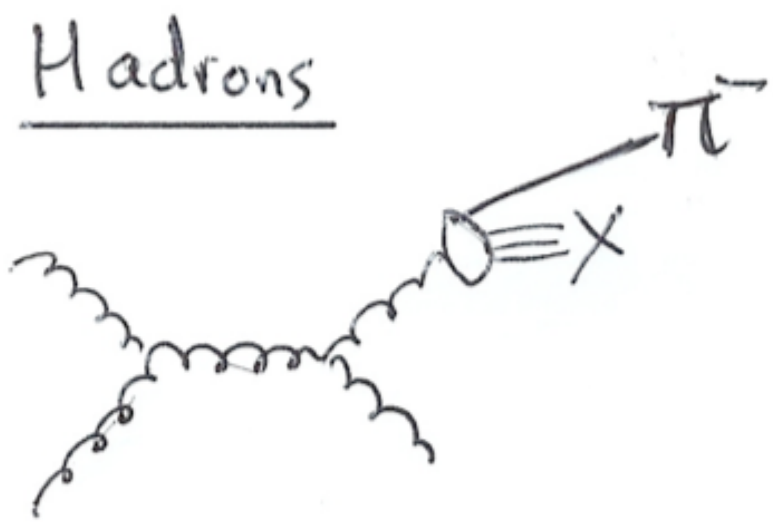
Electron identification in hadron colliders

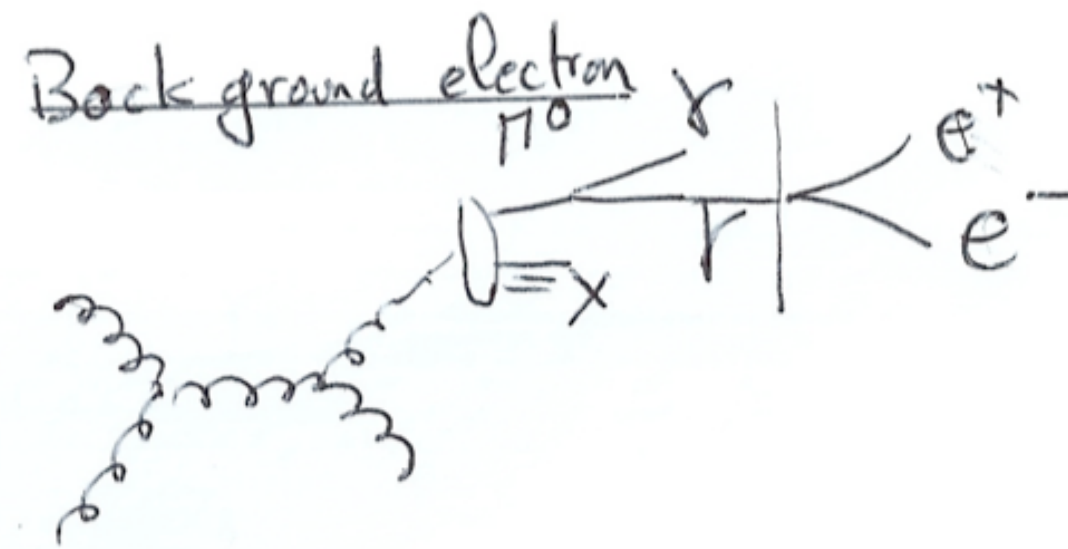
- High energy charged leptons are usually indication of «interesting» physics events, for instance decays of W or Z boson
- What are the backgrounds ?
- How to distinguish «good» electrons from them ?

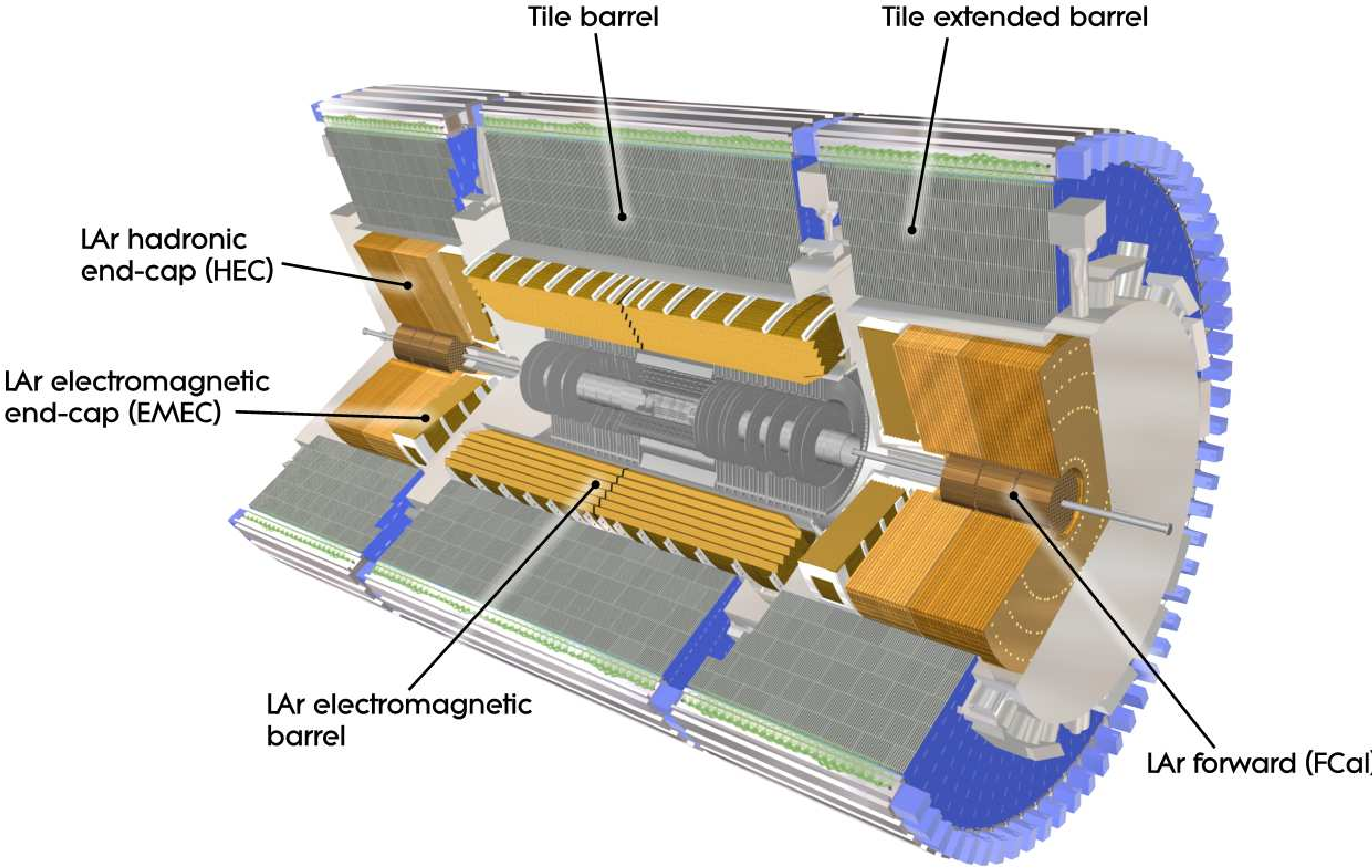
Description of different type of electron backgrounds





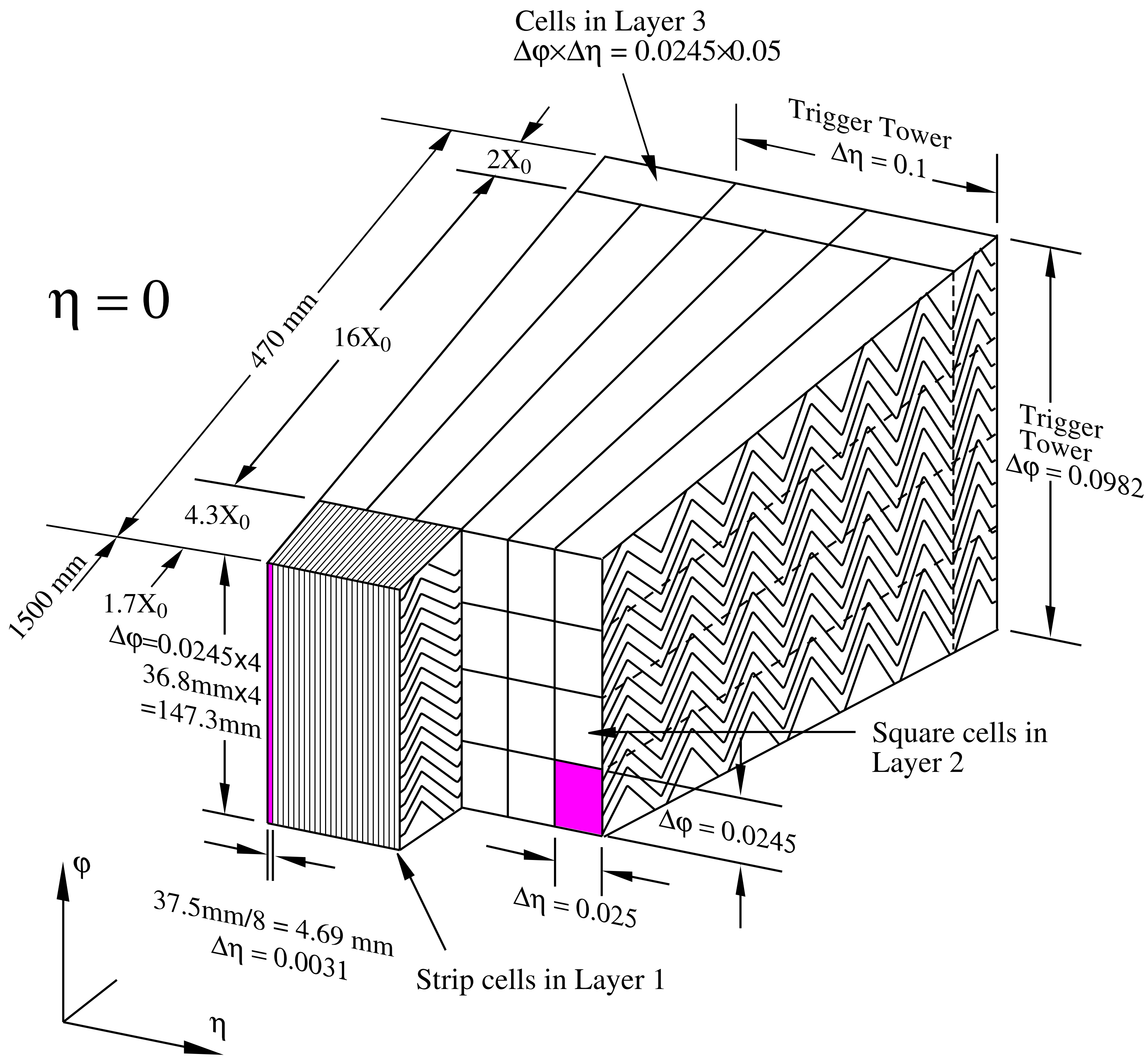


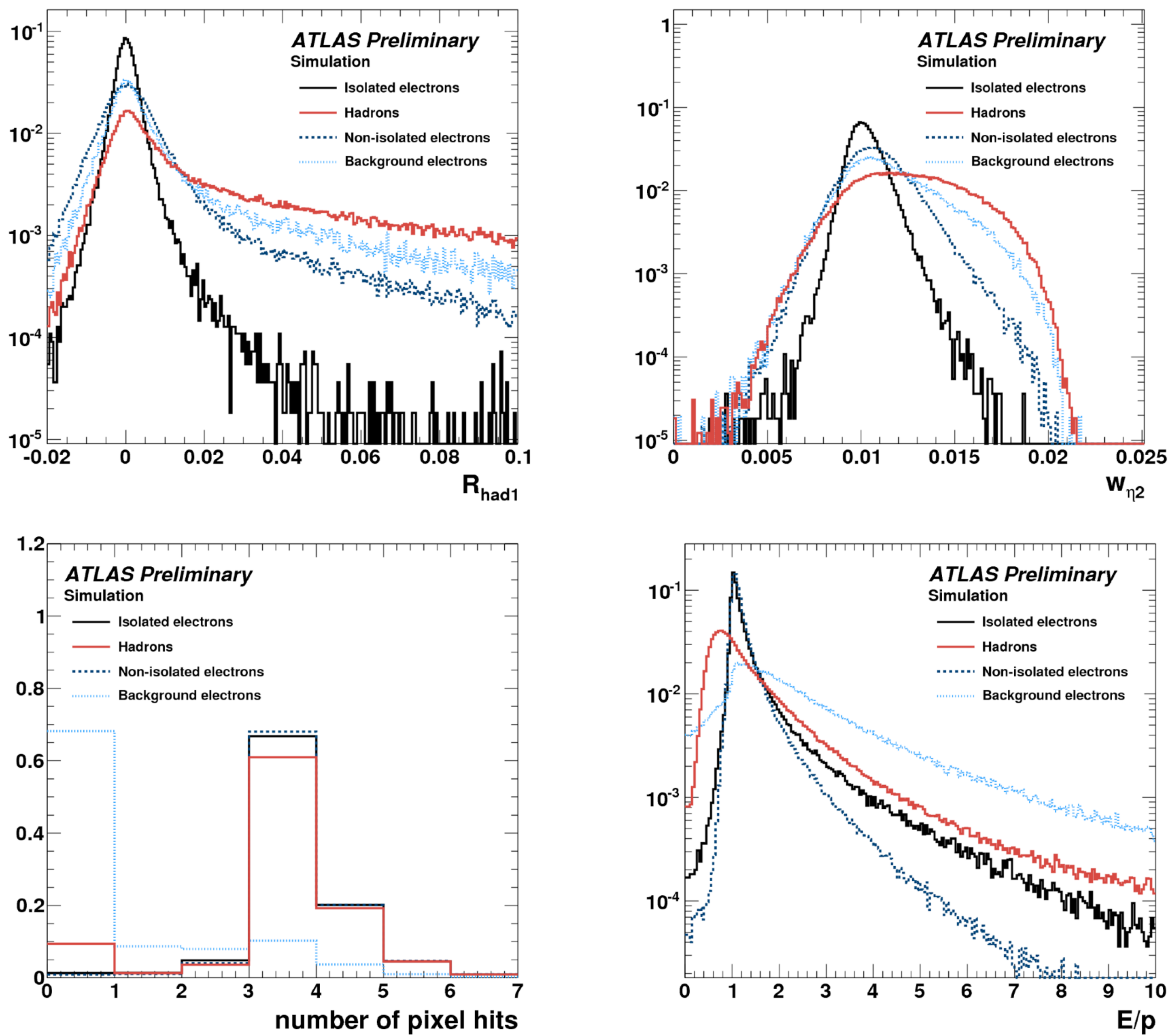


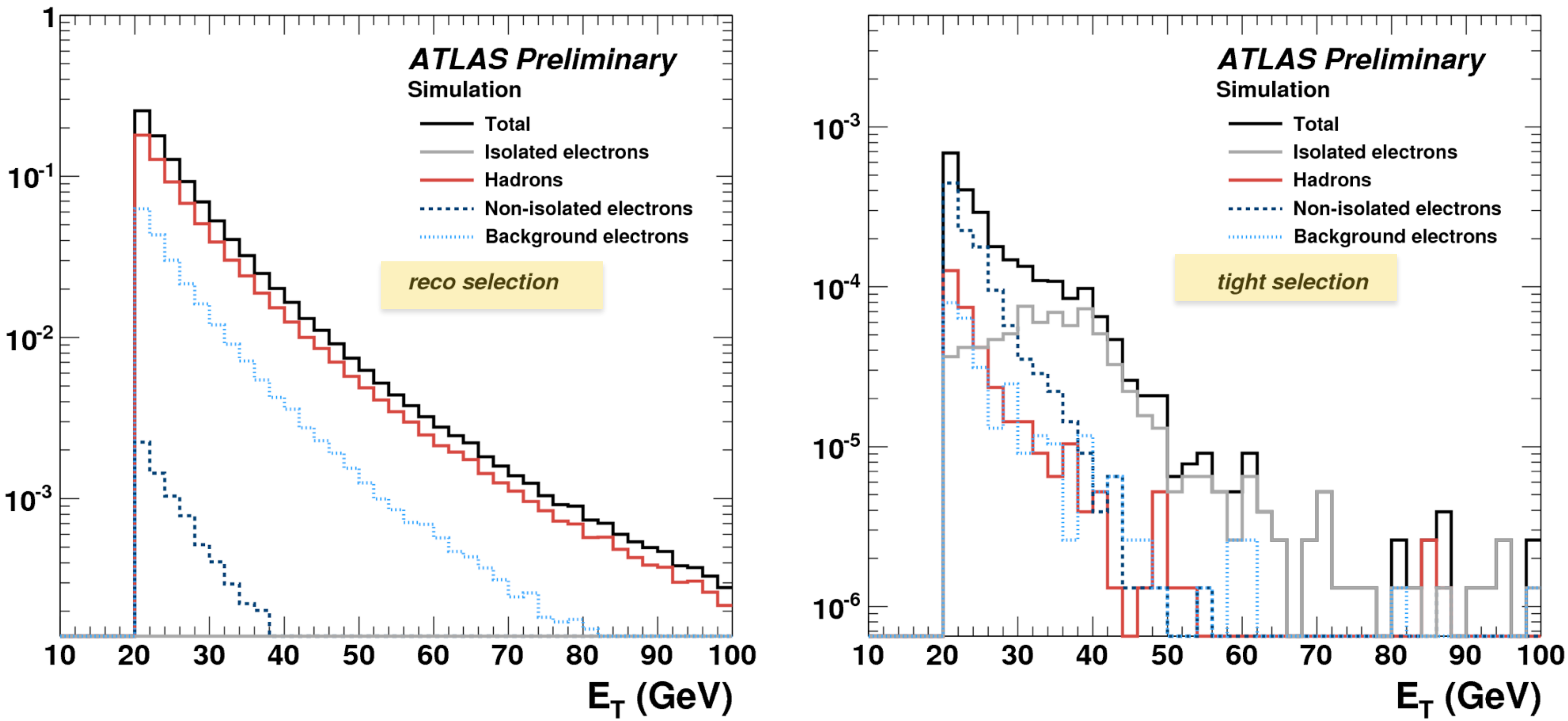


Tile barrel
Tile extended barrel
LAr hadronic
end-cap (HEC)
LAr electromagnetic
end-cap (EMEC)
LAr electromagnetic
barrel
LAr forward (FCal)

Granularity of EM calorimeter to measure shower development



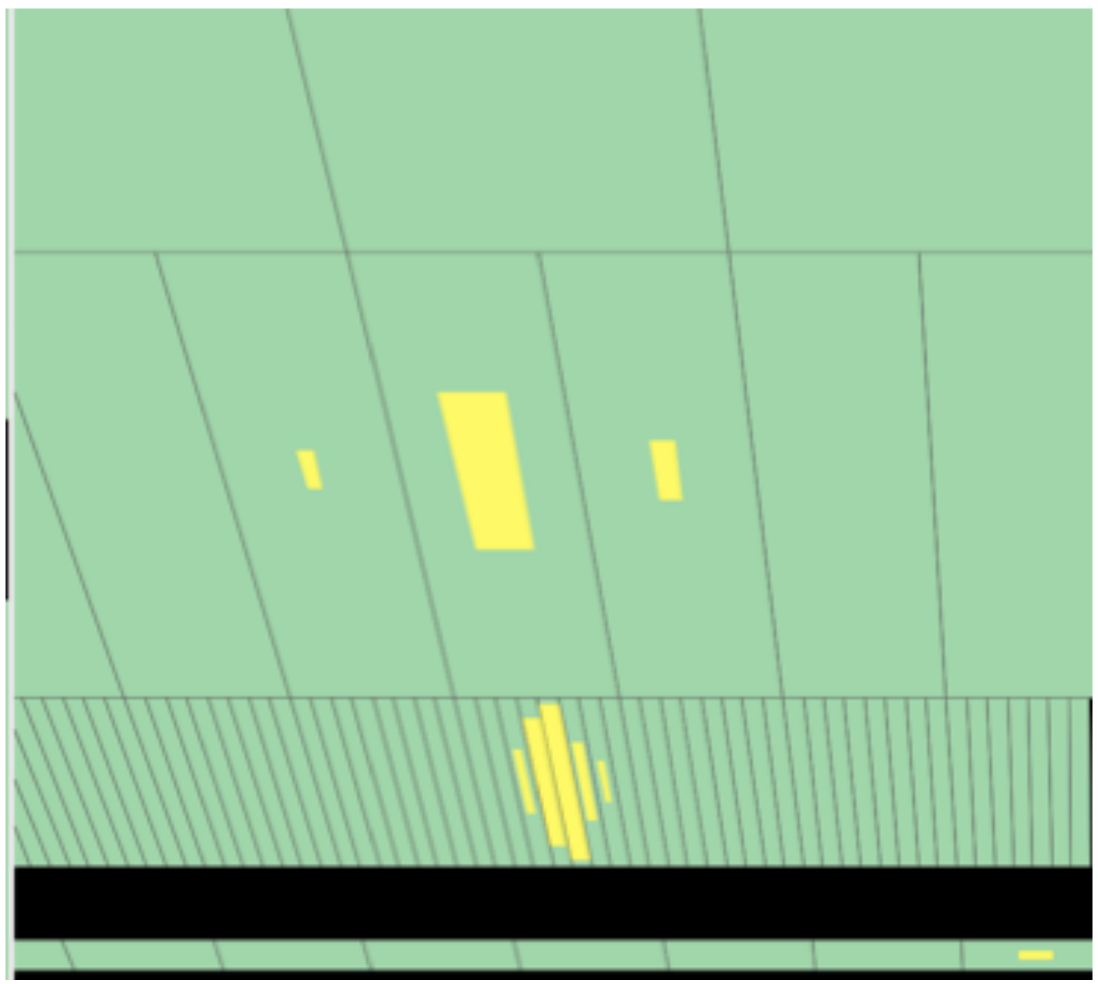

ATLAS Preliminary
Simulation
Isolated electrons
Hadrons
Non-isolated electrons
Background electrons
R_had1
w_η2
number of pixel hits
E/p

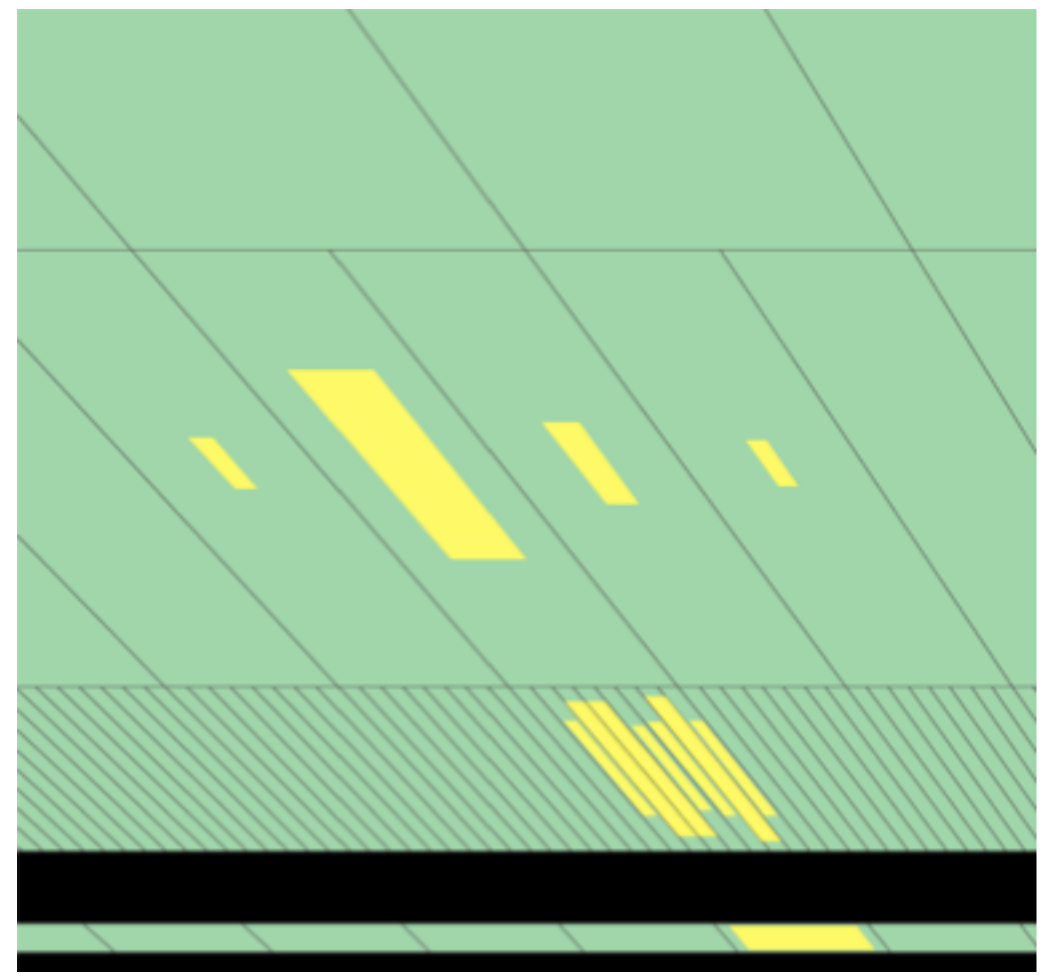

ATLAS Preliminary
Simulation
Total
Isolated electrons
Hadrons
Non-isolated electrons
Background electrons
reco selection
1
10-1
10-2
10-3
10 20 30 40 50 60 70 80 90 100
E_T (GeV)
ATLAS Preliminary
Simulation
Total
Isolated electrons
Hadrons
Non-isolated electrons
Background electrons
tight selection
10-3
10-4
10-5
10-6
10 20 30 40 50 60 70 80 90 100
E_T (GeV)

Photon identification in collider experiment

Background from high energy pi0->gamma gamma
What is the separation between the photons ?
What information can be exploited ?

theta_min ~2/gamma
~0.0067 at E=40 GeV
=> 1cm @ R=150cm





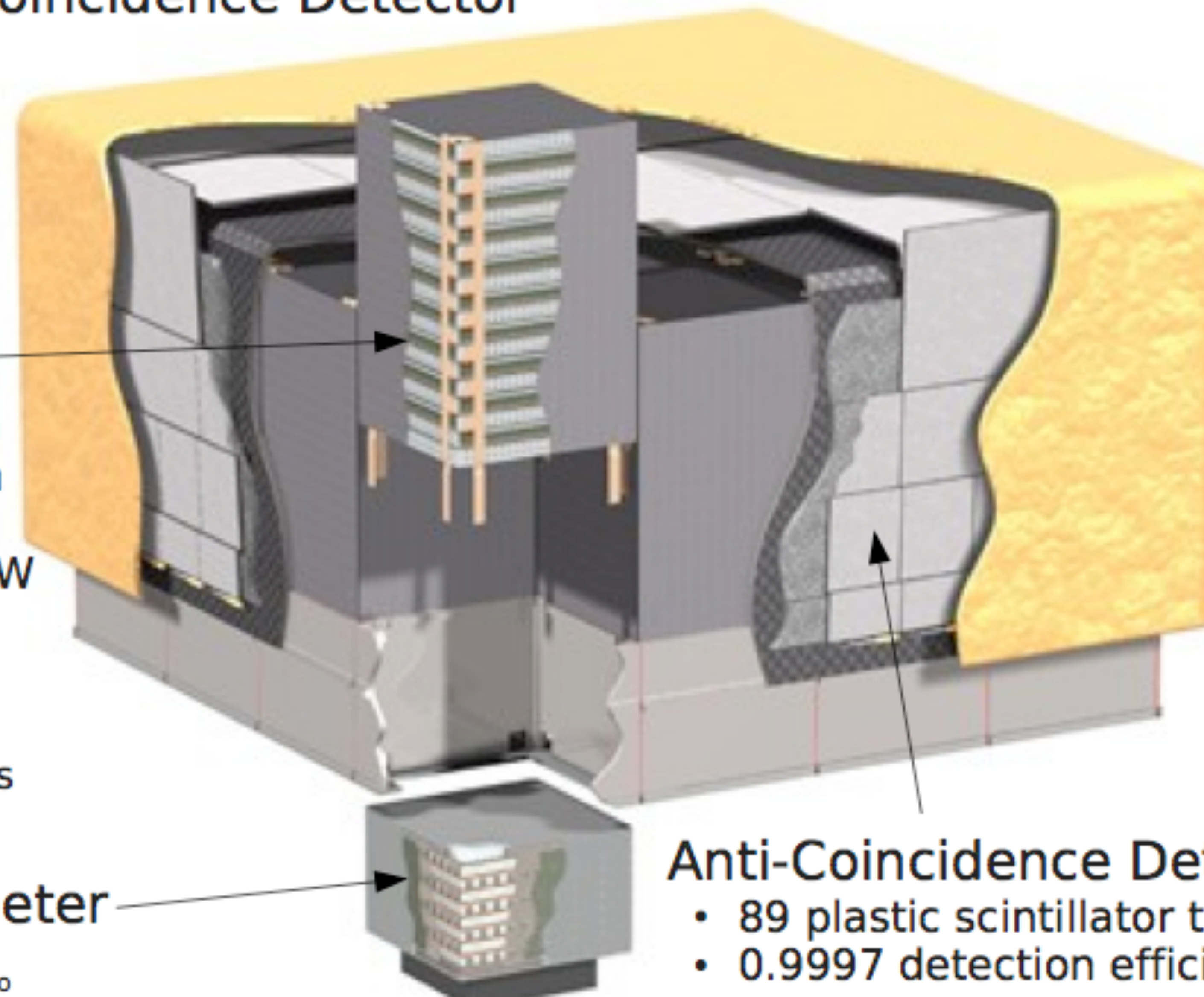
Which one is the single photon shower ?

Some of these techniques are also used in Space

- Fermi LAT : identify and measure ~50 MeV to ~300 GeV gamma rays with good angular resolution

Fermi LAT

4x4 array of identical towers (tracker + calorimeter) surrounded by an Anti-Coincidence Detector



Tracker
- 18 layers (x-y) with silicon strip detectors + tungsten conversion foil
- 2 sections (depending on W thickness):
  - Thin (front) : $12 \times 0.03 X_o$
  - Thick (back) : $4 \times 0.18 X_o$
  - No W in the 2 bottom layers
- $1.4\ X_o$ on axis

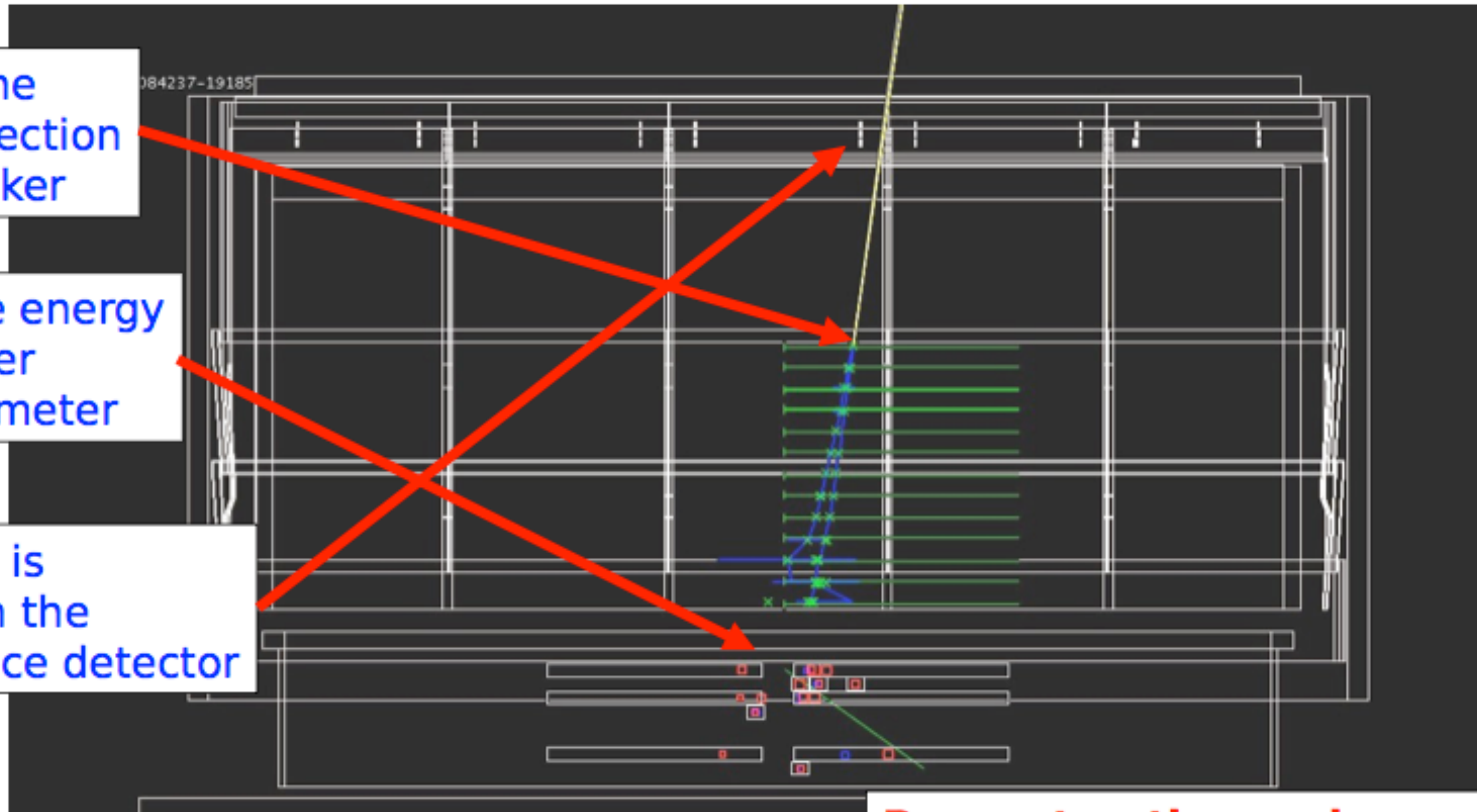
Calorimeter
- $8.6\ X_o$
- 96 CsI crystals per module

Anti-Coincidence Detector
- 89 plastic scintillator tiles
- 0.9997 detection efficiency for minimum-ionizing particles

Determine the
incoming direction
with the tracker

Determine the energy
with the tracker
and the calorimeter

Check if there is
some signal in the
anti-coincidence detector

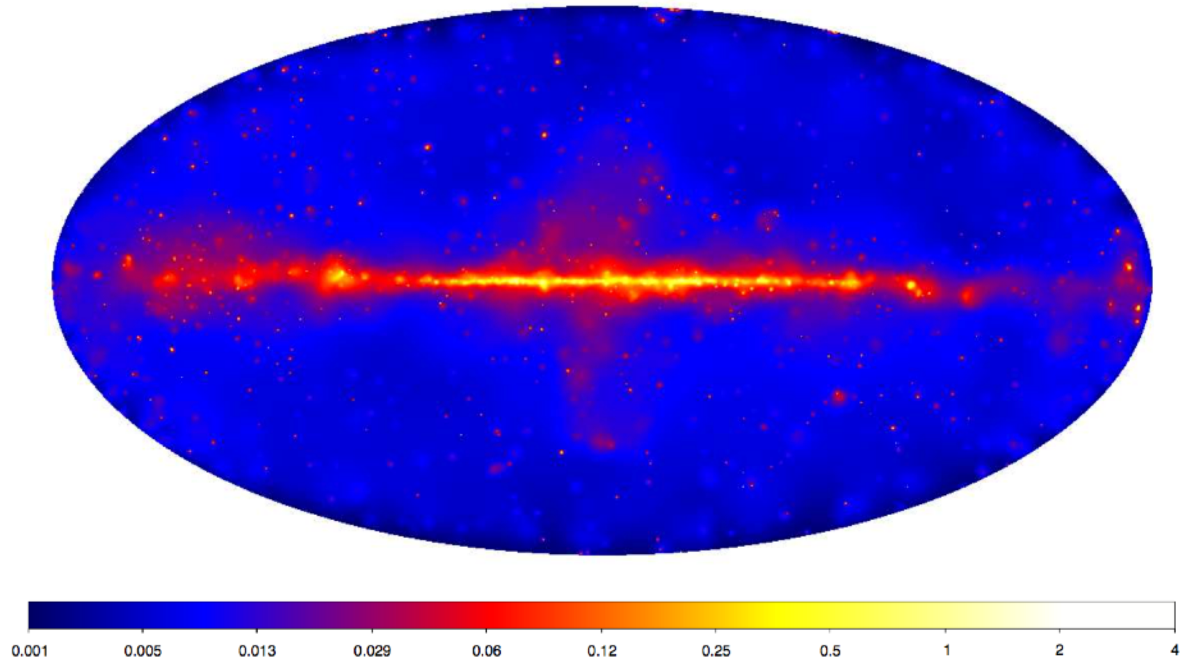


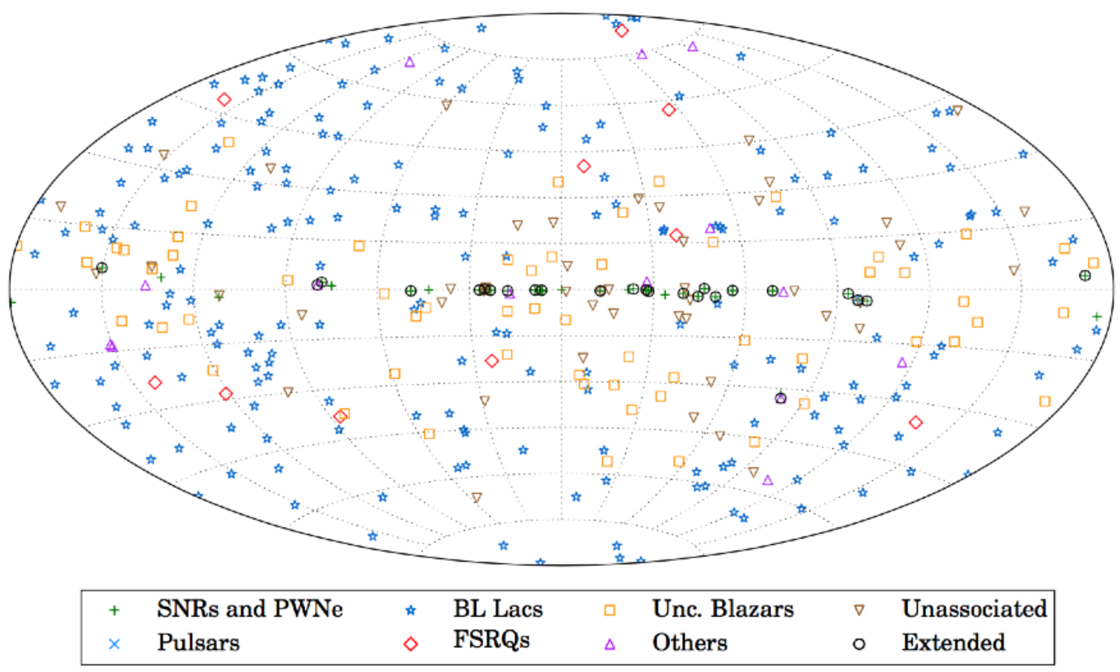
Reconstruction and selection are optimized using classification trees.

The calorimeter is used in the event selection :
match between the track and the cluster
(position, angle), cluster transverse size.

FERMI-LAT map of gamma-ray sources with E>50 GeV

https://arxiv.org/abs/1508.04449



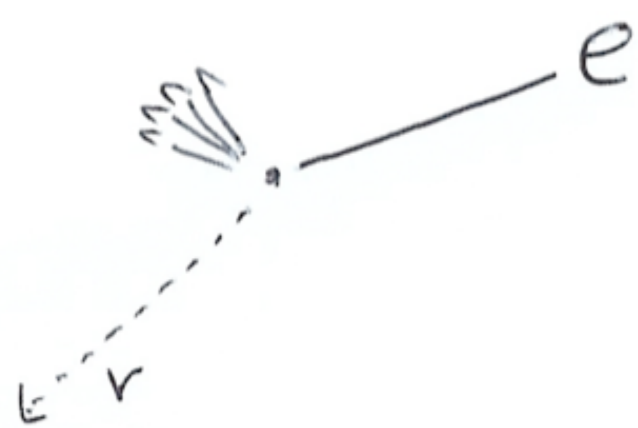


Muon identification in hadron colliders

- Muons are usually clean signatures, less background than electrons
- Main sources of «muons»
  - punch through of hadronic showers
  - pi/k decays in the inner detector
  - Semileptonic B-hadron decays => «true» non-isolated muons
    - Usually main background at high energy in collider experiments
- Precise measurement of muons requires large magnetic detectors

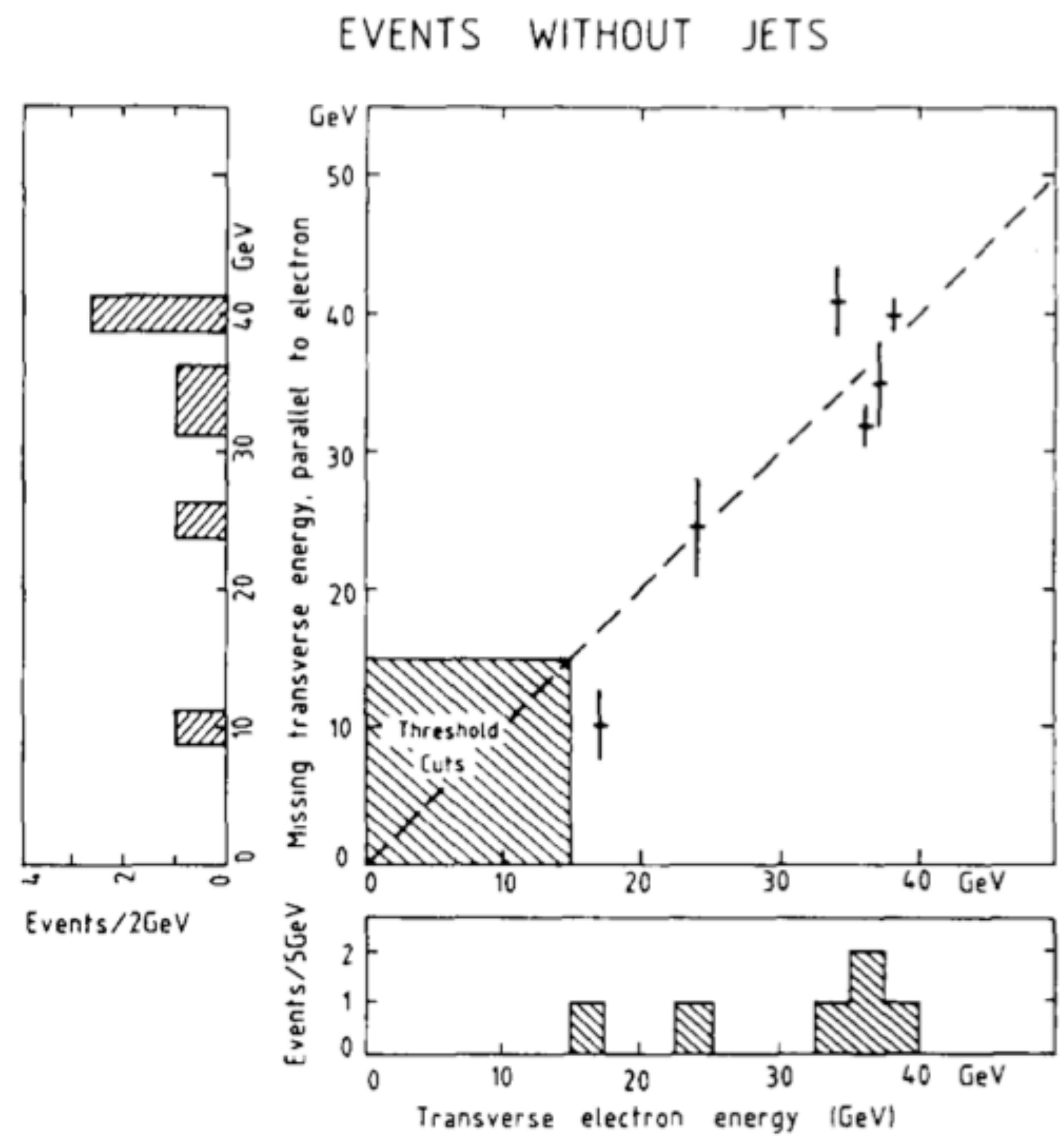
Neutrino «identification» in hadron colliders

- The probability of neutrino interaction in a collider experiment is ~null
- How to measure something that one does not detect ?



$$\vec{p}_T(\nu) = -\sum_i \vec{p}_T(\text{seen})$$

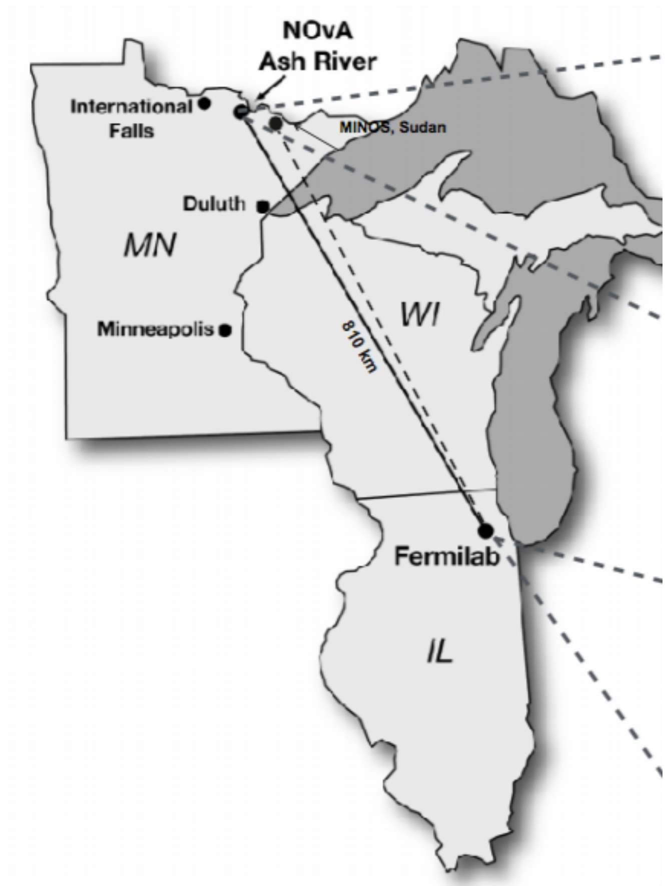
Missing transverse momentum for W boson discovery (1983)



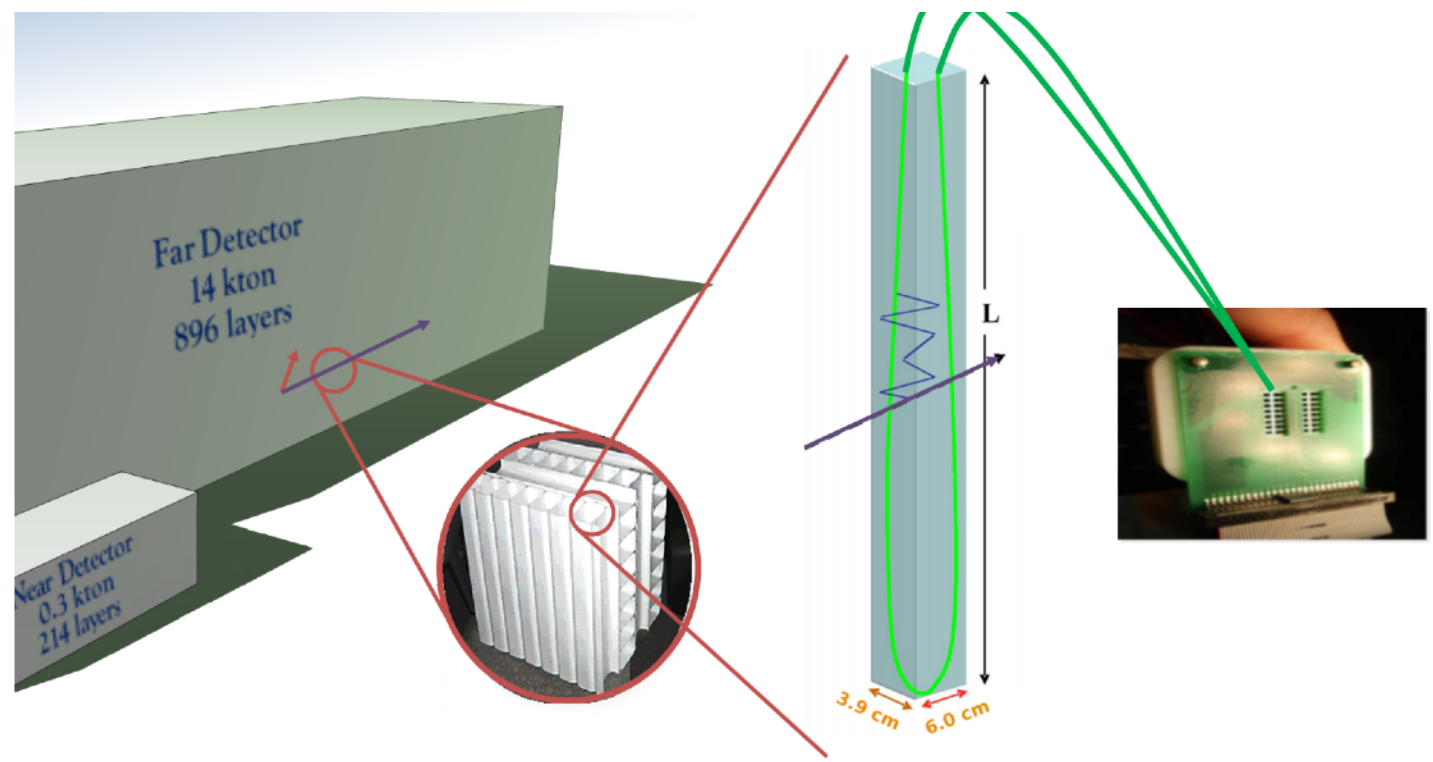
Direct detection of neutrinos

- High flux of incoming neutrinos (for instance neutrino beams)
- High mass detector
- => can observe neutrino interactions
  - Charged currents: produce e,mu or tau depending on neutrino flavor at the interaction => identify flavor of neutrino
  - Neutral currents: ~universal for all (non-sterile) neutrinos
- Neutrino cross-section increases with energy
  - at O(> PeV) energy, earth becomes opaque to neutrinos

NOVA neutrino experiment



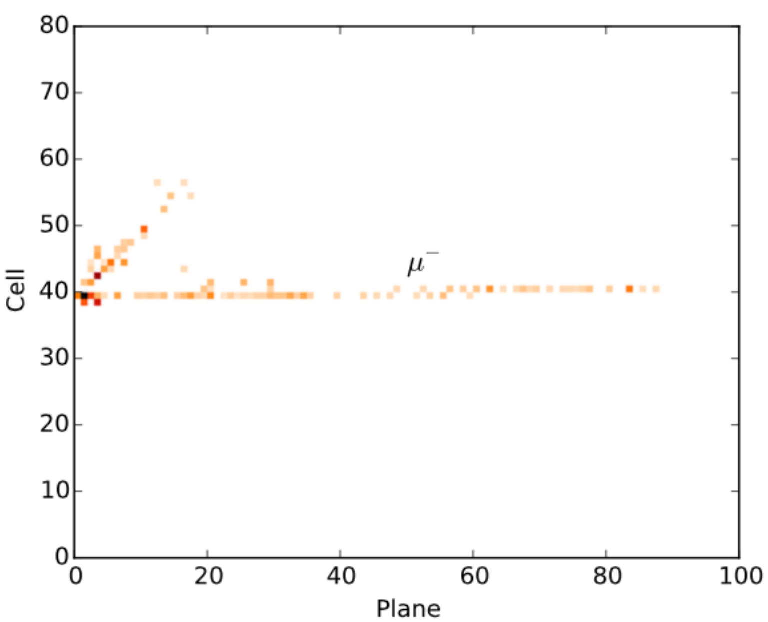
Start with muon neutrino beam
and look at rate of remaining muon neutrino
and appearing electron neutrino at a long distance



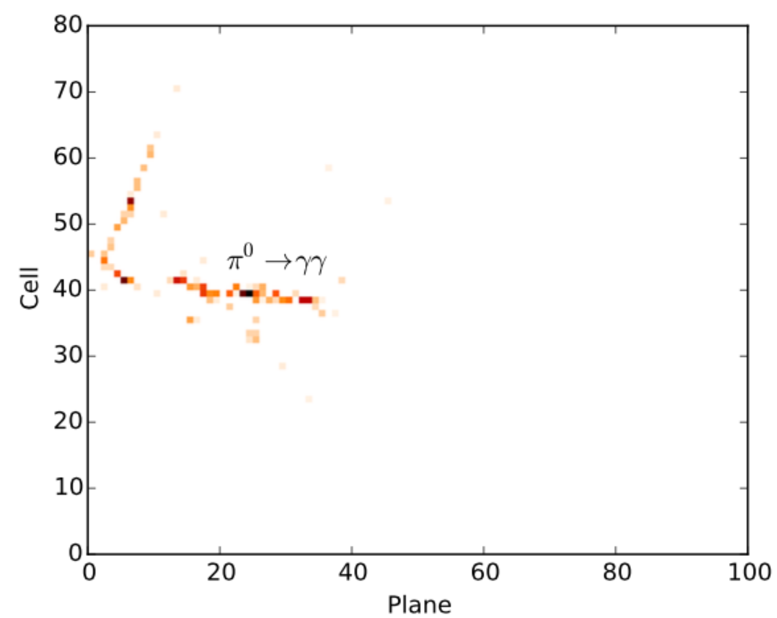
Charged current reaction used to identify flavor of interacting neutrino
=> need good identification of electrons and muons induced by neutrinos
(+ rejection of cosmics background)

Use algorithm inspired by computer vision to optimize particle identification

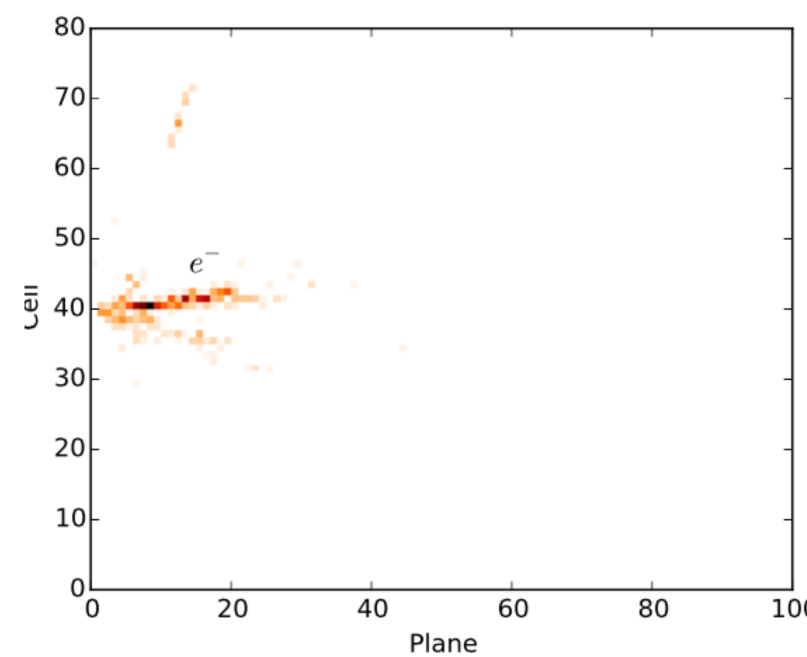
https://arxiv.org/abs/1604.01444



X-view



X-view



X-view

many other examples of this kind of application need good reference samples to "train" AI algorithm

Measure beta or gamma of particle

- Direct measurement of velocity («time of flight»
  - $v = d/t$
- Measurement of beta.gamma through ionization energy loss
- Measurement of beta through Cherenkov radiation
- Measurement of gamma through Transition radiation

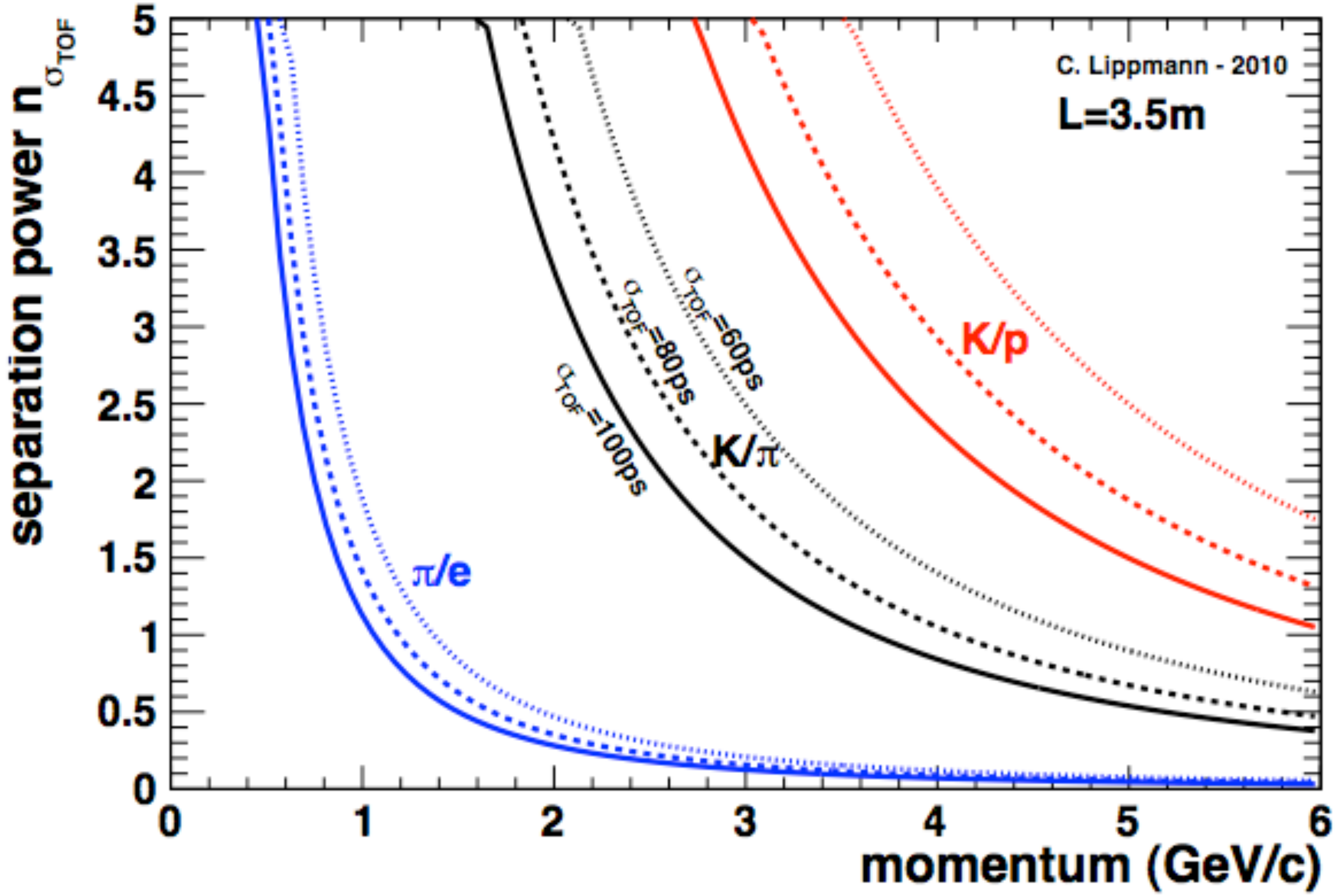
time of flight

$$\beta = \frac{v}{c} = \frac{L}{t \cdot c}$$

$$m = \frac{p}{c}\sqrt{\frac{c^2 t^2}{L^2} - 1} \qquad \frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right)$$

For 2 hypothesis m_A, m_B:

$$|t_A - t_B| = \frac{Lc}{2p^2}\left|m_A^2 - m_B^2\right|$$



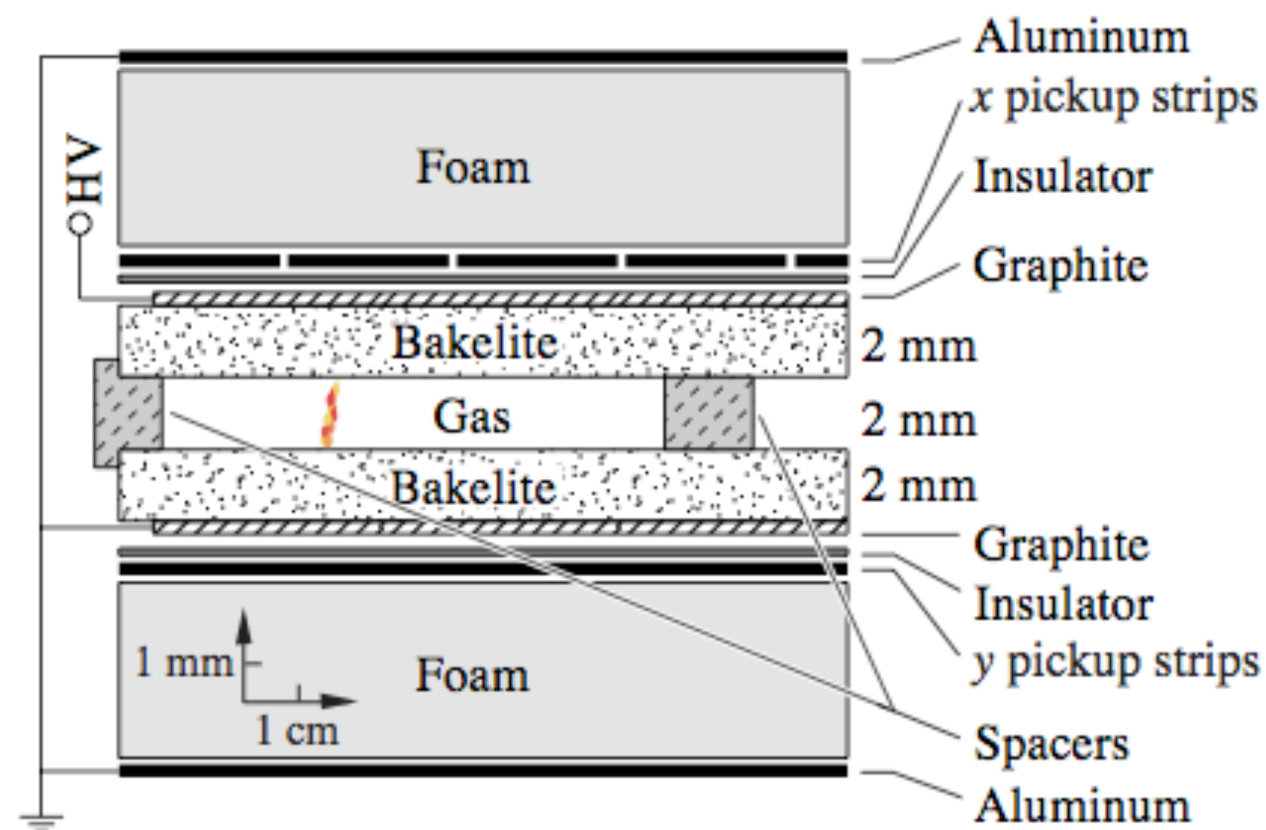
Dedicated detectors for time measurement can reach < 100 ps accuracy even on large system

At LHC, the collision time has an intrinsic jitter of ~140 ps (bunch length)

Need dedicated measurement to remove this contribution from time resolution

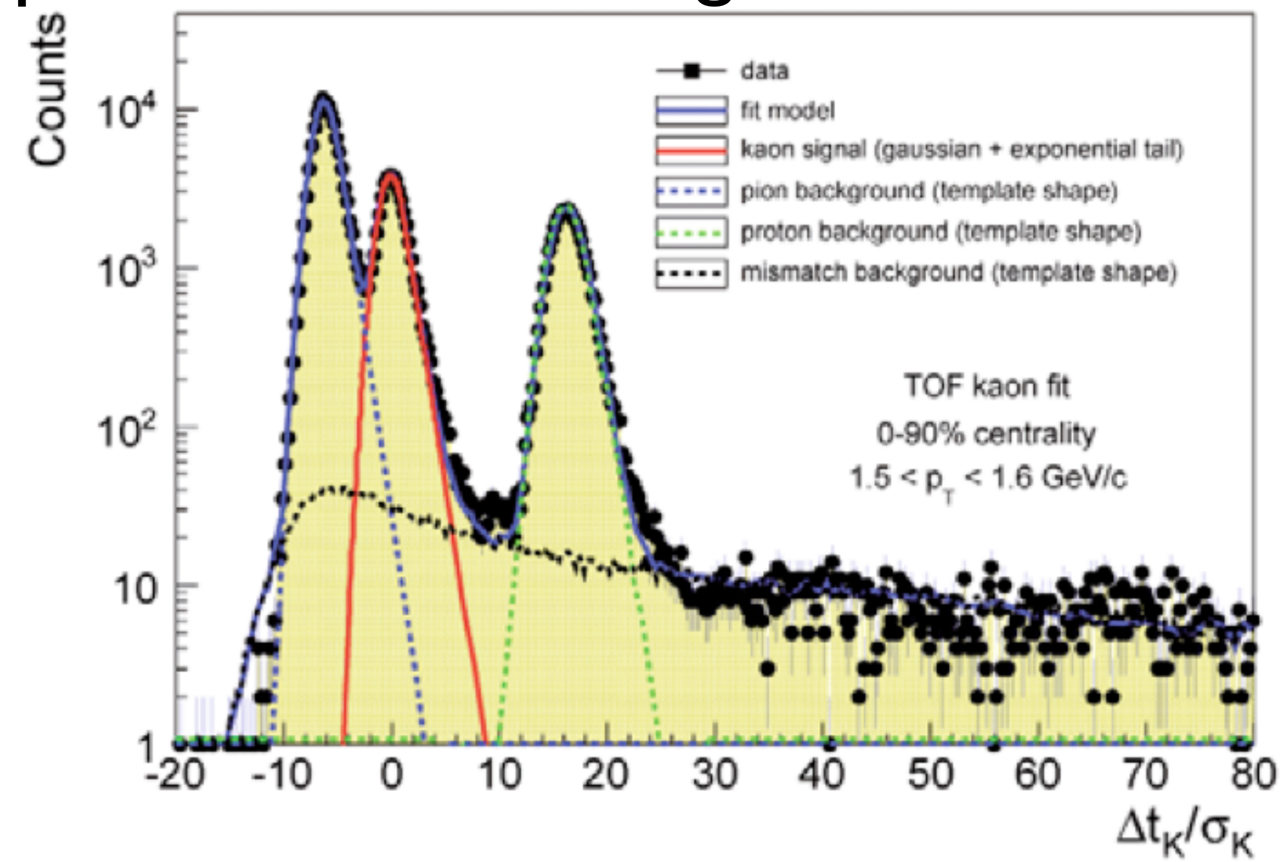
Most commonly used detectors for timing were based on scintillation
(can also use other techniques like calorimetry, etc..)

Gaseous ionization detectors like RPC developed to cover large area in a cost-effective way

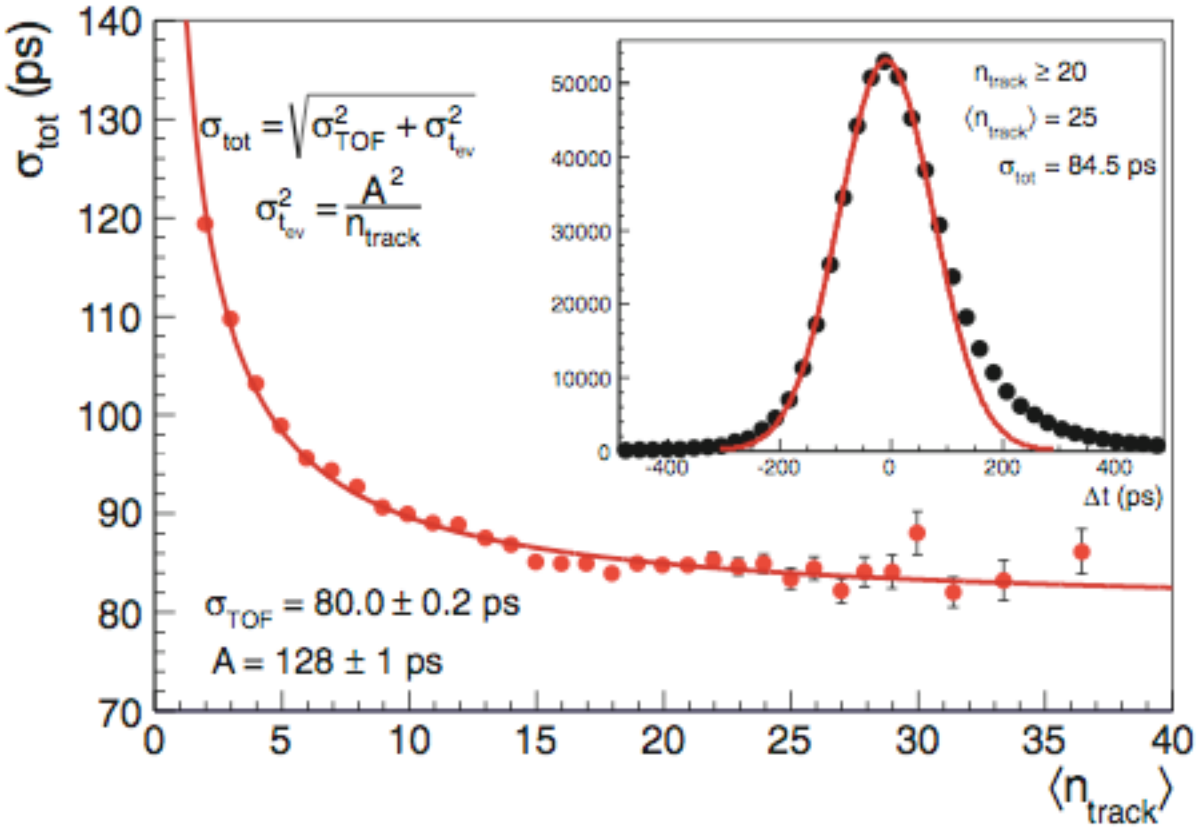


Strong uniform electric field => avalanche starts immediately after primary ionization
Can reach intrinsic time resolution of ~ 50 ps for multigap RPC
Rate limitation O(kHz/cm2)

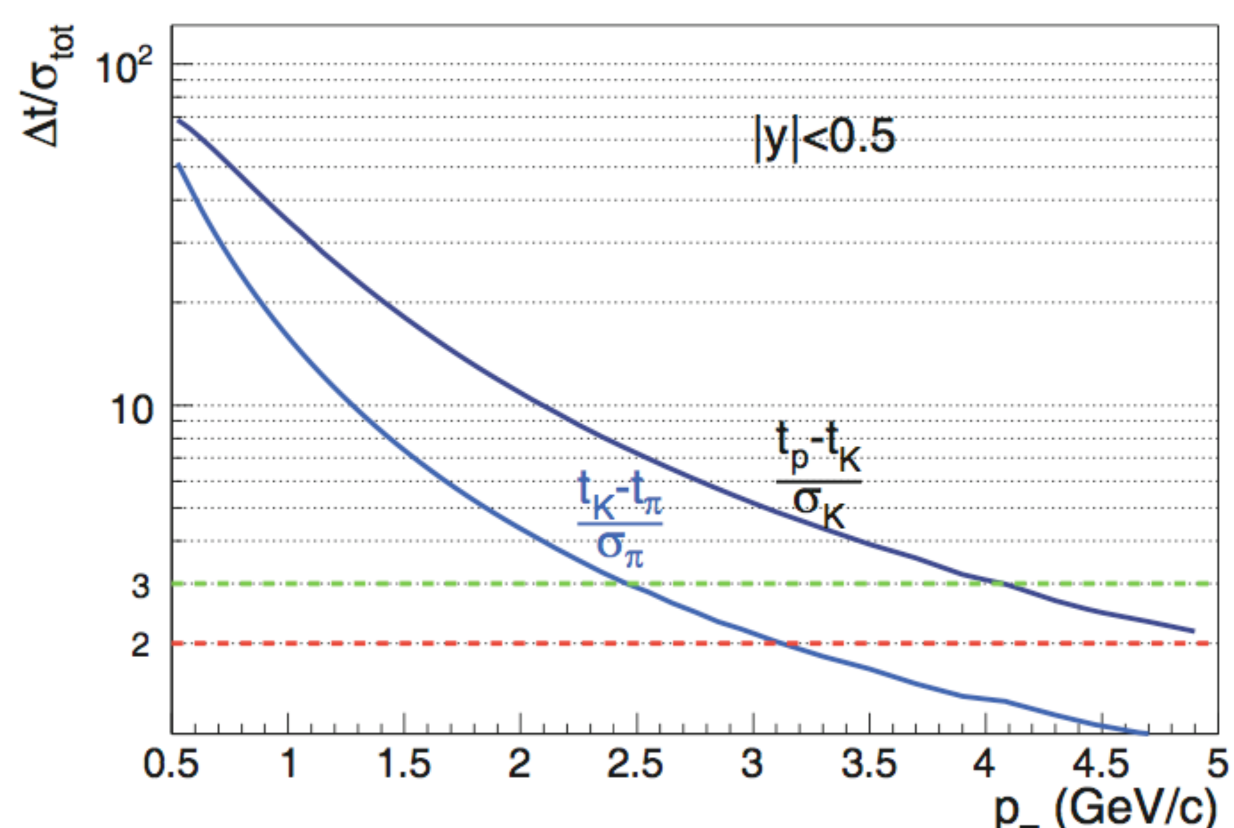
- measure time of flight over 3.7 m distance
- measure momentum
- compare time of flight to predicted time of flight assuming M= M(K+)



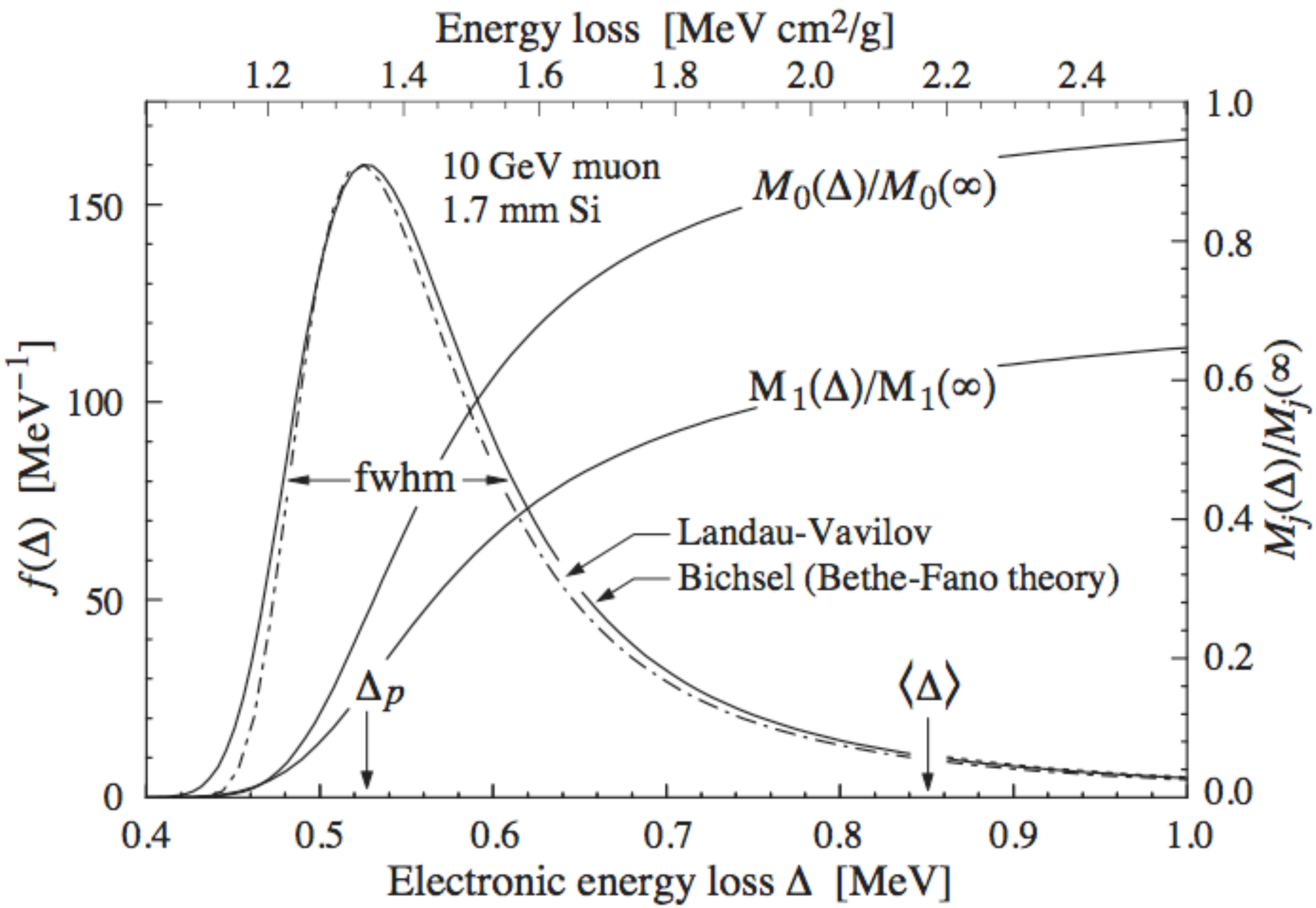
Measured time resolution in ALICE



Intrinsic resolution + time jitters (electronics, clock)+ channel to channel variation + residual time slewing effects



Ionization measurement



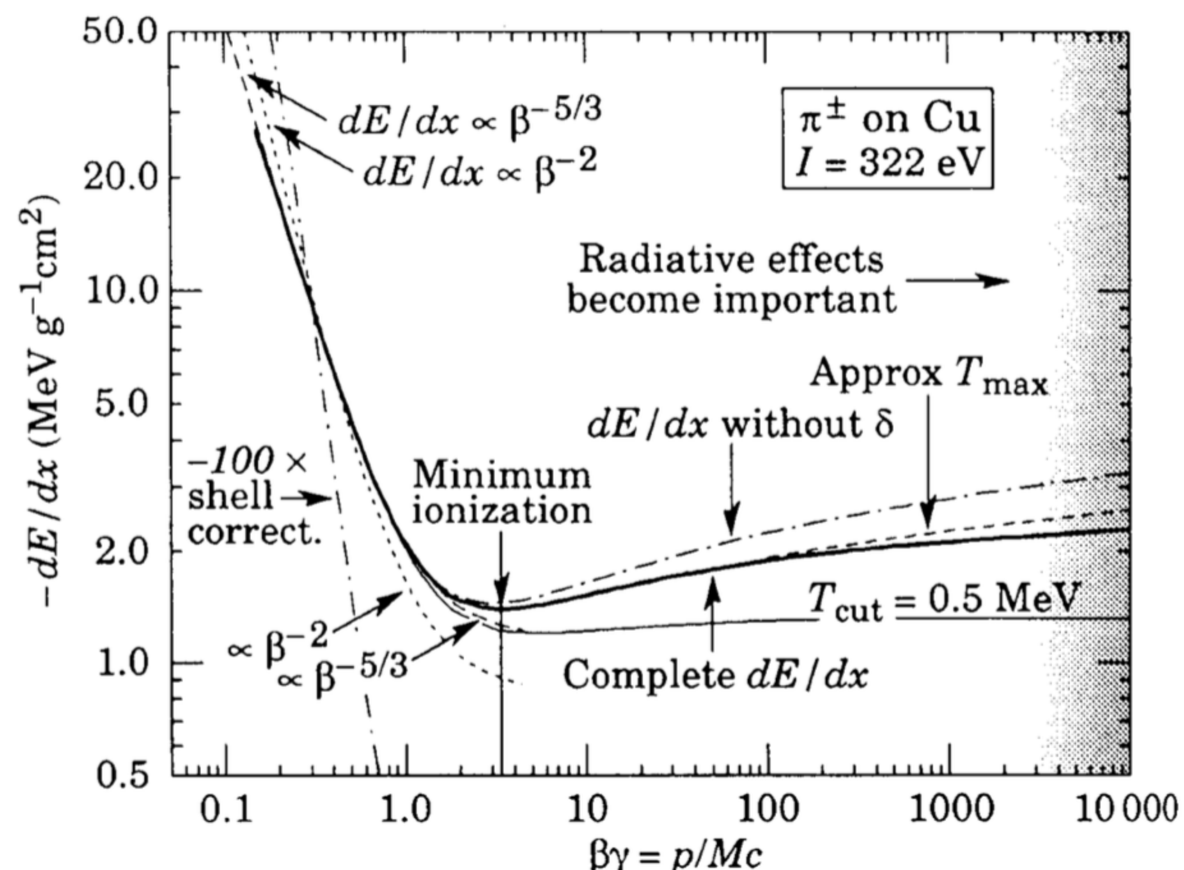
Formula for restricted energy loss

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{z^2}{\beta^2}\left(\log \frac{\sqrt{2m_ec^2 E_{cut}}\,\beta\gamma}{I} - \frac{\beta^2}{2} - \frac{\delta}{2} \right)$$

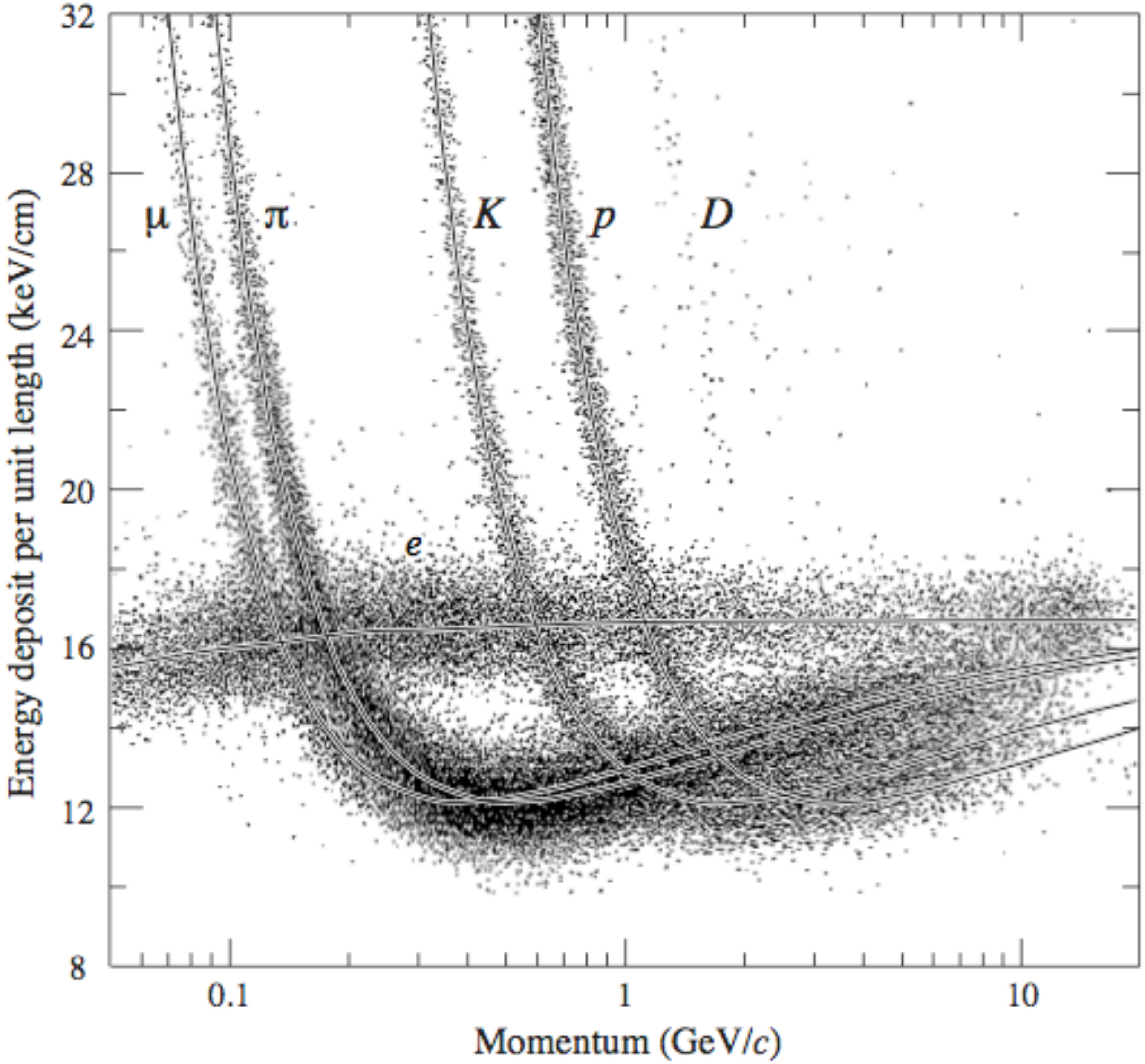
I = effective excitation energy

δ = density correction effect

E_{cut} = upper limit for energy transfer in single collision



Ionisation measurement in a TPC



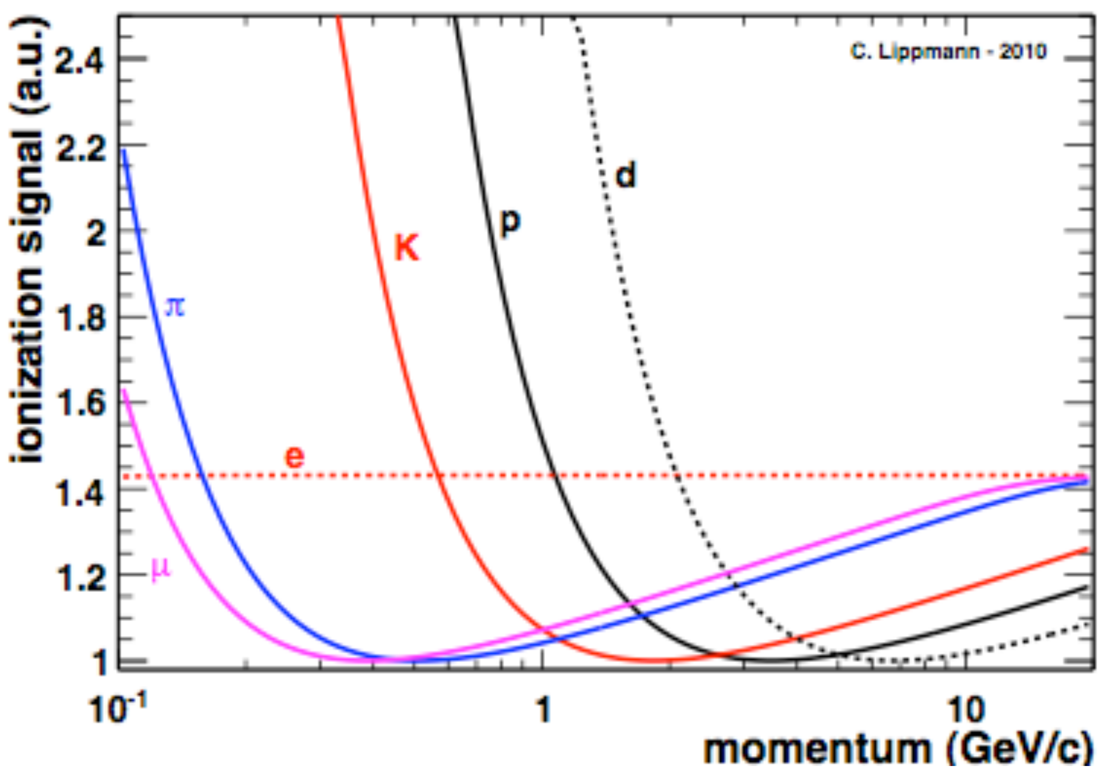
Can use gaseous or solid state counter to measure ionisation

Provide signal pulse height ~ N(electrons liberated in ionization) and measurement of track length
=> allows one to compute dE/dx

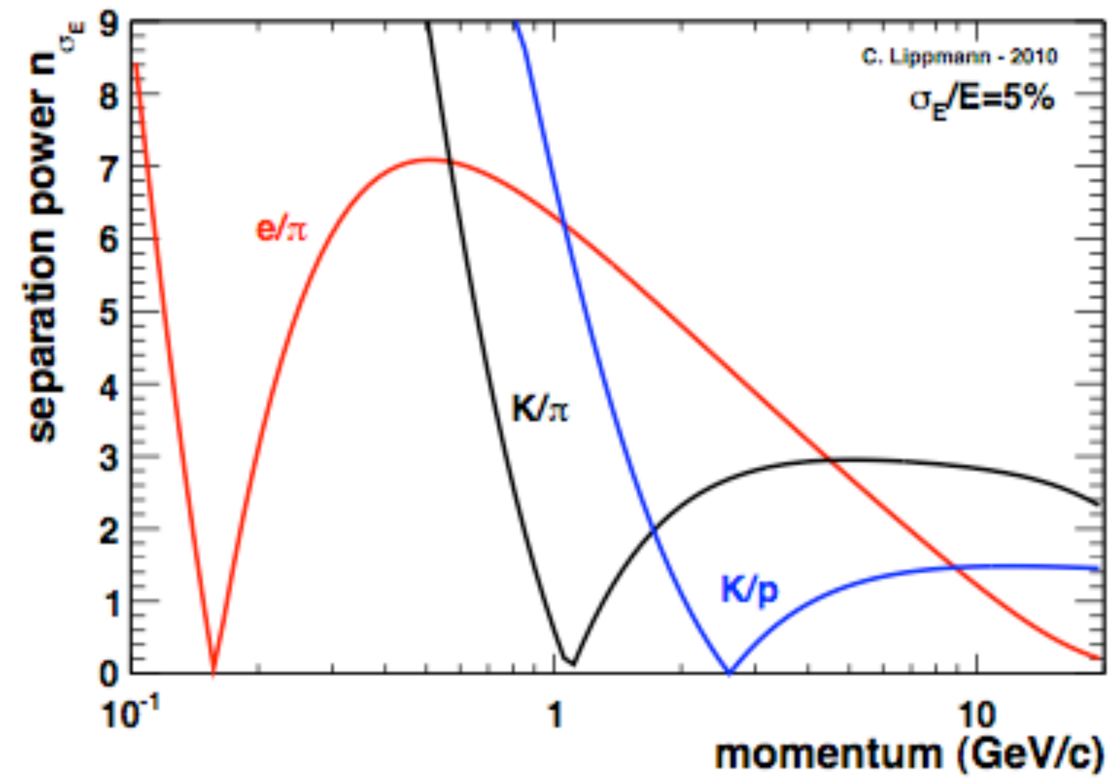
Average several measurements with a truncated mean to reduce tail impact

Typical other errors affecting measurement:
- energy calibration of the detector
- detector conditions (for instance gas pressure)
- detector geometry and track orientation (affects track length)
- overlapping tracks in dense environment
- etc..

Typical ionization signals vs p (gaseous detector)
(for Si detector, plateau only slightly above minimum => less separation at high energy)



Separation assuming 5% resolution

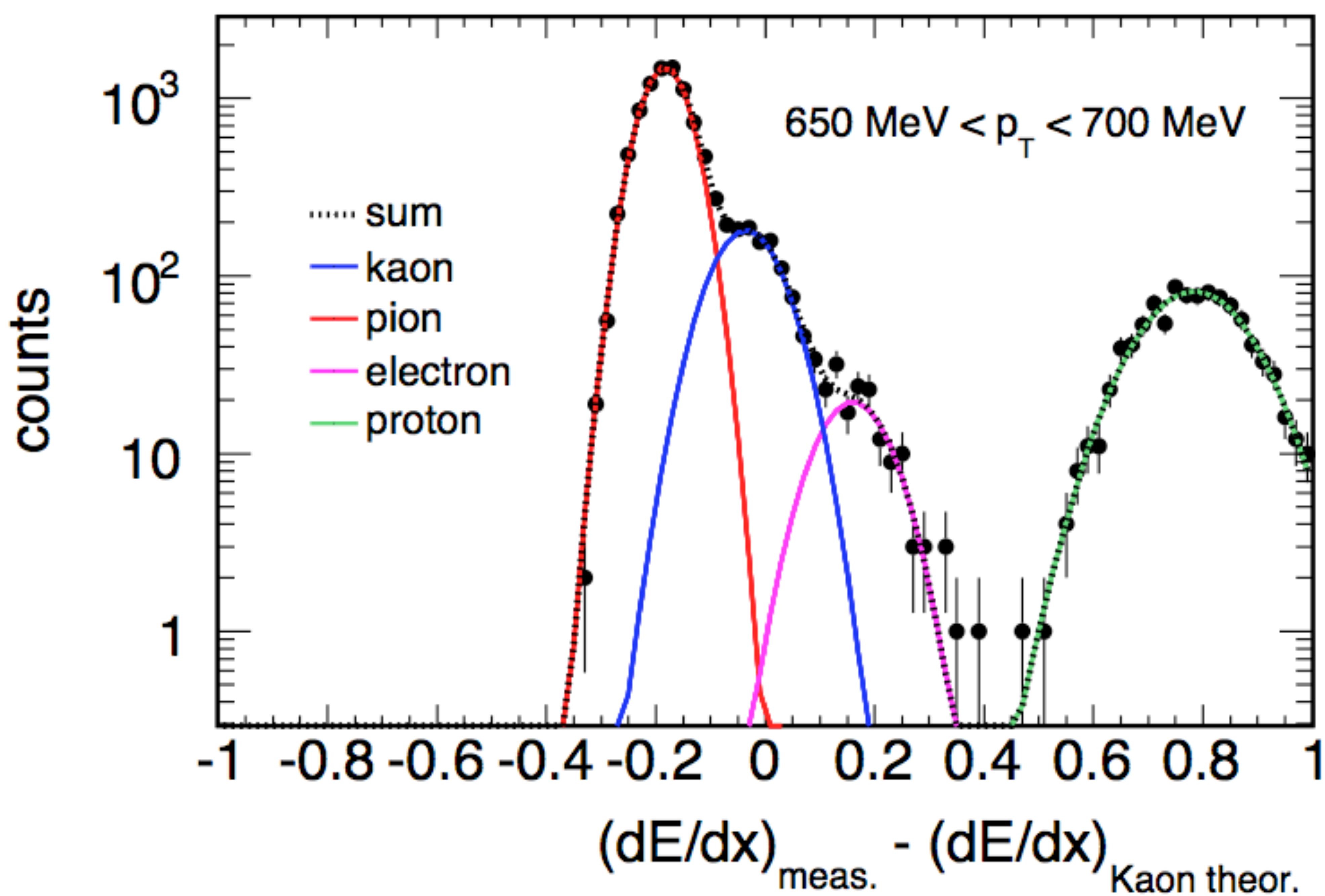


Empirical scaling formula for resolution in gaseous detector:

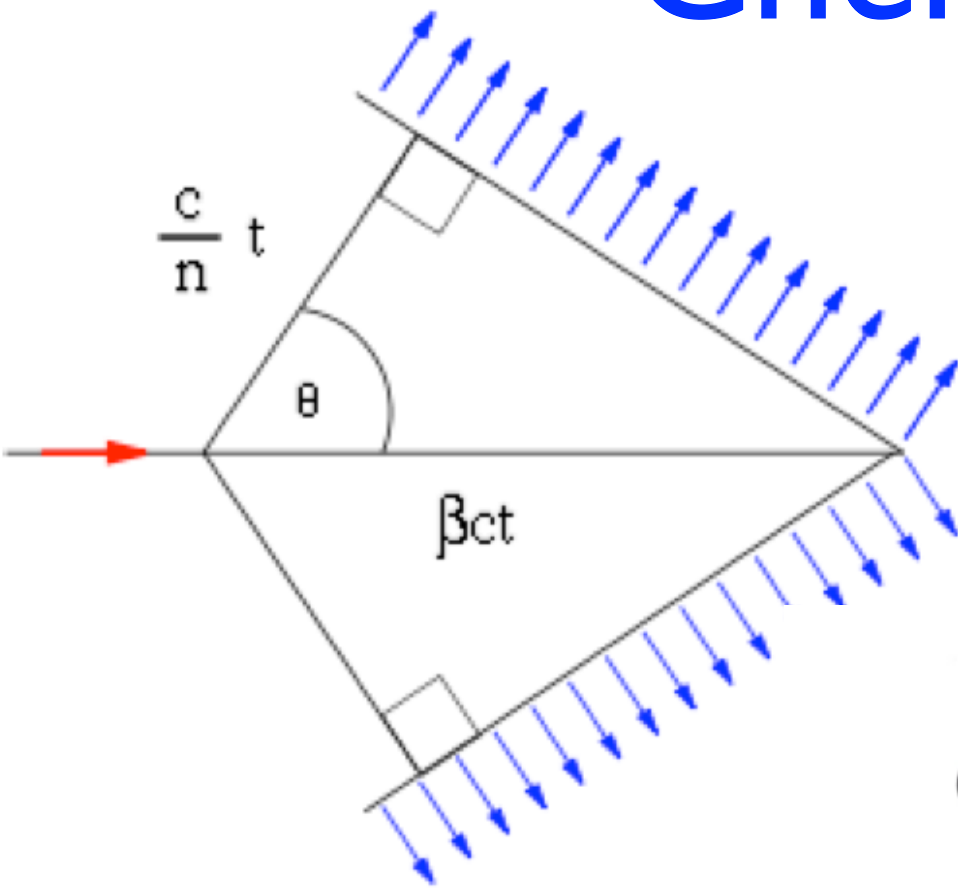
$$\sigma_E = 0.41\, N_R^{-0.43} (xP)^{-0.32} \,.$$

Nr = number of measurements
x = thickness of sampling layers
(x.Nr = total detector thickness)
P = pressure

ALICE TPC detector reaches ~5% dEdx resolution



Cherenkov radiation



$$\cos\theta_c = \frac{1}{\beta n} \qquad (n = n(E_{photon}))$$

Threshold velocity $\beta_t = \frac{1}{n}$

$$\frac{d^2 N_\gamma}{dE\,dx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c \qquad \text{or} \qquad \frac{d^2 N}{d\lambda\,dx} \propto \frac{1}{\lambda^2}$$

$$\approx 370 \sin^2\theta_c(E)\ \mathrm{eV^{-1}\,cm^{-1}} \text{ for } z=1$$

different type of Cherenkov detectors

- threshold Cherenkov detectors: yes/no decision depending if particle is above/below threshold beta=1/n
  - main issue is optimising photon detection and minimising noise
- Imaging Cherenkov detectors

$$\frac{\sigma_\beta}{\beta} = \tan\theta_C \; \sigma(\theta_C)$$

with $$\sigma(\theta_C) = \frac{\langle \sigma(\theta_i) \rangle}{\sqrt{N_{p.e}}} \oplus C$$

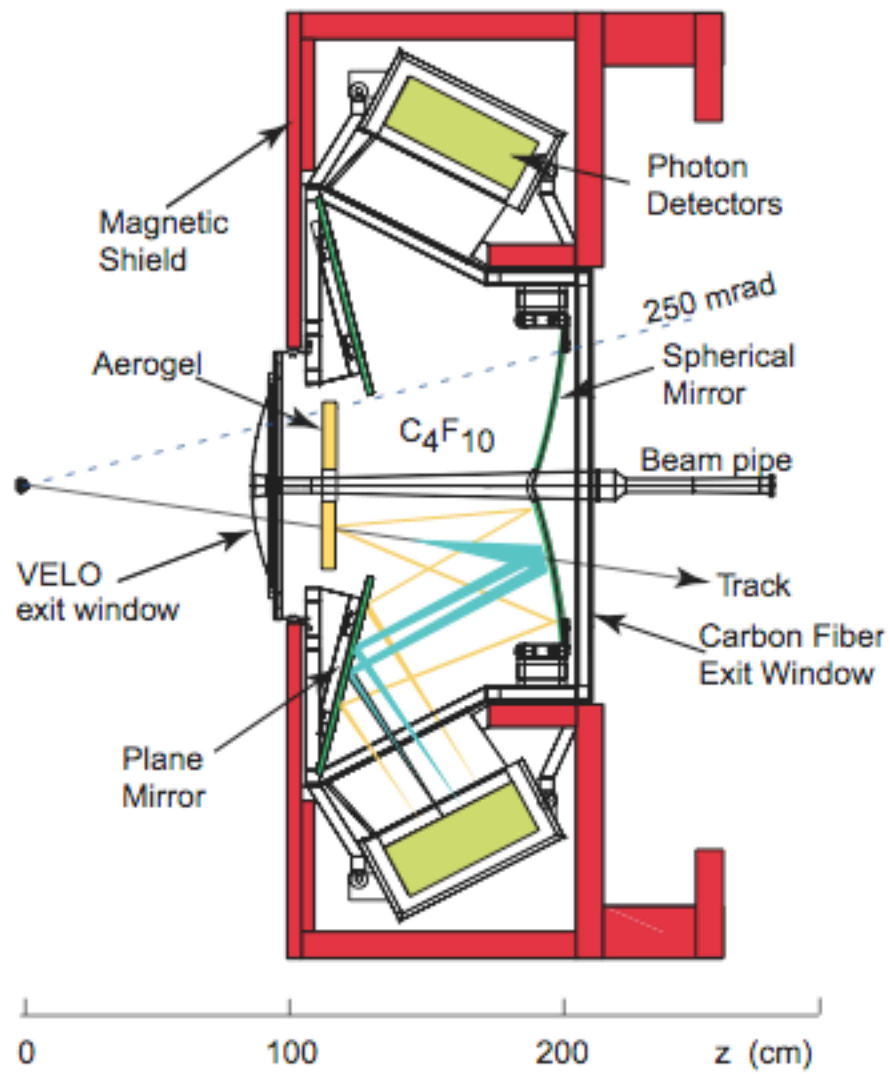
$\langle \sigma(\theta_i) \rangle$ = average single photo electron resolution (optics, detector geometry, ...)

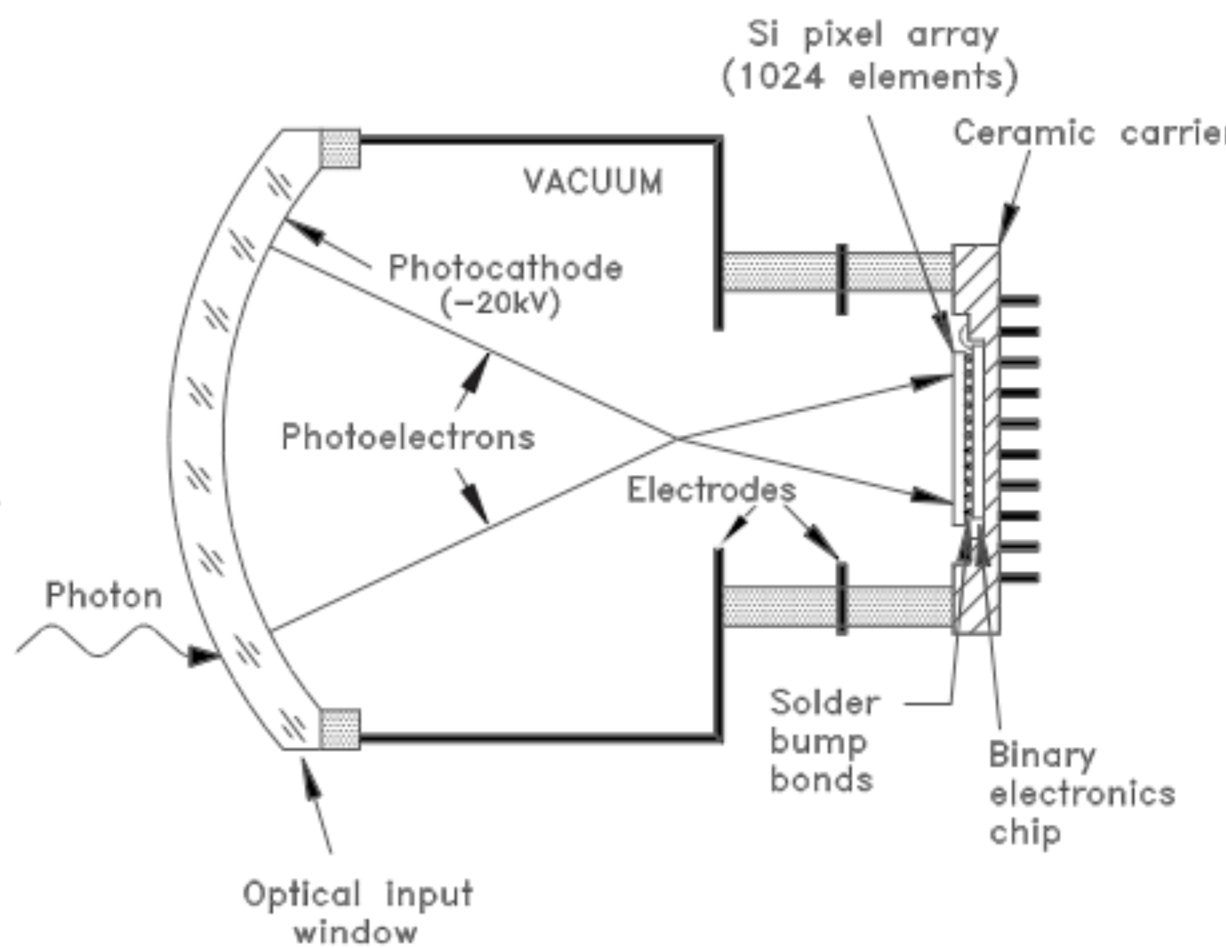
$N_{p.e}$ = number of photo electron detected

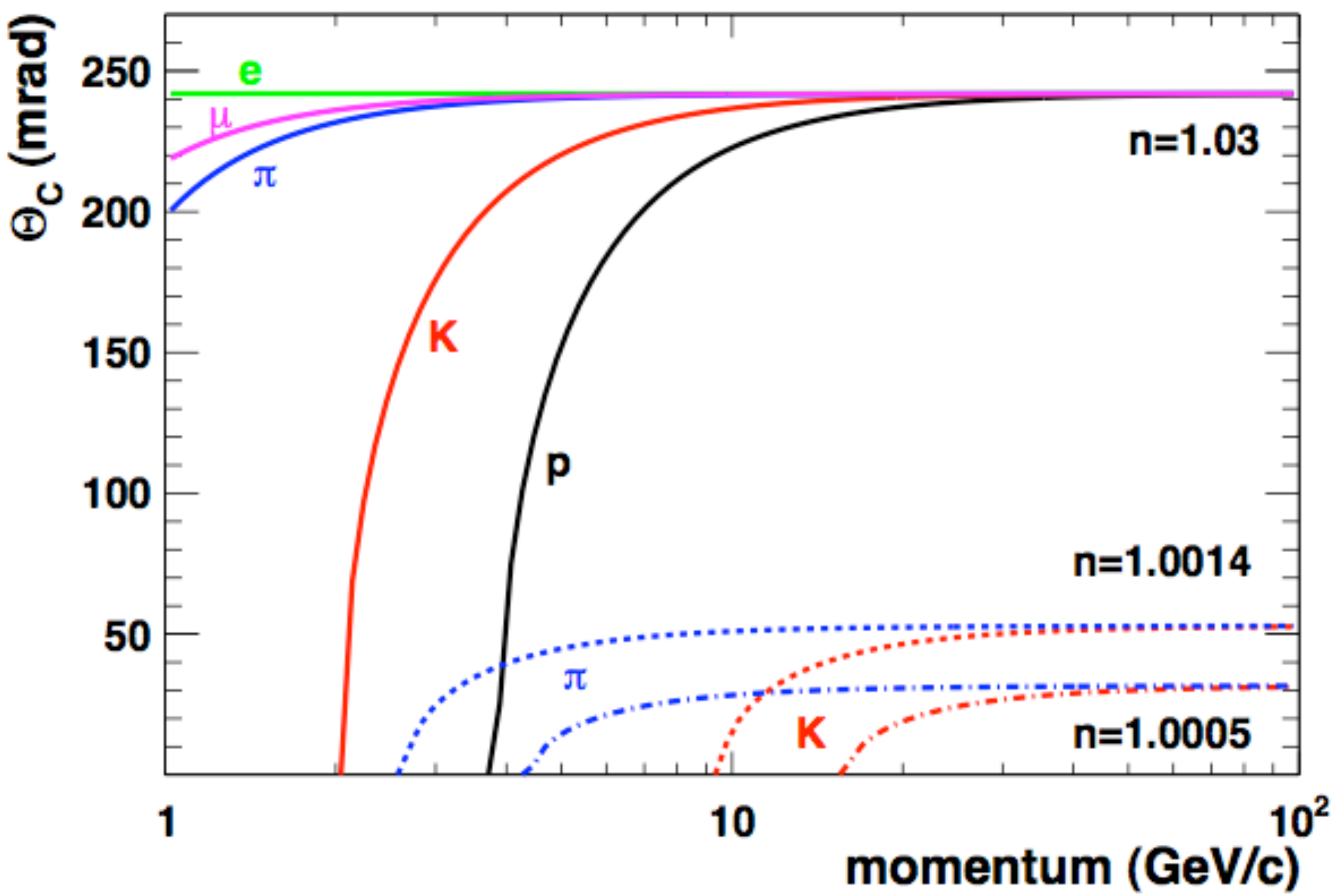
C : alignement, multiple scattering, ambiguities background, etc..

$$N_{sigma} \simeq \frac{|m_1^2 - m_2^2|}{2p^2\,\sigma(\theta_c)\sqrt{n^2-1}}$$

Cherenkov imaging detector
LHCb example







Θ_C (mrad)
250
200
150
100
50
e
μ
π
K
p
n=1.03
n=1.0014
π
K
n=1.0005
1
10
10^2
momentum (GeV/c)

in real life:

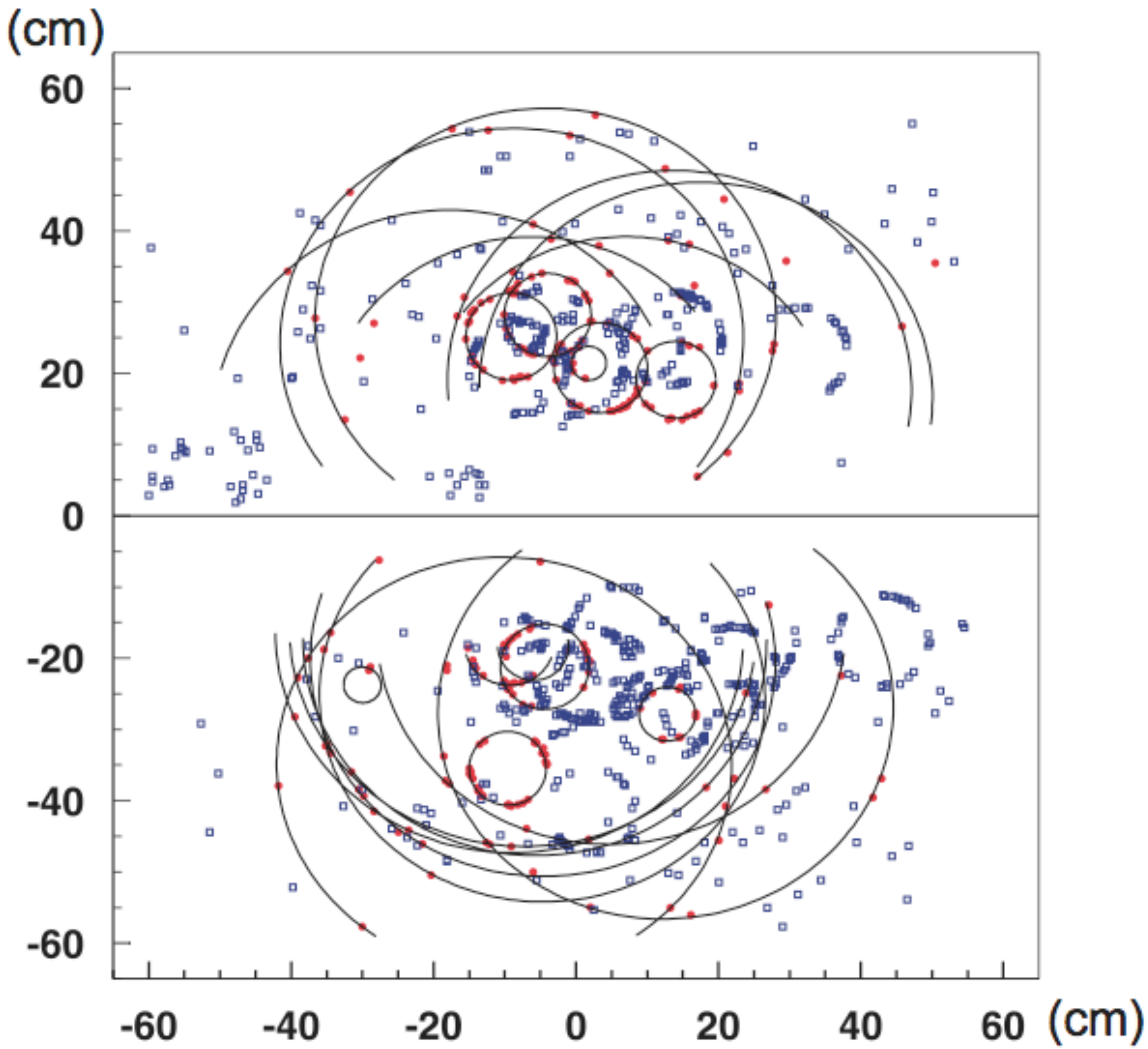
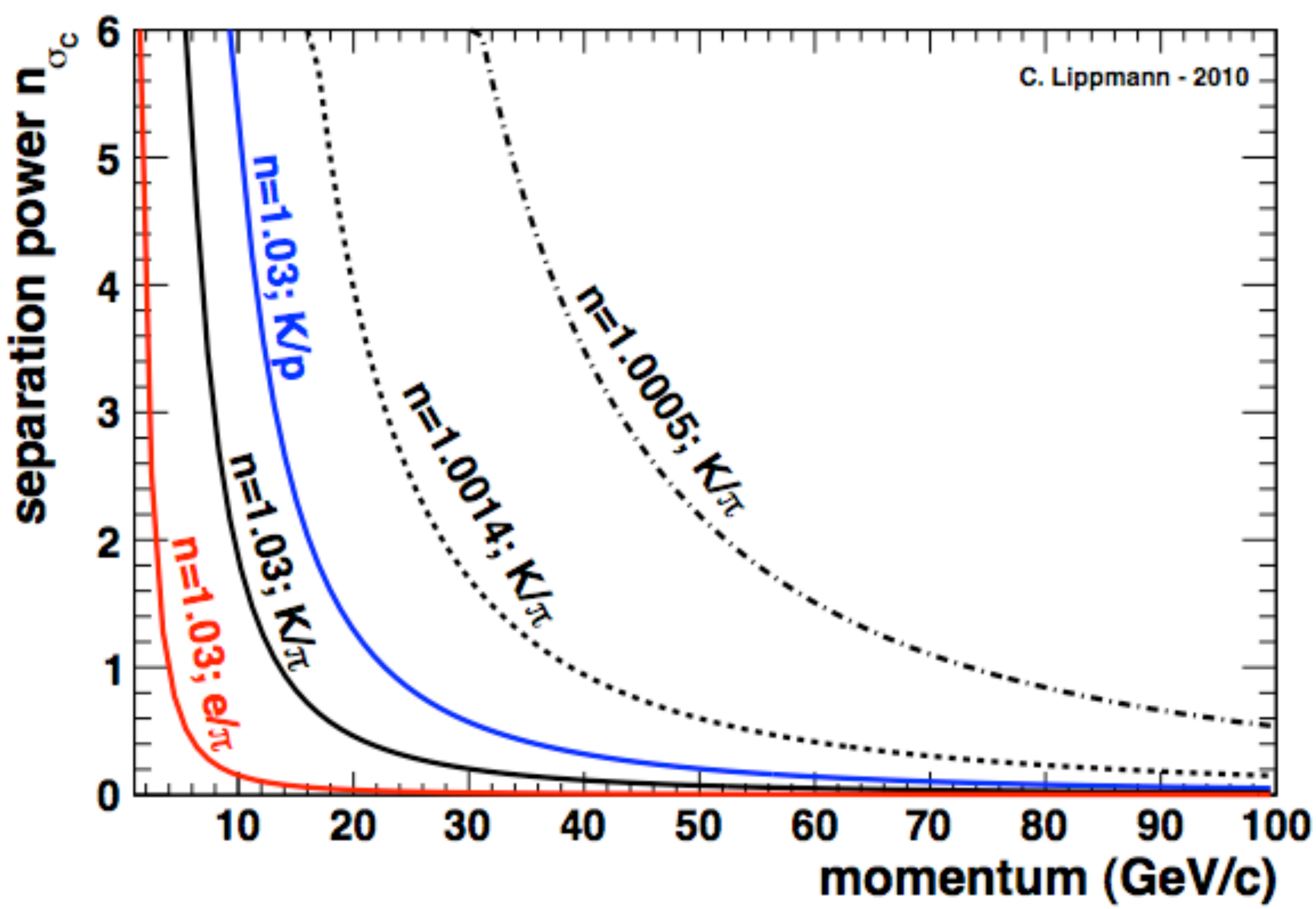
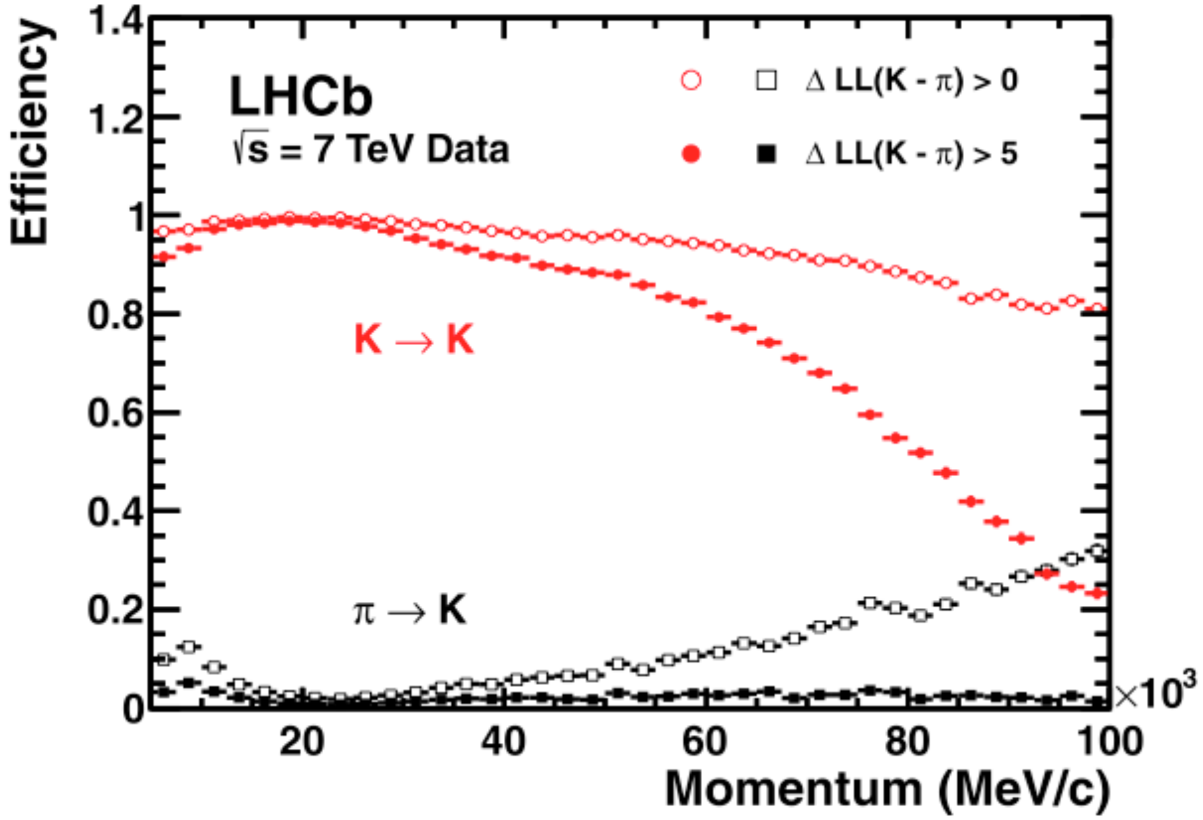


Table 3: Some parameters of the LHCb RICH detectors. The measured single photoelectron angular resolutions [87] are for the preliminary alignment available from the first data sample with p–p collisions at $\sqrt{s} = 7$ TeV.

		RICH1		RICH2
		Silica aerogel	C_4F_{10}	CF_4
Momentum range [GeV/c]		≤ 10	$10 \lesssim p \lesssim 60$	$16 \lesssim p \lesssim 100$
Angular acceptance [mrad]	vertical	± 25 to ± 250		± 15 to ± 100
	horizontal	± 25 to ± 300		± 15 to ± 120
Radiator length [cm]		5	95	180
Refractive index n		1.03 (1.037)	1.0014	1.0005
Maximum Cherenkov angle [mrad]		242 (268)	53	32
Expected photon yield at $\beta \approx 1$		6.7	30.3	21.9
σ_{Θ_i} [mrad]	expected	2.6	1.57	0.67
	measured	$\sim$7.5	2.18	0.91





pi/kaon separation using RICH in LHCb

Impact on physics analysis

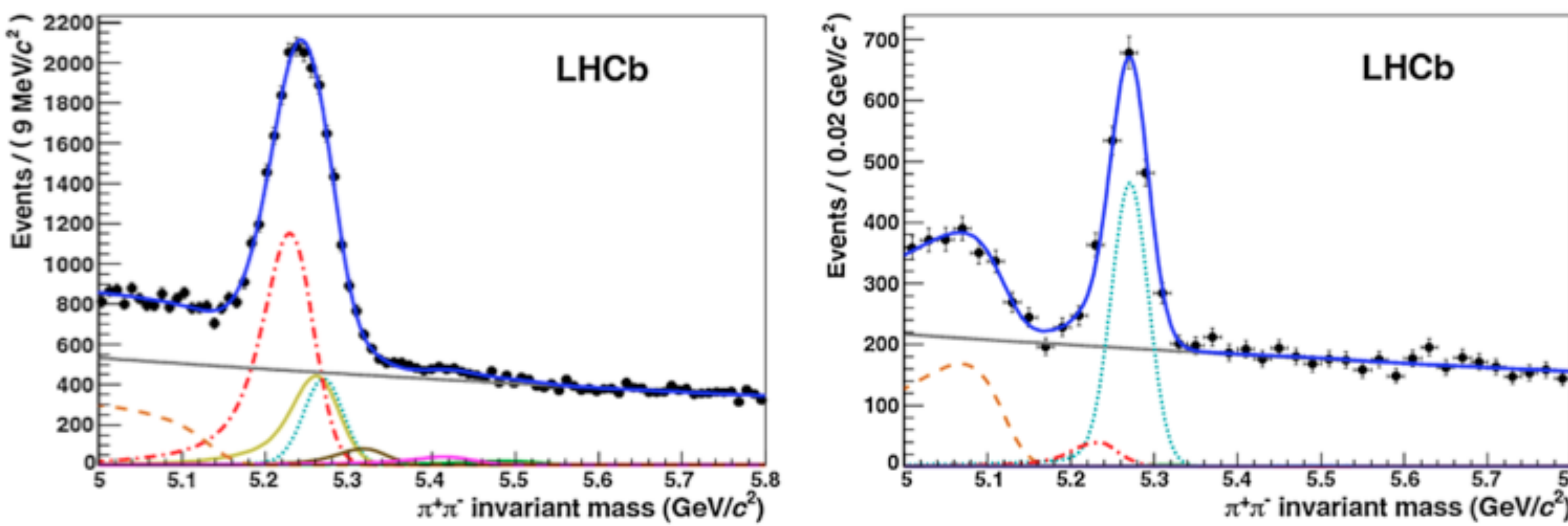
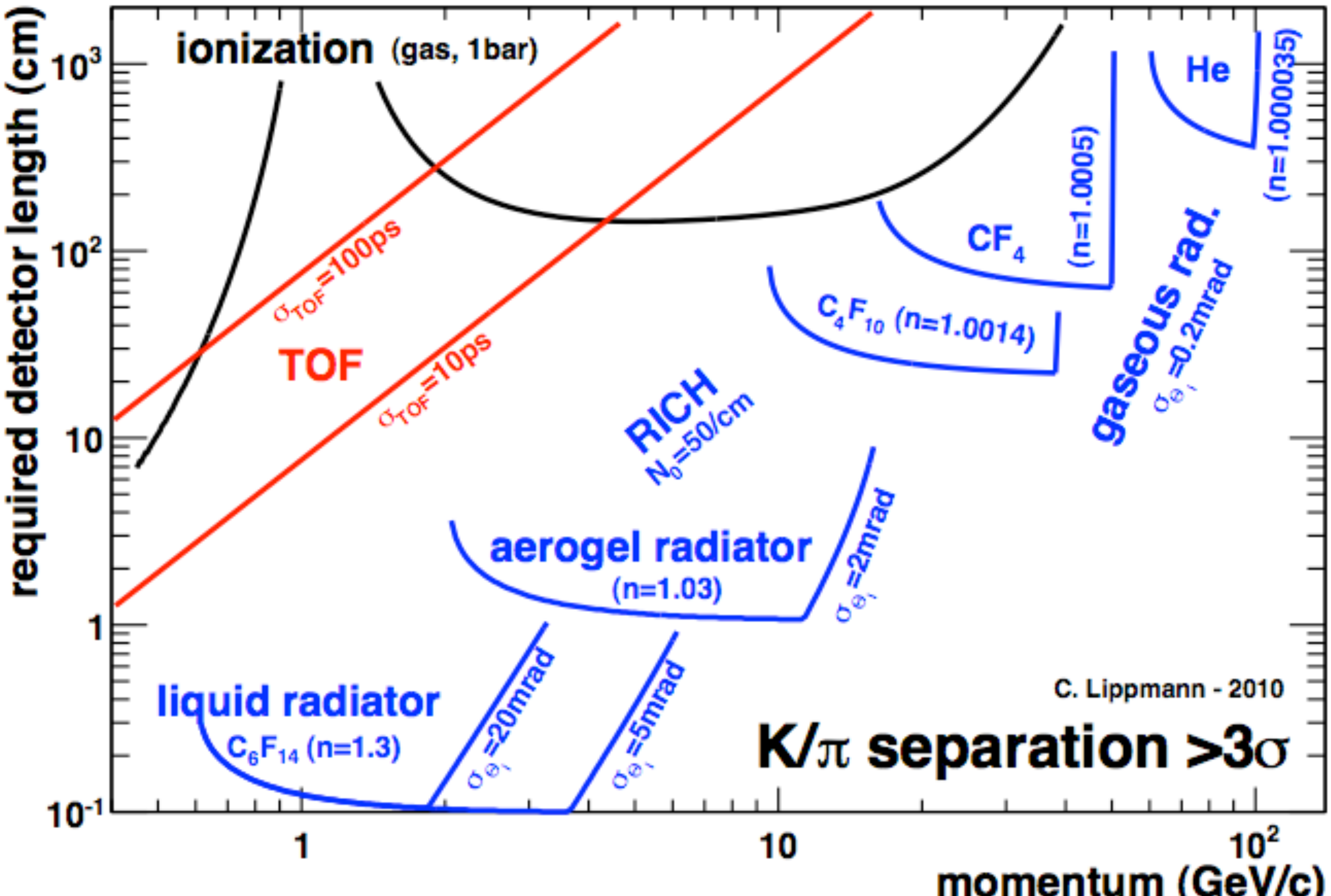


Fig. 2 Invariant mass distribution for $B \to h^+h^-$ decays [6] in the LHCb data before the use of the RICH information (*left*), and after applying RICH particle identification (*right*). The signal under study is the decay $B^0 \to \pi^+\pi^-$, represented by the turquoise *dotted line*. The contributions from different *b*-hadron decay modes ($B^0 \to K\pi$ *red dashed-dotted line*, $B^0 \to$ 3-body *orange dashed-dashed line*, $B_s \to KK$ *yellow line*, $B_s \to K\pi$ *brown line*, $\Lambda_b \to pK$ *purple line*, $\Lambda_b \to p\pi$ *green line*), are eliminated by positive identification of pions, kaons and protons and only the signal and two background contributions remain visible in the plot on the right. The *grey solid line* is the combinatorial background (Color figure online)

Comparison of different techniques



Transition radiation

When charge $z \cdot e$ crosses boundary vacuum/medium

$$I = \frac{1}{3} \alpha z^2 \gamma \hbar \omega_p$$

$$\hbar \omega_p = \sqrt{4\pi N_e r_e^3} \frac{m_e c^2}{\alpha} = \sqrt{\rho/(g/cm^3) \langle \frac{Z}{A} \rangle} \times 28.81 eV$$

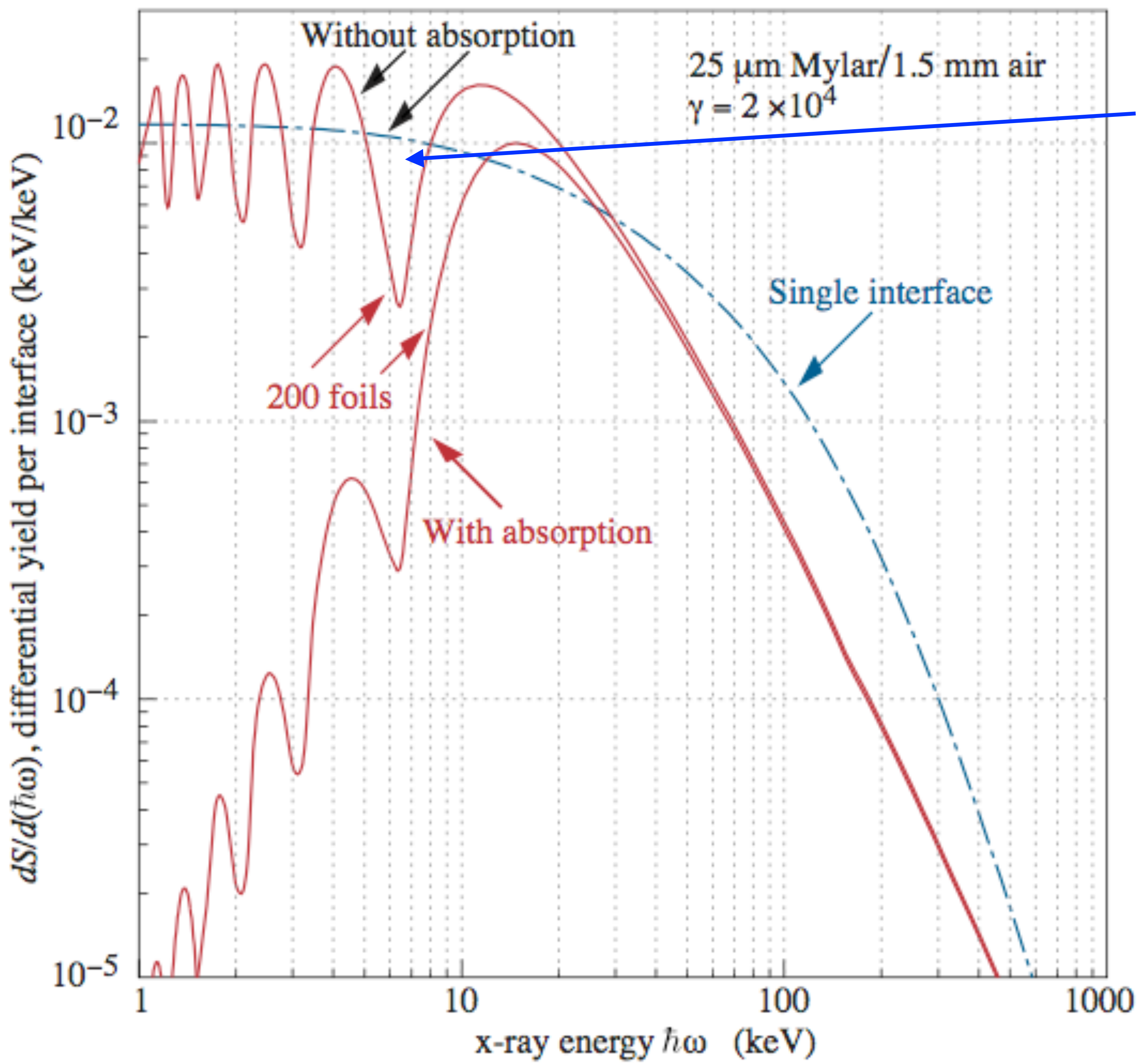
Typical values $\hbar \omega_p \sim 20$ eV (0.7 for air)

Half energy between 0.1 and $1 \times \gamma \hbar \omega_p$

Typically $\sim 0.005 \gamma$ with $\hbar \omega > 0.1 \gamma \hbar \omega_p$

Formation length $\sim$ tens of μm

Needs many interfaces to increase photon yield



What is this pattern ?
=>Interference

X-rays detected for instance by photo-electric effect in high Z material like Xenon gas
=> Detector consists of radiator + photon detector

Photon interaction in matter

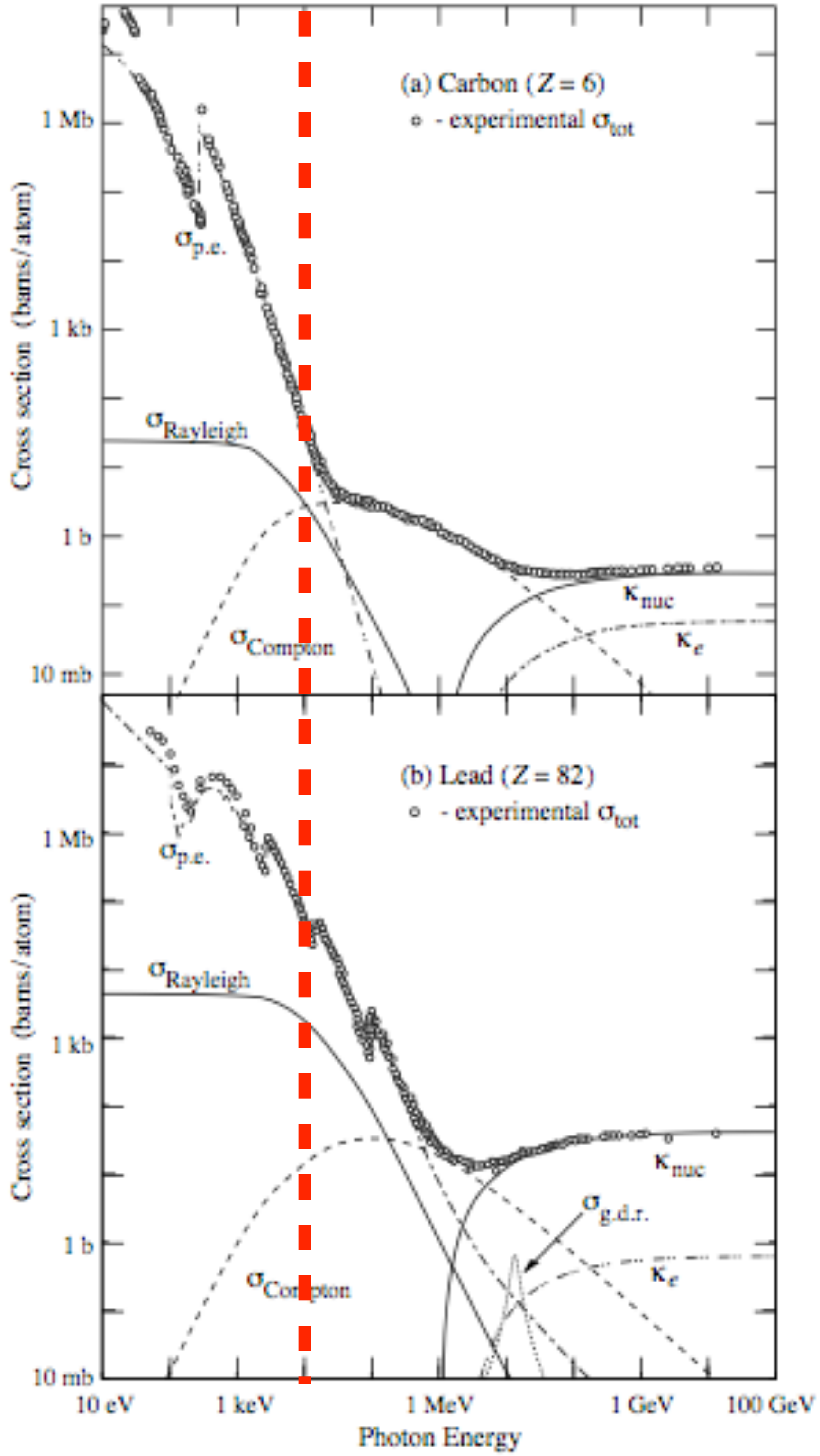


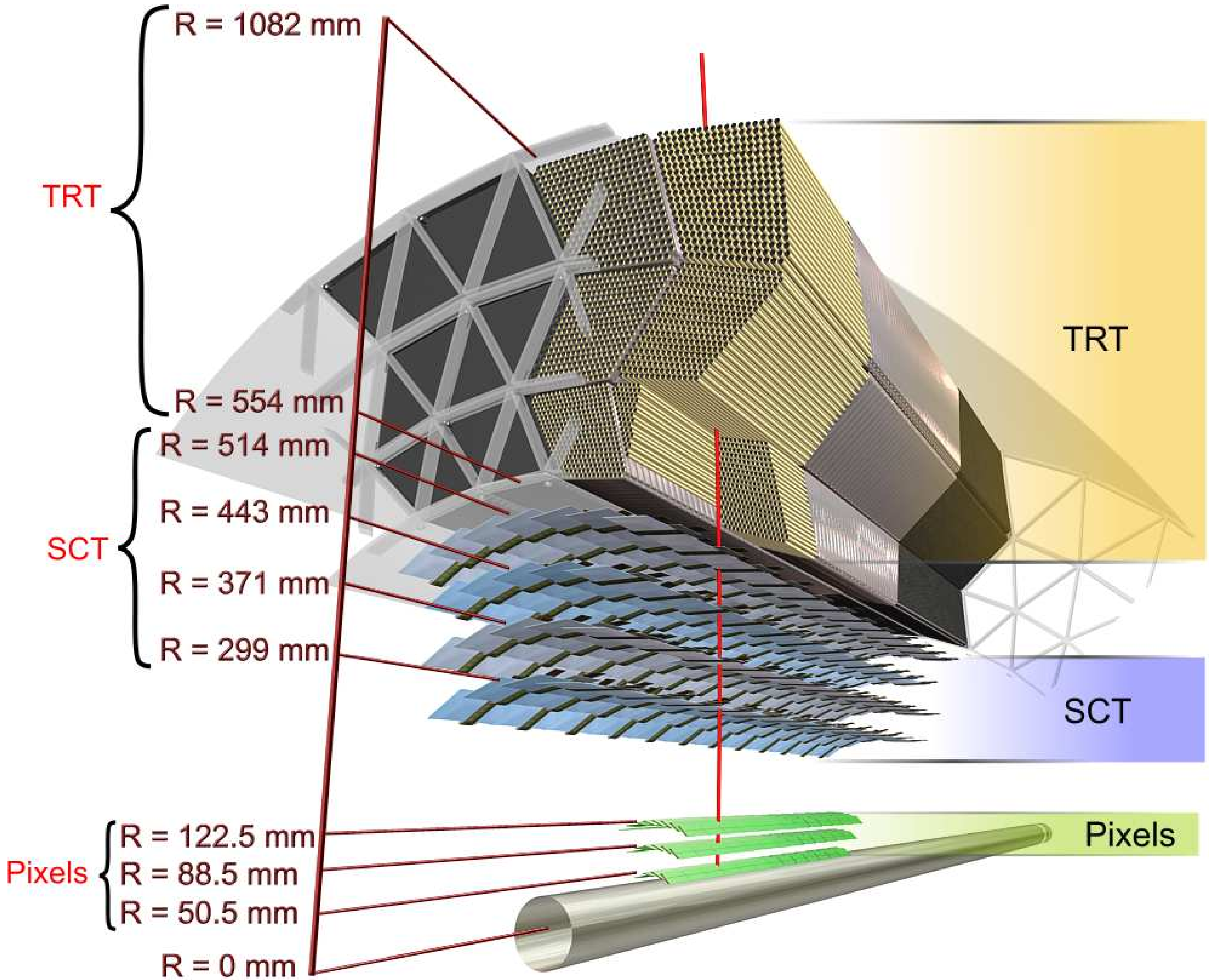
Figure 31.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [51]:

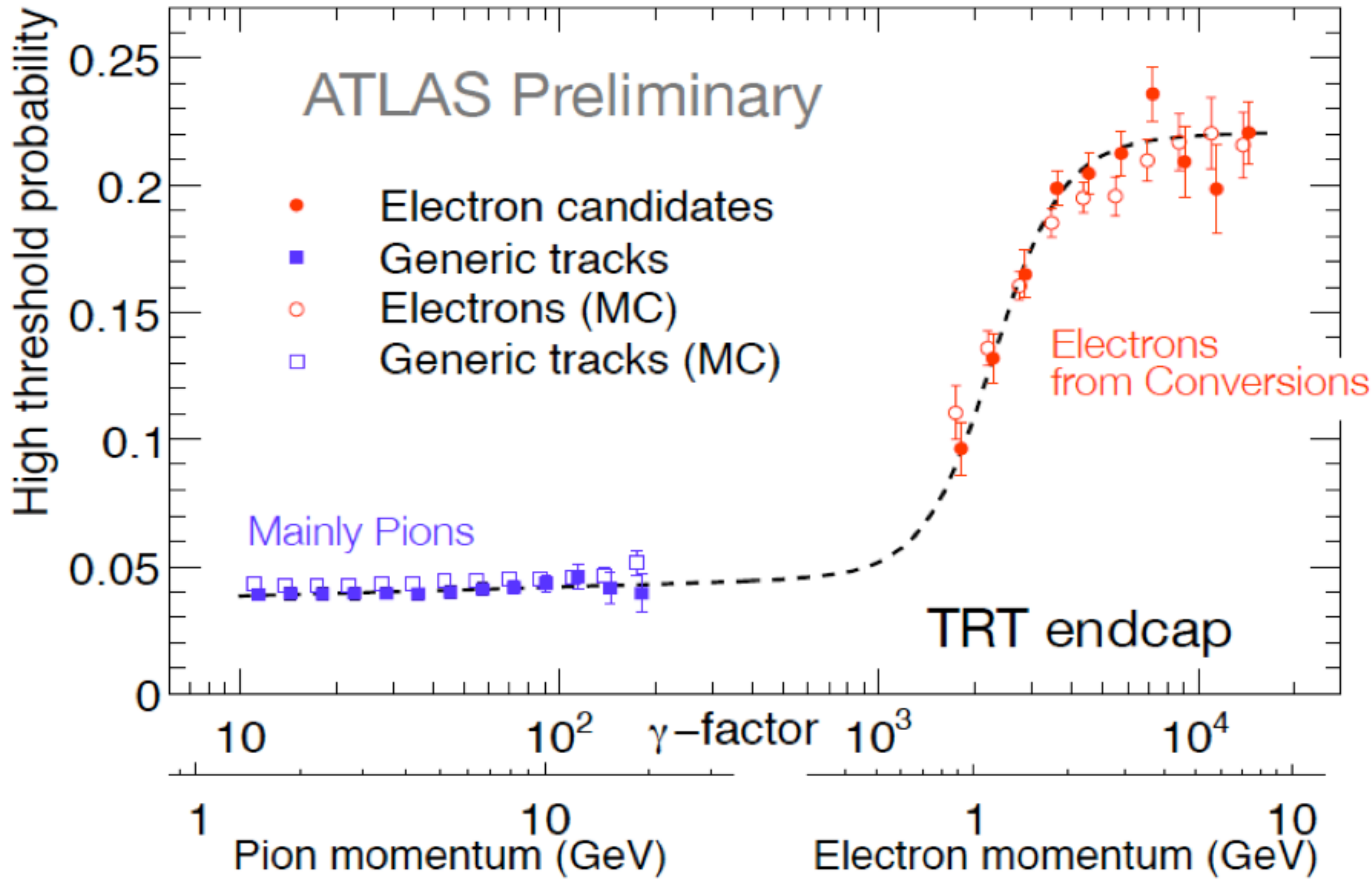
$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [52]. In these interactions, the target nucleus is broken up.

Radiator = polypropylene foils

Detector = Straws with wire in the middle containing Xe (to absorb X-rays)

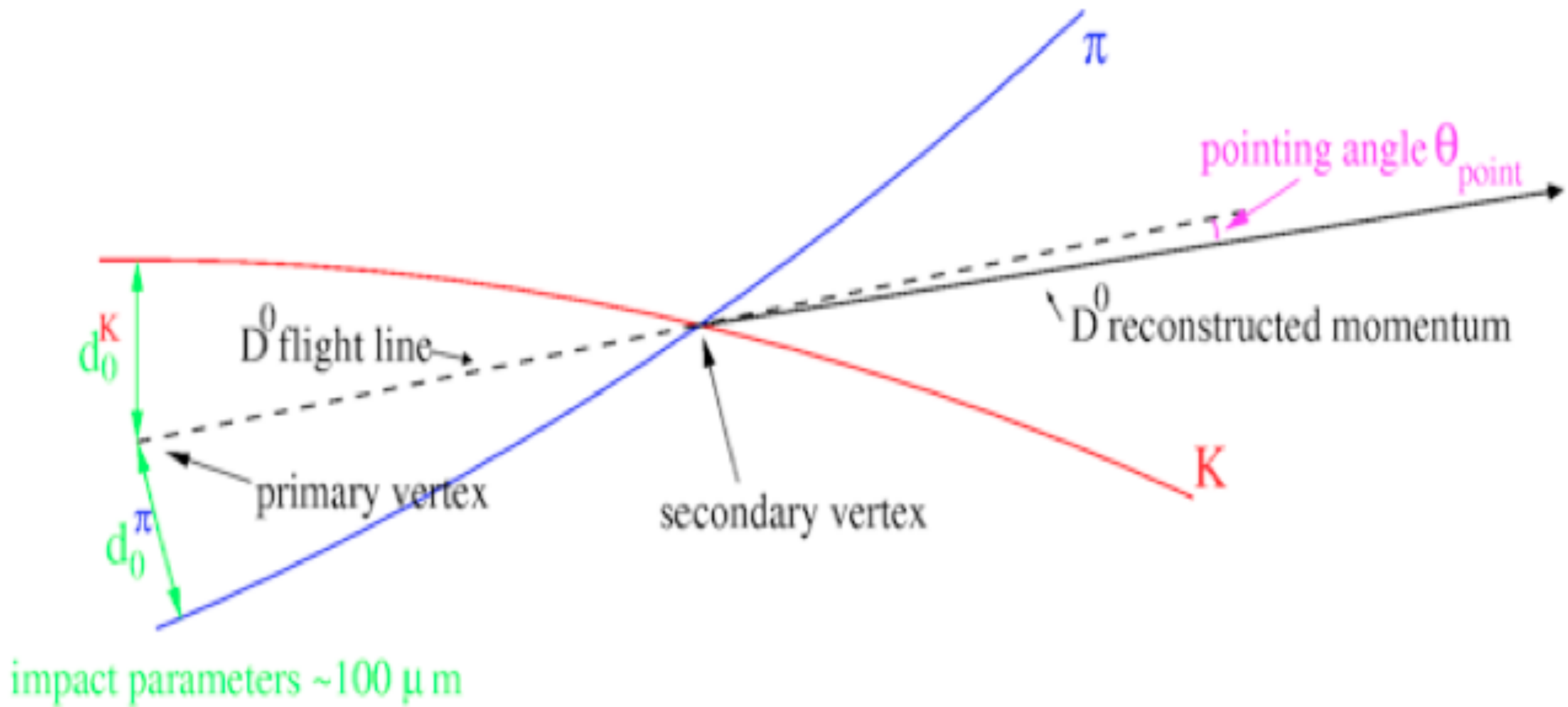
Edeposited ~2 keV from ionization, ~8-10 KeV from TR photons




ATLAS Preliminary
Electron candidates
Generic tracks
Electrons (MC)
Generic tracks (MC)
Electrons
from Conversions
Mainly Pions
TRT endcap
High threshold probability
0.25
0.2
0.15
0.1
0.05
0
10
10^2
γ−factor
10^3
10^4
1
10
Pion momentum (GeV)
1
10
Electron momentum (GeV)

Reconstruction of particle decay

- Useful for short lived particles
  - very short lived => use invariant mass of daughter particles
    - Examples are Ks-> pi+pi-, J/psi-> mu+ mu-, W,Z decays, etc..
  - not so short lived => can measure distance between production and decay positions:
    - tau lepton
    - B-hadron



lifetimes: D0: 4.10^{-13}s, B0d 1.5 10^{-12}s, tau: 2.9 10^{-13}s

Decay length beta.gamma.c.tau => beta.gamma. 450 microns for B0d

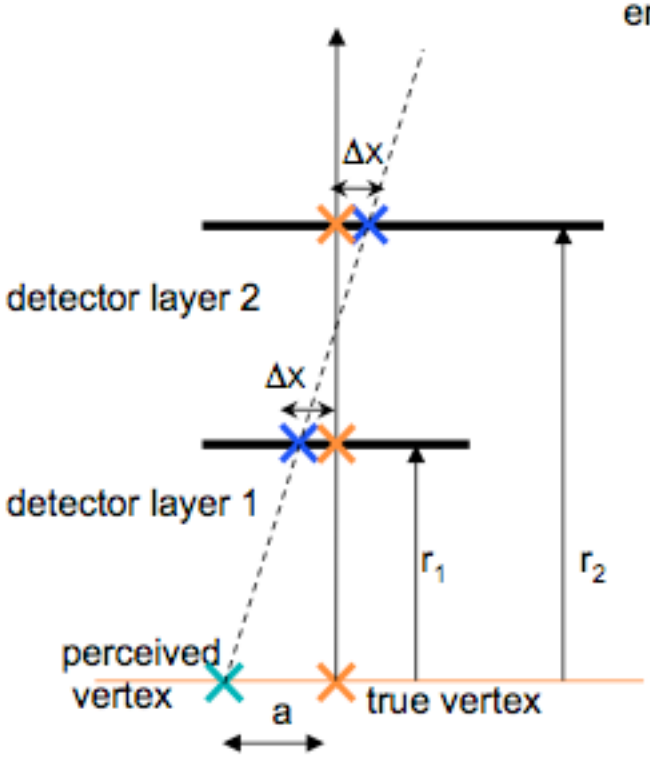
Impact parameter ~ (c.tau)

Vertex projection from two points: a simplified approach (telescope equation)

pointing resolution = (a $\oplus$ b) µm

from detector position error

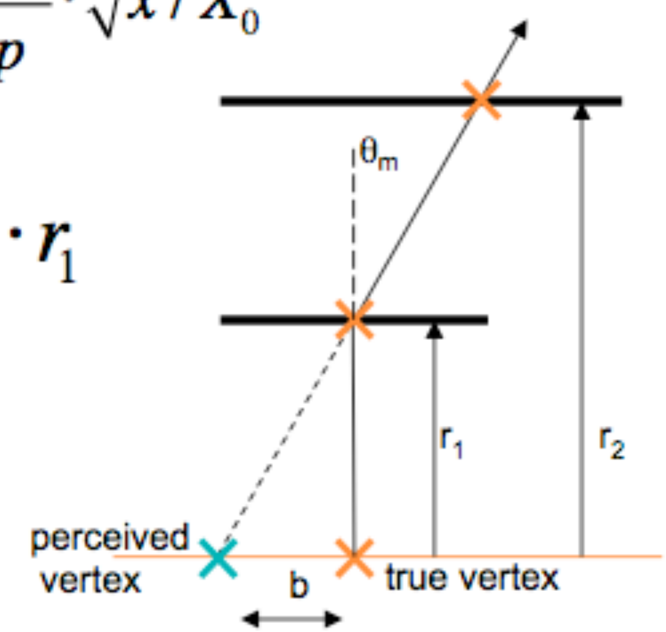
from coulomb scattering



$$a = \Delta x \bullet \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

$$\theta_m = \frac{13.6 Mev}{\beta \cdot c \cdot p} \cdot \sqrt{x / X_0}$$

$$b = \theta_m \cdot r_1$$



Detector Granularity, minimize Δx:

e.g. 50um pixel and r_2 very large compared to r_1

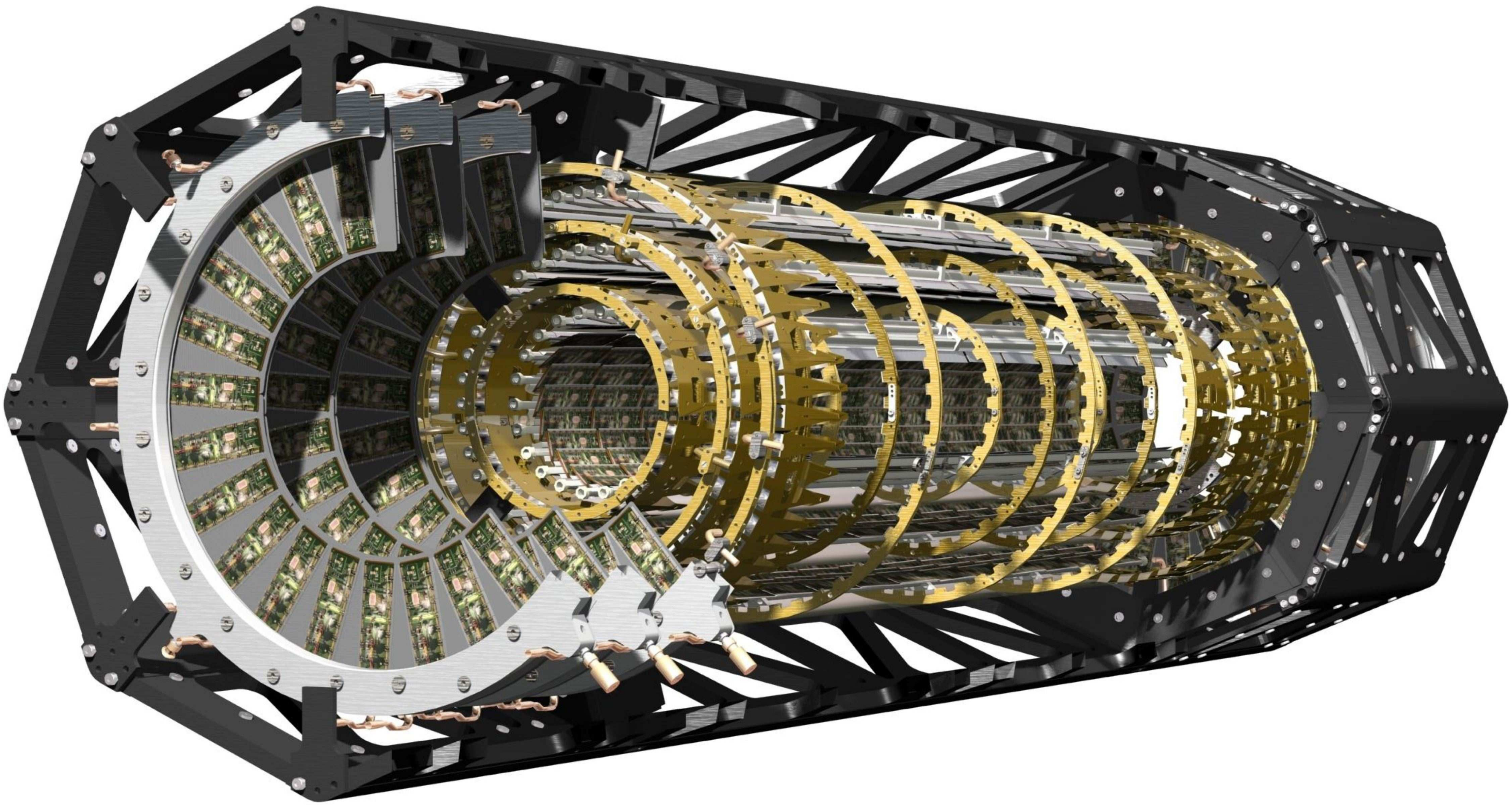
→ a=Δx=50/√12 = 15um

First layer as close as possible to the vertex and
First layer with minimal amount of material.

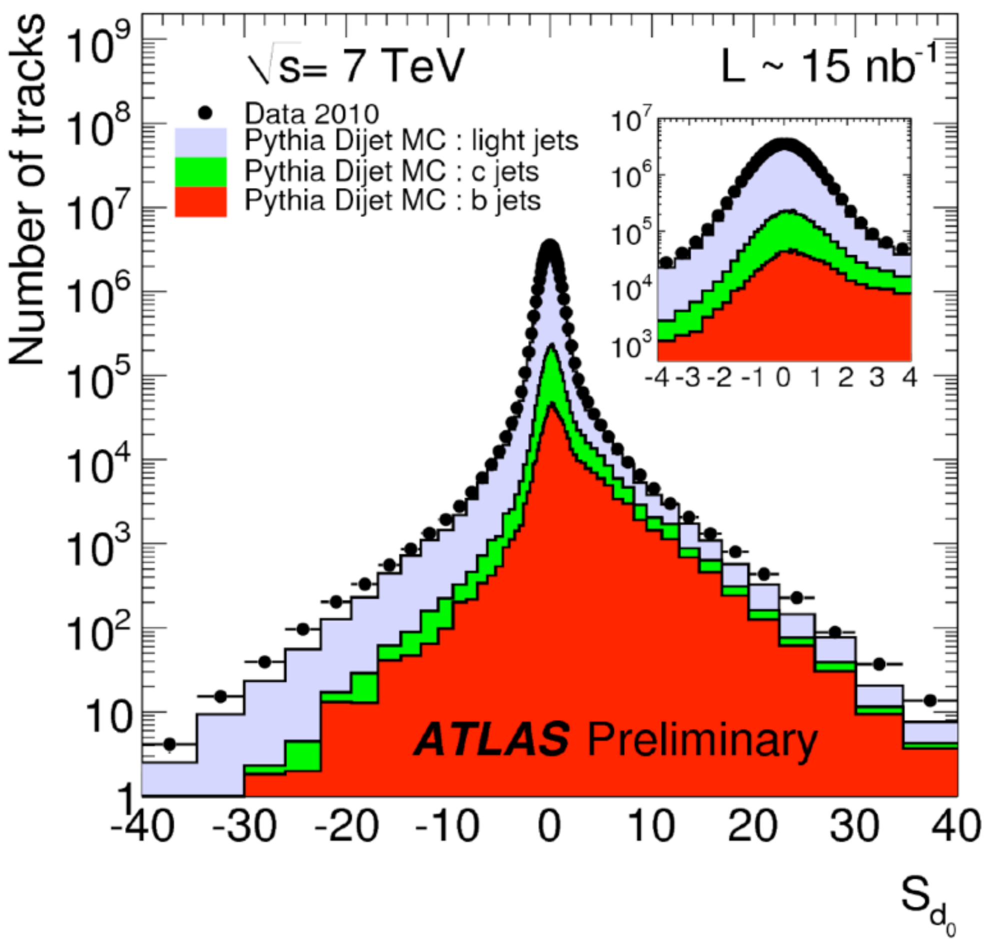
e.g. x/X_0 = 0.0114, r_1= 39mm

→ b= 57um for p=1GeV/c

Example of ATLAS pixel silicon detector

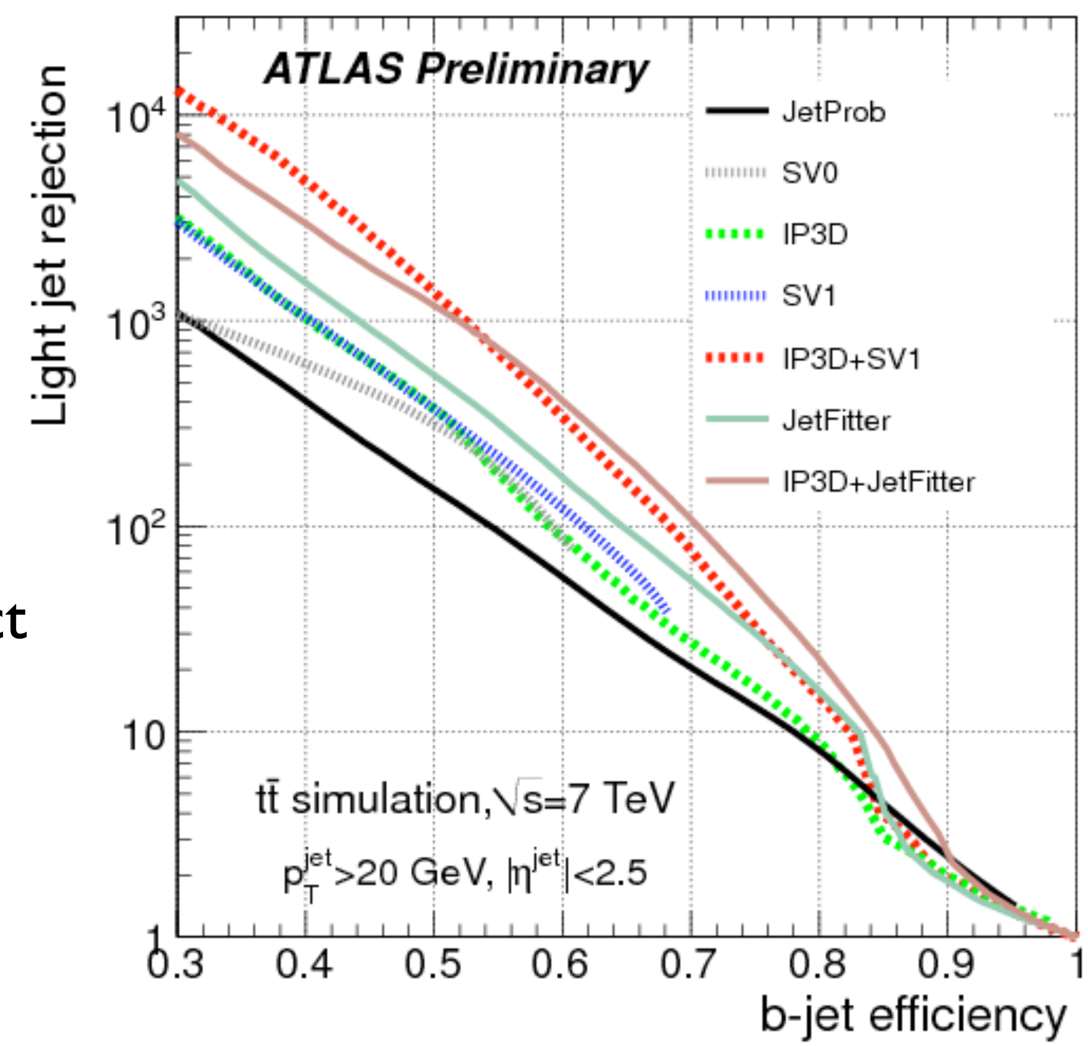


b-tagging performances



Track impact parameter/error

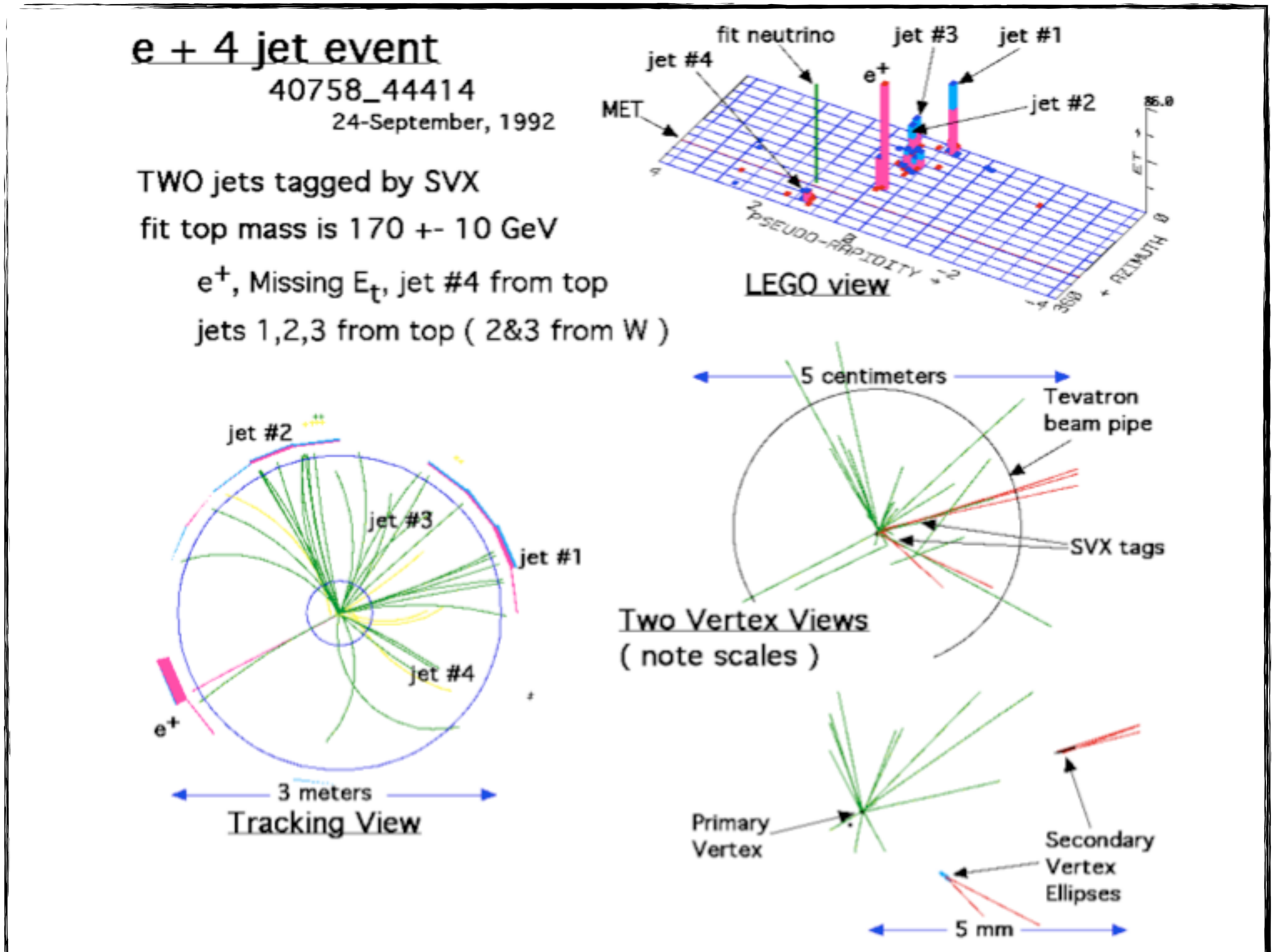
Algorithms combining impact parameter information + secondary vertex reconstruction



Example of b-tagging usage for top quark discovery

Signal t tbar -> W W b bbar, one W->lepton, one W->jets

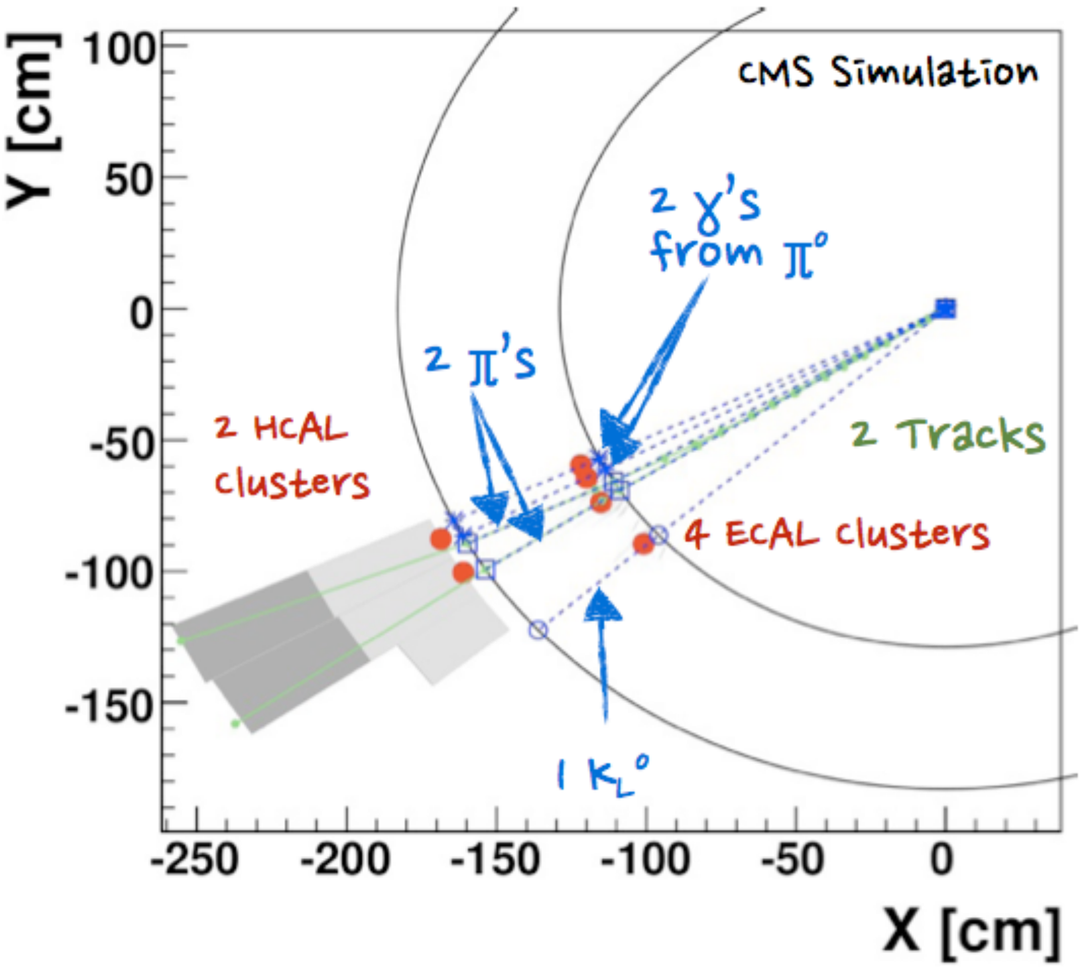
Background: W(->lepton)+ jet
Only a small amount of these jets have b quarks.



Particle Flow techniques in collider experiments

- Different particles species are measured more accurately with different techniques
  - What is the most precise technique for E=100 GeV electron energy measurement in a LHC experiment ? => EM Calorimeter
  - What is the most precise technique to measure a few GeV charged pion ? => tracking detector
  - What is the most precise technique to measure a 5 GeV K0L ? => Hadronic calorimeter (even if not very precise)
  - How can one separate particles from different interactions in the same bunch crossing at the LHC ? => for charged particles, reconstructed vertex from which it is coming. Different pp interactions are typically separated by few cm in z. Resolution is much better. But this becomes challenging for high number of collisions

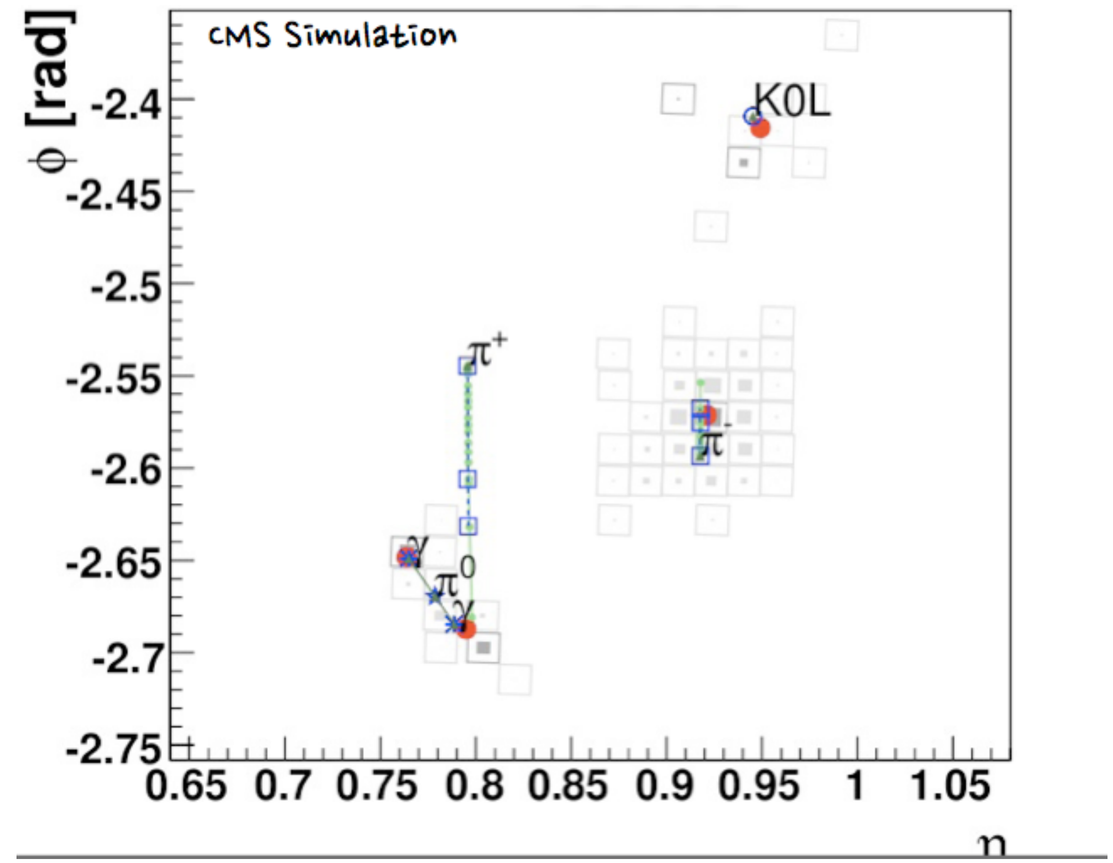
Particle flow principle

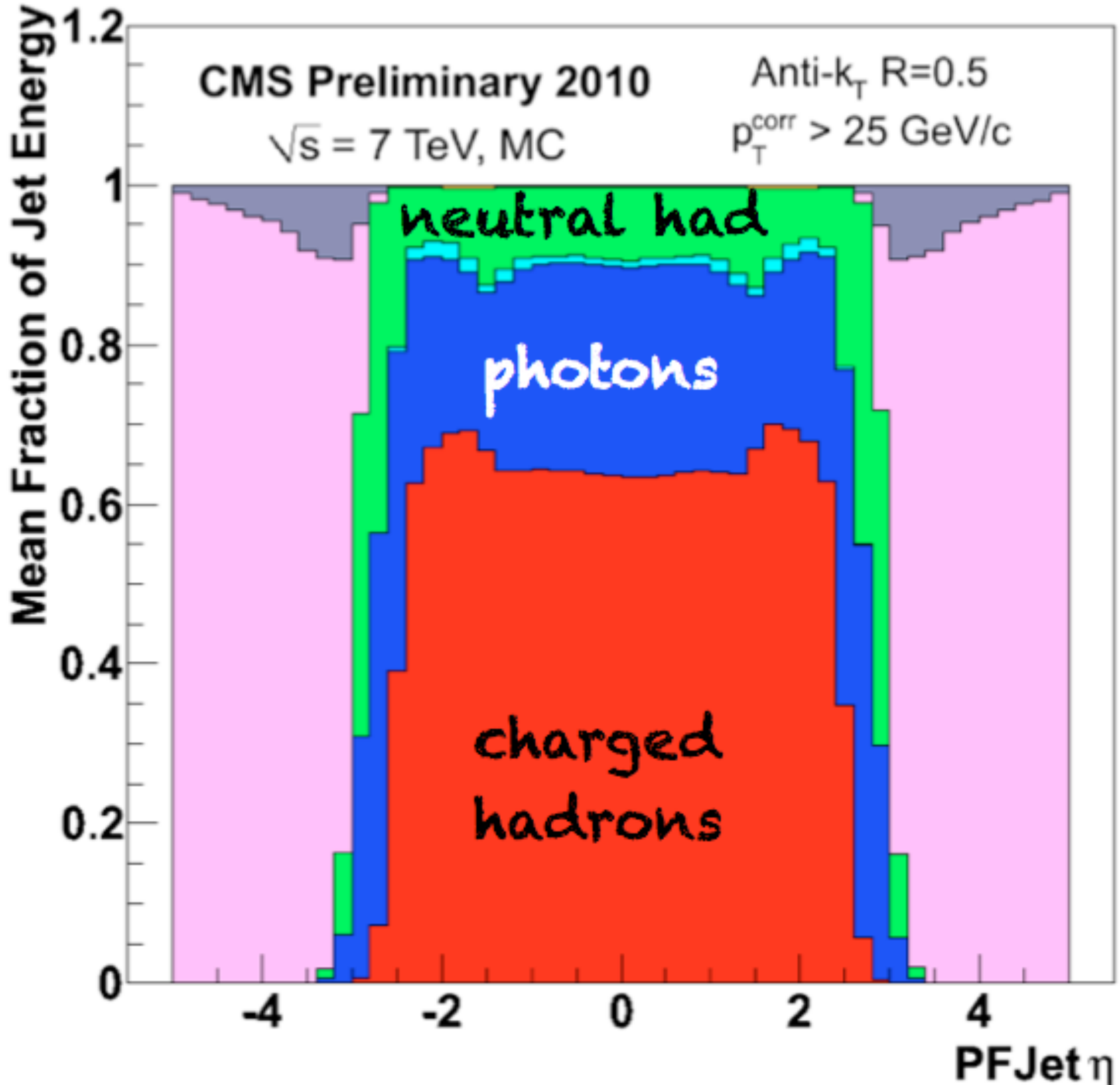


Jet PT = 65 GeV/c

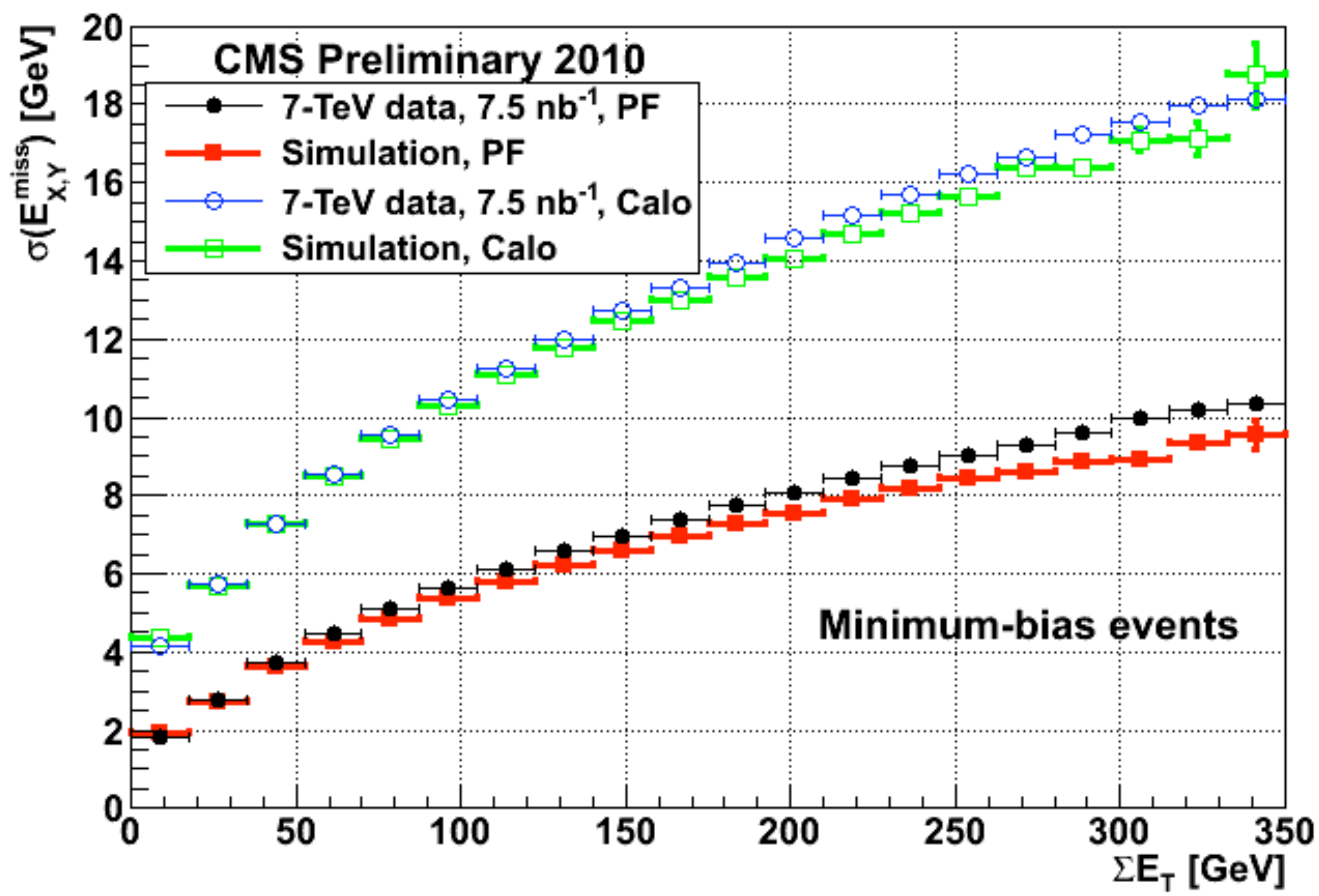
Four true particles:

π^+, π^-, π^0, K_L^0





CMS Preliminary 2010
√s = 7 TeV, MC
Anti-k$_T$ R=0.5
p_T^{corr} > 25 GeV/c
neutral had
photons
charged
hadrons
Mean Fraction of Jet Energy
PFJet η
1.2
1
0.8
0.6
0.4
0.2
0
-4
-2
0
2
4



CMS Preliminary 2010
7-TeV data, 7.5 nb-1, PF
Simulation, PF
7-TeV data, 7.5 nb-1, Calo
Simulation, Calo
Minimum-bias events
σ(E miss X,Y) [GeV]
ΣE T [GeV]
0
2
4
6
8
10
12
14
16
18
20
0
50
100
150
200
250
300
350

some references/links

- PDG reviews on particle interactions and particle detectors http://pdg.lbl.gov/
- C.Lippmann, hep-ex arXiv:1101.3276
- ATLAS, CMS, LHCB, ALICE performance papers
- R.Cavanaugh's lectures at HCP school 2012
- D.Bortoletto's lectures for CERN summer student
- W.Riegler's CERN academic training lectures, February 2014