Particle identification at *Belle II* with the Electromagnetic Calorimeter (ECL)

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Outline

1. Overview of particle identification at *Belle II*.
2. Review of particle interactions with matter $\rightarrow$ cf. Christian Wessel's lecture.
3. The Electromagnetic Calorimeter (ECL).
   3.1 Pulse Shape Discrimination.
4. Overview of ECL clustering algorithm.
5. Neutral particle identification with the ECL.
   5.1 Photons
   ~~5.2 K^0_L~~
6. Charged particle identification with the ECL.
   6.1 Standard proxy: E/p
   6.2 Novel improvements at low momentum $\rightarrow$ machine learning

1. Particle identification at *Belle II*

1. Particle identification at *Belle II*

- Particle Identification (PID): identify "long lived" particles passing through the detector by means of their interaction with matter.

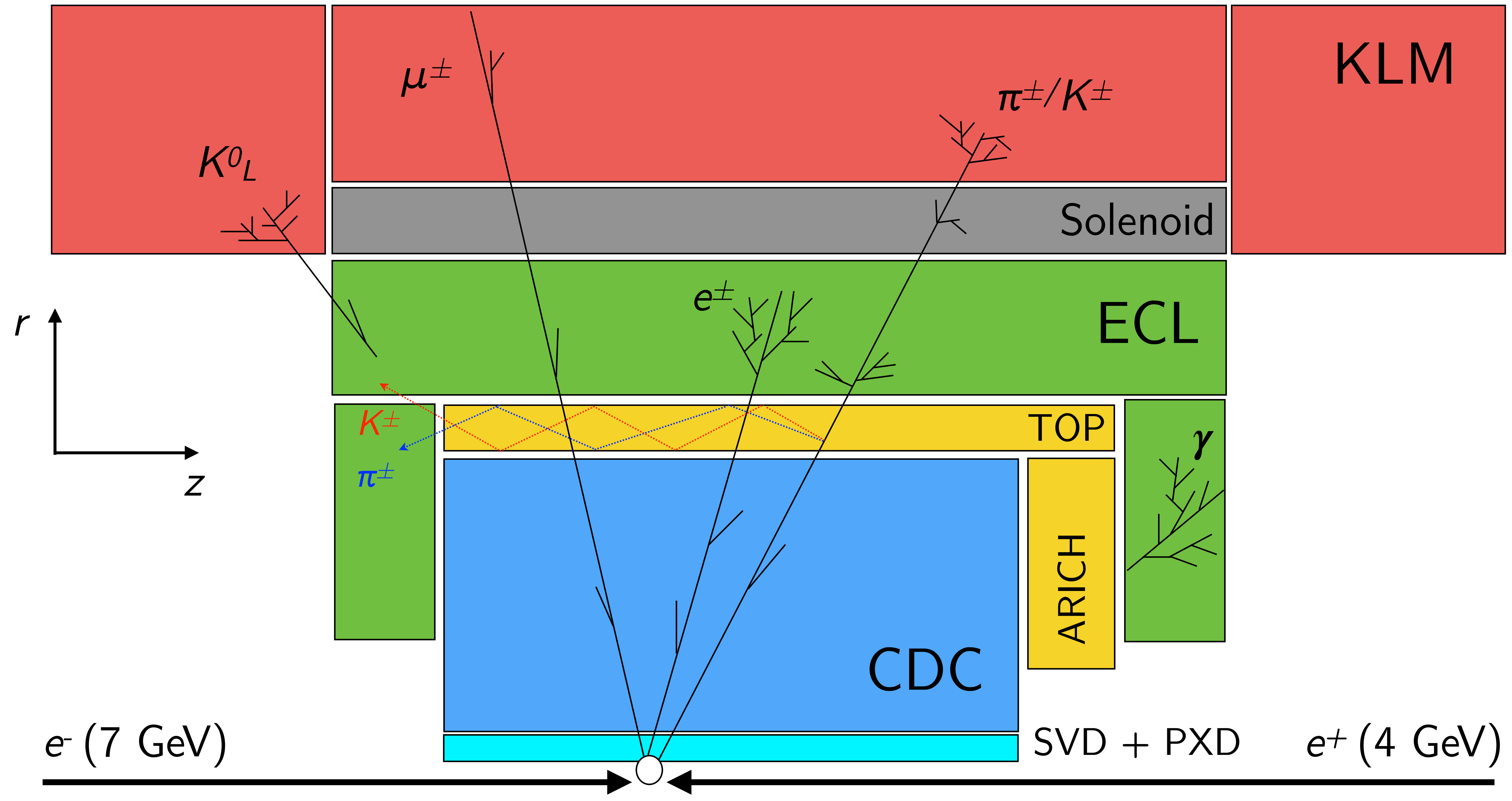
(In *Belle II*) "standard charged": $\{e^\pm, \mu^\pm, \pi^\pm, K^\pm, p^\pm, d^\pm\}$, "standard neutral": $\{\gamma, K^0{}_L\}$

- Often one of the most crucial factors determining sensitivity/precision of a physics measurement.

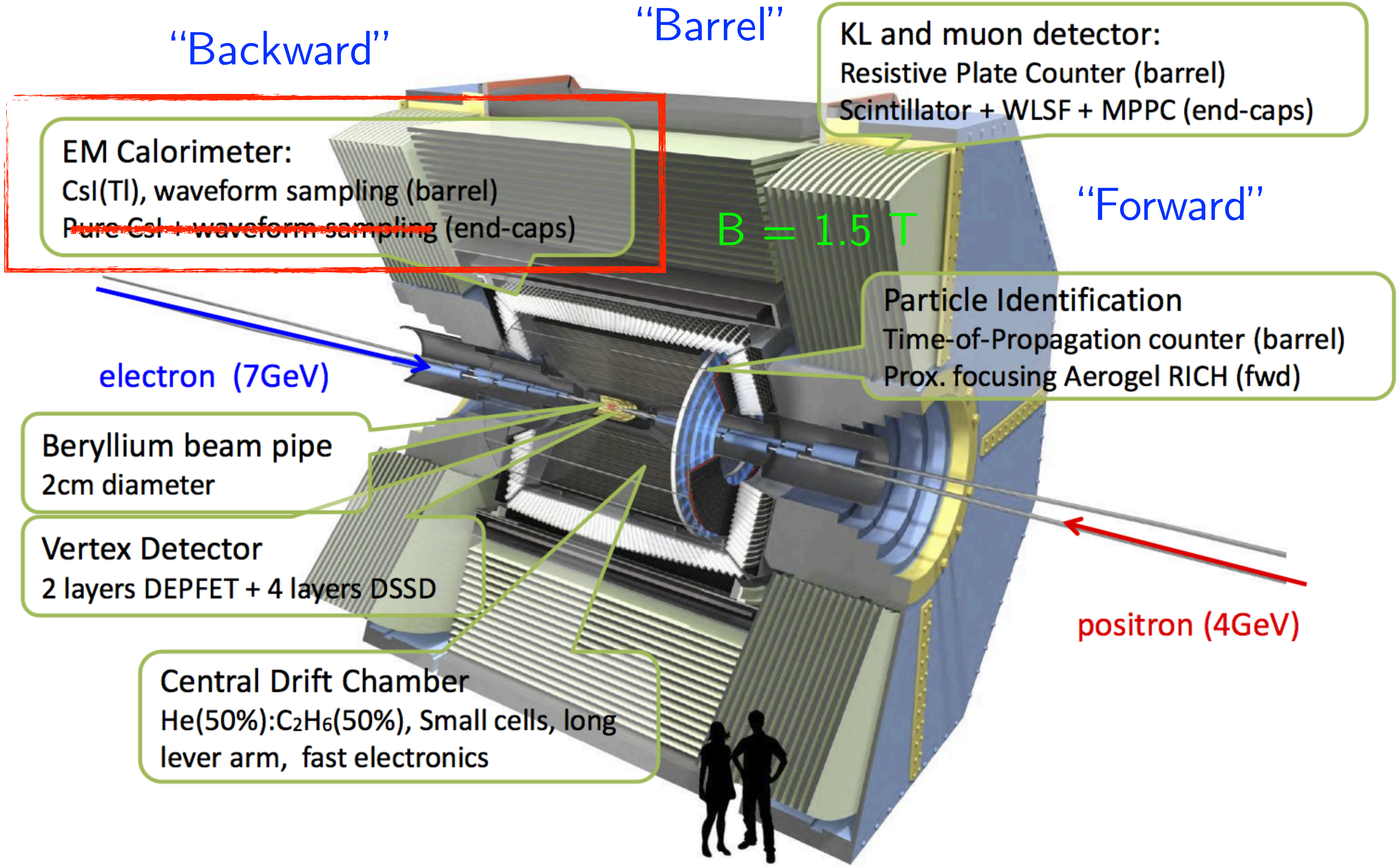
- PID algorithm works by encoding measurements from different sub-detectors into a likelihood ratio → cf. Umberto Tamponi's lecture.

This lecture focuses on the PID reach of the *Belle II* Electromagnetic Calorimeter (ECL).

(Sub-detectors not to scale)



The *Belle II* detector



2. Particle interactions with matter

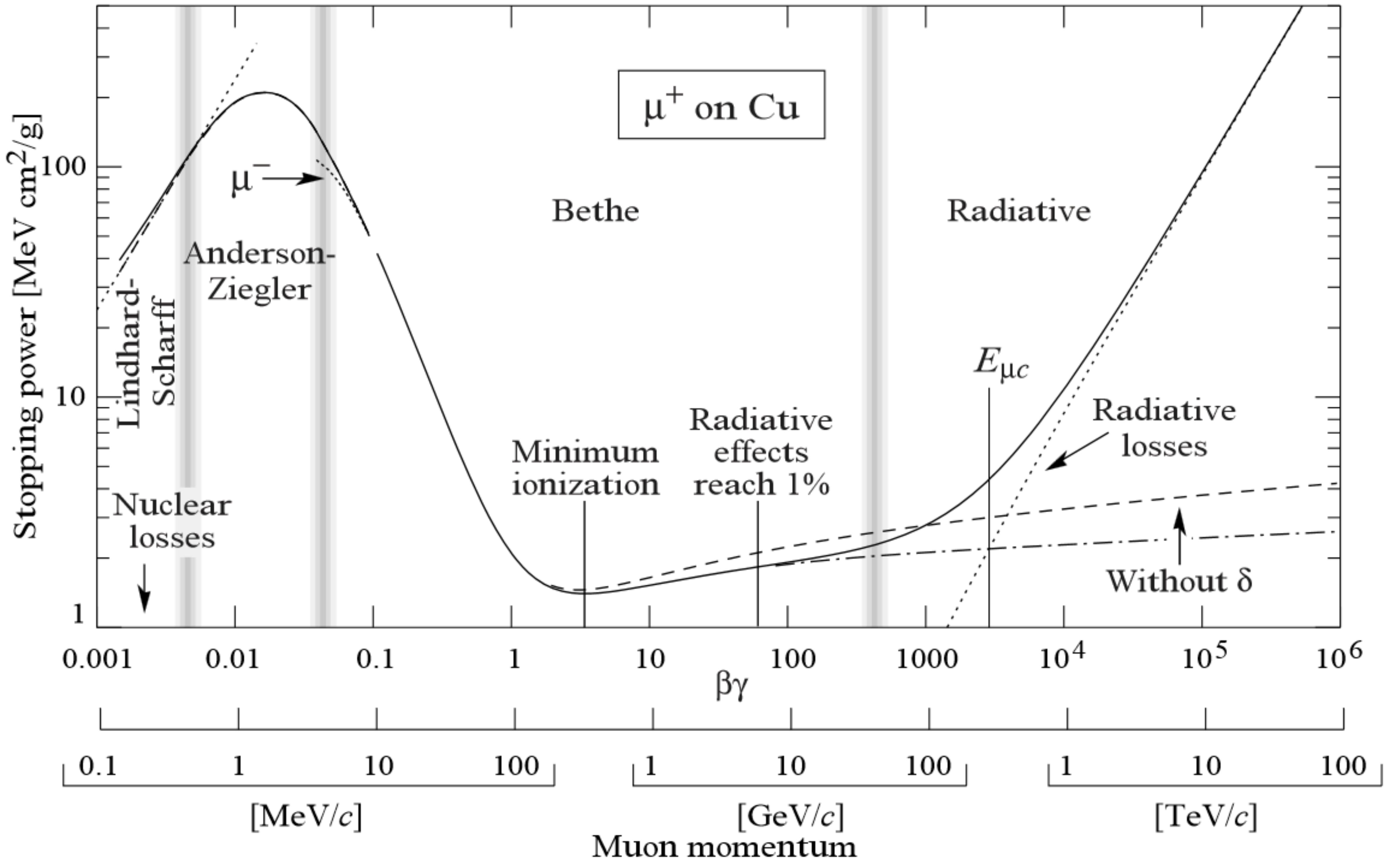
2. (Very brief) review of particle interactions with matter

Muons:

- In $p \sim [10^{-1}–10^{3}]$ GeV/c, mostly lose energy by *ionisation* $\rightarrow$ *minimum ionising (M.I.P)* up to several GeV, $dE/dx \sim O(2 \cdot \rho$ MeV/cm$)$.

➤ As a result, muons unlikely to be stopped by detector material, will escape through.

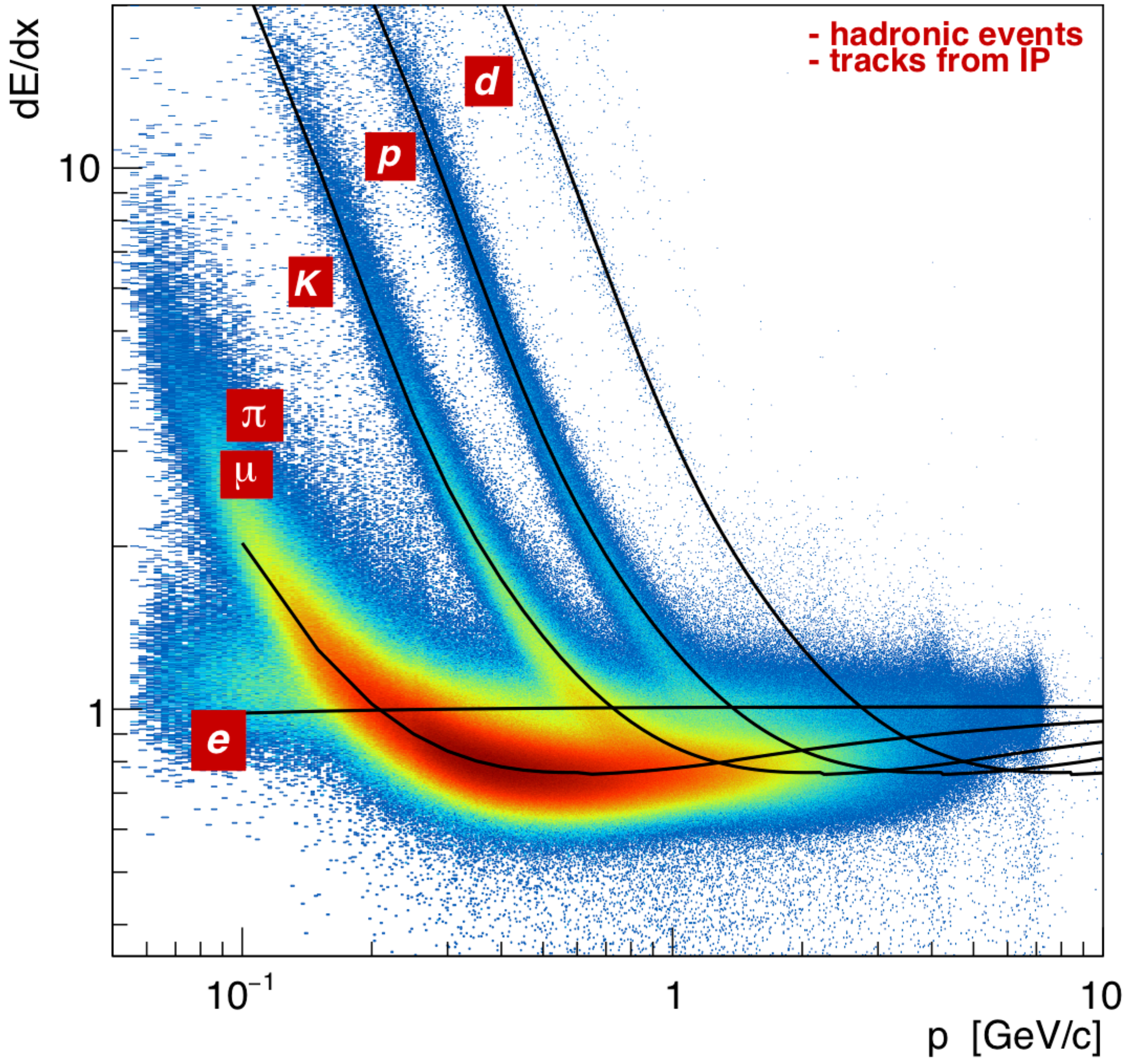
➤ $m_\mu = 105$ MeV/c^2 $\approx$ $m_\pi = 139$ MeV/c^2 implies measuring *dE/dx* has low power to discriminate the two species.



Bethe-Bloch (approx.) formula of average *E* loss per unit distance:

$$\frac{dE}{dx} \approx \rho(2\mathrm{MeVcm}^2/\mathrm{g})\frac{Z^2}{\beta^2} \qquad \left(p = m\beta\gamma c, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}\right)$$

CDC-dE/dx distribution and predictions



2. (Very brief) review of particle interactions with matter

Electrons:

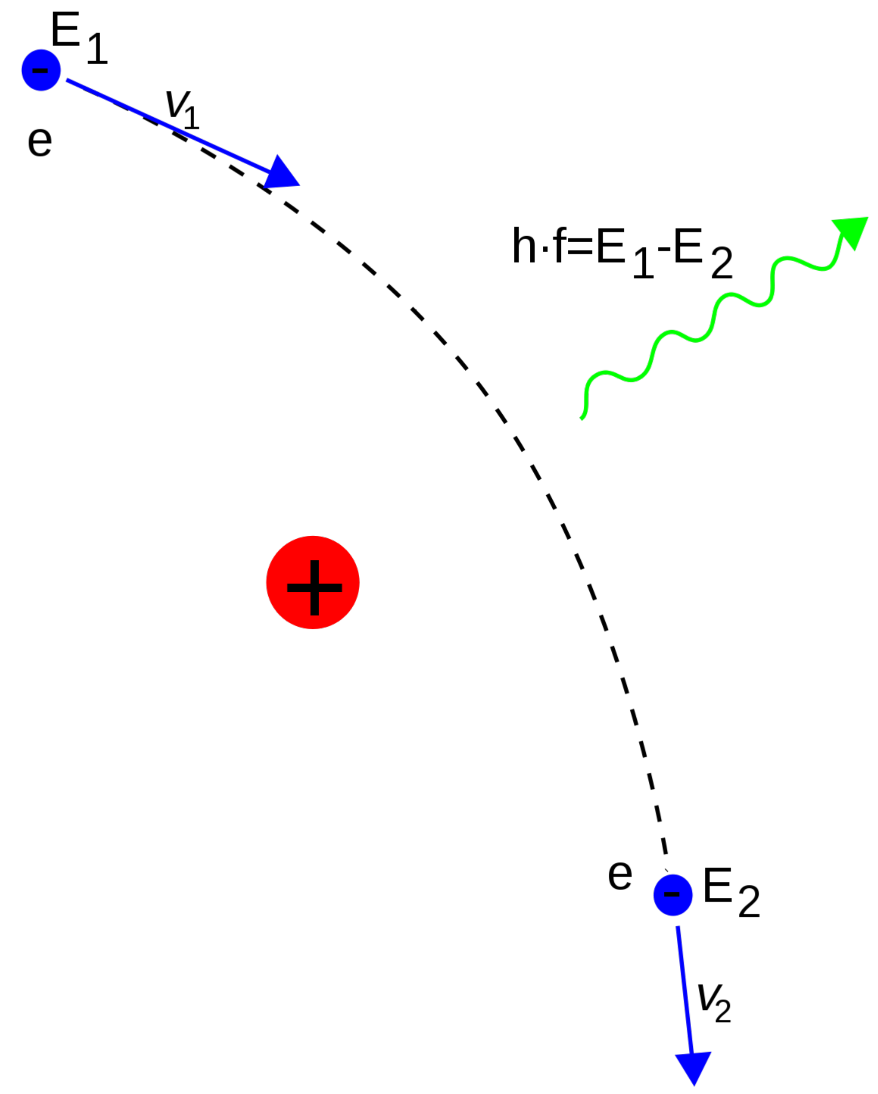
- almost always β≈1, *dE/dx* ~ O(2 MeV/cm) in light absorbers → not stopped by VXD and CDC

(unless tracks curl in *B* field: $p_T < 200$ MeV/c).

- For *E* ~ [100-1000] MeV → loss dominated by *bremsstrahlung*:

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

(X_0: *radiation length*→ property of material)



(NB: for muons, brems loss suppressed by a factor $(m_e/m_\mu)^2$ up to *E* ≈ O(TeV).

Photons in same range lose *E* by analogous mechanism: pair production *(γ→ee)*

➤ EM *shower* progresses until *critical energy* reached: E_c: brems = ionisation

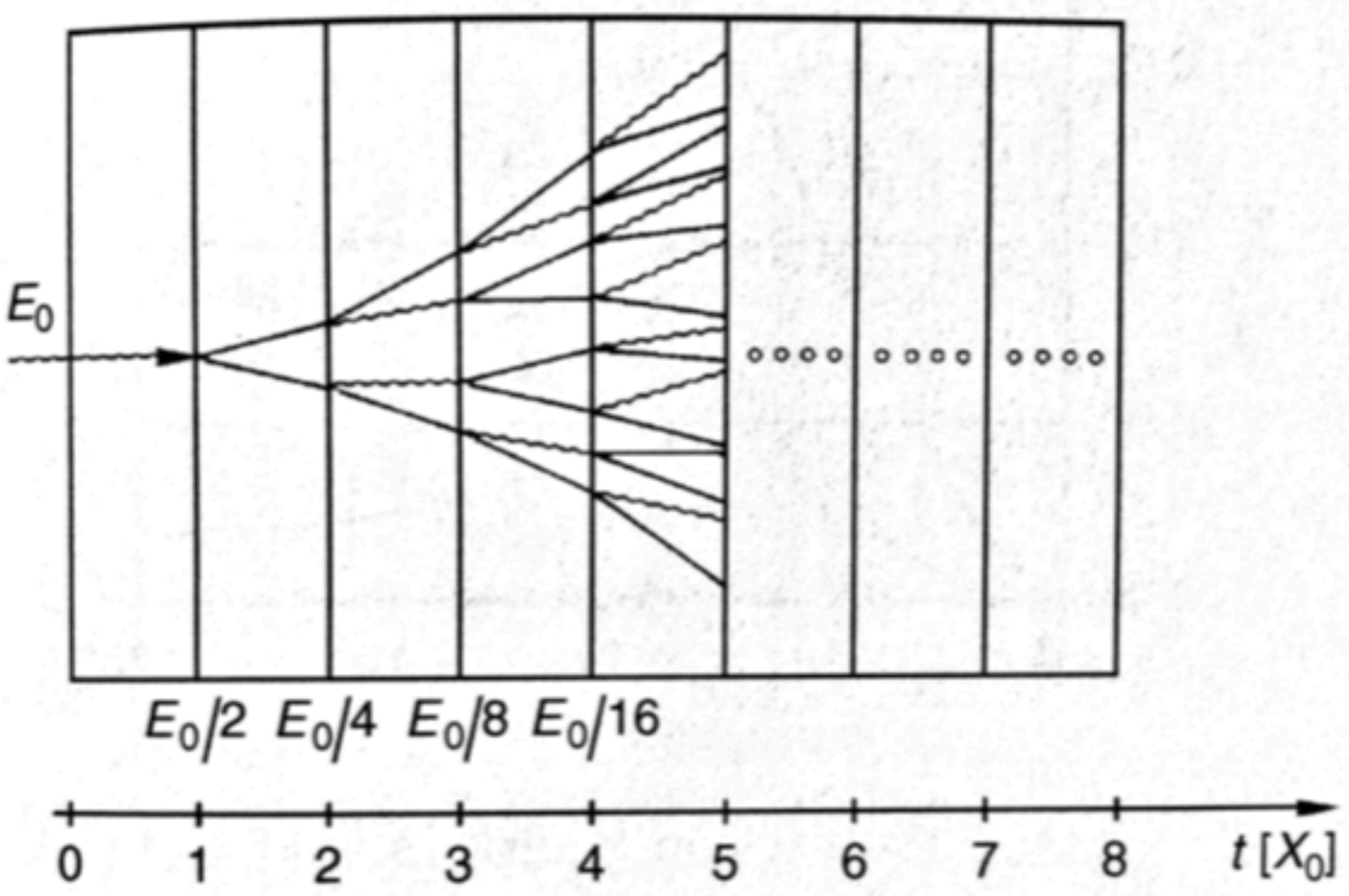
➤ Max *longitudinal* shower depth t_{max} depends only on ln(E_0).

$$t_{max} \propto \ln\left(\frac{E_0}{E_c}\right)$$

➤ 95% of *lateral* width < 2R_M, independently of E_0.

$$R_M = \frac{21\mathrm{MeV}}{E_c} X_0 \ [\mathrm{g/cm^2}]$$

Moliere radius



2. (Very brief) review of particle interactions with matter

Hadrons (π, K, p):

- As other charged massive particles, in $E \sim [10^{-1}–10^{3}]$ GeV, show *M.I.P* behaviour.
- Strong interactions with material atoms also lead to inelastic scattering loss.

$$\lambda_I = \frac{1}{N\sigma} \approx \frac{A^{1/3}}{\rho} 35\ \mathrm{g/cm^2}$$

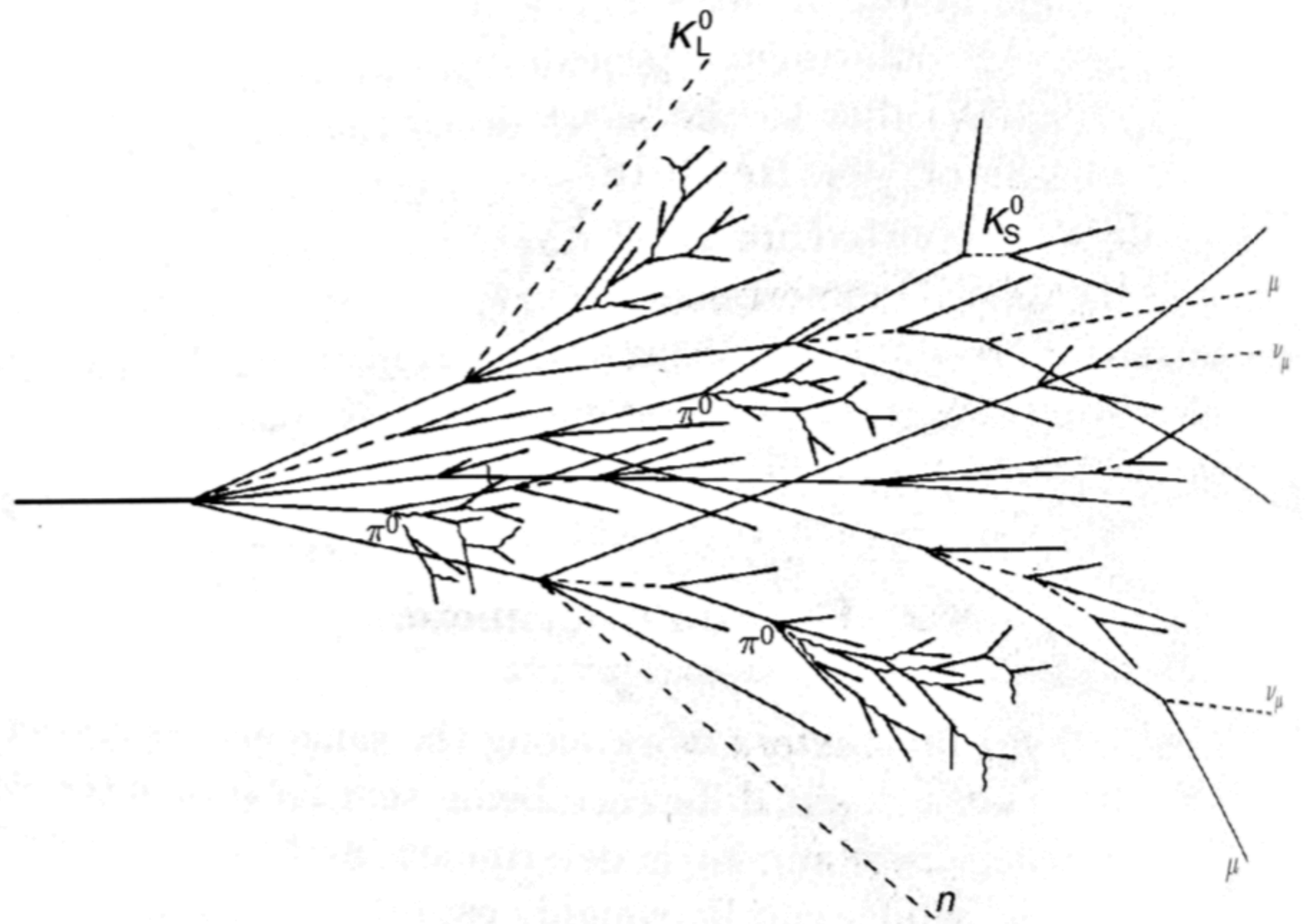
(λ_I: *interaction length* $\rightarrow$ *hadronic mean free path*)

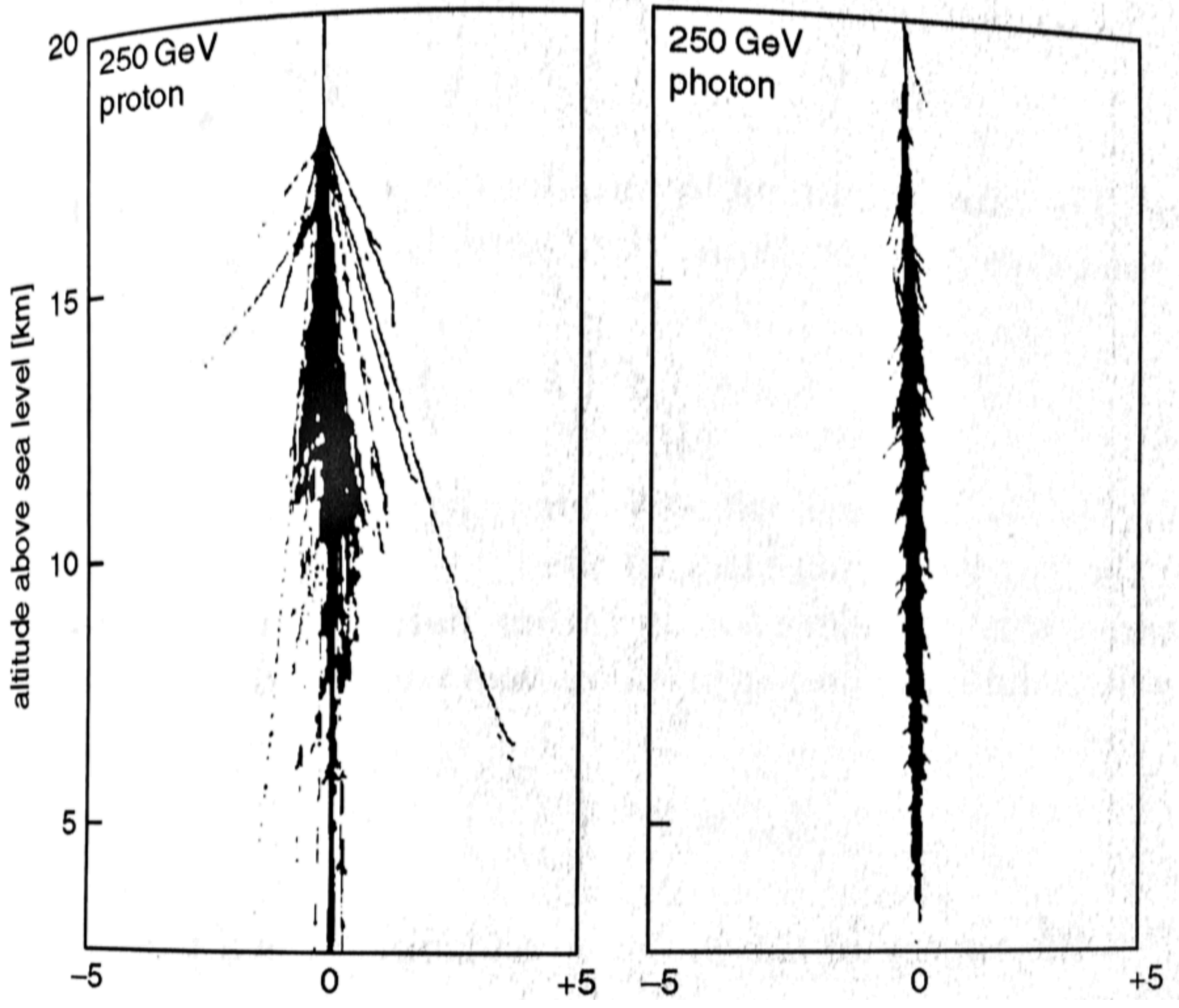
➤ For Z ≥ 6, $\lambda_I \gg X_0$ → *hadrons are likely to punch-through the EM calorimeter.*

➤ Inelastic interactions lead to fuzzier shapes of hadronic showers vs. EM showers.

➤ Modelling of simulated hadronic interactions w/ detector material not a trivial task:

cross-section energy dependence, different particle type responses...





3. The Electromagnetic Calorimeter

3. The *Belle II* Electromagnetic Calorimeter (ECL)

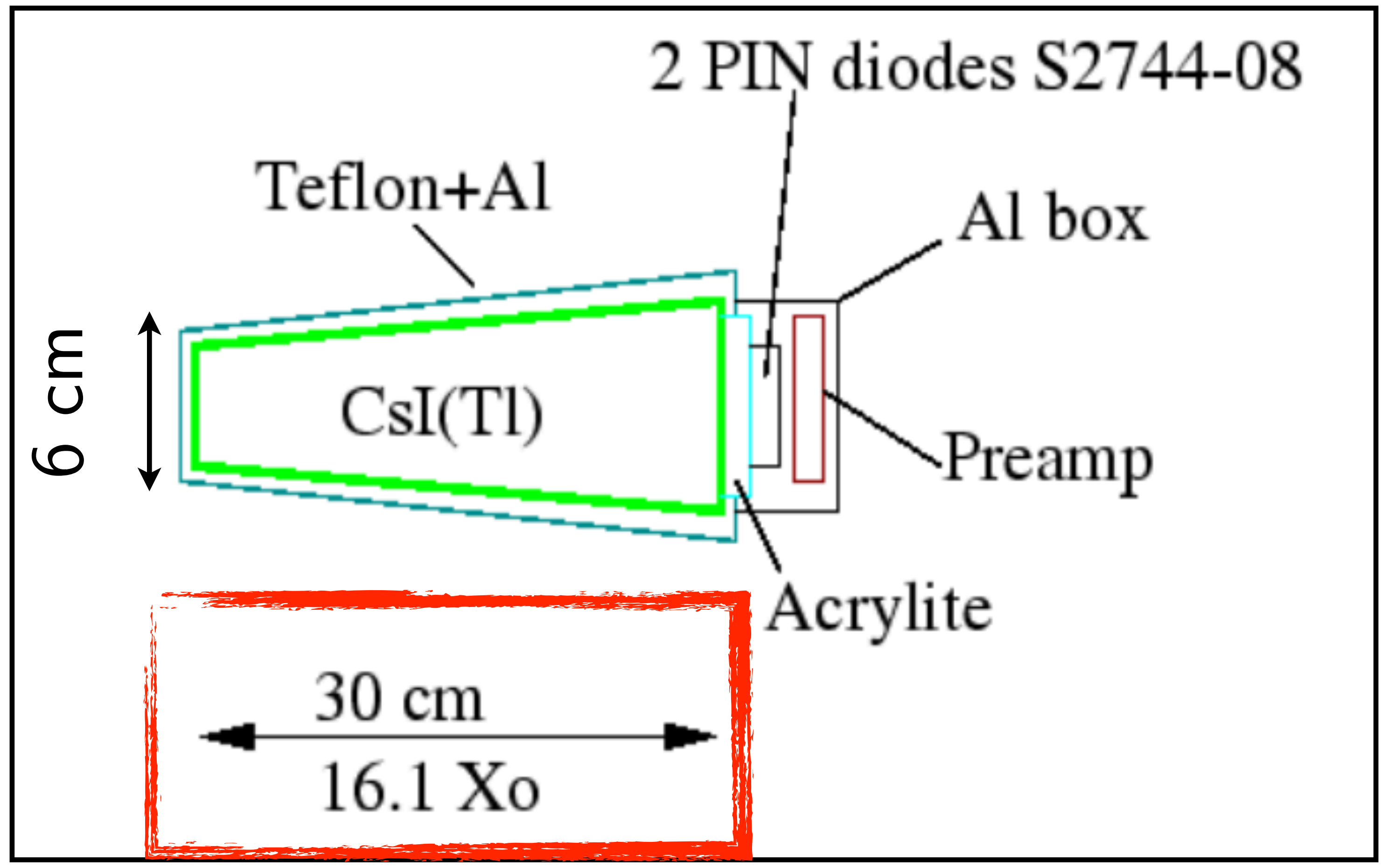
Main tasks of the ECL:

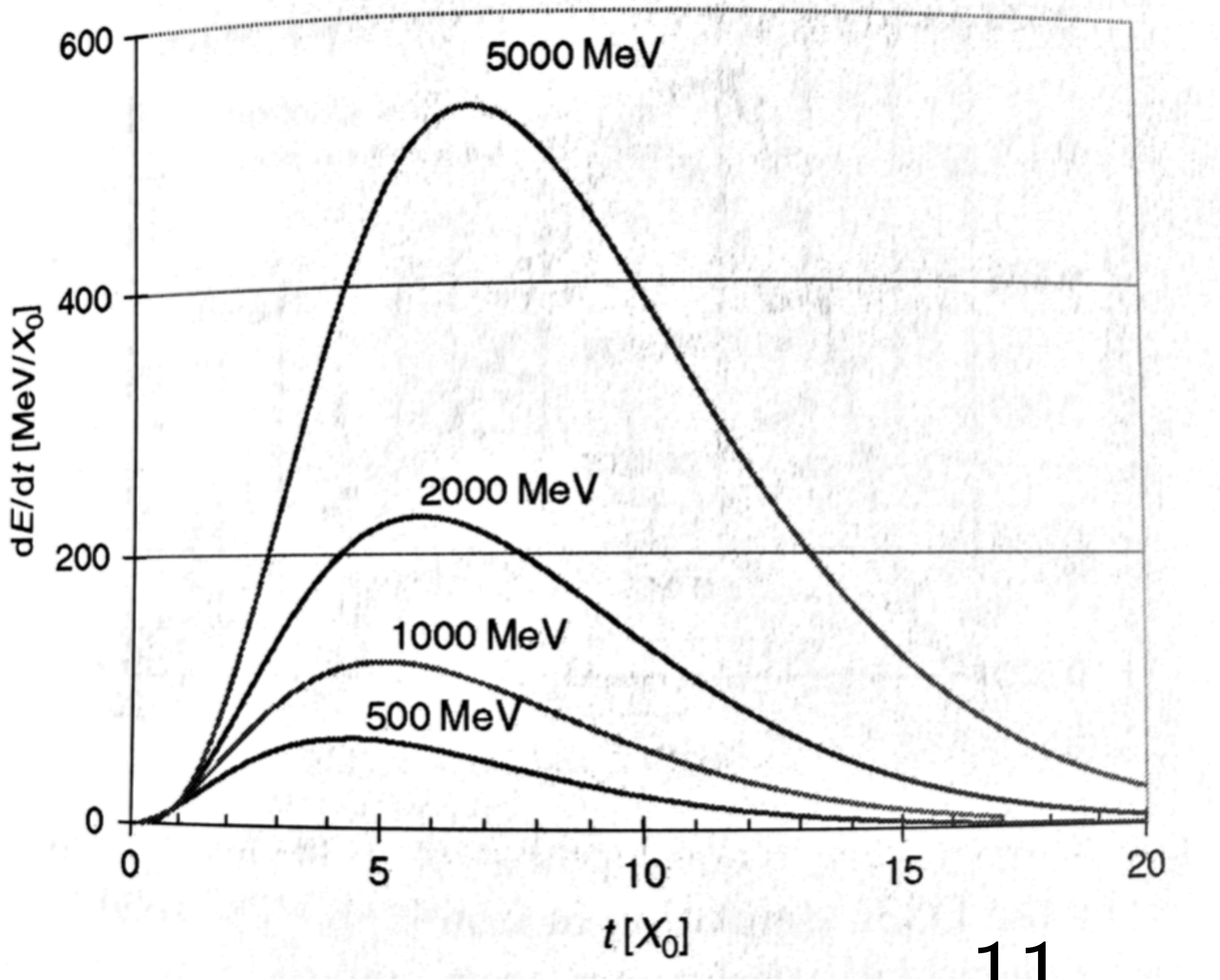
- Photon (γ) detection with high efficiency.
- Precise determination of γ energy and angular coordinates.
- Electron/hadron separation.

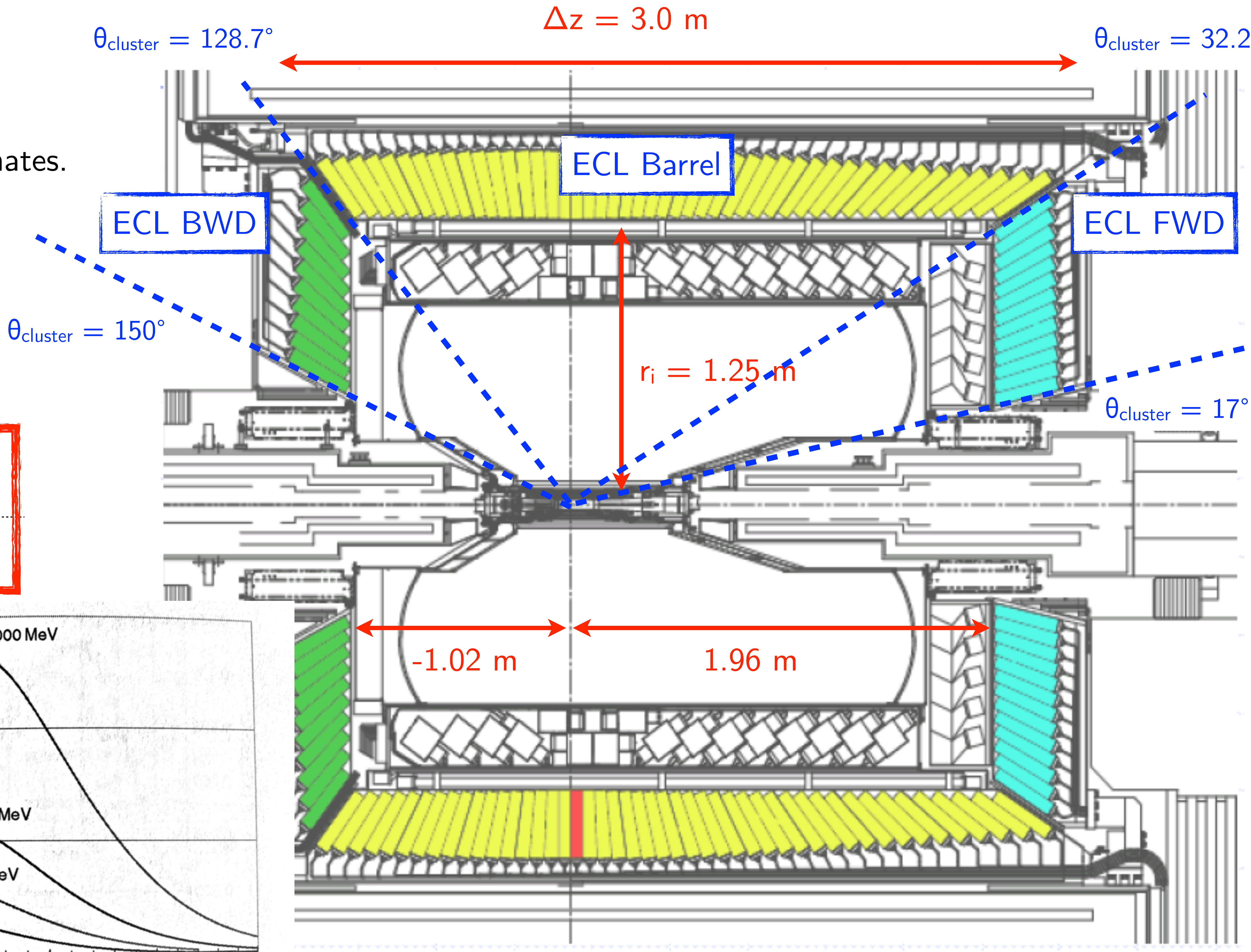
Made up of 8736 laterally segmented CsI(Tl) crystals.

Designed to longitudinally contain ~any EM cascade.

X_0 [cm]	λ_I [cm]	R_M [cm]
1.86	44.12	1.86



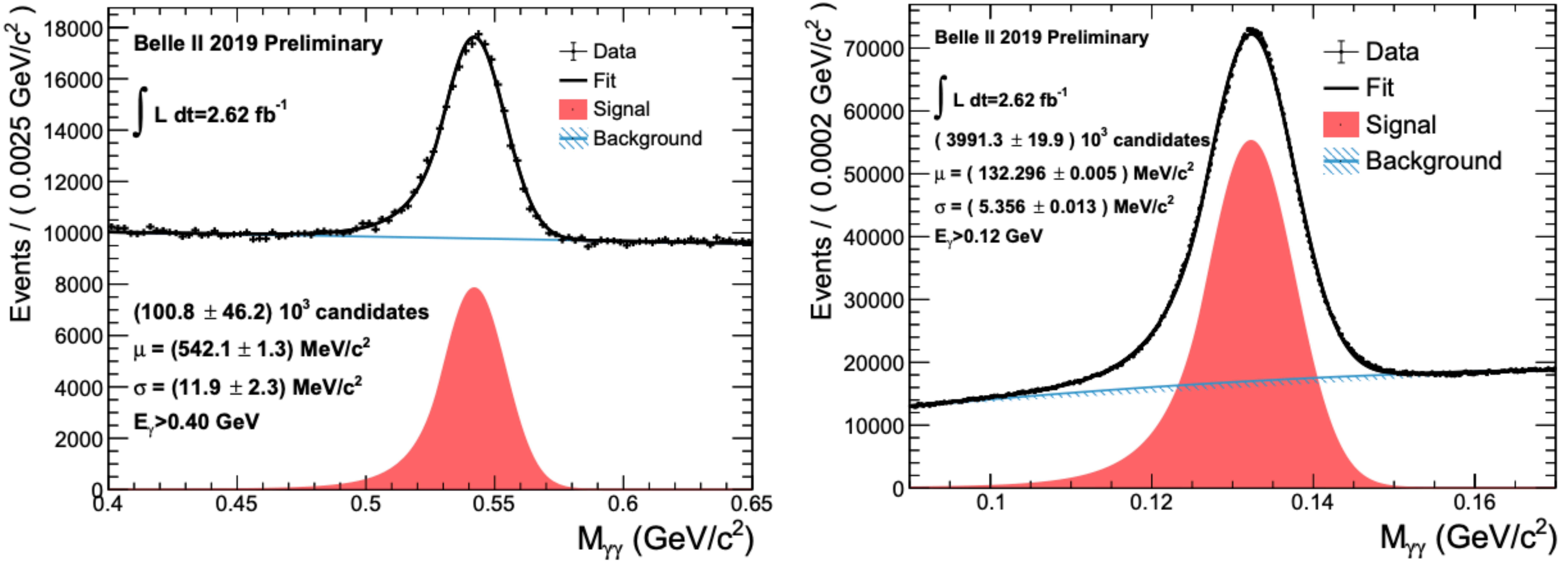




3. The *Belle II* Electromagnetic Calorimeter (ECL)

We can clearly observe resonances decaying to photons in the early *Belle II* data, with good mass resolution.

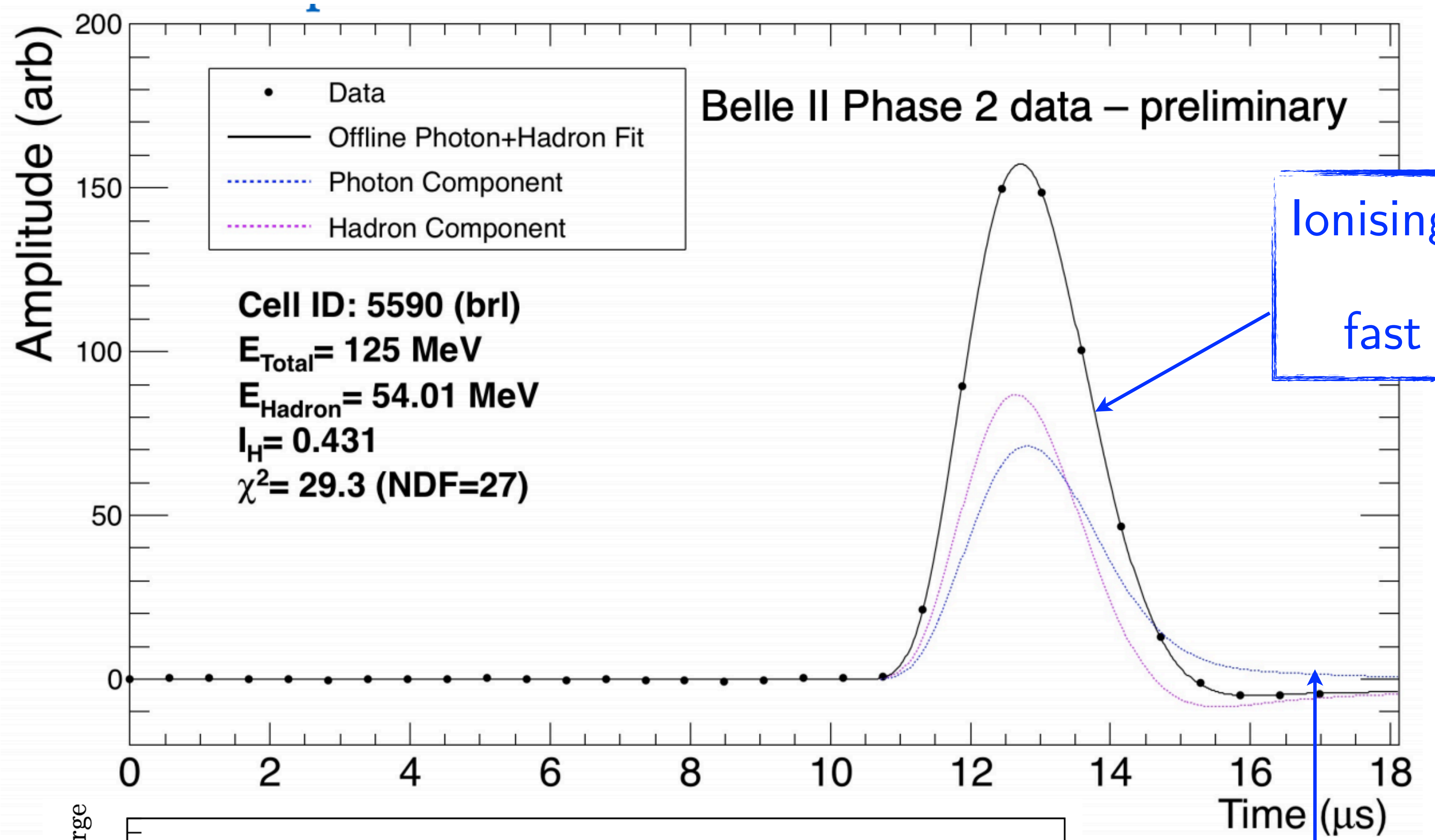
$\eta \to \gamma\gamma$ $\pi^0 \to \gamma\gamma$



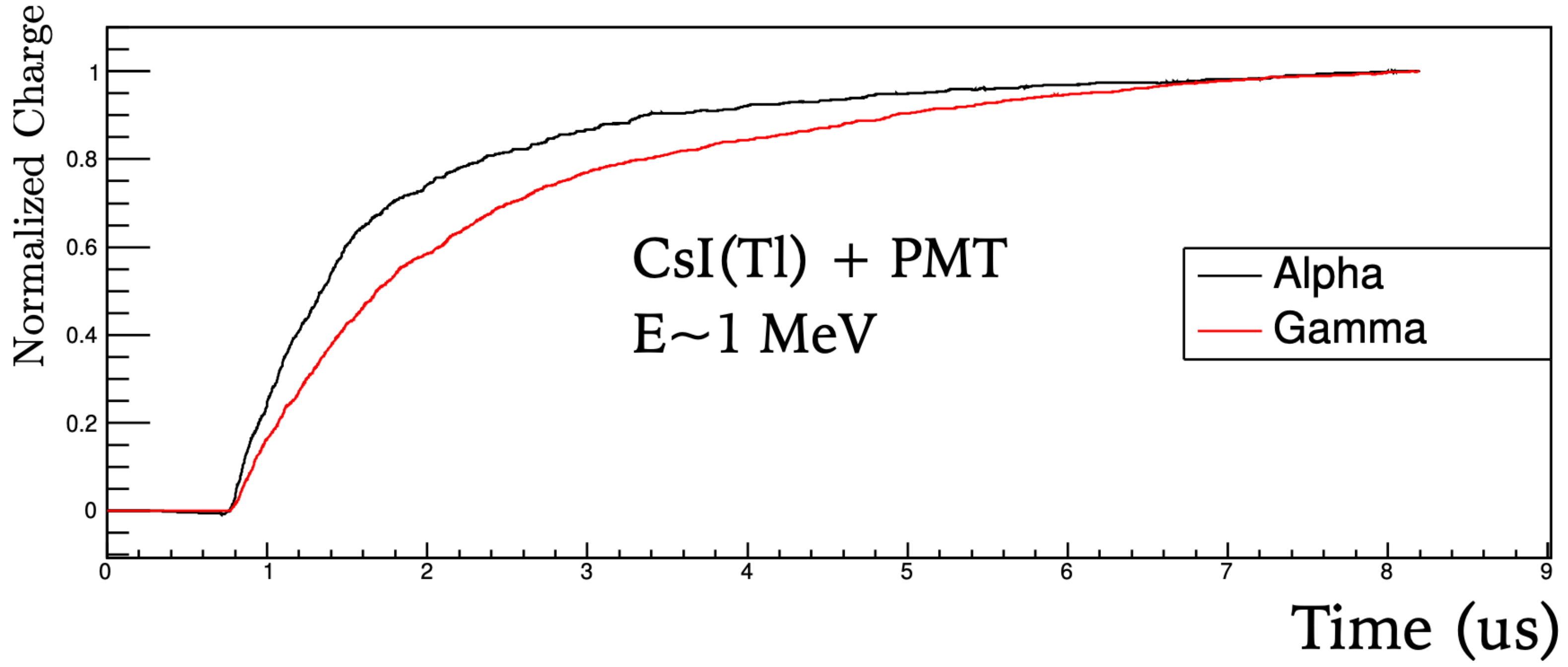
3.1 Pulse Shape Discrimination (PSD)

Upgraded ECL readout electronics in *Belle II* (waveform sampling) allows offline analysis of the shape of the CsI(Tl) crystal signal waveform $\rightarrow$ *pulse shape discrimination.*

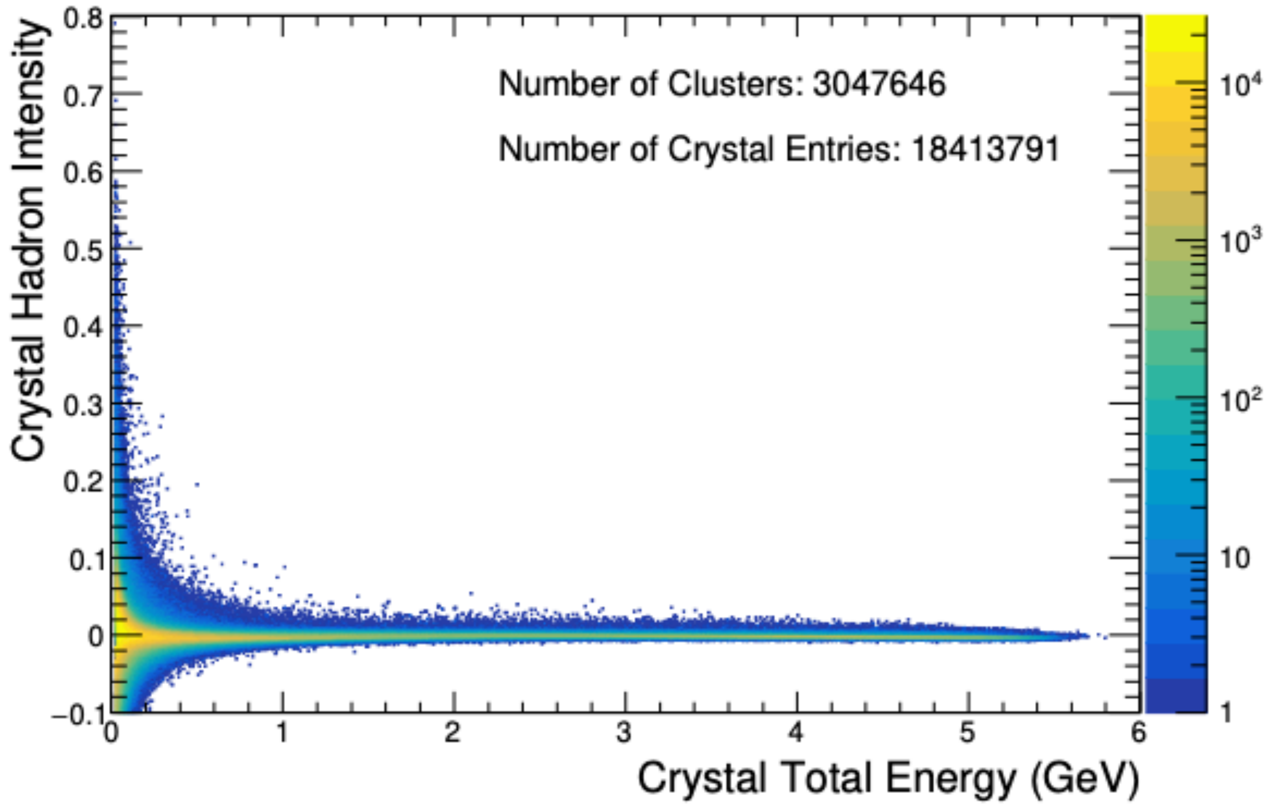
➤ Exploit different hadronic (π,K,p) vs.E.M. (γ, e) scintillation response as a powerful handle for particle identification.



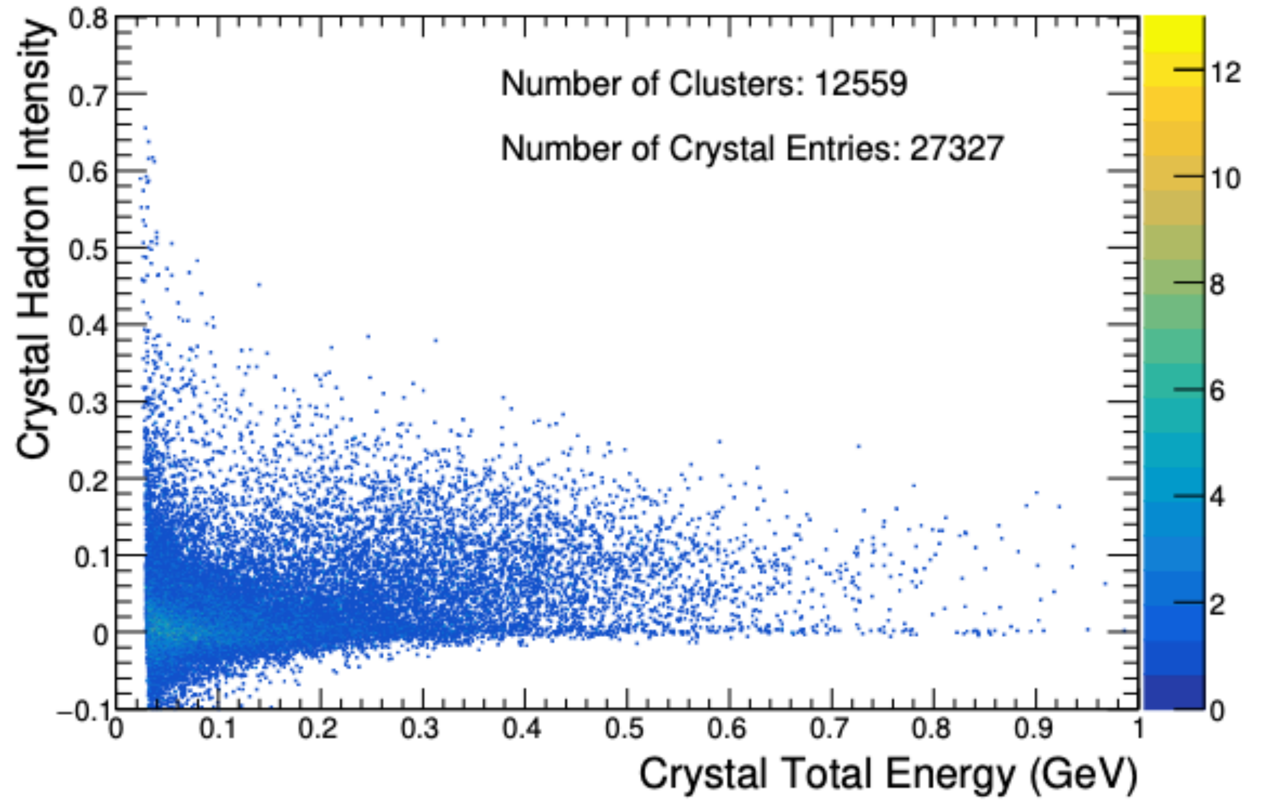
Ionising particles→ fast scintillation



EM particles→ slow scintillation



(a) e^- Data

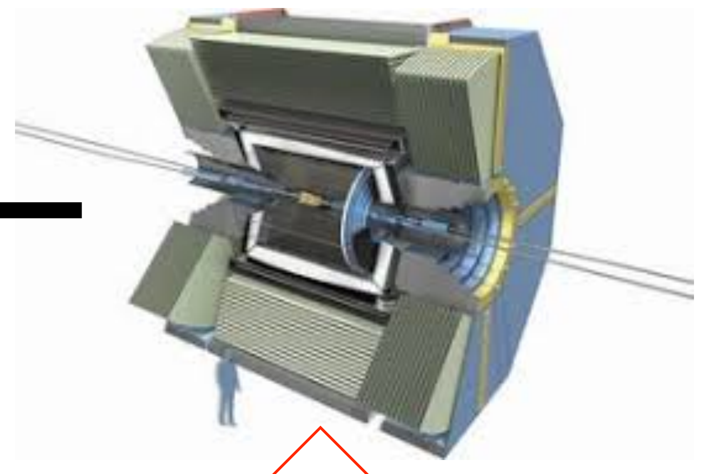


(a) K^- Data

3. Overview of ECL clustering algorithm

4. Overview of ECL clustering (very simplistic)

Real/GEANT4



ECL(Cal)Digit
(32 bit string w/ waveform amplitude (calibrated $\rightarrow E$) & time info)

ECLConnectedRegion
(contains all info not directly correlated with other info in the event.)

Find local maxima

ECLShower
(up to 5x5 cells, excluding corners)

Split if >1 local maxima

E correction (leakage, beam bkg)

Position determination

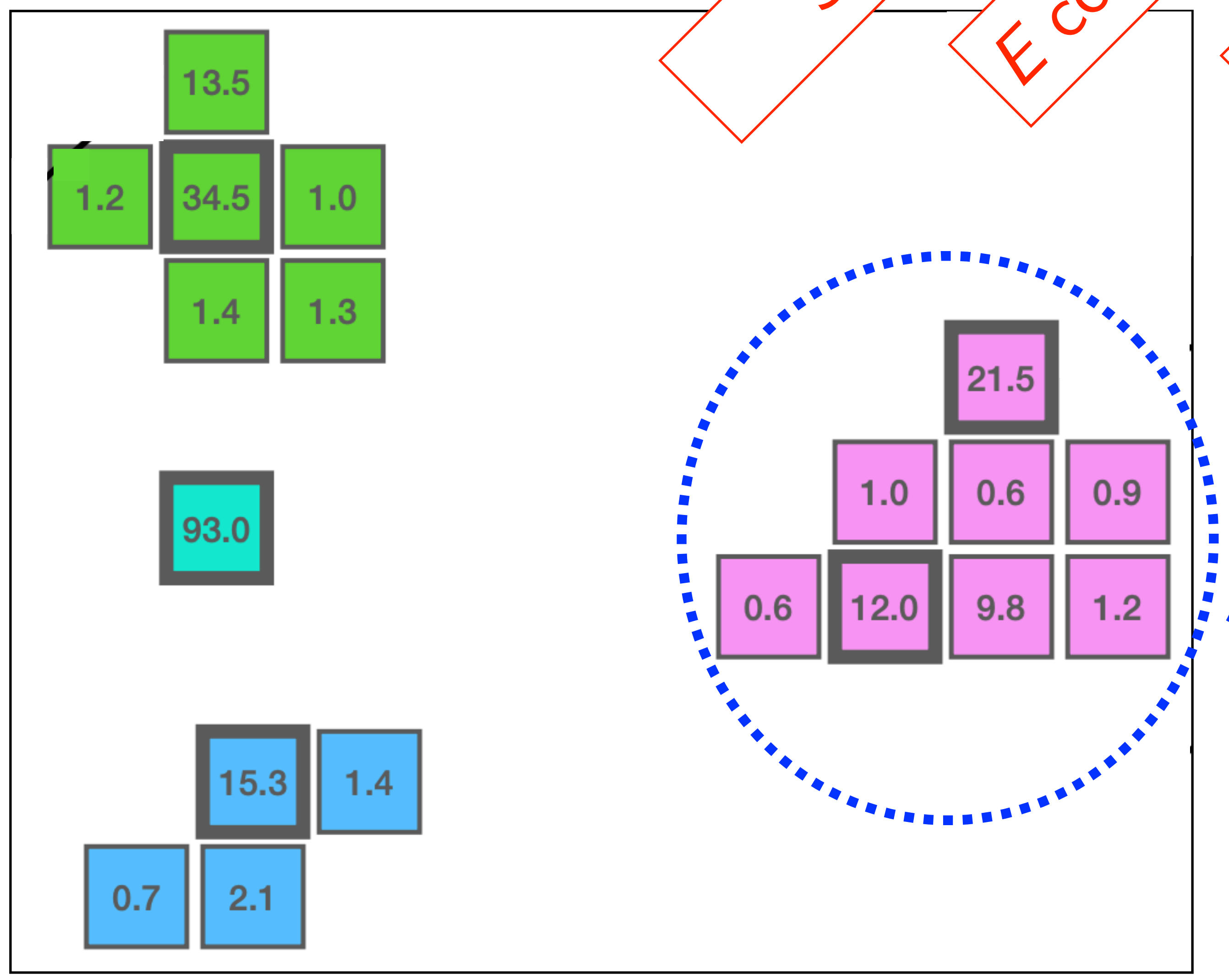
Track-cluster matching

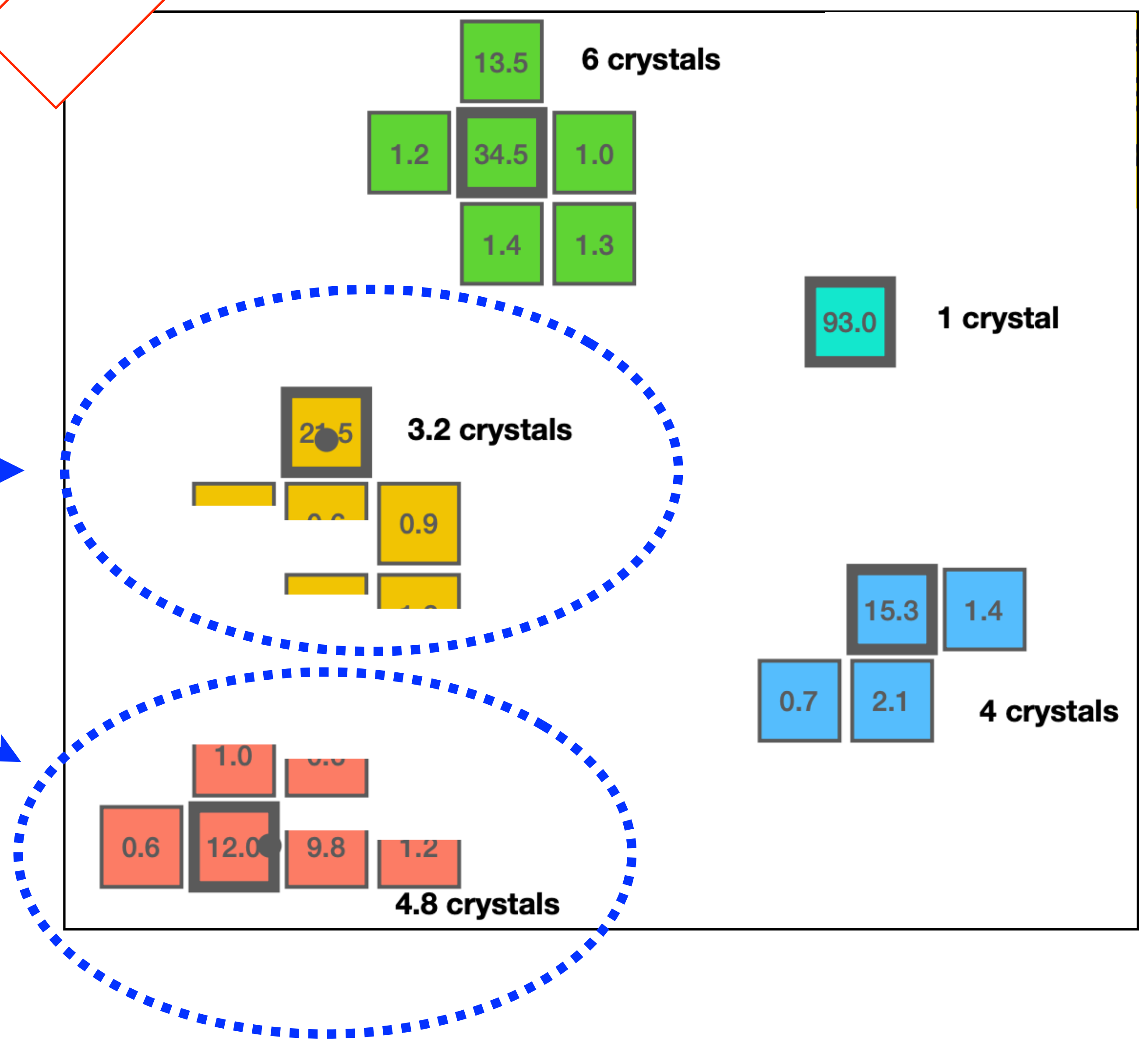
ECLCluster
(mdst object, E>20 MeV)

Exhaustive overview of the ECL clustering algorithm:

M. De Nuccio T. Ferber, June 2019 B2SK.

	13.5				21.5	
1.2	34.5	1.0		1.0	0.6	0.9
	1.4	1.3	0.6	12.0	9.8	1.2
	0.9					
9.5		0.2		93.0		1.0
1.0						
		0.4	15.3	1.4	1.6	
		0.7	2.1			





4. Overview of ECL clustering

Simulation of single particles' energy deposition in a 15x15 ECL crystal array (pre-clustering):

γ

- Radially symmetric shape
- Usually contained in 5x5 cells

e

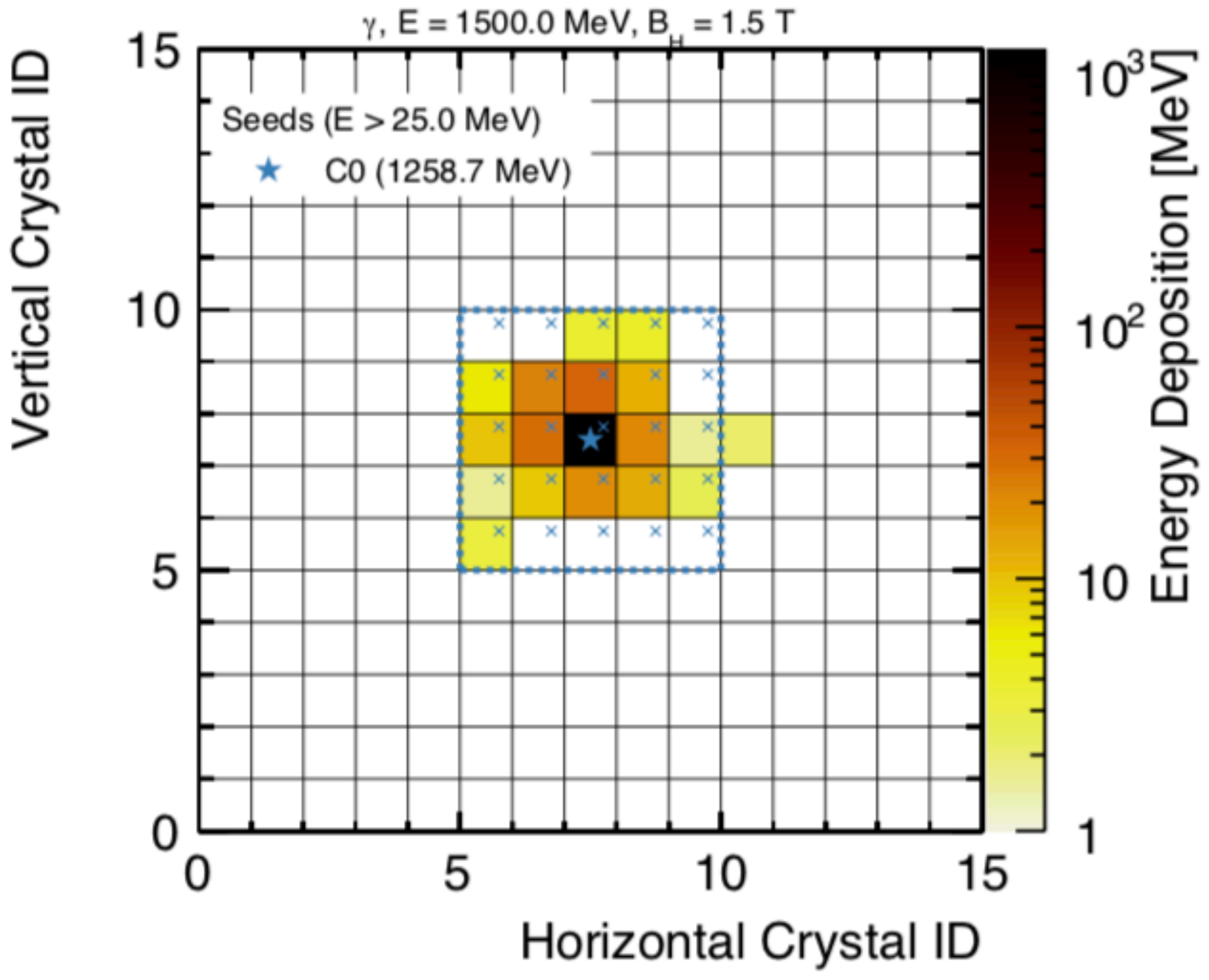
- Similar shape of γ
- Less symmetric (B field bend, brems γ emitted before the ECL)

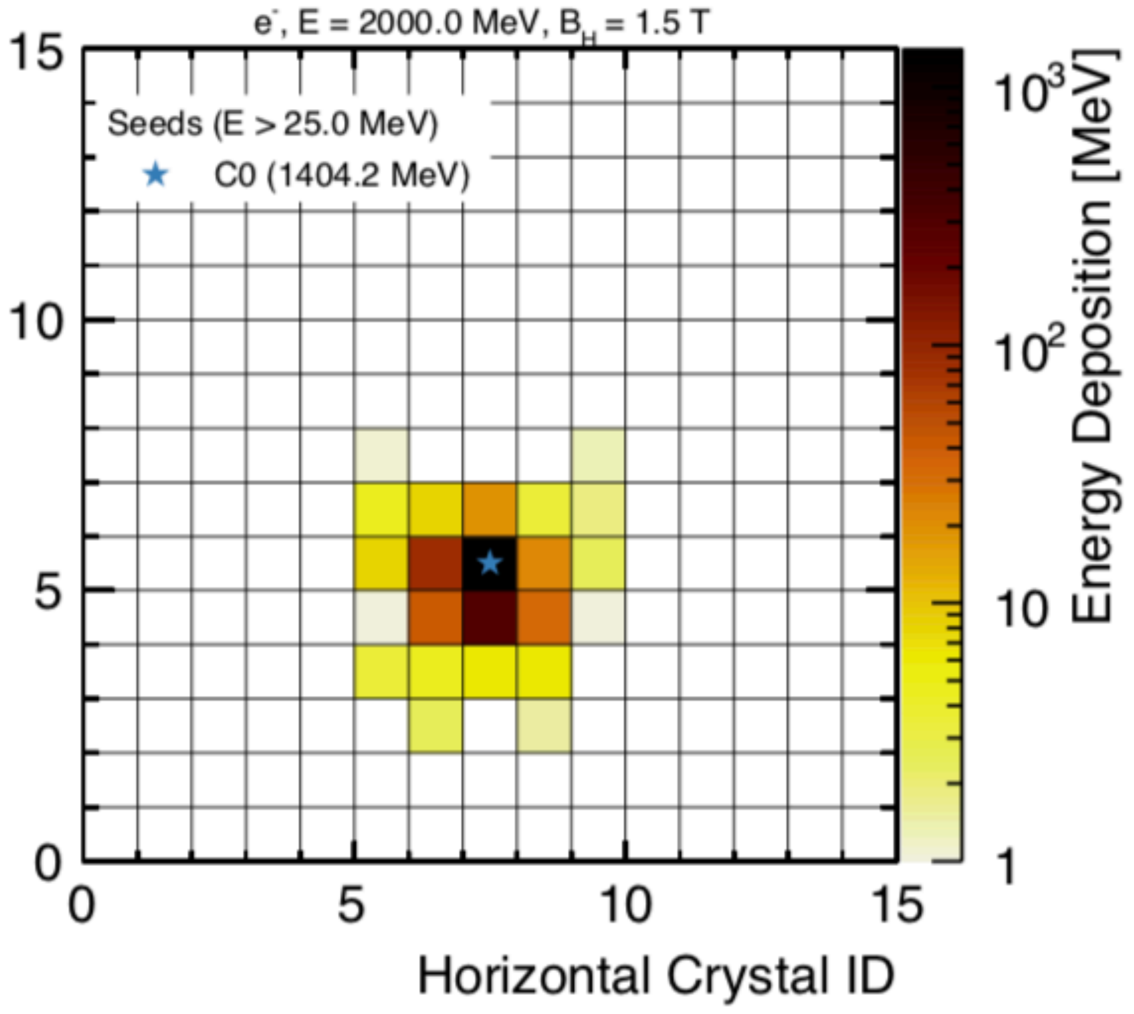
π

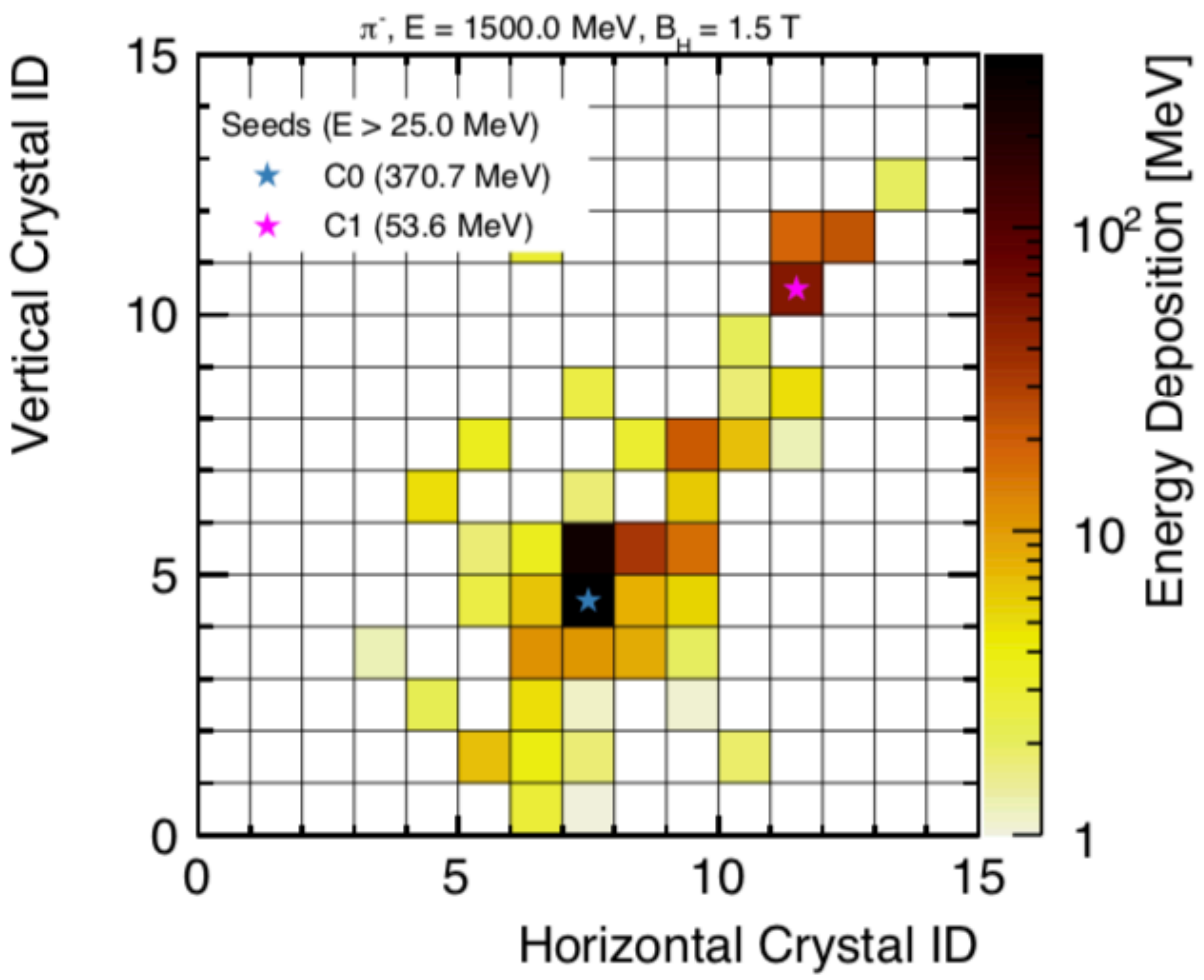
- Ionisation loss contained in 1-2 cells.
- Asymmetric lateral spread due to hadronic interactions

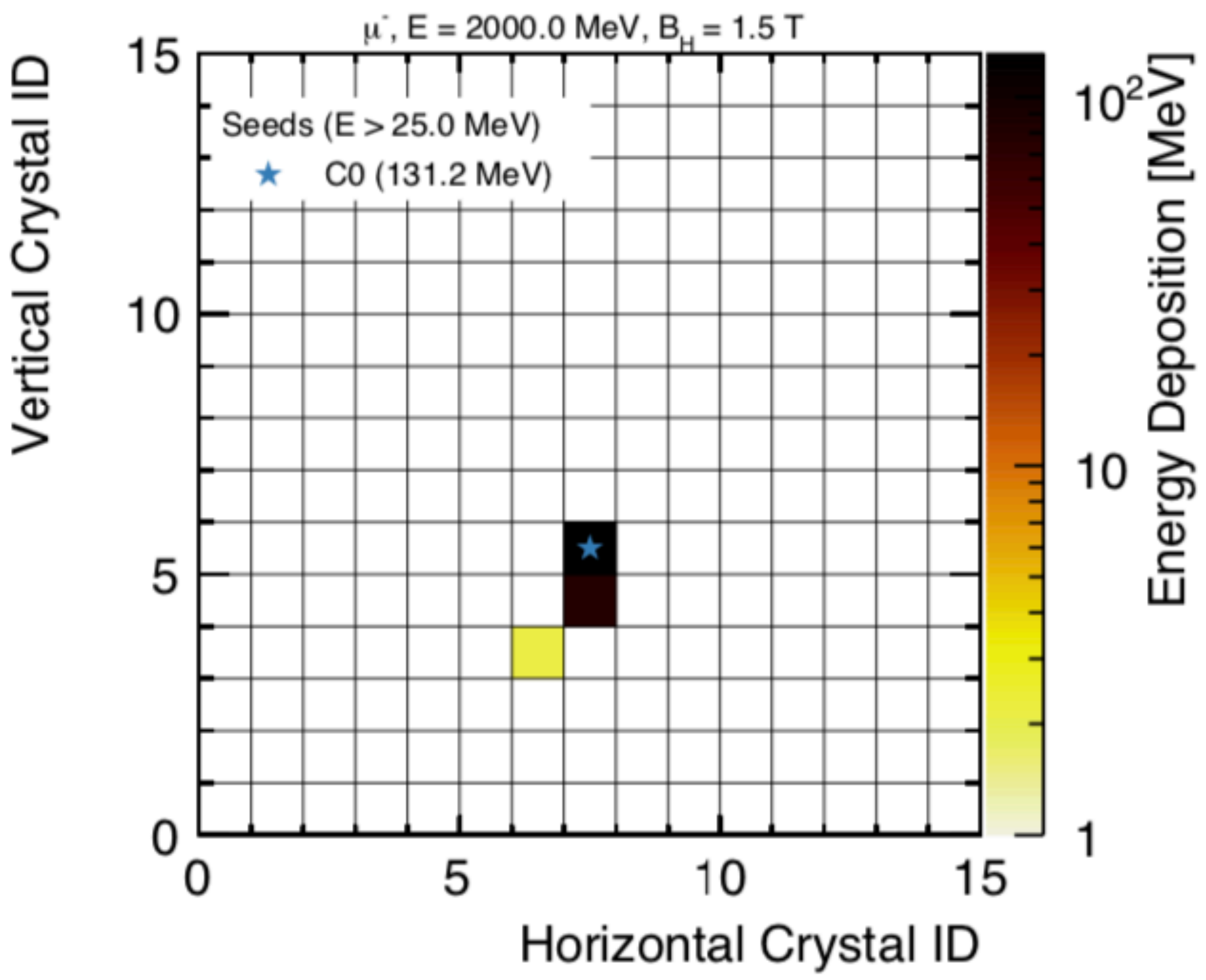
μ

- Pure MIP behaviour.
- $\langle E_{cluster} \rangle \sim 200$ MeV









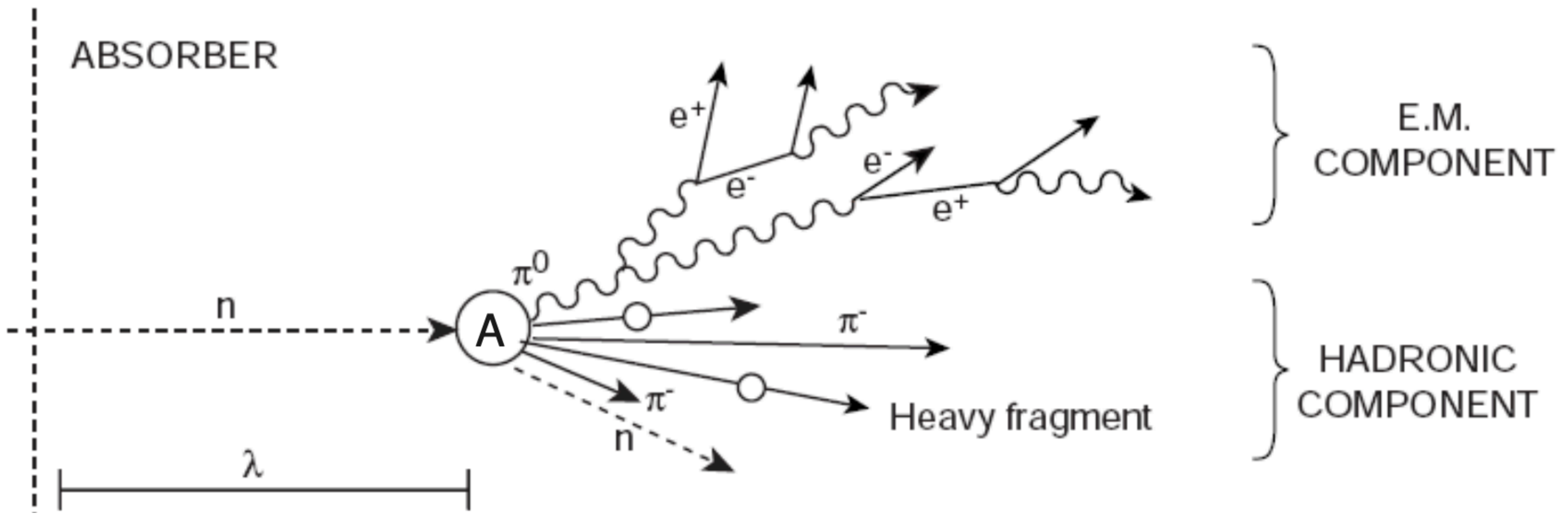
5. Neutral PID with the ECL

5. Neutral PID with the ECL

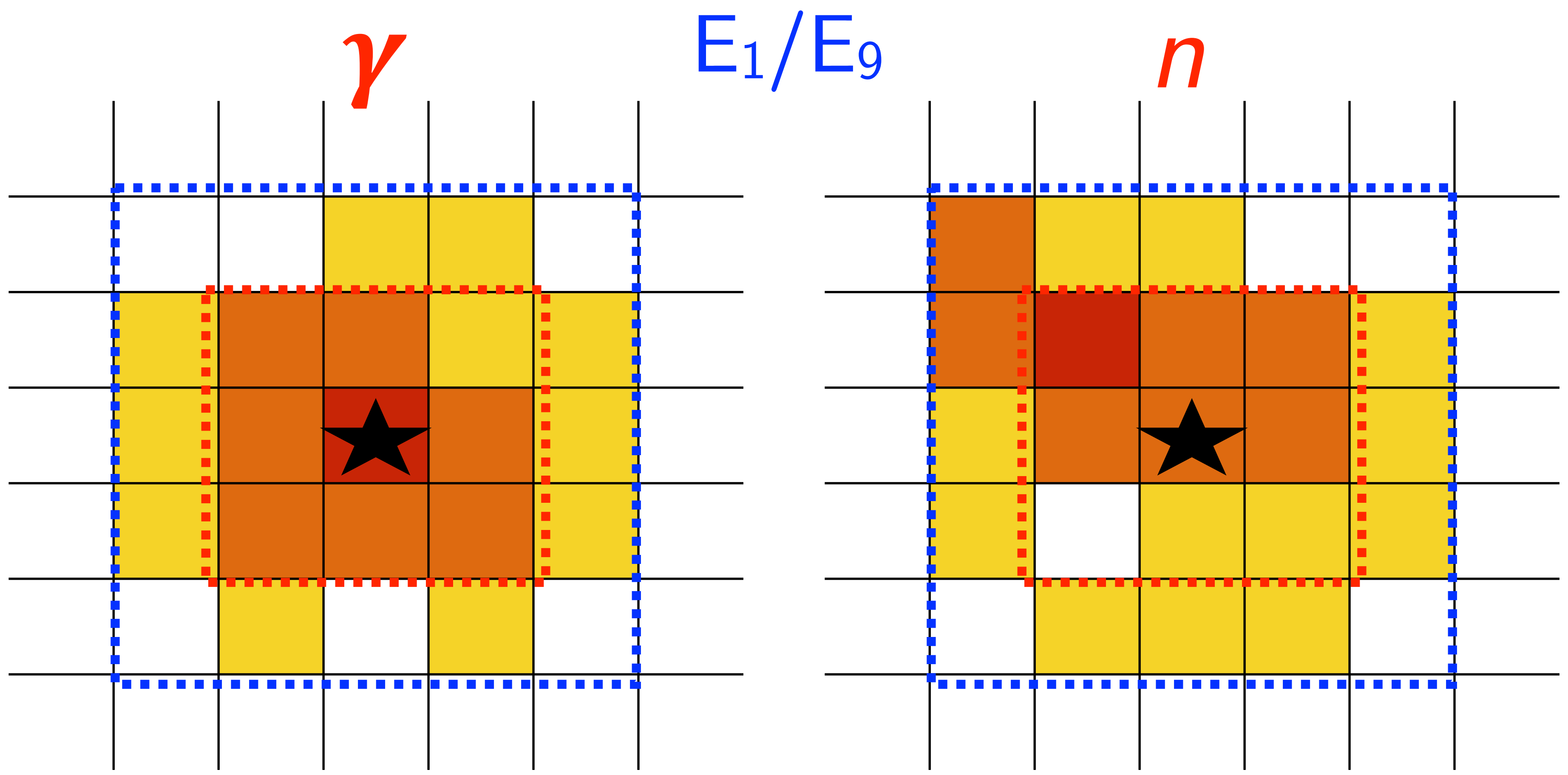
Photons can be mimicked by:

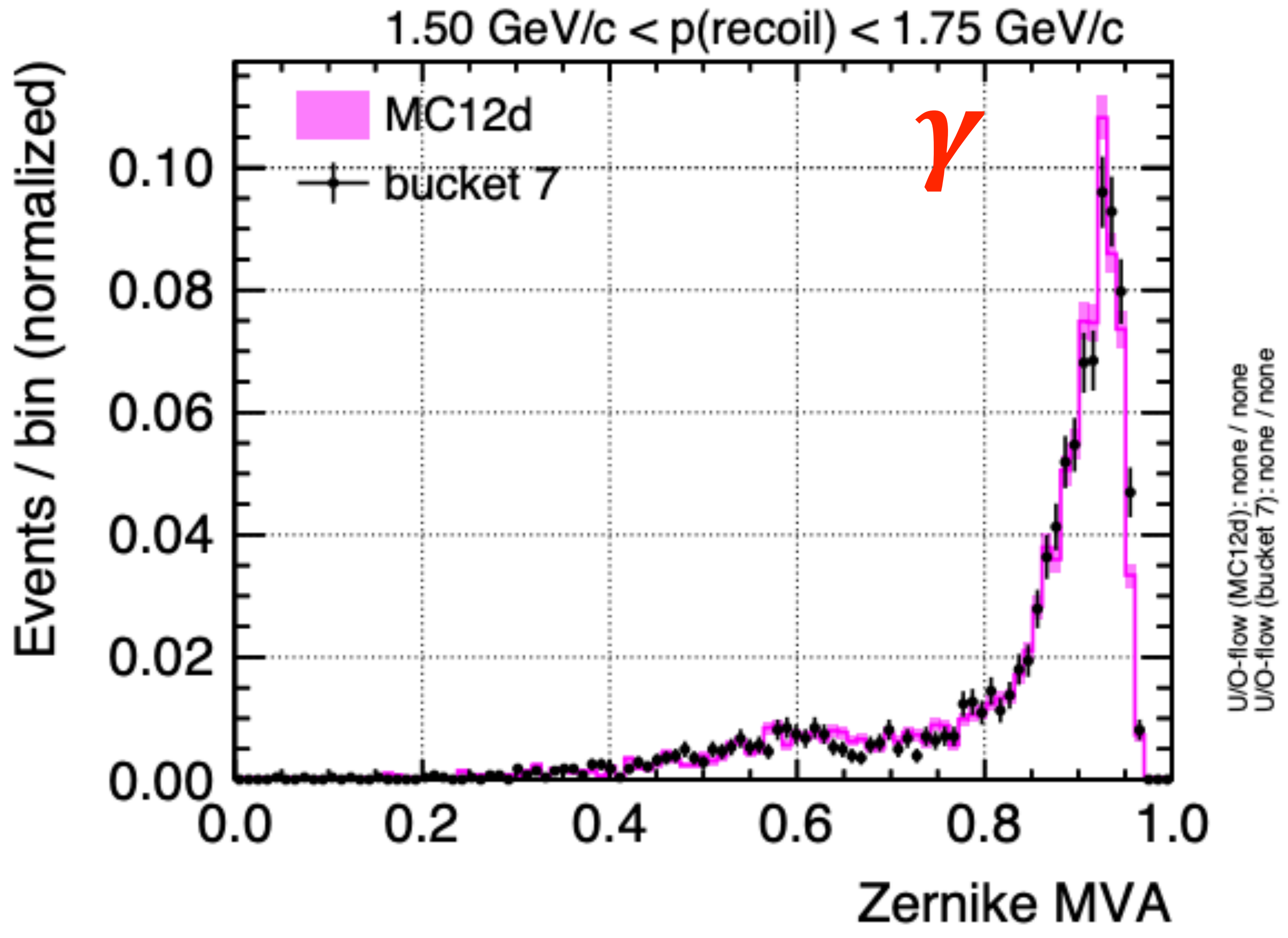
- Neutral hadrons
- Charged hadrons → "secondary" clusters

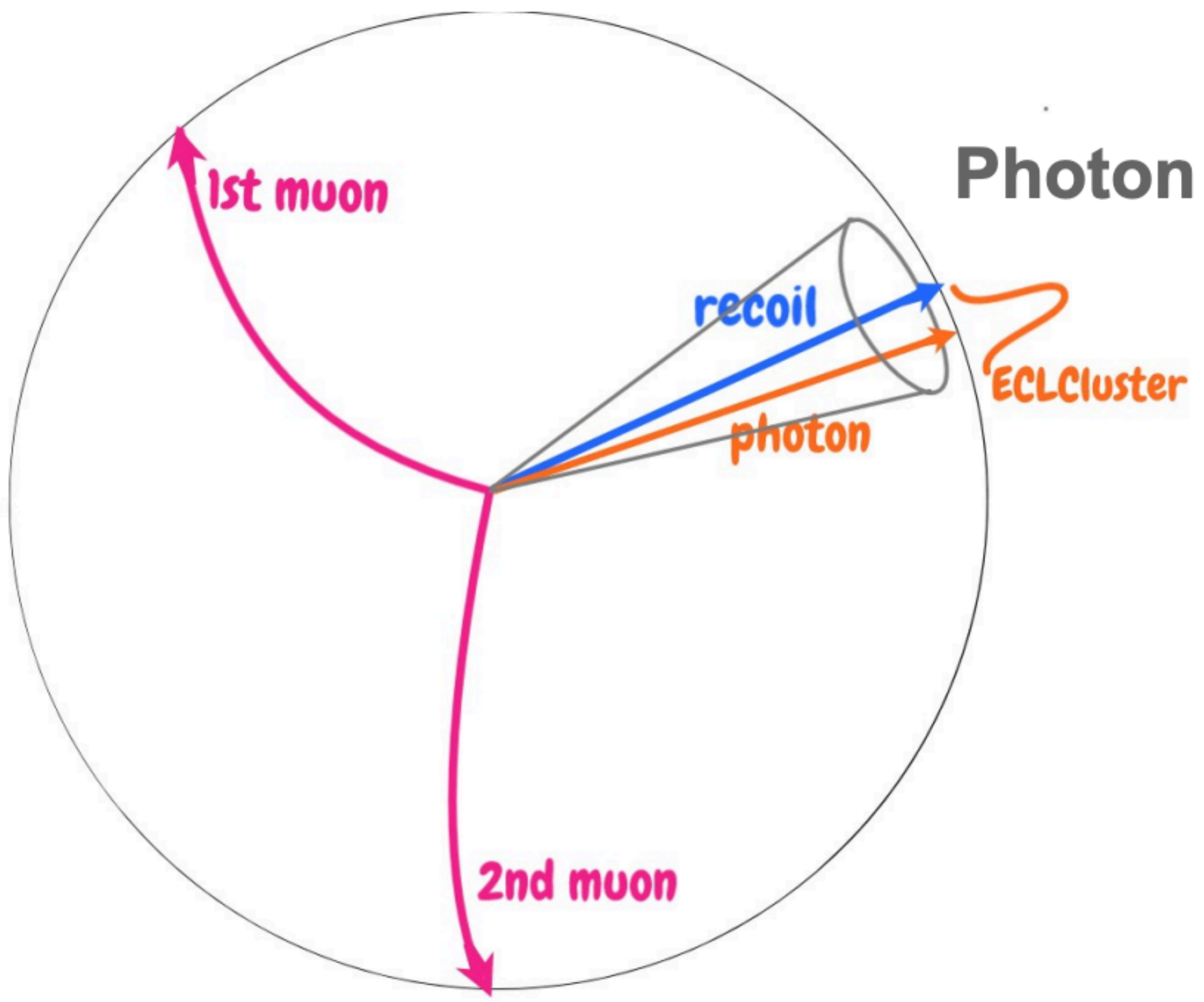
w/o matching track due to hadronic splitoffs.



➤ Identification mostly relies on variables describing the lateral shower shape development → E1/E9, Zernike moments.







Standard "candle" to test ID performance in data: $ee \to \mu\mu\gamma$

6. Charged PID with the ECL

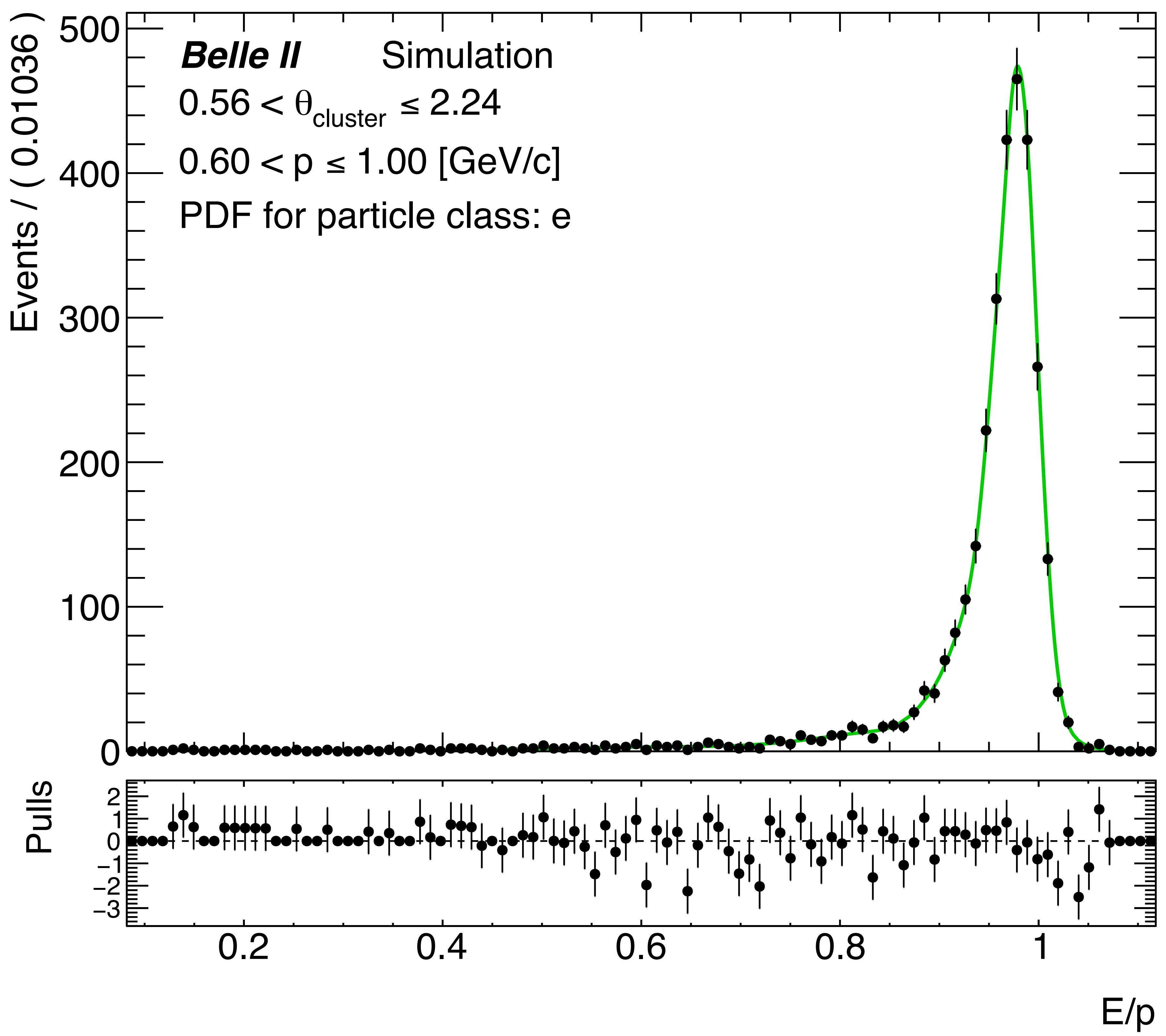
6.1 Standard proxy for *charged* ECL PID: *E/p*

Ratio of $E_{cluster}$ over p_{track} : "standard" variable, mostly designed for *electron* identification ($\rightarrow$ peaks at 1!)

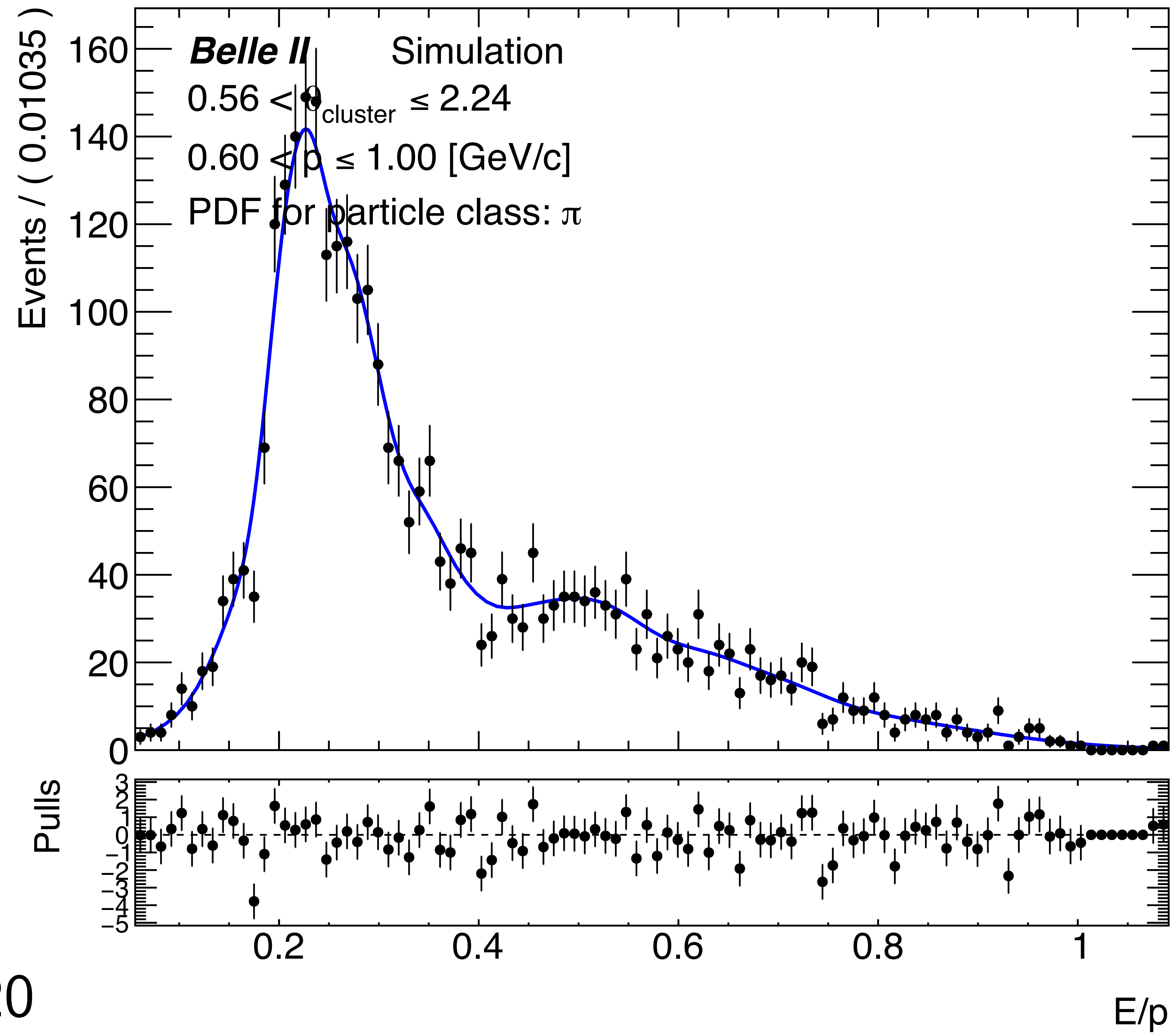
- *PDFs* defined in MC simulation from one-dimensional fits of *E/p* templates (single particle samples).

- Used to calculate likelihood of i-th particle type: $$\mathcal{L}_i^{ECL} = \mathcal{L}(x|i) = \mathcal{L}\left((E/p)_{obs}|(E/p)_i^{MC}\right)$$

e

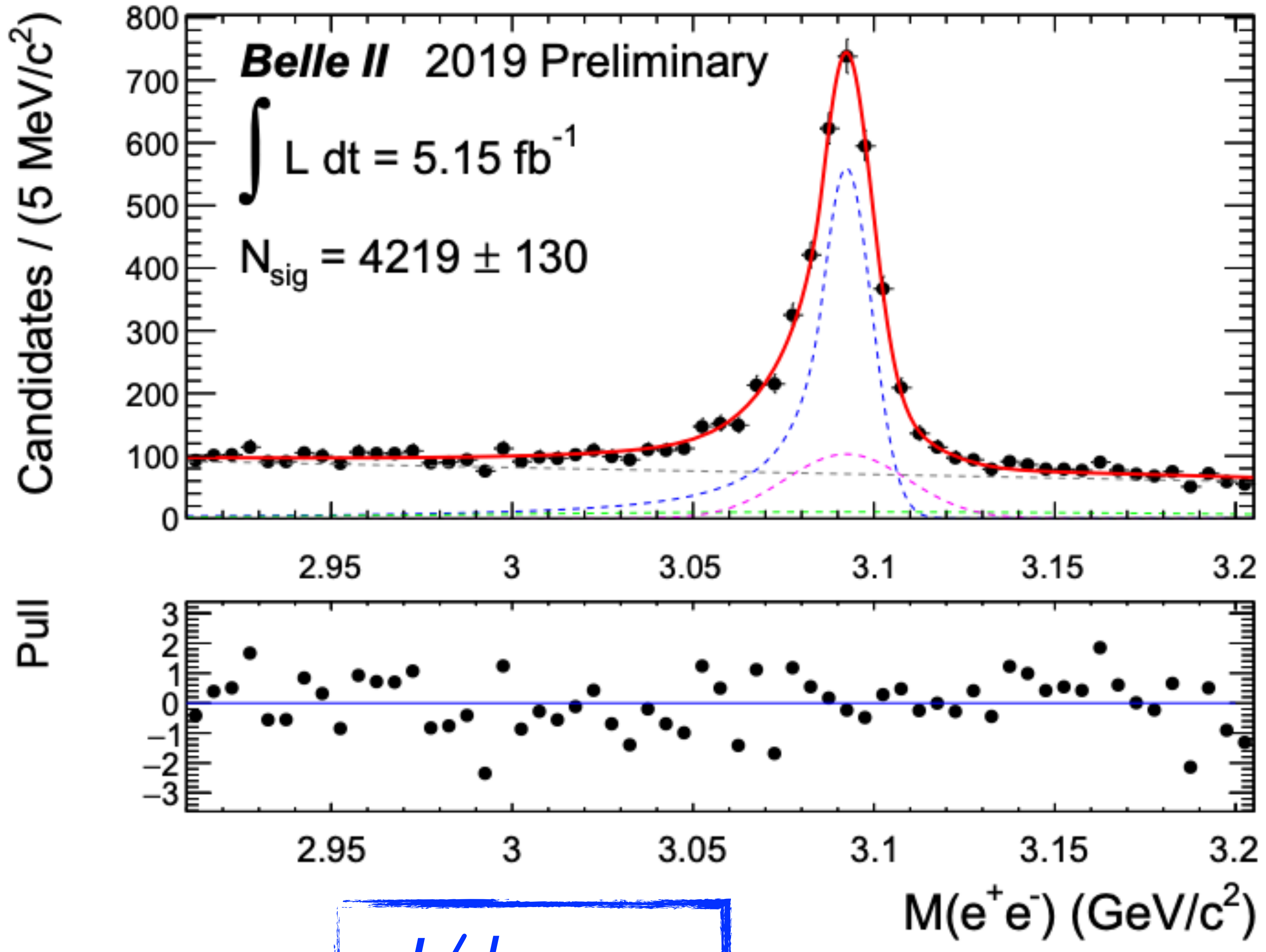


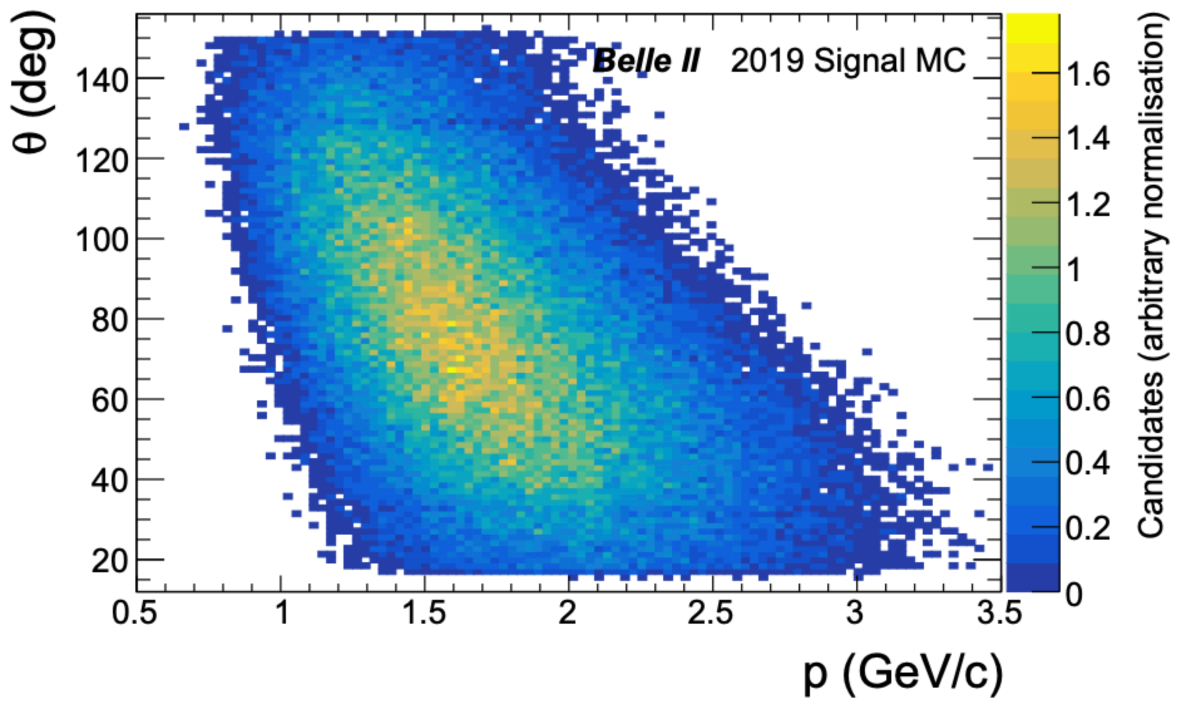
π



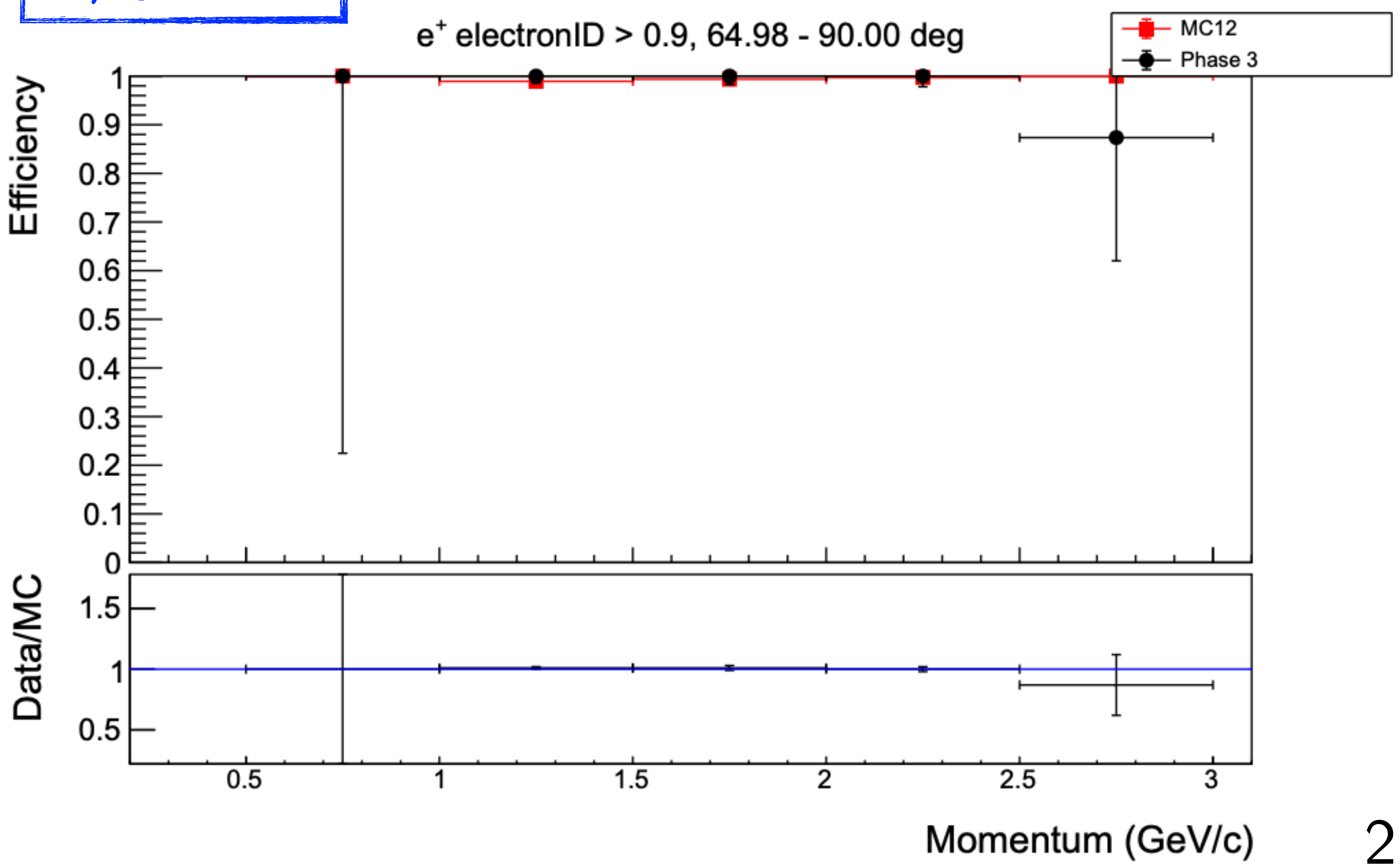
6.1 Standard proxy for *charged* ECL PID: E/p

(E/p-based) electron identification performance in early *Belle II* data studied in J/ψ decays, as well as $ee \to eeee$ events

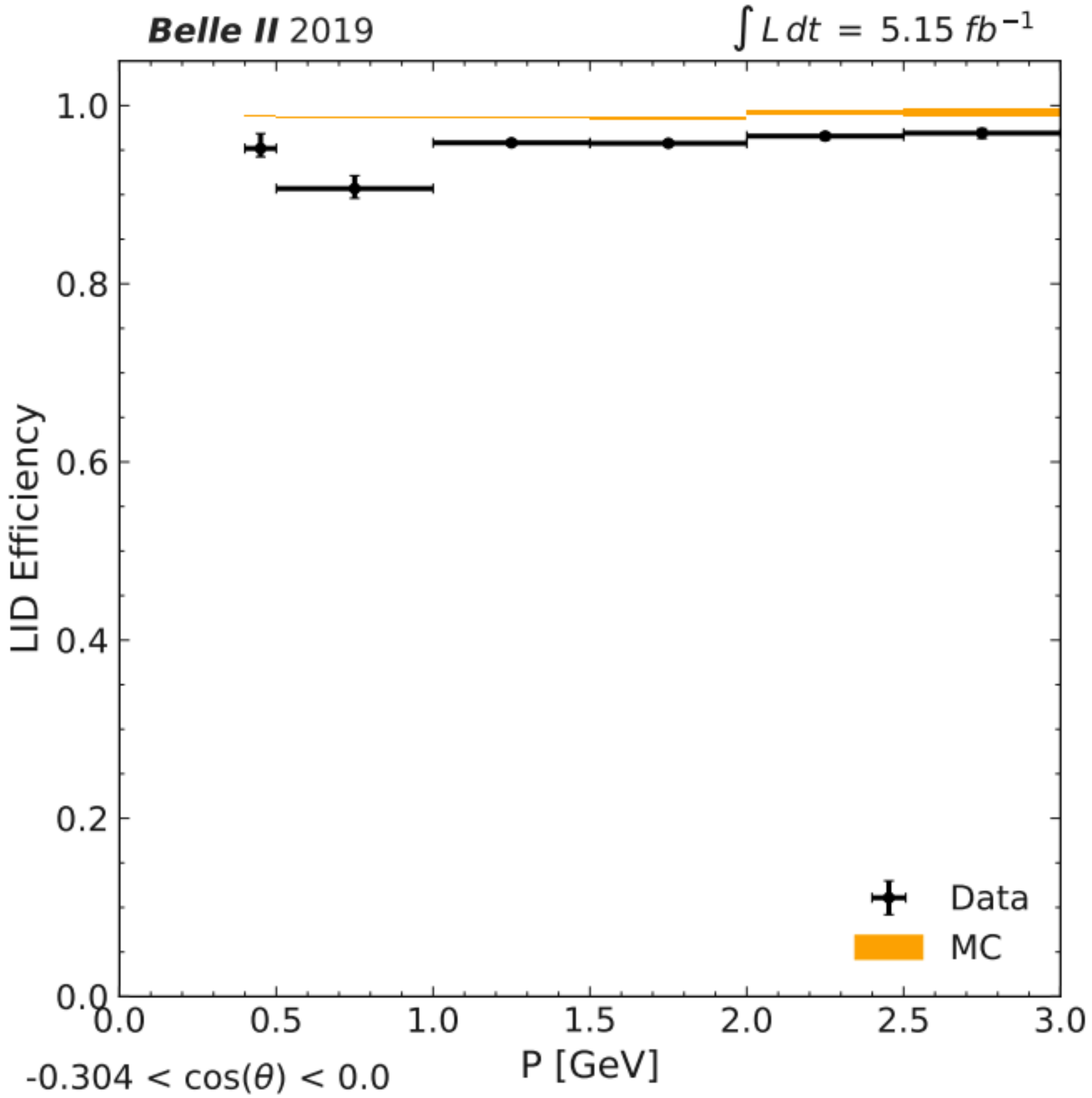




$J/\psi \to ee$



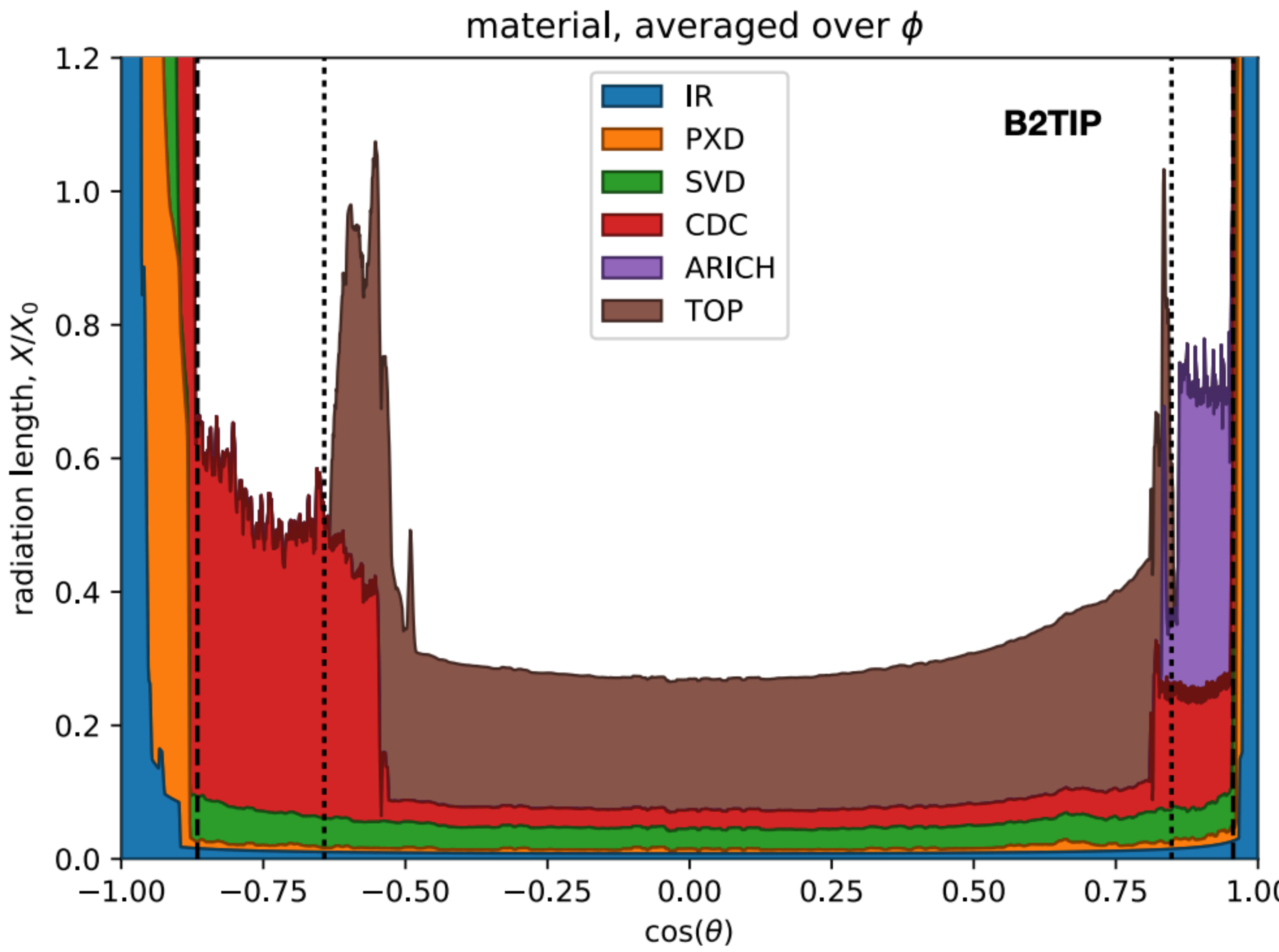
$ee \to eeee$

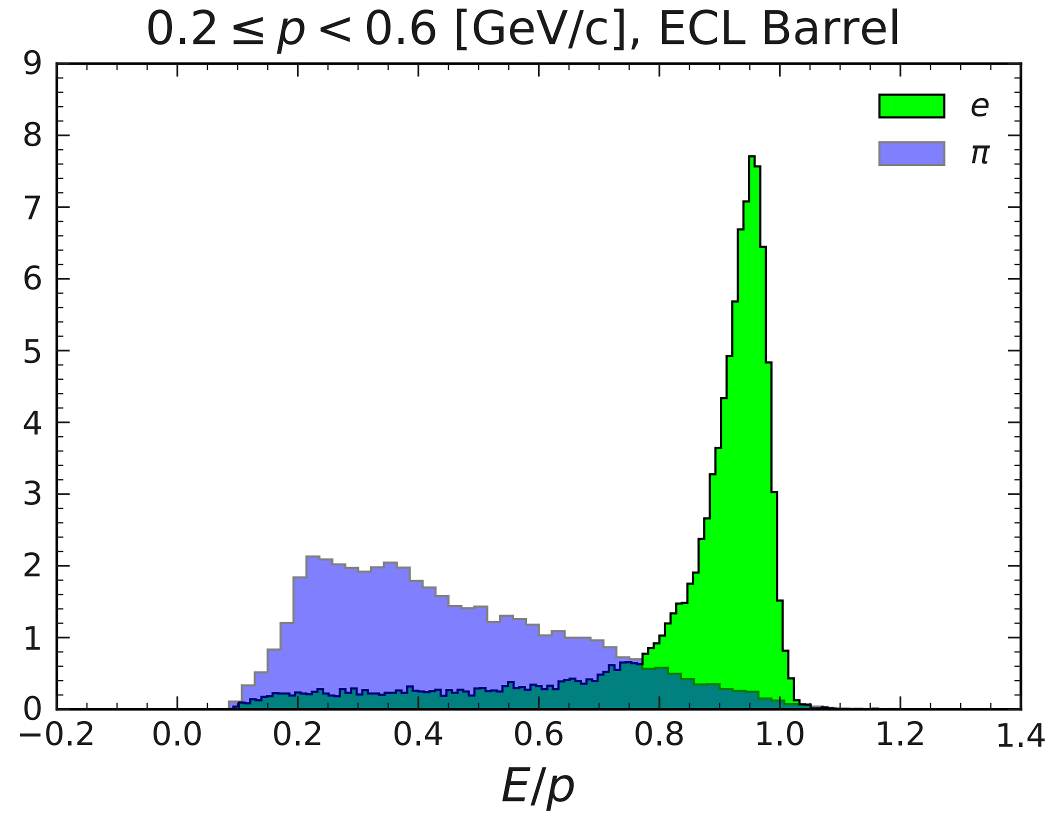


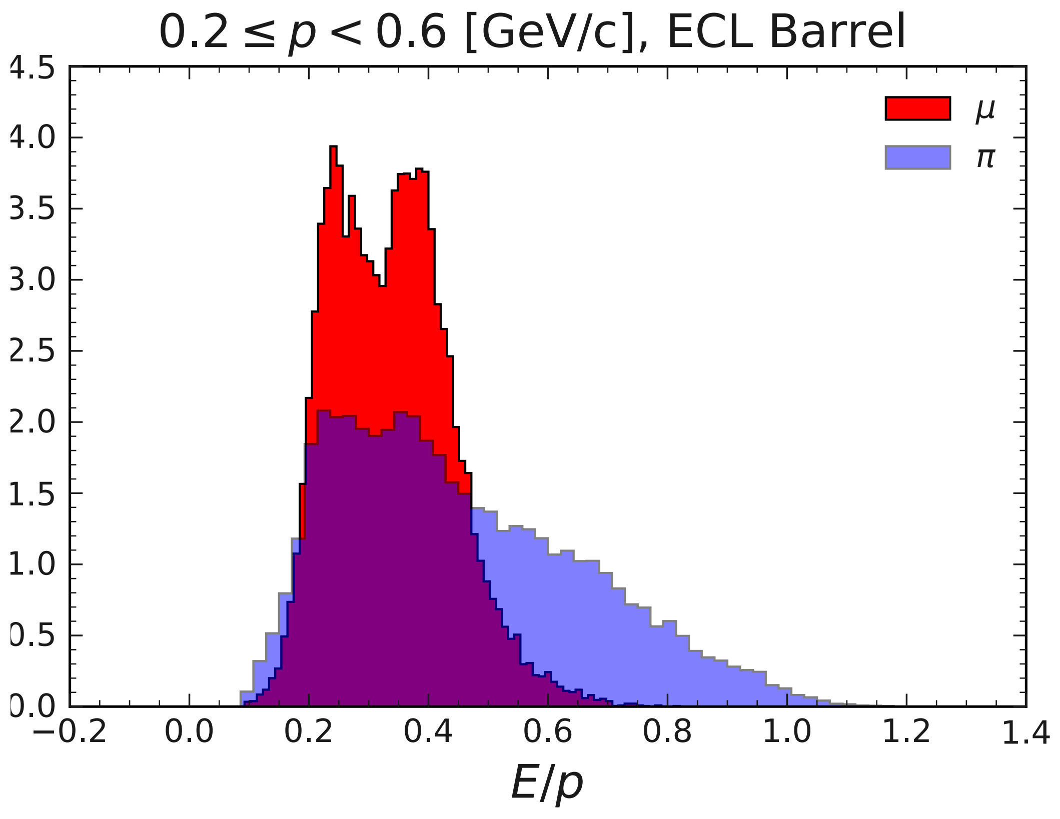
6.2 The low momentum PID challenge

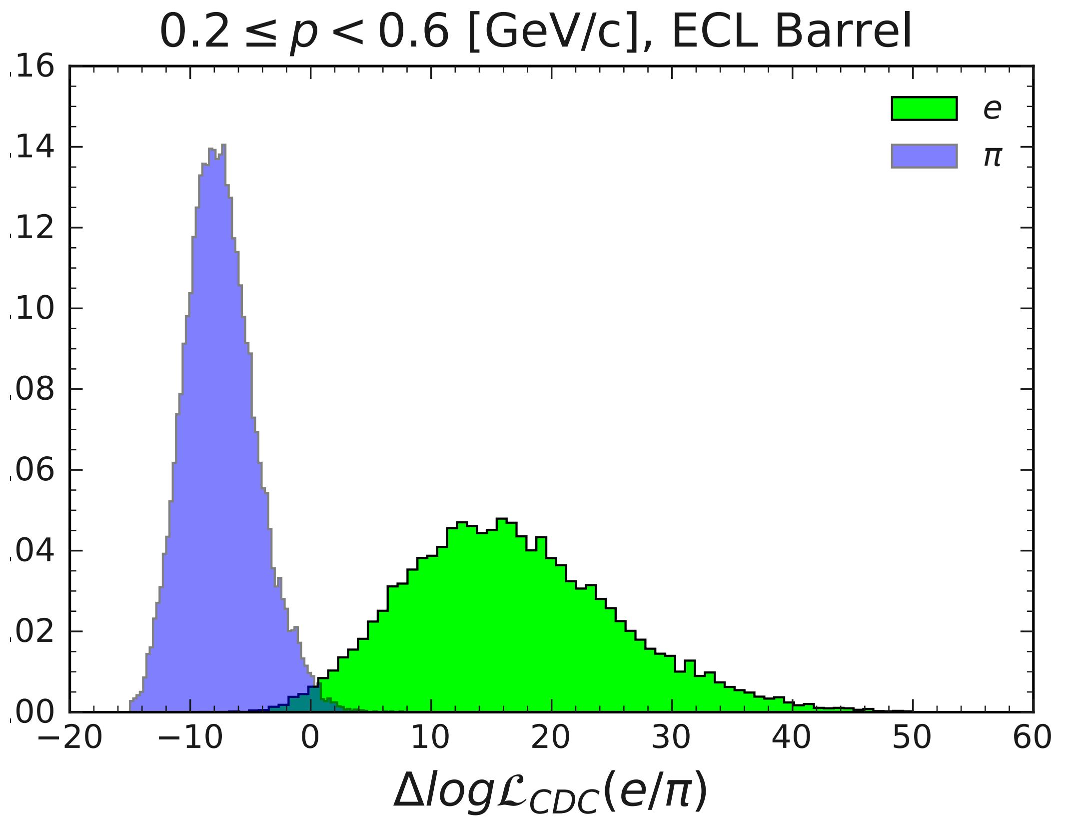
At low momenta, E/p by itself becomes sub-optimal for PID purposes:

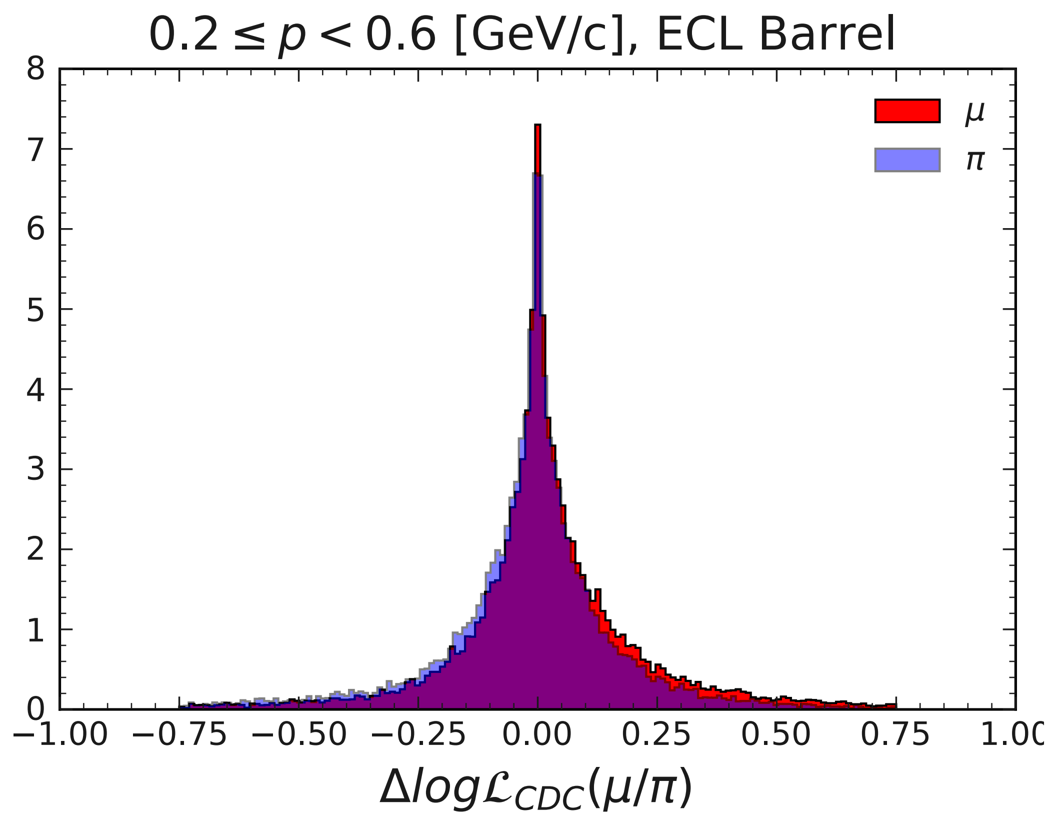
- Electrons: larger bremsstrahlung losses before the ECL + stronger track bending.
  - Separation power partially recovered by CDC.
- Muons: if $p_T < 600$ GeV/c, they fall outside of the KLM acceptance.

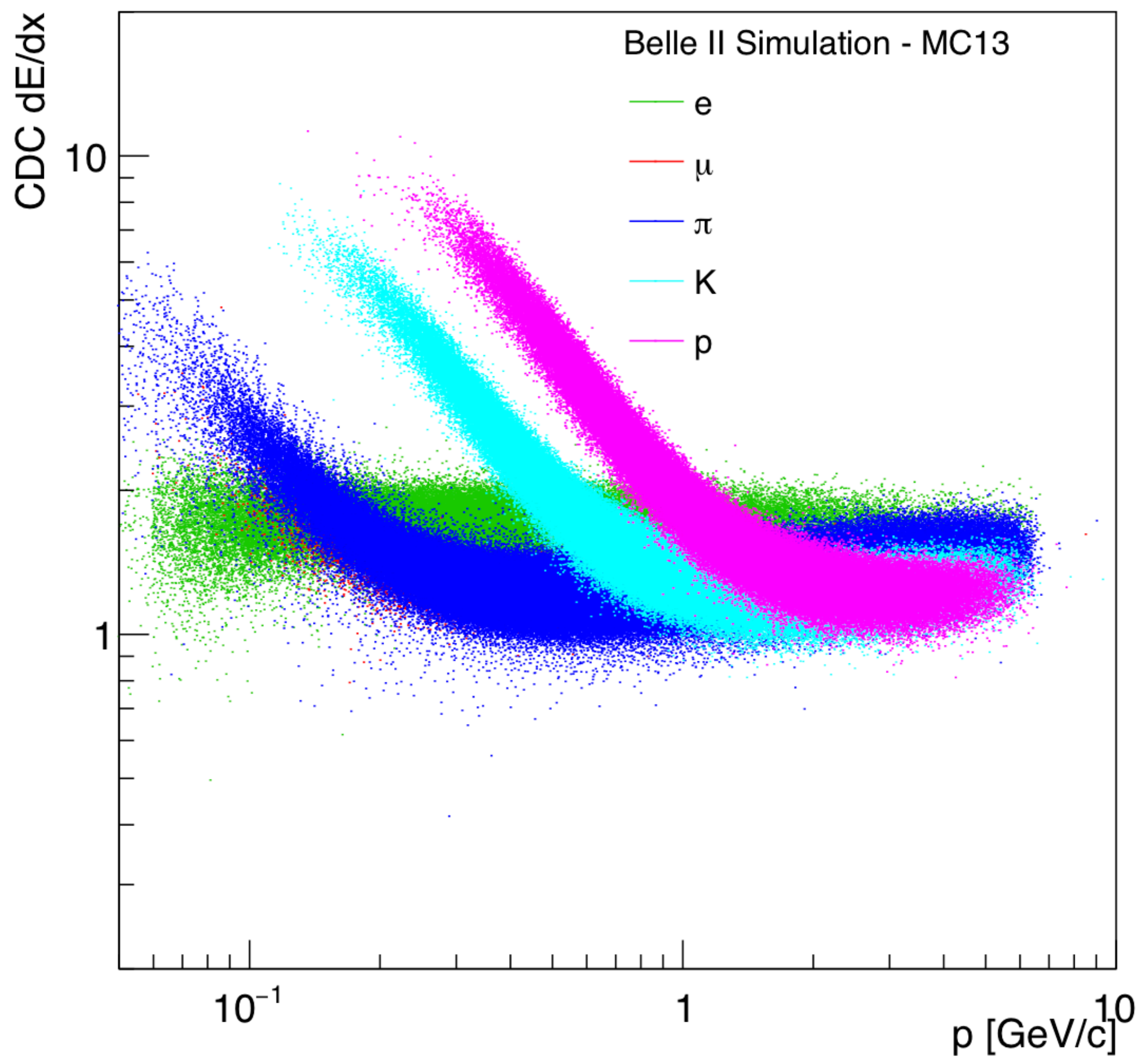


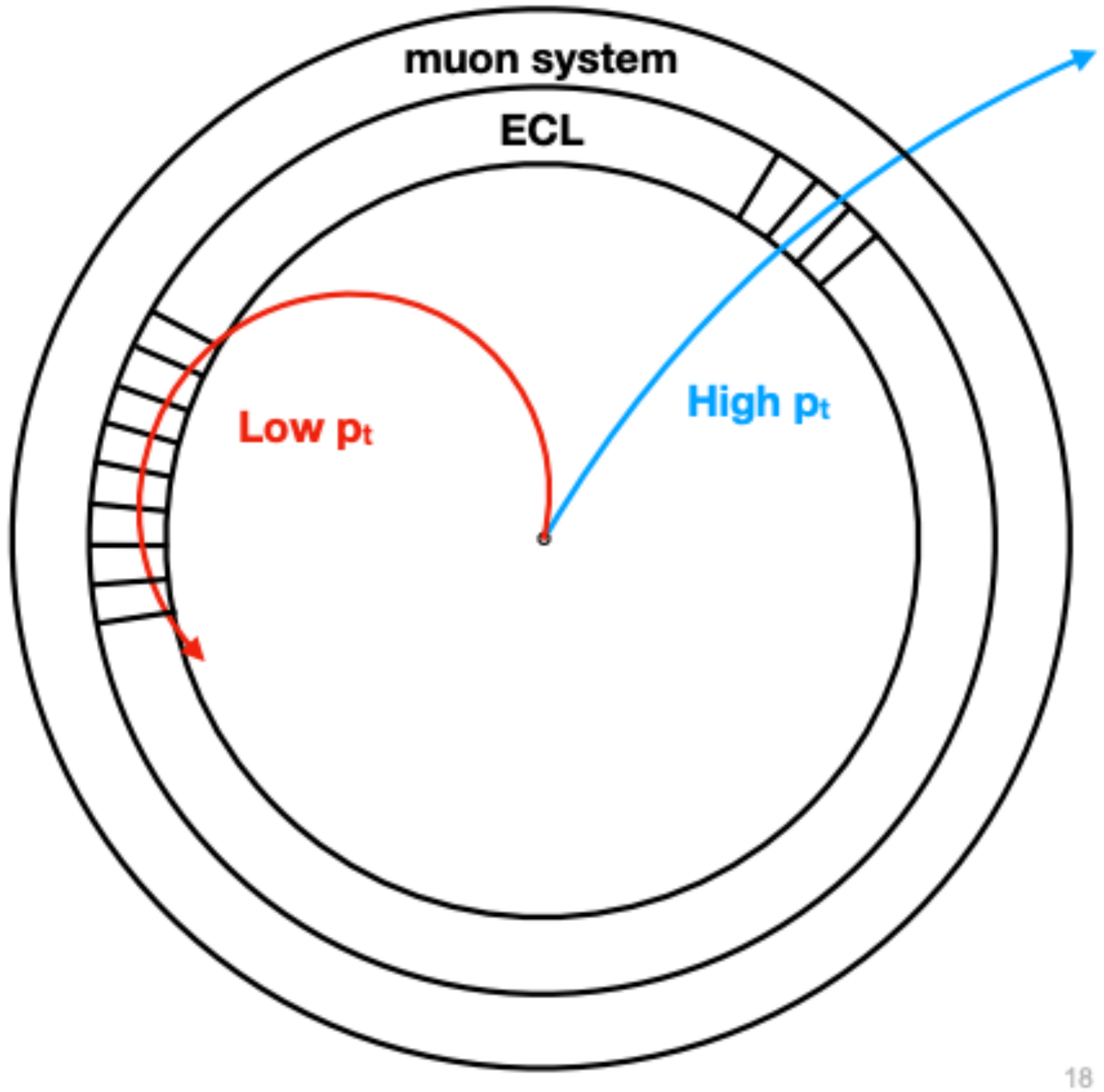










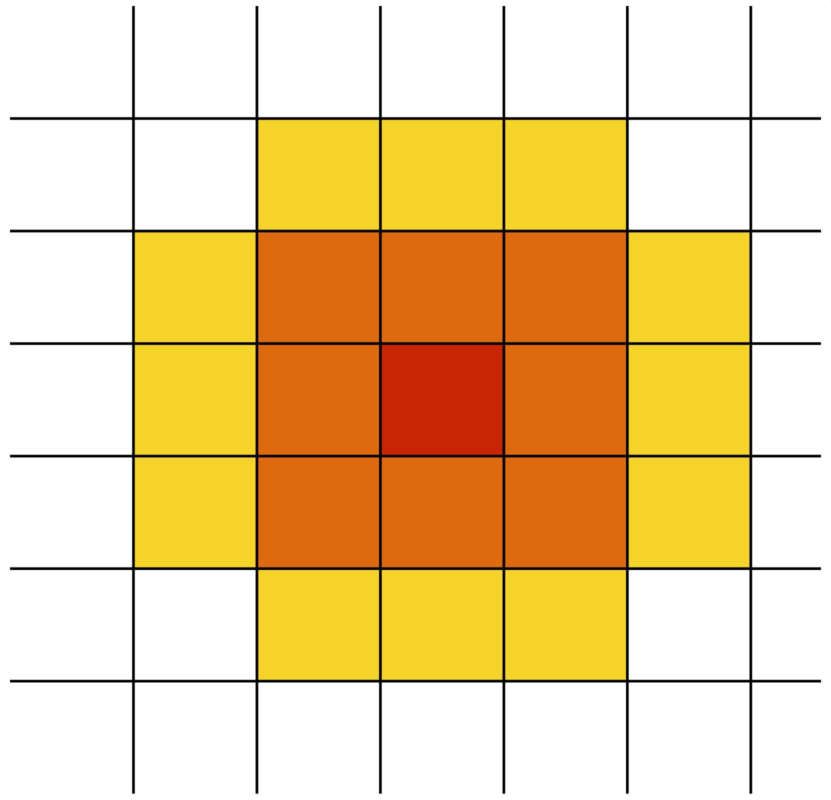


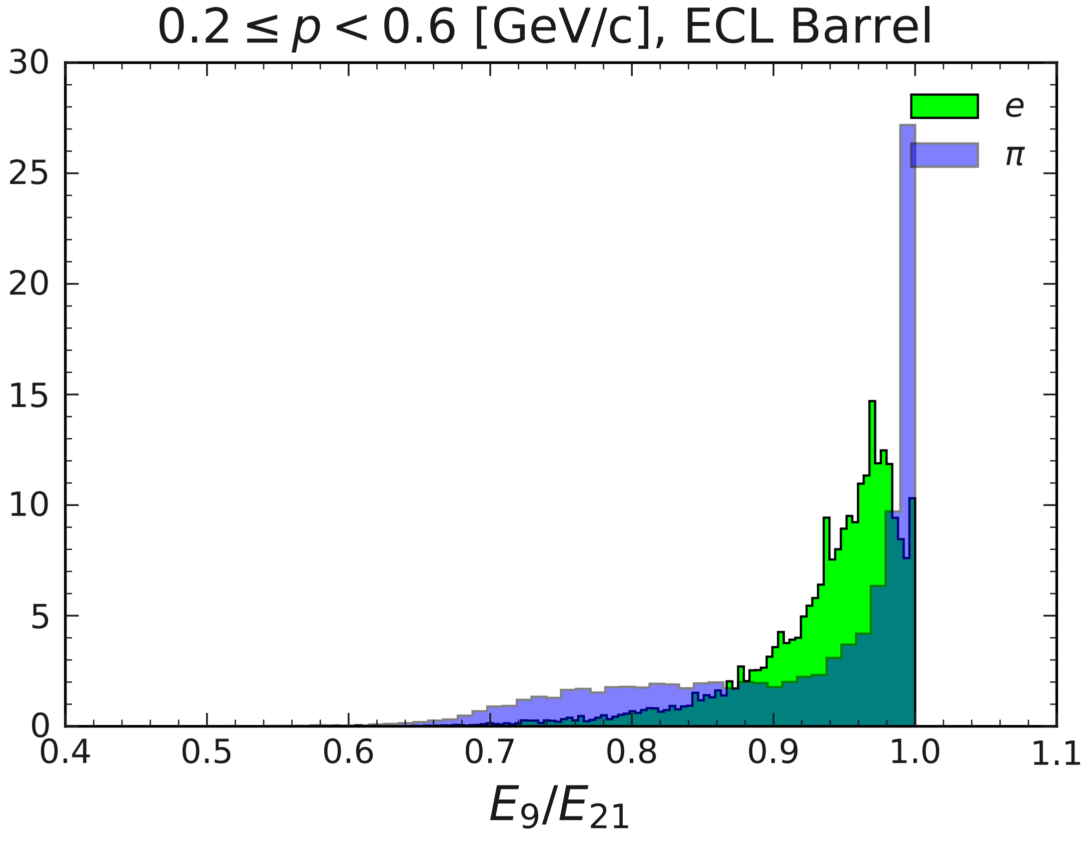
6.2 Novel improvements to (low *p*) ECL PID - BDT

Combine several ECL observables in a BDT → exploit non-trivial correlations among shower shape variables, *E*/*p*, PSD...

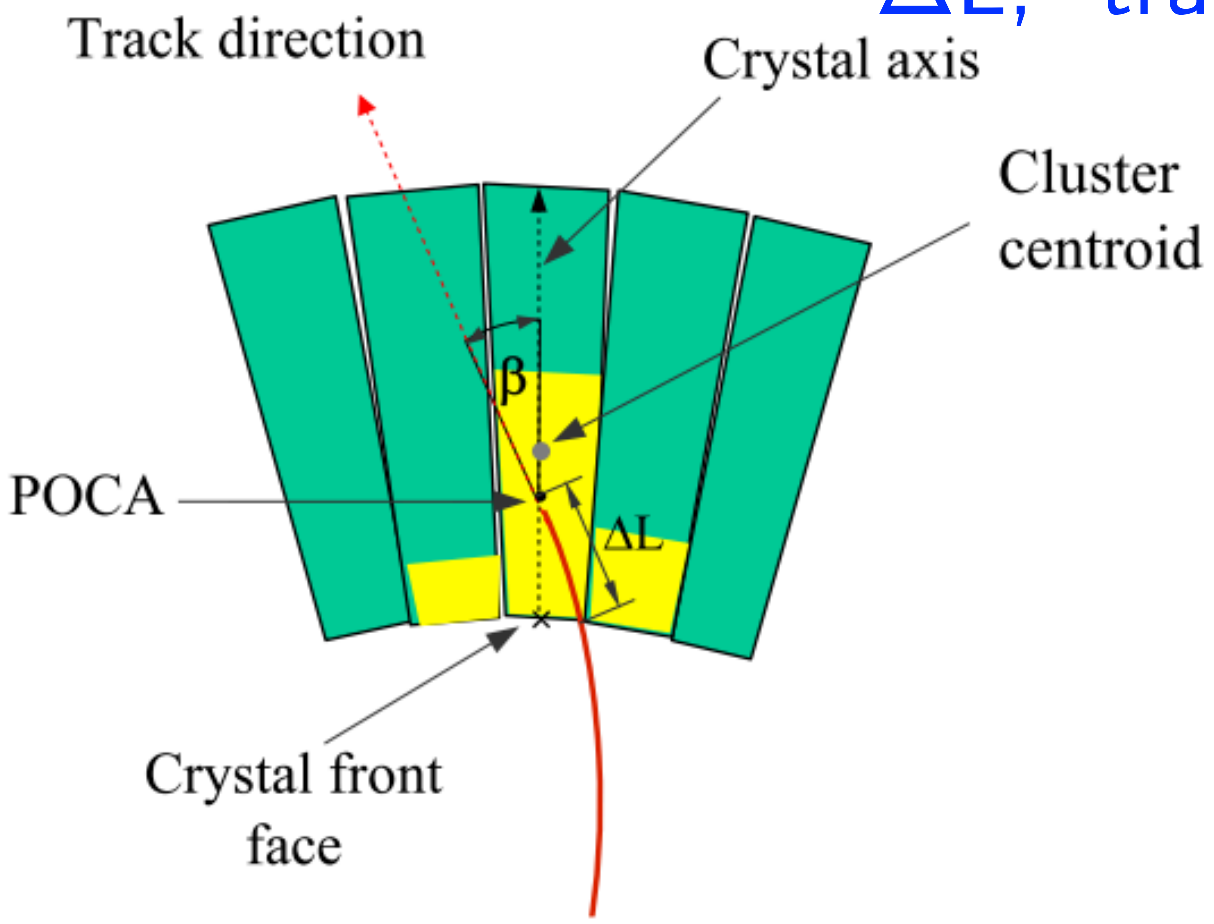
Examples:

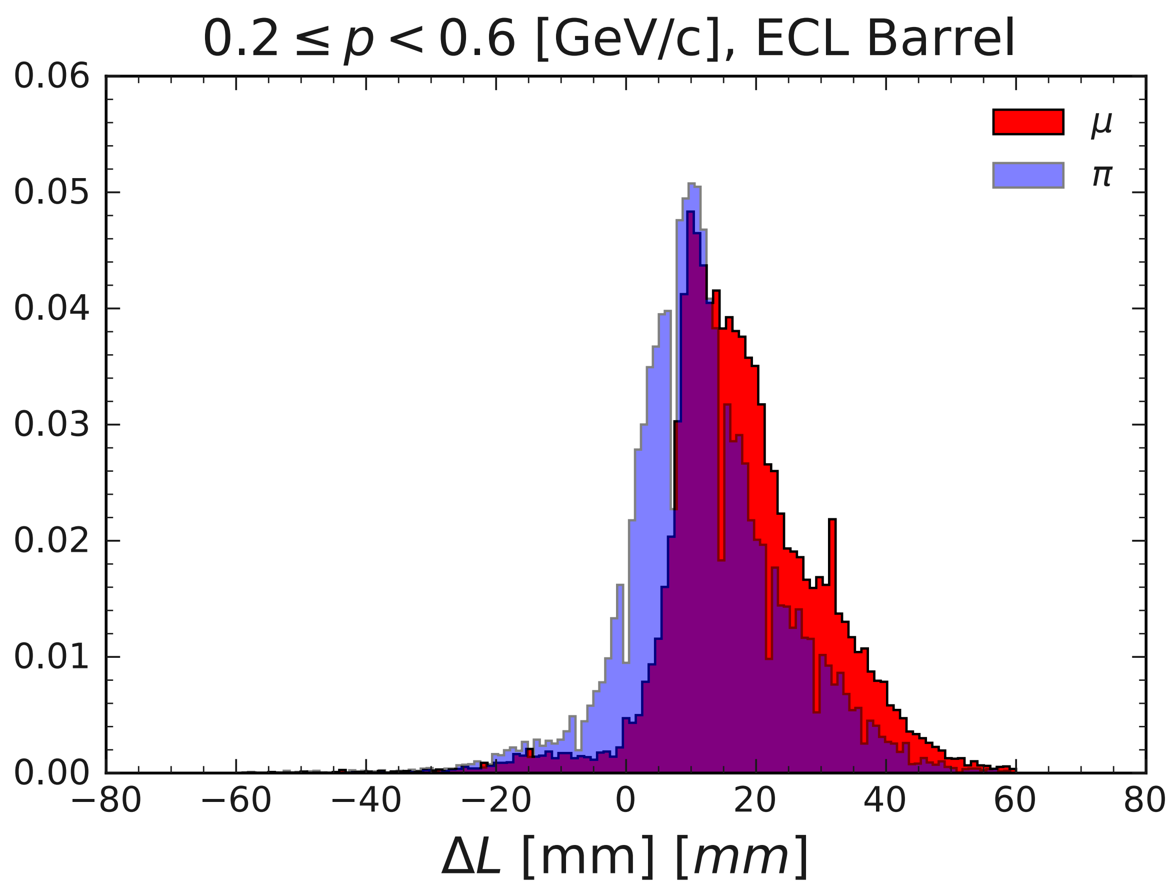
E_9/E_{21}





ΔL, "track depth"

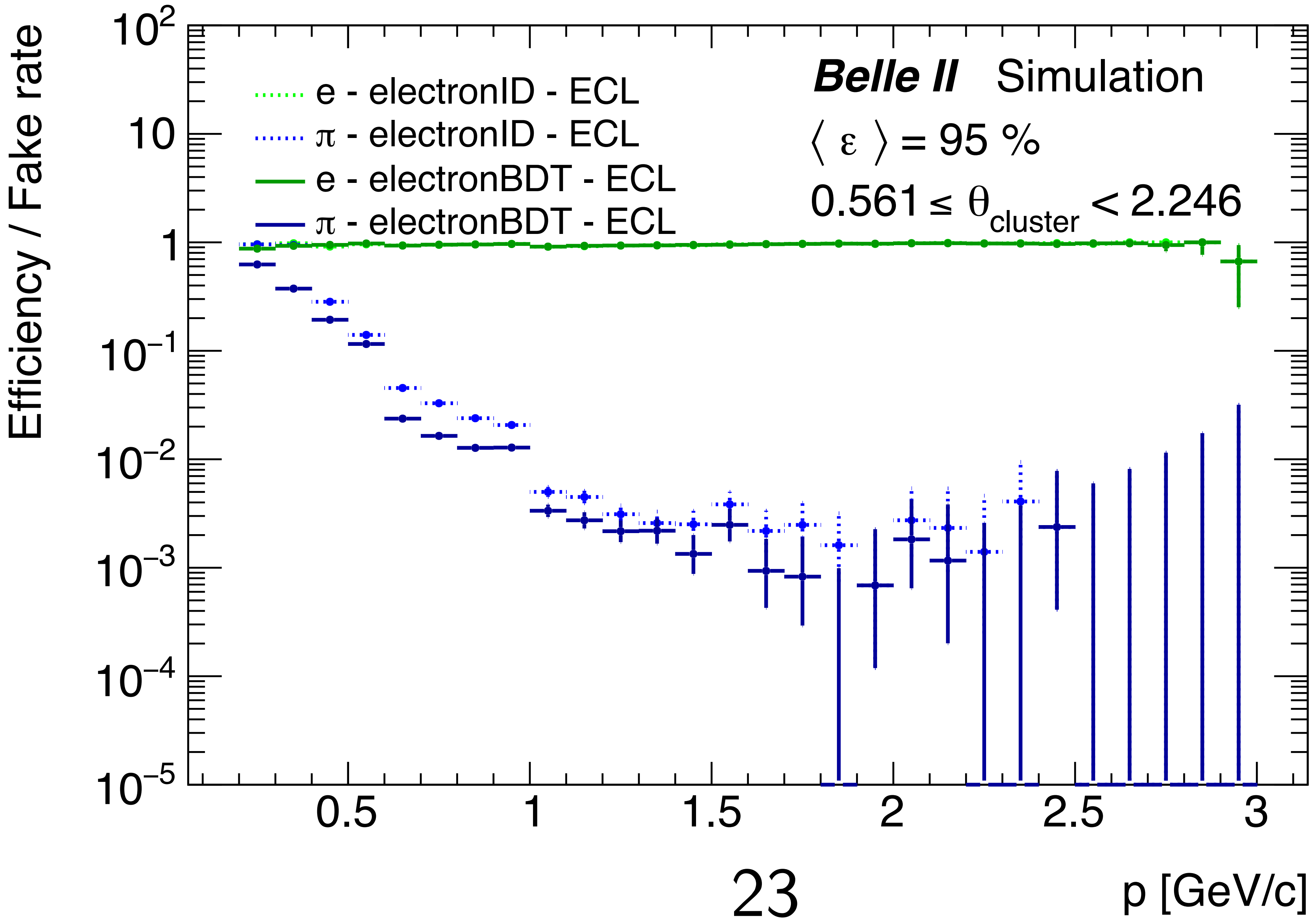


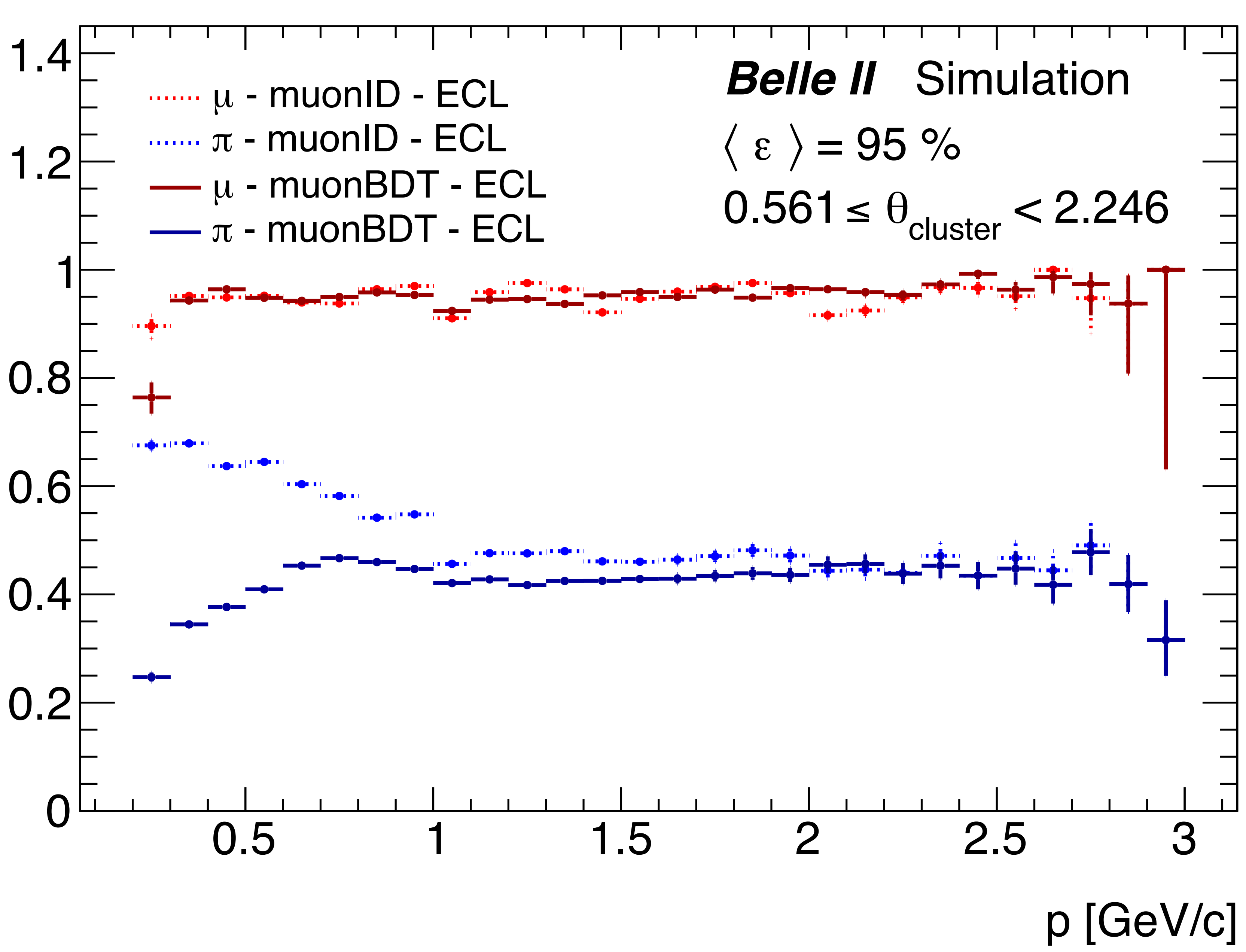


- Background (π) rejection

(→1/fake rate) strongly improved

wr.t simple *E*/*p*-based PID:

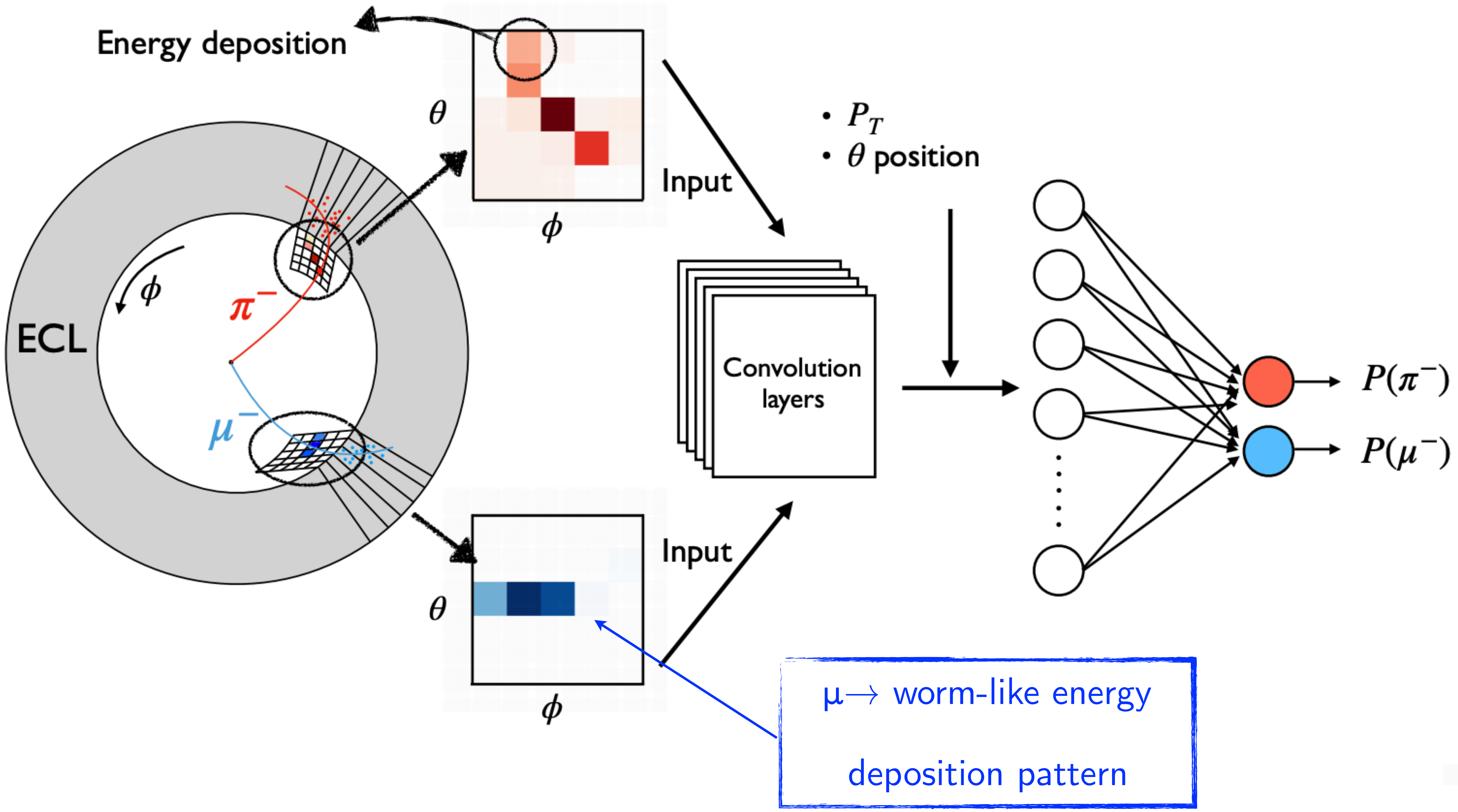


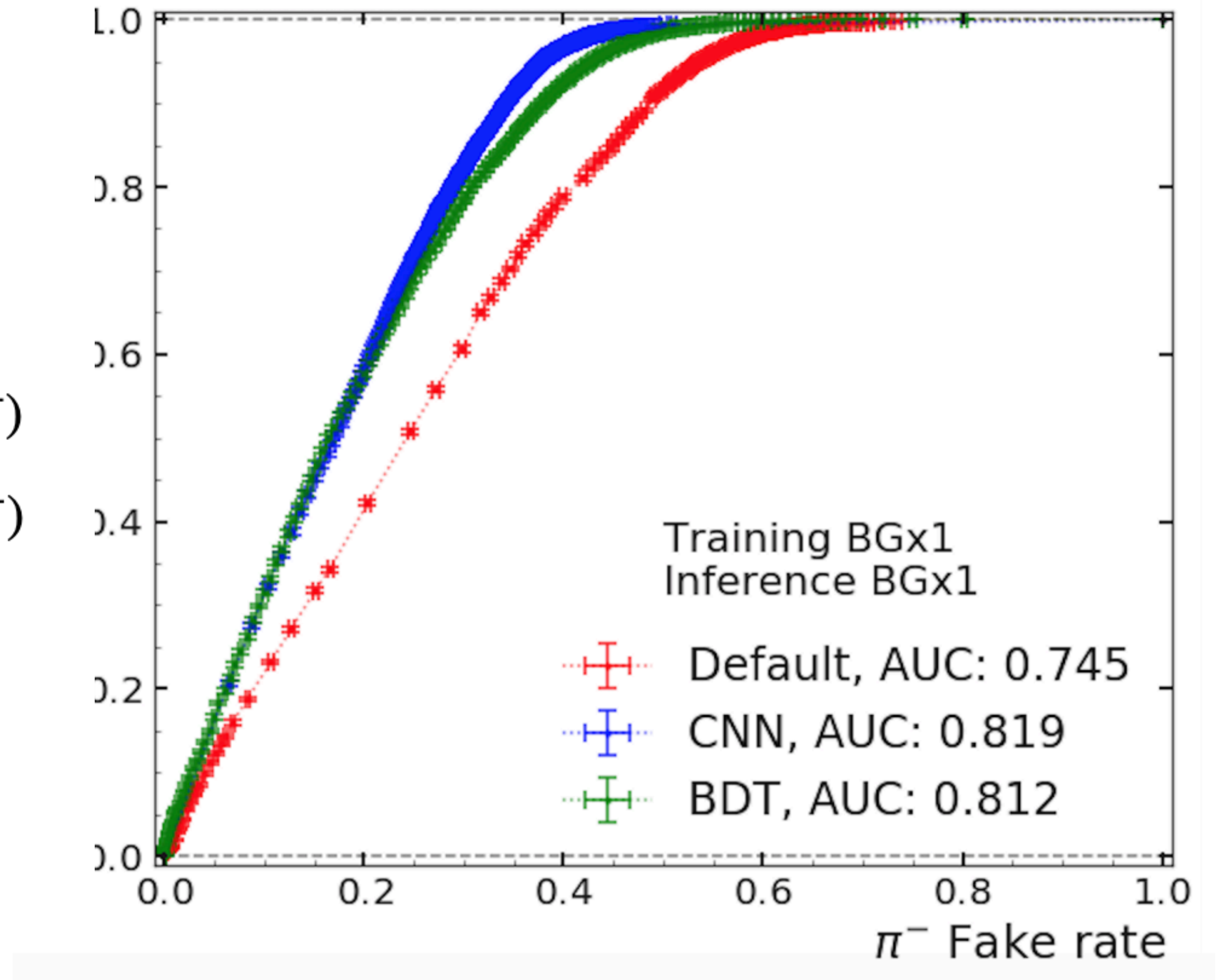


6.2 Novel improvements to (low p) ECL PID - Convolutional NN

Feed raw energy information (instead of higher level variables like shower shapes) in a convolutional NN architecture.

- Train algorithm on (pre-processed) calorimeter cells images for μ and π.
- Idea is by-pass clustering algorithm shortcomings when dealing with "atypical" energy deposition patterns.





Questions?

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