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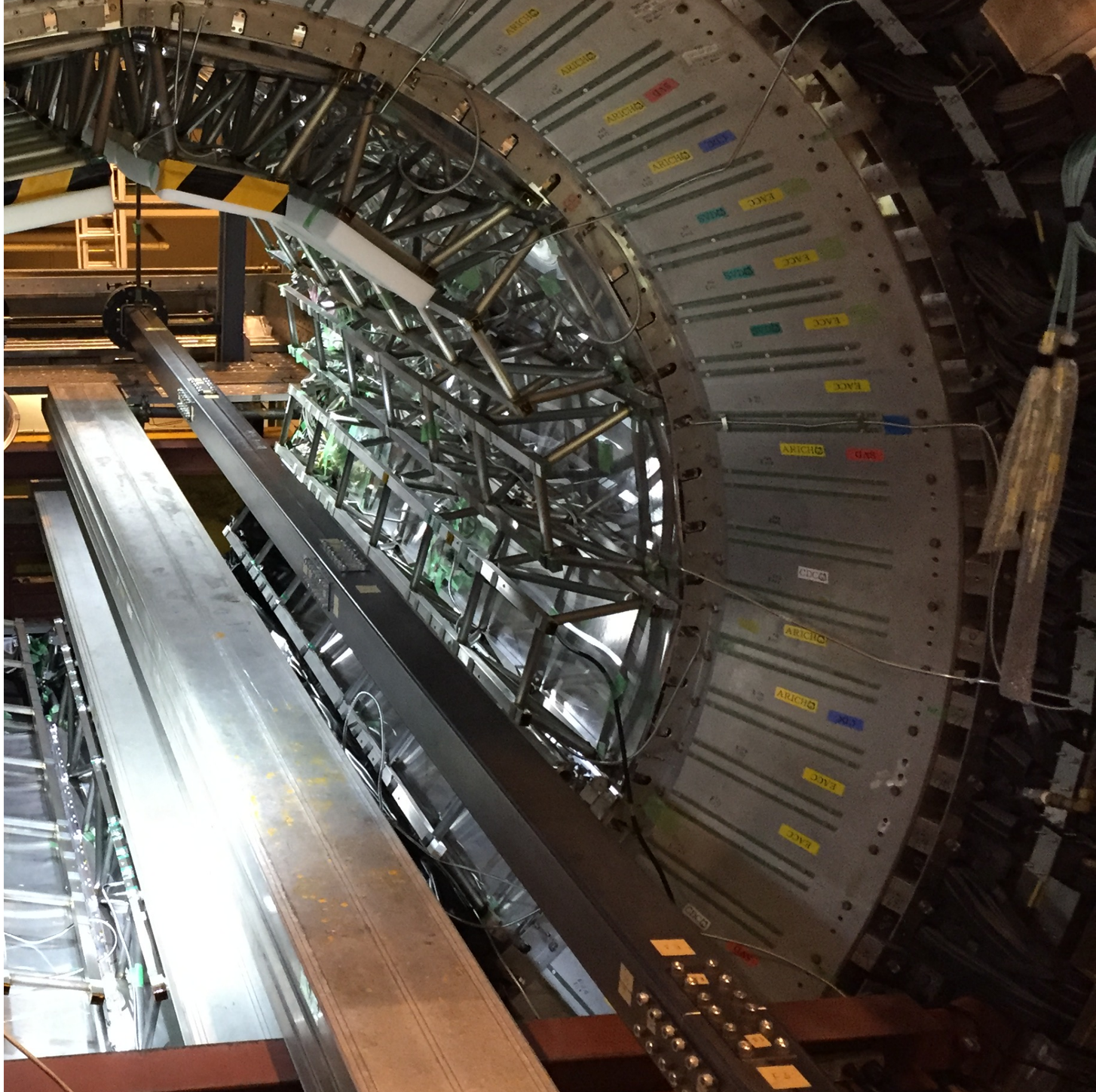
Charged Particle ID in Belle II

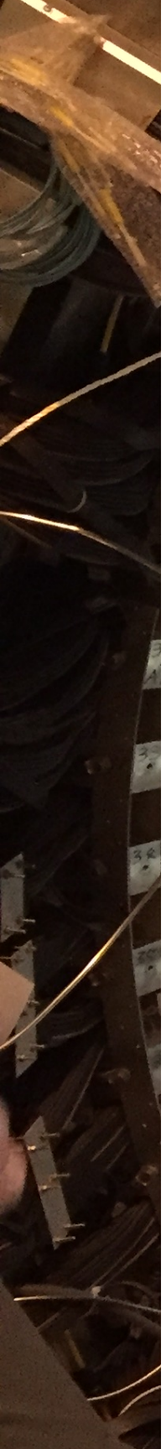
October 28, 2019

Jan Strube



U.S. DEPARTMENT OF ENERGY BATTELLE

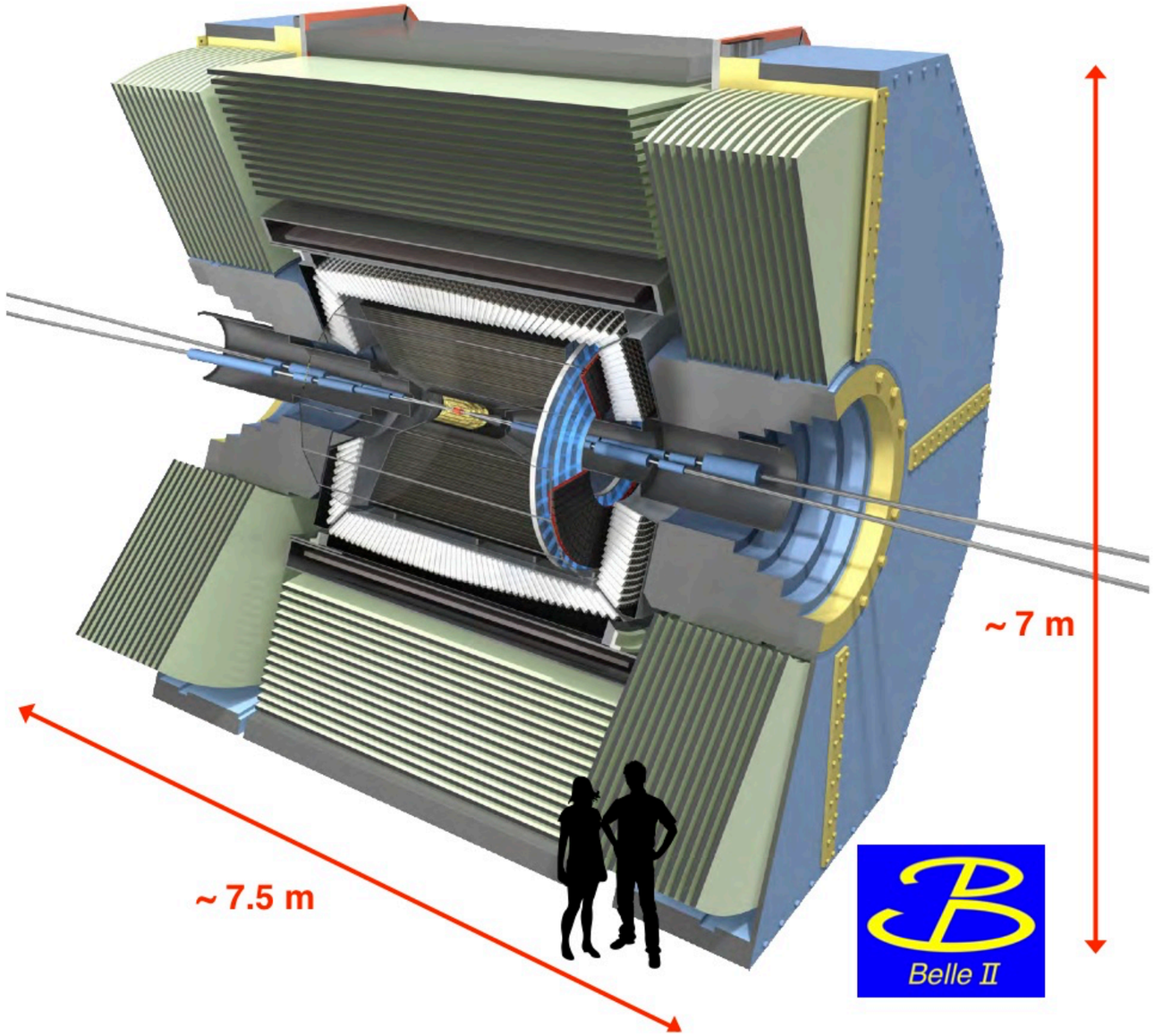
PNNL is operated by Battelle for the U.S. Department of Energy

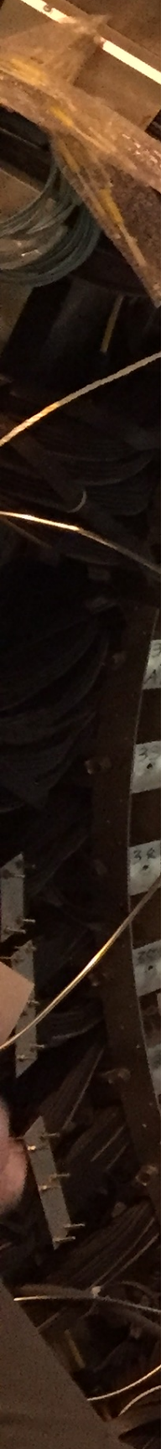


Outline

- Background
  - How to measure particle ID
- PID Detectors in Belle II
- Hands-on session
  - Reconstruction of D* decays and study of PID performance

The Belle II detector





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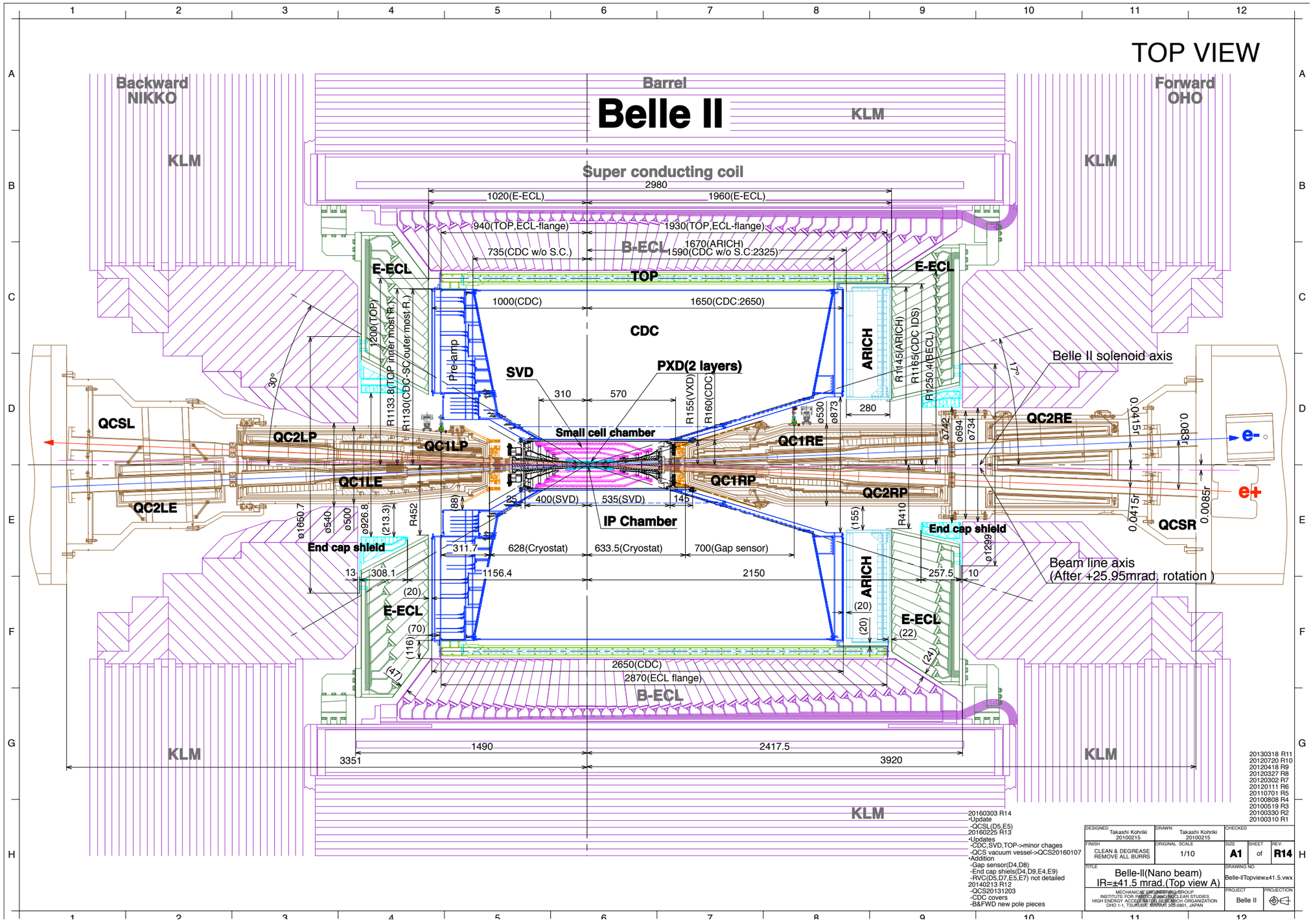
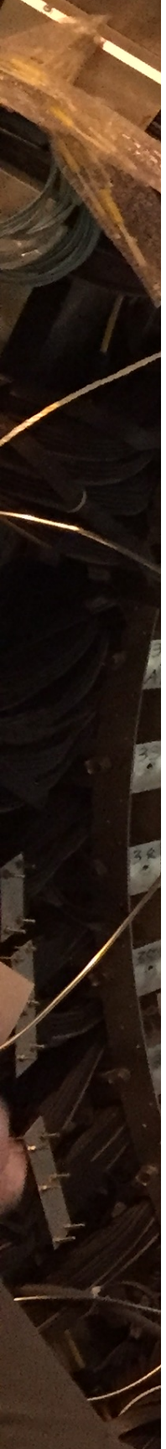
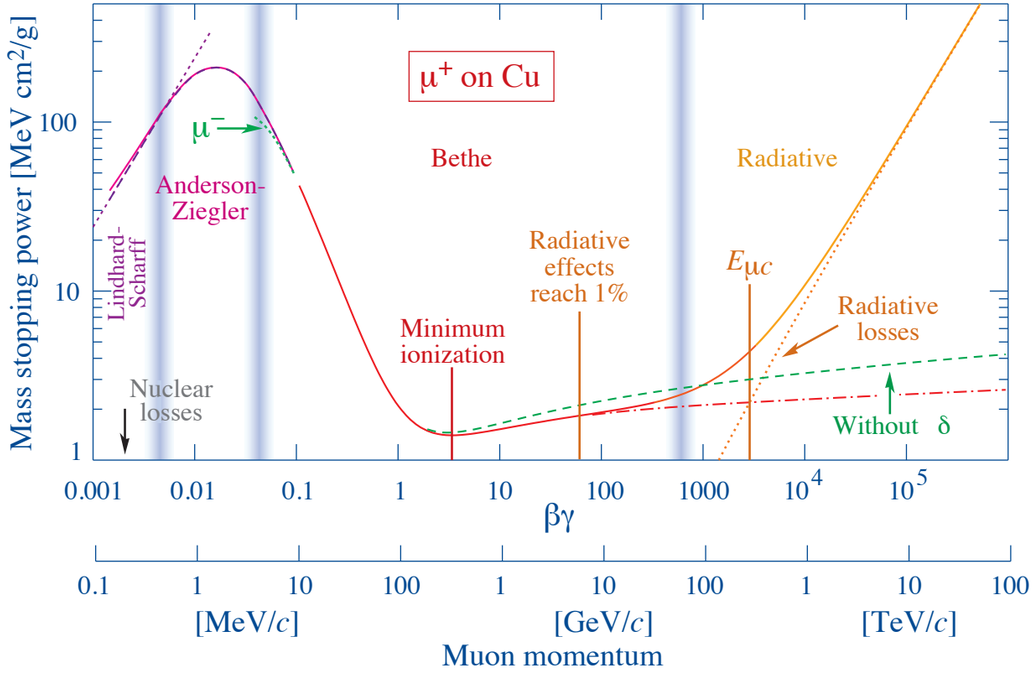




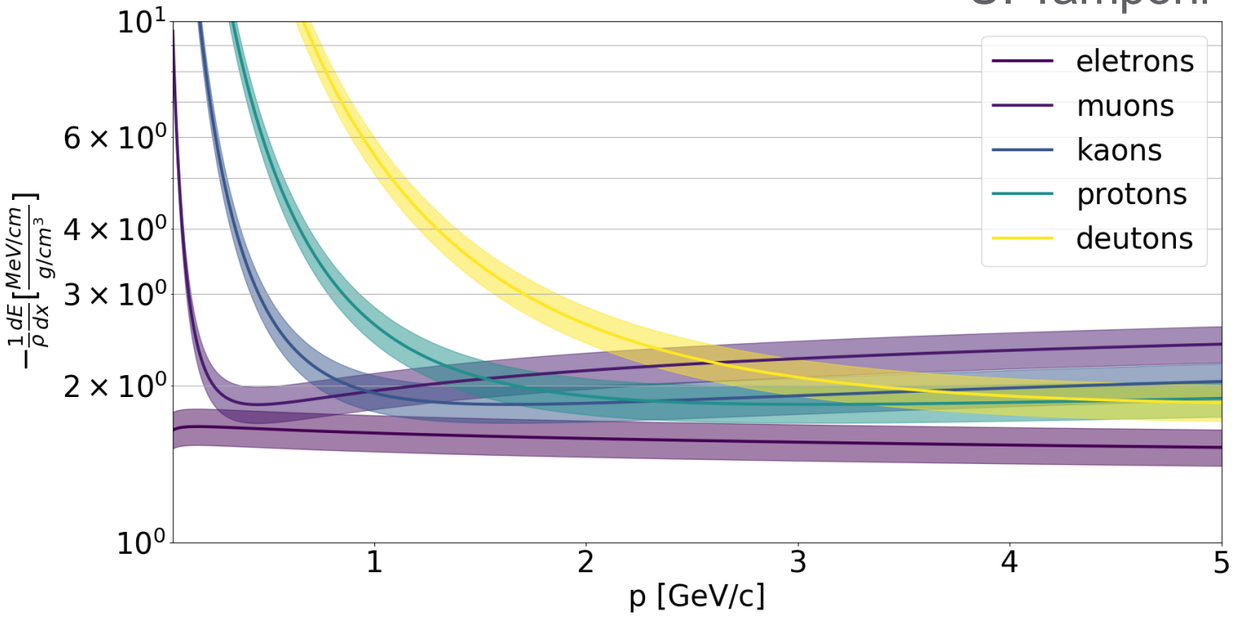
Density correction:
Density dependent polarization effect ...
Shielding of electrical field far from particle path;
effectively cuts of the long range contribution ...
More relevant at high γ

For **heavy** particles ($m >> m_e$):

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



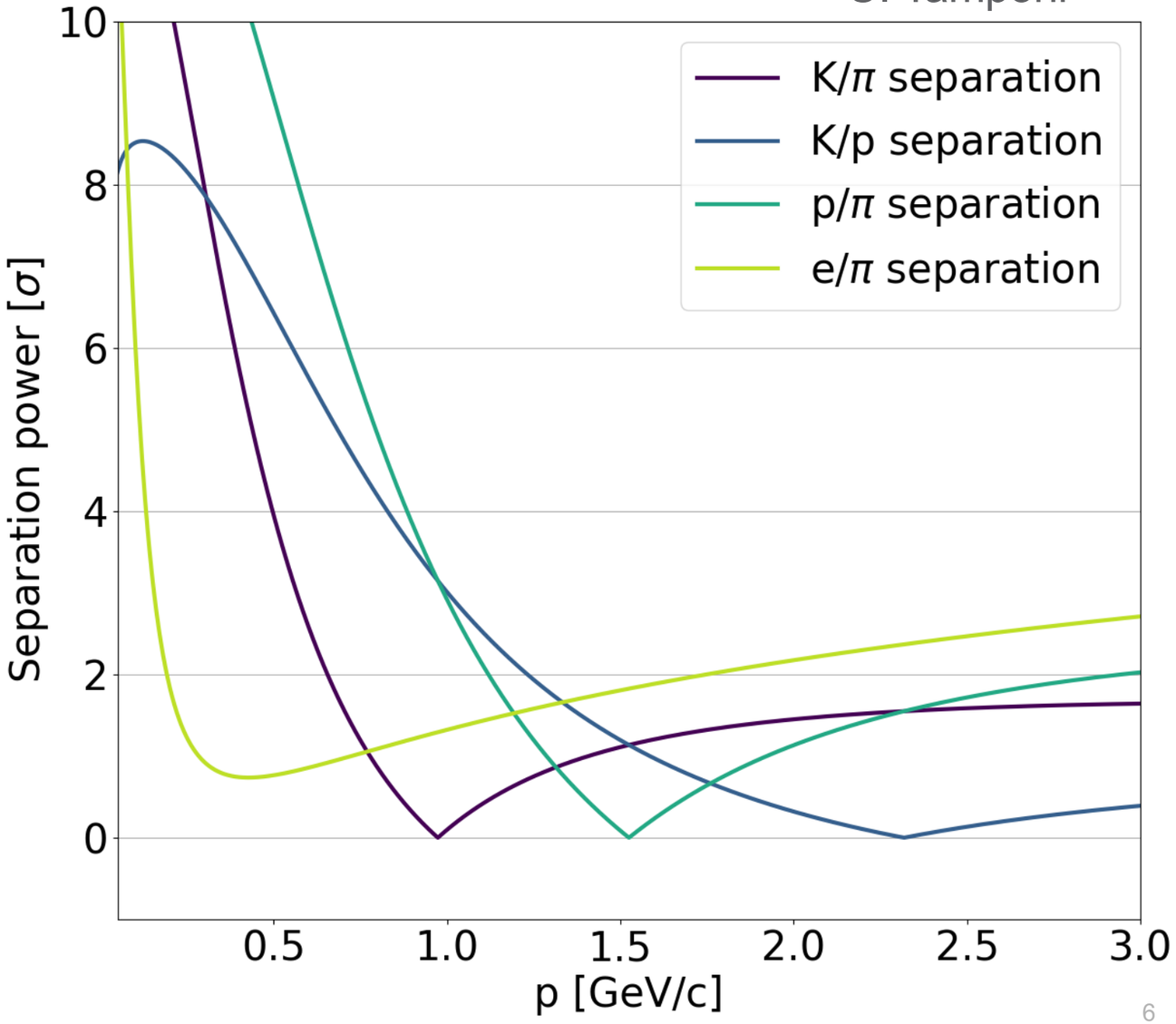
U. Tamponi



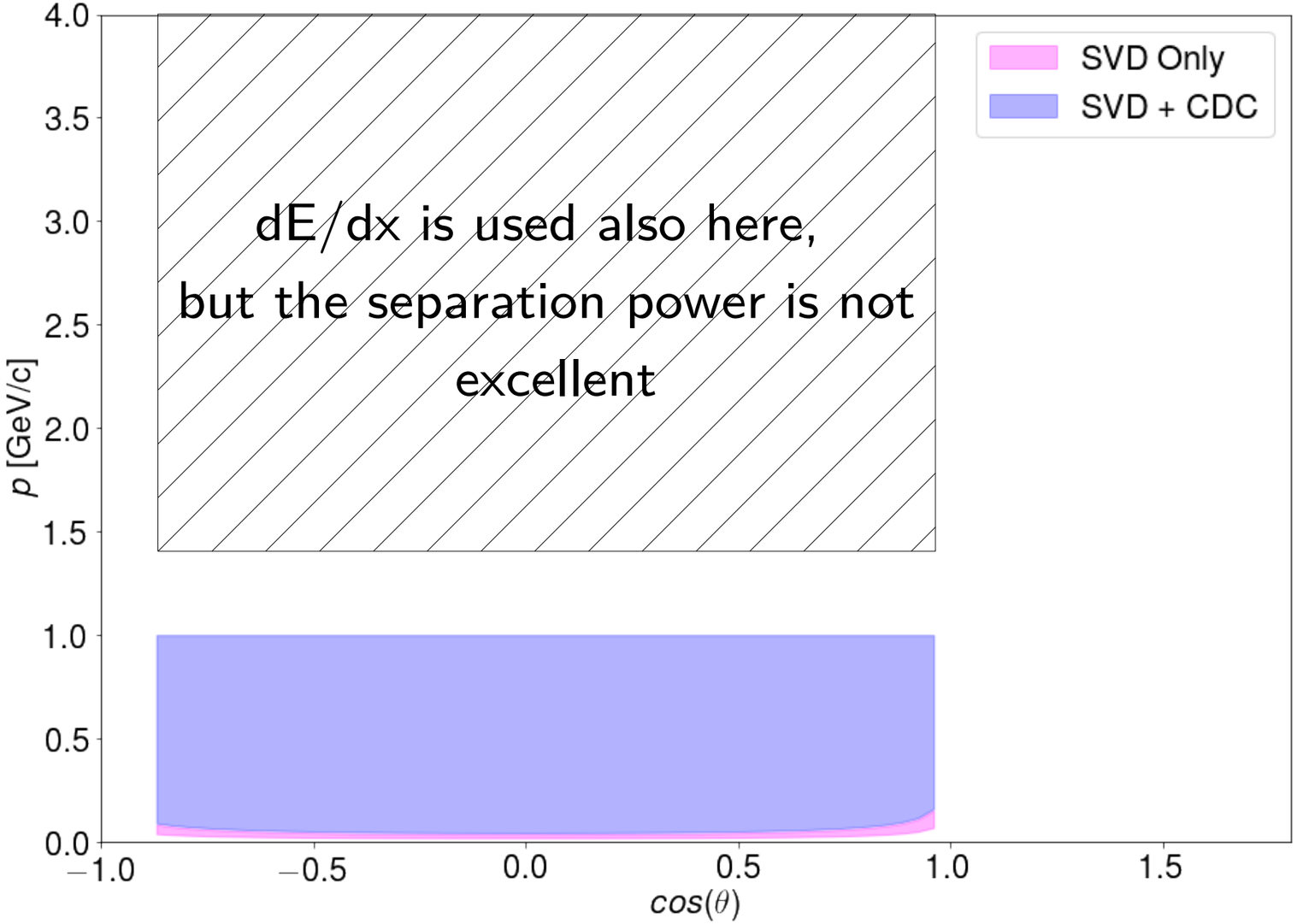
Separation power of dE/dx in Belle II

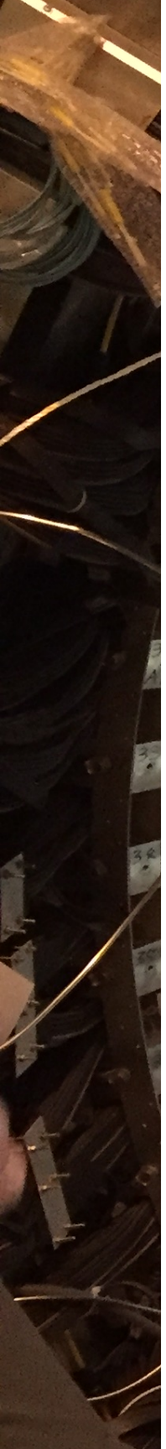
U. Tamponi

Using a sample of single particles, we can measure the degree of separation between different particle species

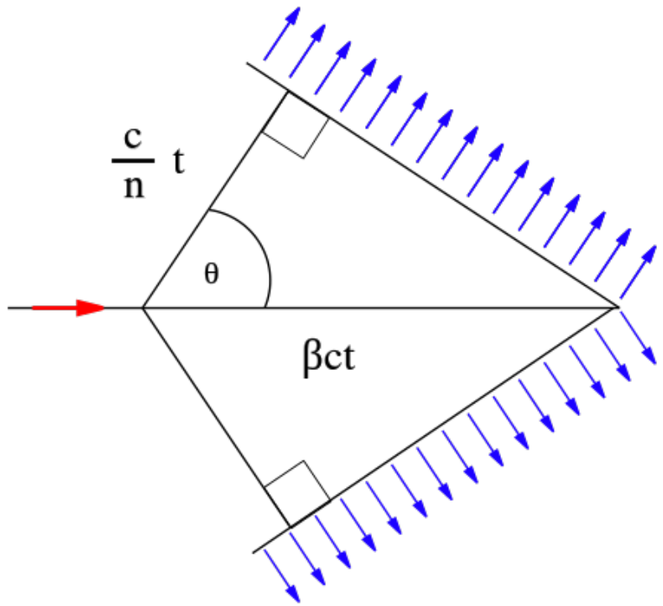


Coverage of the tracking detectors

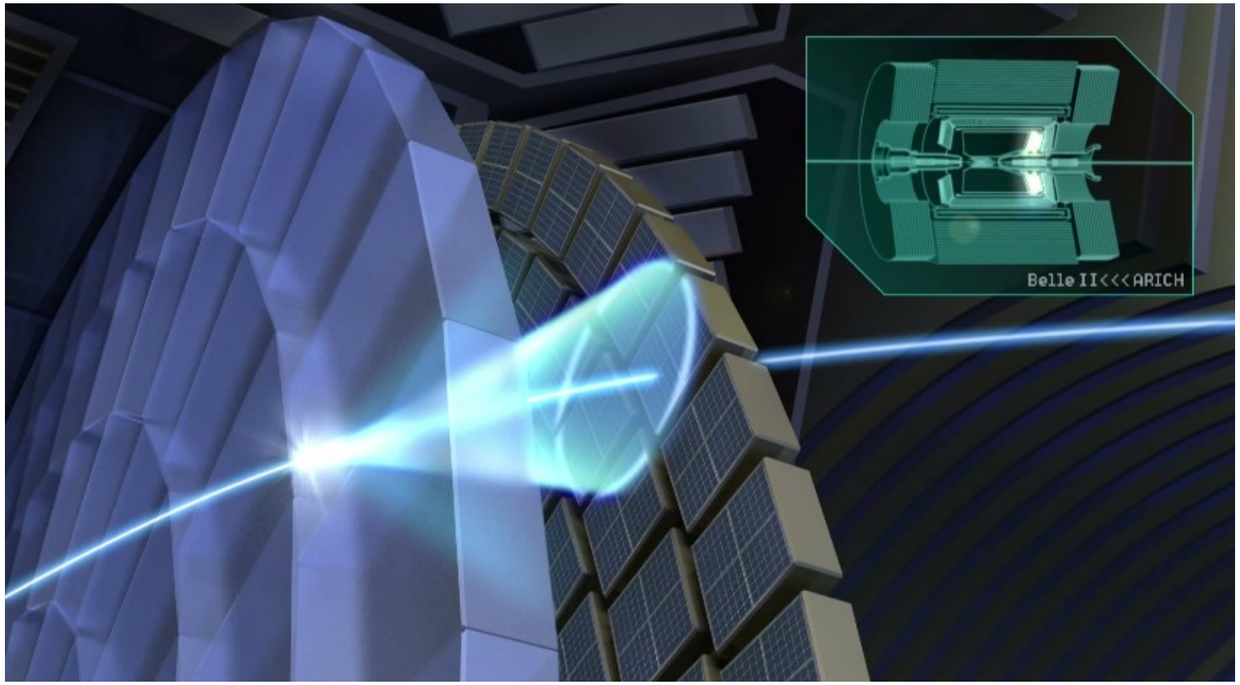


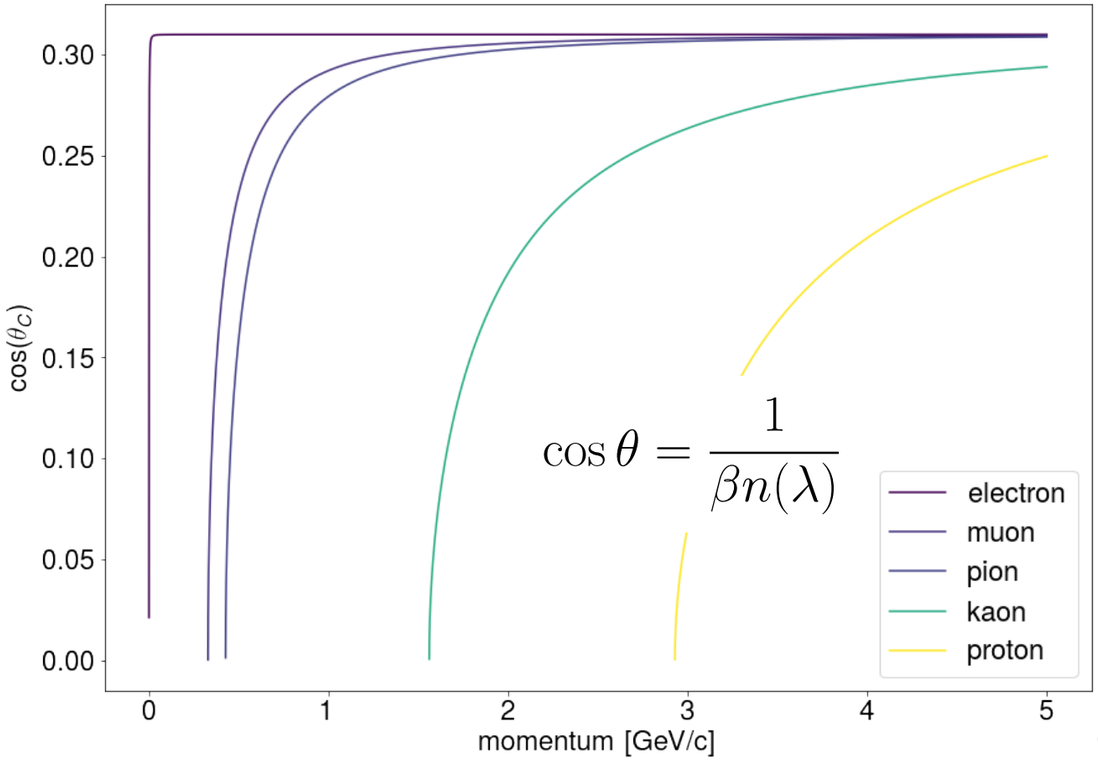


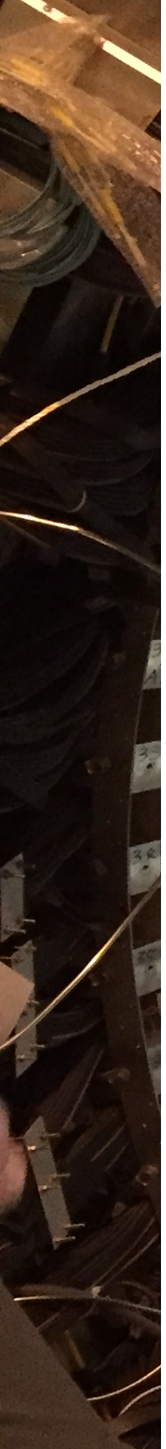
Cherenkov Detectors



When a charged particle in a medium moves faster than the speed of light in that medium, the particle emits Cherenkov radiation

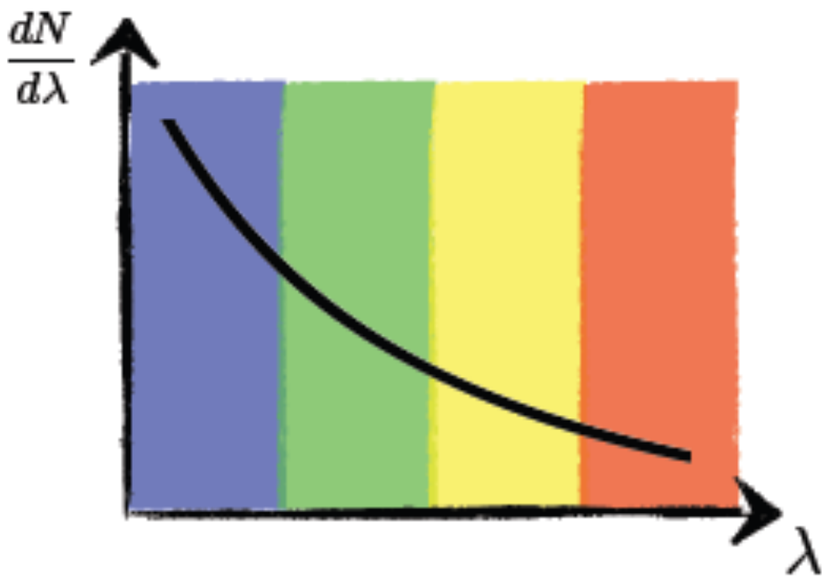






Properties of Cherenkov Radiation

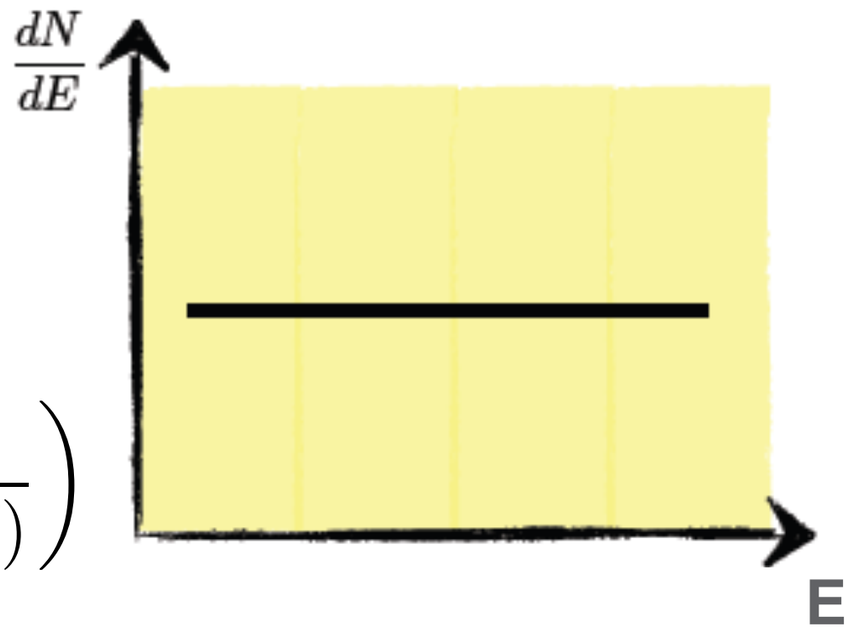
$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$



Integrate over sensitivity range:
[for typical Photomultiplier]

$$\frac{dN}{dx} = \int_{350\text{ nm}}^{550\text{ nm}} d\lambda \frac{d^2N}{d\lambda dx}$$

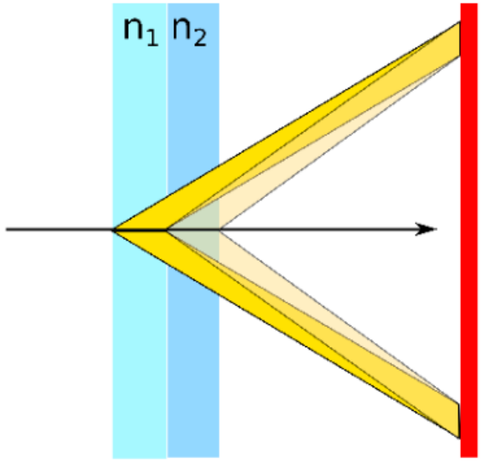
$$= 475\, z^2 \sin^2\theta_C \text{ photons/cm}$$

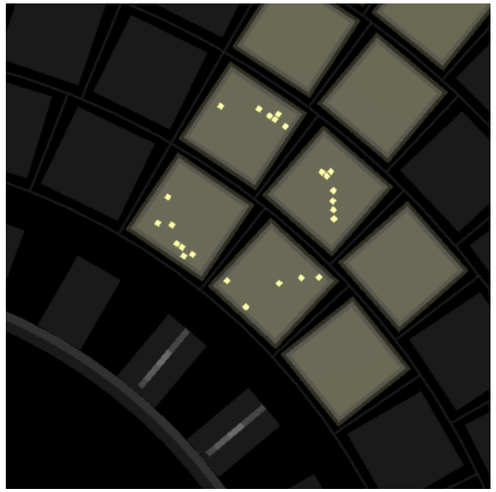


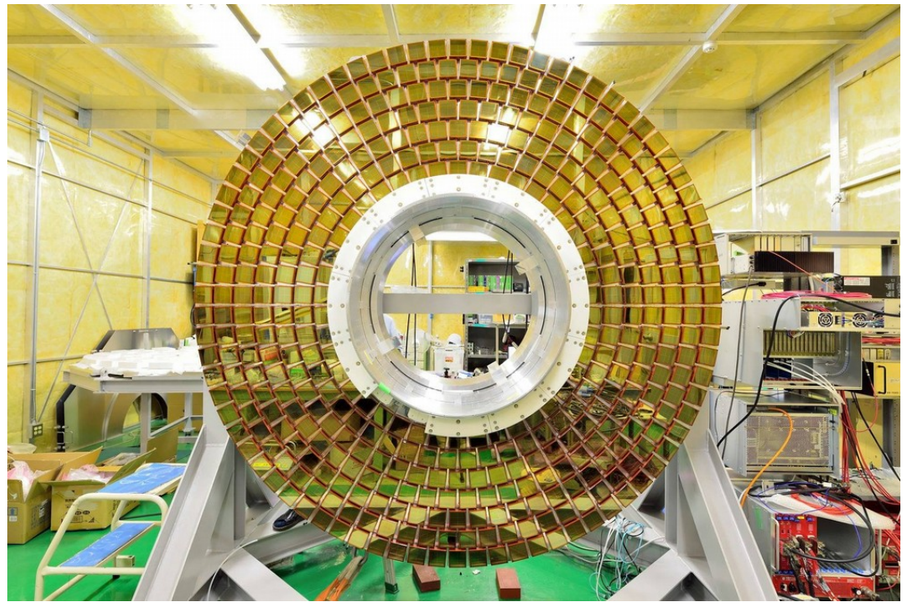
$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_c = \frac{\alpha^2 z^2}{r_e\, m_e c^2}\left(1 - \frac{1}{\beta^2 n^2(E)}\right)$$

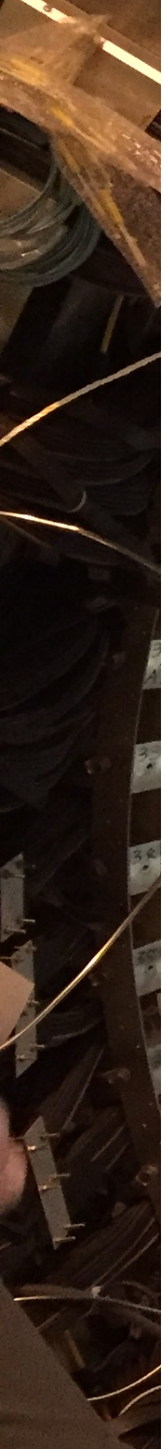
Endcap Particle ID

- Aerogel Ring Imaging Cherenkov Detector
- Two aerogel layers with different refractive indices (1.045/1.055) result in a sharper image
- K/π separation for a wide momentum range (0.7 GeV – 4.0 GeV)

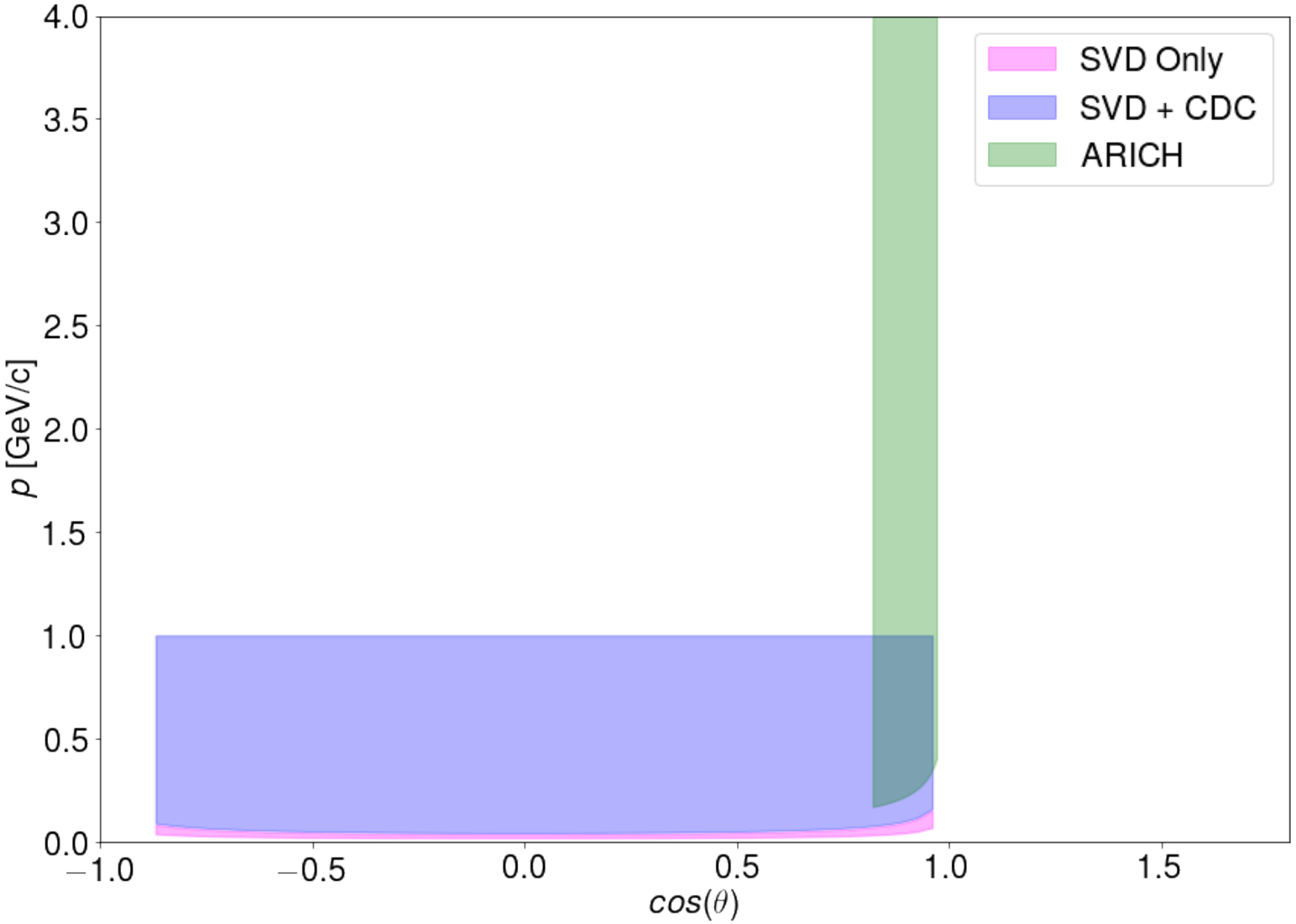


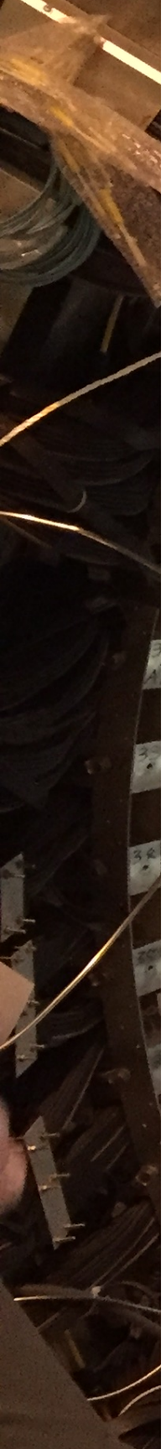






Coverage of the tracking detectors + ARICH





ARICH reconstruction

- Likelihood is based on the comparison of expected photon patterns for a given particle type with the measured photon patterns.

$$\mathcal{L}^h = \prod_{i \in \text{pixels}} p_i^h$$

$$p_i'(m_i) = \exp(-n_i) n_i^{m_i} / m_i!$$

Poissonian probability for a pixel with n_i average hits to show m_i hits for this track

In our case, the pixel is either hit (m_i=1) or not hit (m_i=0)

$$p_i(0) = \exp(-n_i)$$

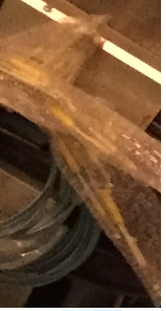
$$p_i(1) = 1 - p_i(0) = 1 - \exp(-n_i)$$

$$\ln \mathcal{L}^h = -\boxed{N^h} + \sum_{i \in \text{hits}} \boxed{n_i^h} + \ln(1 - \exp(-\boxed{n_i^h}))$$

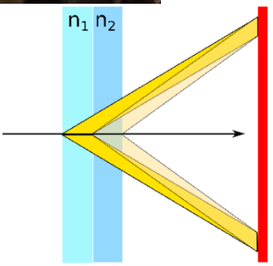
Expected total number of hits

Average number of hits on pixel i

But only for pixels that were hit



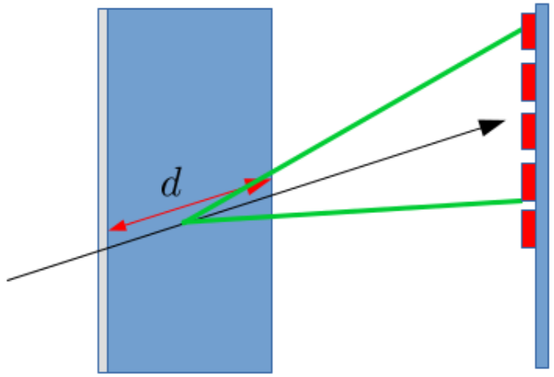
ARICH expected number of hits

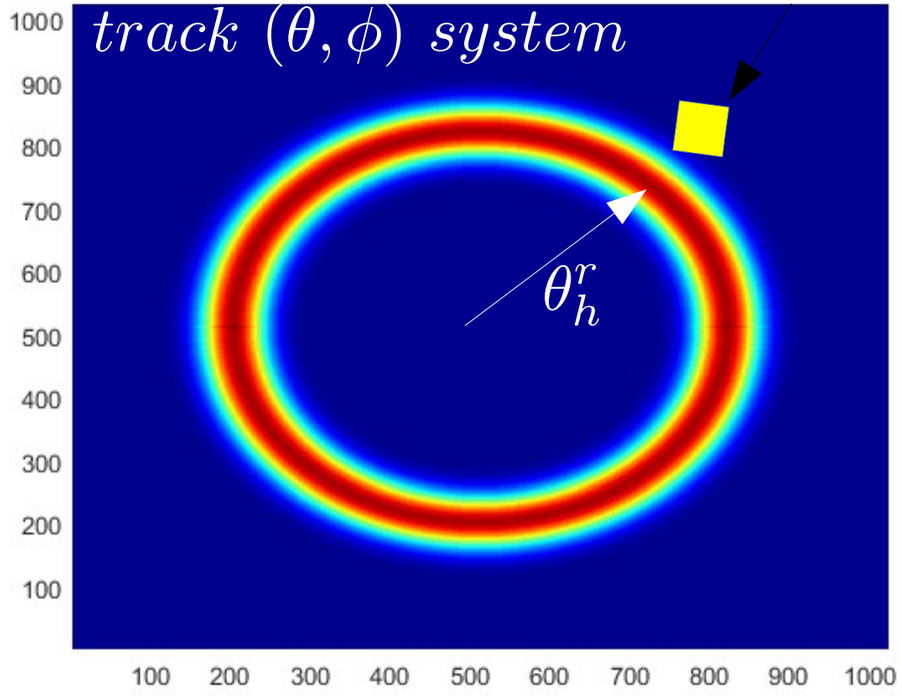


Expected number of hits on pixel i

$$n_i = n_i^1 + n_i^2 + n_i^{\mathrm{bg}}$$

$$n_i^r = \epsilon_{\mathrm{det}} N^r \int_{\Omega_i} \frac{1}{2\pi} G(\theta, \theta_h^r, \sigma_h^r) \mathrm{d}\theta \mathrm{d}\phi$$





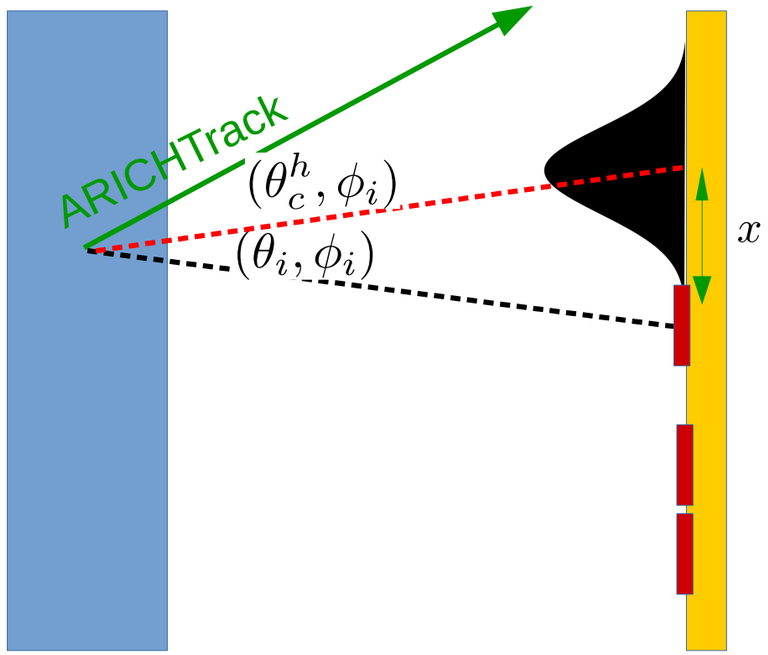
$$N^r = \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}x} \lambda_{\mathrm{abs}} (1 - \exp(-d/\lambda_{\mathrm{abs}}))$$

Expected number of photons emitted from layer r

Implementation of ARICH probabilities

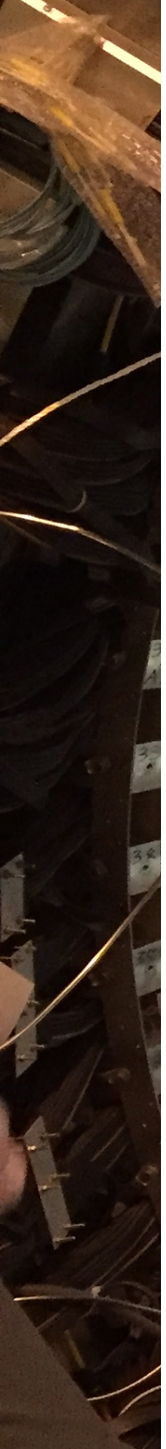
We reconstruct (θ_i, ϕ_i) of each photon hit in the track coordinate system (taking into account refractions)

Then we apply ray tracing from the emission point at the angle (θ^h_c, ϕ_i) to the detection plane.



$$\int_{\Omega_i} \frac{1}{2\pi} G(\theta, \theta_h^r, \sigma_h^r) \mathrm{d}\theta \mathrm{d}\phi$$

$$\int_{S_i} G(x, 0, \sigma_x) \mathrm{d}x \mathrm{d}y$$



ARICH hit patterns

Detection efficiency

background

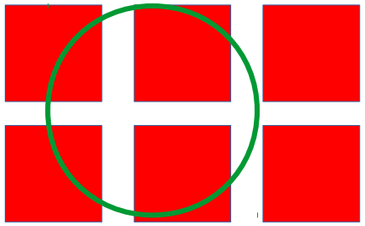
$$N = \epsilon_{\mathrm{acc}}\epsilon_{\mathrm{det}}(N^1 + N^2) + N_{\mathrm{bg}}$$

Ring acceptance

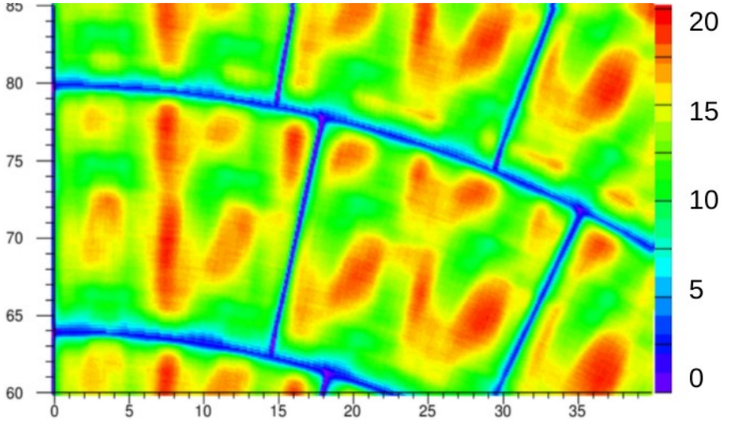
Number of photons from 1st and 2nd layer, respectively

The expected number of photons depends on the particle hypothesis

ϵ_{acc} Geometric acceptance of the Cherenkov ring



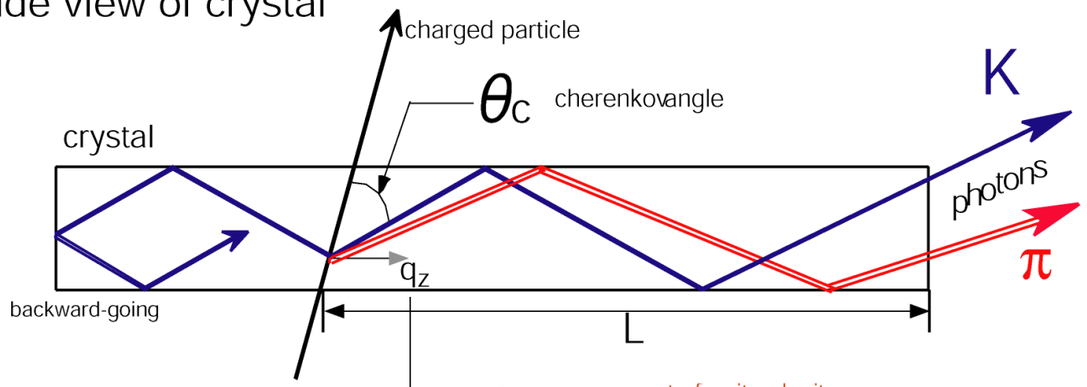
After propagating 200 “dummy photons” at the expected θ^h_c and uniformly distributed in ϕ, we can just count how many fall on HAPDs



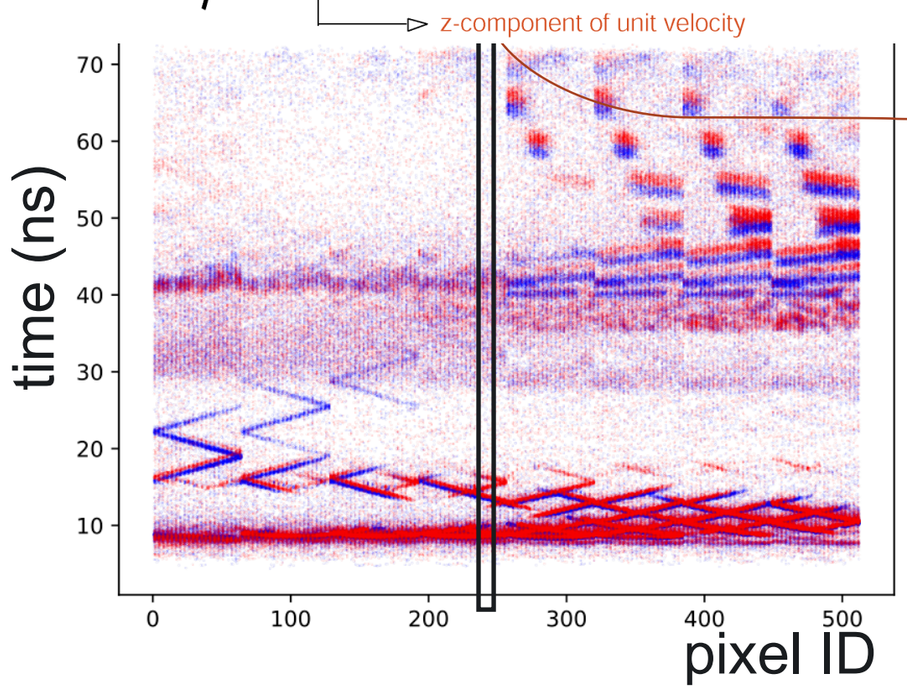
Expected number of photons in Cherenkov ring for 3 GeV pions vs. track position on the aerogel plane

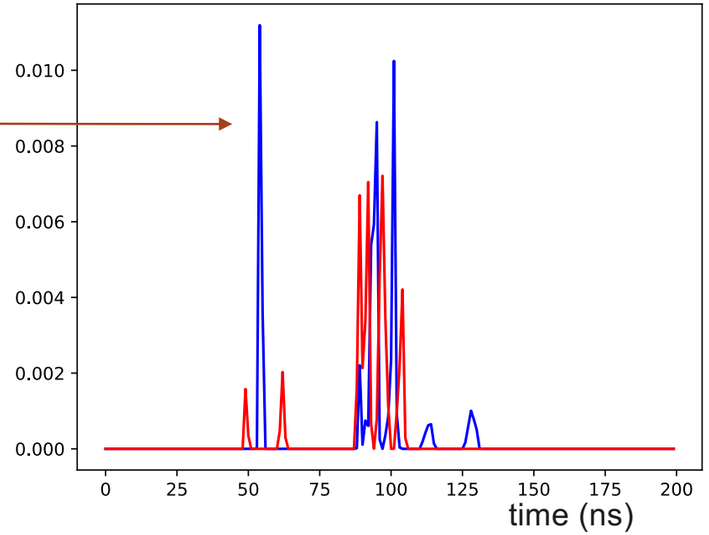
From photon times to particle ID

Side view of crystal



The different reflections in the bar result – for a given incident position on the bar – in different photon arrival times in each channel

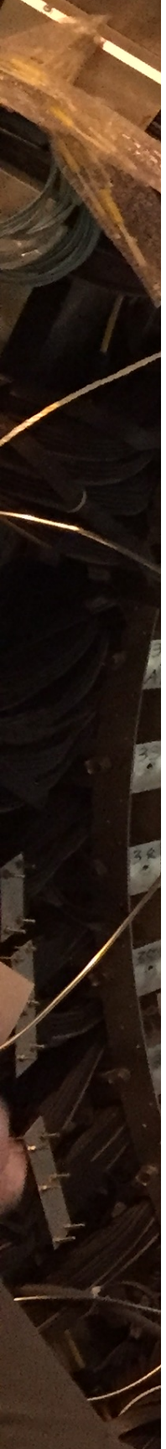




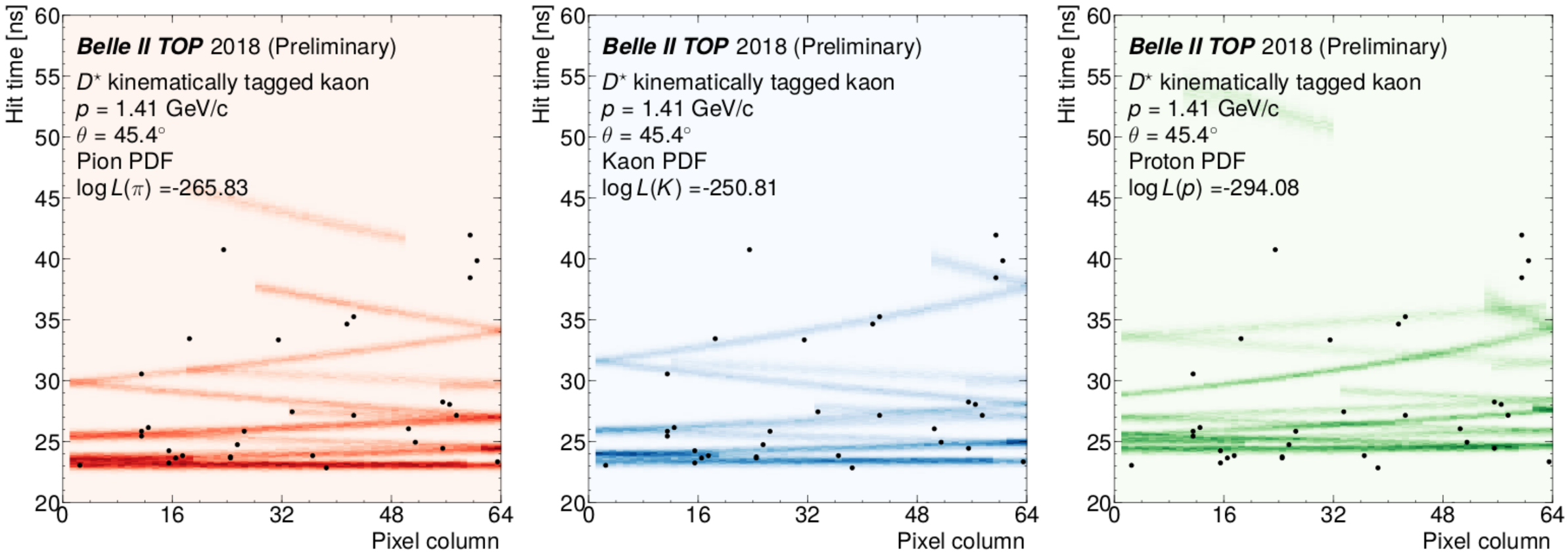
Probability distribution for a given type, momentum, incidence

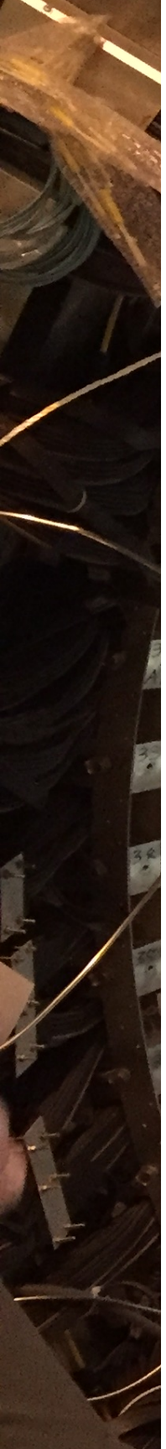
The combined likelihood of all of the measured photons is the input to the PID

10k K (red) and π (blue) with otherwise equal properties

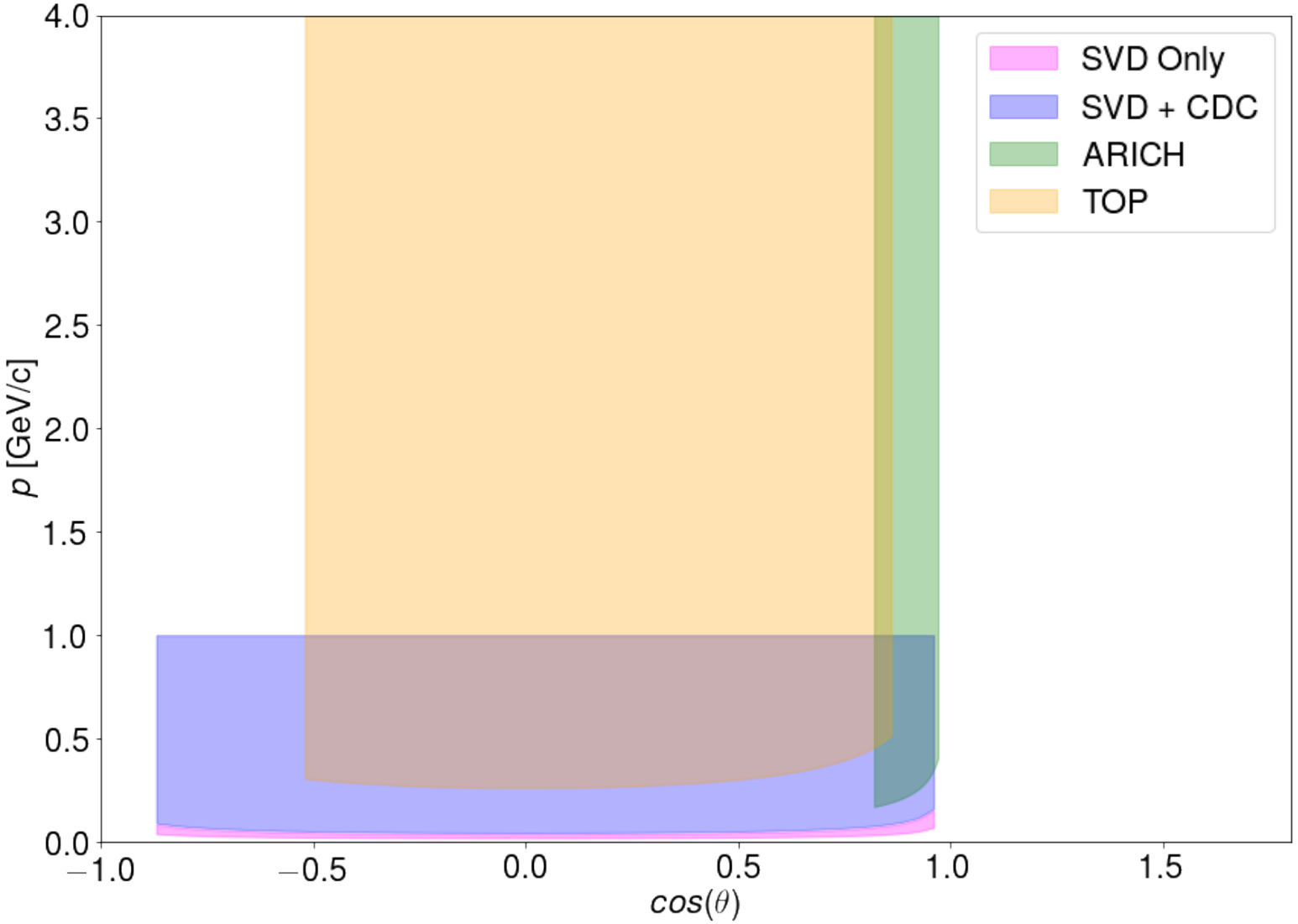


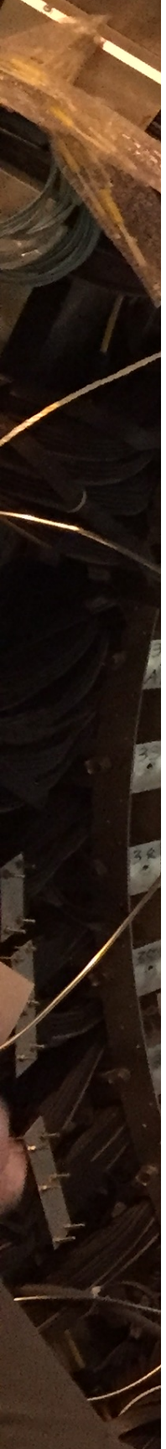
An example of a Likelihood analysis in the iTOP





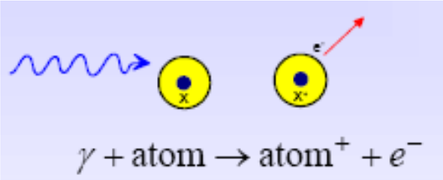
Coverage of the tracking detectors and Cerenkov detectors (most of the PID system)



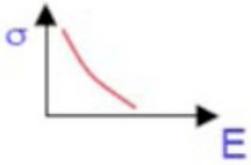


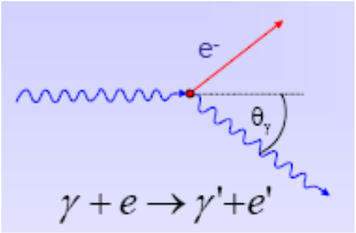
Electromagnetic interactions

Gammas

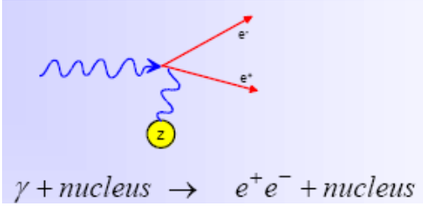


- Photoelectric effect

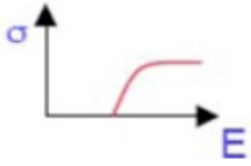




- Compton effect

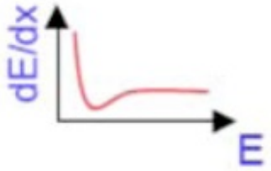


- Pair production

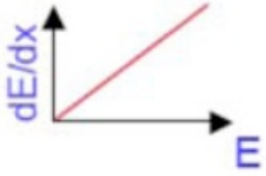


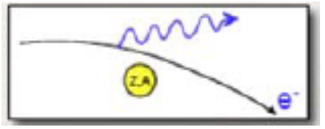
Electrons

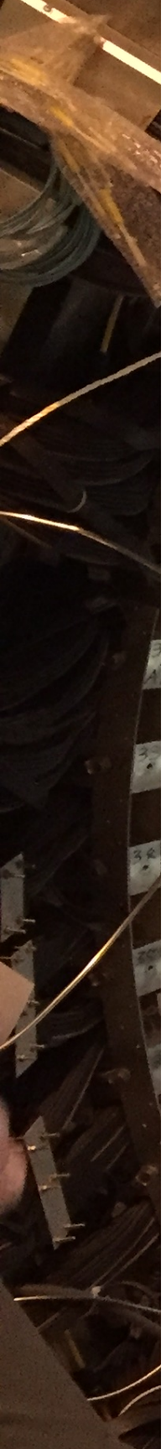
- Ionisation



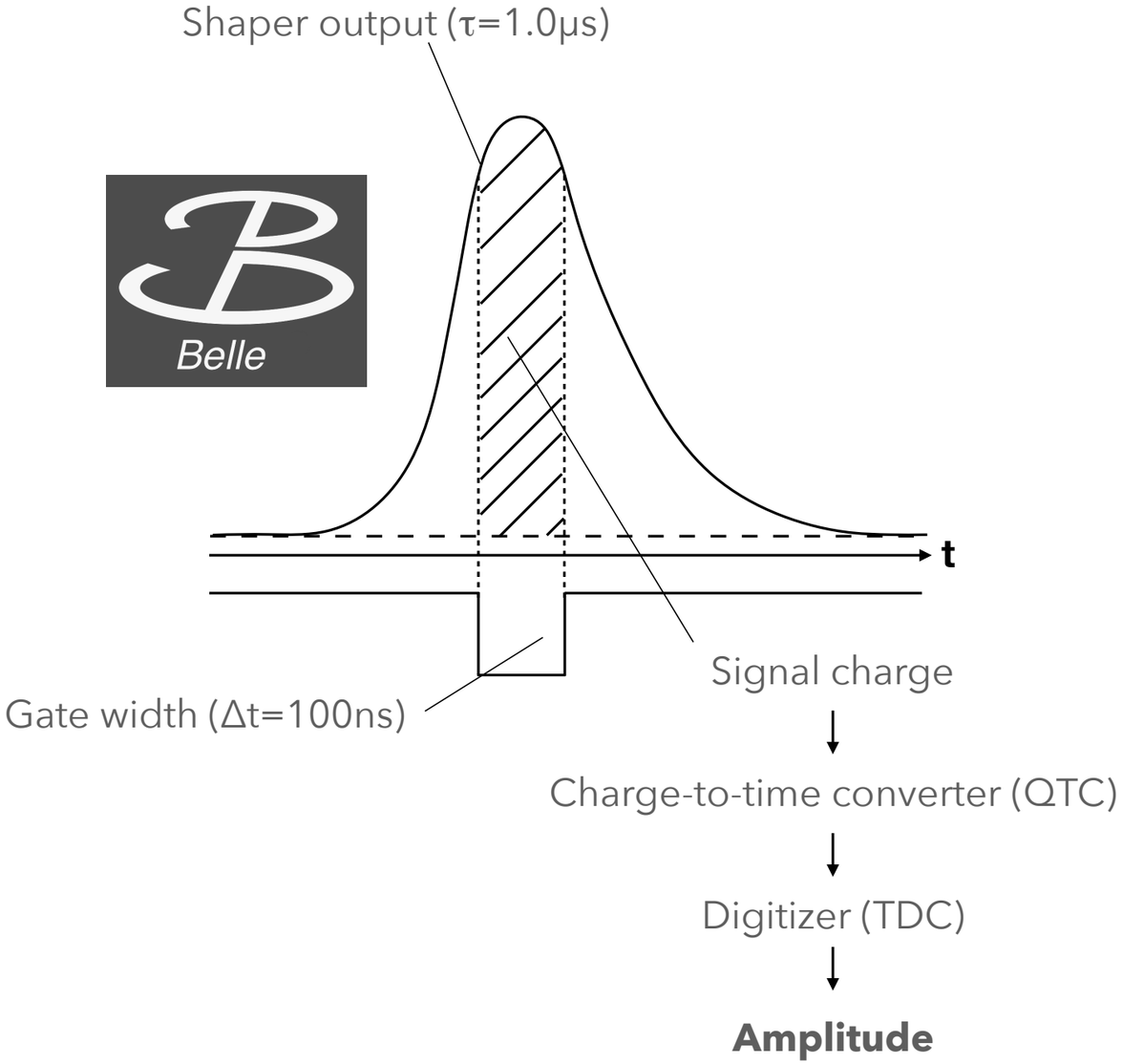
- Bremsstrahlung

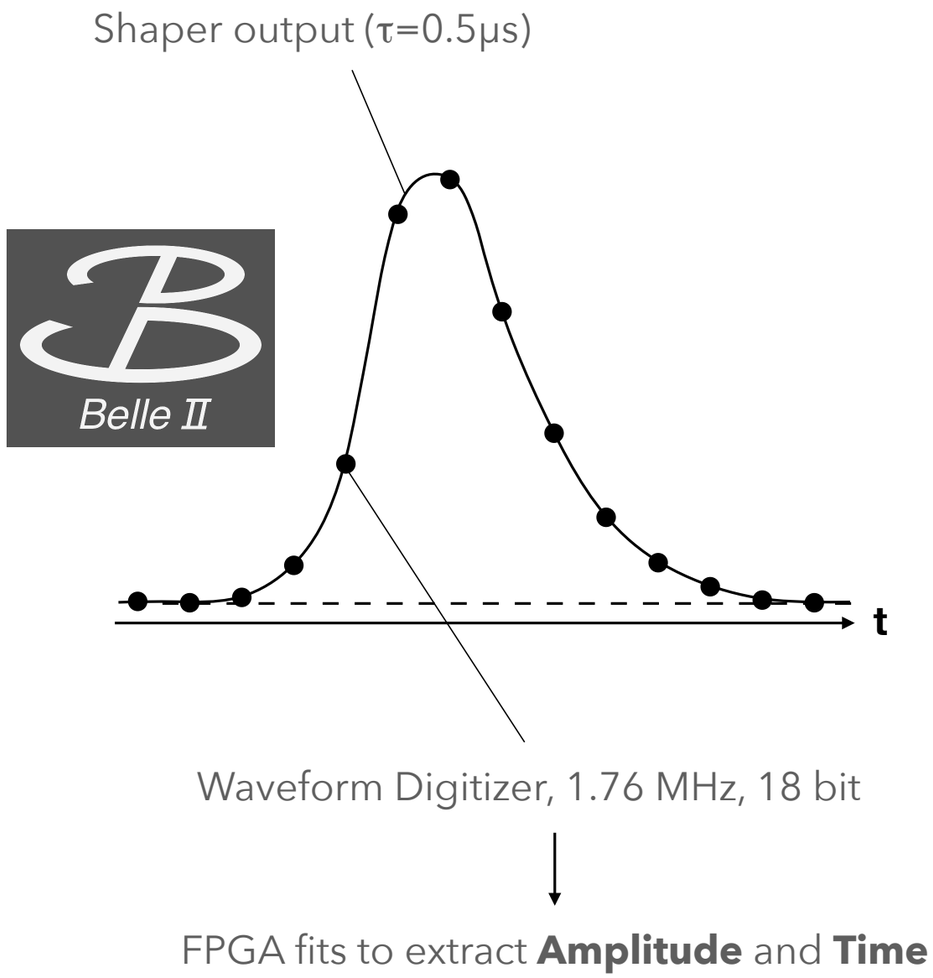


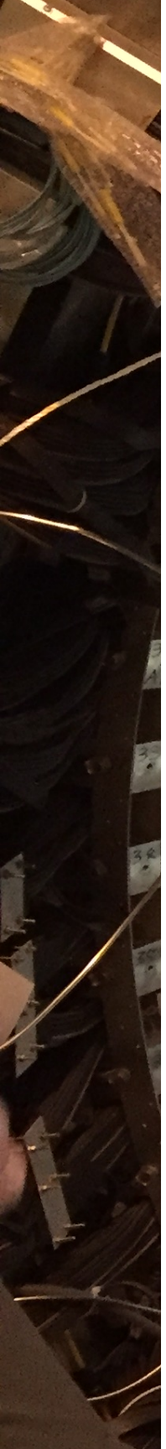




The signal processing in the ECL improved between Belle and Belle II







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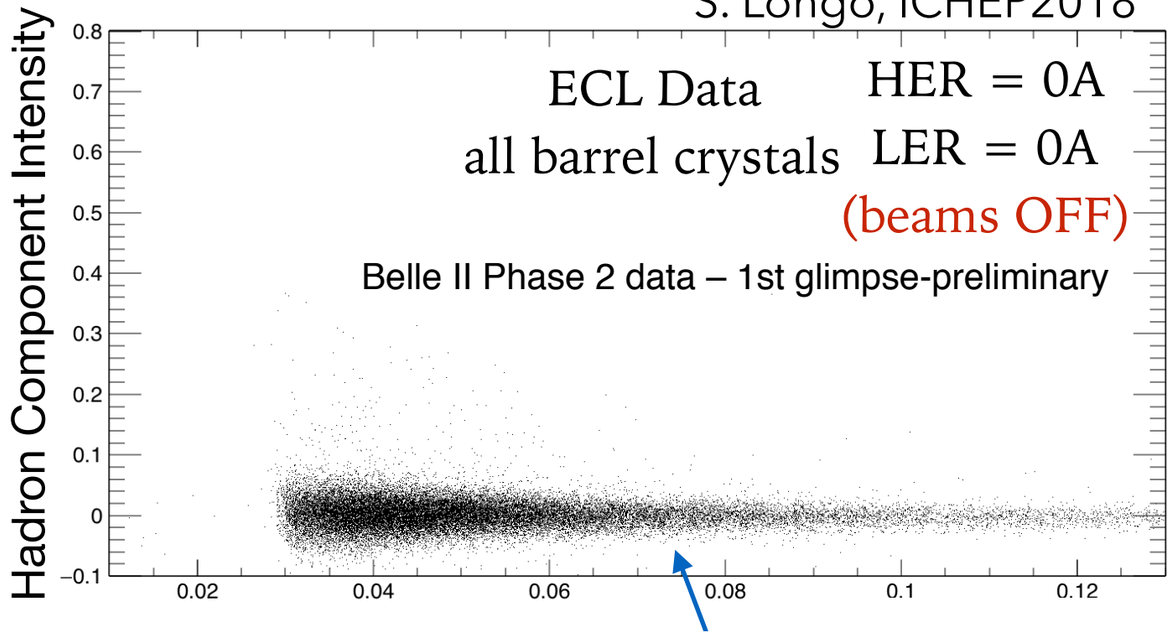
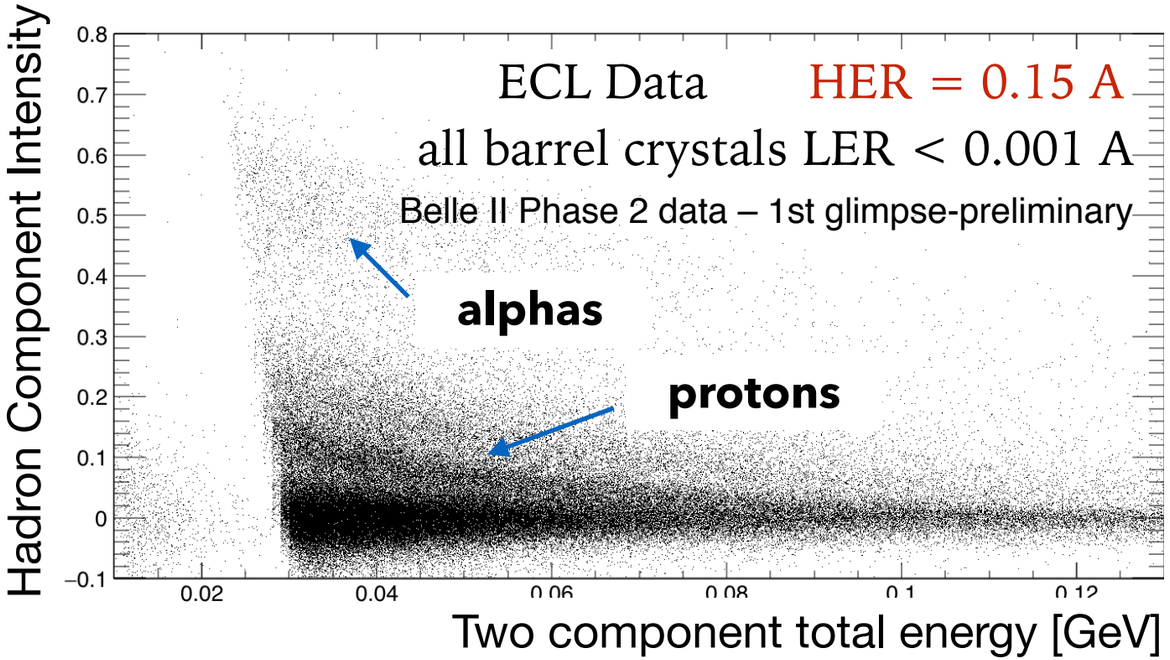
Pulse-Shape Discrimination (PSD)

- First time pulse shape discrimination (PSD) is used in an e^+e^- collider experiment
- New variable based on a BDT trained (on MC) to separate photons and K^0_L using all pulse shapes in a cluster
- Will be included in charged particle identification to improve muon vs. pion separation

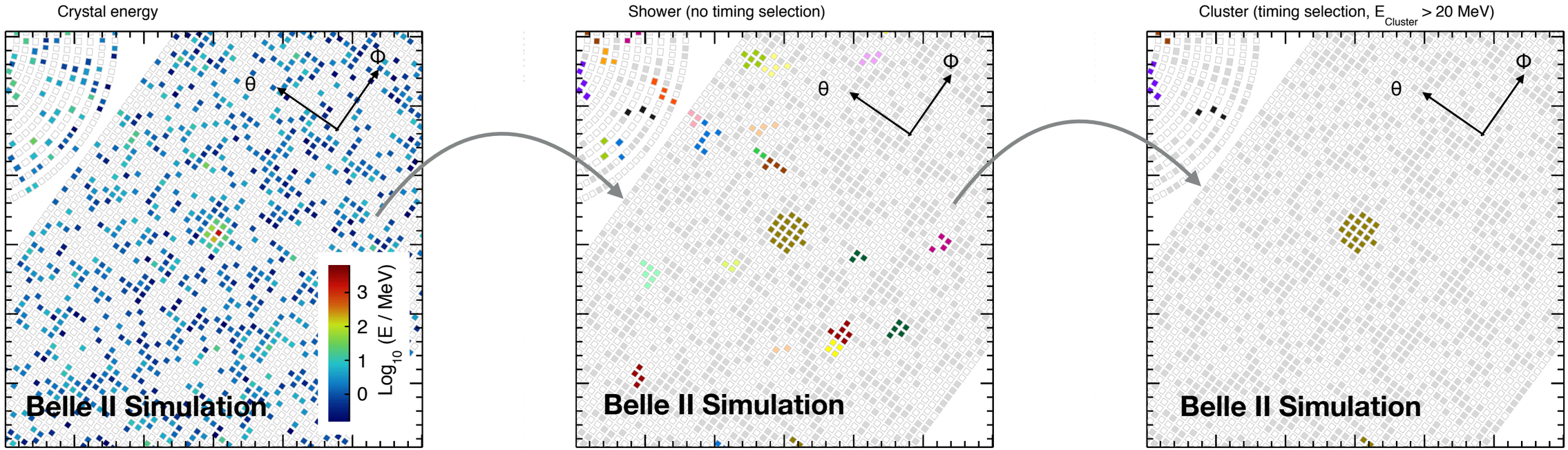
S. Longo, ICHEP2018



Electromagnetic pulse shapes



Different stages of reconstruction in the ECL



Clustering

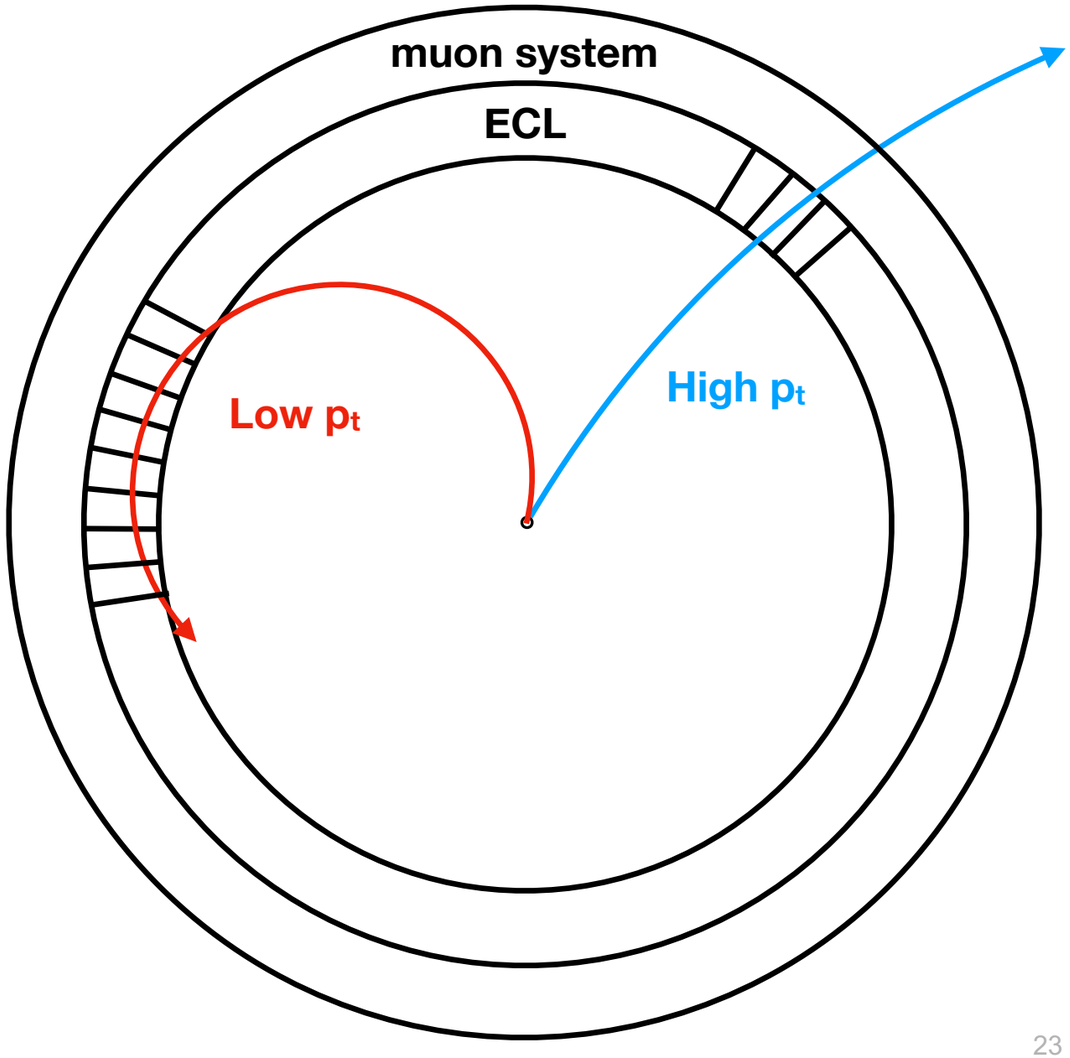
User analysis

Particle ID in the ECL

- Particles with low transverse momentum (pt < 0.5 GeV/c) do not reach our muon system:

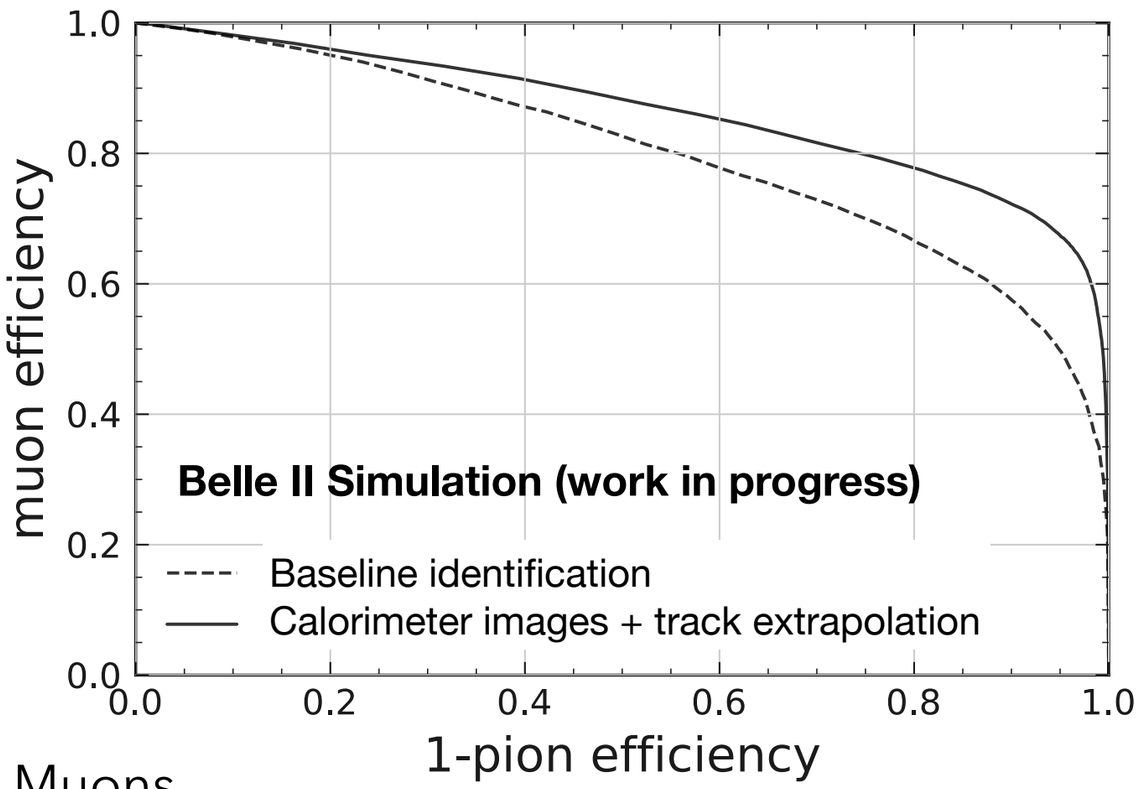
  → Baseline particle identification depends on E/p and is very poor

  → Clustering itself difficult, since these particles leave long, charge dependent, trails in the calorimeter

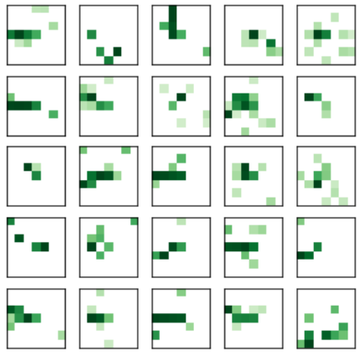


Deep learning methods to improve the PID in the ECL

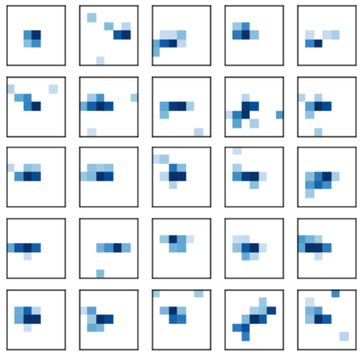
- Approach under study:
  - No clustering
  - Extrapolate tracks to calorimeter
  - Analyse 5×5 pixel calorimeter images around impact crystal using convolutional networks



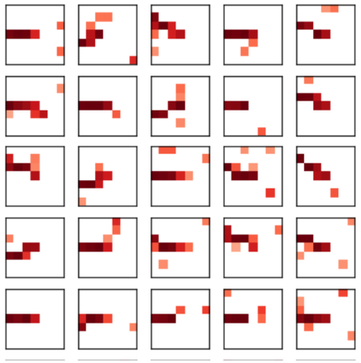
Pions

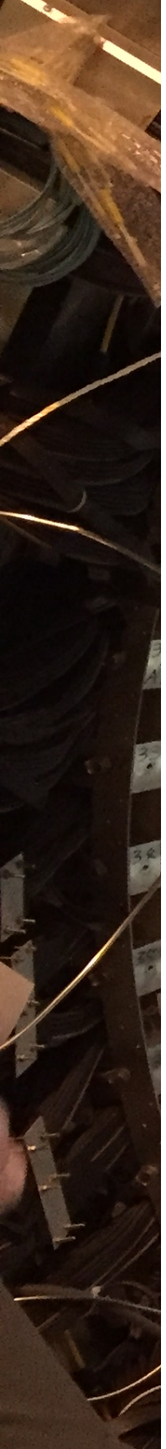


Electrons

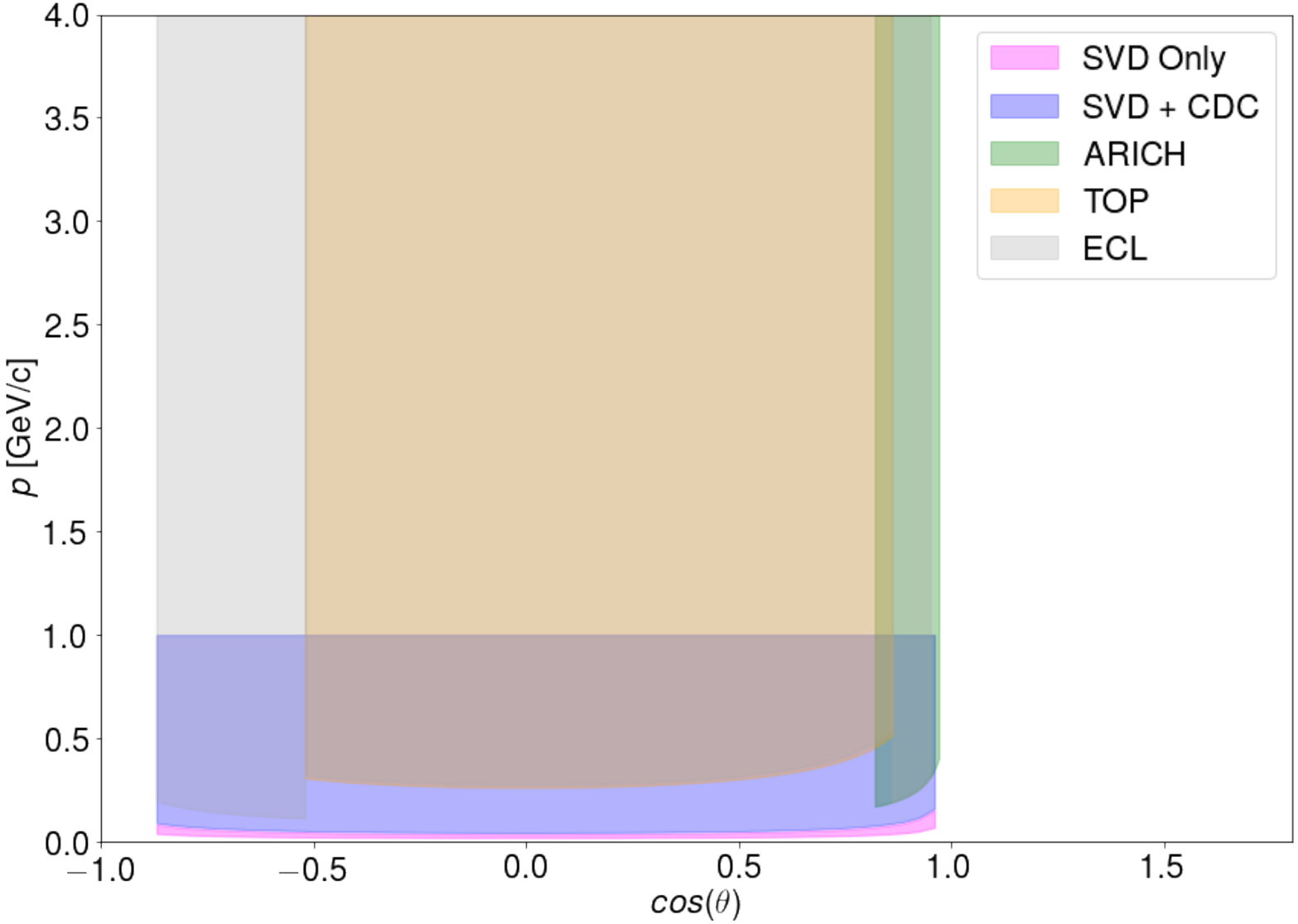


Muons

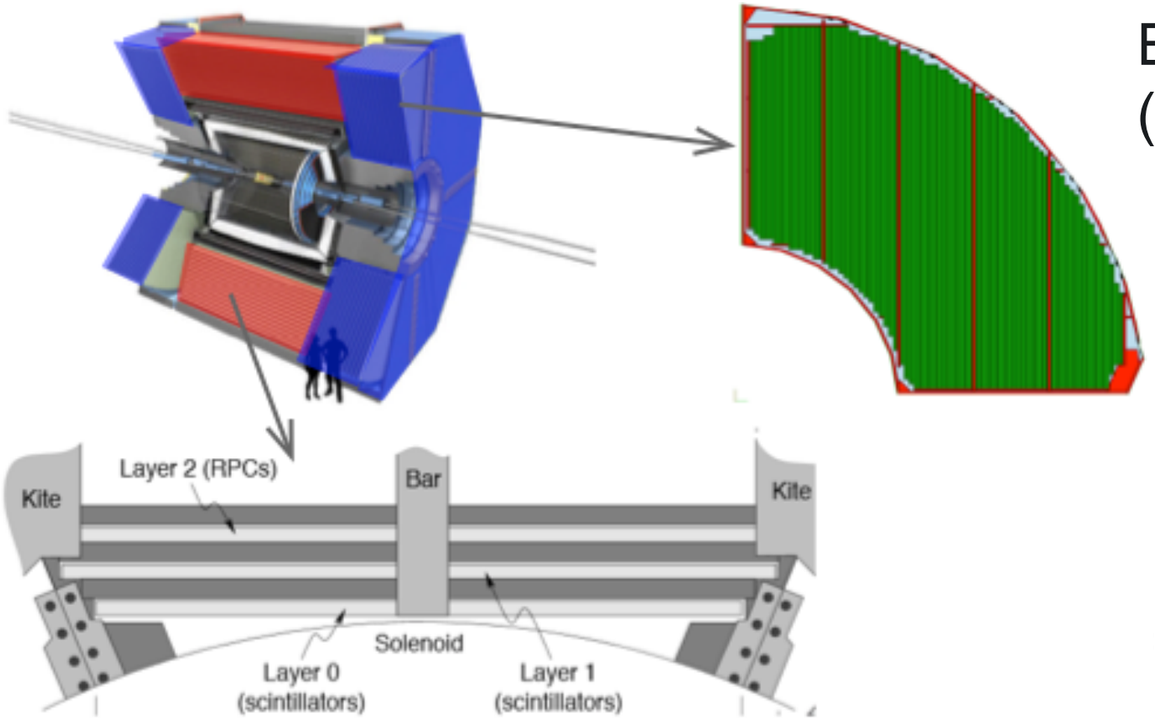




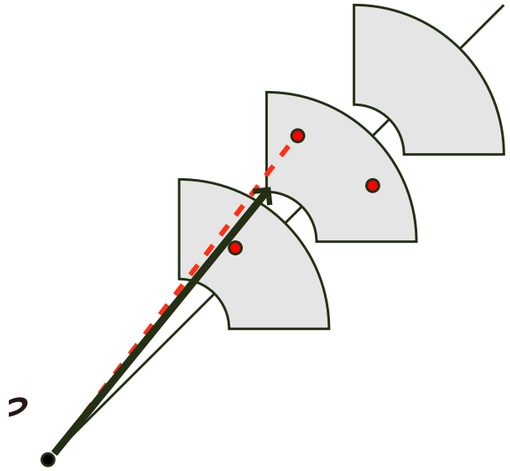
Coverage of all of the detectors surrounded by the solenoid magnet



The K^0_L – Muon detector (KLM)

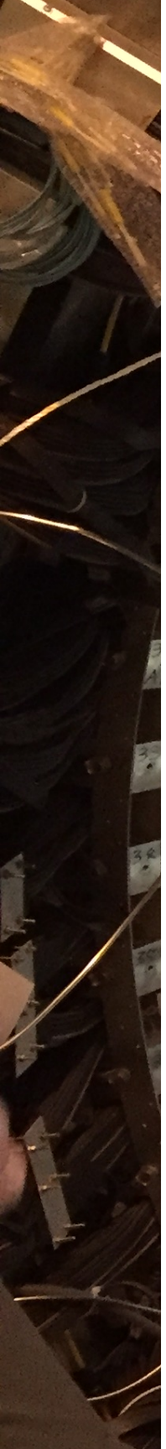


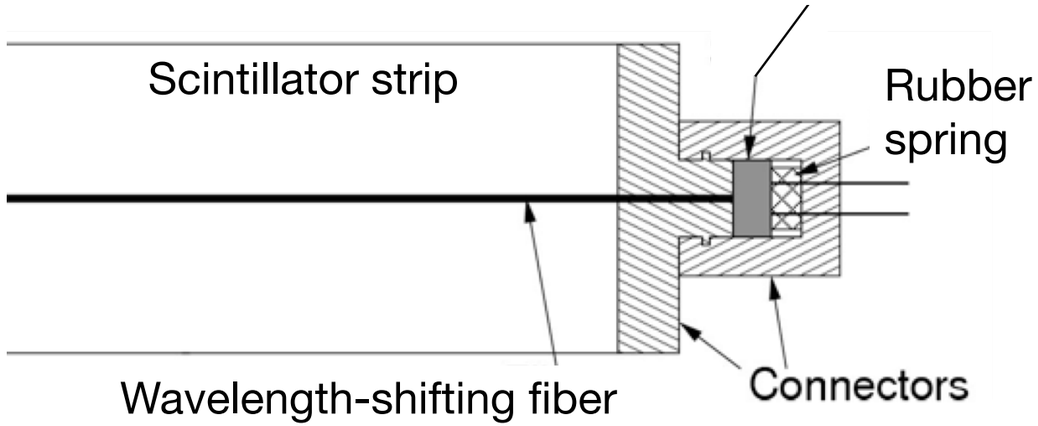
Endcap KLM: scintillator strips
(14 layers fwd, 12 layers bwd)



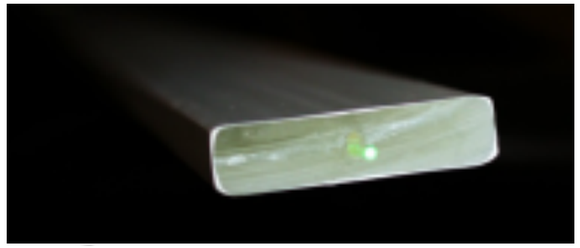
Barrel KLM:
Inner 2 layers: Scintillator strips
Outer 13 layers: RPC
(glass, not bakelite)

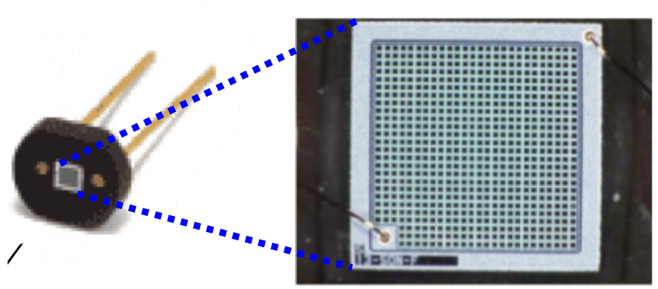
Angular resolution of hit from the IP: better than 10 mrad (4 cm)





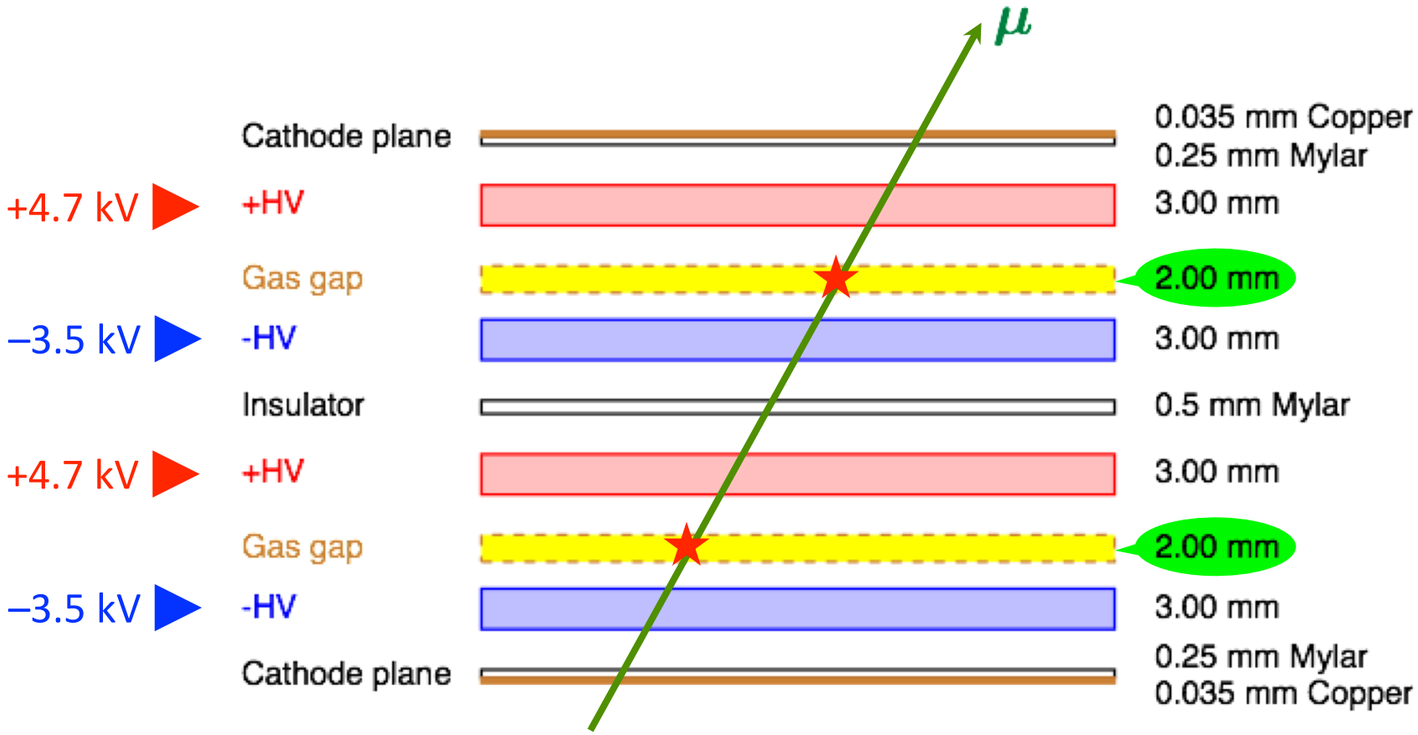
FNAL scintillator for barrel

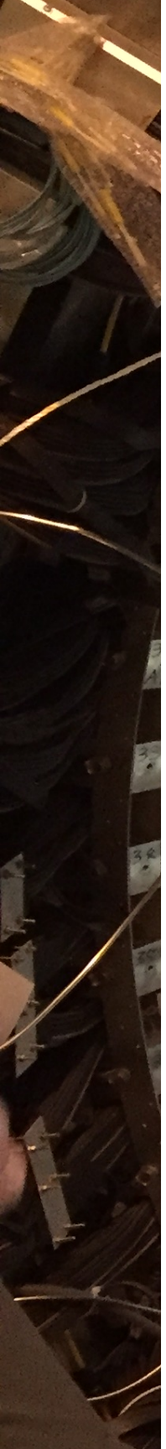




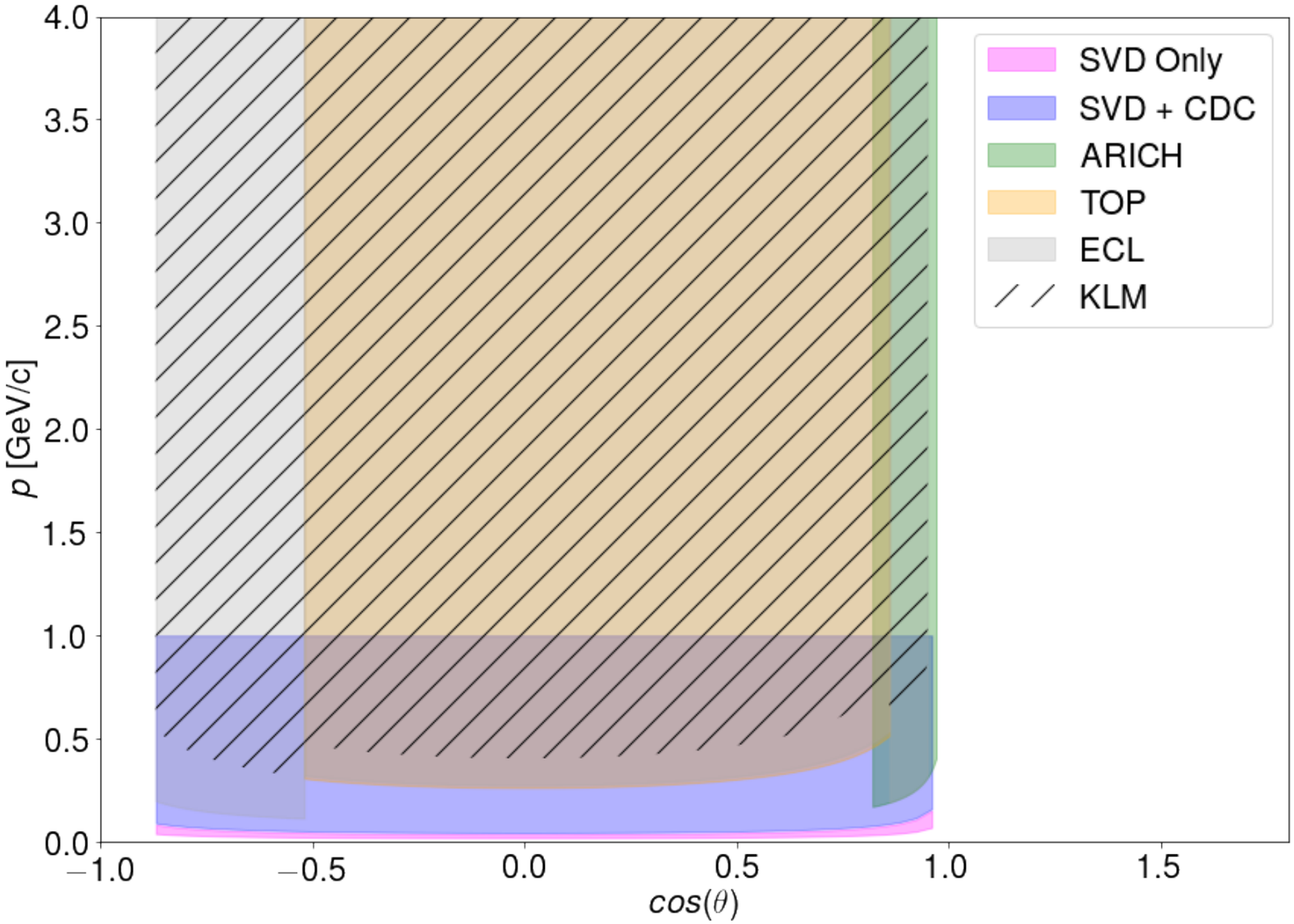
1.3 x 1.3 mm^2

667 pixels





Coverage of the detectors in the Belle II experiment

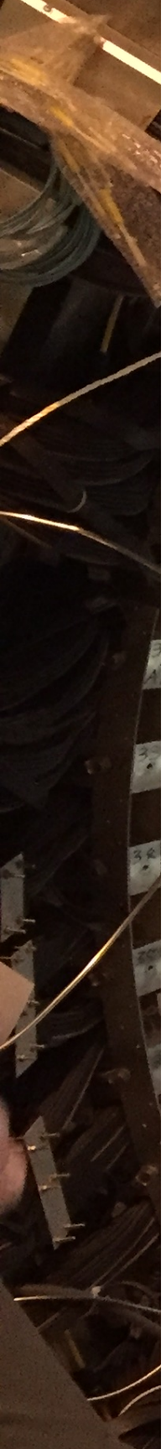


Particle ID in Belle II analyses

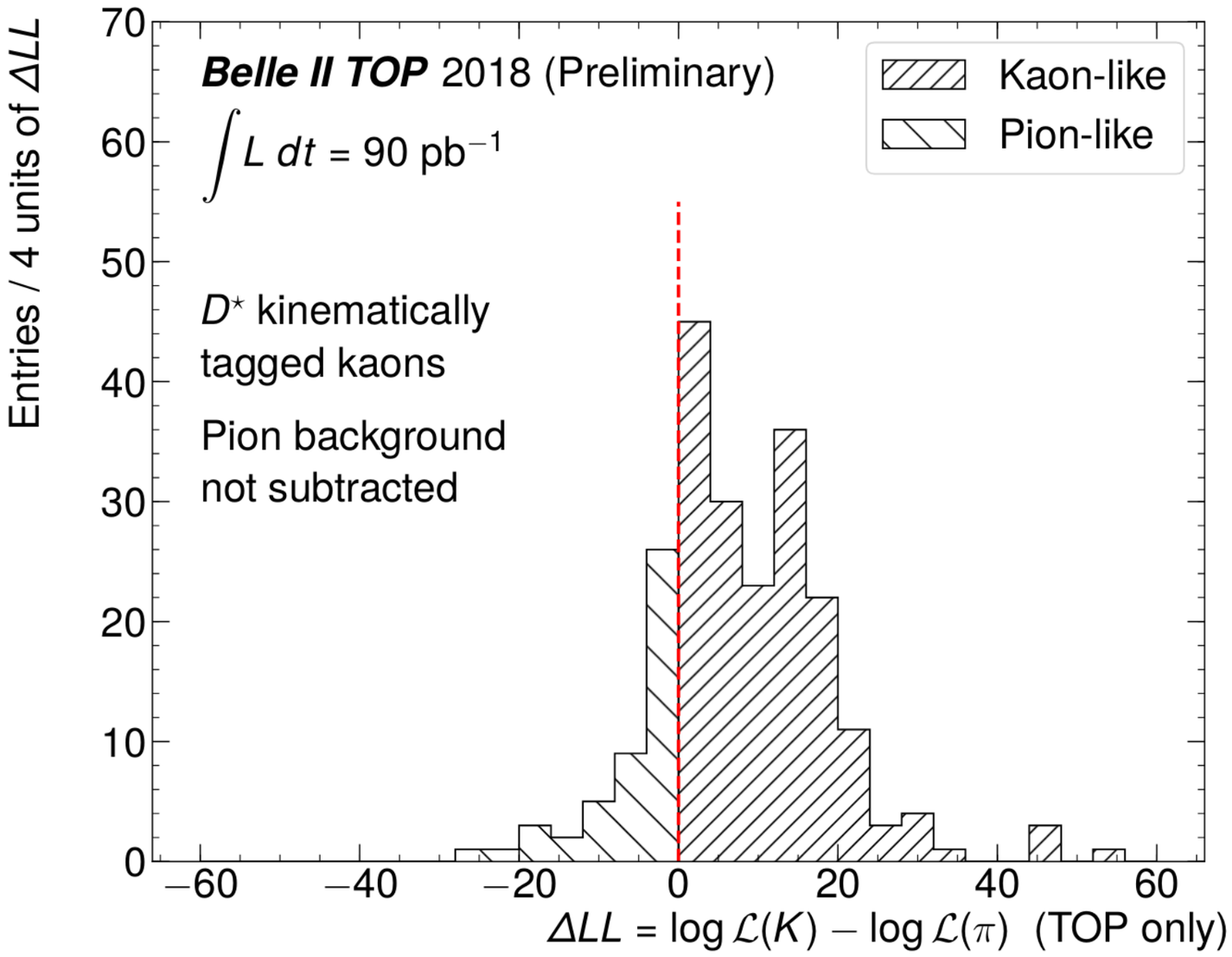
Current implementation:

- Each subdetector measures the likelihoods for 6 basic species
  - Electron
  - Muon
  - Pion
  - Kaon
  - Proton
  - Deuteron
- Particle ID for a given species is the combination for all detectors

$$\log \mathcal{L}_\pi = \log \mathcal{L}_\pi^{\mathrm{SVD}} + \log \mathcal{L}_\pi^{\mathrm{CDC}} + \log \mathcal{L}_\pi^{\mathrm{TOP}} + \log \mathcal{L}_\pi^{\mathrm{ARICH}} + \log \mathcal{L}_\pi^{\mathrm{ECL}} + \log \mathcal{L}_\pi^{\mathrm{KLM}}$$



Example: Particle separation in the iTOP detector

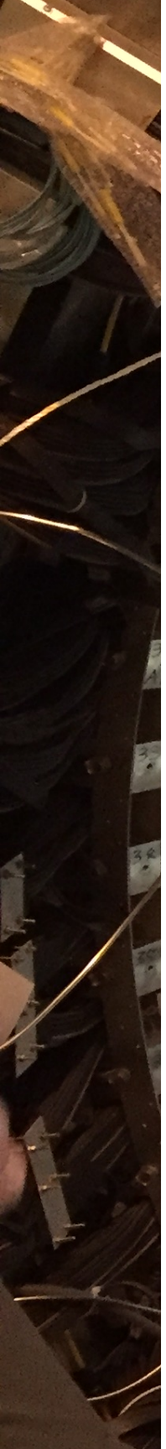


Performance characterization

- Two basic concepts to characterize the performance of a detector
  - Efficiency
  - Purity
  - Usually the likelihoods overlap, so deciding on a cut is always a trade-off between the two
- Some people like to quote a “fake-rate”. I find this confusing and will use only efficiencies
  - The efficiency to correctly identify a particle of type A in a sample of mostly As
  - The efficiency to erroneously identify a particle of type B in a sample of mostly As
    - ✓ This latter term is sometimes called “fake rate”
    - ✓ Except by people who confuse A and B…

Hands-on session

- In the hands-on session you will follow the steps to reconstruct the decay $D^* \rightarrow D0\ (K\ \pi)\ \pi$
- The Kaons and pions can be very cleanly reconstructed without using particle ID, so this is a good channel to test the PID performance
- The notebook is making a couple of plots you can use to study the performance of the different detectors



Acknowledgements

- Thank you to
  - Umberto Tamponi
  - Erika Garutti
  - Torben Ferber
  - Leo Piilonen
  - Luka Santelij

- For preparing excellent slide decks that made my job easier

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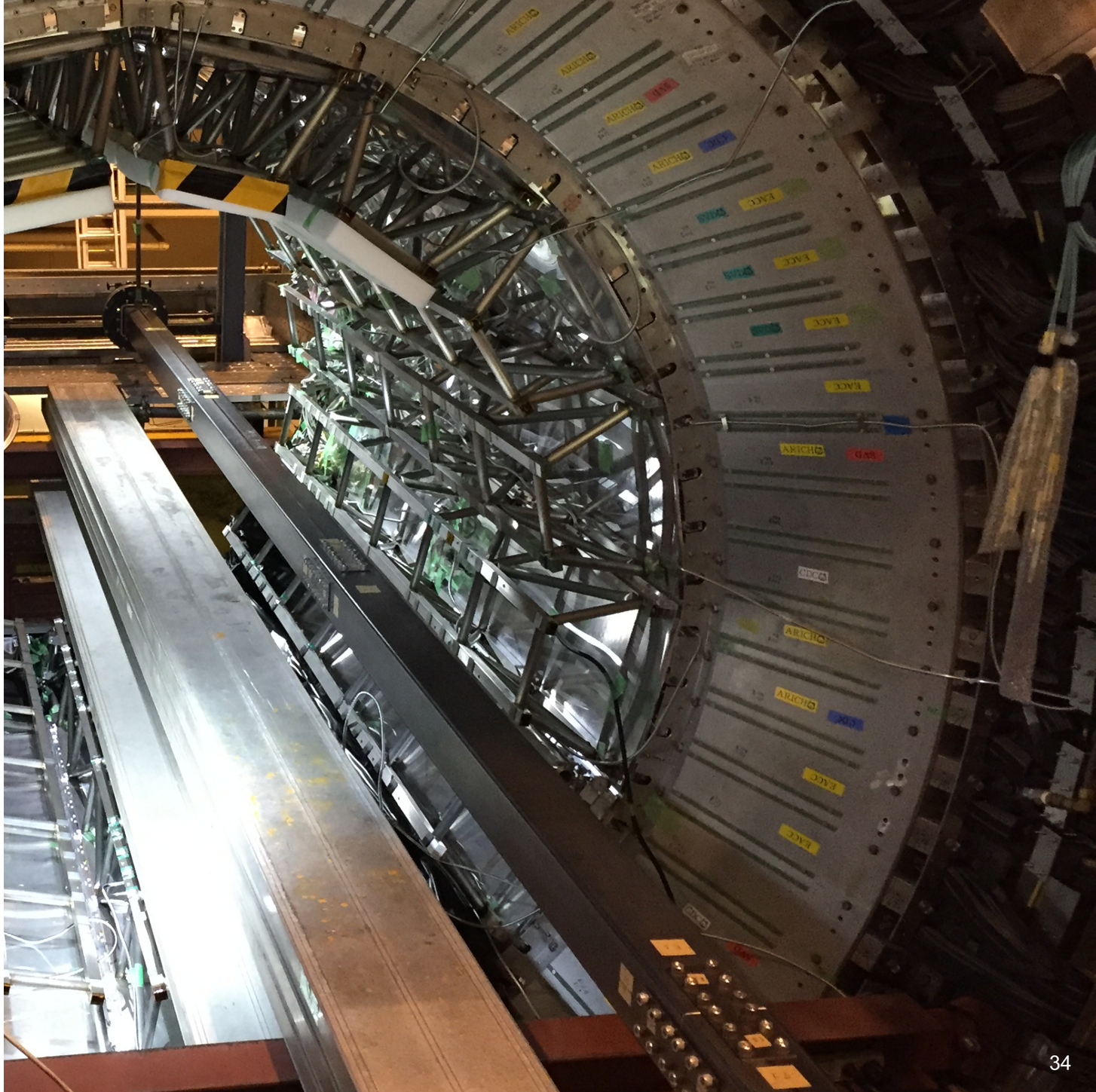
Thank you



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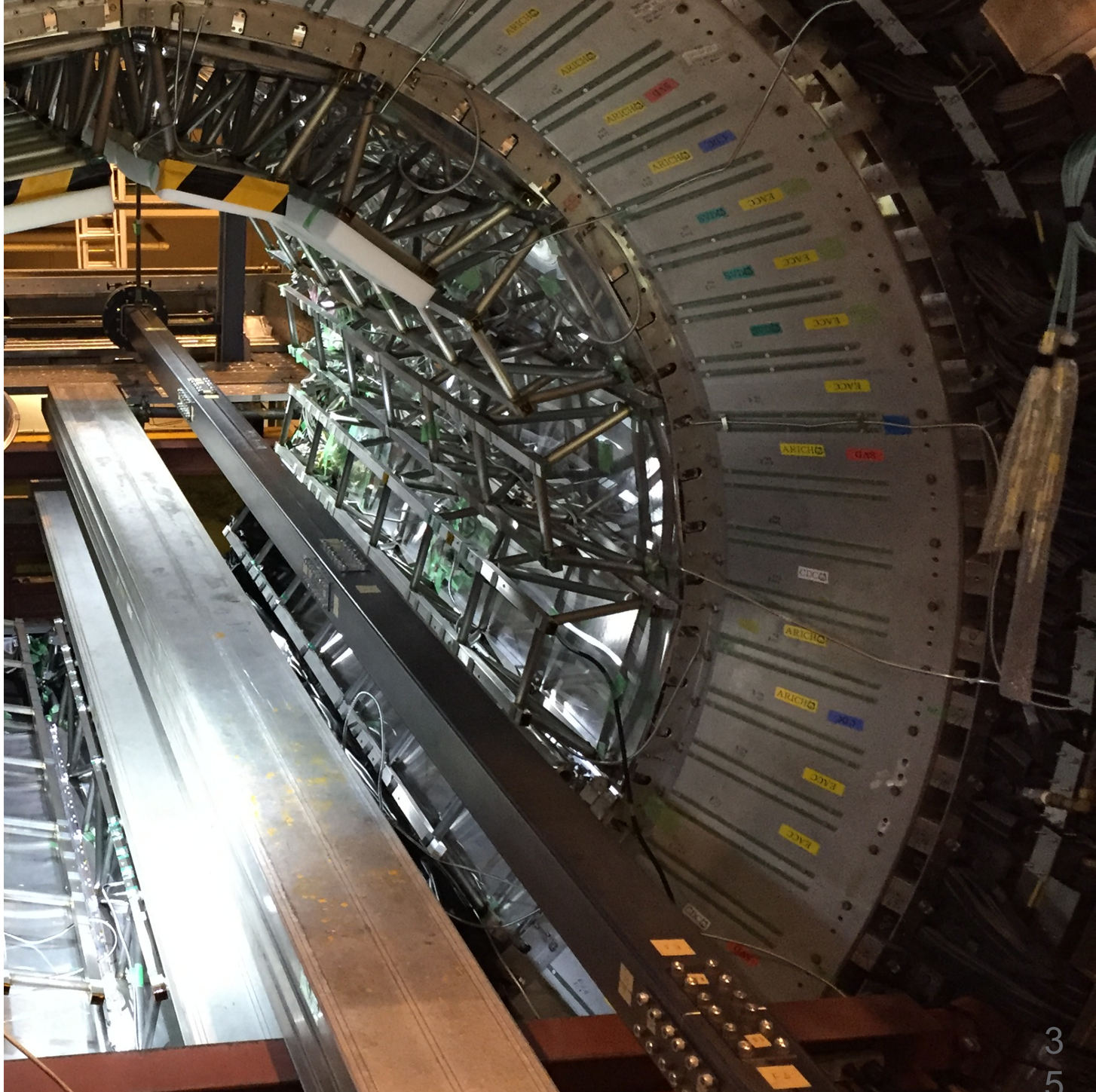
Backup



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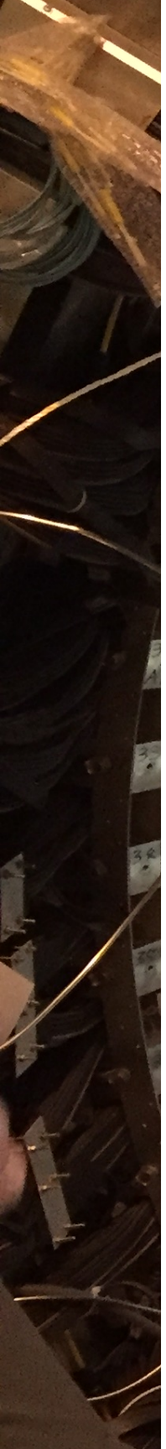


KLM

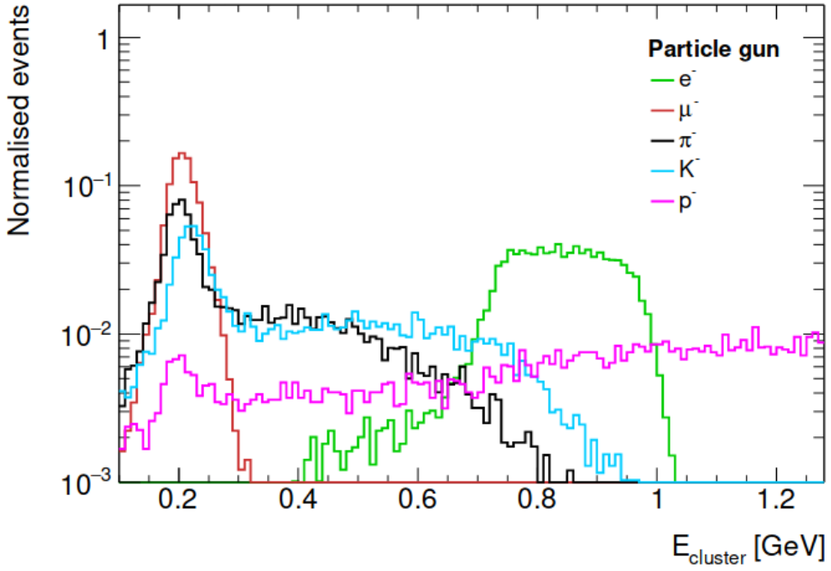
→ Muons do not interact that much (why?)

→ Muons are more likely than any other particle to survive the solenoid and the steel plates

ECL

→ Electrons are showering as photons are (why?)

→ Hadrons may leave distinctive signatures (hadronic showers)



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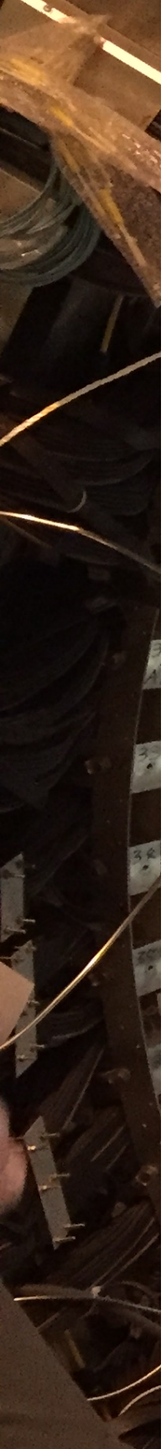

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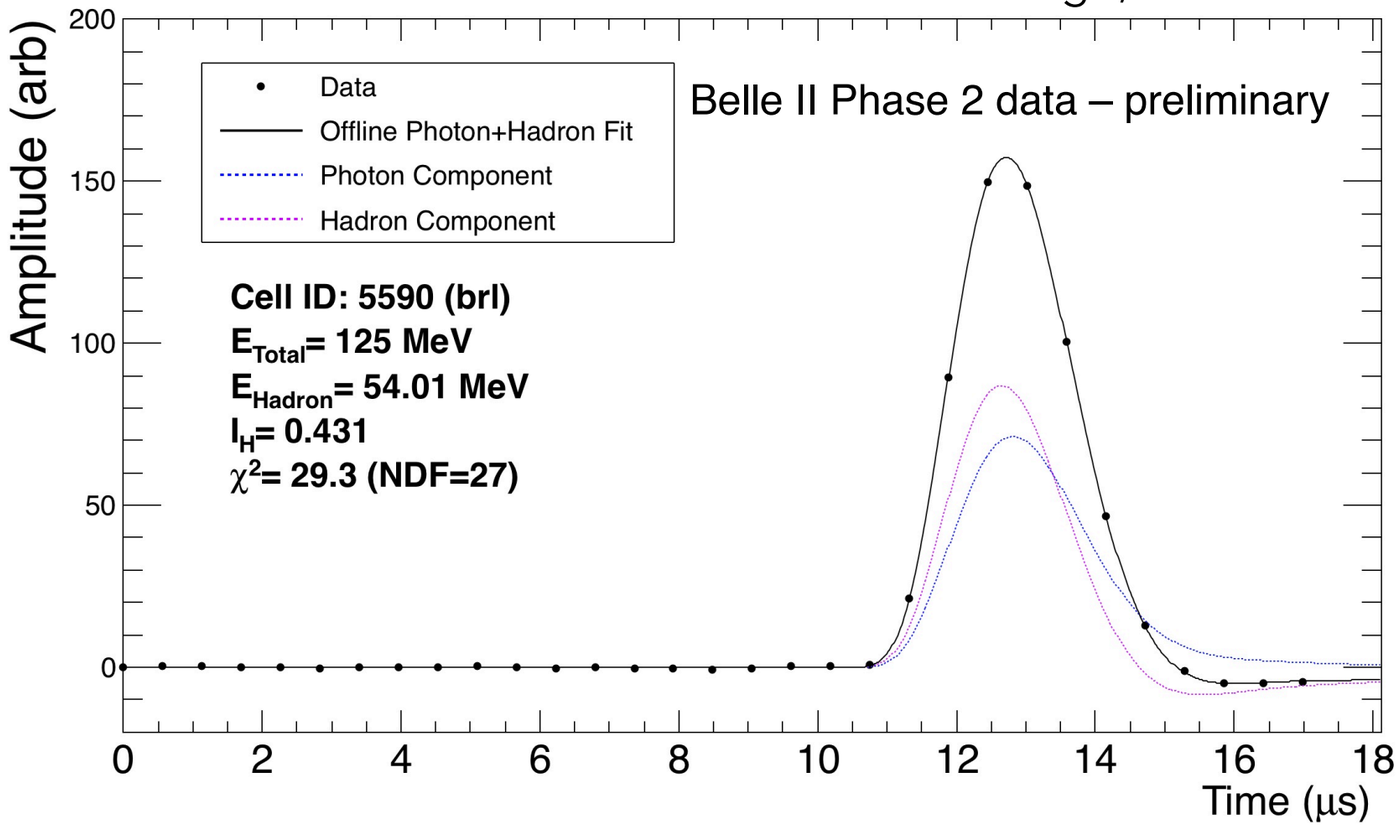
Pulse-Shape Discrimination (PSD)

- Online FPGA waveform fits use photon templates only and provide time and amplitude fit results (2 variables)
- New: Exploit the fact that hadronic and electromagnetic scintillation components are different
  - If crystal energy E > 30 MeV: Store waveform data (31 variables) and repeat fit offline with different templates.
- Third information from a crystal: PSD

S. Longo, ICHEP2018



Binary or global PID?

A very simple example: a magic universe where only pions and kaons exist.

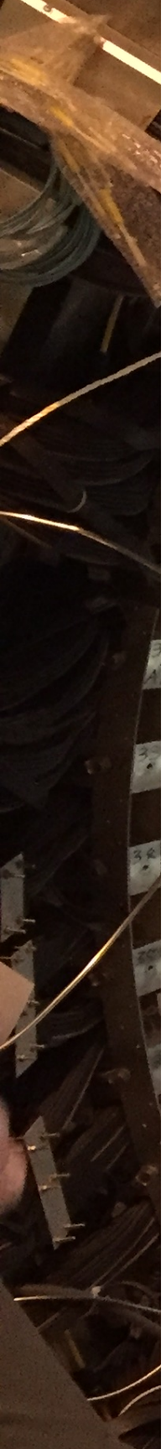
We observe a "kaon-like" signal. What's the probability for that particle to be a kaon?

Posterior probability

$$P(\text{S is from K}) = \frac{P(\text{K gives S}) \cdot P(K)}{P(\text{K gives S}) \cdot P(K) + P(\pi \text{ gives S}) \cdot P(\pi)}$$

Prior probability

35



Binary or global PID?

The likelihood value is actually a proxy (i.e. is proportional) exactly to the conditional probability!

$$P(\text{S is from K}) = \frac{L(K) \cdot P(K)}{L(K) \cdot P(K) + L(\pi) \cdot P(\pi)}$$

$$P(A) = \frac{L_A}{L_e + L_\mu + L_\pi + L_K + L_p + L_d}$$

→ **Global and binary PID are simply different priors schemes**

→ **Non-trivial priors are not implemented yet**

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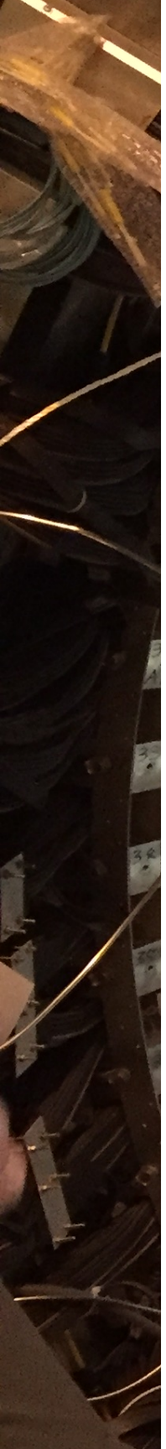

Performances

Few metrics are used to characterize the performances of a PID detector

→ **Efficiency: ability to correctly assign the ID**

$\varepsilon(\mathrm{K}) = \mathrm{N}(\mathrm{K}$ identified as $\mathrm{K})/\mathrm{N}(\text{real } \mathrm{K})$

Equal, by definition, to the "probability of a kaon to be called kaon"

→ **Mis-ID probability: ability not to assign the incorrect ID**

$\text{Mis-ID}(\mathrm{K}) = \mathrm{N}(\text{non-}\mathrm{K}$ identified as $\mathrm{K})/\mathrm{N}(\text{non } \mathrm{K})$

Equal, by definition, to the "probability for a non-kaon to be called kaon"

→ **Fake rate: fraction of particles with the wrong ID**

$\mathrm{F}(\mathrm{K}) = \mathrm{N}(\text{non-}\mathrm{K}$ identified as $\mathrm{K})/\mathrm{N}(\text{identified as } \mathrm{K})$

Equal, by definition, to the "fraction of non-kaons in my collection of kaons"