Particle Identification

Lesson 2 - Methods

M. Contalbrigo – INFN Ferrara

2nd European School on the Physics of the EIC and Related Topics, 22th June – 2nd July, 2025

Arguments

Specific Particle-ID Detectors	Time-of-Flight Cherenkov Radiation
Reconstruction example	
Analysis Methods	Chi2 Maximum Likelihood Machine Learning techniques
ePIC Requirements	
ePIC Solution	pfRICH TOF hpDIRC dRICH

PID by Tracking

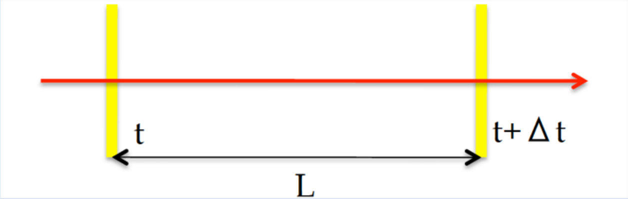
Assume to know the momentum (by tracking the bending in a magnetic field)

$p = \gamma m \beta c$

Get the mass by measuring the velocity (βc)

Process	Particle	Equipment
Energy Loss (dE/dx)	Hadrons	Tracking
Transition Radiation (TDR)	Electrons	Tracking sensitive to X-ray
Time-of-Flight (TOF)	Hadrons	Timing
Cherenkov Radiation	Hadrons	Cherenkov

The T_0 Problem



In a time of flight application one needs two layers (impractical) or a reference t_0 with better (or comparable) precision with respect TOF.

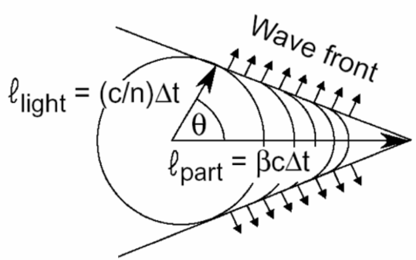
The t_0 is typically given at the interaction point by back-tracking:

- Reference particle (e.g. lepton in deep-inelastic scattering)
- Average over particles (requires large multiplicity)
- Bunch RF information (require to “just” identify the beam bunch crossing)

Cherenkov Radiation

Photo emission by a charged particle travelling in a dielectric medium with a velocity greater than the velocity of light in that medium:

$$\cos\theta_c = \frac{(c/n)\Delta t}{\beta c \Delta t} = \frac{1}{\beta n} \qquad v_{\text{particle}} > \frac{c}{n} \quad \left(\beta_{\text{thr}} = \frac{1}{n}\right)$$



Momentum threshold:

$$\epsilon = n - 1$$

$$\beta = \frac{p}{\sqrt{p^2+m^2}} = \frac{1}{1+\epsilon} \quad \Rightarrow \quad p = \frac{1}{\sqrt{2\epsilon+\epsilon^2}} \cdot m$$

Scales with particle mass

Decreases with n

Photon yield:

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

$$\frac{dN}{dx} = 2\pi z^2 \alpha \sin^2\theta_C \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

$\propto \sin^2(\theta_c) = 1-(1/\beta n)^2 \Rightarrow$ small when $n \approx 1$!

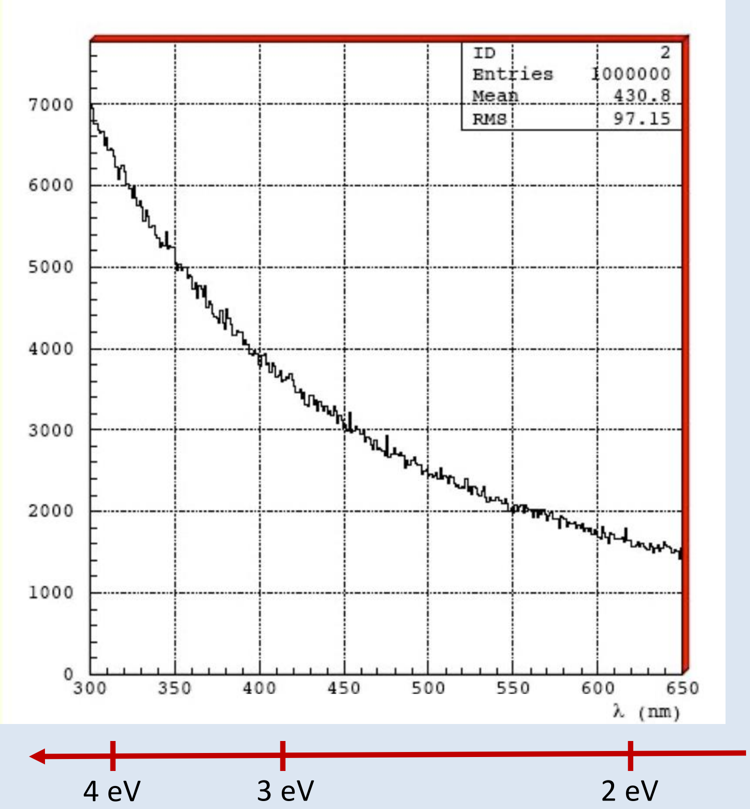
$\propto 1/\lambda^2 \Rightarrow$ mostly blue light!

$$\hbar c = 2 \cdot 10^{-5} \ \text{eVcm}$$

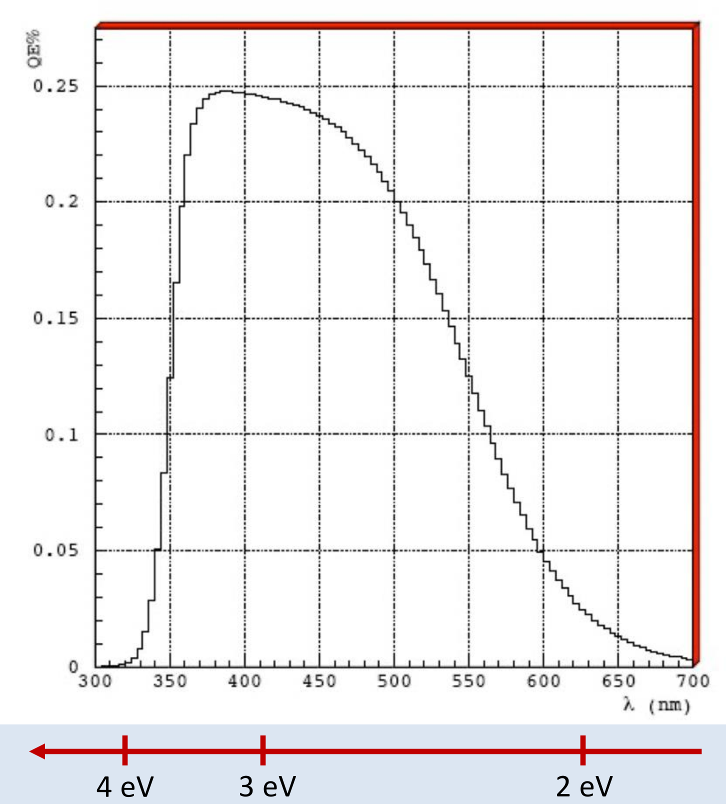
$$\frac{d^2N_{ph}}{dLdE}[\text{cm}^{-1}\text{eV}^{-1}] = \frac{\alpha Z^2}{\hbar c}\sin^2\theta = 370 Z^2 \sin^2\theta \qquad E_{ph}[\text{eV}] = 2\pi\hbar\frac{c}{\lambda} = \frac{1240}{\lambda[\text{nm}]}$$

Photon Yield

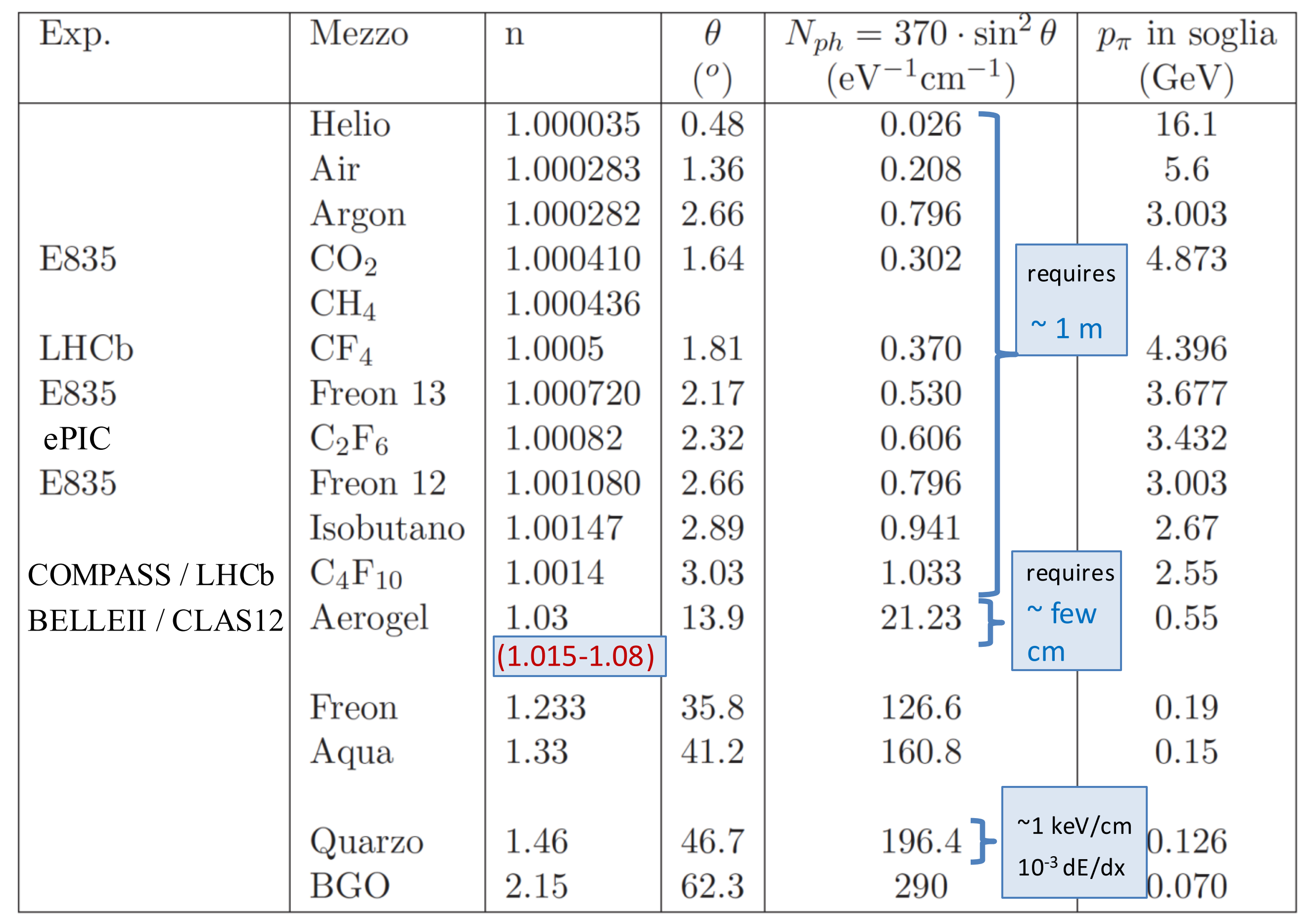
Spectrum of Cherenkov photons



Typical sensitivity (quantum efficiency) of a PMT



Cherenkov Radiators



Exp.	Mezzo	n	θ $(^o)$	$N_{ph} = 370 \cdot \sin^2\theta$ $(\mathrm{eV}^{-1}\mathrm{cm}^{-1})$	p_π in soglia (GeV)
	Helio	1.000035	0.48	0.026	16.1
	Air	1.000283	1.36	0.208	5.6
	Argon	1.000282	2.66	0.796	3.003
E835	CO_2	1.000410	1.64	0.302	4.873
	CH_4	1.000436			
LHCb	CF_4	1.0005	1.81	0.370	4.396
E835	Freon 13	1.000720	2.17	0.530	3.677
ePIC	C_2F_6	1.00082	2.32	0.606	3.432
E835	Freon 12	1.001080	2.66	0.796	3.003
	Isobutano	1.00147	2.89	0.941	2.67
COMPASS / LHCb	C_4F_{10}	1.0014	3.03	1.033	2.55
BELLEII / CLAS12	Aerogel	1.03 (1.015-1.08)	13.9	21.23	0.55
	Freon	1.233	35.8	126.6	0.19
	Aqua	1.33	41.2	160.8	0.15
	Quarzo	1.46	46.7	196.4	0.126
	BGO	2.15	62.3	290	0.070

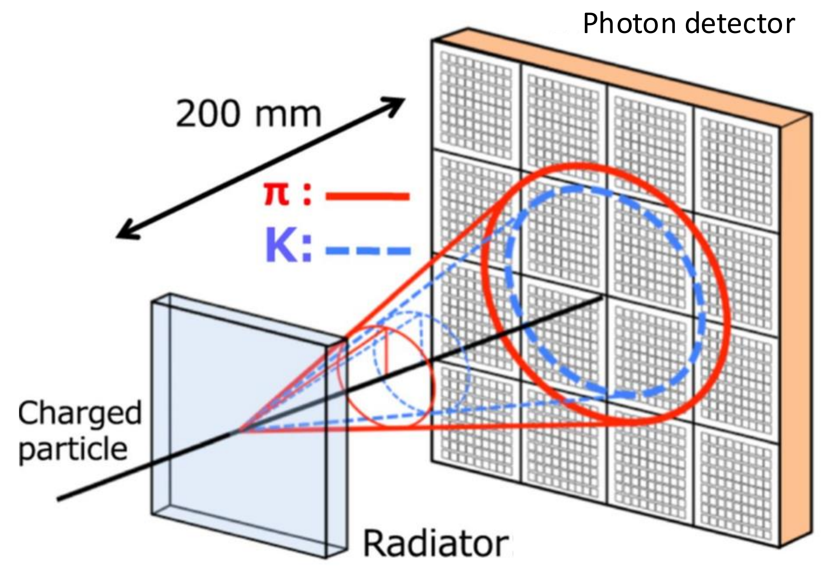
requires ~ 1 m

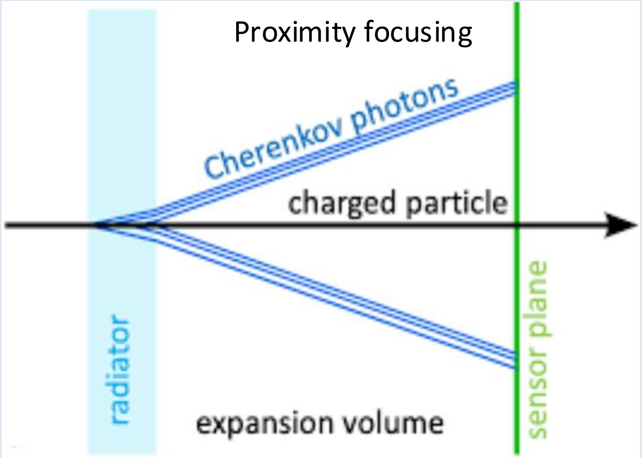
requires ~ few cm

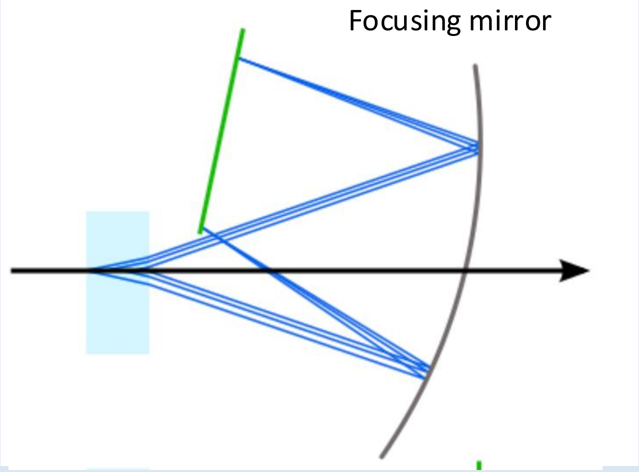
~1 keV/cm 10^{-3} dE/dx

Real PID starts at 3x (kaon)

Photon Detection







Chromatic Dispersion

Gas Radiator

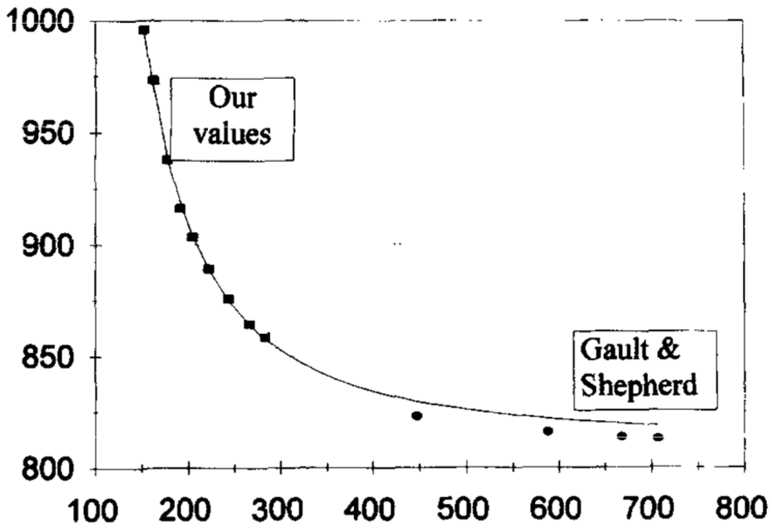
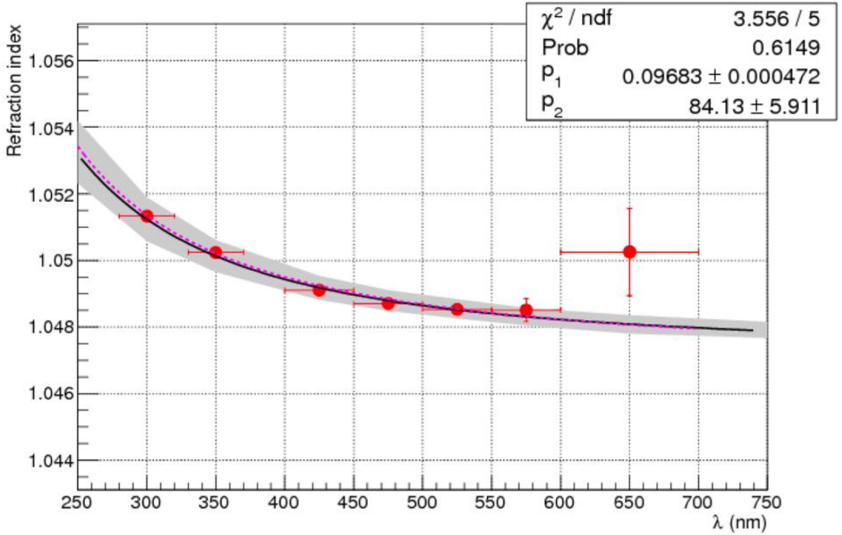


Fig. 1. The refractivity of C_2F_6 (hexafluoroethane) expressed as $(n-1)\times10^6$ is plotted versus the wavelength in nm. The solid line corresponds to the Sellmeier formula fitted with our measurements.

Aerogel Radiator



Refractive index as a function of the Cherenkov light wavelength for the aerogel with n = 1.05 and trad = 20 mm obtained selecting pions with 8 GeV/c momentum.

Sellmeier parameterization

$$n^2(\lambda) = 1 + \frac{p_1\lambda^2}{\lambda^2 - p_2^2}$$

Cherenkov Resolution

$$\sigma_{CH} = \sqrt{\sigma_{co}^2 + \frac{\sigma_{em}^2 + \sigma_{ch}^2 + \sigma_{px}^2}{N_{pe}}}$$

σ_{co} correlated uncertainty (tracking, misalignment, magnetic bending, multiple scattering, ….)

σ_{em} uncertainty on the photon emission point (radiator depth)

σ_{ch} radiator chromatic dispersion (uncertainty on the photon wavelength)

σ_{px} sensor spatial resolution (pixel size)

$$\frac{d^2N}{dxd\lambda} = \left(\frac{d^2N_C}{dxd\lambda}\right) QE(\lambda)\epsilon_{pe}e^{-\frac{t_{rad}-x}{\Lambda(\lambda)\cos(\eta_C)}}$$

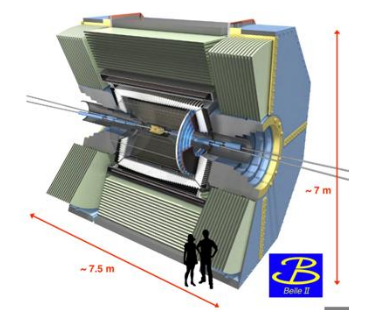
$Q(\lambda)$ Sensor quantum efficiency

$\Lambda(\lambda)$ Radiator transmission length

ε_{pe} detection efficiency (sensor and mirror)

t_{rad} radiator thickness

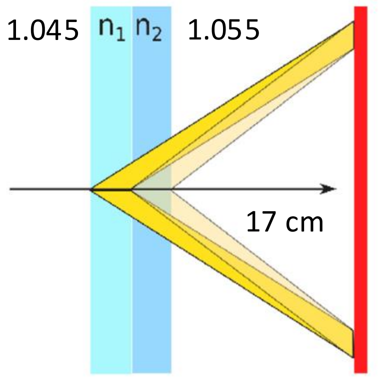
BELLE ARICH



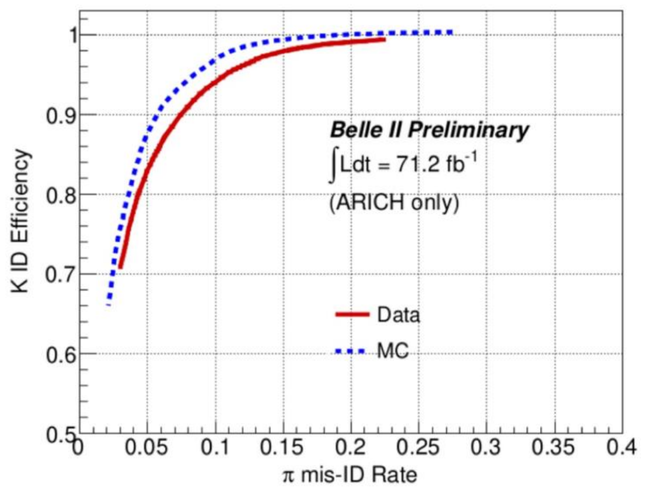
BELLE-II: B-factory

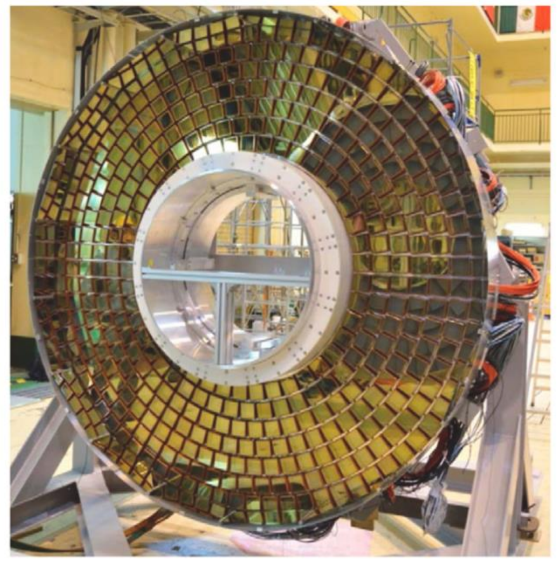
Limited space --> Proximity focusing & radiator focusing

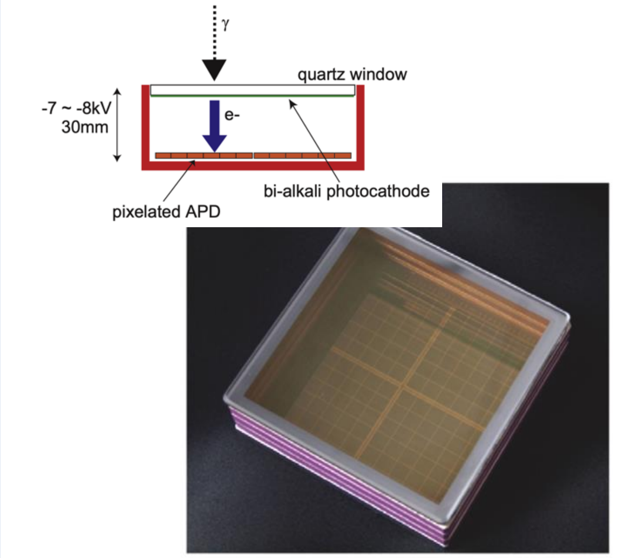
High B field (1.5T) --> Custom Hybrid photon detector
Super bialkali photocatode
Gain 4.5 10^6
PDE ~ 28 %



D^0--> $K^-\pi^+$ 0.5 - 3.5 GeV/c

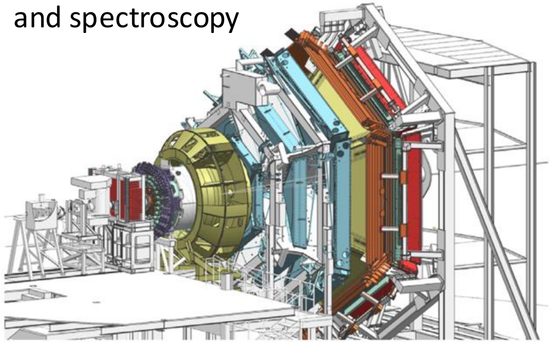


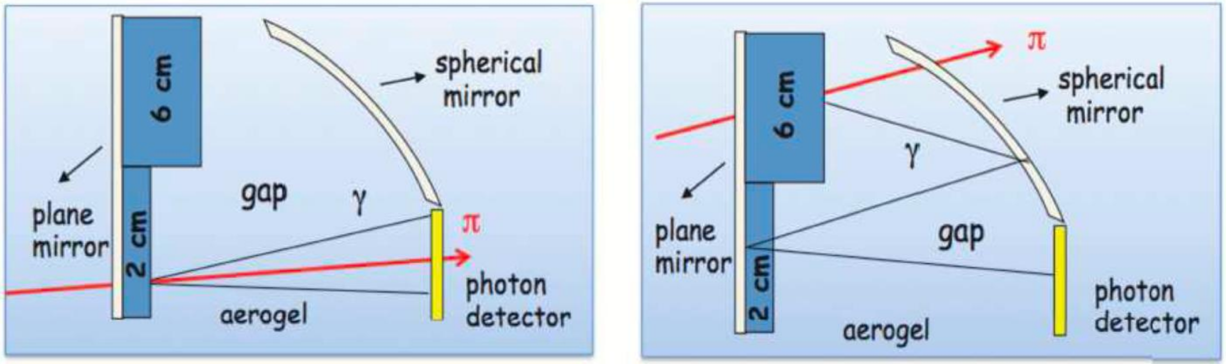


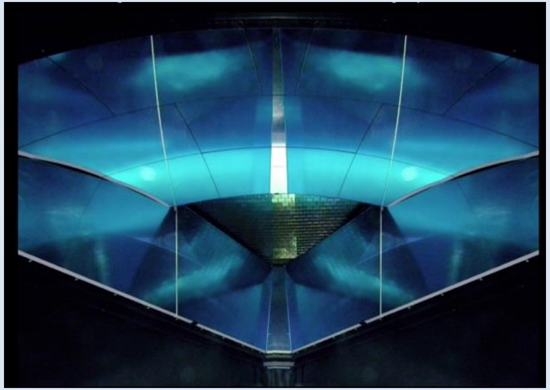


CLAS12 RICH

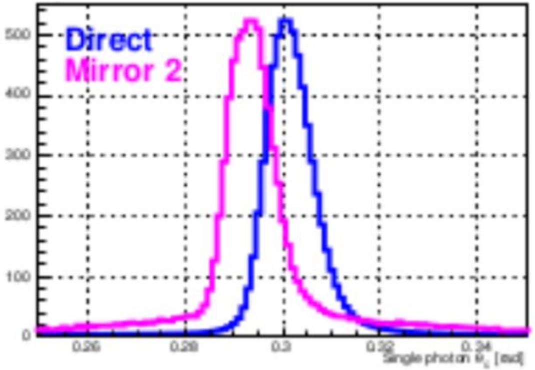
CLAS12: Nucleon structure and spectroscopy



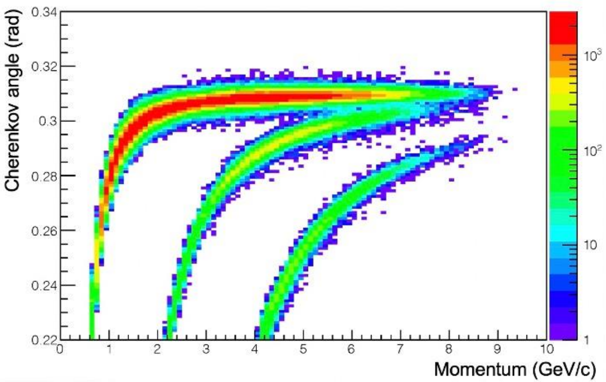




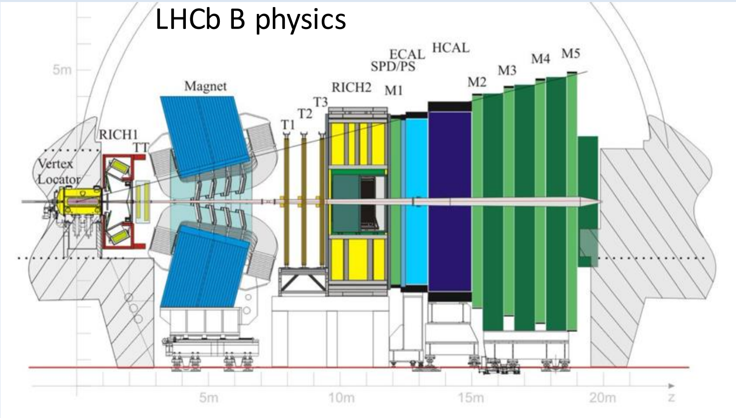
Electrons: direct vs spherical reflection



95 % kaon efficiency
(<1% pion mis-ID) up to 8 GeV/c



LHCb RICH

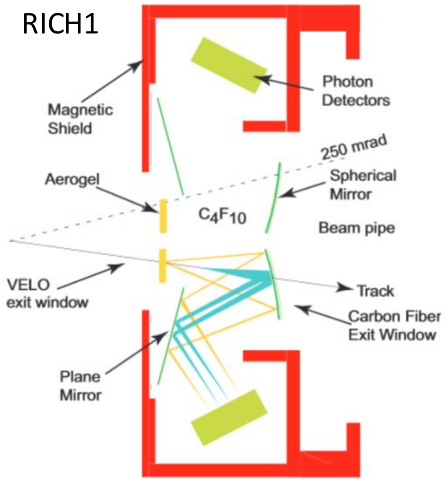

LHCb B physics

LHCb Precisin measurements of B-decays and search fro BSM signals

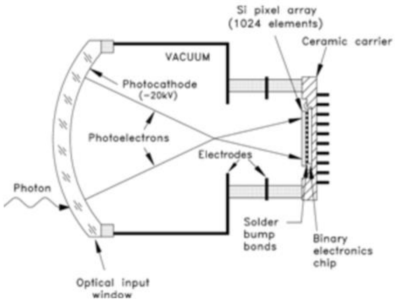
RICH1: Aerogel (5 cm) n=1.03
2-10 GeV/c

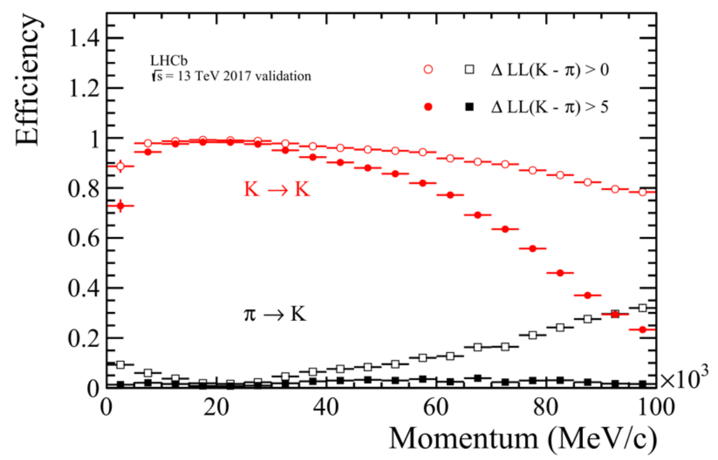
C_4F_{10} (85 cm) n=1.0014
up to 70 GeV/c

RICH2: CF_4 (196 cm) n=1.0005
up to 100 GeV/c


RICH1

Hybrid photomultiplier
Photocatode @ - 20 kV
Silicon sensor

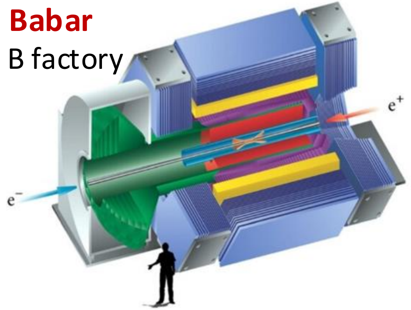




DIRC

Babar

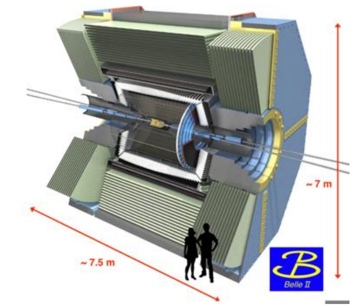
B factory

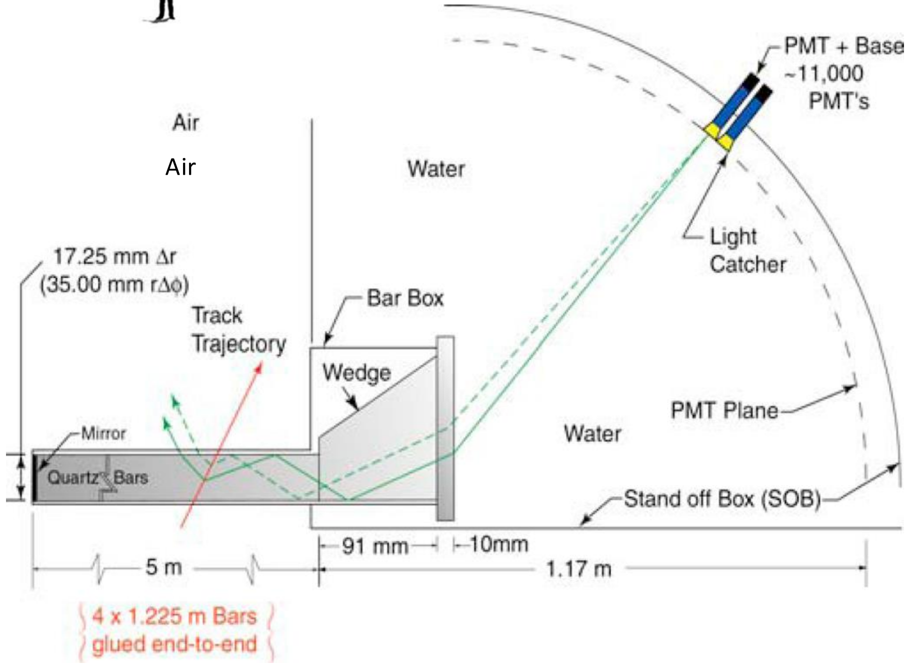


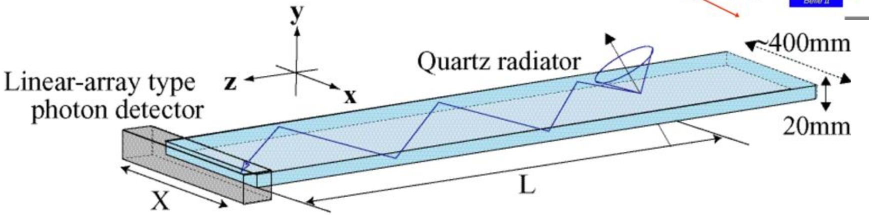
Detection by internal reflection: compact detection volume (thickness)

Critical aspects: quartz surface quality (parallelism, roughness)
proper imaging system

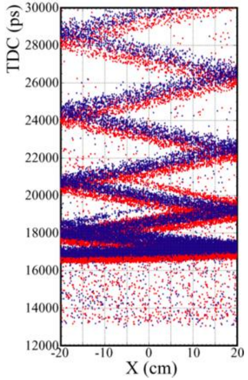
Belle-II B factory

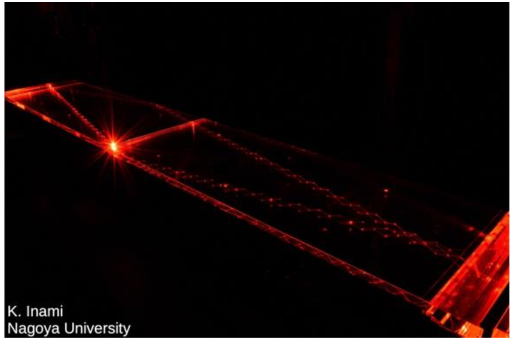






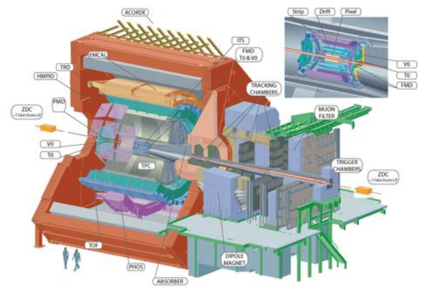
1D + time maging – Belle-II



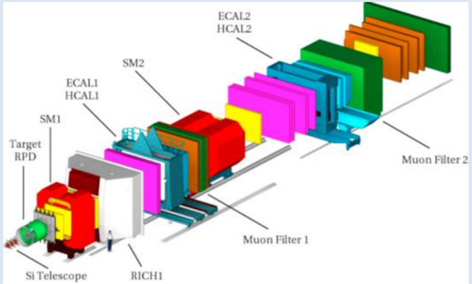


CsI Photocatode

ALICE: Quark-gluon plasma in heavy ion collisions



COMPASS: Nucleon structure and spectroscopy

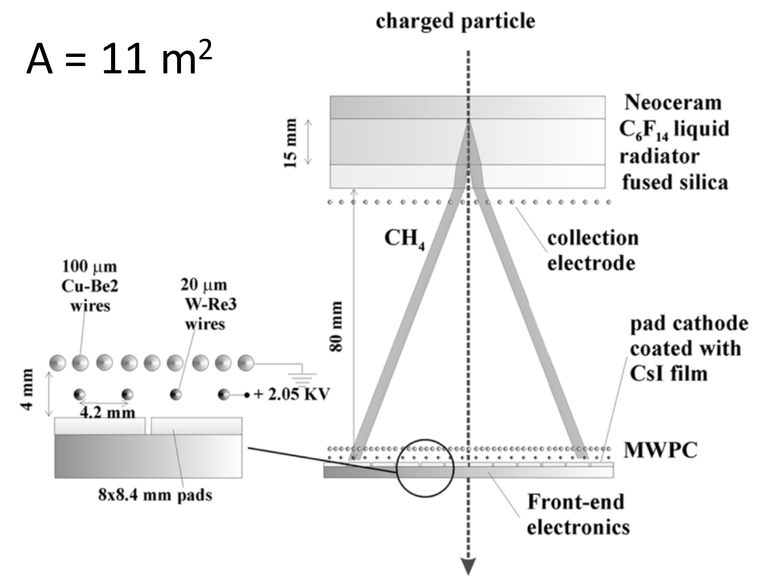


Large instrumented area

Multi-wired proportional chambers with a CsI photocatode

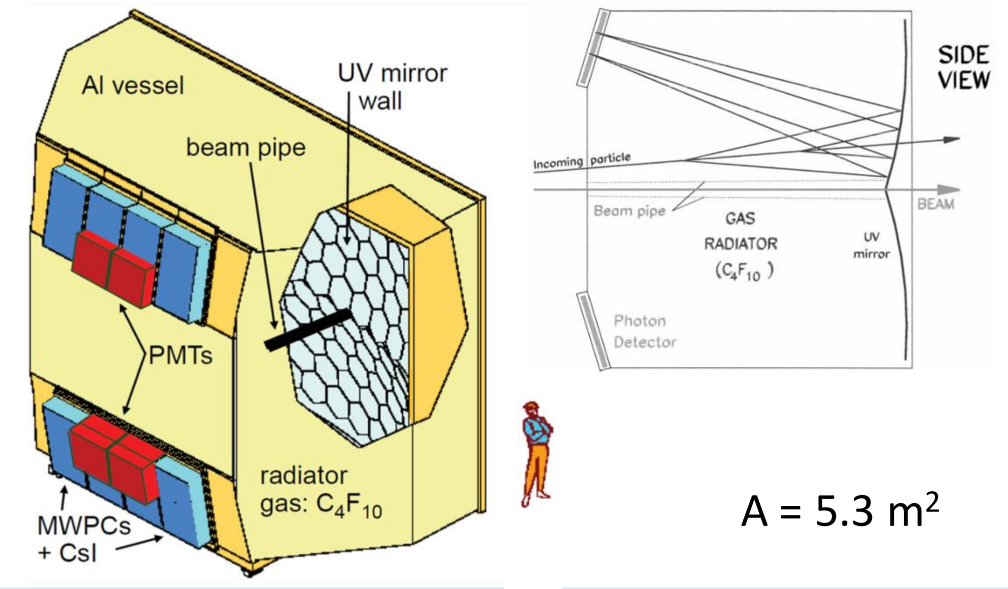
Quantum efficiency is around 16-24% at 170 nm

High-Momentum PID



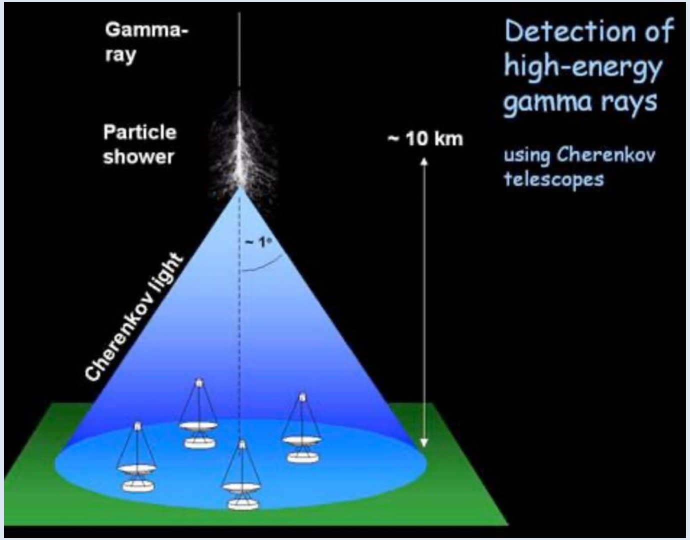
A = 11 m^2

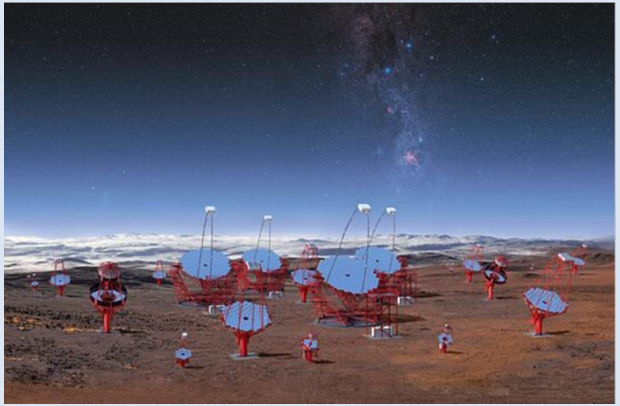
RICH



A = 5.3 m^2

Cosmic Rays





A cosmic gamma ray generates a particle shower in the atmosphere

Showering charged particles generates Cherenkov radiation

The number of detected photons is proportional to the initial energy

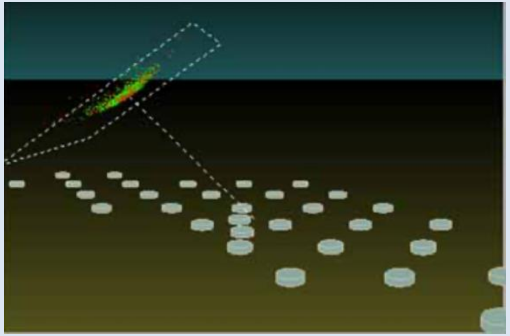
Air refractive index is n = 1.00028

Threshold energy is 4.4 GeV for muons and 21 MeV for electrons

Cherenkov angle is 23 mrad ~ 1.3°

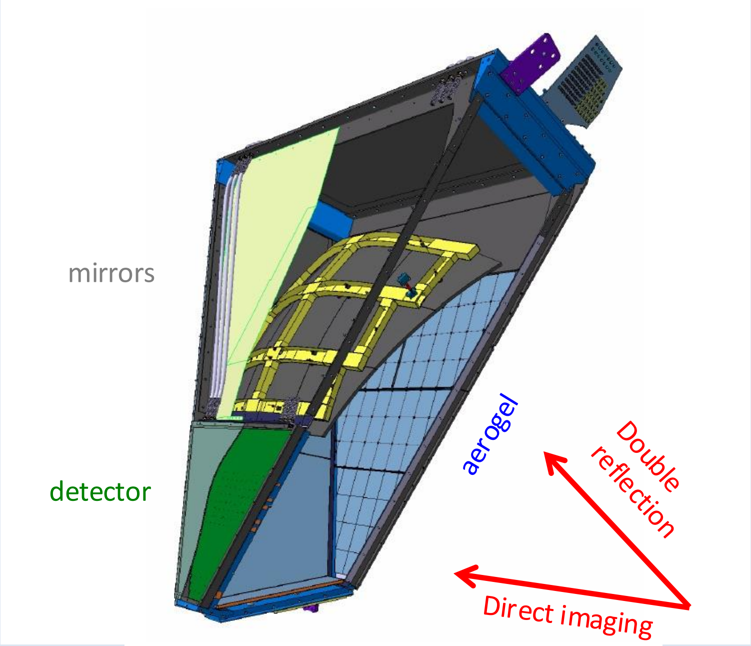
The shower maximum is at 10 km and generates a cone of 230 m

Extended detection pattern in space and time gives the direction

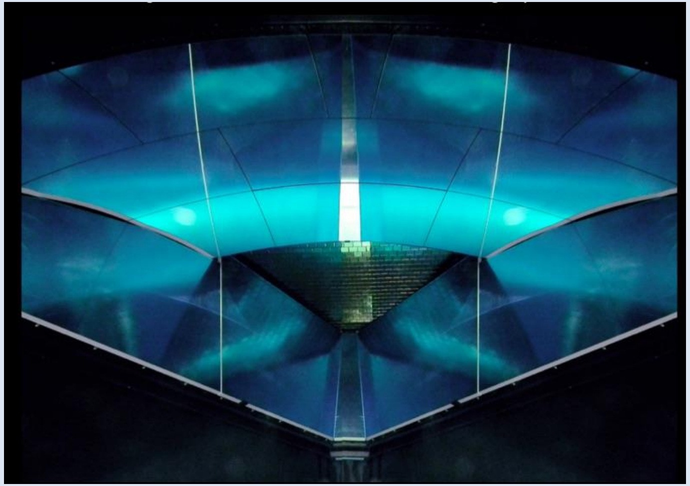


PID Reconstruction

CLAS12 RICH



Goal: Hadron identification rom 3 GeV/c up to 8 GeV/c



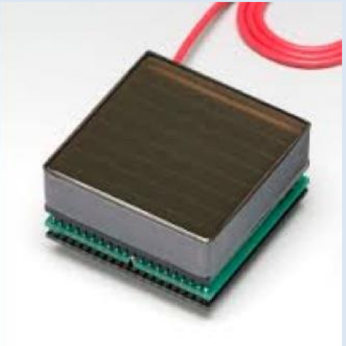
Hamamatsu H12700 (+ H8500)

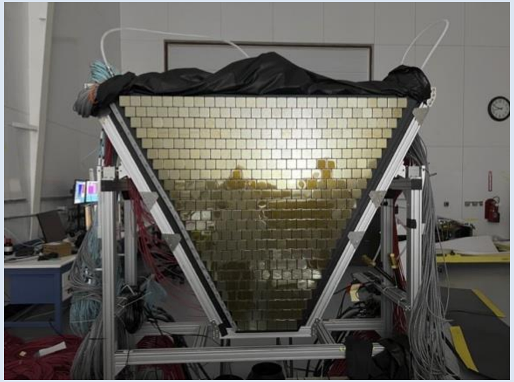
< 1 cm spatial resolution

< 1 ns time resolution

Average gain ~ 2.7 10^6

eq. to SPE ~ 400 fC





Geometry

Read CSG volumes from CAD stl files

Convert volumes into tracking surfaces (Shape3D) and spheres (Sphere3D) with given orientation

Each Sphere3D has an associated Shape3D to define its solid angle of acceptance

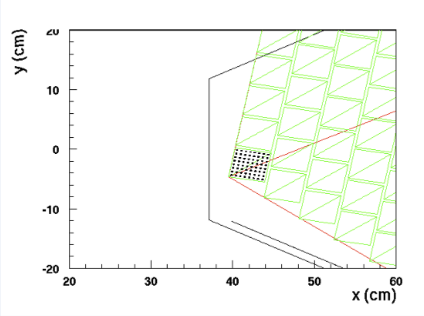
Align the tracking surfaces (as per mounting points)

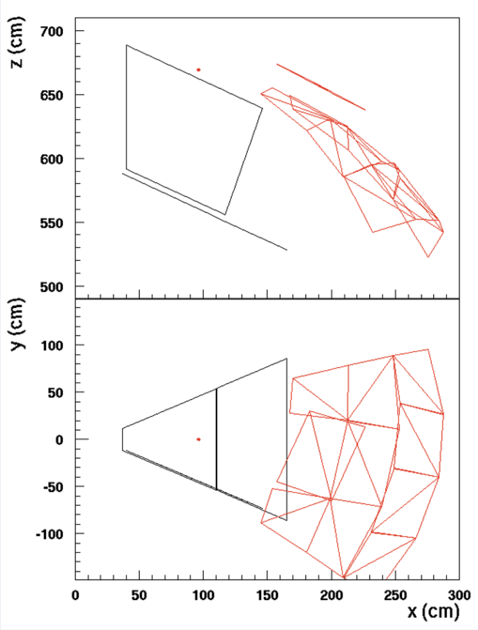
Global RICH

Layer (aerogel, MaPMTs, spherical mirror assembling)

Components (each single mirror, aerogel tile)

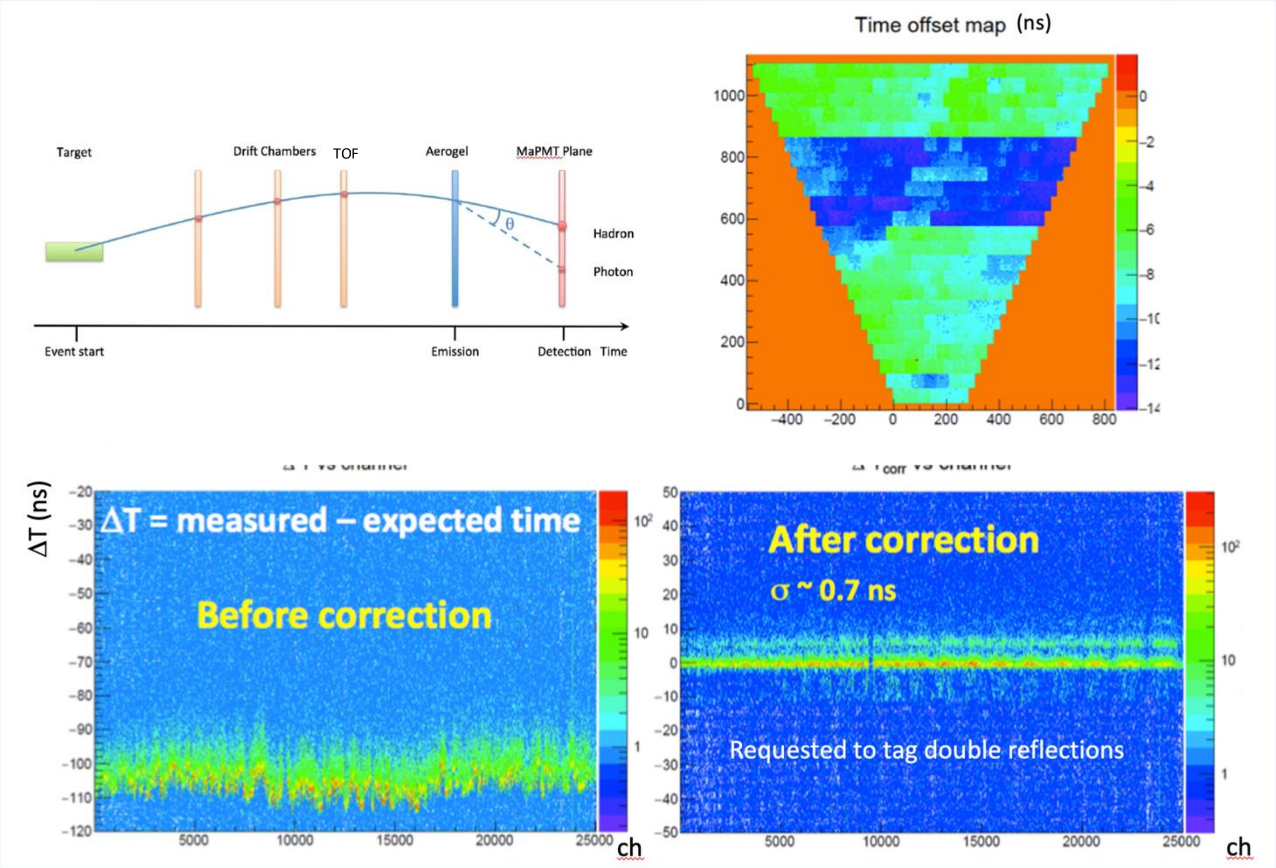
Detail MaPMT pixel geometry (on the misaligned plane)





Time

RICH time calibration with CLAS12 time-of-flight detector + bunch crossing (t_0)



ΔT = measured – expected time

Before correction

After correction

σ ~ 0.7 ns

Requested to tag double reflections

Ray Tracing

Complex geometry with various photon paths (reflections) off the same particle

From CLAS12:

particle momentum
photon emission point and time

From RICH:

hit time and position

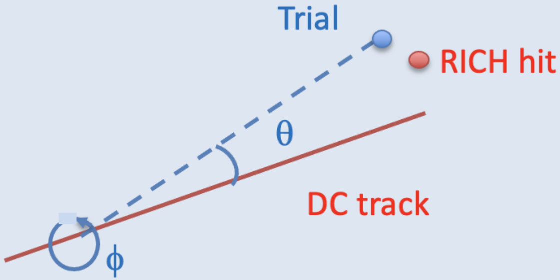
Direct ray-tracing:

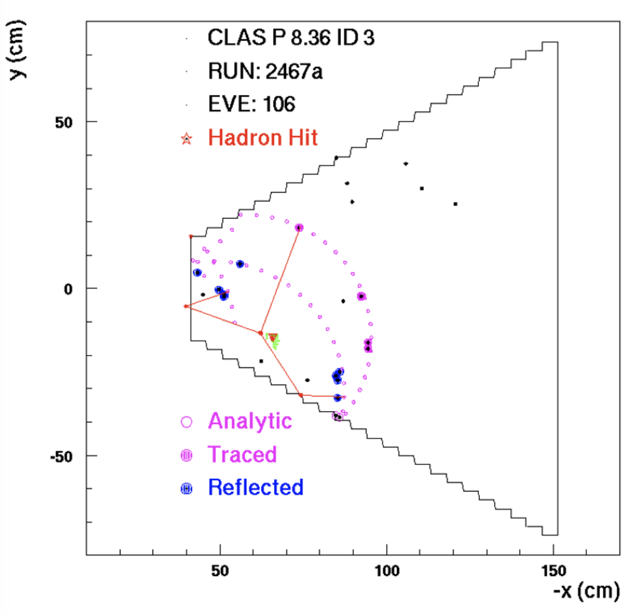
assume an ID hypothesis (e, π, k, p)

ray-trace a limited sample of photon trials (selection of ϕ's for given θ)

adjust the angles to match the hit starting from the closest trial (convergence in 2-3 iterations)

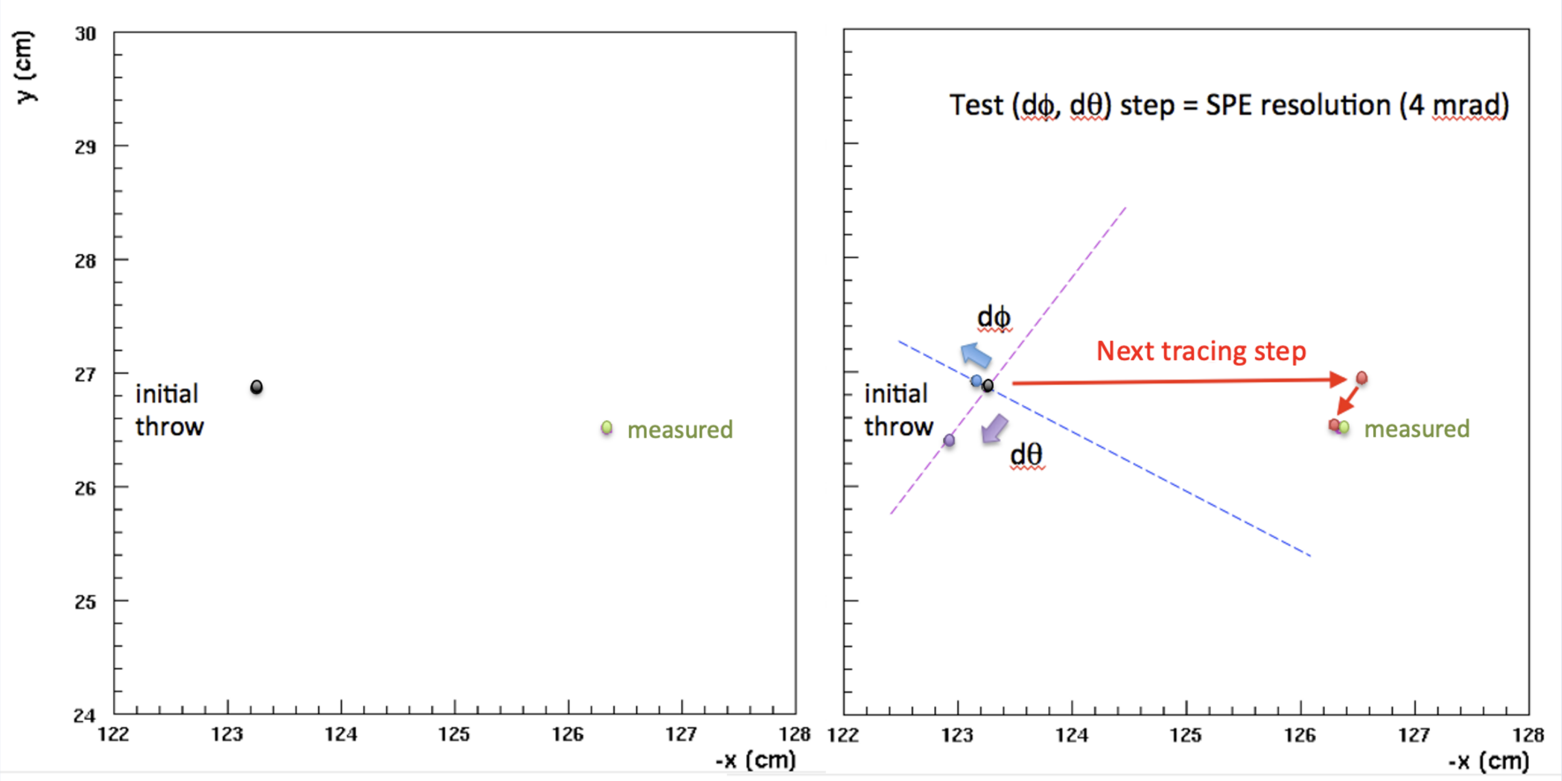
validate photon reconstructed Cherenkov angle and transit time





Convergence

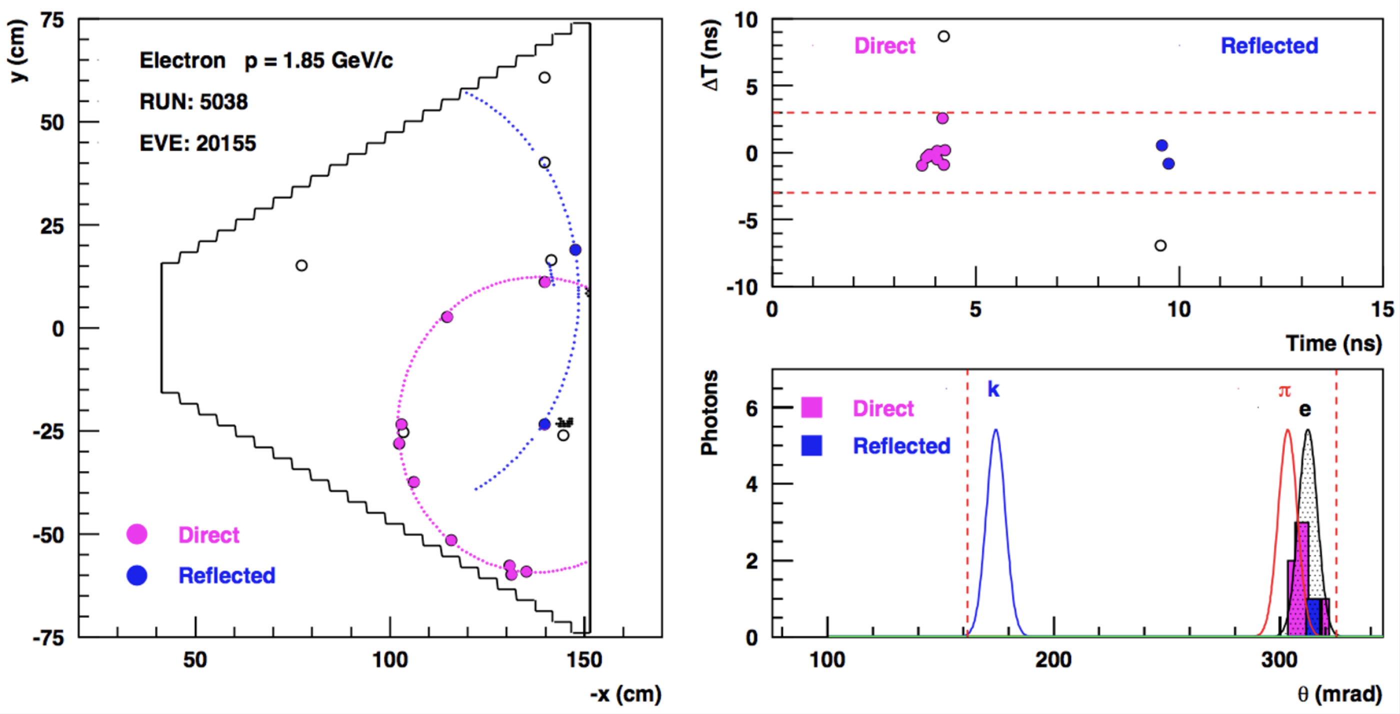
Trial position and refraction at boundaries [θ,n(β)] depend on particle hypothesis
Stop when closer than half expected (angular) resolution



Reconstruction

Photon path reconstruction allow to assign the photon to the most likely hypothesis:

- be robust and easy to control (easy to handle multi-reflections, up to e.g. 5)
- discriminate background (hit far from trials, no solution foreseeable)
- provide full information (photon path, time, position and component of each reflection)
- allow relation with nominal optical components, resolution and efficiency

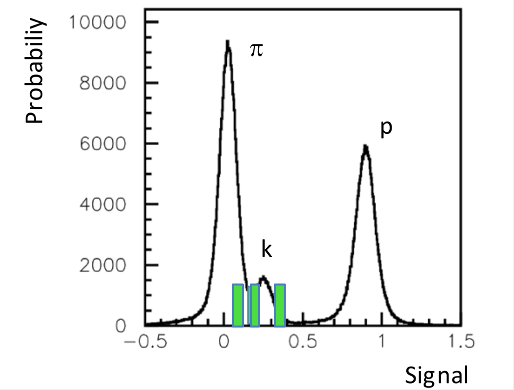


PID Analysis

Analysis

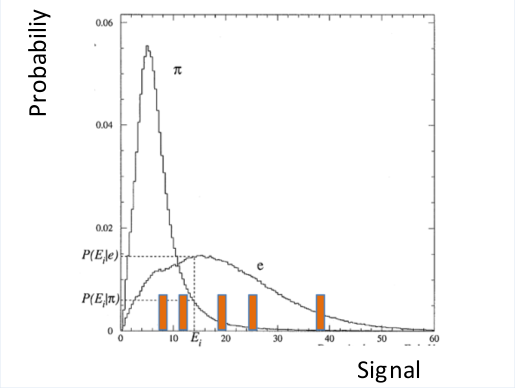
Least squares minimization

$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - x(\boldsymbol{\theta}))^2}{\sigma^2}$$

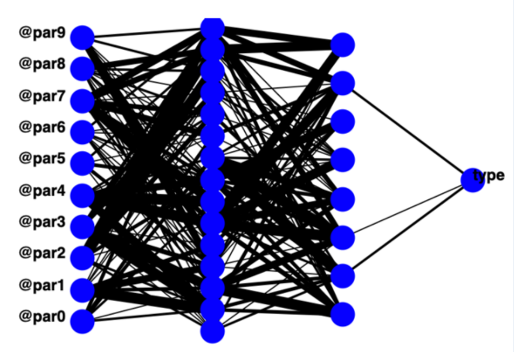


Likelihood maximization

$$L(\boldsymbol{\theta}) = \prod_{i=1}^{n} f(x_i; \boldsymbol{\theta})$$



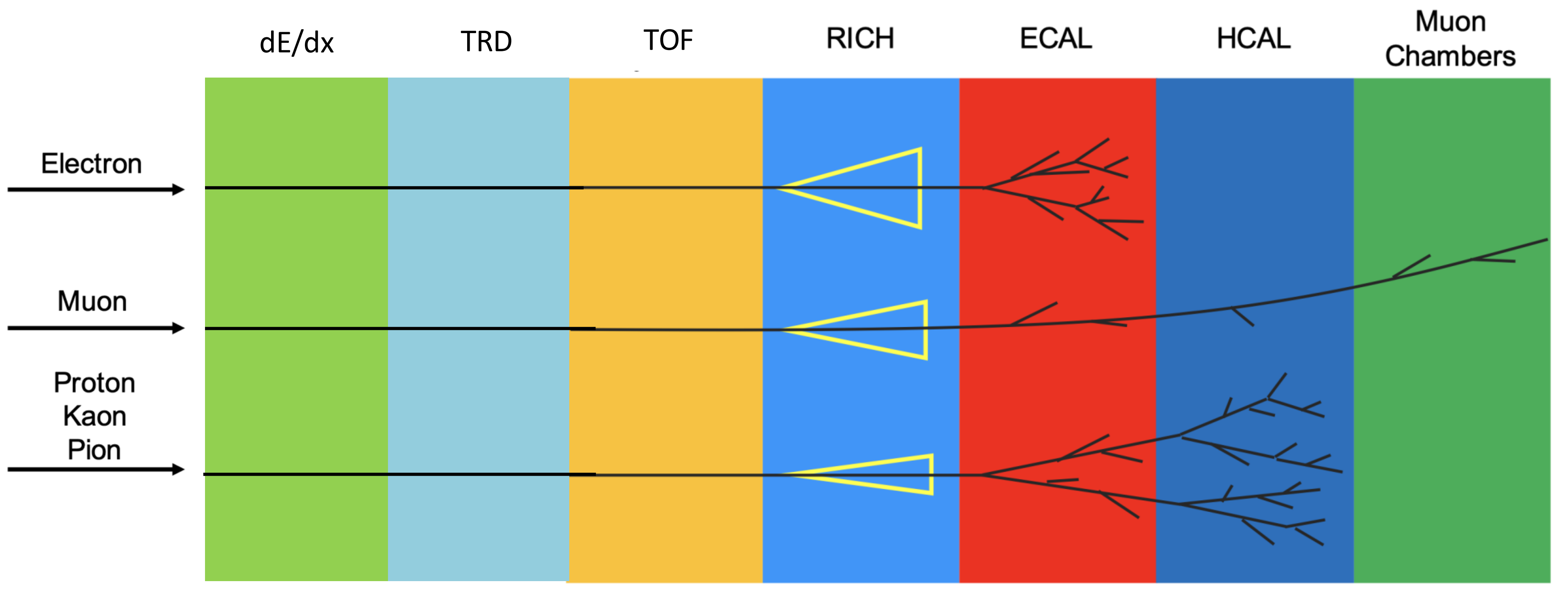
Machine learning techniques



Particle Identification

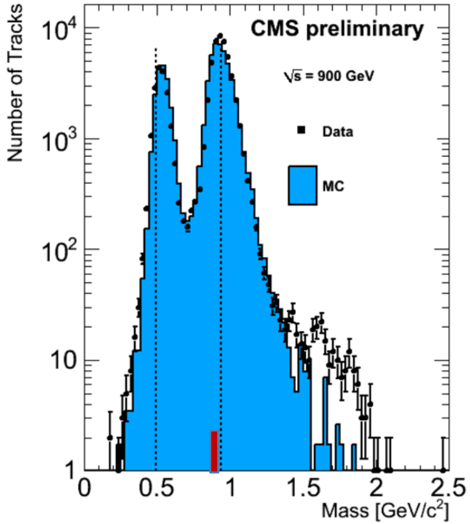
Best performance is with an holistic approach

Correlating featured signals from the same detector (dE/dx points, TRD layers, ring photons,….) or from different detectors

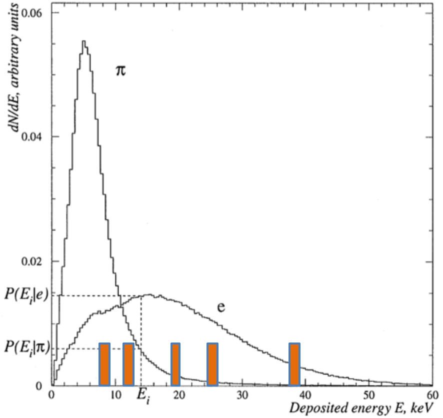


Holistic Approach

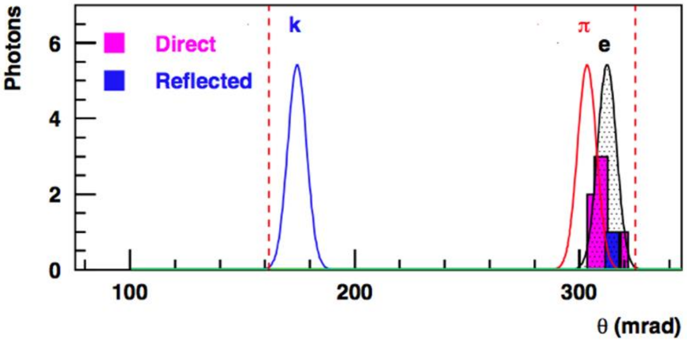
dE/dx



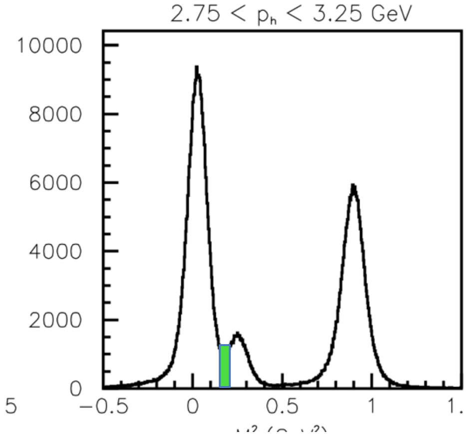
TRD



RICH



TOF



Extended Maximum Likelihood

Observe *n* events x_i and expect a total of μ

$$L(\boldsymbol{\theta}) = \underbrace{\frac{\mu^n}{n!} e^{-\mu}}_{\textbf{Poisson}} \underbrace{\prod_{i=1}^{n} f(x_i; \boldsymbol{\theta})}_{\textbf{Unbinned ML}}$$

In the *logL* any constant is irrelevant, i.e. any term that does not depend on the parameters θ.

In case f(x_i;θ) is a binned PDF with poisson probability the above reduces (except for a constant) to the binned maximum likelihood

$$L_{\mathrm{P}}(\boldsymbol{n}; \boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{\mu_i^{n_i}}{n_i!} e^{-\mu_i}$$

Extended Maximum Likelihood

$$-2\ln\lambda(\boldsymbol{\theta}) = 2\sum_{i=1}^{N}\left[\mu_i(\boldsymbol{\theta}) \boxed{- n_i} + n_i \ln\frac{\boxed{n_i}}{\mu_i(\boldsymbol{\theta})}\right]$$

Taking a likelihood ratio, vs an ideal model corresponding to the measurement (μ_i=n_i), provides a chi2-like estimator (goodness of fit) if μ_i are not too small

* μ_i is the expected yield in bin i (signal + background)

* pdf normalization to 1 is given by Poisson

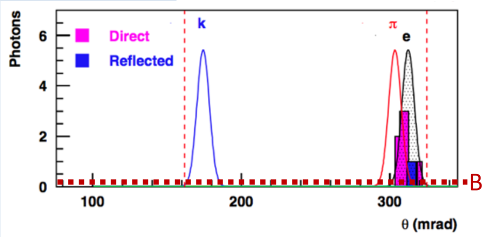
* the μ_i – n_i term is optional (less stringent except close to threshold)

* one can have bins with zero counts (last term is taken to be zero)

Cherenkov Example

$$\mu_i(\theta) = \varepsilon(i)\ \underbrace{\frac{d\phi}{2\pi}}_{\text{Flat probability}}\ e^{-\frac{(\theta-\boxed{\theta_i})^2}{2\sigma^2}}\ \frac{\mathrm{d}\theta}{\sqrt{2\pi}\sigma}\ \underbrace{e^{-\frac{(t(\theta)-\boxed{t_i})^2}{2\sigma_t^2}}}_{\text{t may change due to path (direct or reflected)}}\ \frac{dt}{\sqrt{2\pi}\sigma_t} + \mathrm{B(i)}$$

Measured values



All these quantities are defined at pixel level

- dθ and dϕ are known by RICH reconstruction.

- ε(i) can reflect dead (0) or hot (1) channels, or the quantum/reflection efficiency ([0:1])

- B(i) can be derived from random triggers or electron control sample

Reference values could accounts for second order effects
(photon path and pattern change among various mass hypotheses).

Likelihood Ratio

$$\mu_i'(\theta) = \varepsilon(i)\ \frac{d\phi}{2\pi}\ \overbrace{1}^{\theta=\theta_i}\ \frac{d\theta}{\sqrt{2\pi}\sigma}\ \overbrace{1}^{t=t_i}\ \frac{dt}{\sqrt{2\pi}\sigma_t}$$

One might take the likelihood ration with he model corresponding to the “observed measurement” in which all the hit are at the right (expected) angle

$$-2ln\lambda(\theta) = 2\sum_{i=1}^{N}\left[\mu_i(\theta)\ - n_i + n_i ln\frac{\mu_i'(\theta)}{\mu_i(\theta)}\right]$$

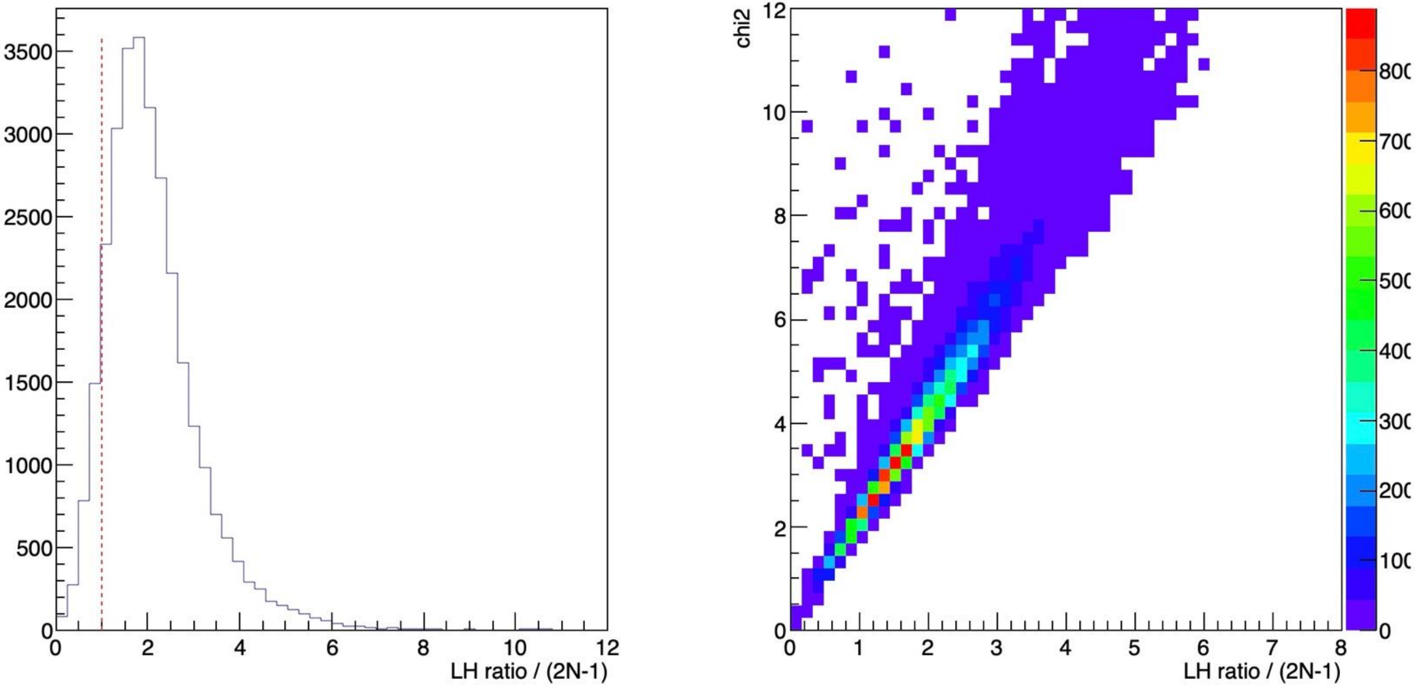
$$= 2\left(N_{exp} - N\right) + \sum_{i=1}^{N}\left[\frac{(\theta-\theta_i)^2}{\sigma^2}\right] + \left[\frac{(t(\theta)-t_i)^2}{\sigma_t^2}\right]$$

Should reduce to a sort of chi2.

Beyond non gaussian effects and the optional normalization term, the difference is in the background that defines a sort of cutoff: an accepted hit that is background for all the hypotheses does not count in the likelihood, whereas the ordinary chi2 weights anyway its distance from the expected value (provides a preference) except it is explicity excluded

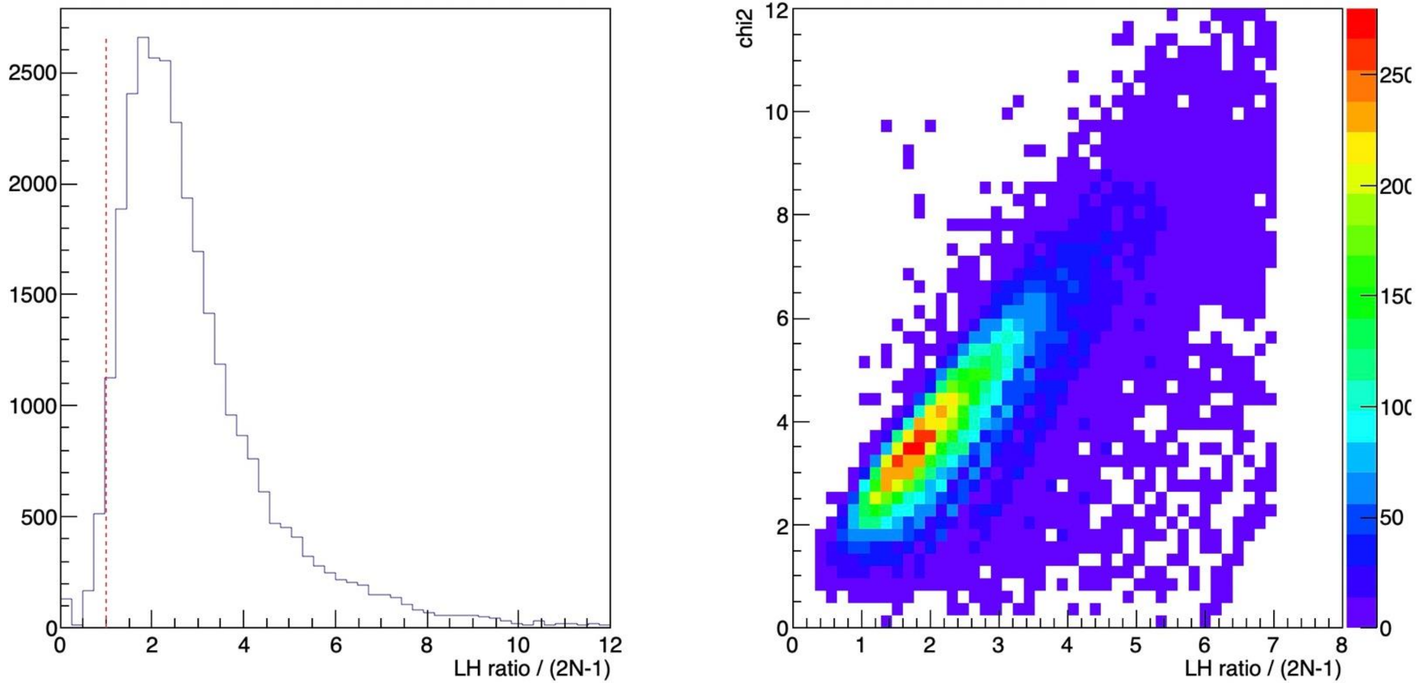
Extended Maximum Likelihood

Without $2(N_{exp}\text{-}N)$ term



Extended Maximum Likelihood

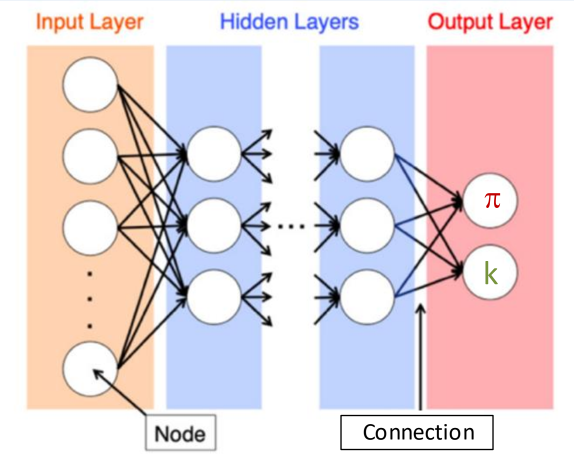
With $2(N_{exp}-N)$ term



Neural Networks

Classifier

Features of data



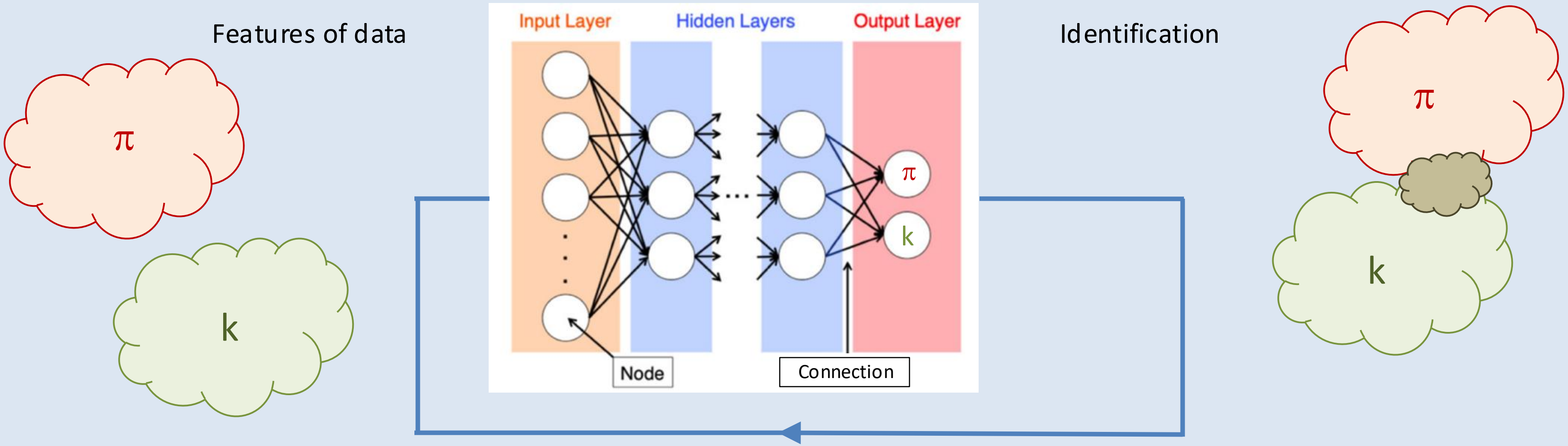
Identification

Connection: got a weight defining the strenght

Node: got an activation function for the output value from weighted inputs plus bias

NN Training

Classifier


Features of data

Identification

Connection: got a weight defining the strenght

Node: got an activation function for the output value from weighted inputs plus bias

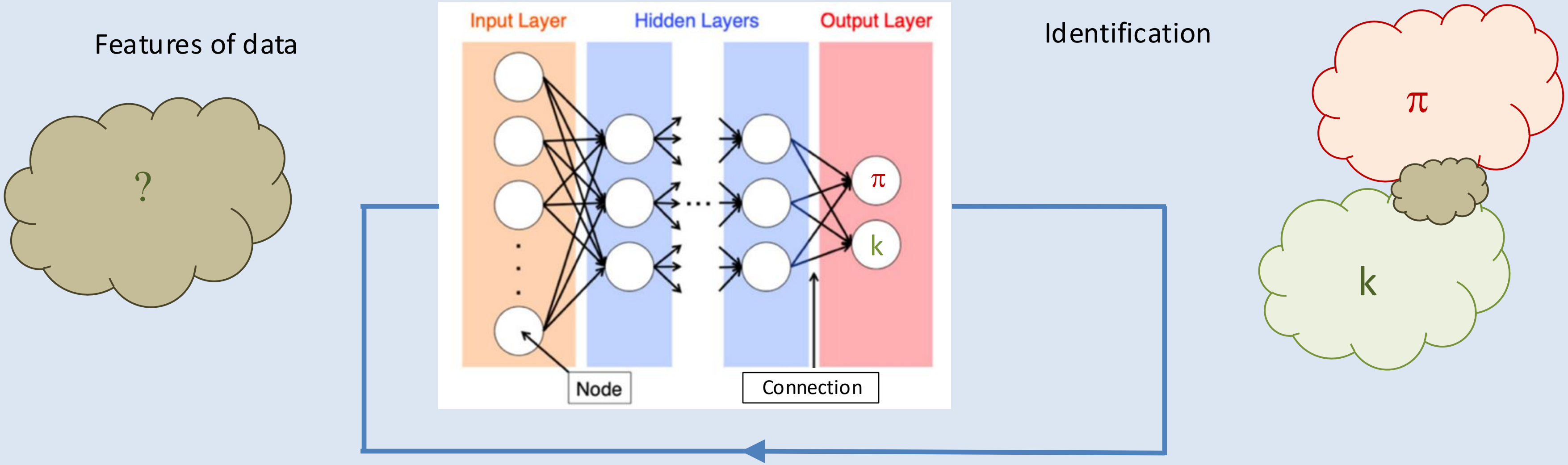
During iterative learning, the network parameters are automatically tuned on training samples to minimize the difference between estimate and correct answer in several cycles (epochs)

Neural Networks

Classifier

Features of data

Identification



The network is then ready to classify sets of data and represents a correlation map over distinctive features

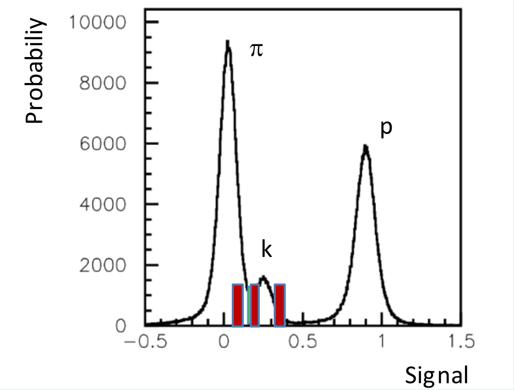
Potential biases: relevance of the features, should bring discrimination power
type of classifier, should provide enough flexibility (e.g. node and layer number
goodness of training, should provide an acceptable convergence
training sample, pseudo-data should reflect the real data features ⇦ *Critical as assumes an a-priori knowledge*

Analysis

Least squares minimization

Correlations via covariance matrix

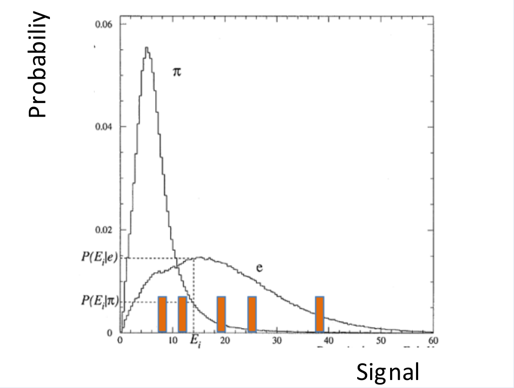
$$\chi^2 = \sum_{i=1}^{N} \frac{(x_i - x(\boldsymbol{\theta}))^2}{\sigma^2}$$



Likelihood maximization

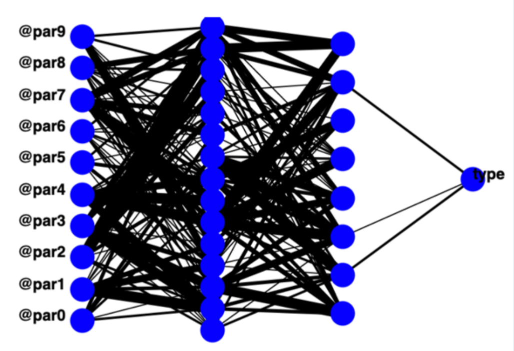
Correlations via multi-D p.d.f.

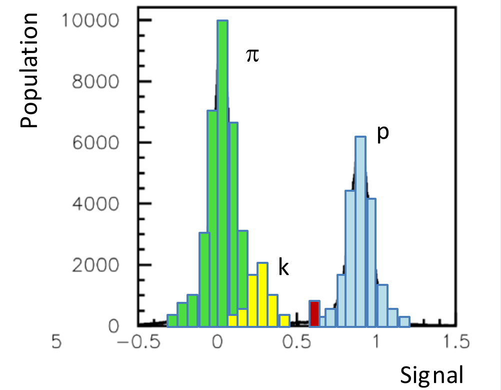
$$L(\boldsymbol{\theta}) = \prod_{i=1}^{n} f(x_i; \boldsymbol{\theta})$$



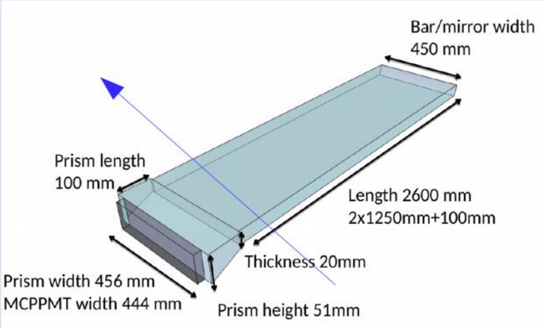
Machine learning techniques

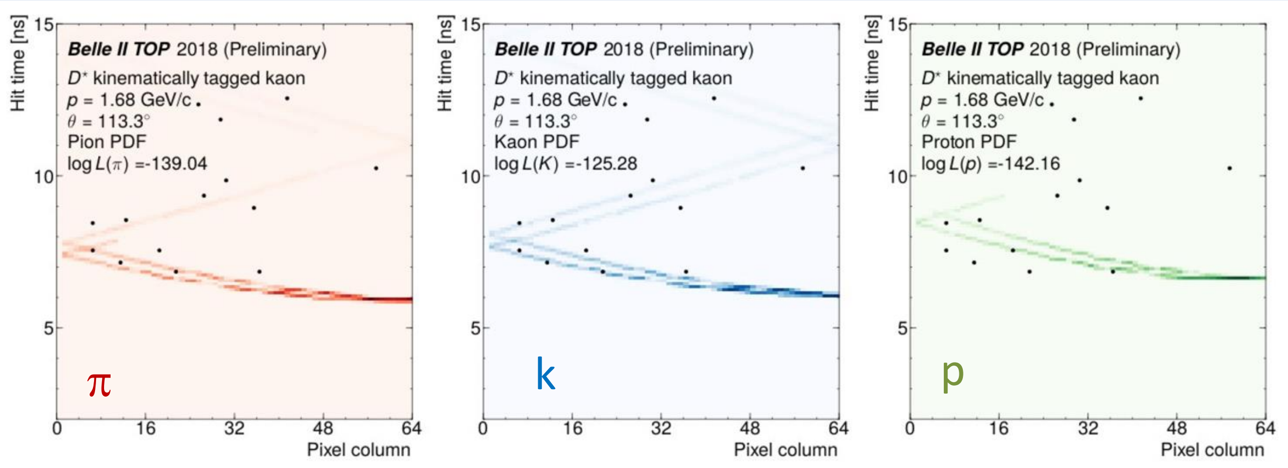
Correlations via NN training



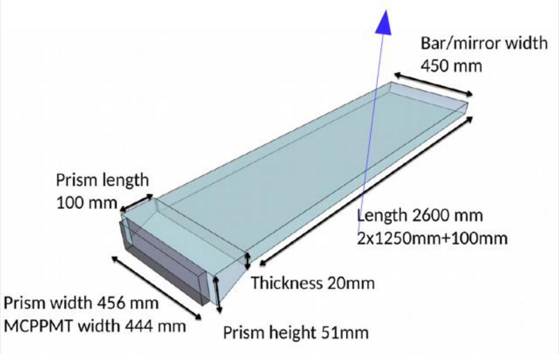


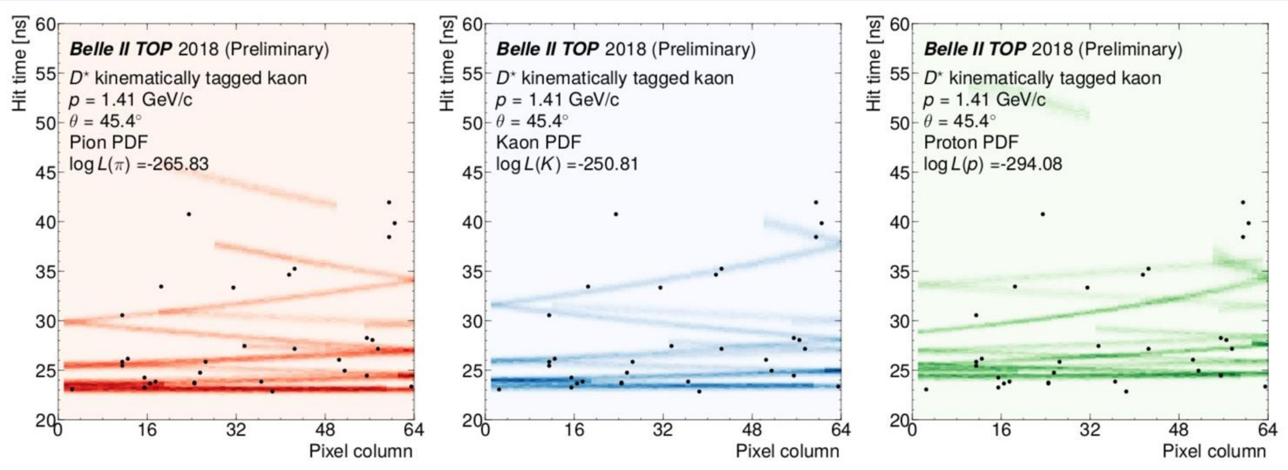
Patter Recognition





TOP BELLEII





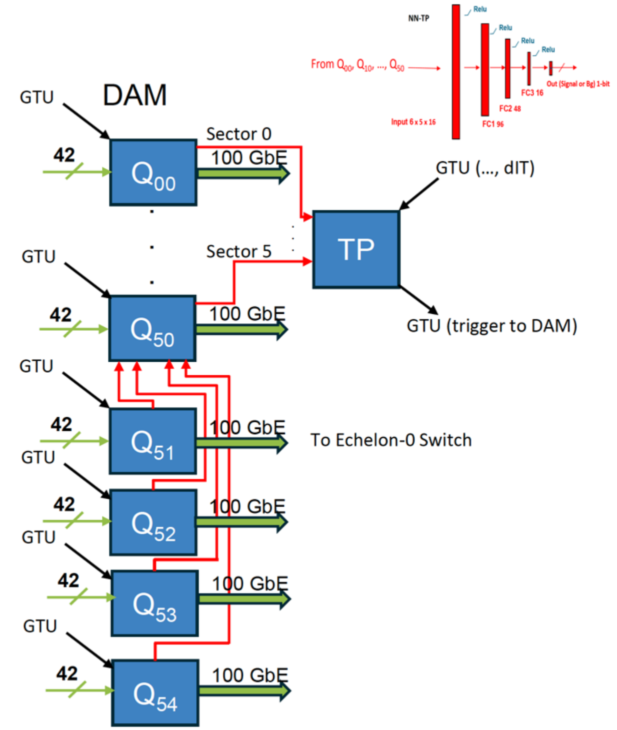
Online Filtering

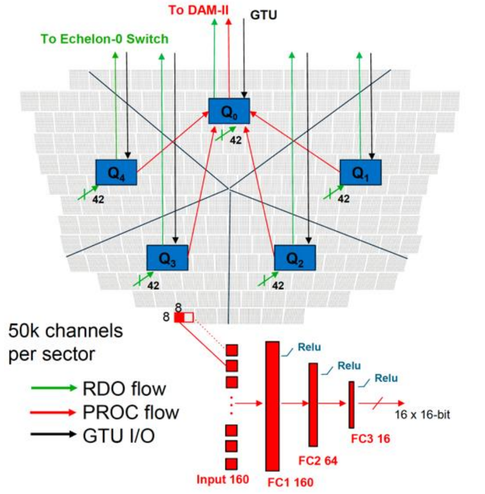
Efficiency increase (resources saving) when useless degrees of freedom are removed, i.e. the NN architecture is aligned to the real detector layout

Scheme based on ePIC DAM (Felix) &
APEIRON communication network (INFN)

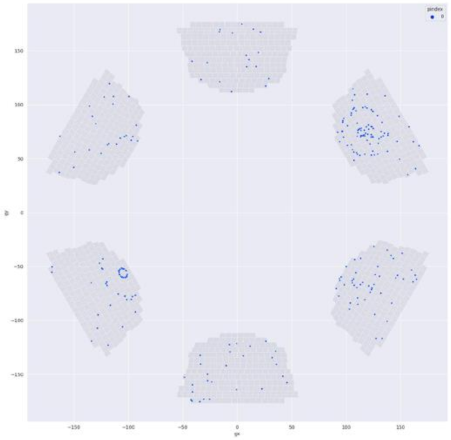
sub-sector integrated analysis

detector integrated analysis





Phys Signal+Phys Background+Noise

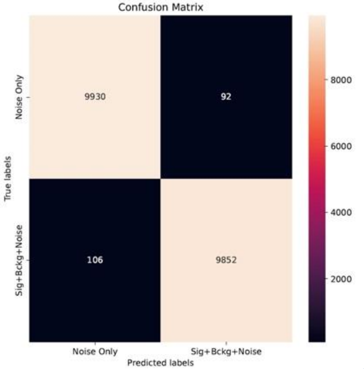


Preliminary tests

Classifier

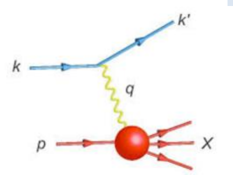
- ○ **Accuracy = (TP+TN)/(TP+TN+FP+FN) = 0.990**
- ○ **Precision = TP/(TP+FP) = 0.989**
- ○ **Recall = TP/(TP+FN) = 0.991**

➔Through **quantization**, we defined:
quantized fixed point<16,6> inputs
quantized fixed point<8,1> weights
quantized fixed point<8,1> biases



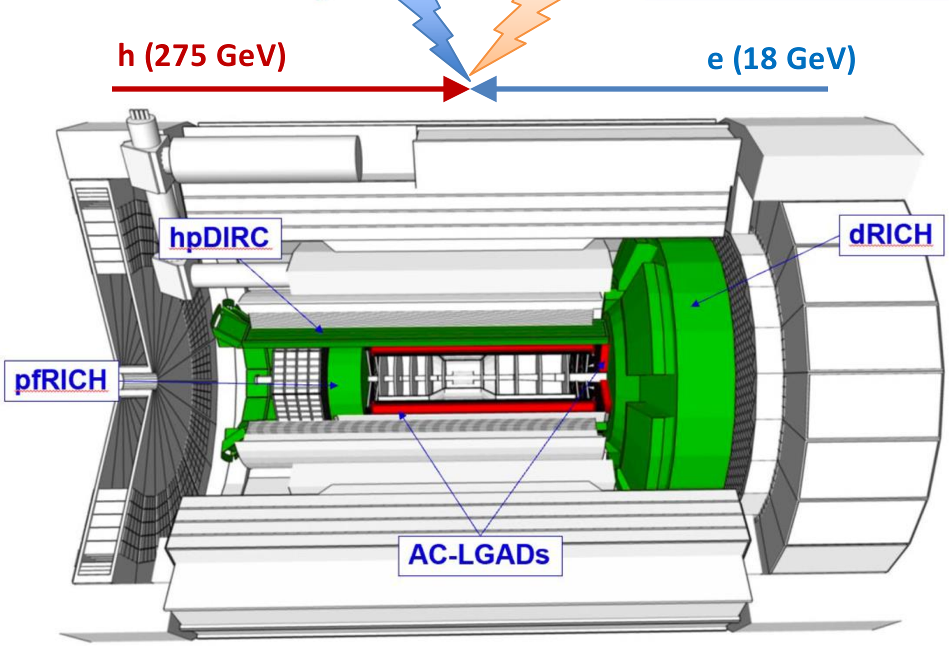
ePIC PID Requirements

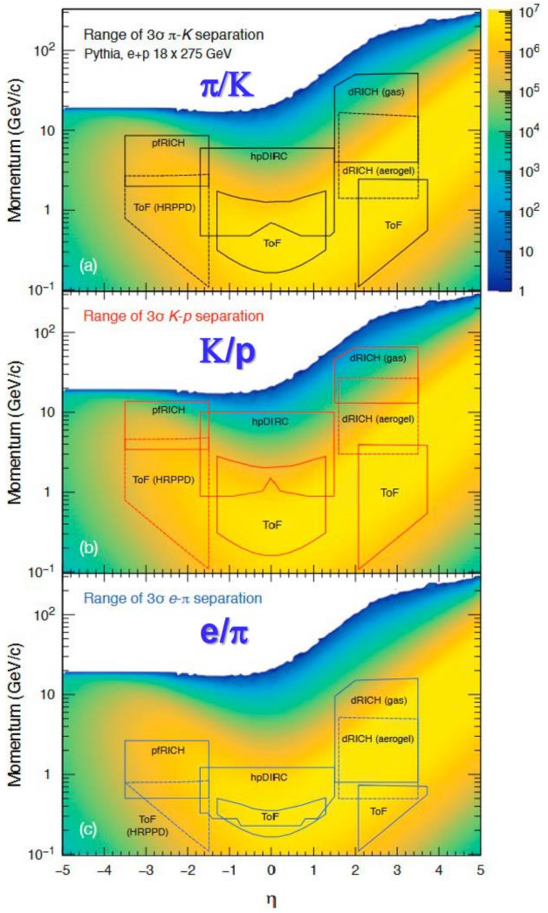
ePIC Detector



DIS Pythia, e+p 18 x 275 GeV

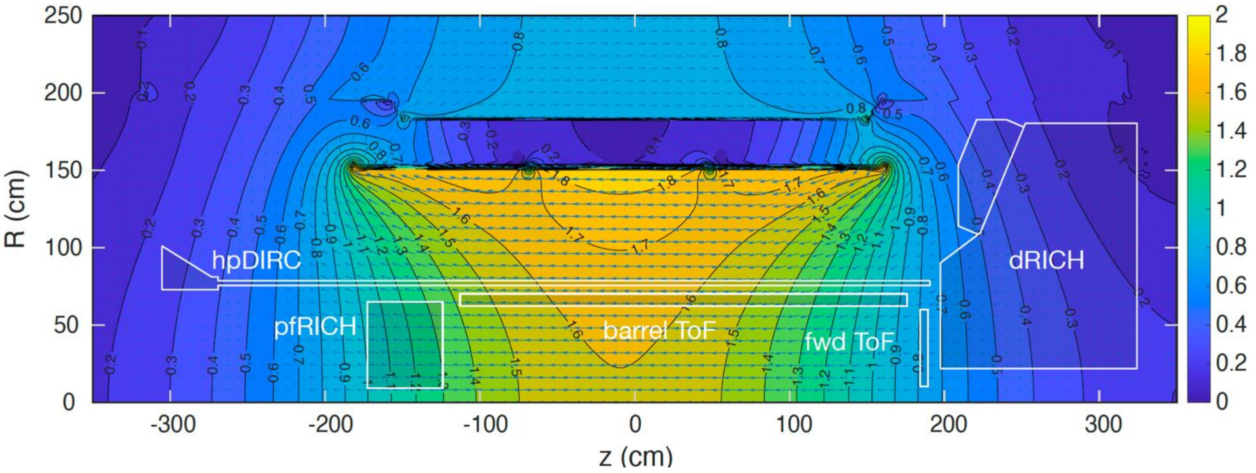
3 σ separation areas



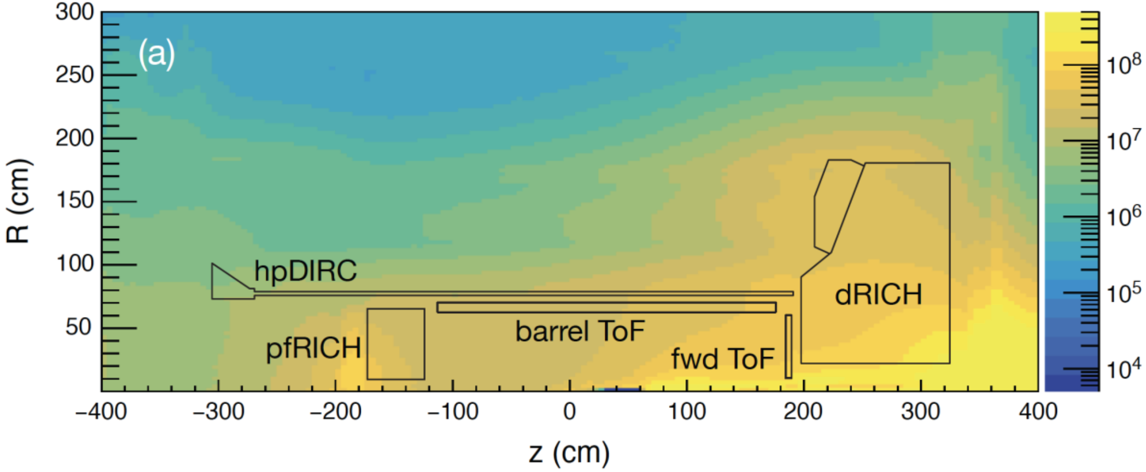


ePIC Environment

Magnetif field



Radiation Map (1 MeV eq. neutron fluence cm^{-2} fb^{-1})

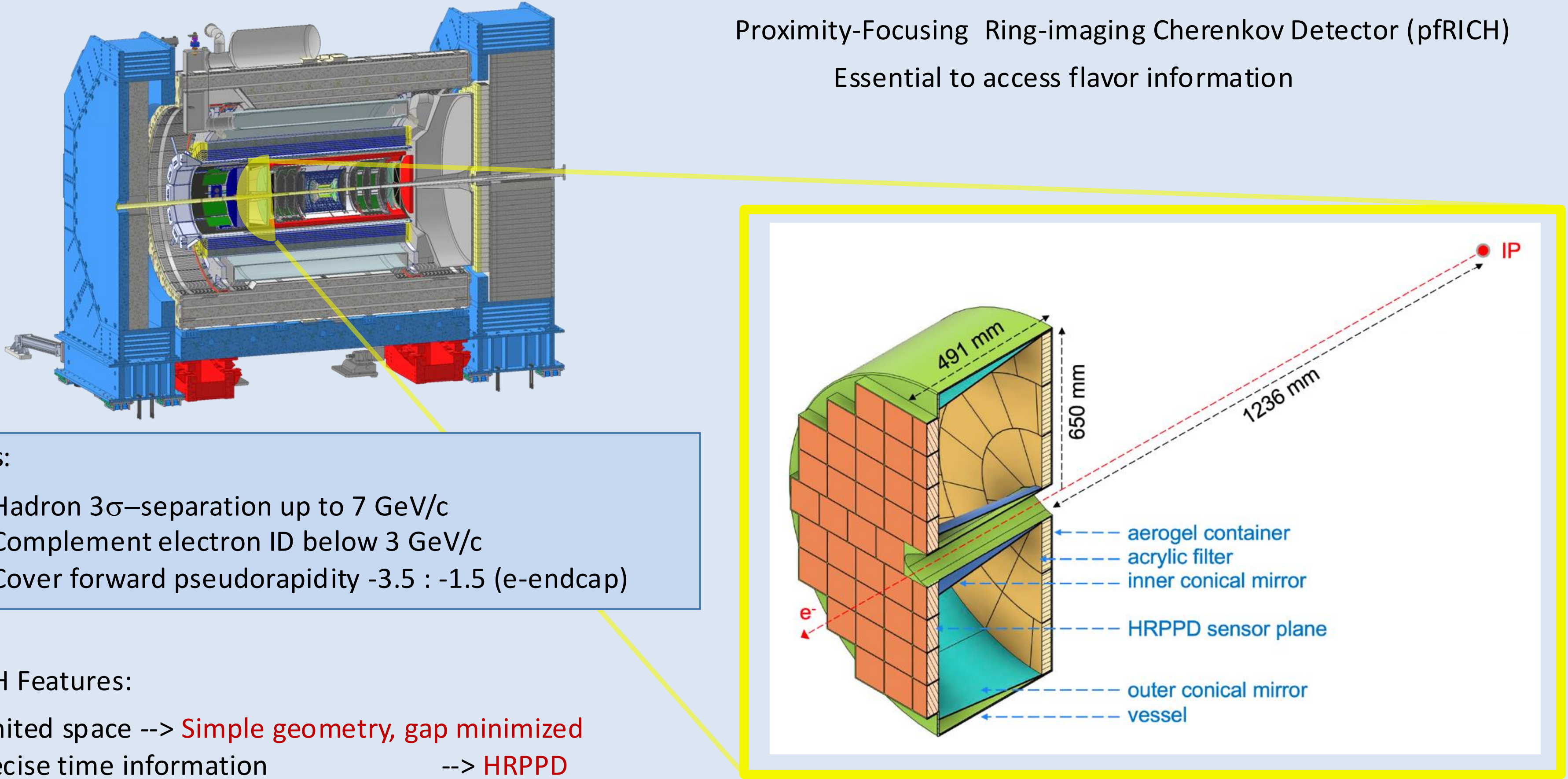


ePIC PID Solutions

ePIC pfRICH

Proximity-Focusing Ring-imaging Cherenkov Detector (pfRICH)

Essential to access flavor information



Goals:

- Hadron 3σ–separation up to 7 GeV/c
- Complement electron ID below 3 GeV/c
- Cover forward pseudorapidity -3.5 : -1.5 (e-endcap)

dRICH Features:

- Limited space --> Simple geometry, gap minimized
- Precise time information --> HRPPD
- Single-photon detection in high Bfield --> HRPPD

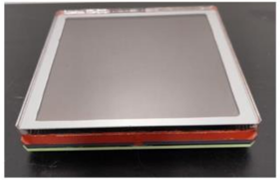
HRPPD

High Rate Picosecond Photon Detector (HRPPD) overview

Planar geometry MCP-PMT featuring:

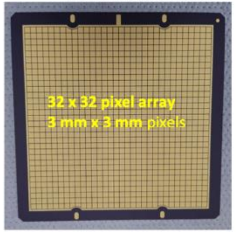
- **120 mm x 120 mm footprint, 104 mm x 104 mm active area**
- **75% active area ratio**
- **ALD functionalized glass 10 μm pore MCPs**
- **Direct (32 x 32 pixelated anode array)**

or Capacitively coupled readout

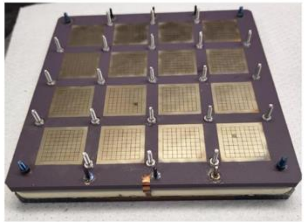


Anode plate directly coupled (DC) signal readout

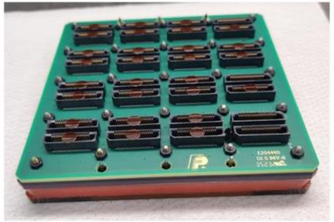
Vacuum Side

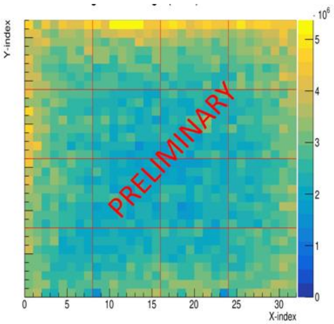


Air Side



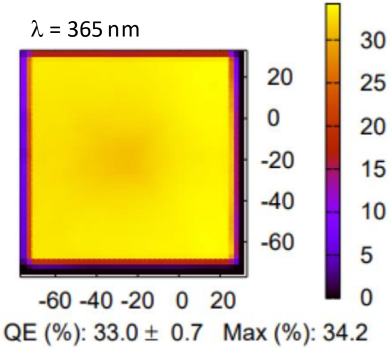
Test PCB board attachment using Samtec compression interposers





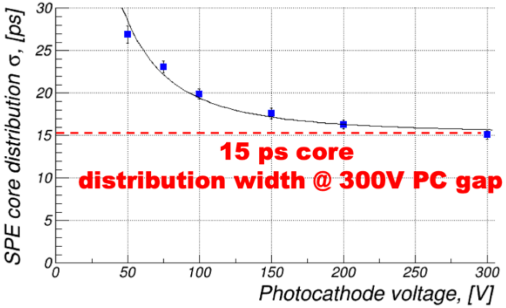
Gain uniformity

Average QE (5 over 7)



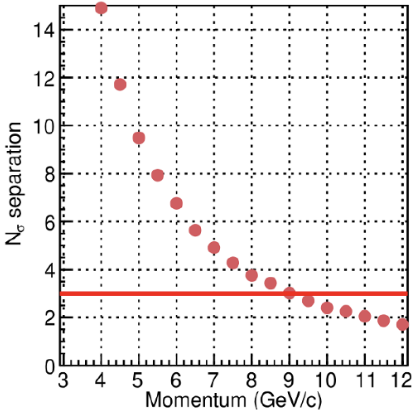
QE (%): 33.0 ± 0.7 Max (%): 34.2

A.V. Lyashenko e-Print: 2505.10658

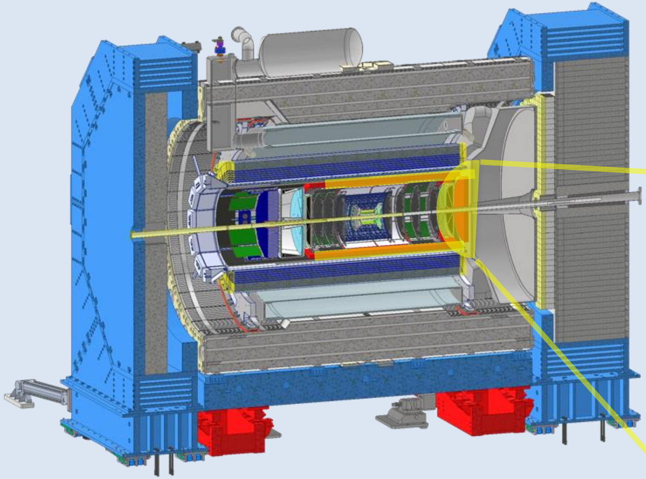


15 ps core distribution width @ 300V PC gap

C. Chatterjee PoS DIS2024 (2025) 266

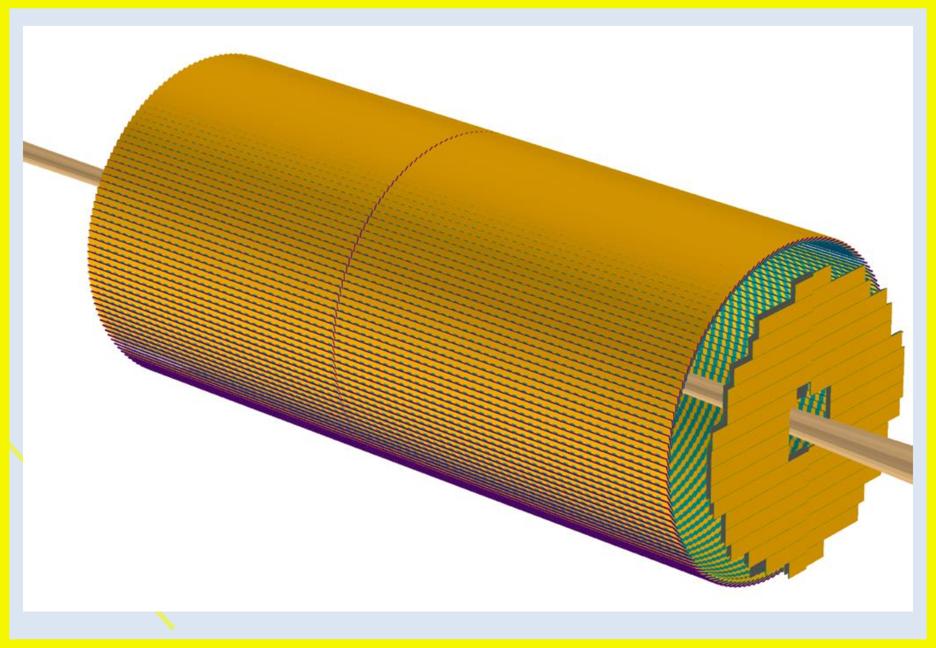


ePIC TOF



Time-of-Flight Detector (TOF)

Essential to access flavor information



Goals:

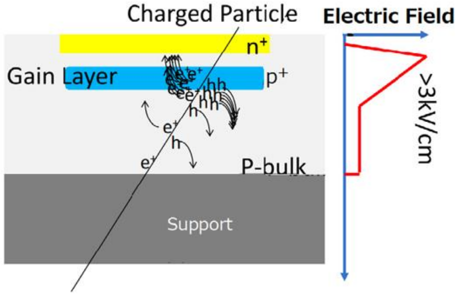
Hadron 3σ–separation up to 1.2 Gev/c (barrel)
Hadron 3σ–separation up to 2.5 Gev/c (h-endcap)
Cover mid-forward pseudorapidity -1.5 : 3.5

dRICH Features:

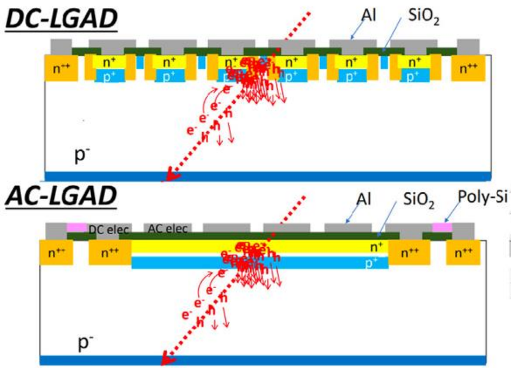
Precision in limited space --> silicon detector
Up to 2.5 GeV/c momentum range --> AC-LGAD
Coplement tracking --> AC-LGAD

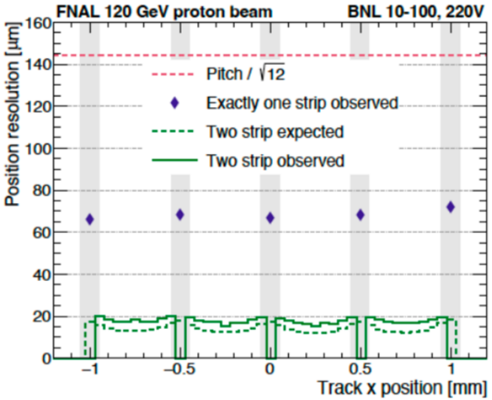
AC-LGAD

LGAD adds a p+ layer with large Boron doping to create a region of high field and concentrated avalanche

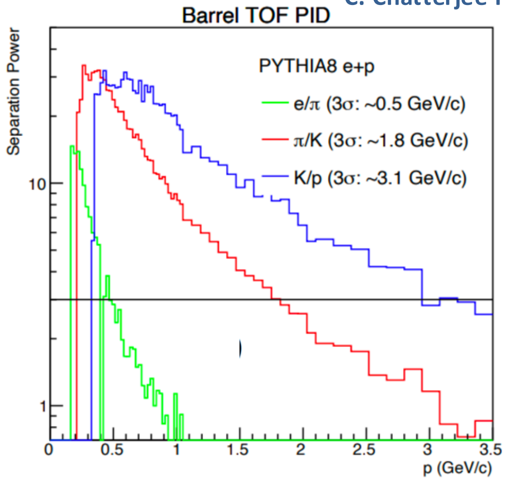


AC-coupling allows space precision without affecting the uniformity of the gain layer

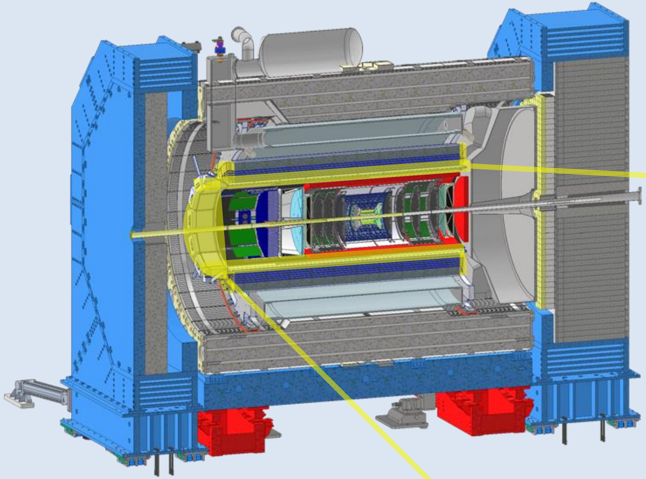




C. Chatterjee PoS DIS2024 (2025) 266

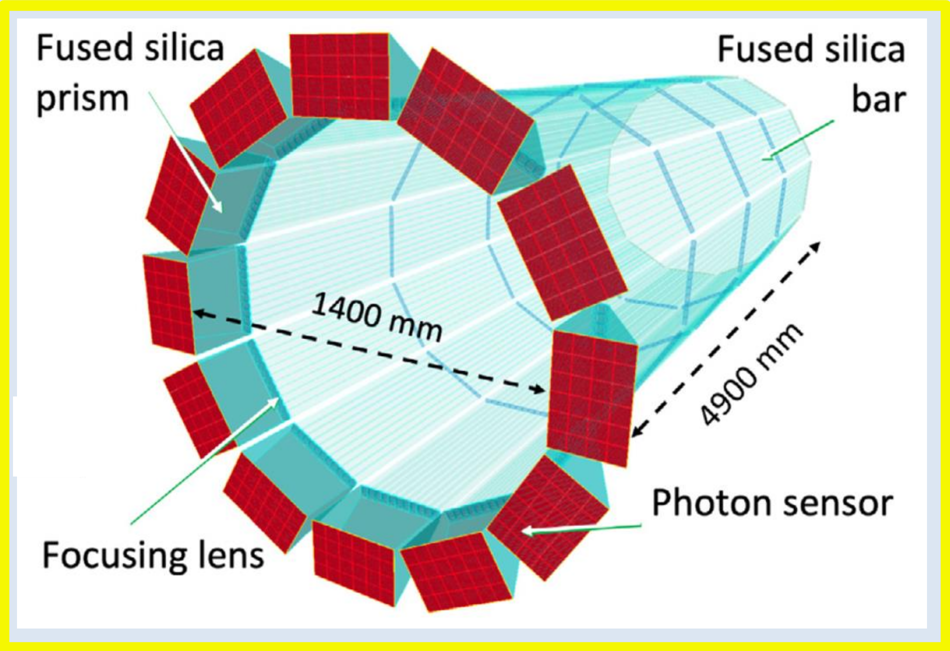


ePIC hpDIRC



High-Performance (dRICH)

Essential to access flavor information



Goals:

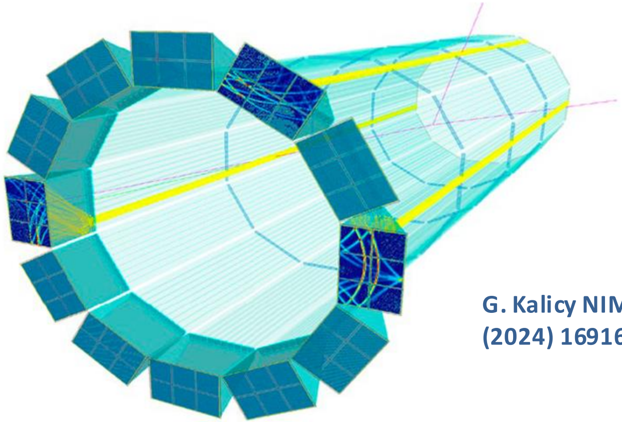
- Hadron 3σ–separation between 3 - 6 GeV/c
- Complement electron ID below 1.2 GeV/c
- Cover forward pseudorapidity -1.5 - 1.5 (barrel)

dRICH Features:

- Limited space --> Internal reflection
- Up to 6 GeV/c momentum range --> Lens
- Single-photon detection in high Bfield --> MCP-PMT

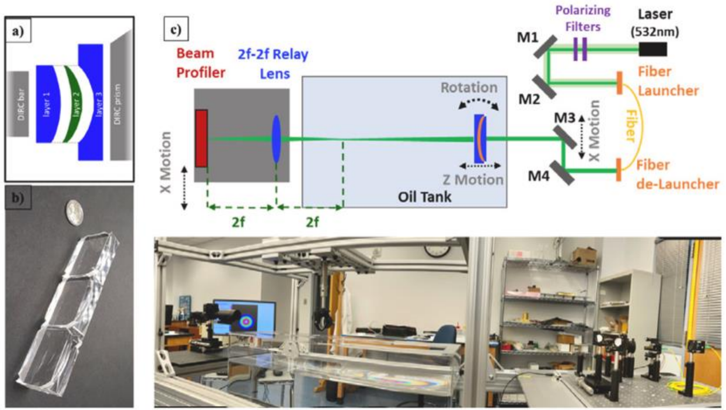
ePIC hpDIRC

Compact, high-performance (+50%) design

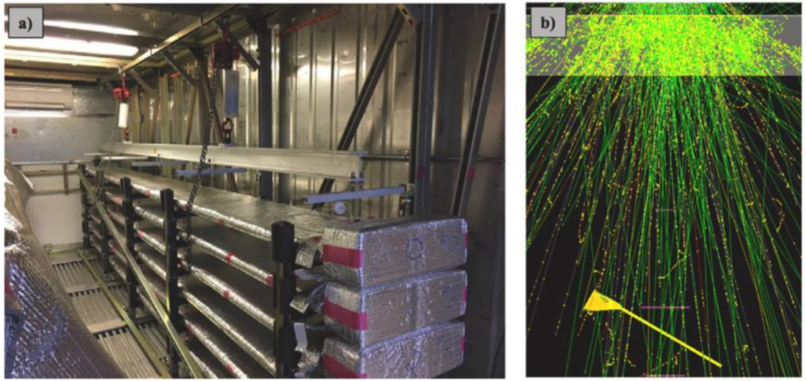


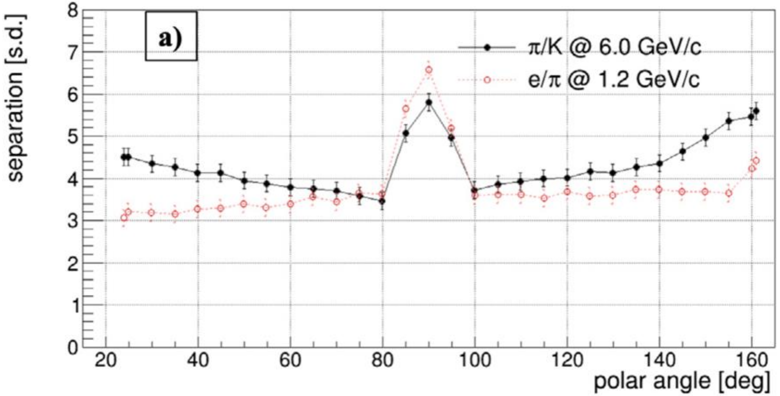
G. Kalicy NIMA 1062 (2024) 169168

Quartz prism with focalizing sapphire lens

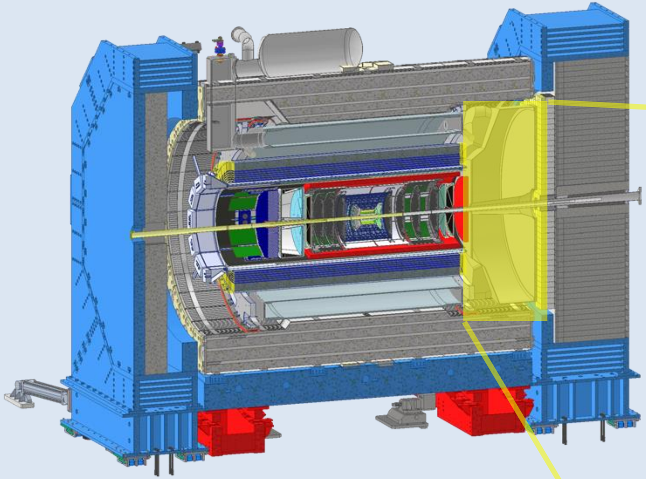


Re-use of BABAR DIRC bars and cosmic test



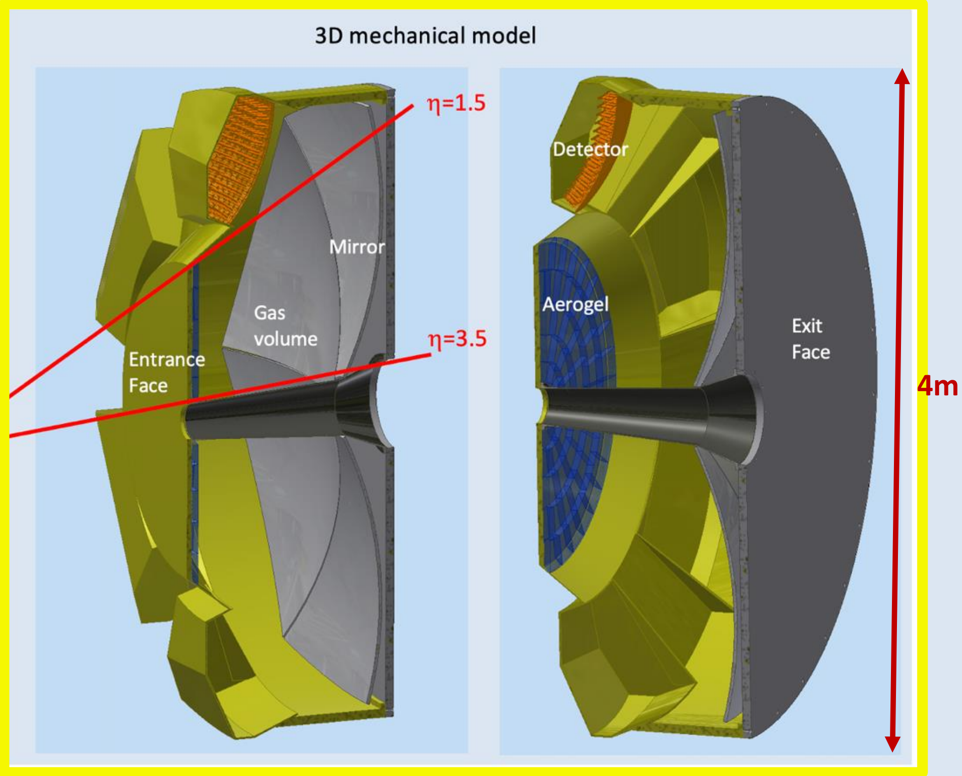


ePIC dRICH



Dual-radiator Ring-imaging Cherenkov Detector (dRICH)

Essential to access flavor information



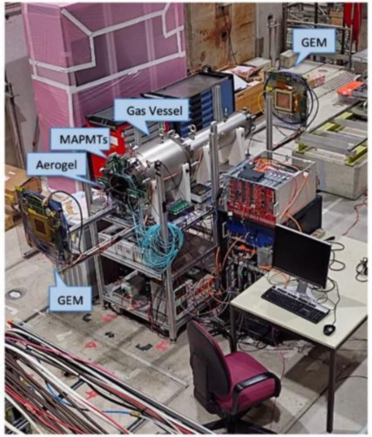
Goals:

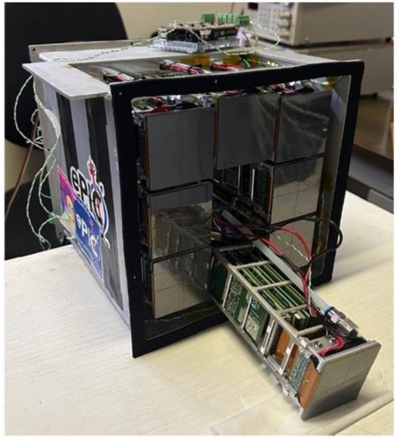
Hadron 3σ–separation between 3 - 50 GeV/c
Complement electron ID below 15 GeV/c
Cover forward pseudorapidity 1.5 - 3.5 (h-cap)

dRICH Features:

Extended 3-50 GeV/c momentum range --> Dual radiator
Single-photon detection in high Bfield --> SiPM
Limited space --> Compact optics with curved detector

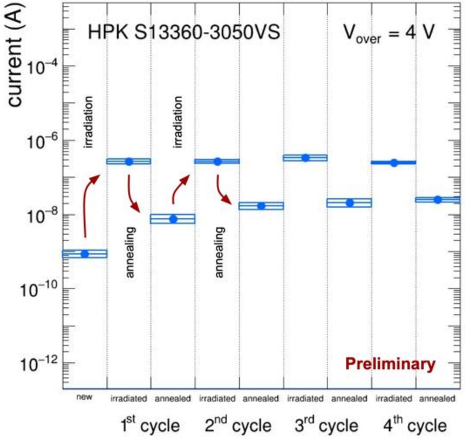
ePIC dRICH

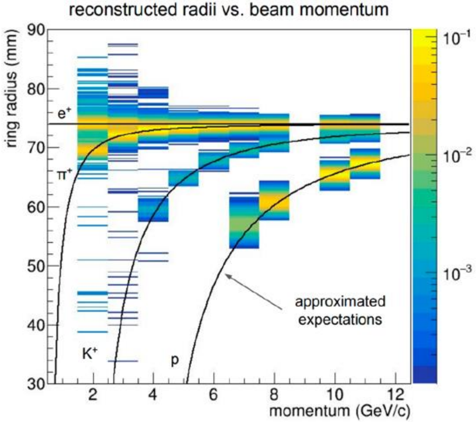


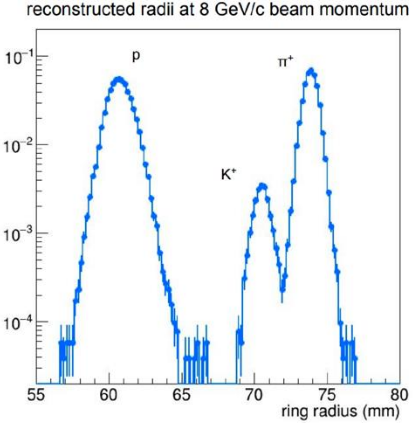


Imaging study

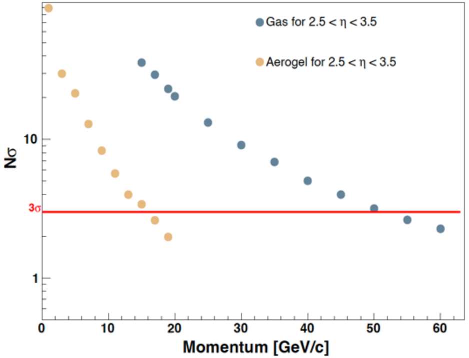
Annealing study







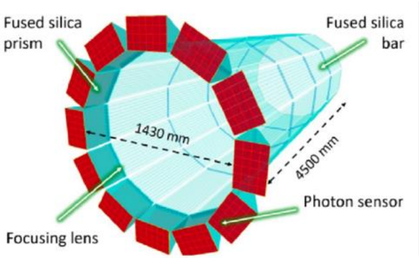
C. Chatterjee PoS DIS2024 (2025) 266



ePIC PID System

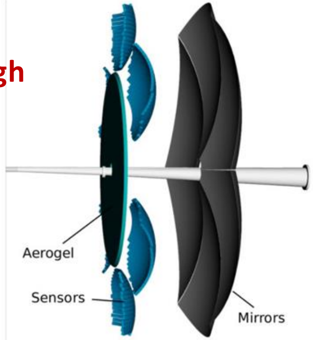
+50% momentum reach with lens

High-Performance DIRC (hpDIRC)



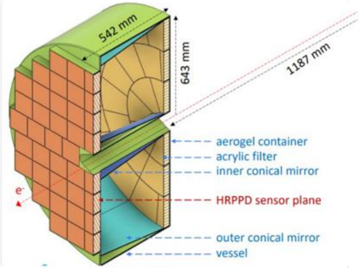
Dual-Radiator RICH (dRICH)

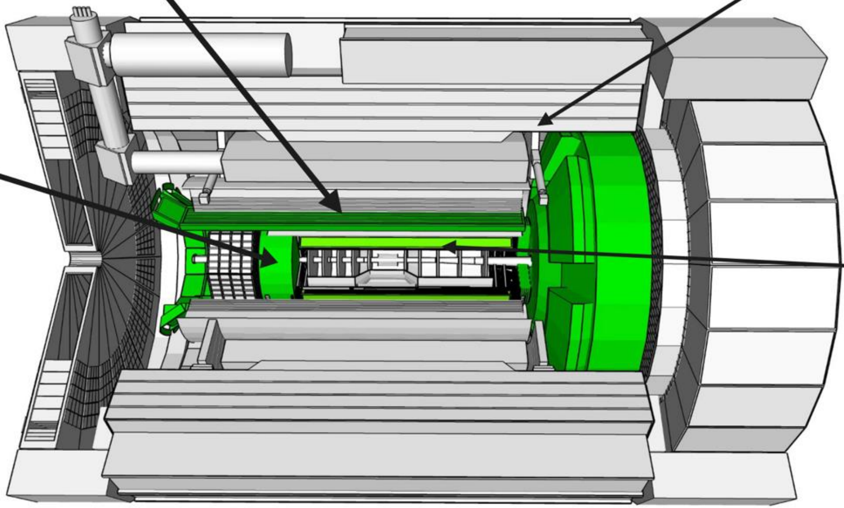
Detectionin in high B-field with SiPM



Precise timing with HRPPD

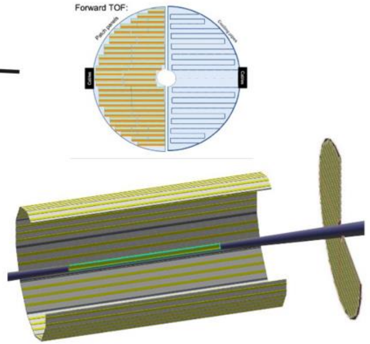
Proximity Focusing RICH (pfRICH)





Precise tracking by AC-LGAD

Time-of-Flight (ToF)



Arguments

Specific Particle-ID Detectors	Time-of-Flight Cherenkov Radiation
Reconstruction example	
Analysis Methods	Chi2 Maximum Likelihood Machine Learning techniques
ePIC Requirements	
ePIC Solution	pfRICH TOF hpDIRC dRICH