

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

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



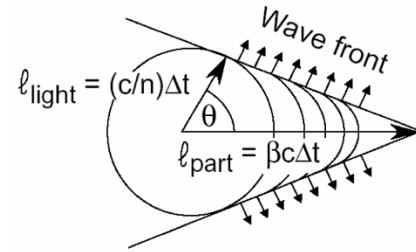
In a time of flight application one needs two layers (impractical) or a reference t_0 with better (or comparable) precision with respect TOF.

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)

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

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



Momentum threshold:

$$\epsilon = n^2 - 1$$

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

Scales with particle mass
Decreases with n

Photon yield:

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

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

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

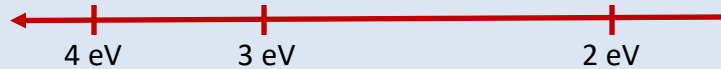
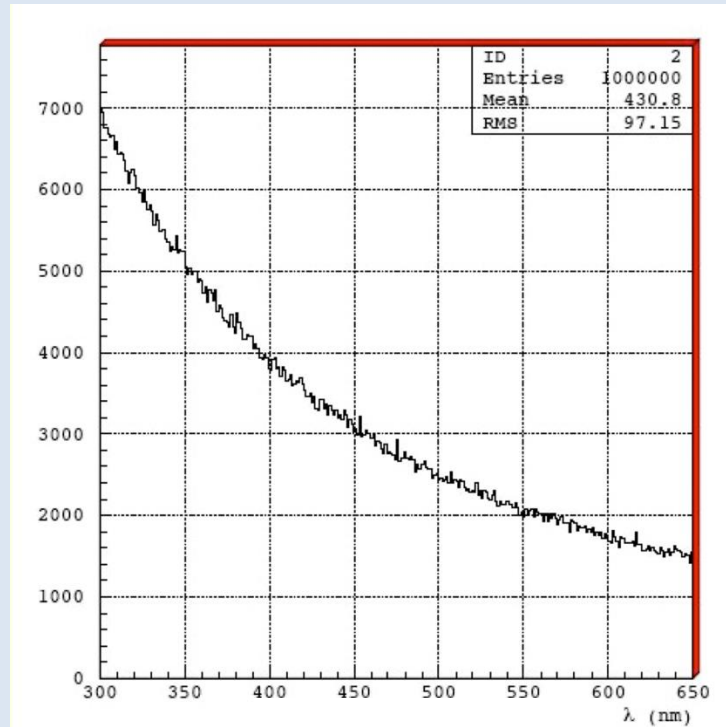
$$\hbar c = 2 \cdot 10^{-5} \text{ eVcm}$$

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

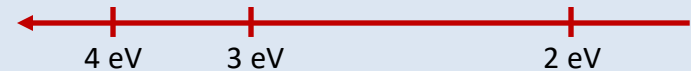
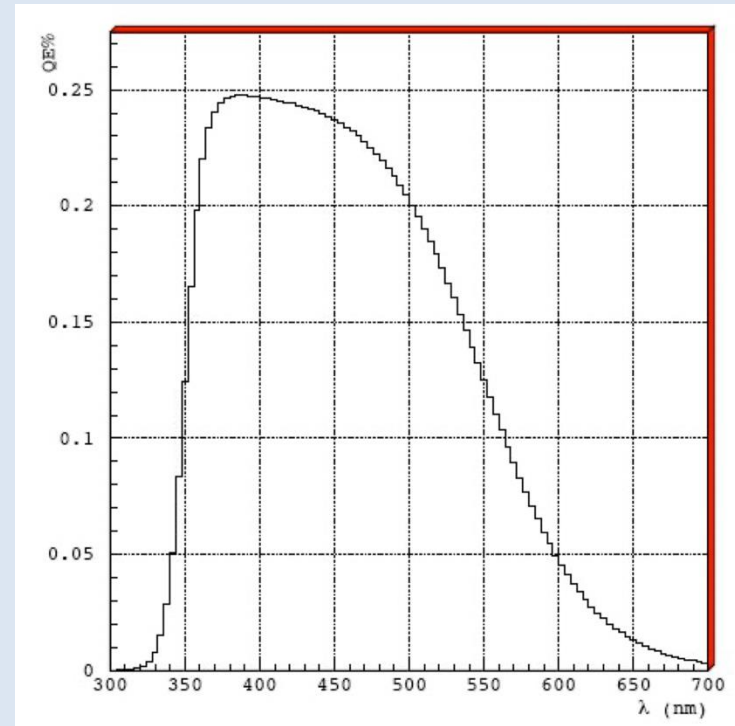
$$\frac{d^2 N_{ph}}{dL dE} [\text{cm}^{-1} \text{eV}^{-1}] = \frac{\alpha Z^2}{\hbar c} \sin^2 \theta = 370 Z^2 \sin^2 \theta$$

$$E_{ph} [\text{eV}] = 2\pi \hbar \frac{c}{\lambda} = \frac{1240}{\lambda [\text{nm}]}$$

Spectrum of Cherenkov photons



Typical sensitivity (quantum efficiency) of a PMT



Exp.	Mezzo	n	θ ($^{\circ}$)	$N_{ph} = 370 \cdot \sin^2 \theta$ ($\text{eV}^{-1}\text{cm}^{-1}$)	p_{π} in soglia (GeV)
E835	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
	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 ₂ F ₆	1.00082	2.32	0.606	3.432
E835	Freon 12	1.001080	2.66	0.796	3.003
COMPASS / LHCb	Isobutano	1.00147	2.89	0.941	2.67
	C ₄ F ₁₀	1.0014	3.03	1.033	2.55
	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

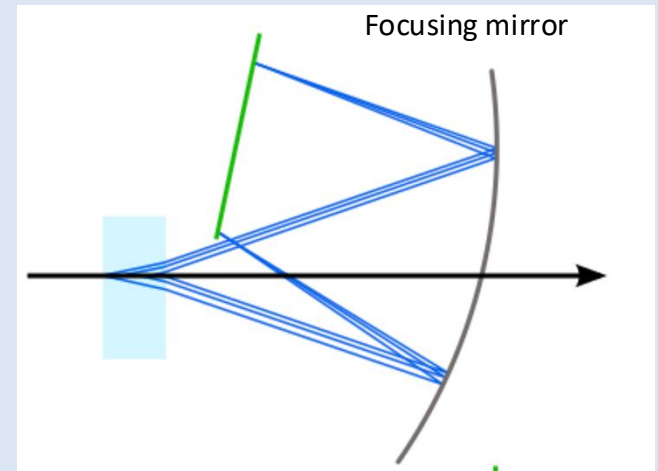
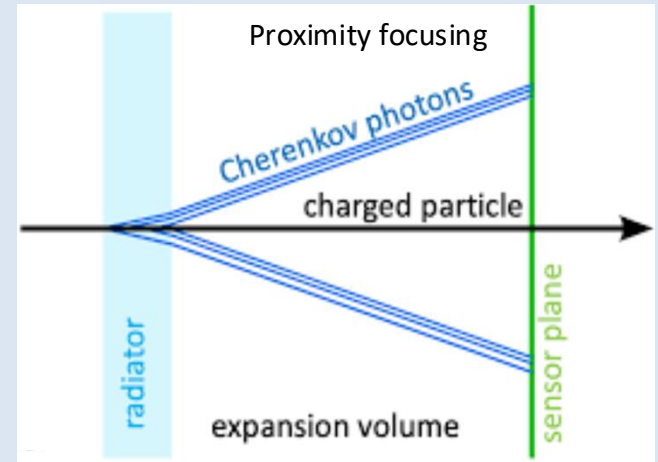
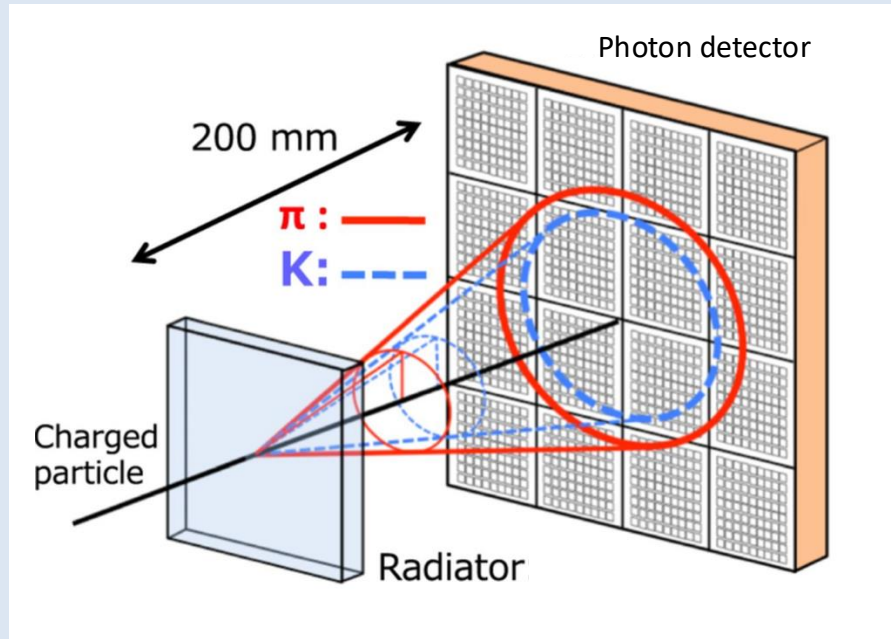
requires

~ few
cm

~1 keV/cm

10^{-3} dE/dx

Real PID
starts at
3x (kaon)



Gas Radiator

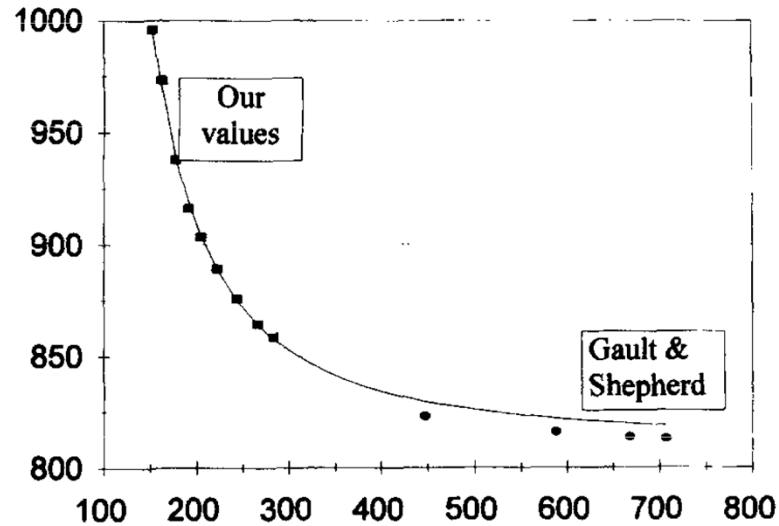
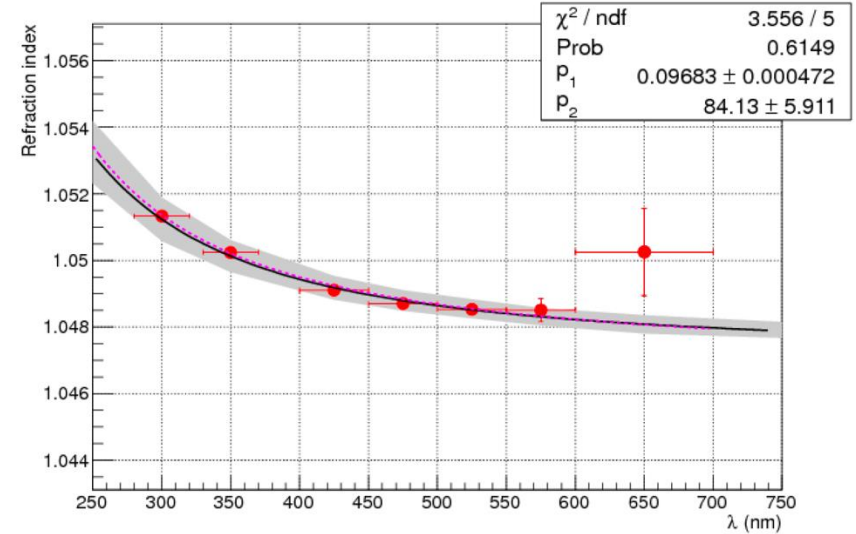


Fig. 1. The refractivity of C_2F_6 (hexafluoroethane) expressed as $(n-1) \times 10^6$ is plotted versus the wavelength in nm. The solid line corresponds to the Sellmeier formula fitted with our measurements.

Aerogel Radiator



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

Sellmeier parameterization

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

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

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)

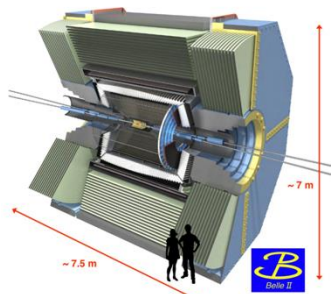
$$\frac{d^2N}{dx d\lambda} = \left(\frac{d^2N_C}{dx d\lambda} \right) QE(\lambda) \epsilon_{pe} e^{-\frac{t_{rad}-x}{\Lambda(\lambda) \cos(\eta_C)}}$$

$Q(\lambda)$ Sensor quantum efficiency

ϵ_{pe} detection efficiency (sensor and mirror)

$\Lambda(\lambda)$ Radiator transmission length

t_{rad} radiator thickness



BELLE-II: B-factory

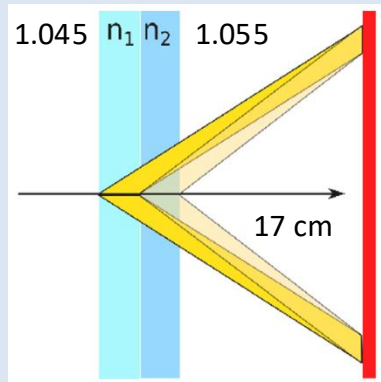
Limited space --> Proximity focusing & radiator focusing

High B field (1.5T) --> Custom Hybrid photon detector

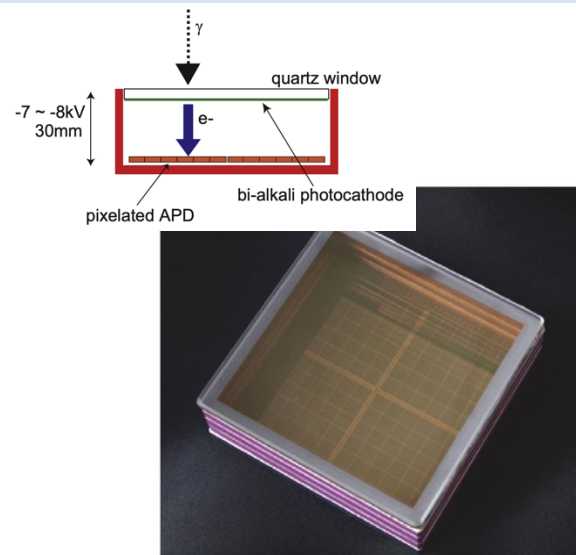
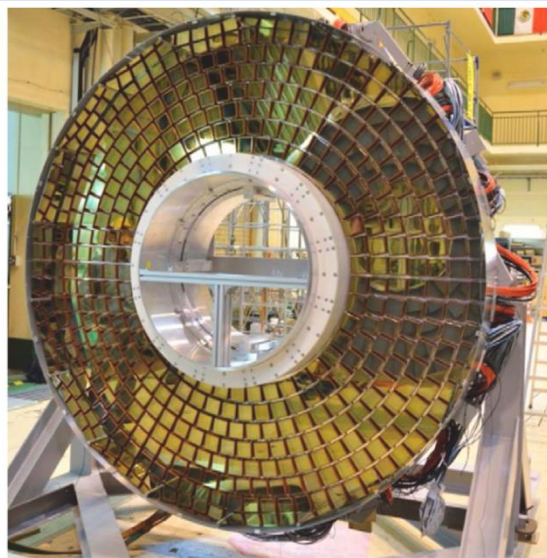
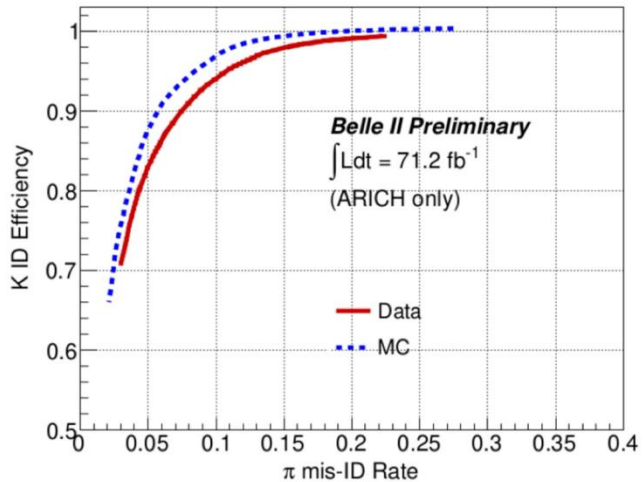
Super bi-alkali photocatode

Gain $4.5 \cdot 10^6$

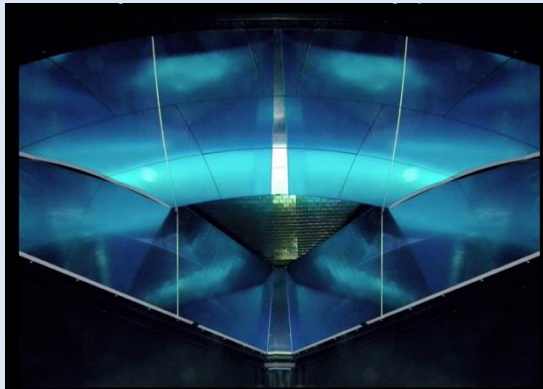
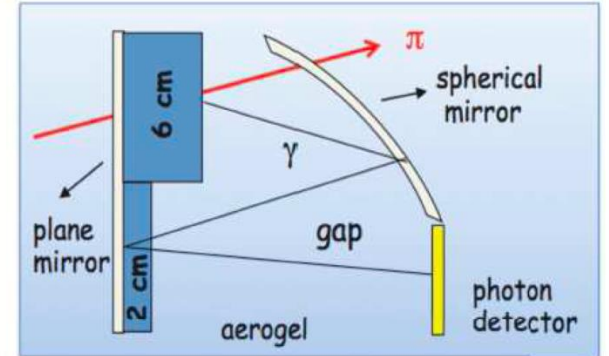
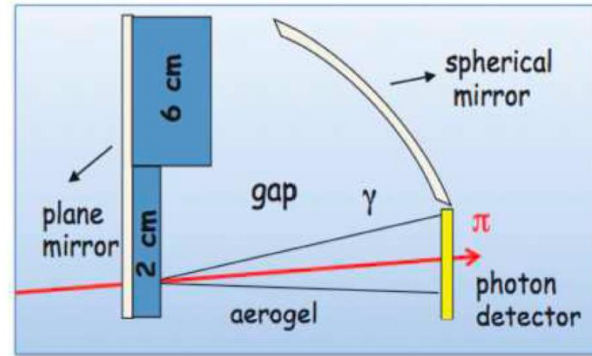
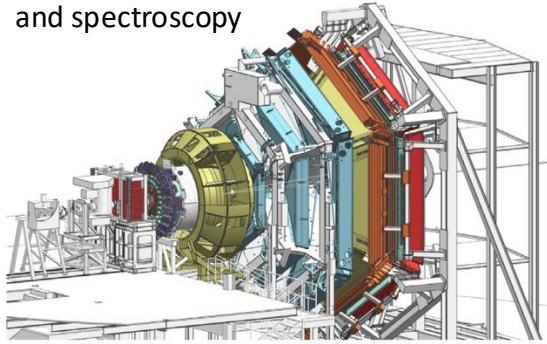
PDE $\sim 28\%$



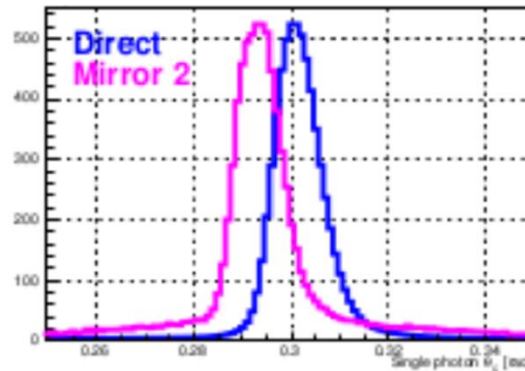
$D^0 \rightarrow K^- \pi^+$ 0.5 - 3.5 GeV/c



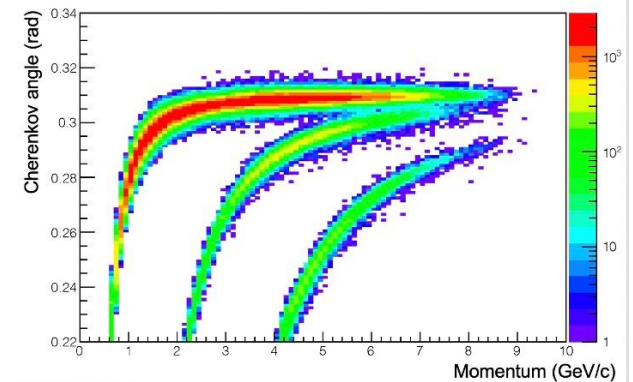
CLAS12: Nucleon structure and spectroscopy

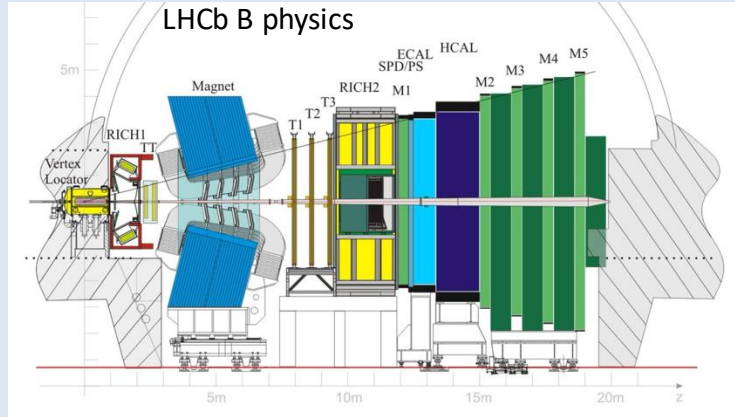


Electrons: direct vs spherical reflection



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



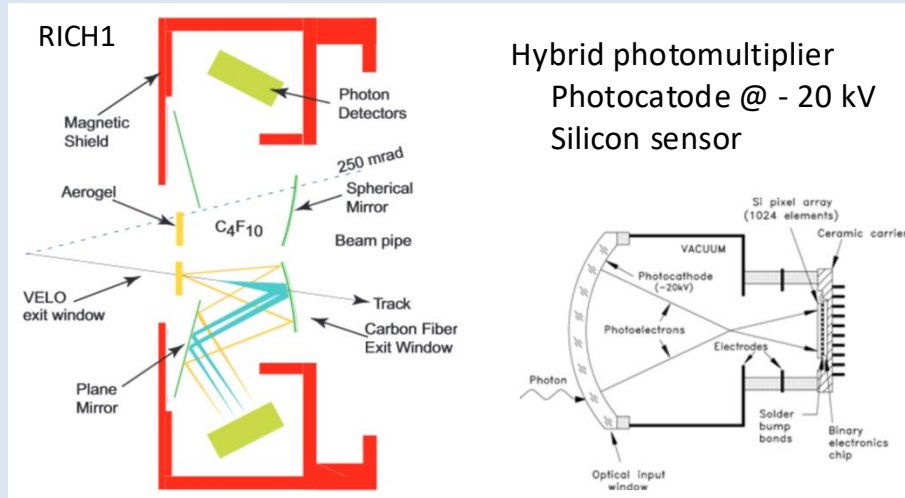


LHCb Precisin measurements of B-decays
and search fro BSM signals

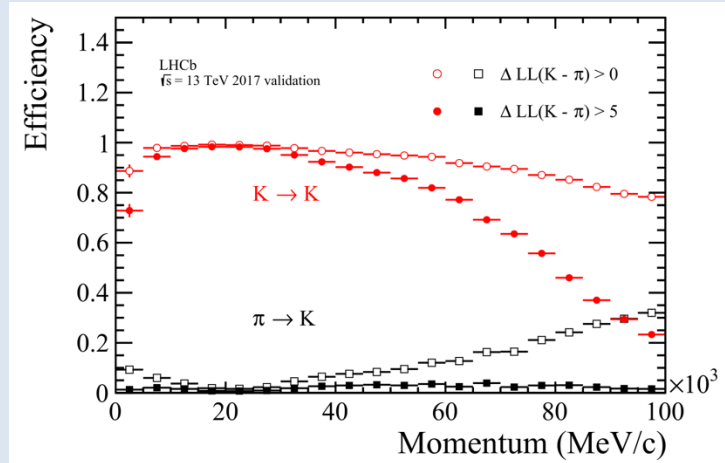
RICH1: Aerogel (5 cm) $n=1.03$
2-10 GeV/c

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

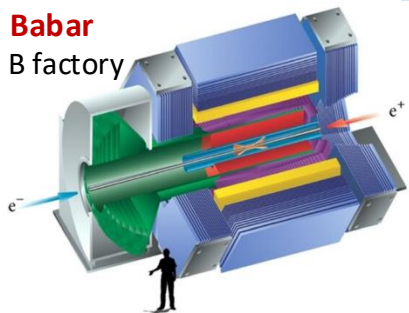


Hybrid photomultiplier
Photocathode @ - 20 kV
Silicon sensor

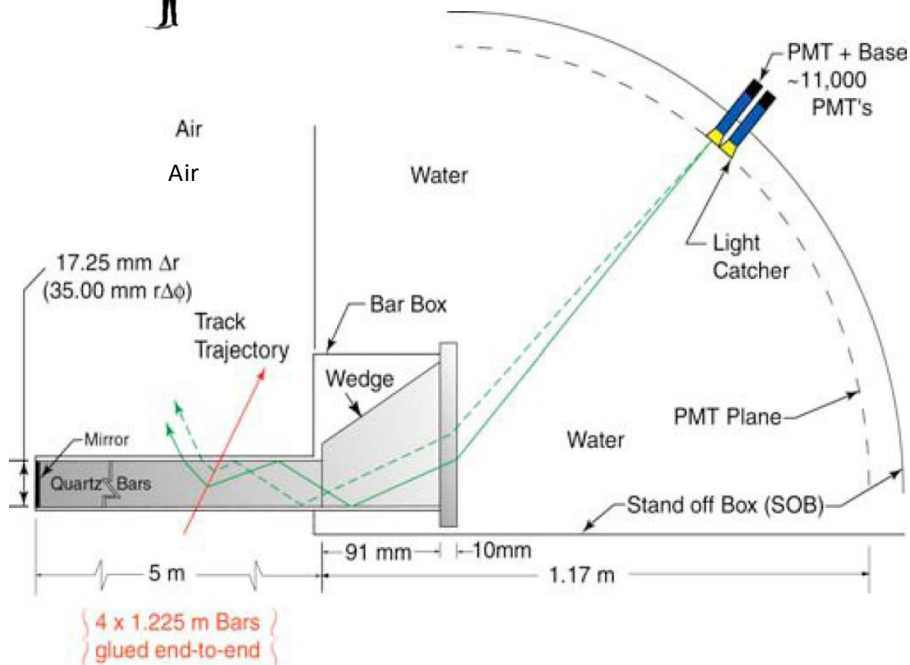


Babar

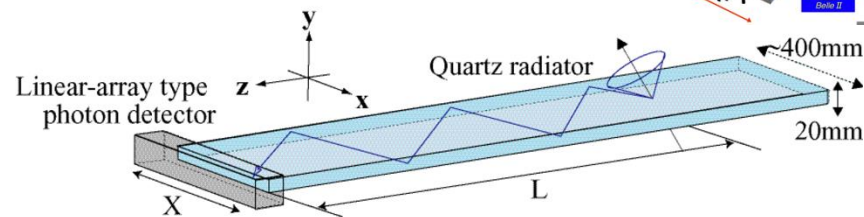
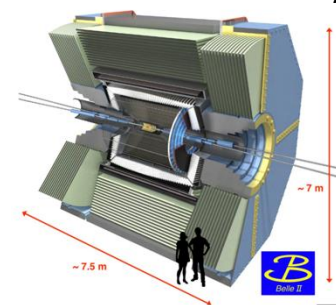
B factory



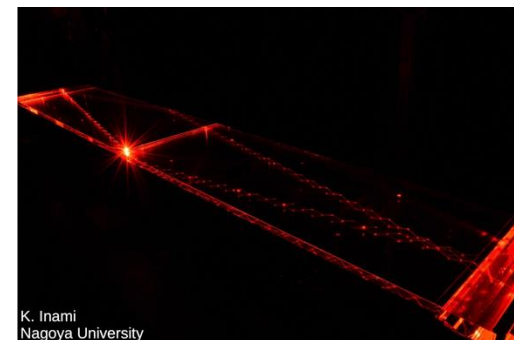
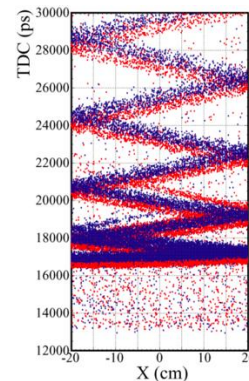
Detection by internal reflection: compact detection volume (thickness)

Critical aspects: quartz surface quality (parallelism, roughness)
proper imaging system**Belle-II**

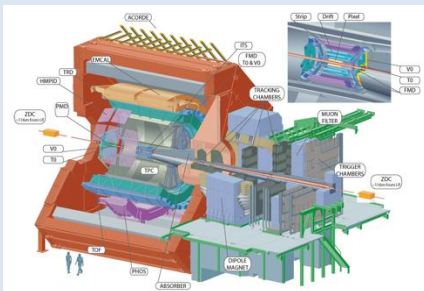
B factory



1D + time maging – Belle-II

K. Inami
Nagoya University

ALICE: Quark-gluon plasma in heavy ion collisions



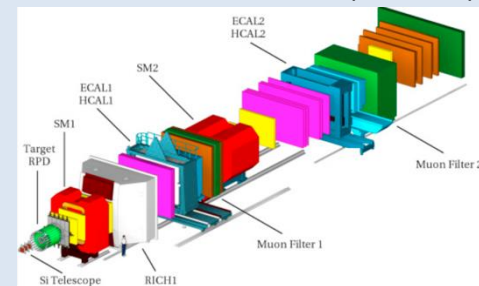
Large instrumented area

Multi-wired proportional chambers with a CSi photocatode

Quantum efficiency is around 16-24% at 170 nm

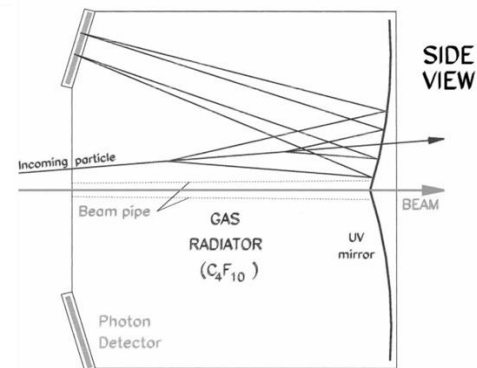
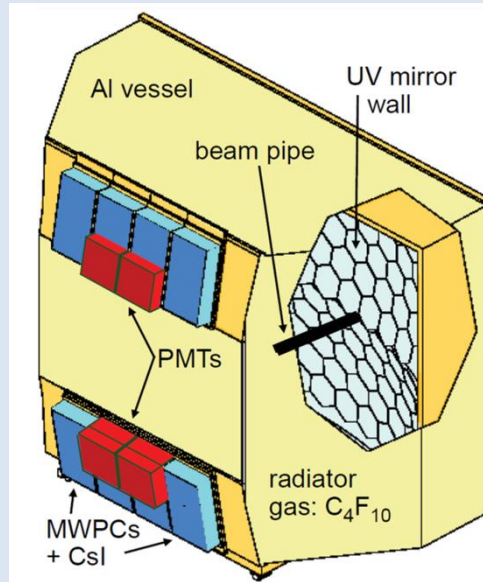
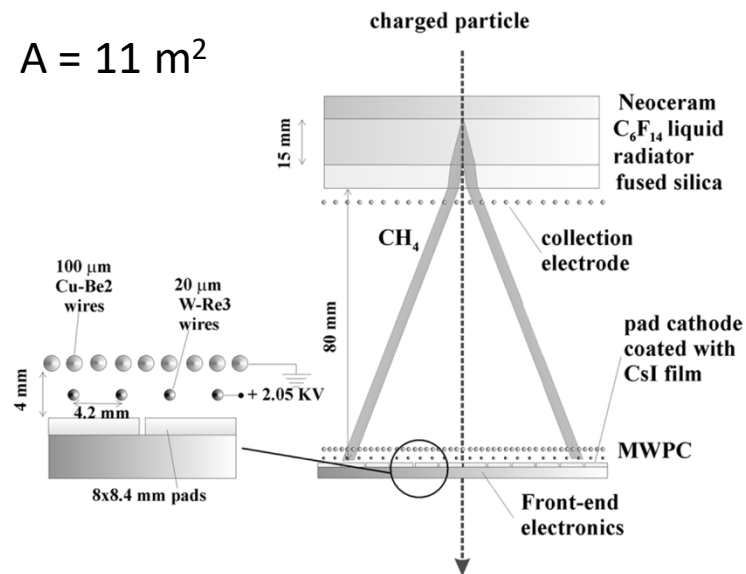
High-Momentum PID

COMPASS: Nucleon structure and spectroscopy

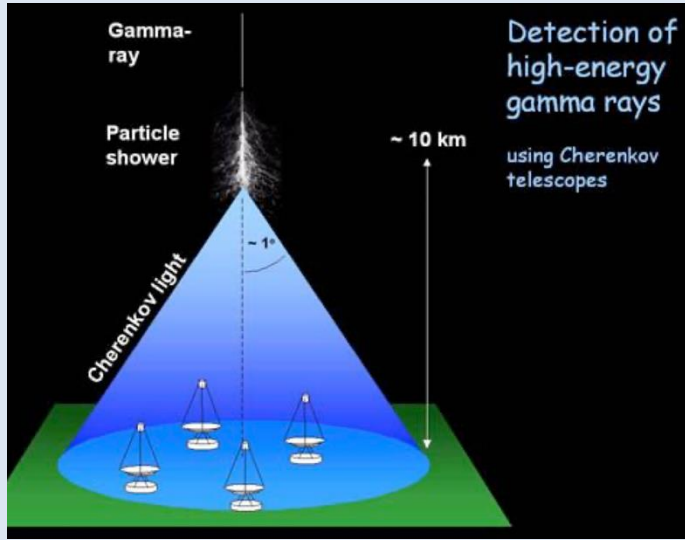


RICH

$$A = 11 \text{ m}^2$$



$$A = 5.3 \text{ m}^2$$



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

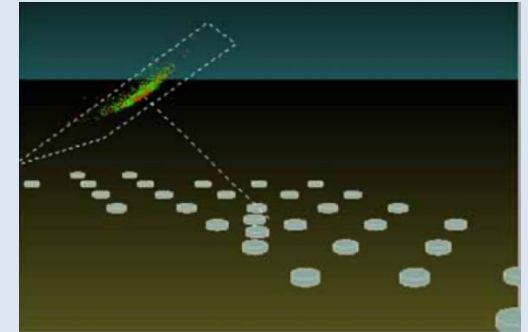
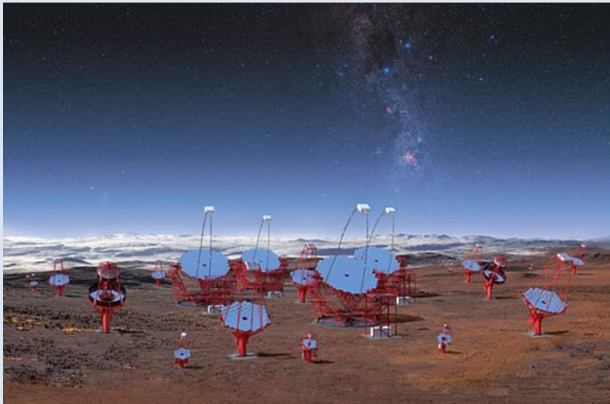
Air refractive index is $n = 1.00028$

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

Cherenkov angle is $23 \text{ mrad} \sim 1.3^\circ$

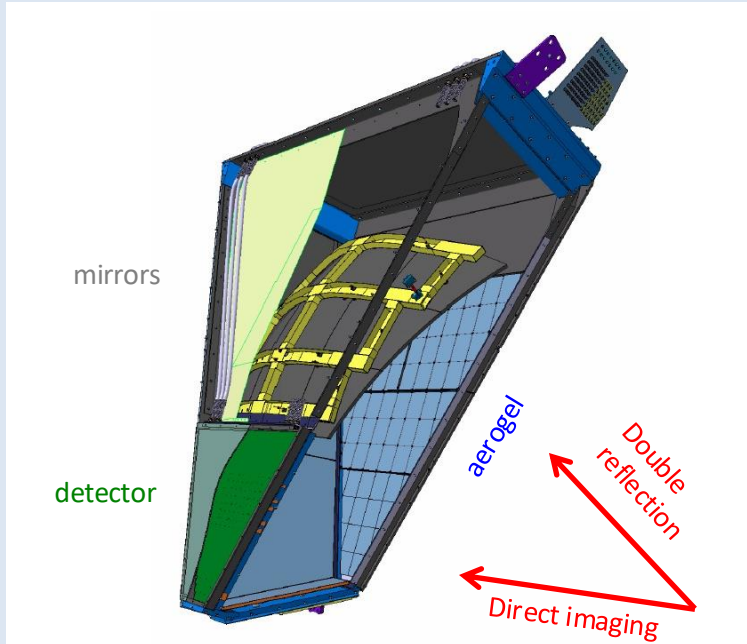
The shower maximum is at 10 km and generates a cone of 230 m

Extended detection pattern in space and time gives the direction



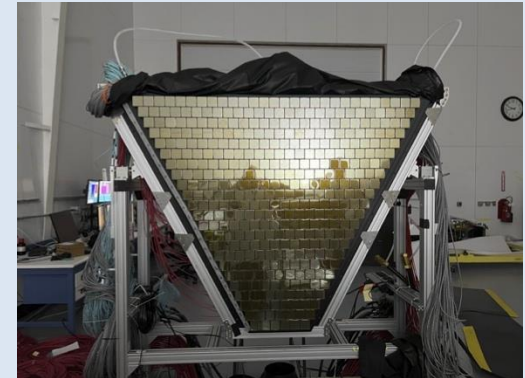
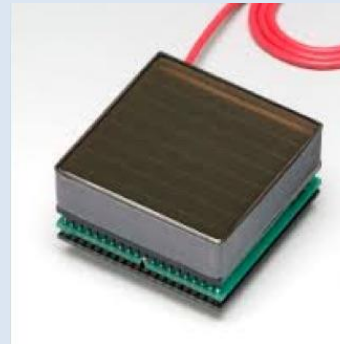
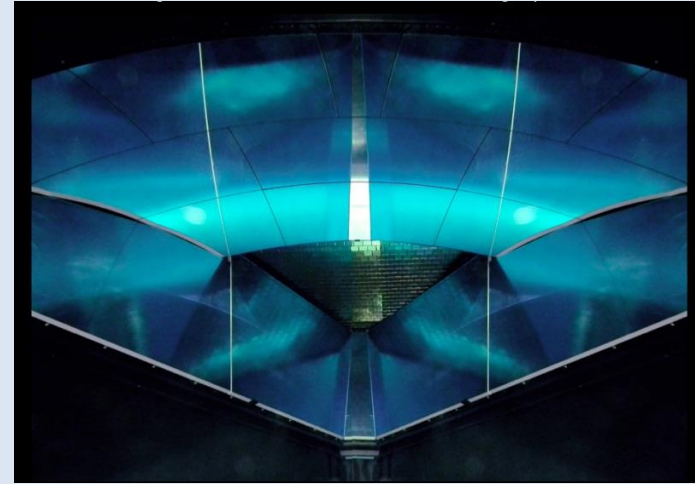
PID Reconstruction

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



Hamamatsu H12700 (+ H8500)

- < 1 cm spatial resolution
- < 1 ns time resolution
- Average gain $\sim 2.7 \cdot 10^6$
- eq. to SPE ~ 400 fC



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

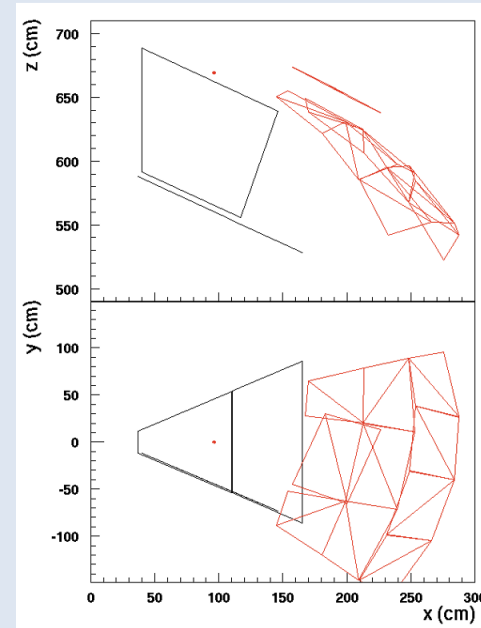
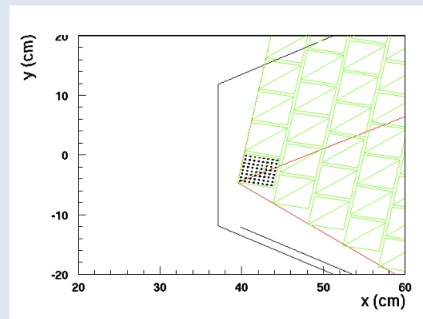
Align the tracking surfaces (as per mounting points)

Global RICH

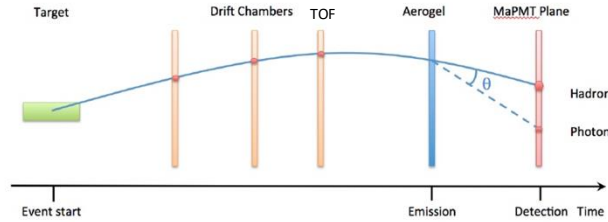
Layer (aerogel, MaPMTs, spherical mirror assembling)

Components (each single mirror, aerogel tile)

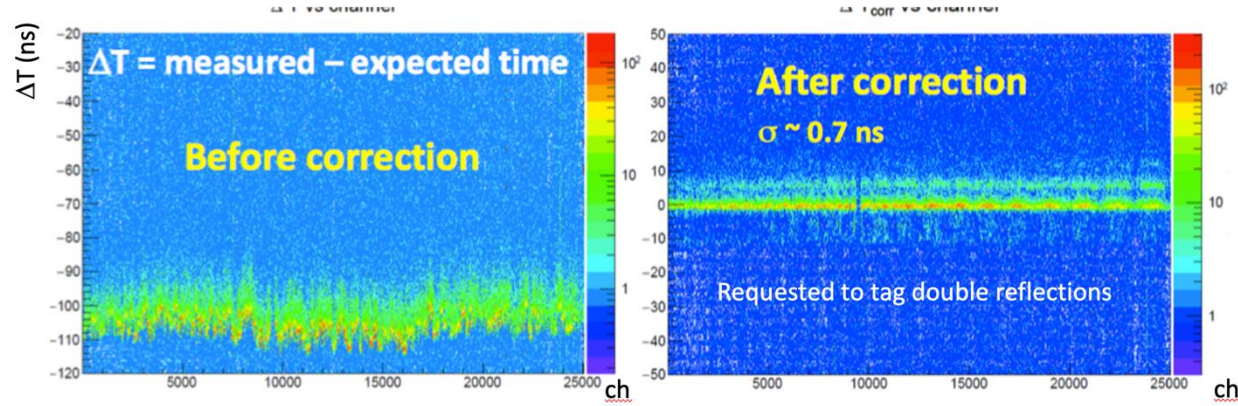
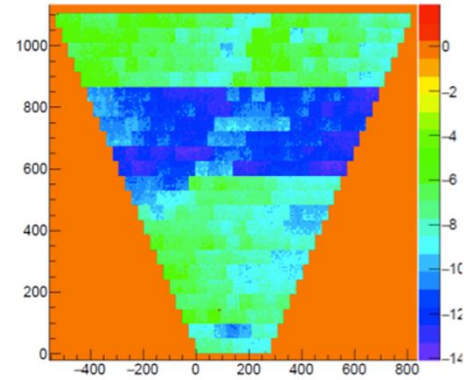
Detail MaPMT pixel geometry (on the misaligned plane)



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



Time offset map (ns)



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

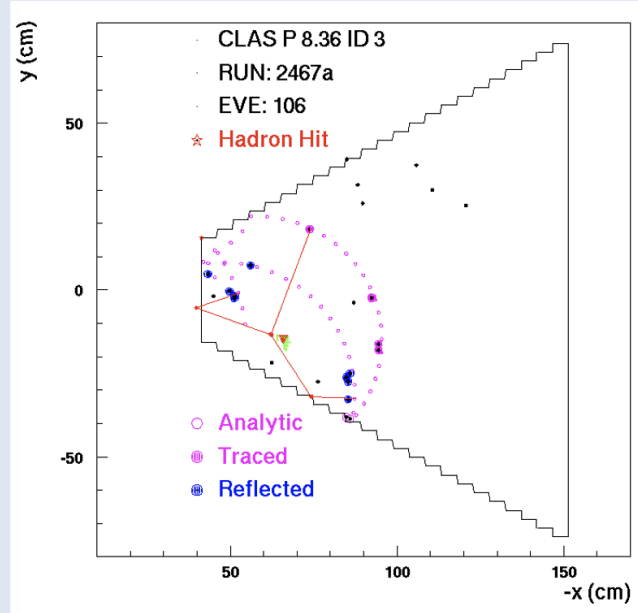
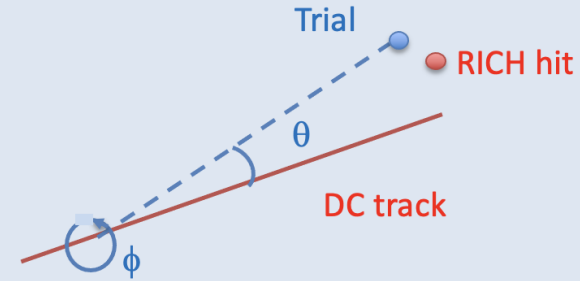
Direct ray-tracing:

assume an ID hypothesis (e, π , k, p)

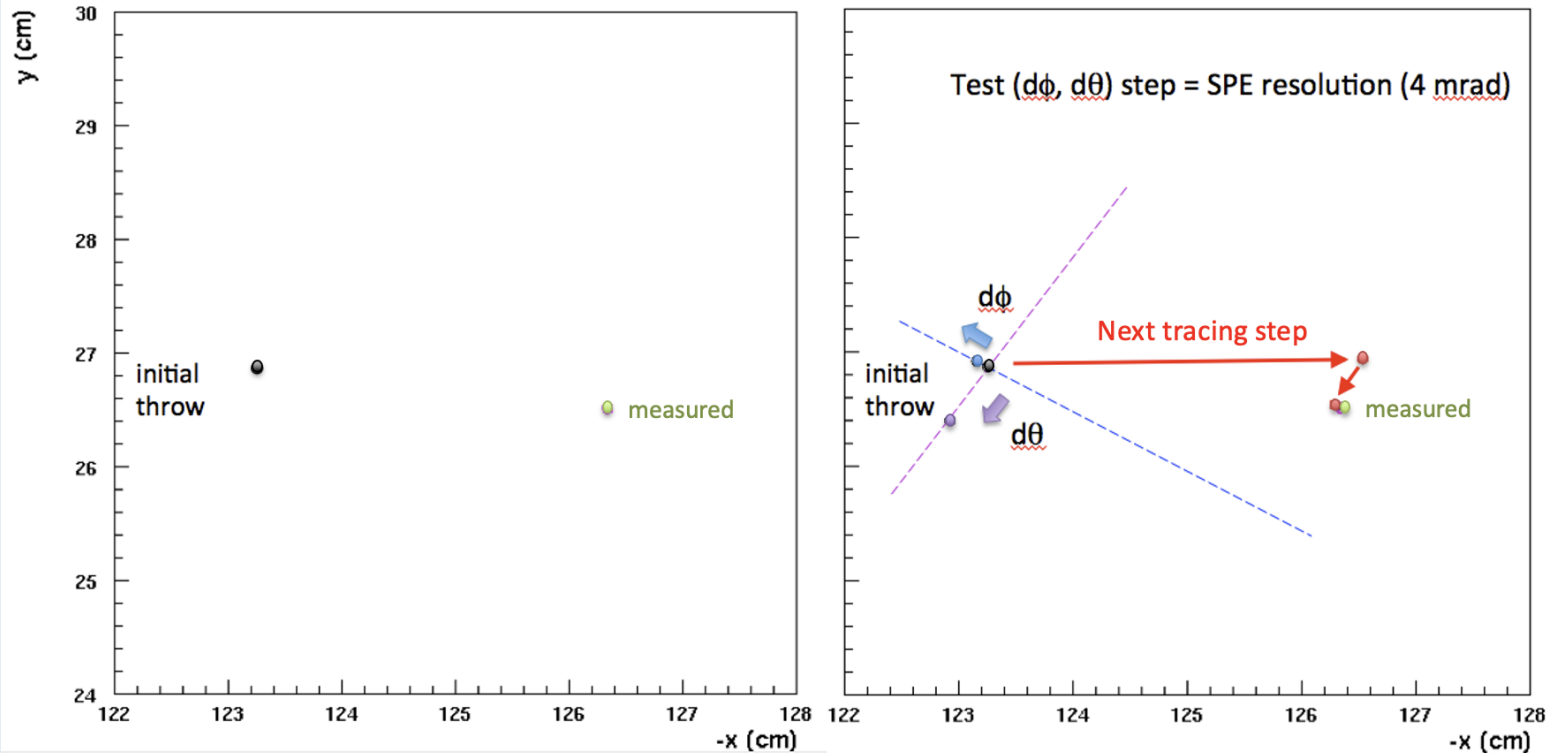
ray-trace a limited sample of photon trials
(selection of ϕ 's for given θ)

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

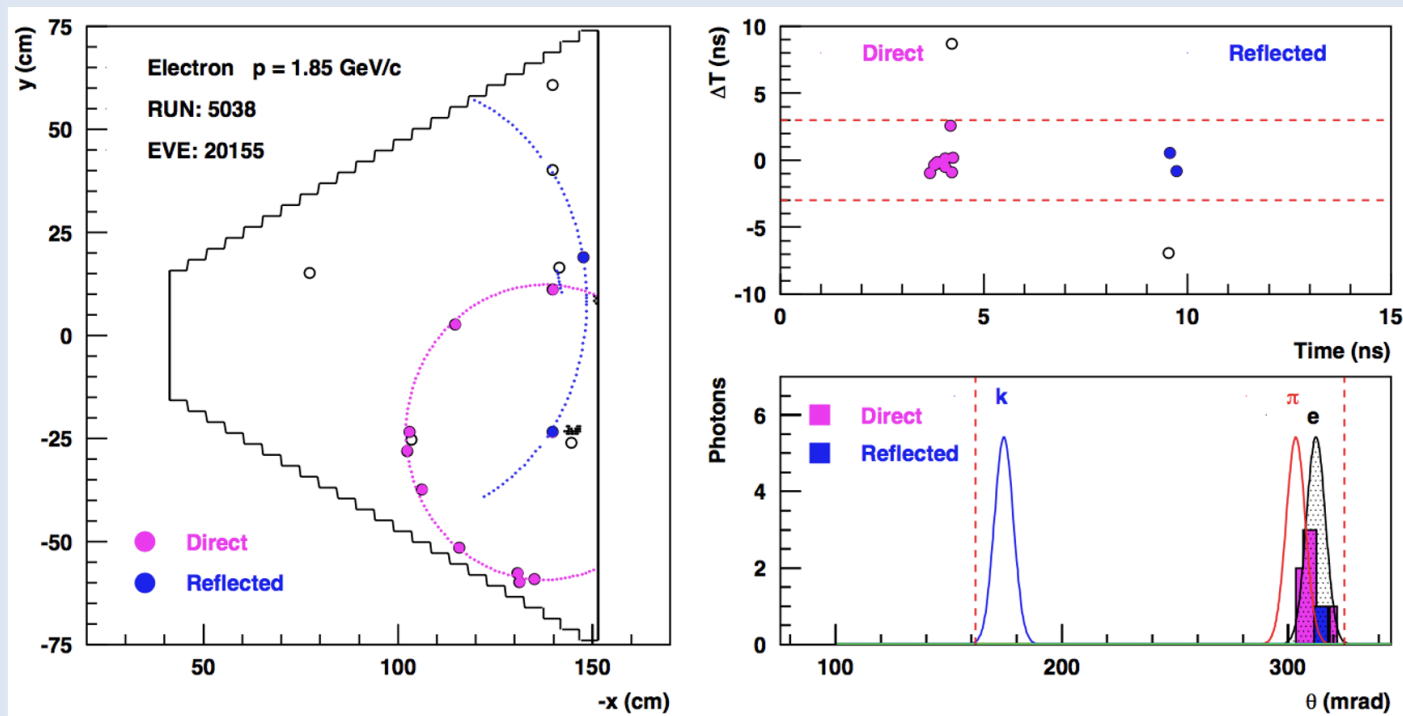


Trial position and refraction at boundaries $[\theta, n(\beta)]$ depend on particle hypothesis
 Stop when closer than half expected (angular) resolution



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

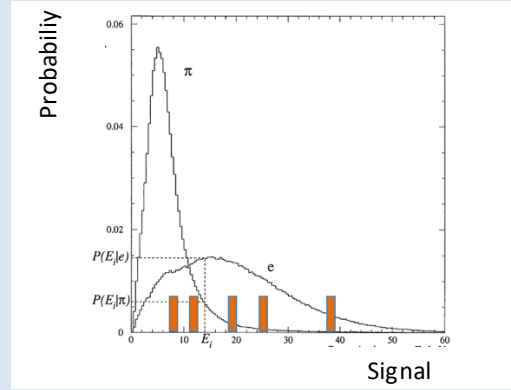
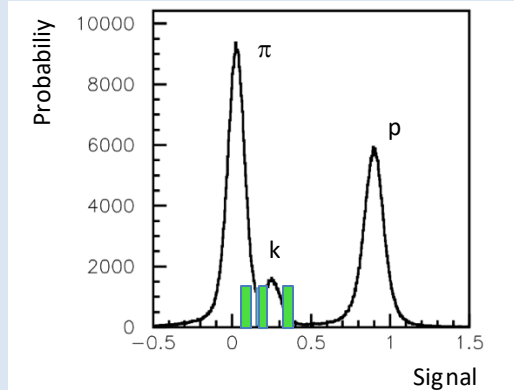
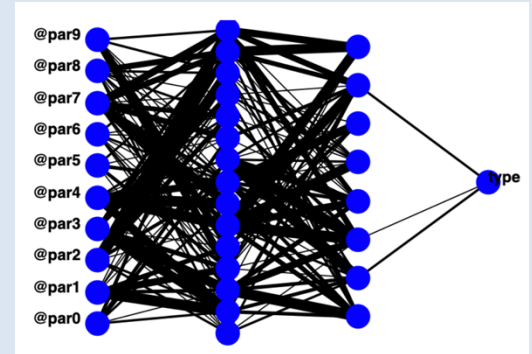
Least squares
minimization

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

Likelihood
maximization

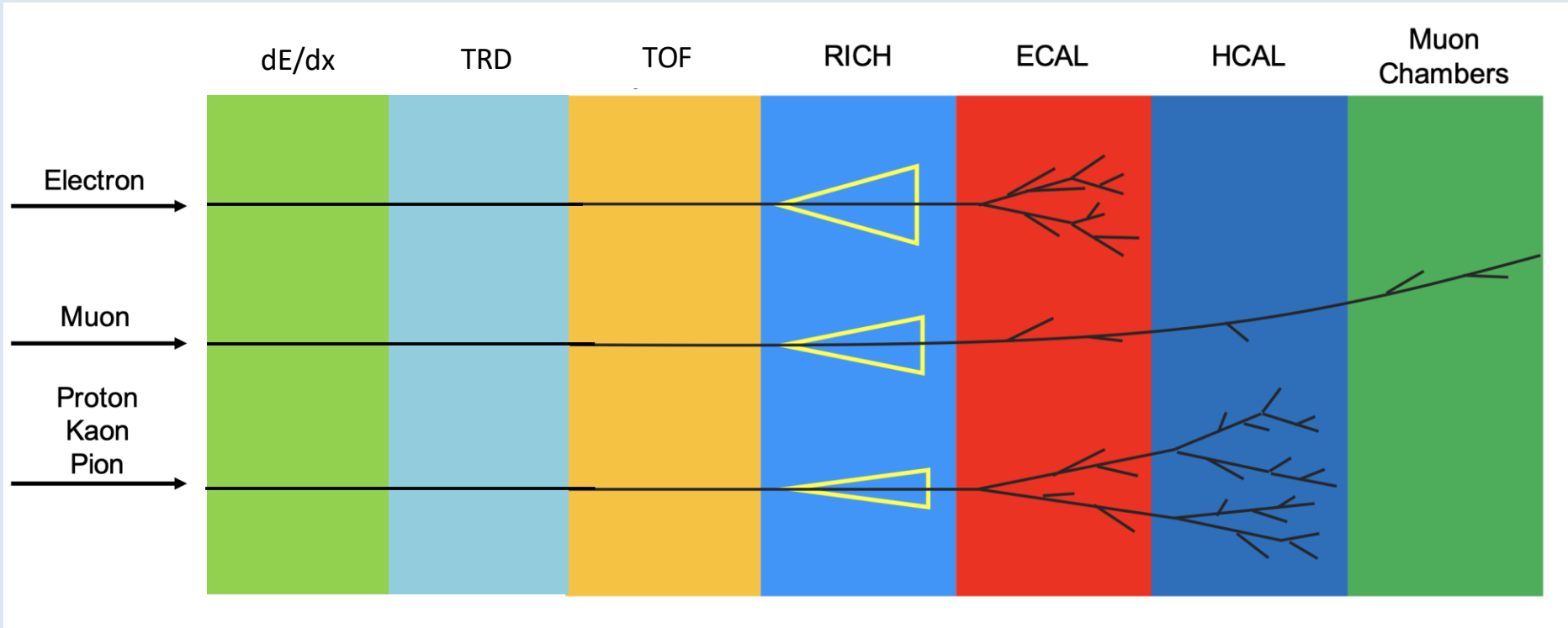
$$L(\boldsymbol{\theta}) = \prod_{i=1}^n f(x_i; \boldsymbol{\theta})$$

Machine learning
techniques

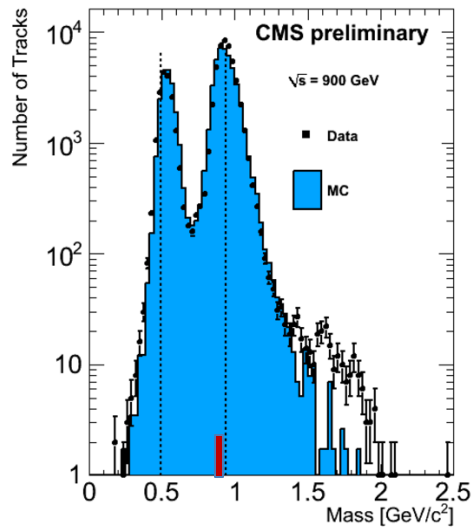


Best performance is with an holistic approach

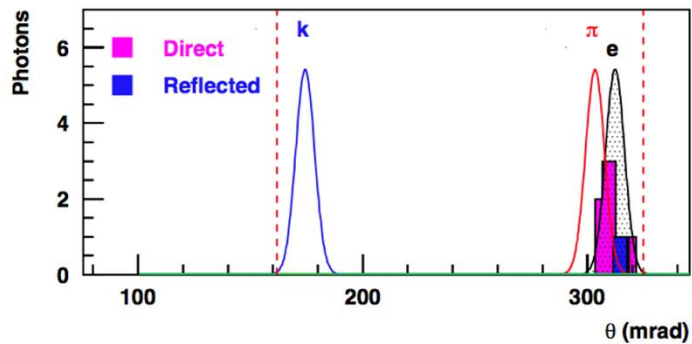
Correlating featured signals from the same detector (dE/dx points, TRD layers, ring photons,...) or from different detectors



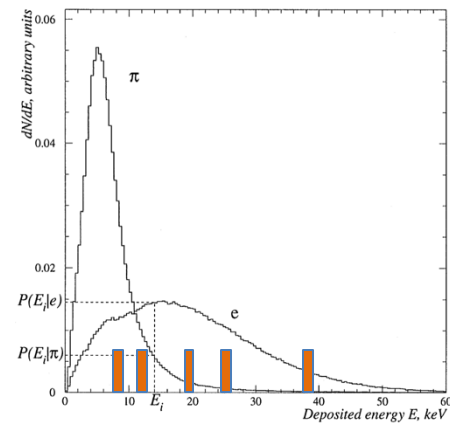
dE/dx



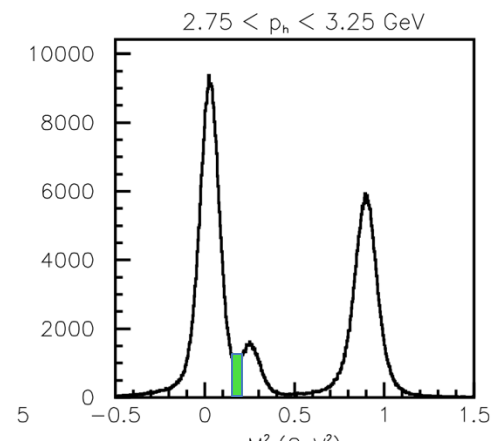
RICH



TRD



TOF



Observe n events x_i and expect a total of μ

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

In the $\log L$ any constant is irrelevant, i.e. any term that does not depend on the parameters $\boldsymbol{\theta}$.

In case $f(x_i; \boldsymbol{\theta})$ is a binned PDF with poisson probability the above reduces (except for a constant) to the binned maximum likelihood

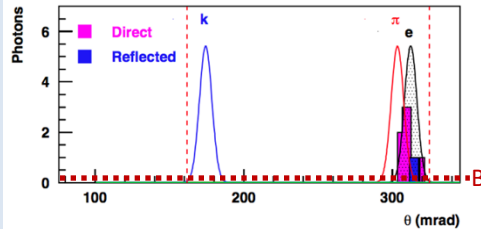
$$L_P(\boldsymbol{n}; \boldsymbol{\theta}) = \prod_{i=1}^N \frac{\mu_i^{n_i}}{n_i!} e^{-\mu_i}$$

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

Taking a likelihood ratio, vs an ideal model corresponding to the measurement ($\mu_i=n_i$), 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 $\mu_i - n_i$ term is optional (less stringent except close to threshold)
- * one can have bins with zero counts (last term is taken to be zero)

$$\mu_i(\theta) = \underbrace{\varepsilon(i) \frac{d\phi}{2\pi}}_{\text{Flat probability}} e^{-\frac{(\theta - \theta_i)^2}{2\sigma^2}} \underbrace{\frac{d\theta}{\sqrt{2\pi}\sigma} e^{-\frac{(t(\theta) - t_i)^2}{2\sigma_t^2}} \frac{dt}{\sqrt{2\pi}\sigma_t}}_{\text{Measured values}} + B(i)$$



Flat
probability

t may change due to
path (direct or reflected)

All these quantities are defined at pixel level

- $d\theta$ and $d\phi$ are known by RICH reconstruction.
- $\varepsilon(i)$ 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).

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

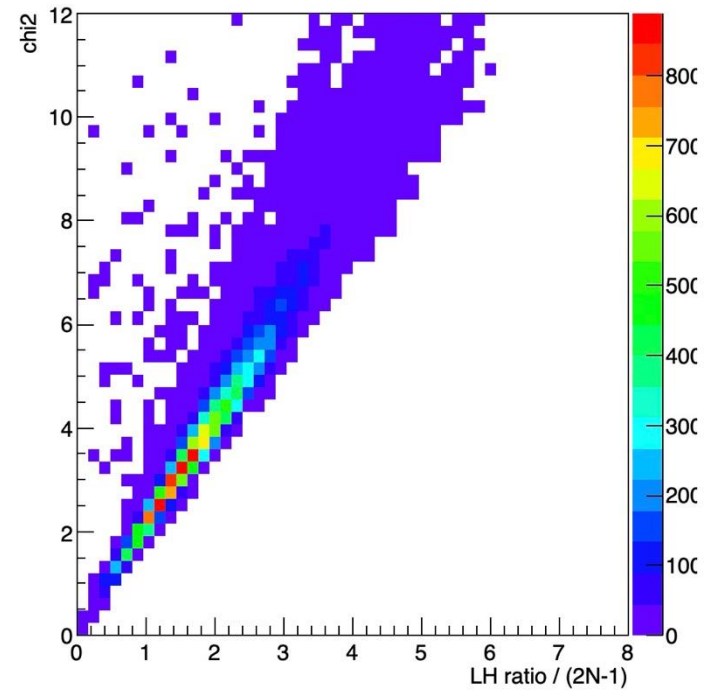
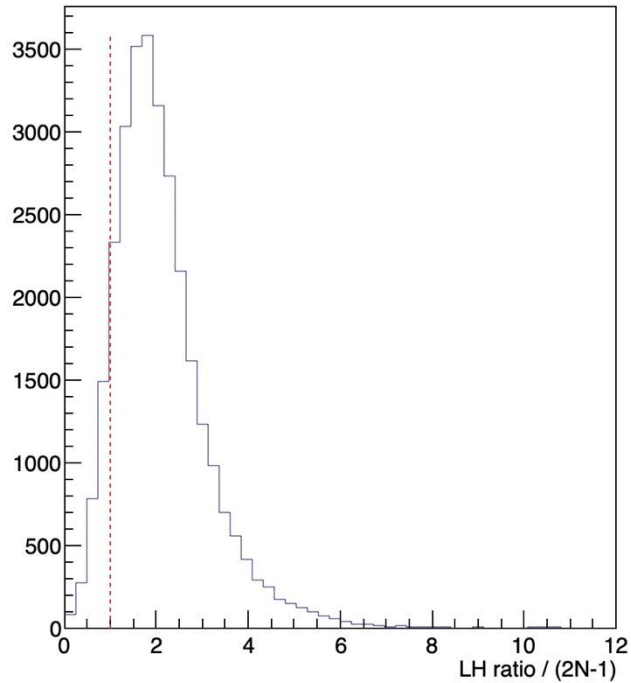
One might take the likelihood ratio with the model corresponding to the “observed measurement” in which all the hits are at the right (expected) angle

$$\begin{aligned} -2\ln\lambda(\theta) &= 2 \sum_{i=1}^N \left[\mu_i(\theta) - n_i + n_i \ln \frac{\mu_i'(\theta)}{\mu_i(\theta)} \right] \\ &= 2 (N_{exp} - N) + \sum_{i=1}^N \left[\frac{(\theta - \theta_i)^2}{\sigma^2} \right] + \left[\frac{(t(\theta) - t_i)^2}{\sigma_t^2} \right] \end{aligned}$$

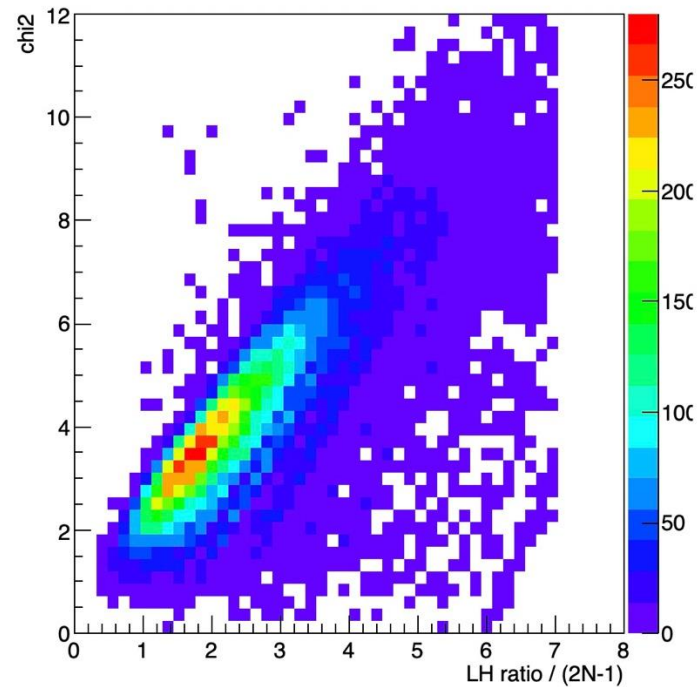
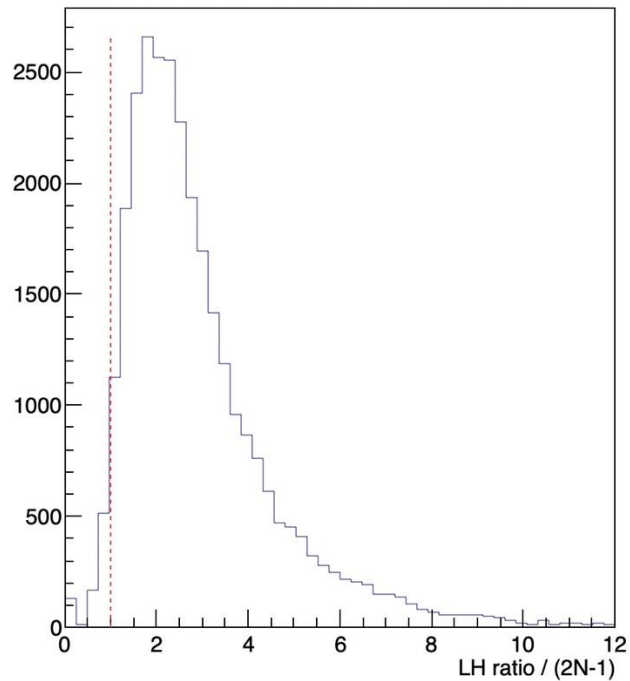
Should reduce to a sort of chi2.

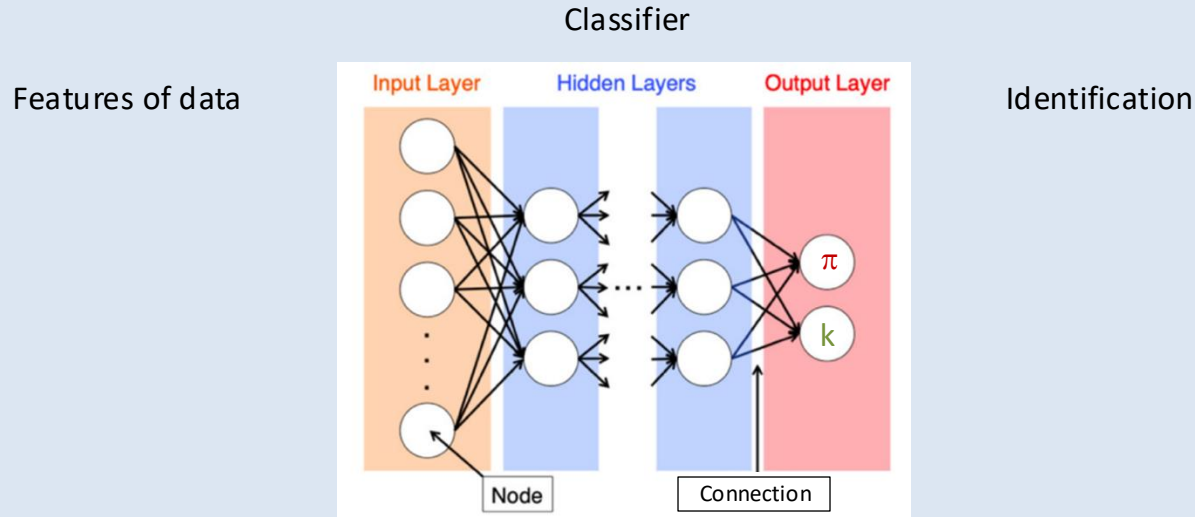
Beyond non gaussian effects and the optional normalization term, the difference is in the background that defines a sort of cutoff: an accepted hit that is background for all the hypotheses does not count in the likelihood, whereas the ordinary chi2 weights anyway its distance from the expected value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

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



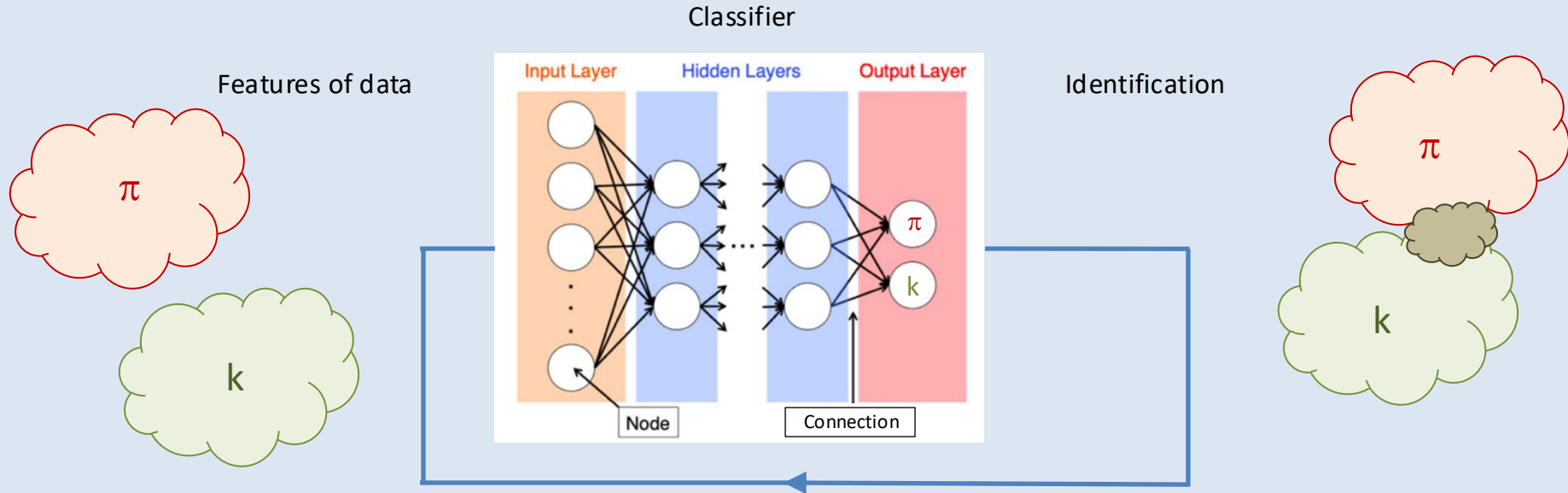
With $2(N_{\text{exp}} - N)$ term





Connection: got a **weight** defining the strenght

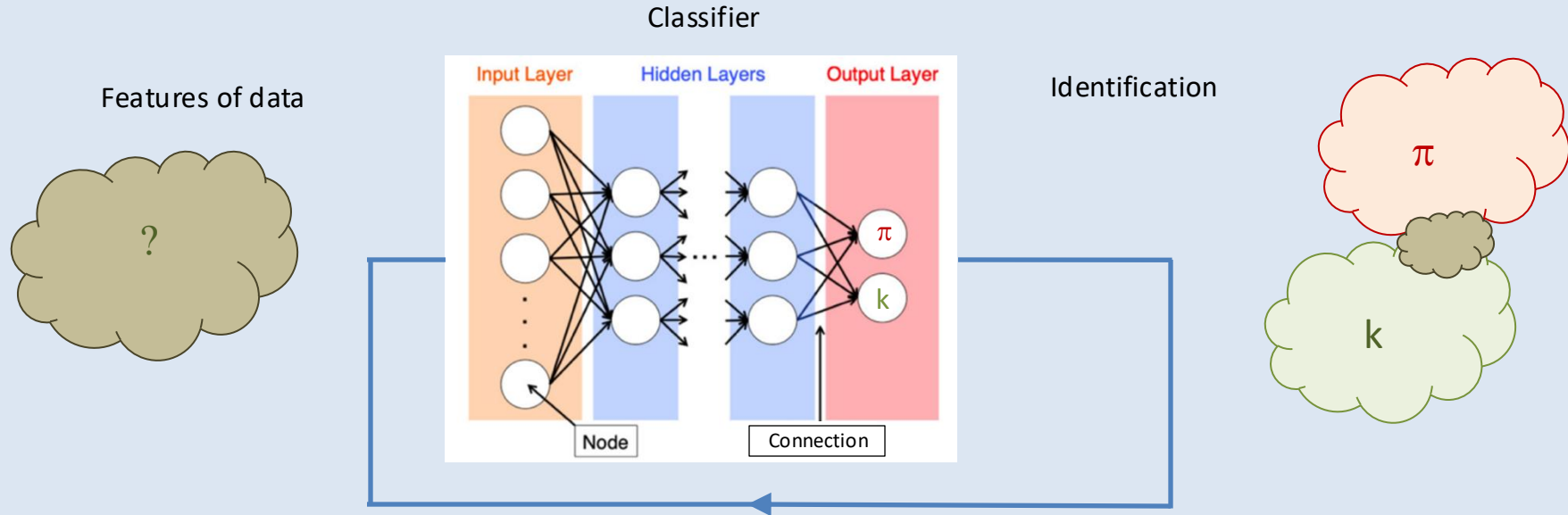
Node: got an activation function for the output value from **weighted** inputs plus **bias**



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)



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

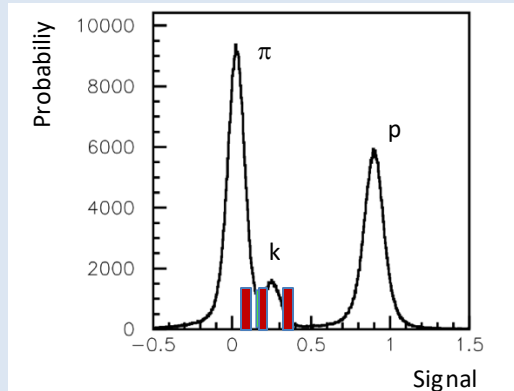


Critical as assumes an a-priori knowledge

Least squares
minimization

Correlations via covariance matrix

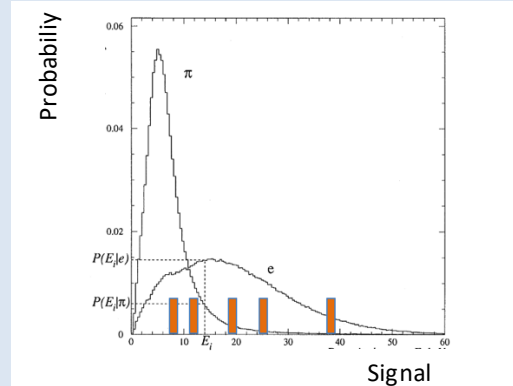
$$\chi^2 = \sum_{i=1}^N \frac{(x_i - x(\theta))^2}{\sigma^2}$$



Likelihood
maximization

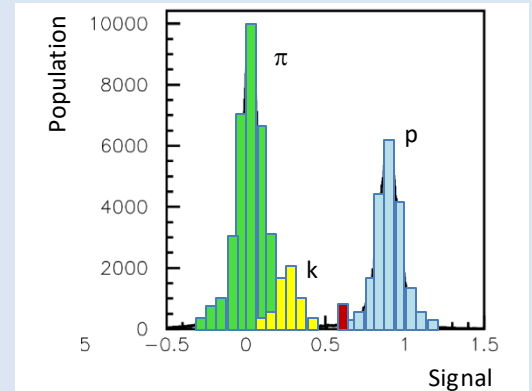
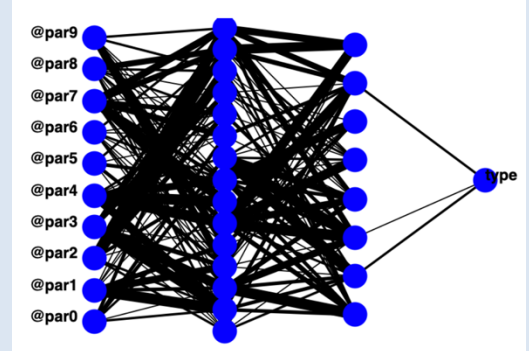
Correlations via multi-D p.d.f.

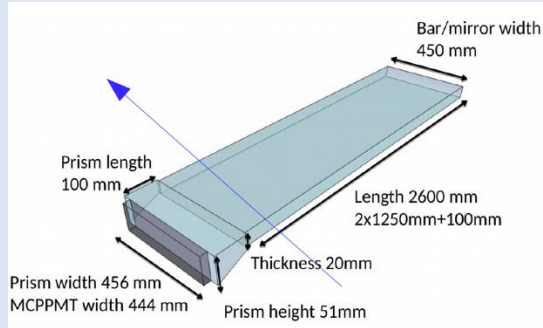
$$L(\theta) = \prod_{i=1}^n f(x_i; \theta)$$



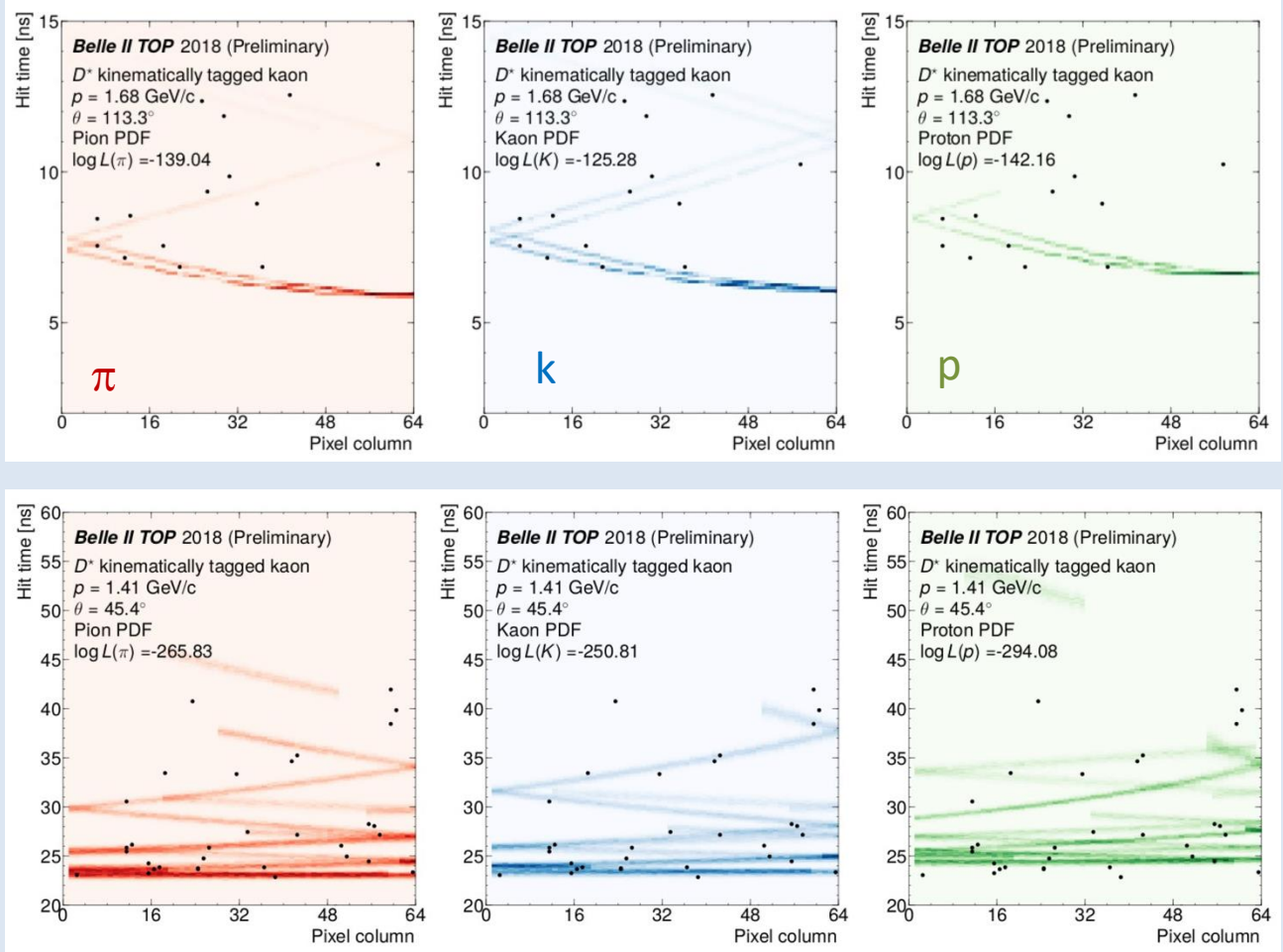
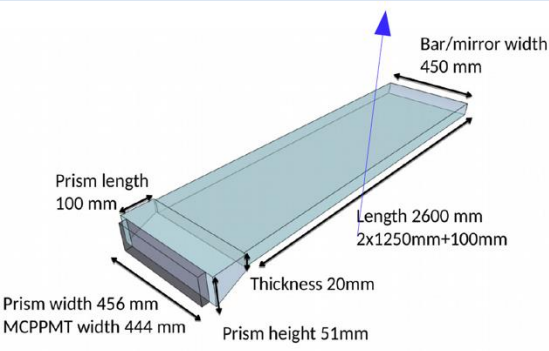
Machine learning
techniques

Correlations via NN training





TOP BELLEII

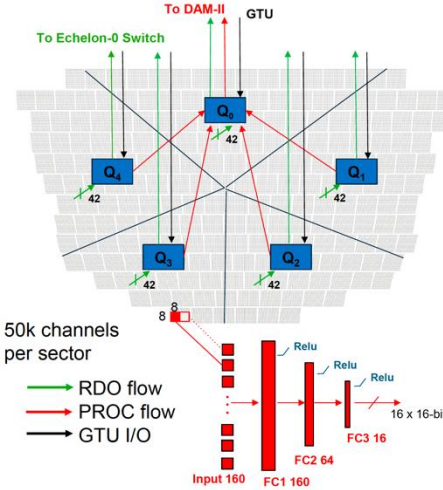
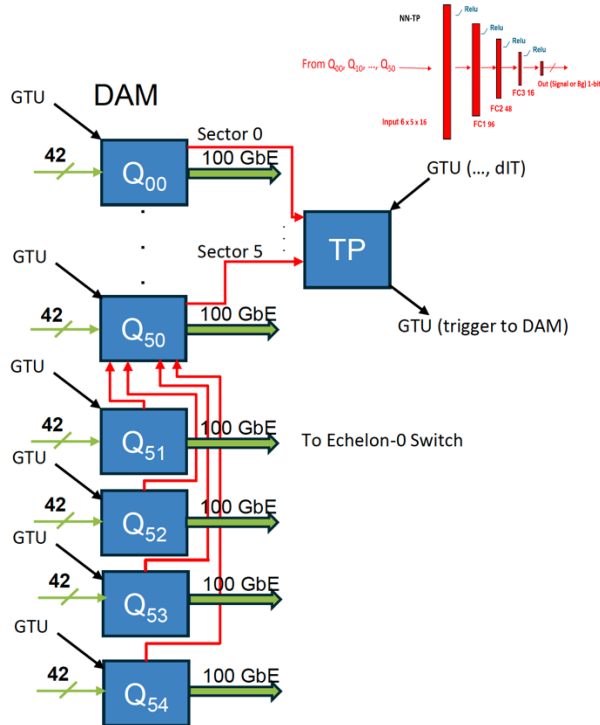


Efficiency increase (resources saving) when useless degrees of freedom are removed, i.e. the NN architecture is aligned to the real detector layout

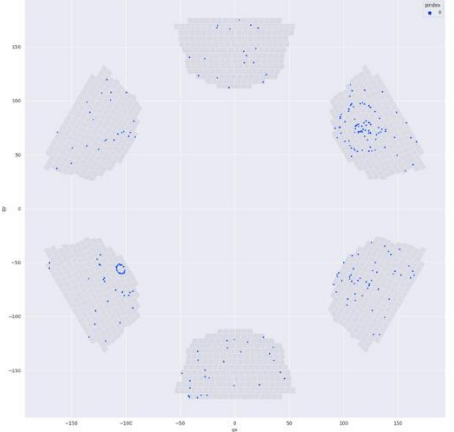
Scheme based on ePIC DAM (Felix) & APEIRON communication network (INFN)

sub-sector integrated analysis

detector integrated analysis



Phys Signal+Phys Background+Noise

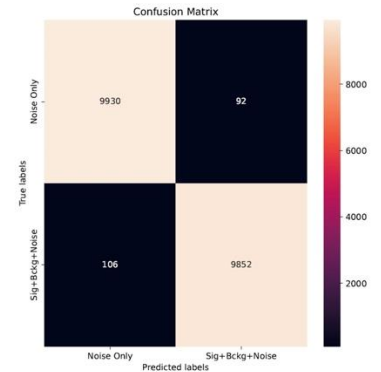


Preliminary tests

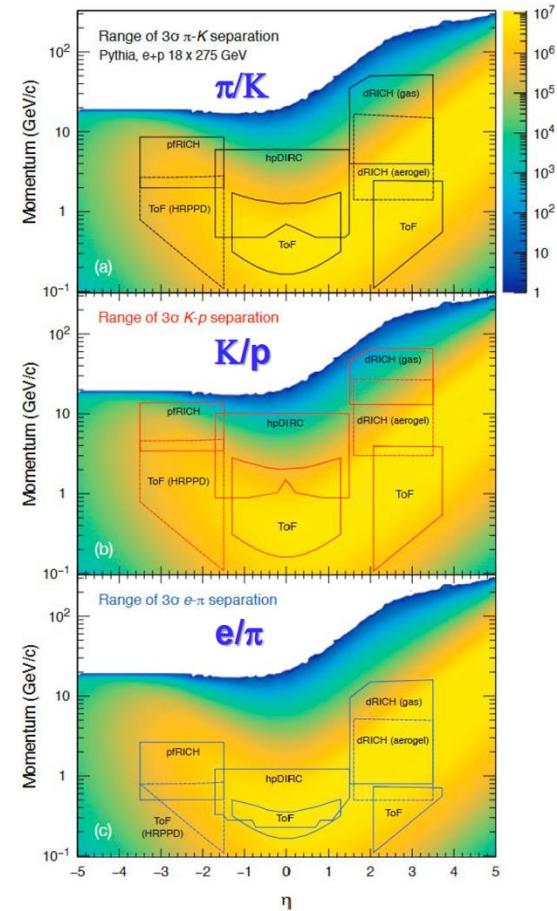
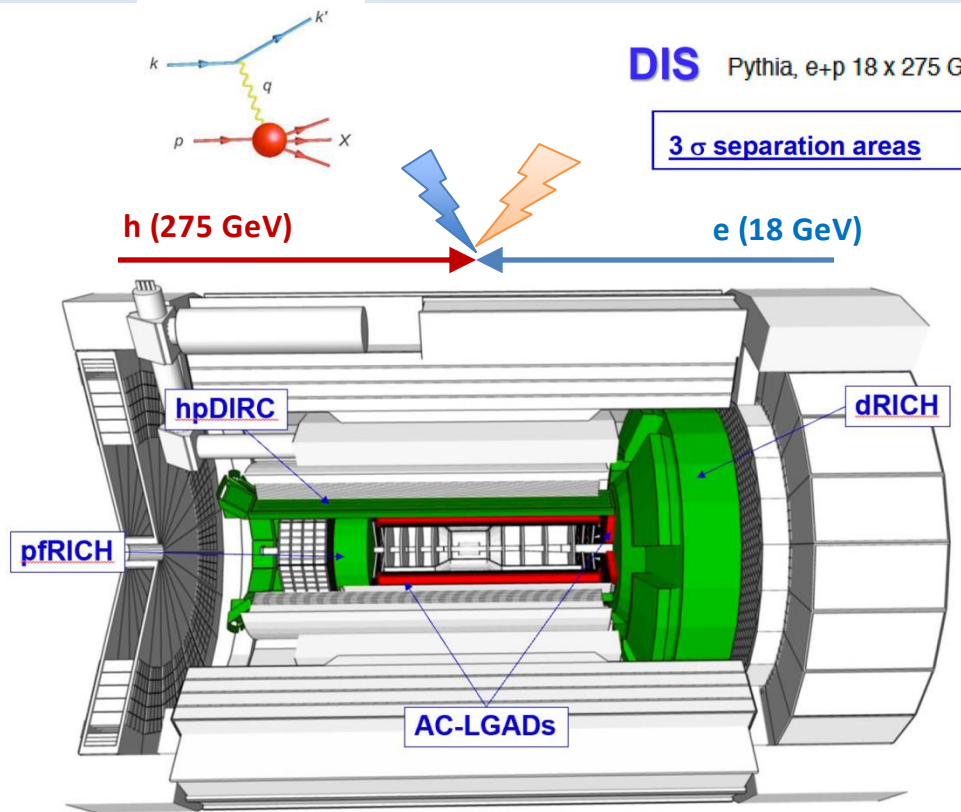
Classifier

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

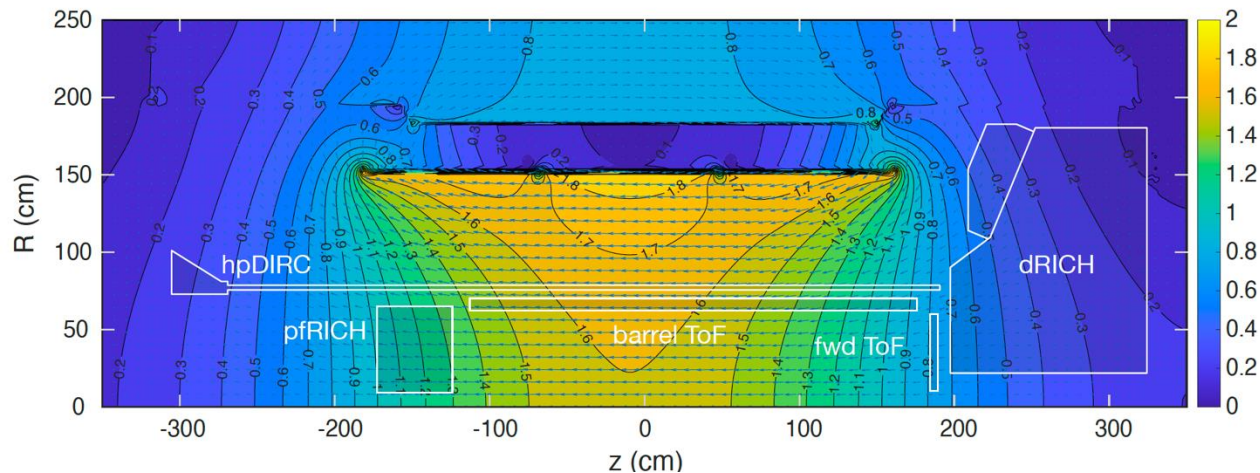
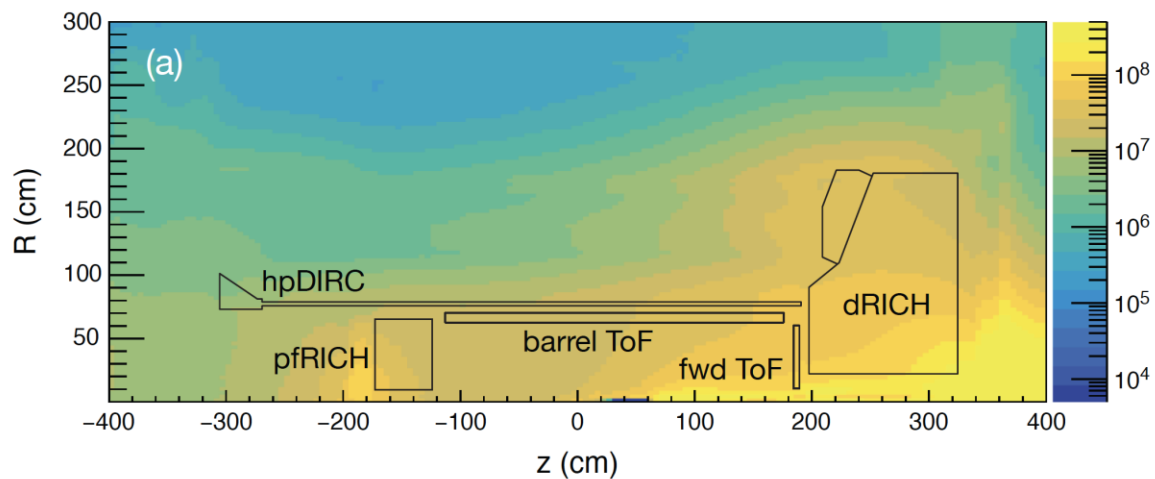
→ Through **quantization**, we defined:
quantized fixed point<16,6> inputs
quantized fixed point<8,1> weights
quantized fixed point<8,1> biases



ePIC PID Requirements



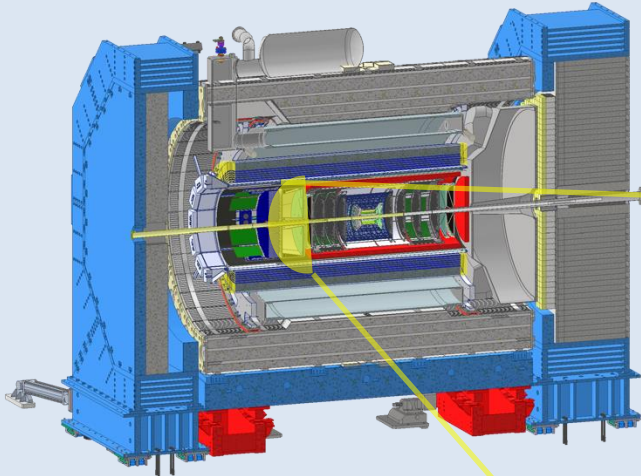
Magnetic field

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

ePIC PID Solutions

Proximity-Focusing Ring-imaging Cherenkov Detector (pfRICH)

Essential to access flavor information

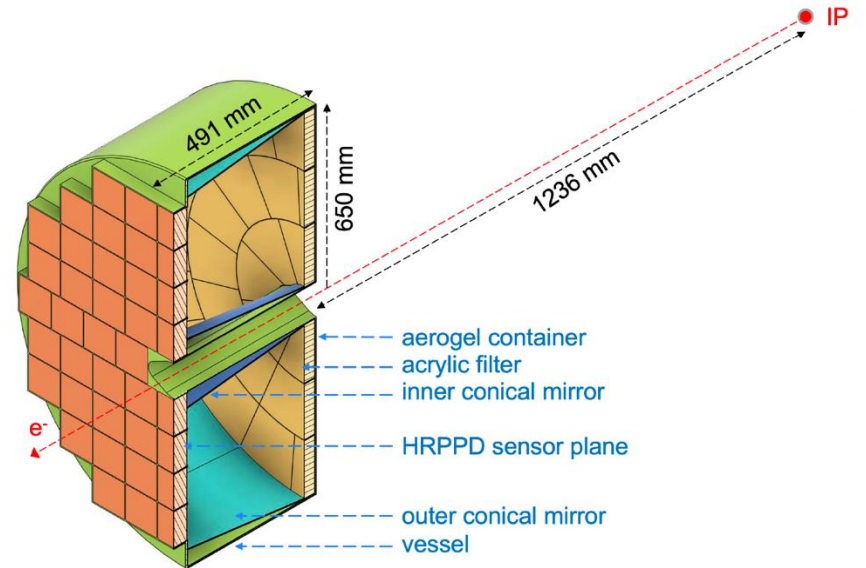


Goals:

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

pfRICH Features:

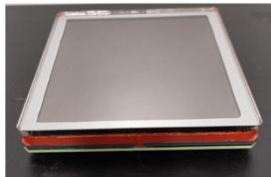
Limited space --> **Simple geometry, gap minimized**
 Precise time information --> **HRPPD**
 Single-photon detection in high Bfield --> **HRPPD**



High Rate Picosecond Photon Detector (HRPPD) overview

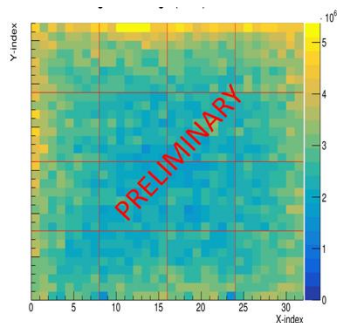
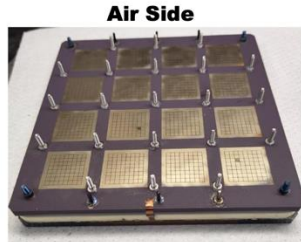
Planar geometry MCP-PMT featuring:

- 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

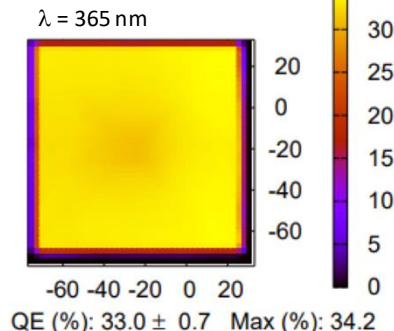
Test PCB board attachment using Samtec compression interposers



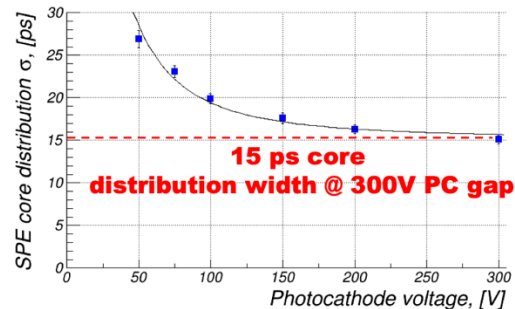
Gain uniformity



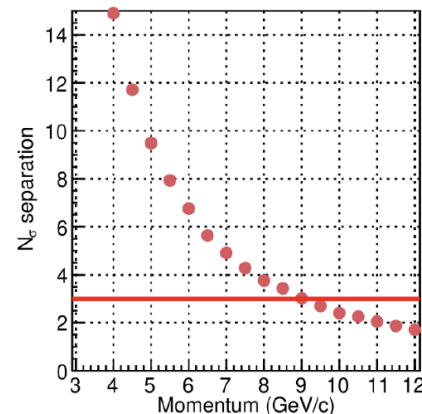
Average QE (5 over 7)



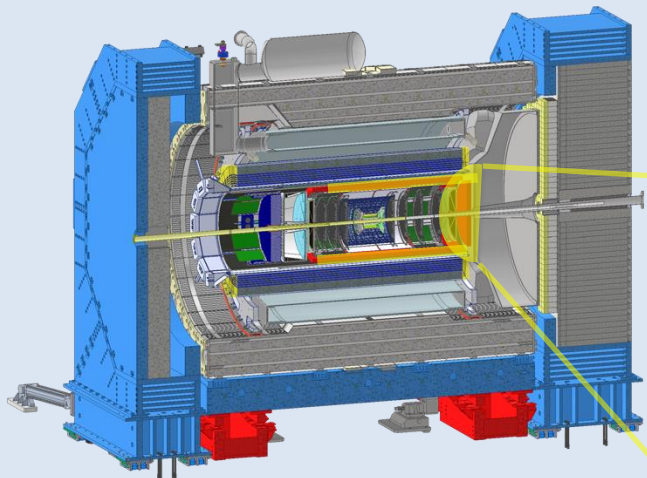
A.V. Lyashenko e-Print: [2505.10658](#)



C. Chatterjee PoS DIS2024 (2025) 266



Time-of-Flight Detector (TOF)
Essential to access flavor information

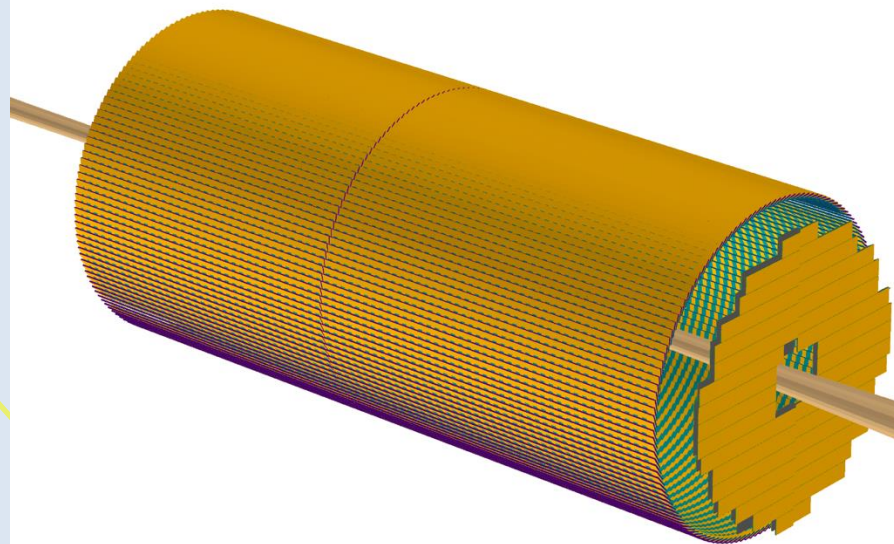


Goals:

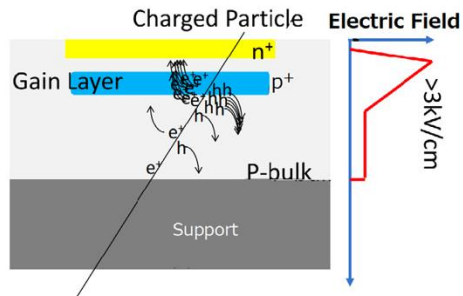
Hadron 3σ -separation up to 1.2 GeV/c (barrel)
Hadron 3σ -separation up to 2.5 GeV/c (h-endcap)
Cover mid-forward pseudorapidity -1.5 : 3.5

dRICH Features:

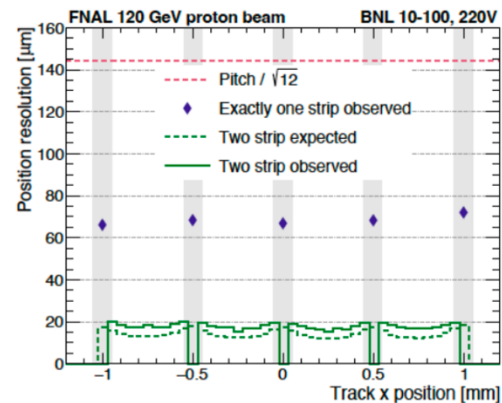
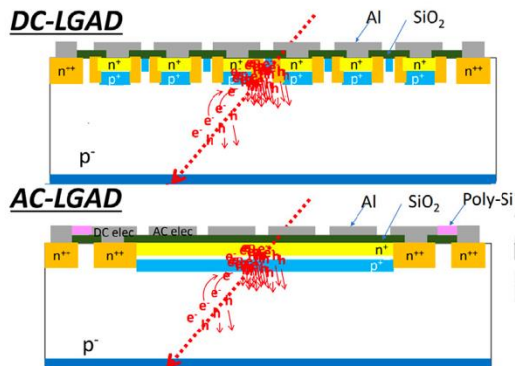
Precision in limited space --> **silicon detector**
Up to 2.5 GeV/c momentum range --> **AC-LGAD**
Complement tracking --> **AC-LGAD**



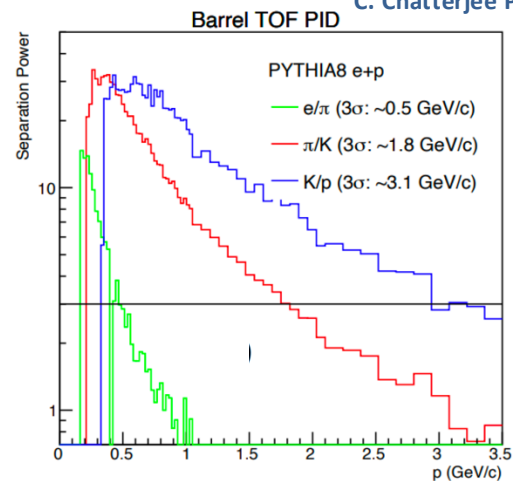
LGAD adds a p+ layer with large Boron doping to create a region of high field and concentrated avalanche



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

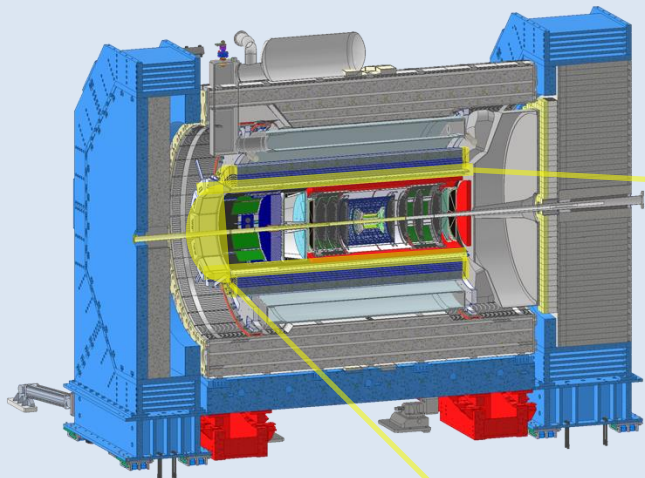


C. Chatterjee PoS DIS2024 (2025) 266



High-Performance (dRICH)

Essential to access flavor information

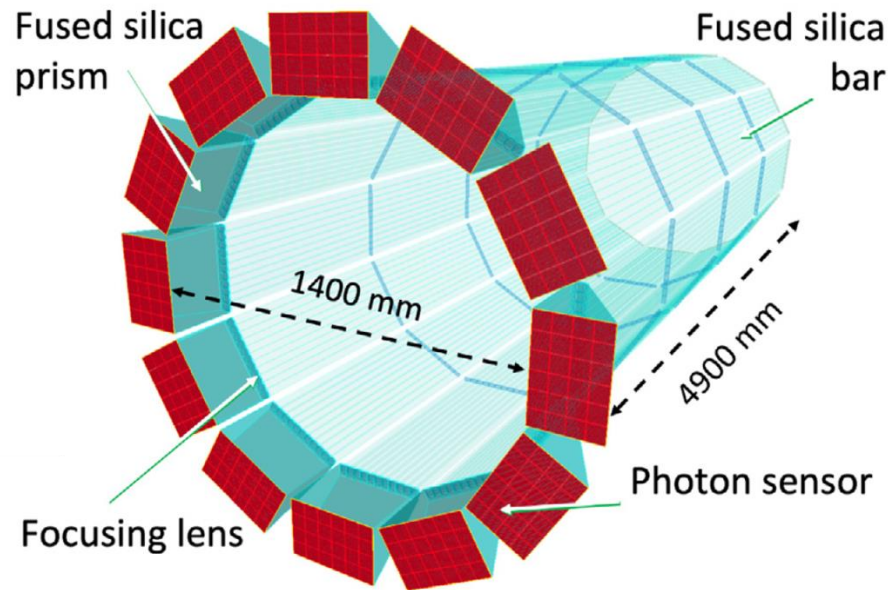


Goals:

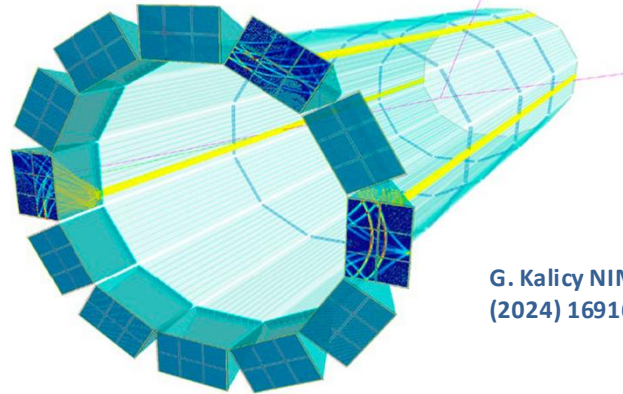
Hadron 3σ -separation between 3 - 6 GeV/c
 Complement electron ID below 1.2 GeV/c
 Cover forward pseudorapidity -1.5 - 1.5 (barrel)

dRICH Features:

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

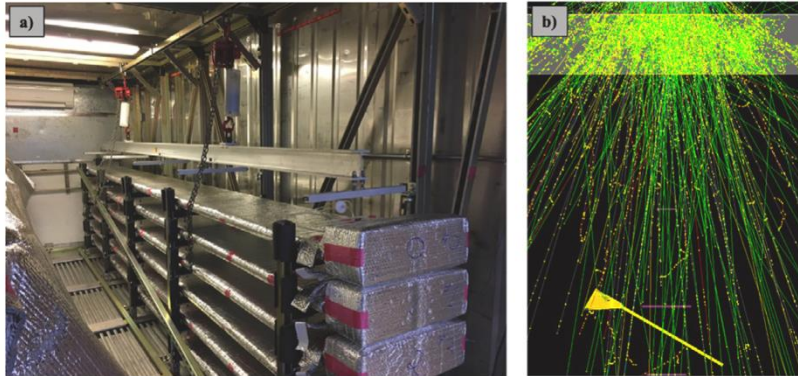


Compact, high-performance (+50%) design

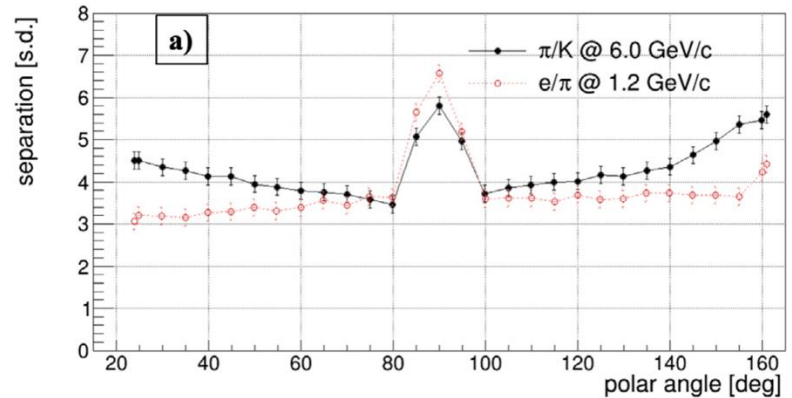
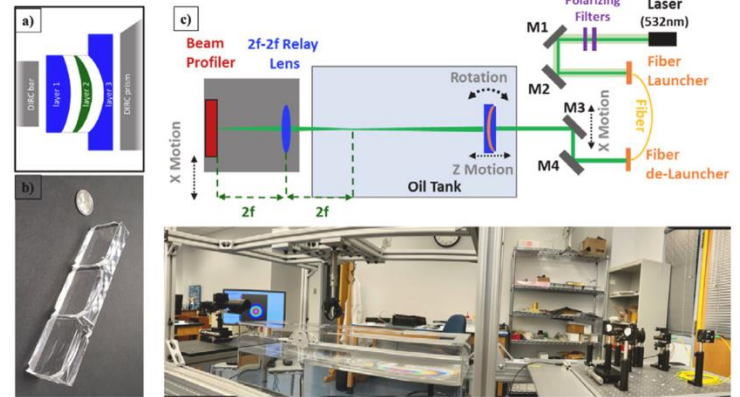


G. Kalicy NIMA 1062
(2024) 169168

Re-use of BABAR DIRC bars and cosmic test

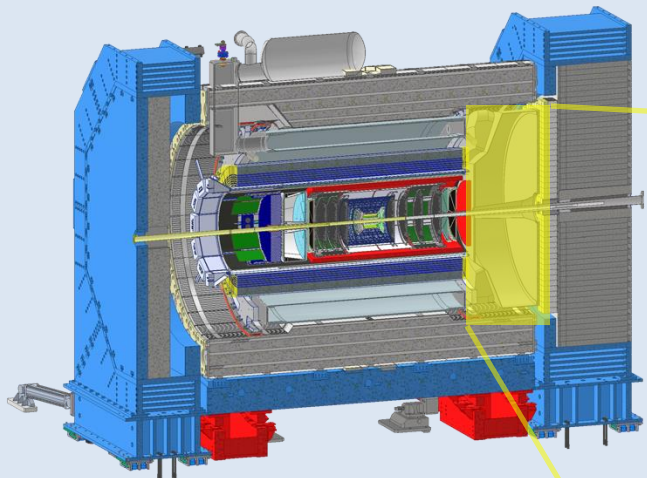


Quartz prism with focalizing sapphire lens



Dual-radiator Ring-imaging Cherenkov Detector (dRICH)

Essential to access flavor information



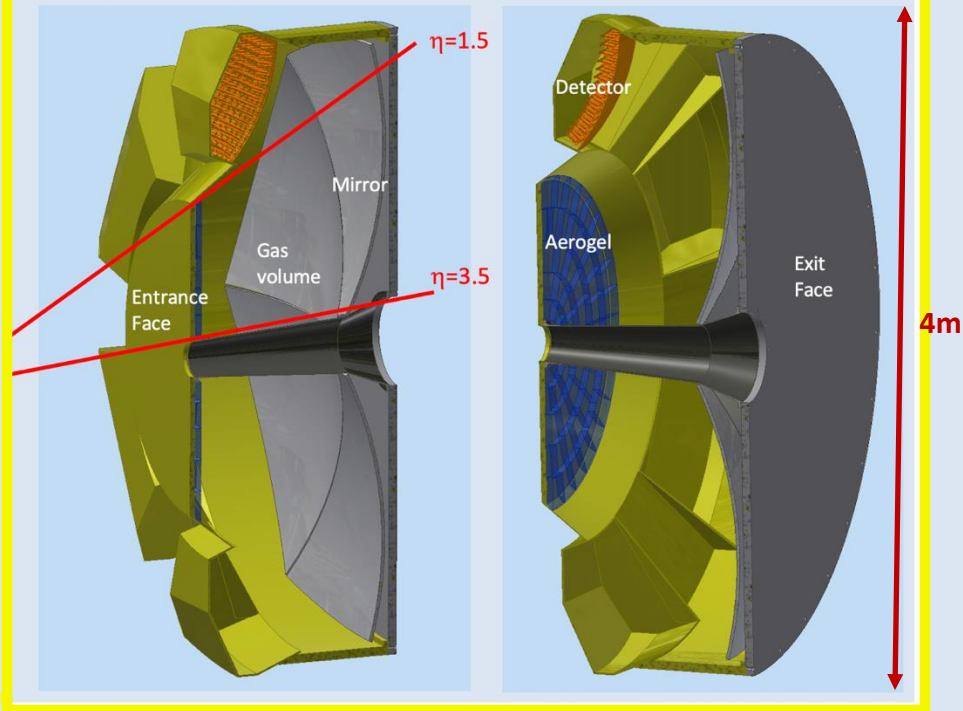
Goals:

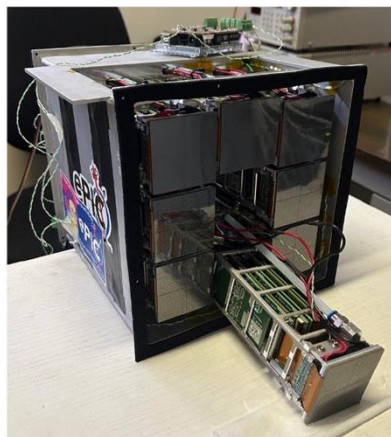
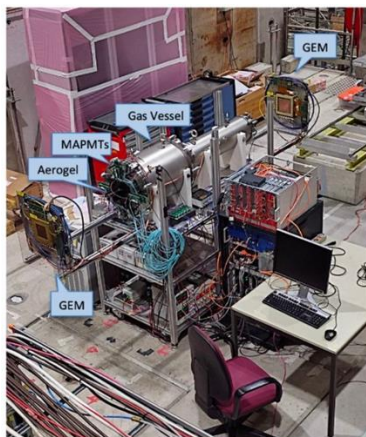
Hadron 3σ -separation between 3 - 50 GeV/c
 Complement electron ID below 15 GeV/c
 Cover forward pseudorapidity 1.5 - 3.5 (h-cap)

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**

3D mechanical model

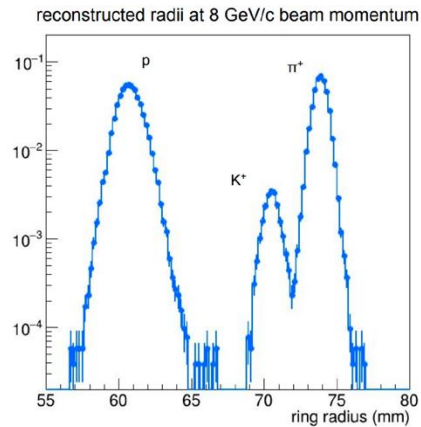
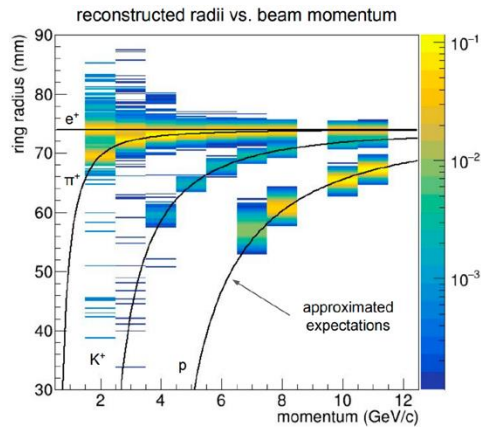
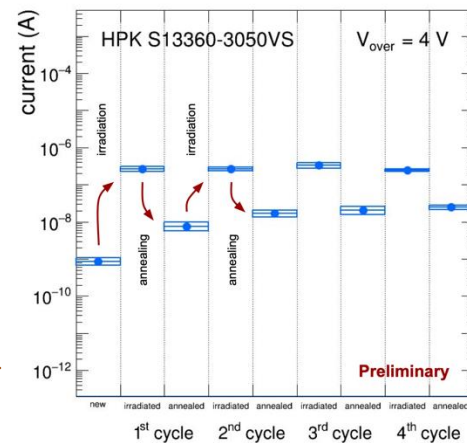




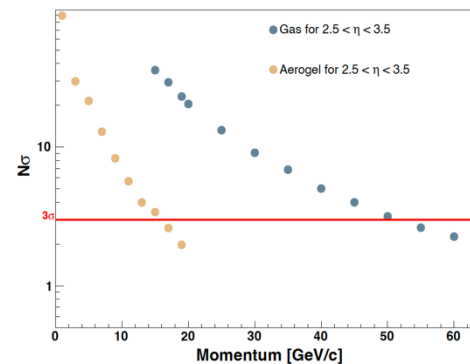
Imaging study



Annealing study

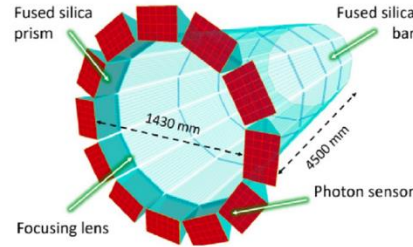


C. Chatterjee PoS DIS2024 (2025) 266



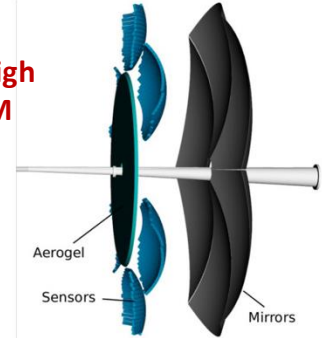
+50% momentum reach with lens

**High-Performance
DIRC (hpDIRC)**

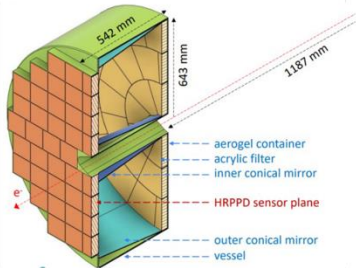


**Dual-Radiator RICH
(dRICH)**

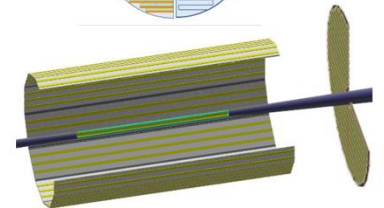
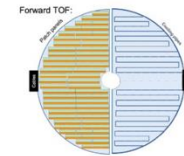
**Detection in high
B-field with SiPM**



**Precise timing with HRPPD
Proximity Focusing
RICH (pfRICH)**



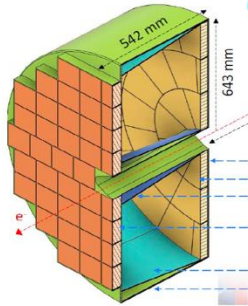
**Precise tracking by AC-LGAD
Time-of-Flight (ToF)**



Cherenkov imaging PID in backward endcap:

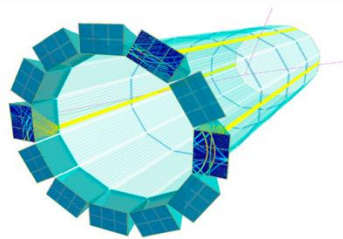
proximity focusing RICH (pfRICH)

The long proximity gap (~ 35 cm) enhances the resolution

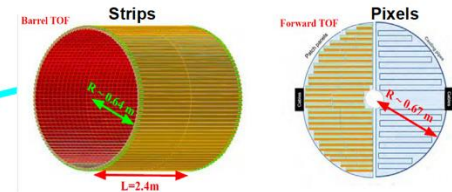
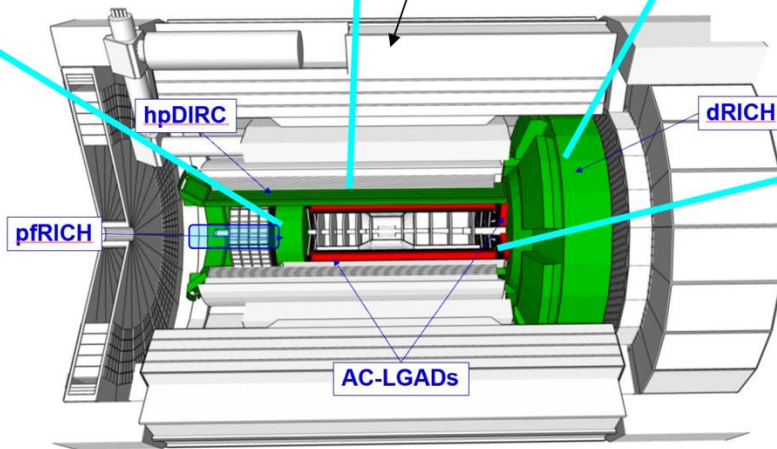
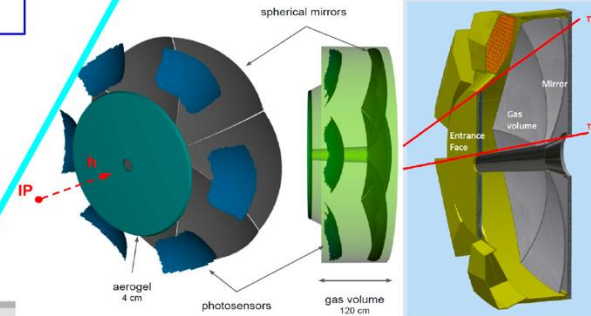


High performance DIRC (hpDIRC)

High performance thanks to **focalization** and **fine photosensor pizelization**



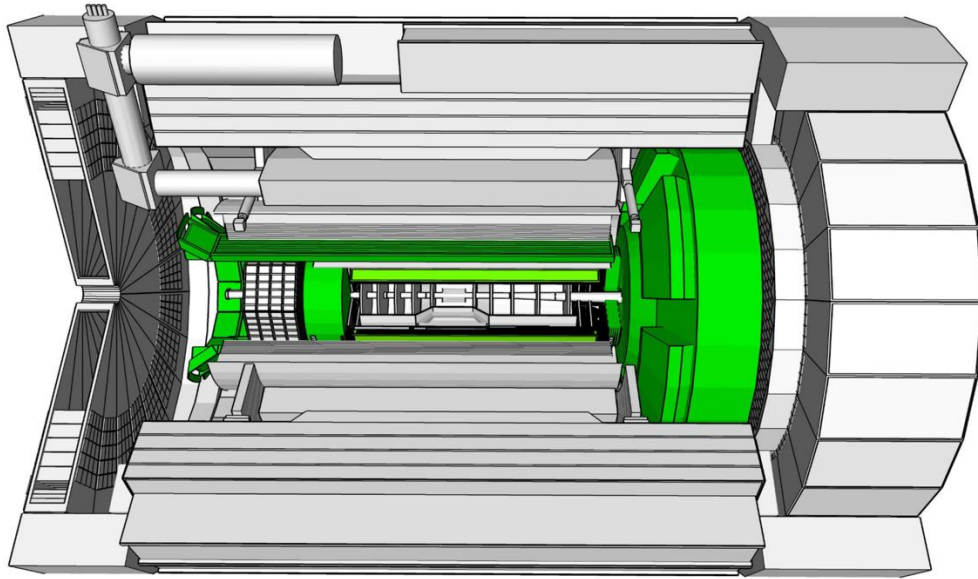
Dual radiator RICH (dRICH); Areogel and gas



ToF by AC-LGADs

Goals for the application in ePIC:

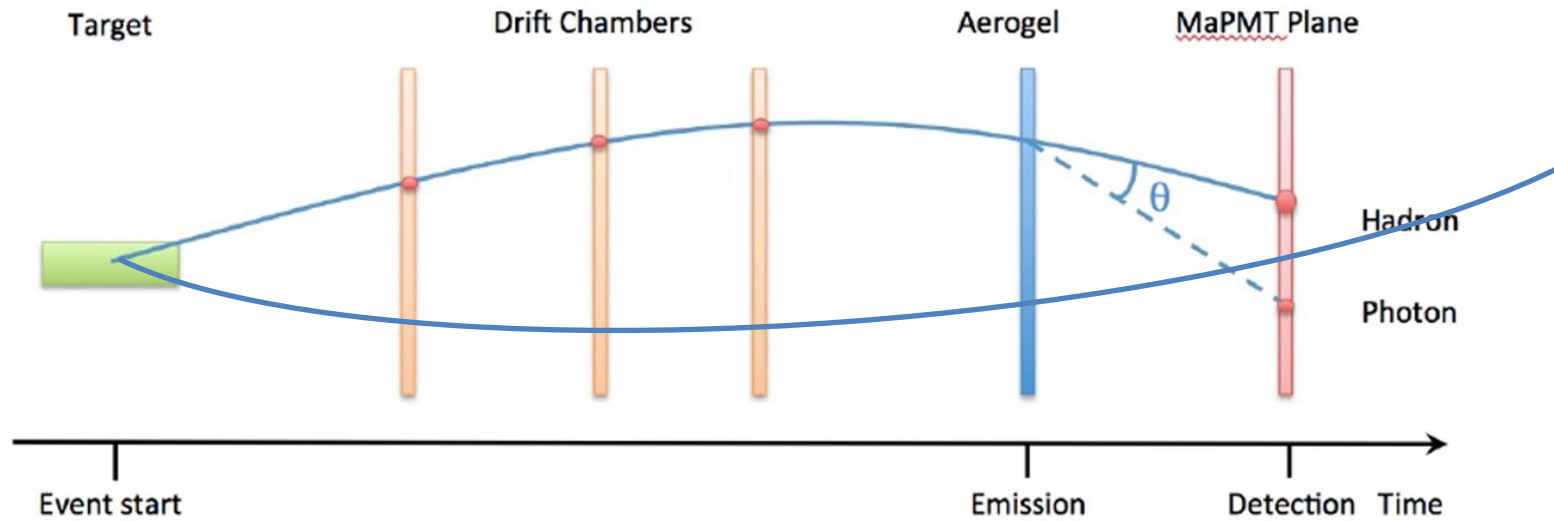
- 30 μm space resolution
- 25-35 ps time resolution



Rapidity	$\pi/K/p$ and π^0/γ	e/h	Min p_T (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

Particle Separation Needs

- Electrons from photons $\rightarrow 4\pi$ coverage in tracking
- Electrons from charged hadrons $\rightarrow$ mostly provided by calorimetry and tracking, PID detectors at low p
- Charged pions, kaons and protons from each other on track level $\rightarrow$ **Cherenkov detectors**
- Cherenkov detectors, complemented by other technologies **at lower momenta: ToF**
- **Demands on PID are unique to ePIC**

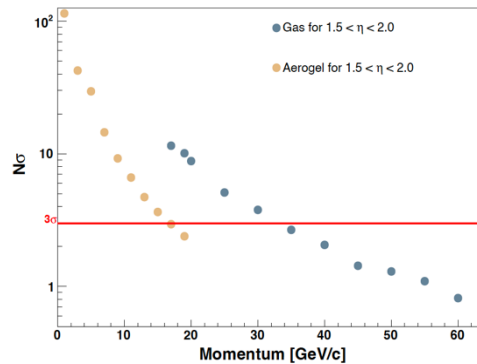
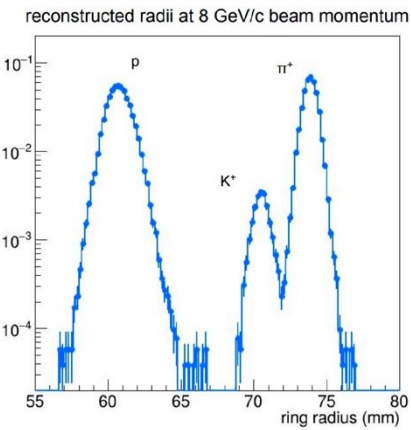
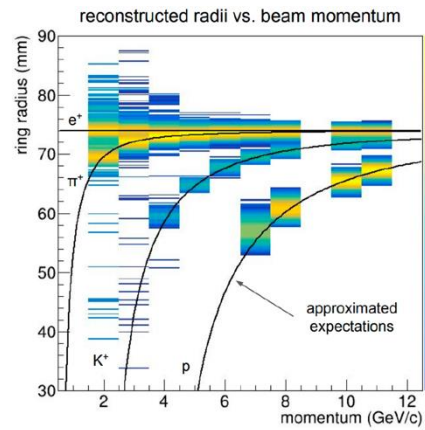
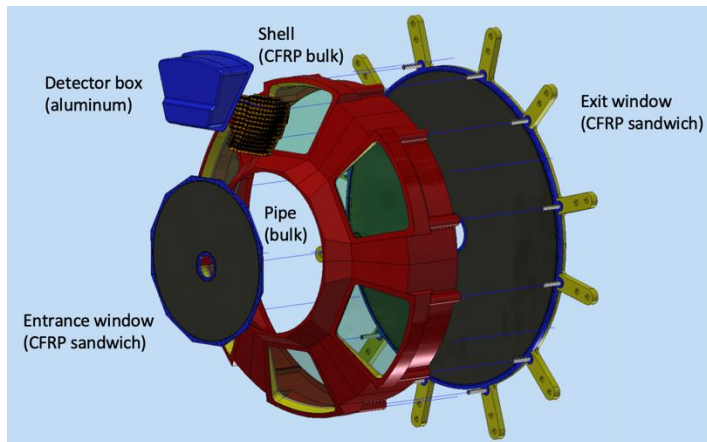


$$\mu(i, \theta) = \varepsilon(i) \frac{d\phi}{2\pi} e^{-\frac{(\theta-\theta_i)^2}{2\sigma^2}} \frac{d\theta}{\sqrt{2\pi}\sigma} e^{-\frac{(t(\theta)-t_i)^2}{2\sigma_t^2}} \frac{dt}{\sqrt{2\pi}\sigma_t}$$

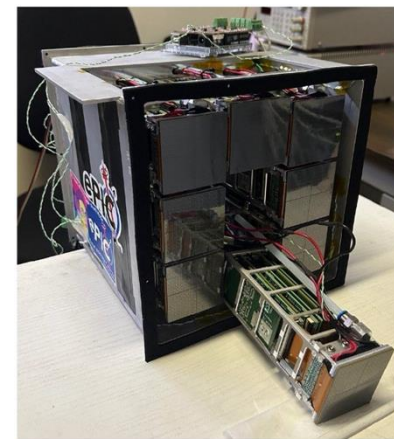
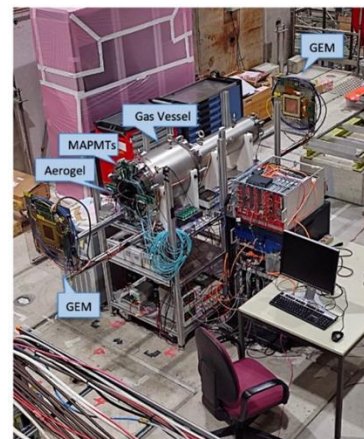
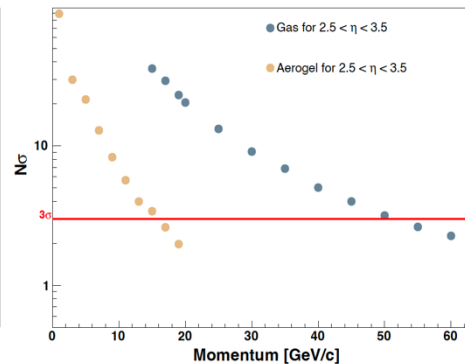
With negligible $B(i)$, at first order all the terms not depending on θ change the likelihood value but not the minimum location (best θ , or mass, estimator).

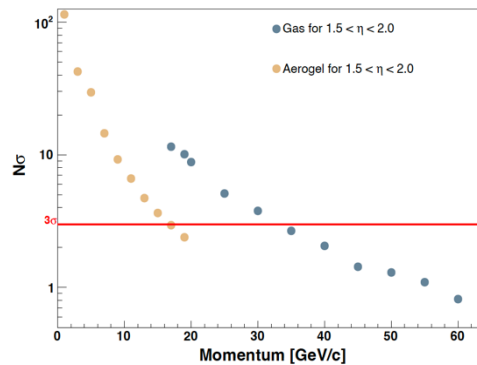
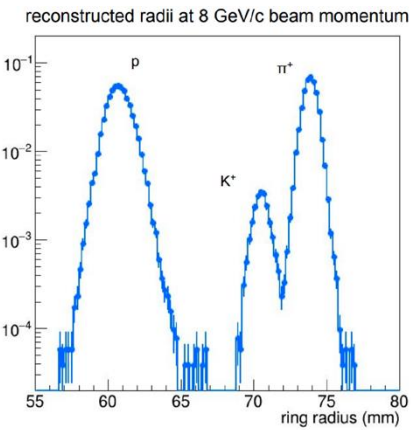
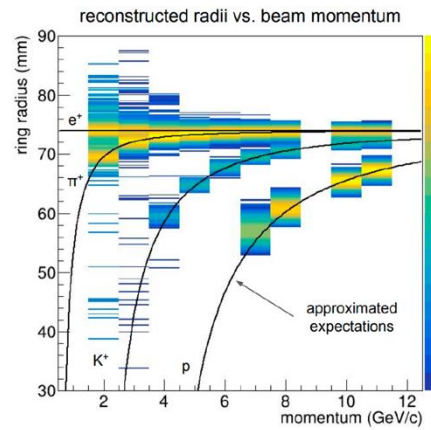
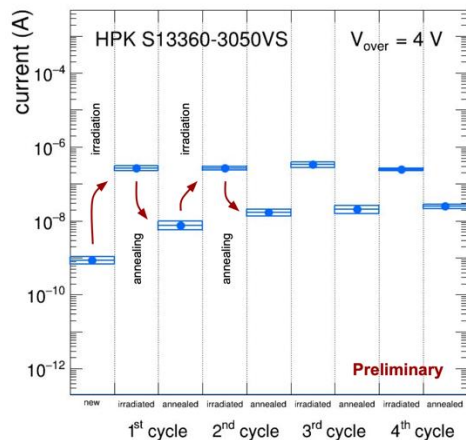
One might take the likelihood ratio with the model corresponding to the “observed measurement” in which all the hits are at the right (expected) angle

$$\mu'(i, \theta) = \varepsilon(i) \frac{d\phi}{2\pi} \underbrace{1}_{\theta=\theta_i} \frac{d\theta}{\sqrt{2\pi}\sigma} \underbrace{1}_{t=t_i} \frac{dt}{\sqrt{2\pi}\sigma_t}$$

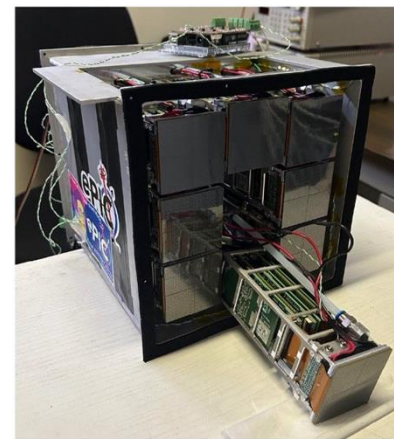
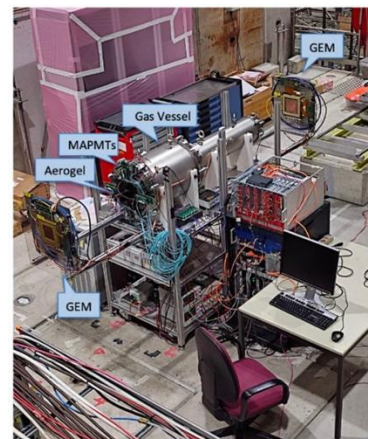
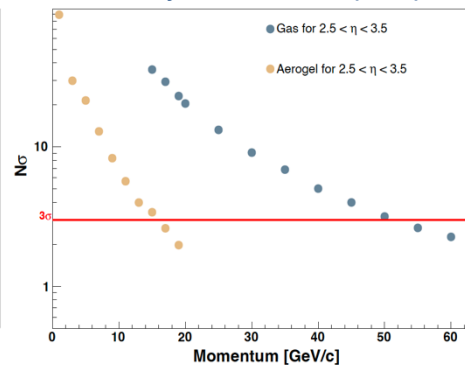


C. Chatterjee PoS DIS2024 (2025) 266

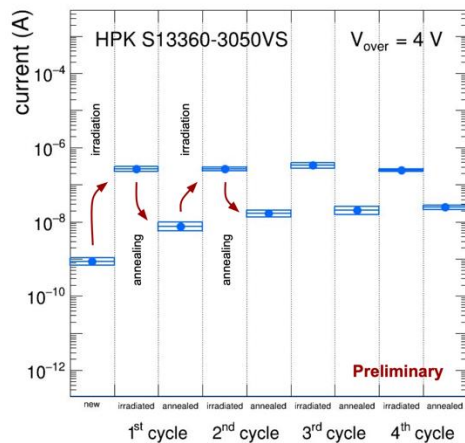




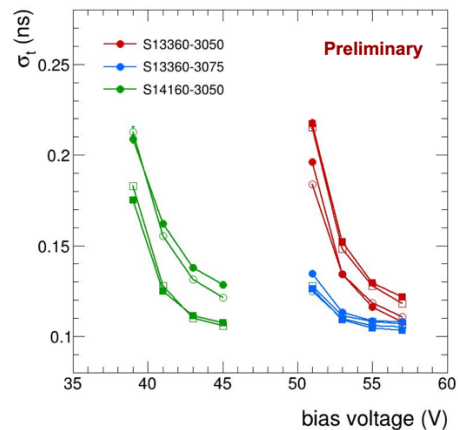
C. Chatterjee PoS DIS2024 (2025) 266



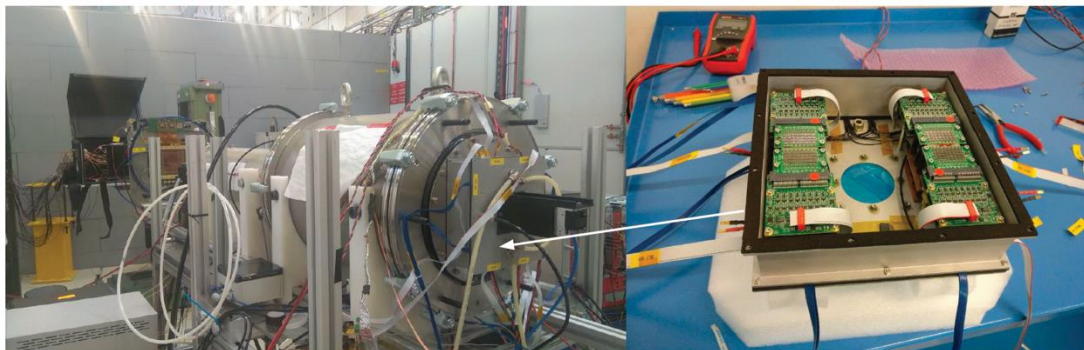
Annealing (high-T) cure after irradiation



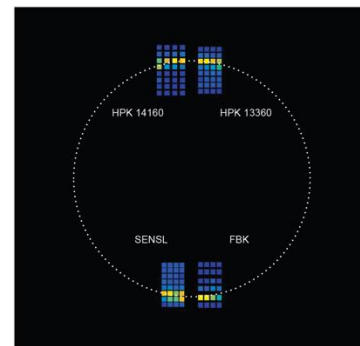
Time resolution



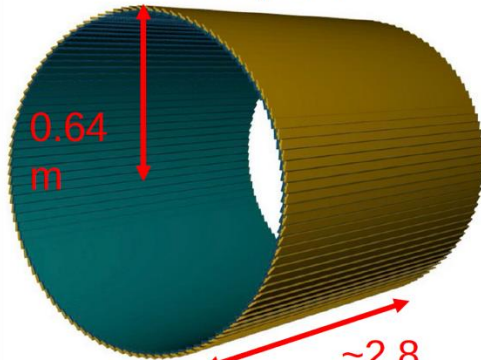
Validation at a beam beam



R. Preghenella PoS EPS-HEP (2023) 515

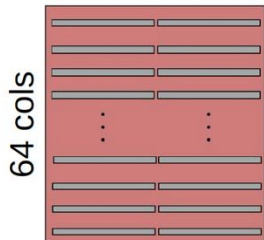


Barrel-TOF (BTOF)

$$-1.33 < \eta < 1.74$$


~2.8
m

2 rows

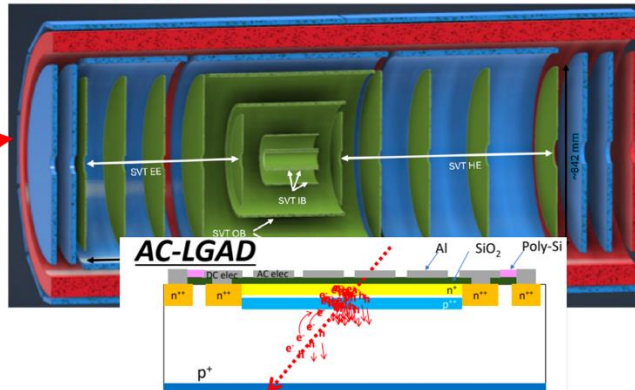


- **Strip-type for BTOF**

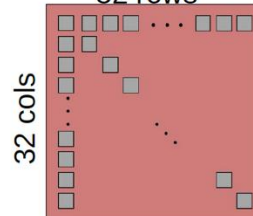
- ~12 m²
- ~2.4 M channels
- Strips: 0.05x10 mm²

Resolutions: $\sigma_t \sim 30\text{ps}$; $\sigma_x < 30\mu\text{m}$;

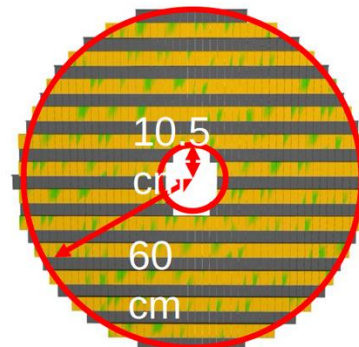
SVT; MPGDs; TOF (fiducial volume);



32 rows

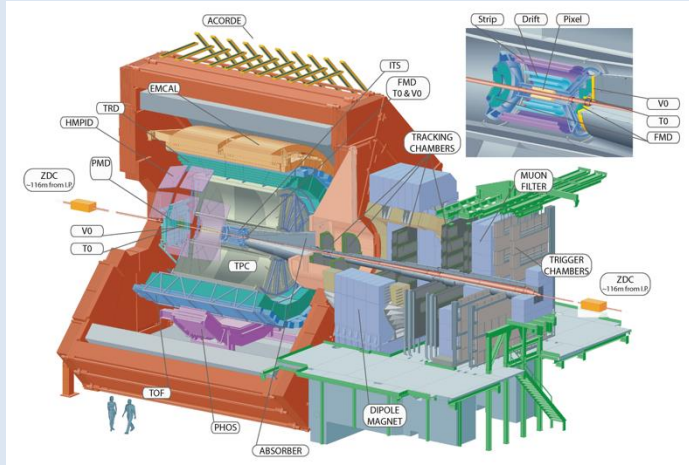


Forward-TOF (FTOF)

$$1.84 < \eta < 3.61$$


- Pixel-type for FTOF

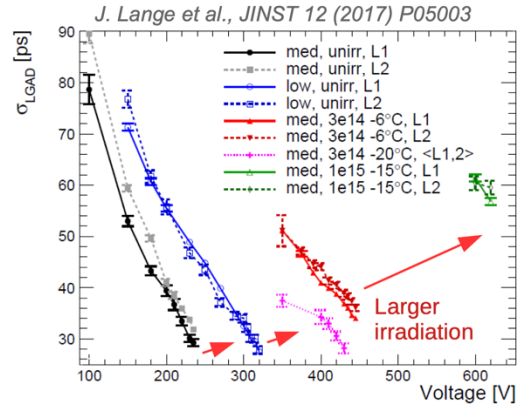
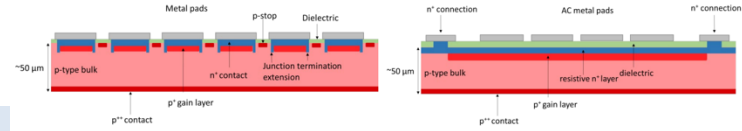
- ~1.1 m²
- ~3.6 M channels
- Pixel: 0.05x0.05mm²

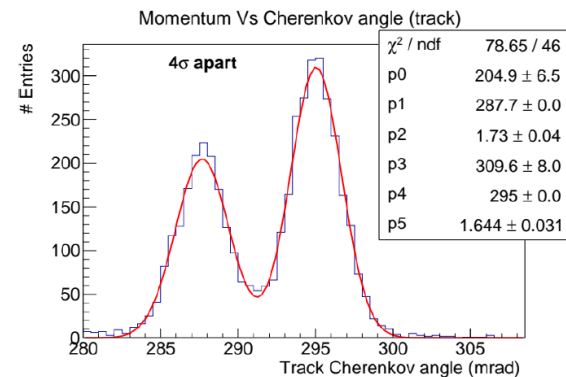
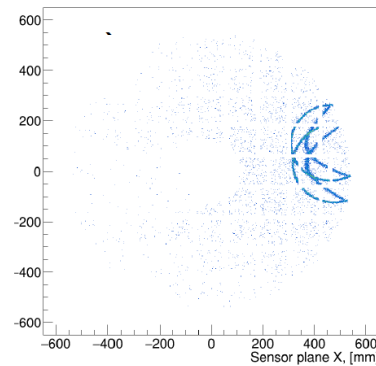
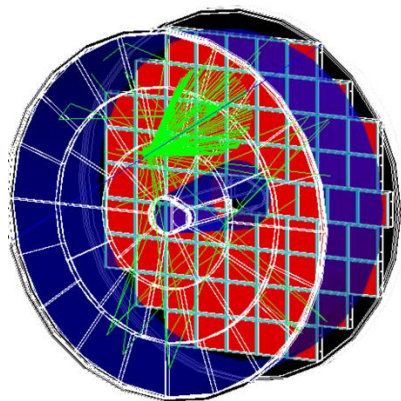


Silicon detectors – (AC)-LGAD

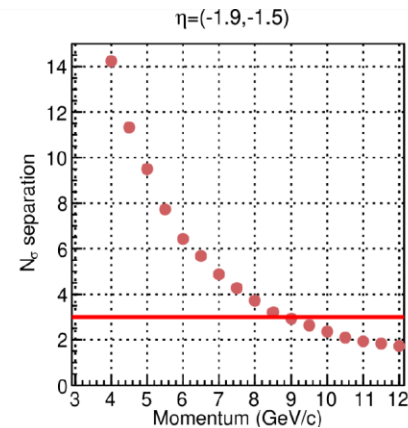
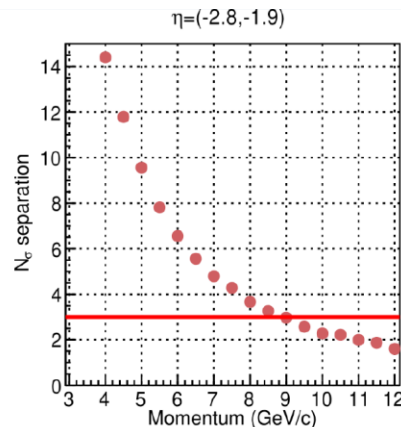
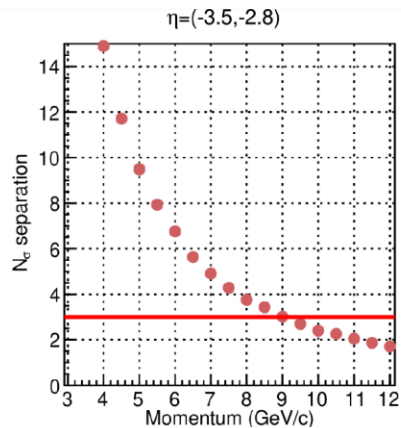
Silicon low-gain avalanche diode (LGAD)

- Thin sensors ($\sim 50\mu\text{m}$)
- Gain range 5-50, provided by the multiplication in the p+ multiplication layer
- Very good timing resolution 20-30ps
- Good radiation hardness

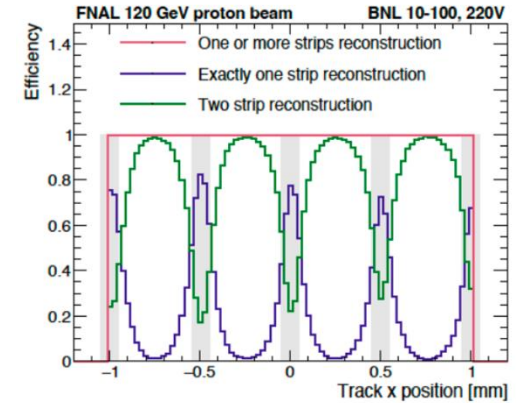
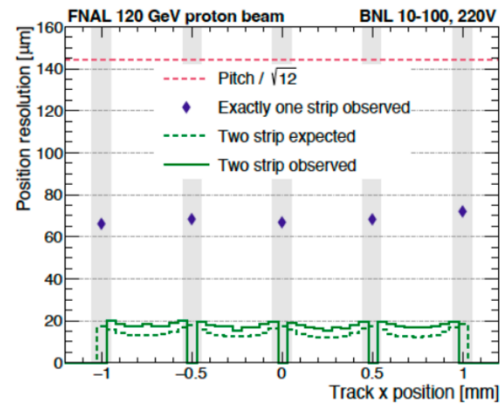
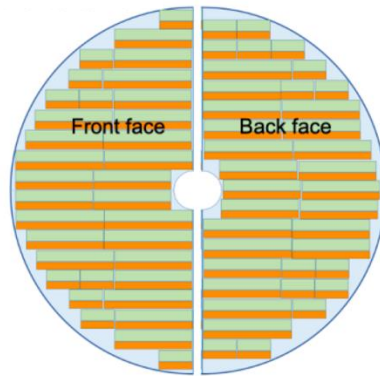




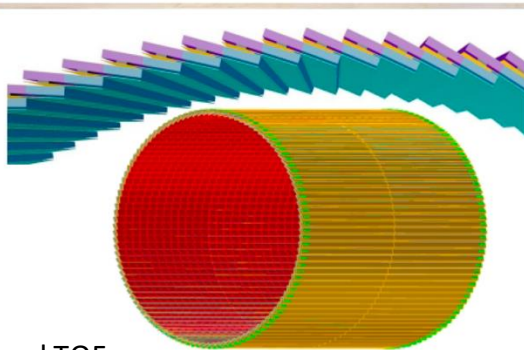
C. Chatterjee PoS
DIS2024 (2025) 266



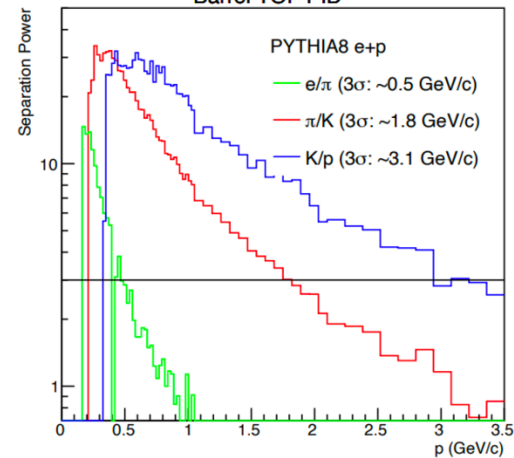
Forward TOF



Barrel TOF



Barrel TOF PID



C. Chatterjee PoS
DIS2024 (2025) 266