DIRC2019 Workshop

September / 11-13 / 2019

Schloss Rauischholzhausen

RICH detector development for hadron identification at (JL)EIC

design, prototyping and reconstruction algorithm

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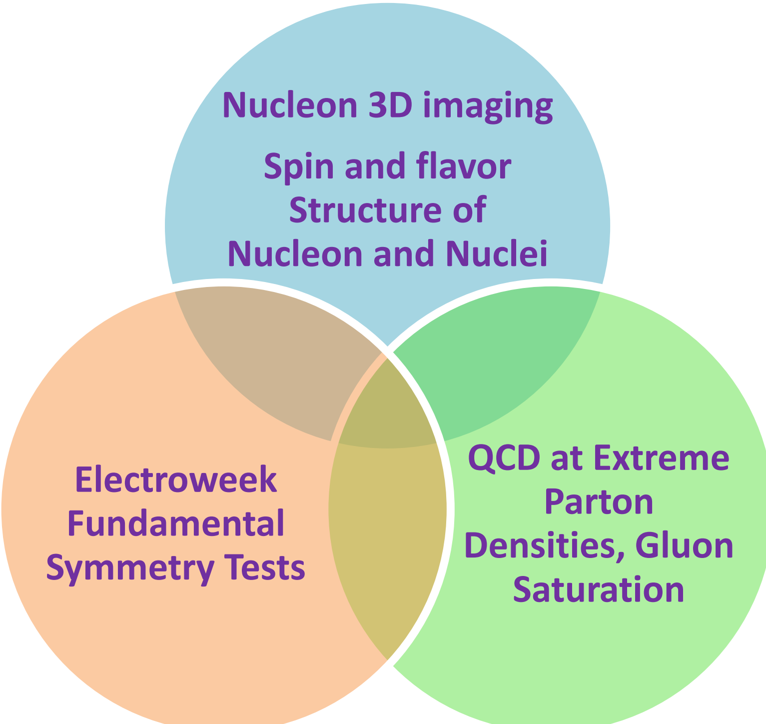
for the EIC/eRD14 - mRICH and dRICH groups

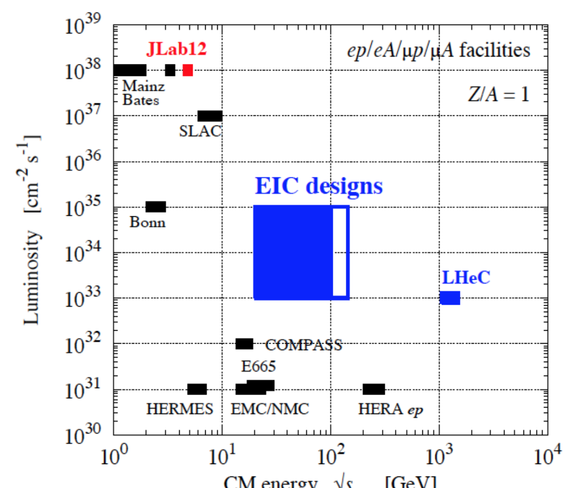
- **EIC and impact of Hadron PID**
- **mRICH design and prototype tests**
- **dRICH design, expected performance, prototyping**
- **dRICH event reconstruction**

EIC Physics, Specs and Needs

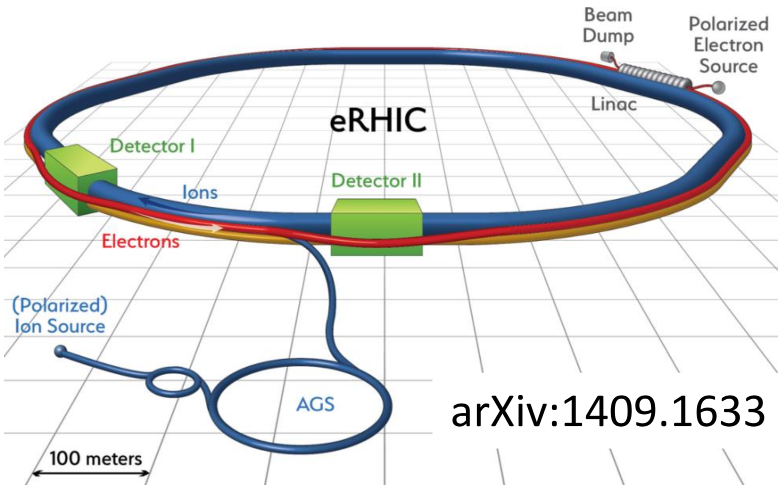


- **Electron (and positron) and ion beams from proton to Pb/U**
- **Polarization (e, p, d, ^{3}He) >70%, e-polarimetry precision down to 1% for e**
- **Luminosity up to ≈10^{34}/(cm s) (≈10^3 HERA)**
- **CM energy large and variable (20-100 GeV)**
- **Reach very low $x \approx 10^{-4}$**

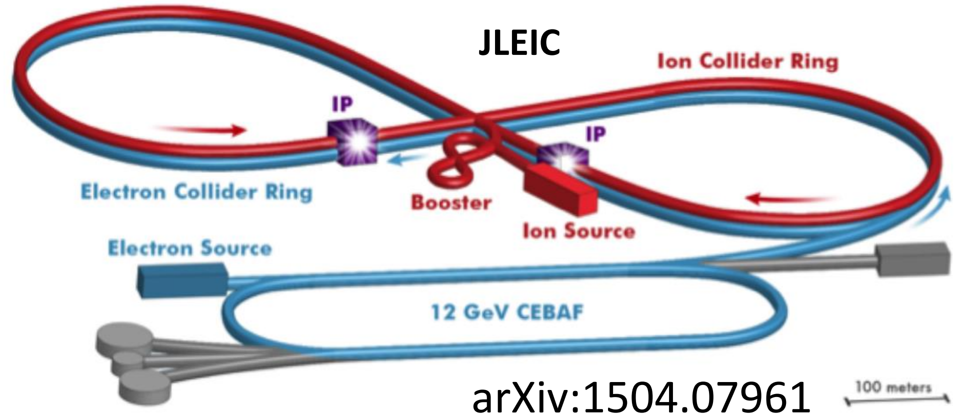
- **Inclusive, Seminclusive and Exclusive reactions**
- **Good Particle ID (for hadrons and leptons)**
- **Vertex Resolution down to 0.1 mm**
- **Momentum Resolution (down to ≈100 MeV ≈1%)**



Current **EIC** project options



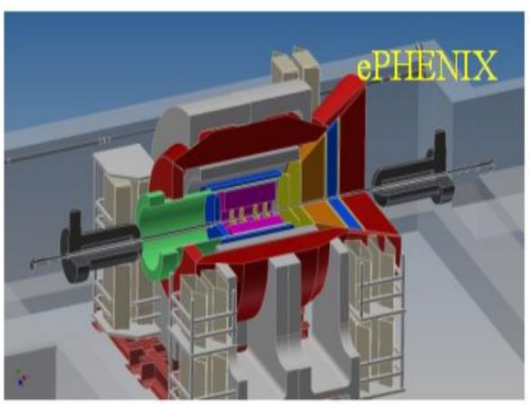
arXiv:1409.1633

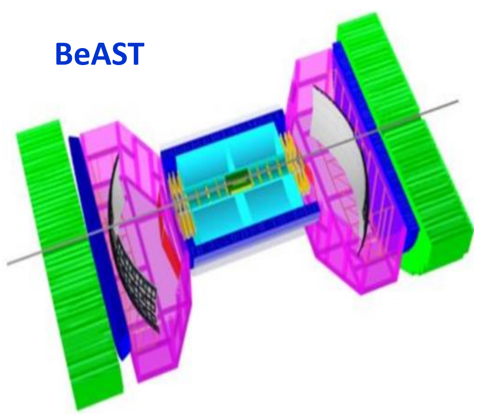


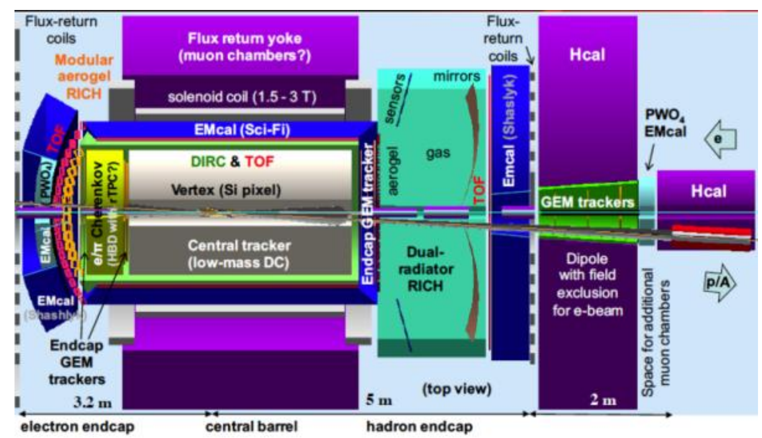
arXiv:1504.07961

Existing RHIC, 20 GeV e on 275 GeV p
Lumi 10^{33} /cm²/s

Existing CEBAF, 12 GeV e on 100→140 GeV p,
Lumi 10^{34} /cm²/s, 8-shape optimized for high beam polarization (net spin precession is 0)





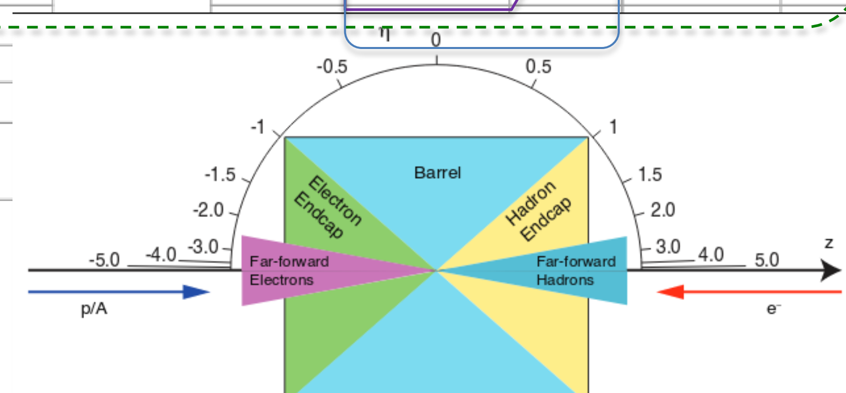


Three central spectrometer options: key aspects are basically very similar

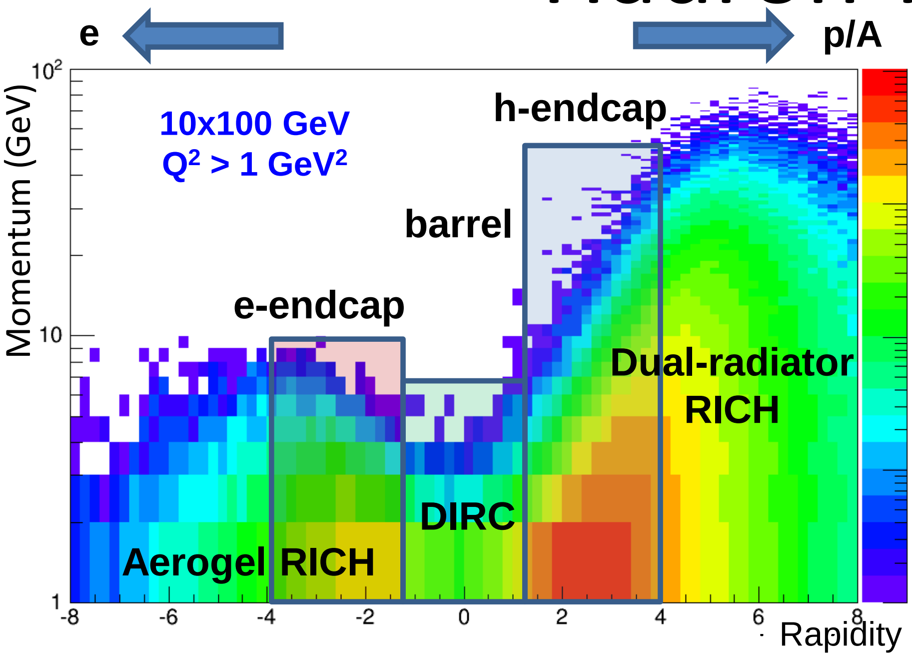
Requirements for EIC - Detectors

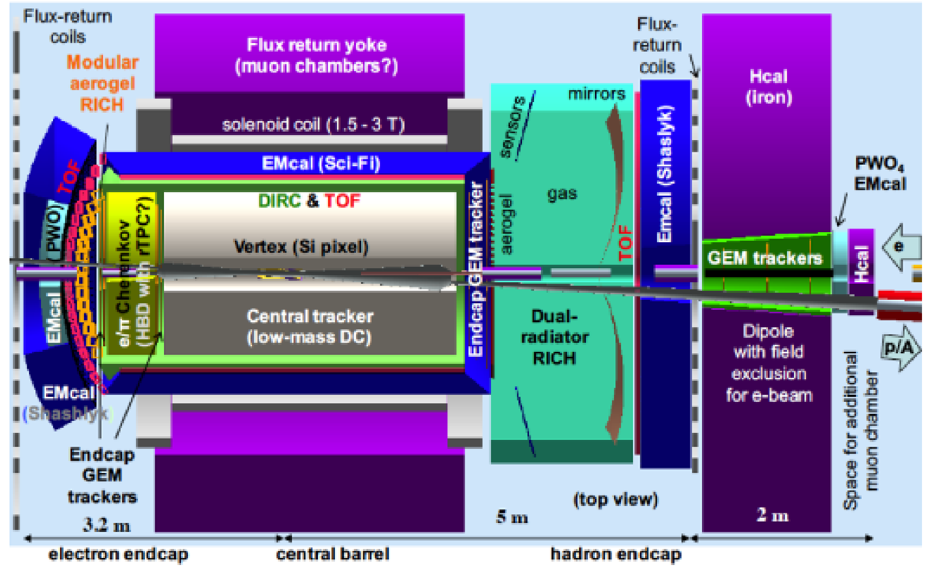
η	Nomenclature			Tracking			Electrons		π/K/p PID		HCAL	Muons
				Resolution	Allowed X/X_0	Si-Vertex	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q^2 tagger	$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV²								
...												
-4.5 — -4.0			Instrumentation to separate charged particles from photons				2%/√E					
-4.0 — -3.5												
-3.5 — -3.0		Central Detector	Backwards Detectors	$\sigma_p/p \sim 0.1\% \times p+2.0\%$	~5% or less	TBD		π suppression up to 1:10⁴		≥3σ	~50%/√E	TBD
-3.0 — -2.5									≤ 7 GeV/c			
-2.5 — -2.0				$\sigma_p/p \sim 0.05\% \times p+1.0\%$								
-2.0 — -1.5							7%/√E					
-1.5 — -1.0												
-1.0 — -0.5			Barrel	$\sigma_p/p \sim 0.05\% \times p+0.5\%$		$\sigma_{xyz} \sim 20$ µm, $d_0(z) \sim d_0(r\phi) \sim 20/p_T$ GeV µm + 5 µm	(10-12)%/√E		≤ 5 GeV/c		TBD	
-0.5 — 0.0												
0.0 — 0.5												
0.5 — 1.0												
1.0 — 1.5			Forward Detectors	$\sigma_p/p \sim 0.05\% \times p+1.0\%$		TBD			≤ 8 GeV/c		~50%/√E	
1.5 — 2.0												
2.0 — 2.5									≤ 20 GeV/c			
2.5 — 3.0				$\sigma_p/p \sim 0.1\% \times p+2.0\%$								
3.0 — 3.5									≤ 45 GeV/c			
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from photons									
4.0 — 4.5												
...												
> 6.2			Proton Spectrometer	$\sigma_{intrinsic}(\|t\|)/\|t\| < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c								

PID detectors have to work in magnetic field and at relatively high irradiation conditions



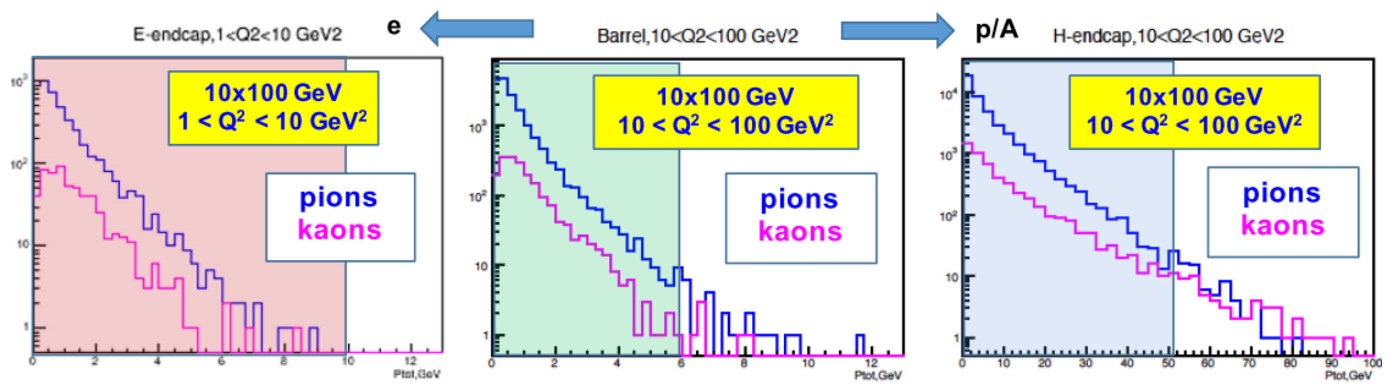
Hadron-ID in JLEIC





Hadron ID beneficial for many physics cases, expecially in the high-momentum tails:

- SIDIS
- 3D tomography
- Diffraction
- Gluon saturation
- Open charm



→ eRD14 offers an integrated PID program at EIC

eRD14 (PID) consortium in EIC

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1. **Design and develop PID detectors covering the full phase space required in EIC**
2. **R&D on cost-effective sensor and electronics solutions**
3. **Maximize synergies and minimize costs of R&D**

h-endcap: A RICH with two radiators (gas + aerogel) is needed for
π/K separation up to ~50 GeV/c — **dRICH**

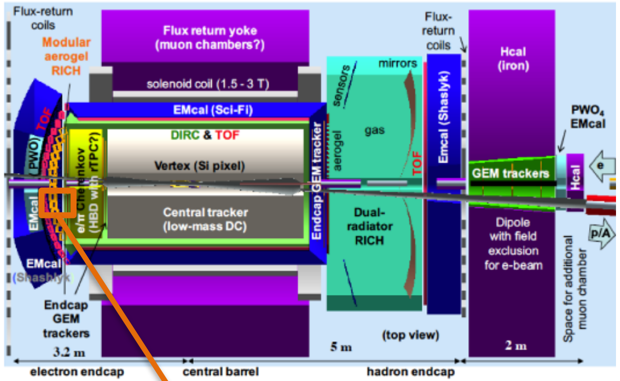
e-endcap: A compact aerogel RICH which can be projective
π/K separation up to ~10 GeV/c — **mRICH**

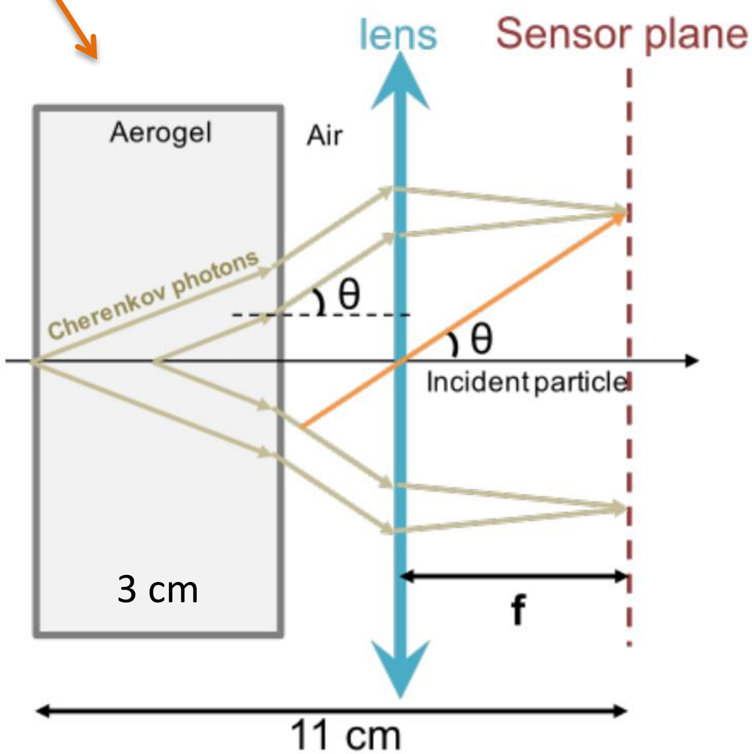
barrel: A high-performance DIRC provides a compact and cost-effective way to cover the area.
π/K separation up to ~6-7 GeV/c — **DIRC**

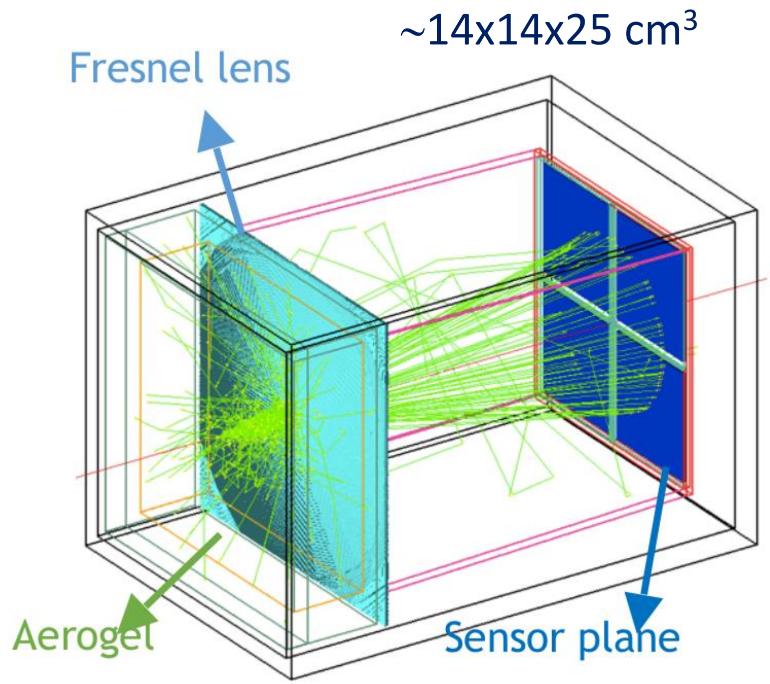
Greg Kalicy talk

mRICH in e-endcap

Designed for π/K separation from 3 to 10 GeV/c and e/π up to 2 GeV/c







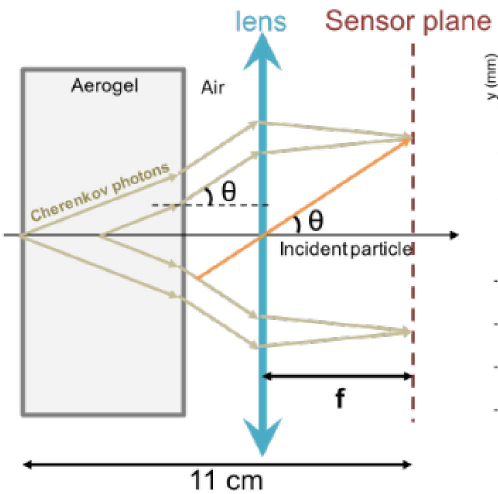
Geant4 Simulation

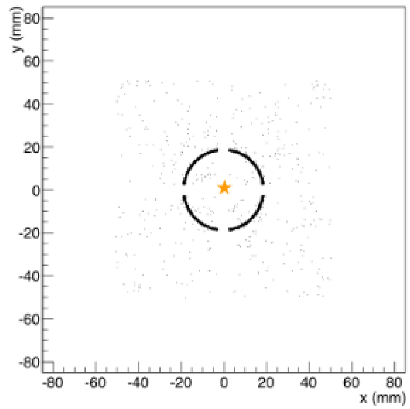
Modular, compact and flexible geometry,
focusing optics by tiny Fresnel lens, sensor spatial resolution ≤3 mm

mRICH optics

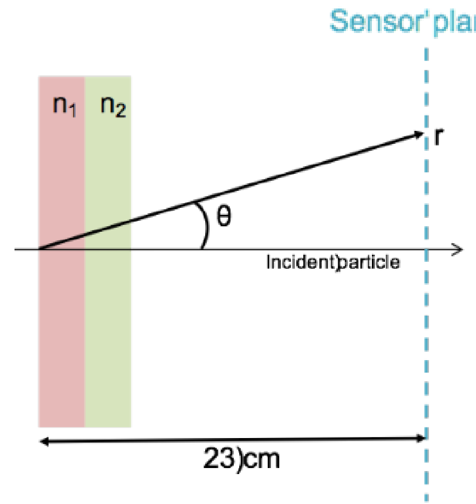
9 GeV/c pions

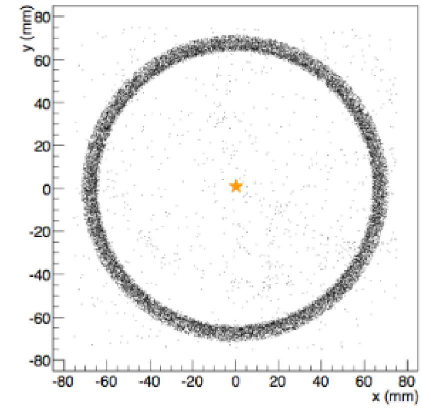
focusing mRICH



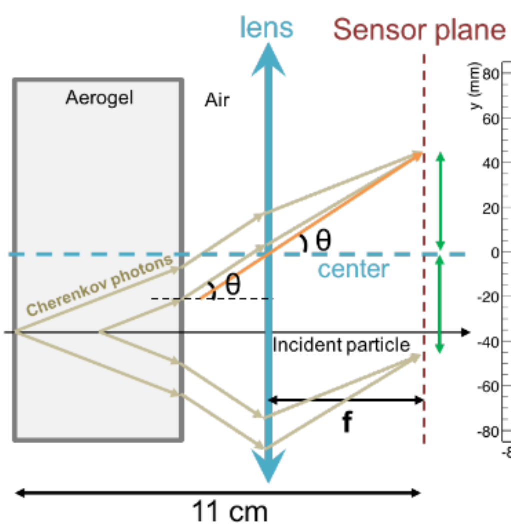


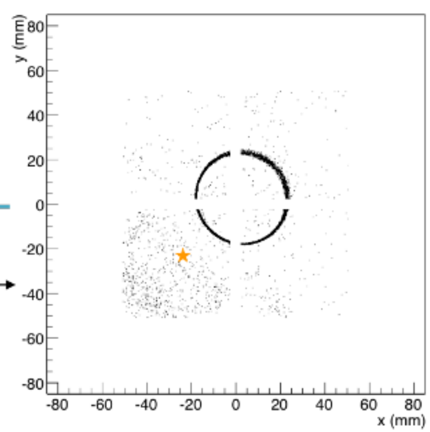
2 layers proximity RICH (Belle2)

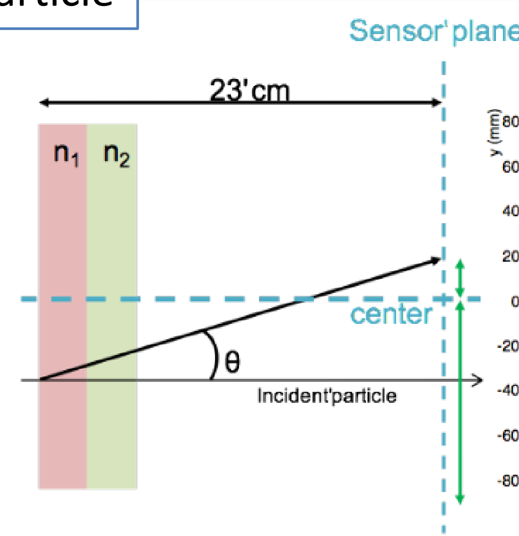


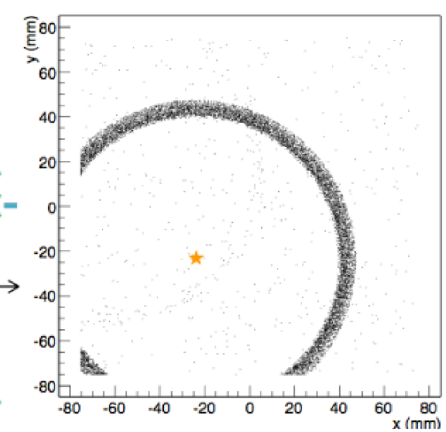


Off axis particle



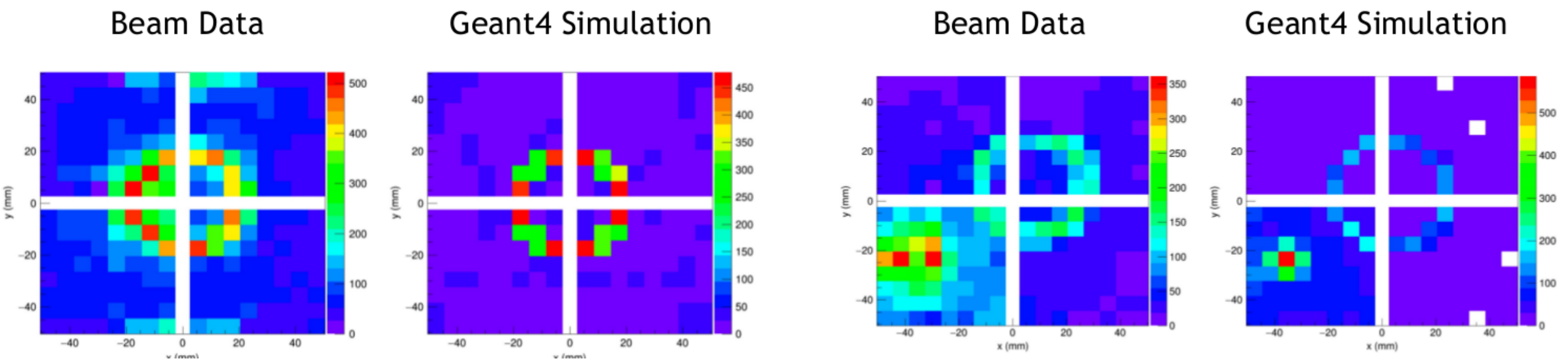






mRICH beam tests @ FERMILAB

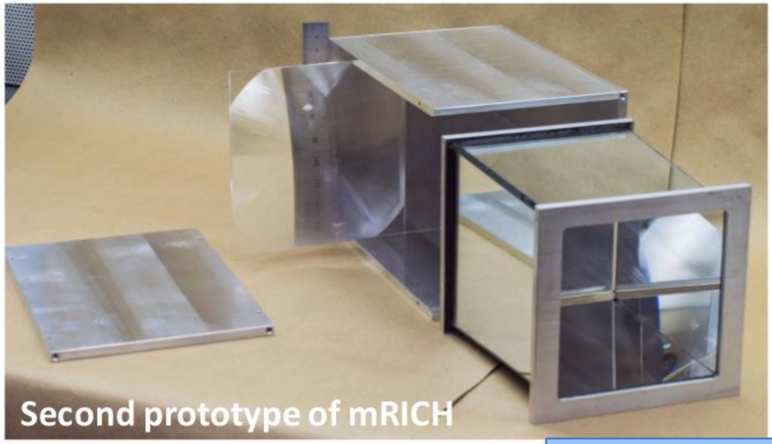
- Working principle proved in 2016/1st beam test



- PID performance evaluation in 2018/2nd beam test

2nd prototype main improvements:

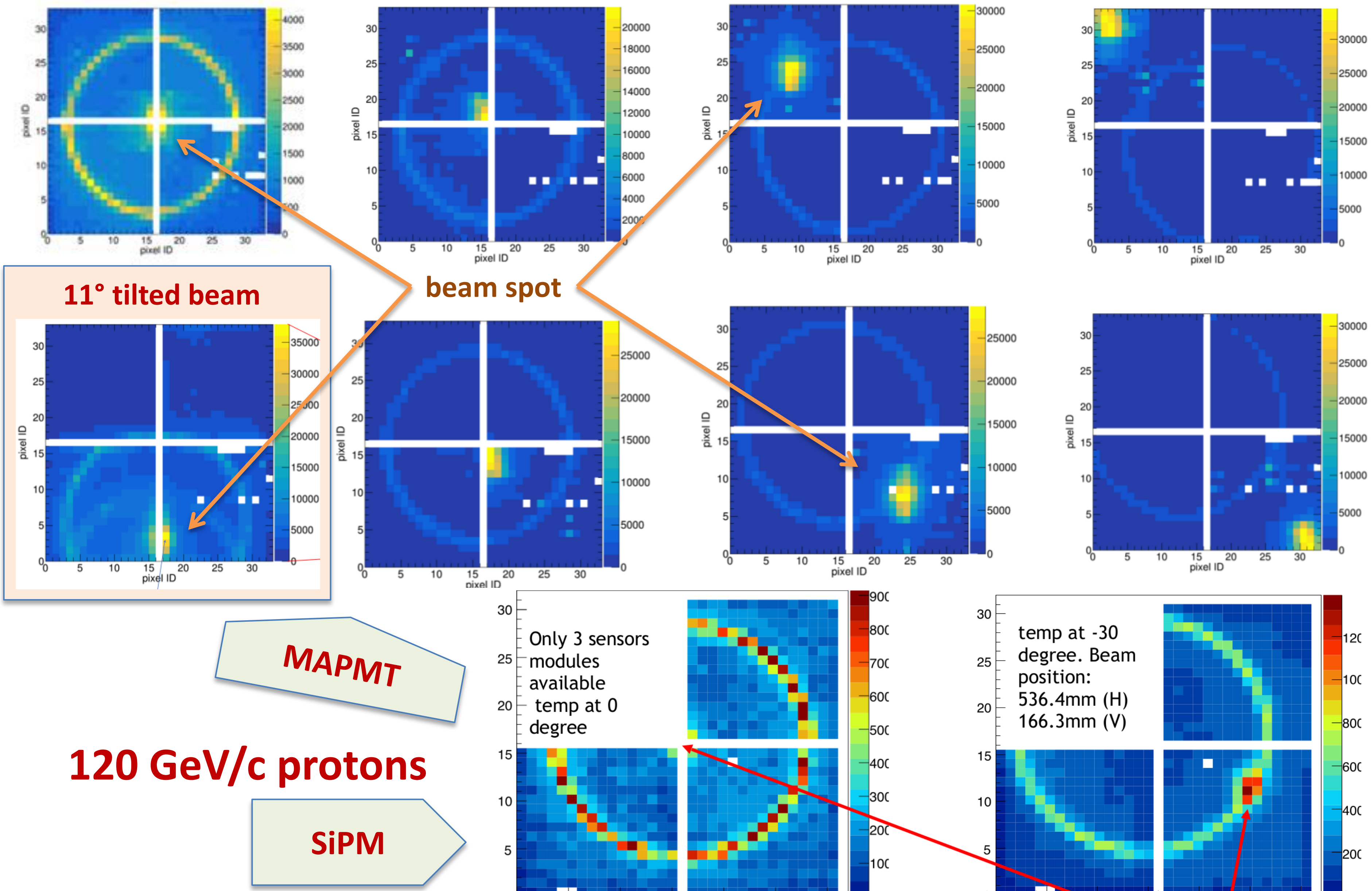
- Longer focal length (6 inches)
- Smaller (3 mm) sensor pixel size
- Tested both MAPMT H13700 an SiPM sensors



(Readout electronics: MAROC based readout system from CLAS12/RICH)

Marco Contalbrigo talk

mRICH 2nd test: beam position scan



mRICH 2nd test: Offline analysis

Preliminary results (from MAPMTs configuration) give:

# photoelectrons on ring (signal)	≈ 8.8
# photoelectrons off ring (background)	≈ 4.8
angular resolution (sigma_theta)	≈ 5.9 mrad

Likely affected by:

- sub-optimal internal alignment and positioning
- partial aerogel tiles characterization

Comparison with simulations in progress

The mRICH group enjoing the online results

Photosensors need to be radiation hardness and able to work in magnetic field with potentially different orientations and intensities;
candidates: SiPM, PMT-MCP/LAPPD

dRICH in JLEIC h-endcap

Aerogel

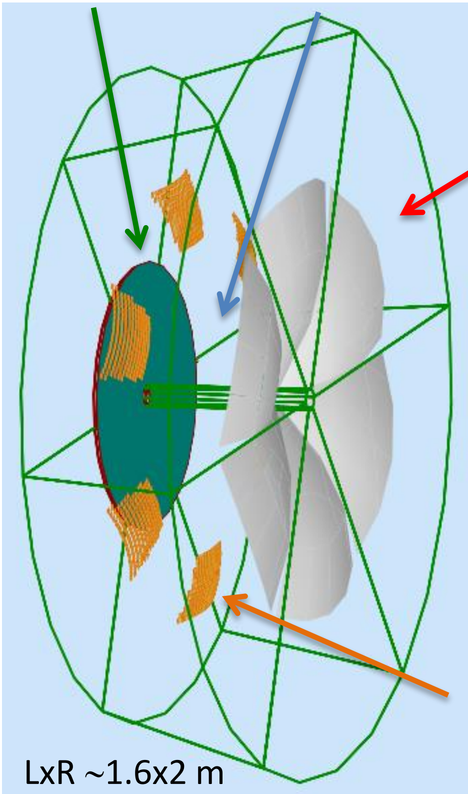
Gas

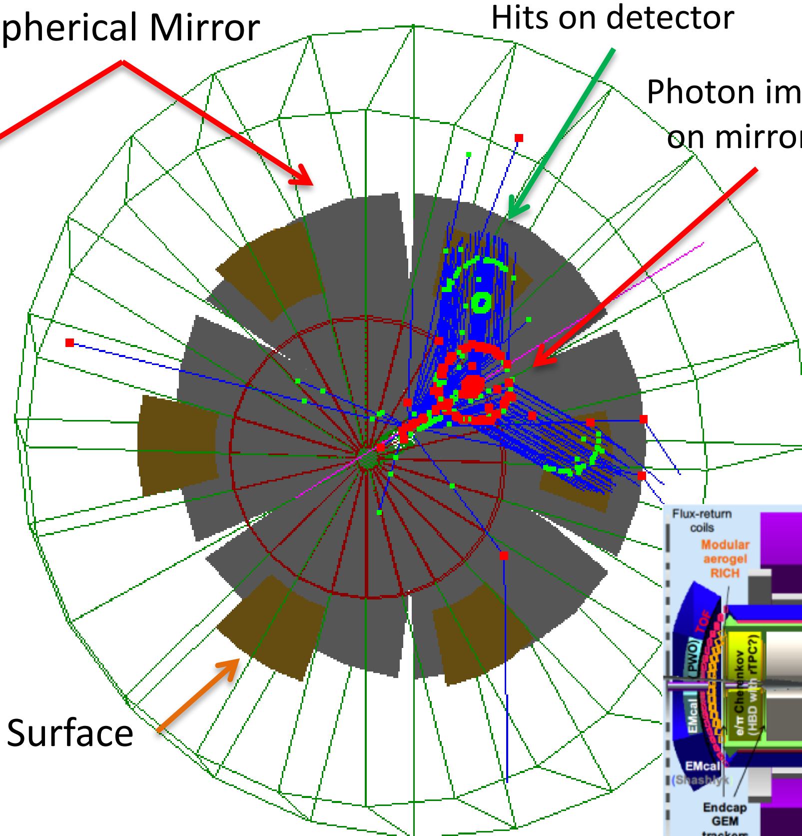
Spherical Mirror

Hits on detector

Photon impact on mirror(s)

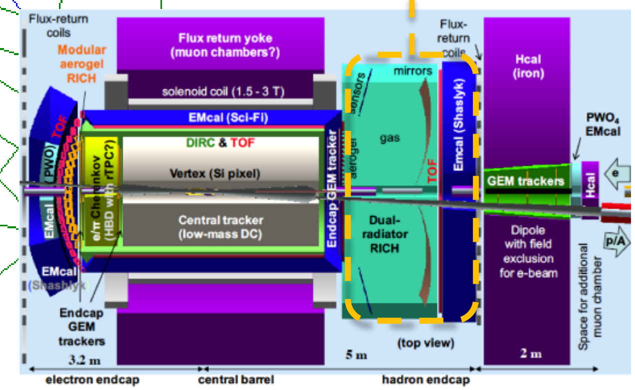
Precursors: HERMES and LHCB RICHes





Sensor Surface

LxR ~1.6x2 m



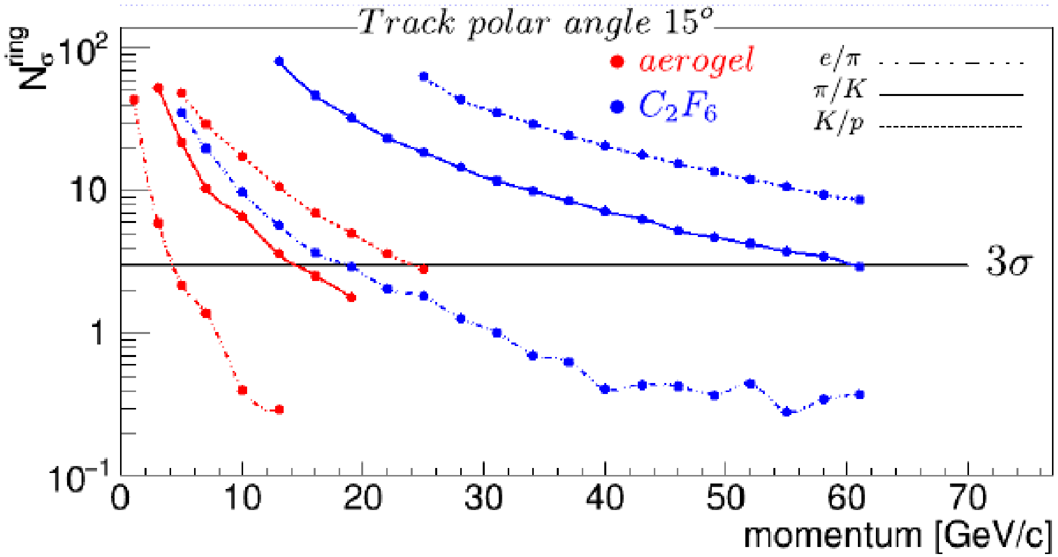
- Radiators: Aerogel (4 cm, $n_{(400nm)}$~1.02) + 3 mm acrylic filter, Gas (1.6 m, n_{C2F6}~1.0008)
- 6 Identical Open Sectors (Petals):
  - Large Focusing Mirror with R ~2.9 m
  - Optical sensor elements: ~4500 cm^2/sector, 3 mm pixel size, UV sensitive, out of charged particles acceptance

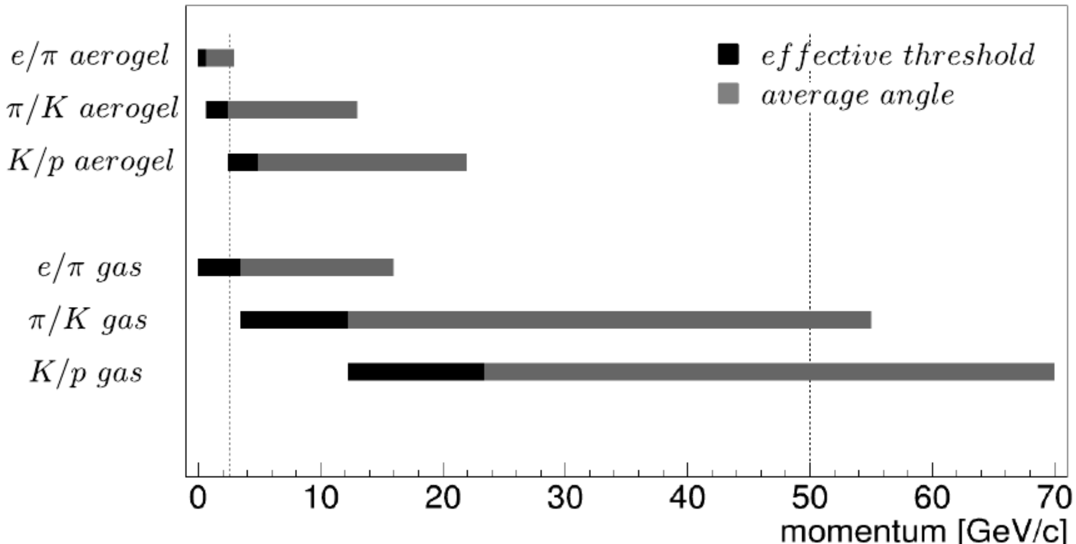
Advantages:

- Full momentum, continuous coverage
- Relatively simple geometry/optics
- Expected to be Cost Effective (respect to 2 x detectors solution)

dRICH baseline MC performance

- Montecarlo: GEMC (Geant4)
- Aerogel Optical properties from CLAS12 RICH data, scaled to 1.02
- Acrylic Filter (<300nm) after the aerogel to minimize Rayleigh
- Gas number of photons normalized by 0.7 factor respect to literature
- Include 3T central magnetic field
- Assumed PMT H12700 (200-500 nm)
- Mirrors reflectivity from CLAS12
- Cherenkov Angle reconstruction based on Inverse Ray Tracing





Hadron identification (π/K/p, better than 3 sigma apart)
from 3 to ~50 GeV/c for π/K and **up to ~15 GeV/c for e/π**

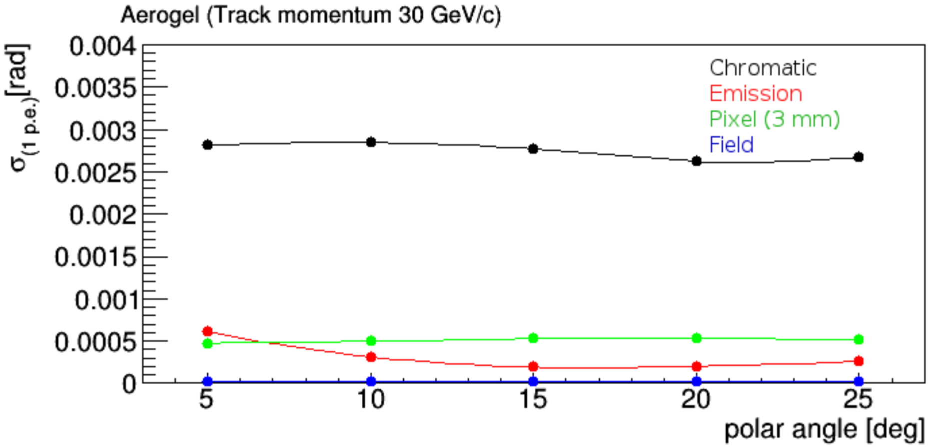
Cristiano Fanelli talk for further optimizations

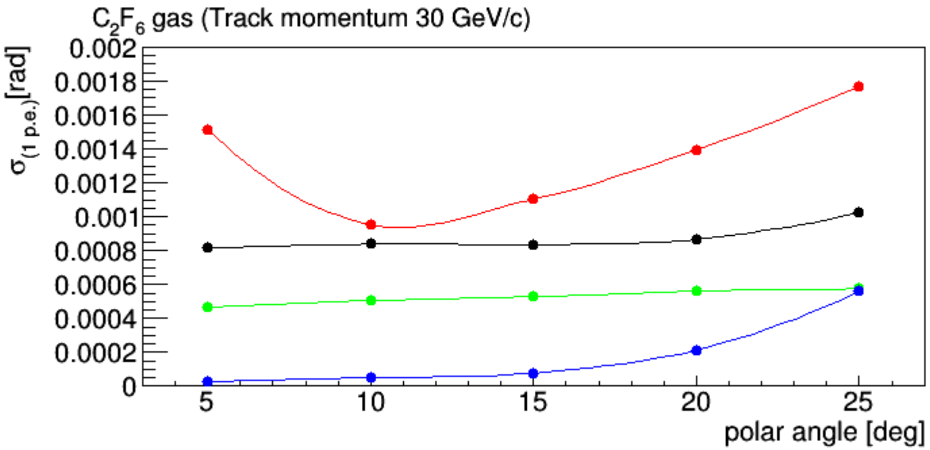
dRICH: Angular resolution

All the main contributions to the Cherenkov angle resolution have been evaluated by MC

Largest effects from

- Aerogel chromatic
(variation of refractive index with wavelength)
- Gas emission
(unknow emission position of the photons and focusing optics)





dRICH demands for excellent and stable performance from aerogel (and gas) radiator(s)!

Toward dRICH prototype

Goals:

- **Validate main design choices**
- **Consolidate the estimated performances**
- **Identify potential technical issues that are hard to model**
- **Evaluate alternatives to reduce costs and risks**

First phase (use «well known» MAPMTs):

- Measure realistic number of direct Cherenkov photons coming out from both radiators
- Evaluate quality of aerogel in terms of Cherenkov photons (e.g. chromatic dispersion of refractive index)
- Estimate other effects (e.g. impact of scintillation photons in Freon gases)

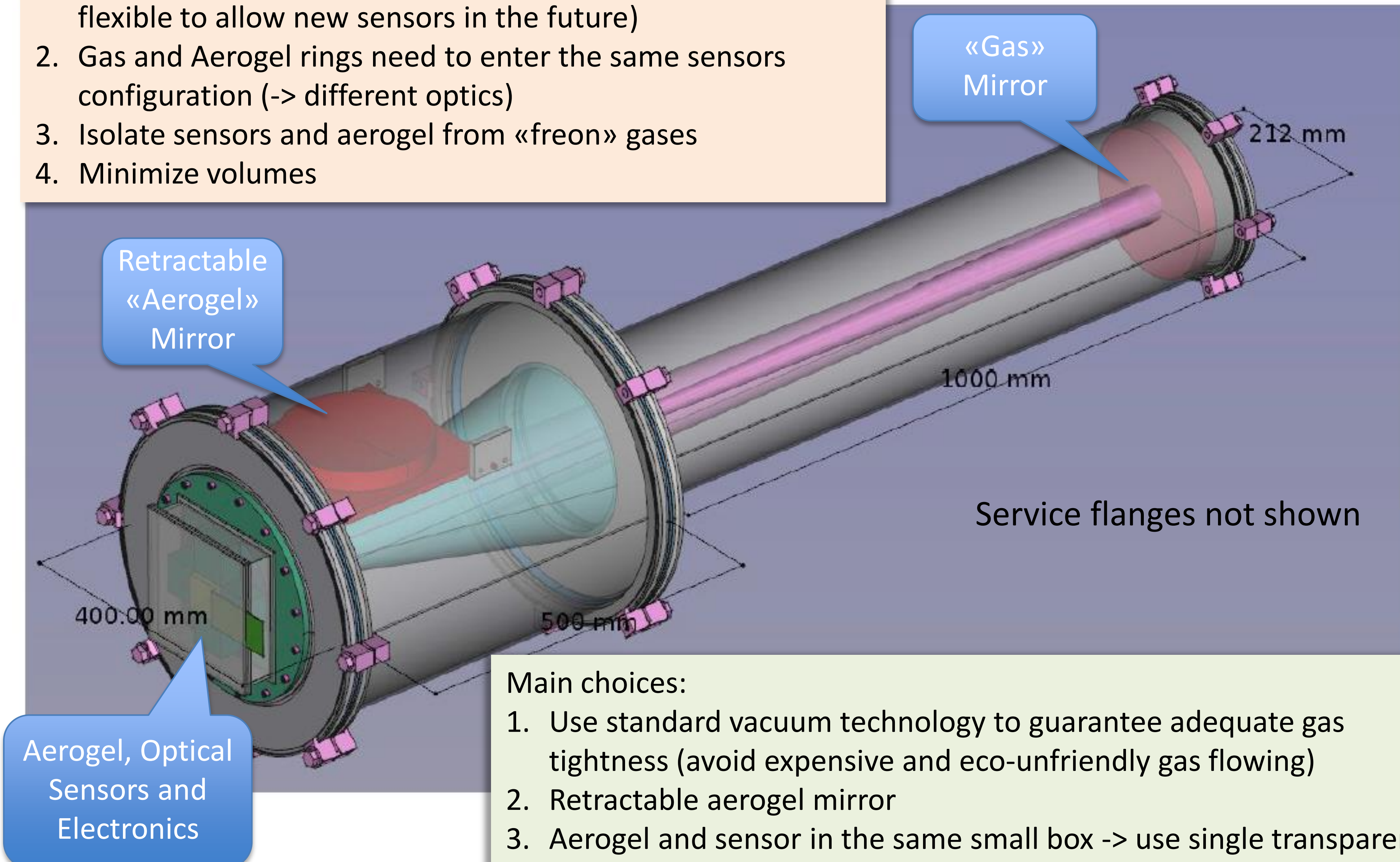
Second phase:

- Test promising alternatives (e.g. SiPM vs MCP/LPPD, new electronics …)
- Test implementation details (e.g. sensor-gas interface, mirror alternatives …)

dRICH Prototype Consolidated Design

Driving items:

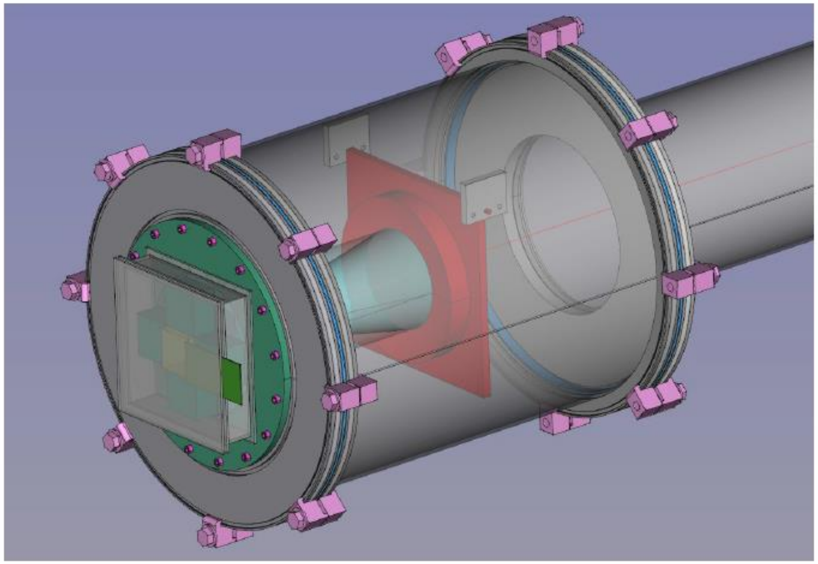
1. Reuse available sensors and electronics as in mRICH (but be flexible to allow new sensors in the future)
2. Gas and Aerogel rings need to enter the same sensors configuration (-> different optics)
3. Isolate sensors and aerogel from «freon» gases
4. Minimize volumes

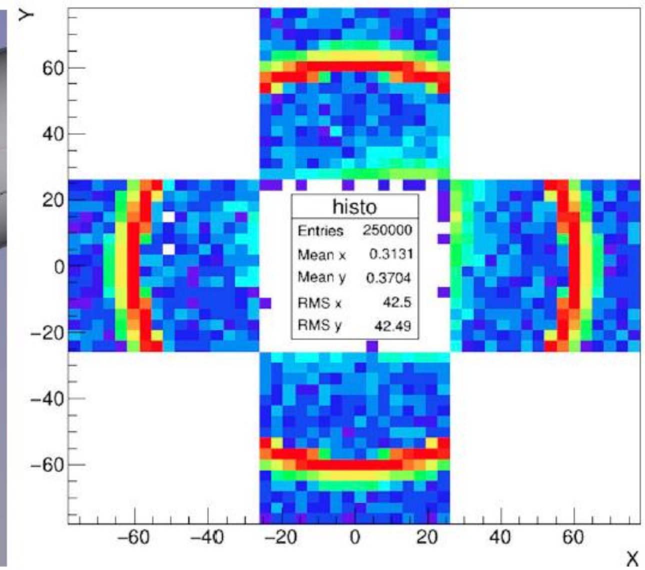


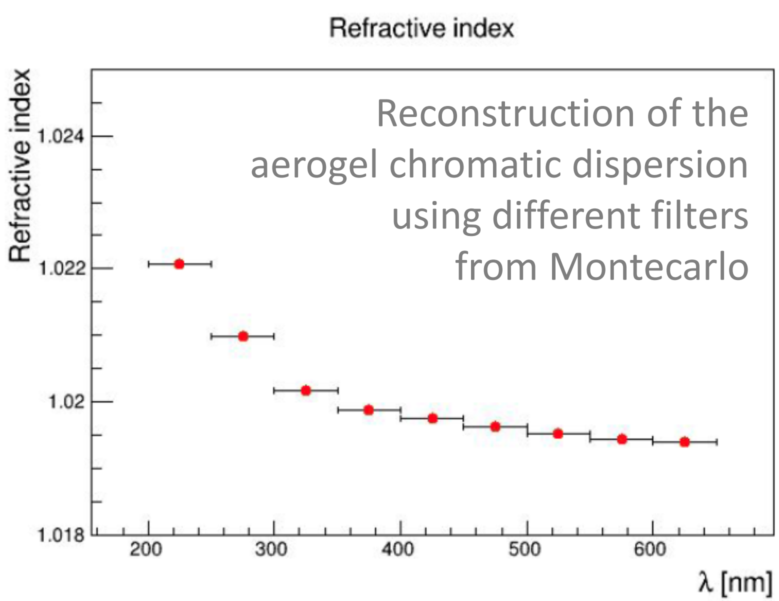
Main choices:

1. Use standard vacuum technology to guarantee adequate gas tightness (avoid expensive and eco-unfriendly gas flowing)
2. Retractable aerogel mirror
3. Aerogel and sensor in the same small box -> use single transparent window (compatible with Fermilab test beam specificities)

dRICH Consolidate Prototype “Aerogel Mode”





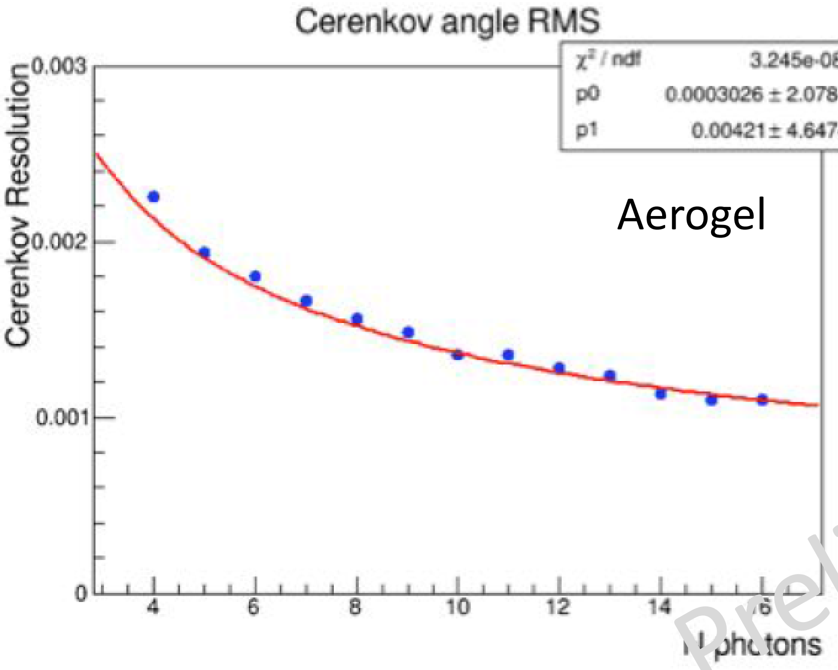


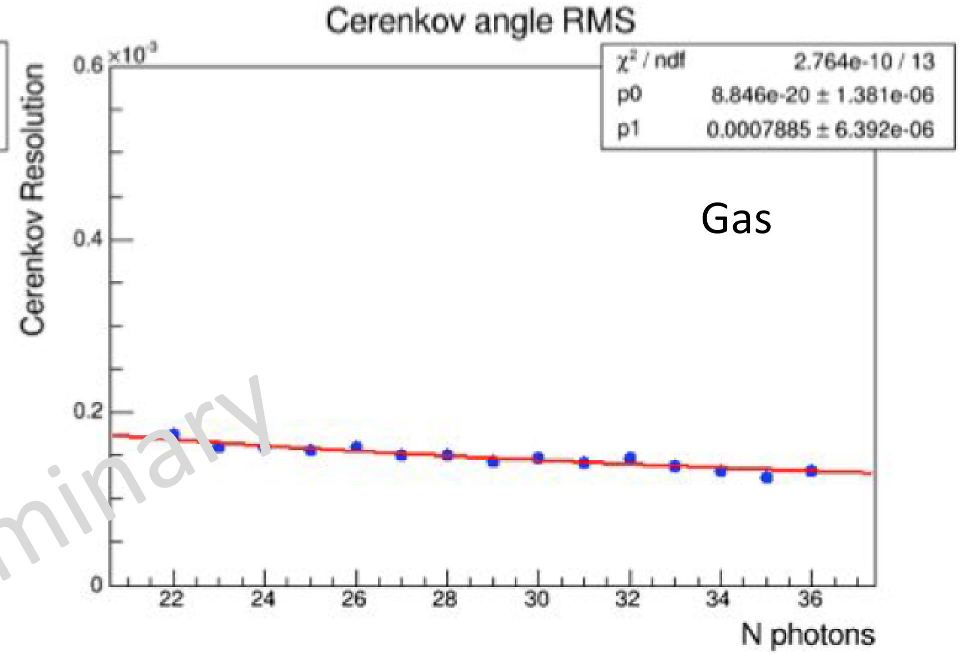
- Gas optics similar to dRICH model
- Aerogel optics is pretty different than in dRICH -> different contributions to σ_{ϑ}

Measurement of the aerogel chromatic dispersion and UV filter optimization feasible

dRICH Consolidated Prototype Expected Performance

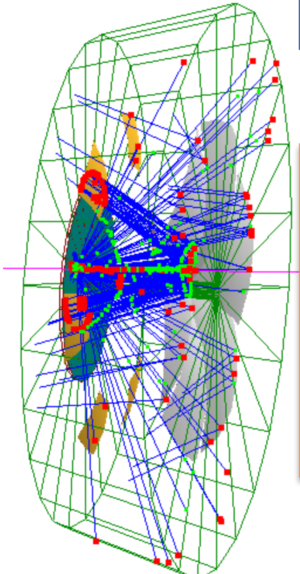
Montecarlo simulation





1 p.e. Error (mrad)	Aerogel	C_2F_6 Gas
Chromatic error	3.2 (2.9)	0.51 (0.8)
Emission	0.5 (0.5)	0.5 (1.2)
Pixel	2.5 (0.5)	0.42 (0.5)

Chormatic and pixel erros are comparable in prototype



Inverse Ray-Tracing

IRT Event Based Reconstruction

Nt : tracks (+ background «dummy track»)

Nh : photon hits (photoelectrons)

Nr : radiators (aerogel and gas)

Np : potential particle types (e,pi,K,p)

~40% of PYTHIA events have multiple tracks in dRICH
~50% of them overlapping rings;
Simple track based IRT → π/K contamination>10%

Global naive «brute force» approach: explore all possible combinations of

Track ∈ Particle type hypothesis: Np^Nt

Photon hits ∈ (Track ⊗ Radiator + Background) : **(Nt*Nr+1)^Nh**

Each combination has an associated Likelihood; take the maximum

Our approach:

- Determine (by IRT) the potential emission angles corresponding to each photon hit
- Split the problem in two steps (for each event):
  1) Sequential hits association to tracks/radiators using a first likelihood L1 (combinations drop to **(Nt*Nr+1)*Nh**)
  2) Once all hits are associated, estimate a global Likelihood (L2) for each (track ∈ particle) combination; choose the combination with max L2

Example: event with 2 tracks and 15 hits

Brute Force: up to **~488 billion** combinations
Our approach: **1200** combinations

Detailed analysis on L1

$$L_1(p,t,r;h) \equiv G(\theta_h^{t,r}|\theta^{c,r},\sigma_{\theta^{c,r}}) \cdot P_S(N_a^{c,r}+1;N^{c,r})$$

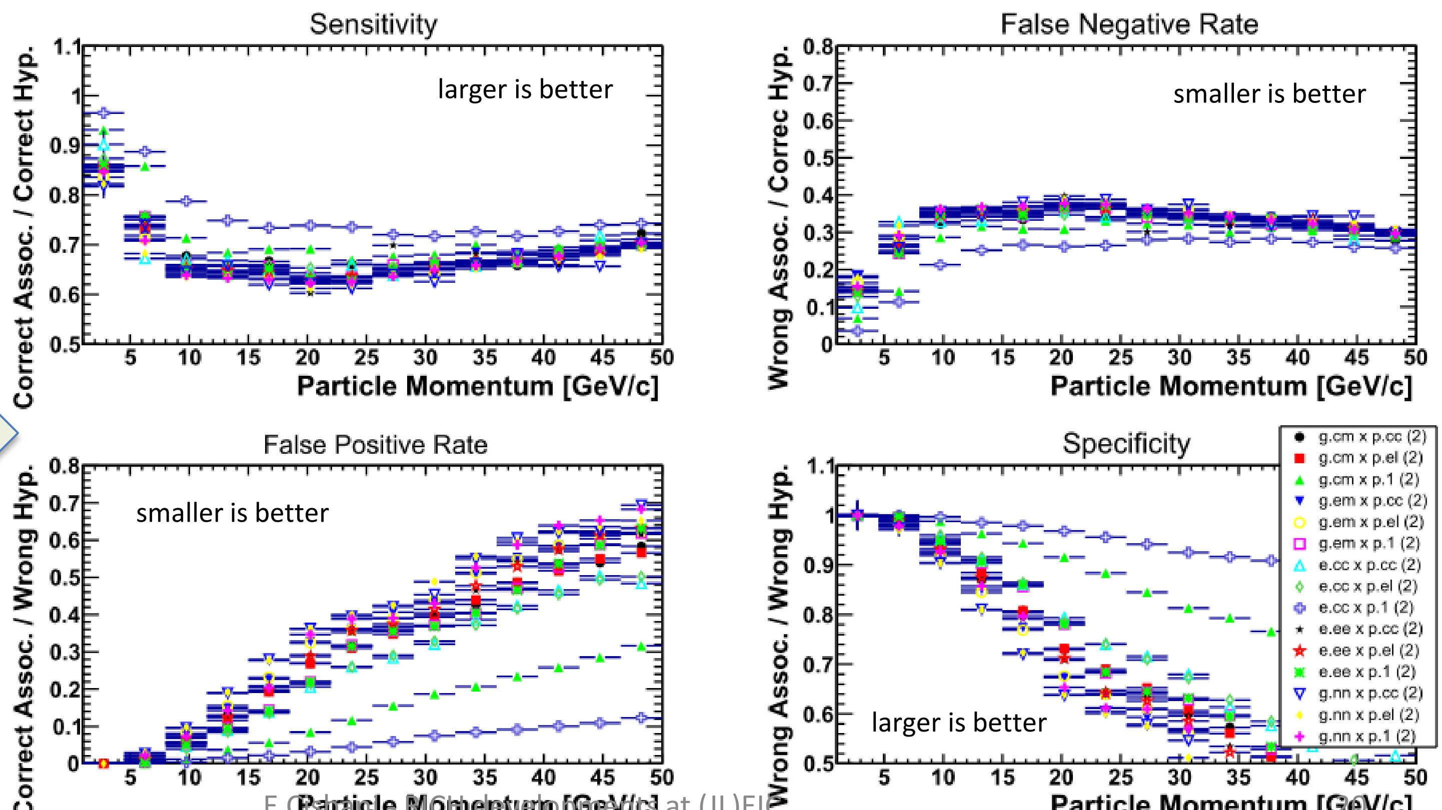
Degree of correlation of estimated and expected angle

- Gaussian distribution with max=1
- Normalized gaussian (integral = 1)
- ERF function
- =1 (no contribution)
- Combine correlation and anti-correlation

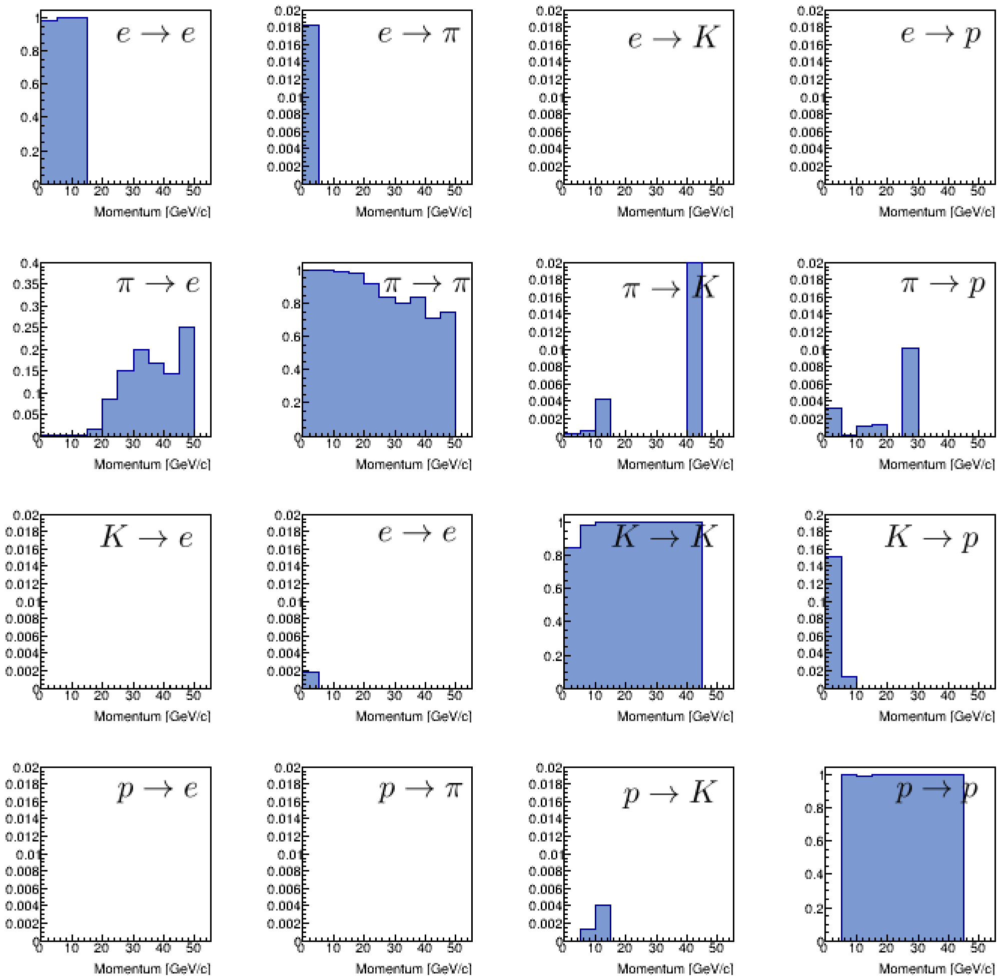
Probability to assign a new photon to the track/rad/part by random choice

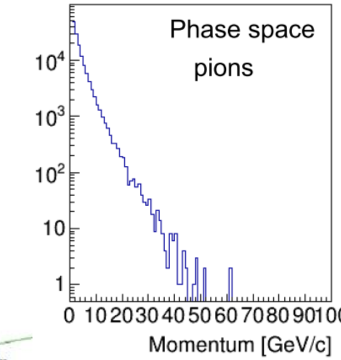
- Cumulated Poisson: prob. assign one or more photon to a given track/rad…)
- Partitioning: enumerate all combinations on "n" photons into "m" partitions (track/rad..);
- =1 (no contribution)

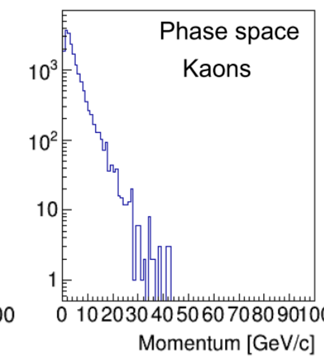
L1=(1-ERF) provides best predictions

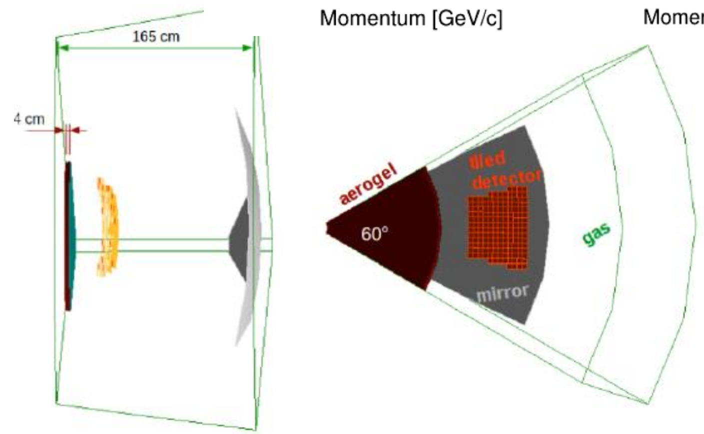


dRICH performance for a key process (PYTHIA DIS simulation)









one of the six dRICH sectors

Momentum Threshold (GeV/c)		
Particle	Aerogel (1.02)	C2F6 (1.0008)
e	0.003	0.013
pi	0.694	3.49
K	2.46	12.3
p	4.67	23.5

The PID capability fulfills the design goals

Summary

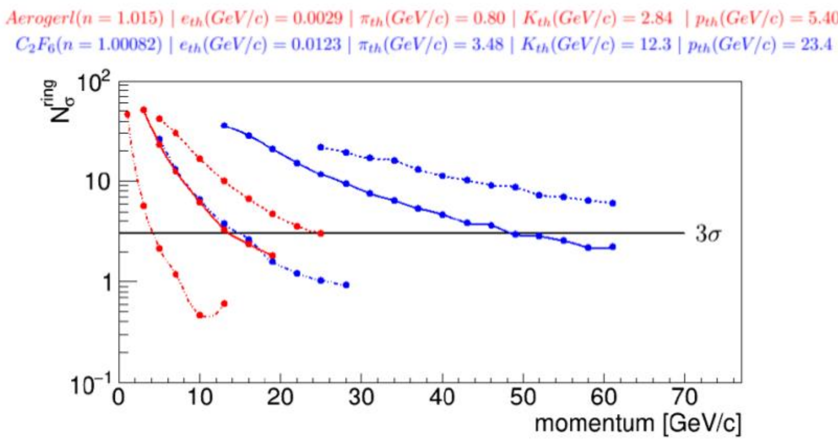
- The EIC/eRD14 consortium is carring on several R&D activities to fulfill the demanding hadron PID requirements of EIC; amoung them, 2 very different RICHes are under development for the electron and hadron endcaps of (JL)EIC
  - mRICH: prototypes demonstrated working principle and first preliminary real performances; working on improving angular resolution and search for suitable sensor/electronics
  - dRICH: design and MC analysis deeply investigated (event based reconstruction method implemented); prototyping started to validate the MC analysis and improve design
  - Both detectors need (at different levels) photosensors development to stand magnetic field, irradiation levels and reduce costs
- EIC/eRD6 carring promising R&D on gas RICH with UV sensitive MPGD photocathode – combined to the mRICH may represent an alternative to the dRICH; but it is currently unable to cover the full range in RICH mode.

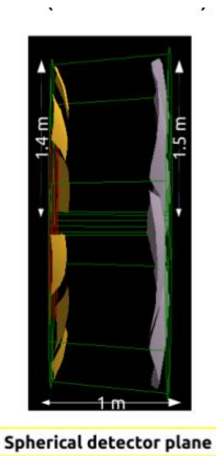
Support Slides

dRICH vs gas only RICH in ePHENIX

dRICH
(From GEMC simulation)

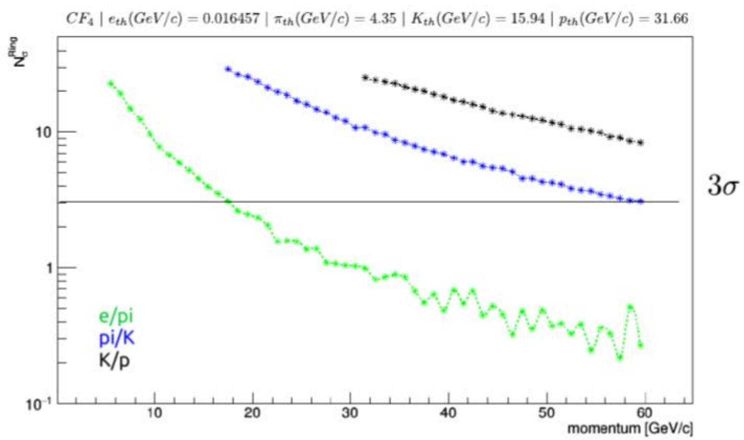
- aerogel + C_2F_6
- outward reflecting mirrors
- six azimuthal sectors
- SiPM or LAPPD sensors



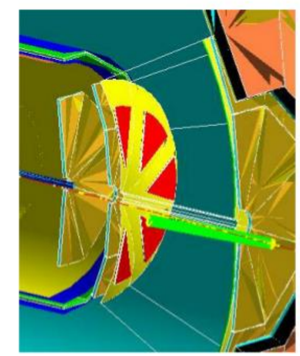


eRD6 RICH
(From Fun4All simulation)

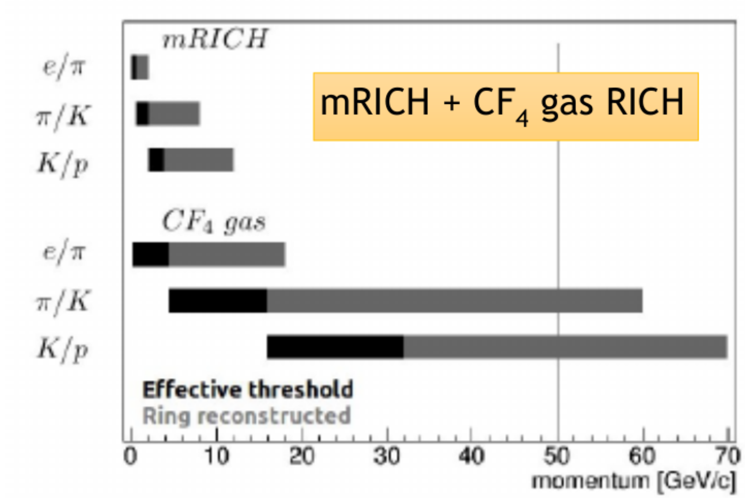
- CF_4 gas only
- inward reflecting mirrors
- eight azimuthal sectors
- GEM photosensors (sensitive in the UV)

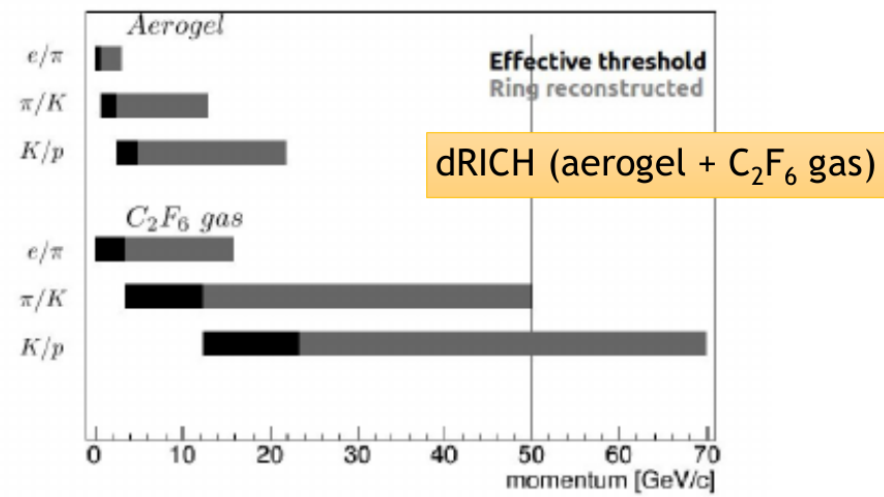


CF_4 gas RICH (ePHENIX)



RICH alternatives in ePHENIX hadron endcap

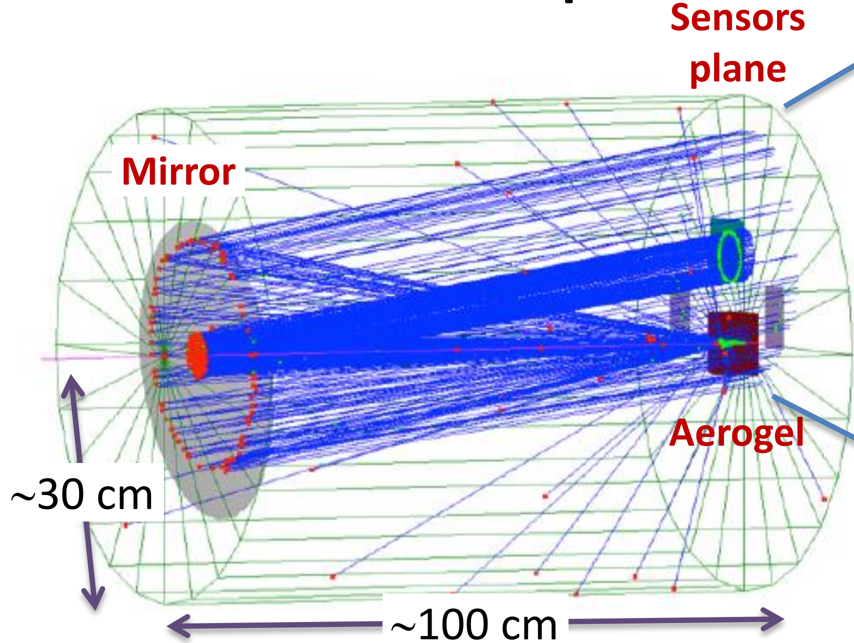


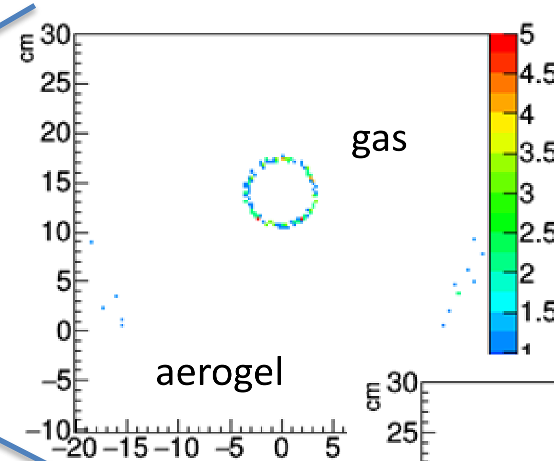


- UV GEMs: chromatic dispersion in CF_4 gas dominates the resolution.
- mRICH + CF_4 gas do not provide continuous coverage in RICH mode for pi/K and not at all for K/p.
- Joint eRD14/eRD6 simulation and reconstruction effort.

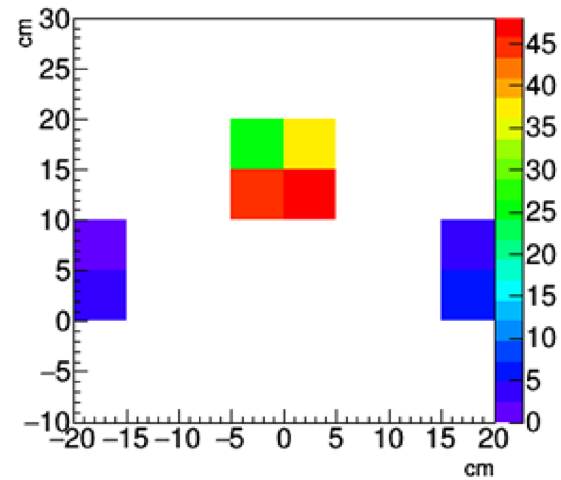
- Outward-reflecting spherical mirror: errors important at small angles with flat sensor plane. Can be optimized.
- The dRICH provides continuous momentum coverage in RICH mode.
- Small scale prototype needed to validate simulation and other critical aspects.

dRICH: First preliminary prototype concept





4 + 4 PMTs



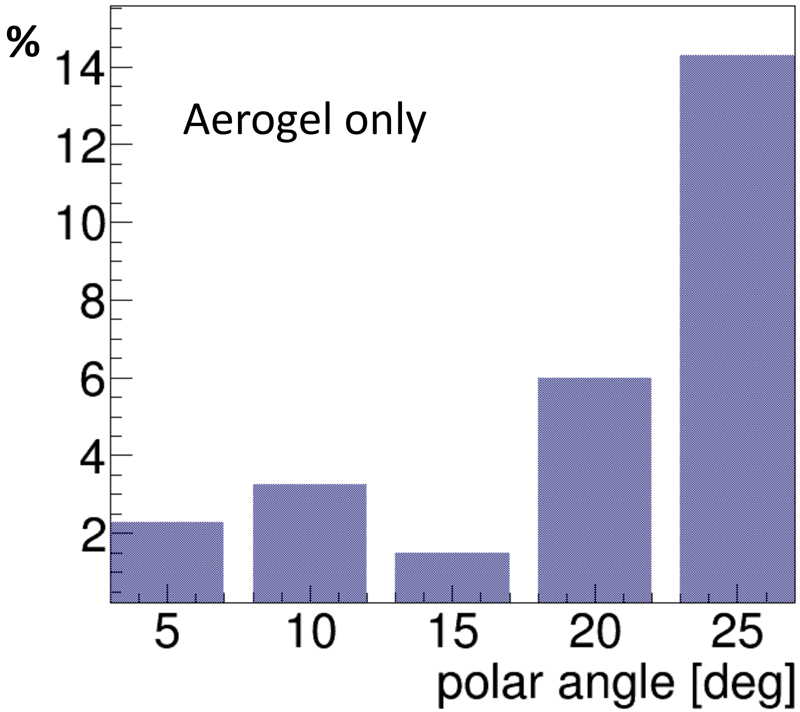
Montecarlo prediction

- ☺ Geometry similar to dRICH; comparable relative contributions to σ_ϑ
- ☹ Only small fraction of aerogel ring (with available sensors/electronics)
- ☹ Switch between two different sensor/electronics setups

1 p.e. error (mrad)	Aerogel	Gas (C2F6)
Chromatic	3.7	0.85
Emission	0.2	0.85
Pixel (3 mm)	0.9	1

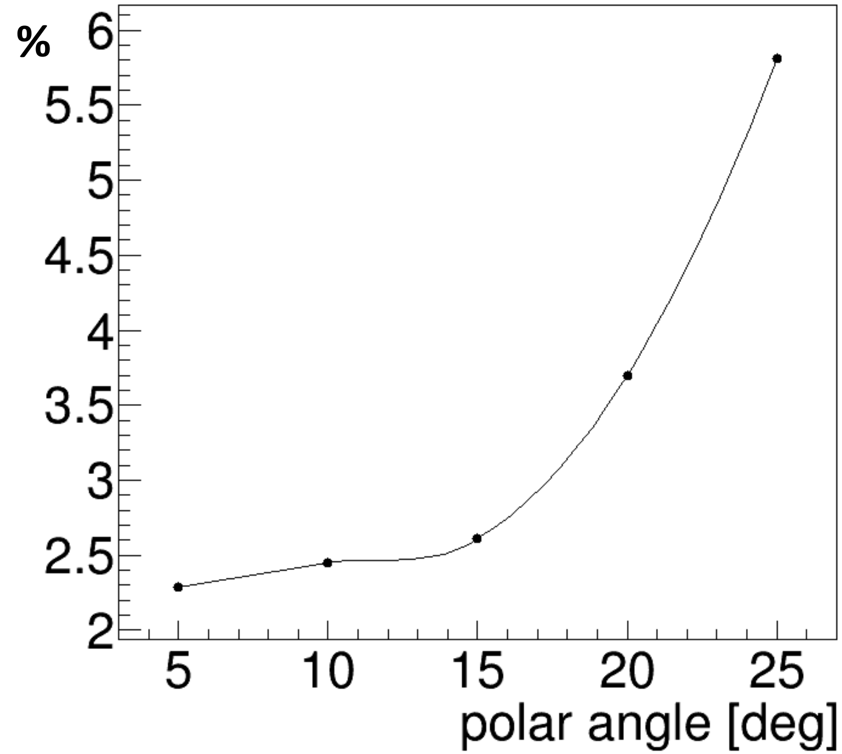
dRICH: other Montecarlo predictions

Inefficiency



Probability of Nph < 3 / track
Poissonian distribution
300 nm filter in

Background / Direct Cherenkov Photons

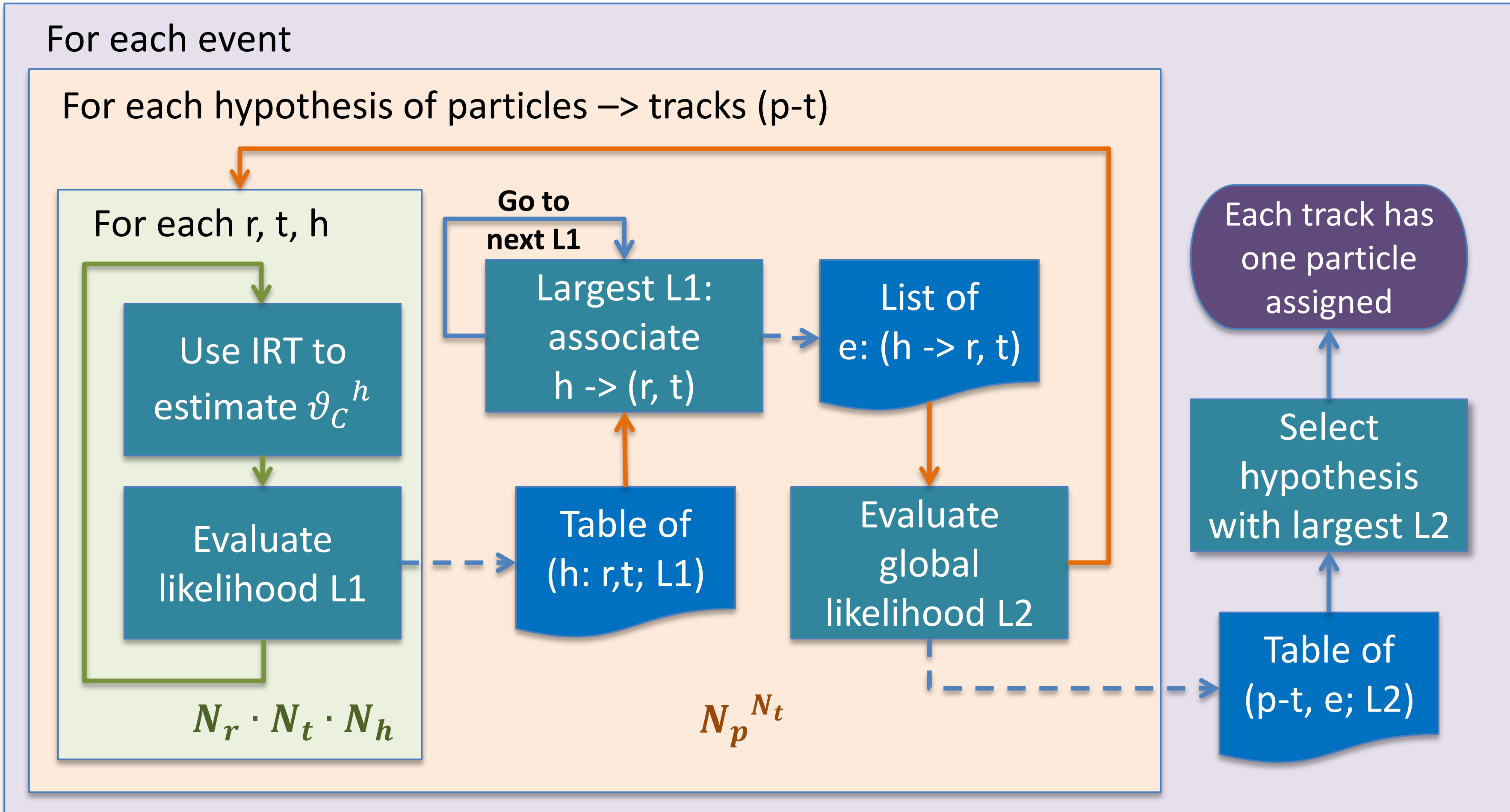


Assuming track multiplicity = 1

Need prototyping to get more realistic results

Based Global Reconstruction

Particle Type (p), Radiator (r), Track (t), Hit (h)



L1: Function of distance between estimated and expected ϑ_C normalized to σ_ϑ

L2: $\sum_{(t,r)} Gaus(\langle\vartheta_C\rangle) \times Poisson(N_{pe})$