dRICH Montecarlo, optimization and reconstruction

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RICH Simulation

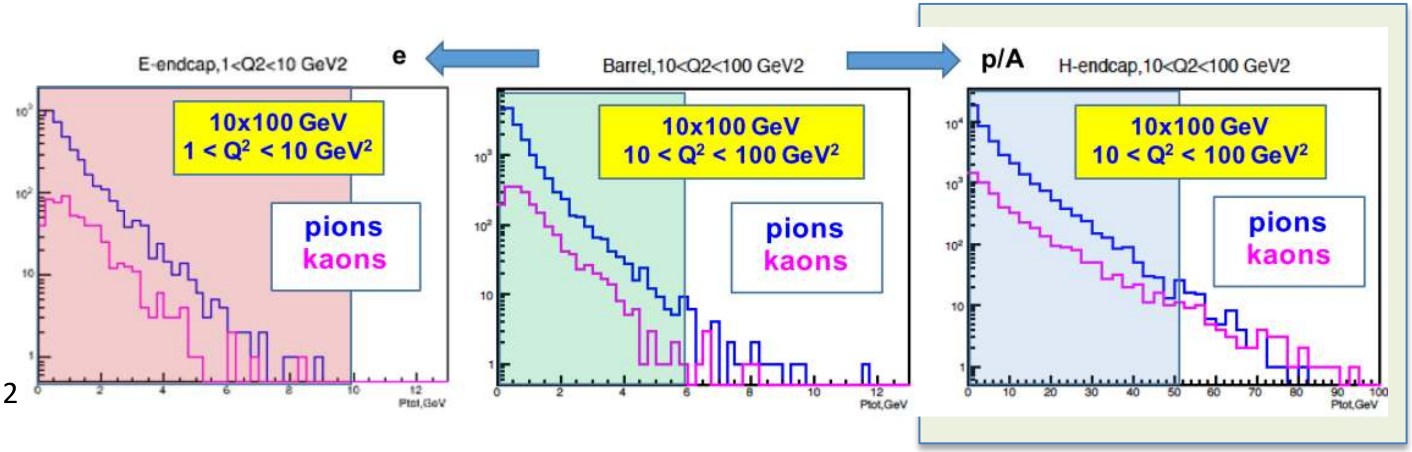
A. Del Dotto, C. Fanelli, E. Cisbani
EIC-eRD14 – PID Consortium

Hadron ID @ EIC h-endcap

“**Simulations show that in order to satisfy the physics goals of the EIC, it is desirable to provide π/K identification** in the central barrel up to 5-7 GeV/c, in the electron-going endcap up ~10 GeV/c, and **in the hadron-going endcap one would need to reach ~50 GeV/c**.”, from the “Electron-Ion Collider Detector Requirements and R&D Handbook”, January 10, 2019

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

Luminosity ≈ 10^{34}/s/cm^2



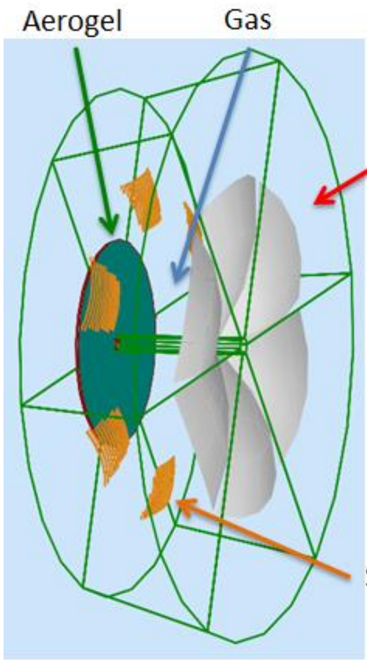
Physics Requirement:

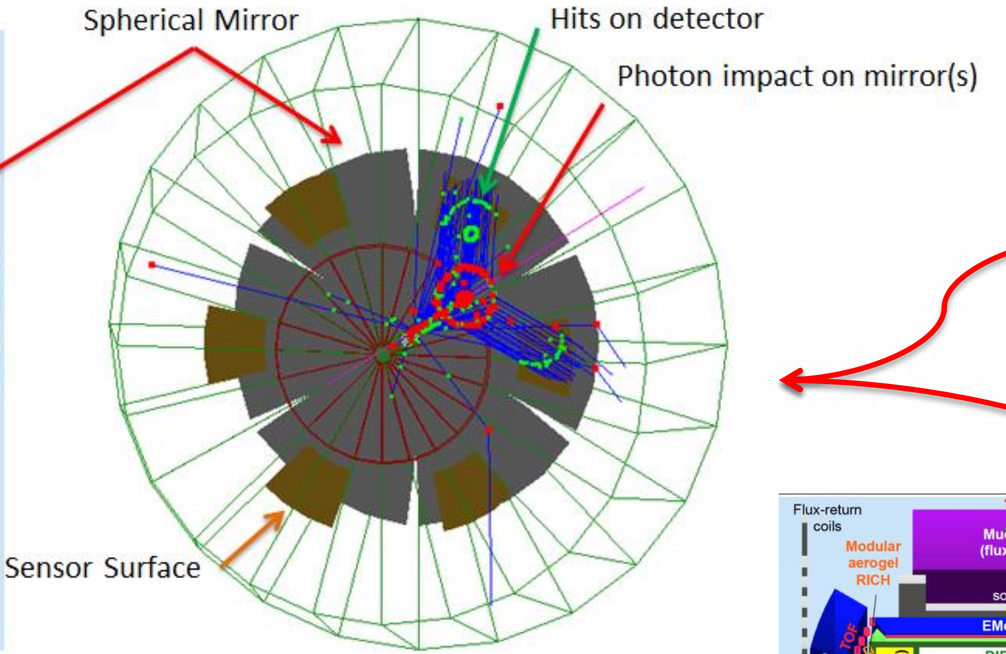
1. **Continuous *π/K/(p) identification up to ~50 GeV/c* in hadron endcap**

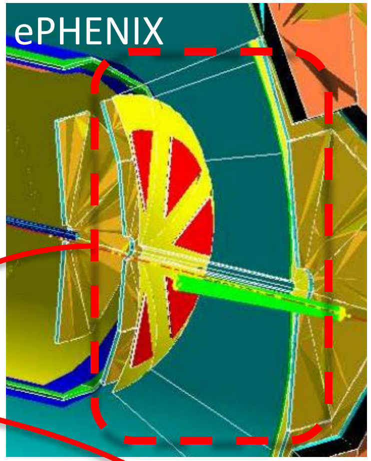
Main Technological Challenges:

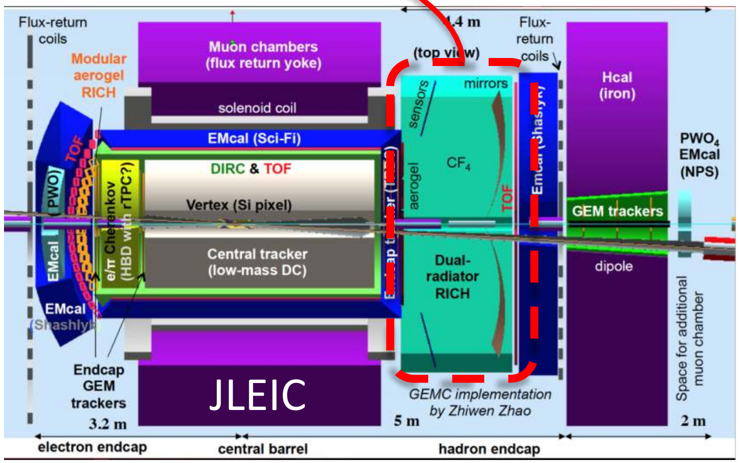
2. **Geometrical constraints (relatively small longitudinal space and large transverse space)**
3. **Solenoid Magnetic Field**
4. **Radiation levels**

Dual Radiator RICH in EIC Hadron-endcap









Radiators:

- Aerogel: 4 cm, $n_{(400nm)}$~1.02 + 3 mm acrylic filter
- Gas: 1.6m (1.1m ePHENIX), n_{C2F6}~1.0008

6 Identical Open Sectors (Petals):

- Large Focusing Mirror with R ~2.9m (~2.0m ePHENIX)
- Optical sensor elements: ~4500 cm^2/sector, 3 mm pixel size, UV sensitive, out of charged particles acceptance

Optimized for JLEIC, preliminary implementation in ePHENIX

Phase Space:
- Polar angle: 5-25 deg
- Momentum: 3-50 GeV/c

dRICH – Software Status

Standalone Montecarlo (GEMC/Geant4)

- Cherenkov angle reconstruction by Inverse Raytracing Method (no uncertainty in detector geometry)
- Source code: github.com/EIC-eRD11/dualRICH_inMEIC

AI-driven Optimization (original idea by C. Fanelli)

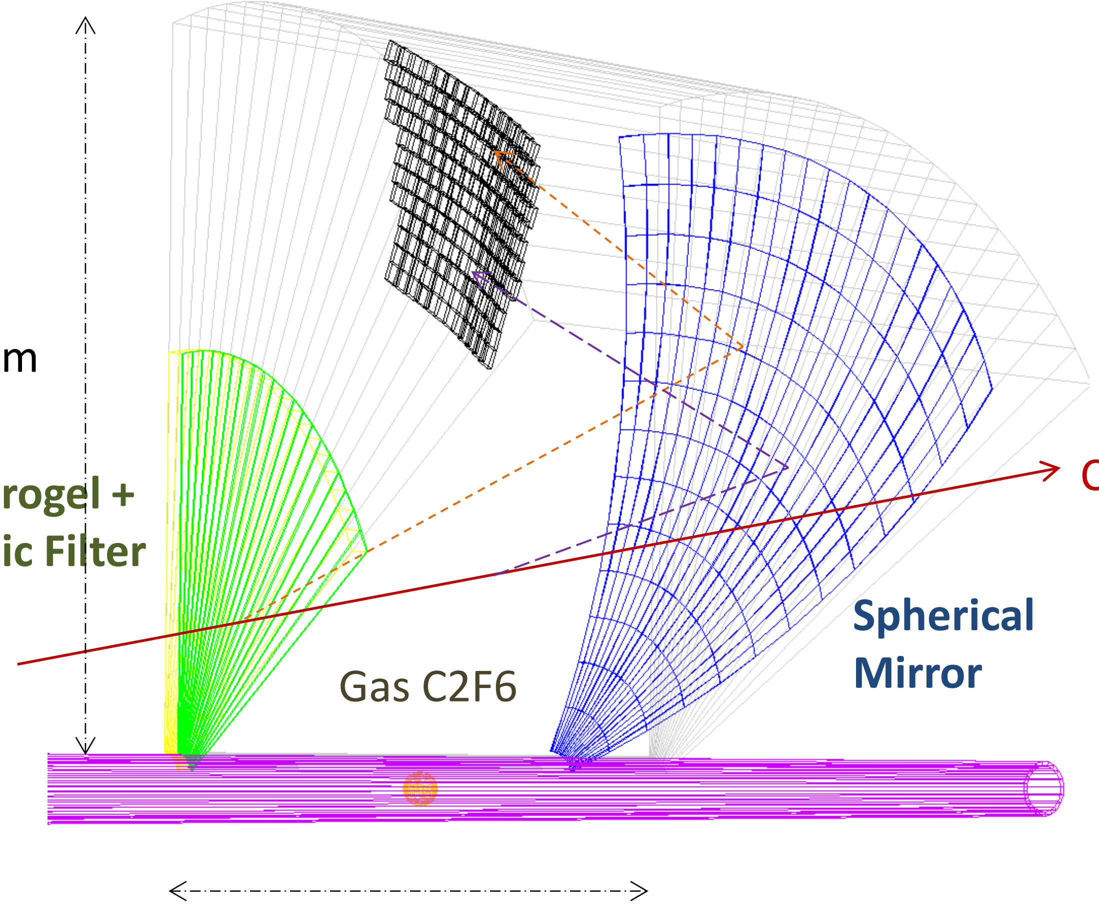
- Use Montacarlo model and an efficient maximization strategy of a figure of merit (e.g. for dRICH: combinations of nσ's in different momentum regions)
- Flexible tool, can be ported to different detectors and combination of them!

PID reconstruction (beta) of MC data (Zhiwen Zhao contrib.)

- Event based reconstruction (from Indirect RayTracing Method)
- Provide confusion/Migration matrix (tested on PYTHIA DIS events)

Fast Parameterized Model (R. Preghenella)

Single Sector dRICH model



Photon Detectors

≈210 cm

Aerogel + Acrylic Filter

Gas C2F6

Spherical Mirror

Charged particle

Beam pipe(s) region

100 ÷ 160 cm

Open geometry:
photons from a Cherenkov cone may split over 2 or more sectors (mirrors and relative photosensors)

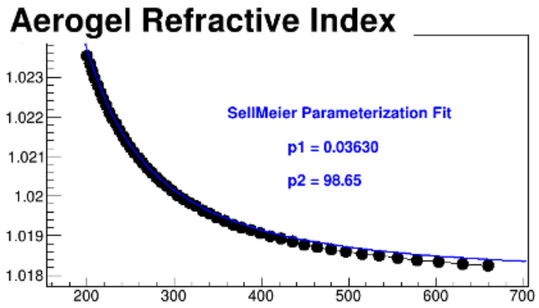
dRICH - MC External Assumptions

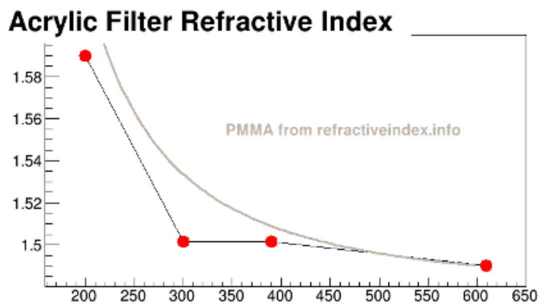
Tracking	
Angular resolution	σ = 0.5 mrad (1 mm over 2 m) – whole momentum range
Impact point resolution	σ = 0.3 mm
Momentum resolution dP/P	+/- few percent negligible effects in Cherenkov angle reconstruction
Magnetic Field	3 Tesla Central Field in JL-MEIC spectrometer
Space Requirement	(based on original spectrometer constraints)
longitudinal length	JLEIC: ≈1.6 m, ePHENIX: ≈1.0 m
transverse radius	JLEIC: ≈2.5 m, ePHENIX: ≈2 m
beam pipe radius	<10 cm
Background	no direct external background only backrground produced by the simulated charged particle: delta-rays, Rayleigh scattering …

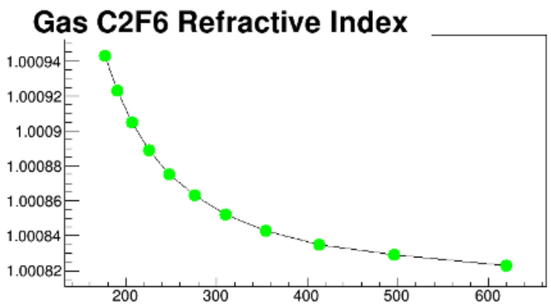
dRICH - MC Internal Assumptions

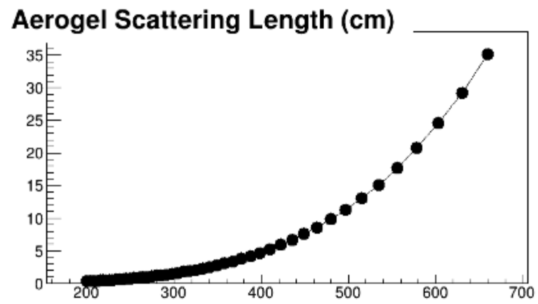
Aerogel radiator	n=1.02, 4 cm Characteristics scaled from CLAS12/RICH measurements
Gas radiator	n=1.0008, 160/100 cm - C2F6 yield scaled from CF4 data (x0.7); chromaticity from literature (NIMA 354(1995)417); constant absorption length (need to be measured)
Mirror	Reflectivity from CLAS12/RICH measurement; Roughness not included
Photon Detector	3 mm pixel size; 200-500 nm MAPMT (binary readout mode) Characteristics from CLAS12 measurements
Vessel	no thickness assumption so far
Background	
Sensor Electronics	Random - spatially uniform on photosensor, poissonian with 30 hits/event mean (assuming 1kHz/pixel dark count x 100 ns) Note: uniform background hits do not influence noticeably the angular resolution; they influence the PID and therefore the migration matrix
Acrylic filter	3.2 mm (from HERMES and LHCb), remove aerogel photons (Rayleigh scattering) below 300 nm impact on ≈1% of signal photons
Particle Generation	All charged particles originate from the vertex and are uniformely distributed in the angular phase space,

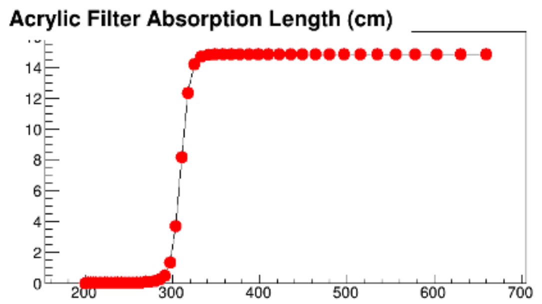
Main Optical Characteristics

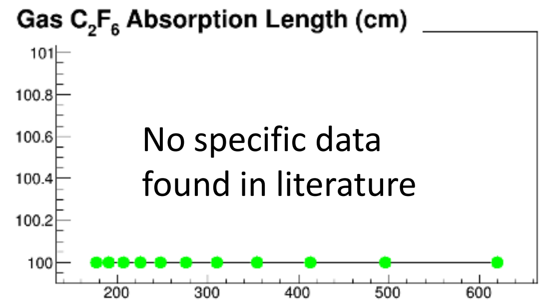

Aerogel Refractive Index


Acrylic Filter Refractive Index

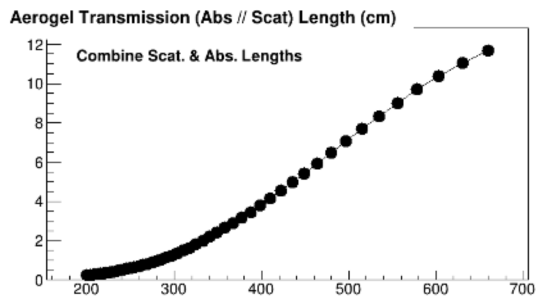

Gas C2F6 Refractive Index

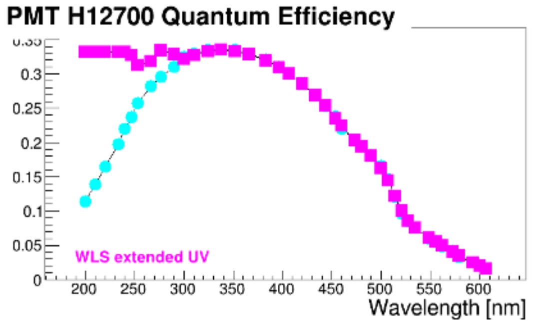

Aerogel Scattering Length (cm)

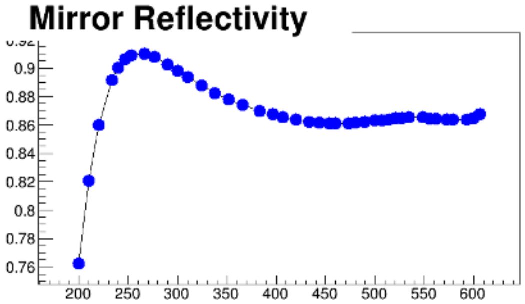

Acrylic Filter Absorption Length (cm)


Gas C_2F_6 Absorption Length (cm)

No specific data found in literature


Aerogel Transmission (Abs // Scat) Length (cm)

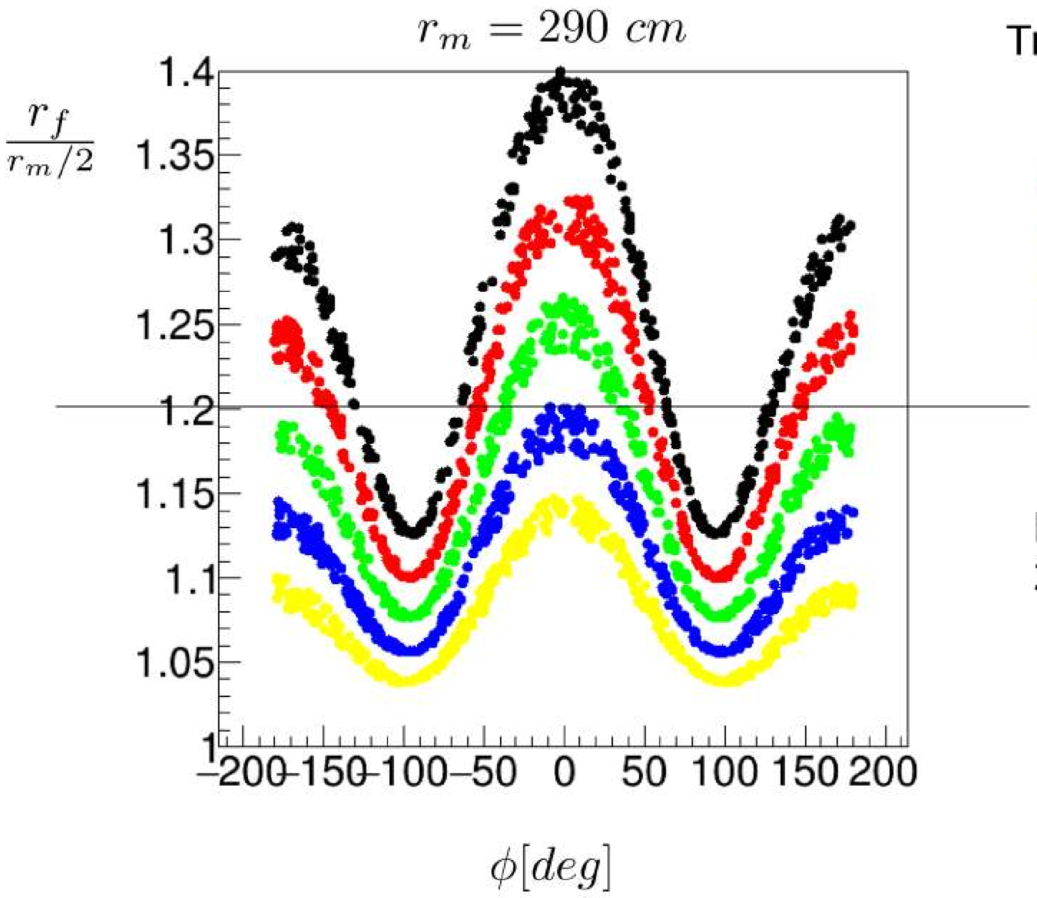

PMT H12700 Quantum Efficiency


Mirror Reflectivity

Focal surface – C_2F_6 gas

Spherical aberrations of the mirror grows up with the tilt angle; they are sizable in a small space outward-reflecting configuration!

Position of the focal r_f with respect to the “naive” sphere $r_m/2$



Track polar angle

θ = 5°
θ = 10°
θ = 15°
θ = 20°
θ = 25°

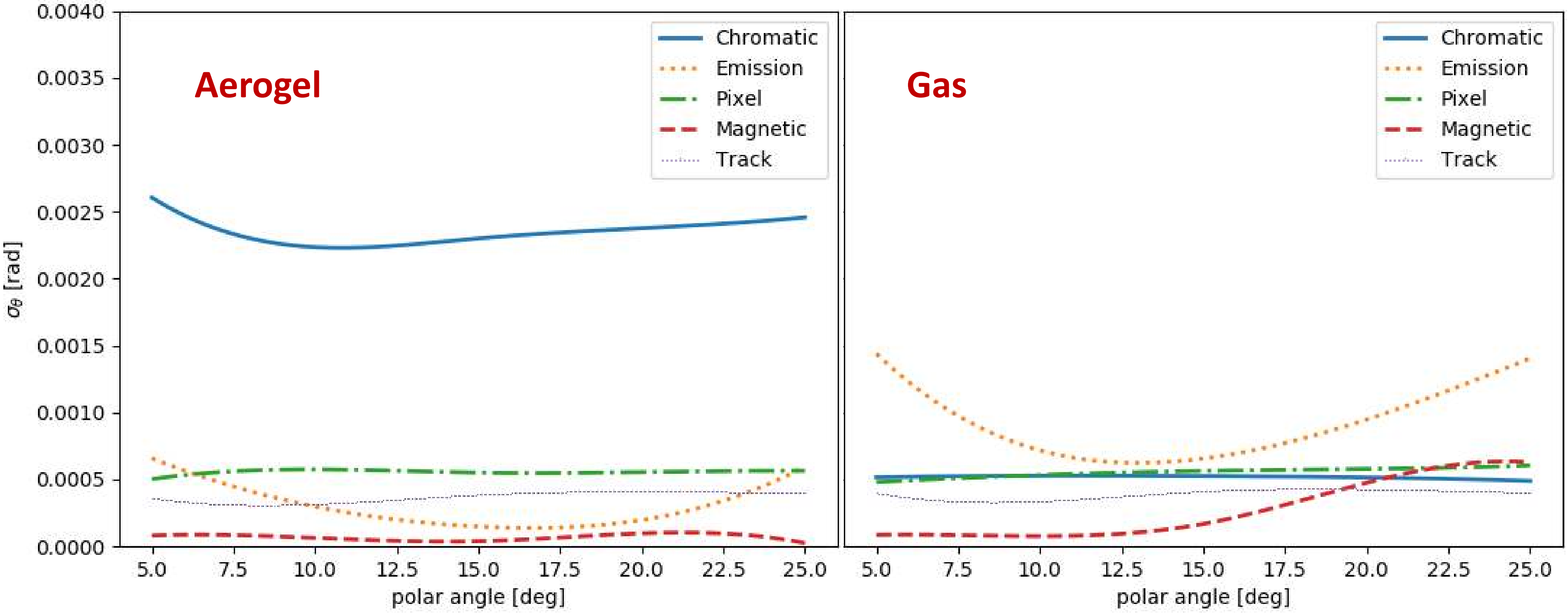
Detector position (spherical - like)

Mirror tilt angle: 28°

dRICH MC Cherenkov Angle Resolution

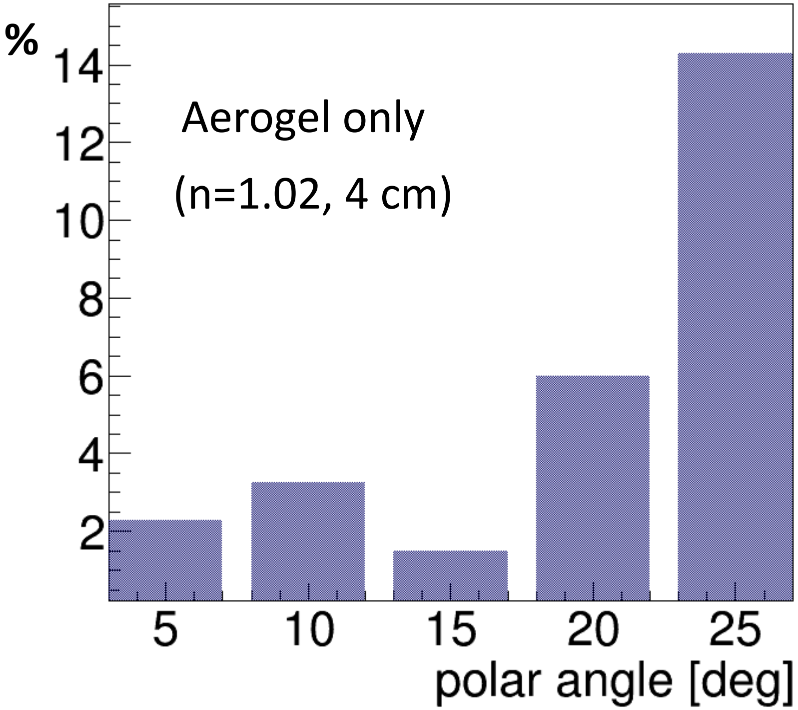
Single Photon Cherenkov Angle Resolution

- Main contributors shown
- Charged particle momentum 30 GeV/c
- Photo sensor surface "optimized" (slightly curved)



dRICH: other Montecarlo predictions

Inefficiency

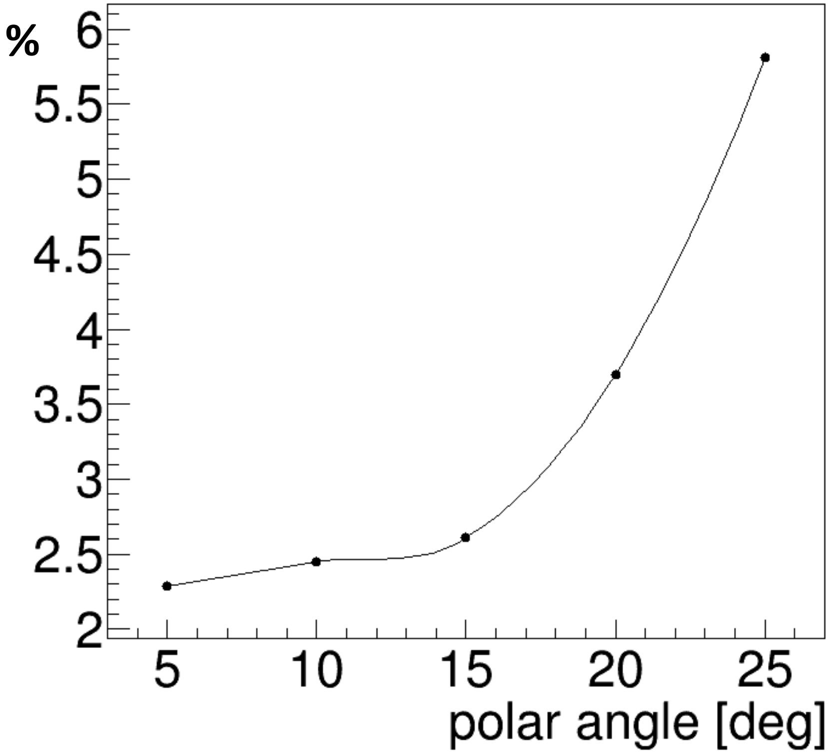


Aerogel only

(n=1.02, 4 cm)

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

Background / Direct Cherenkov Photons

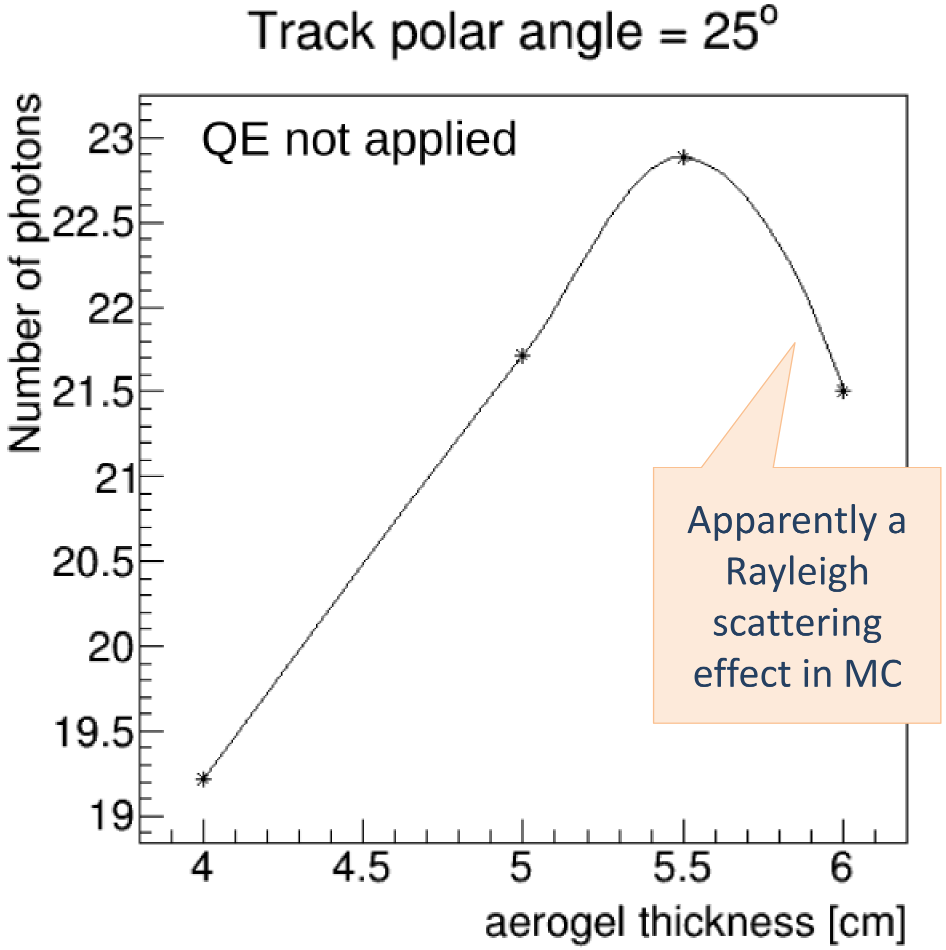


Assuming track multiplicity = 1

Need prototyping to get validation

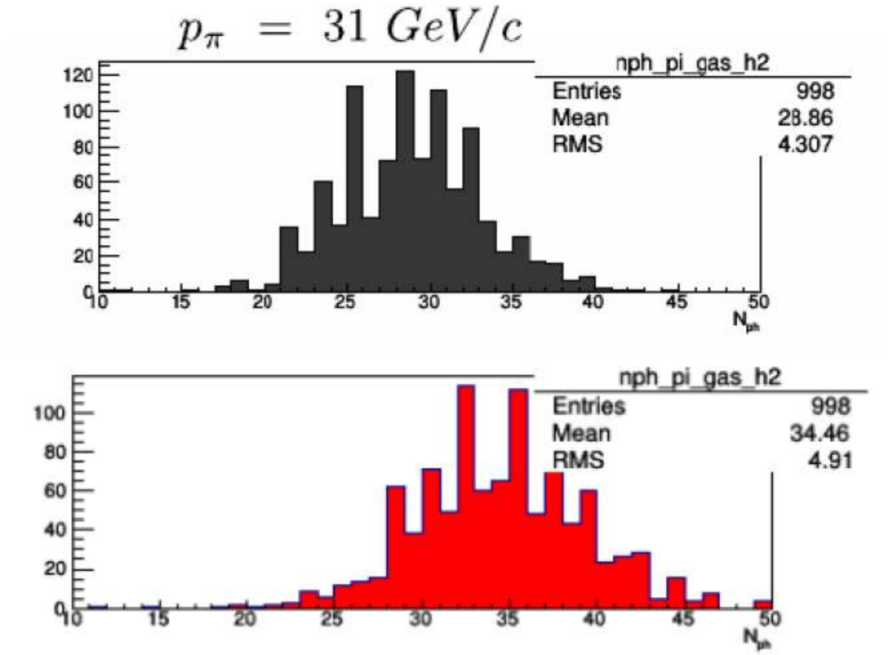
Aerogel – thickness vs number of photons

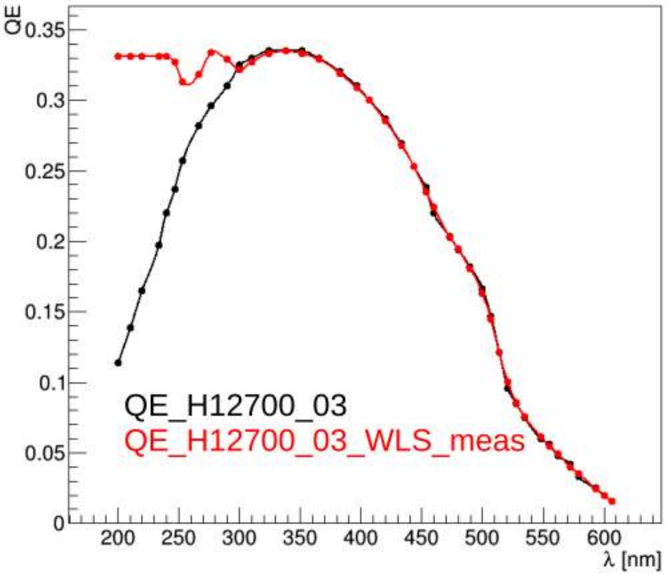
- Aerogel can be extended to 5 cm thickness to gain some photon at high angles



Apparently a Rayleigh scattering effect in MC

Number of p.e. for the gas – C_2F_6 (n = 1.00086)

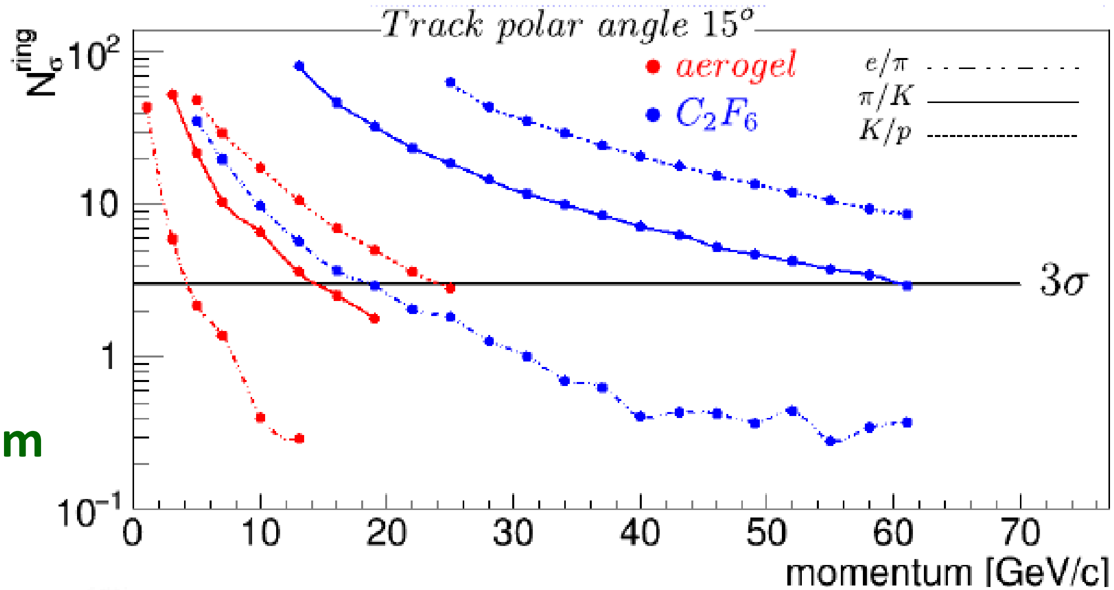




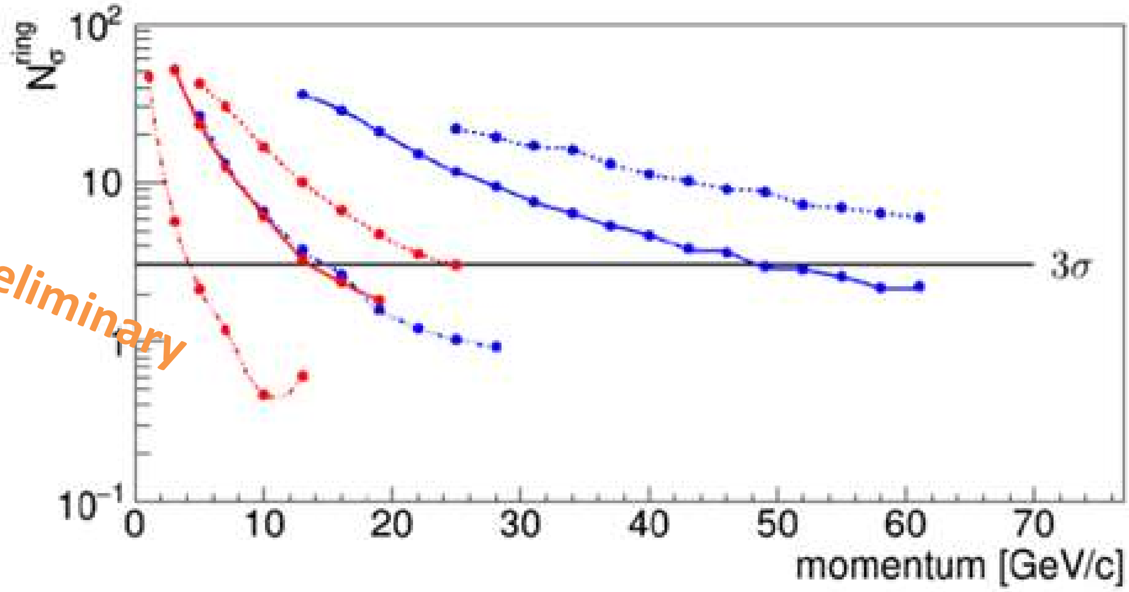
$$\lim_{\beta \to 1} N_{ph} = C \cdot L \cdot \epsilon(\lambda) \cdot \frac{n^2 - 1}{n^2} \propto \frac{n^2 - 1}{n^2}$$

The above distributions are resized by 0.7*Npe, assuming the same normalization of CF4

dRICH separations in JLeic and ePHENIX



dRICH in JLEIC spectrometer
Optics manually optimized for 1.6 m



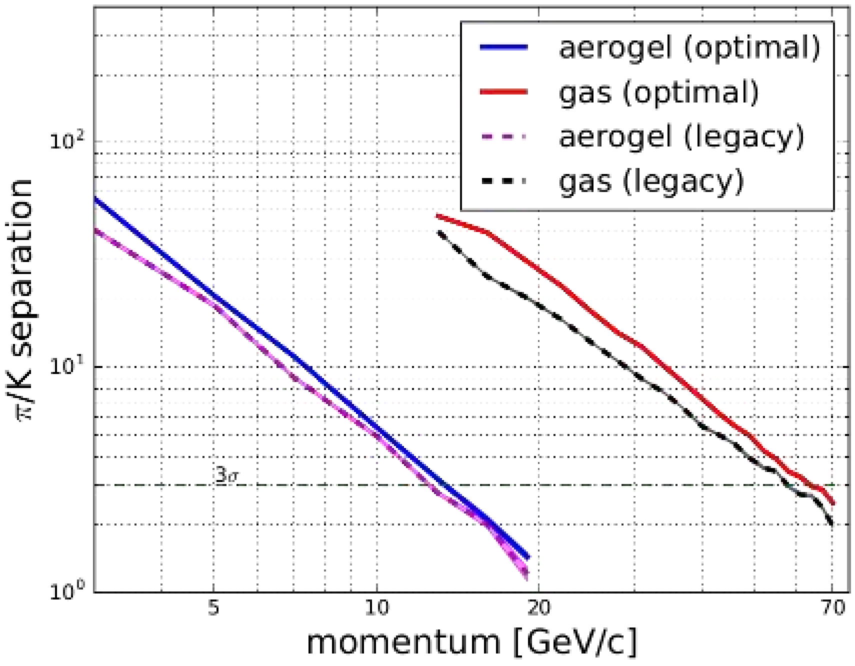
dRICH in ePHENIX spectrometer
Optics barely adapted to 1.0 m

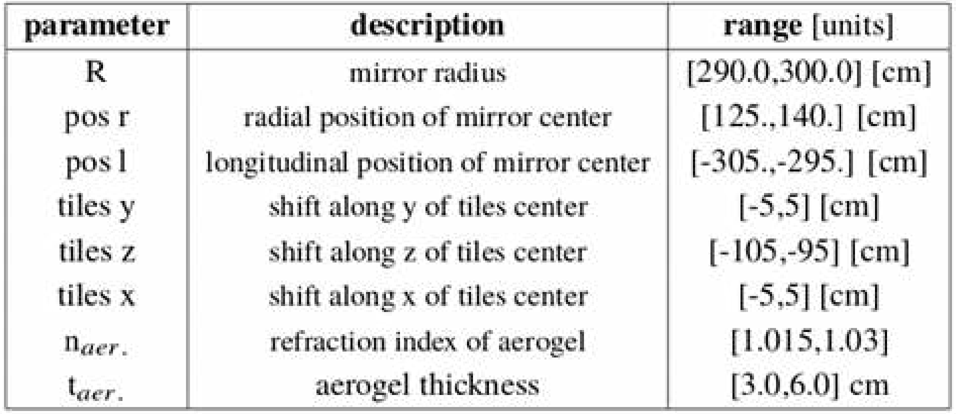
dRICH Model Integrated in Bayesian Optimizer

- **Use Bayesian Inference to efficiently maximize proper Figure of Merit:**

  π-K Cherenkov angles separation in critical phase space regions

  (e.g. TOF-aerogel, aerogel-gas transitions, high momentum limit …)





parameter	description	range [units]
R	mirror radius	[290.0,300.0] [cm]
pos r	radial position of mirror center	[125.,140.] [cm]
pos l	longitudinal position of mirror center	[-305.,-295.] [cm]
tiles y	shift along y of tiles center	[-5,5] [cm]
tiles z	shift along z of tiles center	[-105,-95] [cm]
tiles x	shift along x of tiles center	[-5,5] [cm]
$n_{aer.}$	refraction index of aerogel	[1.015,1.03]
$t_{aer.}$	aerogel thickness	[3.0,6.0] cm

Use case implementation used 8 parameters, but is not limited to them.

- The optimization approach can be ported to any detector (or combination of detectors) development where a detailed MonteCarlo exists

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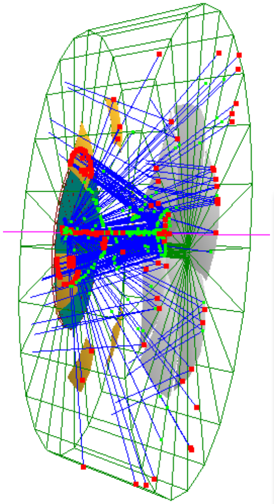


Inverse Ray-Tracing

IRT Event Based Reconstruction

Reconstruction essential to get physics results

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: run over 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:

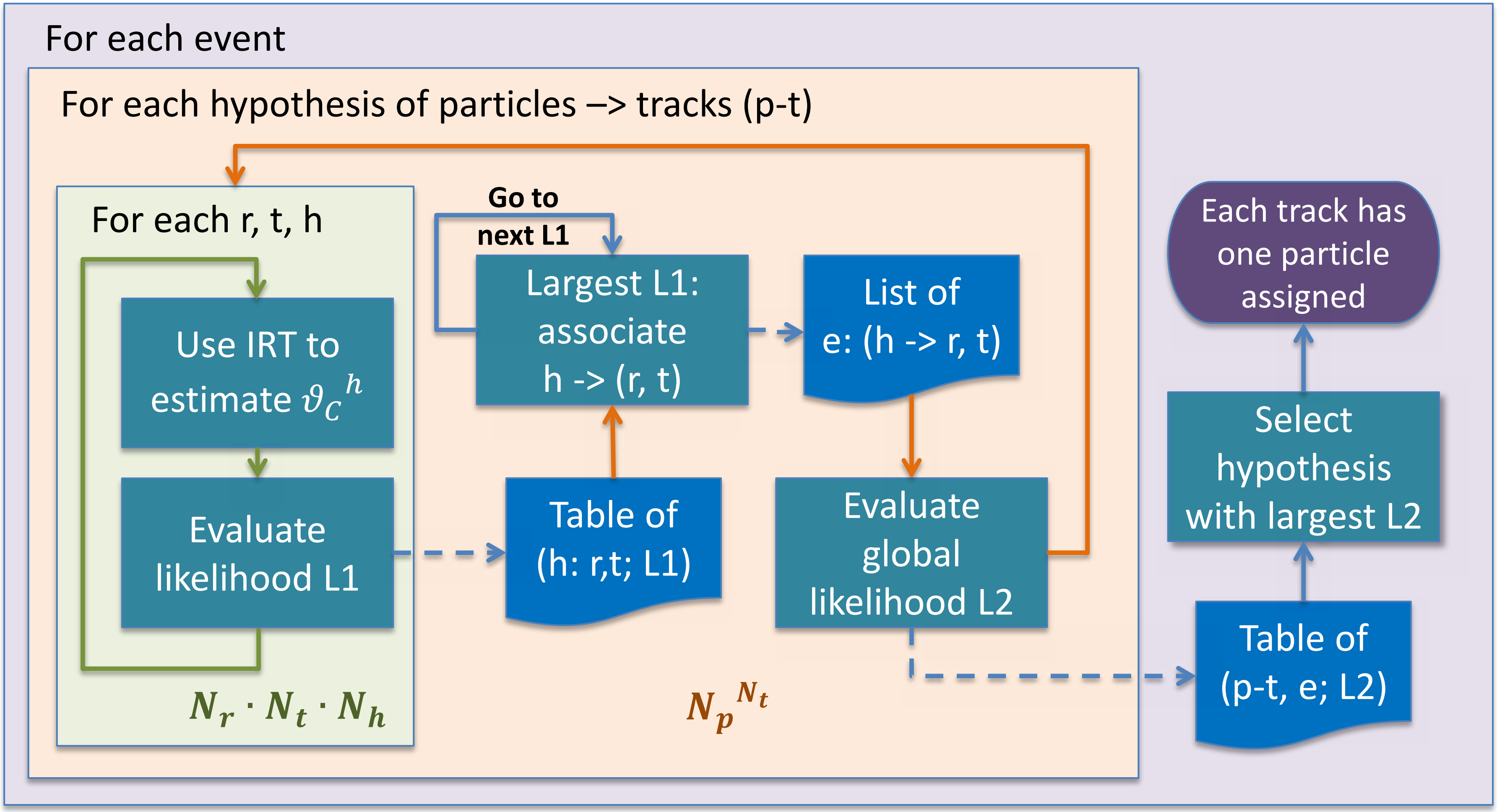
- Determine (by IRT) the potential emission angles corresponding to each photon hit
- Split the problem in two steps (for each event):
  1) Sequential hits association to tracks/radiators using a first likelihood L1 (combinations drop to **(Nt*Nr+1)*Nh**)
  2) Once all hits are associated, estimate a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

Based Global Reconstruction

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



For each event

For each hypothesis of particles –> tracks (p-t)

For each r, t, h

Use IRT to estimate $\vartheta_C{}^h$

Evaluate likelihood L1

$N_r \cdot N_t \cdot N_h$

Table of (h: r,t; L1)

Go to next L1

Largest L1: associate h -> (r, t)

List of e: (h -> r, t)

Evaluate global likelihood L2

$N_p{}^{N_t}$

Table of (p-t, e; L2)

Select hypothesis with largest L2

Each track has one particle assigned

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

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

Detailed analysis on L1

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

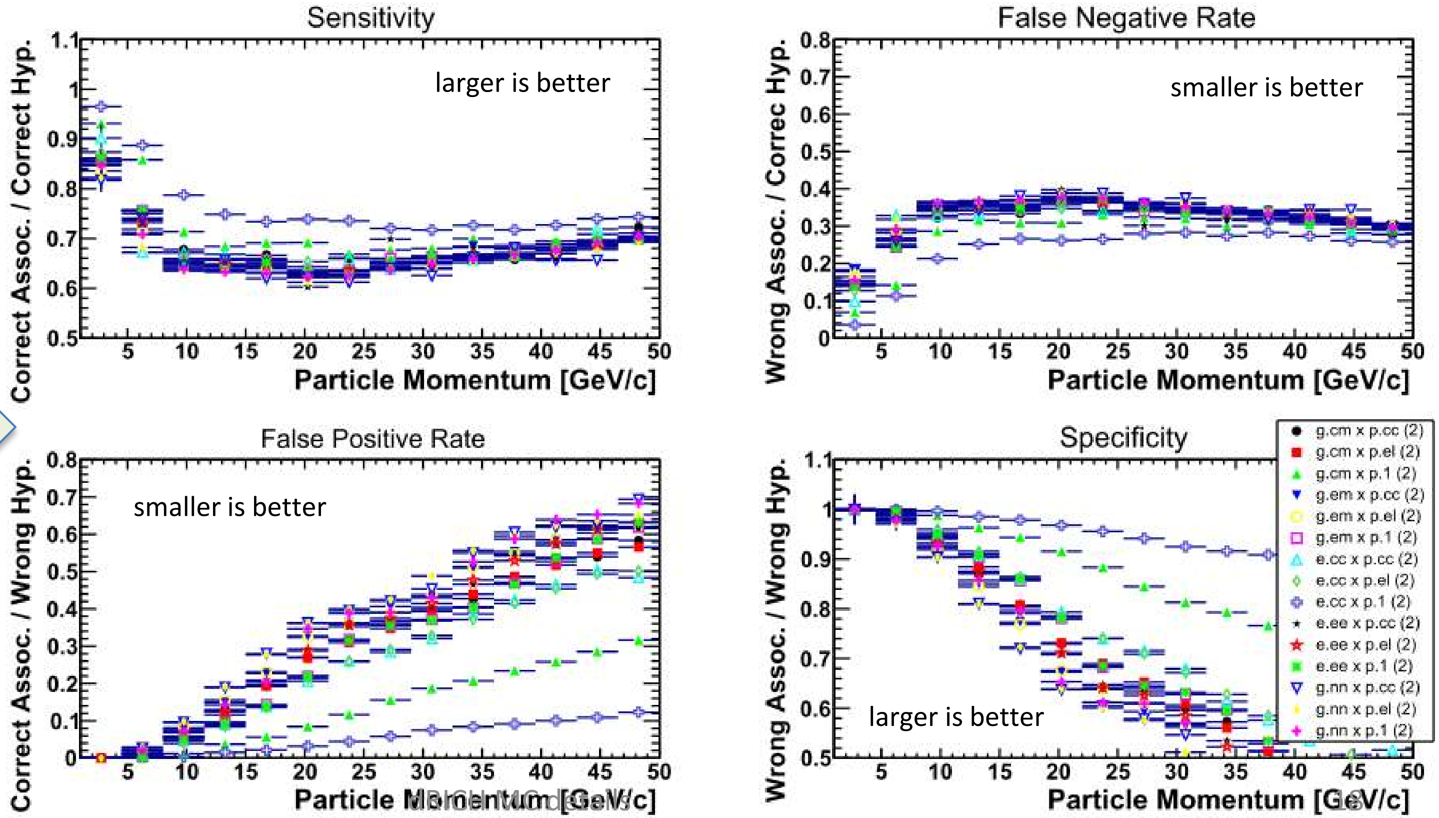
Degree of correlation of estimated and expected angle

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

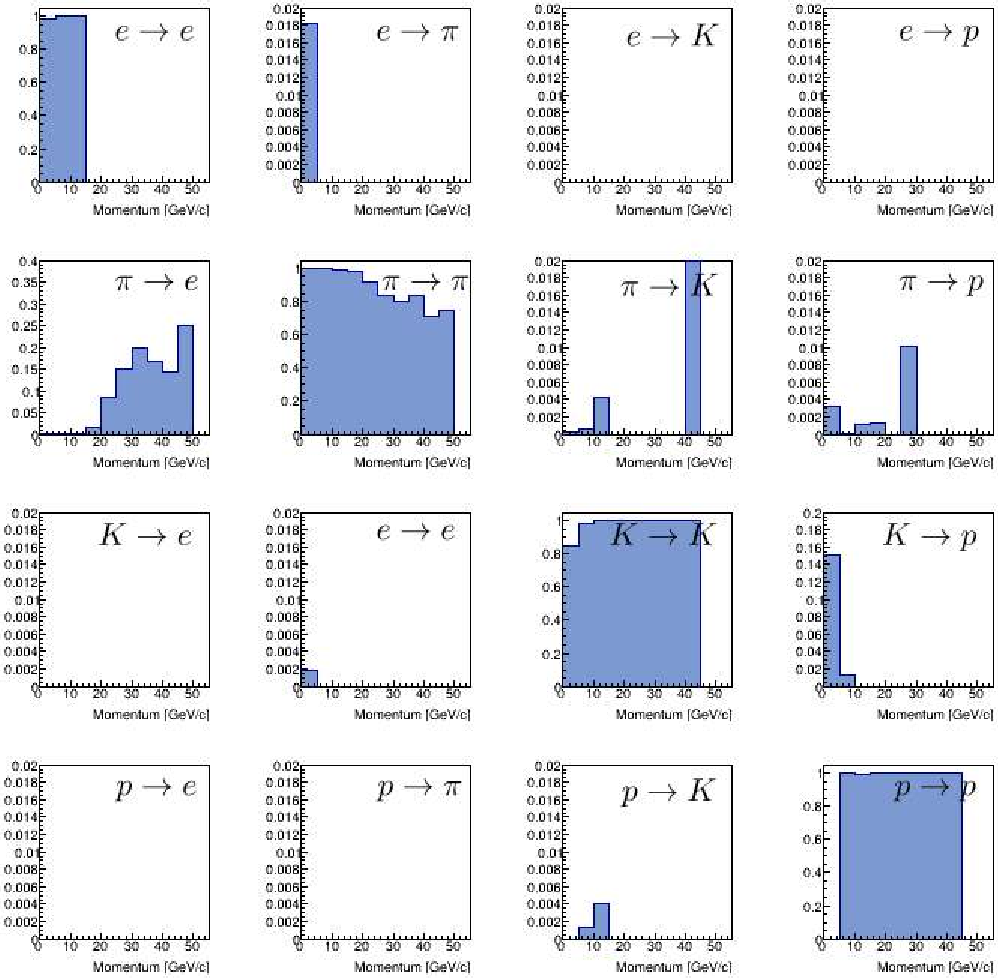
- Gaussian distribution with max=1
- Normalized gaussian (integral = 1)
- ERF function
- =1 (no contribution)
- Combine correlation and anti-correlation

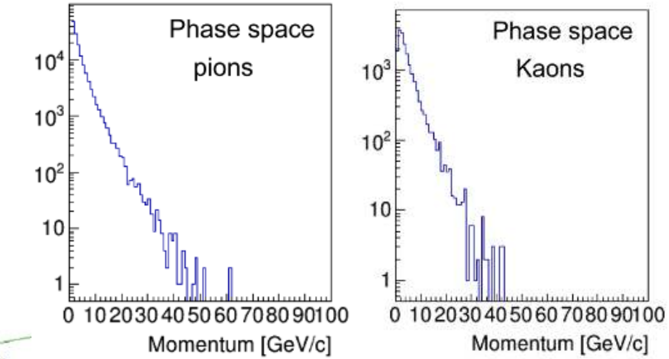
- Cumulated Poisson: prob. assign one or more photon to a given track/rad…)
- Partitioning: enumerate all combinations on "n" photons into "m" partitions (track/rad..);
- =1 (no contribution)

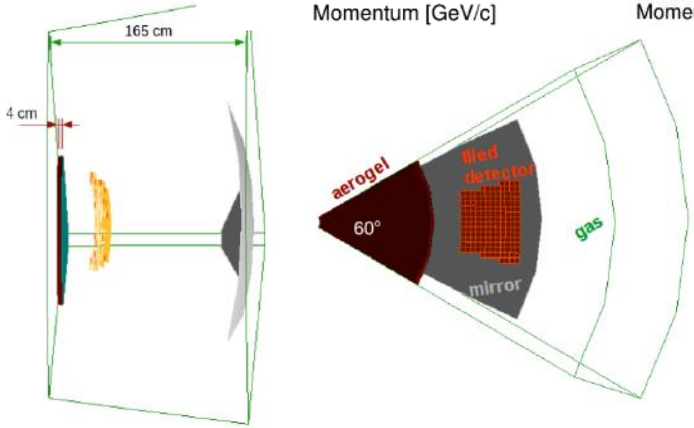
L1=(1-ERF) provides best predictions



dRICH performance for a key process (PYTHIA DIS simulation)





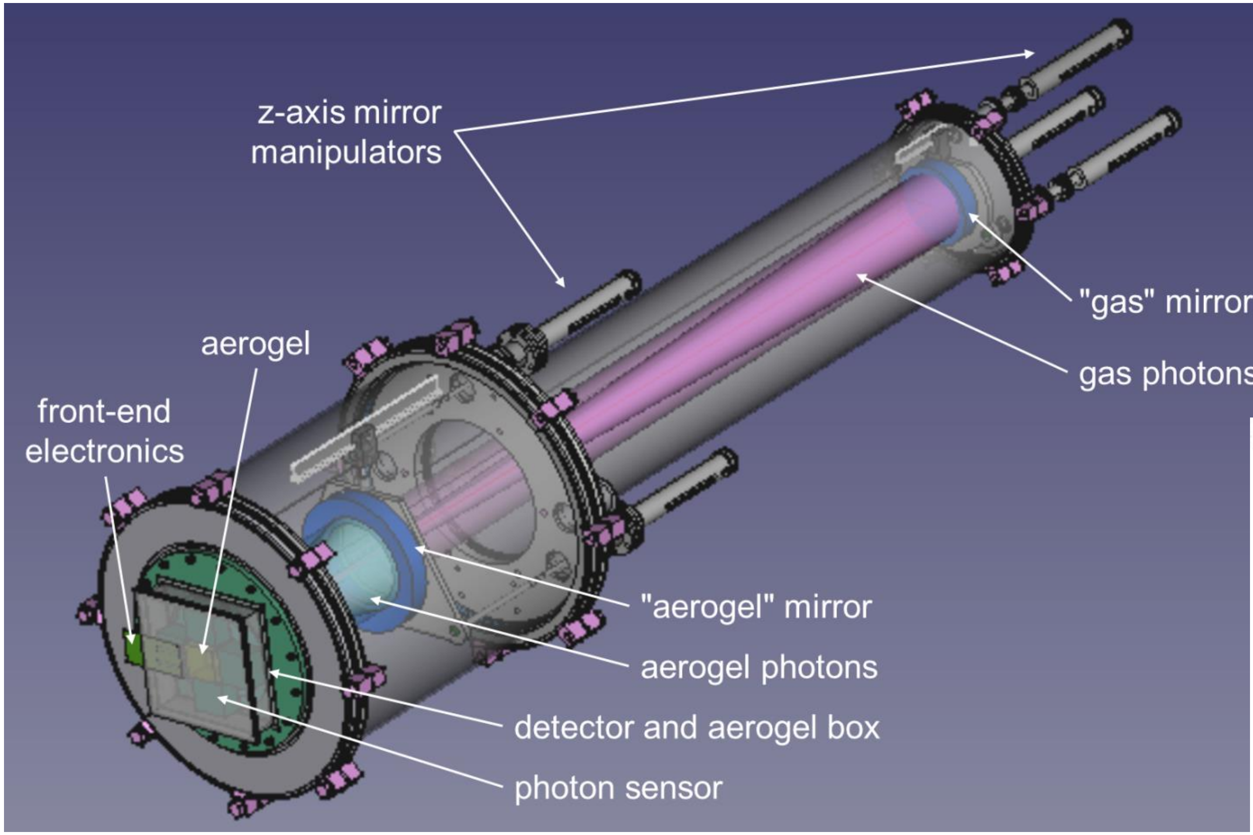


one of the six dRICH sectors

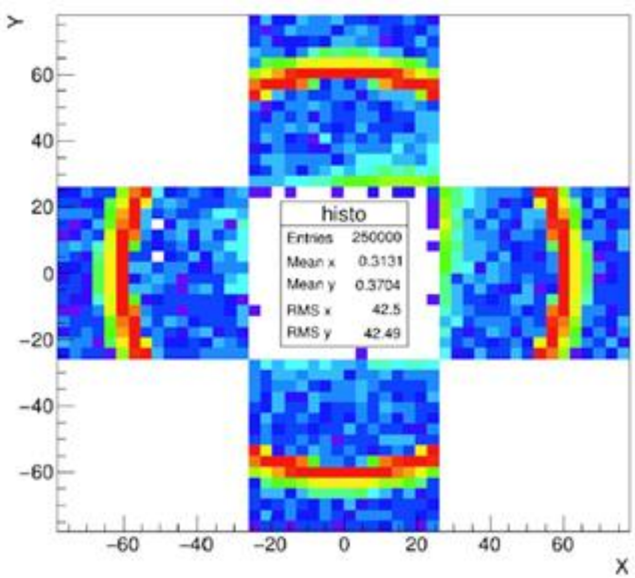
Momentum Threshold (GeV/c)		
Particle	Aerogel (1.02)	C2F6 (1.0008)
e	0.003	0.013
pi	0.694	3.49
K	2.46	12.3
p	4.67	23.5

with contributions of Zhiwen Zhao

dRICH Prototype Design



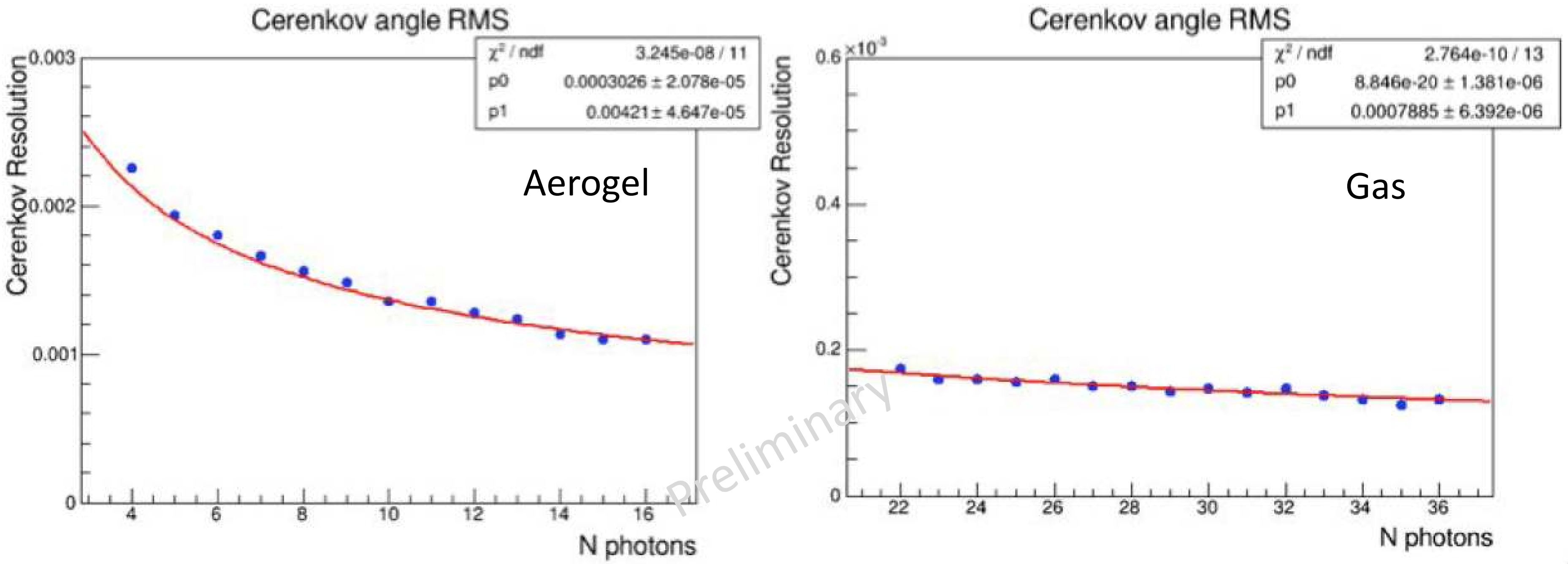
Same MonteCarlo on prototype model



- Design in advanced stage, mechanical details being finalized
- Standard Vacuum Technologies to optimize gas handling
- Two tuneable mirrors system for using the same detector
- Common (small) sensitive surface for both aerogel and gas photons
- Detector and aerogel box isolated from the gas tank

L. Barion
M. Contalbrigo

dRICH Consolidated Prototype Expected Performance



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-gas errors are comparable in prototype

L. Barion
M. Contalbrigo