FCT

Cherenkov detector for electron event veto status & considerations

-

ALICE Upgrade Week Krakow 2024

Special thanks for helpful discussions to:
Nicola Nicassio, Antonello di Mauro and Andrea Dainese

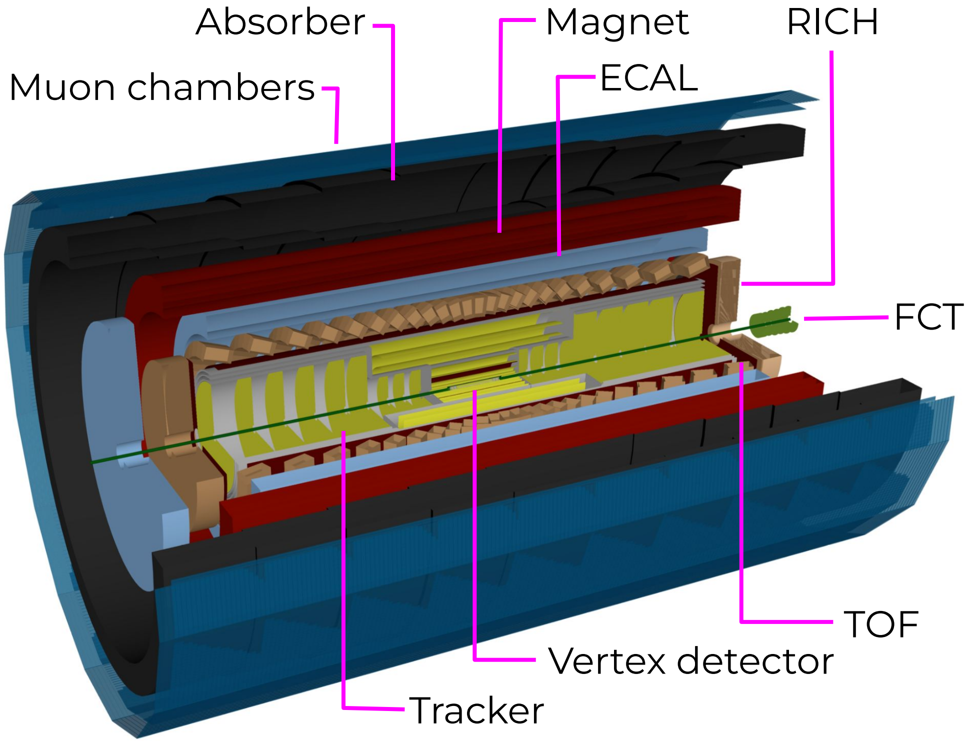
Cas van Veen (they/them)
Physikalisches Institut, Ruprecht-Karls Universität, Heidelberg

The FCT - A short overview

Goal: Measure the soft photon spectrum predicted by Low's theorem

- 11 consecutive silicon discs with monolithic pixel trackers
- Pseudorapidity coverage: $4 < \eta < 5$
- Dipole magnet with a magnetic field of 0.25 T
- PID for e^+/e^- event veto

Cherenkov detector behind the FCT needed for good signal over background



Reference - 100% identification efficiency

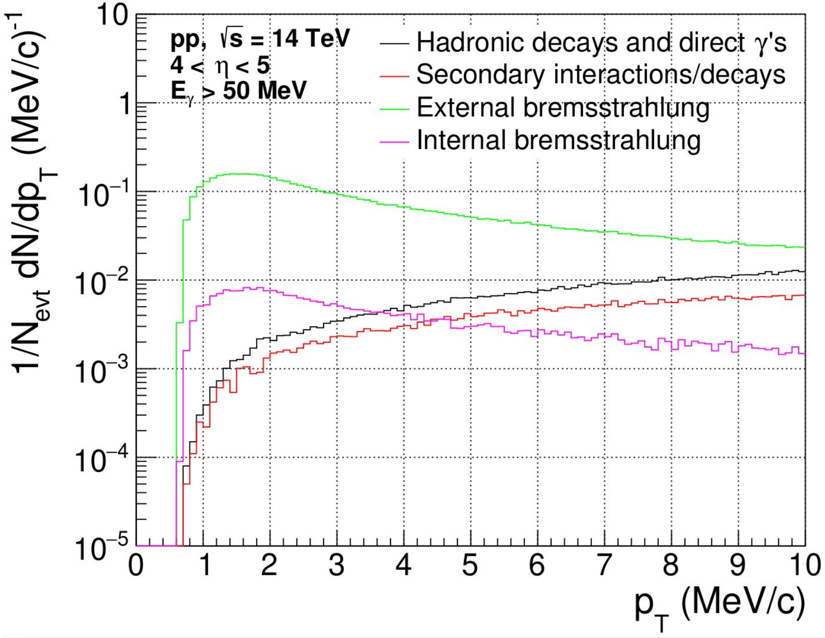
These will serve as the reference to compare the cherenkov detector (CD) performance to.

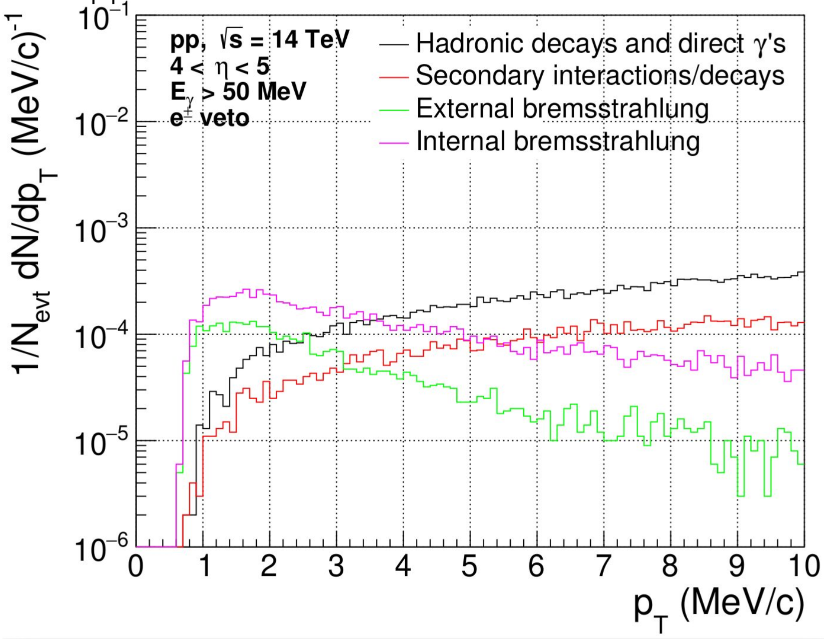
With 100% PID, the measurement is more than possible

No electron event veto

Both: Pointing angle cut applied

100% PID electron event veto





How do we achieve a good enough PID efficiency?

With a cherenkov detector (CD) - simulation strategy

What would such a Cherenkov detector look like?

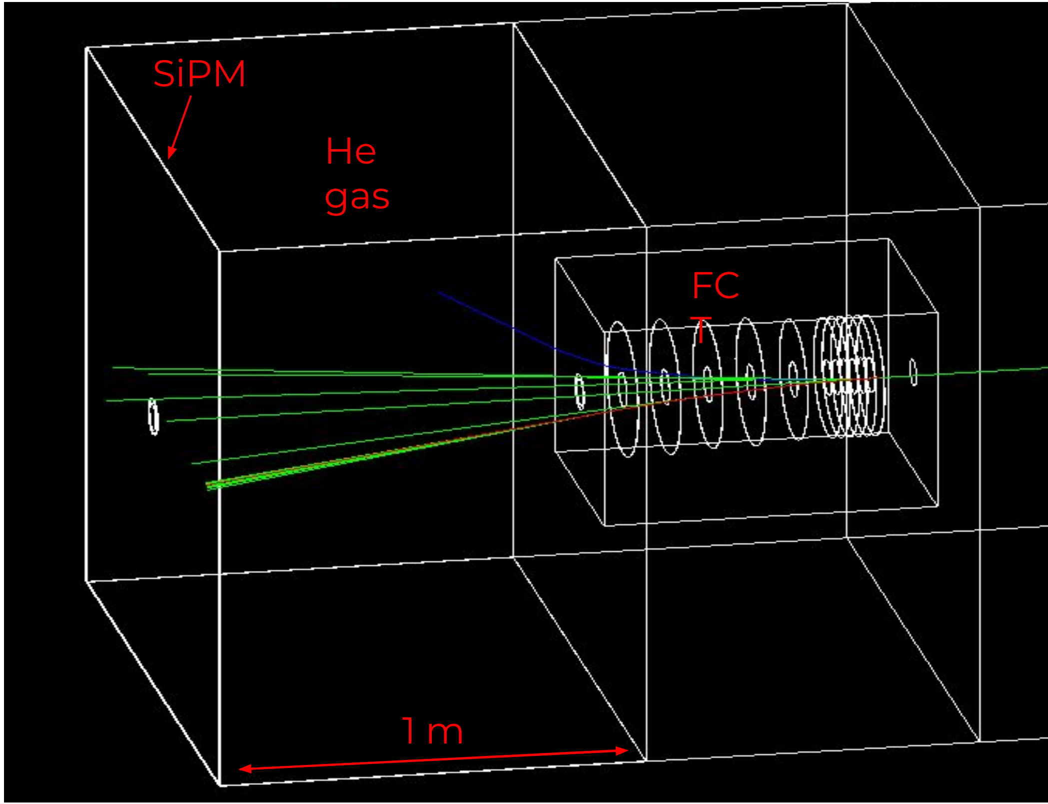
Simulations done with the following setup

Radiation volume filled with He or Ne gas
Radiation length: 0.5 - 2.5 m

Square grid of SiPMs. (Hamamatsu, FBK)
Response of SiPMs is based on

- Dark count rate (DCR) ~ 1 MHz/mm^2
- Dead zone ~ 18-28 %
- PDE ~ peak around 450 nm
- Granularity ~ 3x3 mm
- Read-Out-Frame ~ 2 - 20 ns

GEANT4 representation, but simulation is done as toy MC



With a cherenkov detector (CD) - simulation strategy

What would such a Chere kov de tor
look like?

Simulations don ith t

Radiatio
Radiation lengt

Square grid of
Response of SiPM

- Dark count r
- Dead zone ~ 18-28
- PDE ~ peak aro d 450
- Granularity ~ 3x3 mm
- Read-Out-Frame ~ 2 - 20 ns

GE NT4 rep sentation, but simulation is done as toy MC

The setup is not realistic, but it is good enough to study the performance.

A realistic setup would need a focusing mirror to bring the SiPMs out of the high radiation zone of the FCT acceptance.

Electron / charged particle separation strategy

1. Photons are emitted along the track of a charged particles in a circle
2. In this circle, there will be hits from
   - Photons
   - Charged particle
   - Dark counts
3. Count the total number of hits in the so-called "check area" dictated by the maximum cherenkov angle
4.

Electron tagging logic	$p < p_{\text{th. } \pi}$	$p > p_{\text{th. } \pi}$
$N_{\text{Hits}} < N_{\text{Hits th.}}$	Not electron	Not electron
$N_{\text{Hits}} >= N_{\text{Hits th.}}$	Electron	Not electron

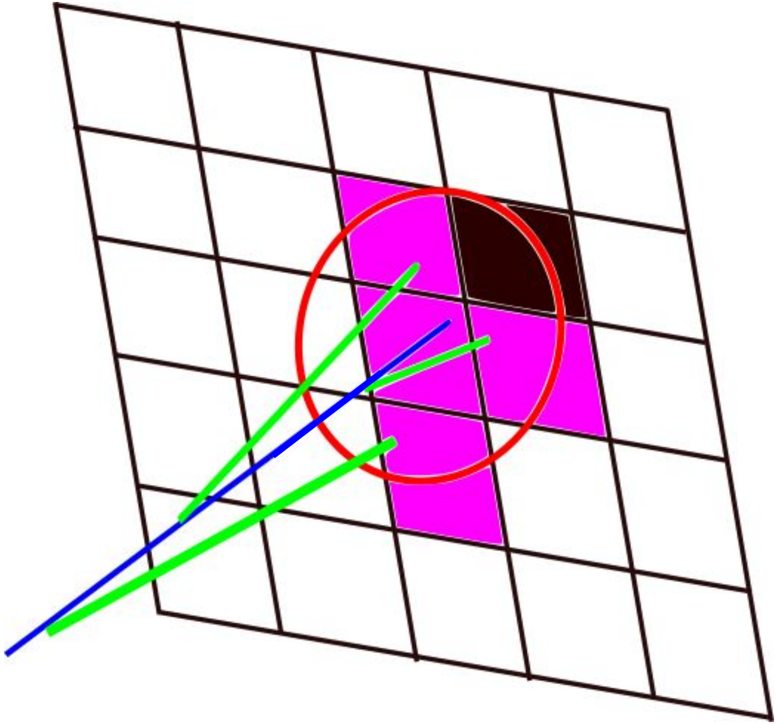
The momentum threshold is decided via

$$p_{\text{th}} = \frac{m\beta_{\text{th}}}{1-\beta_{\text{th}^2}}$$

For He: $p_{\text{th. e}}$ ~ 60 MeV/c

For He: $p_{\text{th. } \pi}$ ~ 16.4 GeV/c

SiPM grid with incident charged particle and cherenkov radiation within a "check area"



SiPMs: the readout time and dark count rate (DCR)

The **read-out-frame** (ROF) of ALICE 3 will be **500 ns** for the MAPS
In this timeframe, on average, **20 bunch crossings** (BCs) will occur

The typical **DCR** of these SiPMs is **1 MHz/mm²**

Calculate the number of **dark counts per ROF per SiPM** via: $N_{\mathrm{DC}} = \mathrm{DCR} \times \mathrm{ROF} \times A_{\mathrm{SiPM}}$

Synching the ROF of the SiPM with the MAPS (i.e. 500 ns) gives

SiMP	DCR	N_{DC}
Hamamatsu 3050cs	1 MHz/mm²	4.5
Hamamatsu 3075cs	1 MHz/mm²	4.5
FBK 3 OV	0.7 MHz/mm²	3.15

Which is obviously way too much

Problem and a solution

The FCT is positioned in the forward direction with as little material in front as possible to suppress photons from external bremsstrahlung.

In the forward direction, the z position resolution is (likely) weak such that we cannot distinguish tracks from the ~20 primary vertices per ROF of the MAPS (500 ns).

An alternative is **single event analysis** during the initial **low-intensity phase of the HL-LHC** such that there will be **1 collision per 500 ns**. e.g. a dedicated low luminosity run.

Then we can use a ROF of 2 - 20 ns for the SiPMs, drastically reducing the DCR.

Gaining insight - Typical values and importance of DCR

		Scales with		
Radiator:	Helium		Radiator:	Helium
Radiator length:	1 m		Radiator length:	1.8 m
Number of photons:	8.1	L * $\tan^2(\theta_{ch})$	Number of photons:	14.7
Number detected:	1.6	det. efff * L * $\sin^2(\theta_{ch})$	Number detected:	2.9
DCR per ROF per SiPM:	0.018		DCR per ROF per SiPM:	0.018
N. SiPMs in check area:	24.4	L^2 * $\tan^2(\theta_{ch})$	N. SiPMs in check area:	80.4
Number Dark Counts:	0.44		Number Dark Counts:	1.45

Frank-Tamm theory

$$N_{\text{prod}} = \frac{\alpha}{\hbar c} Z^2 L \int_{E_1}^{E_2} \sin^2 \theta dE_\gamma$$

CCC:
Current status
Considerations
& Conclusions

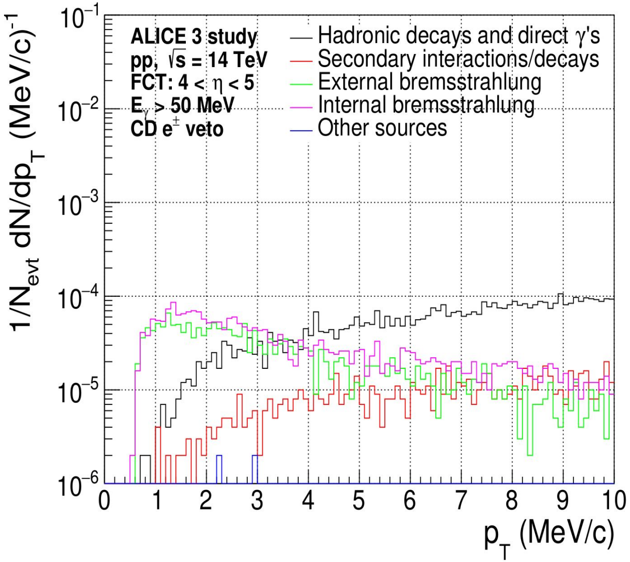
Current status

Results - Helium - Signal over background is ~ unity

H3050CS

L = 1.81 m

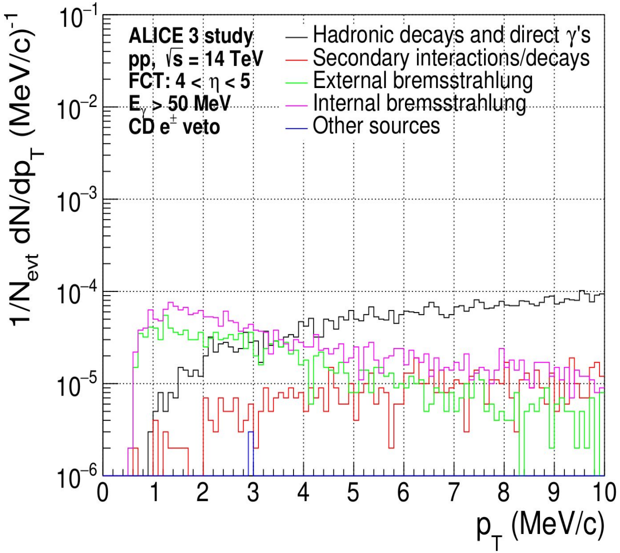
$N_{\text{Hits th.}} = 2$



H3075CS

L = 2.45 m

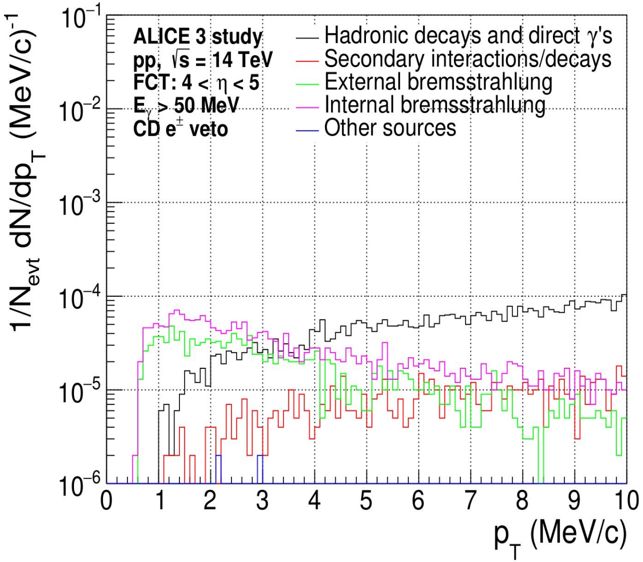
$N_{\text{Hits th.}} = 3$



FBK 3V OV

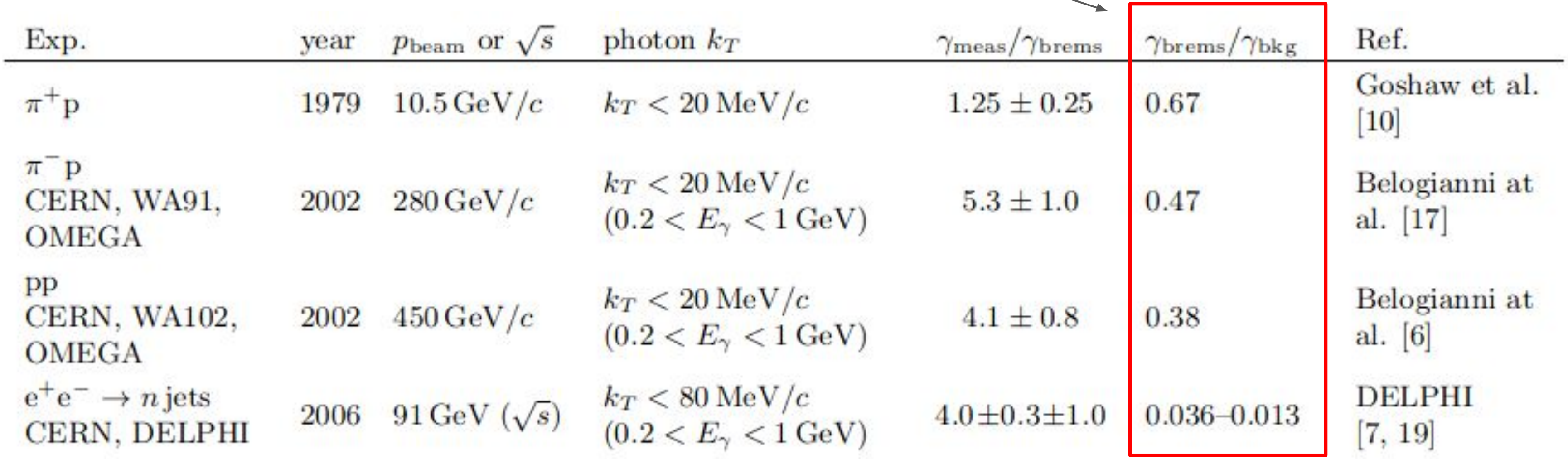
L = 2.98 m

$N_{\text{Hits th.}} = 3$



This holds up quite well to previous experiments

Expected signal over background of some previous experiments. No enhancement



Exp.	year	p_{beam} or $\sqrt{s}$	photon k_T	$\gamma_{\text{meas}}/\gamma_{\text{brems}}$	$\gamma_{\text{brems}}/\gamma_{\text{bkg}}$	Ref.
π^+p	1979	$10.5\,\text{GeV}/c$	$k_T < 20\,\text{MeV}/c$	1.25 ± 0.25	0.67	Goshaw et al. [10]
π^-p CERN, WA91, OMEGA	2002	$280\,\text{GeV}/c$	$k_T < 20\,\text{MeV}/c$ $(0.2 < E_\gamma < 1\,\text{GeV})$	5.3 ± 1.0	0.47	Belogianni at al. [17]
pp CERN, WA102, OMEGA	2002	$450\,\text{GeV}/c$	$k_T < 20\,\text{MeV}/c$ $(0.2 < E_\gamma < 1\,\text{GeV})$	4.1 ± 0.8	0.38	Belogianni at al. [6]
$e^+e^- \to n$ jets CERN, DELPHI	2006	$91\,\text{GeV}$ $(\sqrt{s})$	$k_T < 80\,\text{MeV}/c$ $(0.2 < E_\gamma < 1\,\text{GeV})$	$4.0 \pm 0.3 \pm 1.0$	0.036–0.013	DELPHI [7, 19]

Anomalous soft photons: status and perspectives : 2406.17959

Considerations

We can do better

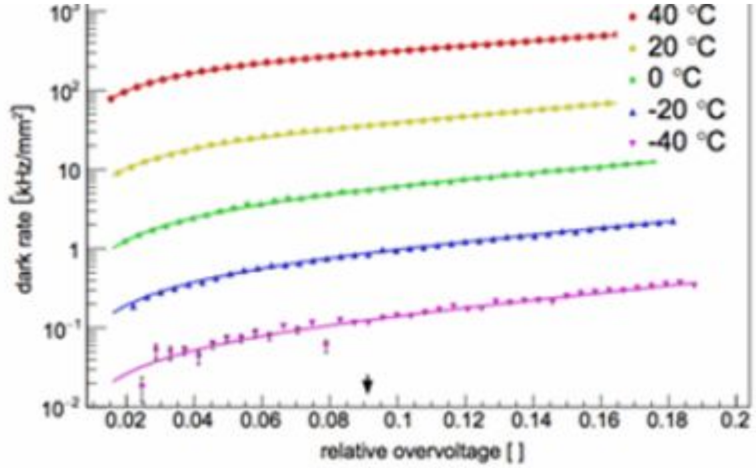
Cooling the Hamamatsu SiPM down to reduce DCR

Cooling the SiPM down looks like it can achieve a reduction for the DCR in the order of 2 orders of magnitude

Bringing the DCR potential down to 10 KHz/mm^2.

However, the effect of being in a high radiation zone and cooling the SiPM is unknown. Needs to be studied

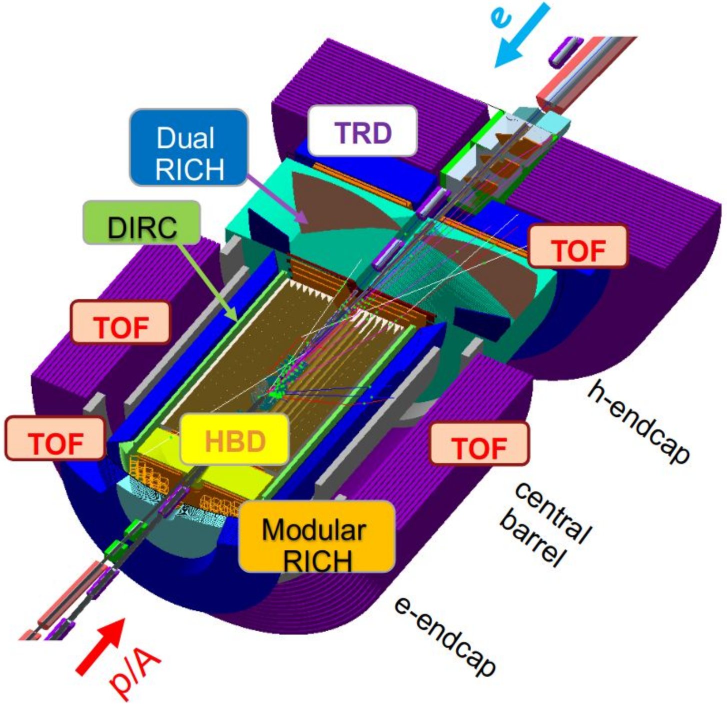
For the SiPM 13360-3050cs

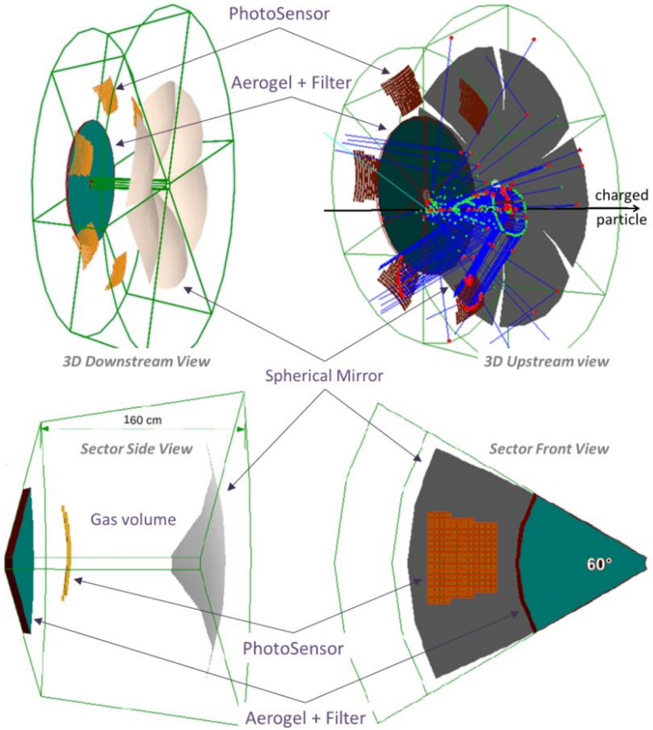


Source: How does temperature affect the performance of an SiPM?

*Sorry for the low quality picture. It was already bad in the source

The dual RICH of the ePIC detector at EIC





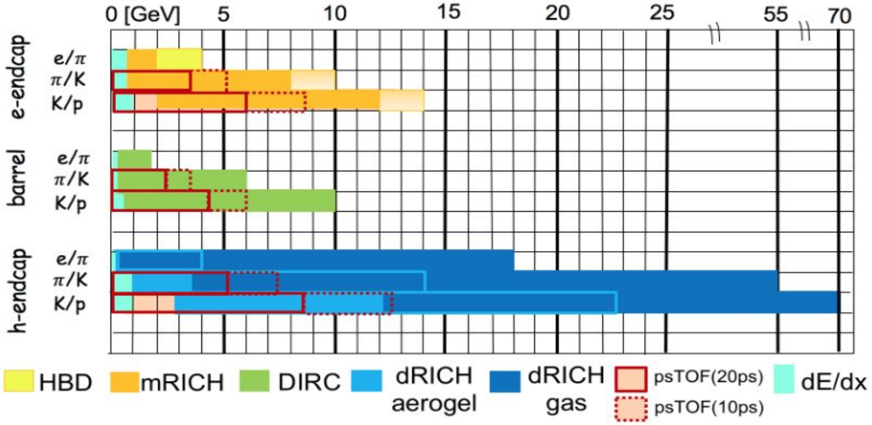
EIC Yellow report

Good performance of the dual RICH

The goal of the dRICH is to provide full hadron identification (π/K/p better than 3 σ apart) from a few GeV/c up to ~50 GeV/c in the outgoing ion-side

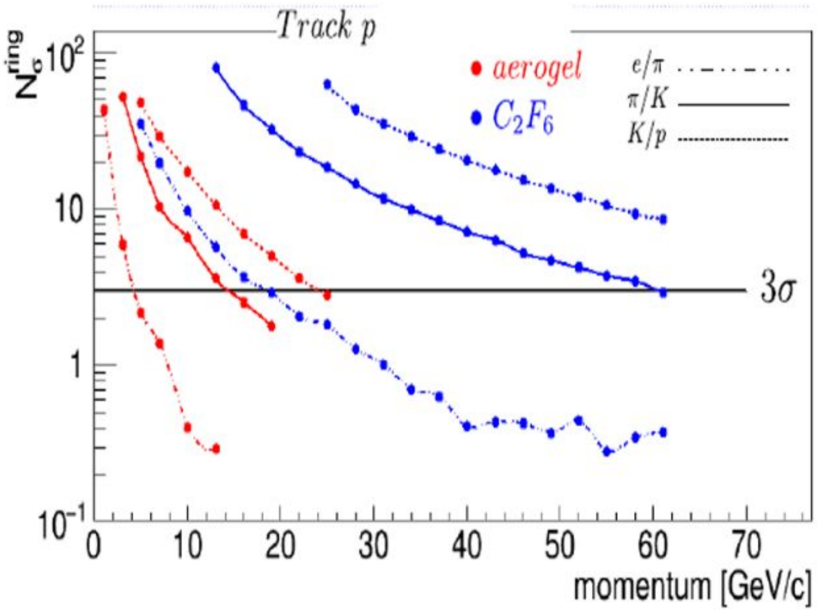
e/π separation up to about 15 GeV/c as a byproduct

Projection of momentum ranges covered



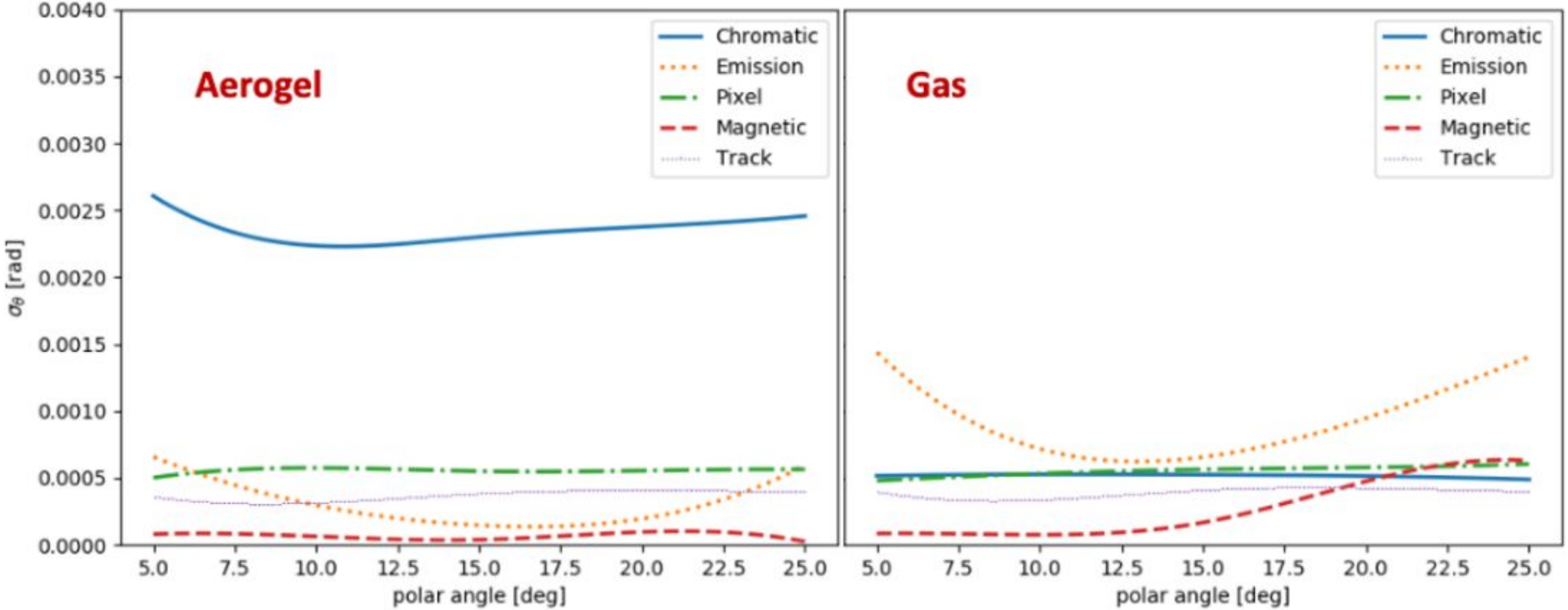
AI-optimized detector design for the future Electron-Ion Collider: the dual-radiator RICH case

Performance of dRICH for different particle types



EIC Yellow report

How do they achieve this? - Good angular resolution

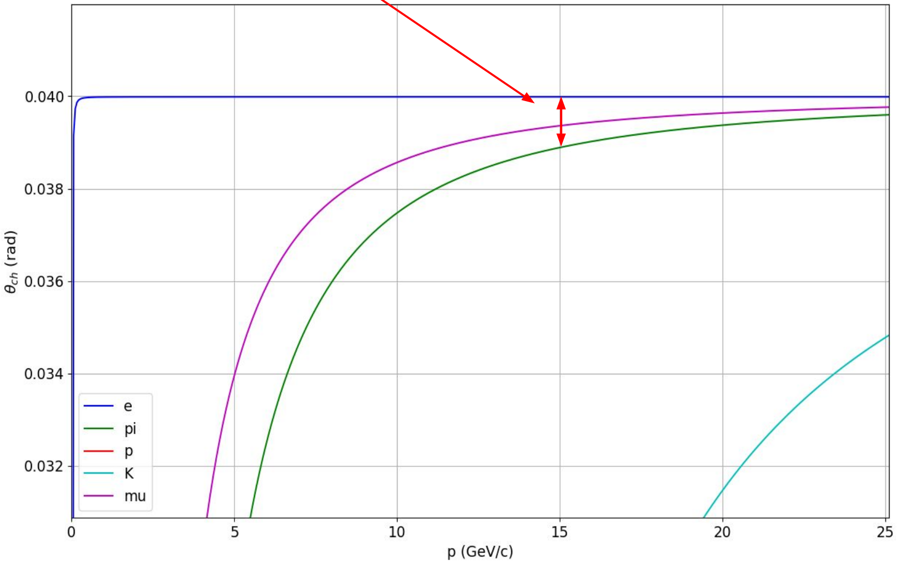


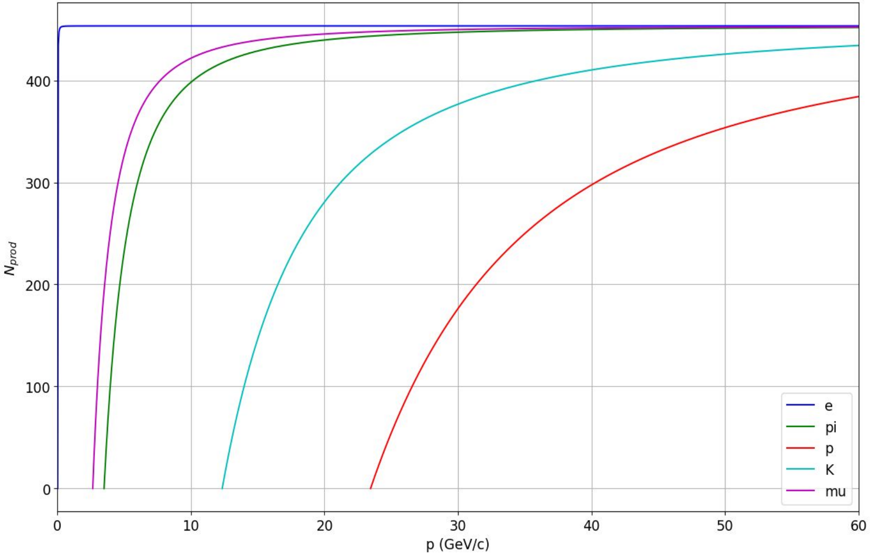
EIC Yellow report

How do they do this?

They use C_2F_6 with n = 1.0008
With $\sigma_\theta < 0.0015$, they can
achieve this separation

They also produce plenty of photons. In comparison, with helium, you produce ~15 photons



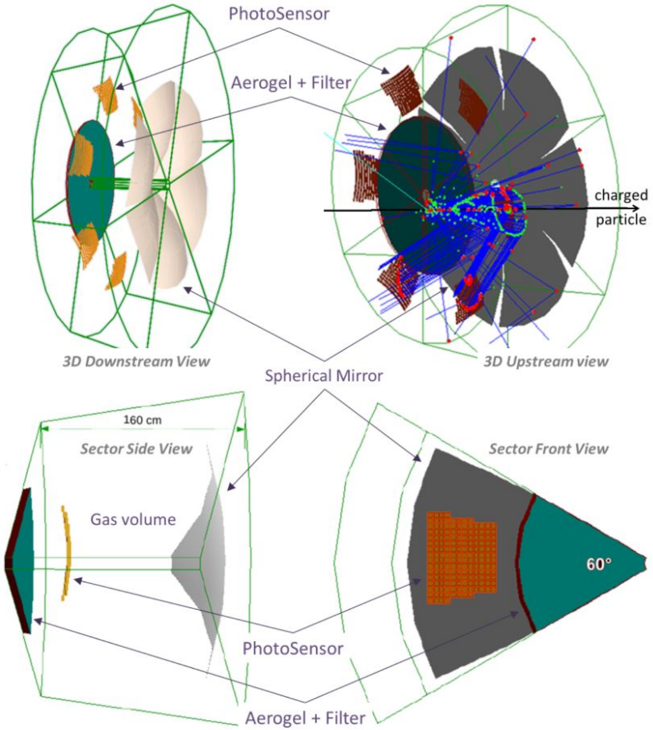


Focusing mirrors - Instrumented area reduction

dRICH divided in 6 identical, open sectors (petals) which map the produced photons on a smaller area (A_s): 4500 cm^2/sector located outside of acceptance

Mirror radius 2.9 m, so an area (A_m) of 26.4 m^2 shared by both radiators
A quick calculation of the mapping factor $A_{m/6}/A_s \cong 9.8^*$

With GEANT4 simulations for the barrel rich, Nicola Nicassio reached an area reduction of a factor of 4.



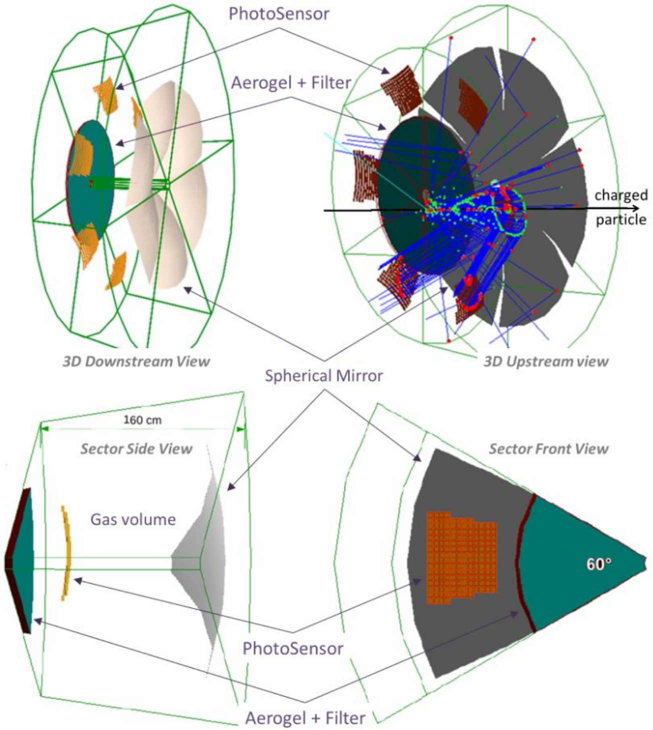
EIC Yellow report

*This factor could be off. I suspect they made the mirror bigger than the pseudorapidity coverage they were aiming for (i.e. that of the aerogel), but I could not find a statement on this.

Focusing mirrors - Benefits CD for the FCT

This reduction of active area (4 - 9) helps lower the measured number of dark counts

It also brings the SiPMs out of the high radiation zone of the FCT, which then in turn reduces the DCR.



EIC Yellow report

Why helium and this strategy?

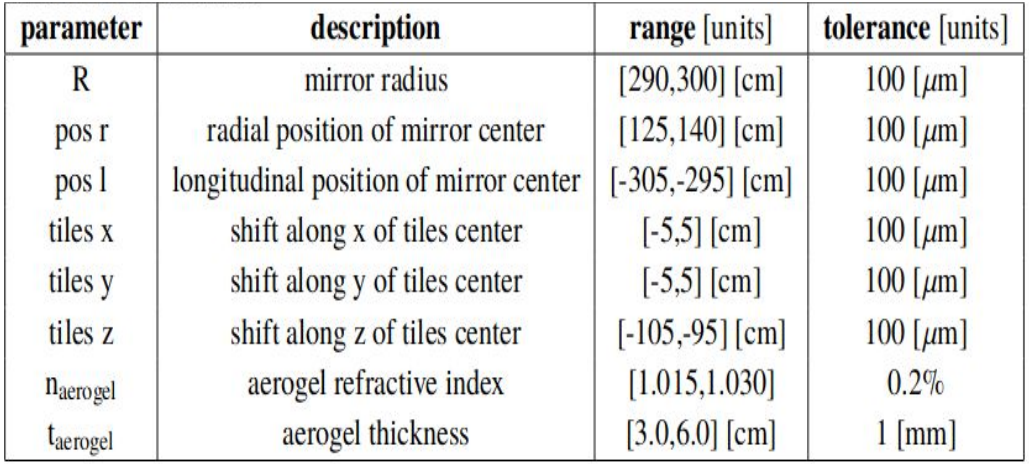
Why not copy the design and strategy of the dRICH?

1. It is conceptually easy to implement

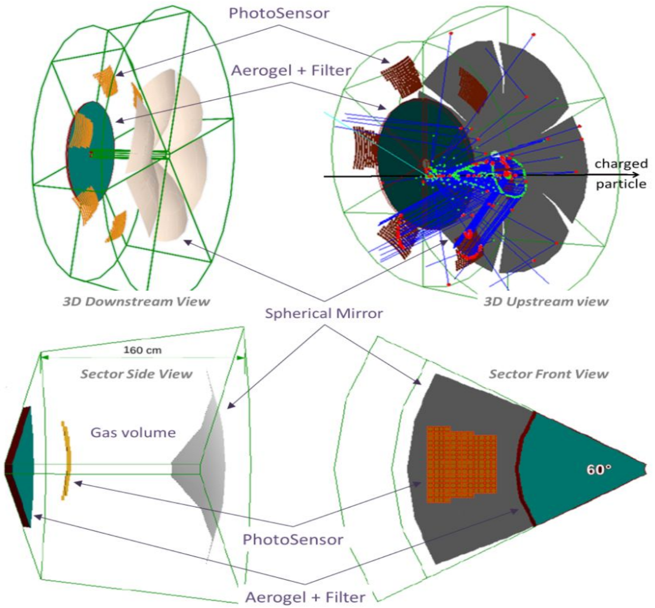
2. I did not have enough time since I am finishing my PhD soon

What is so hard about the dRICH design?

The dual-radiator Ring Imaging Cherenkov detector at the future Electron-Ion Collider (EIC) was optimized based on Bayesian optimization and machine learning that encodes detector requirements. http://arxiv.org/abs/1911.05797



parameter	description	range [units]	tolerance [units]
R	mirror radius	[290,300] [cm]	100 [μm]
pos r	radial position of mirror center	[125,140] [cm]	100 [μm]
pos l	longitudinal position of mirror center	[-305,-295] [cm]	100 [μm]
tiles x	shift along x of tiles center	[-5,5] [cm]	100 [μm]
tiles y	shift along y of tiles center	[-5,5] [cm]	100 [μm]
tiles z	shift along z of tiles center	[-105,-95] [cm]	100 [μm]
$n_{aerogel}$	aerogel refractive index	[1.015,1.030]	0.2%
$t_{aerogel}$	aerogel thickness	[3.0,6.0] [cm]	1 [mm]

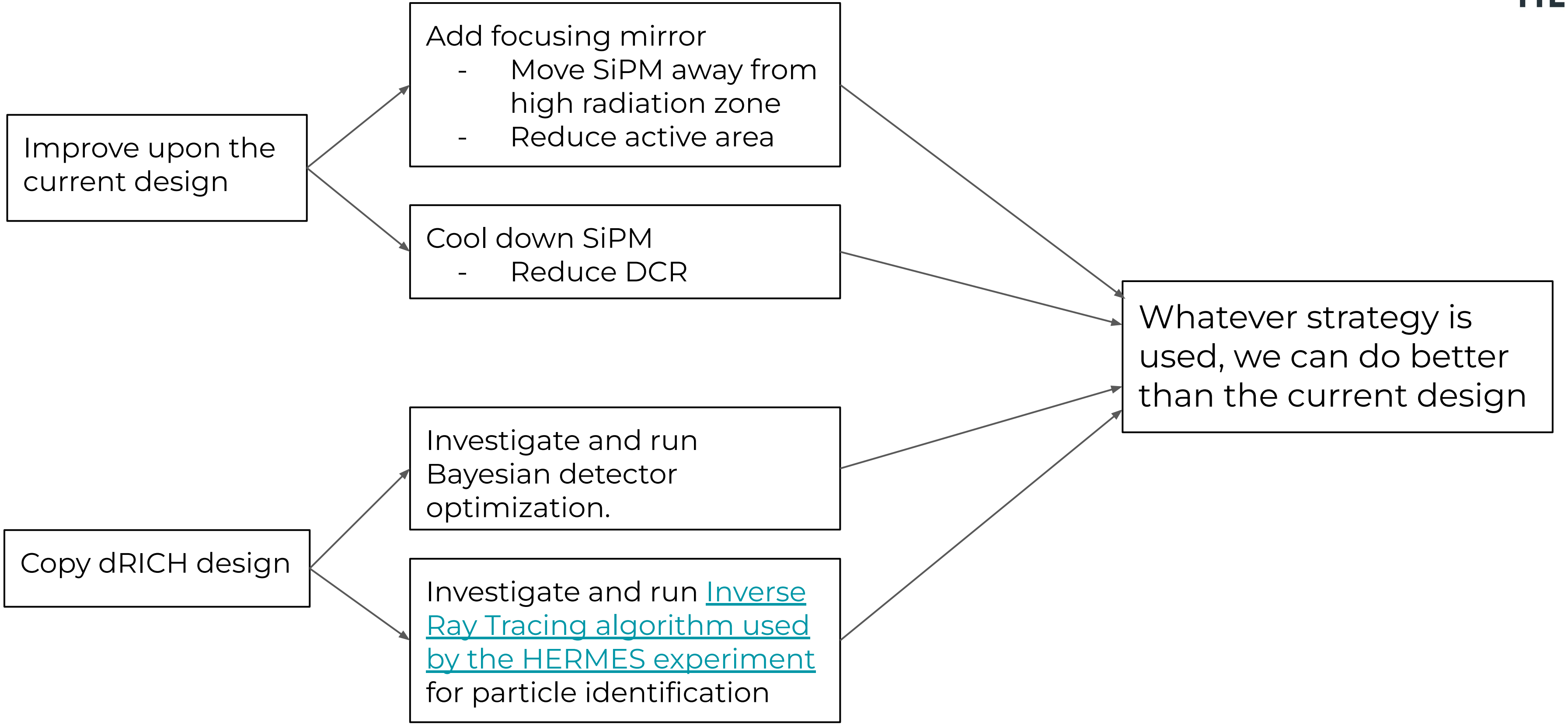


In addition, understanding optics and how to shape mirrors is a time consuming process.
For ring reconstruction they used Inverse Ray Tracing algorithm used by the HERMES experiment

Conclusions

(of this section)

Copy dRICH or improve current design?



Improve upon the current design

Add focusing mirror
- Move SiPM away from high radiation zone
- Reduce active area

Cool down SiPM
- Reduce DCR

Copy dRICH design

Investigate and run Bayesian detector optimization.

Investigate and run [Inverse Ray Tracing algorithm used by the HERMES experiment]() for particle identification

Whatever strategy is used, we can do better than the current design

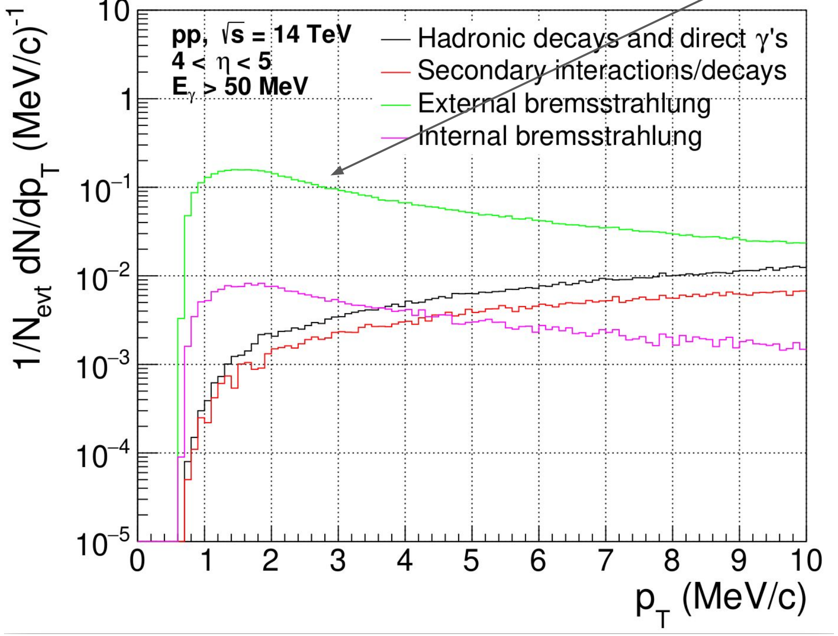
Additional strategy: Calculate the theoretical external bremsstrahlung spectrum without adding a cherenkov detector

Calculate the external bremsstrahlung spectrum

How do we disentangle this?

Anomalous soft photons: status and perspectives : 2406.17959

No electron veto



We measure the passive material in front of the FCT in terms of x/X_0. Due to the forward boost, electrons and positrons from photon conversions have large enough energies for the following approximation:

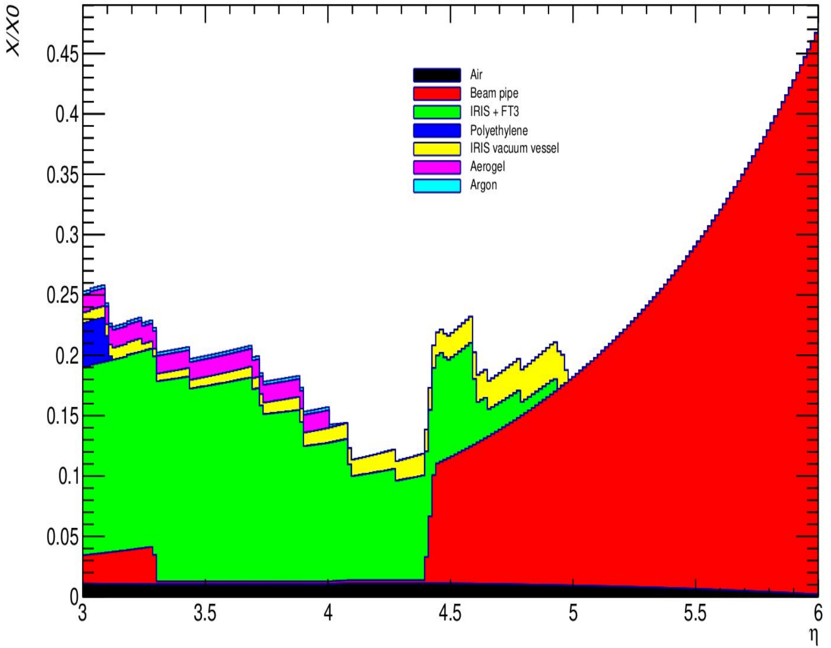
$$\frac{dN_\gamma^{\text{ext. brems}}}{d\omega_k} = \frac{x}{X_0}\left(\frac{4}{3}\frac{1}{\omega_k} - \frac{4}{3}\frac{1}{E_e} + \frac{\omega_k}{E_e^2}\right) \approx \frac{4}{3}\frac{x}{X_0}\frac{1}{\omega_k}$$

Photons, e.g. from a π^0 decay, convert in passive material with a probability $7/9\ x/X_0$. So for a pseudorapidity density of the decay photons

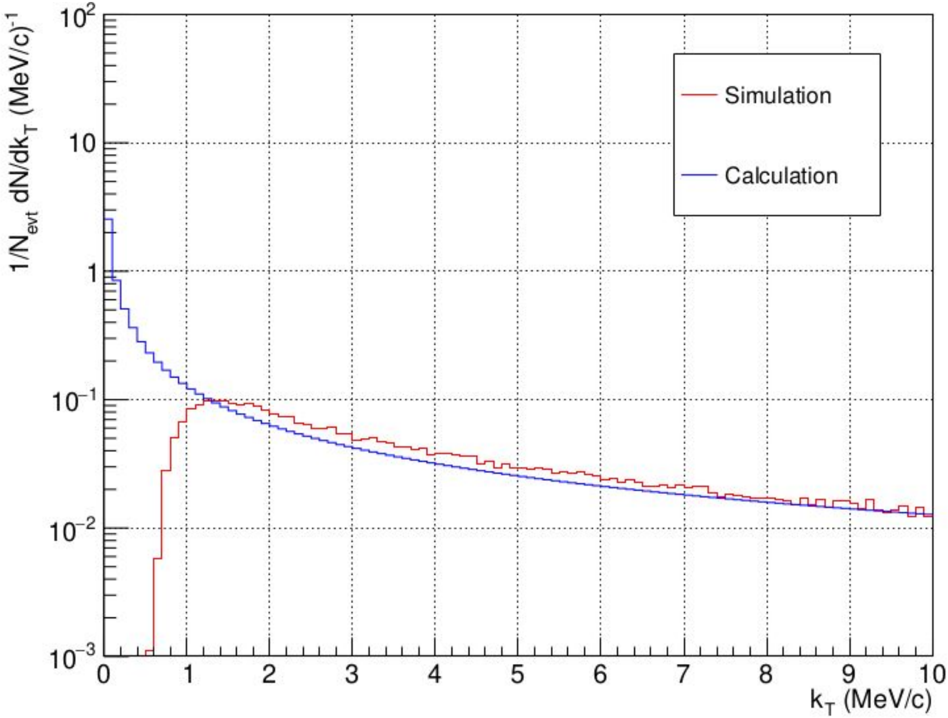
$$\frac{dN_\gamma^{\text{ext. brems}}}{d\omega_k dk_T} = \frac{28}{27}\frac{dN_\gamma^{\text{decay}}}{d\eta}\left(\frac{x}{X_0}\right)^2\frac{1}{k_T}$$

Calculate the external bremsstrahlung spectrum

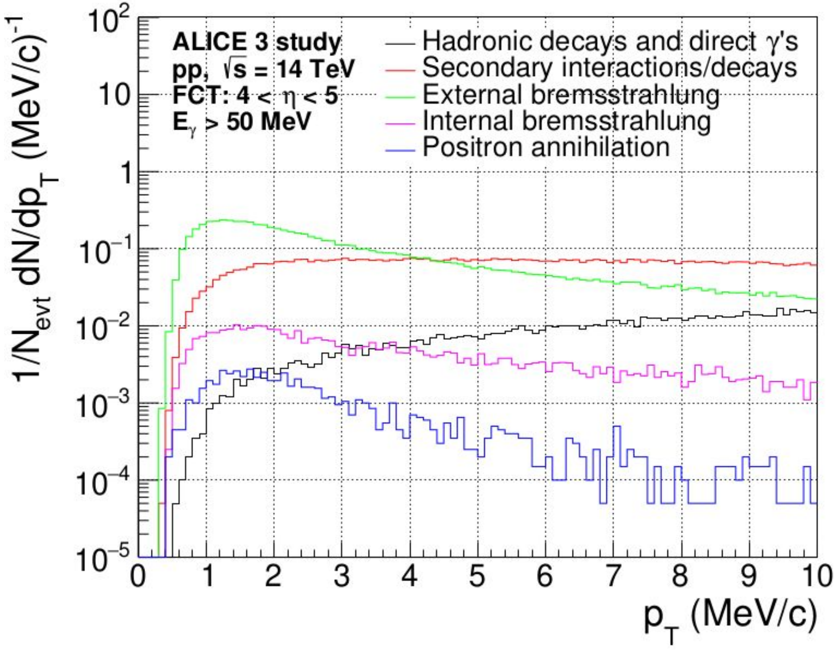
Material budget in front of the FCT



Spectrum of external bremsstrahlungs photons produced by e+e- from decay photons conversions

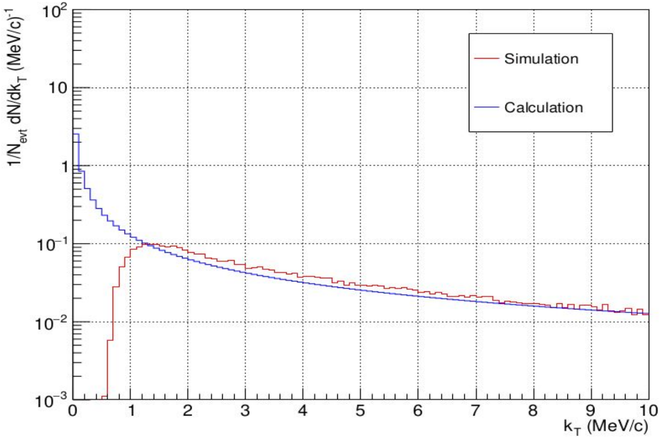


Does not explain the full spectrum, but it is a start



Note: No pointing angle cut was applied here

Spectrum from decay photons converting to e+e- that then produce external bremsstrahlung. Simulation and calculation agree quite well



Full spectra doesn't match because there are lots of other effects:
- Electrons coming from other pseudorapidity regions, e.g. η > 5
- Electrons coming from other production processes
- π^0/η coming from other production processes
- Photons coming from other production processes

Good agreement is a start, but full spectra not yet complete

Summary and outlook

(Of the presentation)

Summary & Outlook

With the simulated setup, the prospected s/b we can achieve is unity => Measurement possible

To improve the performance, the DCR can be lowered by
- Introducing a focusing mirror to reduce the active area of SiPMs (max. 1 order of magnitude)
- Cooling the SiPMs down (max. 2 orders of magnitude)

Copying the design of the dRICH of the ePIC detector at the EIC is promising, but requires more research

A start has been made to calculate the theoretical background spectrum, but also requires more research. The precision with which we can eventually do this is unknown as of yet

The results so far are promising: we need more people to perform further studies, optimize the setup and build the detector. Unique chance for an interesting physics case

Outlook

Tracking to start soon. Going to study ACTS with Pavel

Backup

Simulation strategy - Detailed explanation

- Use O^2 to simulate 10M pp interactions for ALICE 3
- Do the analysis event-by-event
- For each charged particle in each event, calculate how many photons are emitted in the sensitive range of the SiPM with Frank-Tamm theory and draw from poisson
- $1/\lambda^2$ for cherenkov photon energy spectrum
- Randomly select emission angle. Use Rodrigues' rotation
- Calculate where the photon will end up in the SiPM layer
- Check if photon is detected - PDE of SiPM and dead zone
- Calculate the expected number of Dark Counts and draw from poisson
- Charged particle makes signal if in active zone of SiPM
- Check if there are overlaps of photons, dark counts and charged particle
- Predict if particle is electron or not based on number of SiPM hits in the vicinity of the particle (nHits = nPhotons + nDCs + chargedParticle)
- Check if event contains electron. If so => Veto

$$N_{\mathrm{prod}} = \frac{\alpha}{\hbar c} Z^2 L \int_{E_1}^{E_2} \sin^2 \theta dE_\gamma$$

Optimal detector length

$$N_{\gamma\mathrm{Det}} = aL - bL - c$$

a: Number of photons produced multiplied by detection efficiency. The following enters:

- PDE of SiPM
- $1/\lambda^2$cherenkov photon wavelength spectrum
- N photons produced - Frank-Tamm Theory ~ L
- Dead zone of SiPM

b: Average number of dark counts. The following enters:

- ROF
- DCR of SiPM
- Check area around charged particle ~ L^2
- Notable: Area of SiPM drops out

c: Number of hits by charged particle. The following enters:

- Dead zone of SiPM
- No L dependence

Optimizing this

$$\frac{dN_{\gamma\mathrm{Det}}}{dL} = 0$$

Solving for L gives

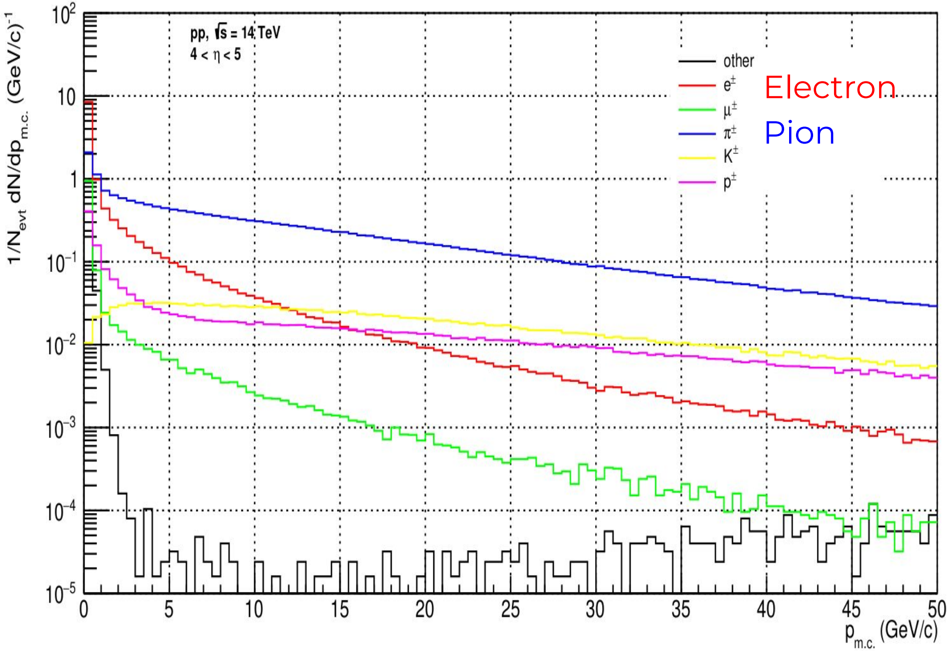
$$L = \frac{a}{2b}$$

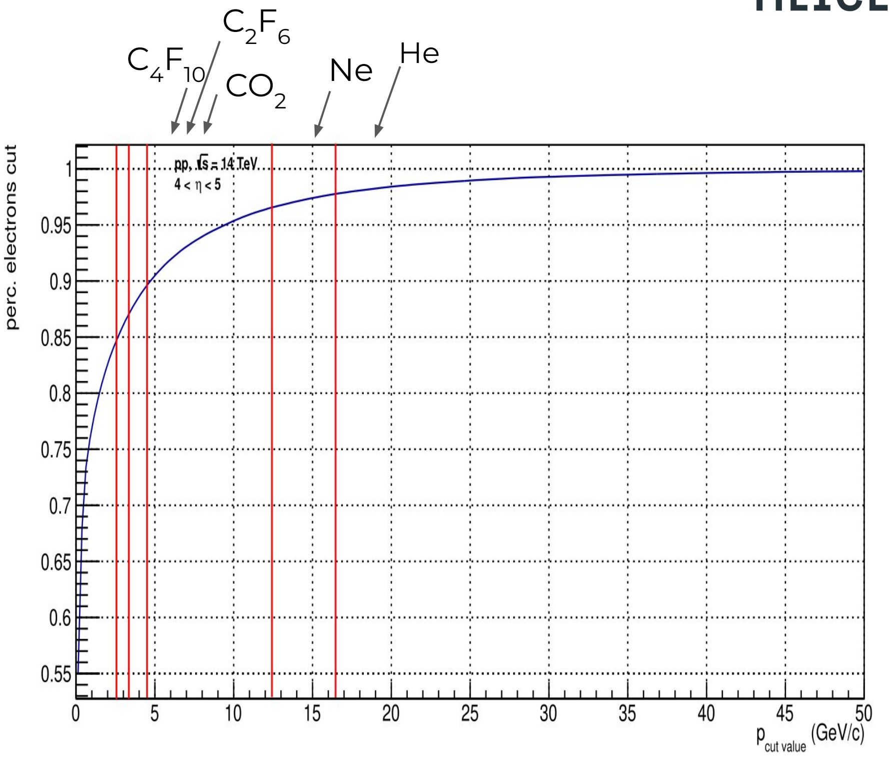
Result independent of θ_{ch} since

$$\frac{\sin^2\theta_{\mathrm{ch}}}{\tan^2\theta_{\mathrm{ch}}} \approx 1 \text{ for } \theta_{\mathrm{ch}} << 1$$

Not the full story. Differences helium and neon

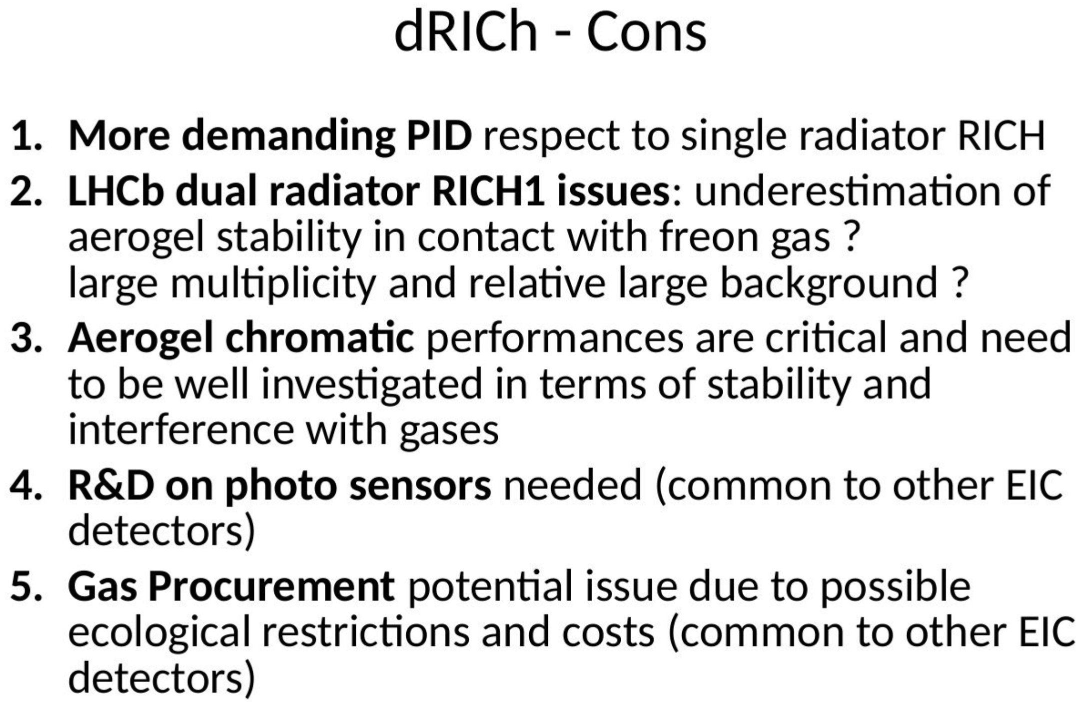
Charged particle spectrum of FCT





By using neon, you lose some access to higher momentum electrons

dRICH restriction



dRICh - Cons

1. **More demanding PID** respect to single radiator RICH
2. **LHCb dual radiator RICH1 issues**: underestimation of aerogel stability in contact with freon gas ?
   large multiplicity and relative large background ?
3. **Aerogel chromatic** performances are critical and need to be well investigated in terms of stability and interference with gases
4. **R&D on photo sensors** needed (common to other EIC detectors)
5. **Gas Procurement** potential issue due to possible ecological restrictions and costs (common to other EIC detectors)

Source: https://indico.bnl.gov/event/11053/contributions/46968/attachments/33320/53537/EIC-CORE-drich-2103.pdf

Inverse ray tracing - backup slide

They used: [Inverse Ray Tracing algorithm used by the HERMES experiment]

It can be boiled down to asking the question:
“[...] given a track and a hit in the RICH photon detector plane, at which angle was the photon emitted? Assume that the emission point can be estimated.”
- Quote from the paper

Given:

- Point E : likely emission point
- Point D : detection point
- Point C : center of spherical mirror the photons scatter from

=> Find point S on the surface of the mirror where the photon scattered.

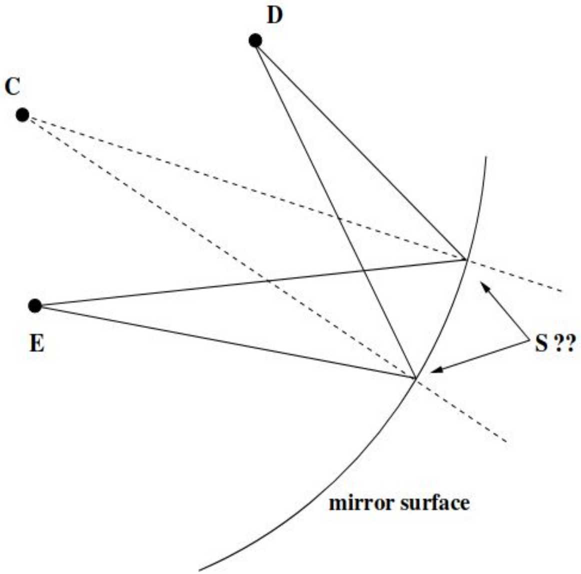


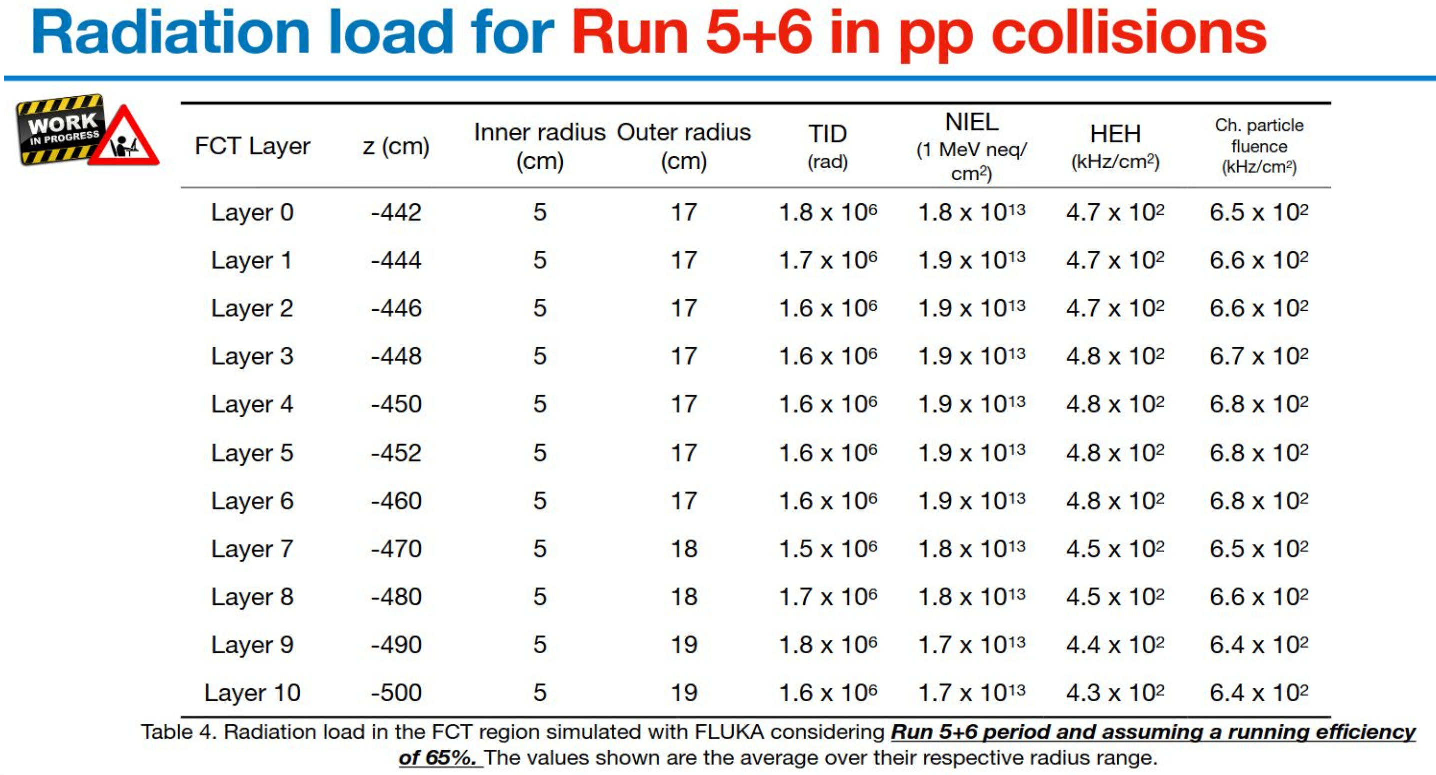
Fig. 13. The problem of inverse ray tracing.

High radiation zone

High radiation zone has an impact on the DCR and longevity of the SiPMs

The question is:
How much statistics do we need?
And if not much, then the NIEL over the period of time used to collect these statistics is a lot less.

Radiation load studies by Jesús Muñoz



Radiation load for Run 5+6 in pp collisions

FCT Layer	z (cm)	Inner radius (cm)	Outer radius (cm)	TID (rad)	NIEL (1 MeV neq/cm^2)	HEH (kHz/cm^2)	Ch. particle fluence (kHz/cm^2)
Layer 0	-442	5	17	1.8×10^{6}	1.8×10^{13}	4.7×10^{2}	6.5×10^{2}
Layer 1	-444	5	17	1.7×10^{6}	1.9×10^{13}	4.7×10^{2}	6.6×10^{2}
Layer 2	-446	5	17	1.6×10^{6}	1.9×10^{13}	4.7×10^{2}	6.6×10^{2}
Layer 3	-448	5	17	1.6×10^{6}	1.9×10^{13}	4.8×10^{2}	6.7×10^{2}
Layer 4	-450	5	17	1.6×10^{6}	1.9×10^{13}	4.8×10^{2}	6.8×10^{2}
Layer 5	-452	5	17	1.6×10^{6}	1.9×10^{13}	4.8×10^{2}	6.8×10^{2}
Layer 6	-460	5	17	1.6×10^{6}	1.9×10^{13}	4.8×10^{2}	6.8×10^{2}
Layer 7	-470	5	18	1.5×10^{6}	1.8×10^{13}	4.5×10^{2}	6.5×10^{2}
Layer 8	-480	5	18	1.7×10^{6}	1.8×10^{13}	4.5×10^{2}	6.6×10^{2}
Layer 9	-490	5	19	1.8×10^{6}	1.7×10^{13}	4.4×10^{2}	6.4×10^{2}
Layer 10	-500	5	19	1.6×10^{6}	1.7×10^{13}	4.3×10^{2}	6.4×10^{2}

Table 4. Radiation load in the FCT region simulated with FLUKA considering ***Run 5+6 period and assuming a running efficiency of 65%.*** The values shown are the average over their respective radius range.