A Large Ion Collider Experiment

Designing the Forward Conversion Tracker for ALICE 3

HighRR presentation

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Exciting news! I am co-author on a published paper!

ALICE

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Anomalous soft photons: Status and perspectives

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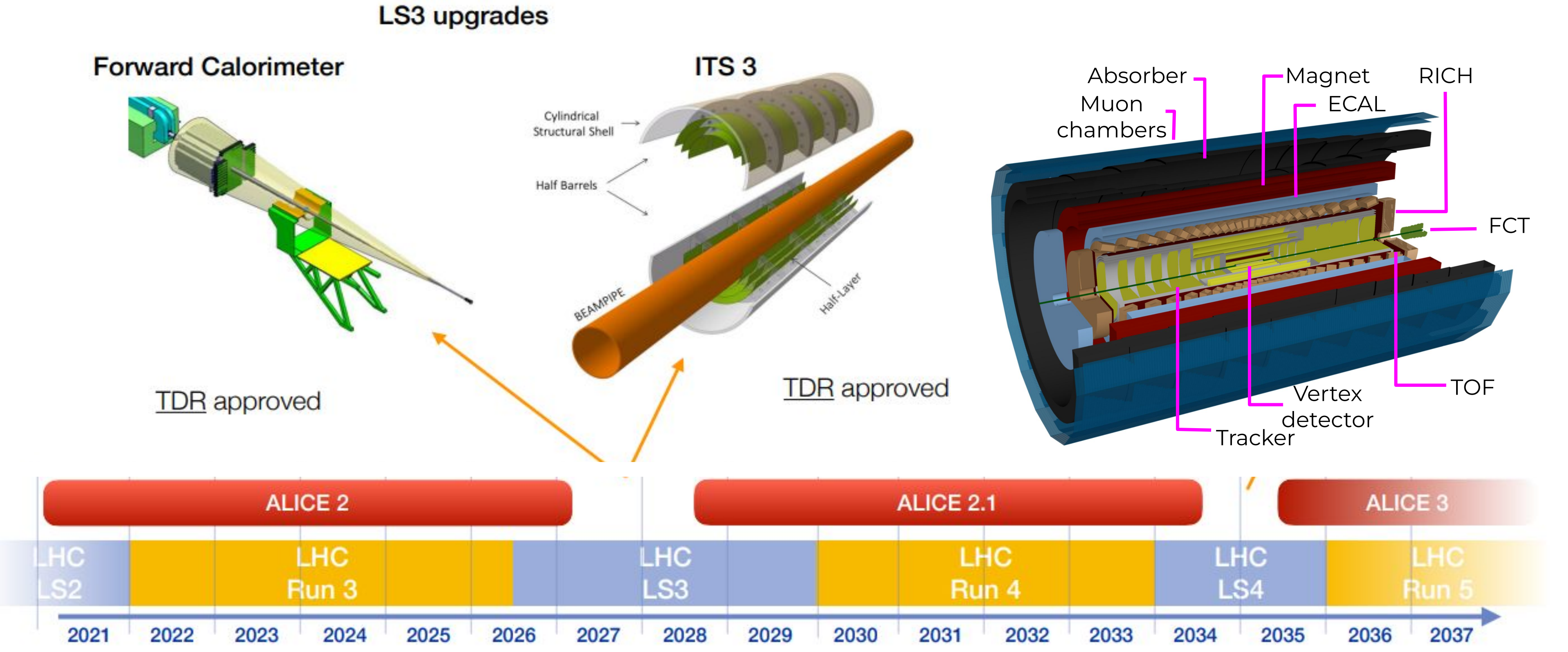
Abstract

This report summarizes the work of the EMMI Rapid Reaction Task Force on “Real and Virtual Photon Production at Ultra-Low Transverse Momentum and Low Mass at the LHC”. We provide an overview of the soft-photon puzzle, i.e., of the long-standing discrepancy between experimental data and predictions based on Low’s soft-photon theorem, also referred to as “anomalous” soft photon production, and we review the current theoretical understanding of soft radiation and soft theorems. We also focus on low-mass dileptons as a tool for determining the electrical conductivity of the medium produced in high-energy nucleus–nucleus collisions. We discuss how both topics can be addressed with the planned ALICE 3 detector at the LHC.

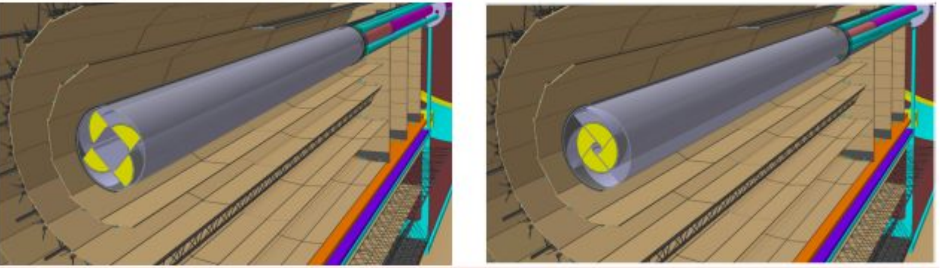
https://www.sciencedirect.com/science/article/pii/S0370157324003478

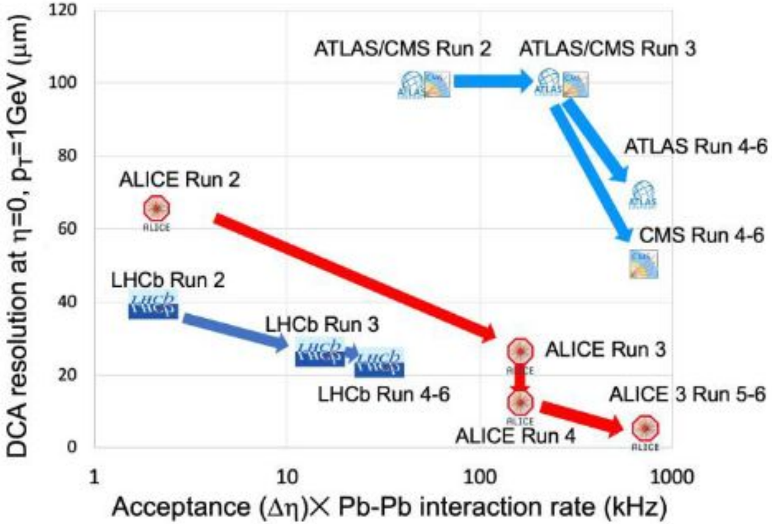
ALICE - Timetable

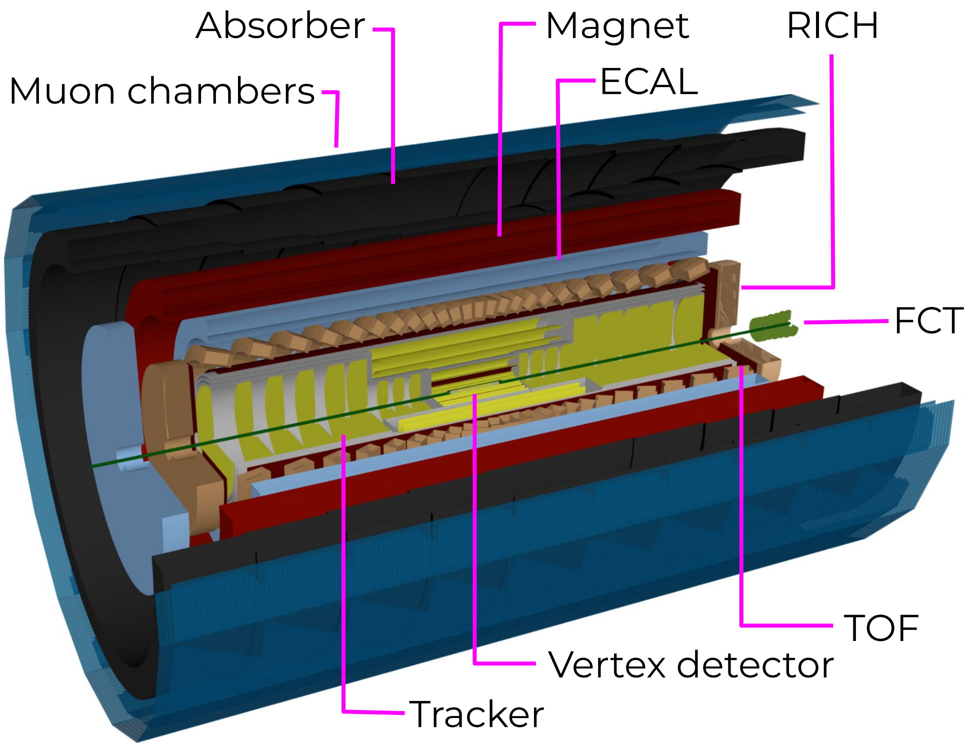


ALICE 3 - A Large Ion Collider Experiment - the next gen

Retractable vertex tracker



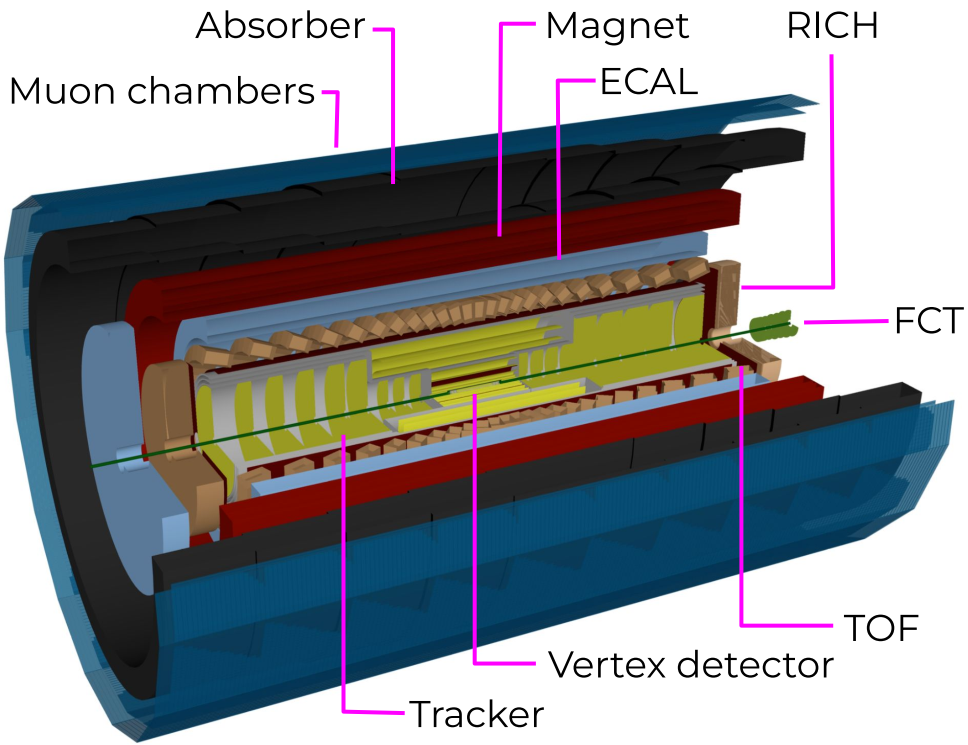




ALICE 3 - A short overview of the physics program

- High-precision beauty measurements
- Multi-charm baryons, P-wave quarkonia, exotic hadrons
- $D\bar{D}$ azimuthal correlations
- QGP thermal radiation
- Chiral symmetry restoration
- Fluctuations of conserved charges
- Ultra-soft photons and tests of quantum field theories
- And more, see Letter of Intent arXiv: 2211.02491

New detector for LHC Runs 5&6



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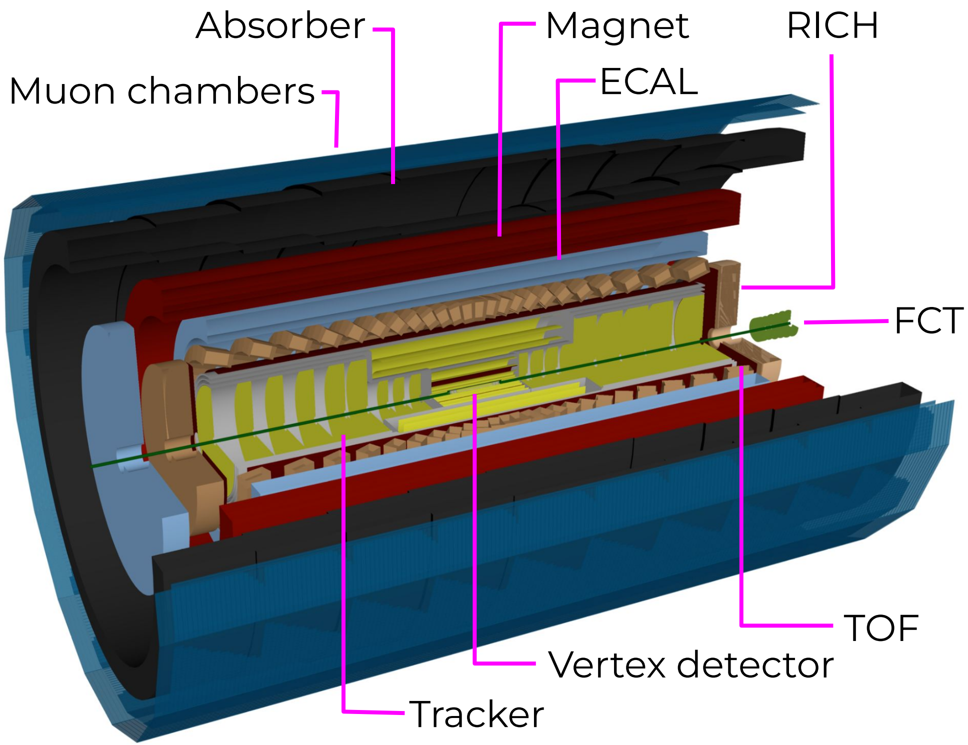
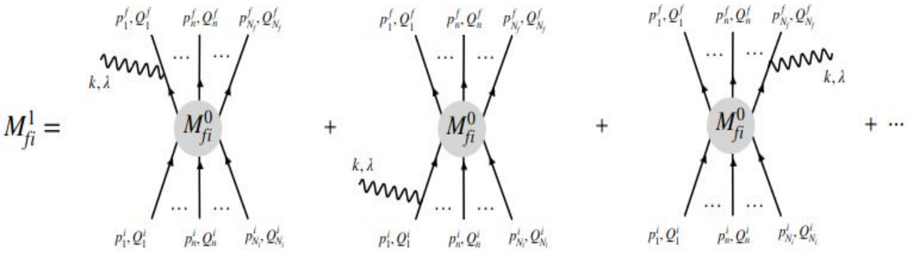


The soft inner-bremsstrahlung spectrum

Very short:

- Particle collision
- Accelerating charged particles (incoming and outgoing) produce the soft inner-bremsstrahlung spectrum
- Low's theorem predicts the inner-bremsstrahlung spectrum in the ultra low energy limit (~MeV scale)
- The measurement of which lead to the so-called "Soft-photon puzzle"



$$M^1_{fi} = \frac{e}{\sqrt{2\omega_k}} \sum_{n=1}^{N_i+N_f} \eta_n Q_n \frac{\epsilon^*(\boldsymbol{k},\lambda)\cdot p_n}{k\cdot p_n} M^0_{fi} + \mathcal{O}(\omega_k^0)$$

- η_n: Outgoing particle: +1, Incoming particle: -1
- Q_n: Charge
- $\epsilon^*(\boldsymbol{k},\lambda)$: Photon polarization 4-vector
- p_n: Charged particle 4-vector
- M^0_{fi}: Non-radiative charged particle production
- $\mathcal{O}(\omega_k^0)$: Higher order corrections

For a more complete overview on the current standing: https://www.sciencedirect.com/science/article/pii/S0370157324003478

Most previous experiments show an excess of a factor of 4-8

Experiment	Year	Collision energy	Photon p_T	Photon / Brems Ratio	Detection method	Reference (click to go to paper)
π^+p	1979	10.5 GeV	p_T < 30 MeV/c	1.25 ± 0.25	bubble chamber	Goshaw et al., Phys. Rev. Lett. 43, 1065 (1979)
K^+p WA27, CERN	1984	70 GeV	p_T < 60 MeV/c	4.0 ± 0.8	bubble chamber (BEBC)	Chliapnikov et al., Phys. Lett. B 141, 276 (1984)
π^+p CERN, EHS, NA22	1991	250 GeV	p_T < 40 MeV/c	6.4 ± 1.6	bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
K^+p CERN, EHS, NA22	1991	250 GeV	p_T < 40 MeV/c	6.9 ± 1.3	bubble chamber (RCBC)	Botterweck et al., Z. Phys. C 51, 541 (1991)
π^-p, CERN, WA83, OMEGA	1993	280 GeV	p_T < 10 MeV/c ($0.2 < E_\gamma < 1$ GeV)	7.9 ± 1.4	calorimeter	Banerjee et al., Phys. Lett. B 305, 182 (1993)
p-Be	1993	450 GeV	p_T < 20 MeV/c	< 2	pair conversion, calorimeter	Antos et al., Z. Phys. C 59, 547 (1993)
p-Be, p-W	1996	18 GeV	p_T < 50 MeV/c	< 2.65	calorimeter	Lissauer et al., Phys.Rev. C54 (1996) 1918
π^-p, CERN, WA91, OMEGA	1997	280 GeV	p_T < 20 MeV/c ($0.2 < E_\gamma < 1$ GeV)	7.8 ± 1.5	pair conversion	Belogianni et al., Phys. Lett. B 408, 487 (1997)
π^-p, CERN, WA91, OMEGA	2002	280 GeV	p_T < 20 MeV/c ($0.2 < E_\gamma < 1$ GeV)	5.3 ± 1.0	pair conversion	Belogianni et al., Phys. Lett. B 548, 122 (2002)
pp, CERN, WA102,	2002	450 GeV	p_T < 20 MeV/c ($0.2 < E_\gamma < 1$ GeV)	4.1 ± 0.8	pair conversion	Belogianni et al., Phys. Lett. B 548, 129 (2002)
$e^+e^- \to$ 2 jets CERN, DELPHI	2006	91 GeV (CM)	p_T < 80 MeV/c ($0.2 < E_\gamma < 1$ GeV)	4.0 ± 0.3 ± 1.0	pair conversion	DELPHI, Eur. Phys. J. C 47, 273 (2006)
$e^+e^- \to \mu^+\mu^-$ CERN, DELPHI	2008	91 GeV (CM)	p_T < 80 MeV/c ($0.2 < E_\gamma < 1$ GeV)	~ 1	pair conversion	DELPHI, Eur. Phys. J. C57, 499 (2008)

Overview made by Klaus Reygers

A short overview of the Soft Photon Puzzle and ALICE 3

Forward Conversion Tracker of ALICE 3 aims to measure the soft photon spectrum via conversions to e+e-

p_T in the range of 1 to 10 MeV/c

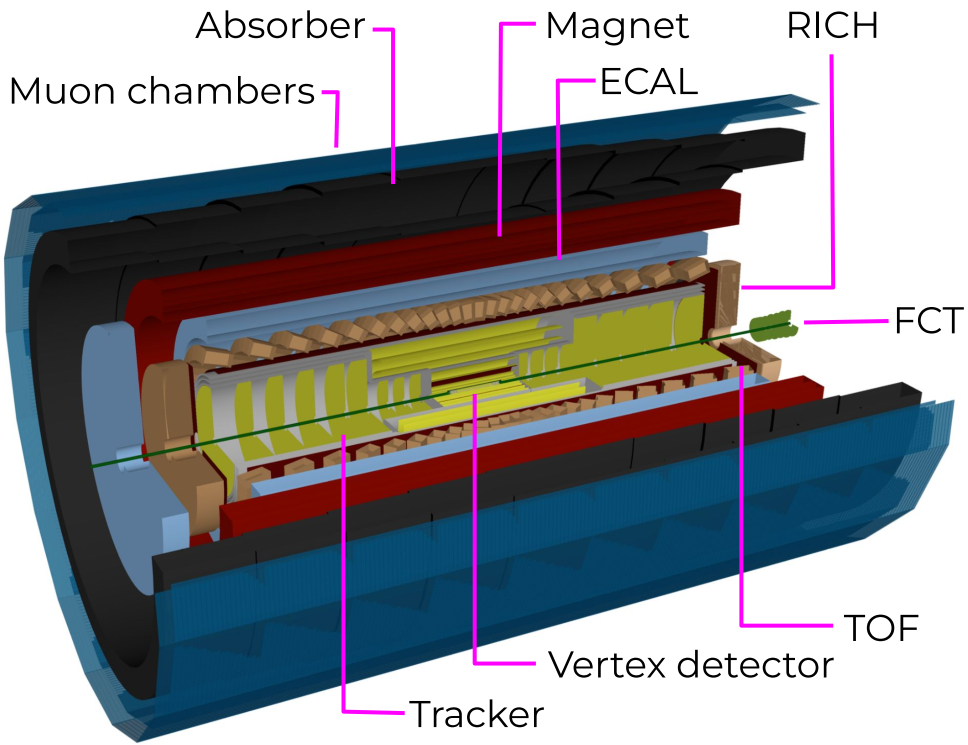
11 consecutive silicon ~~discs~~ (probably squares) with MAPS

Covering a pseudorapidity range of

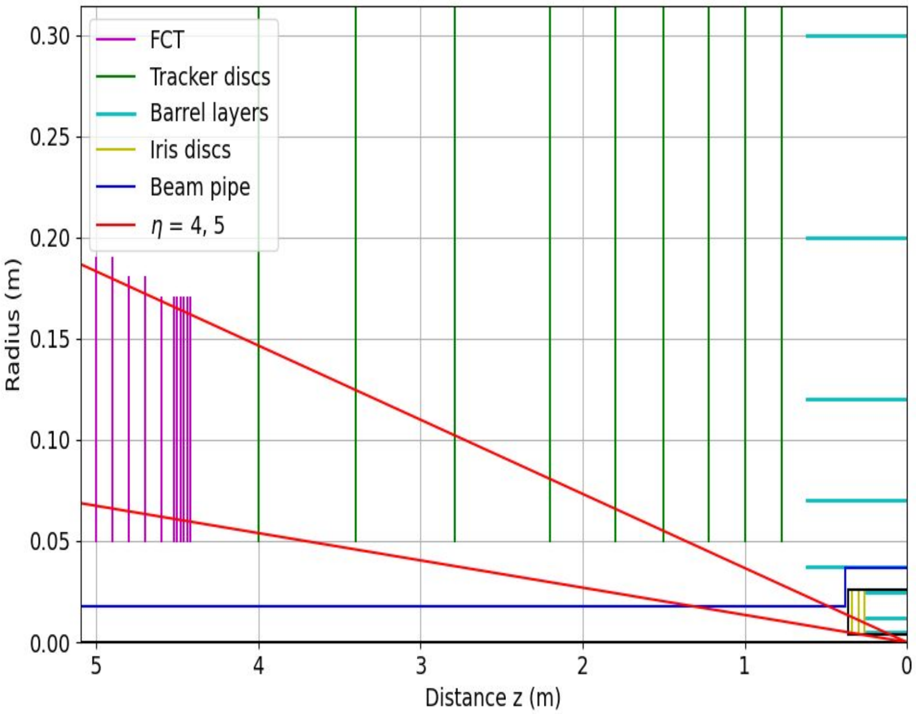
$$4 < \eta < 5$$

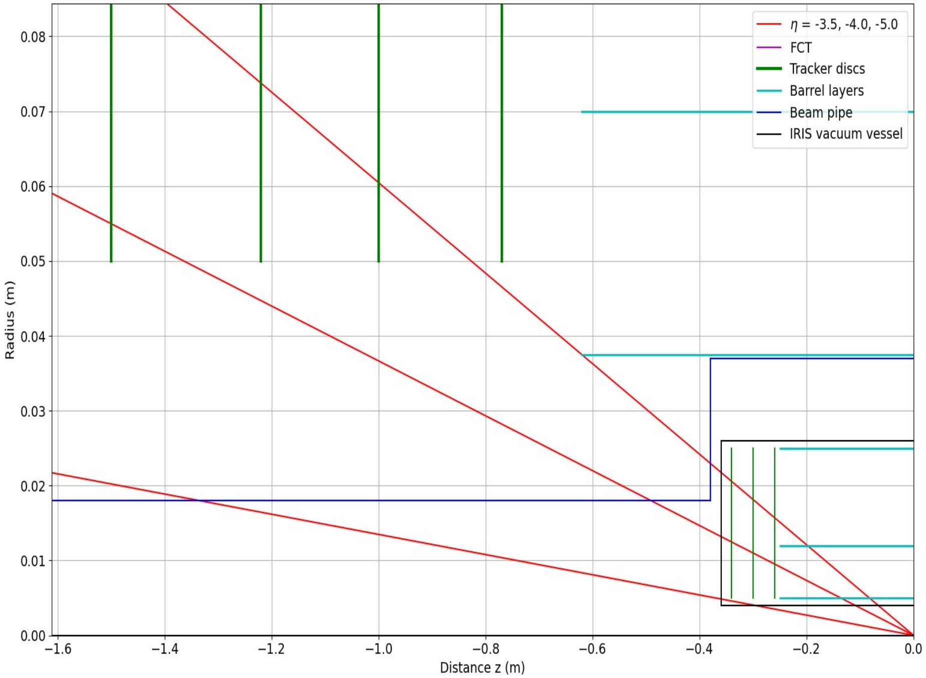
Dipole magnet with $\hat{B}_y$ = 0.25 T instead of a solenoid for better tracking

Cherenkov detector (RICH?) behind the FCT for veto of events containing an electron



Layout and zooming in





Performing simulations of ALICE 3 and the FCT with O^2

The generator

The simulation of 14 TeV pp collisions.

Added the Low photon signal via rejection sampling. Github link

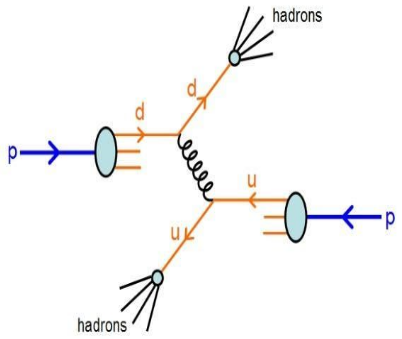
The engine

Transport the particle through the geometry with GEANT4.

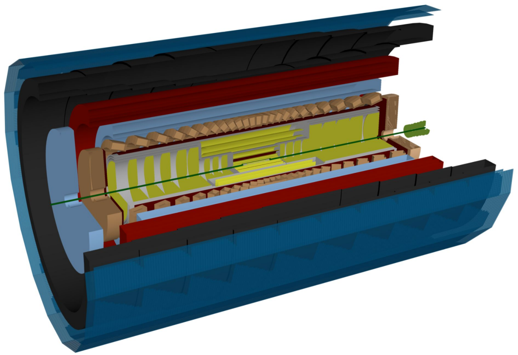
FCT geometry here

The digitizer

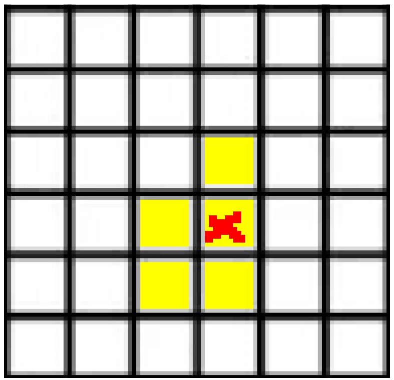
Specific detector response done through the digitization step



Particle stack



Hits



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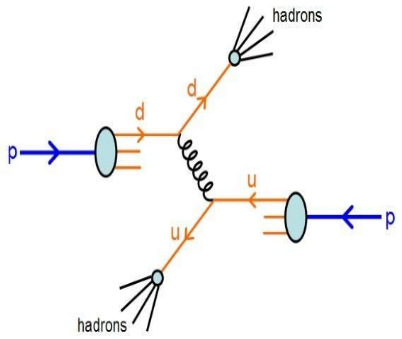

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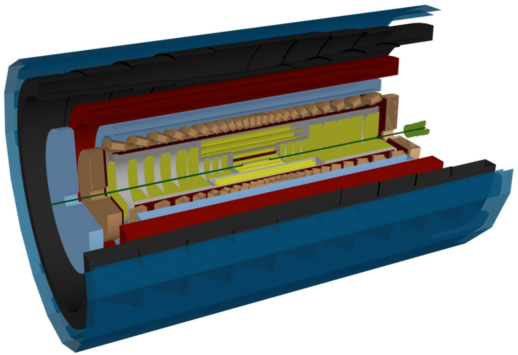
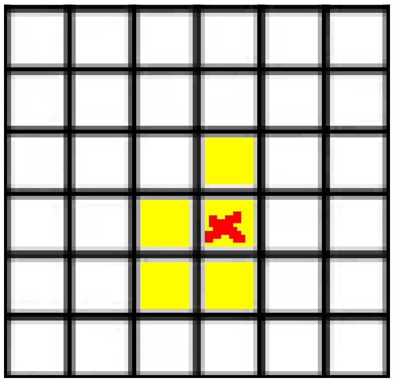


We use this

Hits

The digitizer

Specific detector response done through the digitization step



Reference - 100% identification efficiency

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

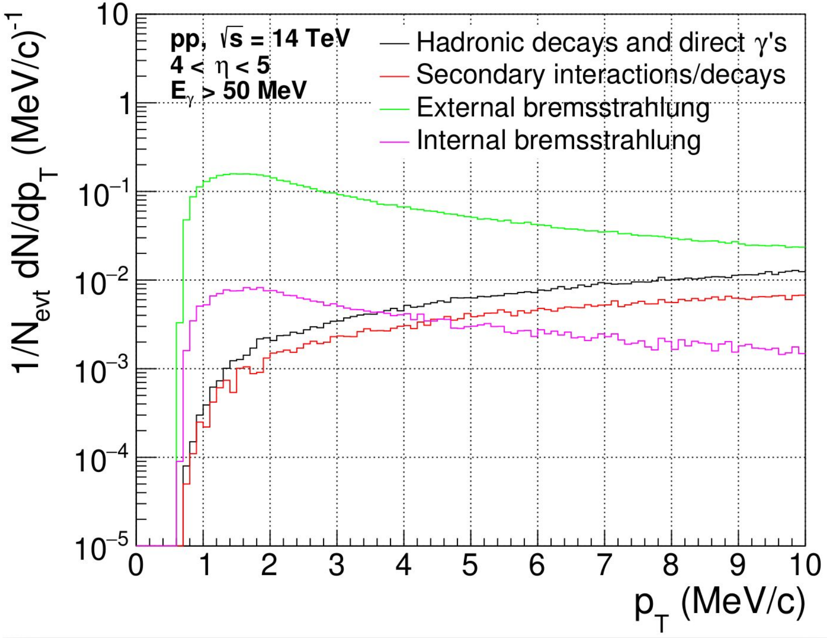
With 100% PID, the measurement is more than possible

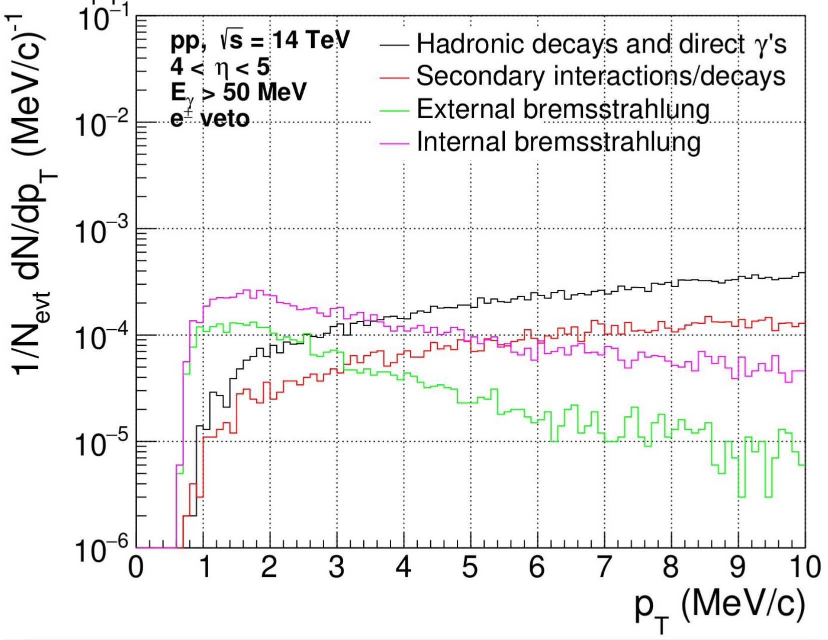
Accept V0's, but veto if single electron present

No electron event veto

Both: Pointing angle cut applied

100% PID electron event veto





With a cherenkov detector (CD) - simulation strategy

What would such a Cherenkov detector look like?

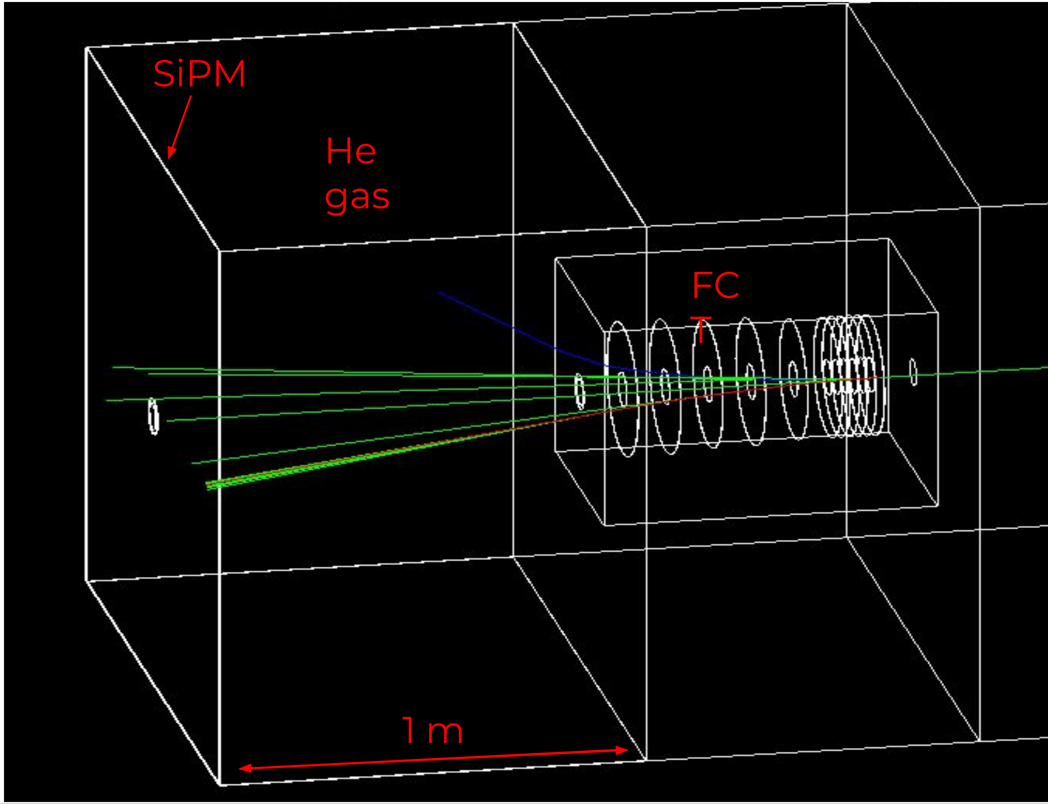
Simulations done with the following setup

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



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Simulations done with t…

Radiation …
Radiation length …

Square grid of …
Response of SiPM…

- Dark count r…
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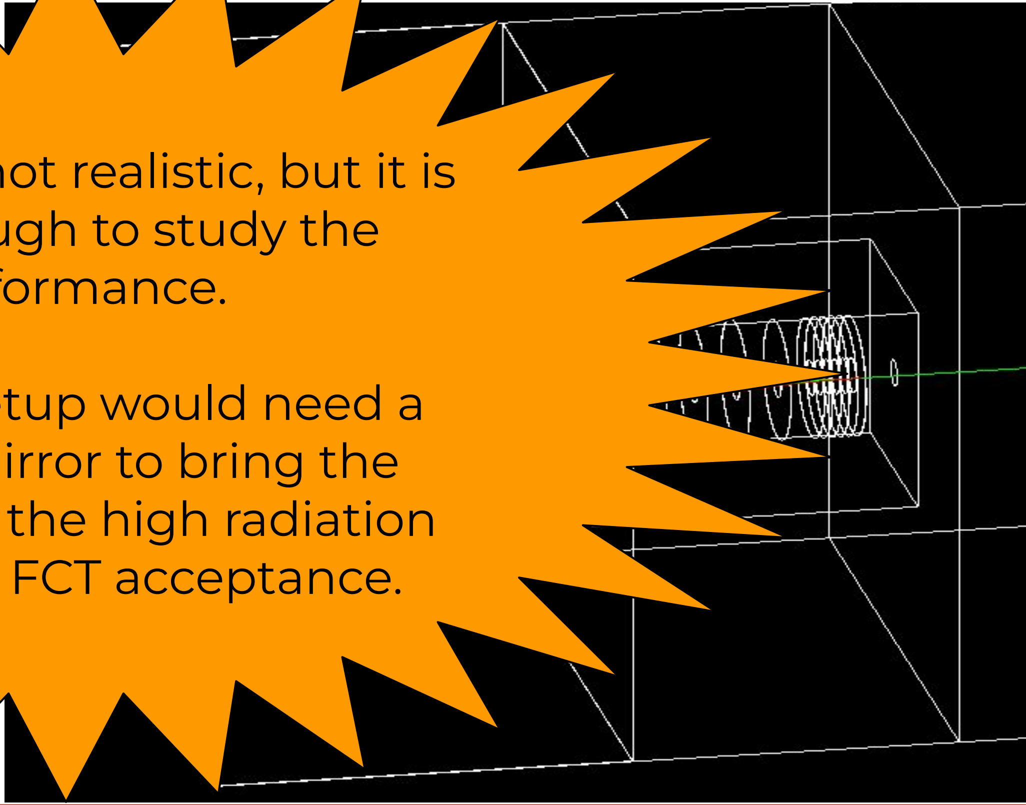


The setup is not realistic, but it is good enough to study the performance.

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.

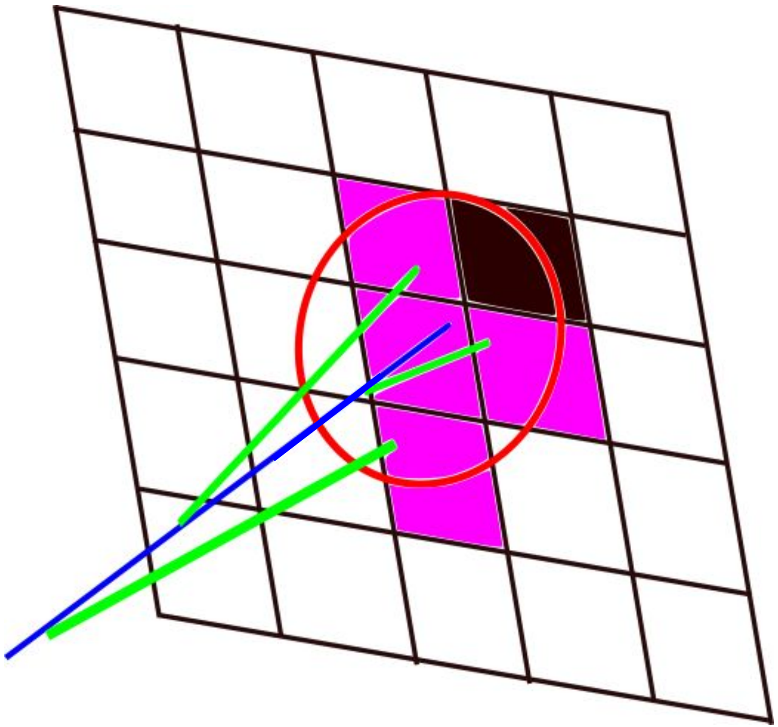
Electron tagging logic	$p < p_{th.\,\pi}$	$p > p_{th.\,\pi}$
$N_{Hits} < N_{Hits\,th.}$	Not electron	Not electron
$N_{Hits} >= N_{Hits\,th.}$	Electron	Not electron

The momentum threshold is decided via

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

For He: $p_{th.\,e}$ ~ 60 MeV/c
For He: $p_{th.\,\pi}$ ~ 16.4 GeV/c

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



Gaining insight - Typical values and importance of DCR

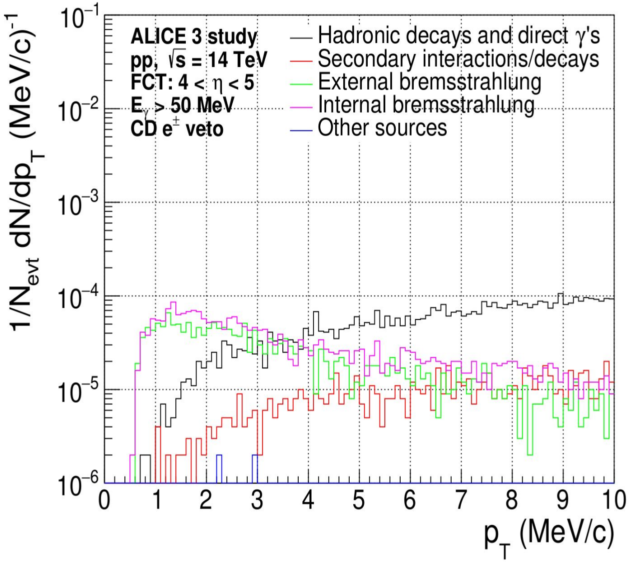
		Scales with		
Radiator:	Helium		Radiator:	Helium
Radiator length:	1 m		Radiator length:	1.8 m
Number of photons:	8.1	$L * \tan^2(\theta_{ch})$	Number of photons:	14.7
Number detected:	1.6	det. efff * $L * \sin^2(\theta_{ch})$	Number detected:	2.9
DCR per ROF per SiPM:	0.018		DCR per ROF per SiPM:	0.018
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

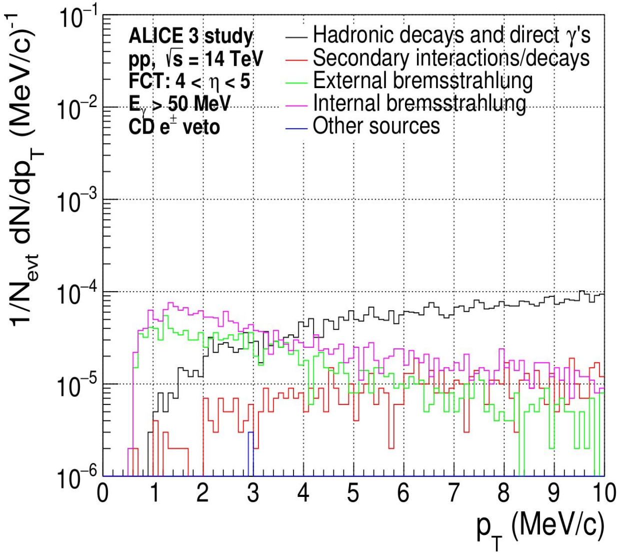
Frank-Tamm theory

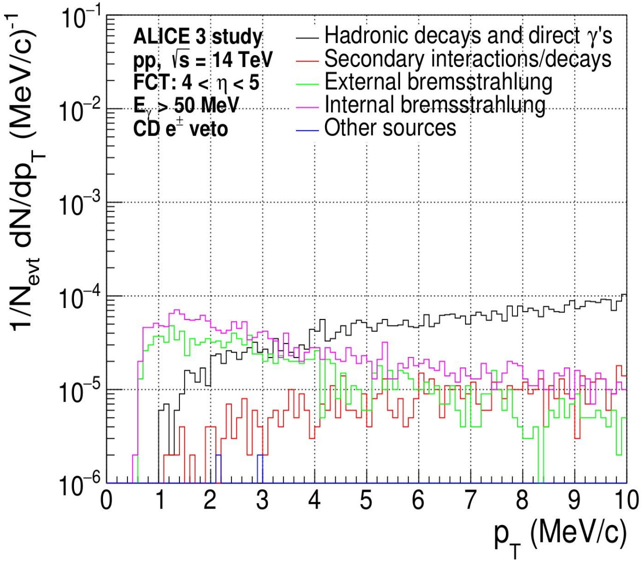
$$N_{\text{prod}} = \frac{\alpha}{\hbar c} Z^2 L \int_{E_1}^{E_2} \sin^2 \theta dE_\gamma$$

Results - Helium - Signal over background is ~ unity

H3050CS	H3075CS	FBK 3V OV
L = 1.81 m	L = 2.45 m	L = 2.98 m
$N_{\text{Hits th.}} = 2$	$N_{\text{Hits th.}} = 3$	$N_{\text{Hits th.}} = 3$







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]
$e^+e^- \rightarrow n$ 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

Hamamatsu 30xxCS SiPM - The Dark Count Rate

DCR ~ 1 MHz/mm^2 - Where do I get this number from? The source shows 55 - 111 KHz/mm^2

But that is for non-irradiated SiPMs which have a very nice DCR.

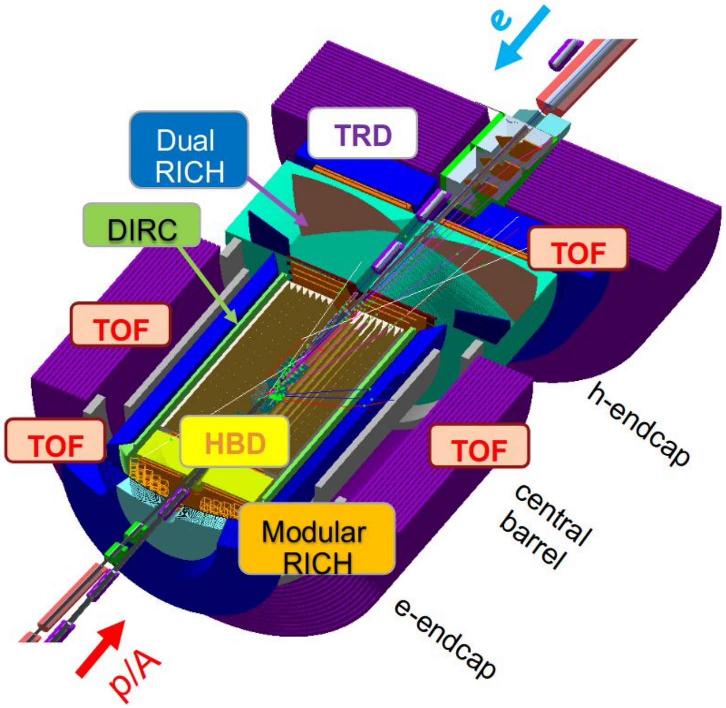
1 MHz/mm^2 takes the following into account

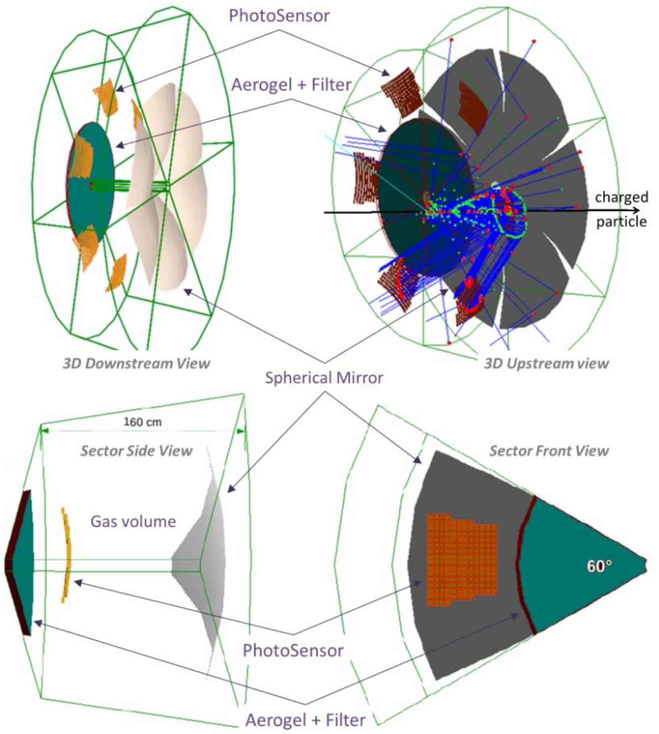
- Cooling to - 40°C
- A 10^{12} NIEL
- Periodical annealing
- Possible overvoltage regulation during operation (if necessary)

The FCT operates in a radiation zone where the NIEL ~ 10^{13} ... Yikes

However, we might not need so many of them and this is a big open question which I'll address now

The dual RICH of the ePIC detector at EIC





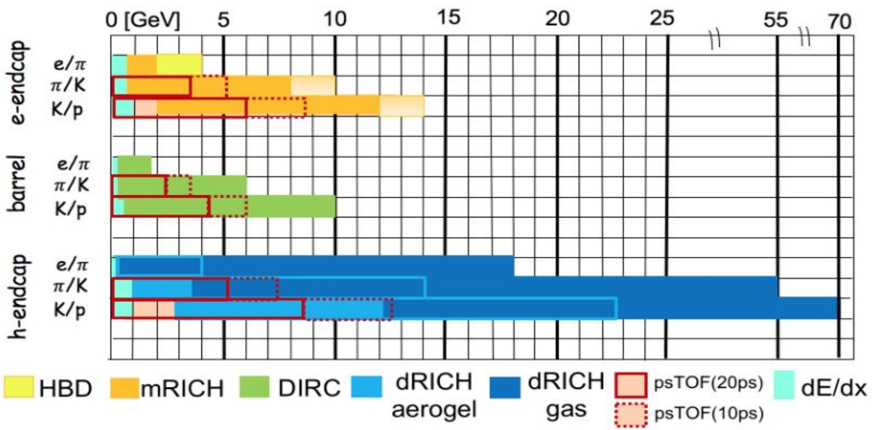
EIC Yellow report

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

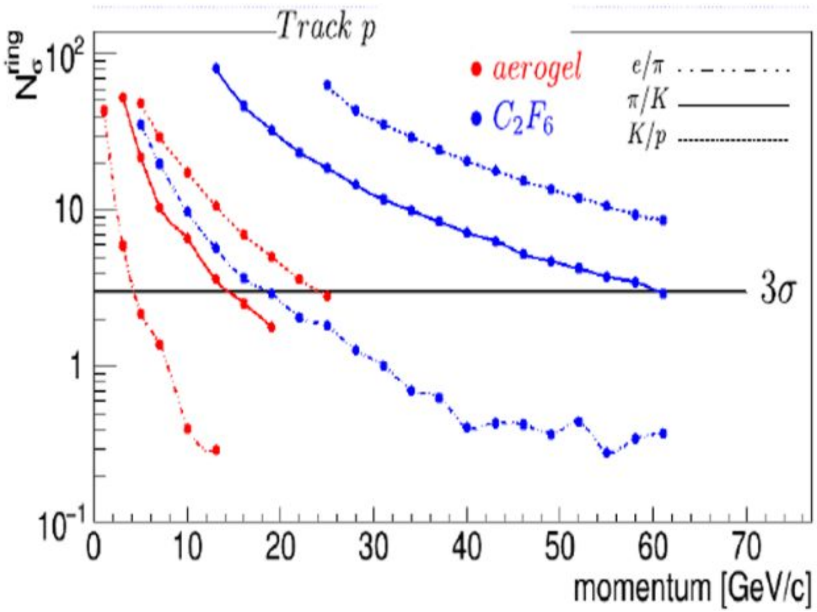
e/π separation up to about 15 GeV/c as a byproduct

Projection of momentum ranges covered



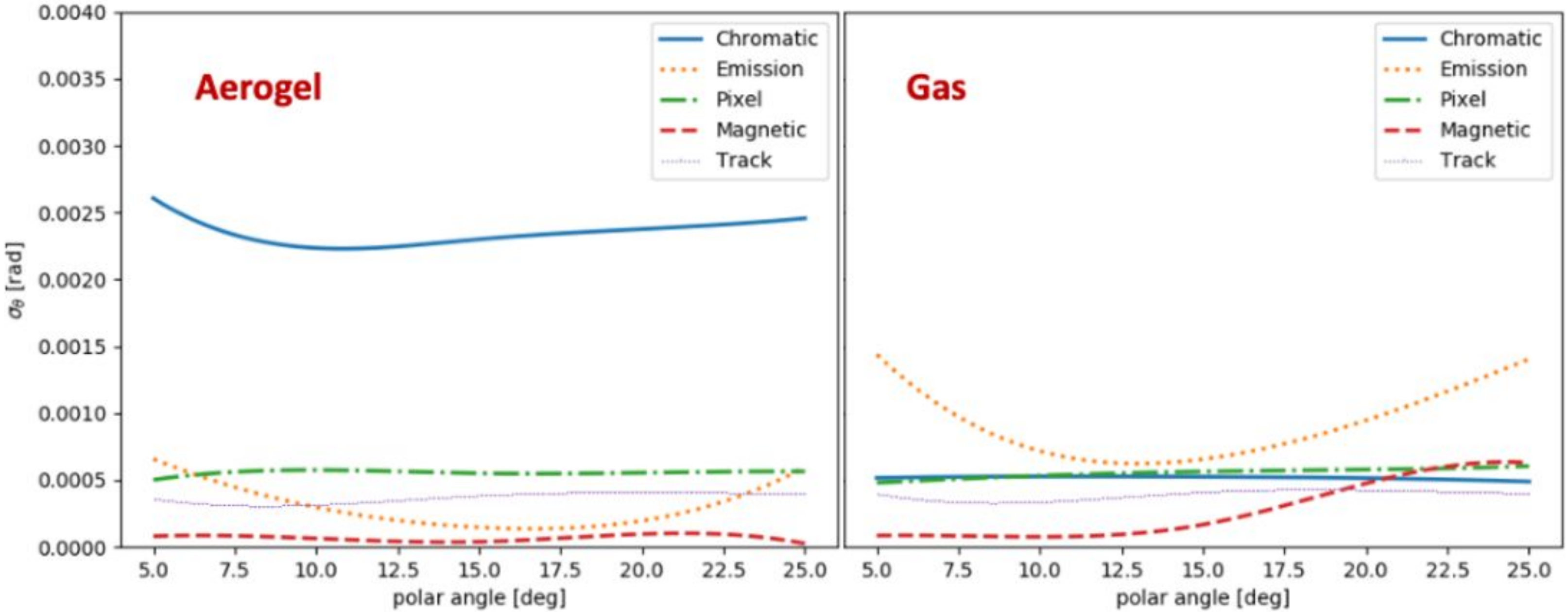
[AI-optimized detector design for the future Electron-Ion Collider: the dual-radiator RICH case]

Performance of dRICH for different particle types



[EIC Yellow report]

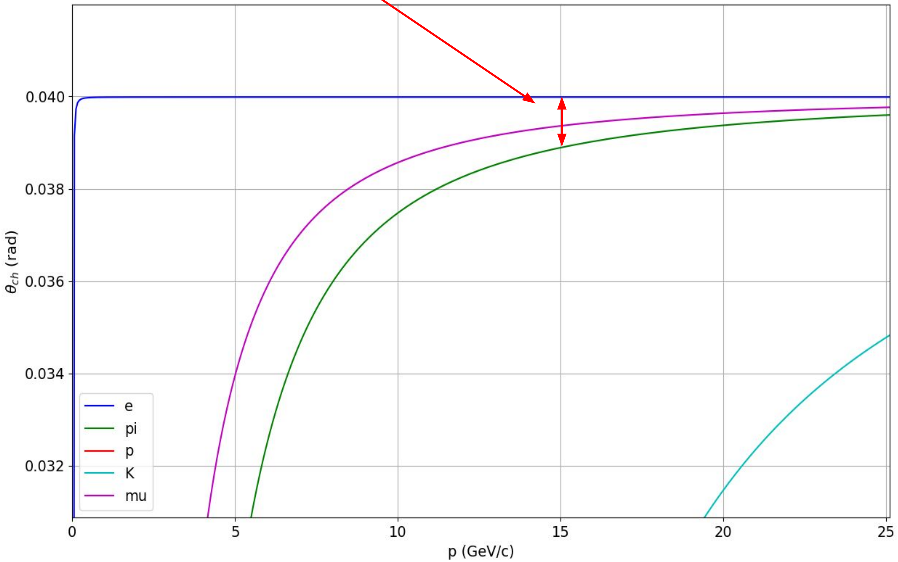
How do they achieve this? - Good angular resolution



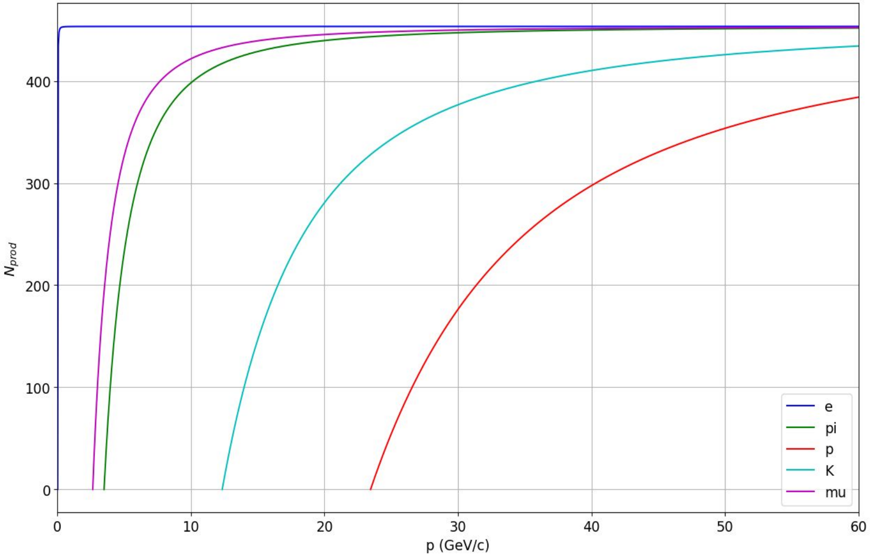
EIC Yellow report

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

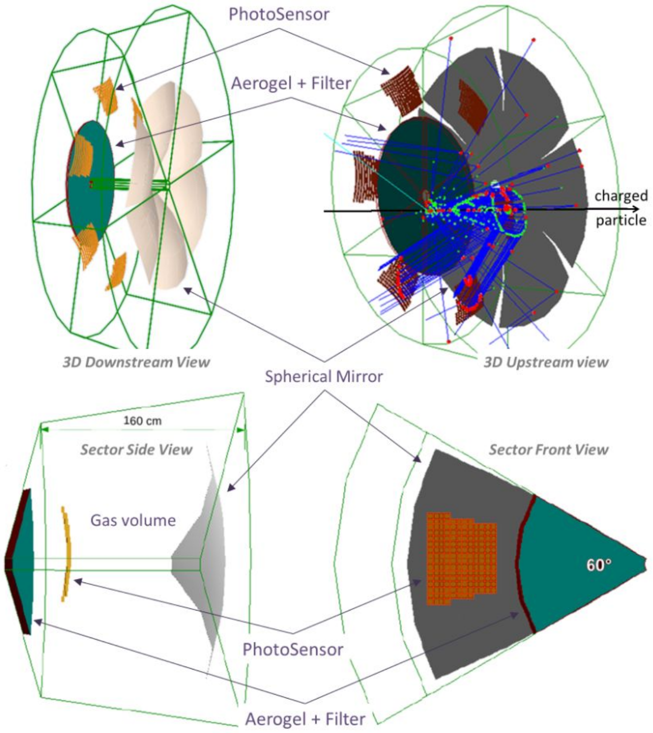


Focusing mirrors - Instrumented area reduction

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 $A_{m/6}/A_s \cong 9.8^*$

*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.



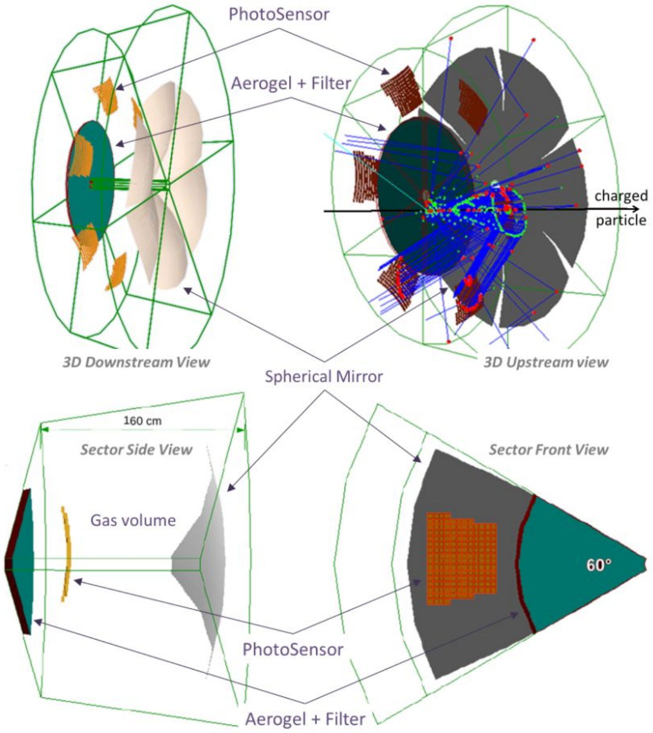
EIC Yellow report

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.

With the right gas this then allows for ring reconstruction. More photons will be emitted and the focussing mirrors project a ring on the SiPMs.



EIC Yellow report

How many SiPMs would we need if we adopt such a strategy? First quick estimate

We would consider a radiator of length 1.6 m. The last layer of the FCT is at z = 5 m

At z = 6.6 m and $\eta = 4$, R = 0.242 m, giving an area A = 0.184 m^2

As a first estimation, let's assume we would need a mirror that is 30% bigger in radius since particles get deflected by the FCT dipole (dedicated simulation on the way).

So, A = 0.31 m^2, then, after focusing this with a dedicated focusing mirror with a mapping factor of 10 - 5 (like the dRICH mirror), gives 3450 - 6900 SiPMs.

Compare this to the area that is needed to equip the barrel rich in ALICE 3 with (A ~ 30 m^2), this is very little.

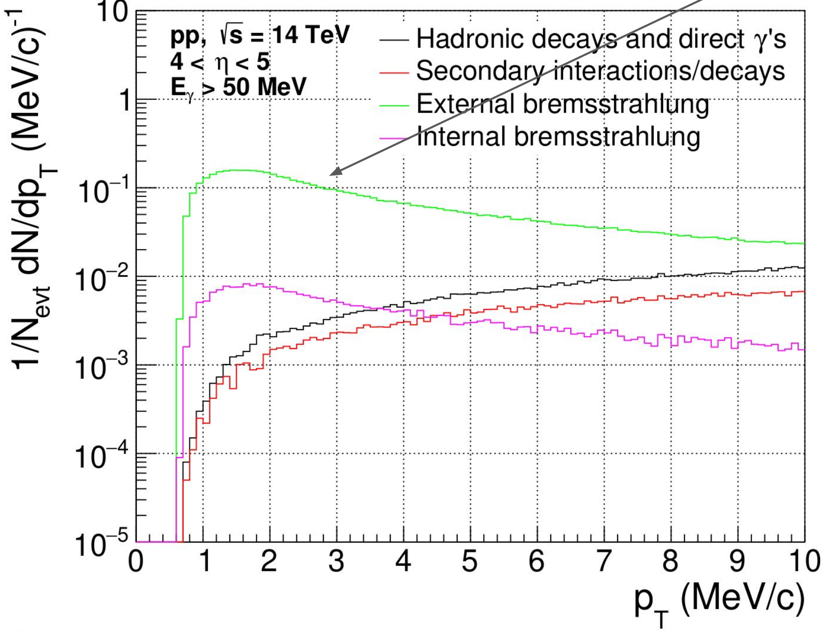
Additional strategy: Calculate the theoretical external bremsstrahlung spectrum without adding a cherenkov detector

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:

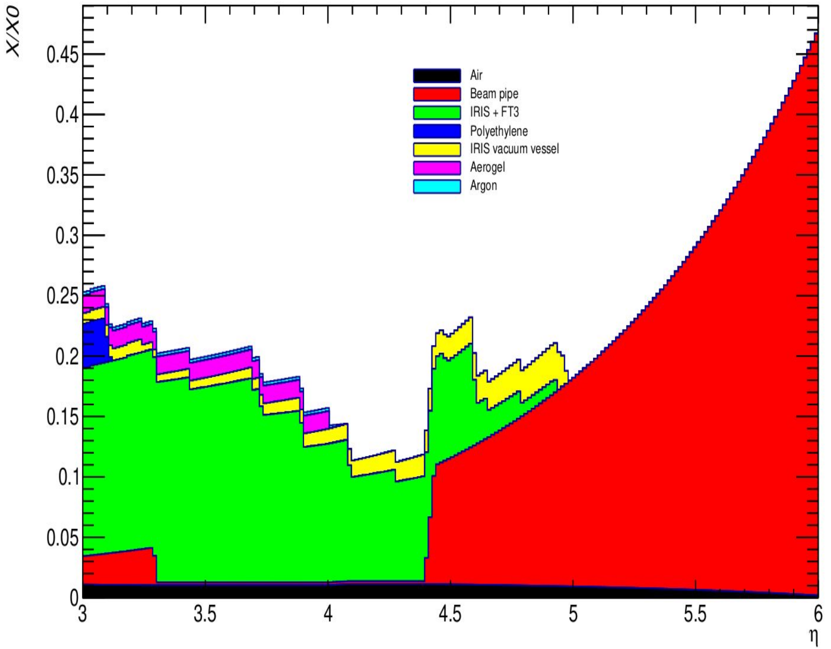
$$\frac{dN_\gamma^{\text{ext. brems}}}{d\omega_k} = \frac{x}{X_0}\left(\frac{4}{3}\frac{1}{\omega_k} - \frac{4}{3}\frac{1}{E_e} + \frac{\omega_k}{E_e^2}\right) \approx \frac{4}{3}\frac{x}{X_0}\frac{1}{\omega_k}$$

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

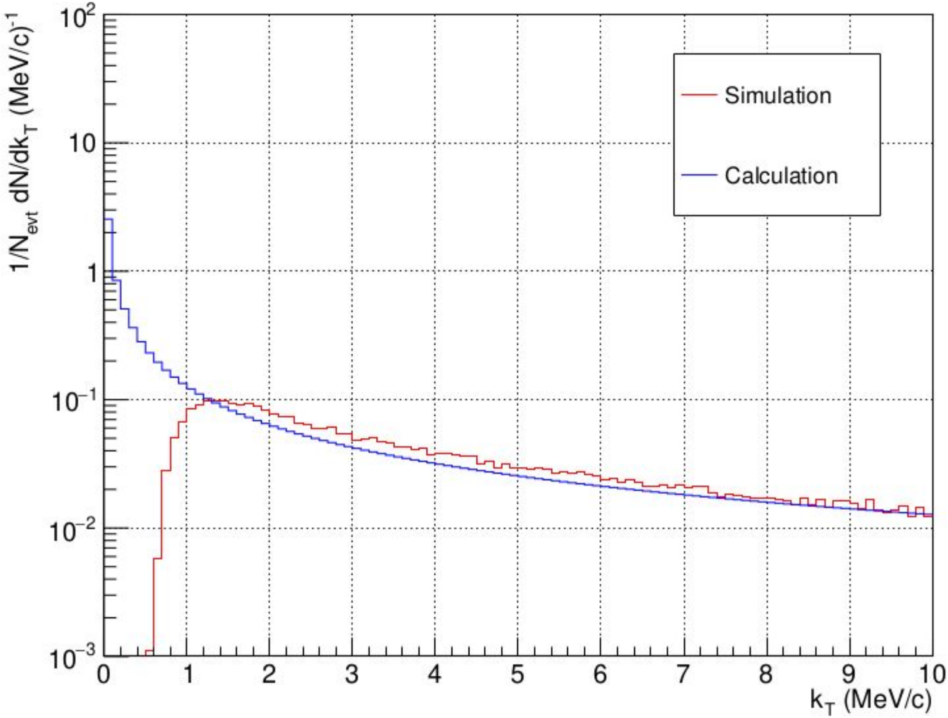
$$\frac{dN_\gamma^{\text{ext. brems}}}{d\omega_k dk_T} = \frac{28}{27}\frac{dN_\gamma^{\text{decay}}}{d\eta}\left(\frac{x}{X_0}\right)^2\frac{1}{k_T}$$

Calculate the external bremsstrahlung spectrum

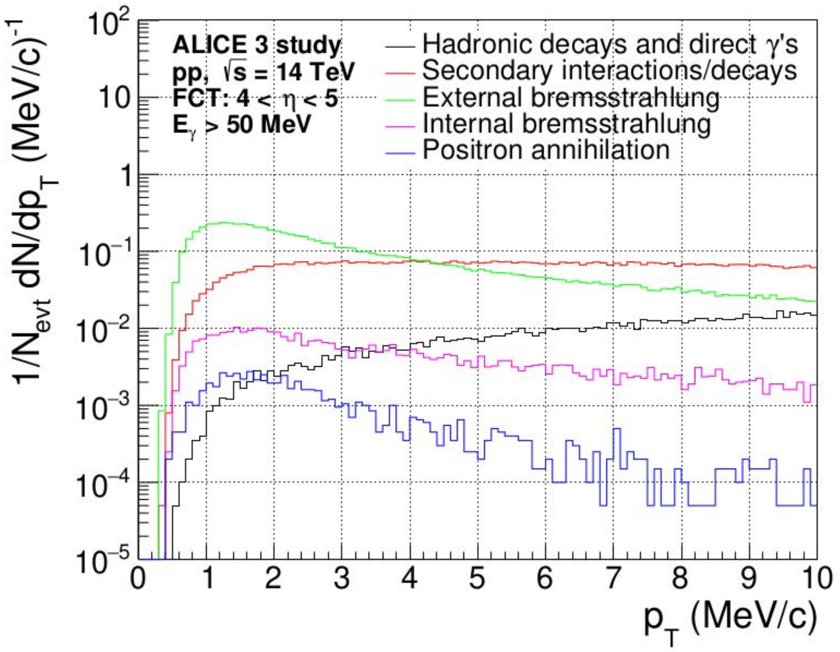
Material budget in front of the FCT (as per O^2)



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

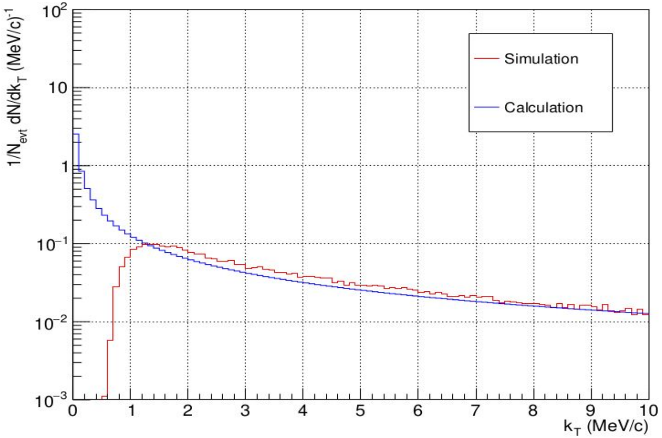


Does not explain the full spectrum, but it is a start



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

What are the open questions remaining?

What about the tracking?

- I will go to the ACTS workshop hosted by CERN this November
- In the coming three months I hope to be able to do some tracking with ACTS

What about the shape of the layers?

- Depends on the acceptance we are looking for. GEANT4 code is ready to be run
- Most likely a square above the beam pipe to improve acceptance

What is the luminosity required?

- Solve this equation:

$$N_{\text{Col}} = 1/N_{\text{Low phot/col}} * 1/P_{\text{Phot. conv.}} * 1/P_{\text{Meas. V0}} * N_{\text{Phot. for acc. stat.}}$$

~1/33 in $4 < \eta < 5$
Assuming circular layers

~ 7/9 x/X_0. 2%
for first 2 layers

Depends on acceptance. Study ongoing. Let's assume 10%

Previous experiments had ~100k. Can we do 1M?

=> $N_{Col} \cong 21 * 10^9$ => $t_{op} \cong$ 3 hours at low luminosity

Conclusion

Already a possibility for a measurement of s/b ~ unity. Expected to be improved.

The DCR of the SiPMs is an important factor that needs to be studied more

The finalization of the design of the FCT is in sight

- Spacing and layer shape (GEANT 4 simulation and ACTS for tracking)
- RICH design based on the dRICH of the ePIC detector at EIC

I will start writing my thesis soon! (Aiming for defense in July 2024)

Backup

Why did I not design the FCT like the dRICH of ePIC at the EIC?

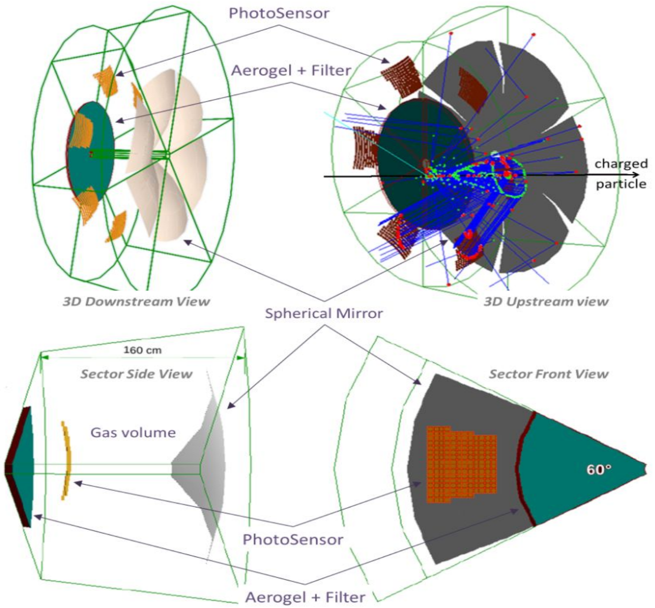
1. It is conceptually easy to implement

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]()