A novel SiPM-based aerogel RICH detector for the future ALICE 3 apparatus at the LHC

Nicola Nicassio (University and INFN Bari)

feat. the ALICE Collaboration

XXXIV International School "Francesco Romano"

Monopoli, Italy, 23/09/2023

Outline

Detector concept

Simulation studies

Test beam results

The ALICE 3 upgrade

High luminosity for ions | HL-LHC | Higher luminosities for ions

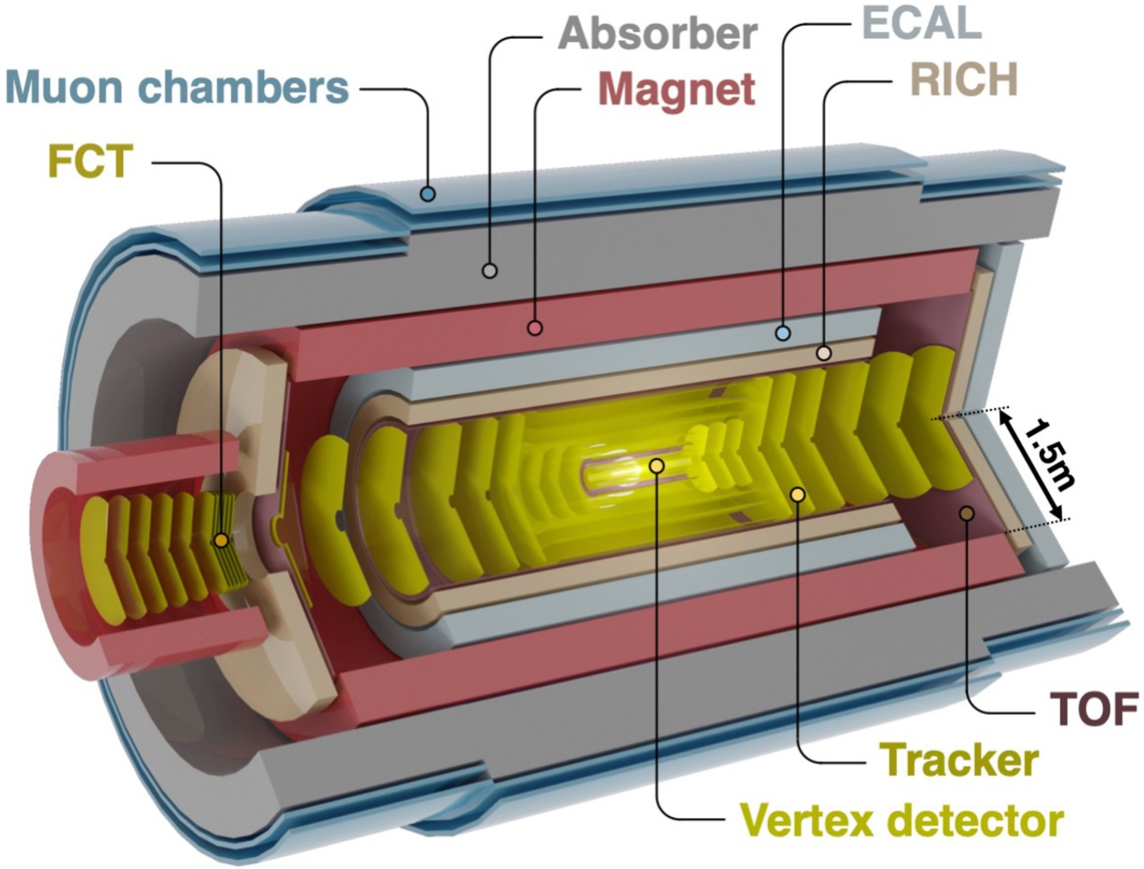
Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5	Run 6

ALICE 1		ALICE 2	ALICE 2.1 upgrade	ALICE 3 upgrade	

ALICE 3 motivation and concept

- **ALICE main goal**: access the dynamics of the strongly interacting matter produced in heavy-ion collisions
- **Fundamental questions will remain open** after LHC Run 4, demanding for a next-generation experiment
  - Pointing resolution: ≈ 10 μm at 200 MeV/c
  - Tracking relative p_T resolution: ≈ 1-2 %
  - Extensive particle identification
  - Pseudorapidity coverage: $|\eta| < 4$
- **Letter of Intent for ALICE 3**: Review concluded with very positive feedback by the LHCC in March 2022

ALICE CERN-LHCC-2022-009



ALICE 3 barrel RICH motivation

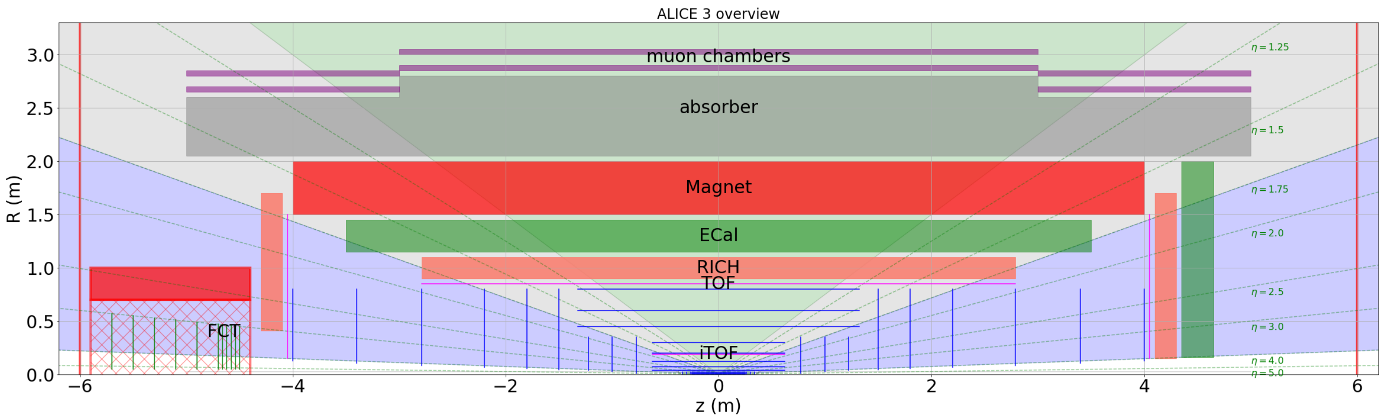
ALICE 3 charged PID systems

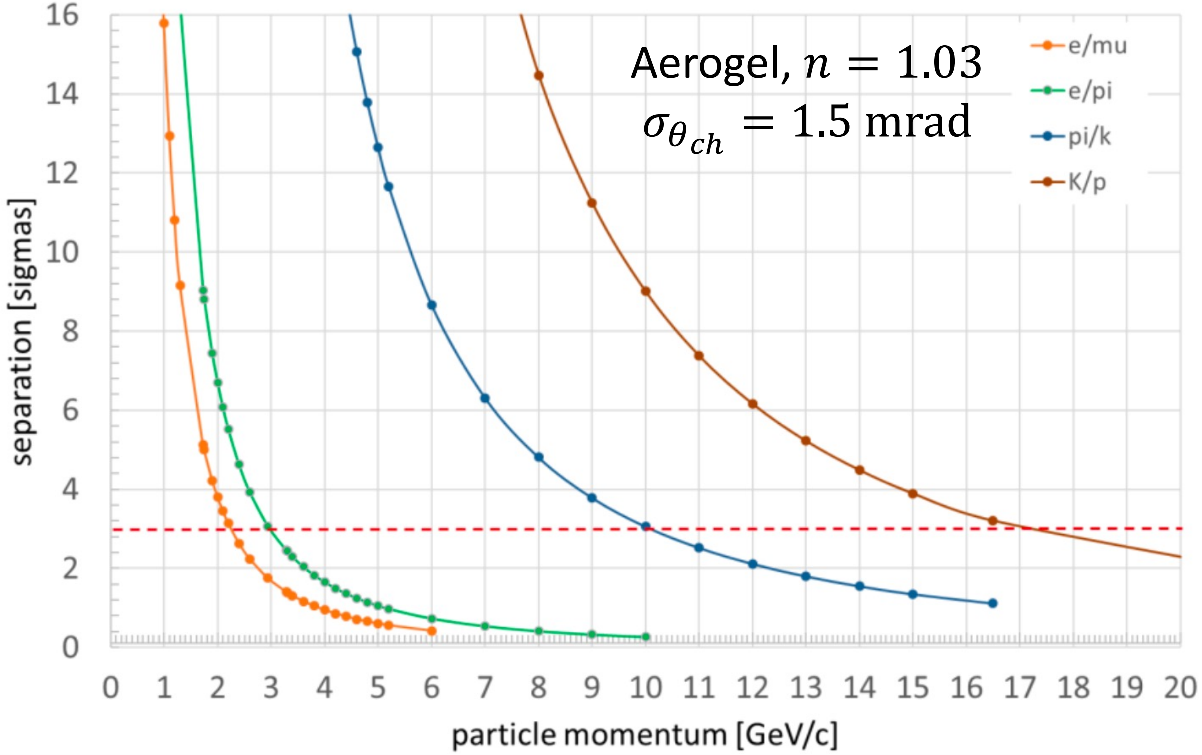
- Time-Of-Flight (TOF)
- Ring-Imaging Cherenkov (RICH)
- EM Calorimeter (ECal)
- Muon Identifier Detector (MID)

bRICH motivation

- Extend charged PID beyond the TOF limits
  - π/e in the p range 0.5 – 2.0 GeV/c
  - K/π in the p range 2.0 – 10.0 GeV/c
  - p/K in the p range 4.0 – 16.0 GeV/c

→ Achieved using aerogel radiator with $\mathrm{n} \approx 1.03$
+ requiring angular resolution $\sigma_{\theta_{ch}} \approx 1.5$ mrad

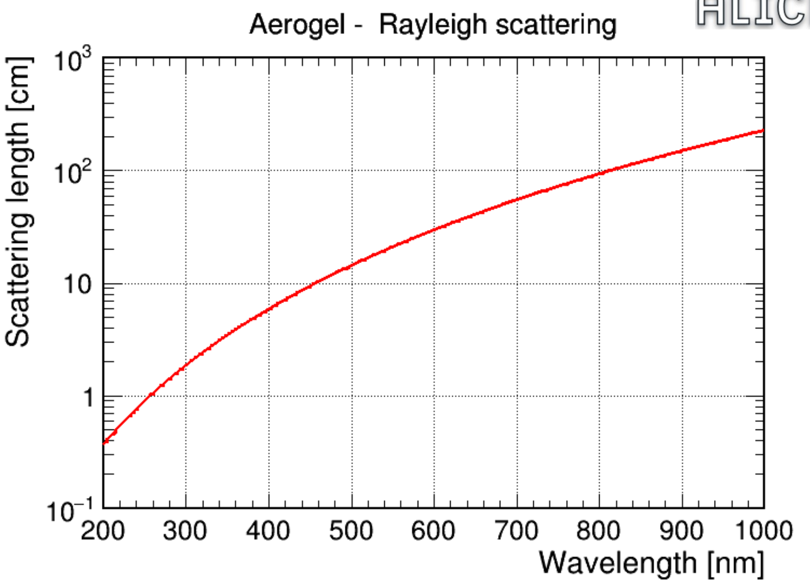




bRICH technology

Aerogel radiator (n=1.03)

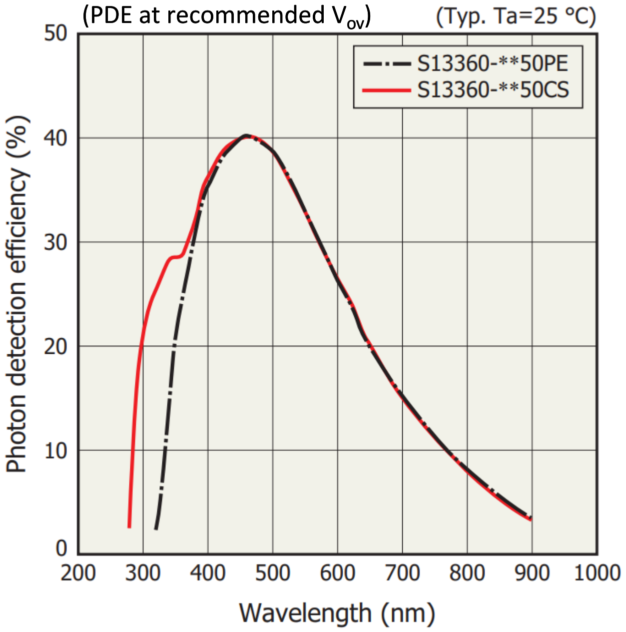
- Lattice of SiO_2 grains filled with trapped air
- Tunable index in the range 1.006-1.250
- Transmittance dominated by Rayleigh scattering
  - Transparent in the visible, opaque in the UV

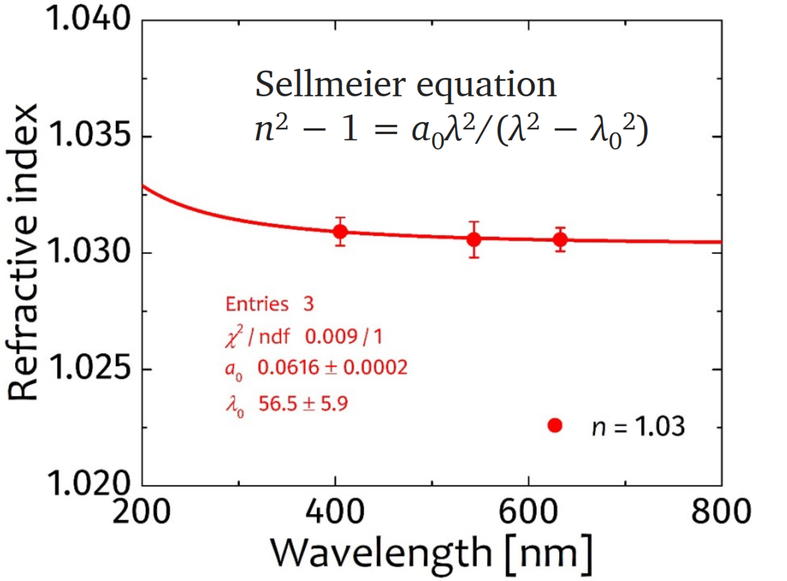


SiPM-based photodetector

- Sensors must be sensitive to visible light
- Operation in magnetic field
- Granularity from 3x3 to 1x1 mm^2
- Example: HPK 13360-3050CS SiPMs

Aerogel n	βth	Momentum threshold [GeV/c]				
		e	μ	π	K	p
1.01	0.99009901	0.0036	0.7453	0.9845	3.4821	6.6181
1.02	0.98039216	0.0025	0.5257	0.6944	2.4561	4.6681
1.03	0.97087379	0.0021	0.4281	0.5656	2.0005	3.8021
1.04	0.96153846	0.0018	0.3699	0.4886	1.7282	3.2846
1.05	0.95238095	0.0016	0.3300	0.4359	1.5420	2.9307





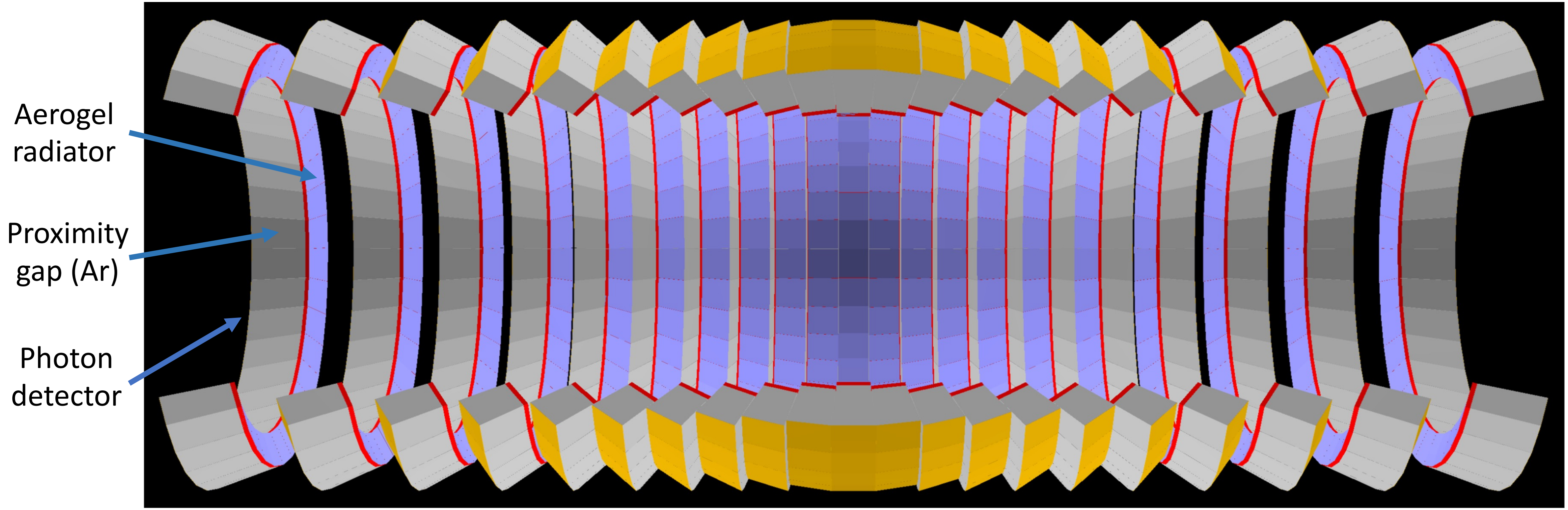
Projective bRICH layout

Assumptions

- All tiles oriented toward nominal interaction point
- Full coverage to charged particles without overlaps
- Trapezoidal tile profile to maximize the acceptance

Implementation

- 21 sectors in z
- 36 modules in $r\phi$ for each sector
- Photosensitive surface: 25.74 m^2



Simulation – Angular resolution

Single photon resolution

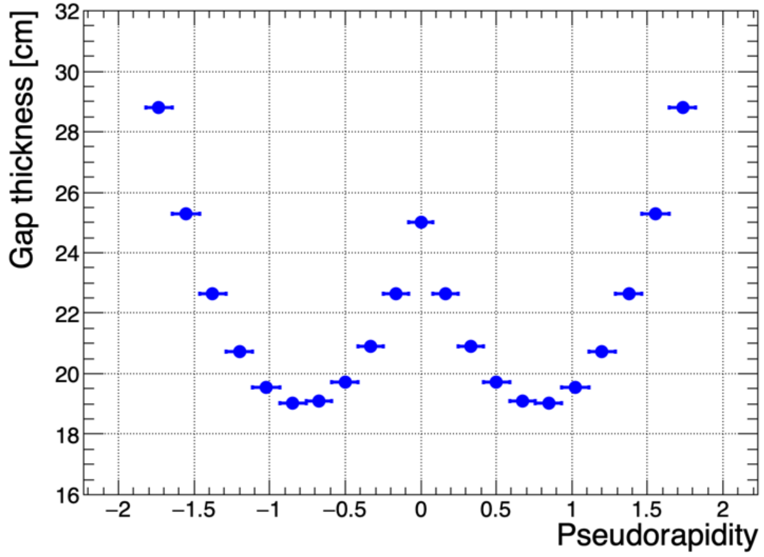
- Expected: $\sigma_{\theta_c}^{p.e.} = \sqrt{\sum_i \sigma_{\theta_c}^2(i)}$
- i = chromatic ($\propto dn/d\lambda$), pixel ($\propto \Delta x/T_{gap}$), **geometric** ($\propto T_{rad}/T_{gap}$), noise uncertainty

Detected photoelectrons

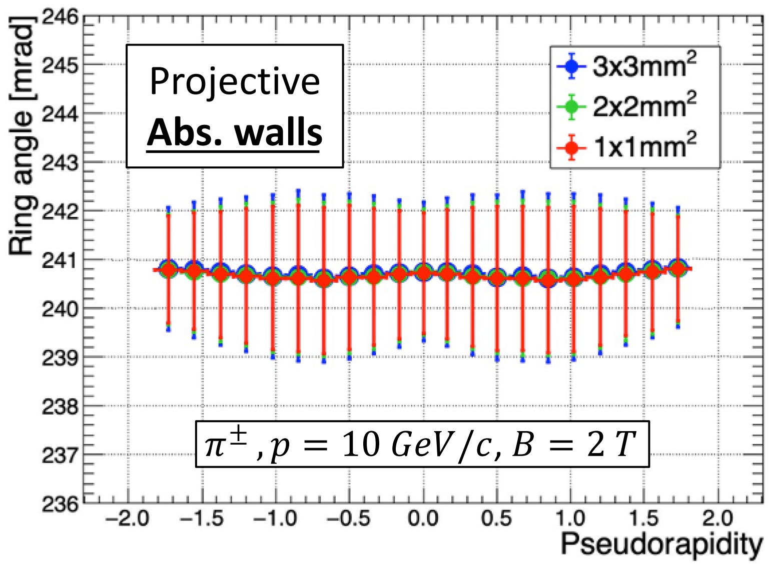
- Expected: $N_{p.e} \propto sin^2\theta_c \oplus$ acceptance

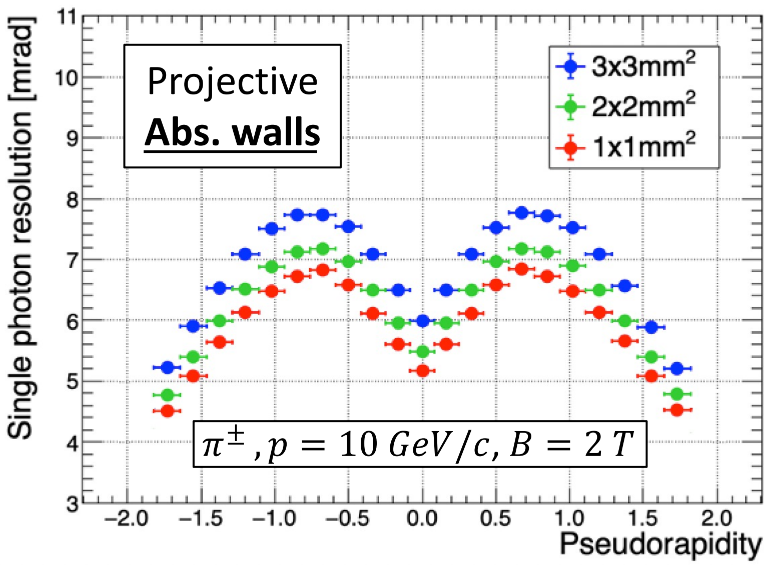
Ring angular resolution

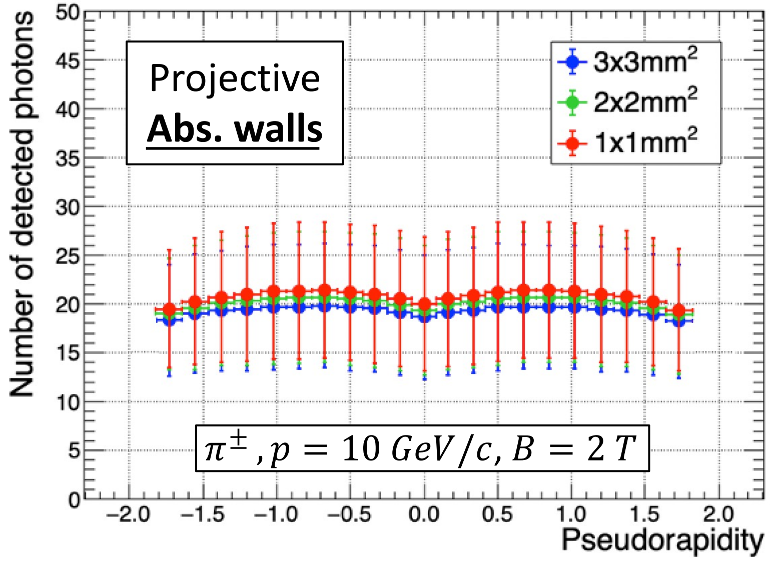
- Expected: $\sigma_{\theta_c}^{ring} = \frac{\sigma_{\theta_c}^{p.e.}}{\sqrt{N_{p.e}}} \oplus \sigma_{\theta_c}^{track}$

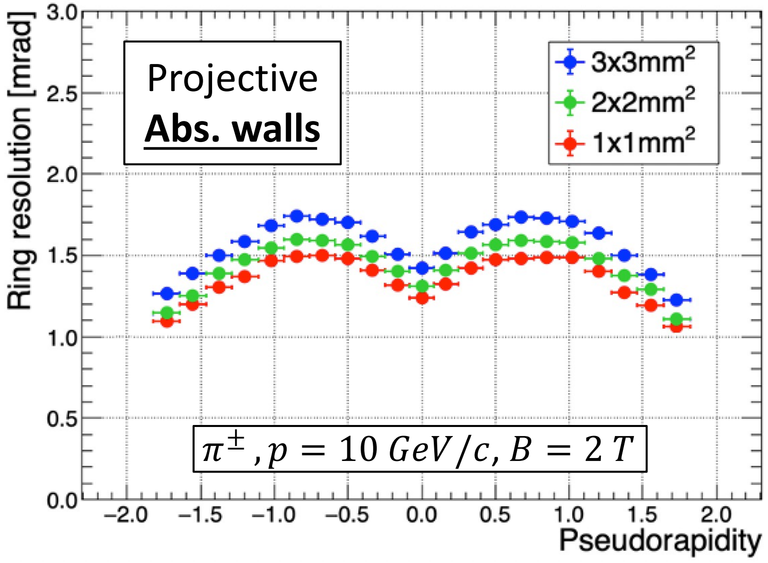


*Horizontal bars represent sector coverage









Simulation – Identification purity

Angle reconstruction

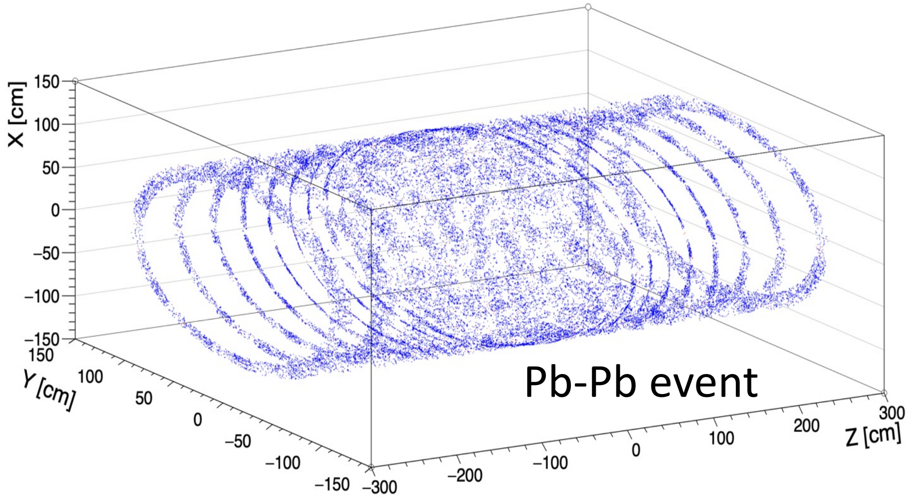
- Based on Hough Transform method
- Timing cut on hit-track matching
- HTM $N_{ph,min}$ cut on clustered hits

Particle identification

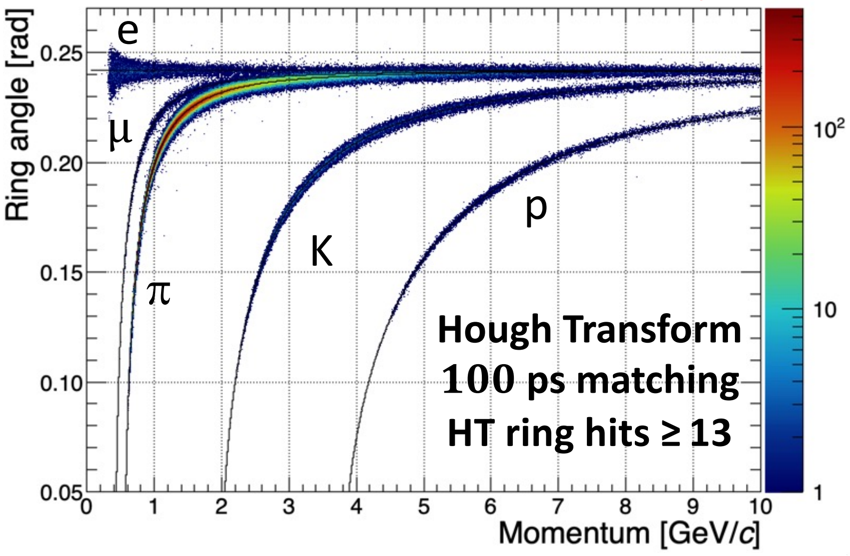
- Bayesian approach + probability cut

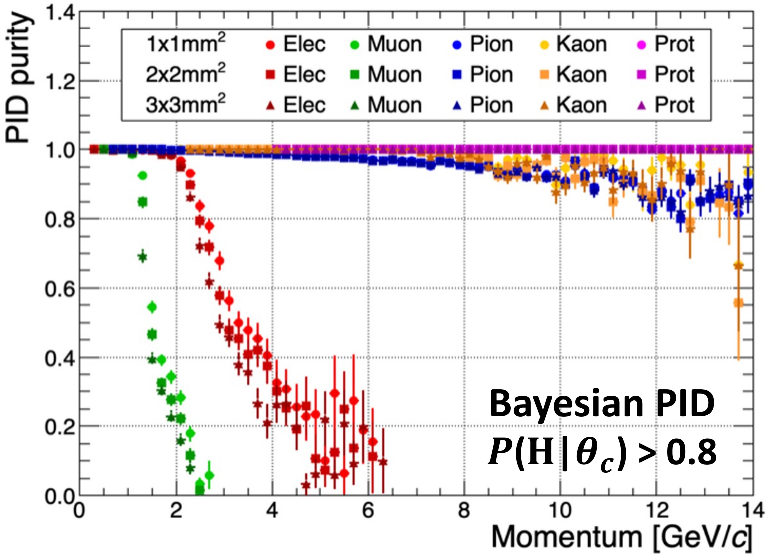
Background

- Photons emitted by different tracks
- Aerogel Rayleigh scattered photons
- SiPM dark count hits (50 kHz/mm^2)

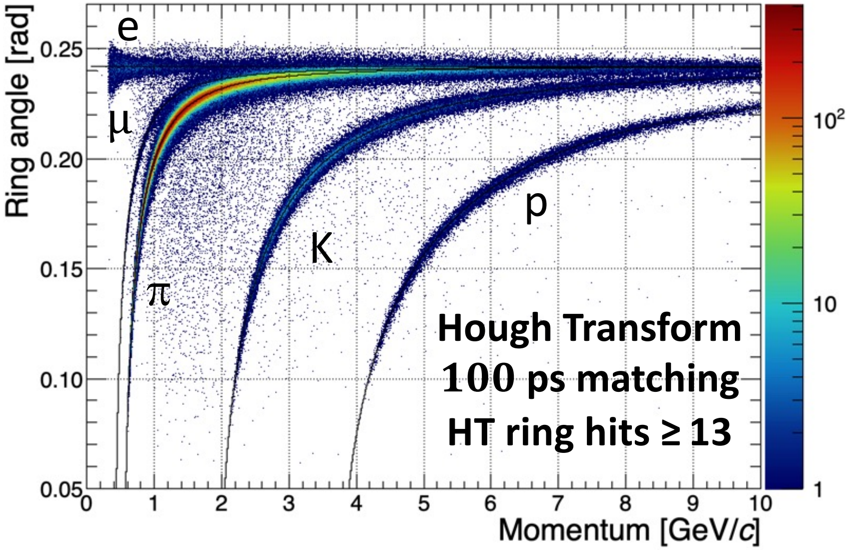


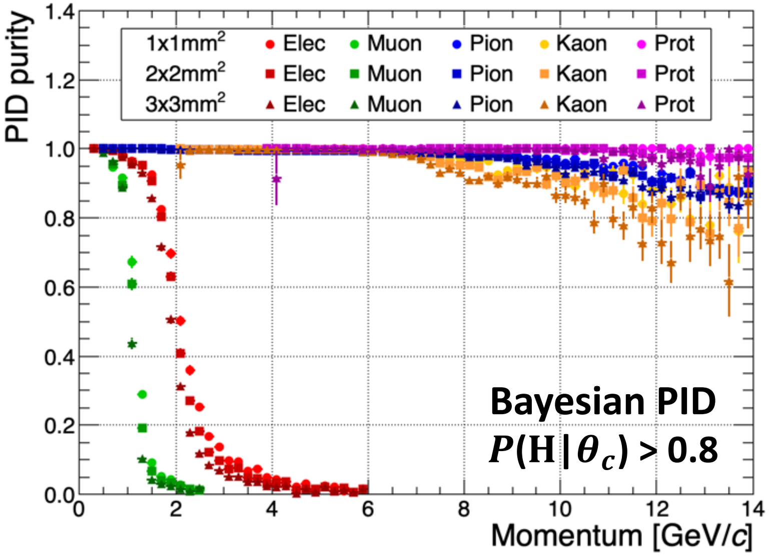
p-p , $c\bar{c}$ biased, $\sqrt{s_{NN}} = 14$ TeV, Pythia8, B = 2 T





Pb-Pb, b < 3.5 fm (0-5%) , $\sqrt{s_{NN}} = 5.52\ TeV$, Pythia8, B = 2 T





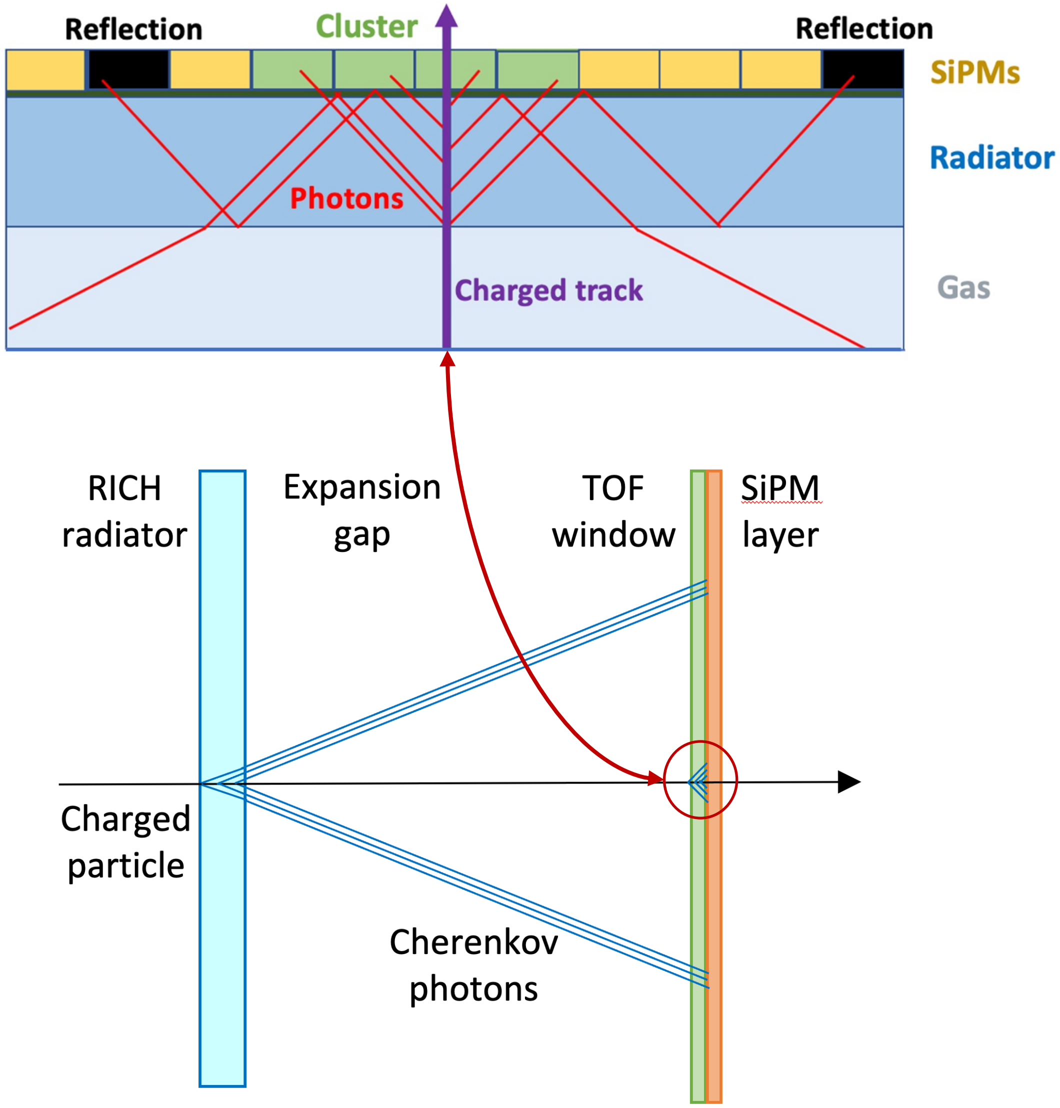
Option: TOF using bRICH SiPMs

Principle of operation

- Introduction of Cherenkov radiator coupled to SiPM layer
- Use clusters of SiPMs fired due to radiator photons timing

$$\langle t \rangle = \frac{\sum_i N_{pe,i} t_i}{N_{pe}} \Rightarrow \sigma_{\langle t \rangle} \approx \frac{\sigma_{SiPM,\langle N_{pe},i \rangle}}{\sqrt{\langle N_{SiPMs} \rangle}}$$

- **With $\sigma_{SiPM} \approx$ O(100 ps), $\sigma_{\langle t \rangle}$< 20 ps can be achieved !!!**

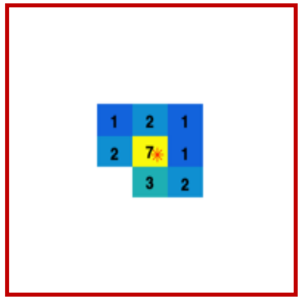


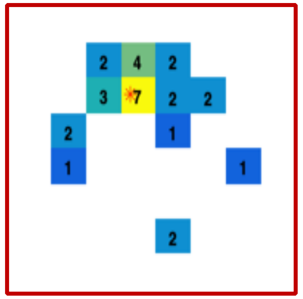
Radiator choice

- Use high refractive index material to minimize Cherenkov thresholds and to enhance both photon yield and spread

1 mm SiO_2 (n=1.47) + 0.45 mm epoxy resin (n=1.55), 1x1 mm^2 SiPMs

*MIP at 0° incidence





*MIP at 50° incidence

Assuming PDE of S13360-CS SiPMs at recommended overvoltage**

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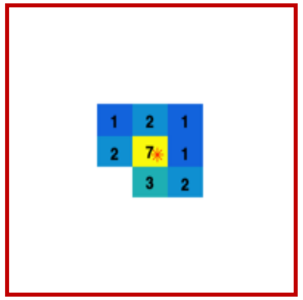

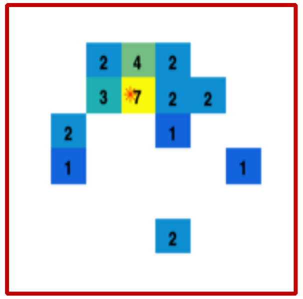

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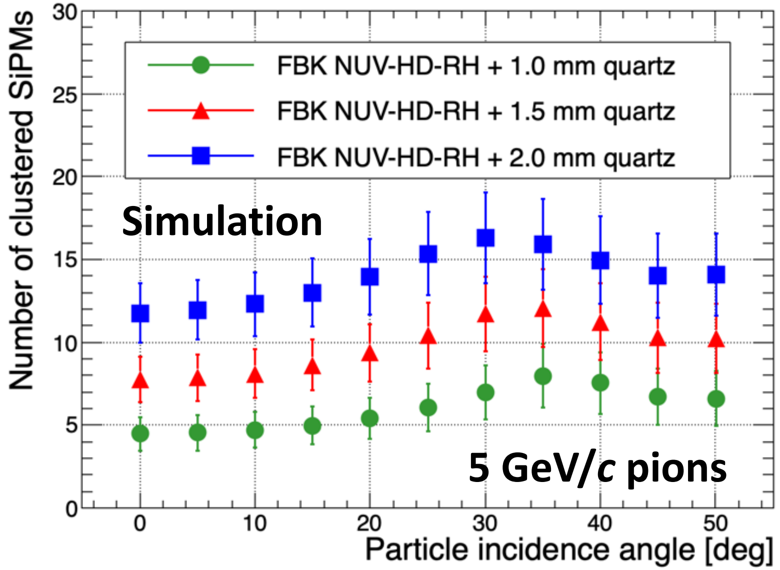
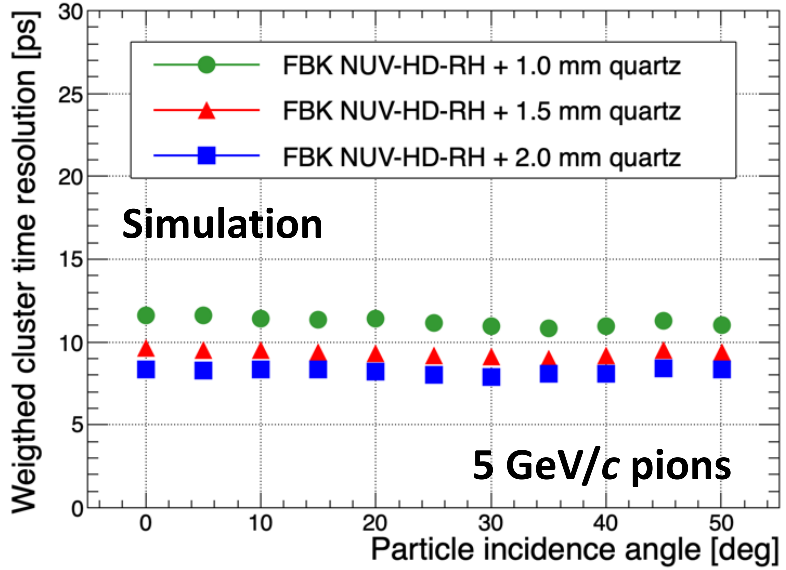
Using σ_{SiPM} from arXiv:2305.17762





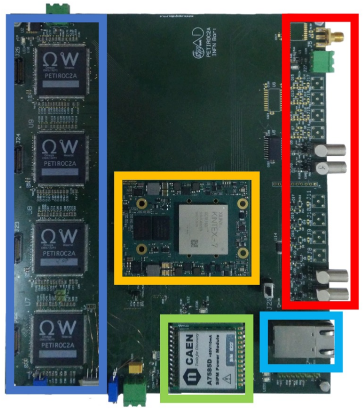
2022 beam test campaign @ PS/T10

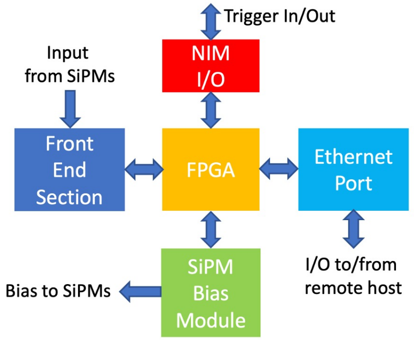
Experimental setup

- **Radiator**: Aerogel, n = 1.03, T_r = 2 cm
- **Gap**: Argon, n = 1.00028, T_g = 23.8 cm
- **Sensors**: 8 x HPK S13552, V_{ov} = 8.0 V

Angular resolution

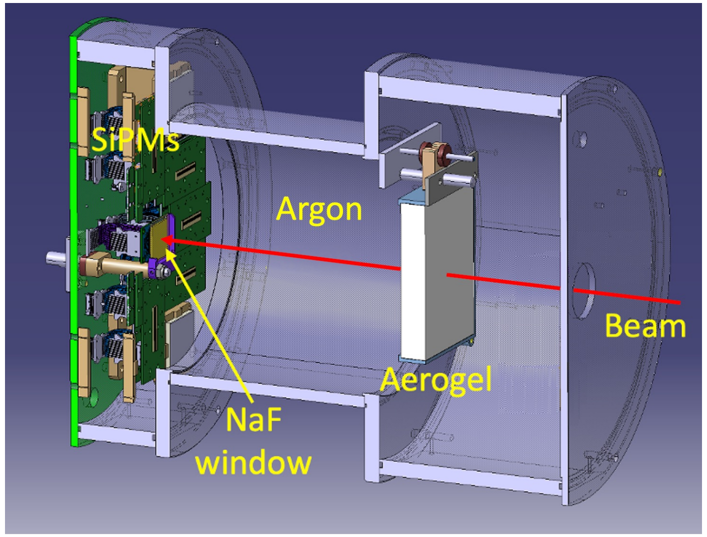
- Number of ring detected photons
  - In the 8 arrays: $\langle N_8 \rangle = 0.938$
  - Full ring coverage: $\langle N_r \rangle = 28.6$
- Single photon angular resolution
  - $\sigma_\theta^\gamma = 4.8$ mrad
- Extrapolated ring angular resolution
  - $\sigma_\theta^r \approx \sigma_\theta^\gamma \,/\, \sqrt{\langle N_r \rangle} \approx 0.9$ mrad

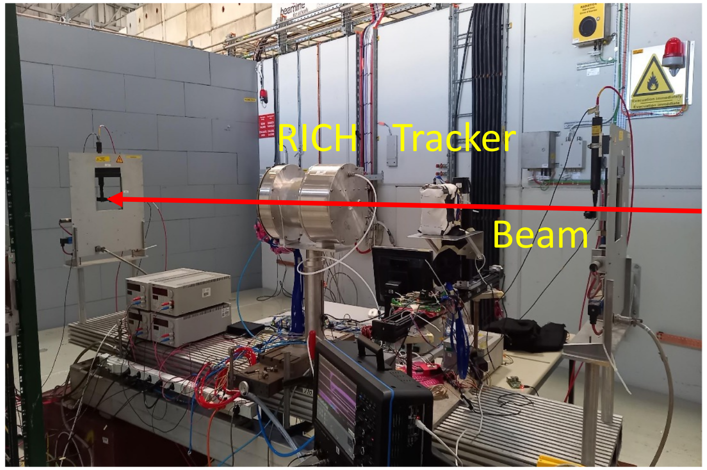


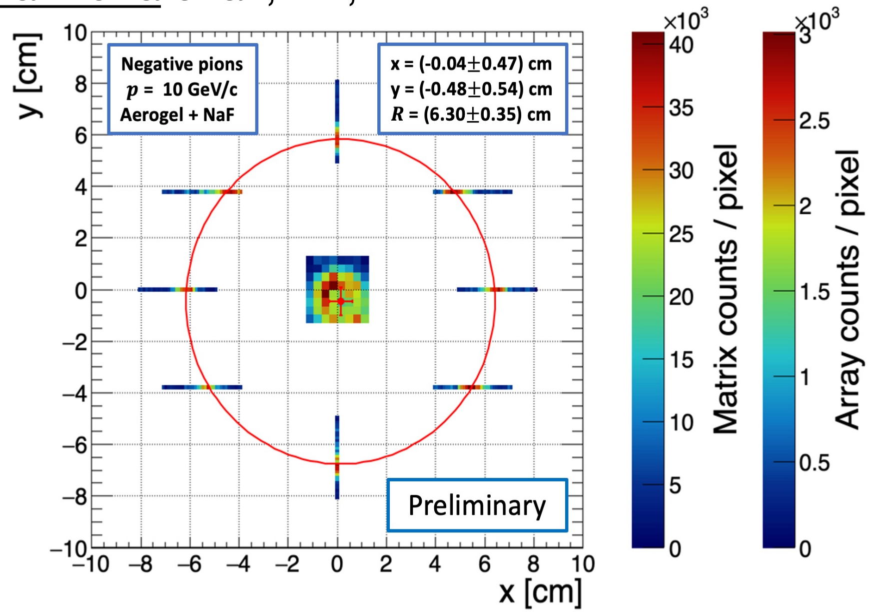


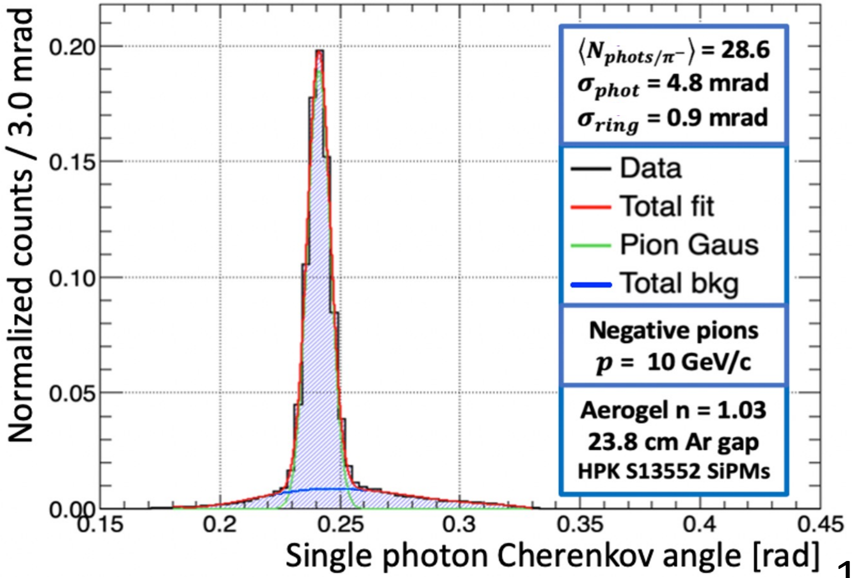
Front-End Boards developed in Bari
[10.1016/j.nima.2022.167040](https://doi.org/10.1016/j.nima.2022.167040)

In collaboration with M. N. Mazziotta et al., BA, INFN









Conclusions

Summary

- Simulation studies show that the **proposed bRICH** fulfills the ALICE 3 PID requirements, in particular in the extreme high-multiplicity environment expected in central Pb-Pb events
- Breakthrough concept of **TOF measurements** using bRICH SiPMs is currently under study and very promising results on the achievable arrival time resolution have been obtained
- **R&Ds**: Aerogel and SiPM characterization, radiation hardness, bRICH mechanics, cooling

Outlook

- **2023-2025**: Selection of technologies, small-scale prototypes
- **2026-2027**: Large-scale prototypes, Technical Design Report

Thank you for your attention

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Feat.

A. R. Altamura, A. Di Mauro, M. N. Mazziotta, E. Nappi, G. Volpe and others

Backup

Simulation assumptions

Barrel RICH sector modeling

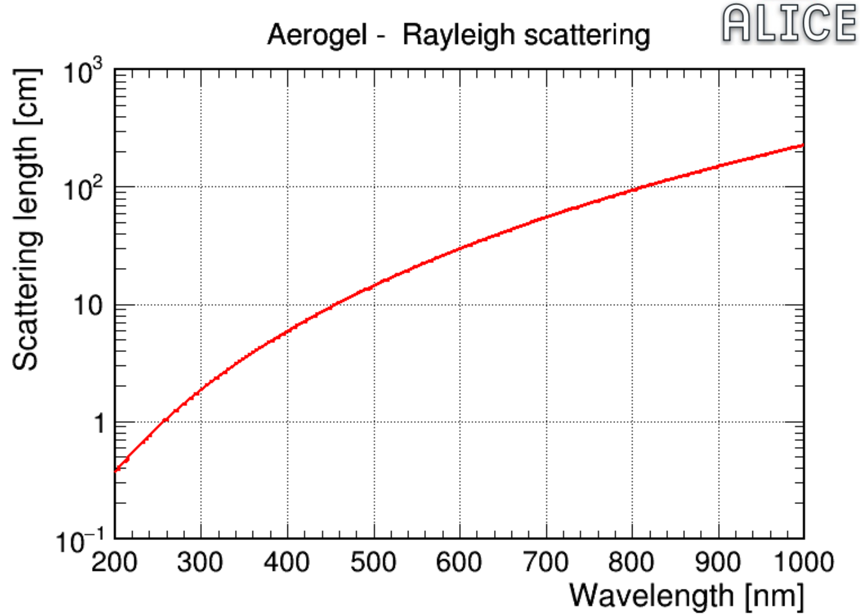
- Aerogel radiator (n=1.03) + Ar gap + SiPM-based photodetector

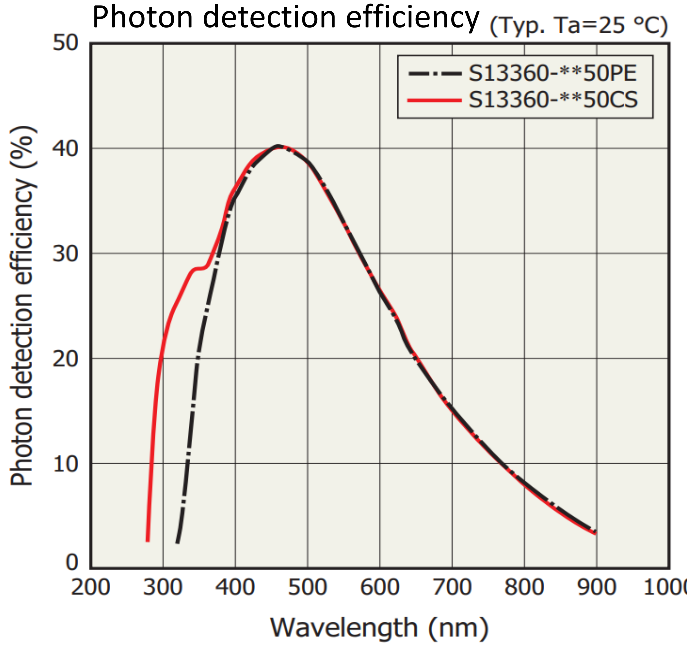
Detector parameters

- Aerogel T and n from Aerogel Factory Co., Ltd. (Chiba, Japan) data
- Photosensitive surface integration fill factor = 91%
- PDE: HPK 13360-3050CS SiPMs @ recommended V_{ov}
- Intrinsic single SiPM time resolution: 50 ps
- DCR: 50 kHz/mm^2

Cherenkov angle reconstruction

- Evaluate the angle associated to detected hits seen as candidate Cherenkov photons emitted by the charged particle of interest
- Selection of photons in rings via **Hough Transform method**

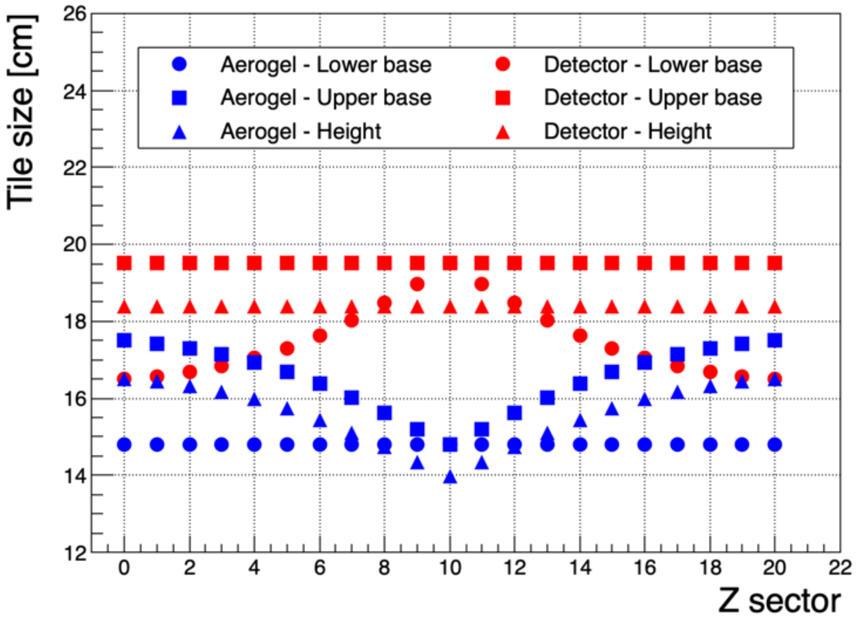




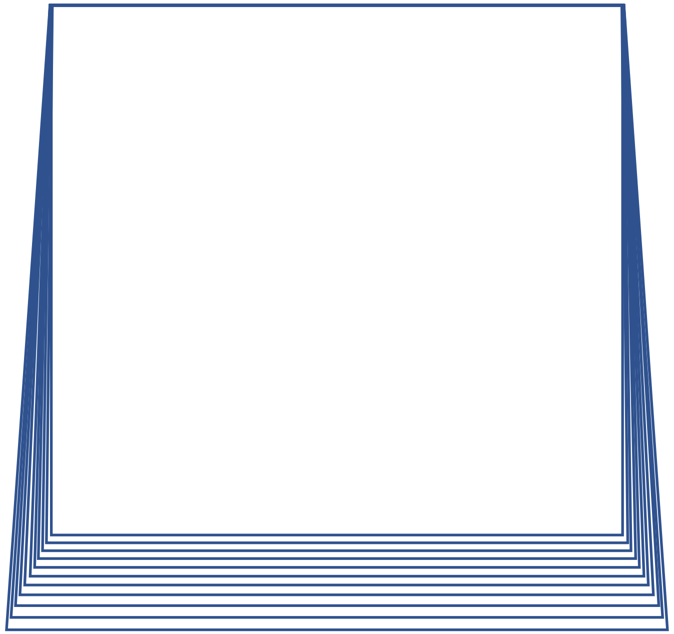
Trapezoidal tile profile

Barrel RICH layout with |z|<285 cm, |η|<1.82 ⇒ 21 sectors ·36 modules

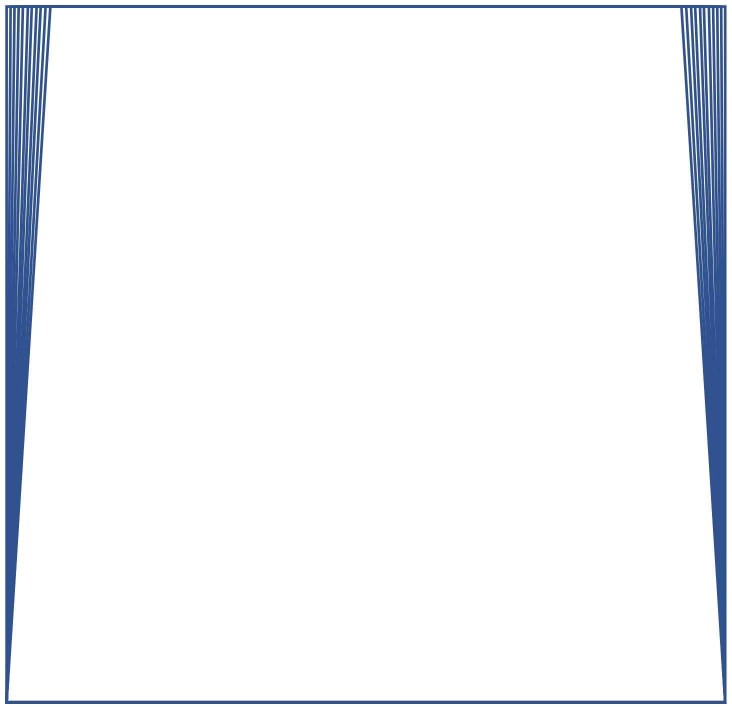
Trapezoidal tile size



Aerogel tiles



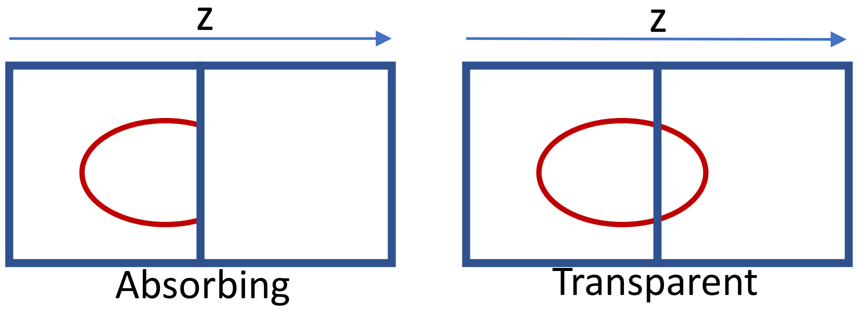
Photodetector tiles

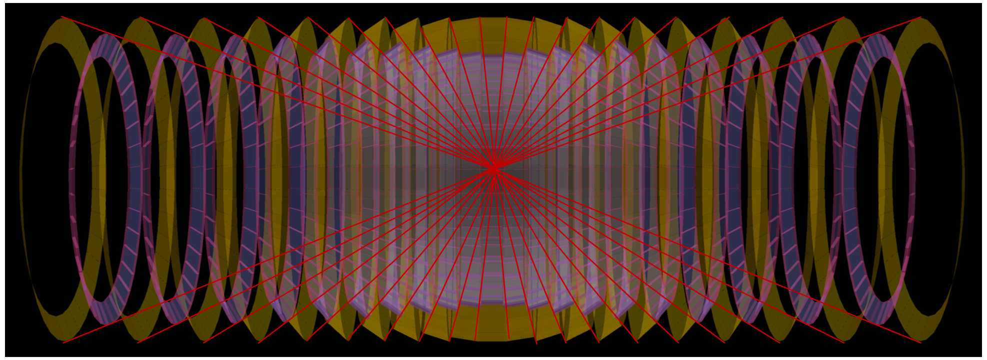


There are 11 different tiles for aerogel and photodetector, but some sizes are in common

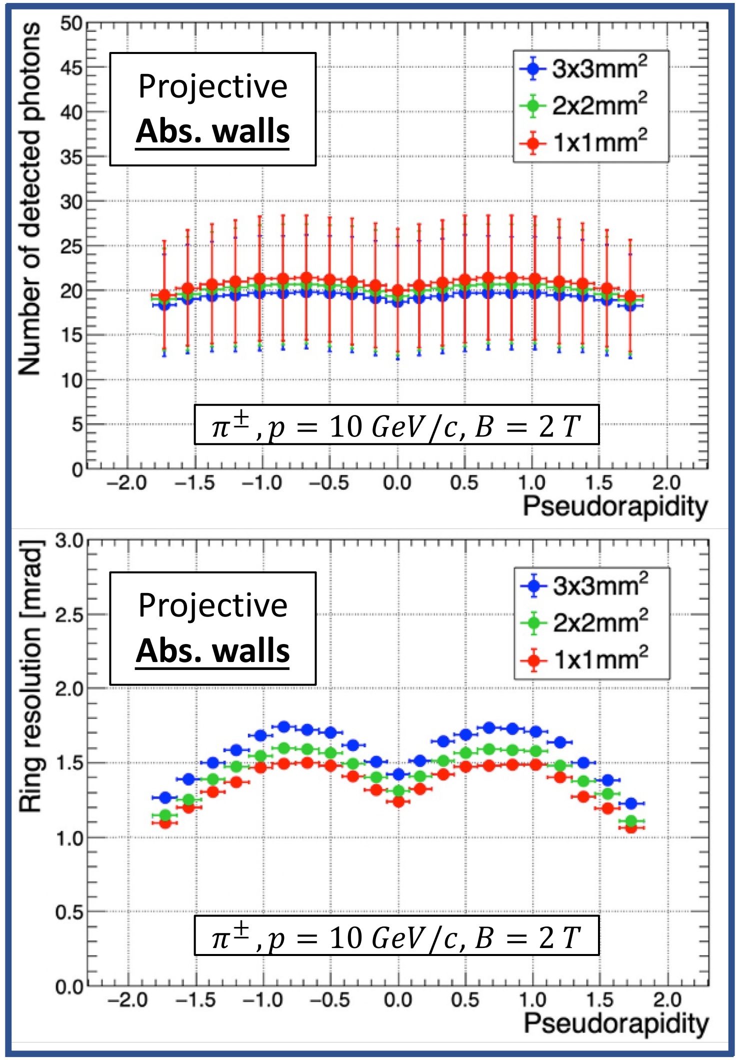
Effect of photon absorbing walls

- **We are currently treating each 36-modules Z sector as surrounded by absorbing walls**
- **NO walls in rϕ for good photon collection**
- **Realistic and useful choice for pattern recognition in high multiplicity events**
- **Here we quantify how much photons we lose with respect to using transparent walls**

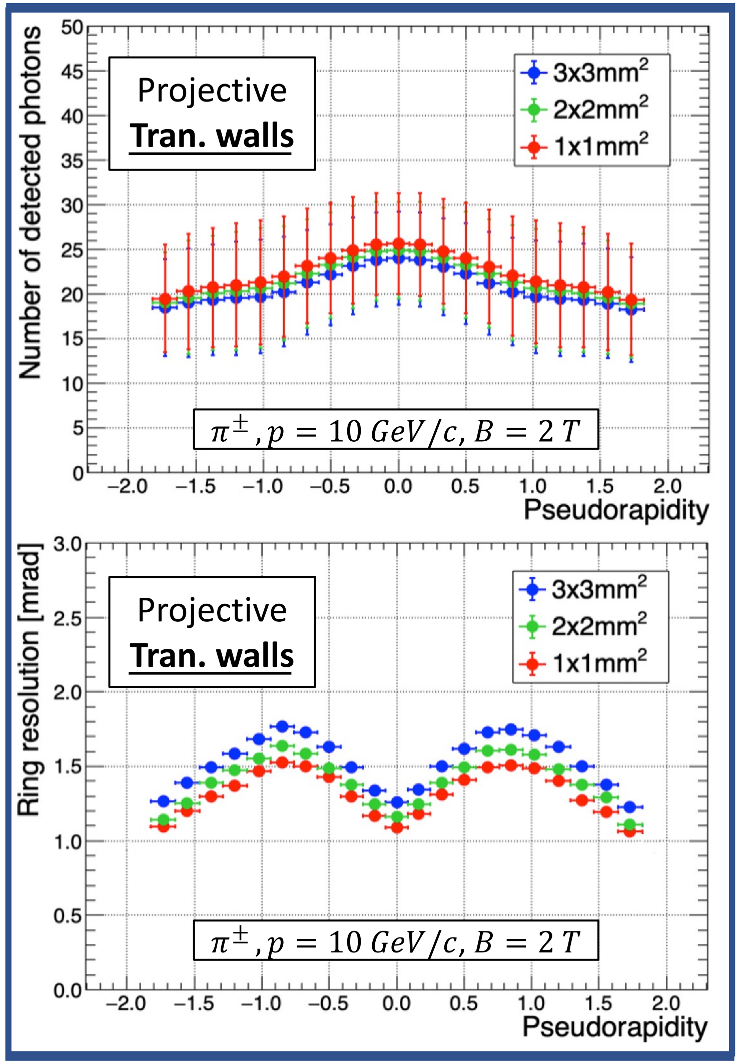




Photon absorption walls

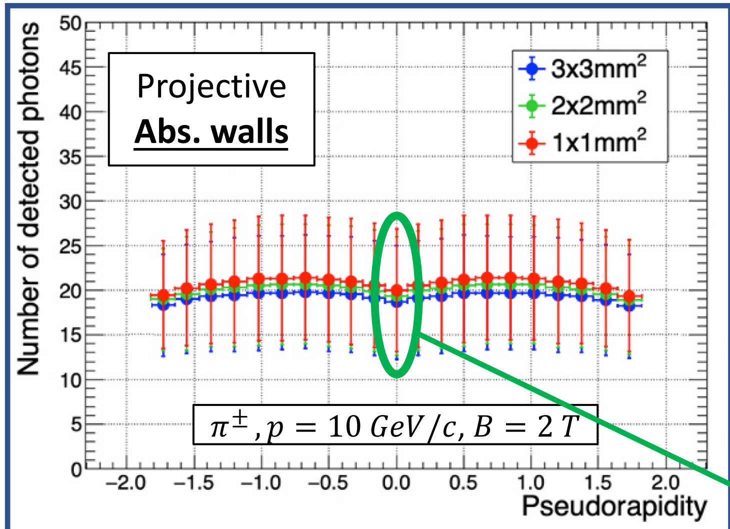


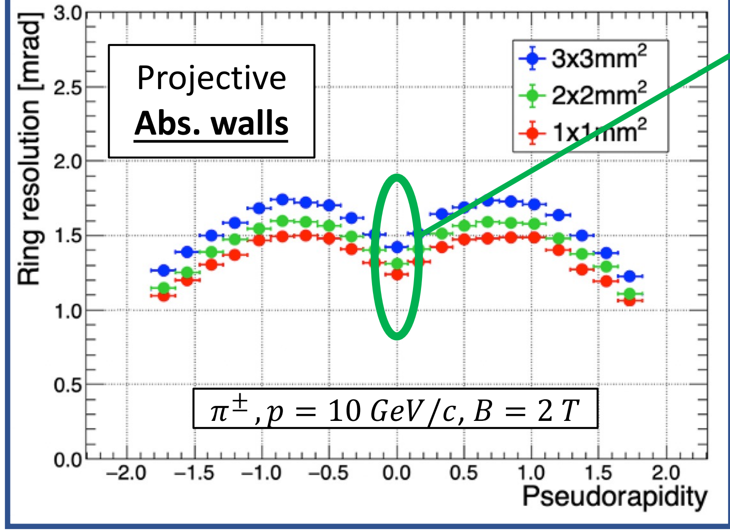
Transparent walls



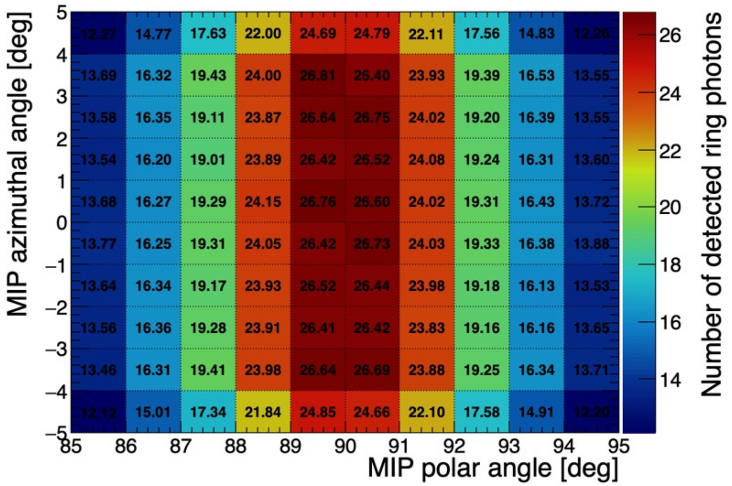
Fine θ-ϕ performance scan

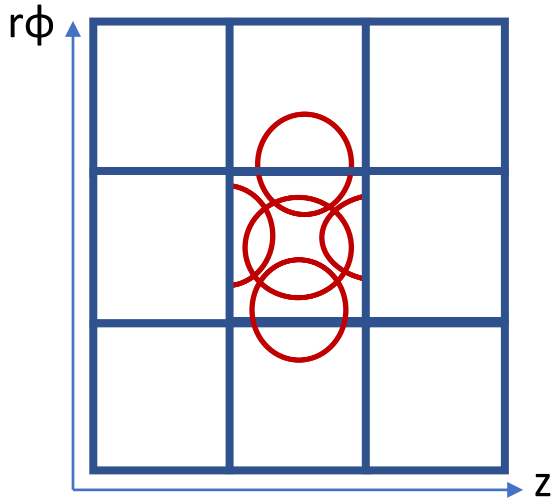
Absorbing walls between Z sectors

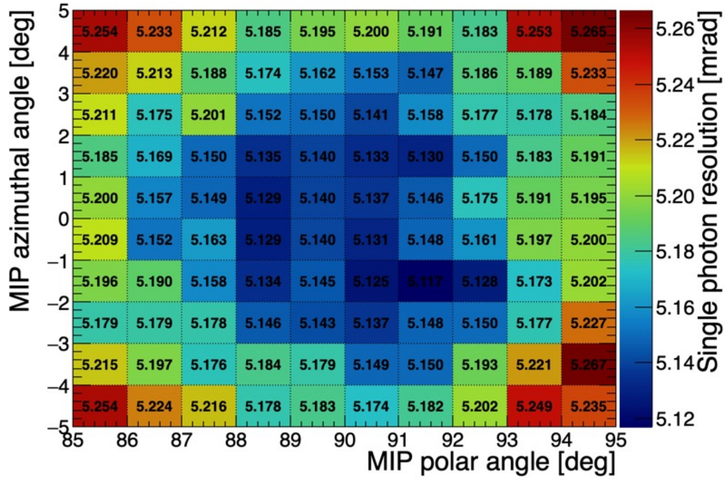


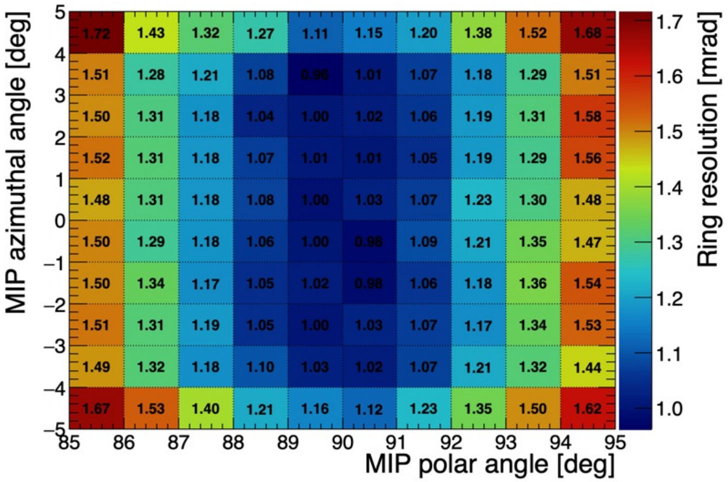


1x1 mm² - Scan on MIP polar and azimuthal angle central sector









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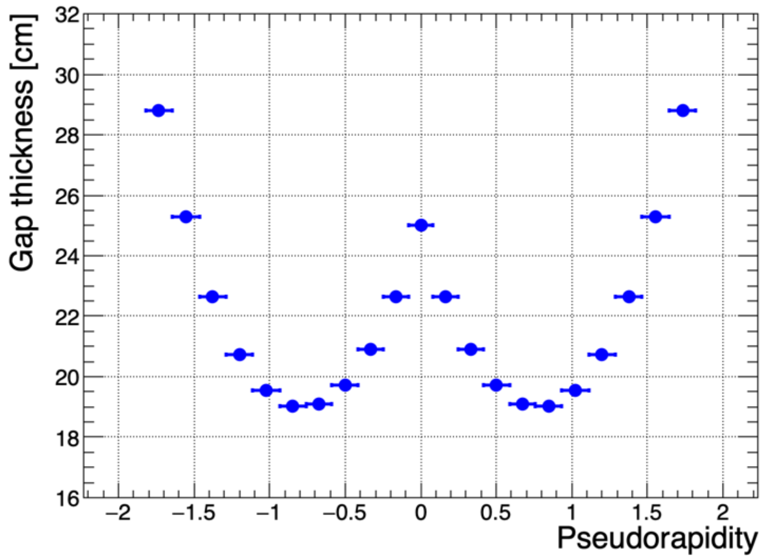
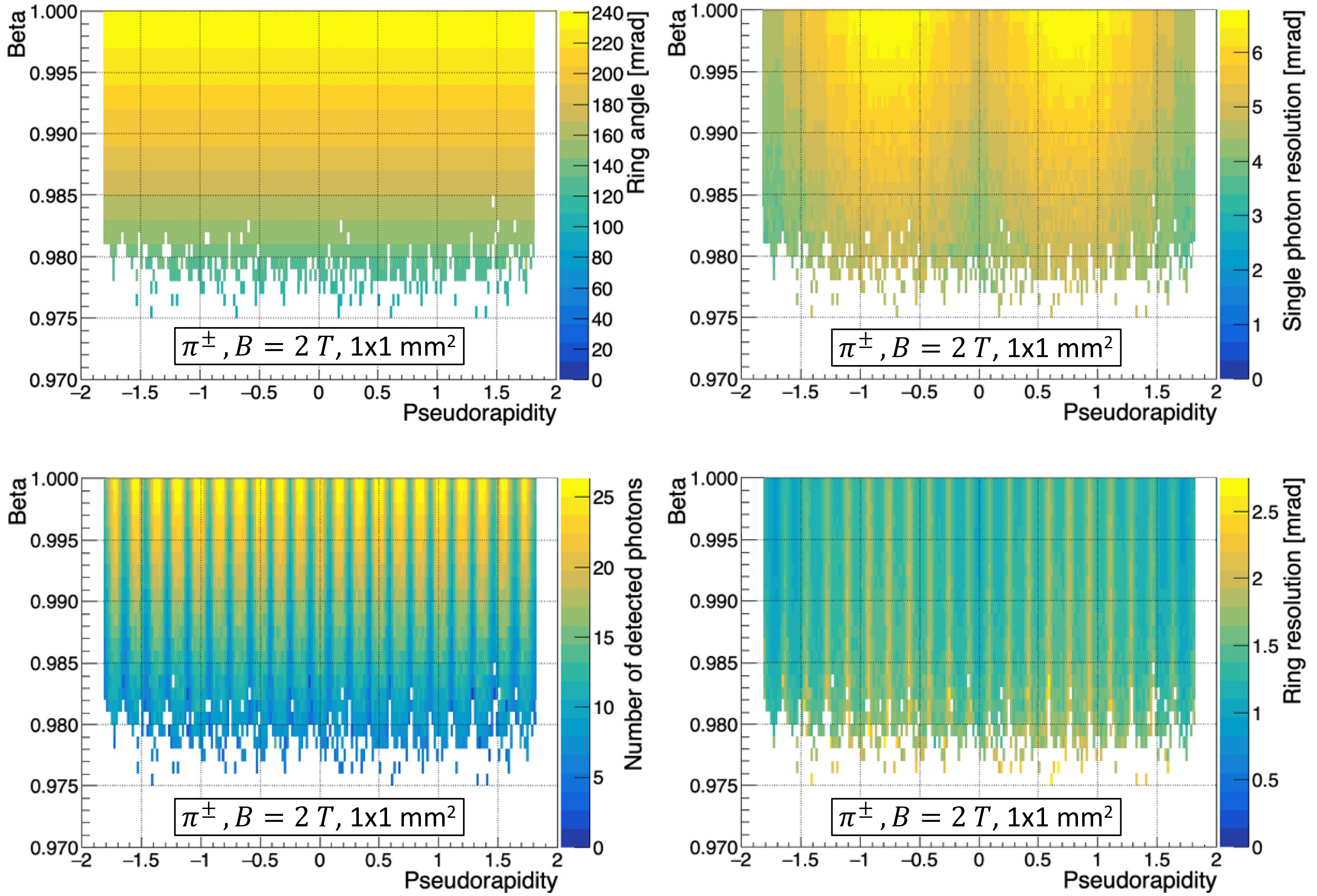
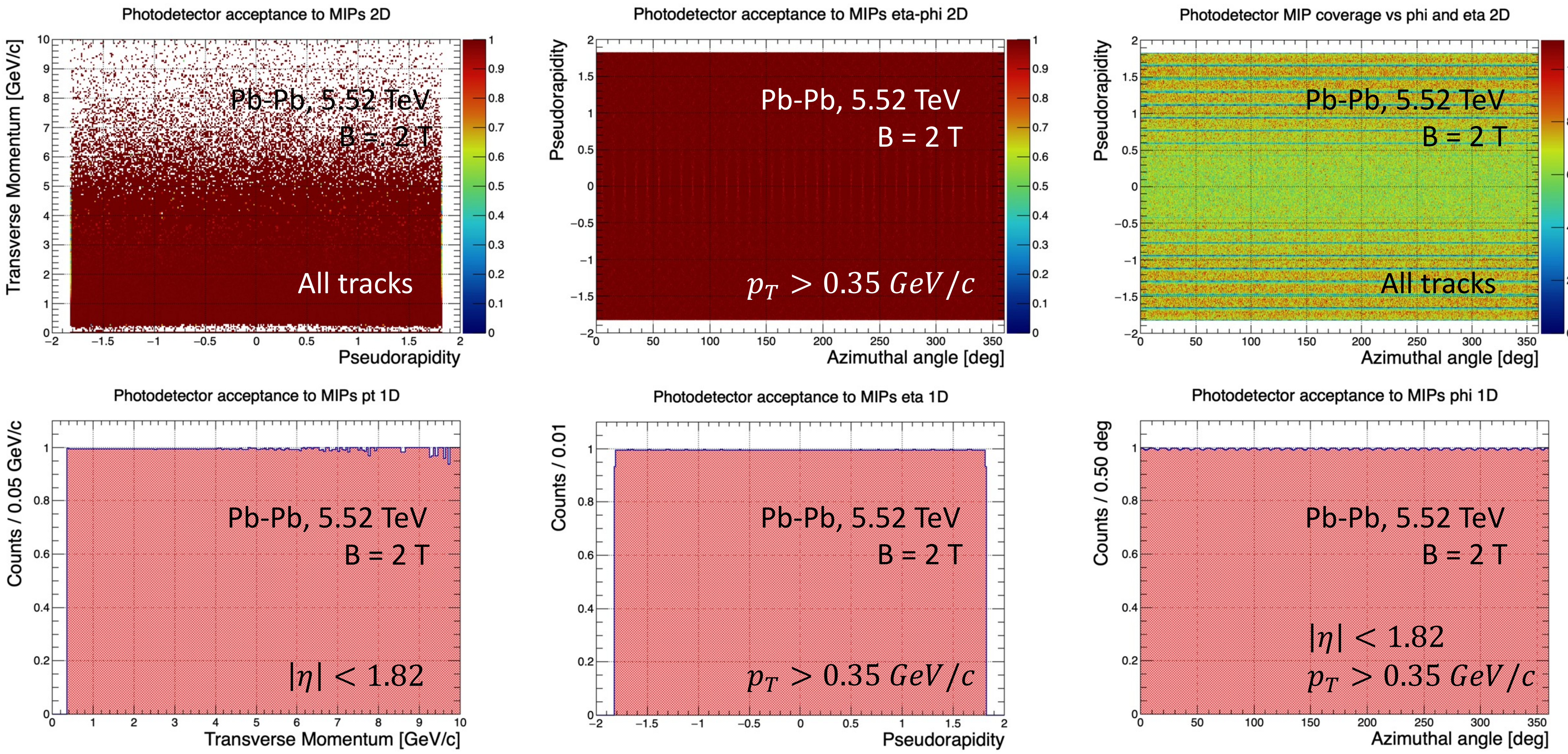
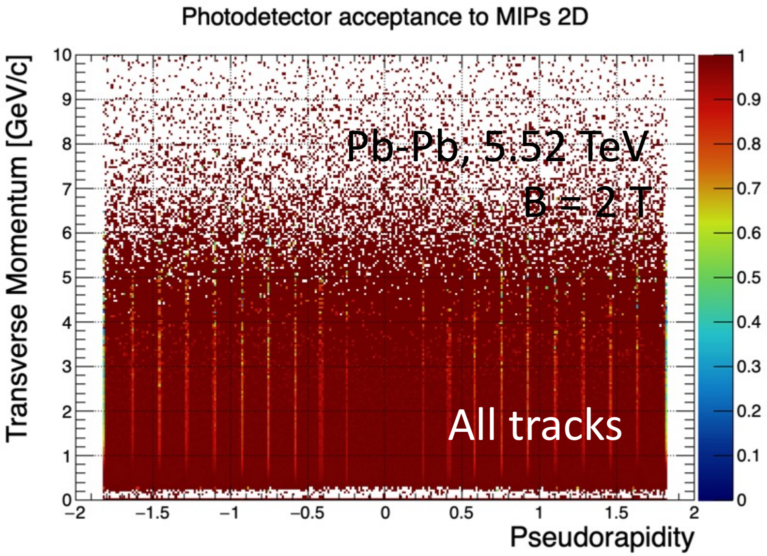


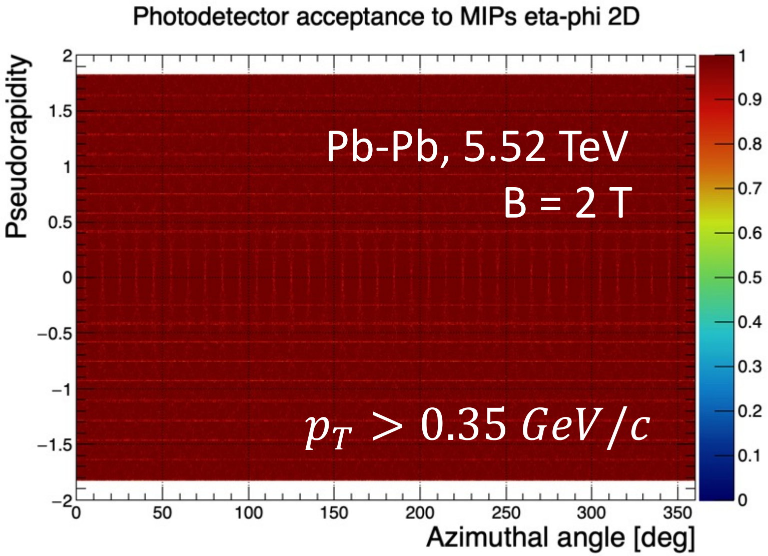


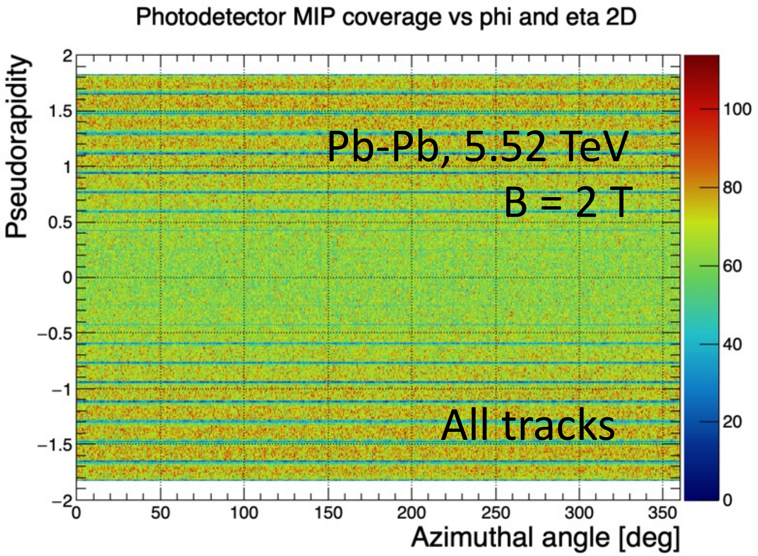
Acceptance: Vertex (0,0,0)

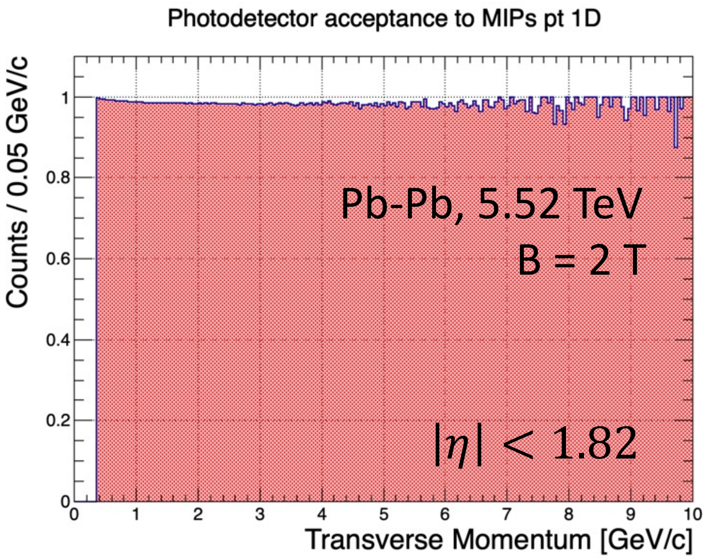


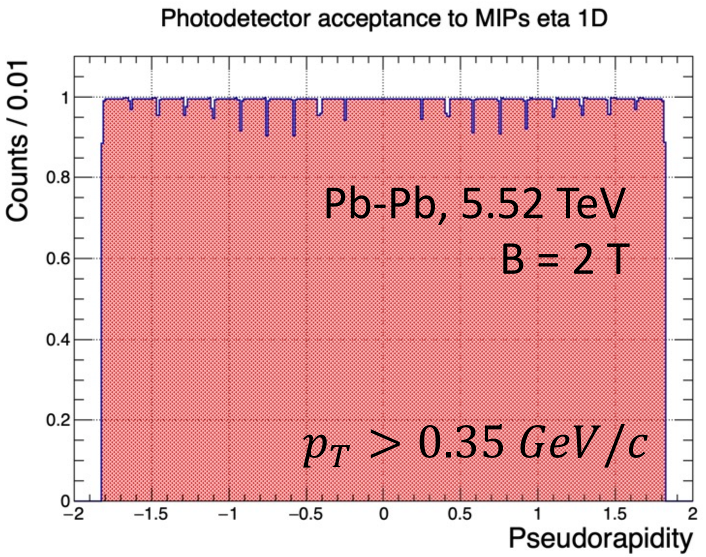
Acceptance: Vertex σ_z=10 cm

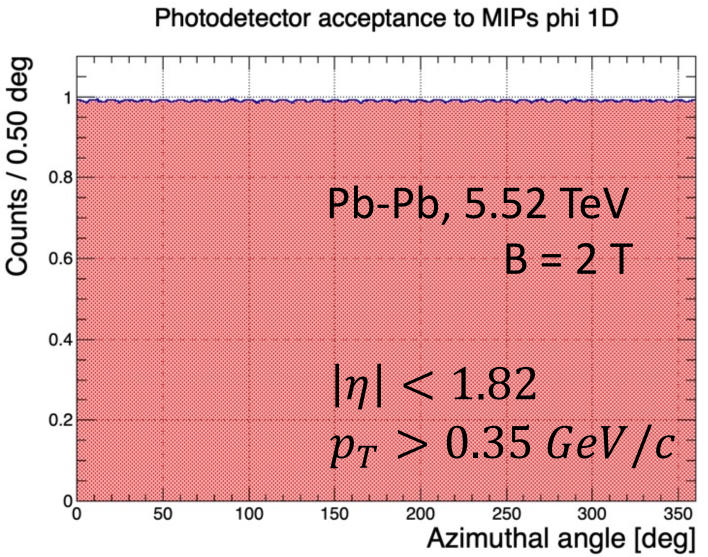






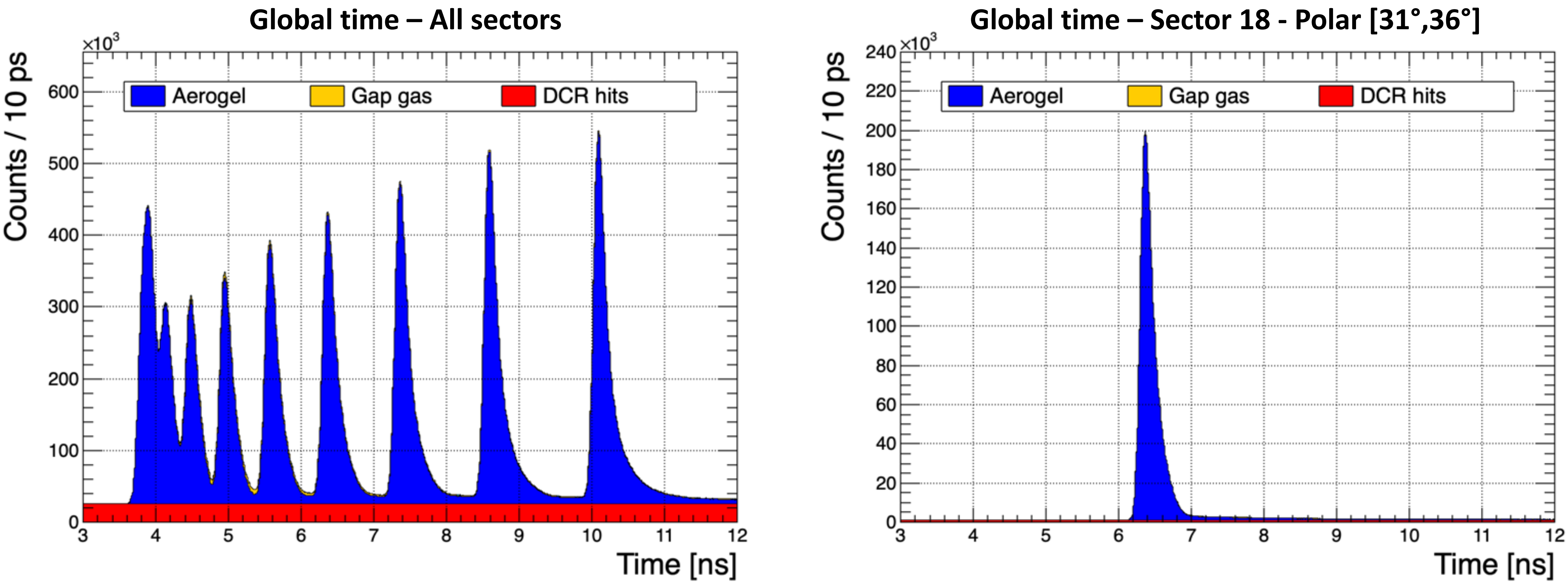






Global timestamp in central Pb-Pb

Pb-Pb, b < 3.5 fm , $\sqrt{s_{NN}} = 5.52\ TeV$, Pythia8, B = 2T

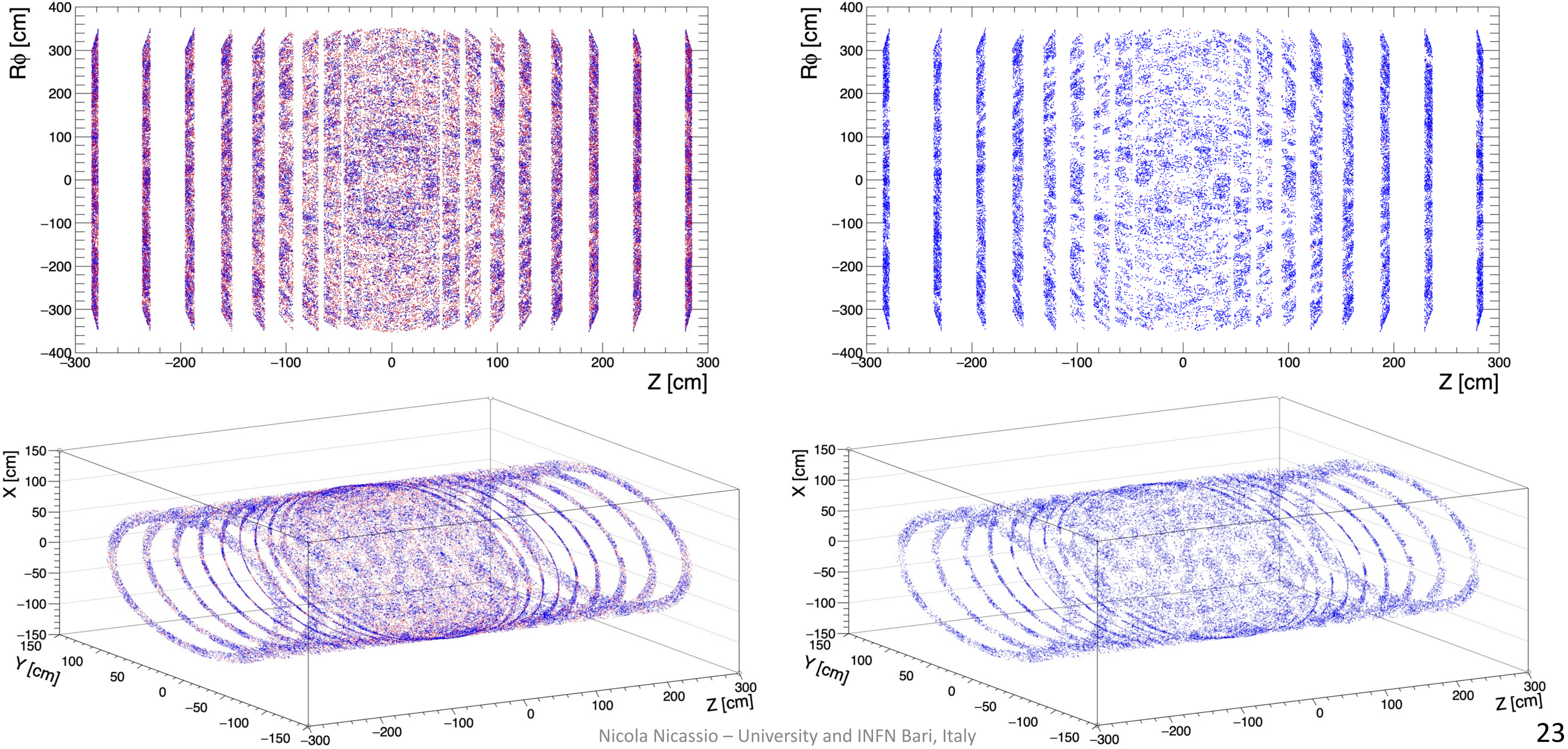


- DCR = 50 kHz/mm² → Many hits, but uncorrelated from signal hits in each sector, so easy to suppress
- Data volume efficiently reduced with acquisition time gate of ≈ 1 ns with different origin for each sector

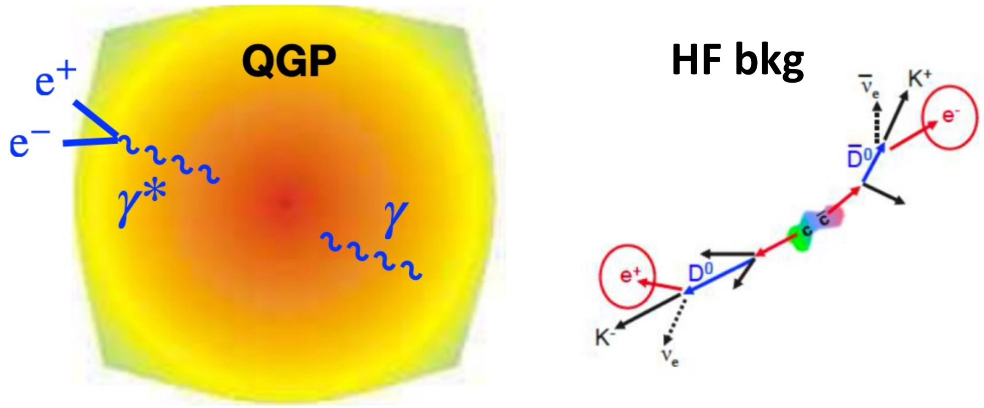
Event display of central Pb-Pb

Hits is 25 ns window – Signal and DCR bkg

Hits is 1 ns (tuned) window – Signal and DCR bkg



QGP temperature measurement



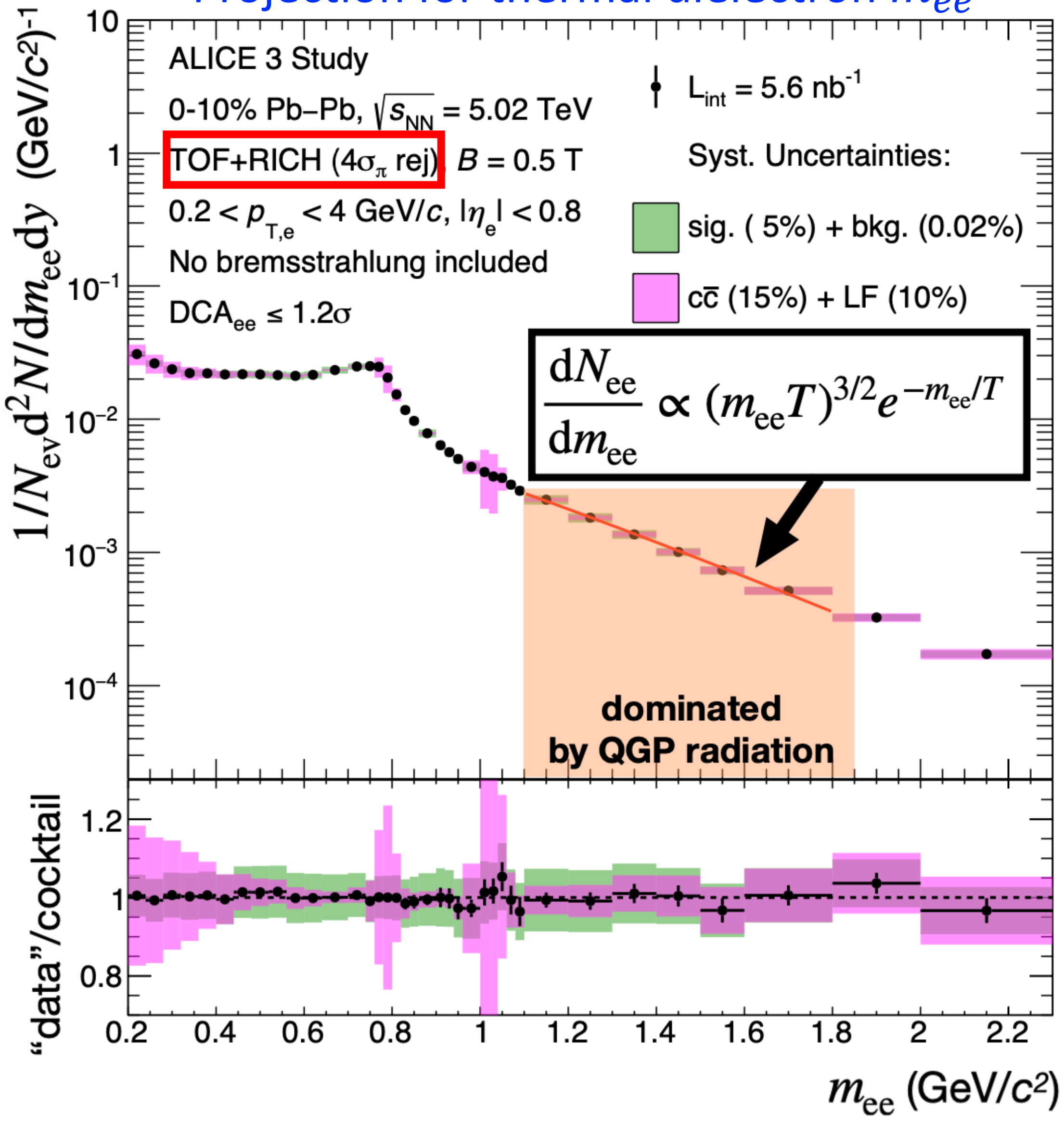
Averaged temperature T of the QGP using thermal dielectron m_{ee} spectrum at $\boldsymbol{m_{ee}}$ **> 1.1 GeV/c^2**

Crucial requirements

- Small material budget (γ conversion background)
- Good pointing resolution (heavy flavour decays)
- Very good electron identification down to low p_T

ALICE 3 barrel RICH mandatory for high-precision dielectron based QGP temperature measurements

Projection for thermal dielectron m_{ee}



Thank you for your attention

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