RICH 2022

11th International Workshop on Ring Imaging Cherenkov Detectors, University of Edinburgh, Edinburgh (UK), 12 - 16 September 2022

Aerogel RICH detector for the next generation heavy-ion experiment at LHC

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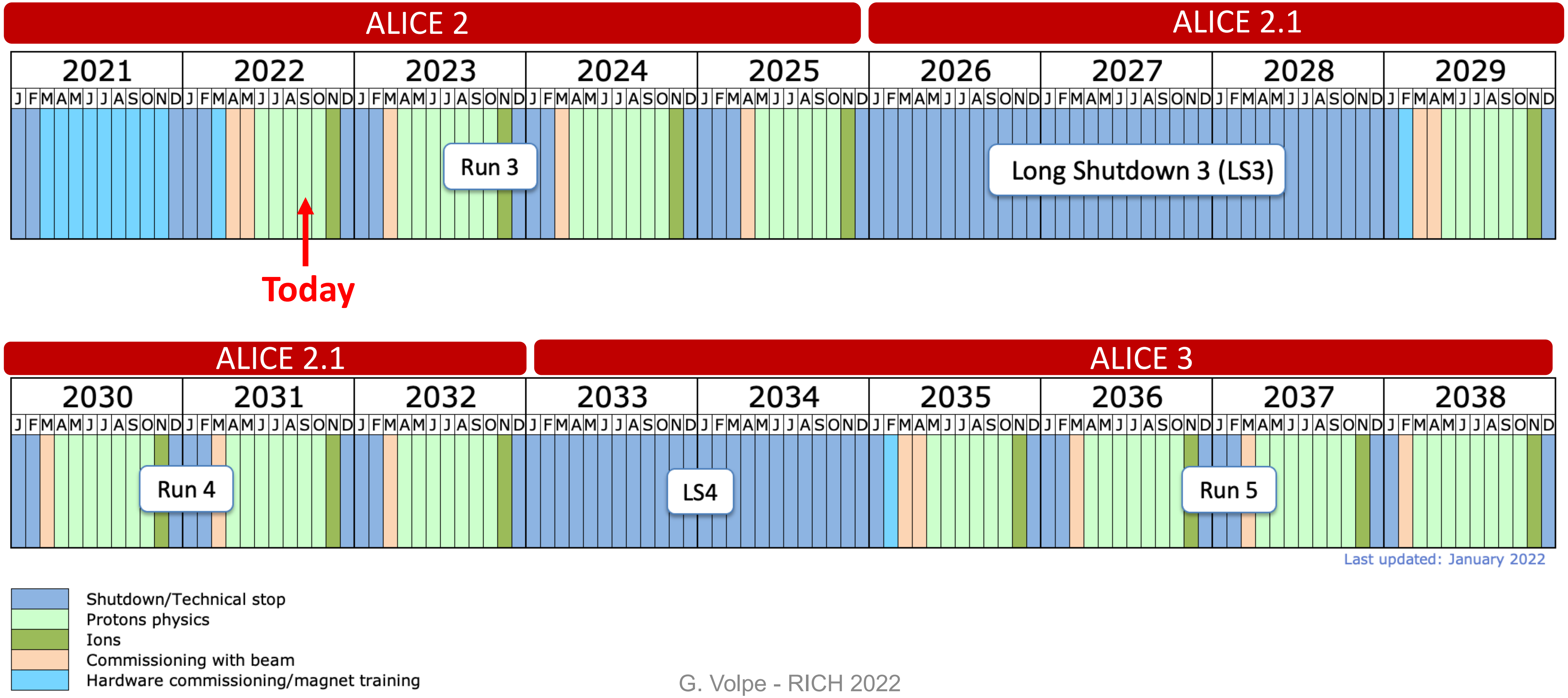
Outline

- ALICE roadmap
- “ALICE 3“ detector requirement
- RICH system
  - Radiator
  - Photon detector
  - Possible layouts
  - Simulation studies
- Ongoing and future studies
- Summary and outlook

ALICE roadmap

- Ideas for dedicated **heavy-ion programme for Run 5 and 6 at the LHC**
  - developed within ALICE in the course of 2018/19
  - **Letter of Intent** prepared over the course of 2021
  - **LHCC review process** started in October 2021



ALICE roadmap

- Ideas for dedicated **heavy-ion programme for Run 5 and 6 at the LHC**
  - developed within ALICE in the
  - **Letter of Intent** prepared over
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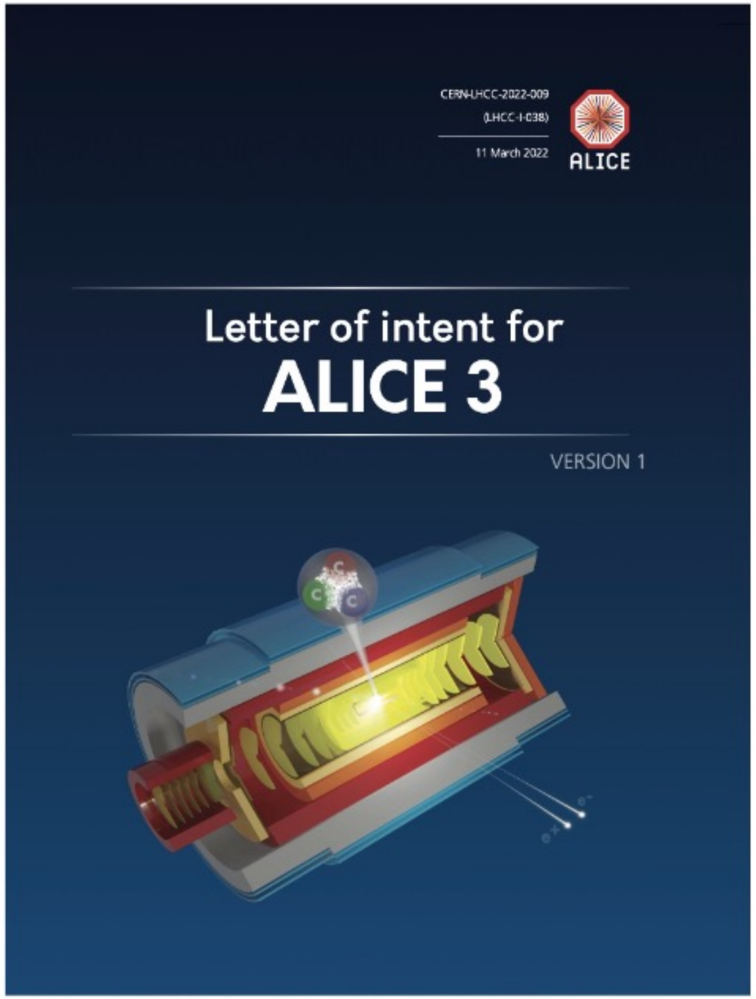

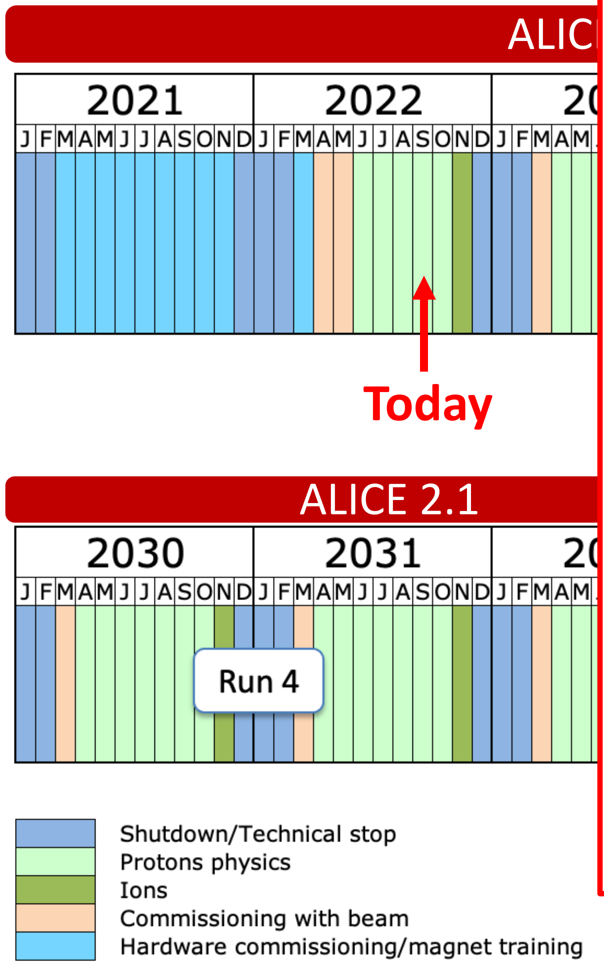
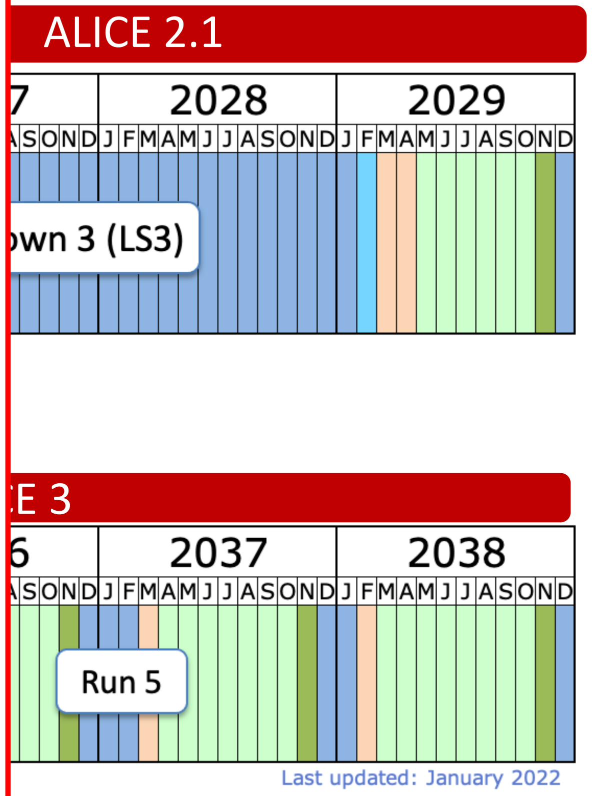

ALICE 3 detector requirements

Component	**Observables**	**Barrel** ($\lvert\eta\rvert < 1.75$)	**Forward** ($1.75 < \lvert\eta\rvert < 4$)	**Detectors**
Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{\rm DCA} \approx 10\,\mu$m at $p_{\rm T} = 200\,$MeV/c, $\eta = 0$	Best possible DCA resolution, $\sigma_{\rm DCA} \approx 30\,\mu$m at $p_{\rm T} = 200\,$MeV/c, $\eta = 3$	retractable Si-pixel tracker: $\sigma_{\rm pos} \approx 2.5\,\mu$m, $R_{\rm in} \approx 5\,$mm, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	(Multi-)charm baryons, dielectrons, photons ...	$\sigma_{p_{\rm T}}/p_{\rm T} \approx 1--2\,\%$		Silicon pixel tracker: $\sigma_{\rm pos} \approx 10\,\mu$m, $R_{\rm out} \approx 80\,$cm, $L \approx \pm 4\,$m $X/X_0 \approx 1\,\%$ per layer
Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{\rm tof} \approx 20\,$ps RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,$mrad
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to 2–3 GeV/c		Time of flight: $\sigma_{\rm tof} \approx 20\,$ps RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,$mrad
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/ψ at rest, i.e. muons from $p_{\rm T} \sim 1.5\,$GeV/c at $\eta = 0$		steel absorber: $L \approx 70\,$cm muon detectors
ECal	Photons, jets	large acceptance		Pb-Sci sampling calorimeter
ECal	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Soft photon detection	Ultra-soft photons		measurement of photons in $p_{\rm T}$ range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker

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Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{DCA} \approx 10\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{DCA} \approx 30\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 3$	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\,\mu m$, $R_{in} \approx 5\,mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	(Multi-)charm baryons, dielectrons, photons …	$\sigma_{p_T}/p_T \approx 1 - -2\,\%$		Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$ $X/X_0 \approx 1\,\%$ per layer
Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
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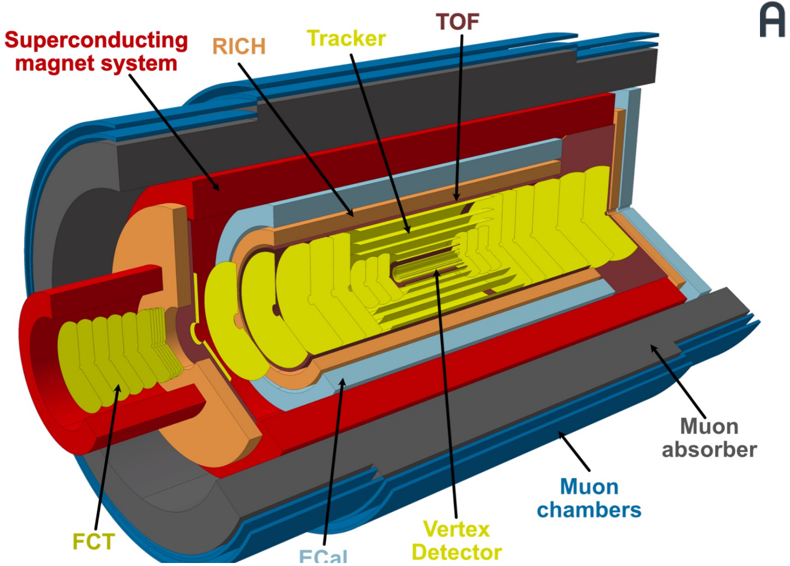
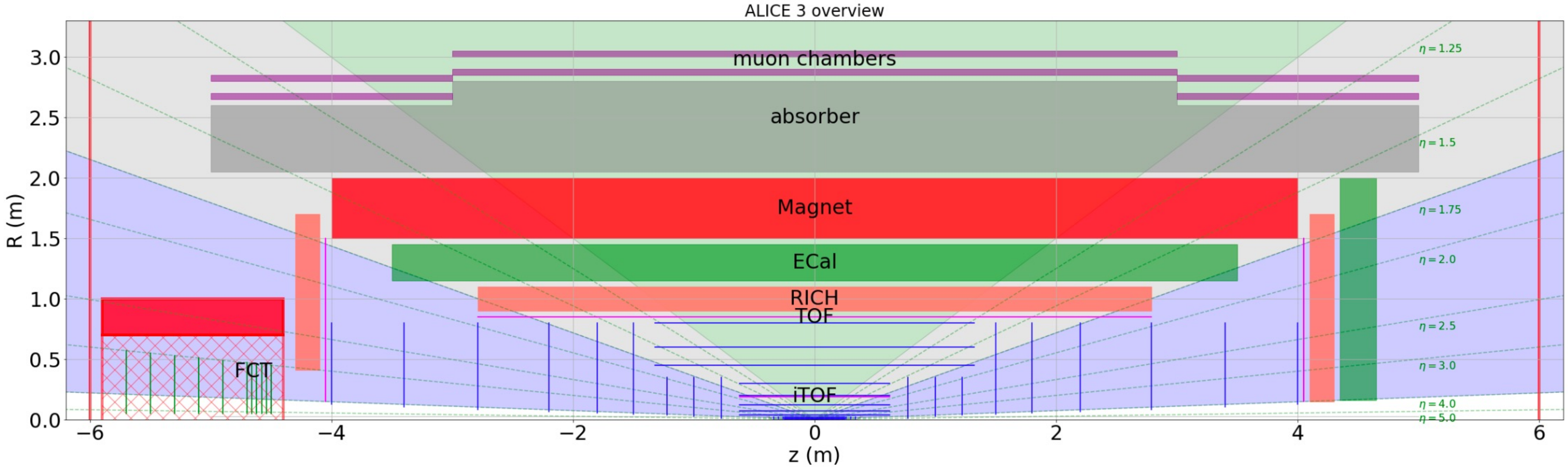
RICH system in the ALICE 3 layout

Barrel RICH:
- $\eta = \pm 1.75$, total length 5.6 m
- R = 0.9 - 1.1 m

Forward RICH:
- Ecal side:
  - $+1.75 \leq \eta \leq +4.0$
  - R= 0.2-1.5 m
- FCT side:
  - $-1.75 \leq \eta \leq -3.0$
  - R= 0.5-1.5 m



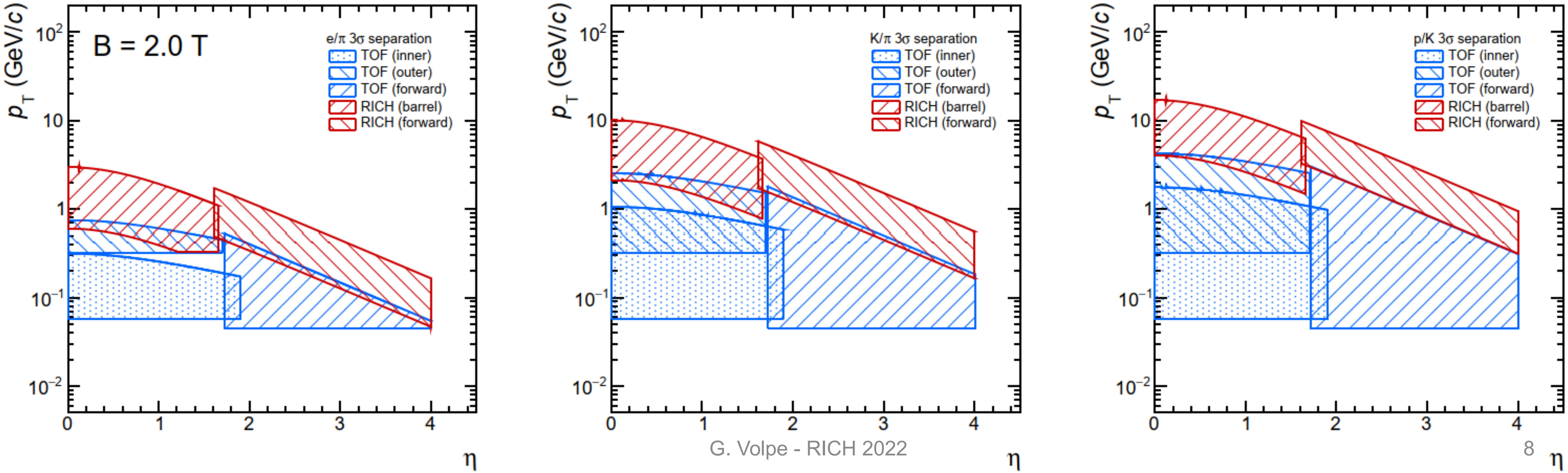


RICH system motivation

Extend electron and charged hadron ID at momenta higher than the TOF range, e.g in the barrel:
e/π : 0.5 - 2 GeV/c
π/K : 2.0 - 10.0 GeV/c
K/p : 4.0 – 16.0 GeV/c

- Barrel RICH: aerogel Cherenkov radiator (2cm, n=1.03) + 20 cm expansion gap + SiPM photon detector
- Forward RICH: idem, but aerogel n = 1.006

Results from "fast" parametric simulation, assuming a Cherenkov angle resolution at saturation of 1.5 mrad and a TOF time resolution of 20 ps



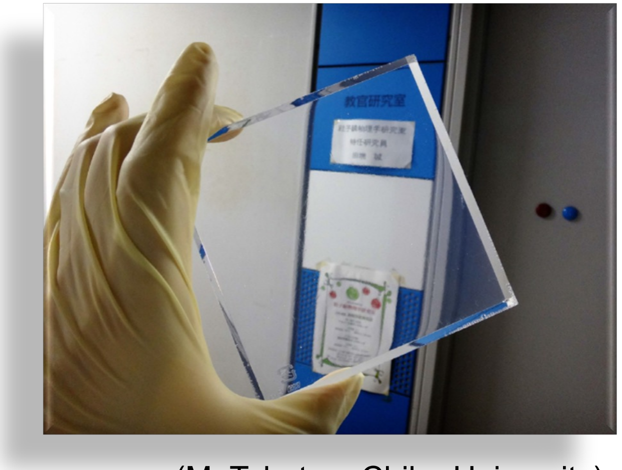
Aerogel Cherenkov radiator

Cherenkov relation *momentum threshold for Cherenkov emission*

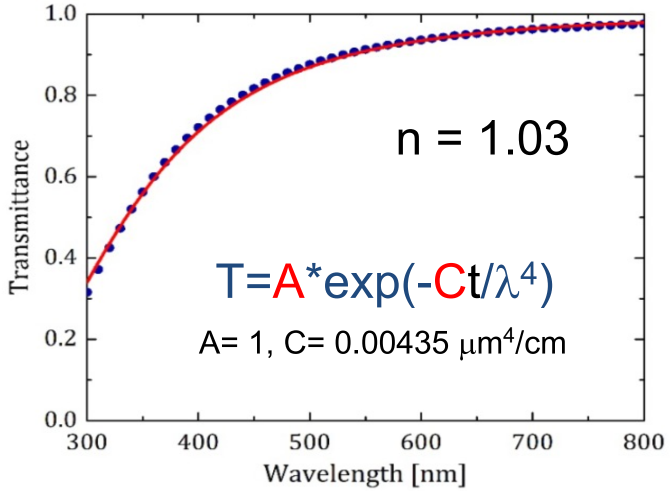
$$\cos\vartheta_c = \frac{1}{n\beta} \rightarrow \beta_{th} = \frac{1}{n} \rightarrow p_{th} = \frac{m}{\sqrt{n^2 - 1}}$$

aerogel n	β_{th}	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
1.06	0.94339623	0.0015	0.3005	0.3970	1.4042	2.6688
1.07	0.93457944	0.0013	0.2776	0.3667	1.2969	2.4649
1.08	0.92592593	0.0013	0.2590	0.3421	1.2102	2.3001
1.09	0.91743119	0.0012	0.2436	0.3218	1.1383	2.1634
1.14	0.87719298	0.0009	0.1930	0.2550	0.9019	1.7142

- **Best match with PID requirements, large choice of refractive indexes**
- **Possibility to fine tune PID threshold and range**



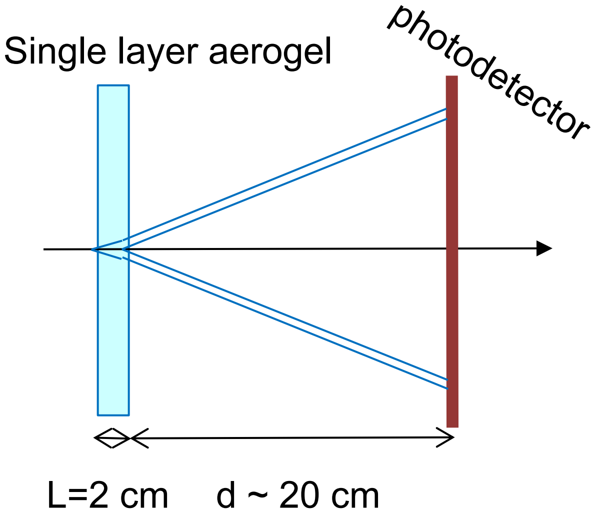
(M. Tabata – Chiba University)



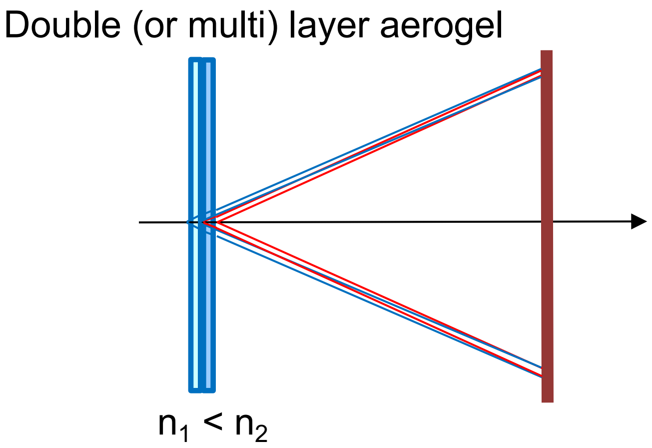
Hydrophobic silica aerogel from Aerogel Factory Co. Ltd (Chiba, Japan):
- No degradation for exposure to humidity, easy storage
- Excellent transparency in the range 1.02-1.05
- Stable up to 10 Mrad

Barrel RICH layout options

Baseline layout:
- No aerogel focusing
- Aerogel layer @ 0.9 m from IP
- Photodetector @ 1.1 m
- Aerogel ~ 32 m^2, p.d. ~ 39 m^2

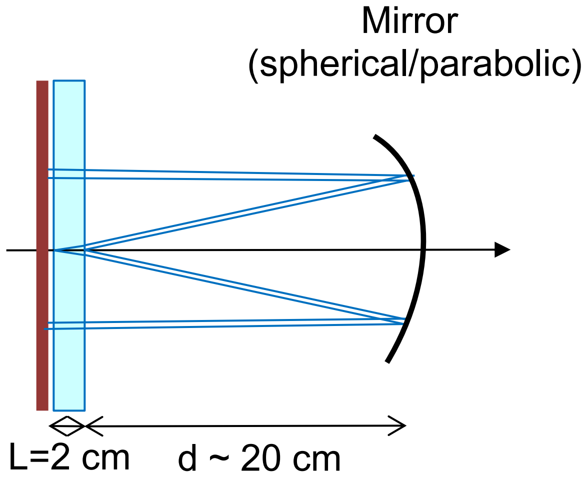


Aerogel focusing layout:
- Two or more aerogel layers with increasing n
- Aerogel layers @ 0.9 m from IP
- Photodetector @ 1.1 m
- Aerogel ~ 32 m^2, p.d. ~ 39 m^2



→ **pro's:**
- photons produced in the second layer reach the pd @ same radius as the first one, thus reducing the geometric aberration error in saturation

Mirror layout:
- With or w/o aerogel focusing
- aerogel layers @ 0.95 m from IP
- photodetector @ 0.9 m
- Aerogel ~ 33 m^2, p.d. ~ 32 m^2



→ **pro's:**
- **Reduce/suppress geometric aberration** depending on mirror:
  - flat: doubling of gap
  - cylindrical: focusing in one direction + doubling of gap
  - parabolic: full focusing
- **reduce p.d. area by 60%**

→ **con's:**
- ~ 20% photon loss due to double crossing of aerogel and mirror reflection
- spherical aberration and mirror alignment to be taken into account

Analytical estimation of Cherenkov angle resolution

ALICE

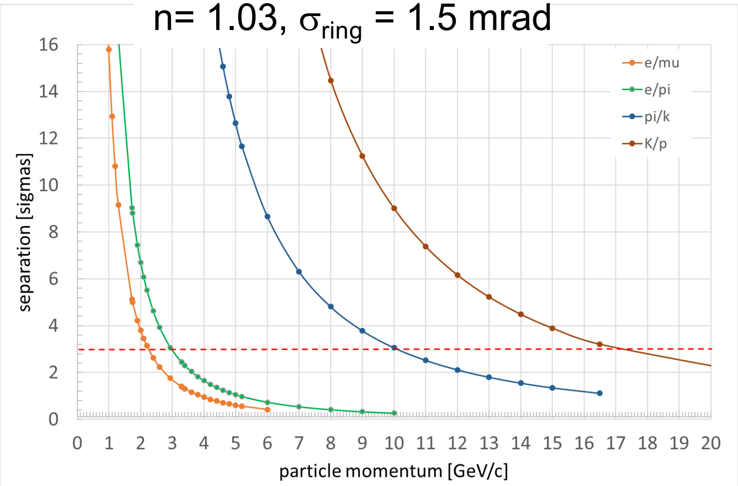
The particle separation depends on single photon angular resolution and on the amount of detected photons

$$\sigma_{\vartheta_c}(tot) = \frac{\sigma_{\vartheta_c}(p.e.)}{\sqrt{N_{p.e.}}} \oplus \sigma_{\vartheta_c}(track)$$

$$\sigma_{\vartheta_c}\text{ (p.e.)} = \sqrt{\sigma^2_{\vartheta_c}\text{ (chromatic)} + \sigma^2_{\vartheta_c}\text{ (geometric)} + \sigma^2_{\vartheta_c}\text{ (pixel)} + \sigma^2_{\vartheta_c}\text{ (noise)}}$$

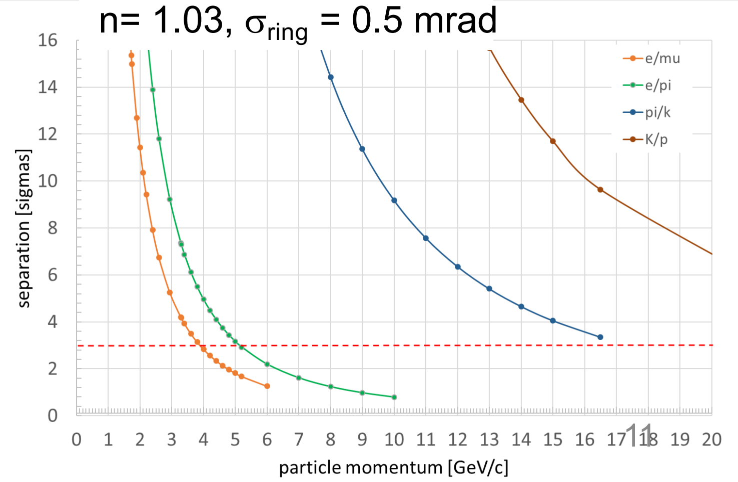
$$\propto \frac{dn(\lambda)}{d\lambda} \qquad \propto \frac{L}{d} \qquad \propto \frac{x}{d}$$

layout	GAP [cm]	radiator L [cm]	pixel [cm]	chrom_err	geom_err	pixel_err	σ_single p.e. [mrad]	# of photoel.	σ_ring [mrad]
baseline	20	2	0.3	1.4	6	3.9	7.4	24	1.5
two aerogel layers in focusing	20	2 x 1	0.3	1.4	3.1	3.9	5.2	24	1.1
spherical mirror	20	2	0.3	1.4	1.0	3.9	4.2	20	0.9
spherical mirror+ smaller pixel	20	2	0.1	1.4	1.0	1.3	2.1	20	0.5



PID reach for various *n* and angle resolution options

3 σ separation	n= 1.03 σ = 1.5 mrad	n= 1.03 σ = 0.5 mrad	n= 1.02 σ = 0.5 mrad	n= 1.01 σ = 0.5 mrad
e/π	3.0 GeV/c	5 GeV/c	5.5 GeV/c	6.8 GeV/c
π/K	10 GeV/c	17 GeV/c	20.0 GeV/c	23 GeV/c
K/p	18 GeV/c	24 GeV/c	32 GeV/c	39 GeV/c



The photon detector

Main requirements

- Single photon sensitivity in the visible range (Photon Detection Efficiency (PDE) > 40-50%)
- Integration fill factor > 90%
- Pixel ~ 3x3 mm^2
- Time resolution σ < ~ 100 ps
- Magnetic field B ≤ 2 T
- Expected radiation load: NIEL ~ 10^{12} 1-MeV n_{eq} /cm^2

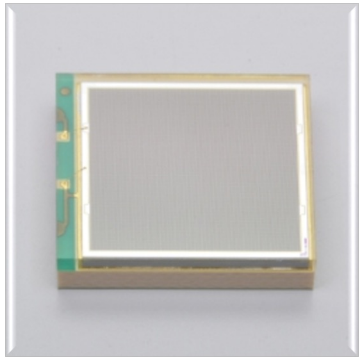
- **Vacuum-based devices (MCPs, LAPPDs)**
  - Single photon detection efficiency ~ 25-30%
  - Low noise and good radiation tolerance
  - Time resolution ~ 30 ps
  - ***Main limitations:***
    - Sensitivity to B (x10 gain drop above 0.5 T, no gain for ⊥ B)
    - HV operation
    - Bulky, reduced fill factor ~ 70%, large X_0
    - Cost of commercial devices
- **SiPM**
  - PDE ~ 50%
  - LV operation
  - Time resolution ~ 50 ps
  - ***Main limitations:***
    - Noise at room temperature, increase above 10^{11} 1-MeV n_{eq} /cm^2
    - Cost of commercial devices

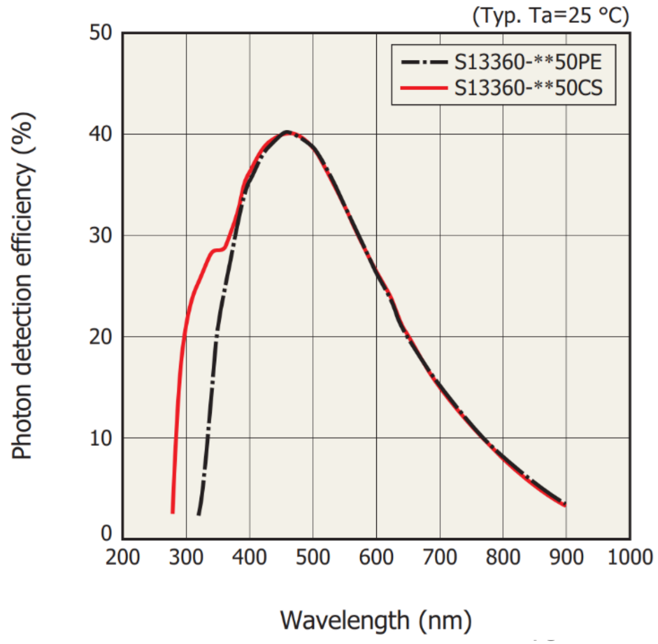
The photon detector

Significant enhancement on the semiconductor process over past decades, excellent improvement of CMOS SPAD performance → renewed interest for the **development of digital-SiPM** for large area coverage in HEP applications (e.g.: development ongoing in Sherbrooke University and FBK)

- **R&D on digital SiPM based on CMOS Imaging technology**
  - Reduce cost
  - Explore solutions for:
    - noise performance improvement (beyond online/offline time gate)
    - radiation hardness improvement (1-2 orders of magnitude, 10^{12} 1-MeV n_{eq} /cm^2 required)
    - TOF applications (MIPs detection with time resolution ~ 20 ps)

- **Backup option: commercial SiPM**
  - Example: SiPM HPK 13360 3050CS
  - 3x3 mm^2 pixel (3600 SPADs with 50 μm pitch)
  - Dark count rate (DCR) ~ 50 kHz/mm^2
  - 50 ps time resolution
  - Above 10^{11} 1-MeV n_{eq} /cm^2 → DCR increasing

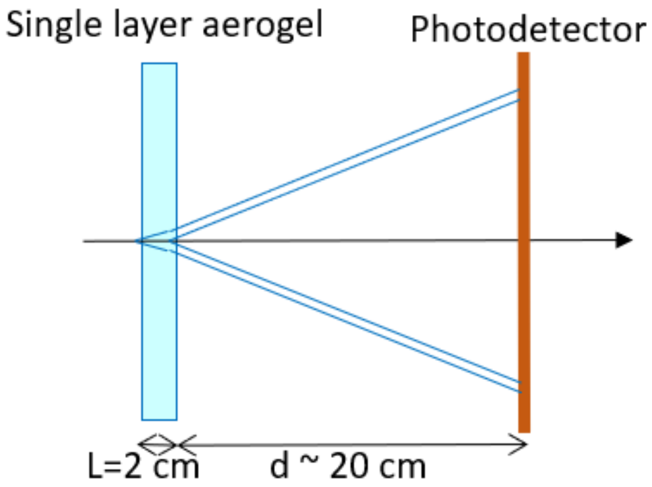


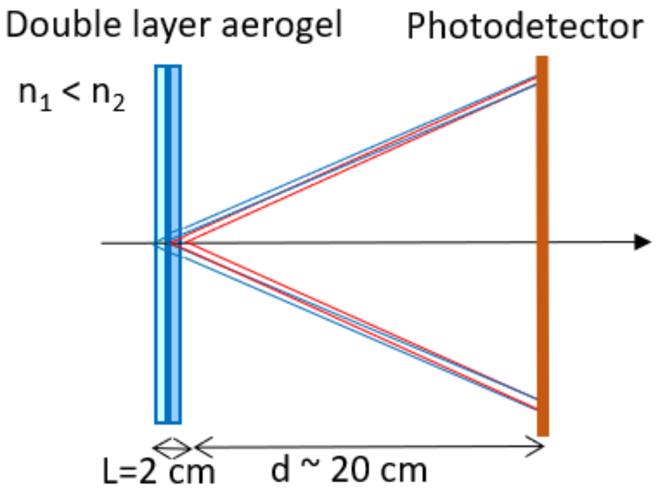


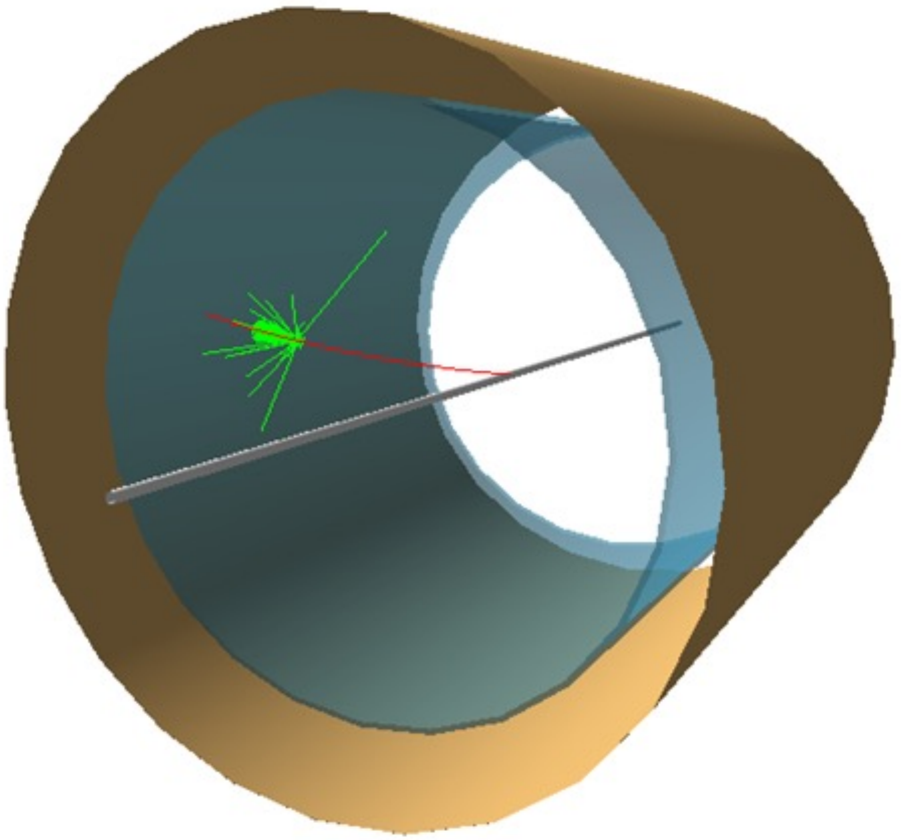
Simulation studies

Aerogel n=1.03, p.d. @ R=1.2 m, HPK 13360 3050CS (pixel 3x3 mm^2, DCR 50 kHz/mm^2, 90% fill factor)

- **single particle events**
  - uniform energy distribution
  - isotropic angular distribution
  - origin from (0, 0, 0)
  - one particle per event: e^- π^- μ^- K^- p
  - 10 k events/particle
- **Pythia8 pp collisions**
  - √s = 14 TeV
  - c-cbar biased processes
  - 100k events
- **Pythia8 Xe-Xe and Pb-Pb collisions**
  - √s = 5.76 TeV
  - minimum bias
  - 1k events



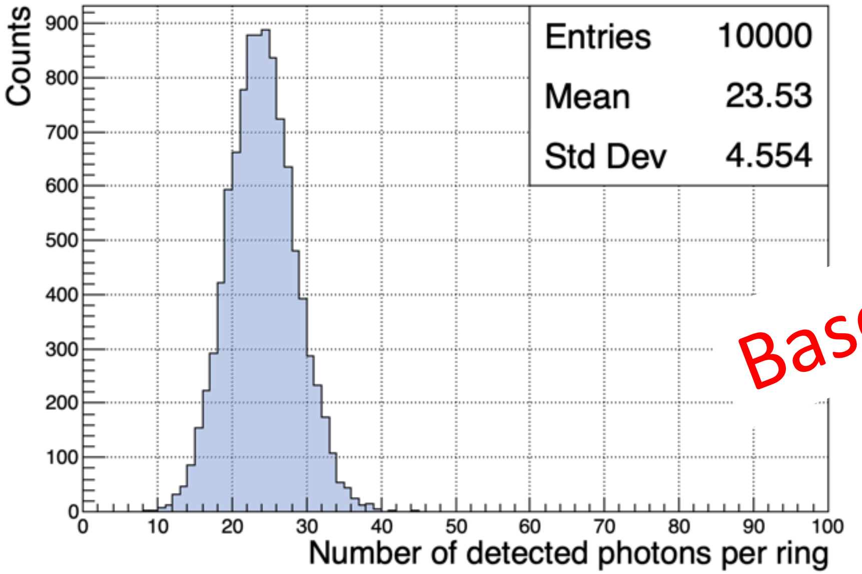


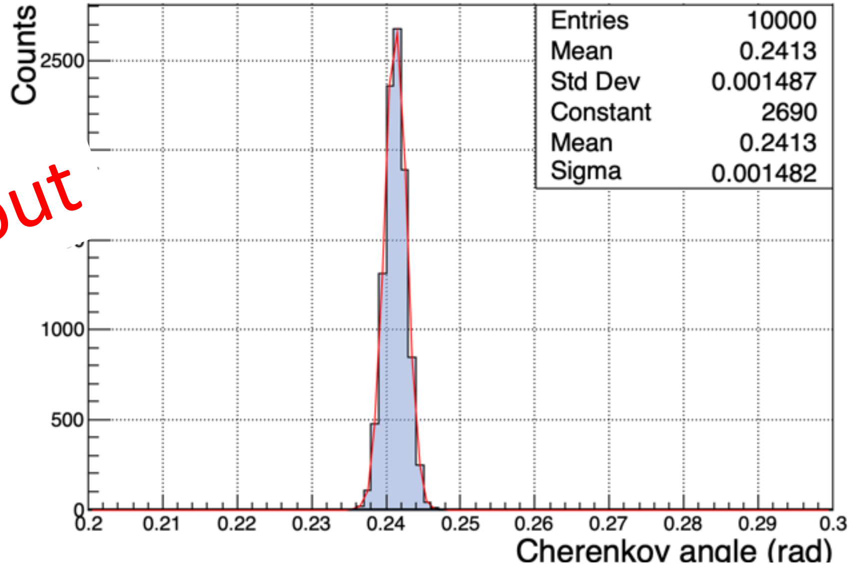


Tracking and TOF layers not shown

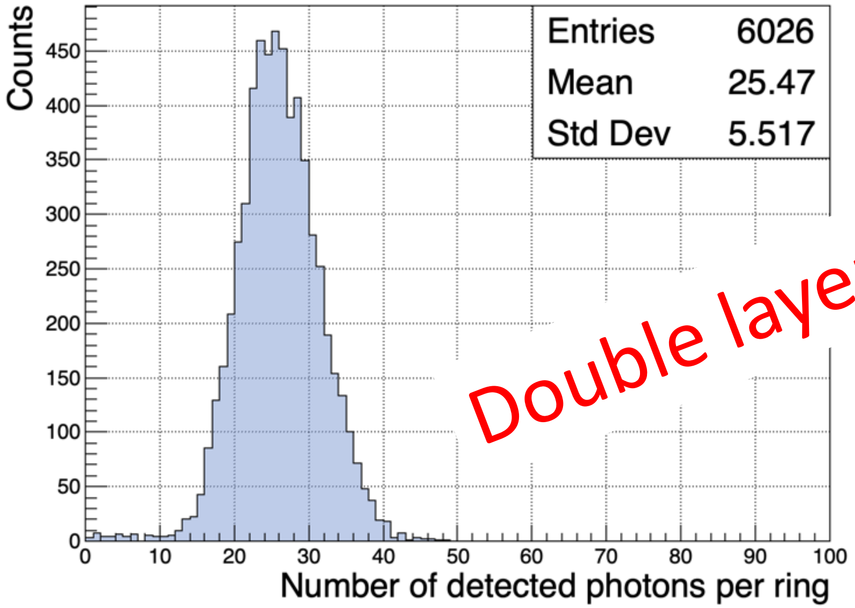
Simulation studies

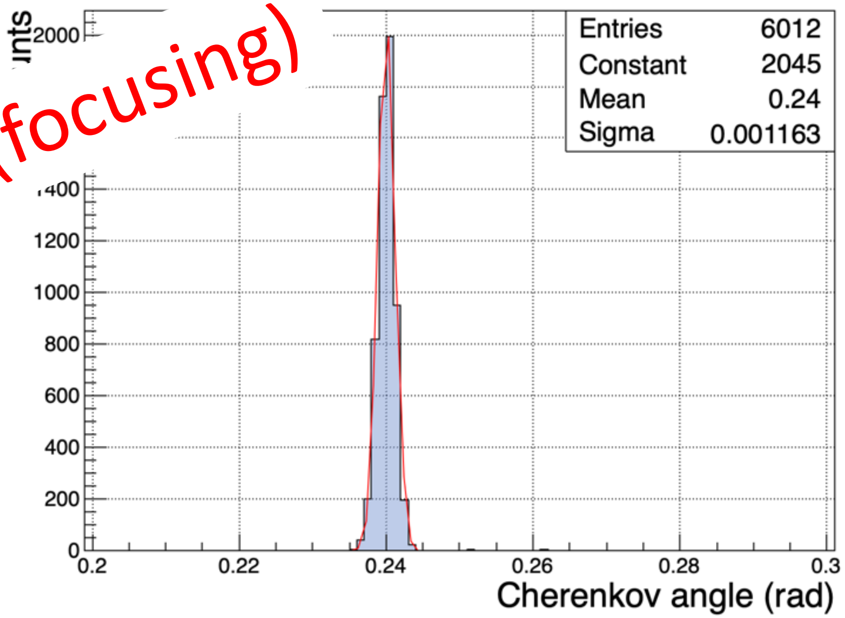
Baseline layout



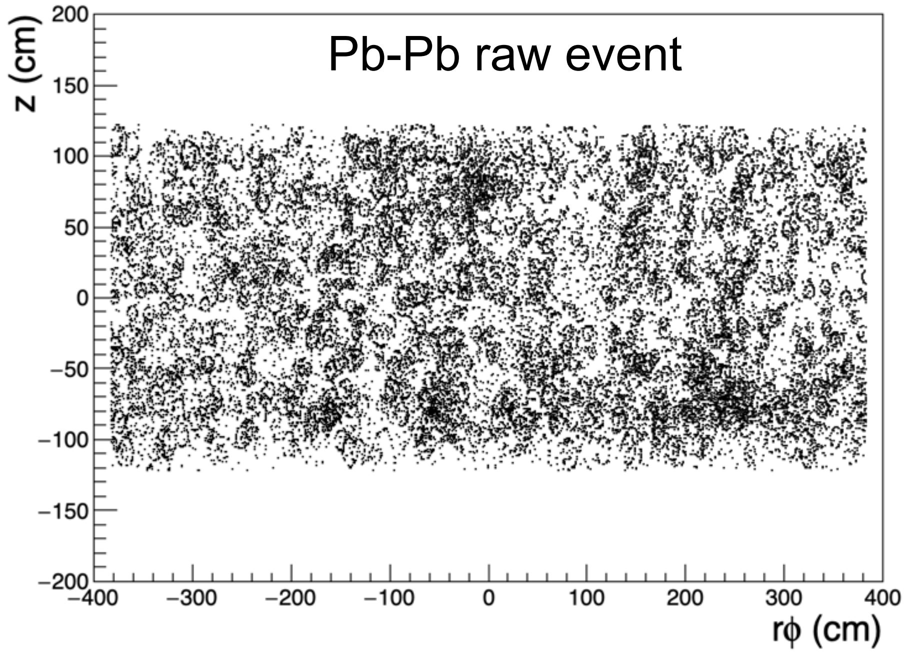


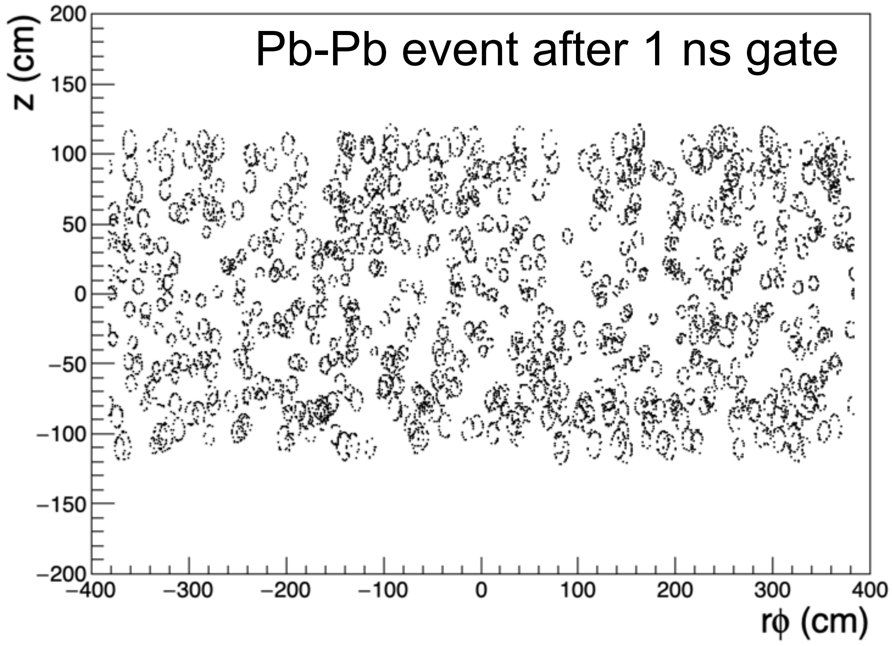
Double layer aerogel (focusing)

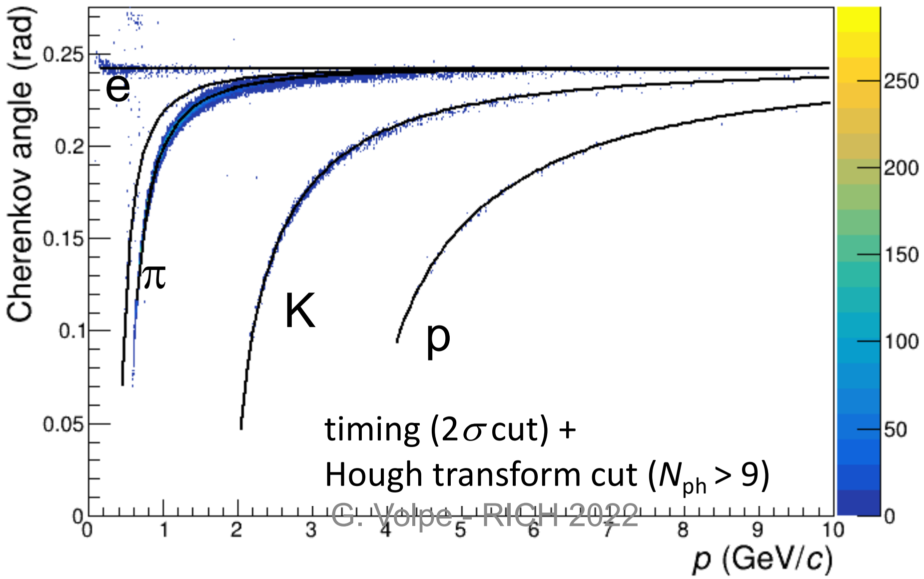




Simulation studies







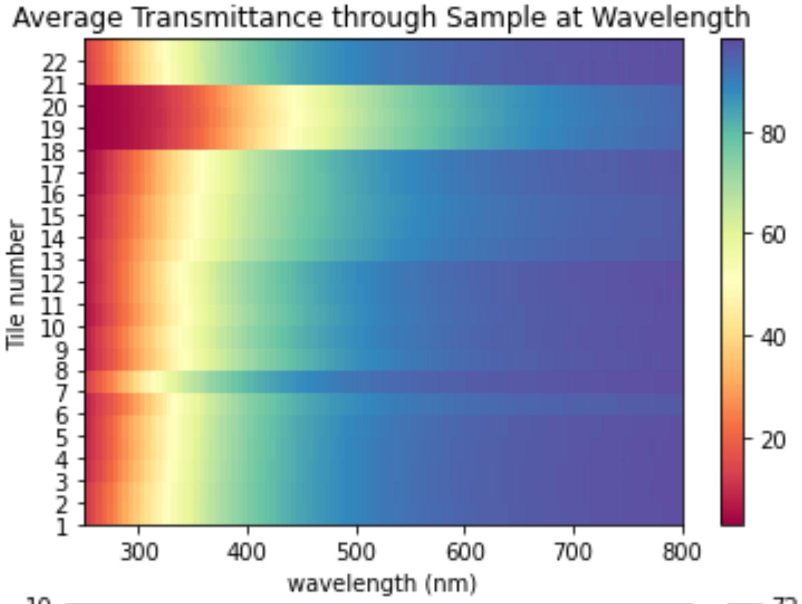
Ongoing and future studies

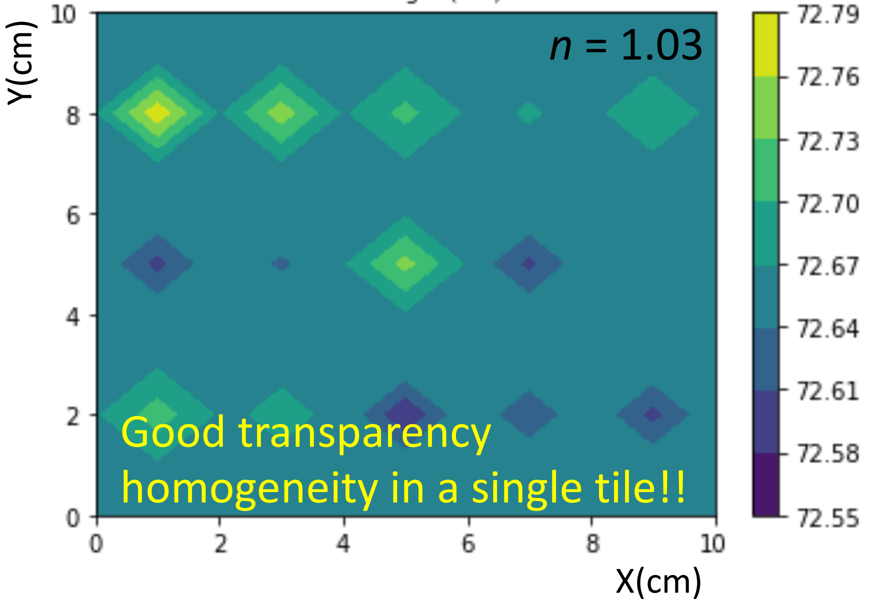
- Design
  - Performance vs Layout (options: aerogel n, focusing aerogel, mirror shape, SiPM pixel size)
  - Next
    - MonteCarlo (Geant4) simulations:
      - ✓ bRICH performance: aerogel n tuning (vs TOF performance), focusing aerogel, mirrors

- Aerogel
  - Optical properties (transparency, Rayleigh+Mie scattering), tile size, multiple layer focusing performance, barrel integration (segmentation, mechanical support, mounting)
  - Ongoing: basic characterization of hydrophobic aerogel (2x10x10 cm^3 tiles) from Aerogel factory, JP (optical properties, mechanical tolerances)
  - Characterization of larger tiles (2x15x15 cm^3)
  - Characterization of lower *n* and multi-layer (focusing)
  - Integration/Mounting issues

Ongoing and future studies: aerogel tile characterization

Transparency measurement in lab!





#	Sample	n	Max t (mm)	Measured abs. length
1	LEC4-1b	1.03	21.2302	71.6598
2	LEC4-2a	1.03	21.3703	72.0948
3	LEC6-1a	1.03	20.783	68.774
4	LEC6-1b	1.03	21.2154	68.9515
5	LEC6-2b	1.03	20.961	67.9965
6	SP3-0	1.03	11.7749	32.2599
7	SP3-1	1.03	12.5724	44.6441
8	LEC11-6	1.04	20.8677	57.823
9	LEC11-7	1.04	21.4847	61.4199
10	LEC12-1	1.04	20.9313	57.6797
11	LEC12-4	1.04	21.1525	60.1764
12	LEC12-6	1.04	21.5779	61.1588
13	LEC8-1	1.05	21.1954	51.7276
14	LEC8-2	1.05	21.0821	49.4528
15	LEC8-6	1.05	21.8642	48.9281
16	LEC9-1	1.05	21.0111	47.2045
17	LEC9-2	1.05	21.07	48.0334
18	TSA41-2a	1.00539	20.3624	19.8812
19	TSA41-2b	1.00544	21.2492	19.3864
20	TSA41-3a	1.00548	21.1344	19.7495
21	TSA38-2	1.0312	21.443	70.9995
22	TSA38-8	1.0311	21.4538	72.2721

HERMES 1998

Ongoing and future studies: aerogel tile characterization

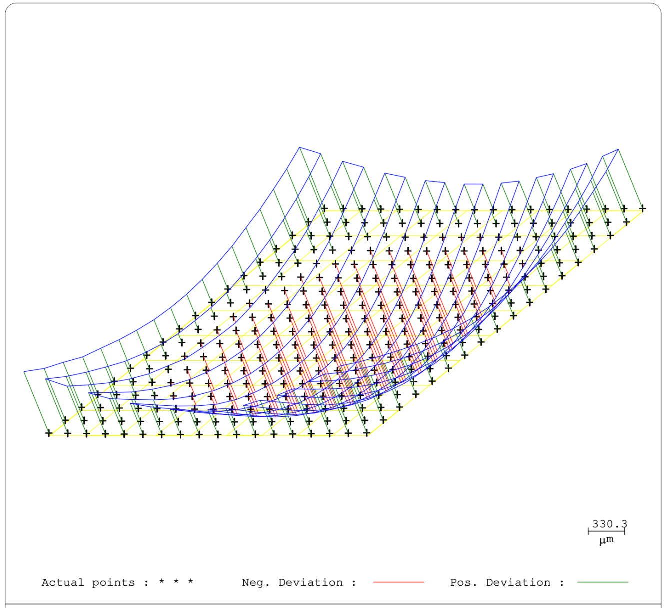
Thickness and flatness measurement in metrology lab at CERN!

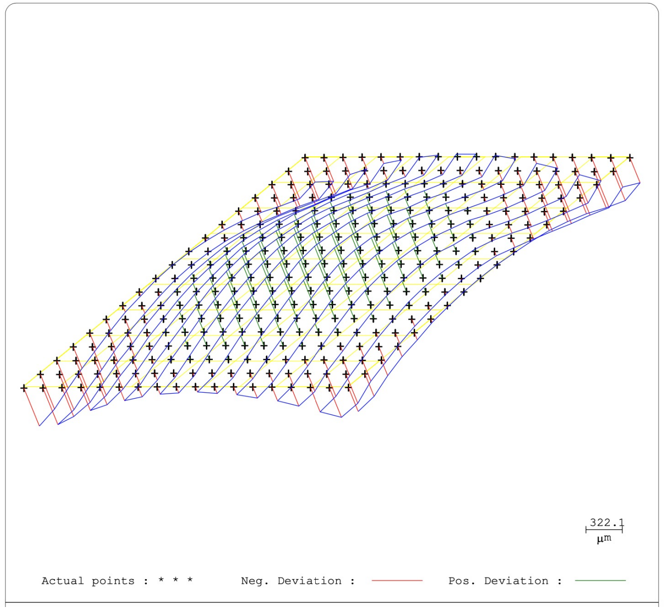
- Results obtained on a tile of n = 1.03 with the touch probe system (force applied by the probe is 2 gr).
- The measuring system is the LEITZ PMMC with ± 0.3 μm of precision

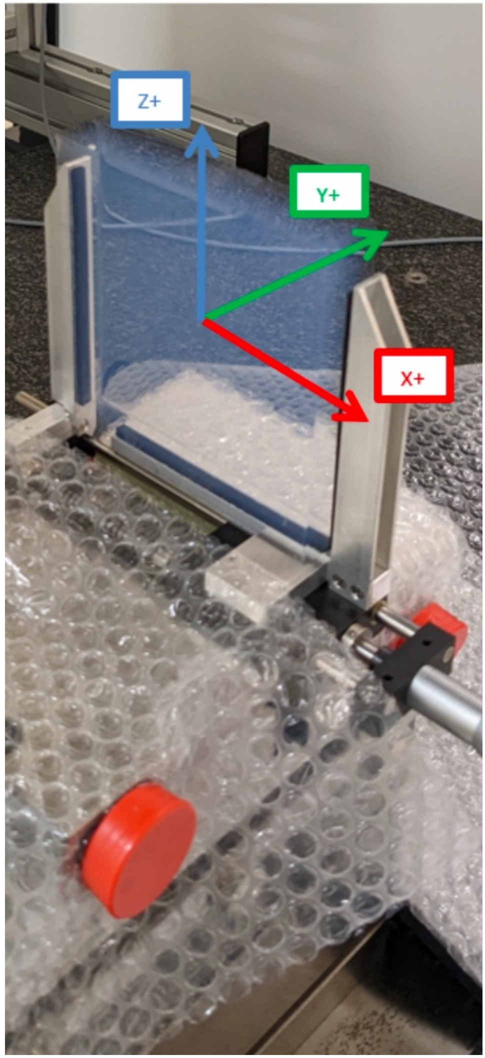
Thickness = 19.96 ± 0.17

Plane Y- side = 0.7060

Plane Y+ side = 1.2716







There is a variation in thickness from the centre to the edges, of the order of 0.4 mm, and a different planarity in the two faces, one 0.7 mm, the other 1.27 mm. In general the tiles have the shape of a dome.

- The manufacturer (Aerogel Factory Ltd, Chiba, JP) stated that it is possible to improve the flatness and the thickness uniformity;
- the planarity can be mapped, to include the defect in the reconstruction of the Cherenkov angle.

Ongoing and future studies: photon detector

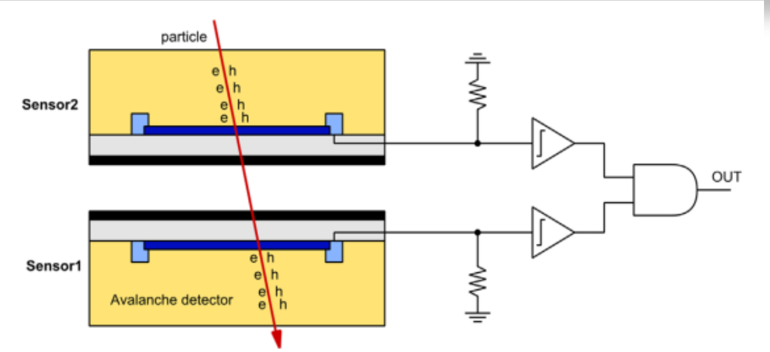
A few examples of SiPM R&D ideas

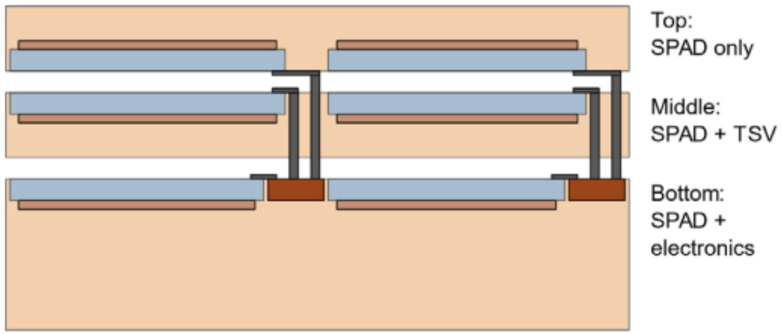
- ***Need to instrument large area without minimal gaps, solutions***: integrate sensor + front-end with 3D manufacturing (+ active quenching, fast signal processing and TDC integration, disabling of hot SPADs, ...)

- Implementation of MIP detection for TOF measurements in the same photo-detector layer (***F. Carnesecchi et al., arXiv:submit/4155801***): detection efficiency and time resolution for MIPS?
- Exploit Cherenkov photons from thin SiO_2 coating?

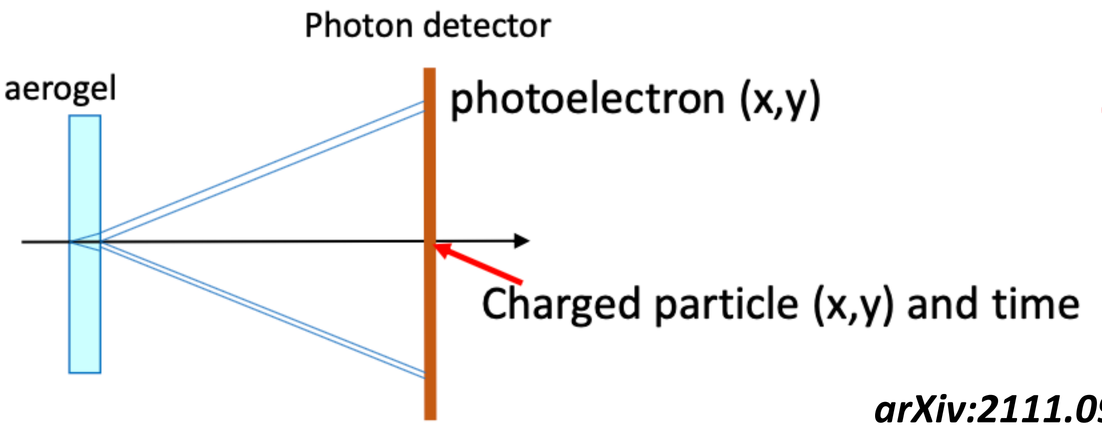
- "Monolithic" 3D approach for double layer pixel coincidence (DCR suppression), APIX/ASAP concept (***L. Pancheri et al. NIM A 845 (2017) 143-146***, ***P. Brogi et al. NIM A 958 (2020) 162546, L. Ratti et al. doi: 10.3389/fphy.2020.607319***)

  ➡ 10 ps measured in test beam (***L. Gramuglia et al., arXiv:2111.09998v1***)



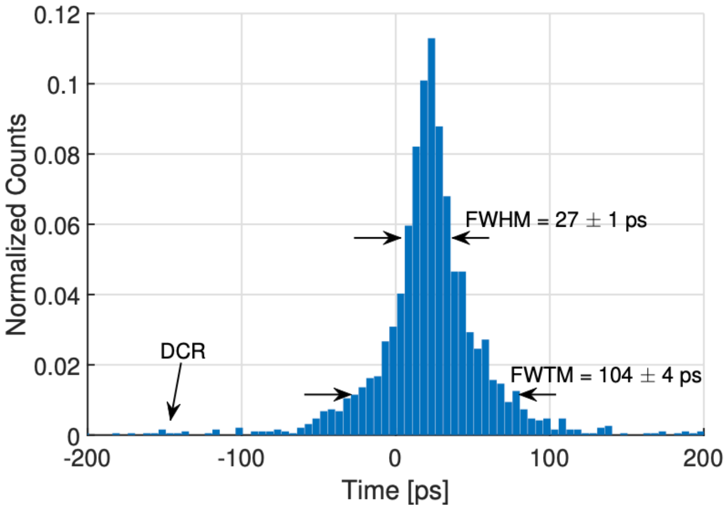


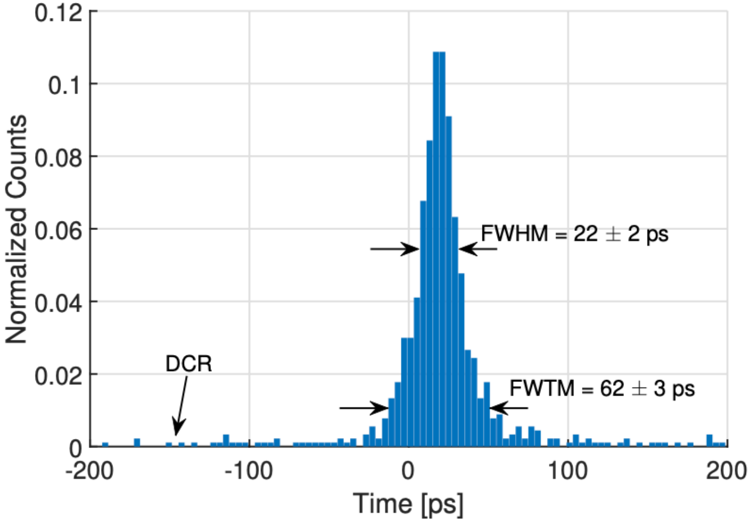
Ongoing and future studies: photon detector



Can SiPMs be used for both detection of Cherenkov photons and TOF for charged particles?!

arXiv:2111.09998v1 [physics.ins-det]





Bias (V)	FWHM (ps)	FWTM (ps)	σ (ps)	σ_{single} (ps)
24	27 ± 1	104 ± 4	11.5 ± 0.4	8.1 ± 0.3
27	22 ± 2	62 ± 3	9.4 ± 0.7	6.6 ± 0.5

Ongoing and future studies: photon detector

A step forward: Cherenkov-based TOF system

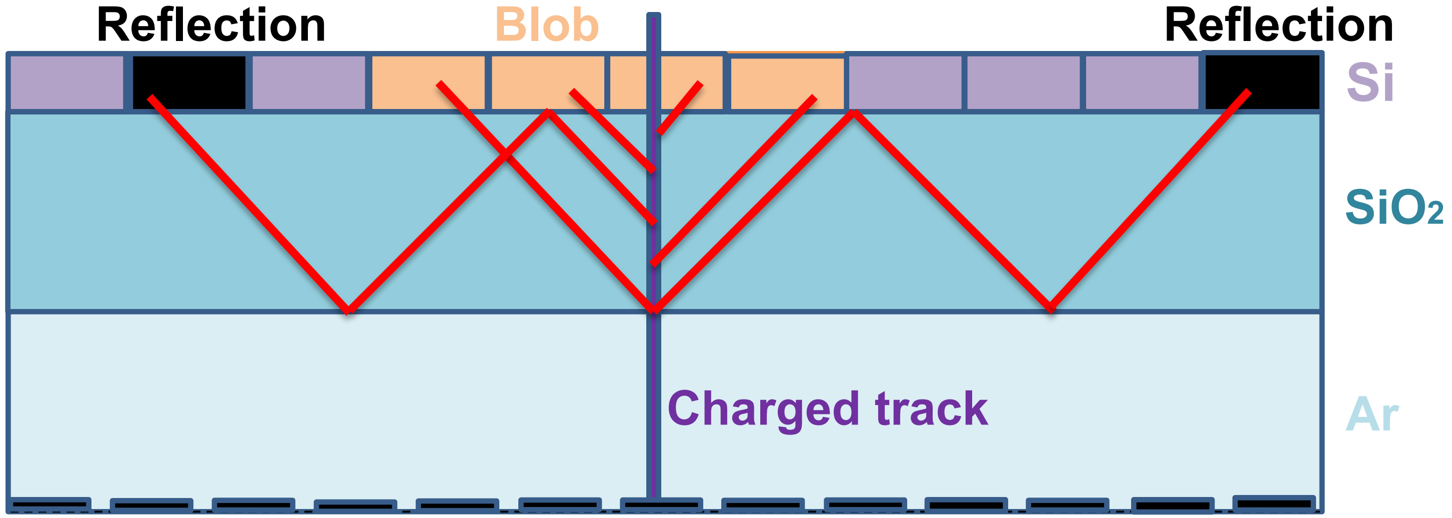
Reflection background

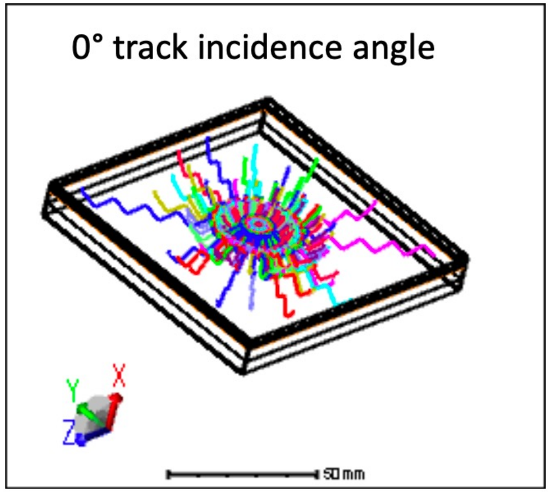
About 30% of photons reflected at SiO_2 - Si
Total reflection at SiO_2 - Ar

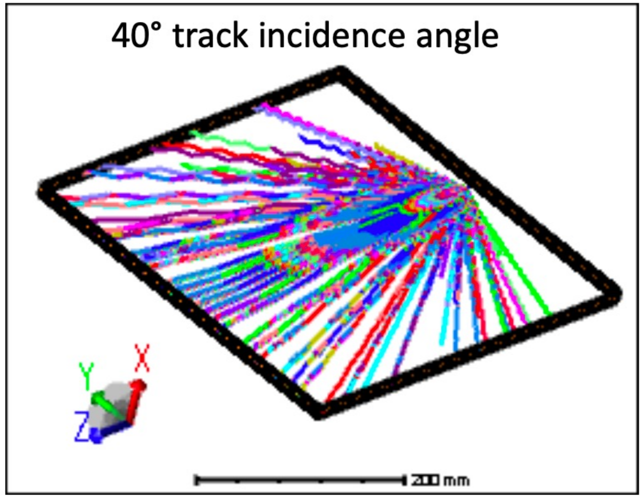
Track time resolution

Determined by single photon resolution and blob size

$$\sigma_{\theta_t}^{trk} = \frac{\sigma_t^{\gamma}}{\sqrt{N_{blob}}}$$







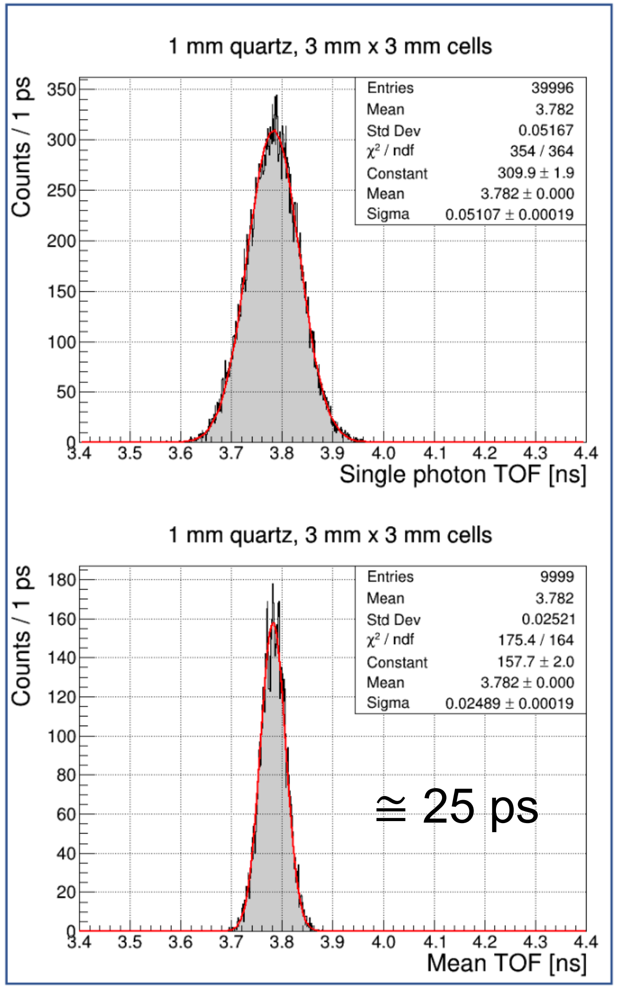
Ongoing and future studies: photon detector

Simulations with different window materials have been performed in ZEMAX [***https://www.zemax.com***]
(Assuming intrinsic SiPM time resolution = 50 ps)

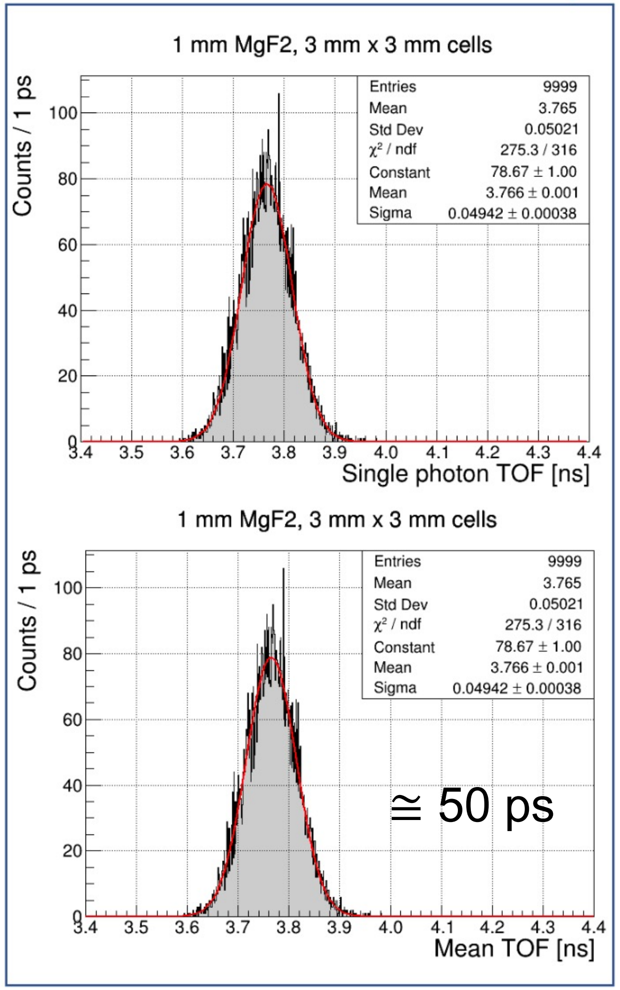
Single photons

Avarage of all photons for track

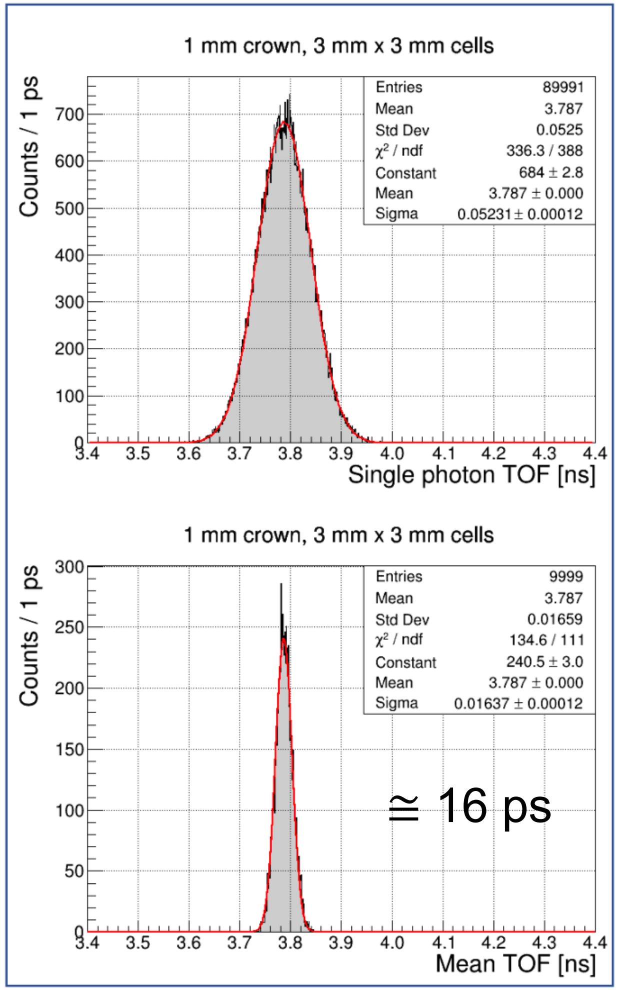
Quartz



MgF_2



Crown glass



Participating institutes

Institute	Interest
CERN, Geneva, Switzerland	D-SiPM
INFN, Bari, Italy	Design studies (simulations), aerogel, D-SiPM
INFN, Bologna, Italy	D-SIPM: synergy with EIC (SiPM radiation tolerance) and ALICE 3 timing layer (MIPS induced signal in SiPM)
UNAM, Mexico City, Mexico	Design studies (simulations), D-SiPM

Further contributions are more than welcome!

Summary and outlook

ALICE

- The RICH system studied and presented in the ALICE 3 LoI was conceived to fulfill preliminary PID requirements.
- Depending on final timing performance of the TOF system and finalization of PID requirements, the detector layout can be further optimized (aerogel n, focusing, mirror integration, …) to achieve full coverage of electron and charged hadron ID.
- The evolution of CMOS SPAD technology has renewed the interest for digital SiPM to be exploited in HEP large systems.
  - The challenging R&D could profit of the synergy among research institutes, academy and industry.

Backup

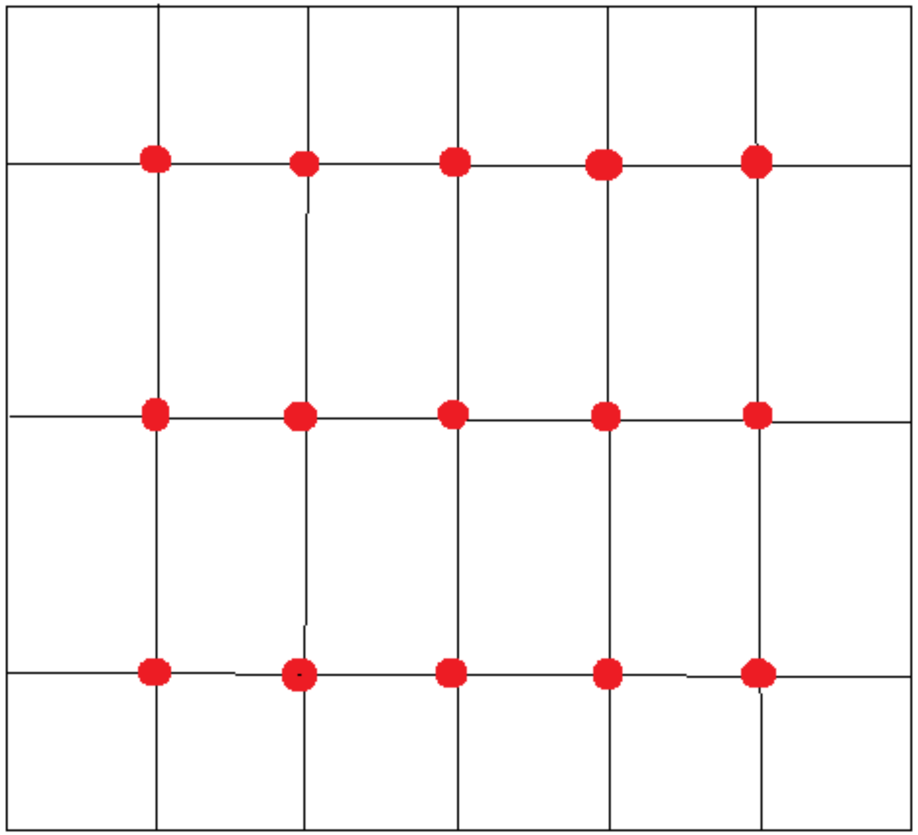
ALICE 3 Motivation

- After Run 3 and 4 some QGP features will still remain unrevealed
- Qualitative steps needed in detector performance and statistics
  - next-generation heavy-ion experiment!

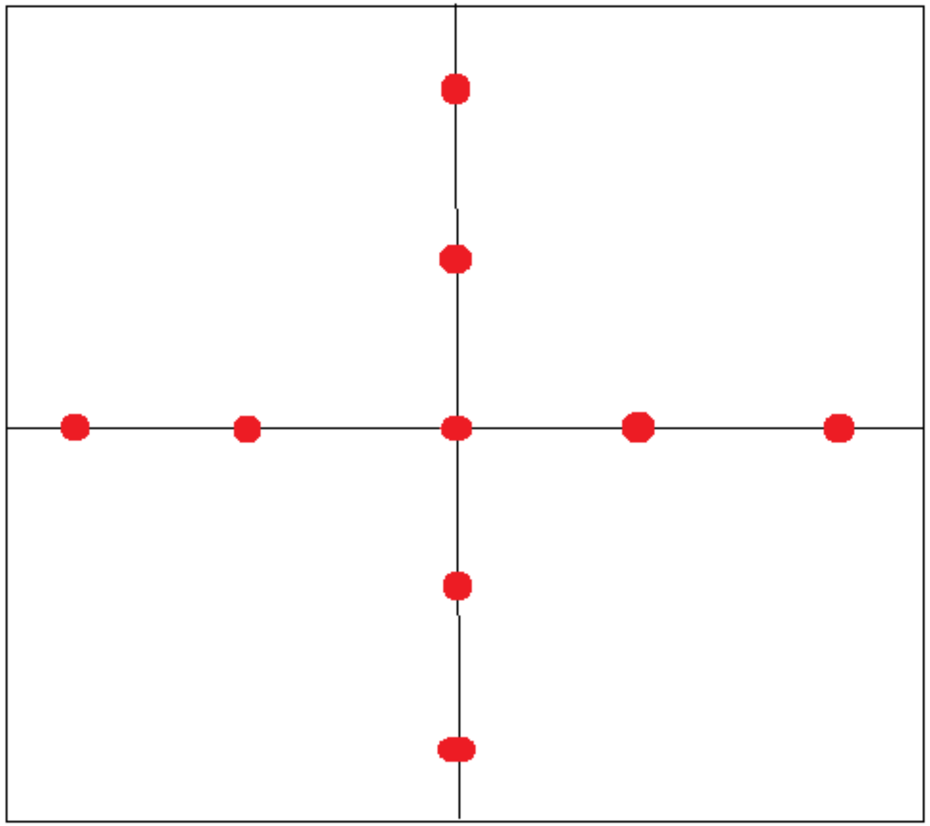
Key physics objects and the respective kinematic ranges of interest for ALICE 3

Observables	**Kinematic range**
Heavy-flavour hadrons	$p_{\mathrm{T}} \to 0$, $\lvert\eta\rvert < 4$
Dielectrons	$p_{\mathrm{T}} \approx 0.05$ to $3\,\mathrm{GeV}/c$, $M_{\mathrm{ee}} \approx 0.05$ to $4\,\mathrm{GeV}/c^2$
Photons	$p_{\mathrm{T}} \approx 0.1$ to $50\,\mathrm{GeV}/c$, $-2 < \eta < 4$
Quarkonia and exotica	$p_{\mathrm{T}} \to 0$, $\lvert\eta\rvert < 1.75$
Ultrasoft photons	$p_{\mathrm{T}} \approx 1$ to $50\,\mathrm{MeV}/c$, $3 < \eta < 5$
Nuclei	$p_{\mathrm{T}} \to 0$, $\lvert\eta\rvert < 4$

Measuring points



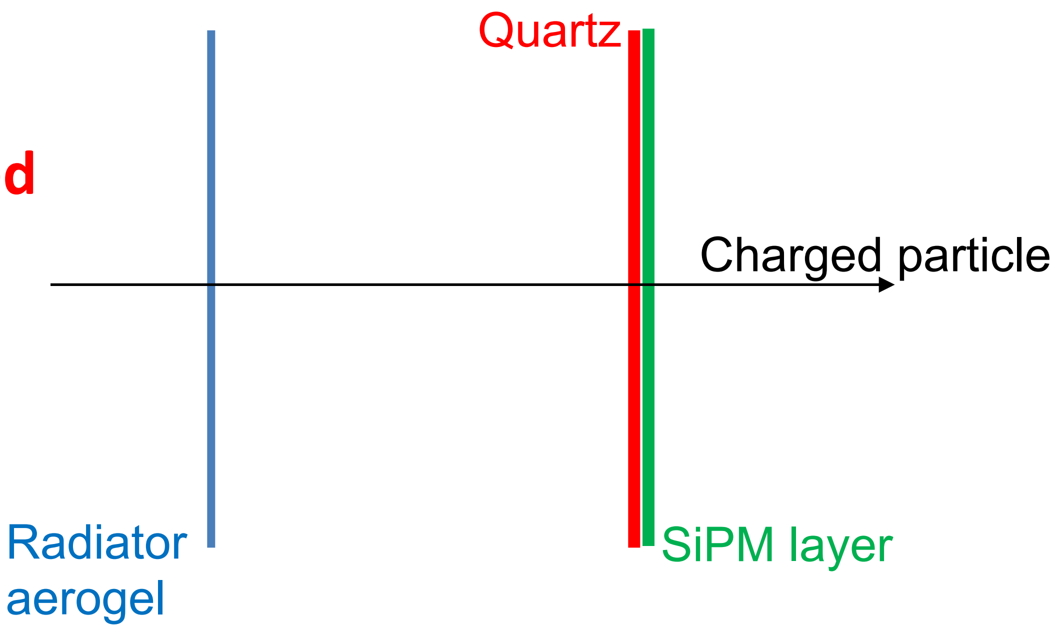
10x10 cm

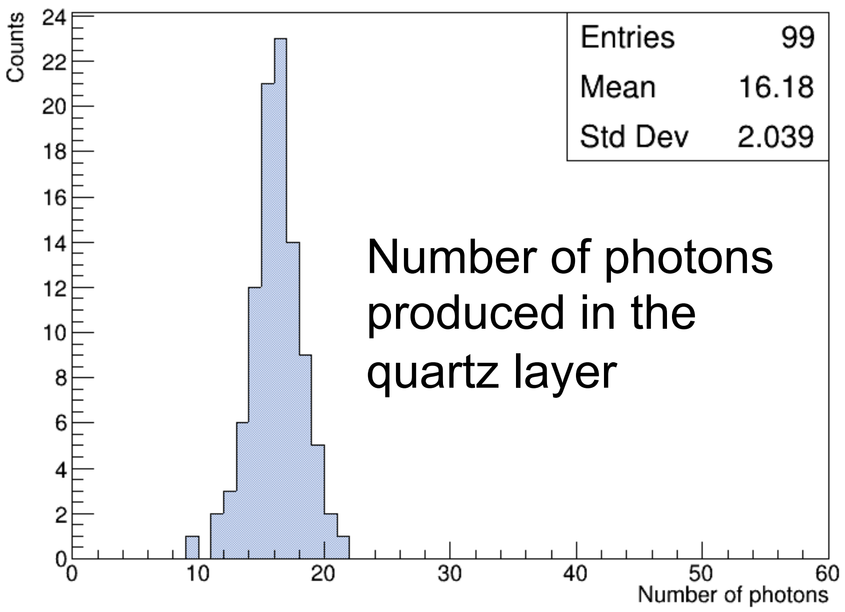


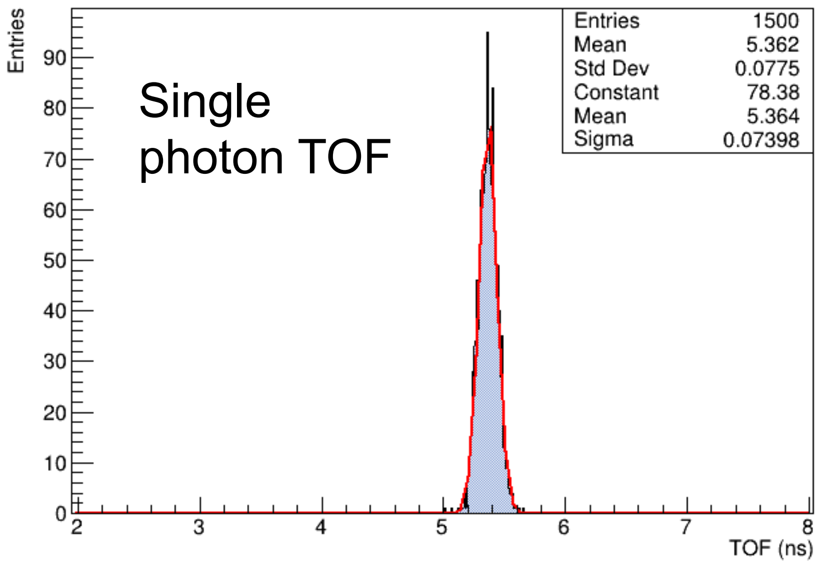
15x15 cm

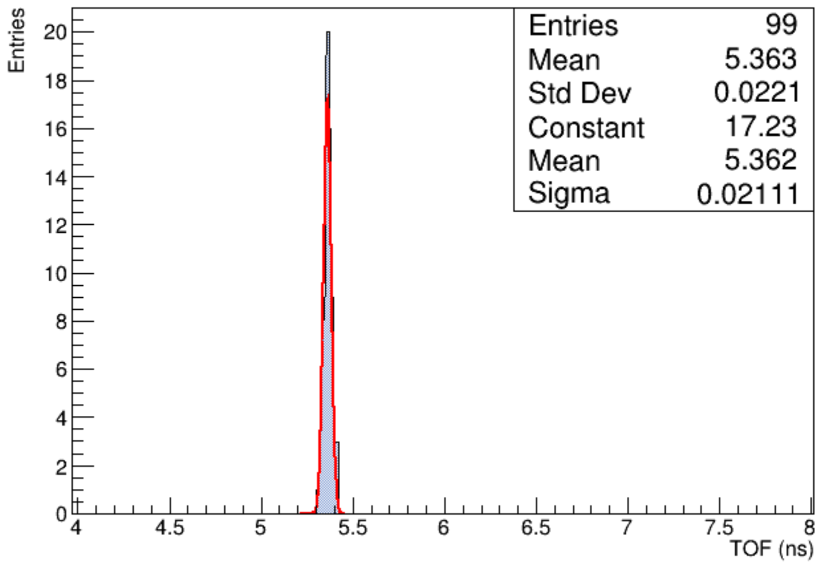
Ongoing and future studies: photon detector

A step forward: Cherenkov-based TOF system









Ongoing and future studies: photon detector

3 mm x 3 mm cells, SPTR = 50 ps

Normal incidence

Material	Thickness (mm)	Time resolution (ps)
SiO2	5	12.3
	3	11.7
	1	24.9
MgF2	5	14.2
	3	14.9
	1	49.4
Crown	5	8.5
	3	12.0
	1	16.4

MIP at 40° wrt normal

Material	Thickness (mm)	Time resolution (ps)
SiO2	5	8.5
	3	10.8
	1	17.4
MgF2	5	8.3
	3	10.8
	1	20.2
Crown	5	8.5
	3	11.1
	1	14.9

3 mm x 3 mm cells, SPTR = 60 ps

Normal incidence

Material	Thickness (mm)	Time resolution (ps)
SiO2	5	14.9
	3	14.0
	1	29.8
MgF2	5	17.0
	3	18.0
	1	59.0
Crown	5	10.2
	3	14.3
	1	19.6

MIP at 40° wrt normal

Material	Thickness (mm)	Time resolution (ps)
SiO2	5	10.2
	3	12.9
	1	20.8
MgF2	5	9.9
	3	12.9
	1	24.2
Crown	5	10.2
	3	13.2
	1	17.9

3 mm x 3 mm cells, SPTR = 70 ps

Normal incidence

Material	Thickness (mm)	Time resolution (ps)
SiO2	5	17.3
	3	16.3
	1	34.6
MgF2	5	19.8
	3	20.9
	1	68.4
Crown	5	11.9
	3	16.7
	1	23.0

MIP at 40° wrt normal

Material	Thickness (mm)	Time resolution (ps)
SiO2	5	12.0
	3	15.0
	1	24.3
MgF2	5	11.5
	3	15.1
	1	28.2
Crown	5	11.9
	3	15.5
	1	20.9

Preparing for October 2022 test beam

- New photo-detector based on Hamamatsu sensors arranged in strip of 128 13552 (0.25x1.62 mm2) and matrix of 8x8 13361-3050AE (3x3 mm^2)