Particles & Plasmas Symposium 2024 – 10-12 June 2024, Budapest, Hungary

The ALICE 3 detector concept for LHC Runs 5 and 6 and its physics performance

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This work has been supported by the Hungarian NKFIH OTKA FK131979, OTKA K135515, TKP2021-NKTA-10 and 2021-4.1.2-NEMZ_KI-2024-00034 grants, and uses VLAB infrastructure.

LHC timeline

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA
LHC schedule	Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5	Run 6

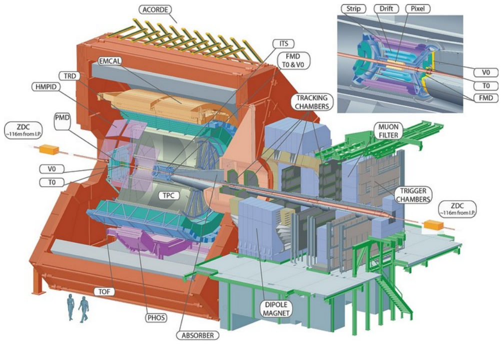
Experiment				
ATLAS	ATLAS	ATLAS phase I upgrades	ATLAS phase II upgrades	
CMS	CMS	CMS phase I upgrades	CMS phase II upgrades	
LHCb	LHCb	LHCb upgrade I(a)	LHCb upgrade Ib	LHCb upgrade II
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 upgrade

intermediate upgrade | major upgrade

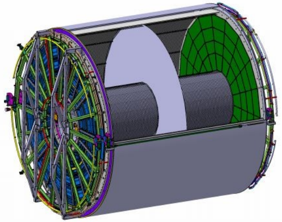
LHC timeline – ALICE to ALICE 3

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA
LHC schedule	2009 - 2013	2015 - 2018	2022 - 2025	2029 - 2032		

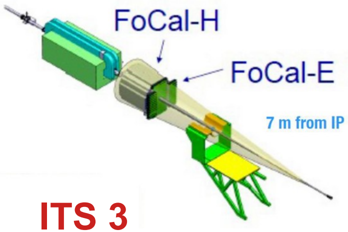
ALICE (Runs 1+2)



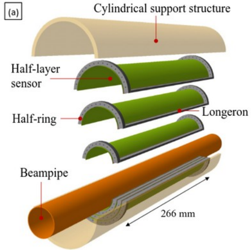
LS2 upgrades



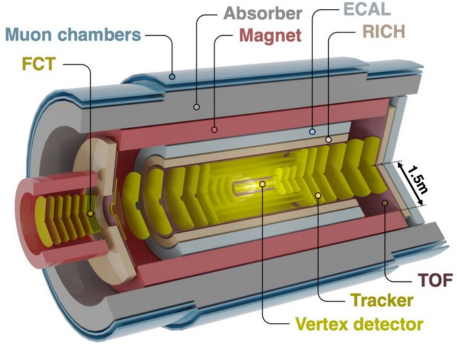
FoCal



ITS 3



ALICE 3



ALICE 1

LH upgra

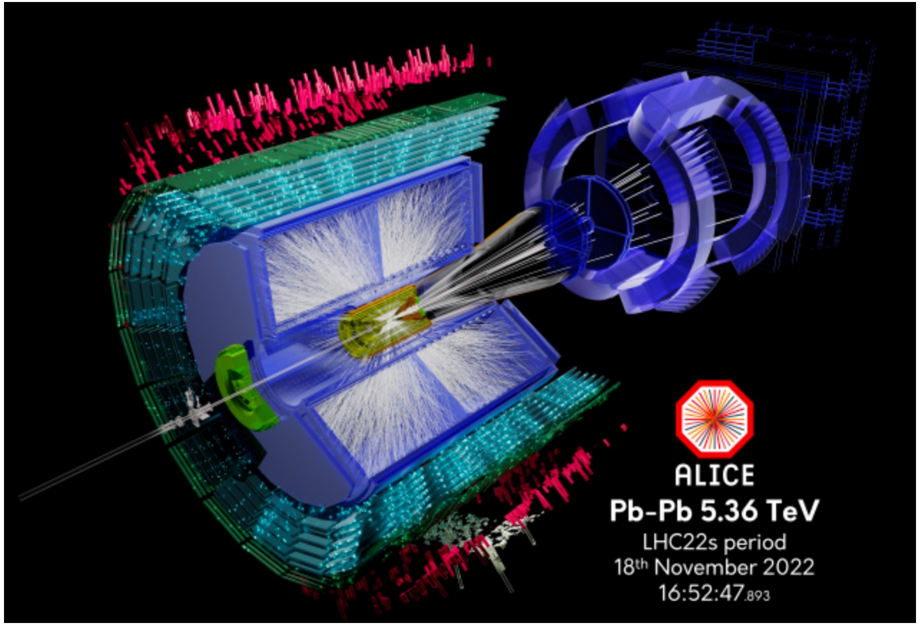
ALI upg

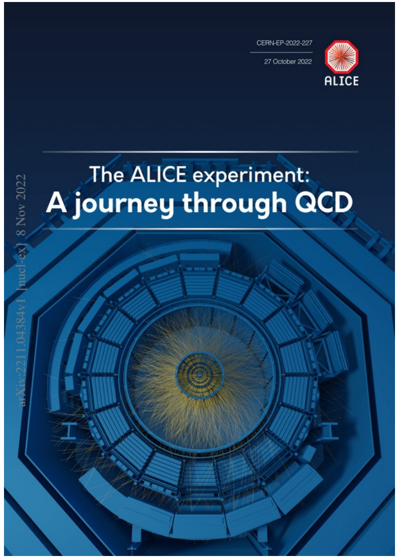
ALICE

intermediate upgrade

major upgrade

ALICE – current status



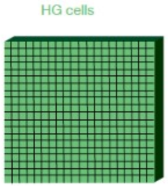


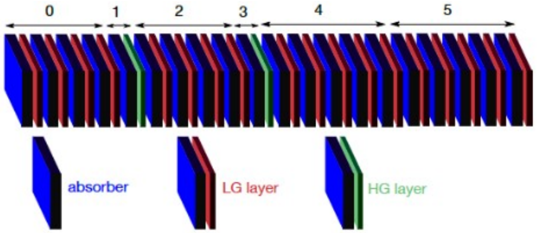
CERN-EP-2022-227, arXiv:2211.04384

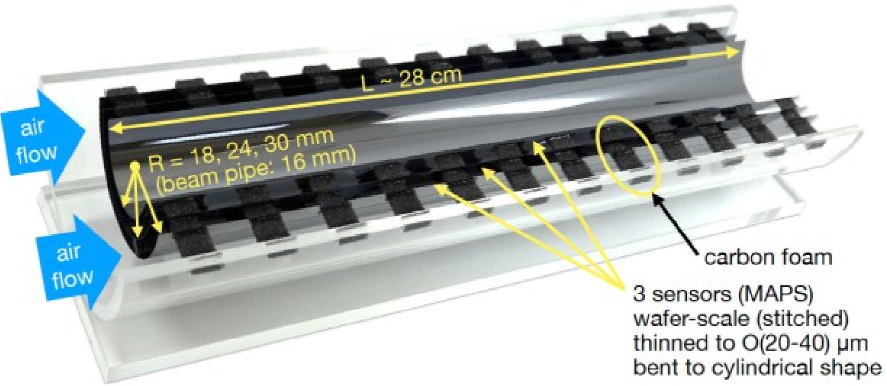
- Central Barrel: tracking and particle ID, EM calorimetry ($|\eta|<0.9$)
- Forward muon arm: $2.5< \eta < 4.0$
- **Major upgrades in LS2**: - New inner tracking system (ITS2)
  - Forward muon tracker
  - TPC upgrade with GEM technology

FoCAL (Forward Calorimeter)

- Parton distributions in protons and nuclei
- Long range correlations in pp and p-A
- Forward jets and ultra-peripherial collisions







ITS 3 (inner tracking system)

- Replacement of 3 innermost layers of ITS2
- Curved wafer-scale ultra-thin silicon sensors:
- - perfectly cylindrical layers
  - low power → air cooling → low material
  - material budget: 0.05% X_0 per layer
- High-precision, efficient low-p_T tracking

ALICE 3 – rationale

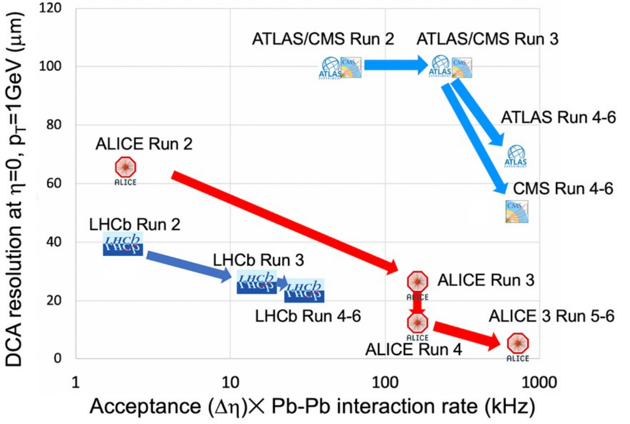
ALICE 2 – 2.1 (Runs 3 + 4)

- Medium effects on single heavy-flavour hadrons
- Time averaged thermal QGP radiation
- Collective effects from small to large systems

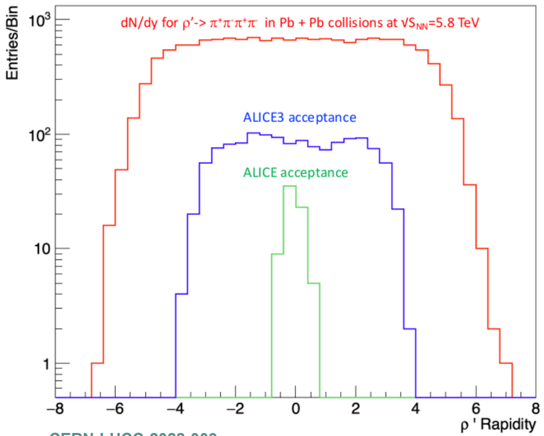
Fundamental questions will remain open

- QGP properties driving constituents to equilibrium
- Partonic EoS and its temperature dependence
- Underlying dynamics of chiral symmetry restoration
- Hadronization mechanisms of the QGP

→ **need for a next generation heavy-ion experiment: ALICE 3 (Runs 5 + 6)**



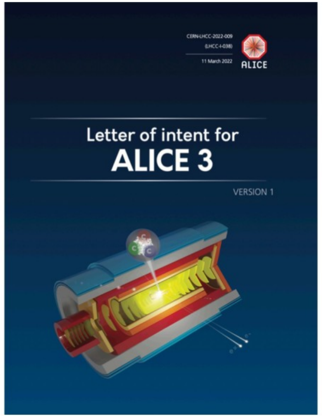
arXiv:2311.10164



CERN-LHCC-2022-009

ALICE 3 – timeline

- 2019: Expression of Interest to the European Strategy for Particle Physics Update (2019)
  arXiv:1902.01211
- 2022: Letter of Intent for ALICE 3
- 2023–25: Selection of technologies
  proof of concept prototypes
- 2024: Scoping Document – in preparation
- 2026–27: Large-scale prototypes
  Technical Design Reports
- 2028–29: Construction and testing
- 2033–34: Preparation of cavern
  Installation



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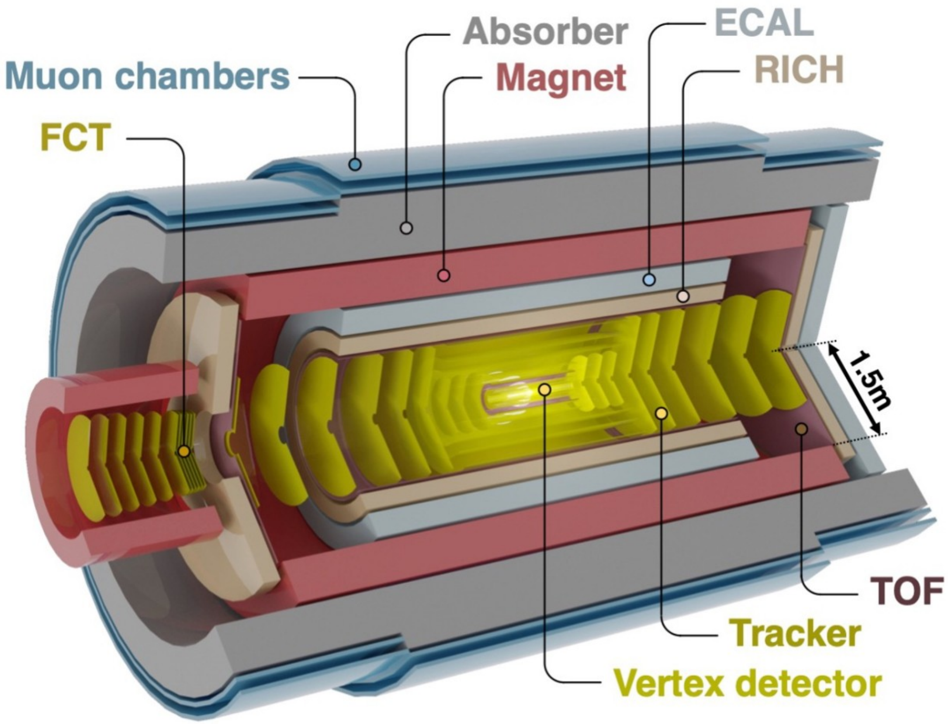
arXiv:2211.02491

ALICE 3 – the detector concept

- **Compact silicon tracker** with a very low material budget
- Superconducting magnet system (Max field: B = 2 T)
- **Particle identification** in a wide range of momenta and $|\eta|<4$
- **Precise vertexing** capabilities and **great momentum resolution**
- Continuous readout, online data processing



Tracking – vertex detector

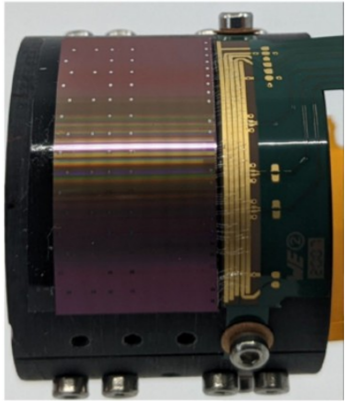
- **Iris concept**:
  retractable tracker in vacuum
  (3 layers + 3 disks)

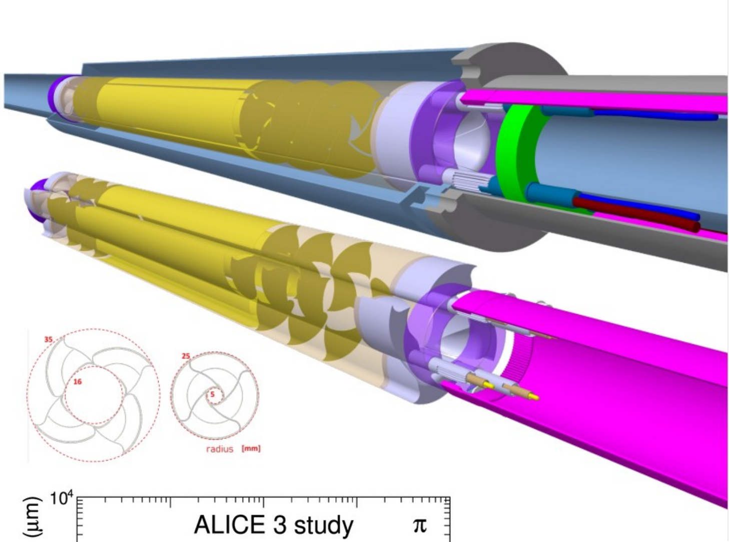
- **Pointing resolution ~3-4 μm**
  at p_T=1 GeV/c

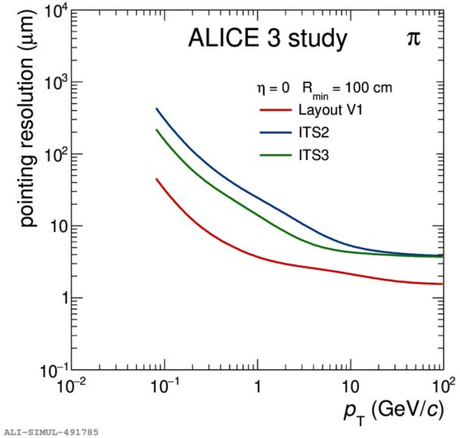
- Wafer-size sensors based on CMOS Monolithic Active Pixel Sensors (**MAPS**) technology

- Extremely low material budget
  (**~ 0.1% X_0** per layer)

- Pixel pitch of ~10 μm
  ~2.5 μm intrinsic resolution

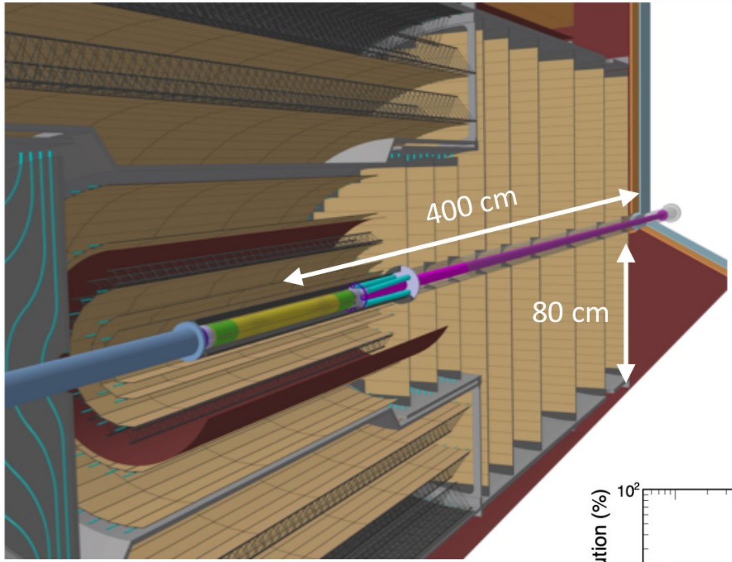


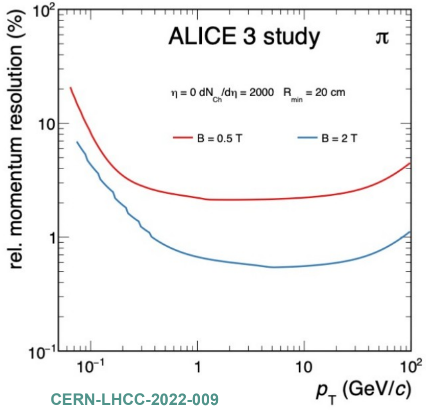




Tracking – outer tracker

- 8 layers and 9 disks based on **MAPS** technology (~67m² total area)
- **Compact design** (R<80 cm, $|z|$<4 m)
- Pixel pitch ~40 µm
  ~10 µm intrinsic resolution
- Material budget 1% X_0 per layer
- **Low power consumption**: ~20 mW/cm²
- Industrialized production process, modular structure

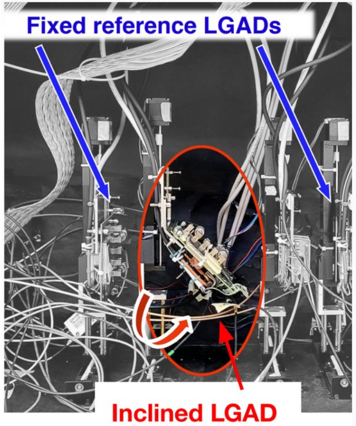


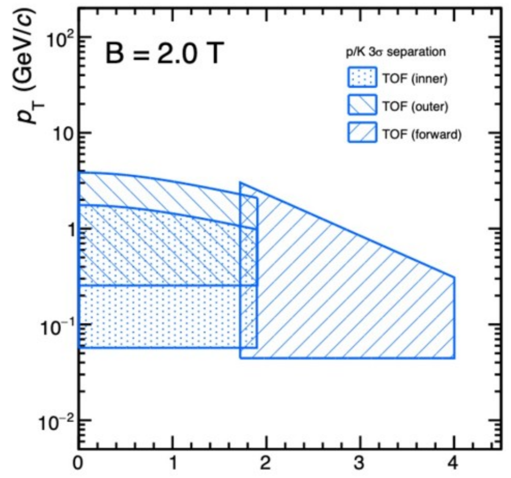


ALICE 3 tracker

PID – Time-of-flight detector

- **Silicon detector for particle identification**
- Barrel time-of-fight (2 layers, |η|<1.75)
  - inner TOF at 19 cm, outer TOF at 85 cm
  - Total surface ~ 31.5 m^2 (1.5 inner + 30 outer)
- Forward disks (2 disks, 1.75<|η|<4)
  - r_{in} = 15 r_{out}=50 cm, z = 405
  - Total surface of 14 m^2
- Specs:
  - **time resolution ~20 ps**
  - material budget: 1-3% X_0
- Technology options:
  - **MAPS**: uniform charge collection, high signal-to-noise ratio
  - CMOS **SPAD**s: common readout with RICH
  - **LGAD**: sensor-grade wafers, dedicated readout





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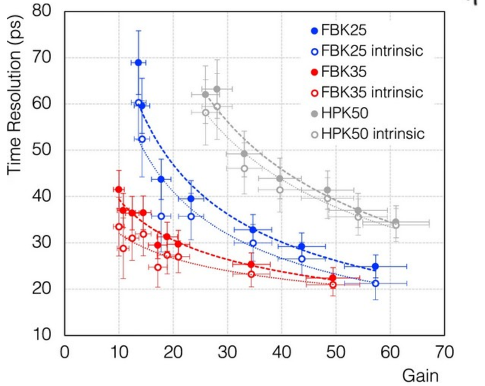
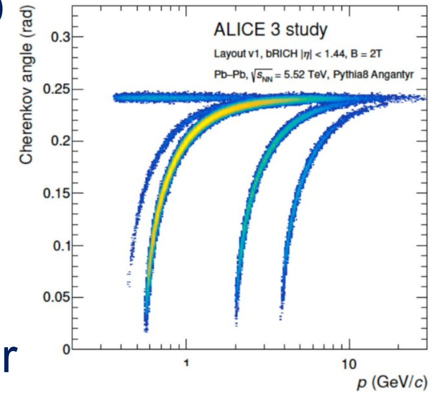
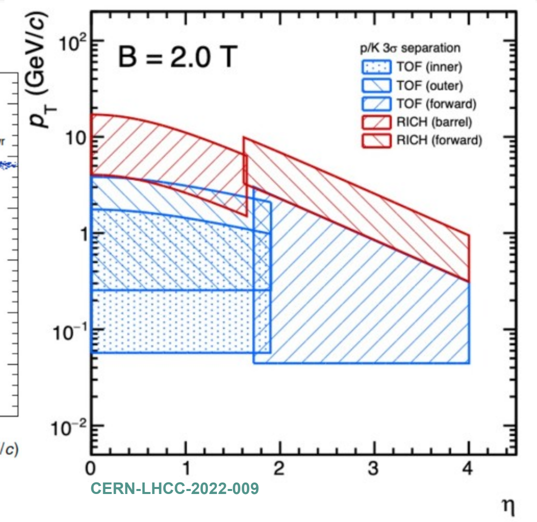


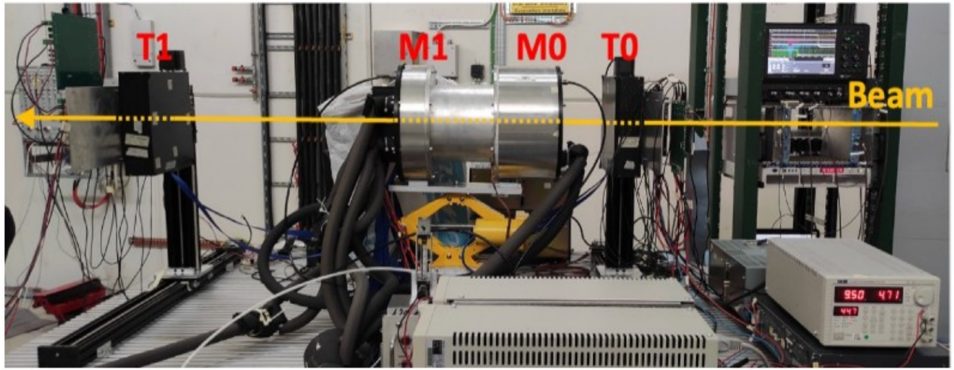
Eur. Phys. J. Plus 138, 99 (2023)

PID – Ring Imaging Cherenkov detector

- **Cherenkov detector** to extend TOF PID capabilities toward **higher p_T**
  - **Aerogel** radiator refraction index (determines p_T reach) n = 1.03 (barrel), n=1.006 (forward)
  - 2 cm thick aerogel tile, SiPM photo-detection layer at 20 cm from the radiator
- Projective barrel RICH: improves coverage at large $|\eta|$, while saving on overall photosensitive area
- Merged outer TOF+barrel RICH system using a common SiPM layer coupled to a thin radiator window



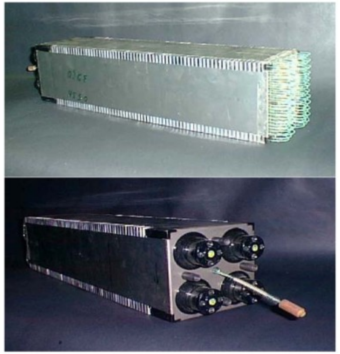




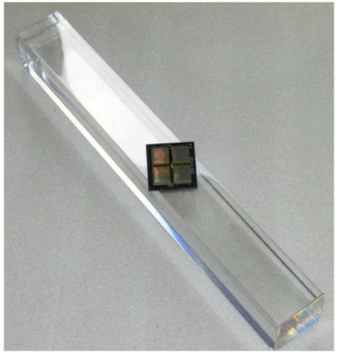
PID – Electromagnetic Calorimeter

- **High-energy electron and photon ID**
- 2 barrel +1 disk layers
  - Up to 100 GeV for $|\eta| < 1.5$
  - Up to 250 GeV for $1.5 < |\eta| < 4$
- Technology
  - Sampling Pb + scintillator at $-1.6 < |\eta| < 4$ pseudorapidity
  - High-resolution segment $PbWO_4$ crystal segment $|\eta| < 0.22$ (precise measurements without back-to-back detection)
  - Silicon Photomultiplier readout

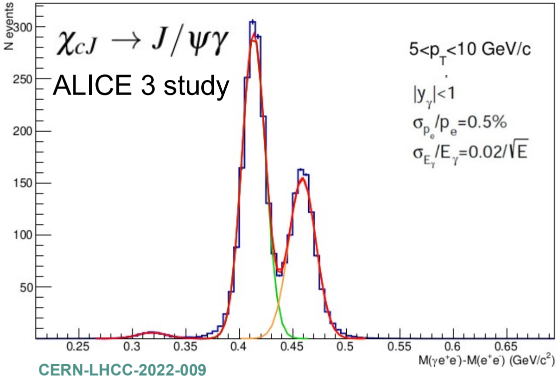
Sampling sector



$PbWO_4$ sector



Simulation: $PbWO_4$



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Energy resolution

$$\frac{\sigma_E}{E} = \frac{a}{E} \oplus \frac{b}{\sqrt{E}} \oplus c$$

Assumptions:

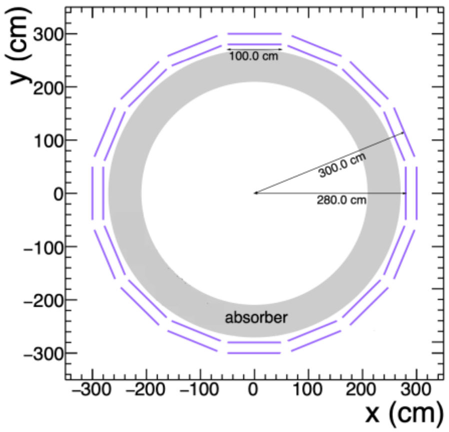
$a = 0.001$

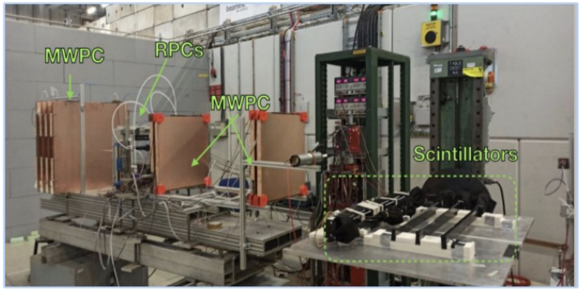
$b = 0.2\ \mathrm{GeV}^{1/2}$

$c = 0.01$

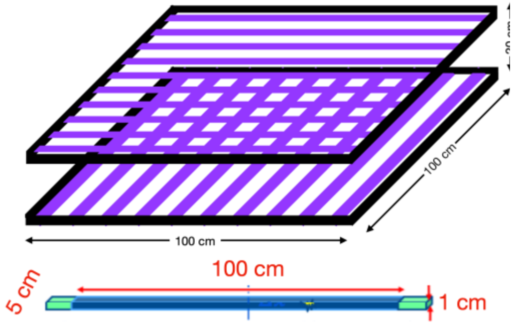
PID – Muon Identification Detector

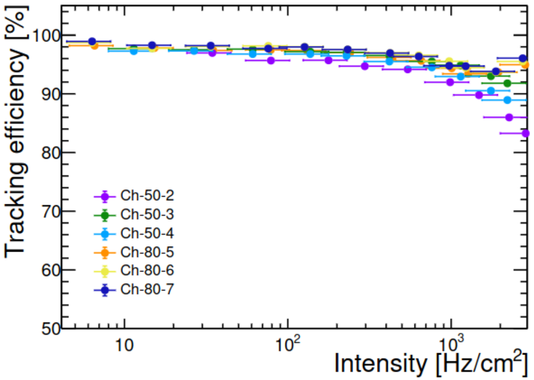
- **Muon identification**
  down to $p_T \approx 1.5$ GeV/c
- Pseudorapidity coverage $|\eta| < 1.38$
- Hadron absorber ($\approx$ 70 cm at η = 0)
  magnetic/non-magnetic steel options
- Technology options:
  - **Scintillator bars** - base option
    2 layers, 5 x 5 cm granularity
    Silicon photomultiplier readout
  - **MWPC** (multiwire chambers)
    5mm pad x 8mm wire spacing
  - **RPC** (resistive plate chambers)





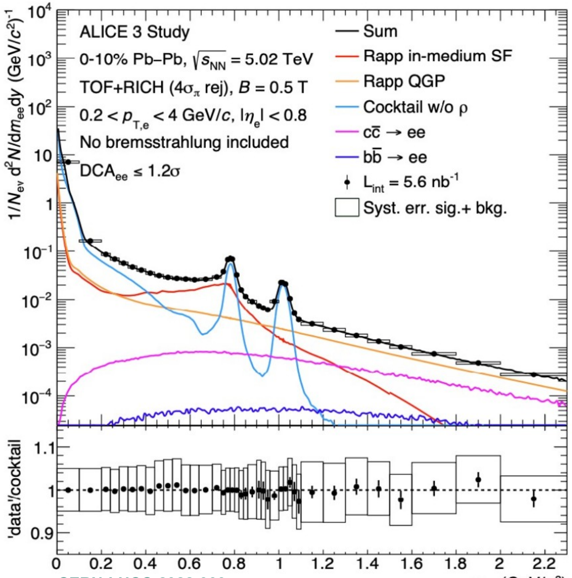
Test beam setup July 2023





Test beam results (MWPC)
JINST 19 (2024) 04, T04006

Dileptons – chiral symmetry restoration



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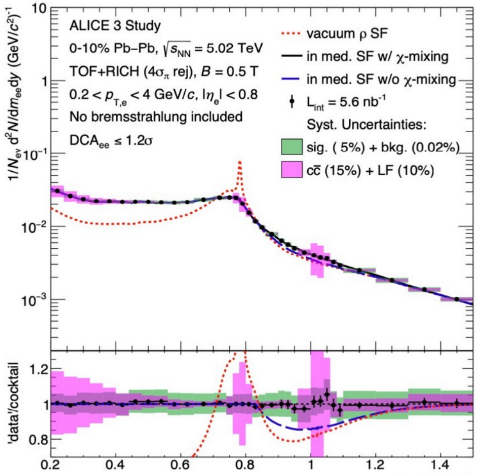

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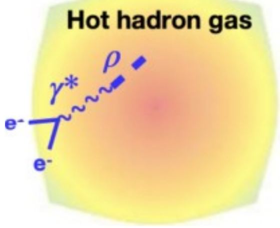
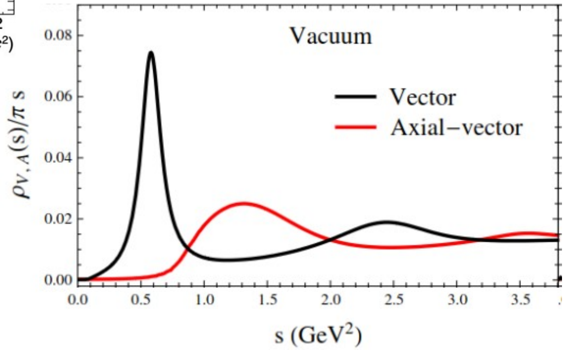
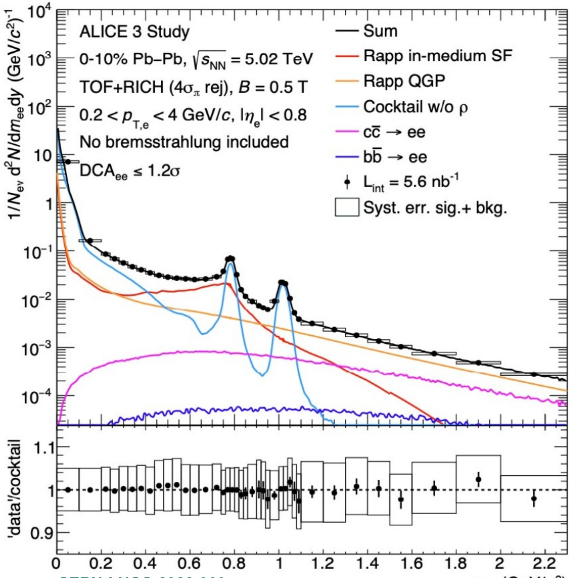




P. M. Hohler – R. Rapp, Phys. Lett. B731 (2014) 103

- **Chiral symmetry restoration:** Fundamental feature of high-temperature lattice QCD
- Consequence: modification of spectral functions
- **Thermal dielectron spectrum:** Access to ρ,ω,Φ,η,η' mesons as well as quarkonia
- Key experimental requirements:
  - excellent electron identification down to low p_T
  - low material budget
  - good pointing resolution (for heavy-flavor decays)

Dileptons – chiral symmetry restoration



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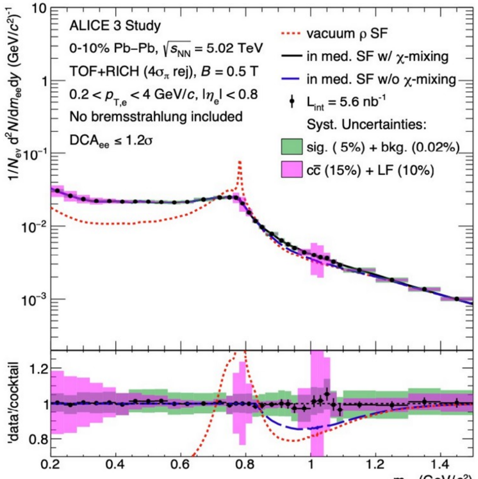

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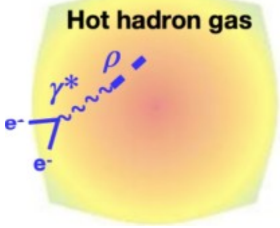

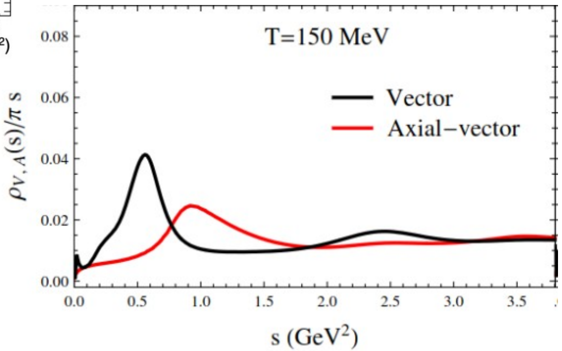

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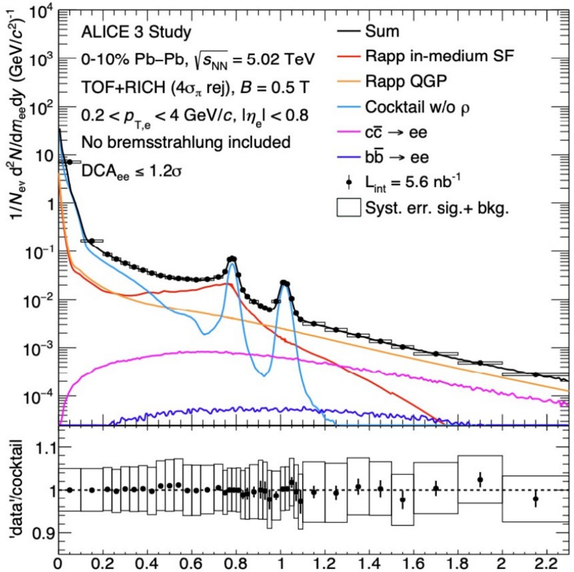

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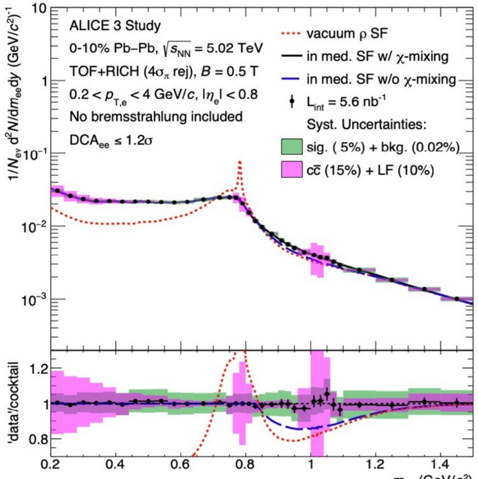

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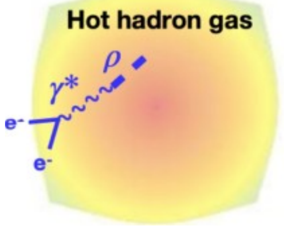

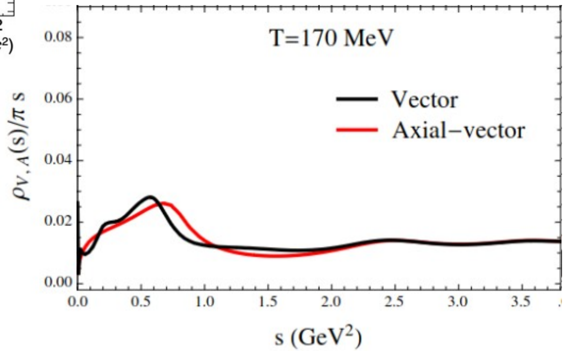

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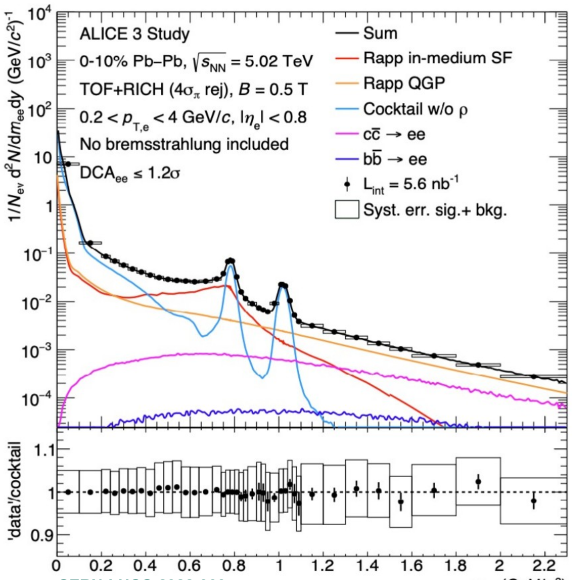
Dileptons – QGP temperature



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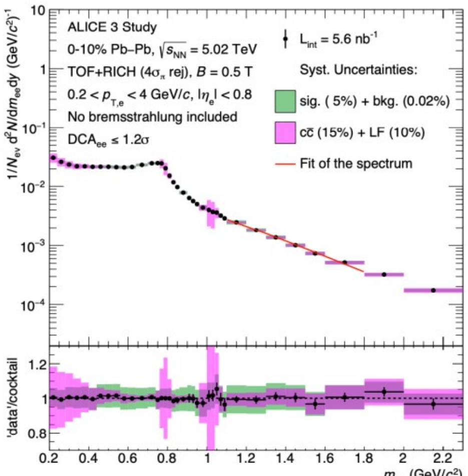

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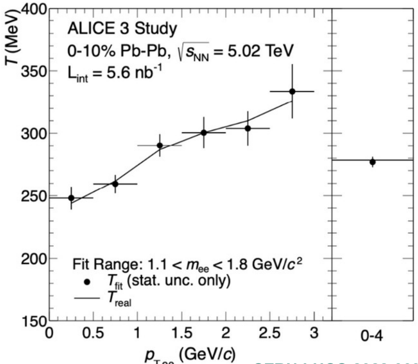

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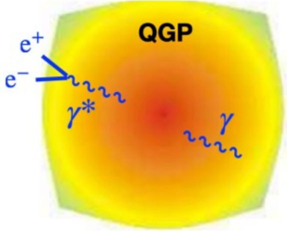
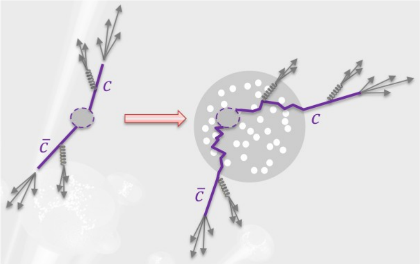
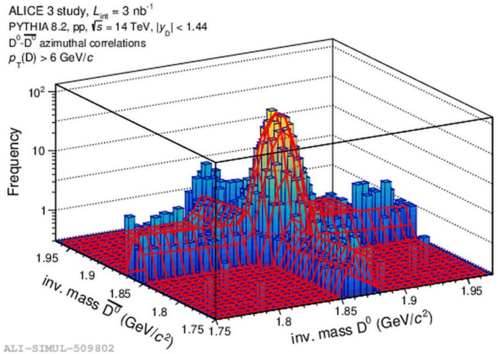


- Inference of **QGP temperature** using **thermal radiation**
  PHENIX, Phys.Rev.Lett. 104 (2010) 132301
- Precision measurement of $\gamma^* \rightarrow e^+e^-$ at $m_{ee} > 1.1$ GeV/c^2
- Double-differential measurement in m_{ee} and $p_{T,ee}$: information on the **time evolution** of thermal properties
- Experimental challenges:
  - conversion γ background
  - open heavy-flavor production

Heavy flavor correlations

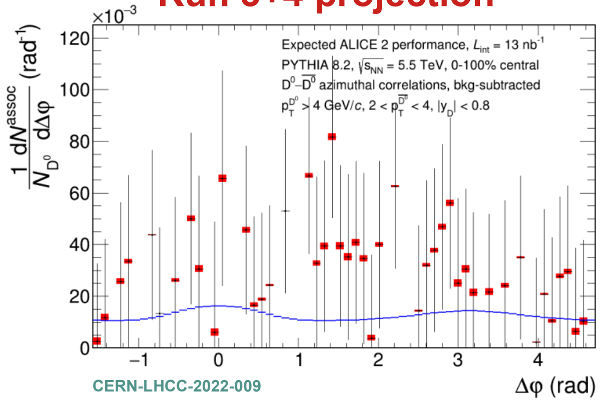




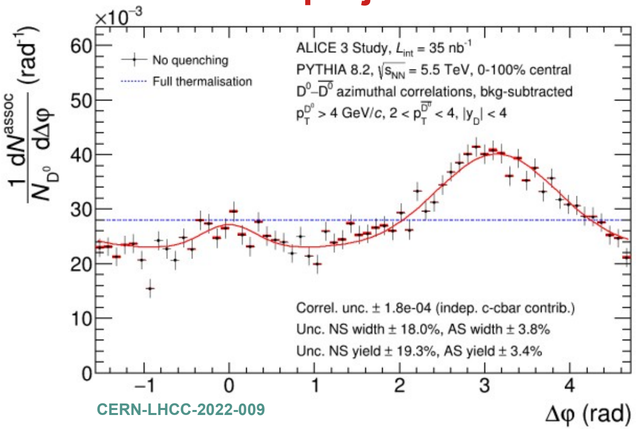
$$F(M_{D^0}, M_{\overline{D}^0}) = N_{SS} f_S^{D^0}(M_{D^0}) f_S^{\overline{D}^0}(M_{\overline{D}^0}) + N_{SB} f_S^{D^0}(M_{D^0}) f_B^{\overline{D}^0}(M_{\overline{D}^0})$$
$$+ N_{BS} f_B^{D^0}(M_{D^0}) f_S^{\overline{D}^0}(M_{\overline{D}^0}) + N_{BB} f_B^{D^0}(M_{D^0}) f_B^{\overline{D}^0}(M_{\overline{D}^0})$$

- Scattering in QGP leads to angular decorrelation of heavy-flavor hadrons
- Two-particle D correlations **probe microscopic QGP charm diffusion** directly
- - Sensitive to energy loss and thermalization degree
  - Strongest signal expected at low p_T
- Requires high purity, efficiency and η coverage

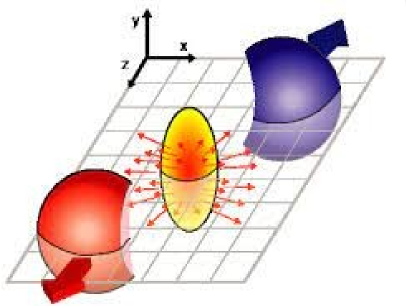
Run 3+4 projection



Run 5+6 projection



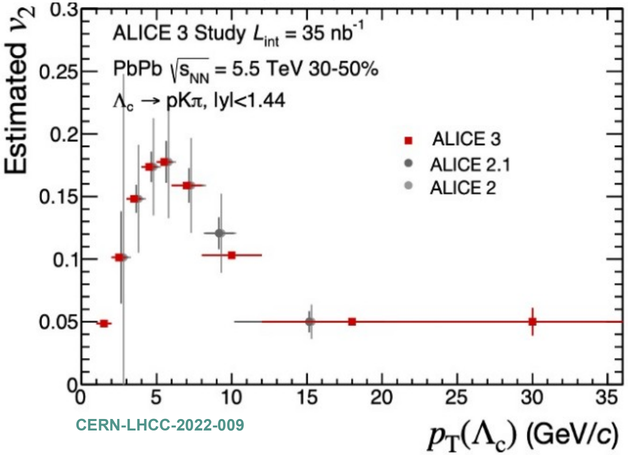
Heavy flavor baryon flow



$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2(\varphi - \psi)$$

Semi-central collisions:
Initial pressure anisotropy in the QGP
→ final-state azimuthal anisotropy ("flow")

- **Azimuthal anisotropy: access to heavy quark transport properties in the QGP at hadron level**
  - Degree of thermalization, diffusion coefficients
  - Weaker beauty thermalization → Smaller v_2 expected
- Fragmentation differences via the baryonic sector
- ALICE 3 pointing resolution, efficiency and acceptance are needed for flow measurements down to low p_T



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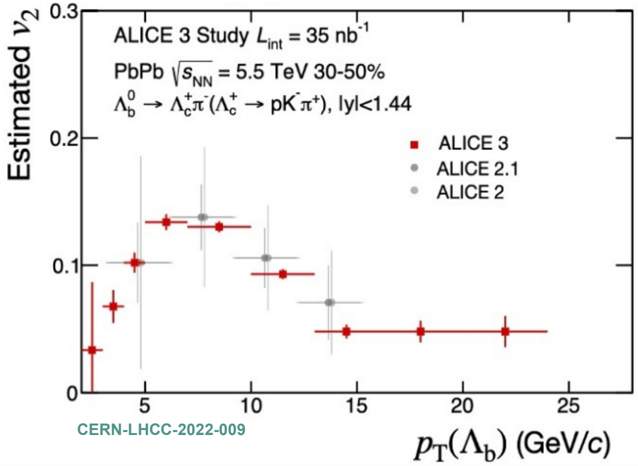

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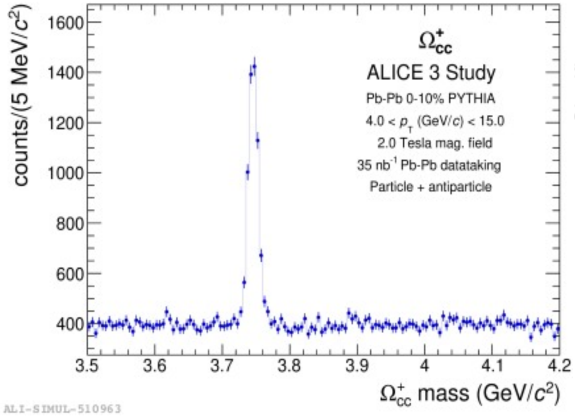
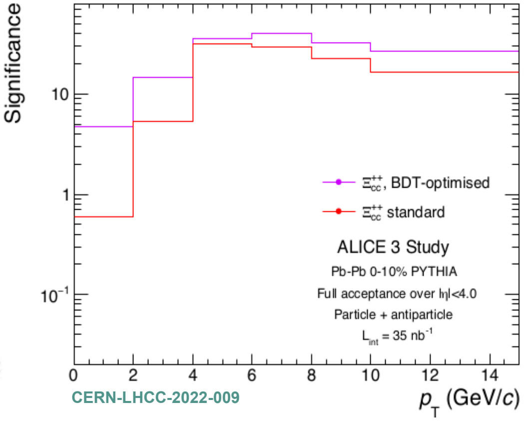
Heavy flavor – multi-charm baryons

- **Hadronization of the heavy-flavor baryonic sector** is still an open question.
- - **ALICE 3 is well-suited for** the measurement of **multi-charm baryons** that can efficiently address this question
- Search for anti-hyper nuclei with A>5 (e.g. ${}^{5}_{\Lambda}He$ or ${}^{6}Li$) and super-nuclei (e.g. c_d, c_t)





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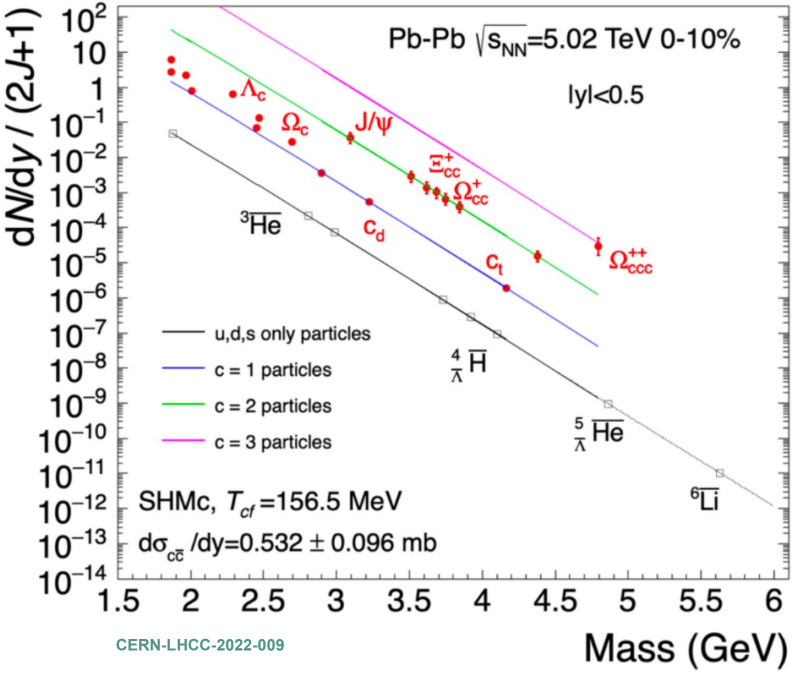

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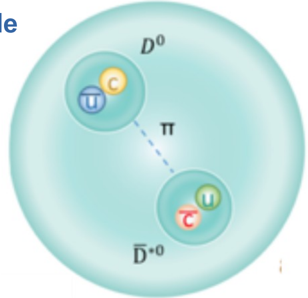
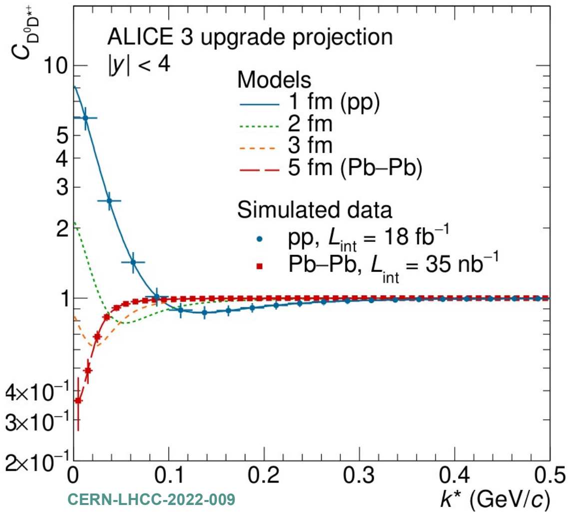
Hadronic interactions and exotic nuclei

D^0 – D^{*0} molecule
r ~ 5 fm

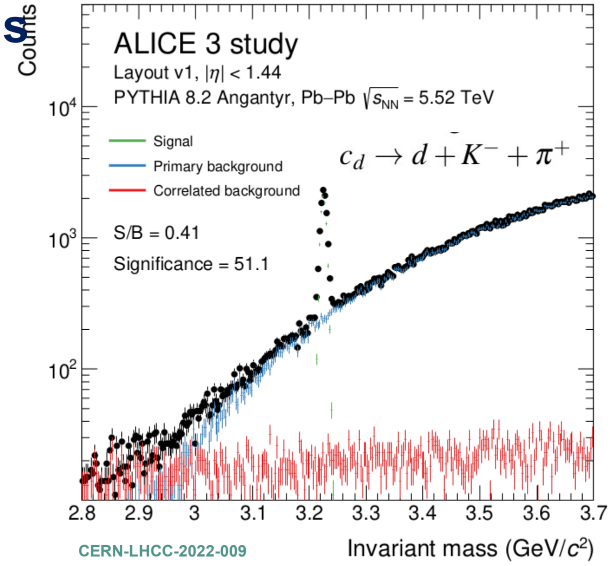


D^0 – D^{*0} correlation femtoscopy



- **D – D momentum correlations** accessible via two-particle **femtoscopy** measurements
- Unique tests of long range strong interaction with rare hadrons
- Investigation of the **molecular nature of exotic states**

c-deuteron decays

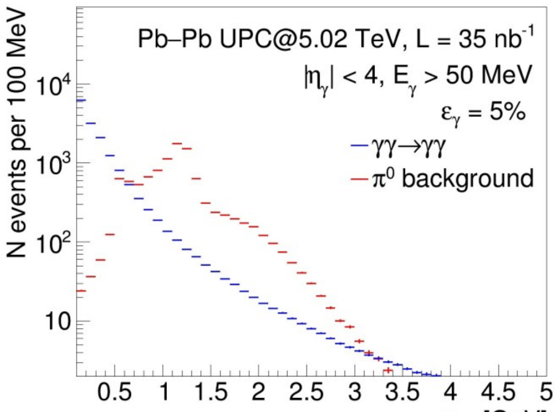


- **Super-nuclei:**
  - c-deuteron (c_d) and c-triton (c_t)
  - first observation feasible

The Standard Model and beyond

Light-by-light scattering

- Competitive **limits on axion searches**
- UPCs provide a clean environment for di-photon final states
- final state photons reconstructed either via photon conversions or via ECal measurements



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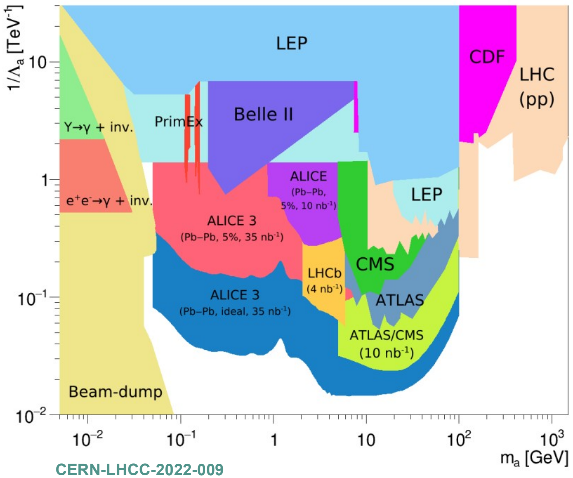

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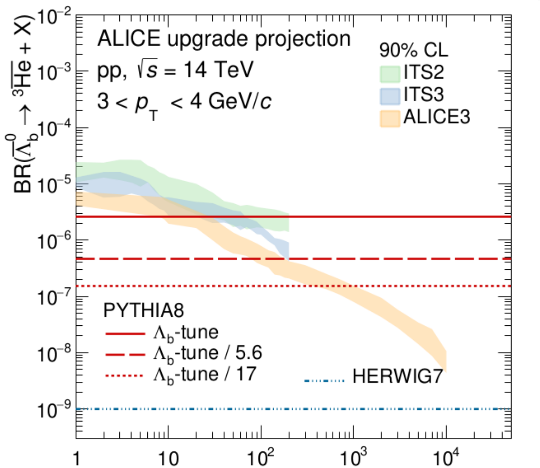

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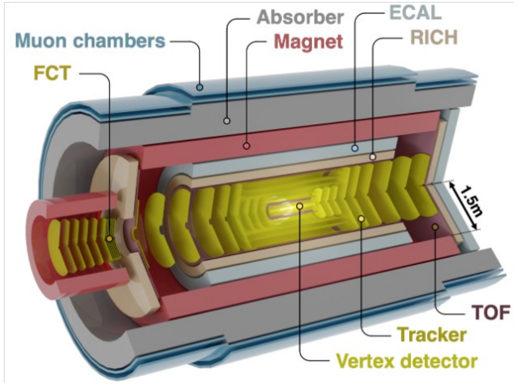
Anti-nuclei from b quarks

- Recent AMS discovery of **cosmic-ray anti-nuclei** (^{3}He) can be a signature of the **dark matter**
- Constraints on branching ratio from Λ_b^0 decays

Summary

ALICE 3 is an innovative detector concept that...

- addresses fundamental open questions of QCD and beyond SM
- is needed to explore the microscopic dynamics of the quark-gluon plasma
- will fully exploit the capabilities of LHC



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arXiv:2211.02491

Next steps in scoping and preparations

- Wide ongoing research efforts, tests, simulations
- Selection of technologies, small-scale prototypes until 2025
- Large-scale prototypes, Technical Design Reports until 2027

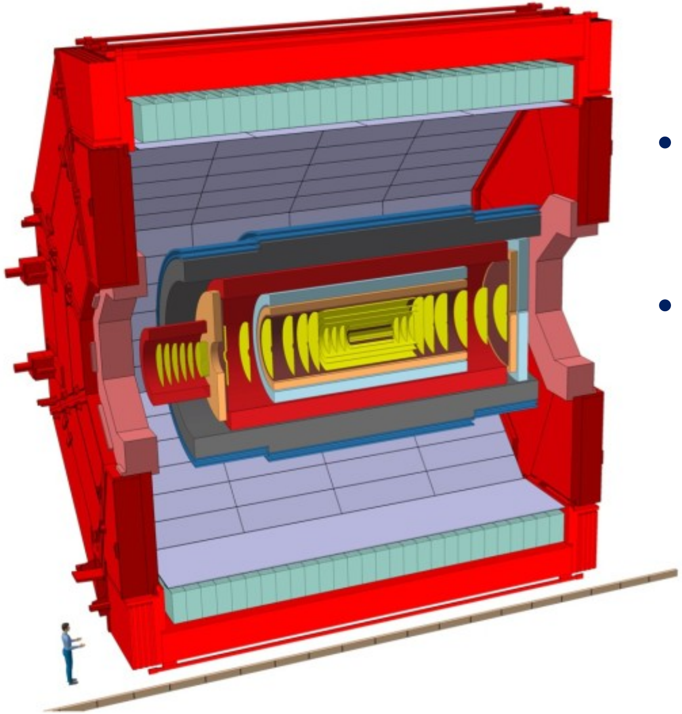
This work has been supported by the Hungarian NKFIH OTKA FK131979, OTKA K135515, TKP2021-NKTA-10 and 2021-4.1.2-NEMZ_KI-2024-00034 grants, and uses VLAB infrastructure.

LHC performance

Quantity	pp	O–O	Ar–Ar	Ca–Ca	Kr–Kr	In–In	Xe–Xe	Pb–Pb
$\sqrt{s_{NN}}$ (TeV)	14.00	7.00	6.30	7.00	6.46	5.97	5.86	5.52
L_{AA} ($cm^{-2}s^{-1}$)	3.0×10^{32}	1.5×10^{30}	3.2×10^{29}	2.8×10^{29}	8.5×10^{28}	5.0×10^{28}	3.3×10^{28}	1.2×10^{28}
$\langle L_{AA} \rangle$ ($cm^{-2}s^{-1}$)	3.0×10^{32}	9.5×10^{29}	2.0×10^{29}	1.9×10^{29}	5.0×10^{28}	2.3×10^{28}	1.6×10^{28}	3.3×10^{27}
$\mathscr{L}_{AA}^{month}$ (nb^{-1})	5.1×10^{5}	1.6×10^{3}	3.4×10^{2}	3.1×10^{2}	8.4×10^{1}	3.9×10^{1}	2.6×10^{1}	5.6
$\mathscr{L}_{NN}^{month}$ (pb^{-1})	505	409	550	500	510	512	434	242
R_{max} (kHz)	24 000	2169	821	734	344	260	187	93
μ	1.2	0.21	0.08	0.07	0.03	0.03	0.02	0.01
$dN_{ch}/d\eta$ (MB)	7	70	151	152	275	400	434	682
	at $R = 0.5\,cm$							
R_{hit} (MHz/cm^2)	94	85	69	62	53	58	46	35
NIEL (1 MeV n_{eq}/cm^2)	1.8×10^{14}	1.0×10^{14}	8.6×10^{13}	7.9×10^{13}	6.0×10^{13}	3.3×10^{13}	4.1×10^{13}	1.9×10^{13}
TID (Rad)	5.8×10^{6}	3.2×10^{6}	2.8×10^{6}	2.5×10^{6}	1.9×10^{6}	1.1×10^{6}	1.3×10^{6}	6.1×10^{5}
	at $R = 100\,cm$							
R_{hit} (kHz/cm^2)	2.4	2.1	1.7	1.6	1.3	1.0	1.1	0.9
NIEL (1 MeV n_{eq}/cm^2)	4.9×10^{9}	2.5×10^{9}	2.1×10^{9}	2.0×10^{9}	1.5×10^{9}	8.3×10^{8}	1.0×10^{9}	4.7×10^{8}
TID (Rad)	1.4×10^{2}	8.0×10^{1}	6.9×10^{1}	6.3×10^{1}	4.8×10^{1}	2.7×10^{1}	3.3×10^{1}	1.5×10^{1}

Table 1: Projected LHC performance: For various collision systems, we list the peak luminosity L_{AA}, the average luminosity $\langle L_{AA} \rangle$, the luminosity integrated per month of operation $\mathscr{L}_{AA}^{month}$, also rescaled to the nucleon–nucleon luminosity $\mathscr{L}_{NN}^{month}$ (multiplying by A^2). Furthermore, we list the maximum interaction rate R_{max}, the minimum bias (MB) charged particle pseudorapidity density $dN/d\eta$, and the interaction probability μ per bunch crossing. For the radii 0.5 cm and 1 m, we also list the particle fluence, the non-ionising energy loss, and the total ionising dose per operational month (assuming a running efficiency of 65%).

ALICE 3 installation and running



- To be installed around IP2, inside the L3 magnet (not used)
- Running scenario:
  - 6 running years with 1 month / year with heavy ions
  - Pb-Pb $\sqrt{s_{NN}} = 5.52$ TeV, 35 nb^{-1} (Run 3-4 x2.5)
  - pp at $\sqrt{s} = 14$ TeV: 3^{-1} fb / year (Run 3-4 x100)
  - further collision species considered

ALICE 3 – detector requirements

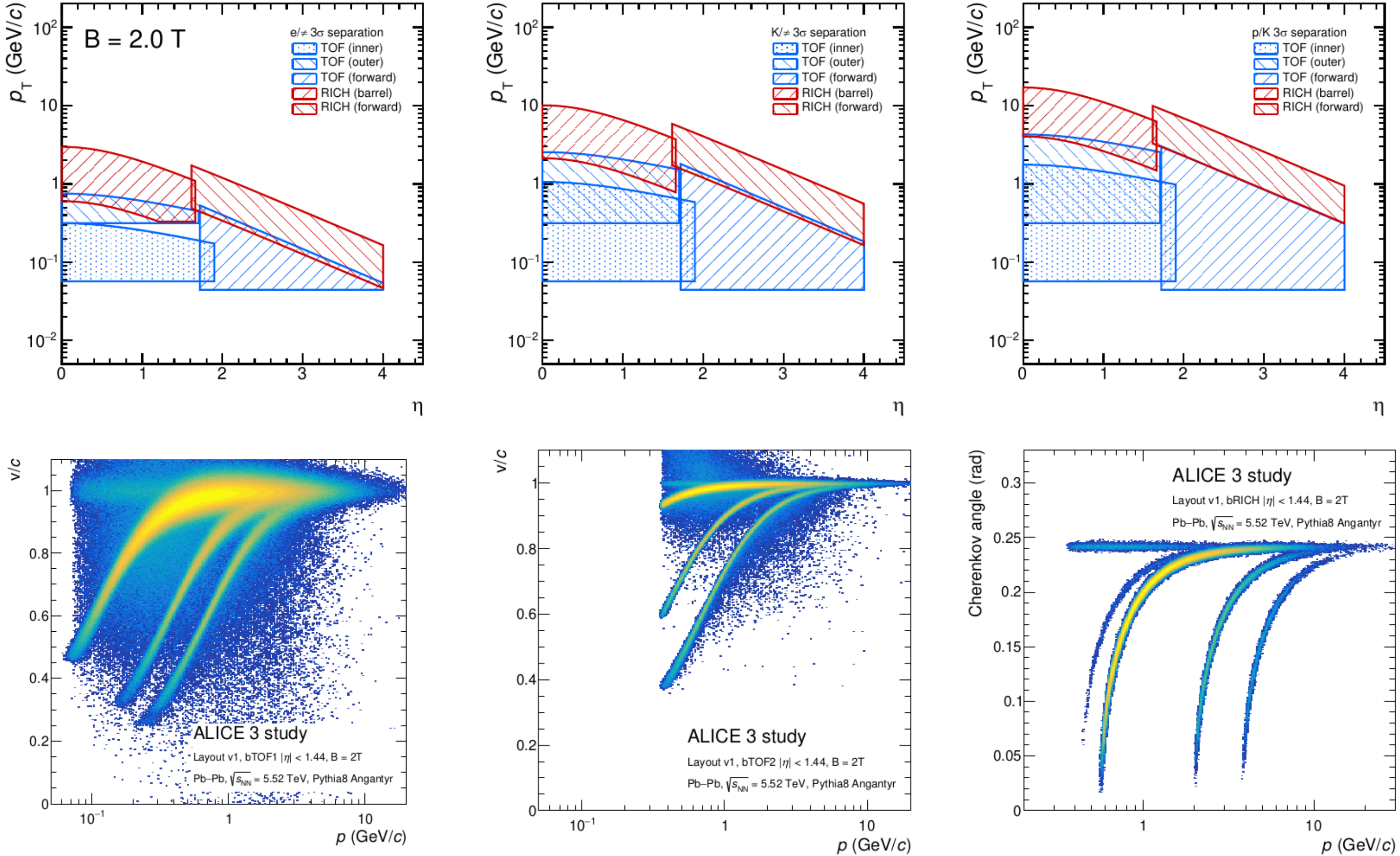
Component	Observables	Barrel ($\|\eta\| < 1.75$)	Forward ($1.75 < \|\eta\| < 4$)	Detectors
Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{DCA} \approx 10\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{DCA} \approx 30\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 3$	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: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to 2–3 GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ 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 $p_T \sim 1.5\,GeV/c$ 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_T range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker

Table 4: Detector requirements

ALICE 3 – summary of ongoing R&D 2024

Detectors	Activities	Plans for 2024
SC Magnet	Conceptual design of SC magnet	Initial design, investigation of cable options (Nb-Ti/Cu, Nb-Ti/Al, MgB_2)
Inner Tracker	Sensor rad. hard. (ITS3 MLR1), mechanics (IRIS), components outgassing	New irradiation tests (NIEL, TID), sensor specs, lab tests (mechanics, vacuum,...)
Outer Tracker	Module concept, mechanics, cooling	Sector mechanical prototype, sensor specs, lab tests
TOF	LGAD and SiPM time resolution, CMOS-LGAD design and characterization	New FEE with picoTDC, new CMOS-LGAD, PS testbeam in Apr, July, Oct
RICH	Angle resolution, time resolution for TOF (SiPM+window)	Focusing aerogel, new FEE with picoTDC, PS testbeam in Oct
ECal	SiPM timing, test new FEC32 with HPTDC	PbWO4 crystal +dual chan. photodet. +FEC32, energy and time resolution, SPS testbeam in May
MID	Scintillator selection, SiPM response, MWPC, RPC	Scintillator prototype module, new FEE, PS testbeam in Oct of all options

ALICE 3 – PID



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ALICE 3 – further physics topics

- Ultra soft forward photon production:
  testing Low's theorem and the infrared limits of QED and QCD
- Heavy-flavor jet-to-photon correlations:
- Light-flavor correlations at large pseudorapidity difference:
  probe early time dynamics
- Dilepton flow
  primordial/resonance hadronic and QGP components
- Different collision systems:
  explore nuclear structure