Contributo Commissione Nazionale Scientifica 3 alla discussione dell´input INFN alla European Strategy for Particle Physics

- Italian Nuclear and Hadron Physics has undergone recently two major strategy processes
  - Review in 2022 of the medium-term strategy for Nuclear and Hadron Physics at the Italian National Laboratories https://web.infn.it/nucphys-plan-italy/. The conclusions have been structured in a set of comprehensive papers published in EPJPlus https://epjplus.epj.org/component/toc/?task=topic&id=1894.
  - NUPECC Long Range Plan (LRP) 2024 LPR, representing the strategic vision of the European Hadron and Nuclear Physics community, presented in Brussels on Nov 19th, 2024. The INFN scientists of CSN3 have very actively participated in the organization, writing and discussing of the NUPECC LRP, which therefore embeds the vision for the future of our community. More information can be found in https://www.nupecc.org/?display=lrp2024/main

Key factors in ESPP
for the CNS3 scientific community

- **Physics beyond colliders**
  - CERN hosts a very rich, diverse and unique program of non-collider experiments, many of which are the main focus of scientific groups in CSN3. These experiments have produced a continuous flow of world-class results and have solid future plans for at least a decade.
  - **AD** low-energy antiproton program
  - Nuclear Structure and Nuclear Astrophysics programs at **n-TOF** and **ISOLDE**
  - The Fixed-Target **SPS** program, in particular towards the future NA60+ Heavy-Ion experiment
- **It is crucial for the activities at ISOLDE, at n-TOF and at the AD, and for the SpS fixed-target program that CERN remains the international reference laboratory for particle physics in the more general sense.**

Key factors in ESPP for the CNS3 scientific community

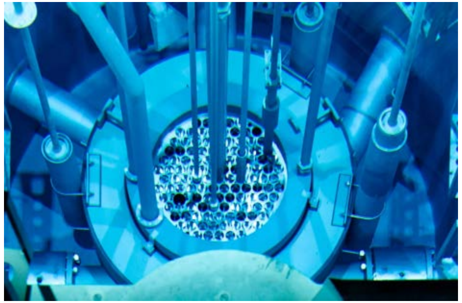
- **The future of the Heavy-Ion community**
  - The INFN HI community has focused for the last >20 years on ALICE
- Medium-term priorities:
  - → Heavy ions at HL-LHC: **new detector ALICE 3** for Run 5
    - Strong programme, with participation of upgraded ATLAS, CMS, LHCb
    - First priority of NuPECC LRP 2024
  - → Heavy ions at SPS: interest for **new experiment NA60+**
    - Availability of ion beams for fixed-targer experiments to be continued during LHC runs 4/5
- **The HI community advocates that the LHC High-Luminosity programme should remain a top priority in the European Particle Physics Strategy, including a strong heavy-ion programme pursuing the exploration of the emergent properties of hot QCD matter and the measurement of its fundamental physics parameters**
- Long-term interest:
  - → Heavy ions at **FCC-hh**: keep possibility to run ions in addition to pp

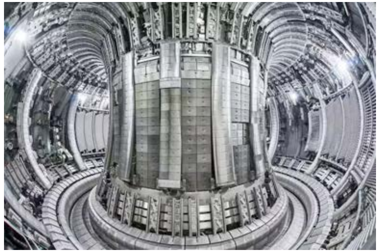
Technology developments

- There is a robust R&D of innovative detectors program ongoing, with common work and synergies among ALICE (ITS3 and ALICE3), EPIC@EIC and NA60+
  - ePIC is a CERN recognized experiment since October 2024, fully embedded in the European nuclear/particle physics landscape
- Breakthrough technologies for **vertexing, tracking and particle identification**:
  - Ultra-thin, bendable Monolithic Pixel Sensors, with stitching allowing large areas
  - 20 ps resolution Si-based TOF PID detectors
    - Hybrid Low-Gain Avalanche Diodes (LGADs)
    - Monolithic CMOS LGAD
  - Si-based RICH PID detectors
- Efforts closely cooperating among each other and aligned with related developments for particle physics experiments at the FCC => DRD
  - The requirements are similar to those of the FCCee detectors

Scientific and Technological research fields at n_TOF

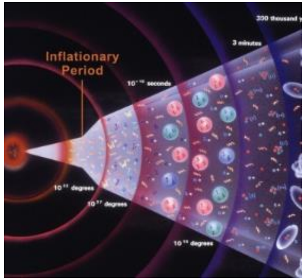
Nuclear Technology





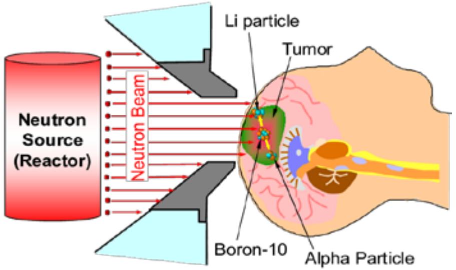
- *Fission reactors (IV Gen e ADS)*
- *Nuclear waste transmutation*
- *Materials ageing in fusion reactors*

Nuclear Astrophysics



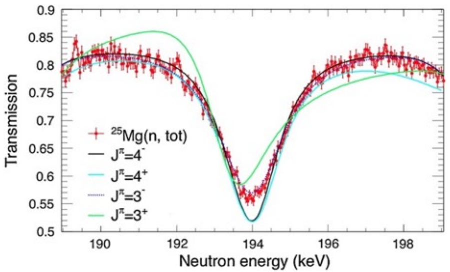
- *Big Bang Nucleosynthesis*
- *s-process*
- *r-process: fission recycling cycles*

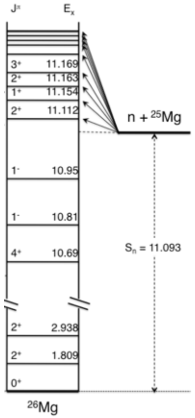
Medical applications



- *Neutron capture therapy*
- *Radioisotope for theranostics??*

Fundamental Physics





- *Fission*
- *Nuclear interactions*
- *Excited levels*

LEA (Low Energy Antimatter) Project

Experiments at CERN's AD/ELENA facility (the only low-energy p̄ source):

- AEgIS, ALPHA, ASACUSA

Italian experiments for positronium studies:

- PsICO, QUPLAS

Physics Motivations:

- Study of CPT Violation

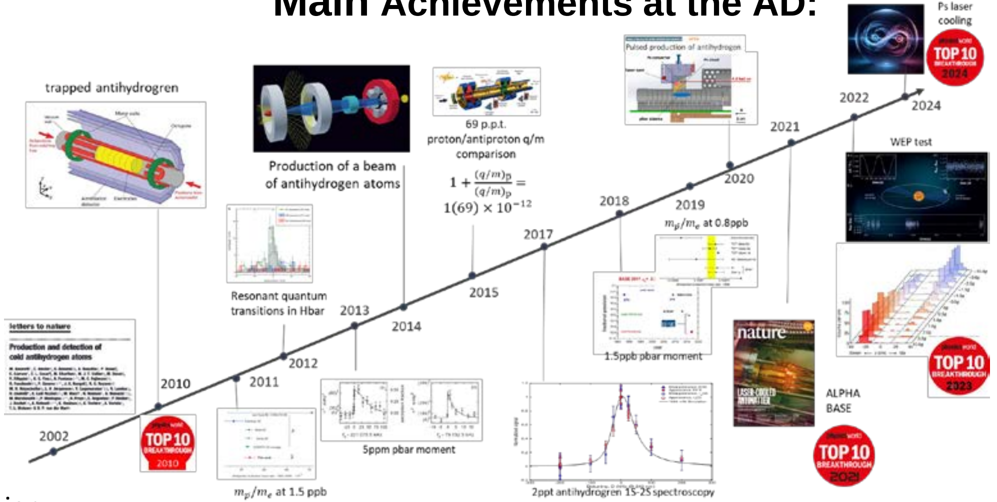
  scarcity of antimatter in the Universe and matter-antimatter asymmetry

  ← Laser and MW spectroscopy of antihydrogen

- Test of the Weak Equivalence Principle (WEP)

  ← Measurement of the gravitational behavior of antihydrogen

Main Achievements at the AD:



(Anderson et al., Nature 2023)

(Glöggler et al., PRL 2024)

The future of LEA

Many ideas are being considered (not yet approved), for example:

- AEgIS: Direct WEP test with antihydrogen in a magnetic-field-free region
- ALPHA: Improved gravity measurements and spectroscopy of antihydrogen
- ASACUSA: Measurement of antihydrogen GS-HFS at ppb resolution; Advanced p̄-He spectroscopy

Expanding focus into Nuclear & Hadronic Physics: studies on a p̄-atoms, dark matter research, n̄ investigations, Pontecorvo reactions, p̄ and n̄ cross-sections, the use of antideuterons, etc.

- Possible modifications required for AD/ELENA

ISOLDE

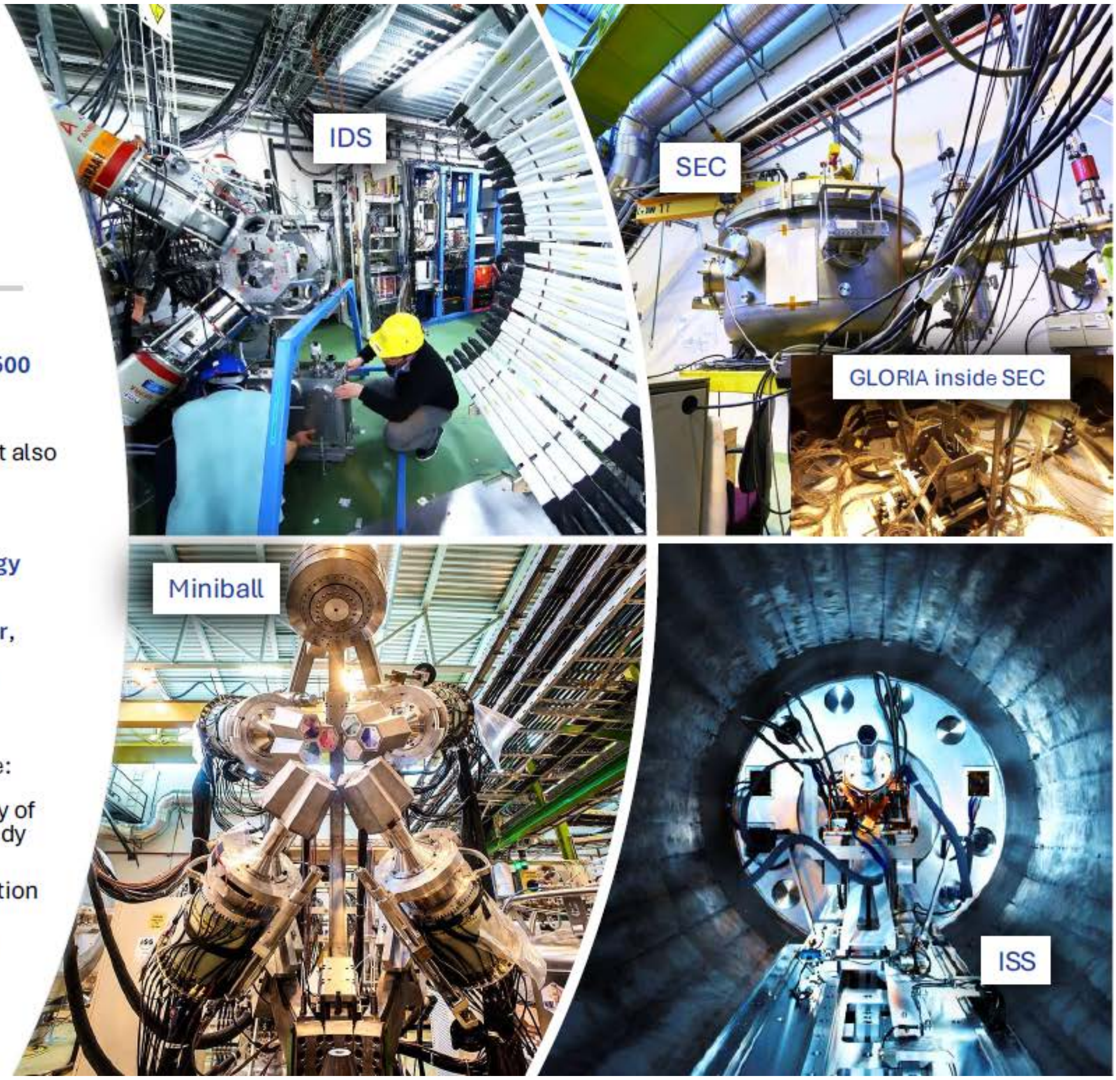
The **I**sotope **S**eparator **O**n-**L**ine **DE**vice at CERN

- The **world-leading facility** in the production and acceleration of Radioactive Ion Beams (**RIBs**) with the ISOL technique, with about **500 users** from **16 countries** every year

- Fields of interest: primarily **Nuclear Physics and Astrophysics**, but also Biology, Condensed-Matter Physics, Medicine, Applied Physics, Engineering Applications

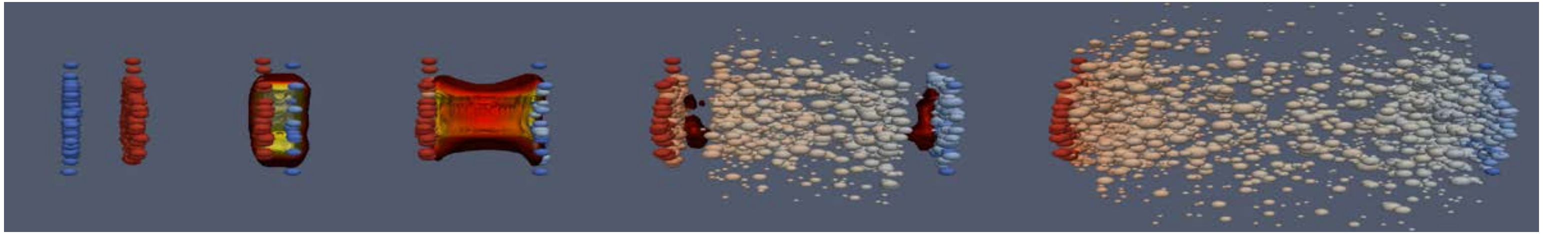
- Several **setups** are available for experiments with RIBs at **low-energy (≈ 10-50 keV)** and **high-energy (≈ 5-10 MeV/u)**
  - The INFN-CSN3 operates at the **Miniball γ-ray spectrometer**, the **ISOLDE Decay Station (IDS)**, the **ISOLDE Solenoidal Spectrometer (ISS)**, the **Scattering Experiments Chamber (SEC)**, and the **GLObal ReactIon Array (GLORIA)**

- The **plans for the future** of ISOLDE are part of the ESPP and include:
  - **After LS3** – Fully exploit the higher energy and higher intensity of the proton beams for improved production yields of the already available RIBs
  - **During LS4** – The upgrade of the facility with also the installation of new instrumentation
  - **Long-term plan** – New experimental hall and second target station



Future of heavy-ion physics at CERN

Major (expected) open questions after LHC Run 4



- Scale dependence of different mechanisms of parton transport in the QGP

→ **D-Dbar correlations as scattering experiment**

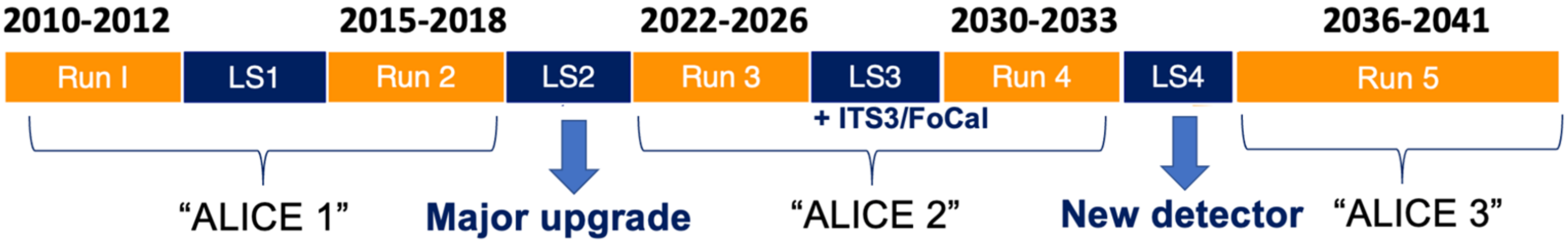
- To what extent do quarks of different mass reach thermal equilibrium ?
- What are the mechanisms of hadron formation in QCD?

→ **Systematic measurement of (multi-)charm hadrons**

- Time evolution of thermal electromagnetic radiation from the QGP
- What are the mechanisms of chiral symmetry restoration in the QGP?

→ **Precision measurements of dileptons**

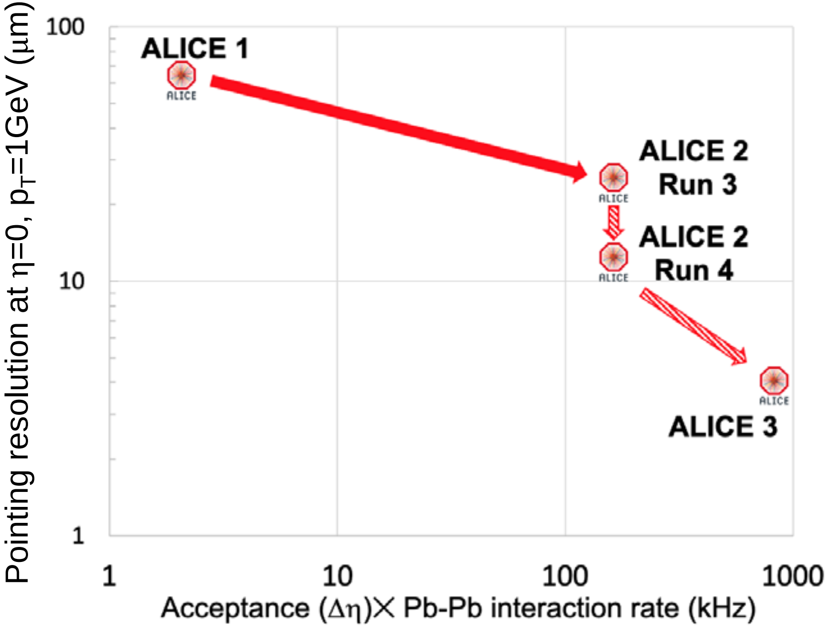
ALICE future: pushing the frontiers of precision



Enhance physics reach by improving:

- rate capabilities & acceptance
- tracking precision

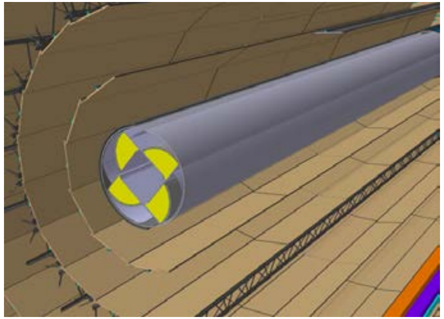
→ high precision,
reduce backgrounds,
access rarer probes

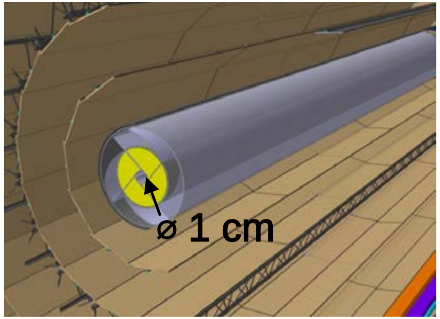


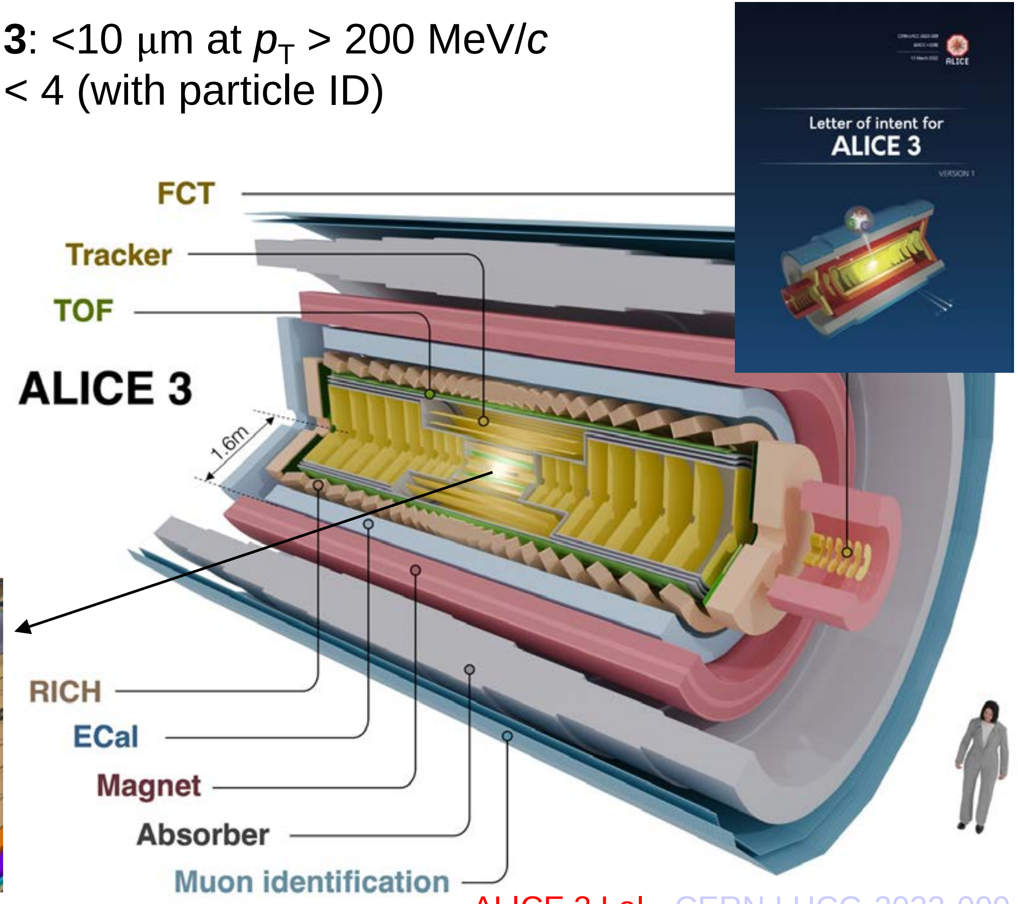
ALICE 3: next-generation heavy-ion detector

→ **Tracking precision** $\times$ **3**: <10 μm at p_T > 200 MeV/c
→ **Acceptance** $\times$ **4.5**: $|\eta| < 4$ (with particle ID)
→ **A-A rate** $\times$ **5 (pp** $\times$ **25)**

- Compact and light-weight all-pixel tracker
- Retractable vertex detector in vacuum
- Large acceptance with particle ID
- Superconducting solenoid (2T)
- Continuous readout and online processing





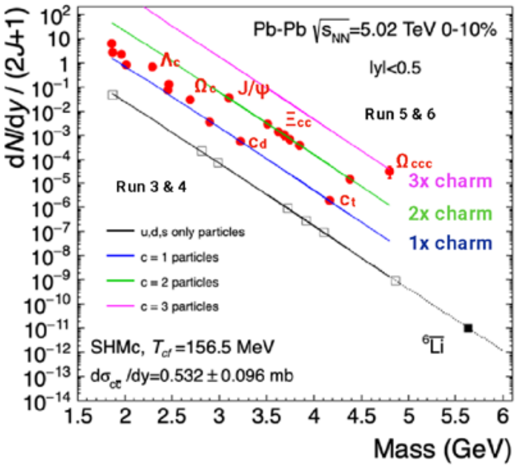


ALICE 3 LoI, CERN-LHCC-2022-009

ALICE 3: a major leap in physics reach

→ full exploitation of LHC potential for physics of hot QCD matter

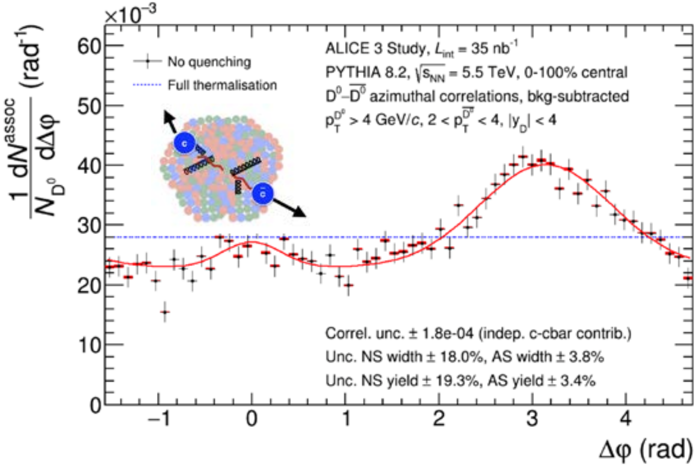
e.g.: multi-charm baryons



- pure recombination
  - unlike J/ψ
- up to 10³ enhancement predicted

→ huge sensitivity to degree of thermalisation

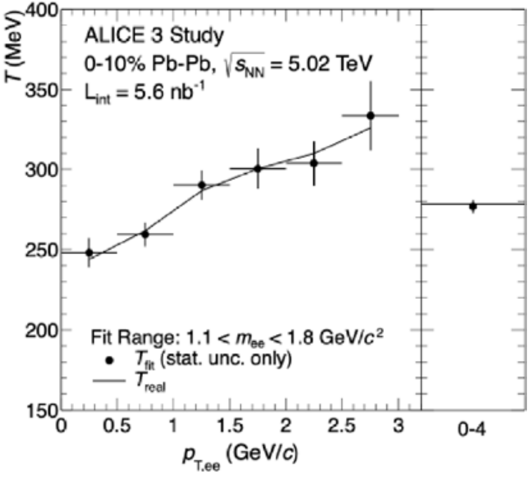
e.g: D-Dbar correlations



- "Rutherford experiment" on QGP
- correlate Eloss with deflection vs p
  - scale of scattering centres vs momentum scale

→ collisional vs radiative Eloss vs p scale

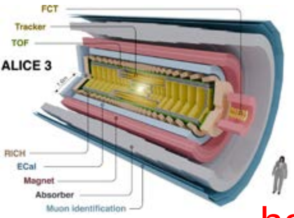
e.g: thermal dileptons



- e.m. radiation from QGP
- ultimate HF rejection & high stats
  → e.g.: asymmetry vs time

→ time evolution of emission

\+ chiral symmetry restoration

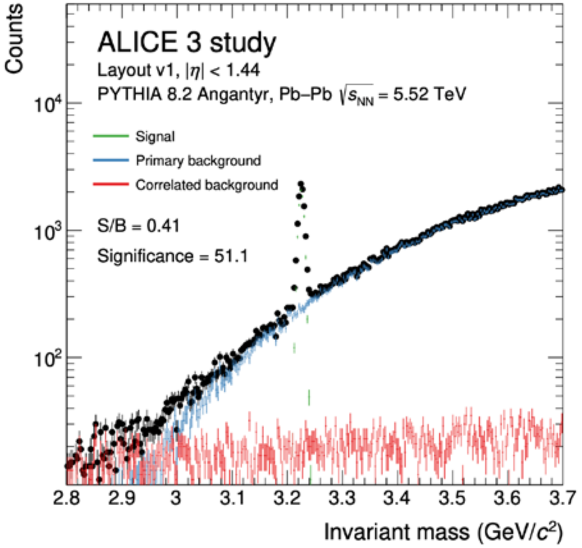


ALICE 3: a unique instrument at the LHC

→ beyond QGP physics: new windows not accessible otherwise

hadronic physics

→ e.g. c-nuclei (nuclei with c-baryons)



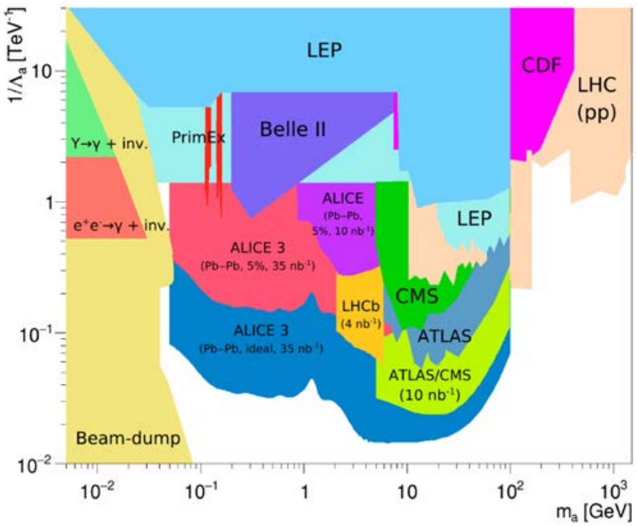
→ discover of exclude

- if yields of c and nuclei are found at SHMc equilibrium

+ femtoscopy, exotic hadrons, photoproduction, …

BSM searches

→ e.g. axion-like particles (ALPs)

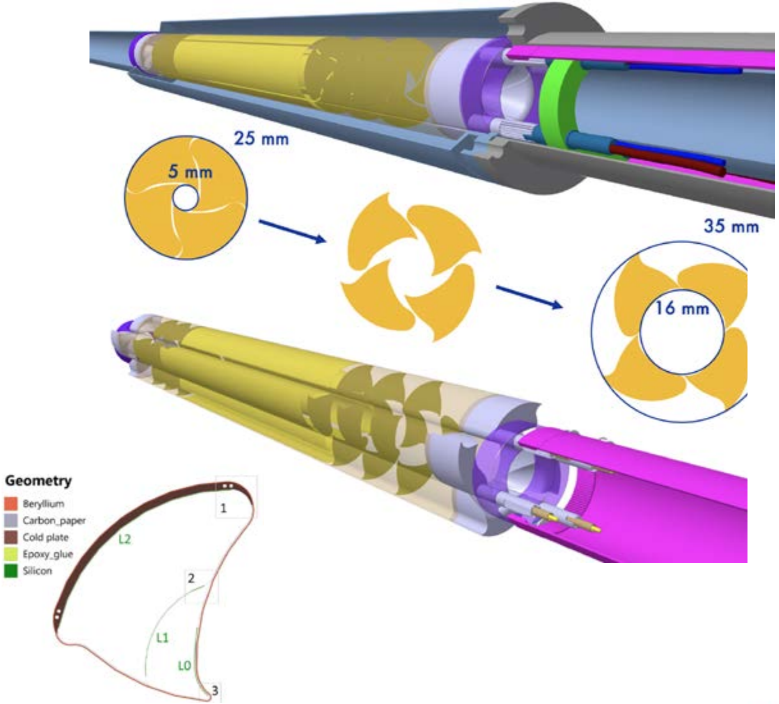


→ access to unique region

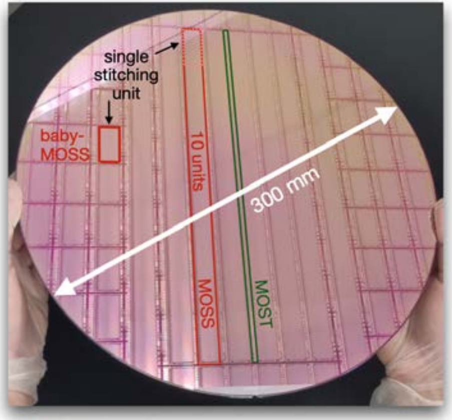
+ dark photons, light-by-light, …

R&D on Monolithic Pixel Sensor

- ALICE 3 retractable vertex detector
- Target sensor specs: 10x10 μm^2 pixels, <50 μm thickness, NIEL: ~10^{16} 1 MeV n_{eq}/cm^2

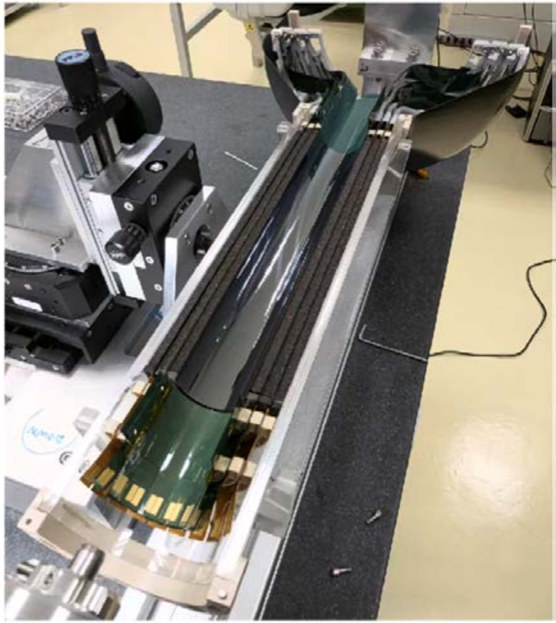


- Evolution of R&D for ITS3: ultralight wafer-size MAPS
  - Also of interest for NA60+, ePIC (EIC)



Engineering Run 1 wafer with various dies

Monolithic Stitched Sensor (MOSS)



ALICE ITS3 Engineering Model 3

R&D on Si-based TOF PID detectors

ALICE 3 Si-TOF target resolution: 20 ps

R&D lines lead by INFN:

- **Hybrid** ***Low-Gain Avalanche Diodes*** **LGADs**: R&D with thin sensors
  → close to target time resolution in beam tests

- **CMOS LGAD (baseline):**

  → single chip with sensor and readout

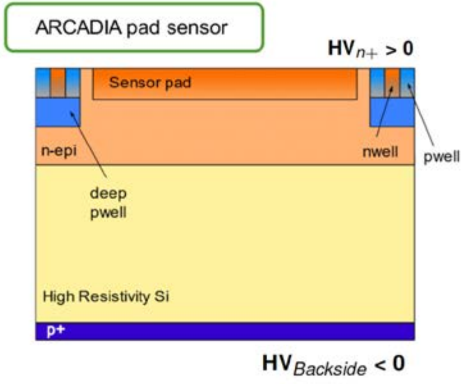
  → significant cost reduction

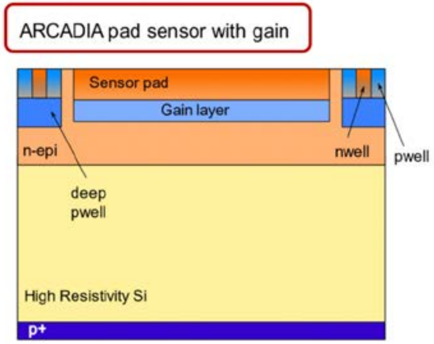
  → first prototypes, test beams, promising outlook to reach target resolution

- **SiPM with resin layer:**

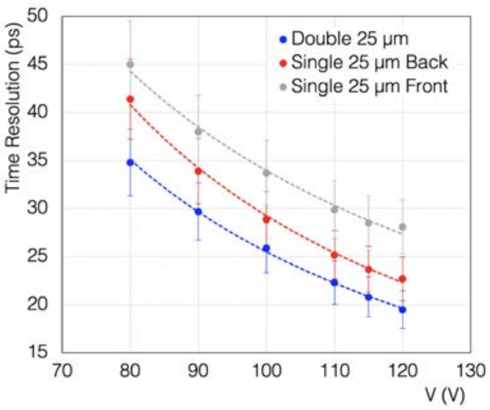
  → charged hadrons radiate several photons in resin layer

  → close to target time resolution in test beams



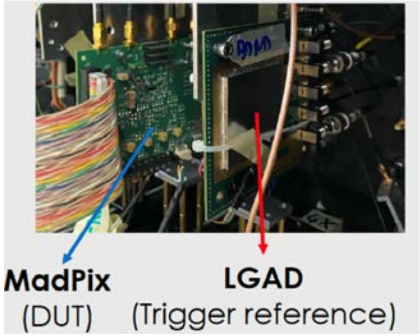


Hybrid LGAD time resolution

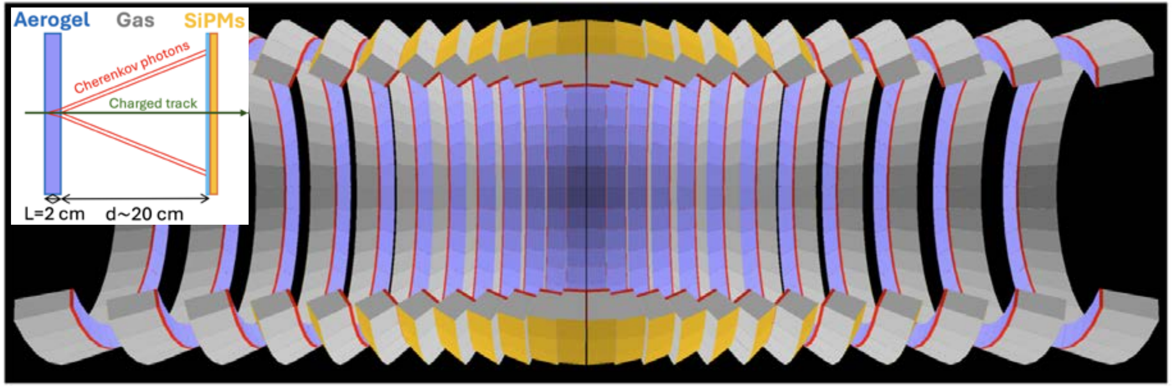


Carnesecchi et al. Eur. Phys. J. Plus (2023) 138:990

CMOS-LGAD (MadPix)

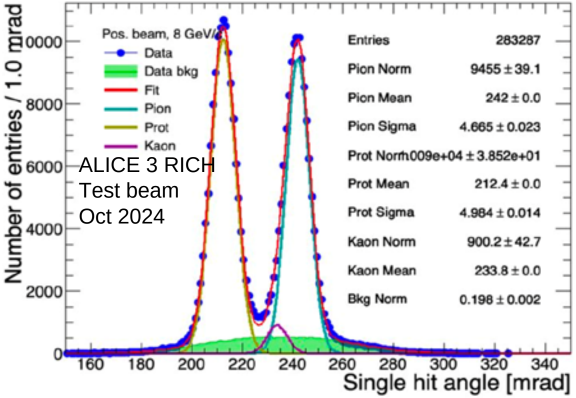


R&D on Si-based RICH PID detectors



ALICE 3 RICH ($|\eta|<2$ + $2<|\eta|<4$)

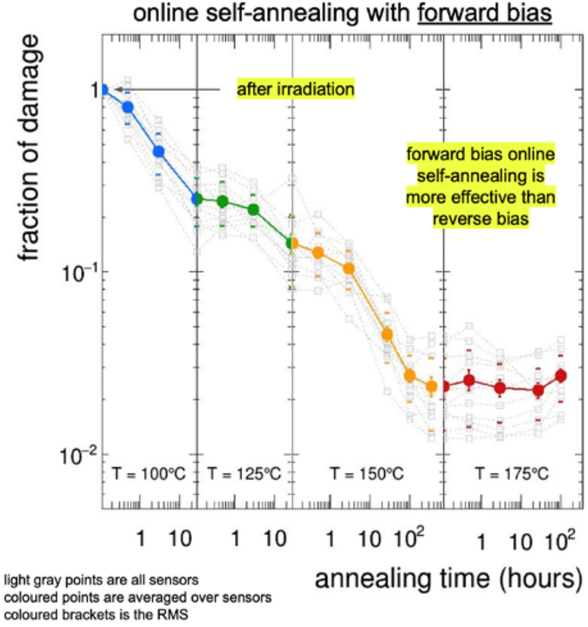
- photon detection area 53~ m^2
- readout cell size = 2 x 2 mm^2
- radiation ~10^{12} 1 MeV n_{eq}/cm^2



Target Cherenkov angle resolution achieved in beam tests

R&D focuses on readout, choice of SiPM and radiation damage mitigation (cooling and annealing):
→ benefits from R&D for dual RICH of ePIC (EIC)

https://indico.bnl.gov/event/24127/contributions/93833/attachments/56075/95953/[20240725][EICUG][ePIC Lehigh] dRICH SiPM and electronics integration.pdf



ePIC SiPM annealing R&D

ALICE R&D and future HEP experiments

ALICE 3 and FCC-ee det. have similar pixel vertex specs:

	ITS3	ALICE 3 VTX	FCC-ee
Single point resolution (μm)	5	2.5	3
Time resolution (ns RMS)	2000	100	20
In-pixel hit rate (Hz)	54	94	few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	
Power consumption (mW / cm^2)	35	70	50
Particle hit density (MHz/cm^2)	8.5	94	200
NIEL (1 MeV n_{eq})	4×10^{12}	1×10^{16}	10^{14} (per year)
TID (Mrad)	0.3	300	10 (per year)
Material budget (% X_0/layer)	0.09	0.1	˜0.3
Pixel size (μm)	20	10	15-20

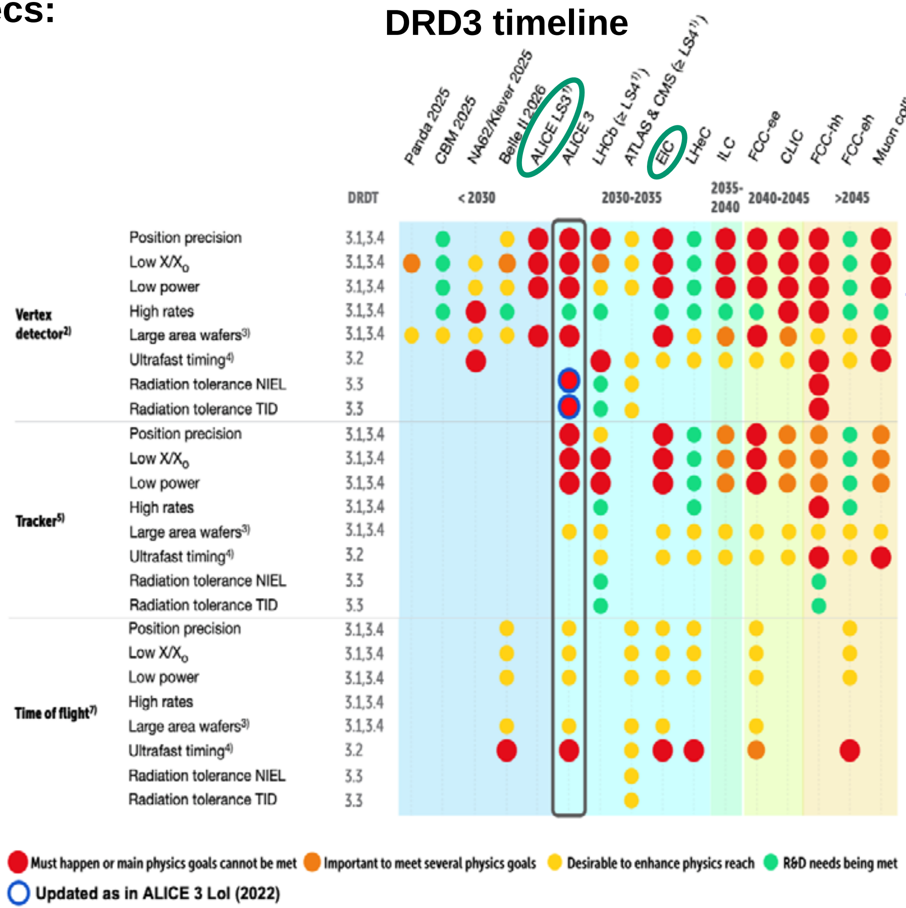
ECFA Detector R&D Roadmap:

→ R&D for ALICE upgrades is coherent with the long-term strategic R&D lines defined by ECFA

→ R&D activities in DRD3 and DRD4

→ DRD3: solid state detectors

DRD3 timeline



ALICE R&D and future HEP experiments

Common goals also for PID and photon detection

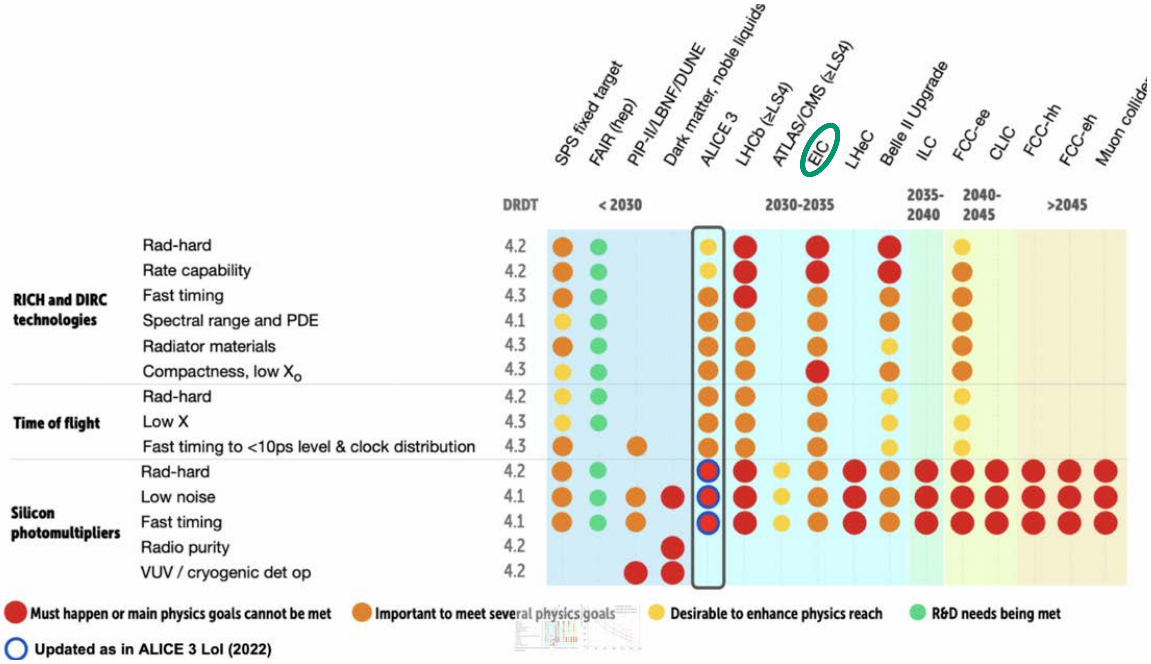
ECFA Detector R&D Roadmap:

→ R&D for ALICE upgrades is coherent with the long-term strategic R&D lines defined by ECFA

→ R&D activities in DRD3 and DRD4

→ DRD4: Particle Identification and Photon Detectors

DRD4 timeline



https://cds.cern.ch/record/2784893

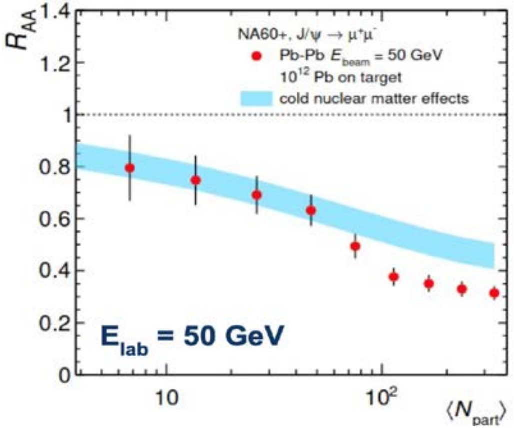
CSN3 R&D in the DRD framework

DRD1: Gaseous Detectors
DRD3: Solid State Detectors
DRD4: Particle Identification and Photon Detectors
DRD7: Electronics & On-detector Processing

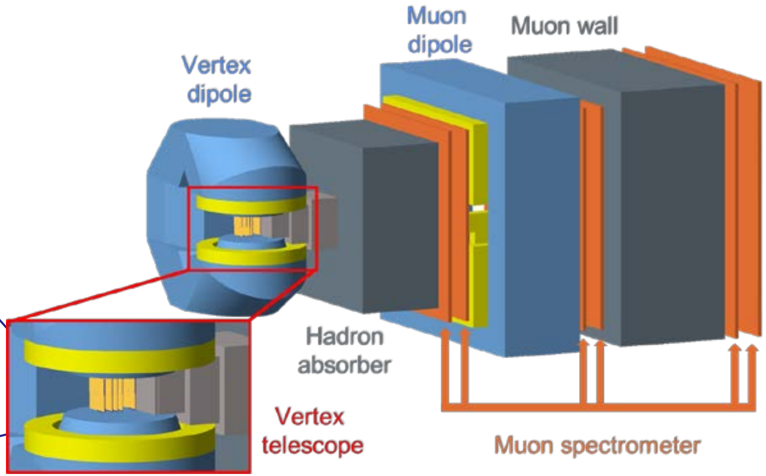
CSN3 R&D activity	Synergic DRD
ALICE 3 RICH	DRD4
ALICE 3 TOF	DRD3
ALICE 3 tracker & ITS3 (LS3)	DRD3 / DRD7
ePIC dRICH	DRD4
ePIC SVT	DRD3
NA60+ pixel tracker	DRD3
ePIC and n_TOF μRwell	DRD1

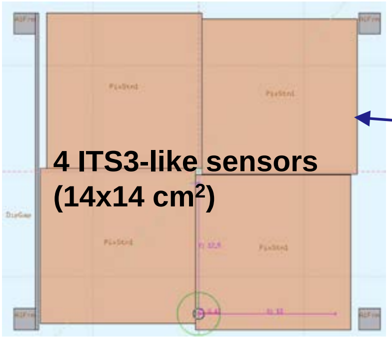
NA60+ at the CERN SPS

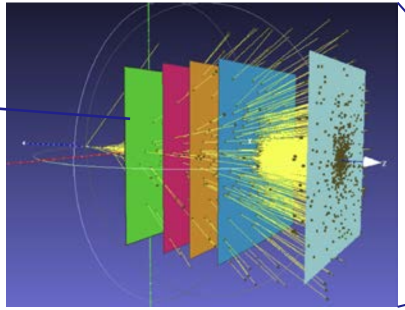
- Fixed-target setup: dimuon spectrometer after a silicon pixel tracker (MAPS). Energy scan (6<sqrt(s)<17 GeV) and large L_int to access rare probes of QGP
- Main physics goals:
  → caloric curve of QCD matter via thermal radiation
  → search for onset of colour deconfinement
- Letter of Intent approved by SPSC in 2023; Technical Proposal planned for 2025
- Data taking ~ 2029-2036



Onset of J/ψ suppression vs centrality



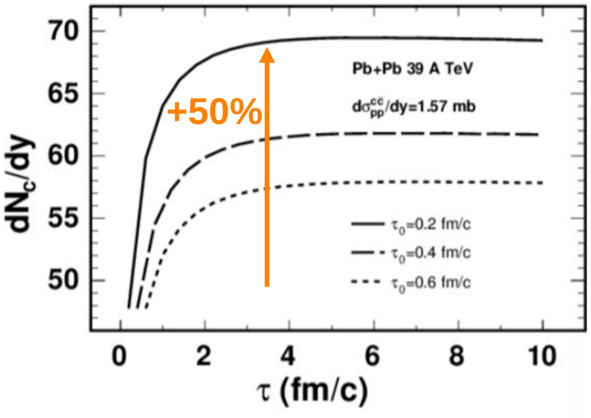




Long-term future: heavy ions at FCC-hh

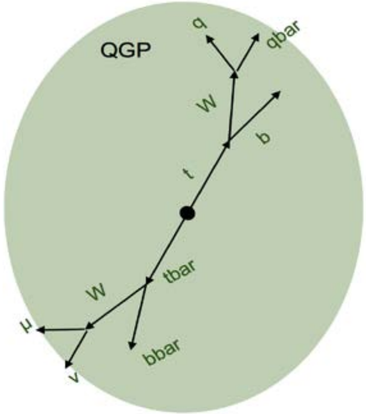
- FCC-hh HI performance: Pb-Pb $\sqrt{s_{NN}}$ = 39 TeV **~ 7 x LHC $\sqrt{s_{NN}}$**
- >100 nb^{-1}/month in "ultimate" luminosity scenario: **~ 20-30 x LHC L_{int}**
- QGP from LHC to FCC: volume x2, energy density x3, initial temperature ~1 GeV

Thermal charm-anticharm from QGP gluons at *T*~1 GeV



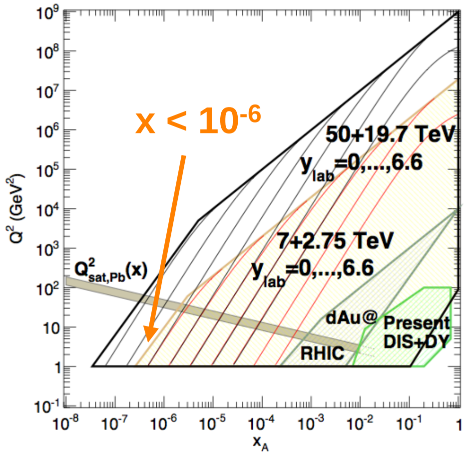
Ko, Liu, JPG43 (2016) 12, 125108
Zhou et al., PLB758 (2016) 434

New probes: boosted tops → QGP density vs. time



Apolinario et al., PRL120 (2018) 23, 232301

Smallest Bjorken-x ever for gluons in nuclei



Dainese et al., arXiv:1605.01389