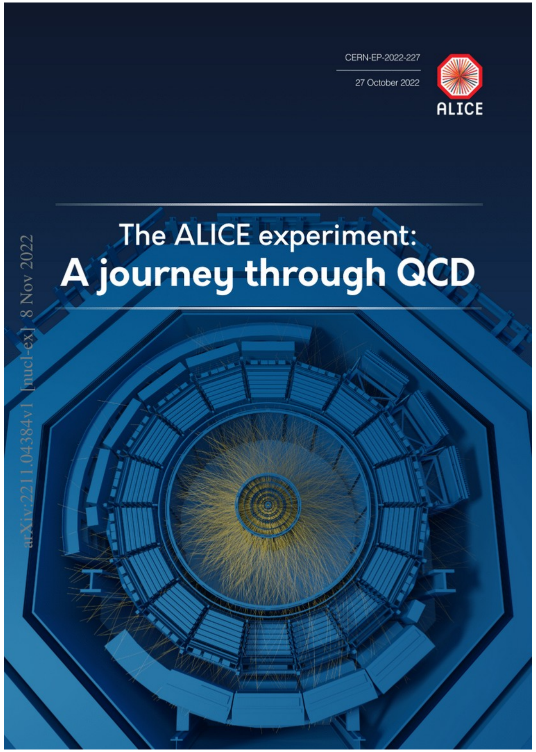
ALICE 3:
A next-generation heavy-ion detector for LHC Run 5 and Run6

Ionut Cristian Arsene (Oslo)
28/09/2023, NorCC workshop

What have we learned so far?



ALICE, arXiv:2211.04384

A comprehensive overview of what we learned with the results from Run 1 and 2

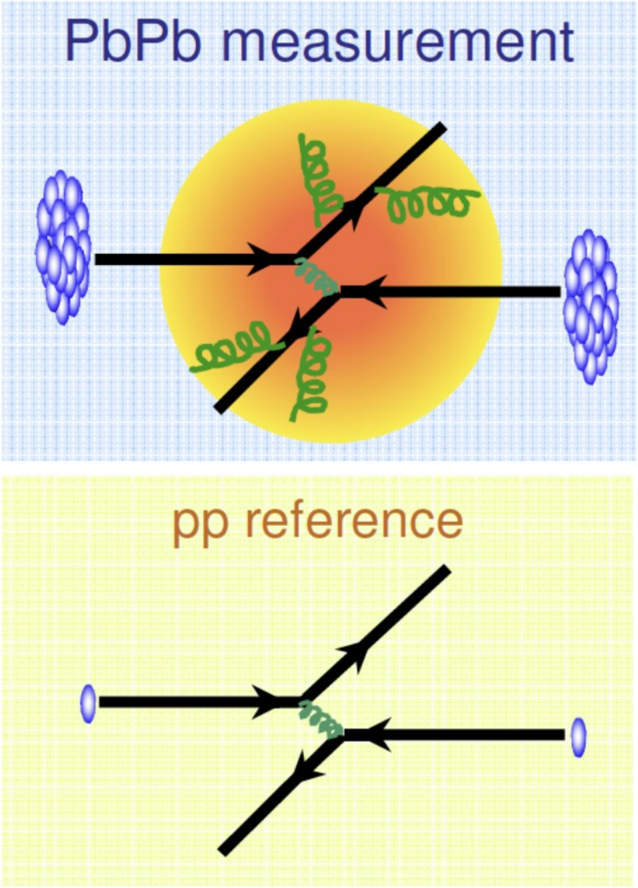
What have we learned so far?

- In this talk:
  - Heavy flavours
  - Real and virtual photons

“Standard” observables: R_{AA}

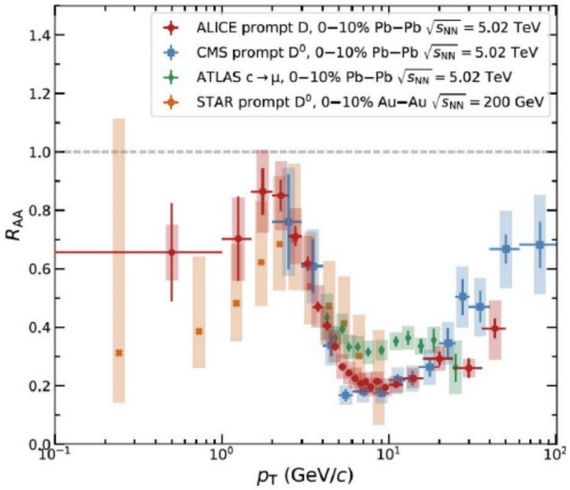
$$R_{AA} = \frac{1}{N_{coll}} \frac{Y_{AA}}{Y_{pp}} = \frac{QCD\ Medium}{QCD\ vacuum}$$

- No nuclear effects: $R_{AA} = 1$
- Hot or cold nuclear effects: $R_{AA} \neq 1$

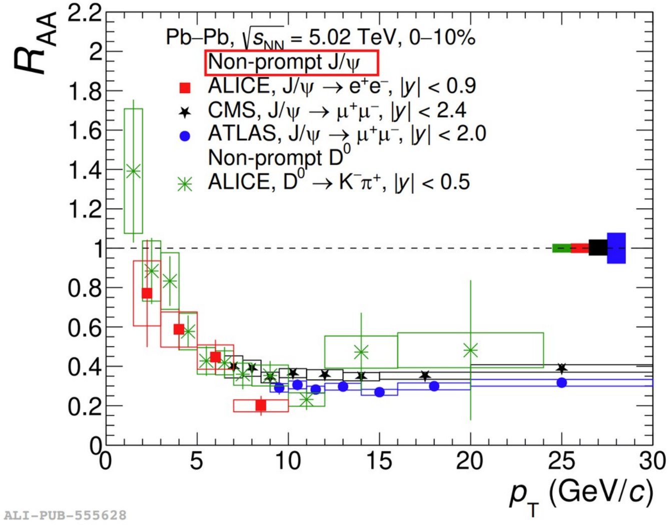


“Standard” observables: R_{AA}

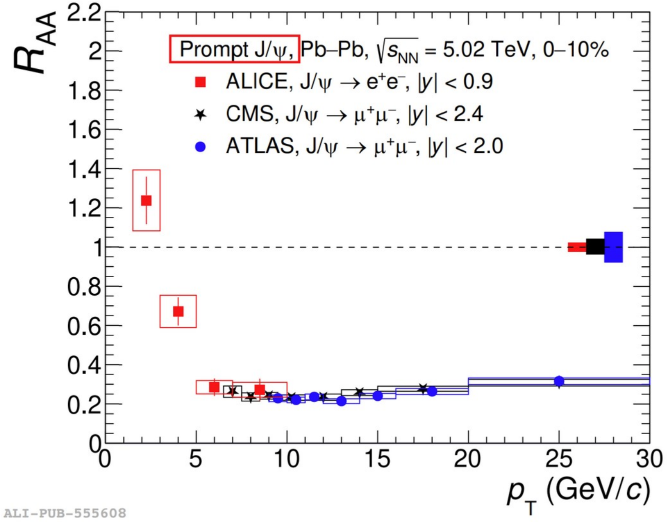
D^0



Non-prompt J/ψ (beauty)



Prompt J/ψ

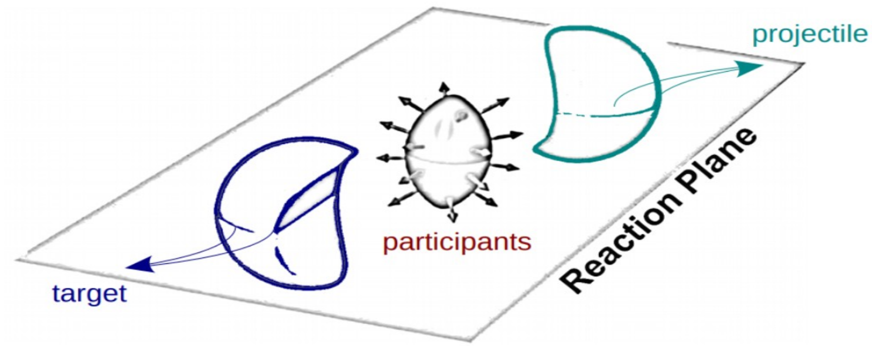


ALICE arxiv:2308.16125

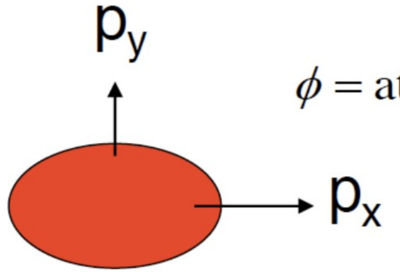
ALICE:
JHEP 01 (2022) 174 PLB 813 (2021) 136054
CMS:
PLB 782 (2018) 474 PLB 816 (2021) 136253
ATLAS:
PLB 829 (2022) 137077
PLB 807 (2020) 135595
STAR:
PRC 99 (2019) 34908
PRL 118 (2017) 212301

- Low-p_T: moderate suppression or enhancement
- High-p_T: Strong suppression

“Standard observables”: anisotropic flow



Pressure and multiple collisions



$$\phi = \mathrm{atan}\frac{p_y}{p_x}$$

coordinate space: initial anisotropy

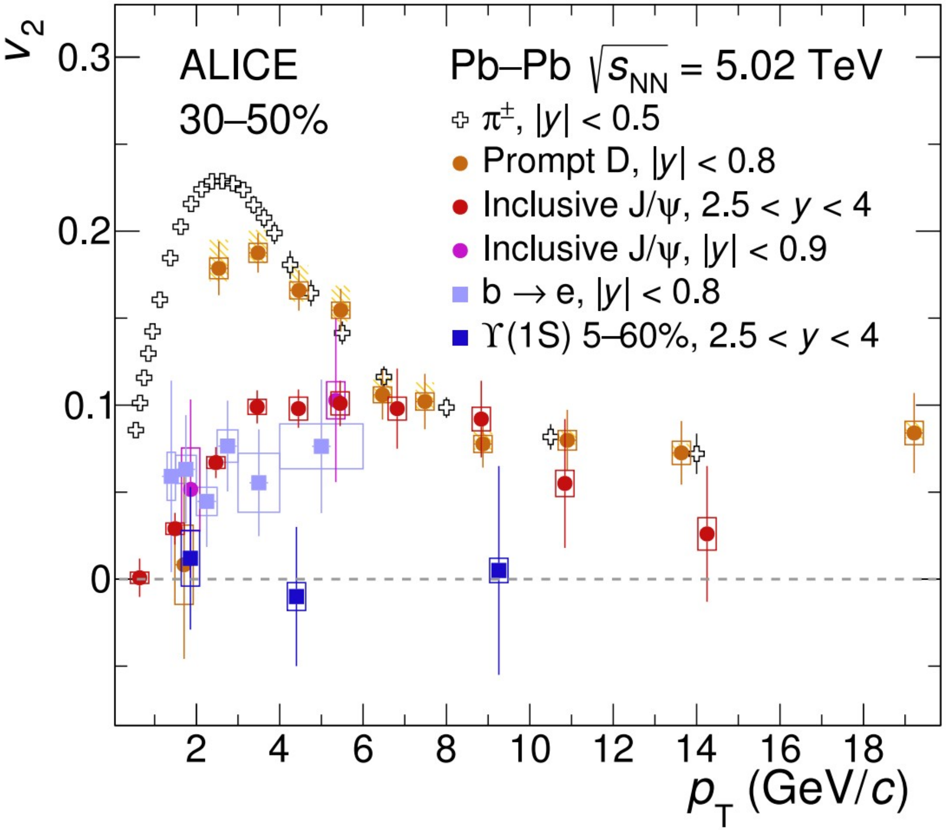
momentum space: final anisotropy

- Typically quantified via a Fourier expansion wrt reaction plane Ψ:

$$\frac{dN}{d\phi} \approx \left(1 + 2\sum_n v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

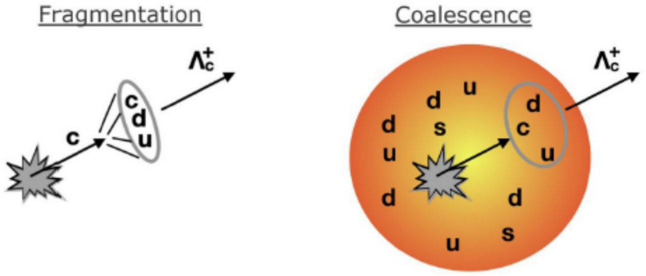
- Dominated by the elliptic flow coefficient: v_2

“Standard observables”: anisotropic flow of heavy quarks



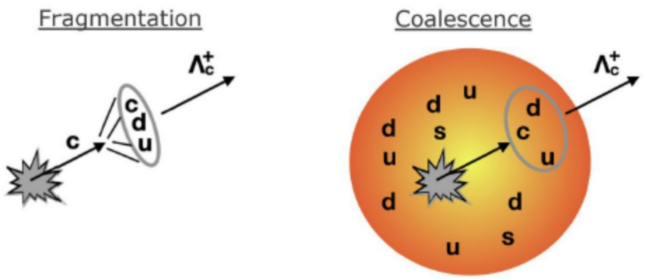
- Quark mass hierarchy seen in the flow measurements
- Open and hidden charm: strong flow
- Open beauty: possible flow
- Bottomonia: compatible with no flow

Charm hadronization



Fragmentation: break-up of charm quark as in e^+e^- collisions (expected also in pp)
Coalescence: combination of quarks close in phase space

Charm hadronization



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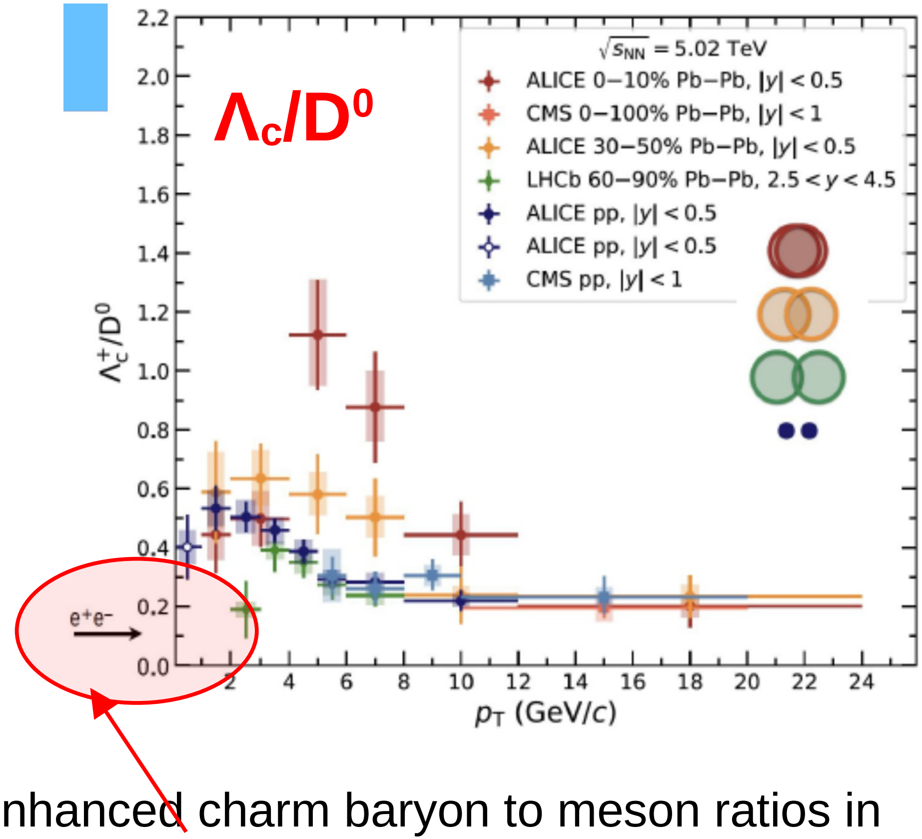
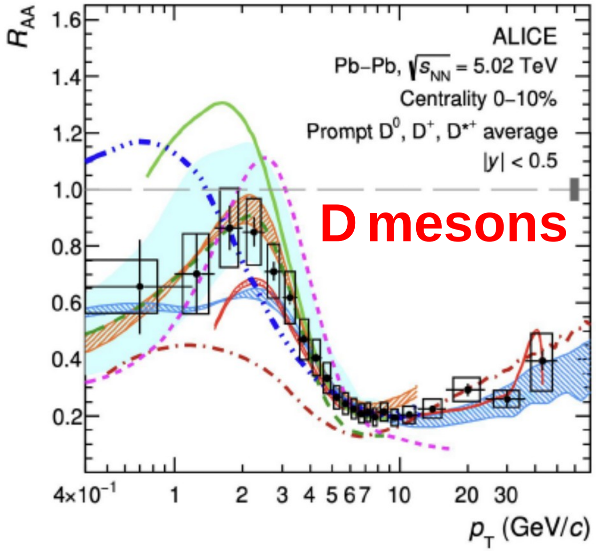
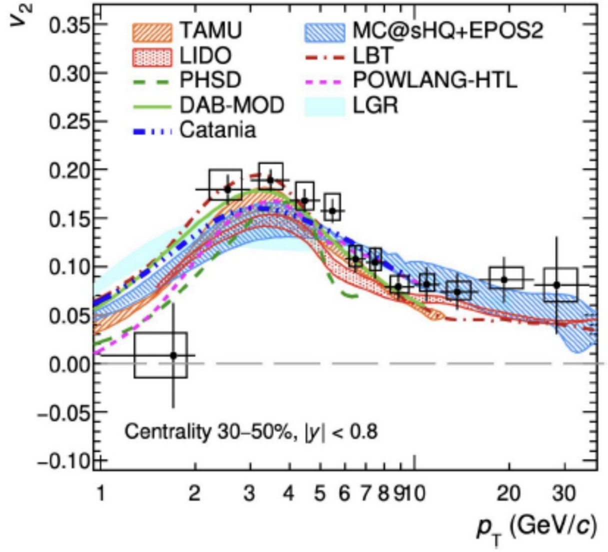


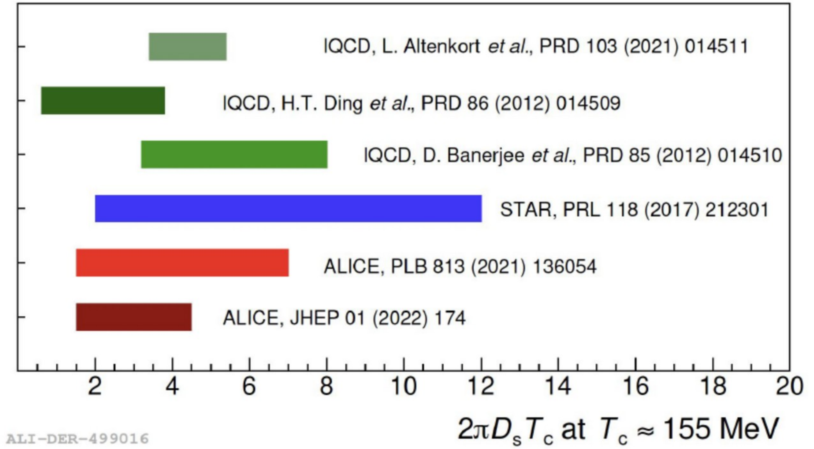
LHCb:
arXiv:2210.06939 Phys. Rev. D 100, 031102
CMS:
PLB 803 (2020) 135328
CMS-PAS-HIN-21-004
ALICE:
arXiv:2112.08156 PLB 839 (2023) 137796 PRL 127 (2021) 202301

- Largely enhanced charm baryon to meson ratios in pp collisions wrt e^+e^-
- Baryon/meson ratios even larger in Pb-Pb

Some conclusions on open charm





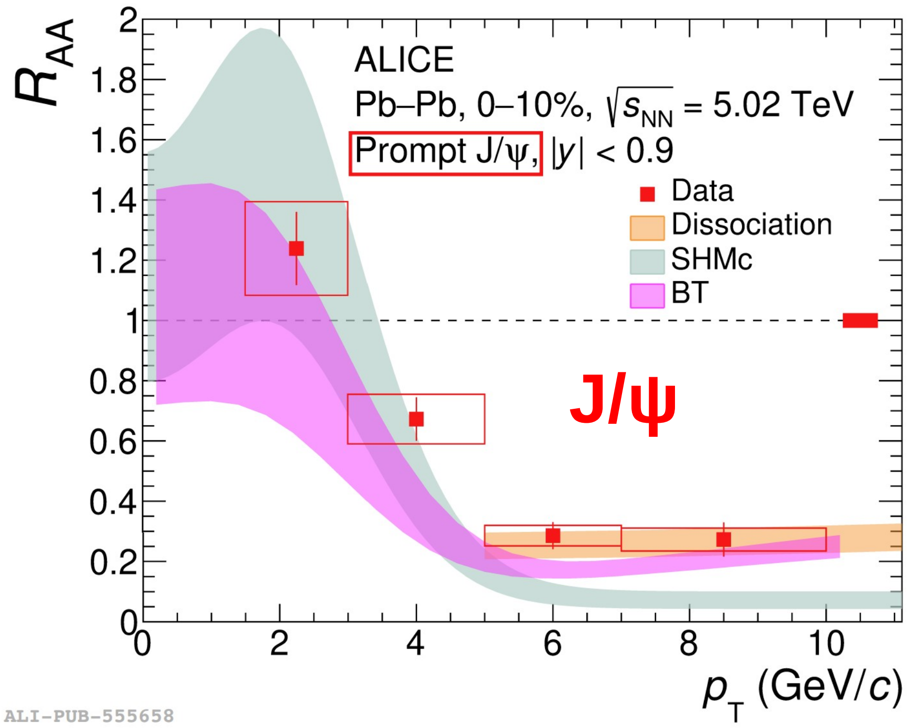


- Low-p_T: multiple elastic collisions in the medium
  - Diffusion (Brownian) motion
  - Possible thermalization in the medium
- High-p_T: radiative energy loss (gluon emission)

- **1.5 > $2\pi D_s T_c$ < 4.5** which corresponds to a **2 < τ_{charm} < 9fm/c**
  - Charm thermalization time compatible with the QGP lifetime

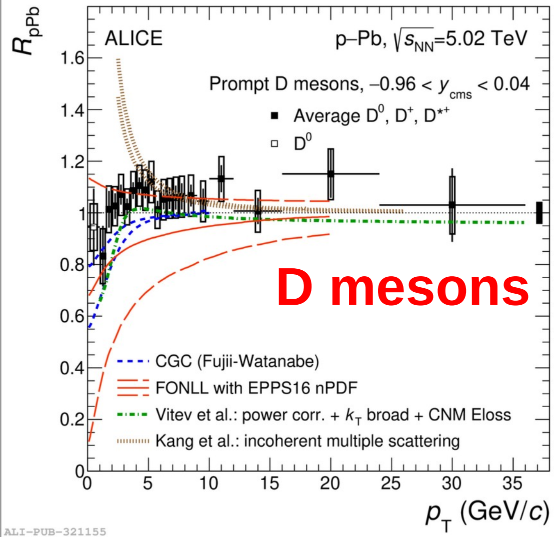
Charmonia

ALICE arxiv:2308.16125

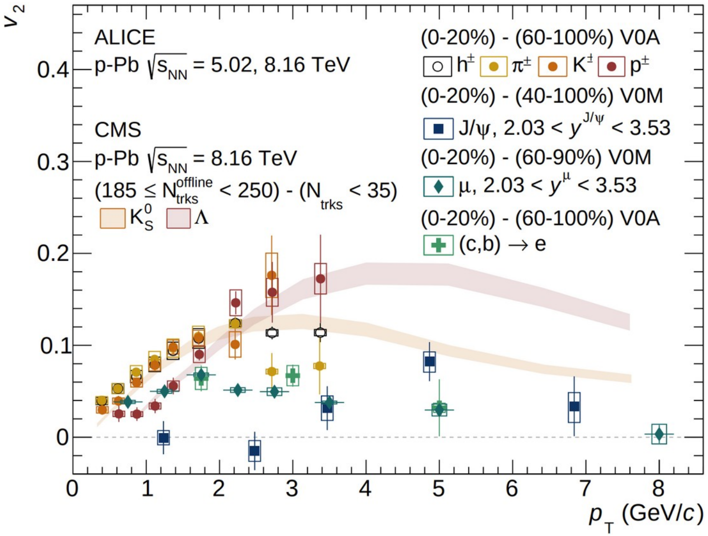


- Charmonium production dominantly via regeneration, but
  - No agreement on the phenomenology
  - Large uncertainties due to the initial state (gluon saturation, shadowing, etc.)

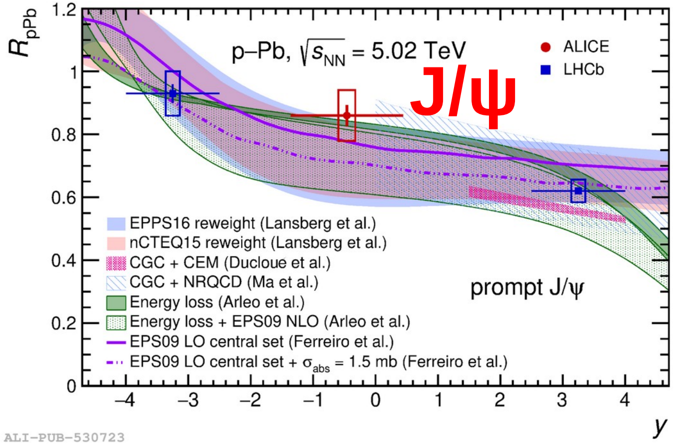
Charm production in p-Pb



ALI-PUB-321155



J/ψ
c,b

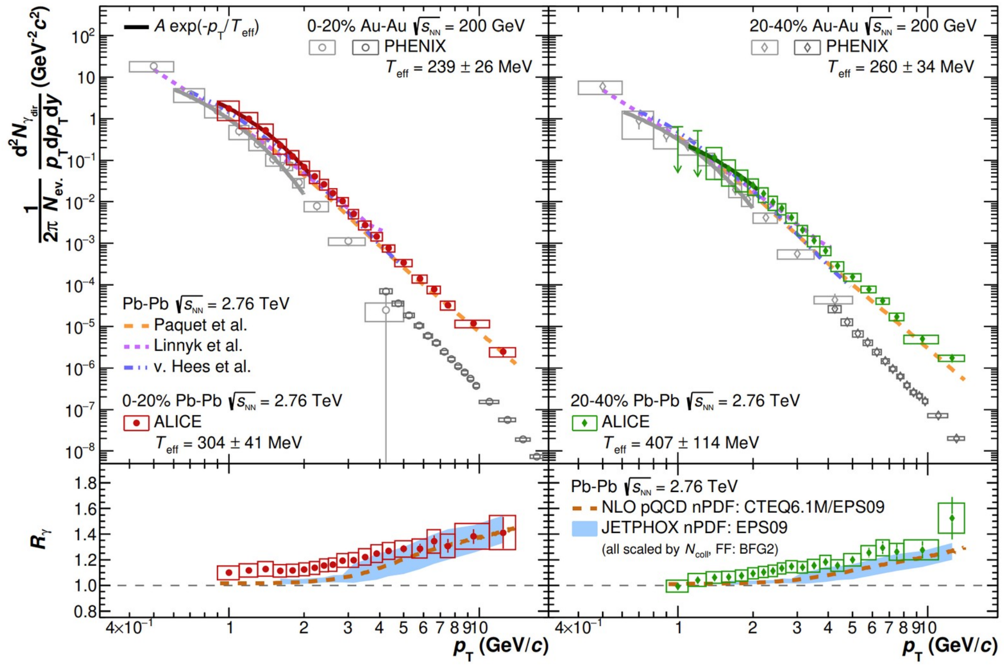


ALI-PUB-530723

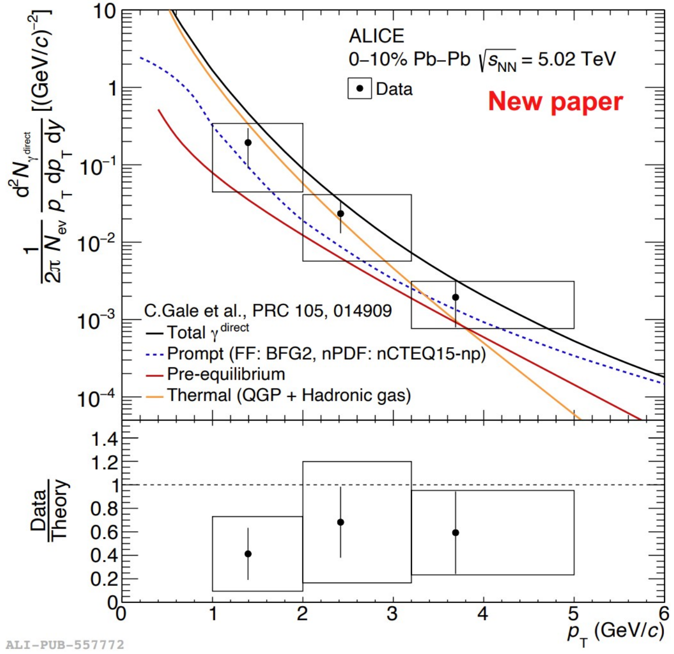
- p-Pb collisions: reference for cold nuclear matter effects
- Both open charm and charmonia exhibit
  - $R_{AA} \neq 1$
  - Non-zero elliptic flow
- Suppression could be a hint of gluon saturation (fundamental QCD phenomena at low-*x*)
- $v_2 > 0$: possible collective effects in small systems

Thermal photons

Real photons



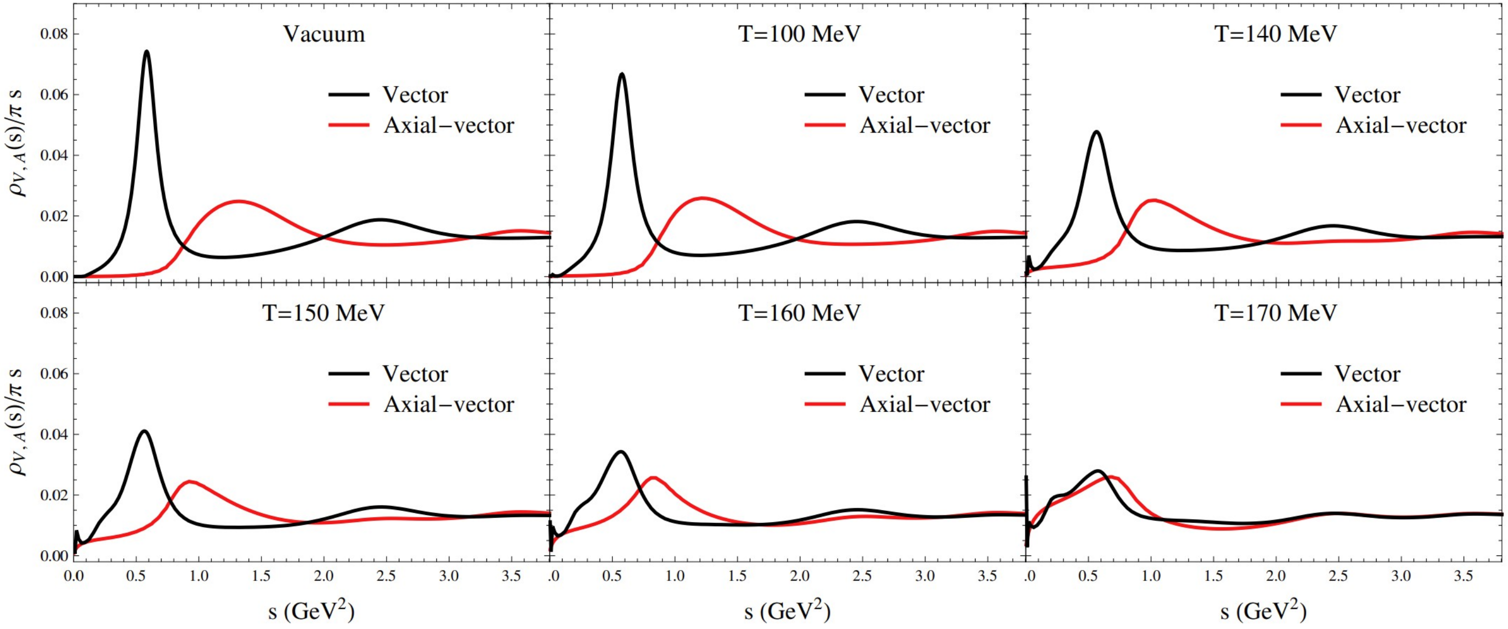
Virtual photons



ALICE, arxiv:2308.16704

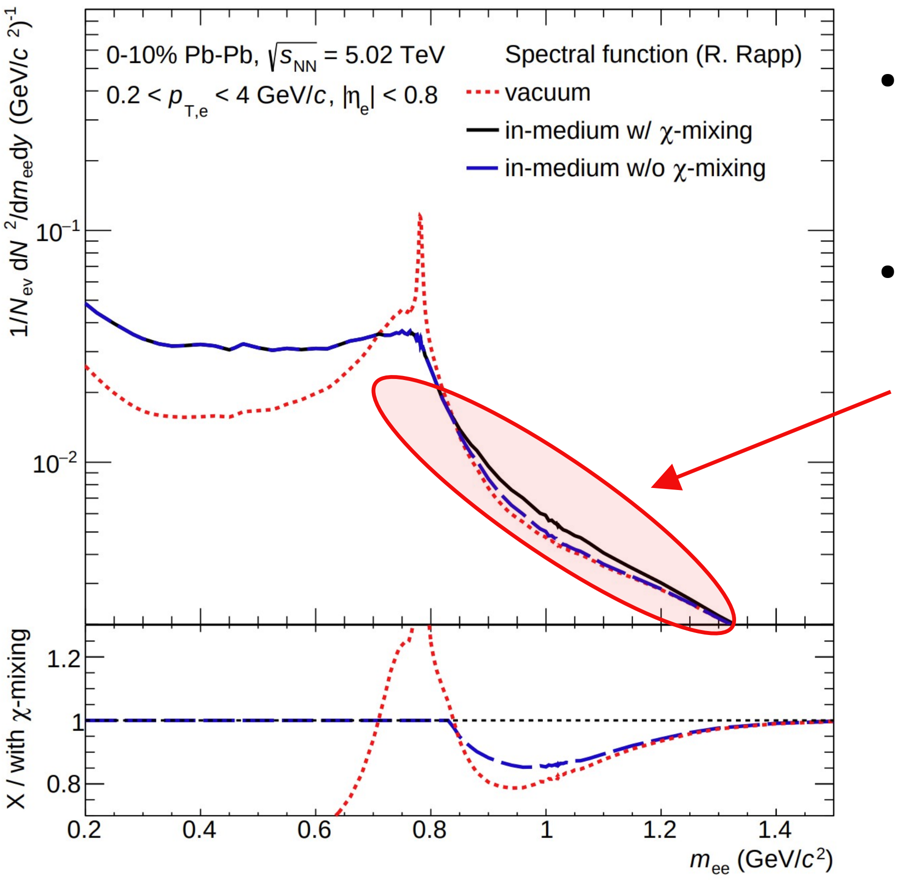
- Direct photons as probes of the QGP temperature
- Real photons: **T_{eff}: 300-400 MeV**
  - Caveats: blue shift due to expanding QGP
- Virtual photons (dielectrons): too low stats to conclude

Chiral symmetry restoration



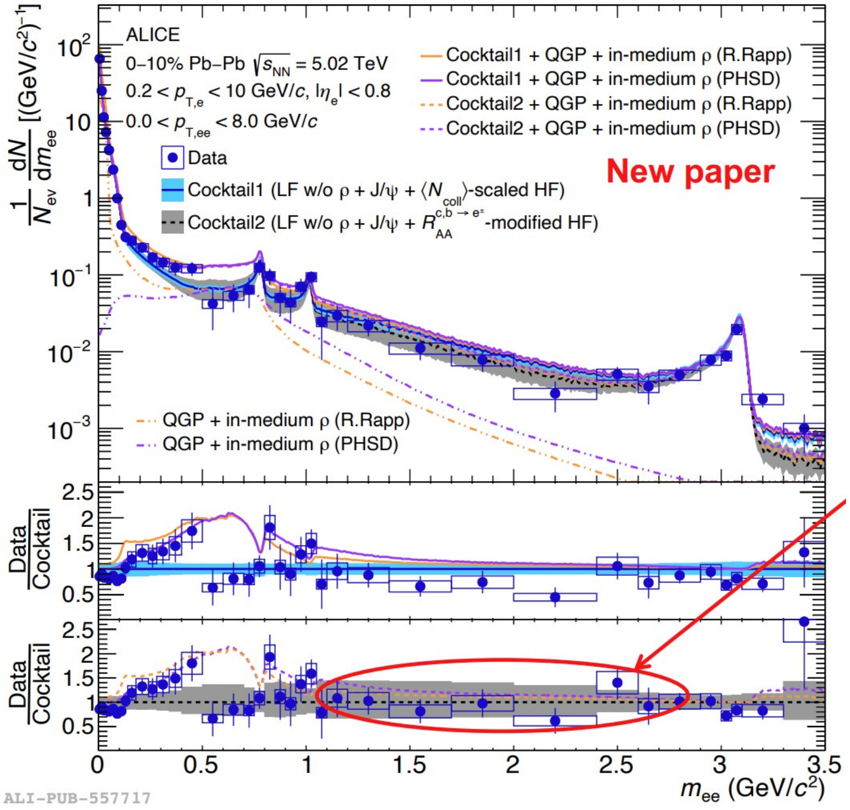
- Chiral symmetry breaking generates most of the ordinary matter
  - Fundamental aspect of QCD
- Heavy-ion collisions can be used to restore this symmetry
- Lattice QCD calculations indicate
  - strong broadening of vector mesons
  - Vector and axial vector mesons become degenerate

Chiral symmetry restoration



- **ρ meson**: prime candidate for probing in-medium modifications
  - Short lifetime **< t_{QGP}**
- Unambiguous way to observe chiral symmetry restoration:
  - Measure both **ρ meson** and its chiral partner **a_1**

Dielectron production in Pb-Pb collisions: current status



ALICE arxiv:2308.16704

- Signal region for thermal radiation from QGP and in chiral mixing of the ρ and a1
  - Large statistical and systematic uncertainties

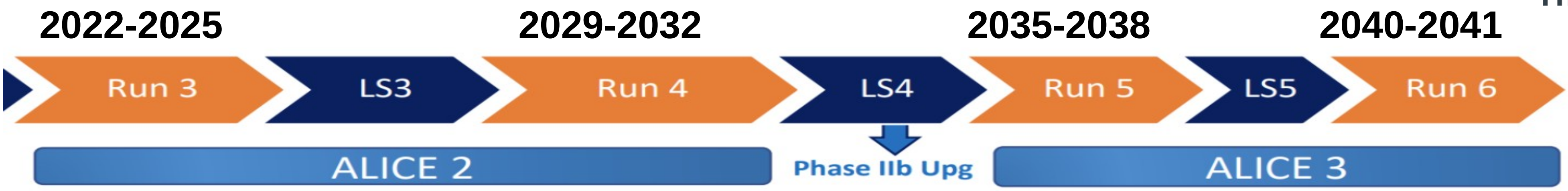
What can we answer in the next ~20 years ?

- *Obtain a global understanding of parton transport, collective phenomena and hadronization*
  - Requires extension of the study of parton energy loss down to momenta typical of diffusion phenomena
  - Needs precision measurement of beauty quarks
- *Understand hadronization from deconfined QGP*
  - Requires multi charm hadrons, heavy quarkonia
  - Exotica
- *Complete picture of the QGP temperature time dependence*
  - Requires precision measurements of electromagnetic radiation

And more...

- *Chiral symmetry restoration*
- *Collectivity in small systems*
- *Nature of hadron-hadron potential*
- *(anti-)(hyper-)nuclei and possible discovery of charm nuclei*
- *Physics beyond standard model*

ALICE 3

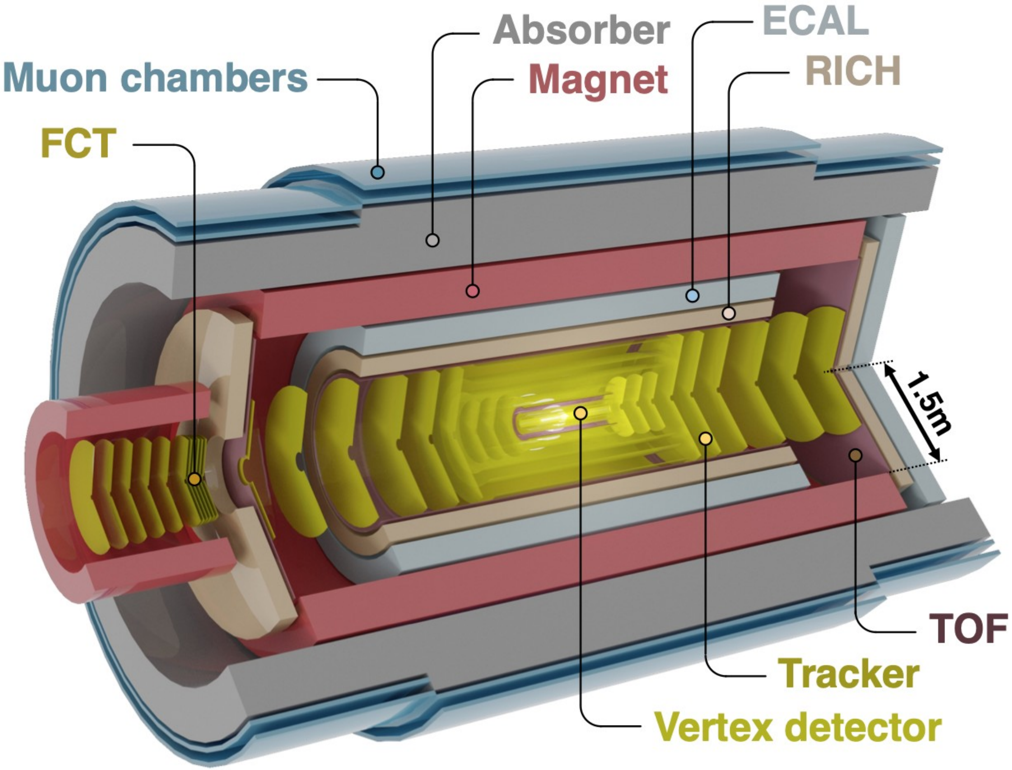


- Answering these questions means:
  - Large acceptance in η and p_T
  - Superior tracking and particle identification in a wide momentum range
  - High data rate
- Foreseen integrated luminosities
  - pp collisions: $L_{pp} \sim 18\ fb^{-1}$
  - Pb-Pb collisions: $L_{pp} \sim 33.6\ nb^{-1}$

ALICE arxiv:2211.02491

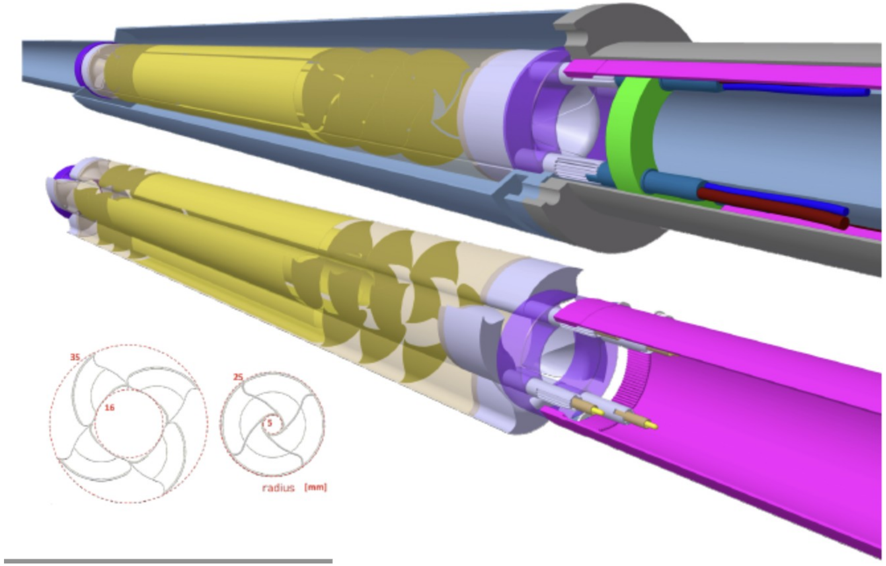
ALICE 3

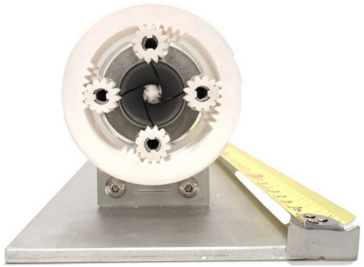
- Compact: ~2 x 8 m
- Large acceptance: |η|<4, p_T>0.02 GeV/c
- Superconducting magnet system
- Max field: B=2T
- Continuous readout and online processing
- Pointing resolution: ~3-4 μm
- p_T resolution better than 1% at 1 GeV/c
- PID in a wide range of momenta and |η|<4



Vertex tracker

- In vacuum, retractable
  - 5mm from the beam
  - 3 layers
- Wafer-size bent sensors based on MAPS technology
- Low material budget: ~0.1% X_0 per layer
- Radiation hard

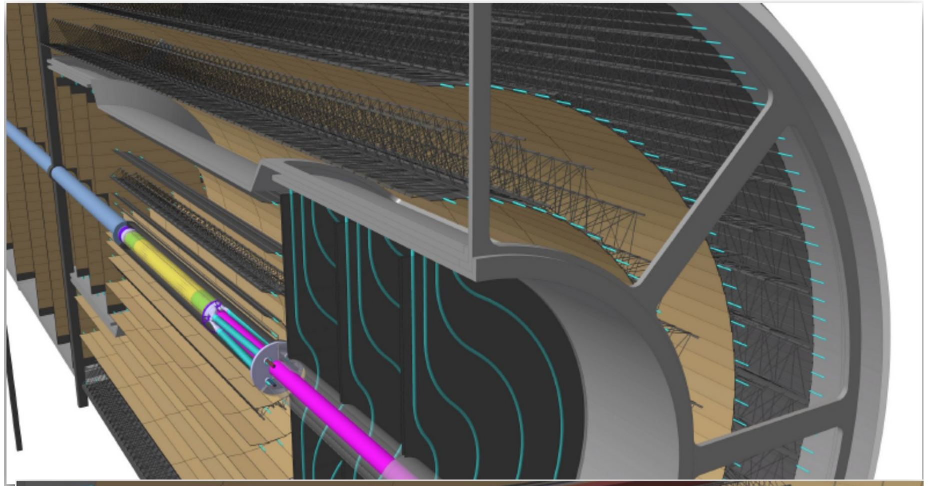


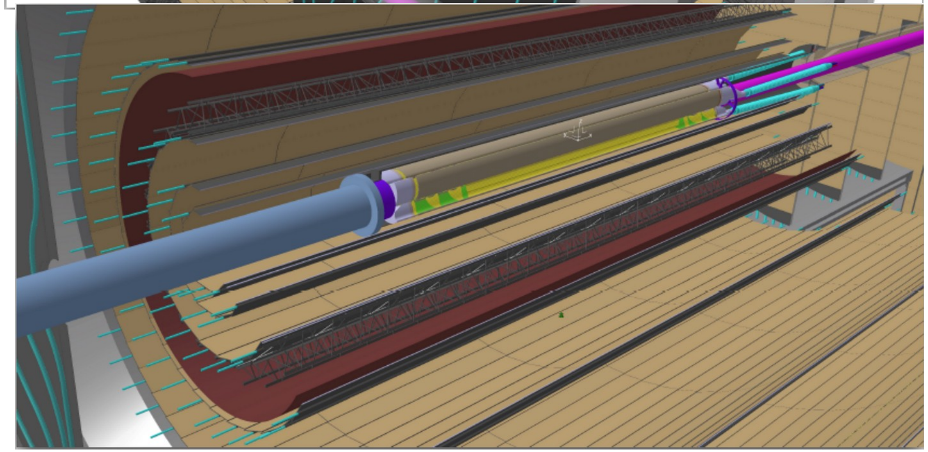


Latest breadboard model

Outer tracker

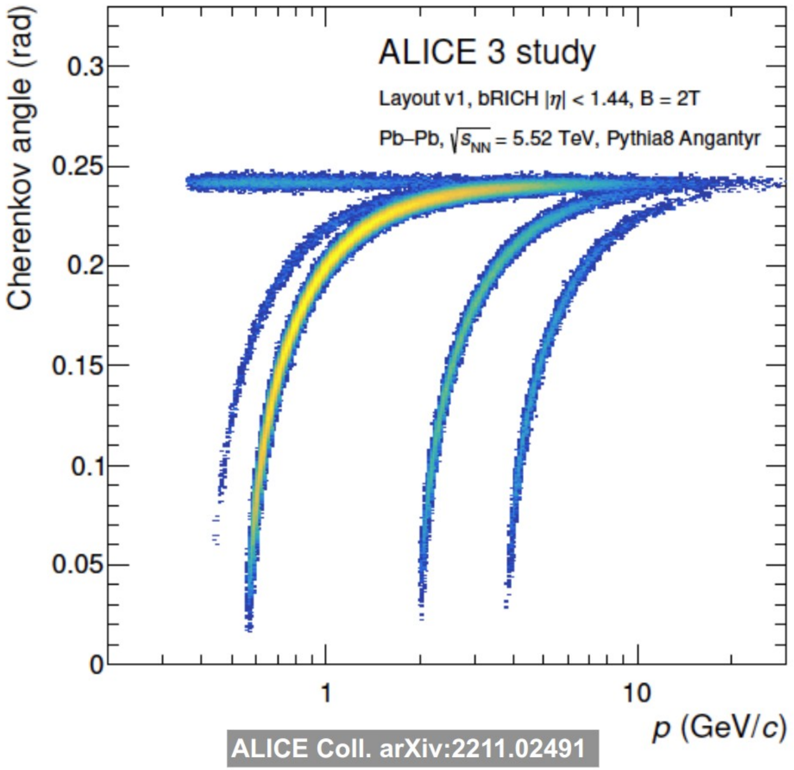
- 8 layers and 9 disks based on MAPS sensors
- Compact design with outer layer at 80cm
- Material budget: 1% X_0 per layer
- Low power



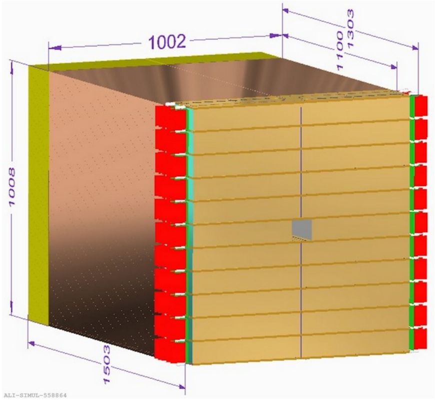


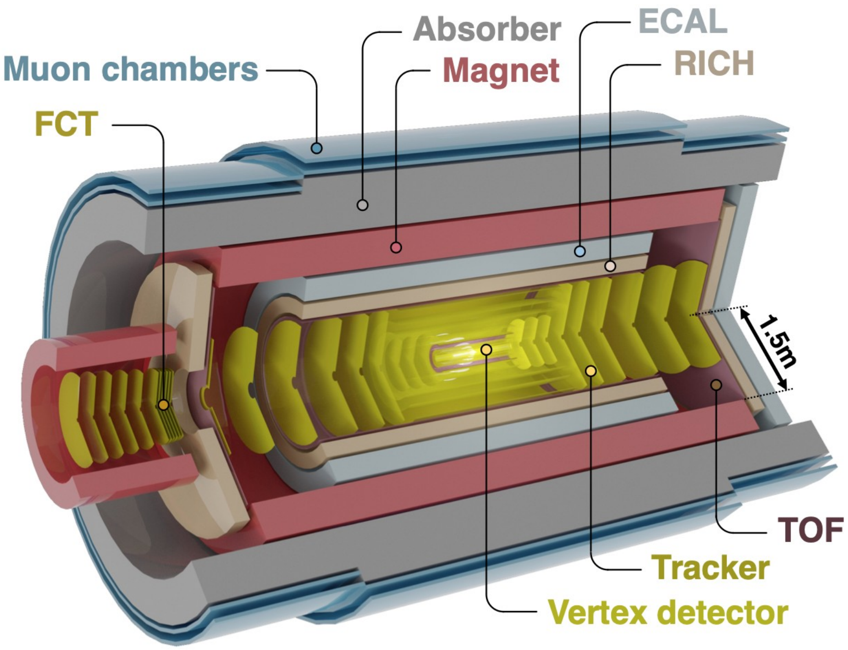
Particle identification systems

- Barrel Time-of-Flight (TOF)
  - Two layers (r=19, 85cm)
  - Time resolution: 20ps
  - Coverage: |η|<1.75
- Two forward disk TOF
  - 1.75<|η|<4
- Ring Imaging Cherenkov (RICH)
  - Complement TOF systems at higher p_T



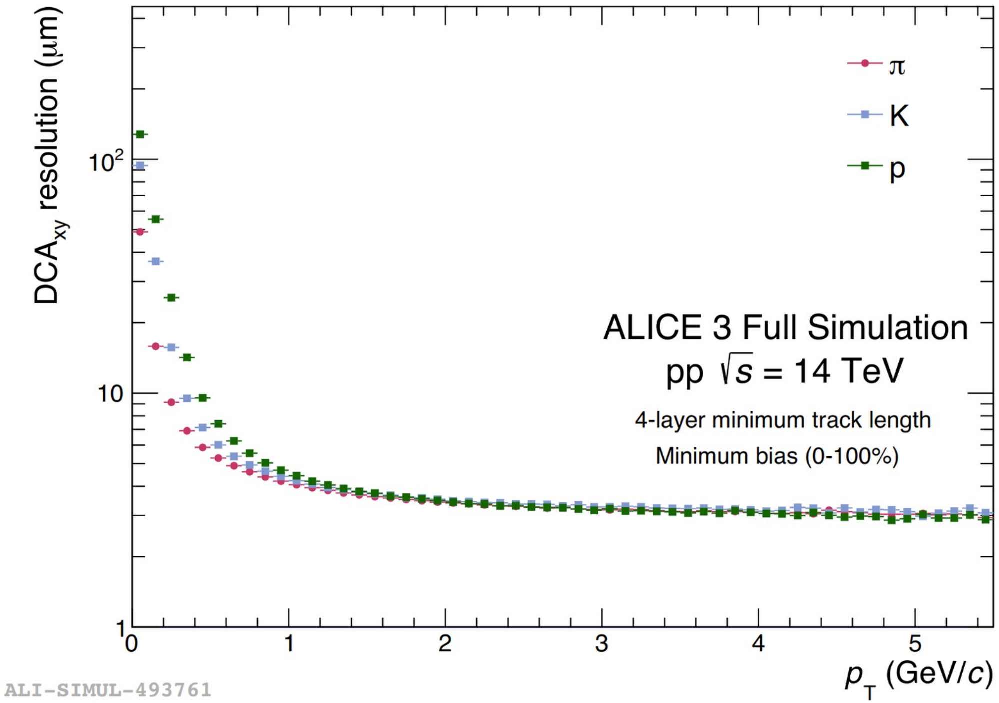
Possibly a FoCal in ALICE3 ?





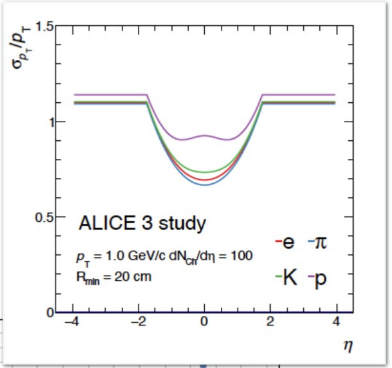
- Add an upgraded FoCal in the ALICE3 setup at very forward rapidity
- Possible goals:
  - Saturation physics
  - Heavy-ion collisions initial state

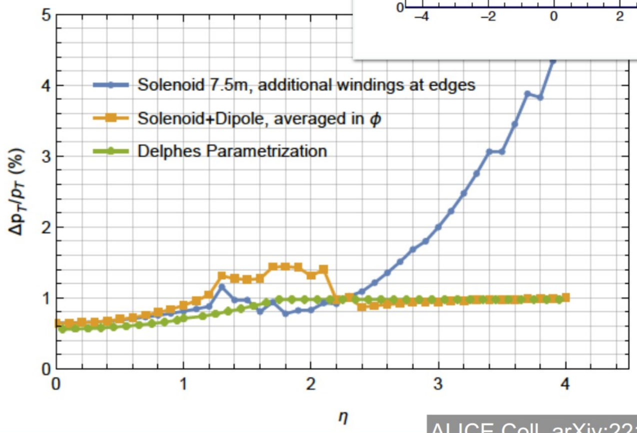
Pointing and momentum resolution



σ_{pT}/p_T @ B =2 T

- Resolution better than 1% at central rapidity
- Resolution for 1 GeV muon with solenoid+ dipole magnet better than 1% up to η = 4.



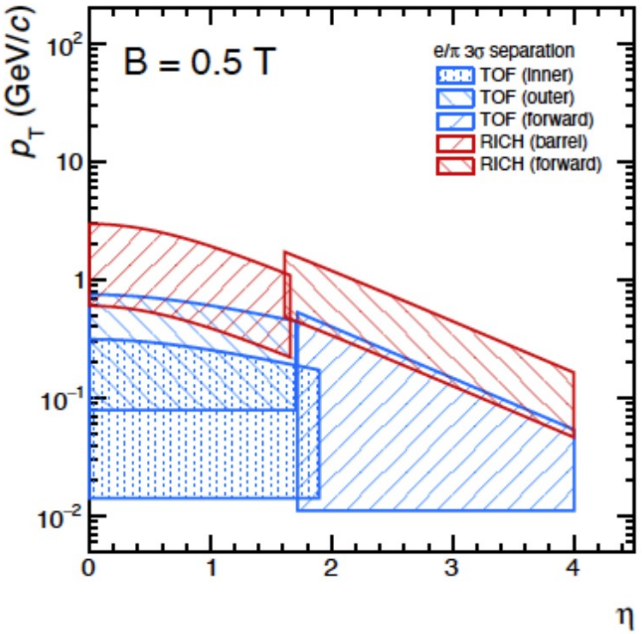


ALICE Coll. arXiv:2211.02491

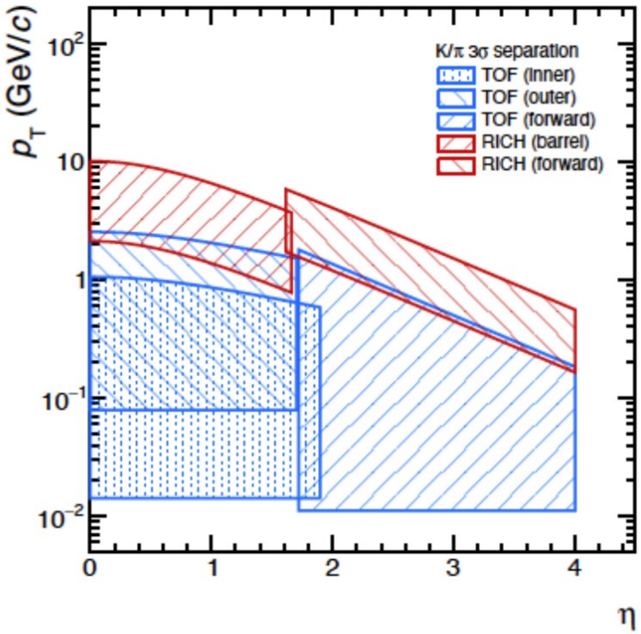
- DCA(xy) resolution of 3-4µm
- p_T resolution below 1 GeV/c at mid-rapidity

Particle identification: TOF + RICH

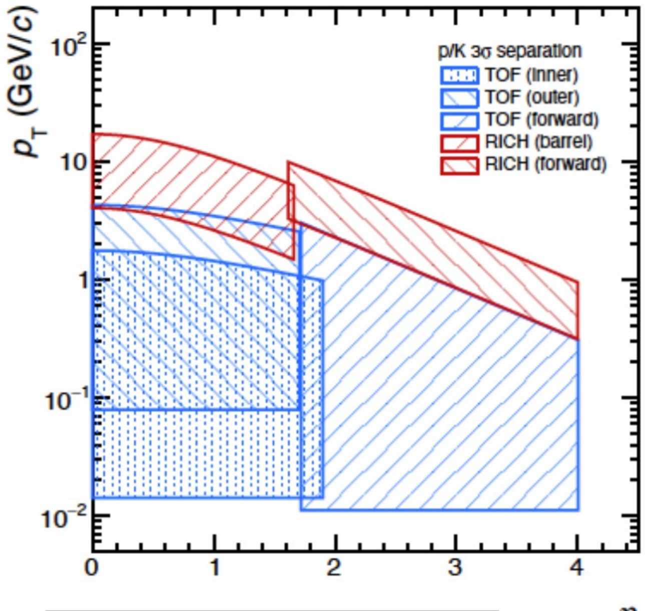
3σ separation TOF+ RICH
e/π



3σ separation TOF+ RICH
K/π



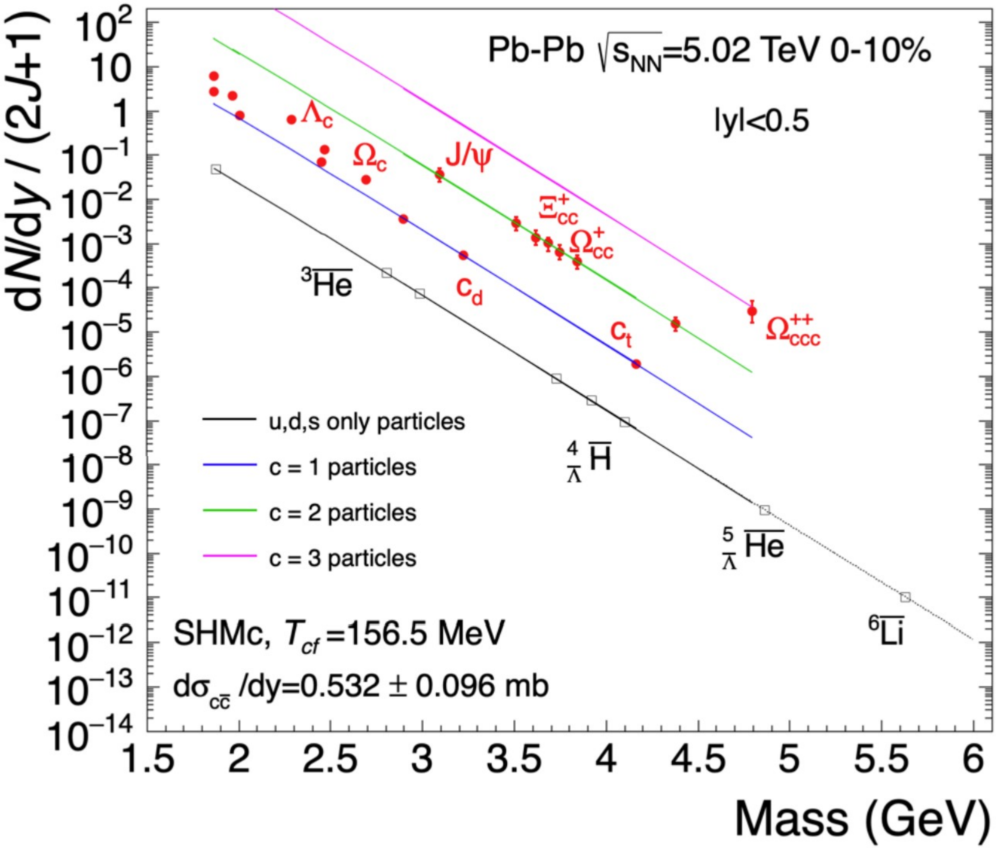
3σ separation TOF+ RICH
p/K



ALICE Coll. arXiv:2211.02491

Particles and nuclei measurements

- Multi charm baryons up to Ω_{ccc}
- Anti-hyper nuclei with A≥5 (yet to be discovered)
- Discovery potential for c-deuteron, c-triton and c-^{3}He



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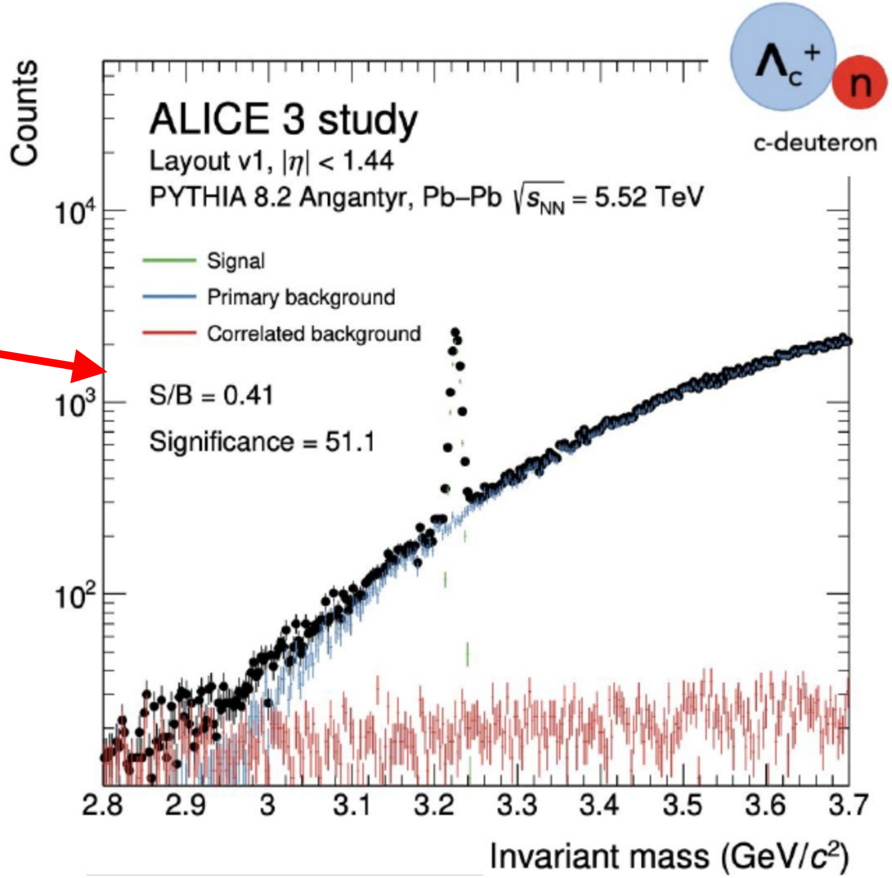
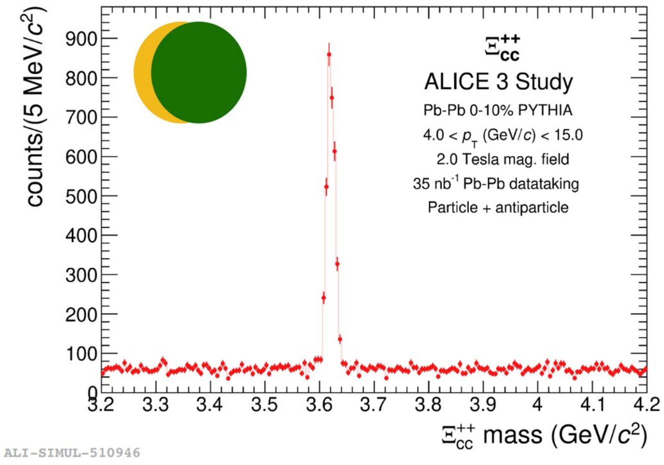
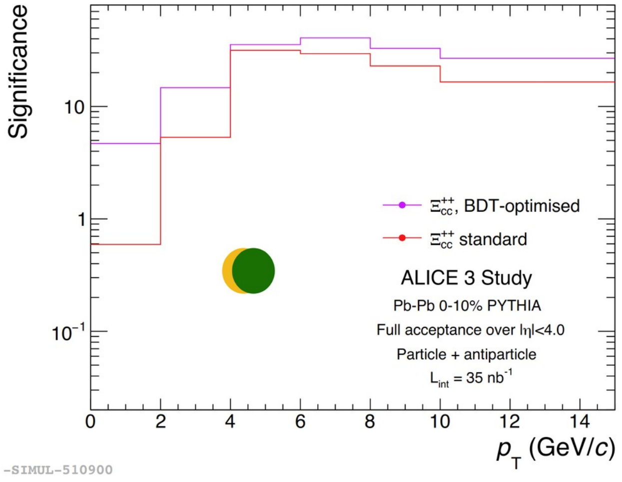
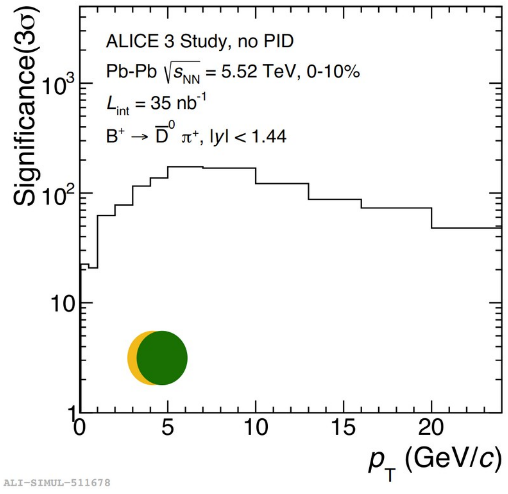
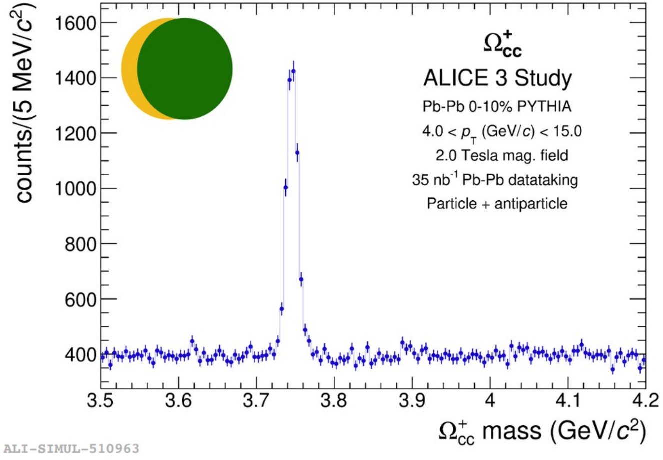


Multi-charm baryons and open beauty in Pb-Pb





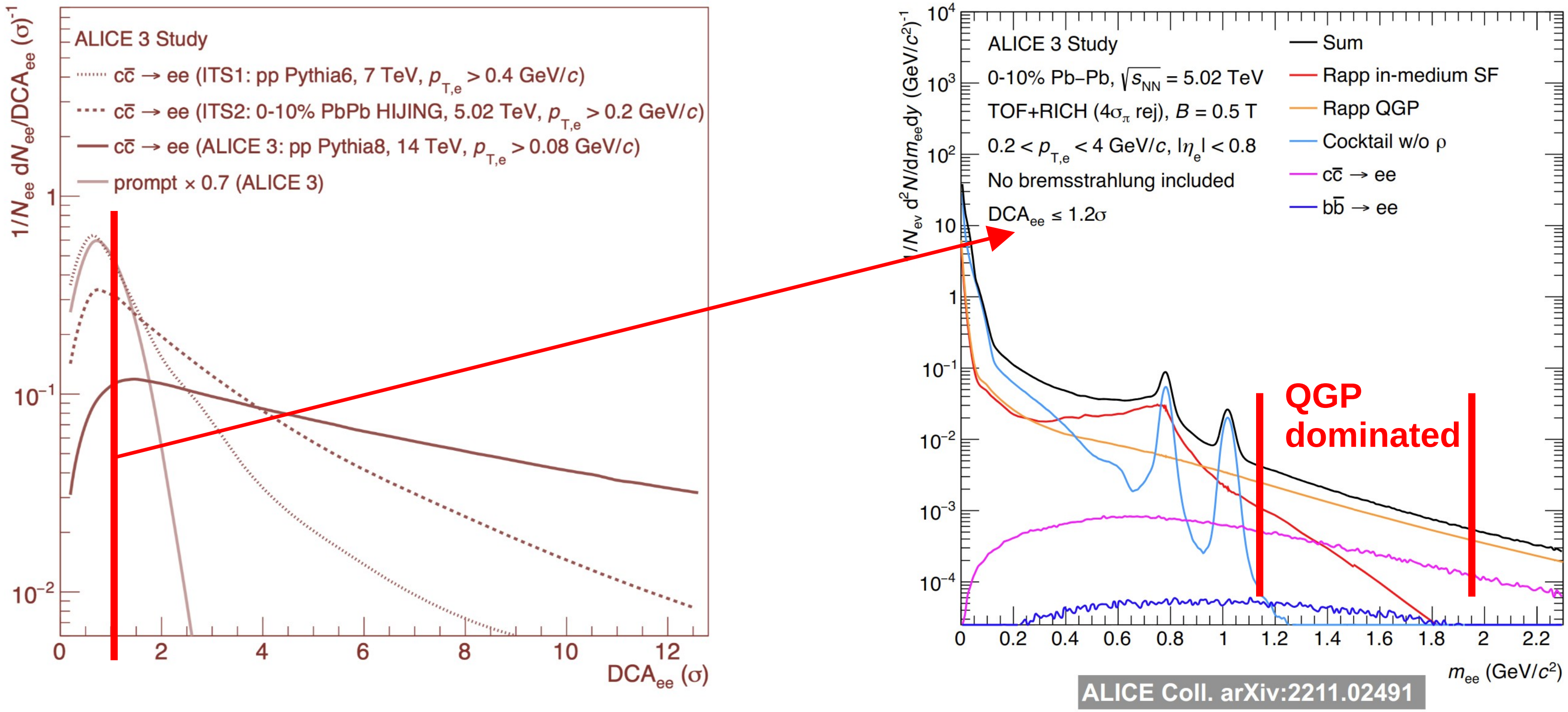




- Multi-charm baryons
  - $\Xi_{cc}^{++} \rightarrow \Xi_c^{+} \pi^{+} \rightarrow \Xi^{-} \pi^{+}\pi^{+}\pi^{+}$
  - $\Omega_{cc}^{++} \rightarrow \Omega_c^{0} \pi^{+} \rightarrow \Omega\text{-}\ \pi^{+}\pi^{+}$

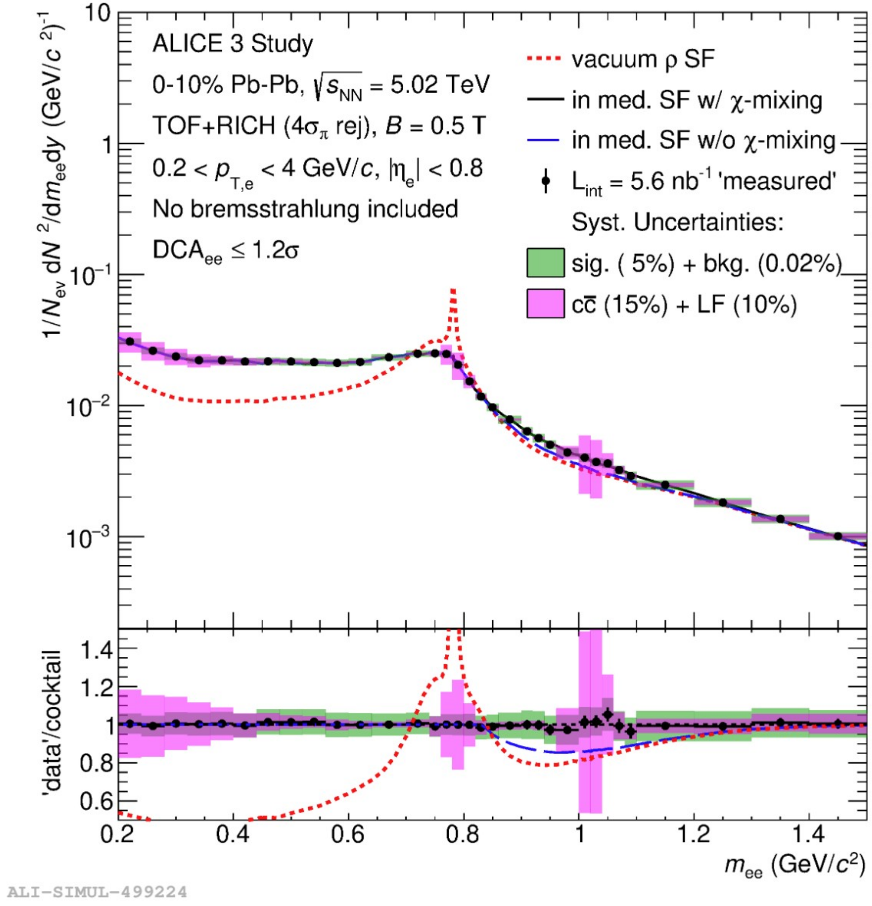
- Beauty hadrons
  - $B^{+} \rightarrow \overline{D}^{0} + \pi^{+}$

Thermal radiation



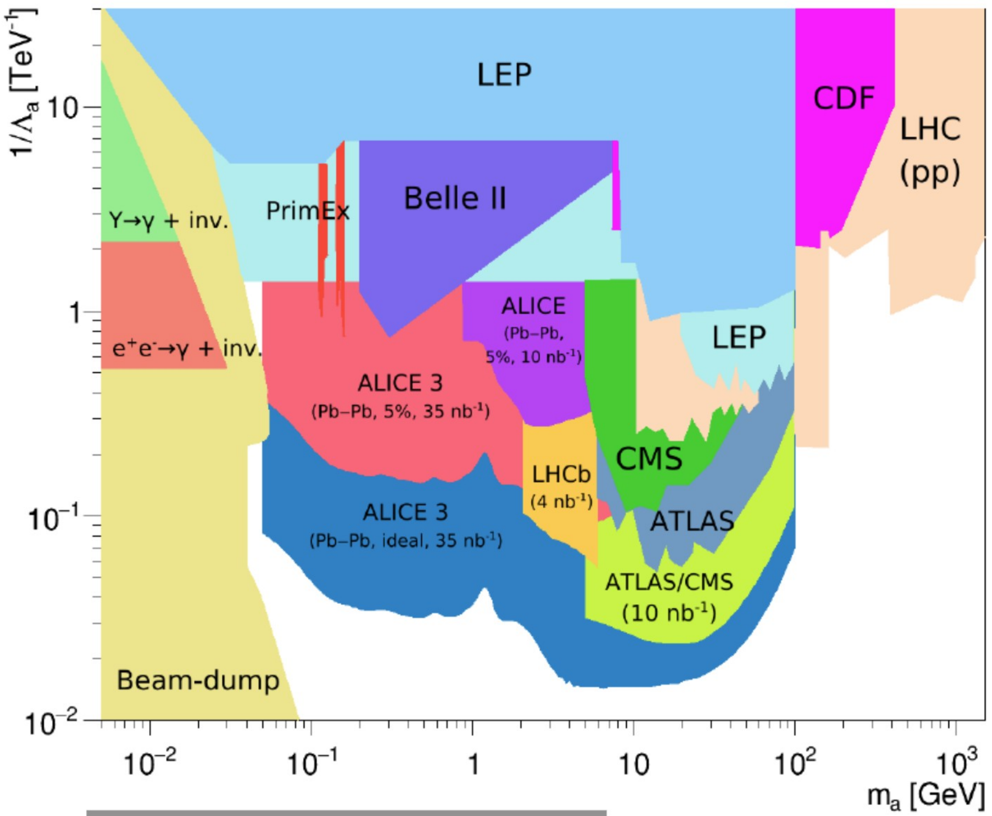
- Large suppression of charm and beauty contribution by exploiting the high precision vertexing

Chiral symmetry



- Spectral function of low mass dielectrons determined with **6-8%** accuracy
- Chiral mixing produces a **20-25%** change wrt vacuum expectation (**$0.8<m_{ee}<1.2$ GeV/c^2**)
- ALICE3 can observe the chiral mixing effect

BSM searches in ultra-peripheral collisions (UPC)



ALICE Coll. arXiv:2211.02491

- UPCs provide a clean environment for axion-like (ALP) studies
- Searches via **γγ → a → γγ**
  - Signal would be visible as a peak in the di-photon inv mass disribution
- ALICE3 significantly extends the phase space coverage towards low masses

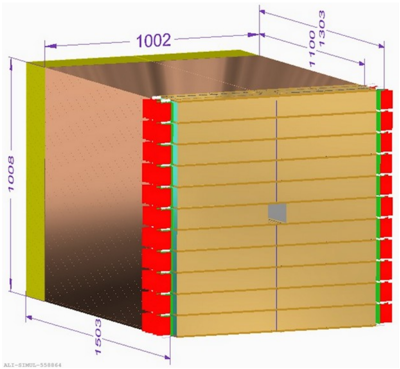
Conclusions

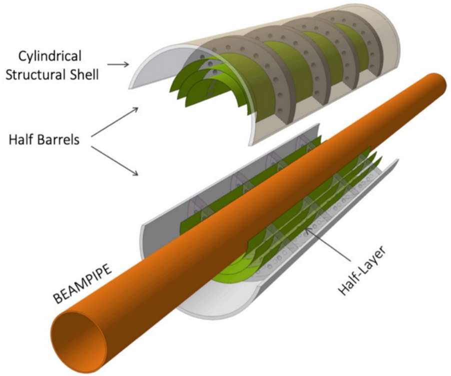
- There were many progresses in the understanding of the QGP since the start of the LHC, but there are still remaining questions
- ALICE3 sets technological challenges that can lay the foundation of heavy-ion physics during Run 5/6 and beyond
- ALICE Norway has strong synergies with ALICE3 on both the physics objectives and detector developments
  - Our default option to continue doing high energy heavy-ion physics beyond Run 4

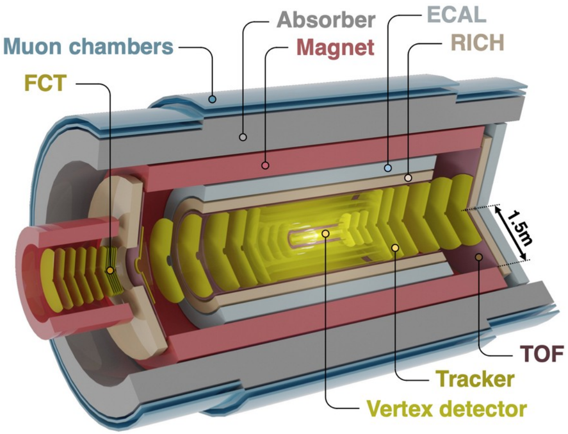
Backup

ALICE upgrades timeline

2022-2025 **2029-2032** **2035-2038** **2040-2041**



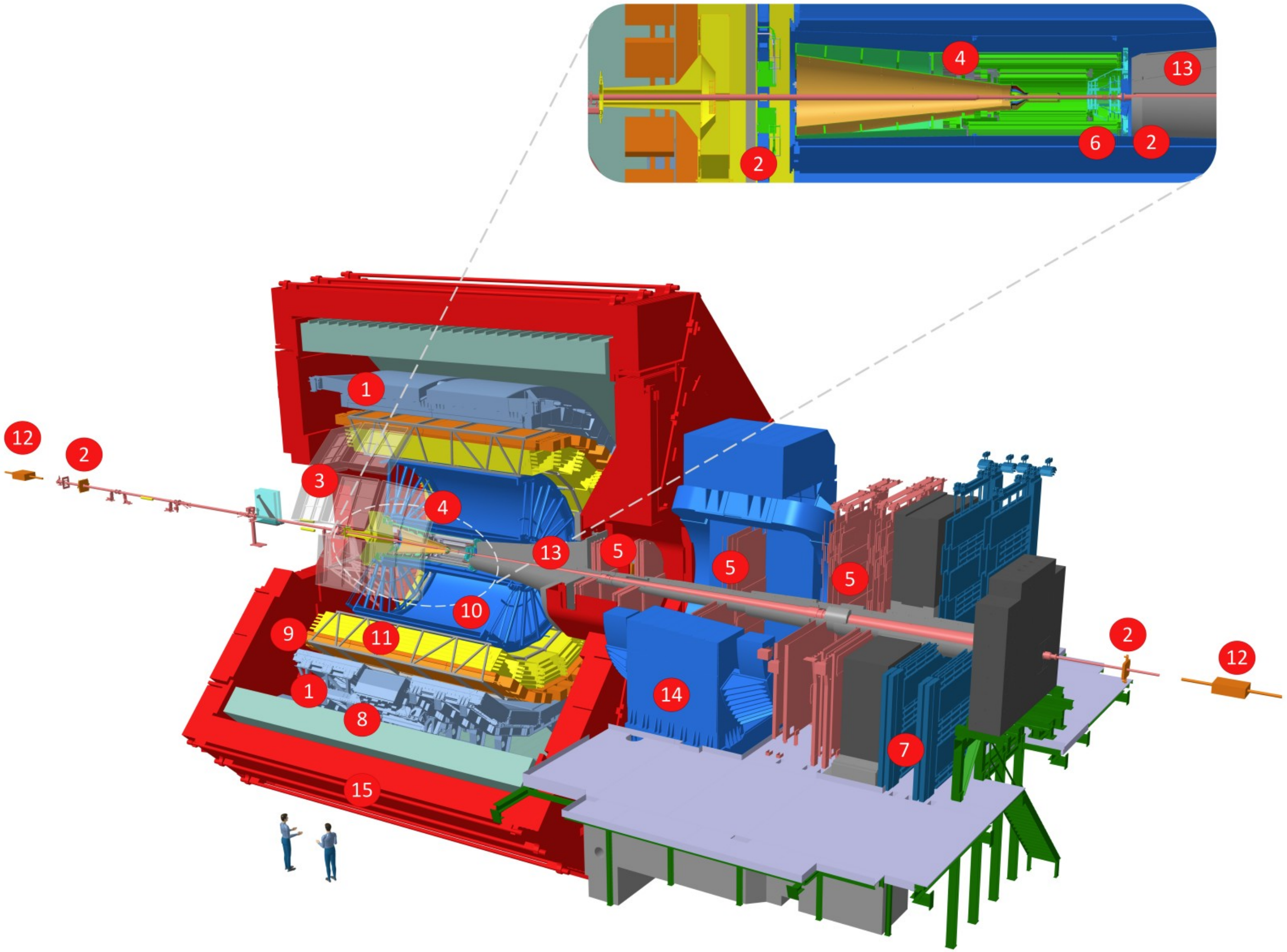




FoCal and ITS3

ALICE3

ALICE 2



1. **EMCAL |** Electromagnetic Calorimeter
2. **FIT |** Fast Interaction Trigger
3. **HMPID|** High Momentum Particle Identification Detector
4. **ITS|** Inner Tracking System
5. **MCH|** Muon Tracking Chambers
6. **MFT|** Muon Forward Tracker
7. **MID|** Muon Identifier
8. **PHOS/CPV|** Photon Spectrometer
9. **TOF|** Time Of Flight
10. **TPC|** Time Projection Chamber
11. **TRD|** Transition Radiation Detector
12. **ZDC|** Zero Degree Calorimeter
13. **Absorber**
14. **Dipole Magnet**
15. **L3 Magnet**