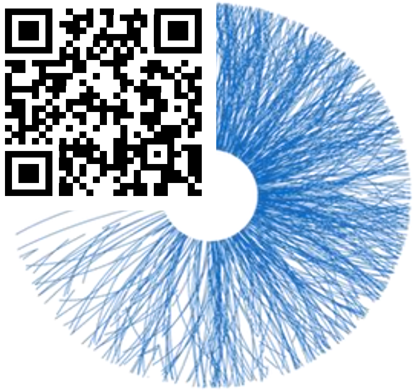


ALICE Highlights and Upgrade Plans

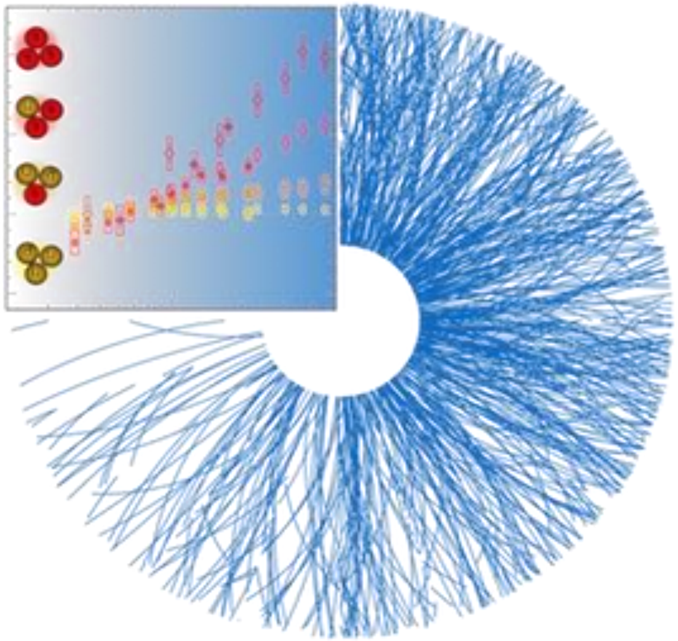
Jacek Otwinowski

Institute of Nuclear Physics (Polish Academy of Sciences)

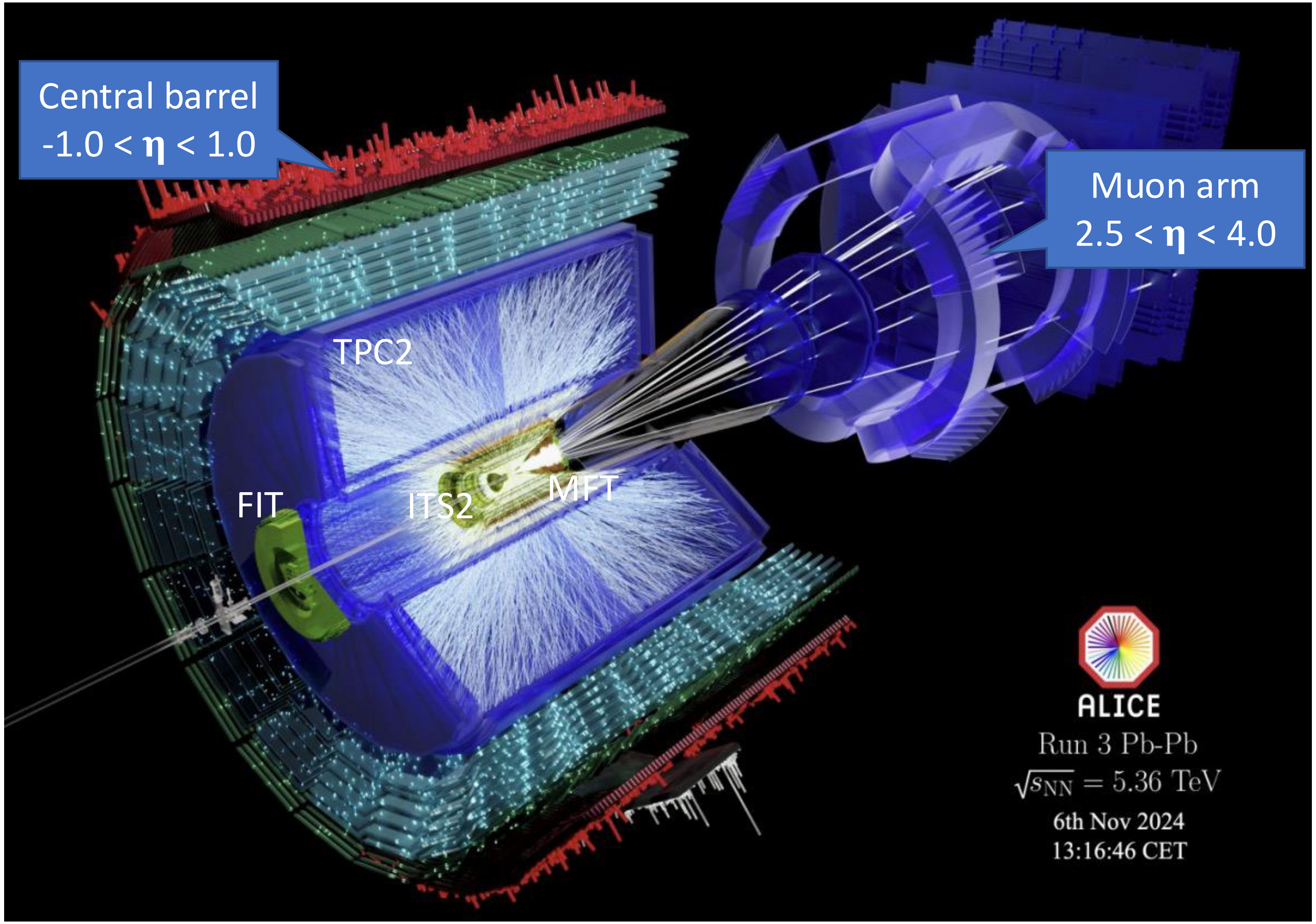
on behalf of the ALICE Collaboration

Outline

- Introduction
- Recent Highlights
- Upgrade Plans
- Summary & Outlook



A Large Ion Collider Experiment (ALICE)



Excellent particle identification and tracking in the broad momentum range!

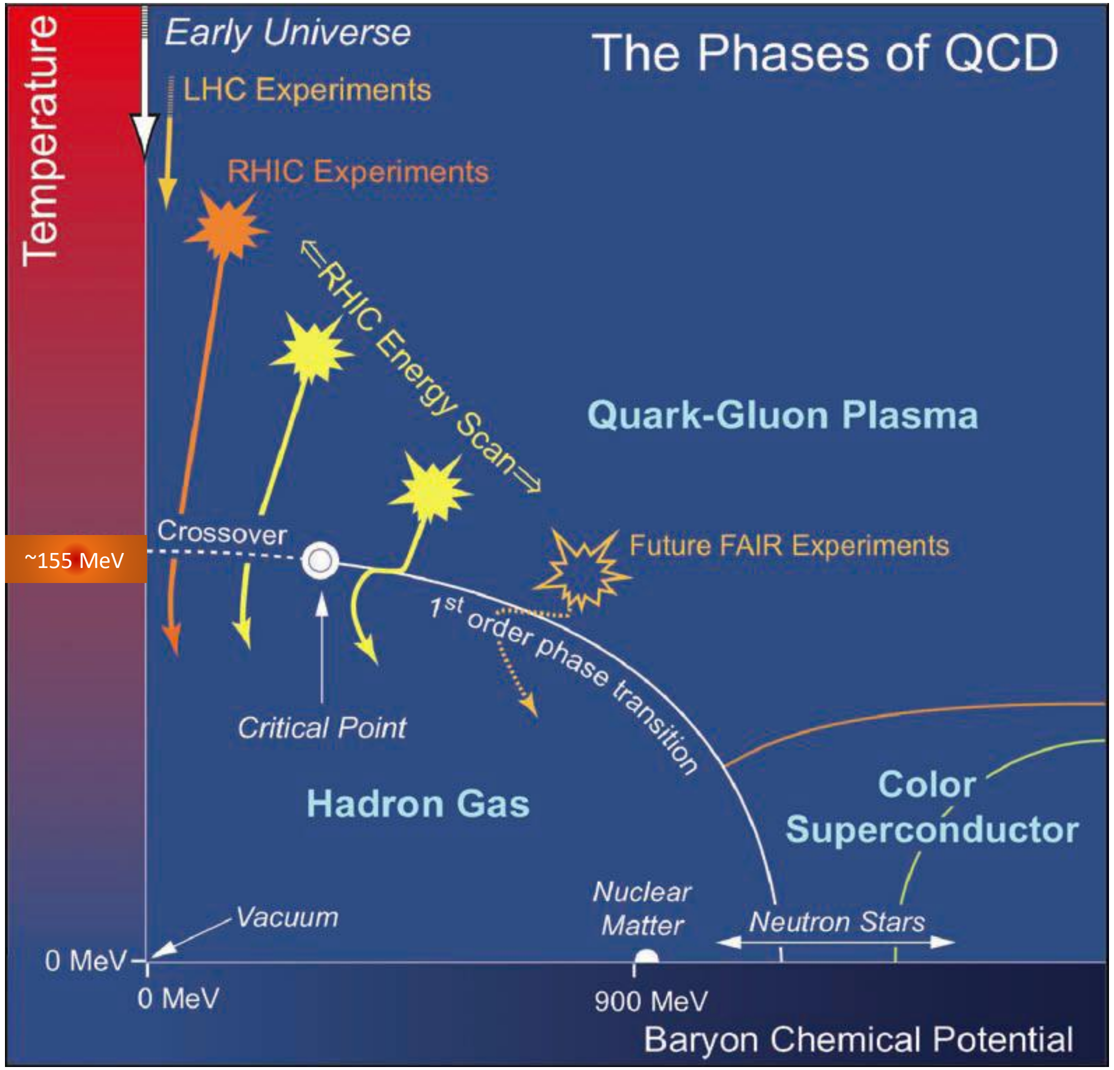
LHC Run 1 (2009-2013), Run 2 (2015-2018) and Run 3 (2022-2026)

Collision systems:
pp, p-Pb, p-O, OO, Ne-Ne, Xe-Xe and Pb-Pb

Massive upgrade LS2 (2019-2021): ITS2, TPC2, MFT, FIT …

x1000 (x30) more pp (Pb-Pb) events already recorded in Run 3 than in Run 1 & Run 2 (analyses are ongoing)

ALICE purpose

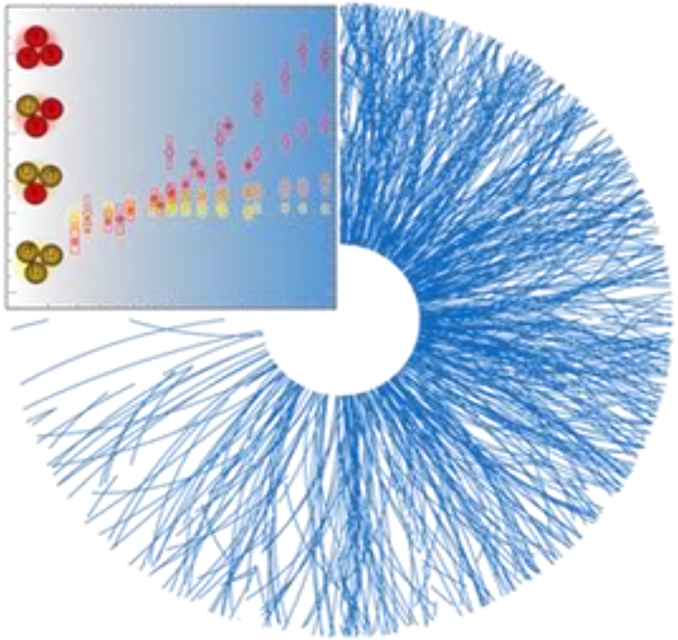


- Properties of QCD matter at extreme conditions
- … indirect dark matter searches

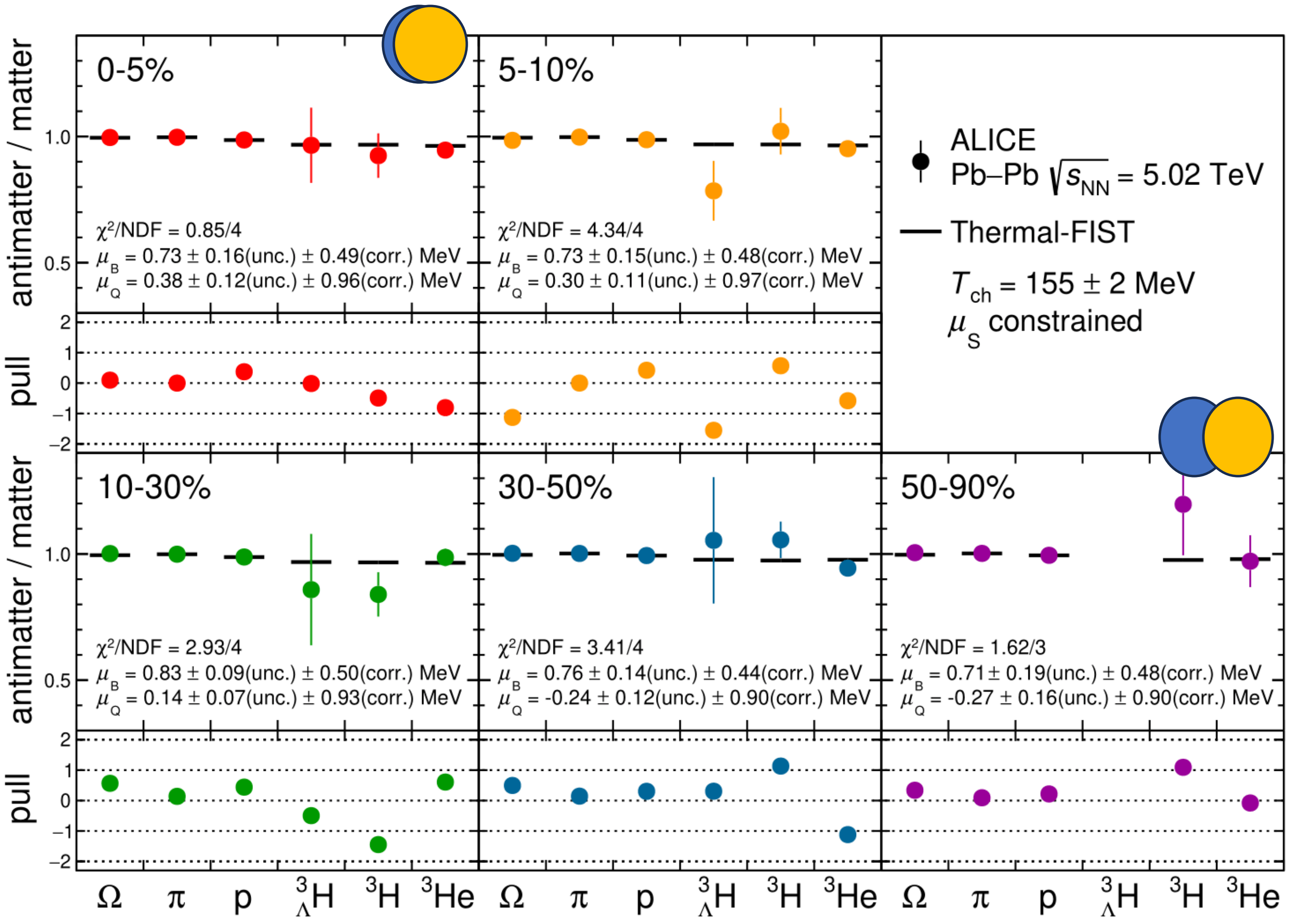
Deconfinement predicted by Lattice QCD at ~155 MeV (μ_B = 0)

A. Bazavov et al. Phys. Lett. B 795 (2019) 15

Light flavour



Antimatter/matter imbalance at the LHC



Phys. Rev. Lett. 133 (2024) 092301

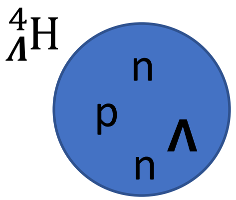
$$\frac{\bar{h}}{h} \propto e^{-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T}-2Q\frac{\mu_Q}{T}}$$

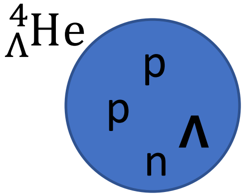
System created in Pb-Pb collisions is baryon-free and electrically neutral at midrapidity

Thermal-Fist, V. Vovchenko et al. Comput. Phys. Commun. 244 (2019) 295

Statistical Hadronization Model (SHM) A. Andronic et al. Nature 561 (2018) 321

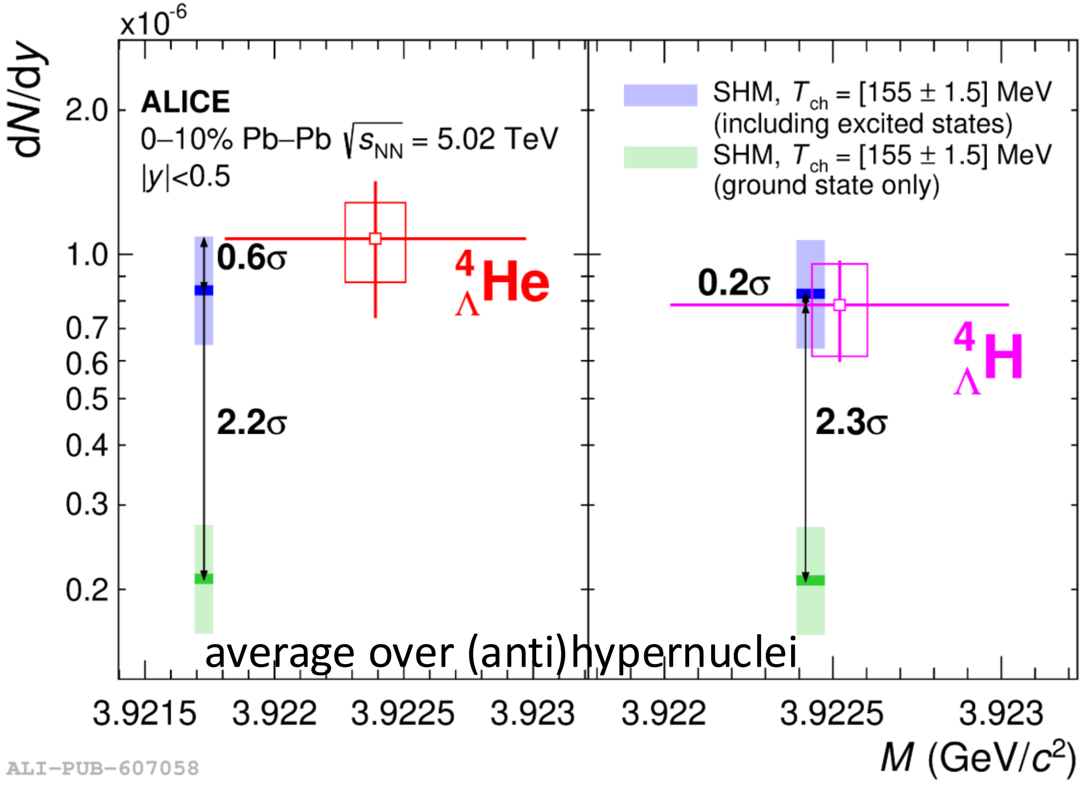
First measurement of A = 4 (anti)hypernuclei at the LHC



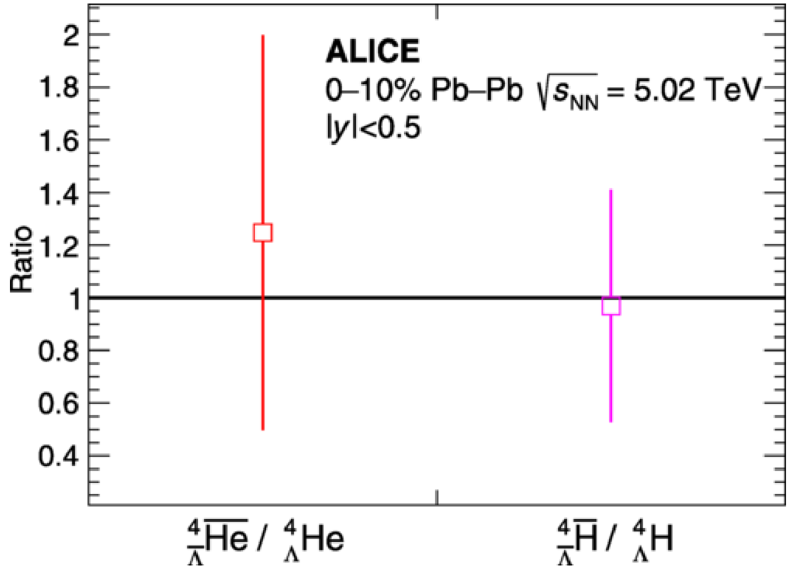


First evidence of the antihyperhelium – 4!

Phys. Rev. Lett. 134 (2025) 162301



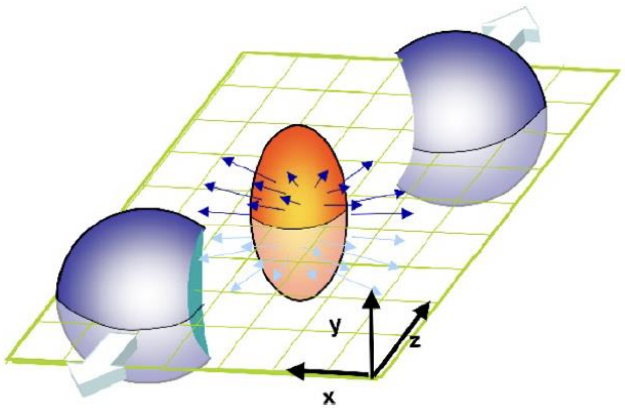
average over (anti)hypernuclei



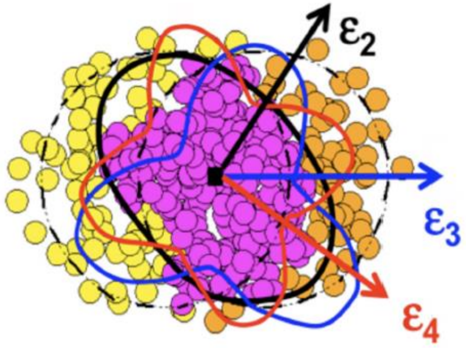
SHM describes data after including excited states

Much larger statistics expected from Run 3

Anisotropic flow

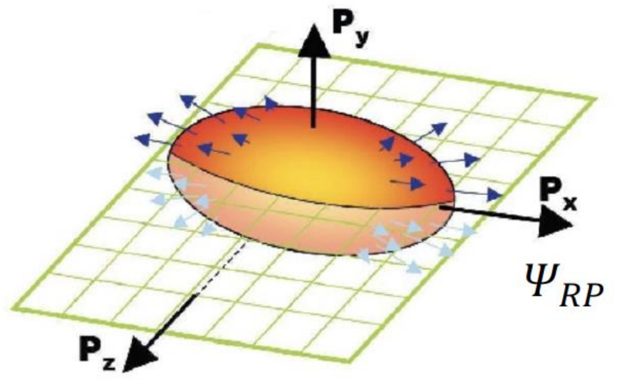


$$\varepsilon_n = \frac{\sqrt{(r^n \cos(n\phi))^2 + (r^n \, sin(n\phi))^2}}{\langle r^n \rangle}$$



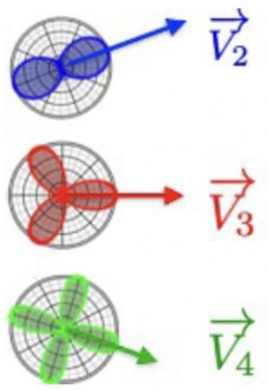
System expansion

$$v_n \propto \varepsilon_n$$



$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

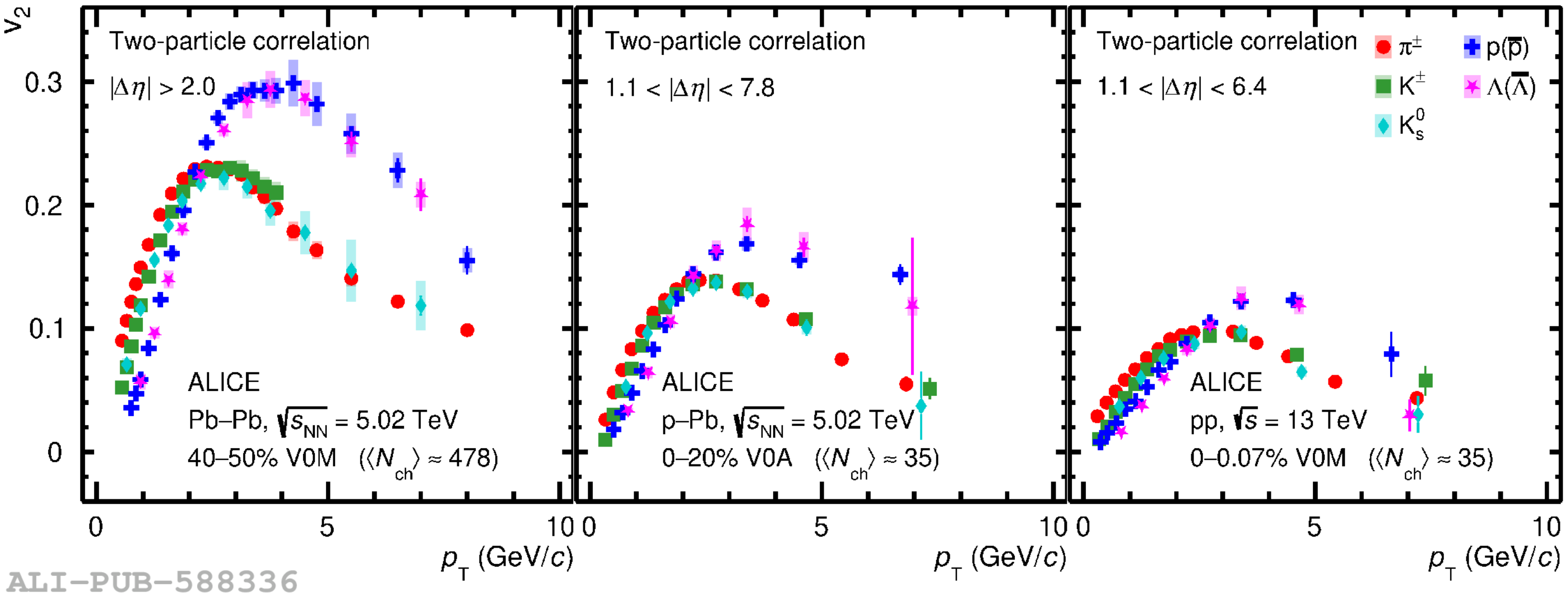
$$\vec{V_n} = v_n e^{in\Psi_n}$$



Anisotropic flow in various collision systems

Collective flow observed in large and small systems

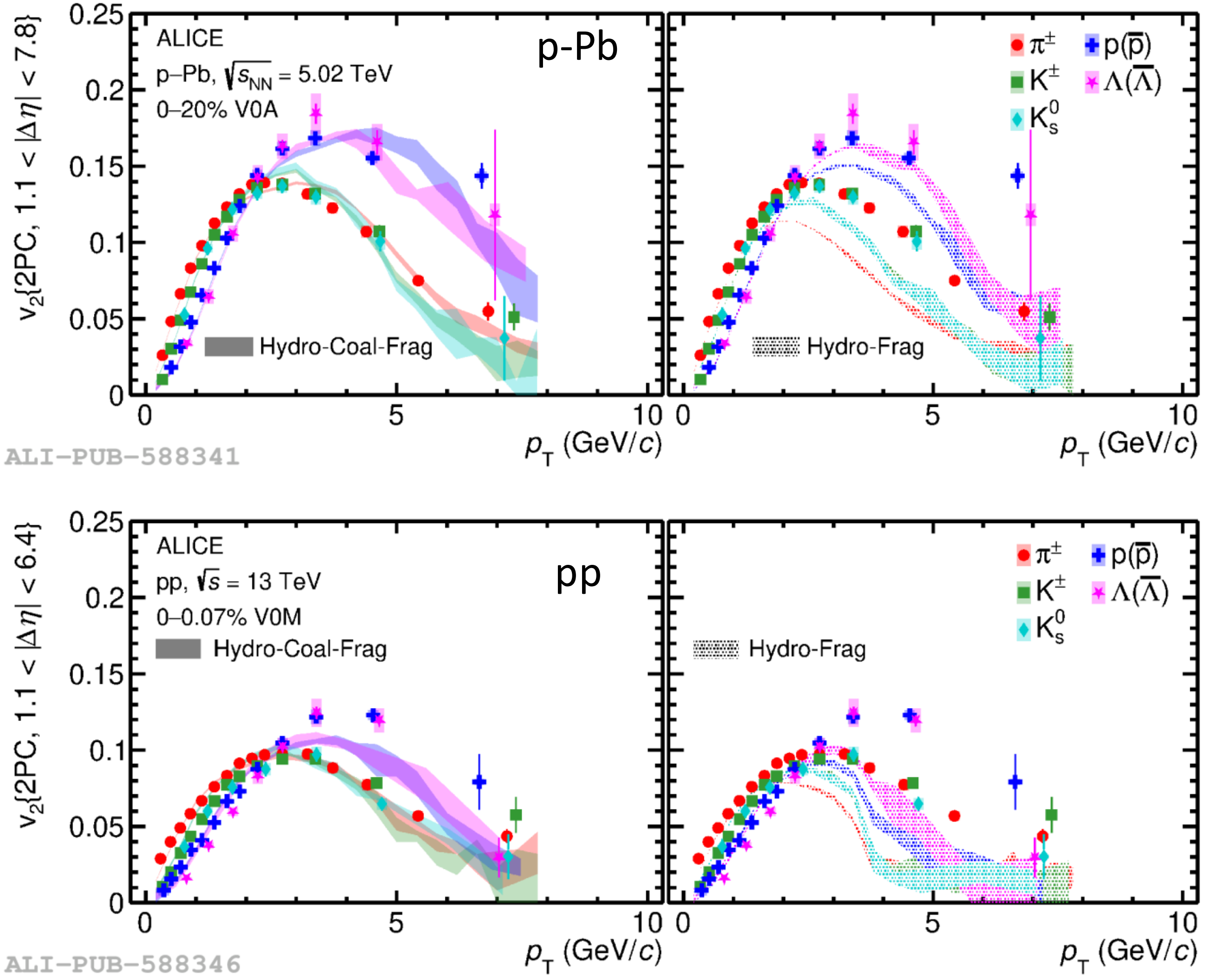
arXiv:2411.09323, accepted by Nature Communications



- Low p_T: mass ordering
- Intermediate p_T: baryon-meson grouping and splitting

Anisotropic flow in various collision systems

Collective flow observed in large and small systems



arXiv:2411.09323, accepted by Nature Communications

→ quark coalescence and partonic collectivity

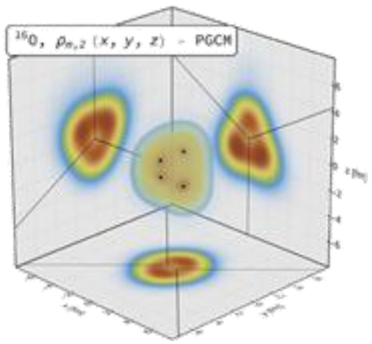
What is role of initial state effects on v_2 in low multiplicity collisions?

Anisotropic flow in OO and Ne-Ne collisions

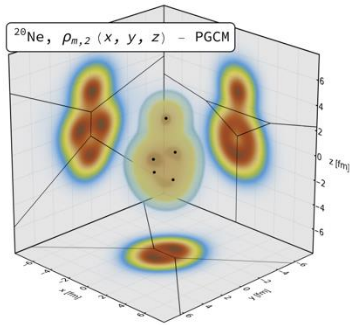
Collective flow measured in OO and Ne-Ne (different internal structure…)

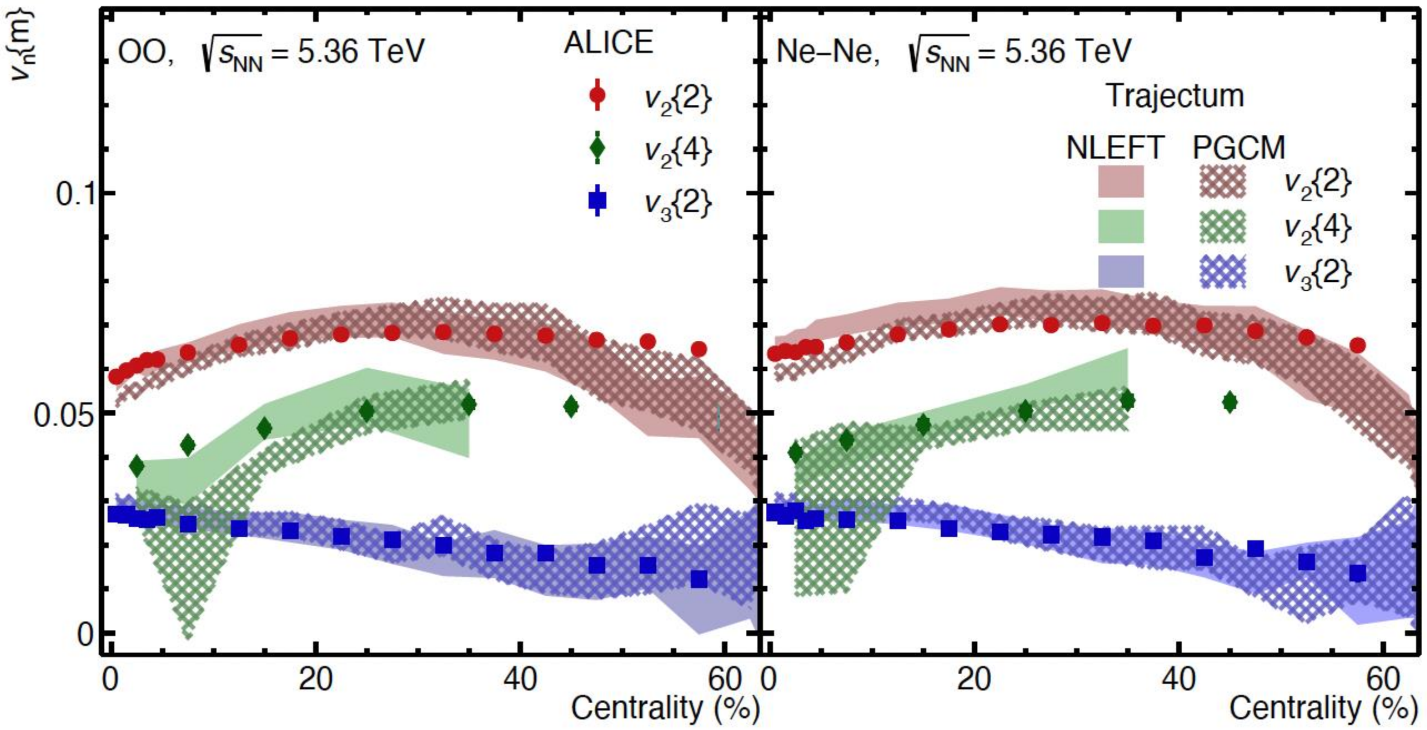
arXiv:2509.06428

^{16}O



^{20}Ne





Characteristic centrality dependence similar to Pb-Pb

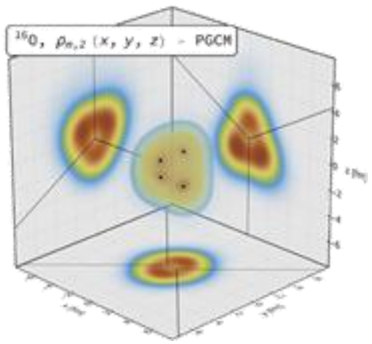
Measurements in line with expectations from initial state geometry based on nuclear structure models + hydrodynamical evolution

Anisotropic flow in OO and Ne-Ne collisions

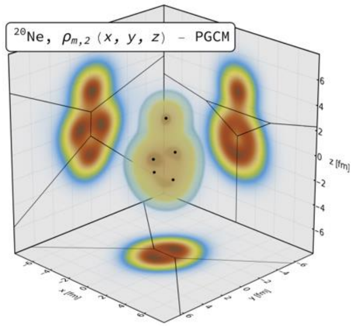
Collective flow measured in OO and Ne-Ne (different internal structure…)

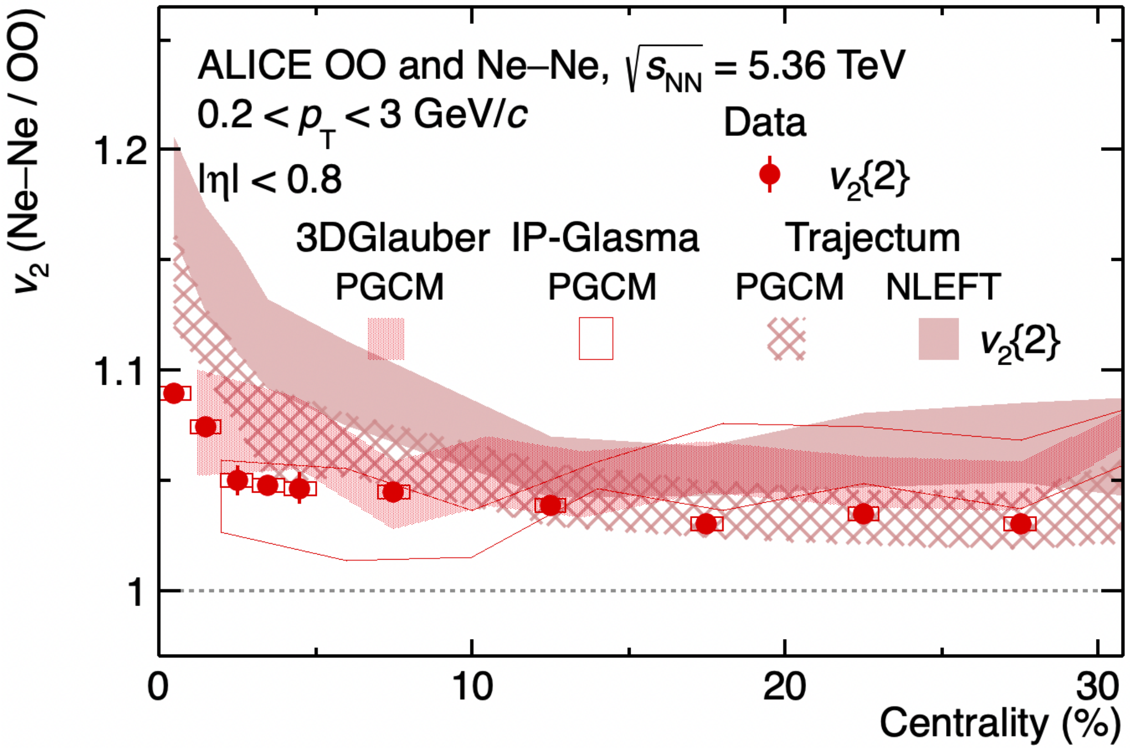
arXiv:2509.06428

^{16}O



^{20}Ne

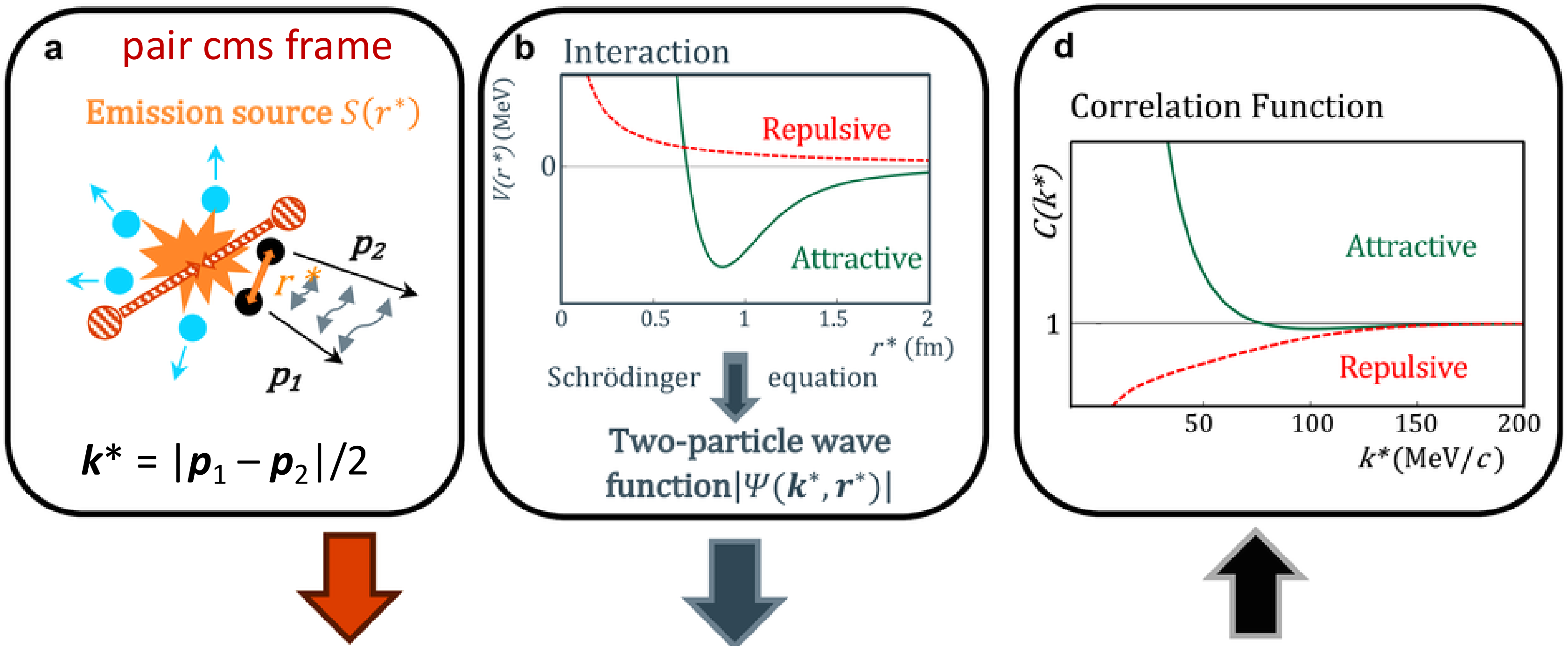




Pronounced enhancement of v_2(Ne-Ne/OO) in central collisions

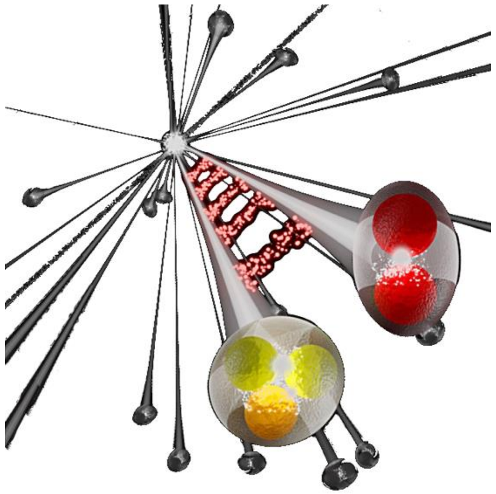
→ Probing of early-state dynamics and substructure of nuclei

Femtoscopy correlations to study hadron interactions



c

$$C(k^*) = \int S(r^*) \, |\Psi(k^*, r^*)|^2 \, d^3r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$



M. Lisa, S. Pratt et al., ARNPS 55 (2005), 357-402
L. Fabbietti et al., ARNPS 71 (2021), 377-402
D. Mihaylov et al., EPJC 78 (2018), 5, 394

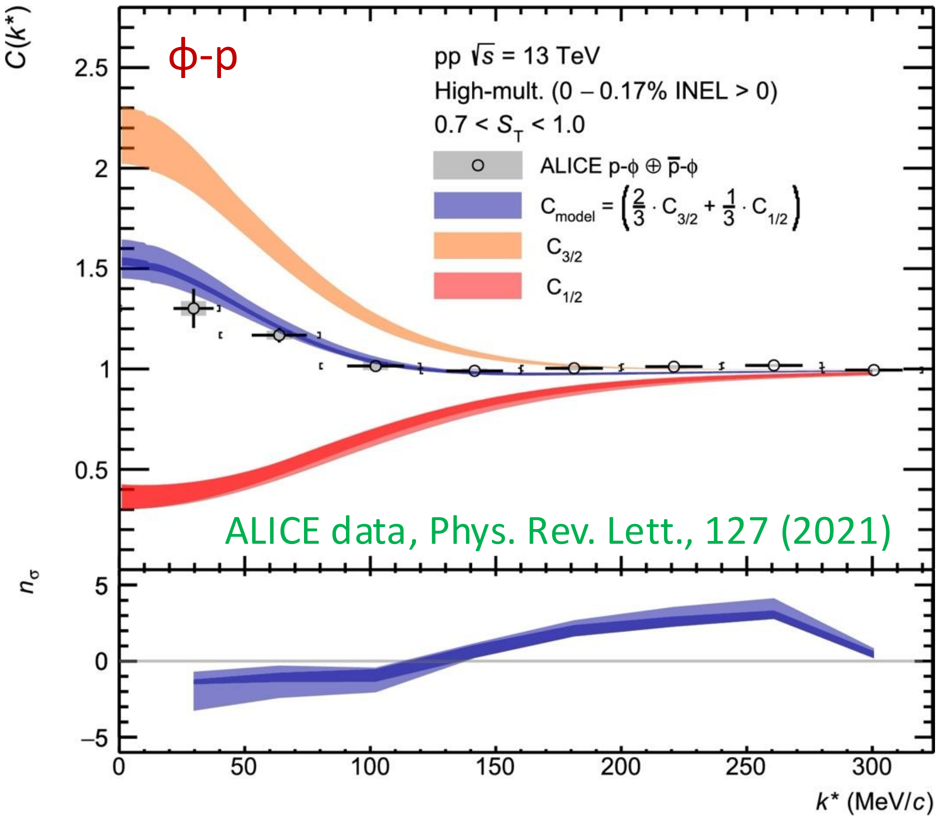
Origin of correlations: quantum interference, resonances, conservation laws or final-state interactions

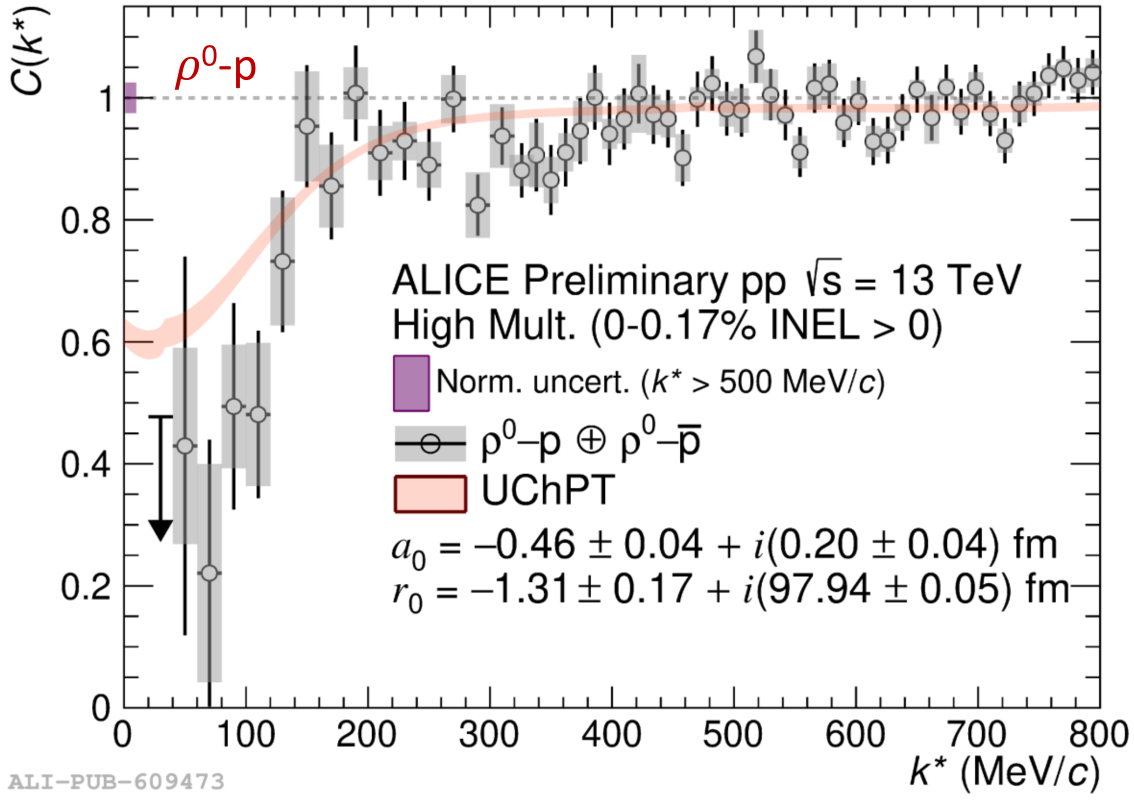
Final-state interactions dominate at small k*

Vector meson – baryon interactions

Foundation for chiral symmetry restoration searches

arXiv:2508.09867





ϕ-p bound state with B = 12.8 – 56.1 MeV
from theoretical analysis

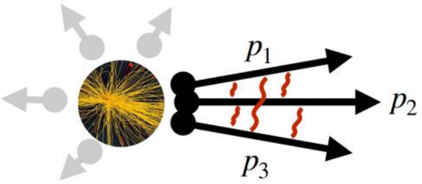
E. Chizzali et al. Phys. Lett. B (2024) 138358

First observation of the ρ^0-p strong interaction for $k^* < 200$ MeV/c
Data analyzed within χEFT using a coupled-channel approach

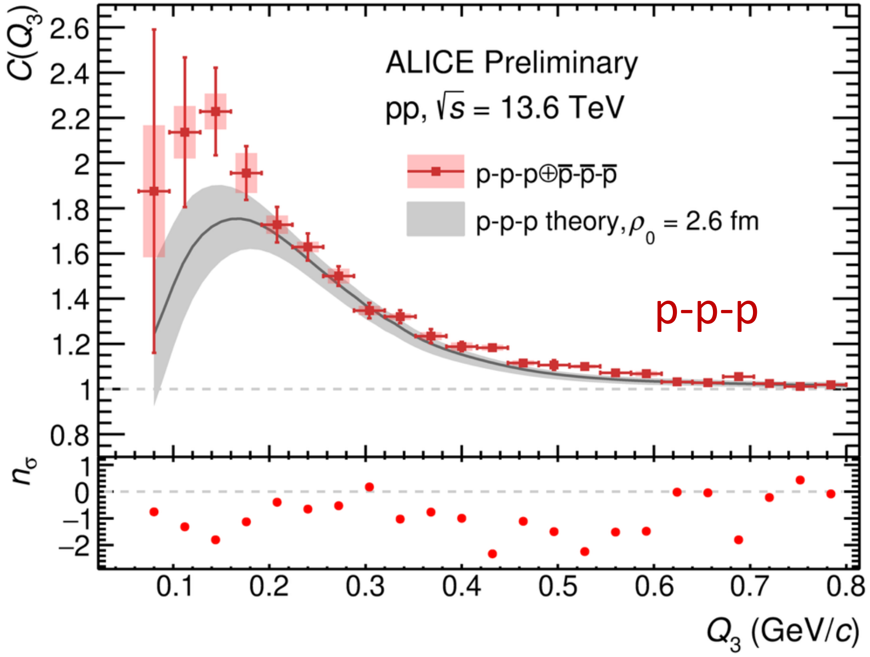
Femtoscopy correlations for many-body interactions

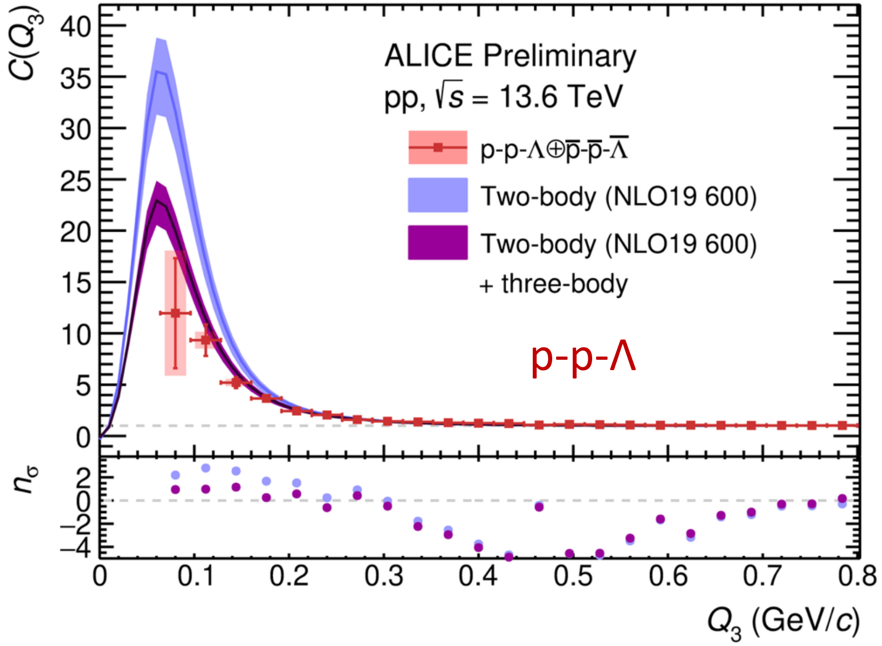
$$C(Q_3) = \int \rho^5 d\rho d\Omega_\rho S(\rho, \rho_0) \left| \Psi(\rho, Q_3) \right|^2$$

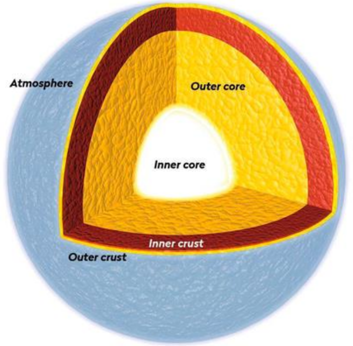
hyperradius



Neutron Stars EoS & hyperons ($M_{NS} > 2\ M_\odot$)?







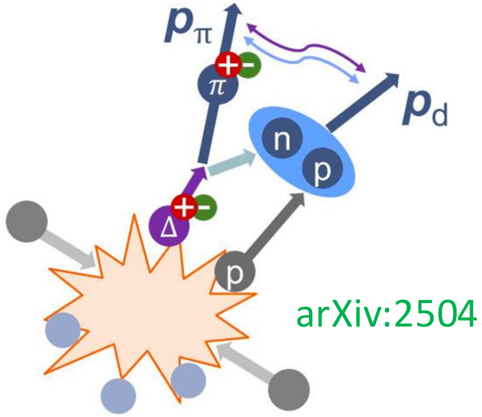
Measured p-p-p correlations described by full three body calculations

First observation of repulsive three-body p-p-Λ interactions

A. Kievsky et al., Phys.Rev.C 109 (2024) 3, 034006

E. Garrido et al., Phys.Rev.C 110 (2024) 5, 054004

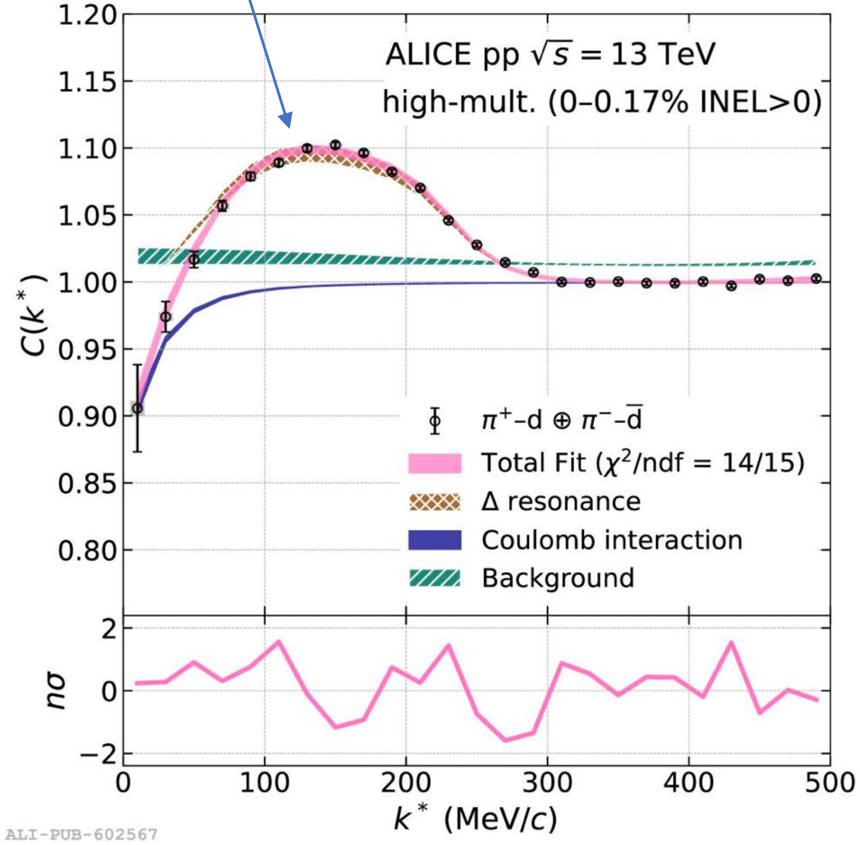
Pion-deuteron femtoscopy

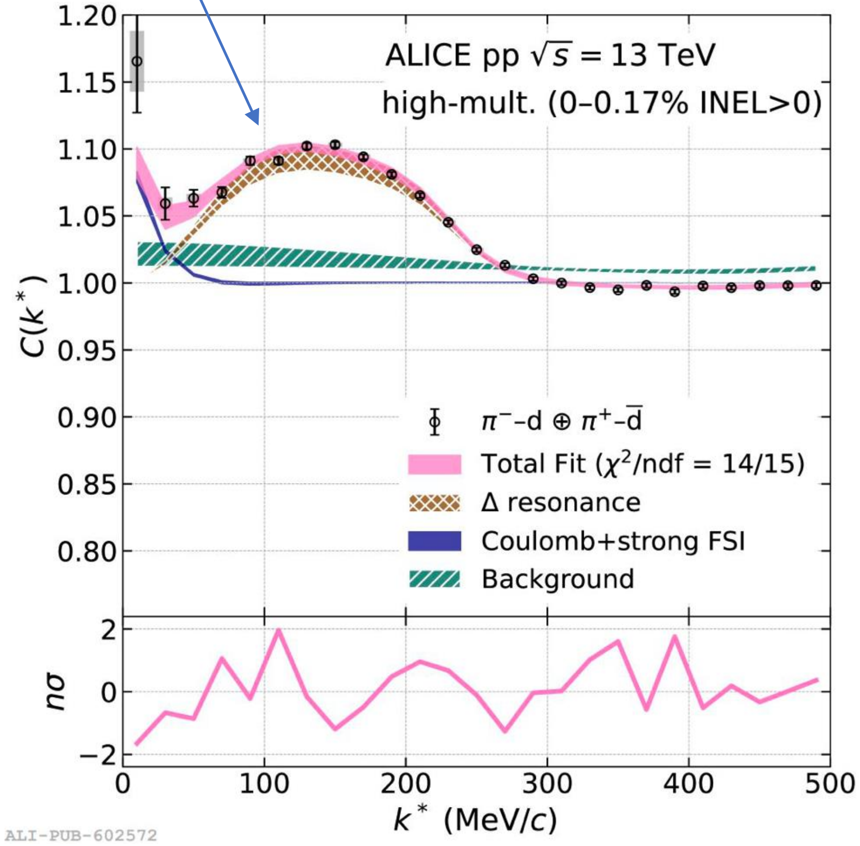


arXiv:2504.02393, Nature in press.

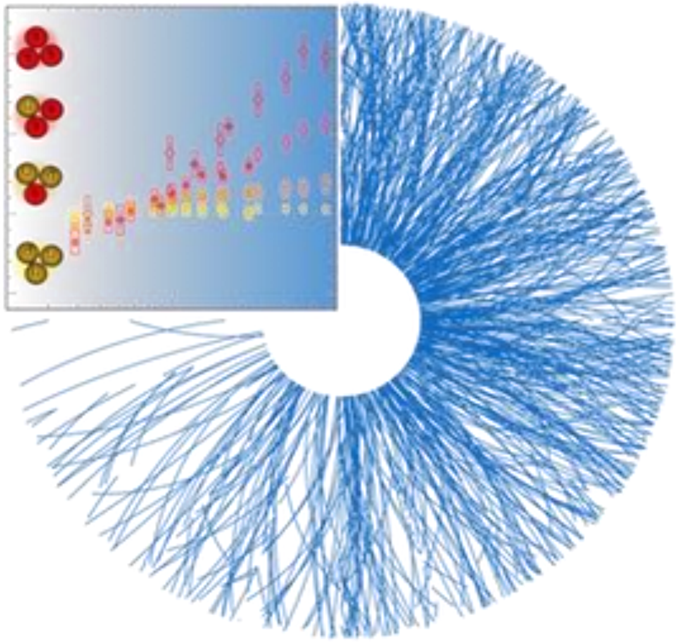
Addressing production of light (anti)nuclei and deuterons

Enhancement caused by Δ decay inherited during fusion process!





~80% of the observed deuterons are produced via resonance-mediated channels

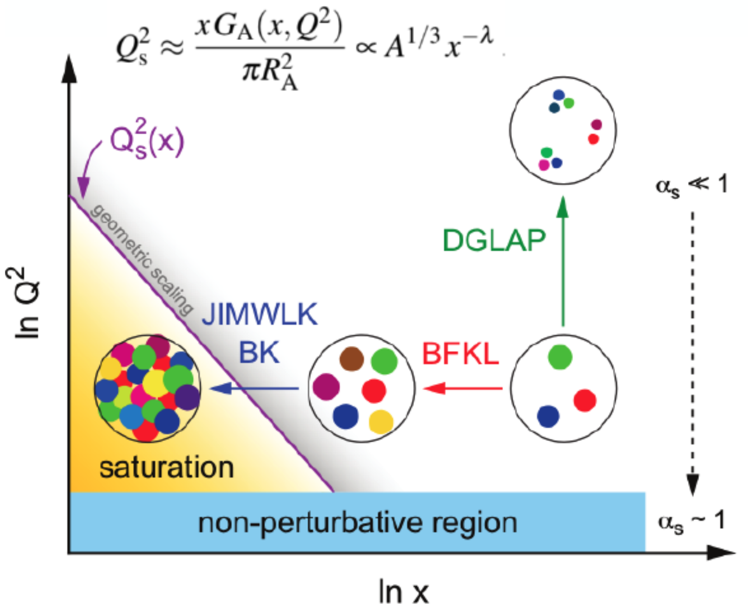


Heavy flavors and quarkonia

Heavy flavors and quarkonia

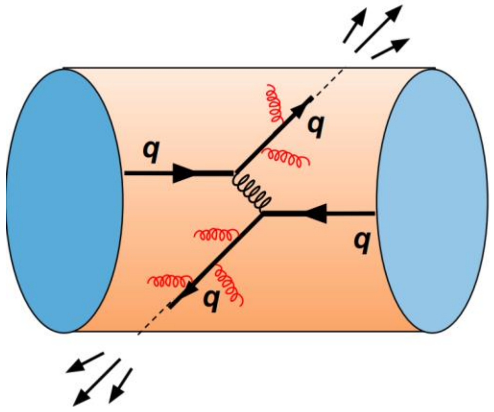
Hard probes of QGP!

Initial state (gluon saturation)



L. McLerran, R. Venugopalan,
Phys. Rev. D 49 (1994) 2233

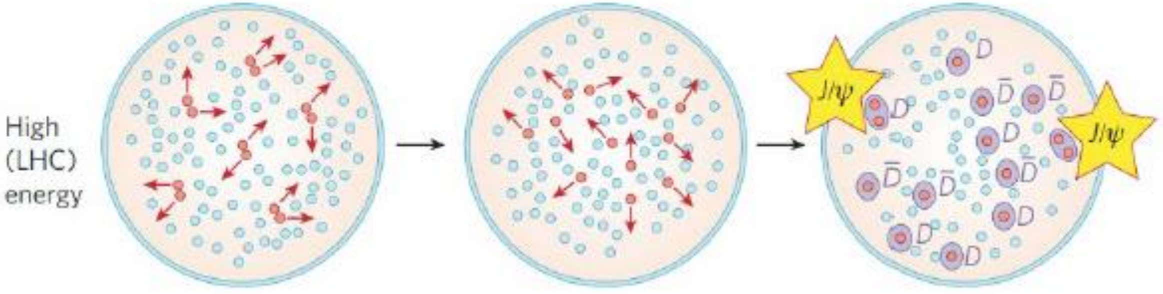
Parton energy loss in QGP



$\Delta E_g > \Delta E_q > \Delta E_Q$

Yu. L. Dokshitzer et al., J. Phys. G: Nucl. Part. Phys. 17 (1991) 1602

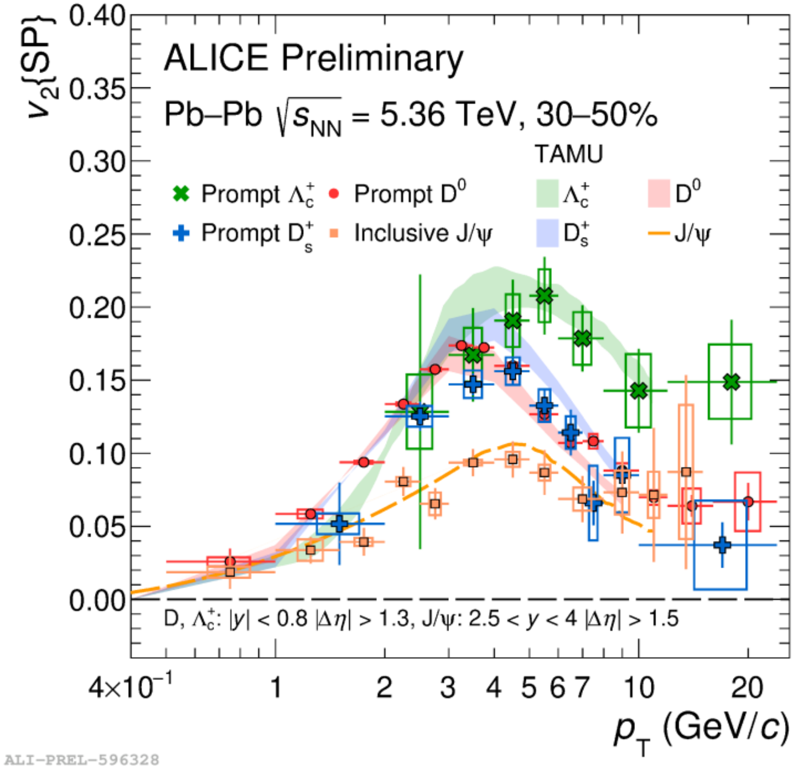
Color screening vs regeneration

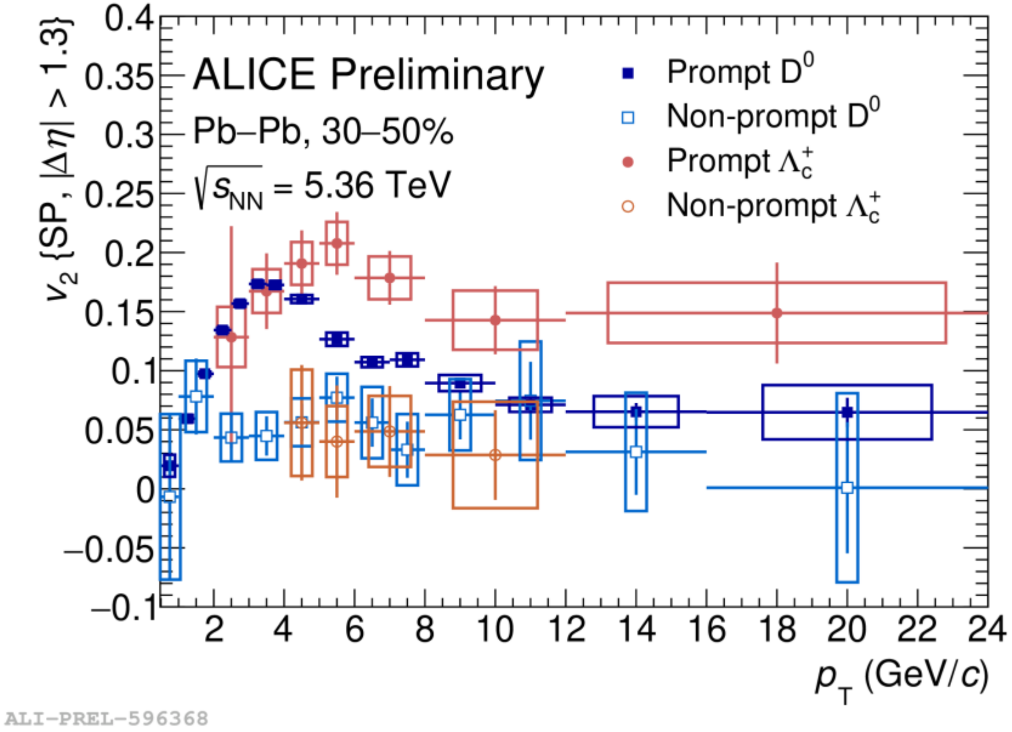


T. Matsui & H. Satz, Phys. Lett. B178 (1986) 416
P. Braun-Munzinger & J Stachel, Phys.Lett. B490 (2000) 196
R Thews et al., Phys. Rev. C 63:054905

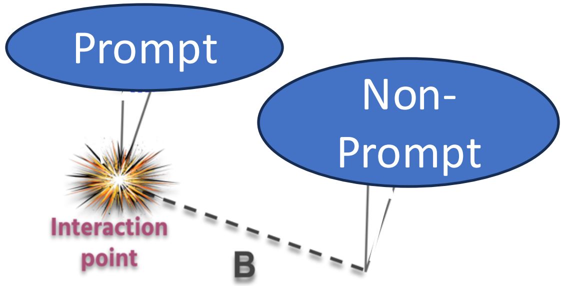
Flow of charm and beauty quarks in Pb-Pb

ALICE Run 3 measurements





- ❑ First charm baryon v_2 measurement
- ❑ Charm baryon-meson splitting
- ❑ Stronger degree of equilibration for c than b quarks
- ❑ TAMU transport model describes data

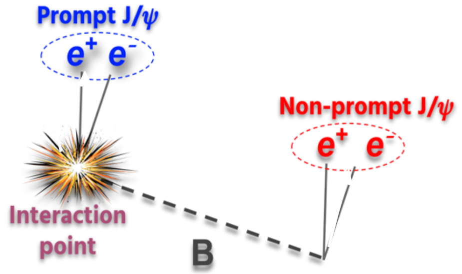


Prompt and non-prompt J/ψ production

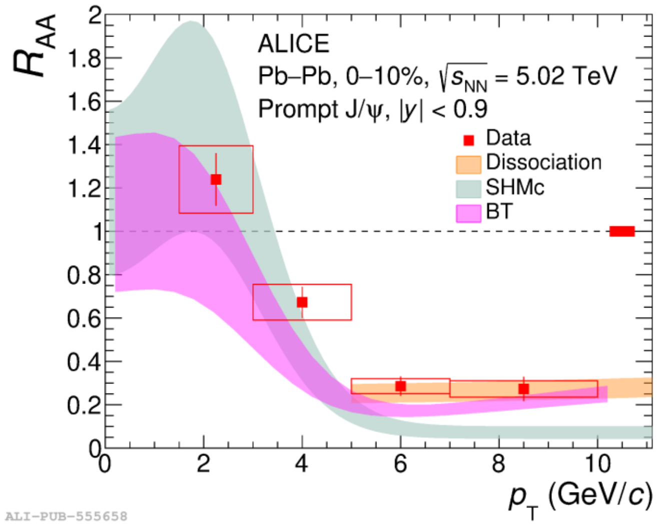
JHEP 02 (2024) 066

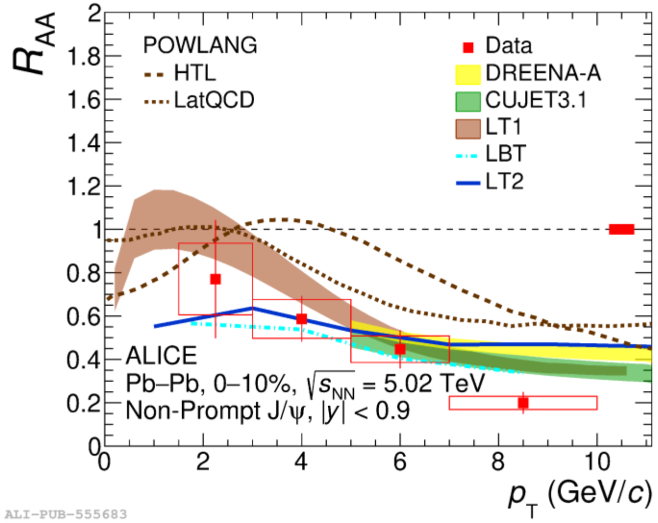
Parton energy loss, dissociation vs regeneration

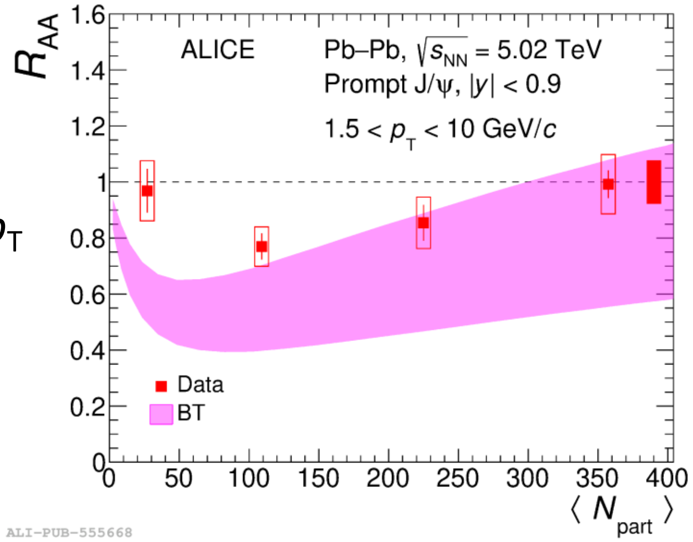
$$R_{AA} = \frac{d^2N_{AA}}{dp_T dy} \Big/ \frac{d^2N_{pp}}{<N_{coll}>\, dp_T dy}$$

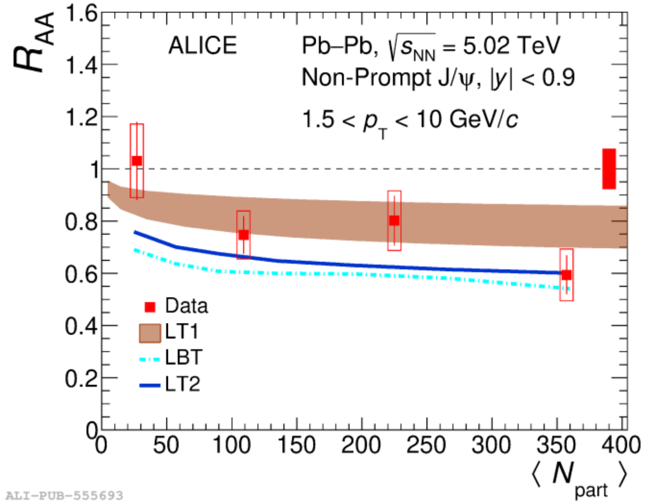


- Sign of prompt J/ψ (re)generation in central collisions
- Prompt J/ψ R_{AA} described by models including quarkonium dissociation (regeneration) at high (low) p_T
- Non-prompt J/ψ described by LT1 transport model



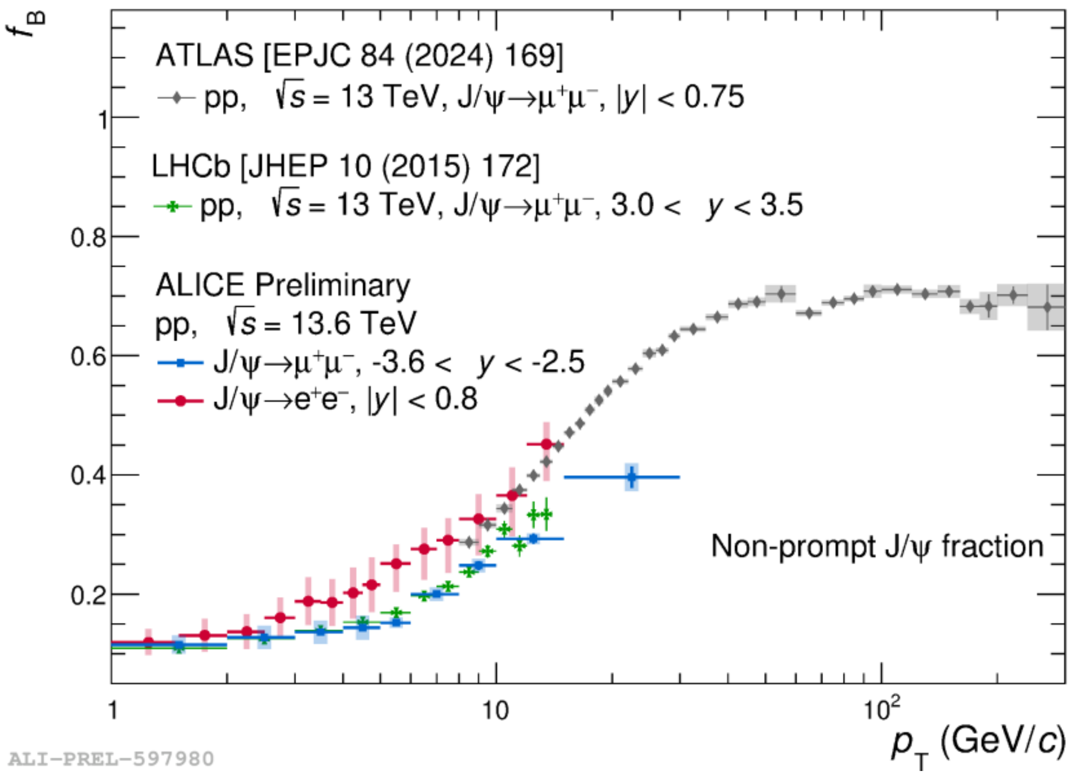


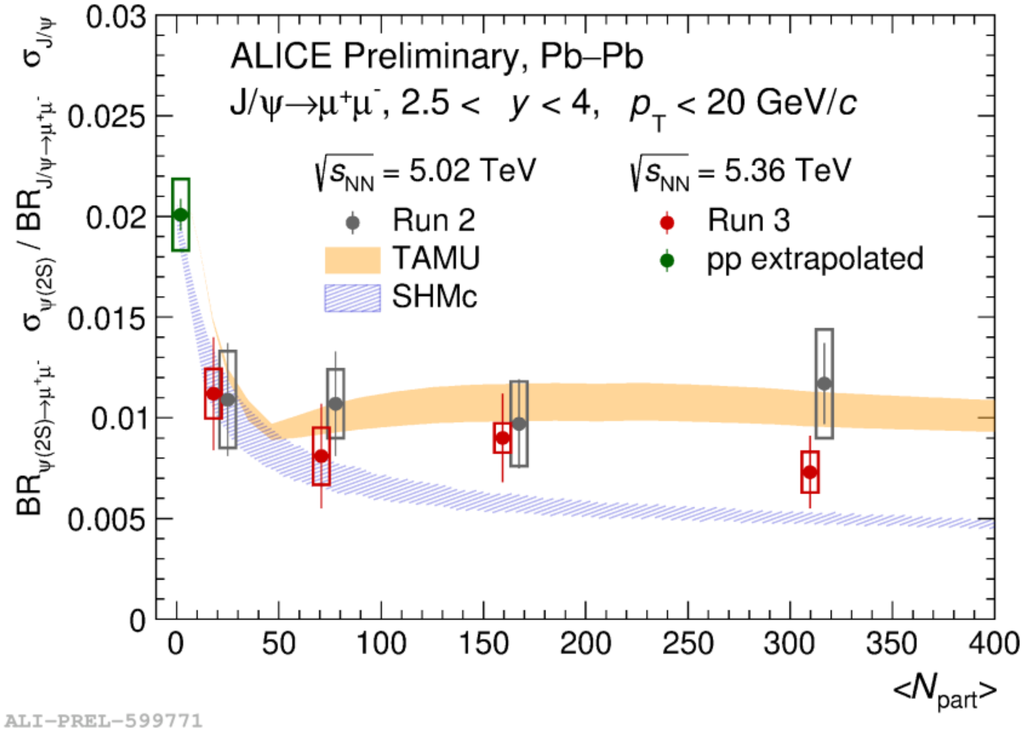




J/ψ and $\psi(2S)$ measurements at forward rapidity

ALICE Run 3 measurements

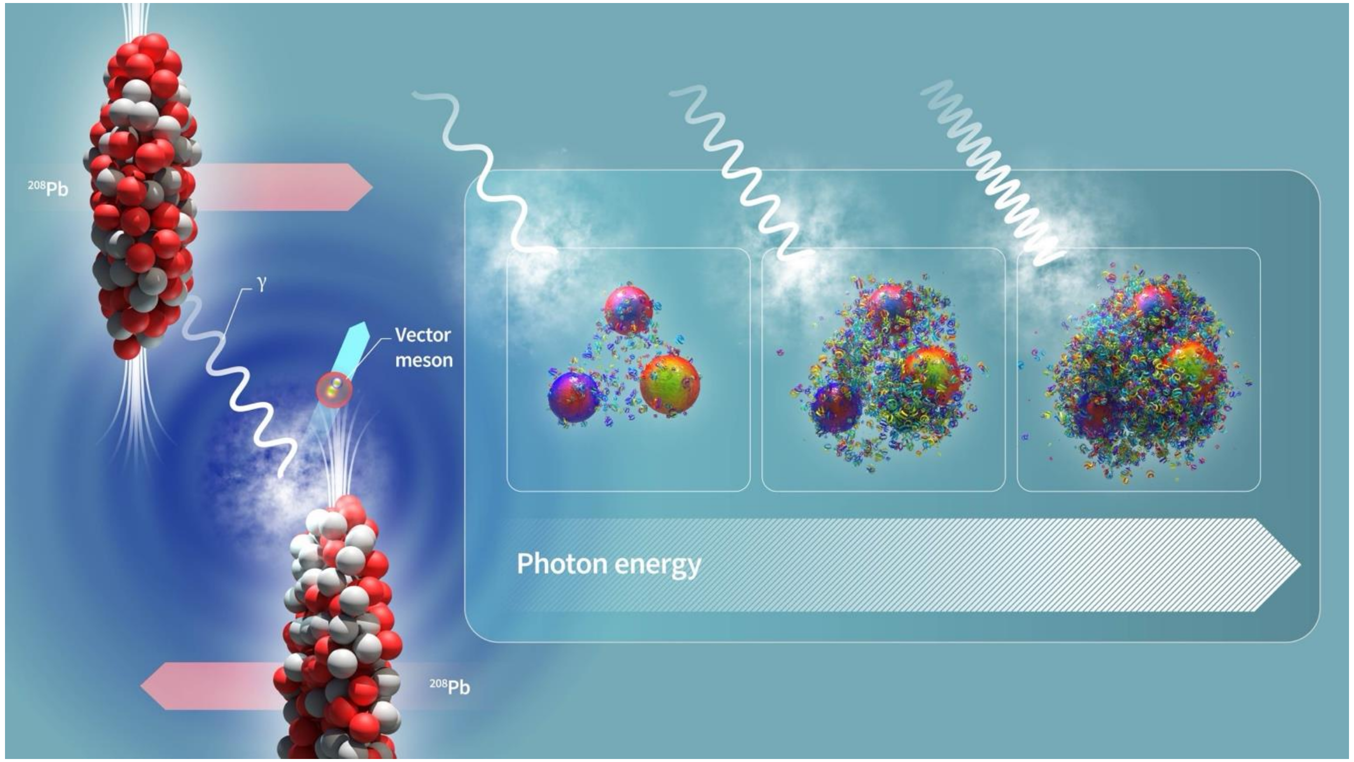




ALICE first non-prompt J/ψ measurement at forward rapidity down to low p_T with MFT detector

Precise $\psi(2S)$ / J/ψ suppression measurements at forward rapidity

Ultraperipheral Collisions (UPC)

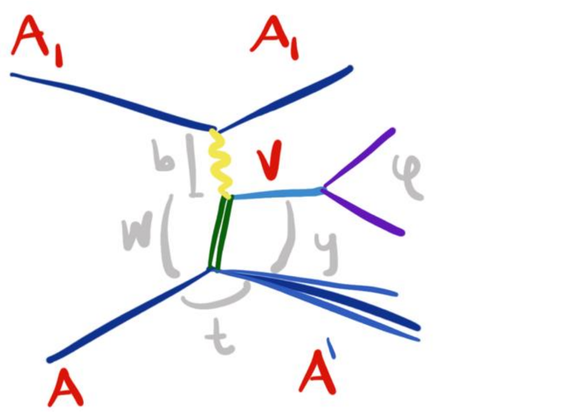


D. Dominguez/CERN-GRAPHICS-2023-008-1

Evidence of J/ψ suppression in UPC

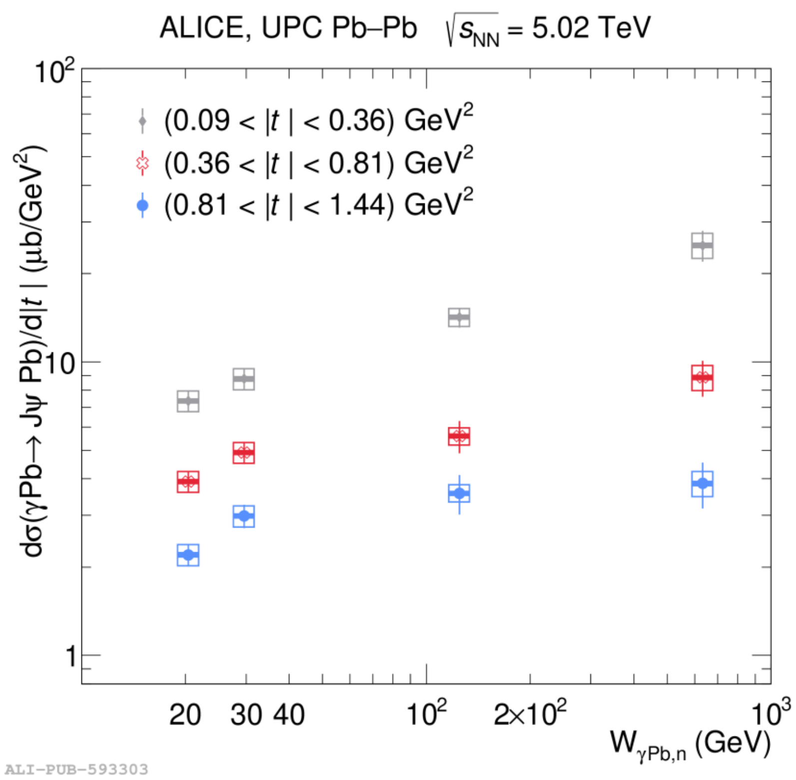
Incoherent J/ψ photonuclear cross section measured for the first time vs $W_{\gamma Pb,n}$ and |t|

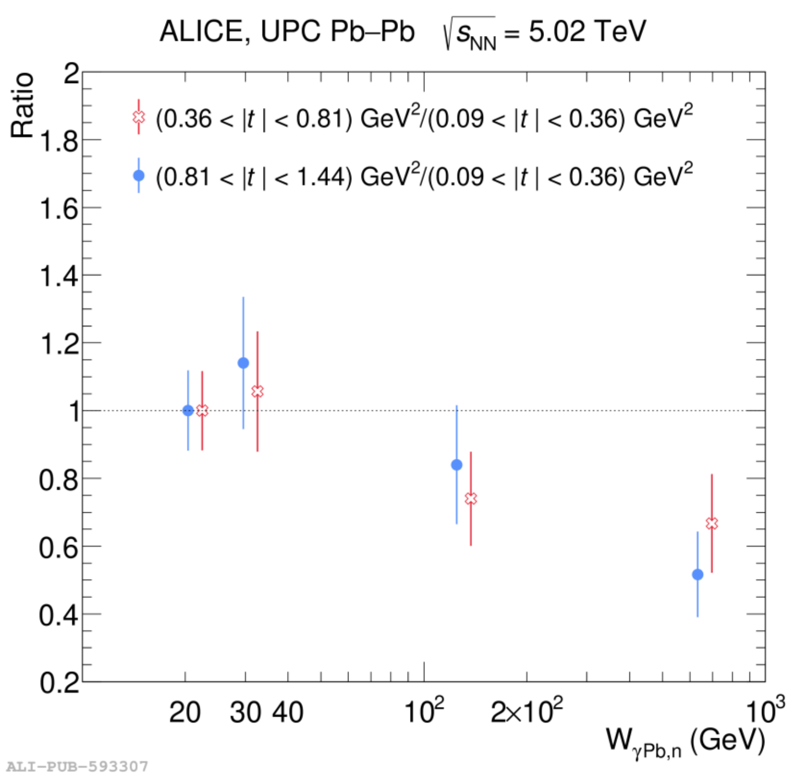
arXiv:2503.18708



$$(W_{\gamma Pb,n})^2 = m\sqrt{S_{NN}}exp(-y)$$

$$|t| = p_T^2$$

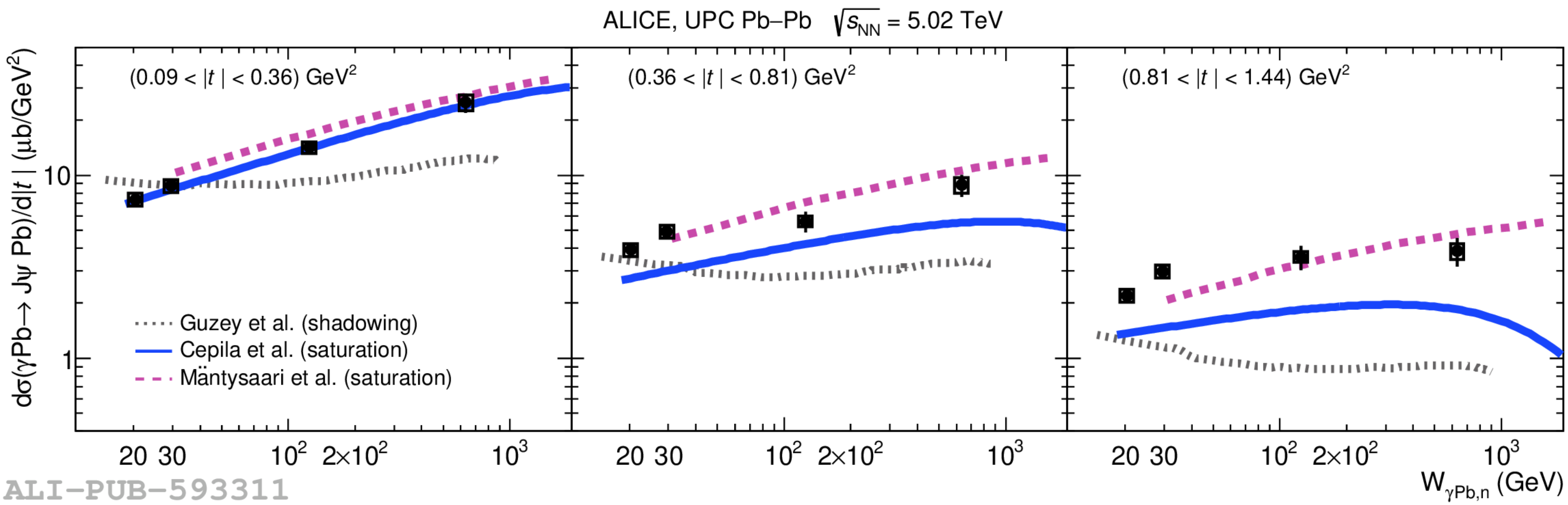




Suppression visible at large energy with increasing |t| and $W_{\gamma Pb,n}$ (smaller Bjorken - x)

Evidence of J/ψ suppression in UPC

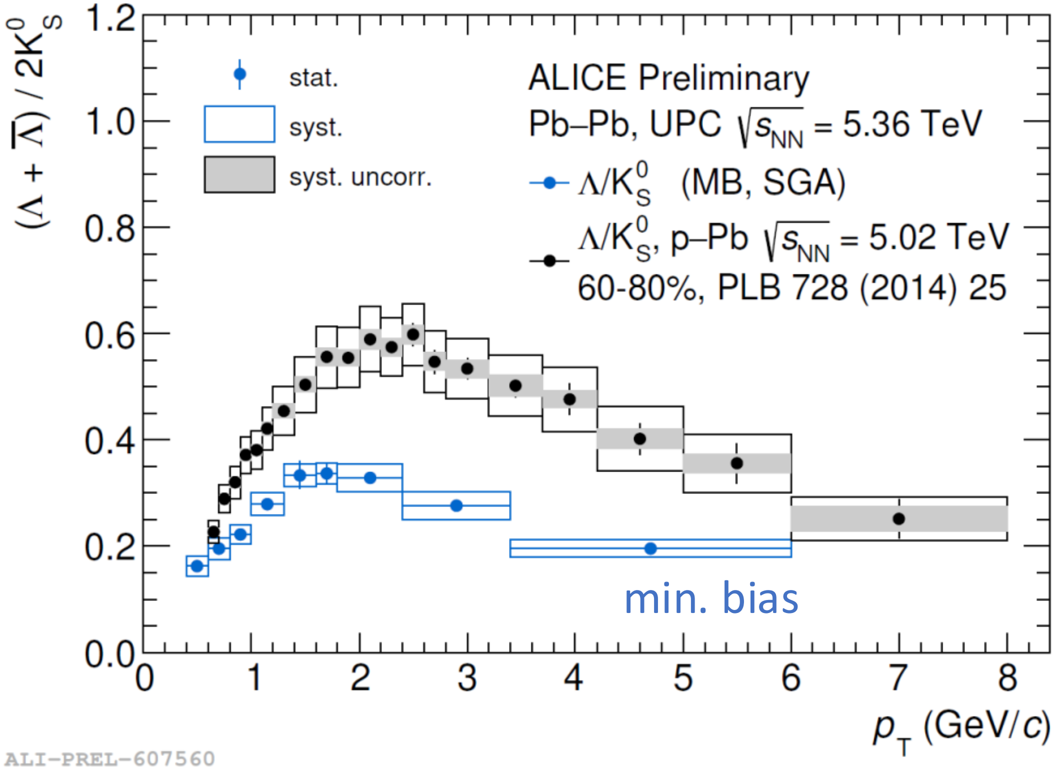
arXiv:2503.18708

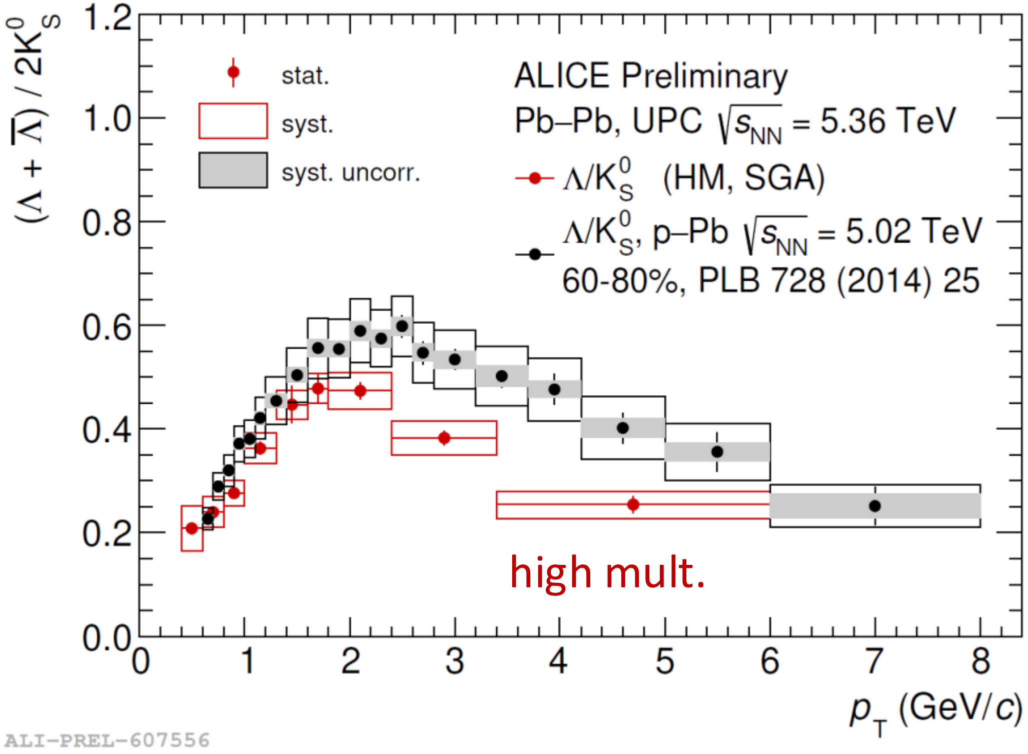


Gluon saturation models predict similar pattern

Strangeness and collectivity

ALICE Run 3 measurements



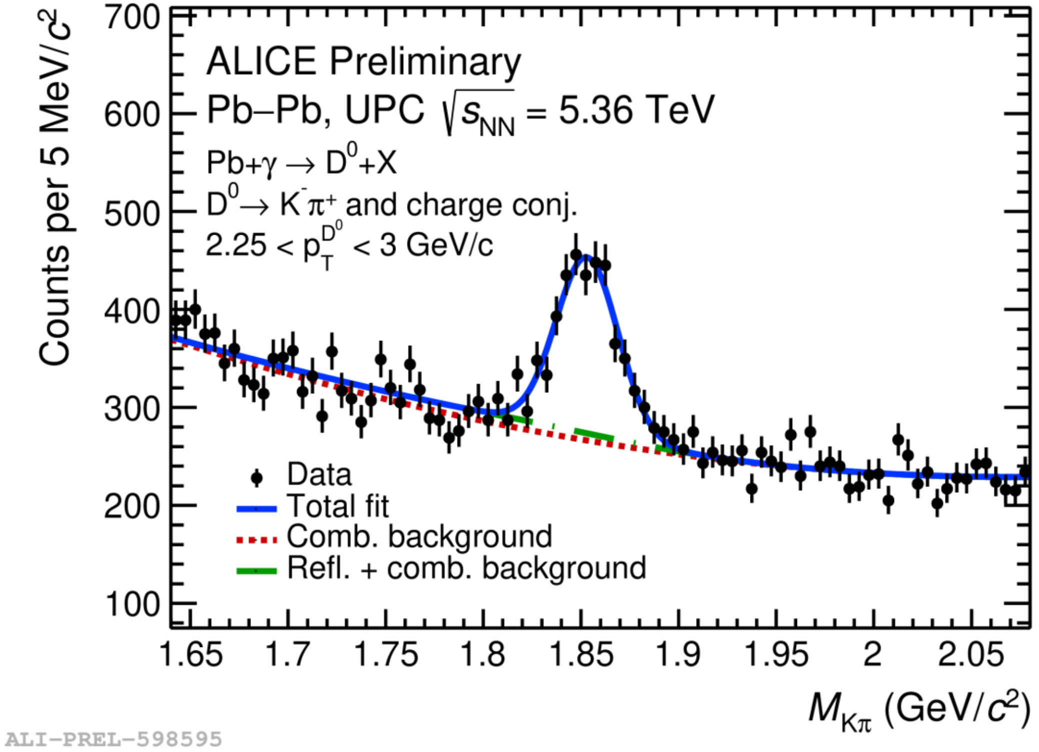


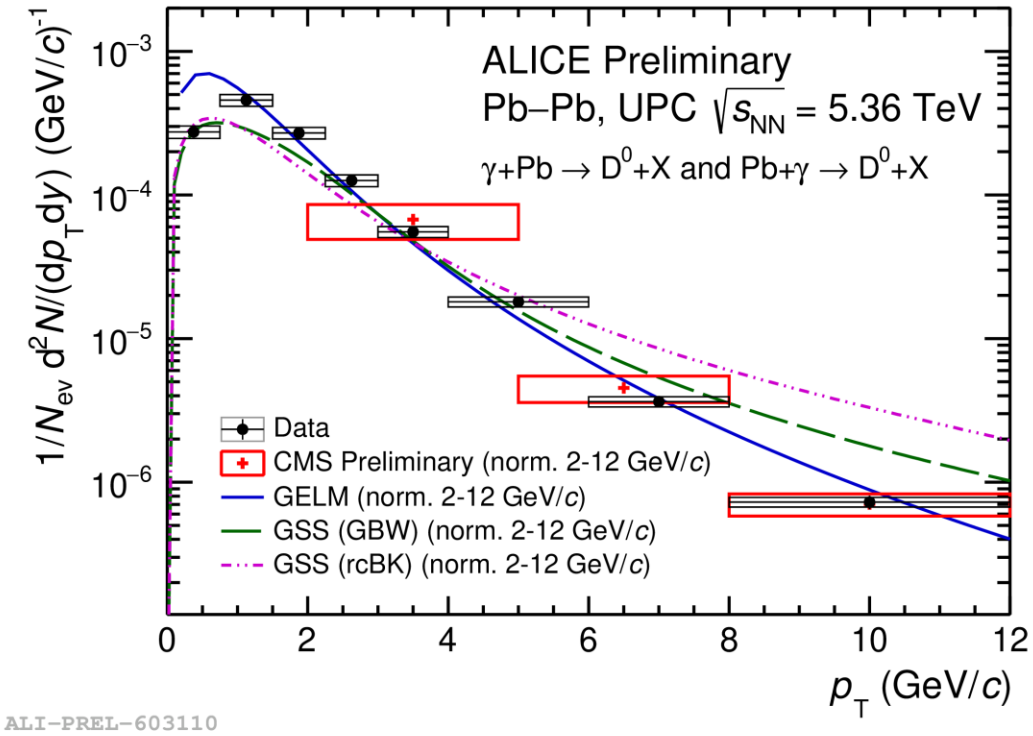
- Λ/K shows similar trend in γ-Pb and p-Pb collisions (baryon/meson enhancement at intermediate p_T)
- Consistent results for high multiplicity γ-Pb events

→ γ-Pb collisions ruled mainly by Vector Meson Dominance model (effectively meson-Pb interaction)

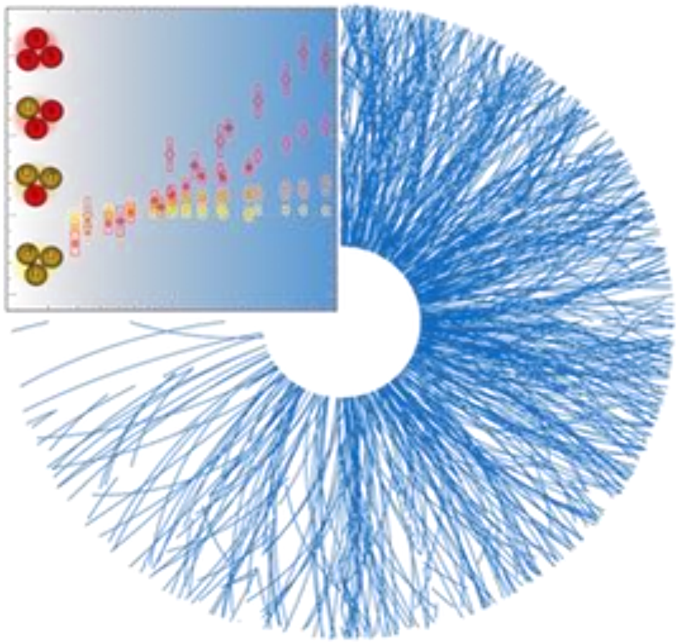
D^0 production in UPC

ALICE Run 3 measurements





- Measuring charm hadrons gives access to gluon PDF down to Bjorken-$x < 10^{-4}$
- Several charm production channels to explore



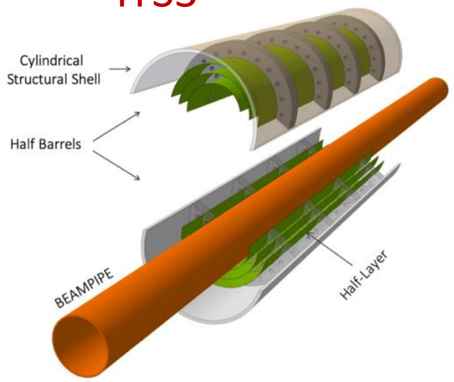
ALICE upgrade plans

ALICE Upgrades

Run 3	LS3	Run 4	LS4	Run 5
	2026-2029	2030-2034	2034-2035	2036 -

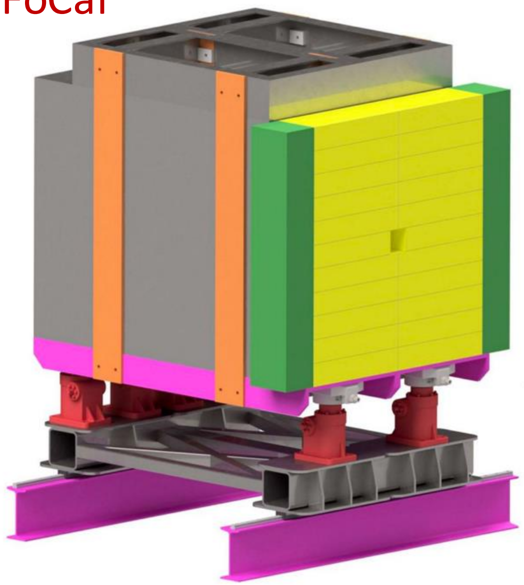
LS3: Inner Tracking System 3 (ITS3) & Forward Calorimeter (FoCal)

ITS3



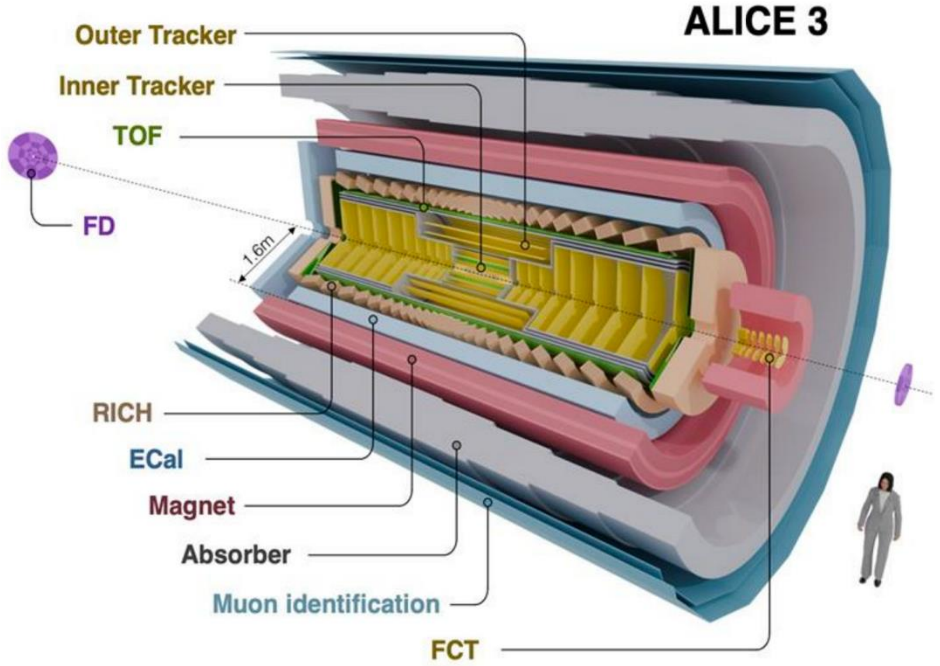
TDR: CERN-LHCC-2024-003

FoCal



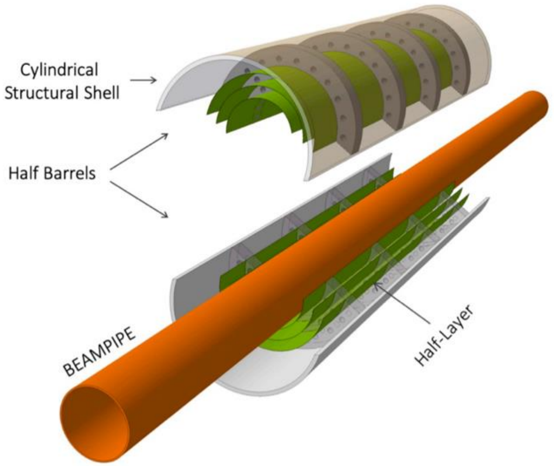
TDR: CERN-LHCC-2024-004

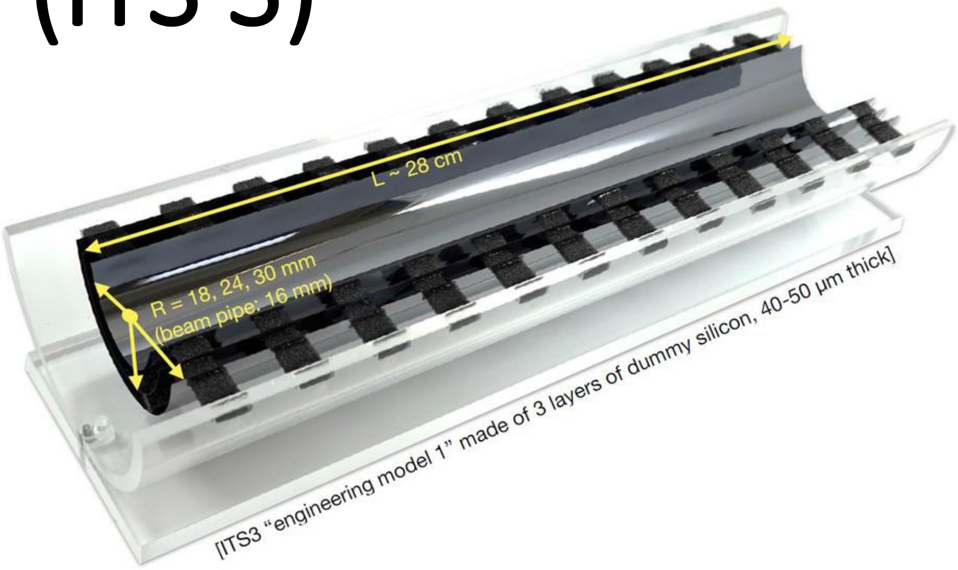
LS4: New heavy-ion detector (ALICE 3)



ALICE3 LoI: CERN-LHCC-2022-009
Scoping document: CERN-LHCC-2025-002
Ongoing R&D

Inner Tracking System 3 (ITS 3)

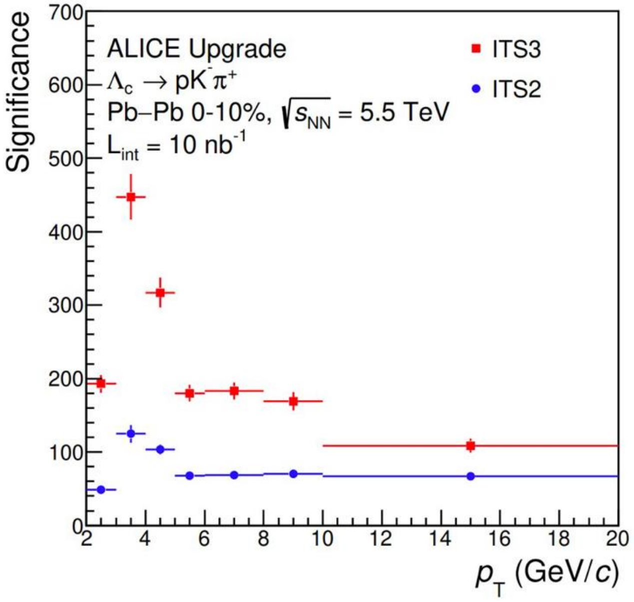


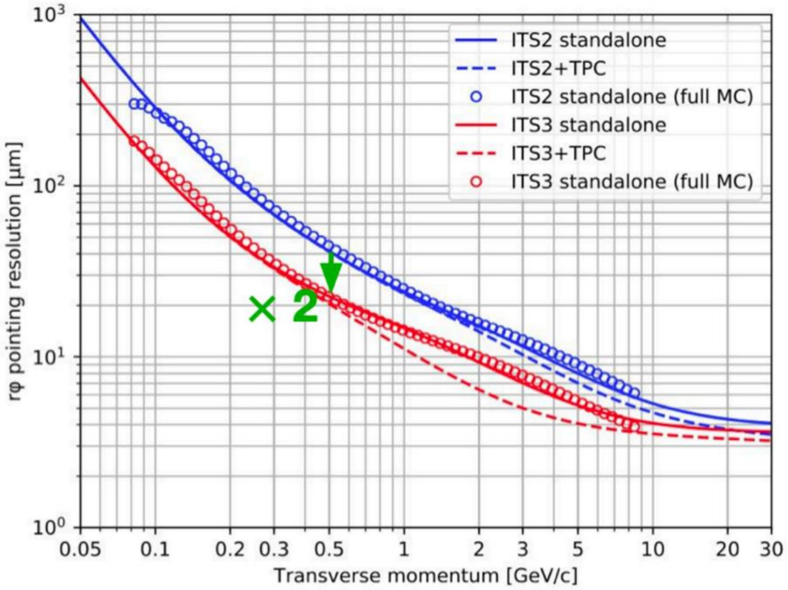


- ❑ Truly cylindrical (silicon sensor bending)
- ❑ 65 nm MAPS sensors in CMOS thechnology

Main physics motivation

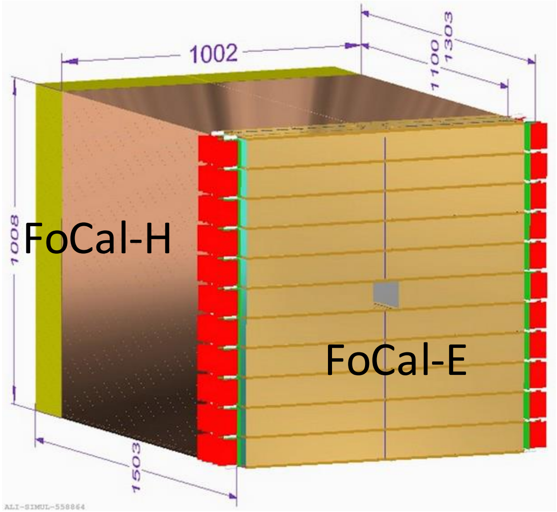
- ❑ Improve performance for heavy flavour and dielectron measurements





LoI: CERN-LHCC-2019-018
Physics performance: ALICE-PUBLIC-2023-002

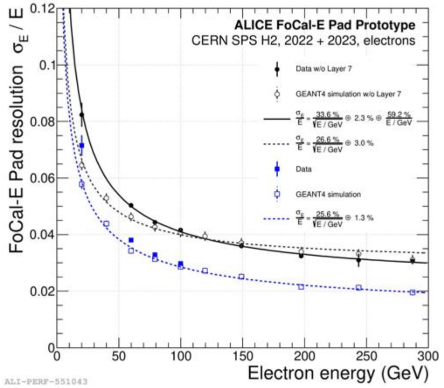
Forward Calorimeter (FoCal)



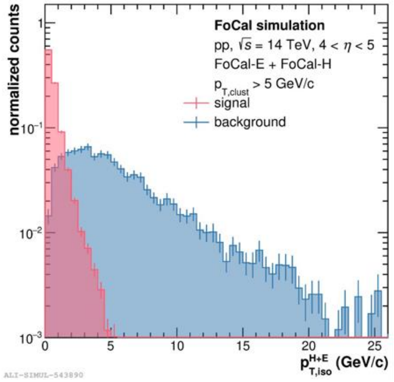
- Electromagnetic (FoCal-E) and hadronic (FoCal-H) calorimeter
- Acceptance: $3.2 < \eta < 5.8$

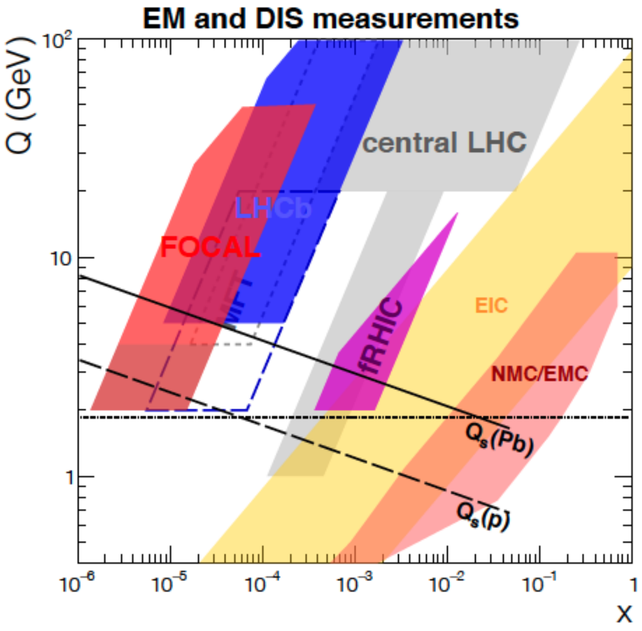
Main physics motivation

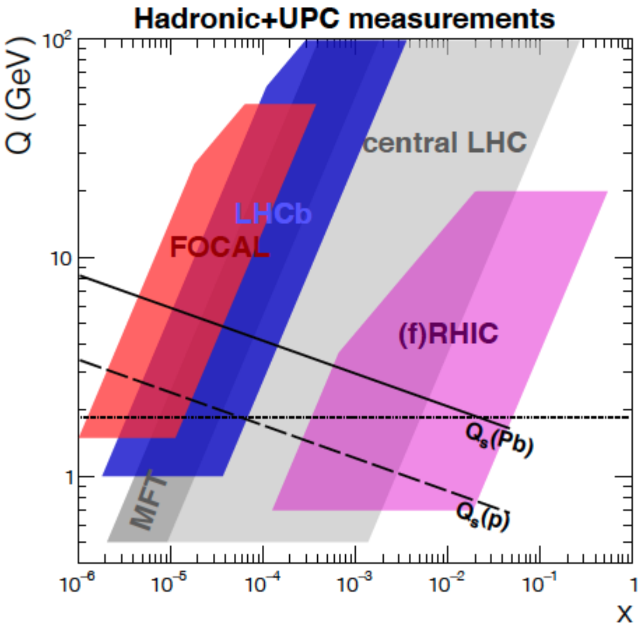
- Explore non-linear QCD evolution at small Bjorken-*x*
- Measurements of isolated-γ, DY, open charm, jets and UPC



Isolated photons



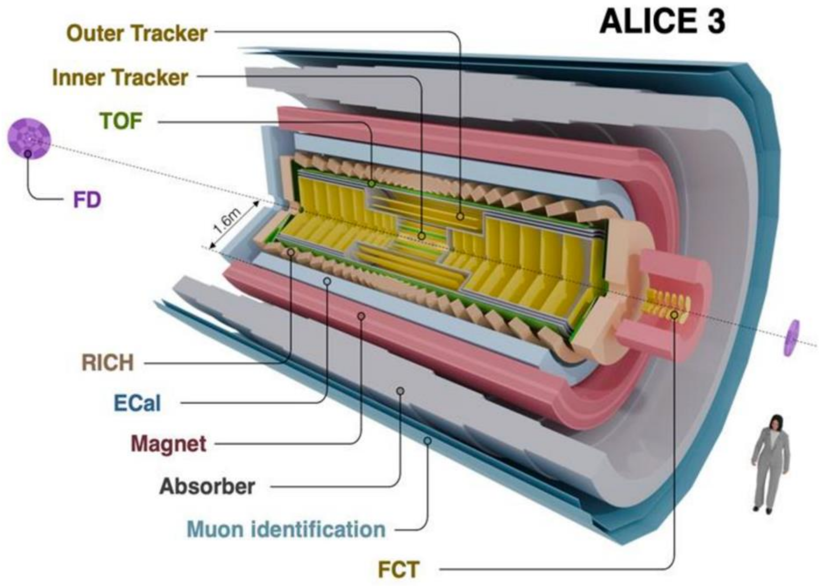


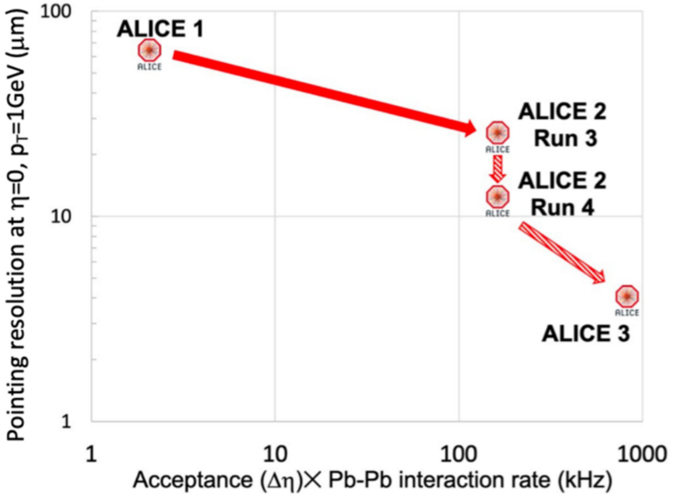


LoI: ALICE, LHCC-I-036 (2020)
Physics case: ALICE-PUBLIC-2023-001
Physics performance: ALICE-PUBLIC-2023-004

ALICE 3

Acceptance: $-4.0 < \eta < 4.0$

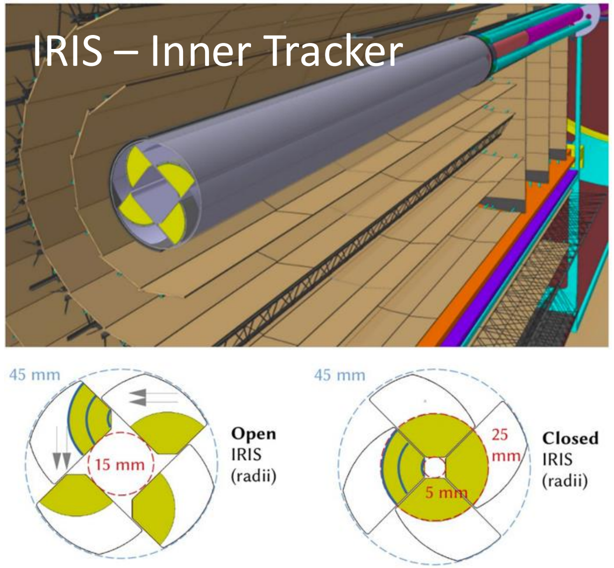




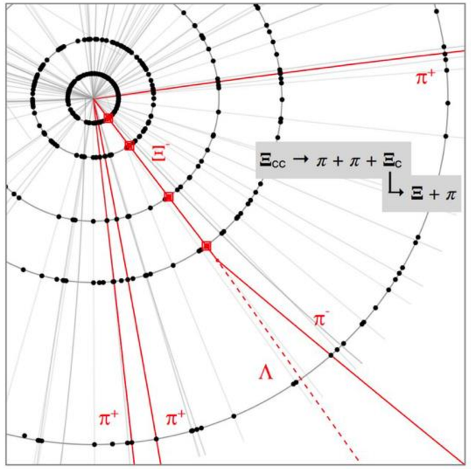
Main physics motivation

- QGP transport properties
- Hadronization mechanisms of charm and beauty hadrons, and nuclei
- Chiral symmetry restoration (photon and dileptons)
- BSM searches
- …

- Strong R&D on innovative sensors (large-area MAPS, LGADs time-of-flight and SiPM RICH)



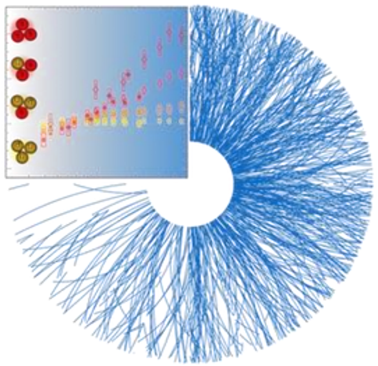
Multi-charm hadron production



LoI: CERN-LHCC-2022-009

Scoping document: CERN-LHCC-2025-002

Summary & Outlook

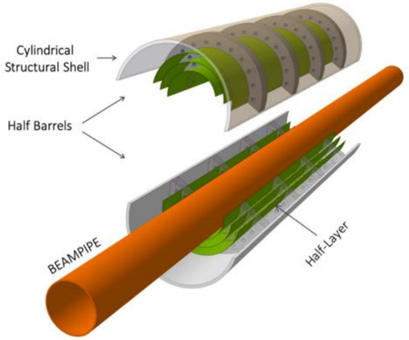


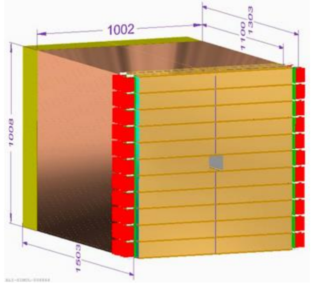
Light flavour

- Extended rapidity range for ALICE measurements in Run 3
- System created in Pb-Pb collisions is baryon-free and electrically neutral at midrapidity
- First evidence of the antihyperhelium – 4!
- Collective flow observed in large and small systems with characteristic pattern
- Femtoscopy correlations excellent tool to study strong interactions

Heavy flavour

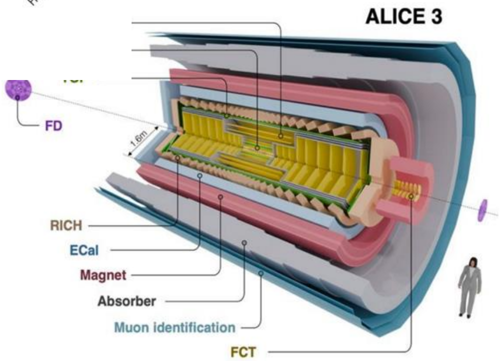
- First charm baryon v_2 measurement
- Sign of prompt J/ψ (re)generation in central collisions
- ALICE first non-prompt J/ψ measurements at forward rapidity





Ultraperipheral collisions

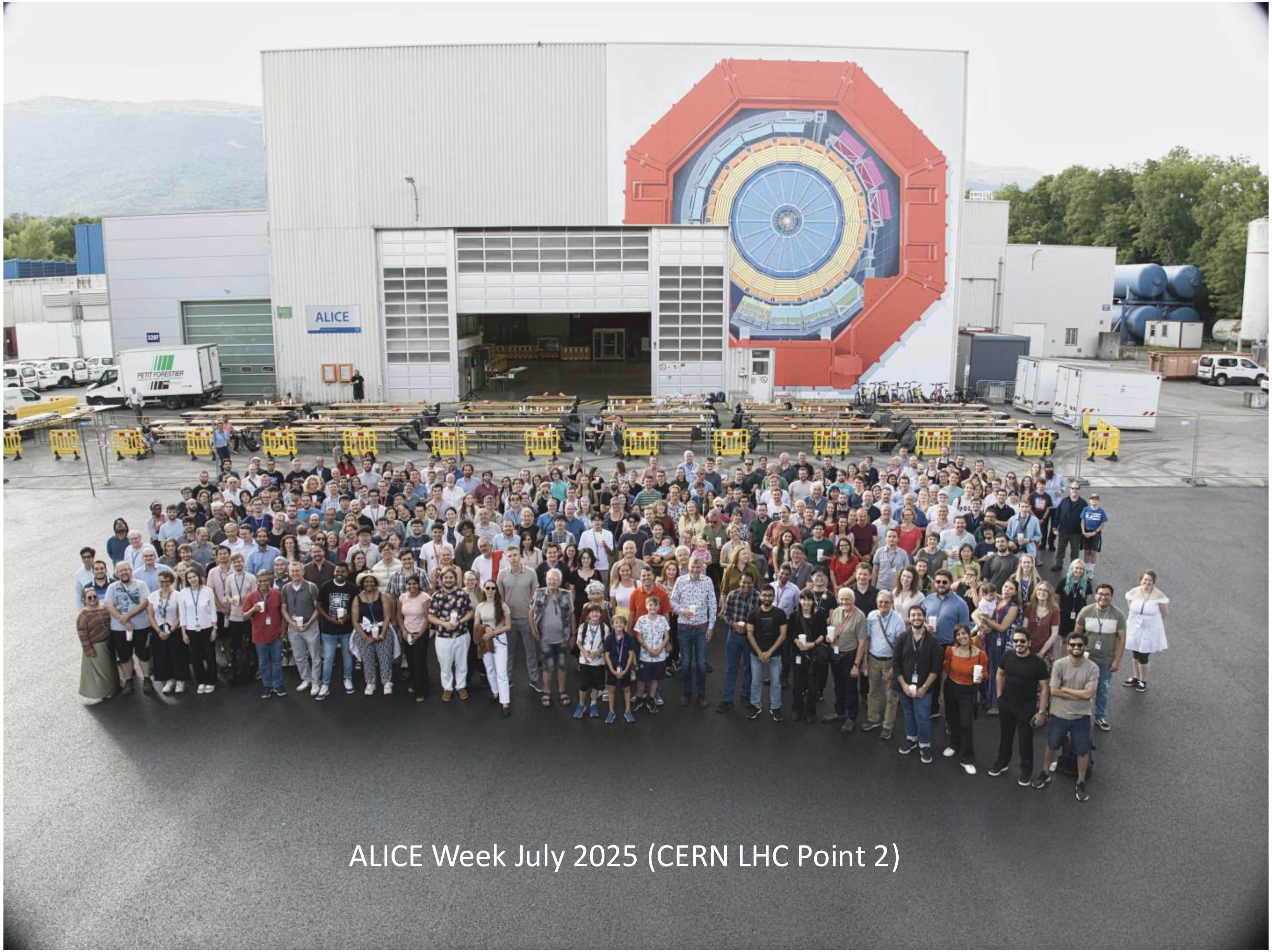
- J/ψ suppression in UPC
- γ-Pb collisions ruled mainly by Vector Meson Dominance
- Charm meson production (access to gluon PDF down to Bjorken-$x < 10^{-4}$)



Upgrades

- ALICE has ambitious upgrade plans: ITS 3, FoCal (Run 4) and ALICE 3 (beyond Run 4)

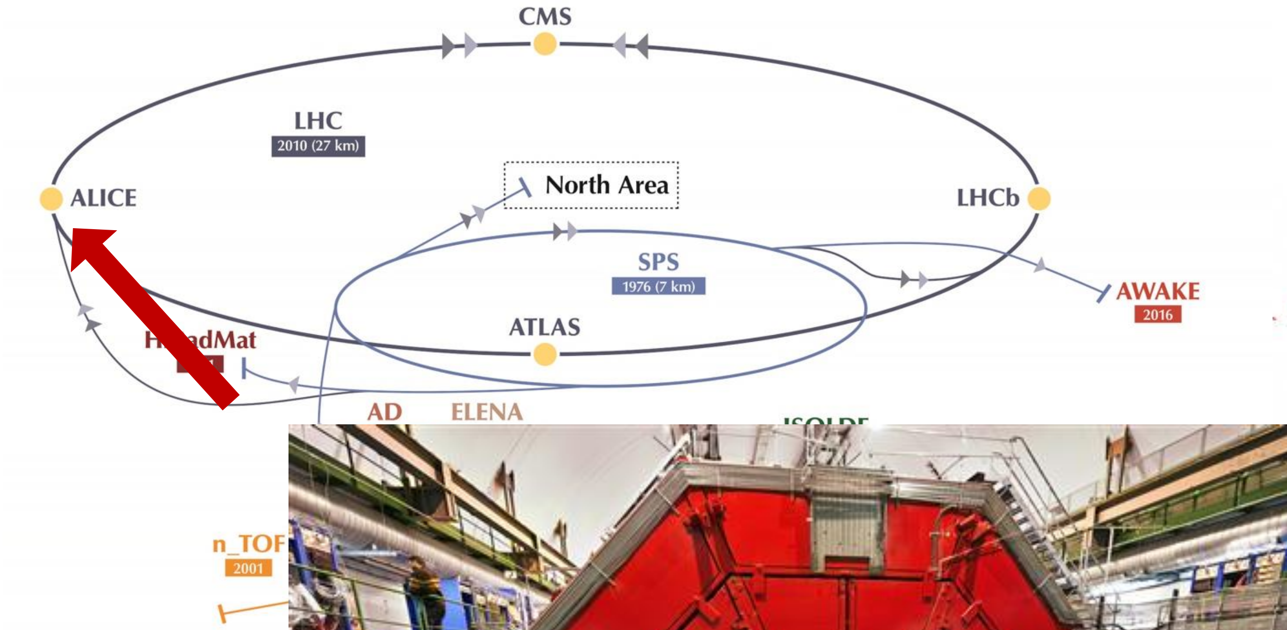
ALICE

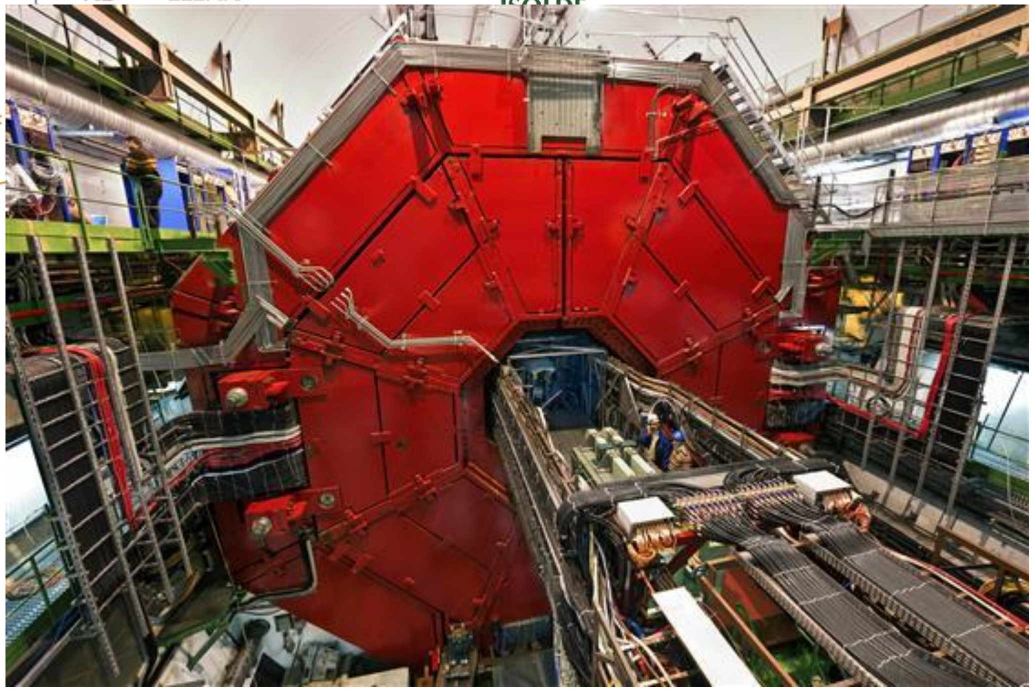


ALICE Week July 2025 (CERN LHC Point 2)

backup

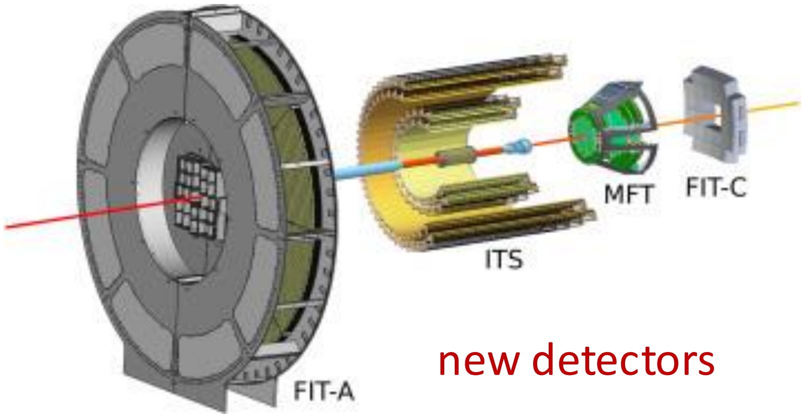
A Large Ion Collider Experiment (ALICE)



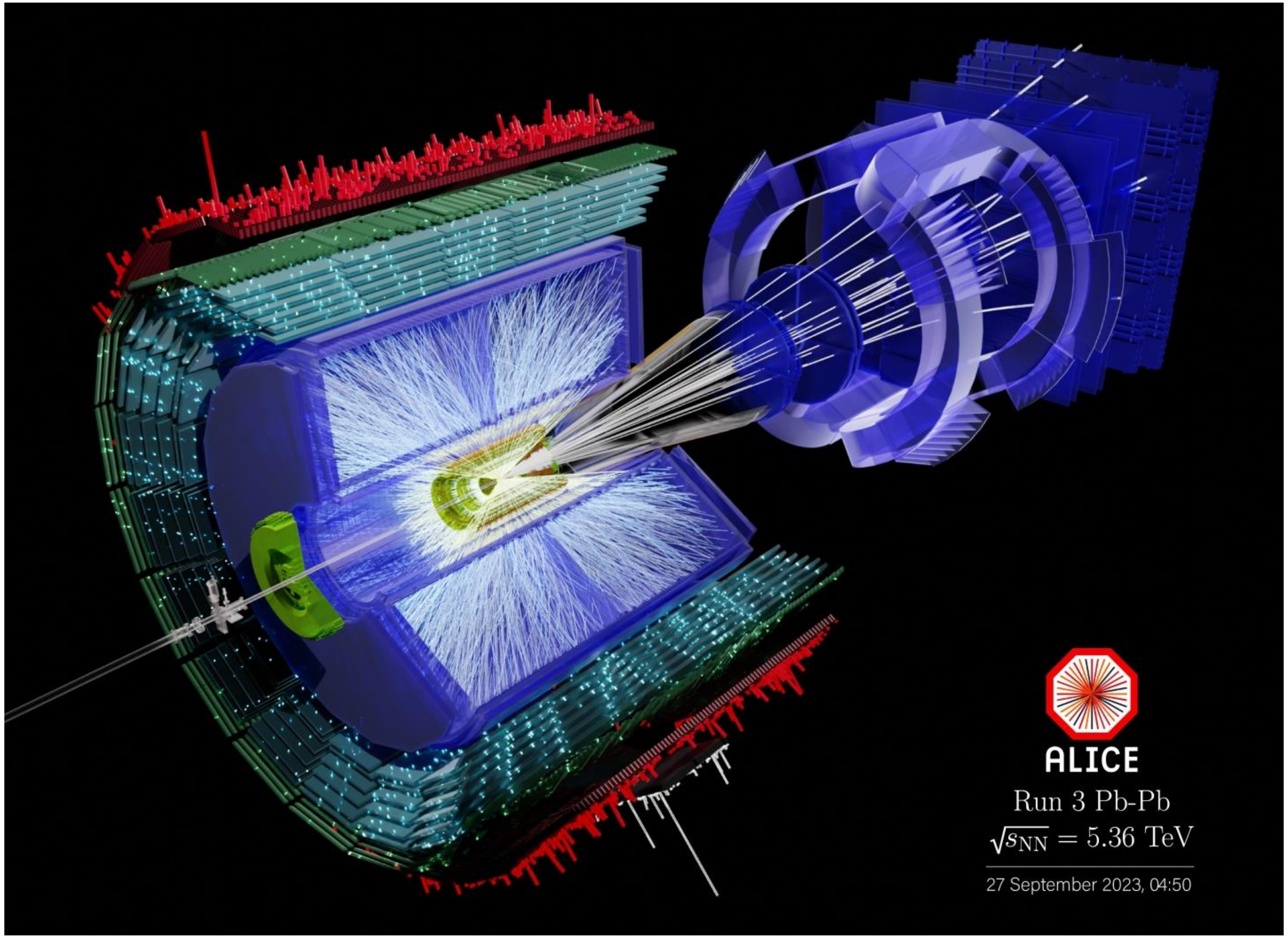


39 countries, 174 institutes, 1927 members

FIT in Run 3

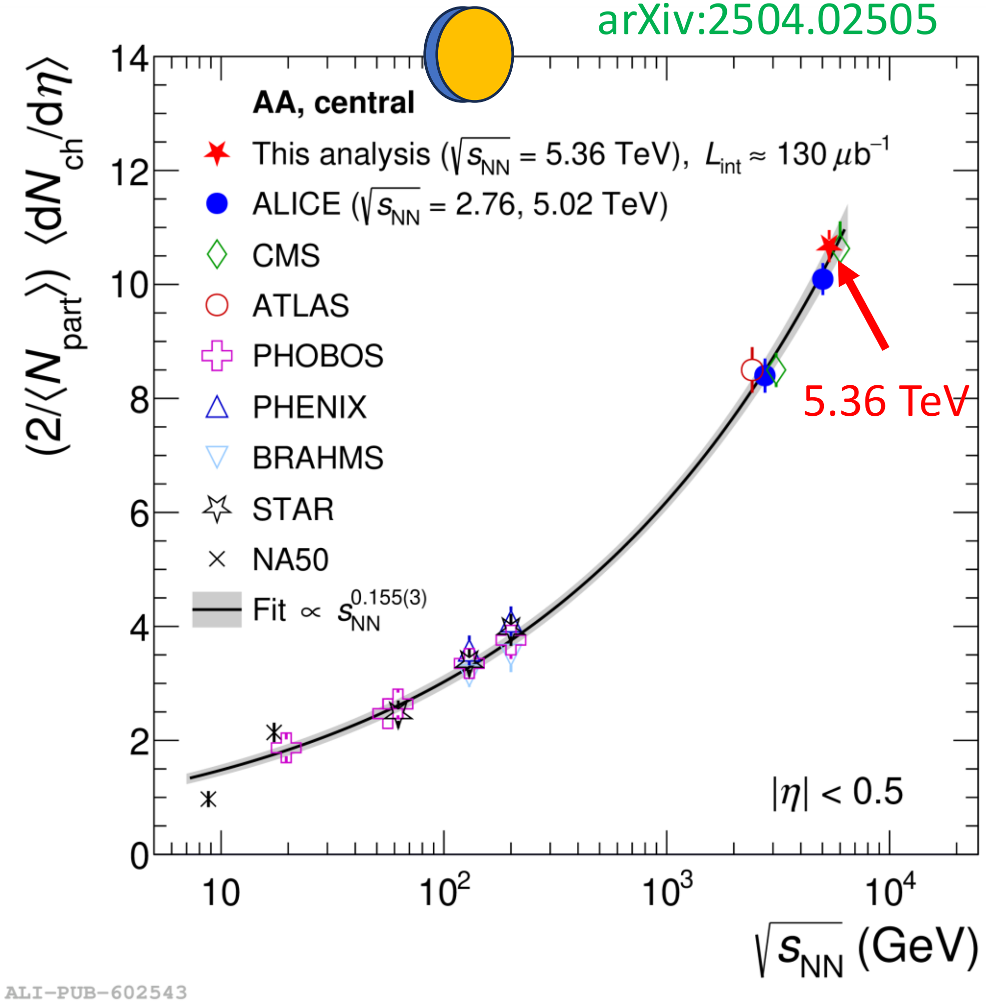


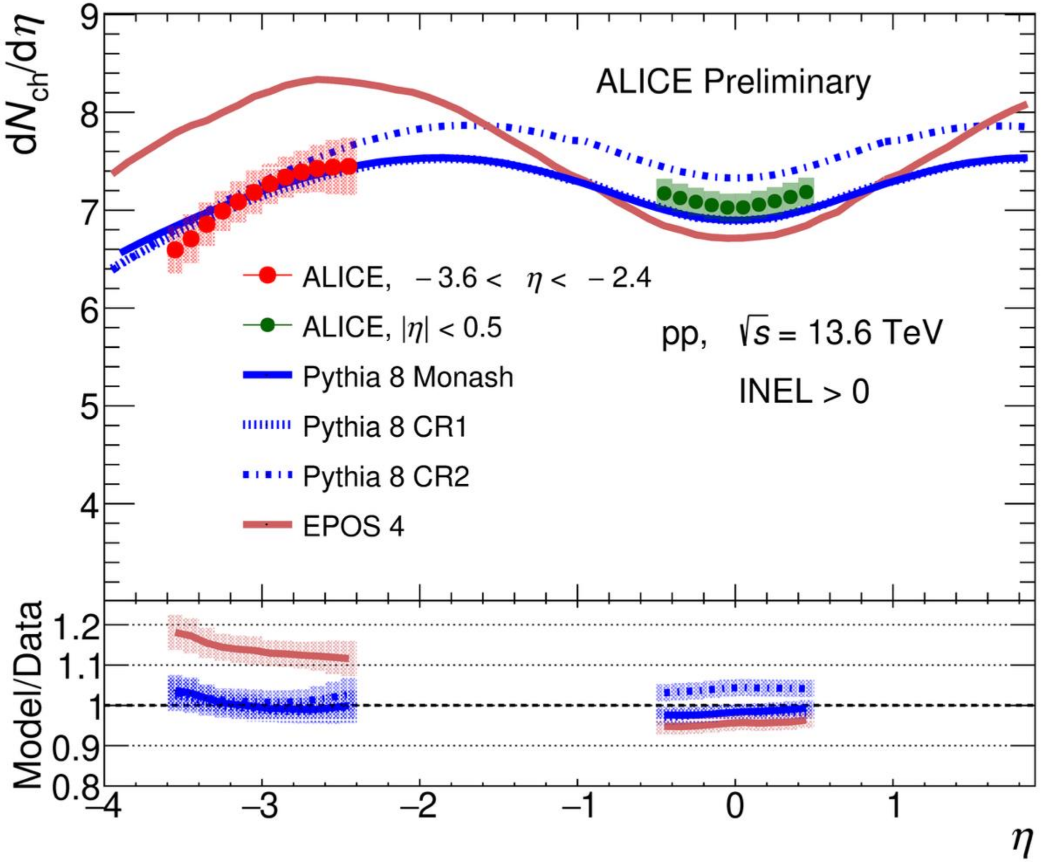
new detectors



Charged particle production in ALICE

arXiv:2504.02505



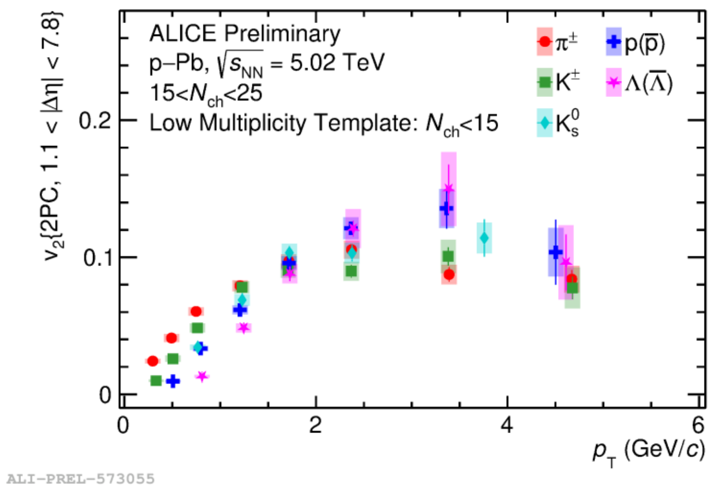


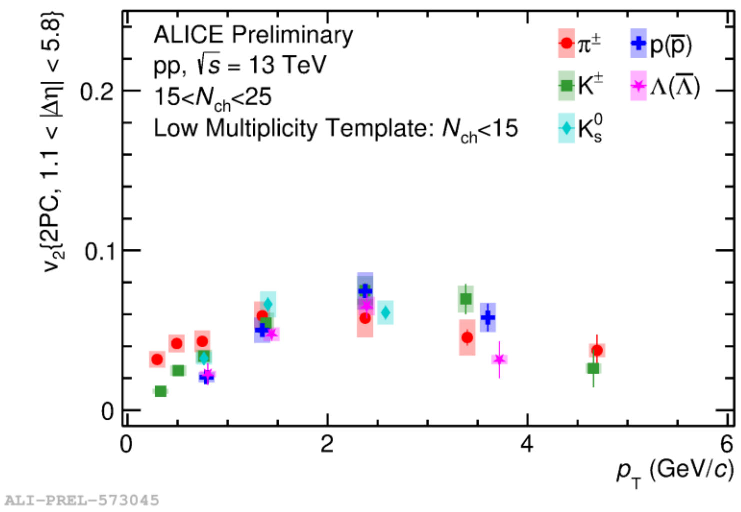
- ❑ ALICE first Run 3 publication
- ❑ Energy dependence in line with expectations

- ❑ ALICE first charged particle measurements in pp collisions at forward rapidity with new MFT detector
- ❑ Consistent with PYTHIA calculations

Anisotropic flow in various collision systems

Collective flow observed in large and small systems



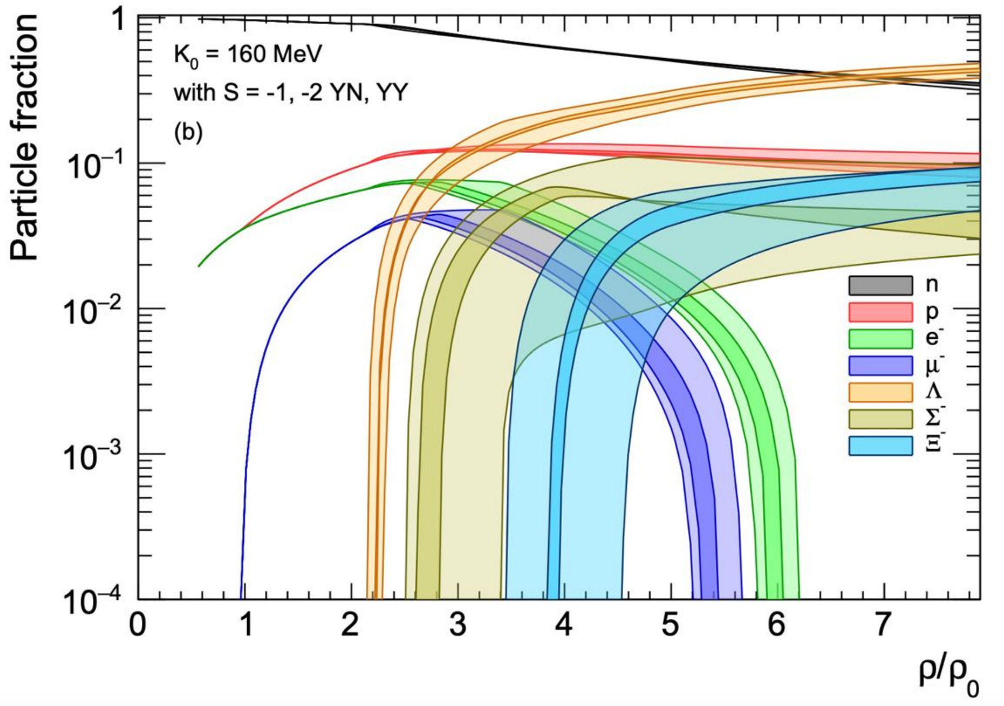


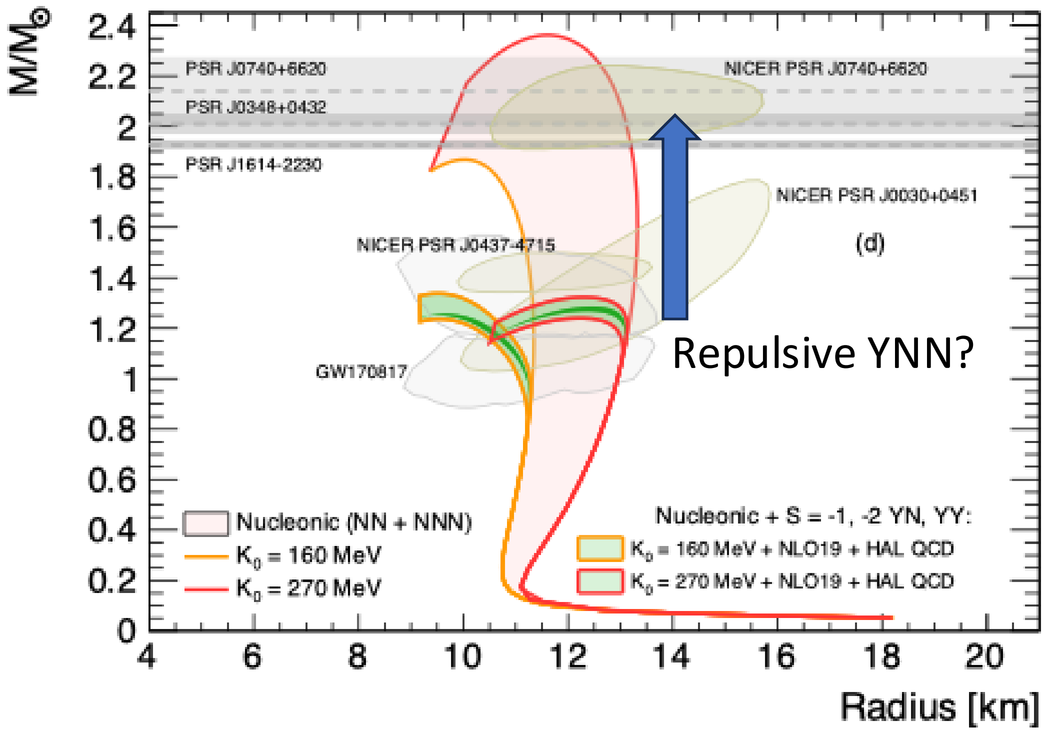
- v_2 is non-zero for low multiplicity events
- Baryon-meson grouping diminishes for N_{ch} < 25

What is role of initial state effects on v_2 in low multiplicity collisions?

Strangeness in Neutron Stars

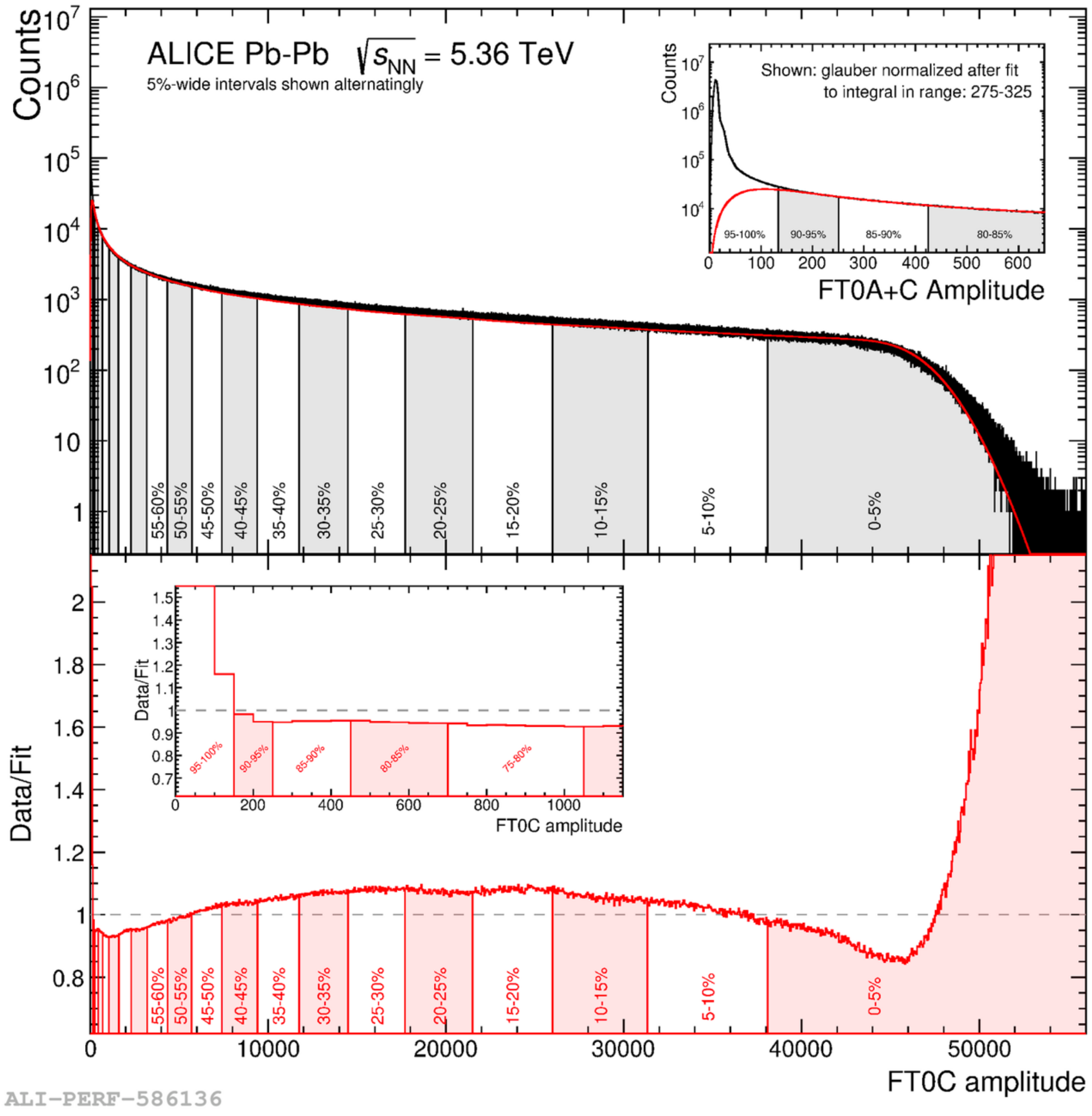
Equation of state with state-of-the-art interactions for NN, NNN, YN (S=-1 and S=-2) and YY fail to reproduce observed heavy neutron stars





I. Vida.a, V. Mantovani Sarti, J. Haidenbauer, D. Mihaylov, L. Fabbietti, EPJ.A 61 (2025) 3, 59

Multiplicity and centrality determination in ALICE



The multiplicity is estimated based on the signal amplitudes from FT0 detectors at forward rapidity

Centrality is determined based on a fit of Glauber models and Negative Binomial distribution (NBD)

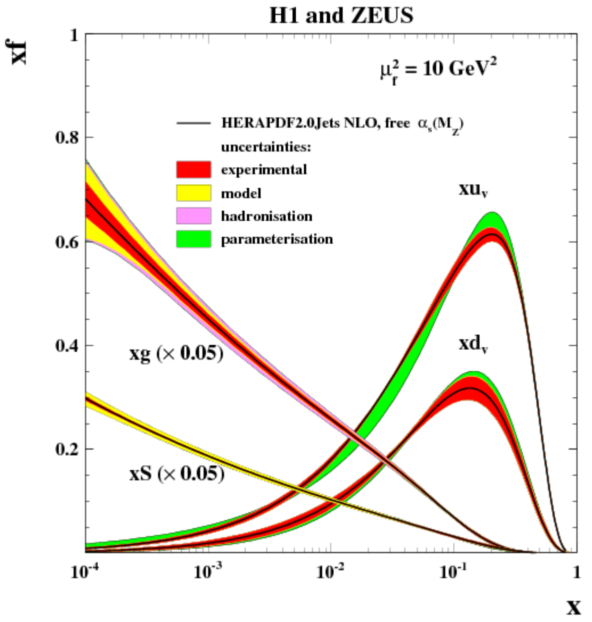
→ Glauber MC: generate the collision geometry using nuclear shape parameters
→ Glauber Nancestors + NBD: model particle production and fitting of the data

Nancestors = f Npart + (1-f) Ncoll
Each ancestor emits particles according to NBD with parameters (μ, k)

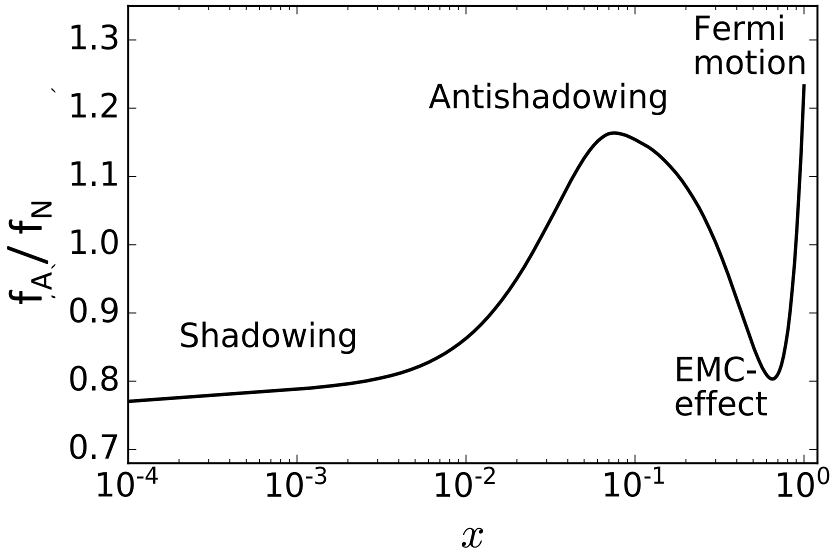
Probing parton distributions

- Hadron and nuclear PDFs at high energy
- Shadowing and gluon saturation at small Bjorken-x?
- Universal state of matter at high energy - Color Glass Condensate (CGC)?

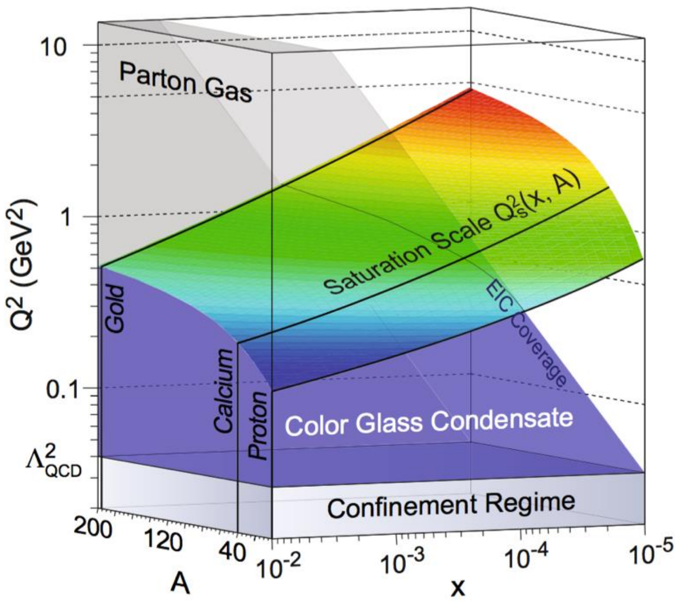
L. McLerran, R. Venugopalan, Phys. Rev. D 49 (1994) 2233



H1 and Zeus, EPCJ 75 (2015) 580



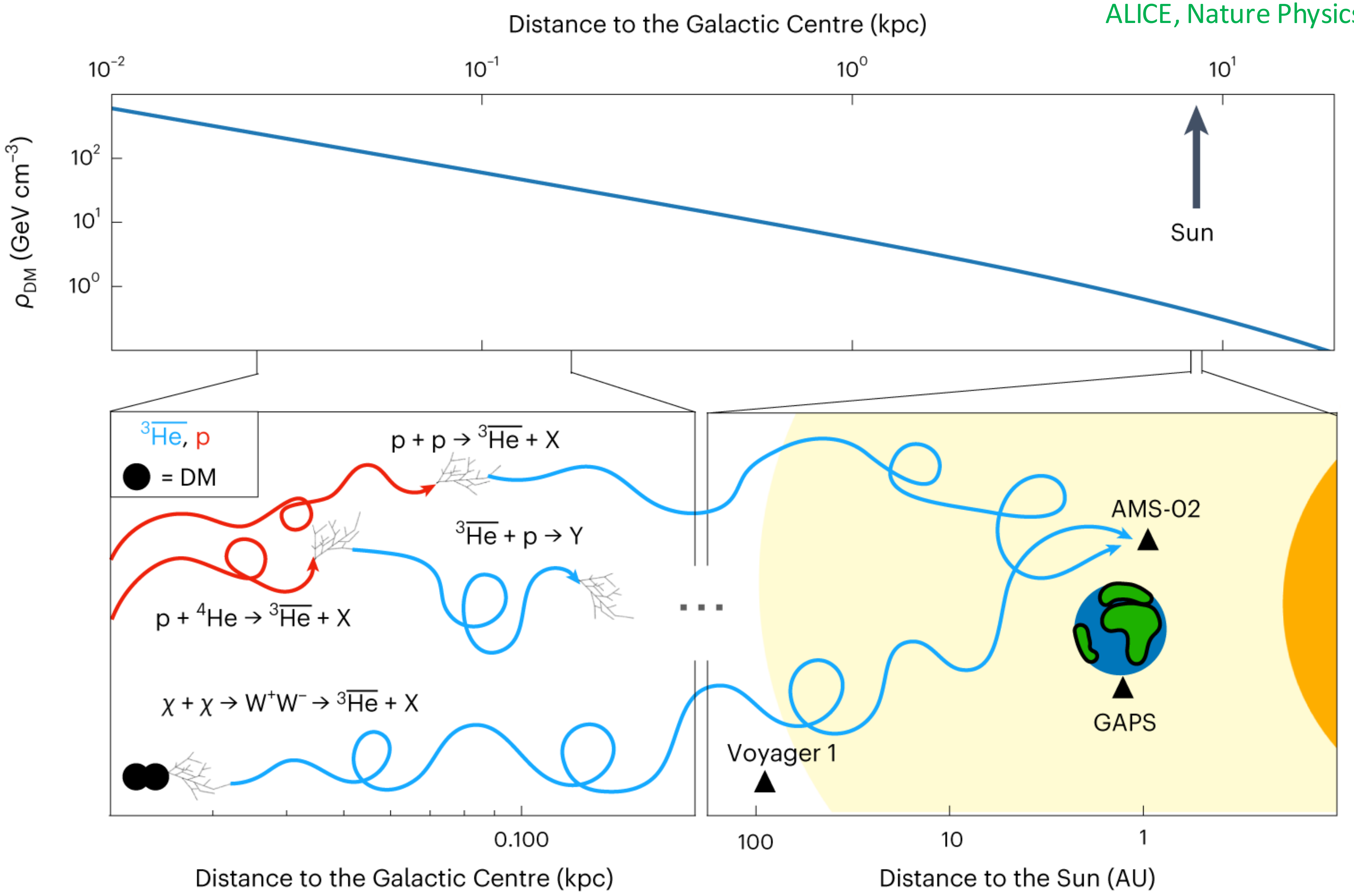
EMC, J.J. Aubert et al. Phys. Lett B123 (1983) 275



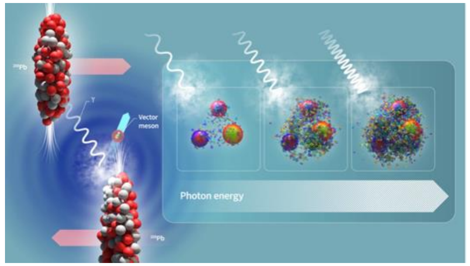
Accardi et al, EPJA 52 (2016) 268

Dark Matter Searches in ALICE

ALICE, Nature Physics 19 (2023) 61



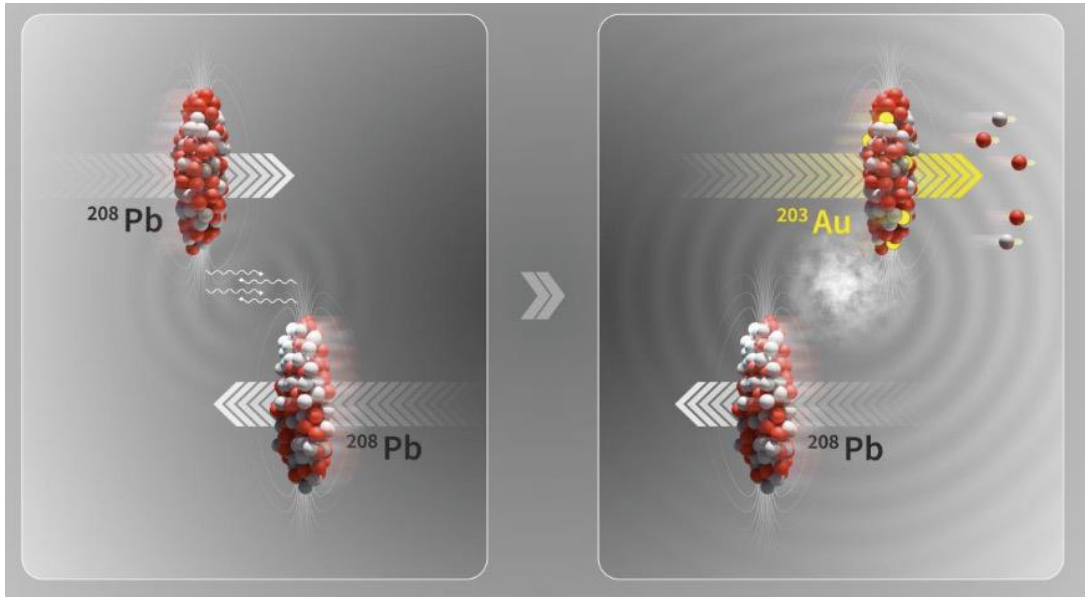
Modern form of Alchemy ☺

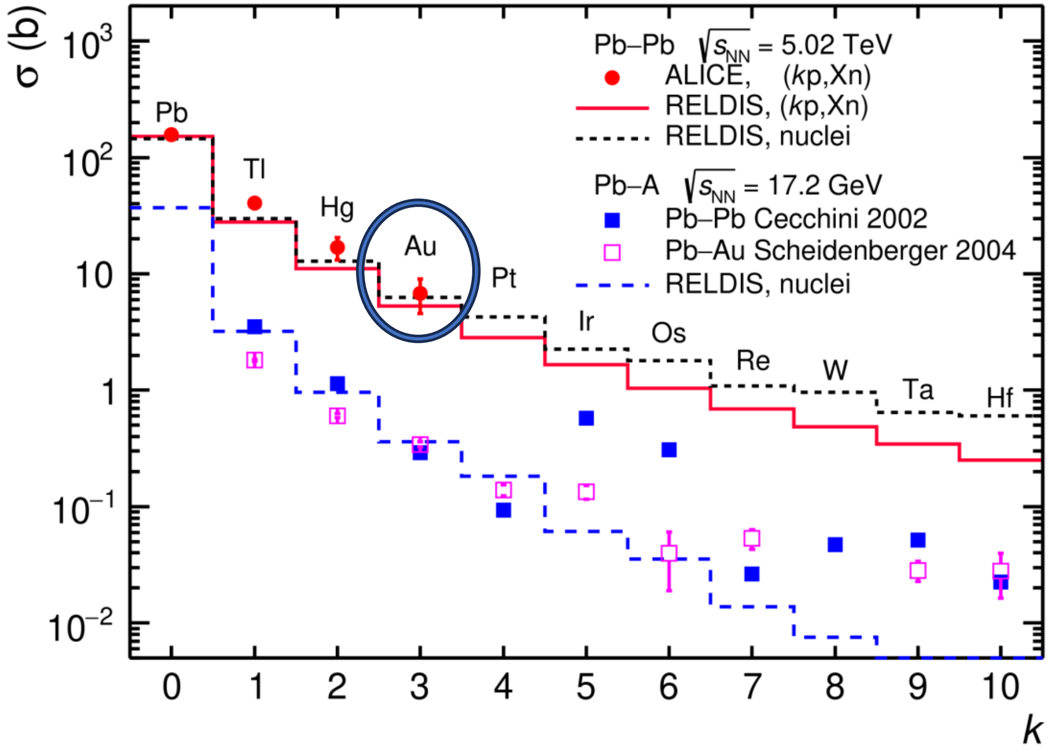


Electromagnetic dissociation of Pb in UPC

Emission of 3 protons: transmutation of Pb to Au by light

Phys. Rev. C111 (2025) 054906





ALI-PUB-606626

In total **~2.9×10^{-11}g** of various gold isotopes produced at the LHC during Run 2 (2015–2018)