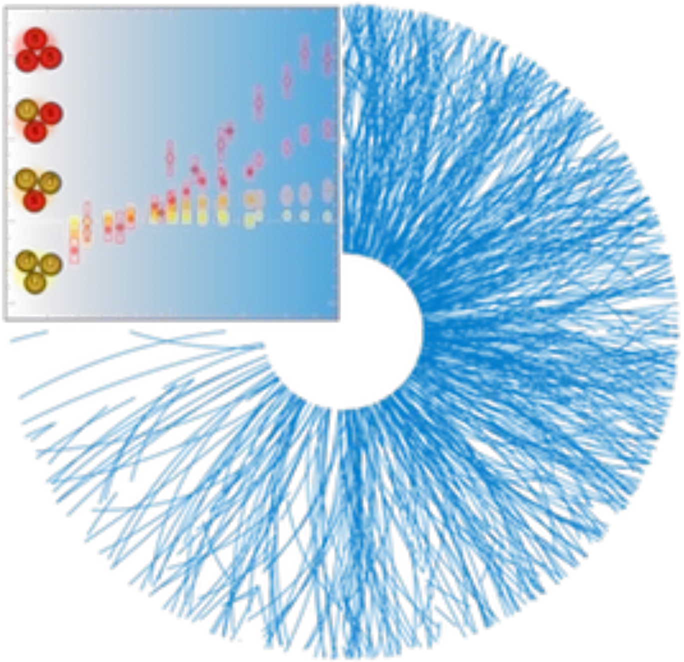
ALICE Highlights and Future

Jacek Otwinowski

(on behalf of the ALICE Collaboration)

Outline

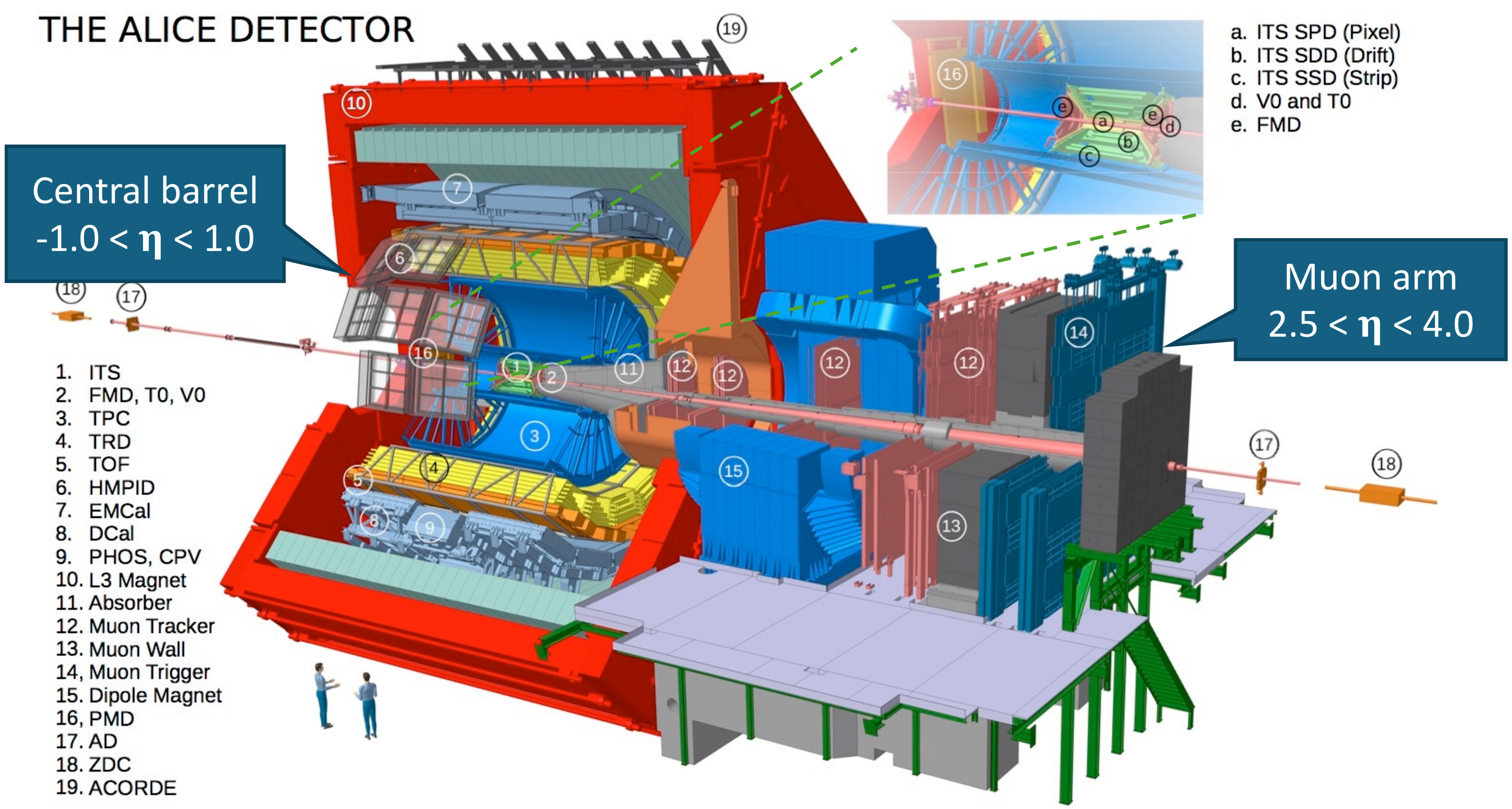
- ❑ Light flavour & nuclei
- ❑ Heavy flavour & charmonia
- ❑ ALICE Run-3 performance
- ❑ ALICE upgrades

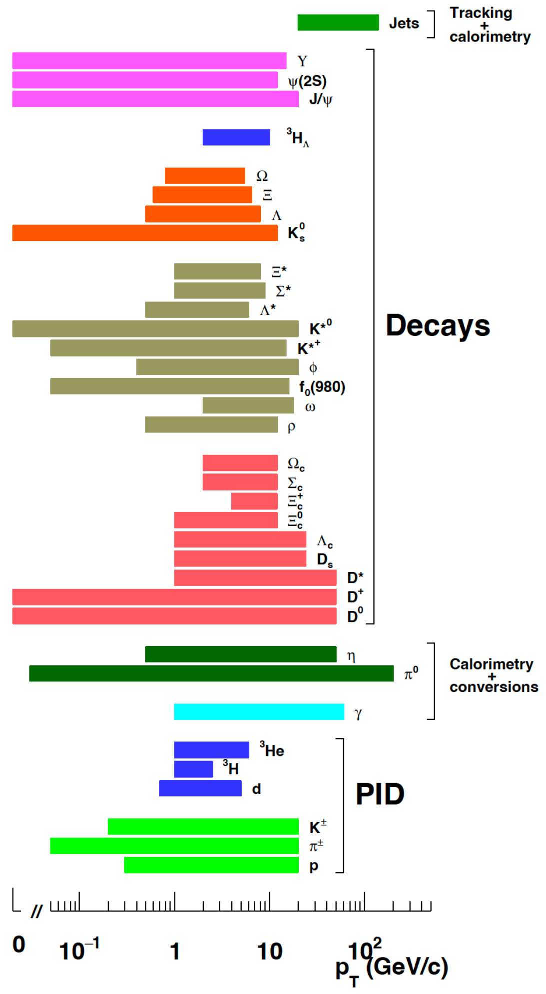


Focus on the LHC Run-2 (2015-2018) results!

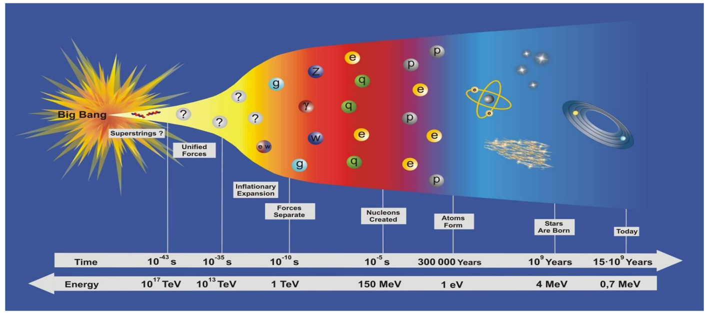
A Large Ion Collider Experiment (ALICE)

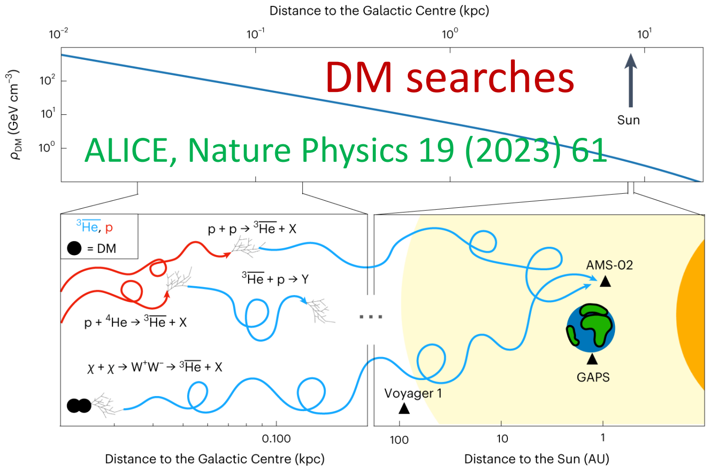
Excellent particle identification and good tracking in the broad momentum range!





ALICE Purpose





DM searches

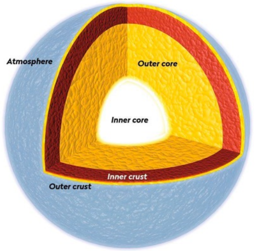
ALICE, Nature Physics 19 (2023) 61

- Properties of QCD matter at extreme conditions
- Characterization of Quark-Gluon Plasma (QGP)

  N. Cabibbo & G. Parisi. Phys. Lett. B59 (1975) 67

  J. C. Collins and M. J. Perry. Phys. Rev. Lett. 34 (1975) 1353

- Influence of initial- and final-state effects on particle production
- Dark Matter searches…

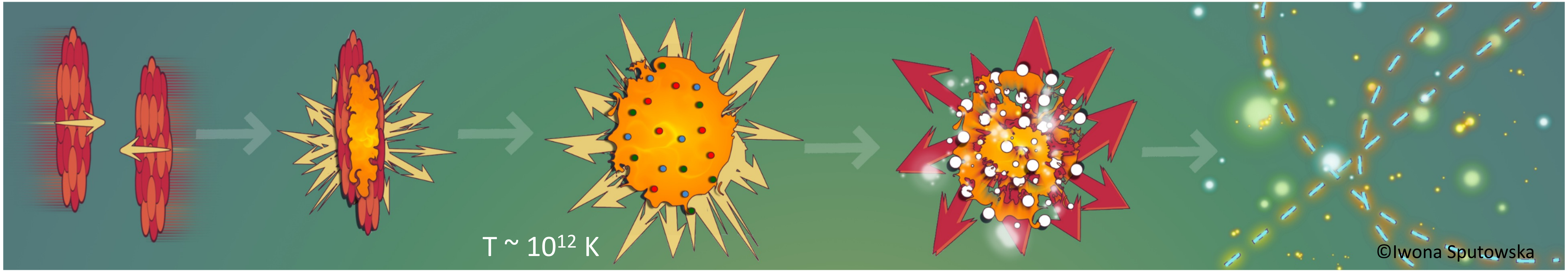


"Quark Stars"

D. D. Ivanenko & D. F. Kurdgelaidze

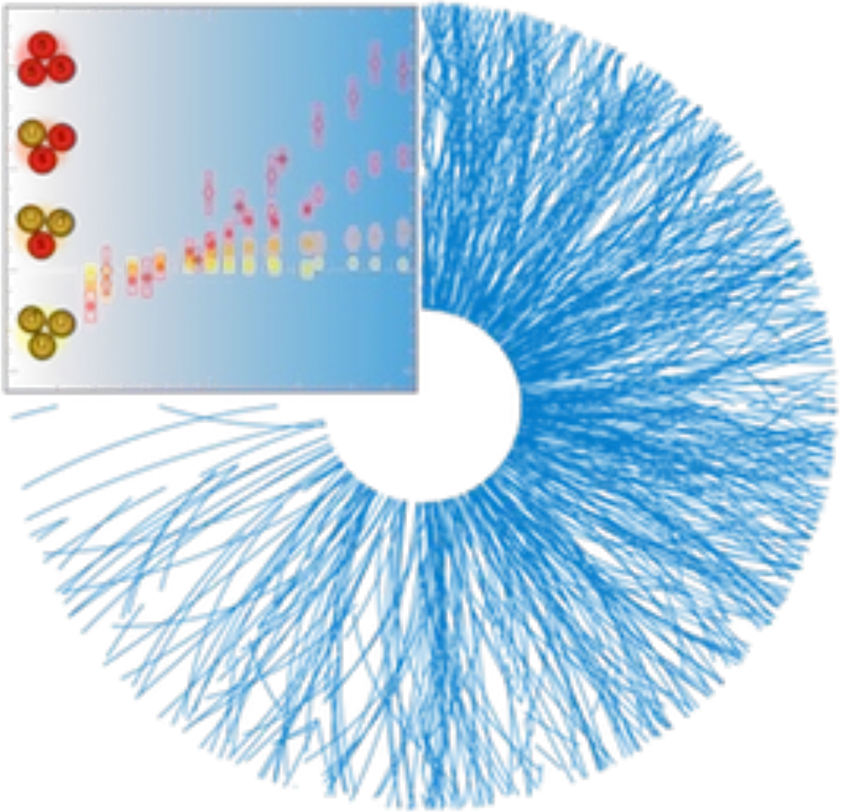
Astrofizika (1965) 479

Initial PDFs | Little Big Bang | Quark-Gluon Plasma | Collective expansion | Freeze-out



Measurements in A-A and reference p-p and p-A collisions!

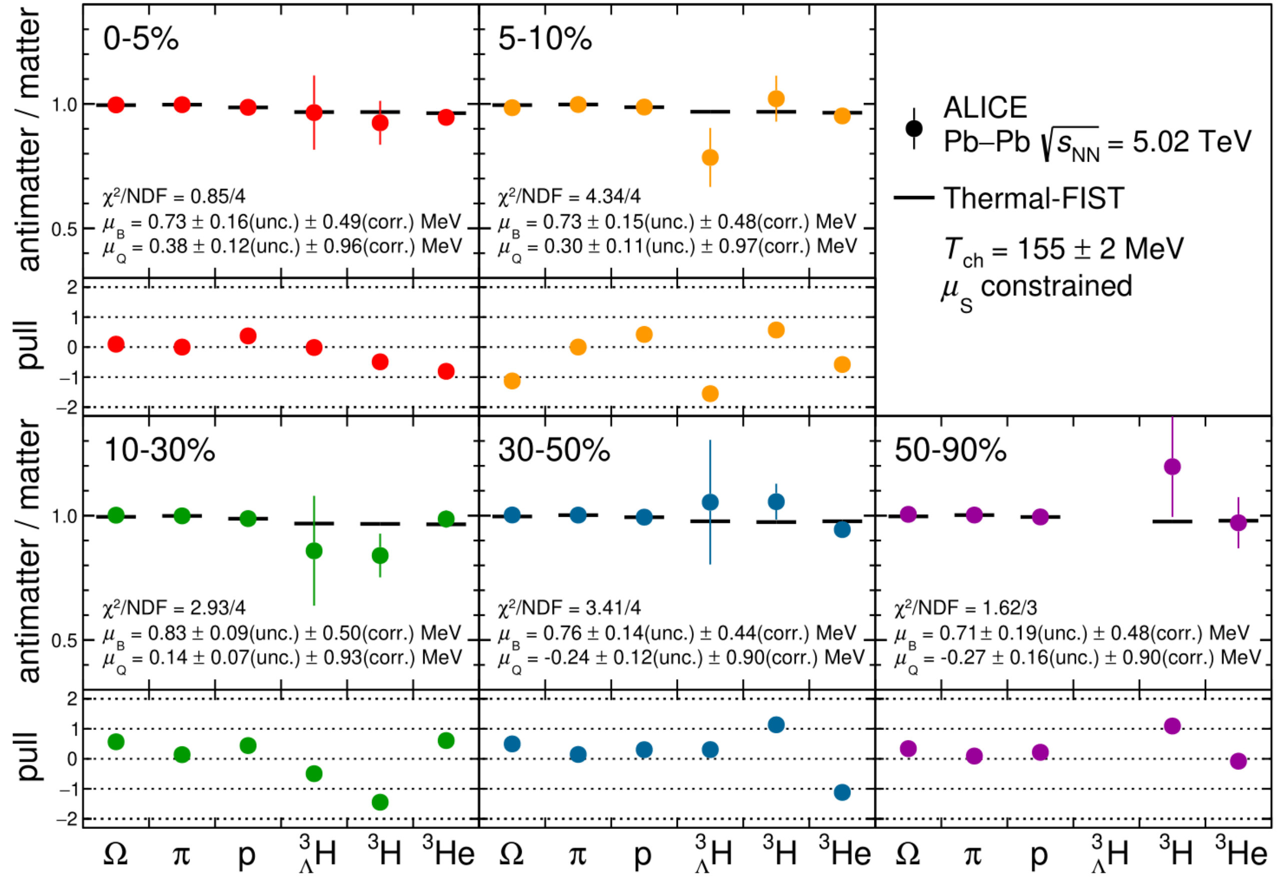
Time

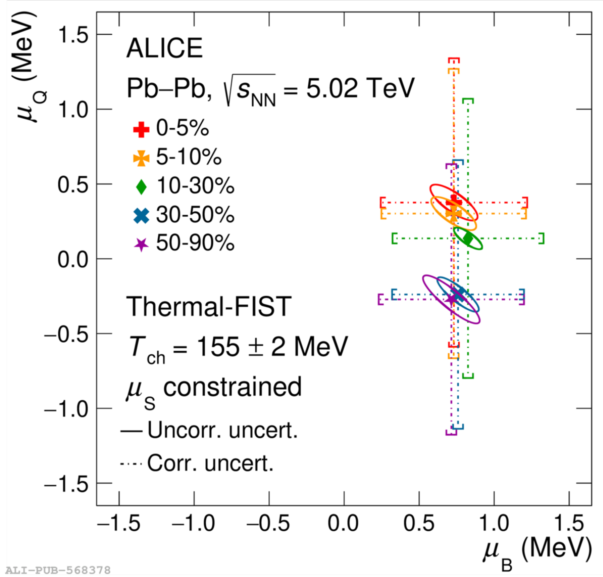


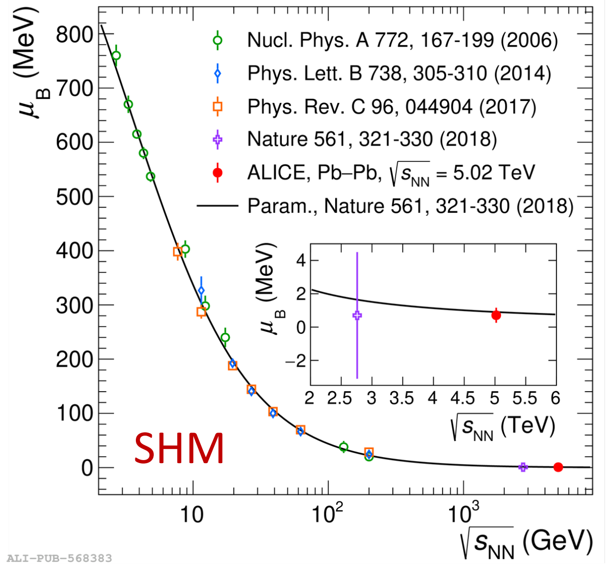
Light flavour & nuclei

Antimatter/matter imbalance at the LHC

Phys. Rev. Lett. 133 (2024) 092301







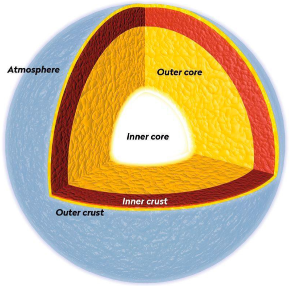
$$\frac{\bar{h}}{h} \propto e^{-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T}-2Q\frac{\mu_Q}{T}}$$

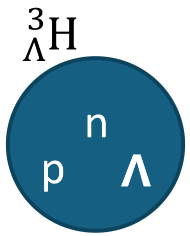
System created in Pb-Pb collisions is baryon-free and electrically neutral at midrapidity

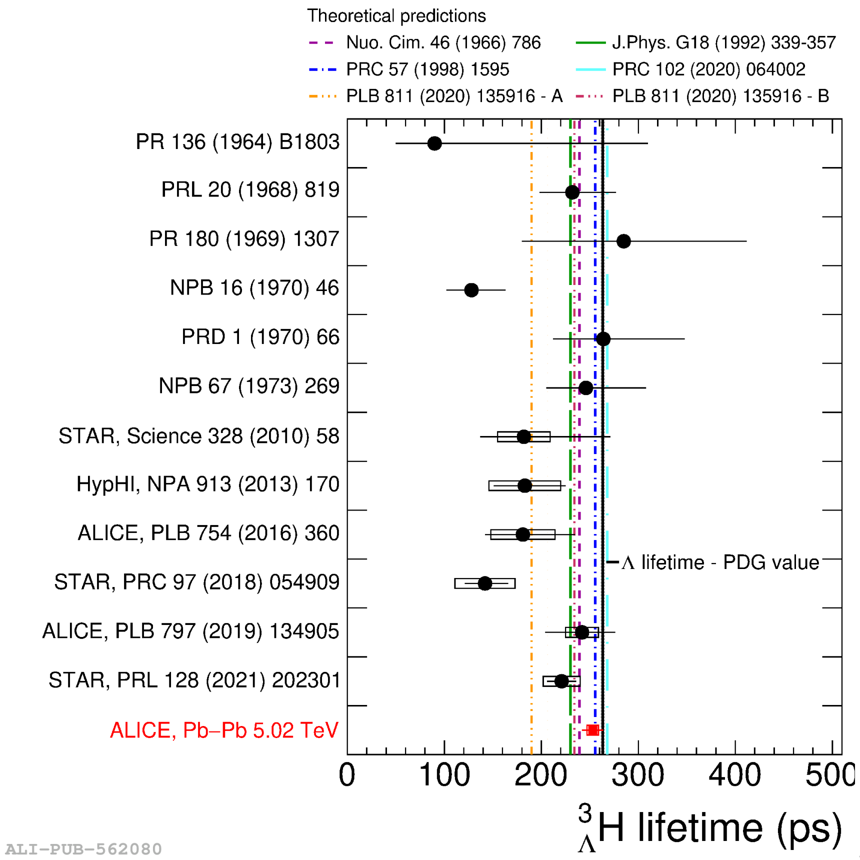
Thermal-Fist, V. Vovchenko et al. Comput. Phys. Commun. 244 (2019) 295
Statistical Hadronization Model (SHM) A. Andronic et al. Nature 561 (2018) 321

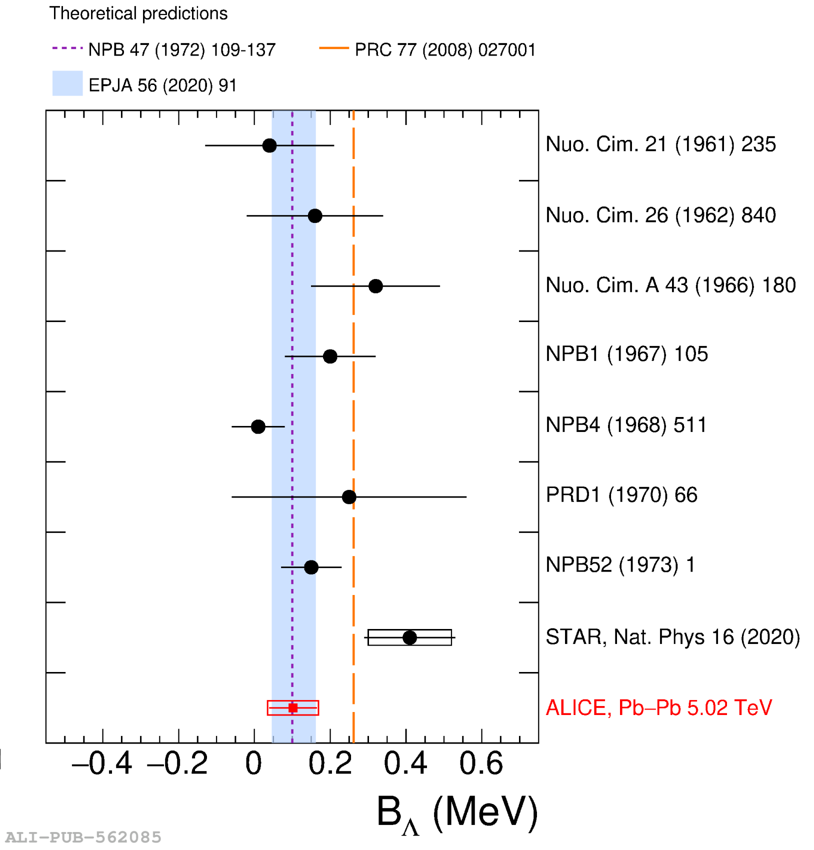
(Anti)hypertriton lifetime

Neutron Stars EoS - hyperon "puzzle" ($M_{NS} > 2\ M_{\odot}$)









Phys. Rev. Lett. 131 (2023) 102302

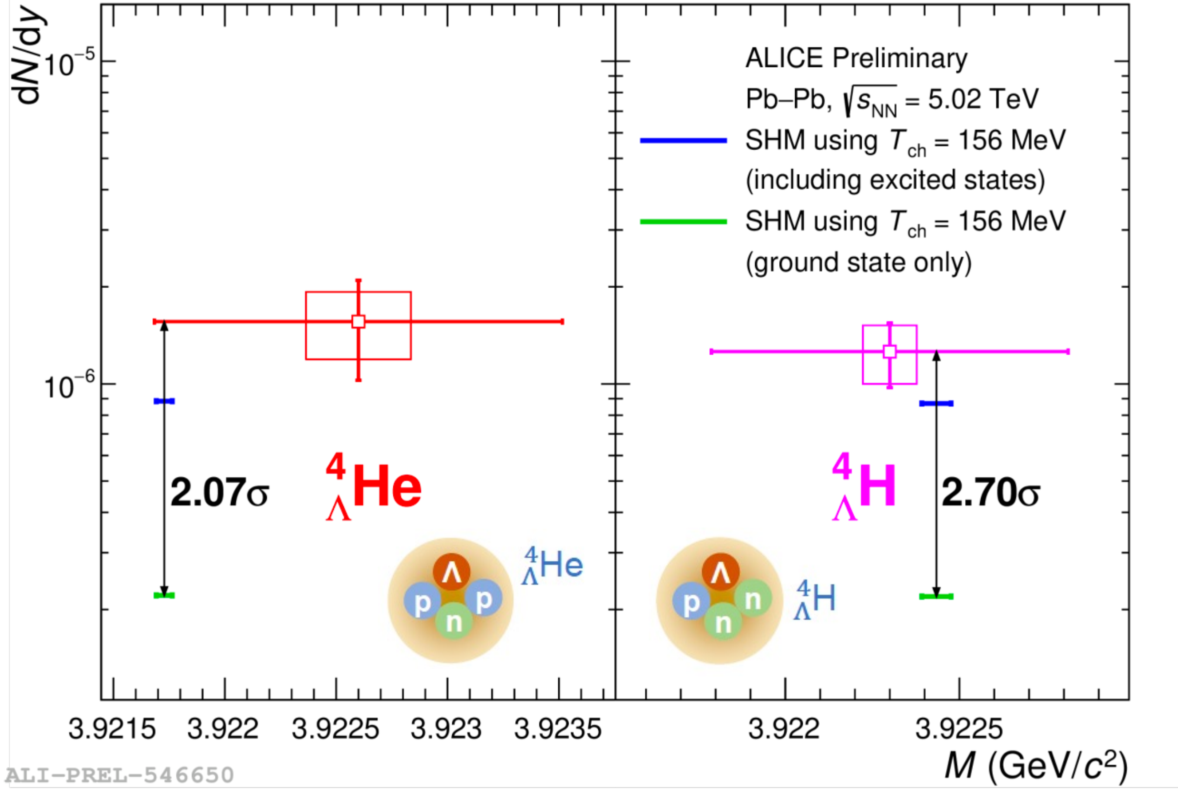
$\tau = 253 \pm 11(\text{stat.}) \pm 6\ (\text{syst.})$ ps

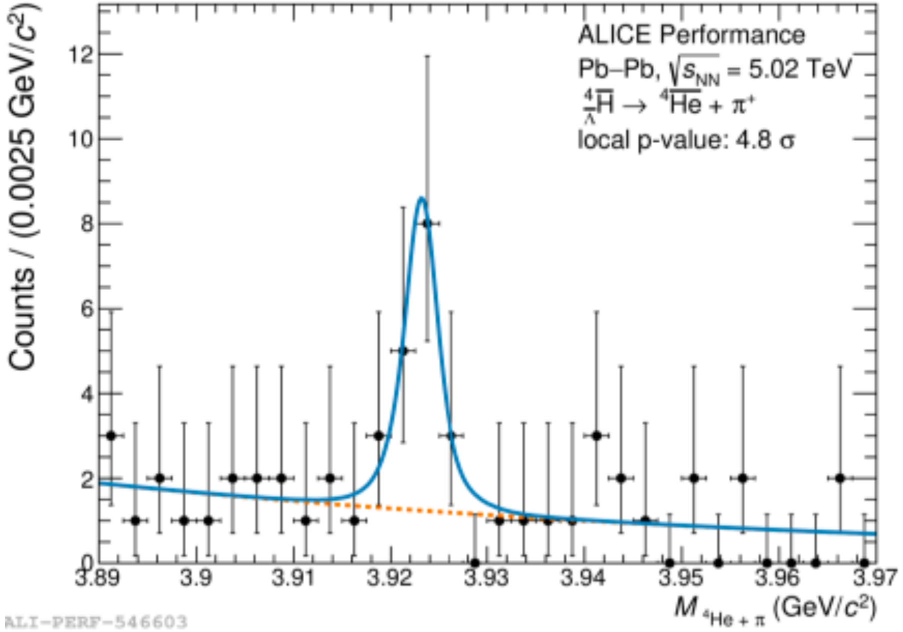
$B_{\Lambda} = 72 \pm 63(\text{stat.}) \pm 36\ (\text{syst.})$ keV

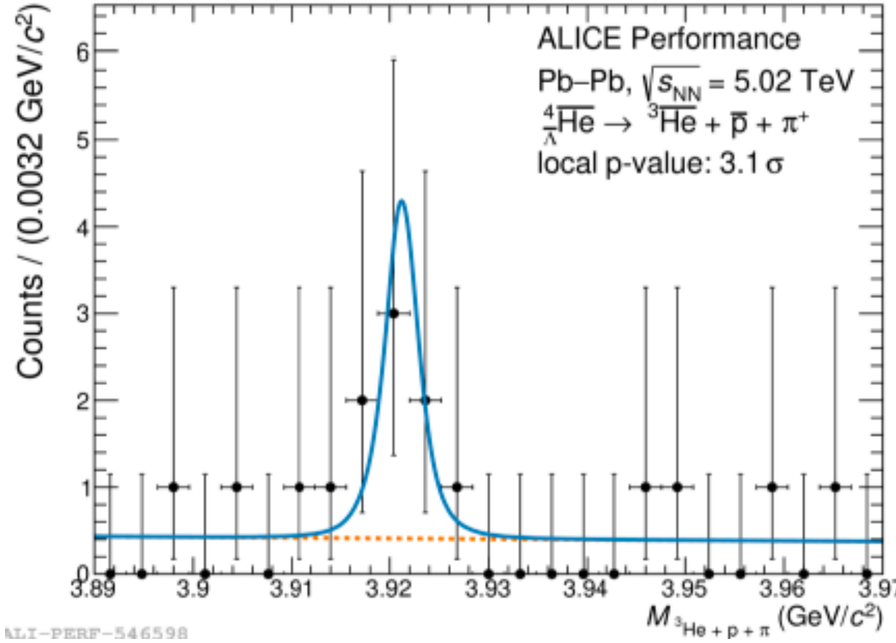
- Most precise measurement of hypertriton lifetime
- Models confirms that hypertriton is a weakly bound state

First A = 4 hypernuclei at LHC

First observation of the ${}^{4}_{\Lambda}\overline{\mathrm{He}}$ ever!

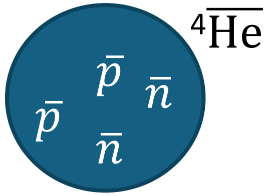






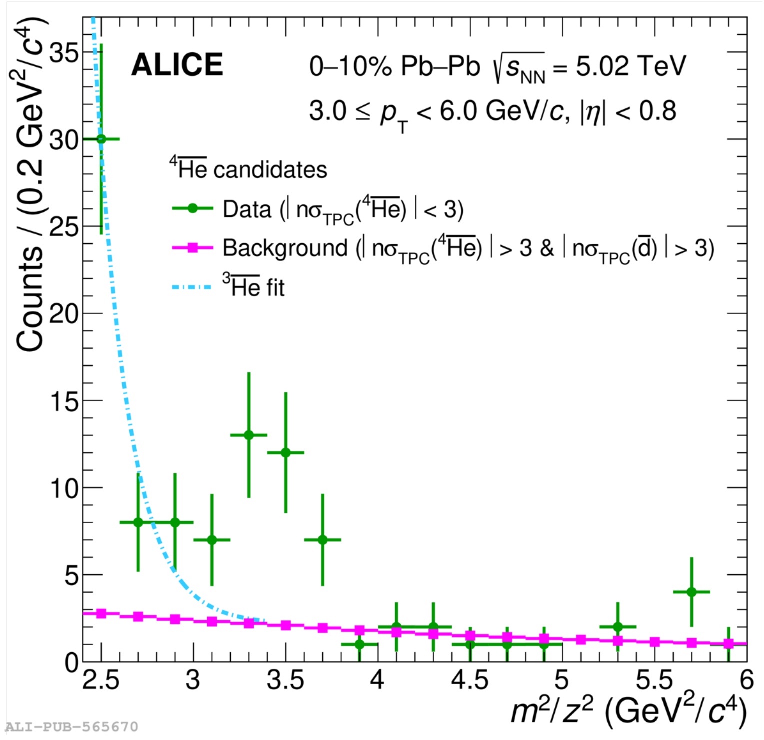
- SHM predictions consistent with the data
- Increase of statistics with Run 3 data ongoing

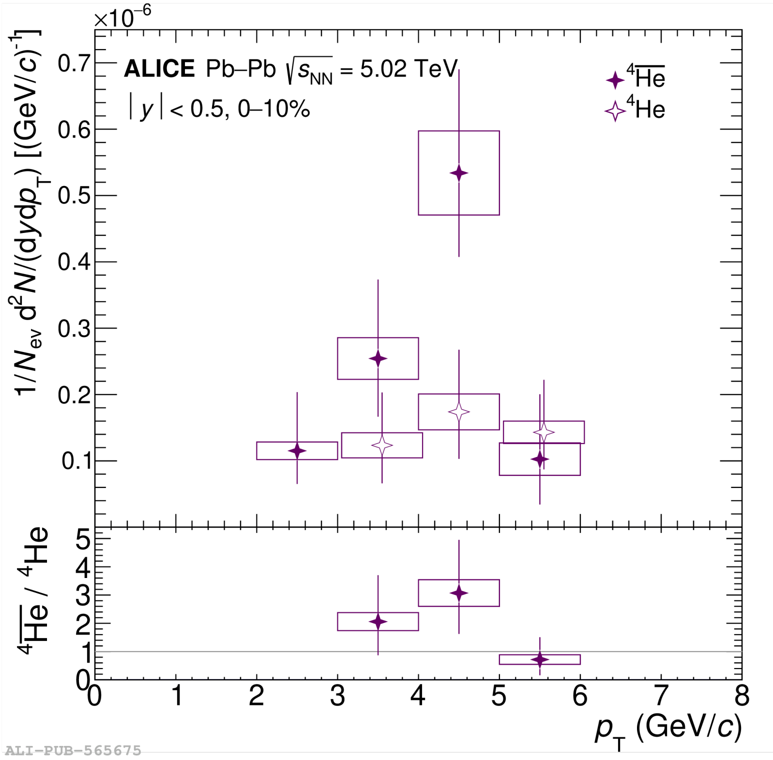
(Anti)alpha production at the LHC

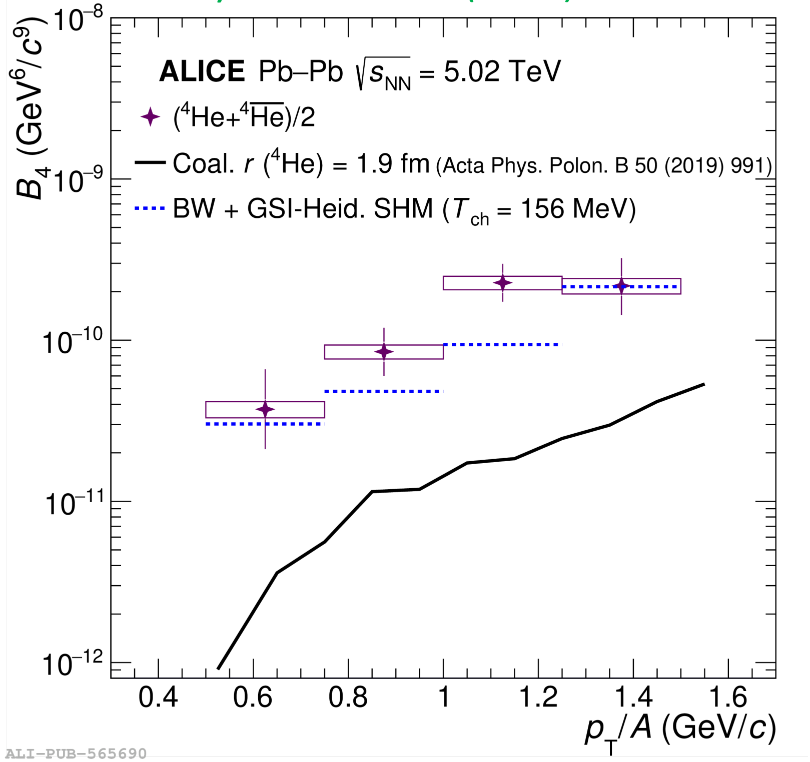


Test particle production mechanism with light nuclei

Phys. Lett. B 858 (2024) 138943







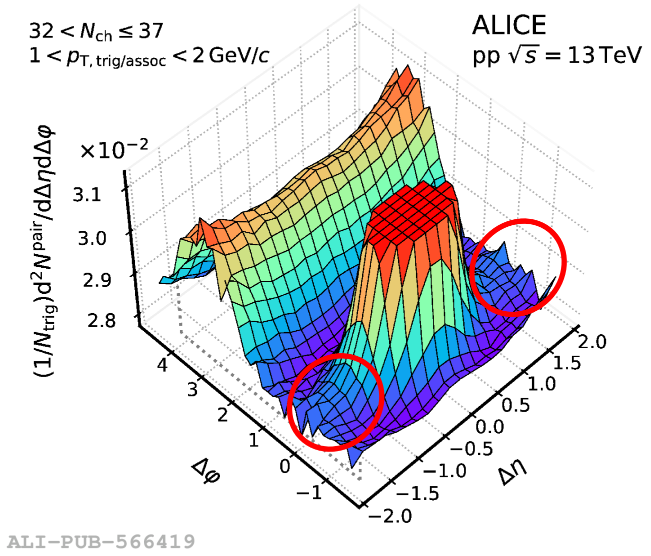
- $^4\overline{\text{He}}$ p_T distributions measured for the first time at the LHC
- (Anti)alpha production underestimated by the coalescence model (different picture than for the lighter nuclei)

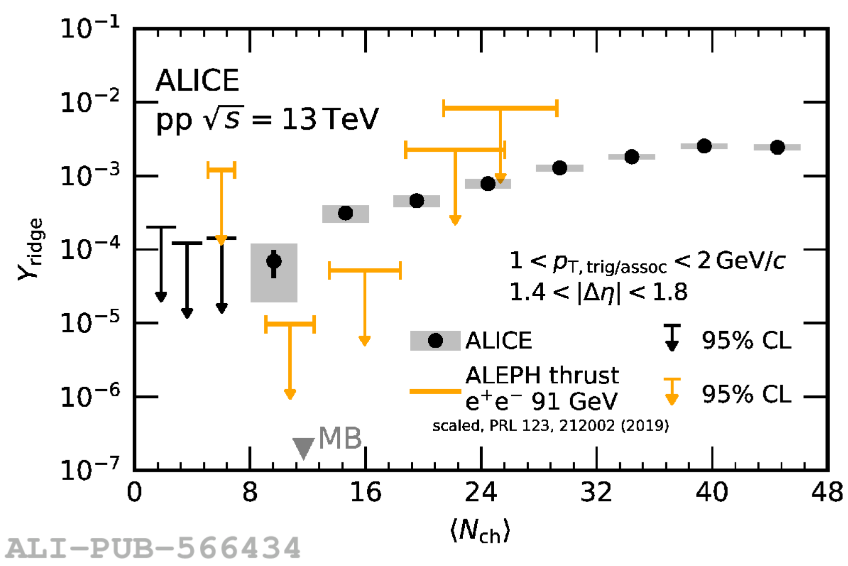
$$B_A = E_A \frac{d^3N_A}{dp_A^3}\left(E_p \frac{d^3N_p}{dp_p^3}\right)^{-A}$$

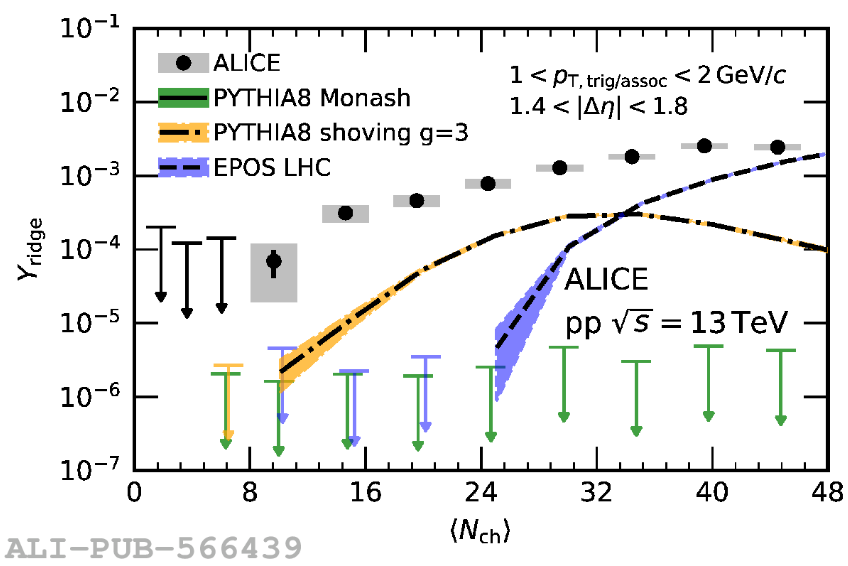
Emergence of long-range angular correlations ("ridge") in low-multiplicity pp collisions

The "ridge" – sign of collective expansion of QGP in Pb-Pb collisions

Phys. Rev. Lett. 132 (2024) 172302





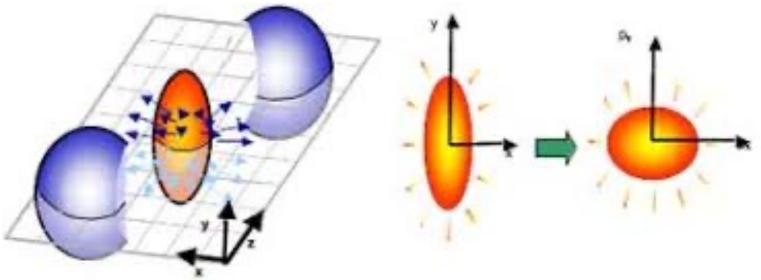


- The ridge is also visible in low multiplicity pp collisions
- Processes involved e^+e^- annihilation (ALEPH) do not contribute to the ridge in pp collisions (also confirmed at higher energy Y.-Ch. Chen et al. arXiv:2312.05084)
- Pythia tunes underestimate the ridge

Identified particle flow in Pb-Pb collisions

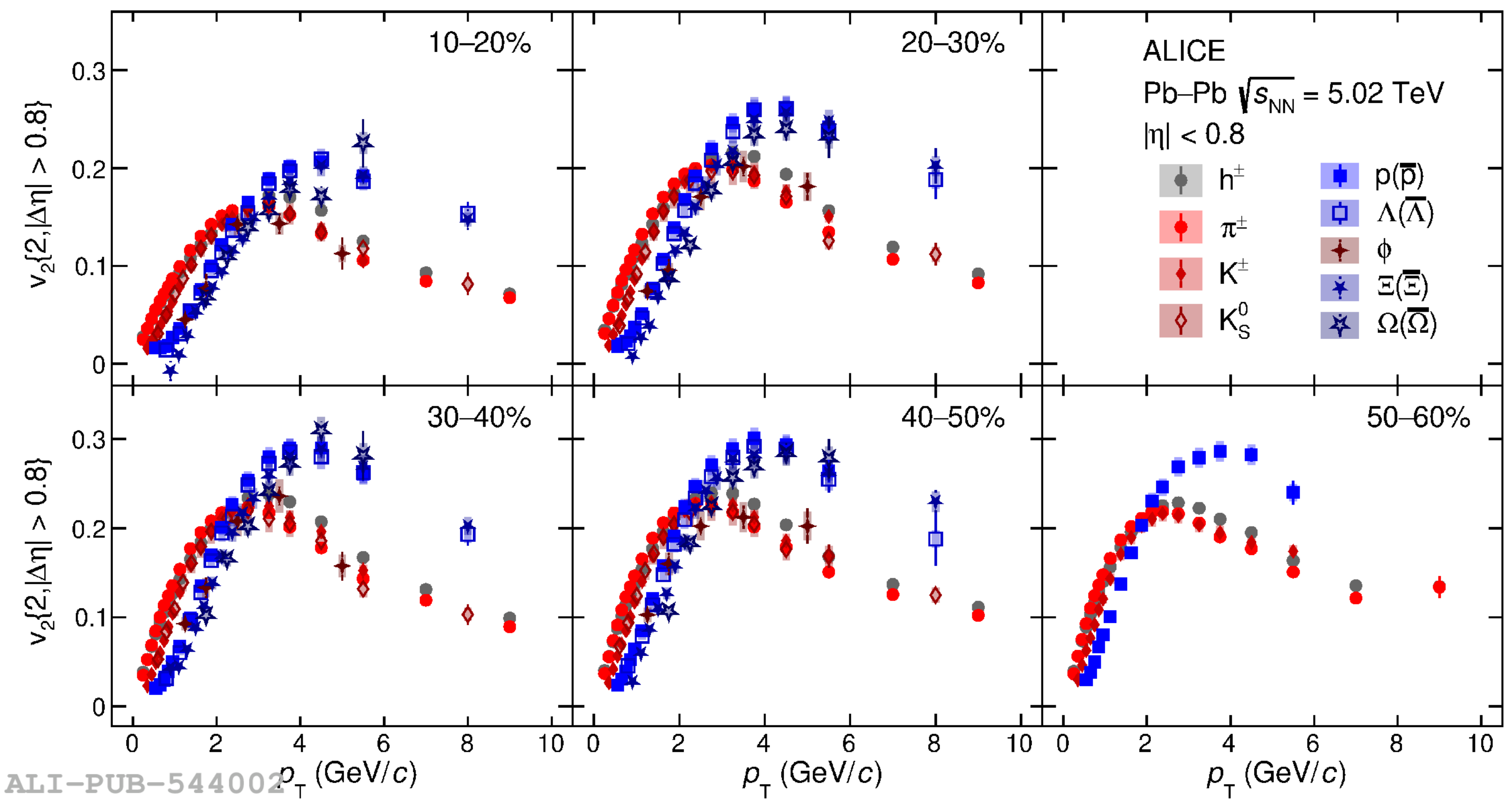
JHEP 05 (2023) 243

non-central heavy-ion collision



$$\frac{dN}{d\phi} \approx 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \psi_n))$$

v_n – flow coefficient

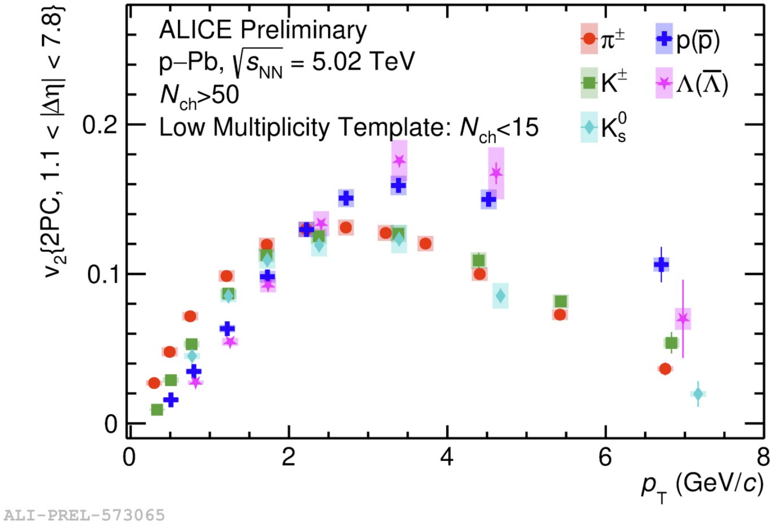


- Low-p_T (<2 GeV/c): mass ordering (hydrodynamics)
- Interm.-p_T (2-7 GeV/c): baryon-meson grouping and splitting (partonic collectivity, quark coalescence,...)
- High-p_T (>7 GeV/c): fragmentation in jets

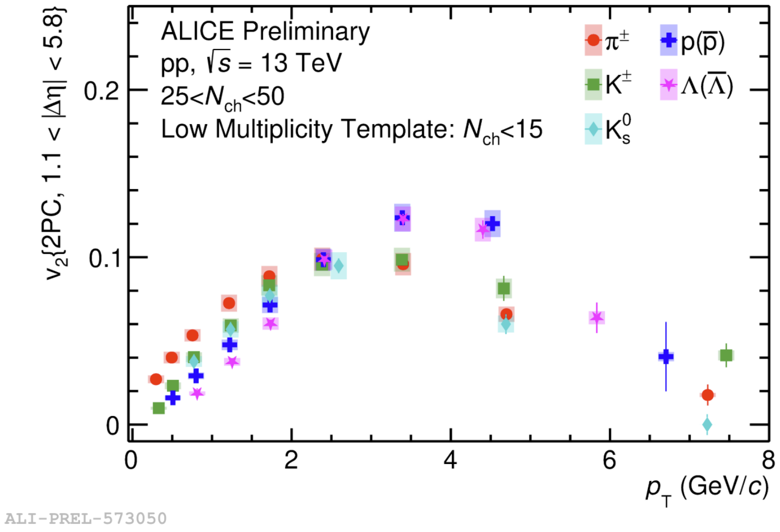
Identified particle flow in p-Pb collisions

Similar pattern to flow in heavy-ion collisions (initial vs final state effects)

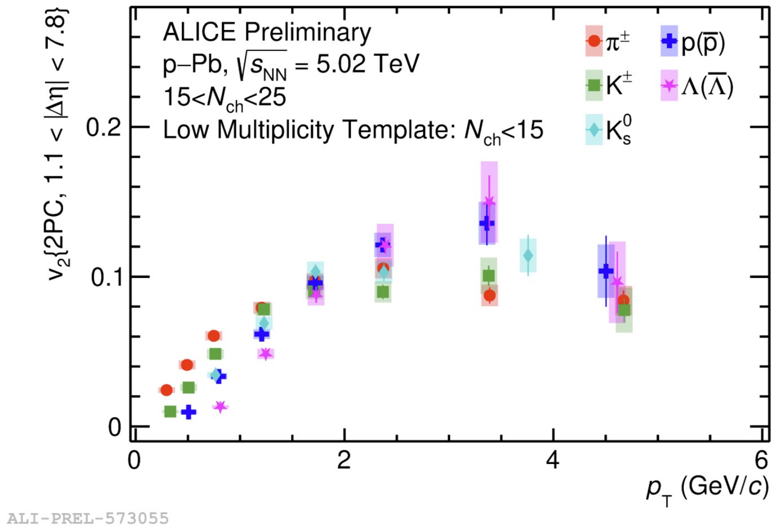
$N_{ch} > 50$



$25 < N_{ch} < 50$



$15 < N_{ch} < 25$

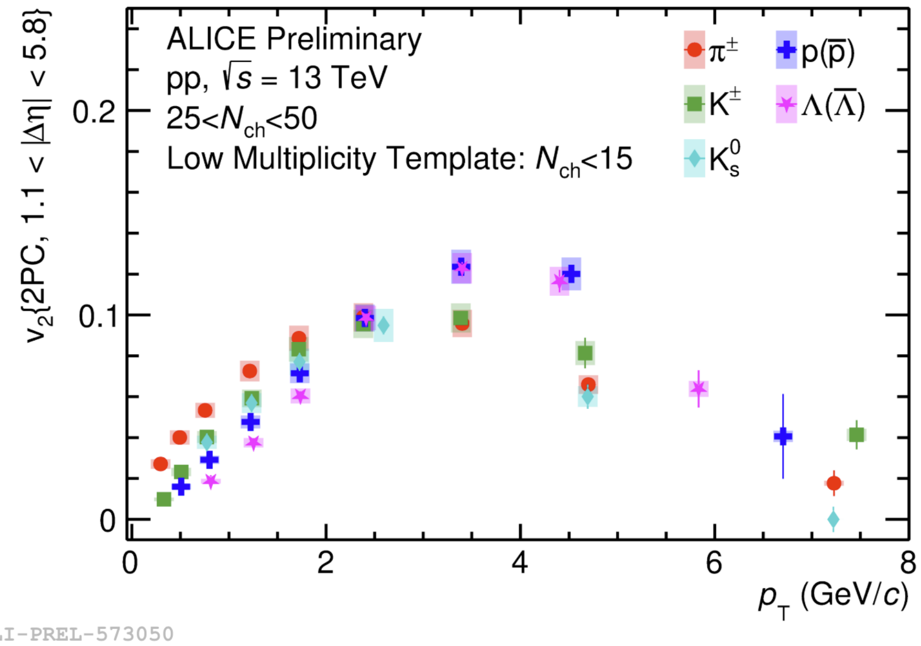


- Low-p_T (<2 GeV/c): mass ordering
- Interm.-p_T (2-7 GeV/c): baryon-meson grouping and splitting for N_{ch} > 25 (diluted for N_{ch} < 25)
- High-pT (>7 GeV/c): fragmentation in jets

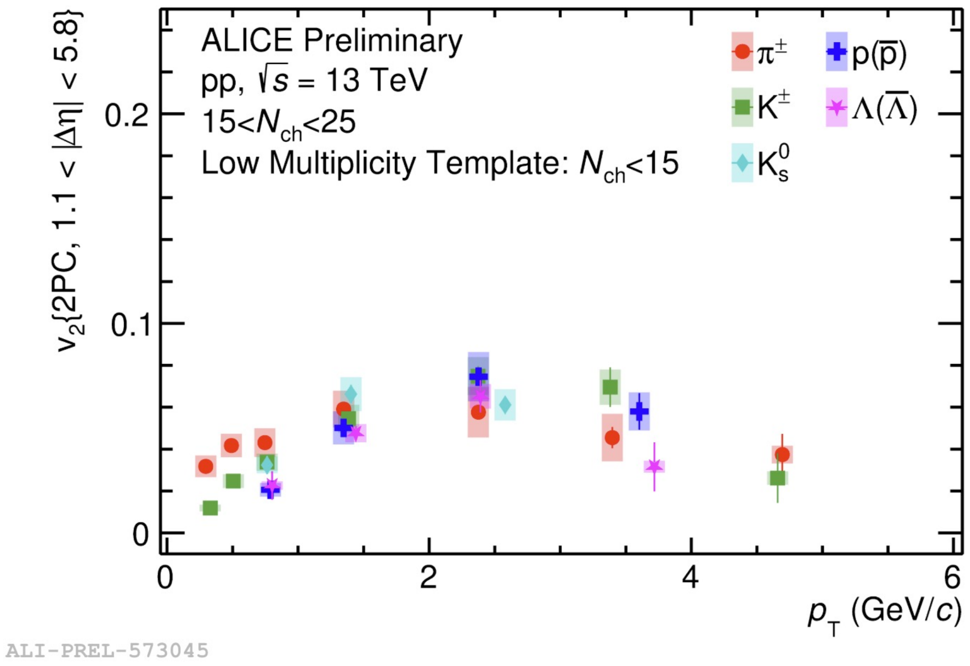
Identified particle flow in p-p collisions

Similar pattern to flow in heavy-ion collisions (initial vs final state effects)

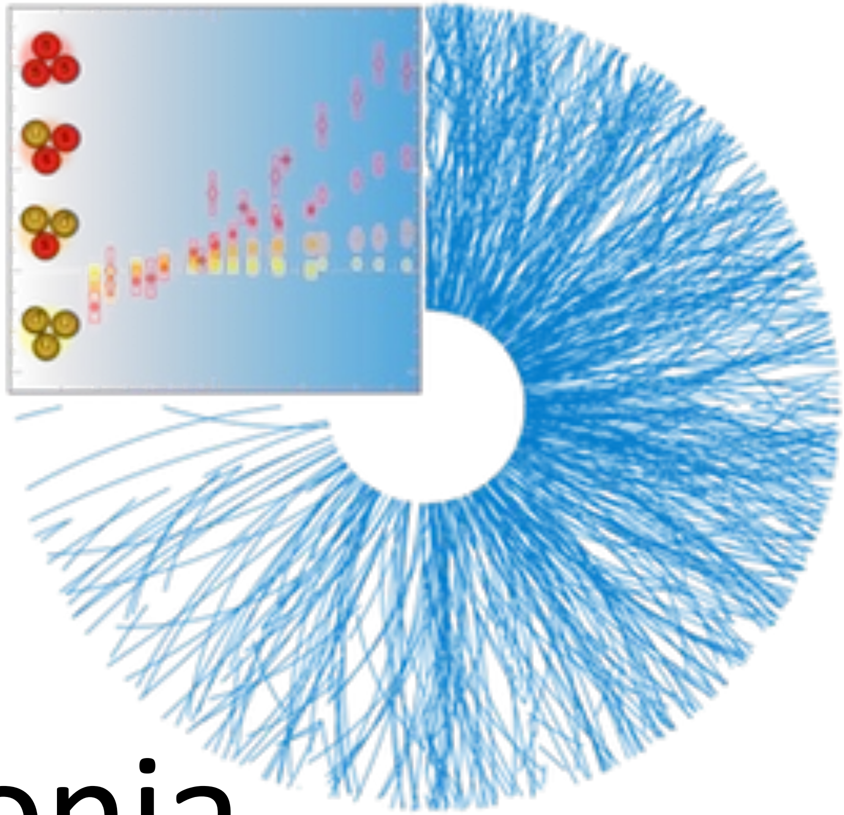
$25 < N_{ch} < 50$



$15 < N_{ch} < 25$



- Low-p_T (<2 GeV/c): mass ordering
- Interm.-p_T (2-7 GeV/c): baryon-meson grouping and splitting for N_{ch} > 25 (disappears for N_{ch} < 25)
- High-p_T (>7 GeV/c): fragmentation in jets



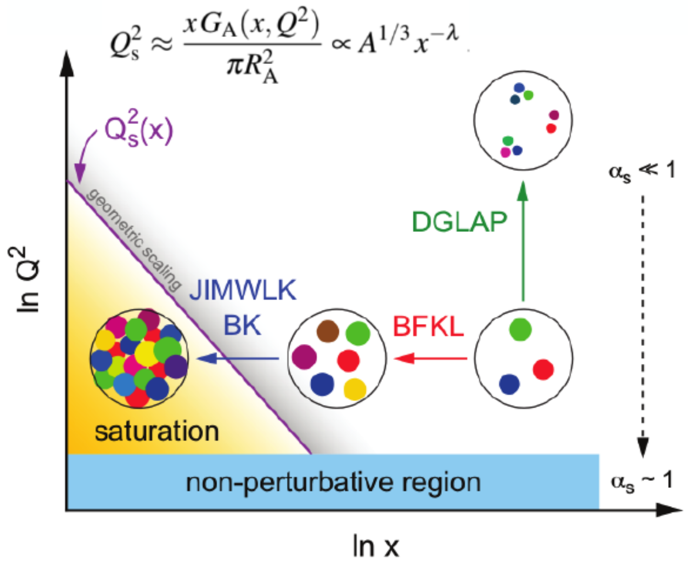
Heavy flavour & charmonia

Heavy flavour (hard probes)

Ideal probes to study initial and final state effects on particle production

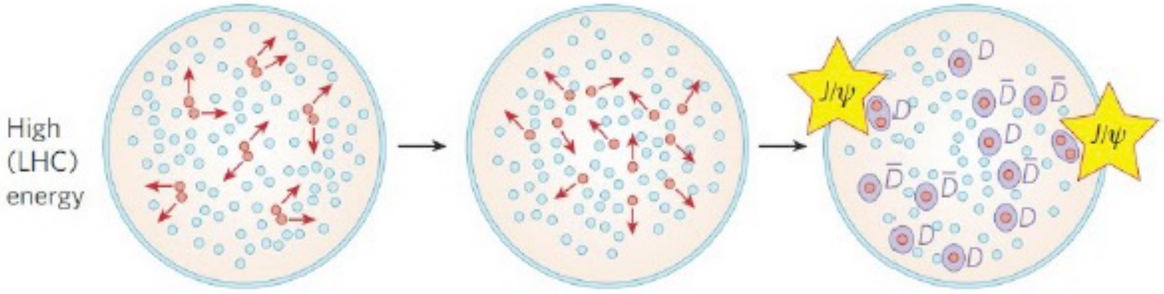
Initial state

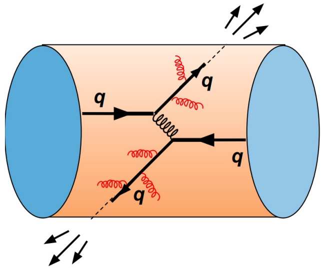
- Modification of Parton Distribution Functions
- Gluon saturation and Color-Glass Condensate (CGC)
  L. McLerran, R. Venugopalan, Phys. Rev. D 49 (1994) 2233



Final state

- Parton energy loss in QGP (collisional/radiative, $\Delta E_g > \Delta E_q > \Delta E_Q$)
  Yu. L. Dokshitzer et al., J. Phys. G: Nucl. Part. Phys. 17 (1991) 1602
- Hadronization mechanisms (fragmentation/recombination)
- Dissociation of charmonium states in hot medium
  T. Matsui & H. Satz, Phys. Lett. B178 (1986) 416
- Recombination of charm and anti-charm quarks
  P. Braun-Munzinger & J Stachel, Phys.Lett. B490 (2000) 196
  R Thews et al., Phys. Rev. C 63:054905

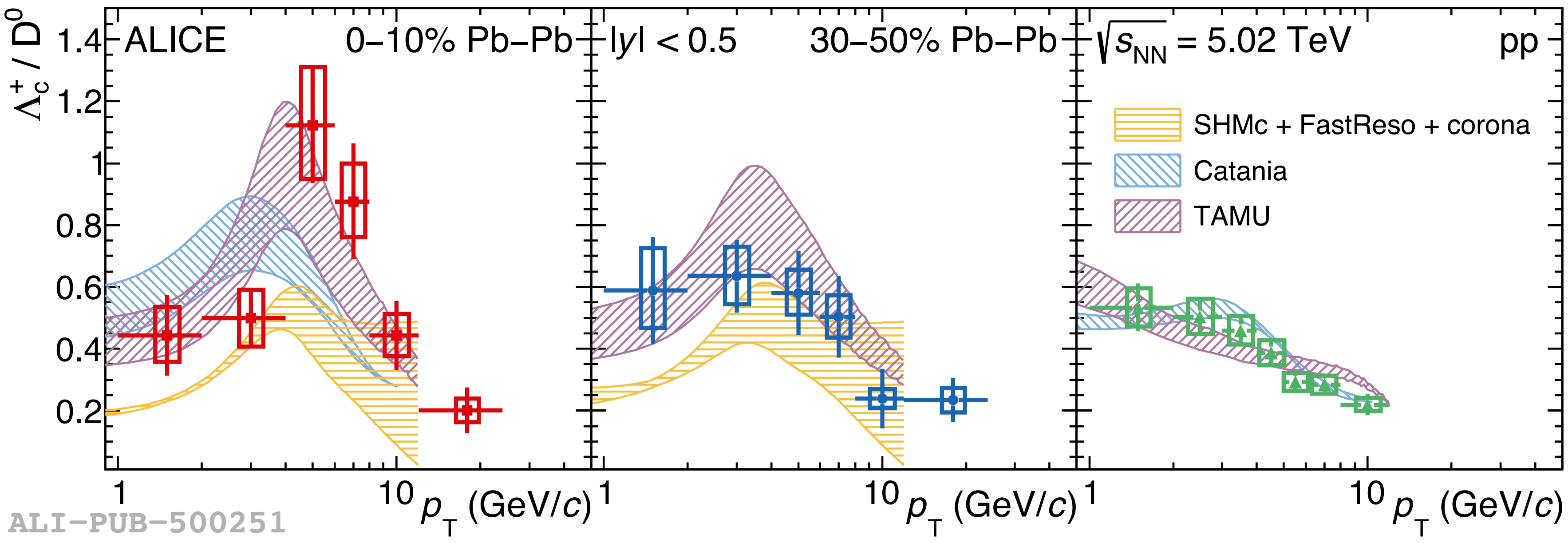


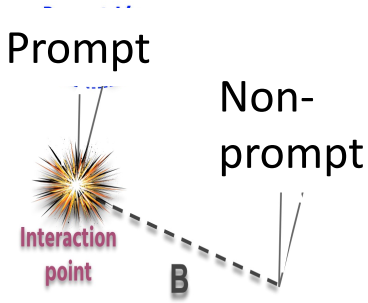


Prompt Λ_c baryon production in pp and Pb-Pb

Constraining hadronization mechanisms

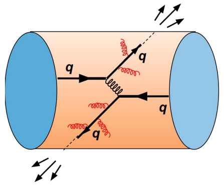
Phys. Lett. B 839 (2023) 137796

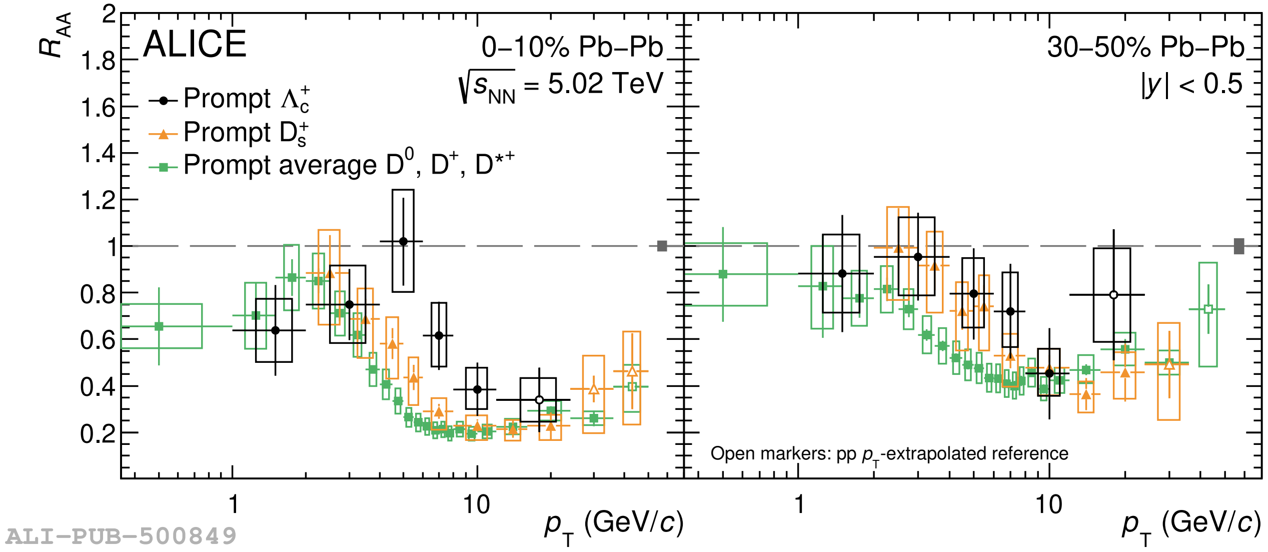


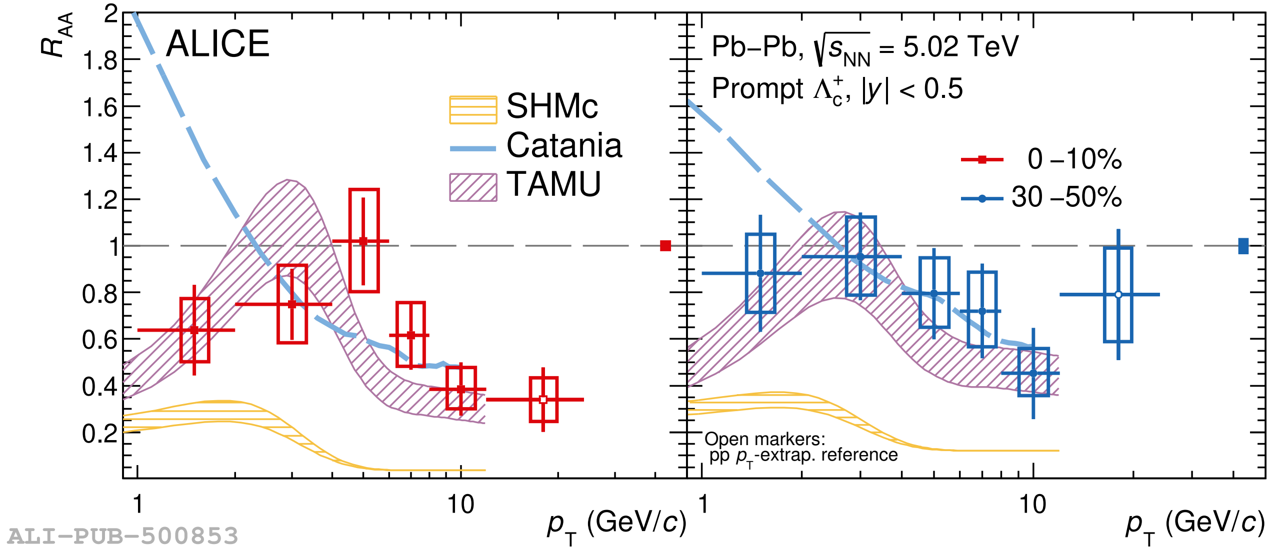


- Prompt Λ_c / D meson ratio in pp and Pb-Pb compared to model predictions
- Catania and TAMU models include hadronization mechanisms via coalescence and fragmentation
- Statistical hadronization model (SHMc) include only measured charmed mesons and baryons (p_T distributions modeled with core-corona approach)
- Λ_c / D ratio increases from pp to central Pb-Pb collisions at intermediate p_T → enhanced production via coalescence or/and feed-down from higher mass resonances

R_{AA} of prompt Λ_c baryon in Pb-Pb







Phys. Lett. B 839 (2023) 137796

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

- Hint of hierarchy in central collisions:
  $R_{AA}(\Lambda_C) > R_{AA}(D_s^+) > R(D^0)$

→ Hadronization via charm quark coalescence or/and feed-down from higher mass resonances

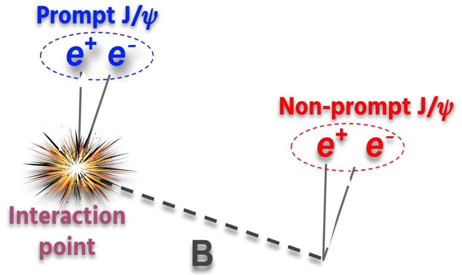
- Catania and TAMU models do not include charm-quark radiative energy loss
- TAMU model provides a good description of the R_{AA} over the whole p_T range in both centrality classes

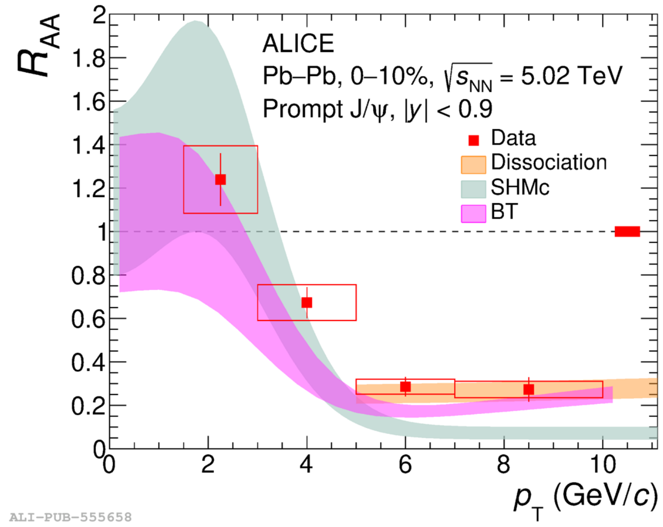
Prompt and non-prompt J/ψ production

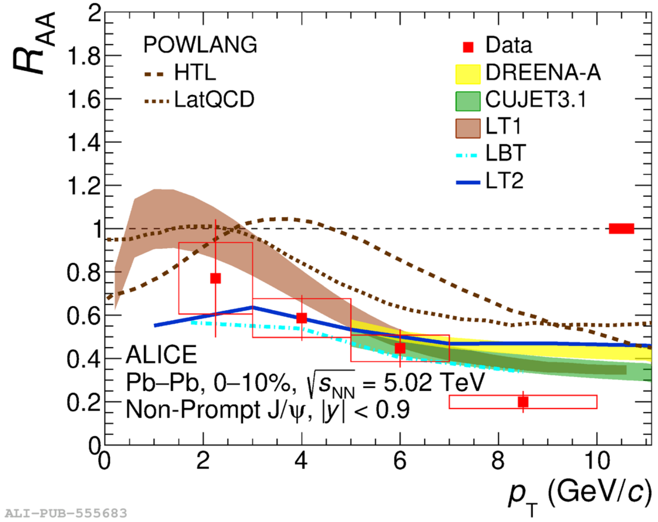
JHEP 02 (2024) 066

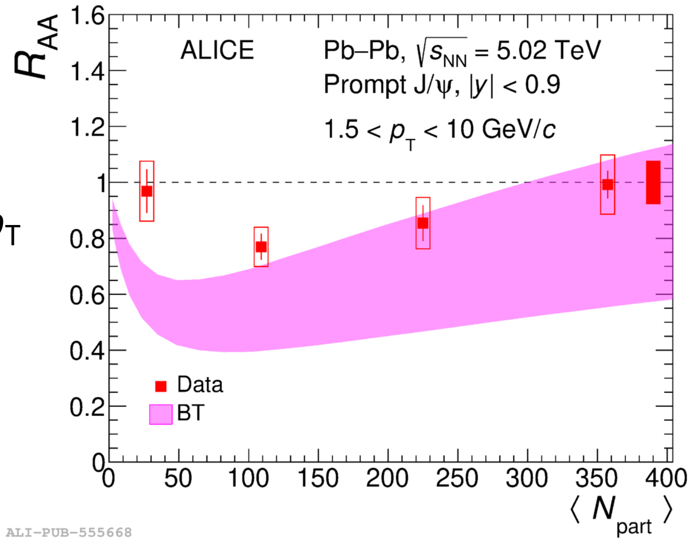
Parton energy loss, dissociation vs regeneration

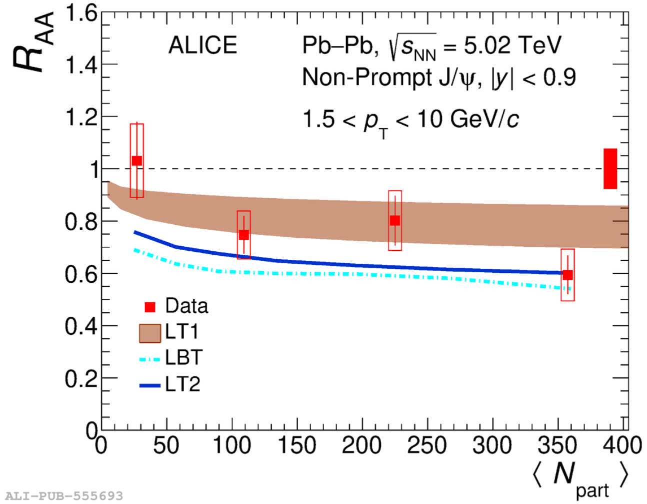
$$R_{AA} = \frac{d^2N_{AA}}{dp_T dy} \Big/ \frac{d^2N_{pp}}{<N_{coll}> dp_T dy}$$





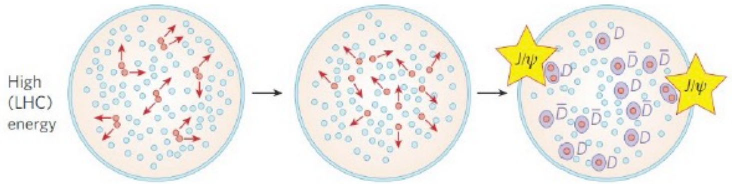




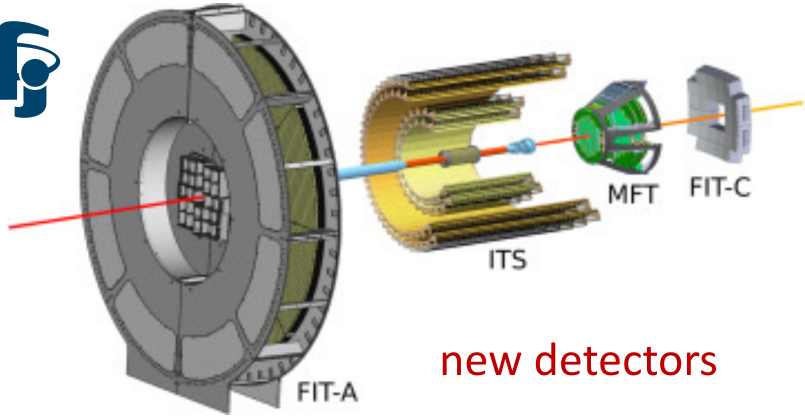


- Sign of prompt J/ψ (re)generation in central collisions
- Prompt J/ψ R_{AA} described by models including quarkonium dissociation (regeneration) at high (low) p_T

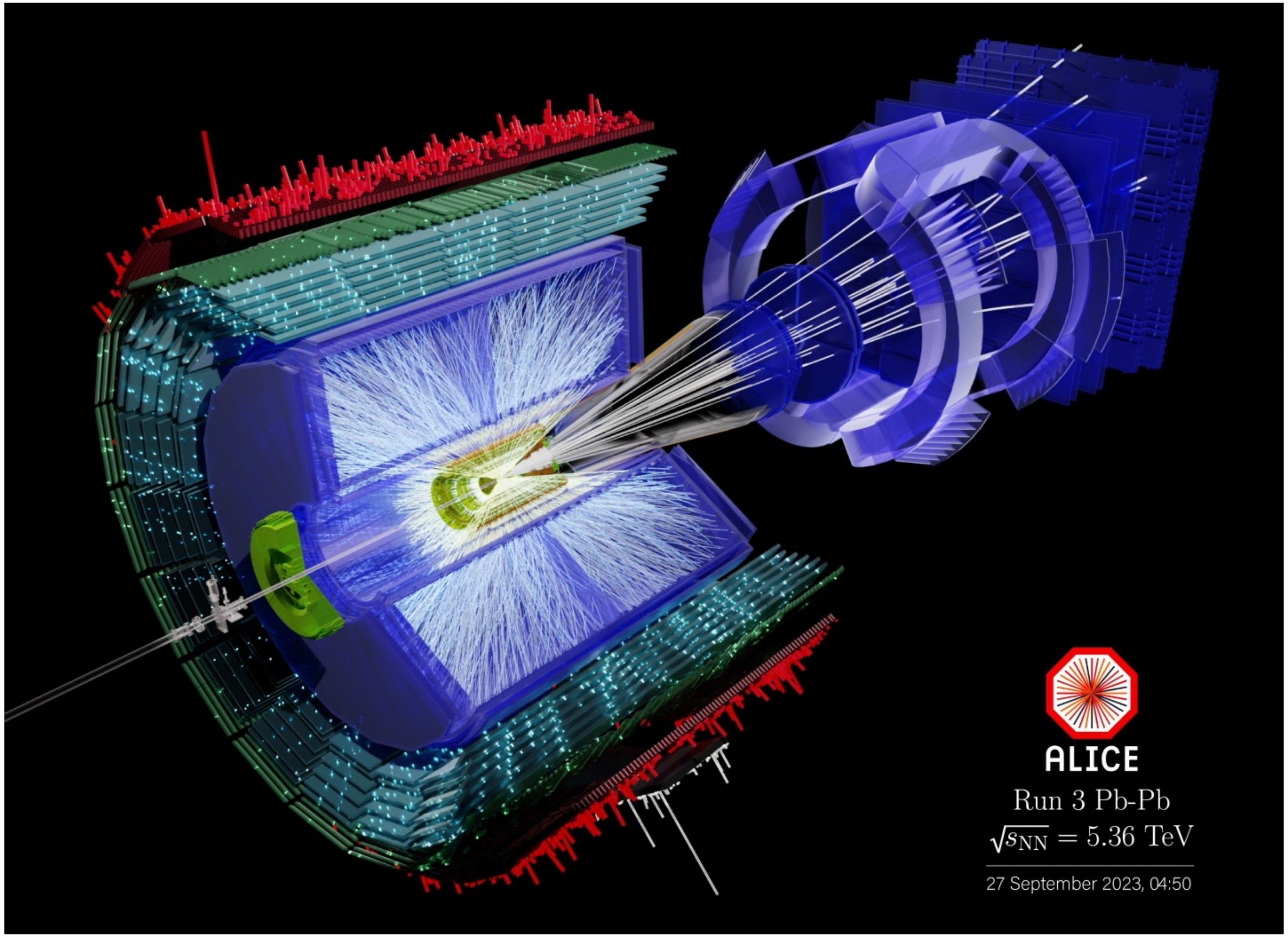
- Non-prompt J/ψ described by LT1 transport model



ALICE in Run 3

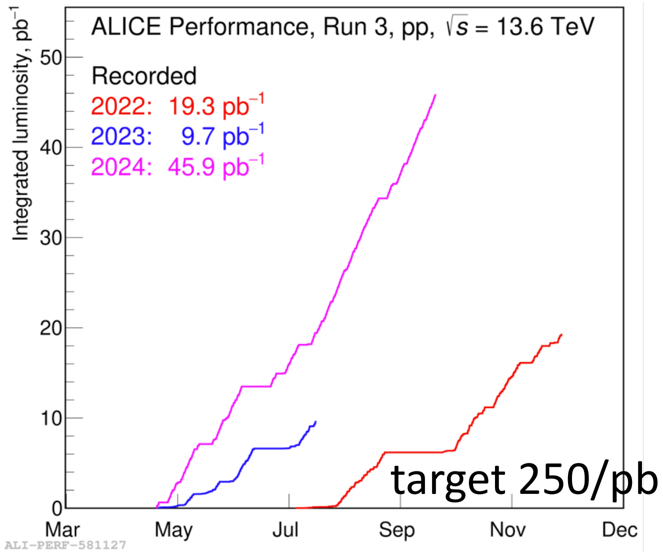


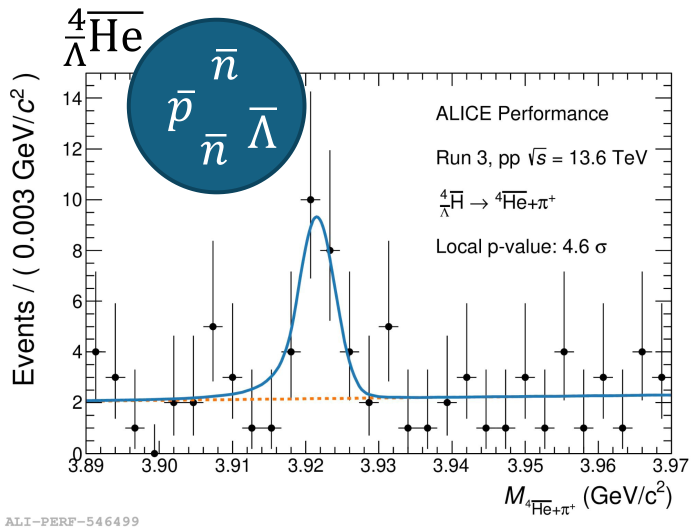
new detectors

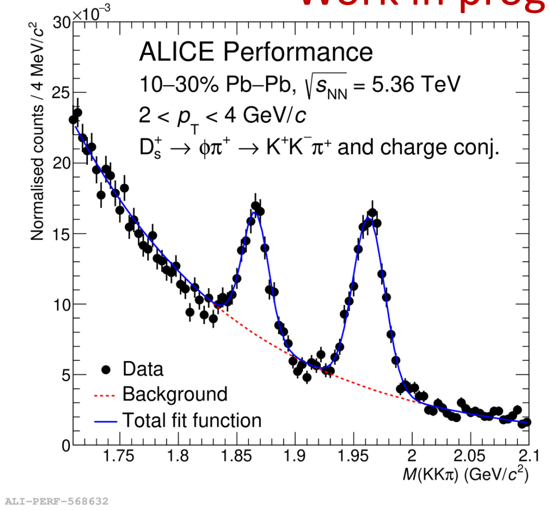


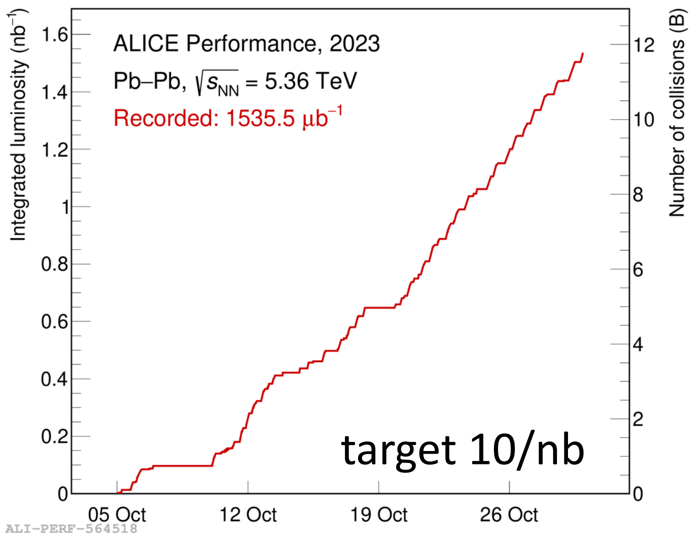
ALICE Run 3 Performance

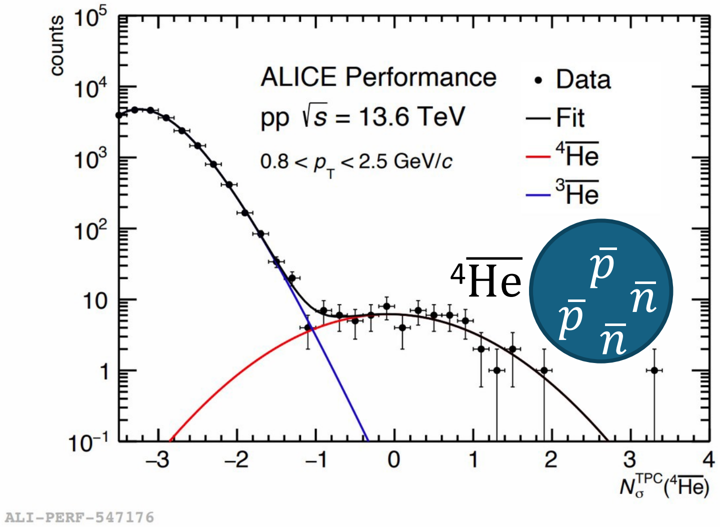
Work in progress!

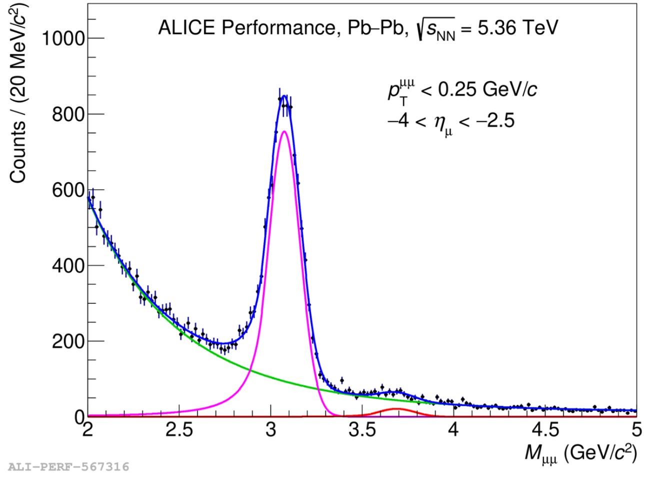




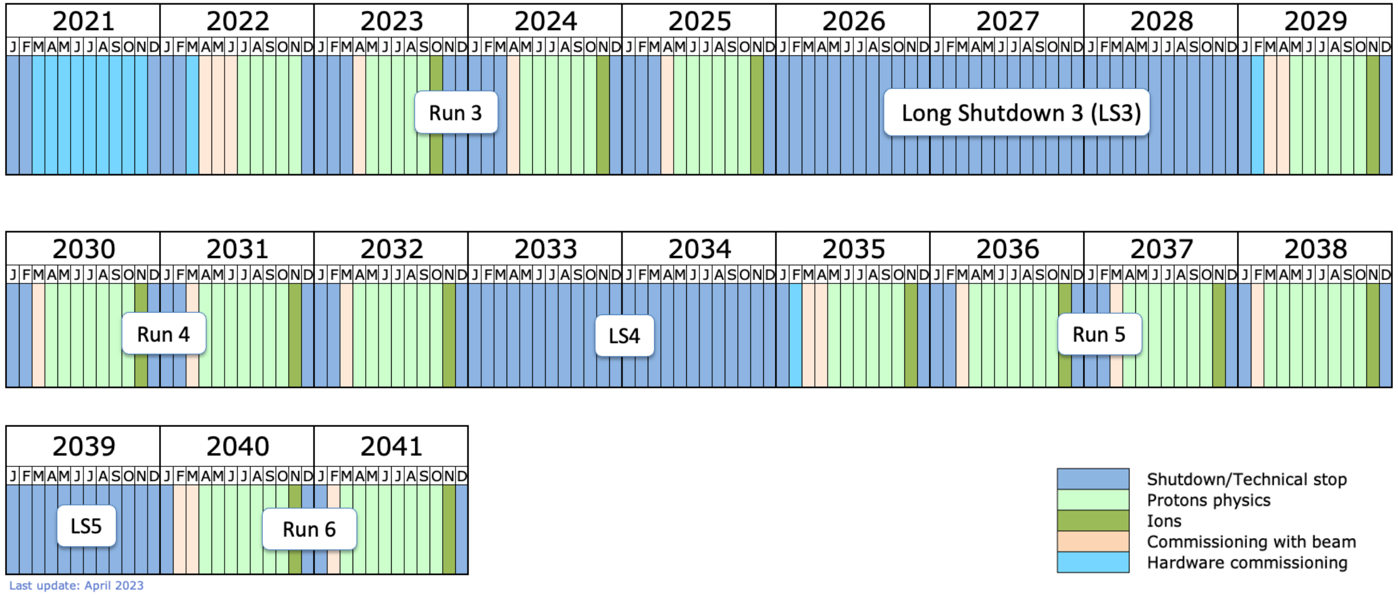




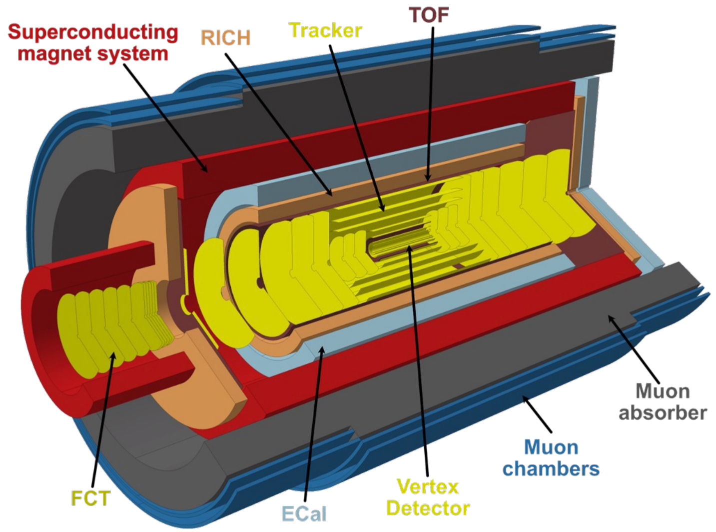




ALICE Upgrades

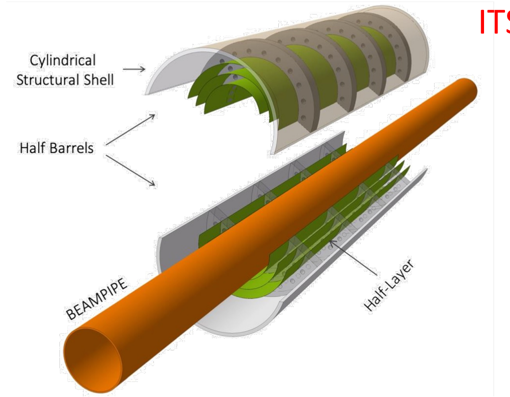


LS4: Future heavy-ion detector (ALICE 3)

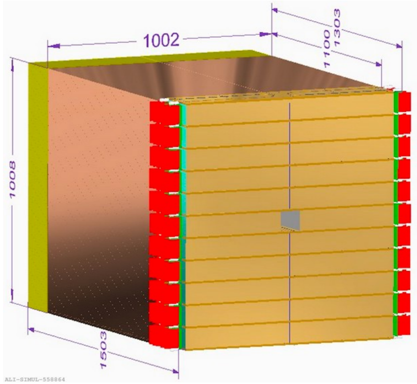


LS3: ITS3 and FoCal

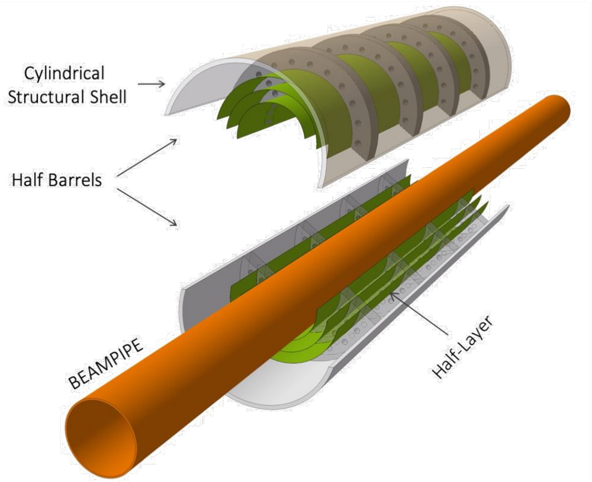
ITS3

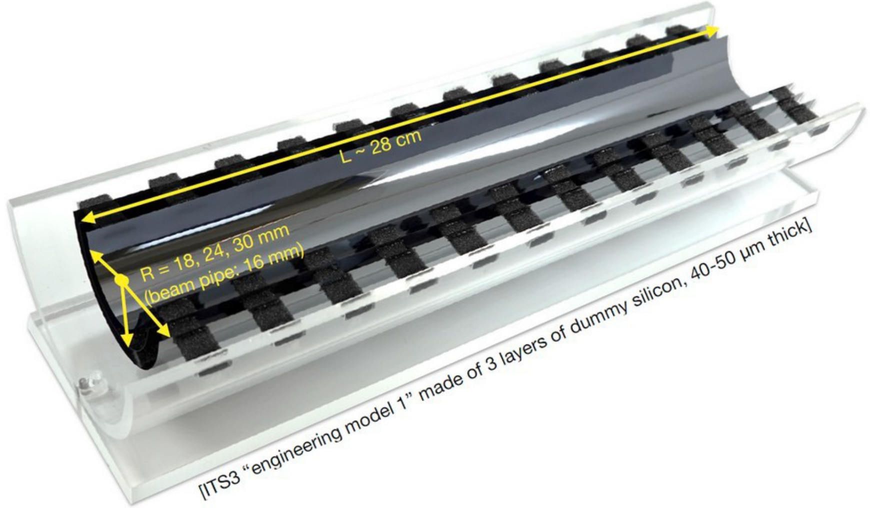


FoCal



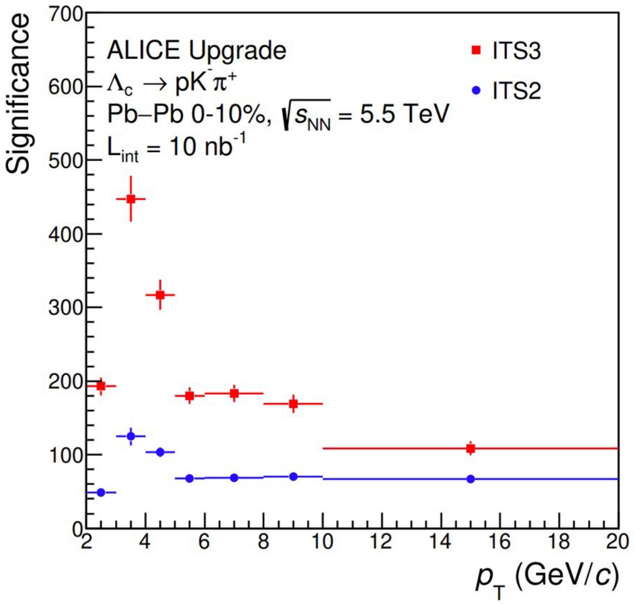
Inner Tracking System 3 (ITS 3)

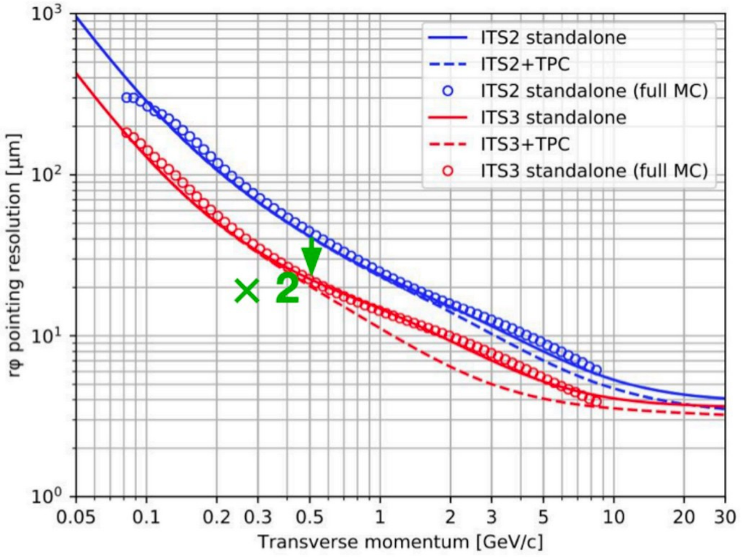




- Truly cylindrical (silicon sensor bending)
- 65 nm MAPS sensors
- Sensor stitching (30 cm wafers)

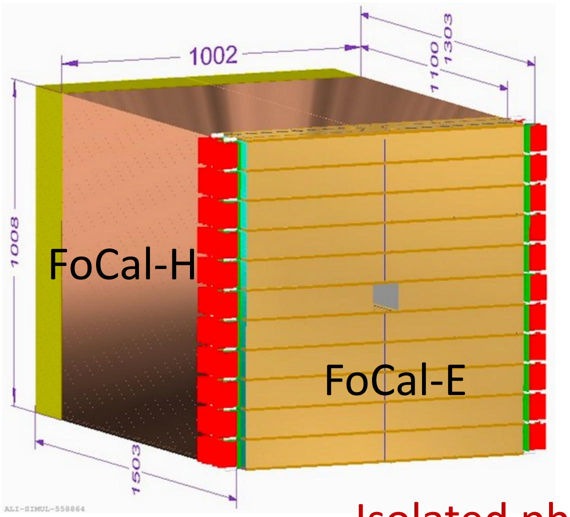
- Main physics motivation
  - Improve performance for heavy flavour and dielectron measurements





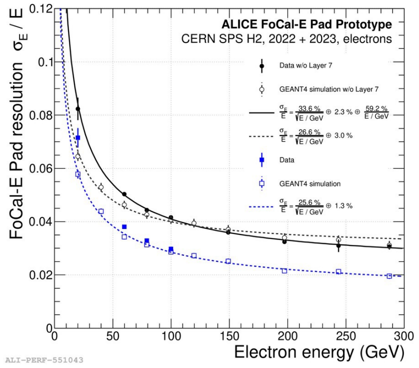
LoI: CERN-LHCC-2019-018
Physics performance: ALICE-PUBLIC-2023-002

Forward Calorimeter (FoCal)

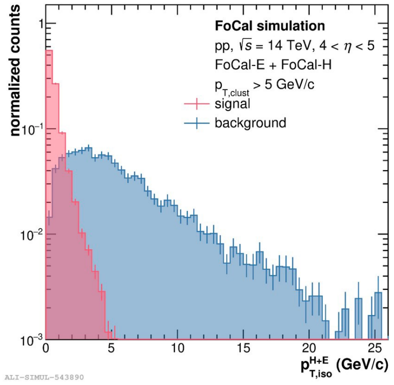


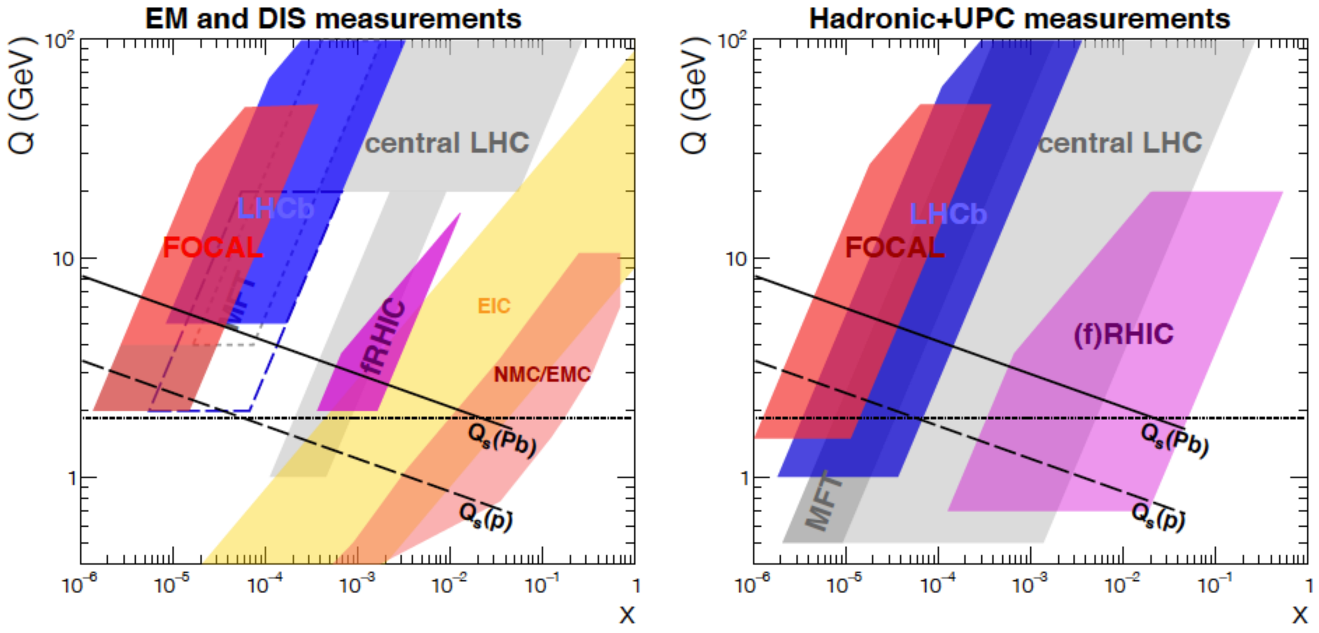
- Electromagnetic (FoCal-E) and hadronic (FoCal-H) calorimeter
- Acceptance: $3.2 < \eta < 5.8$

- Main physics motivation
  - Explore non-linear QCD evolution at small-x
  - Measurements of isolated-γ, DY, open charm and UPC



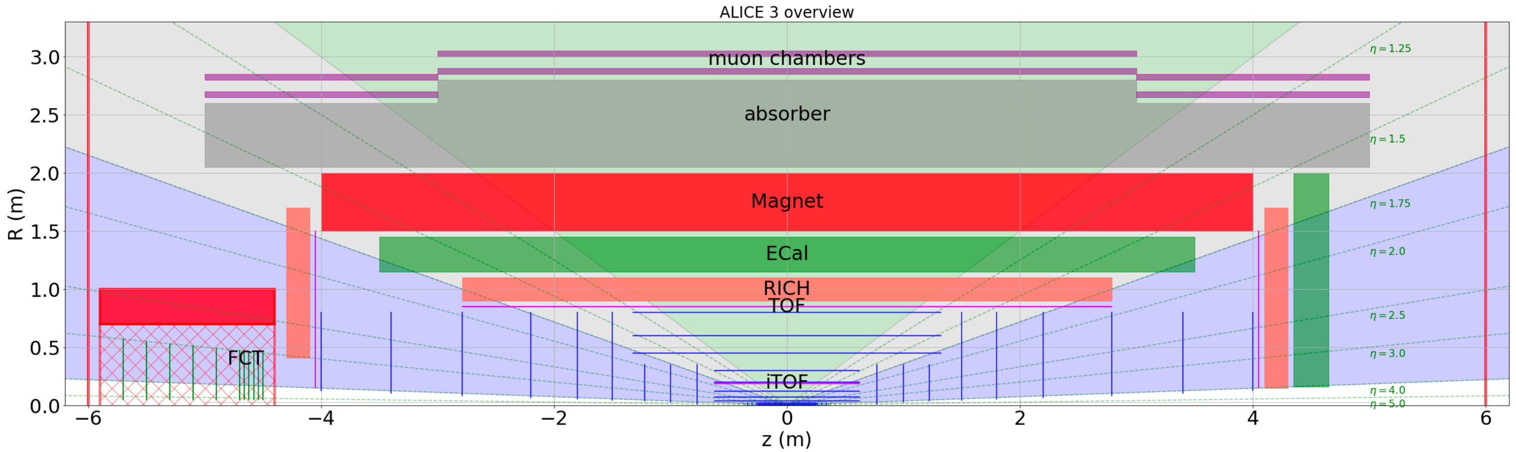
Isolated photons





LoI: ALICE, LHCC-I-036 (2020)
Physics case: ALICE-PUBLIC-2023-001
Physics performance: ALICE-PUBLIC-2023-004
Technical Design Report: CERN-LHCC-2024-*004*

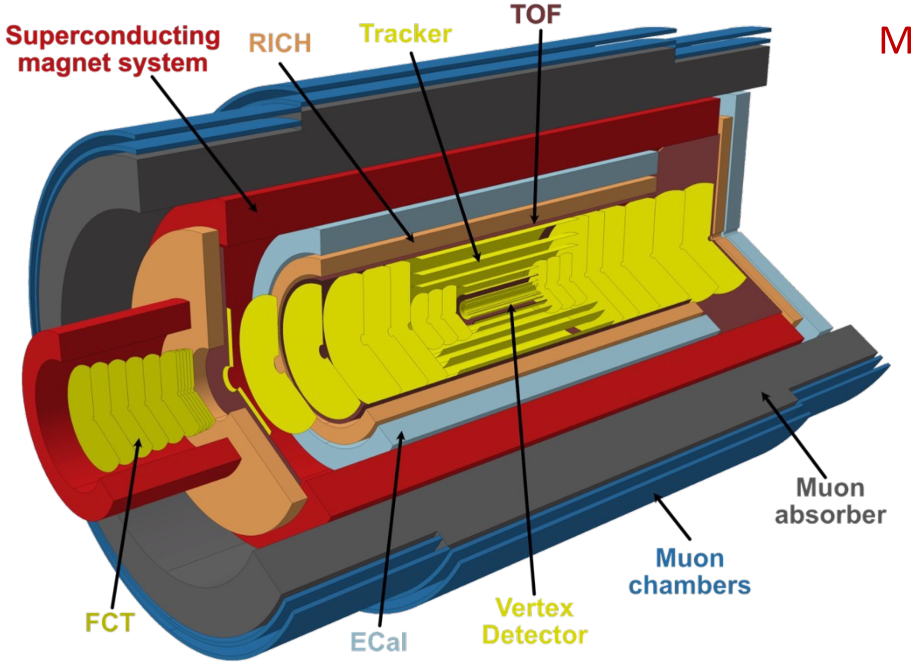
ALICE 3



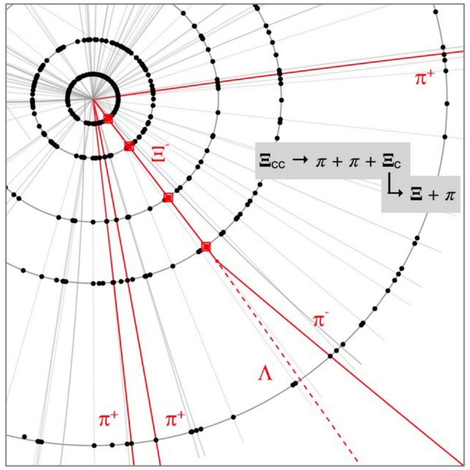
Main physics motivation

- 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 ongoing (large-area MAPS Tracker, Si TOF and SiPM RICH)



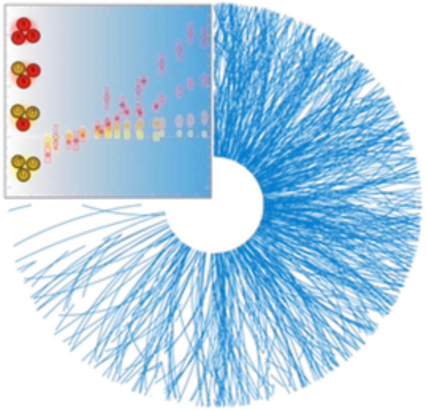
Multi-charm hadron production



LoI: CERN-LHCC-2022-009

https://indico.cern.ch/event/1415726

Summary



Light flavour

- System created in Pb-Pb collisions is baryon-free and electrically neutral at midrapidity
- Most precise measurement of hypertriton lifetime (hypertriton is a weakly bound state)
- Anti-alpha p_T differential distributions measured for the first time at the LHC
- The “ridge” is also observed in low multiplicity pp collisions
- Flow develops in small systems (different pattern depending on multiplicity)

Heavy flavour

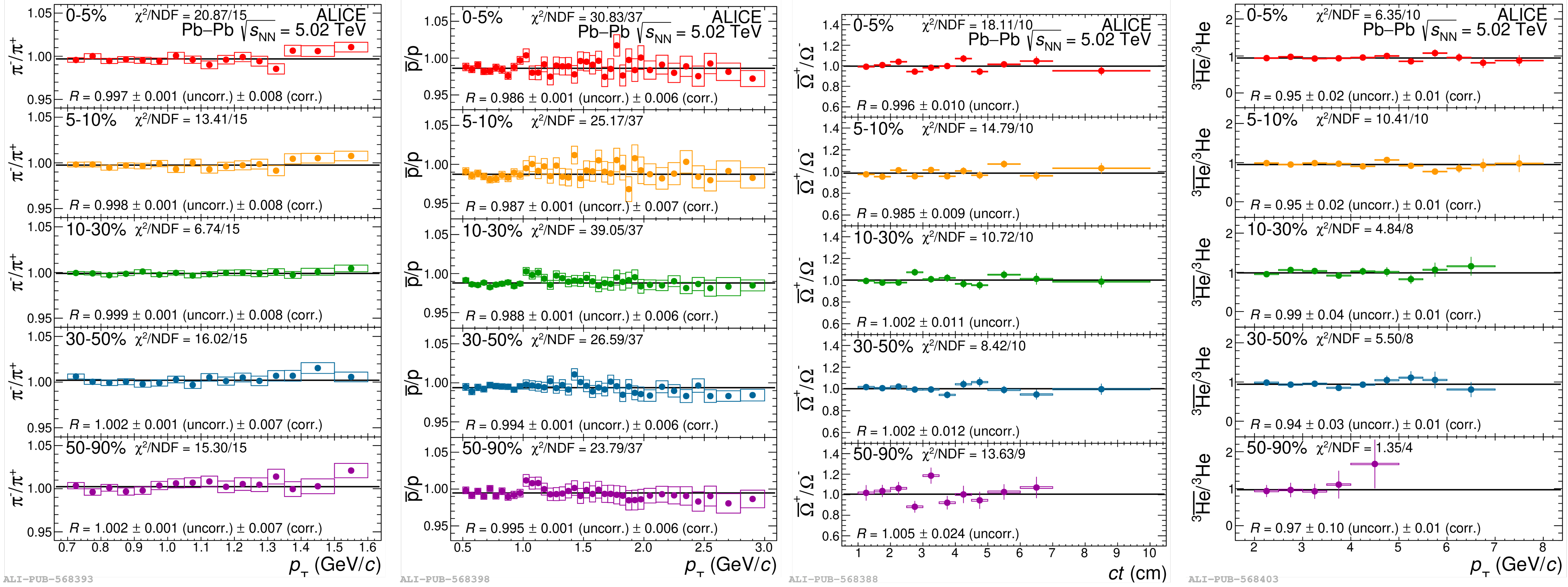
- Λ_C / D ratio increases from pp to central Pb-Pb collisions at intermediate p_T (enhanced production via coalescence)
- Sign of prompt J/ψ (re)generation in central collisions

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

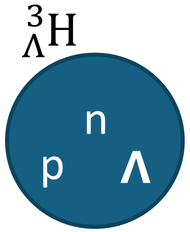
backup

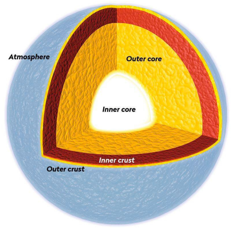
Antimatter/matter imbalance at the LHC

Phys. Rev. Lett. 133 (2024) 092301

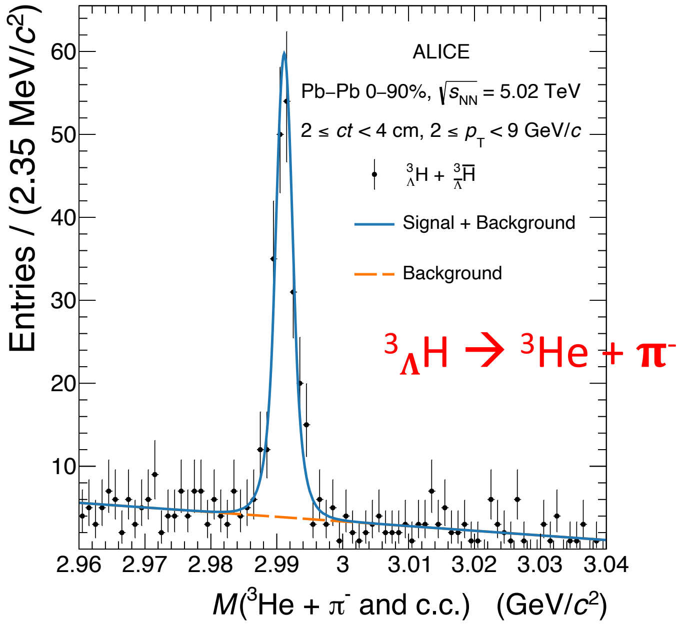


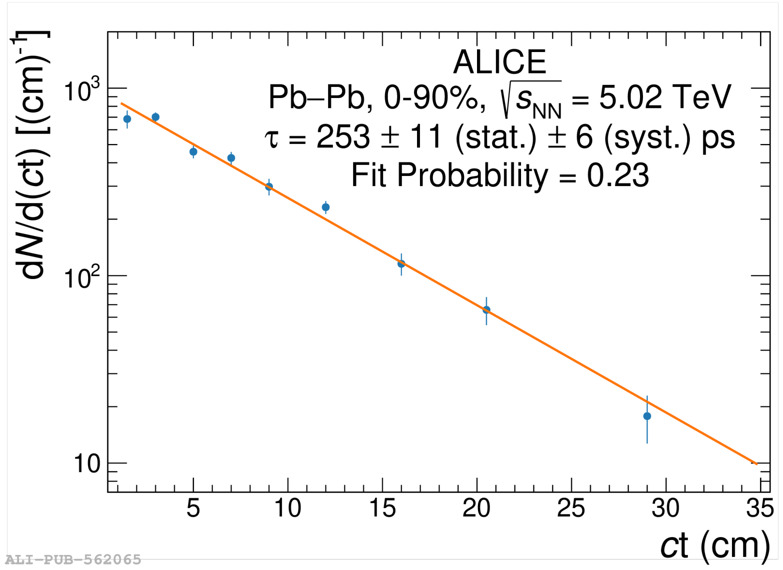
(Anti)hypertriton lifetime

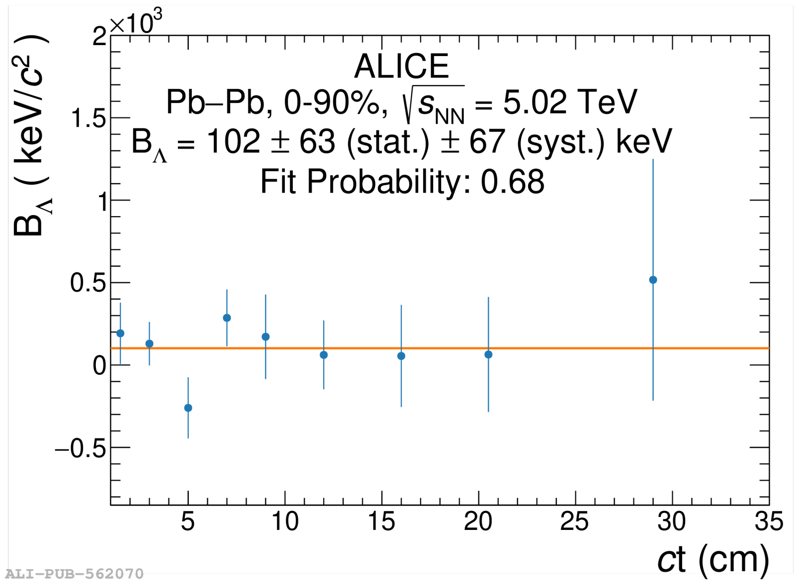




Phys. Rev. Lett. 131 (2023) 102302







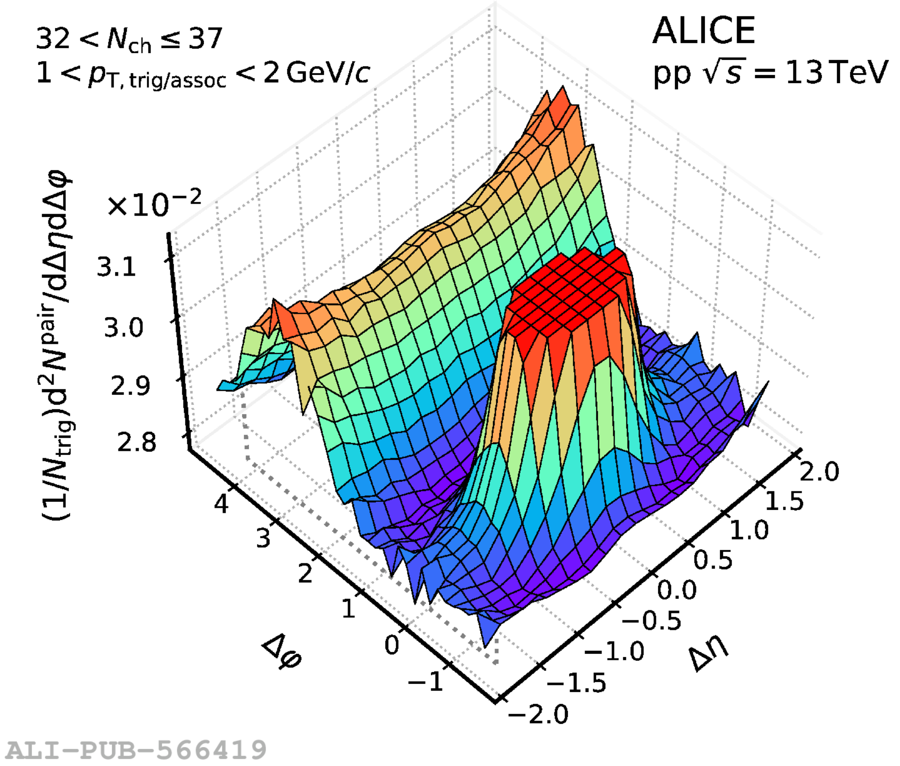
$$c \cdot t = M \cdot L \cdot c/p$$

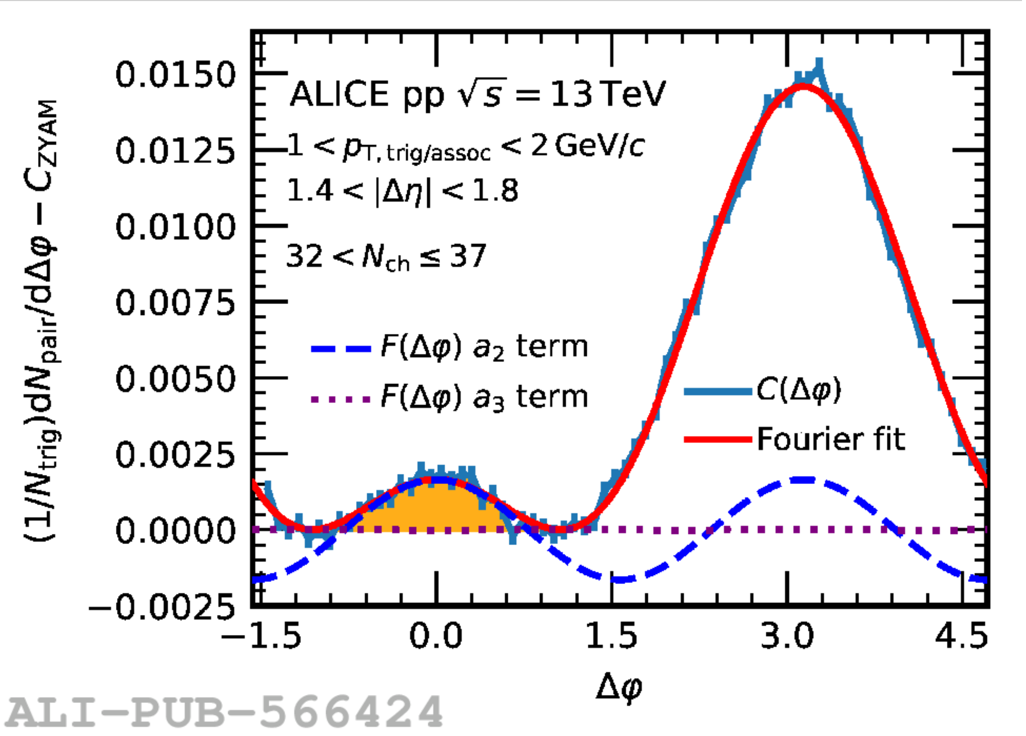
L - decay length

p - hypertriton momentum

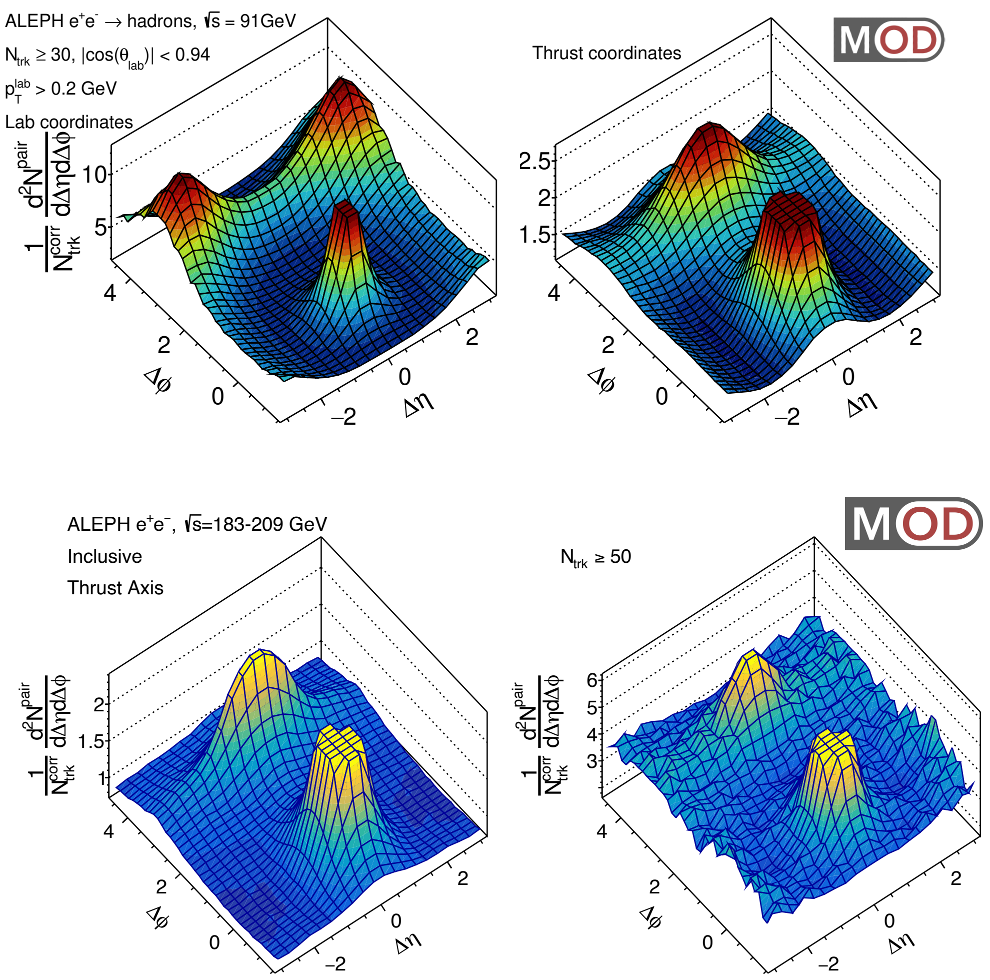
Emergence of long-range angular correlations in low-multiplicity proton-proton collisions

Phys. Rev. Lett. 132 (2024) 172302

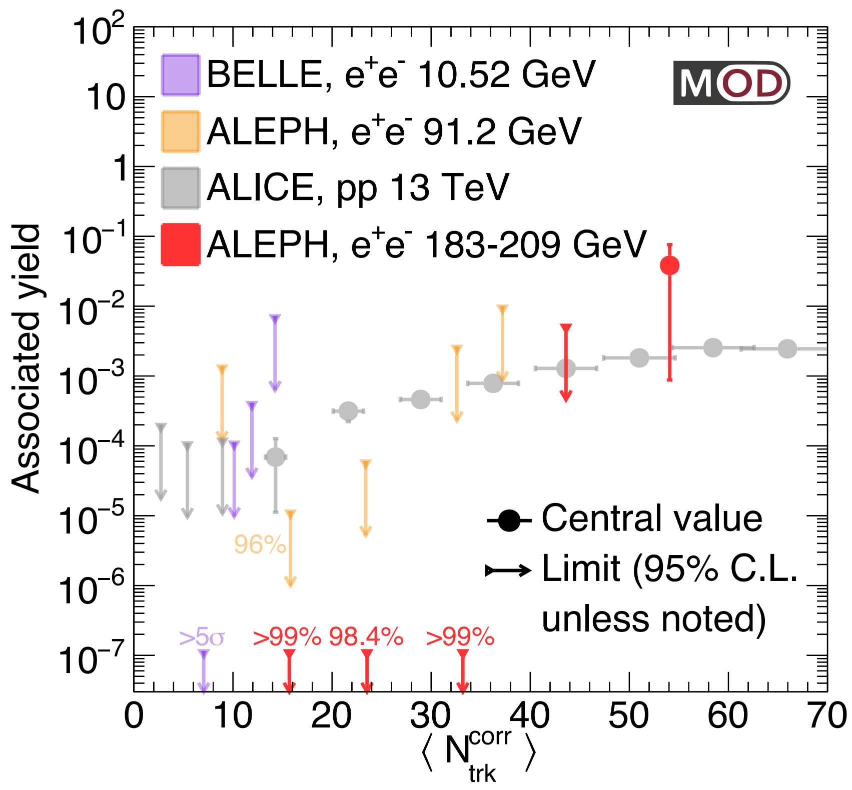




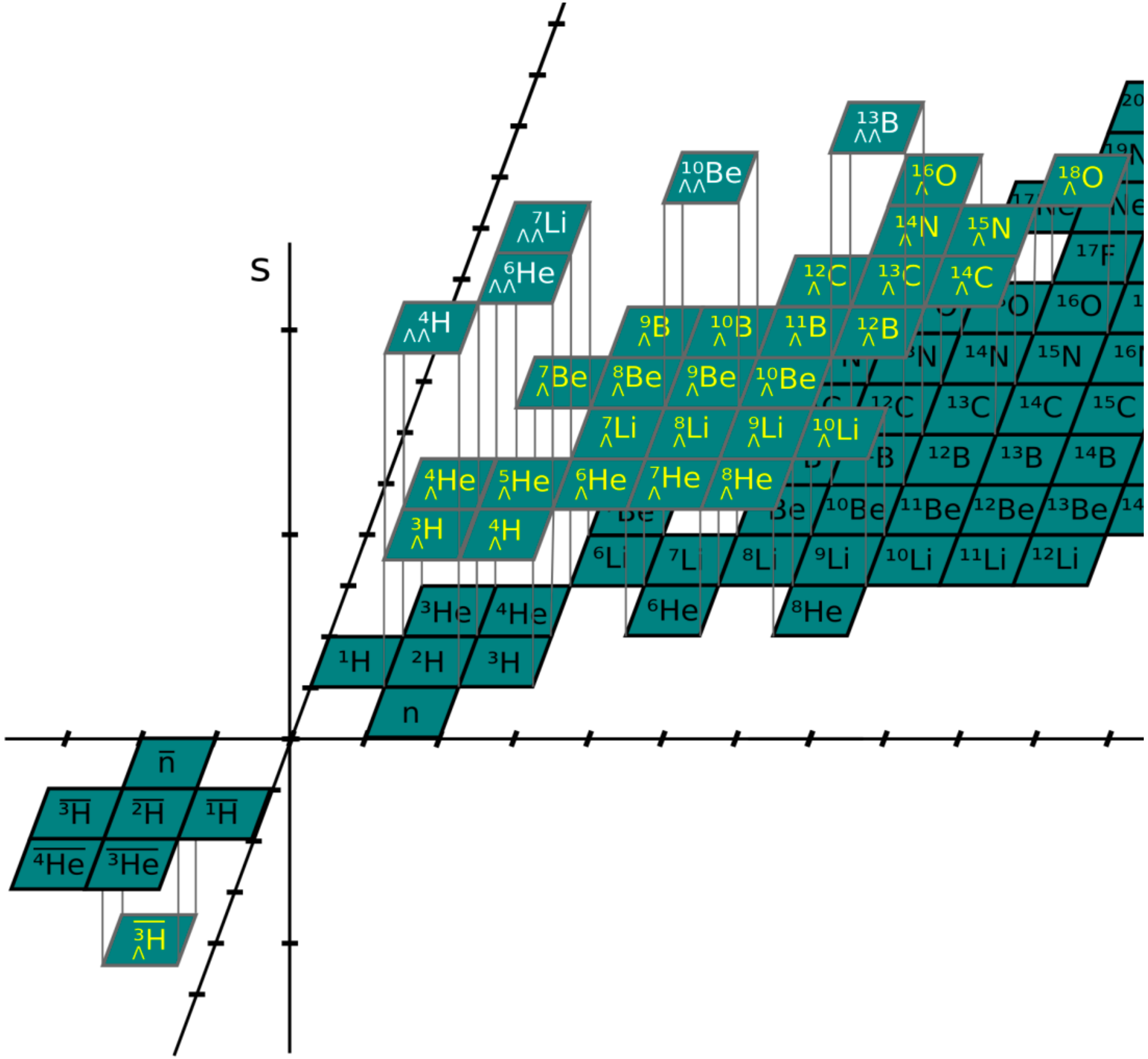
Long-range near-side correlation in e^+e^- Collisions at 91 GeV and 183-209 GeV with ALEPH



A. Badea et al. Phys. Rev. Lett. 123, 212002 (2019)
Yu-Chen Chen et al. arXiv:2312.0508



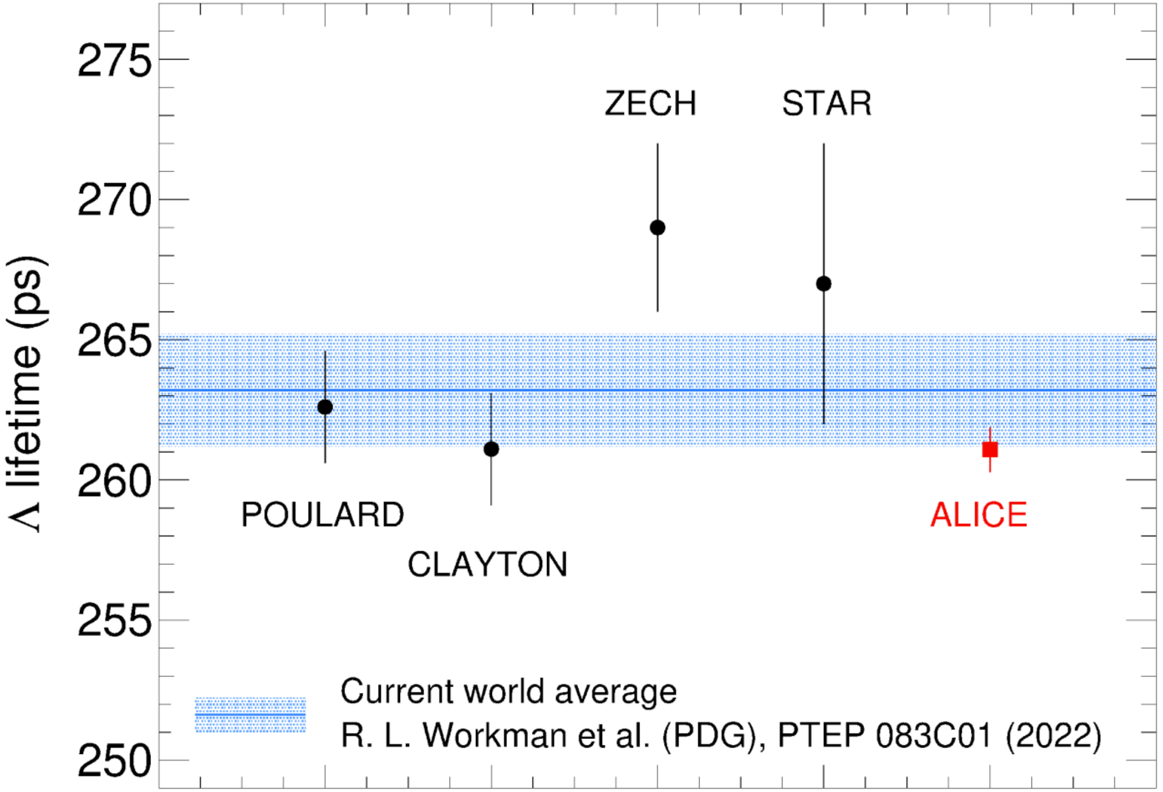
Hypernuclei



Free Λ lifetime

Phys. Rev. D 108, 032009 (2023)

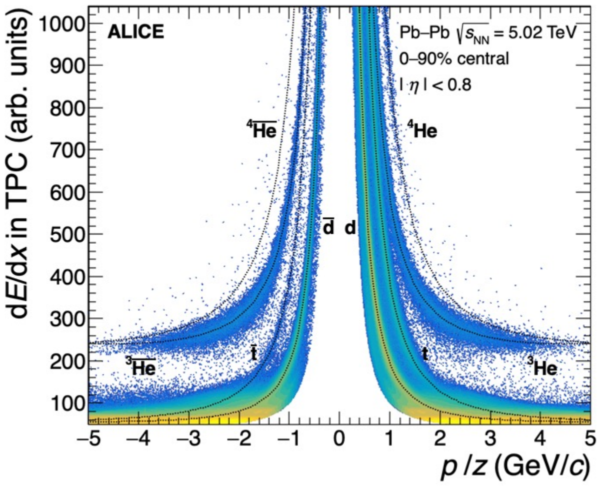
$\tau = 261.07 \pm 0.37(\text{stat.}) \pm 0.72\ (\text{syst.})\ \text{ps}$

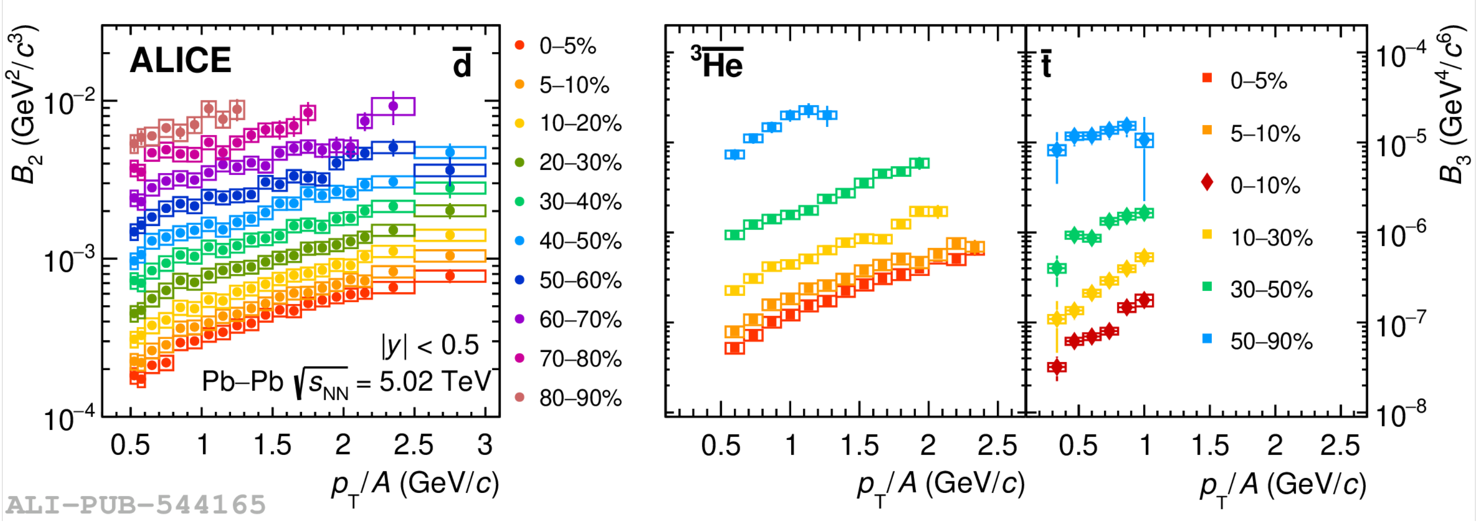


ALI-PUB-561575

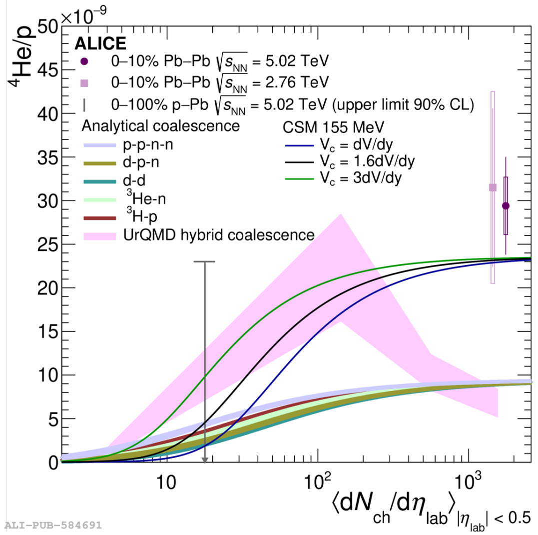
Light (anti)nuclei production

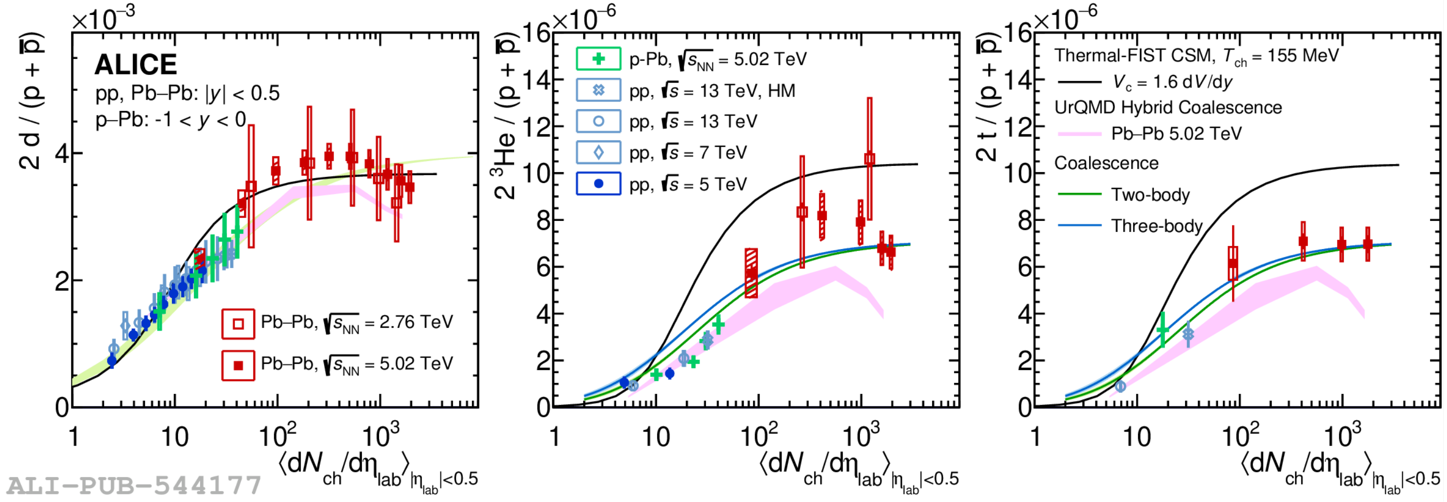
PRC 107, 064904 (2023)



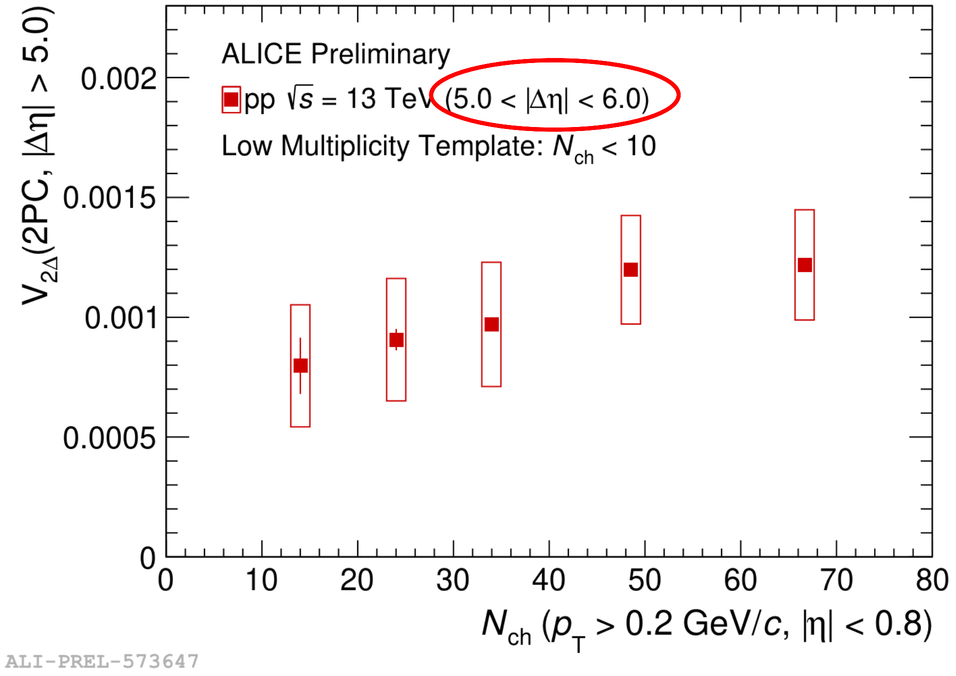


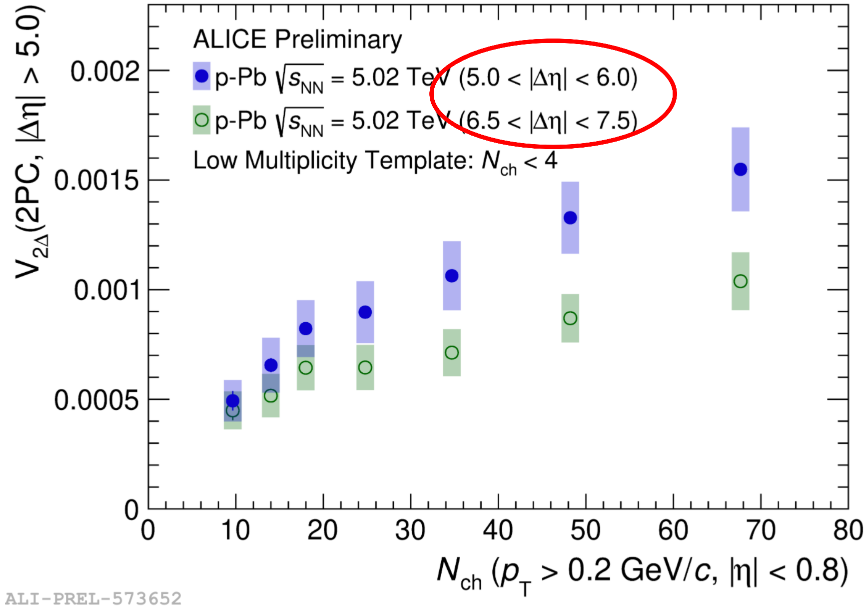
Phys. Lett. B 858 (2024) 138943

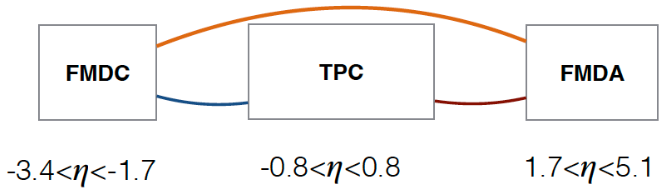




Ultra long-range angular correlations in ALICE







- ❑ Ultra long-range correlations in low multiplicity pp and p-Pb collisions
- ❑ What is origin of such correlations?

$$v_n\{2\} = \sqrt{\frac{V_{n\Delta}^{\mathrm{TPC-FMDA}} V_{n\Delta}^{\mathrm{TPC-FMDC}}}{V_{n\Delta}^{\mathrm{FMDA-FMDC}}}}$$