Review of recent results of heavy-ion physics in ALICE at LHC

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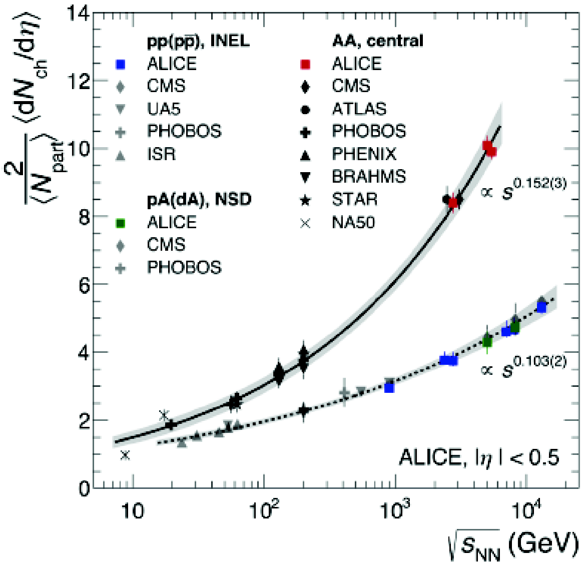
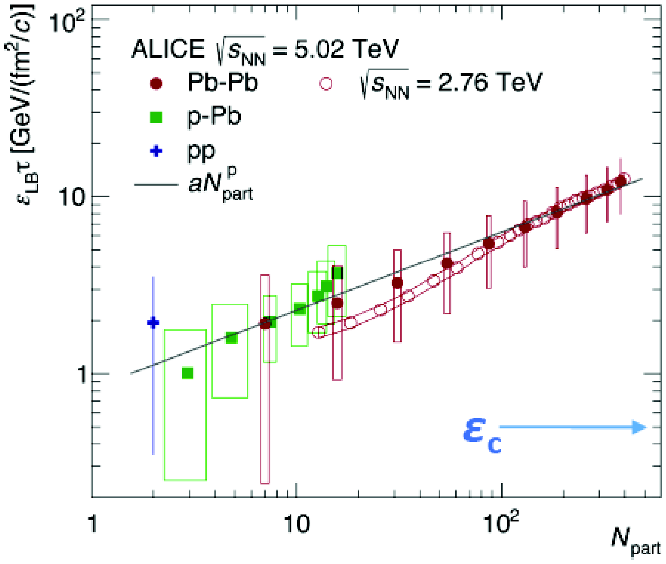
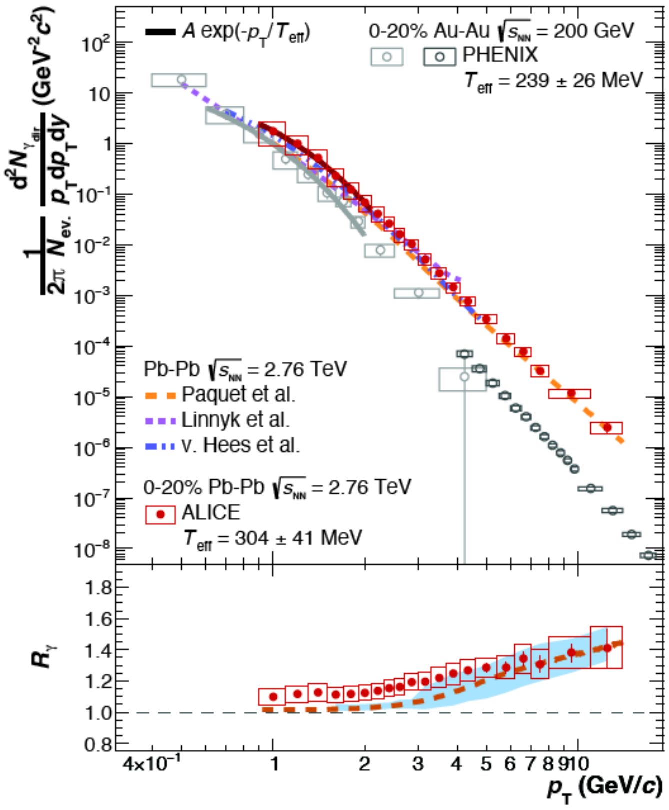
Global properties of nuclear collisions



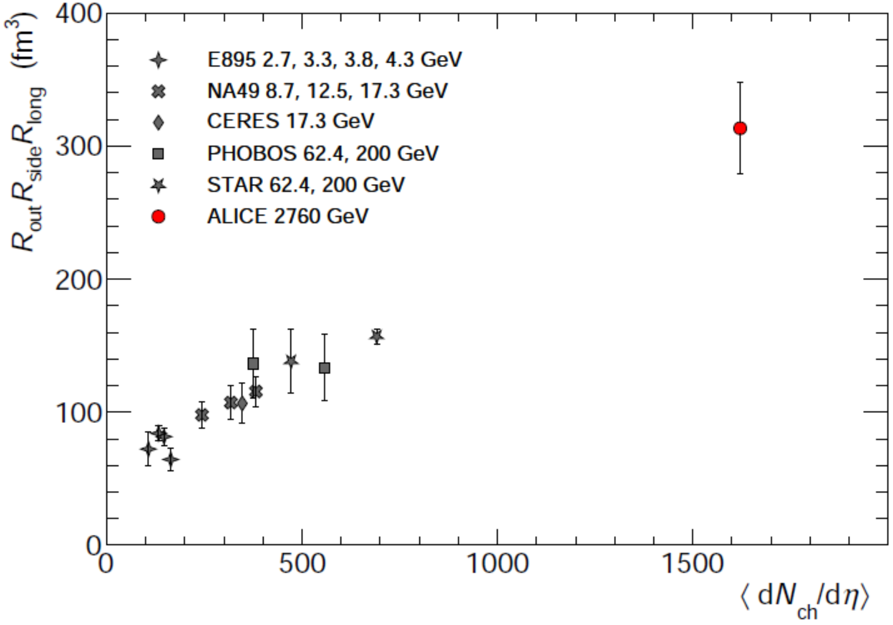




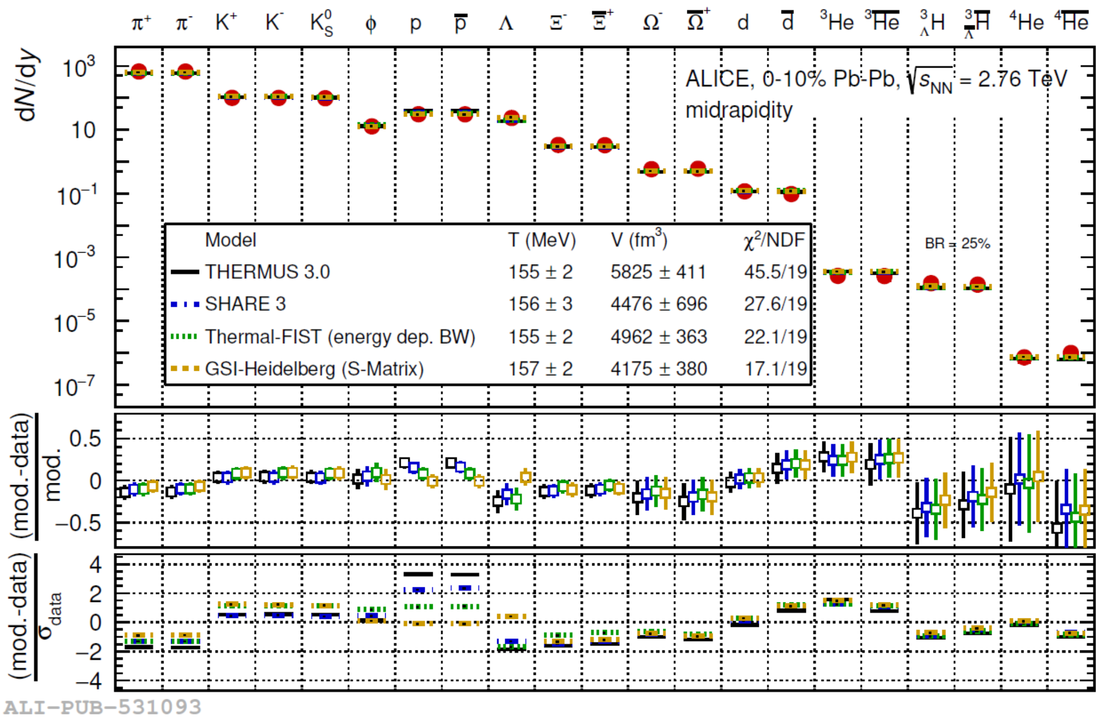
- Charged hadron production per nucleon is maximal in Pb-Pb at LHC
- Central Pb-Pb initial energy density 30x is larger than $\varepsilon_c \approx 0.7$ MeV/fm^3.
- Photon effective temperature is twice $T_c \approx 150$ MeV.

- ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]
- ALICE. *Direct photon production in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV.* Physics Letters B 754 (2016) 235–248

Hot matter properties at freeze-out



Freeze-out volume linearly rises with $dN_{ch}/d\eta$ from AGS to LHC

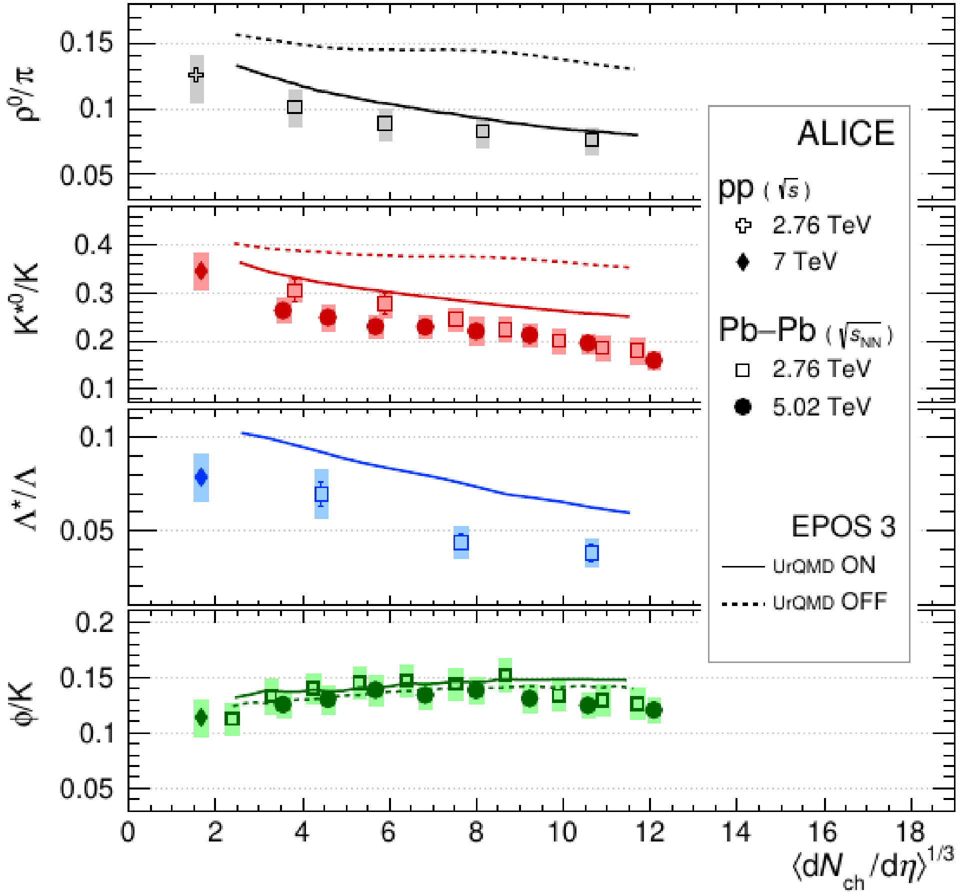


- Hadron and light nuclei yields described by statistical models over 10 orders of magnitude
- Implies hadrons subject to chemical equilibrium close to QGP transition temperature $T_{chem} \approx T_c \approx 156$ MeV

ALICE. *Two-pion Bose–Einstein correlations in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV*. Physics Letters B 696 (2011) 328–337

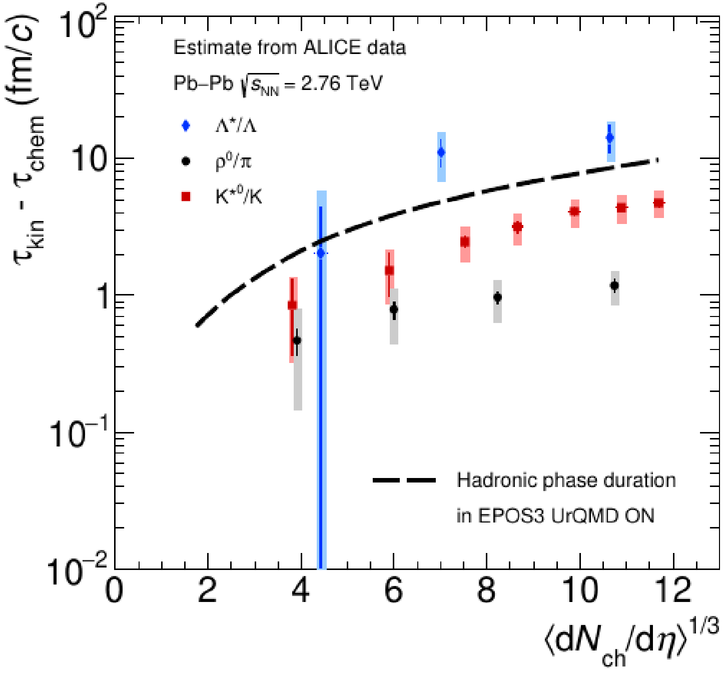
ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

Hadronic phase duration



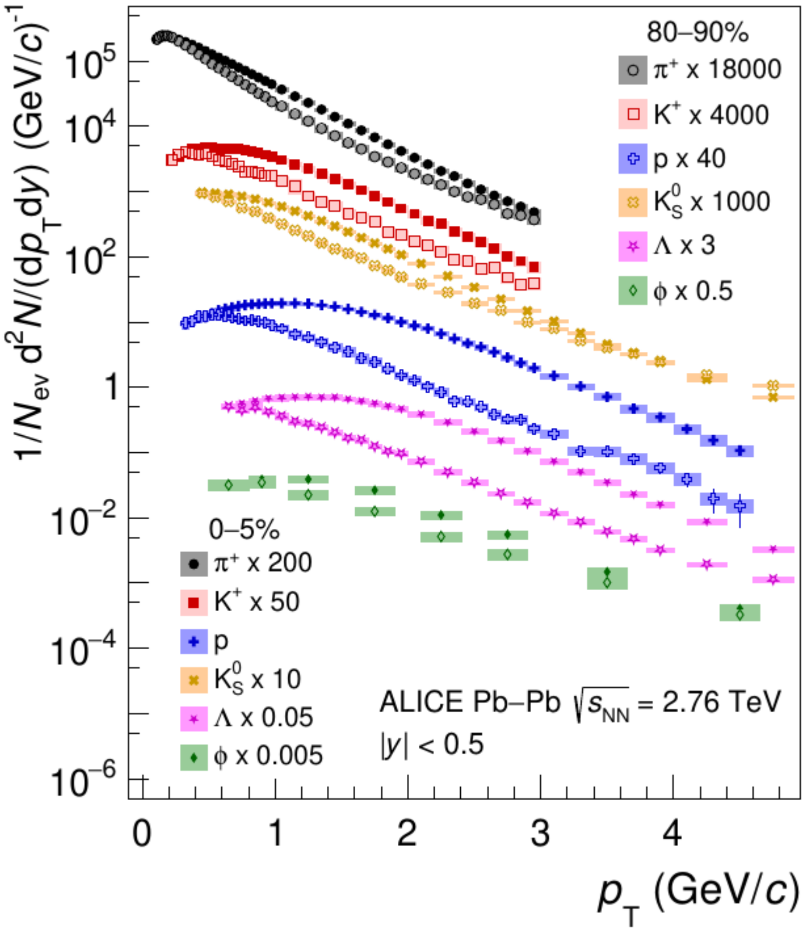
ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

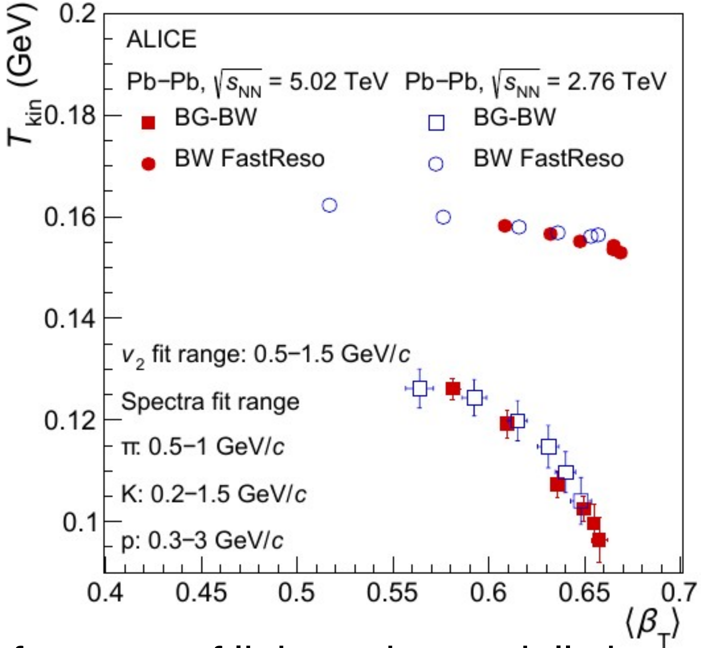
$\rho(770)^0$
τ^{rf}=1.3 fm/c
$K^*(892)^0$
τ^{rf}=4.16 fm/c
$\Lambda(1520)$
τ^{rf}=12.6 fm/c
$\phi(1020)$
τ^{rf}=46.3 fm/c



- Suppression of short-lived resonances increasing from peripheral to central collisions
- Possible interpretation: rescattering of resonance decay products in the hadronic phase
  - Hadronic phase duration 1 – 10 fm/c
  - Times estimated from different resonances differ by order of magnitude. Different freeze-out times for different species?

Collective expansion – radial flow

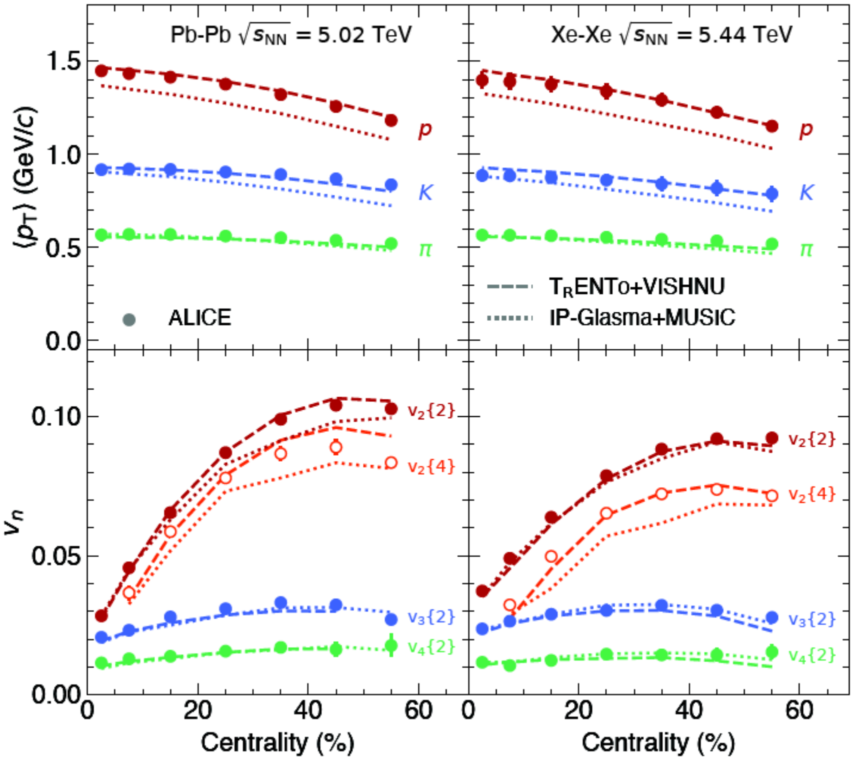


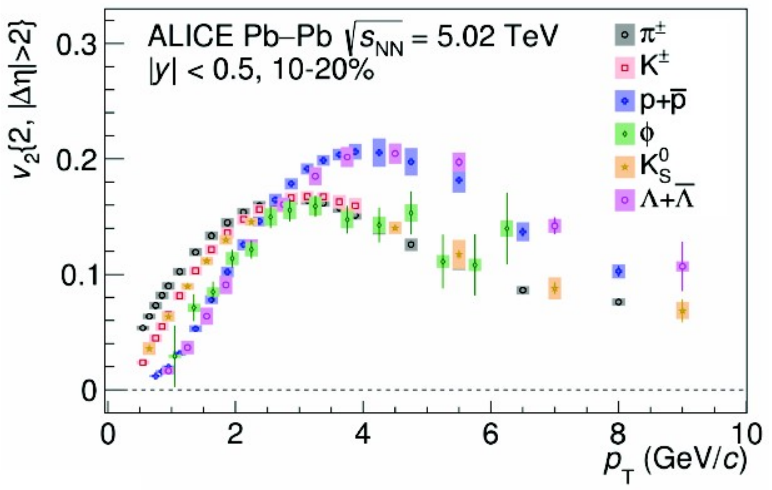


ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

- Shapes of spectra of light and especially heavy hadrons change from peripheral to central collisions
- Consistent with radial flow hydrodynamic expectations
- Blast Wave parametrization shows lower kinetic freeze-out temperature but higher mean radial flow in central collisions

Collective expansion - momentum anisotropy



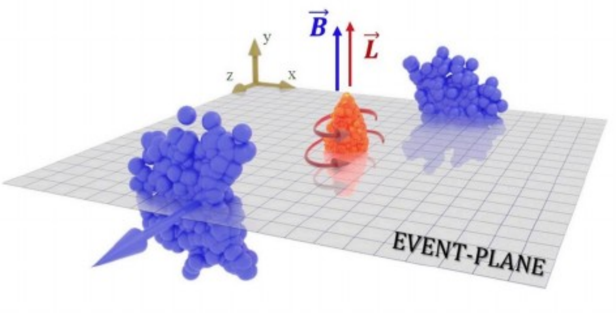


- Global QGP radial and anisotropic expansion described by hydrodynamics
- Achieved with QGP equation of state and small but finite QGP viscosities

$$\frac{dN}{d\phi} = 1 + 2v_1\cos(\phi - \Psi_{RP}) + 2v_2\cos[2(\phi - \Psi_{RP})] + 2v_3\cos[3(\phi - \Psi_{RP})] + \ldots$$

ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

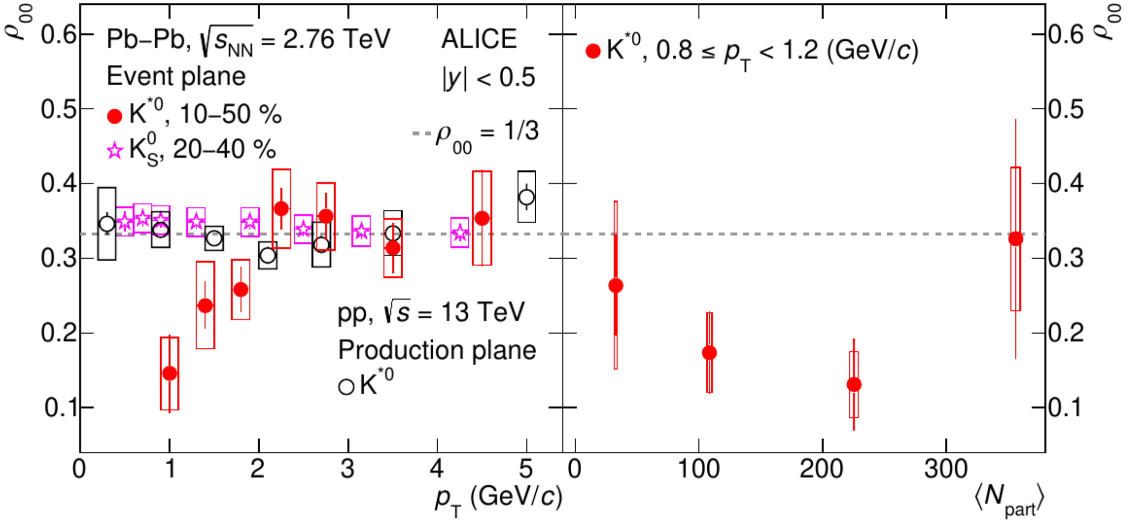
The most vortical fluid

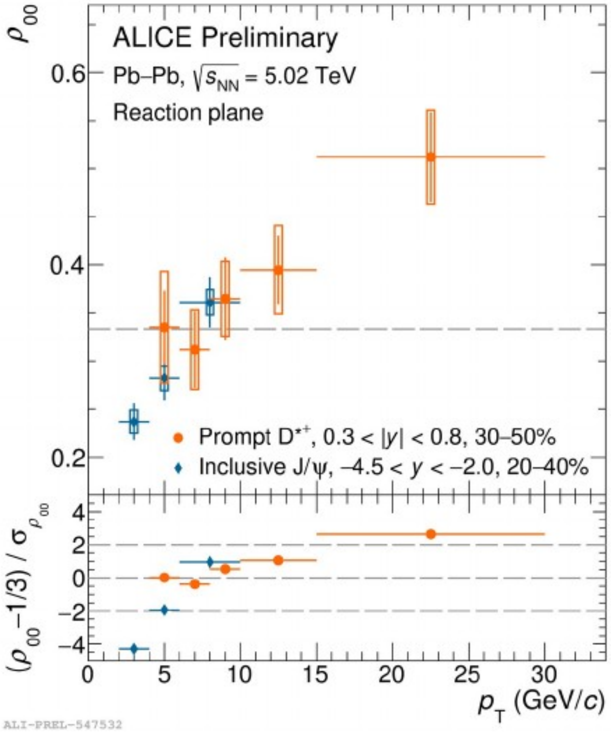


$$W(\cos\theta) \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta$$

$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}}$$

$\rho_{00} = 1/3$ no spin alignment

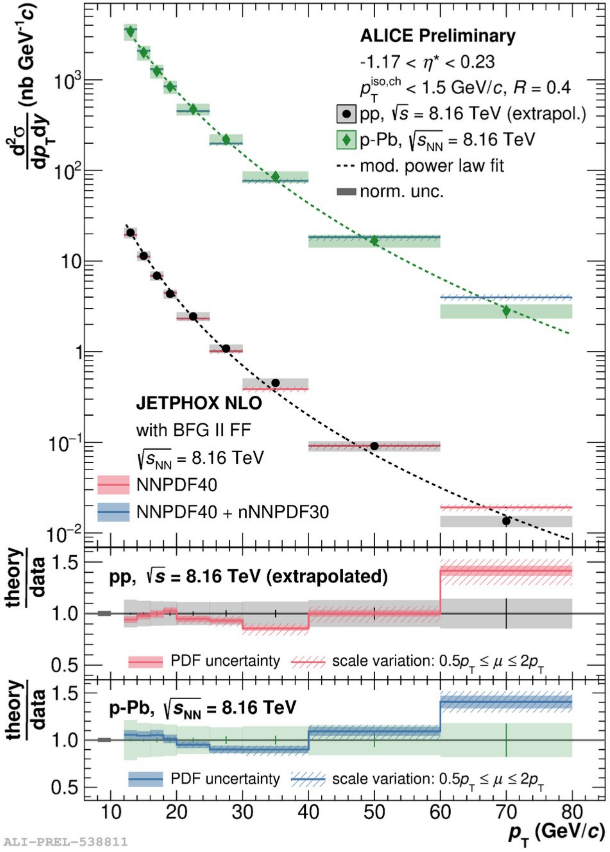


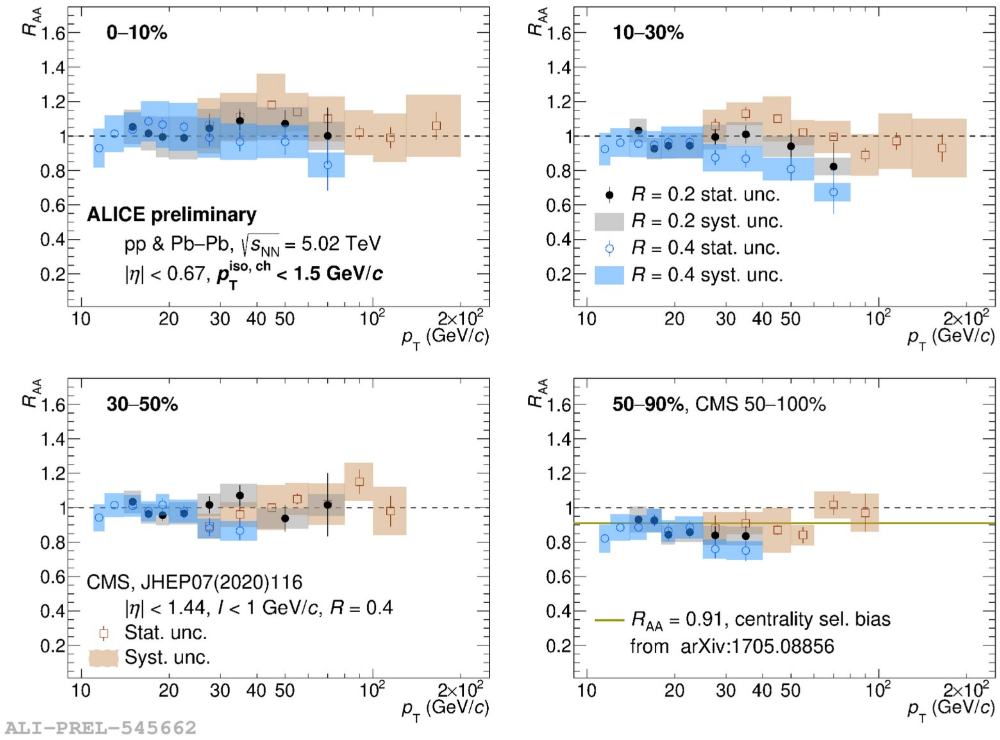


- Global angular momentum from incoming nuclei induces polarization wrt reaction plane direction
- First measurement of D^{*+} spin alignment. Hint of polarization for $p_T > 10$ GeV/*c*
- Alignment sign opposite wrt previous observations for low-p_T J/ψ and light vector mesons

ALICE. Measurement of the J/ψ Polarization with Respect to the Event Plane
in Pb-Pb Collisions at the LHC, PRL131 (2023)042303
ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

Probing initial state



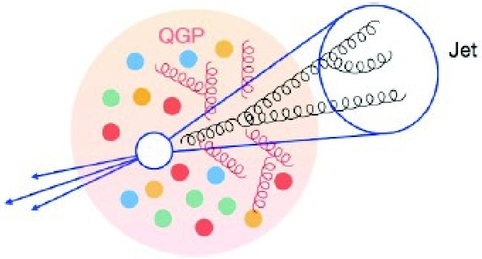


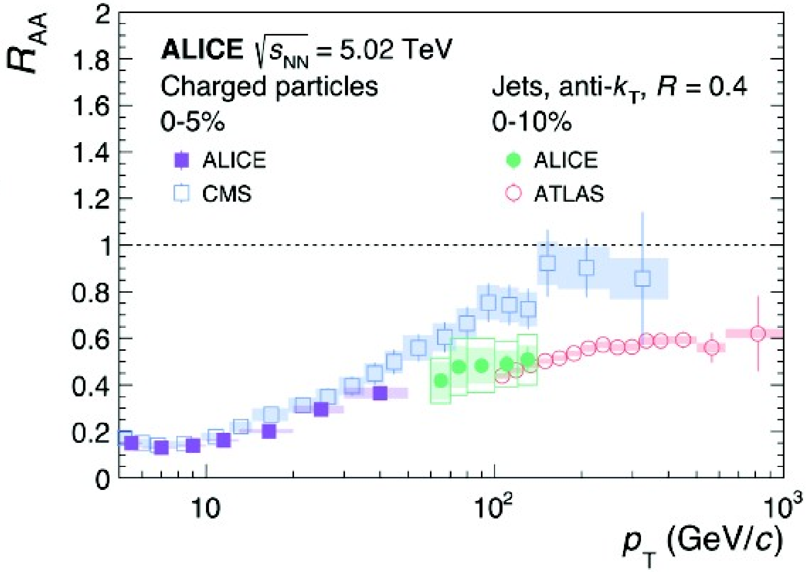
$$R_{AA} = \frac{dN^{AA}/dp_T}{\langle N_{coll} \rangle dN^{pp}/dp_T}$$

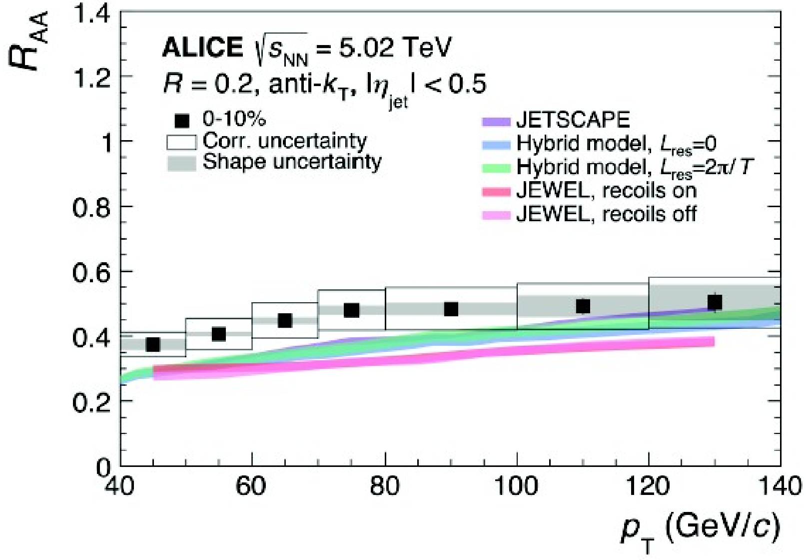
- Isolated photon production in pp collisions agrees with NLO pQCD predictions
- In p-Pb collisions R_{AA} agrees with unity
- No direct-photon suppression in the centrality range 0-50%
- Suppression in peripheral collisions (50-90%) explained by the centrality bias

Loizides et al., PLB773 (2017) 408

Parton energy loss





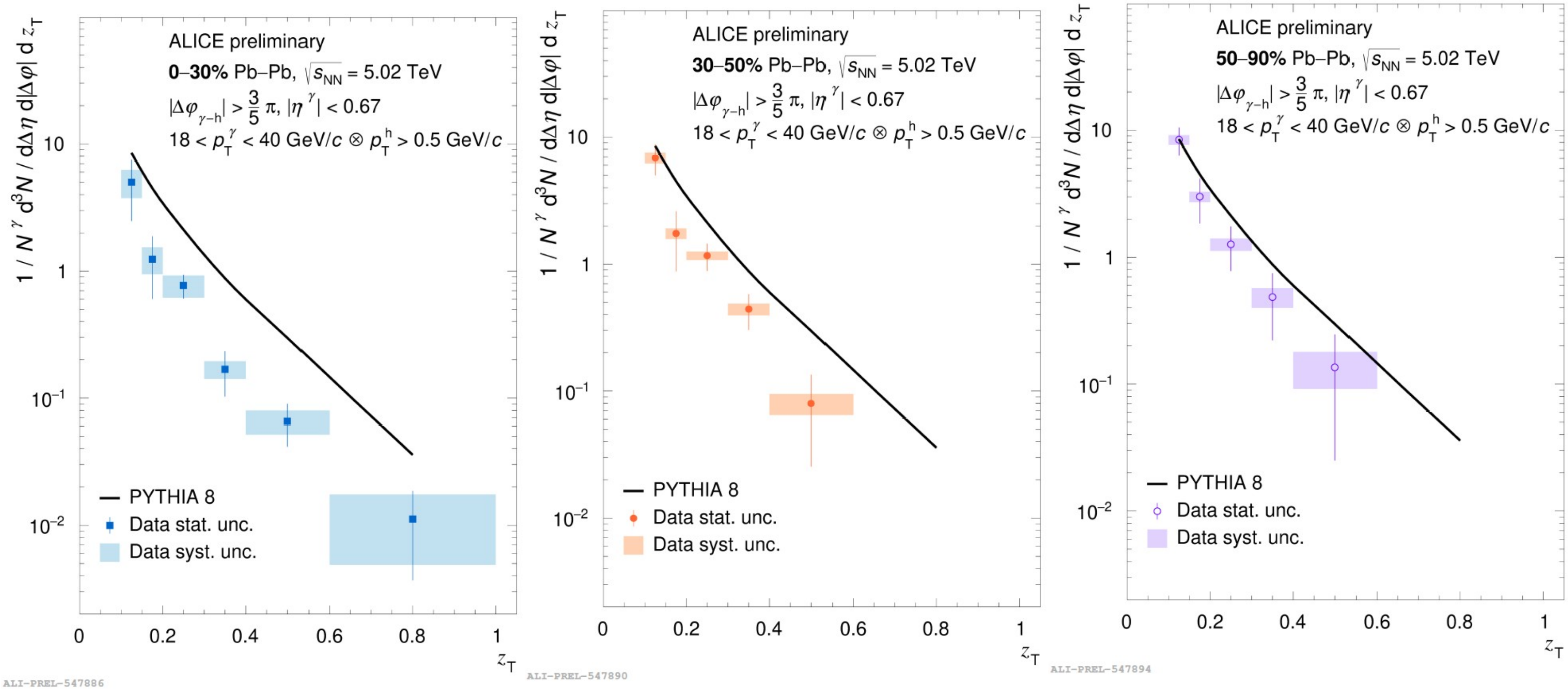


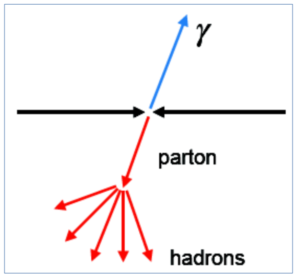
- Hard partons that shower into jets are produced early and interact with QGP
- Jet and high p_T hadron suppression observed over extensive range [1,2]
- Dominated by radiative emission. Extracted energy loss at LHC 8±2 GeV [3] (at RHIC 3.3±0.8 [4])
- New ML-based techniques allow for the extension to lower p_T and larger R = 0.6

[1] ALICE. *Transverse momentum spectra and nuclear modification factors of charged particles in pp, p-Pb and Pb-Pb collisions at the LHC*, JHEP 11 (2018) 013
[2] ALICE. *Measurements of inclusive jet spectra in pp and central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, Phys. Rev. C 101 (2020) 034911
[3] ALICE. *Measurement of jet quenching with semi-inclusive hadron-jet distributions in central Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV.* JHEP (2015) 170
[4] STAR. *Measurement of inclusive charged-particle jet production in Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV*. Phys.Rev.C 102 (2020) 5, 054913

Modification of parton fragmentation

New: ALICE preliminary

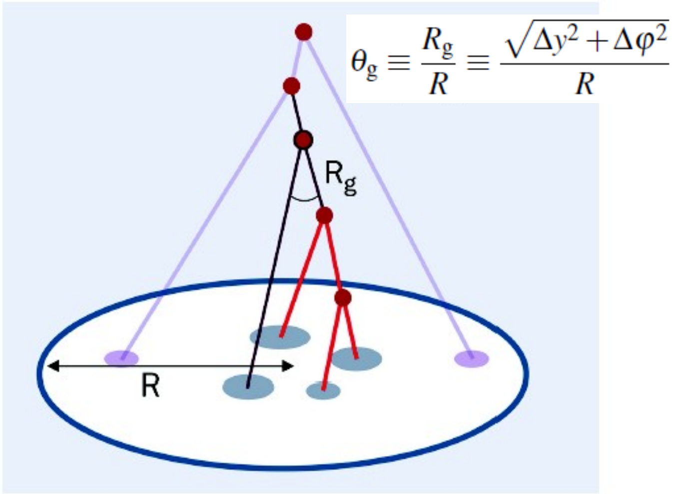


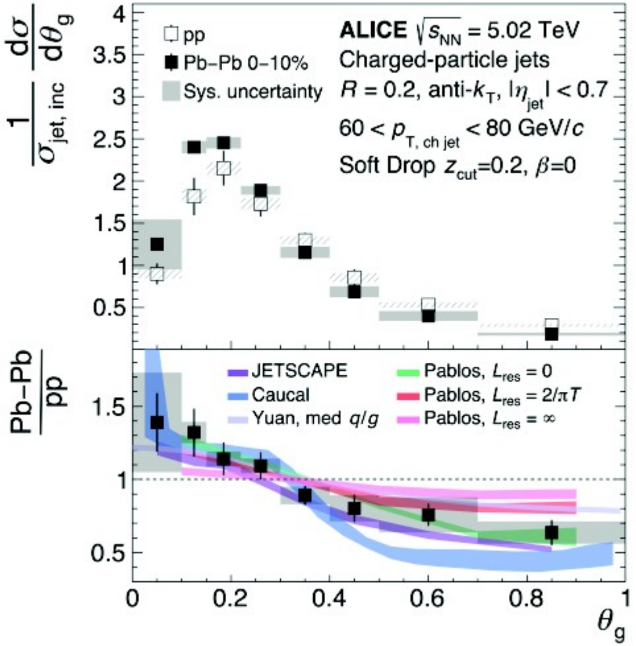


$$z_T = \frac{p_T^h}{p_T^{\gamma}}$$

- Isolated photons tag jets and probe parton energy loss in medium
- Suppression of hadrons in away-side peak is stronger in central Pb-Pb collisions

Modification of jet shower in the QGP

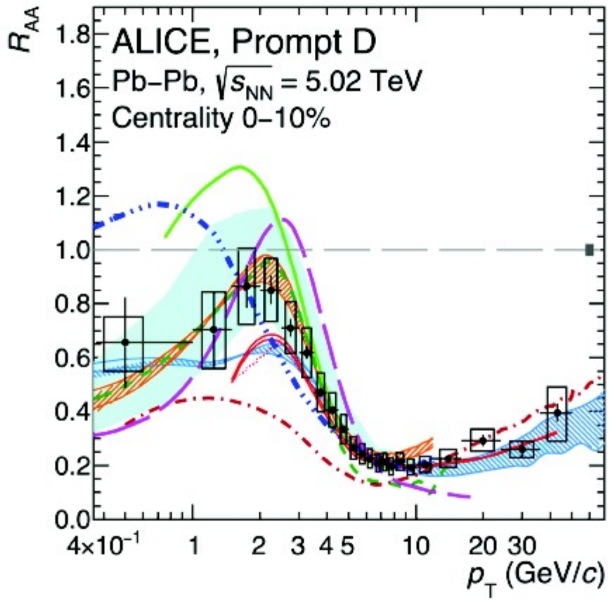


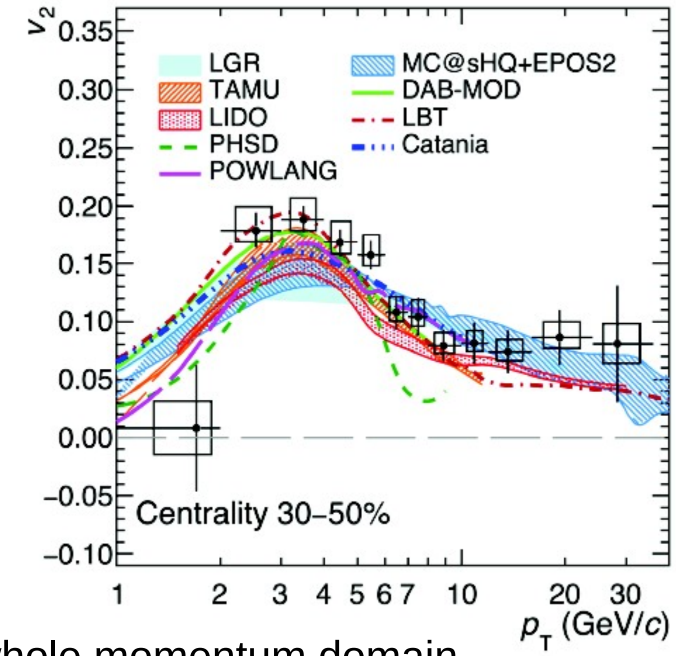


- Jet substructure measurements explore jet shape at earliest parton splittings
- Pb-Pb jet substructure more narrow than pp
- Indicates QGP jet energy loss mechanisms suppress wider angle jets

ALICE. *Measurement of the groomed jet radius and momentum splitting fraction in pp and Pb−Pb collisions at* $\sqrt{s_{NN}}$ *= 5.02 TeV*, Phys. Rev. Lett. 128 (2022) 102001

Heavy flavor interactions



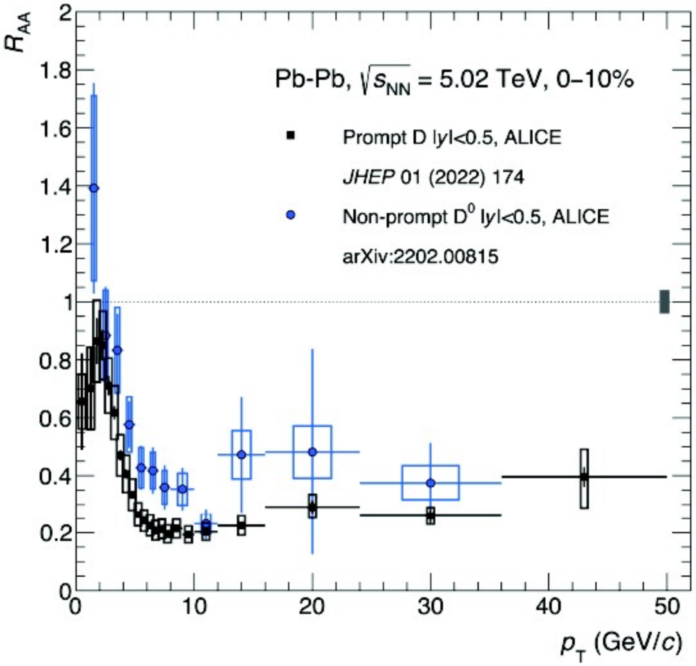


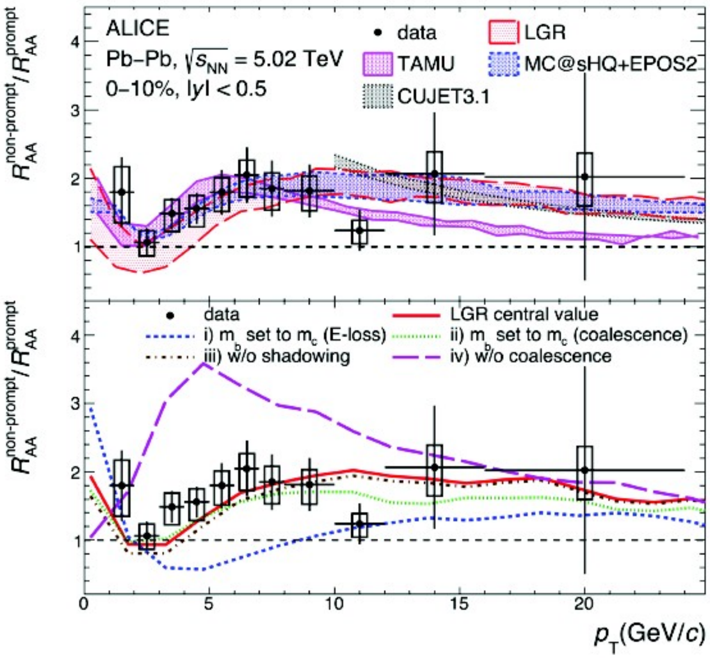
Heavy quarks as hard probes investigate medium for whole momentum domain

- Hard scale given by the quark mass
- Most charm-quark transport models describe both the R_{AA} and anisotropic flow (v_2)
- Similar to light flavors, radiative energy loss defines production spectra at high momenta

- ALICE. *Prompt D^0, D^+, and D^{*+} production in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, JHEP 01 (2022) 174
- ALICE. *Transverse-momentum and event-shape dependence of D-meson flow harmonics in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, Phys. Lett. B 813 (2021) 136054

Charm vs beauty energy loss

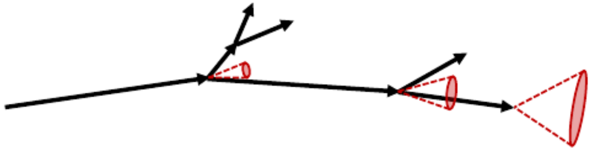




- D mesons from bottom decays less suppressed than those formed from charm
- Indication of mass dependent collisional and radiative suppression e.g. dead cone effect

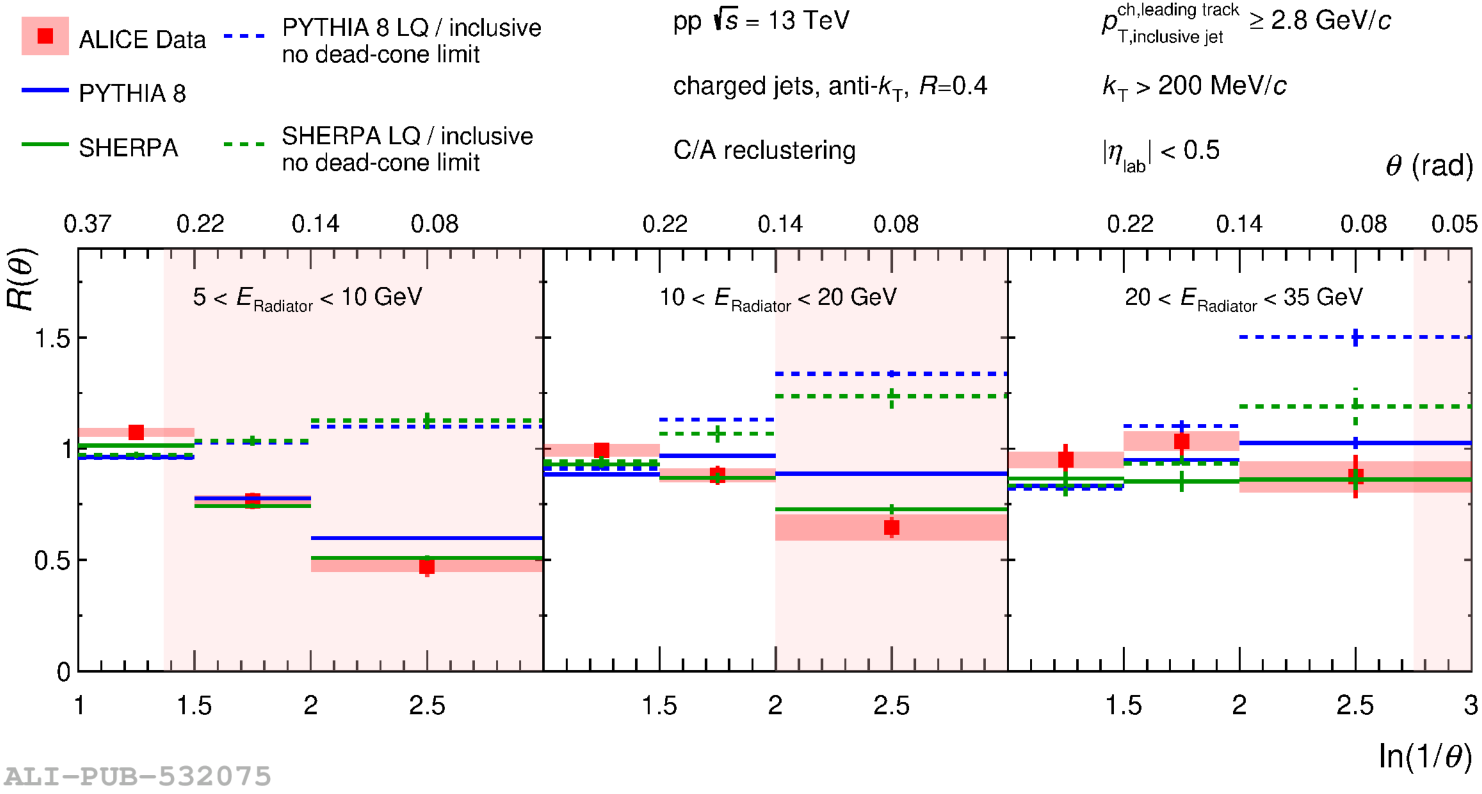
- ALICE. *Prompt D^0, D^+ , and D^{*+} production in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, JHEP 01 (2022) 174
- ALICE. *Measurement of beauty production via non-prompt D^0 mesons in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, JHEP 12 (2022) 126, arXiv:2202.00815

Dead cone effect



$$P_{Q\to Qg} = C_F\left[\frac{1}{z} - 1 + \frac{z}{2} - \frac{z(1-z)m^2}{k_\perp^2 + z^2 m^2}\right]$$

Y. L. Dokshitzer,
J. Phys. G17 (1991) 1602

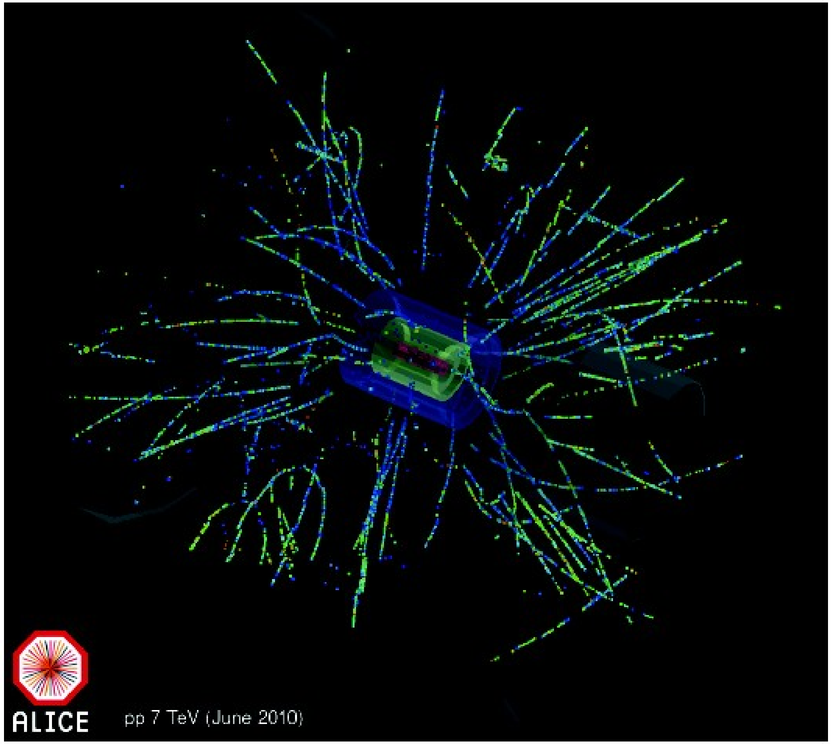


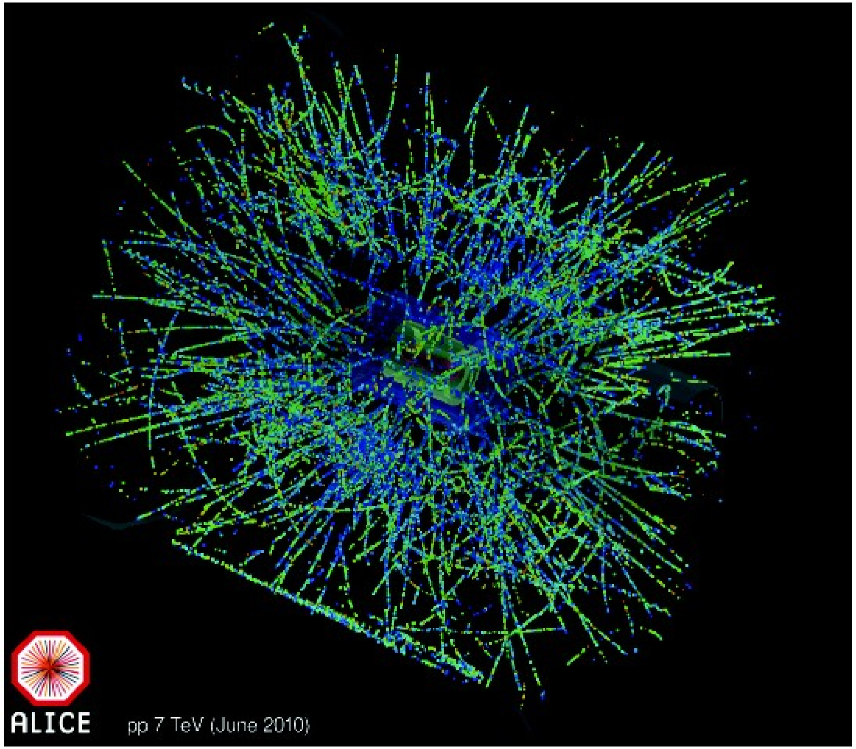
$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}}\frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Big/ \frac{1}{N^{\mathrm{inclusive\,jets}}}\frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)}\Bigg|_{k_\mathrm{T},E_\mathrm{Radiator}}$$

First direct observation of the dead cone effect

ALICE, Direct observation of the dead-cone effect in quantum chromodynamics, Nature 605, p. 440-446 (2022)

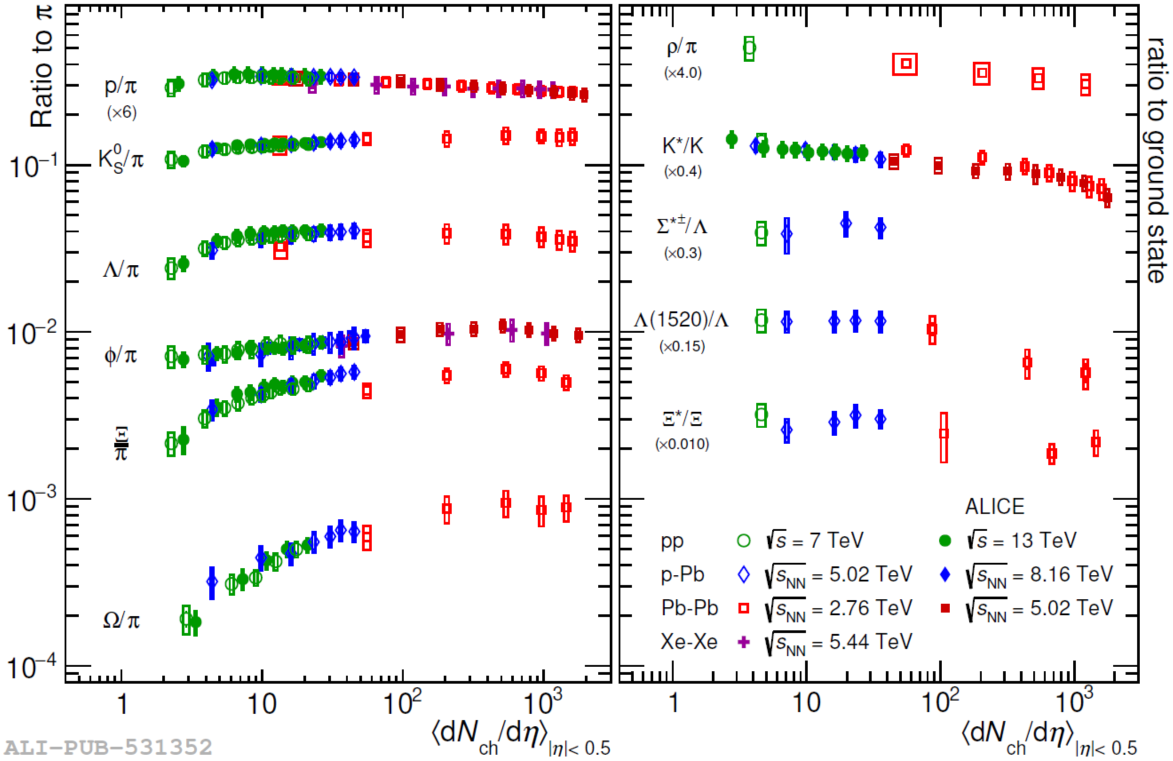
QCD studies in small systems





- Rare **pp** and **p-Pb** collisions can produce very large numbers of hadrons. i.e. high multiplicities
- Do such events have anything to do with deconfined quark-gluon matter?

Strangeness enhancement in small systems

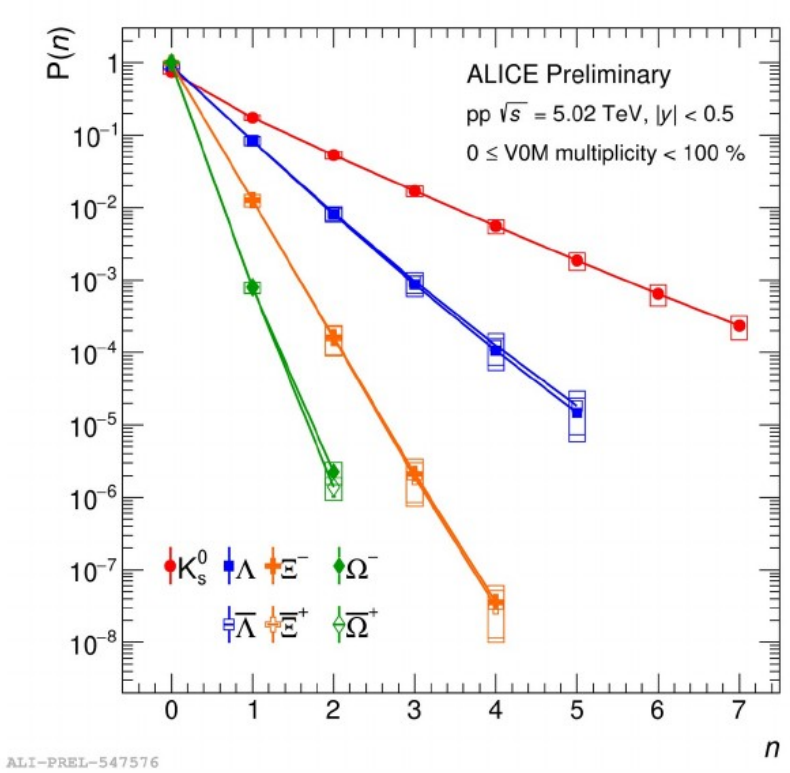


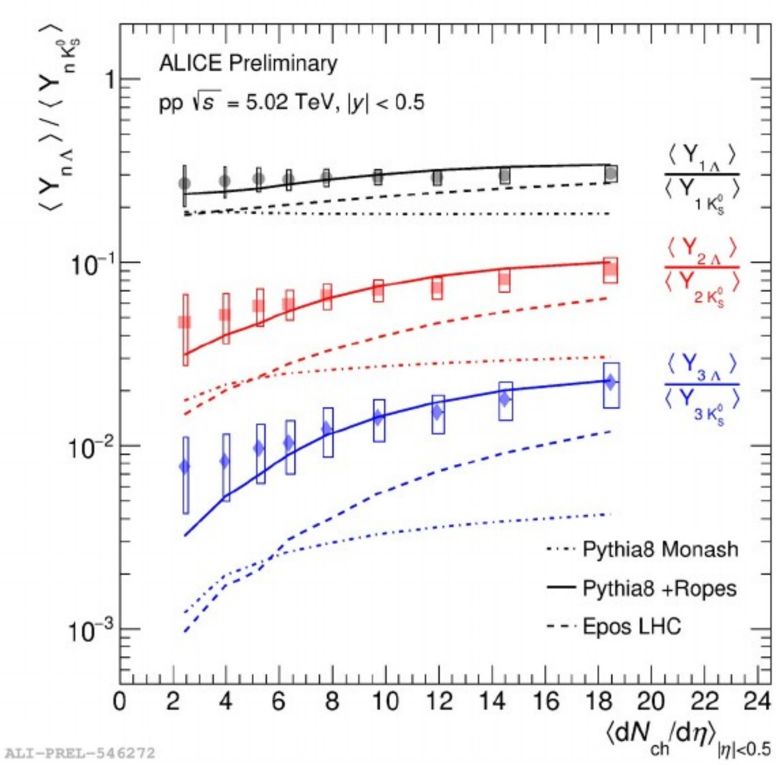
Particle yield ratios depend on $dN_{ch}/d\eta$ rather than colliding species

ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

- Increase of yields of strange particles relative to pions with multiplicity
- Highest multiplicity ratios comparable with central Pb-Pb
- Thermalisation of strangeness? Non-QGP mechanisms?

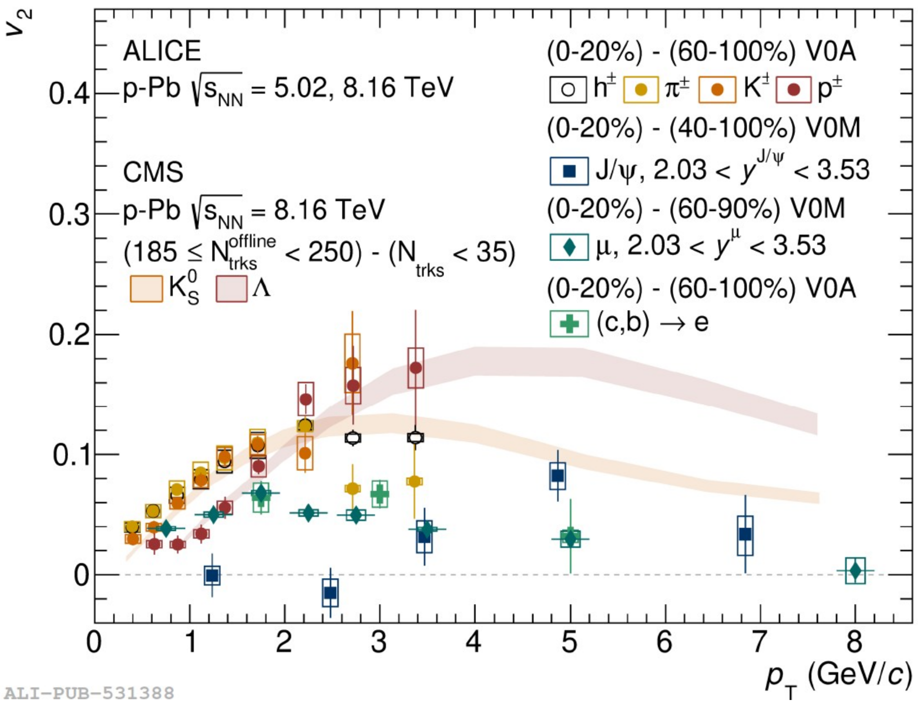
Strangeness in small systems

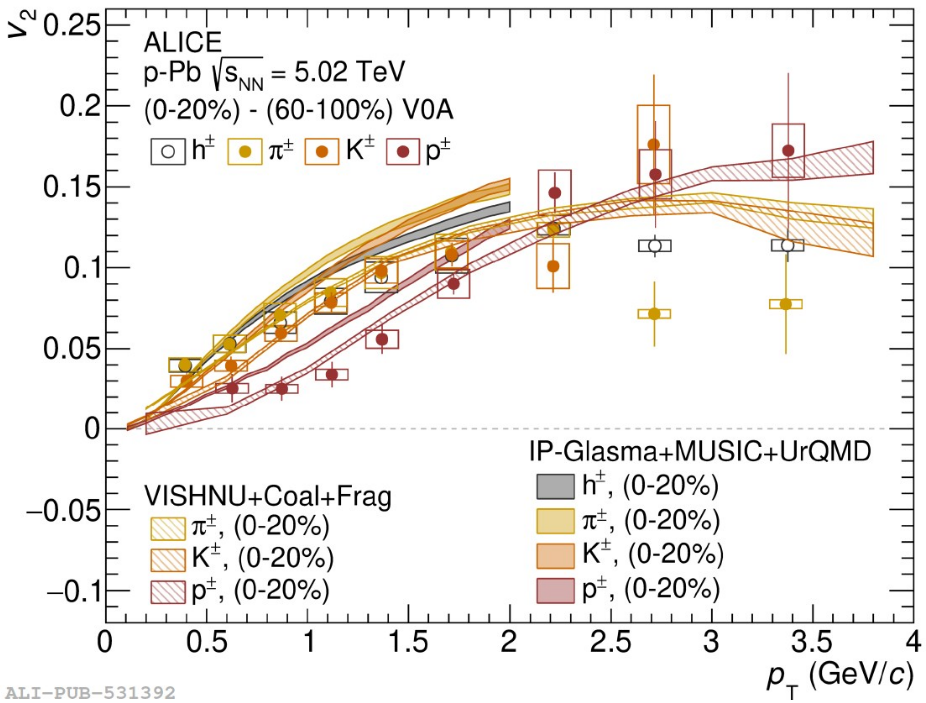




- First measurement of the production probability for > 1 strange particle per event
- Disentangle baryon-related from strangeness-related contributions

Flow in small systems

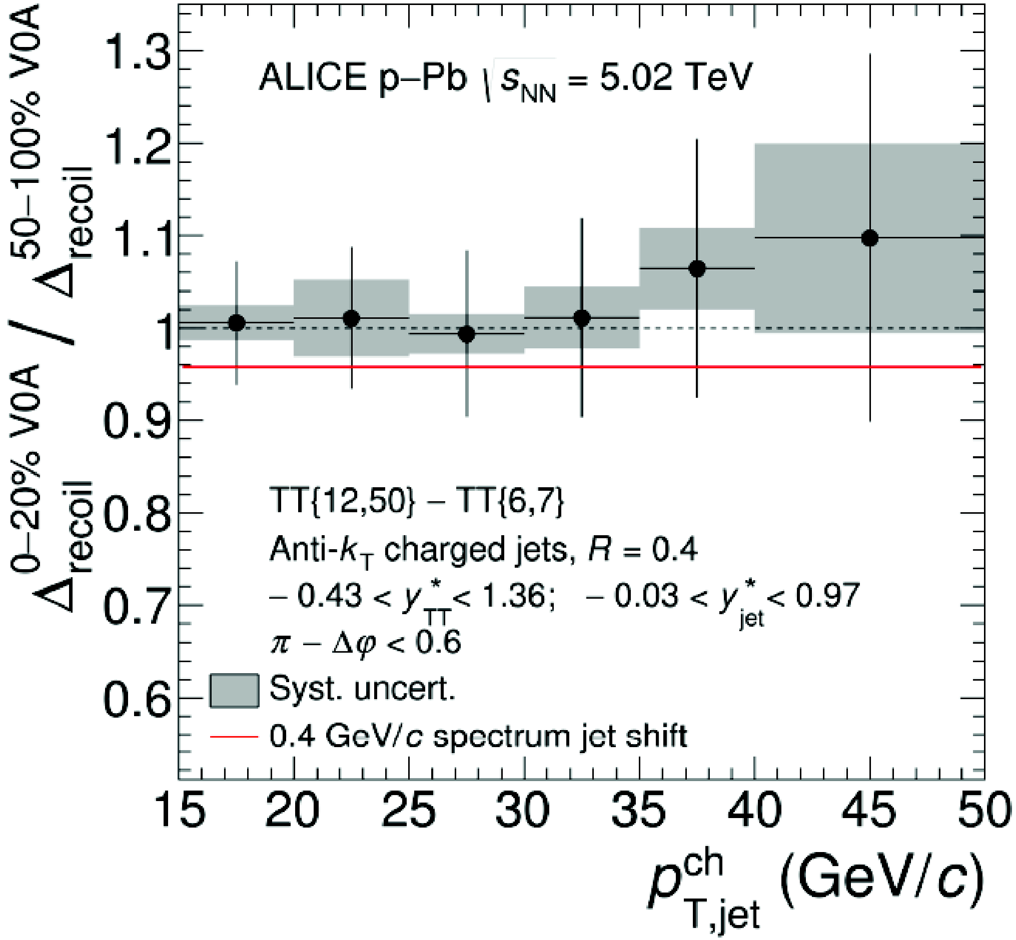




- Light and charmed hadrons exhibit anisotropic flow in small systems
- Described in light sector by hydrodynamics (with QGP equation of state) at LHC and RHIC

ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

No jet energy loss in small systems?



$$\Delta_{recoil}\left(p^{ch}_{T,jet}\right) = \frac{1}{N_{trig}} \frac{d^2 N_{jets}}{dp^{ch}_{T,jet}}\Bigg|_{p_{T,trig} \in TT_{Sig}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jets}}{dp^{ch}_{T,jet}}\Bigg|_{p_{T,trig} \in TT_{Ref}}$$

- Recoil jet distributions show no significant differences between low and high multiplicity p-Pb collisions
- Shift of jet energy spectrum by ~0.4 GeV
- Jet energy loss effects in p-Pb at least 20 times smaller than central Pb-Pb

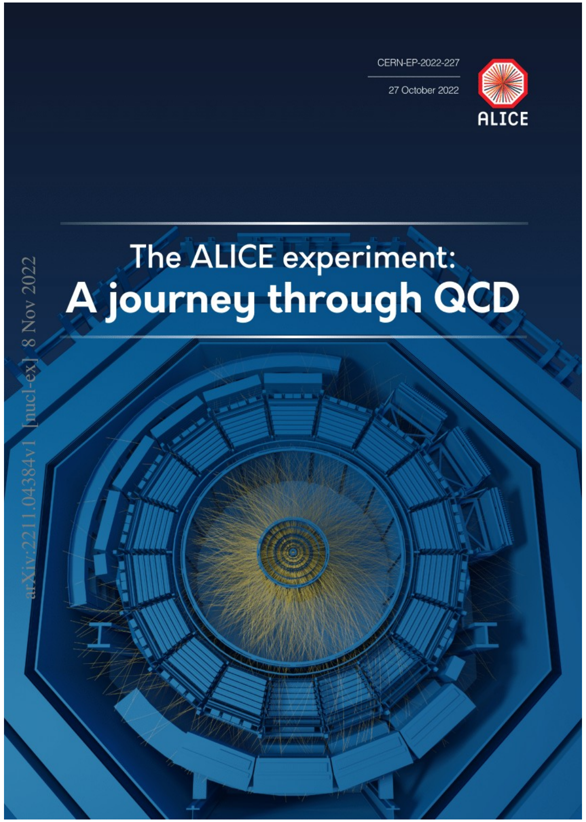
ALICE. *Constraints on jet quenching in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured by the event-activity dependence of semi-inclusive hadron-jet distributions*, Phys. Lett. B783 (2018) 95–113

Is QGP really formed in small systems?

- QGP signatures:
  - Strangeness enhancement
  - Hydrodynamic flow of light hadrons
  - Heavy flavor flow
- No QGP effects:
  - No J/Ψ suppression
  - No jet quenching
- What to do?
  - Increase precision of measurements (more statistics, advanced detectors)
  - Collide light ions
  - Theory development synchronously with experiments

First 13 years of heavy-ion physics at LHC

- High temperature QCD
  - Extensive progress in QGP energy loss
  - Charm and charmonium production mechanisms better understood
  - Hydrodynamics description of QGP
  - Precision tests of hadron and nuclei production at high temperature
  - QGP signatures in small systems
- QCD studies beyond heavy-ion program
  - Probing nuclear and proton structure by photons
  - Rare hadronic interactions
  - Charm fragmentation and dead cone effects



ALICE, arXiv:2211.04384

This work is supported by the Russian Science Foundation grant RSF 22-42-04405

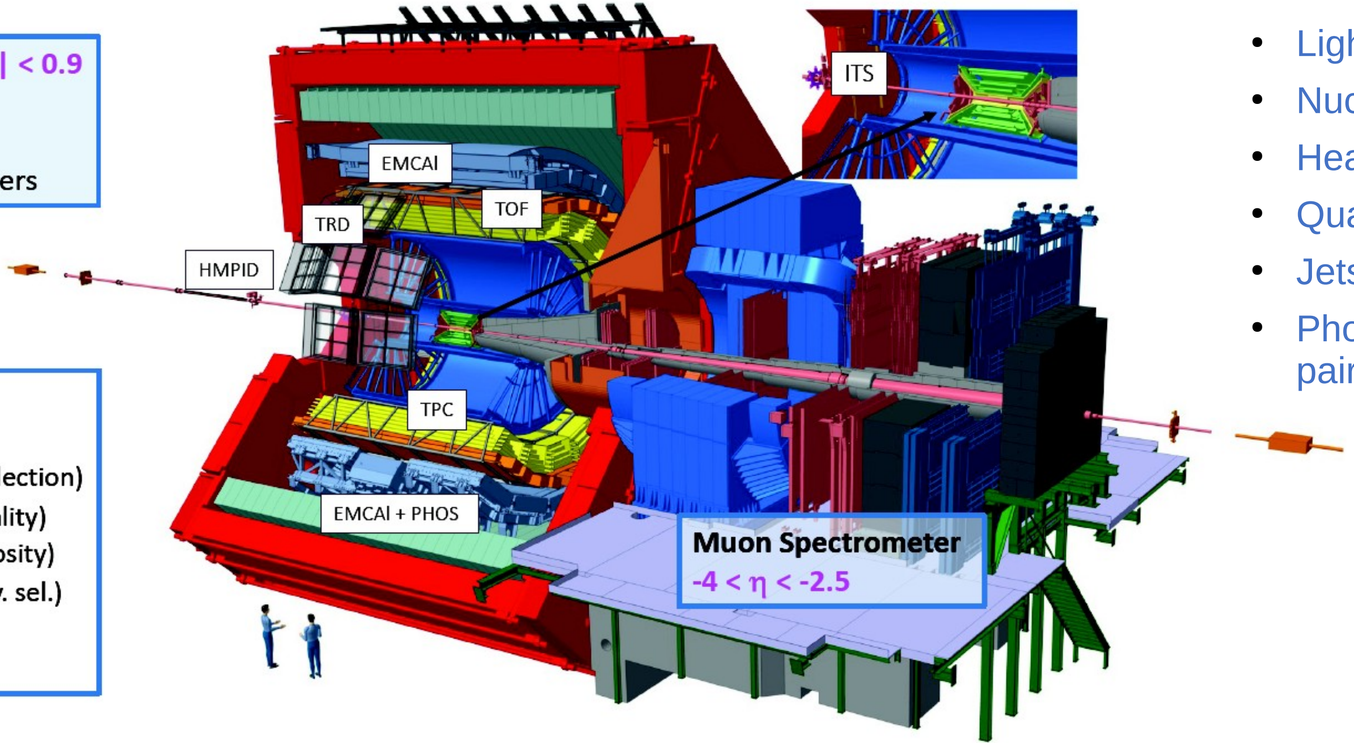
Backup slides

ALICE experiment Runs 1-2

Central Barrel $|\eta| < 0.9$
- Tracking
- PID
- EM-Calorimeters

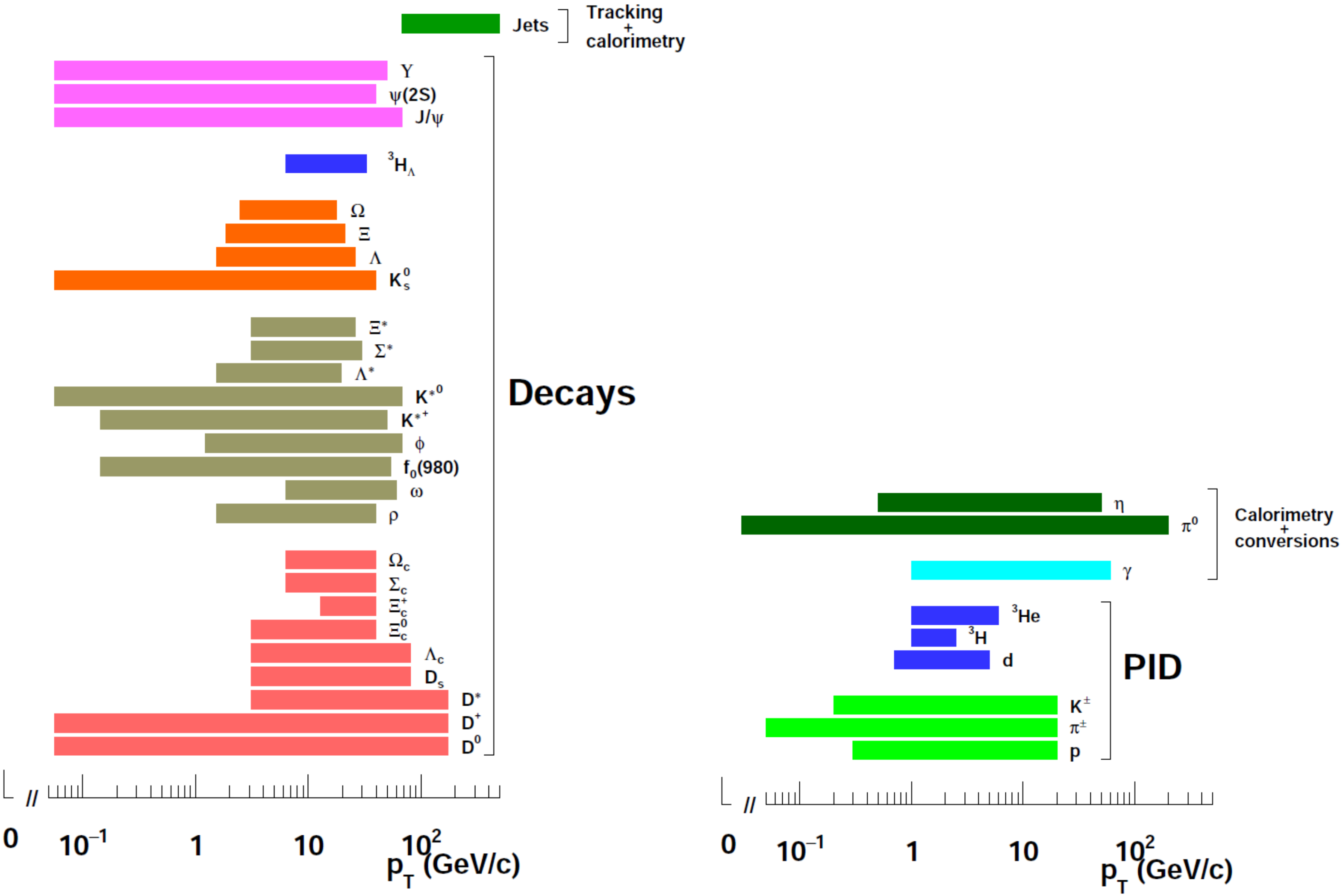
ACORDE (cosmics)

Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD ($N\gamma$, Nch)

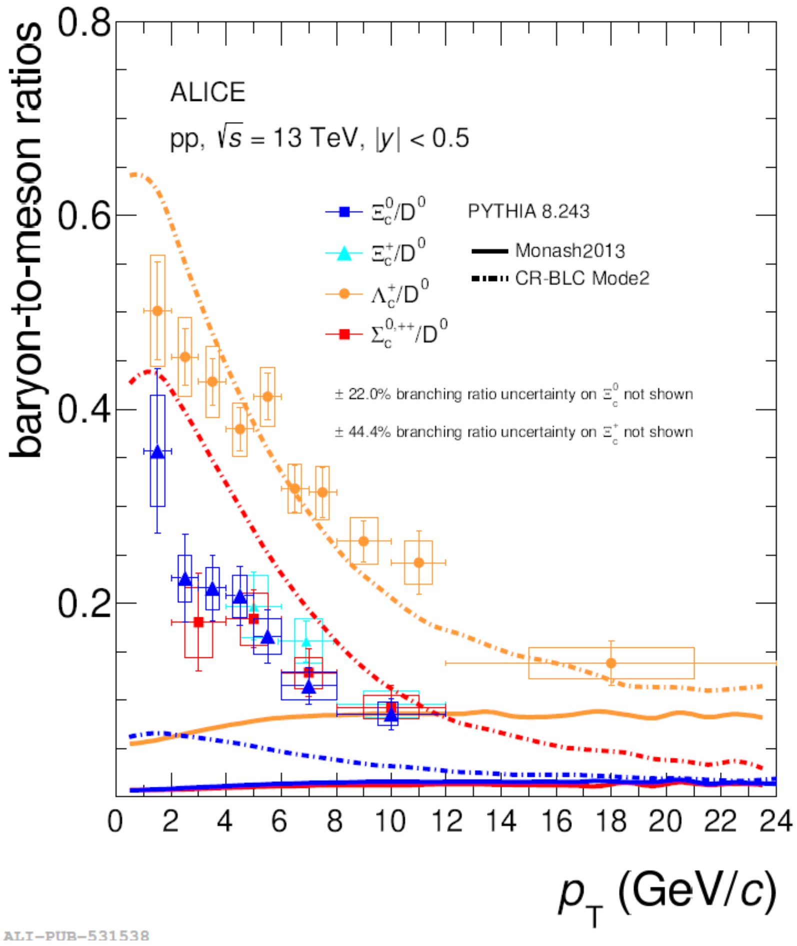


- Light flavour production
- Nuclei
- Heavy flavor production
- Quarkonia
- Jets
- Photons, low-mass lepton pairs

ALICE particle identification and reconstruction



Fragmentation to mesons and baryons



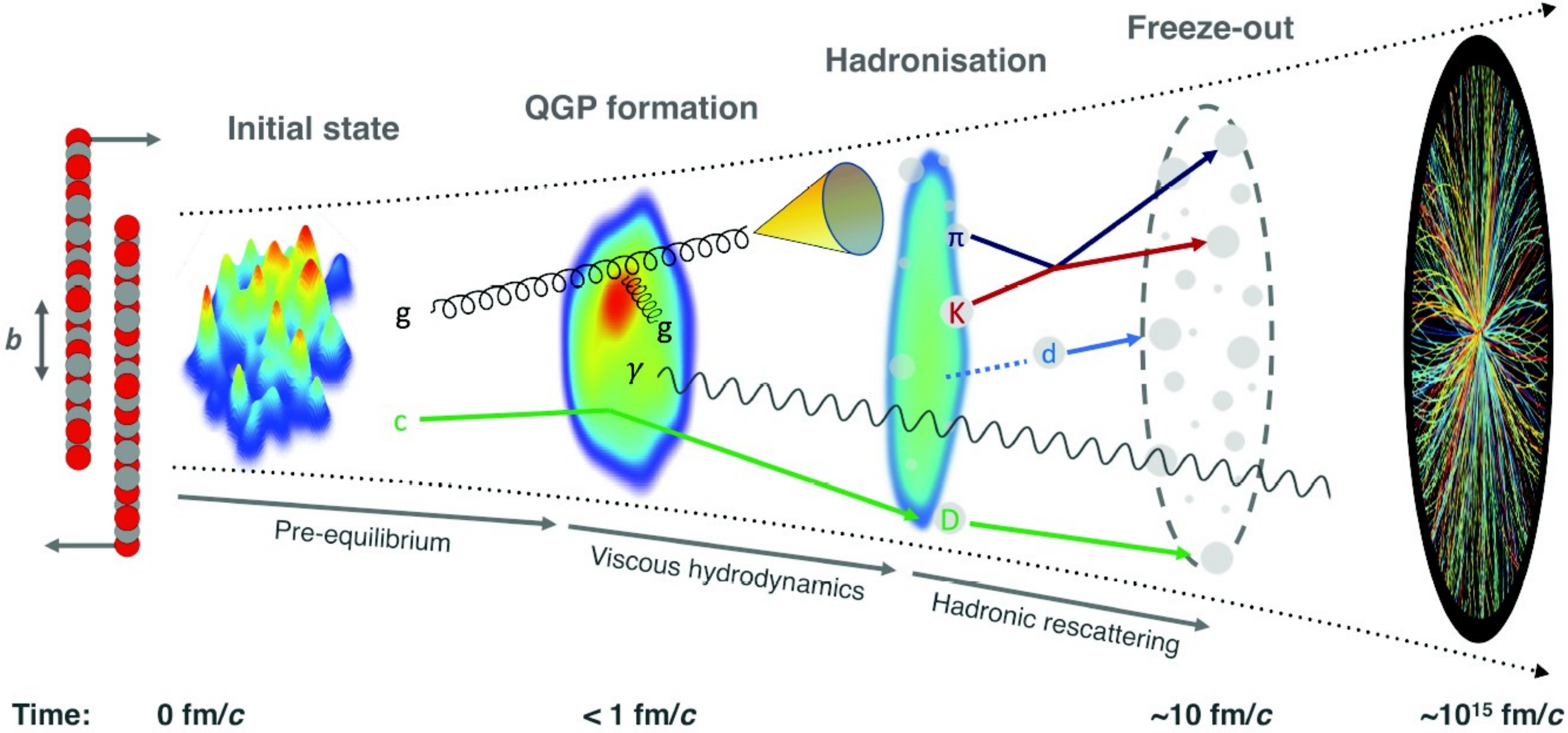
- Charmed baryon/meson ratios in pp underestimated by fragmentation models tuned on e^+e^- collisions

- 30% of charmed quarks hadronize to baryons in pp

- in pp collisions at LHC energies several partons are created via multiple-parton interactions and color reconnections beyond leading-color topologies become important

ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

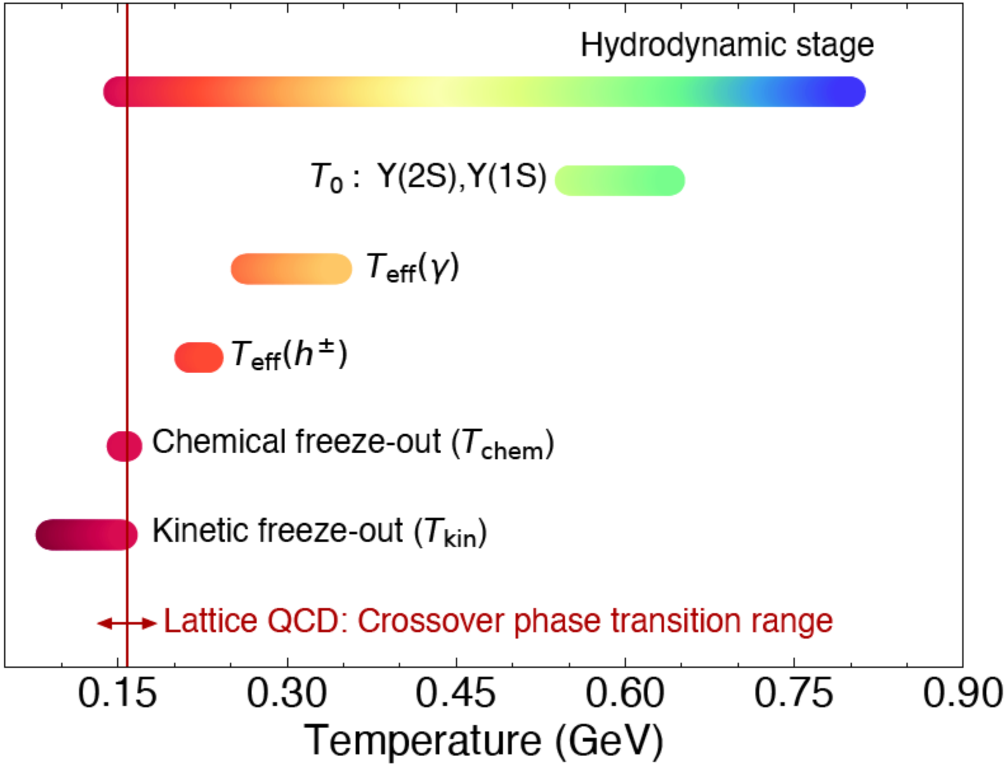
Evolution of a heavy-ion collision at LHC energies



Quark-gluon plasma (QGP) = deconfined strongly-interacting QCD matter with color degrees of freedom

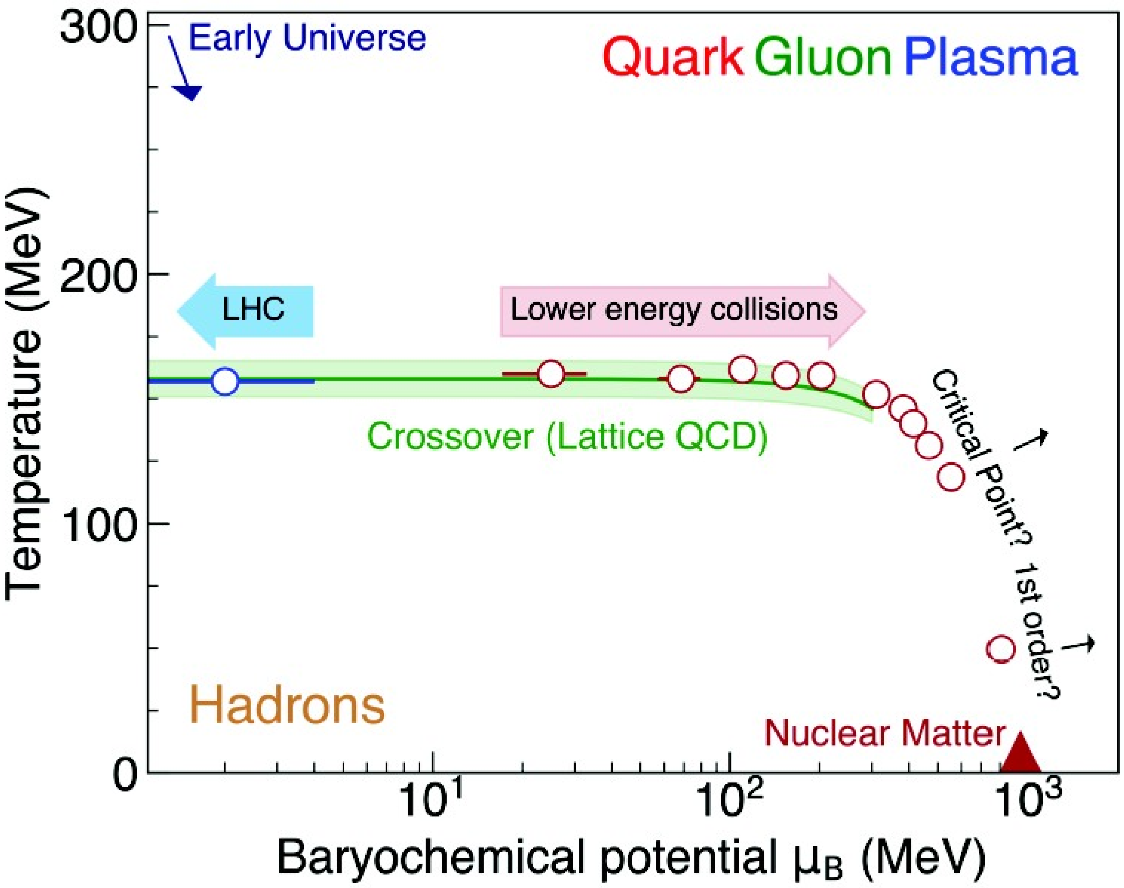
Temperatures of nuclear collisions at LHC

Many observables imply temperatures greater than QGP transition temperature



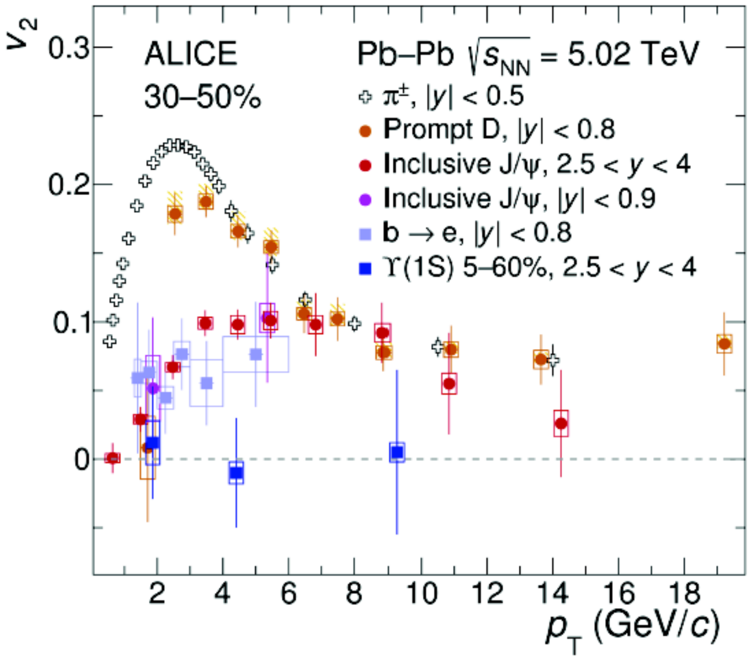
Resonance yields and different pion/kaon emission times indicate a prolonged and complex hadron gas phase

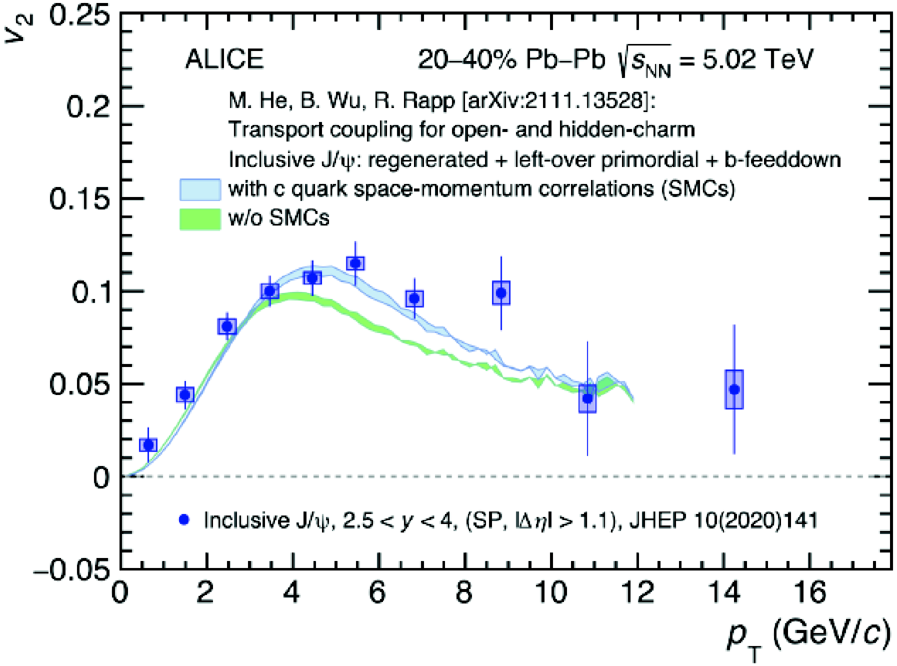
QCD phase diagram



- QGP produced at LHC has highest temperatures and largest matter-antimatter symmetry
- HIC at LHC reproduces early Universe at ~10^{-6} seconds after big bang
- Physics program of LHC experiments inherits experience of RHIC, confirms properties of QGP at high temperature, brings new results based on precision measurements.
- **ALICE paper "A journey through QCD" summarizes the QCD measurements performed in 2010-2018. 2211.04384 [nucl-ex], CERN-EP-2022-227**
- Lower energies at SPS, RHIC, FAIR, NICA complements LHC by search for QCD critical point and thresholds of QGP formation

Heavy quark flow in the QGP

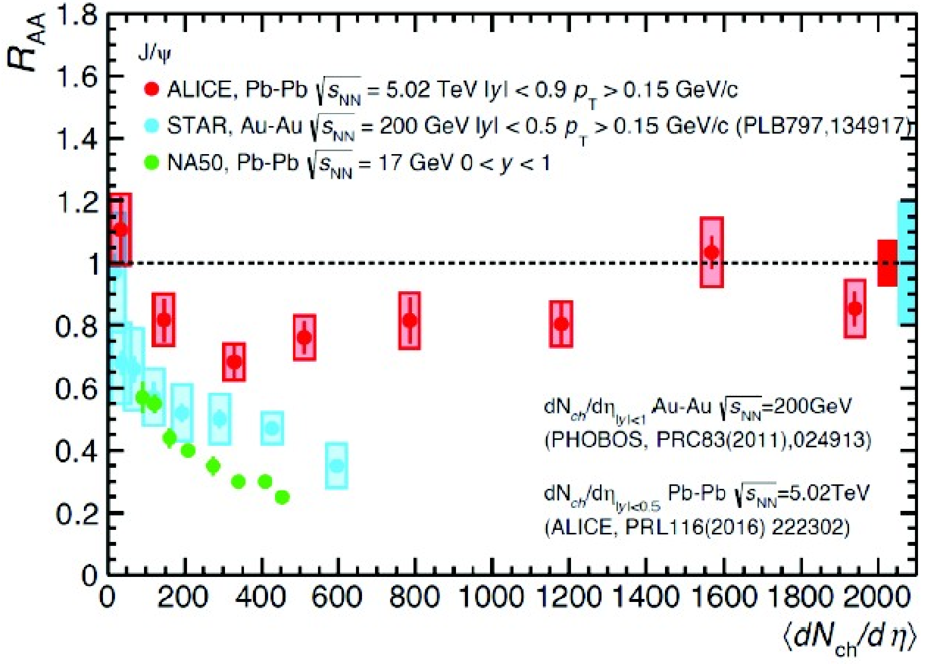


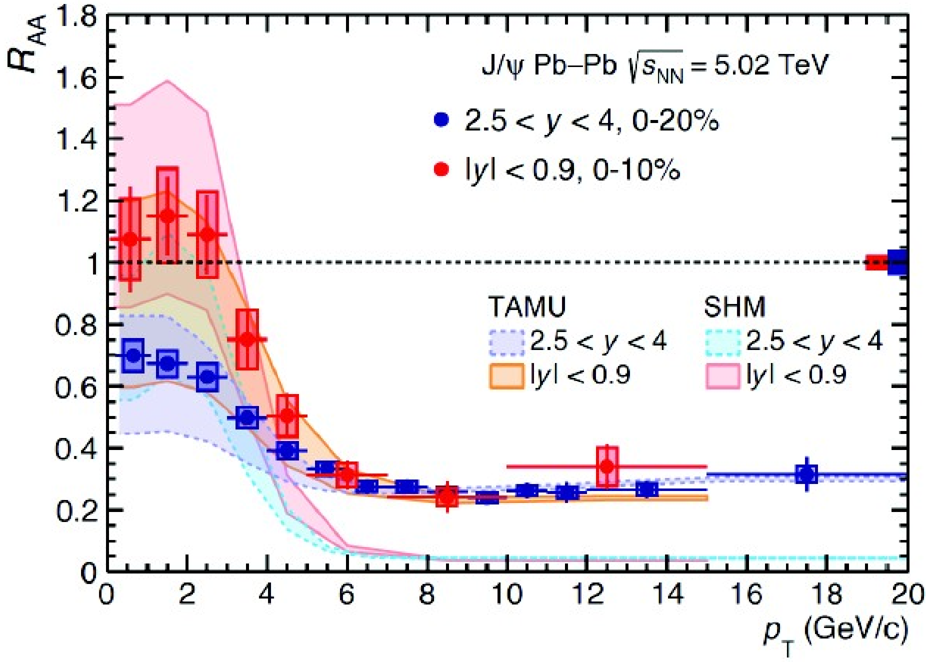


- Finite values of J/Ψ v_2 provide unambiguous signature of charm flow. Bottom quarks also flow
- Transport models using Brownian motion describe charm flow

ALICE. *The ALICE experiment - A journey through QCD*. 2211.04384 [nucl-ex]

Suppression and regeneration of quarkonia

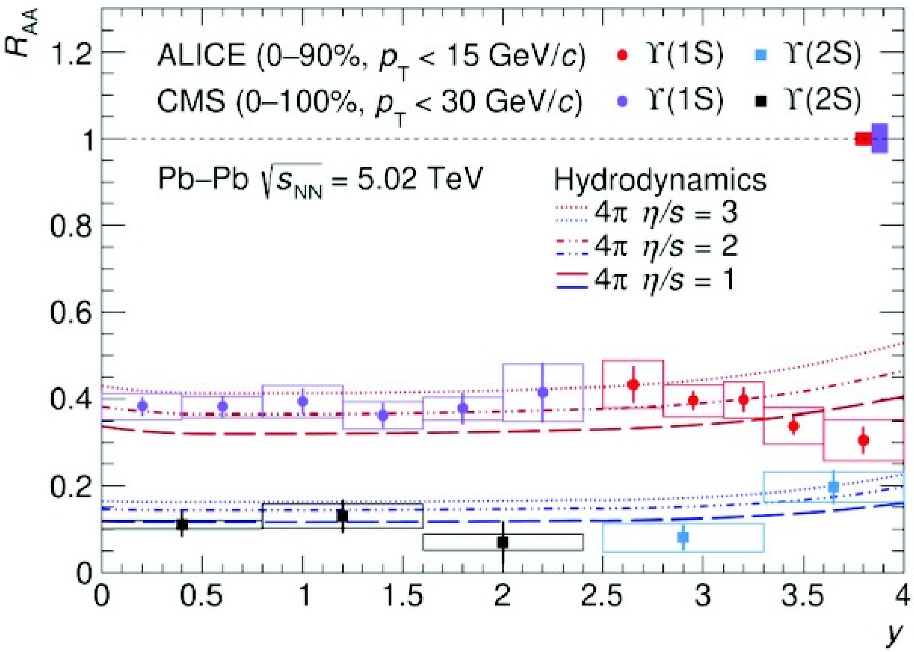


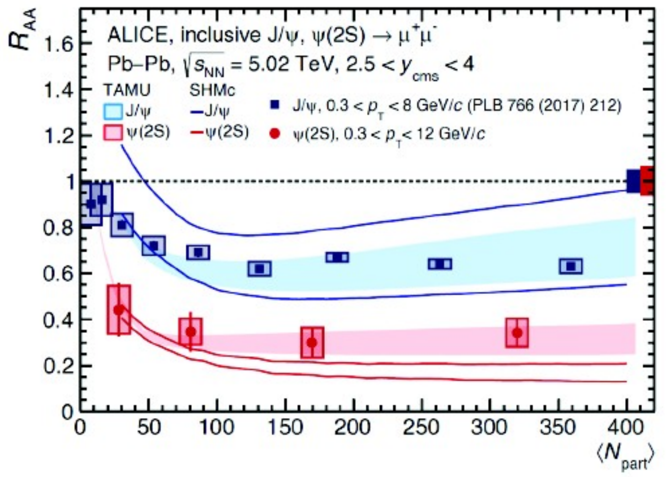


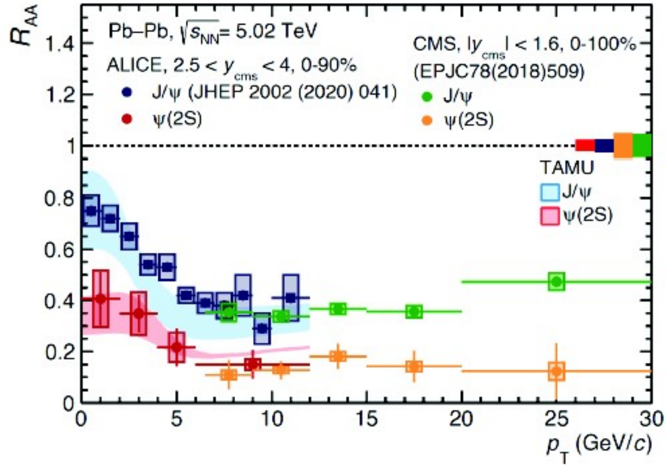
Quarkonia also probe QGP at sub fm scales

- Larger charm cross-section at LHC compared to RHIC/SPS, and mid-rapidity compared to forward, maximize J/Ψ regeneration effects
- Deconfinement: charm quarks free to move distances greater than hadronic size in QGP

Suppression of excited quarkonia





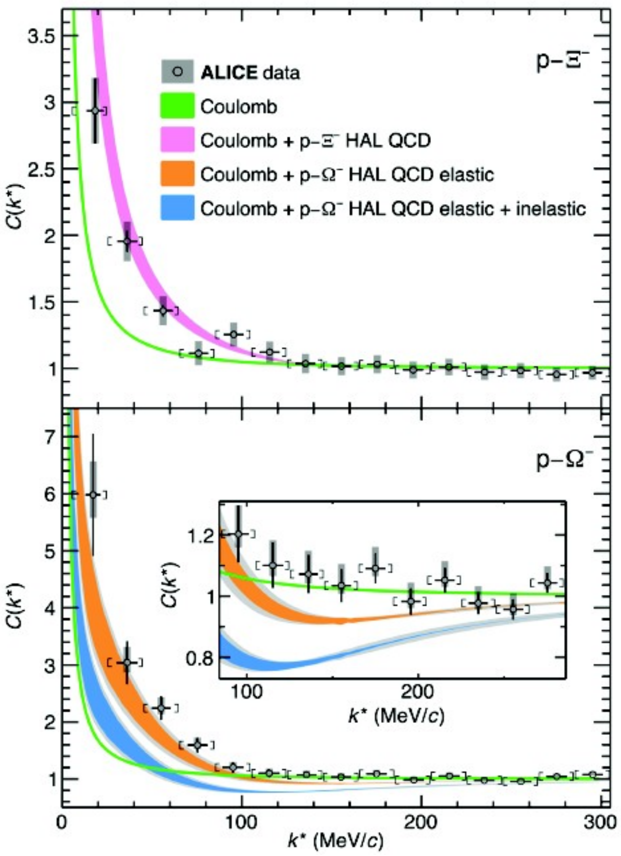


- Bottomonium shows sequential suppression
- Charmonium shows sequential suppression + regeneration
- ψ(2S) with ×10 times less binding energy - × 2 more suppressed than J/ψ
- Precision test of quarkonium transport in the medium.

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

$k^* = |\mathbf{p}_2^* - \mathbf{p}_1^*|/2$

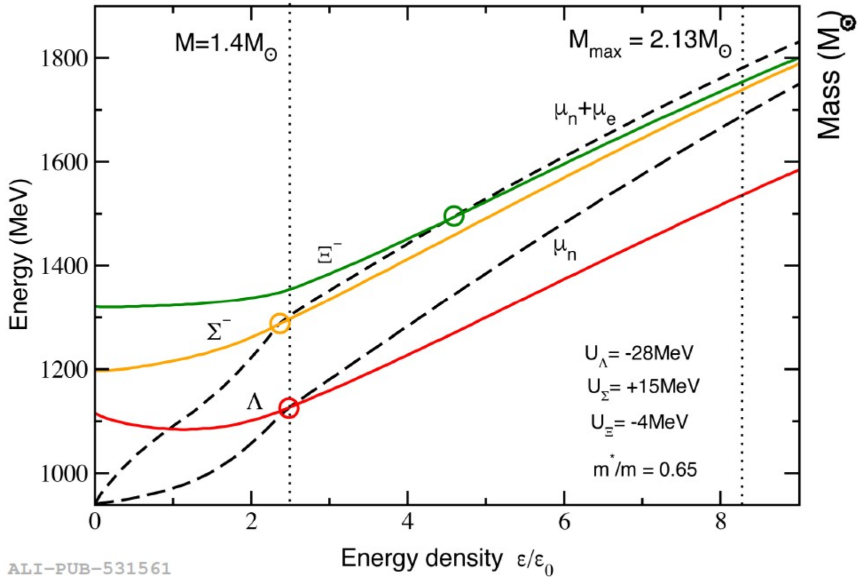
Hadron interactions



p–Ξ and p–Ω momentum correlation functions in pp collisions at 13 TeV

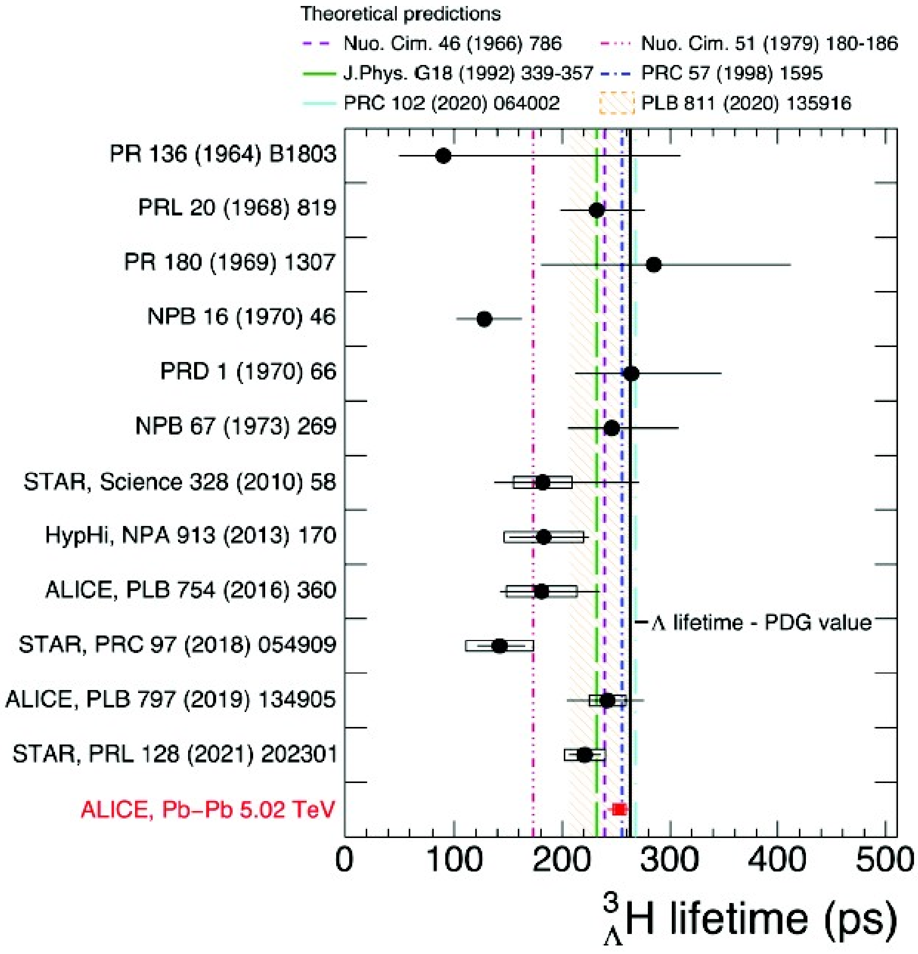
ALICE. *Unveiling the strong interaction among hadrons at the LHC,* Nature 588 (2020) 232–238

Chemical potential μ_i of hyperons produced in the inner core of a NS vs energy density, in units of energy density ε_0 at the nuclear saturation point



- Large production of hyperons in pp 13 TeV provide unique tests of QCD for rare hadronic interactions
- The interaction of hyperons with nucleons is a key ingredient for understanding composition of the most dense stars in our Universe: neutron stars (NS)
- Strength of proton-hyperon interaction influence neutron star equation of state

Nuclear synthesis and nuclear binding



- Hyper-nucleus $^{3}_{\Lambda}H$ has one of the smallest nuclear binding energy among observed nuclei.
- ALICE provided most stringent constraints on hyperthriton lifetime and energy
- Binding energy = 130±30 keV

ALICE. *Measurement of the lifetime and Λ separation energy of* $^{3}_{\Lambda}H$*,* arXiv:2209.07360