TWENTY-FIRST LOMONOSOV
CONFERENCE August, 24-30, 2023
ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Overview of QCD studies in ALICE at LHC

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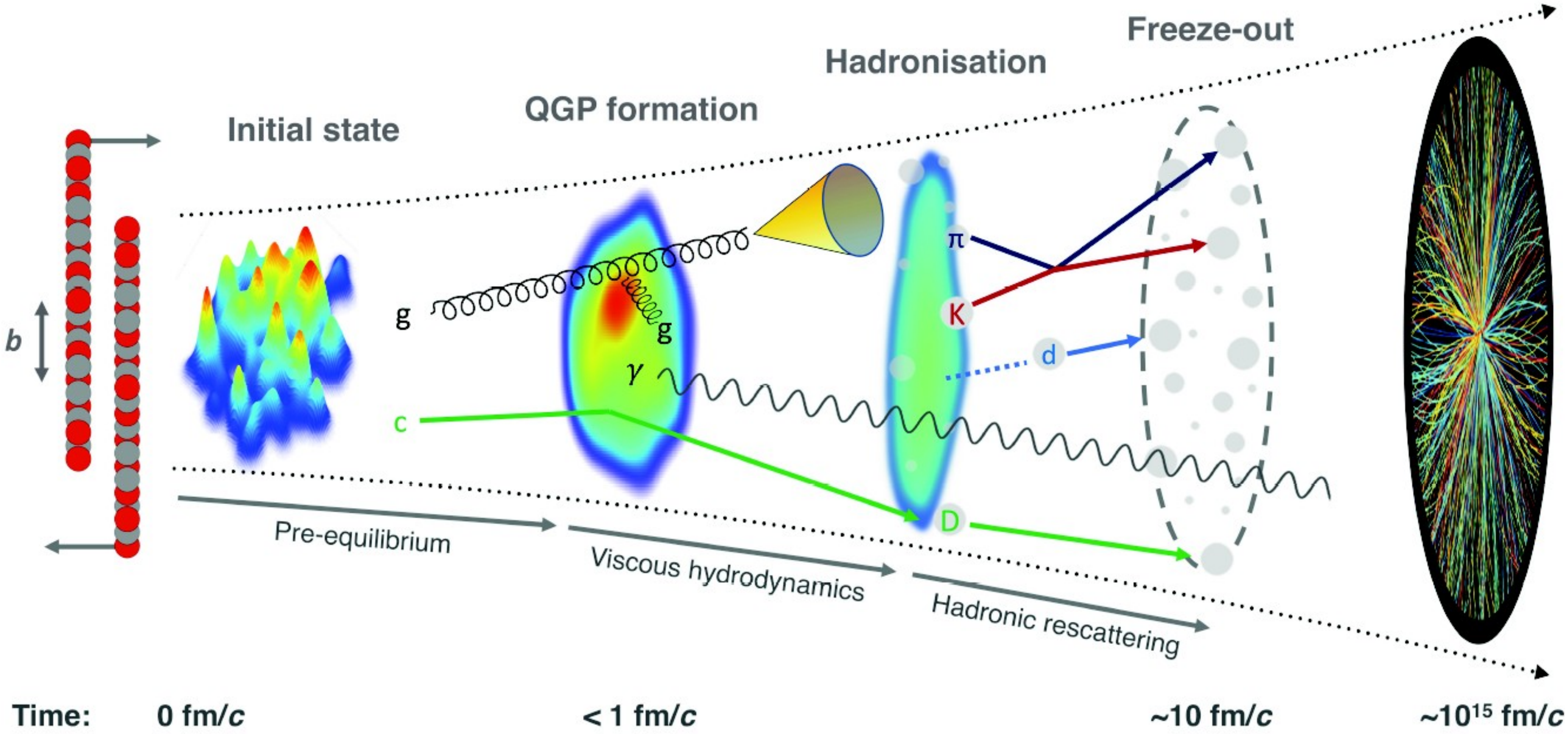
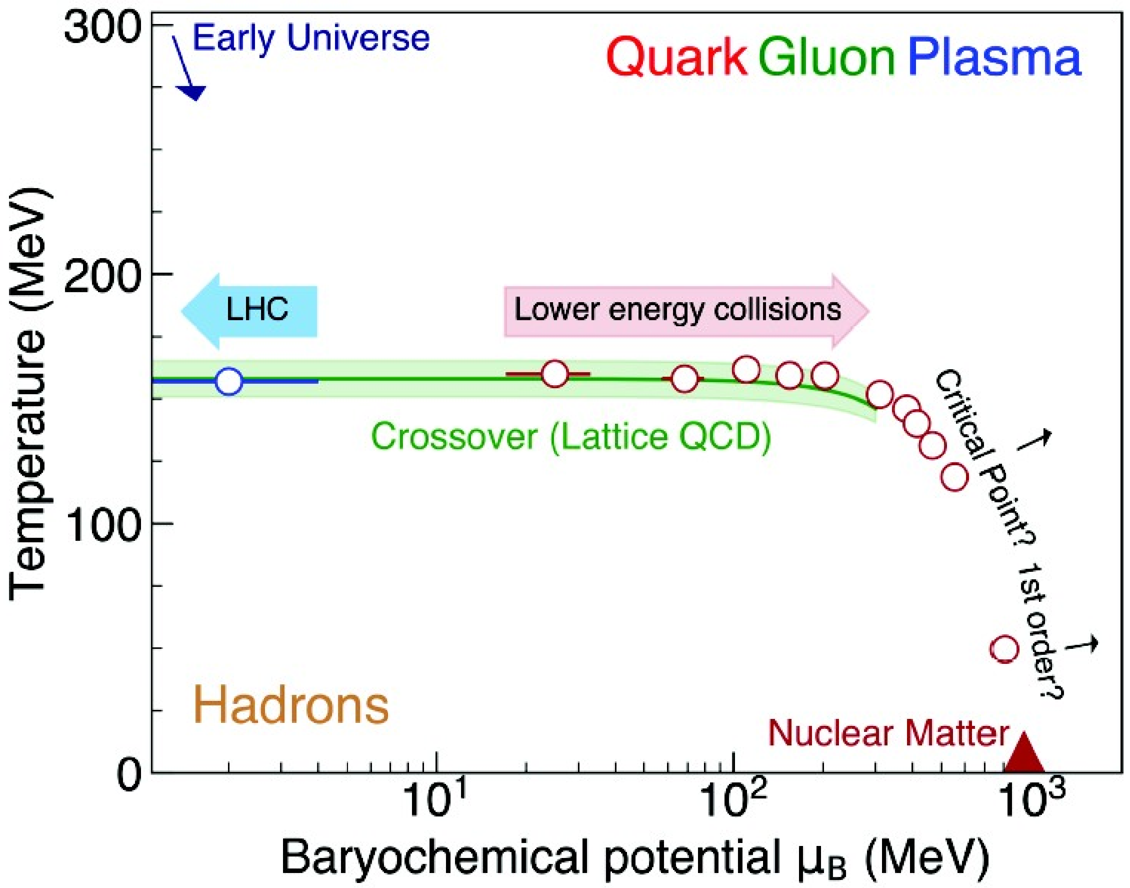
Evolution of a heavy-ion collision at LHC energies



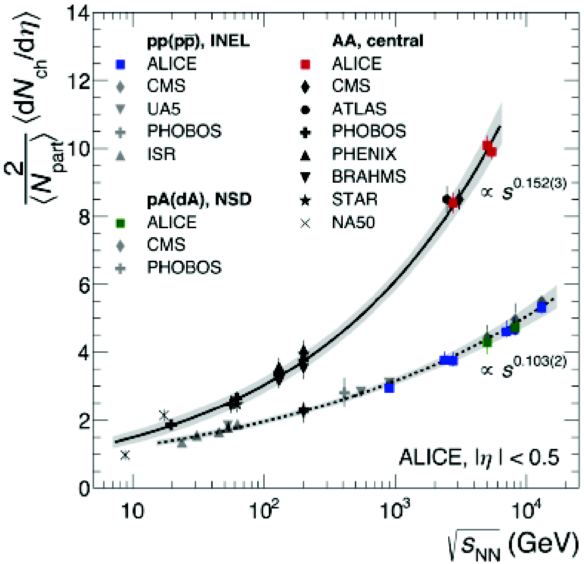
Quark-gluon plasma (QGP) = deconfined strongly-interacting QCD matter with color degrees of freedom

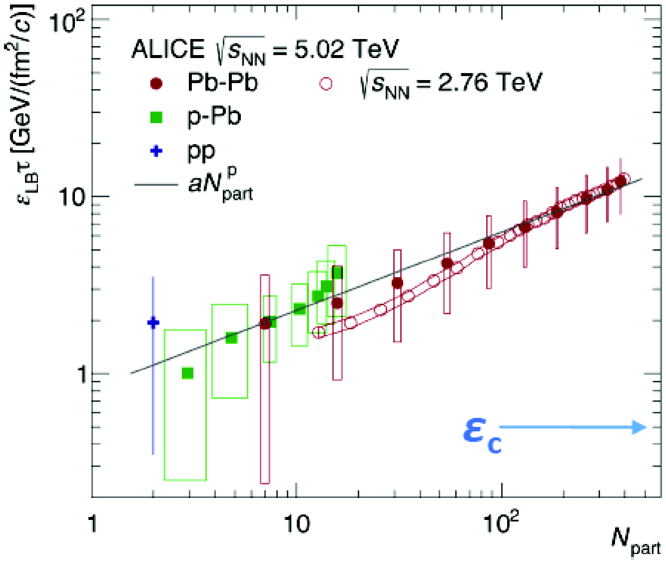
QCD phase diagram

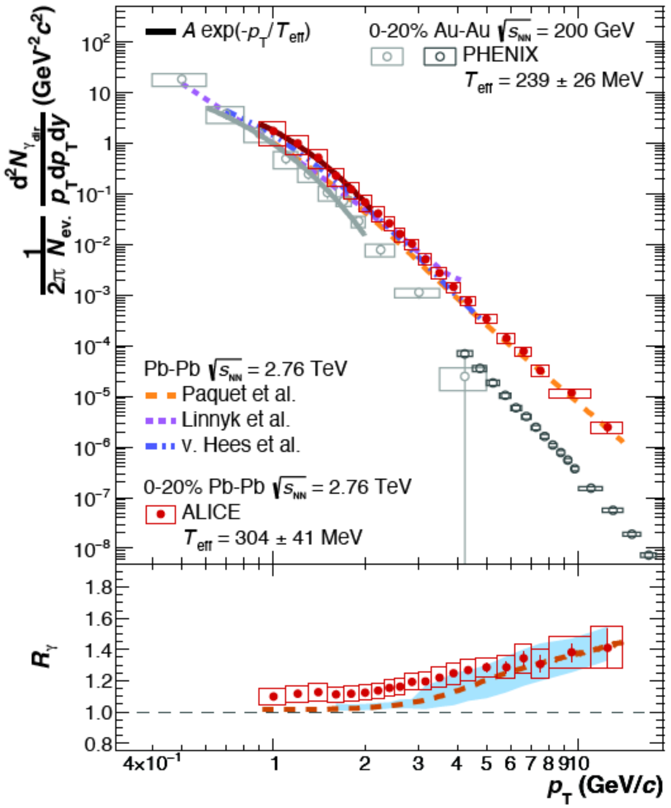


- QGP produced at LHC has highest temperatures and largest matter-antimatter symmetry
- HIC at LHC reproduces early Universe at $\sim 10^{-6}$ seconds after big bang
- Physics program of LHC experiments inherits experience of RHIC, confirms properties of QGP at high temperature, brings new results based 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

Global properties of nuclear collisions



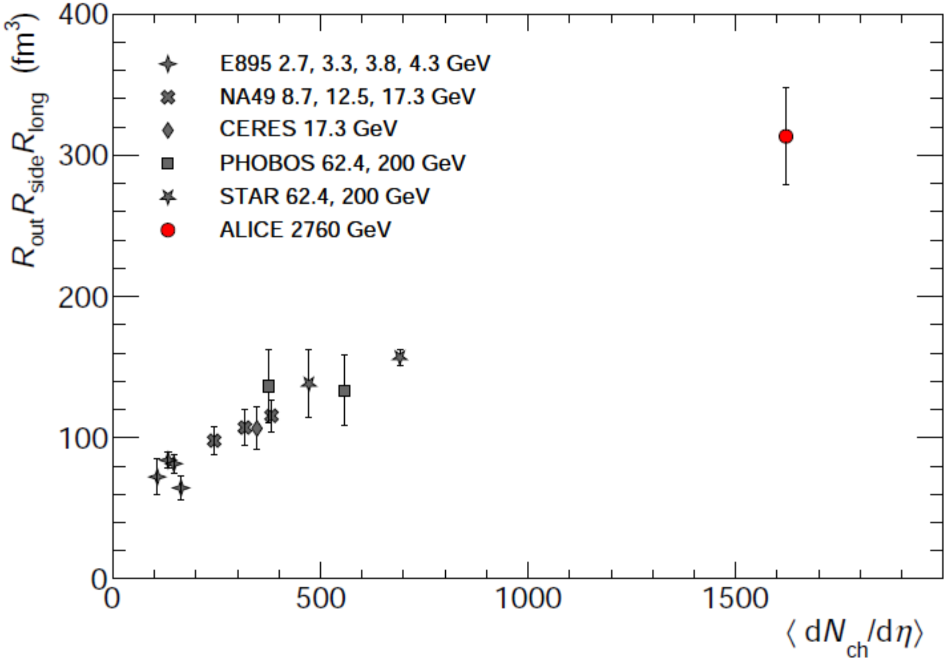


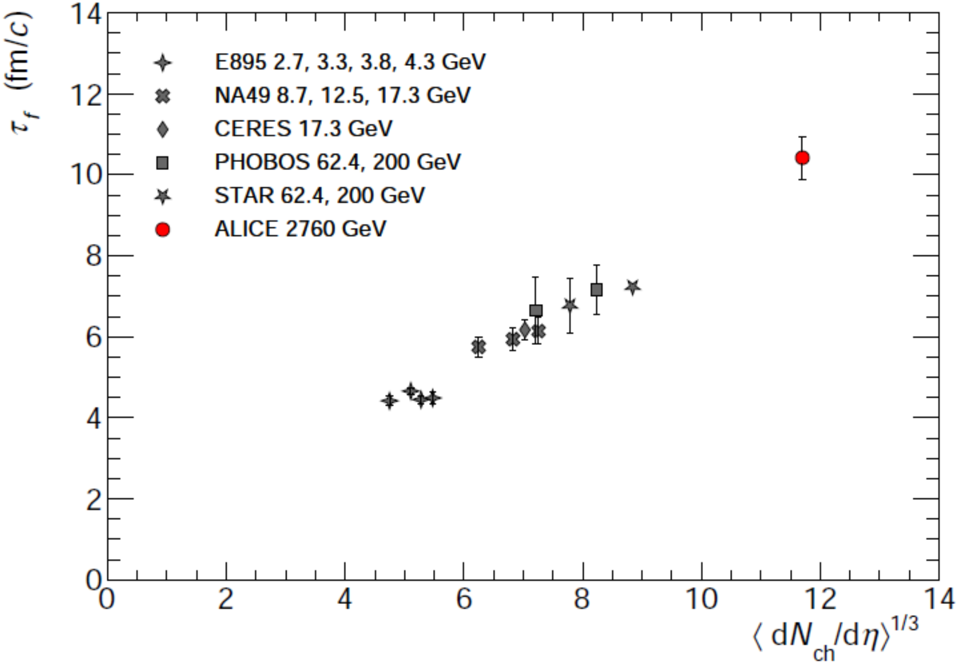


- Charged hadron production per nucleon is maximal in Pb-Pb at LHC
- Central Pb-Pb initial energy density 30x is larger than $\varepsilon_c \approx 0.7$ MeV/fm^3.
- Photon effective temperature is twice $T_c \approx 150$ MeV.

- 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

Size and lifetime of QGP

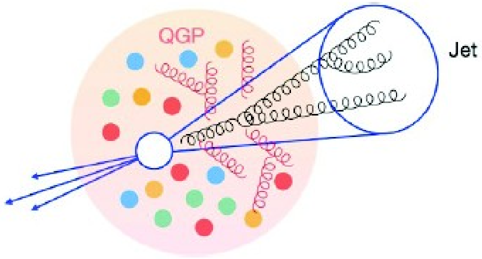


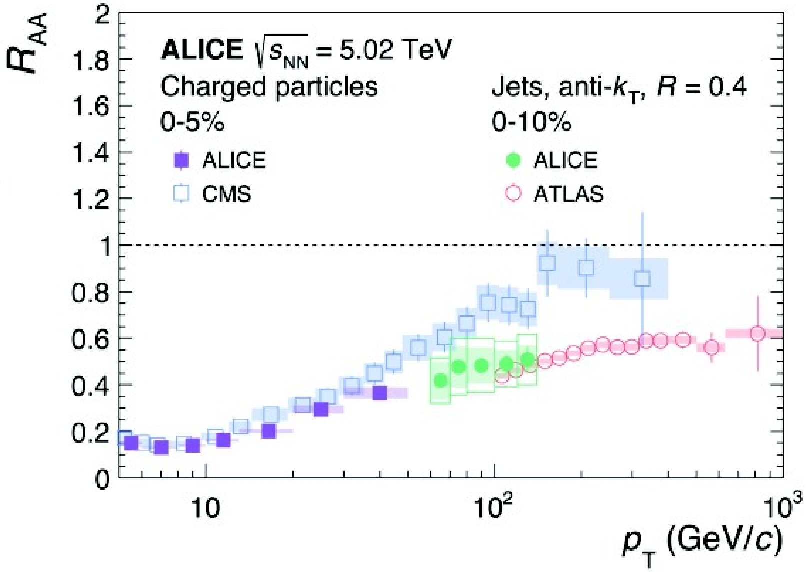


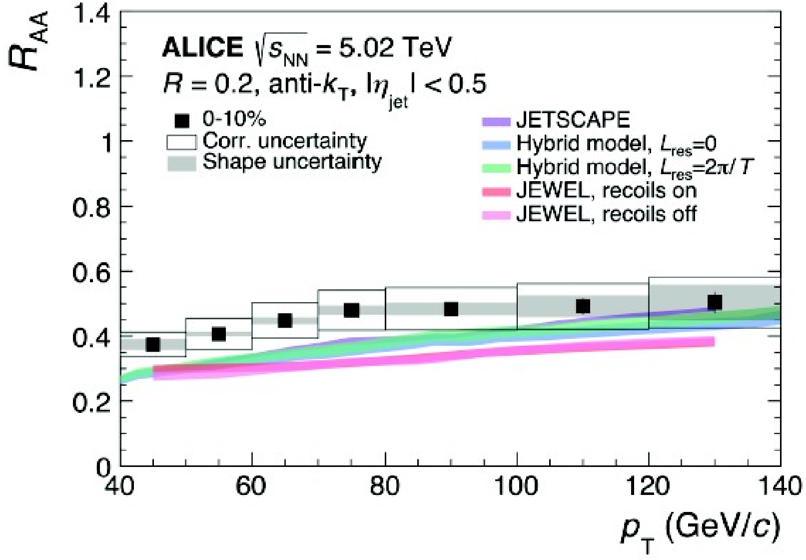
Homogeneity volume and decoupling time τ_f from AGS to LHC

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

Jets as a microscopic probe of medium



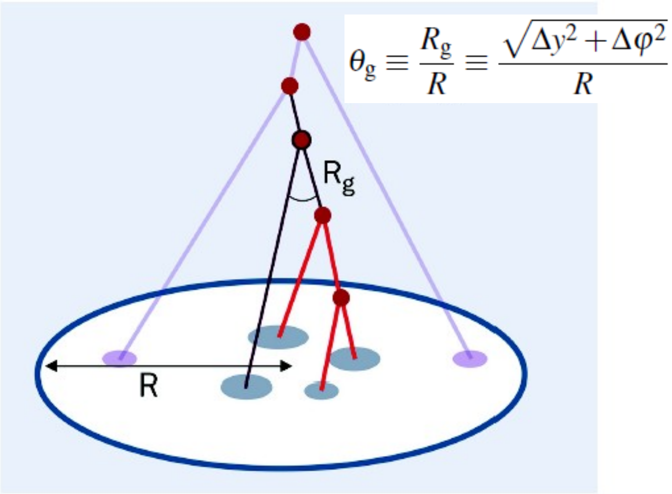


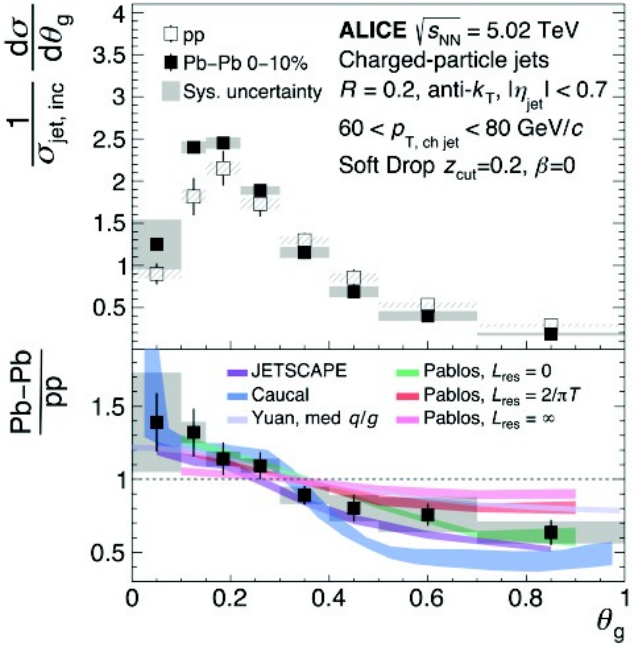


- Hard partons that shower into jets are produced early and interact with QGP
- Jet and high p_T hadron suppression observed over extensive range [1,2]
- Dominated by radiative emission. Extracted energy loss at LHC 8±2 GeV [3] (at RHIC 3.3±0.8 [4])

[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 jet shower in the QGP



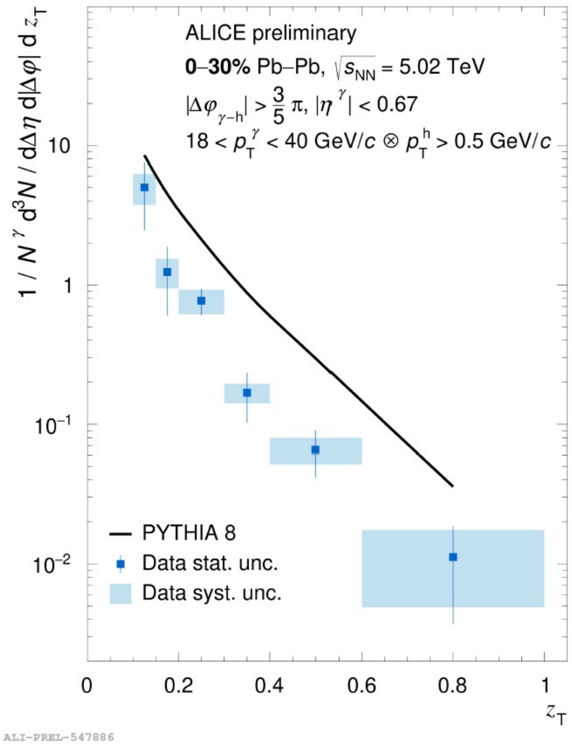


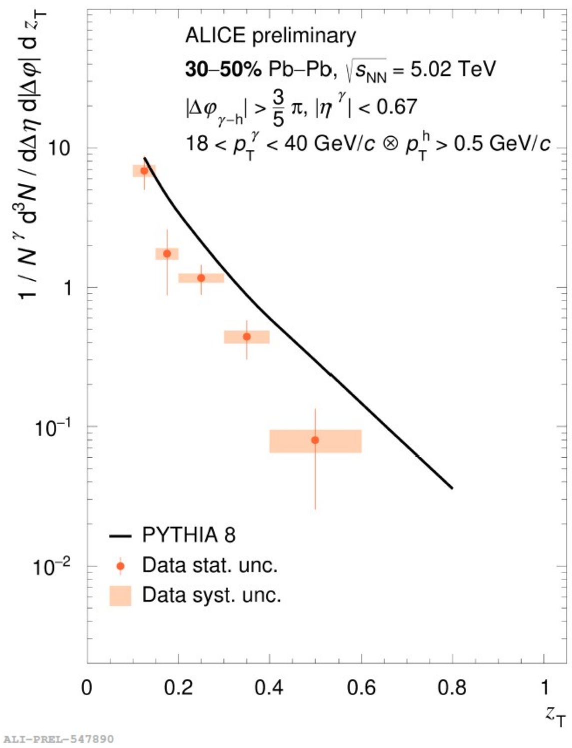
- Jet substructure measurements explore jet shape at earliest parton splittings
- Pb-Pb jet substructure more narrow than pp
- Indicates QGP jet energy loss mechanisms suppress wider angle jets

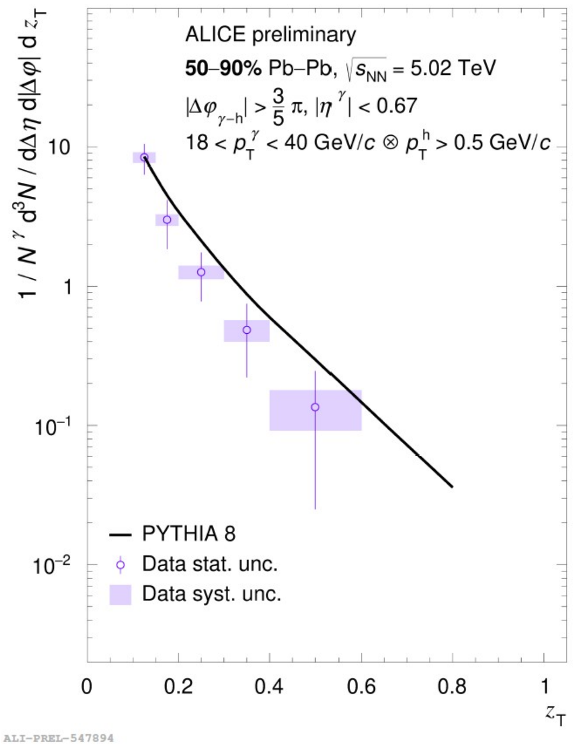
ALICE. *Measurement of the groomed jet radius and momentum splitting fraction in pp and Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, Phys. Rev. Lett. 128 (2022) 102001

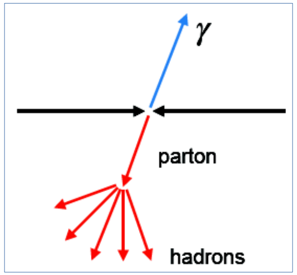
Modification of parton fragmentation

New: ALICE preliminary





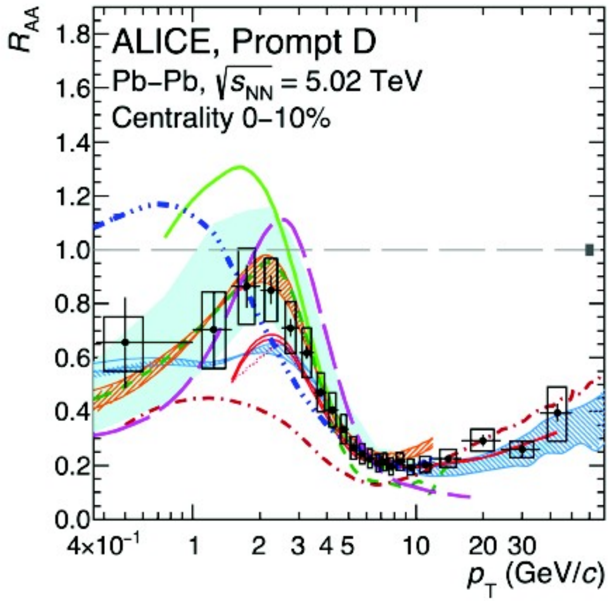


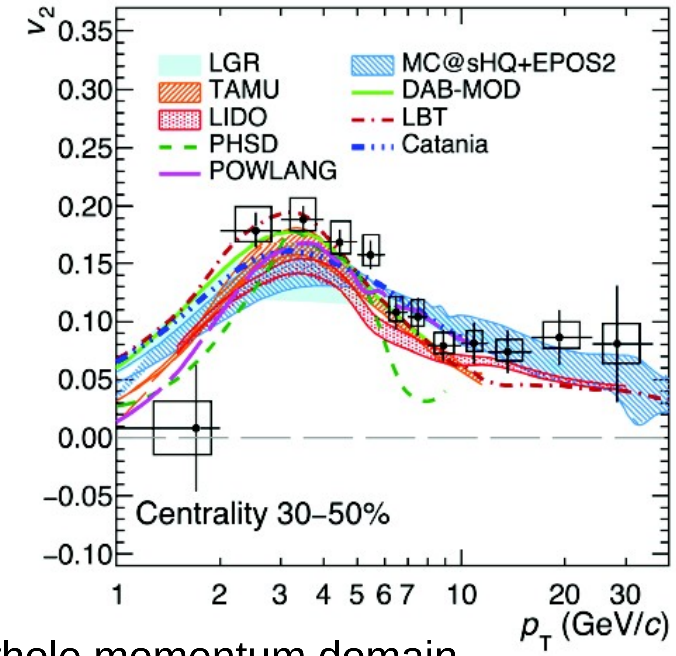


$$z_T = \frac{p_T^h}{p_T^{\gamma}}$$

- 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

Heavy flavour interactions



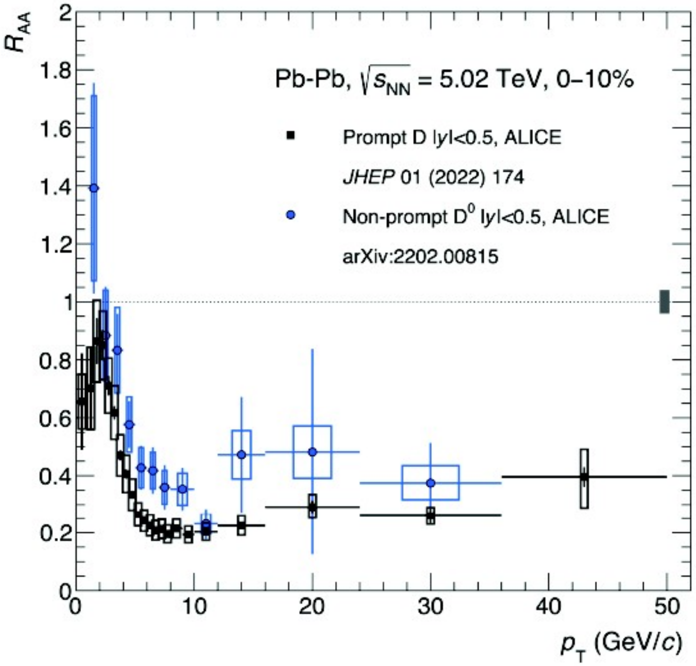


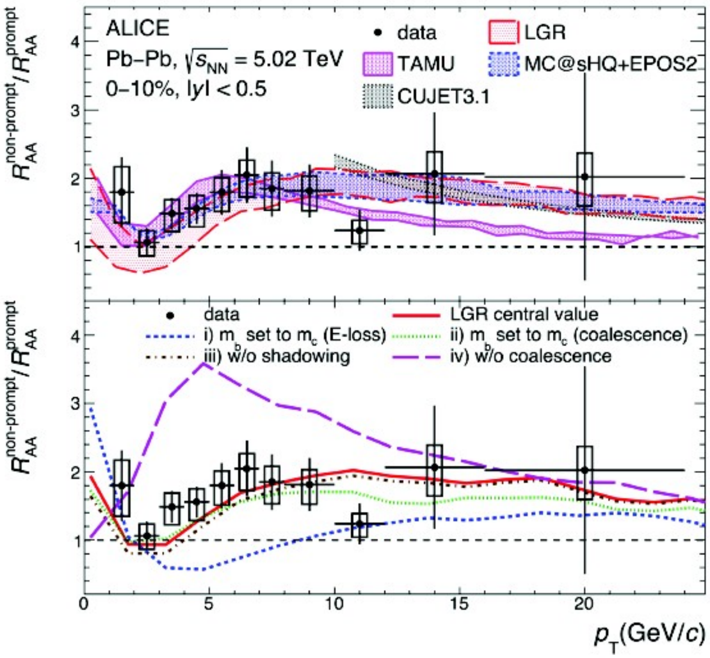
Heavy quarks as hard probes investigate medium for whole momentum domain

- 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 flavours, 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

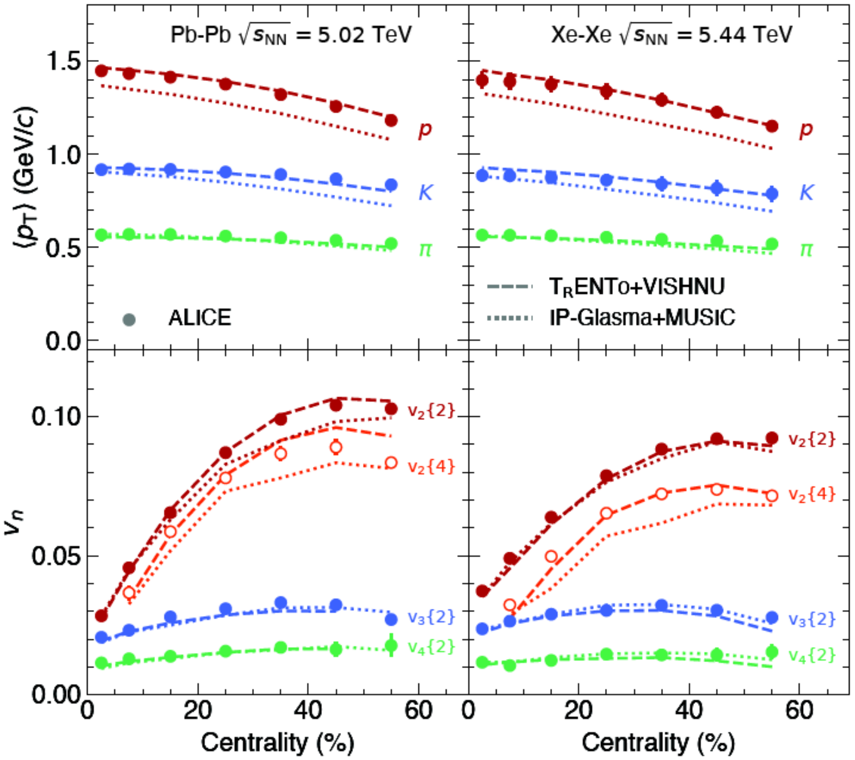


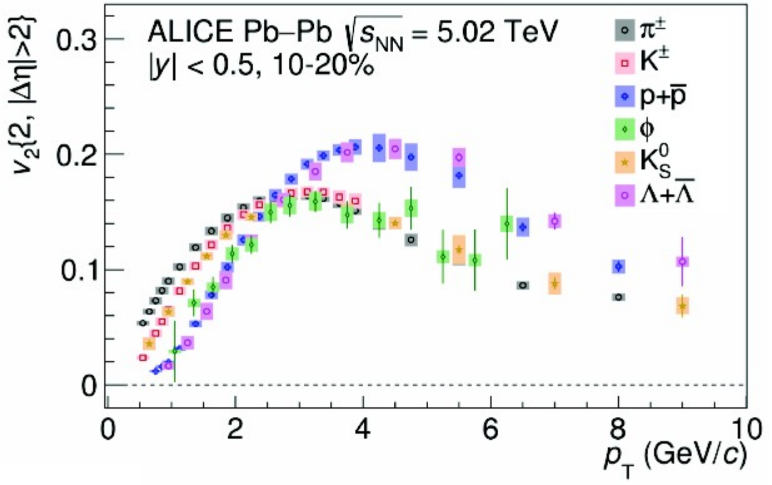


- D mesons from bottom decays less suppressed than those formed from charm
- Indication of mass dependent collisional and radiative suppression e.g. dead cone effect

- 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 D0 mesons in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, JHEP 12 (2022) 126, arXiv:2202.00815

Momentum anisotropy (flow): almost perfect liquid

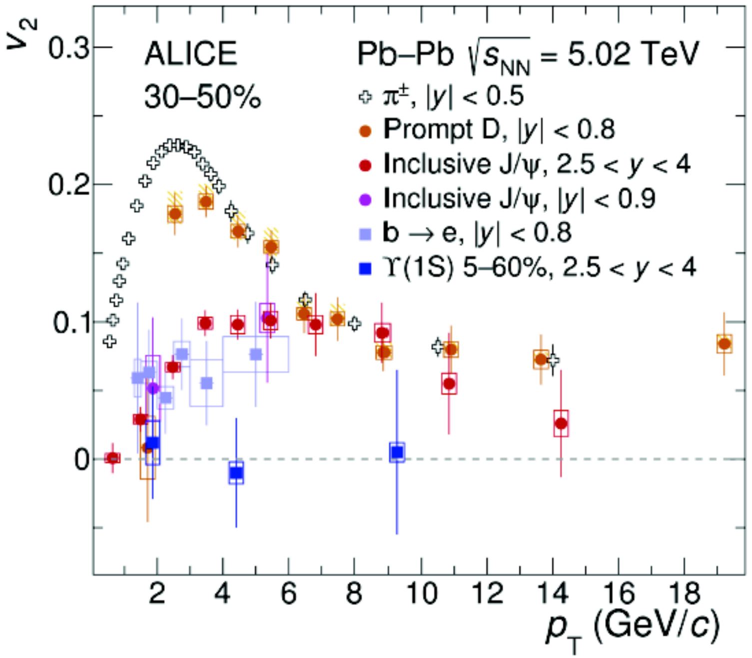


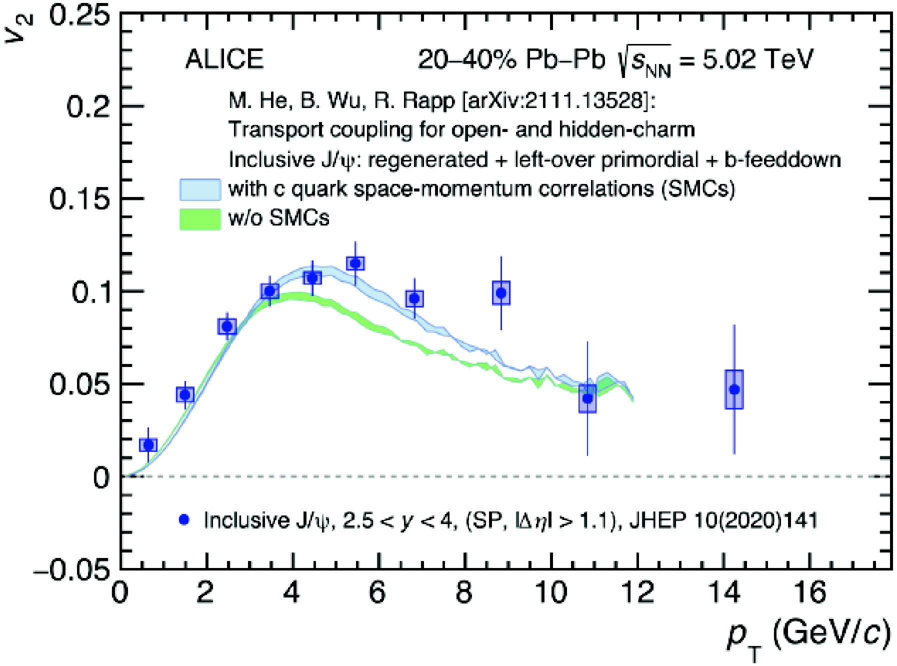


- Global QGP radial and anisotropic expansion described by hydrodynamics
- Achieved with QGP equation of state and small but finite QGP viscosities

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

Heavy quark flow in the QGP



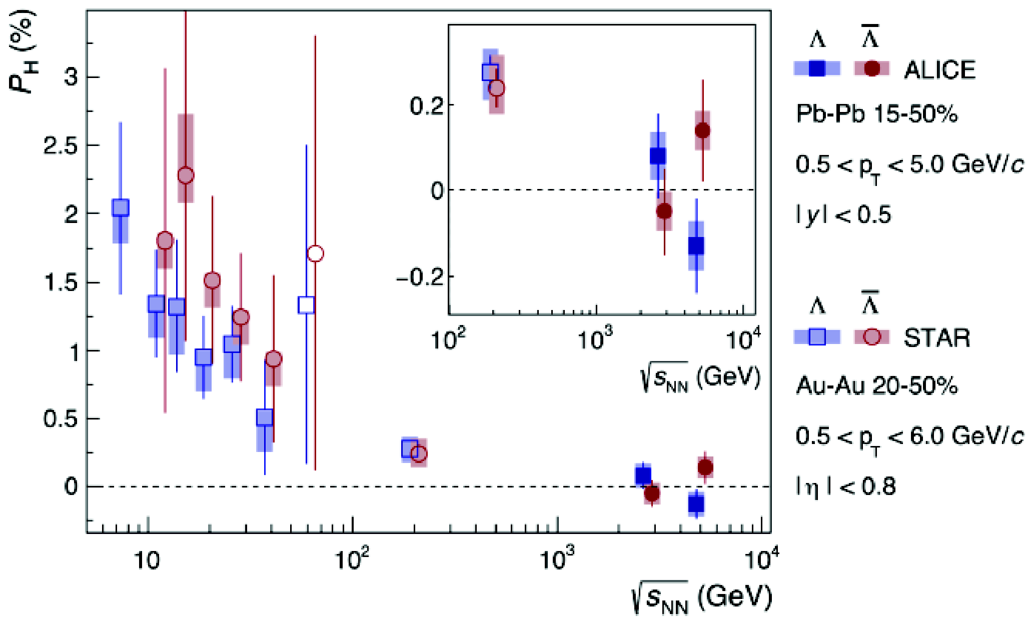


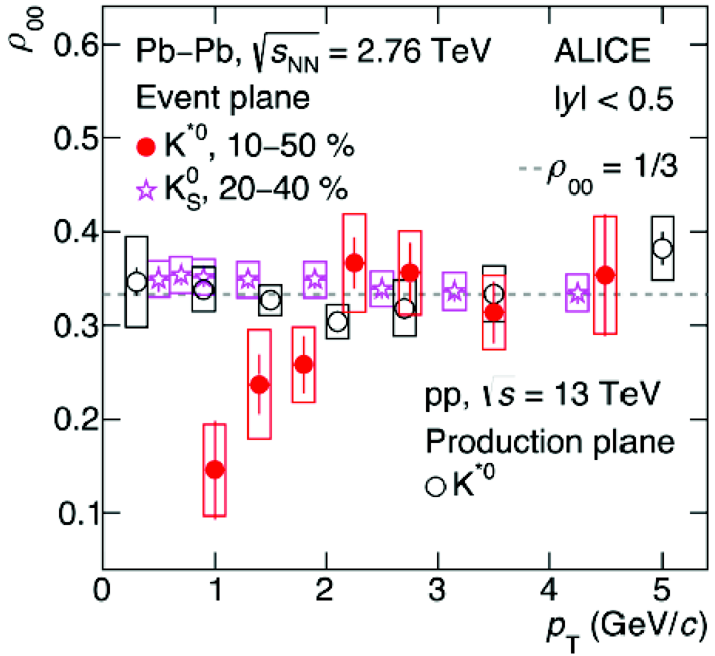
- Finite values of J/Ψ v_2 provide unambiguous signature of charm flow. Bottom quarks also flow
- Transport models using Brownian motion describe charm flow

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

The most vortical fluid

<P>(%) ≈ −0.01 ± 0.05 (stat.) ± 0.03 (syst.)

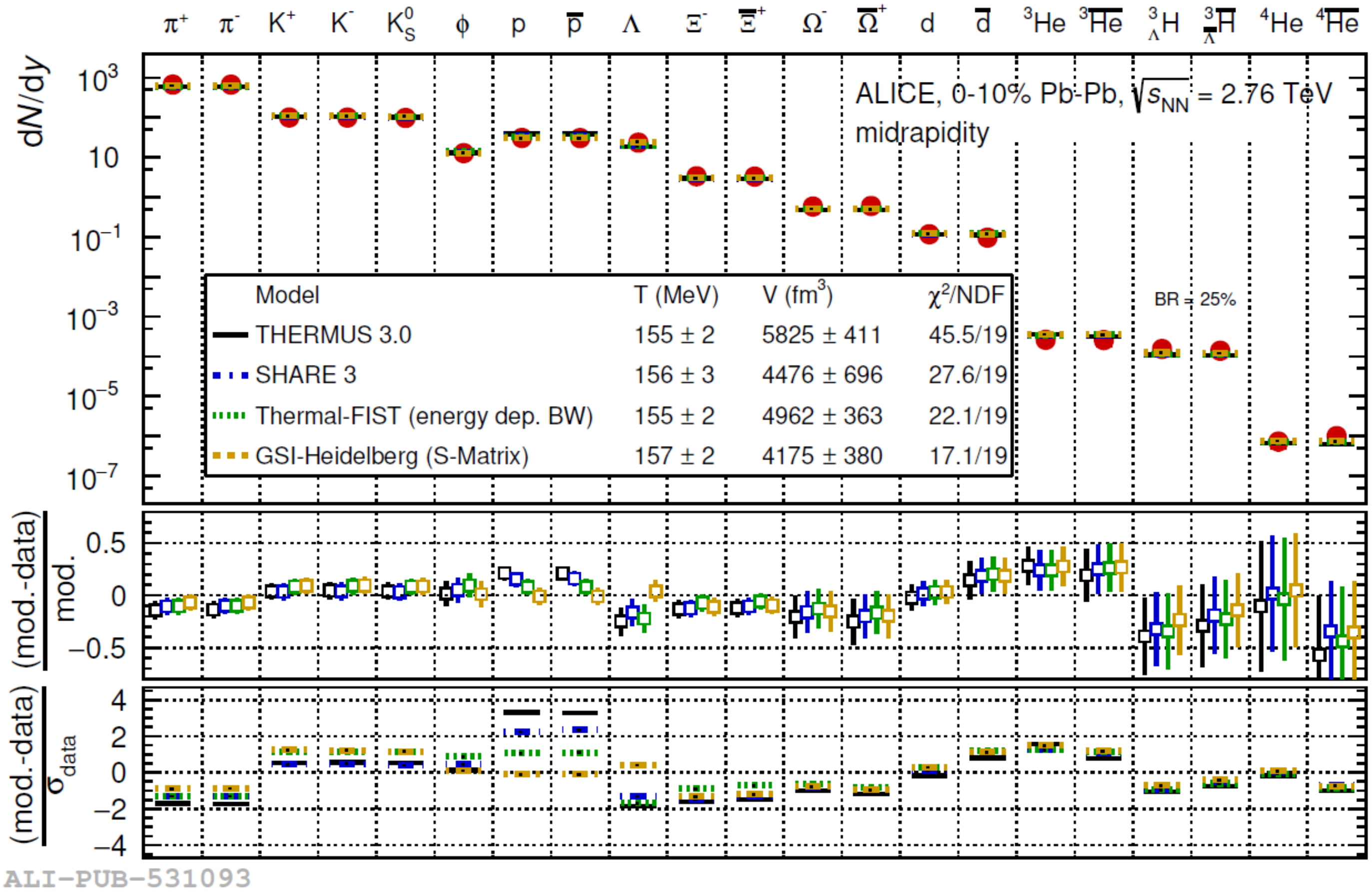




- Global angular momentum from incoming nuclei induces polarization with respect to reaction plane direction
- Effect stronger for K* mesons compared with Λ hyperon
- Theory predicts vanishing polarization and spin alignment at high temperature, not consistent with observation for vector mesons

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

Hadron formation from QGP



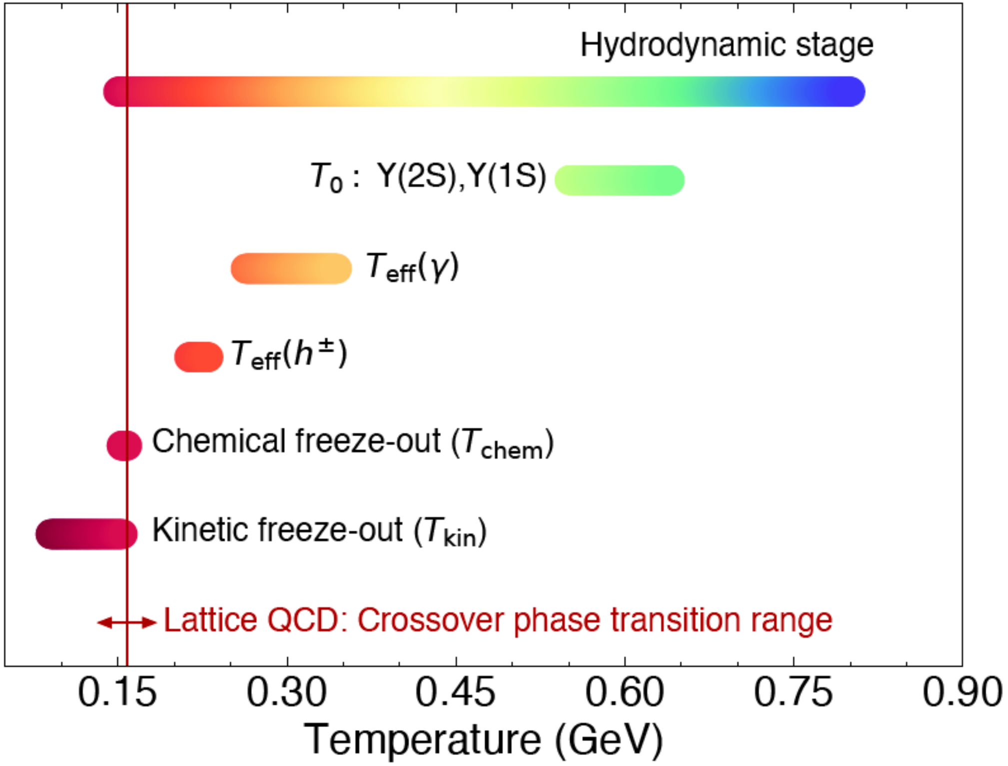
Hadron and light nuclei yields described by statistical hadronisation models over 10 orders of magnitude

Implies hadrons subject to chemical equilibrium close to QGP transition temperature $T_{chem} \approx T_c \approx 156$ MeV

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

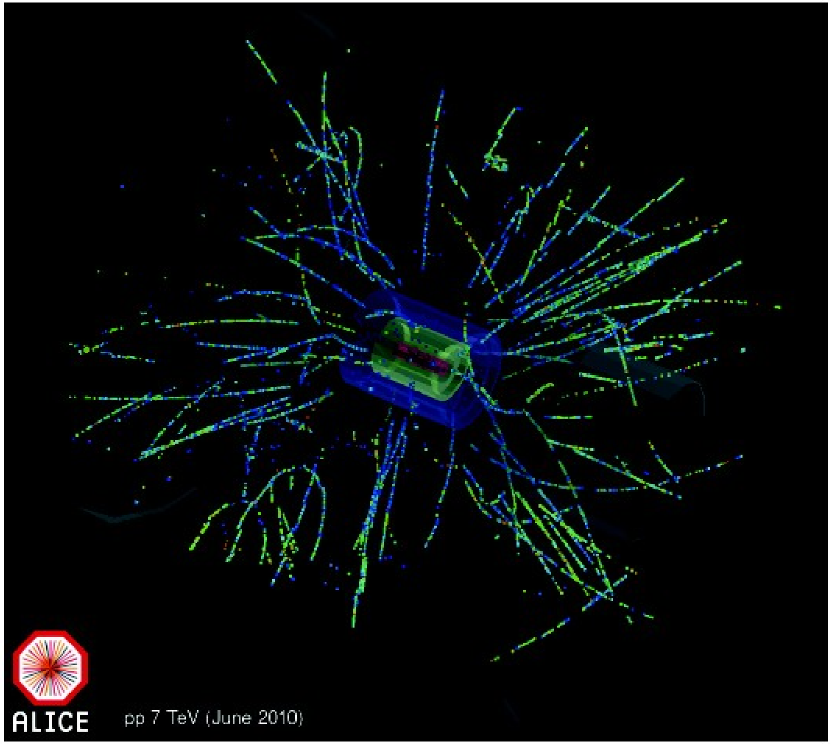
Temperatures of nuclear collisions at LHC

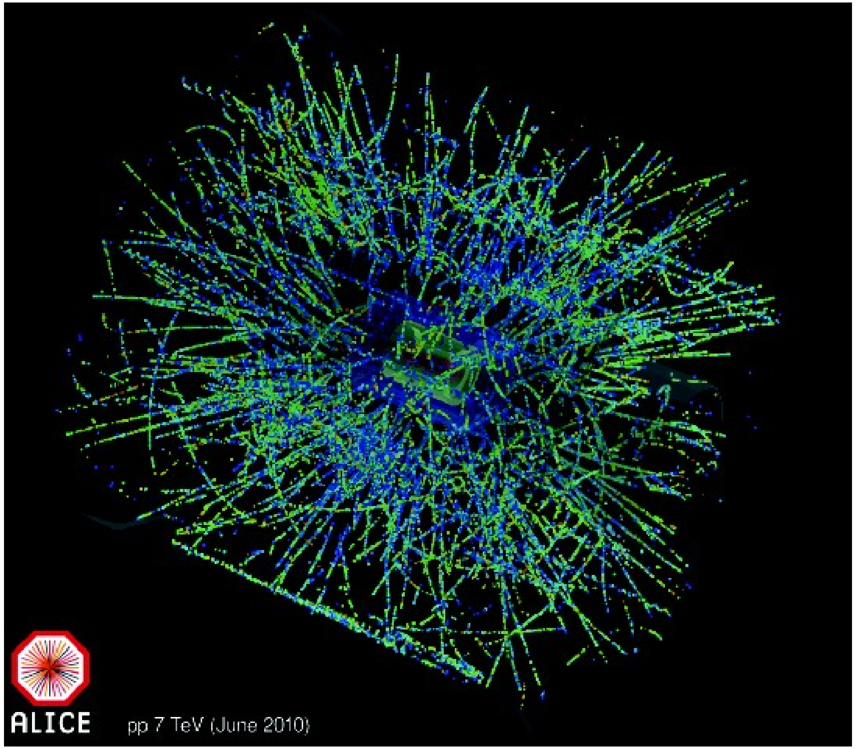
Many observables imply temperatures greater than QGP transition temperature



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

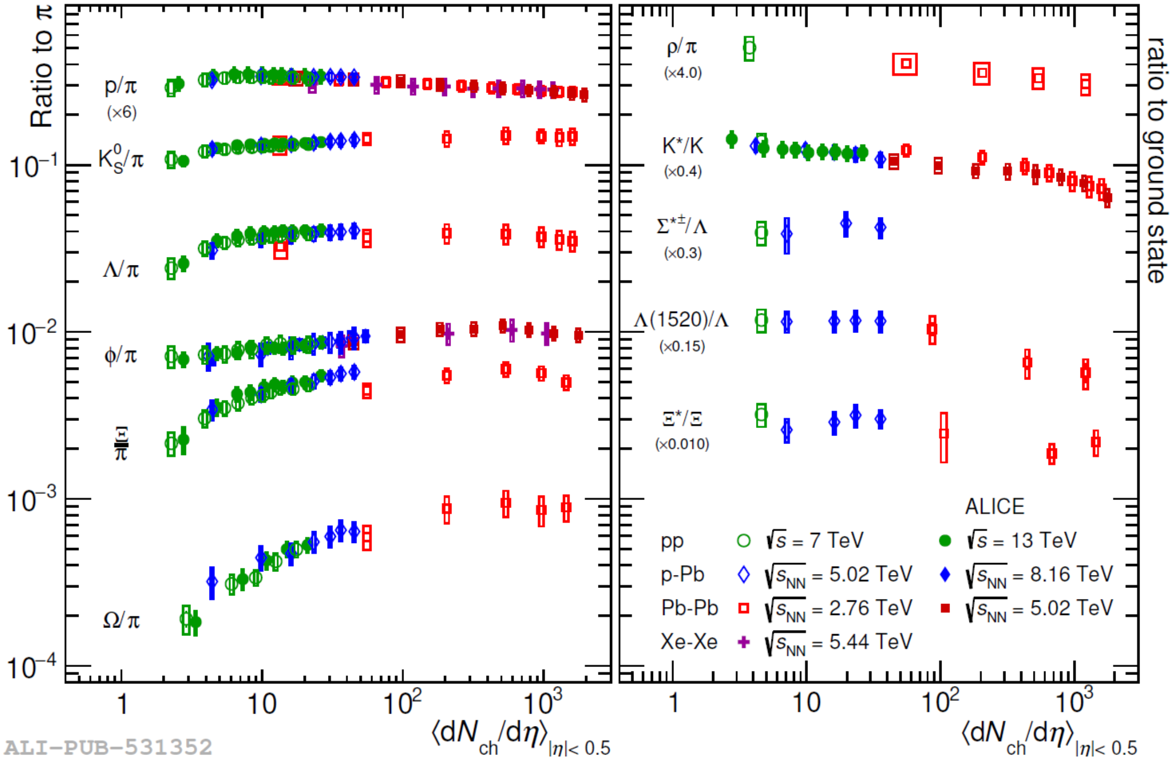
QCD studies in small systems





- 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

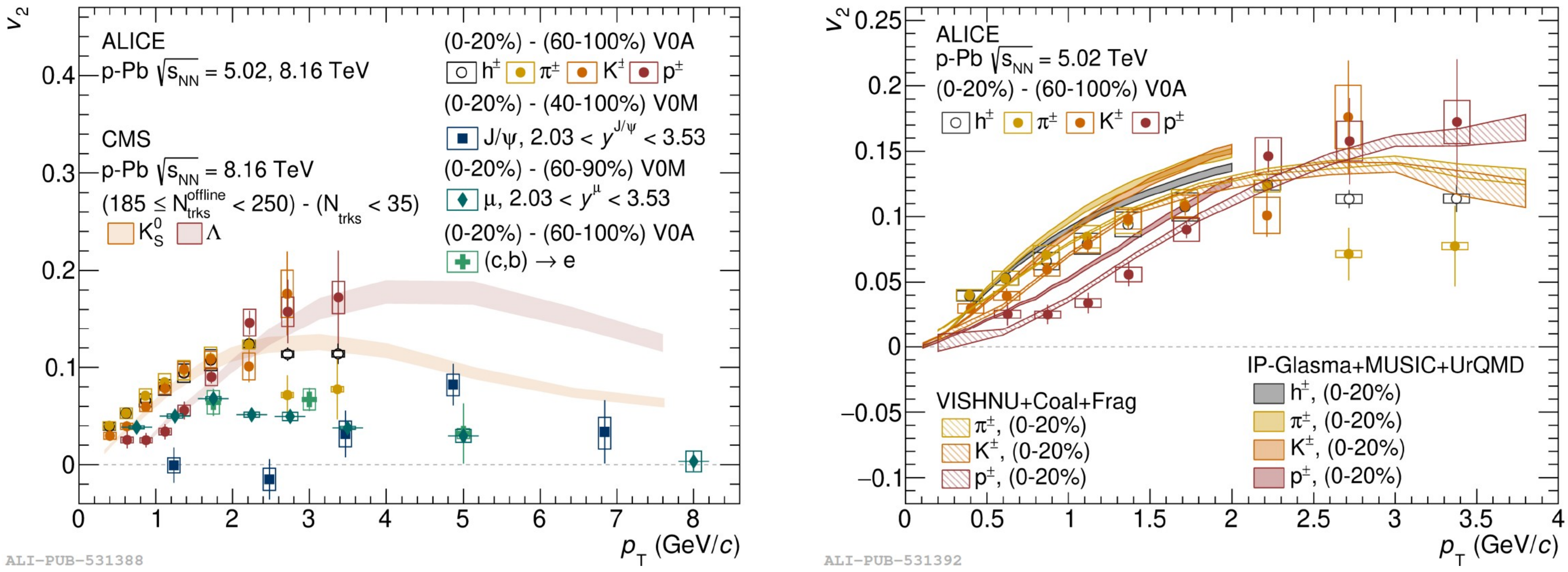


Particle yield ratios depend on $dN_{ch}/d\eta$ rather than colliding species

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?

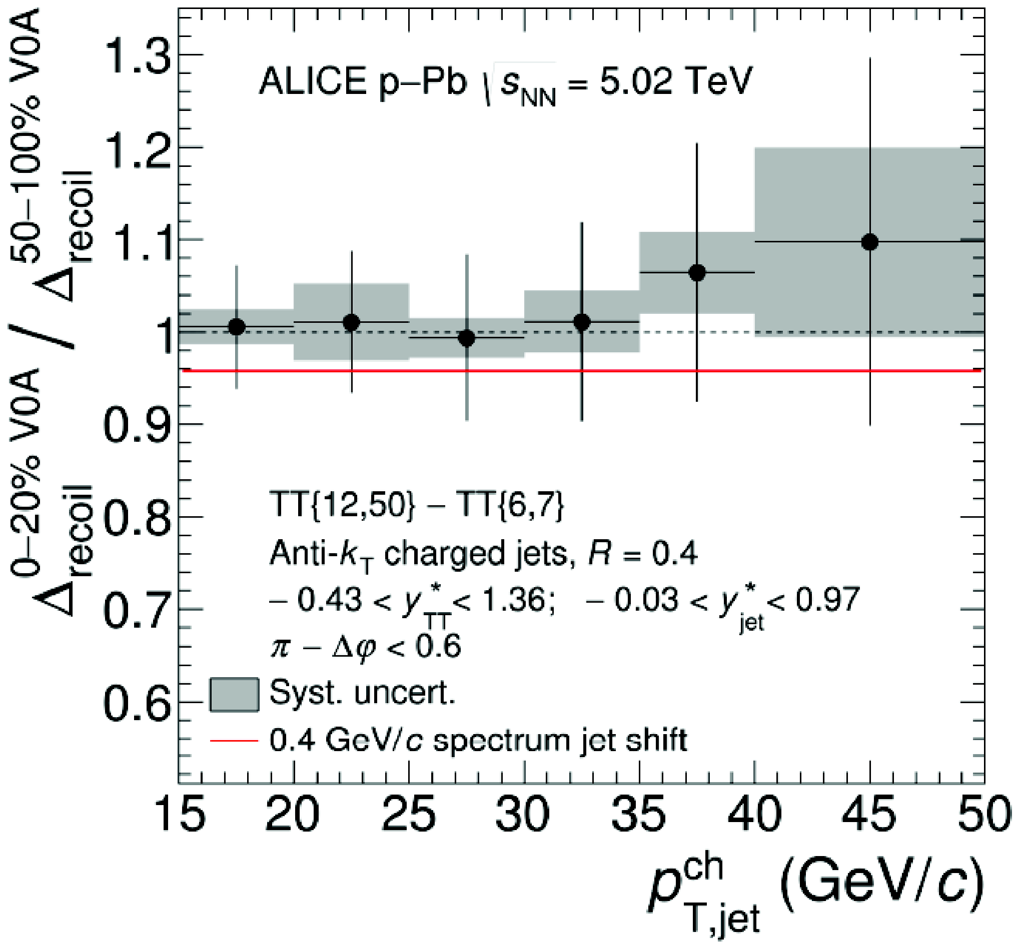
Flow in small systems



- 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?



- 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

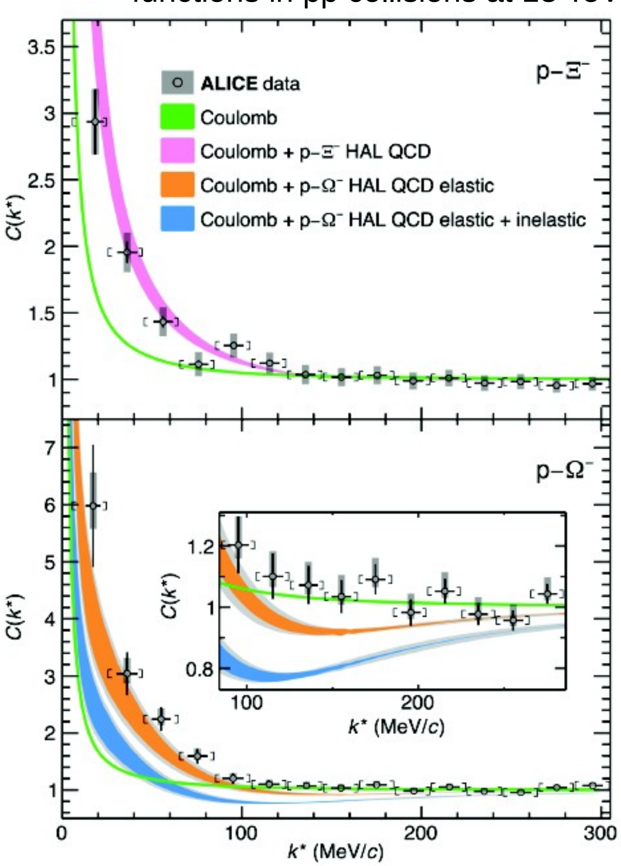
ALICE. *Constraints on jet quenching in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV measured by the event-activity dependence of semi-inclusive hadron-jet distributions*, Phys. Lett. B783 (2018) 95–113

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

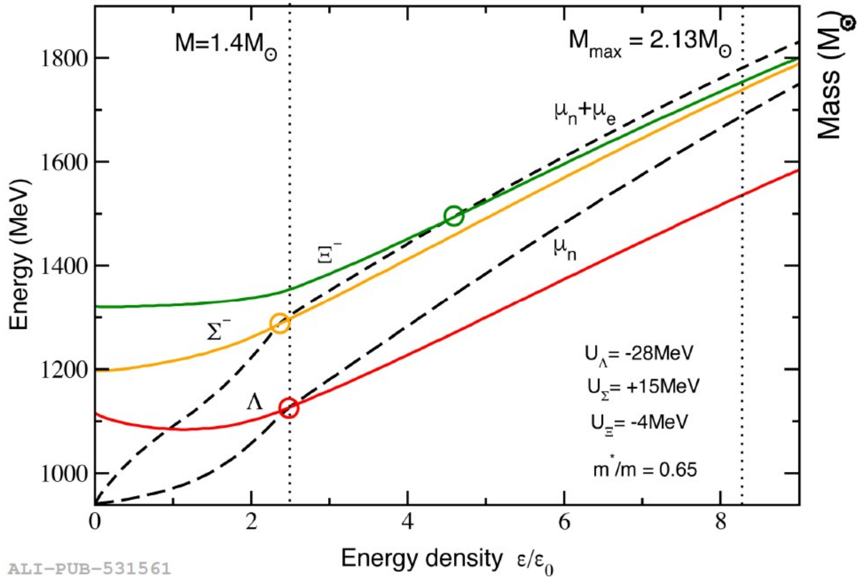
Hadron interactions

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



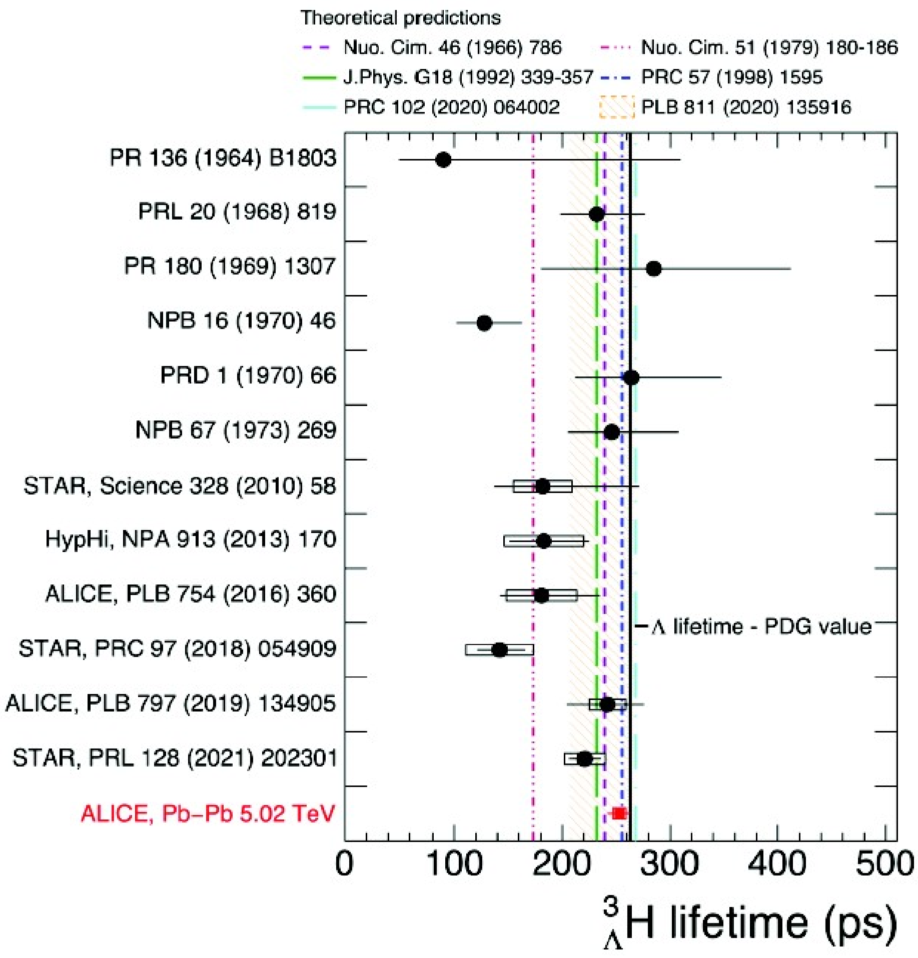
ALICE. *Unveiling the strong interaction among hadrons at the LHC,* Nature 588 (2020) 232–238

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

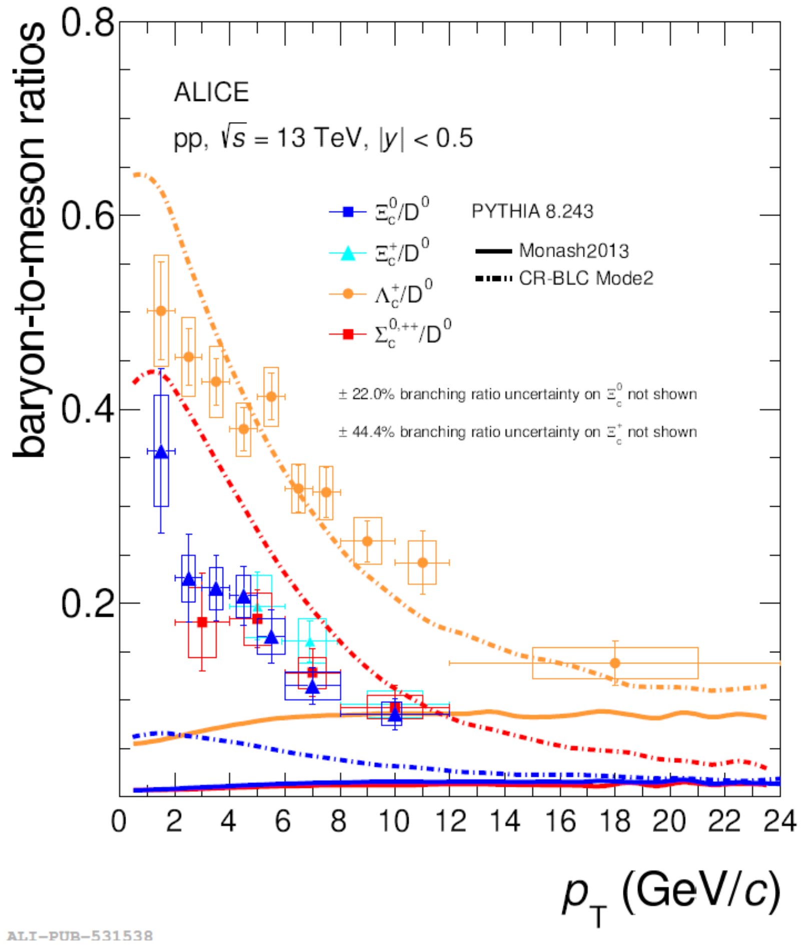
Nuclear synthesis and nuclear binding



- 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

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]

First 10 years of heavy-ion physics at LHC

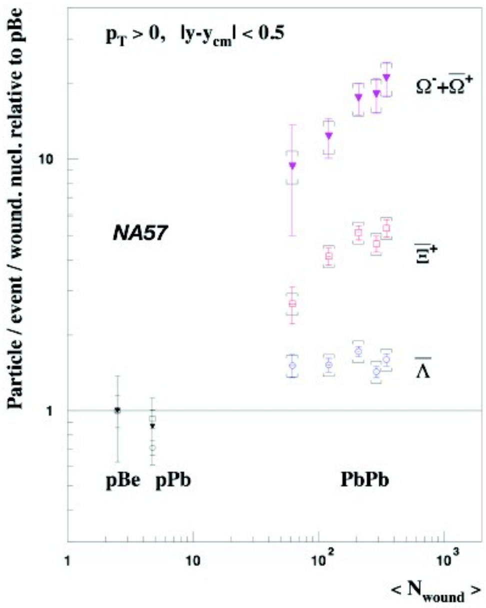
- High temperature QCD
  - Extensive progress in QGP energy loss
  - Charm and charmonium production mechanisms better understood
  - Hydrodynamics description of QGP
  - Precision tests of hadron and nuclei production at high temperature
  - QGP signatures in small systems
- QCD studies beyond heavy-ion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

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

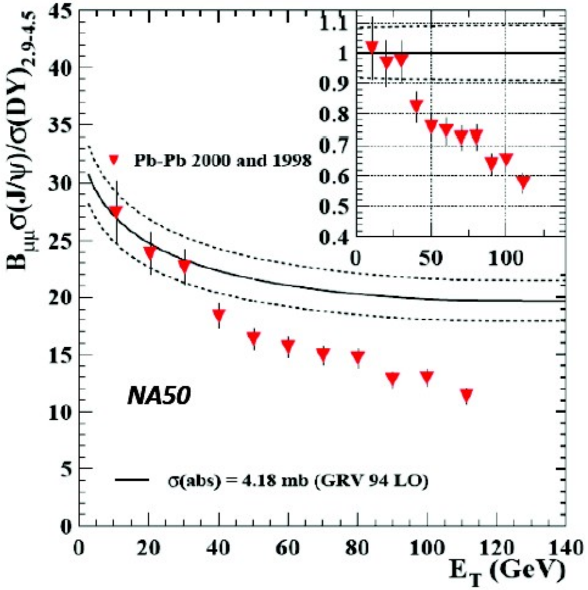
Backup slides

Evidence for existence of QCD matter at SPS

CERN press release 10.02.2000: 7 experiments at SPS reported “New State of Matter created at CERN”
The data from any one experiment is not enough to give the full picture but the combined results from all experiments agree and fit



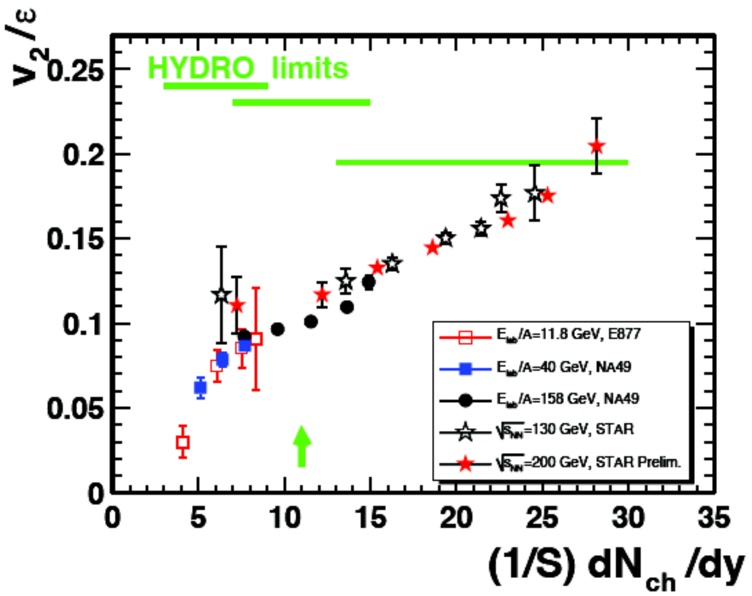
Strangeness enhancement
Strange quarks readily produced in QGP & strange hadrons described by thermal model bound states



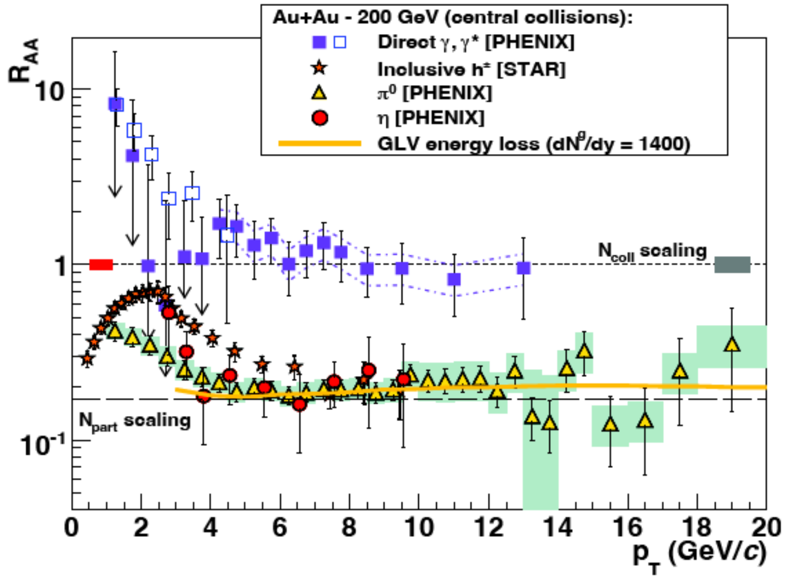
Charmonium suppression
QGP screens force between bound states

Next step: HIC at RHIC

BNL news 2005: 4 RHIC experiments reported QCD properties as 'Perfect' Liquid



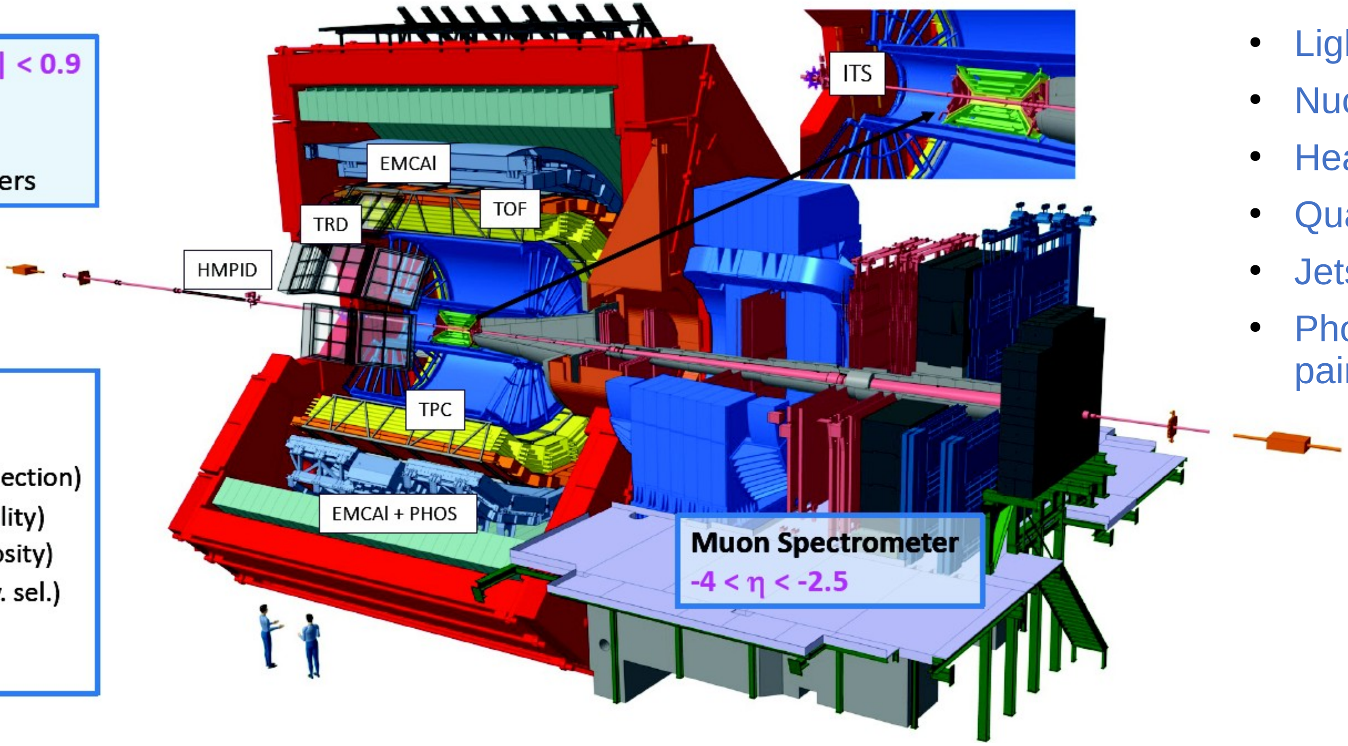
Perfect liquid
Elliptic flow reaches hydrodynamic limit



Jet quenching
Hard partons lose energy in QCD medium

ALICE experiment Runs 1-2

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

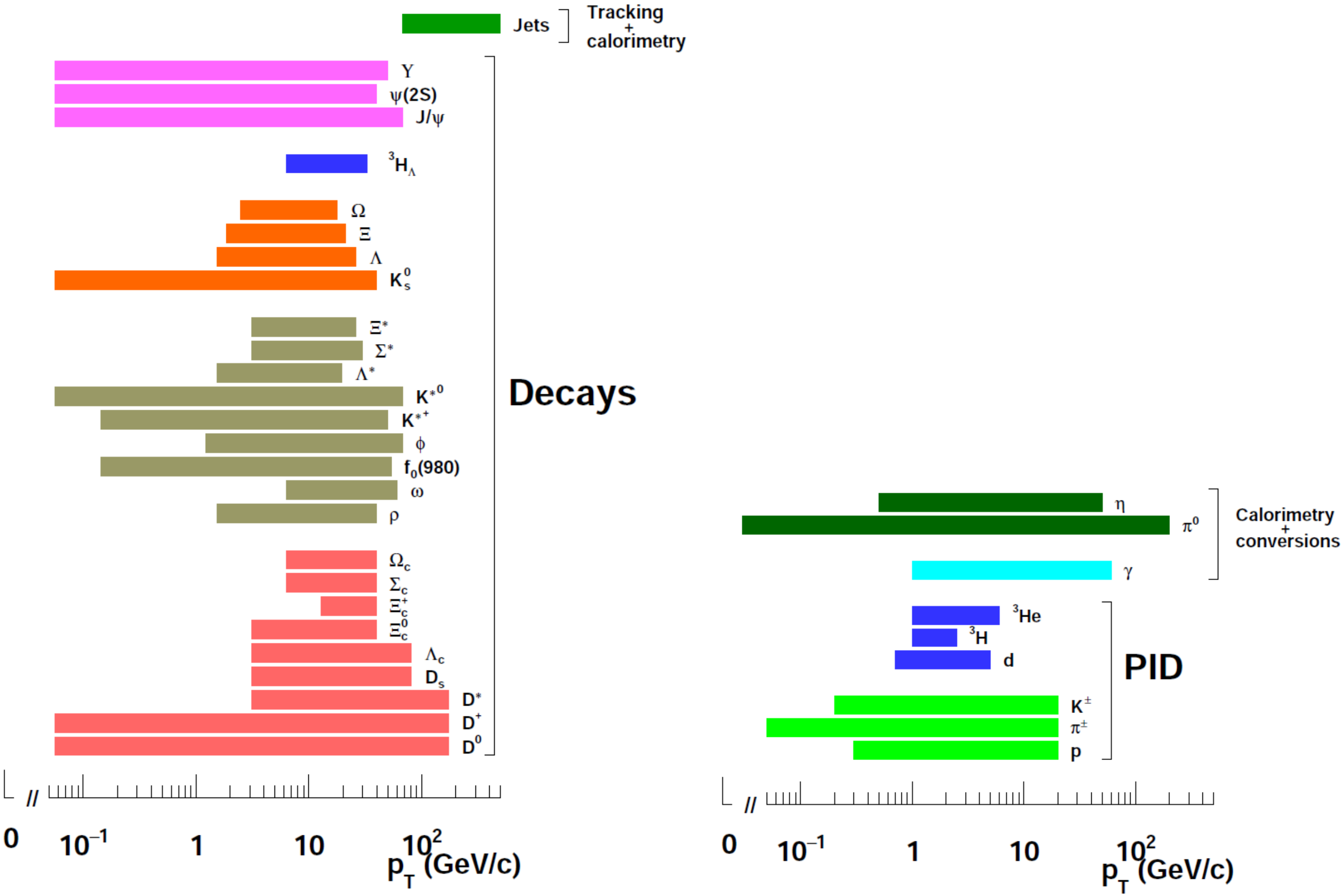


ACORDE (cosmics)

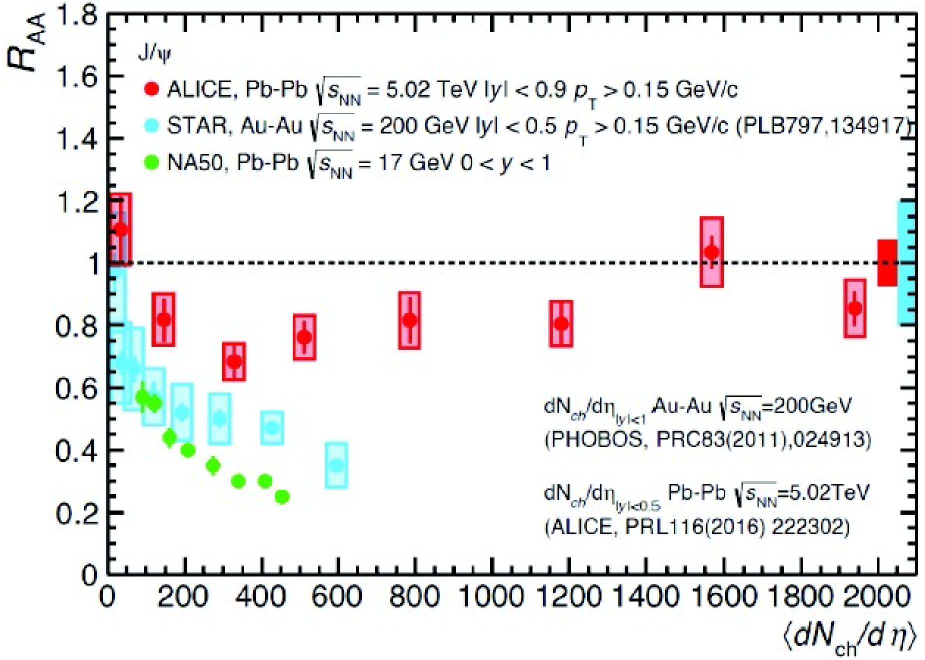
Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD ($N\gamma$, Nch)

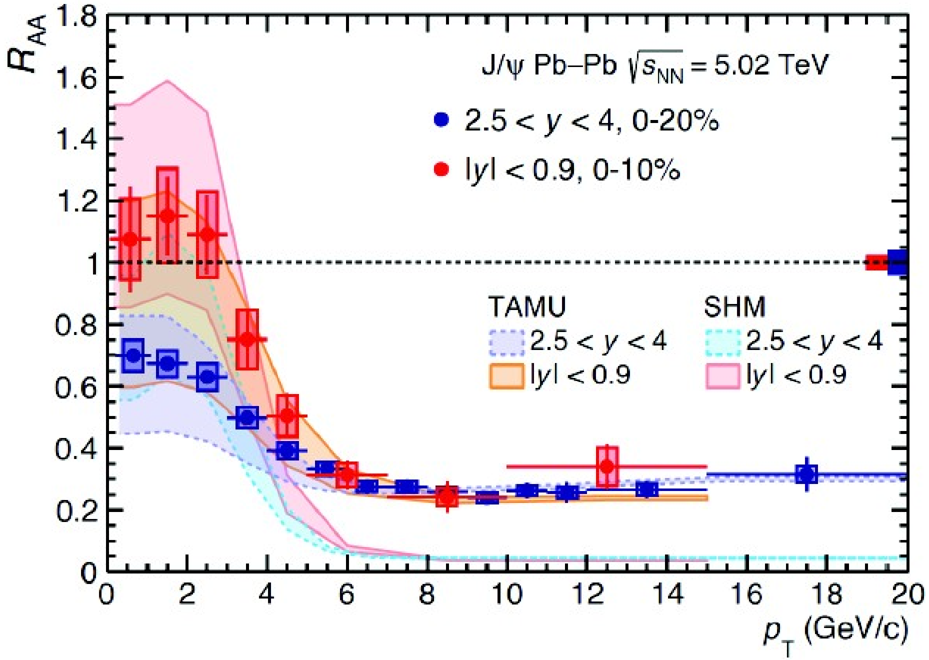
- Light flavour production
- Nuclei
- Heavy flavor production
- Quarkonia
- Jets
- Photons, low-mass lepton pairs

ALICE particle identification and reconstruction



Suppression and regeneration of quarkonia

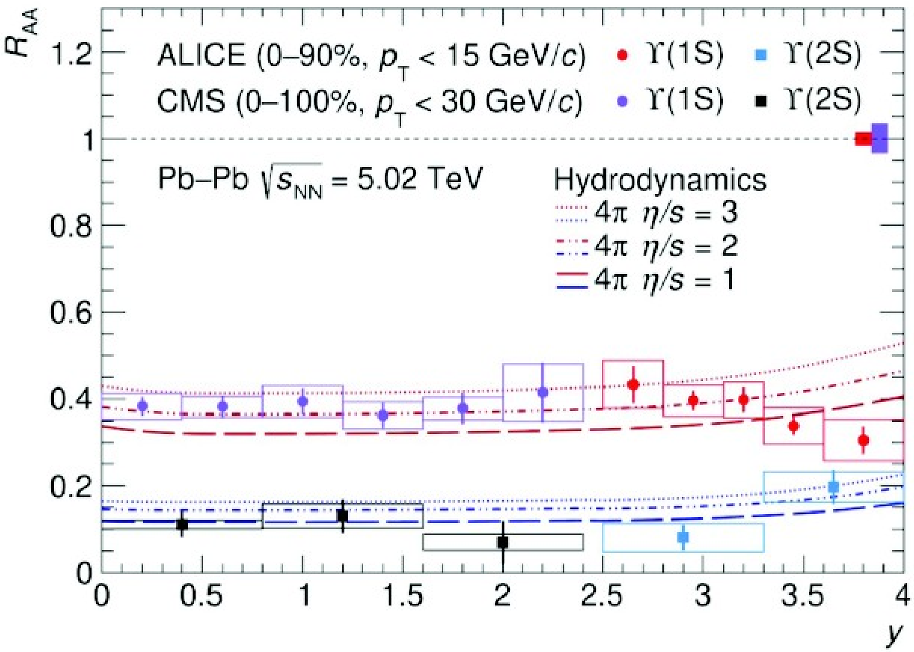


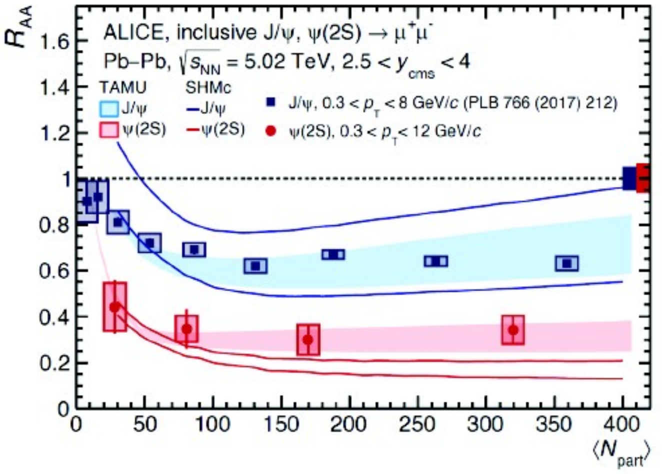


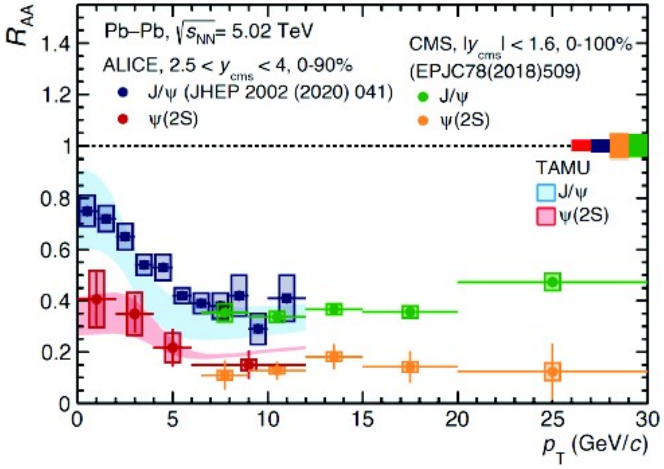
Quarkonia also probe QGP at sub fm scales

- 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

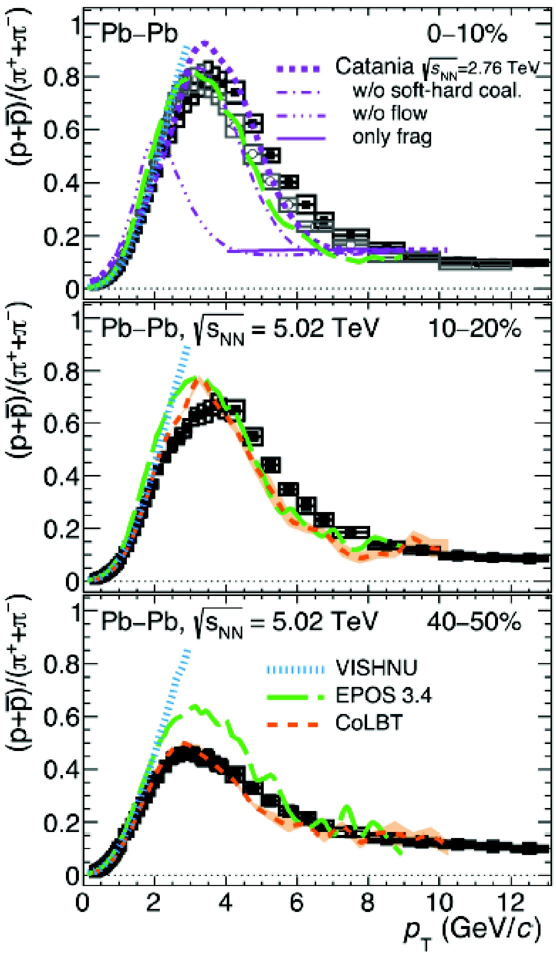


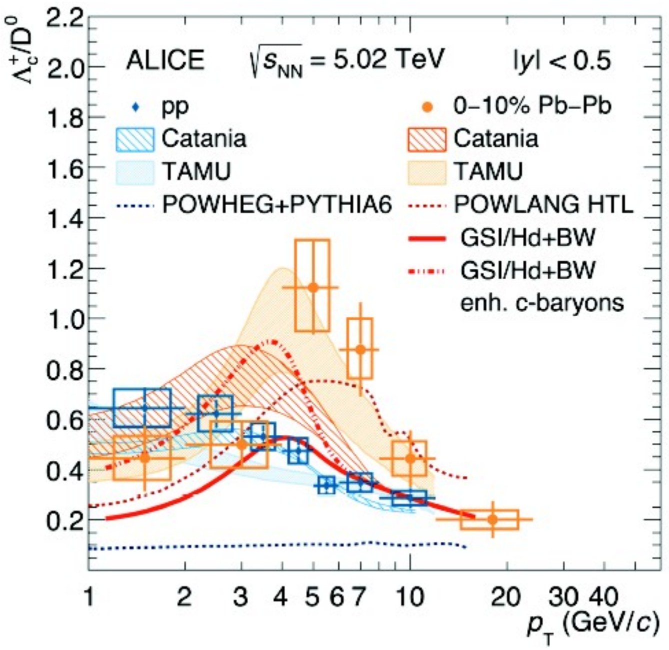




- Bottomonium shows sequential suppression
- Charmonium shows sequential suppression + regeneration
- ψ(2S) with ×10 times less binding energy - × 2 more suppressed than J/ψ
- Precision test of quarkonium transport in the medium.

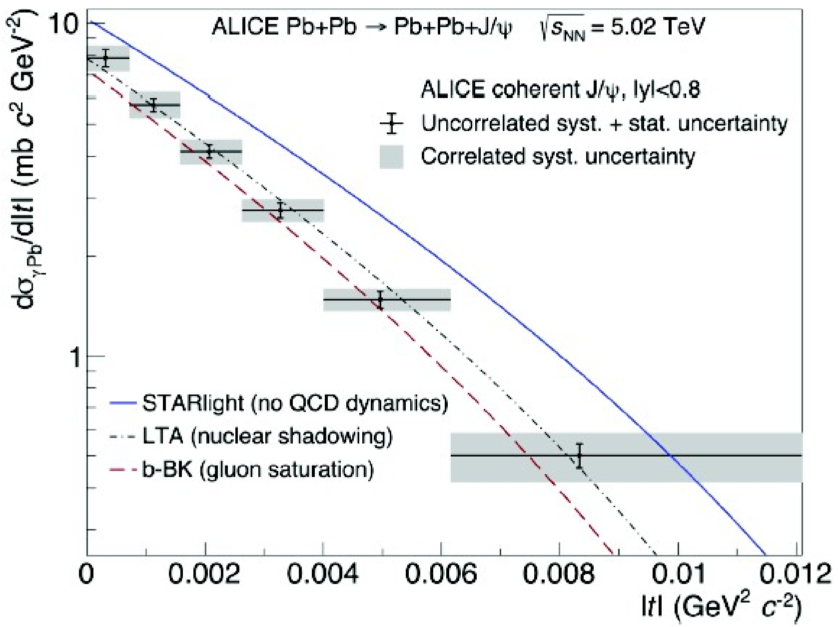
Macro to microscopic hadron formation

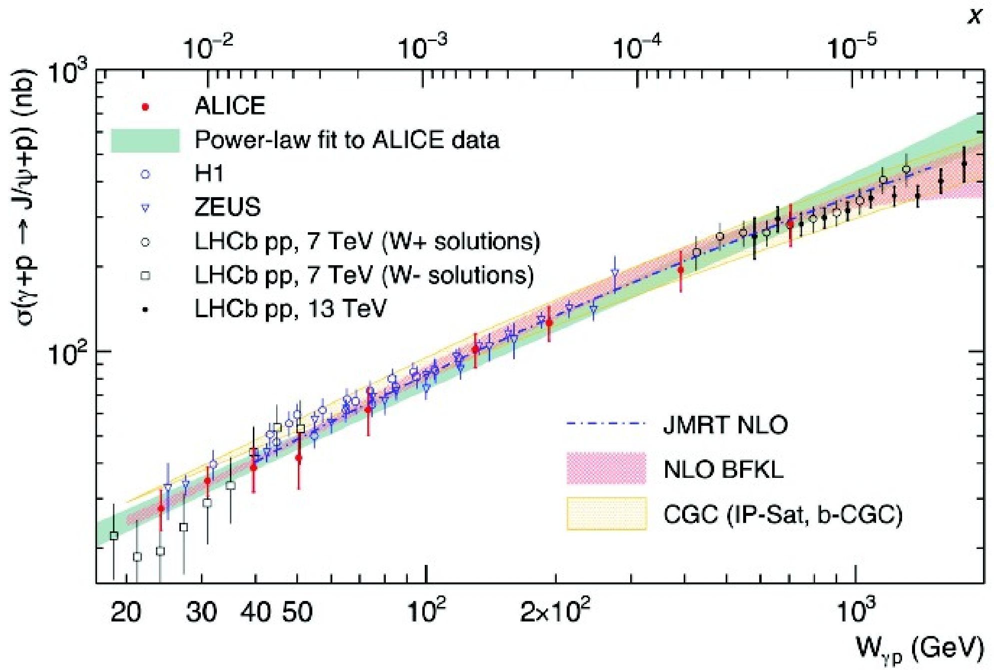




- **Quark coalescence** required to describe light and heavy flavour baryon/meson ratios & **flow** at immediate p_T.
- **Fragmentation** dominates at higher p_T.

Looking deep into the nucleus and proton





- Ultra-peripheral collisions involve photons probing a nuclear or proton target
- Clear evidence of the shadowing of nuclear gluon distribution functions at x~10^{-3}
- No evidence of gluon saturation in proton at x~10^{-5}