Heavy-ion physics at LHC

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For ALICE collaboration

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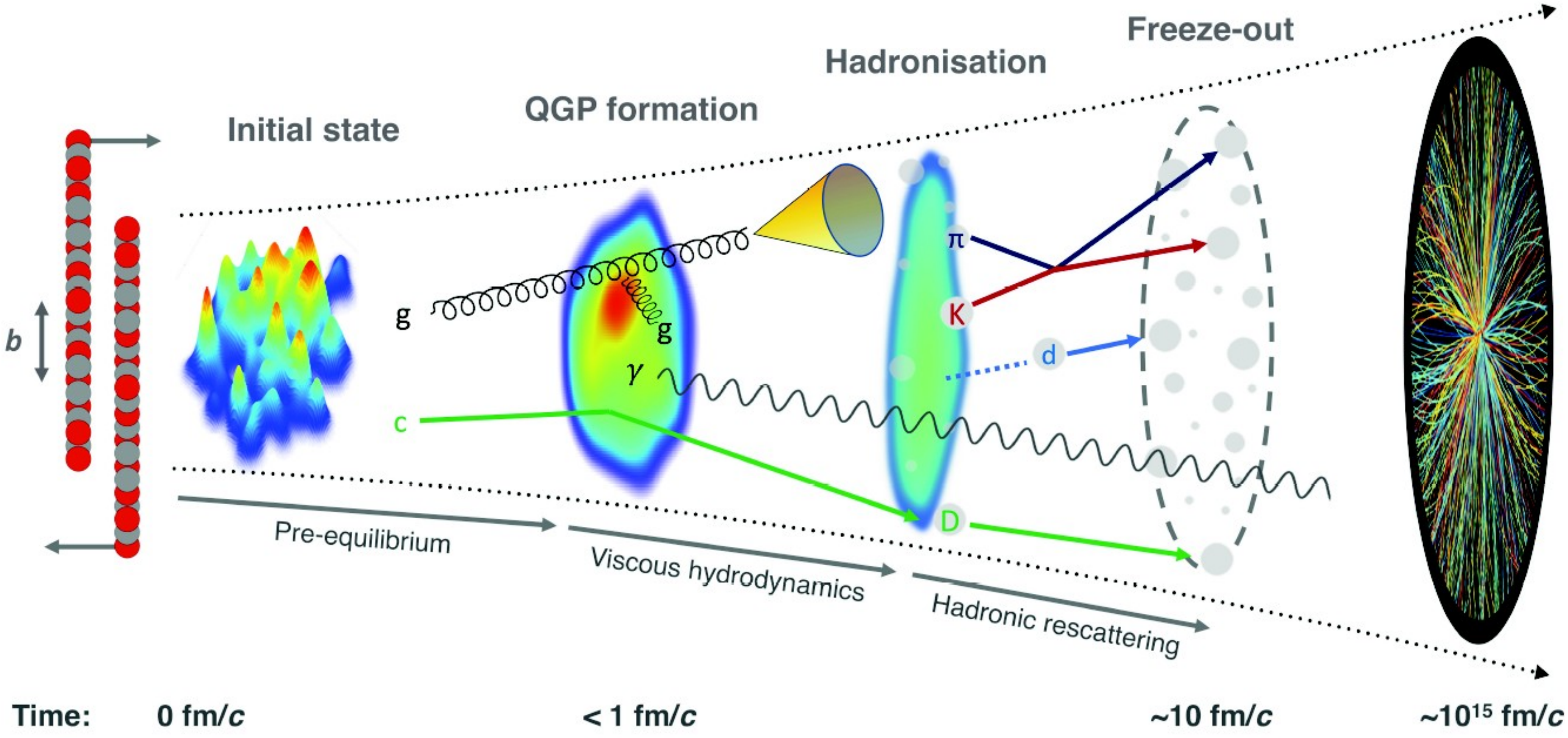
Introduction

- LHC serves as a heavy-ion collider at the highest collision energy $\sqrt{s_{NN}}$=2.76, 5.02 TeV
- Heavy-ion program is extensively studied by ALICE, ATLAS, CMS since 2010.
- Physics program of LHC experiments inherits experience of RHIC, confirms properties of quark-gluon matter 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

Evolution of a heavy-ion collision at LHC energies



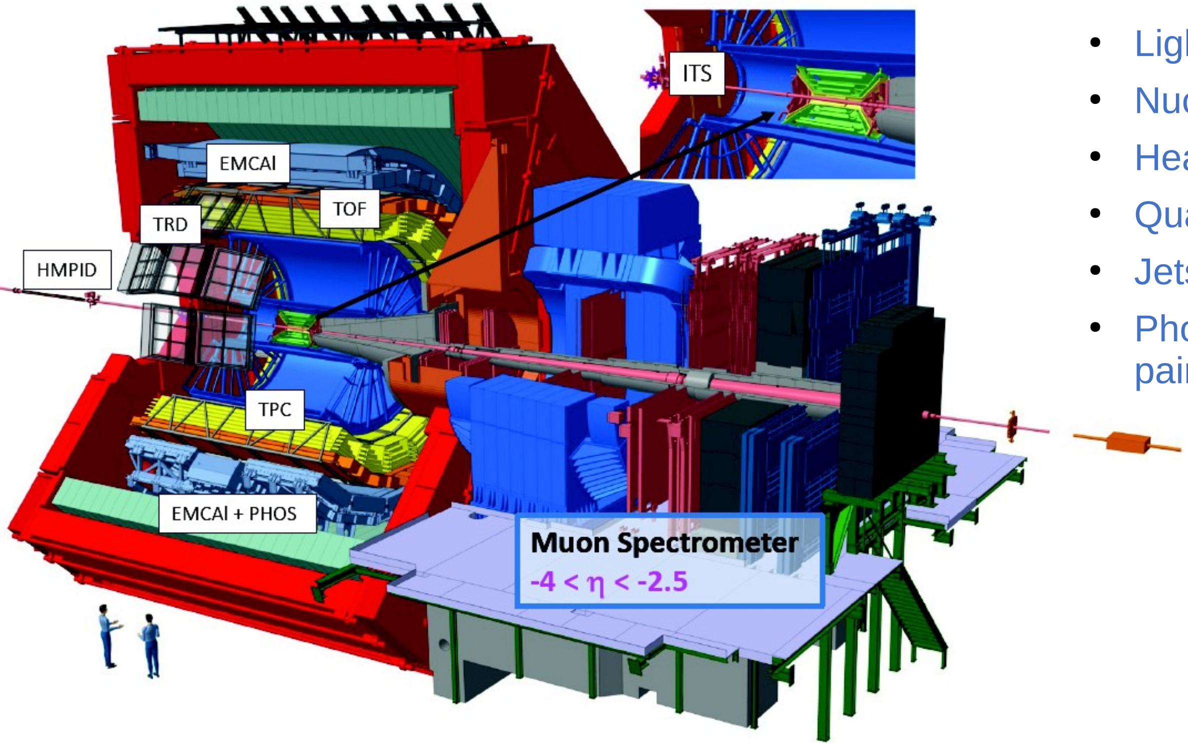
Quark-gluon plasma (QGP) = deconfined strongly-interacting QCD matter with color degrees of freedom

ALICE experiment Runs 1-2

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

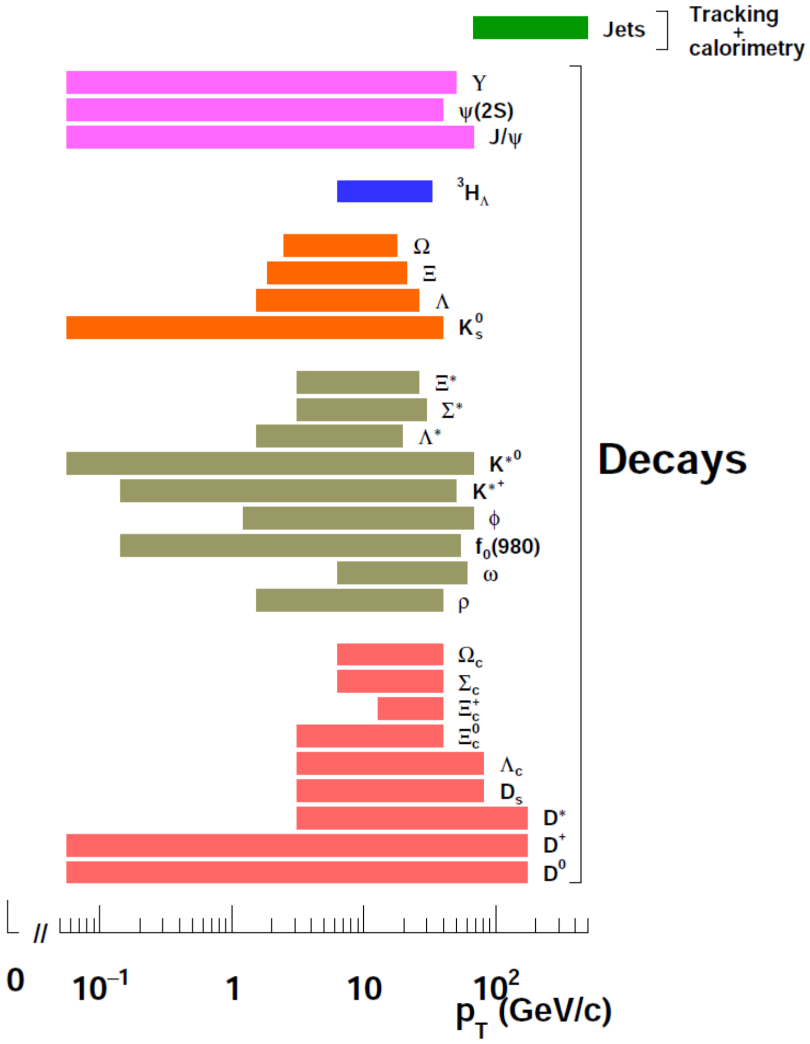
ACORDE (cosmics)

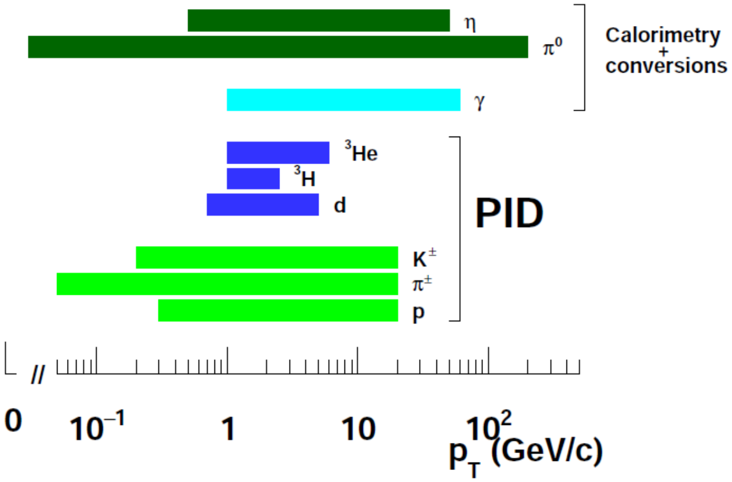
Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD ($N\gamma$, Nch)



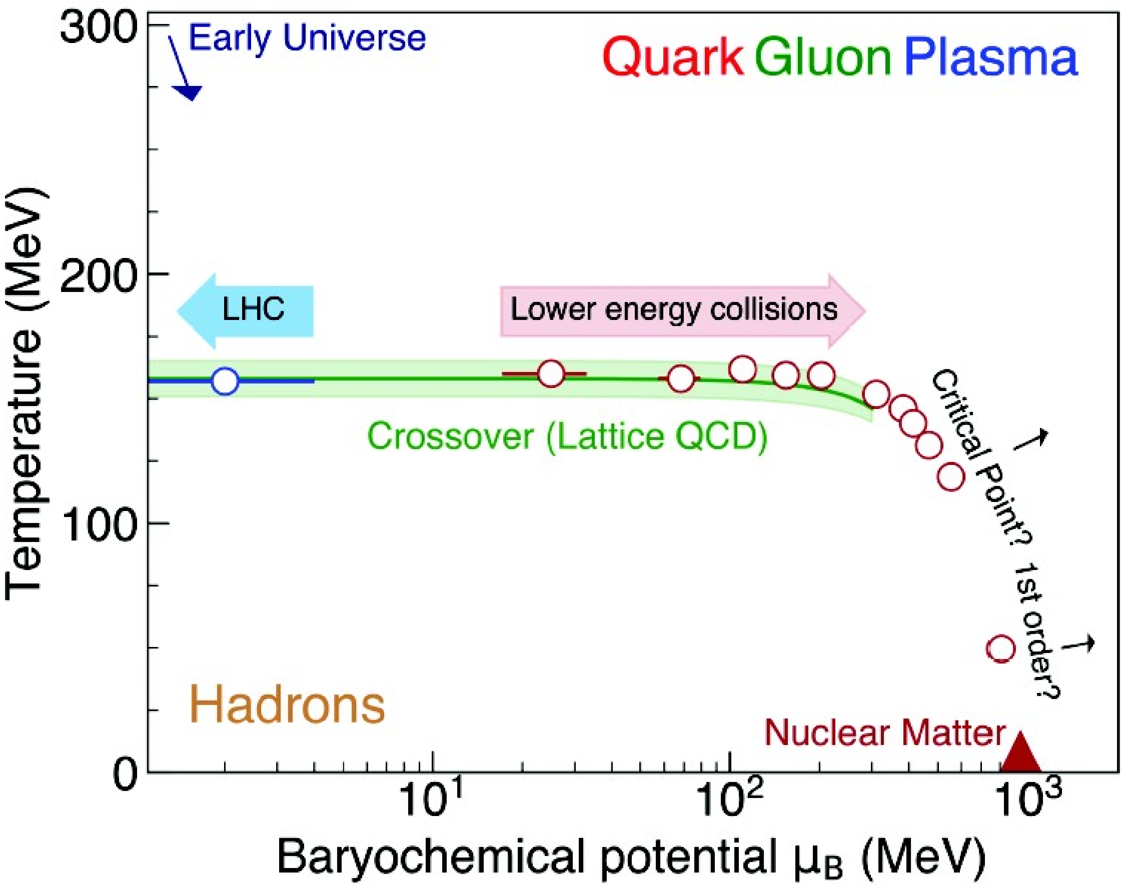
- Light flavour production
- Nuclei
- Heavy flavor production
- Quarkonia
- Jets
- Photons, low-mass lepton pairs

ALICE particle identification and reconstruction





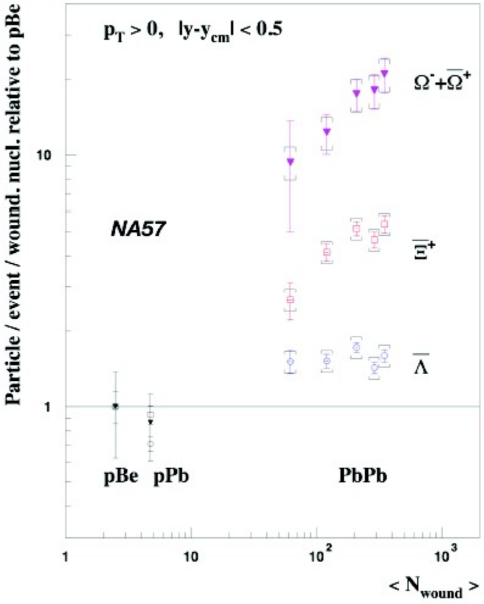
QCD phase diagram



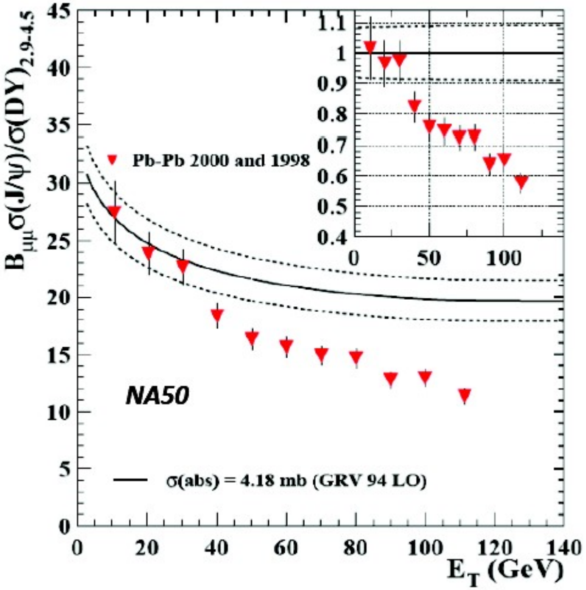
- QGP produced at LHC has highest temperatures and largest matter-antimatter symmetry
- Early universe in this state ~10^{-6} seconds after big bang
- Ongoing dedicated high energy program at RHIC
- Lower energies at SPS, RHIC, FAIR, NICA search for QCD critical point and thresholds of QGP formation

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



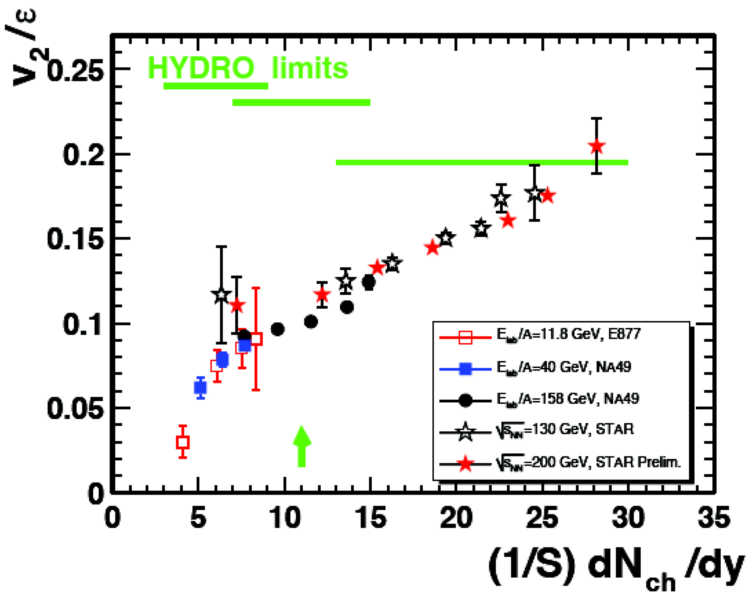
Strangeness enhancement
Strange quarks readily produced in QGP & strange hadrons described by thermal model bound states



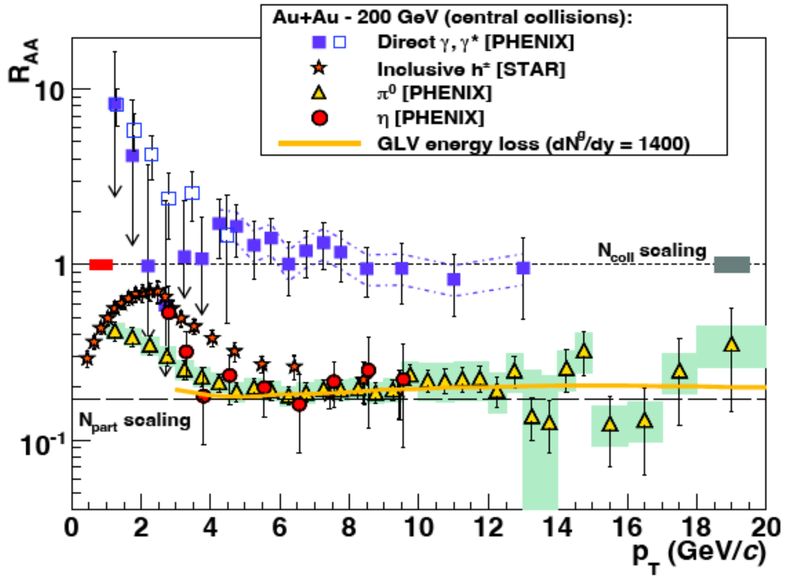
Charmonium suppression
QGP screens force between bound states

Next step: HIC at RHIC

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

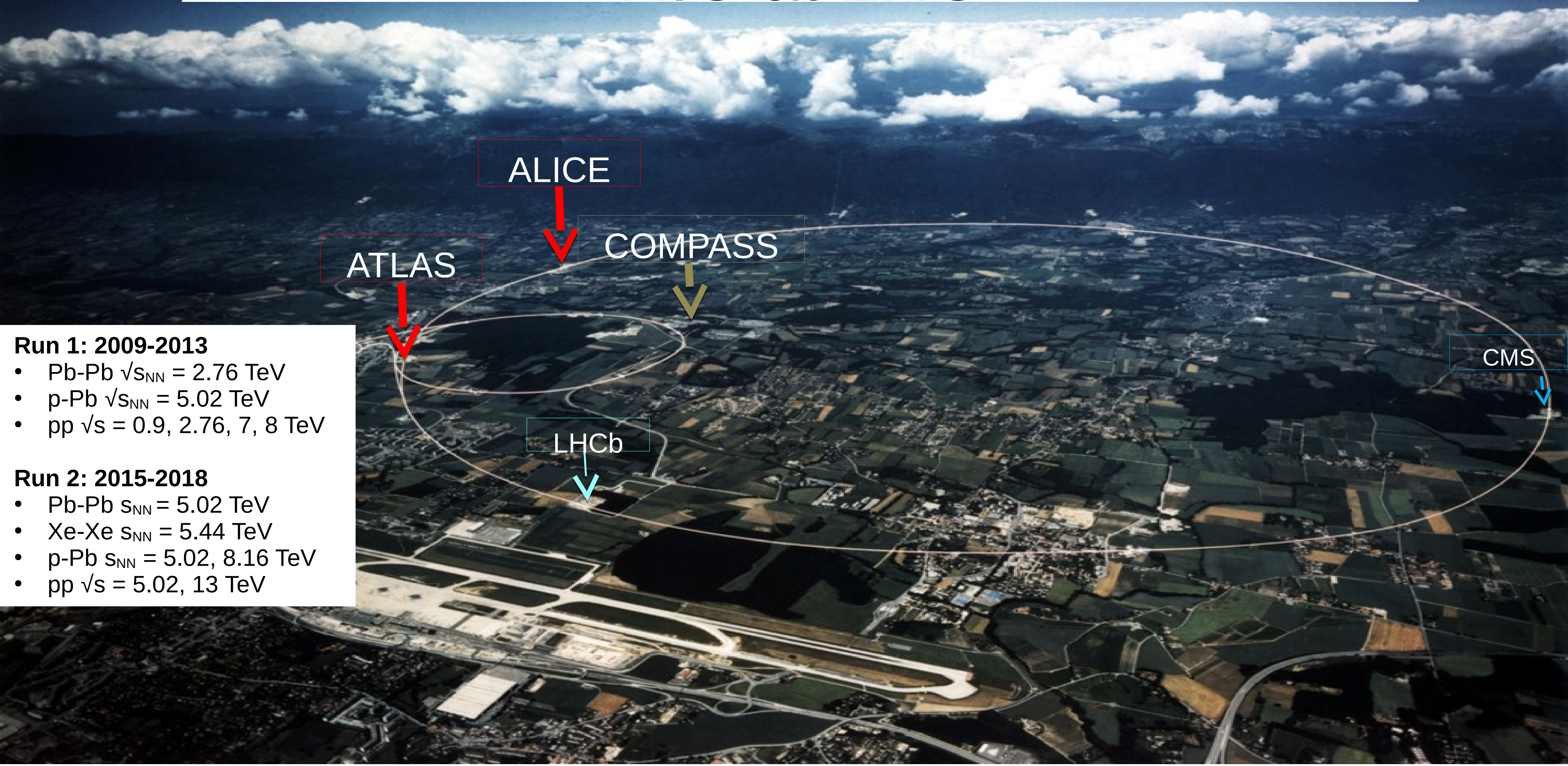


Perfect liquid
Elliptic flow reaches hydrodynamic limit



Jet quenching
Hard partons lose energy in QCD medium

HIC at LHC



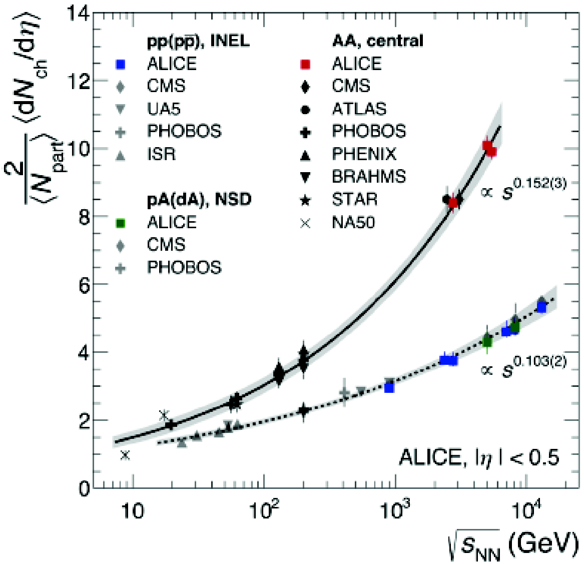
Run 1: 2009-2013
- Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
- p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
- pp $\sqrt{s}$ = 0.9, 2.76, 7, 8 TeV

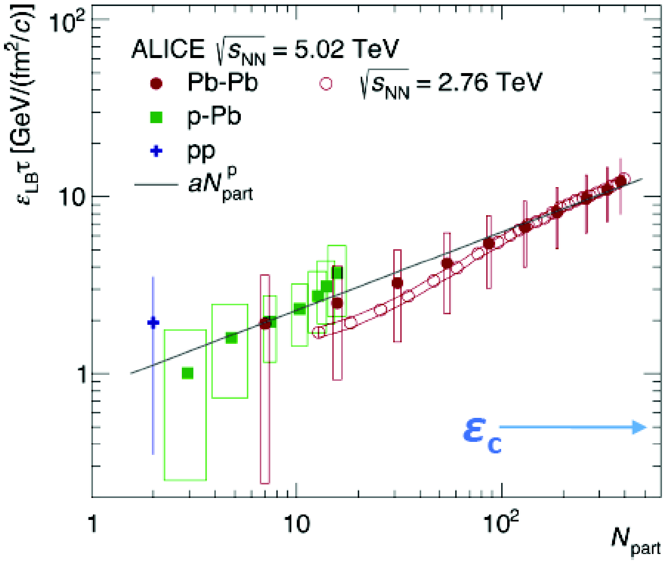
Run 2: 2015-2018
- Pb-Pb s_{NN} = 5.02 TeV
- Xe-Xe s_{NN} = 5.44 TeV
- p-Pb s_{NN} = 5.02, 8.16 TeV
- pp $\sqrt{s}$ = 5.02, 13 TeV

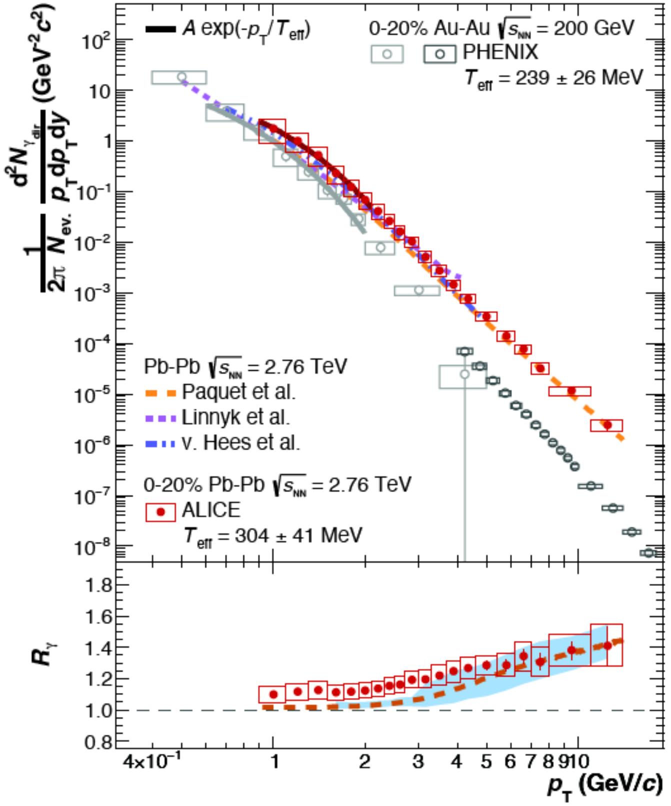
Key questions of QCD studies at LHC

- **Global properties of system?**
- **Microscopic QGP properties from hard probes?**
- **Modification of QCD potential in QGP?**
- Dynamical evolution of QGP?
- Novel QCD effects in QGP?
- Hadron formation from QGP
- Limits of QGP formation?
- Properties of nucleus and proton at high energy?
- Nature of hadron-hadron interactions?
- Elucidation of QCD in proton-proton collisions?

Global properties of nuclear collisions

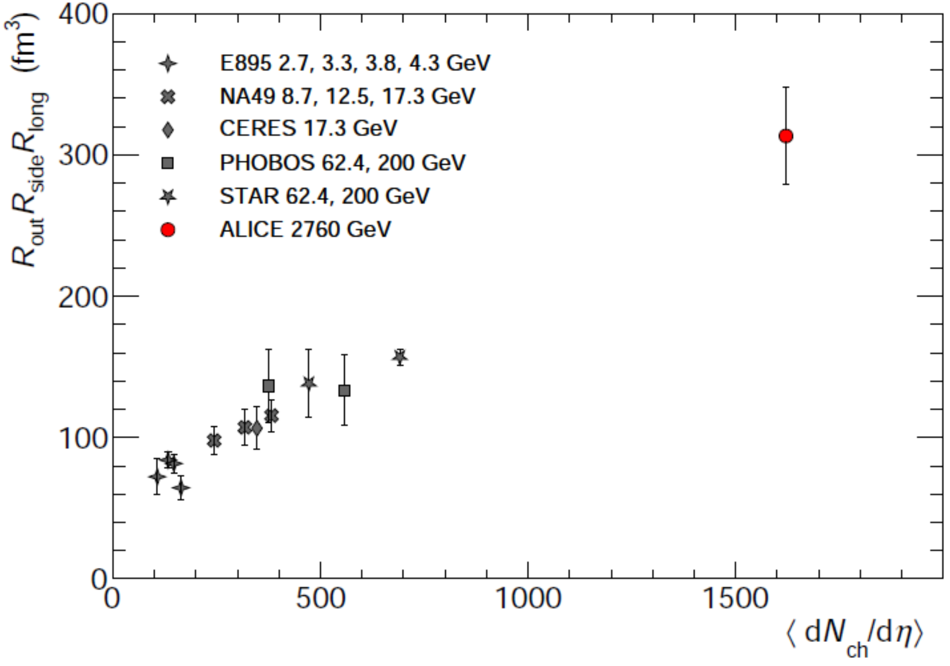


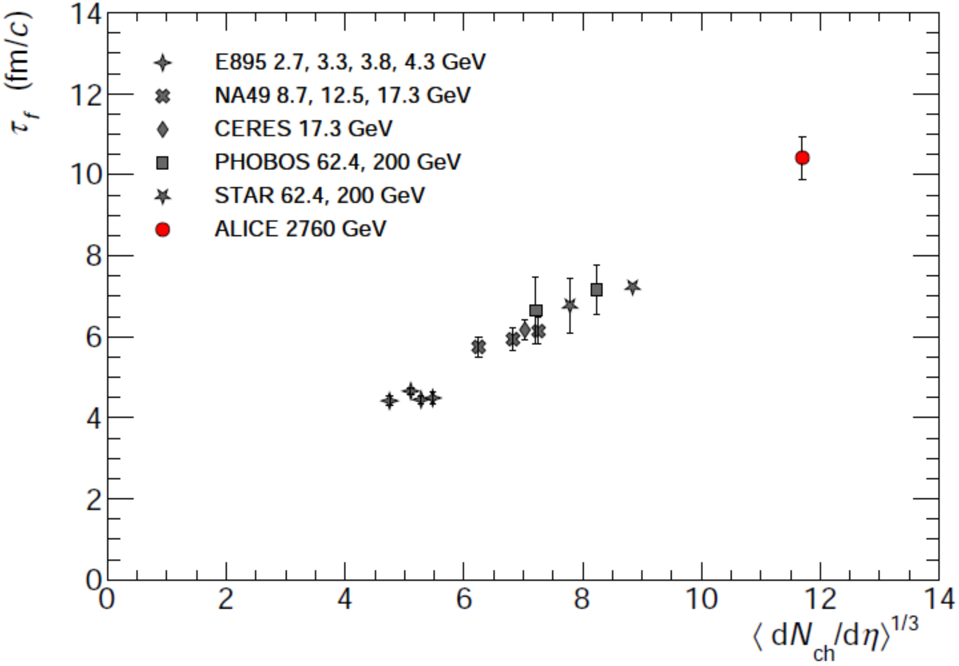




- Charged hadron production per nucleon is maximal in Pb-Pb at LHC
- Central Pb-Pb initial energy density 30x is larger than ε_c.
- Photon effective temperature is twice T_c.

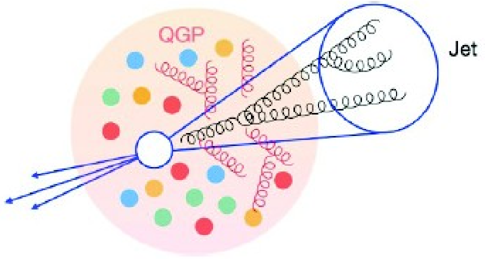
Size and lifetime of QGP

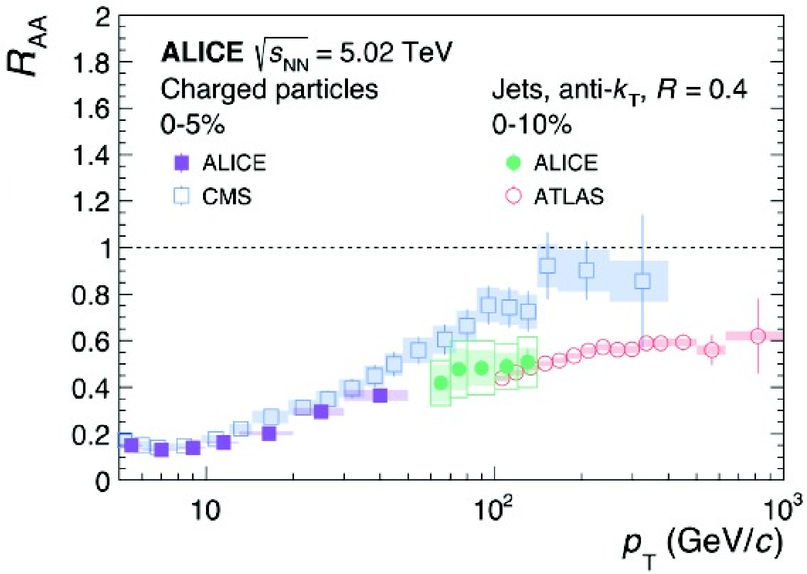


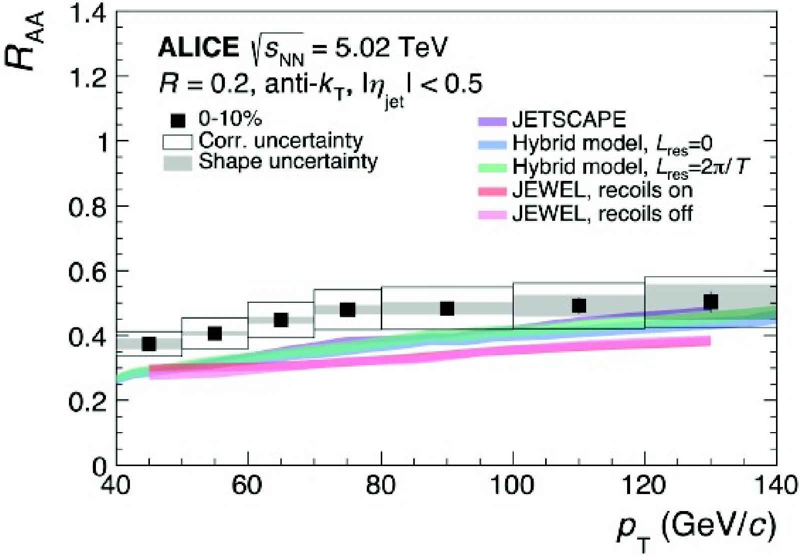


Homogeneity volume and decoupling time τ_f from AGS to LHC

Jets as a microscopic probe

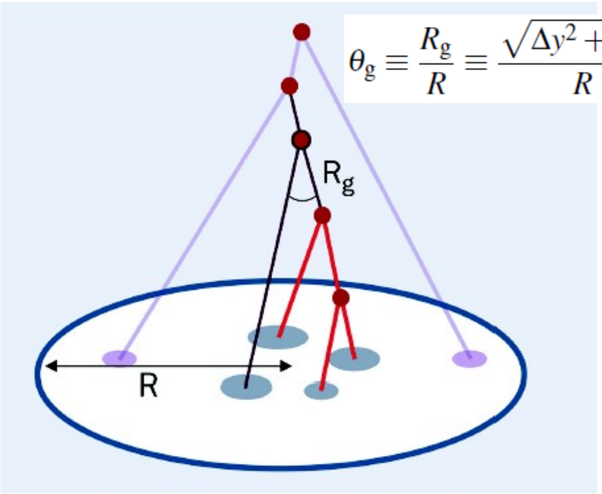


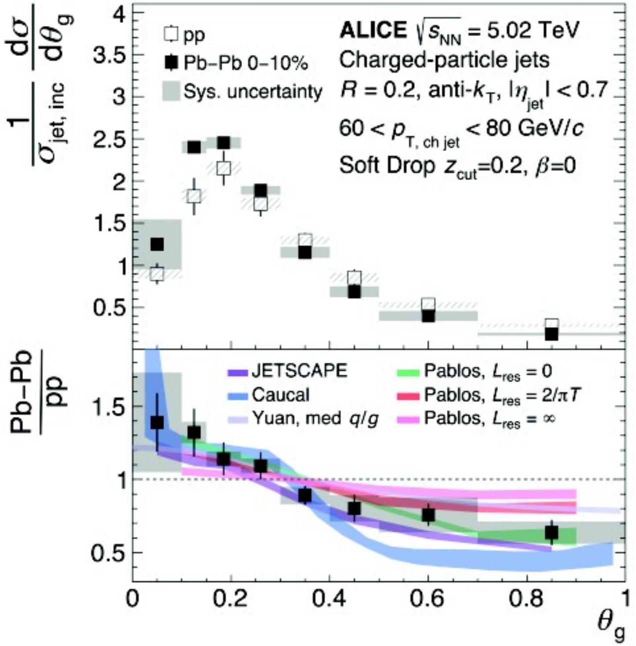




- Hard partons that shower into jets of are produced early and interact with QGP
- Jet and high p_T hadron suppression observed over extensive range
- Dominated by radiative emission and extracted energy loss at LHC 8±2 GeV
  - (3.3±0.8 at RHIC)

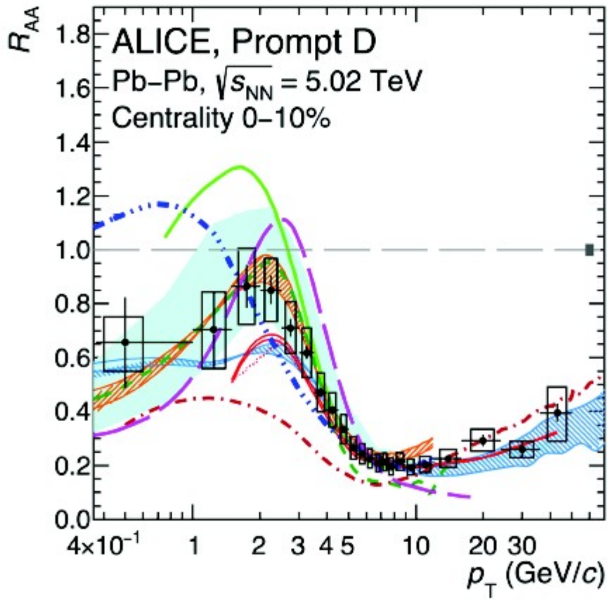
Modification of jet shower in the QGP

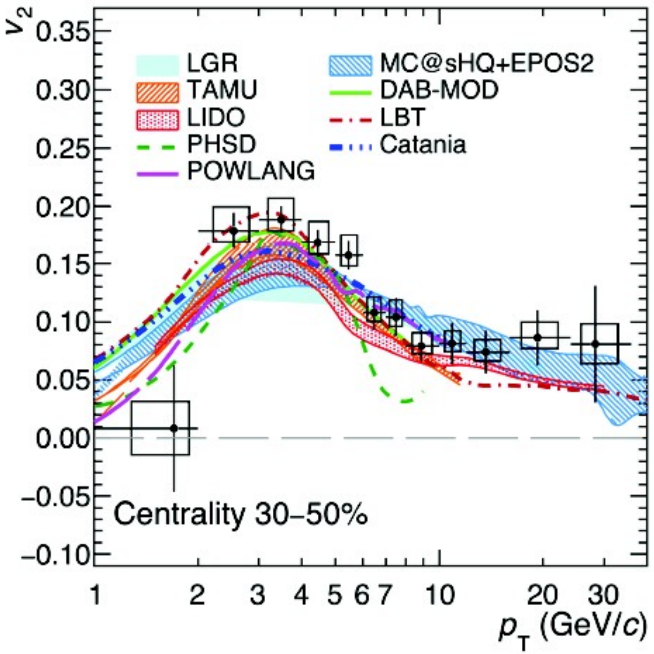




- Jet substructure measurements explore jet shape at earliest parton splittings
- Pb-Pb jet substructure more narrow than pp
- Indicates QGP jet energy loss mechanisms suppress wider angle jets

Heavy flavour interactions

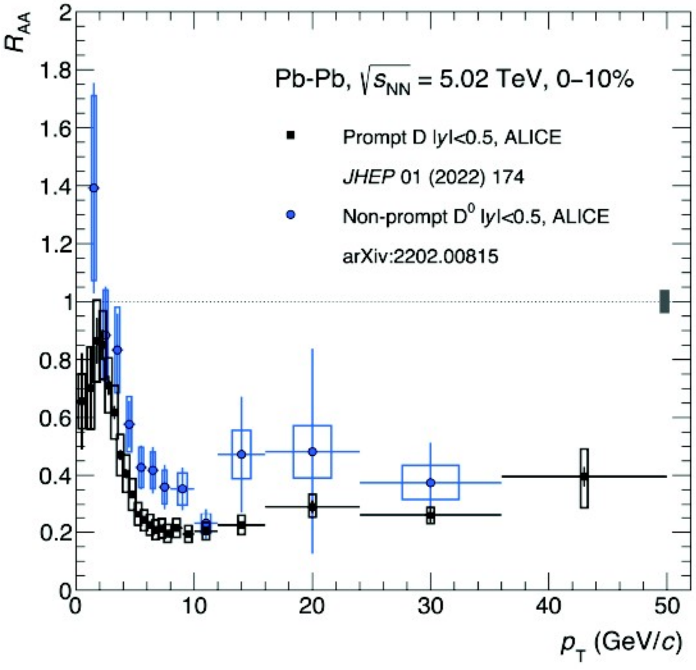


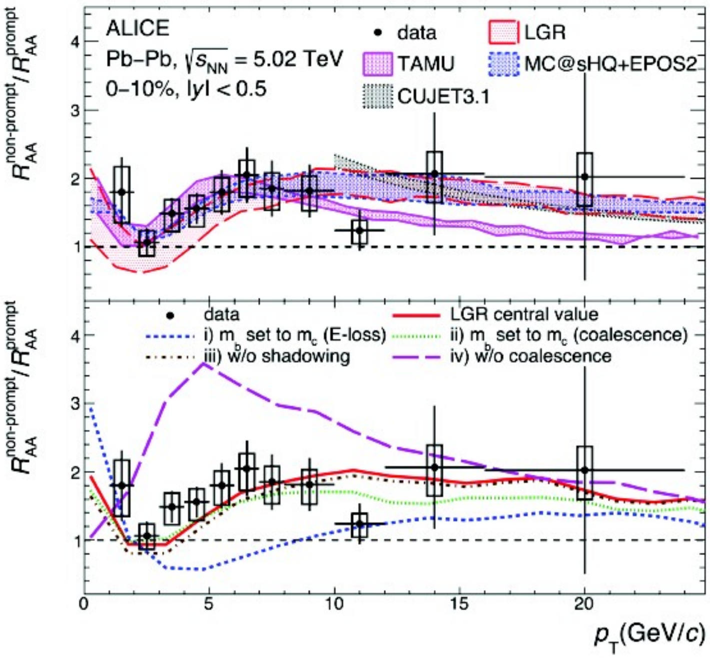


Heavy quarks as hard probes investigate medium for whole momentum domain

- Hard scale given by the quark mass
- Most charm-quark transport models describe both the R_{AA} and anisotropic flow (v_2)
- Radiative energy loss critical for high momentum

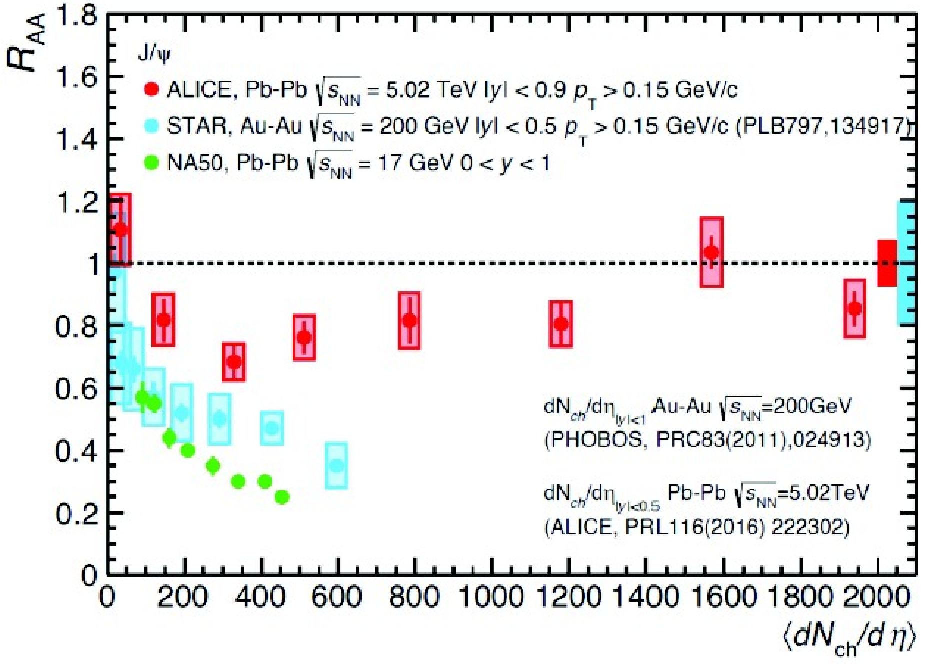
Charm vs beauty energy loss

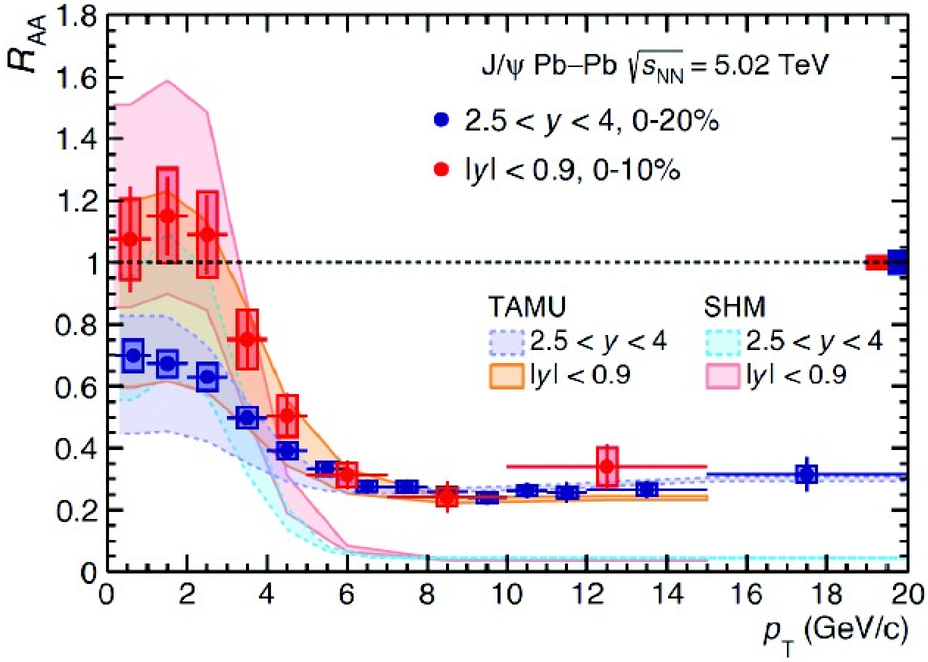




- D mesons from bottom decays less suppressed than those formed from charm
- Indication of mass dependent collisional and radiative suppression e.g. dead cone effect

Suppression and regeneration of quarkonia

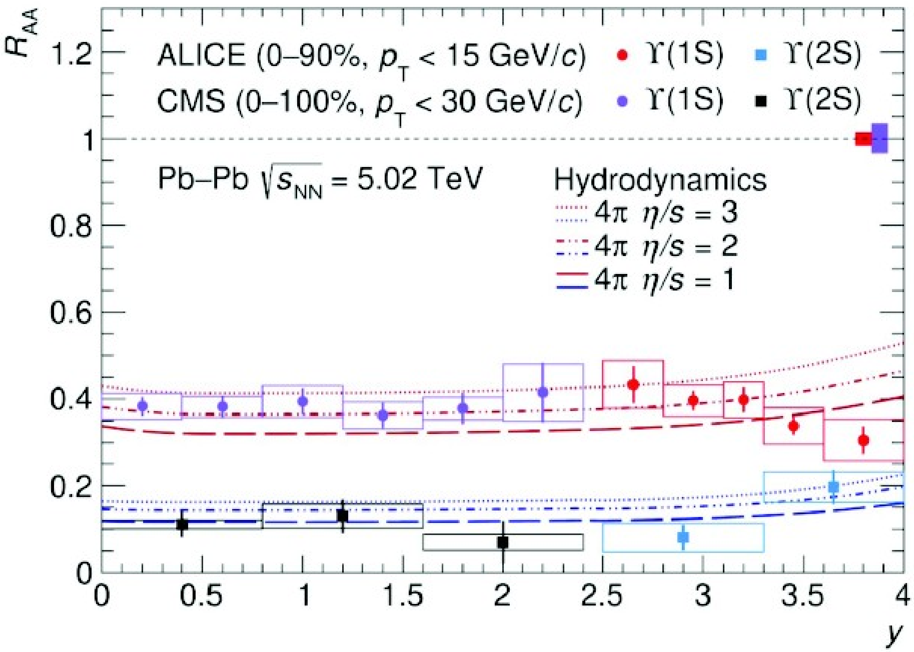


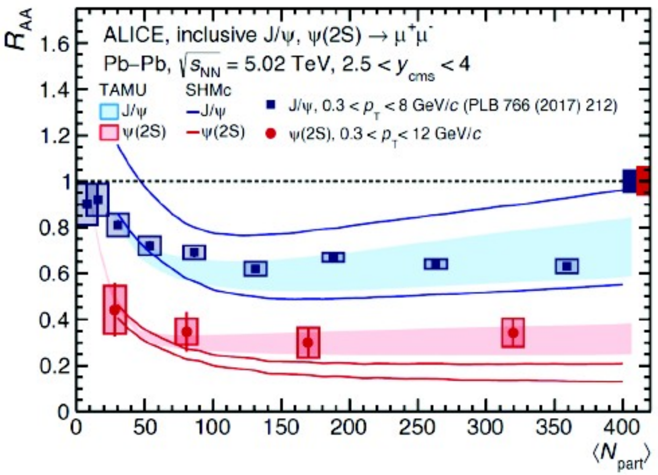


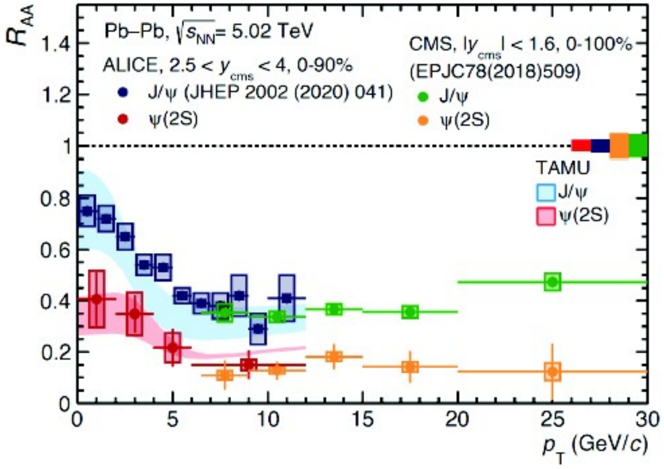
Quarkonia also probe QGP at sub fm scales

- 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.

Key questions of QCD studies at LHC

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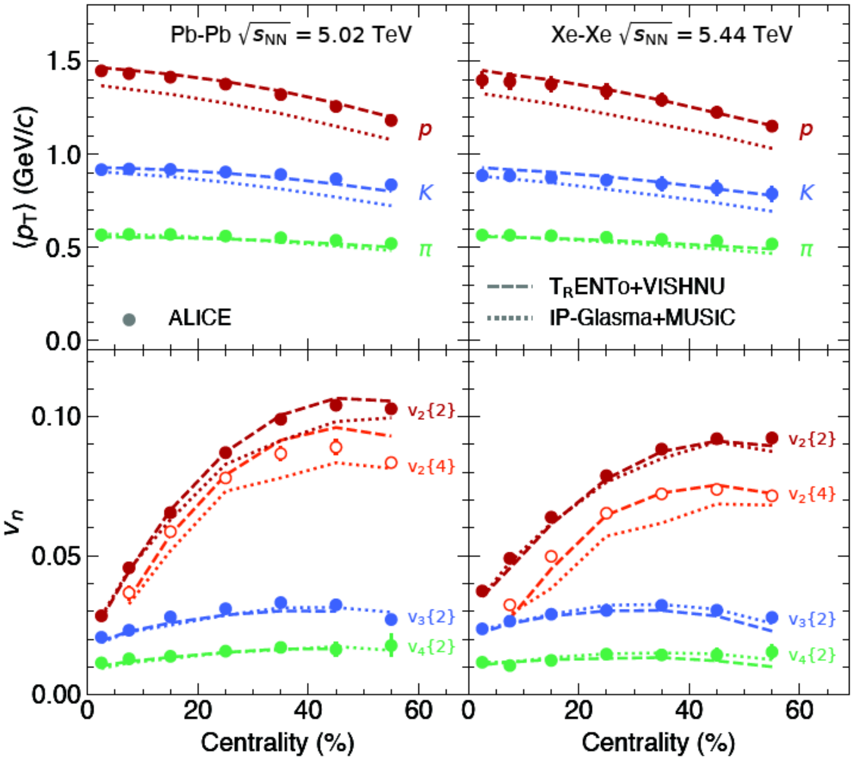
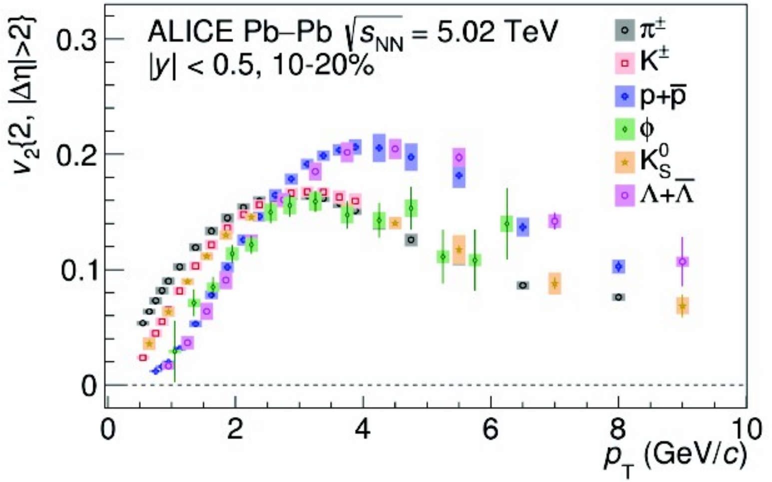
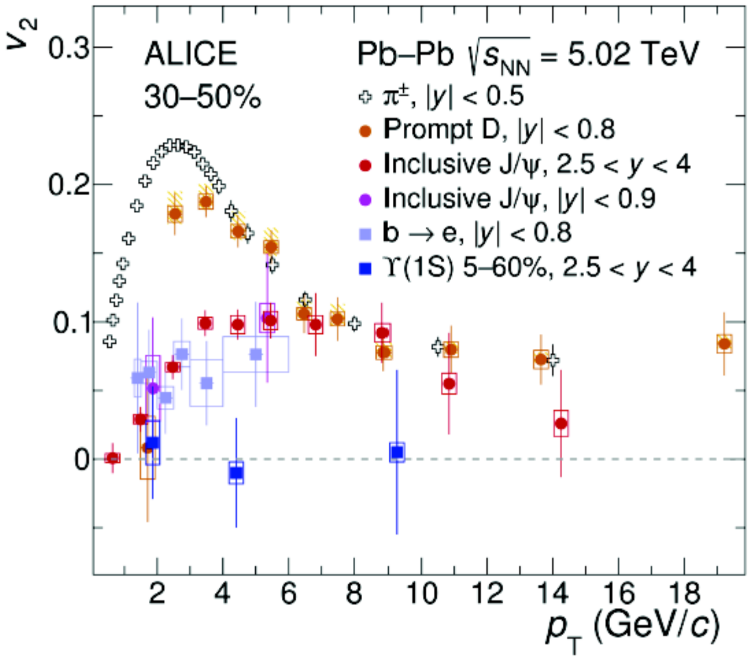
Momentum anisotropy (flow): almost perfect liquid

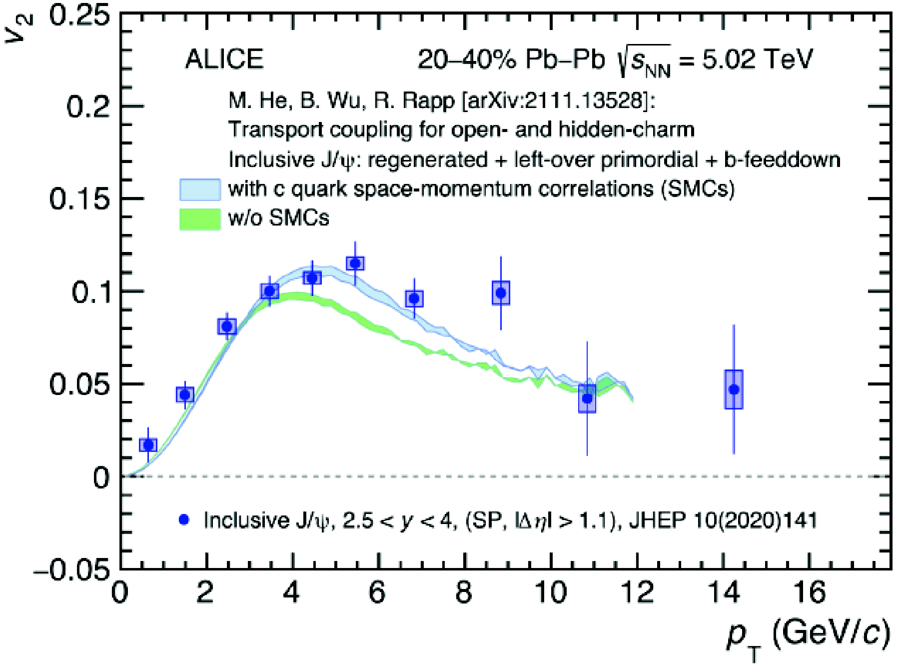




- Global QGP radial and anisotropic expansion described by hydrodynamics
- Achieved with QGP equation of state and small but finite QGP viscosities

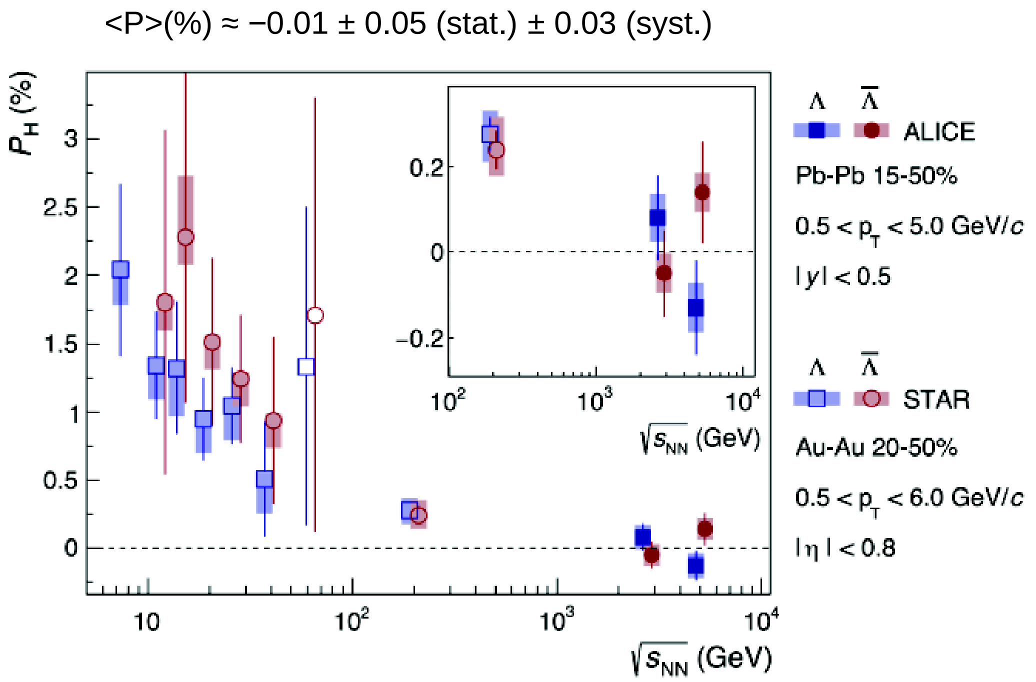
Heavy quark flow in the QGP

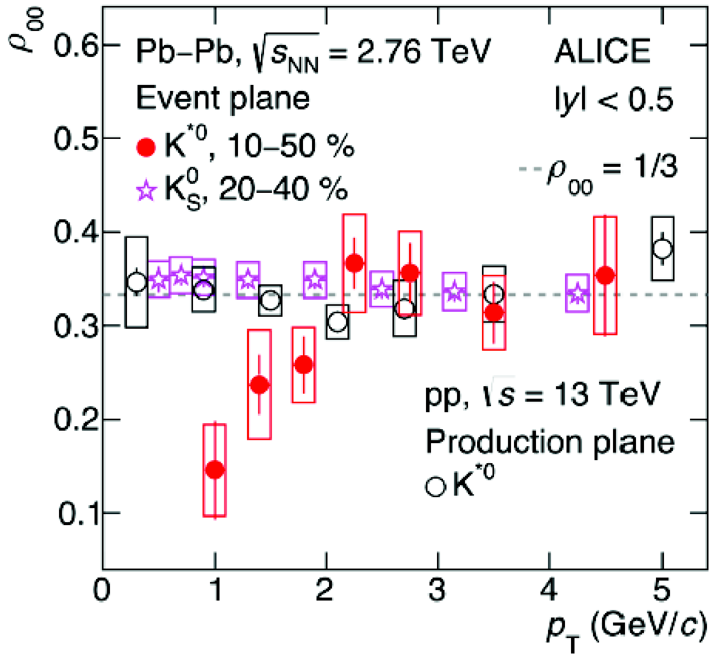




- Finite values of J/Ψ v_2 provide unambiguous signature of charm flow. Bottom quarks also flow
- Transport models using Brownian motion describe charm flow

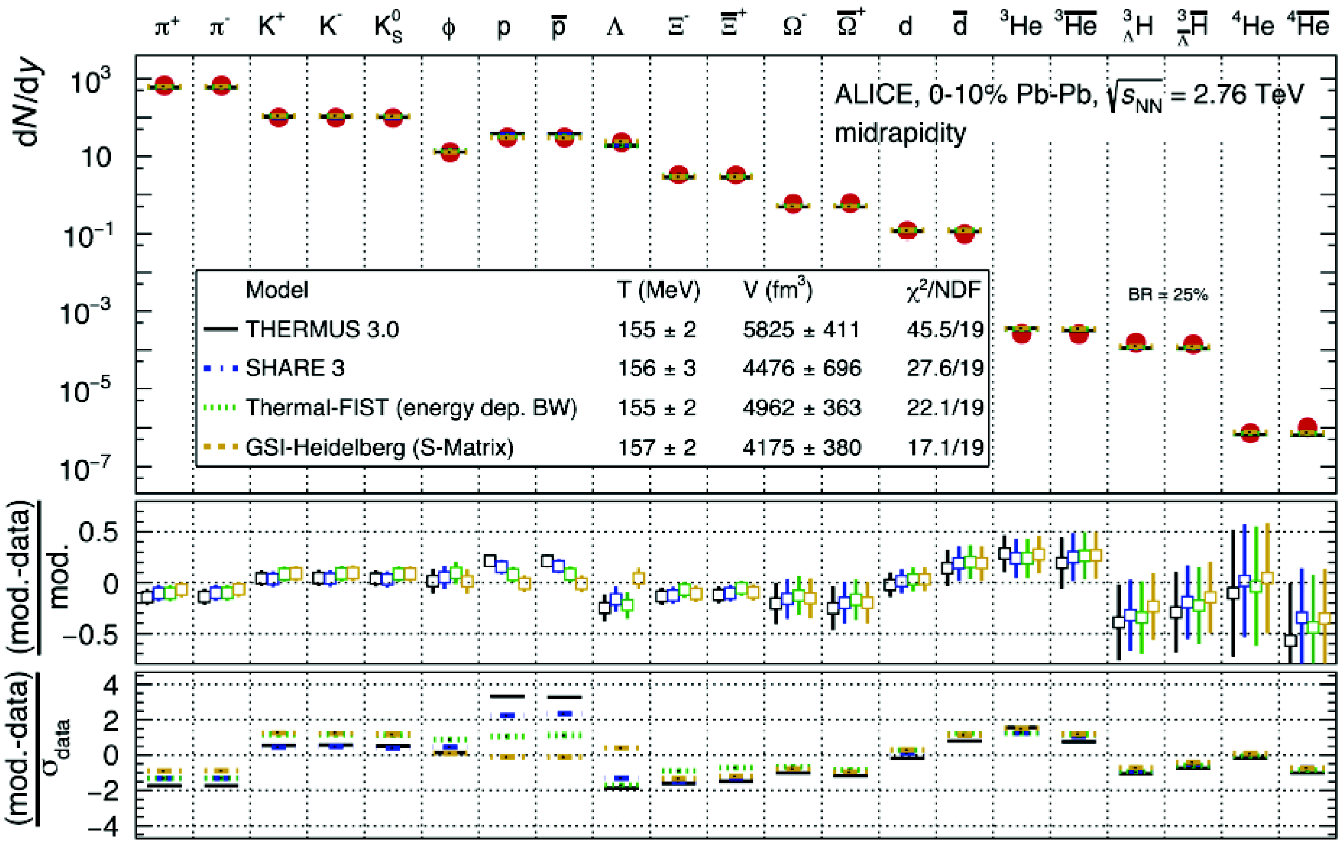
The most vortical fluid





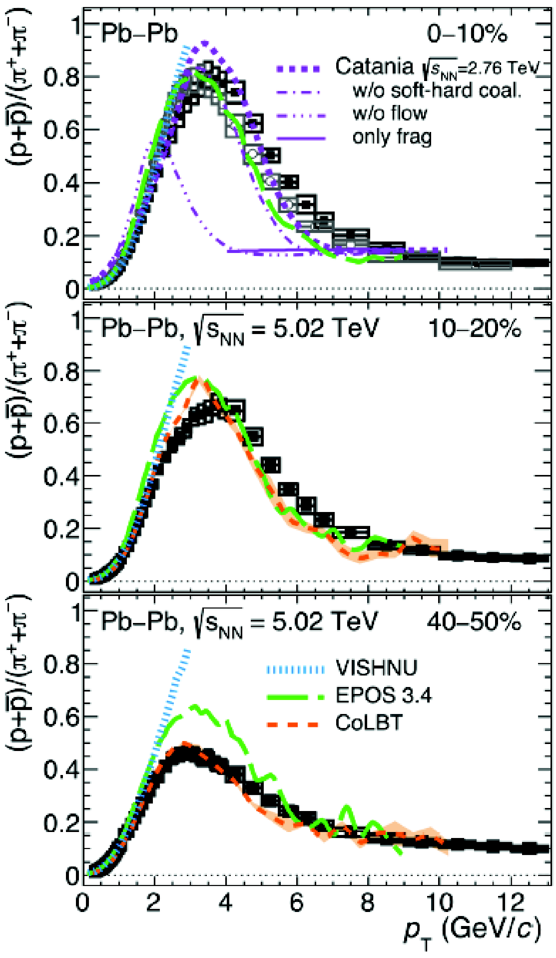
- Global angular momentum from incoming nuclei induces polarization with respect to reaction plane direction
- Effect stronger for K* mesons compared with Λ hyperon
- Theory predicts vanishing polarization and spin alignment at high temperature, not consistent with observation for vector mesons

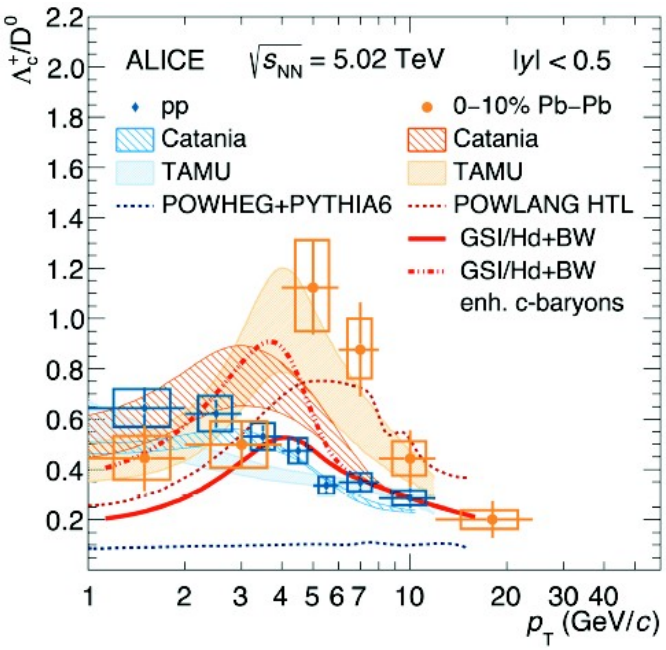
Hadron formation from QGP



- 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

Macro to microscopic hadron formation



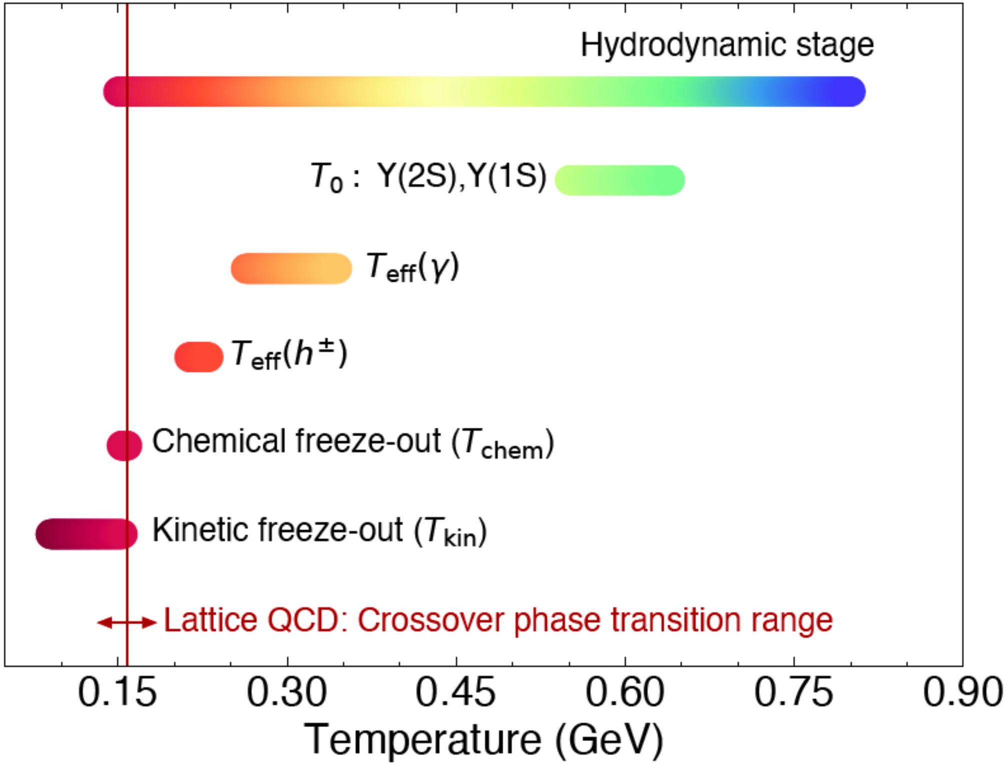


- **Quark coalescence** required to describe light and heavy flavour baryon/meson ratios & **flow** at immediate p_T.

- **Fragmentation** dominates at higher p_T.

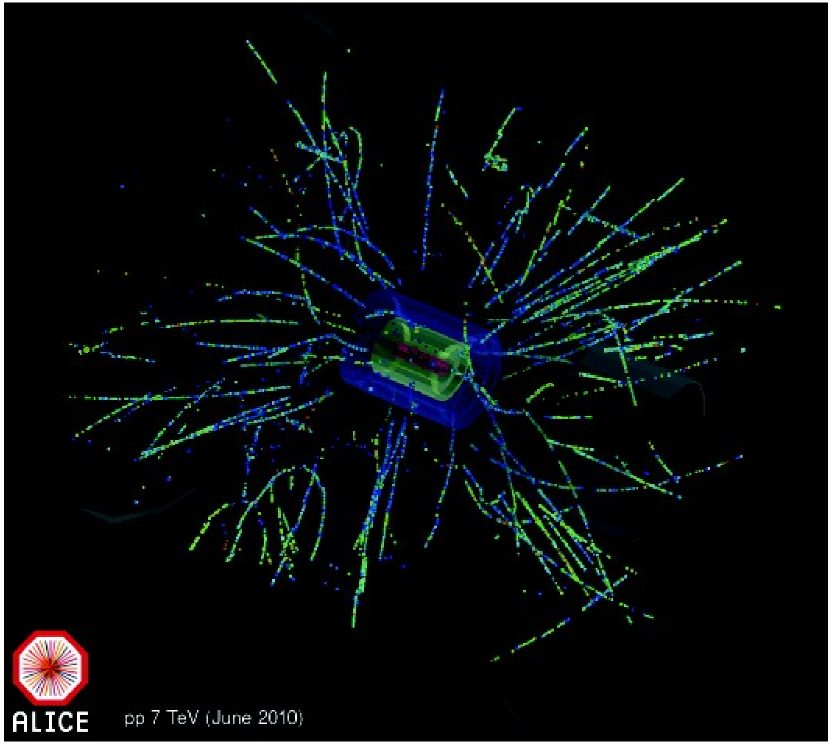
Temperatures of nuclear collisions at LHC

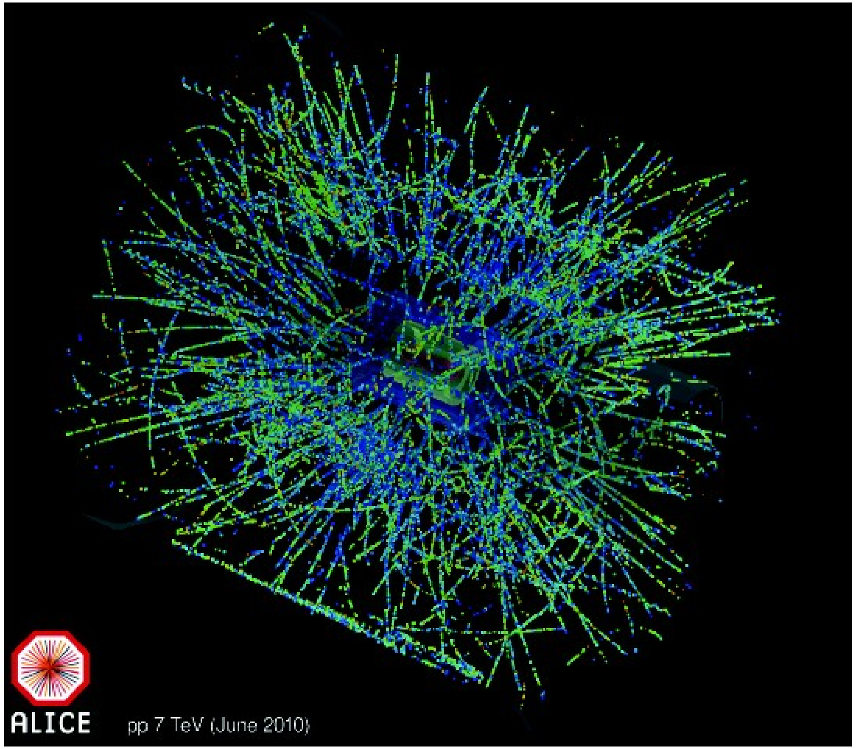
Many observables imply temperatures greater than QGP transition temperature



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

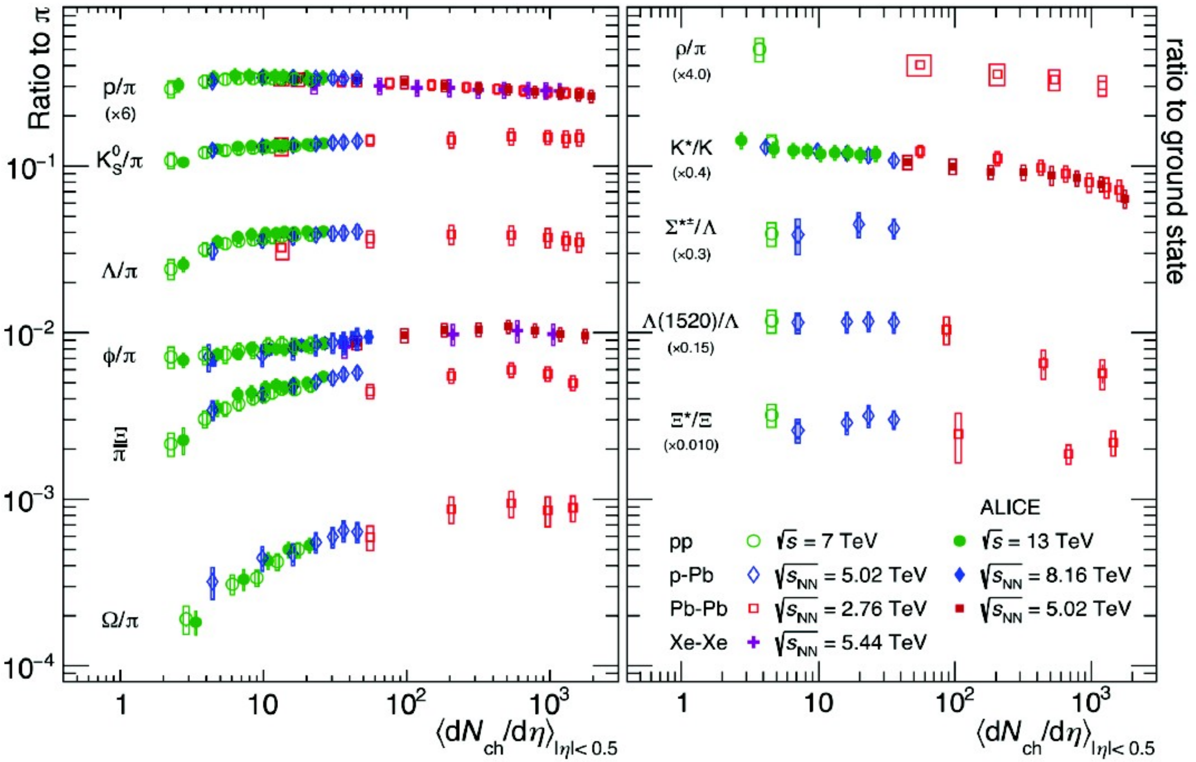
QCD studies in small systems





- 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?

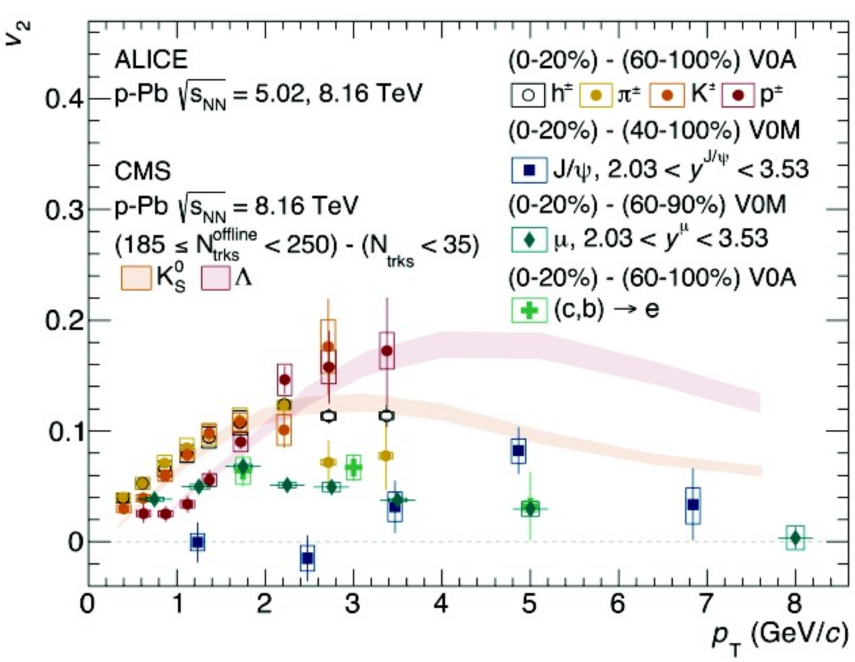
Strangeness enhancement in small systems

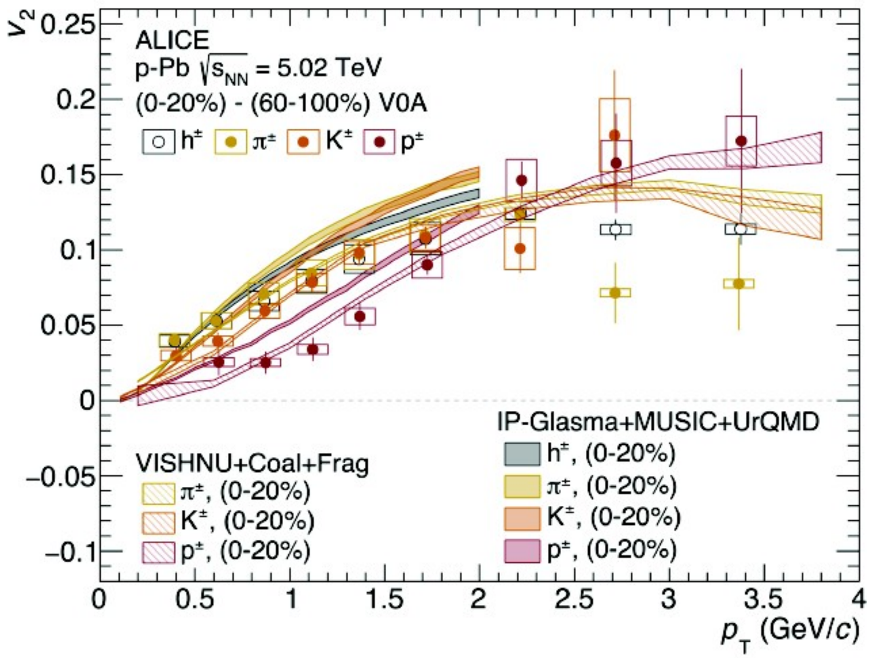


Particle yield ratios depend on $dN_{ch}/d\eta$ rather than colliding species

- 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?

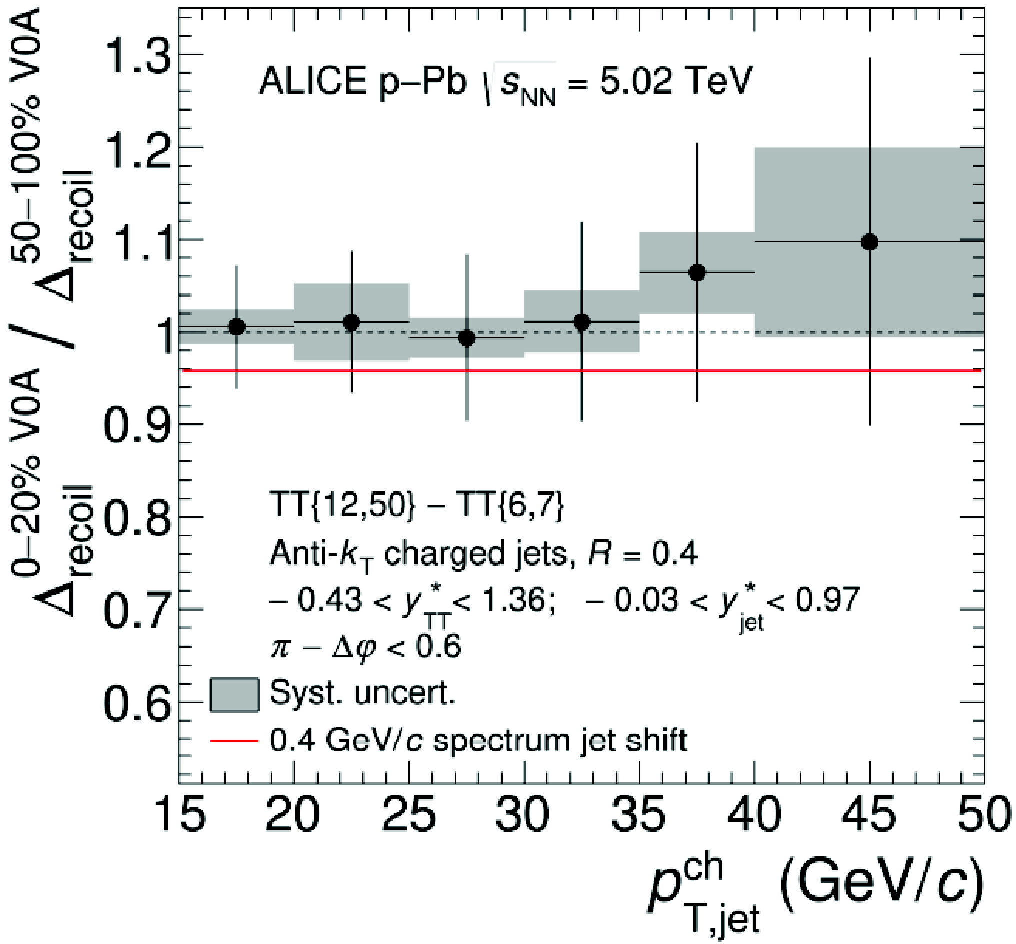
Flows in small systems





- 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

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

Is QGP really formed in small systems?

- QGP signatures:
  - Strangeness enhancement
  - Hydrodynamic flow of light hadrons
  - Heavy flavor flow
  - Suppression of loosely bound quarkonia
- 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

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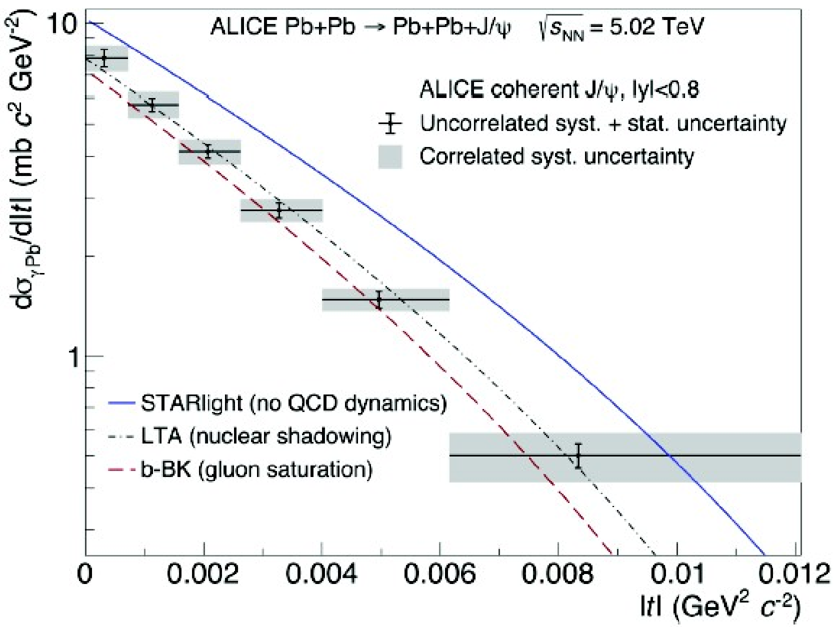
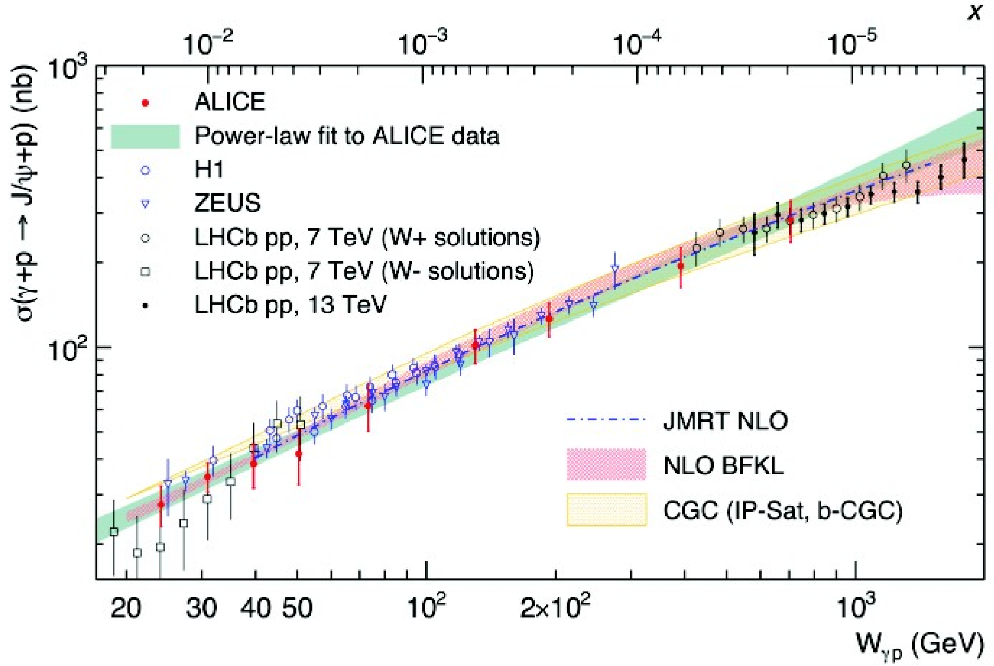
- **Properties of nucleus and proton at high energy?**
- **Nature of hadron-hadron interactions?**
- **Elucidation of QCD in proton-proton collisions?**

Looking deep into the nucleus and proton

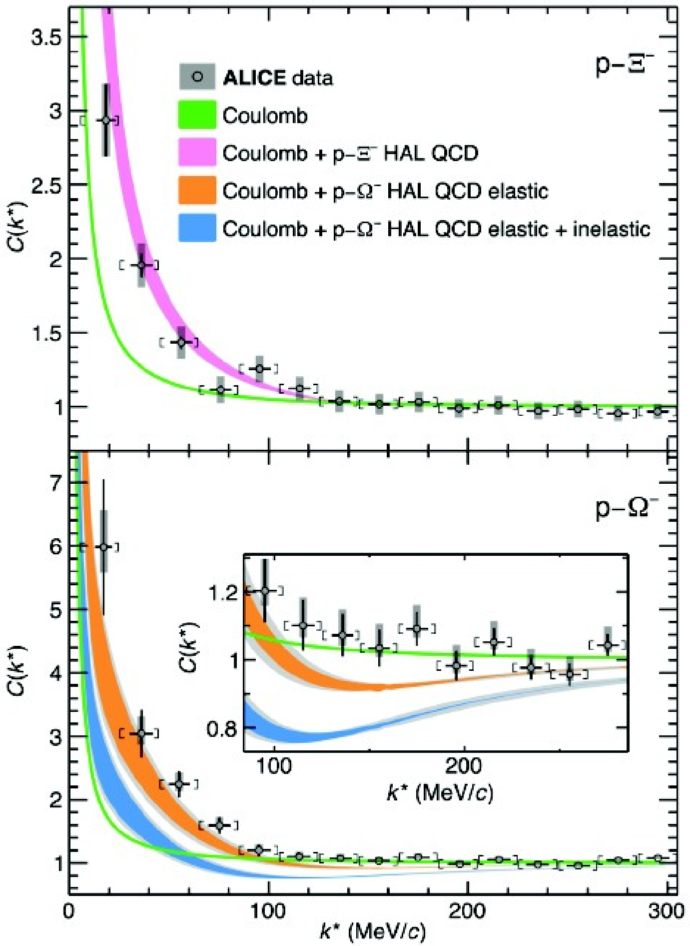




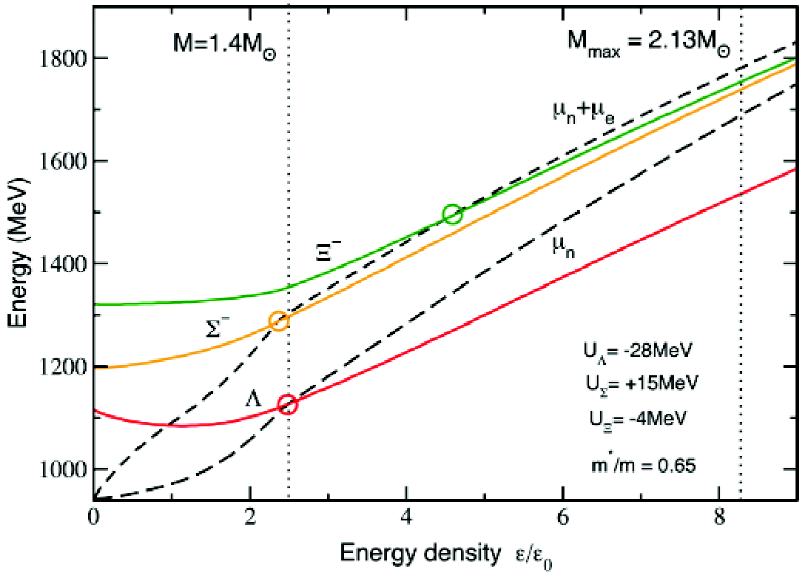
- Ultra-peripheral collisions involve photons probing a nuclear or proton target
- Clear evidence of the shadowing of nuclear gluon distribution functions at $x \sim 10^{-3}$
- No evidence of gluon saturation in proton at $x \sim 10^{-5}$

Hadron interactions

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

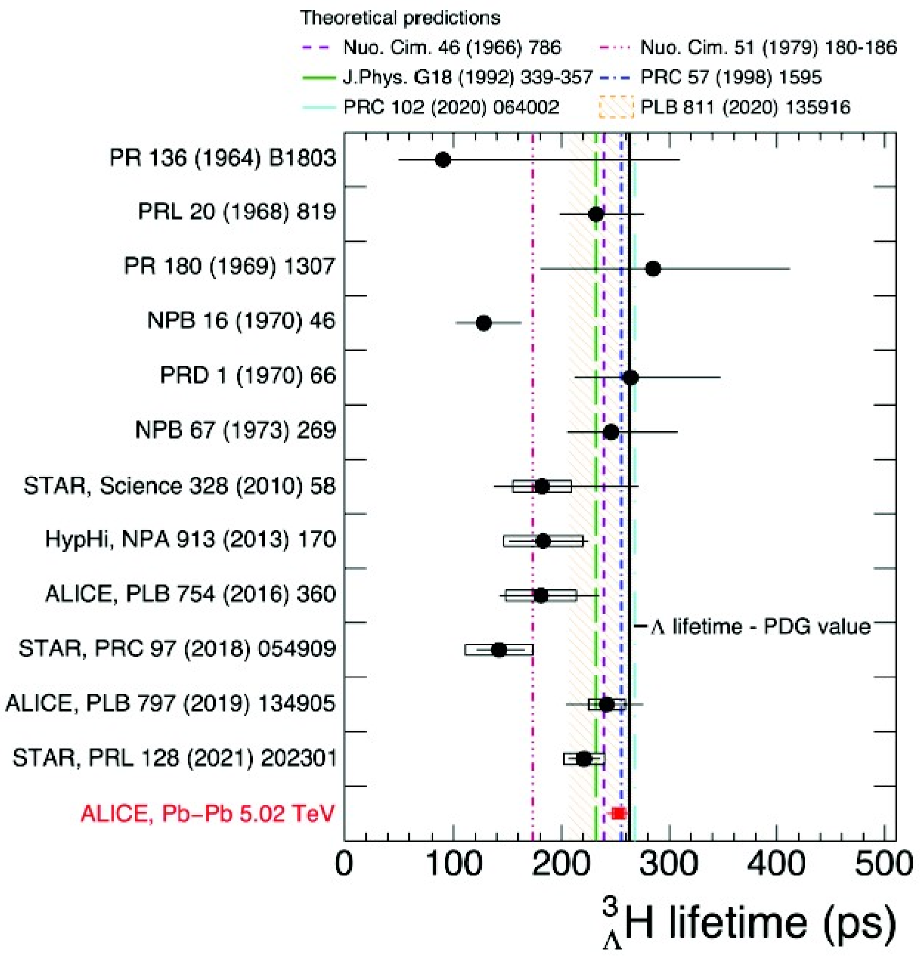


Chemical potential μ i of hyperons produced in the inner core of a NS vs energy density, in units of energy density ε_0 at the nuclear saturation point



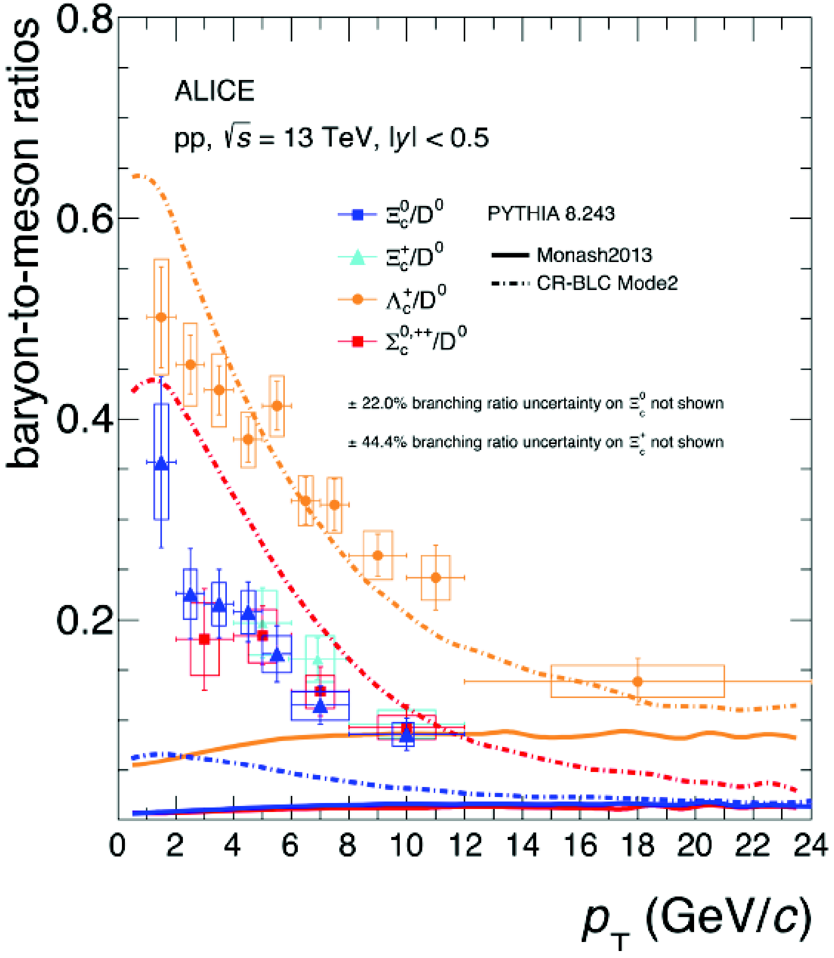
- Large production of hyperons in pp 13 TeV provide unique tests of QCD for rare hadronic interactions
- The interaction of hyperons with nucleons is a key ingredient for understanding composition of the most dense stars in our Universe: neutron stars (NS)
- Strength of proton-hyperon interaction influence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

Fragmentation to mesons and baryons



- Charmed baryon/meson ratios in pp underestimated by fragmentation models that 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

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