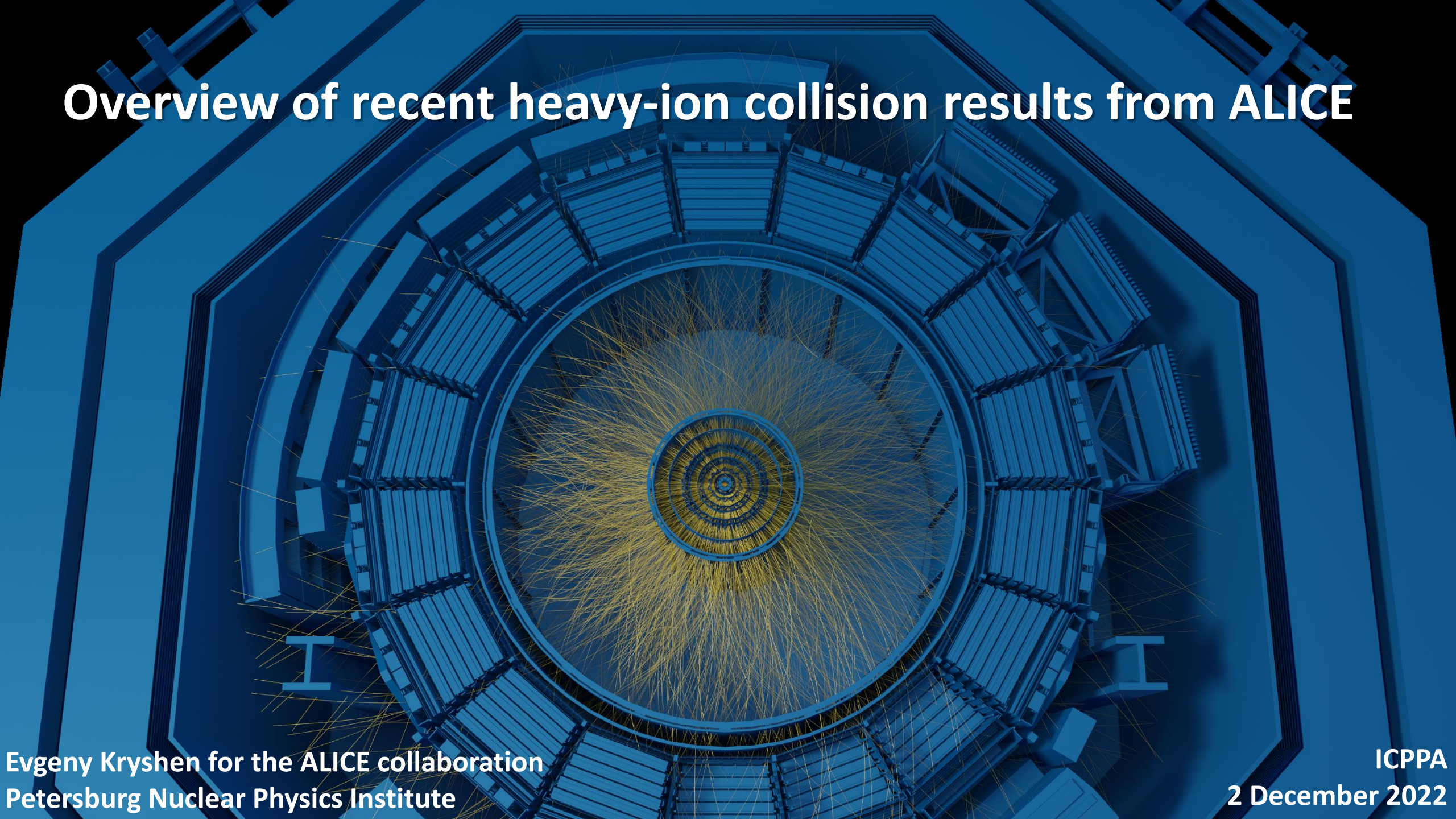
Overview of recent heavy-ion collision results from ALICE



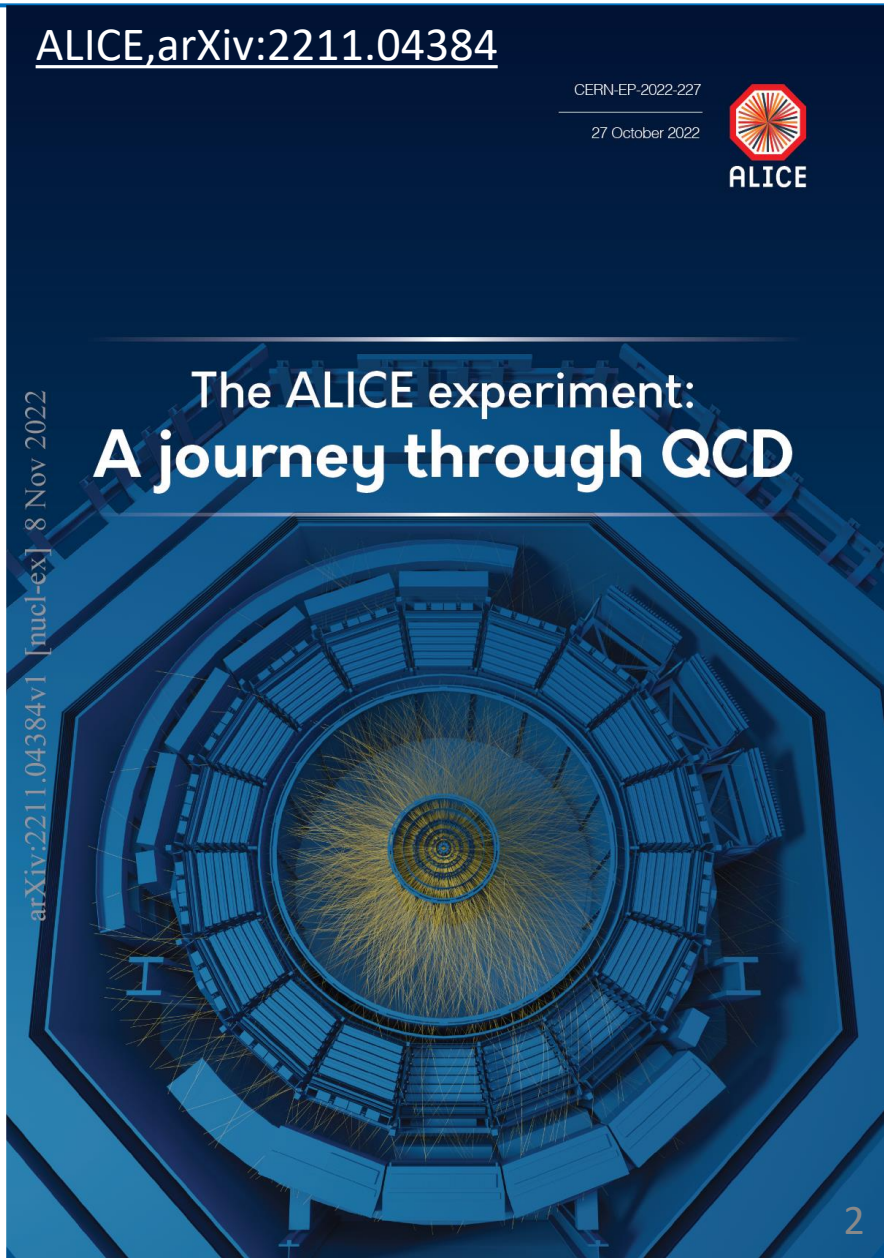
Evgeny Kryshen for the ALICE collaboration
Petersburg Nuclear Physics Institute

ICPPA
2 December 2022

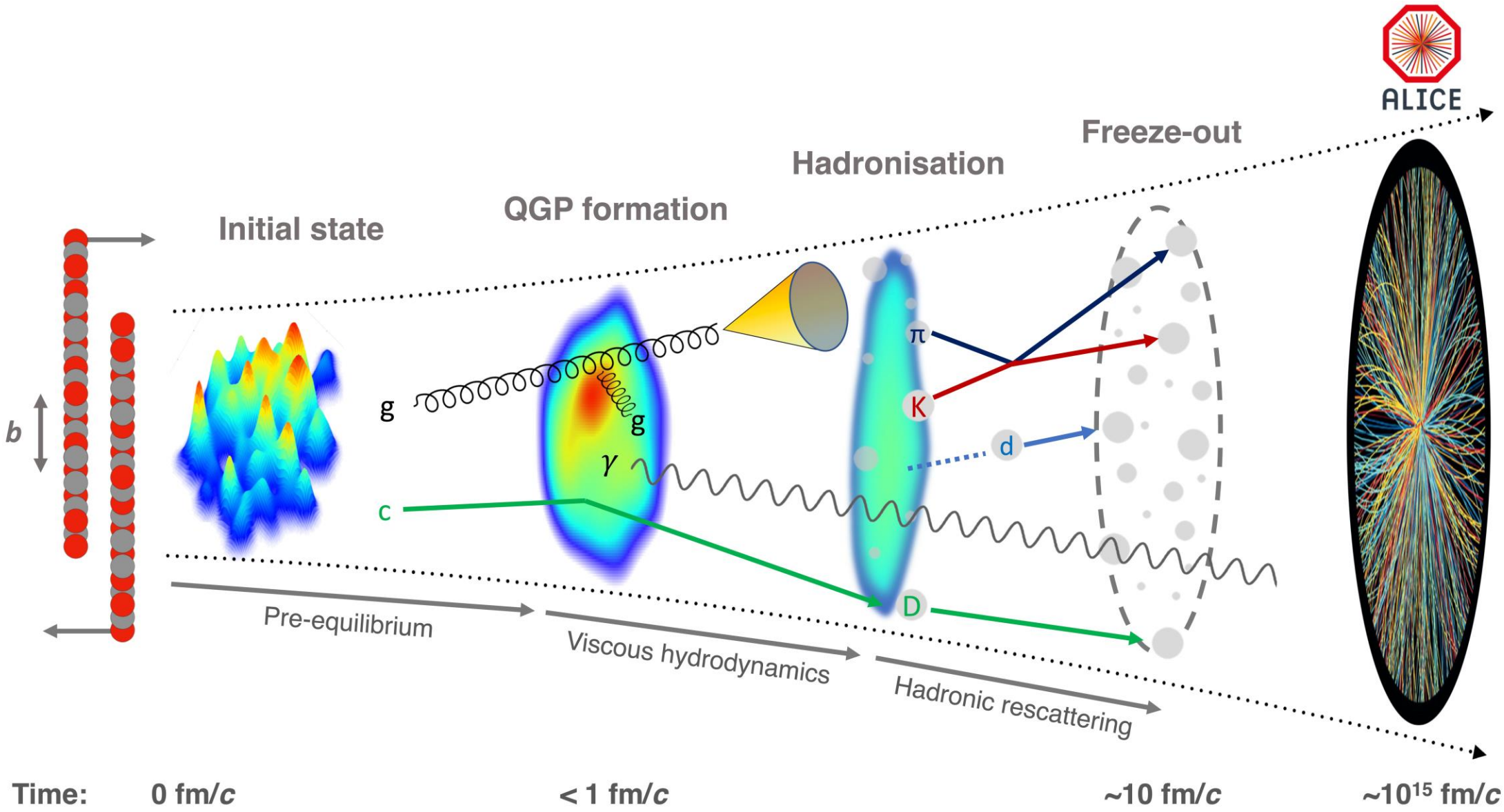
A journey through QCD

ALICE review of Run 1-2 studies:

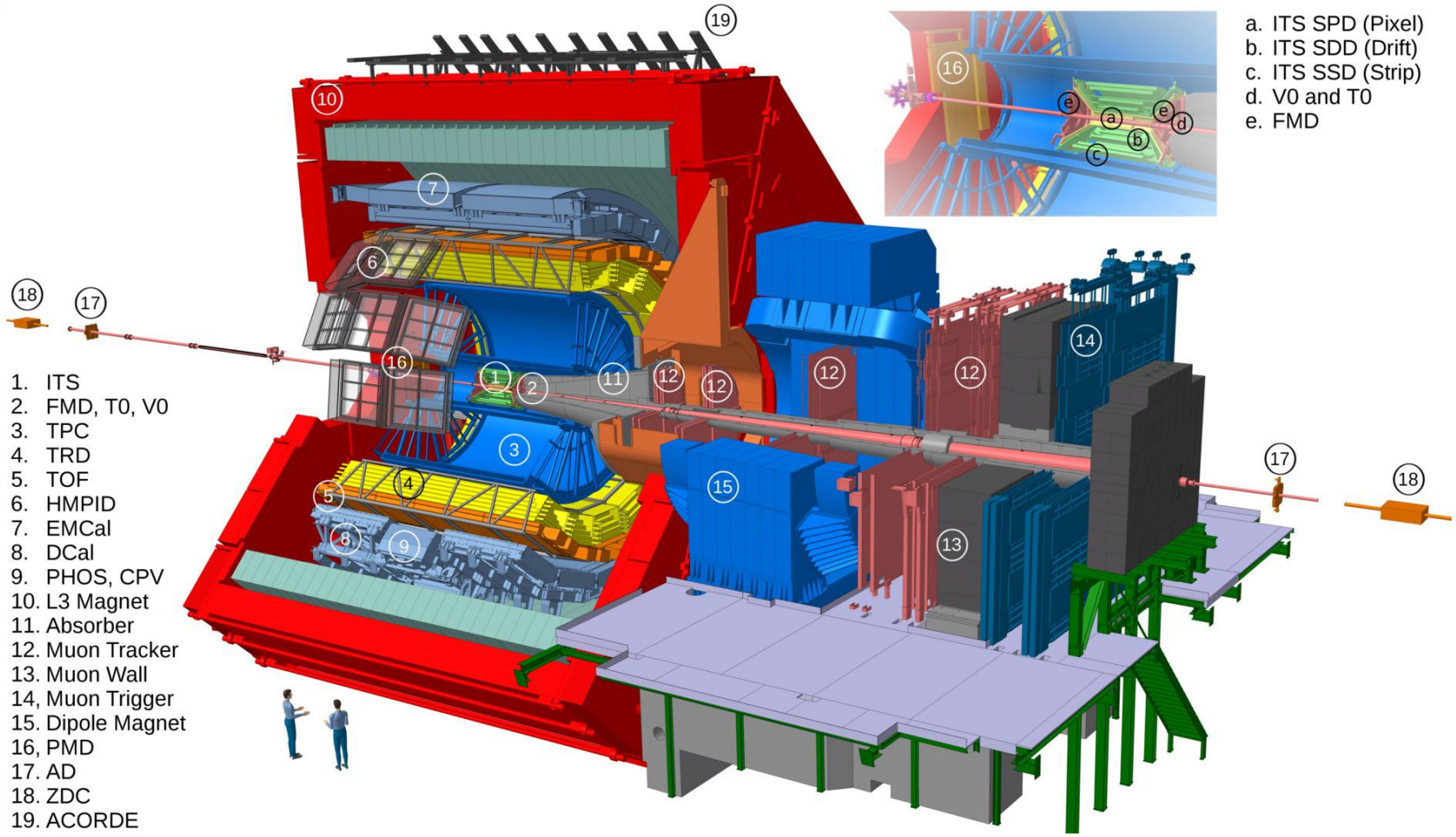
- QGP properties in heavy-ion collisions
  - Macroscopic properties
  - Interactions of partons with QGP medium
  - Hadronization
  - Electromagnetic effects
  - Initial state
- QGP-like effects in small systems
- Many other aspects of QCD and beyond

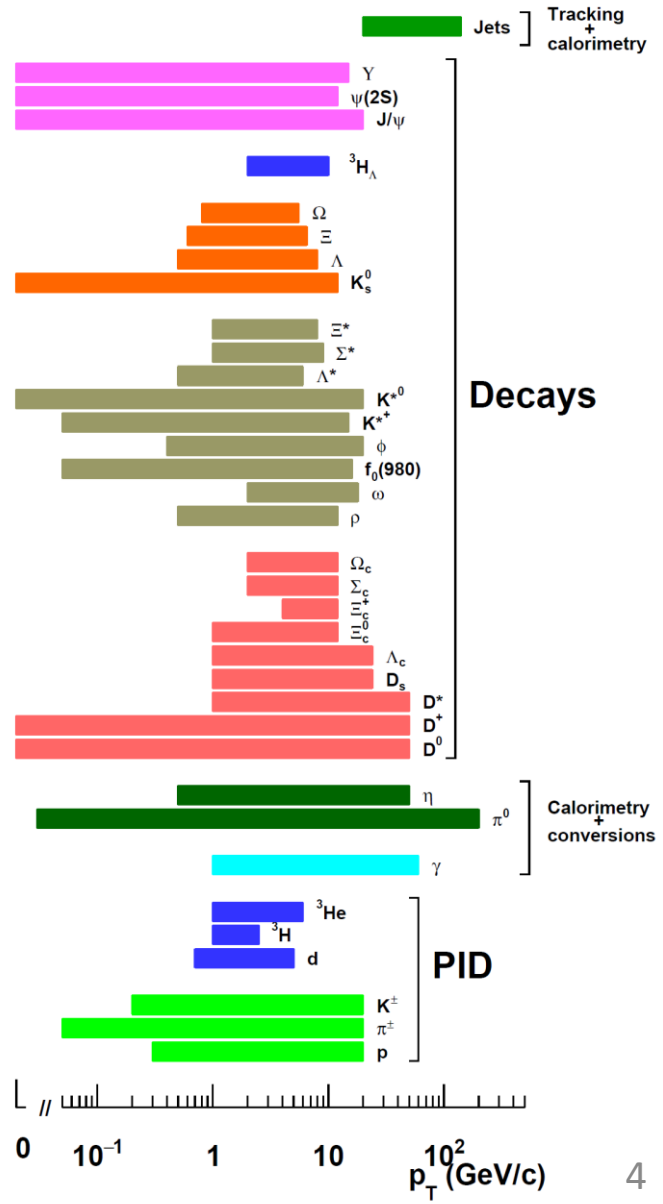


Relativistic heavy-ion collisions



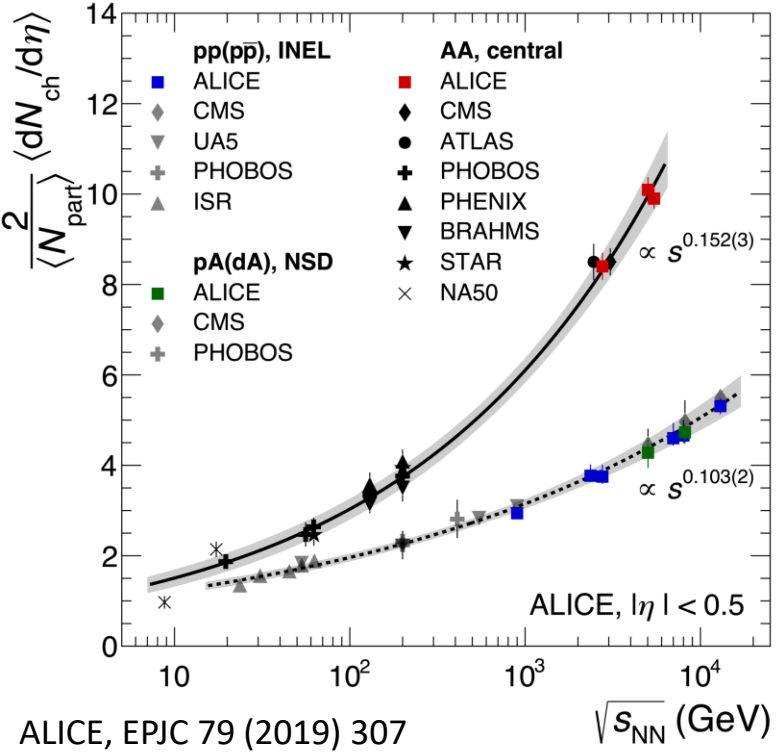
ALICE detector



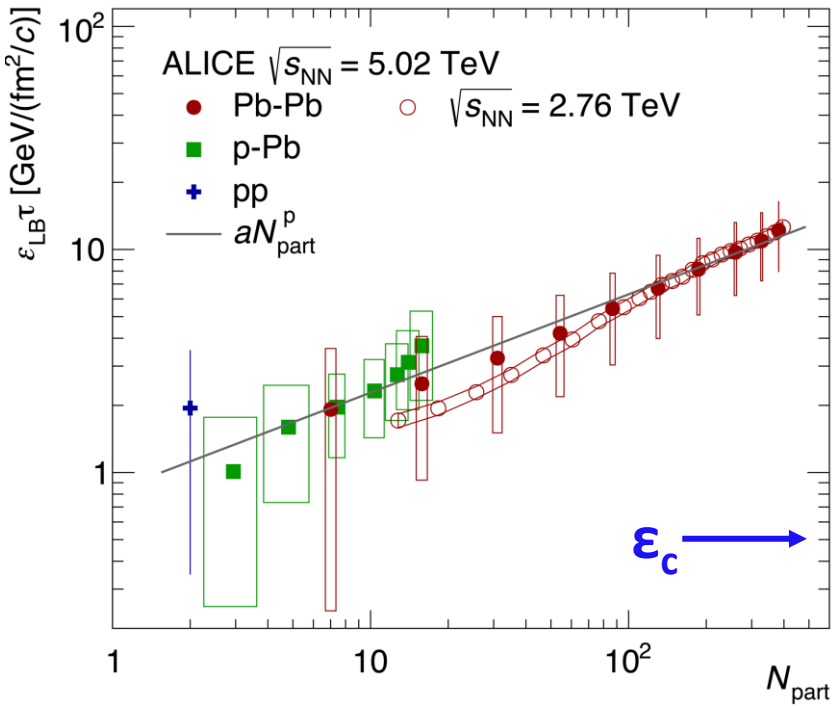


- Broad momentum acceptance
- World leading particle identification
- Precise vertexing

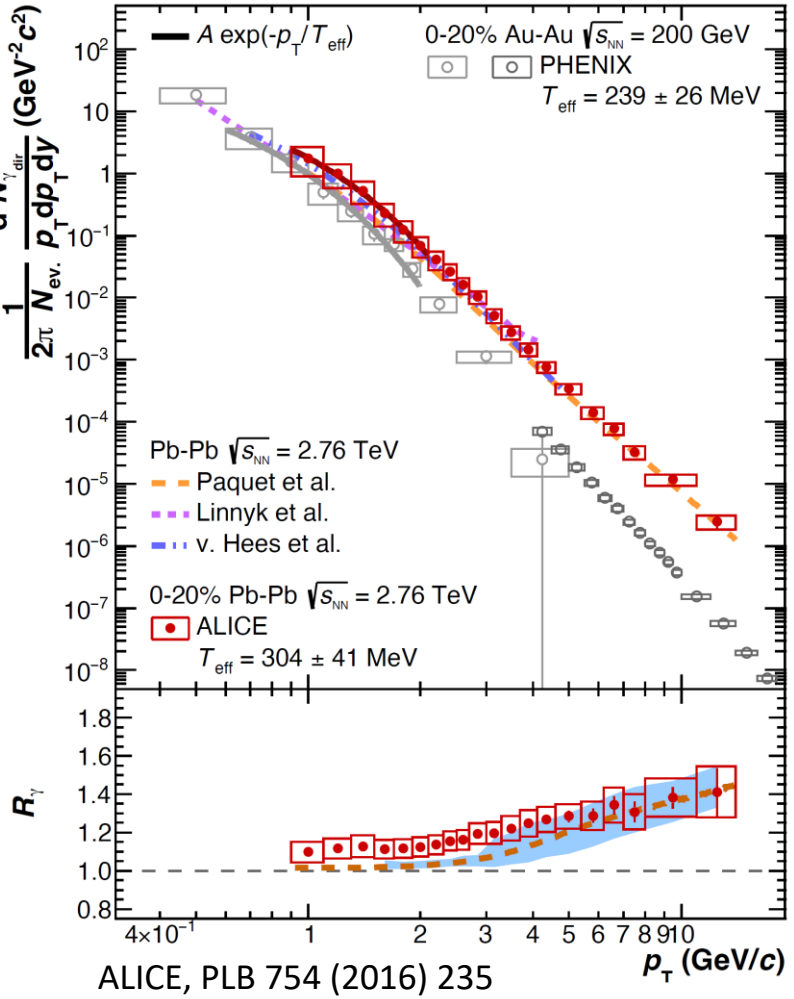
Global properties



ALICE, EPJC 79 (2019) 307



ALICE, arXiv:2204.10210

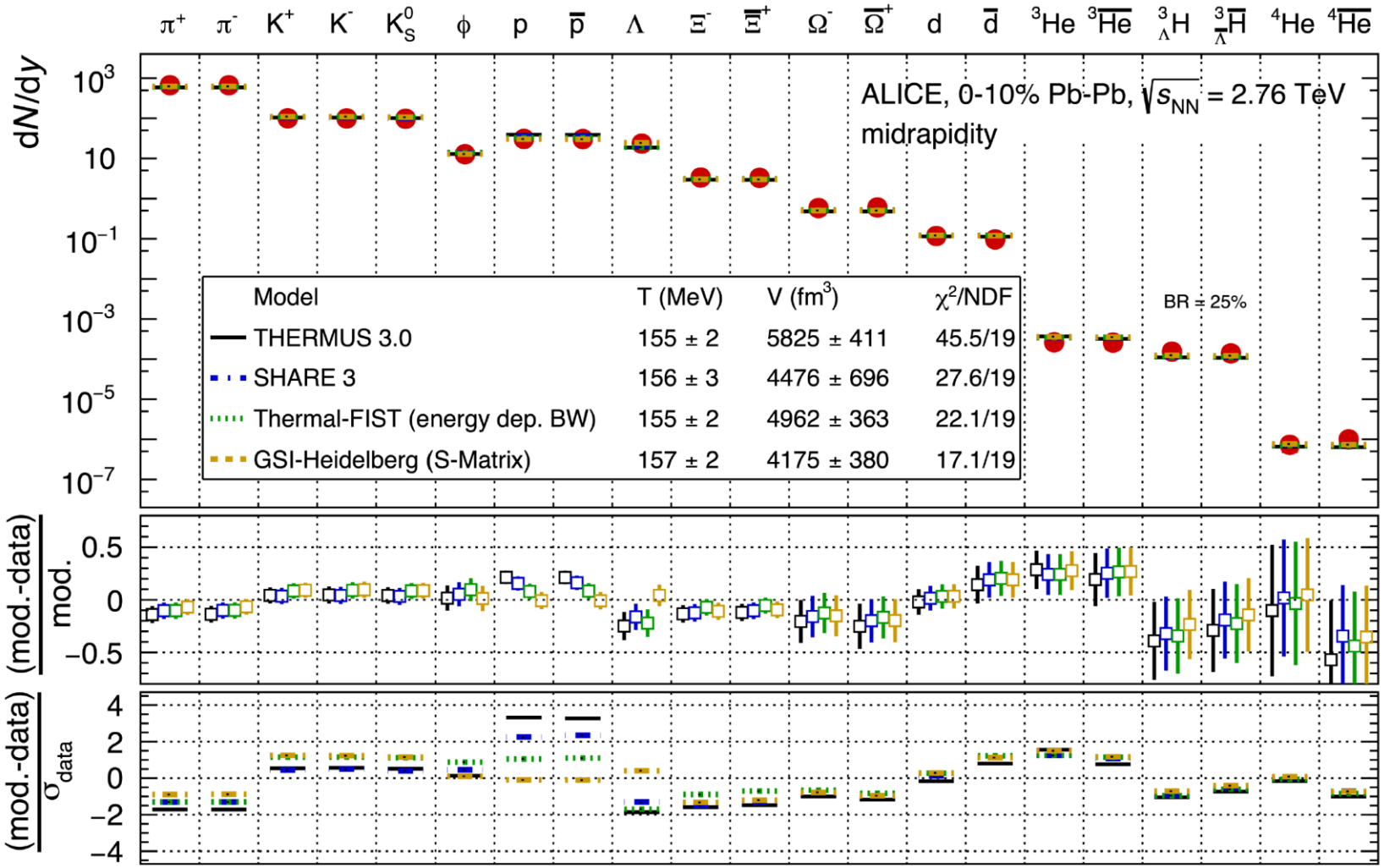


ALICE, PLB 754 (2016) 235

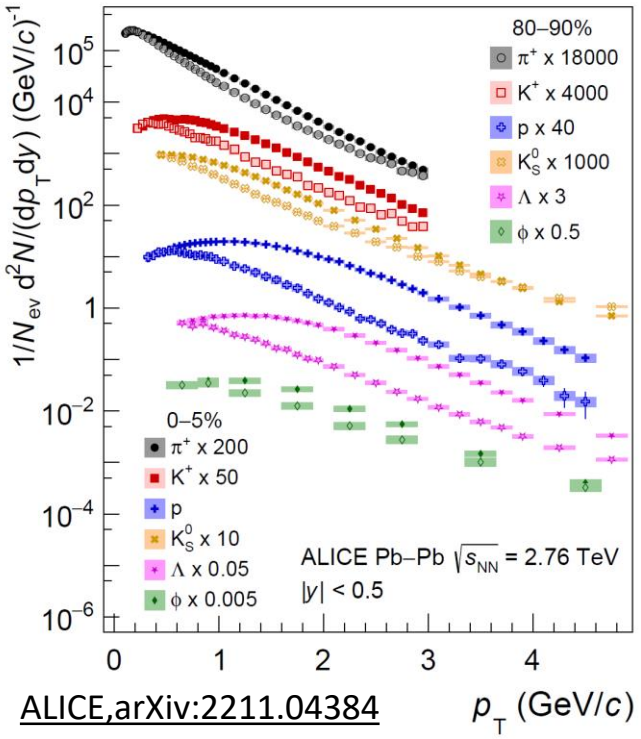
- Charged hadron production per nucleon maximal in Pb-Pb at the LHC
- Initial energy density in central Pb-Pb collisions is 30 times larger than ε_c!
- Effective photon temperature T_{eff} = 304 ± 41 MeV twice larger than T_c ~ 160 MeV

ALICE,arXiv:2211.04384

Light flavour spectra



ALICE,arXiv:2211.04384

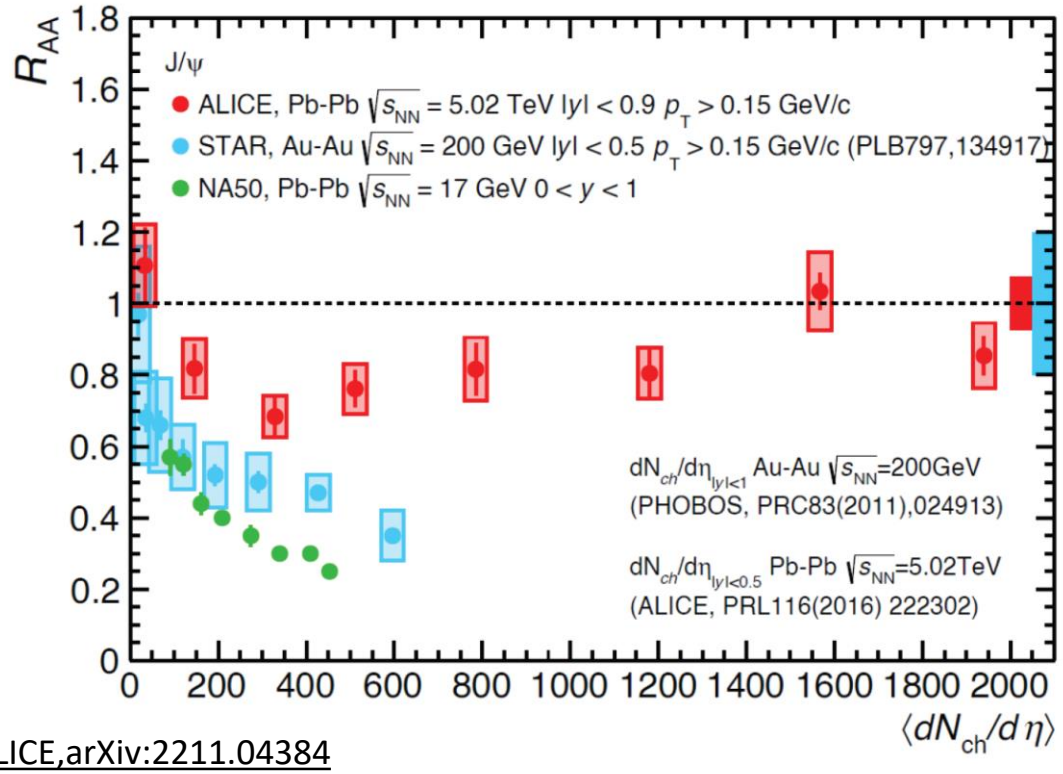


ALICE,arXiv:2211.04384

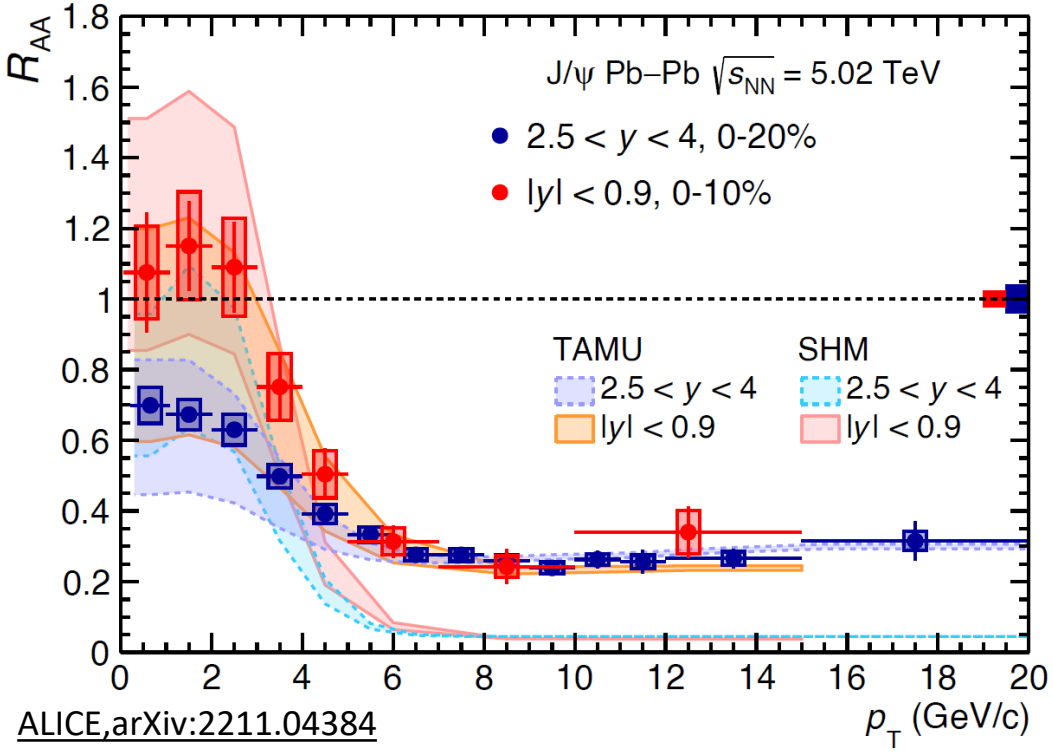
- Hadron yields described by statistical hadronization models over many orders of magnitude
- Chemical equilibrium close to QGP transition temperature

$T_{chem} \approx T_c \approx 156$ MeV

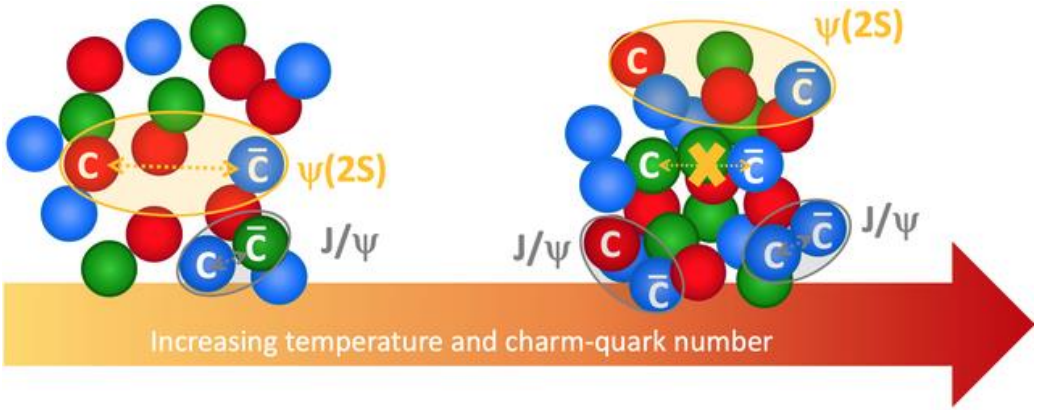
Charmonium melting and regeneration



ALICE,arXiv:2211.04384

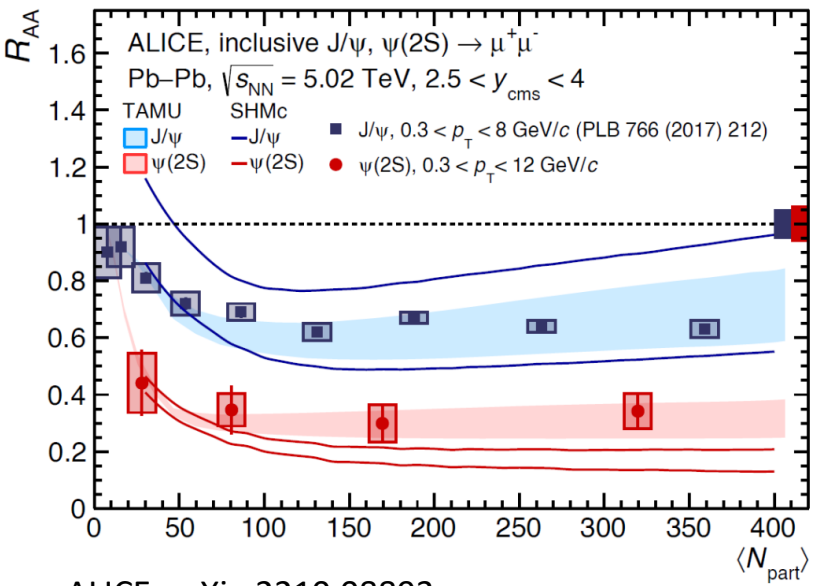


ALICE,arXiv:2211.04384

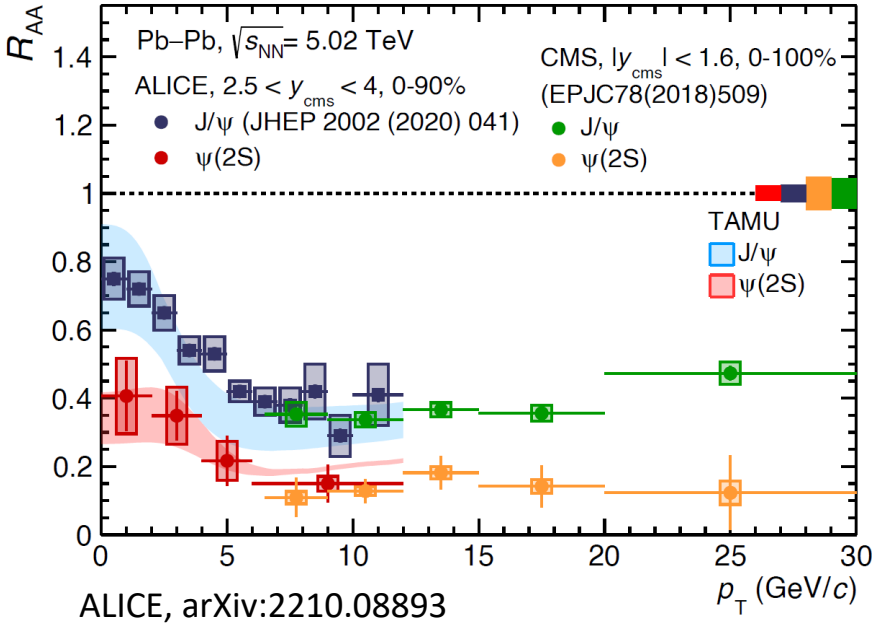


- Interplay of melting and regeneration effects
- Large regeneration effects at the LHC due to much larger charm cross section compared to RHIC/SPS
- Larger regeneration effects at midrapidity and at low p_T

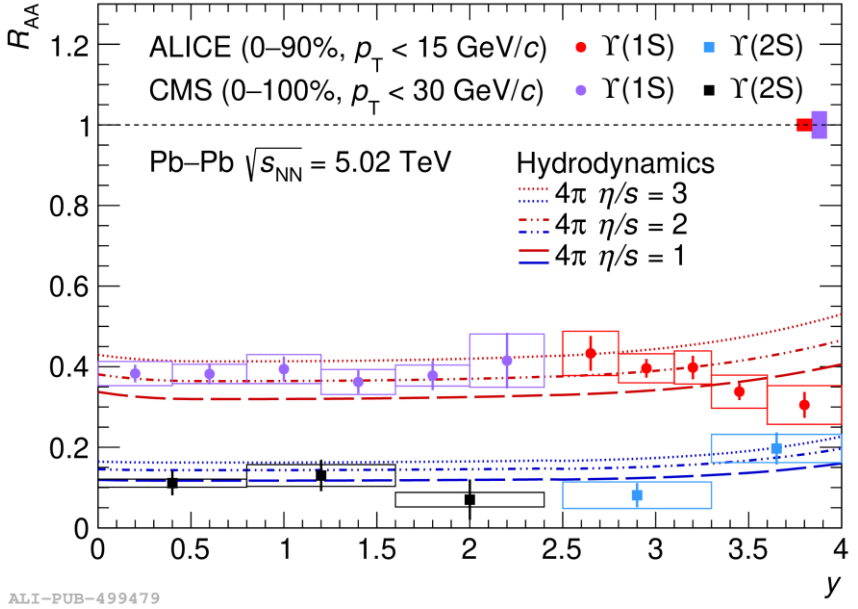
Excited quarkonium states



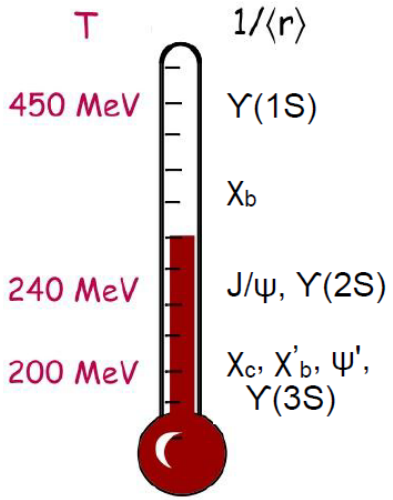
ALICE, arXiv:2210.08893



ALICE, arXiv:2210.08893

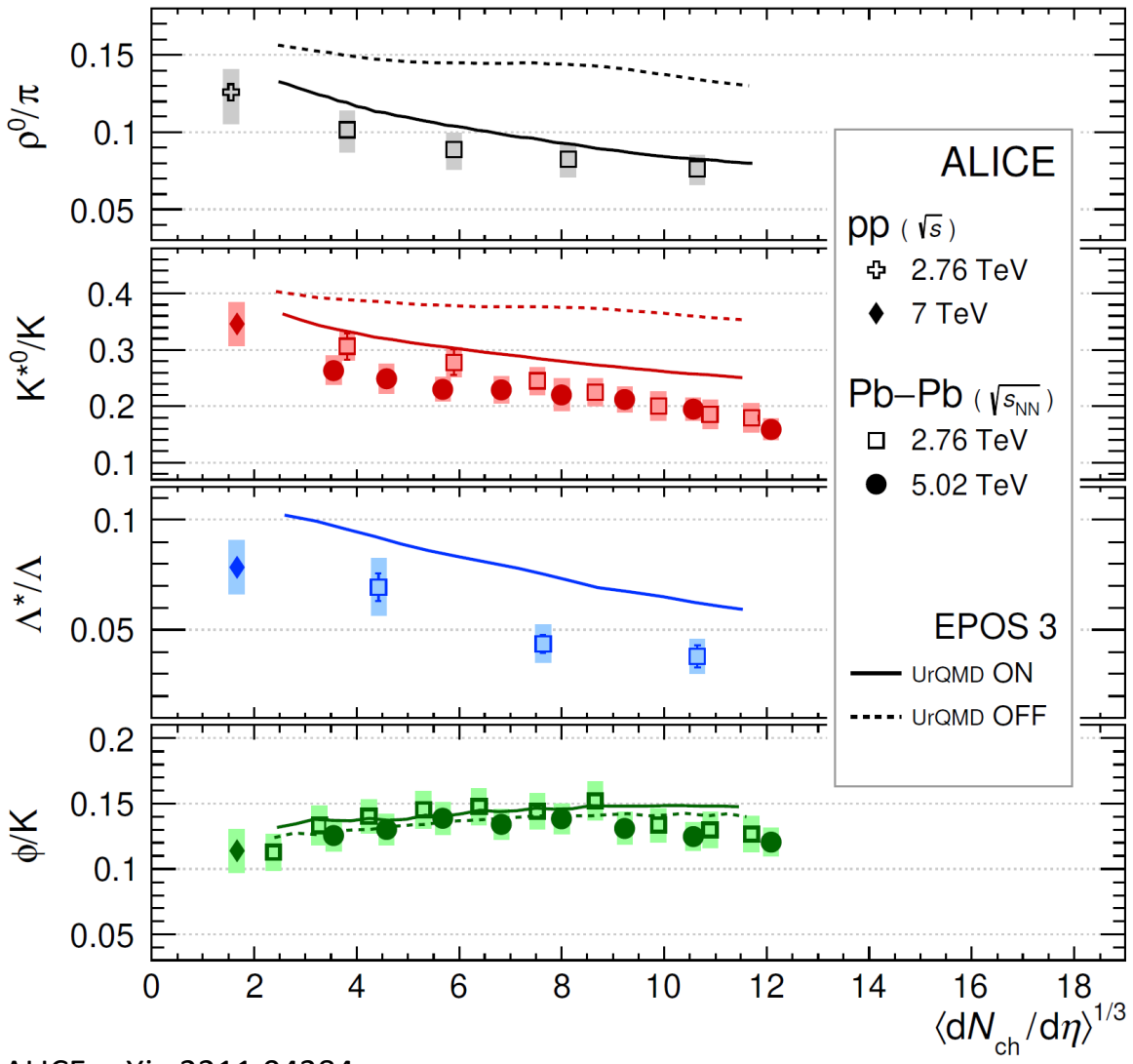


ALICE, Phys. Lett. B 822 (2021) 136579

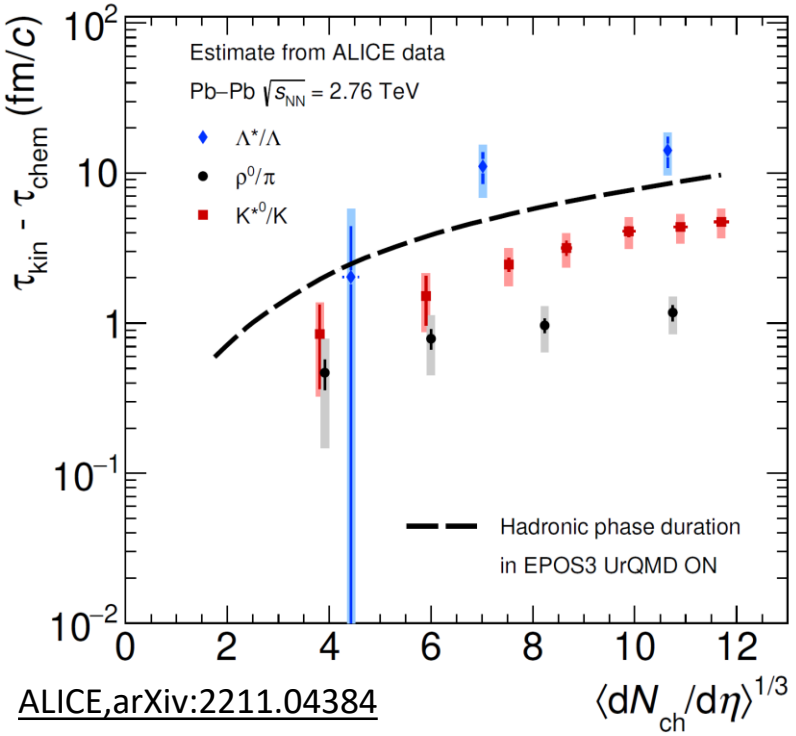


- Different states have different binding energies. Loosely bound states melt first!
- Sequential suppression of individual states provides a "thermometer" of the QGP
- Charmonium: sequential suppression + regeneration effects
- Bottomonium: sequential suppression

Probing hadronic phase with resonances



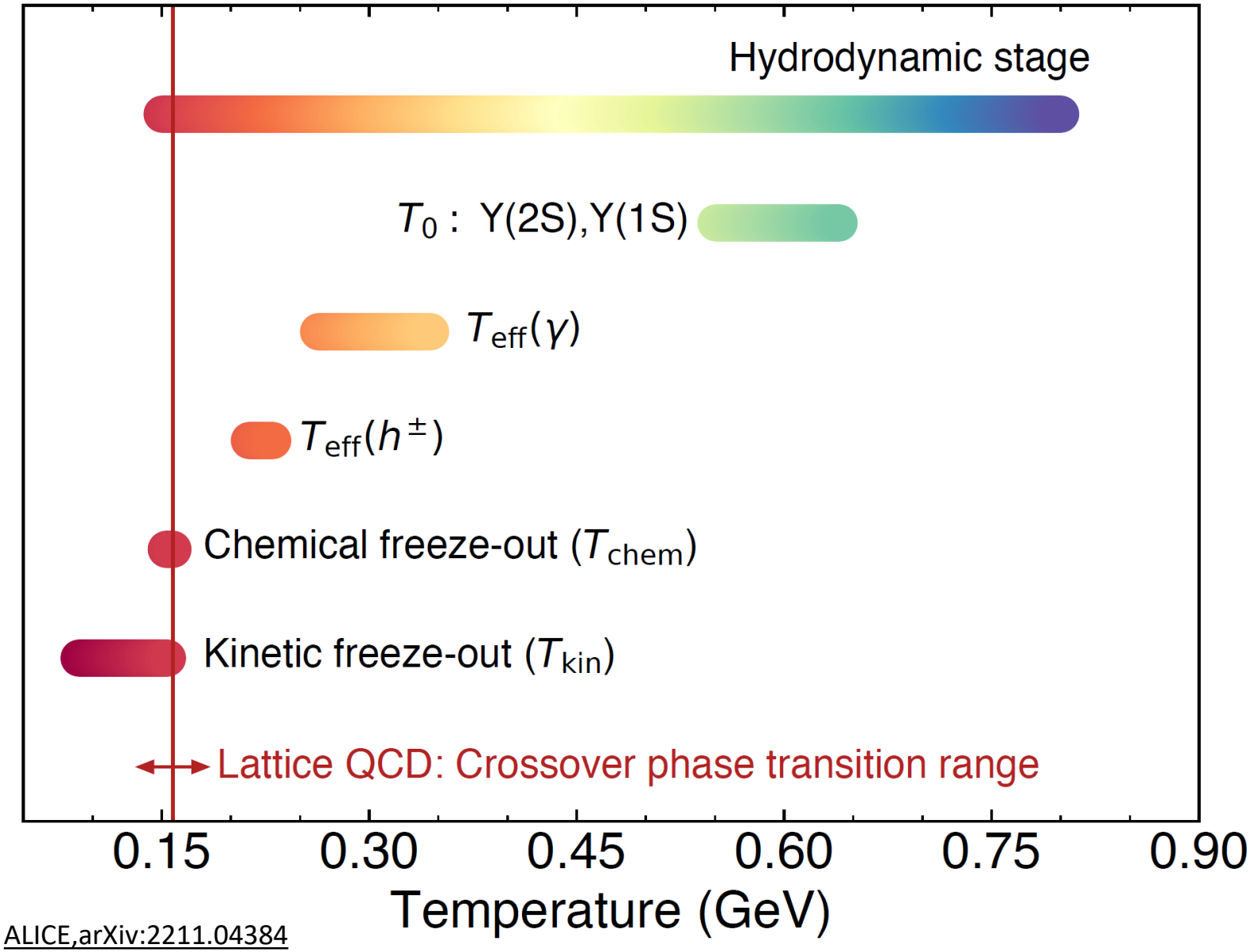
ALICE,arXiv:2211.04384



ALICE,arXiv:2211.04384

- 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?

Temperature scales

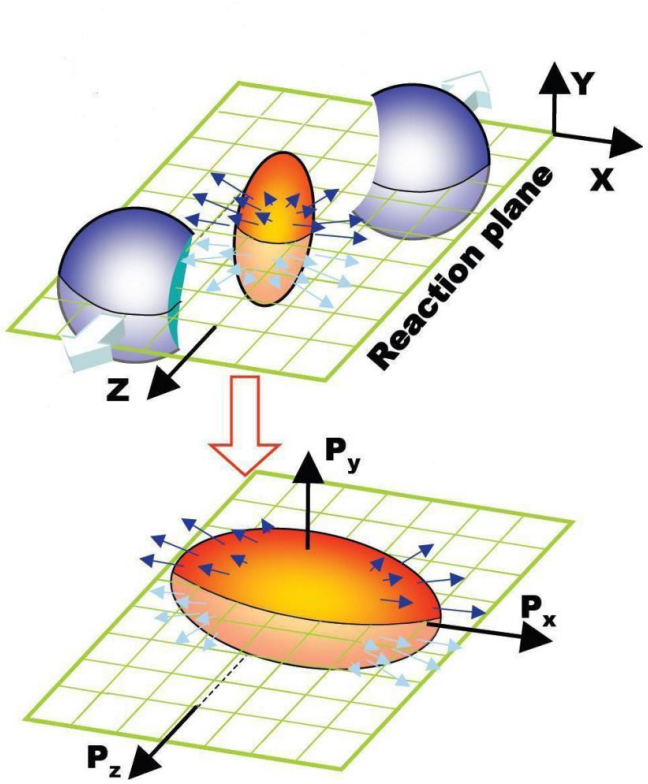


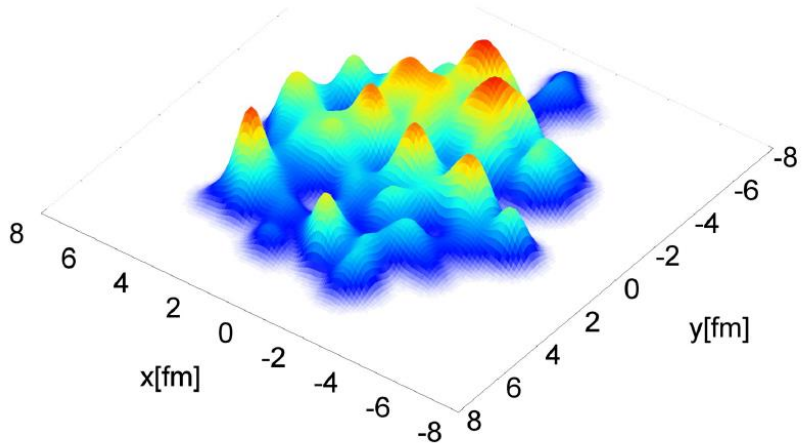
ALICE,arXiv:2211.04384

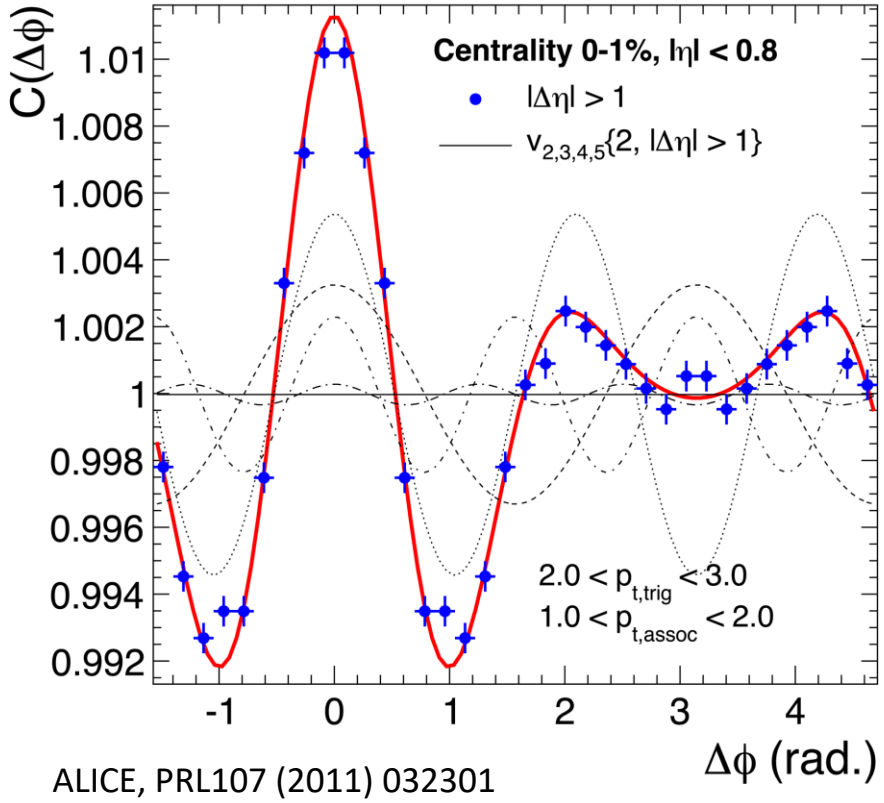
Many observables imply temperatures far greater than T_c

- Sequential melting of quarkonium states
- Effective thermal photon T ~ $2T_c$
- Chemical freeze-out ~ T_c

Anisotropic flow





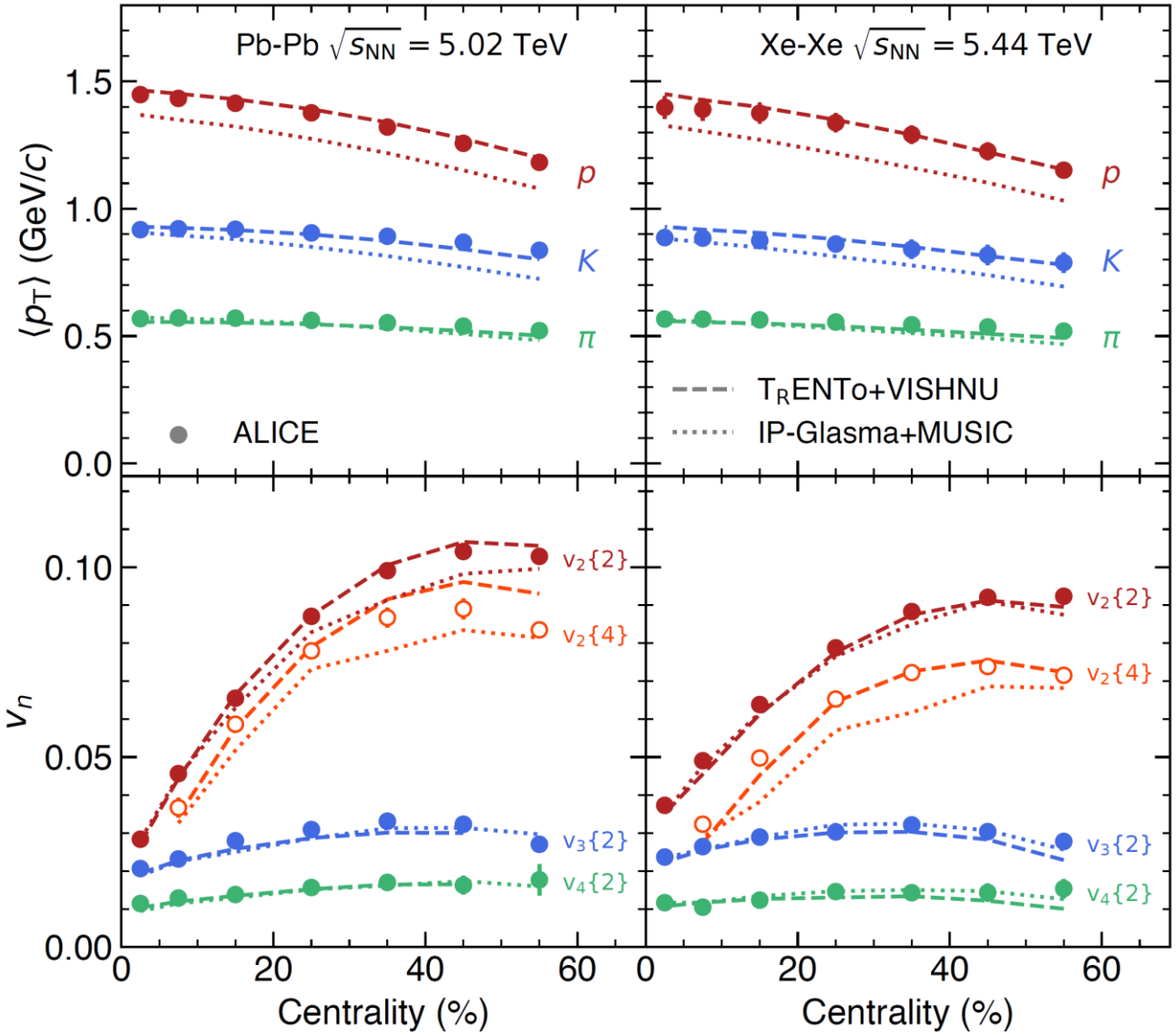


ALICE, PRL107 (2011) 032301

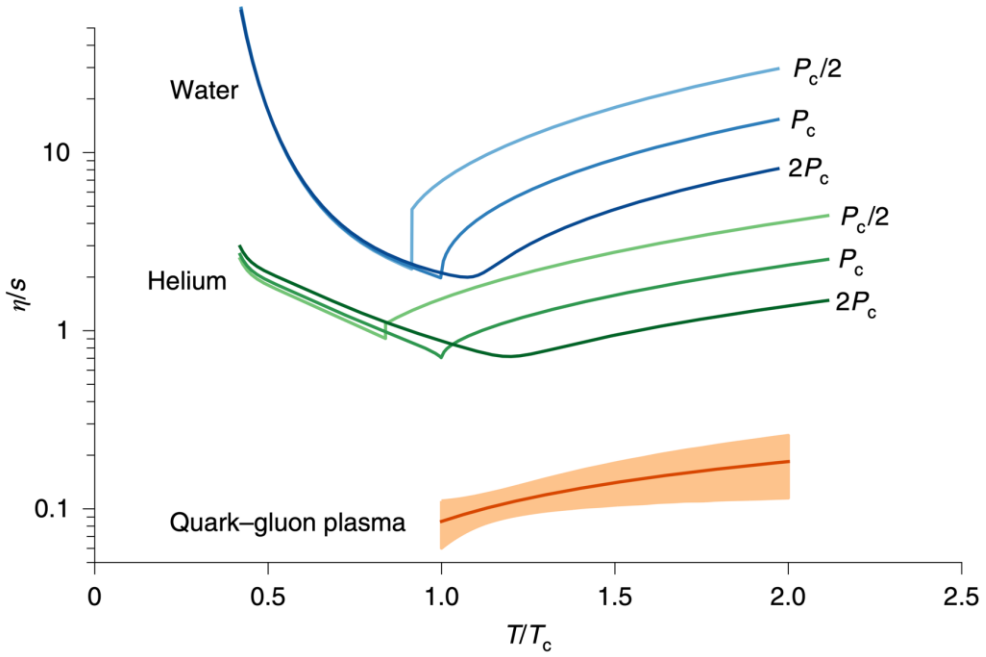
- Spatial anisotropy and density fluctuations of the initial state induce momentum anisotropy via QGP response
- Characterised by anisotropic flow coefficients v_n

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos\left(n(\phi - \Psi_n)\right)$$

QGP properties from anisotropic flow



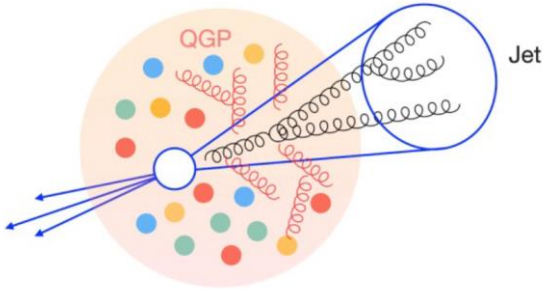
ALICE,arXiv:2211.04384

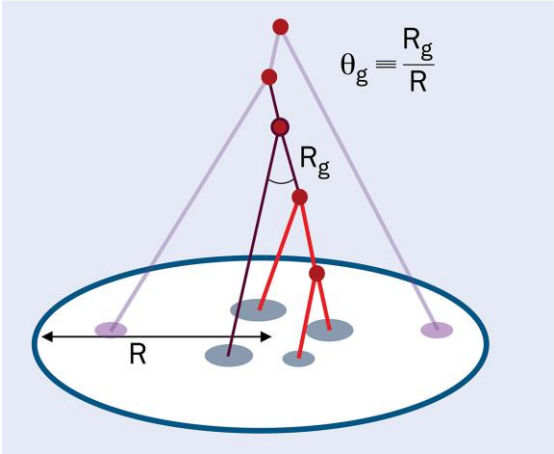


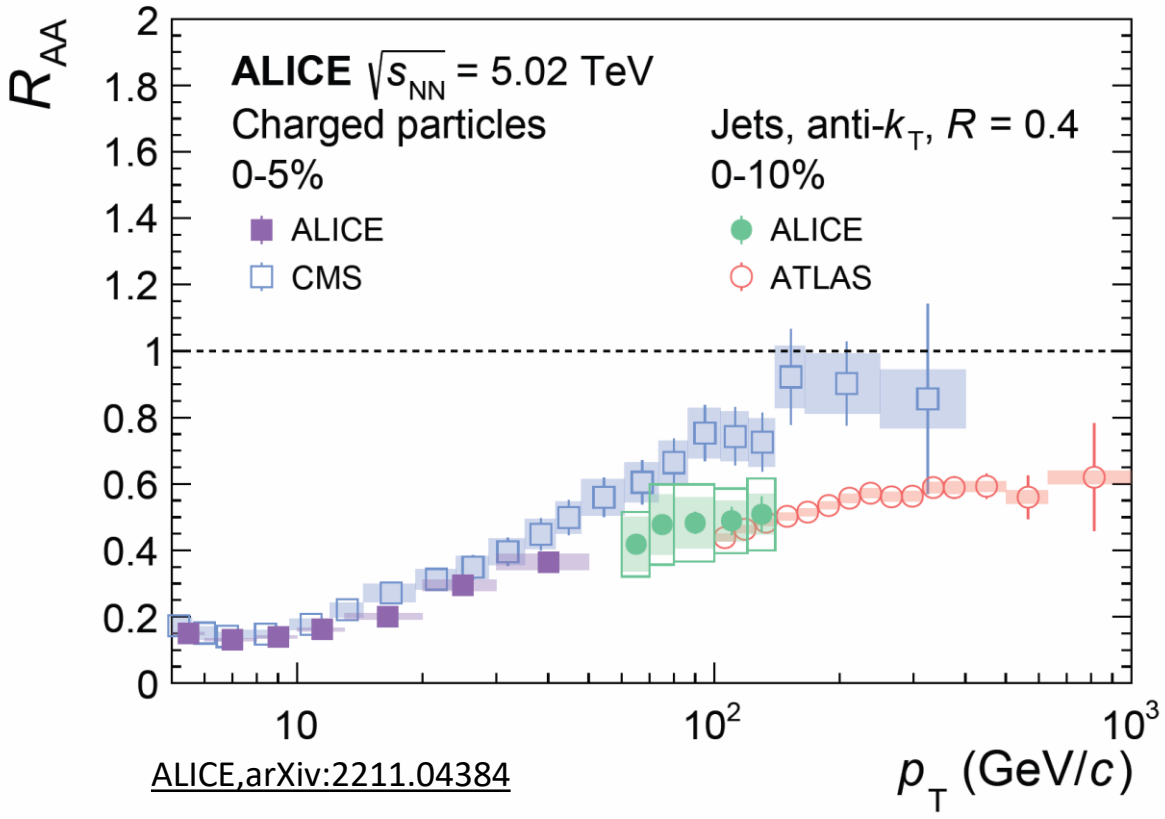
ALICE,arXiv:2211.04384

- Global radial and anisotropic expansion of QGP described by hydrodynamical equation of state with small viscosity close to Ads/CFT limit
- QGP is strongly coupled at this temperature scale

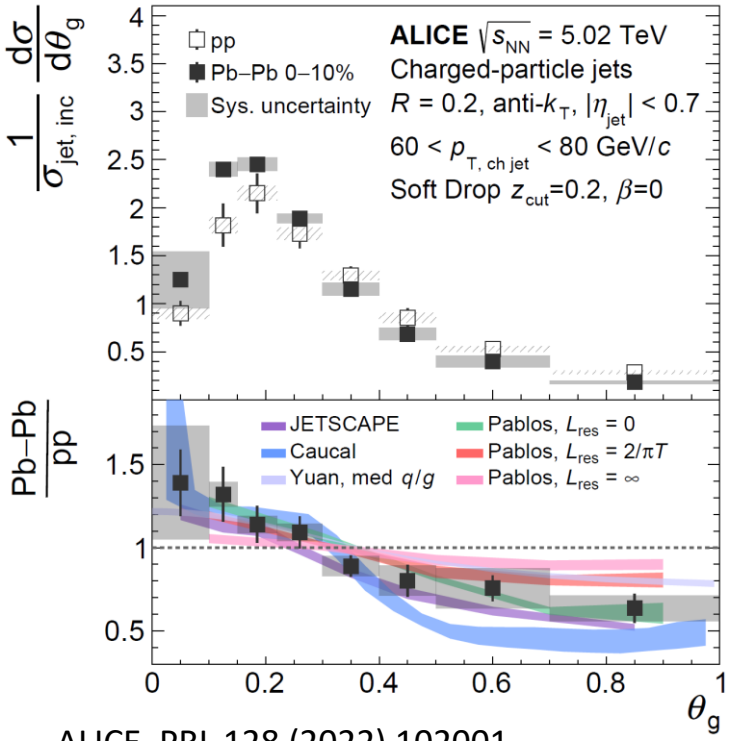
Hard probes







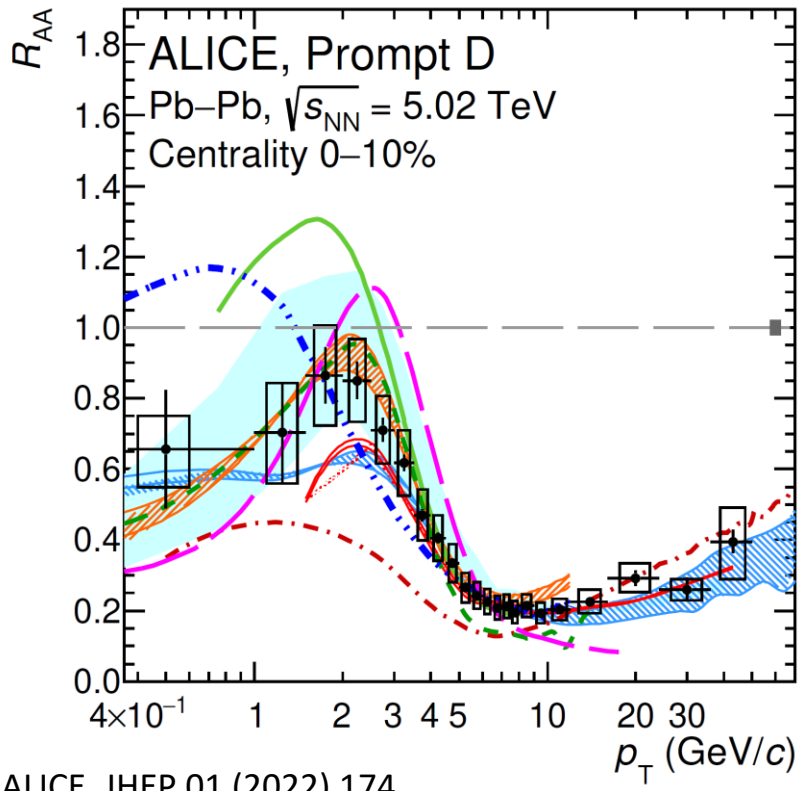
ALICE,arXiv:2211.04384



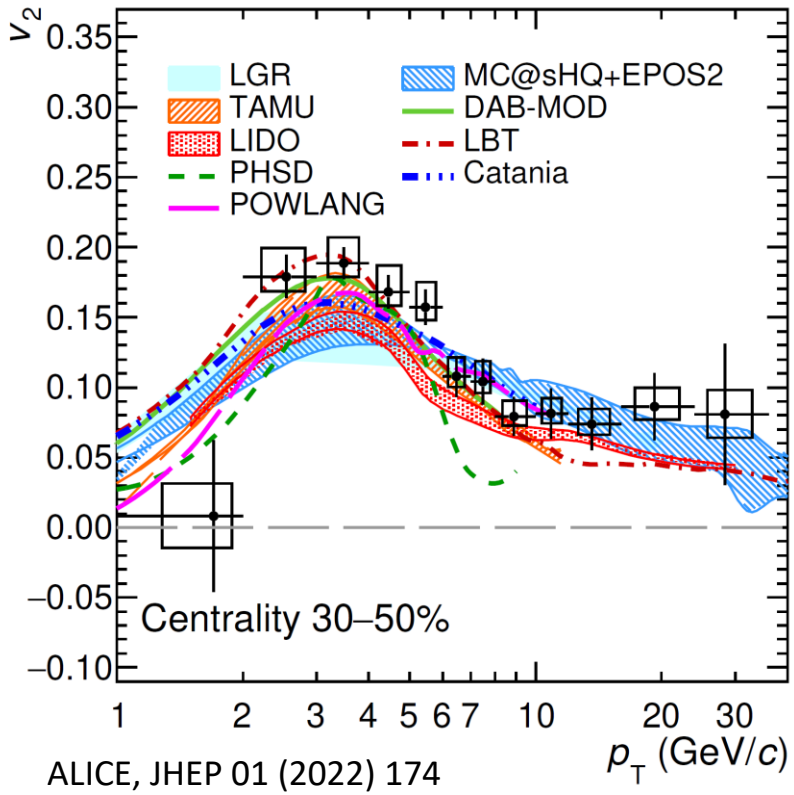
ALICE, PRL 128 (2022) 102001

- Jet and high p_T hadron suppression observed over extensive range
- Explained by energy loss of hard partons interacting with QGP medium
  - Dominated by radiative emission. Extracted energy loss: 8 ± 2 GeV
- Pb-Pb jet substructure narrower than pp
  - Energy loss mechanisms suppress wider angle jets

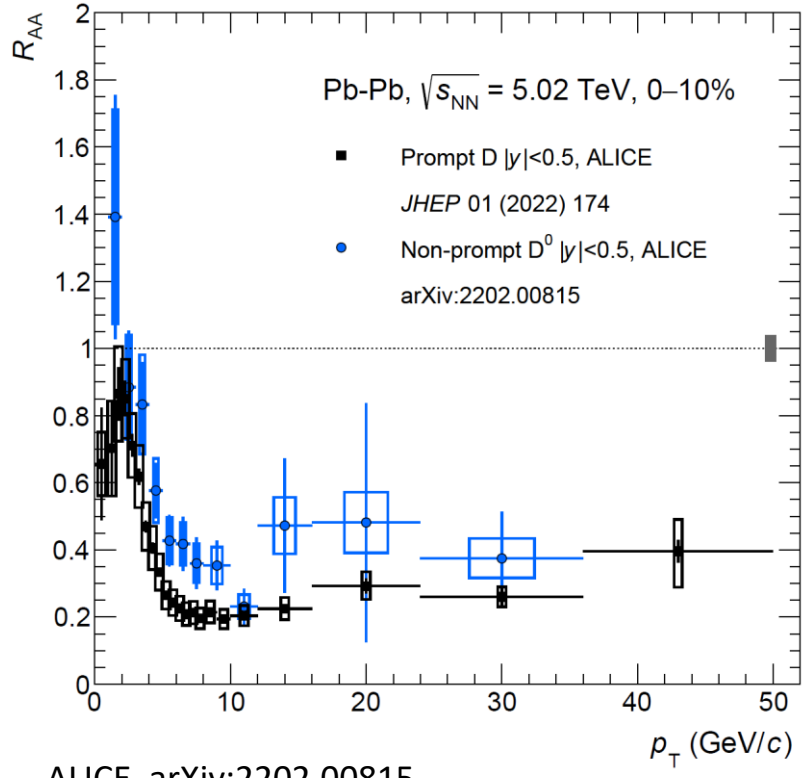
Heavy flavours



ALICE, JHEP 01 (2022) 174



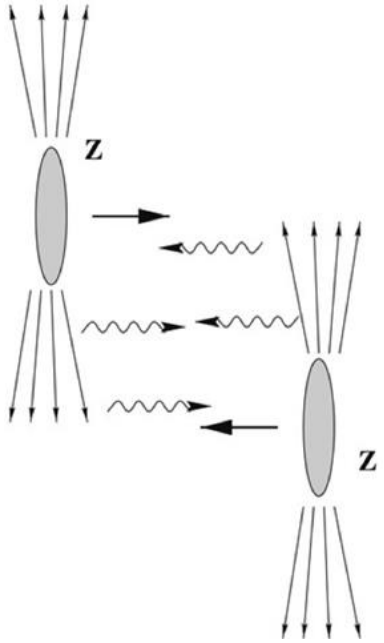
ALICE, JHEP 01 (2022) 174



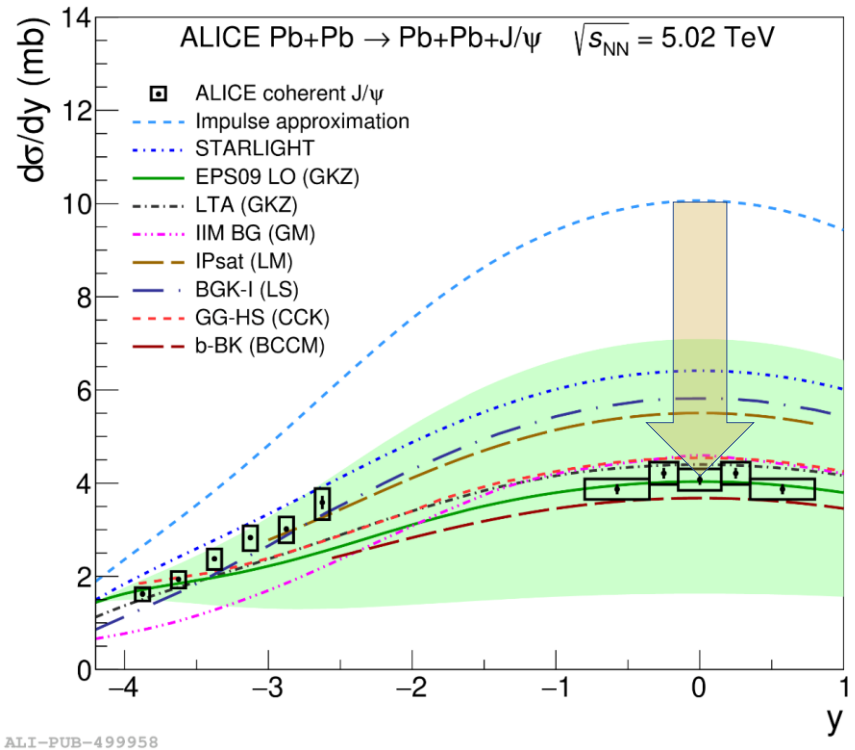
ALICE, arXiv:2202.00815

- D-meson spectra measured down to 0 p_T
- Most charm-quark transport models describe both the R_{AA} and anisotropic flow (v_2)
- D mesons from bottom decays are less suppressed than those formed from charm
  - Indication of mass dependent radiative losses in agreement with expectations from QCD

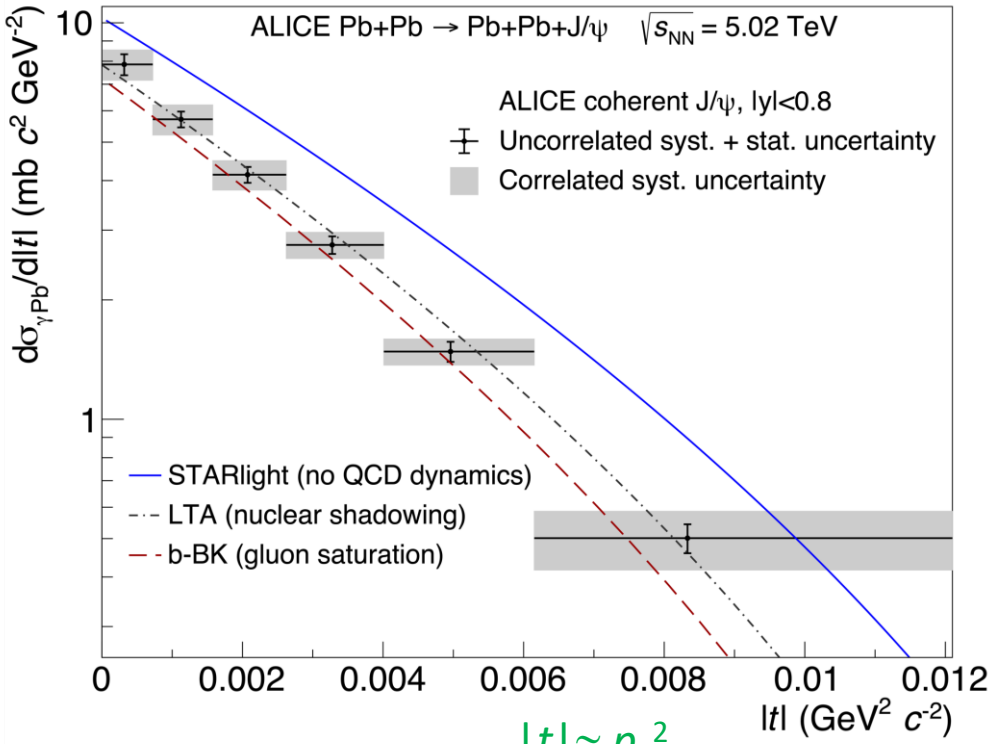
Initial state with ultra-peripheral collisions



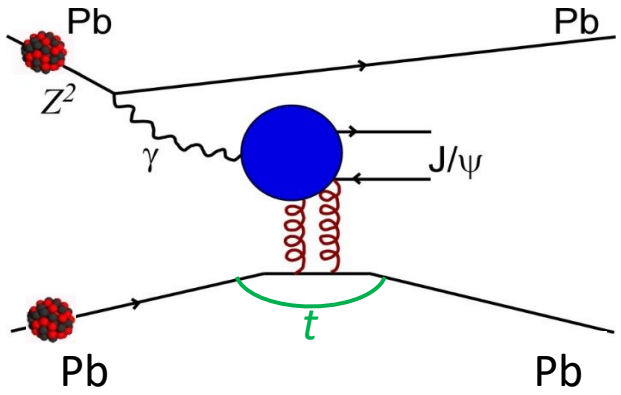
ALICE, PLB 798 (2019) 134926,PLB 817 (2021) 136280



ALICE, EPJC 81 (2021) 8, 712

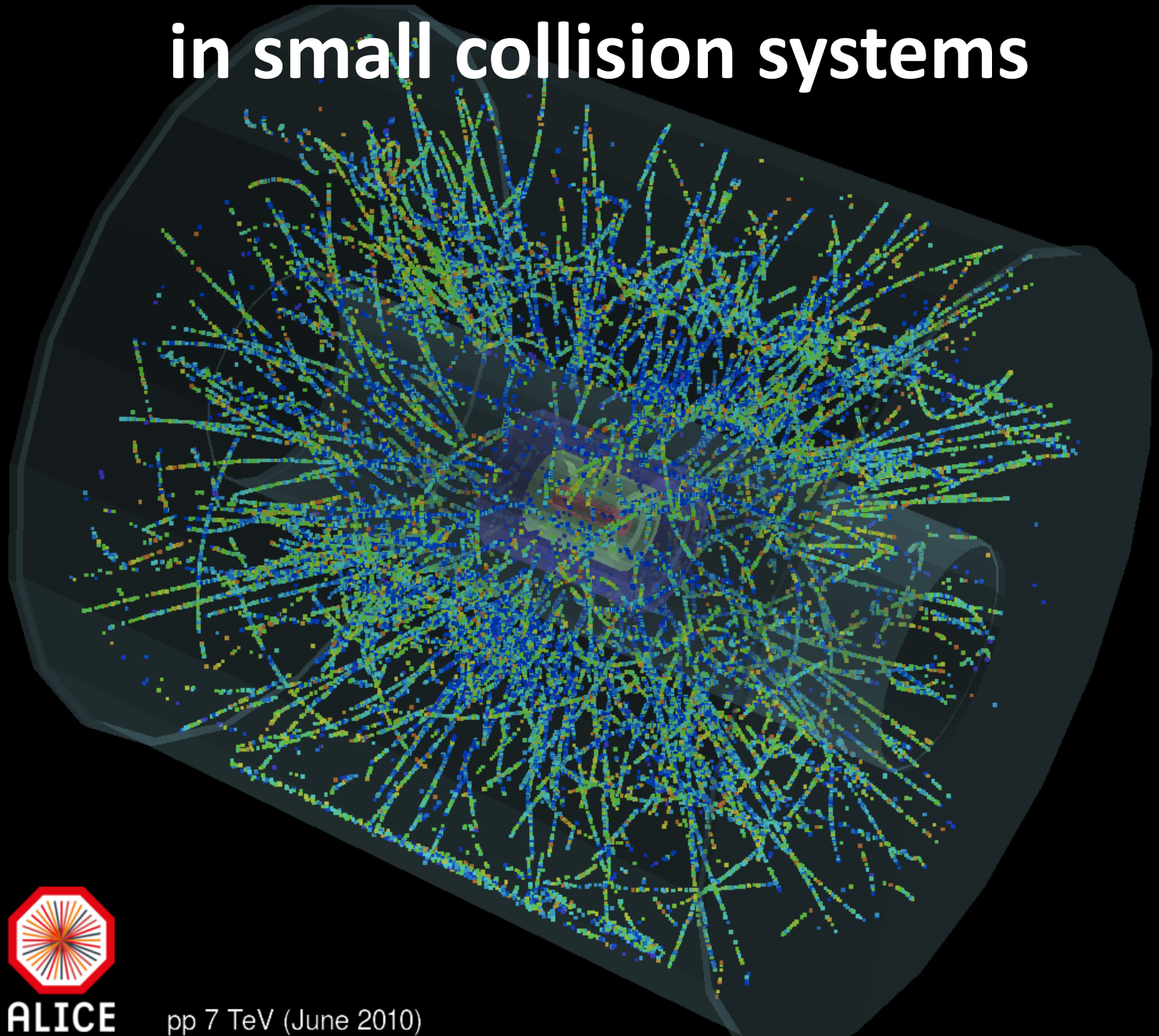


$|t| \approx p_T^2$



- Probing low-x gluon PDFs in the nucleus
- Comparison with the impulse approximation (no nuclear effects) allows for extraction of the gluon shadowing factor: $R_g \sim 0.65$ at $x \sim 10^{-3}$
- *t*-dependence is sensitive to transverse gluon distribution

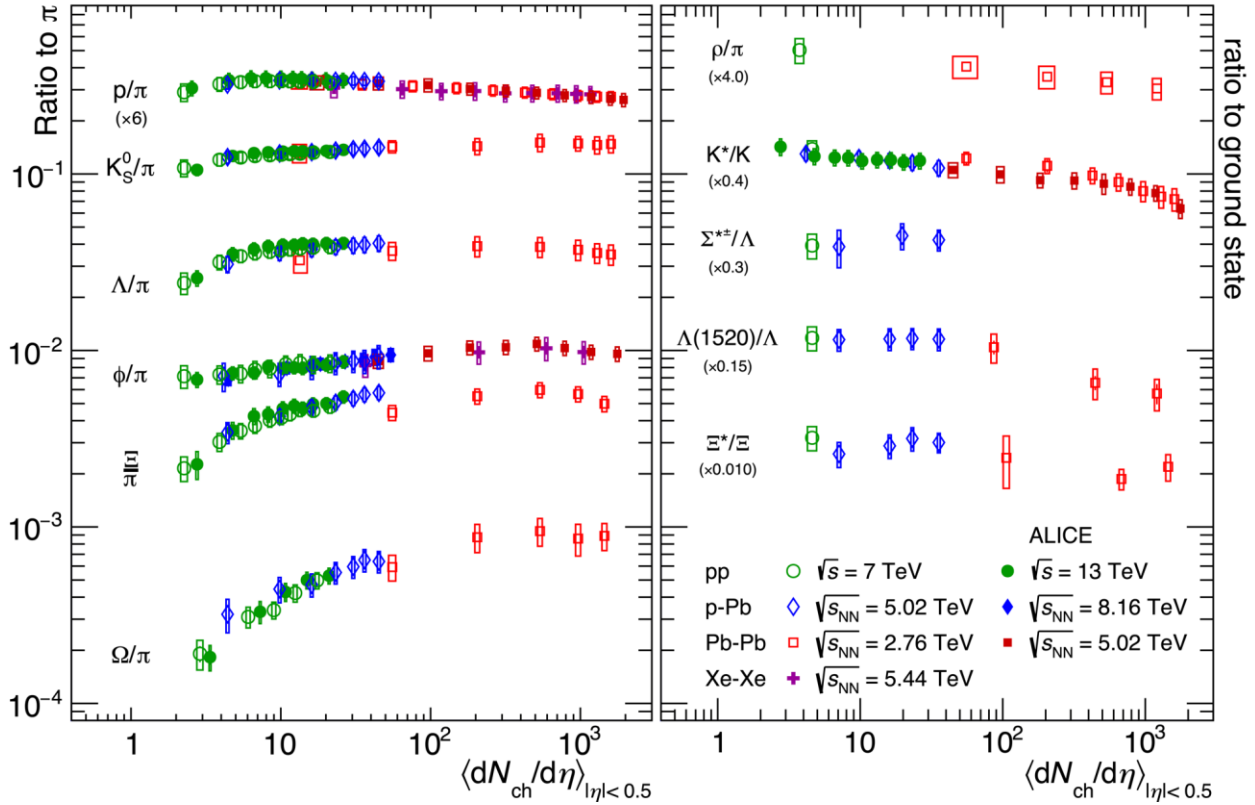
QGP-like effects in small collision systems

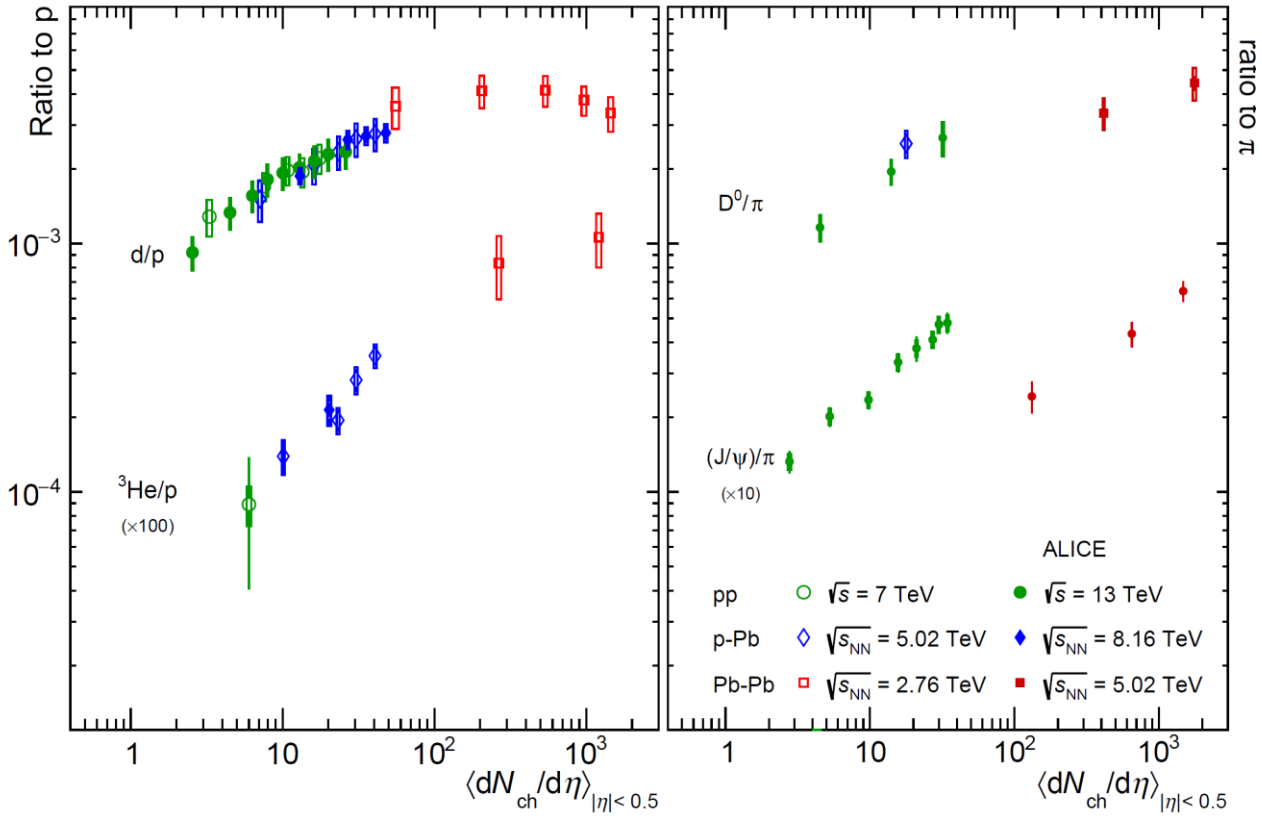


ALICE

pp 7 TeV (June 2010)

Enhancement of particle yields

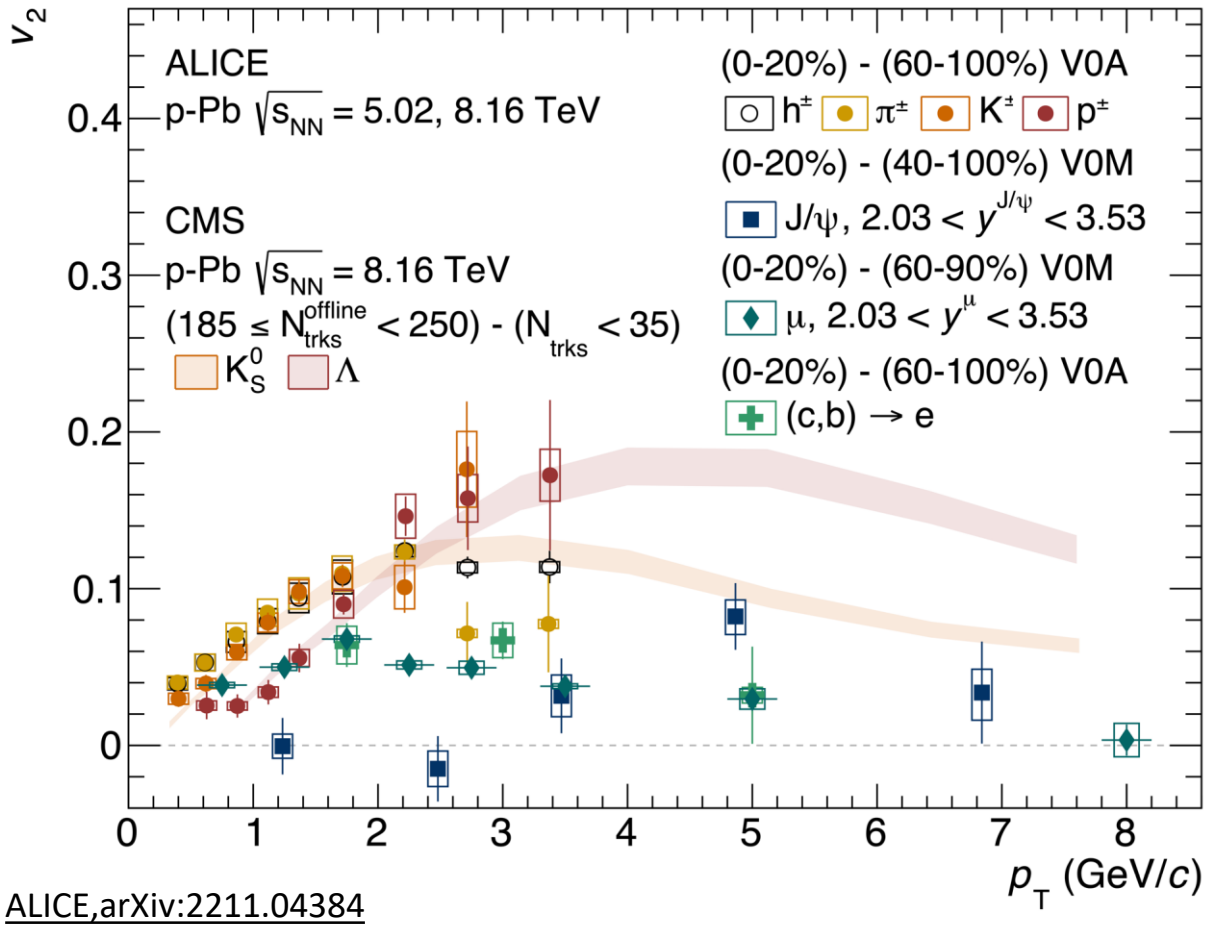




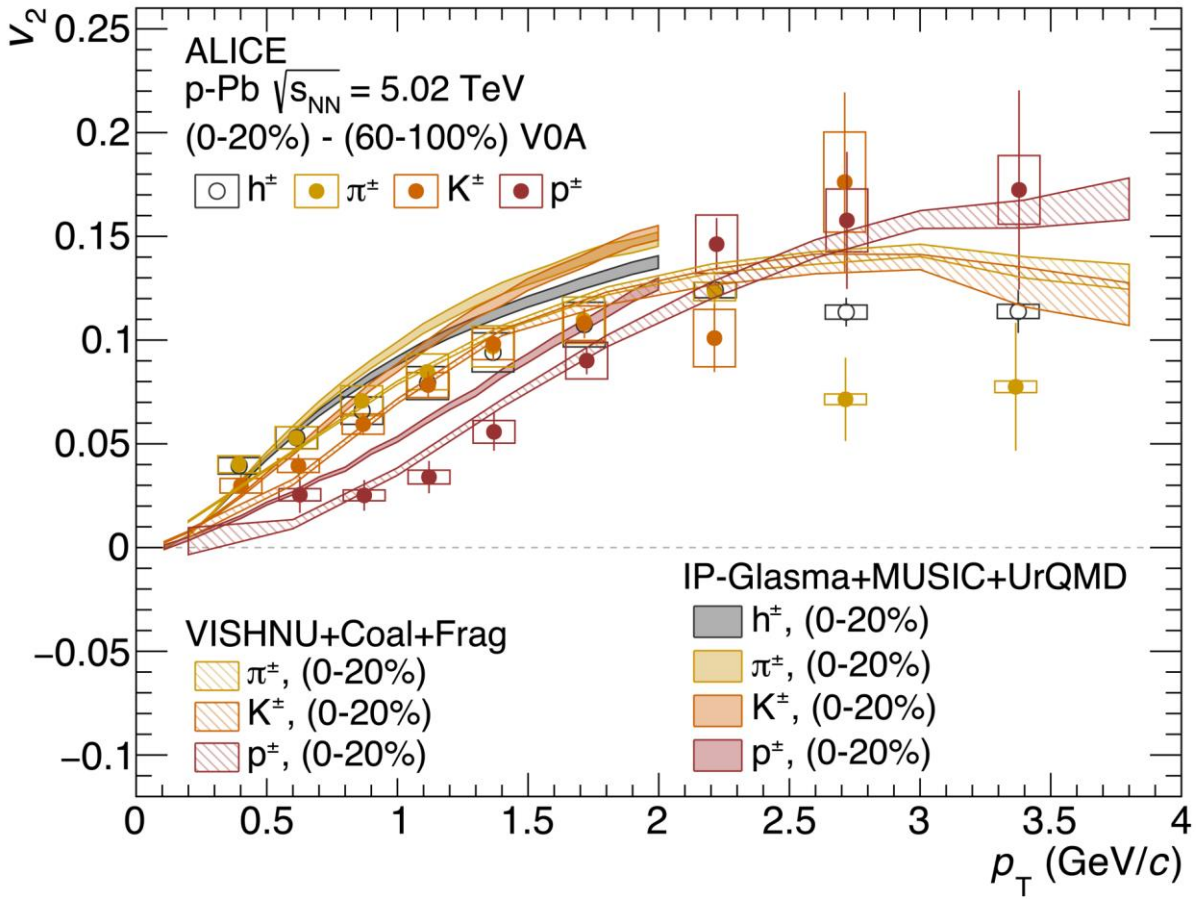
ALICE,arXiv:2211.04384

- Yields of strange and charm particles relative to pions increase with multiplicity
- Same trend for light nuclei relative to protons
- Reaching highest multiplicity ratios comparable with Pb-Pb
- Non-QGP effects playing a role?

Flow in small systems



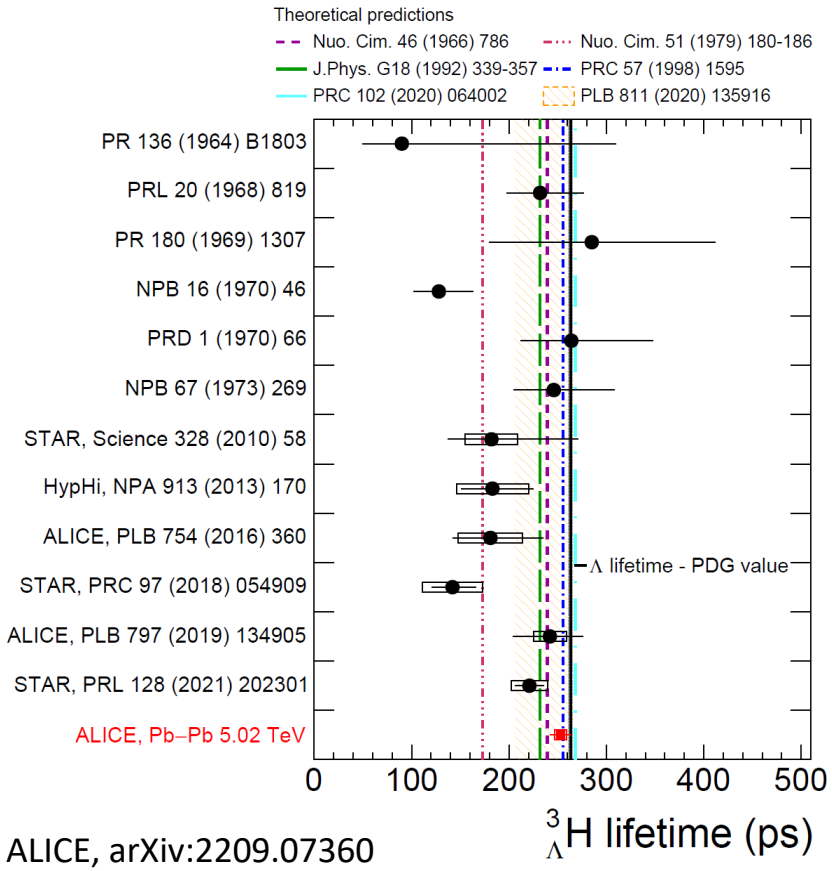
ALICE,arXiv:2211.04384



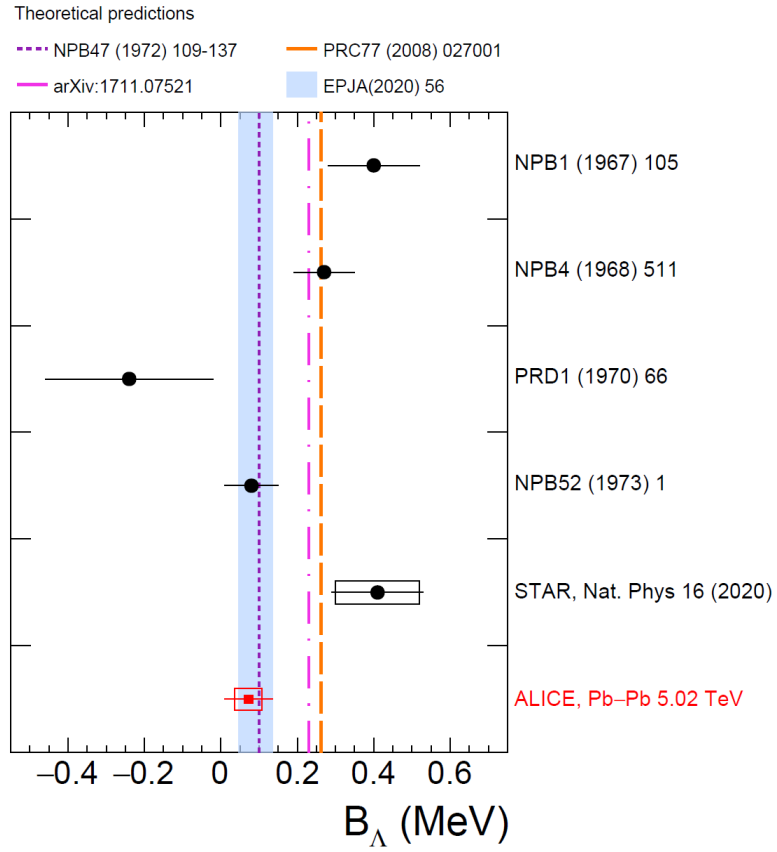
- Light and charmed hadrons exhibit anisotropic flow in small systems
- Light sector described by hydrodynamics with QGP equation of state

QCD aspects beyond QGP

Hypertriton lifetime



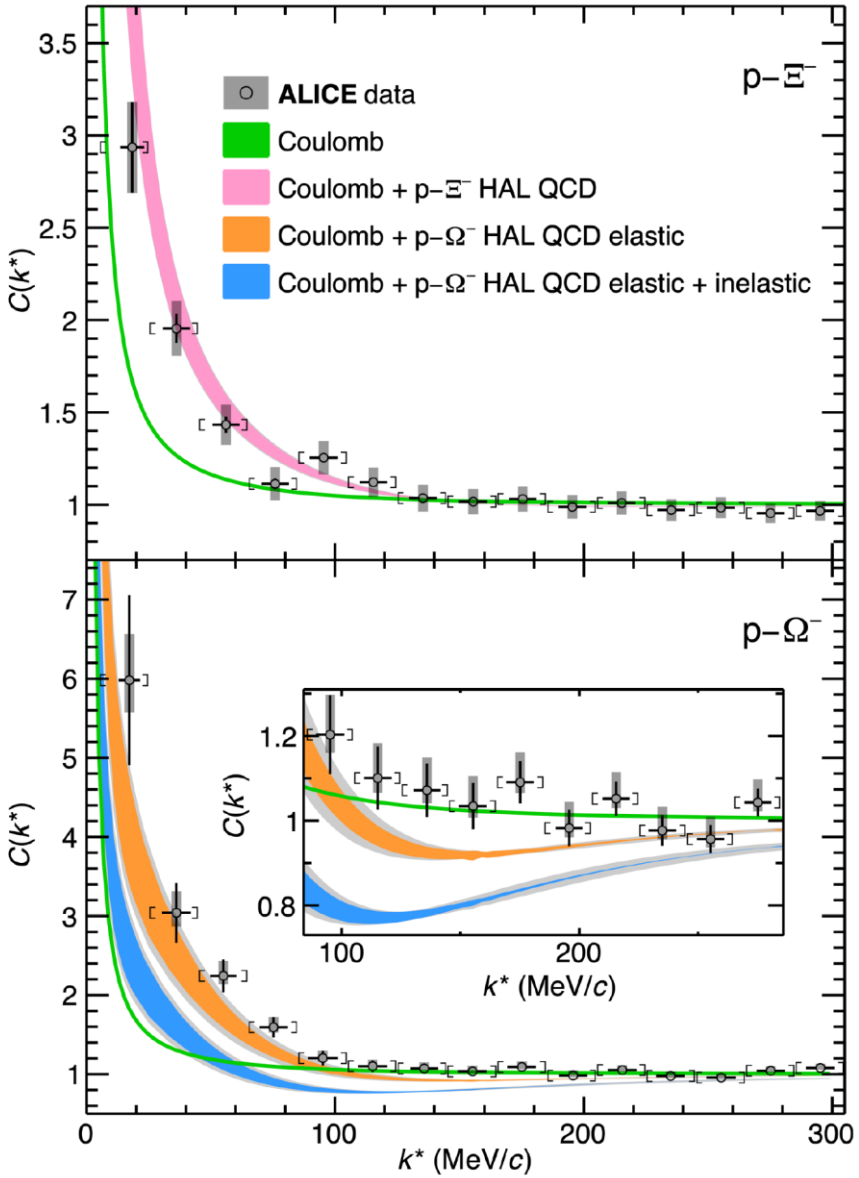
ALICE, arXiv:2209.07360

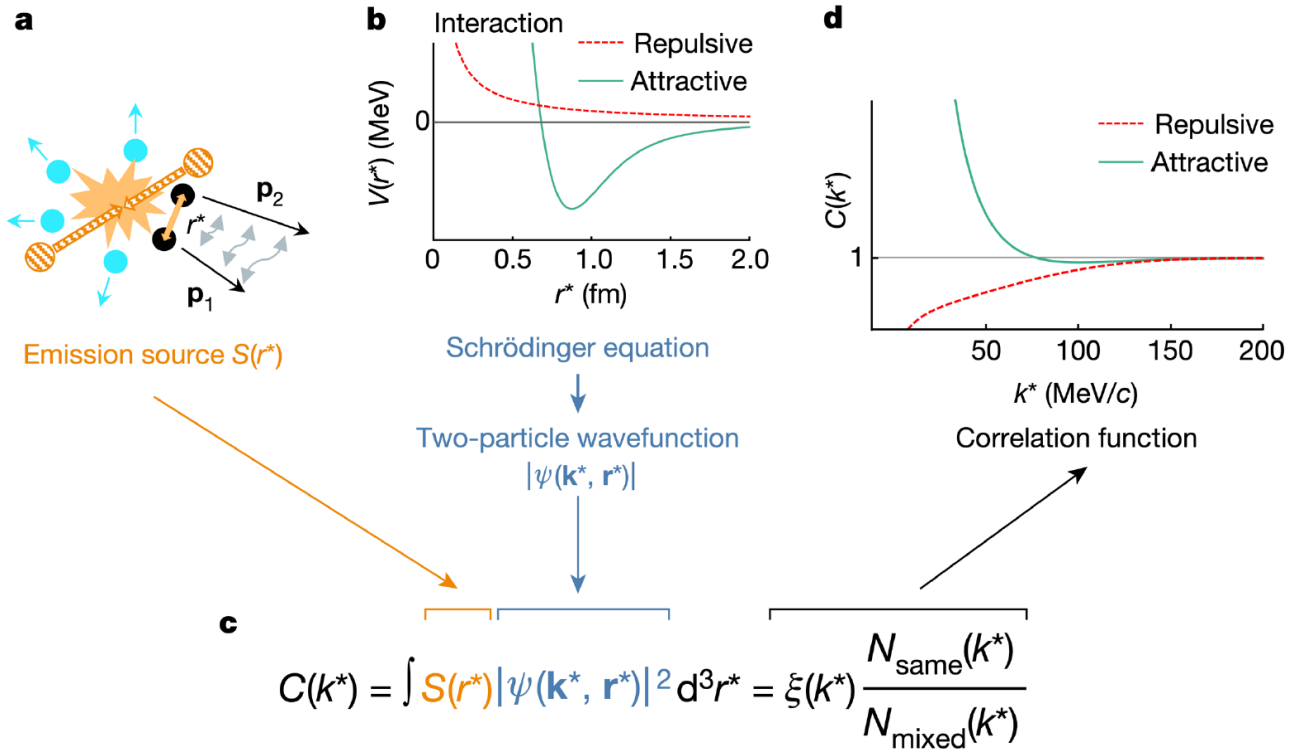


- Unprecedented precision with Pb-Pb Run 2 data
- No deviation from the free Λ lifetime
- Binding energy = 130 ± 30 keV, one of the smallest binding energies observed

  → loosely bound d-Λ molecule
- Produced in Pb-Pb collisions, despite having size comparable to medium (~10 fm)

Probing proton-hyperon interactions

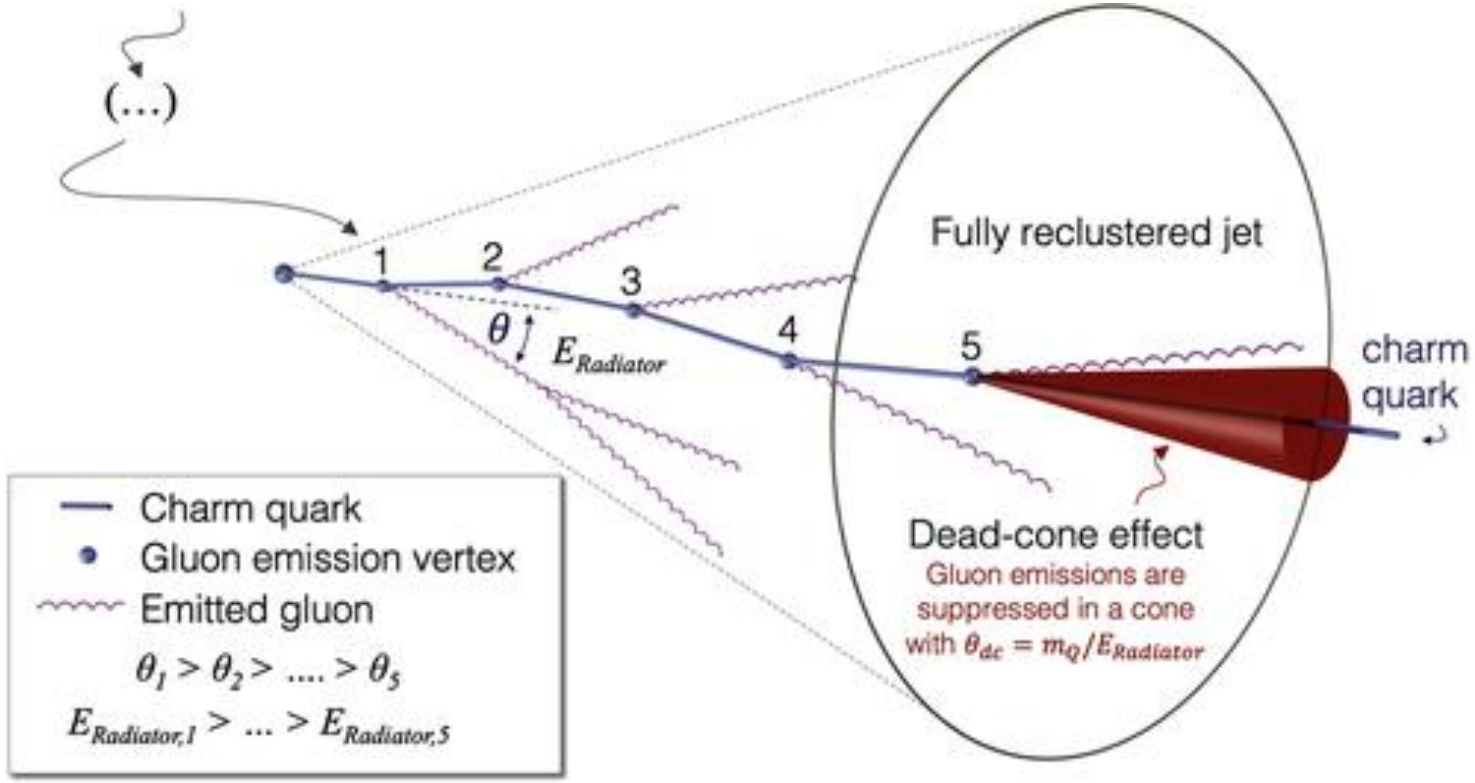


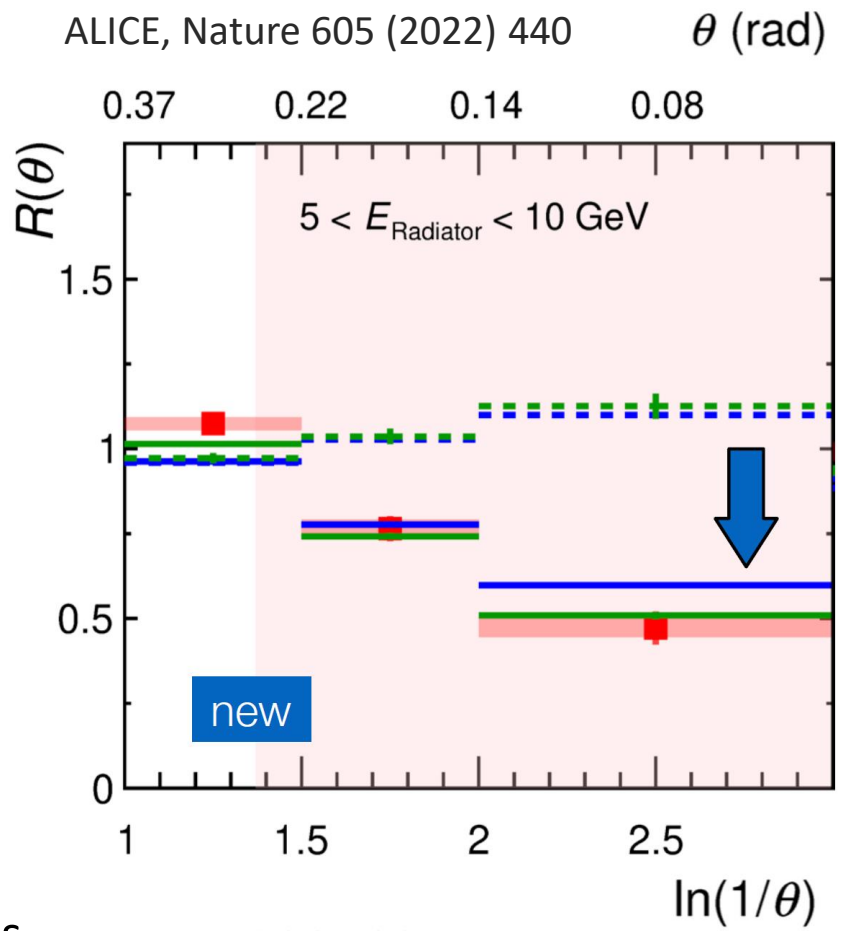


- Large production of hyperons provides unique opportunity to study rare hadronic interactions via femtoscopy measurements
- Strength of proton-hyperon interaction important for equation of state at high density → neutron stars

ALICE, Nature 588 (2020) 232

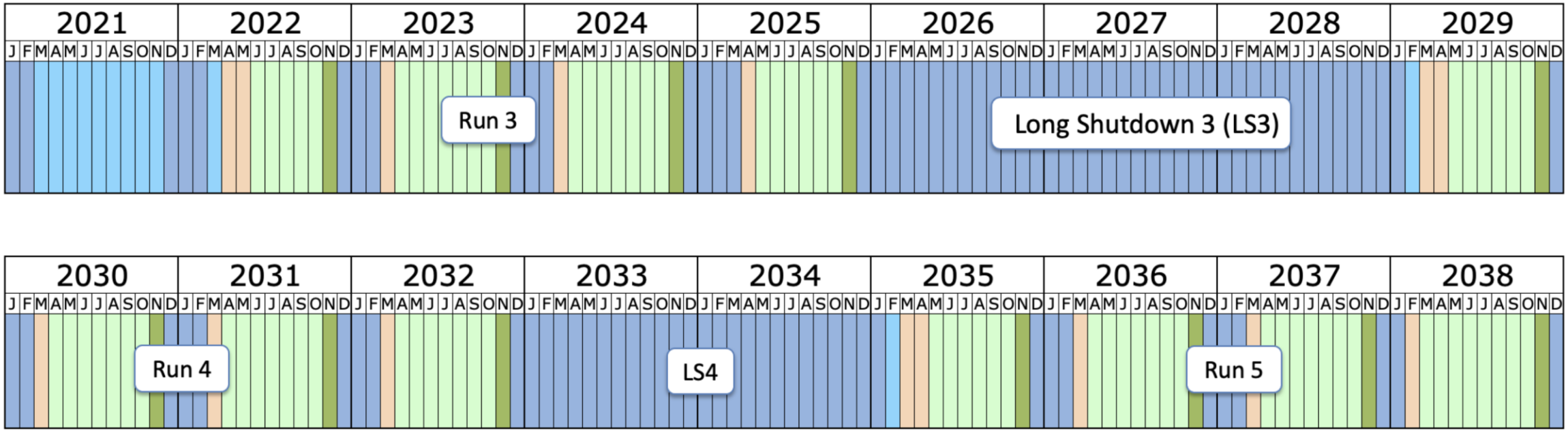
Dead cone effect





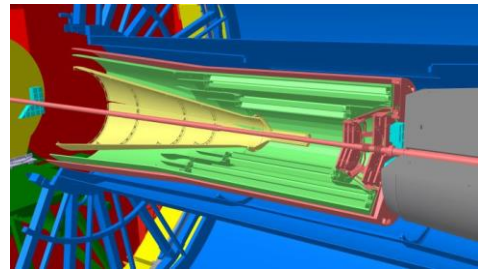
- Dead cone: suppression of gluon radiation from heavy quarks at small angles
- Predicted 30 years ago by Dokshitzer, Khoze and Troyan, J.Phys.G 17 (1991) 1602
- Part of modern parton shower models
- First direct observation with ALICE!

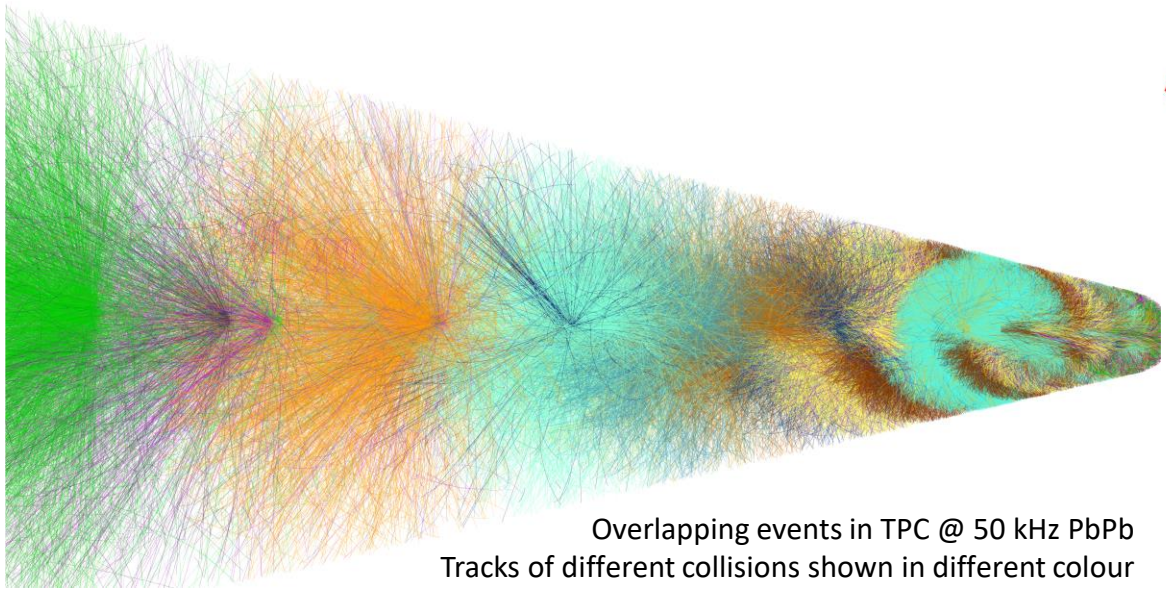
ALICE in Run 3 and beyond



ALICE in Run 3

- All-pixel Inner Tracking System
- GEM-based TPC readout
- Pixel Muon Forward Tracker
- Fast Interaction trigger
- New Online-Offline system
- Readout upgrade of all detectors

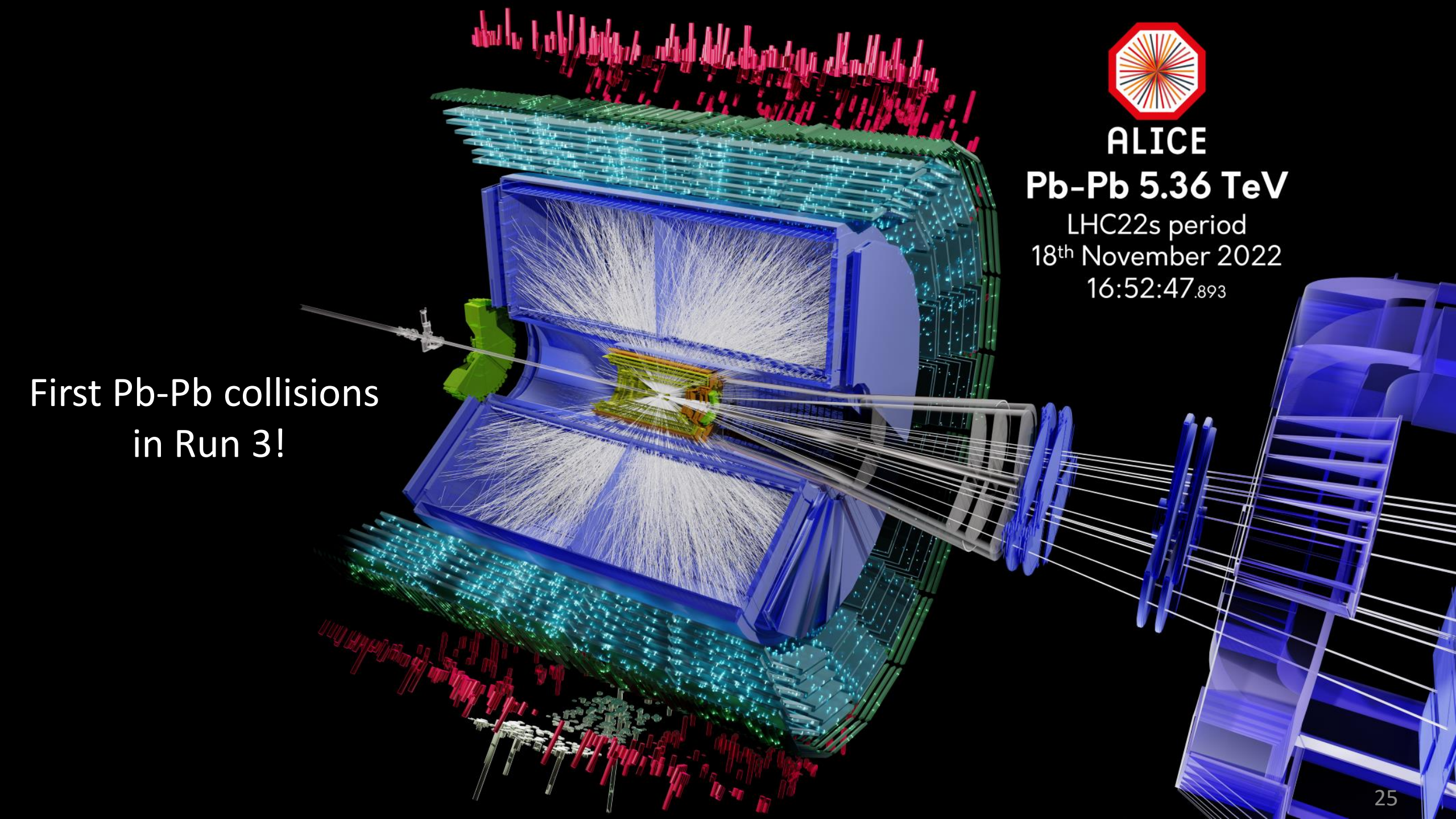




Overlapping events in TPC @ 50 kHz PbPb
Tracks of different collisions shown in different colour

Main goals:

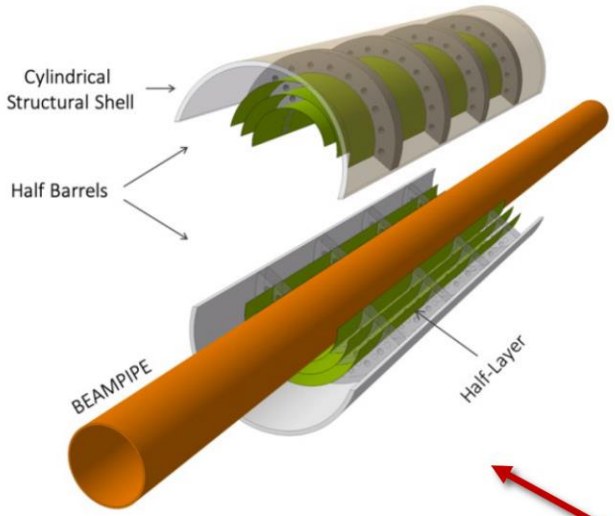
- Collect 13/nb in Run 3 and 4
  (x100 larger minimum bias statistics)
- Improve tracking precision by a factor 3-6



First Pb-Pb collisions in Run 3!

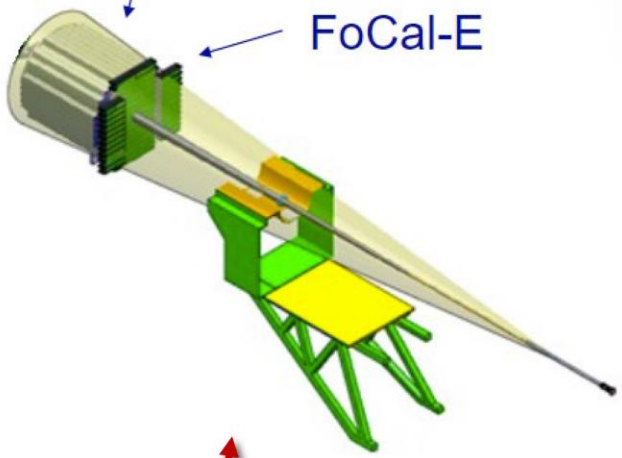
Future upgrades

ITS3

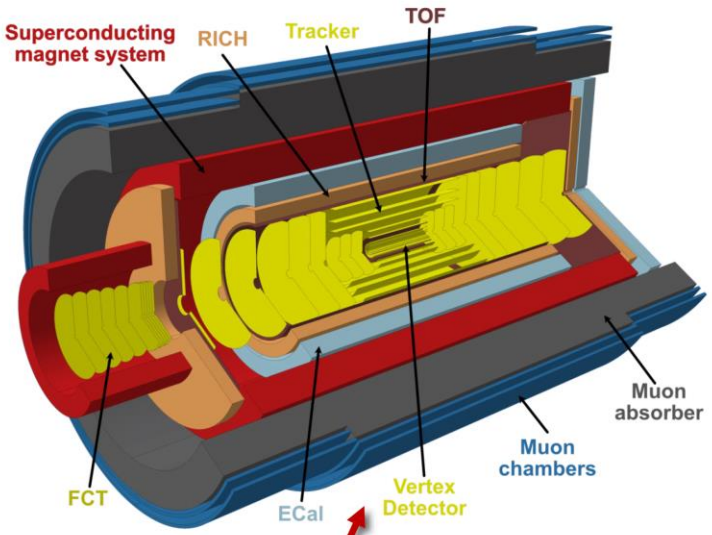


FoCal-H

FoCal-E



ALICE 3



Summary

- A wealth of physics results from Run 1 and 2 now reported in the ALICE review paper
- Providing quantitative estimates on QGP properties
- Investigating QGP-like effects in small collision systems
- Many exciting results beyond QGP physics
- Successful upgrade: continuous readout and improved tracking performance
- Looking forward to new data!