# Overview of recent ALICE results

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Petersburg Nuclear Physics Institute

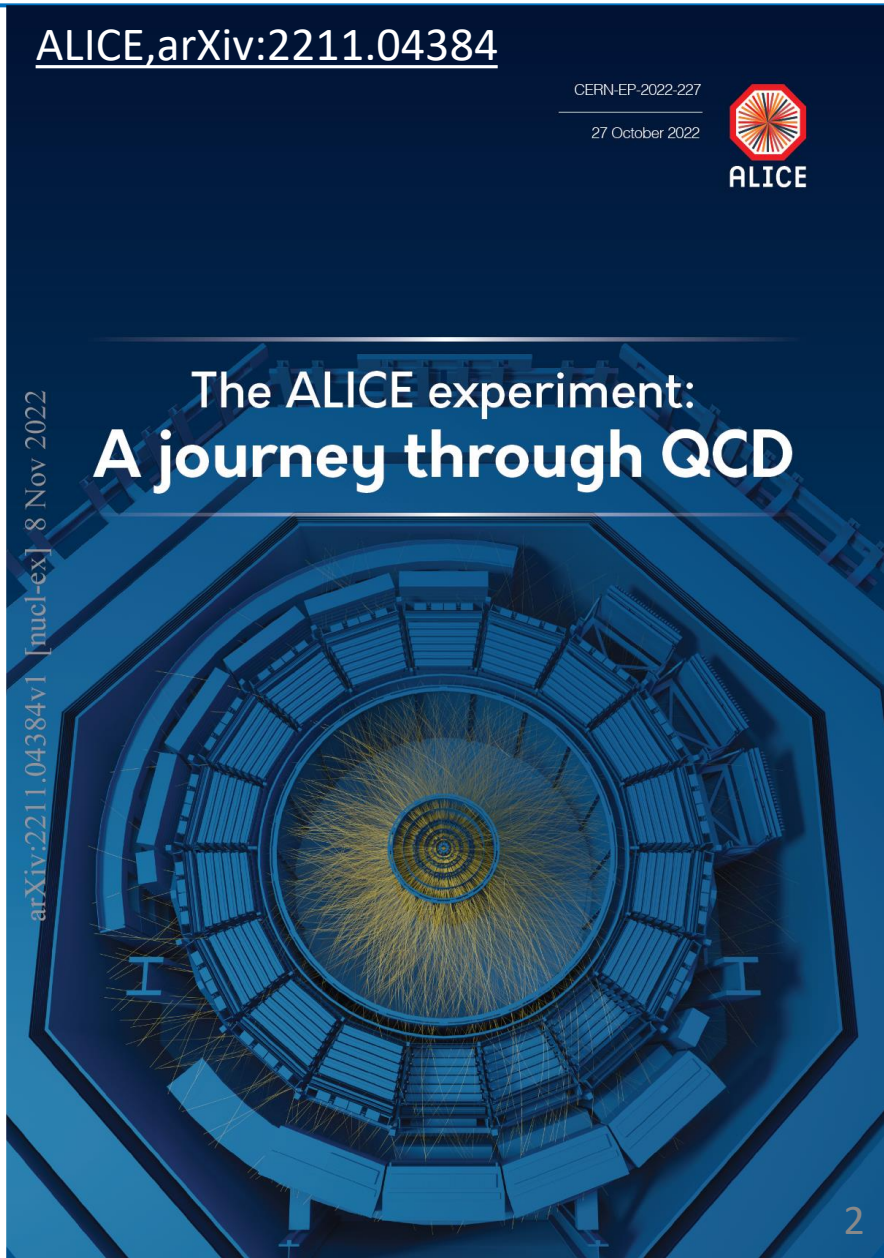
XXI Lomonosov Conference
26 August 2023

# 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

ALICE,arXiv:2211.04384



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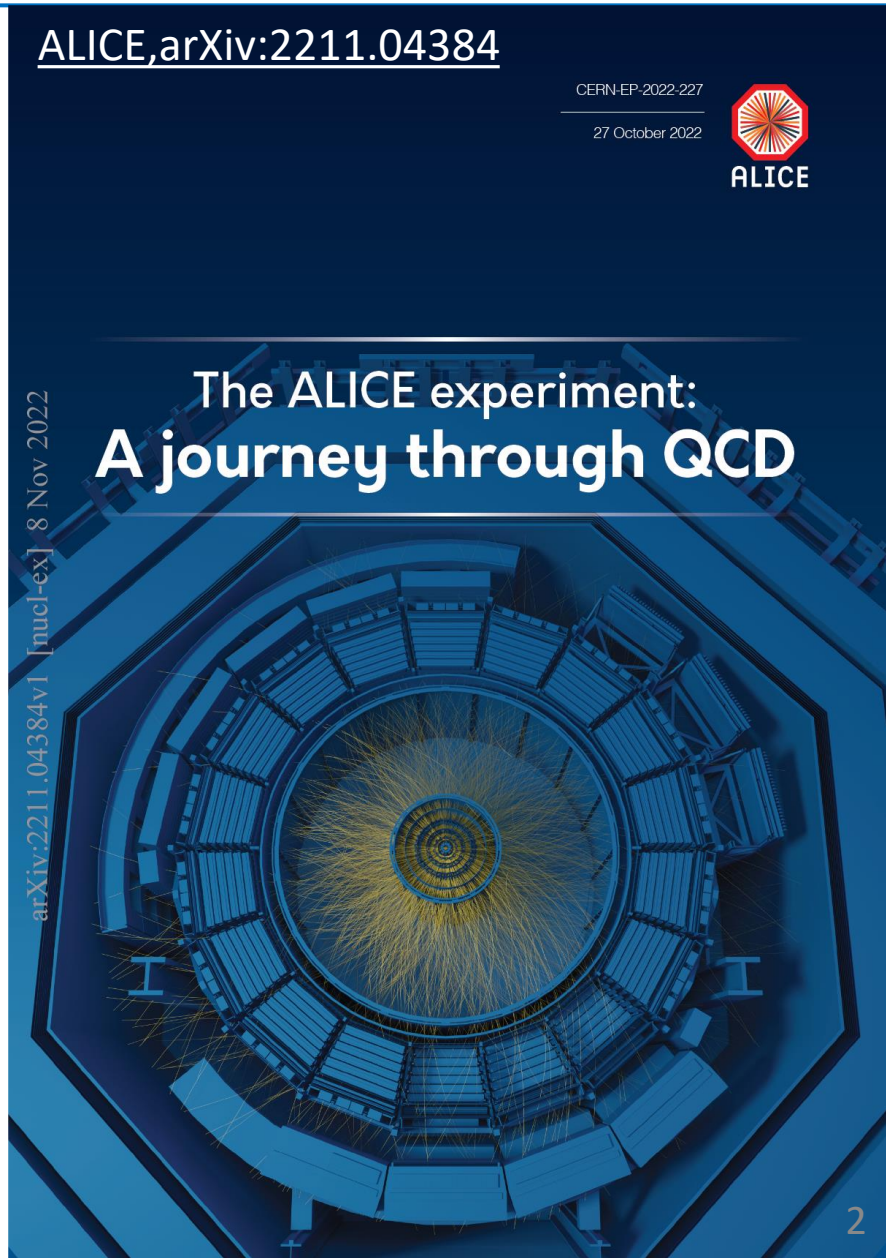
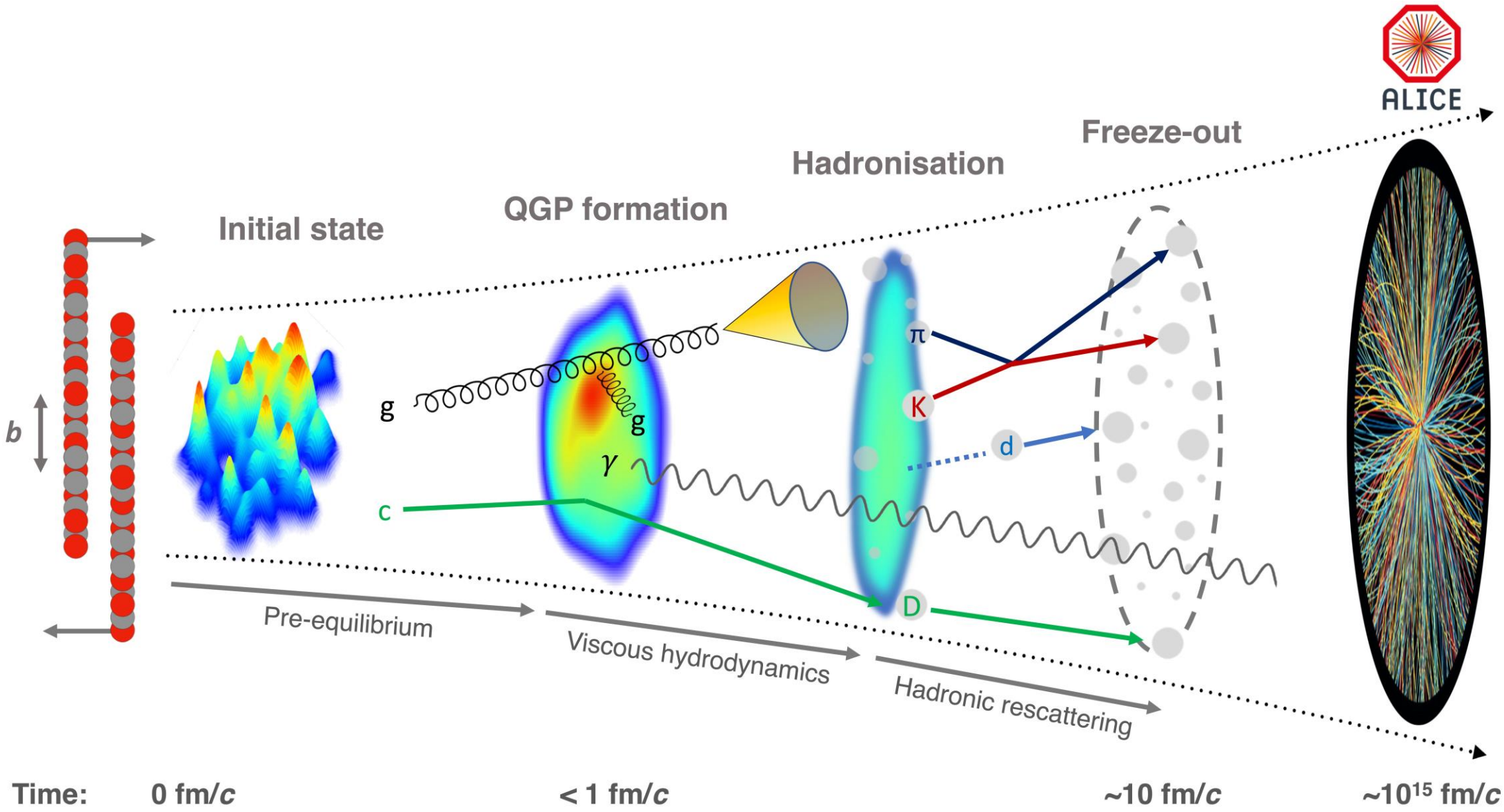
See talk on QCD studies by Yuri Kharlov on August 30

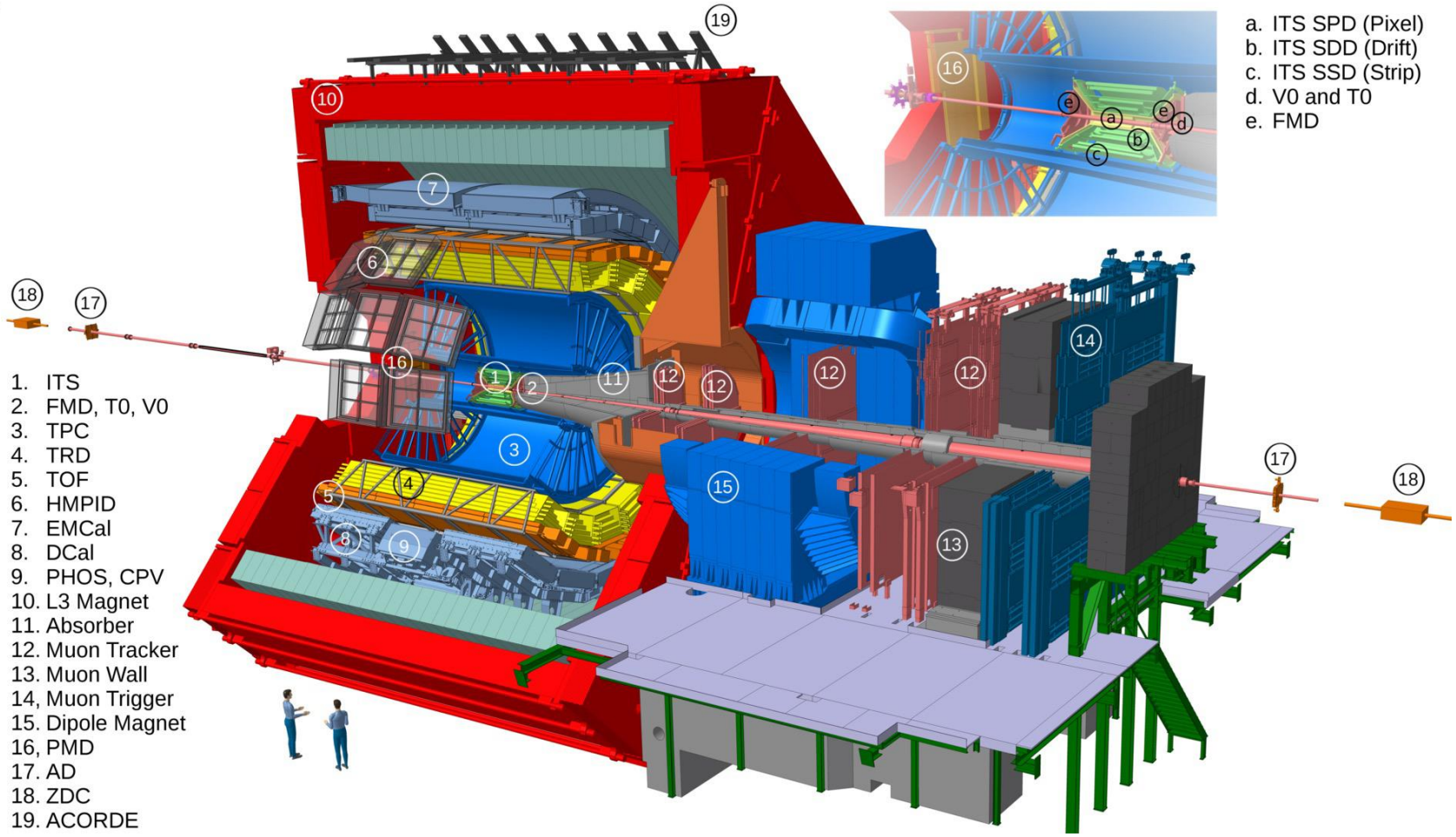
ALICE,arXiv:2211.04384

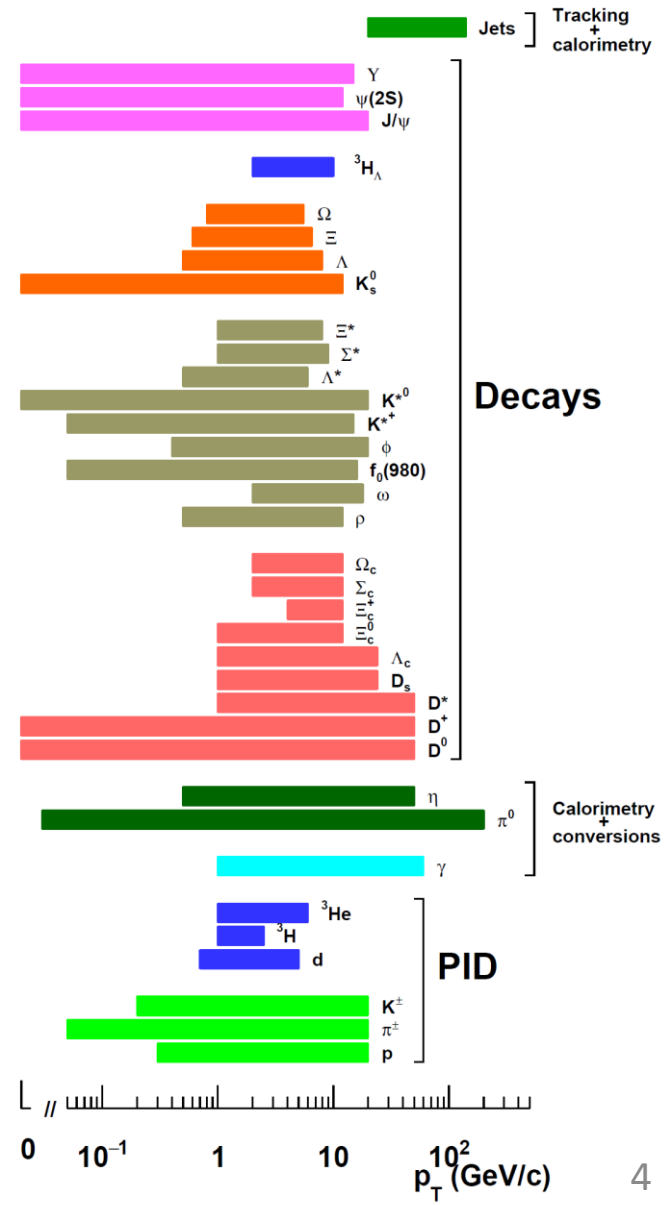


# Relativistic heavy-ion collisions



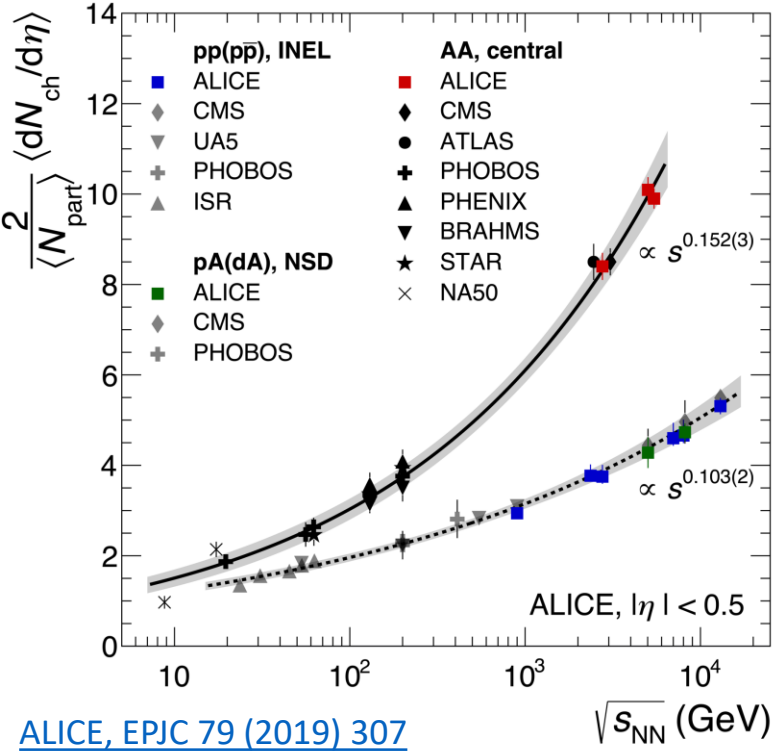
# ALICE detector



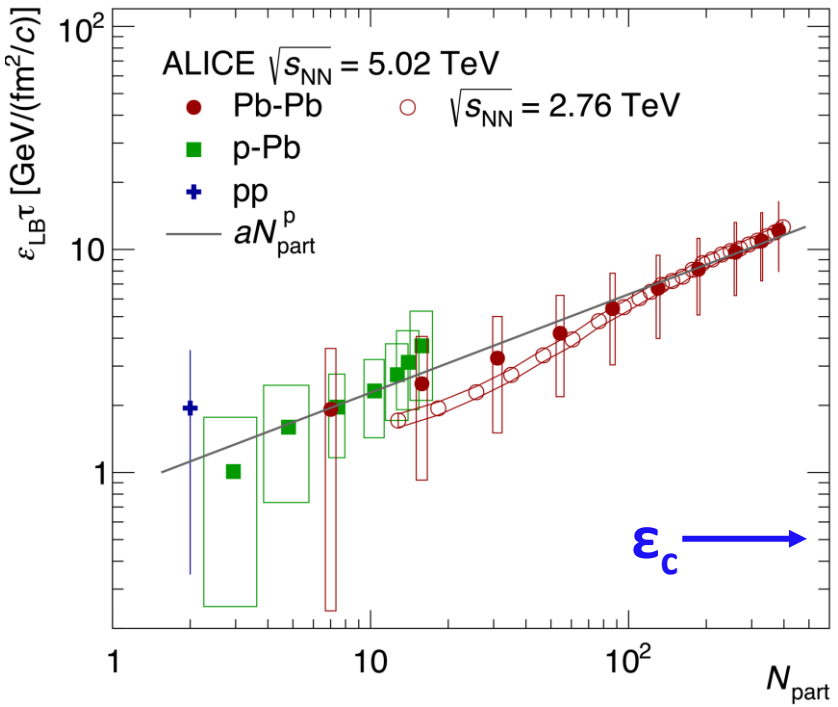




- Broad momentum acceptance
- World leading particle identification
- Precise vertexing

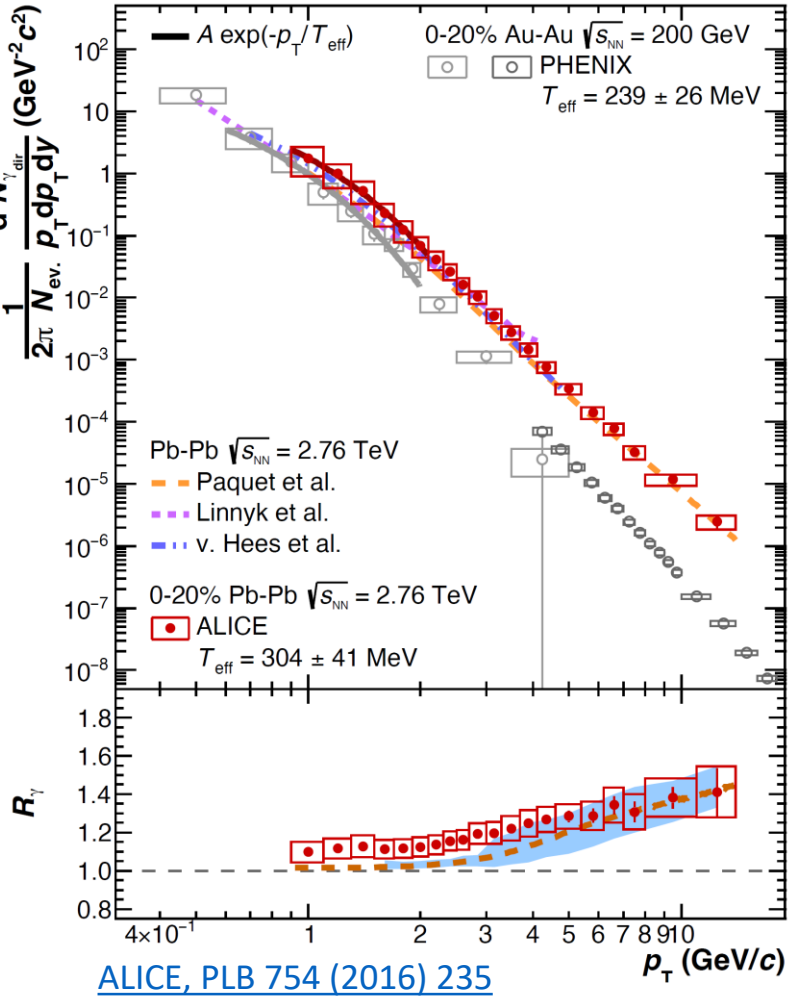
# Global properties




ALICE, EPJC 79 (2019) 307



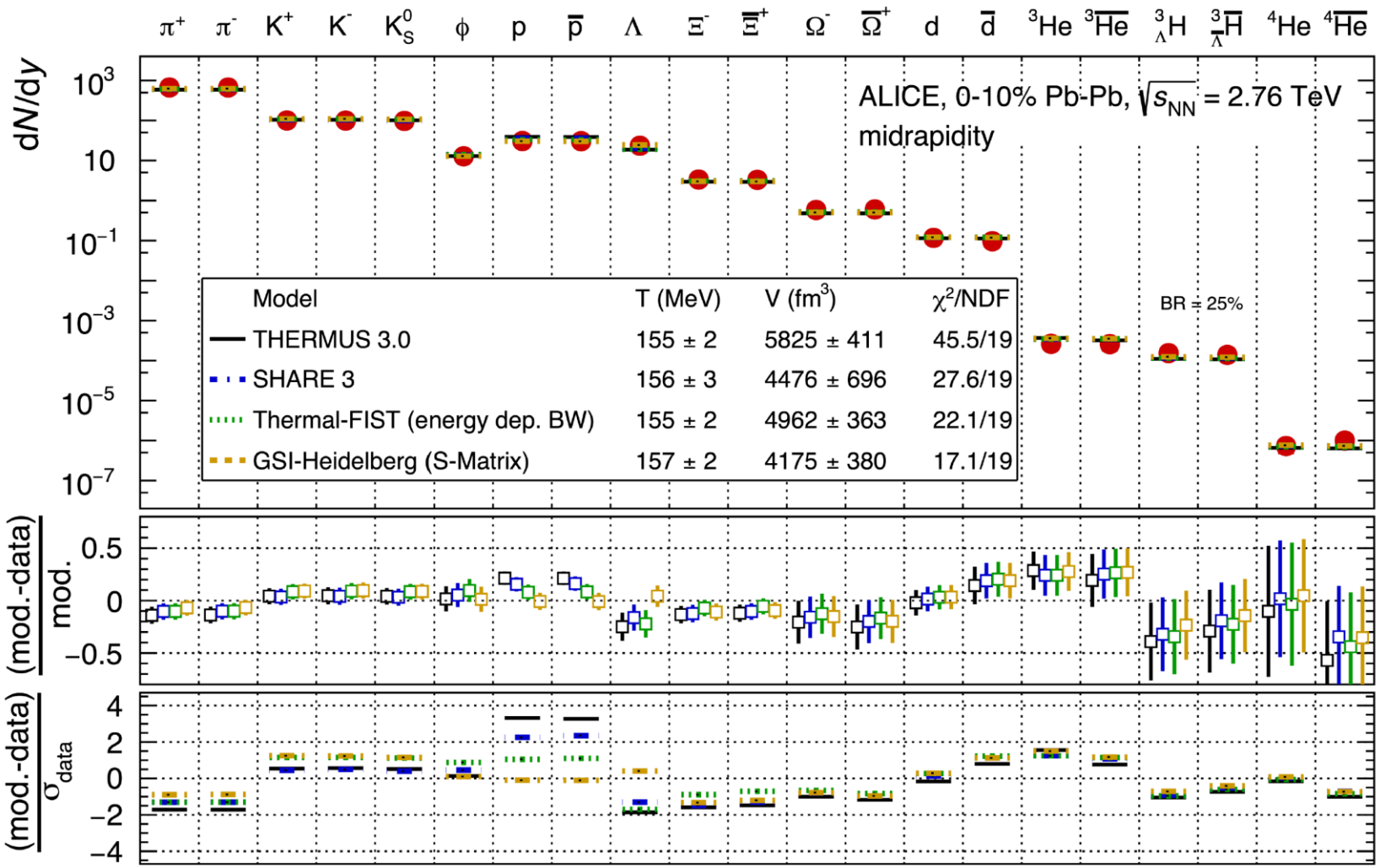

ALICE, arXiv:2204.10210



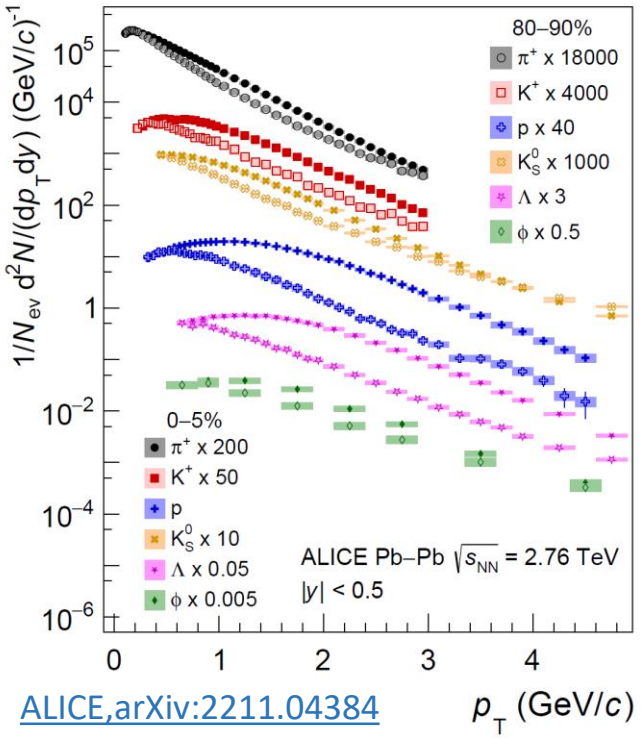

ALICE, PLB 754 (2016) 235

- 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 $\varepsilon_c$!
- Effective photon temperature $T_{eff}$ = 304 ± 41 MeV twice larger than $T_c$ ~ 160 MeV

# Light flavour spectra




ALICE,arXiv:2211.04384

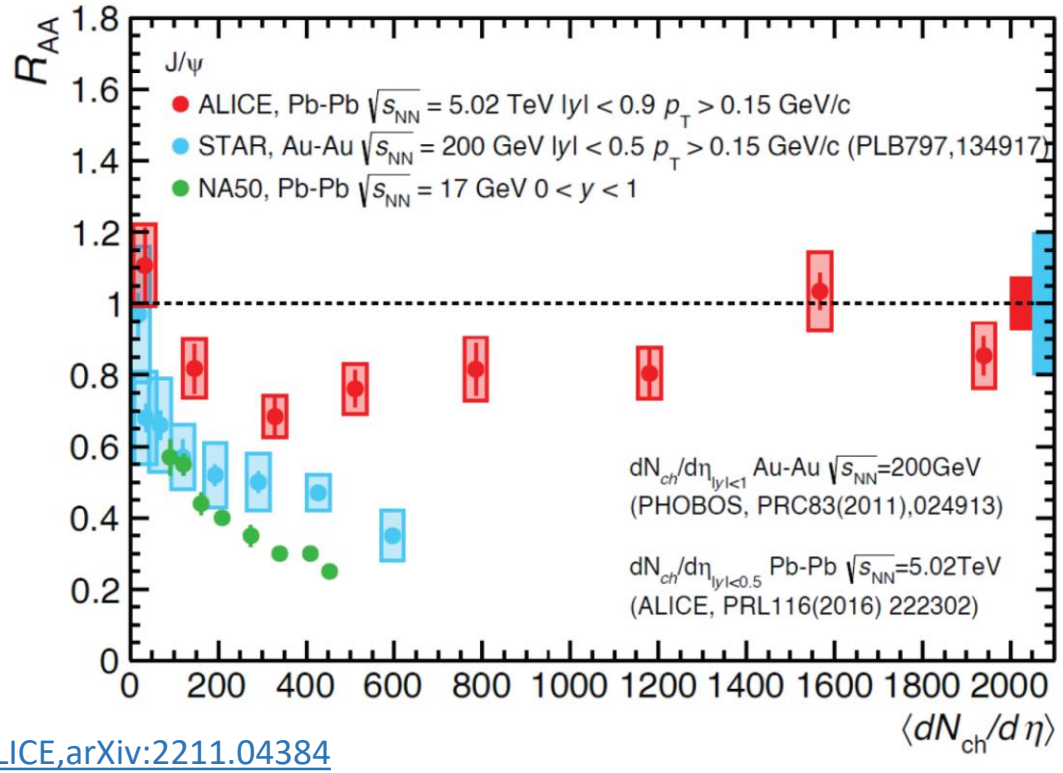



ALICE,arXiv:2211.04384

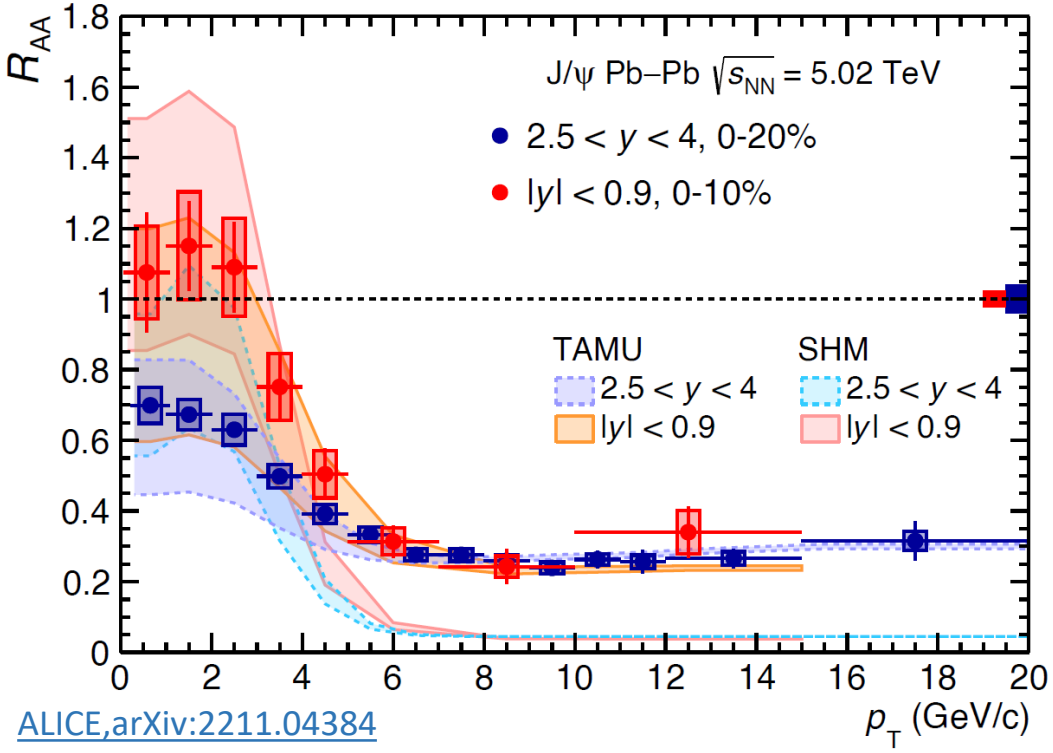
- Hadron yields described by statistical hadronization models over many orders of magnitude
- Chemical equilibrium close to QGP transition temperature

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

# Charmonium melting and regeneration




ALICE,arXiv:2211.04384

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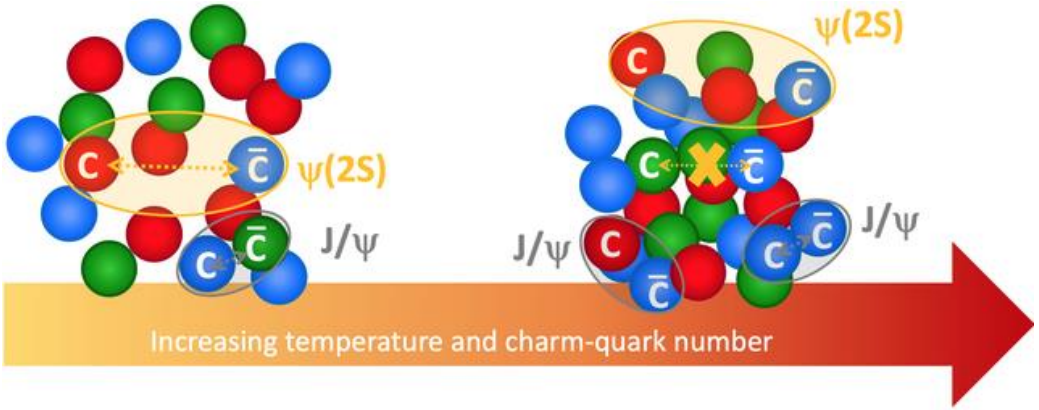
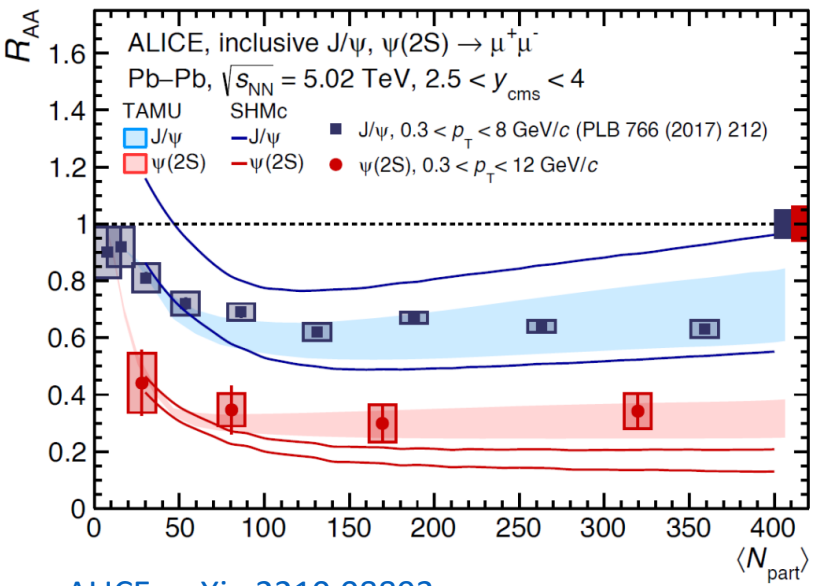
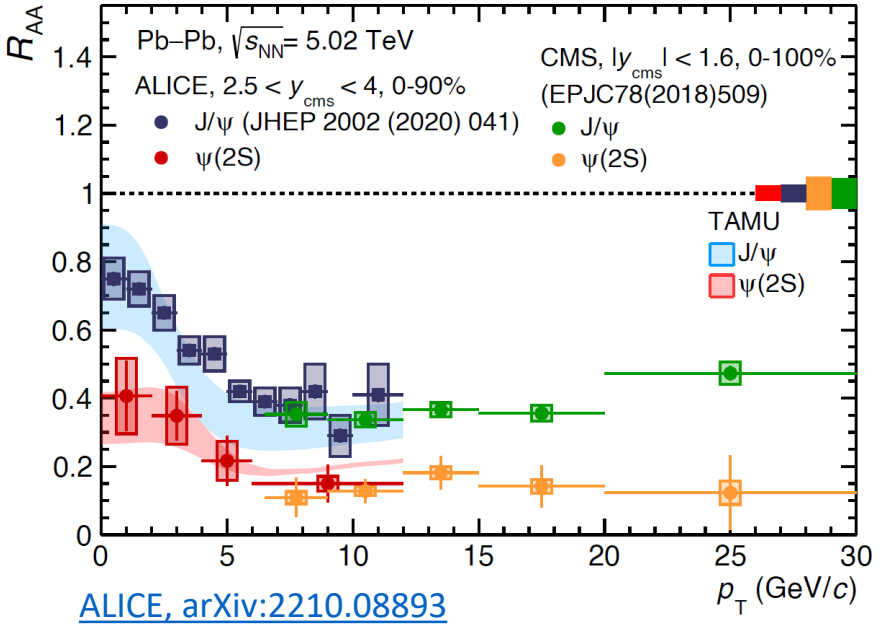



- Interplay of melting and regeneration effects
- Large regeneration effects at the LHC due to much larger charm cross section compared to RHIC/SPS
- Larger regeneration effects at midrapidity and at low $p_T$

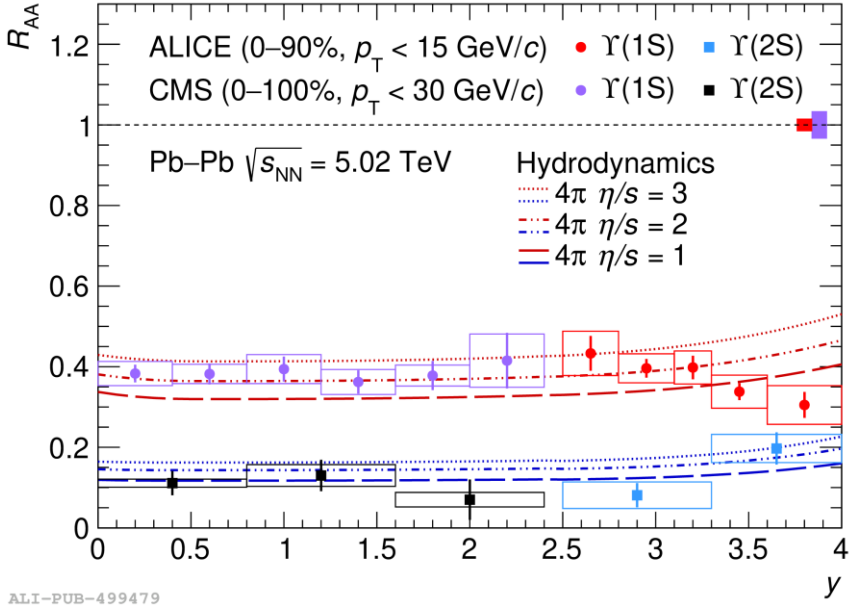
# Excited quarkonium states



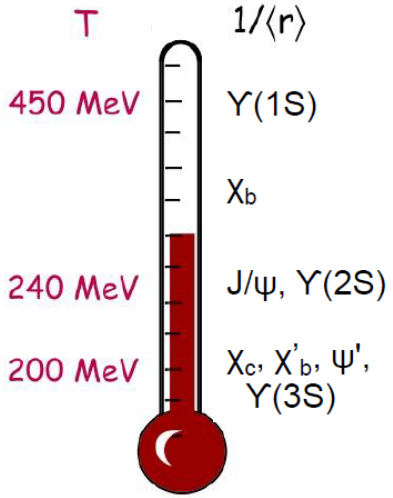

ALICE, arXiv:2210.08893




ALICE, arXiv:2210.08893

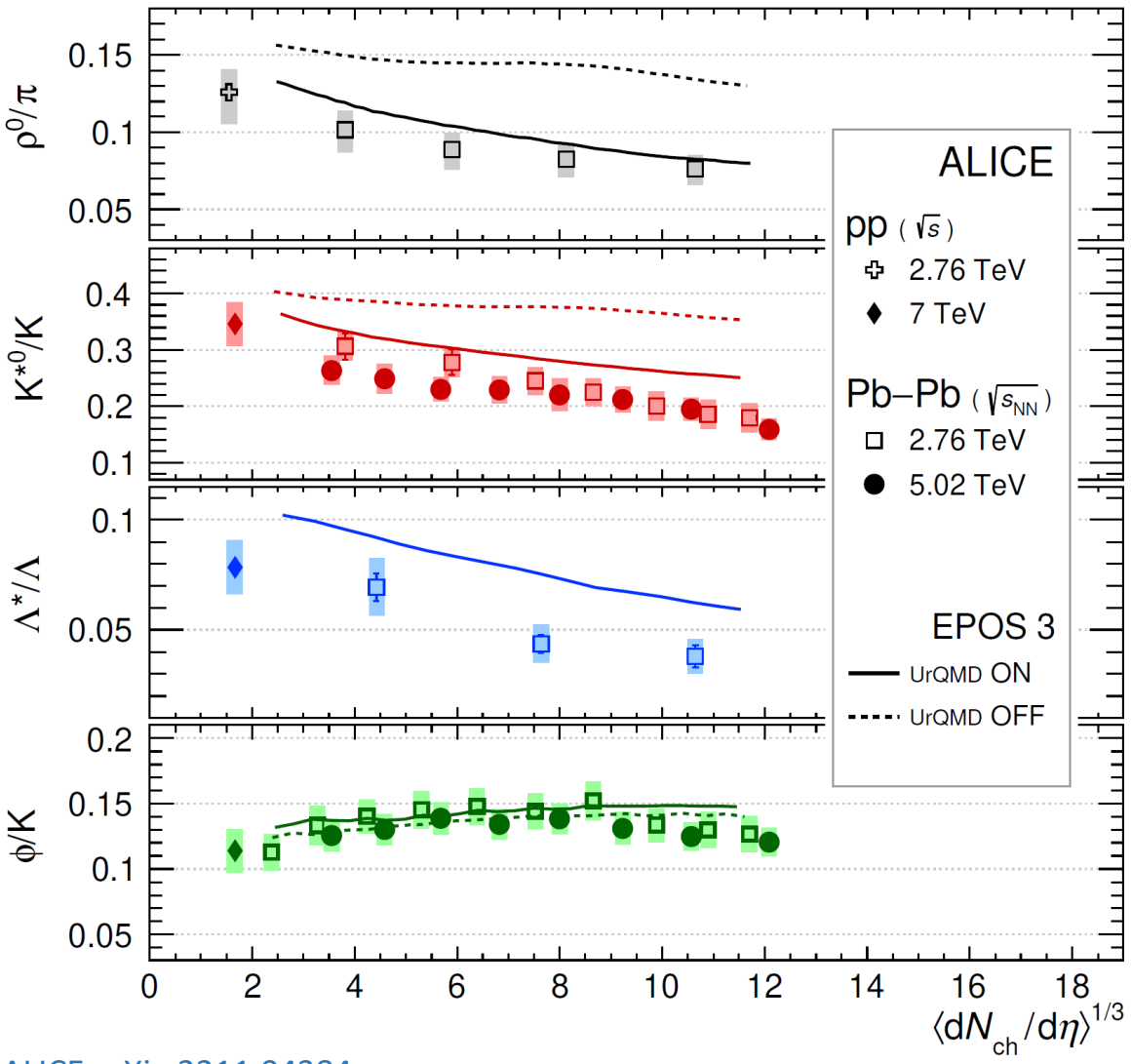



ALICE, PLB 822 (2021) 136579

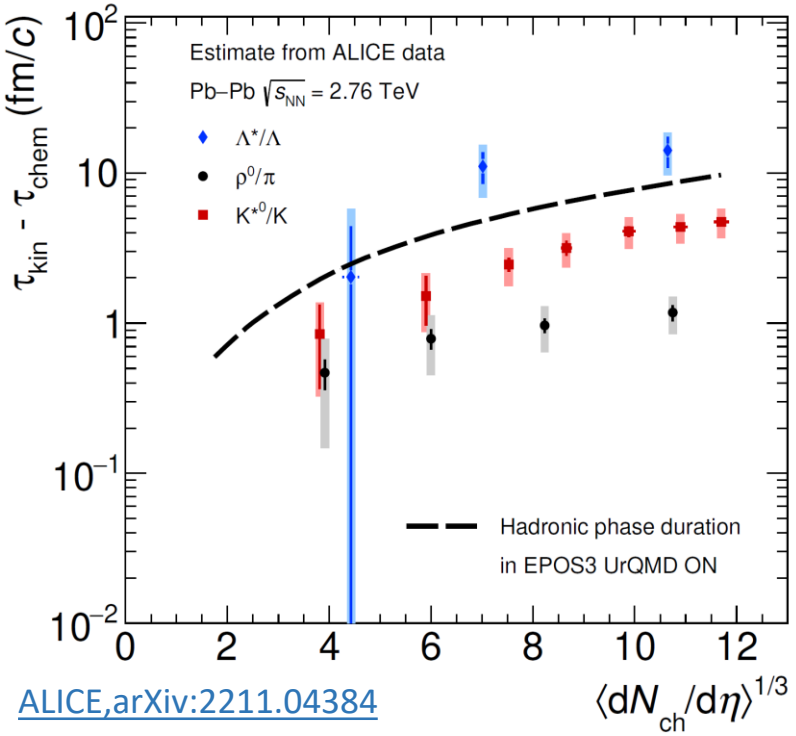



- Different states have different binding energies. Loosely bound states melt first!
- Sequential suppression of individual states provides a "thermometer" of the QGP
- Charmonium: sequential suppression + regeneration effects
- Bottomonium: sequential suppression

# Probing hadronic phase with resonances



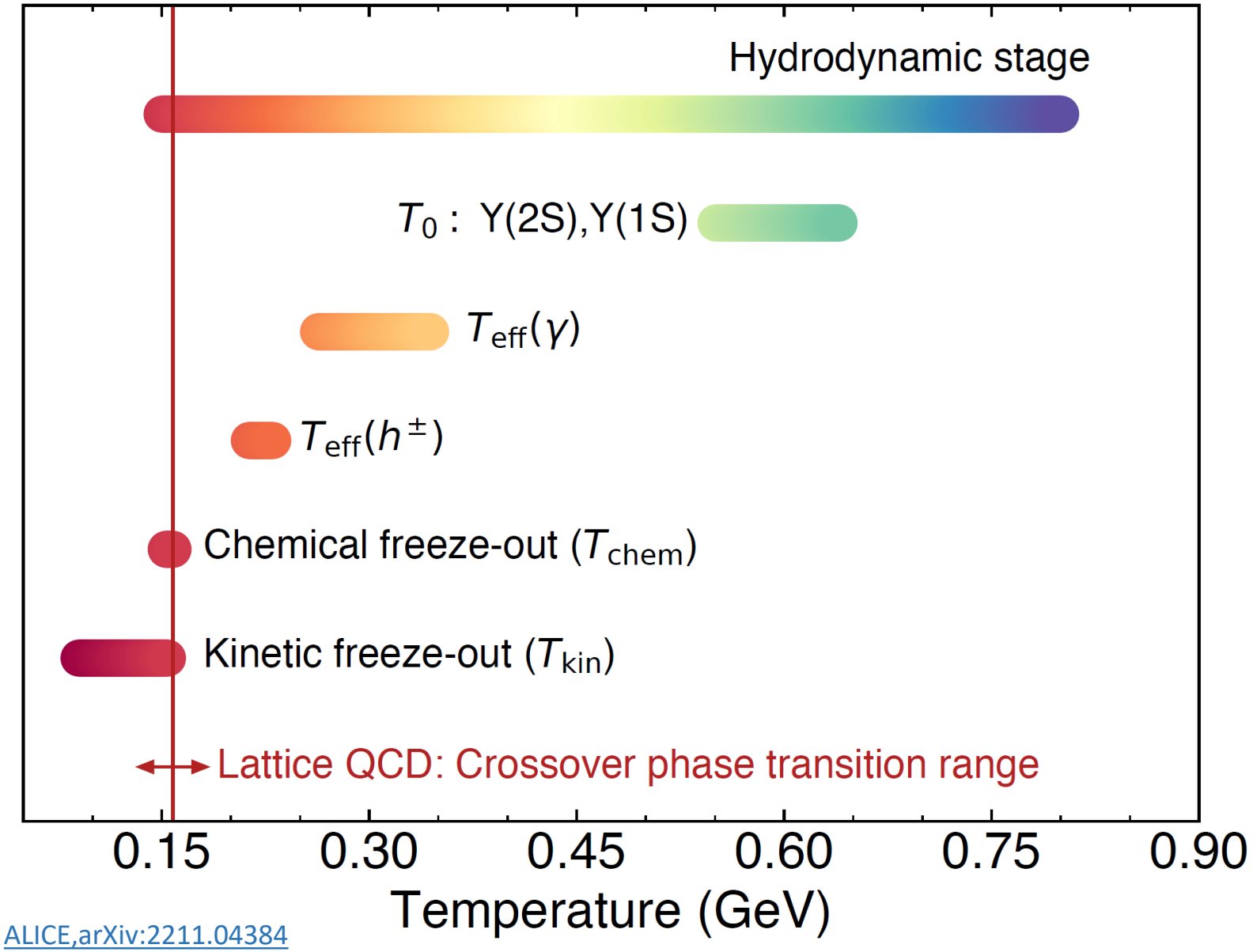

ALICE,arXiv:2211.04384




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

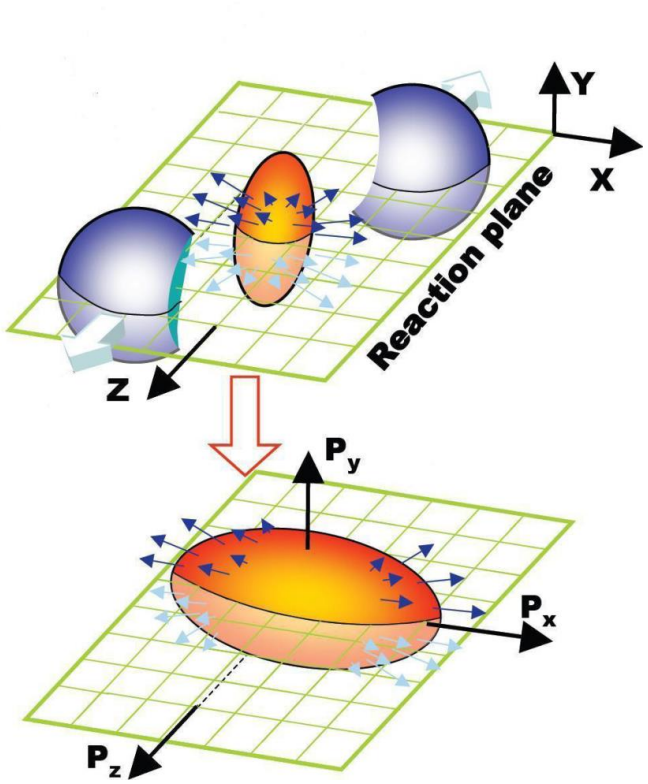


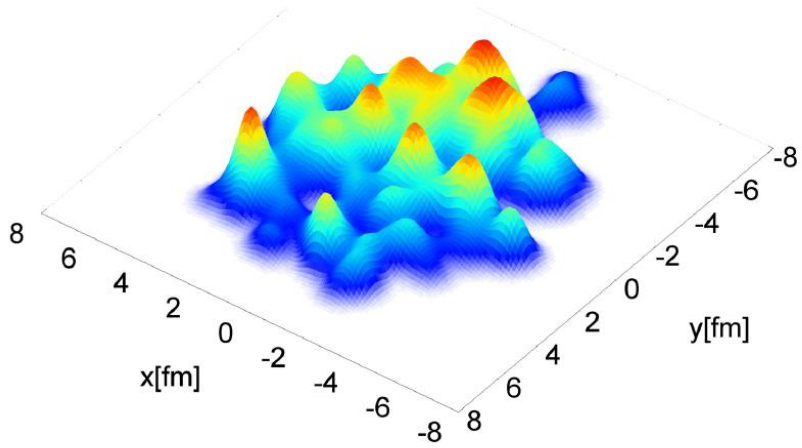

Many observables imply temperatures far greater than $T_c$

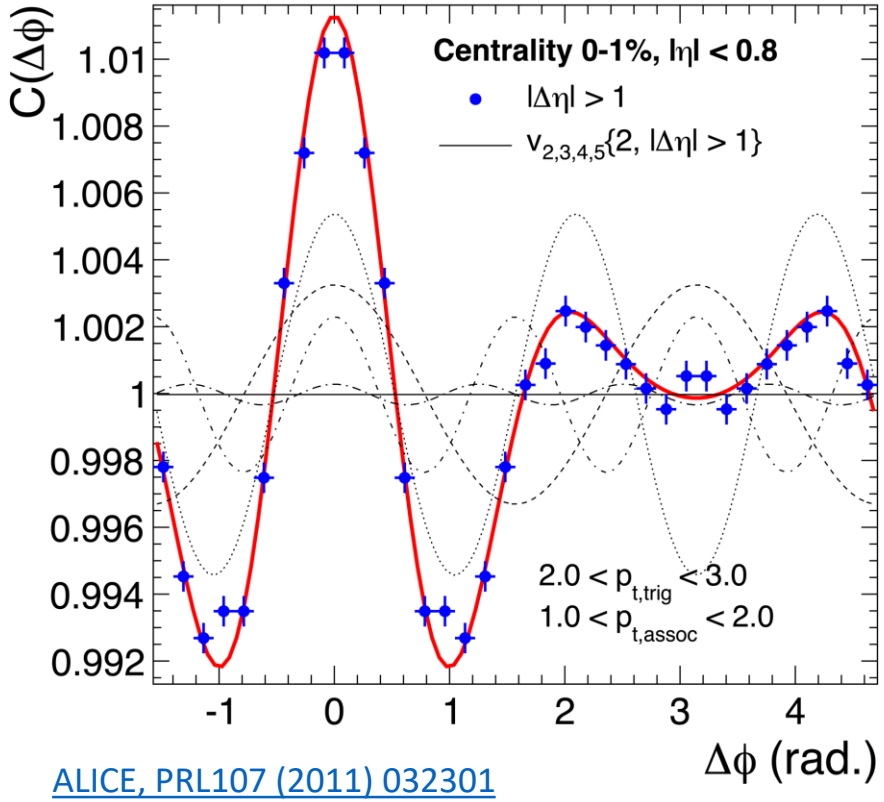
- Sequential melting of quarkonium states
- Effective thermal photon $T \sim 2T_c$
- Chemical freeze-out ~ $T_c$

ALICE,arXiv:2211.04384

# Anisotropic flow



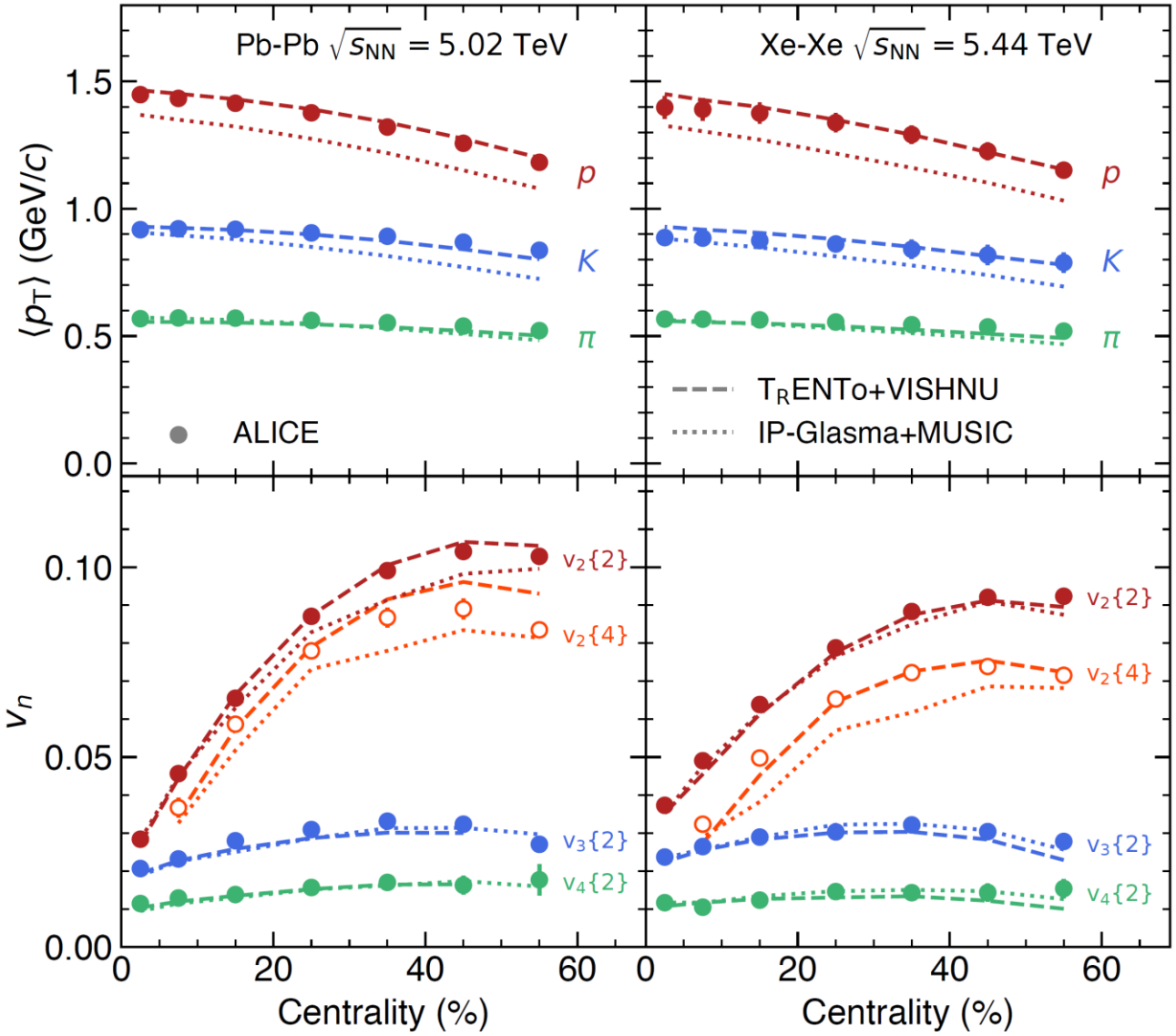




ALICE, PRL107 (2011) 032301

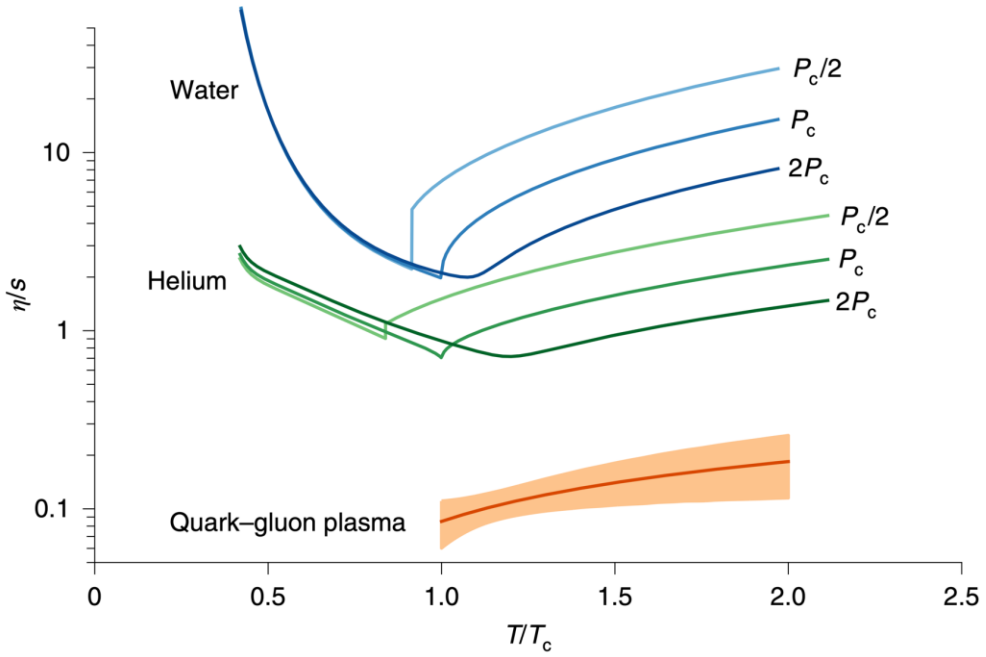
- Spatial anisotropy and density fluctuations of the initial state induce momentum anisotropy via QGP response
- Characterised by anisotropic flow coefficients $v_n$

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

# QGP properties from anisotropic flow



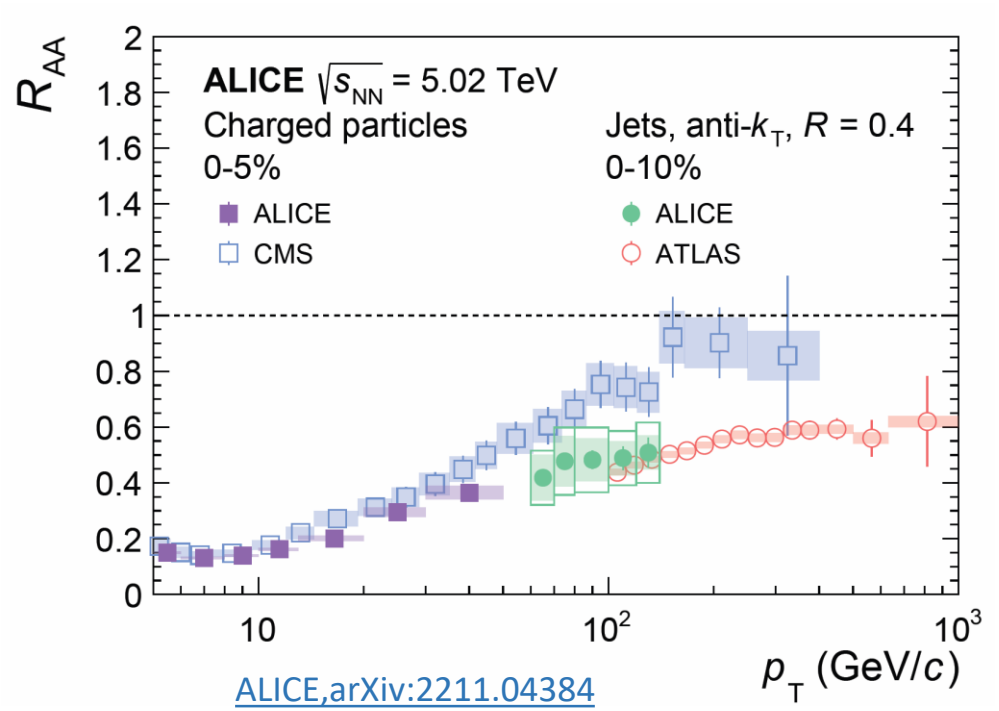

ALICE,arXiv:2211.04384



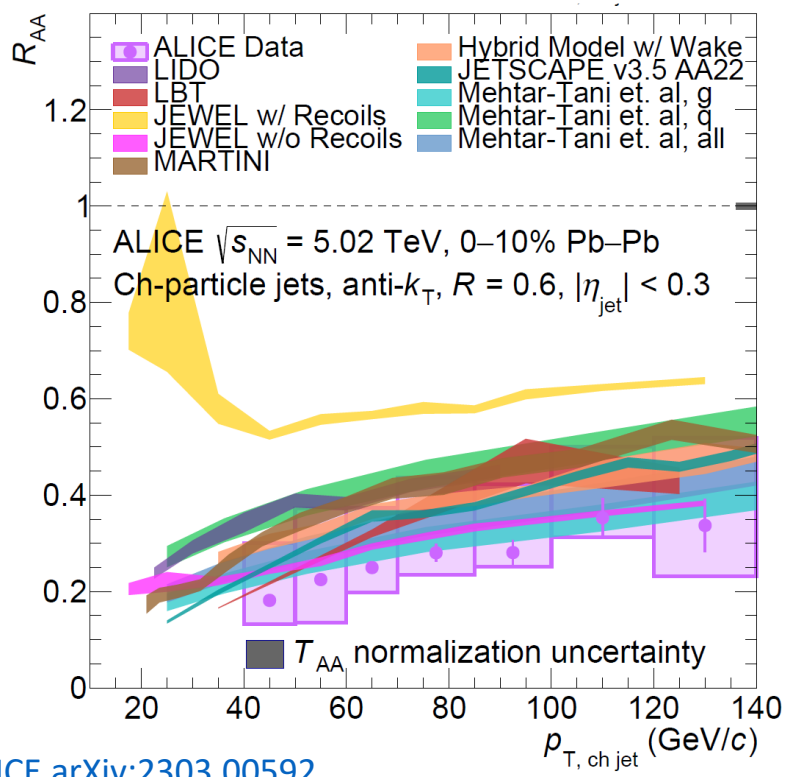

ALICE,arXiv:2211.04384

- 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

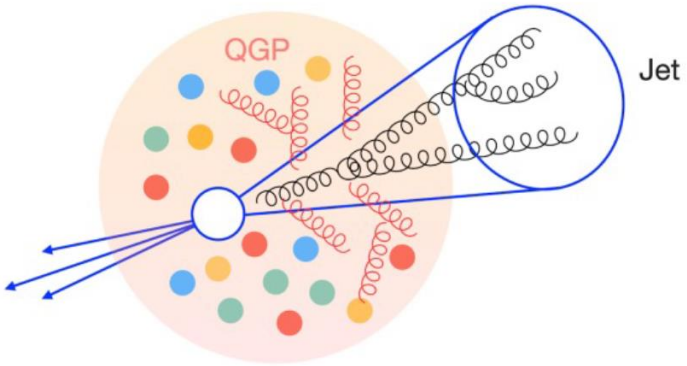
# Hard probes




ALICE,arXiv:2211.04384



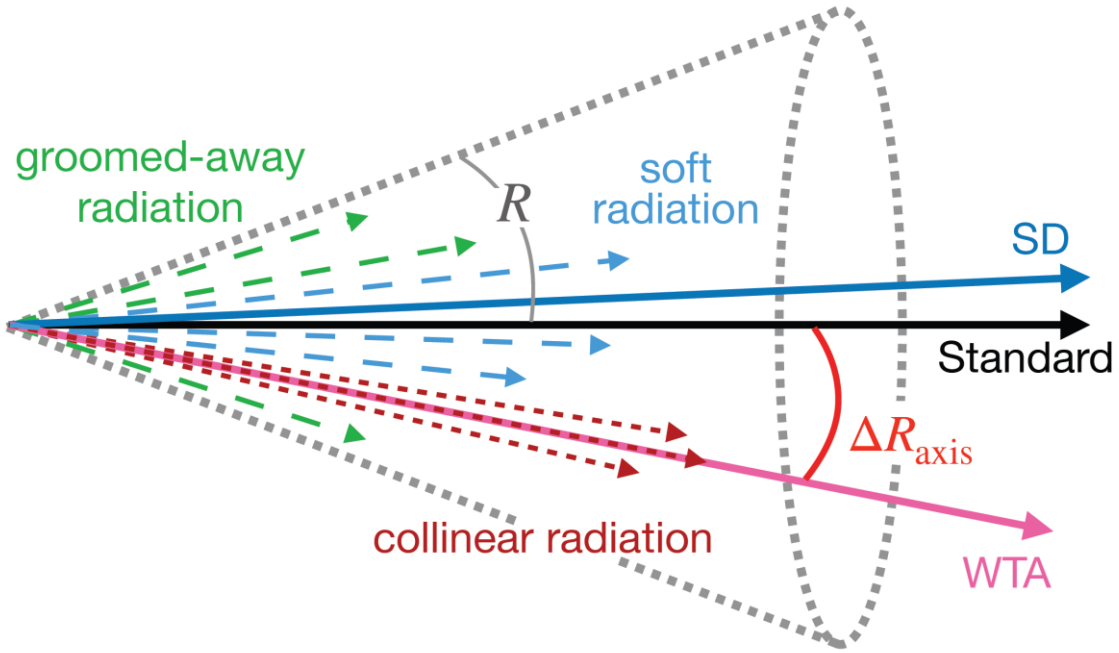

ALICE,arXiv:2303.00592

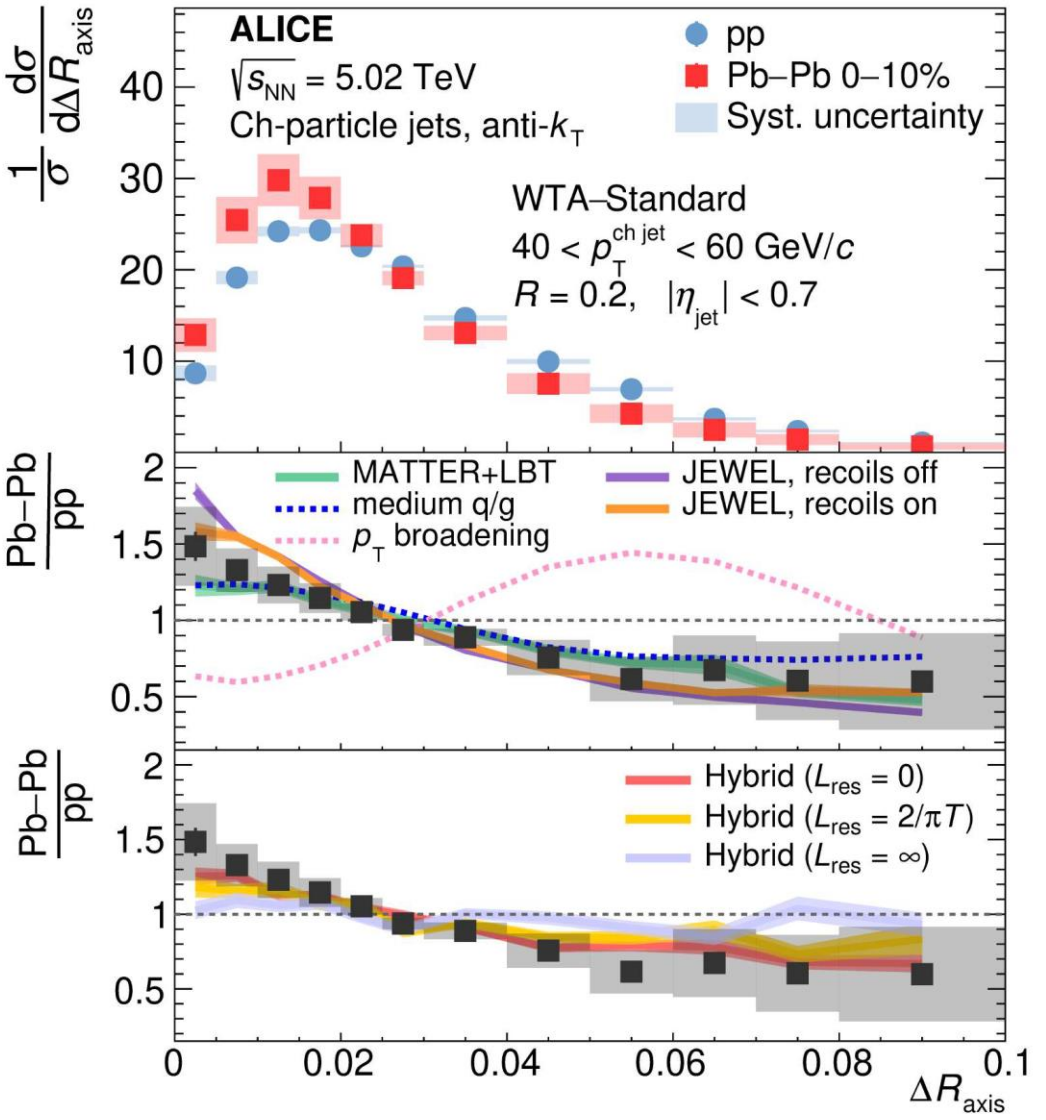



https://www.int.washington.edu/node/776

- 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
- New ML-based techniques allow for the extension to lower $p_T$ and larger $R$ = 0.6

# Jet substructure studies

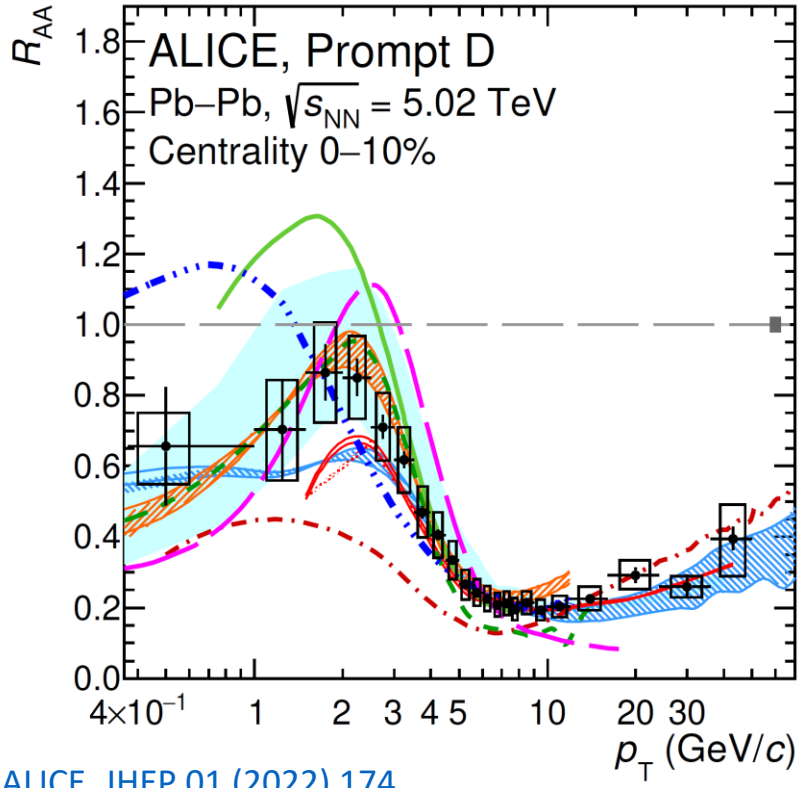


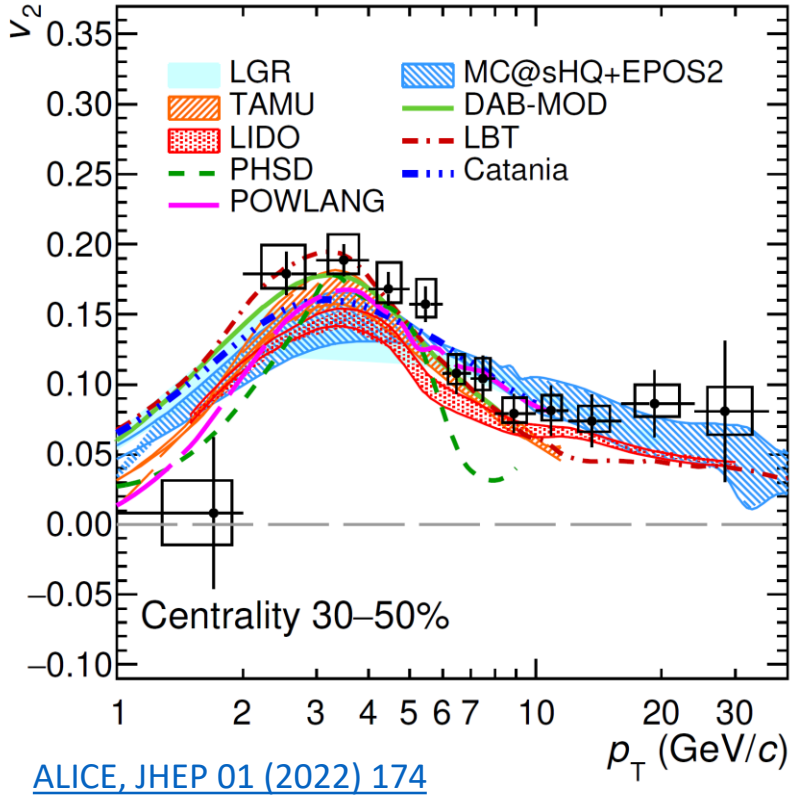

- $\Delta R_{axis}$ - angle between standard E-scheme jet axis and WTA axis (Winner-Takes-All, often consistent with leading particle)
- Narrowing of $\Delta R_{axis}$ distribution in Pb-Pb compared to pp
  - Quark-initiated jets more likely than gluon-initiated jets
  - Intra-jet $p_T$ broadening disfavoured

ALICE, arXiv:2303.13347

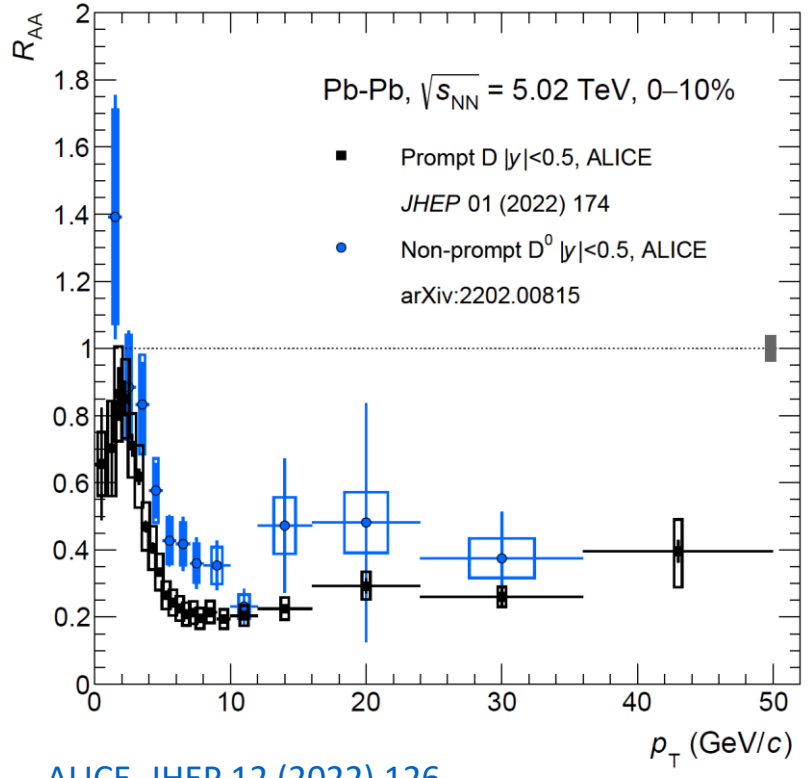
# Heavy flavours




ALICE, JHEP 01 (2022) 174



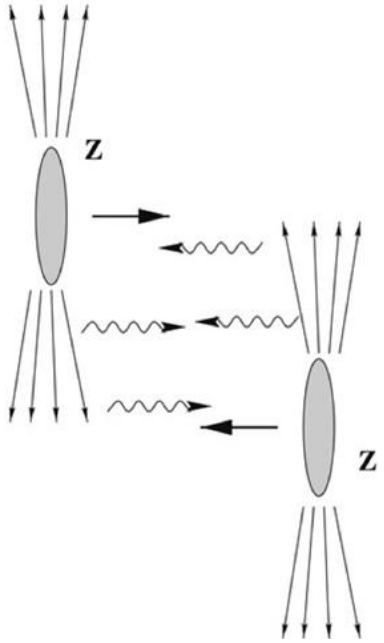

ALICE, JHEP 01 (2022) 174

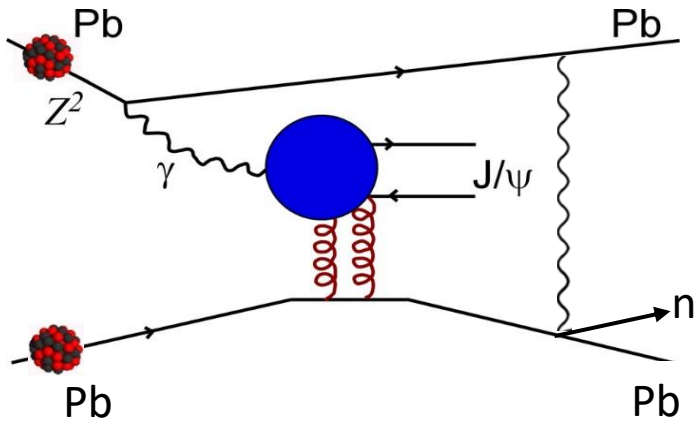



ALICE, JHEP 12 (2022) 126

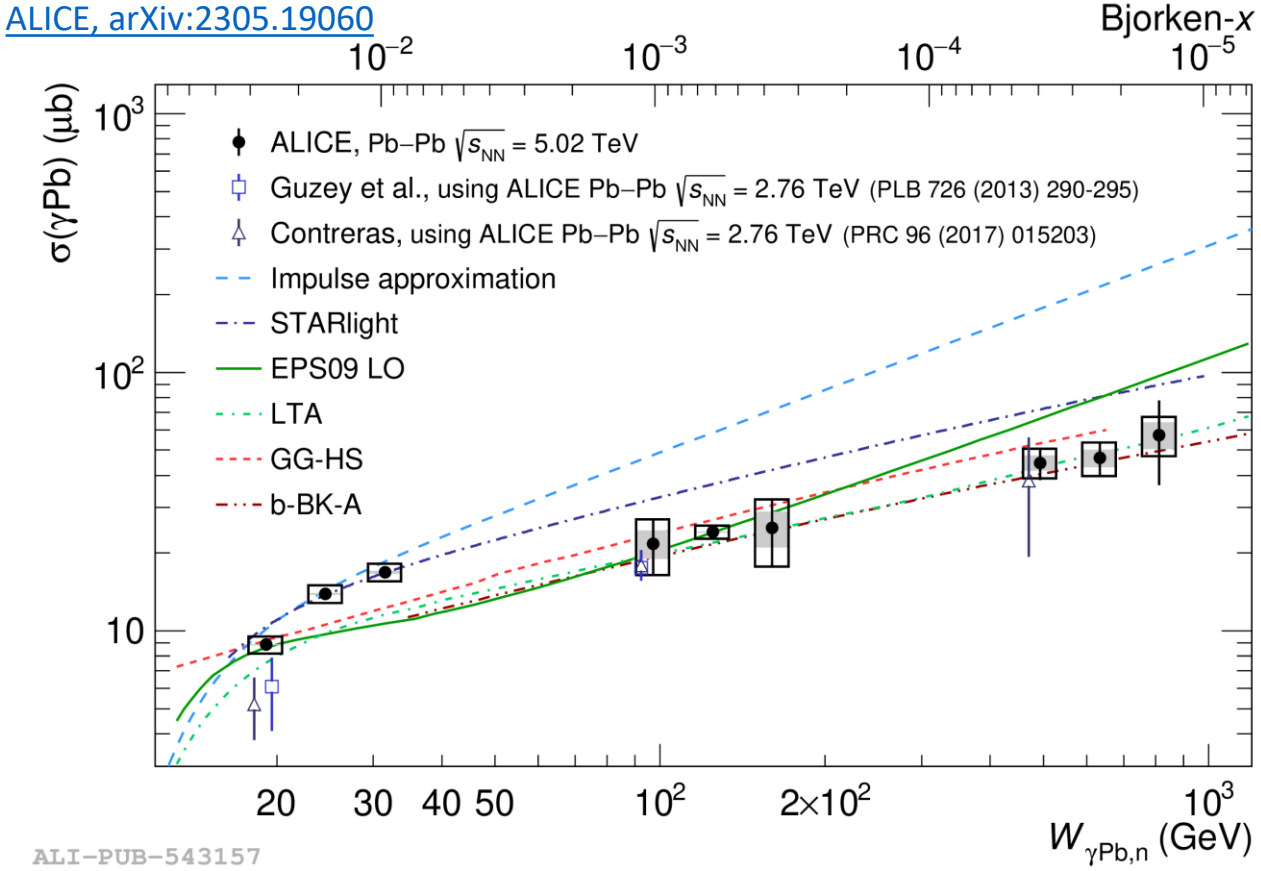
- D-meson spectra measured down to 0 $p_T$
- Challenge for charm-quark transport models to describe both the $R_{AA}$ and anisotropic flow ($v_2$):
  - providing constraints on heavy-quark spatial diffusion coefficient: $1.5 < 2\pi D_s T_c < 4.5$
- D mesons from bottom decays are less suppressed than those formed from charm
  - Indication of mass dependent radiative losses in agreement with expectations from QCD

# Initial state with ultra-peripheral collisions



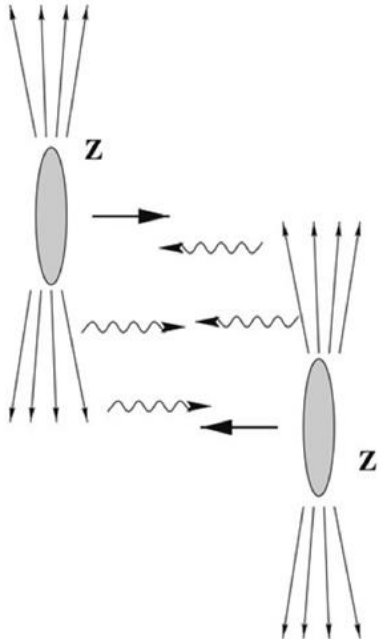



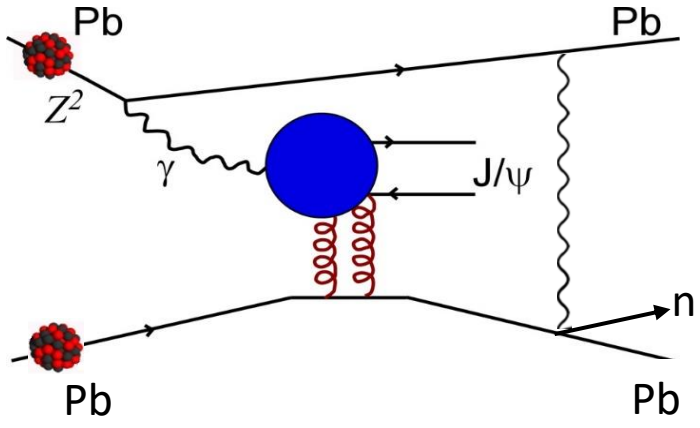

ALICE, arXiv:2305.19060



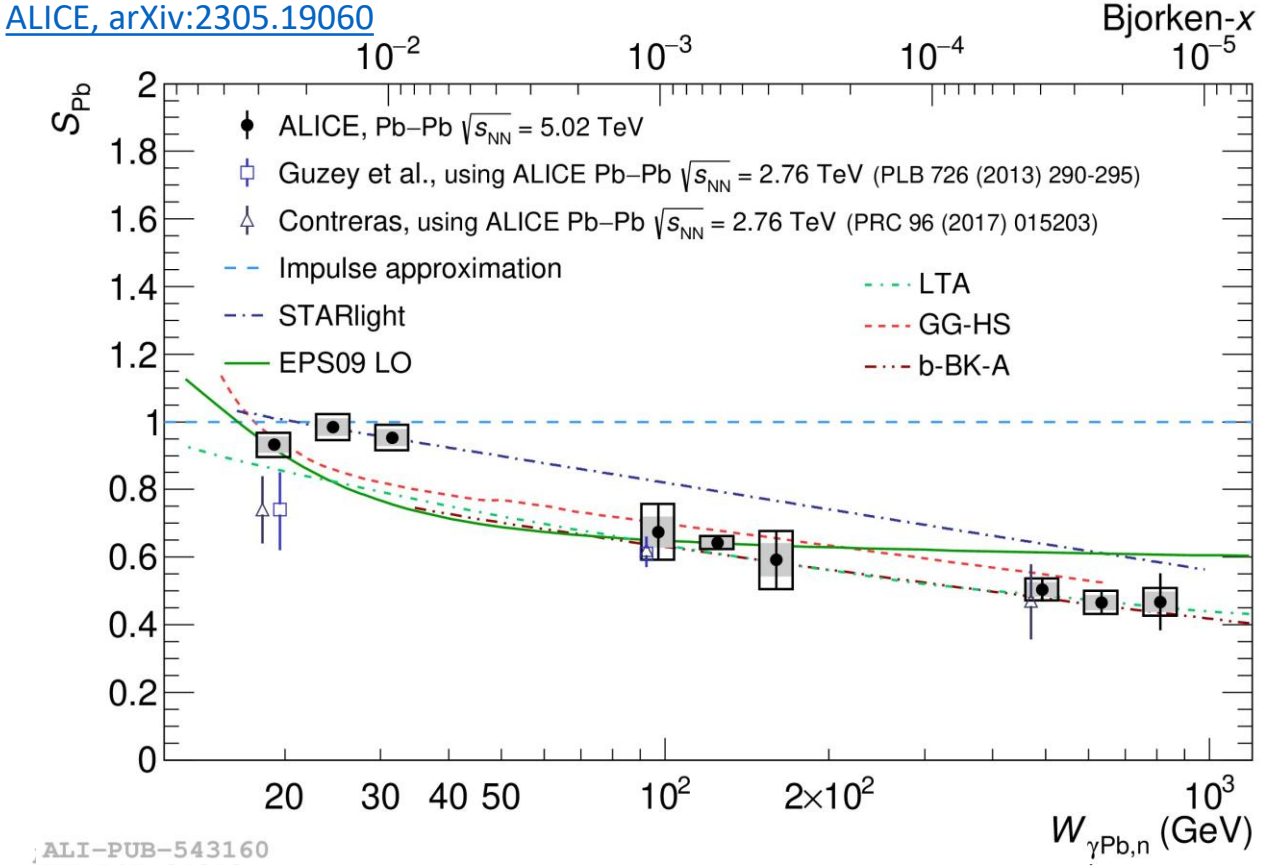

- Coherent J/ψ photoproduction: probing low-x gluon PDFs in the nucleus
- Neutron emission due to EMD helps to decouple low-*x* and high-*x* contributions

# Initial state with ultra-peripheral collisions



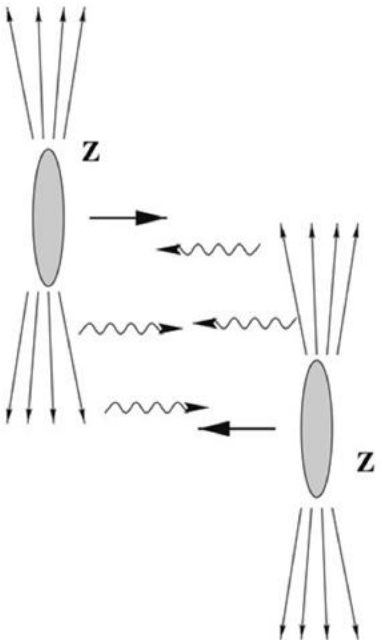




ALICE, arXiv:2305.19060

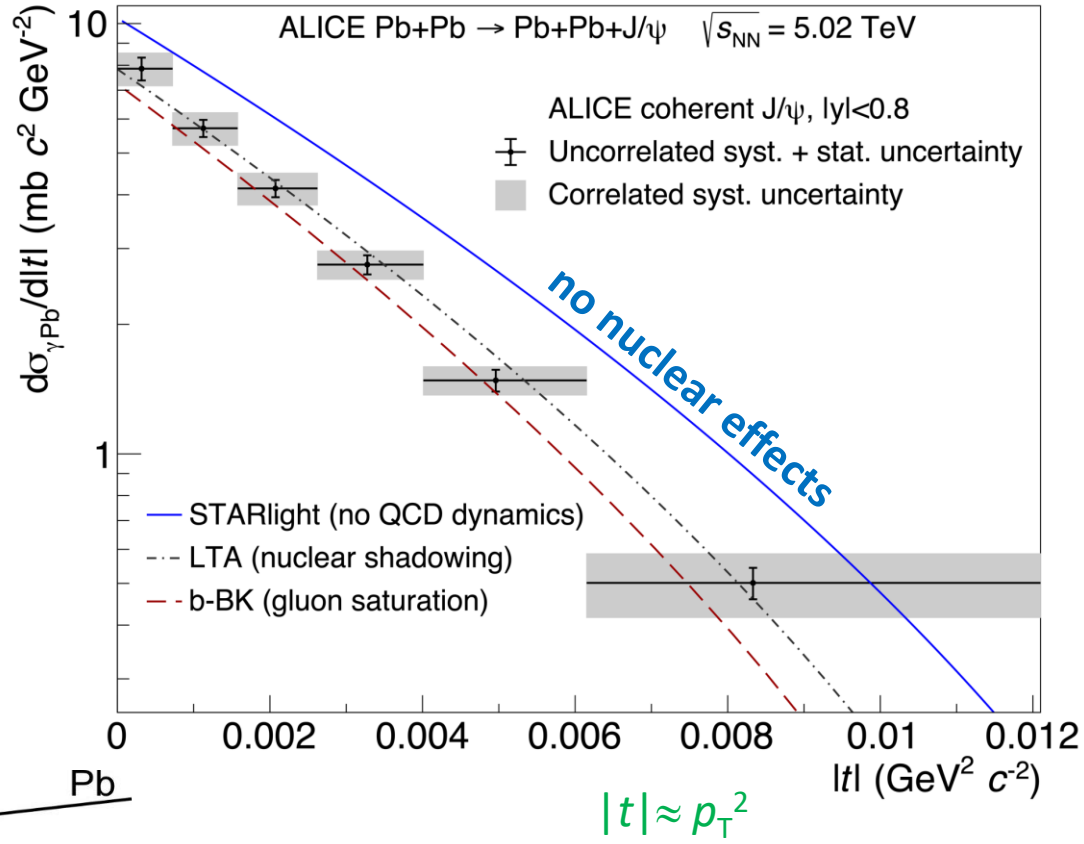



- Coherent J/ψ photoproduction: probing low-x gluon PDFs in the nucleus
- Neutron emission due to EMD helps to decouple low-*x* and high-*x* contributions
- Comparison with the impulse approximation (no nuclear effects) allows for extraction of the gluon shadowing factor: $R_g \sim 0.5$ at $x \sim 10^{-5}$

# Probing transverse profile of Pb nuclei

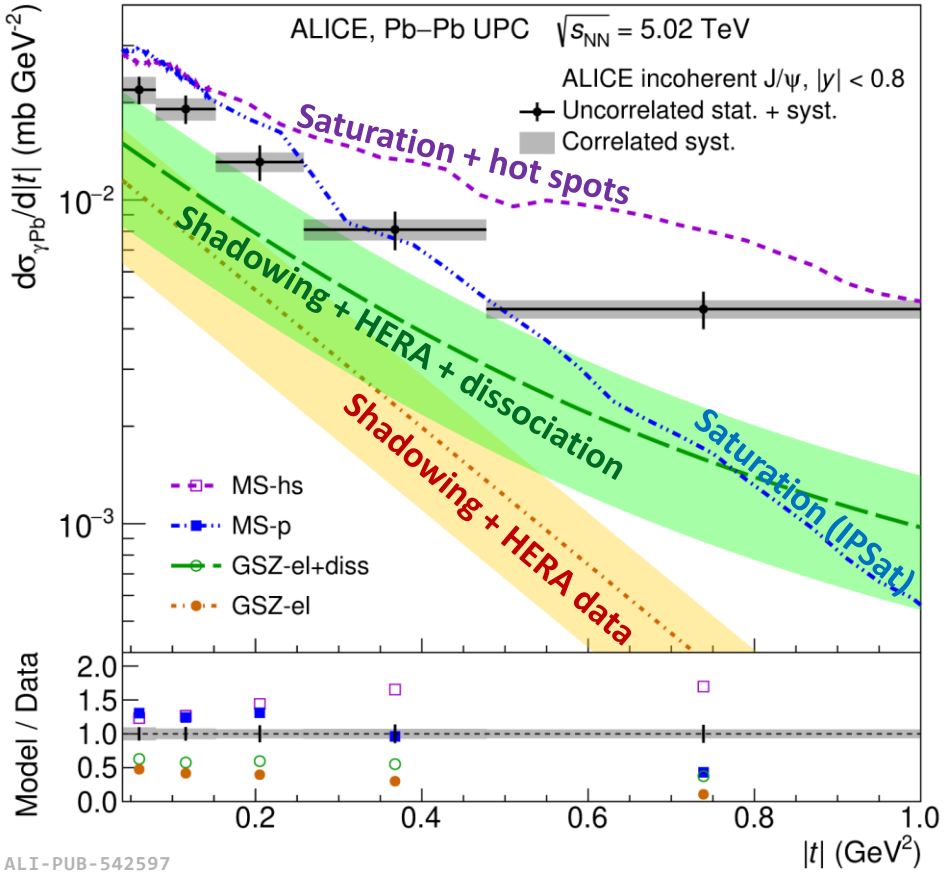


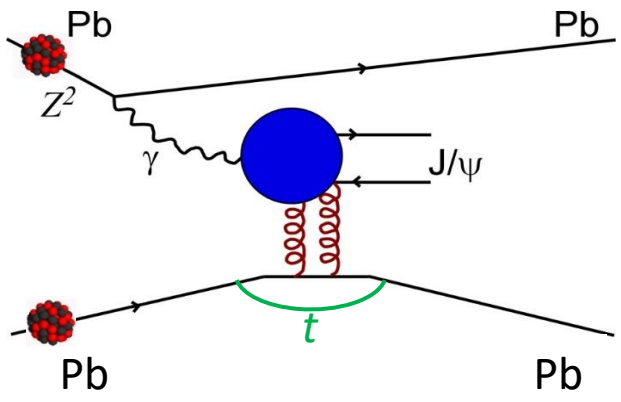

ALICE, PLB 817 (2021) 136280




$|t| \approx p_T^2$

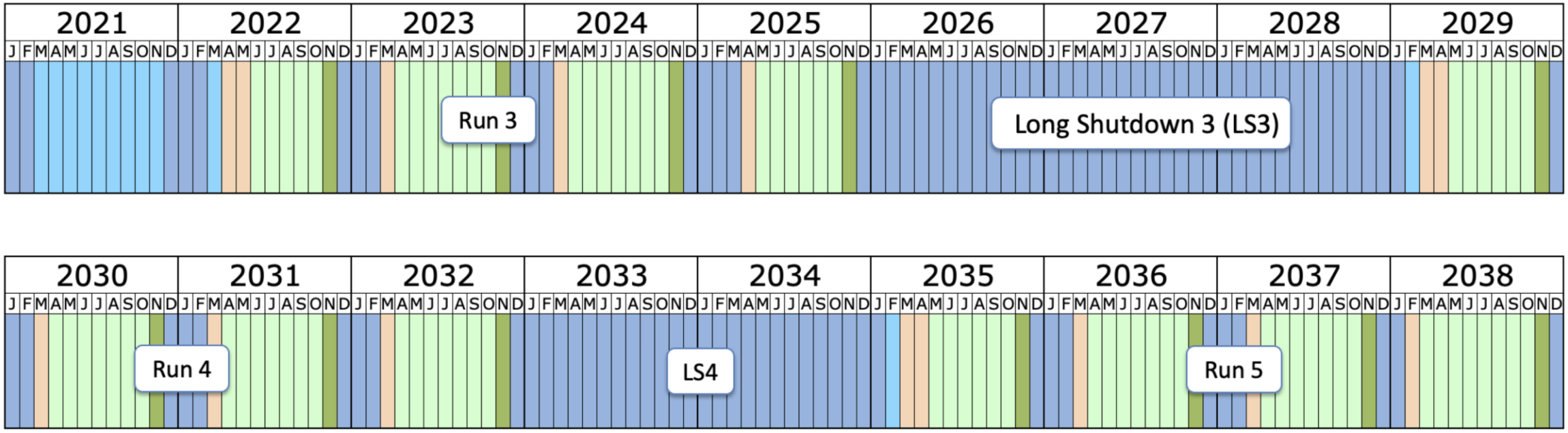
ALICE, arXiv:2305.06169



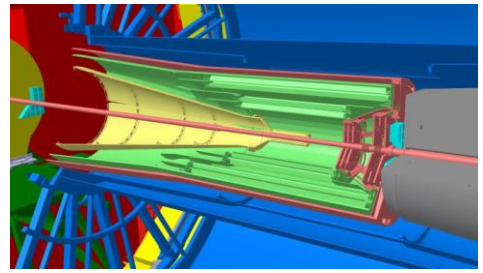

- Coherent J/ψ: *t*-dependence sensitive to transverse gluon distribution
  - need shadowing/saturation effects to describe the data
- Incoherent J/ψ: *t*-dependence sensitive to the variance of the gluon field
  - data better described by models with sub-nucleon degrees of freedom

# ALICE in Run 3 and beyond

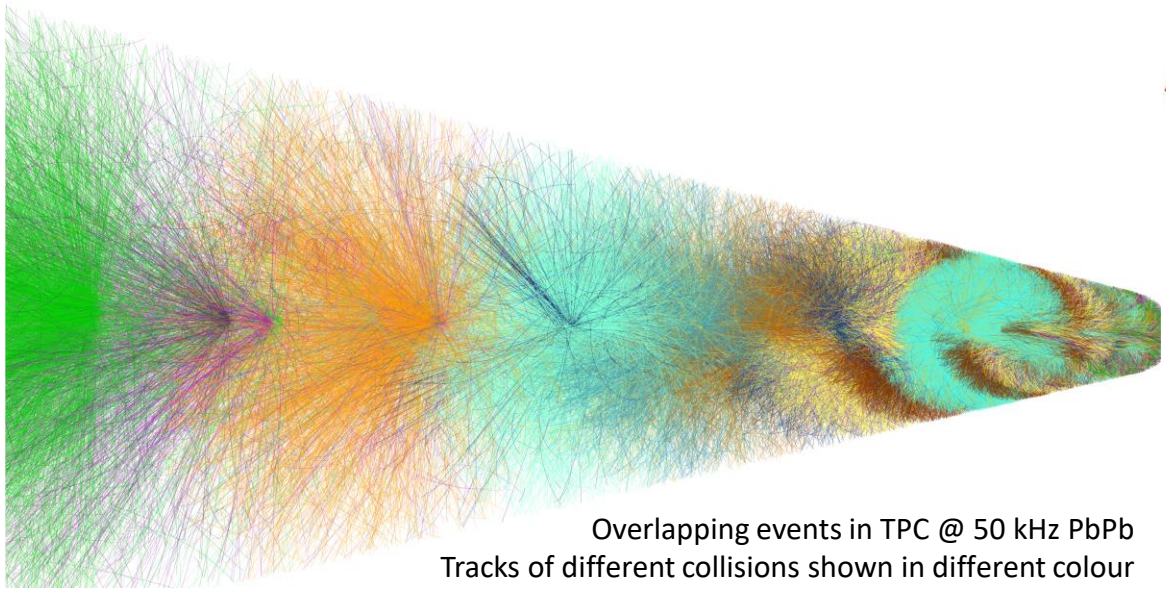


# ALICE in Run 3

- 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





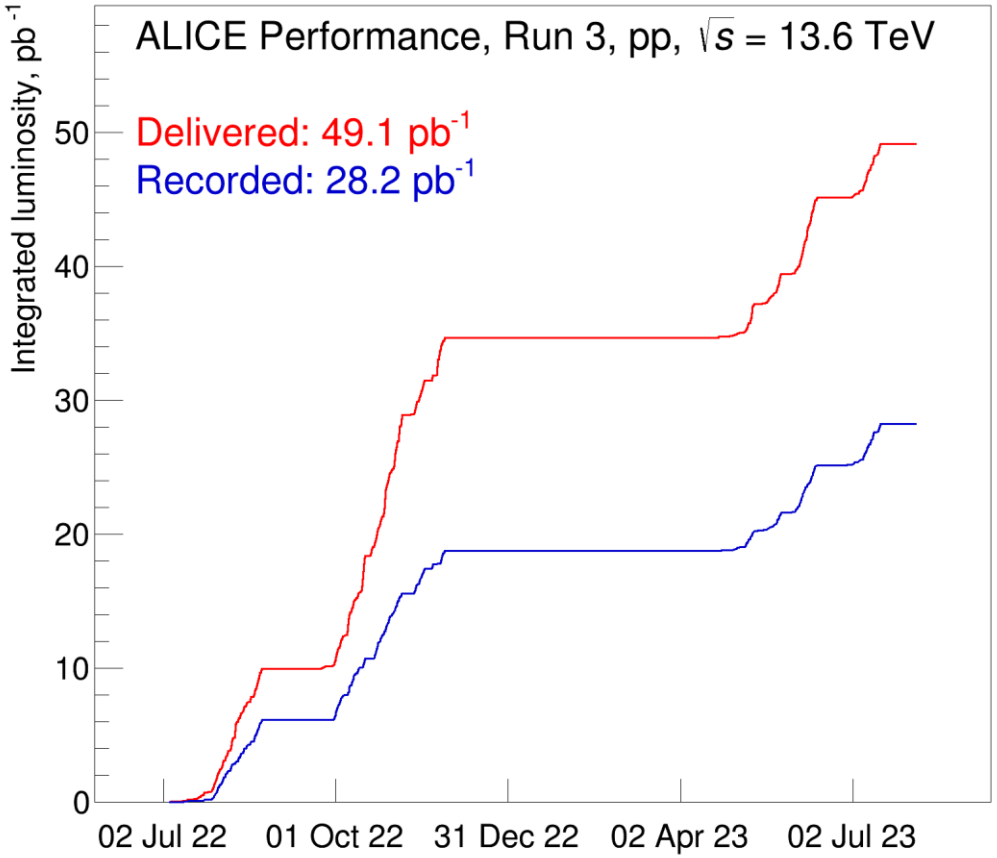


Overlapping events in TPC @ 50 kHz PbPb
Tracks of different collisions shown in different colour

Main goals:

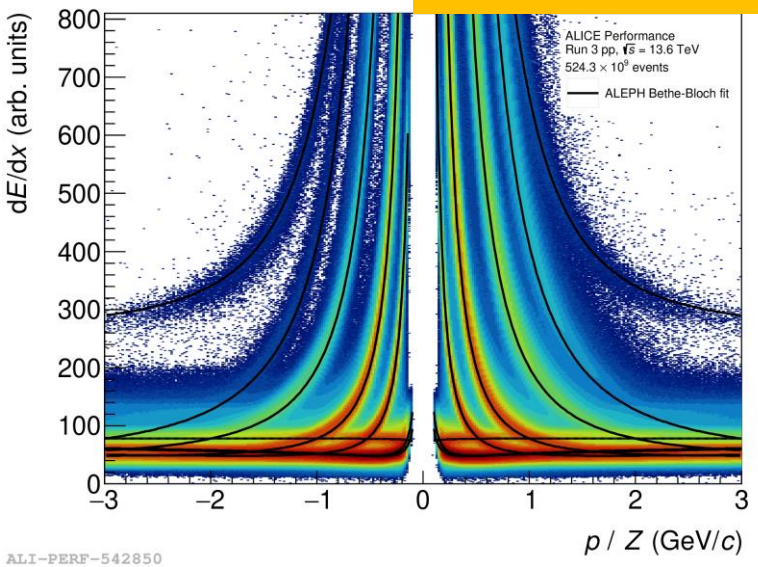
- Collect 13/nb in Run 3 and 4
  (x100 larger minimum bias statistics)
- Improve tracking precision by a factor 3-6

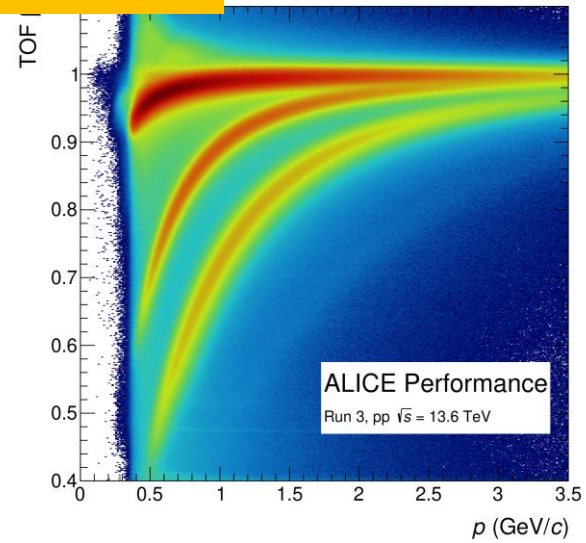
# ALICE performance in Run 3: pp data taking



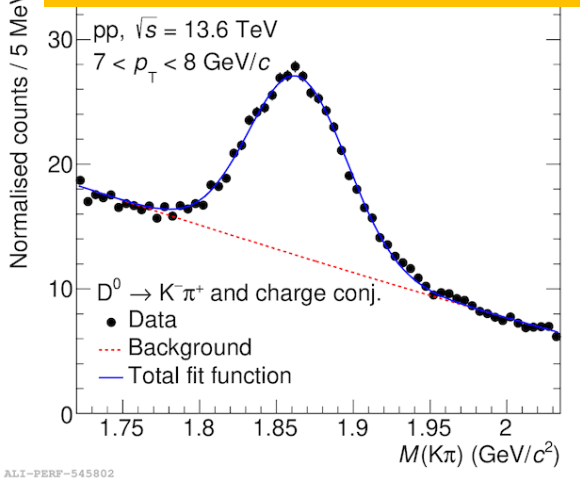

- **pp** data taking at **~500 kHz**
- Permanent storage of $10^{-4}$ selected time frames: using high-level software-based triggers

Excellent PID performance!

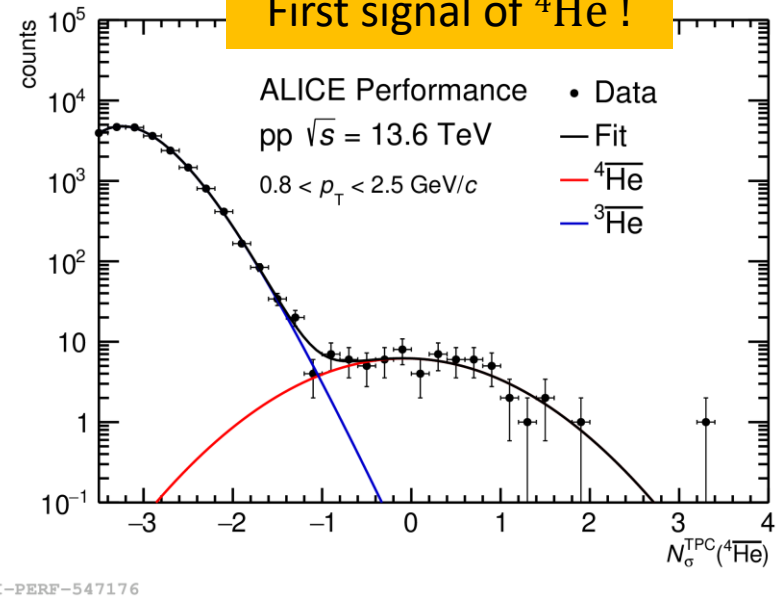


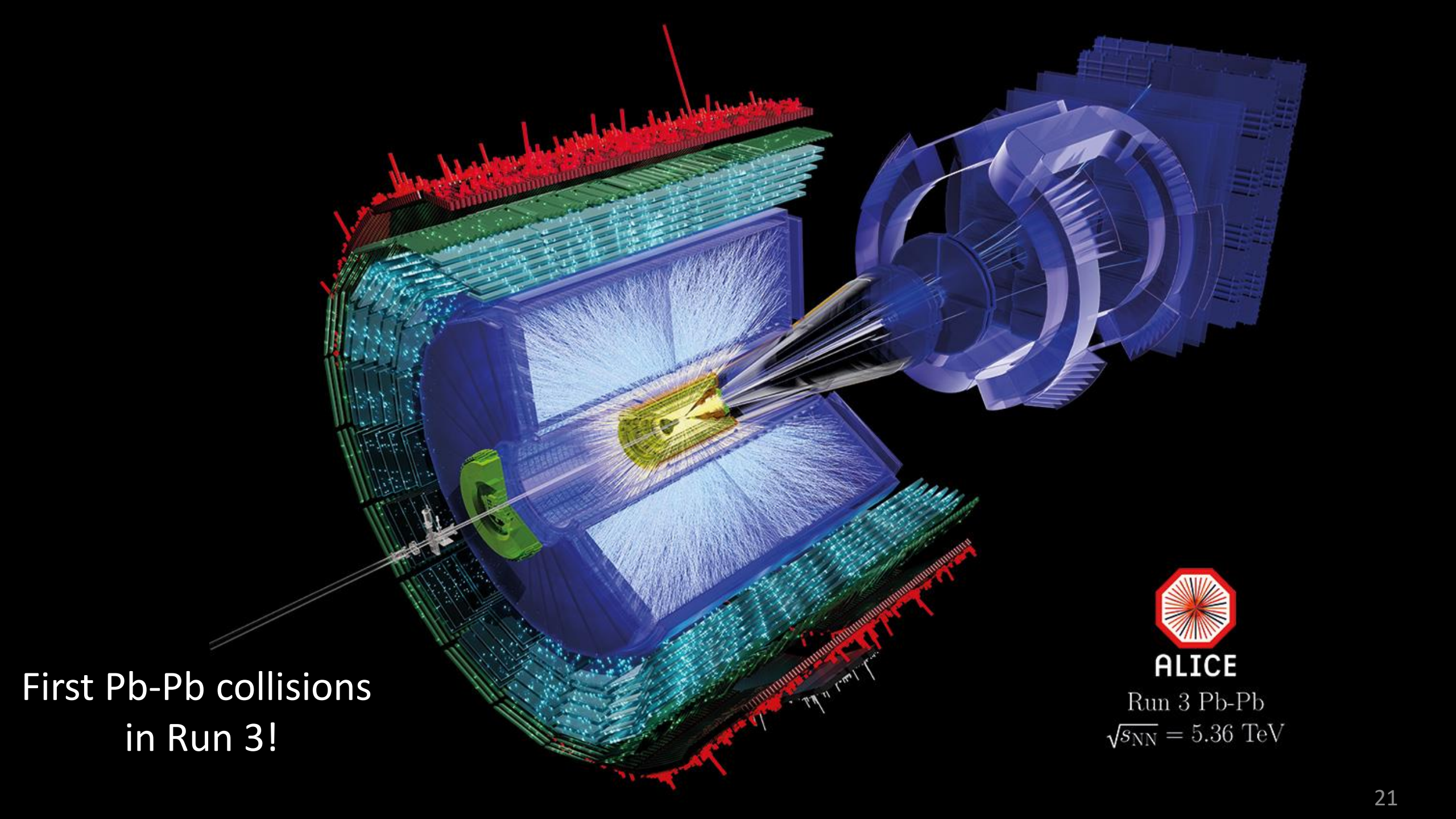




x100 more statistics for charm measurements




First signal of $^4\overline{\text{He}}$ !

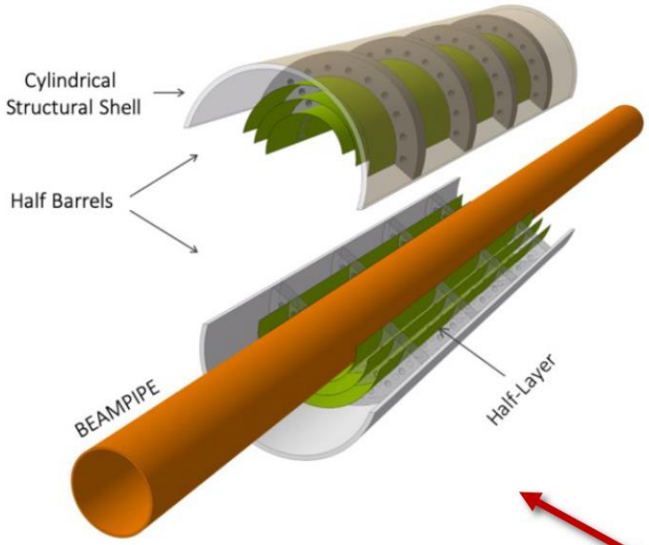





First Pb-Pb collisions
in Run 3!

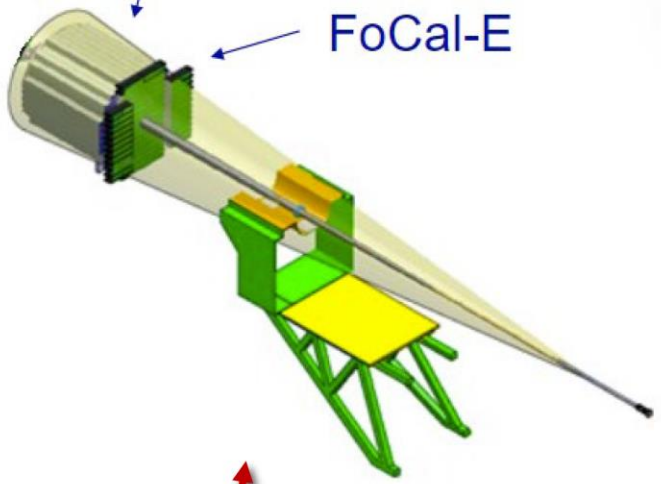
# Future upgrades

## ITS3



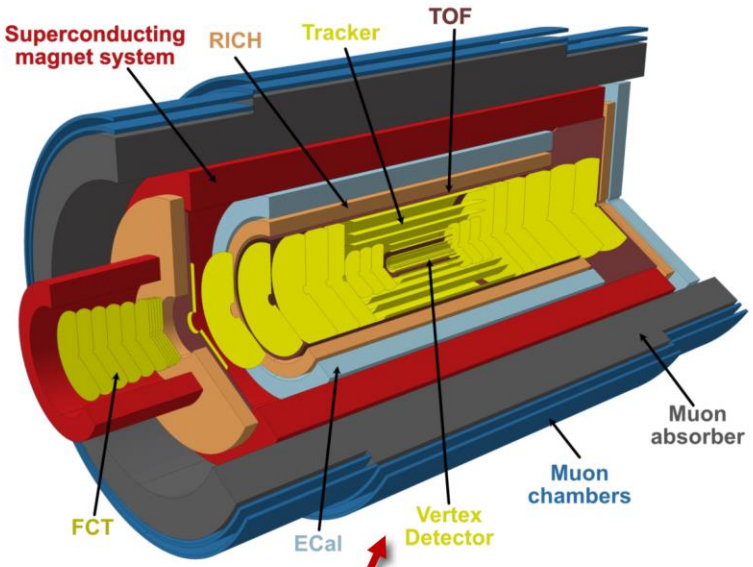

ALICE, CERN-LHCC-2019-018

## FoCal-H / FoCal-E




ALICE, CERN-LHCC-2020-009

## ALICE 3




ALICE, arXiv:2211.02491

# Summary

- A wealth of physics results from Run 1 and Run 2
- Providing quantitative estimates on QGP properties
- Summarized in the ALICE review paper (arXiv:2211.04384)
- Successful upgrade: excellent performance with continuous readout
- Looking forward to new Pb-Pb data this year!