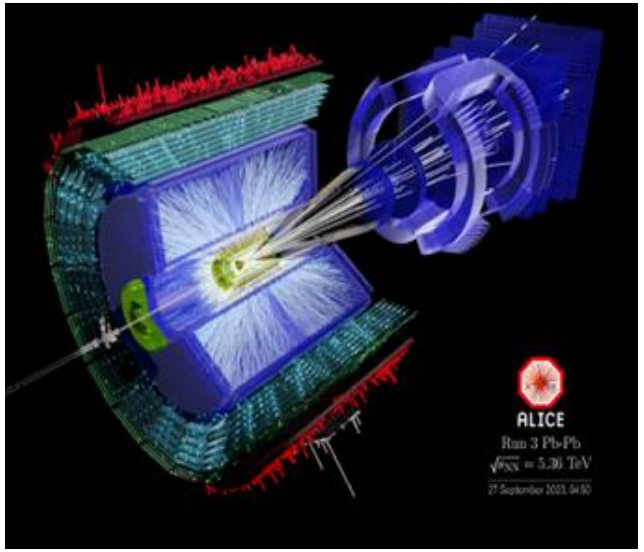
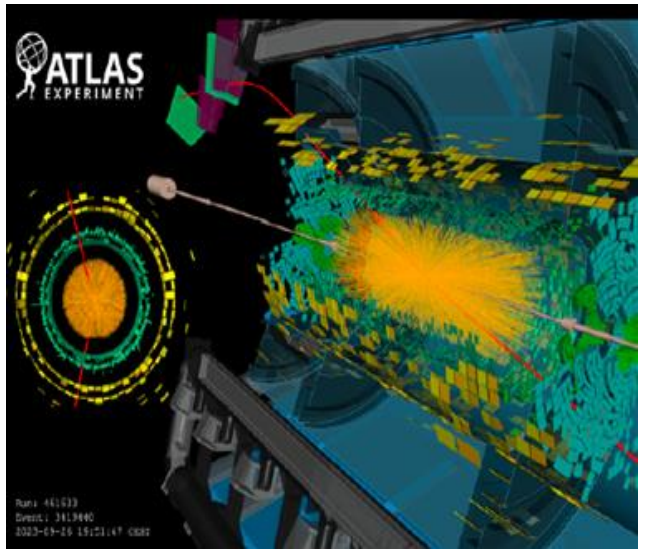
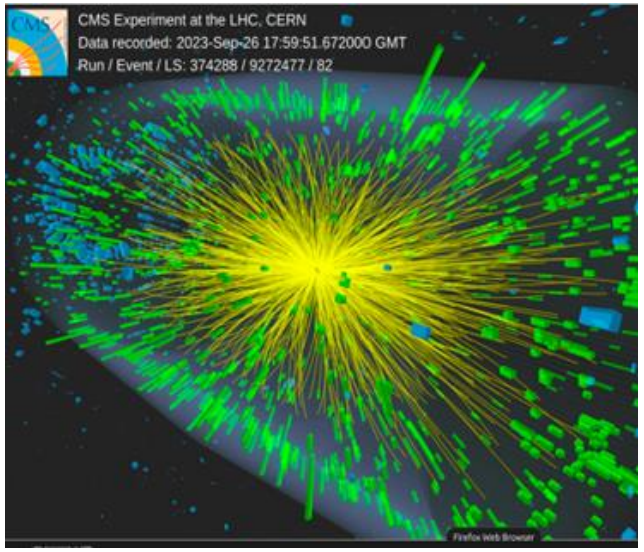


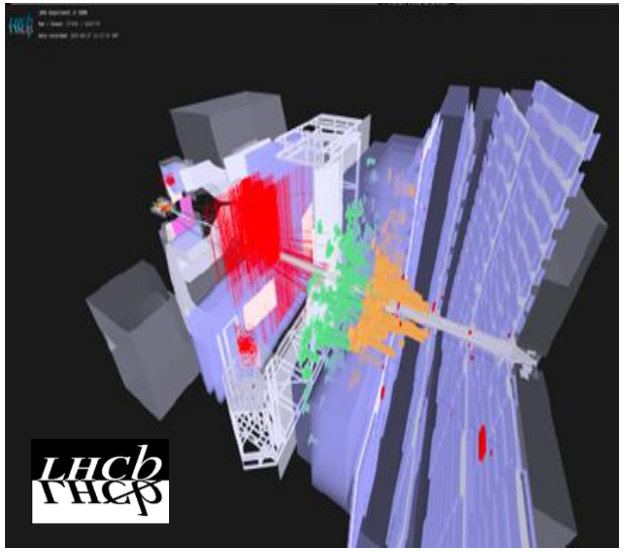


Overview of heavy-ion results at the LHC



Martino Gagliardi
(Università degli Studi and INFN, Torino)

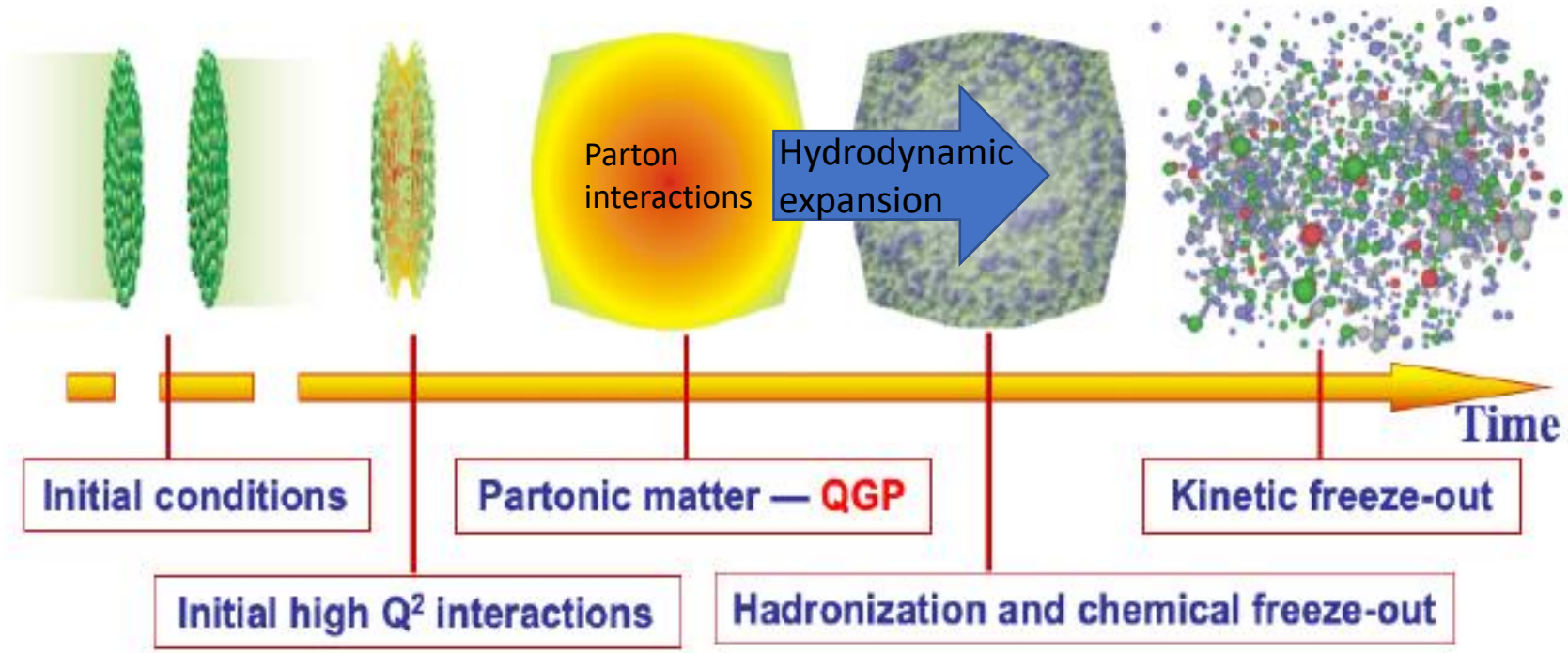
for the
ALICE, ATLAS, CMS, LHCb collaborations



Heavy-ion physics at the LHC

Main physics goal:

characterize the **quark-gluon plasma** formed in heavy-ion collisions at the LHC



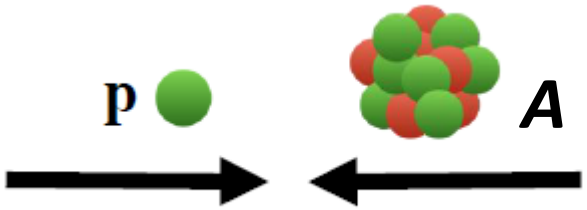
Adapted from figure by S. Bass, Duke University

Pb-Pb collisions at the LHC:
longest-lived, hottest ($\varepsilon > 15$ GeV/fm^3), **largest** (~5000 fm^3) QGP ever studied

Heavy-ion physics at the LHC

p-A collisions

- **p-Pb** (all exp.) + LHCb SMOG*

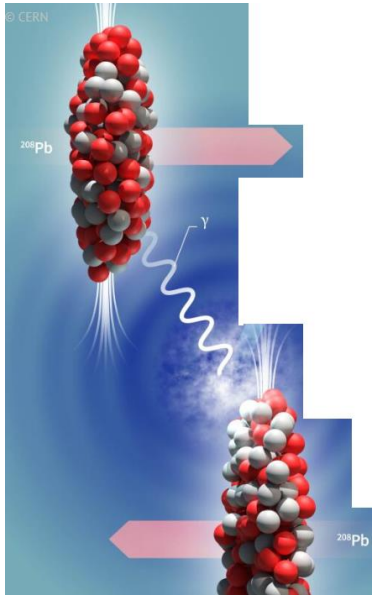


- Investigate the **initial state** (nuclear PDF) and other **"cold" nuclear matter effects**

- search for **QGP-like effects in small systems** (also high mult. pp)
  → more in J. F. Grosse-Oetringhaus's talk

* Injection of gas at the LHCb IP during beam-time
→ **fixed-target program**: p, Pb on He, N, Ar

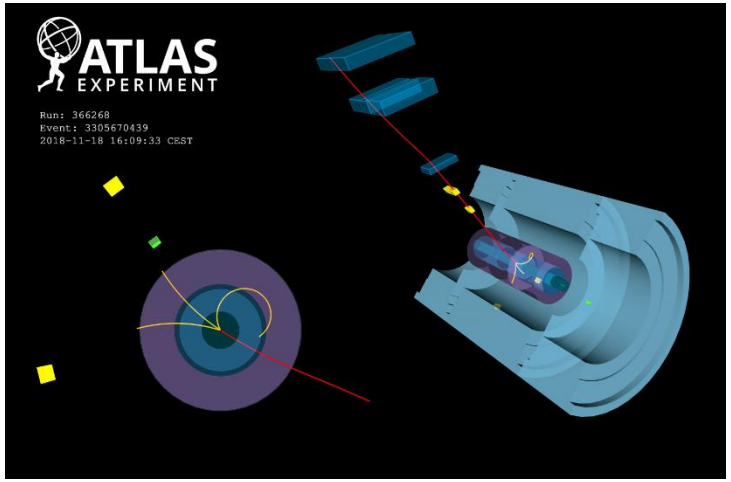
Ultra-Peripheral Pb-Pb collisions



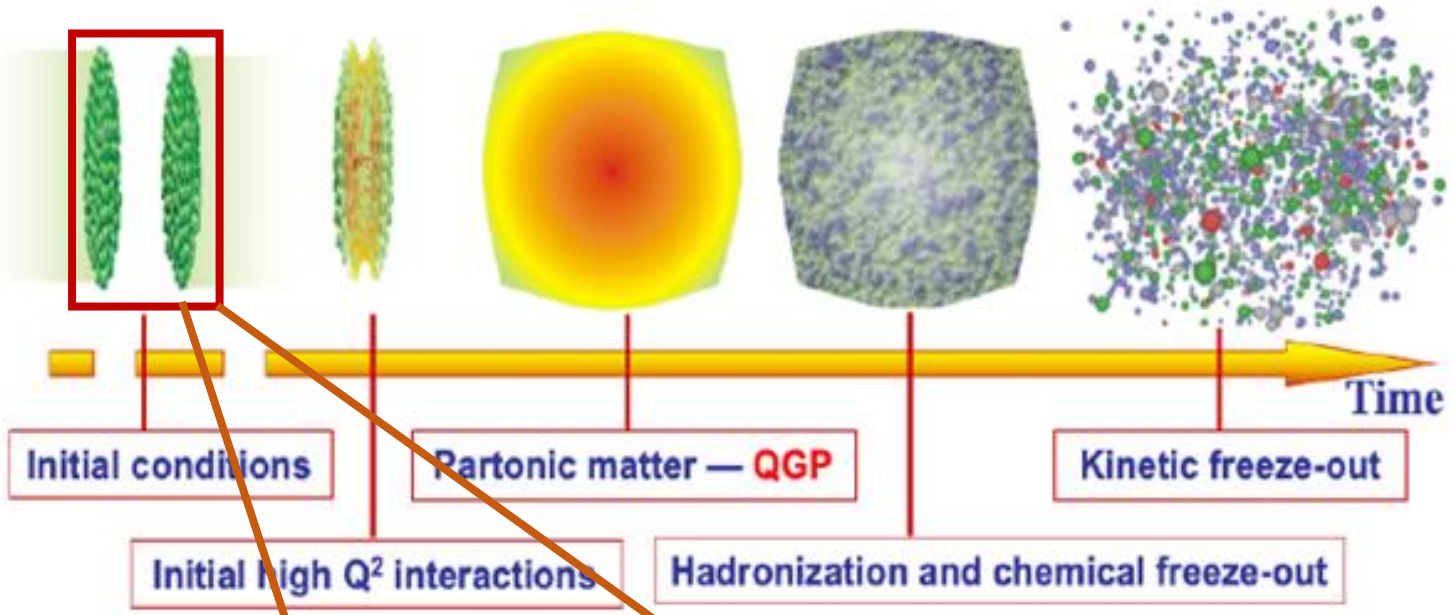
- DIS of **γ on Pb**

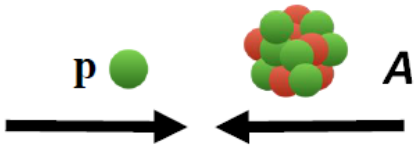
- study of the initial state (**nuclear PDF**)

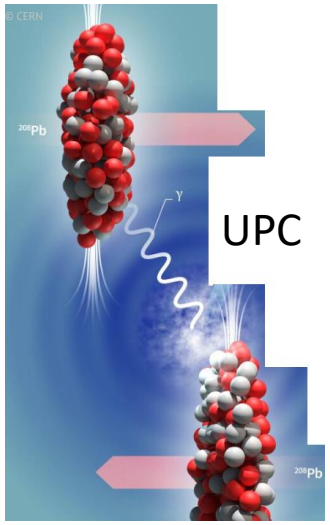
- and much more (search for BSM physics, quantum effects…)

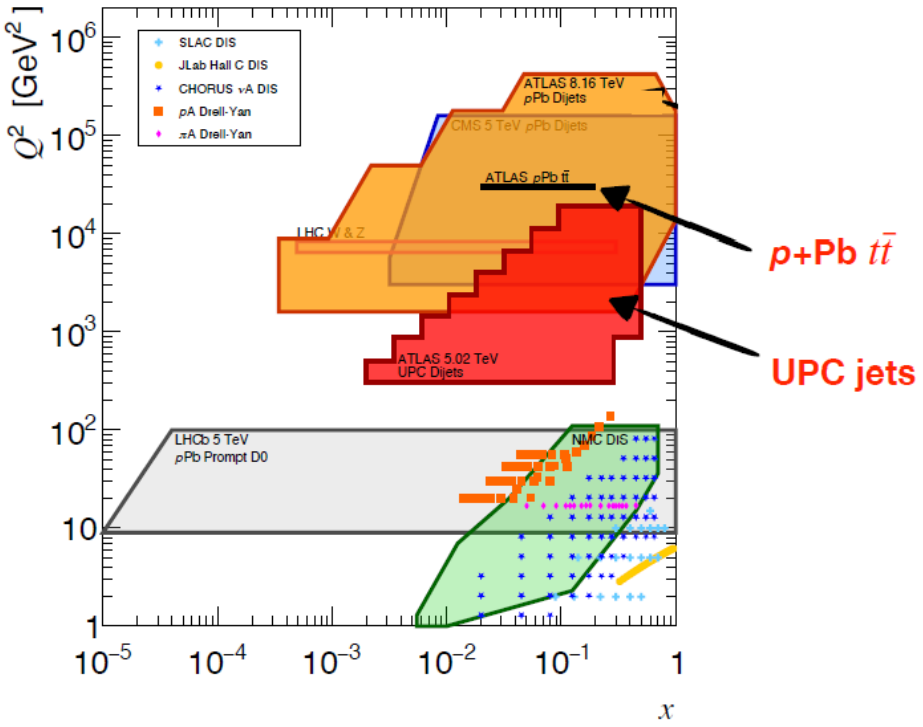


Studying the QCD structure of nuclei

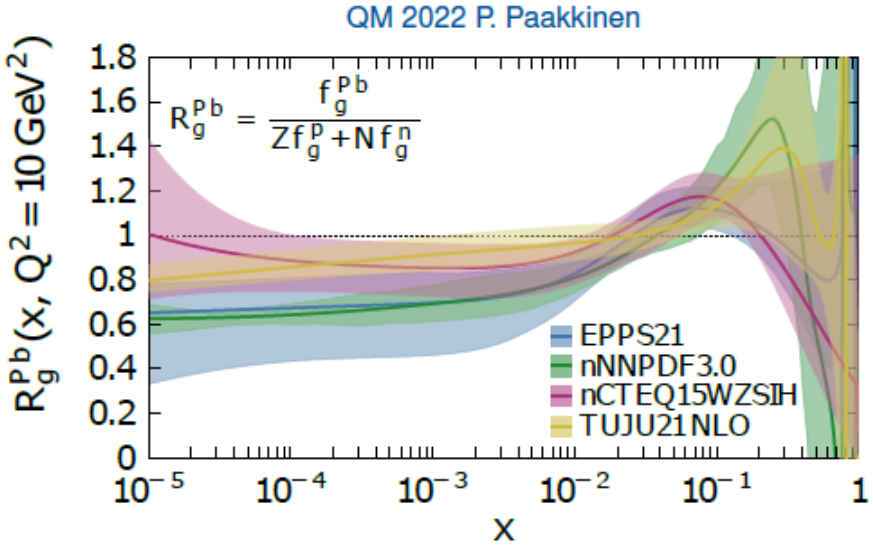


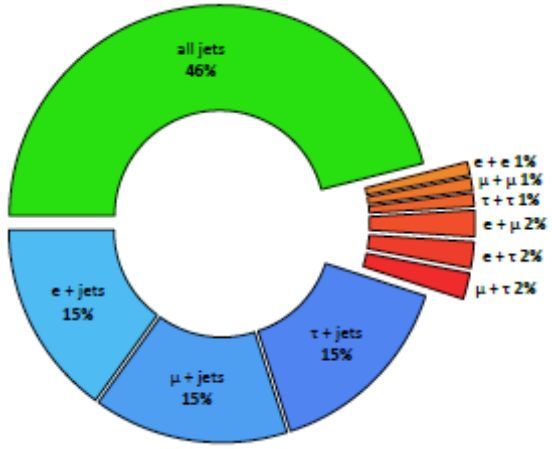


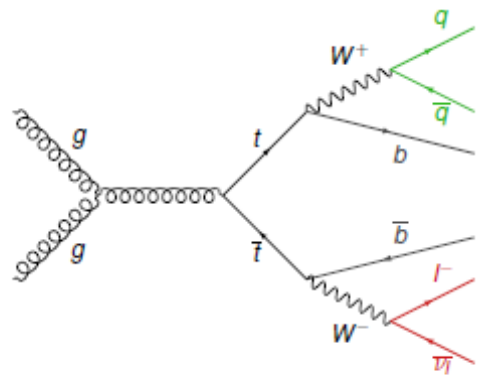


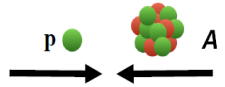


Nuclear PDF studies with p-Pb collisions: top-quark production

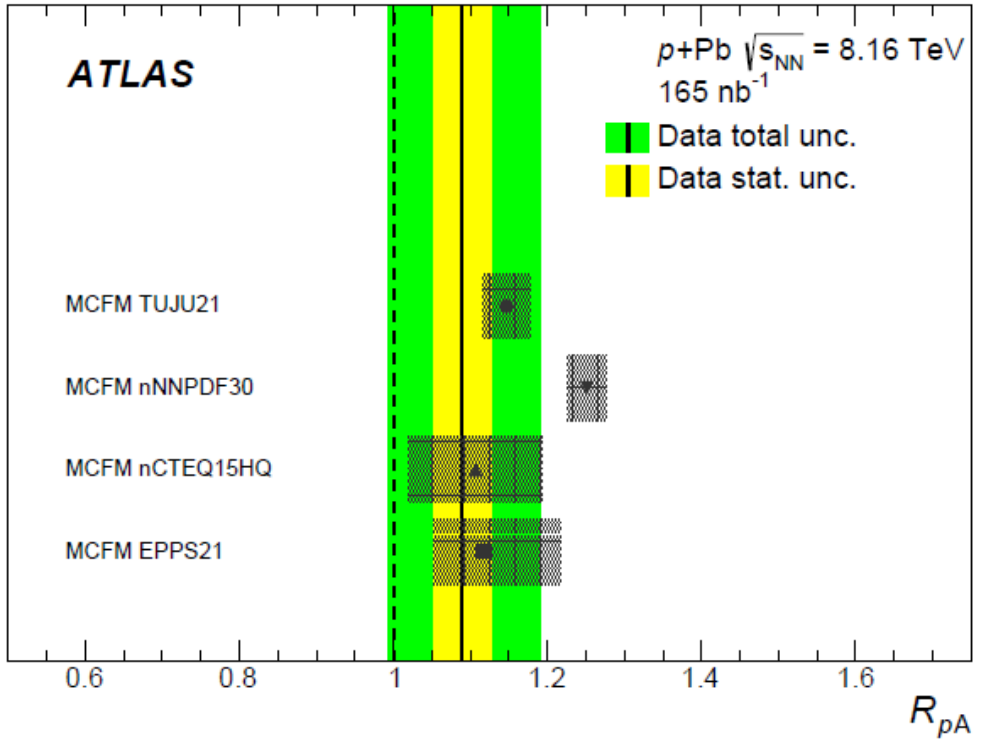








arXiv:2405.05078



Constrain gluon nPDFs at large x (anti-shadowing region), where uncertainties are large

Cross section measured in all dilepton and lepton + jets channels, then combined

Measurement of

$$R_{\mathrm{pPb}} = \frac{\sigma_{\mathrm{pPb}}}{A_{\mathrm{Pb}}\sigma_{\mathrm{pp}}} = 1.090 \pm 0.039\ (\mathrm{stat.})\ ^{+0.094}_{-0.087}\ (\mathrm{syst.}).$$

Comparison to calculations with **several nPDF sets**

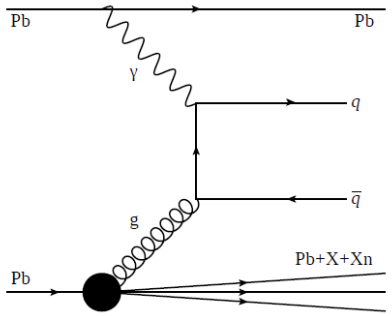
Nuclear PDF studies: jet and D^0 production in UPCs

ATLAS **jets in UPC**:

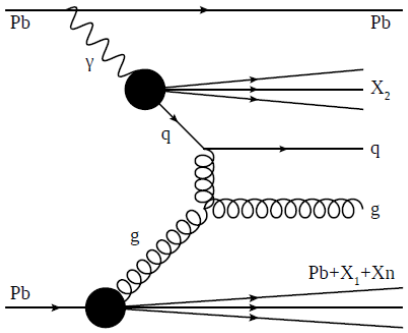
Exclusive production selection via **rapidity gaps**

~**10% precision**, on the order of differences between nPDF sets

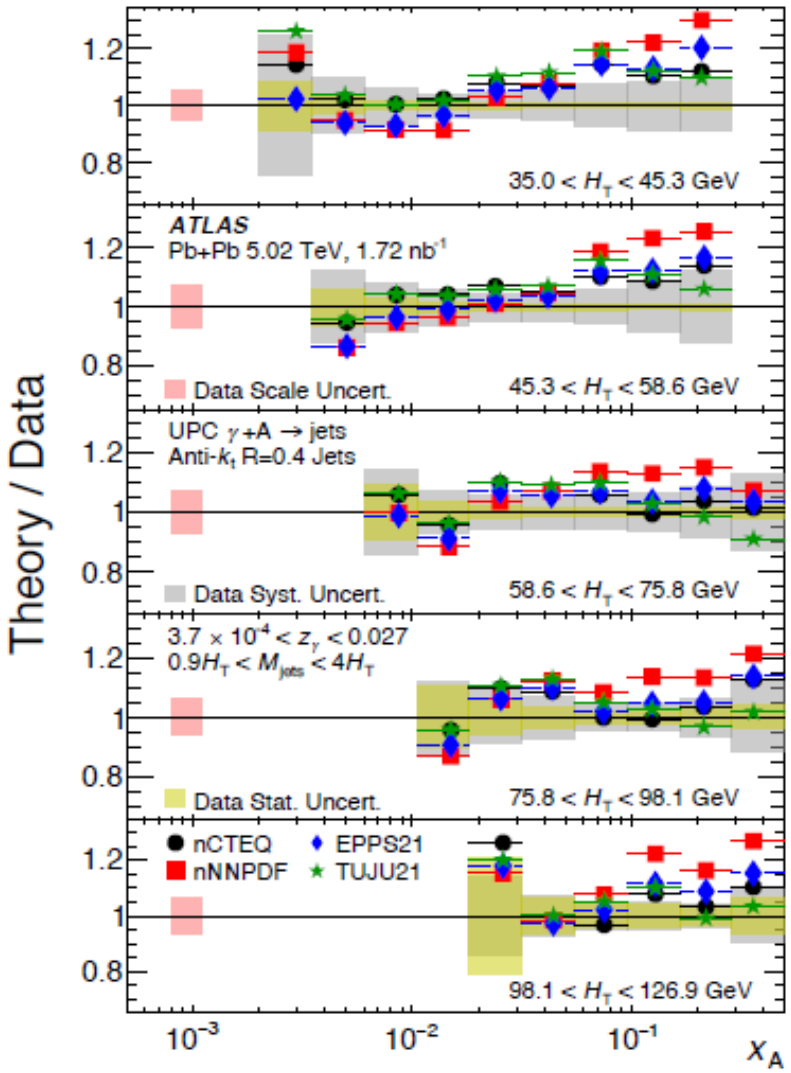
direct



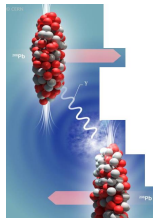
resolved

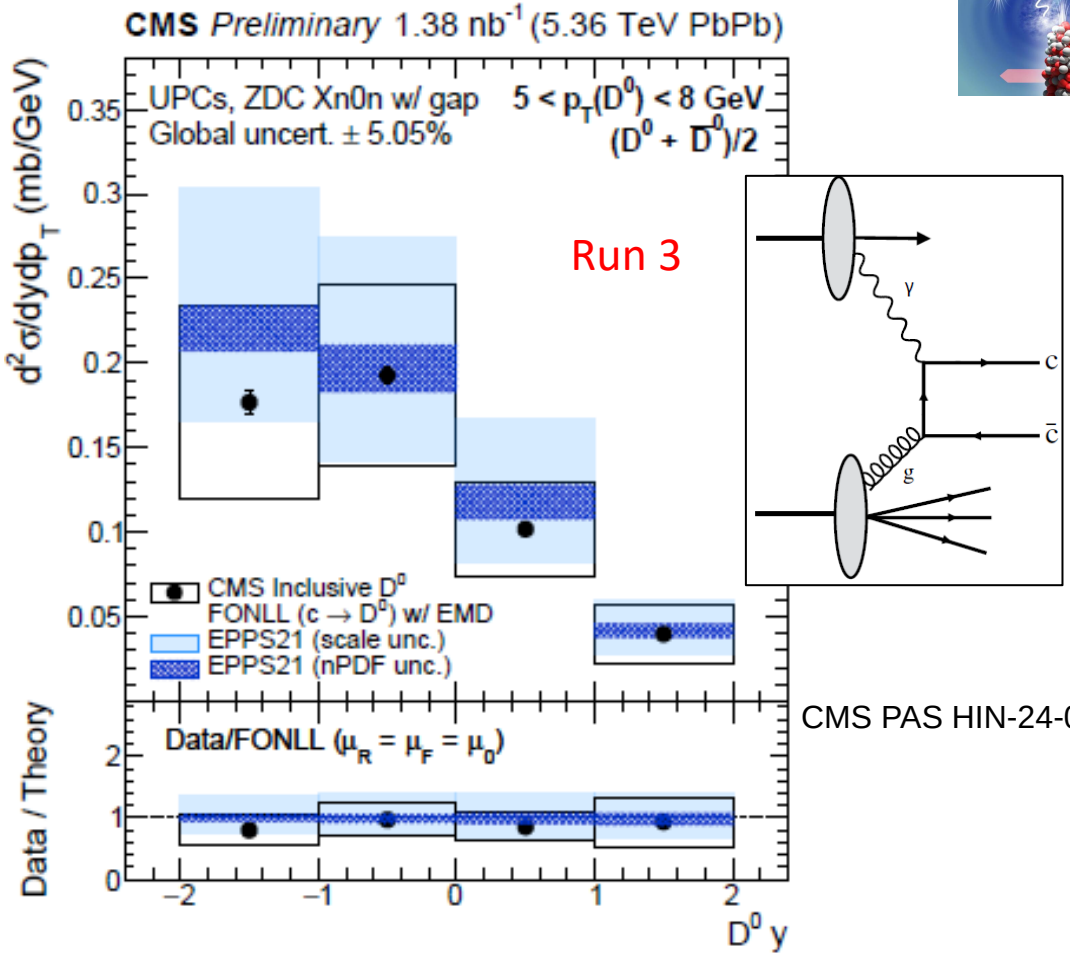


arXiv:2409.11060



CMS D^0 **in UPC**: **sensitive to nPDF at small *x*** over a large range of Q^2

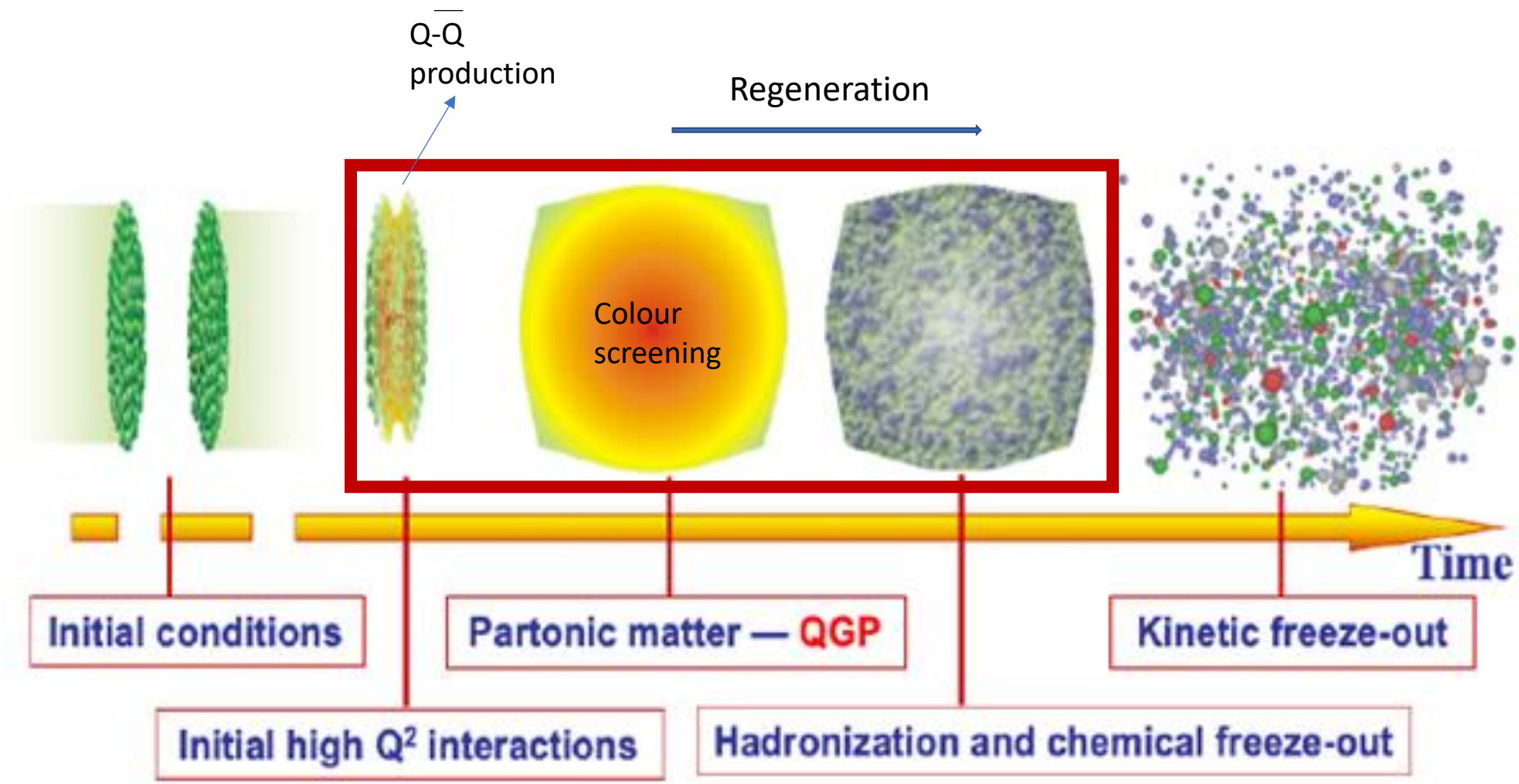




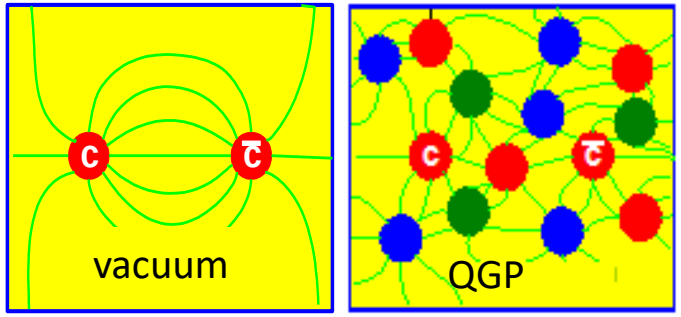
CMS PAS HIN-24-003

Expected yield in Run 3+4 x10^3 larger than in Run 2

Studying the deconfined phase via quarkonium production



Bottomonium suppression



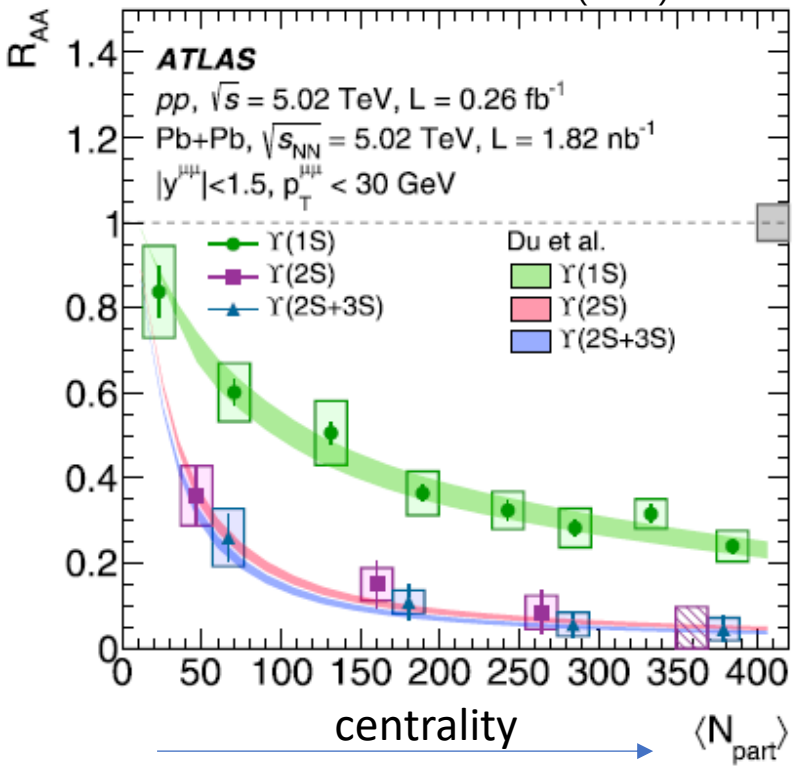
Quarkonium **suppression by colour screening** is a QGP smoking gun

'Textbook' results by ATLAS & CMS on Υ states suppression

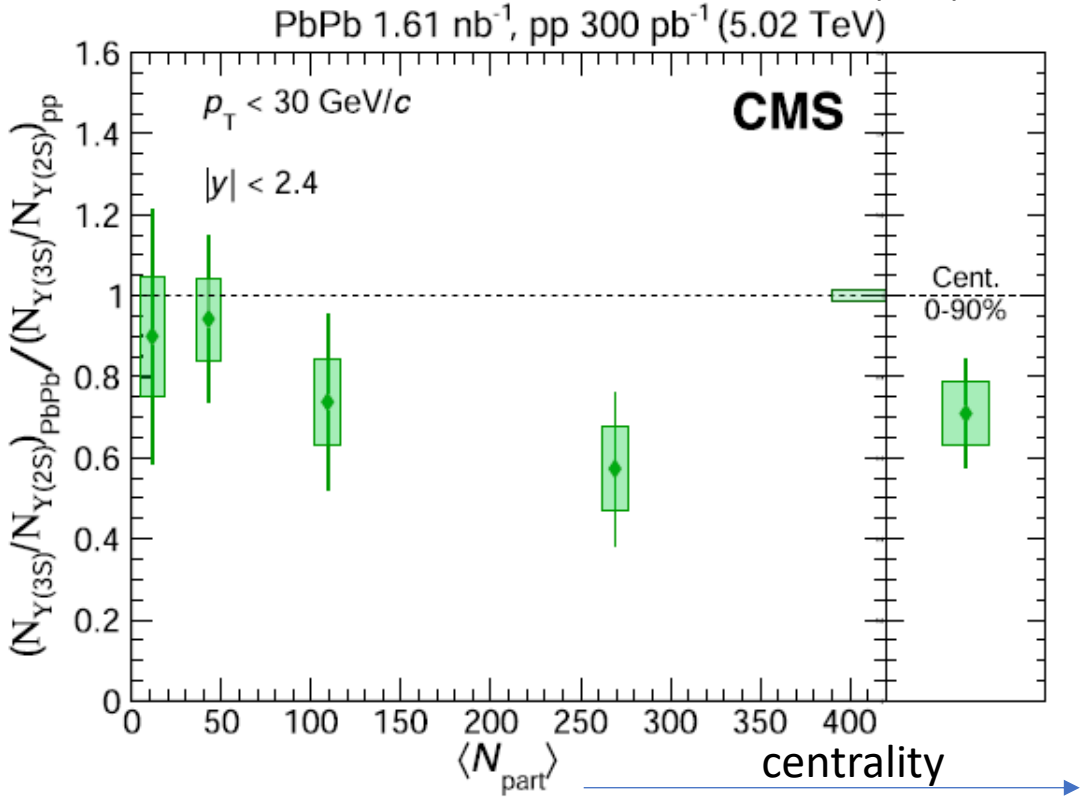
Including **sequential melting**
(larger suppression for more weakly bound states)

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$

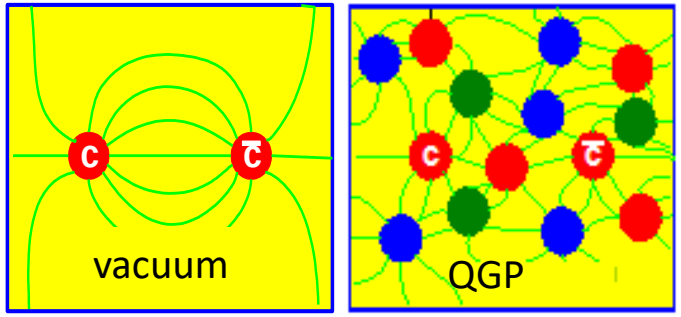
PRC 107 (2023) 054912



PRL 133 (2024) 022302



Charmonium suppression and regeneration

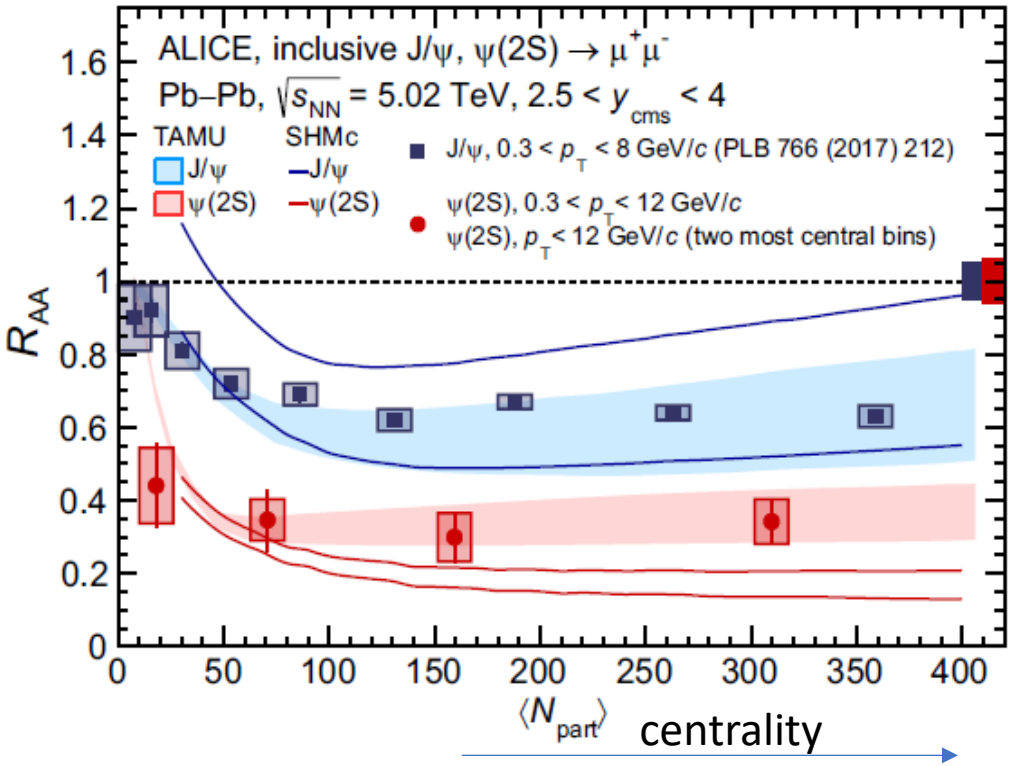


Quarkonium **suppression by colour screening** is a QGP smoking gun

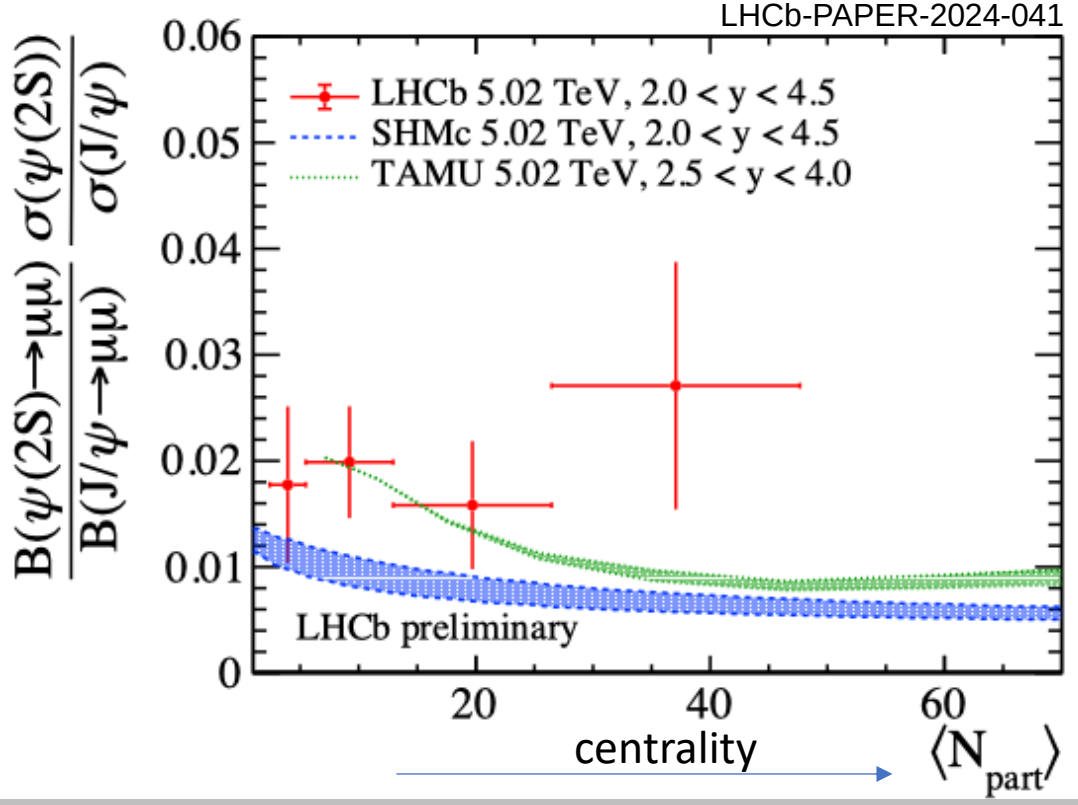
ψ(2S) more suppressed than J/ψ (**sequential melting**)

Large charm cross section at LHC energies
→ **charmonium regeneration** from recombination of uncorrelated $c\bar{c}$ pairs
centrality dependence best reproduced by transport model (TAMU)

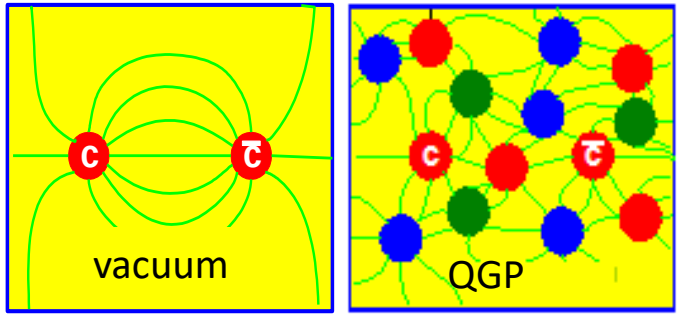
PRL 132 (2024) 042301



LHCb-PAPER-2024-041



Charmonium suppression and regeneration

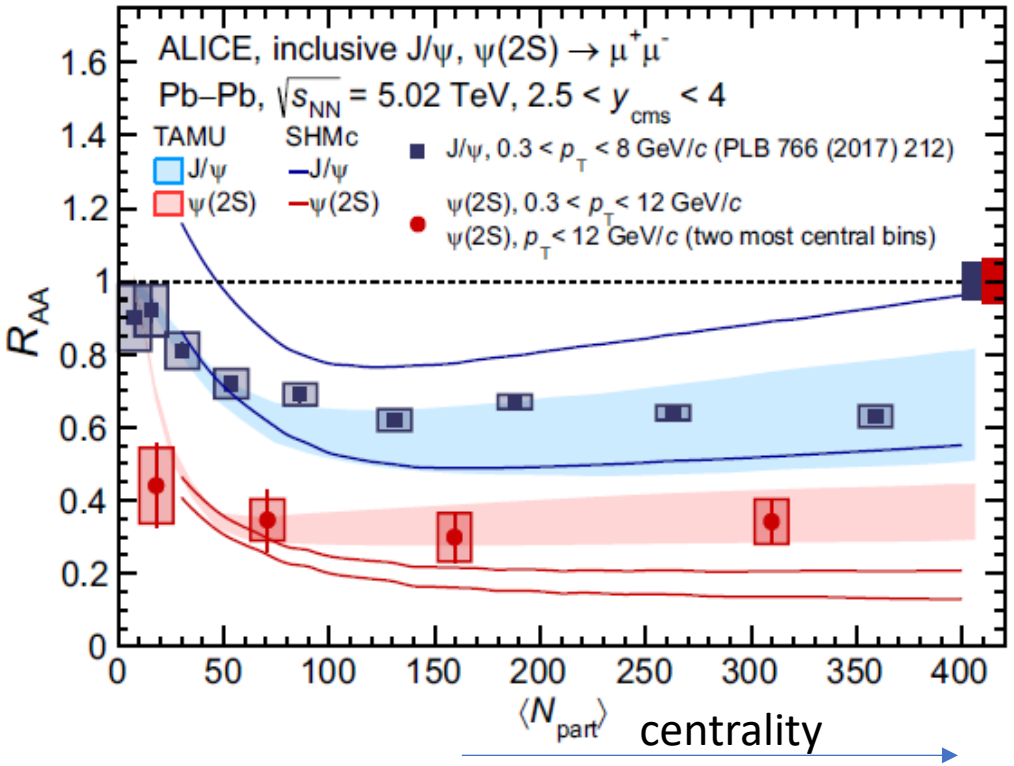


Quarkonium **suppression by colour screening** is a QGP smoking gun

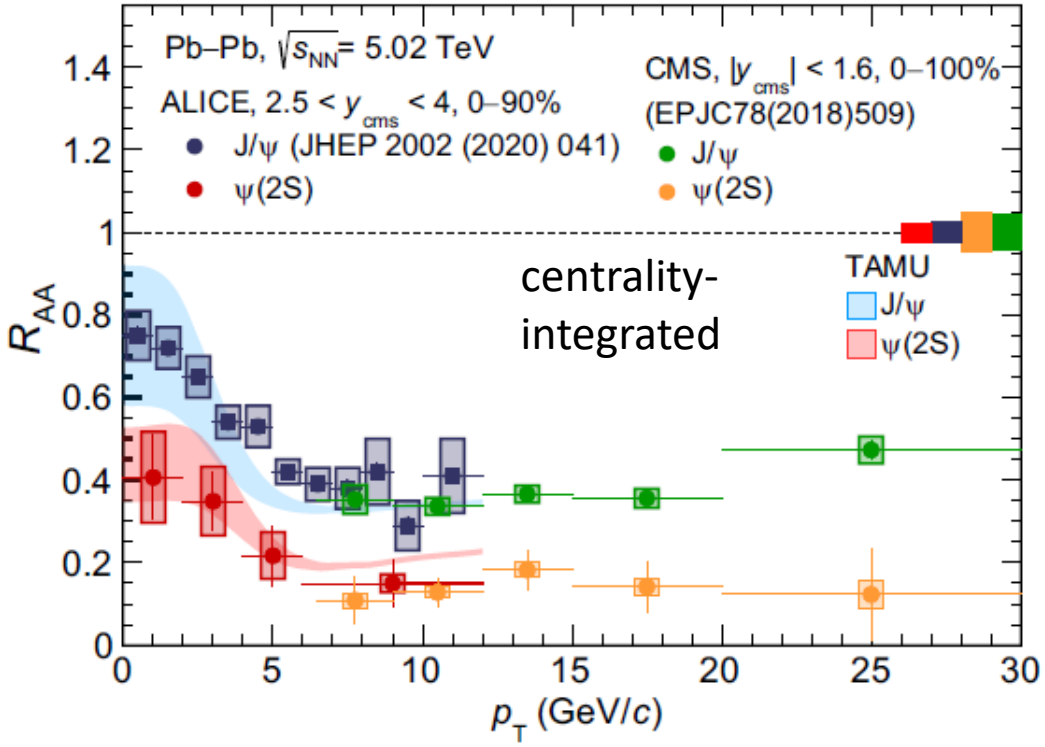
ψ(2S) more suppressed than J/ψ (**sequential melting**)

Large charm cross section at LHC energies
→ **charmonium regeneration** from recombination of uncorrelated $c\bar{c}$ pairs mainly visible at **low** to intermediate p_T

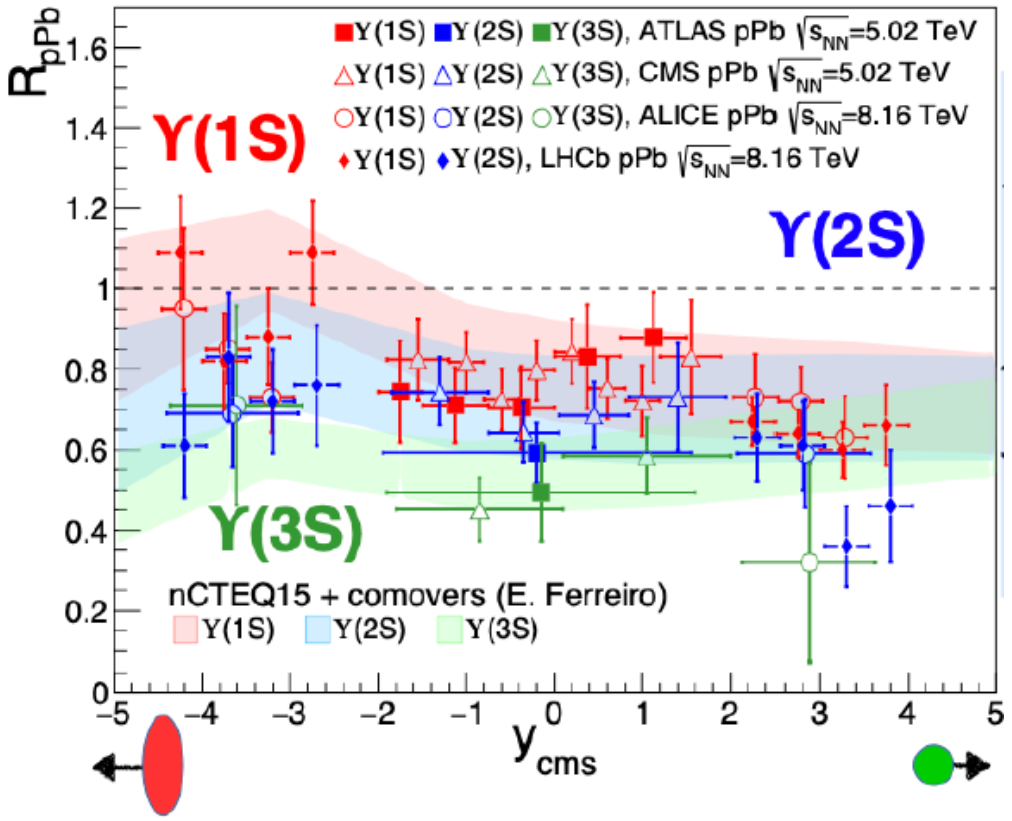
PRL 132 (2024) 042301



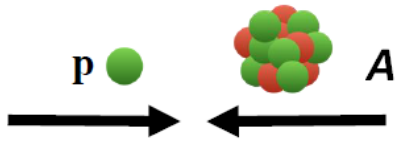
PRL 132 (2024) 042301



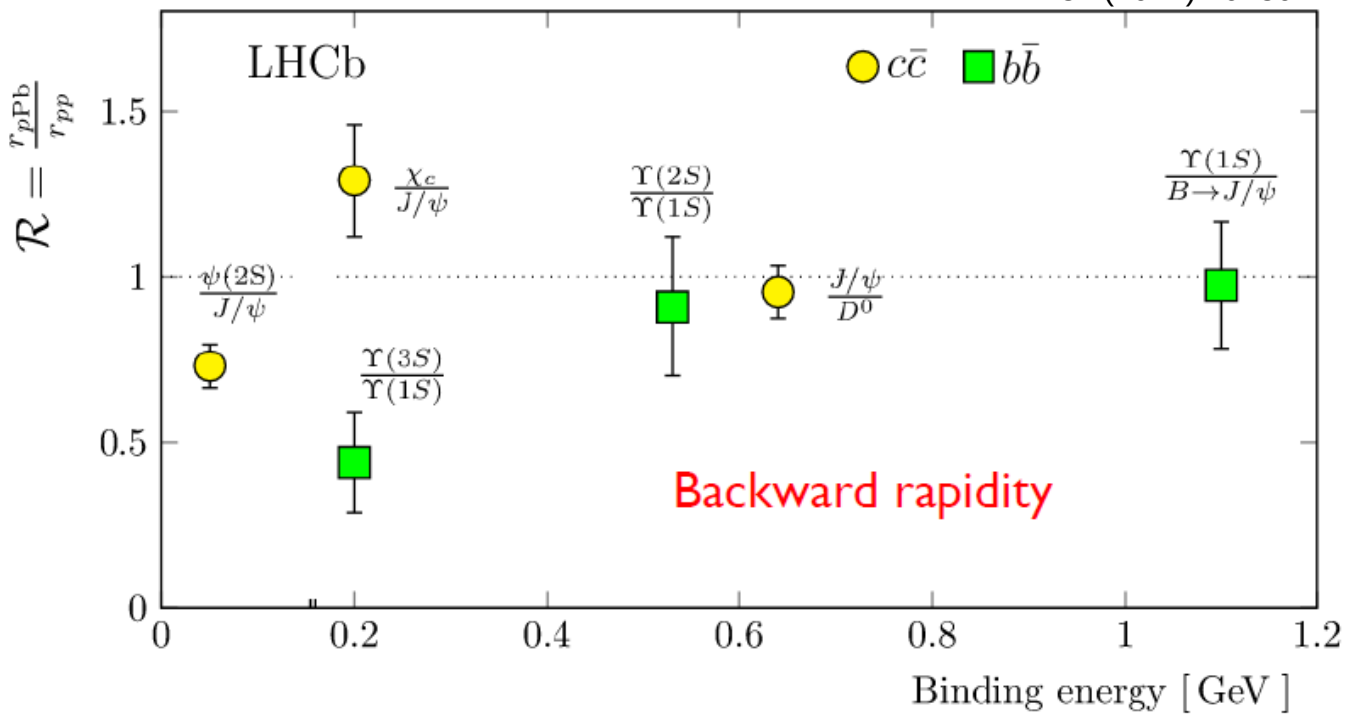
Cold nuclear matter effects in quarkonium production



LHCb JHEP 11 (2018) 194
ATLAS EPJC 78 (2018) 171
ALICE PLB 806 (2020) 135486
CMS PLB 835 (2022) 137397



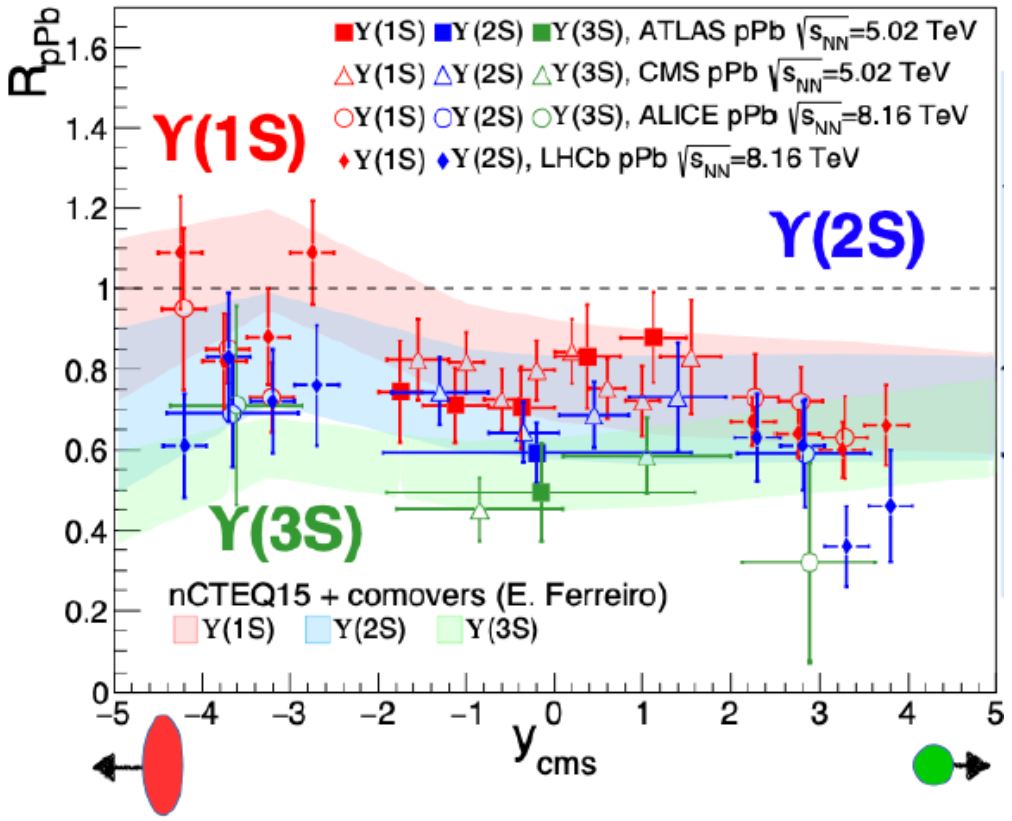
PRL 132 (2024) 102302



Nuclear modification factor in p-Pb is sensitive to **modification of the PDFs**…

.. but **final-state effects** (e.g. dissociation by comovers) would be required to explain **differences between excited and ground states**
→ calls for more precise measurements

Cold nuclear matter effects in quarkonium production



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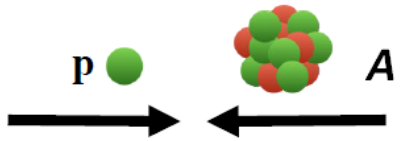
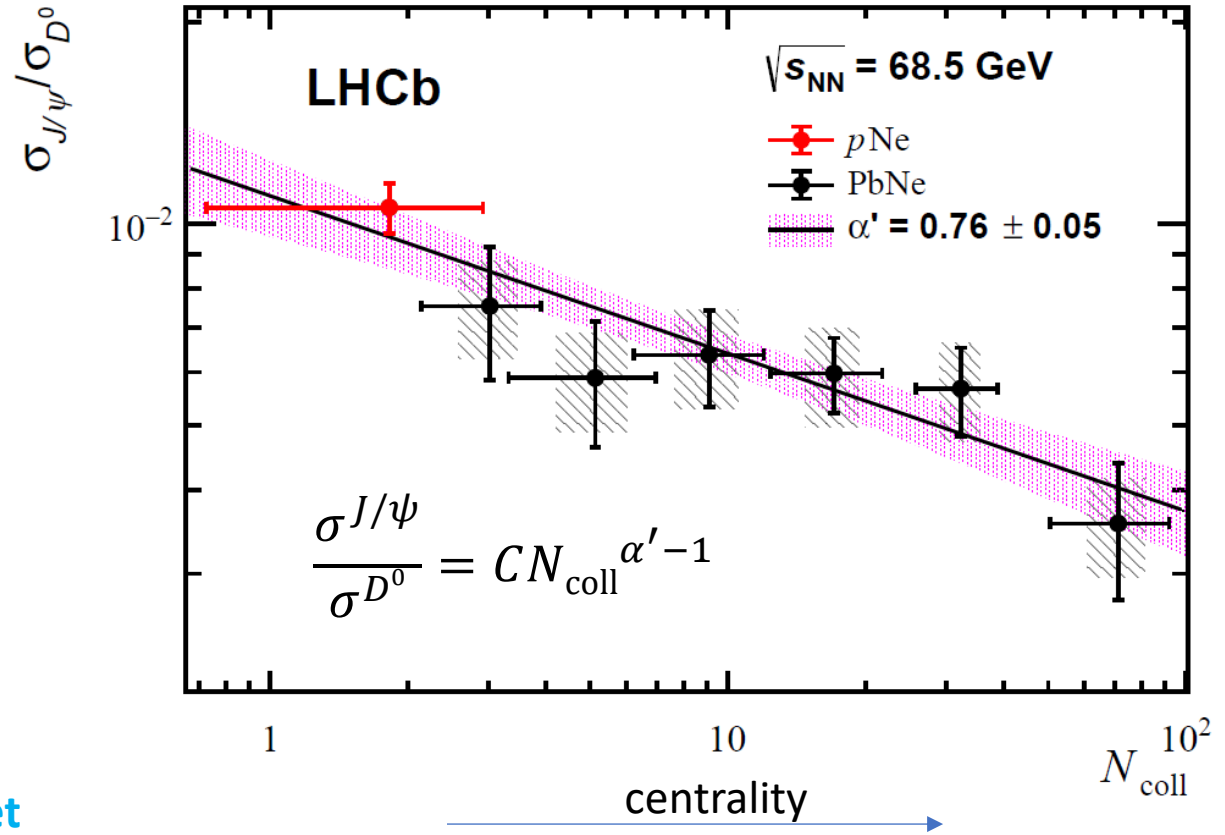


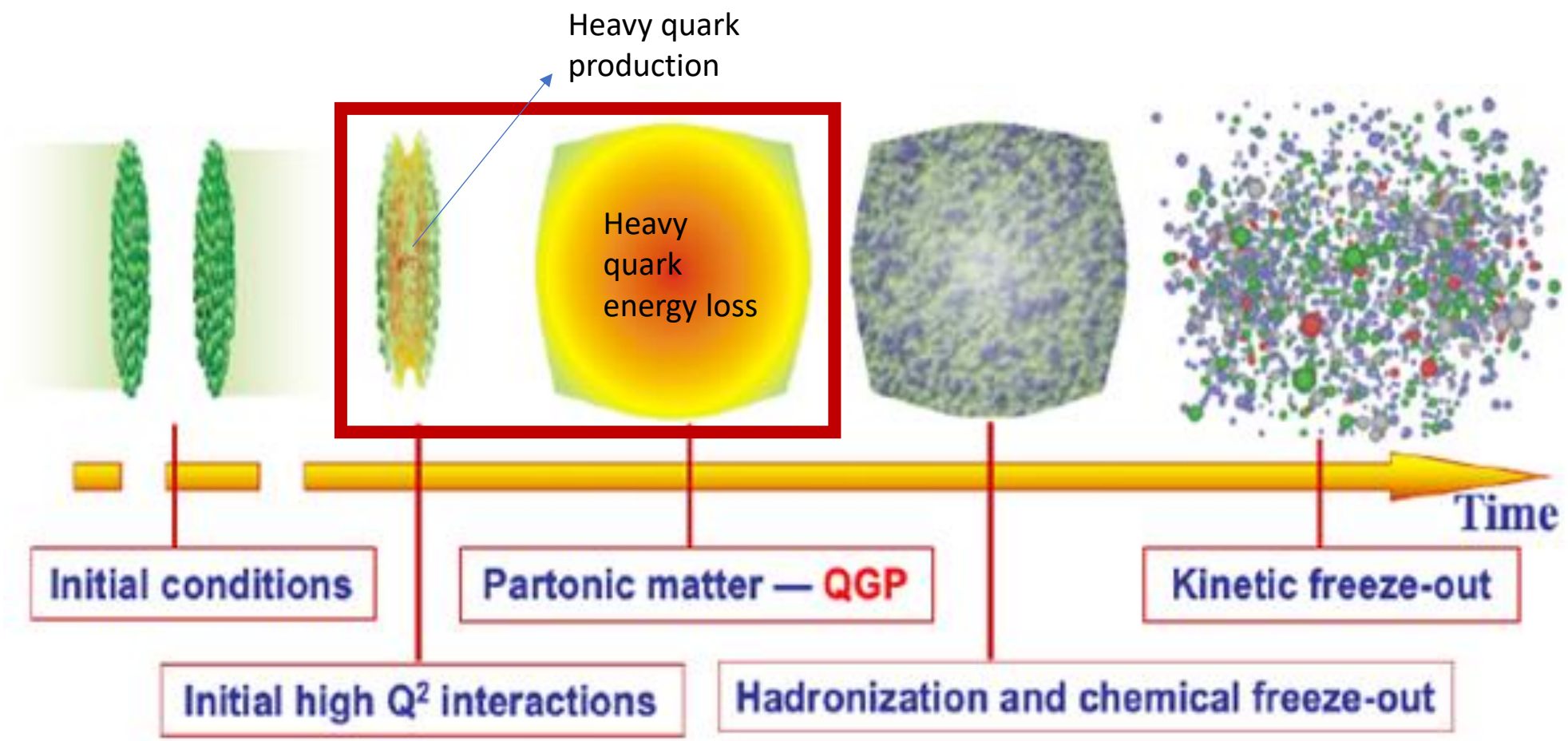
EPJC 83 (2023) 658



Nuclear modification factor in p-Pb is sensitive to **modification of the PDFs**…

J/ψ / D^0 ratio in PbNe and pNe vs N_{coll} from **LHCb fixed-target** program: **different (final?) nuclear effects for J/ψ and D^0**

Parton interactions in the medium: charm and beauty



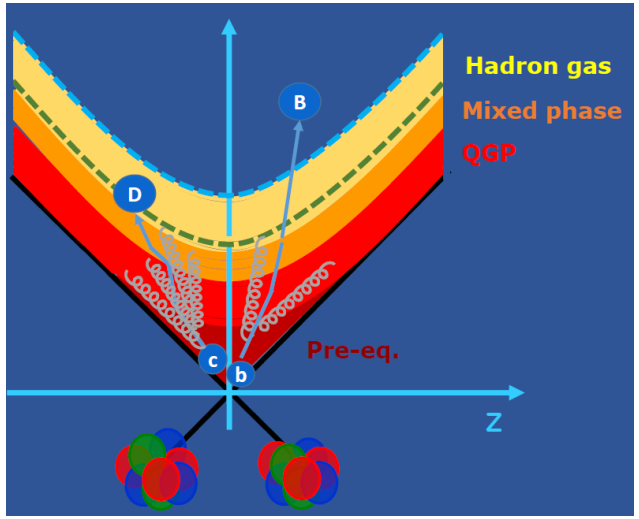
Parton interactions in the medium: charm and beauty

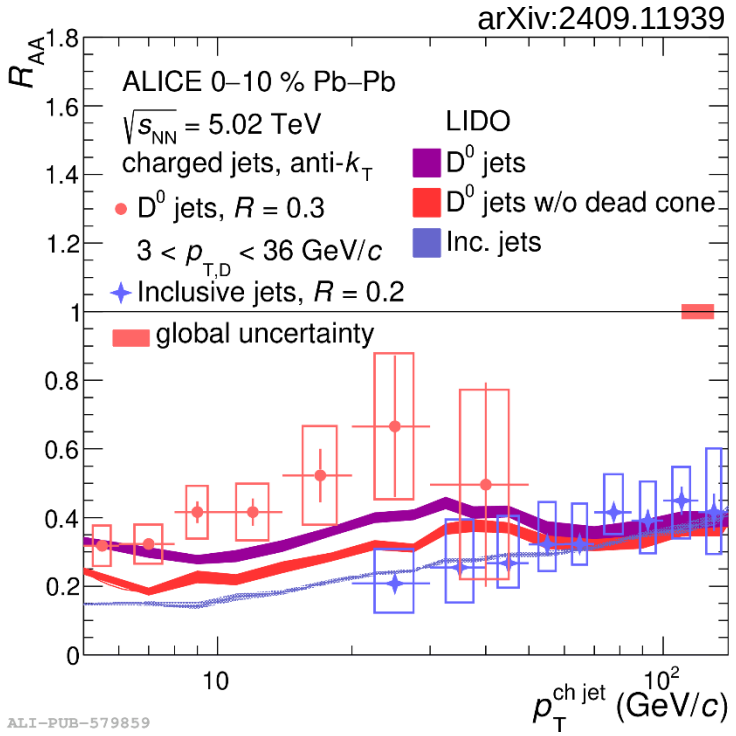
Heavy quarks produced early in the collision,
then **experience the full medium evolution**

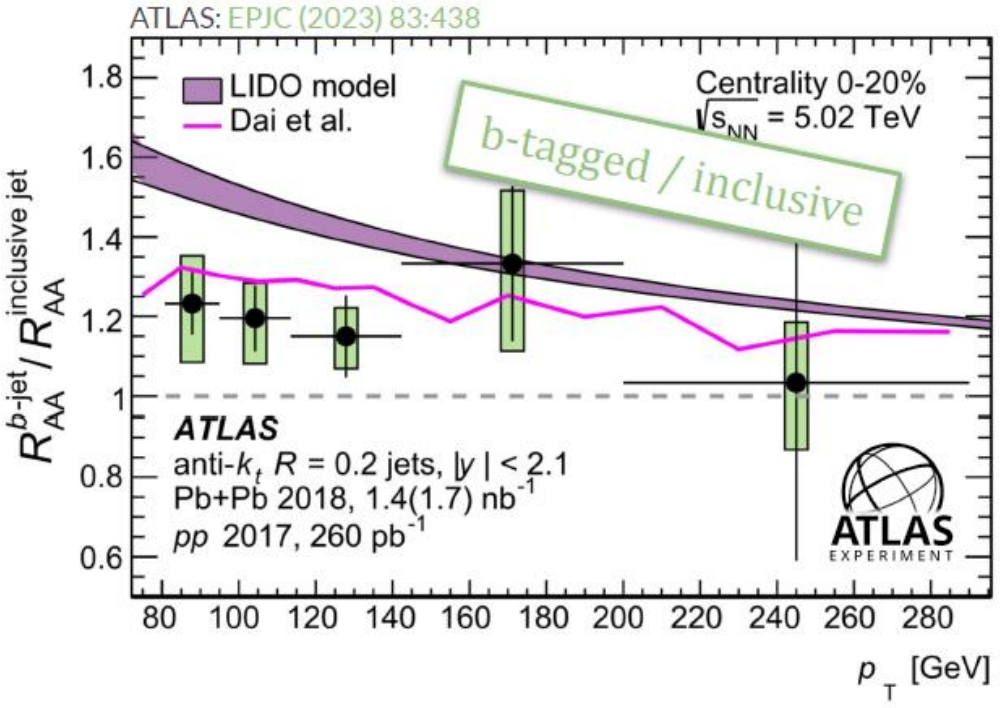
Partonic energy loss
→ **suppression of heavy-flavour particles at intermediate-to-high-p_T**

Suppression hierarchy expected from mass and colour charge:

R_{AA} (heavy quark) > R_{AA} (gluon & light flavour)







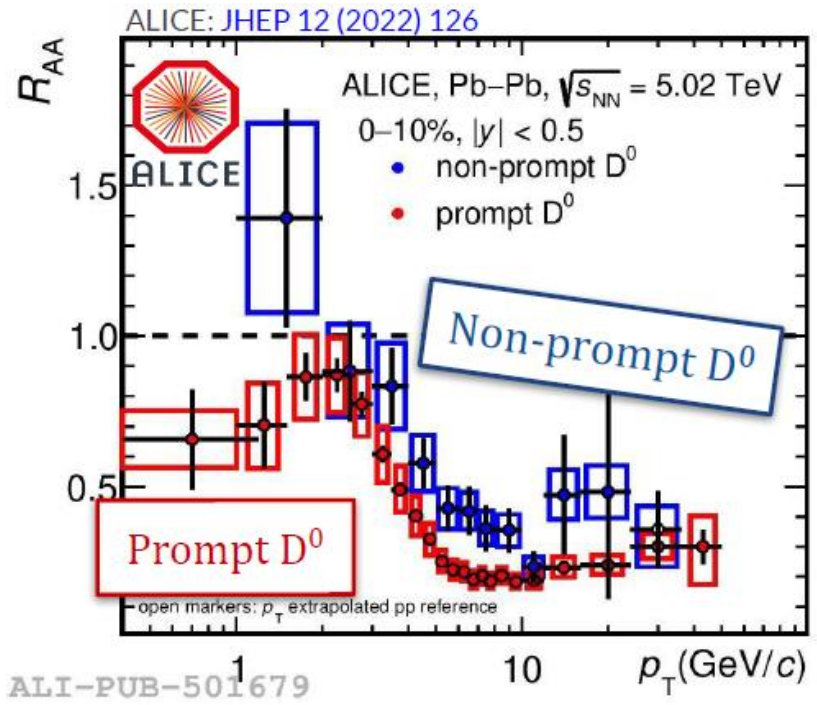
Parton interactions in the medium: charm and beauty

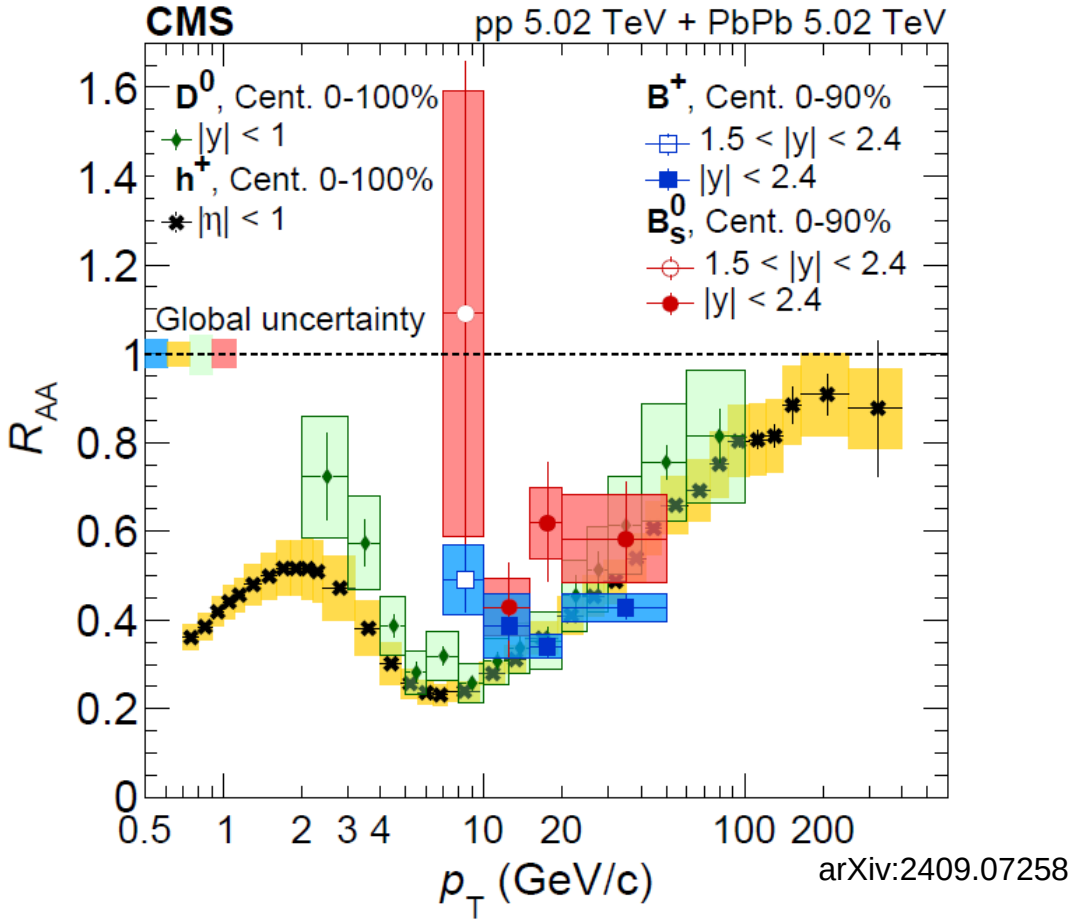
Heavy quarks produced early in the collision,
then **experience the full medium evolution**

Partonic energy loss
→ **suppression of heavy-flavour particles at intermediate-to-high-p_T**

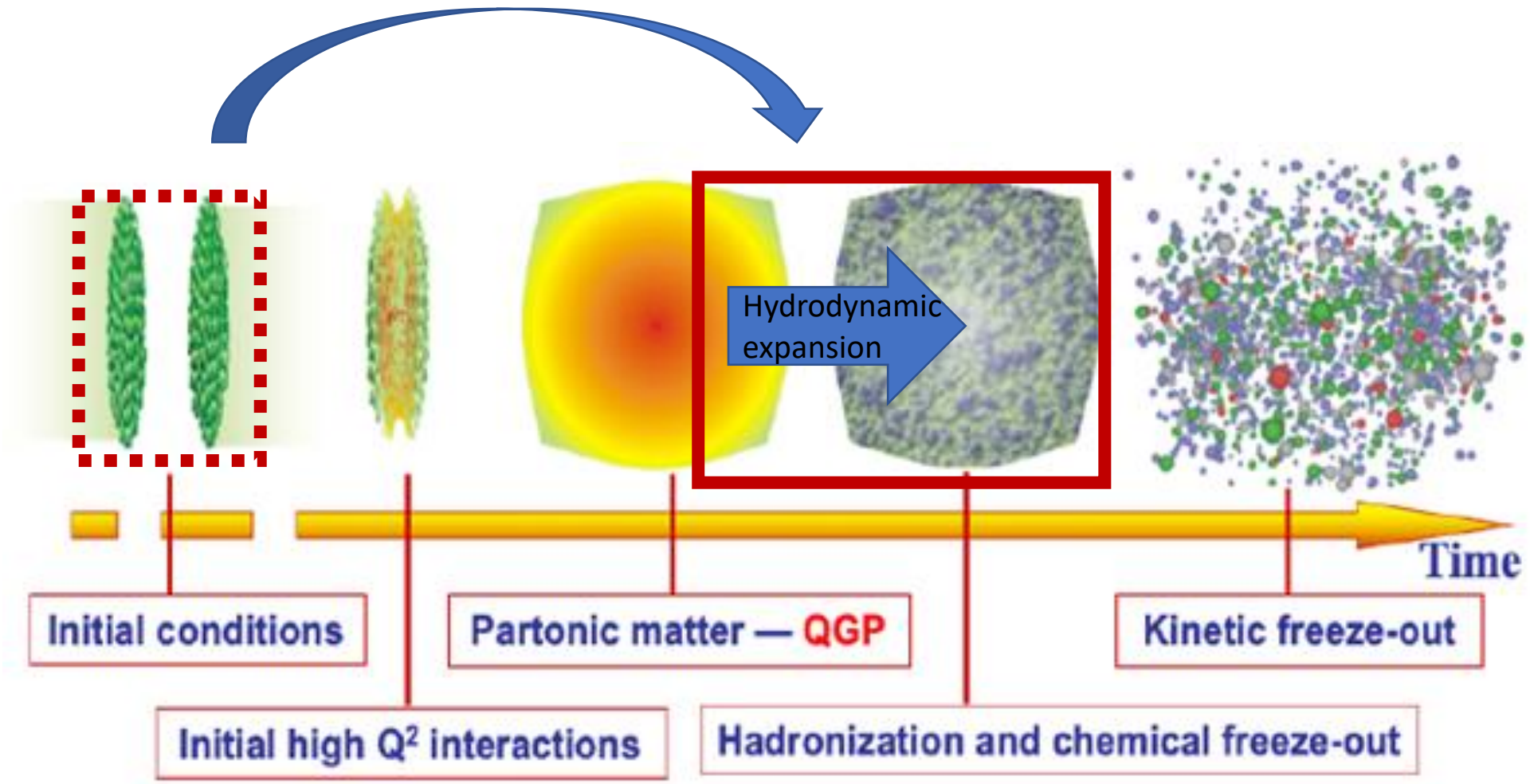
Suppression hierarchy expected from mass:

R_{AA} (beauty) > R_{AA} (charm)





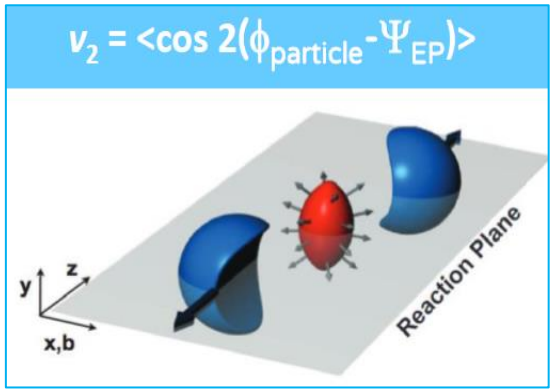
The medium expansion and hydrodynamics

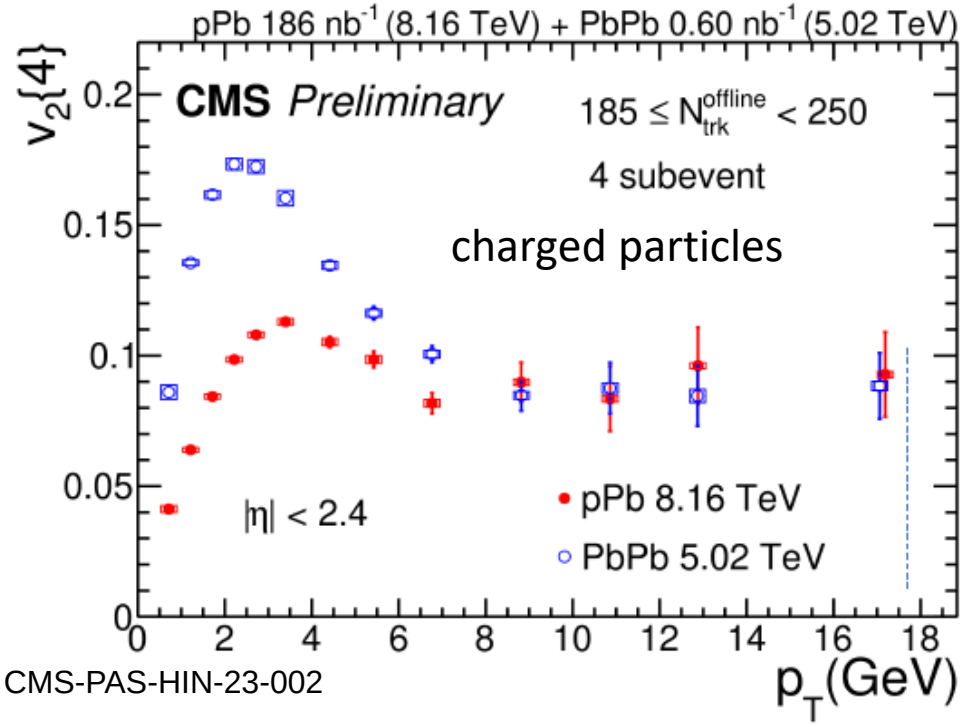


The medium expansion: elliptic flow

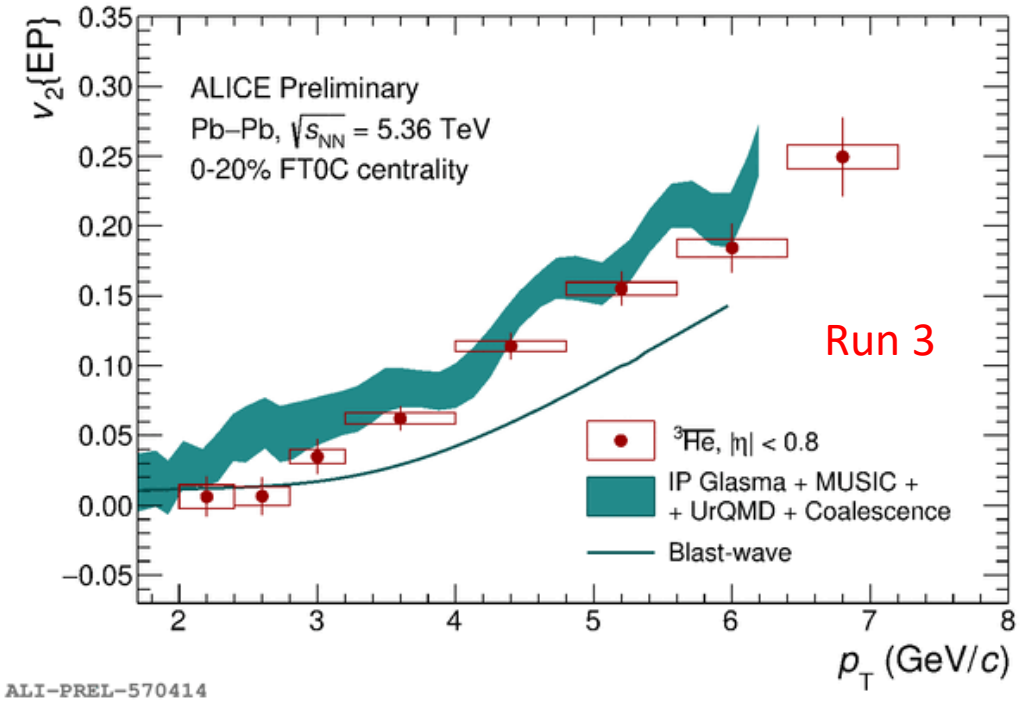
Non-central collisions:
interactions among constituents
convert initial spatial asymmetry to final momentum anisotropy

Sensitive to the **properties of QGP fluid** (such as η/s)





CMS-PAS-HIN-23-002



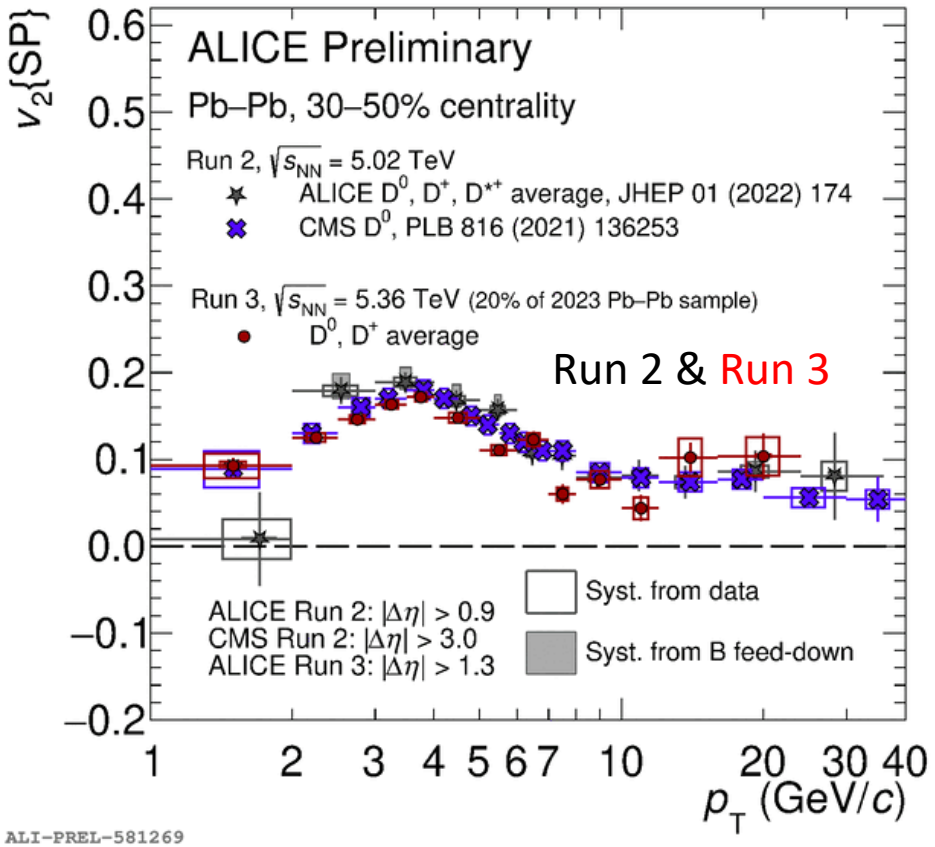
ALI-PREL-570414

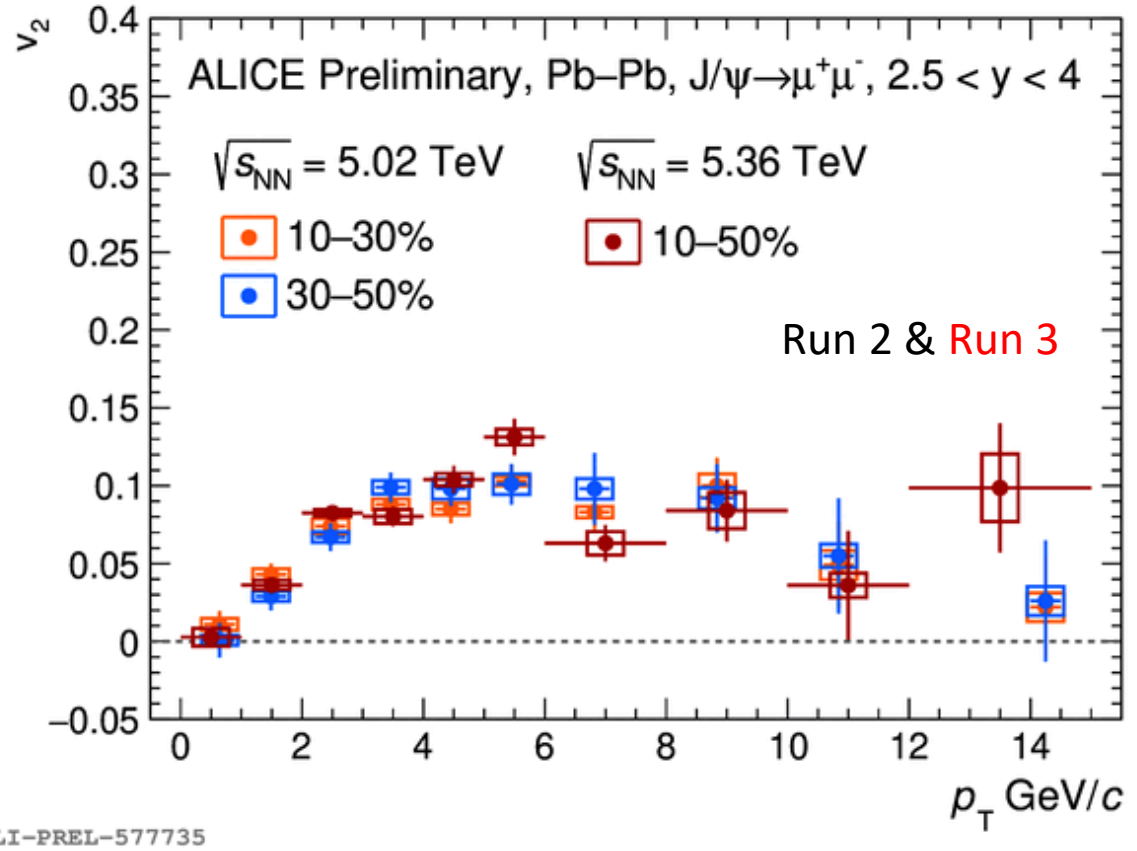
Sizeable v_2 in p-Pb collisions → collectivity in small systems!

$^3\overline{He}$ v_2 well described by coalescence + hydrodynamics

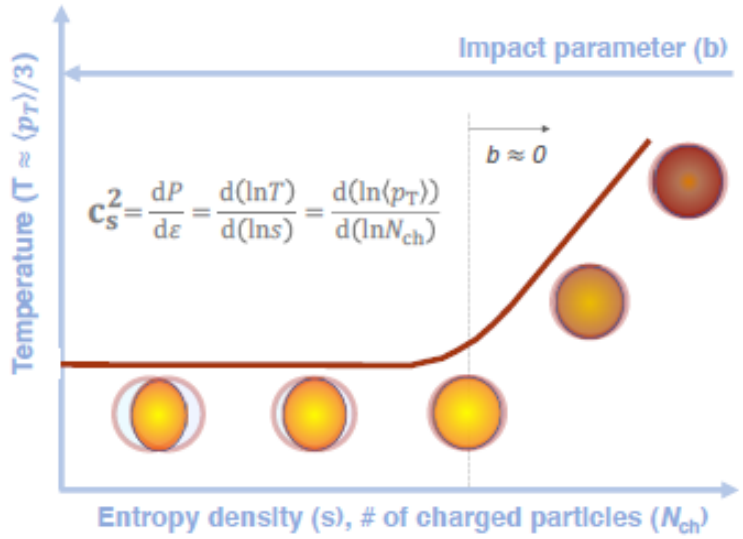
The medium expansion: elliptic flow of heavy quarks

Significant v_2 of open charm and J/ψ → **charm thermalization** in the medium





Ultra-central collisions: speed of sound?

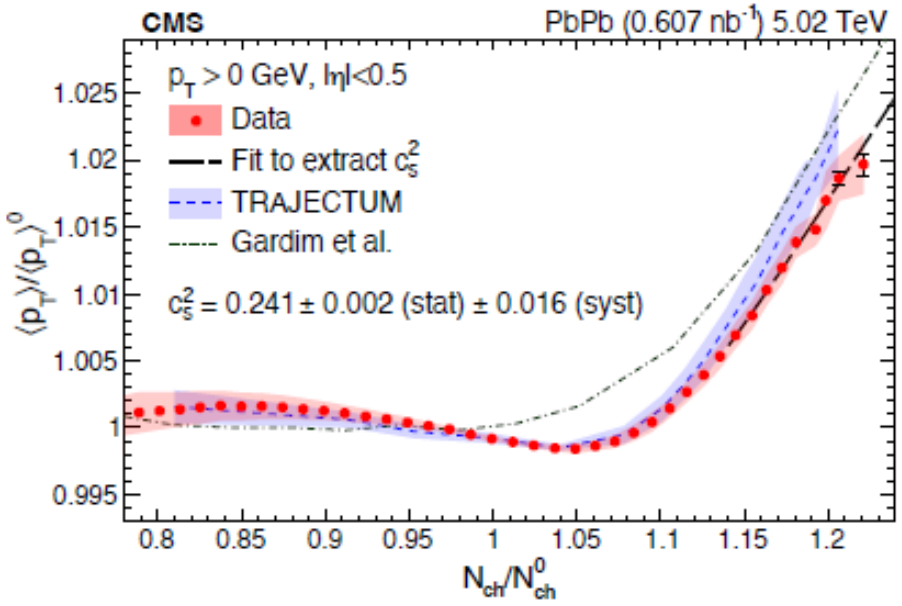


RPP 87 (2024) 077801

Ultra-central Pb-Pb collisions:

- at **fixed geometry (*b* ~ 0)**, the multiplicity N_{ch} quantifies the **system entropy**
- Slope of $\langle p_T \rangle$ (←→ *T*) with N_{ch} (←→ *s*) in UCC provides direct access to the thermodynamics of the system
  → measurement of the **speed of sound**

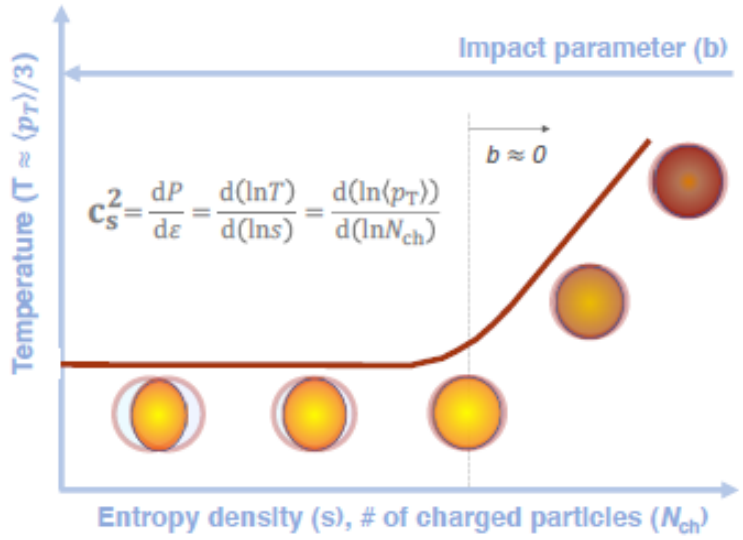
Theory:
Gardim et al., PLB 809 (2020) 135749



CMS: ***E*$_T$-based centrality estimator**
as a handle to vary N_{ch}

Extracted ***c*$_s$ ~ *c*/2**, compatible with lattice QCD

Ultra-central collisions: speed of sound?



RPP 87 (2024) 077801

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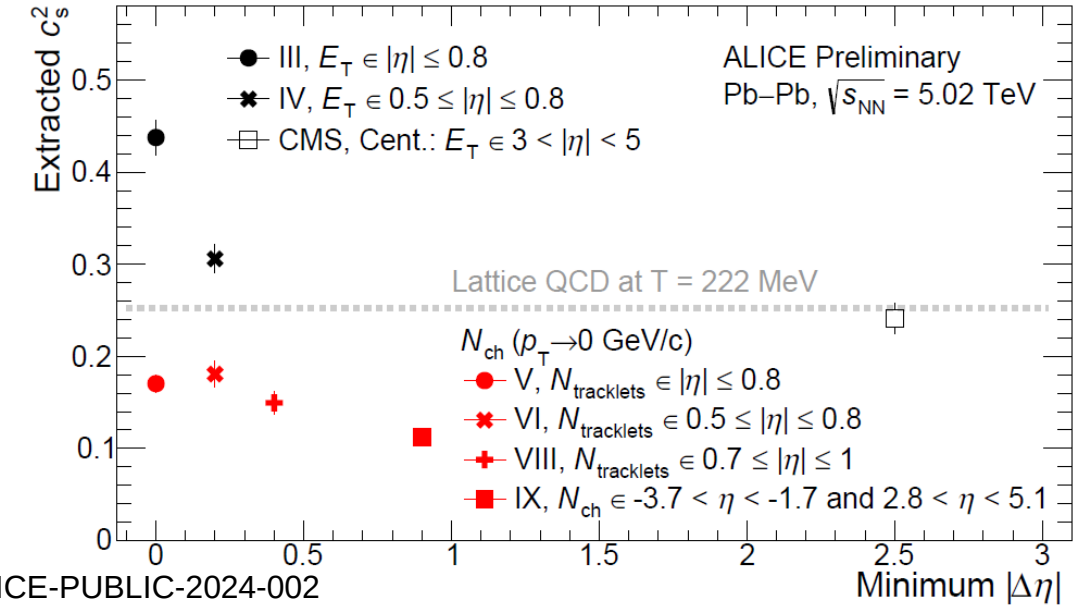
Theory:
Gardim et al., PLB 809 (2020) 135749
G. Nijs, W. v.d. Schee, PLB 853 (2024) 138636

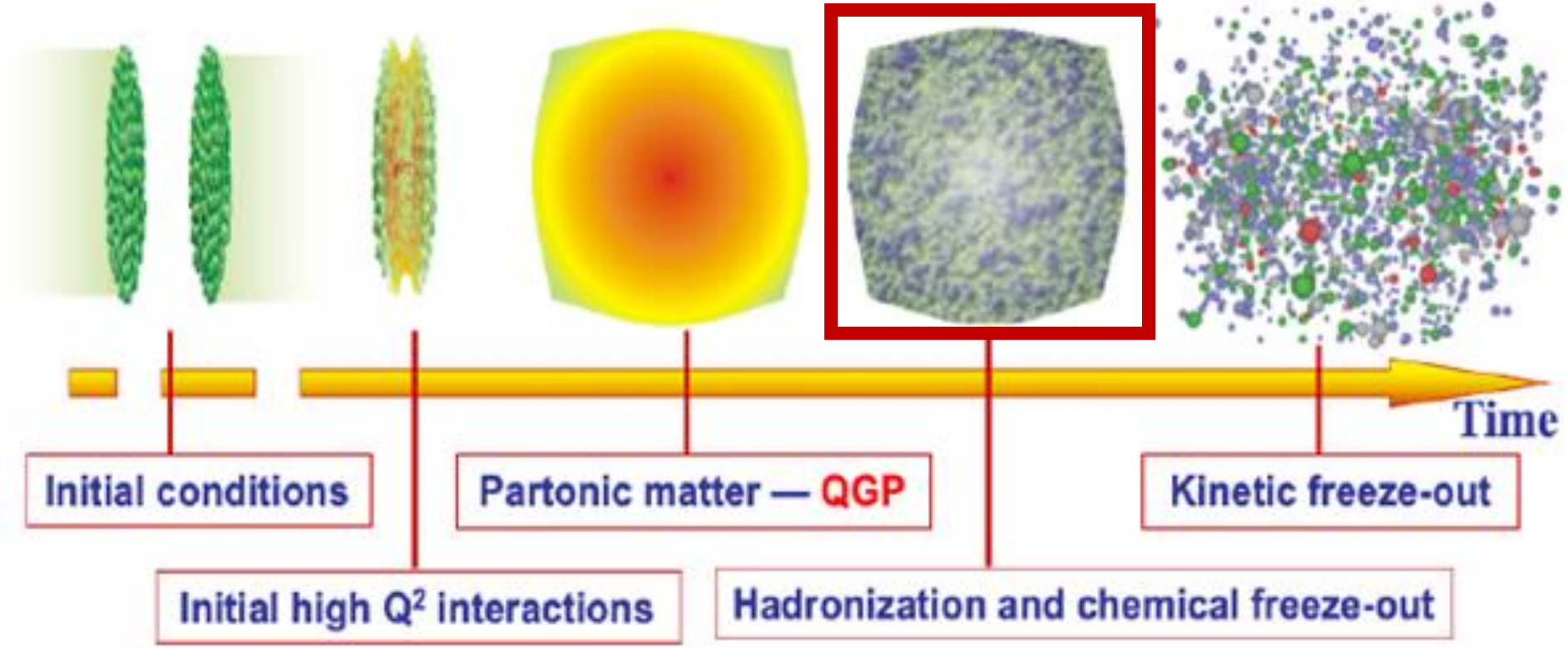


ALICE-PUBLIC-2024-002

ALICE: c_s extracted with different centrality estimators and rapidity gaps

→ **experimental and physical biases**?

Heavy flavour hadronization

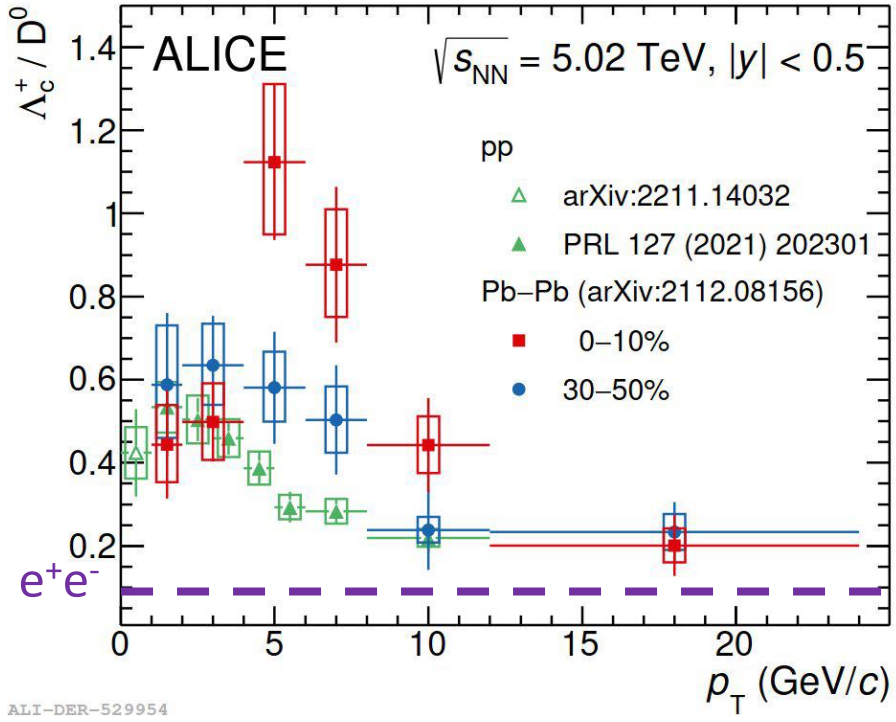


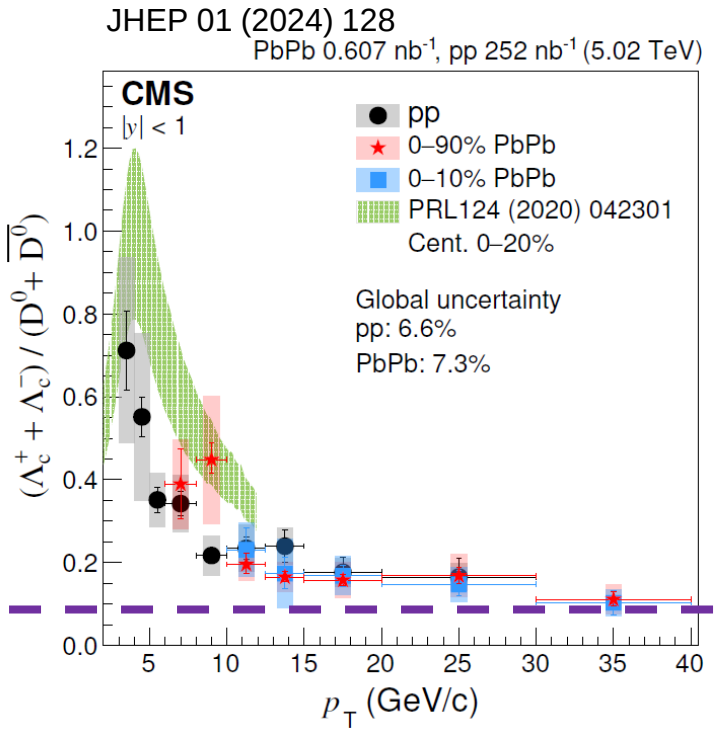
Heavy flavour hadronization via charmed baryon-to-meson ratio

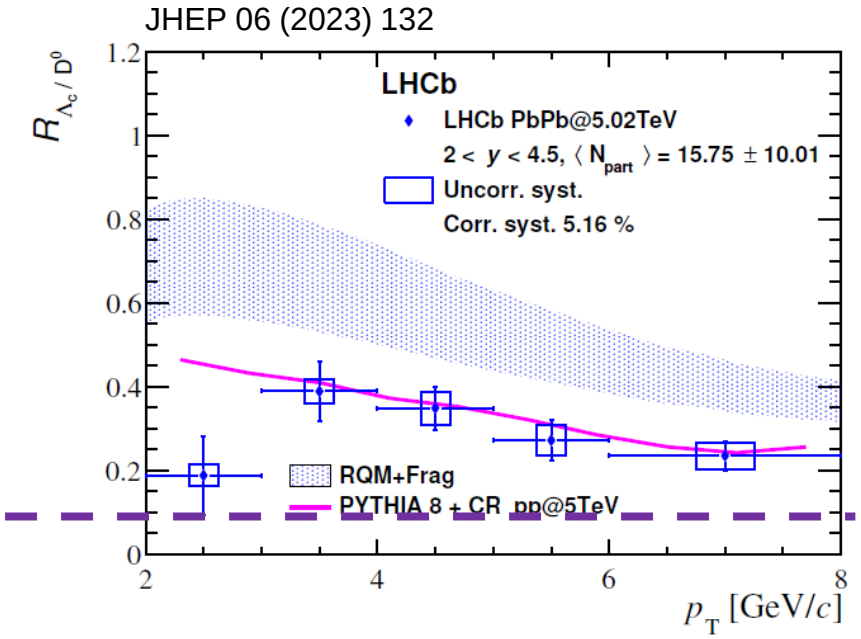
Ratio of charmed barions to mesons → study **hadronisation mechanism across collision systems**

All LHC experiments: **enhancement wrt ee in both pp and Pb-Pb**

-> hadronic environment: additional string topologies, coalescence…







p_T dependence: a **maximum at intermediate p_T** → more pronounced with increasing multiplicity/centrality (radial flow?)

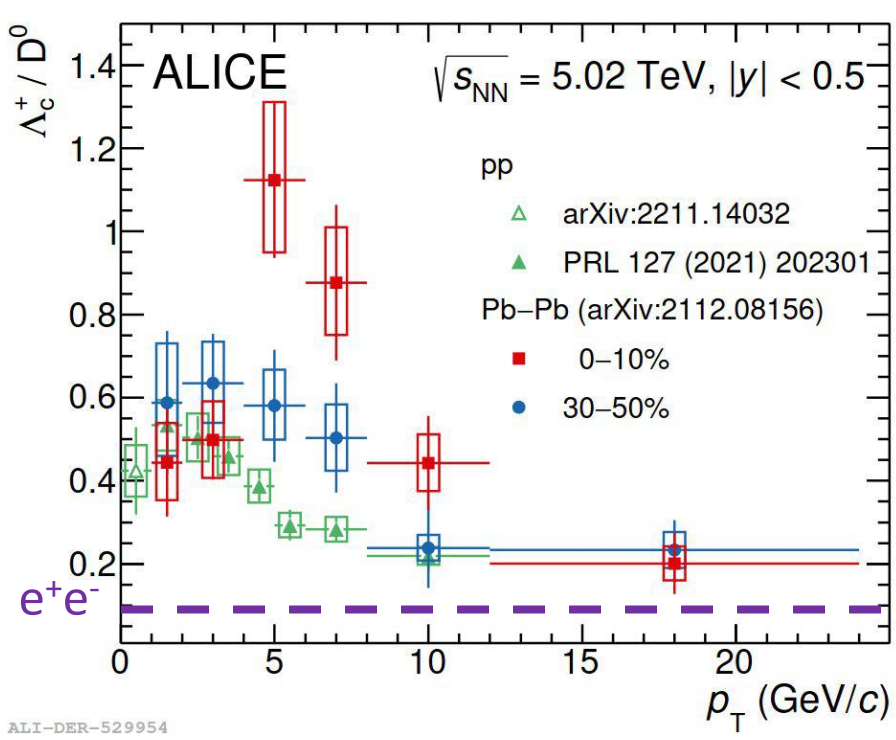
Heavy flavour hadronization via charmed baryon-to-meson ratio

Ratio of charmed barions to mesons → study **hadronisation mechanism across collision systems**

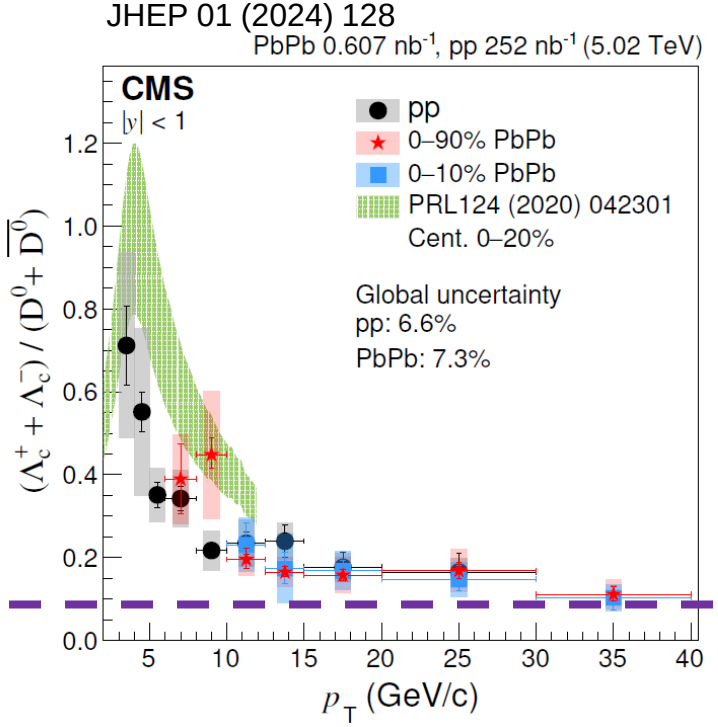
All LHC experiments: **enhancement wrt ee in both pp and Pb-Pb**

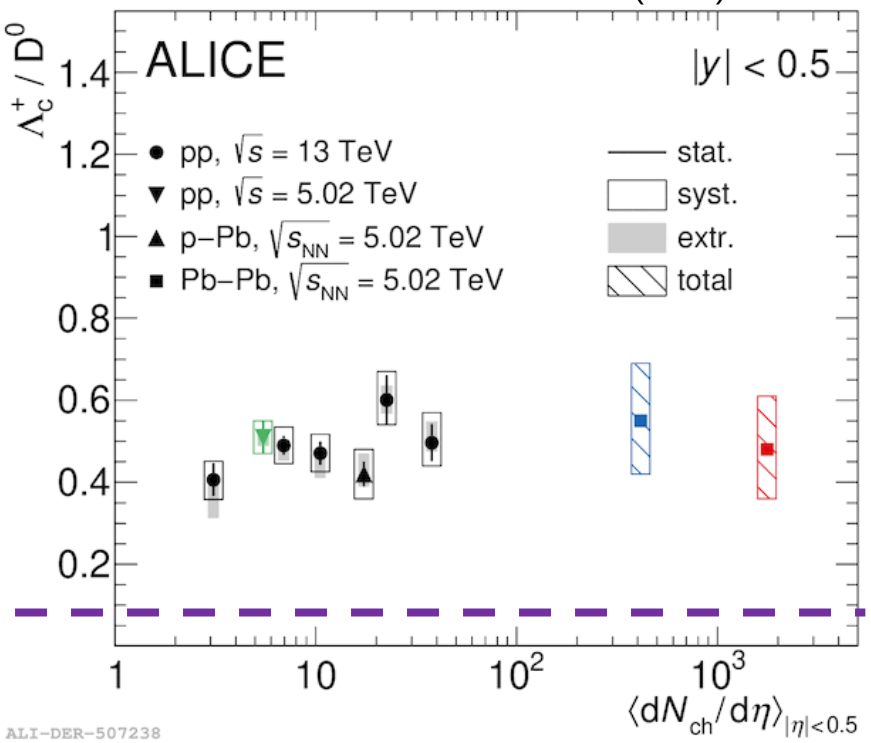
→ **hadronic environment**: additional string topologies, coalescence…

PLB 829 (2022) 137065
PRC 104 (2021) 054905
PLB 839 (2023) 137796



JHEP 01 (2024) 128

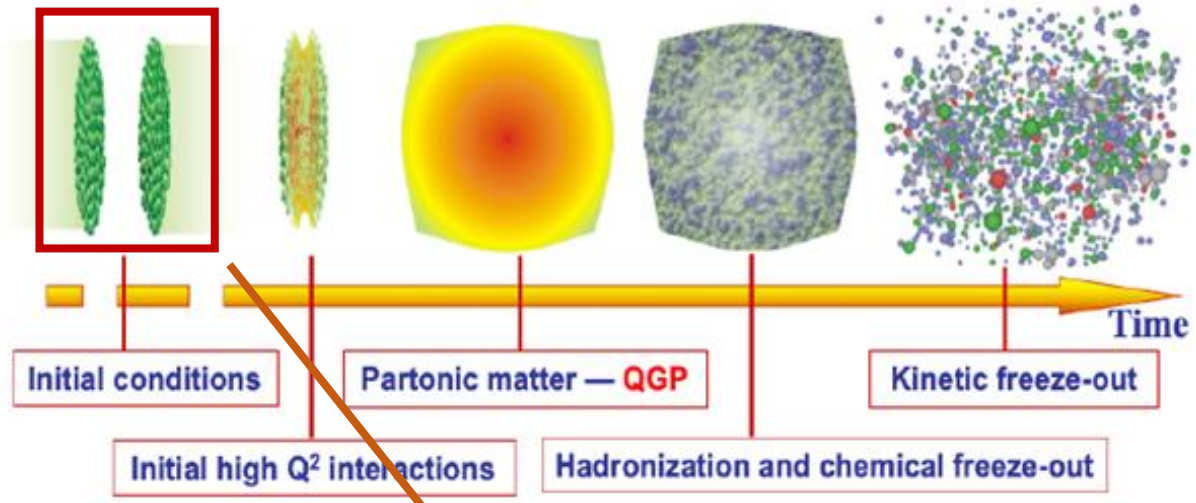


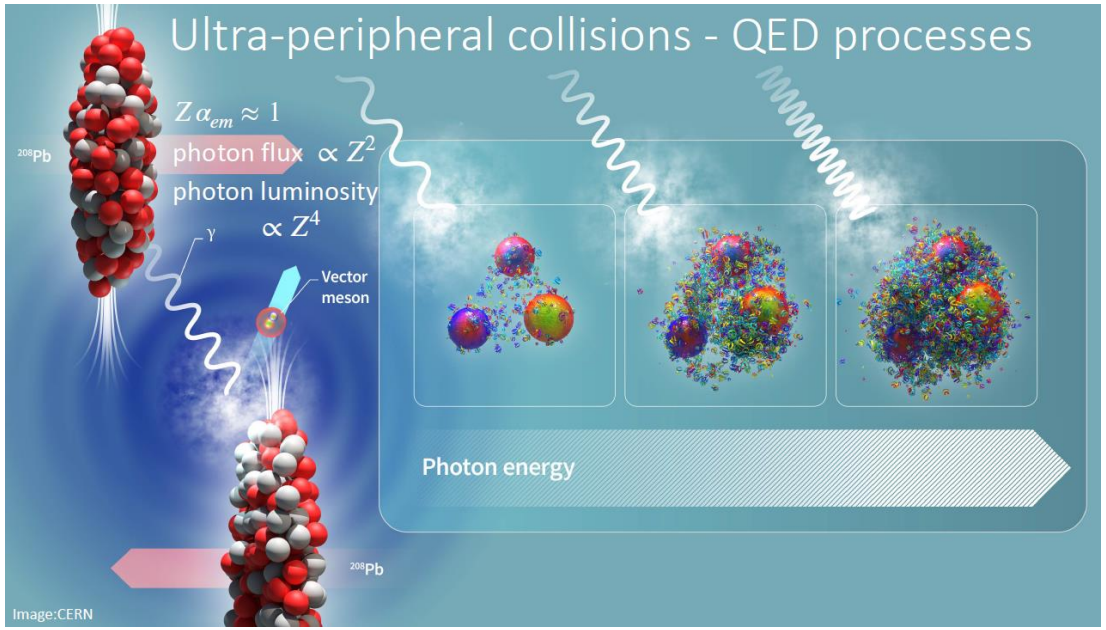


p_T dependence: the ratio has a **maximum at intermediate p_T** → more pronounced with increasing multiplicity/centrality

p_T-integrated ratio compatible with constant from pp to central Pb-Pb → p_T dependence from energy re-distribution

More UPC studies

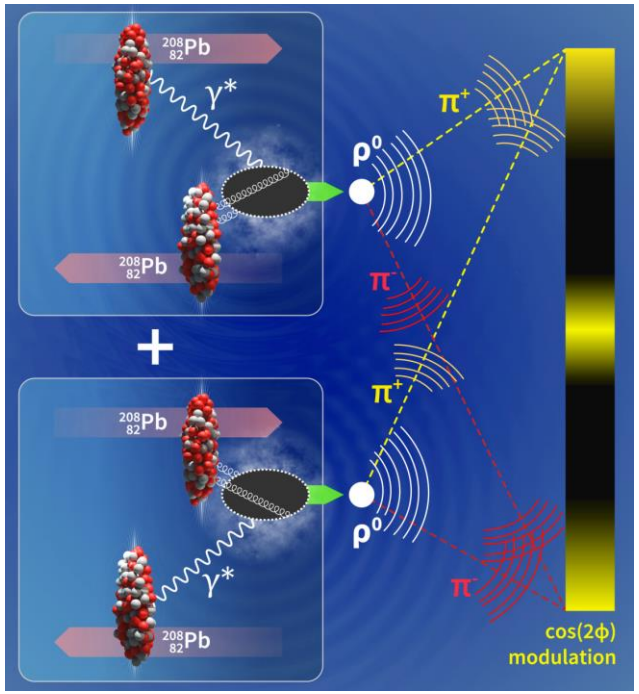


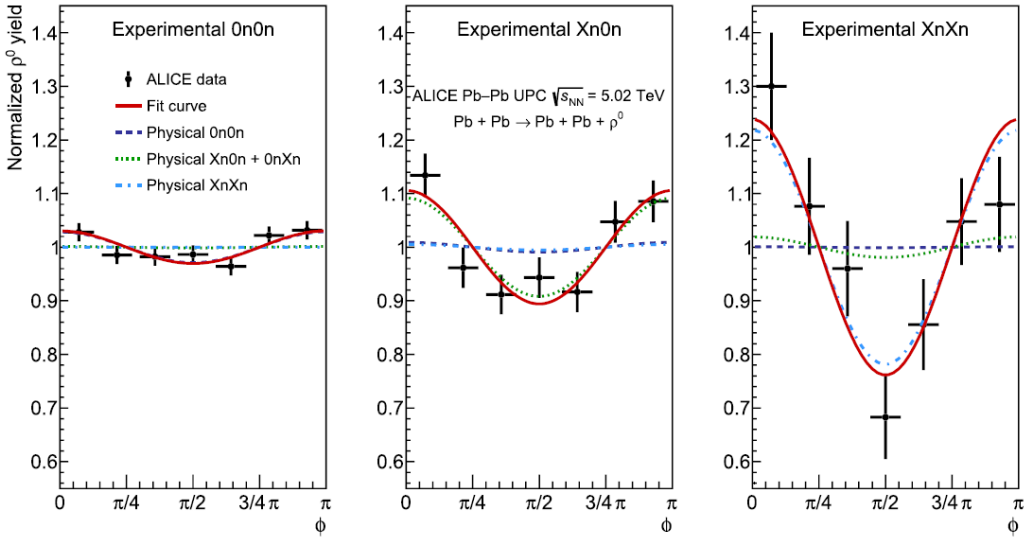


ρ^0 azimuthal anisotropy in UPCs: a double-slit experiment

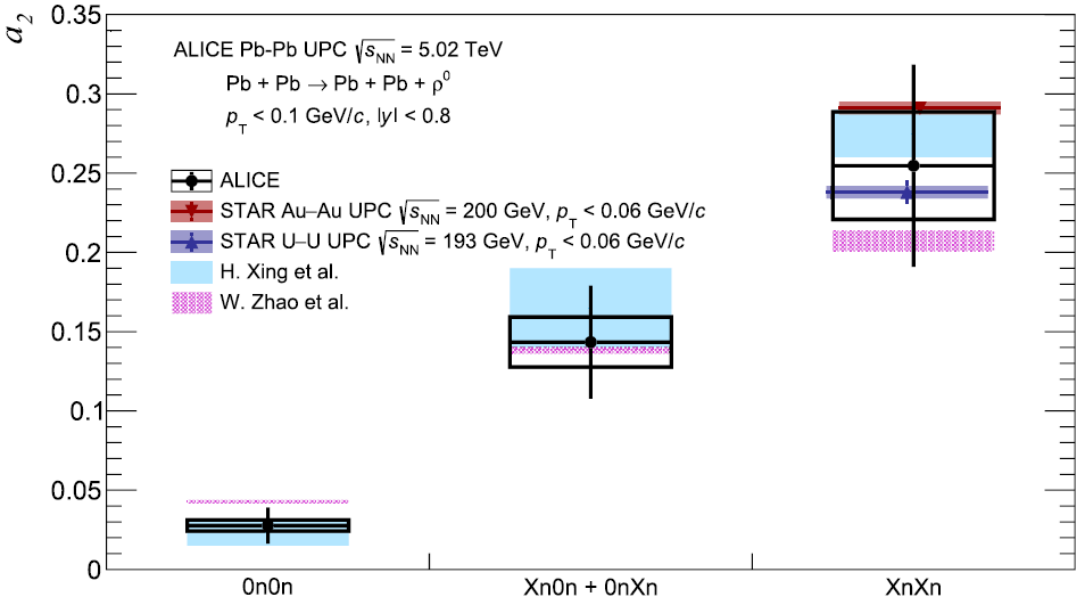
Quantum interference
from emitter/target ambiguity
+ ρ^0 polarization
→ **azimuthal anisotropy**
in $\rho^0 \rightarrow \pi\pi$ decay

Short range of QCD implies
localised production
at the target site
→ **double-slit** analogy
distance from slits
~ *b* ~ tens of fm!





~50 fm ← impact parameter *b* → ~20 fm



PLB 858 (2024) 139017

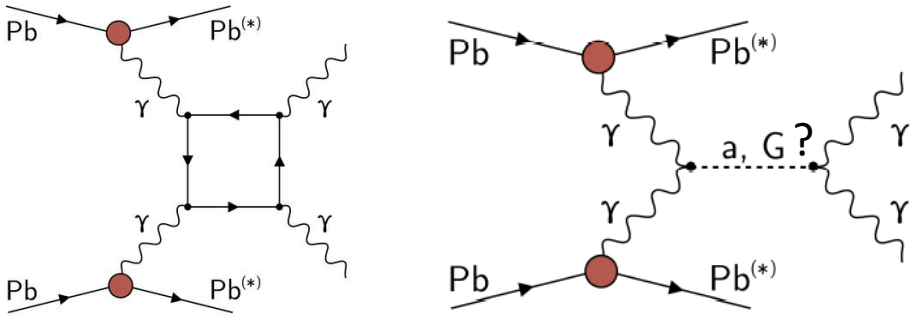
Measure ϕ ~ angle between one pion and the ρ^0

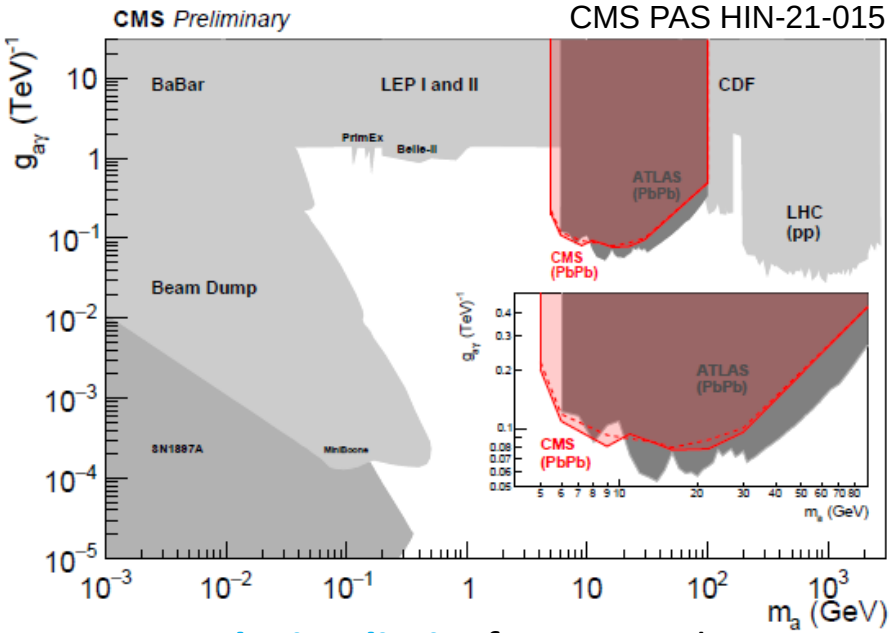
Interference shows up as a *b*-dependent **cos(2ϕ) modulation**

First measurement at the LHC,
first measurement of the *b* dependence

UPCs and the search for new particles

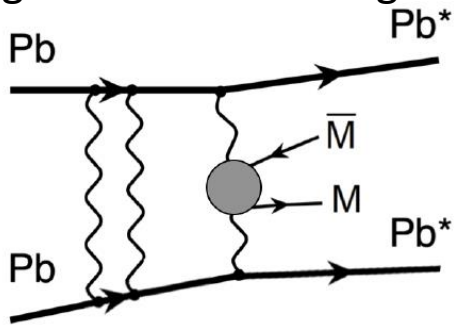
CMS light-by-light scattering:
sensitive to BSM particles (e.g. axion-like)



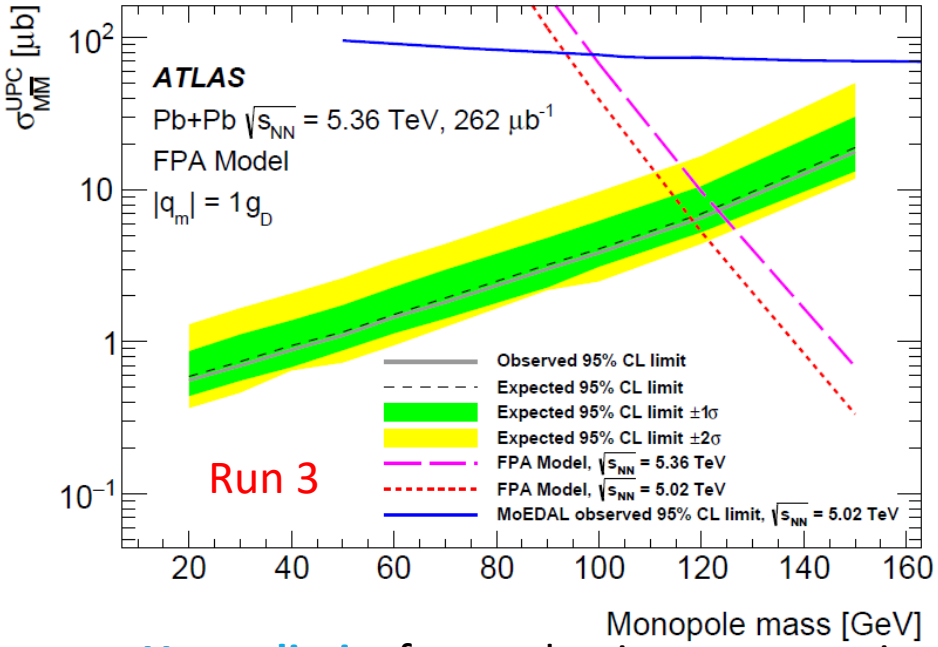


New exclusion limits for axion-photon coupling @ m_a ~5-10 GeV/c^2

ATLAS: search for **magnetic monopoles in UPCs**,
by looking for tracks with large ionization density



arXiv:2408.11035



Upper limits for production cross section for m_M ~20-150 GeV/c^2

Summary

- I presented a (biased) overview of the most exciting heavy-ion results from the four large LHC collaborations

- Four experiments with diverse acceptances, specialties and approaches
  → nice complementarity

- Run 2 results keep coming out, allowing us to study all phases of the collision evolution, including (but not only) the QGP hydro- and thermo-dynamic properties
  → first steps towards extracting quantitative parameters

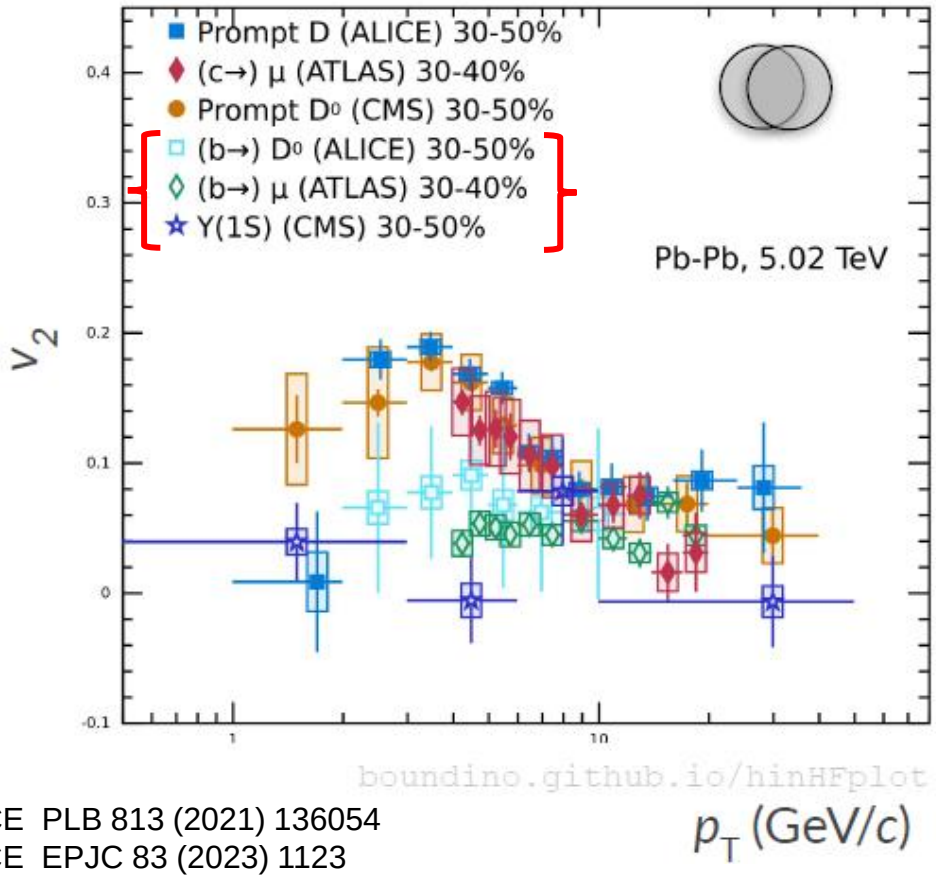
- Moving to the precision era with Run 3 + further upgrades

Material I had to cut

The medium expansion: elliptic flow of heavy quarks

Significant v_2 of open charm and J/ψ → **charm thermalization** in the medium

What about **beauty?**



ALICE PLB 813 (2021) 136054
ALICE EPJC 83 (2023) 1123
ATLAS PLB 807 (2020) 135595
CMS PLB 819 (2021) 136385
CMS PLB 816 (2021) 136253

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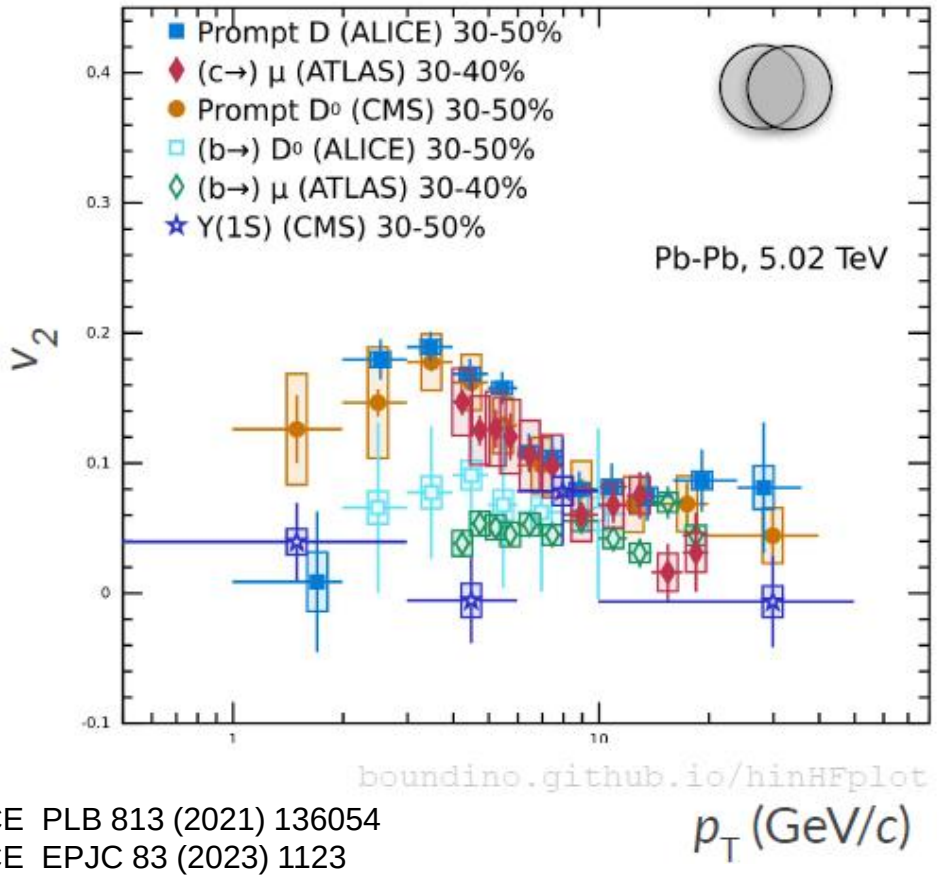
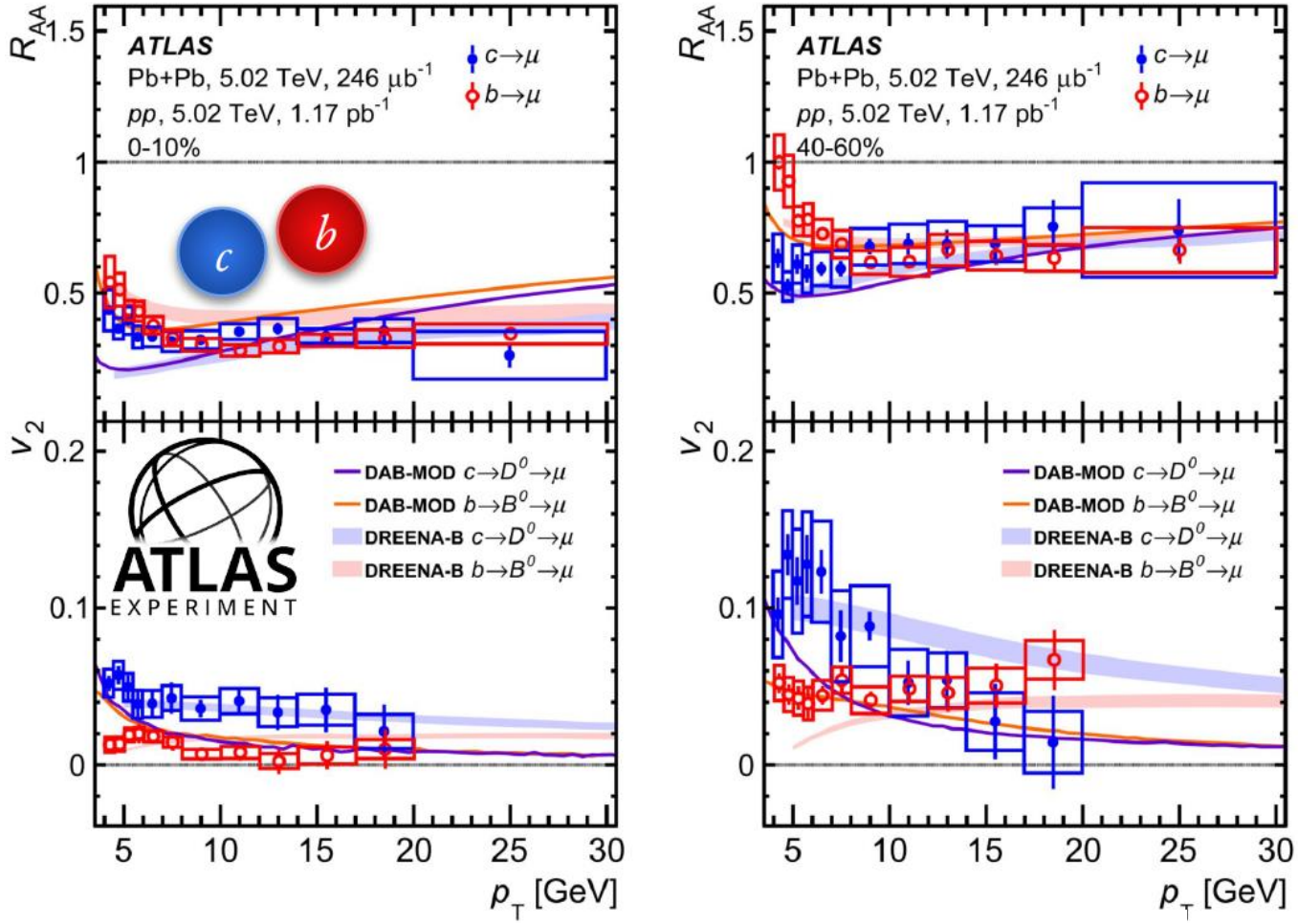


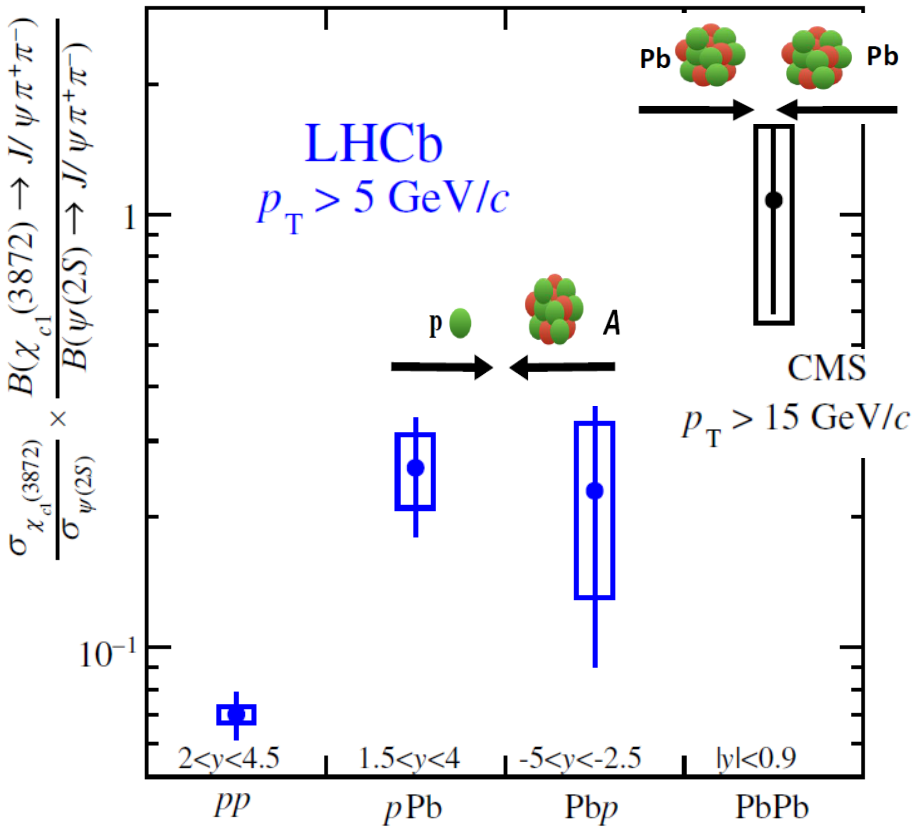
ALICE PLB 813 (2021) 136054
ALICE EPJC 83 (2023) 1123
ATLAS PLB 807 (2020) 135595
CMS PLB 819 (2021) 136385
CMS PLB 816 (2021) 136253

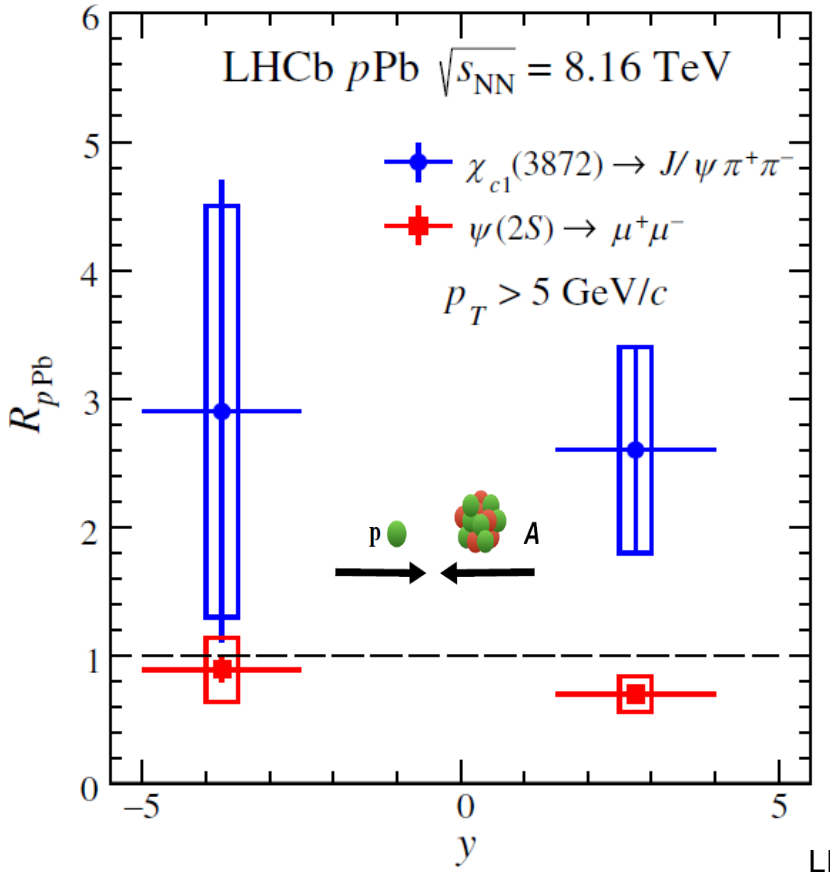
PLB 829 (2022) 137077



Simultaneous measurement of B and D meson R_{AA} and v_2
→ constrain the **charm quark diffusion coefficient** in QGP

Heavy flavour hadronization: the X(3782)





LHCb PRL 132 (2024) 242301
CMS PRL 128 (2022) 032001

- **Exotic multi-quark state**: compact, molecular, hadrocharmonium structure?
- Enhanced production (relative to ψ') in p-Pb and Pb-Pb vs pp despite similar expected initial state effects
- LHCb: hint of $R_{pPb} > 1$ → coalescence mechanism at play?