Review of recent Heavy-Ion Physics results at the LHC

43rd International Symposium on Physics in Collisions
22–25 October 2024, Athens, Greece

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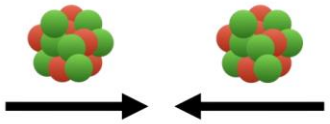
ALICE ATLAS EXPERIMENT CMS LHCb

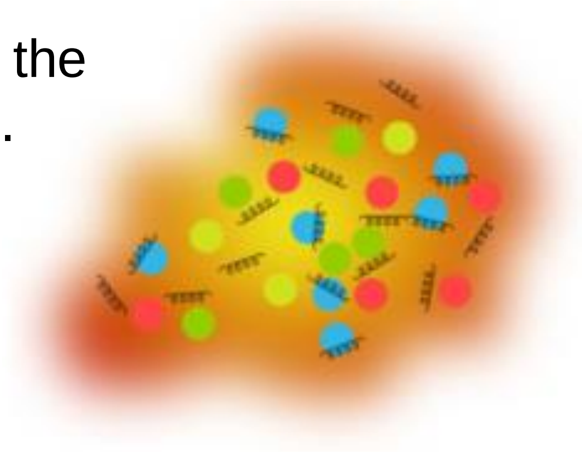
Heavy-ion collisions

- Why heavy-ion collisions?



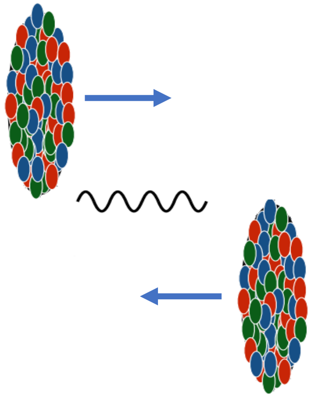
➡ Heavy-ion collisions generate **temperatures** millions of times higher than the core of the Sun (~10^{12} K) and **energy densities** on the order of ~GeV/fm³.

Study of the fundamental properties of matter under extreme conditions.
Creation of the **quark-gluon plasma (QGP)**.



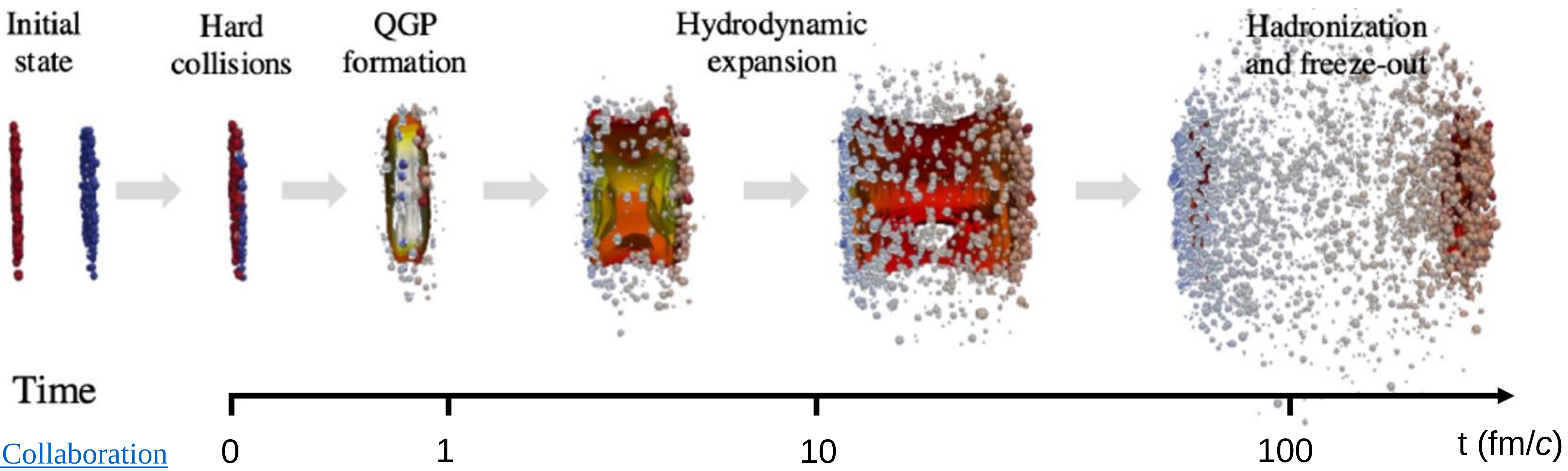
➡ Study of new physics through ultra-peripheral collisions (UPC)

Very clean environment that allows us to study rare processes.



Creation of Quark Gluon Plasma

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

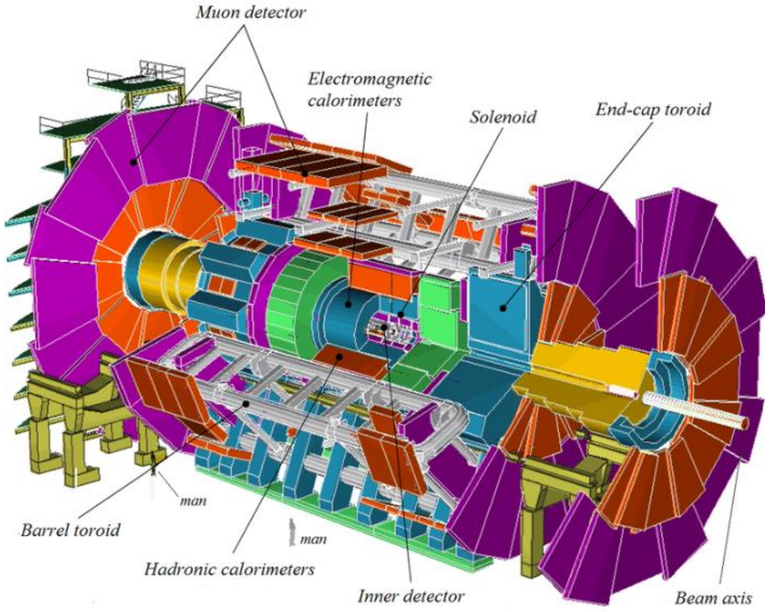


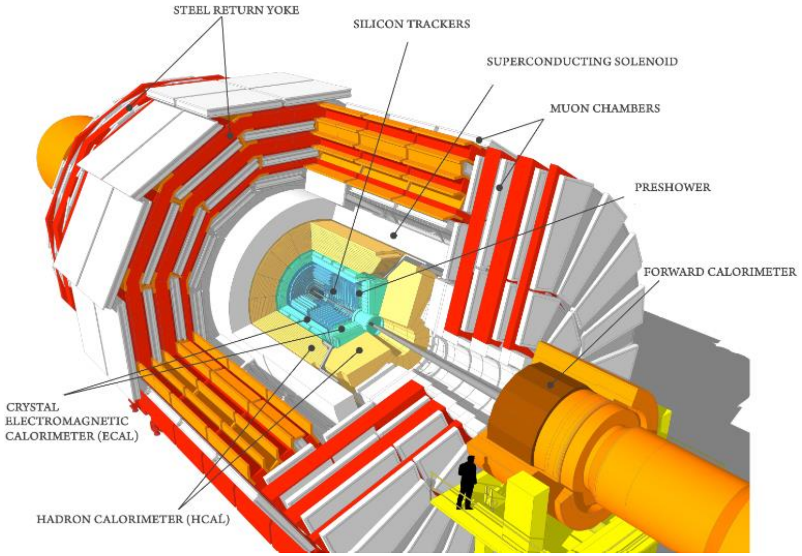
MADAI Collaboration

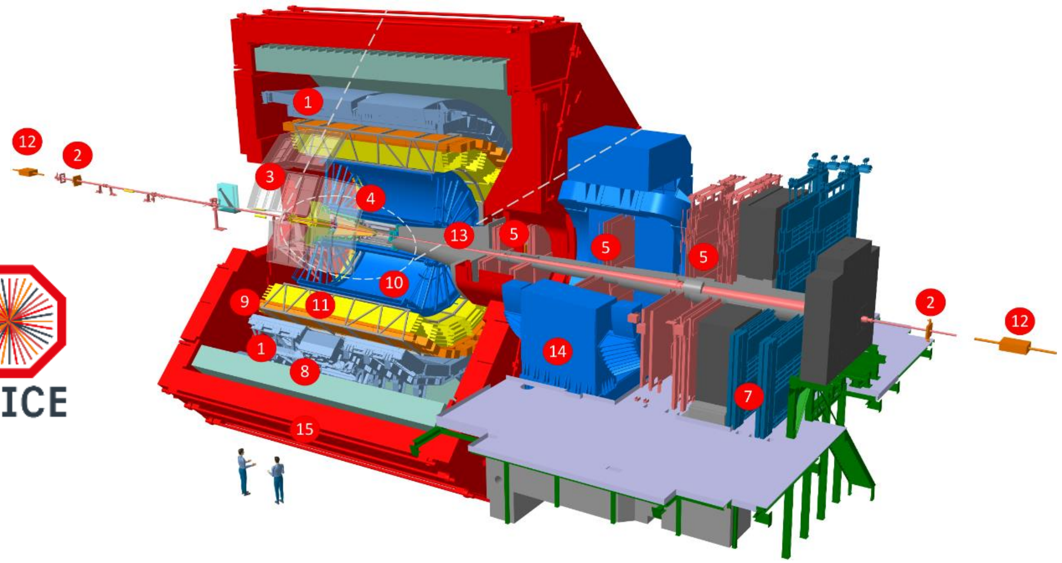
- QGP lifetime ~ few fm/*c.*
- Study of the QGP performed through indirect signals.

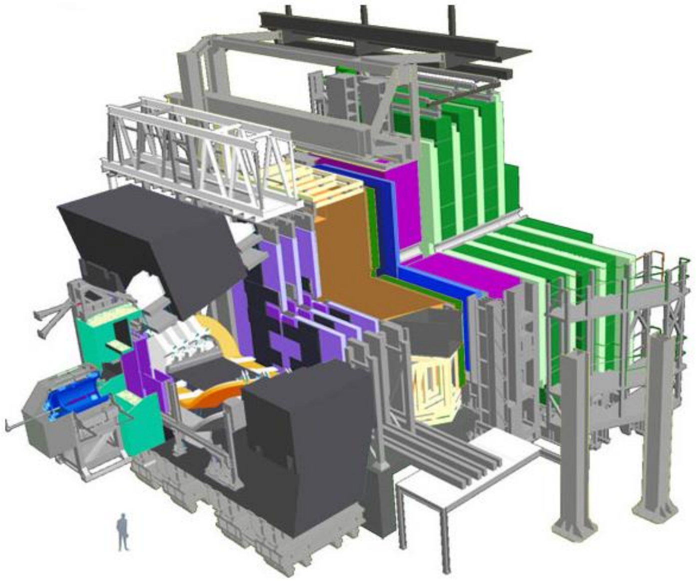
→ Properties of the stream of free particles reaching the detector.

Heavy-ion collisions at the LHC



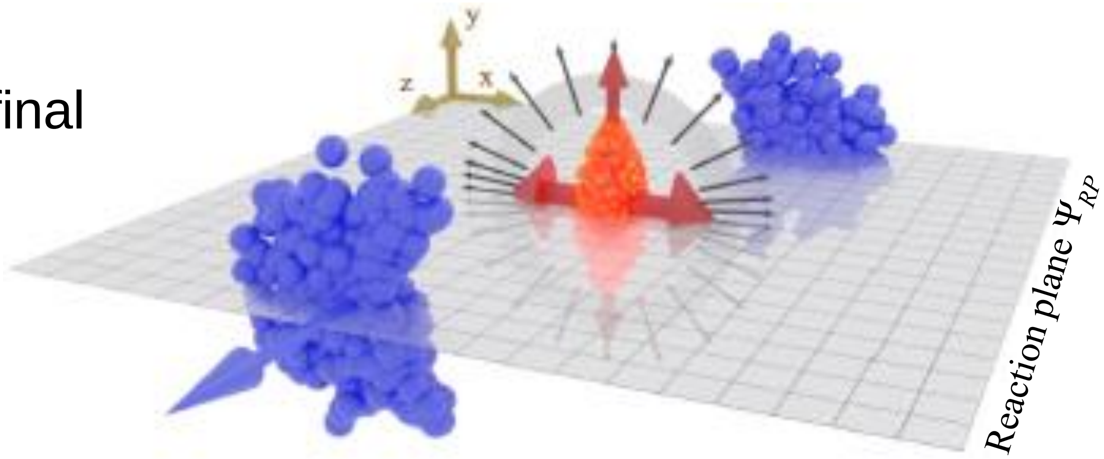






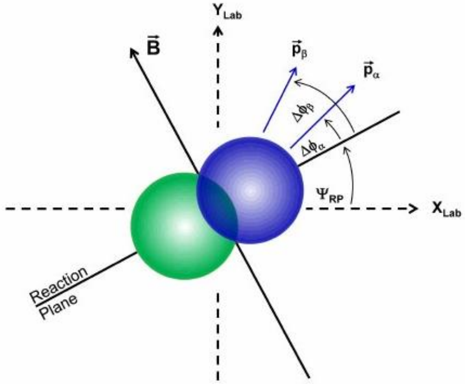
Collective motion in heavy-ion collisions

- Initial spatial anisotropy → pressure gradients lead to final momentum anisotropy of the produced particles.
- The QGP thermalizes developing **collective behavior.**

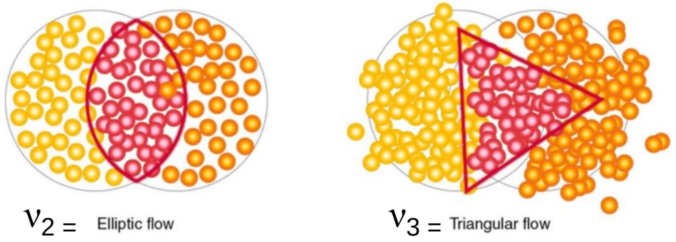


- Expansion of anisotropic distribution in momentum space into Fourier series:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[\,1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_{RP}))\,\right]$$



v_n = flow harmonics



Initial collision geometry

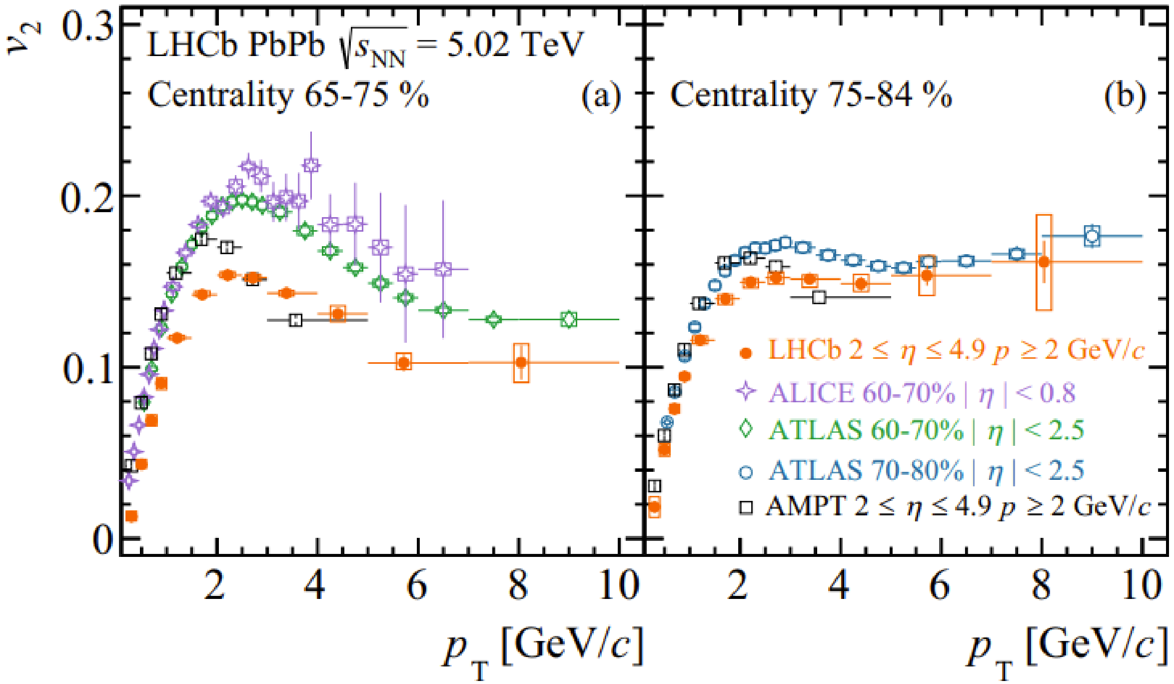
Event-by-event fluctuations

- Probe fundamental properties of the QGP: viscosity, degree of collectivity, and thermalization efficiency.

Charged hadrons flow

charged hadron v_2

ALICE: JHEP (2018) 103
ATLAS: Eur. Phys. J. C78 (2018) 997
LHCb: Phys. Rev. C 109, (2024) 054909
AMPT: NUCL SCI TECH 32 (2021) 113



- Good agreement between ALICE and ATLAS results.
- LHCb results in the forward region show weaker v_2.

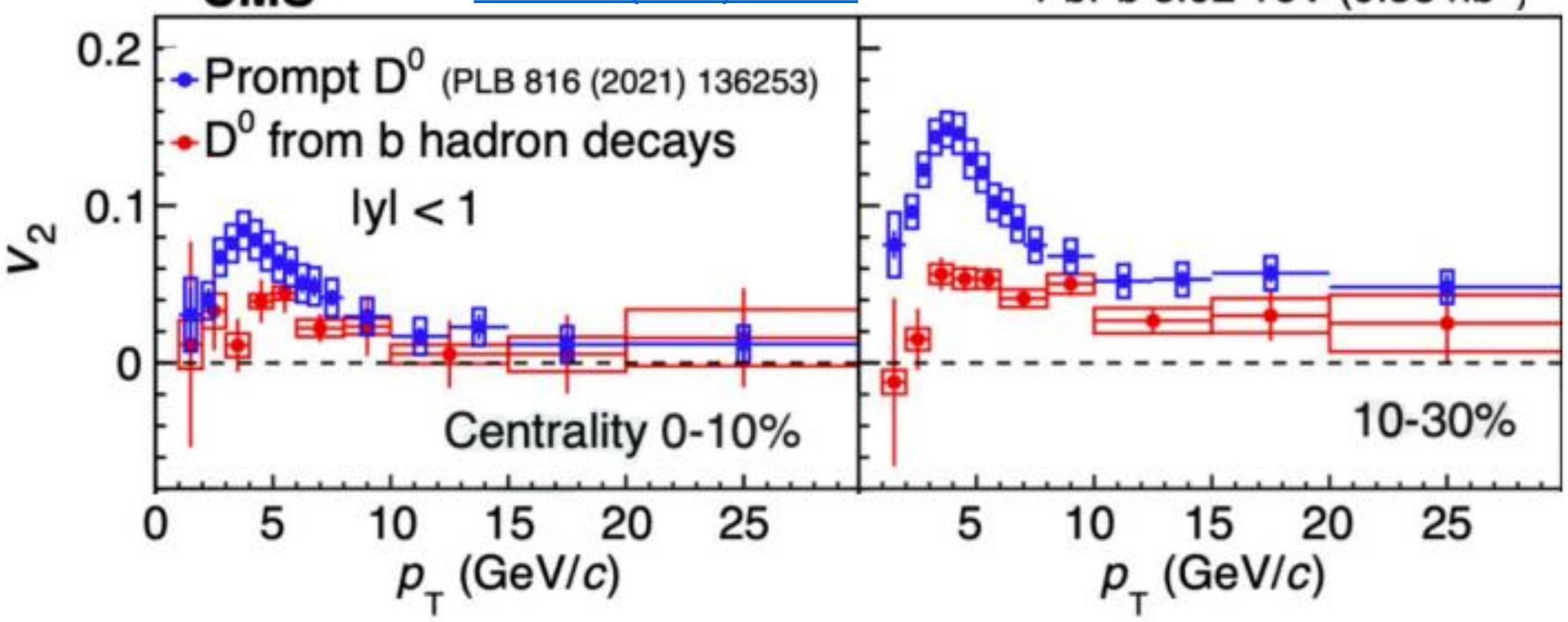
→ η dependence of the elliptic flow.

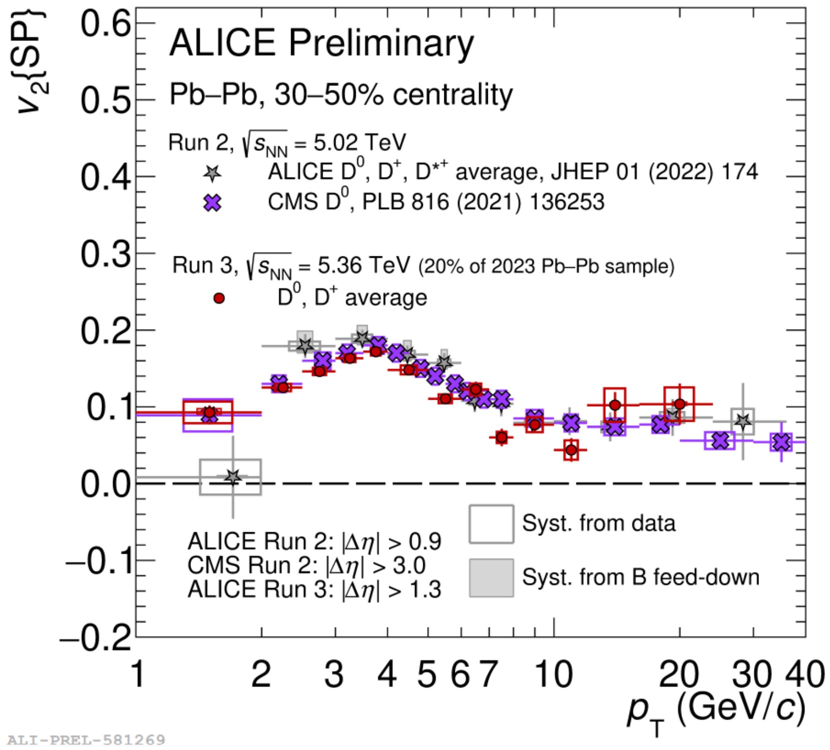
- **AMPT simulations**: string melting model that produces a dense system of partonic matter. It includes quark coalescence.
- AMPT simulations overestimate the results at low p_T (<2.5 GeV/c).

Heavy-flavour hadrons flow

What about heavy flavour?

PLB 850 (2024)138389



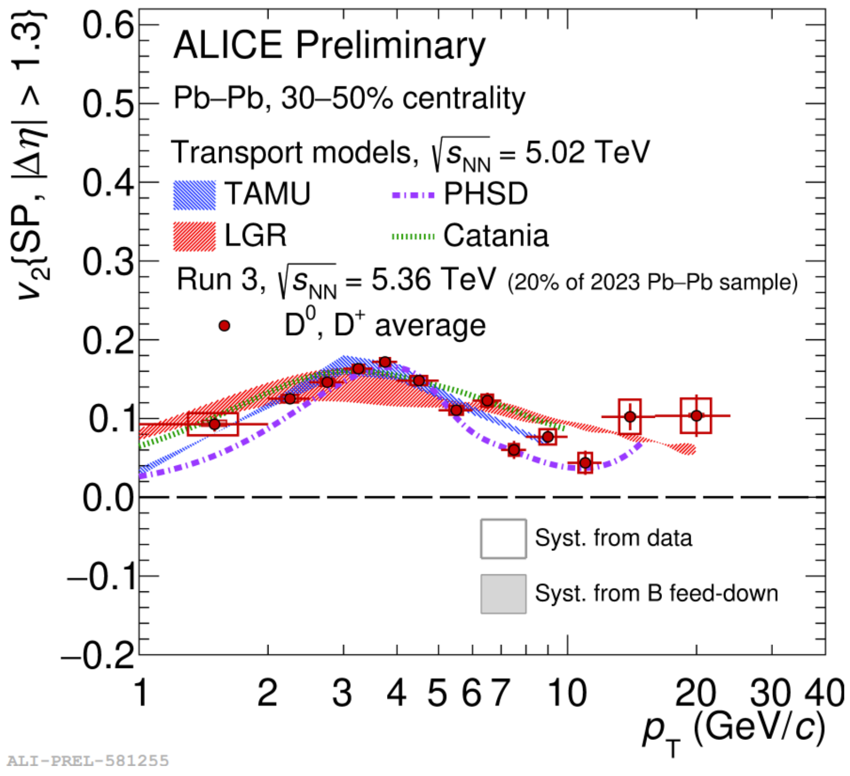


- Sizable v_2 measured for **charm** and **beauty** hadrons as well.

- **Mass ordering** clearly visible (heavier particles flow less).
  v_2 (charded hadrons) > v_2 (prompt D^0) > v_2 (non prompt D^0)

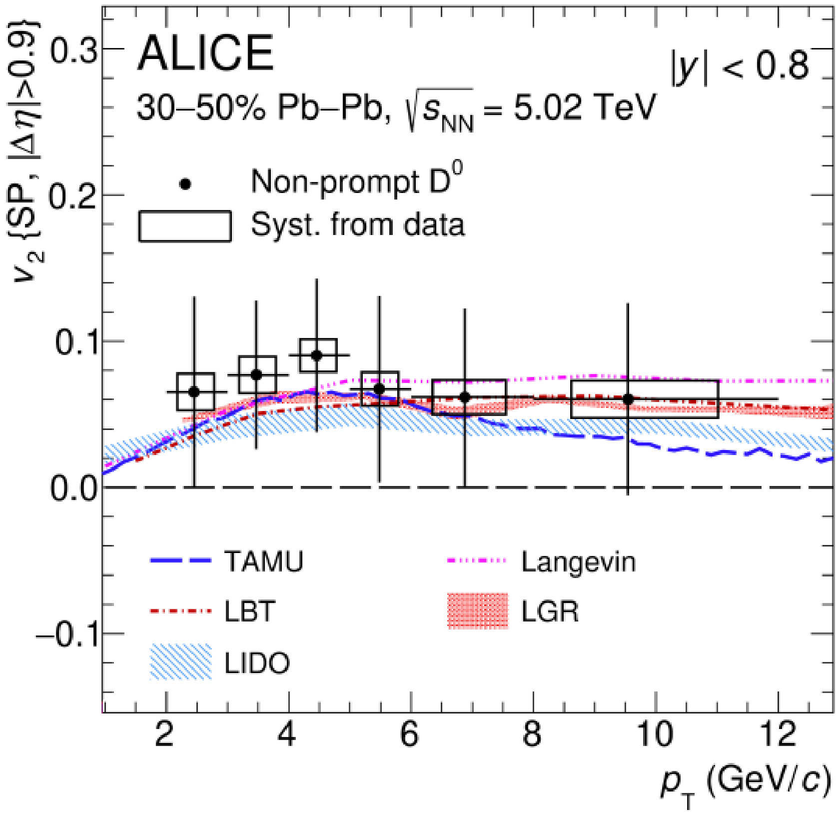
- Good agreement within uncertainties between ALICE and CMS results.

Heavy-flavour hadrons flow



TAMU: PLB 735 (2014) 445
LGR: EPJC 80 (2020) 671
PHSD: Phys. Rev. C 78 (2008) 034919
Catania: PLB 821 (2021) 136622
LBT: PRC 94 (2016) 014909
LIDO: PRC 98 (2018) 064901
Langevin: Chinese Phys. C 44 (2020) 114101

Eur. Phys. J. C 83 (2023) 1123



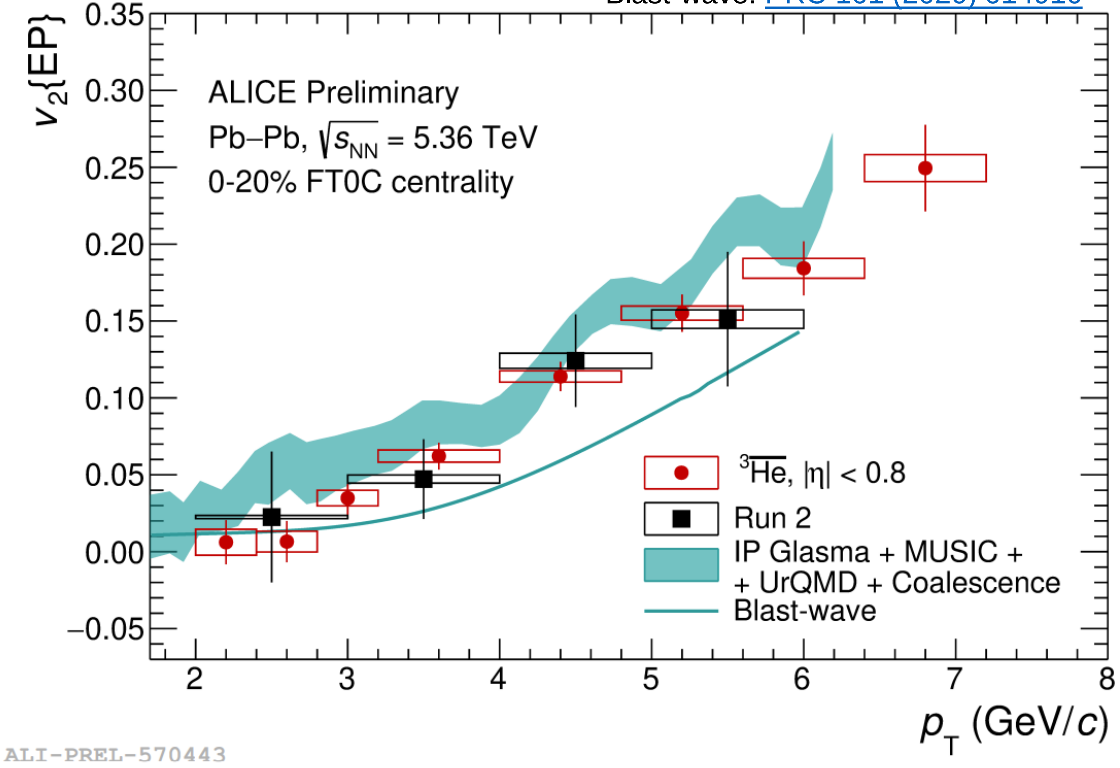
- Qualitatively good agreement between theory and data.

➡ Use comparison to understand which physics effects are relevant.

1. Radiative energy loss important to describe intermediate and high p_T.
2. Hadronization via recombination crucial to describe low and intermediate p_T.

Antinuclei flow

ALICE Run2: PLB 805 (2020) 135414
Blast-wave: PRC 101 (2020) 014910



- Further constraint on hadronization from antinuclei measurements.
- $^{3}\overline{He}$ measurement in Run3 more differential and precise than in Run 2.

  ➡ Possibility to discriminate between different model predictions.

- Blast-wave model tends to underestimate the data.
- Better description provided by coalesce model.

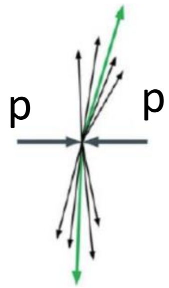
In-medium energy loss

- Interaction with the medium constituents via radiative and collisional processes.

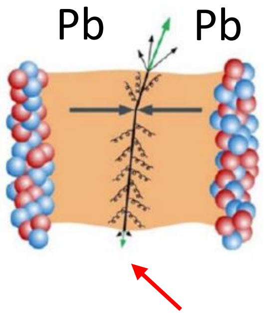
$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{AA}/dp_T dy}{d^2 N_{pp}/dp_T dy}$$

$R_{AA} = 1$	No modification between pp and PbPb.
$R_{AA} < 1$	Suppression in heavy-ion collisions, due to energy loss in the QGP.

Fragmentation in vacuum

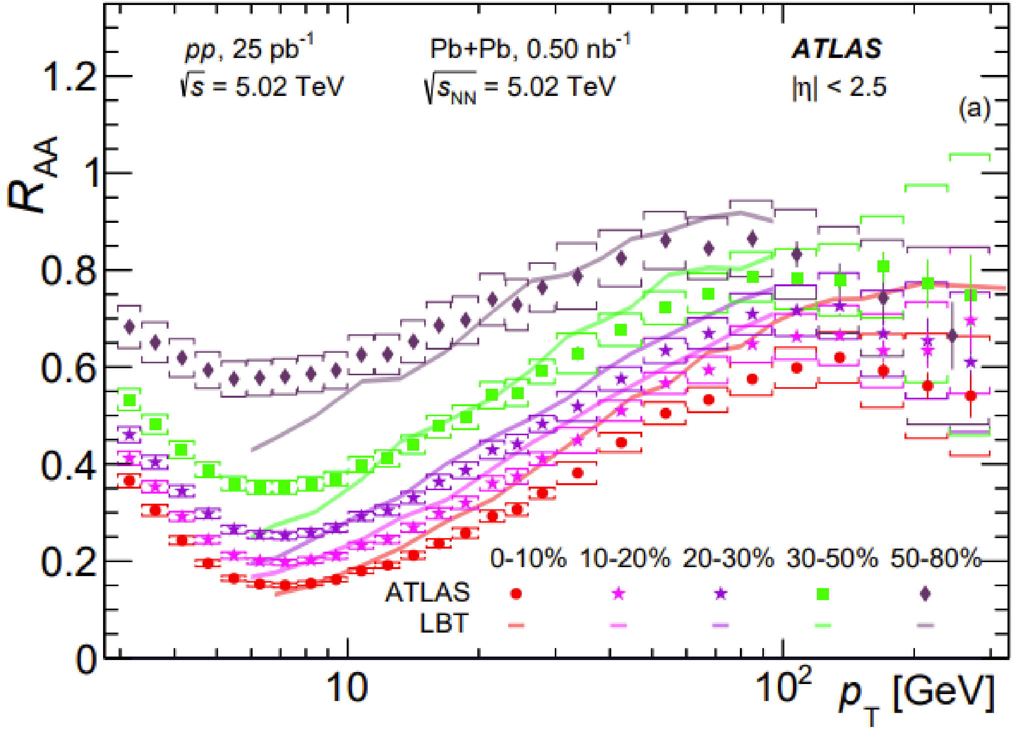


Fragmentation in medium



LBT: Phys. Lett. B 777 (2018) 255

arXiv:2211.15257



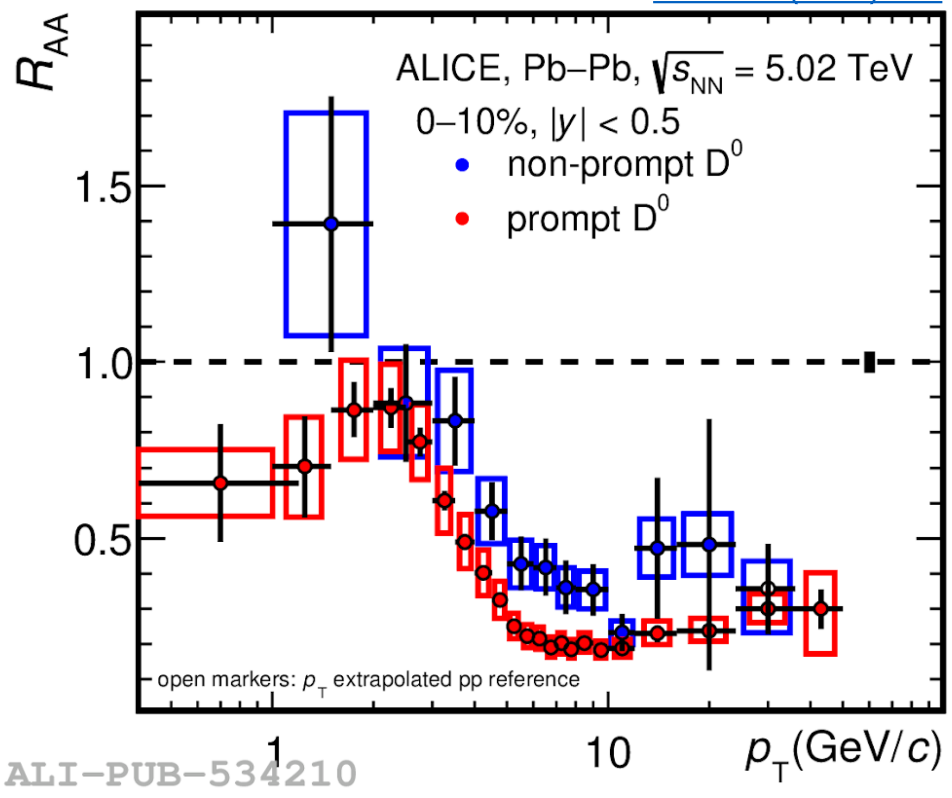
- Larger suppression in central events.

- Fairly good description of the theoretical models.
  - Hydrodinamic evolution of the medium
  - Elastic and inelastic interactions with the medium

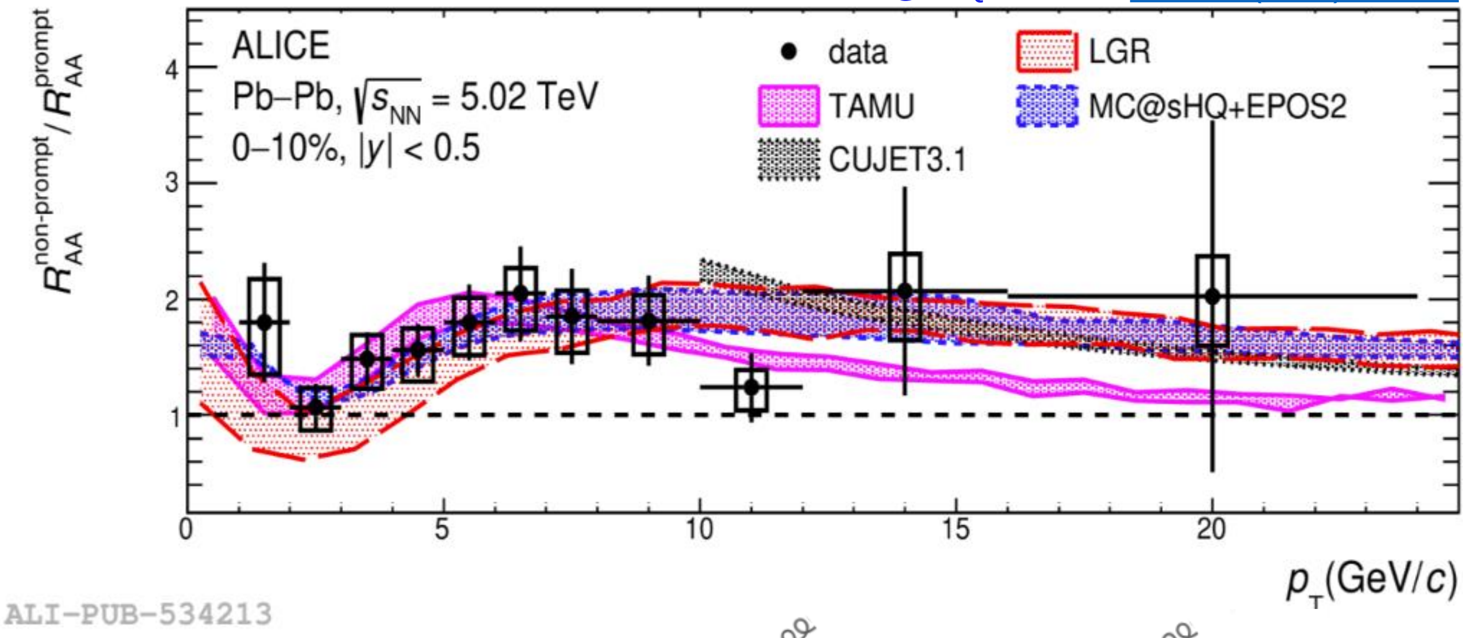
D meson energy loss

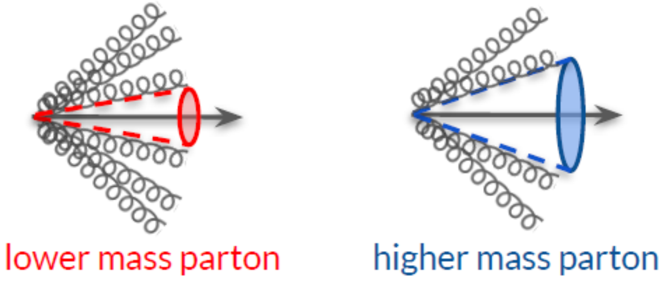
What about heavy flavour?

JHEP 12 (2022) 126



LGR: EPJC 80 (2020) 671
CUJET3: JHEP 02 (2016) 169
MC@sHQ+EPOS2: PRC 89 (2014) 014905



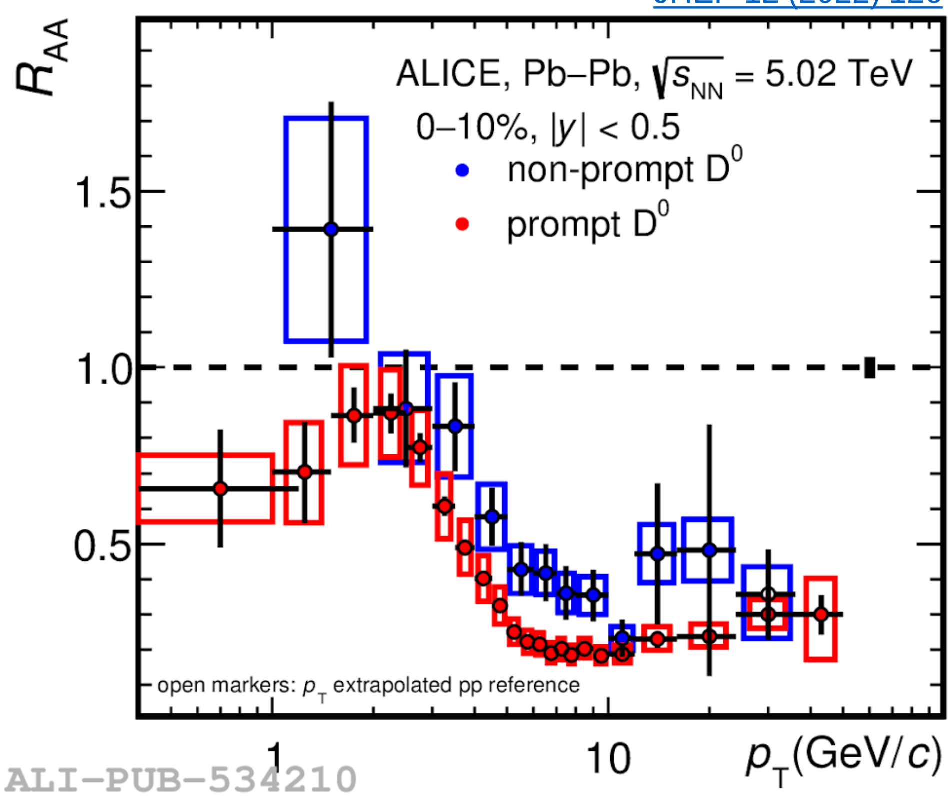


- $R_{AA}(b \rightarrow D^0) > R_{AA}(c \rightarrow D^0)$ at intermediate p_T.
  → in-medium energy-loss mass dependence (dead cone effect)
- Theoretical models catch the data.

D meson energy loss

What about heavy flavour?

JHEP 12 (2022) 126



LGR: EPJC 80 (2020) 671
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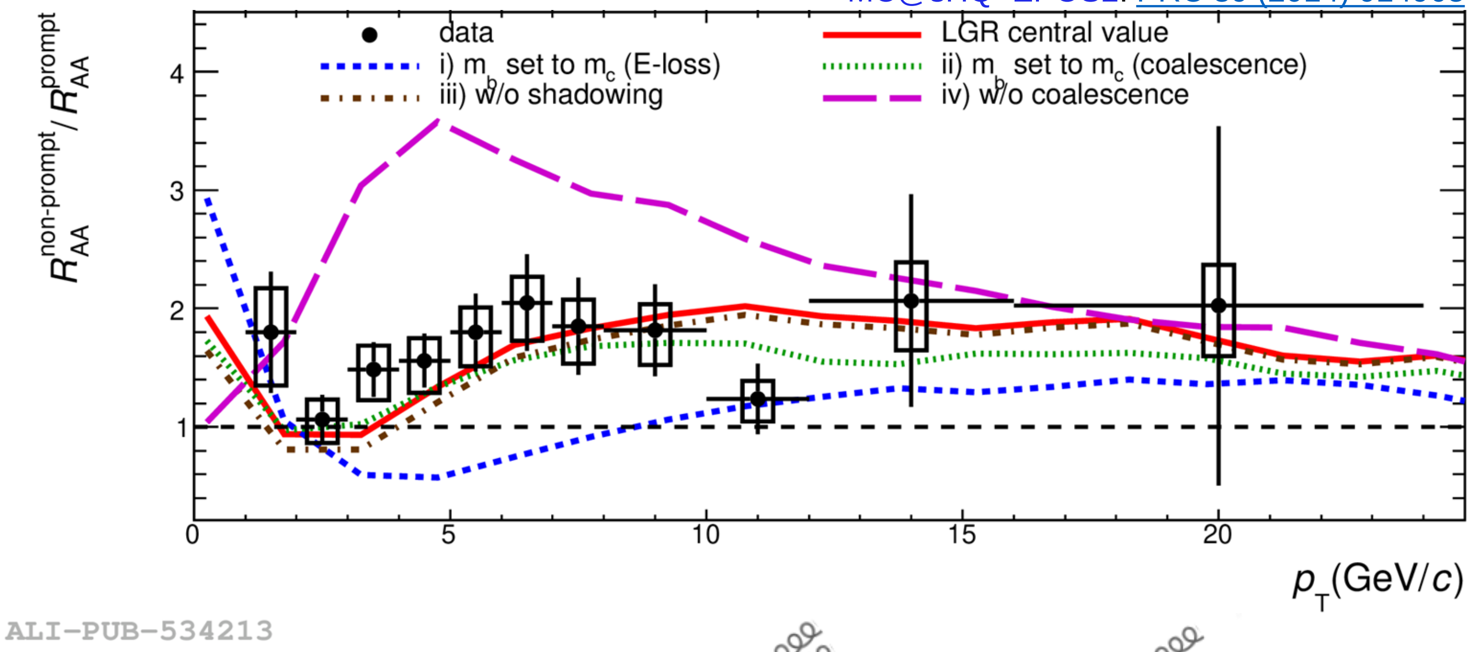
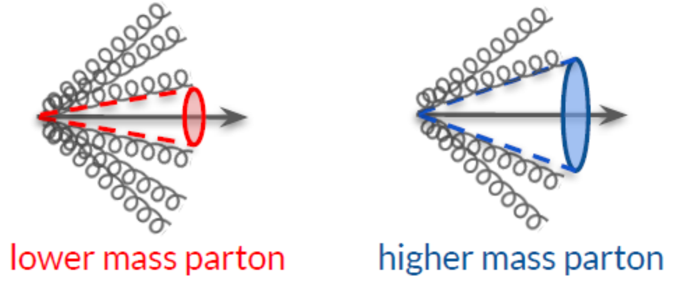




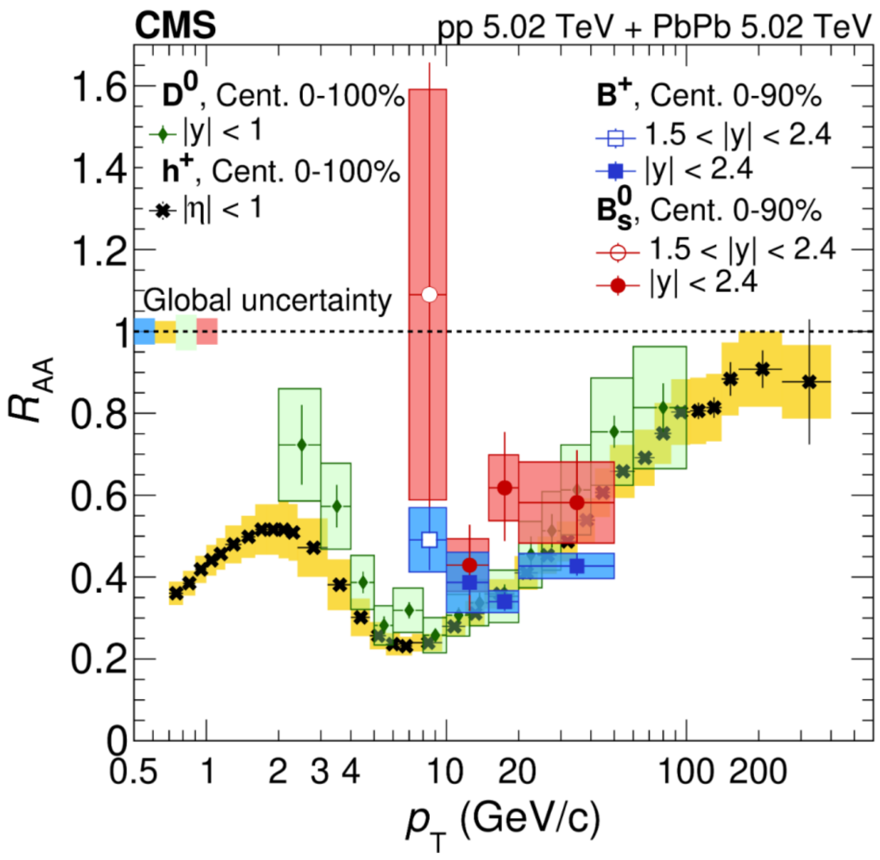
- R_{AA} (b → D^0) > R_{AA} (c → D^0) at intermediate p_T.

  ➡ in-medium energy-loss mass dependence (dead cone effect)

- Theoretical models that include **quark coalescence** and **collisional** and **radiative energy loss** catch the data.

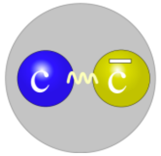
B meson energy loss

arXiv:2409.07258

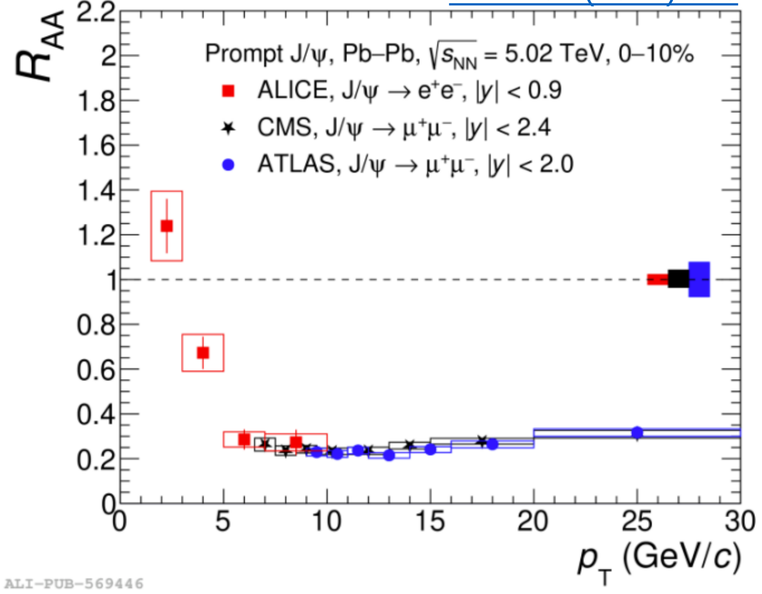


- Hint of lower suppression for both B^+ and B_s^0 below 10 GeV/*c*.
- Compatible suppression at high p_T.
- Further constraints on the bottom quark energy loss mechanism and hadronization in the QGP.

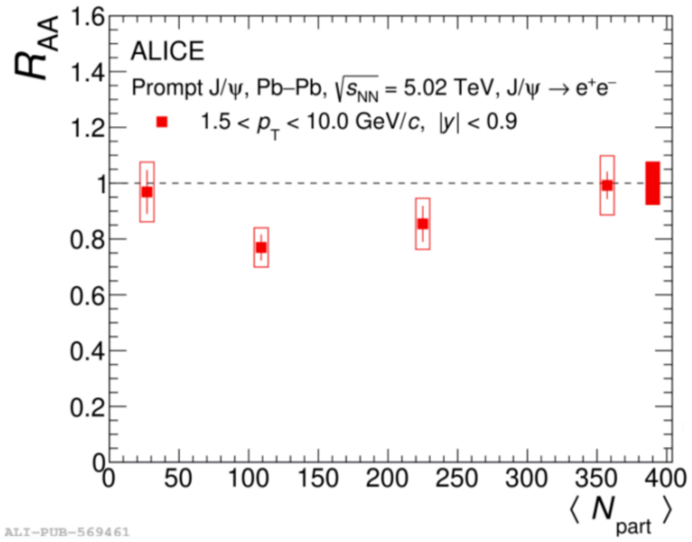
Charmonia

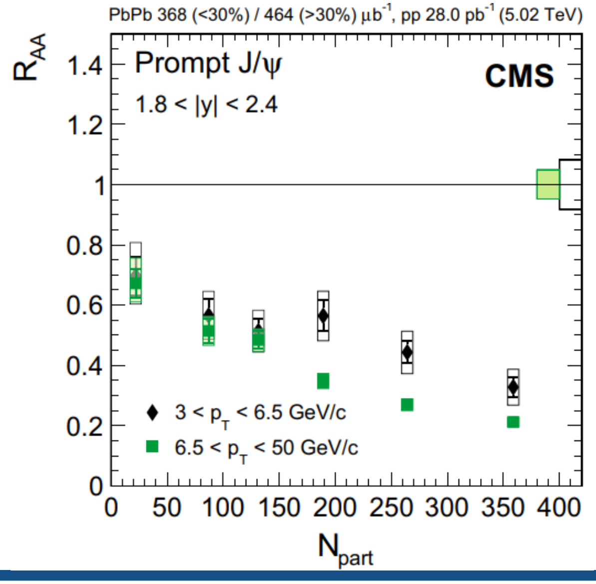


[JHEP 02 (2024) 066]

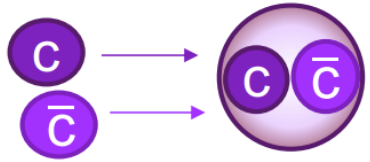


- Agreement among results from LHC experiments.
- Complementary p_T regions covered.



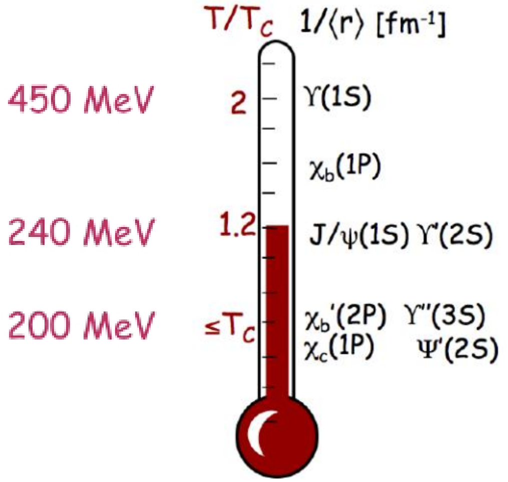


- Reduced suppression at low p_T attributed to a regeneration contribution.



Excited quarkonia states

- The sequential melting of quarkonium as QGP thermometer

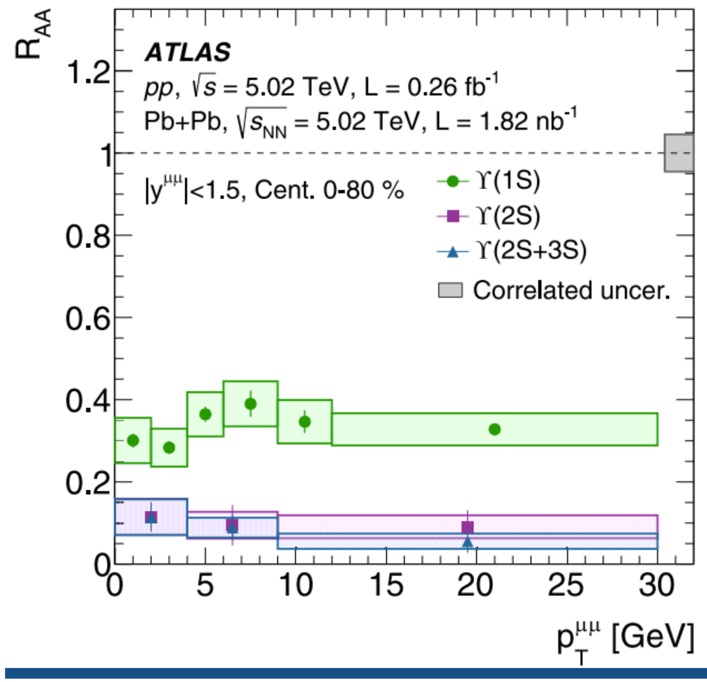


EPJC 61 (2009) 705

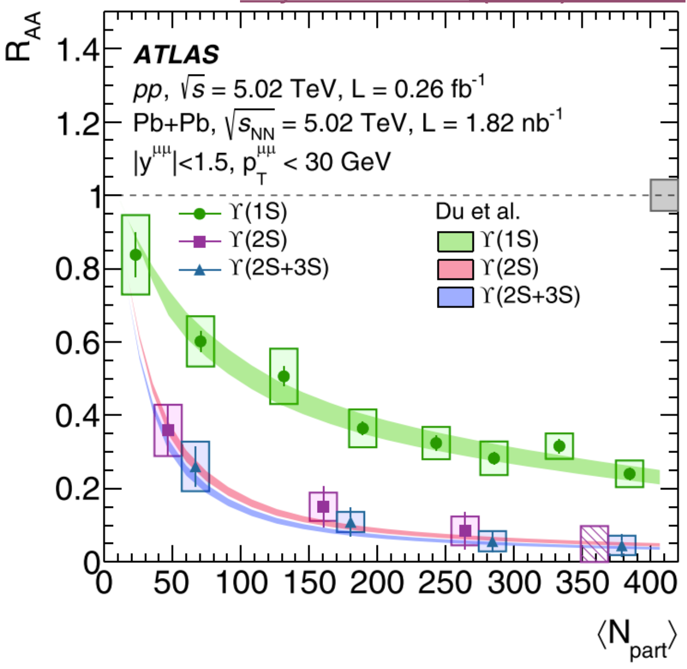
- Excited states are more suppressed than the ground state.
  $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$

- R_{AA} smoothly decreases with increasing centrality.

Phys. Rev. C 107 (2023) 054912



Du et al: Phys. Rev. C 96 (2017) 054901



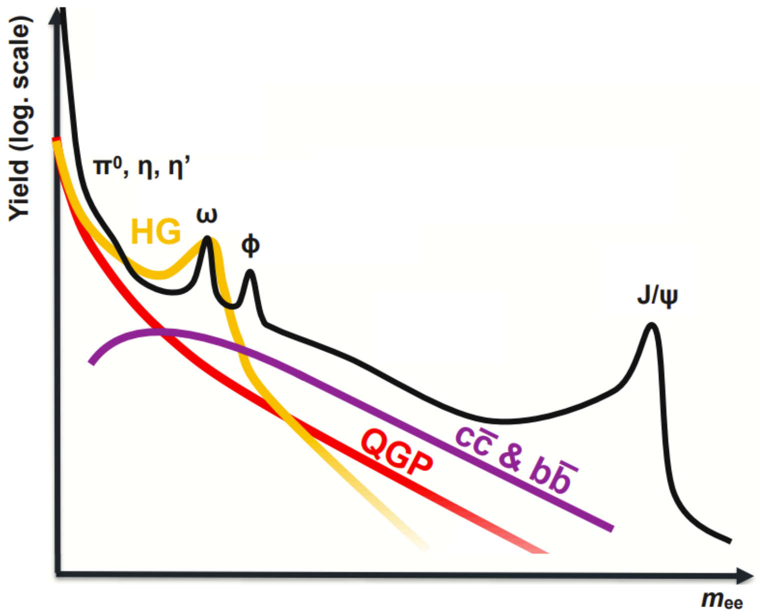
- Good agreement between data and theoretical models with color screening, regeneration and temperature-dependent binding energy.

Dielectron mass spectrum

Still about the QGP temperature

- Dielectrons (e^+e^-) are produced during all stages of the collision.
- Unaffected by strong final-state interactions.
- Thermal radiation from quark-gluon plasma: $\sim e^{-m/T}$

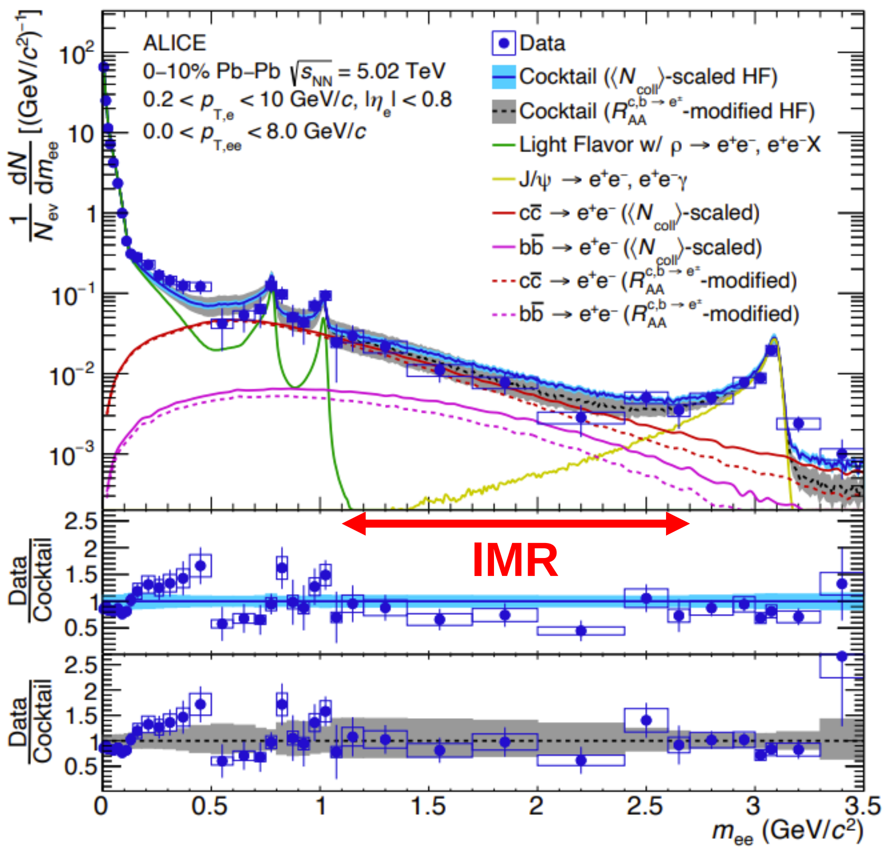
→ Measurement of the QGP temperature.



Thermal radiation from hadron gas (HG) via in-medium ρ
Pseudoscalar and vector mesons (π^0, η, η', ω, ϕ)
Semi-leptonic decays of HF hadrons
Thermal radiation from quark-gluon plasma

Dielectron mass spectrum

arXiv:2308.16704

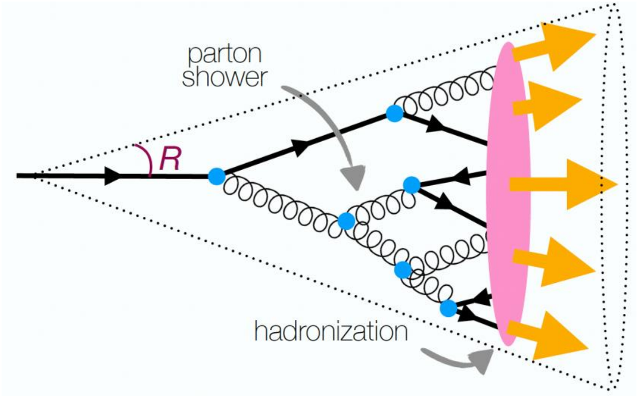


- Implementation of a hadronic decay cocktail to be subtracted to the full spectrum to measure the dielectron thermal yield.
- Measurement of the thermal dielectron in the intermediate mass range (1.1 – 2.7 GeV/c^2).
  ➡ only HF-dielectron production relevant in this range.
- Ratio between data and hadron cocktail compatible with unity
  ➡ QGP radiation in the intermediate mass range (IMR) is absorbed by HF cocktail uncertainty.

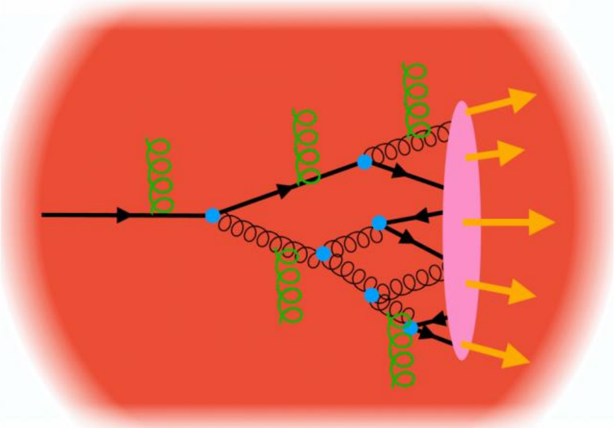
Larger data sample and better control of HF background are needed to quantify the excess!

Jet observables

Vacuum fragmentation

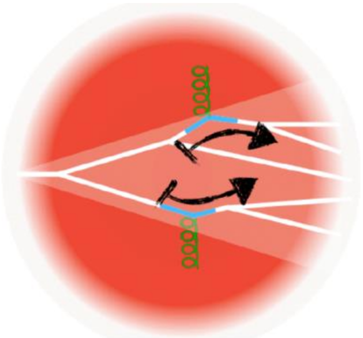


In-medium fragmentation

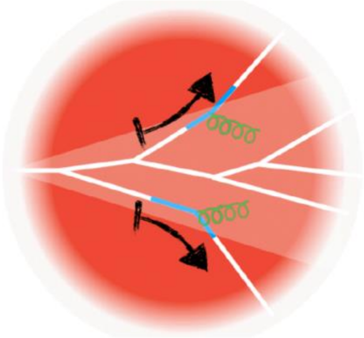


- In the medium, partons lose energy and change direction through medium-induced gluon radiations and collisions with medium constituents.
- **Various jets observables** available to probe the interactions with the medium:

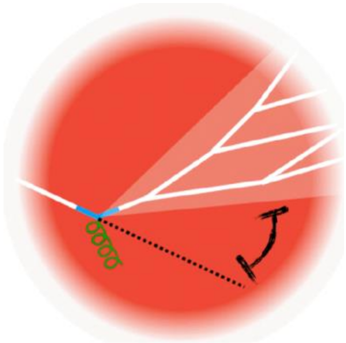
Energy loss



Substructure modification



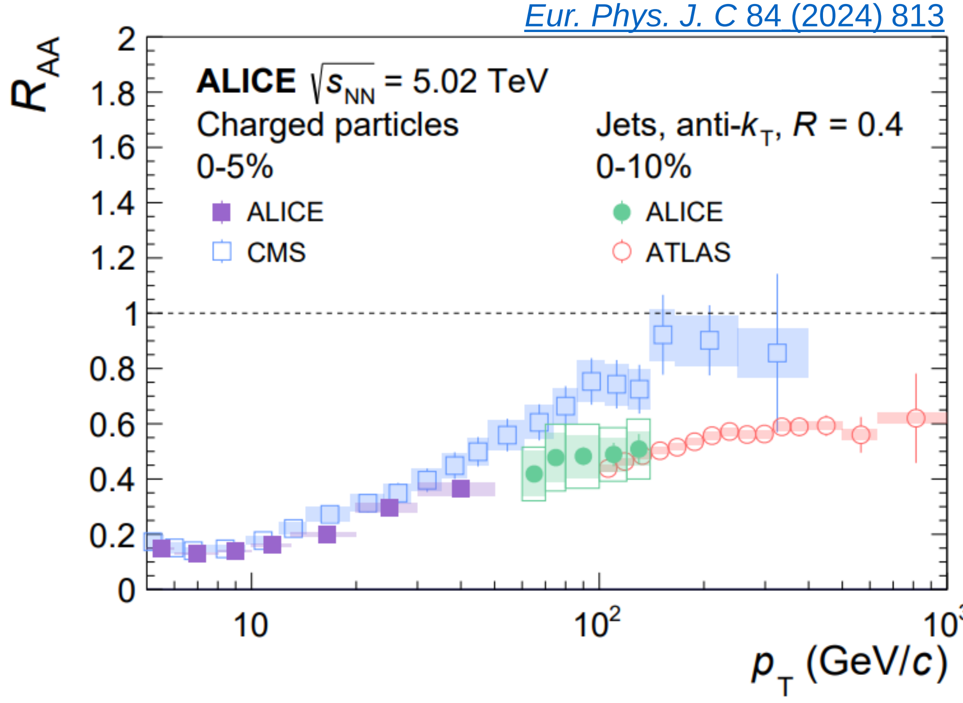
Deflection



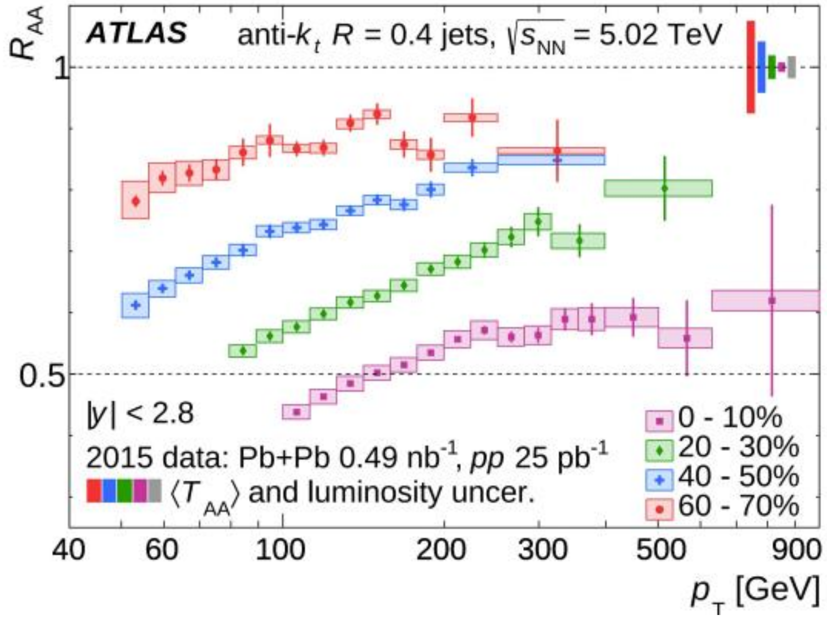
Jet R_{AA}

- High-p_T hadrons and jets allow to explore different aspects of jet quenching:
  - ➢ hadrons are sensitive principally to energy loss in the hardest branch of the jet shower.
  - ➢ jets are sensitive more broadly to modification of the shower.

Eur. Phys. J. C 84 (2024) 813



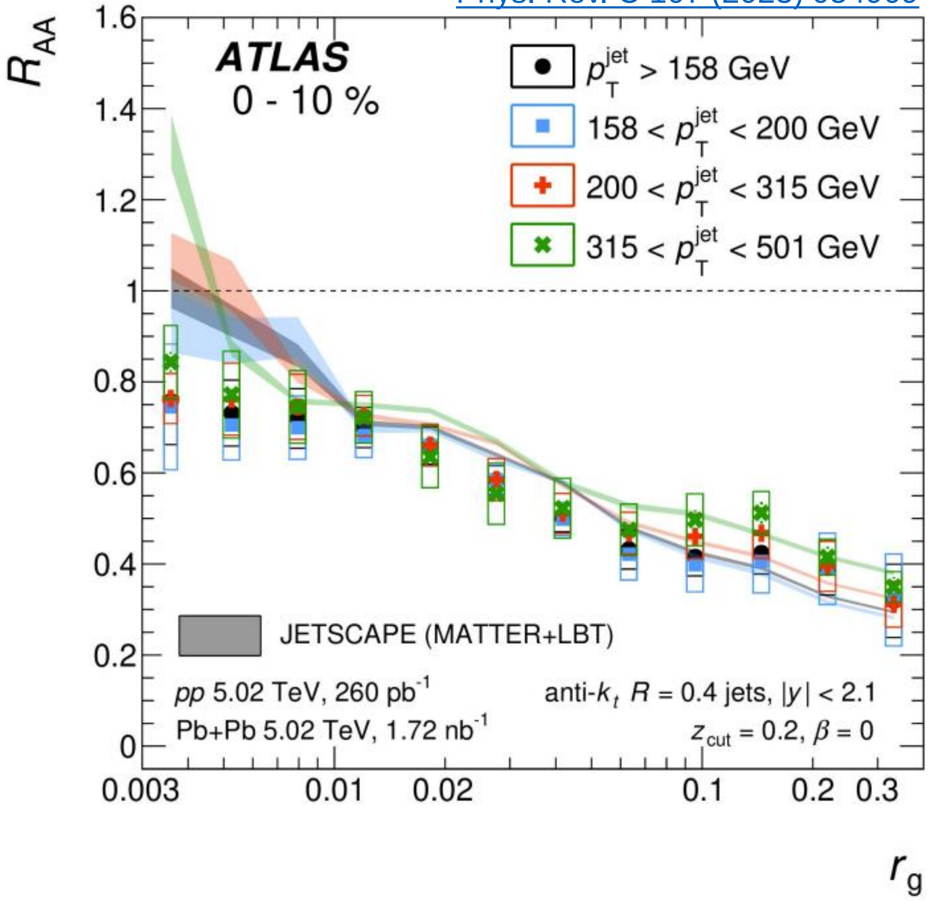
Phys.Lett.B 790 (2019) 108-128



- Jet R_{AA} exhibits larger suppression than hadrons at the same p_T.
  - ➢ Single particle vs multi-particle energy loss.
  - ➢ Jet broadening.
  - ➢ High-p_T hadron selection bias.

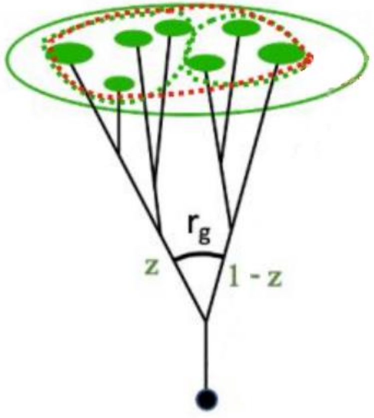
Jet R_{AA} - substructures

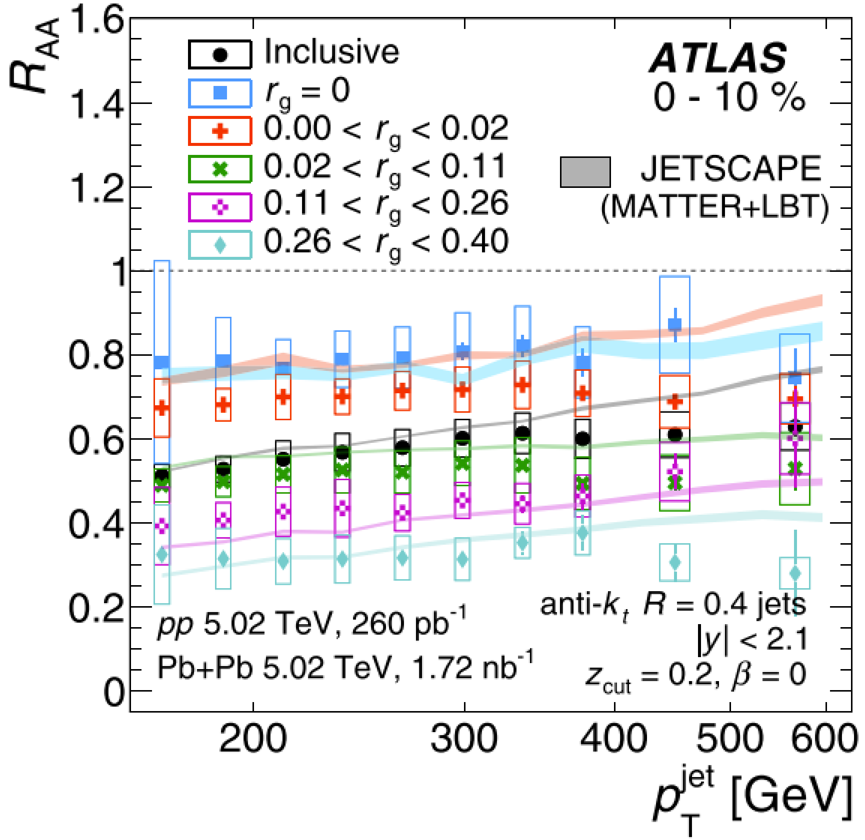
Phys. Rev. C 107 (2023) 054909



More info on jet suppression from jet substructures!

- R_{AA} decreases smoothly with increasing r_g.
- Lack of p_T dependence of R_{AA} for jets with similar structure.



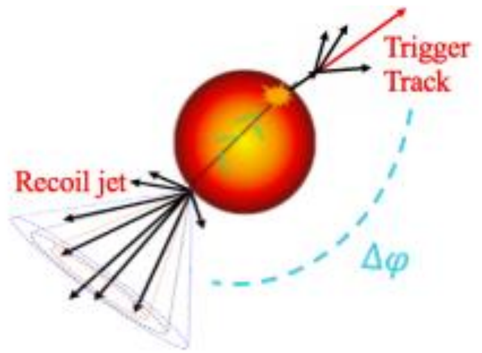


- Strong dependence of jet suppression on r_g.

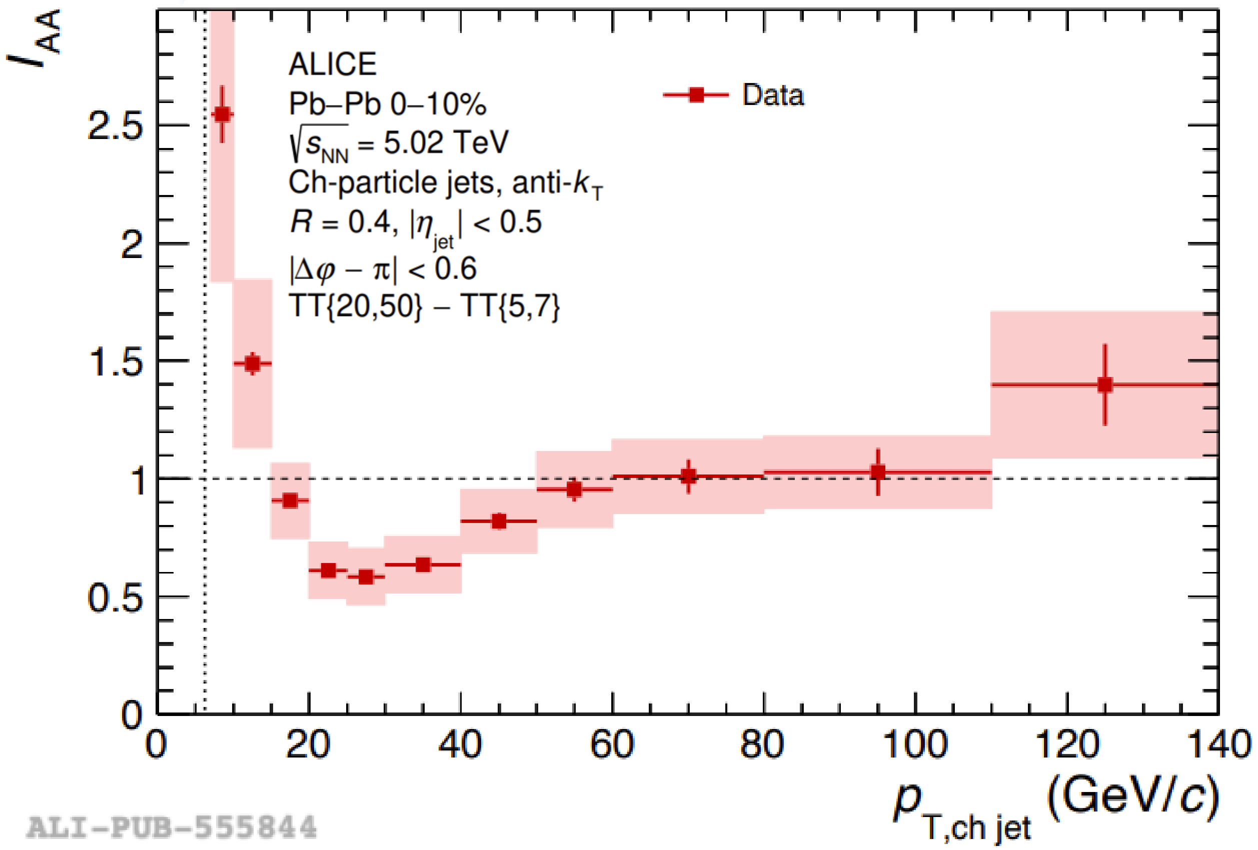
→ More collimated jets lose less energy and are less suppressed.

Jet energy redistributions

$$I_{AA} \equiv \frac{\Delta_{recoil}\,(p_T)_{AA}}{\Delta_{recoil}\,(p_T)_{pp}}$$



PRC 110 (2024) 014906

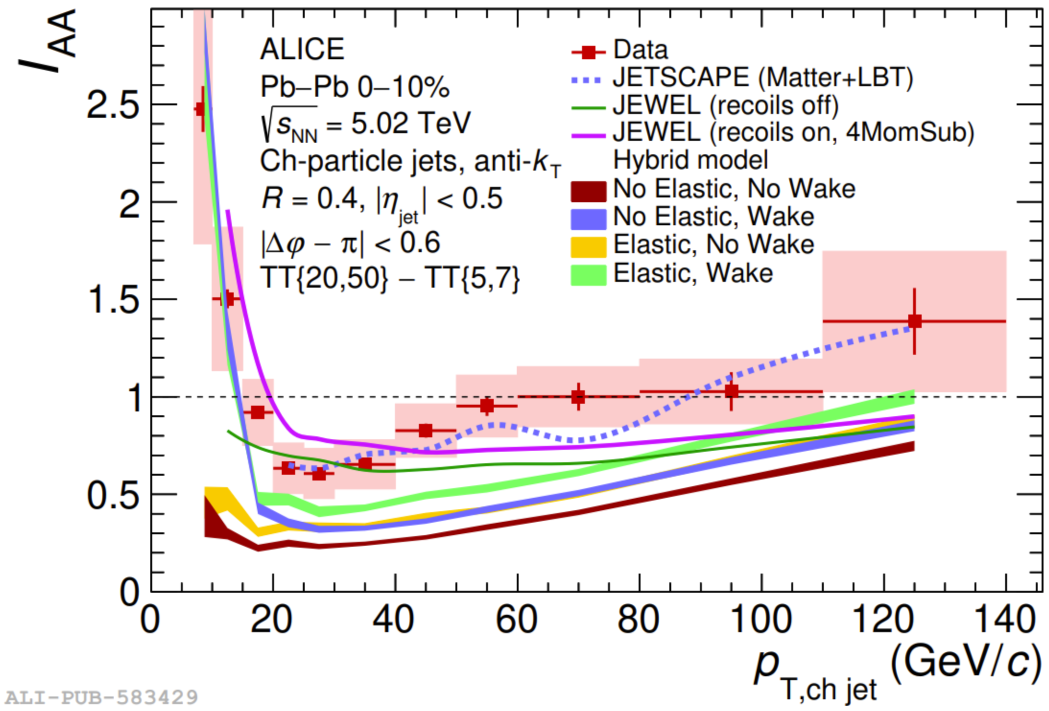


- Jet yield enhancement at $p_{T,\,jet} < 20$ GeV/c.
  - ➡ energy recovery in low-momentum jets.
- Jet yield suppression at $20 < p_{T,\,jet} < 60$ GeV/c.
  - ➡ medium induced yield suppression due to energy loss.
- Jet yield rising trend at $p_{T,\,jet} > 60$ GeV/c.
  - ➡ negligible quenching effect.

Jet energy redistributions

$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}\ (p_T)_{AA}}{\Delta_{\text{recoil}}\ (p_T)_{pp}}$$

JETSCAPE: Phys. Rev. C 107 (2023) 034911
JEWEL: Eur. Phys. J. C 74, 2762 (2014)
Hybrid Model (no wake): JHEP 01 (2019) 172
Hybrid Model (wake): JHEP 02 (2022) 175

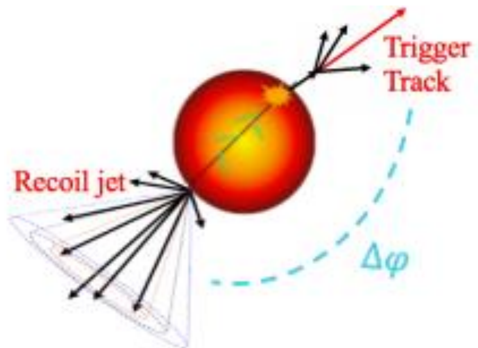


- **Hybrid**: elastic energy loss (i.e. 'Moliere' scattering) medium response with and without wake.
- **JEWELS**: collisional and radiative parton energy loss mechanisms. Medium response effects via treatment of recoils.

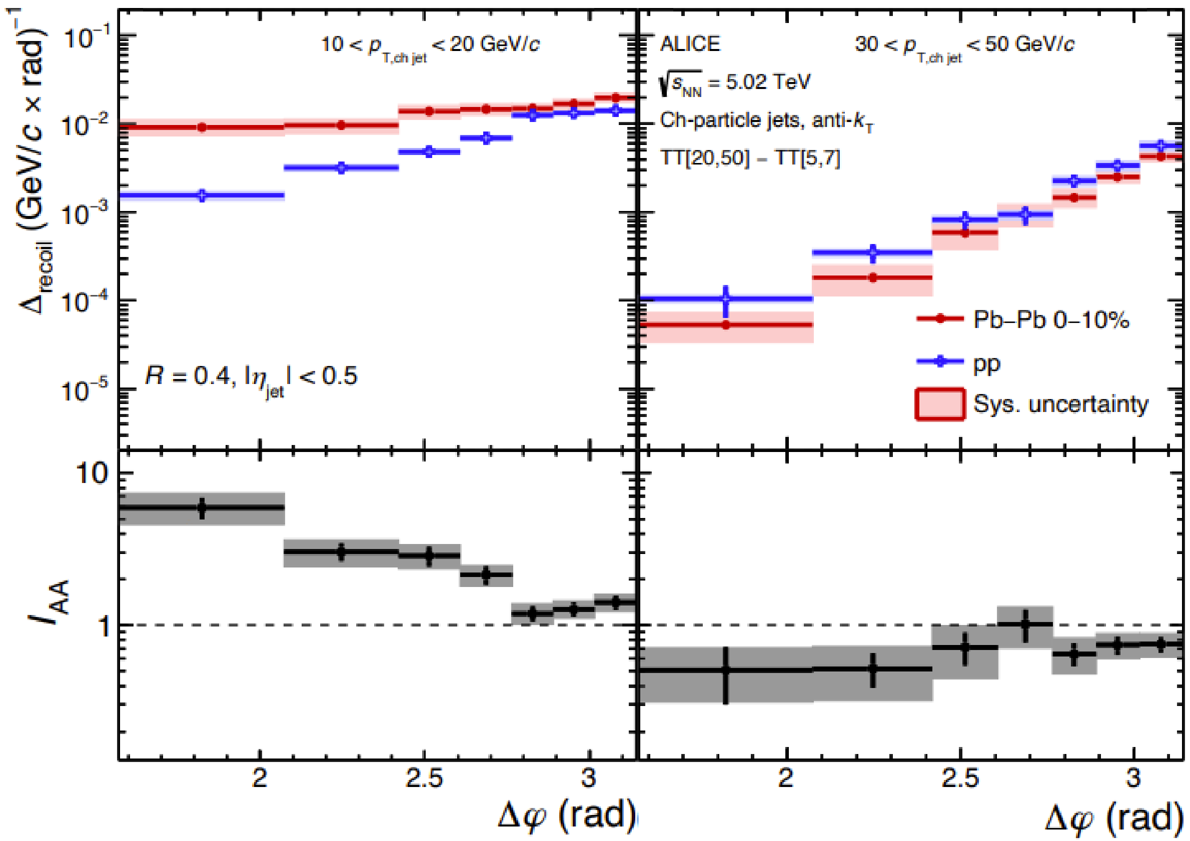
- The rising trend is qualitatively described by all the predictions.
- **Hybrid model with wake effect** and JEWEL with recoils on capture the yield enhancement at low p_T.
  → Medium response could be responsible for enhancement.
- **Hybrid model** and **JEWEL** predictions overestimate the suppression at high p_T.

Jet energy redistributions

- Angle (φ) of the recoil jet relative to trigger track axis:
  - **In vacuum**: transverse broadening due to gluon emissions (Sudakov broadening).
  - **In medium**: deflection of the recoiling jet due to the interaction with the medium.



PRL 133 (2024) 022301

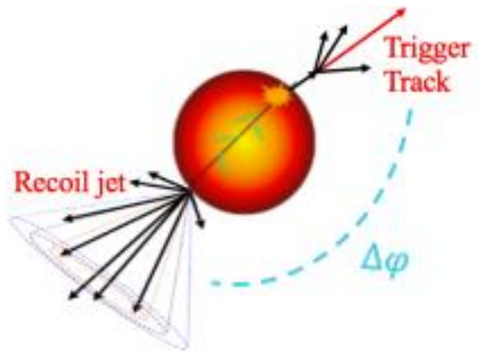


$$I_{AA} \equiv \frac{\Delta_{\text{recoil}}\,(p_T)_{AA}}{\Delta_{\text{recoil}}\,(p_T)_{pp}}$$

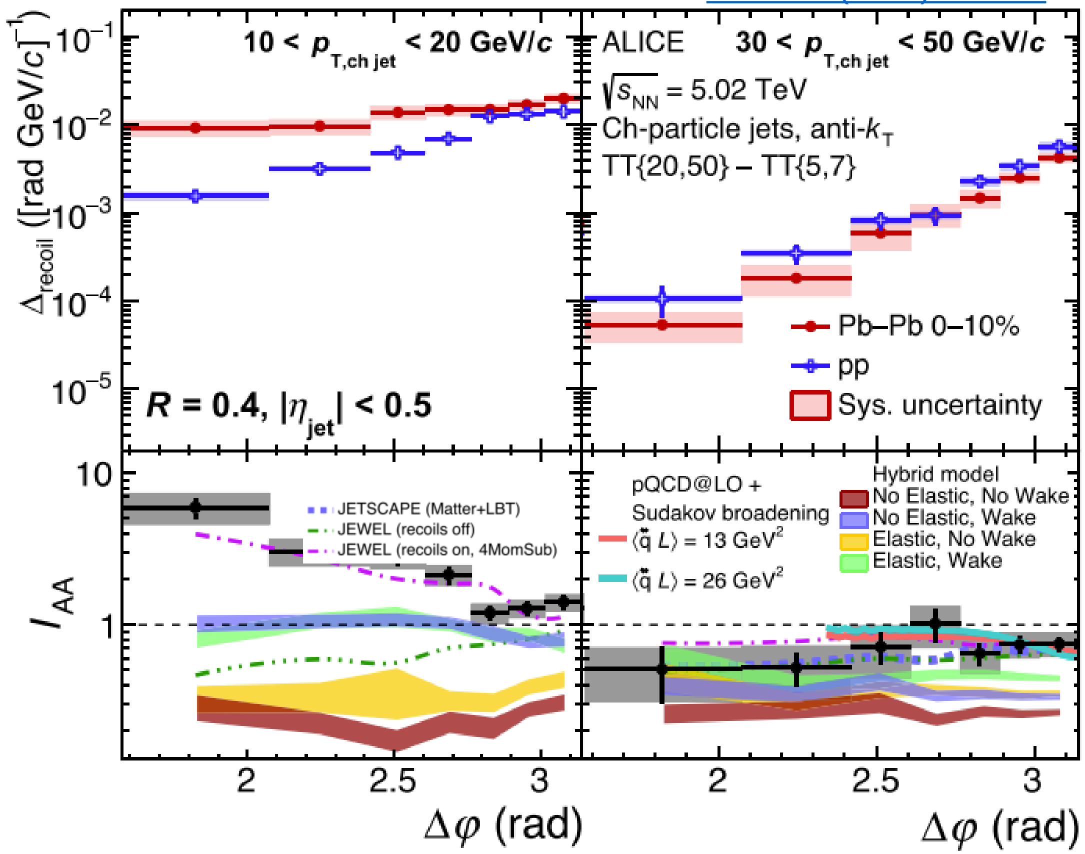
- Recoil jet broadening and jet yield enhancement in Pb-Pb for $10 < p_{T,\,\text{jet}} < 20$ GeV/c.
- Recoil jet yields suppression in Pb-Pb for $30 < p_{T,\,\text{jet}} < 50$ GeV/c.

Jet energy redistributions

- Angle (φ) of the recoil jet relative to trigger track axis:
  - **In vacuum**: transverse broadening due to gluon emissions (Sudakov broadening).
  - **In medium**: deflection of the recoiling jet due to the interaction with the medium.



PRL 133 (2024) 022301



$$I_{AA} \equiv \frac{\Delta_{recoil}\ (p_T)_{AA}}{\Delta_{recoil}\ (p_T)_{pp}}$$

- **Hybrid model** captures the yield enhancement at low p_T but no broadening effect predicted (even with wake on).
- JEWEL with recoils on describes the I_{AA} in all the measured p_T range, including the broadening effect.

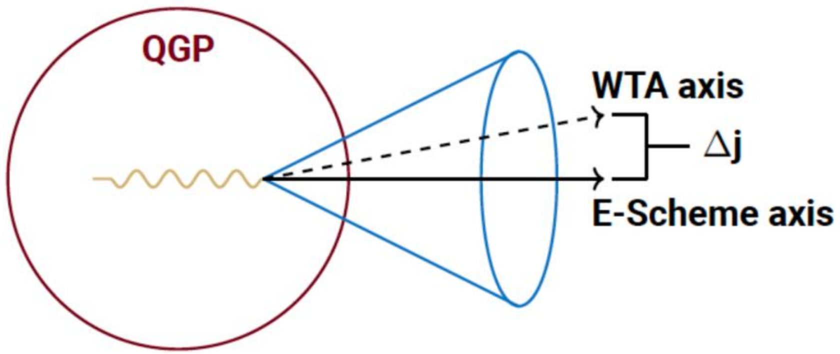
All features of distribution reproduced by JEWEL with recoils on.

→ Observed broadening consistent with medium response rather than Molière scattering.

Jet axis decorrelation

- Study of jet-axis decorrelation through the observable Δj:

$$\Delta j = \sqrt{(\phi_{\mathrm{E-scheme}} - \phi_{\mathrm{WTA}})^2 + (\eta_{\mathrm{E-scheme}} - \eta_{\mathrm{WTA}})^2}$$

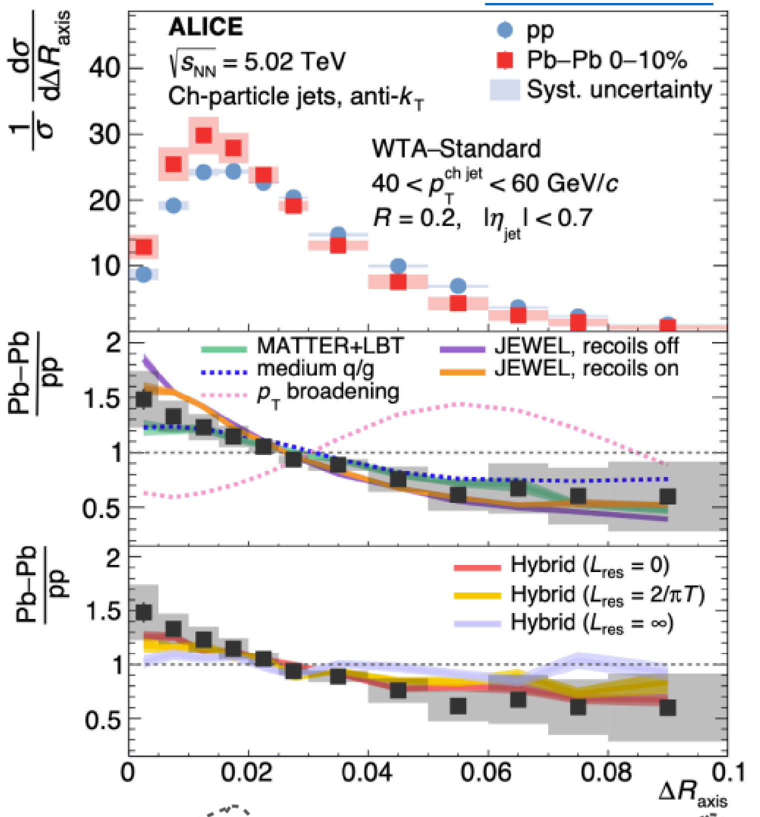


- E-scheme axis from four-vector sum at each step of clustering:
  - ➢ average energy flow of jet
  - ➢ sensitive to soft radiation
- Winner-Take-All (WTA) set axis to harder prong at each step of clustering:
  - ➢ leading energy flow of jet

- Modifications in E-scheme – WTA correlations as a probe of the jet-medium interactions.

Jet axis decorrelation

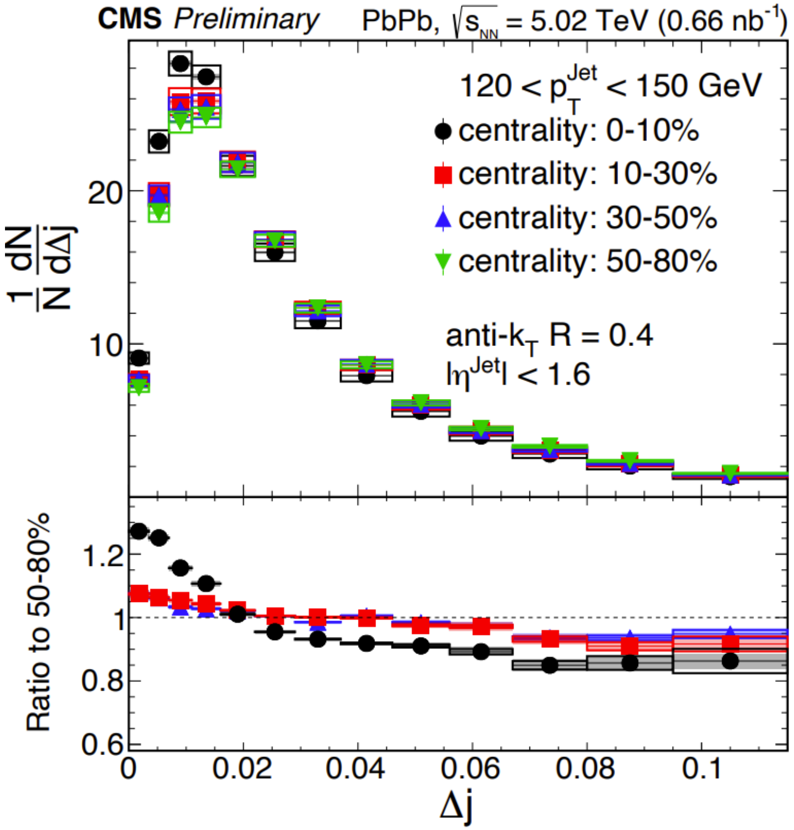
arXiv:2303.13347



- Relative enhancement at lower and suppression at higher Δj in Pb-Pb w.r.t. pp collisions.

- Same Δj trend observed when comparing Pb-Pb central collisions with peripheral collisions.

➢ Pb–Pb distribution dominated by quark-initiated jets?
  - gluon-initiated jets are expected to interact more with the medium.



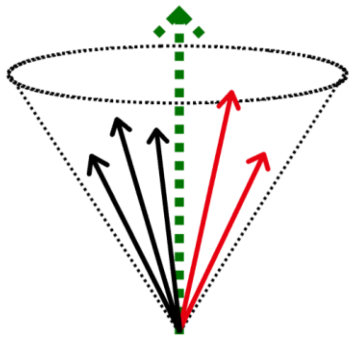
- **Hybrid**, **JEWEL** and JETSCAPE MATTER+LBT catch the data.

Energy-energy correlators

- EECs measure how energy is distributed within a jet.
- Ability to separate with a single observable, perturbative and non perturbative regions.

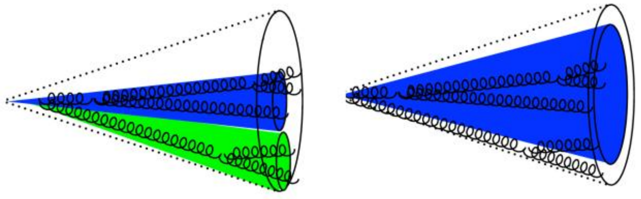
$$\Delta r \equiv \Delta r_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

$$EEC(\Delta r) = \frac{1}{W_{\mathrm{pairs}}} \sum_{\mathrm{jets} \in [p_{\mathrm{T},1}, p_{\mathrm{T},2}]}^{\infty} \sum_{\mathrm{pairs} \in [\Delta r_a, \Delta r_b]}^{\infty} (p_{T,i}\, p_{T,j})^n$$



Angular distance pairs of particles within the jet, weighted by the product of their momenta.

- In heavy-ions collisions, EECs proposed as probe of medium color coherence and jet wake effect.

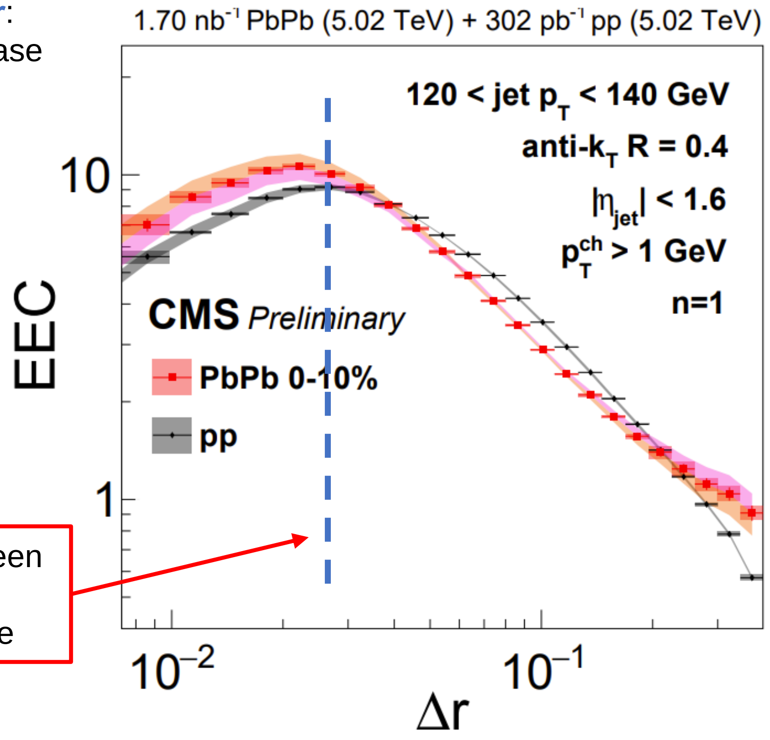


Energy-energy correlators

Intermediate Δr: transition toward hadronic phase

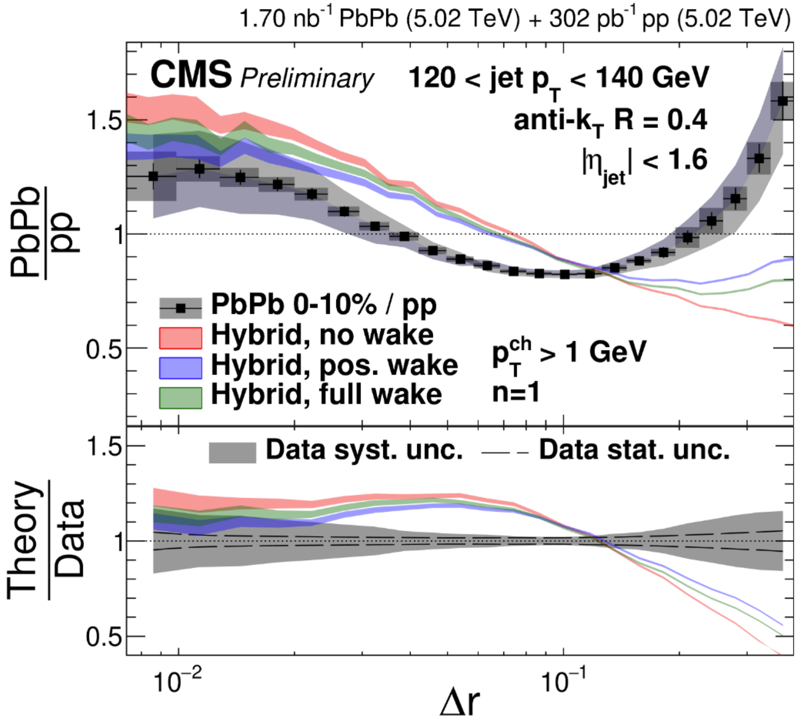
Small Δr: hadron phase

Large Δr: perturbative parton shower



transition between hadrons and partons phase

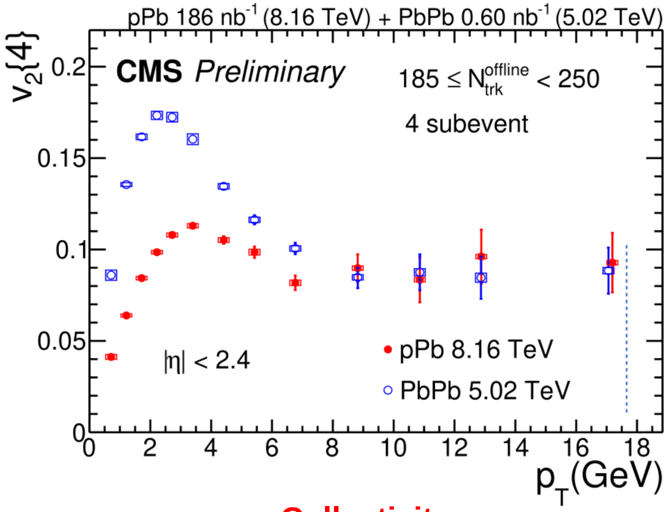
- Hadron, transition, and free quark/gluon regions visible in EECs.
- Pb-Pb enhancement in small Δr (hadron regime).
  ➡ Energy loss moves the peak to smaller Δr.



- Models with jet wake and color coherence show qualitatively similar behavior as data but cannot describe it.
- Pb-Pb enhancement in large Δr non described by any model.

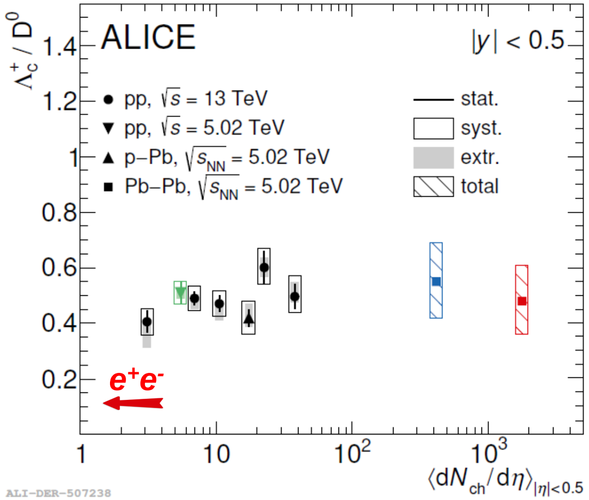
Flash slide on small systems

- Several effects discussed in this talk were considered as **unique signatures of the QGP formation in heavy-ion collisions** w.r.t. the basiline provided by small systems.



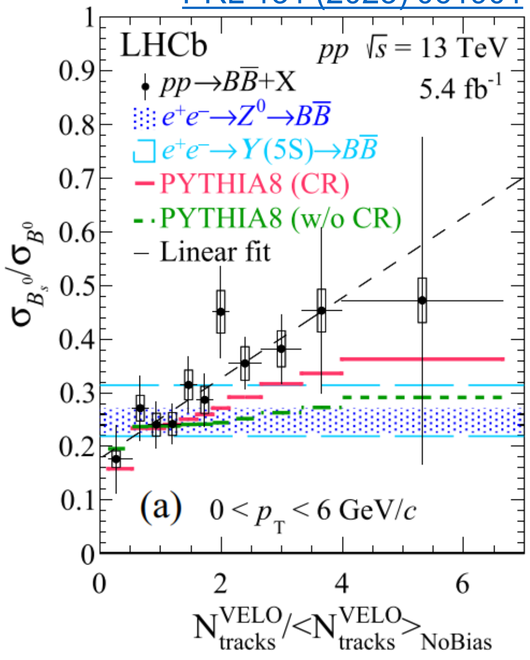
Collectivity

pp: PLB 829 (2022) 137065
p-Pb: Phys. Rev. C 104 (2021) 054905
Pb-Pb: Phys. Lett. B 839 (2023) 137796



Charm baryon enhancement

PRL 131 (2023) 061901

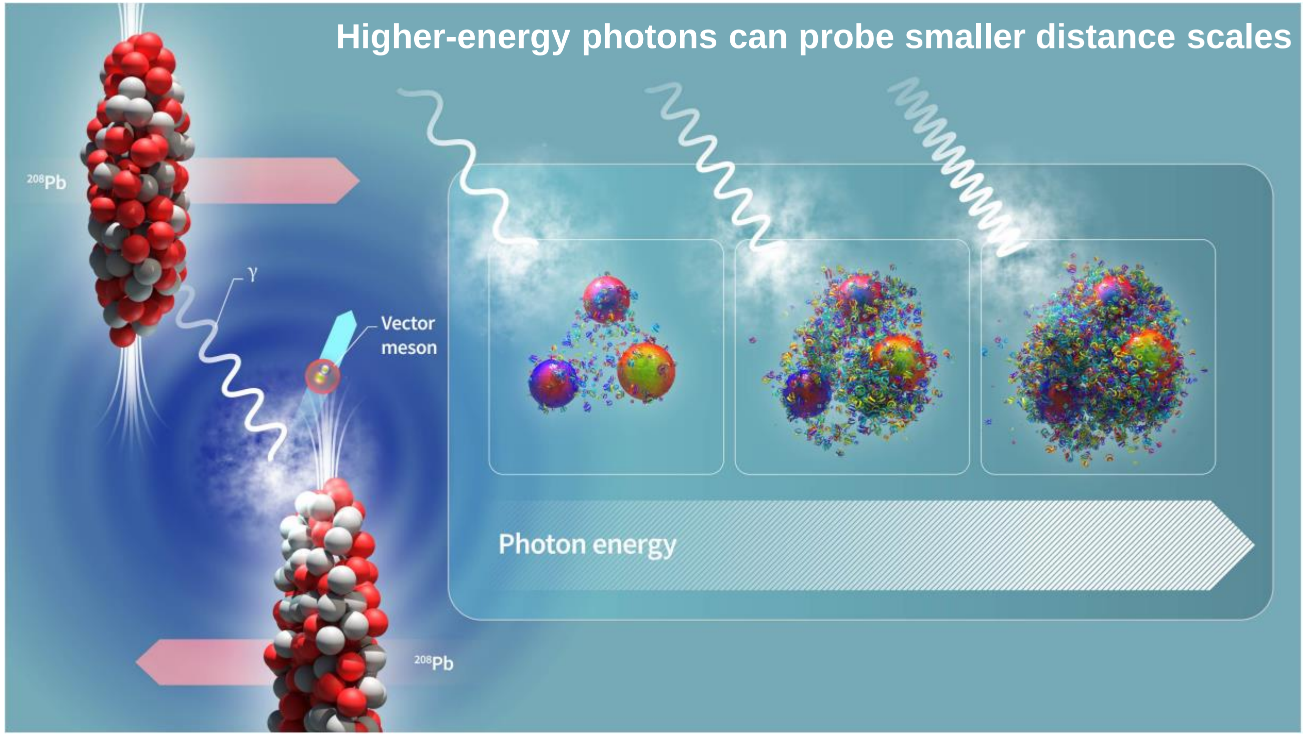


Strangeness enhancement

- Hadronic colliders revealed a totally different situation: **presence of phenomena so far associated to QGP formation in hadronic small systems** as well.

UPC collisions

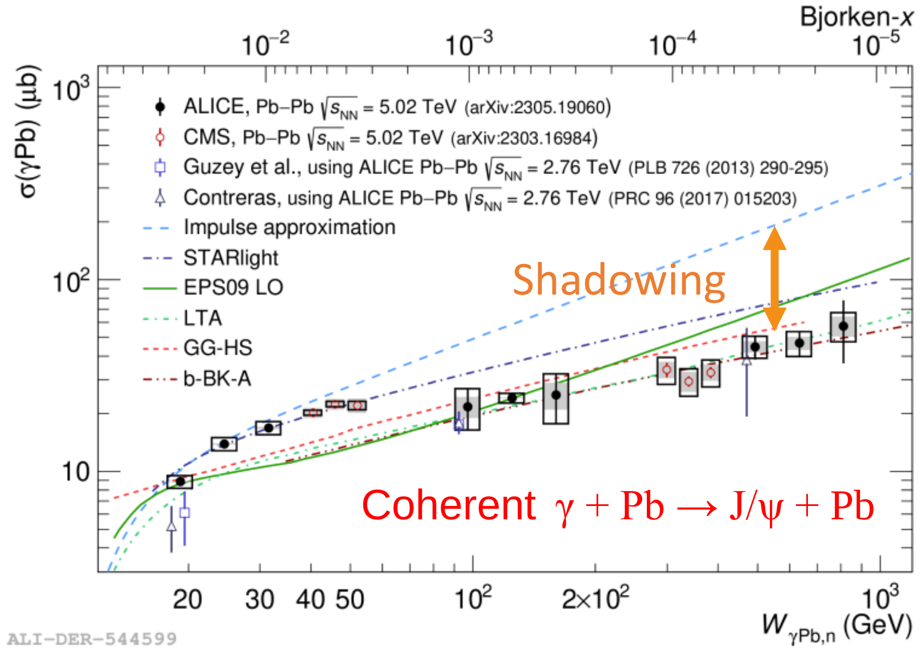
- Ultraperipheral collisions (UPCs) occur when a virtual photons interact w/o nuclear overlap.



- Absence of hadronic interactions.
  - ➡ cleaner and easier to interpret final state
- Access to parton distribution functions (PDFs).
  - ➡ probe the parton distribution functions over a wide range of Bjorken *x*.
- Access to rare processes.
  - ➡ photon-photon collisions, photonuclear interactions

J/Psi in UPC

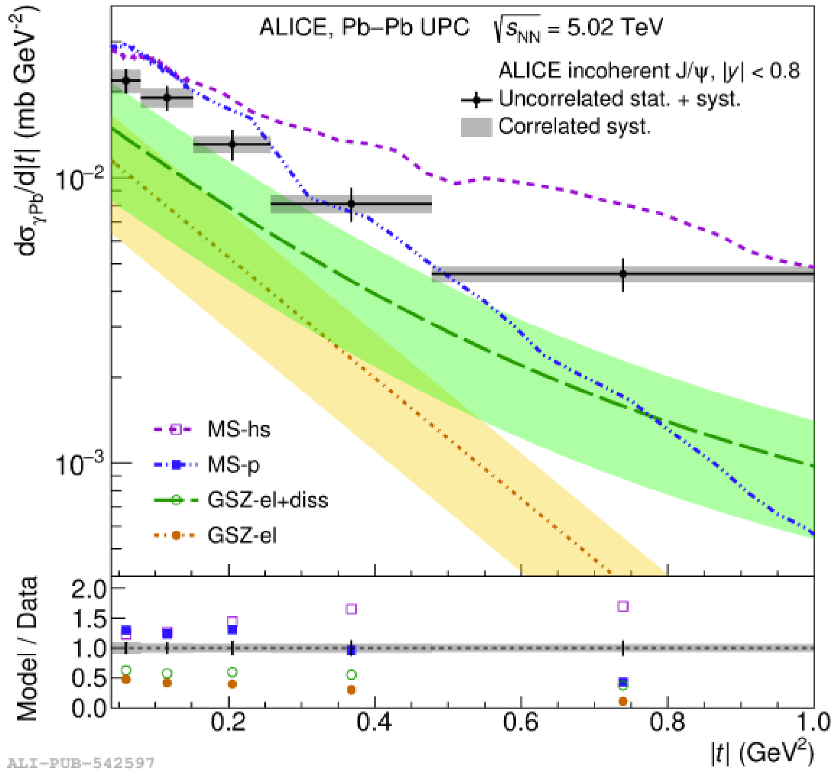
- $\gamma + \mathrm{Pb}$ collisions are sensitive to gluon distribution inside nuclei:
  - ➢ Coherent production: probe the averaged gluon density.
  - ➢ Incoherent production: probe the local gluon density fluctuation (gluon saturation).



ALICE: JHEP 10 (2023) 119
CMS: PRL 131 (2023) 262301

PRL 132 (2024) 162302

Incoherent $\gamma + \mathrm{Pb} \rightarrow J/\psi + \mathrm{Pb}$

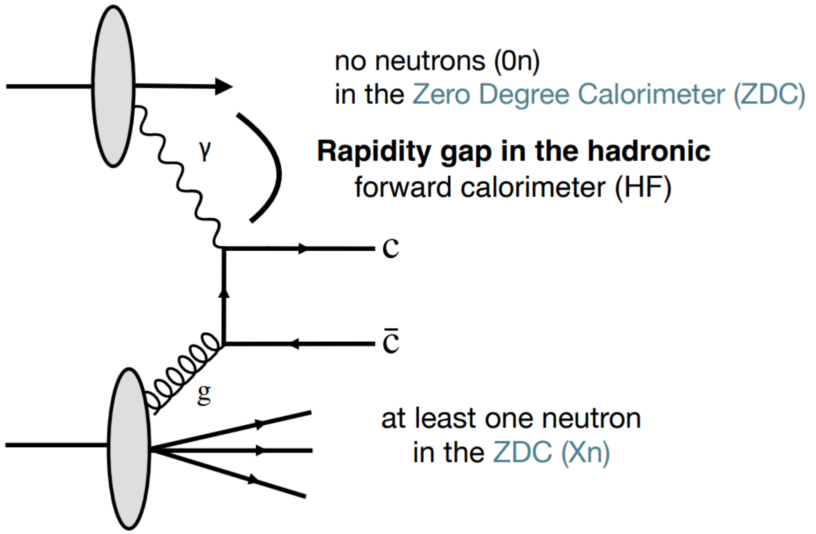


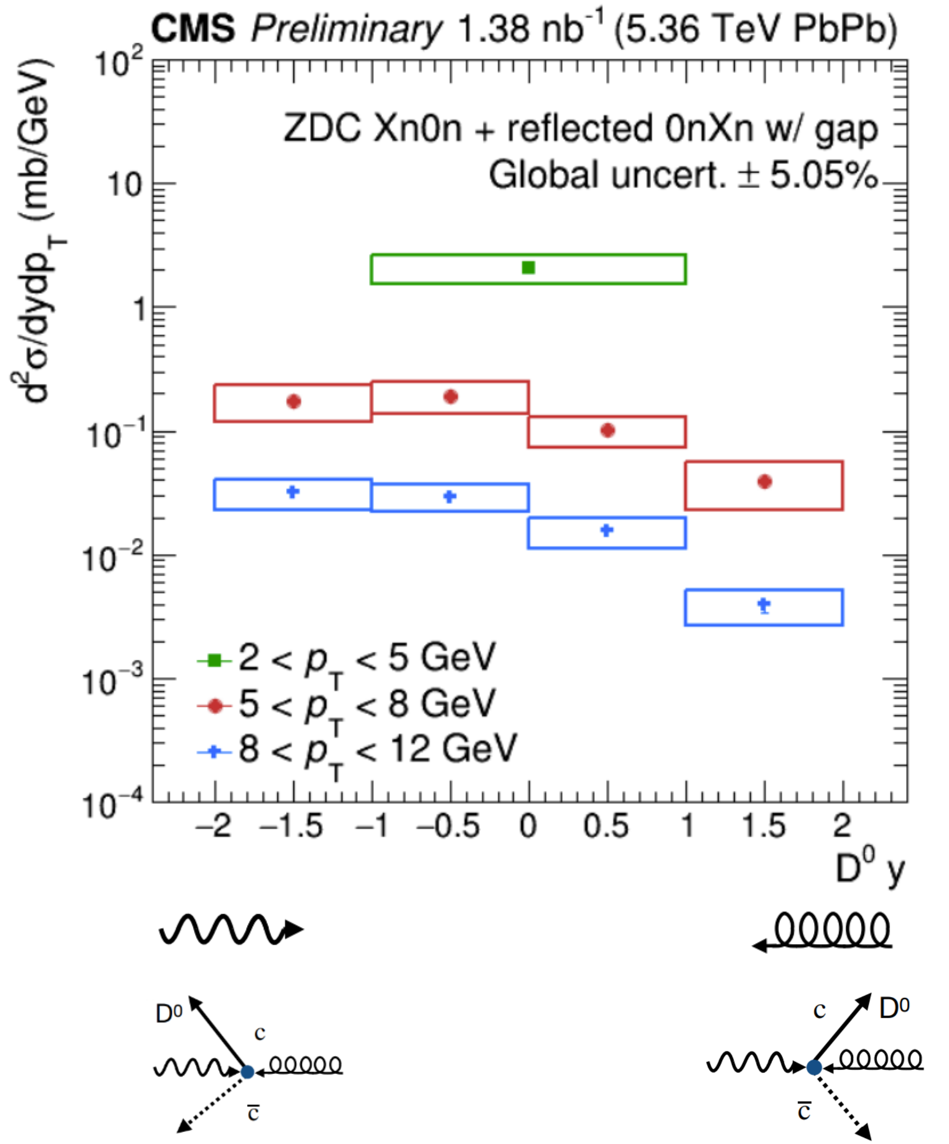
- **Lower-x** better described with models including shadowing/saturation (LTA, b-BK-A,).
- **Higher-x** better described by Glauber calculation (STARlight).

- Models cannot describe the data
- Interplay between shadowing and gluon saturation needed to catch the data.

D^0 photonuclear production in UPC

- Photonuclear D^0 production in UPC collisions.
- Xn0n Pb-Pb events with rapidity gap: (measurement performed also in 0nXn)

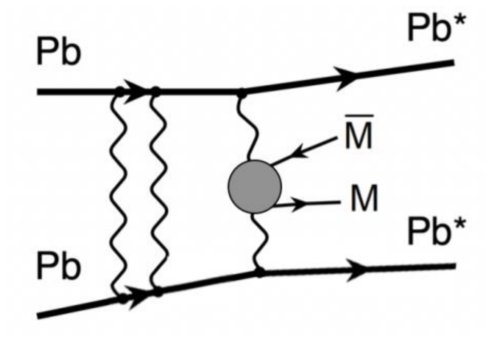




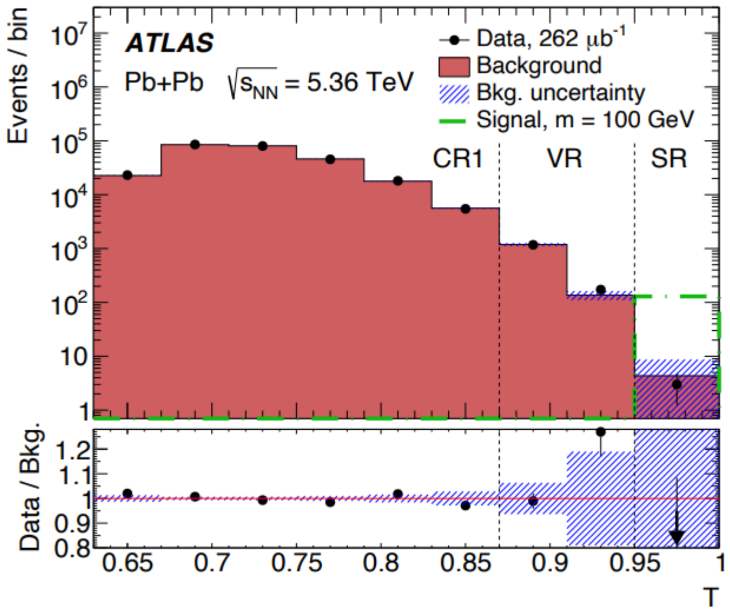
- Clear rapidity dependence of the D^0 cross-section with respect to the incoming photon direction.
- Constraints on PDFs with a clean probe in a large regime of (x,Q^2).

Magnetic monopole search in UPC

- Magnetic monopoles via the Schwinger mechanism in UPC:



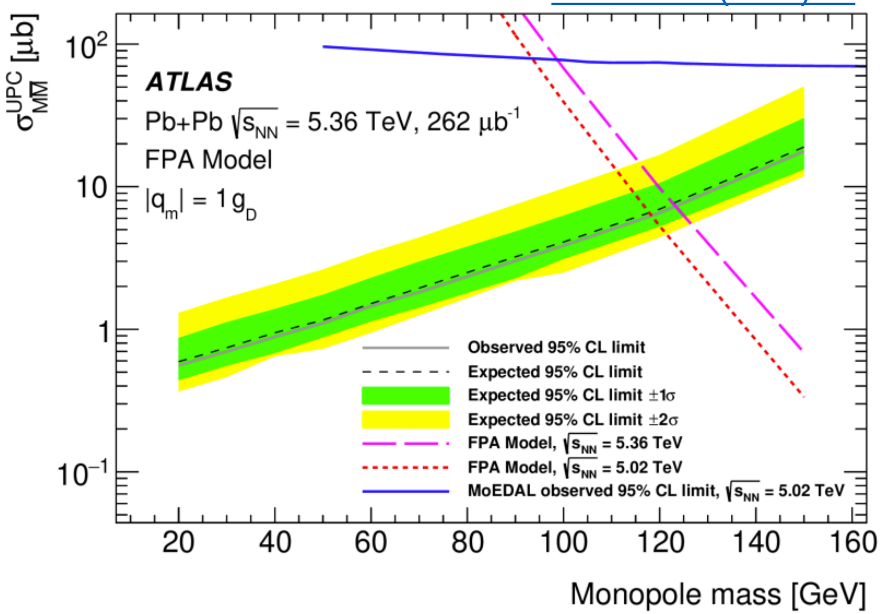
arXiv:2408.11035



$$T = (1/n_{\mathrm{PixCl}}) \sum_{i=1}^{n_{\mathrm{PixCl}}} |\hat{r}_i \cdot \hat{n}|$$

$T > 0.95$ for signal events

MoEDAL: Nature 602 (2022) 63



- 3 events in SR, consistent with background estimate (4 ± 4).

- Better cross-section upper limits w.r.t. MoEDAL for $M\bar{M}$ in mass range between 20 and 150 GeV.

LHC program timeline

LS 2	Run 3	LS 3	Run 4	LS 4	Run 5

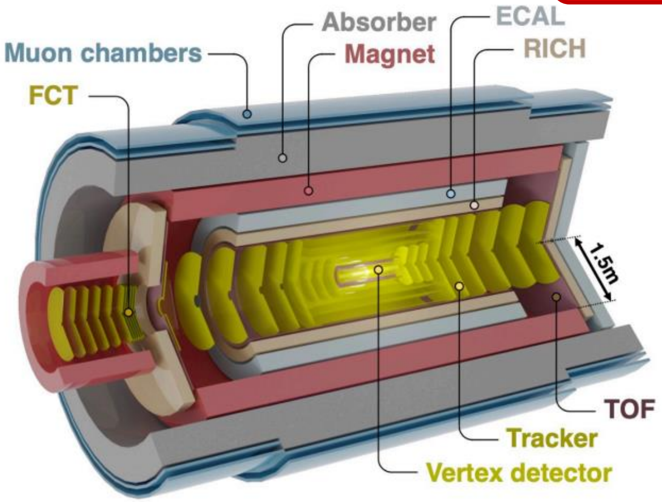
ALICE 2

LHCb

Now

Phase II upgrades

ALICE 3

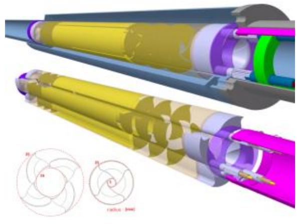


ALICE:
- upgraded **I**nner **T**racking **S**ystem (ITS 2)
- **M**uon **F**orward **T**racker (MFT)
- **F**ast **I**nteraction **T**rigger (FIT)
- Renewed data processing (O^2)

ATLAS and CMS:
- new trackers with CMOS technology
- η coverage up to 4
- faster readout electronics
- New ZDC
- CMS high-granularity calorimeter (HGCAL)
- ATLAS high-granularity timing detector (HGTD)
- …

LHCb:
- upgraded **V**ert**e**x **Lo**cator (VELO)
- **U**pstream **T**racker (UT)
- **Sci**ntillating **Fi**ber tracker (SciFi) + **Si P**hoto-**M**ultipliers (SiPMs)
- Renewed data flow

ALICE:
- ITS 3
- FoCal

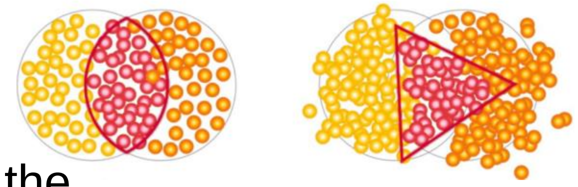


ALICE 3:
- Excellent pointing resolution
- Large η coverage
- Exceptional PID capabilities

LHCb:
- full centrality range in Pb-Pb

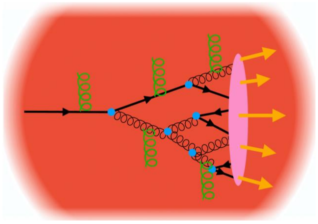
Conclusions

- Heavy-ion collisions provide a unique environment to explore fundamental aspects of QCD.
- Experimental evidences confirm the creation of a hot nuclear medium with deconfined color charges (QGP).



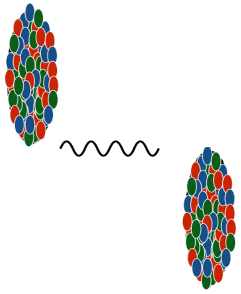
➢ Understand the initial state effects.

➡ Initial anisotropy converted into anisotropy of the final state particles. QGP behaves like a liquid.



➢ Probing QGP with penetrating particles

➡ Energy redistribution in the medium through both radiative and collisional energy exchange.



➢ UPC to probe PDFs and to explore new physics.

Heavy-ion physics program will continue throughout the entire life of the LHC!

➡ Detector upgrades to enable precise measurements of new observables

Thank you for your attention!

Backup

Theoretical models

	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
TAMU	✅	❌	✅	✅	✅
LIDO	✅	✅	✅	✅	✅
PHSD	✅	❌	✅	✅	✅
Langevin	✅	✅	✅	✅	✅
Catania	✅	❌	✅	✅	✅
MC@sHQ+EPOS	✅	✅	✅	✅	✅
LBT	✅	✅	✅	✅	✅
Cujet 3.1	✅	✅	❌	✅	✅
LGR	✅	✅	✅	✅	✅

But more importantly: different **implementations** and **input parameters**.

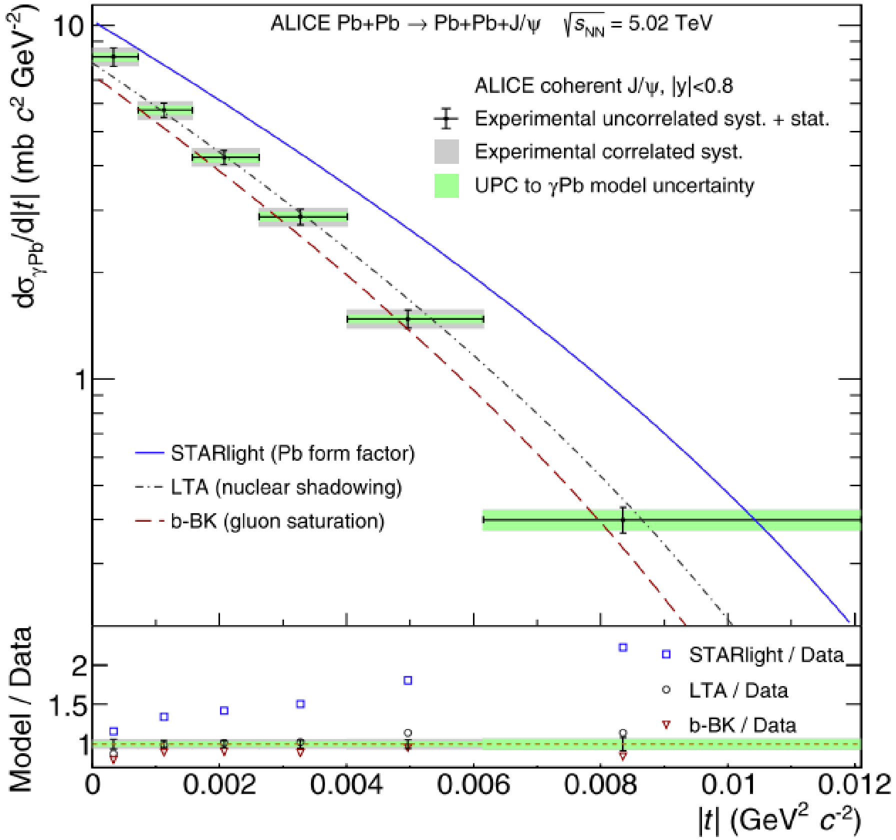
TAMU: PLB 735 (2014) 445
LGR: EPJC 80 (2020) 671
PHSD: Phys. Rev. C 78 (2008) 034919
Catania: PLB 821 (2021) 136622
LBT: PRC 94 (2016) 014909
LIDO: PRC 98 (2018) 064901
Langevin: Chinese Phys. C 44 (2020) 114101
CUJET3: JHEP 02 (2016) 169
MC@sHQ+EPOS2: PRC 89 (2014) 014905

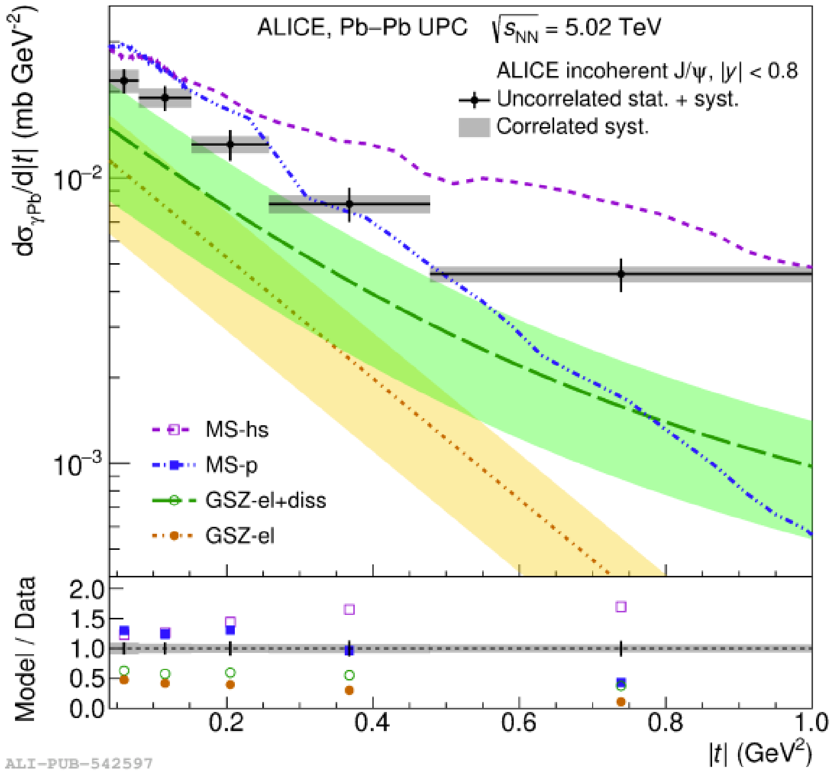
J/Psi in UPC

- $\gamma + \mathrm{Pb}$ collisions are sensitive to gluon distribution inside nuclei:
  - Coherent production: probe the averaged gluon density.
  - Incoherent production: probe the local gluon density fluctuation (gluon saturation).

PRL 132 (2024) 162302

Incoherent $\gamma + \mathrm{Pb} \longrightarrow \mathrm{J}/\psi + \mathrm{Pb}$



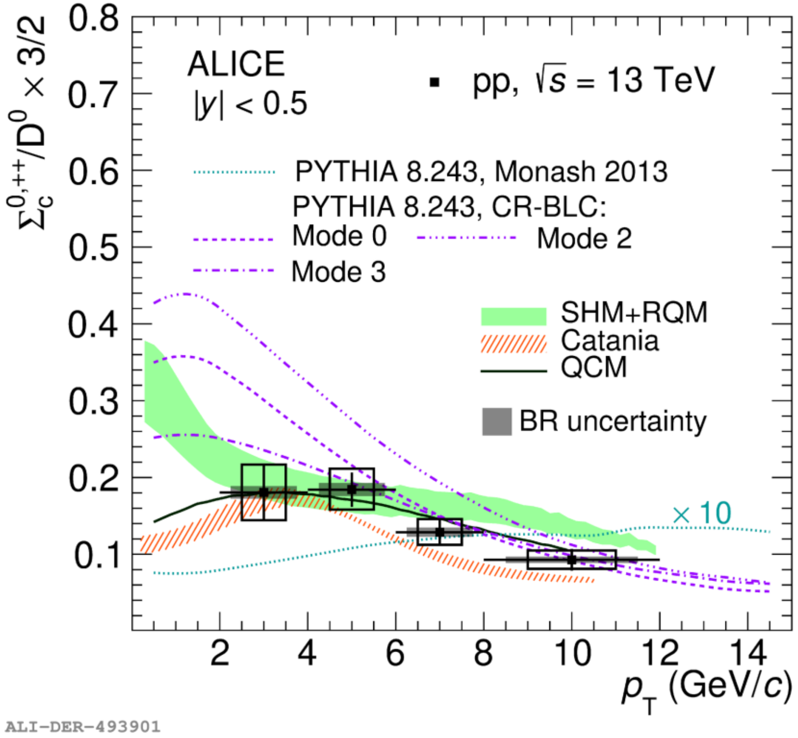


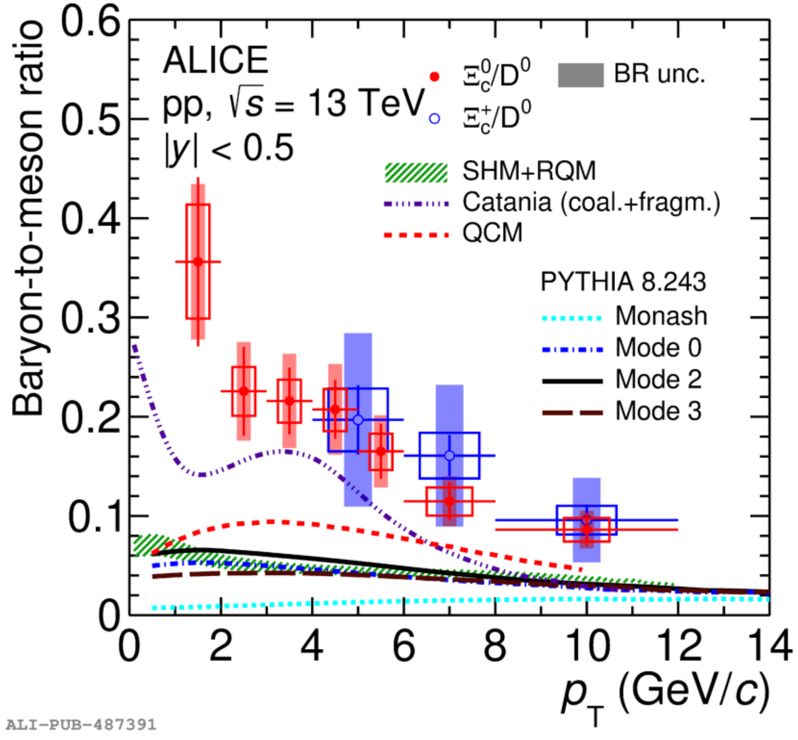
- Models cannot describe the data
- Interplay between shadowing and gluon saturation needed to catch the data.

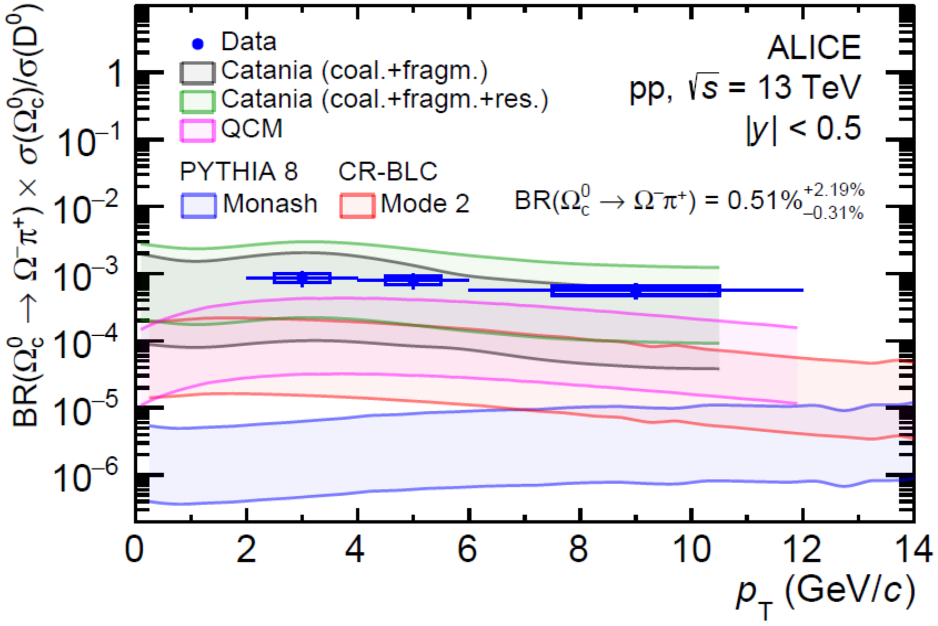
Charm quark hadronization

1. Modified hadronization

- Similar enhancement in pp collisions also for heavier charmed baryons ($\Sigma_c^{0,++}$, $\Xi_c^{0,+}$, Ω_c^0).





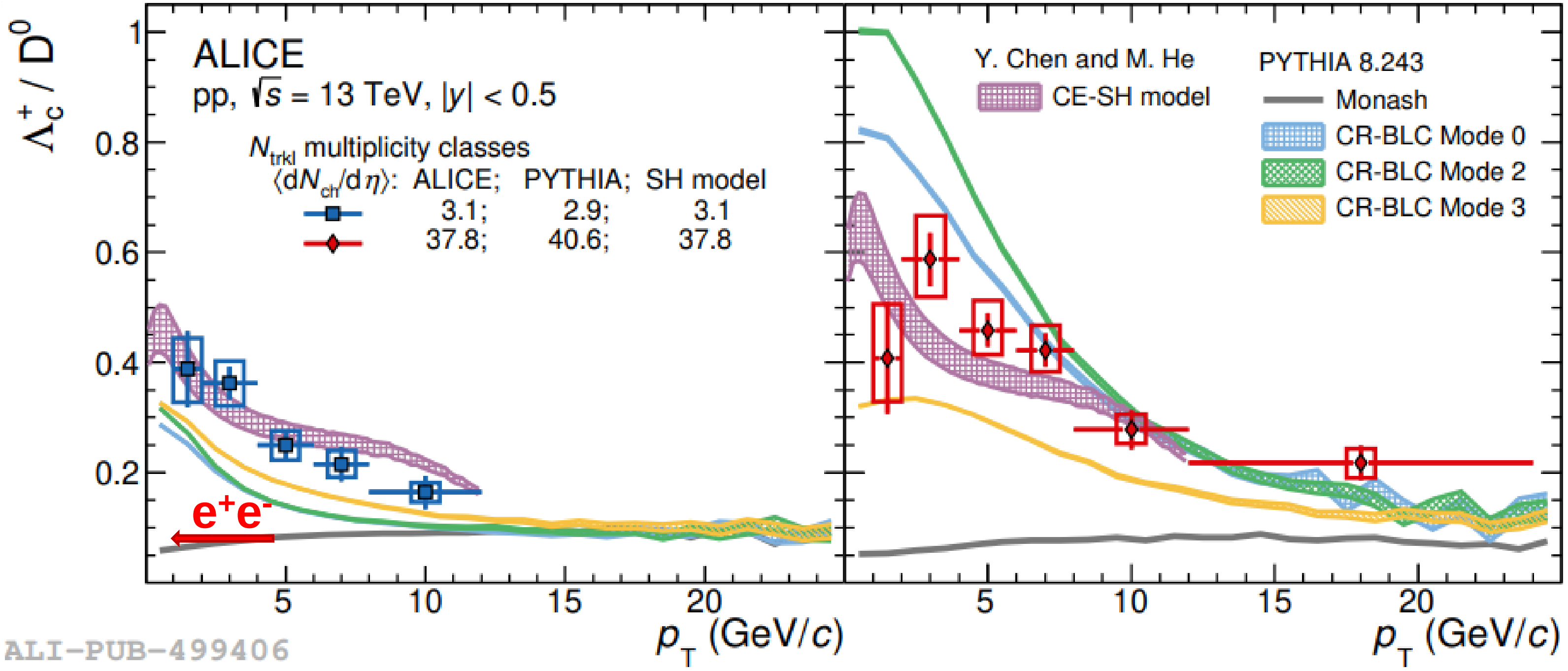


- Pure fragmentation models underestimates most of the charm baryon to meson ratios.

Baryon-to-meson ratio vs multiplicity

1. Modified hadronization

PLB 829 (2022) 137065



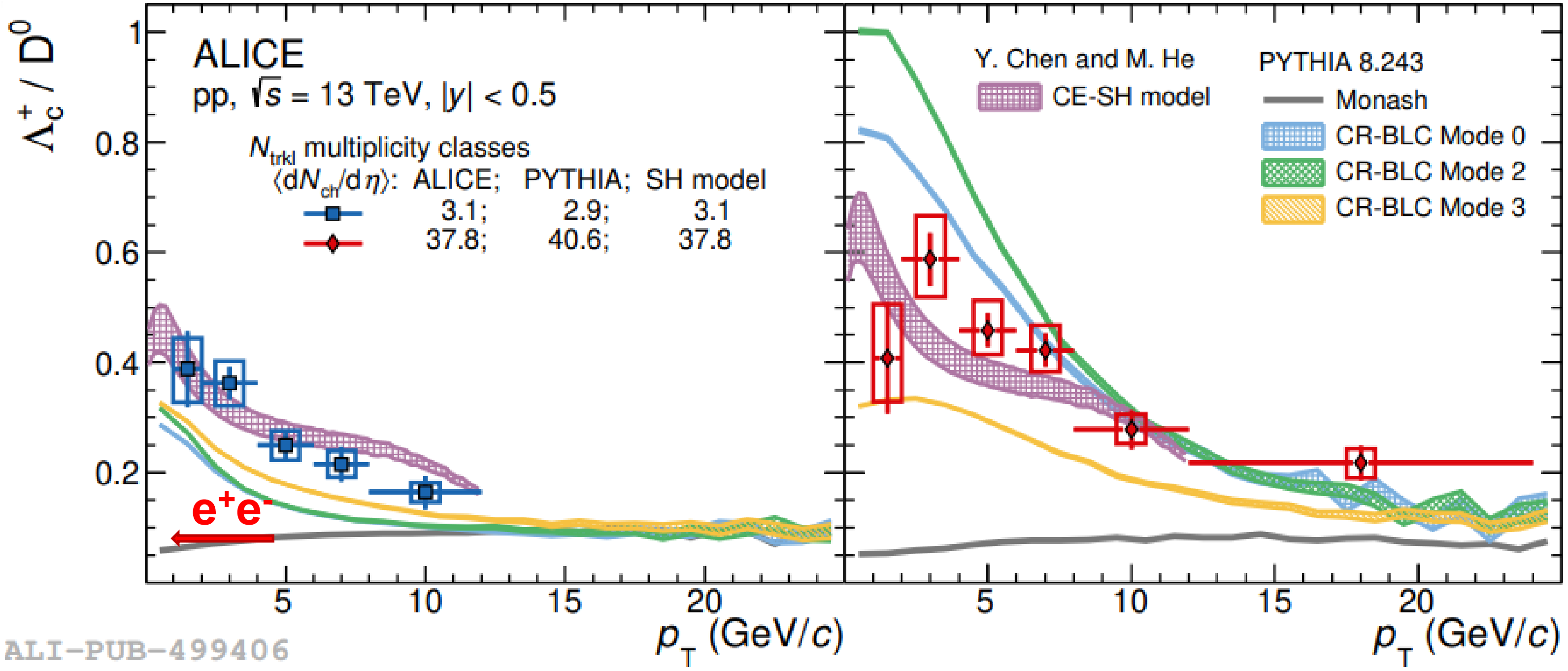
- Increasing trend with multiplicity.
- Λ_c^+/D^0 ratios in pp are enhanced w.r.t. e^+e^- collisions, also in the lowest multiplicity interval.

→ **Fragmentation fractions of charm quarks are not a universal process among different collision systems.**

Baryon-to-meson ratio vs multiplicity

1. Modified hadronization

PLB 829 (2022) 137065



- **PYTHIA Monash** = simple string fragmentation model. Fragmentation functions tuned on e^+e^-. Skands et al, Eur. Phys. J. C 74 (2014) 3024

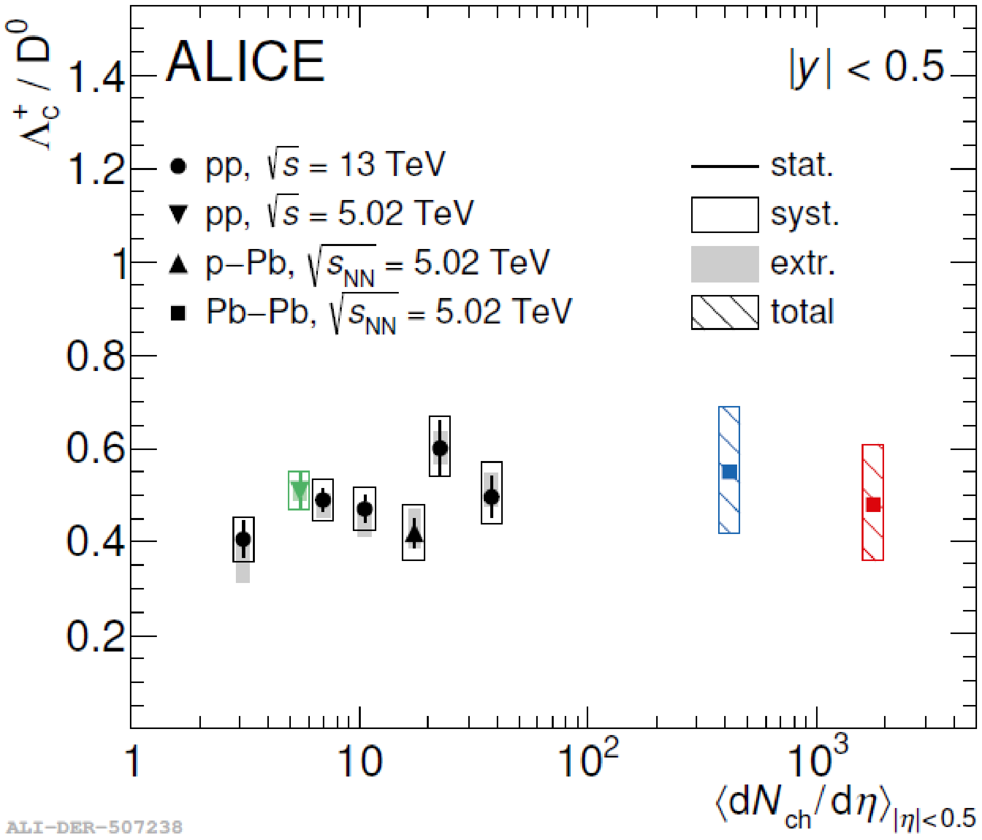
- **PYTHIA CR-BLC** = string formation beyond the leading colour approximation. Baryon production enhanced via **junction**. Christiansen & Skands, JHEP 1508 (2015) 003

- **CE-SH + RQM** = canonical ensemble statistical hadronization model including feed-down from additional excited baryon states predicted by the Relativistic Quark Model (RQM). Hee & Rapp, PLB 795 117-121 (2019)

Integrated prompt Λ_c^+/D^0 baryon-to-meson ratio

p–Pb: Phys. Rev. C **104**, 054905

Pb–Pb: arXiv:2112.08156



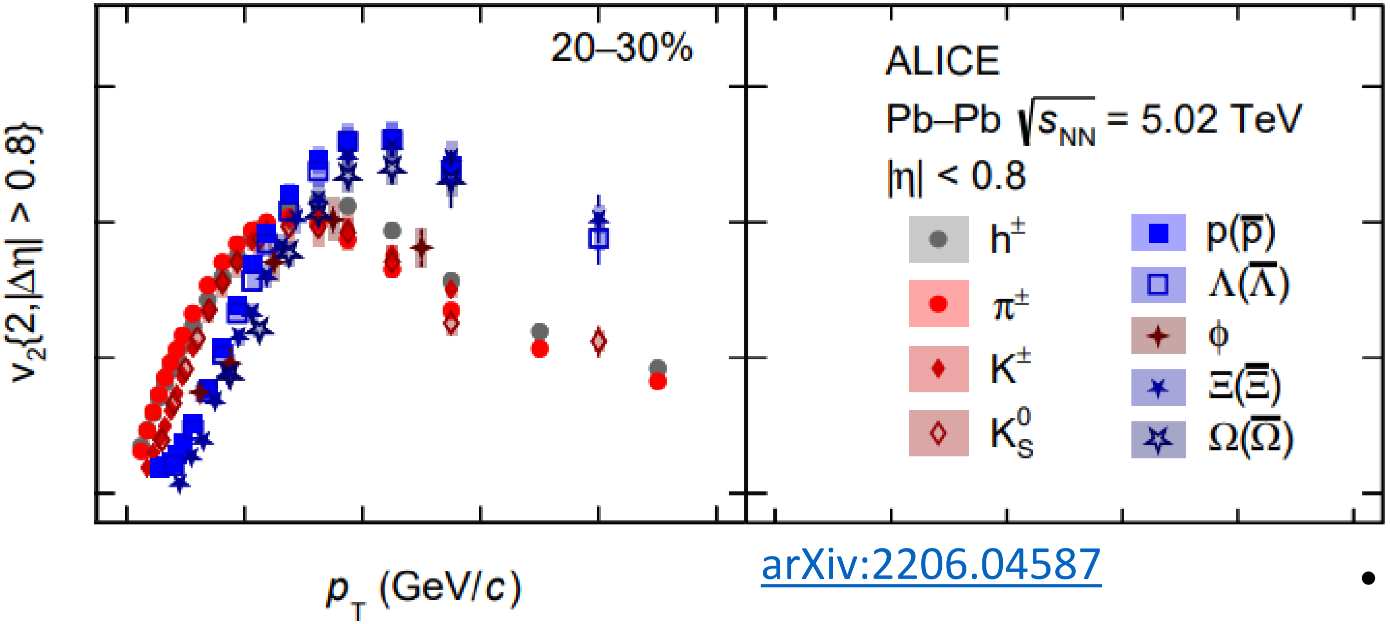
- The p_T-integrated Λ_c^+/D^0 ratio vs multiplicity in pp, p–Pb and Pb–Pb measurements are compatible with each other.
- Re-distribution of p_T that acts differently for baryons and mesons. No modification of overall p_T-integrated yield.

Same mechanism in all collision systems? Modified hadronization? Radial flow?

Flow in heavy-ion collisions

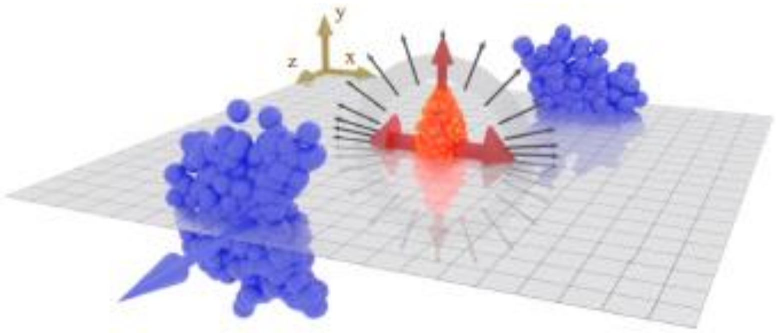
2. Collectivity

$$\frac{dN}{d\phi} = \frac{N}{2\pi} \left[1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_{RP})) \right]$$



arXiv:2206.04587

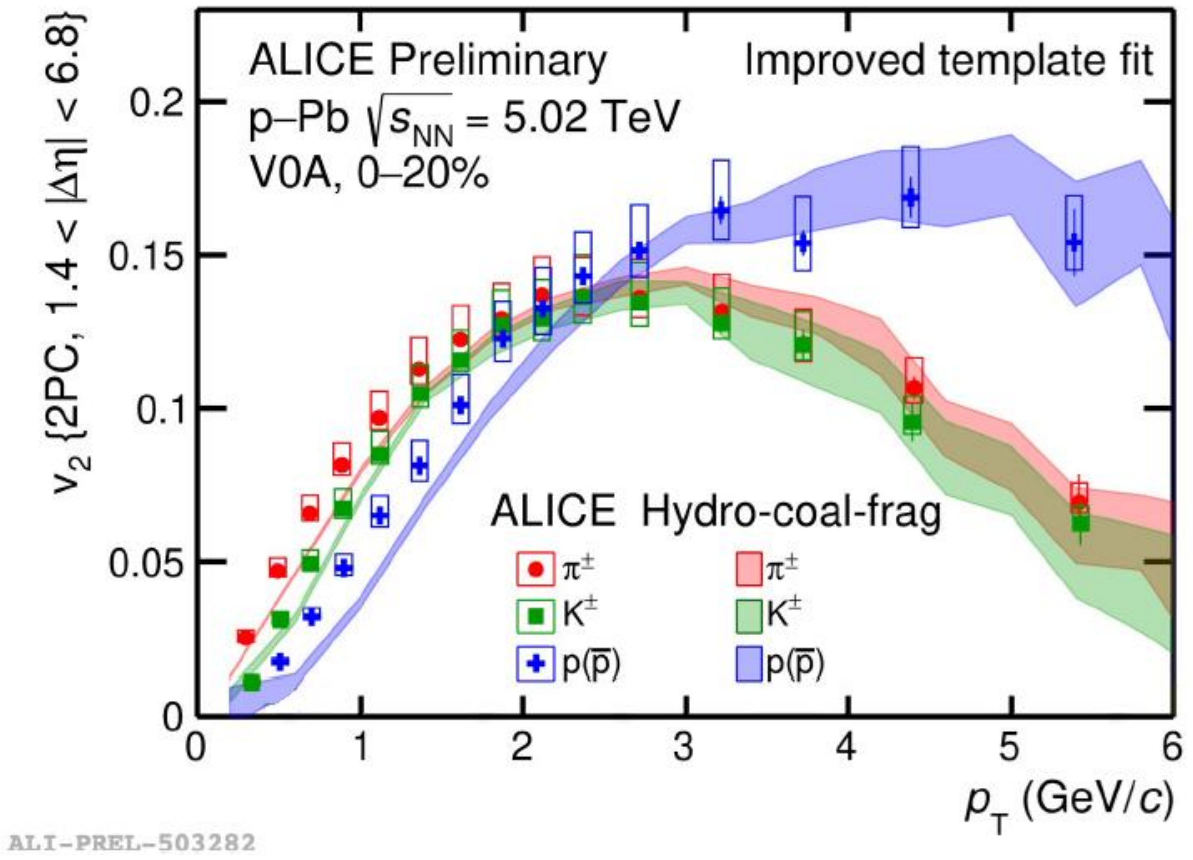
- Collectively expanding medium: modification in momentum and angular distribution.



- Mass ordering at low p_T (heavier particles flow less).
- Baryon-meson splitting at intermediate p_T: flow + recombination at the quark level

Flow in small systems

2. Collectivity



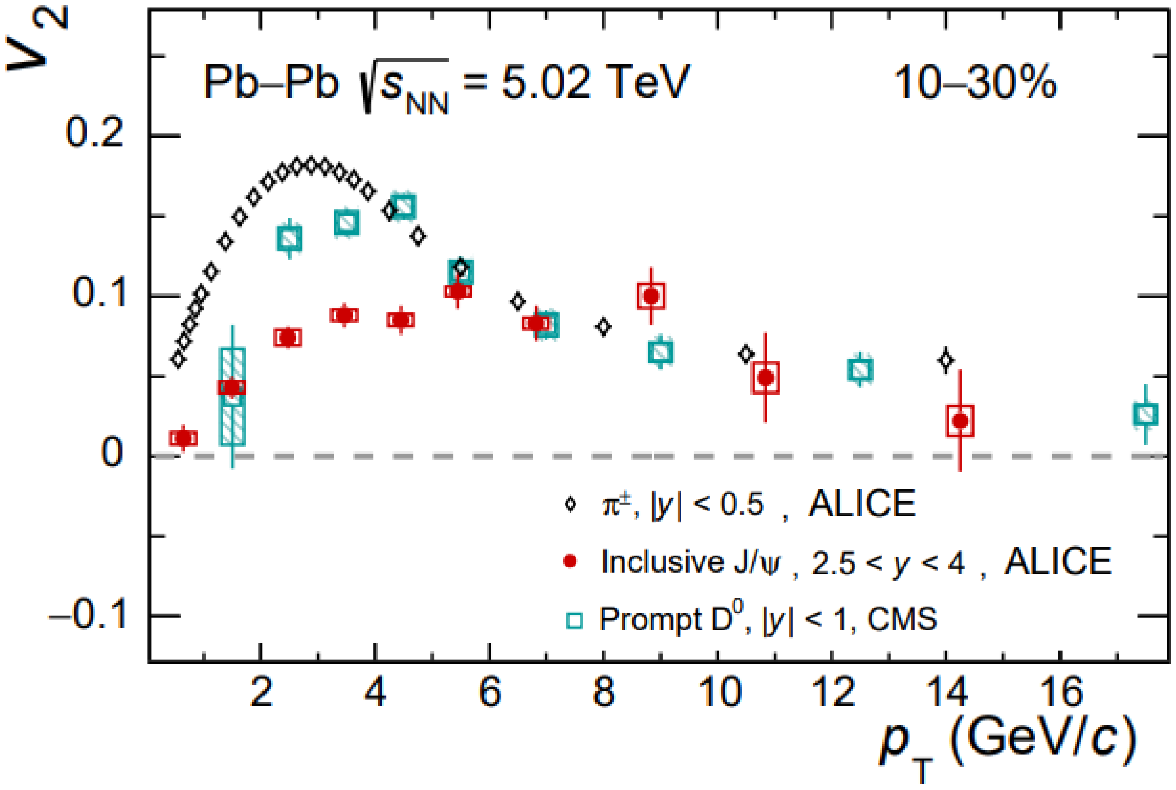
- Mass ordering and baryon-meson splitting observed in high multiplicity p-Pb and pp collisions as well.
- Model with hydrodynamics, quark coalescence and jet fragmentation describes the data.

Flow in the heavy-flavour sector

2. Collectivity

Do heavy quarks participate in the collective expansion?

JHEP 150 (2019)



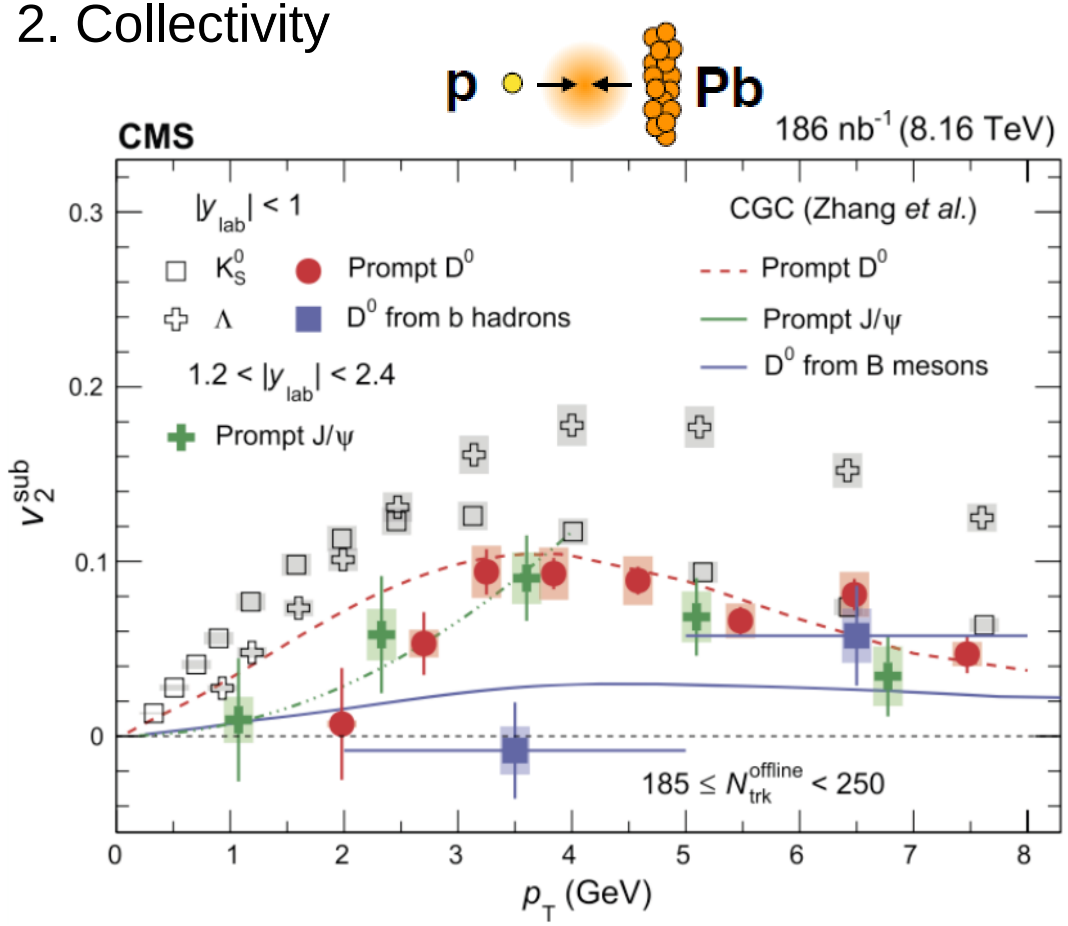
- Non zero anisotropic flow measured in Pb-Pb collisions for **charm** heavy flavour.

- $v_2(\pi^{+,-}) > v_2(\text{prompt } D^0) > v_2(J/\Psi)$ at intermediate p_T.

  → larger flow for light quarks.

Flow in the heavy-flavour sector – Small systems

2. Collectivity

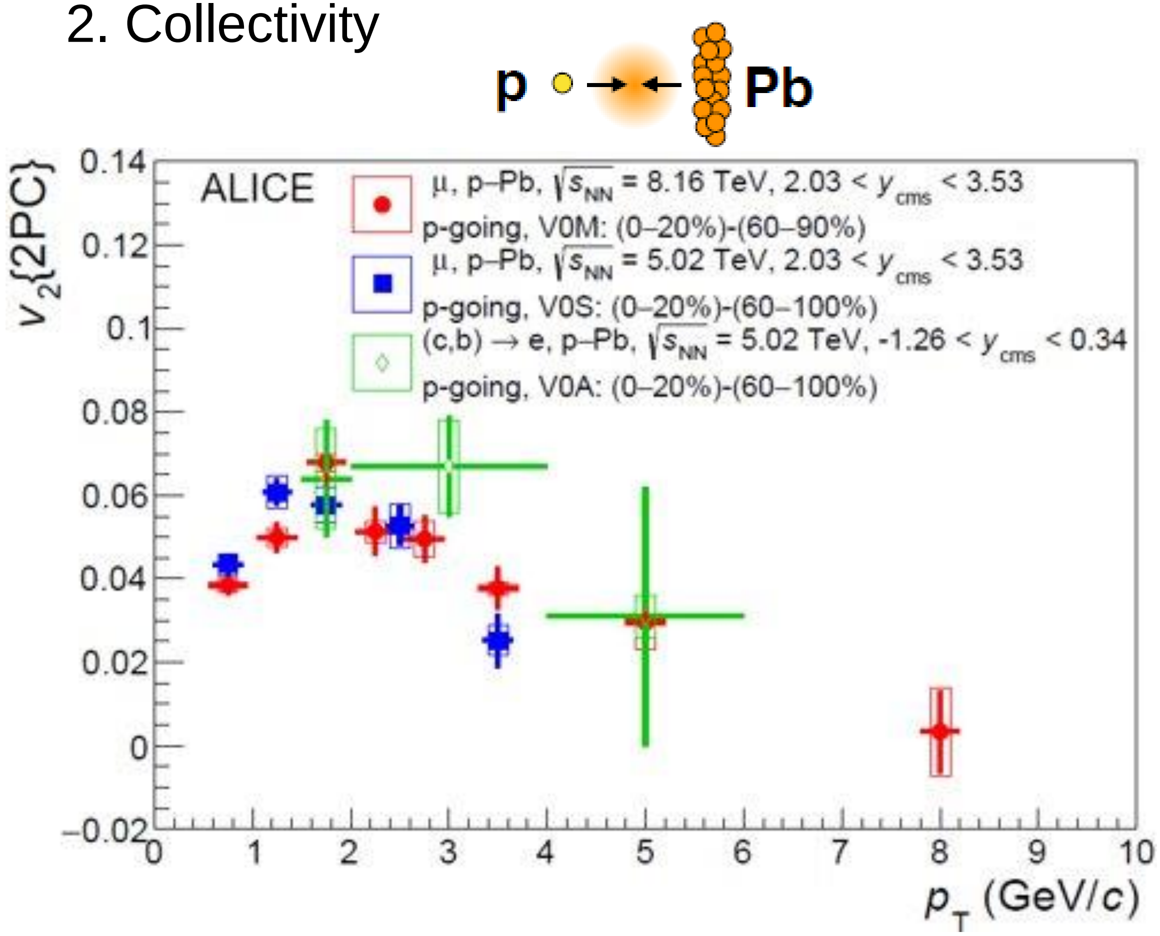


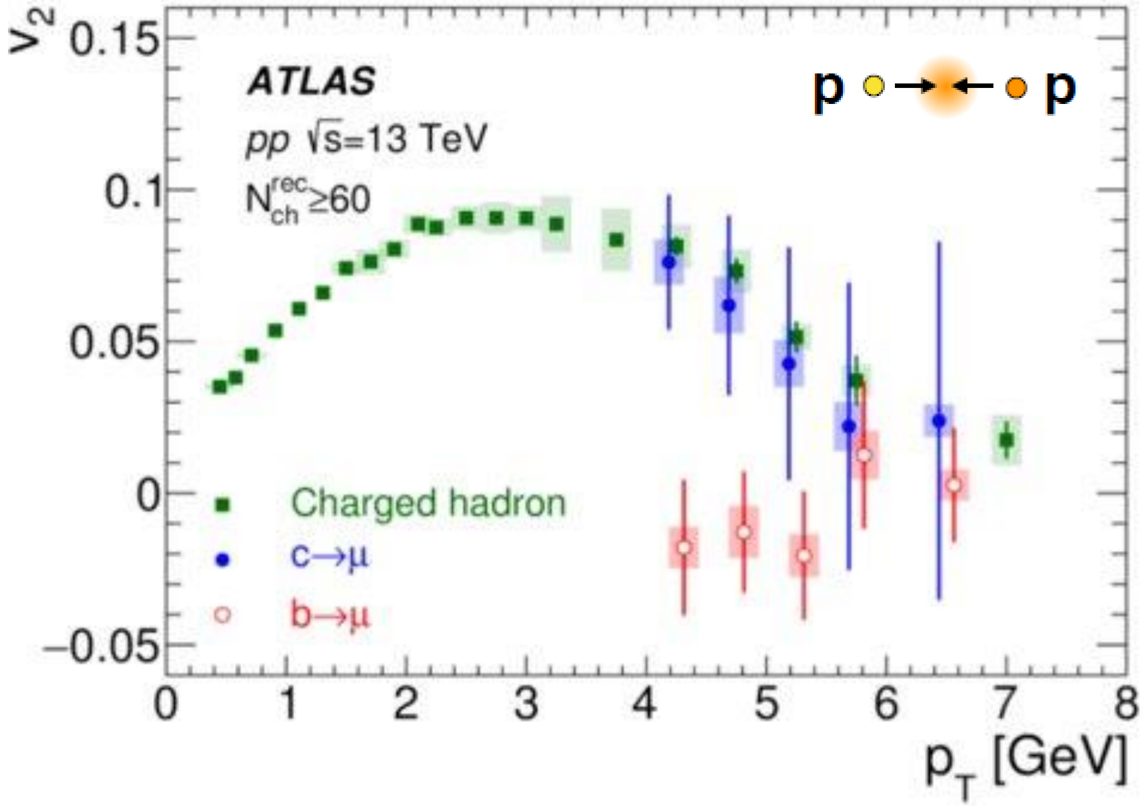
CMS, PLB 813 (2021) 136036

- **Charm** quark anisotropic flow measured in p-Pb and pp collisions as well.

Flow in the heavy-flavour sector – Small systems

2. Collectivity





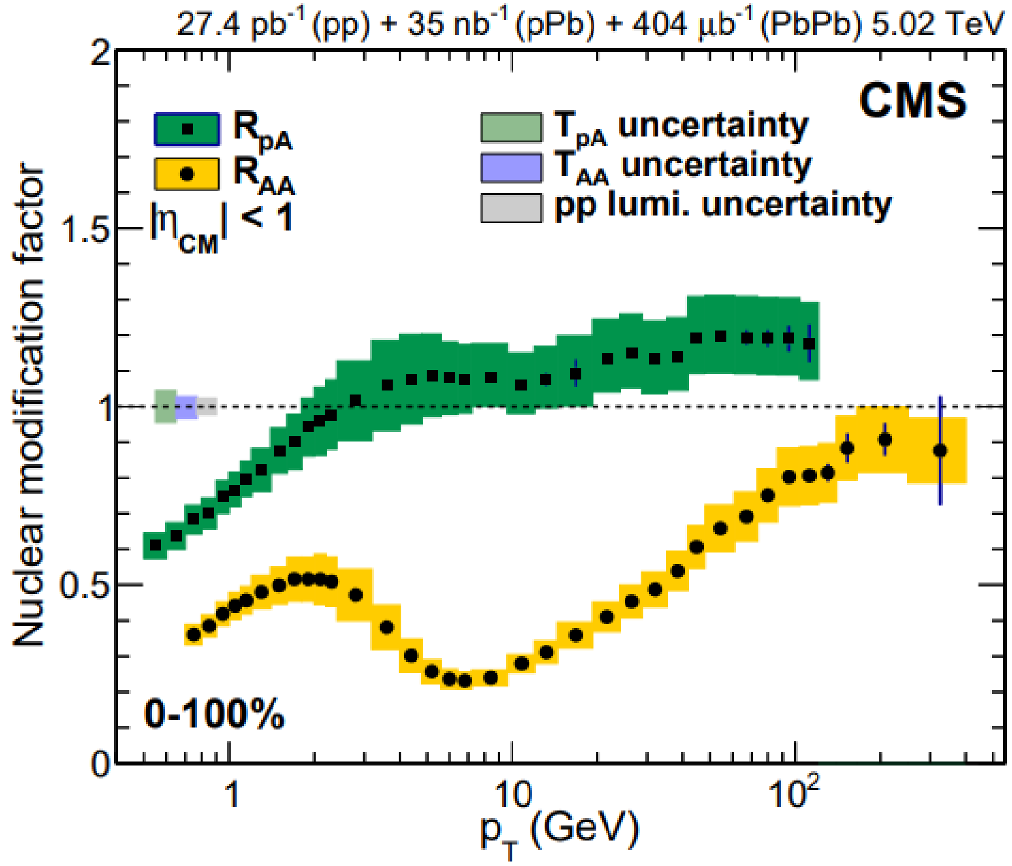
ATLAS, PRL 124, 082301 (2020)

- **Charm** quark anisotropic flow measured in p-Pb and pp collisions as well.
- **Beauty** quark anisotropic flow in small systems compatible with 0.

Quenching

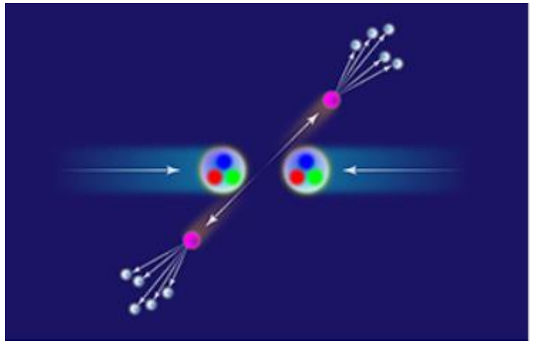
3. Energy loss

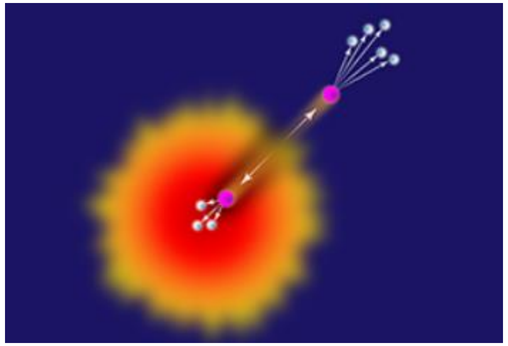
$$R_{AA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{{\rm d}^2N_{AA}/{\rm d}p_{\rm T}{\rm d}y}{{\rm d}^2N_{pp}/{\rm d}p_{\rm T}{\rm d}y}$$



CMS, JHEP 04 (2017) 039

Fragmentation in vacuum **Fragmentation in medium**



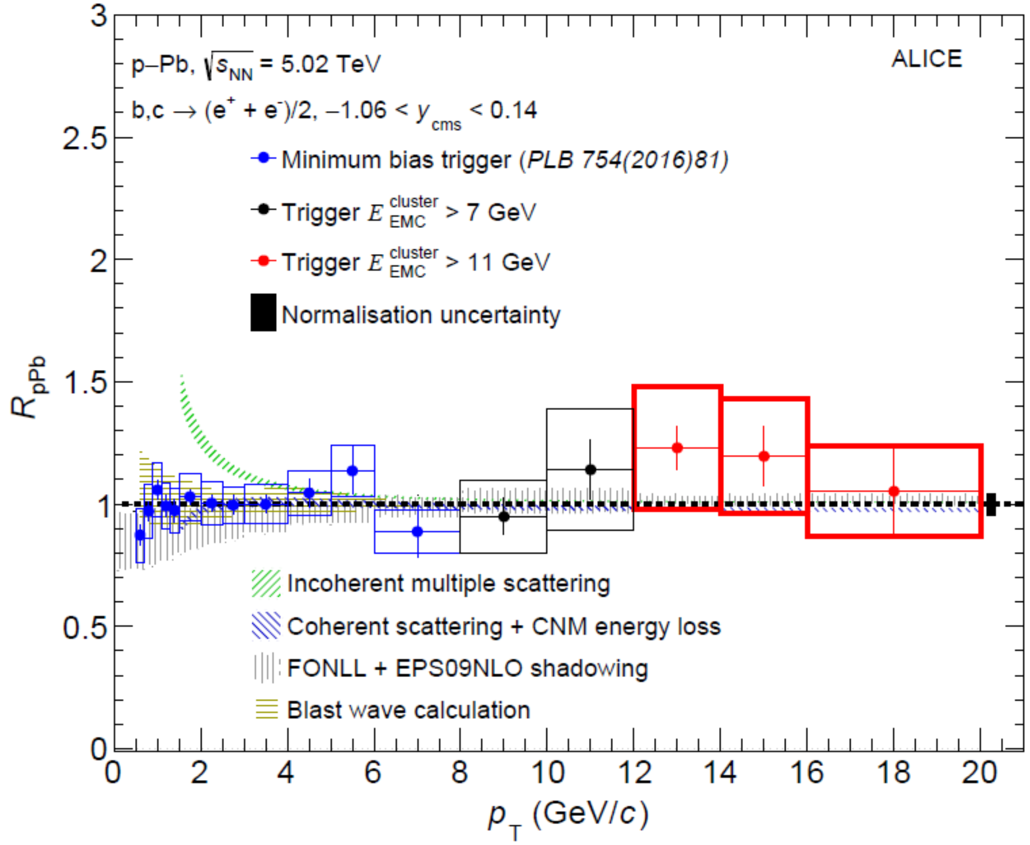


- Measurements presented until now are consistent with the presence of a small-sized medium in pp and p-Pb.
- Absence of suppression in p-Pb collisions.
- Quenching in small systems yet unobserved.

Quenching

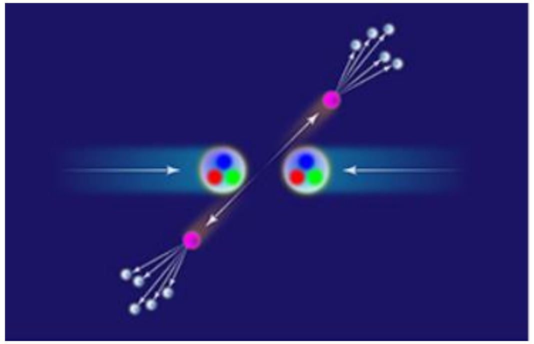
3. Energy loss

$$R_{AA} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}^2 N_{AA}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

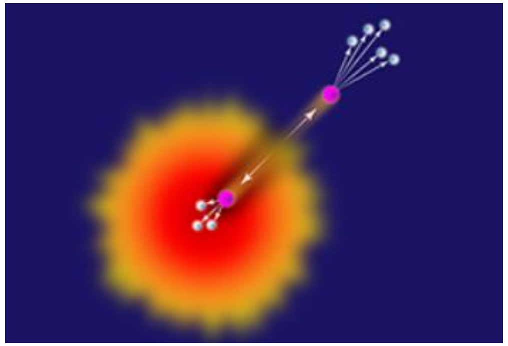


JHEP 77 (2020)

Fragmentation in vacuum



Fragmentation in medium



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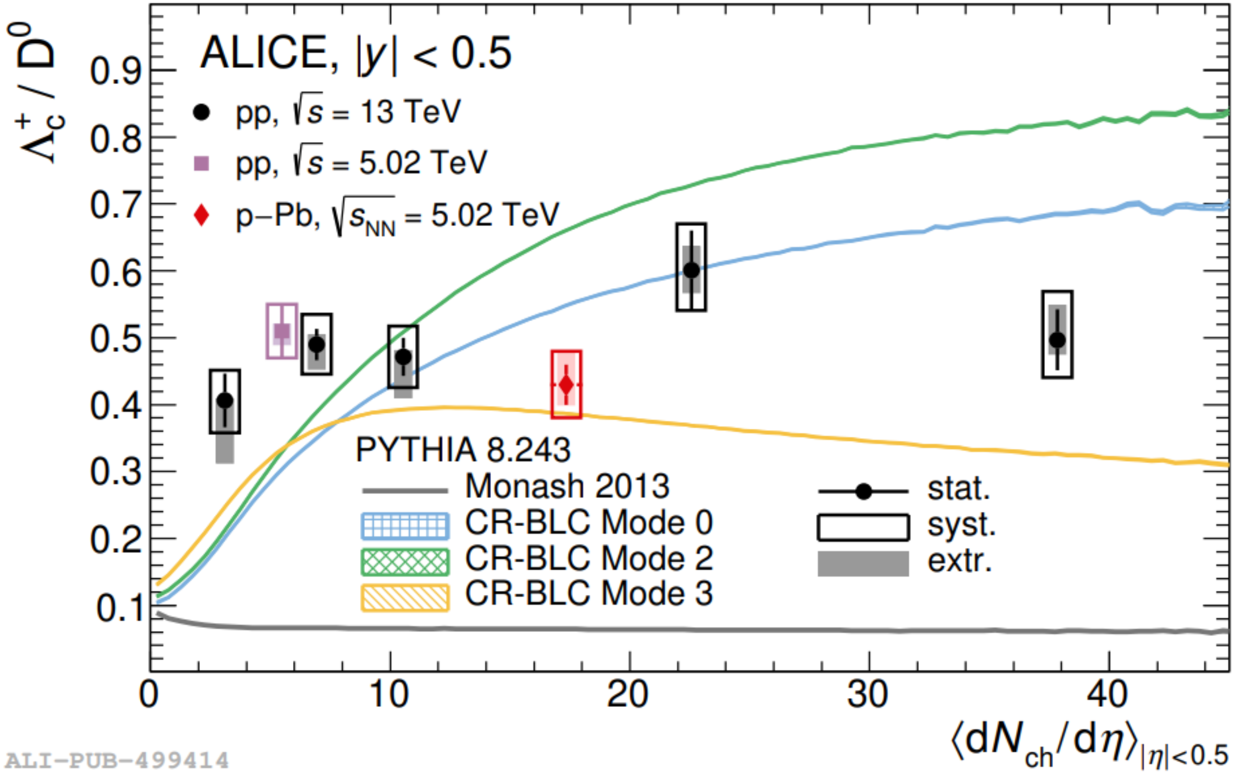
Integrated prompt Λ_c^+/D^0 baryon-to-meson ratio

p–Pb: Phys. Rev. C **104**, 054905

Pb–Pb: arXiv:2112.08156



- The p_T -integrated Λ_c^+/D^0 ratio vs multiplicity in pp, p–Pb and Pb–Pb measurements are compatible with each other.
- Re-distribution of p_T that acts differently for baryons and mesons. No modification of overall p_T-integrated yield.

Same mechanism in all collision systems? Modified hadronization? Radial flow?

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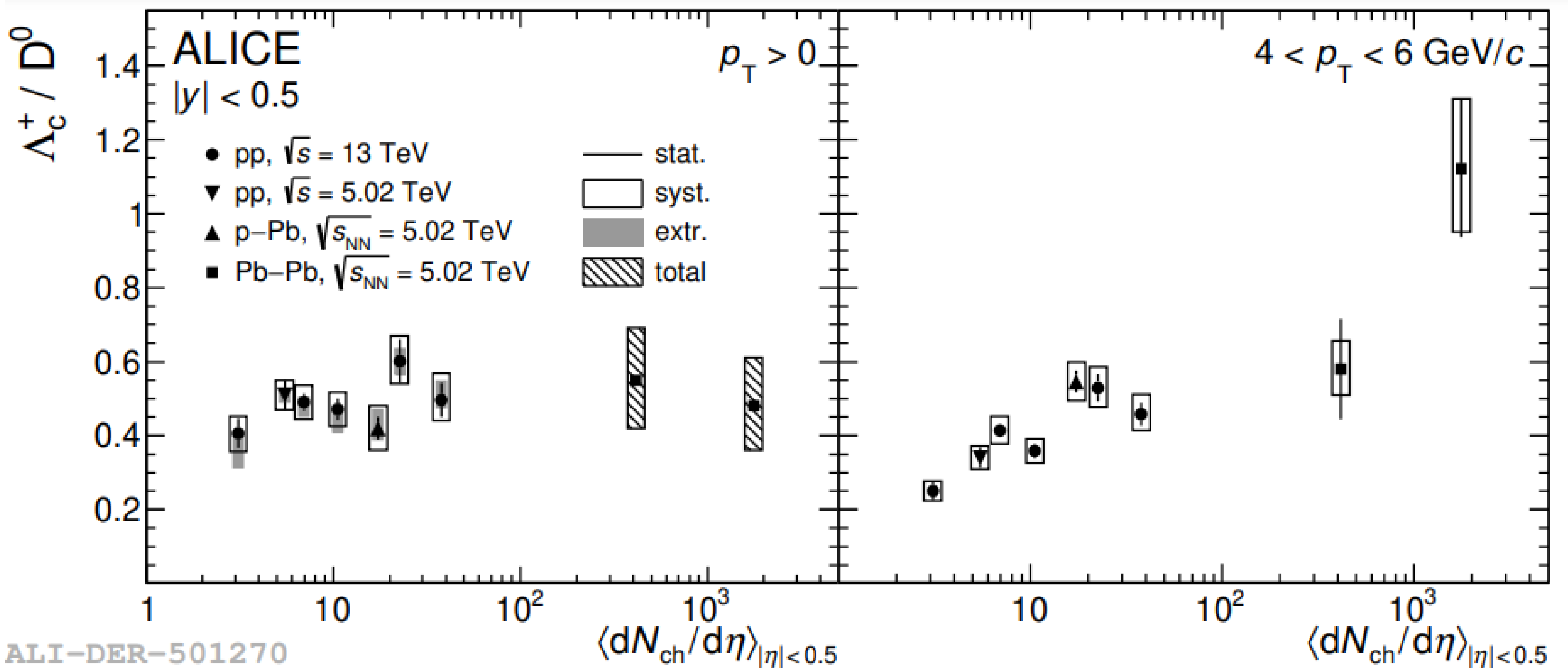

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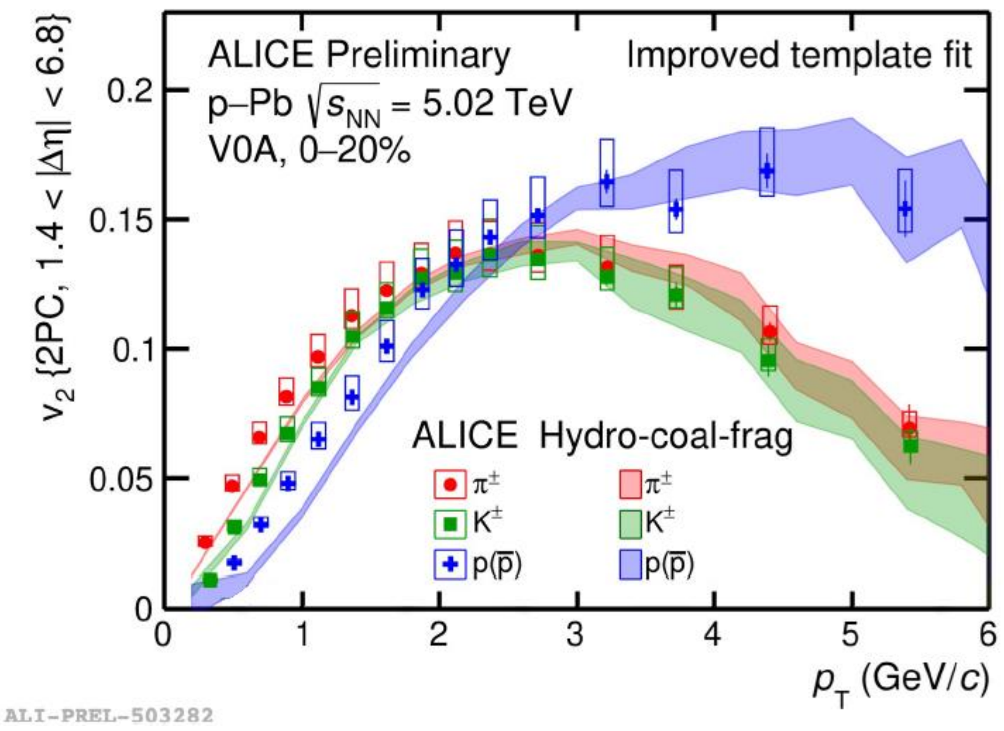
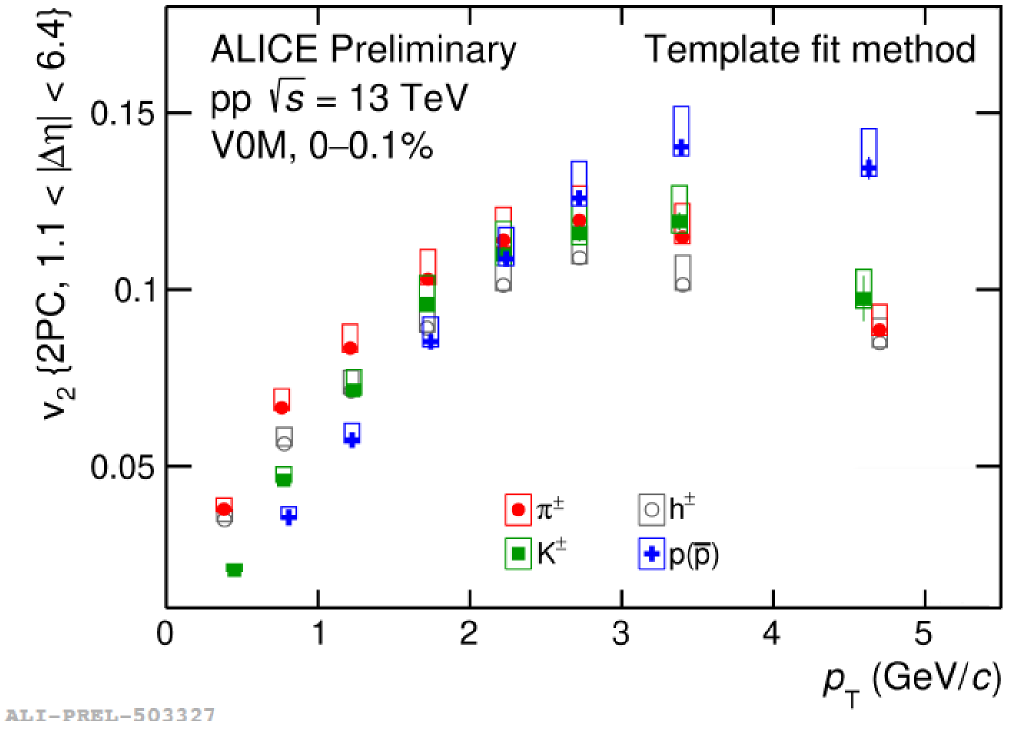
Flow in small systems

2. Collectivity



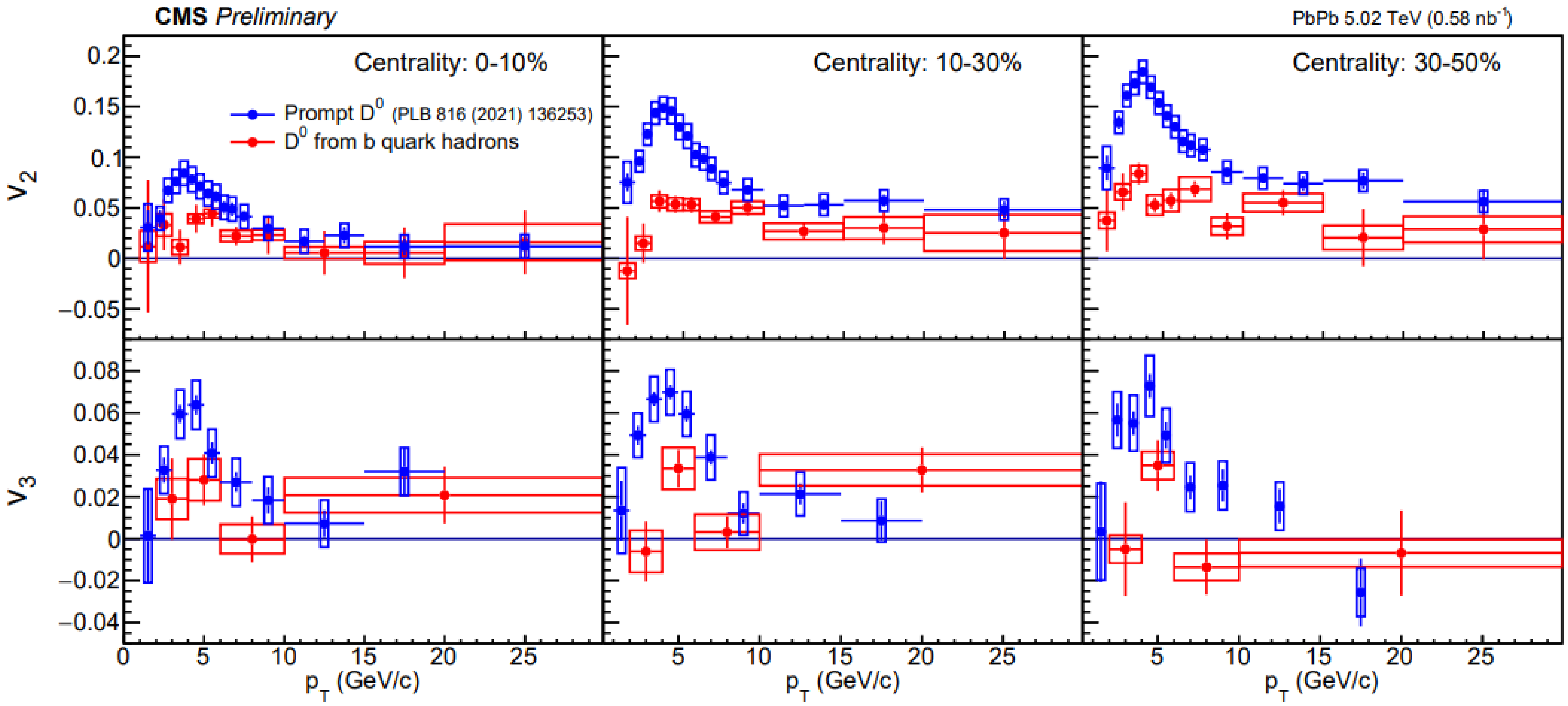


- Mass ordering and baryon-meson splitting observed in p-Pb and pp collisions as well.
- Model with hydrodynamics, quark coalescence and jet fragmentation describes the data.

Flow in the heavy-flavour sector

2. Collectivity

Do heavy quarks partecipate in the collective expansion?



Quenching

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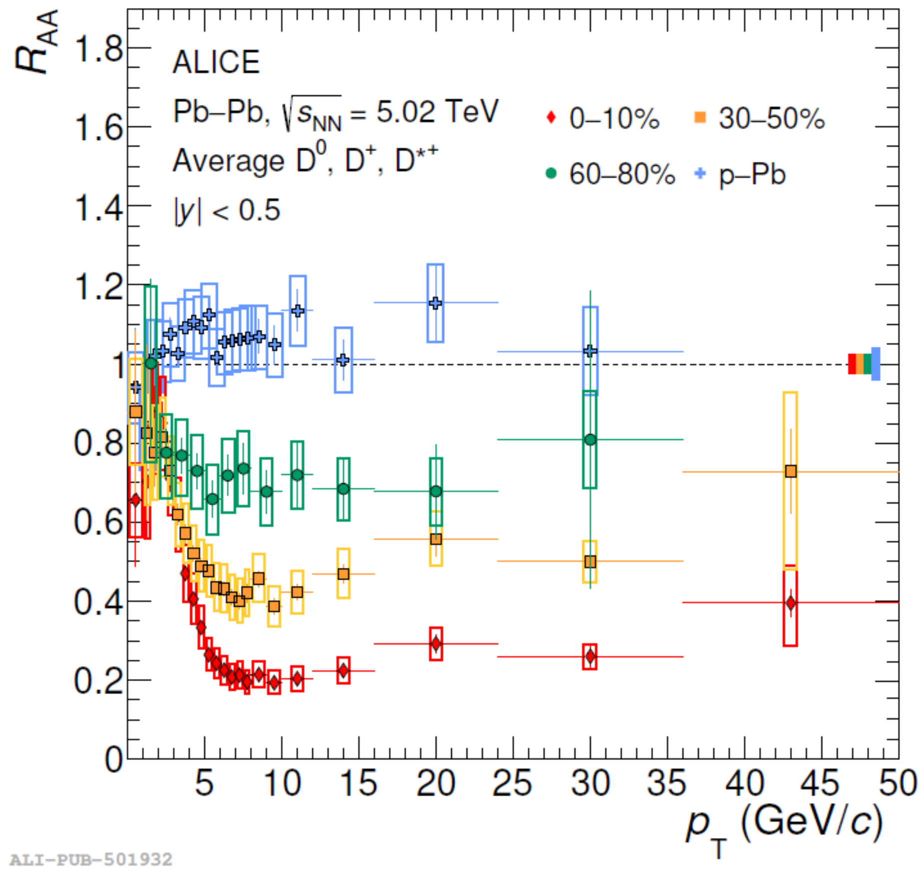
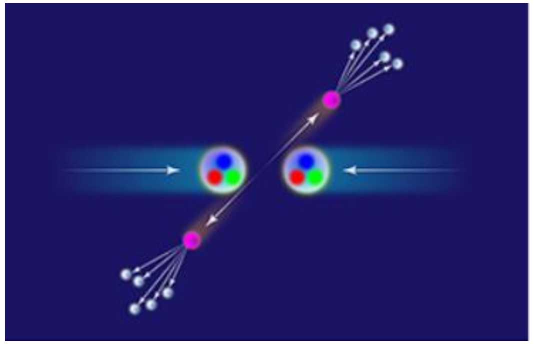
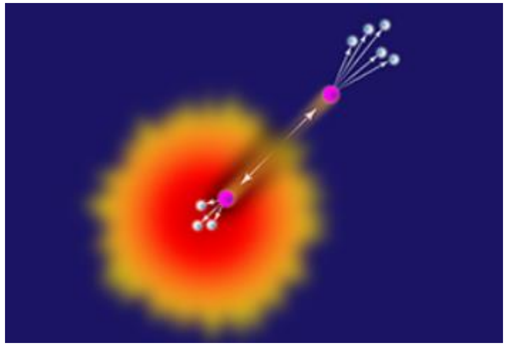


Fragmentation in vacuum



Fragmentation in medium



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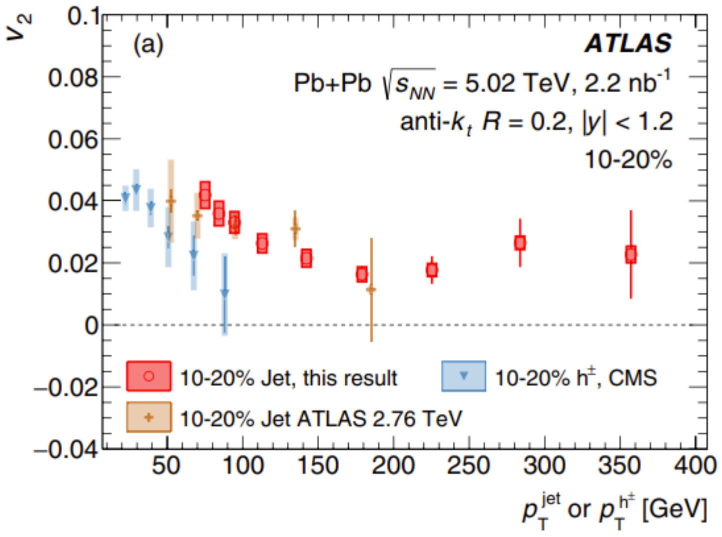
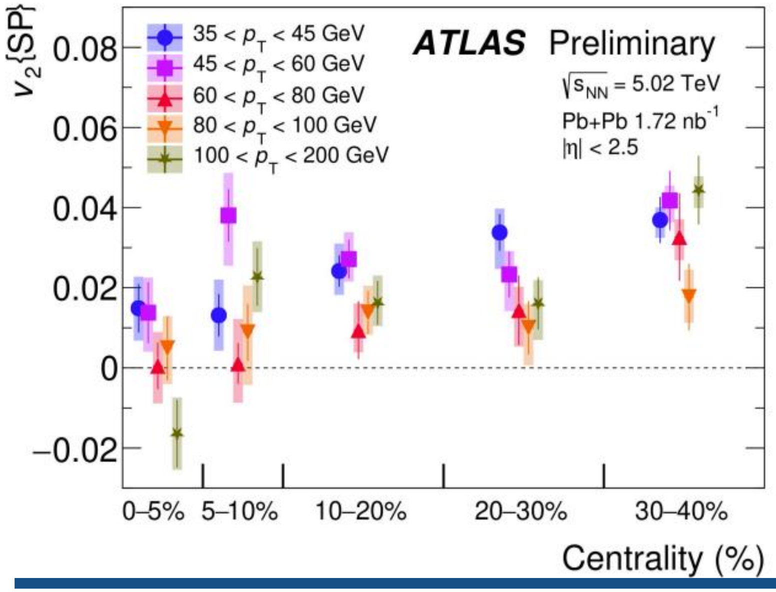
Jets flow

- Understanding the path-length dependence of energy loss

- Similar p_T and centrality dependence of jet and charged-particle v_2.

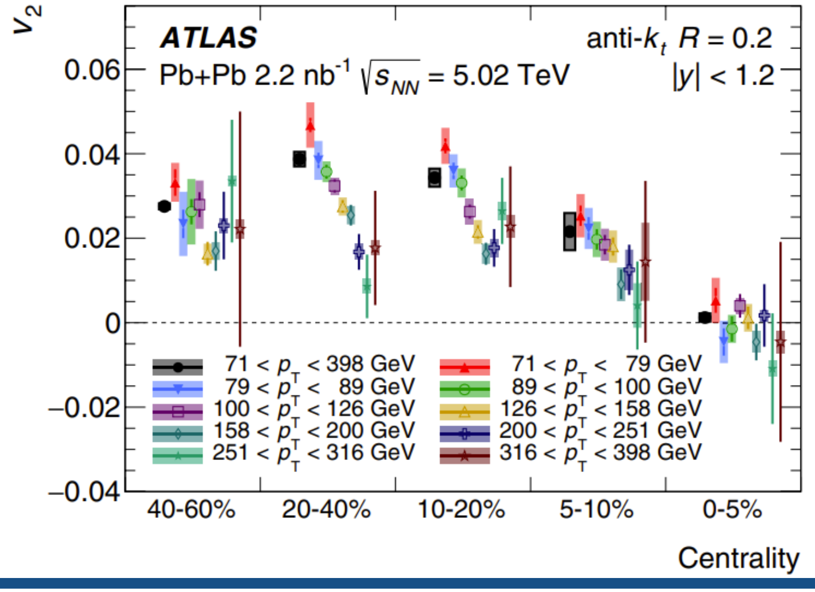


Charged particles



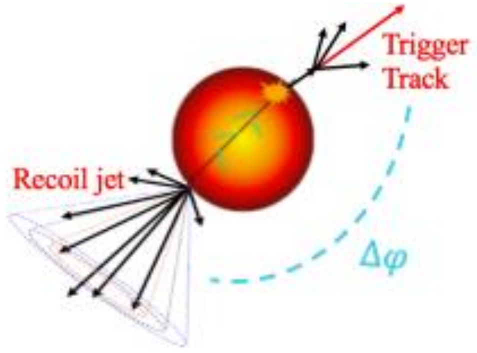
PRC 105 (2022) 064903

Jets

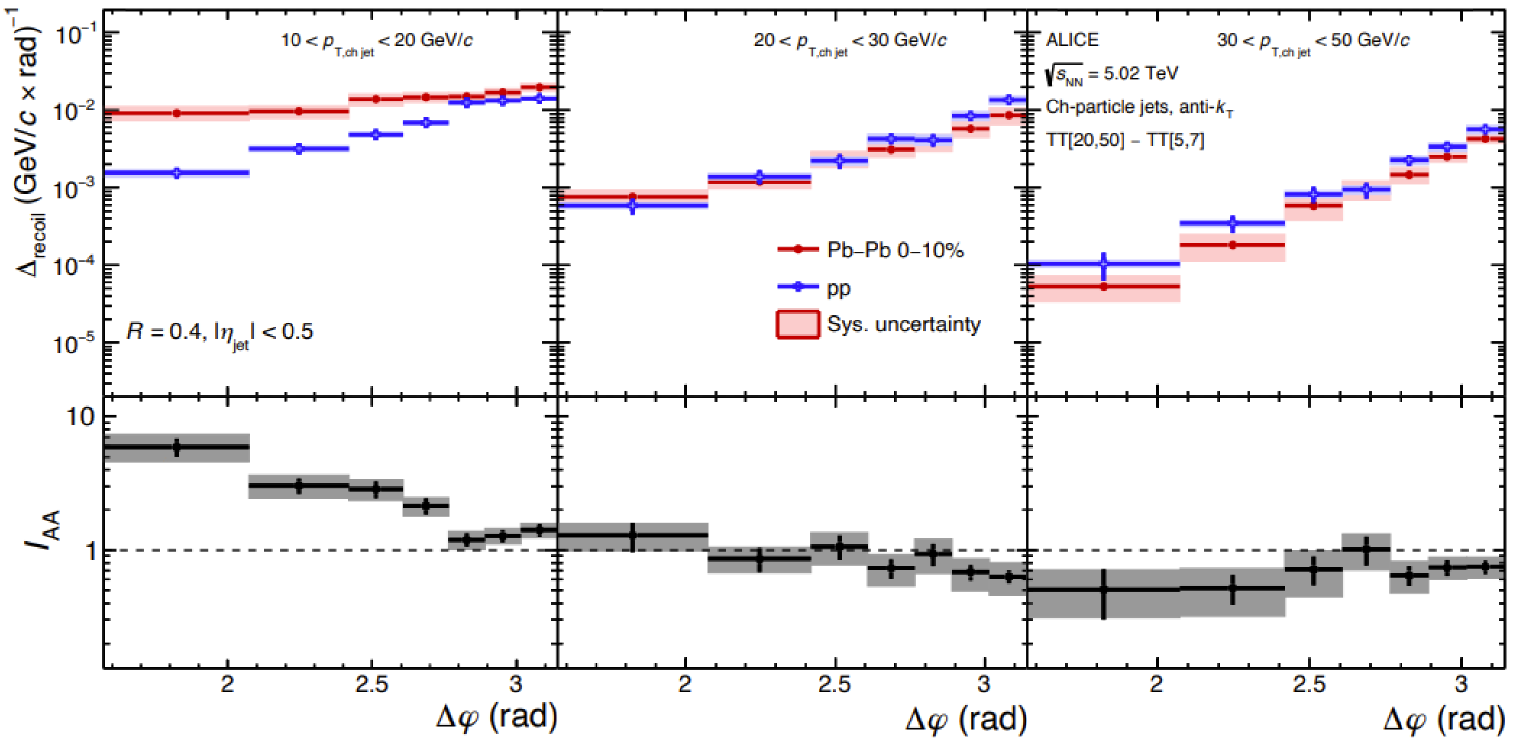


Recoiling jet broadening

- Angle (φ) of the recoil jet relative to trigger track axis:
  - **In vacuum**: transverse broadening due to gluon emissions (Sudakov broadening)
  - **In medium**: deflection of the recoiling jet due to the interaction with the medium.



PRL 133 (2024) 022301



$$I_{AA} \equiv \frac{\Delta_{recoil}\,(p_T)_{AA}}{\Delta_{recoil}\,(p_T)_{pp}}$$

- Recoil jet broadening for $10 < p_{T,\,jet} < 20$ GeV/c.
- No significant deviations for $20 < p_{T,\,jet} < 30$ GeV/c.
- Recoil jet yields suppression for $30 < p_{T,\,jet} < 50$ GeV/c.

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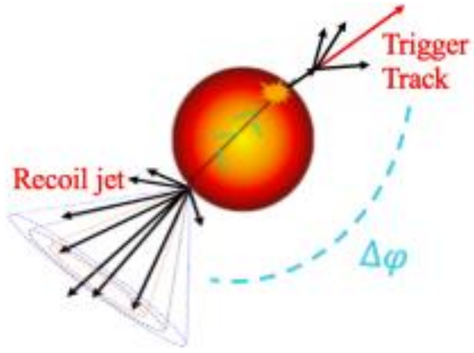
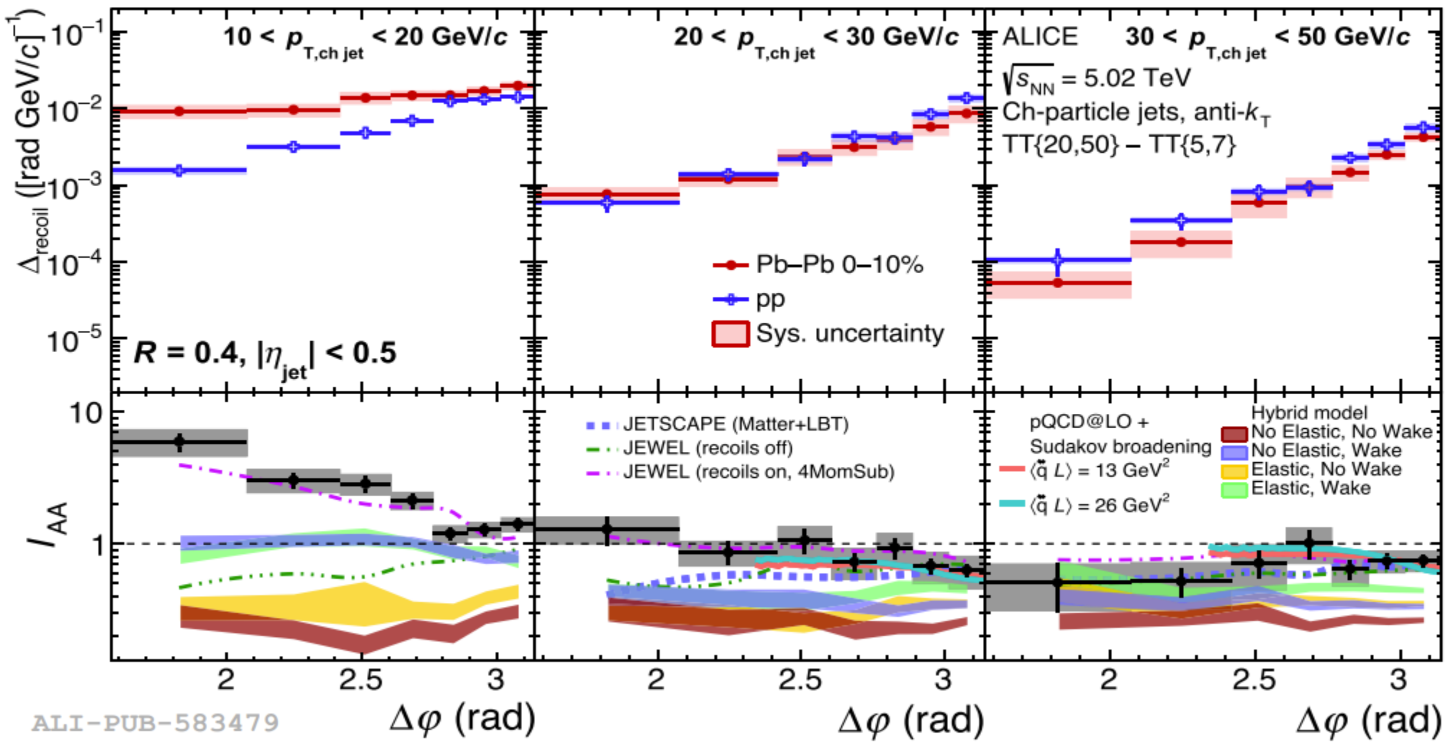


PRL 133 (2024) 022301



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Jet energy redistributions

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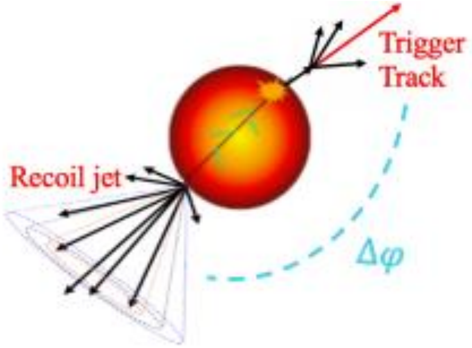
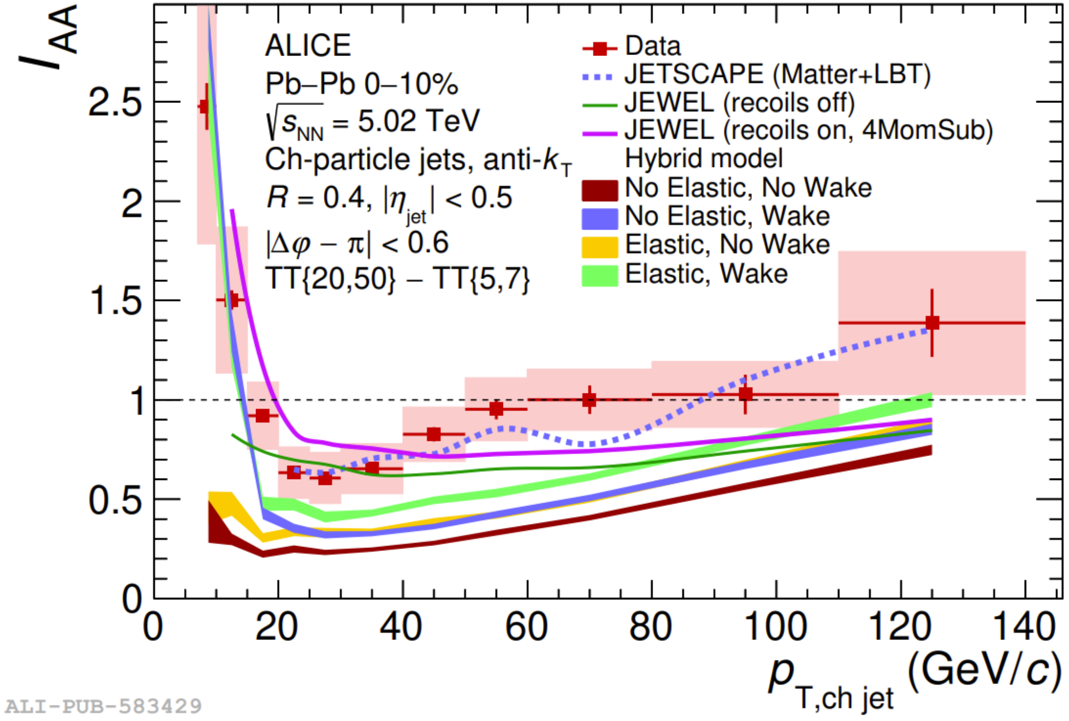


JETSCAPE: Phys. Rev. C 107 (2023) 034911
JEWEL: Eur. Phys. J. C 74, 2762 (2014)
Hybrid Model (no wake): JHEP 01 (2019) 172
Hybrid Model (wake): JHEP 02 (2022) 175

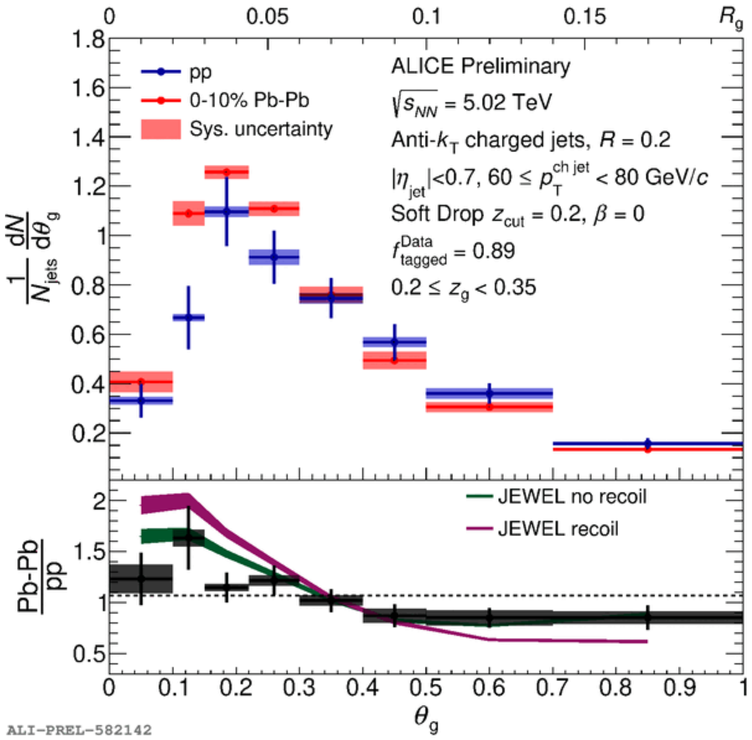


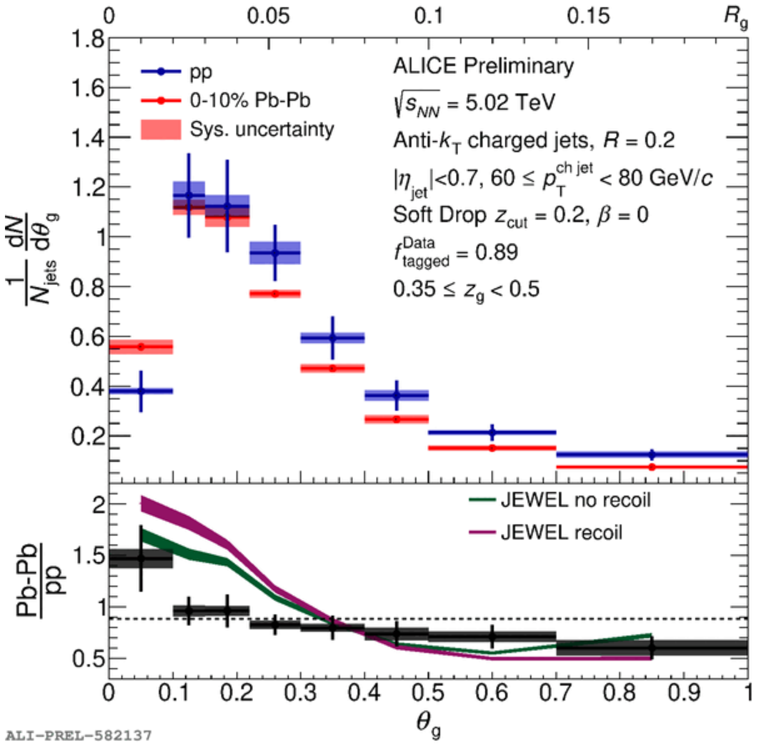
JETSCAPE with Pb-Pb tune:
1903.07706, Phys.Rev.C 107 (2023) 3
Multi-stage energy loss MATTER+LBT

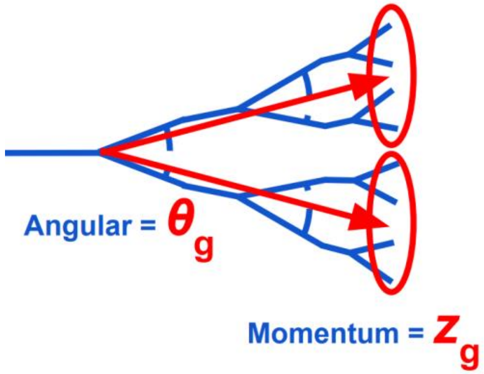
JEWEL:
arXiv:1311.0048, https://jewel.hepforge.org/
Includes collisional and radiative parton energy loss mechanisms in a pQCD approach.
medium response effects via treatment of 'recoils'

Hybrid Model:
JHEP 02 (2022) 175, JHEP01(2019)172
With/without elastic energy loss (i.e 'Moliere' scattering)
medium response via with and without wake.

Jet substructures







- Jets narrower in Pb-Pb compared to pp.

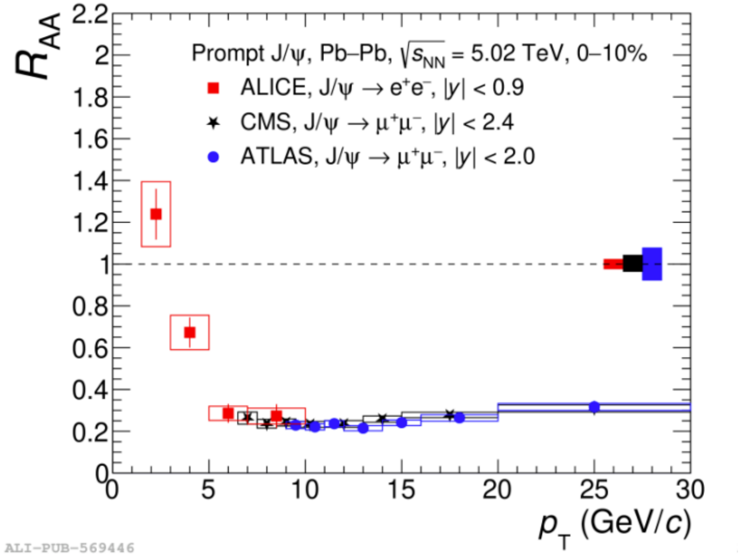
  or

- Wider jets less likely to survive QGP.

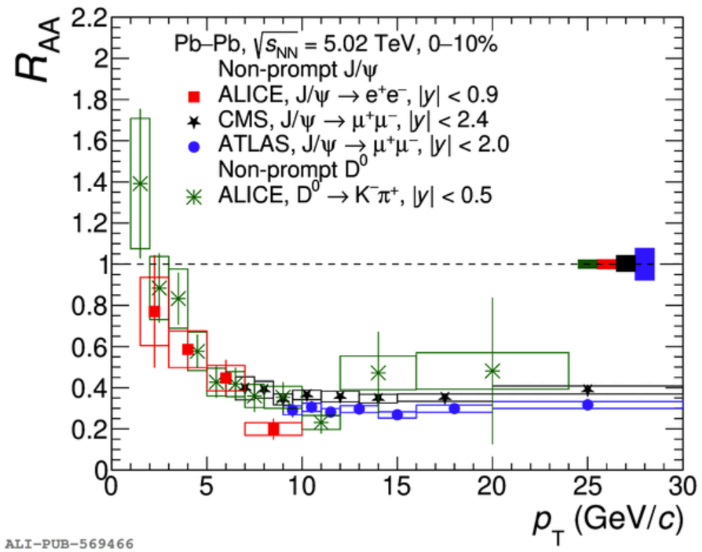
- Significantly more jet narrowing in balanced jets.

Quenching

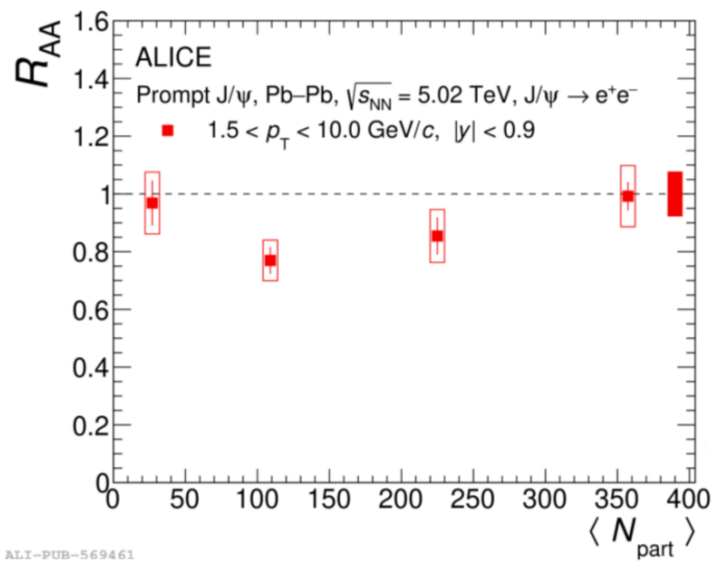
Prompt

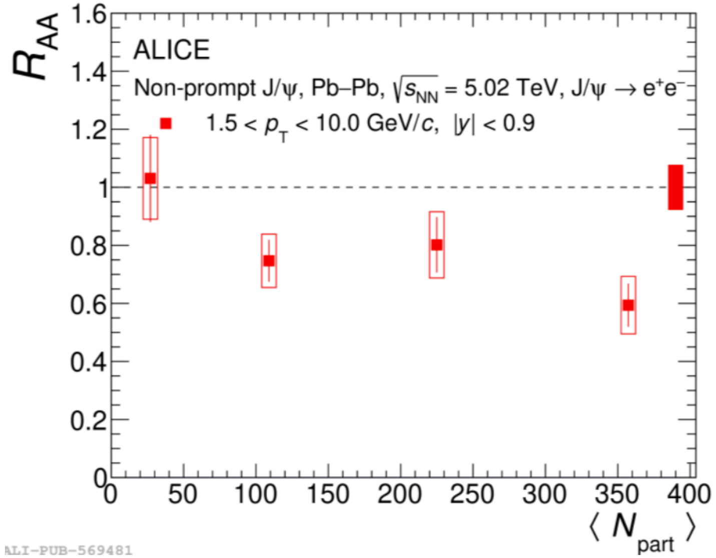


Non prompt

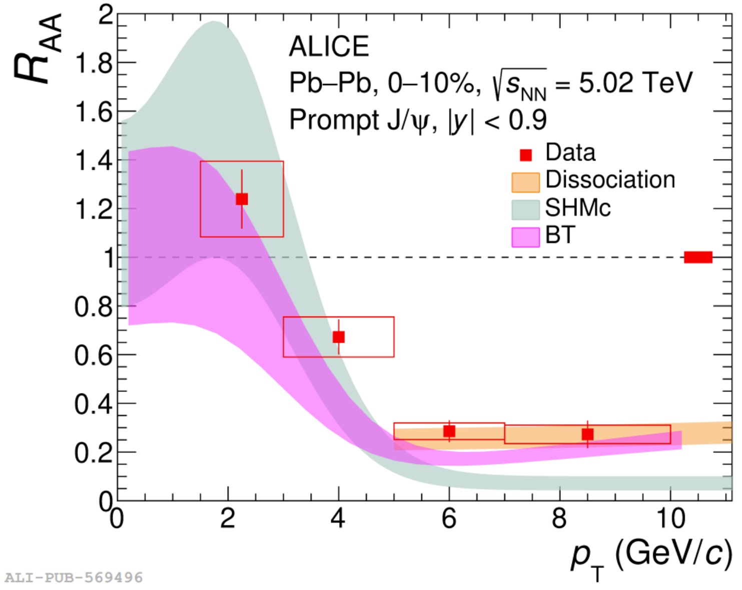


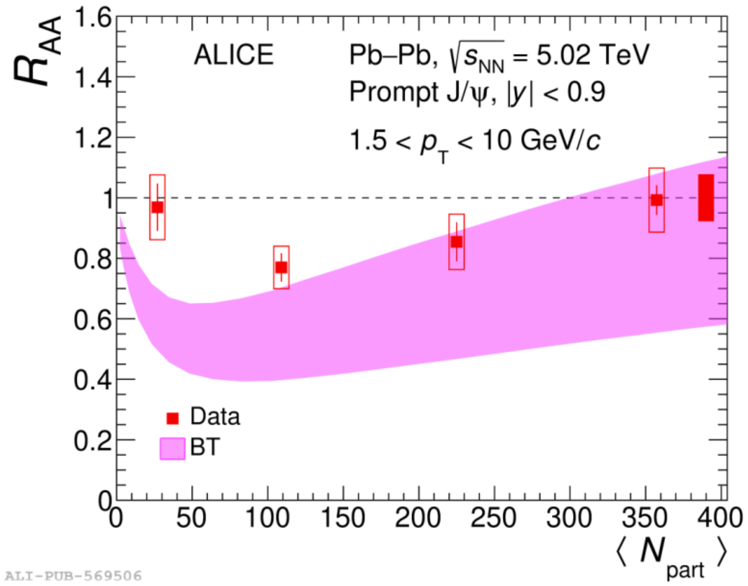
What about heavy flavour?

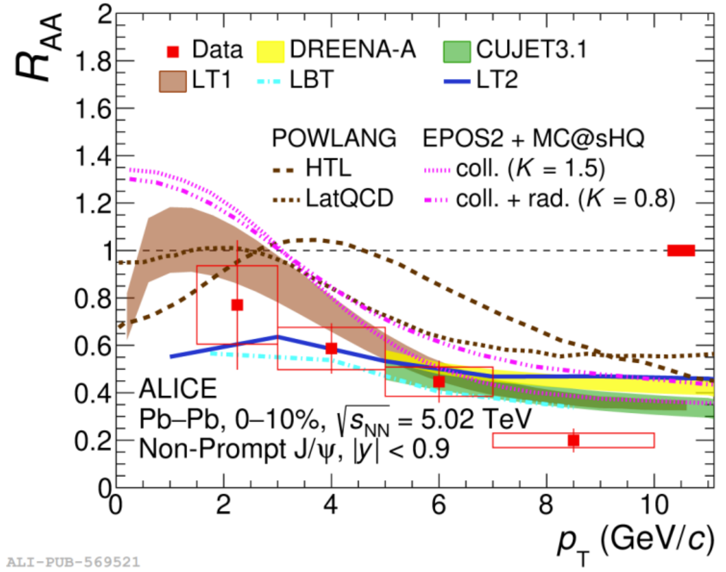


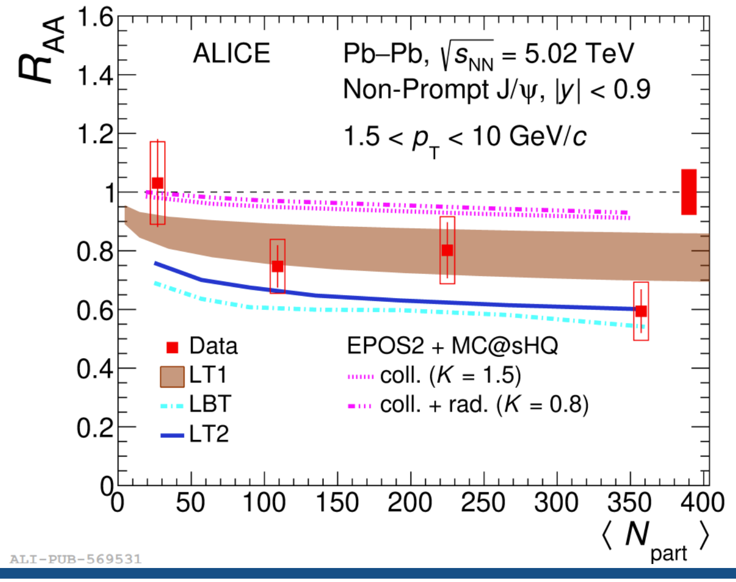


Quenching


ALICE
Pb–Pb, 0–10%, $\sqrt{s_{NN}}$ = 5.02 TeV
Prompt J/ψ, |y| < 0.9
Data
Dissociation
SHMc
BT
R_{AA}
p_T (GeV/c)
ALI-PUB-569496


ALICE
Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Prompt J/ψ, |y| < 0.9
1.5 < p_T < 10 GeV/c
Data
BT
R_{AA}
⟨N_{part}⟩
ALI-PUB-569506


Data
DREENA-A
CUJET3.1
LT1
LBT
LT2
POWLANG
HTL
LatQCD
EPOS2 + MC@sHQ
coll. (K = 1.5)
coll. + rad. (K = 0.8)
ALICE
Pb–Pb, 0–10%, $\sqrt{s_{NN}}$ = 5.02 TeV
Non-Prompt J/ψ, |y| < 0.9
R_{AA}
p_T (GeV/c)
ALI-PUB-569521


ALICE
Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Non-Prompt J/ψ, |y| < 0.9
1.5 < p_T < 10 GeV/c
Data
LT1
LBT
LT2
EPOS2 + MC@sHQ
coll. (K = 1.5)
coll. + rad. (K = 0.8)
R_{AA}
⟨N_{part}⟩
ALI-PUB-569531