

Heavy-flavour production in heavy-ion collisions with ALICE

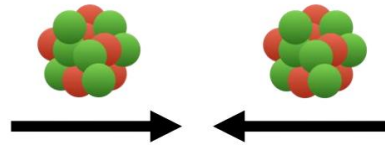
QCD@LHC 2026
September 28th – October 2nd
Oxford, United Kingdom

Luigi Dello Stritto (MBI)
on behalf of the ALICE Collaboration

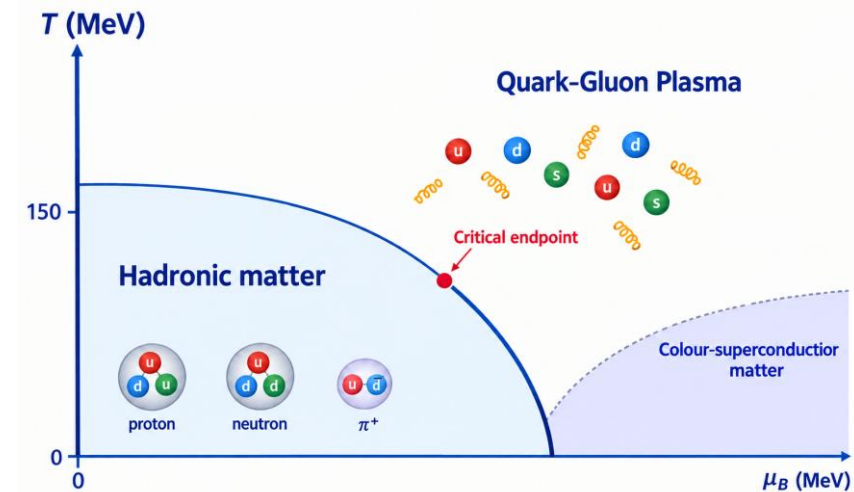


Heavy-ion collisions

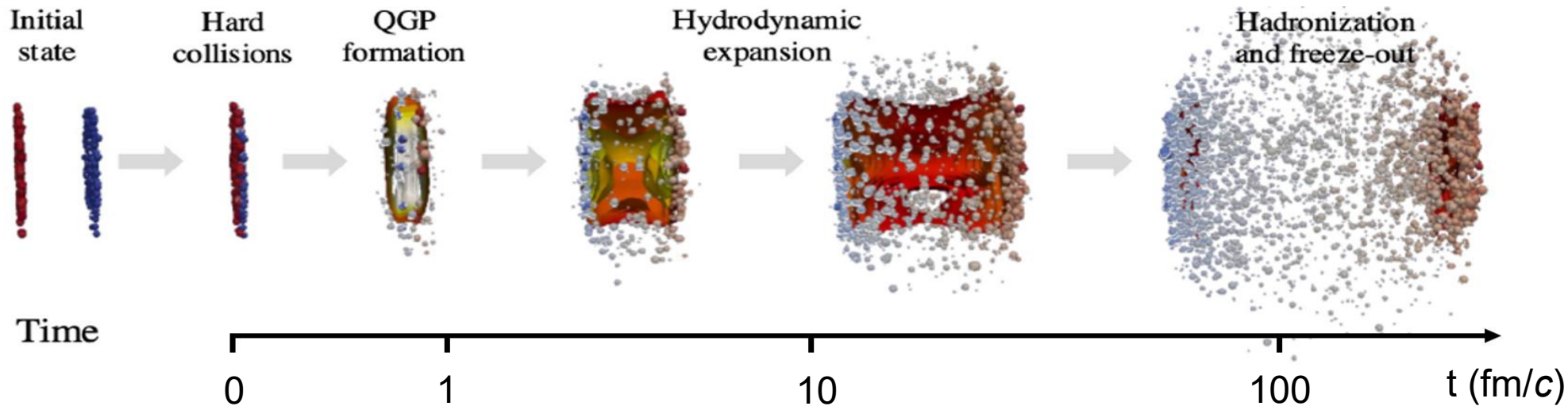
Why heavy-ion collisions?



- QCD is asymptotically free at high energy density/temperature.
 - Heavy-ion collisions are the only way to recreate these extreme conditions in a laboratory.
- Probe the fundamental properties of deconfined QCD matter, the quark-gluon plasma (QGP).



MADAI Collaboration



QGP lifetime
~ few fm/c !!!

-
- The diagram shows the evolution of a heavy-ion collision system in the $(\text{time}, \text{rapidity})$ plane. The vertical axis is time and the horizontal axis is rapidity (labeled z).
- Left Panel (a) without QGP:** Shows the evolution of a system where the initial state (Charm quarks) evolves through a **Pre-Hadronic Phase** into a **Hadron Gas**. The transition is labeled **Hadron Formation**. The system then undergoes **Freeze Out**, producing particles like $\pi, K, p, \dots$ and D^0 . The evolution is described as **Hydrodynamic Evolution**.
- Right Panel (b) with QGP:** Shows the evolution of a system where the initial state (Charm quarks) evolves through a **Pre-Equilibrium Phase ($< \tau_0$)** into a **QGP** (Quark-Gluon Plasma). The QGP then transitions through a **Mixed Phase ?** (indicated by a dashed line) into a **Hadron Gas**. The transition is labeled **Chemical Freeze Out**. The system then undergoes **Freeze Out**, producing particles like $\pi, K, p, \dots$ and Λ_c^+ . The evolution is also described as **Hydrodynamic Evolution**.
- Key parameters and labels include:
- Charm quarks**: Initial state at the origin.
 - Pre-Equilibrium Phase ($< \tau_0$)**: Initial phase in the QGP scenario.
 - QGP**: Quark-Gluon Plasma phase.
 - Mixed Phase ?**: Phase between QGP and Hadron Gas.
 - Hadron Gas**: Final state in both scenarios.
 - Chemical Freeze Out**: Transition from Hadron Gas to Freeze Out in the QGP scenario.
 - Freeze Out**: Final stage of particle production.
 - Hadron Formation**: Transition from Pre-Hadronic Phase to Hadron Gas.
 - Pre-Hadronic Phase**: Initial phase in the no-QGP scenario.
 - Hydrodynamic Evolution**: Describes the expansion and cooling of the system.
 - Mid Rapidity**: Central region of the collision.
 - Beam Rapidity**: Edge region of the collision.
 - Time**: Vertical axis.
 - Rapidity**: Horizontal axis (labeled z).
 - Temperature**: Indicated by T_{fo} (freeze-out temperature) and T_{ch} (chemical freeze-out temperature).
 - Particle Production**: Indicated by arrows pointing to $\pi, K, p, \dots$ and Λ_c^+ .

- Luigi Dello Stritto, QCD@LHC 2026, 01/10/2026*

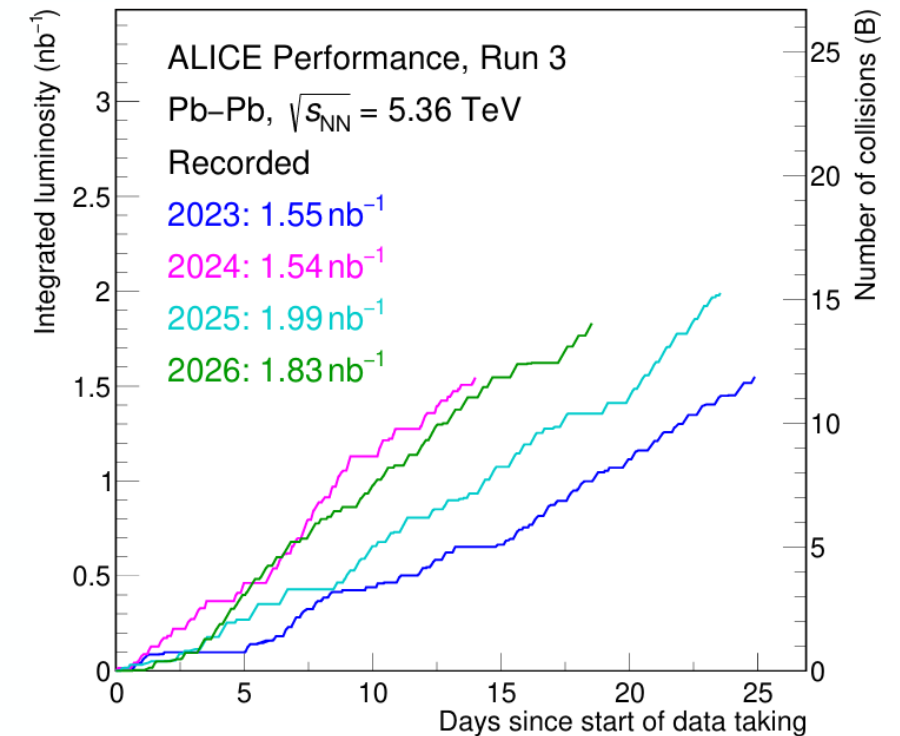
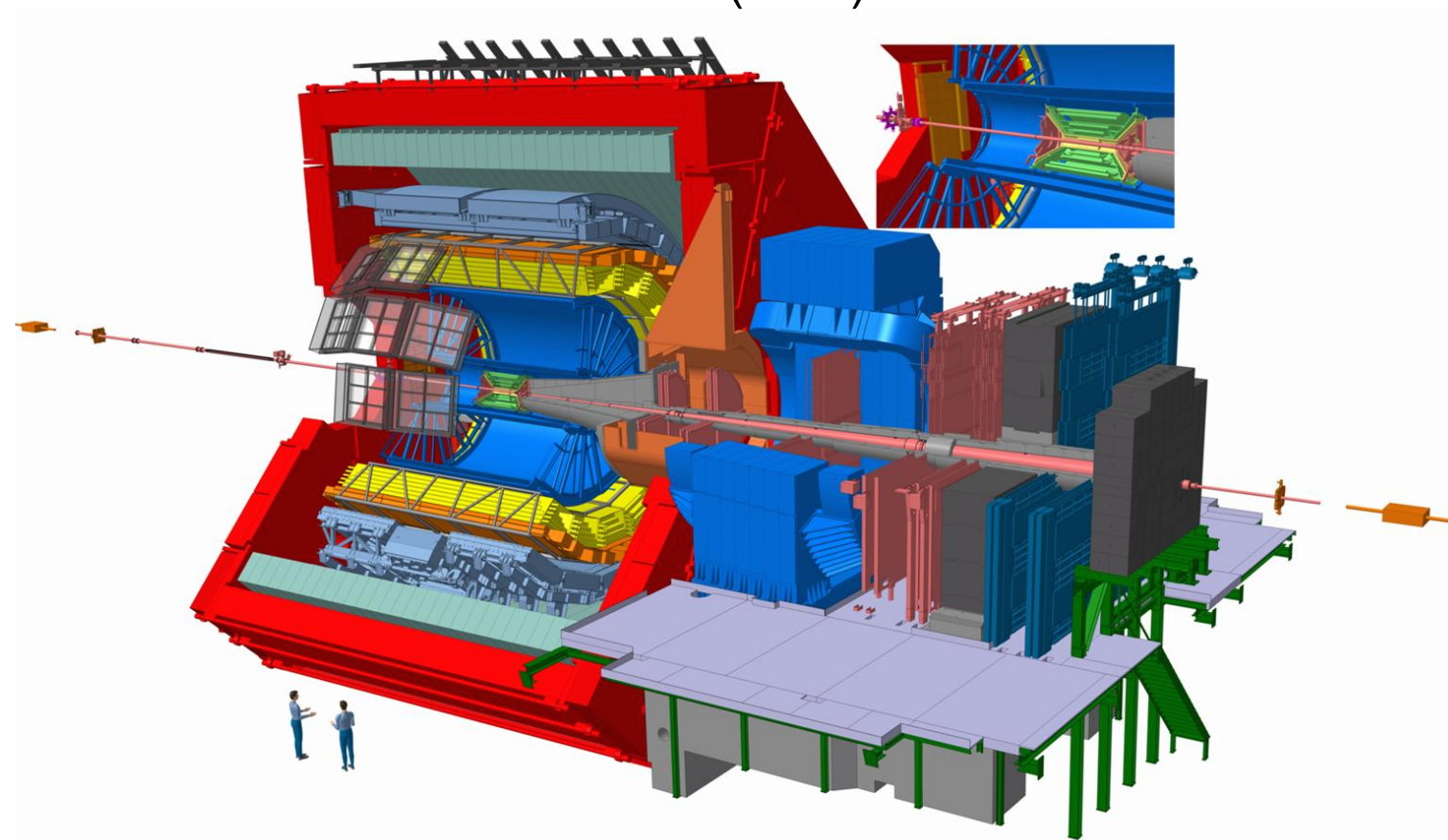
The ALICE detector

Major upgrade of the ALICE detector in LS2:

- Inner Tracking System (ITS)
- Time Projection Chamber (TPC) readout
- Fast Interaction Trigger (FIT)
- Muon Forward Tracker (MFT)

ALICE in Run 3:

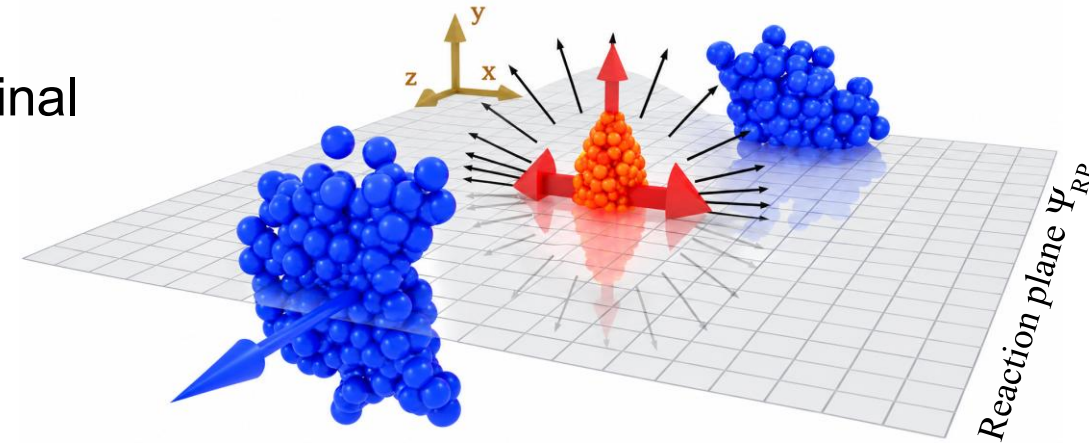
- continuous readout
- larger interaction rate
 - up to 50 kHz in Pb–Pb



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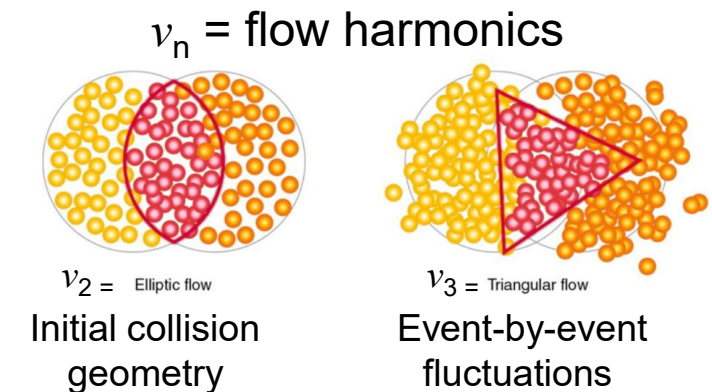
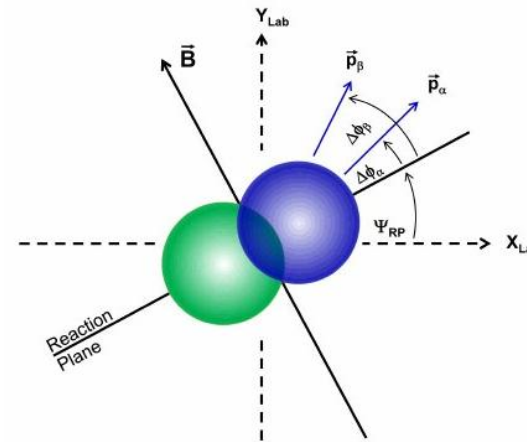
Collective motion in heavy-ion collisions

- Initial spatial anisotropy $\rightarrow$ pressure gradients lead to final momentum anisotropy of the produced particles.
- The QGP thermalises, developing **collective behavior**.

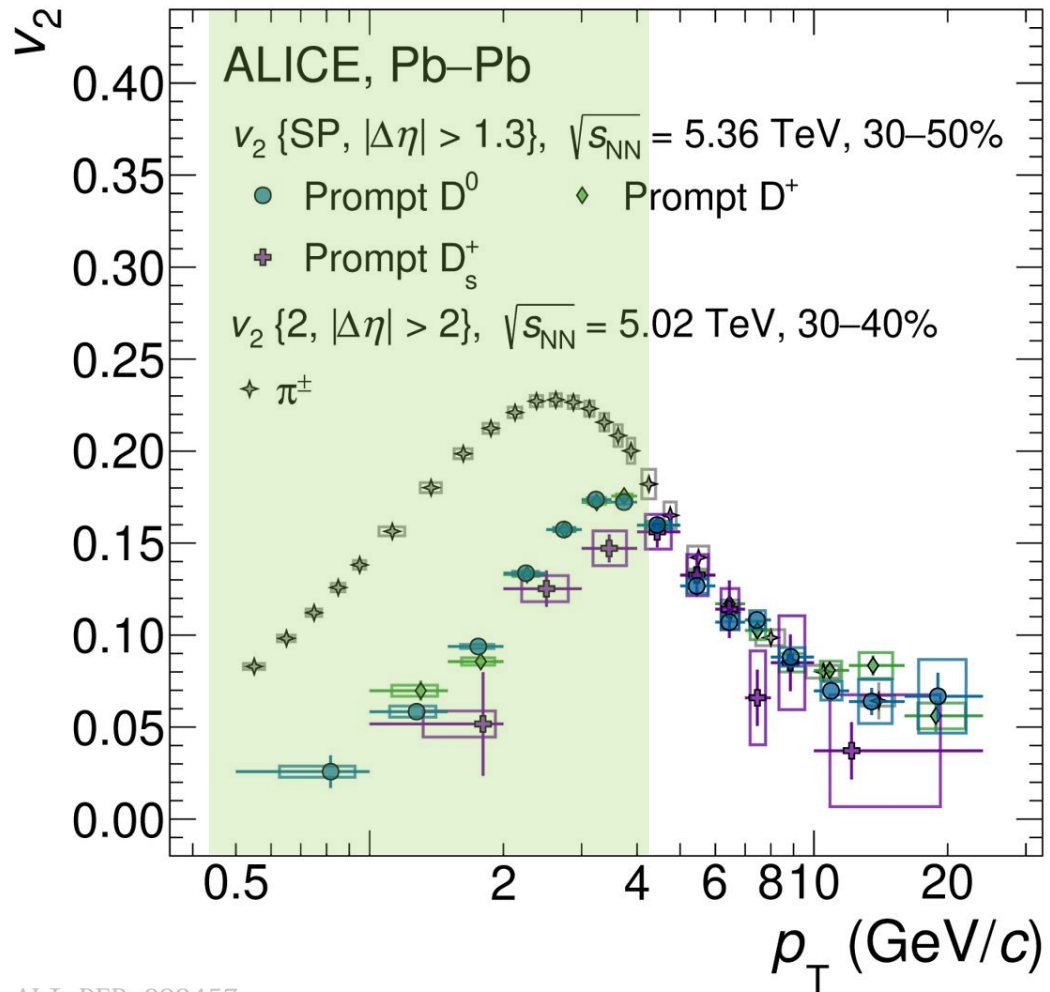


- Fourier expansion of azimuthal-angle distribution of final-state particles:

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



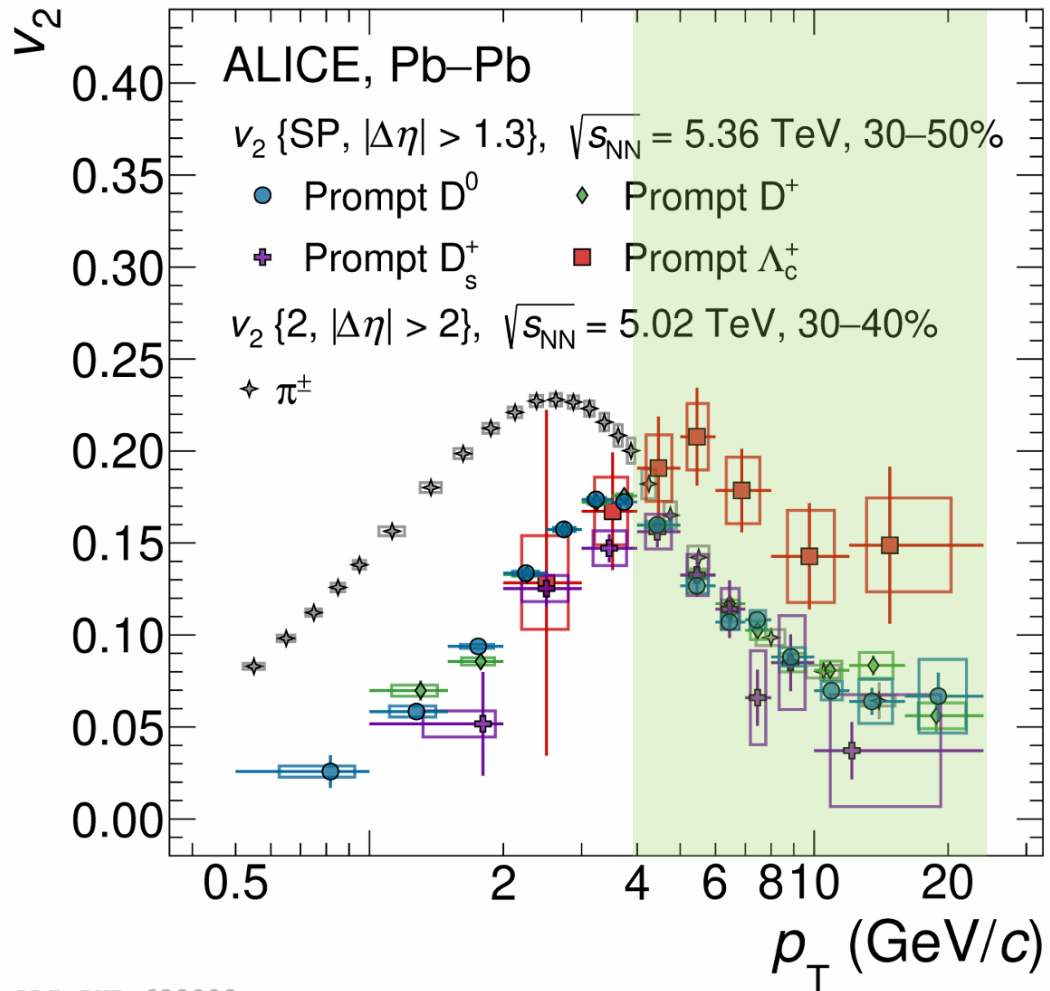
- Probes fundamental properties of the QGP: viscosity, degree of collectivity, and thermalisation.



- **Mass ordering** clearly visible. Heavier particles flow less at low p_T ($p_T < 4 \text{ GeV/c}$): $v_2(\pi^\pm) > v_2(D)$
- Excellent agreement between the D^0 and D^+ v_2 over the measured p_T range.
- Hint of smaller D_s^+ v_2 :
 - Species-dependent hadronic rescattering (D vs D_s) [PRL 110 \(2013\) 112301](#)
 - Charm sequential coalescence [PRL 136 \(2026\) 232301](#)

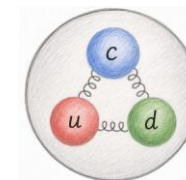
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Prompt charm-hadron v_2



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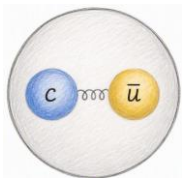
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[PRL 110 \(2013\) 112301](#)
 - Charm sequential coalescence [PRL 136 \(2026\) 232301](#)
- First evidence of **charm baryon–meson splitting**:
 $v_2(\Lambda_c^+) > v_2(D)$ with 3.7σ significance
 - Consistent with **hadronisation via quark recombination**: hadrons inherit the partonic flow of their constituent quarks.



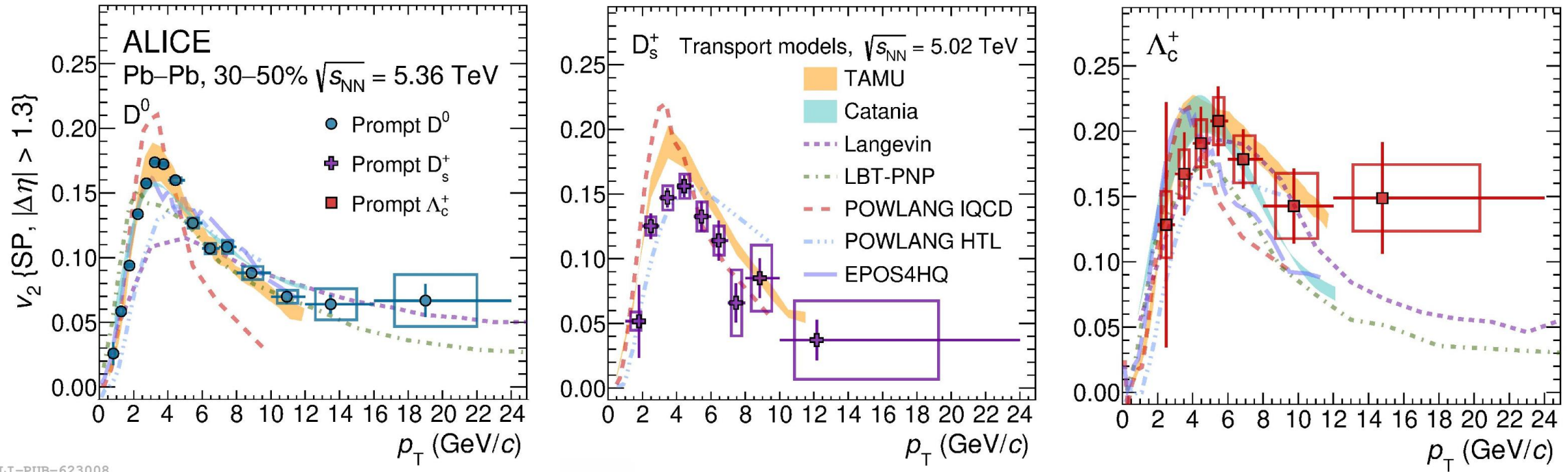
2 light quarks

vs

1 light quark



Prompt charm-hadron ν_2



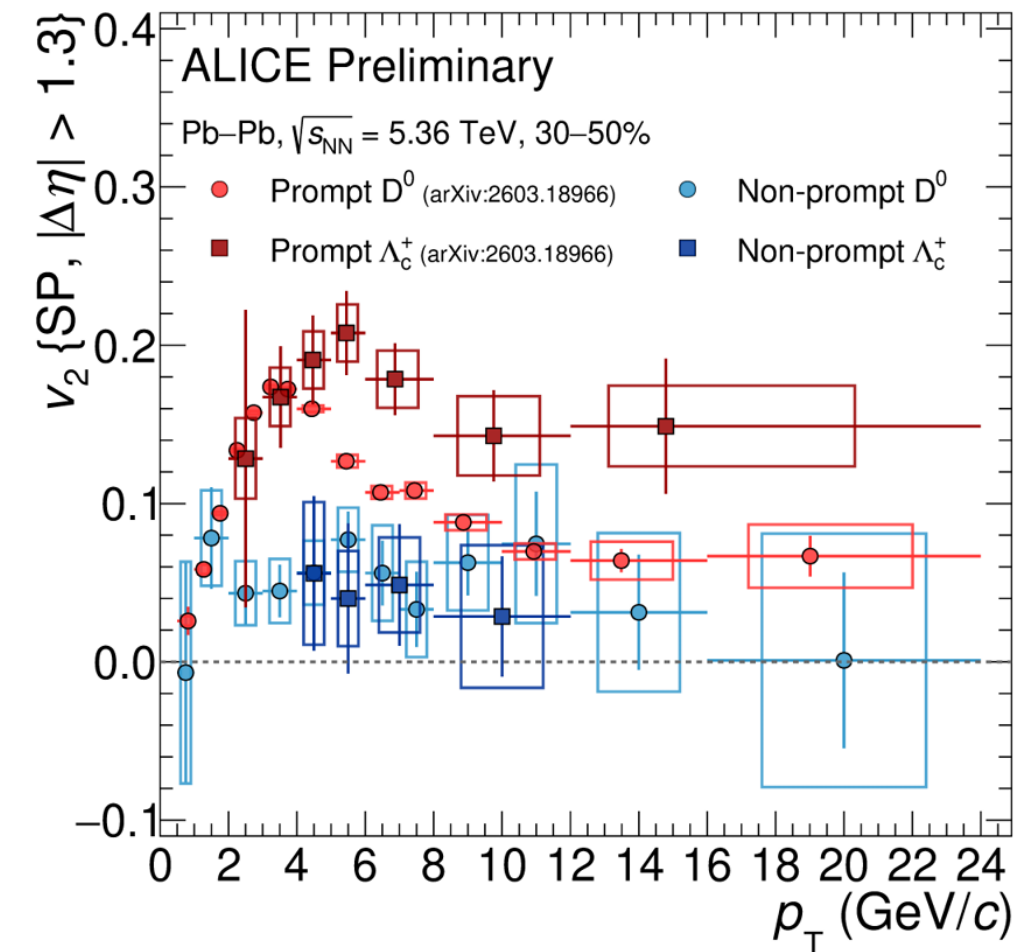
ALI-PUB-623008

- Qualitatively good agreement between theory and data.

➤ Which physics effects are relevant?

- Hadronisation via recombination crucial to describe low and intermediate p_T ($\lesssim 8$ GeV/c).
- Radiative energy loss and hadronisation via fragmentation important to describe high p_T ($\gtrsim 8$ GeV/c).

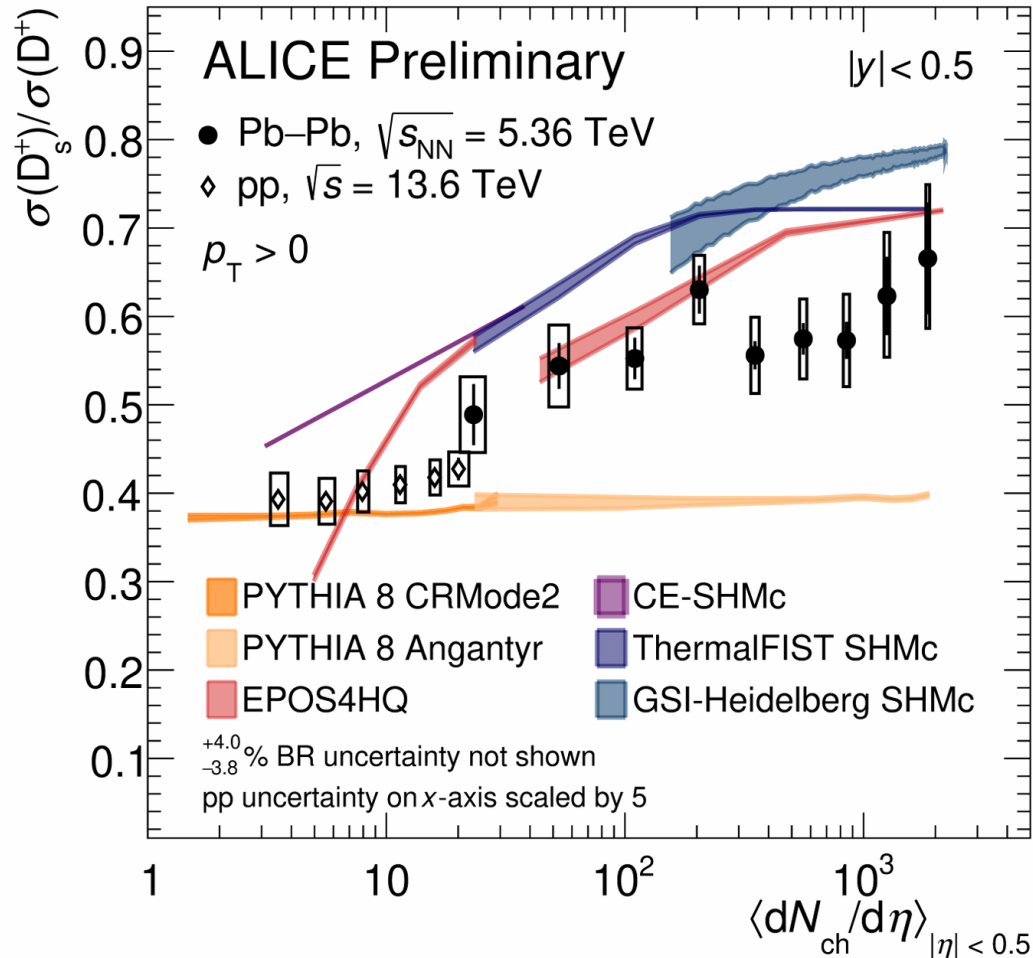
TAMU, [PRL 124 \(2020\) 042301](#)
 Catania, [PRC 96 \(2017\) 044905](#)
 Langevin, [EPJC 81 \(2021\) 1035](#)
 LBT+PNP, [PLB 838 \(2023\) 137733](#)
 POWLANG, [PRD 109 \(2024\) L011501](#)
 EPOS4, [PRC 110 \(2024\) 2, 024909](#)



- **Positive** non-prompt Λ_c^+ and D^0 ν_2 , consistent within uncertainties.
 - **b quarks** participate in the collective motion.
- **Smaller** ν_2 values than those for the prompt case:
 ν_2 (prompt charm hadrons) > ν_2 (non-prompt charm hadrons) > 0
 - Larger mass of the b quark:
 - Longer relaxation time than the QGP lifetime: $\tau_{\text{relax}} \propto M_q$
 - Lower relative contribution to ν_2 transferred via coalescence with light quarks.

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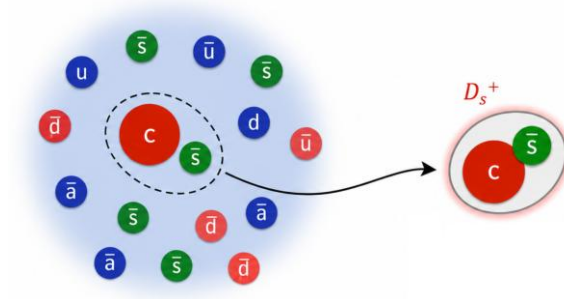
Strangeness enhancement



ALI-PREL-621147

- D_s^+/D^+ production-yield ratio increases from low-multiplicity pp collisions to high-multiplicity Pb–Pb collisions.

➤ Charm quarks hadronise via **recombination with strange quarks** from a strangeness-rich medium.



- D_s^+/D^+ increase qualitatively described by models based on hadronisation via coalescence and SHM.
- No model provides a full description of the trend from pp to Pb–Pb .

CRMode2, [JHEP 08 \(2015\) 003](#)

Angantyr, [JHEP 10 \(2018\) 134](#)

EPOS4HQ, [PRC 110 \(2024\) 2, 024909](#)

CE-SHMc, [PLB 815 \(2021\) 136144](#)

ThermalFIST, [PRC 100 \(2019\) 054906](#)

GSI-Heidelberg SHMc, [JHEP 07 \(2021\) 035](#)

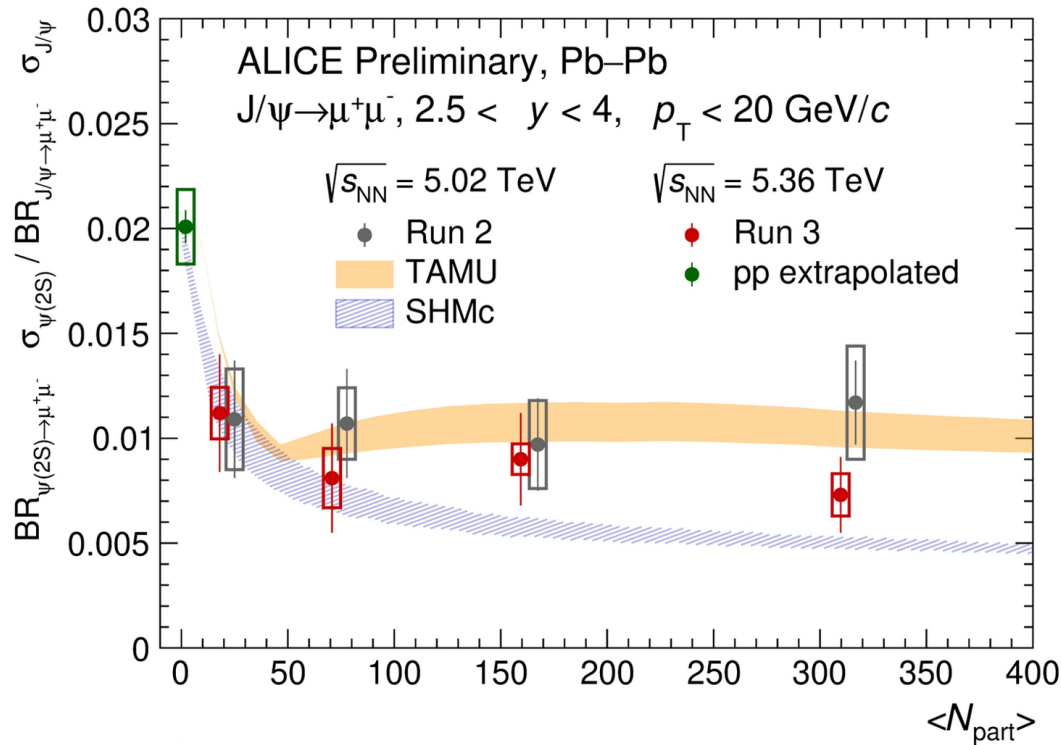
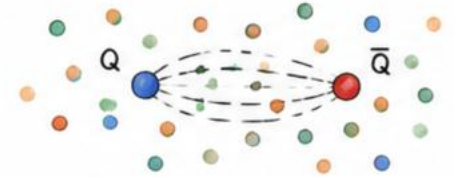
$\psi(2S)$ -to- J/ψ relative suppression

- Excited quarkonium states are more sensitive to **colour screening/dissociation** due to their lower binding energies.
 - Larger suppression expected in a color-dense medium compared to the ground state.

In vacuum



In QGP



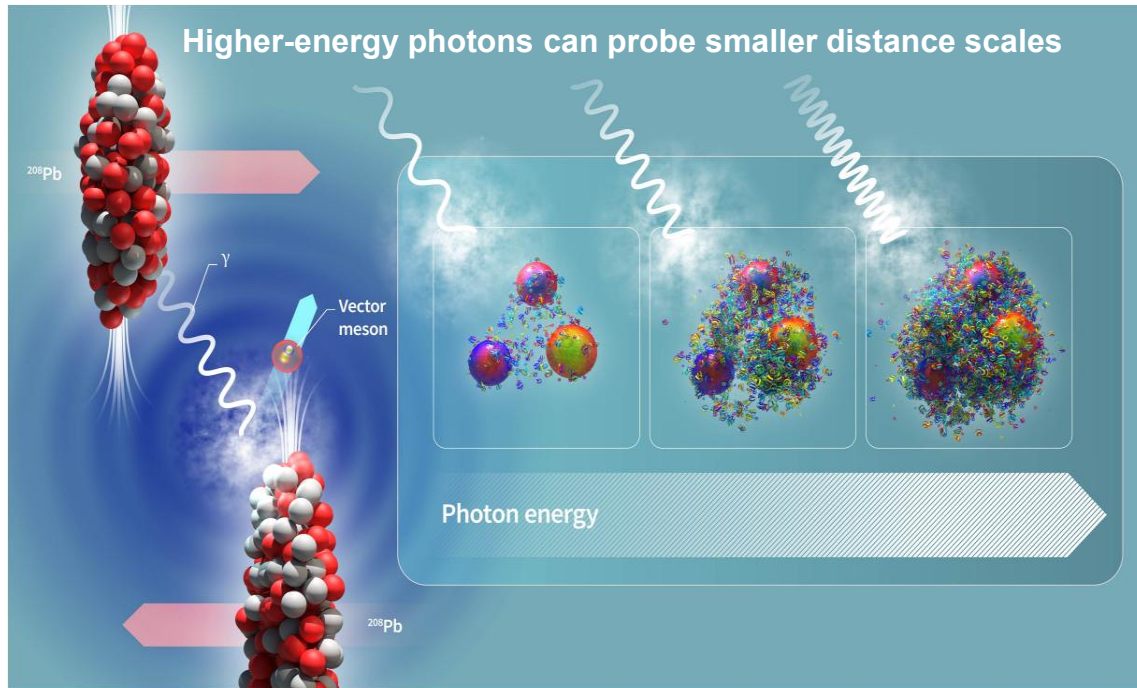
- An increased relative **suppression** by a factor ~ 2 of $\psi(2S)$ is observed in **Pb-Pb** compared to **pp**.
- No dependence on centrality observed.
 - Role of **suppression** and **regeneration** to be investigated.
- Data cannot yet distinguish between the models.
 - **TAMU**: suppression + regeneration compete dynamically.
 - **SHMc**: yields are entirely produced statistically at hadronisation.

ALI-PREL-599771

 **TAMU**: [Nucl.Phys.A 943 \(2015\) 147-158](#)

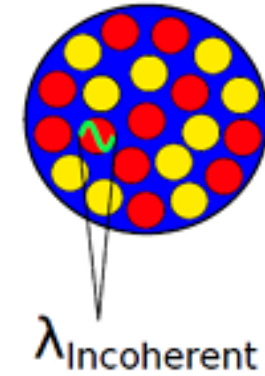
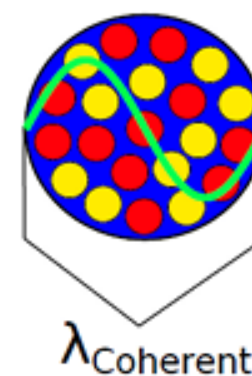
 **SHMc**: [PLB 797 \(2019\) 134836](#)

- **Ultrapерipheral collisions** (UPCs) occur when nuclei do not overlap.
 - interactions driven by photon-induced processes from the nuclei's electromagnetic fields.



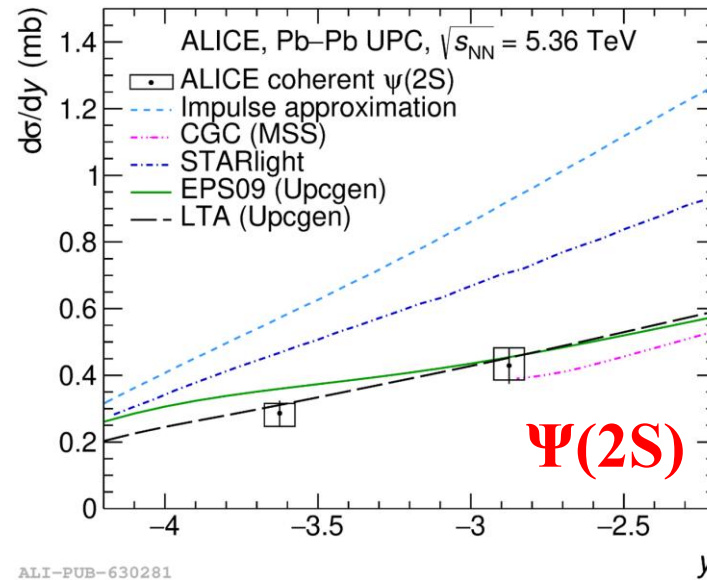
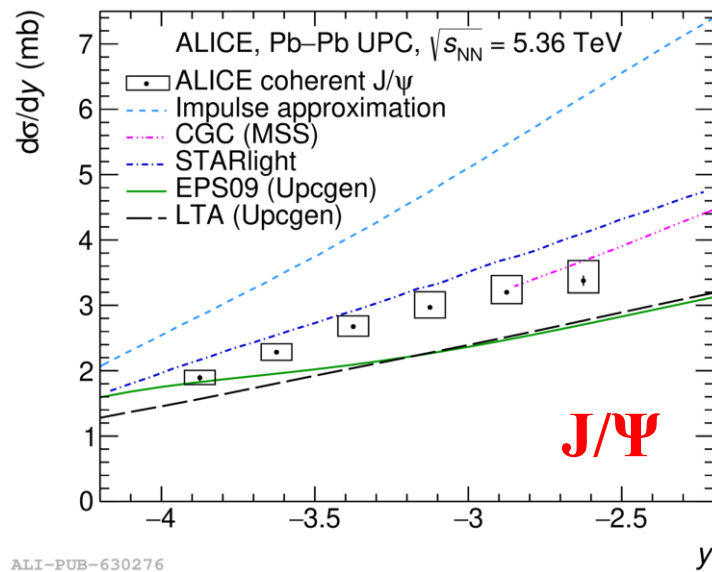
- Access to parton distribution functions (PDFs).
 - Probe the parton distribution functions over a wide range of **Bjorken x** .
- Two possible interactions:
 - **Coherent**: Interaction with the whole nucleus.
 - **Incoherent**: Interaction with single nucleons.

- **Coherent production** is sensitive to the **average spatial distribution of gluons** in the nucleus at low **Bjorken x** .
 - Nuclear shadowing
 - Gluon saturation

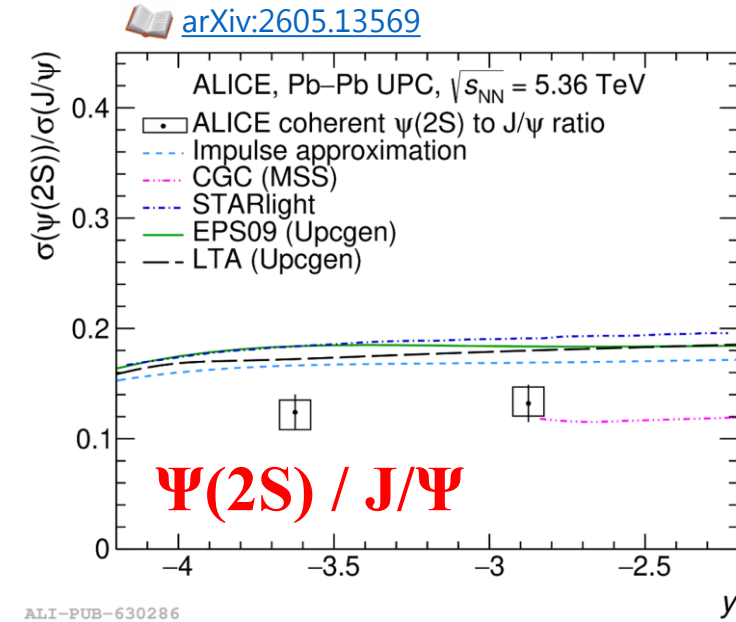


Coherent J/ψ and $\psi(2S)$ photoproduction

- Comparing the measured J/ψ and $\psi(2S)$ cross sections to the "impulse approximation" (no shadowing and no gluon saturation baseline).



Ratio

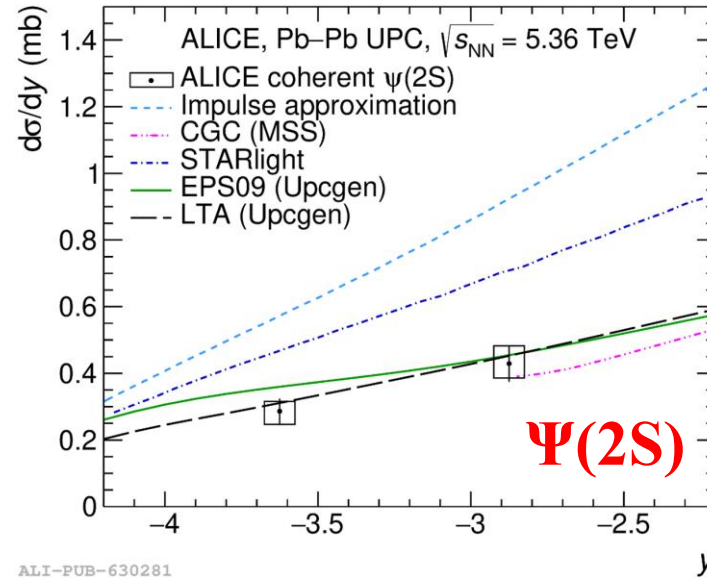
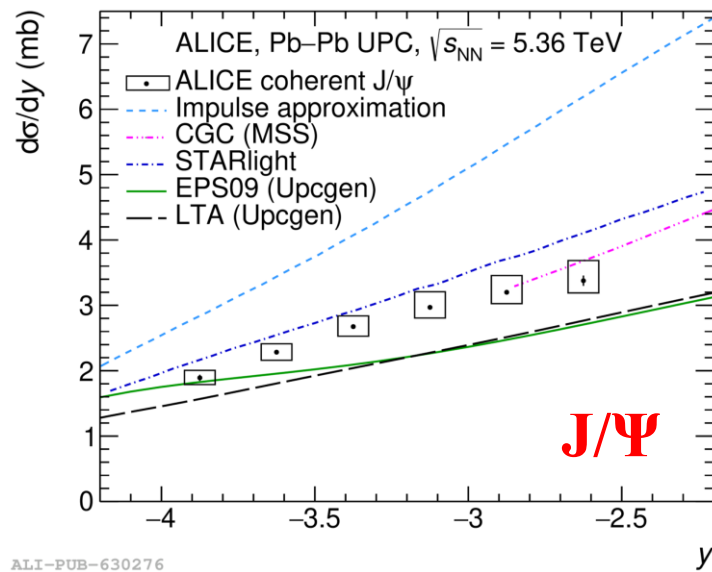


- Data lie significantly below the **impulse approximation**, disfavoring a no-shadowing scenario.
- STARlight**: Glauber-based, accounts for multiple scattering but **no gluon shadowing**.
- Upscgen (**EPS09**, LTA): includes **nuclear shadowing**.
- CGC** (Color Glass Condensate) incorporates **non-linear gluon saturation on top of shadowing**.

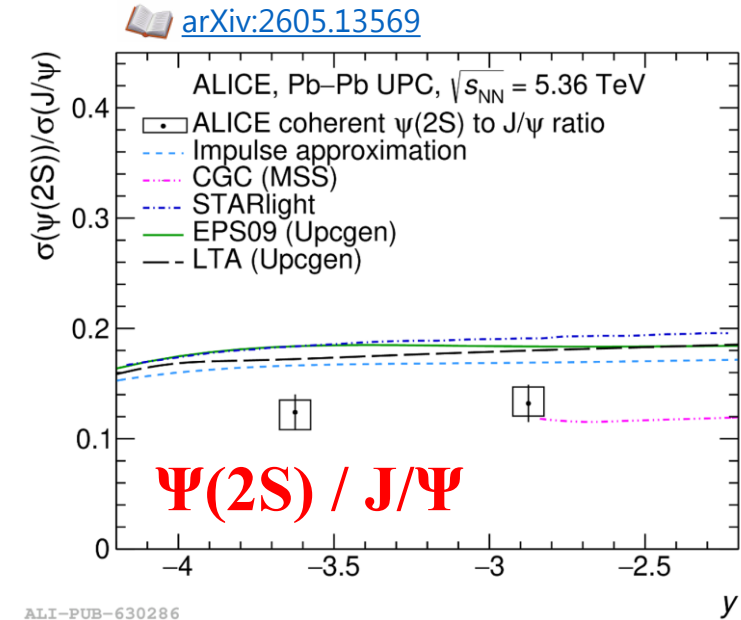
STARlight: [CPC 212 \(2017\) 258](#)
Upscgen: [CPC 277 \(2022\) 108388](#)
CGC: [PRD 109 \(2024\) L071504](#)

Coherent J/ψ and $\psi(2S)$ photoproduction

- Comparing the measured J/ψ and $\psi(2S)$ cross sections to the "impulse approximation" (no shadowing and no gluon saturation baseline).



Ratio
→



- Models without nuclear shadowing overestimate both J/ψ and $\psi(2S)$ cross sections.
- Upcgen with nuclear shadowing matches $\psi(2S)$ but underestimates J/ψ cross section.
- CGC provides the best description of all the observables in its available range.

➤ Including nuclear shadowing and gluon saturation is crucial to describe experimental data!

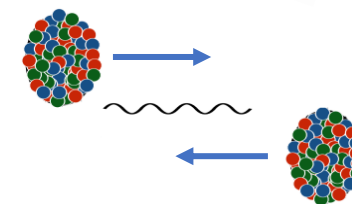
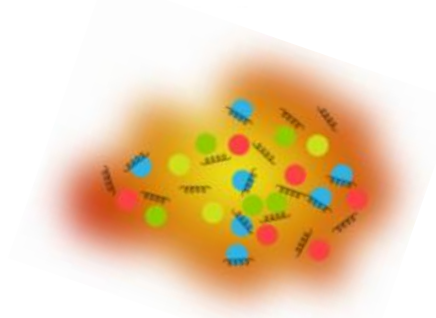
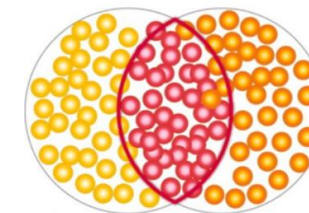
Conclusions

- Heavy-ion collisions provide a unique environment to explore fundamental aspects of QCD.

- Linking the initial state to final-state observables:
 - Initial-state anisotropy converted into final-state observables:
 - Charm and beauty quarks participate in the collective expansion.

- Probe the QGP through hadronisation
 - Charm-quark coalescence with strange quarks.
 - Sequential charmonium suppression and regeneration.

- UPC to probe PDFs.
 - $\psi(2S)$ -to- J/ψ ratio disfavors no-shadowing baselines, consistent with models including nuclear gluon shadowing and saturation.

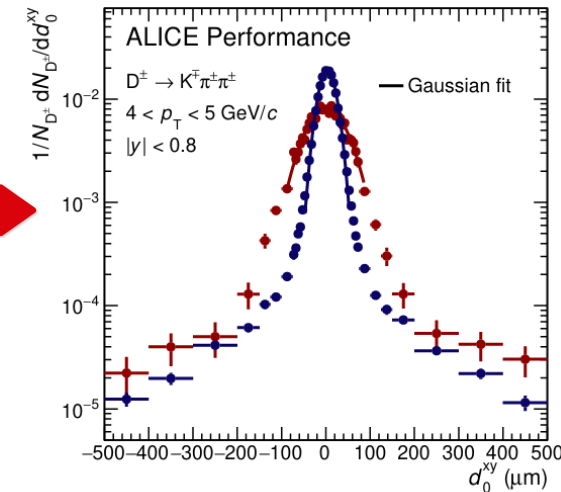
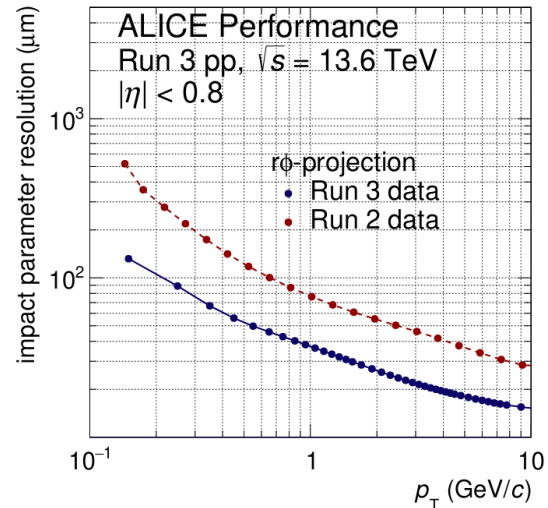
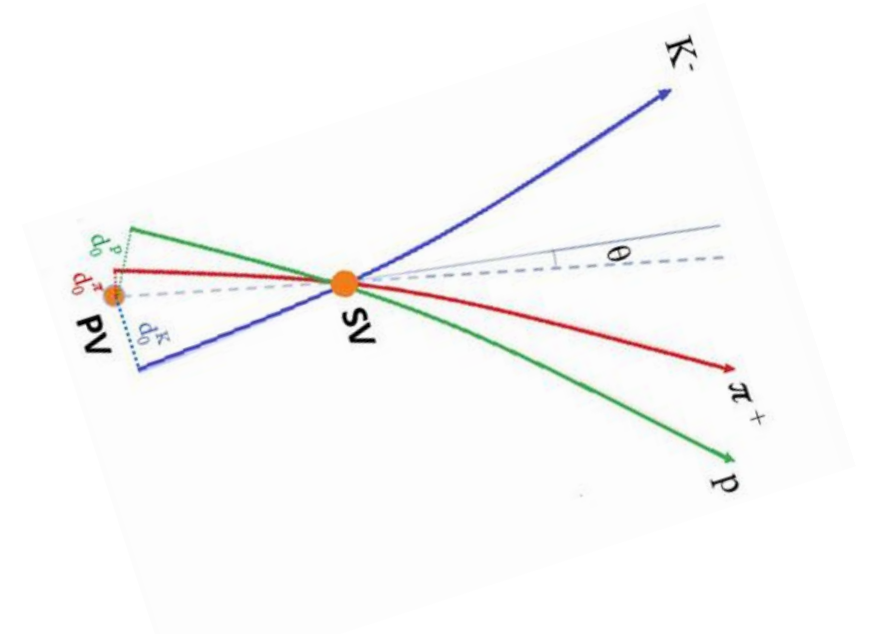


Detector upgrades enabled precise measurements of new observables!
Stay tuned for more heavy-ion physics from ALICE!

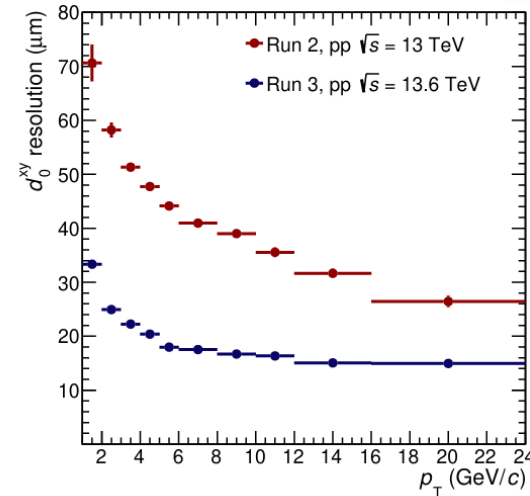
Thank you for your
attention!

Backup

- **Pointing resolution** of the vertexing detector crucial for a precise reconstruction of the decay topology.



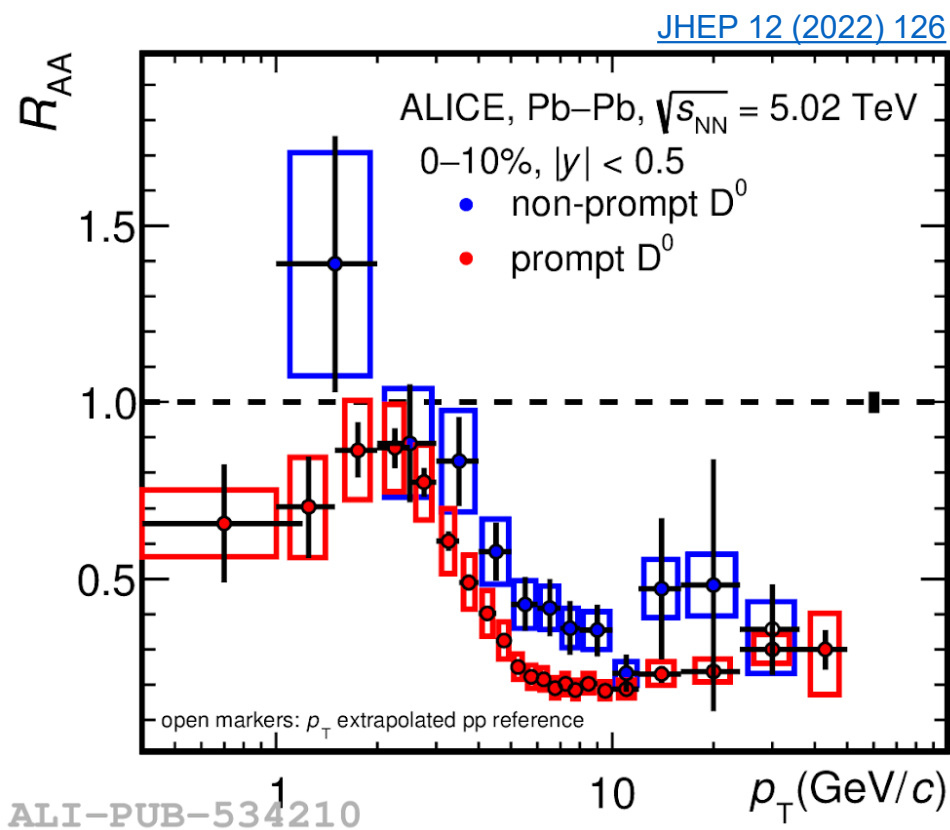
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ITS upgrade:

- **2x** better performance in $r\phi$ and **4x** in z compared to Run 2.

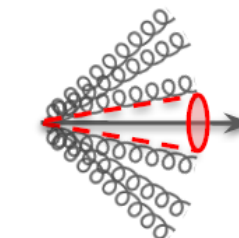
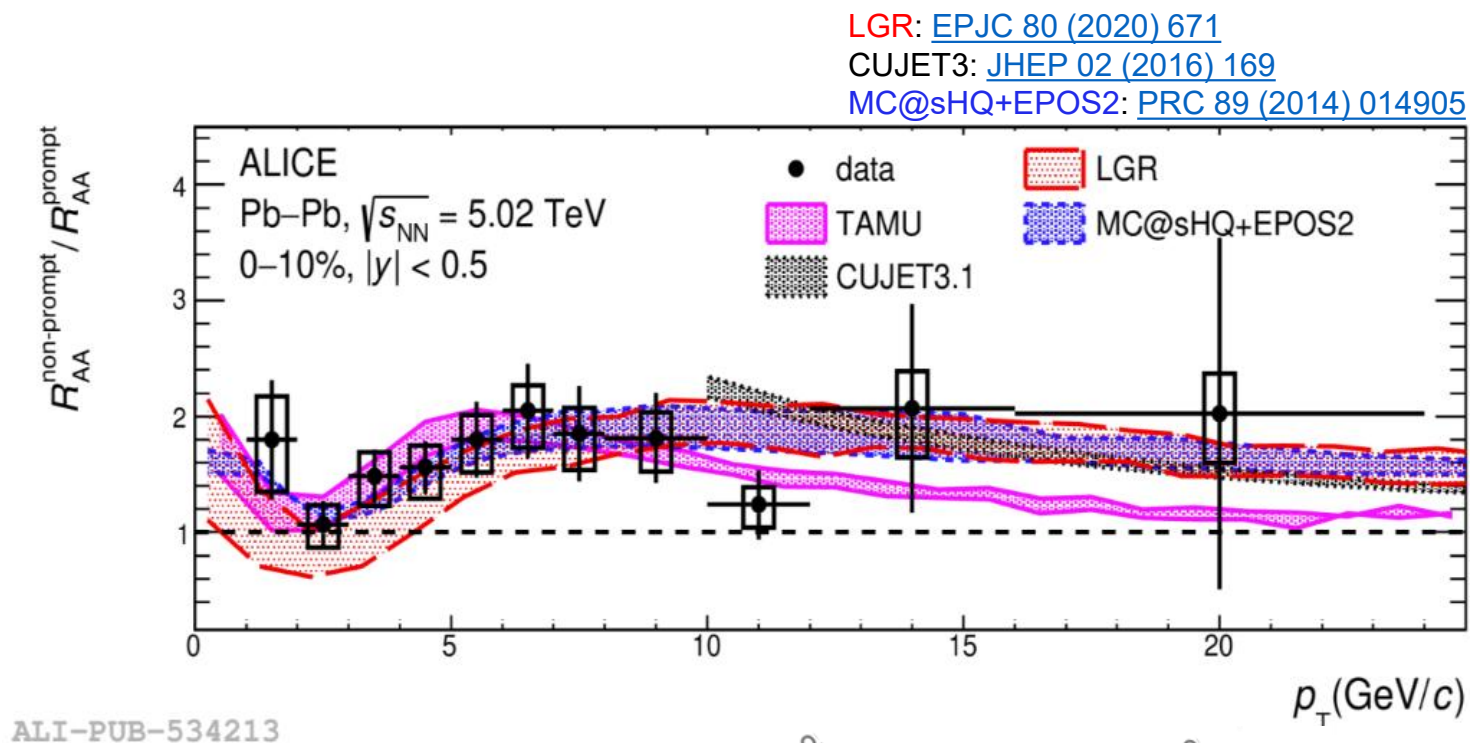
D meson energy loss



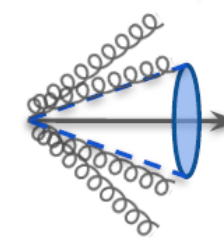
- $R_{AA}(b \rightarrow D^0) > R_{AA}(c \rightarrow D^0)$ at intermediate p_T .

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

- Theoretical models catch the data.

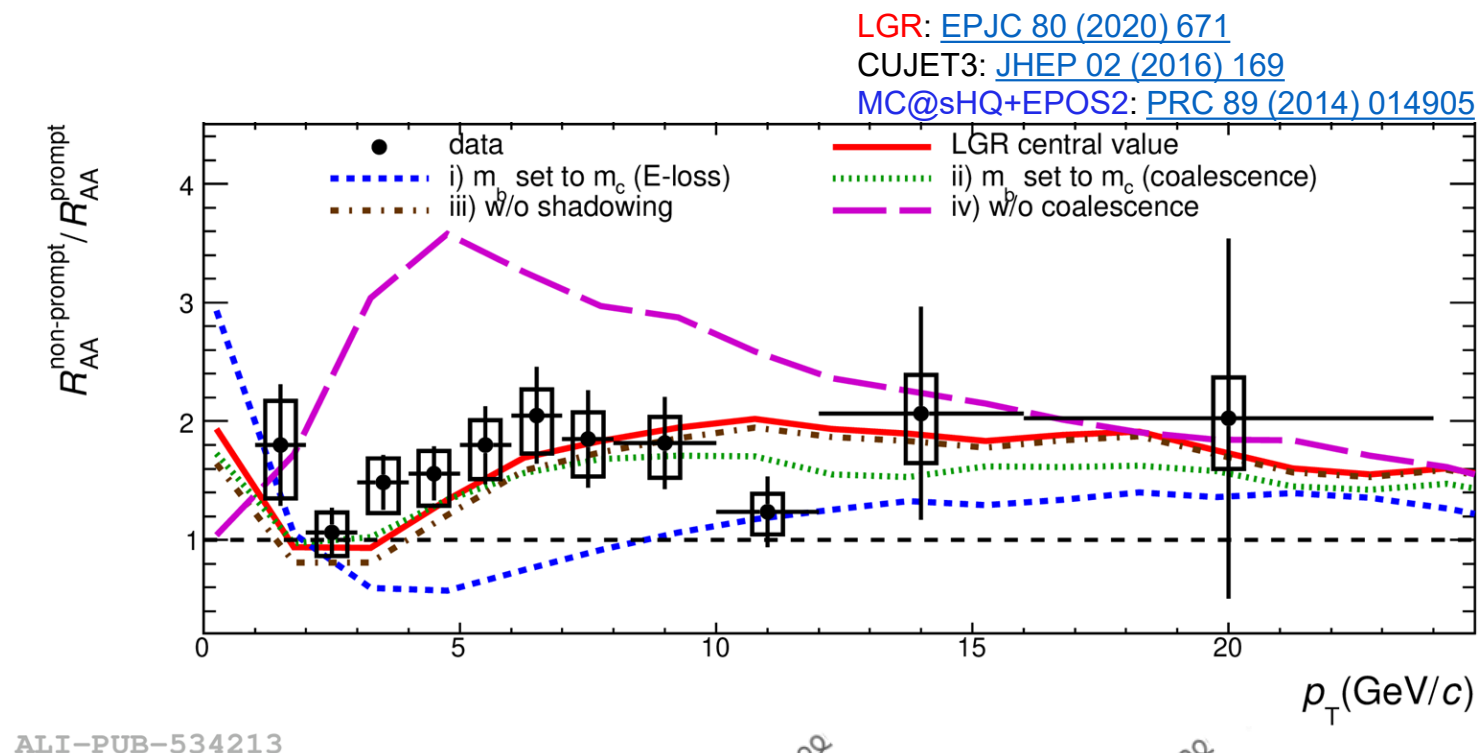
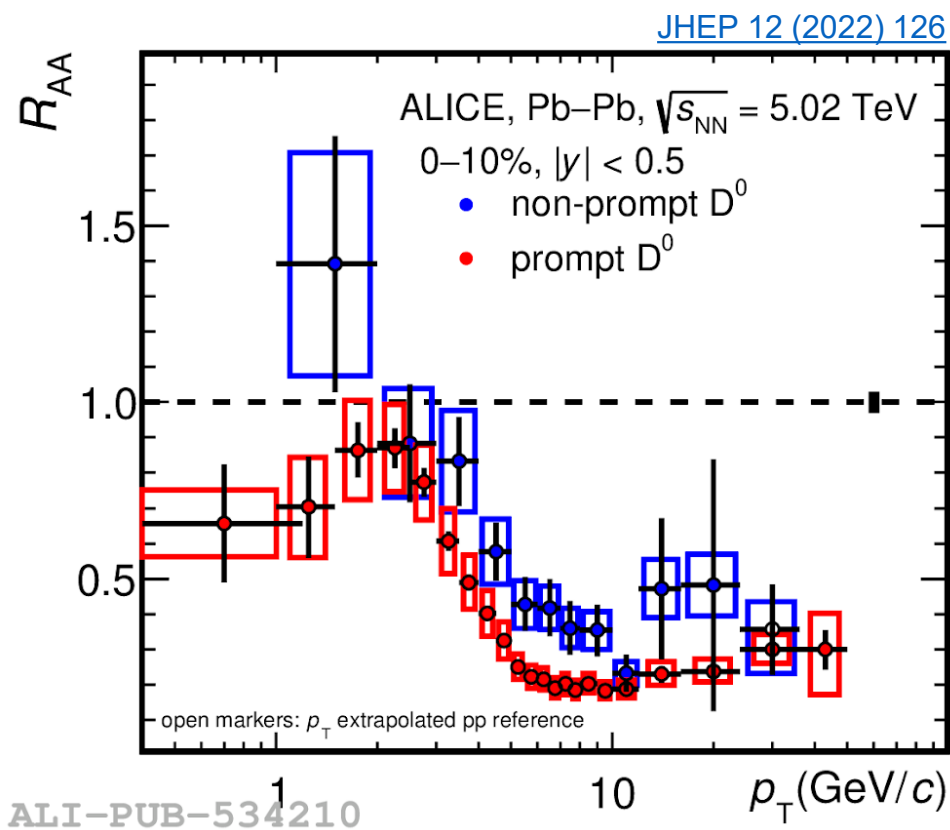


lower mass parton



higher mass parton

D meson energy loss

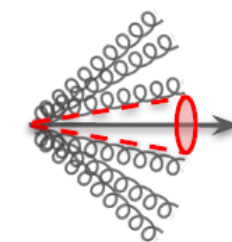


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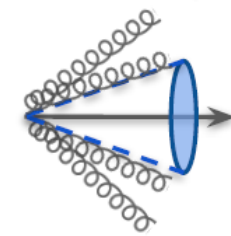


in-medium energy-loss mass dependence (dead cone effect)

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



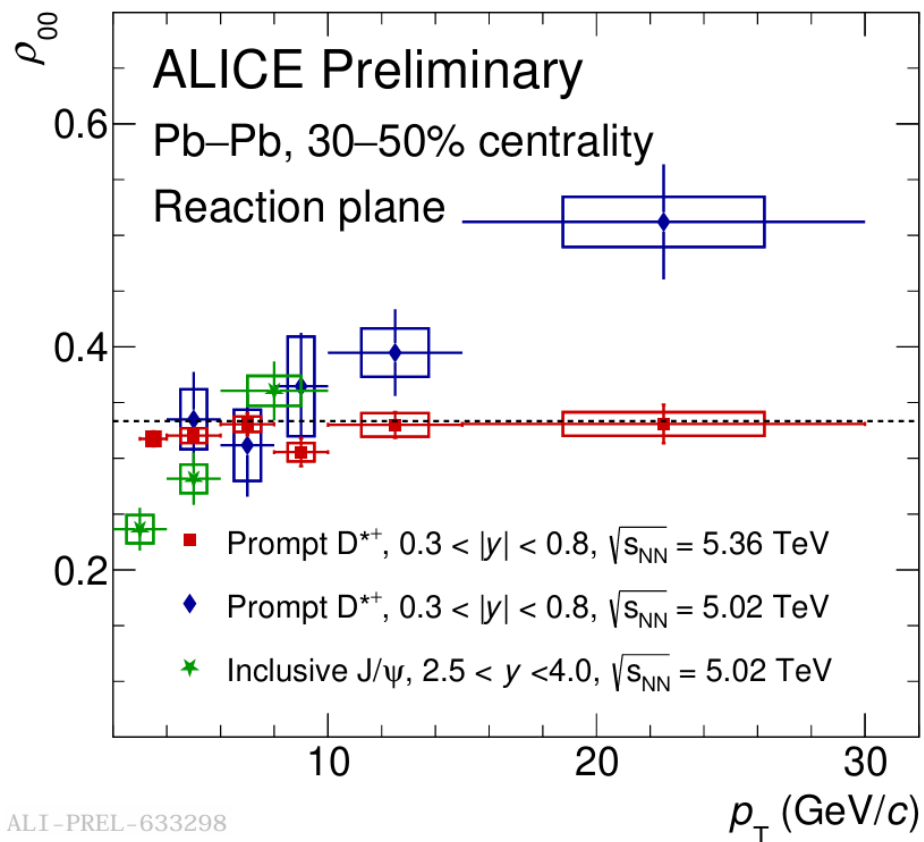
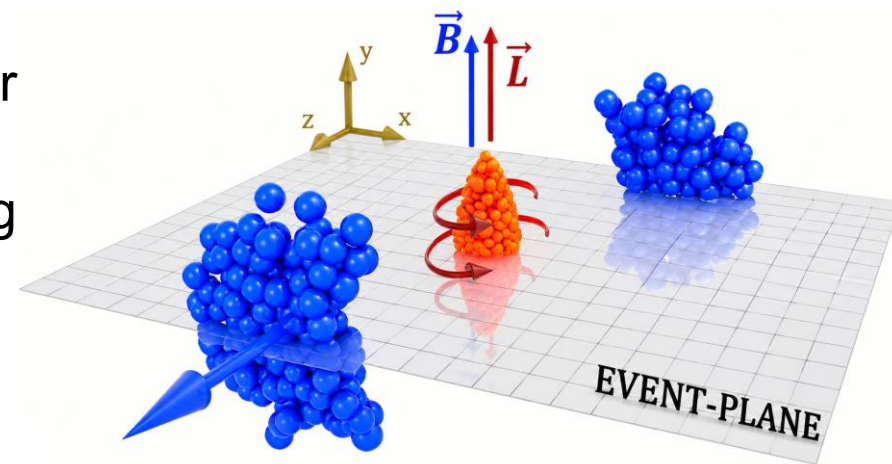
lower mass parton



higher mass parton

Spin alignment

- Extreme conditions in non-central Pb–Pb collisions:
 - **Strong orbital angular momentum, L** : participants near each nucleus carry different amounts of forward momentum.
 - **Intense magnetic field, $B \sim 10^{15}$ T**: due to the fast-moving charged spectators.

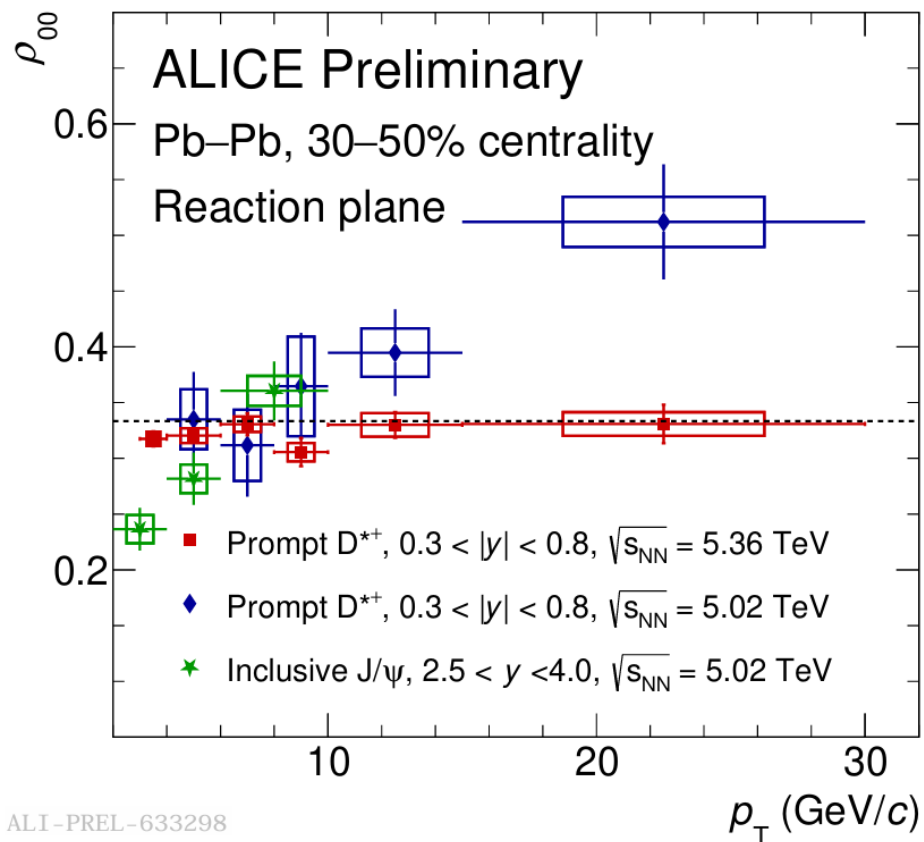
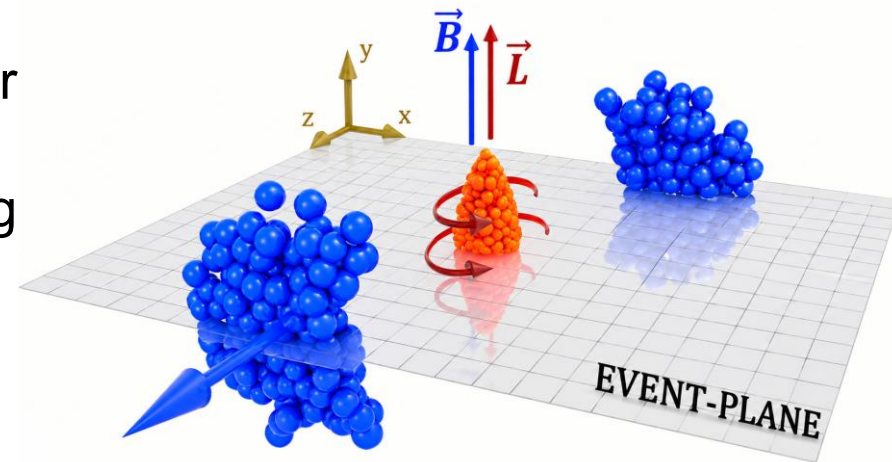


Spin alignment: L and B couple to the spin of the produced particles.

- Spin polarisation is transferred to vector mesons during hadronisation.
- Vector mesons show an uneven population of their three spin states, measured via ρ_{00} ($= 1/3$ if no alignment).

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Within current uncertainties:

- J/ψ : hint of deviation from the null hypothesis at low p_T .
- D^{*+} : Indication of polarisation at high p_T from Run 2 data not supported by more precise Run 3 measurement, which favours no polarization.

- J/ψ deviation at low p_T is compatible with **recombination** hypothesis.
- Theoretical predictions are required for conclusions.

Conclusions

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- Linking the initial state to final-state observables:

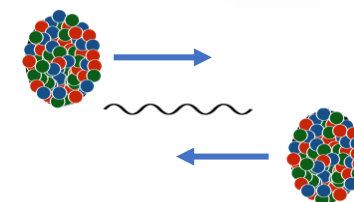
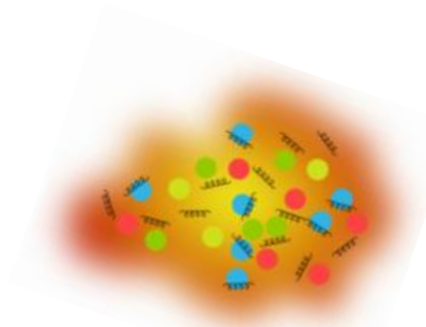
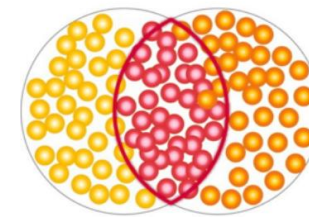
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