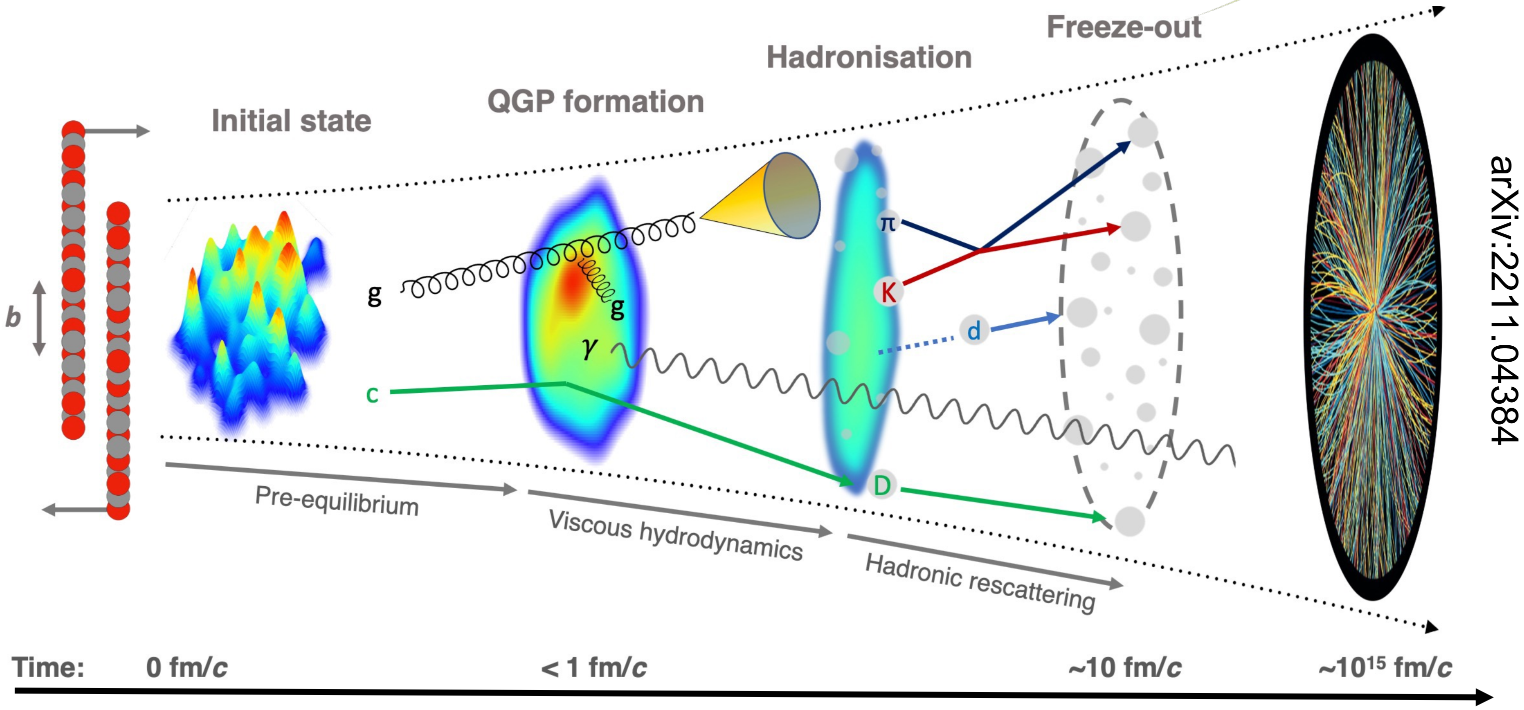
Study of collective phenomena via the production of heavy quarks and quarkonia in hadronic collisions with ALICE

Victor Valencia Torres[1]

On behalf of ALICE Collaboration

1. SUBATECH (IMT Atlantique, Nantes Université, CNRS/IN2P3), Nantes, France

Heavy-flavor and Quarkonia in Pb–Pb collisions



arXiv:2211.04384

Heavy-flavor and Quarkonia in Pb–Pb collisions

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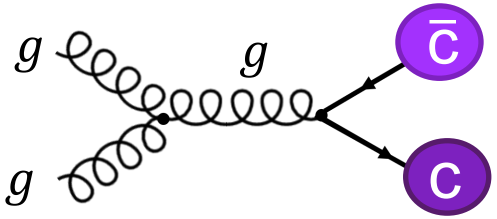
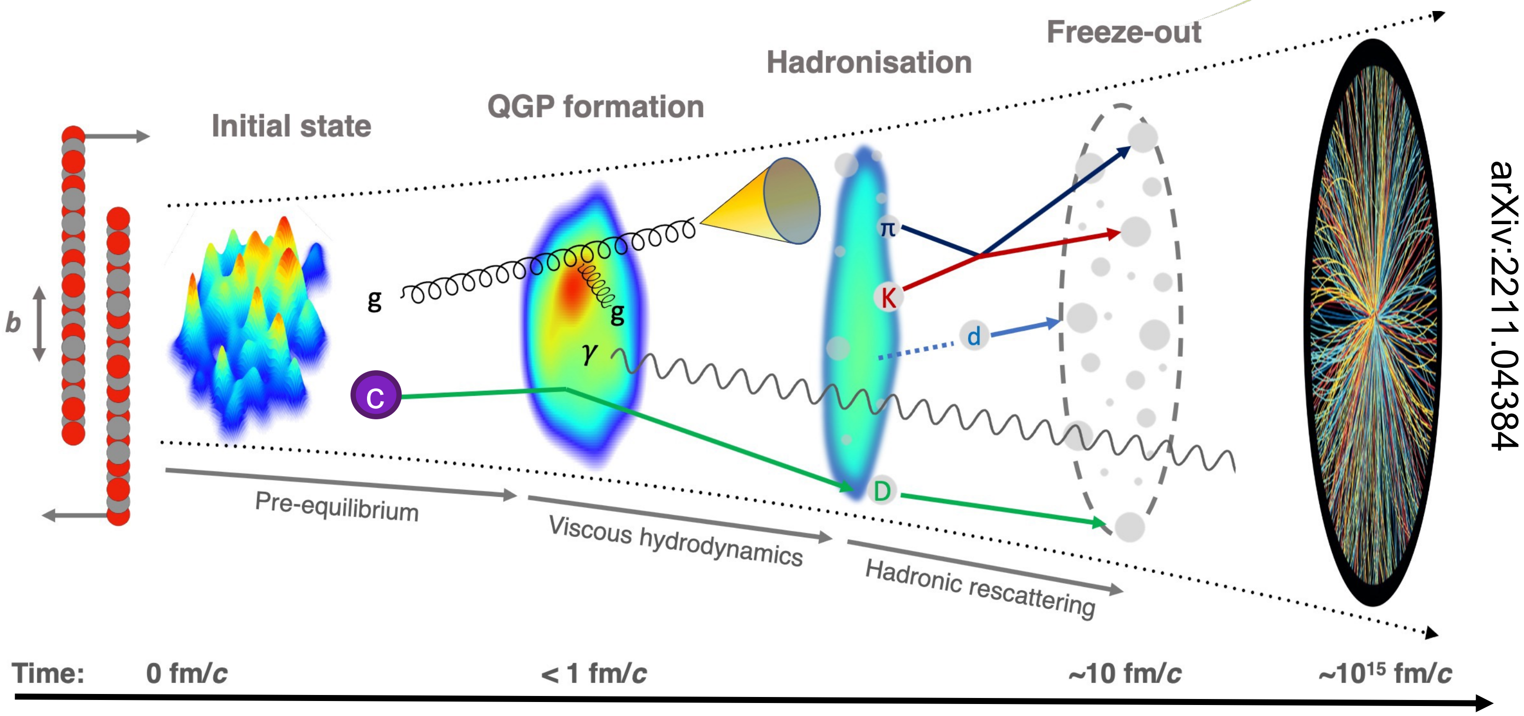
  → $M_{c,b} > \Lambda_{QCD}$ (pQCD applicable)
  → **Sensitive** to the medium evolution





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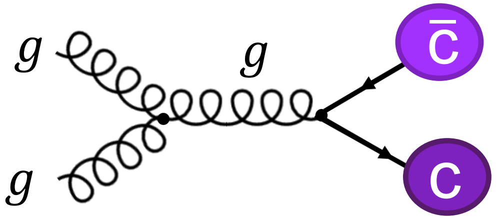

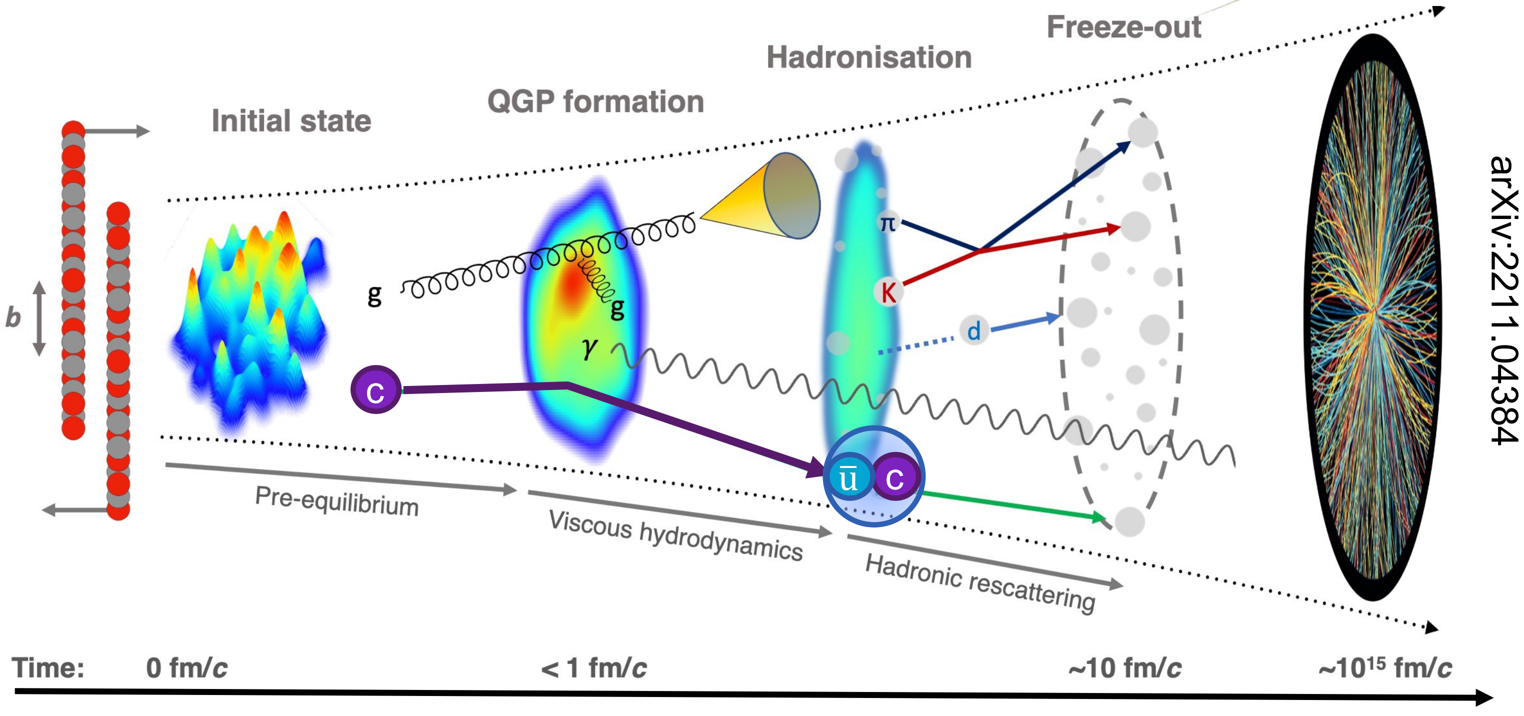

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- **Open heavy-flavor hadrons** (made up of **light** and **heavy** quarks) allow to study the transport coefficient of **QGP**, investigating **charm thermalization**

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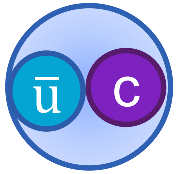

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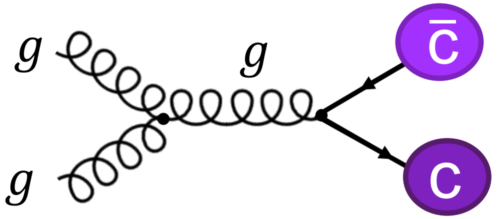

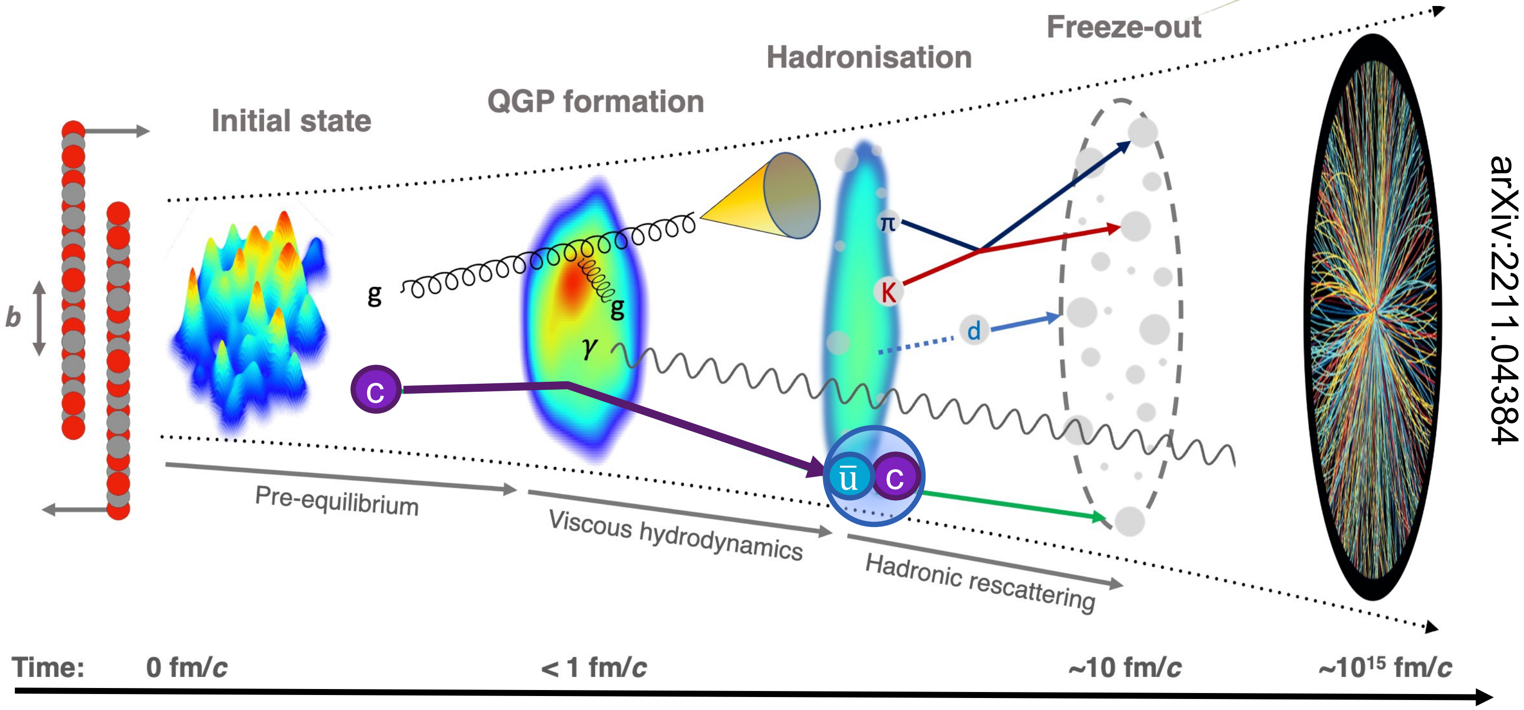

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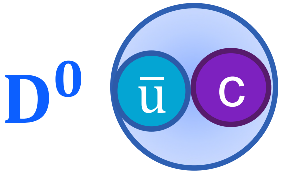

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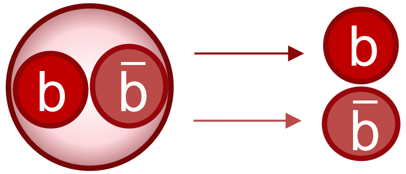

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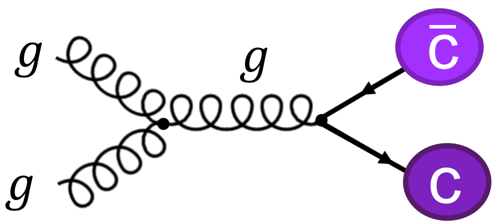

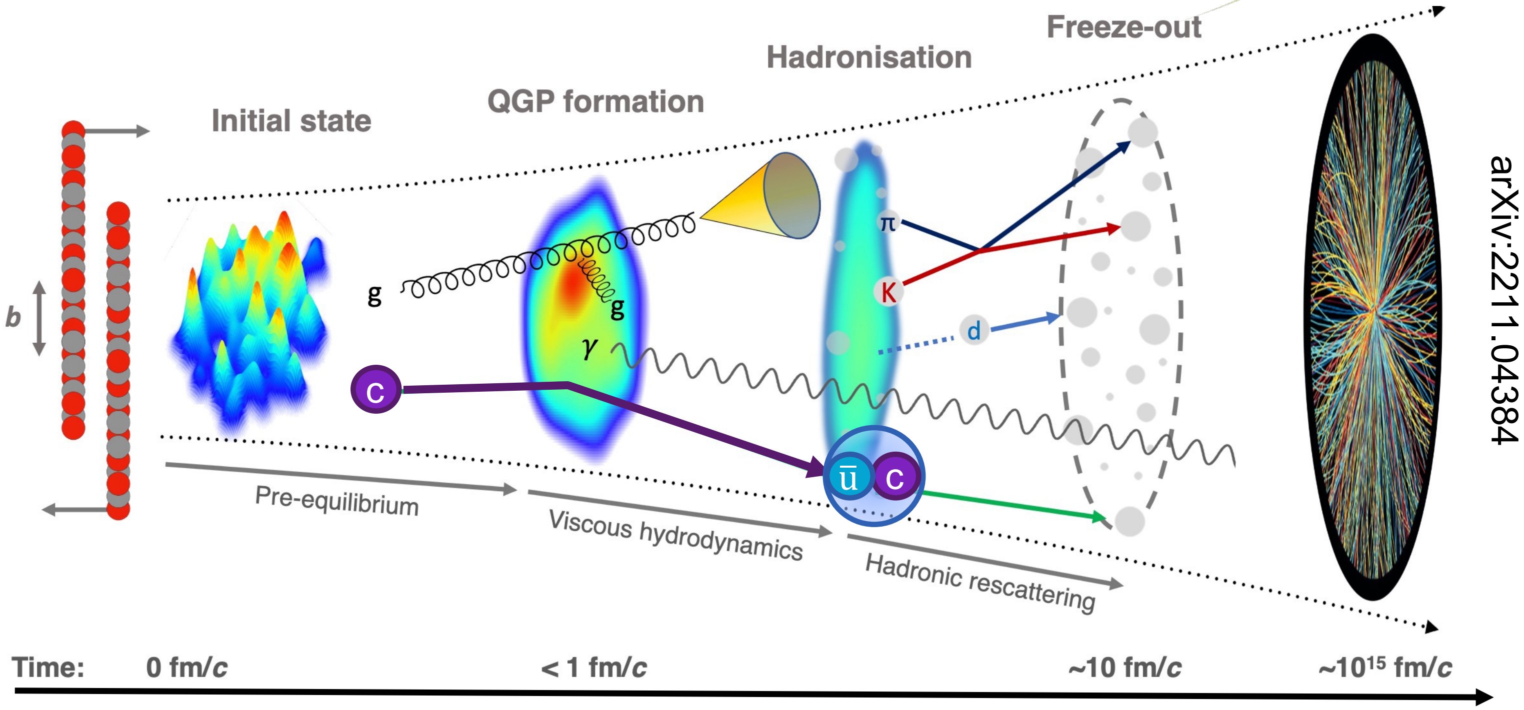

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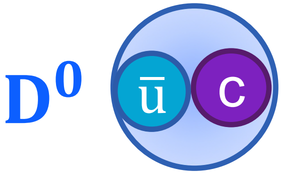

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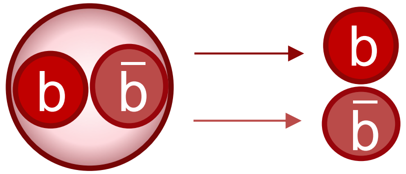
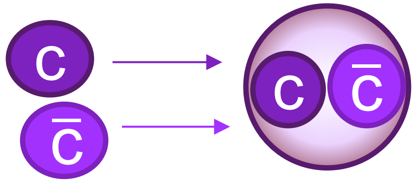
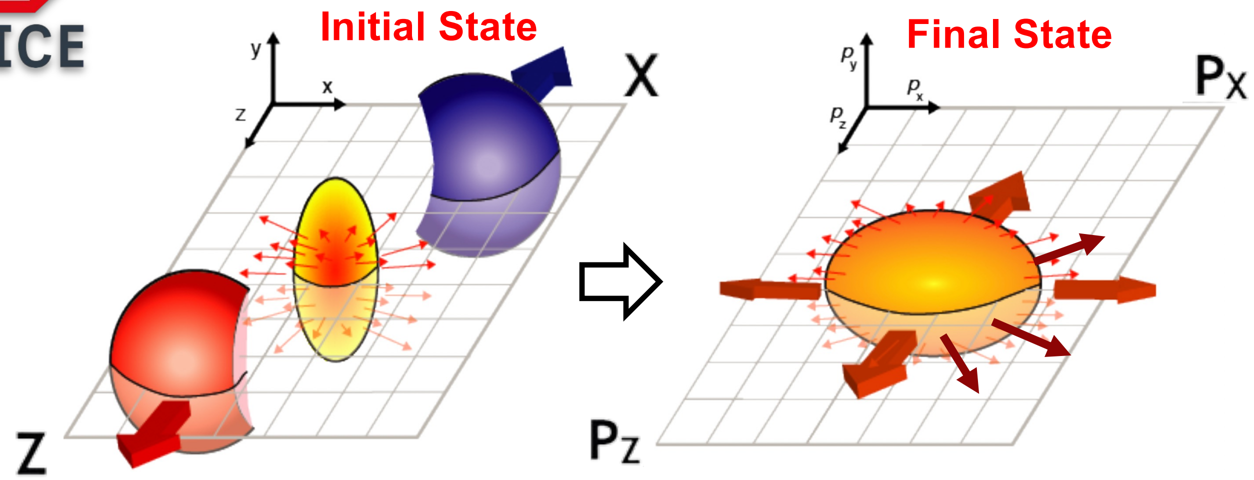


- **Charmonium** state (**c-c̄** quark pairs) **at LHC** can be **produced through recombination** of uncorrelated **c-c̄ pairs** (regeneration)
  → P.Braun-Munzinger and J.Stachel, PLB 490 (2000) 196 → Robert L. Thews et al, PRC 63 (2001) 054905



Collective flow of heavy-flavor/Quarkonia in Pb–Pb



J-Y. Ollitrault, PRD 46 (1992) 229

Anisotropy of particle momentum distribution

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

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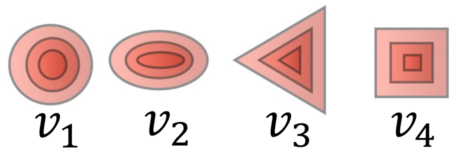

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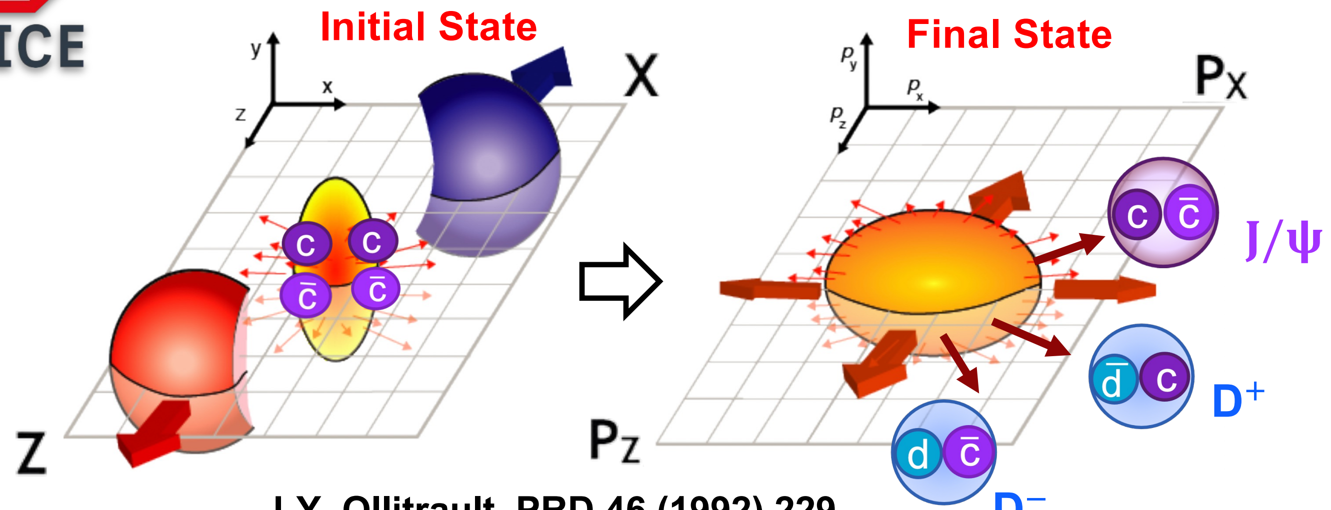

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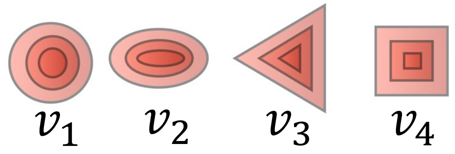

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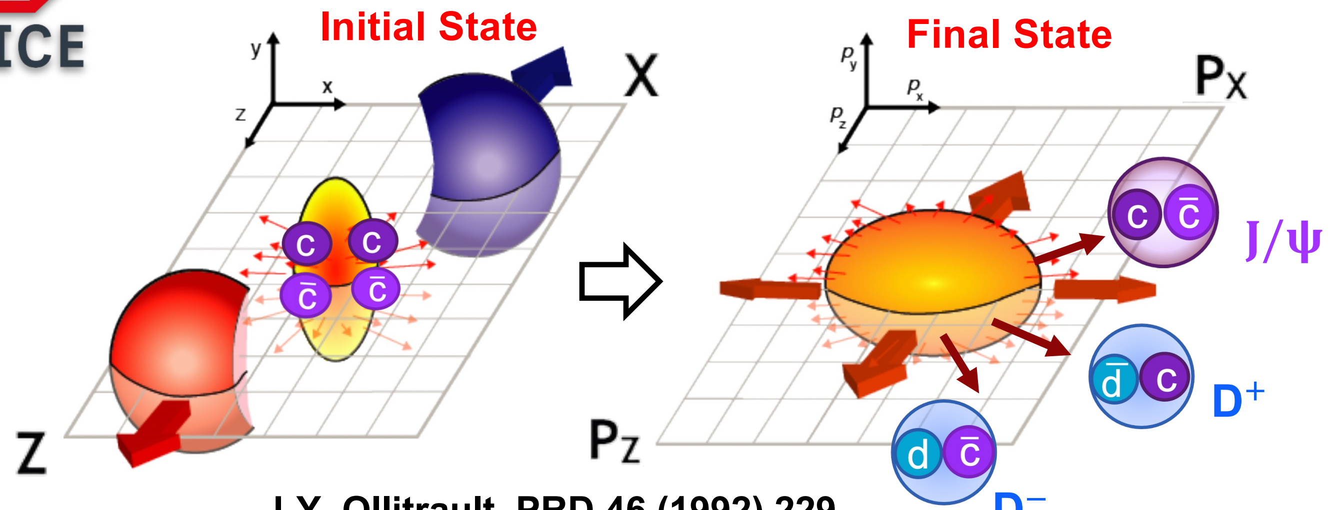

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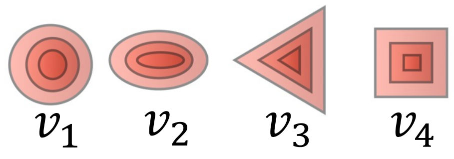

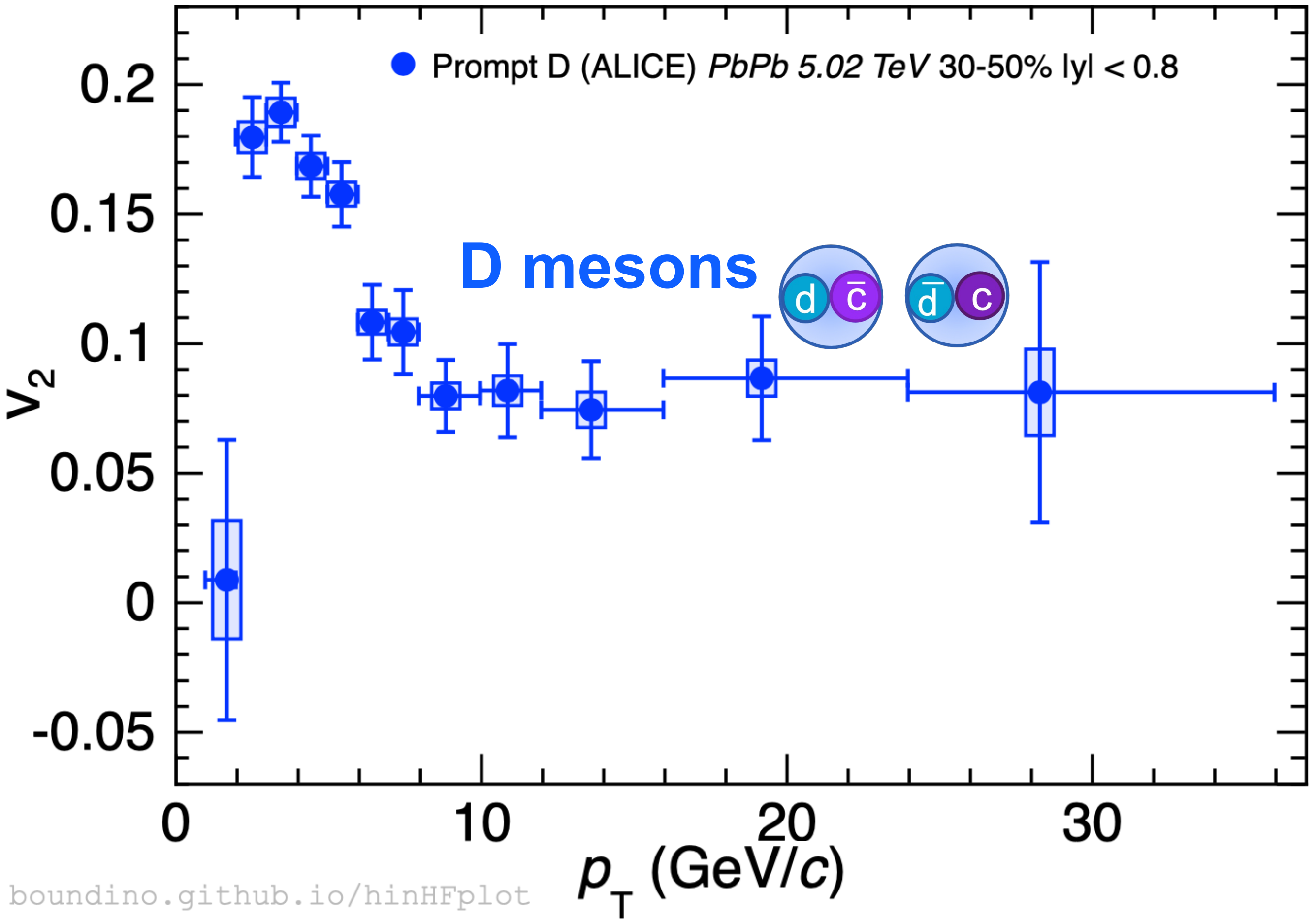

ALICE, PLB 813 (2021) 136054

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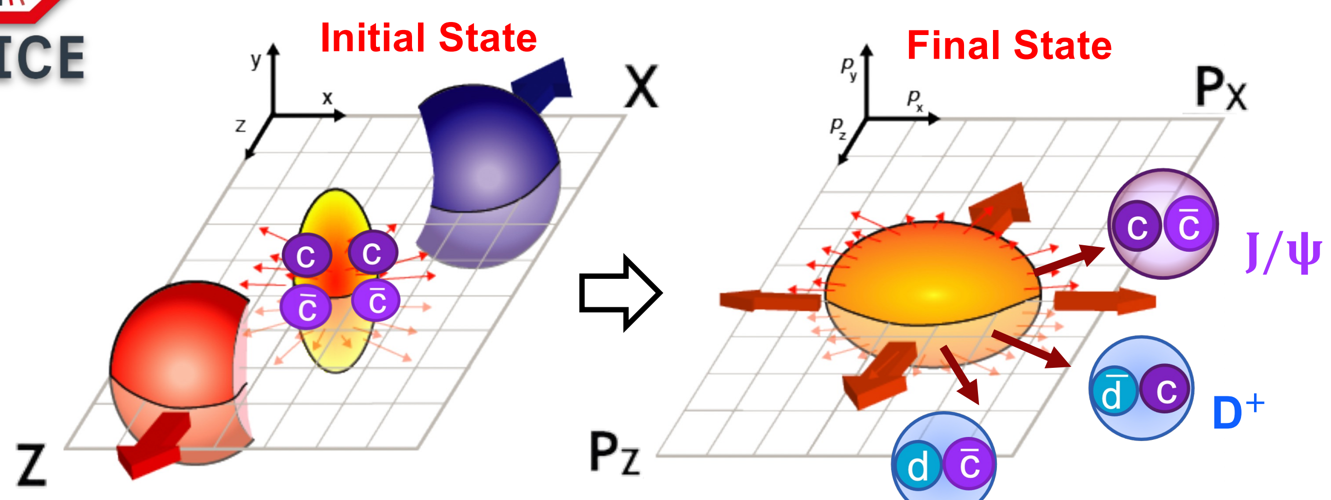

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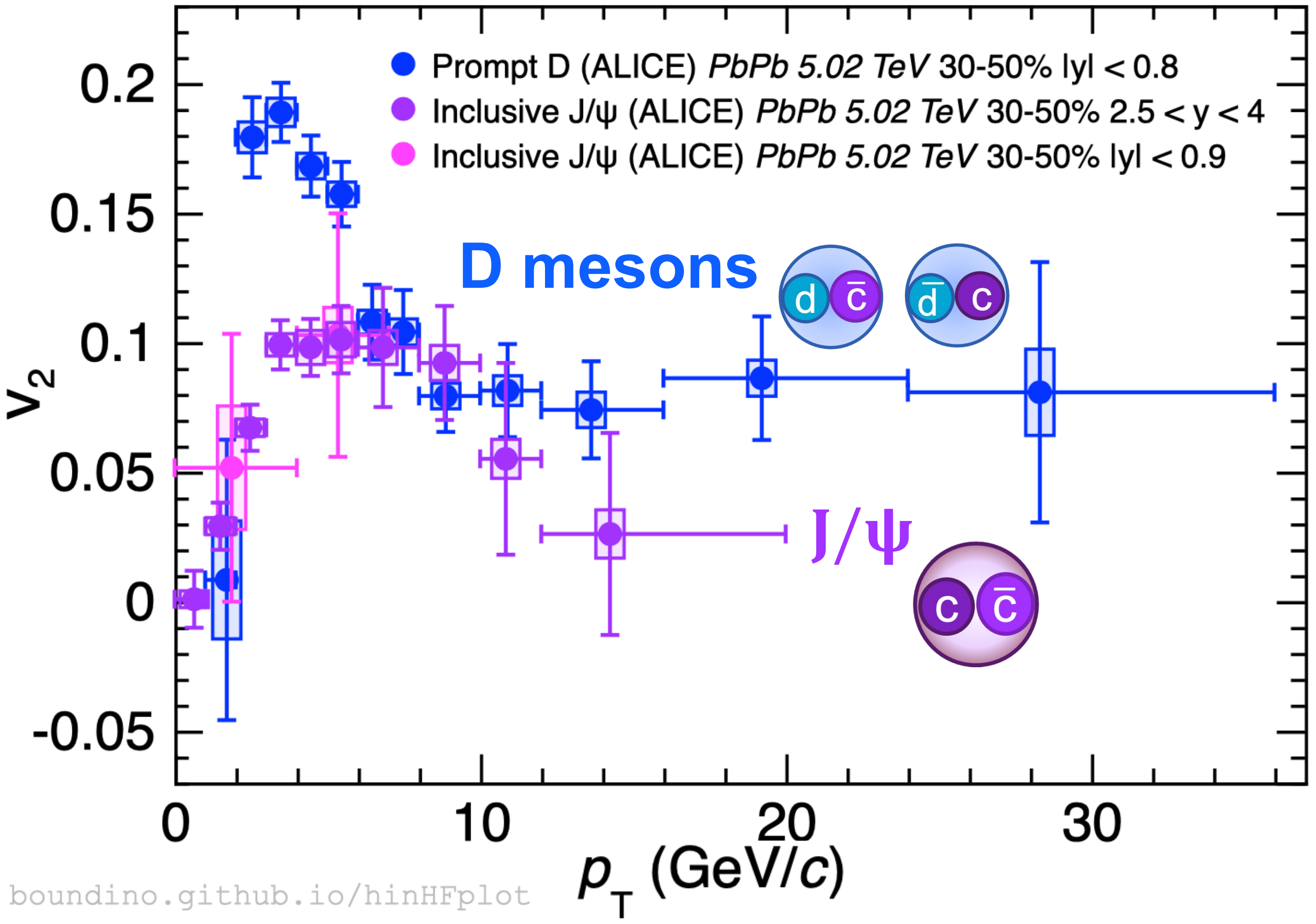
v_1 v_2 v_3 v_4



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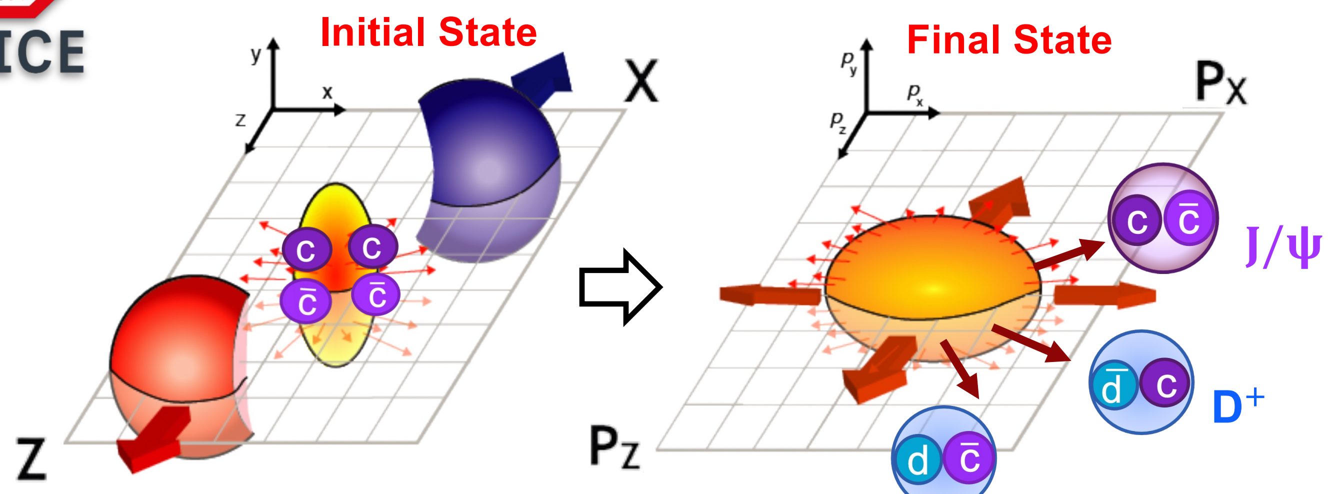

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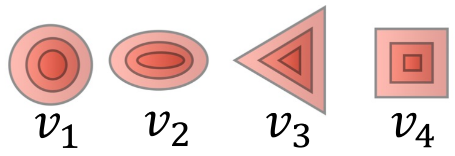

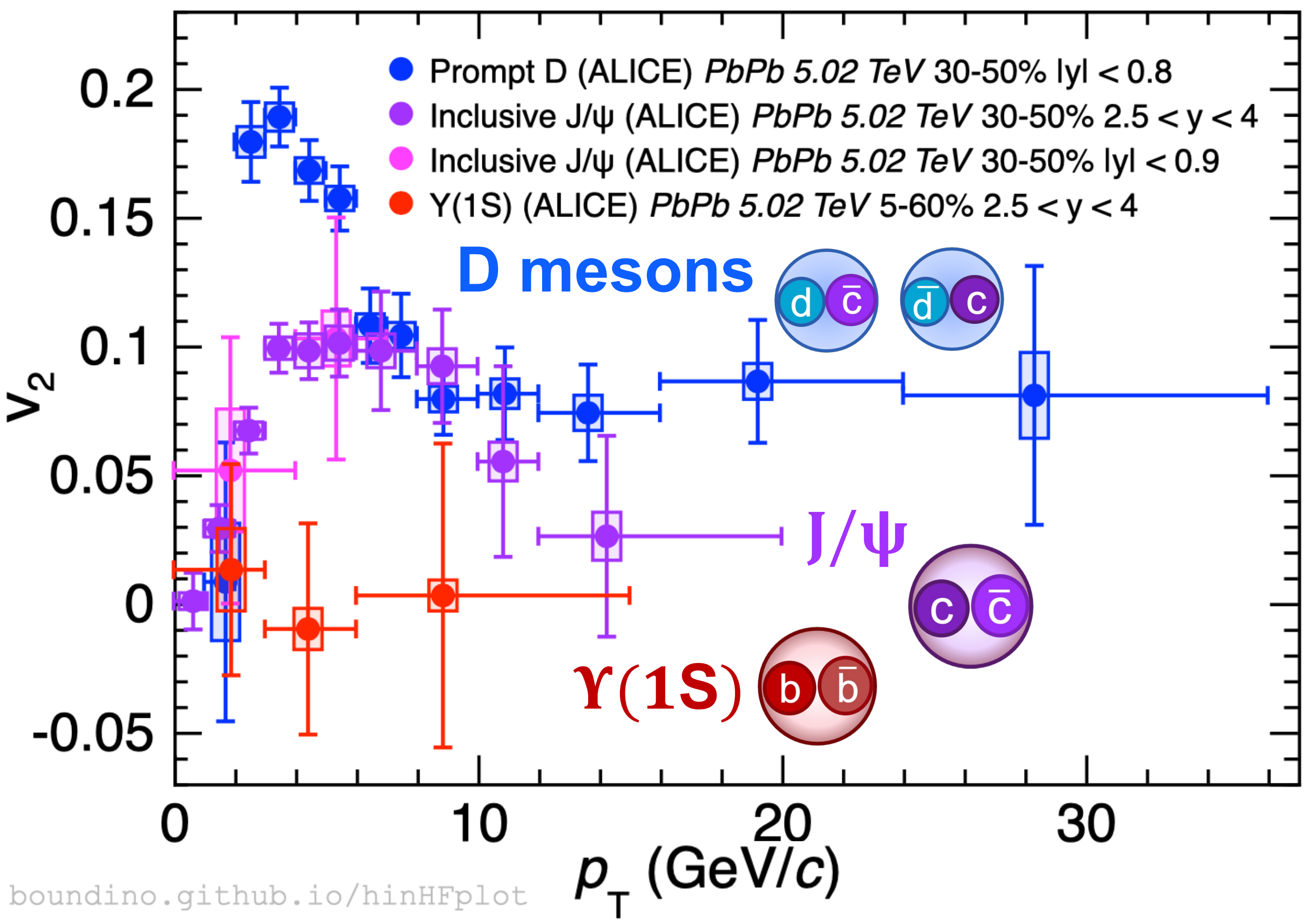

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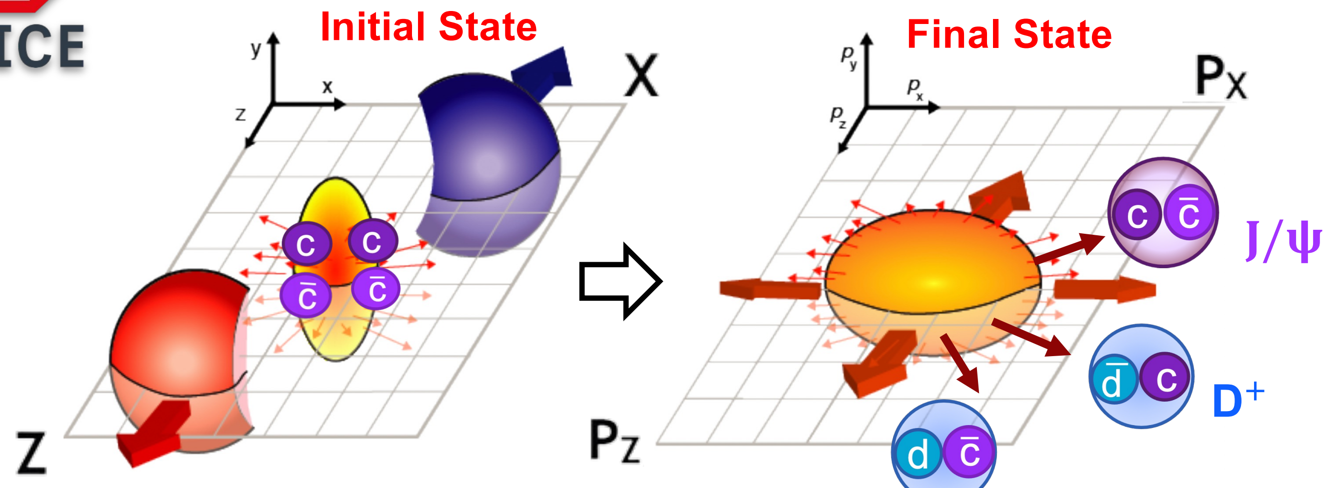

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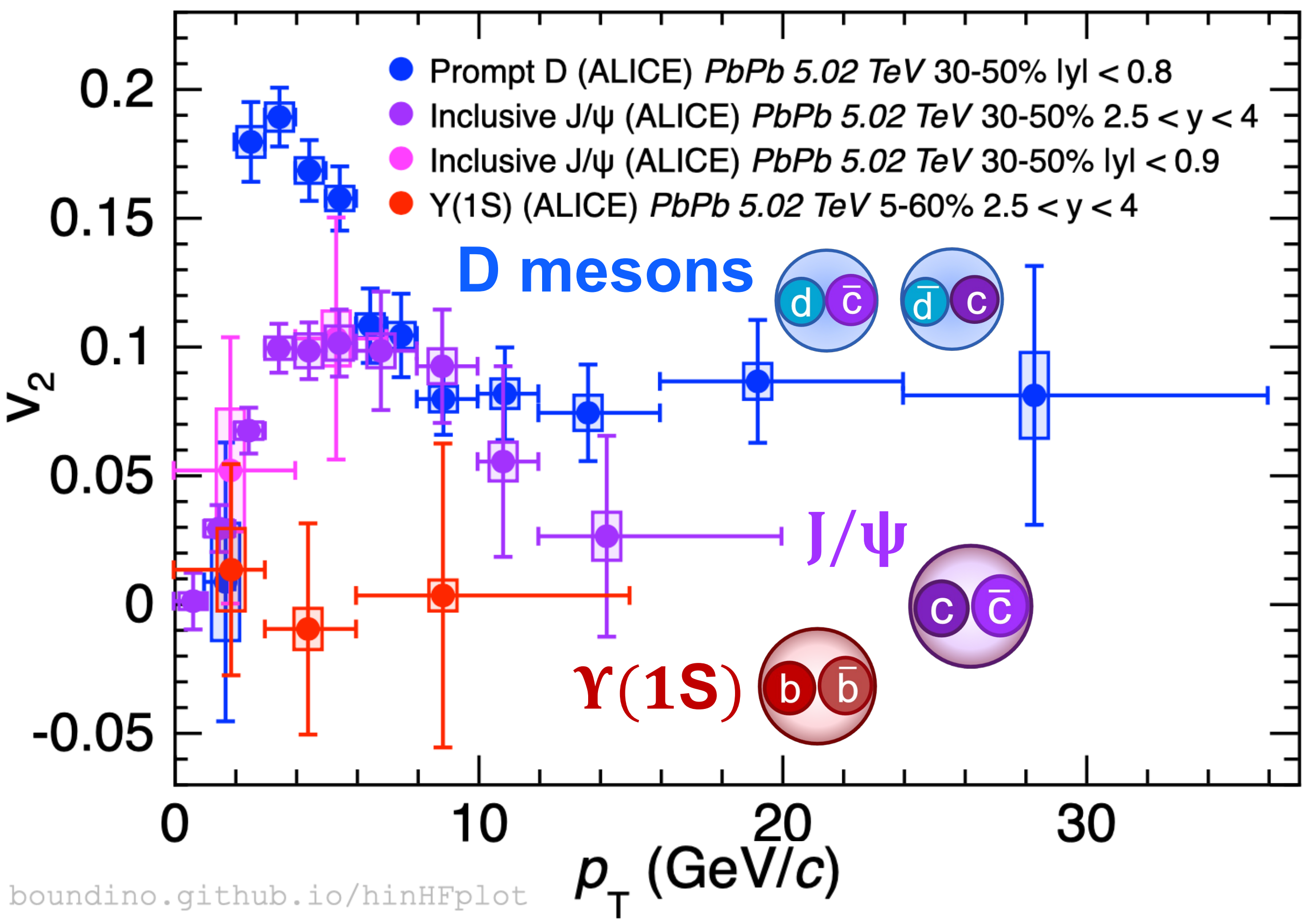
→ $v_2^{\Upsilon(1S)} \ll v_2^{J/\psi} < v_2^{\text{D mesons}}$

→ Charm quarks **exhibit** a **collective behaviour!**

→ **What about smaller systems?**



ALICE, PLB 813 (2021) 136054
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ALICE, PRL 123 (2019) 192301

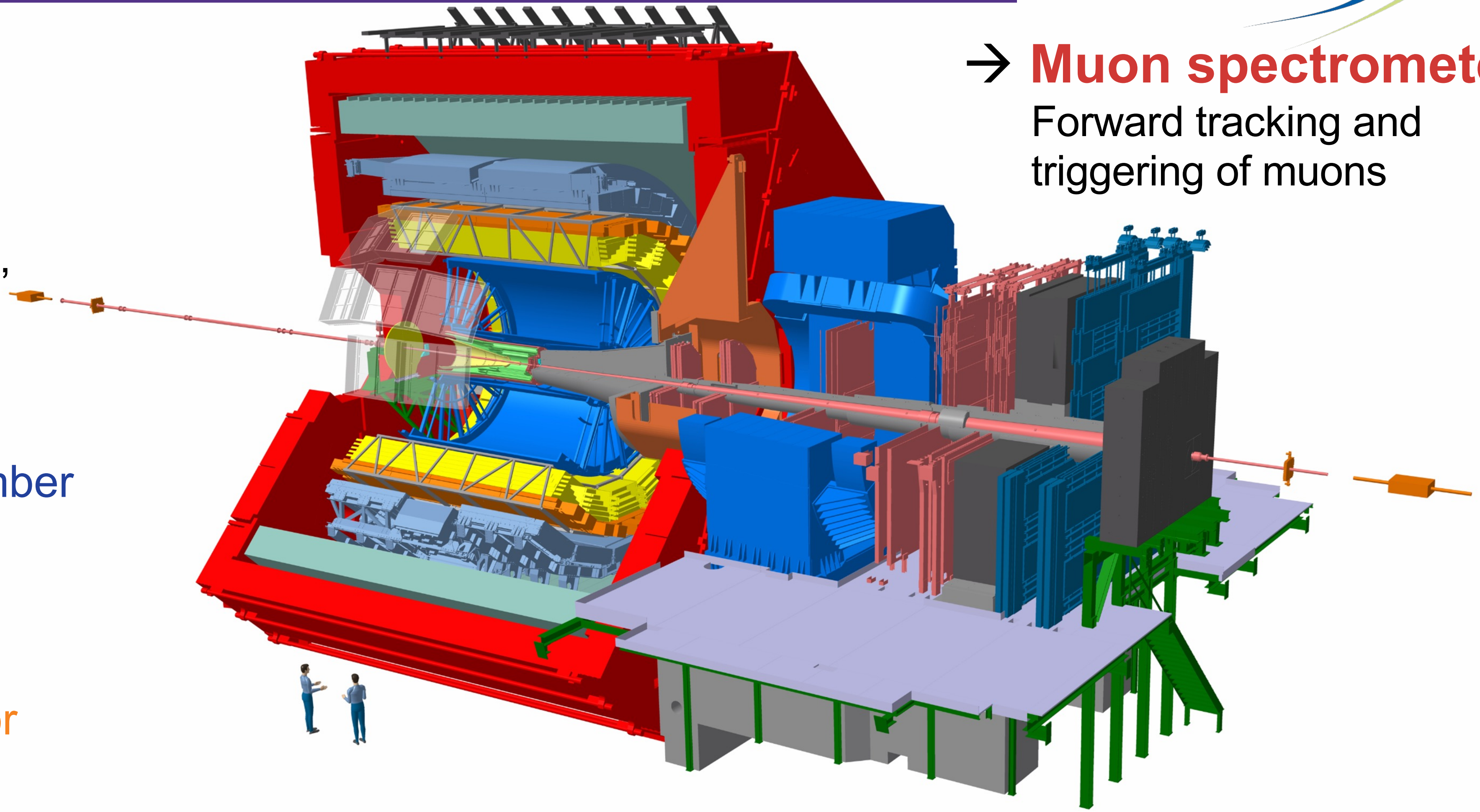
ALICE detector in Run 2

→ Central barrel

- **ITS – Inner Tracking System**
  Tracking, vertex reconstruction, multiplicity estimation

- **TPC – Time Projection Chamber**
  PID, tracking

- **TOF – Time Of Flight detector**
  PID



→ Muon spectrometer

Forward tracking and triggering of muons

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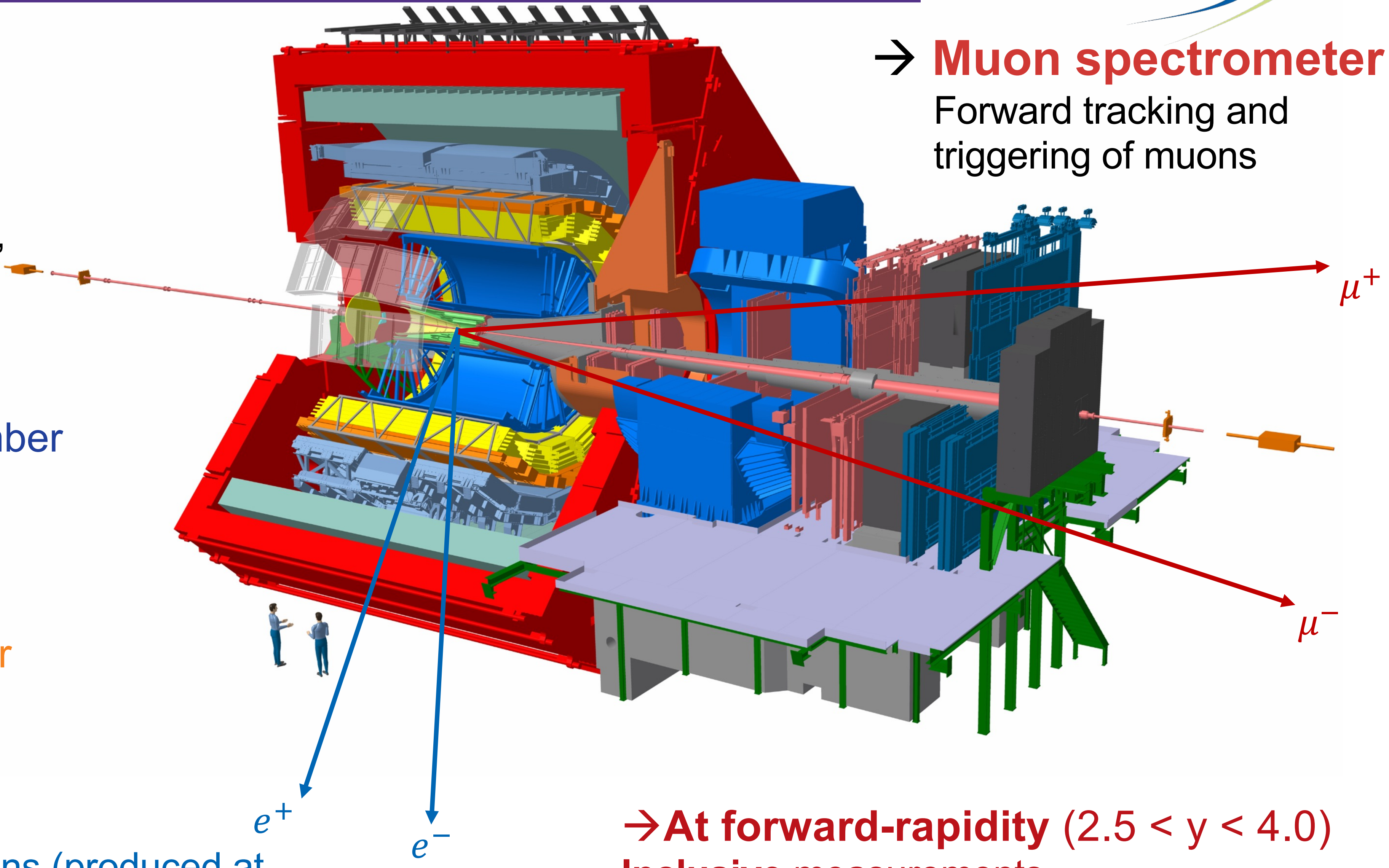


→ Muon spectrometer

Forward tracking and triggering of muons

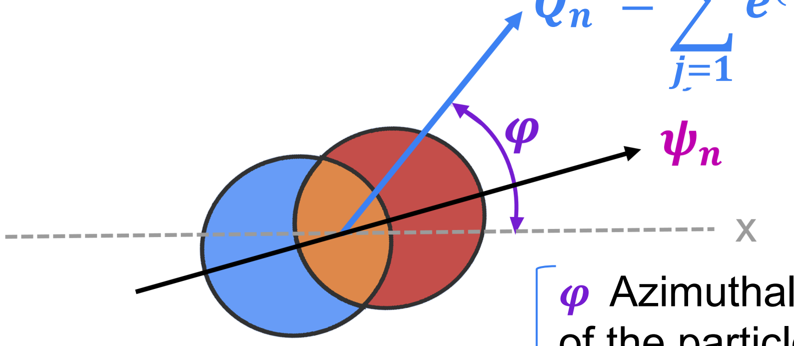
→**At mid-rapidity** (|y| < 0.9)
Distinction between **prompt** hadrons (produced at primary vertex) and **non-prompt** (b-hadron decays)

→**At forward-rapidity** (2.5 < y < 4.0)
Inclusive measurements

→ Inclusive hadrons can be **measured down to p_T = 0** (at midrapidity and forward rapidity)

→ Flow measurements: **analysis techniques**

$$Q_n = \sum_{j=1}^{M_A} e^{(in\varphi_j)}$$



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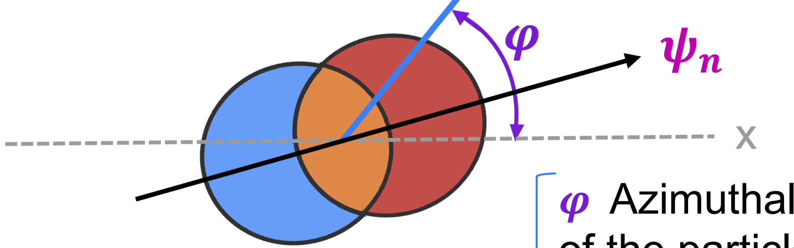

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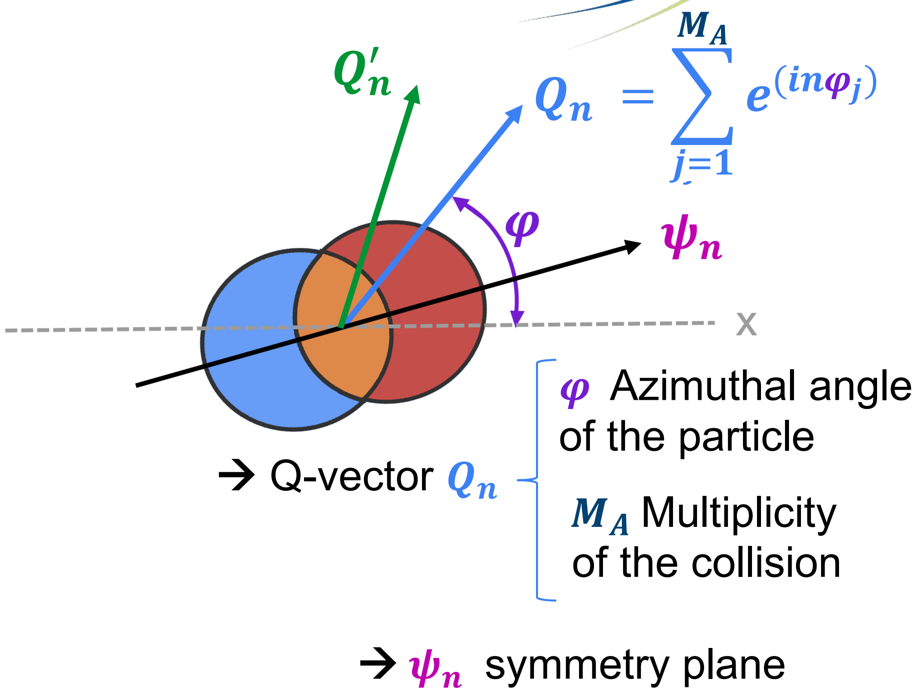

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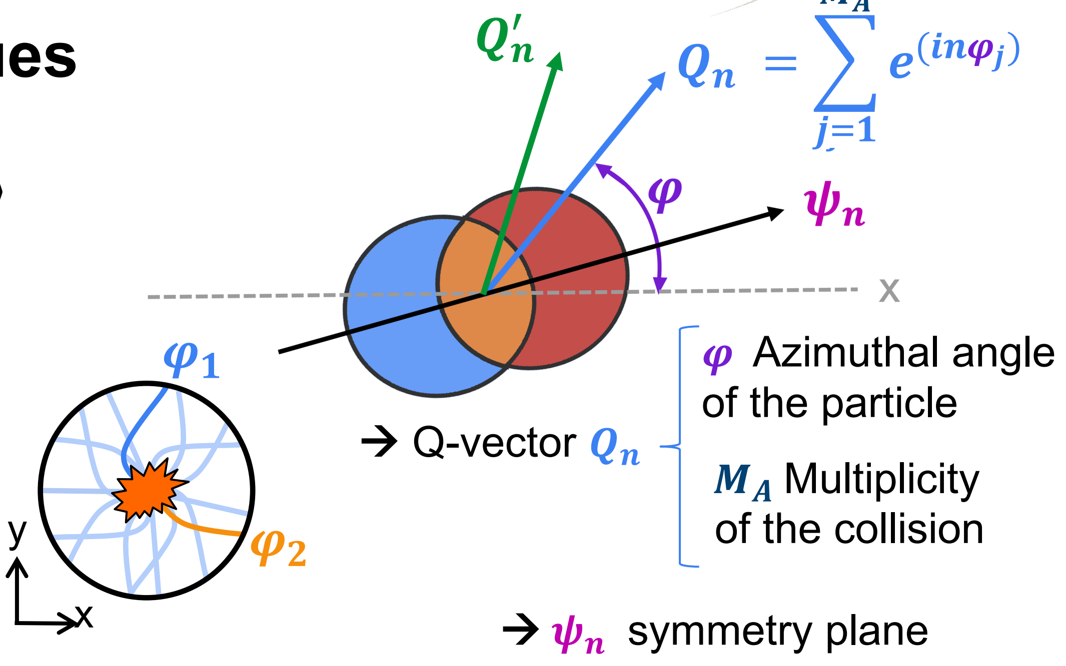

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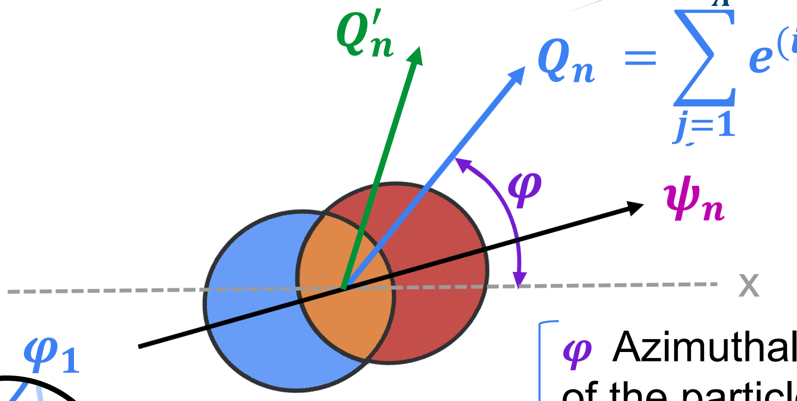

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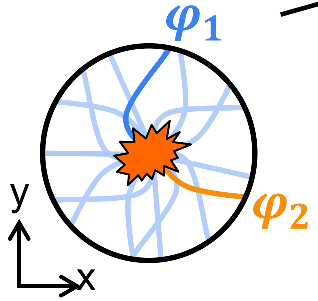

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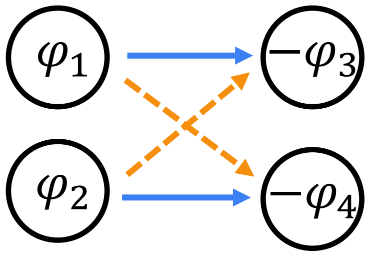

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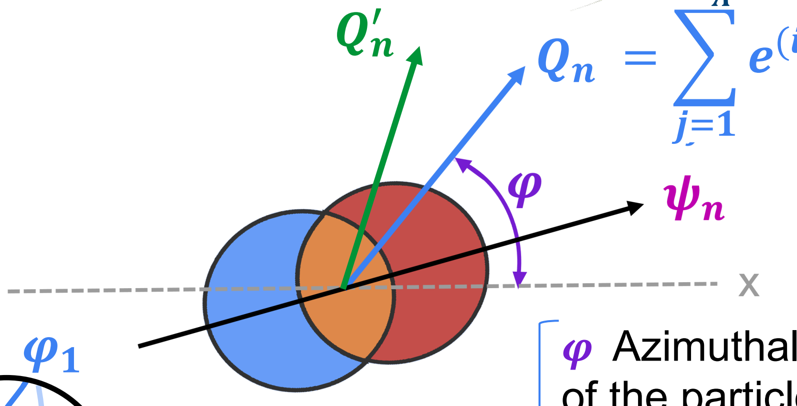

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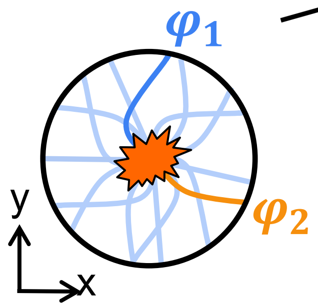

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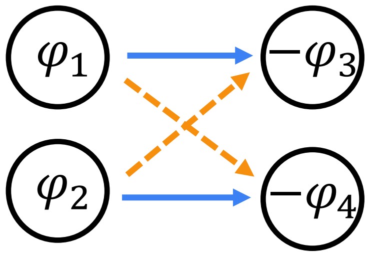
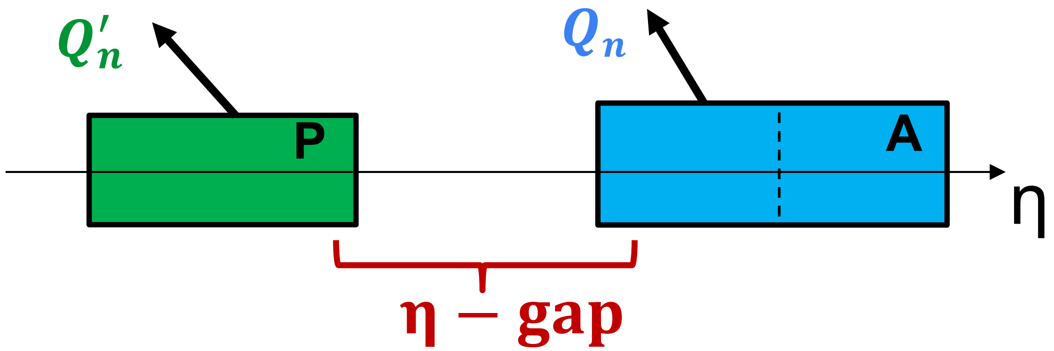


→ **η – gap** between measured particles suppresses **non−flow effects**



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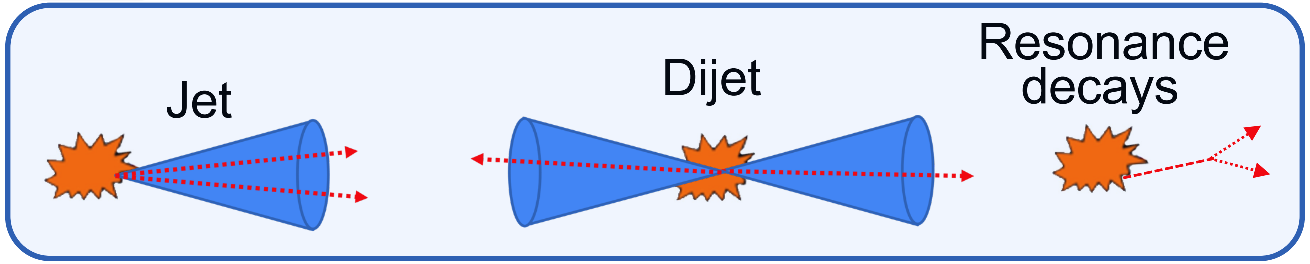
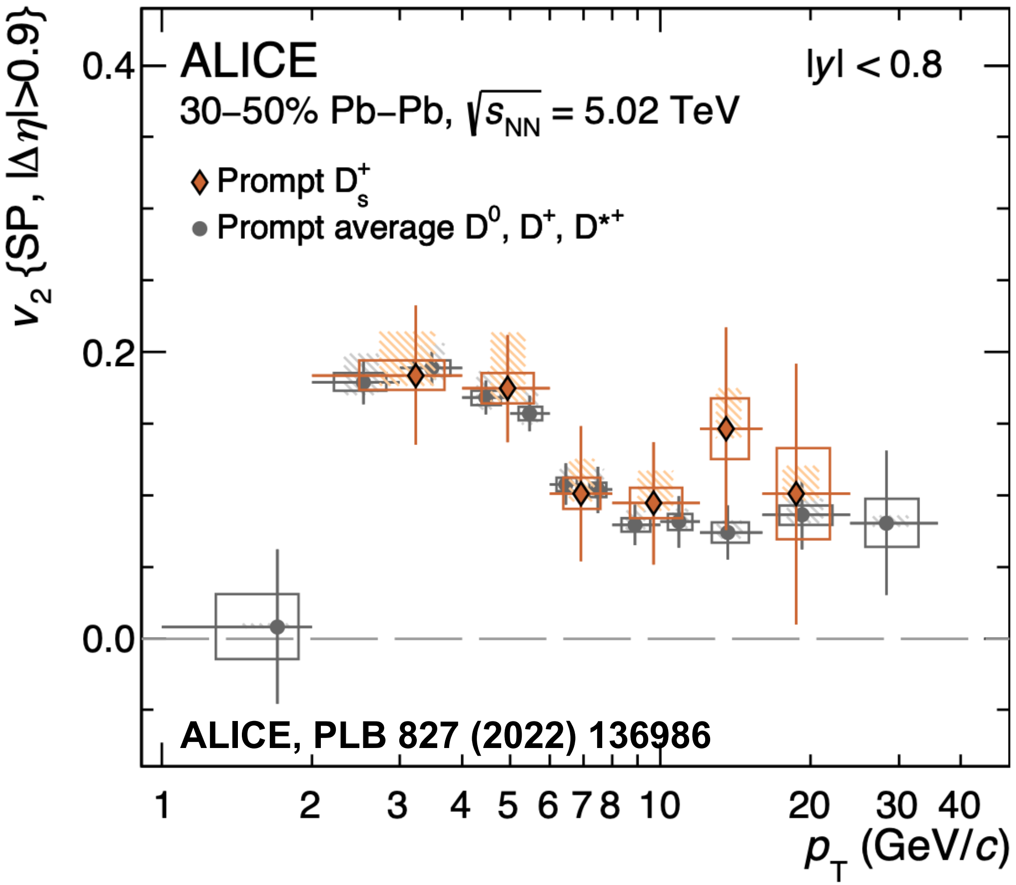


v_2 of *prompt* D_s^+ mesons in **Pb–Pb** collisions

D_s^+ ($\bar{s}$ c) vs D^0 ($\bar{u}$ c) D^+ ($\bar{d}$ c) D^{*+} ($\bar{d}$ c)



→ **D mesons** with different light flavours **(u,d,s)** exhibit **similar flow**

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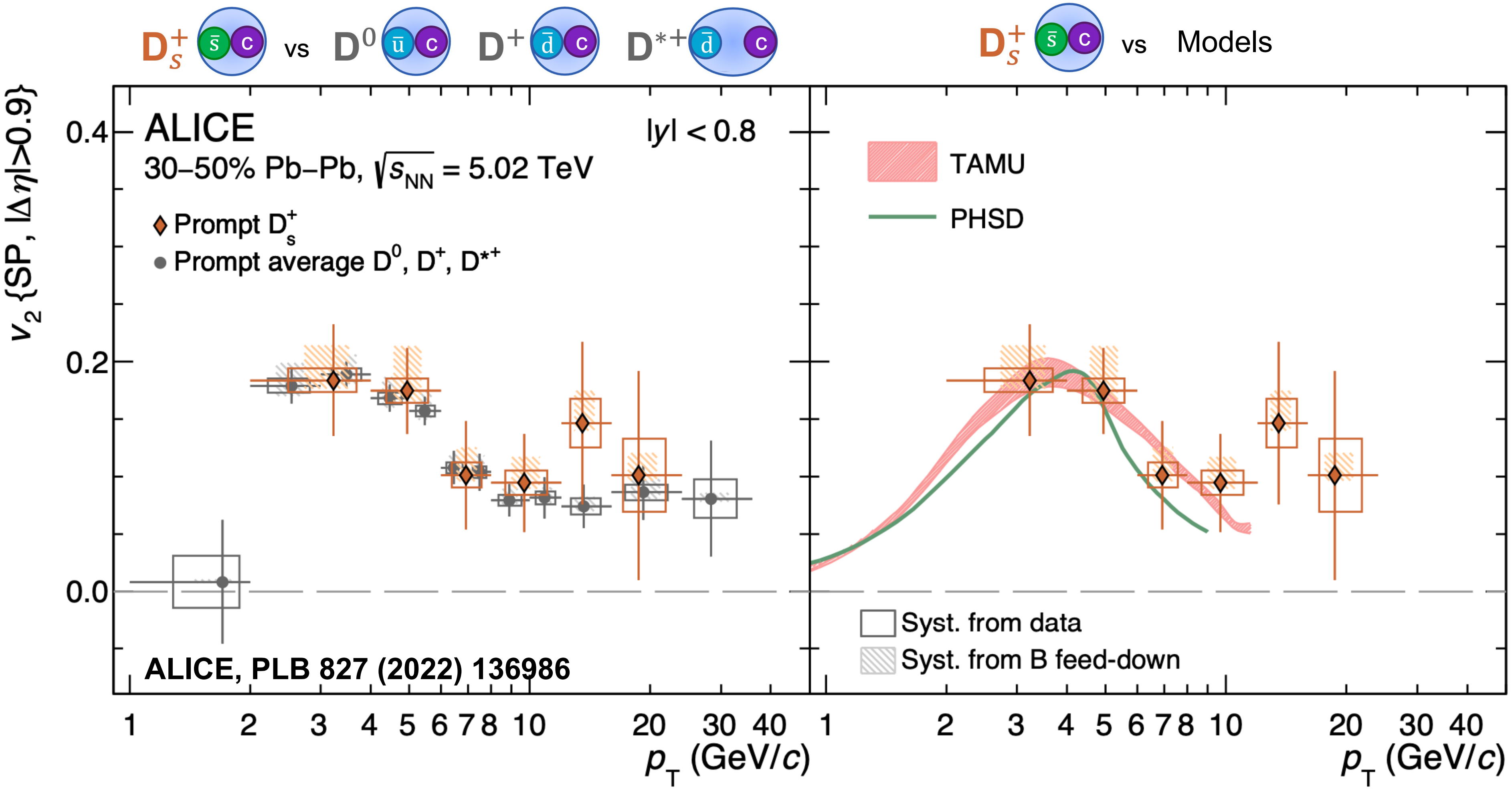

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→ Theoretical **calculations** are based on the **charm−quark transport** in a **hydrodynamically** expanding **QGP**

Transport model TAMU
Min He and Ralf Rapp, **PRL 124 (2020) 042301**

Parton-hadron-string dynamics (PHSD)
Taesoo Song et al, **PRC 92 (2015) 014910**

→ Possibility to **probe hadronization via coalescence**

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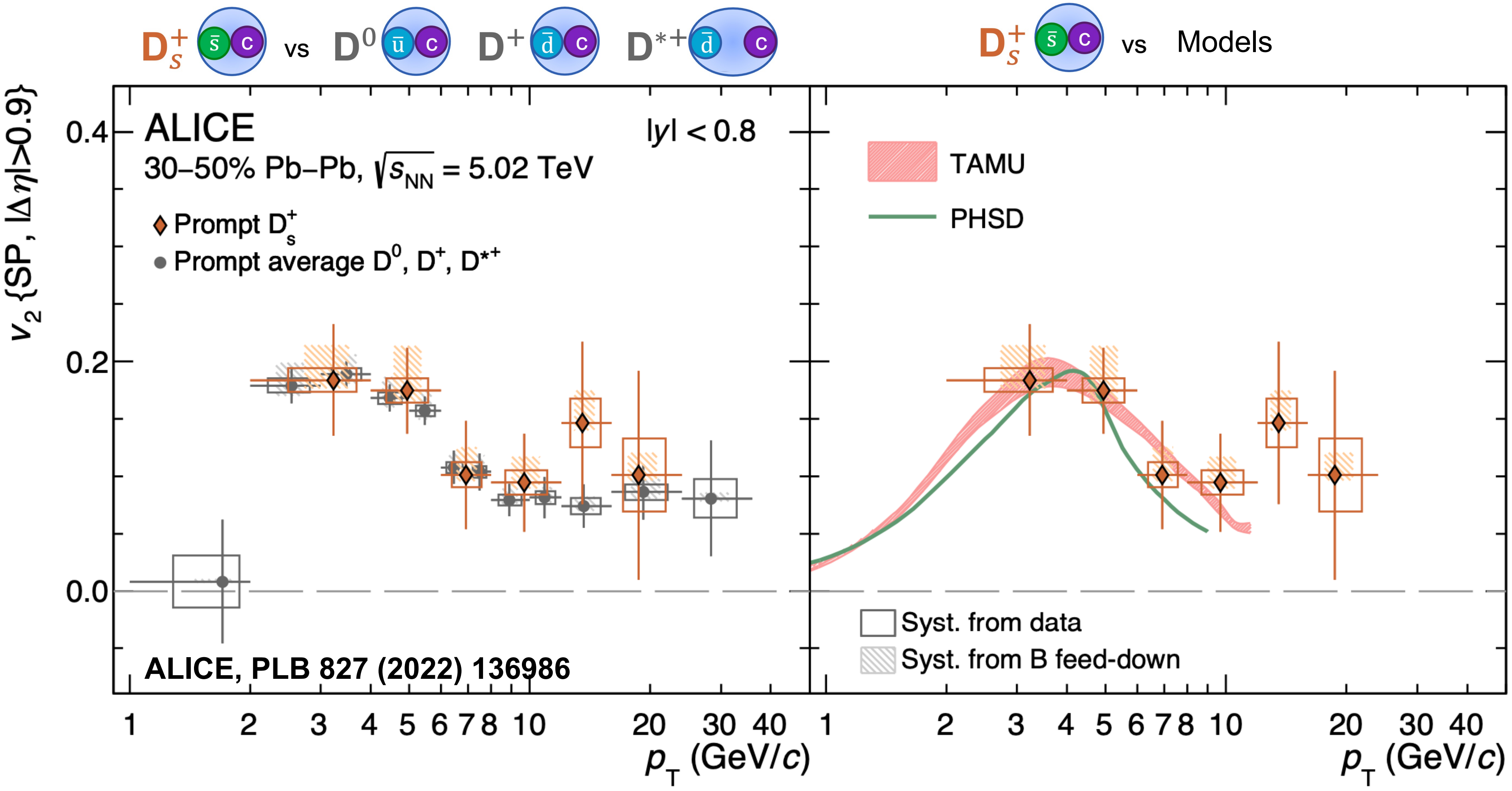

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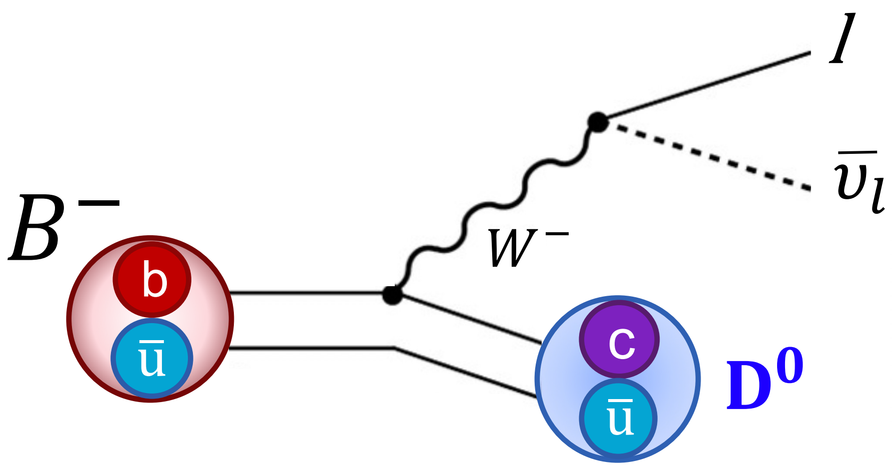
Amanda Flores – talk
20 Jul 2024, 14:47
Characterisation of heavy-quark propagation and thermalisation in QGP with ALICE

v_2 of *non−prompt* $\mathbf{D^0}$ mesons in **Pb–Pb** collisions



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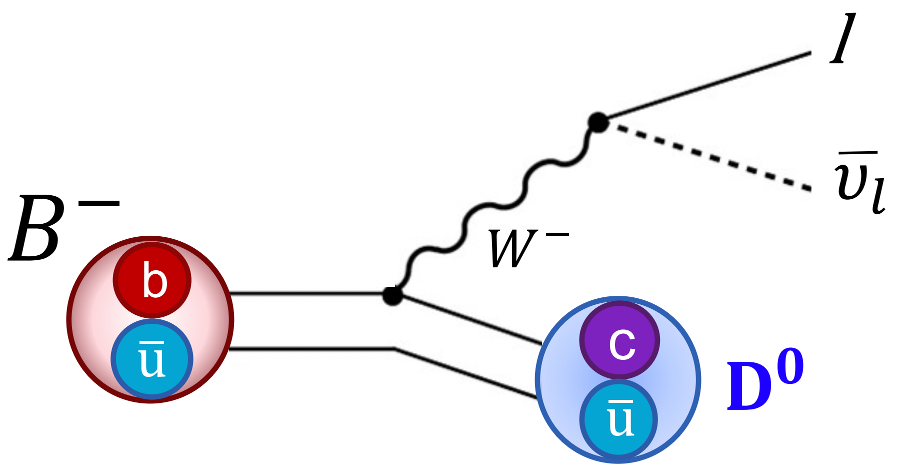
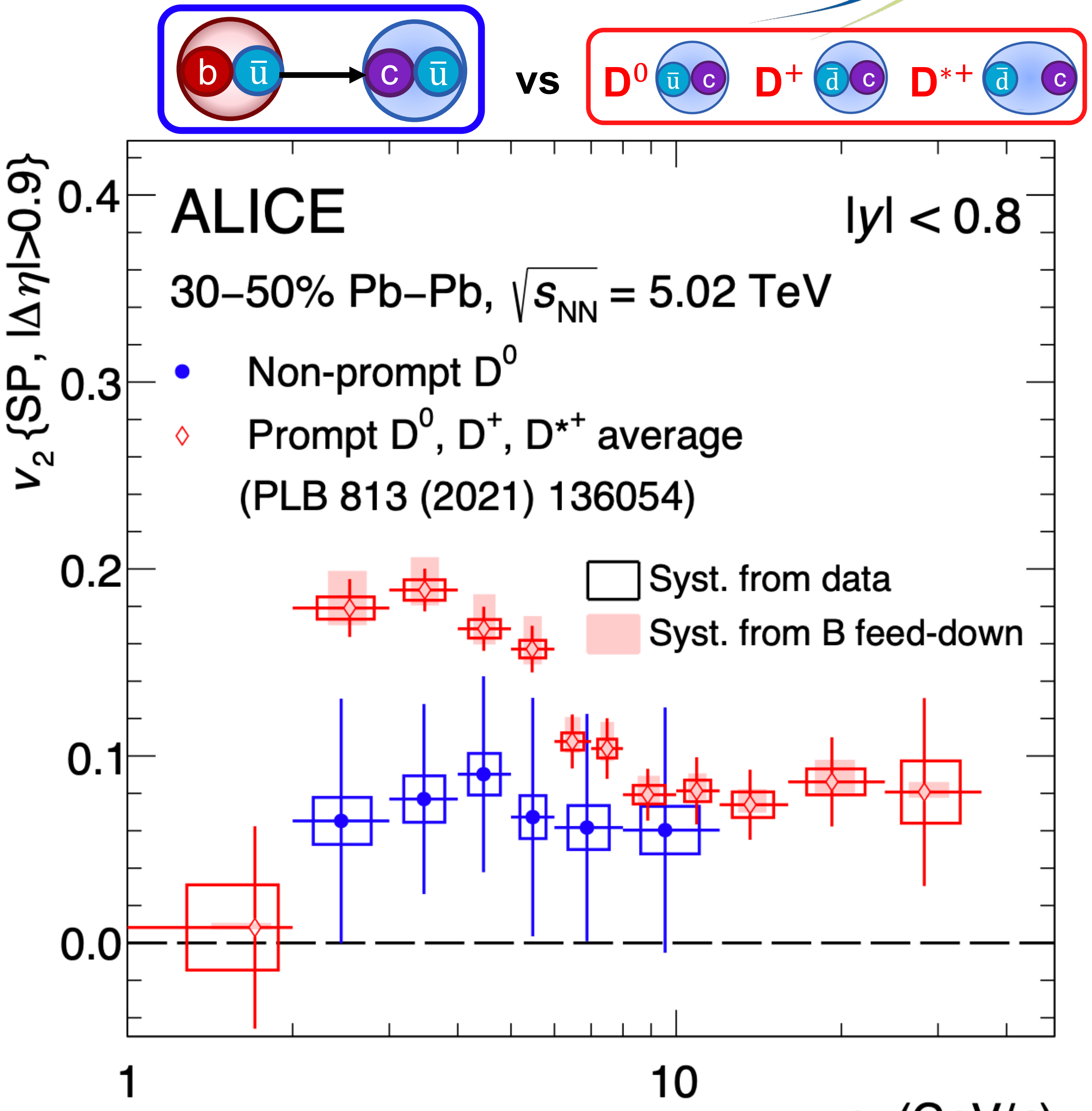


- → The **non-prompt $\mathbf{D^0}$-meson** v_2 is found to be **positive** with a significance of 2.7σ
- → **Non-prompt $\mathbf{D^0}$** is **lower** by 3.2σ **than prompt D-meson** v_2 in the range $2 < p_T < 8$ GeV/c



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

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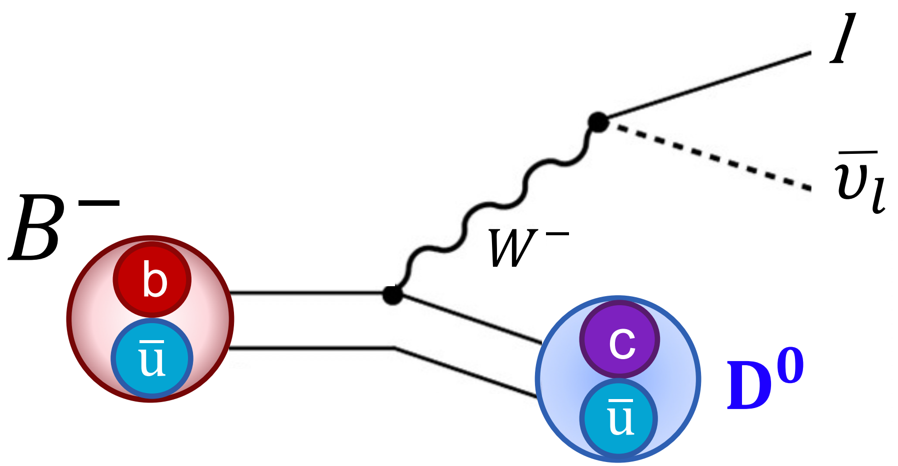

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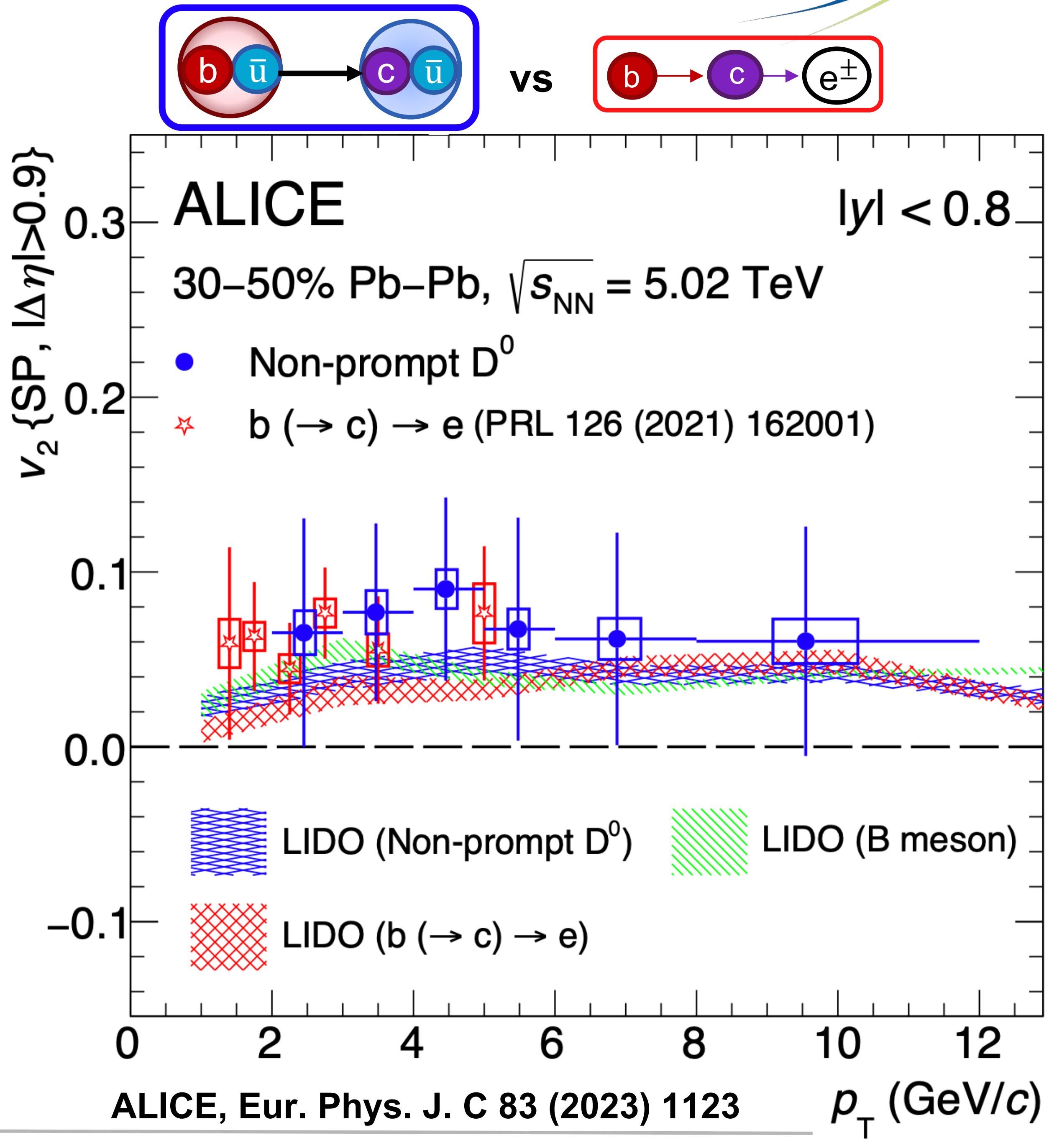
→ **Hybrid transport model LIDO** reproduces the data (Linearized Boltzmann with diffusion)
Weiyao Ke et al, **PRC 98 (2018) 064901**
Weiyao Ke et al, **PRC 100 (2019) 064911**

→ **Decay kinematics doesn't seem to play** a significant role in the **beauty-hadron** v_2 measurements.



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

Inclusive muon v_2 from hadron decays in **p–Pb**

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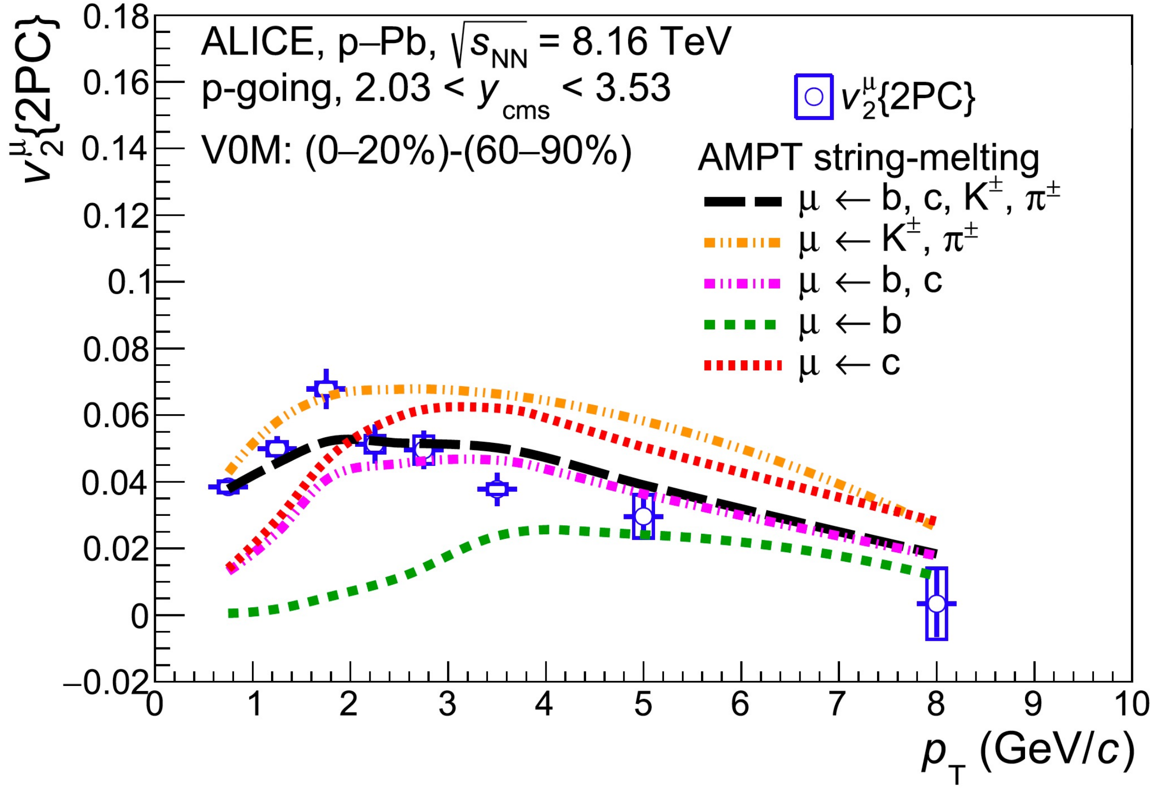
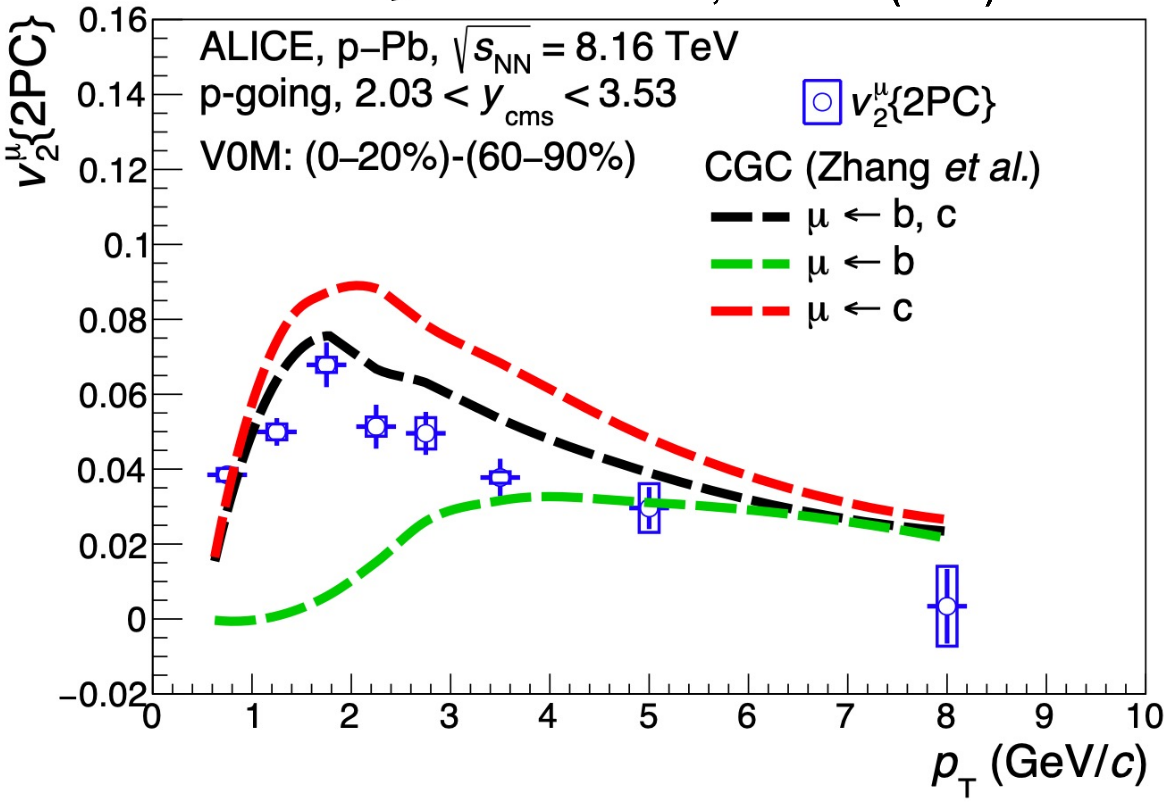
Forward-rapidity (p-going)

ALICE, PLB 846 (2023) 137782





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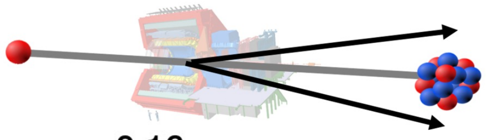

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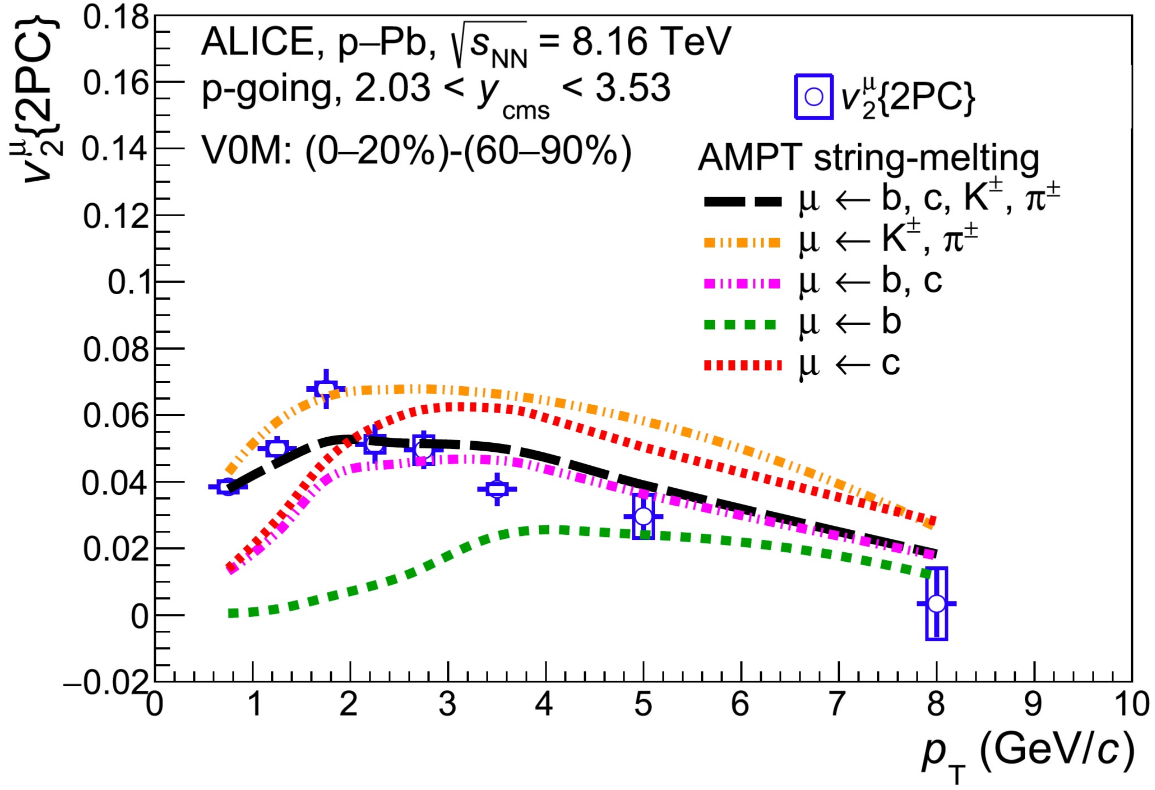
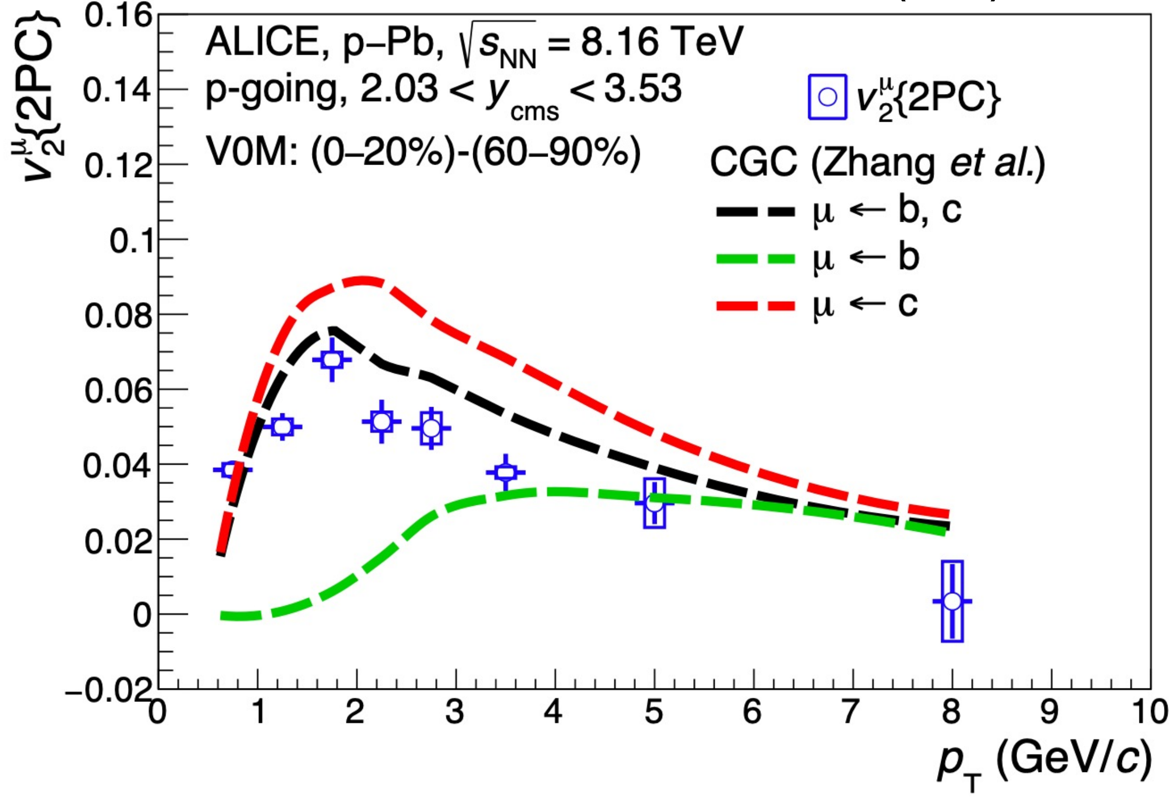
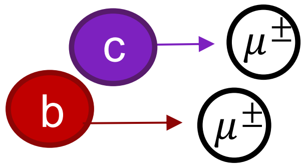




- **Positive muon v_2** measured **for the first time** over a wide p_T interval with a significance of 4.7σ **for 2 < p_T < 6** GeV/c
- **HF-μ dominate** for **p_T > 2** GeV/c



→ **Heavy quarks flow** (at mid and high p_T) in **p–Pb collisions!**

→**AMPT (A Multi−Phase Transport model)**
Z. W. Lin, PRC 72 (2005) 064901

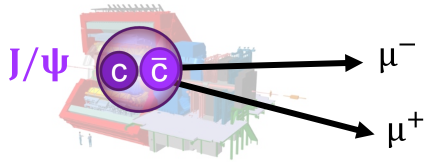
→**CGC (Color Glass Condensate model)**
Cheng Zhang et al, PRC 122 (2019) 172302

Models reproduce the **data** qualitatively

Flow of J/ψ from large to small systems

- Collective behavior in **Pb–Pb collisions**

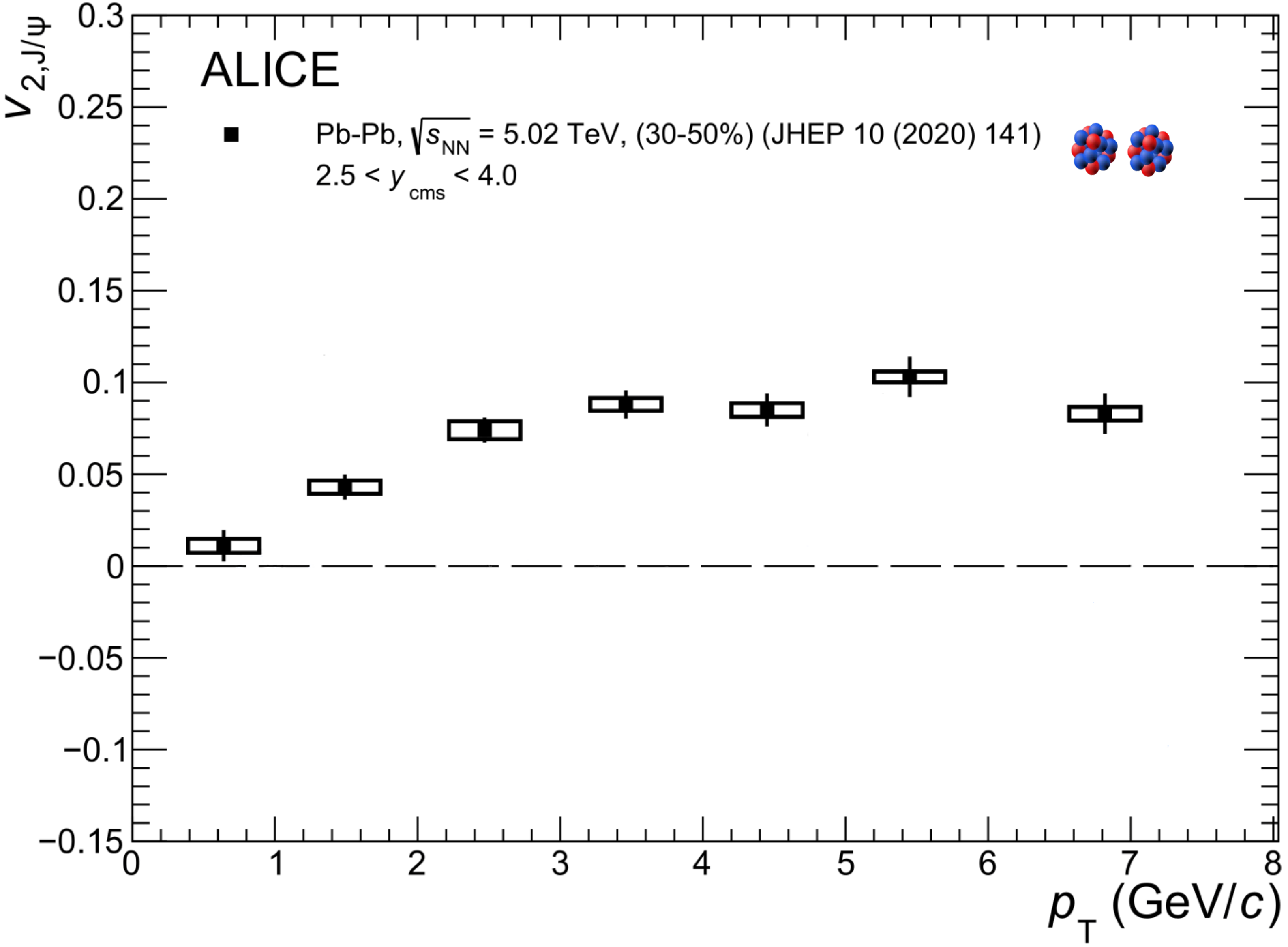
Flow of J/ψ from large to small systems



- Collective behavior in **Pb–Pb collisions**
  - **Significant J/ψ v_2** over a wide p_T range

→ **J/ψ flow** at **low p_T interpreted as** a consequence of **regeneration**

→ Result support **thermalization of charm quarks** in the **QGP**



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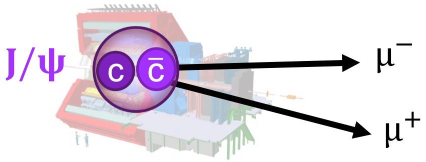

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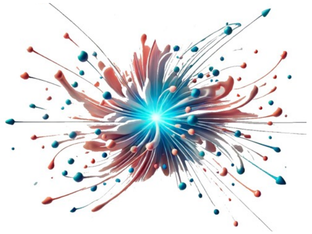

→ **Initial** state **dynamics effects**?

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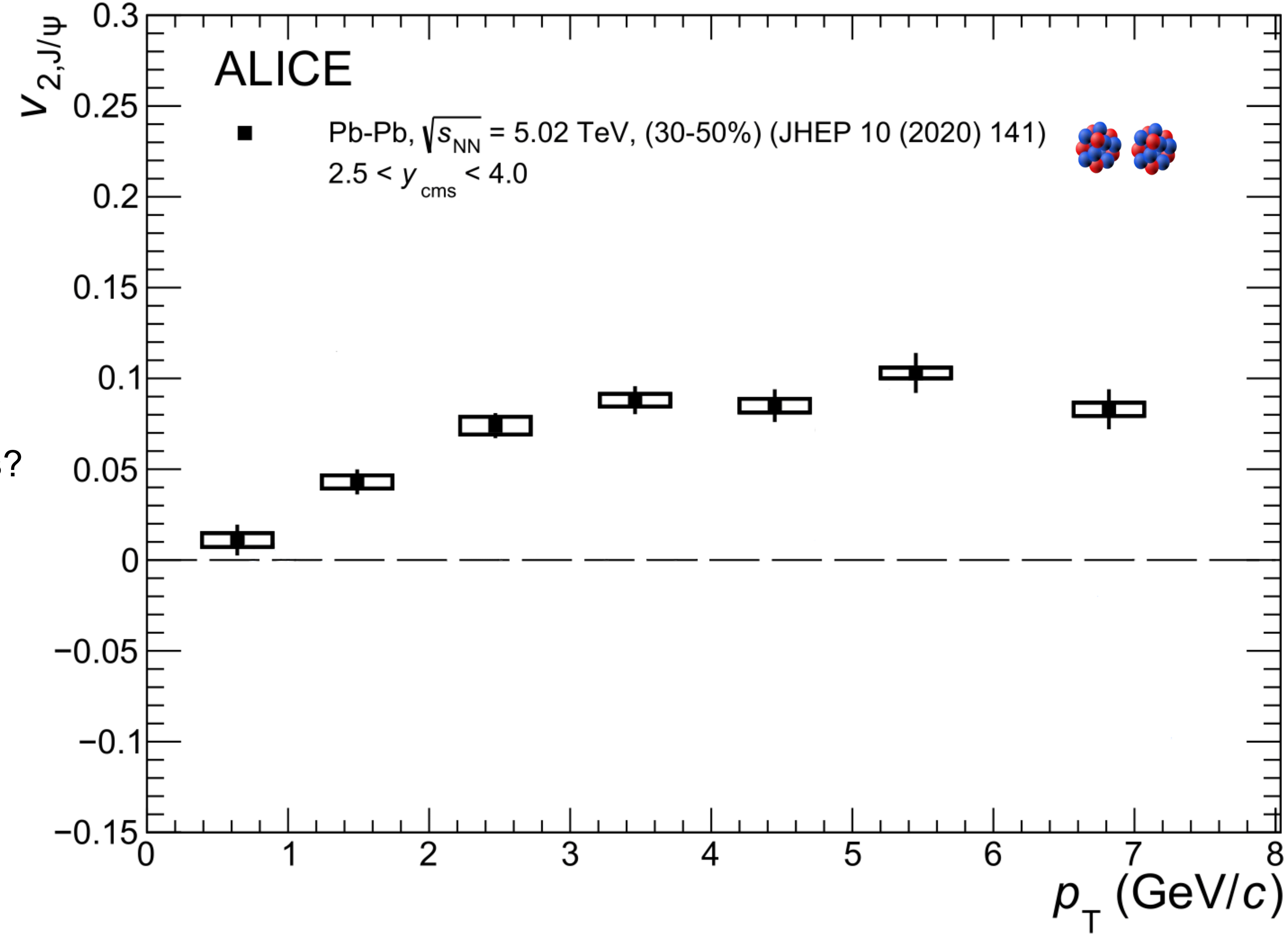

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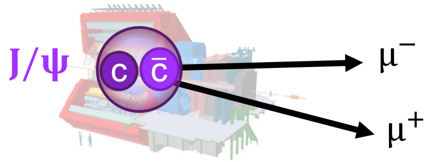

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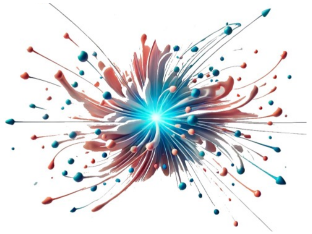

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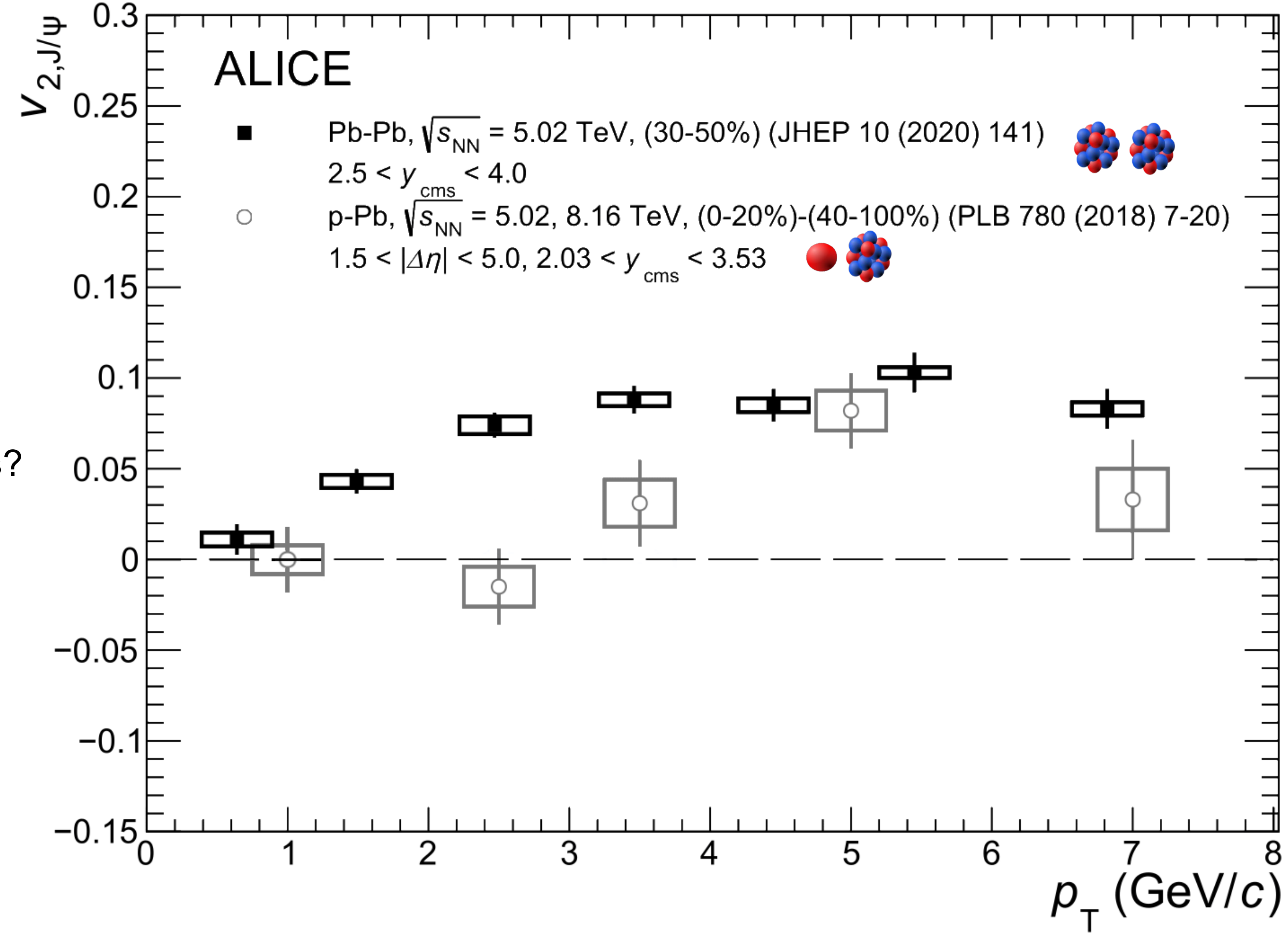

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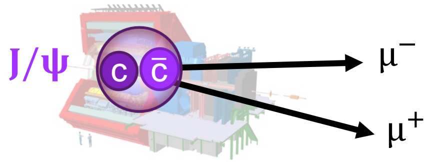

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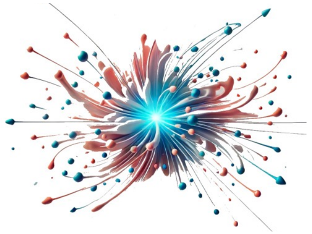

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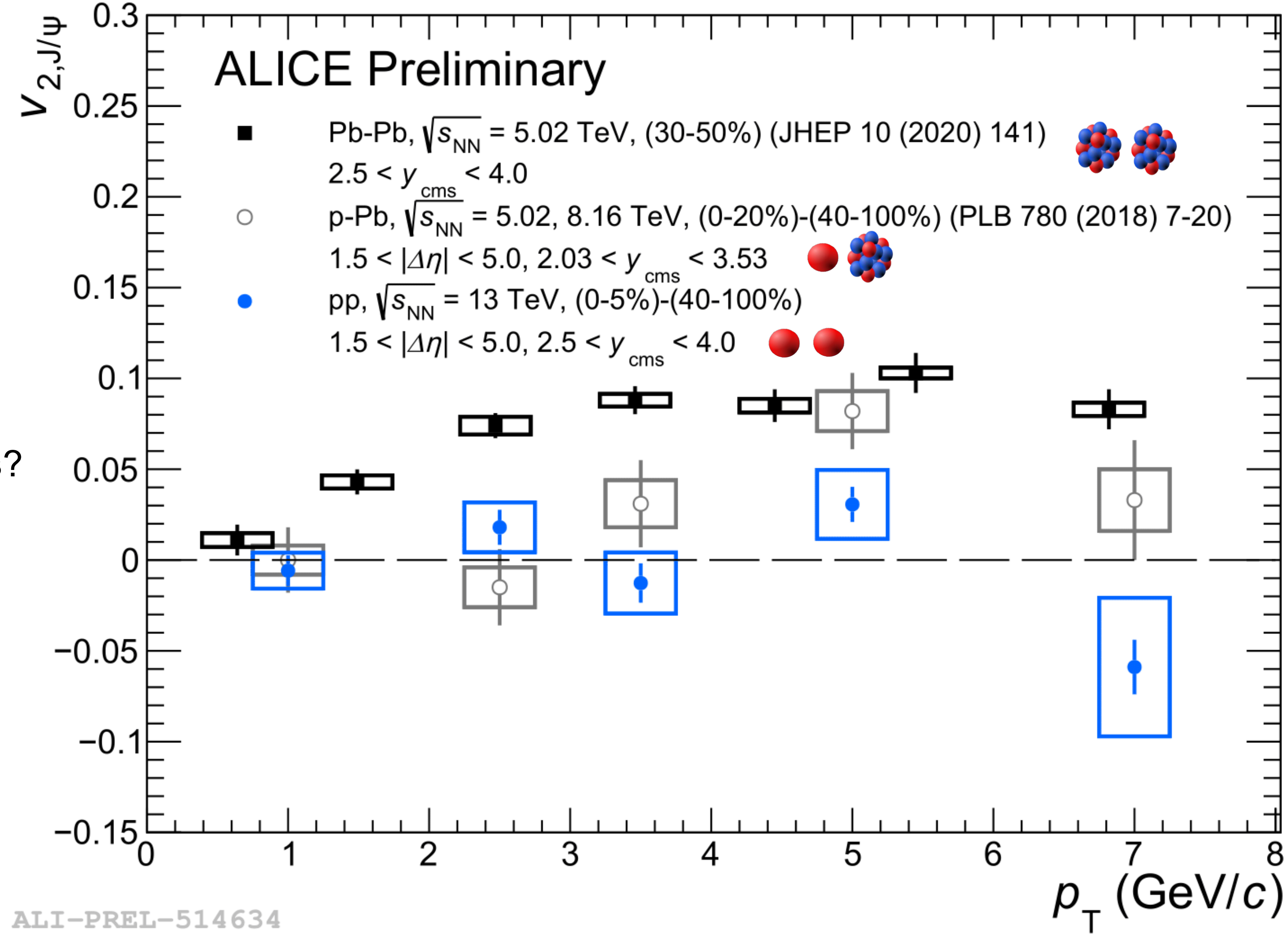
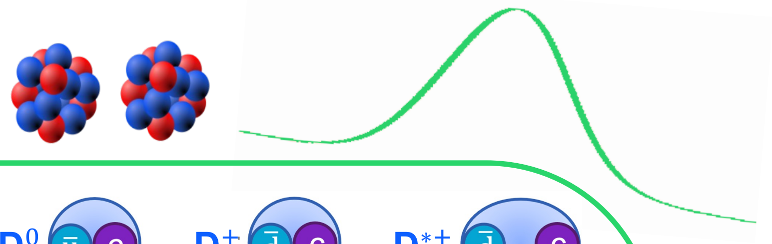
● **J/ψ v_2 compatible with 0** (within uncertainties) in **pp collisions**

$$v_2^{pp} \ll v_2^{p\text{–}Pb} \leq v_2^{Pb\text{–}Pb}$$



Conclusion: v_2 from large to small systems in Run 2

Pb–Pb



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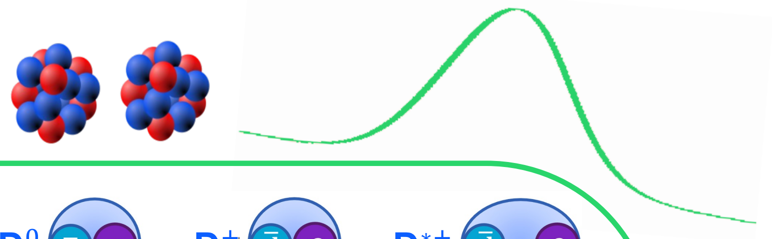

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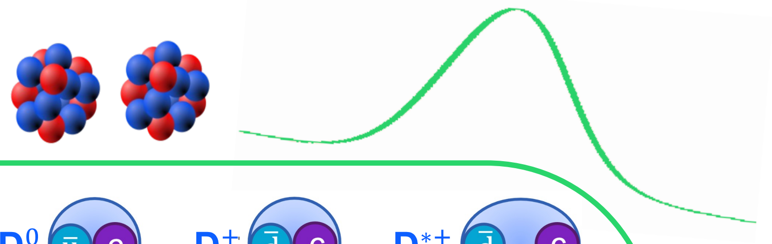

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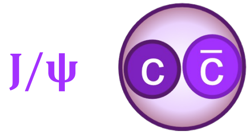

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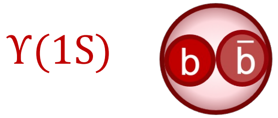

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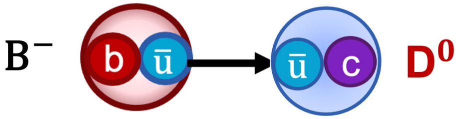

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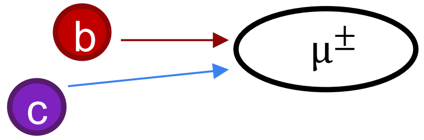

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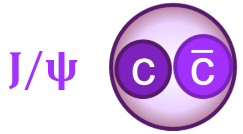

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pp

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ALICE

Subatech

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$$v_2^{\mathrm{Pb-Pb}} \geq v_2^{\mathrm{p-Pb}} \gg v_2^{\mathrm{pp}}$$

Elliptic flow hierarchy across **collision systems**!

Perspectives

→ **Larger Run 3** sample will provide **better precision flow measurements**

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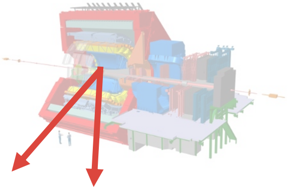
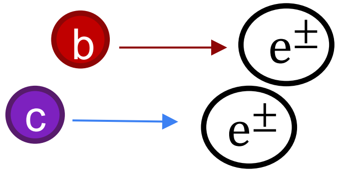
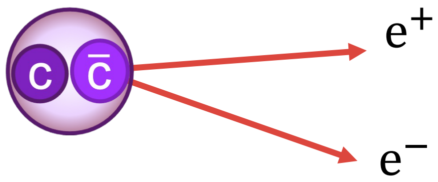
At mid-rapidity:



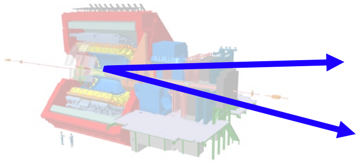
→ Flow of $e^{\pm}$ from charm and beauty decays in Pb-Pb



→ Flow of J/ψ in pp



At forward-rapidity:



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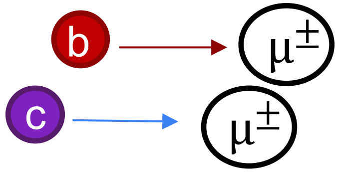
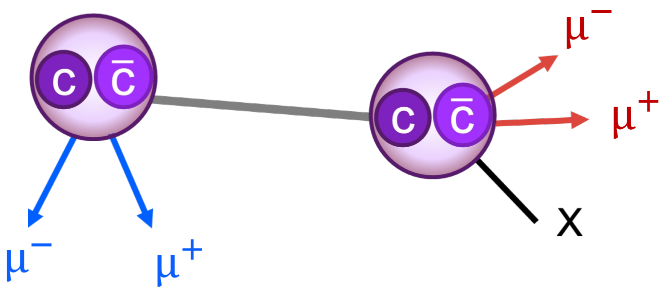


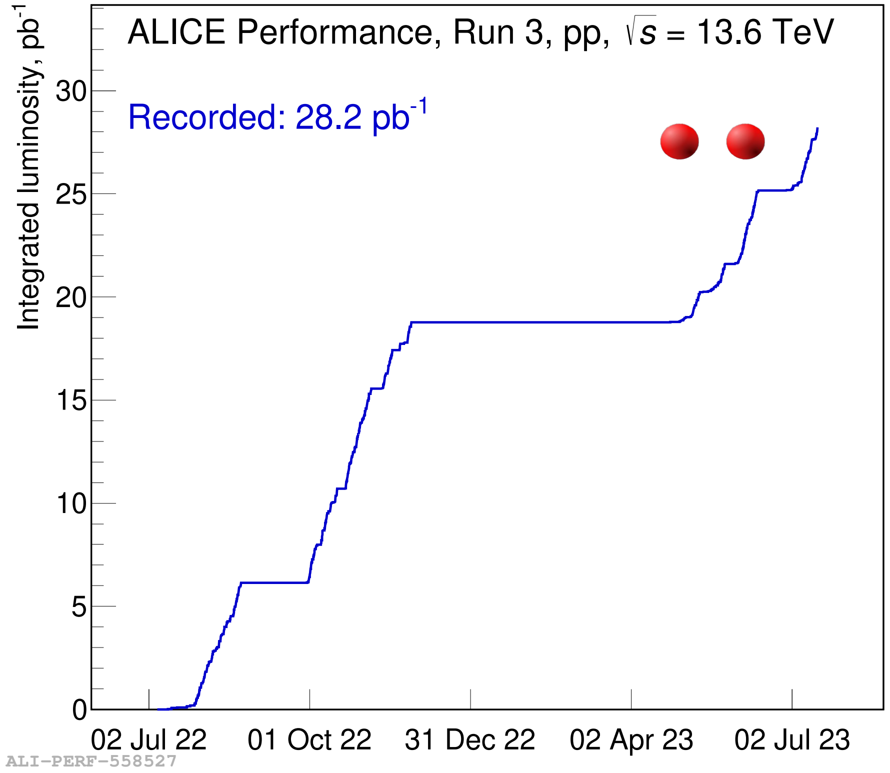
→ Flow of J/ψ prompt and non-prompt in Pb–Pb



→ Thanks to the new Muon Forward Tracker (MFT) detector

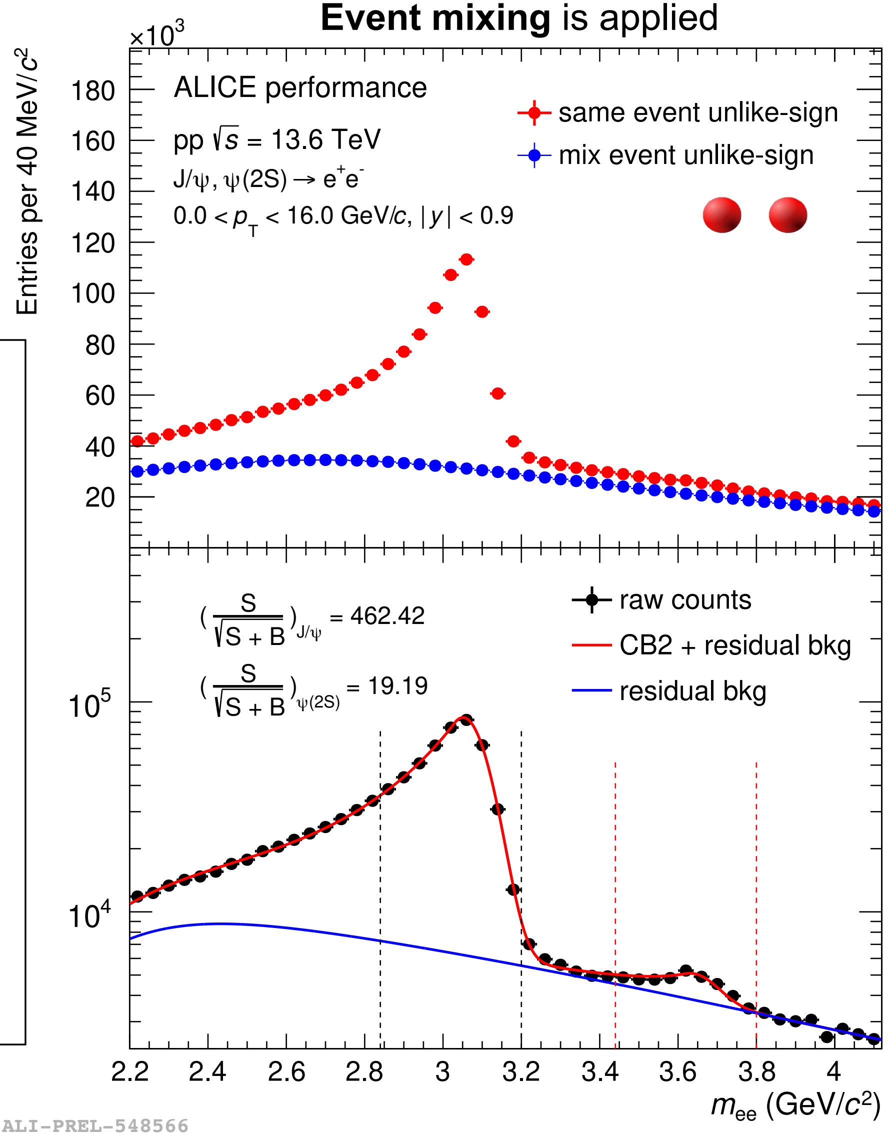
Perspectives: First Run 3 measurements

→ **Run 3 statistics** significantly **larger** than in Run 1–2 allowing **more precise measurements**



→ **Fit of m_{ee}** distribution **at mid-rapidity!**

Event mixing is applied



First **J/ψ signal** extraction in **pp**

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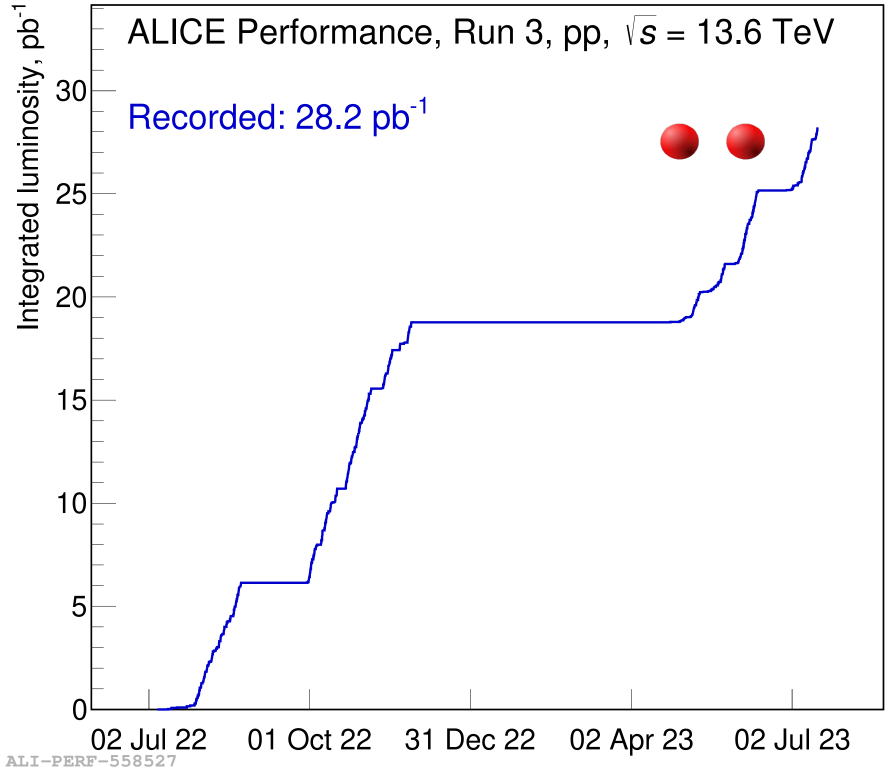

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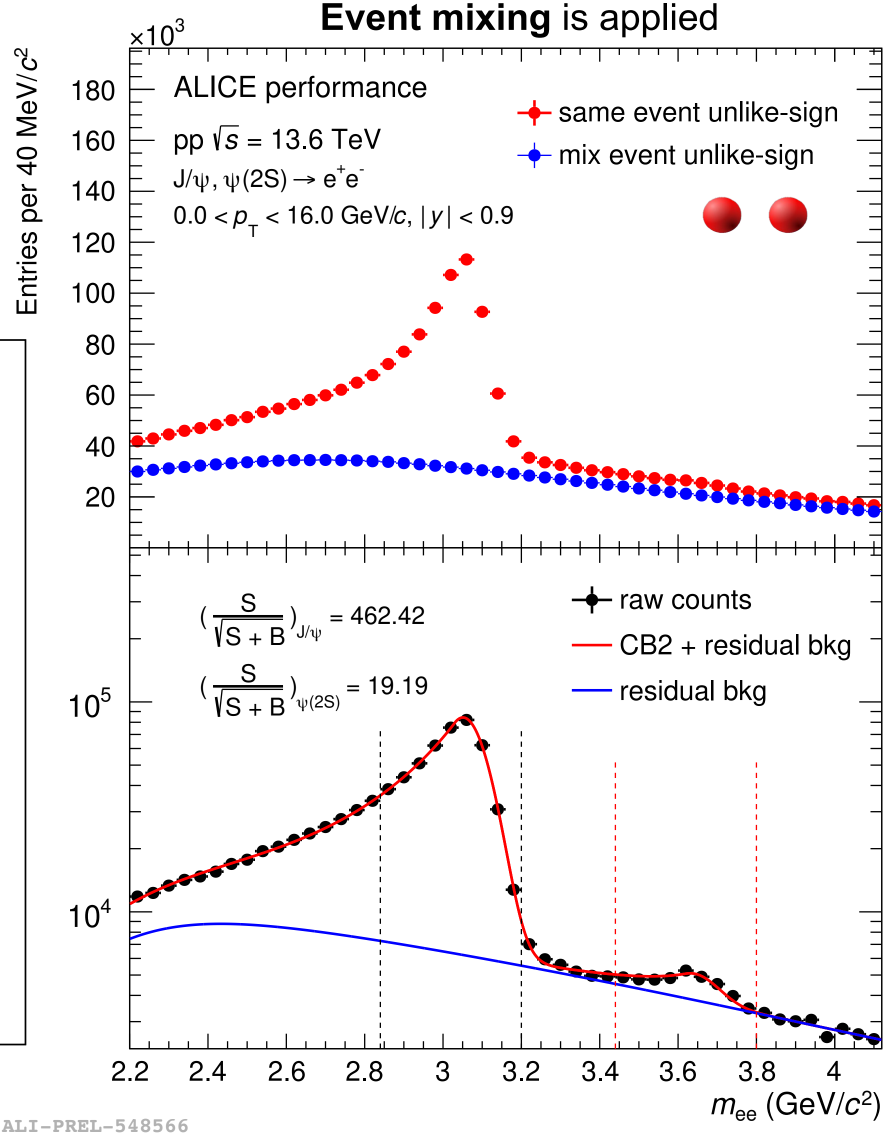
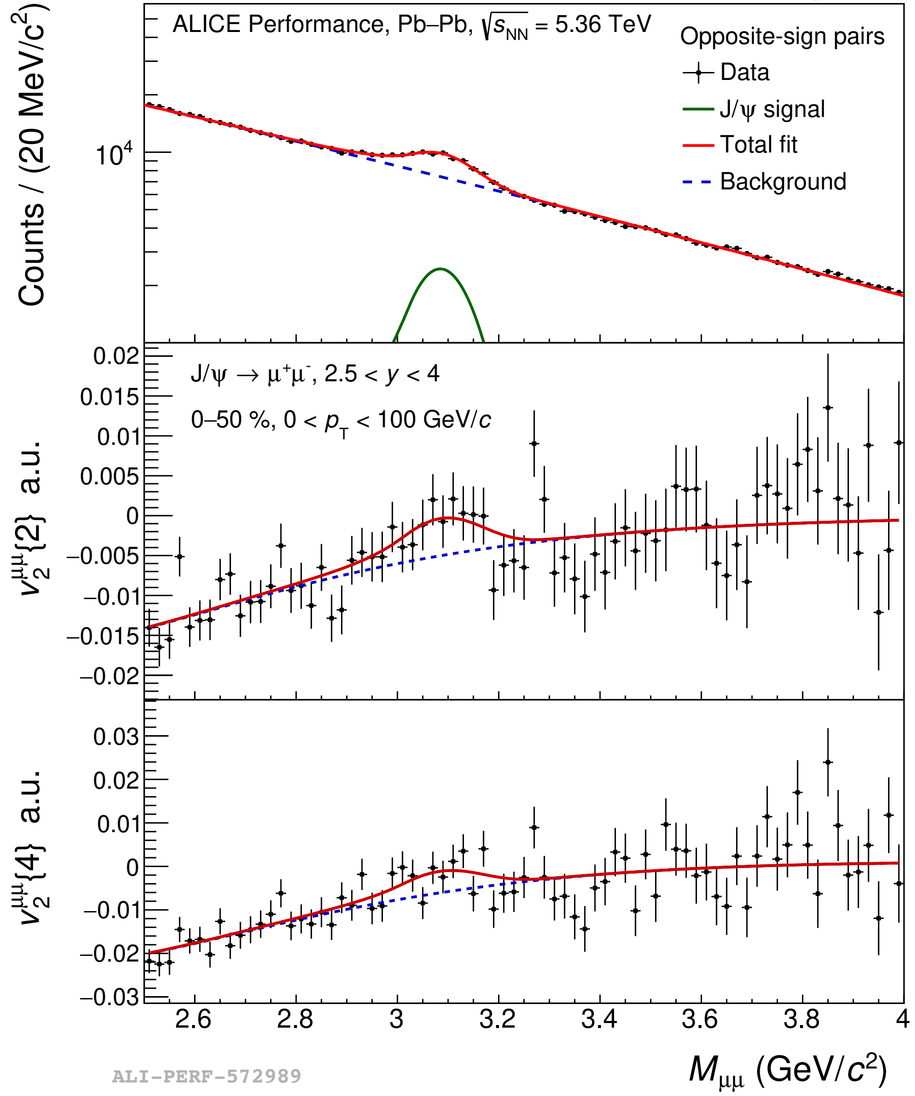


First **J/ψ signal** extraction in **pp**

→ **Fit of $v_2^{\mu\mu}$** distribution at **forward–rapidity!**

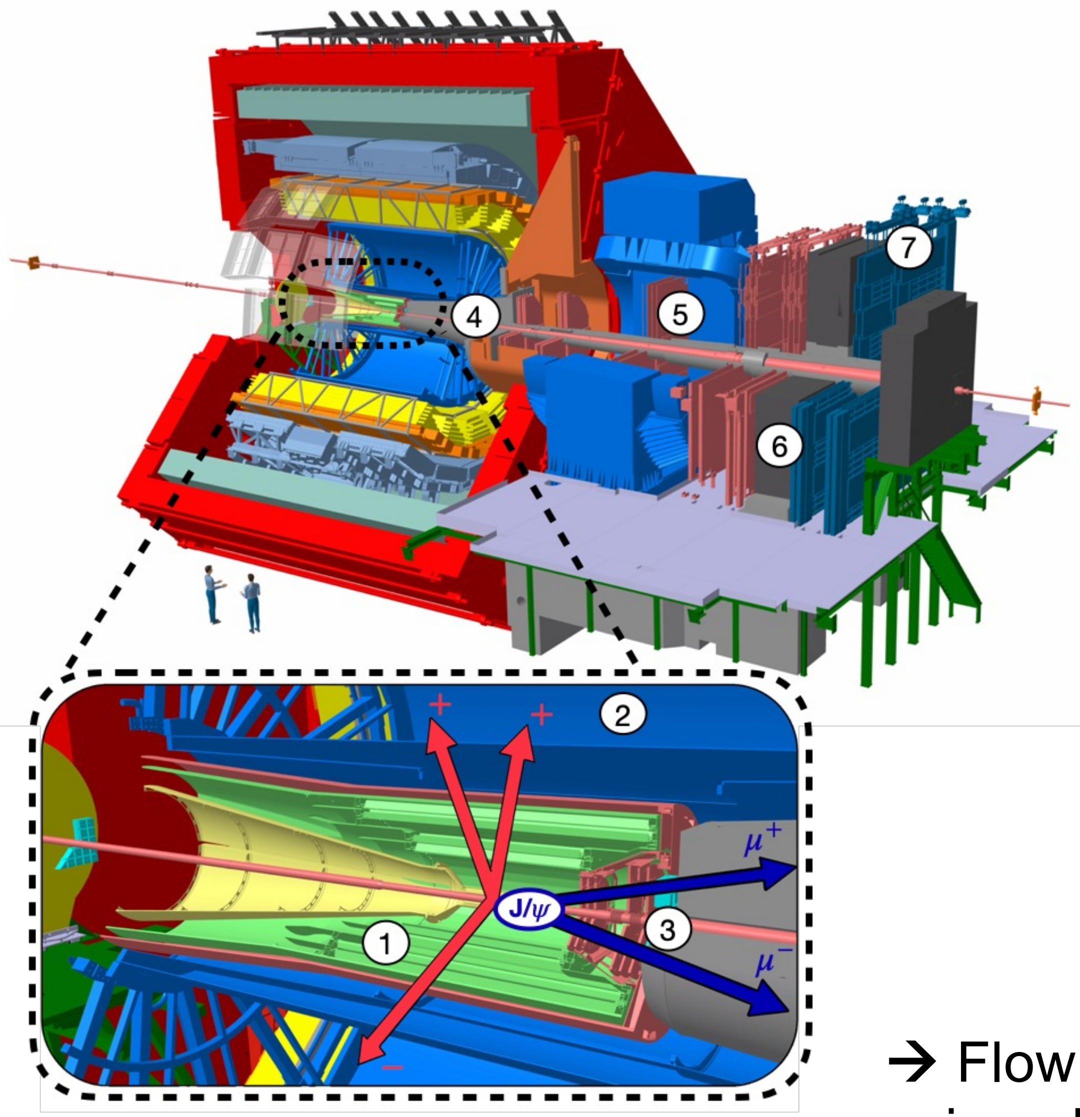
Fraction of the total 2023 Pb–Pb **data**



First $v_2^{J/\psi}\{2,4\}$ **signal** extraction in **Pb–Pb**

BACK UP

Flow measurements in Run 3



ITS ①
→ Vertex identification

TPC ②
→ Charged particles tracking

FT0C ③
→ Centrality estimation of collisions

Front Absorber ④
→ Reduce flux of hadrons by a factor of 100

MCH ⑤
→ Muon tracking system

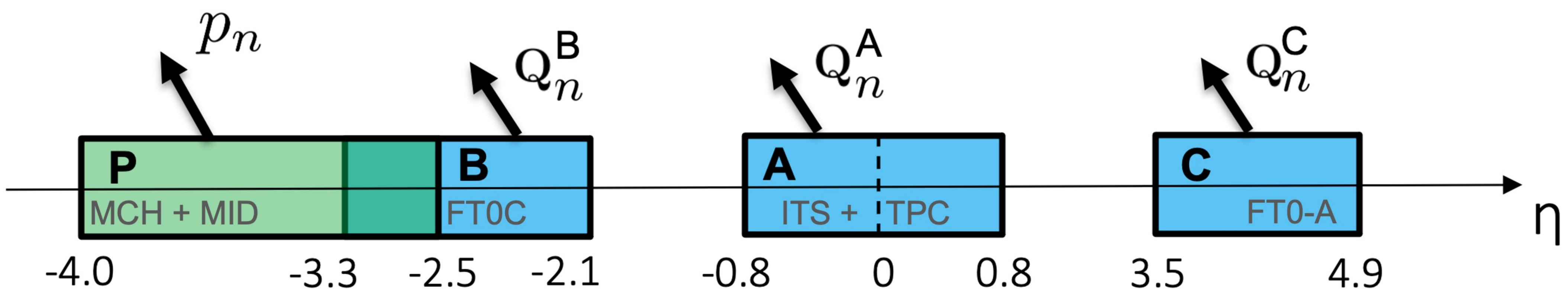
Muon Filter ⑥
→ Punch through hadrons

MID ⑦
→Particle identification of muons

→ Flow measurements using **different methods**

- **Scalar product**
- **Event plane**
- **Multi-particle cumulant**

Scalar product and event plane methods



Barrel Q-vector → $Q_n = \sum_{i=1}^{M} e^{(in\phi_i)} = Q_n^X + iQ_n^Y$

Event plane → $\Psi_n = \frac{1}{n}\arctan\left(\frac{Q_n^Y}{Q_n^X}\right)$

Scalar product

$$v_n^{\mu\mu} = \left\langle \langle p_n \mathbf{Q}_n^{*A} \rangle / R_n \right\rangle = \sqrt{\langle v_n^2 \rangle}$$

$$R_n = \sqrt{\frac{\langle \mathbf{Q}_n^{A} \mathbf{Q}_n^{*B} \rangle \langle \mathbf{Q}_n^{A} \mathbf{Q}_n^{*C} \rangle}{\langle \mathbf{Q}_n^{B} \mathbf{Q}_n^{*C} \rangle}}$$

Event plane

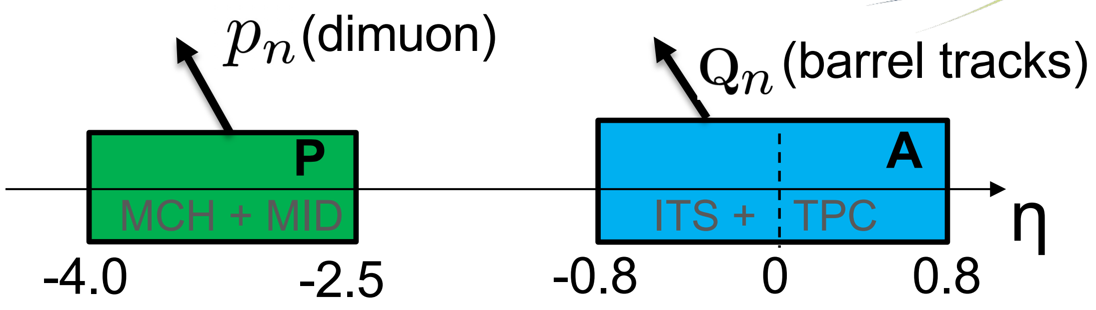
$$v_n^{\mu\mu} = \left\langle \langle \cos n(\varphi - \Psi_n^A) \rangle / R_n \right\rangle = \sqrt{\langle v_n^2 \rangle}$$

$$R_n = \sqrt{\langle \cos n(\Psi_n^B - \Psi_n^C) \rangle}$$

Multi-particle cumulant method (new!)

Dimuon Q-vector → $p_n = p_n^X + i p_n^Y$

Barrel Q-vector → $Q_n = Q_n^X + i Q_n^Y$



Correlators for particles of reference (REF)

$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2 \cdot \mathfrak{Re}\left[Q_{2n} Q_n^* Q_n^*\right]}{M(M-1)(M-2)(M-3)} - 2\,\frac{2(M-2)\cdot|Q_n|^2 - M(M-3)}{M(M-1)(M-2)(M-3)}\,.$$

Correlators for particle of interest (POI)

$$\langle 2' \rangle = \frac{p_n Q_n^*}{m_p M}$$

$$\langle 4' \rangle = \frac{p_n Q_n Q_n^* Q_n^* - p_n Q_n Q_{2n}^* - 2 \cdot M p_n Q_n^* + 2 \cdot p_n Q_n^*}{(m_p M)(M-1)(M-2)}$$

REF cumulants

$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

POI cumulants

$$d_n^{\mu\mu}\{2\} = \langle\langle 2' \rangle\rangle$$

$$d_n^{\mu\mu}\{4\} = \langle\langle 4' \rangle\rangle - 2 \cdot \langle\langle 2' \rangle\rangle \langle\langle 2 \rangle\rangle$$

REF flow

$$v_n^{\mathrm{REF}}\{2\} = \sqrt{c_n\{2\}}$$

$$v_2^{\mathrm{REF}}\{4\} = \sqrt[4]{-c_2\{4\}}$$

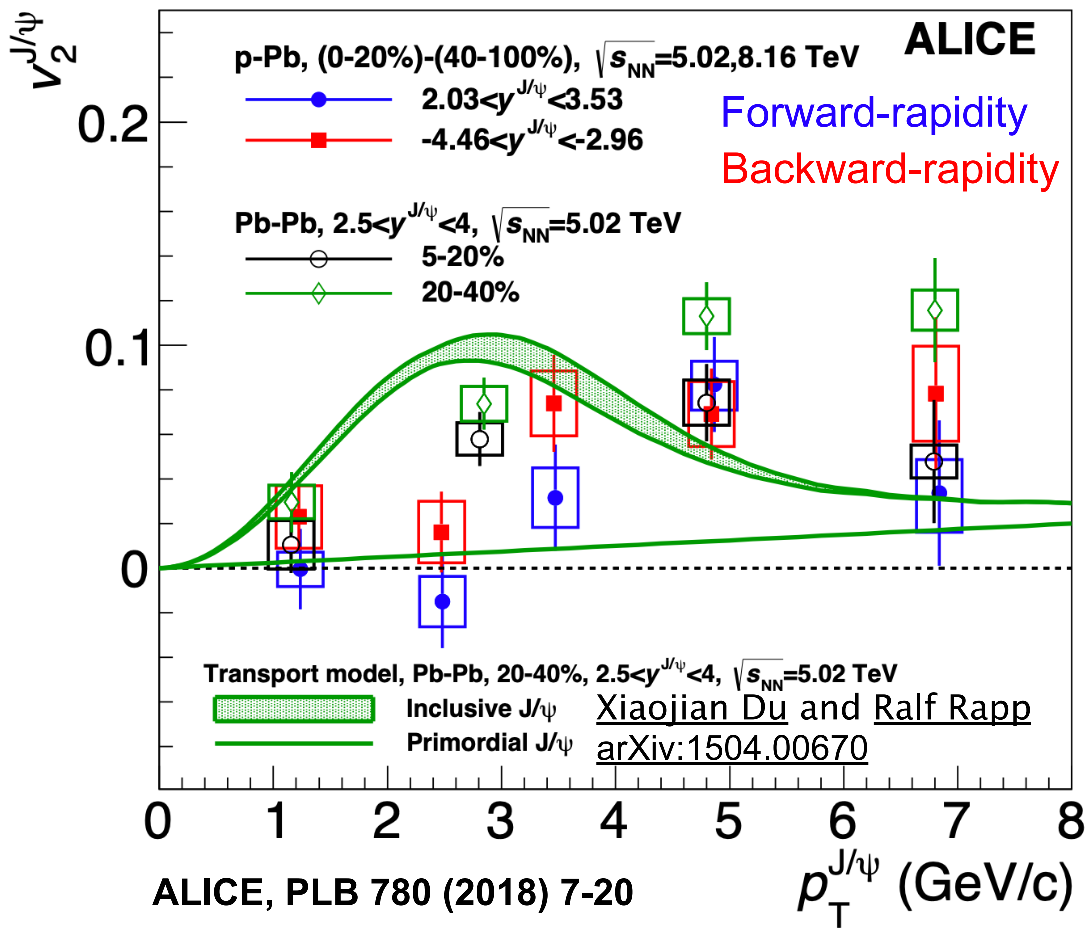
POI flow

$$v_n^{\mu\mu}\{2\} = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}$$

$$v_n^{\mu\mu}\{4\} = -\frac{d_n^{\mu\mu}\{4\}}{(-c_n\{4\})^{3/4}}$$

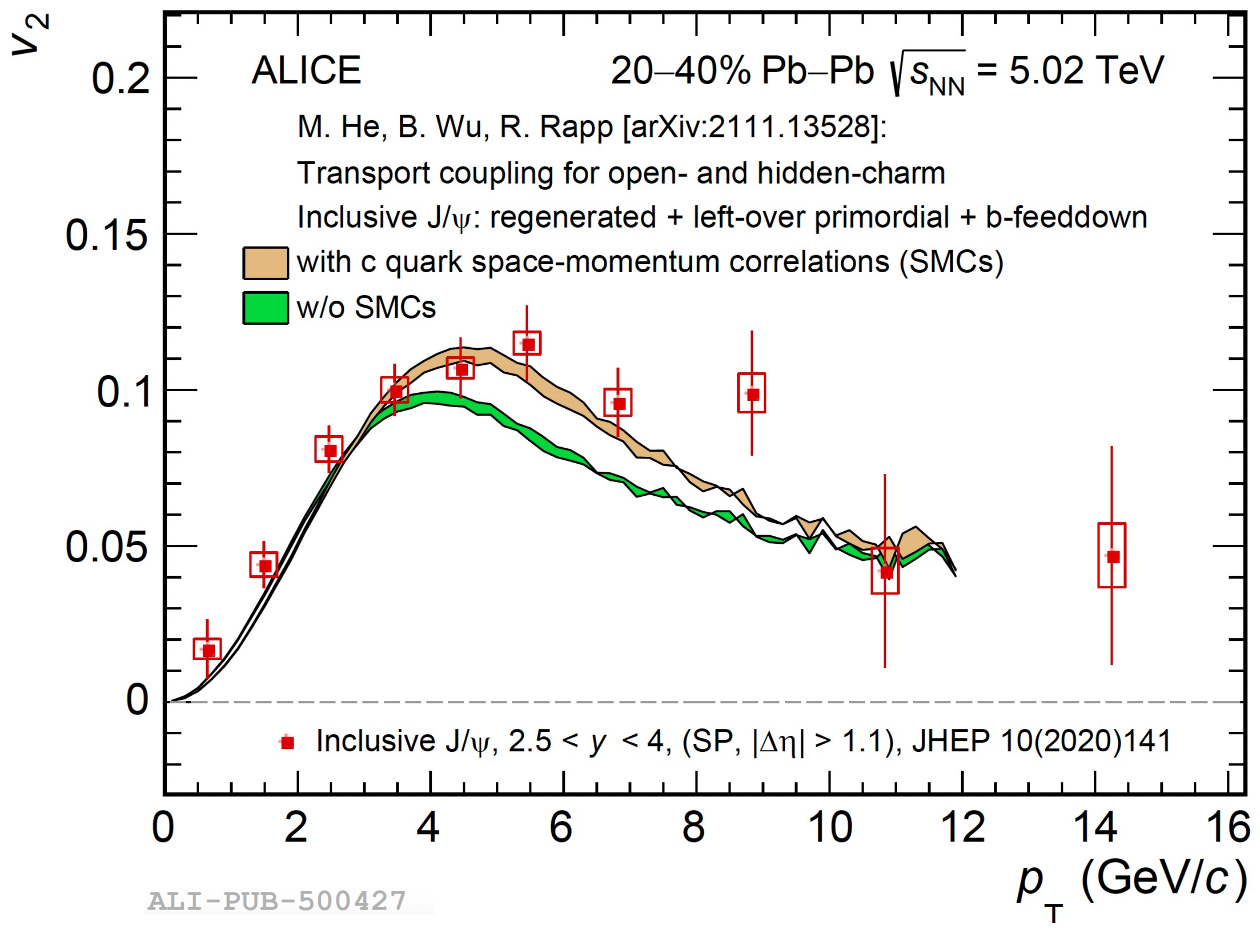
v_2 of J/ψ in p–Pb and Pb–Pb collisions

In **p–Pb → no expected J/ψ regeneration**
(no expected QGP formation)



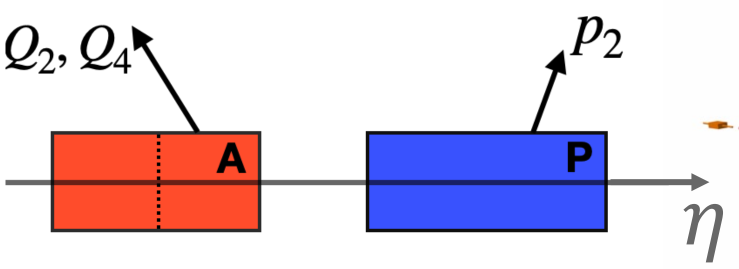
→ Comparable magnitude of v_2 J/ψ at **high p_T** in p–Pb and Pb–Pb collisions!

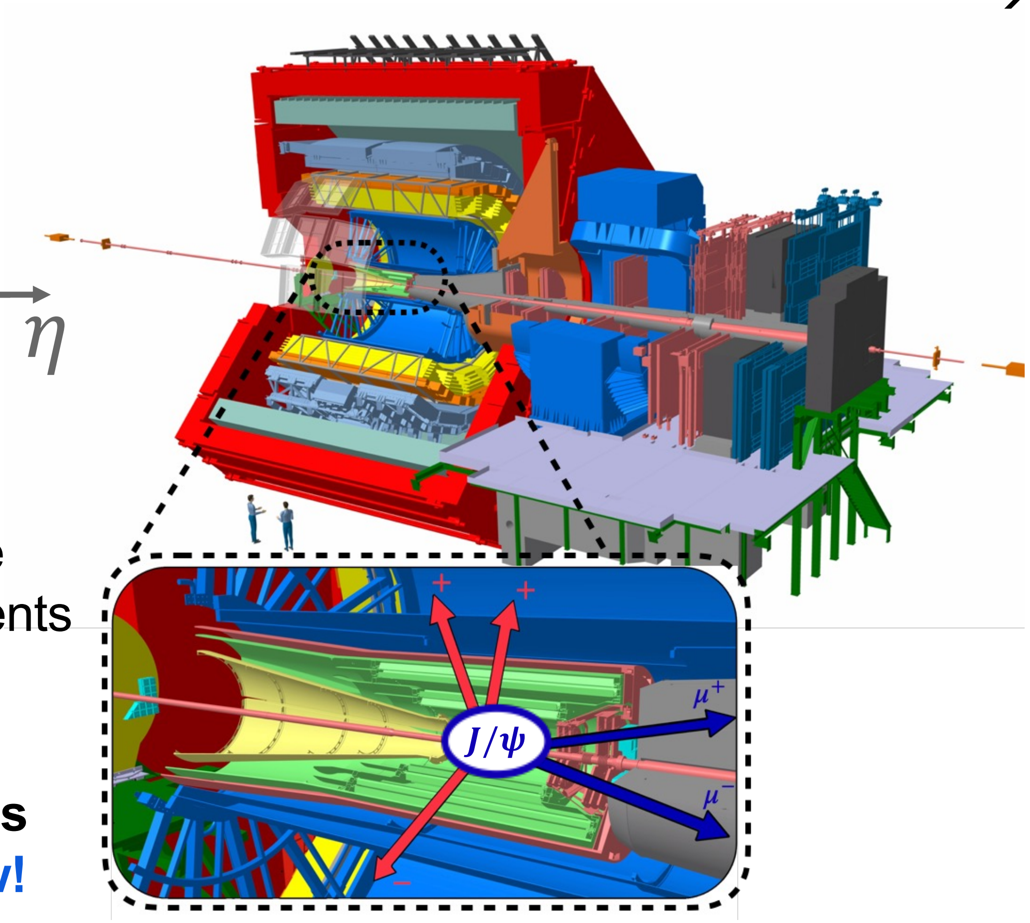
In **Pb–Pb → Flow** of J/ψ at low p_T is **interpreted as** a consequence of **regeneration**



v_2 J/ψ described well by a **transport model** where charm quark thermalized in **QGP**!

Perspective: Flow $v_2^{J/\psi}$ in Run 3





→ **Run 3 data** will enable more precise measurements for $v_2^{J/\psi}$ up to **higher p_T**

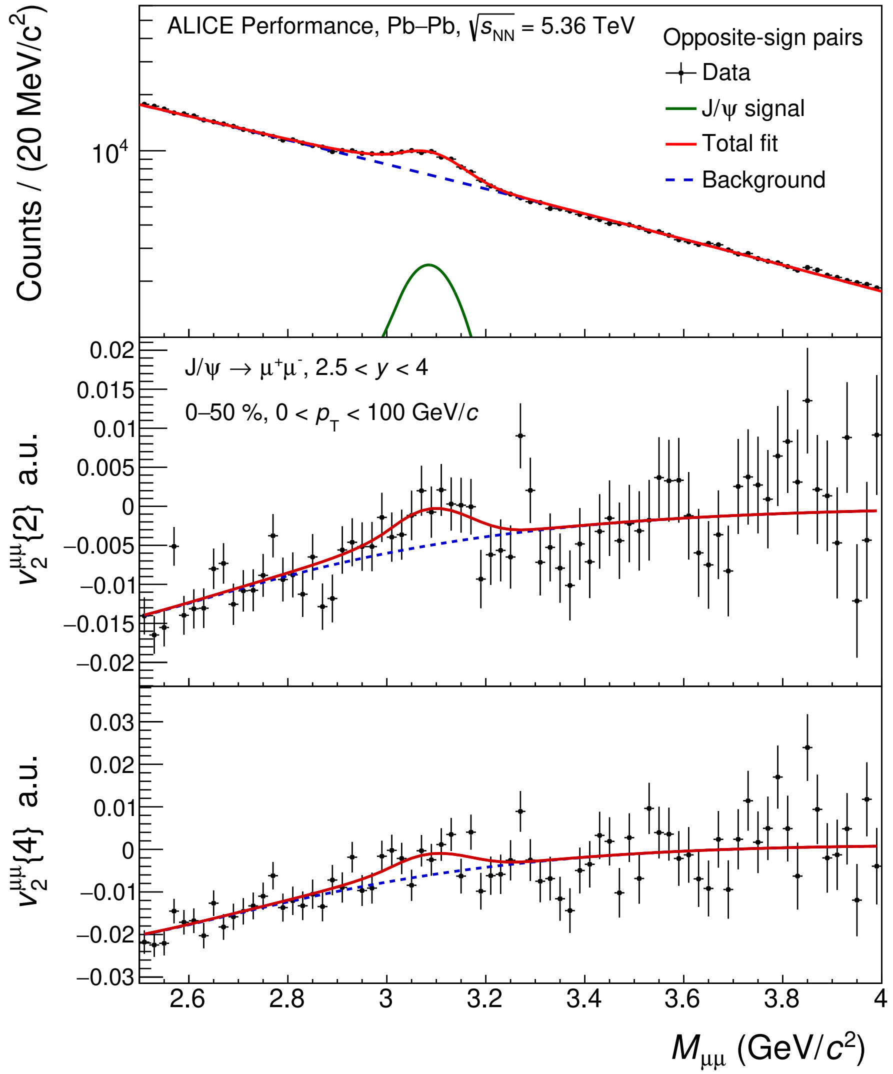
→ **High order cumulants** should suppres **non-flow!**

$$v_2\{2\}^2 = \langle v_2^2 + \delta_2 \rangle \rightarrow \delta_2 \sim 1/M$$

$$v_2\{4\}^4 = -\langle v_2^4 + \delta_4 \rangle \rightarrow \delta_4 \sim 1/M^3$$

Scaling with multiplicity!

→ **Partial statistics** of the total **2023 Pb–Pb** data



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→ First $v_2^{J/\psi}\{2,4\}$ **signal** extraction at **forward-rapidity!**