Workshop Hydrodynamics and related observables in heavy-ion collisions

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

Plan of this talk

Plan of this talk

1) Introduction
   - Production of heavy-flavor and quarkonia in Pb-Pb collisions
   - Flow observables

1) Introduction
   - Production of heavy-flavor and quarkonia in Pb-Pb collisions
   - Flow observables

2) Flow measurements in the **heavy−sector** with **Run 2 data**
   - v_2 from large to small systems

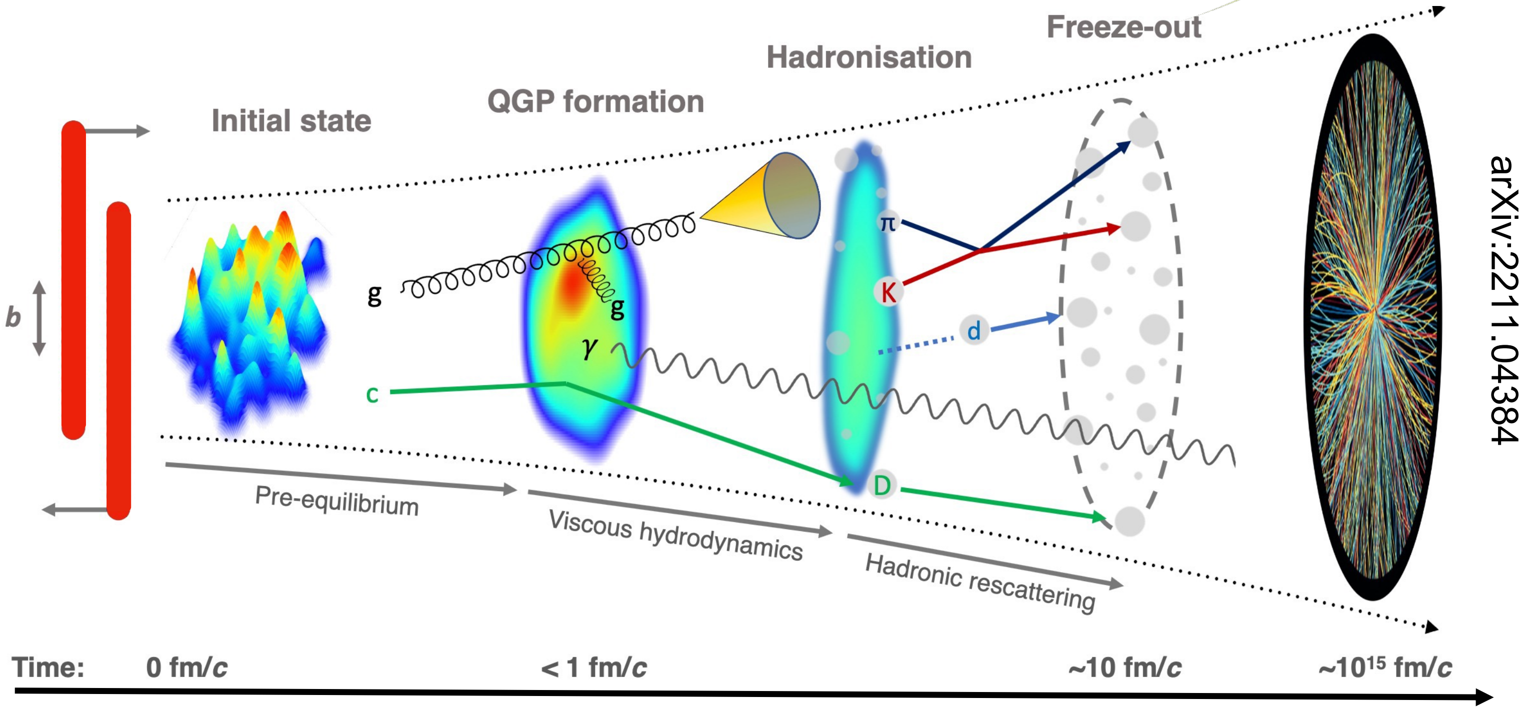
Plan of this talk

1) Introduction
   - Production of heavy-flavor and quarkonia in Pb-Pb collisions
   - Flow observables

2) Flow measurements in the **heavy−sector** with **Run 2 data**
   - v_2 from large to small systems

3) New **flow** measurements of $\mathbf{J/\psi}$ using **Run 3 data**
   - $v_2^{J/\psi}$ using event plane and multi-particle cumulants methods
   - Perspective in Run 3

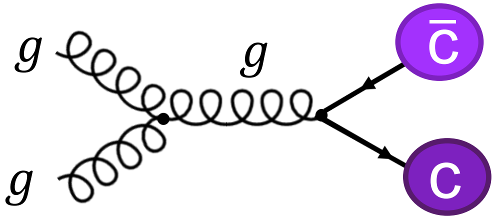
Heavy-flavor and Quarkonia in Pb–Pb collisions

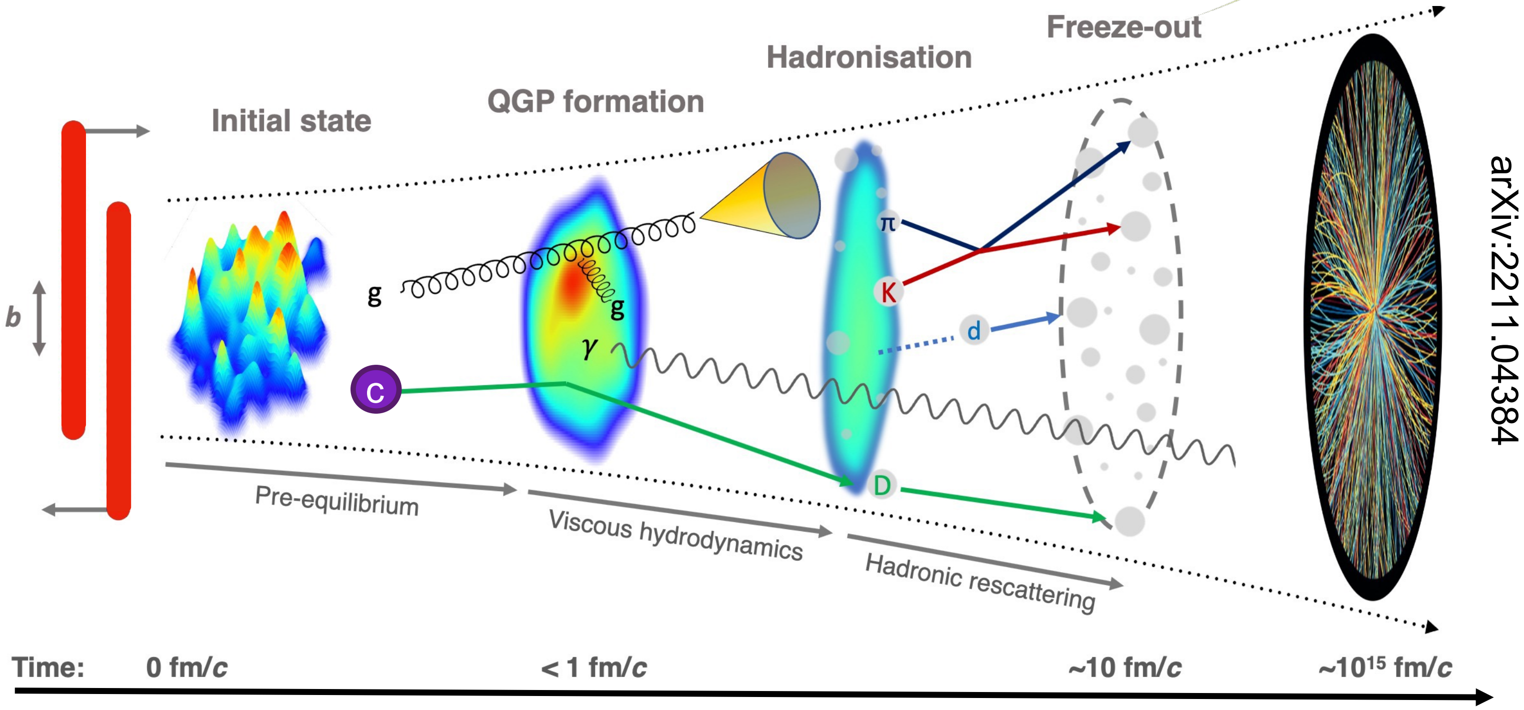


arXiv:2211.04384

Heavy-flavor and Quarkonia in Pb–Pb collisions

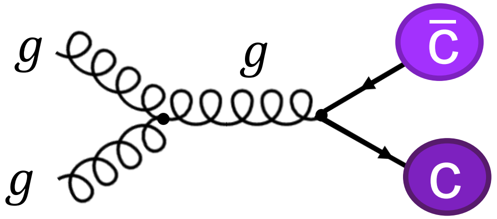
- **Heavy-quark production** occurs at **early times** of the collision
  → $M_{c,b} > \Lambda_{QCD}$ (pQCD applicable)
  → **Sensitive** to the medium evolution

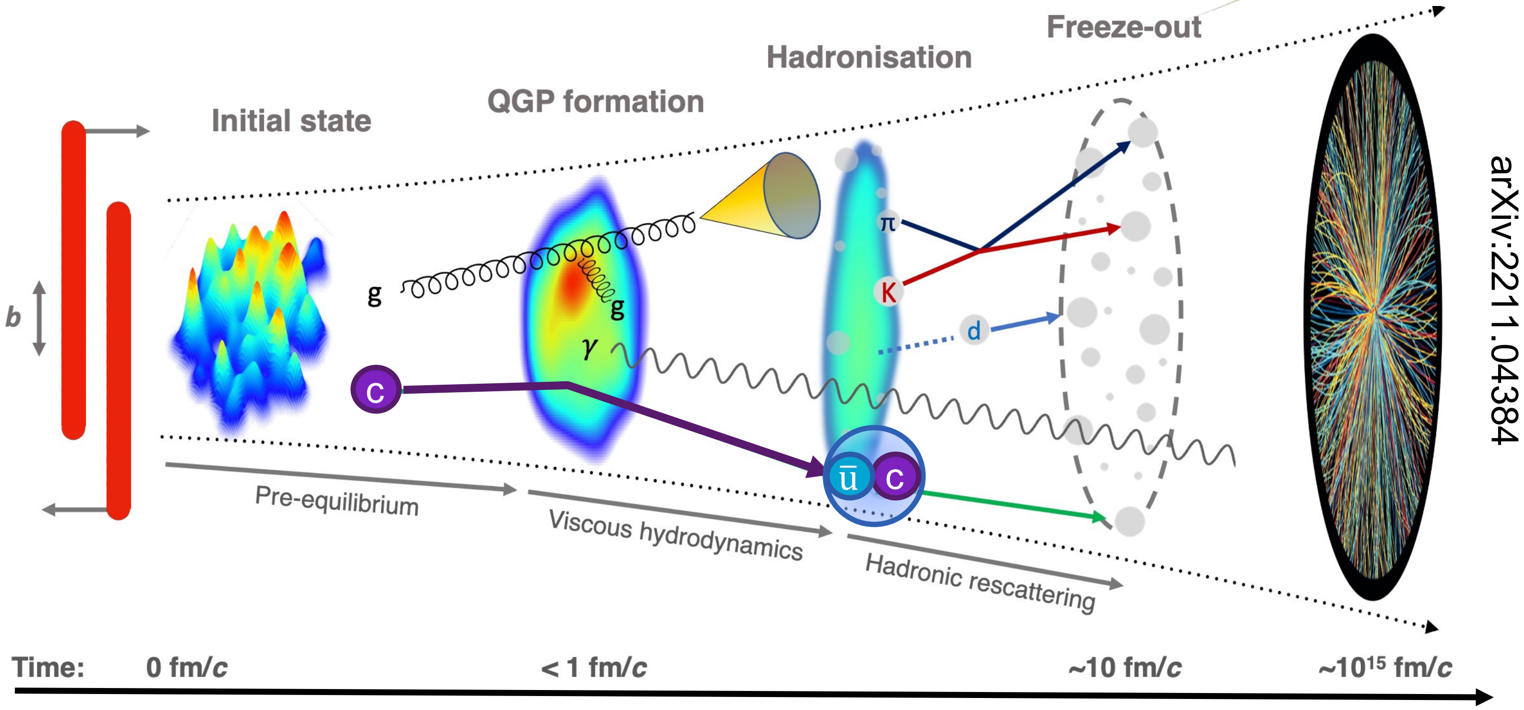




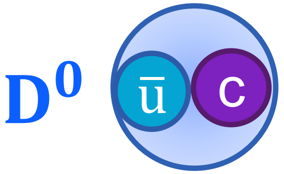
arXiv:2211.04384

- **Heavy-quark production** occurs at **early times** of the collision
  → $M_{c,b} > \Lambda_{QCD}$ (pQCD applicable)
  → **Sensitive** to the medium evolution



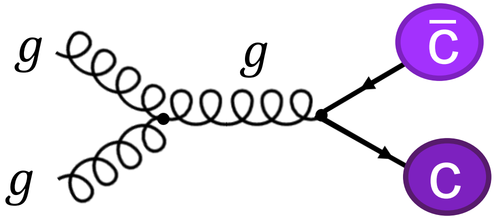


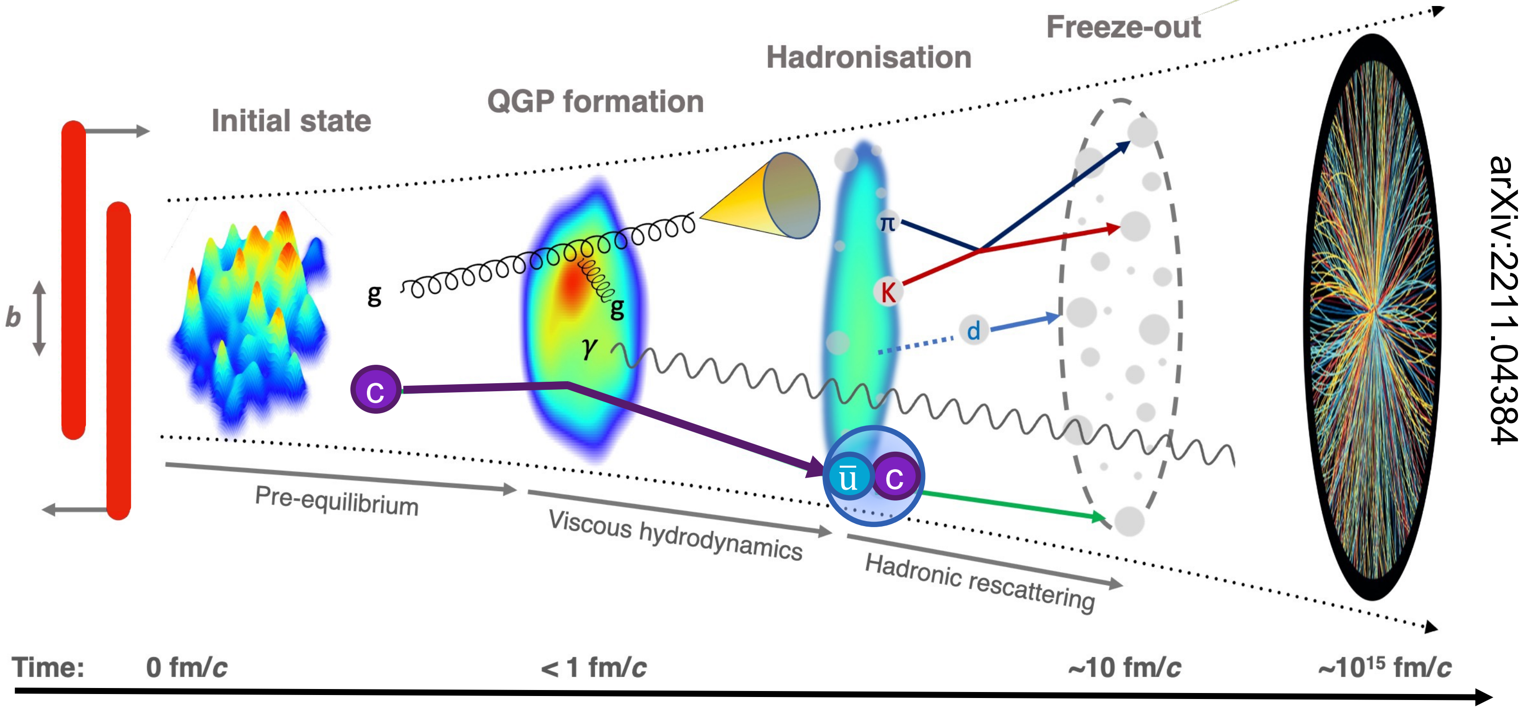
- **Open heavy-flavor hadrons** (made up of **light** and **heavy** quarks) allow to study the transport coefficient of **QGP**, investigating **charm thermalization**



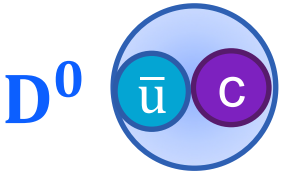
Heavy-flavor and Quarkonia in Pb–Pb collisions

- **Heavy-quark production** occurs at **early times** of the collision
  → $M_{c,b} > \Lambda_{QCD}$ (pQCD applicable)
  → **Sensitive** to the medium evolution

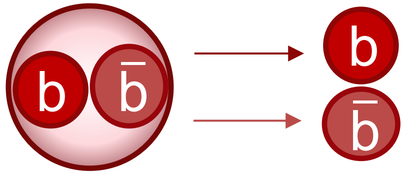




- **Open heavy-flavor hadrons** (made up of **light** and **heavy** quarks) allow to study the transport coefficient of **QGP**, investigating **charm thermalization**

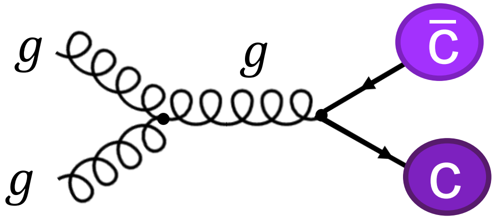


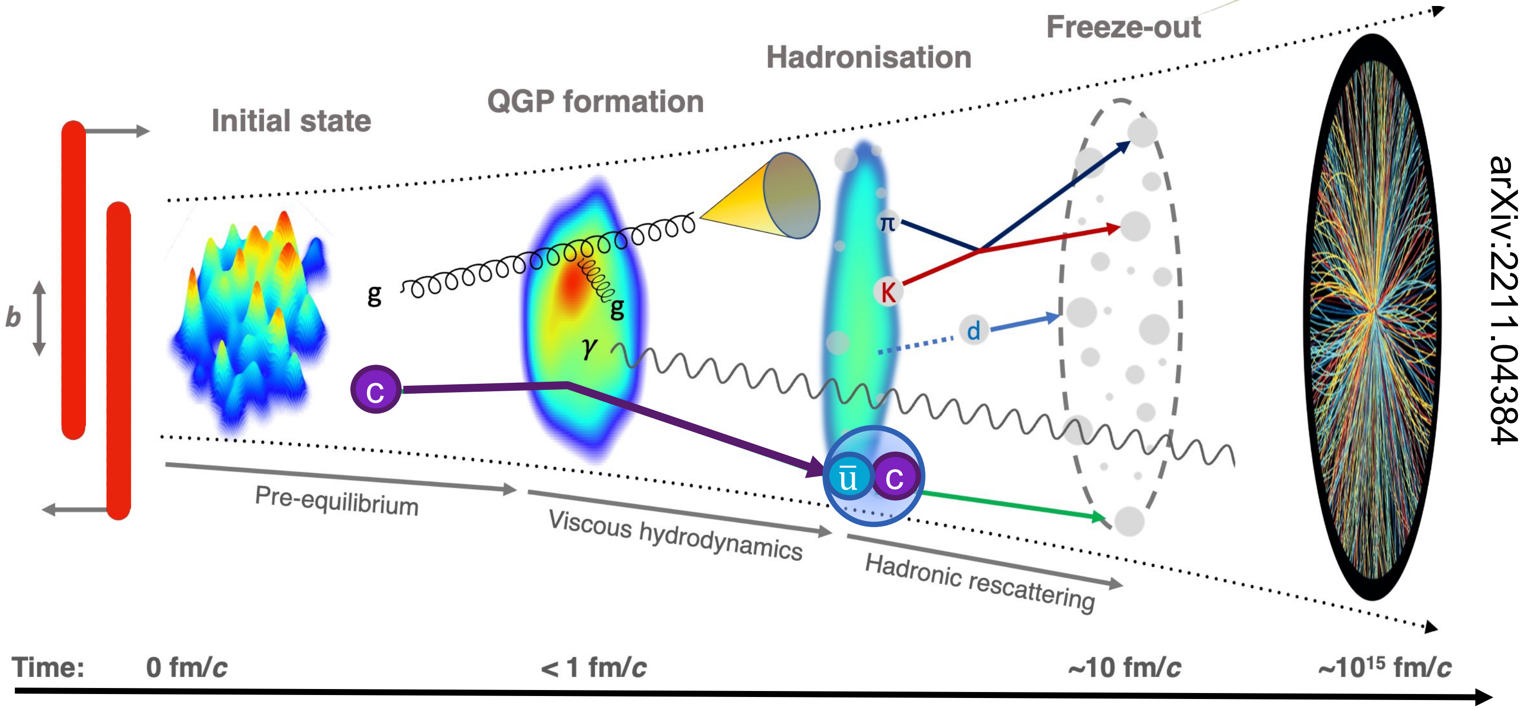
- **Quarkonium** states (**c-c̄** or **b-b̄** quark pairs) **dissociate in QGP** through a color screening mechanism
  →T.Matsui and H.Satz, PLB 178 (1986) 416-422



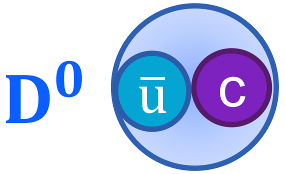
Heavy-flavor and Quarkonia in Pb–Pb collisions

- **Heavy-quark production** occurs at **early times** of the collision
  → $M_{c,b} > \Lambda_{QCD}$ (pQCD applicable)
  → **Sensitive** to the medium evolution

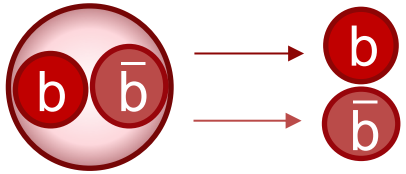




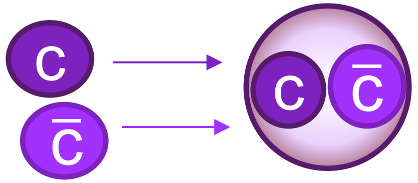
- **Open heavy-flavor hadrons** (made up of **light** and **heavy** quarks) allow to study the transport coefficient of **QGP**, investigating **charm thermalization**



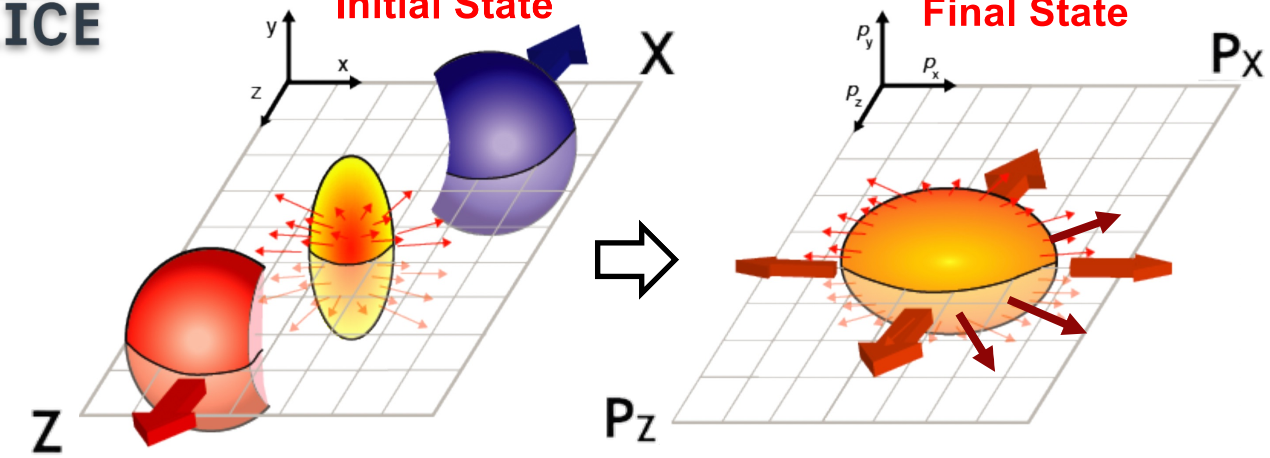
- **Quarkonium** states (**c-c̄** or **b-b̄** quark pairs) **dissociate in QGP** through a color screening mechanism
  →T.Matsui and H.Satz, PLB 178 (1986) 416-422



- **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

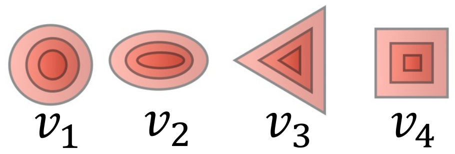


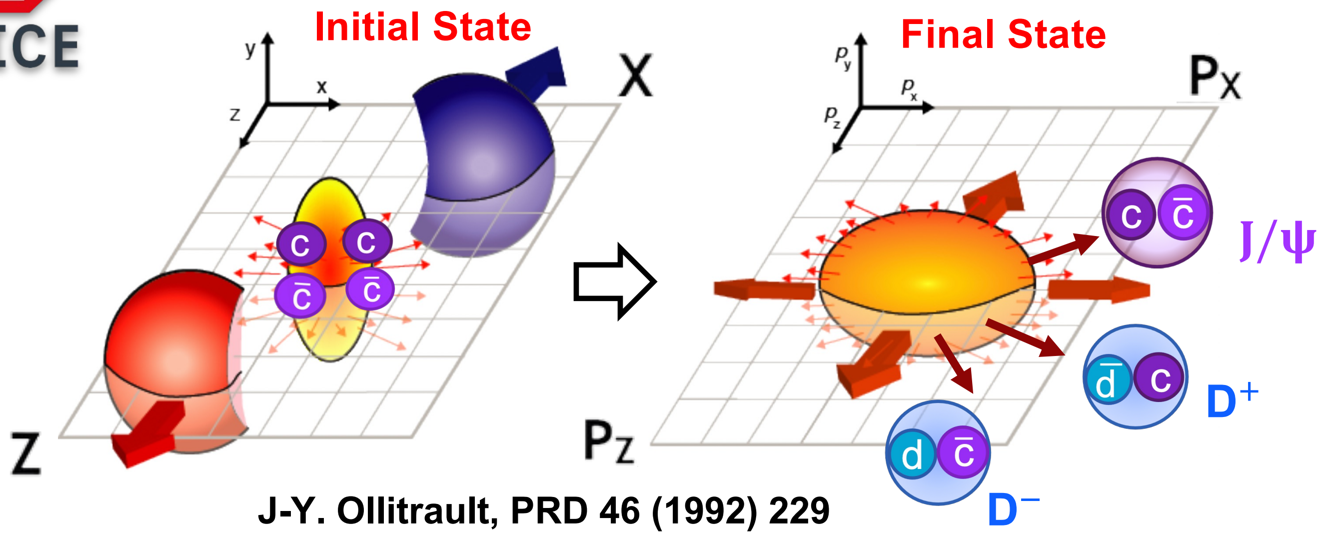
J-Y. Ollitrault, PRD 46 (1992) 229

Anisotropy of particle momentum distribution

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

$$v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$



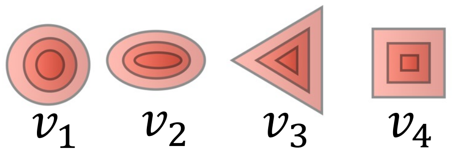


J-Y. Ollitrault, PRD 46 (1992) 229

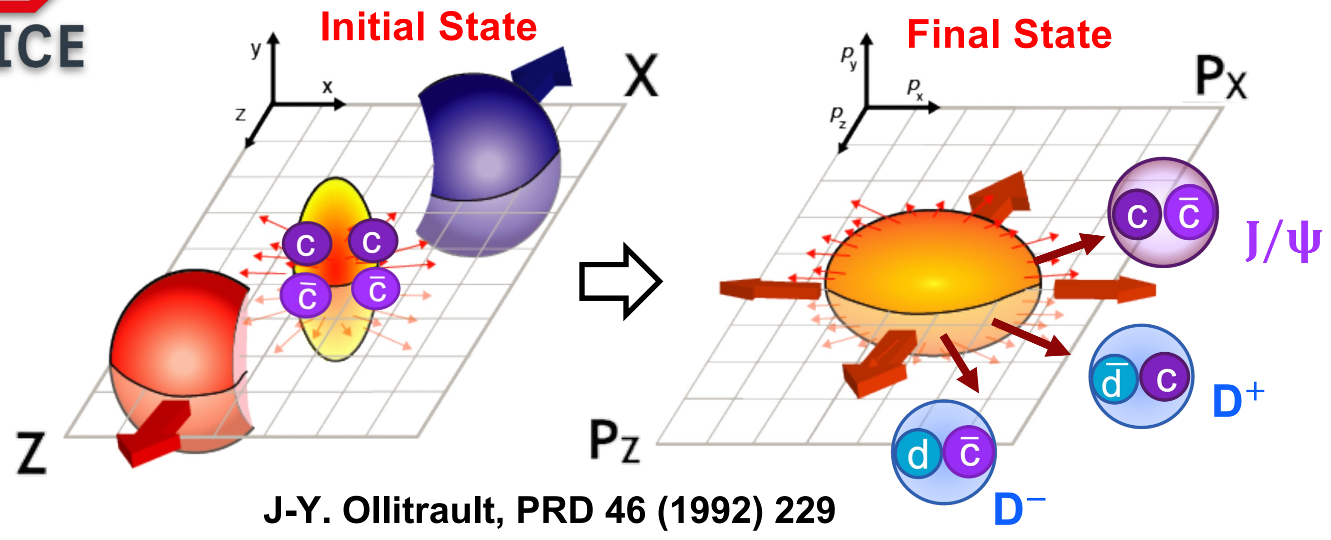
Anisotropy of particle momentum distribution

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

$$v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$



Collective flow of heavy-flavor/Quarkonia in Pb–Pb (Run 2)



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

- **D mesons**: **lightest hadrons** with a **charm** quark

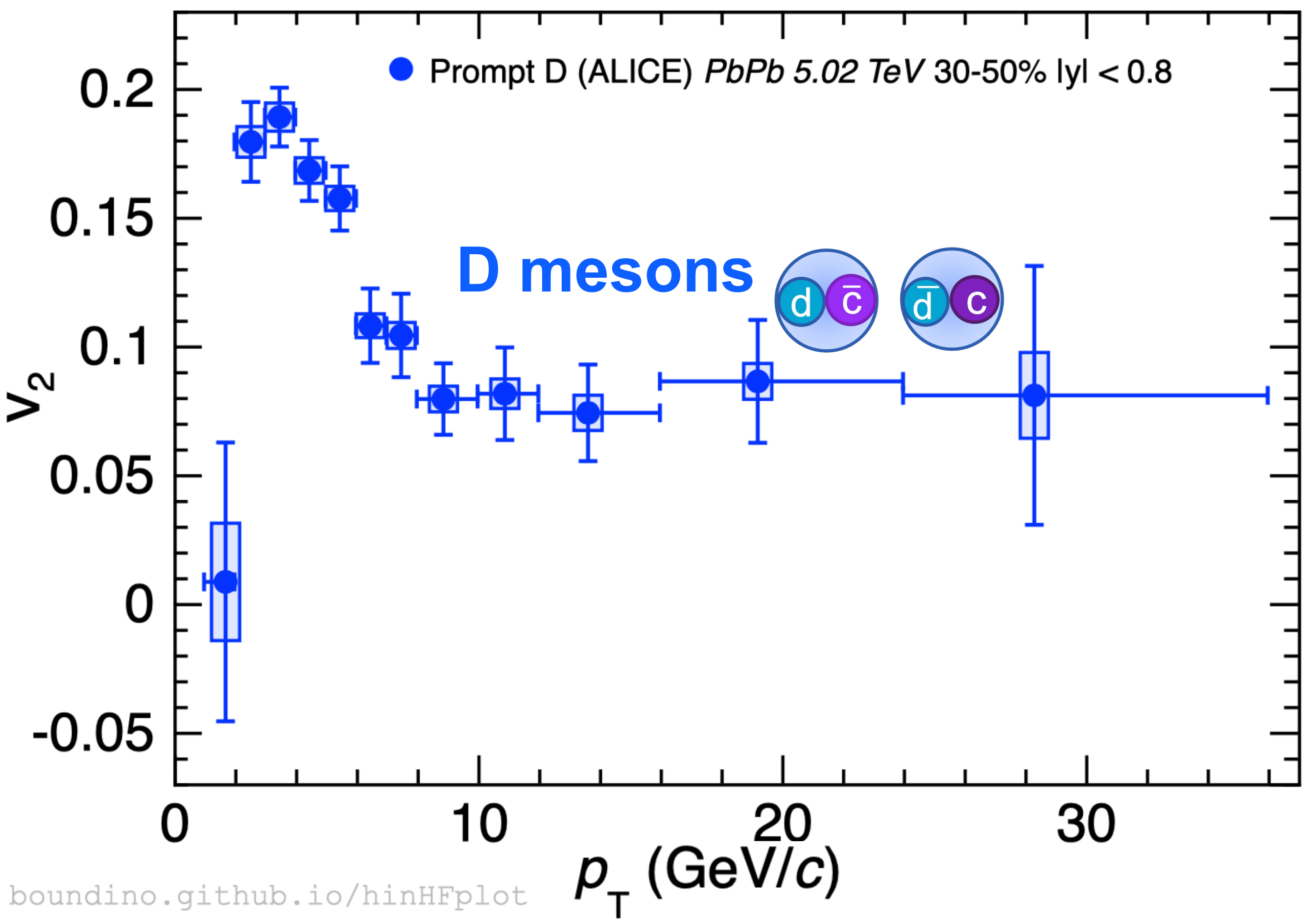
  → **Pronounced flow** attributed to the **thermalization** of **light quarks (u, d, s)** and **charm** quark in the **QGP**

Anisotropy of particle momentum distribution

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

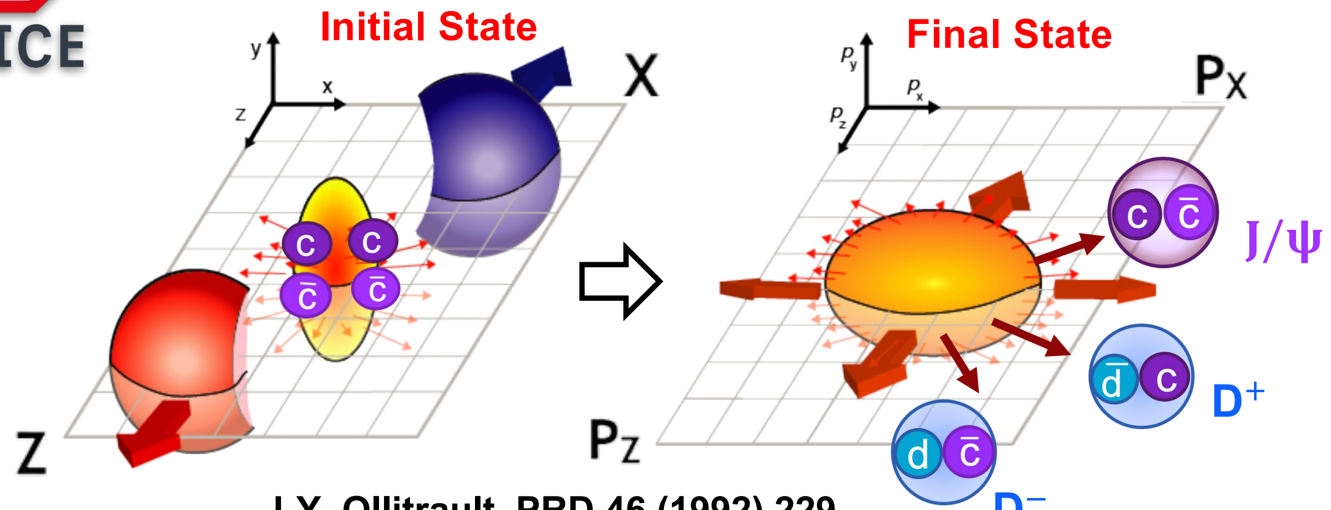
$$v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$

v_1 v_2 v_3 v_4



ALICE, PLB 813 (2021) 136054

Collective flow of heavy-flavor/Quarkonia in Pb–Pb (Run 2)



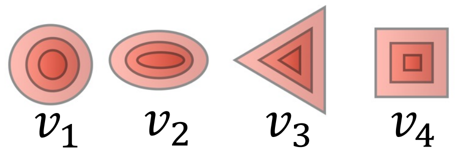
J-Y. Ollitrault, PRD 46 (1992) 229

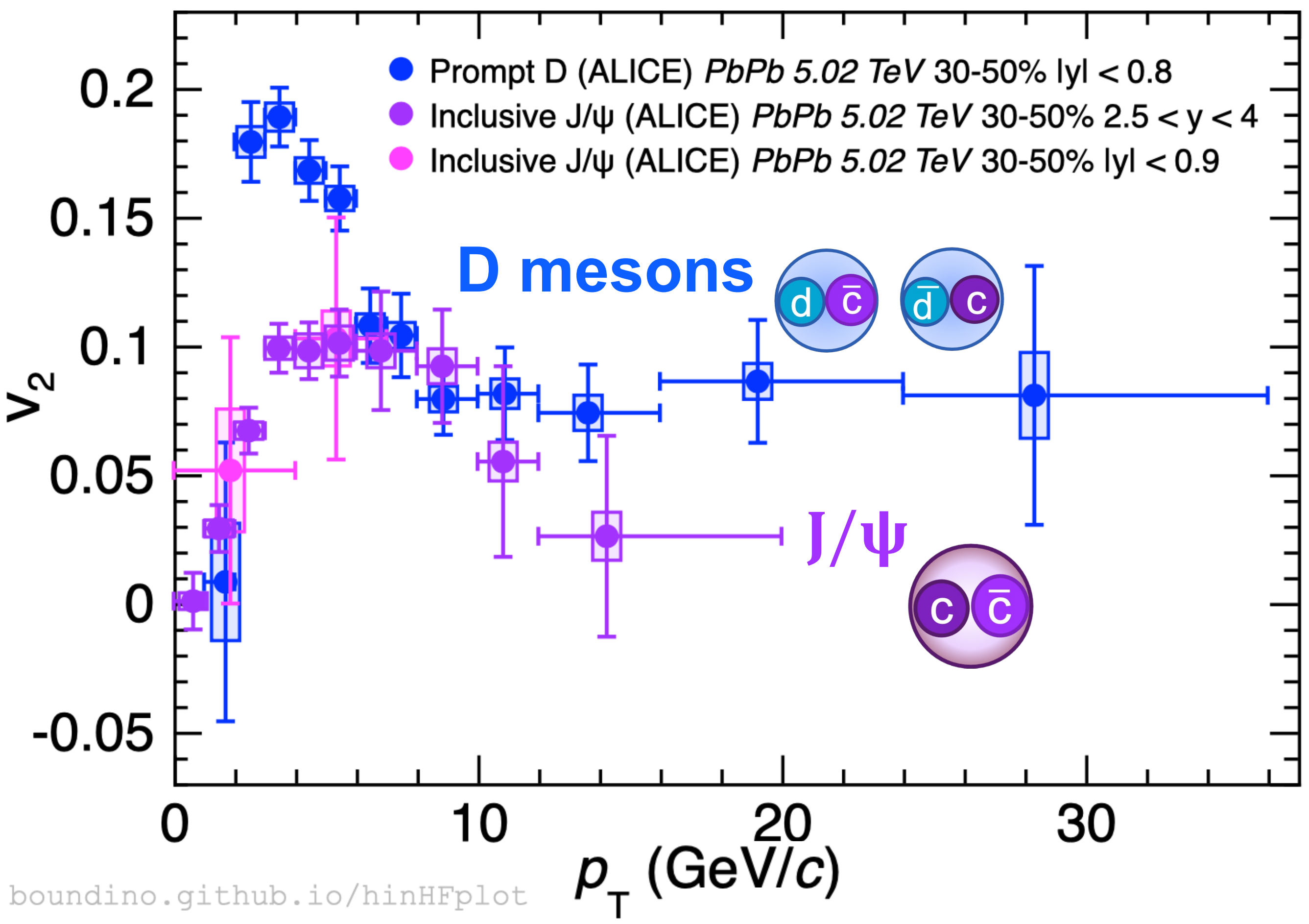
- **D mesons: lightest hadrons** with a **charm** quark
  → **Pronounced flow** attributed to the **thermalization of light quarks (u, d, s)** and **charm** quark in the **QGP**
- **J/ψ** : Significant **flow** at **mid** and **forward** rapidities
  → **Flow** at **low** p_T explained by **regenerated** J/ψ

Anisotropy of particle momentum distribution

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

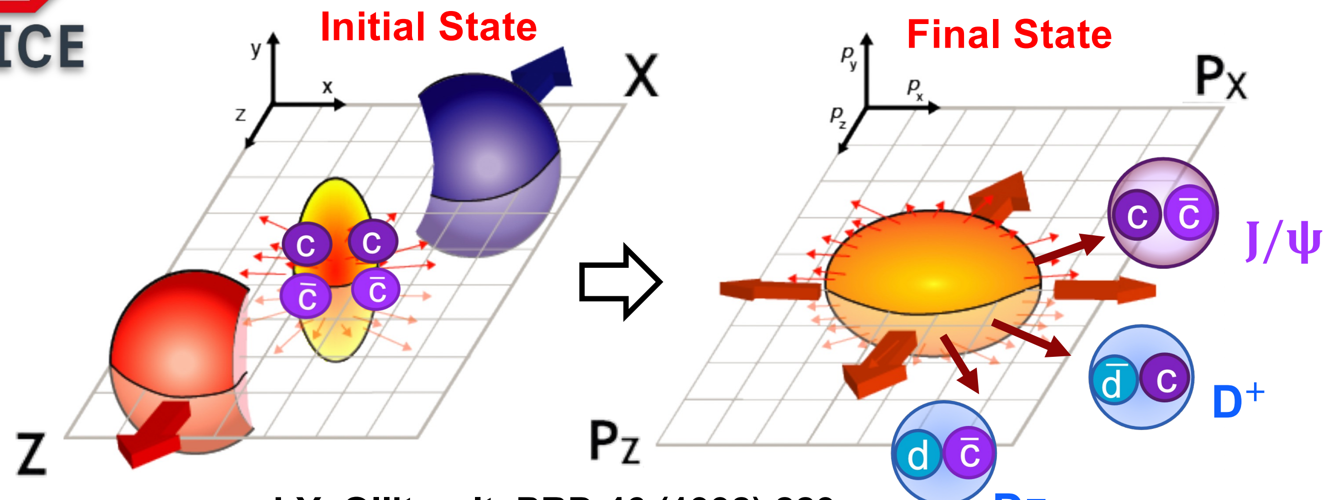
$$v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$





ALICE, PLB 813 (2021) 136054
ALICE, JHEP 10 (2020) 141

Collective flow of heavy-flavor/Quarkonia in Pb–Pb (Run 2)

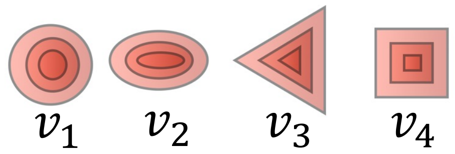


J-Y. Ollitrault, PRD 46 (1992) 229

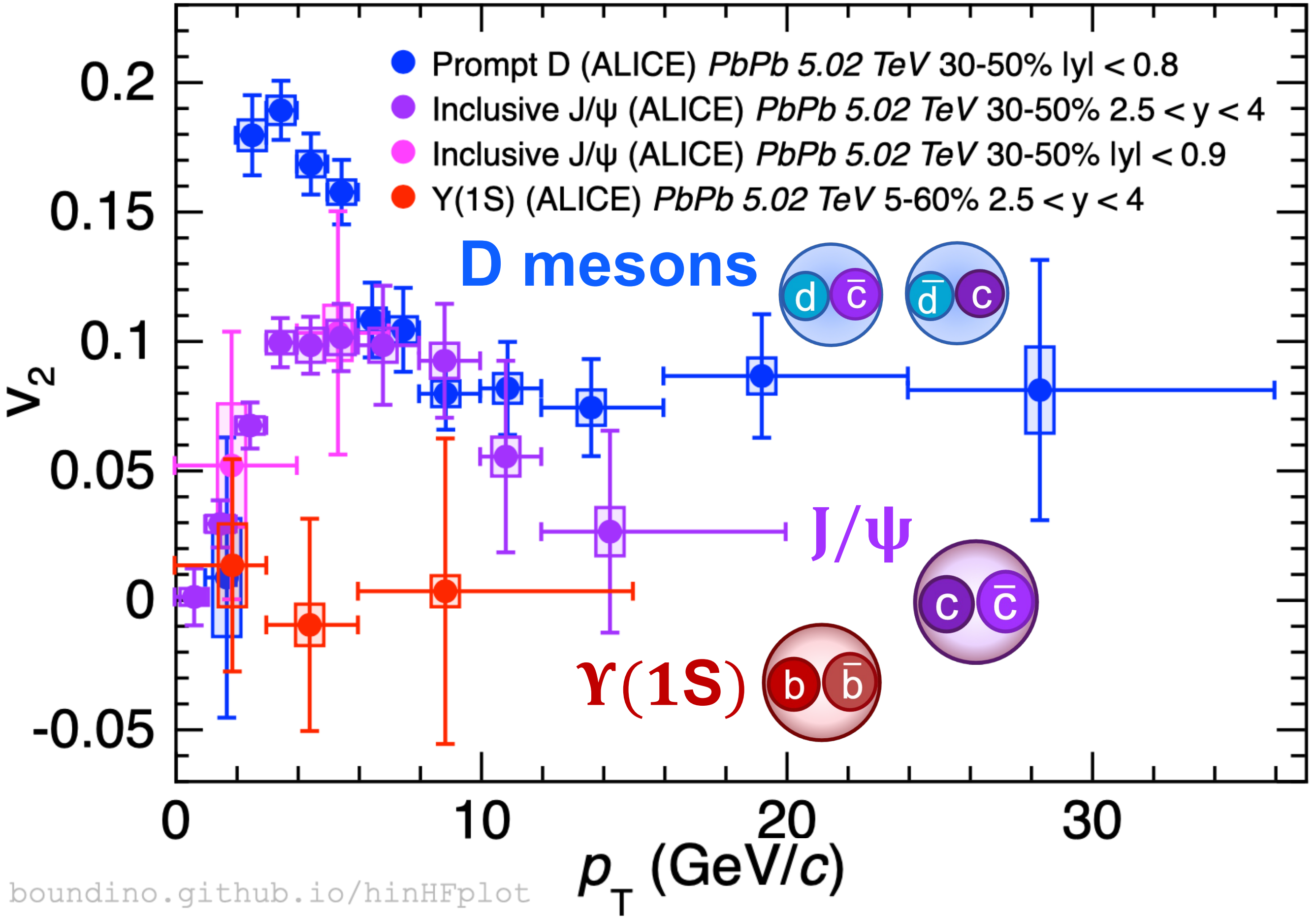
Anisotropy of particle momentum distribution

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

$$v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$

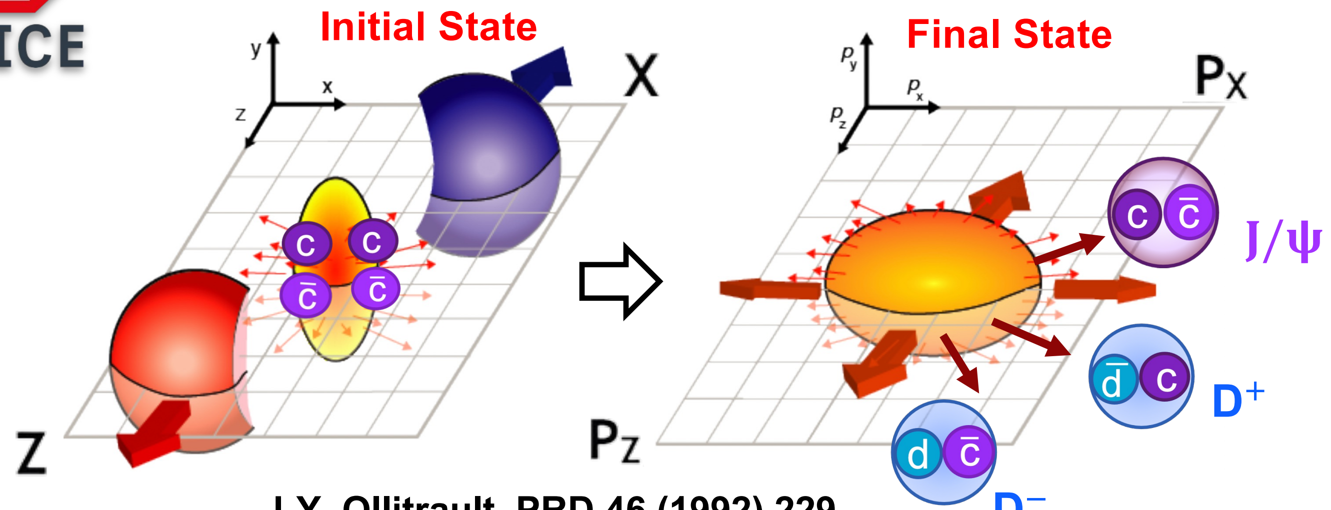


- **D mesons: lightest hadrons** with a **charm** quark
  → **Pronounced flow** attributed to the **thermalization of light quarks (u, d, s)** and **charm** quark in the **QGP**
- **J/ψ** : Significant **flow** at **mid** and **forward** rapidities
  → **Flow** at **low p_T** explained by **regenerated** J/ψ
- **ϒ(1S)**: Elliptic **flow compatible with zero**
  → Do beauty quarks **thermalize** in **QGP**?



ALICE, PLB 813 (2021) 136054
ALICE, JHEP 10 (2020) 141
ALICE, PRL 123 (2019) 192301

Collective flow of heavy-flavor/Quarkonia in Pb–Pb (Run 2)



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

- **D mesons: lightest hadrons** with a **charm** quark
  → **Pronounced flow** attributed to the **thermalization of light quarks (u, d, s)** and **charm** quark in the **QGP**
- J/ψ : Significant **flow** at **mid** and **forward** rapidities
  → **Flow** at **low p_{T}** explained by **regenerated** J/ψ
- **$\Upsilon(1\mathrm{S})$**: Elliptic **flow compatible with zero**
  → Do beauty quarks **thermalize** in **QGP**?

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

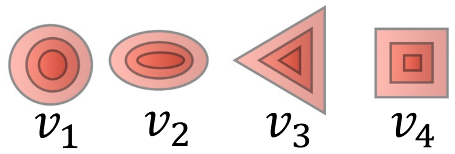
→ Charm quarks **exhibit** a **collective behaviour!**

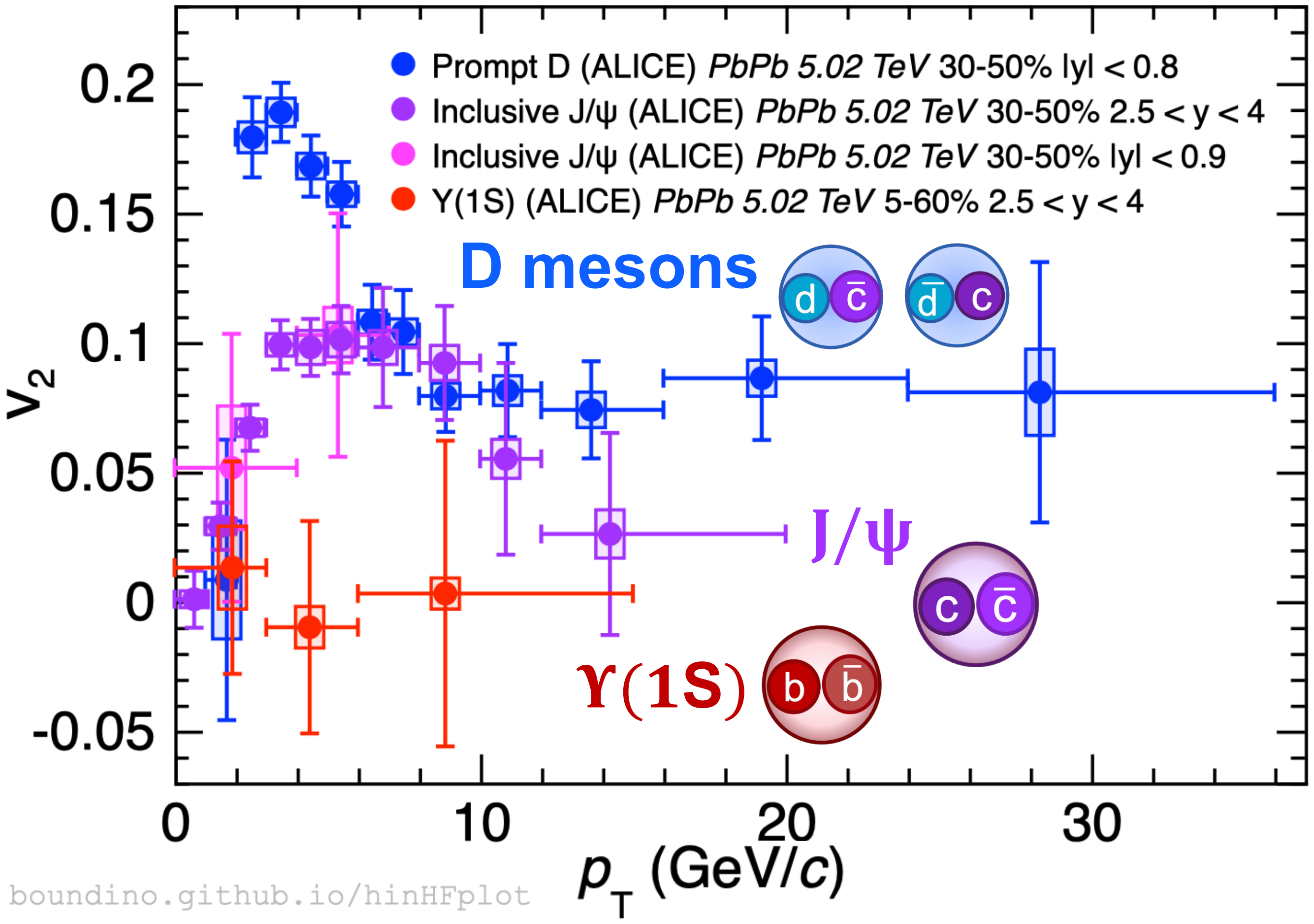
→ **What about smaller systems?**

Anisotropy of particle momentum distribution

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

$$v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$





ALICE, PLB 813 (2021) 136054
ALICE, JHEP 10 (2020) 141
ALICE, JHEP 10 (2020) 141
ALICE, PRL 123 (2019) 192301

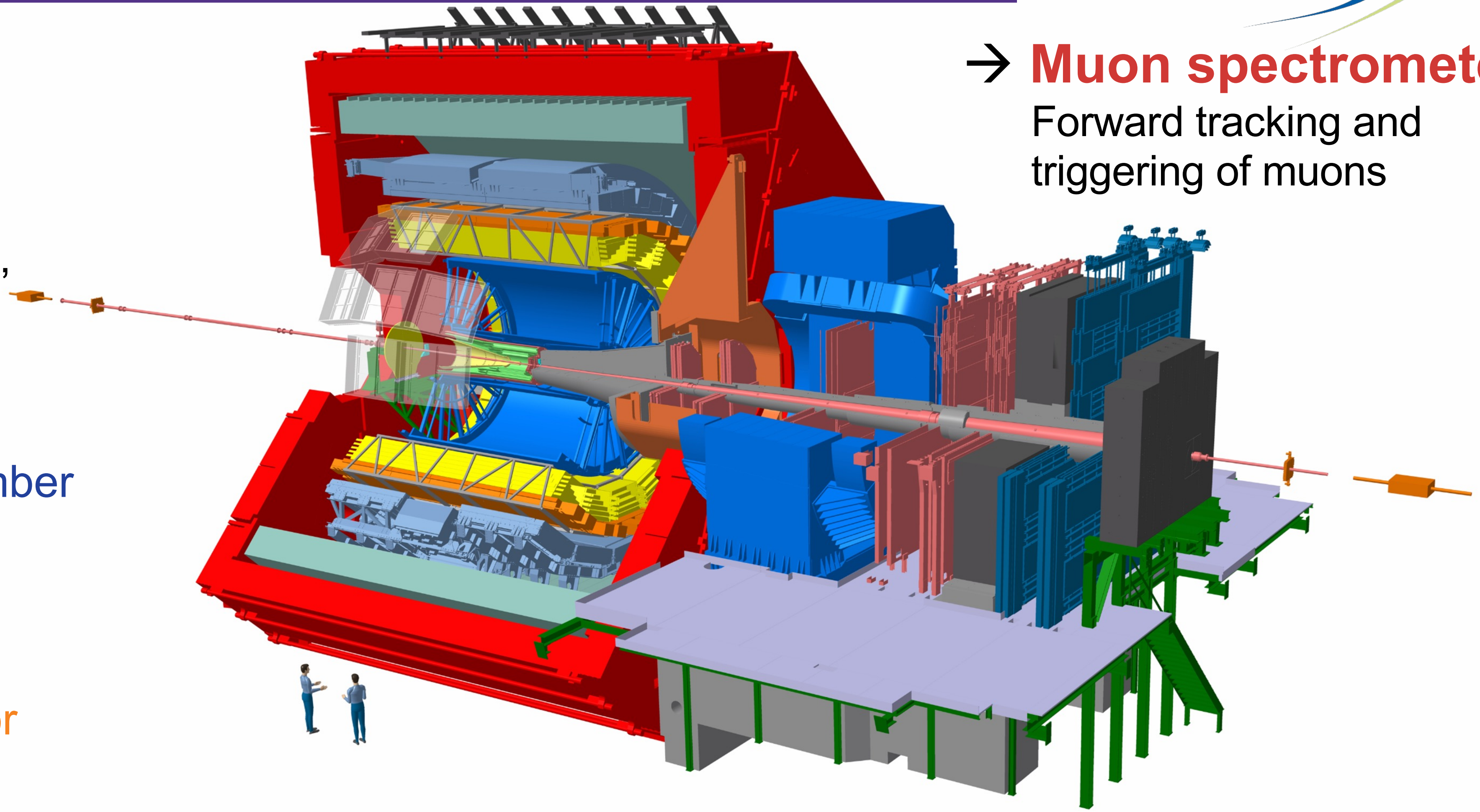
ALICE detector in Run 2

→ Central barrel

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

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

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

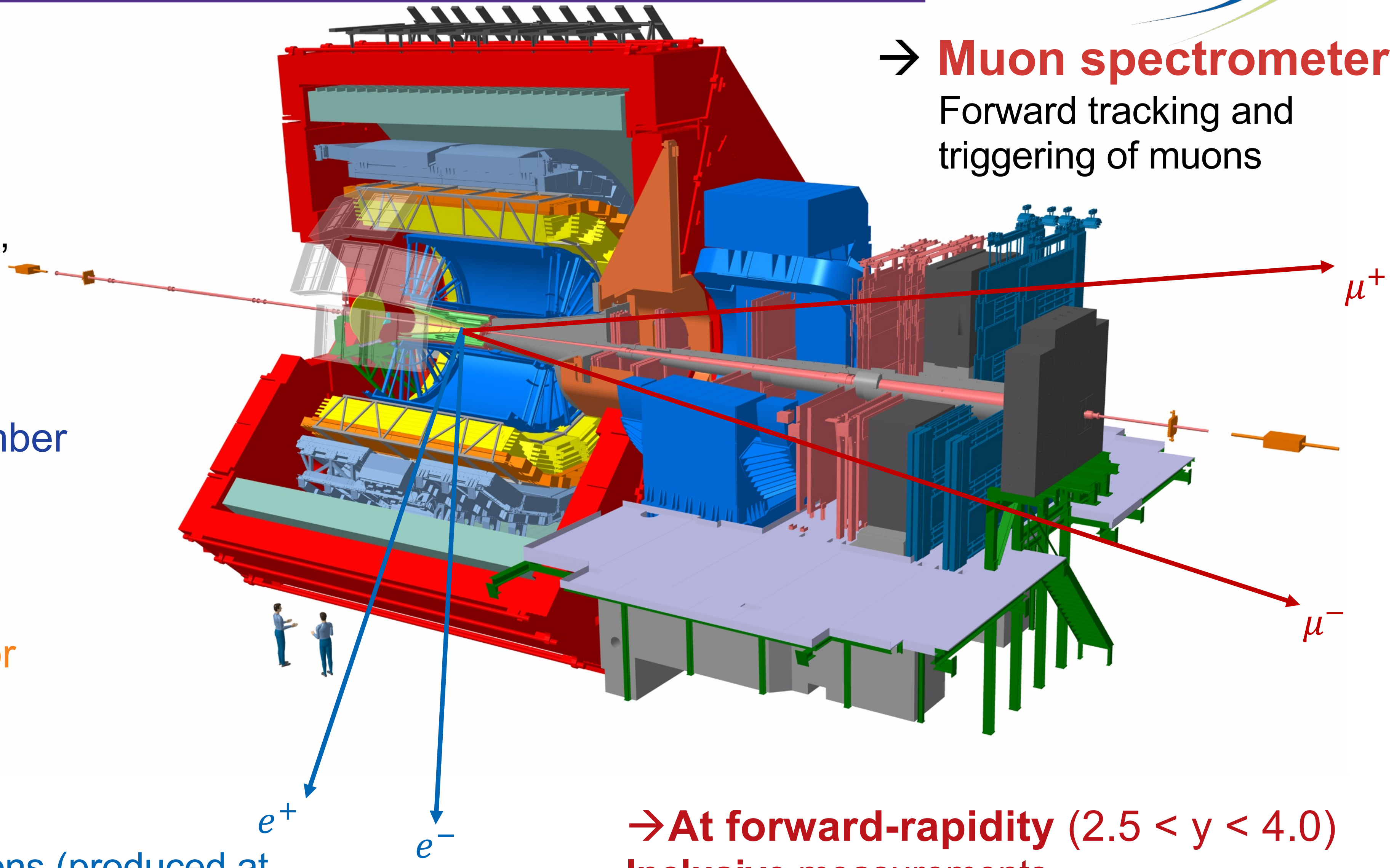


→ **Muon spectrometer**
Forward tracking and triggering of muons

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

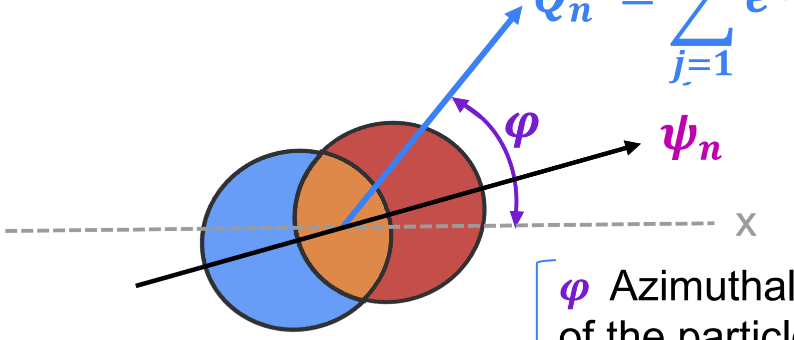
→At mid-rapidity (|y| < 0.9)
Distinction between **prompt** hadrons (produced at primary vertex) and **non-prompt** (b-hadron decays)

→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**

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



→ Q-vector Q_n

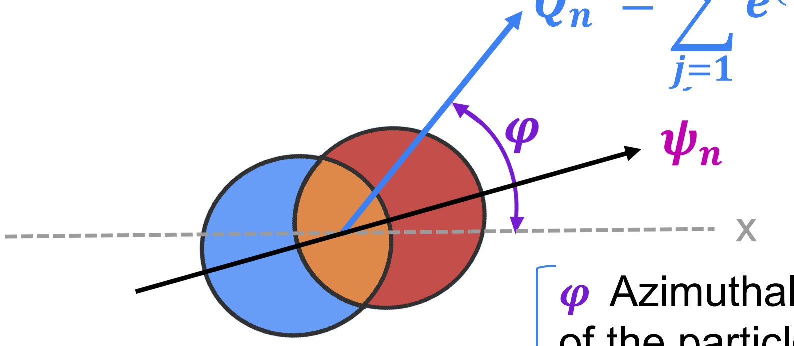
- φ Azimuthal angle of the particle
- M_A Multiplicity of the collision

→ ψ_n symmetry plane

→ Flow measurements: **analysis techniques**

- **Event plane** $v_n\{EP\} = \langle\langle \cos n(\varphi - \psi_n)\rangle / R_n^{EP}\rangle$

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



→ Q-vector Q_n

- φ Azimuthal angle of the particle
- M_A Multiplicity of the collision

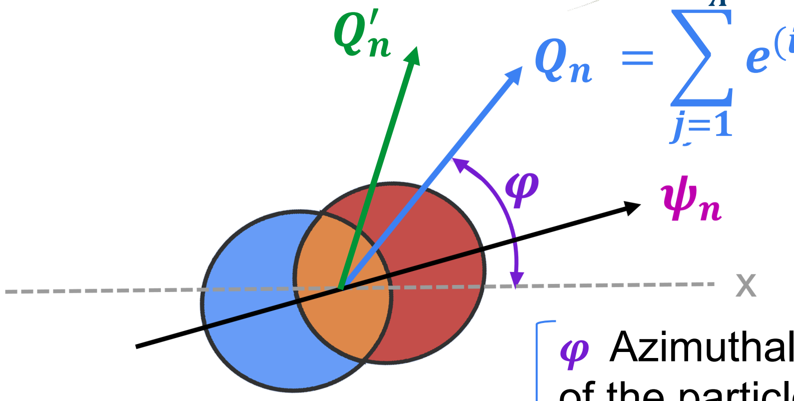
→ ψ_n symmetry plane

→ Flow measurements: **analysis techniques**

- **Event plane** $v_n\{EP\} = \langle\langle \cos n(\varphi - \psi_n)\rangle / R_n^{EP}\rangle$

- **Scalar product** $v'_n\{SP\} = \left\langle \langle Q'_n Q_n^{*}\rangle / R_n^{SP} \right\rangle$

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



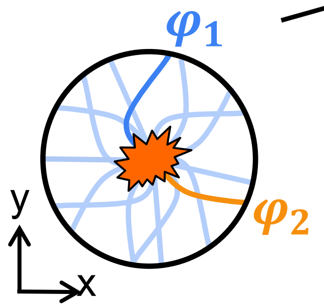
→ Q-vector Q_n

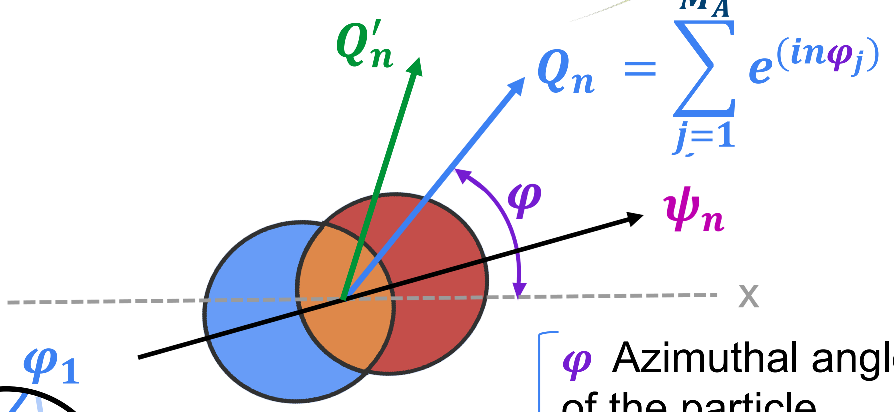
- φ Azimuthal angle of the particle
- M_A Multiplicity of the collision

→ ψ_n symmetry plane

→ Flow measurements: **analysis techniques**

- **Event plane** $v_n\{EP\} = \langle\langle \cos n(\varphi - \psi_n)\rangle / R_n^{EP}\rangle$
- **Scalar product** $v'_n\{SP\} = \left\langle \langle Q'_n Q_n^* \rangle / R_n^{SP} \right\rangle$
- **Two-particle correlation** $v_n\{2PC\}^2 = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$



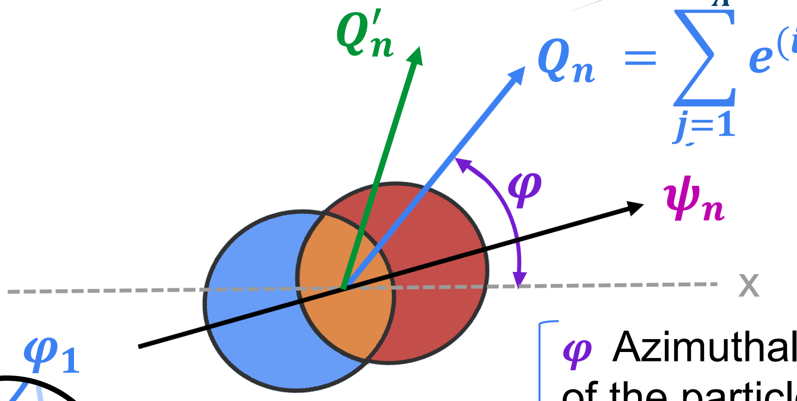


→ Q-vector Q_n
- φ Azimuthal angle of the particle
- M_A Multiplicity of the collision

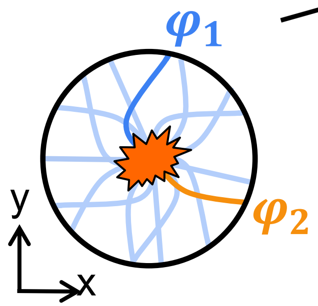
→ ψ_n symmetry plane

→ Flow measurements: **analysis techniques**

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



- **Event plane** $v_n\{EP\} = \langle\langle \cos n(\varphi - \psi_n)\rangle / R_n^{EP}\rangle$
- **Scalar product** $v'_n\{SP\} = \left\langle \langle Q'_n Q_n^* \rangle / R_n^{SP} \right\rangle$
- **Two-particle correlation** $v_n\{2PC\}^2 = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$



→ Q-vector Q_n

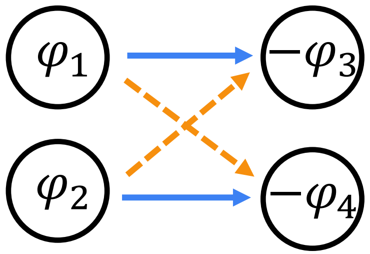
- φ Azimuthal angle of the particle
- M_A Multiplicity of the collision

→ ψ_n symmetry plane

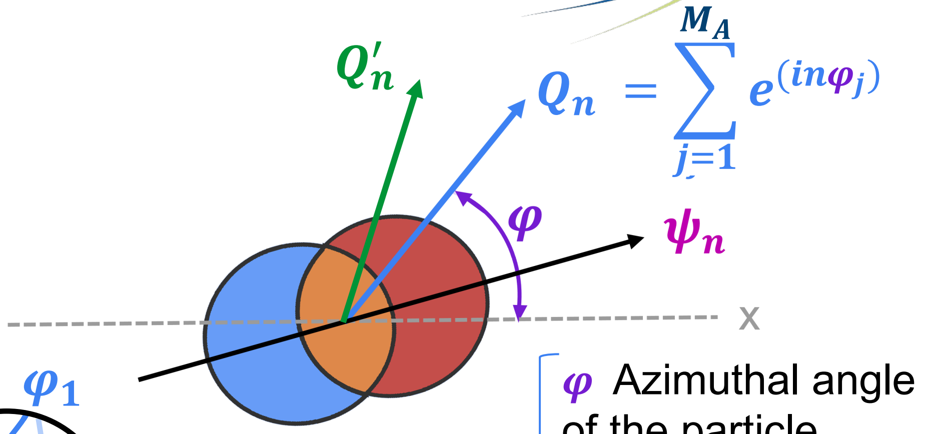
- **Multi-particle cumulant** $c_n\{4\} = -v_n\{4\}^4 = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$

$$-\langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle \langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

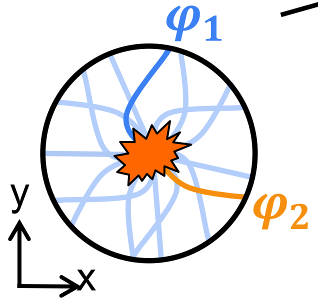
$$-\langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle \langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle$$



→ Flow measurements: **analysis techniques**



- **Event plane** $v_n\{EP\} = \langle\langle \cos n(\varphi - \psi_n)\rangle / R_n^{EP}\rangle$
- **Scalar product** $v'_n\{SP\} = \left\langle \langle Q'_n Q_n^* \rangle / R_n^{SP} \right\rangle$
- **Two-particle correlation** $v_n\{2PC\}^2 = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$

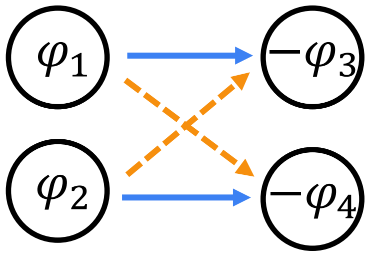


→ Q-vector Q_n
- φ Azimuthal angle of the particle
- M_A Multiplicity of the collision

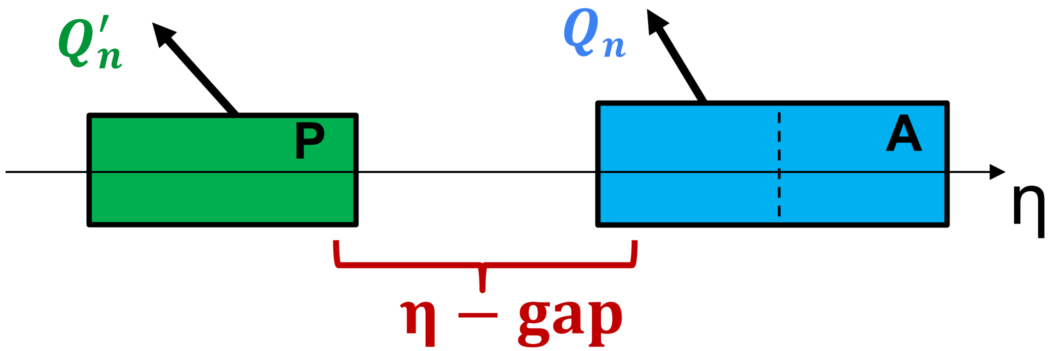
→ ψ_n symmetry plane

- **Multi-particle cumulant** $c_n\{4\} = -v_n\{4\}^4 = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$

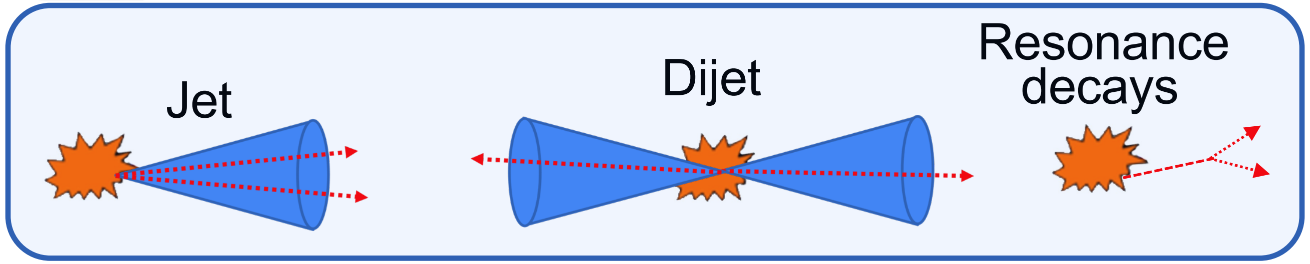
$$-\langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle \langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$
$$-\langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle \langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle$$



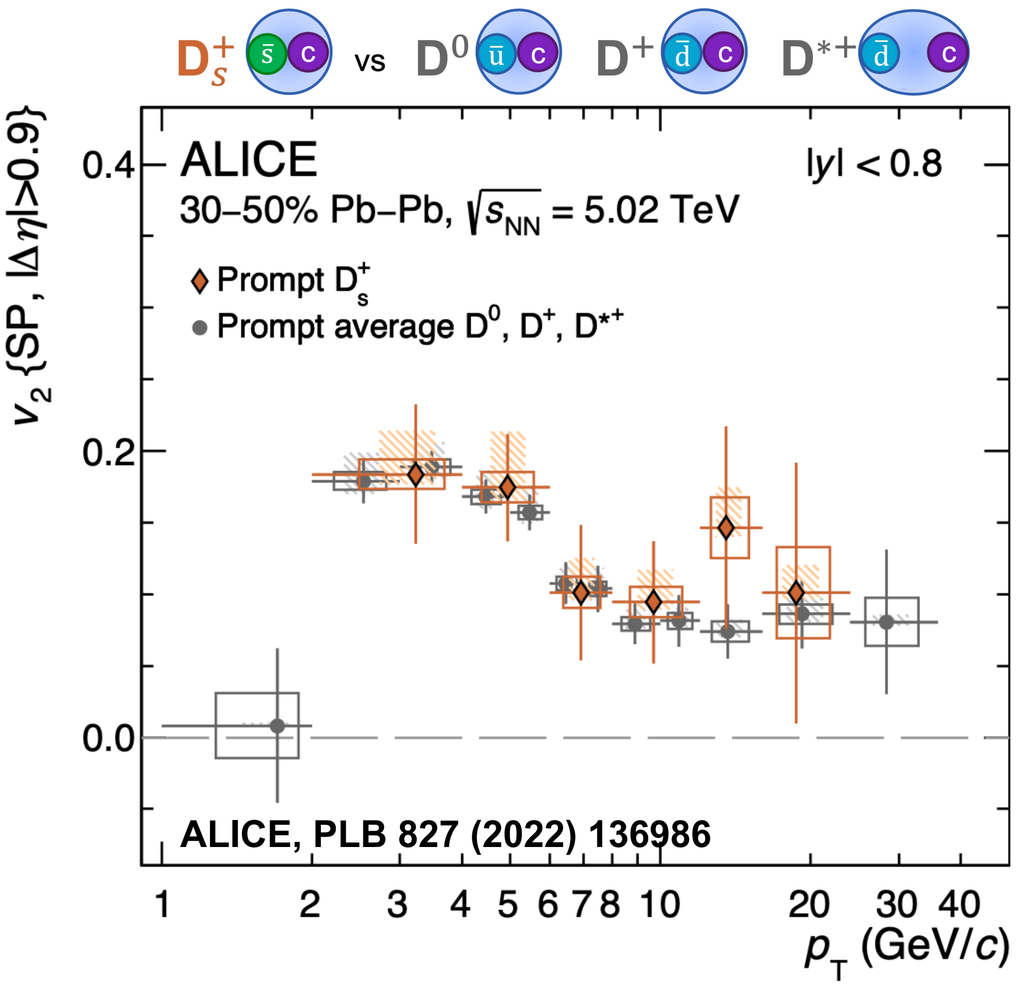
→ **η − gap** between measured particles suppresses **non−flow effects**



⚠ **Non-flow effects**

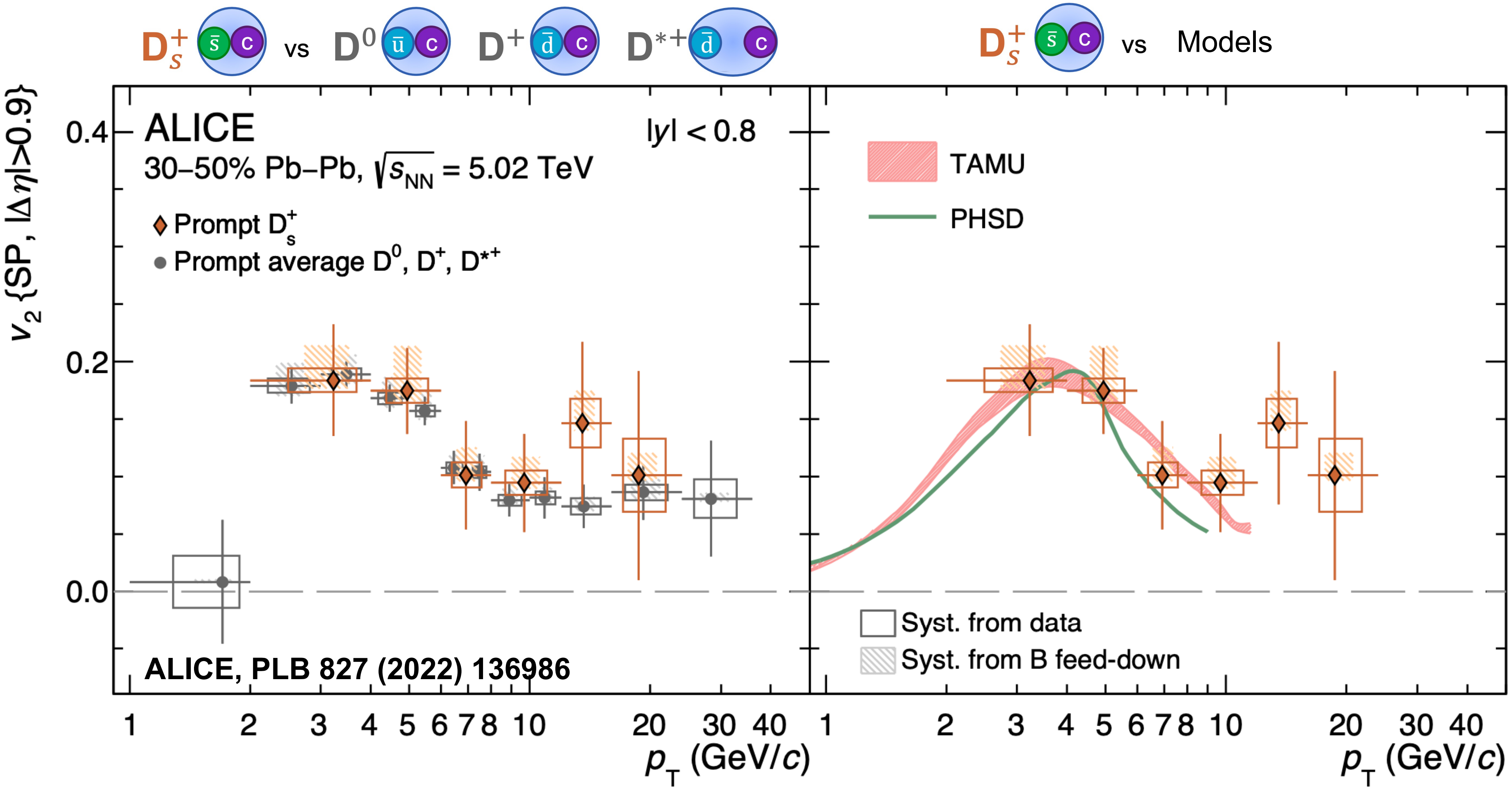


v_2 of *prompt* D_s^+ mesons in **Pb–Pb** collisions (Run 2)



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

v_2 of *prompt* D_s^+ mesons in **Pb–Pb** collisions (Run 2)



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

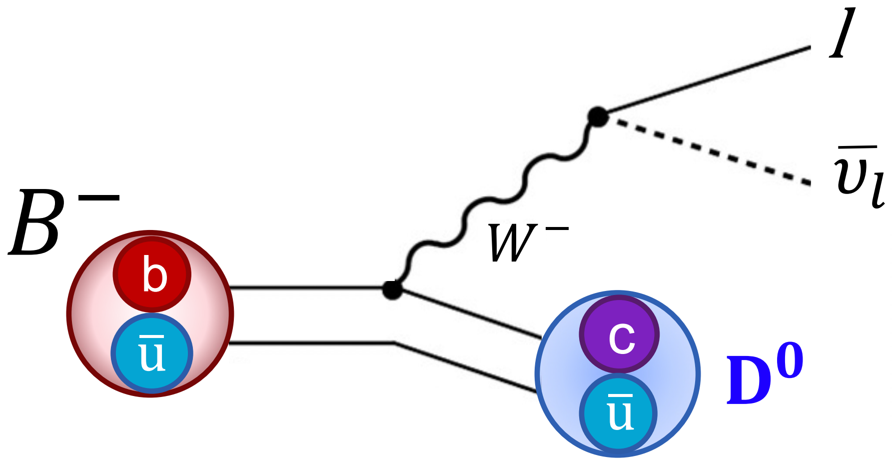
→ Theoretical **calculations** are based on the **charm–quark transport** in a **hydrodynamically** expanding **QGP**

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**

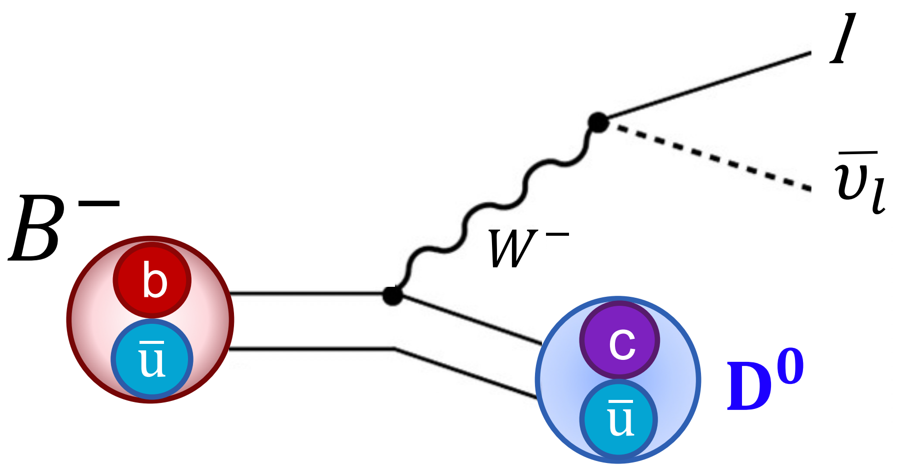
→ Possibility to **probe hadronization via coalescence**

v_2 of *non-prompt* $\mathbf{D^0}$ mesons in **Pb–Pb** collisions (Run 2)



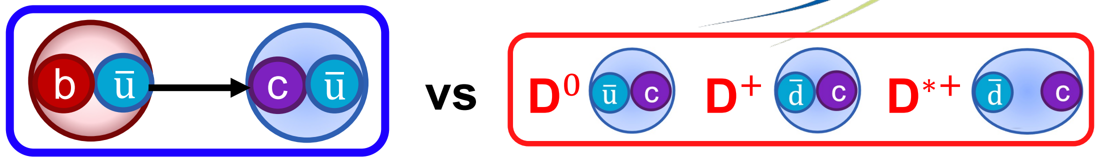
ALICE

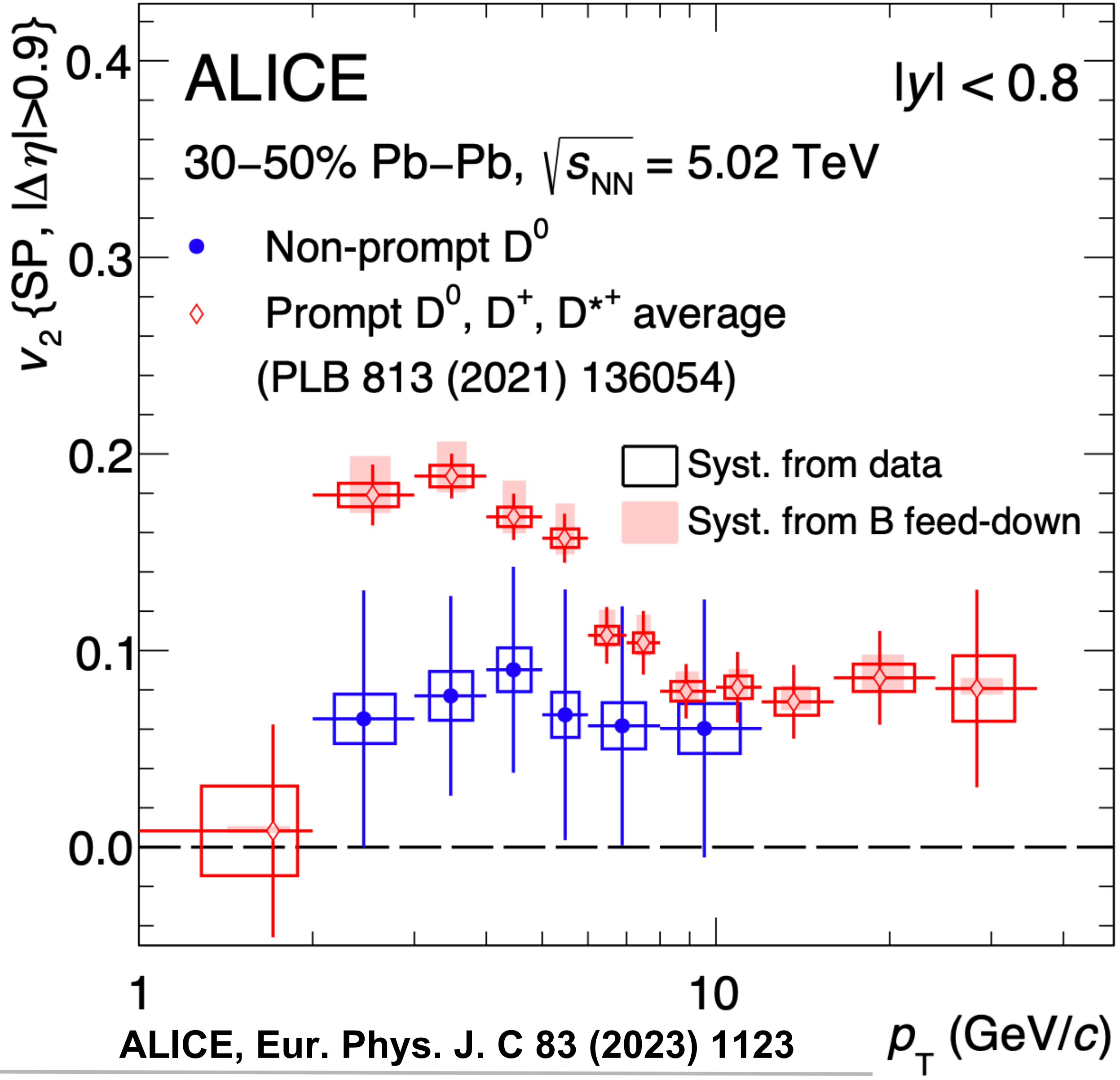
v_2 of *non−prompt* $\mathbf{D^0}$ mesons in **Pb–Pb** collisions (Run 2)



→ The **non-prompt $\mathbf{D^0}$-meson** v_2 is found to be **positive** with a significance of 2.7σ

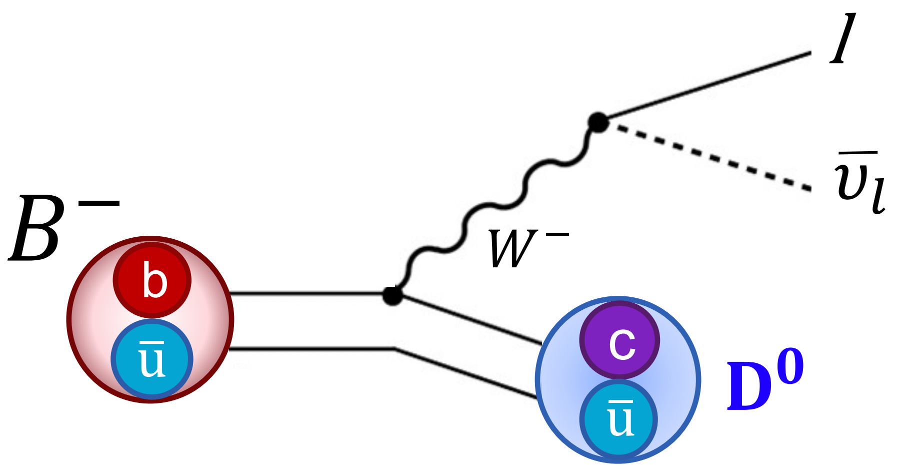
→ **Non-prompt $\mathbf{D^0}$** is **lower** by 3.2σ **than prompt D-meson** v_2 in the range 2 < p_T < 8 GeV/c

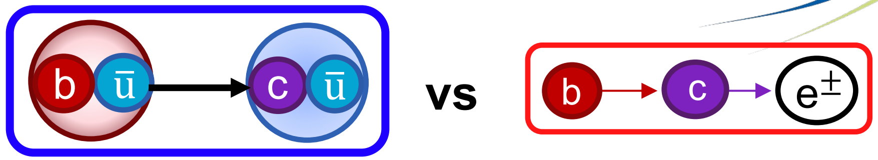


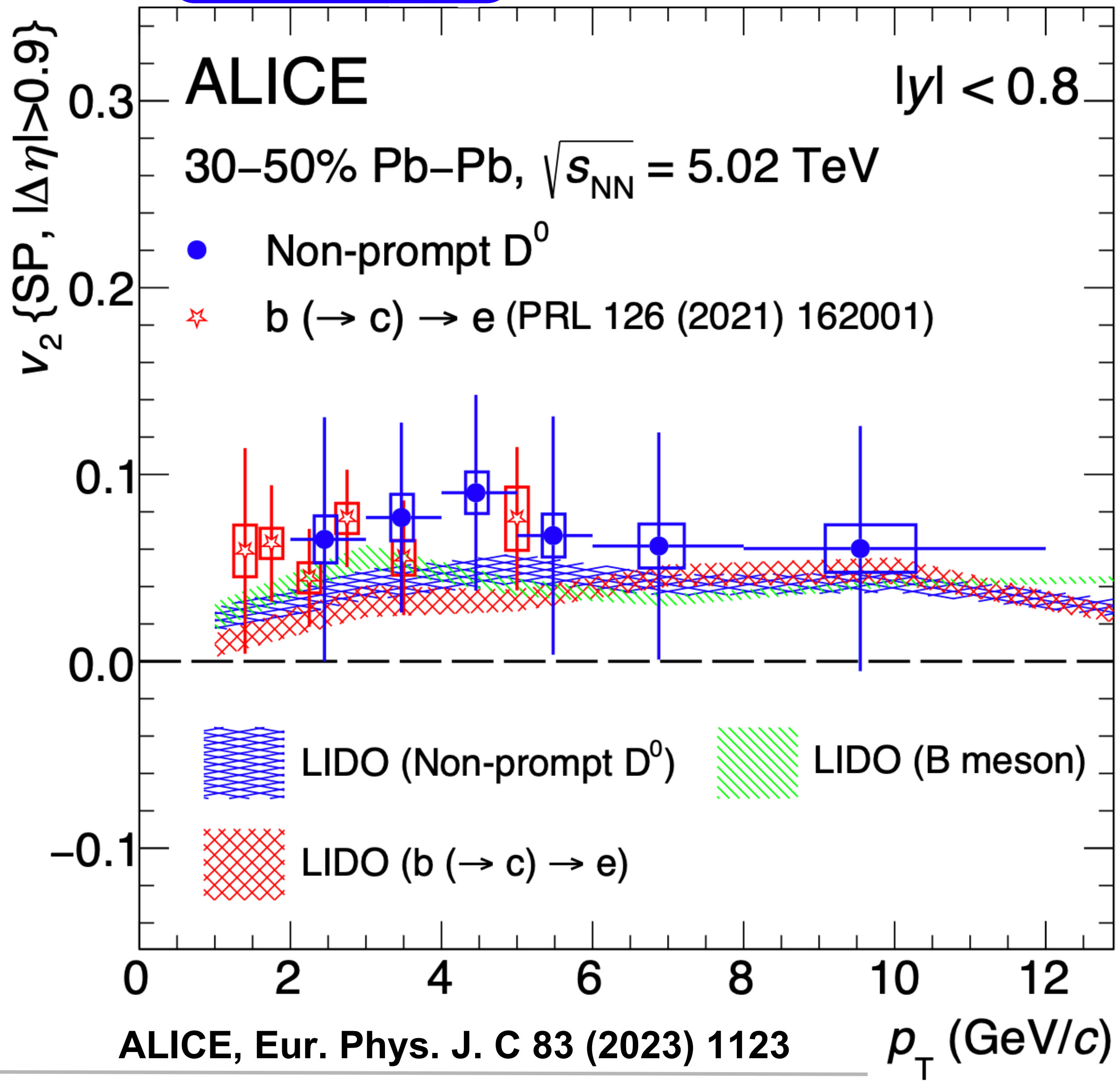


ALICE, Eur. Phys. J. C 83 (2023) 1123

v_2 of *non−prompt* $\mathbf{D^0}$ mesons in **Pb–Pb** collisions (Run 2)







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

→ The **non-prompt $\mathbf{D^0}$-meson** v_2 is found to be **positive** with a significance of 2.7σ

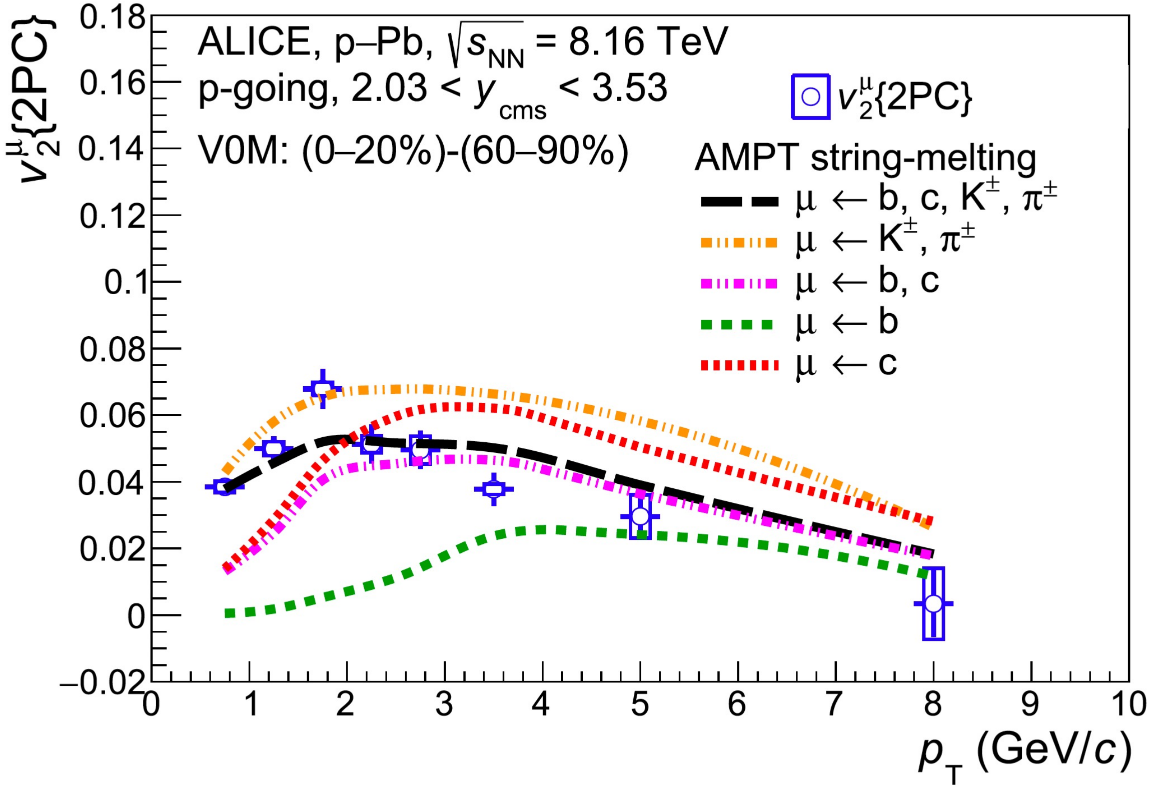
→ **Non-prompt $\mathbf{D^0}$** is **lower** by 3.2σ **than prompt D-meson** v_2 in the range 2 < p_T < 8 GeV/c

→ **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**

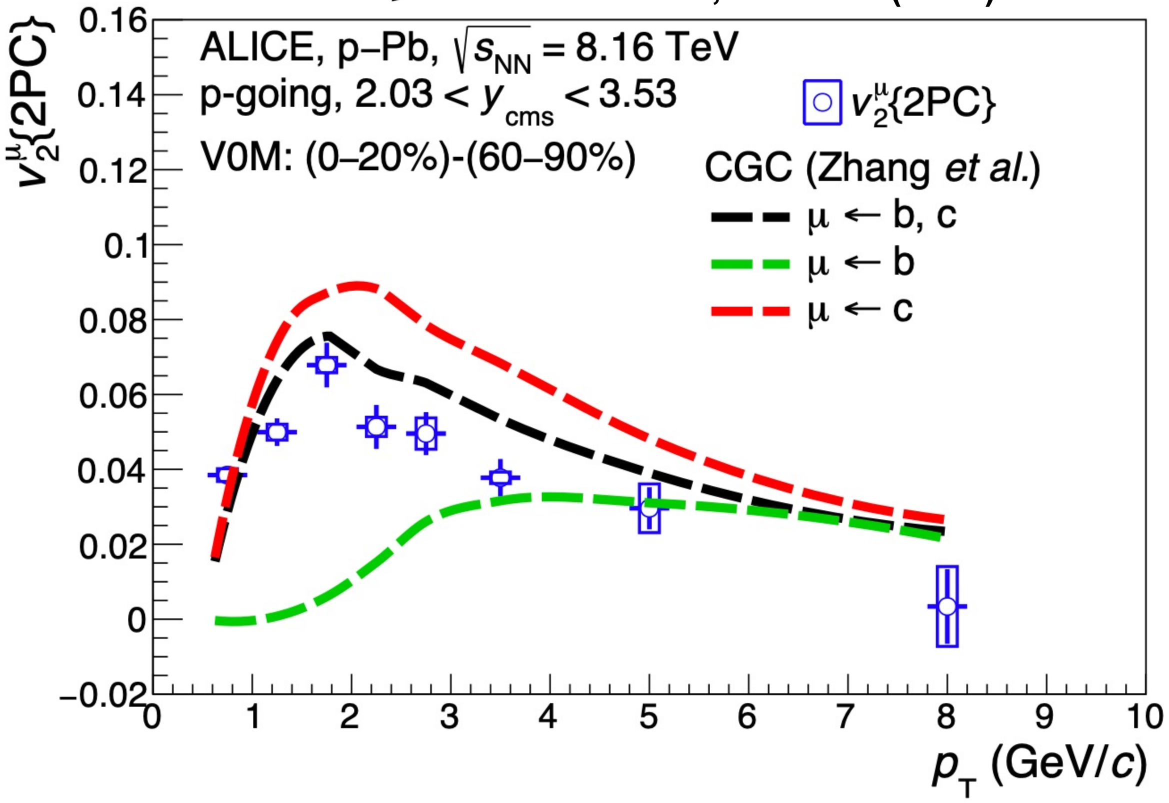
→ **Decay kinematics doesn't seem to play** a significant role in the **beauty-hadron** v_2 measurements.

Inclusive muon v_2 from hadron decays in p–Pb (Run 2)

Forward-rapidity (p-going)



ALICE, PLB 846 (2023) 137782

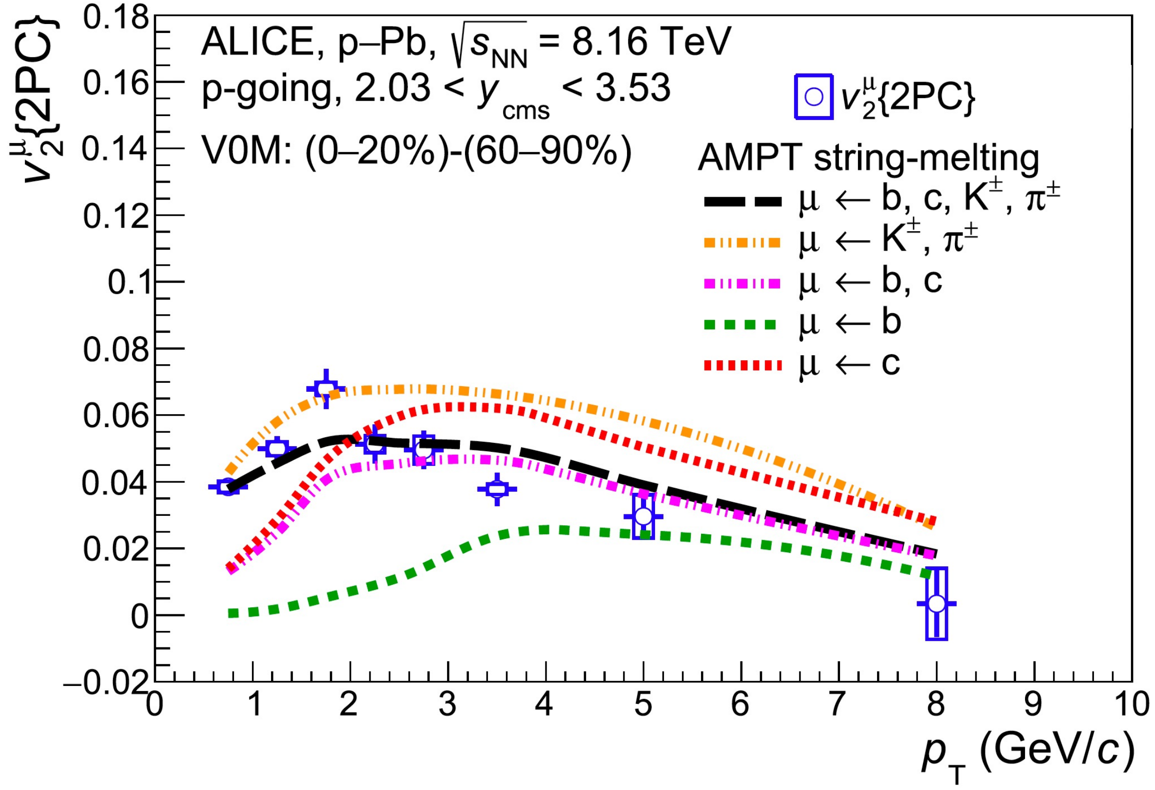


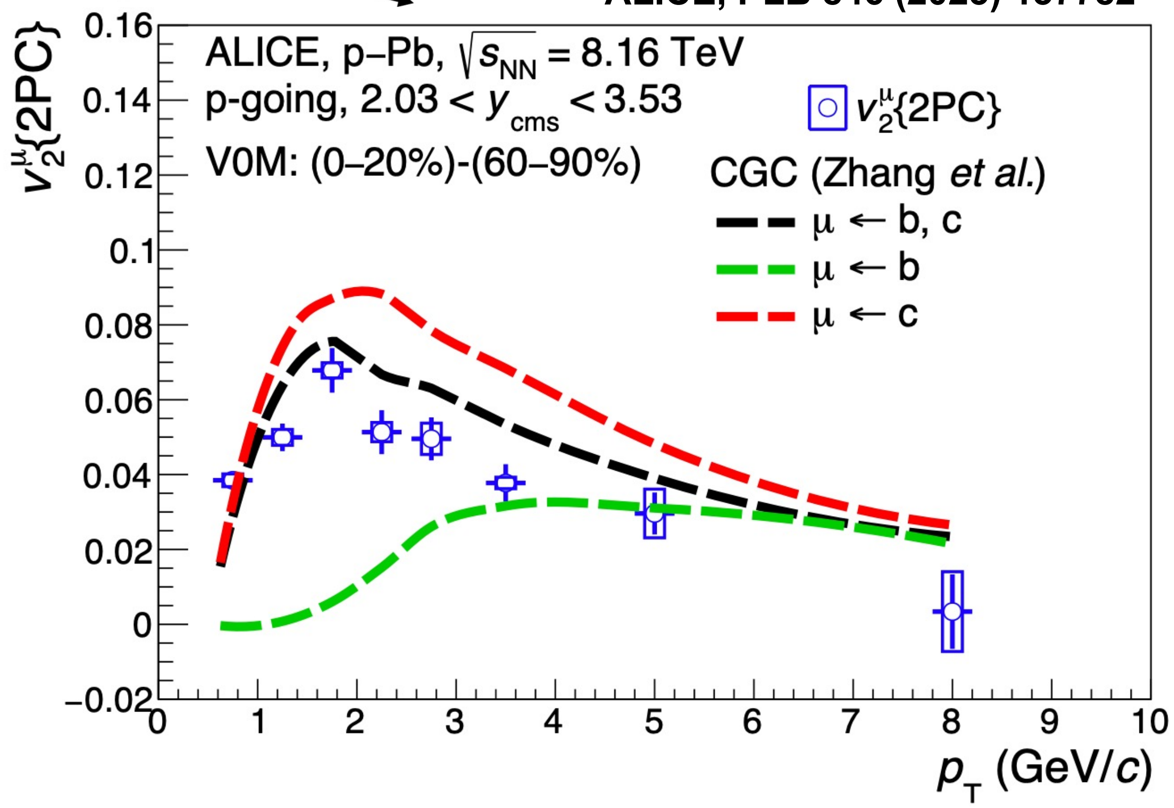
victor.valencia.torres@cern.ch

Inclusive muon v_2 from hadron decays in p–Pb (Run 2)

Forward-rapidity (p-going)

ALICE, PLB 846 (2023) 137782





- **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

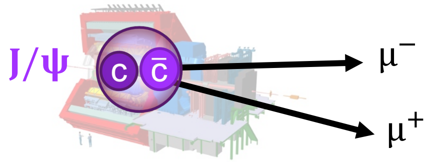
→**CGC (Color Glass Condensate model)**
Cheng Zhang et al, PRC 122 (2019) 172302

Models reproduce the **data** qualitatively

Flow of J/ψ from large to small systems (Run 2)

❖ Collective behavior in **Pb–Pb collisions**

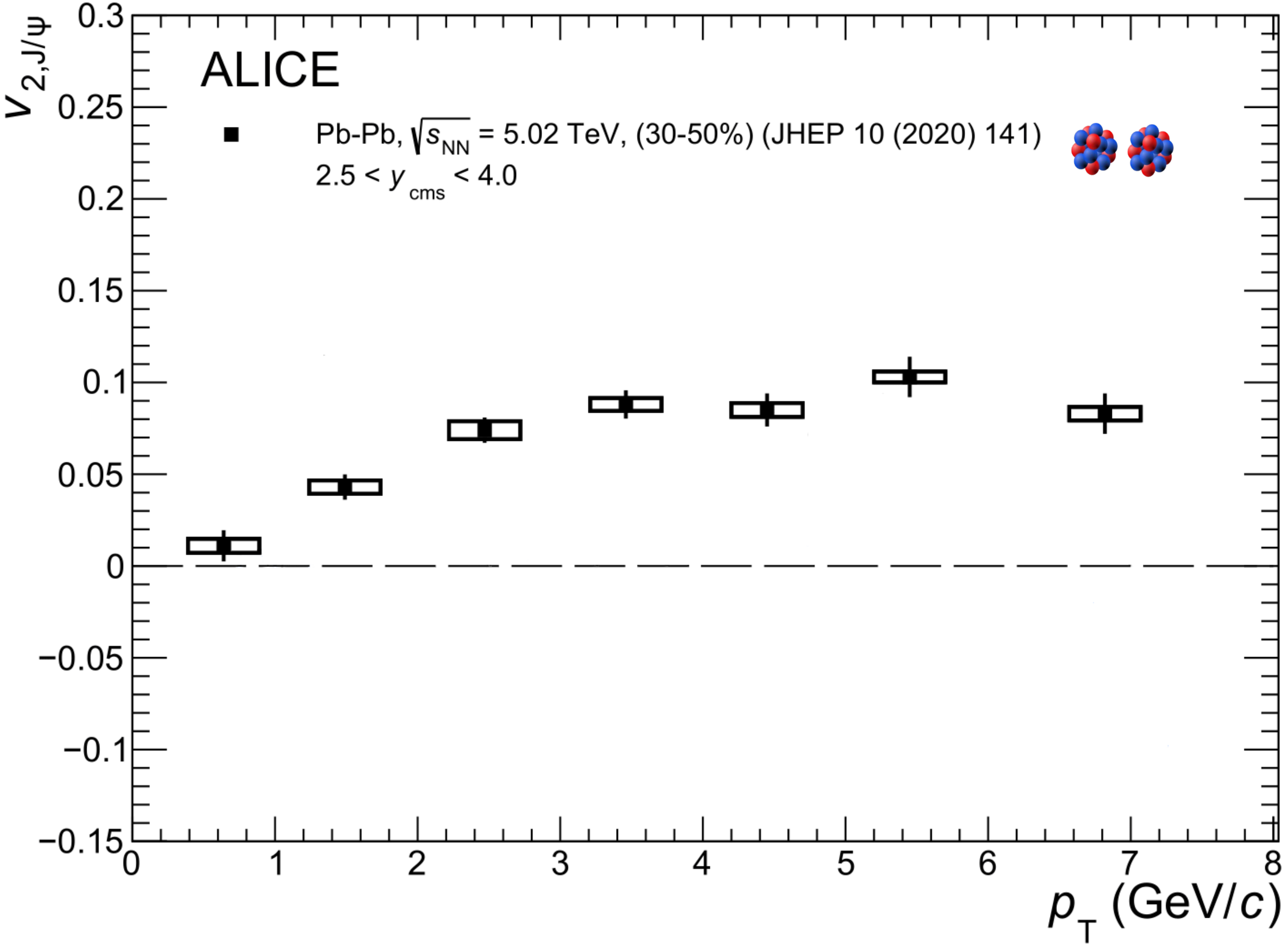
Flow of J/ψ from large to small systems (Run 2)



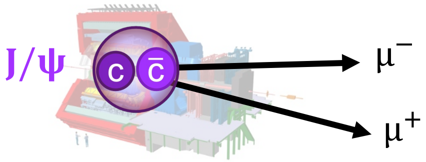
- Collective behavior in **Pb–Pb collisions**
  - **Significant J/ψ v_2** over a wide p_T range

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

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



Flow of J/ψ from large to small systems (Run 2)



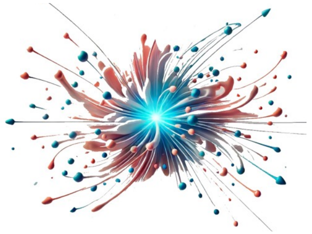
❖ Collective behavior in **Pb–Pb collisions**

- **Significant J/ψ v_2** over a wide p_T range

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

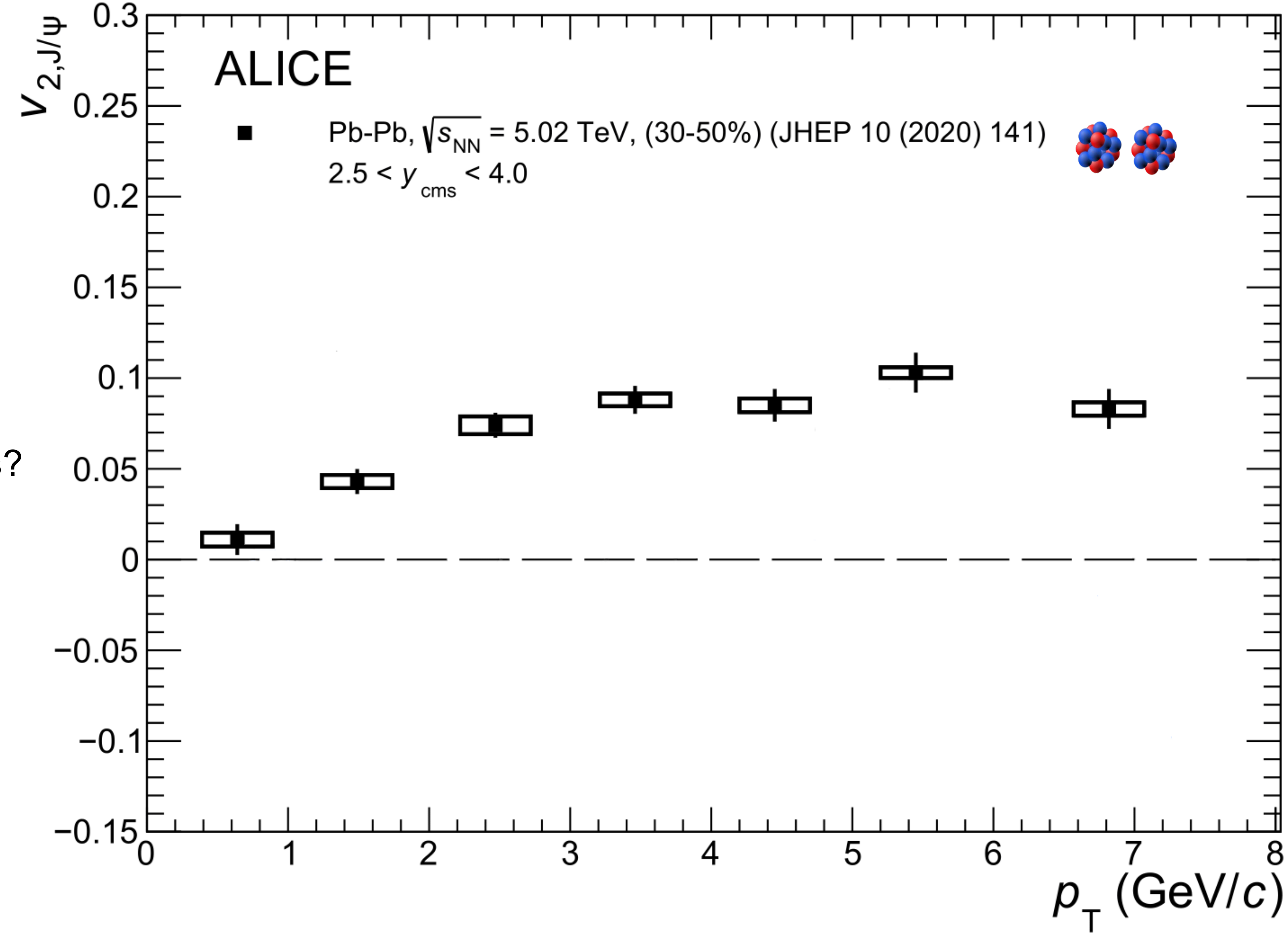
→ Result support **thermalization of charm quarks** in the **QGP**

❖ Collective behavior in **small systems?**

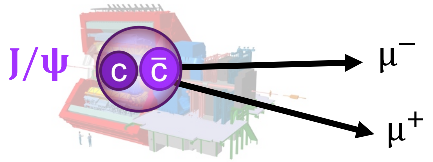


→ **Initial** state **dynamics effects**?

→ **QGP** in **small systems**?



Flow of J/ψ from large to small systems (Run 2)



- ❖ 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**

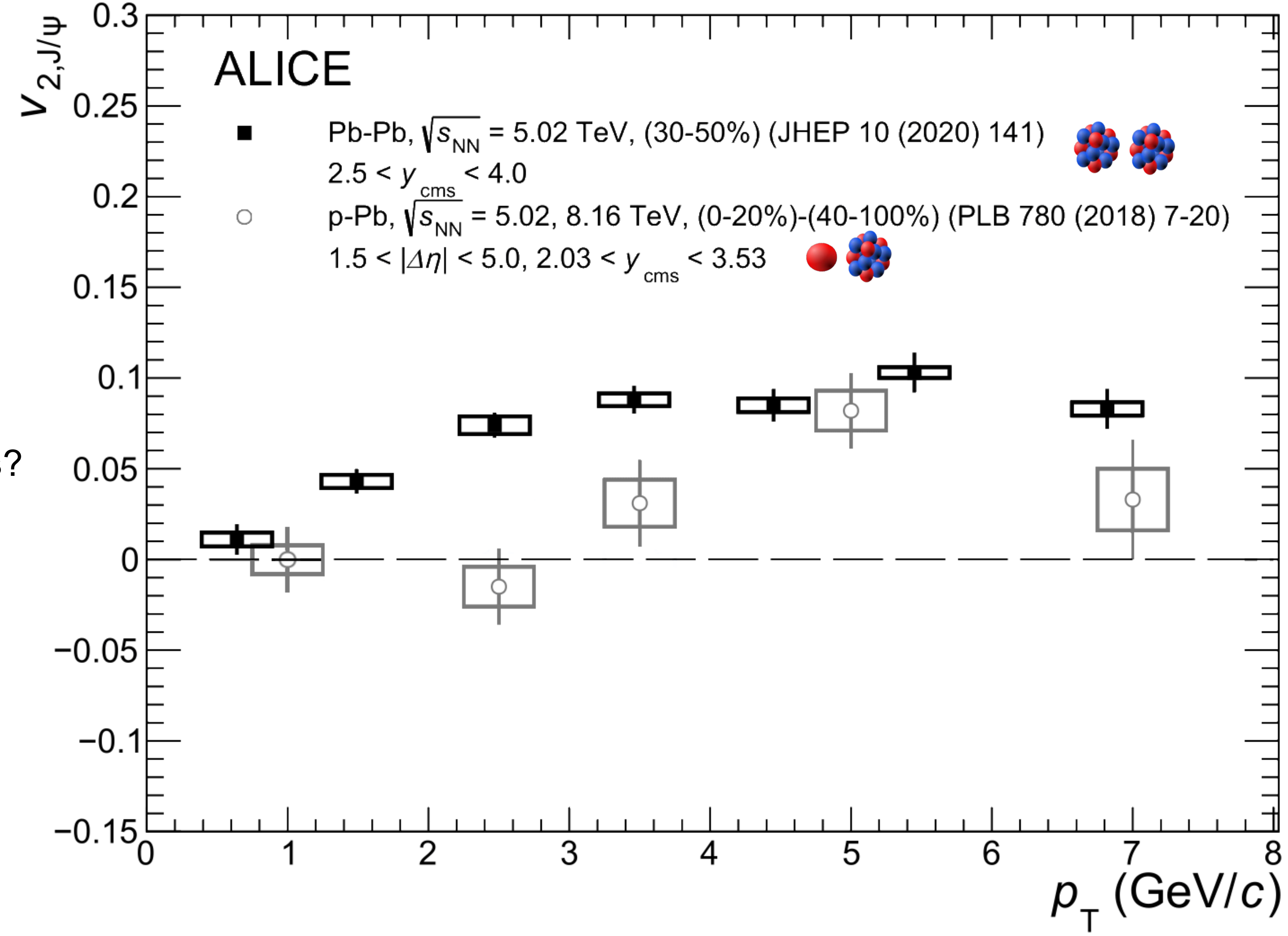
  → Result support **thermalization of charm quarks** in the **QGP**

- ❖ Collective behavior in **small systems?**

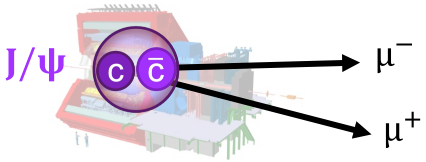
  → **Initial** state **dynamics effects**?

  → **QGP** in **small systems**?

- ○ **Non-negligible J/ψ** v_2 at **high p_T** in **p–Pb collisions**



Flow of J/ψ from large to small systems (Run 2)

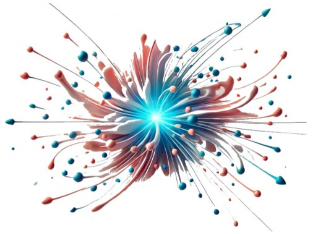


- Collective behavior in **Pb–Pb collisions**
  - **Significant J/ψ v_2** over a wide p_T range

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

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

- Collective behavior in **small systems?**



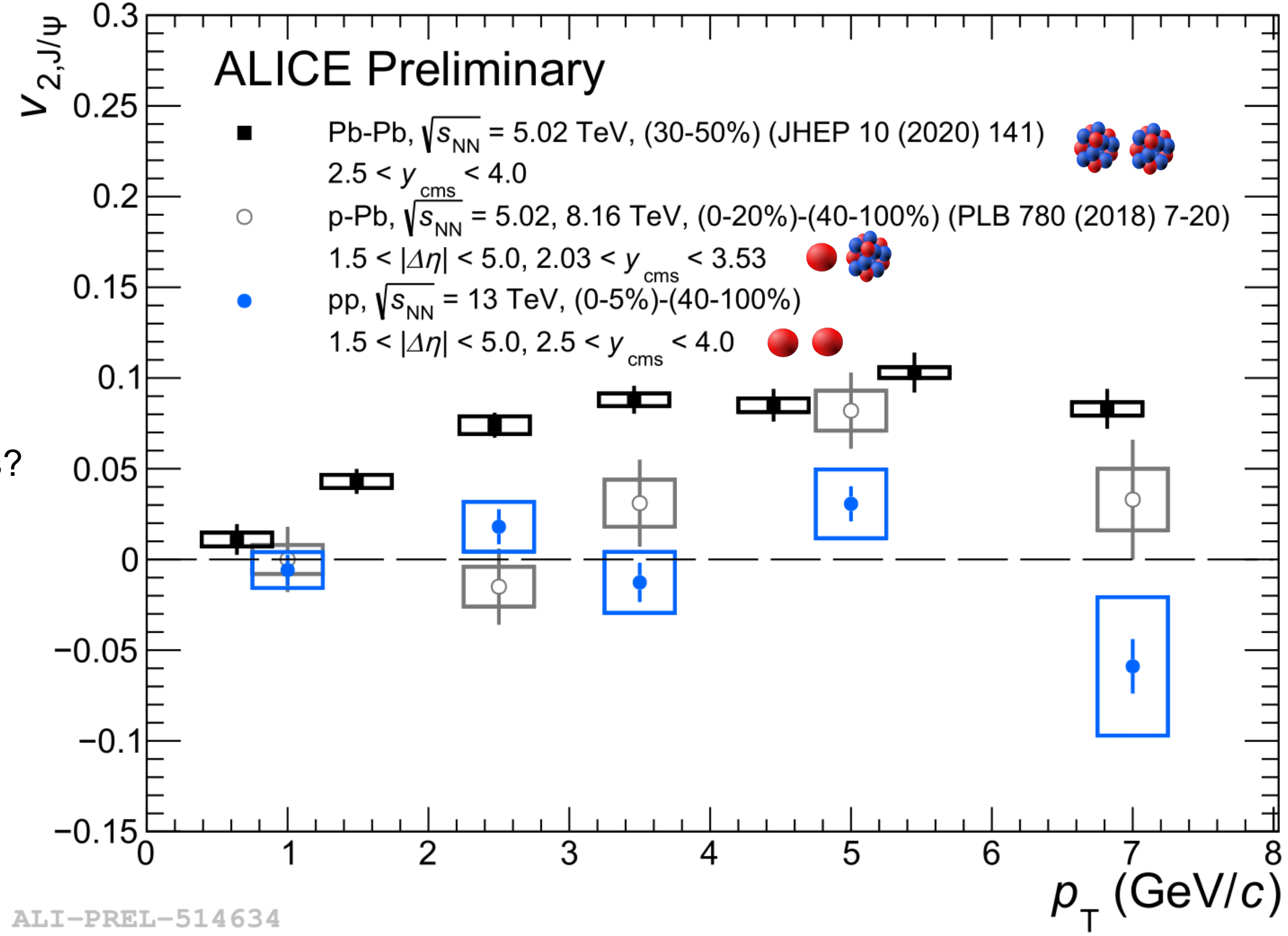
→ **Initial** state **dynamics effects**?

→ **QGP** in **small systems**?

○ **Non-negligible J/ψ v_2** at **high p_T** in **p–Pb collisions**

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

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



v_2 from large to small systems in Run 2

Pb–Pb

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

- All **prompt D meson flow similarly**!

J/ψ (c $\bar{c}$)

- **Significant** J/ψ v_2 is observed (**Regeneration** at **low** p_T)

→Results support the **charm quark thermalization** scenario **in QGP.**

$\Upsilon(1S)$ (b $\bar{b}$)

- Elliptic **flow** of $\Upsilon(1S)$ compatible with **zero.**

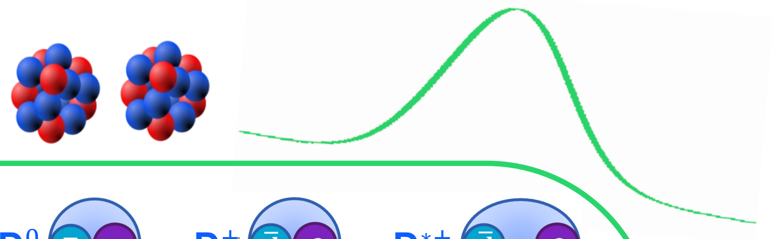
B^- (b $\bar{u}$) → ($\bar{u}$ c) D^0

- **Non-prompt** D_0 −meson v_2 is **positive.**

→ **Transport models** describe the **measurement** within uncertainties.

v_2 from large to small systems in Run 2

Pb–Pb



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

- All **prompt D meson flow similarly**!

J/ψ (c $\bar{c}$)

- **Significant** J/ψ v_2 is observed (**Regeneration** at **low** p_T)

→Results support the **charm quark thermalization** scenario **in QGP.**

Υ(1S) (b $\bar{b}$)

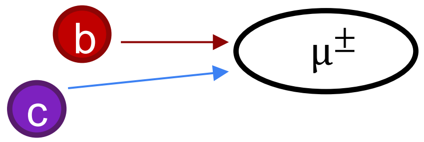
- Elliptic **flow** of **Υ(1S)** compatible with **zero.**

B^- (b $\bar{u}$) → ($\bar{u}$ c) D^0

- **Non-prompt D_0** –meson v_2 is **positive.**

→ **Transport models** describe the **measurement** within uncertainties.

p–Pb



- **Heavy quarks flow significantly** across a wide p_T range.

J/ψ (c $\bar{c}$)

- J/ψ v_2 is **consistent with zero** at **low** p_T.
- **Similar magnitude as** Pb–Pb at **high** p_T.

→ **Imply charm quark flows** at **high** p_T.

v_2 from large to small systems in Run 2

ALICE

Subatech

Pb–Pb

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

- All **prompt D meson flow similarly**!

J/ψ (c $\bar{c}$)

- **Significant** J/ψ v_2 is observed (**Regeneration** at **low** p_T)

→Results support the **charm quark thermalization** scenario **in QGP.**

ϒ(1S) (b $\bar{b}$)

- Elliptic **flow** of **ϒ(1S)** compatible with **zero.**

B^- (b $\bar{u}$) → ($\bar{u}$ c) D^0

- **Non-prompt D_0** −meson v_2 is **positive.**

→ **Transport models** describe the **measurement** within uncertainties.

p–Pb

b → $\mu^{\pm}$ ← c

- **Heavy quarks flow significantly** across a wide p_T range.

J/ψ (c $\bar{c}$)

- J/ψ v_2 is **consistent with zero** at **low** p_T.
- **Similar magnitude as** Pb–Pb at **high** p_T.

→ **Imply charm quark flows** at **high** p_T.

pp

J/ψ (c $\bar{c}$)

- J/ψ v_2 in pp collisions **compatible with 0** within uncertainties.

v_2 from large to small systems in Run 2

Pb–Pb

D_s^+ (s̄ c) D^0 (ū c) D^+ (d̄ c) D^{*+} (d̄ c)

- All **prompt D meson flow similarly**!

J/ψ (c c̄)

- **Significant** J/ψ v_2 is observed (**Regeneration** at **low** p_T)

→Results support the **charm quark thermalization** scenario **in QGP.**

Υ(1S) (b b̄)

- Elliptic **flow** of **Υ(1S)** compatible with **zero.**

B^- (b ū) → (ū c) D^0

- **Non-prompt** D_0 −meson v_2 is **positive.**

→ **Transport models** describe the **measurement** within uncertainties.

p–Pb

b → μ±, c → μ±

- **Heavy quarks flow significantly** across a wide p_T range.

J/ψ (c c̄)

- J/ψ v_2 is **consistent with zero** at **low** p_T.
- **Similar magnitude as** Pb–Pb at **high** p_T.

→ **Imply charm quark flows** at **high** p_T.

pp

J/ψ (c c̄)

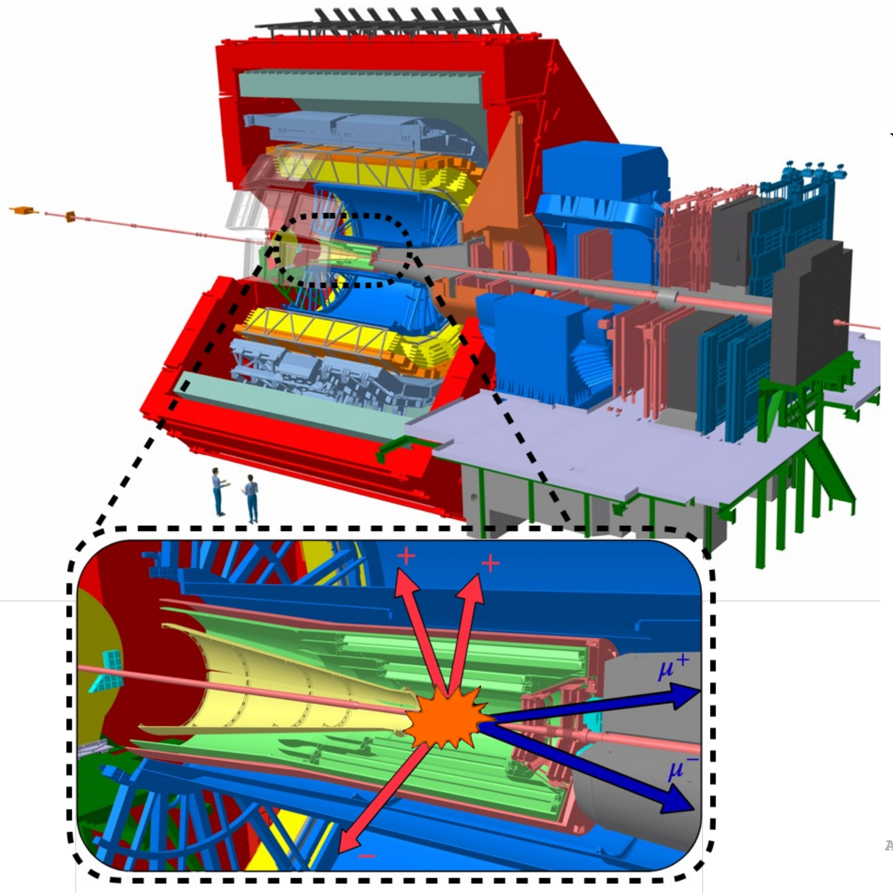
- J/ψ v_2 in pp collisions **compatible with 0** within uncertainties.

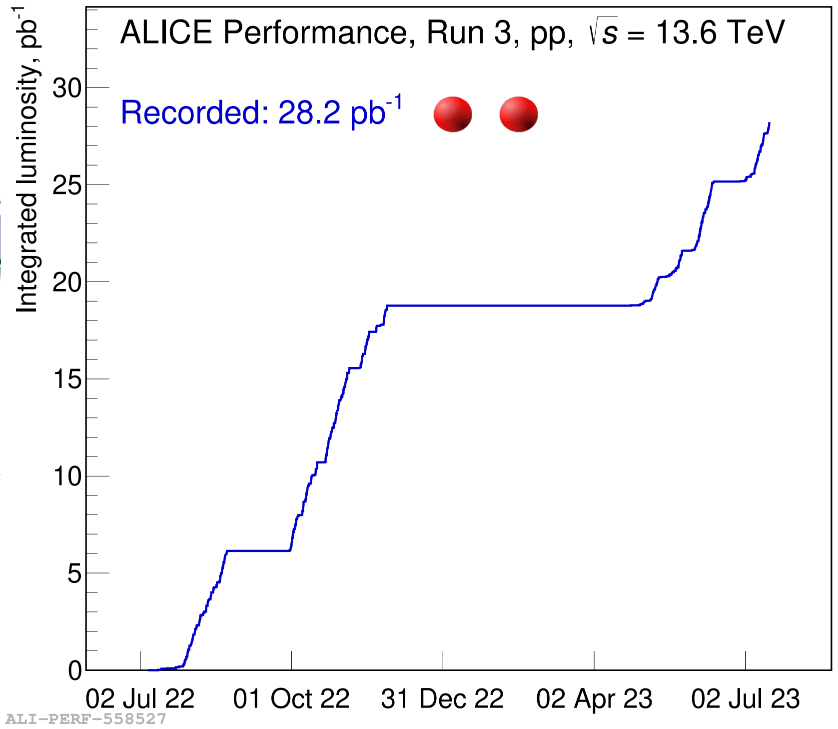
$$v_2^{Pb-Pb} \geq v_2^{p-Pb} \gg v_2^{pp}$$

Elliptic flow hierarchy across **collision systems**!

Run 3 measurements

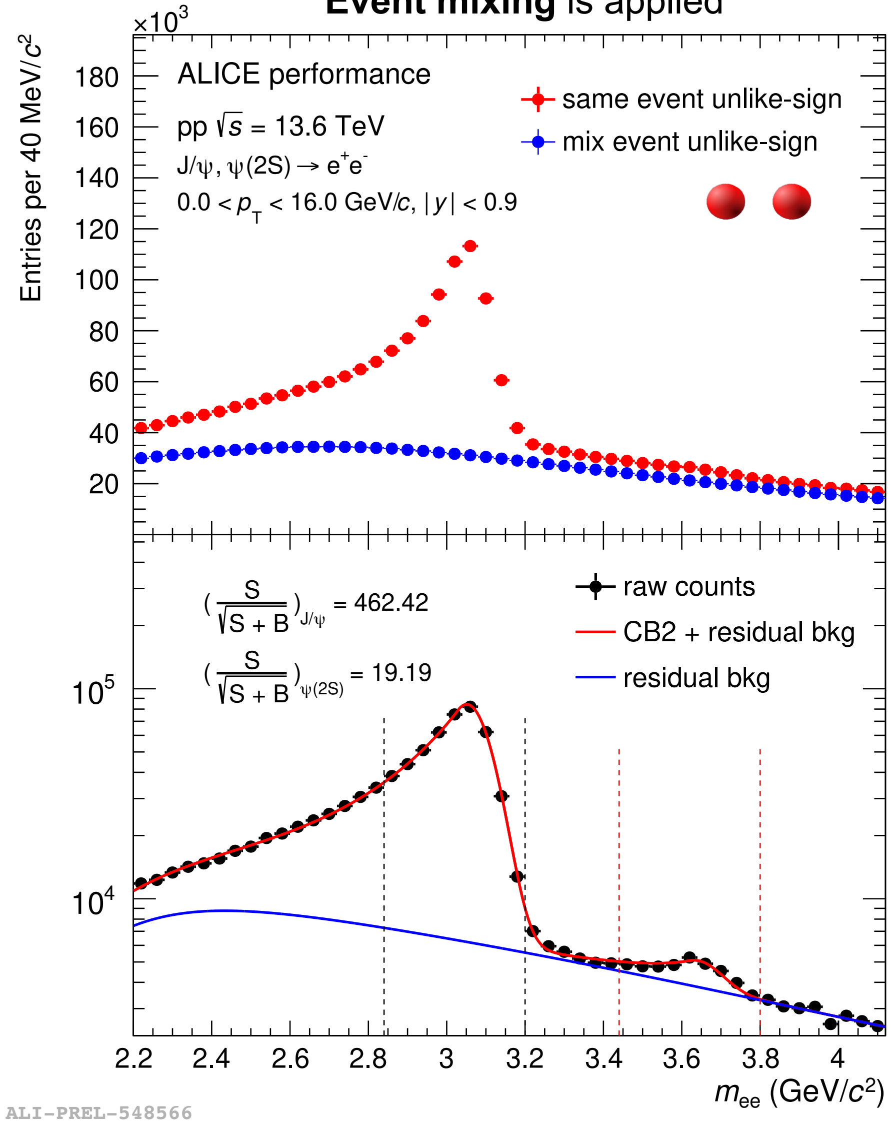
→ **Run 3 statistics** significantly **larger** than in Run 1–2 allowing **more precise measurements!**





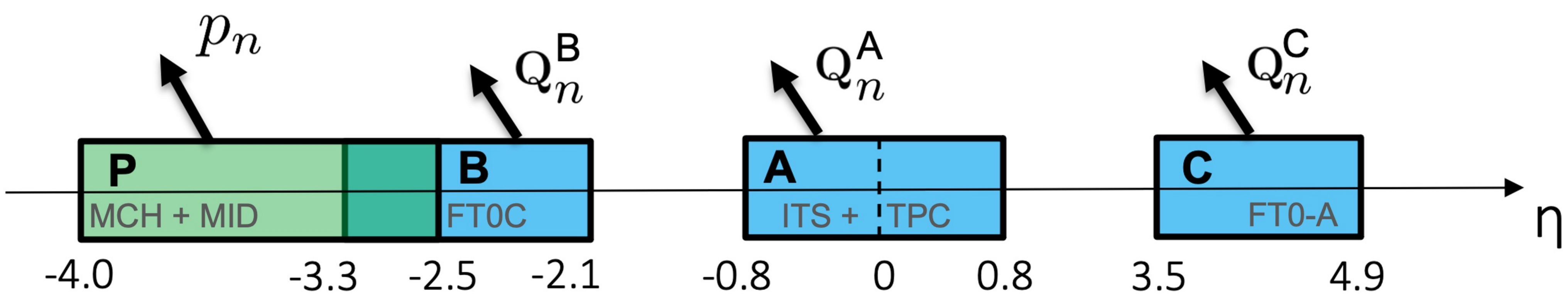
→ **Fit of m_{ee}** distribution **at mid-rapidity!**

Event mixing is applied



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

Flow of J/ψ in Run 3 - Scalar product and Event plane



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

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

Scalar product

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

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

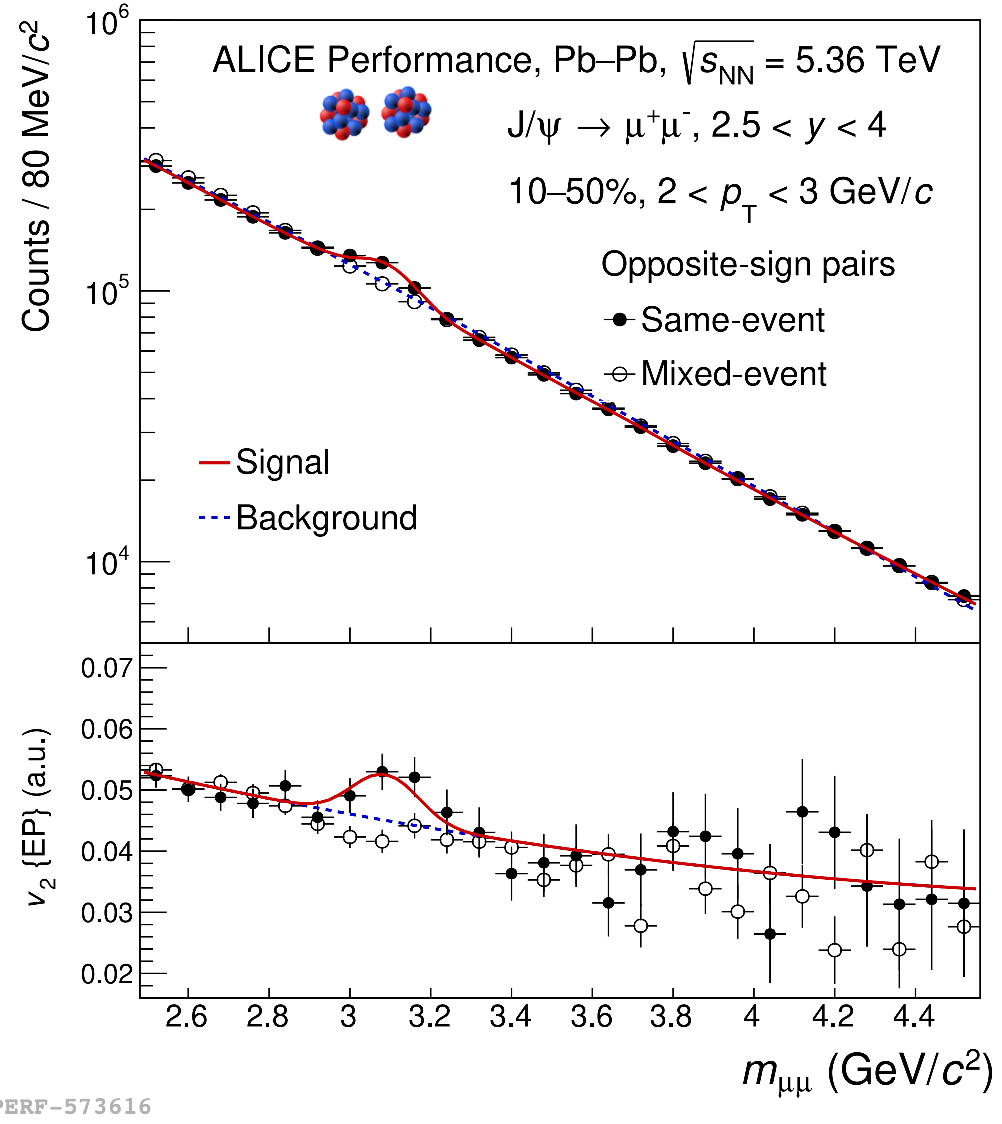
Event plane

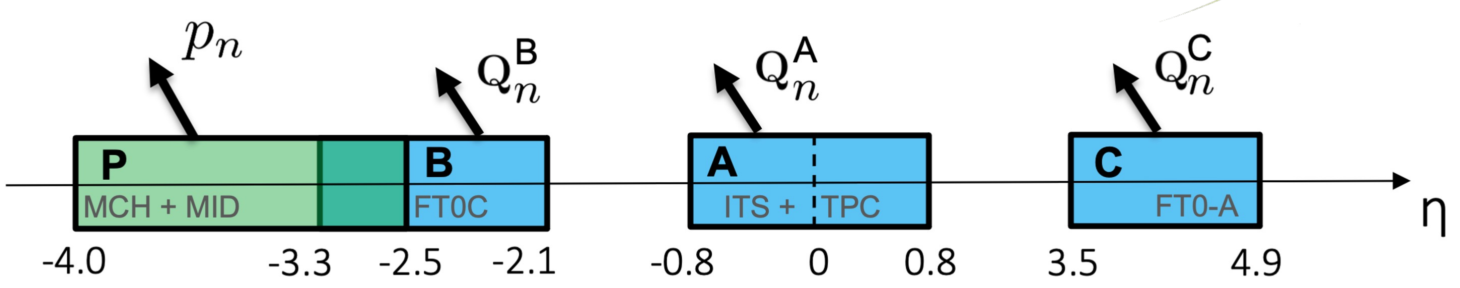
$$v_n^{\mu\mu} = \left\langle \langle \cos n(\varphi - \Psi_n^A) \rangle / R_n \right\rangle = \sqrt{\langle v_n^2 \rangle}$$

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

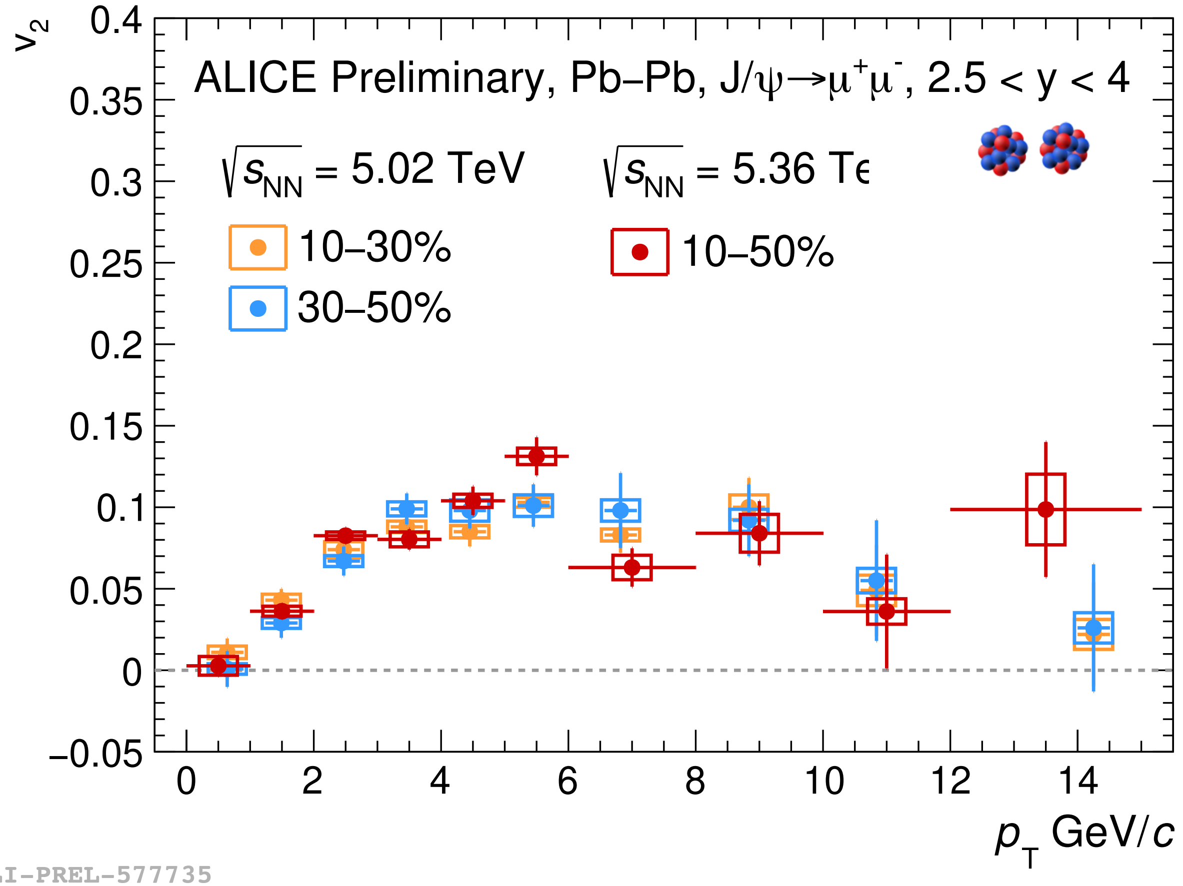
Flow of J/ψ in Run 3 - Event plane results

→ $v_2^{J/\psi}\{EP\}$ extraction at **forward-rapidity!**





→ $v_2^{J/\psi}\{EP\}$ **as function of** p_T



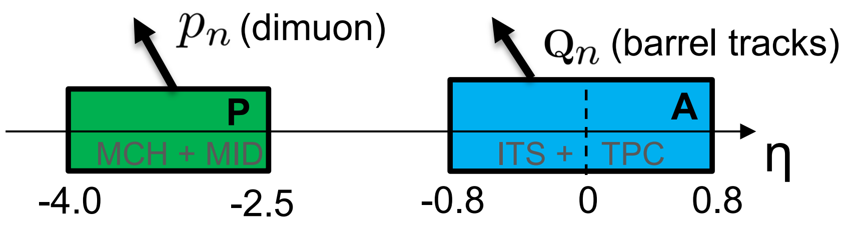
Flow of J/ψ in Run 3 - Multi-particle cumulants

$$Q_{n,k} \equiv \sum_{i=1}^{M} w_i^k e^{in\phi_i} \,,$$

$$S_{p,k} \equiv \left[\sum_{i=1}^{M} w_i^k\right]^p \,,$$

$$\mathcal{M}_{abcd\cdots} \equiv \sum_{i,j,k,l,\ldots=1}^{M}{}' w_i^a w_j^b w_k^c w_l^d \cdots \,.$$

w_i^k → Non-uniform acceptance weights



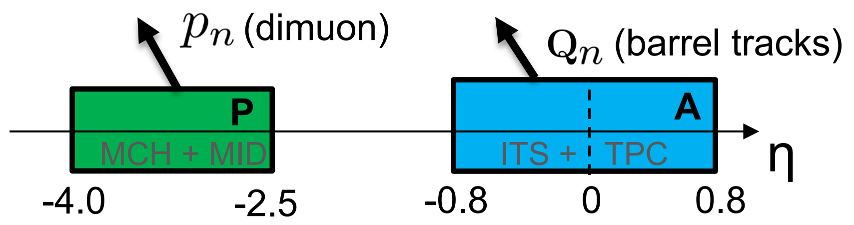
Flow of J/ψ in Run 3 - Multi-particle cumulants

$$Q_{n,k} \equiv \sum_{i=1}^{M} w_i^k e^{in\phi_i} ,$$

$$S_{p,k} \equiv \left[\sum_{i=1}^{M} w_i^k\right]^p ,$$

$$\mathcal{M}_{abcd\cdots} \equiv \sum_{i,j,k,l,\ldots=1}^{M}{}' w_i^a w_j^b w_k^c w_l^d \cdots .$$

w_i^k → Non-uniform acceptance weights



POI correlators

→Average over tracks

$$\langle 2' \rangle = \frac{p_{n,0}Q^*_{n,1} - s_{1,1}}{m_p S_{1,1} - s_{1,1}} ,$$

$$\begin{aligned}\langle 4' \rangle = \Big[& p_{n,0}Q_{n,1}Q^*_{n,1}Q^*_{n,1} \\ & - q_{2n,1}Q^*_{n,1}Q^*_{n,1} - p_{n,0}Q_{n,1}Q^*_{2n,2} \\ & - 2\cdot S_{1,2}p_{n,0}Q^*_{n,1} - 2\cdot s_{1,1}\left|Q_{n,1}\right|^2 \\ & + 7\cdot q_{n,2}Q^*_{n,1} - Q_{n,1}q^*_{n,2} \\ & + q_{2n,1}Q^*_{2n,2} + 2\cdot p_{n,0}Q^*_{n,3} \\ & + 2\cdot s_{1,1}S_{1,2} - 6\cdot s_{1,3}\Big] / \mathcal{M}'_{0111} ,\end{aligned}$$

REF correlators

→Average over tracks

$$\langle 2 \rangle = \frac{\left|Q_{n,1}\right|^2 - S_{1,2}}{S_{2,1} - S_{1,2}} ,$$

$$\begin{aligned}\langle 4 \rangle = \Big[& \left|Q_{n,1}\right|^4 + \left|Q_{2n,2}\right|^2 - 2\cdot \mathfrak{Re}\left[Q_{2n,2}Q^*_{n,1}Q^*_{n,1}\right] \\ & + 8\cdot \mathfrak{Re}\left[Q_{n,3}Q^*_{n,1}\right] - 4\cdot S_{1,2}\left|Q_{n,1}\right|^2 \\ & - 6\cdot S_{1,4} - 2\cdot S_{2,2}\Big] / \mathcal{M}_{1111} ,\end{aligned}$$

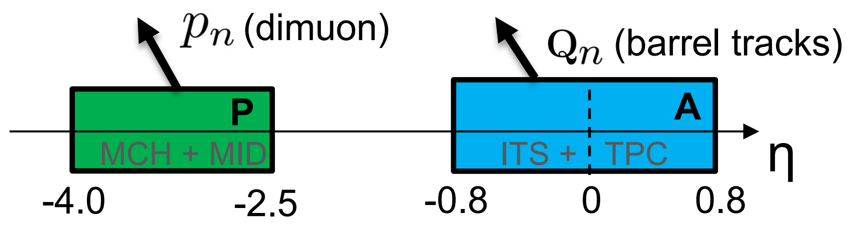
Flow of J/ψ in Run 3 - Multi-particle cumulants

$$Q_{n,k} \equiv \sum_{i=1}^{M} w_i^k e^{in\phi_i},$$

$$S_{p,k} \equiv \left[\sum_{i=1}^{M} w_i^k\right]^p,$$

$$\mathcal{M}_{abcd\cdots} \equiv \sum_{i,j,k,l,\ldots=1}^{M}{}' w_i^a w_j^b w_k^c w_l^d \cdots .$$

w_i^k → Non-uniform acceptance weights



POI correlators

→Average over tracks

$$\langle 2' \rangle = \frac{p_{n,0}Q^*_{n,1} - s_{1,1}}{m_p S_{1,1} - s_{1,1}},$$

$$\begin{aligned}\langle 4' \rangle = \Big[& p_{n,0}Q_{n,1}Q^*_{n,1}Q^*_{n,1} \\ & - q_{2n,1}Q^*_{n,1}Q^*_{n,1} - p_{n,0}Q_{n,1}Q^*_{2n,2} \\ & - 2\cdot S_{1,2}p_{n,0}Q^*_{n,1} - 2\cdot s_{1,1}|Q_{n,1}|^2 \\ & + 7\cdot q_{n,2}Q^*_{n,1} - Q_{n,1}q^*_{n,2} \\ & + q_{2n,1}Q^*_{2n,2} + 2\cdot p_{n,0}Q^*_{n,3} \\ & + 2\cdot s_{1,1}S_{1,2} - 6\cdot s_{1,3}\Big] / \mathcal{M}'_{0111},\end{aligned}$$

→Average over all events

$$\langle\langle 2' \rangle\rangle = \frac{\sum_{i=1}^{N}(\mathcal{M}'_{01})_i \langle 2' \rangle_i}{\sum_{i=1}^{N}(\mathcal{M}'_{01})_i},$$

$$\langle\langle 4' \rangle\rangle = \frac{\sum_{i=1}^{N}(\mathcal{M}'_{0111})_i \langle 4' \rangle_i}{\sum_{i=1}^{N}(\mathcal{M}'_{0111})_i},$$

$$\mathcal{M}'_{01} \equiv \sum_{i=1}^{m_p}\sum_{i,j=1}^{M}{}' w_j$$

$$\mathcal{M}'_{0111} \equiv \sum_{i=1}^{m_p}\sum_{j,k,l=1}^{M}{}' w_j w_k w_l$$

REF correlators

→Average over tracks

$$\langle 2 \rangle = \frac{|Q_{n,1}|^2 - S_{1,2}}{S_{2,1} - S_{1,2}},$$

$$\begin{aligned}\langle 4 \rangle = \Big[& |Q_{n,1}|^4 + |Q_{2n,2}|^2 - 2\cdot \mathfrak{Re}\left[Q_{2n,2}Q^*_{n,1}Q^*_{n,1}\right] \\ & + 8\cdot \mathfrak{Re}\left[Q_{n,3}Q^*_{n,1}\right] - 4\cdot S_{1,2}|Q_{n,1}|^2 \\ & - 6\cdot S_{1,4} - 2\cdot S_{2,2}\Big] / \mathcal{M}_{1111},\end{aligned}$$

→Average over all events

$$\langle\langle 2 \rangle\rangle = \frac{\sum_{i=1}^{N}(\mathcal{M}_{11})_i \langle 2 \rangle_i}{\sum_{i=1}^{N}(\mathcal{M}_{11})_i},$$

$$\langle\langle 4 \rangle\rangle = \frac{\sum_{i=1}^{N}(\mathcal{M}_{1111})_i \langle 4 \rangle_i}{\sum_{i=1}^{N}(\mathcal{M}_{1111})_i},$$

$$\mathcal{M}_{11} \equiv \sum_{i,j=1}^{M}{}' w_i w_j$$

$$\mathcal{M}_{1111} \equiv \sum_{i,j,k,l=1}^{M}{}' w_i w_j w_k w_l$$

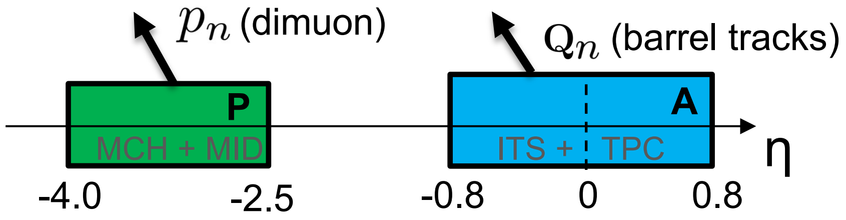
Flow of J/ψ in Run 3 - Multi-particle cumulants

$$Q_{n,k} \equiv \sum_{i=1}^{M} w_i^k e^{in\phi_i} ,$$

$$S_{p,k} \equiv \left[\sum_{i=1}^{M} w_i^k\right]^p ,$$

$$\mathcal{M}_{abcd\cdots} \equiv \sum_{i,j,k,l,\ldots=1}^{M}{}' w_i^a w_j^b w_k^c w_l^d \cdots .$$

w_i^k → Non-uniform acceptance weights



POI correlators

→Average over tracks

$$\langle 2' \rangle = \frac{p_{n,0}Q^*_{n,1} - s_{1,1}}{m_p S_{1,1} - s_{1,1}} ,$$

$$\begin{aligned}\langle 4' \rangle = \Big[& p_{n,0}Q_{n,1}Q^*_{n,1}Q^*_{n,1} \\ & - q_{2n,1}Q^*_{n,1}Q^*_{n,1} - p_{n,0}Q_{n,1}Q^*_{2n,2} \\ & - 2\cdot S_{1,2}p_{n,0}Q^*_{n,1} - 2\cdot s_{1,1}\,|Q_{n,1}|^2 \\ & + 7\cdot q_{n,2}Q^*_{n,1} - Q_{n,1}q^*_{n,2} \\ & + q_{2n,1}Q^*_{2n,2} + 2\cdot p_{n,0}Q^*_{n,3} \\ & + 2\cdot s_{1,1}S_{1,2} - 6\cdot s_{1,3}\Big] / \mathcal{M}'_{0111} ,\end{aligned}$$

→Average over all events

$$\langle\langle 2' \rangle\rangle = \frac{\sum_{i=1}^{N}(\mathcal{M}'_{01})_i \langle 2' \rangle_i}{\sum_{i=1}^{N}(\mathcal{M}'_{01})_i} , \qquad \langle\langle 4' \rangle\rangle = \frac{\sum_{i=1}^{N}(\mathcal{M}'_{0111})_i \langle 4' \rangle_i}{\sum_{i=1}^{N}(\mathcal{M}'_{0111})_i} ,$$

$$\mathcal{M}'_{01} \equiv \sum_{i=1}^{m_p}\sum_{i,j=1}^{M}{}' w_j \qquad \mathcal{M}'_{0111} \equiv \sum_{i=1}^{m_p}\sum_{j,k,l=1}^{M}{}' w_j w_k w_l$$

REF correlators

→Average over tracks

$$\begin{aligned}\langle 4 \rangle = \Big[& |Q_{n,1}|^4 + |Q_{2n,2}|^2 - 2\cdot \mathfrak{Re}\left[Q_{2n,2}Q^*_{n,1}Q^*_{n,1}\right] \\ & + 8\cdot \mathfrak{Re}\left[Q_{n,3}Q^*_{n,1}\right] - 4\cdot S_{1,2}\,|Q_{n,1}|^2 \\ & - 6\cdot S_{1,4} - 2\cdot S_{2,2}\Big] / \mathcal{M}_{1111} ,\end{aligned}$$

$$\langle 2 \rangle = \frac{|Q_{n,1}|^2 - S_{1,2}}{S_{2,1} - S_{1,2}} ,$$

→Average over all events

$$\langle\langle 2 \rangle\rangle = \frac{\sum_{i=1}^{N}(\mathcal{M}_{11})_i \langle 2 \rangle_i}{\sum_{i=1}^{N}(\mathcal{M}_{11})_i} , \qquad \langle\langle 4 \rangle\rangle = \frac{\sum_{i=1}^{N}(\mathcal{M}_{1111})_i \langle 4 \rangle_i}{\sum_{i=1}^{N}(\mathcal{M}_{1111})_i} ,$$

$$\mathcal{M}_{11} \equiv \sum_{i,j=1}^{M}{}' w_i w_j \qquad \mathcal{M}_{1111} \equiv \sum_{i,j,k,l=1}^{M}{}' w_i w_j w_k w_l$$

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 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 flow

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

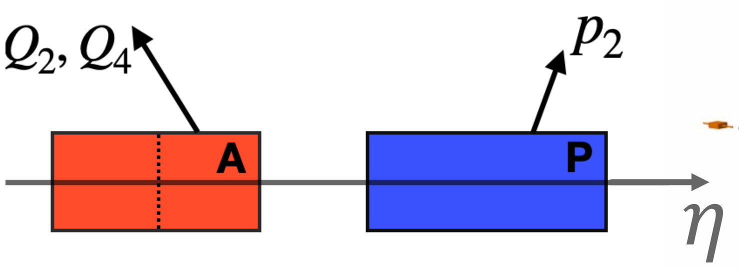
$$v_n^{\mu\mu}\{4\} = -\frac{d_n^{\mu\mu}\{4\}}{(-c_n\{4\})^{3/4}}$$

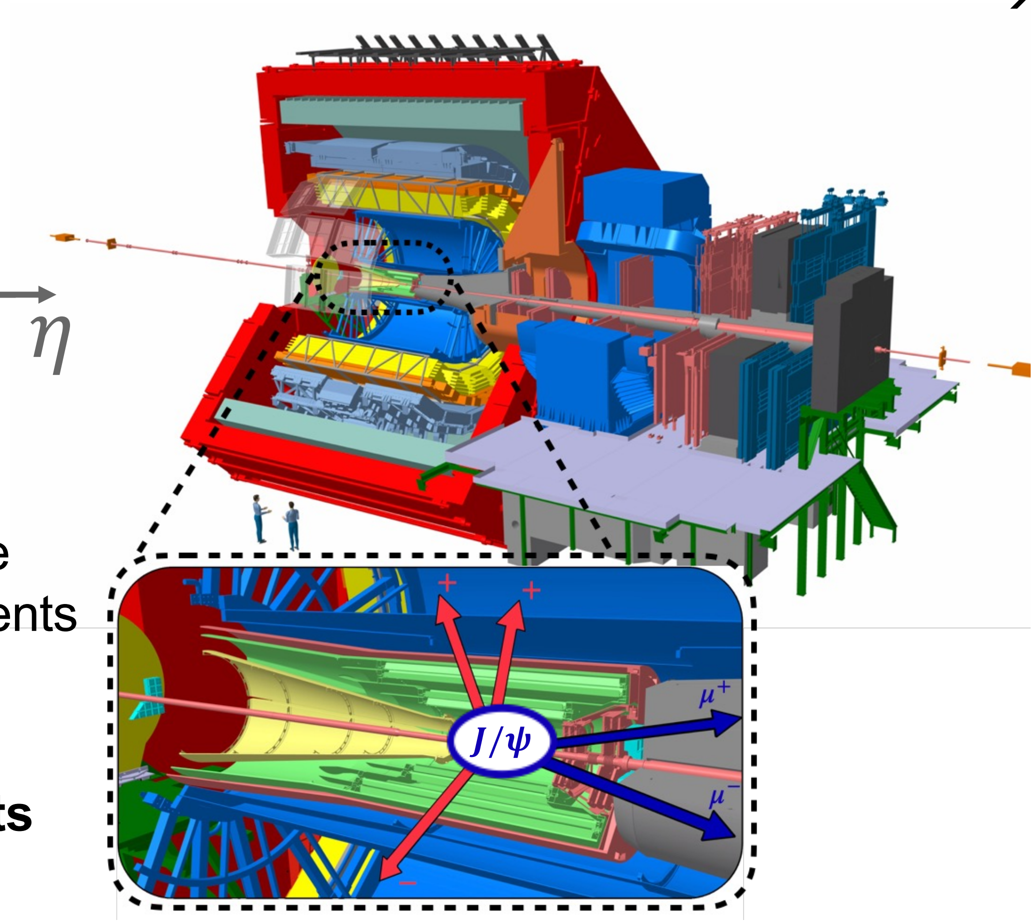
REF flow

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

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

Flow of J/ψ in Run 3 - Multi-particle cumulants

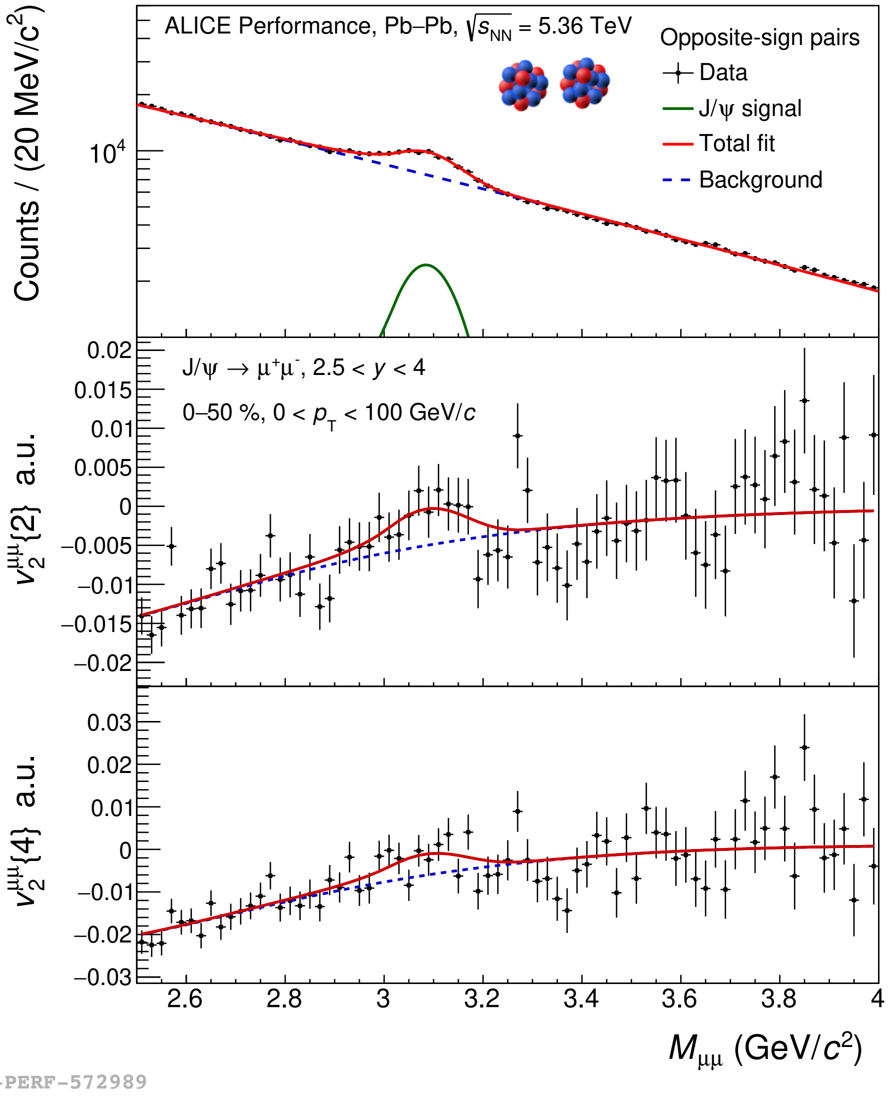




→ **Run 3 data** will enable more precise measurements for $v_2^{J/\psi}$ up to **higher p_T**

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

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



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

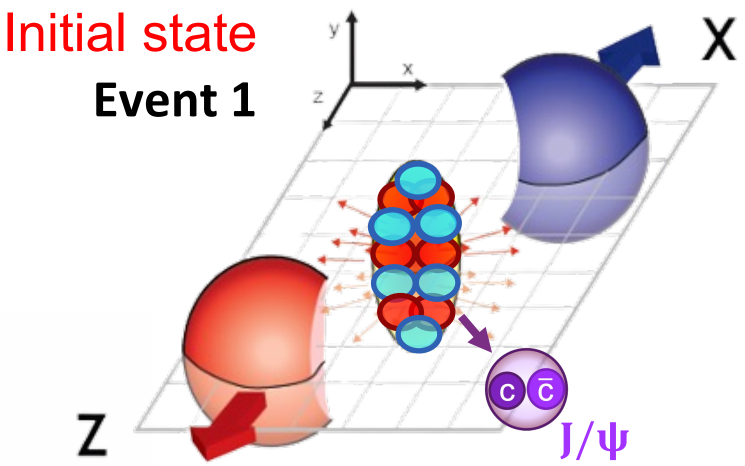
$$v_2\{4\}^4 = -\langle v_2^4 + \boldsymbol{\delta_4} \rangle \rightarrow \delta_4 \sim 1/M^3$$

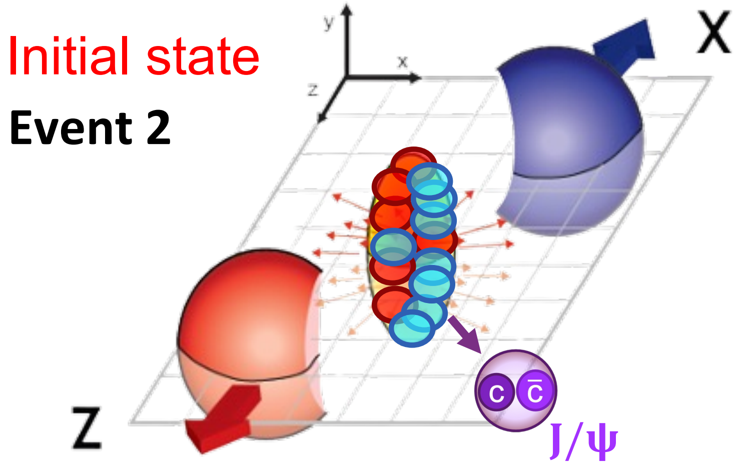
Scaling with multiplicity!

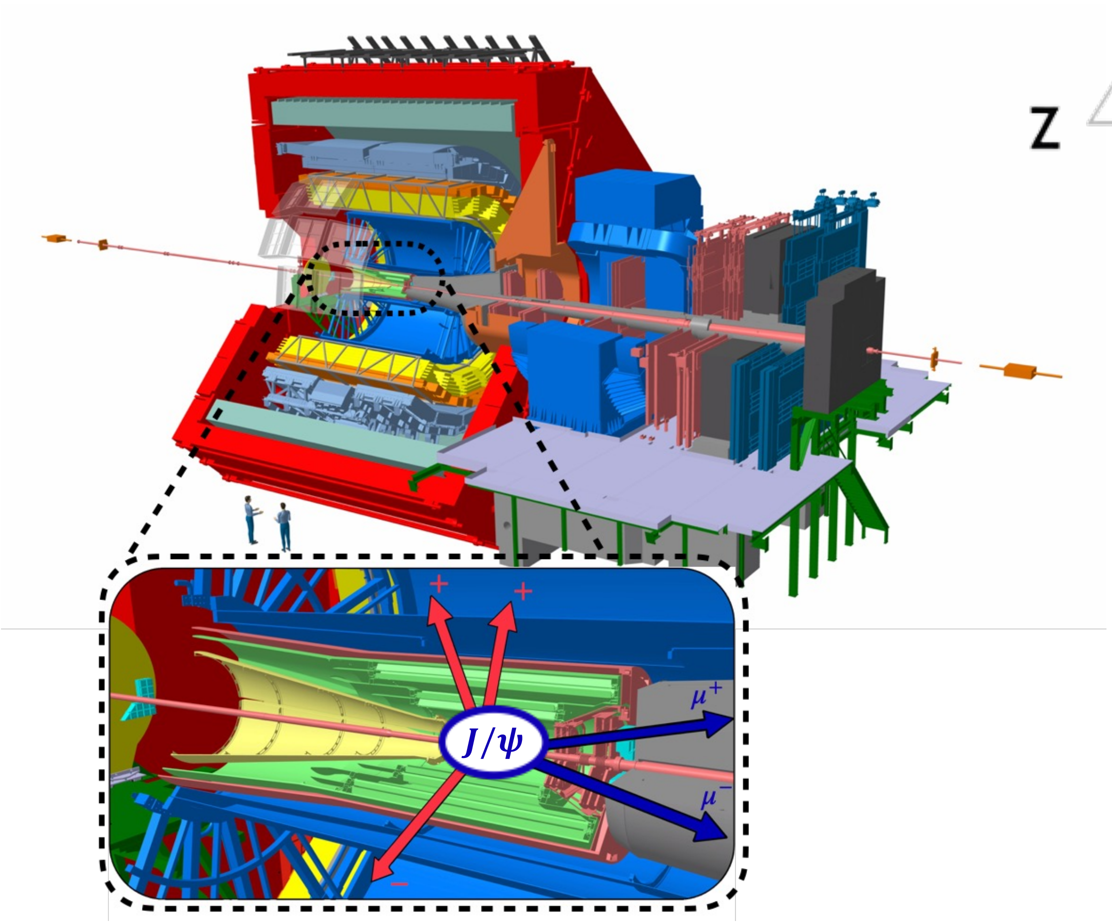
→ First $v_2^{J/\psi}\{2,4\}$ **signal** extraction at **forward-rapidity!**

Flow of J/ψ in Run 3 - Multi-particle cumulants

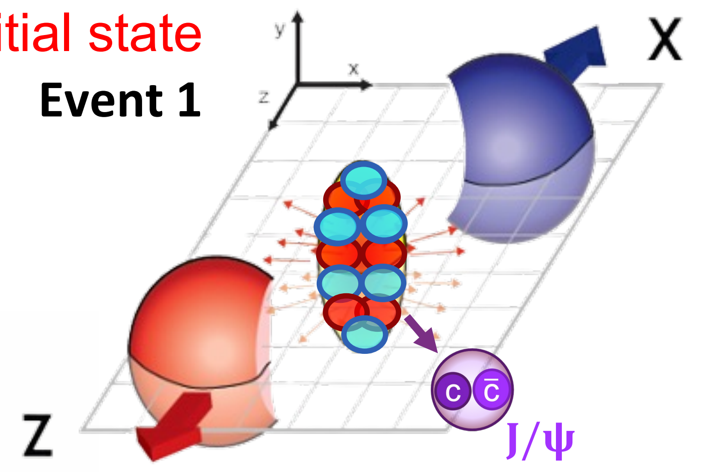
- **Fluctuations** in the positions of nucleons in the overlap region.

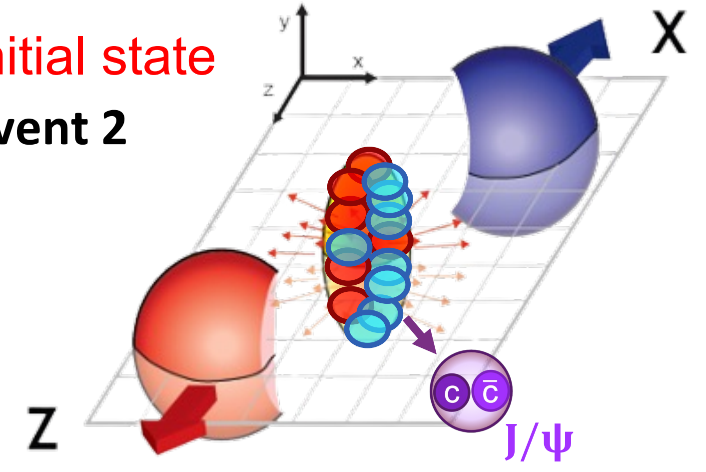


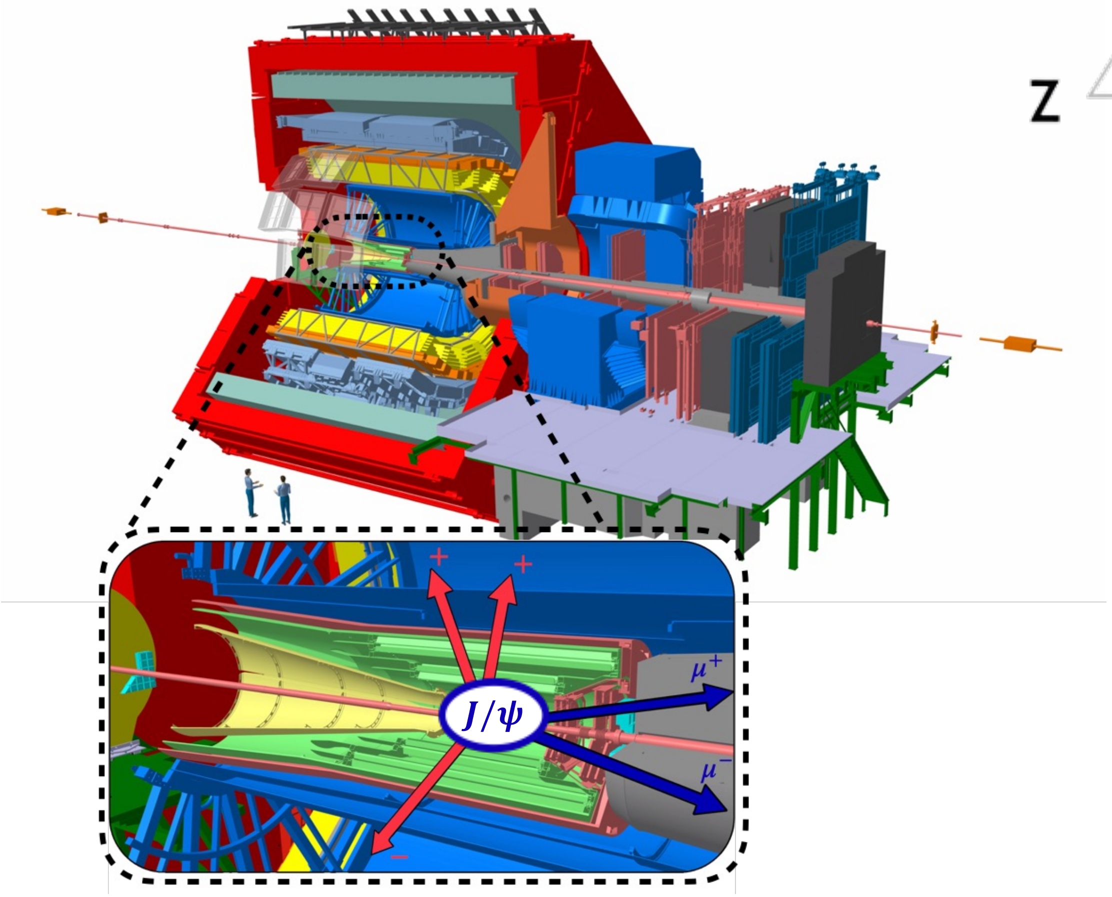




- **Fluctuations** in the positions of nucleons in the overlap region.







Fluctuation ratio σ/⟨v2⟩

$$v_2\{2\}^2 \approx \langle v_2\rangle^2 + \sigma^2$$
$$v_2\{4\}^2 \approx \langle v_2\rangle^2 - \sigma^2$$
$$\frac{\sigma}{\langle v_2\rangle} = \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$$

If $\sigma/\langle v_2^{J/\psi}\rangle$ does not show a p_T dependence, the observed fluctuations are likely due to variations in the initial-state geometry!

Perspectives in Run 3

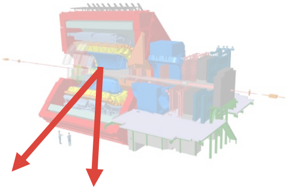
→ **Larger Run 3** sample will provide **better precision flow measurements**

→ **New flow methods** will be used thanks to **the Run 3 continuous readout**!

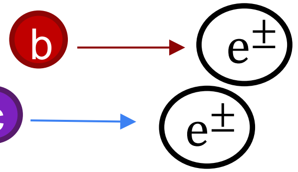
→**Run 3** flow measurements using **different methods**

- **Scalar product**
- **Event plane**
- **Multi-particle cumulant→ Fluctuation Ratio!**

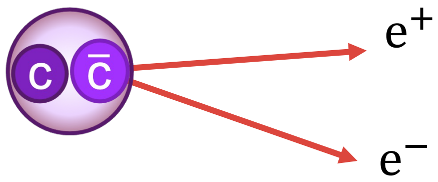
At mid-rapidity:



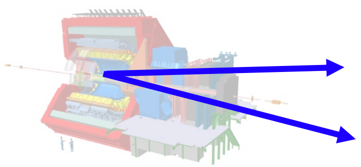
→ Flow of $e^{\pm}$ from charm and beauty decays in Pb-Pb



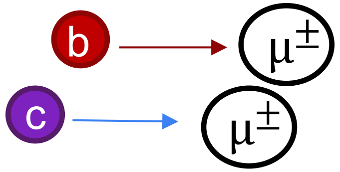
→ Flow of J/ψ in pp



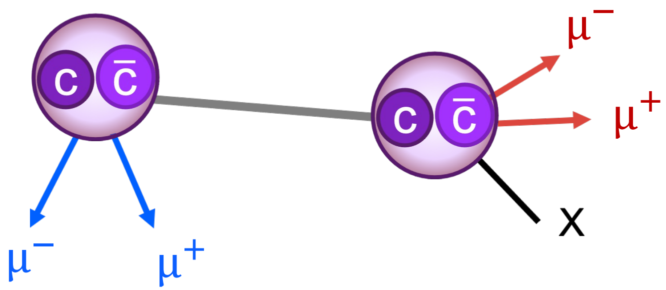
At forward-rapidity:



→ Flow of $\mu^{\pm}$ from charm and beauty decays



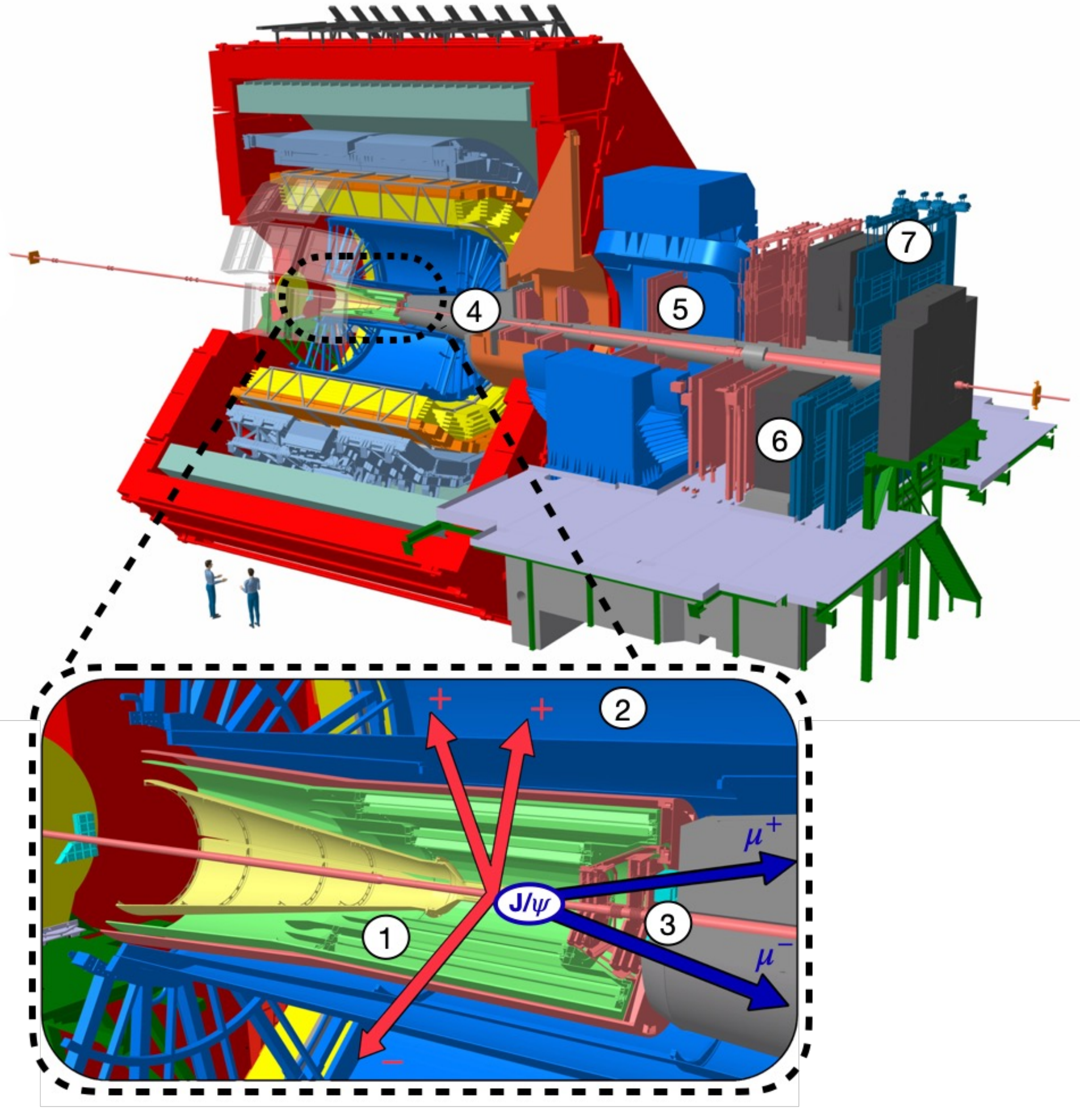
→ Flow of J/ψ prompt and non-prompt in Pb–Pb



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

BACK UP

ALICE detector 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

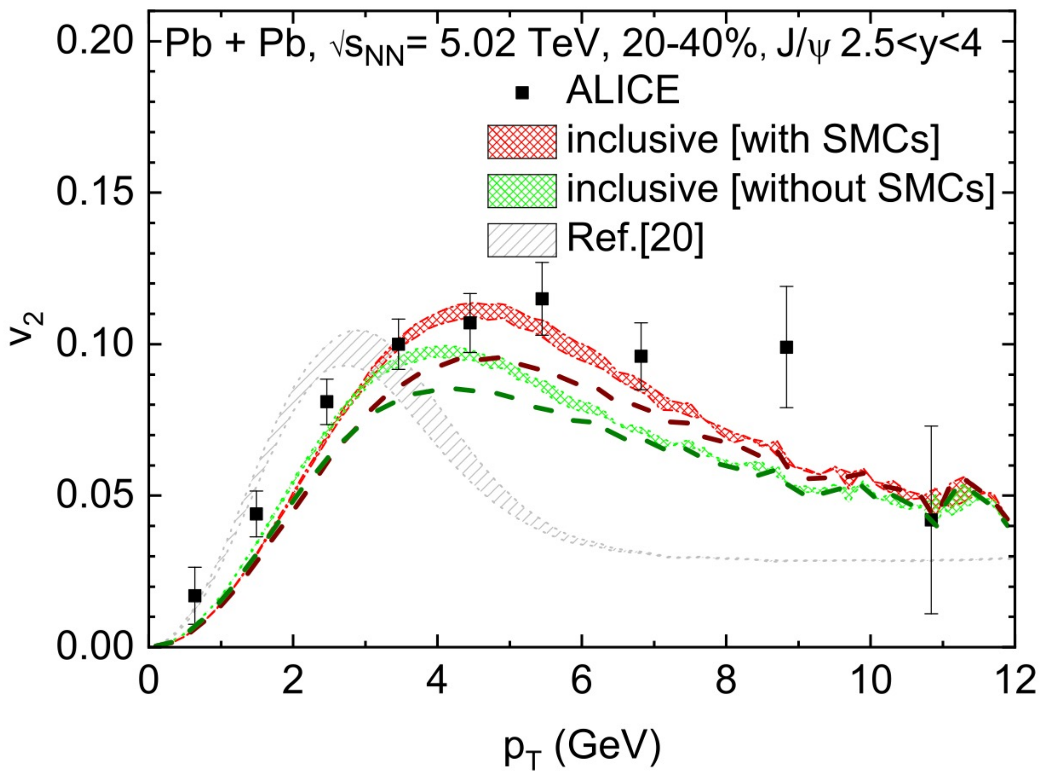
MCH ⑤
→ Muon tracking system

Muon Filter ⑥
→ Punch through hadrons

MID ⑦
→ Particle identification of muons

Flow of **J/ψ measurement vs models**

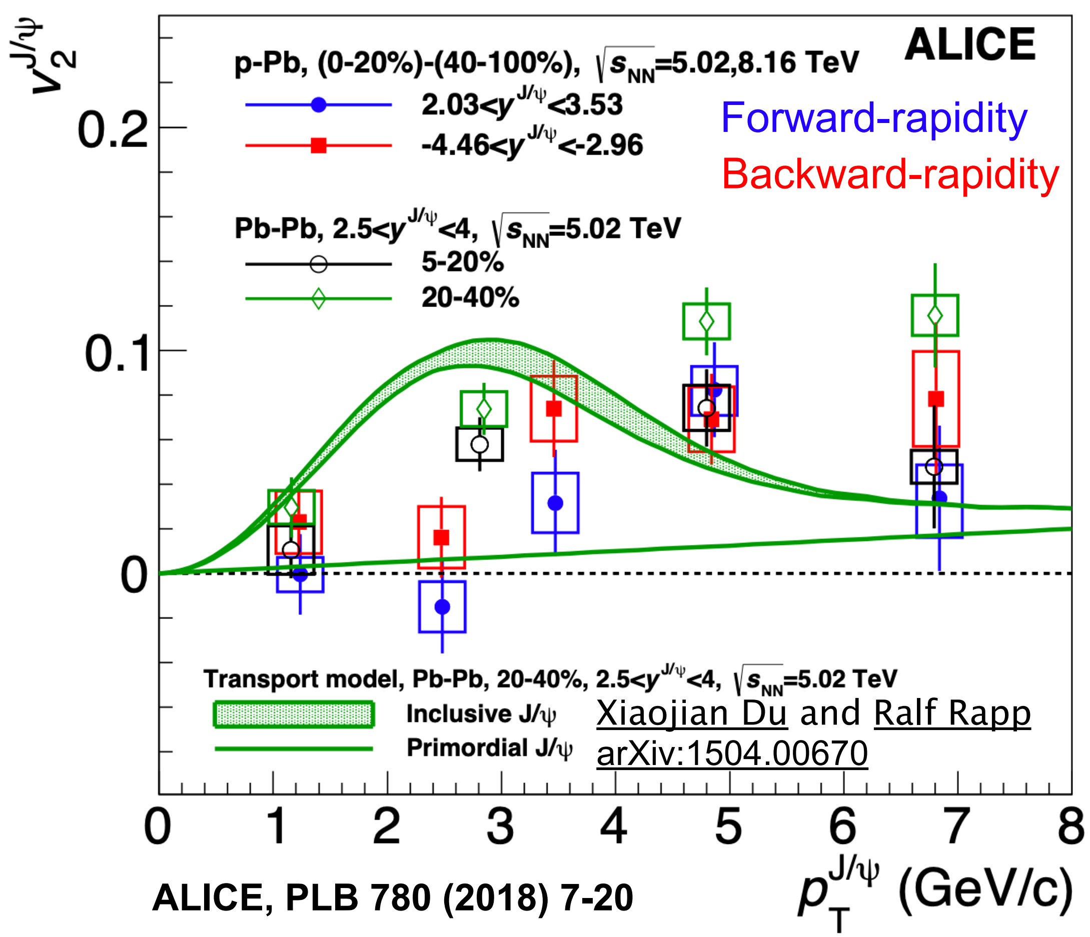
HE-WU-RAPP



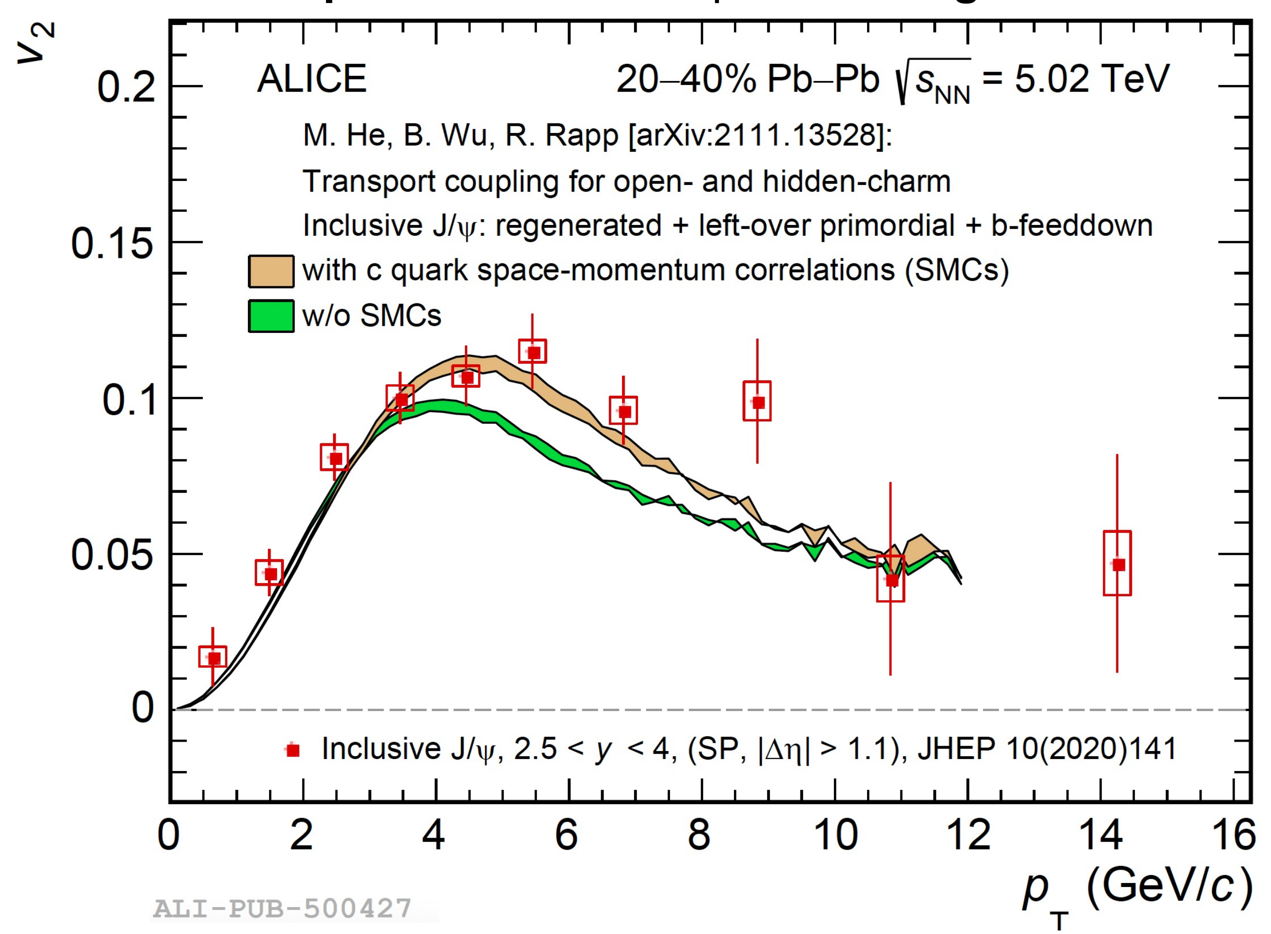
- **Run 2** values were obtained with **Scalar product method**.
- **Data** could be **contaminated by non-flow** (especially at high-p_T)
- **Larger Run 3** sample would provide **better precision measurement for v_2** up to higher p_T and for higher harmonic orders.

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

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



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



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

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