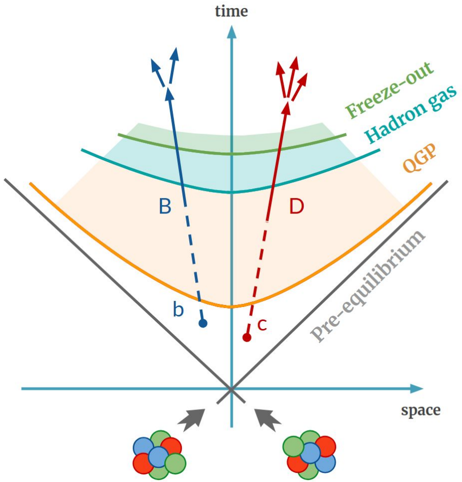
Investigating charm-quark dynamics in the QGP via the charm-hadron elliptic flow in Pb–Pb collisions with ALICE

Marcello Di Costanzo on behalf of the ALICE Collaboration, 09/07/2025

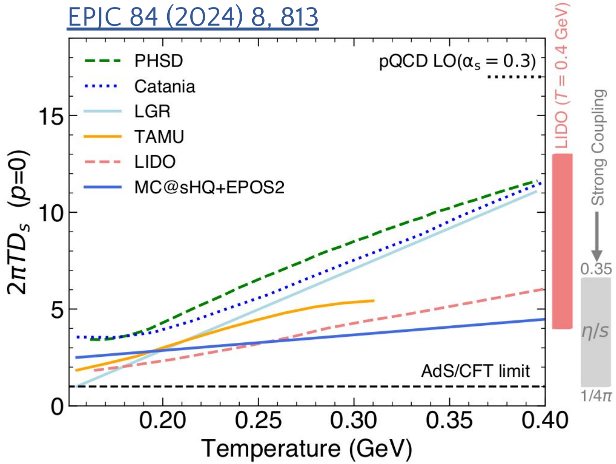
Heavy flavours as probes for QGP

- Quark-Gluon Plasma (QGP)
  - → Colour-deconfined state of matter expected by Lattice QCD to exist at temperature T > **155 MeV**
  - → Conditions can be attained in **ultrarelativistic heavy-ion collisions**
  - → At LHC, QGP is formed after **$\tau \approx$ 0.3 fm/c**
  - → With decreasing temperature, a dense gas of hadrons is formed



- Heavy quarks are produced from hard scatterings **before** the QGP formation
  - → Interaction with medium constituents
  - → Competing hadronization mechanisms
    - ○ Fragmentation
    - ○ Coalescence

EPJC 84 (2024) 8, 813



- Heavy quark interactions with the medium described by the **diffusion coefficient** D_s

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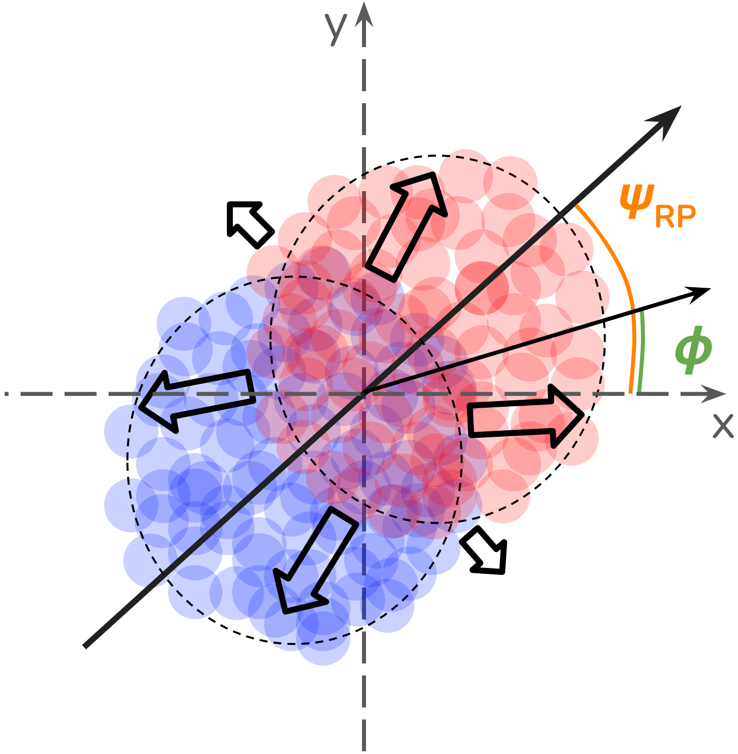
The elliptic flow observable



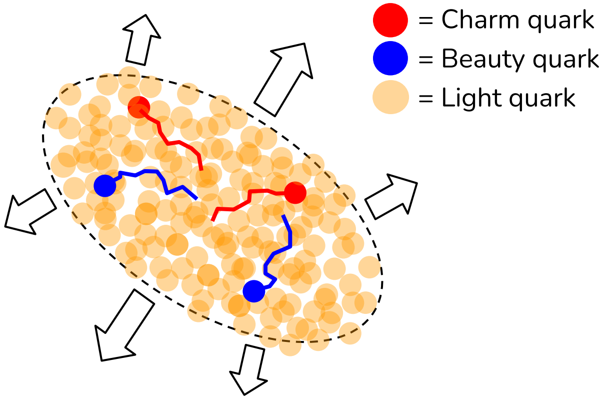
- In non-central collisions the overlap region of colliding nuclei features an **ellipsoidal** shape
  → **Non-isotropic** pressure gradients

- Modulation of particle yields **in momentum space** as a function of ϕ-ψ_{RP} (Reaction Plane)
  → Description via a **Fourier series** expansion

$$\frac{dN}{d\Phi} = \frac{N_0}{2\pi}(1 + 2v_2 \cos[2(\Phi - \Psi_{RP})] + \dots)$$

D^0, D^+, D_s^+, J/ψ and Λ_c^+ v_2 presented for different collision centralities

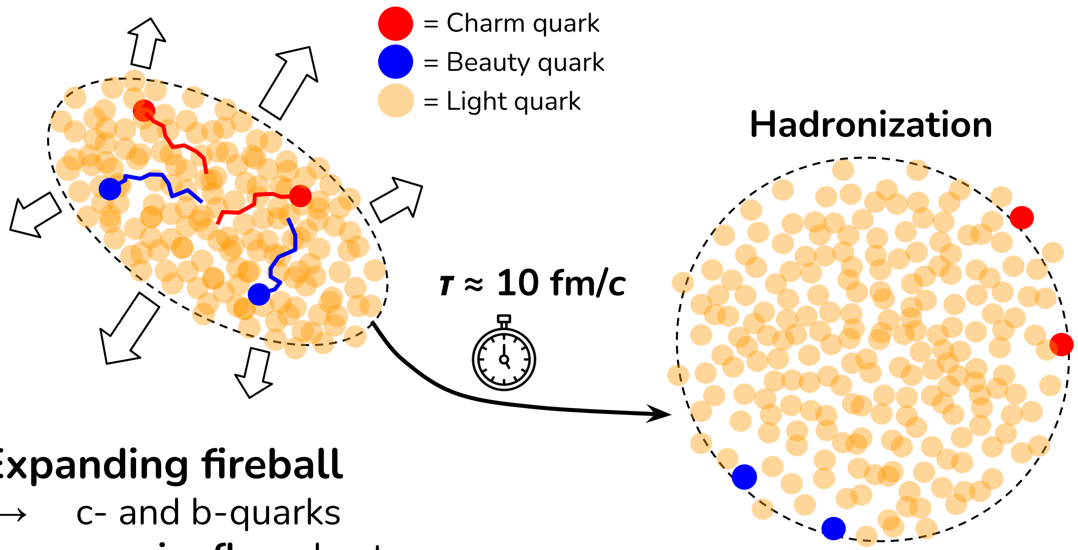
Charm hadron production and elliptic flow



Expanding fireball

→ c- and b-quarks **acquire flow** due to **interaction with medium** constituents

Charm hadron production and elliptic flow



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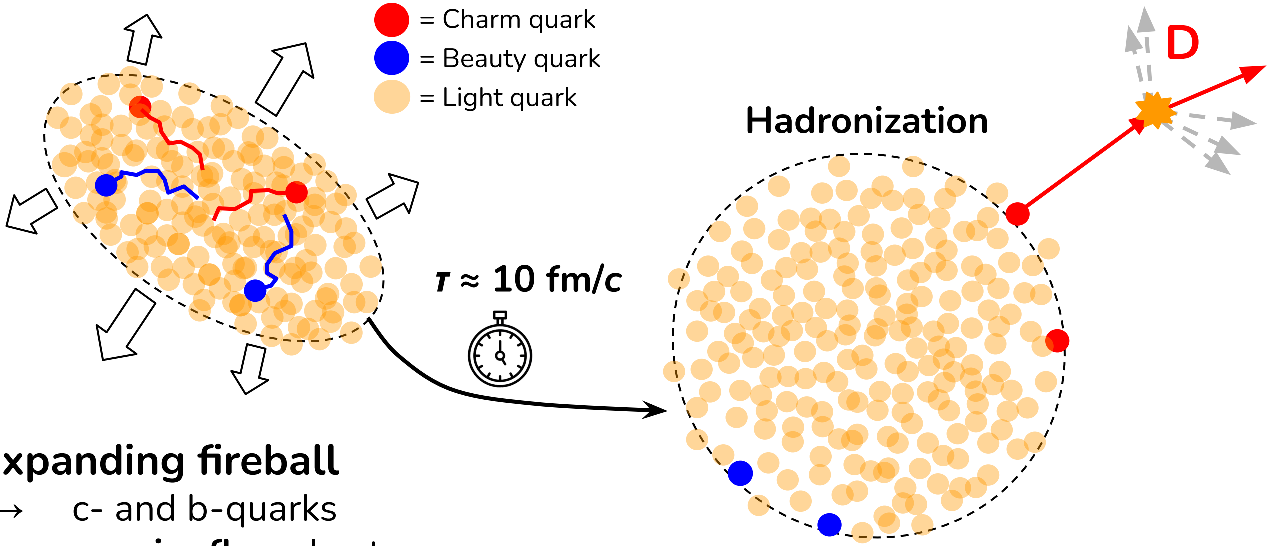
Charm hadron production and elliptic flow



Expanding fireball

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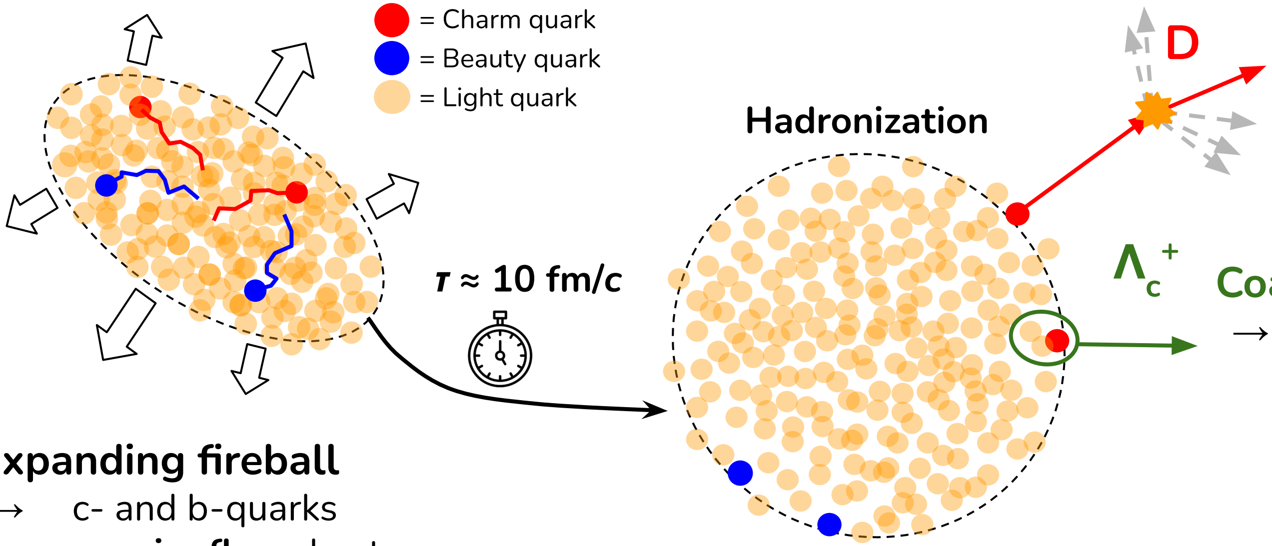
Fragmentation

→ **No additional contribution** to the v_2

Charm hadron production and elliptic flow



Fragmentation
→ **No additional contribution** to the v_2

Coalescence
→ Further contribution to the v_2 **from light quarks**

Expanding fireball
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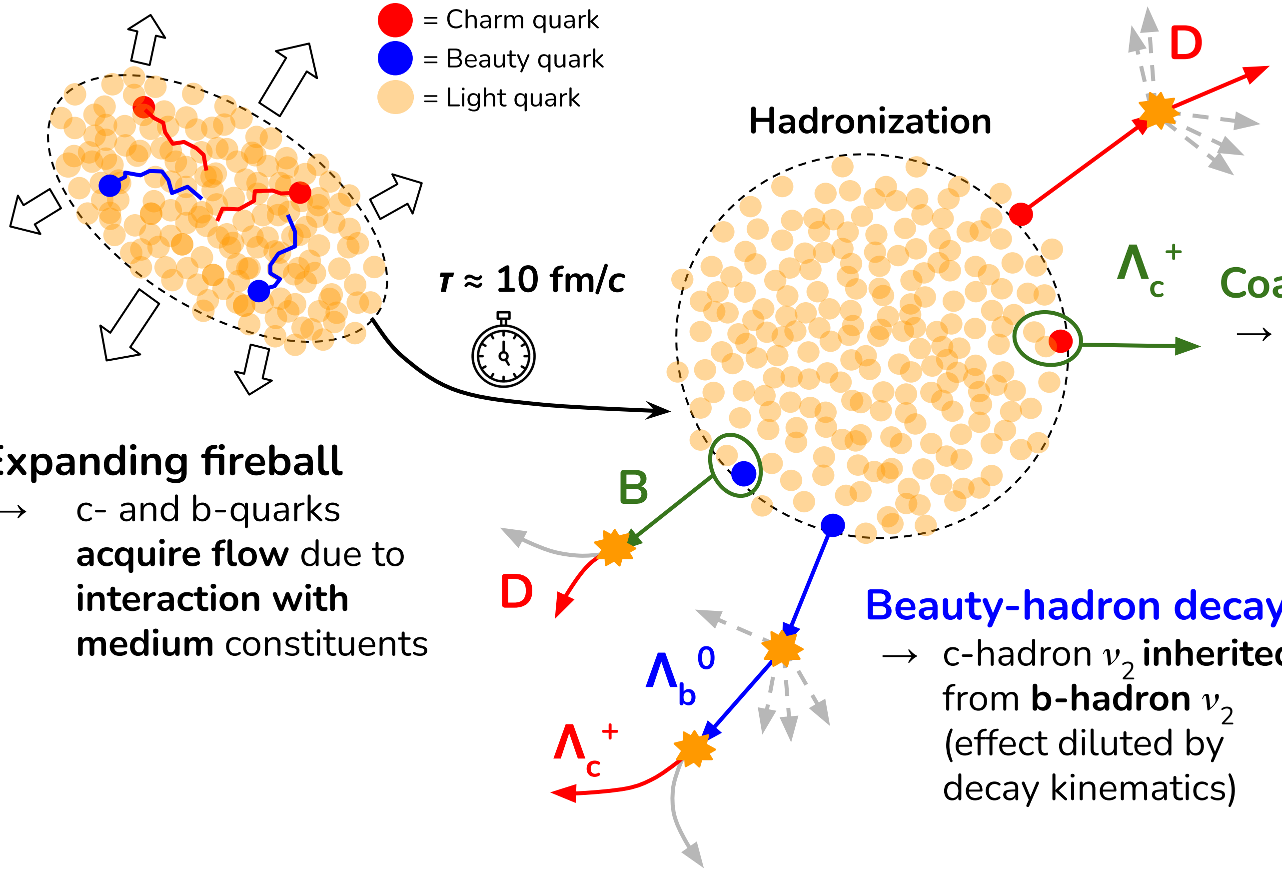
Charm hadron production and elliptic flow



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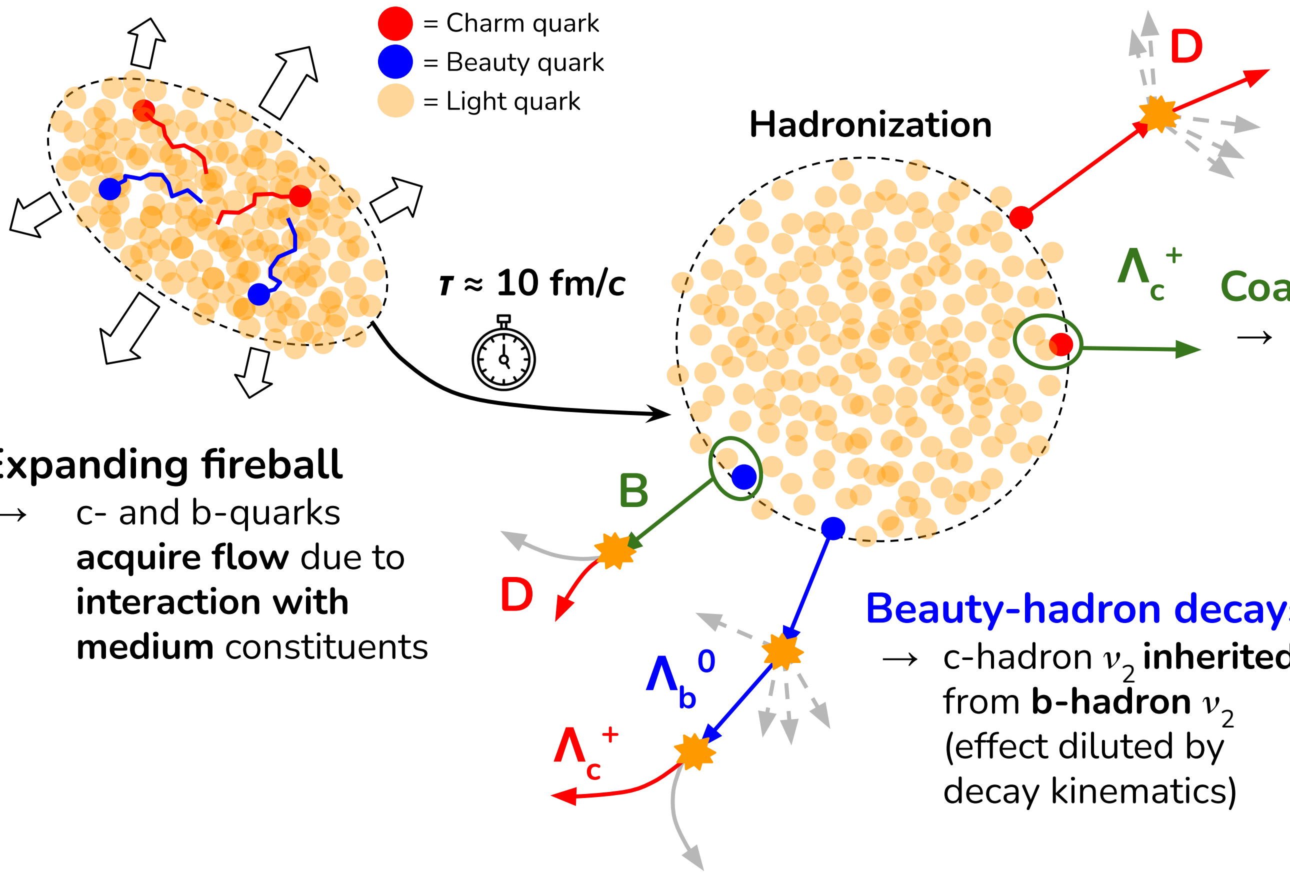
Beauty-hadron decays

→ c-hadron v_2 **inherited** from **b-hadron** v_2 (effect diluted by decay kinematics)

Charm hadron production and elliptic flow



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Beauty-hadron decays
→ c-hadron v_2 **inherited** from **b-hadron** v_2 (effect diluted by decay kinematics)

Subsequent **rescattering among hadrons** (hadronic phase) can contribute to the observed v_2

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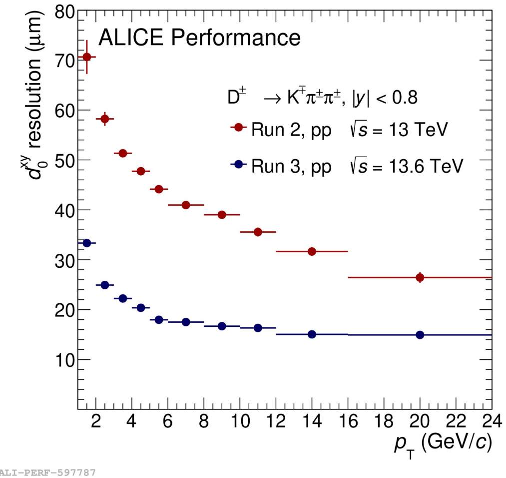
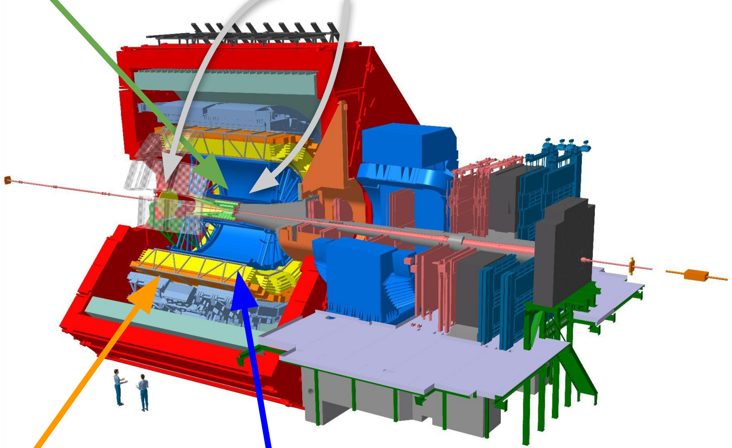
A Large Ion Collider Experiment

Inner Tracking System:
→ 7 layers of silicon sensors
→ Primary and secondary vtx. reco.
→ Tracking



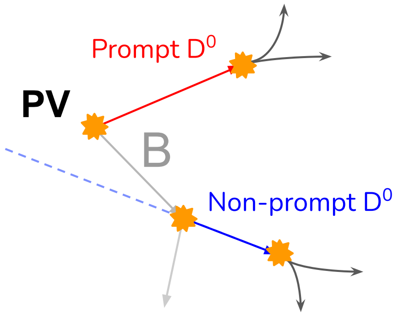
FT0C:
→ centrality determination
→ v_2 resolution
FV0:
→ v_2 resolution



Time-Of-Flight:
→ PID via time of flight

Time Projection Chamber:
→ Tracking
→ PID via dE/dx
→ GEM readout (interaction rate up to 50 kHz in Pb–Pb collisions)
→ v_2 resolution

- Full 2023 Pb–Pb data sample
  - $\sqrt{s_{NN}}$ = 5.36 TeV
  - **Int. Luminosity ≈ 1.5 nb^{-1}**
- Reconstruction channels (|η|<0.8):
  - $D^0 \rightarrow K^-\pi^+$
  - $D^+ \rightarrow K^-\pi^+\pi^+$
  - $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$
  - $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - $J/\psi \rightarrow \mu^+\mu^-$ at forward rapidity (L. Micheletti's talk, Wed., T04, 16:40)



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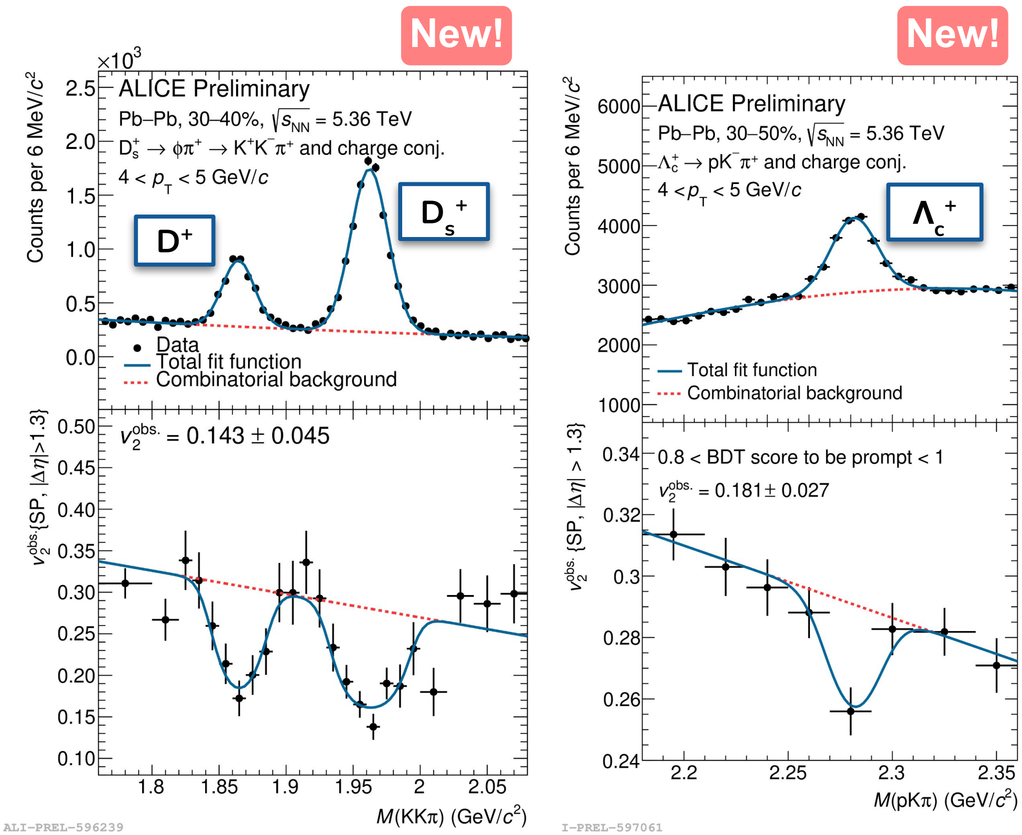
Signal extraction



- **Machine learning** multiclass BDT classification
  - → **Displaced decay topology and PID** information on daughters are exploited
  - → Separation between **prompt (P), non-prompt (NP) and bkg** candidates
- **v_2 vs. mass** spectrum associated to each invariant mass spectrum
- **Simultaneous fit** of signal (*S*) and bkg (*B*) v_2 and mass distributions

$$v_2(M) = v_2^S \frac{S}{S+B}(M) + v_2^B(M)\frac{B}{S+B}(M)$$

Prompt and non-prompt v_2 extraction

- **Non-prompt fraction** estimated via a data-driven method

$$\begin{pmatrix} (\mathrm{Acc}\times\varepsilon)^{\mathrm{P}}_{1} & (\mathrm{Acc}\times\varepsilon)^{\mathrm{NP}}_{1} \\ \vdots & \vdots \\ (\mathrm{Acc}\times\varepsilon)^{\mathrm{P}}_{N} & (\mathrm{Acc}\times\varepsilon)^{\mathrm{NP}}_{N} \end{pmatrix} \times \begin{pmatrix} N^{\mathrm{P}} \\ N^{\mathrm{NP}} \end{pmatrix} - \begin{pmatrix} Y_1 \\ \vdots \\ Y_N \end{pmatrix} = \begin{pmatrix} \delta_1 \\ \vdots \\ \delta_N \end{pmatrix}$$

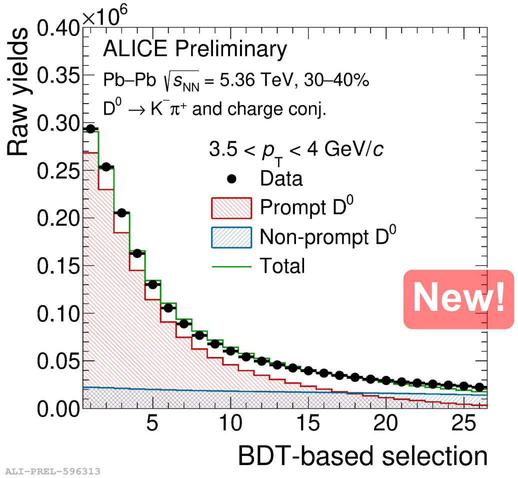
Acceptance and efficiency for the considered cutsets (N) | **Corrected yields** | **Measured yields** | **Residuals**

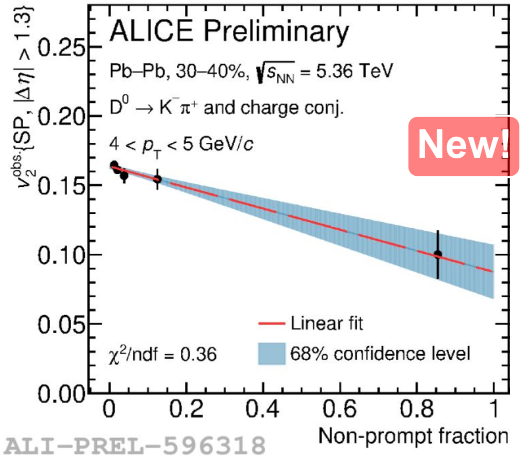
ALICE, JHEP 05 (2021) 220
ALICE, JHEP 10 (2023) 092

- The **corrected yields** are obtained via a χ^2 minimization
- The measured v_2 for a given cutset is expressed as:

$$v_2^{\mathrm{obs}} = f_{\mathrm{NP}} \cdot v_2^{\mathrm{NP}} + (1 - f_{\mathrm{NP}}) \cdot v_2^{\mathrm{P}}$$

- A **linear fit** is performed to extract the prompt and non-prompt values





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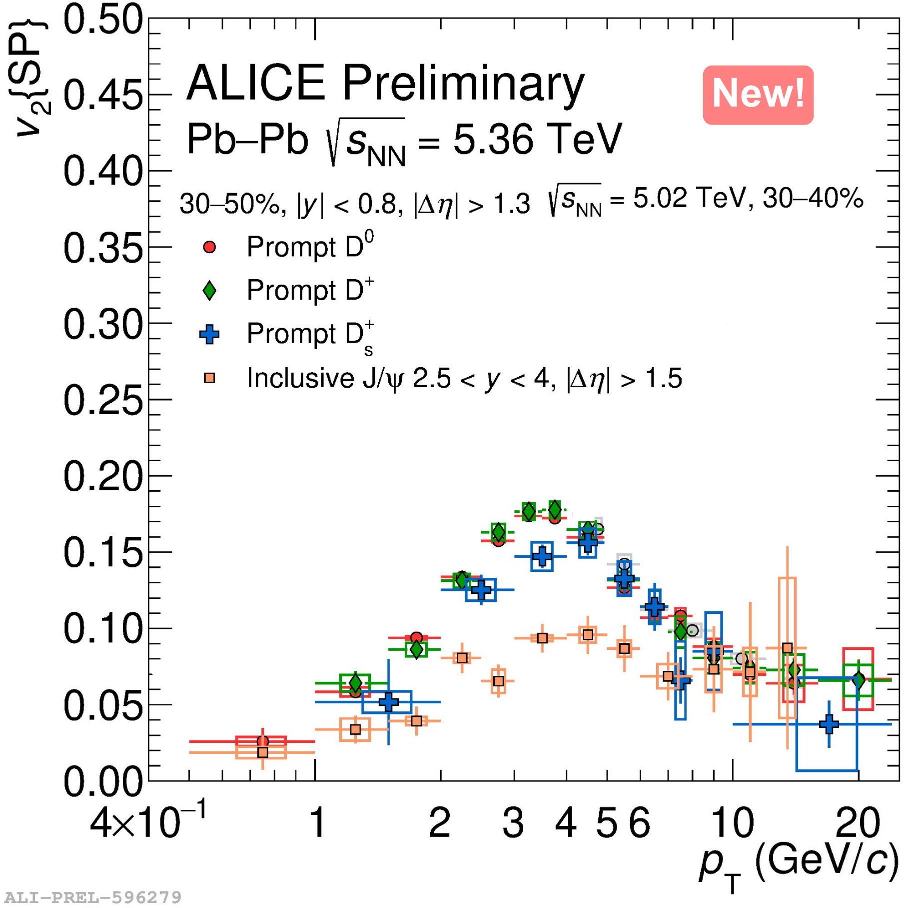
Meson elliptic flow



- **Positive v_2**

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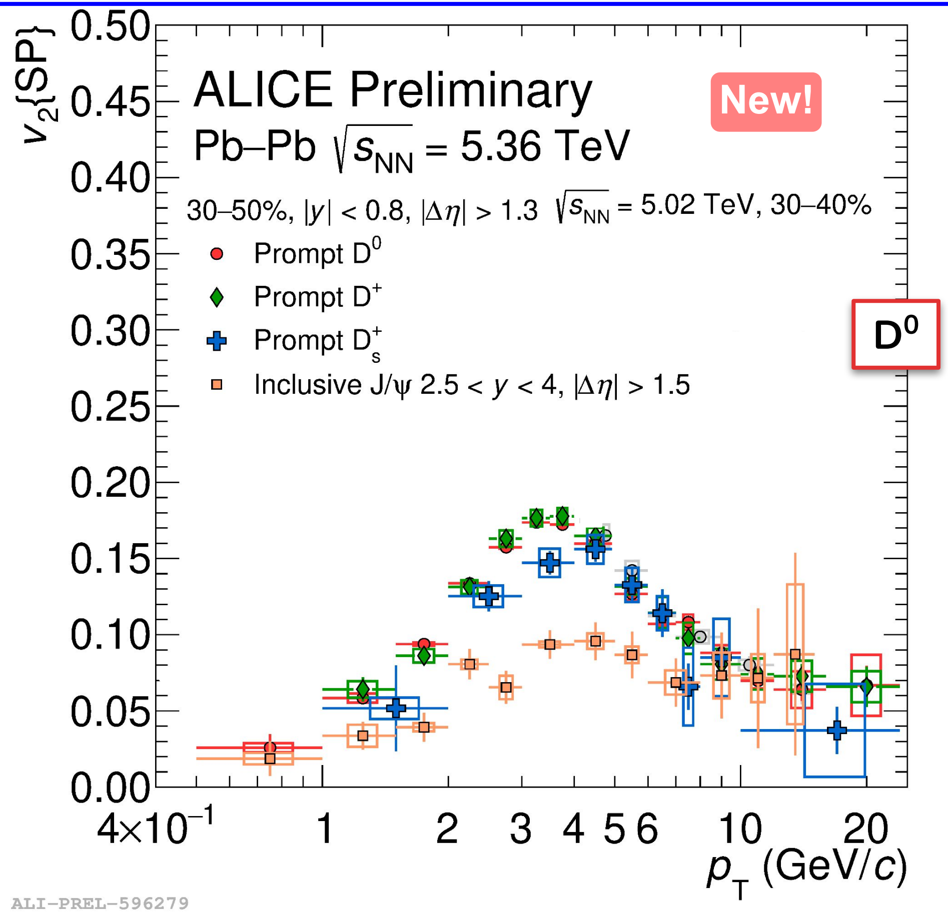
Meson elliptic flow



- **Positive v_2**
- First D^0 measurement **below 1 GeV/c**

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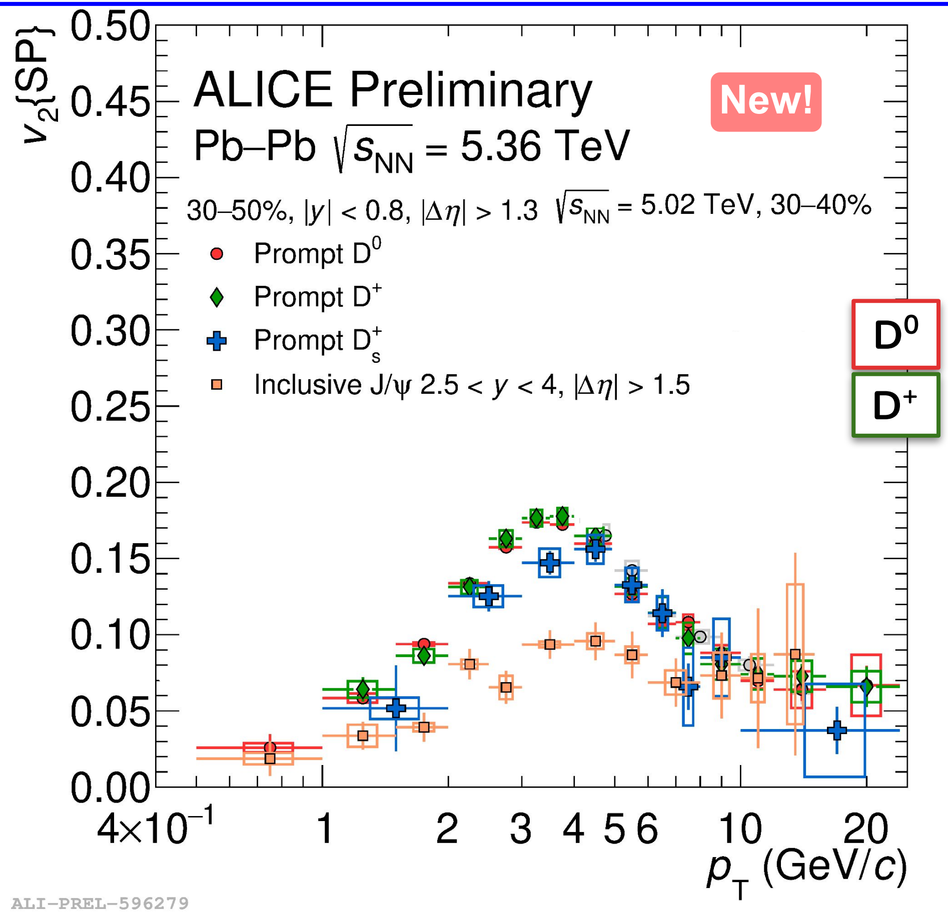

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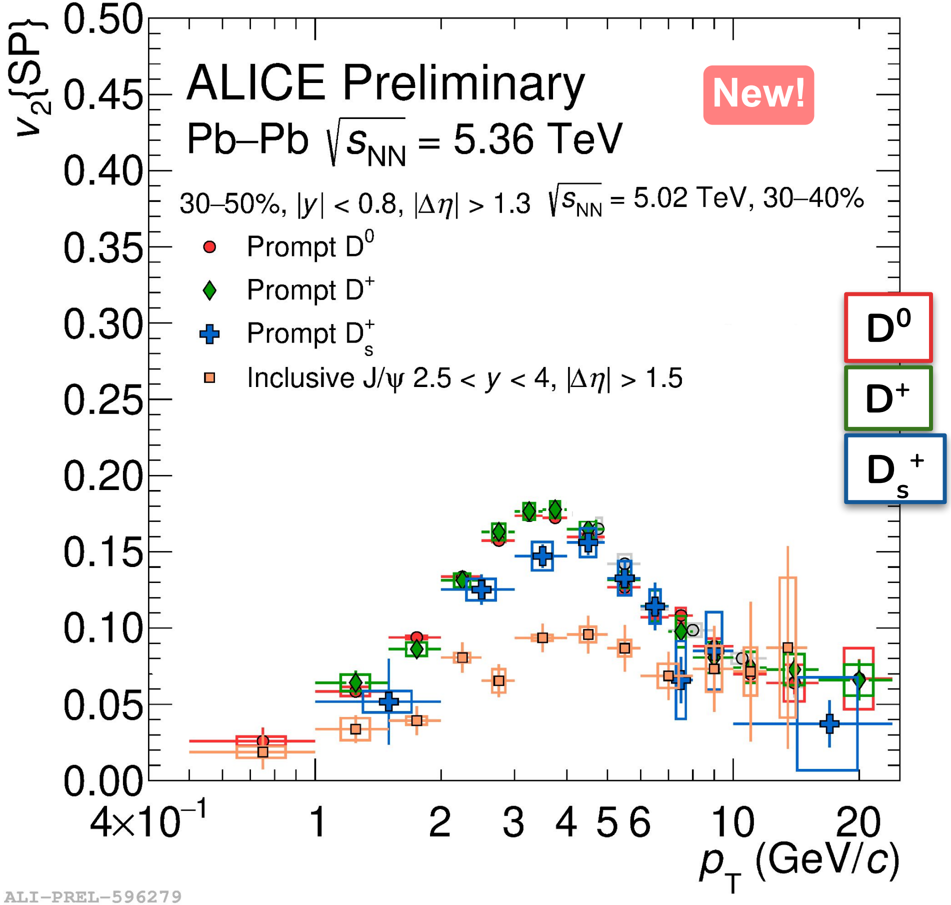
- First D^0 measurement **below 1 GeV/c**
- **Excellent agreement** between D^0 and D^+ over the measured p_T range

Meson elliptic flow



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- **Excellent agreement** between D^0 and D^+ over the measured p_T range
- Hint of **smaller D_s^+ v_2** at low p_T
  - → different contribution of hadronic phase?

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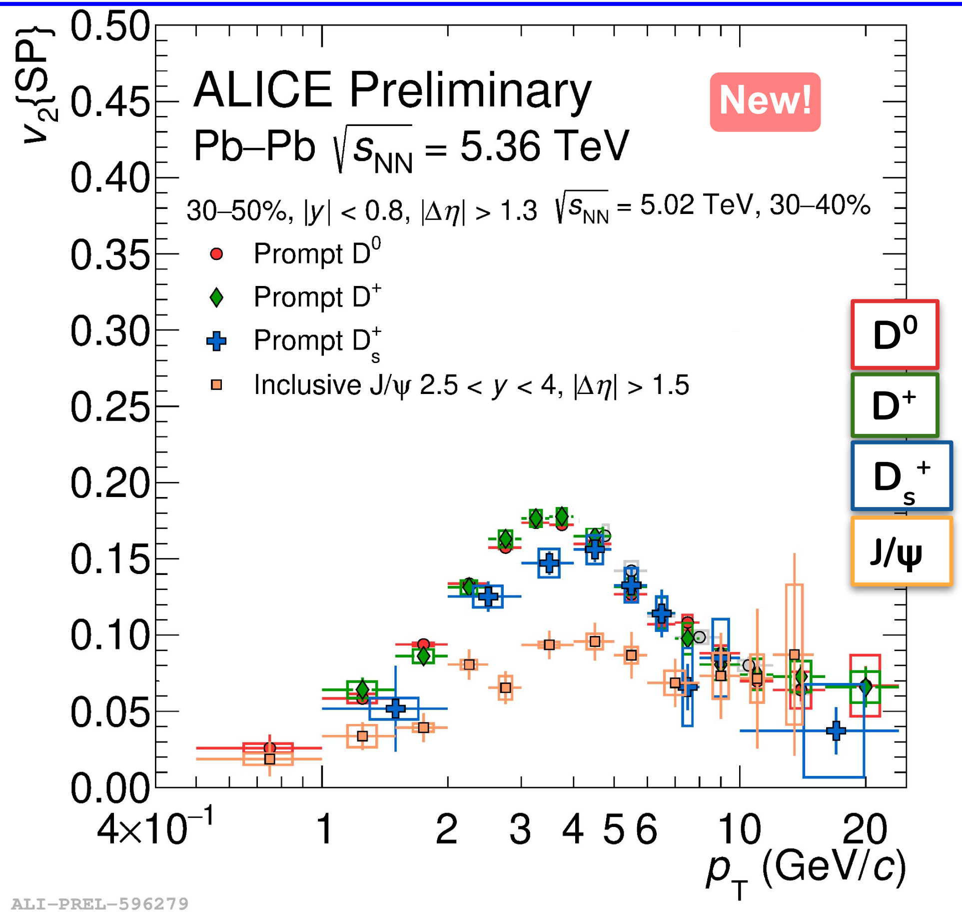
Meson elliptic flow



- **Positive ν_2**
- First D^0 measurement **below 1 GeV/c**
- **Excellent agreement** between D^0 and D^+ over the measured p_T range
- Hint of **smaller D_s^+ ν_2** at low p_T
  - → different contribution of hadronic phase?
- Inclusive J/ψ ν_2 **lower** than prompt D ν_2 at intermediate p_T

L. Micheletti's talk, Wed., T04, 16:40

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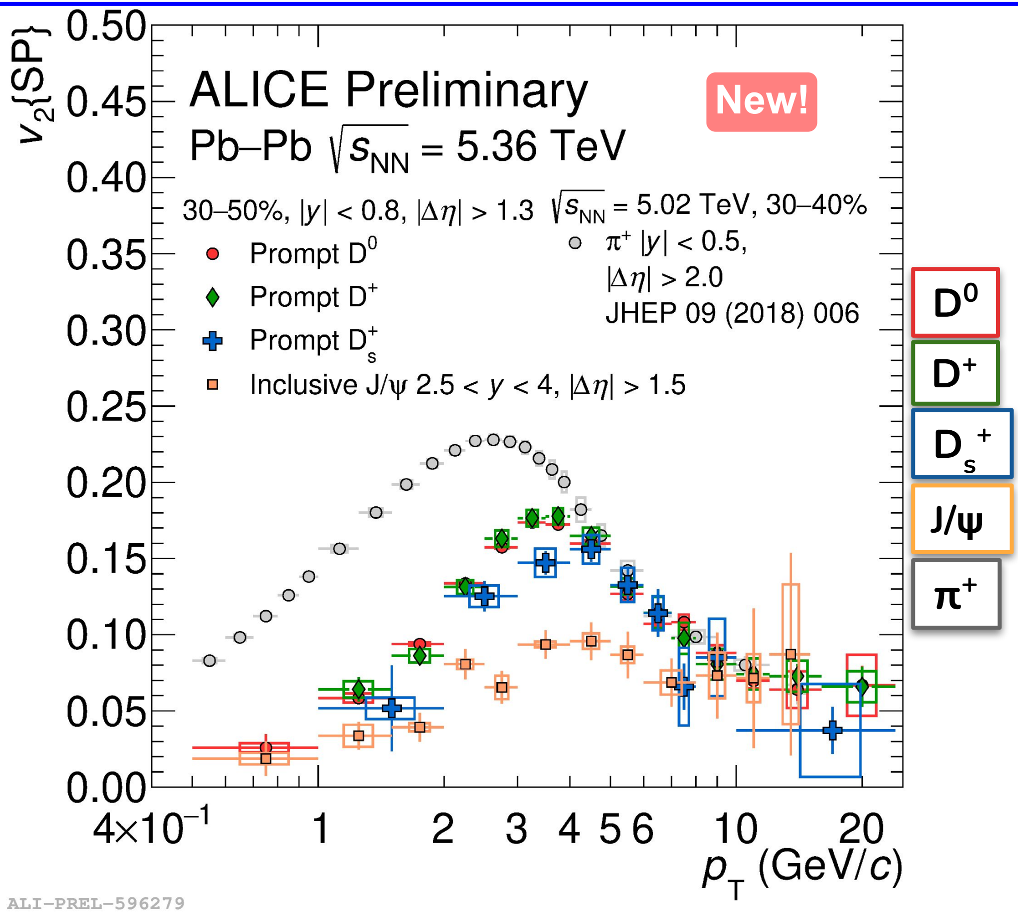
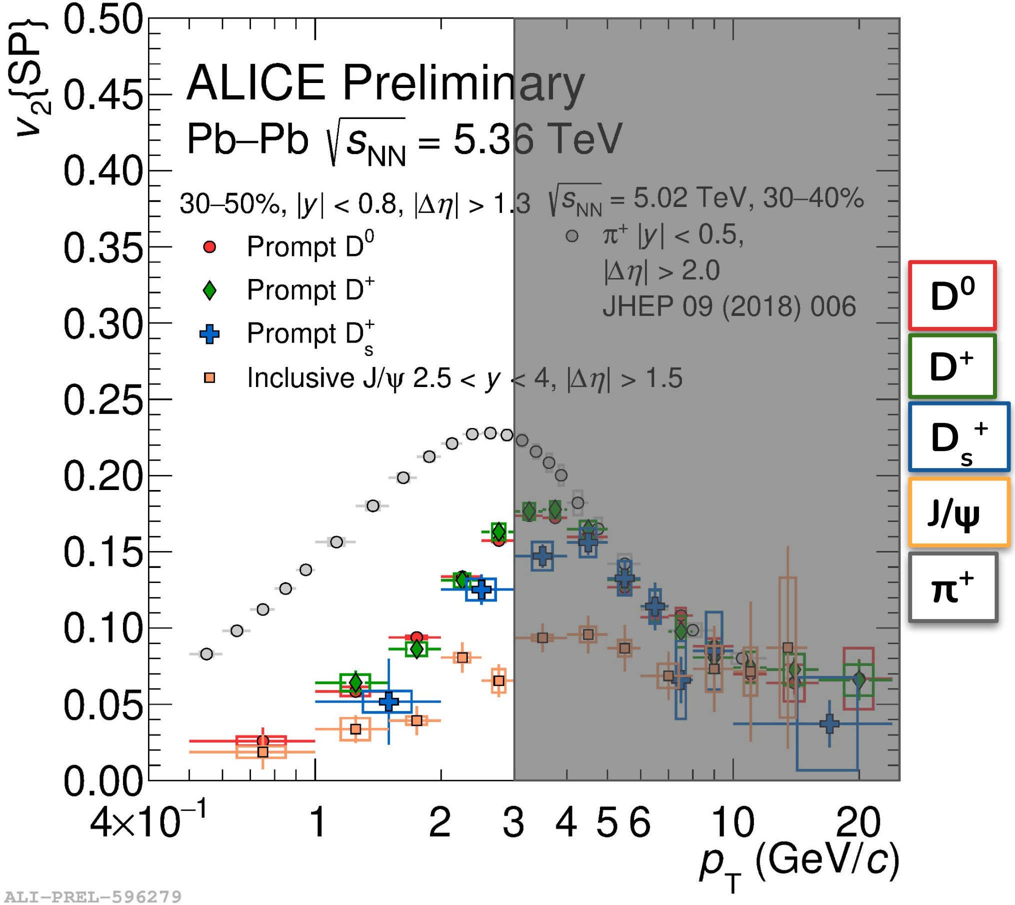
Meson elliptic flow



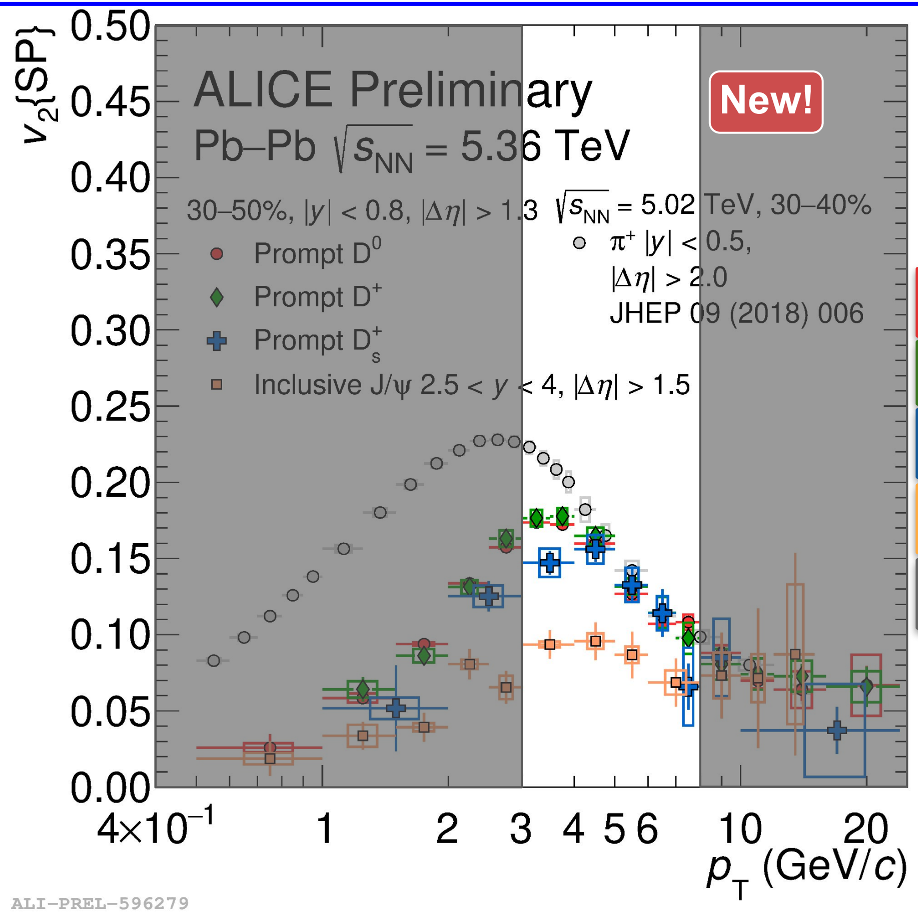
- Maximum v_2 values **not far from pions**
  → (partial) charm thermal equilibration

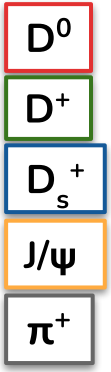
Meson elliptic flow



- Maximum v_2 values **not far from pions**
  - → (partial) charm thermal equilibration
- Clear **mass ordering** below 3 GeV/c
  - → Expected from hydrodynamic picture
  - → $m(J/\psi) > m(D_s^+) > m(D^0) \approx m(D^+)$

Meson elliptic flow – hadronization





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- **Larger** v_2 for open- than hidden-charm states in $3 < p_T < 8$ GeV/c
  - → Expected by hadronization via **coalescence**

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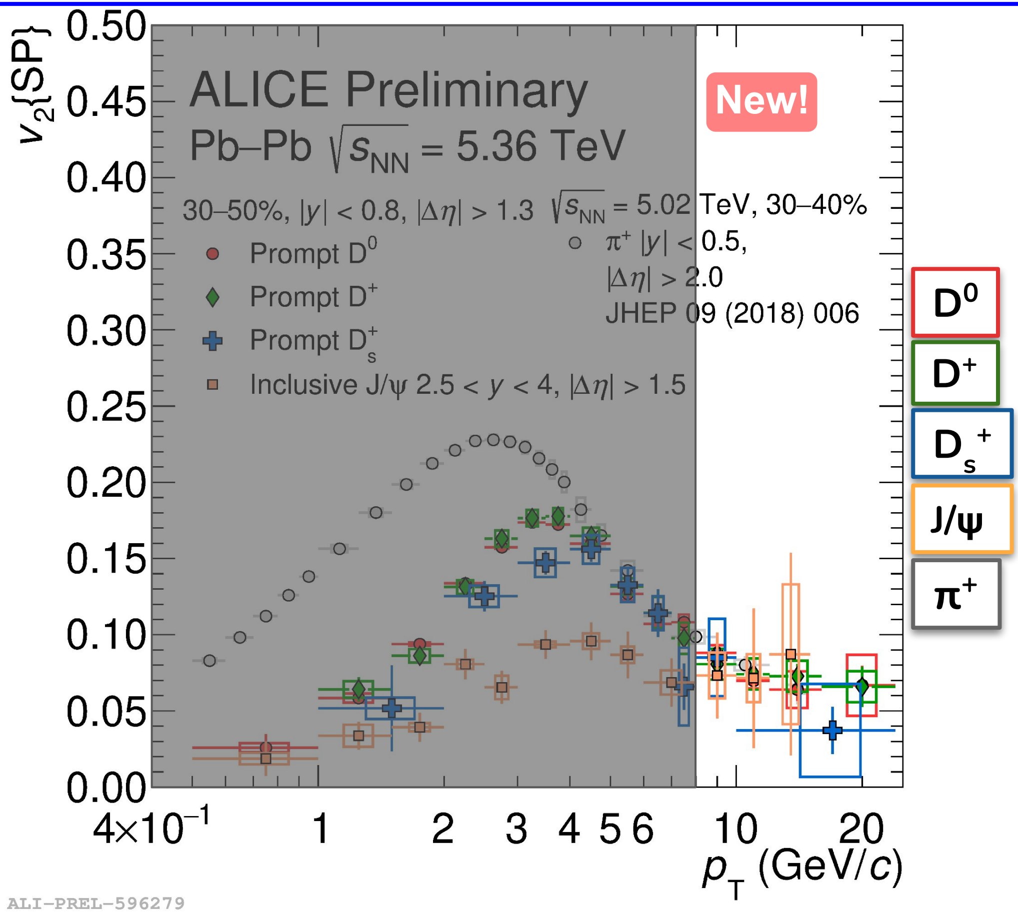
Meson elliptic flow – hadronization



- Maximum ν_2 values **not far from pions**
  - → (partial) charm thermal equilibration
- Clear **mass ordering** below 3 GeV/c
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  - → $m(J/\psi) > m(D_s^+) > m(D^0) \approx m(D^+)$
- **Larger** ν_2 for open- than hidden-charm states in $3 < p_T < 8$ GeV/c
  - → Expected by hadronization via **coalescence**
- **Common** $\boldsymbol{\nu_2} > 0$ for $p_T > 8$ GeV/c
  - → In-medium **energy loss**
  - → **Fragmentation** dominates over coalescence

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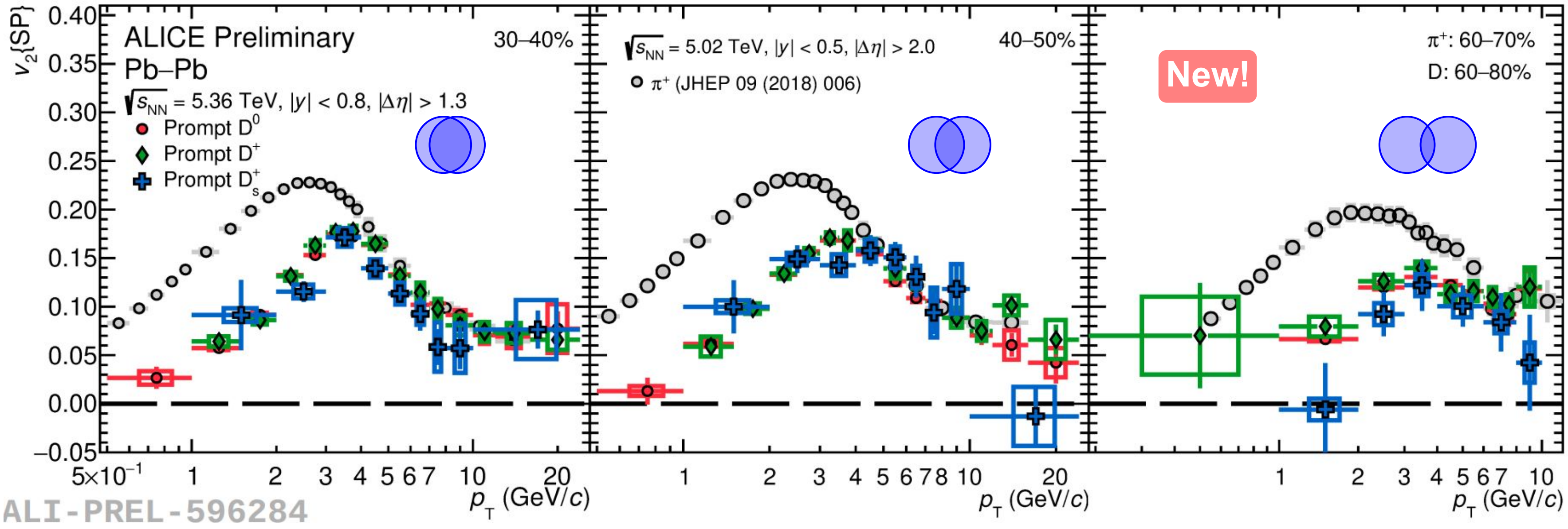
Meson elliptic flow – centrality dependence



- **Centrality dependence** of v_2
  - → transport properties of the QGP
- **Flatter** trend in 60-80%
  - → Sensitive to thermal equilibration of charm quark in a shorter lived fireball?

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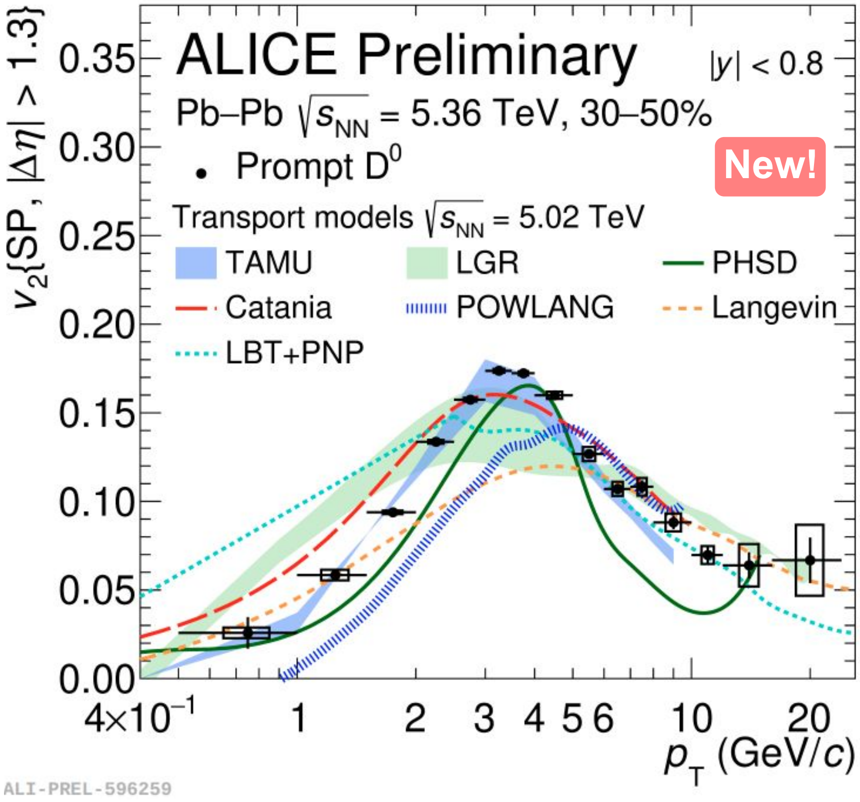
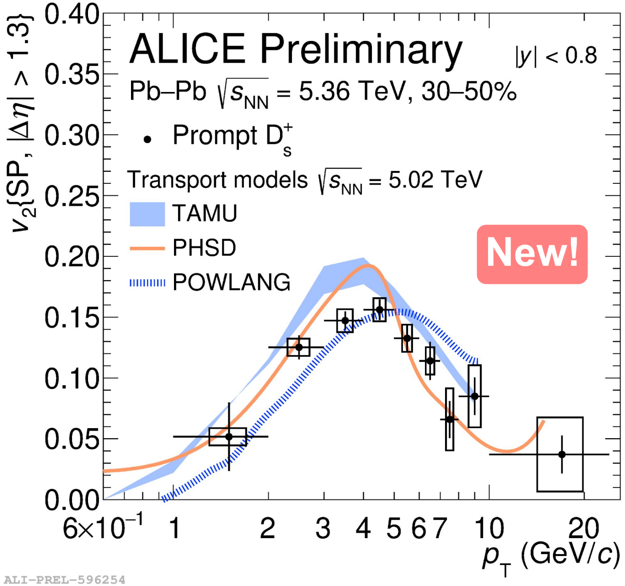
Comparison to model predictions – Prompt D^0

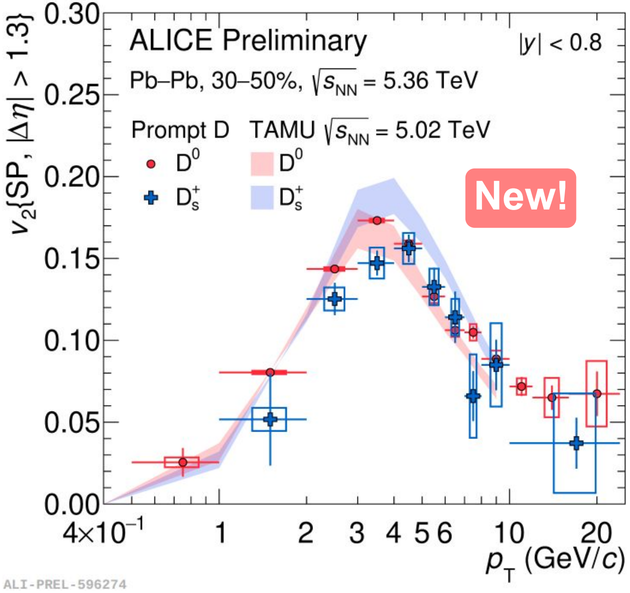
- D^0 v_2 compared with **transport model** predictions
- Model differences:
  - → Balance of coalescence and fragmentation
  - → Hadronic phase implementation
  - → Diffusion coefficient D_s
  - → Underlying hydrodynamics
- **High data precision:** significant constraints to model features



TAMU: PRL 124 (4) (2020) LGR: EPJC 80 (7) (2020) PHSD: PRC 93 (3) (2016)
CATANIA: PRC, 96 (4) (2017) POWLANG: EPJC 82 (2022) 607
LANGEVIN: EPJC 81 (2021) 1035 LBT+PNP: PLB 838 (2023) 137733

Comparison to model predictions – Prompt D_s^+



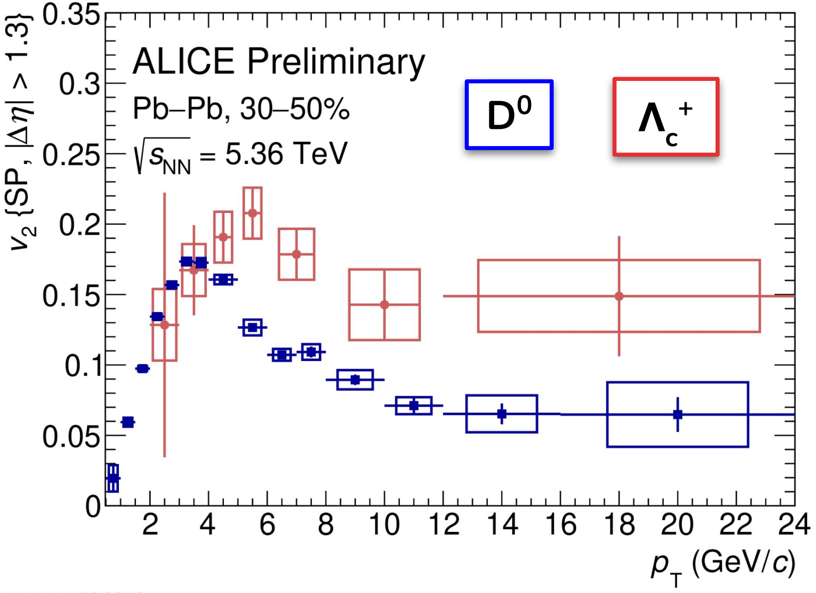


TAMU: PRL 124 (4) (2020)
PHSD: PRC 93 (3) (2016)
POWLANG: EPJC 82 (2022) 607

- D_s^+ vs. D^0 sensitive to: **strange quark dynamics** in QGP medium, **coalescence** and **hadronic phase** interactions
- TAMU predicting **opposite** D_s^+/D^0 hierarchy with respect to data? M. He et al. PRL 110 (2013) 112301

Charm baryon flow

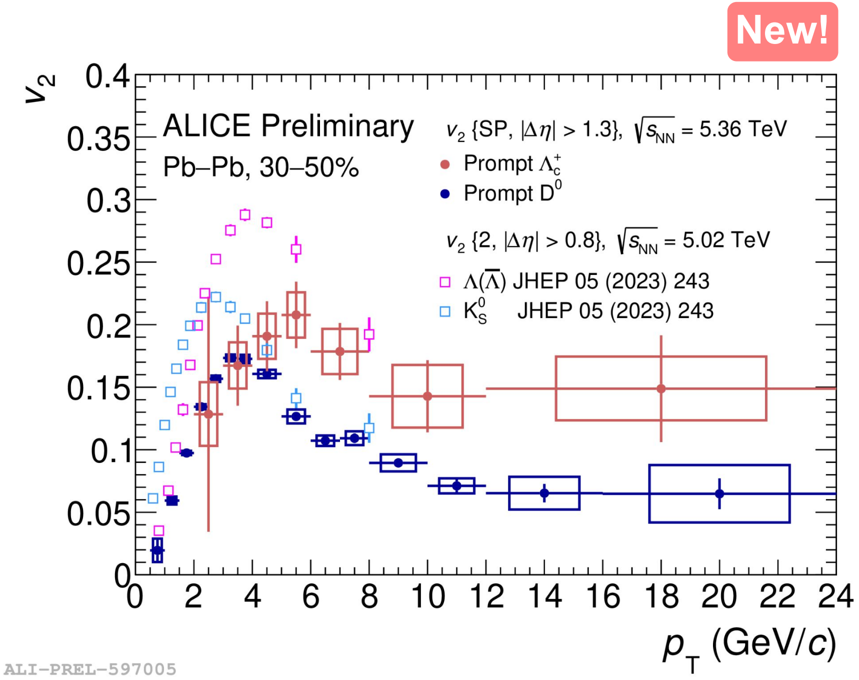
New!



ALI-PREL-596373

- First **prompt charm baryon** v_2 measurement in Pb–Pb collisions
- **Compatible with D^0** within uncertainties for $p_T < 4$ GeV/c
- First evidence of **meson-baryon splitting in the charm sector** with 3.6σ significance for $p_T > 4$ GeV/c

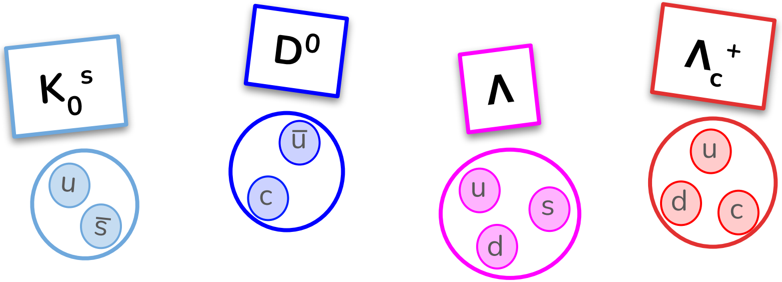
Meson–baryon splitting



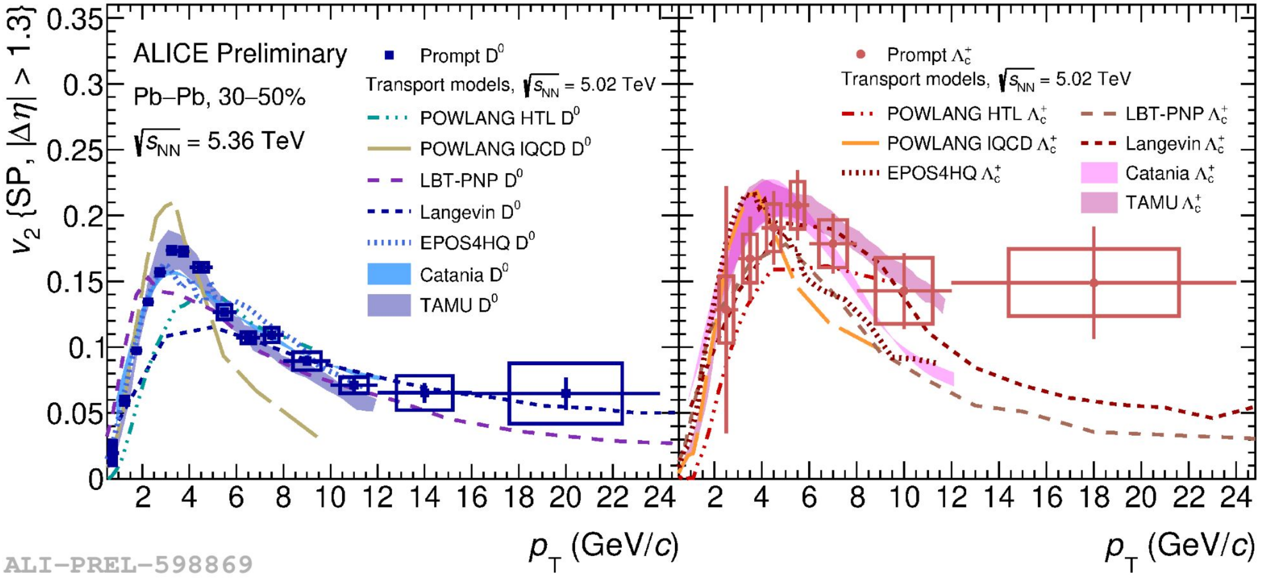
- Comparison with **light flavour** hadrons
- **Mass ordering** at low p_T:

  → $v_2(K_s^0) > v_2(\Lambda) > v_2(D^0) \sim v_2(\Lambda_c^+)$

- **Baryon-meson splitting** at higher p_T, favouring **coalescence** hypothesis



Comparison to model predictions – Prompt Λ_c^+



New!

TAMU: PRL 124 (4) (2020)

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LANGEVIN: EPJC 81 (2021) 1035

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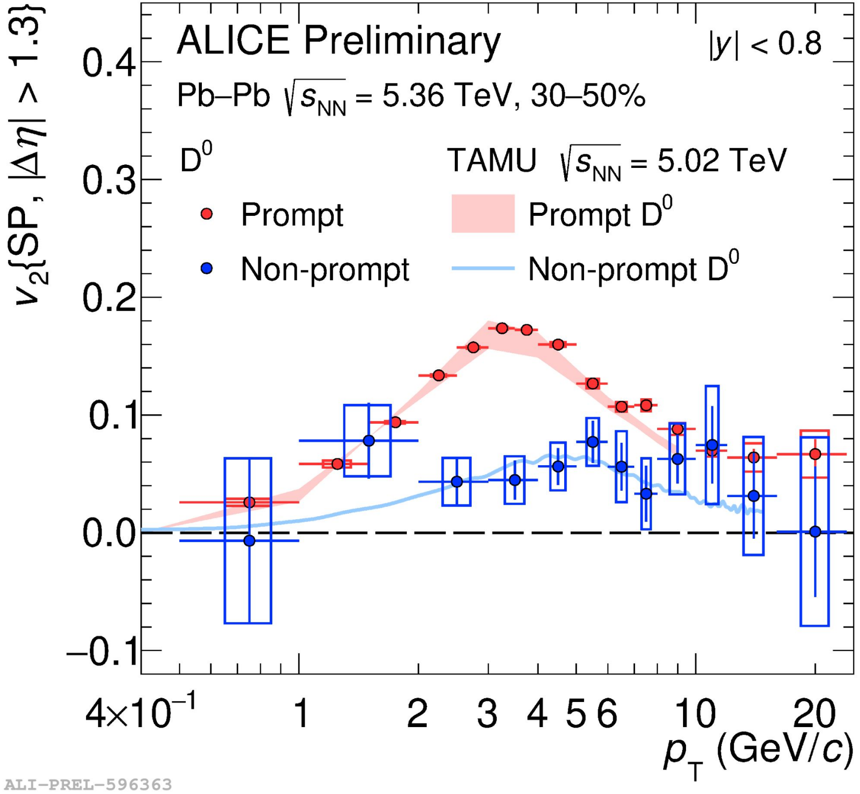
- Most models are able to describe the Λ_c^+ v_2 within uncertainties
  - → **Uncertainty reduction** expected from analysis of 2024 and 2025 data samples
- **New inputs for hadronization implementation** in theoretical models

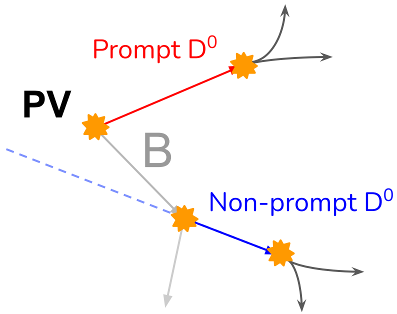
Towards the beauty sector

New!

TAMU: PRL 124 (4) (2020)



- Positive **non-prompt ν_2**, lower than the **prompt one**
- $m_b >> m_c \rightarrow$ **longer** relaxation time



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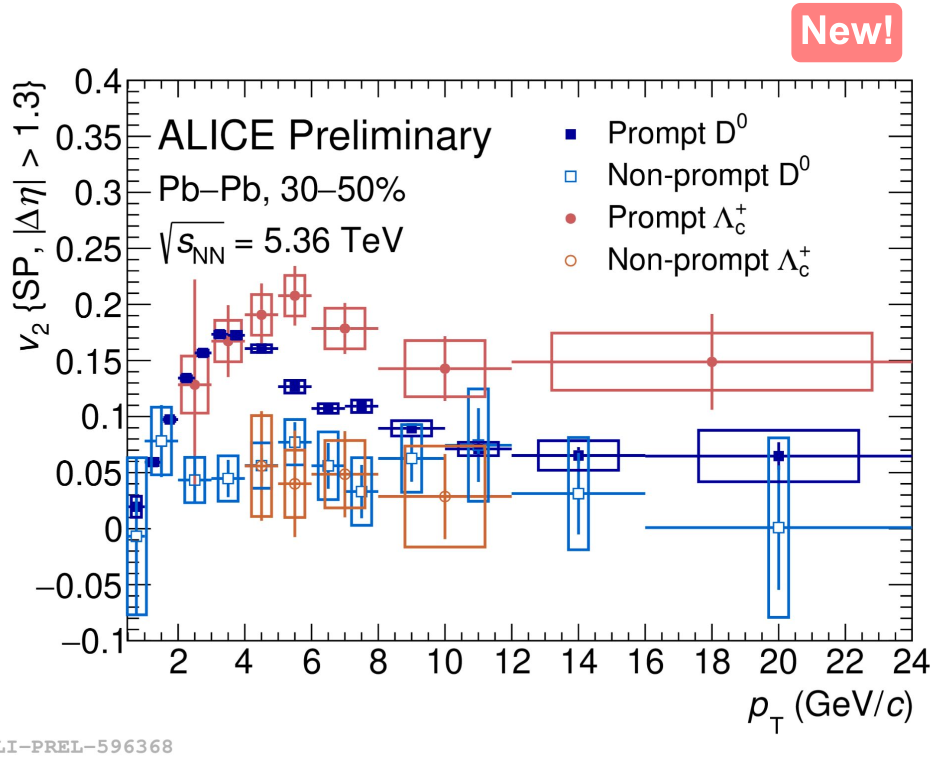
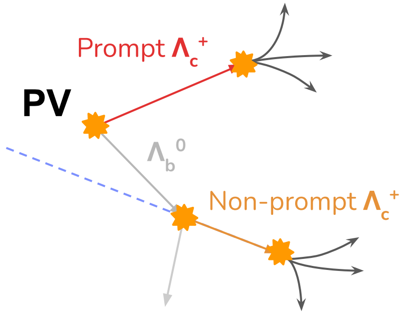
Towards the beauty sector



- Accessing **beauty baryon v_2** for the **first time ever** via **non-prompt Λ_c^+ v_2**
- **Consistent v_2 for non-prompt** for D^0 and Λ_c^+



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Summary and outlook

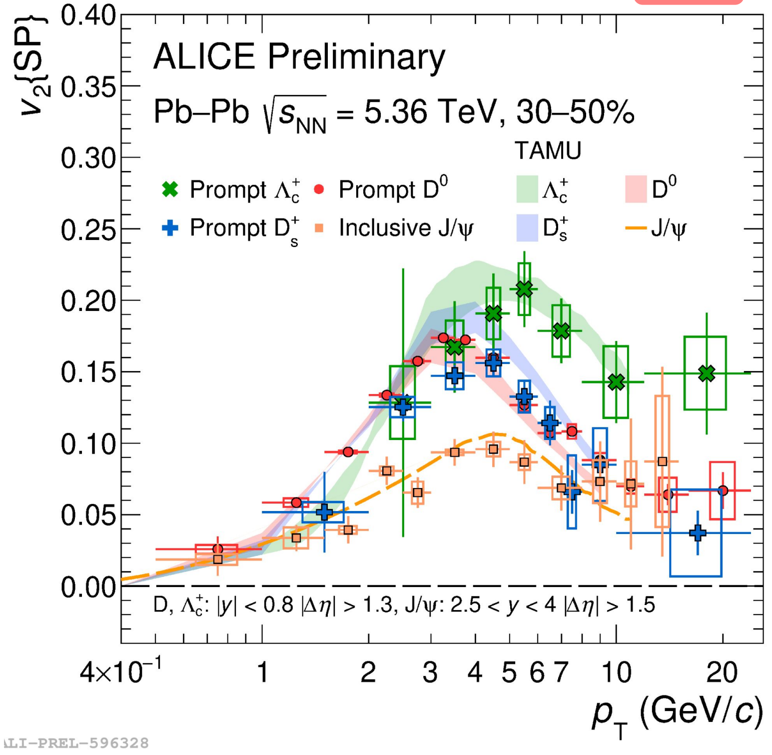
- Information on **charm quark interaction** with the medium through charm hadron v_2 measurements

- Prompt D-meson v_2 measurements in Pb–Pb from 30 to 80% centrality
  - → First measurement **below 1 GeV/c** for D^0
  - → Decreasing v_2 from semicentral to peripheral collisions
  - → **Hint of $v_2(D_s^+) < v_2(D^0)$** in semi-central collisions

- **First measurements of Λ_c^+ v_2** in Pb–Pb in 30-50%
  - → **Baryon-meson splitting** observed in HF sector

- Analyzed int. luminosity of **1.5 nb^{-1}**, more to come:
  - → Int. lumi. **2024: 1.5 nb^{-1}**, expected int. lumi. **2025: 2.6 nb^{-1}**

New!



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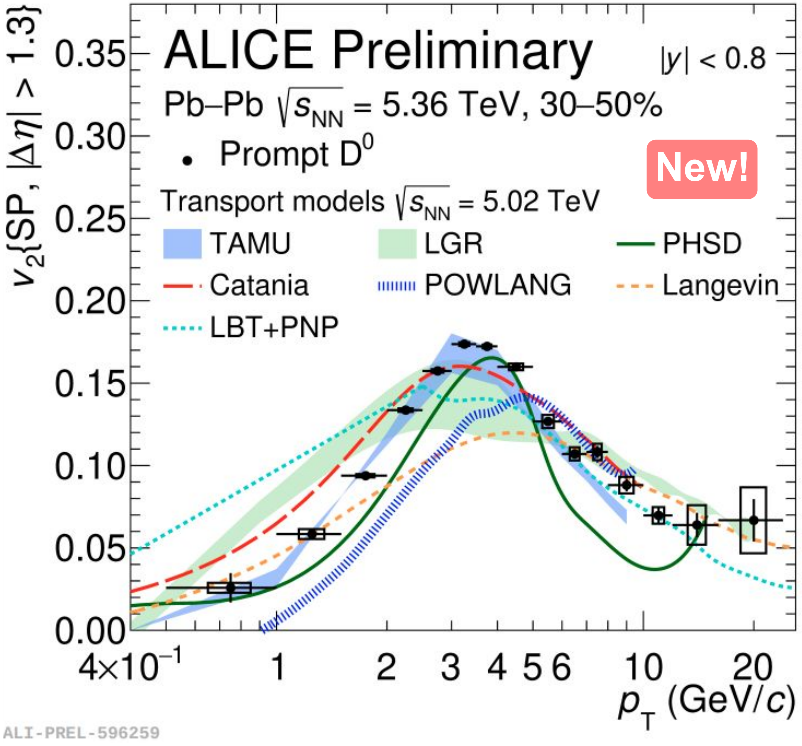
Thank you for the attention!

Transport model properties

Models	Bulk	nPDFs	HQ interactions	Hadronization	Hadron phase	D_s	Ref.
CATANIA	Boltzmann, quasi-particle s		**Langevin**	**Recomb. (Wigner) + Frag.**	No	**3.5-4.5**	Phys. Rev. C 96 (2017) 044905 (R_{AA}) Phys. Lett. B 805 (2020) 135460 (v_2)
DAB-MOD (M&T)	Hydro viscous (v-USPhydro)		**Langevin**	**Recomb. (ICM) + Frag.**	No	**2.5**	Phys. Rev. C 102, 024906 (2020)
LBT	Hydro viscous (VISHNew)	Yes	**Boltzmann coll+rad**	**Recomb. (ICM) + Frag.**	No	**2**	Phys. Rev. C 94 (2016) 014909 Phys. Lett. B 777 (2018) 255
LIDO	Hydro viscous		**Boltzmann Langevin coll+rad**	**Recomb. (ICM) + Frag.**	Yes	**2-4**	Phys. Rev. C 100, 064911
LGR	Hydro viscous	Yes	**Langevin coll+rad**	**Recomb. + Frag.**		**2-4**	Eur. Phys. J. C, 80 (2020) 671
MC@sHQ+ EPOS2	Hydro ideal (EPOS)	Yes	**Boltzmann coll+rad**	**Recomb. (ICM) + Frag.**	No	**1.5**	Phys. Rev. C 89 (2014) 014905
PHSD	Off-shell parton transport	Yes	**Collisional**	**Recomb. (ICM) + Frag.**	Yes	**4**	Phys. Rev. C 93, 034906 (2016) (LHC) Phys. Rev. C 92, 014910 (2015)
POWLANG	Hydro viscous (ECHO-QGP)	Yes	**Langevin coll**	**In-medium strings**	No	**7**	Eur. Phys. J. C 75 (2015) 121 (R_{AA}) JHEP 02 (2018) 043 (v_2)
TAMU	Hydro ideal	Yes	**Langevin T-matrix (coll)**	**Recomb. (RRM) + Frag.**	Yes	**4**	Phys. Rev. Lett. 124, 042301 (2020)

Comparison to model predictions – Prompt D^0

- D^0 v_2 compared with transport models predictions
  - → Model differences: coalescence and hadronic phase implementation, adoption of *n*PDFs, underlying hydro
  - → High data precision allows for constraints to D_s
- LGR, Catania, and LBT+PNP overestimate data for $p_T < 3$ GeV/c
- Good agreement for TAMU, Catania, LGR in the range $3 < p_T < 5$ GeV/c
  - → Suggest the critical role of coalescence/recombination and of space-momentum correlations
- All models except PHSD describe data within uncertainty for $p_T > 5$ GeV/c
  - → Fragmentation dominates hadronization at high p_T



TAMU: PRL 124 (4) (2020) LGR: EPJC 80 (7) (2020) PHSD: PRC 93 (3) (2016)

CATANIA: PRC, 96 (4) (2017) POWLANG: EPJC 82 (2022) 607

LANGEVIN: EPJC 81 (2021) 1035 LBT+PNP: PLB 838 (2023) 137733

The scalar product technique

$$v_n\{\mathrm{SP}\} = \frac{\left\langle \mathbf{u}_n \cdot \frac{\mathbf{Q}^*_{n,A}}{M_A} \right\rangle}{\sqrt{\frac{\left\langle \frac{\mathbf{Q}_{n,A}}{M_A} \cdot \frac{\mathbf{Q}^*_{n,B}}{M_B} \right\rangle \left\langle \frac{\mathbf{Q}_{n,A}}{M_A} \cdot \frac{\mathbf{Q}^*_{n,C}}{M_C} \right\rangle}{\left\langle \frac{\mathbf{Q}_{n,B}}{M_B} \cdot \frac{\mathbf{Q}^*_{n,C}}{M_C} \right\rangle}}}$$

$\mathbf{u}_n$ = $e^{in\phi}$, unit flow vector of the candidate with azimuthal angle φ

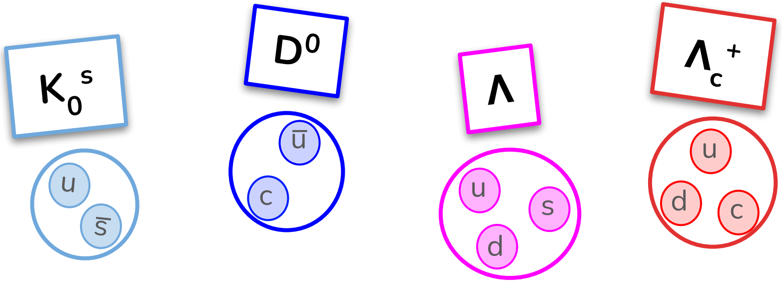
Three detectors define 3 sub-events A, B, C, where M represents the **particle multiplicity** and $\mathbf{Q}_n$ the **harmonic flow vector** defined as

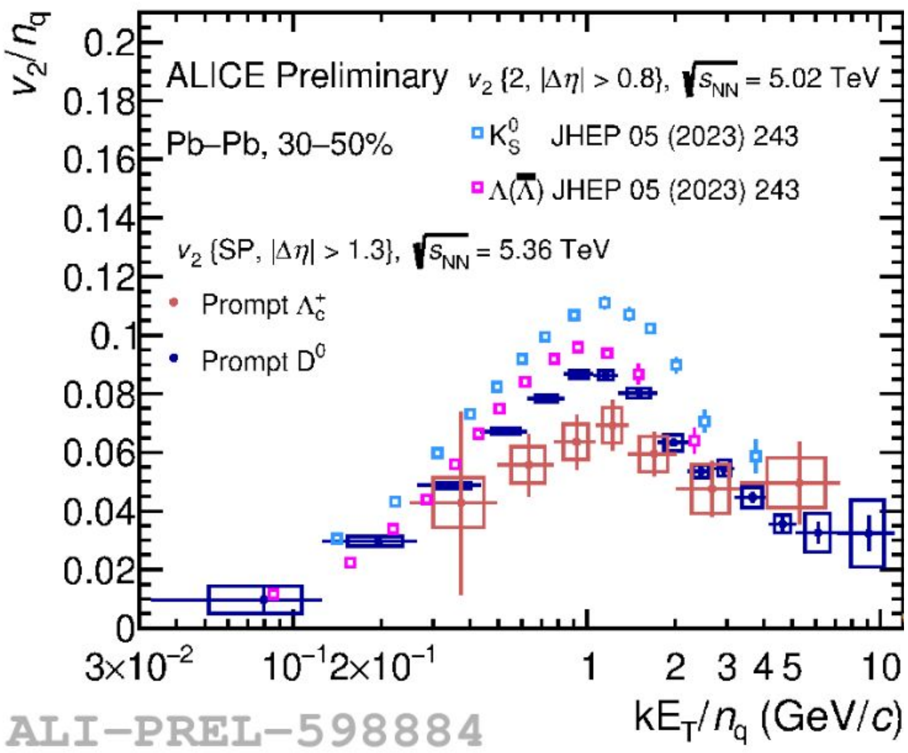
$$\mathbf{Q}_n = \sum_{k=1}^{M} w_k e^{in\phi_k}$$

Resolution term, accounts for **finite angular resolution** in the estimate of the symmetry plane harmonic through the flow vector due to **finite particle multiplicity**

Number of constituent-quark scaling

- **No clear universal scaling** of v_2/n_q between mesons and baryons observed in LF or HF





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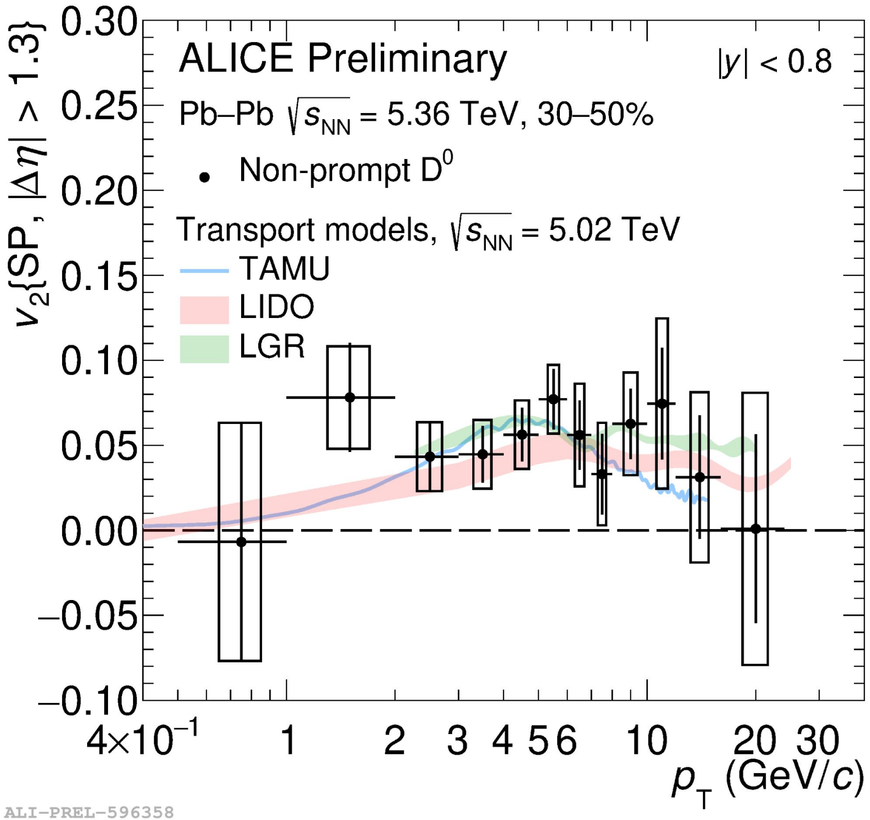
Towards the beauty sector



ALI-PREL-596358

- **Positive non-prompt v_2**, lower than the prompt one
- Models compatible with data within uncertainties

TAMU: PRL 124 (4) (2020)
LIDO: PRC 100 (2019) 064911
LGR: EPJC 80 (2020) 12, 1113