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ISOQUANT
SFB1225

GSI

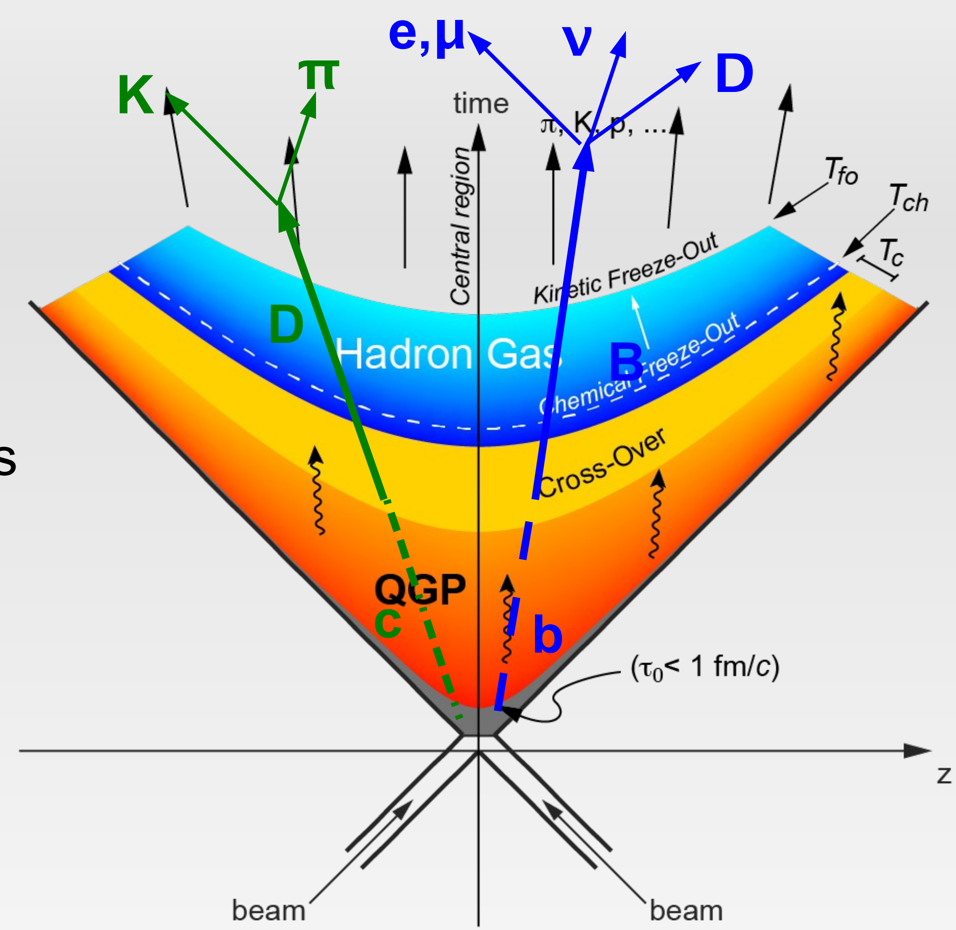
Anisotropic flow correlations of heavy-flavours in heavy-ion collisions

A. Dubla

25/02/2019

Physics motivation

- **Charm and beauty** quarks are produced in hard scattering processes in the early stage of the collision
- Experience the full evolution of the system → sensitive probes of the properties of the hot and dense QCD matter (QGP)
- **Lose energy** while traversing the medium
- Do heavy quarks participate in the **collective expansion** of the medium?



- **Investigation** of the **magnetic filed** created in heavy-ion collisions
- **C**old **N**uclear **M**atter effects and **hadronization**

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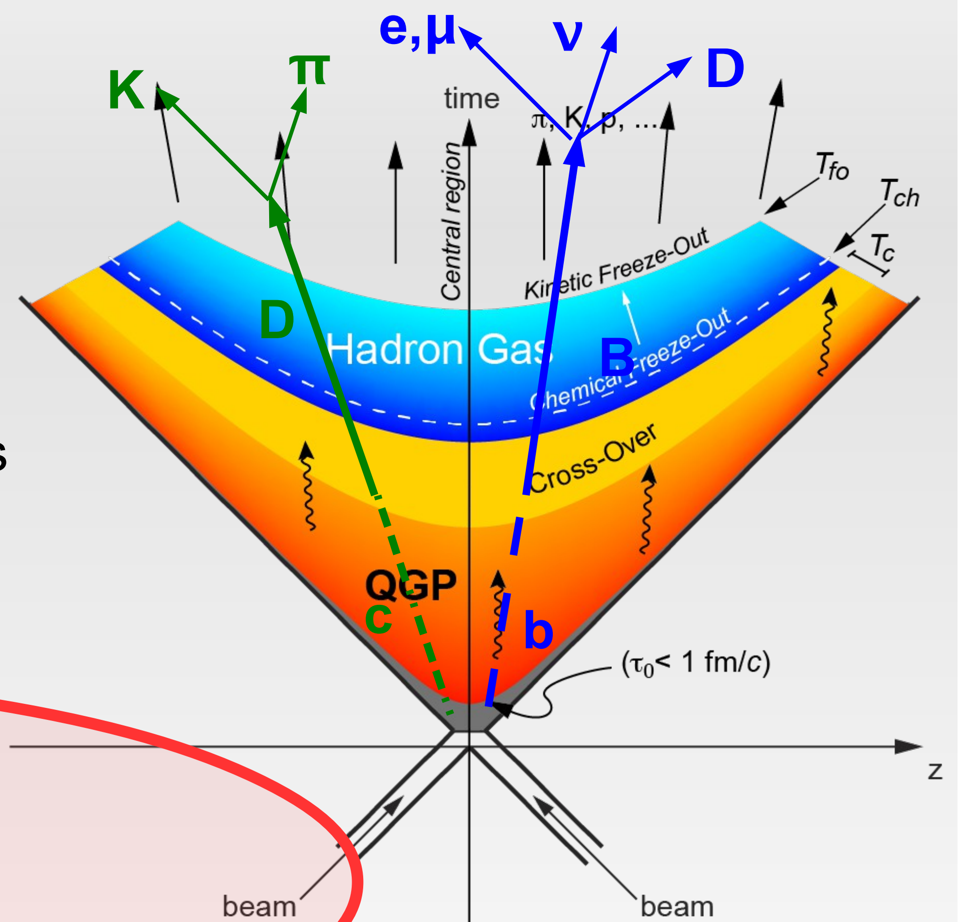
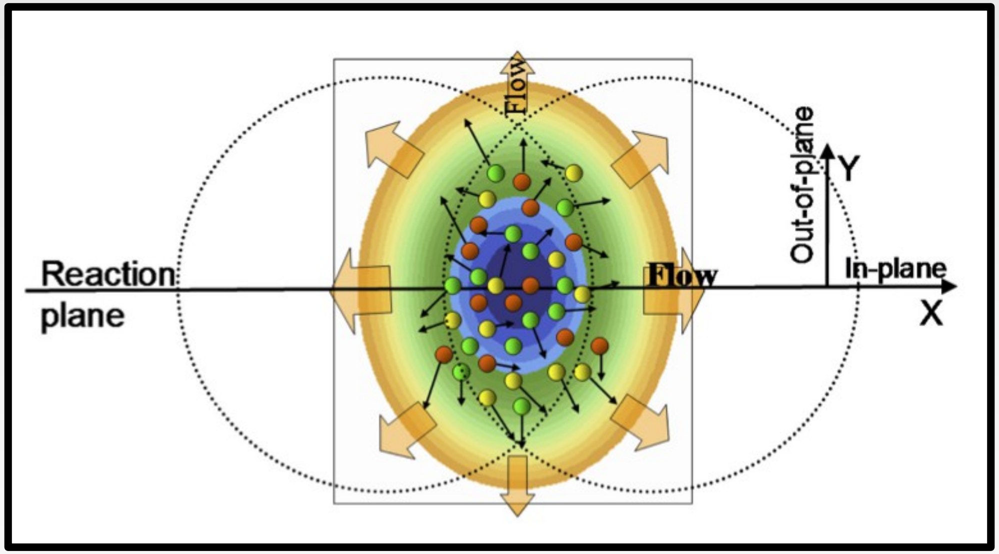


Collectivity: azimuthal anisotropy

– Re-scatterings among produced particles convert the initial **geometrical anisotropy** into an observable **momentum anisotropy**

– In addition, path-length dependent energy loss induces an asymmetry in momentum space

– **Observable**: **elliptic flow v_2 =** 2nd Fourier coefficient of the particle azimuthal distribution



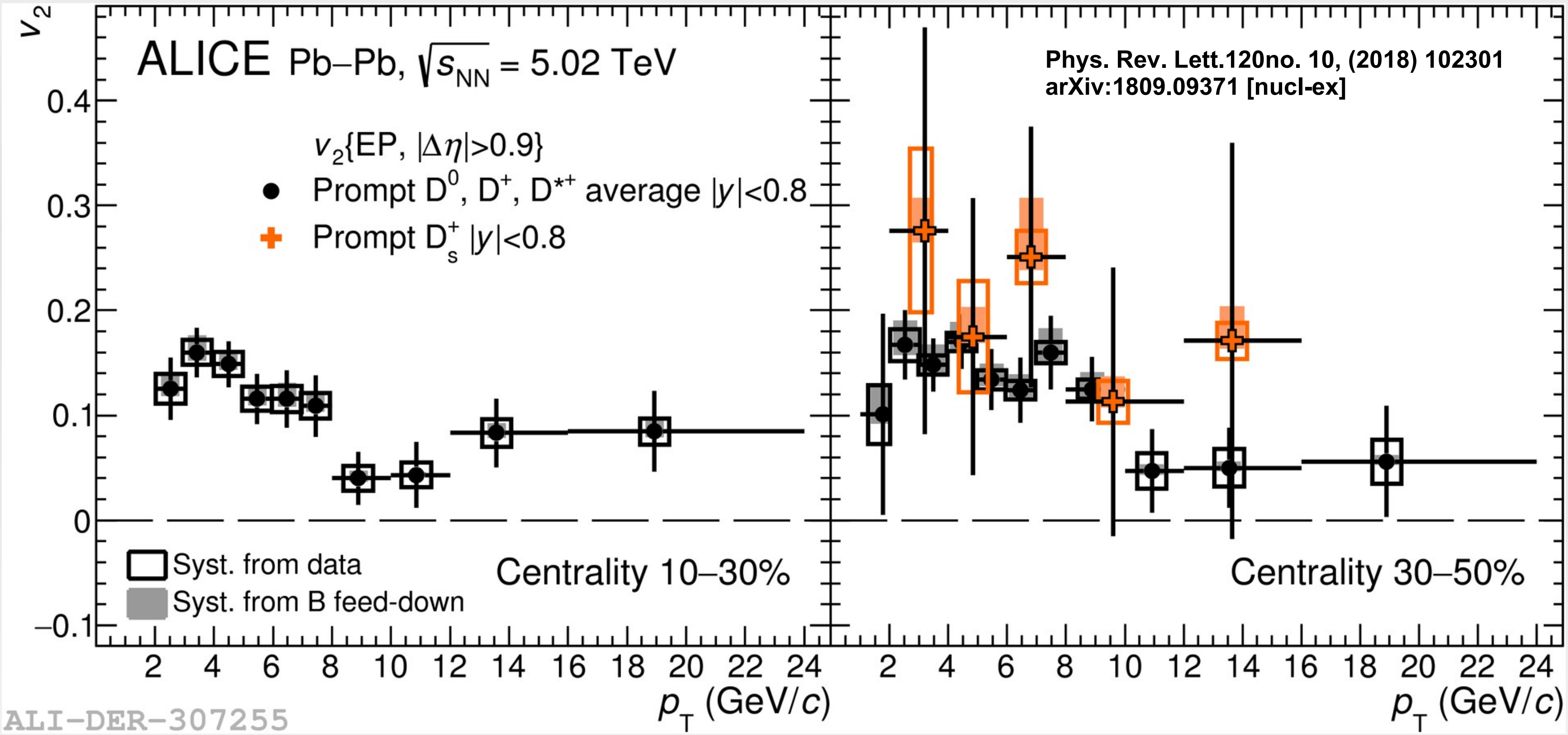
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\varphi - \Psi_{RP})]\right)$$

Heavy-flavour v_2 measurements probe:

– **Low/intermediate p_T:** collective motion, degree of thermalization of heavy quarks and hadronization mechanism (recombination)

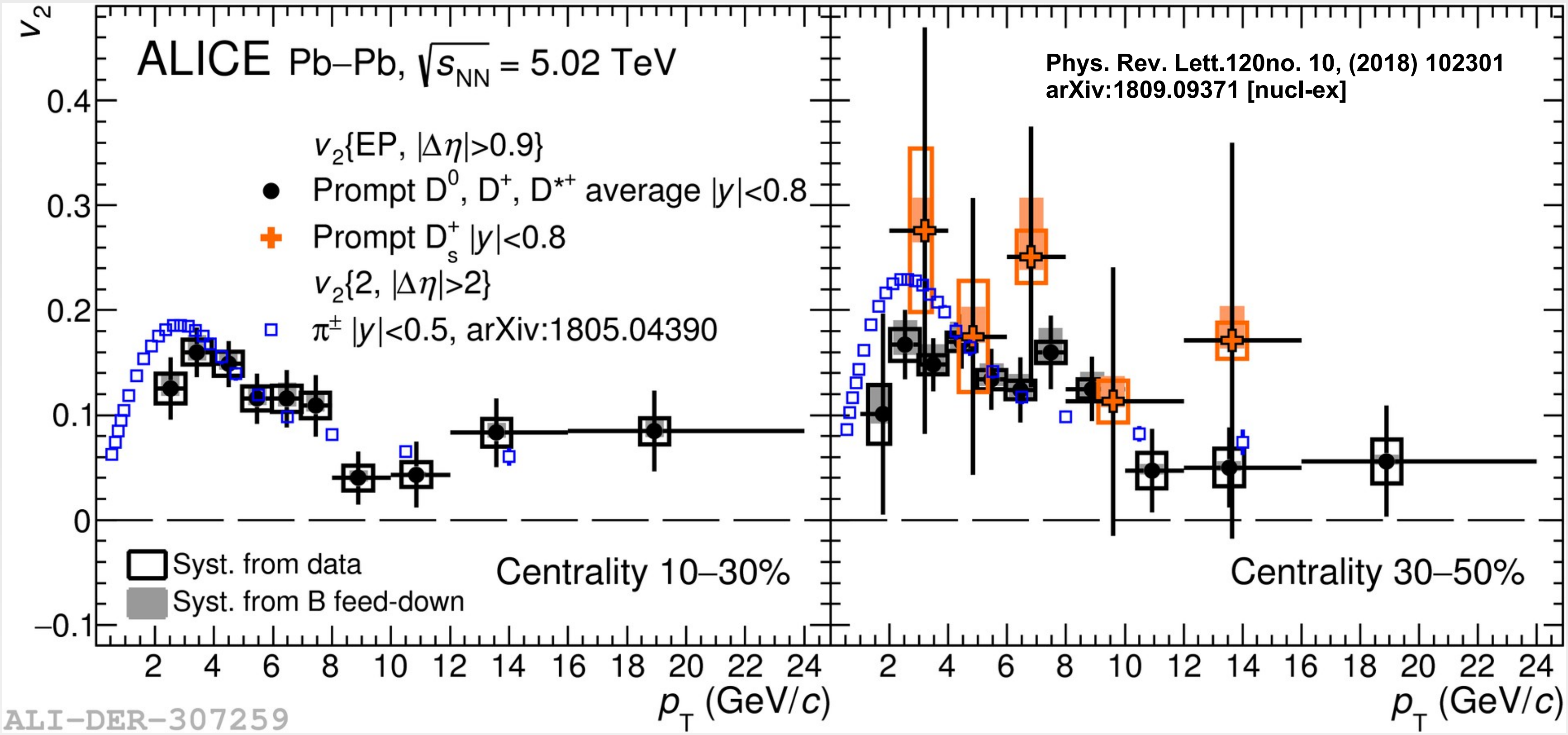
– **High p_T:** path-length dependence of heavy-quark energy loss

Elliptic flow



– positive D meson v_2 for $2 < p_T < 8$ GeV/c in mid-central Pb-Pb collisions

Elliptic flow



– positive D meson v_2 for 2 < p_T < 8 GeV/c in mid-central Pb-Pb collisions

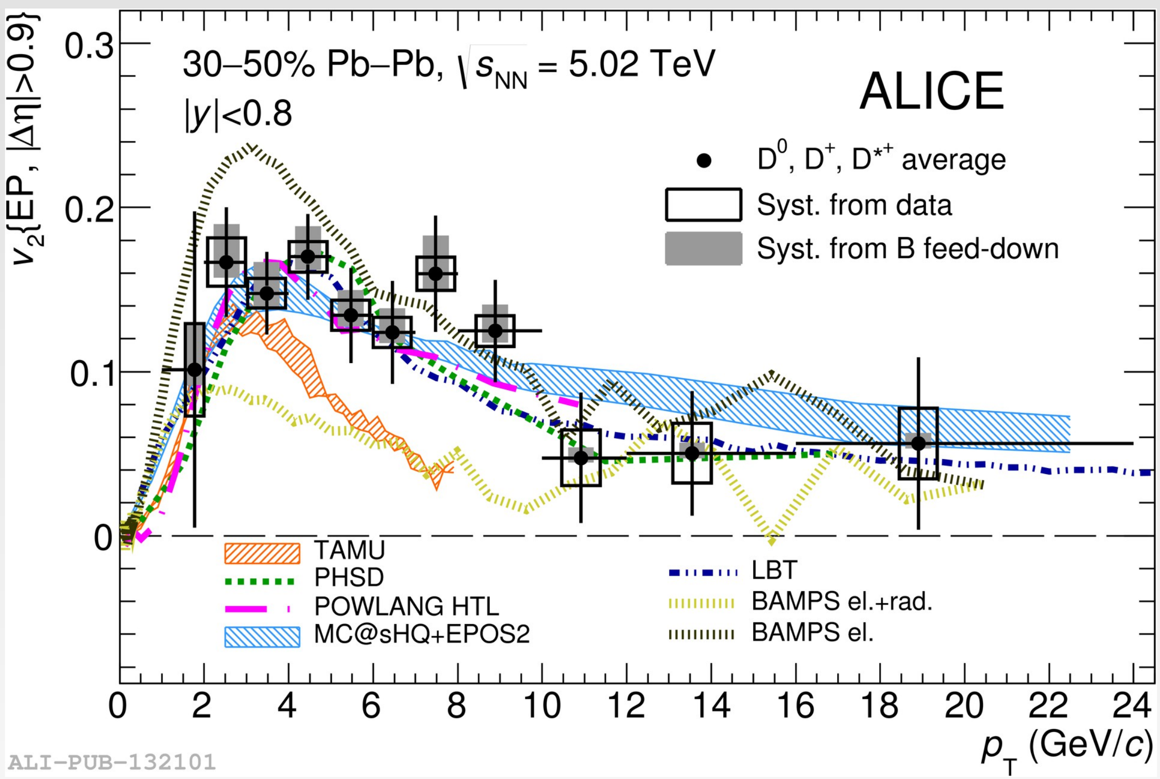
– v_2(D) ~ v_2(π) for p_T > 4 GeV/c in mid-central Pb-Pb collisions

– Hit of v_2(D) < v_2(π) for p_T < 4 GeV/c in mid-central Pb-Pb collisions

Elliptic flow: model comparison

– Improved precision of the measurement can constrain model parameters, e.g. the heavy-flavour spatial diffusion coefficient D_s

$$D_s = (T/m_Q)\tau_Q$$



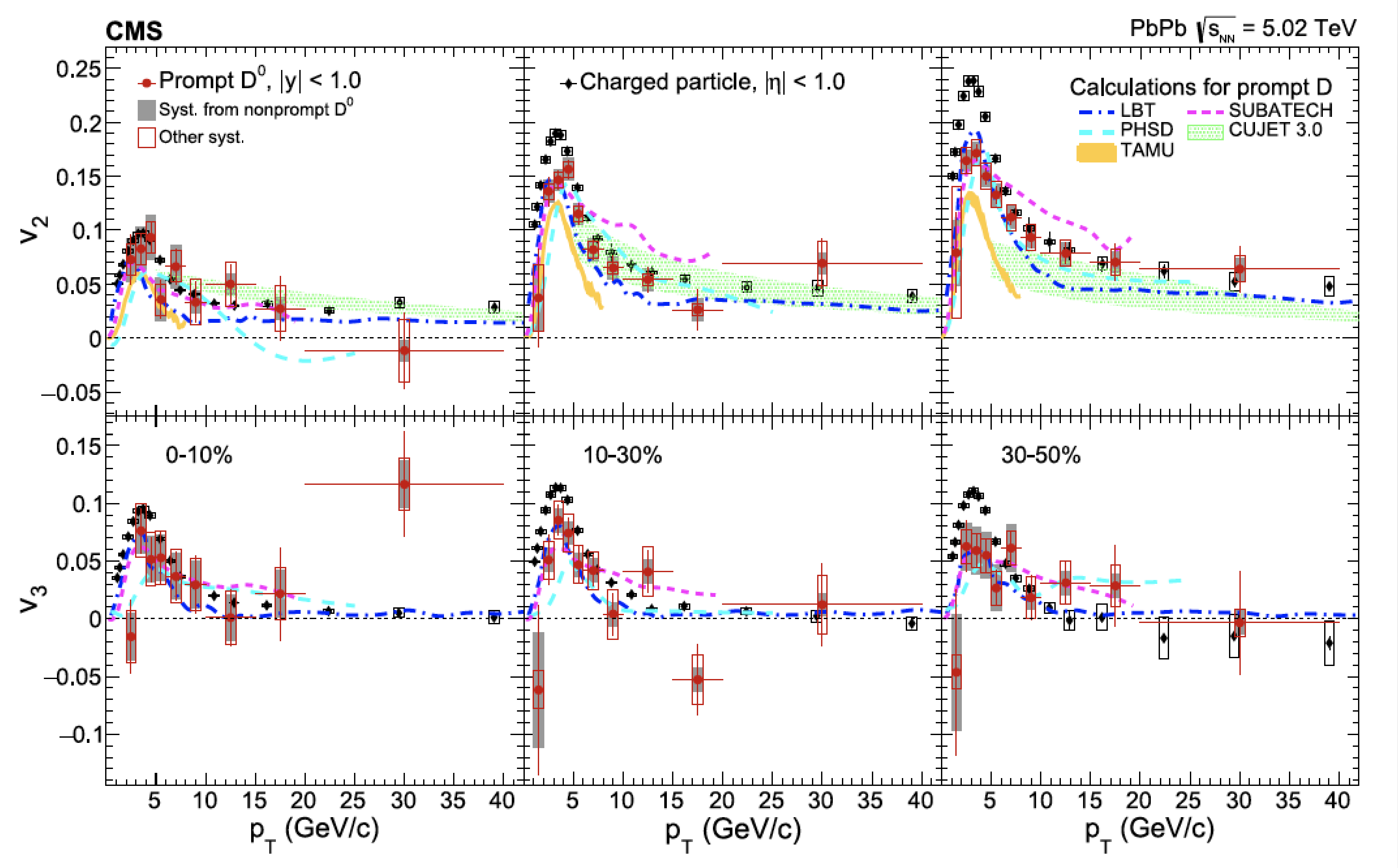
For models describing the data with X^2/ndf < 1:

$$1.5 < 2\pi T_c D_s < 7$$

$$\tau_{charm} = 3 - 14 \text{ fm}/c$$

TAMU: PLB 735, 445-450 (2014)
PHSD: PRC 92, 014910 (2015)
POWLANG: EPJC 75, 121 (2015)
MC@sHQ+EPOS: PRC 89, 014905 (2014)
LBT: PLB 777 (2018) 255-259
BAMPS: JPG 42, 115106 (2015)
Djordevic: PRC 92, 024918 (2015)
CUJET3.0: JHEP 02 (2016) 169
SCET: JHEP 03 (2017) 146

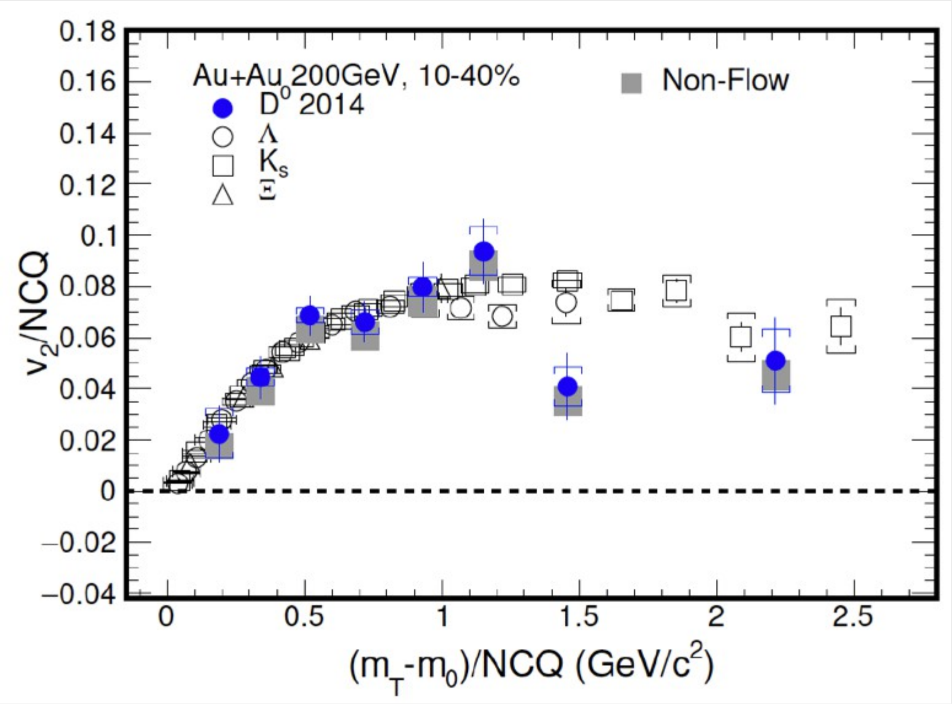
Triangular flow at LHC

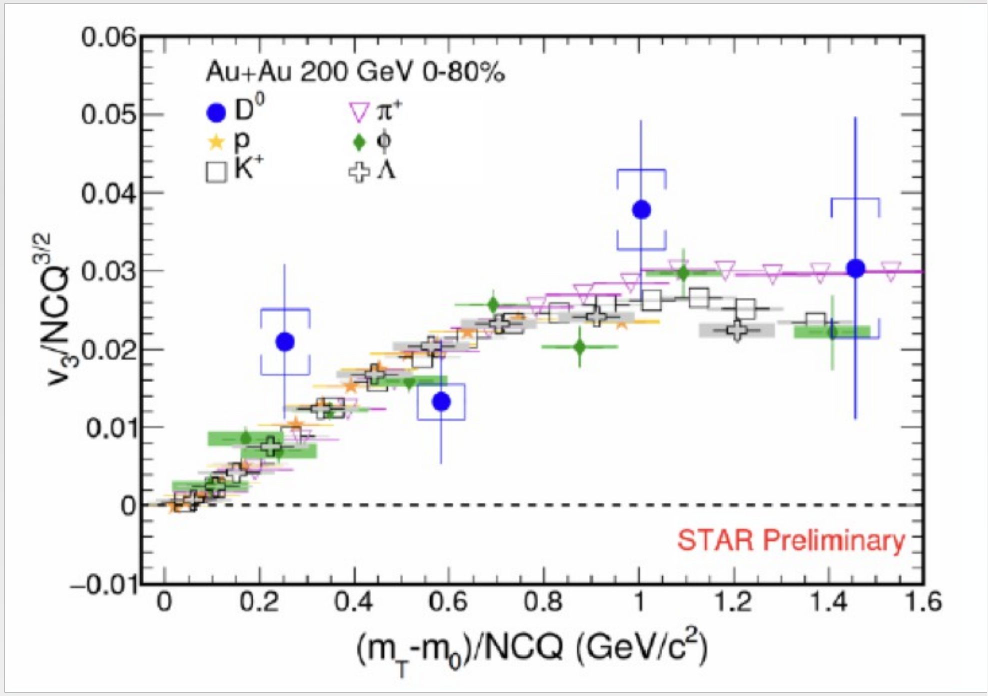


First observations of $v_3 > 0$ for charm at LHC!

- v_3 for charged particle larger that D^0 v_3 although not fully significative

Azimuthal anisotropy at RHIC



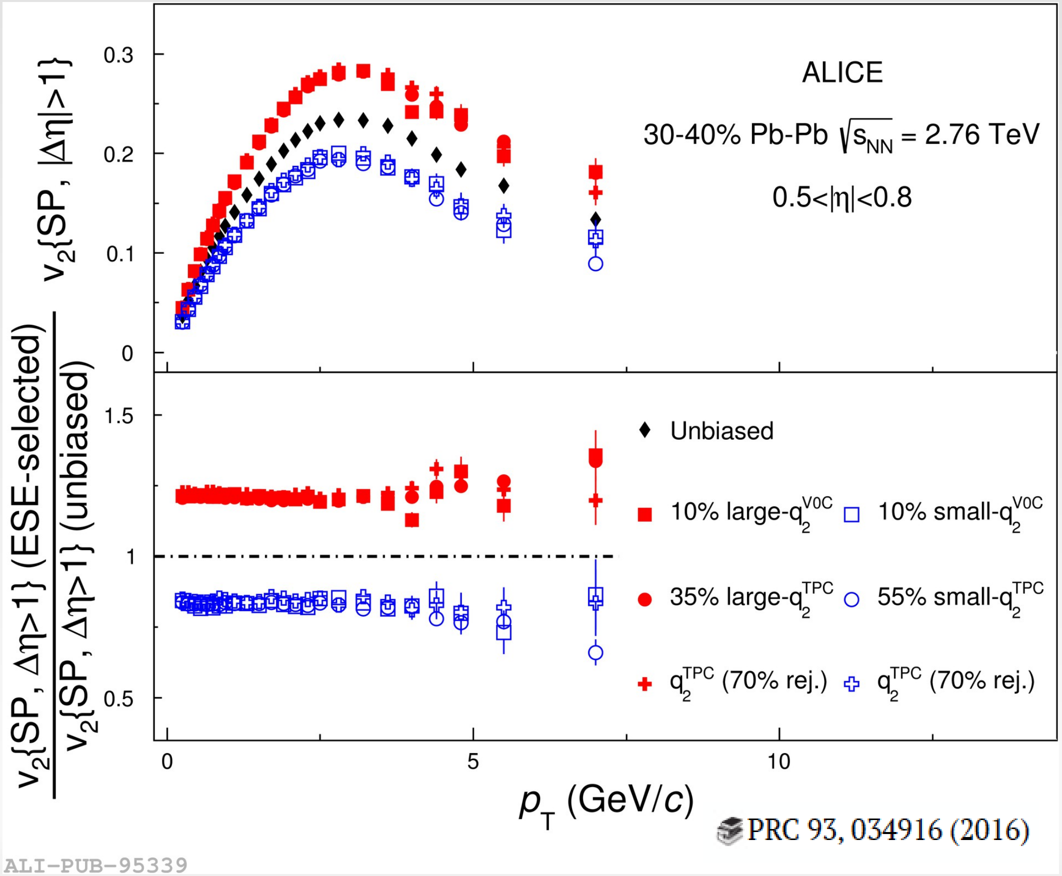


- **Significant v_2(D) > 0 at RHIC** - Mass "ordering" and m_T-m_0 ordering suggest an hydro-dynamic behaviour! - Indication that charm is flowing with the medium!
- **At RHIC v_3 consistent with charged particle one** (although with very large uncertainties)

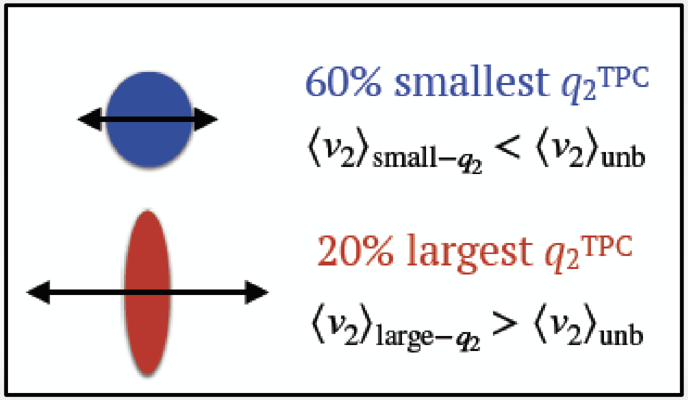
Event Shape Engineering

Technique that allows us to study various observables in classes of events corresponding to the **same centrality**, but **different eccentricity**

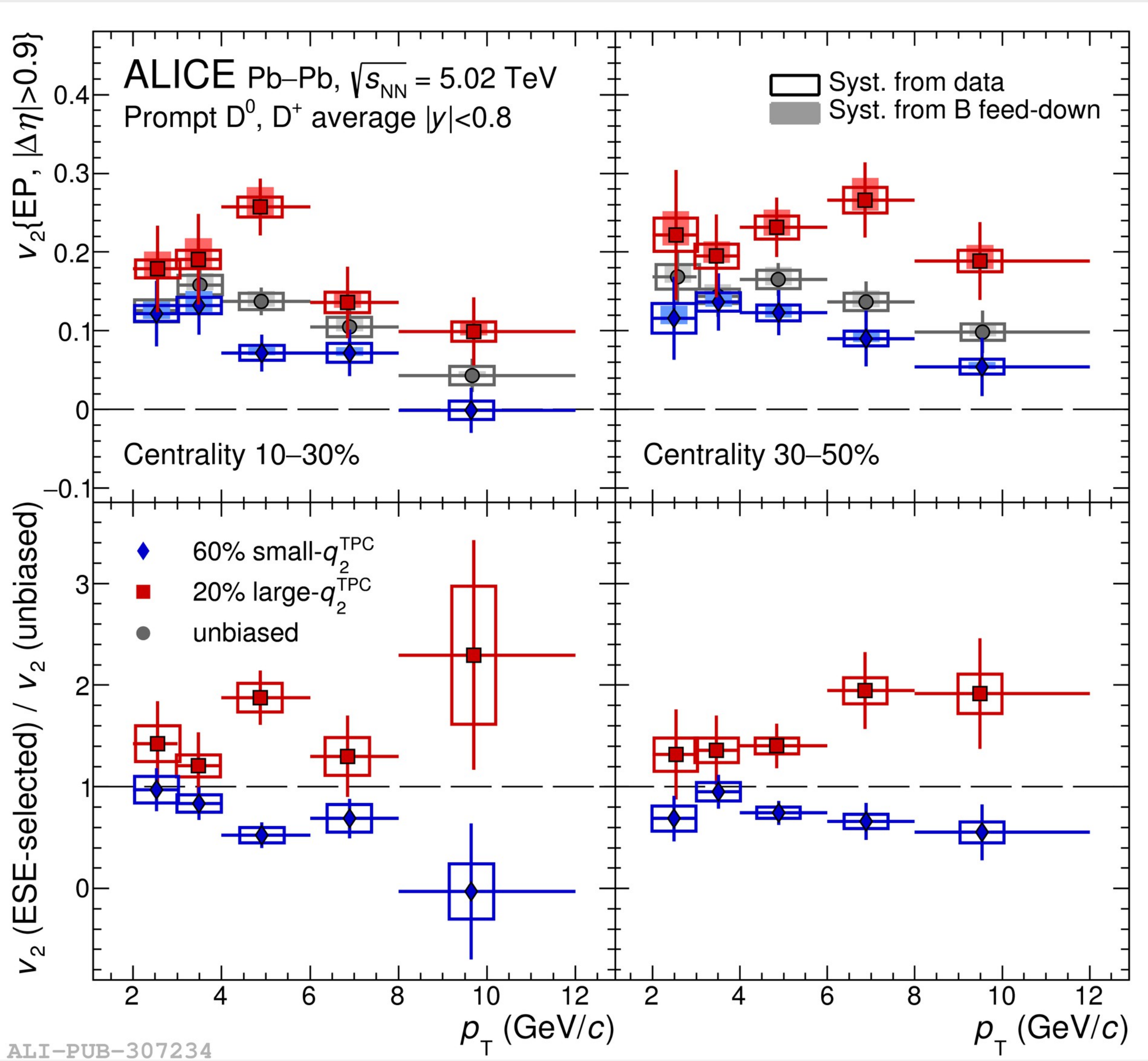
- Technique relies on the **classification** of events at a certain centrality according to the **magnitude of the second-harmonic flow vector**



– D-meson v_2 for different q_2 samples:
investigate correlation between flow coefficients of D mesons and soft hadrons



Azimuthal anisotropy: Event Shape Engineering



- Measurement of D-meson v2 in ESE-selected samples indicate a **positive correlation** between the **D-meson v2** and the **light-hadron v2**
Similar effect in the 10-30% and 30-50% centrality classes within uncertainties

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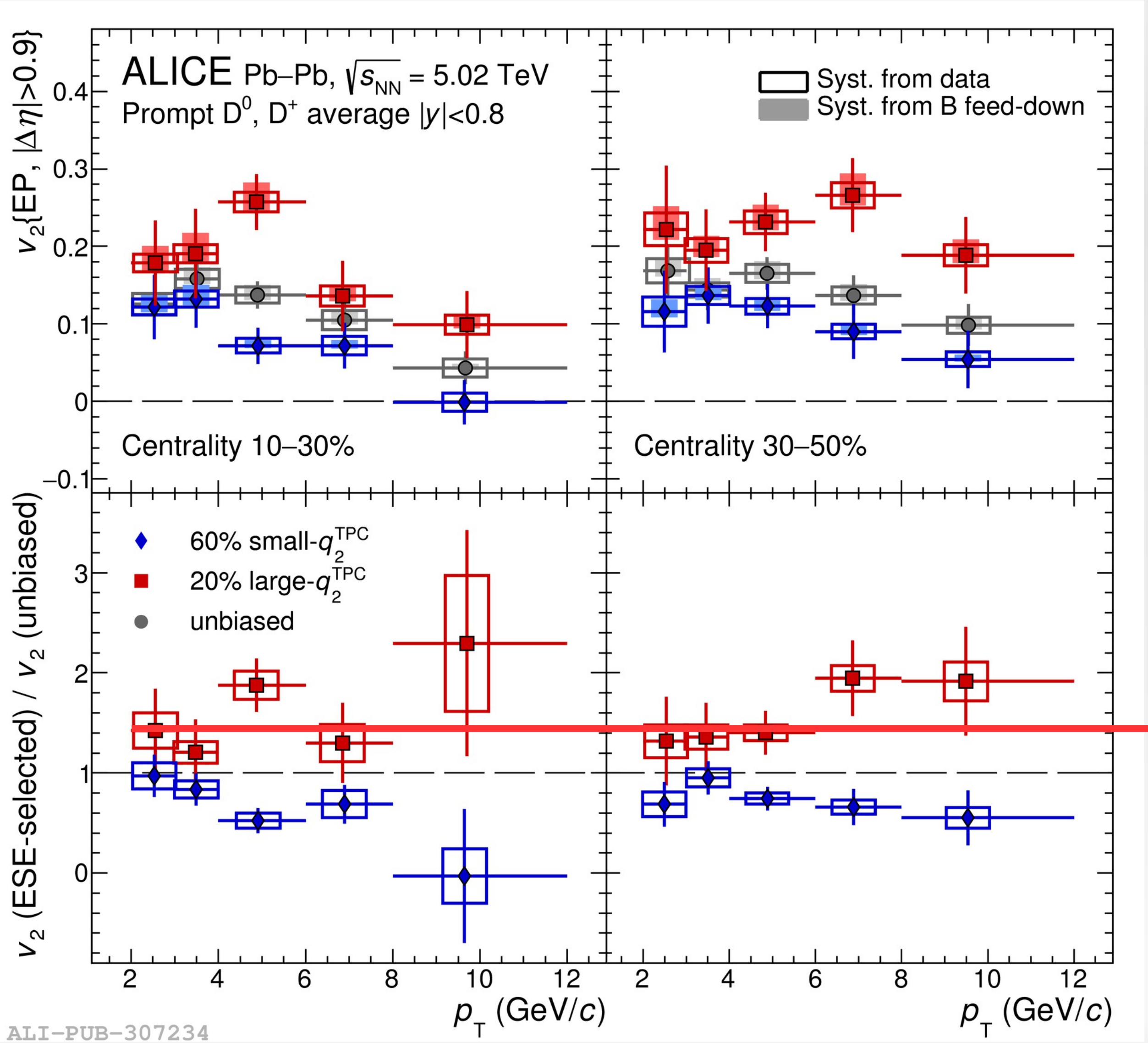

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v_2 (large-q_2) > v_2 (unbiased) of about 40%

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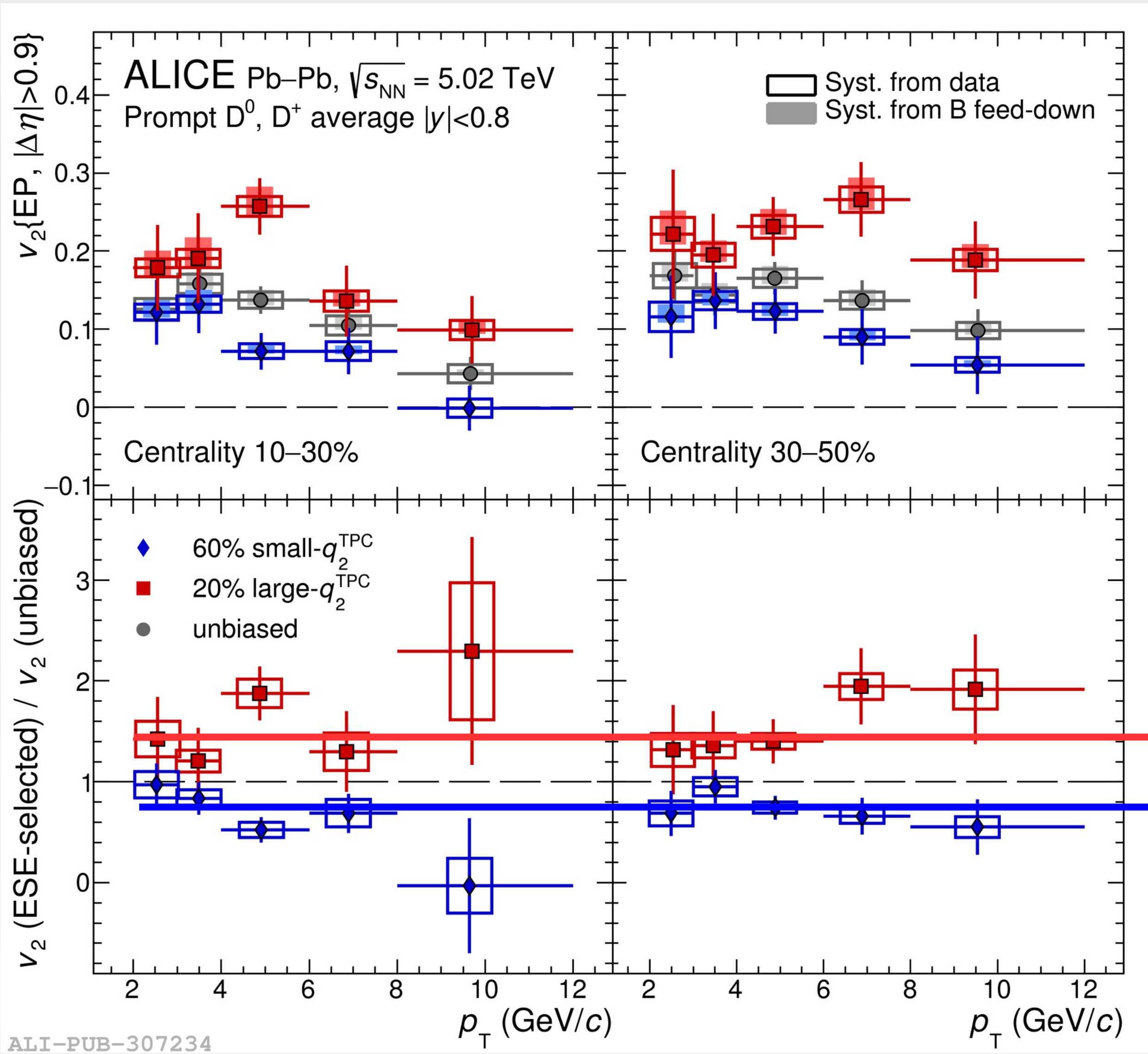

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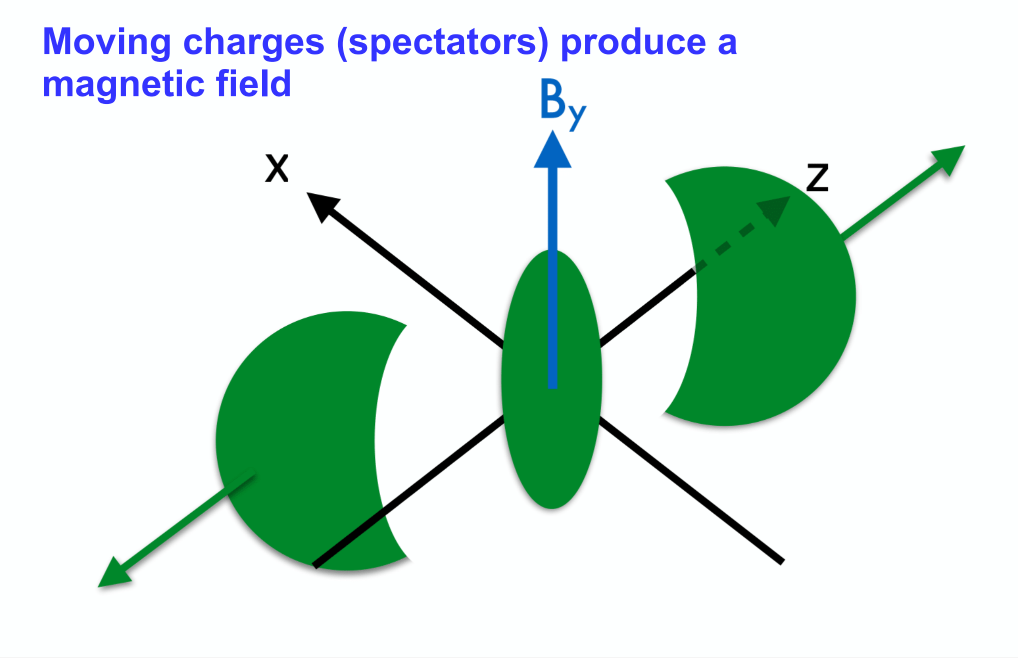
v_2 (large-q_2) > v_2 (unbiased) of about 40%

v_2 (small-q_2) < v_2 (unbiased) of about 25%

Introduction

– In non-central heavy-ion collisions an enormous **magnetic field** (~10^{18} G) is generated by the movement of the **spectator protons** **(Biot-Savart law)**



– quickly decreases (~1 fm/c) as the spectators fly away

Motivation

– magnetic field in non-central heavy-ion collision is expected to lead to several novel phenomena, e.g. **Chiral Magnetic Effect** (CME)

– we face different problems:
→ **hard to decouple signal** (charge separation across reaction plane) **from background** (local charge conservation + flow)
→ **very few constraints from theory**

proposal: measure a simple and clean observable connected to the magnetic field, use it to calibrate its strength and lifetime

The idea*

– **varying magnetic field will influence moving charges**

– very few assumptions needed: **charged and conductive QGP**

– the result: charge-dependent **directed flow**, asymmetric in rapidity

*first proposed by Gursoy, Kharzeev and Rajagopal in ‘14

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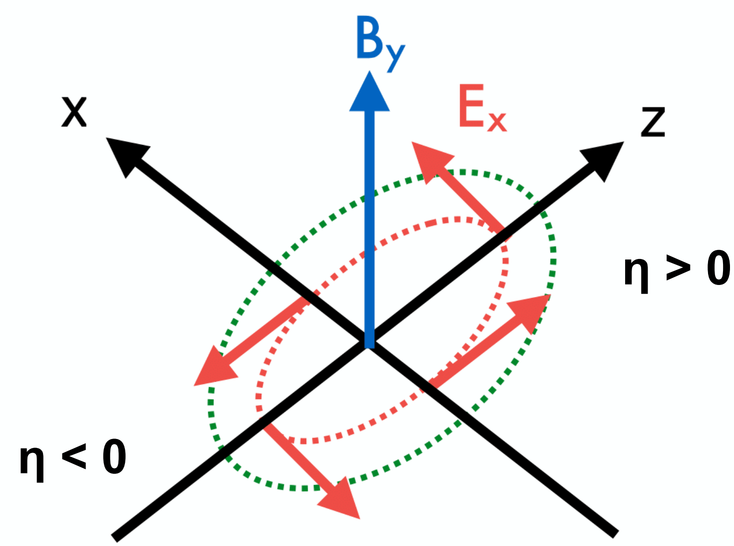
→ electric field induced by decreasing B
(Faraday effect)



$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

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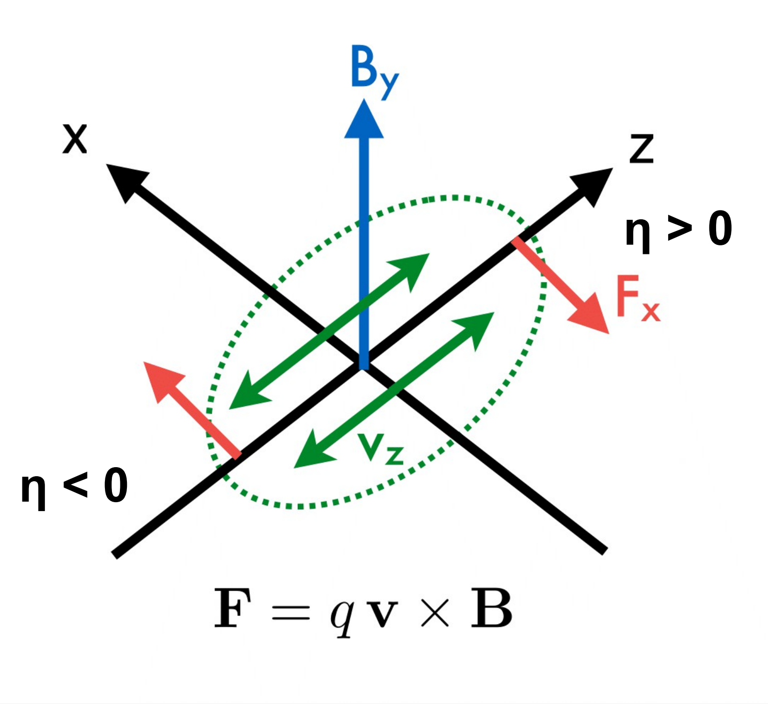
competing effects!



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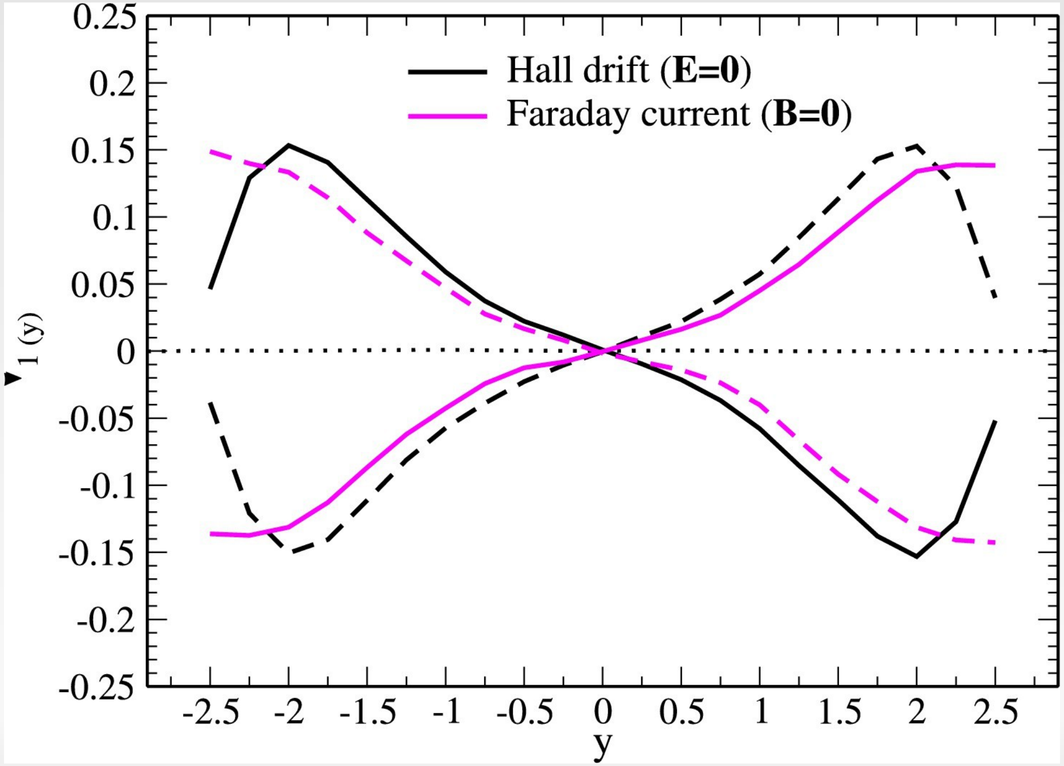

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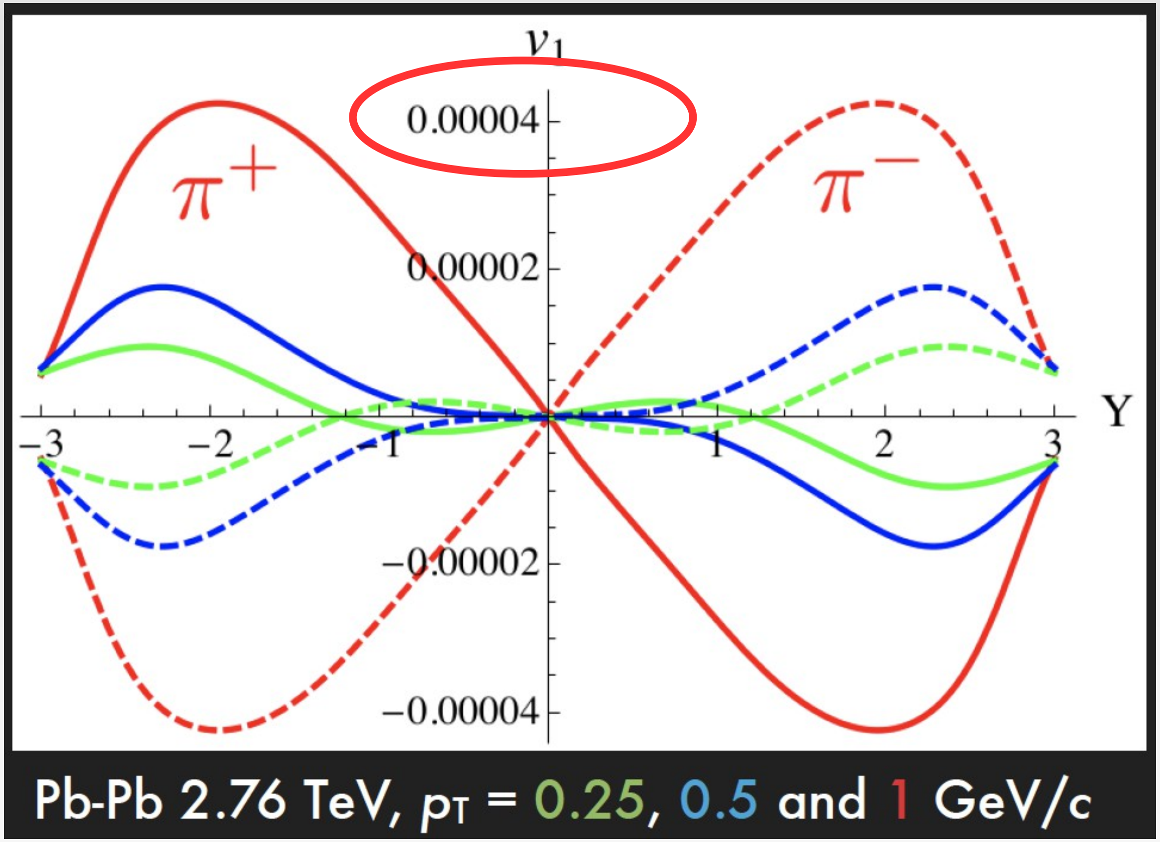
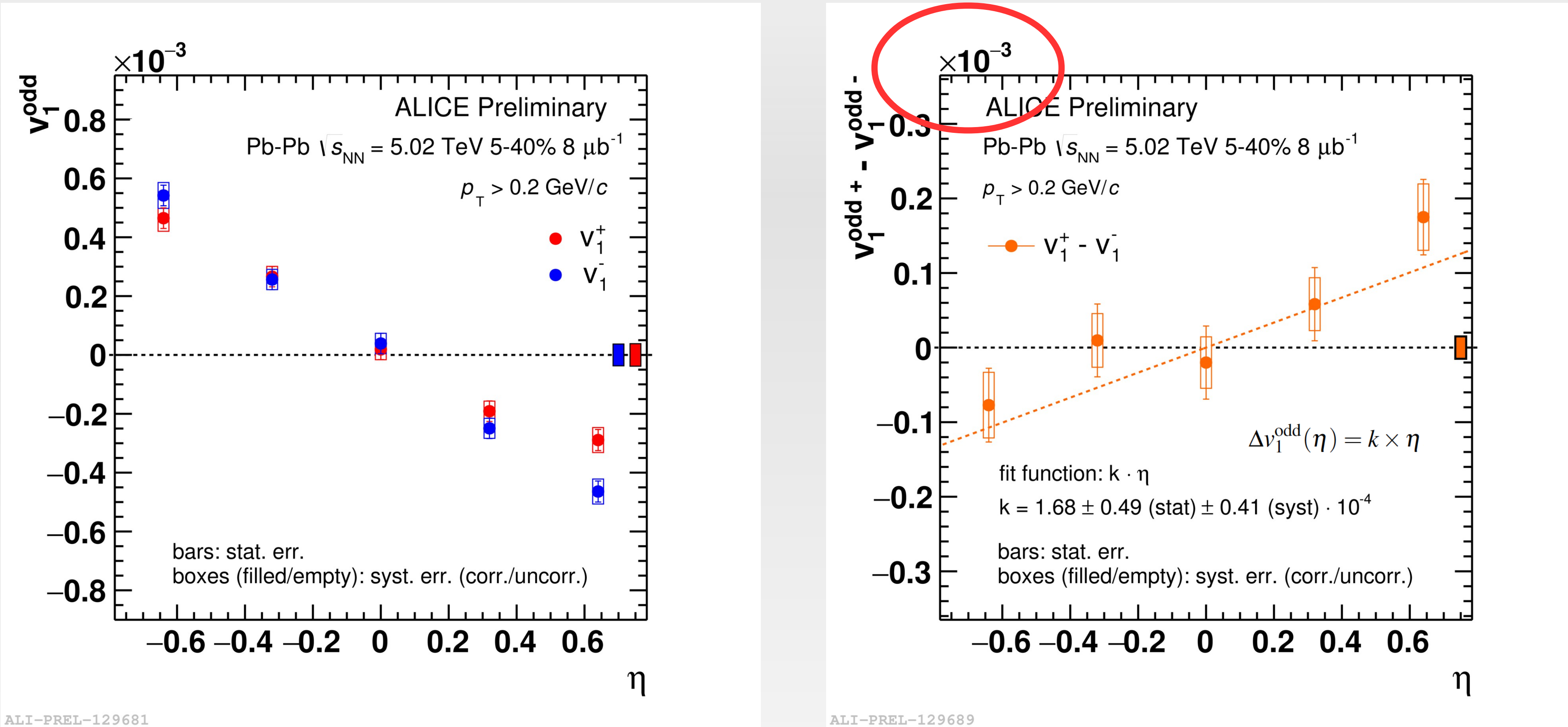
charge-dependence v_1

Challenging measurement: very small signal is expected from theory predictions



the rapidity slope varies with p_T (different contribution of Faraday and Hall effects)

Charge-dependence v_1^{odd}



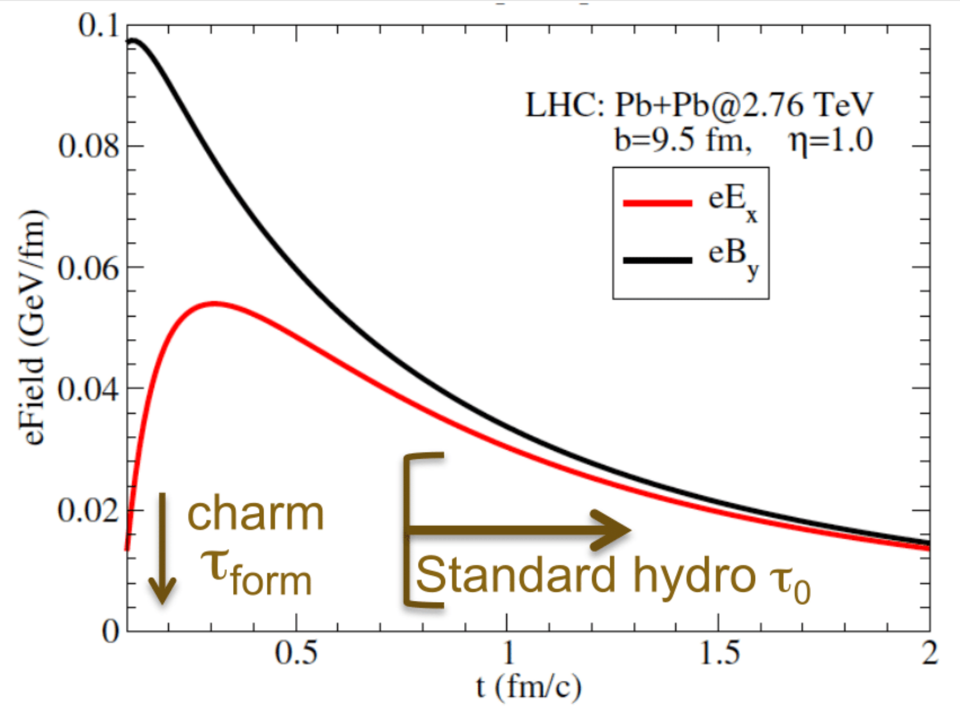
→ hint of a charge difference: Δv_1 odd = v_1 odd(+) - v_1 odd(-) ≠ 0 (**2.6 σ significance)**

→ **1-2 orders of magnitude bigger**: long-lived magnetic field? early thermalization?

→ **opposite sign**:dominance of Hall effect?

Why open heavy-flavour?

- **formation time ~ 0.1 fm/c** → comparable to the time scale when **B is maximum**
- no thermal formation
- the kinetic relaxation time of charm is similar to the QGP lifetime



https://doi.org/10.1016/j.physletb.2017.02.046

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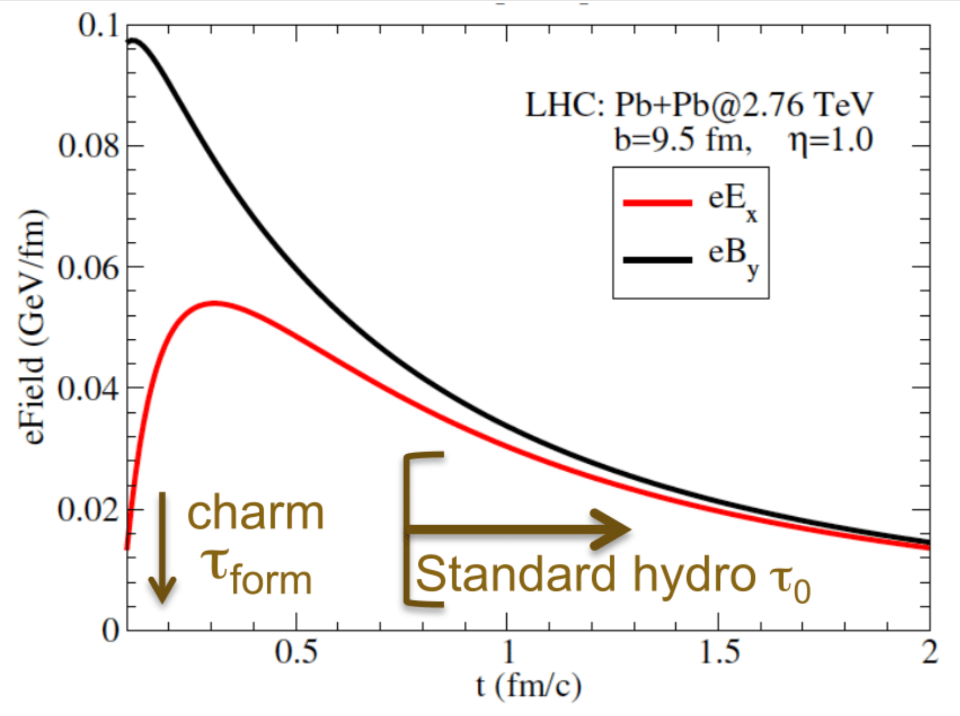
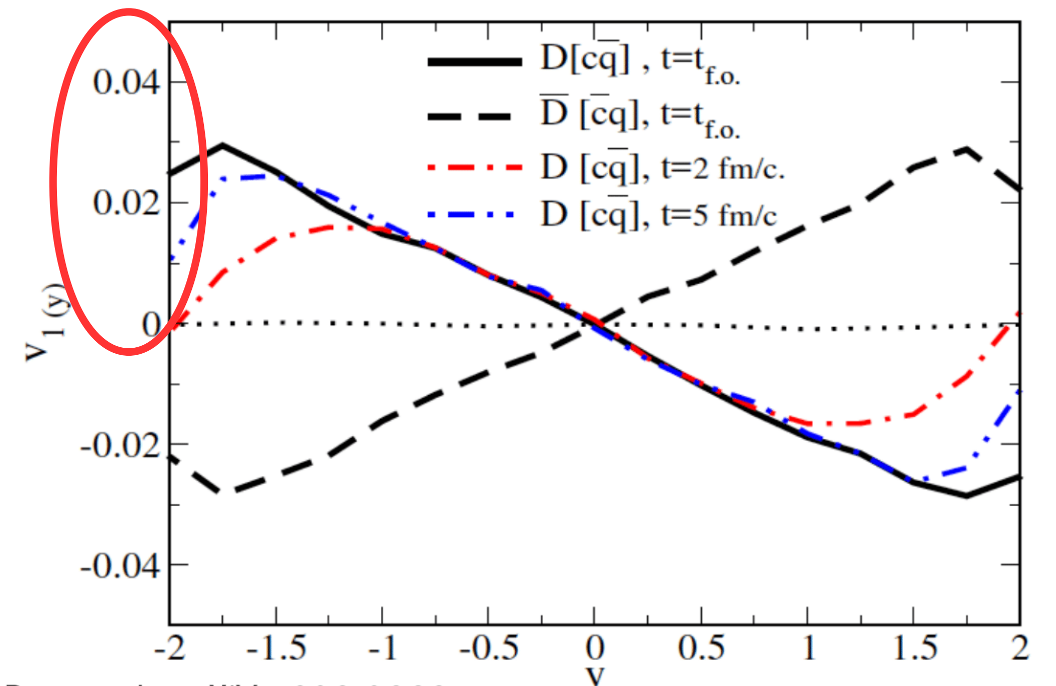
→ resultant effects entail a **significantly large directed flow *v_1*** of charm quarks compared to light quarks





Das et al., arXiV:1608.02231

https://doi.org/10.1016/j.physletb.2017.02.046

Analysis strategy

- SP in which the Q vector is reconstructed from the spectator (ZDC)

$$v_1\{\Psi_{A,C}\} = \frac{\langle \vec{q} \cdot \vec{Q}_{A,C} \rangle}{\sqrt{|\langle \vec{Q}_A \cdot \vec{Q}_C \rangle|}} = \frac{\langle q_x Q_{A,Cx} + q_y Q_{A,Cy} \rangle}{\sqrt{|\langle Q_{Ax} Q_{Cx} + Q_{Ay} Q_{Cy} \rangle|}},$$

Analysis performed as a function of the invariant mass

$$v_1(M) = \frac{S(M)}{S(M)+B(M)} * v_1^S + \frac{B(M)}{S(M)+B(M)} * v_B^1(M).$$

Assumption:

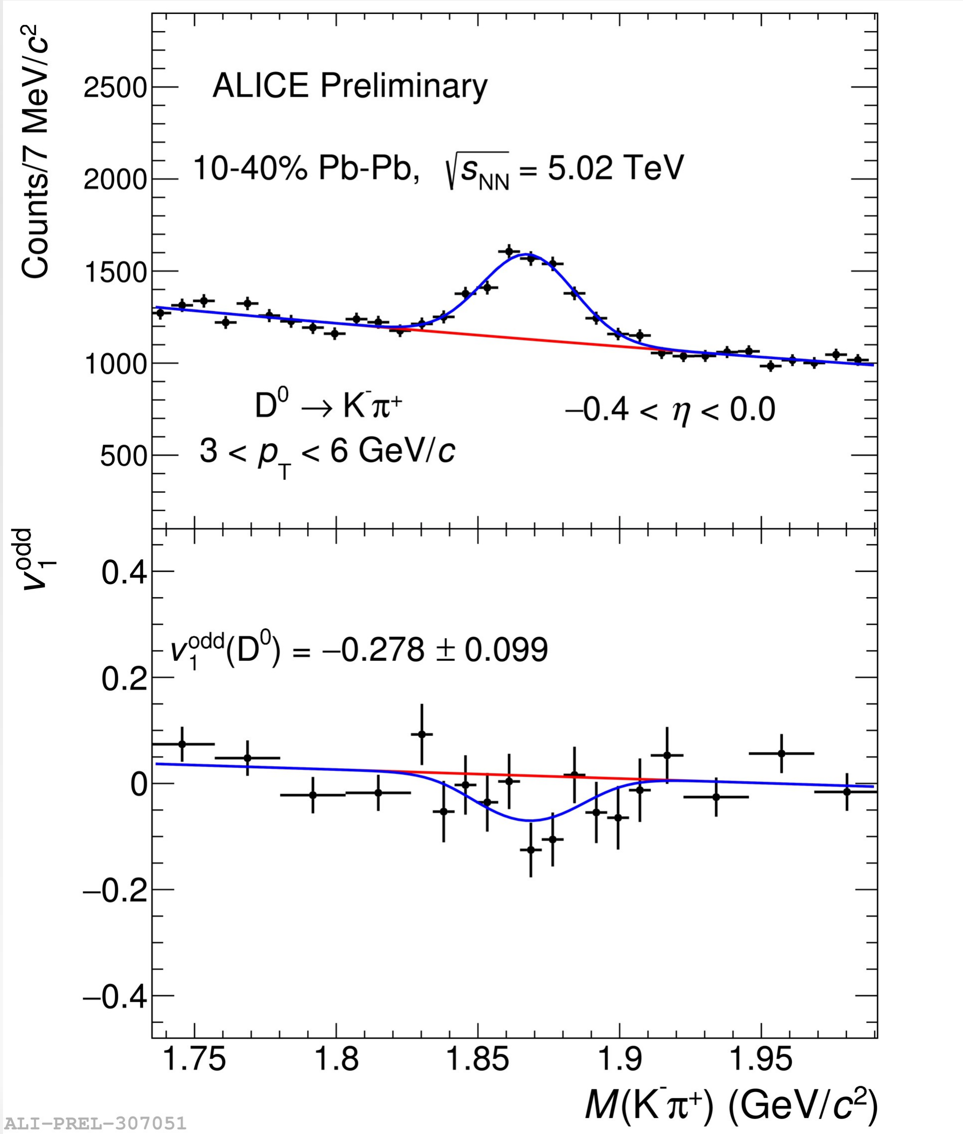
$$v_1^{bg}(M_{INV}) = p_0 + p_1 \times M_{INV}$$

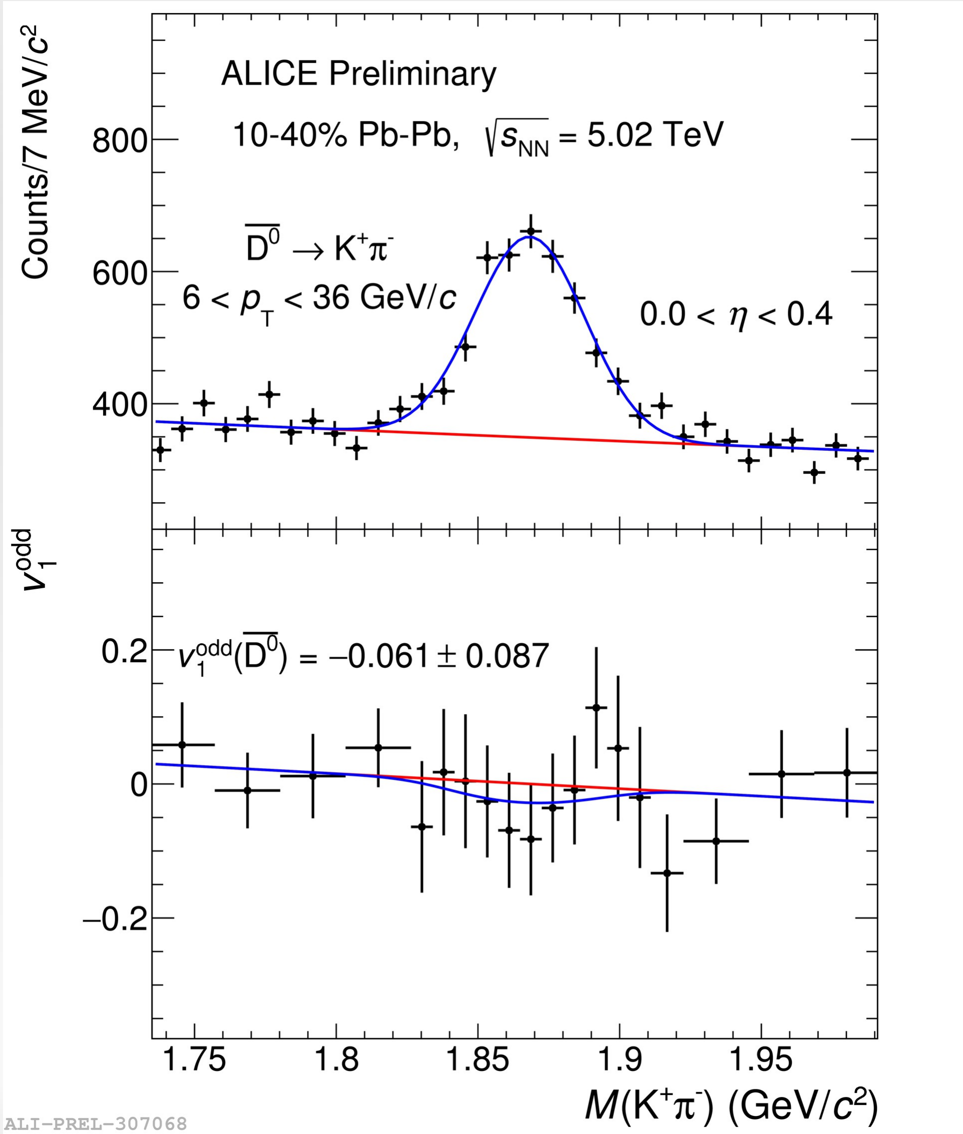
All the ingredients to evaluate v_1 are extracted from a simultaneous fit of the M_{inv} spectra and $v_1(M_{\mathrm{inv}})$

Computed rapidity-odd component for D^0 and $\overline{D}^0$ separately:
- sensitive to the asymmetry induced by the magnetic field

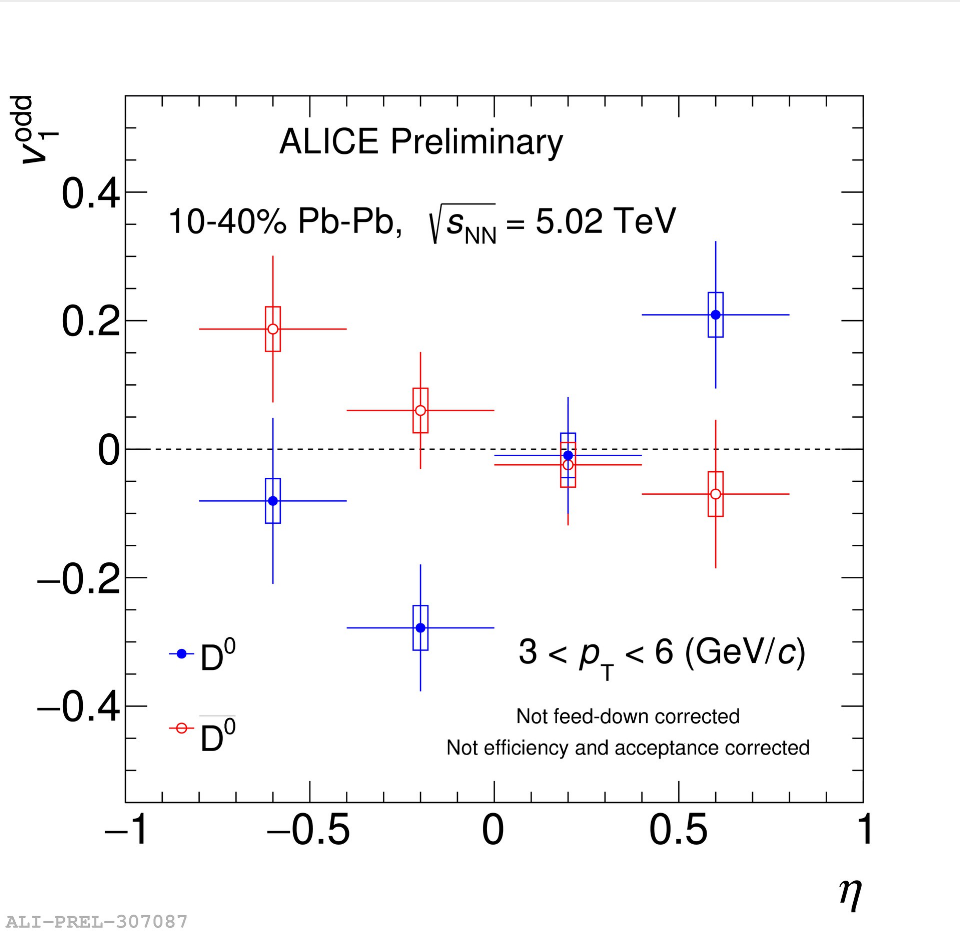
$$v_1^{\mathrm{odd}} = \frac{1}{2}(v_1\{\Psi_A\} - v_1\{\Psi_C\}).$$

Signal extraction





v_1^{odd} for D^0 vs $\overline{D}^0$



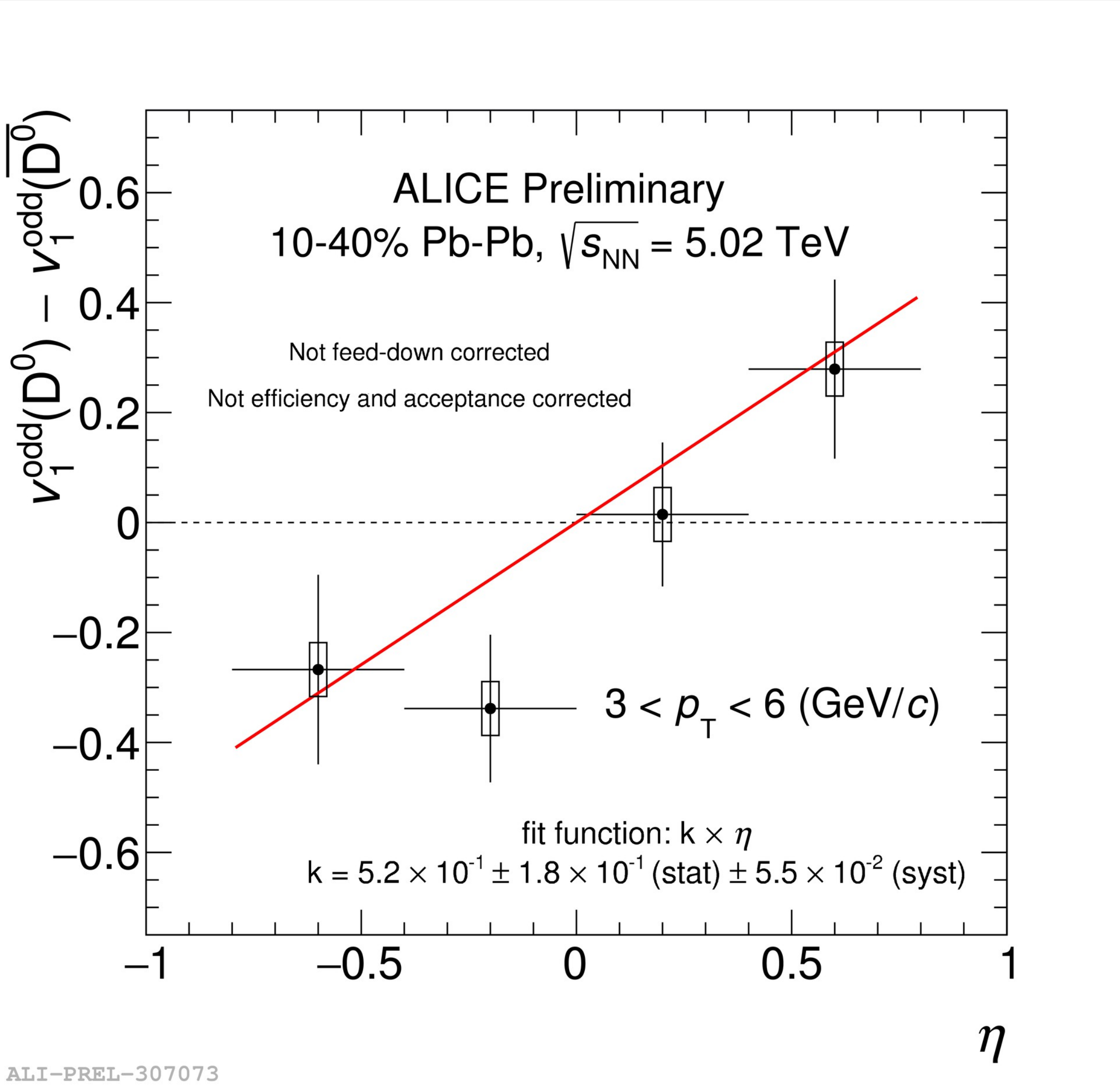
Despite the large uncertainties → hint of an opposite trend for D^0 and $\overline{D}^0$ meson

- **Signal** (central value) is **factor 10 higher** then prediction → *long-lived magnetic field?* → *early thermalisation?*

- **Opposite trend** of D^0 and $\overline{D}^0$ w.r.t prediction → *dominance of Hall effect?*

→ indications already observed for charged particles

Δv_1 to quantify a possible signal



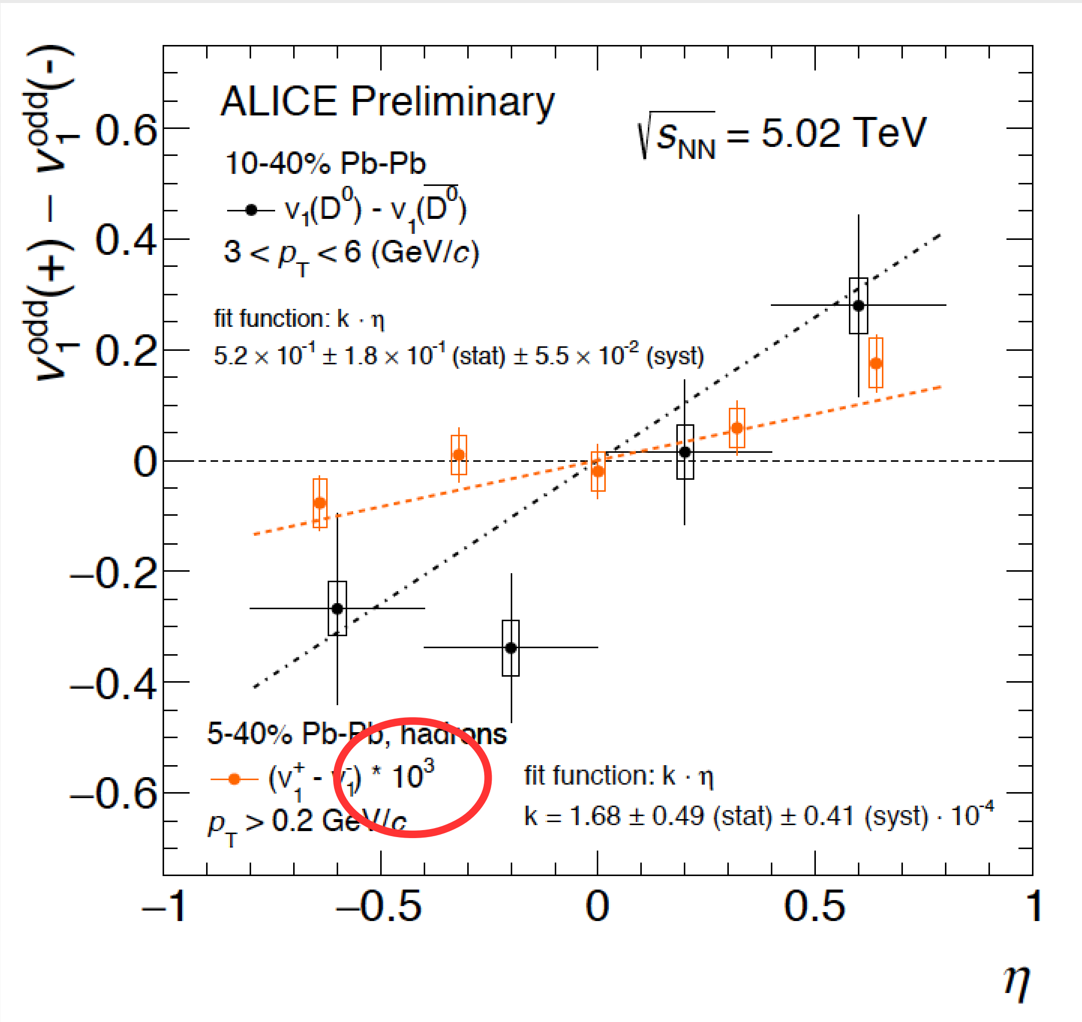
$$\Delta v_1^{odd}(\eta) = k \times \eta$$

rapidity dependence of the charge difference Δv_1 is fitted using a linear function with slope k

***k* = 0.52 +/- 0.18 (stat) +/- 0.05 (syst)**

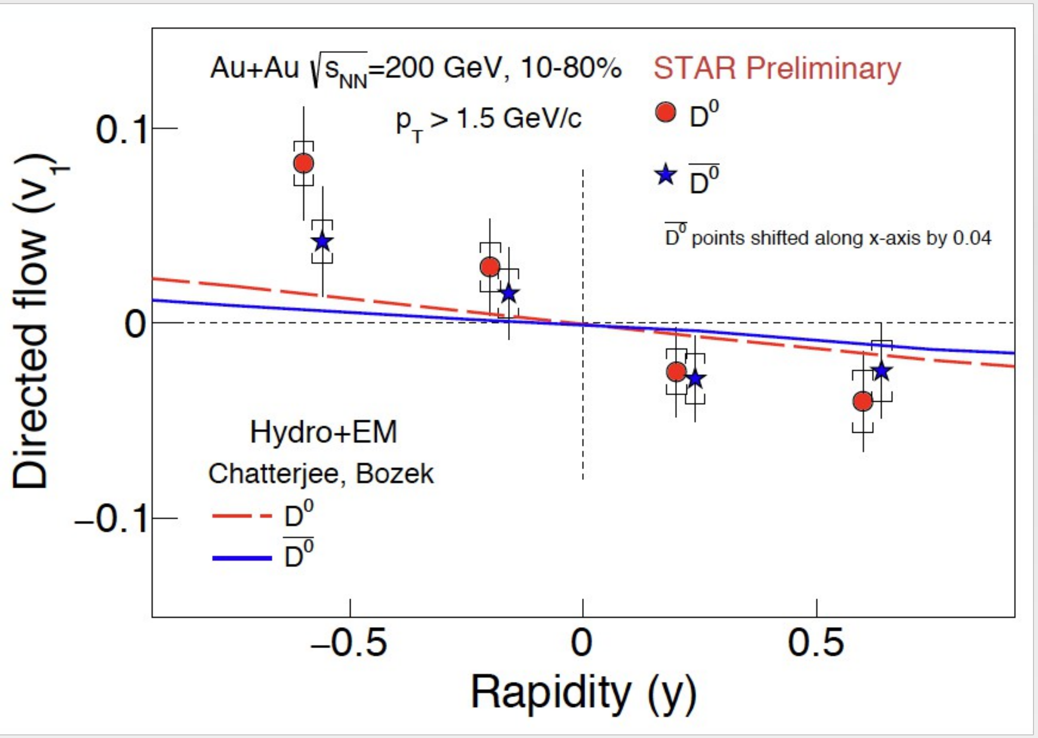
Not yet high significance of the measurements (**2.7σ**)

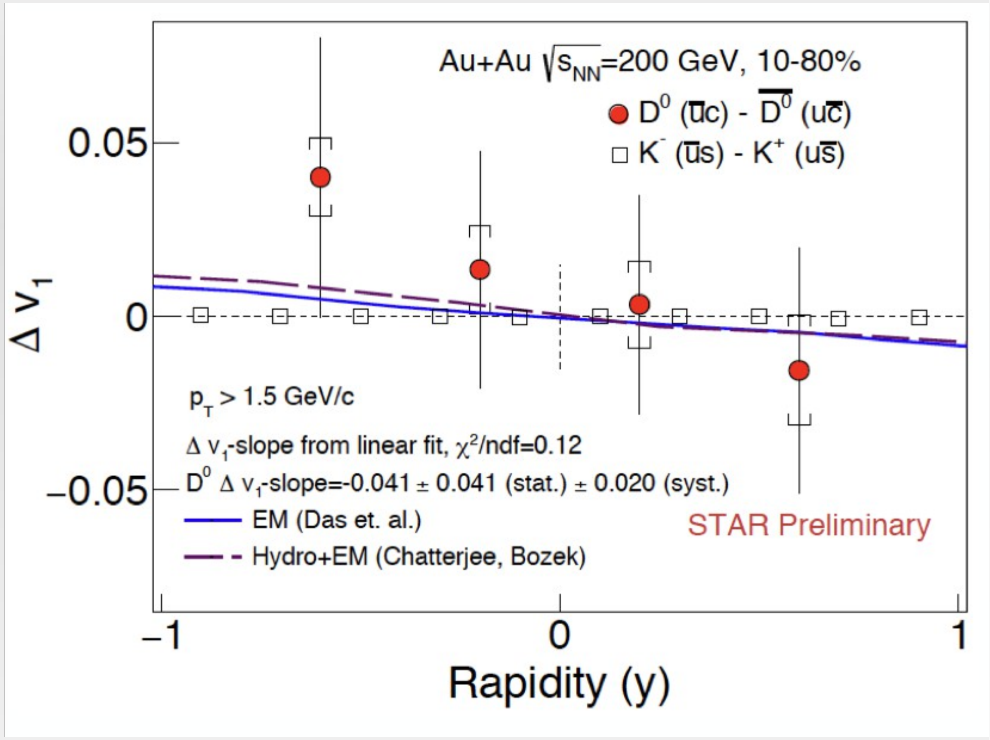
Δv_1 to quantify a possible signal



The **3 orders of magnitude difference** between charged-particle and heavy-flavour predicted by theory are **experimentally accessible**

Charged dependent v_1 at STAR

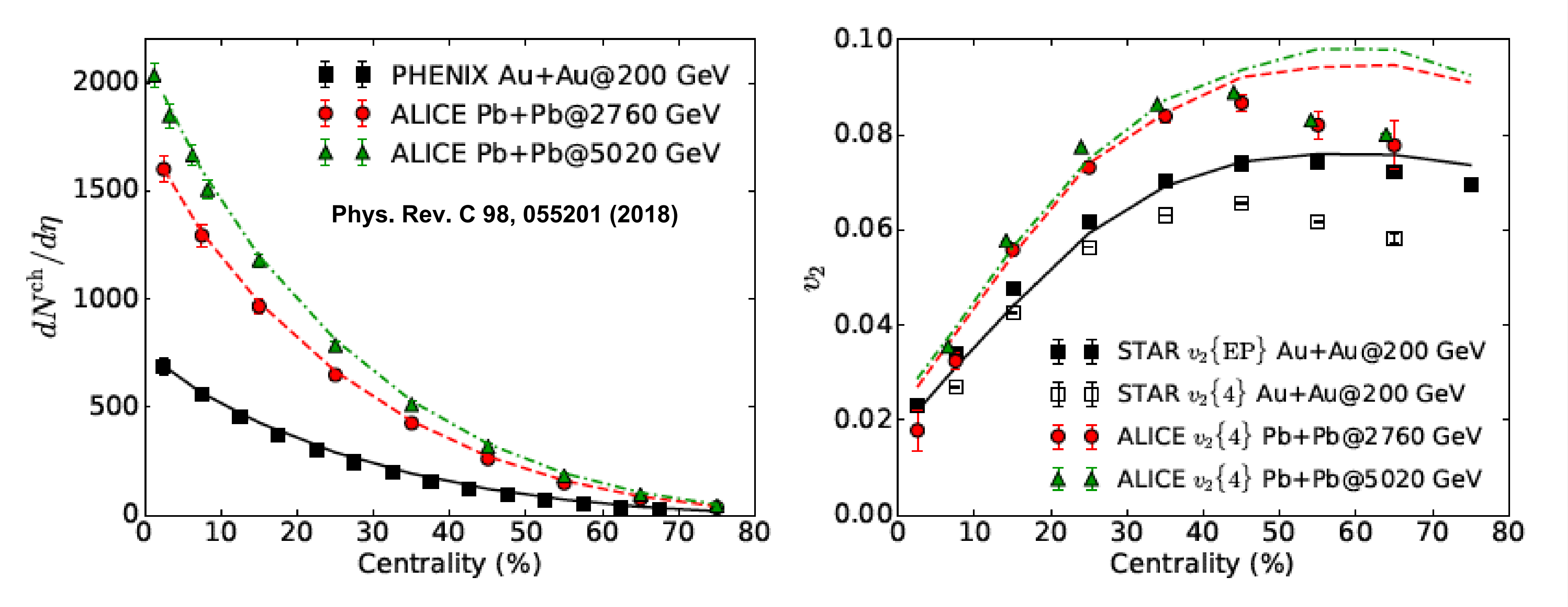




– First observation of non-zero D^0 v_1 - model predicts correct sign but wrong magnitude

- **No firm conclusion yet** on possible magnetic field induced splitting Δv_1
- Very promising **sensitivity to the effect of the early time magnetic field in heavy-ion collisions**, can help constrain QGP properties

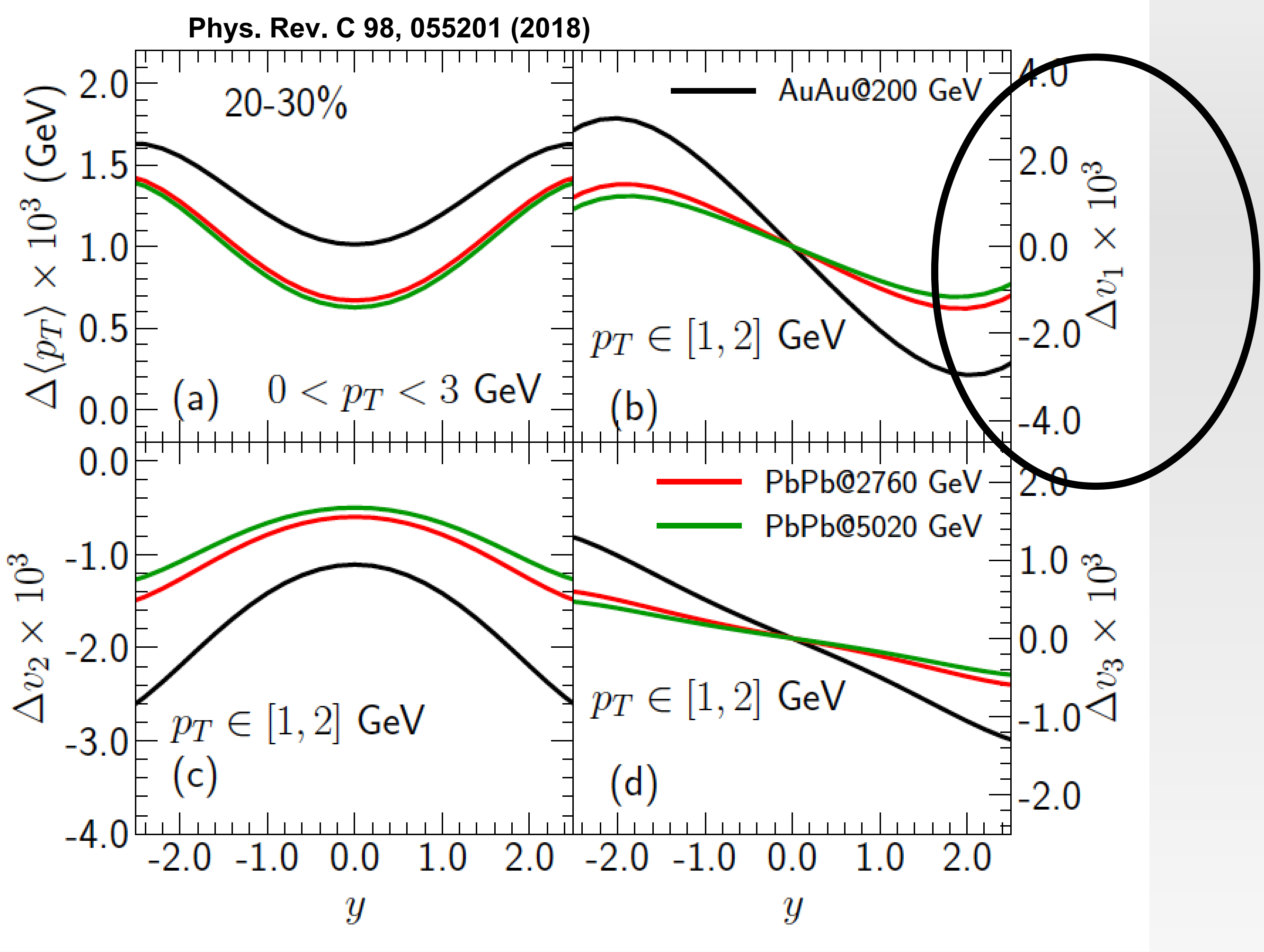
News from theory...



→ charge-dependent flow induced by magnetic and electric fields in heavy- ion collisions.

→ Simulate the evolution of the expanding QGP hydro-dynamically, using the iEBE-VISHNU framework, and add the magnetic and electric fields as well as the electric currents

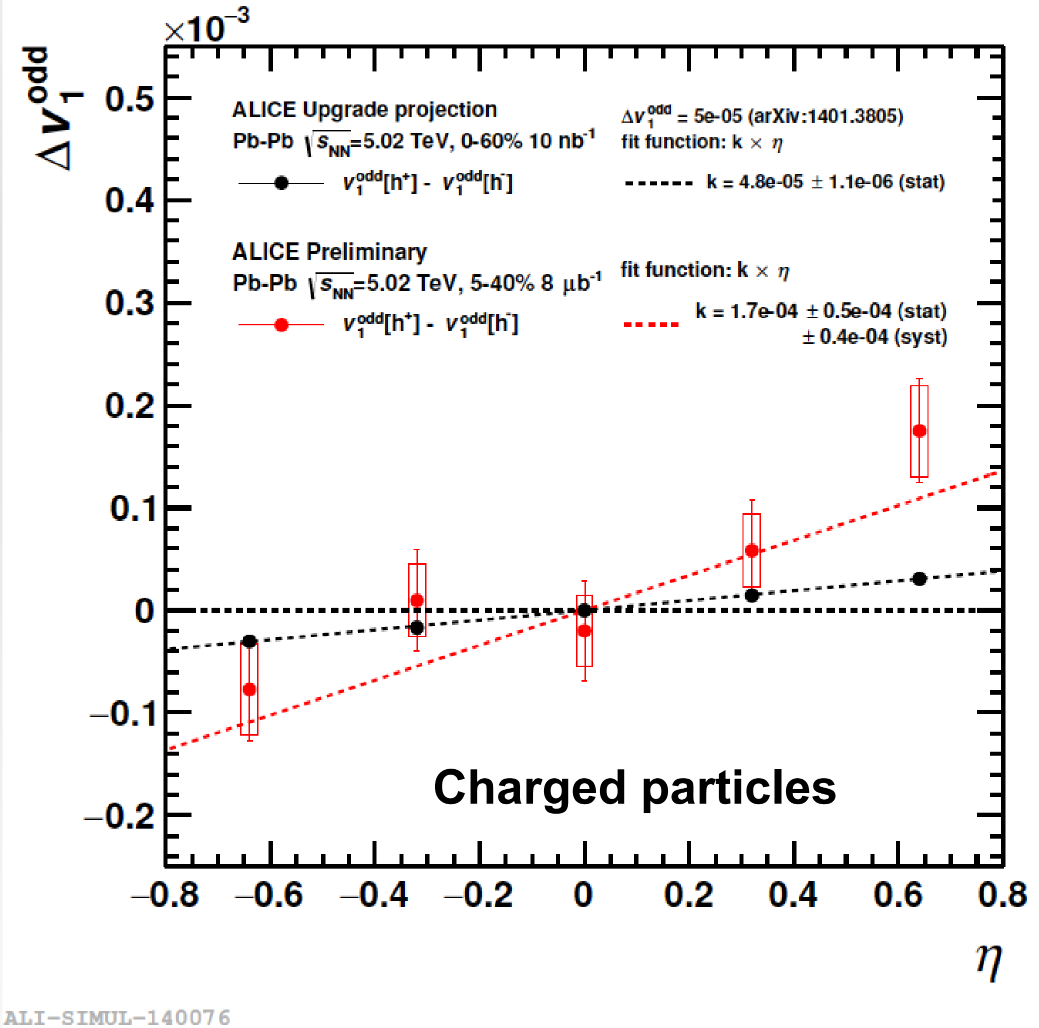
News from theory...

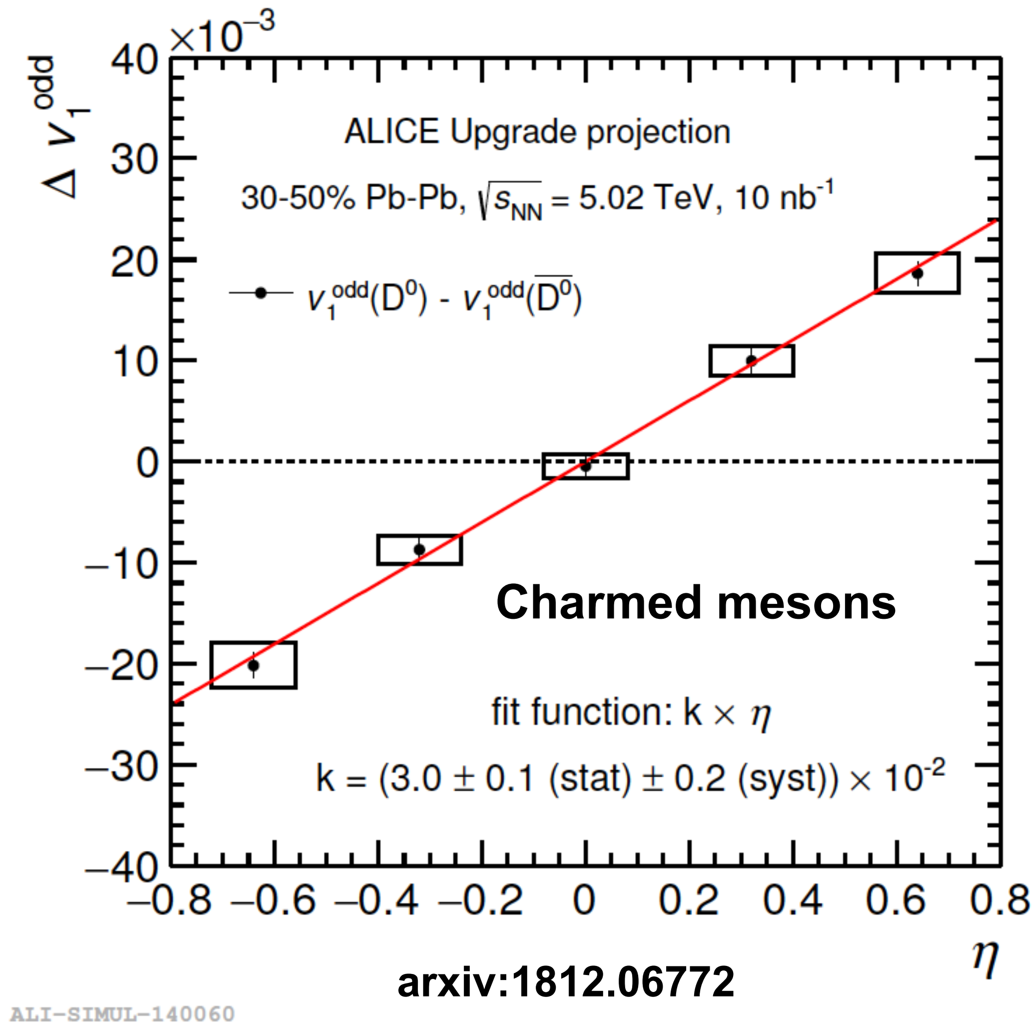


– New theory development shows an **increase of 2 order of magnitude** in the charged dependence directed flow

What about Run3 and Run4?

Charge-dependence v_1 - Run3/4 projections





arxiv:1812.06772

$$v_1^{odd} = \frac{1}{2}(v_1\{\Psi_A\} - v_1\{\Psi_C\}).$$

Simulations are done according to the values predicted by theory for both observables

Conclusion

→ A **non-zero elliptic/triangular flow** of heavy flavours was measured in **mid-central** collisions

→ Hint for an **increase** of heavy-flavour v_2 from **central to semi-central collisions**

– Low p_T D-meson elliptic and triangular flow smaller than for charged-particles

→ Suggests collective motion of low-p_T charm meson

→ **Indication of a charge-dependent directed flow v_1 of open heavy-flavour**

– Hint of much **larger signal for HF** than for charged-particles is measured

BACKUP

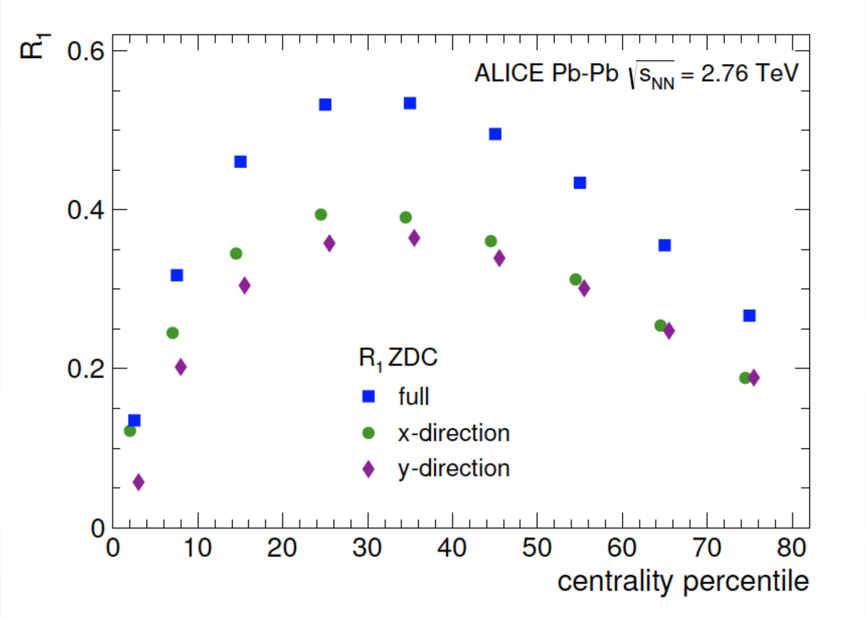
Spectator plane reconstruction and analysis strategy

Zero-Degree Calorimeters (ZDC), energy of spectator neutrons
- located at beam rapidity: $|\eta|> 8.8$

spectator plane from the signal (E_i) into the 4 ZDC segments:

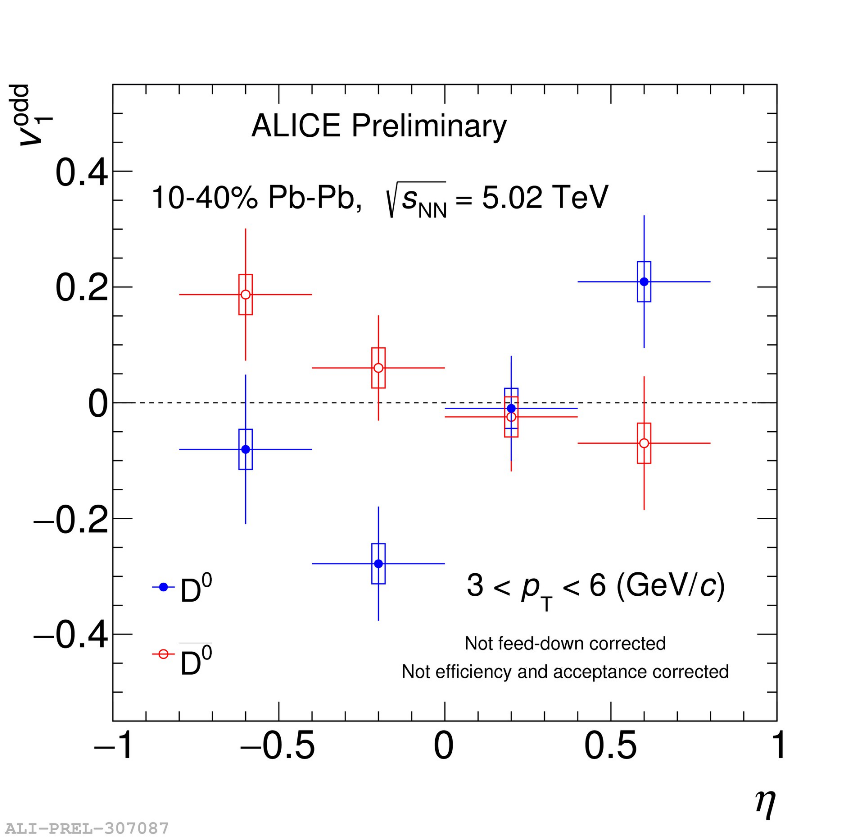
$$\vec{Q}_{A,C} = \frac{\sum_{j=1}^{4} \vec{p}_j E^{\alpha}_{(A,C)j}}{\sum_{j=1}^{4} E^{\alpha}_{(A,C)j}}$$

$$v_1\{\Psi_{A,C}\} = \frac{\langle \vec{q} \cdot \vec{Q}_{A,C} \rangle}{\sqrt{|\langle \vec{Q}_A \cdot \vec{Q}_C \rangle|}} = \frac{\langle q_x Q_{A,Cx} + q_y Q_{A,Cy} \rangle}{\sqrt{|\langle Q_{Ax} Q_{Cx} + Q_{Ay} Q_{Cy} \rangle|}},$$

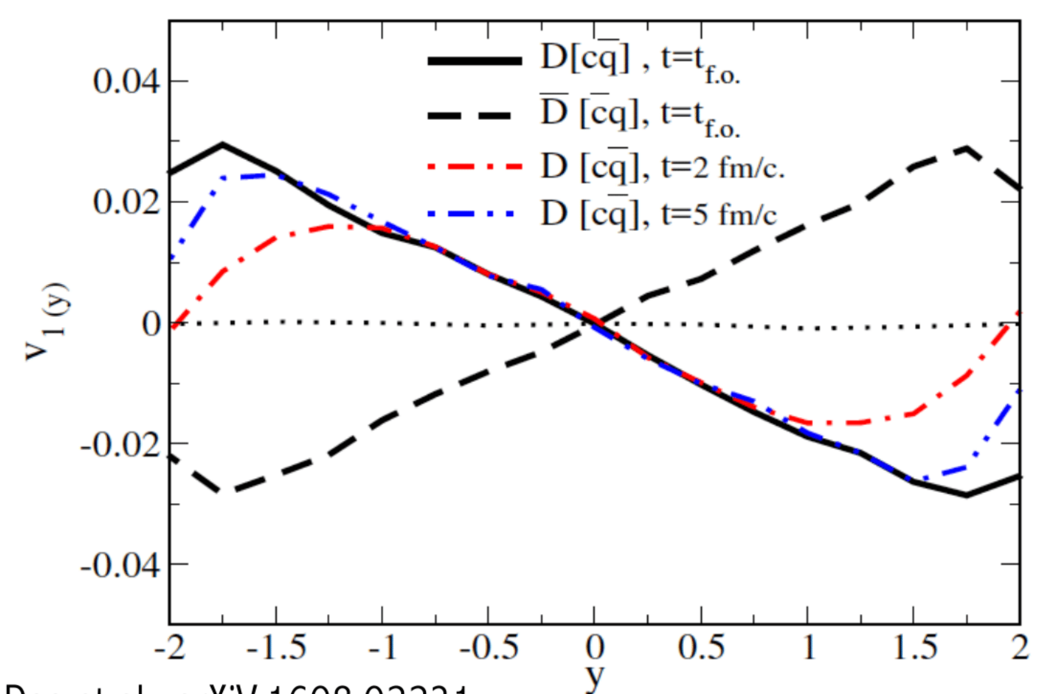


Comparison with STAR

Our results....



EM field



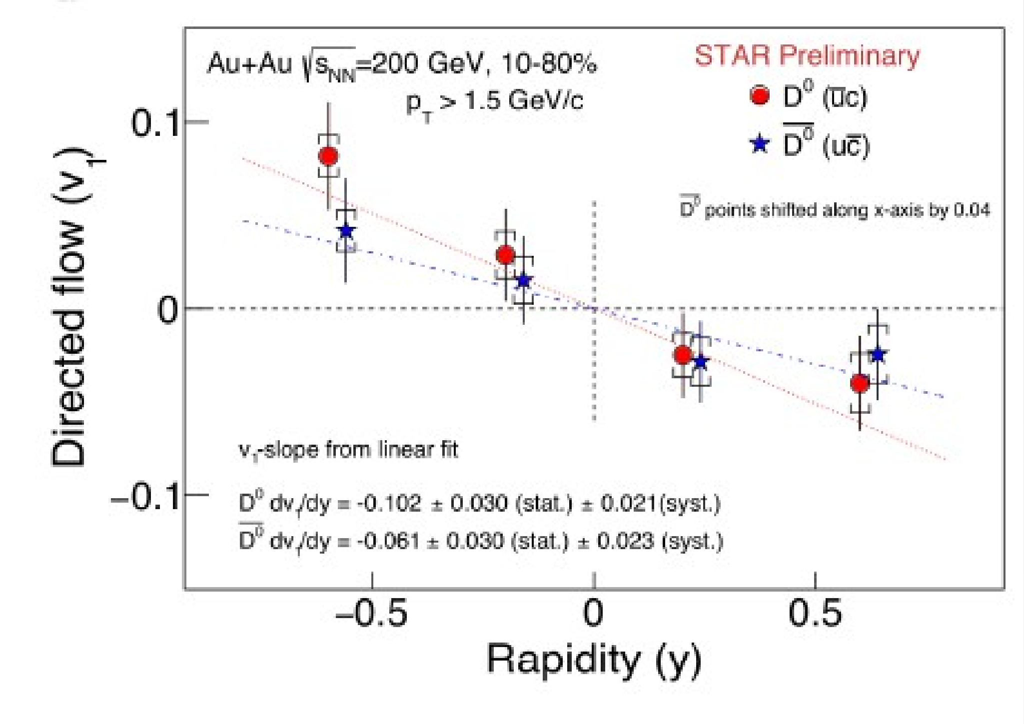
Das et al., arXiV:1608.02231

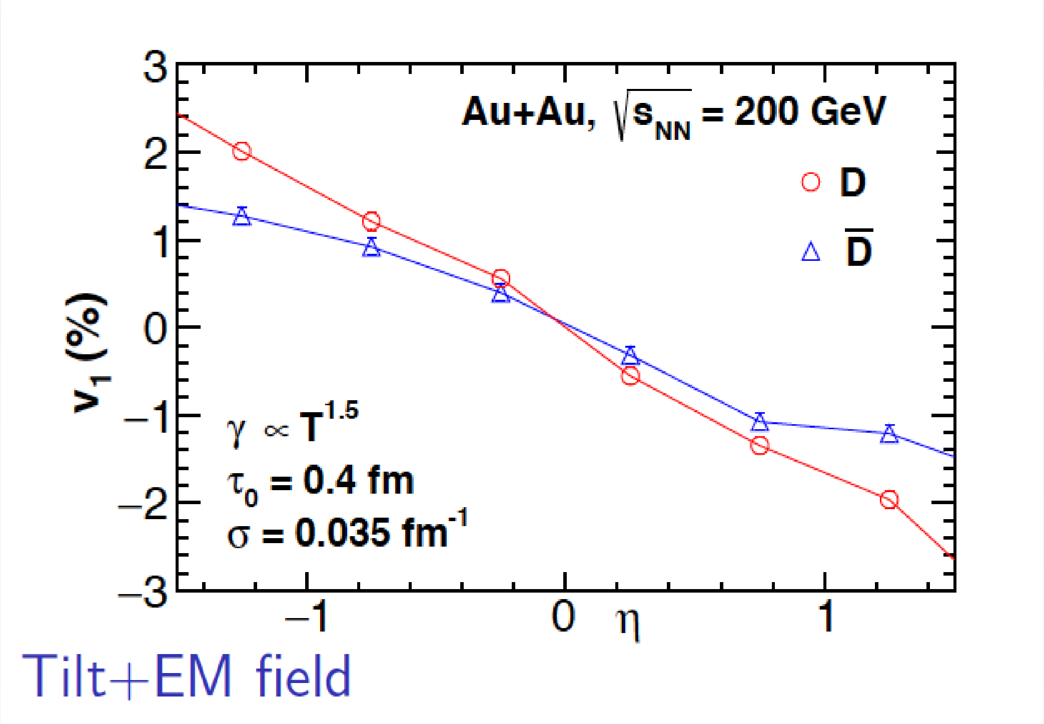
→ from theory we expect: $v_1^{avg} = 0,\ v_1^{diff} \neq 0;$

→ indication of an opposite behavior for D^0 and $\overline{D}^0$
– already observed in the LF sector

Comparison with STAR

STAR results





→ from theory we expect: • $v_1^{avg} \neq 0,\ v_1^{diff} \neq 0$

→ The Tilting seems important at RHIC energies

Comparison with STAR

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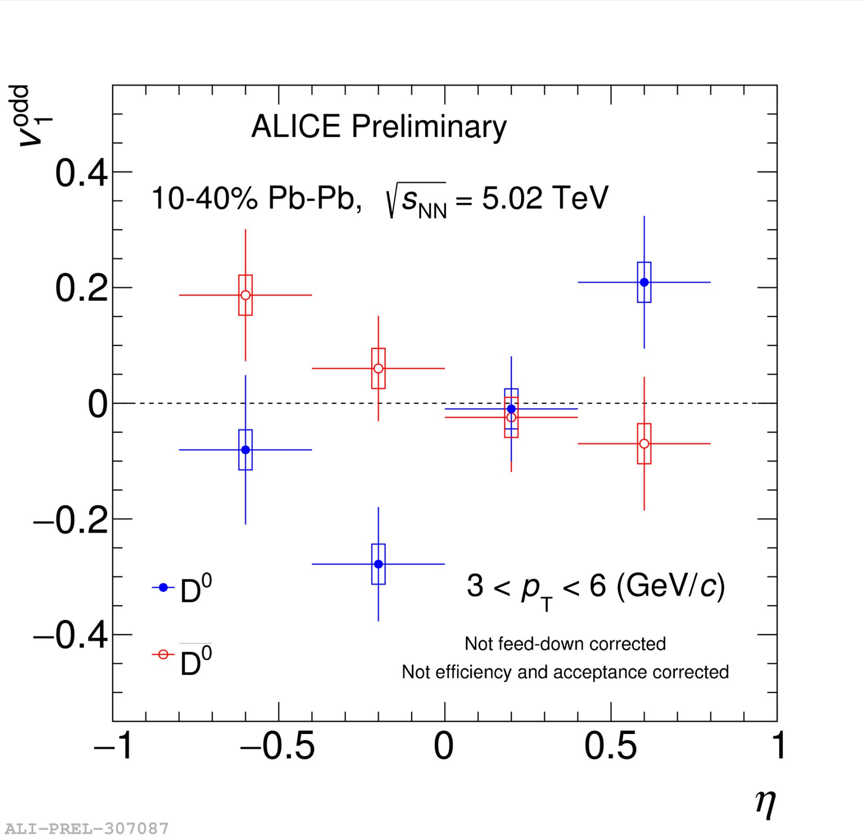

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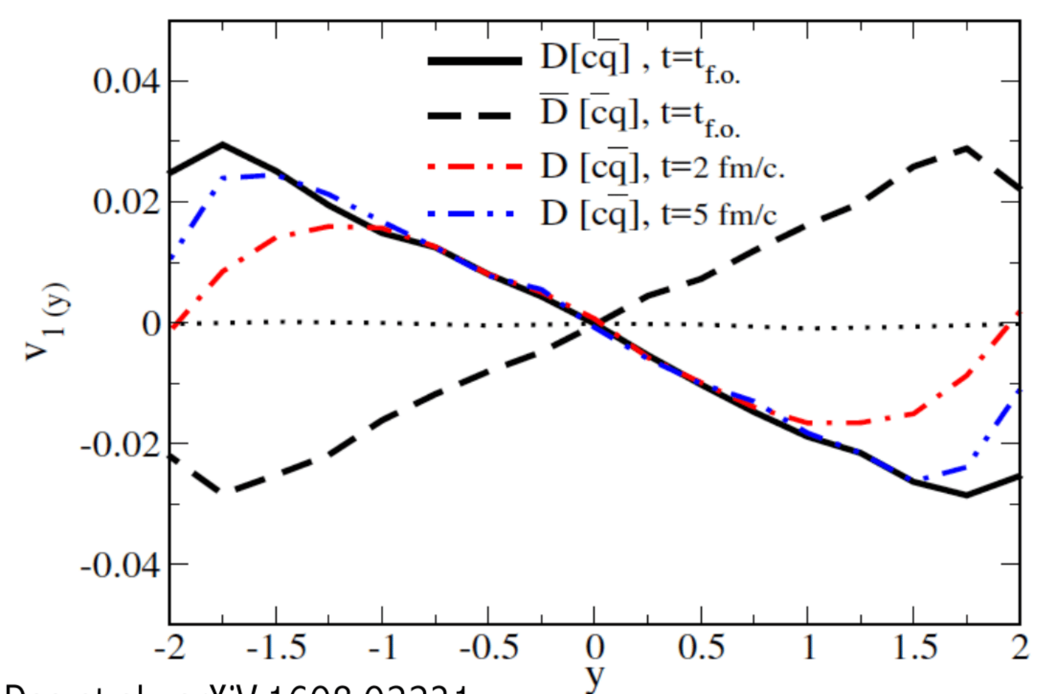

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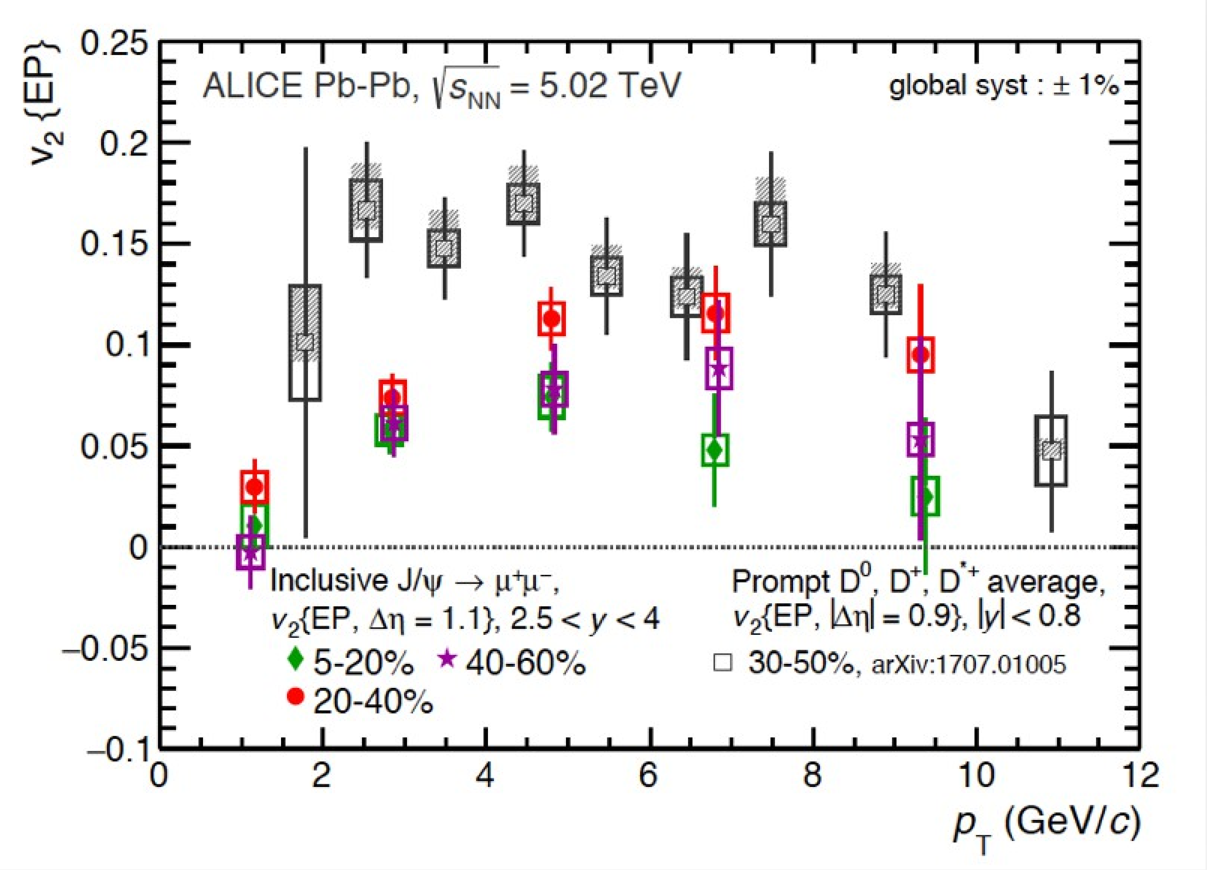
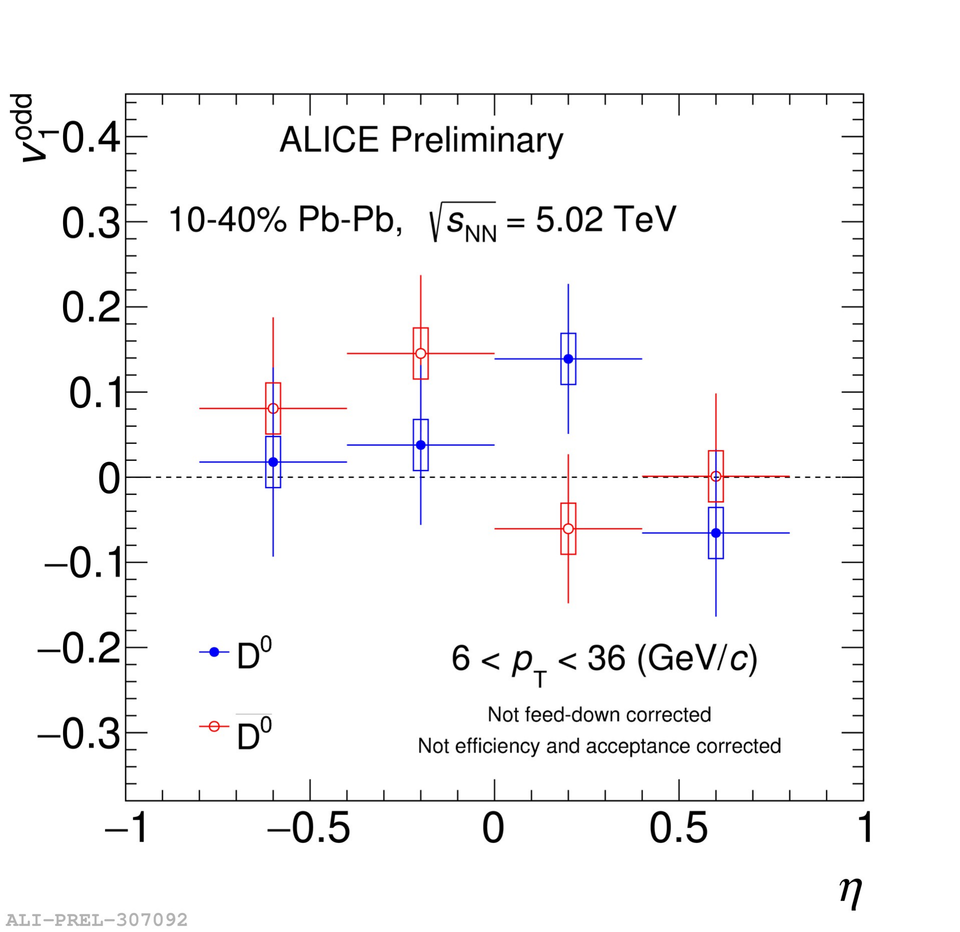
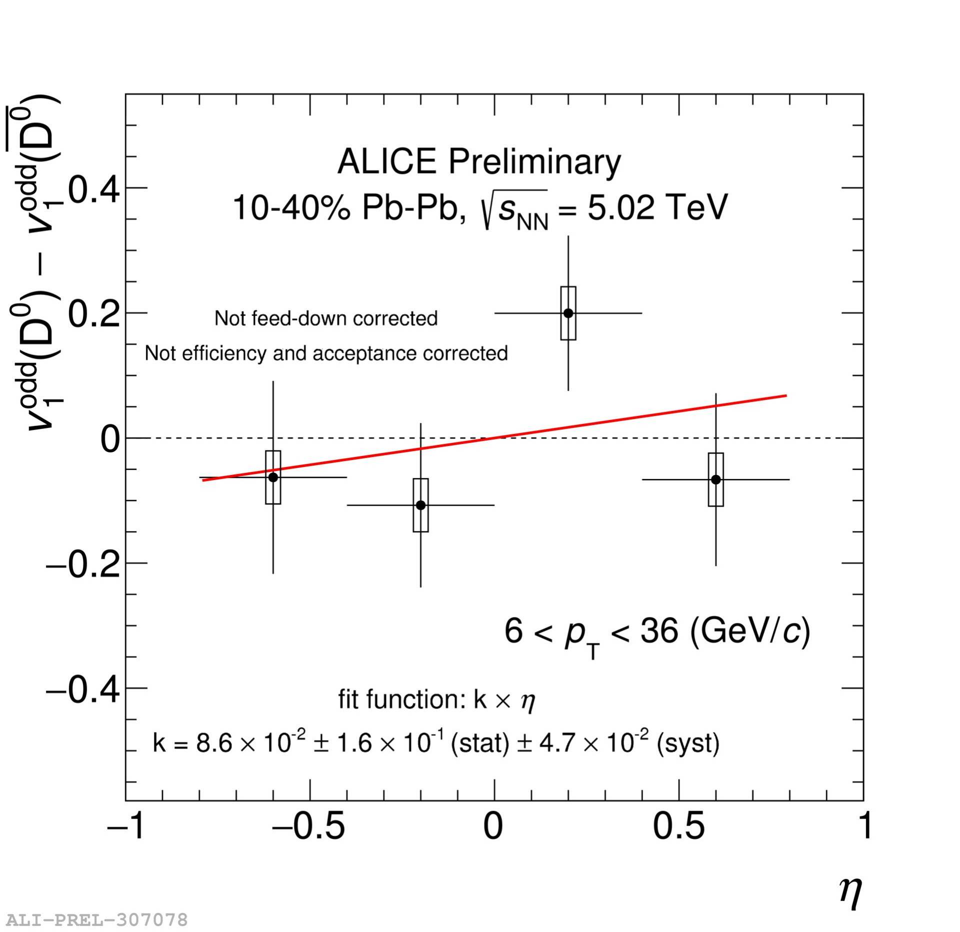
– already observed in the LF sector

Azimuthal anisotropy



Δv1 to quantify a possible signal





rapidity dependence of the charge difference Δv1 is fitted using a linear function with slope k

k **= 0.09 +/- 0.16 (stat) +/- 0.05 (syst)**

v_1^{odd} energy dependence

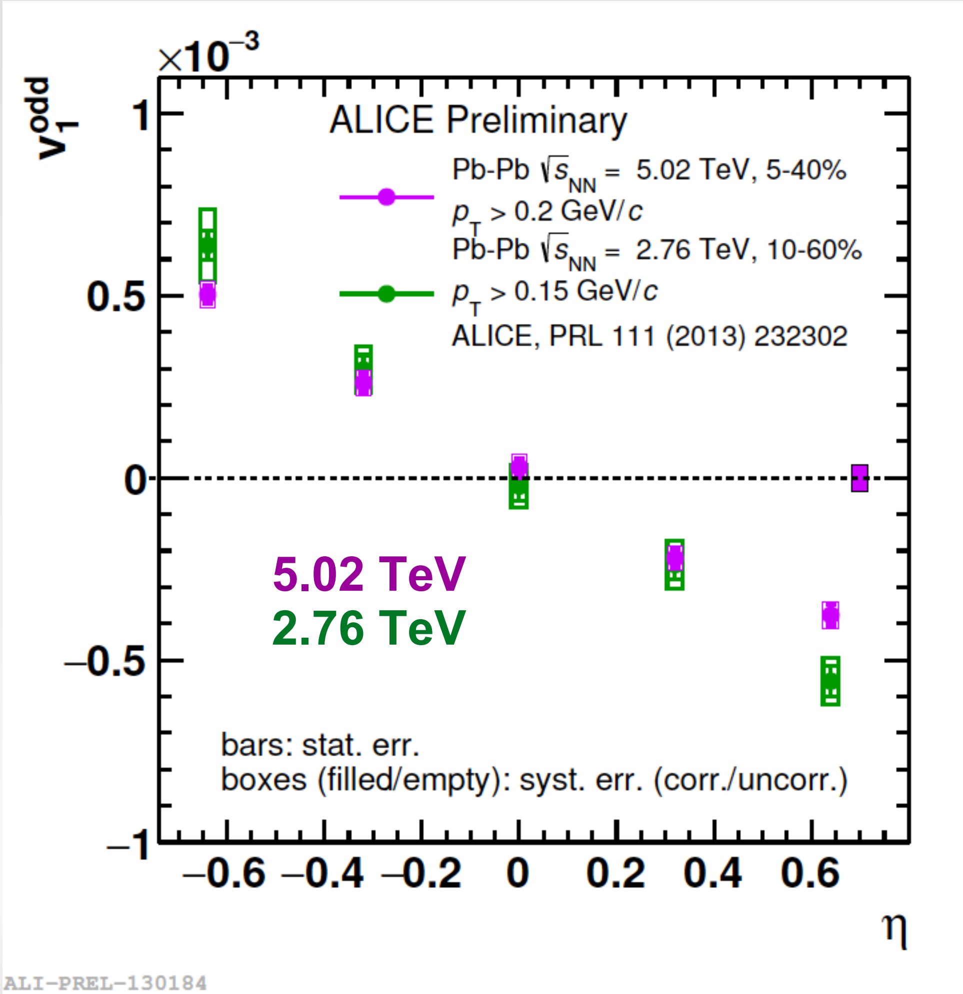
v_1^{odd}: compressibility —> initial tilt / rotation of the system

$$v_1^{\text{odd}} = \frac{1}{2}(v_1\{\Psi_A\} - v_1\{\Psi_C\}).$$

→ $dv_1^{odd}/d\eta$ **decreases by a factor ~1.3** between 2.76 and 5.02 TeV

→ qualitatively consistent with energy dependence observed from RHIC to LHC
- decreased tilting/rotation of initial system

→ different centrality ranges: no significant centrality dependence observed



Projections for Run3/4

Numbers for the D0 were taken from the ITS upgrade

https://aliceinfo.cern.ch/ArtSubmission/sites/aliceinfo.cern.ch.ArtSubmission/files/draft/musa/2012-Mar-13-paper_draft-2012_Mar_6_AliceITSupgrade-CDR-vs2.3.pdf

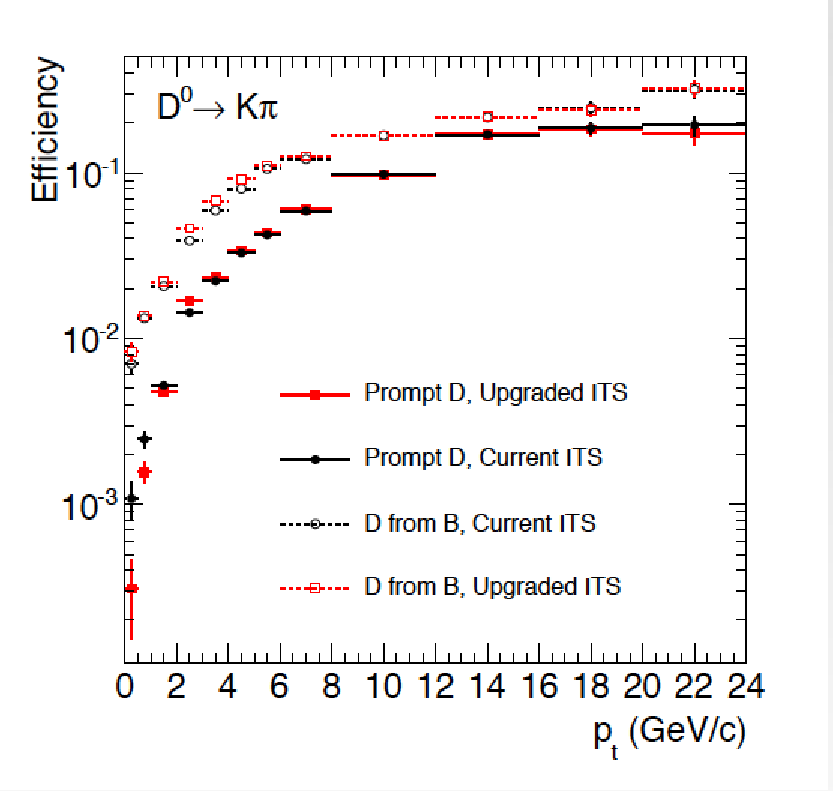
2.3 D0 produced in |y|<0.5 per MB event

reconstruction efficiency 0.05 (at <p_T>)

BR = 3.8%

→ **0.00437 D0 / MB event**

Part.	Yield m.b., 0–10%	$dN/dy\|_{y=0}$ m.b., 0–10%	$c\tau$ [μm]	decay channel	B.R.	Acc.
D^0	23, 110	2.3, 11	≈ 120	$K^-\pi^+$	3.8%	1
Λ_c	2.9, 14	0.29, 1.4	≈ 60	$pK^-\pi^+$	5.0%	1
B	1.3, 6.2	0.2, 0.9	≈ 500	$J/\psi(\to e^+e^-)$	$1.2\% \times 6\%$	1
				$D^0(\to K^-\pi^+)$	$60\% \times 3.8\%$	1
				e^+	10.9%	1.8
B^+	0.6, 2.7	0.1, 0.4	≈ 500	$J/\psi(\to ee)K^+$	$0.1\% \times 6\%$	1
B^0_s	0.2, 0.9	0.03, 0.13	≈ 500	$J/\psi(\to ee)\phi(\to KK)$	$0.14\% \cdot 6\% \cdot 50\%$	1
Λ_b	0.1, 0.5	0.015, 0.07	≈ 400	$\Lambda_c(\to pK^-\pi^+)+e^-$	$9.9\% \times 5\%$	1
				$\Lambda_c(\to pK^-\pi^+)+h^-$	90%(guess)$\times 5\%$	1



Now we have ~100M MB events.
For run3 → 1000x the events now available
→ 2.6e08 D0s in total