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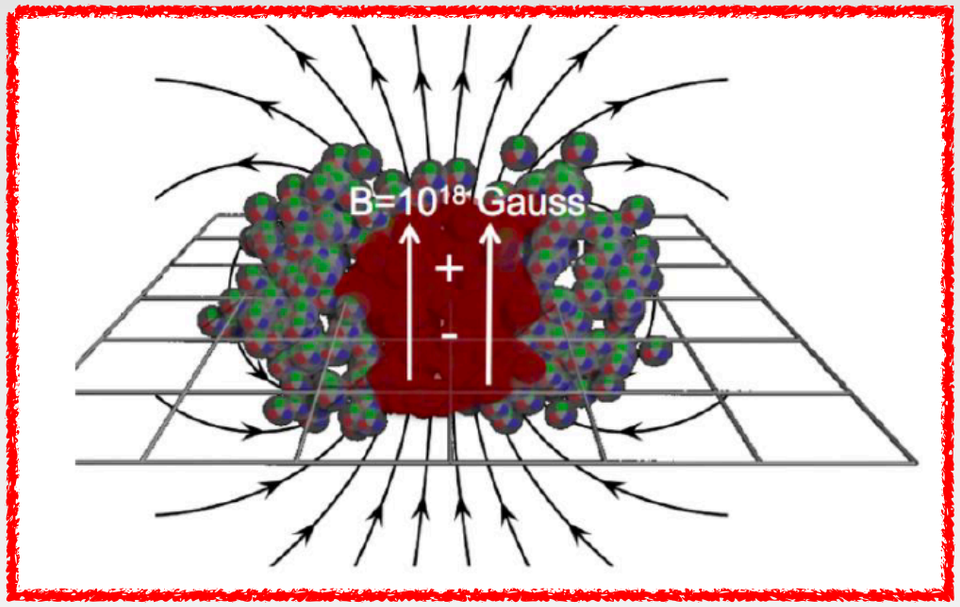
# Evidence for electromagnetic fields in the initial stages

*Dr. Andrea Dubla*

27/06/19

# Introduction

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




⇨ Several anomalous chiral effects have been predicted to be created in the QGP

- **C**hiral **M**agnetic **E**ffect
- **C**hiral **M**agnetic **W**ave
- **C**hiral **V**ortical **E**ffect

and are expected to bring information on possible **local CP violation** in strong interactions and on the **non-trivial topologies of QCD**

⇨ **ALICE, CMS and STAR** experiments have been put **efforts** into such studies for more than a decade

# Snapshot timeline

Observation of charge-dependent azimuthal correlations and possible local strong parity violation in heavy-ion collisions
**Phys. Rev. C 81, 054908 (2010).**

Charge separation relative to the reaction plane in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
**Phys. Rev. Lett. 110, 012301 (2013).**

Fluctuations of charge separation perpendicular to the event plane and local parity violation in $\sqrt{s_{NN}}$ = 200 GeV Au + Au collisions at the BNL Relativistic Heavy Ion Collider
**Phys. Rev. C 88, 064911 (2013).**

Observation of Charge-Dependent Azimuthal Correlations in p-Pb Collisions and Its Implication for the Search for the Chiral Magnetic Effect
**Phys. Rev. Lett. 118, 122301 (2017).**


Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation
**Phys. Rev. Lett. 103, 251601 (2009).**

**ALICE**
**STAR**
**CMS**

Beam-Energy Dependence of Charge Separation along the Magnetic Field in Au+Au Collisions at RHIC
**Phys. Rev. Lett. 113, 052302 (2014).**

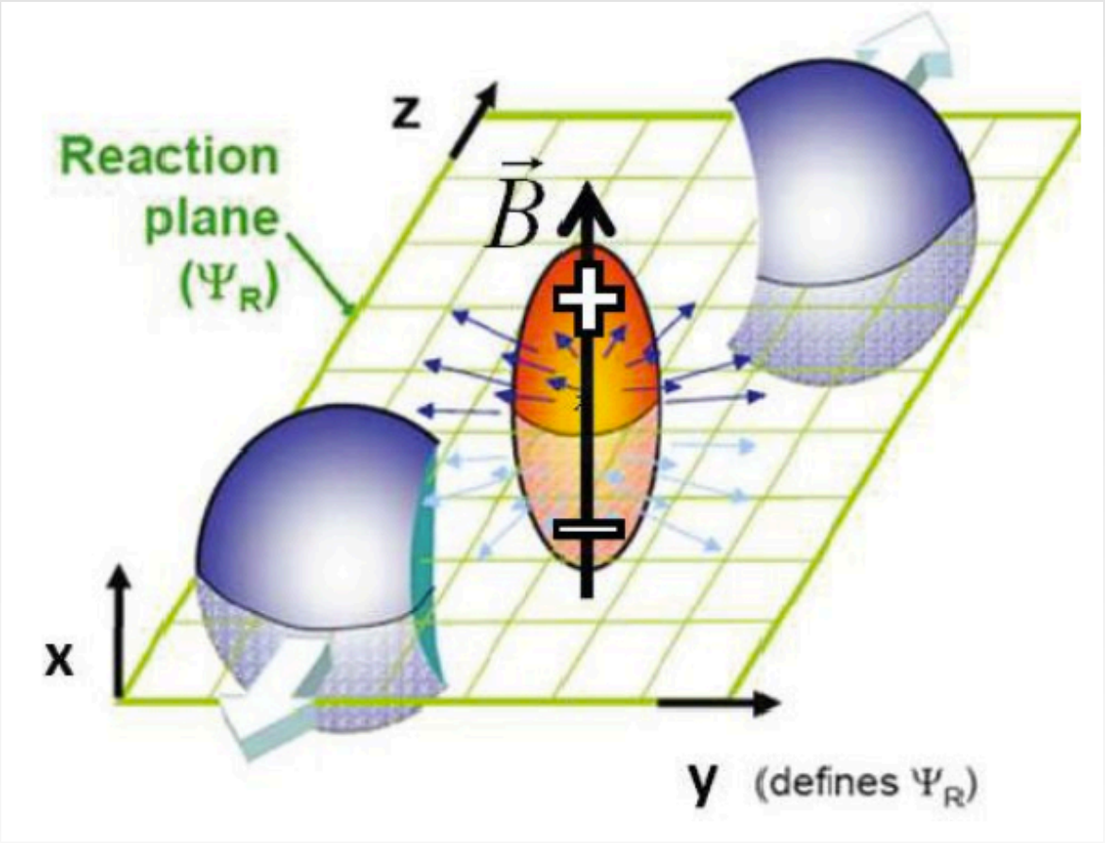
Measurement of charge multiplicity asymmetry correlations in high-energy nucleus-nucleus collisions at $\sqrt{s_{NN}}$ = 200 GeV
**Phys. Rev. C 89, 044908 (2014).**

Constraining the magnitude of the Chiral Magnetic Effect with Event Shape Engineering in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
**Physics Letters B 777, 151 (2018).**

Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the CERN Large Hadron Collider
**Phys. Rev. C 97, 044912 (2018).**

# CME - how do we measure it

⇨ **the experimental observable:** charge separation across the reaction plane




⇨ It can be measured with charge dependent 2- and 3-particle correlators:

$$\delta_{+,-} = \langle cos(\phi_+ - \phi_-) \rangle$$

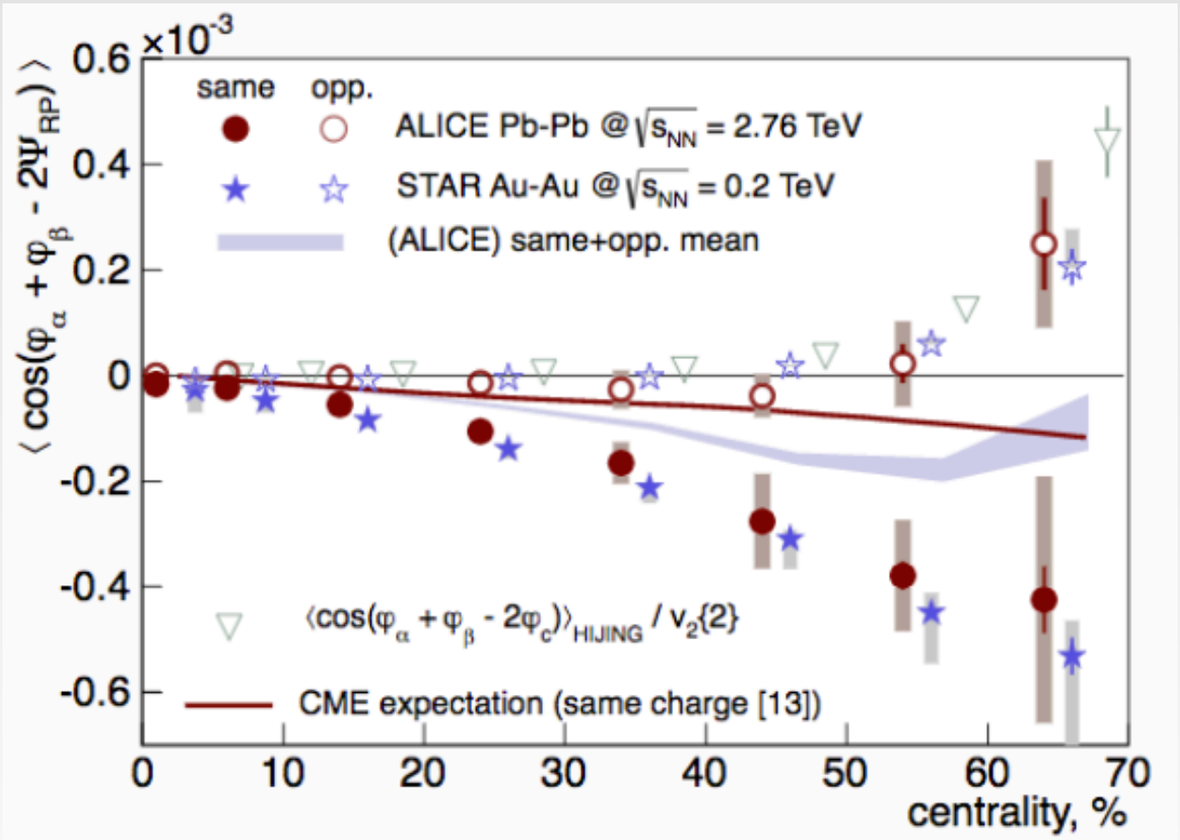
$$\gamma_{+,-} = \langle cos(\phi_+ + \phi_- - 2\Psi_{RP}) \rangle$$

Voloshin: Phys. Rev. C 70, 057901 (2004)

# CME correlators

⇨ **significant difference in $\gamma_{a,b}$** same vs opp.

⇨ sign of the difference correct, but **background largely present!**



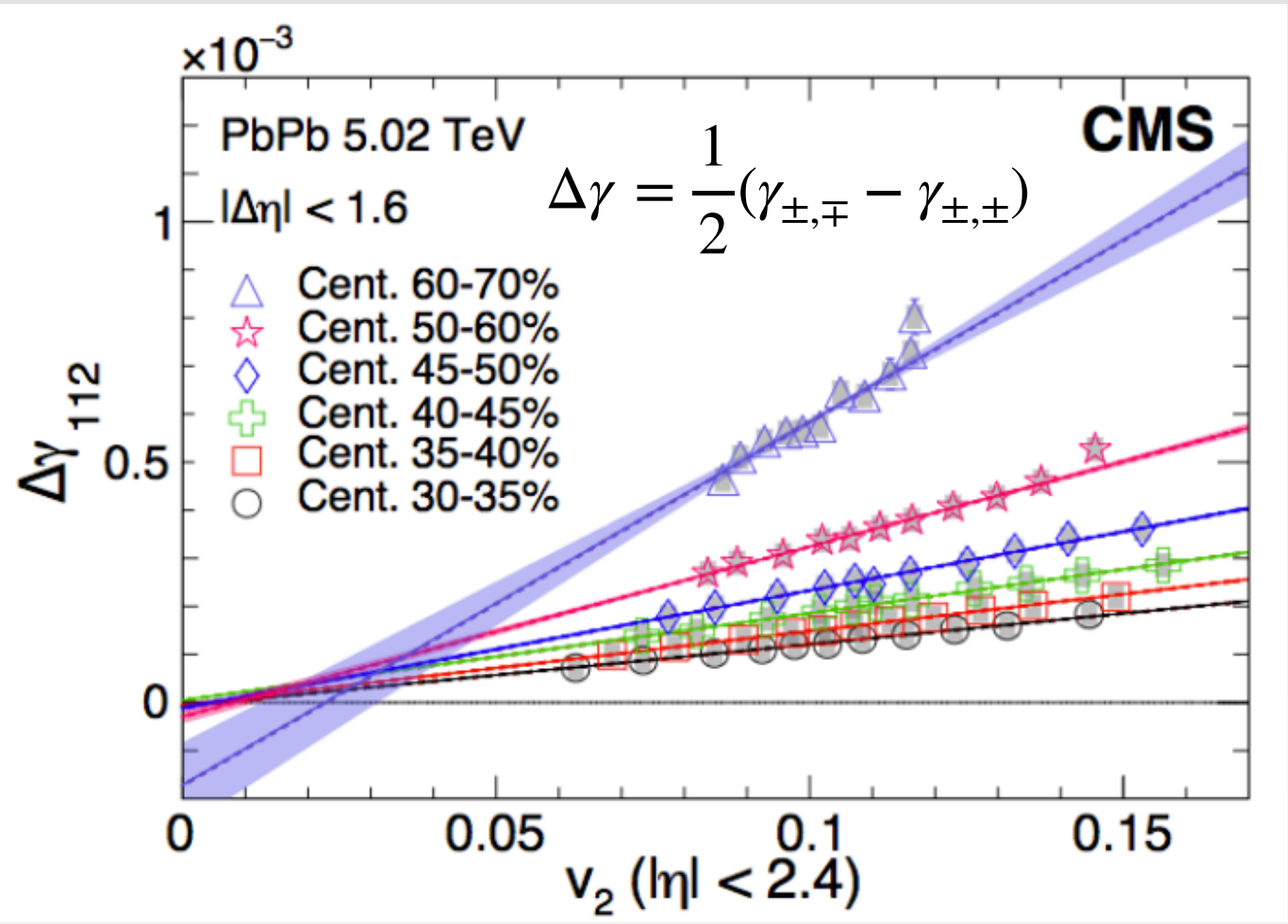

$$\gamma_{+,-} = \langle cos(\phi_+ + \phi_- - 2\Psi_{RP}) \rangle$$

⇨ **Main background sources:**
- transverse momentum conservation
- flow fluctuations
- local charge conservation

STAR: Phys. Rev. Lett. 103, 251601 (2009)
ALICE: Phys. Rev. Lett. 110, 012301 (2013)
CMS: Phys. Rev. Lett. 118, 122301 (2017)

# CME - upper limits

ALICE: Physics Letters B 777, 151 (2018)
CMS: Phys. Rev. C 97, 044912 (2018).




⇨ **CME correlators with Event-Shape-Engineering** in Pb-Pb collisions at the LHC by ALICE and CMS

**Assumption:**
CME is $v_2$-independent, background is not (scale linearly)

**Results:** compatible with background-only hypothesis

**Upper limits** (3.8% CMS, 26-33% ALICE) strongly depend on assumptions on signal and background: **more studies are needed!**

# Recap….

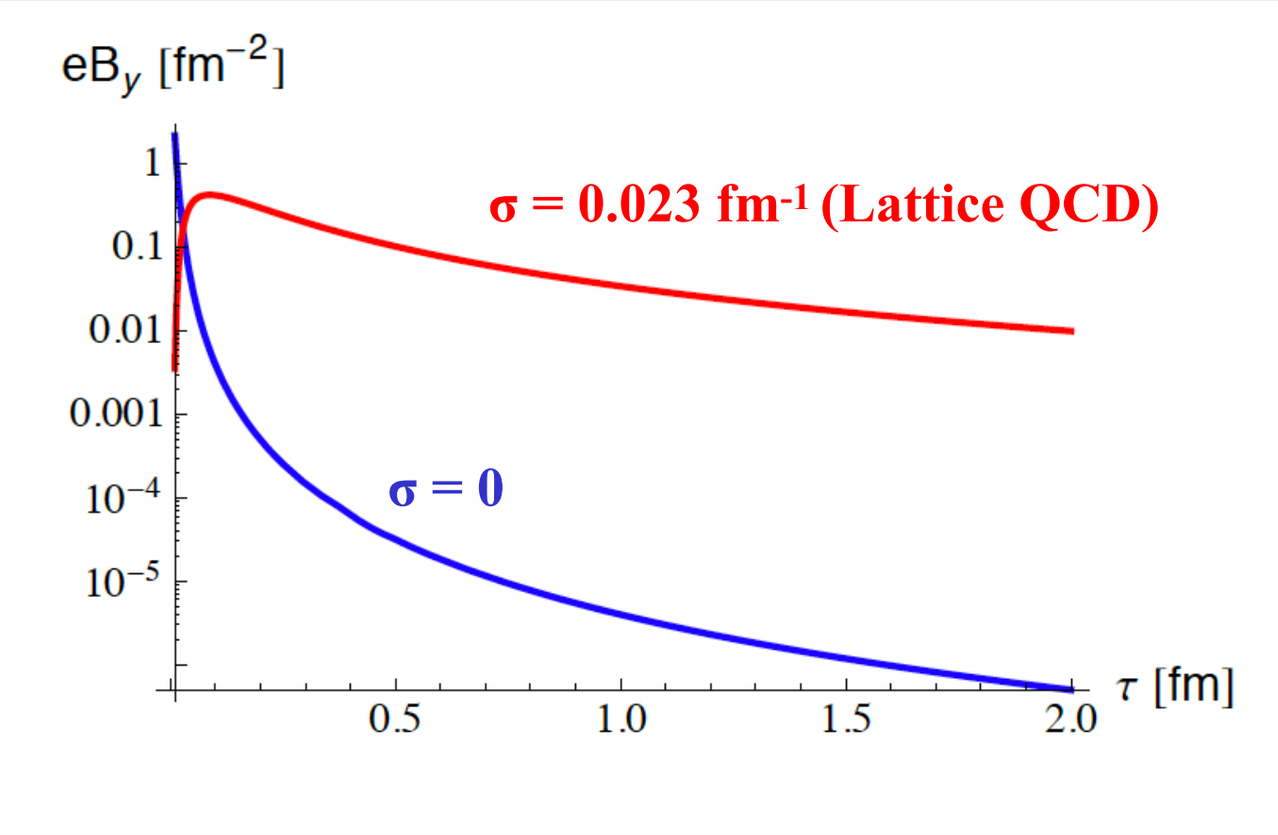
⇨ **magnetic field** in heavy-ion collision is expected to
**lead to several novel phenomena**
e.g. Chiral Magnetic Effect (CME)

⇨ **we face different problems:**
→ **hard to decouple signal** (charge separation across reaction plane)
**from background** (local charge conservation + flow)
→ **very few constraints from theory:** difficult phenomena to model
+ uncertainties in estimating the magnetic field

⇨ **proposal: charge-dependent directed flow**
measure a **simpler and cleaner observable**
(not related to the chiral imbalance),
use it to calibrate the strength and lifetime of the electromagnetic field

# The idea*

- ⇨ **varying magnetic field will influence moving charges (quarks)**
- ⇨ very few ingredients needed: **charged and conductive QGP**




⇨ presence of a conducting QGP substantially delays the decay of the magnetic field

- **assumption**: constant conductivity as a function of temperature

$\sigma = 0.023$ fm$^{-1}$

H.-T. Ding, et al, Phys. Rev. D 83, 034504
B. B. Brandt et al, JHEP 1303, 100 (2013)
A. Amato, et al, Phys. Rev. Lett. 111, 172001 (2013)

*first proposed by Gursoy *et al:* Phys. Rev. C 89, 054905 (2014)

# The idea*

- ⇨ **varying magnetic field will influence moving charges (quarks)**
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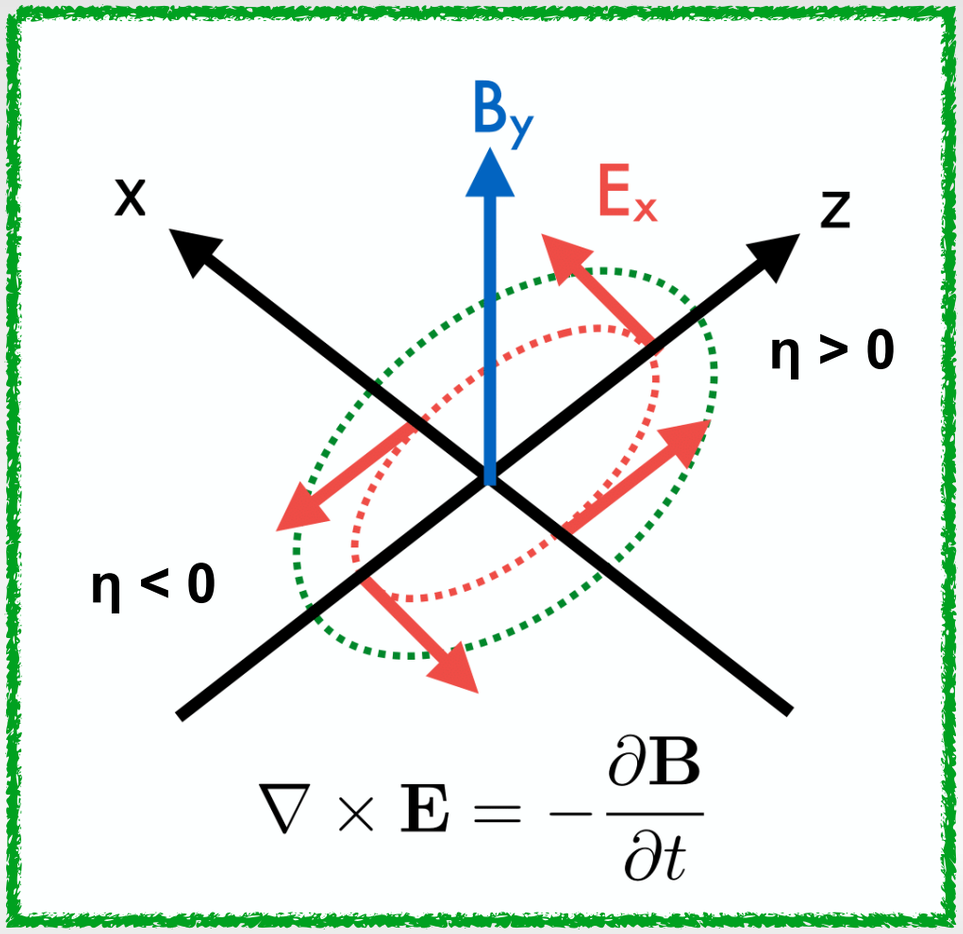
- ⇨ the result: charge-dependent **directed flow**, asymmetric in rapidity

– **where does it come from?**

→ electric field induced by decreasing B
**(Faraday effect)**

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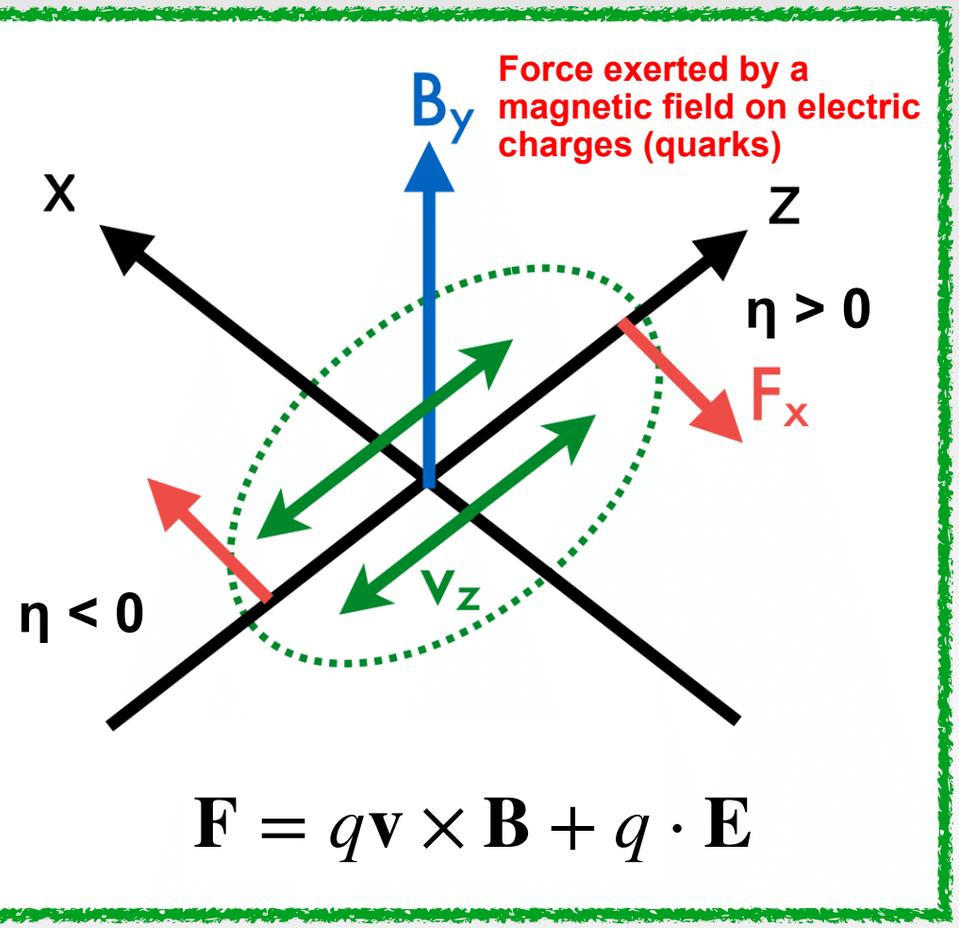
→ Lorentz force on moving charges
**(Hall effect)**

**Competing effects**

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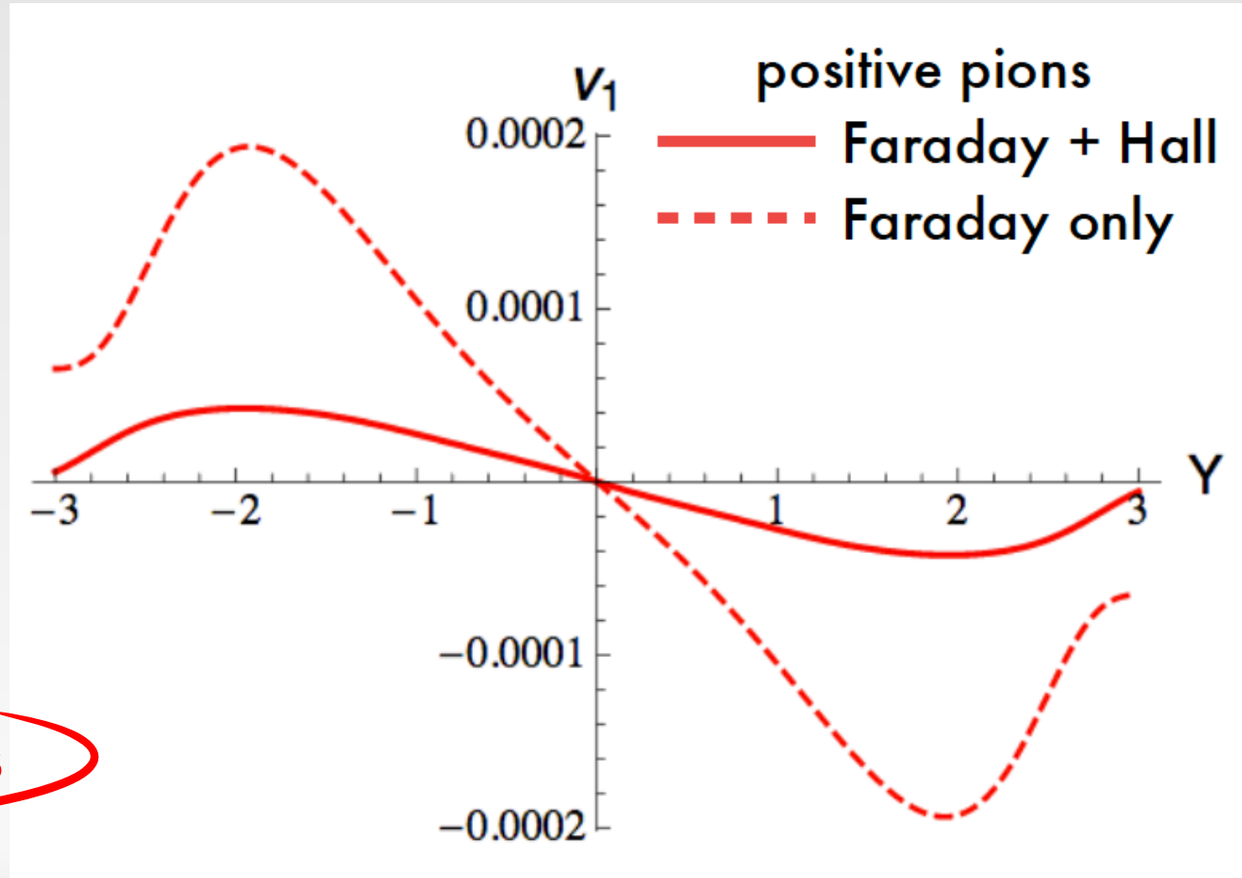
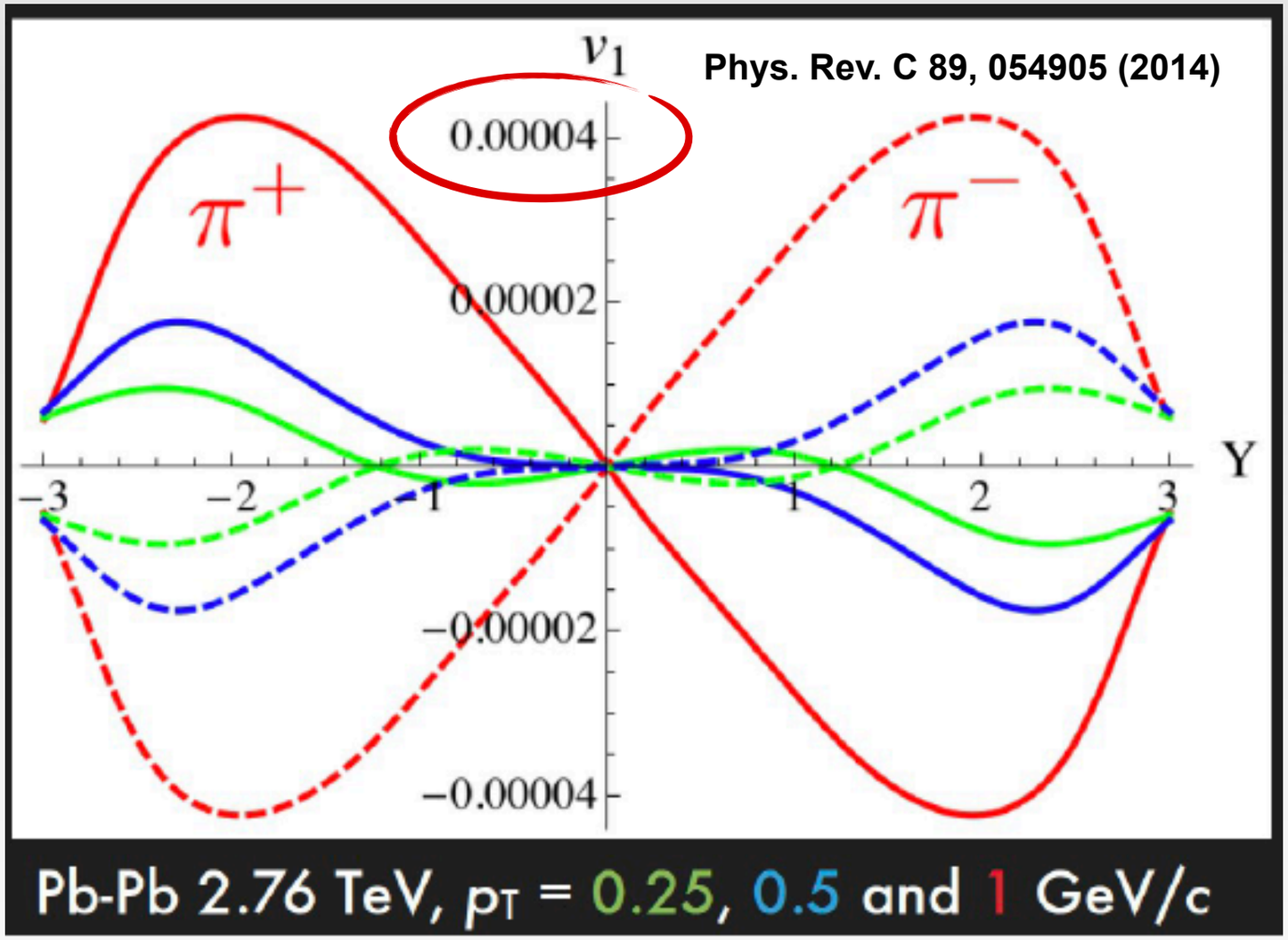



*first proposed by Gursoy *et al:* Phys. Rev. C 89, 054905 (2014)

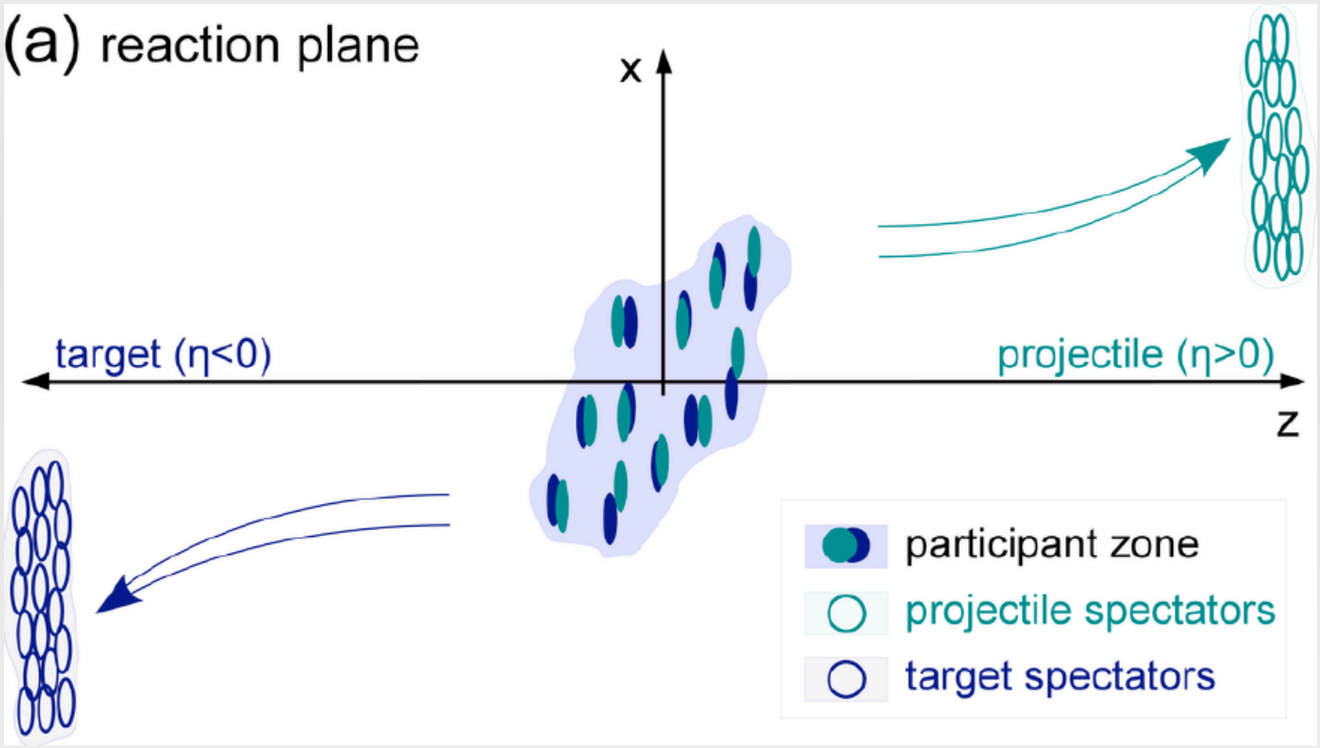
# Charge-dependent $v_1$

⇨ prediction for Pb-Pb collisions at 2.76 TeV: **~$10^{-5}$**




- the rapidity slope varies with $p_T$, different contribution of Faraday and Lorentz

# How do we measure the directed flow




$$v_1(\mathrm{A,C}) = \frac{\langle \mathbf{u}\cdot\mathbf{Q}^{\mathrm{A,C}}\rangle}{\sqrt{\left|\langle \mathbf{Q}^{\mathrm{A}}\cdot\mathbf{Q}^{\mathrm{C}}\rangle\right|}} = \frac{\left\langle u_x\cdot Q_x^{\mathrm{A,C}} + u_y\cdot Q_y^{\mathrm{A,C}}\right\rangle}{\sqrt{\left|\langle Q_x^{\mathrm{A}}\cdot Q_x^{\mathrm{C}} + Q_y^{\mathrm{A}}\cdot Q_y^{\mathrm{C}}\rangle\right|}},$$

N.B. the convention is to choose $v_1 > 0$ for spectators at $\eta > 0$

⇨ need to measure the impact parameter reaction plane, including its sign

- we use the **spectator neutrons** that fly at beam rapidity (ZDCs)
- therefore, we call it spectator plane (~reaction plane)

# $v_1$ energy dependence

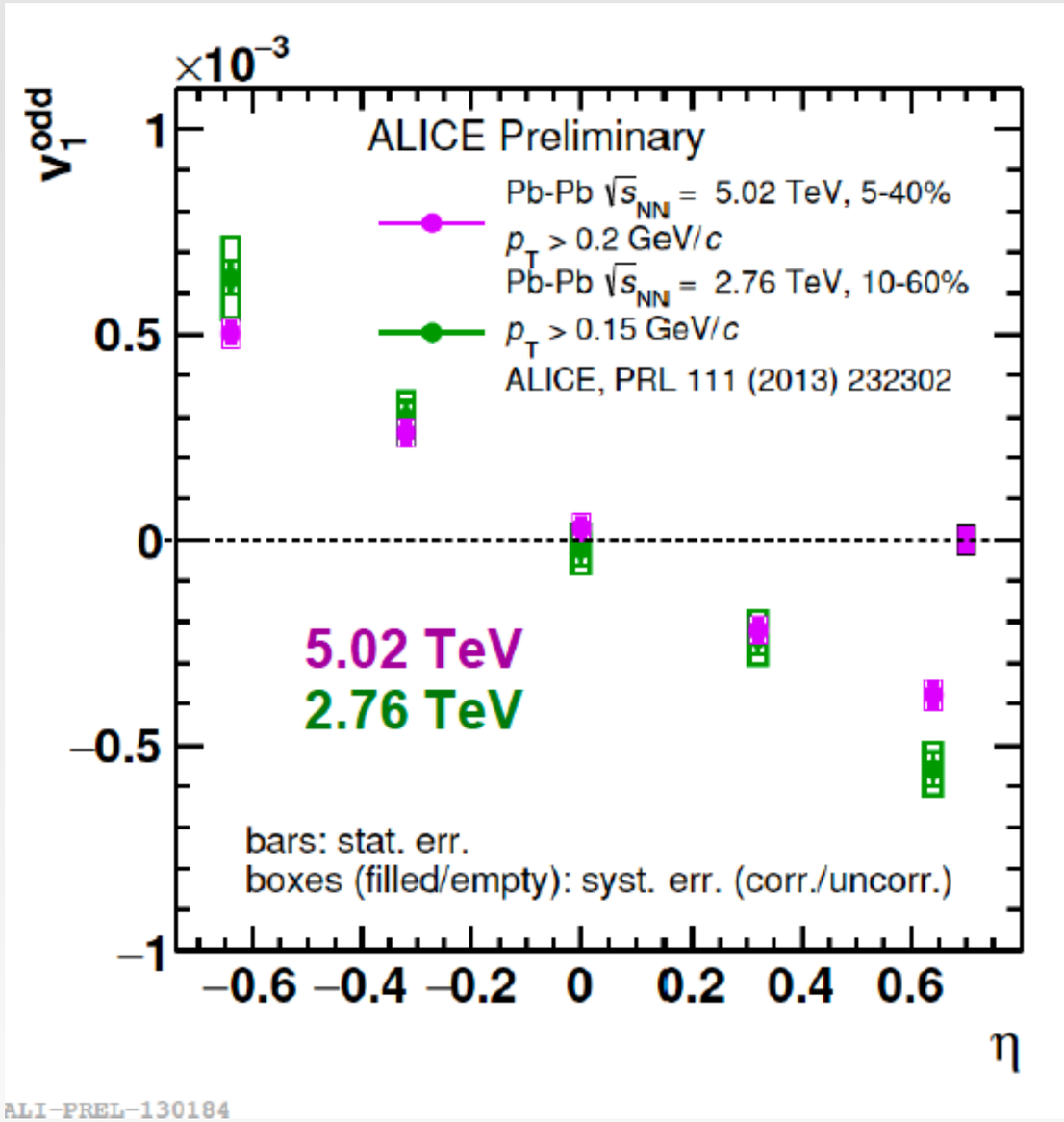
$v_1^{odd}$: compressibility → initial tilt / rotation of the system

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

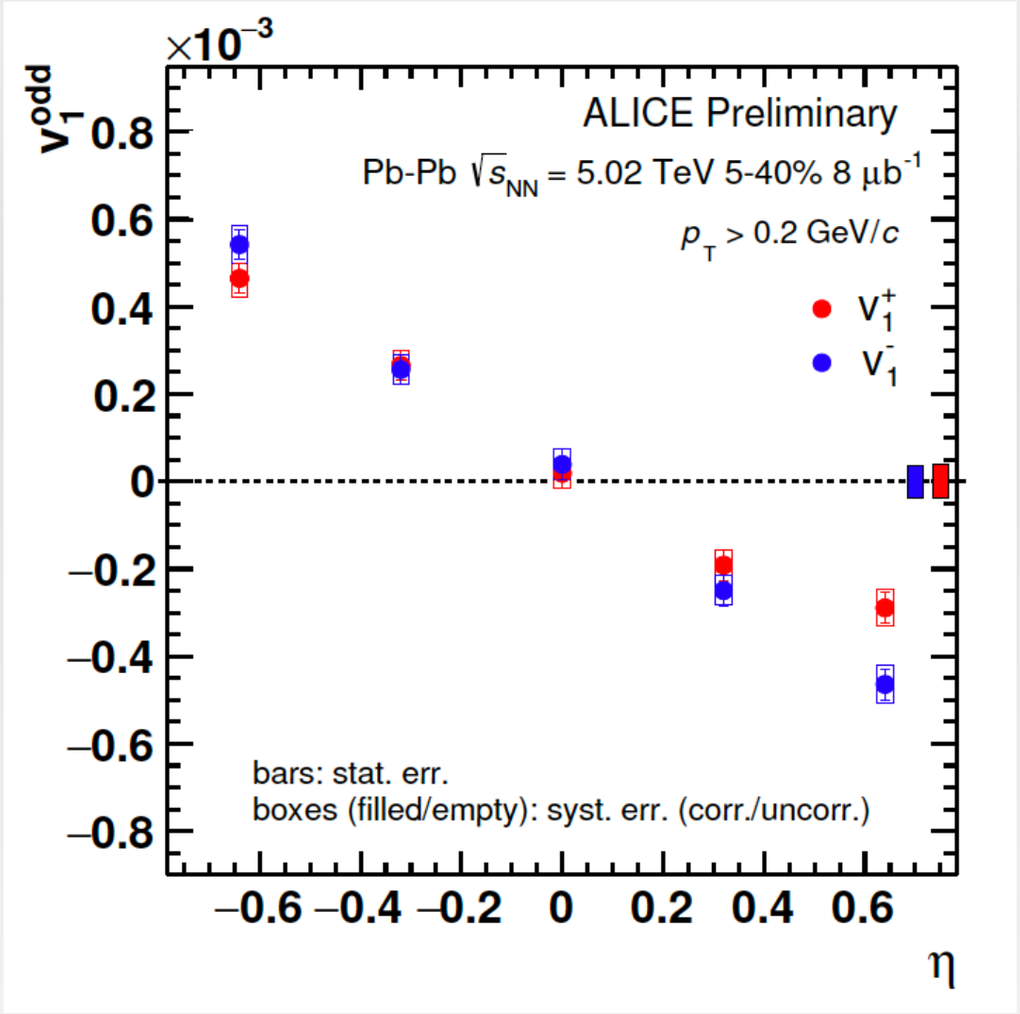
⇨ $dv_1^{odd}/d\eta$ **decreases by a factor ~1.3** between **2.76** and **5.02** TeV

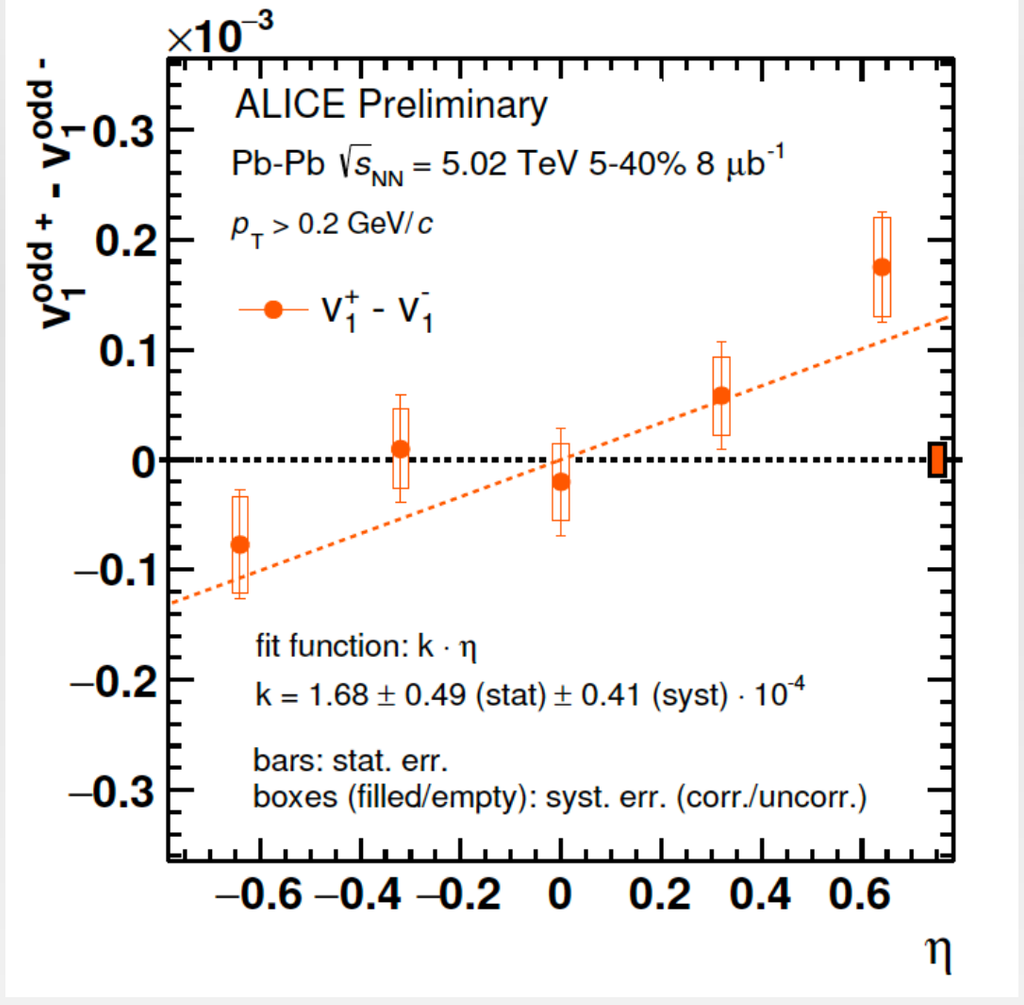
⇨ qualitatively consistent with energy dependence observed from RHIC to LHC
**- decreased rotation of initial system**

⇨ Caveat: different centrality ranges, but no significant centrality dependence observed



# Charge-dependent $v_1$



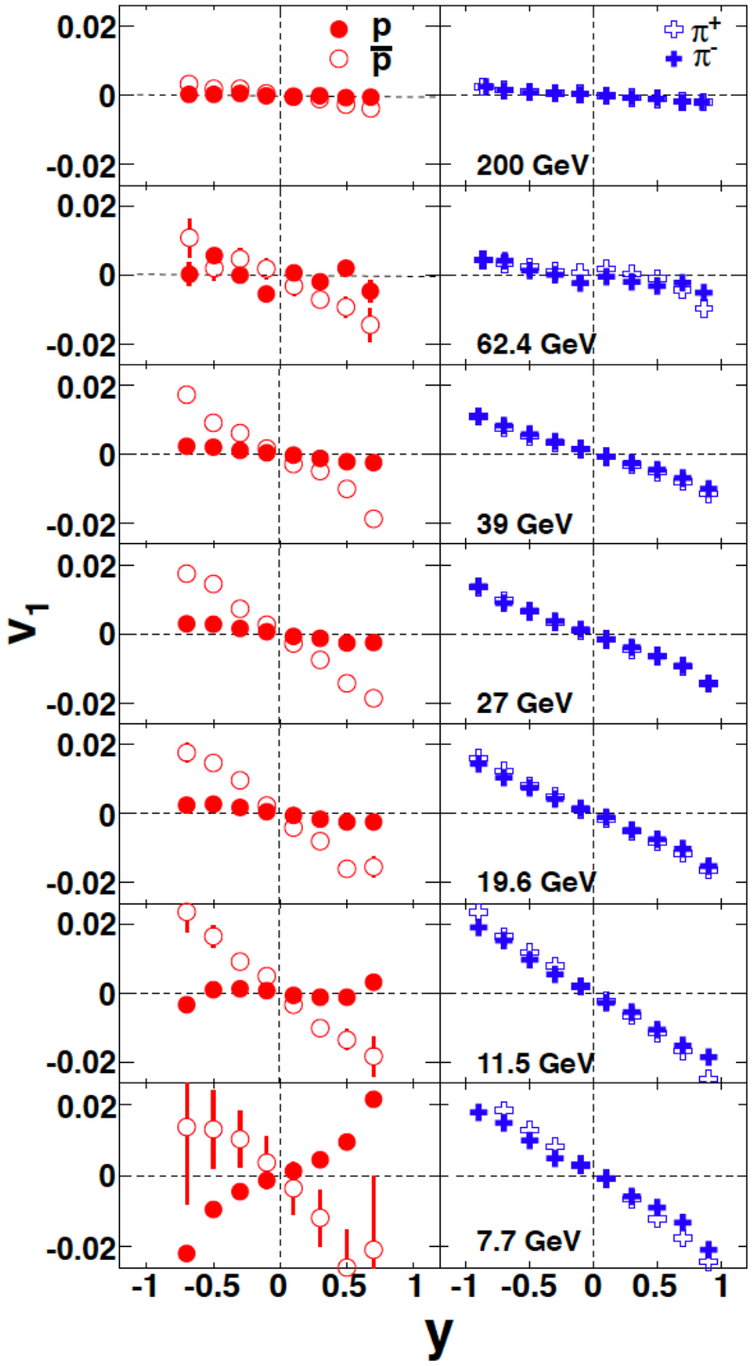




⇨ hint of a charge difference: $\Delta v_1$ odd = $v_1$ odd(+) - $v_1$ odd(-) ≠ 0
(**2.6σ significance)**

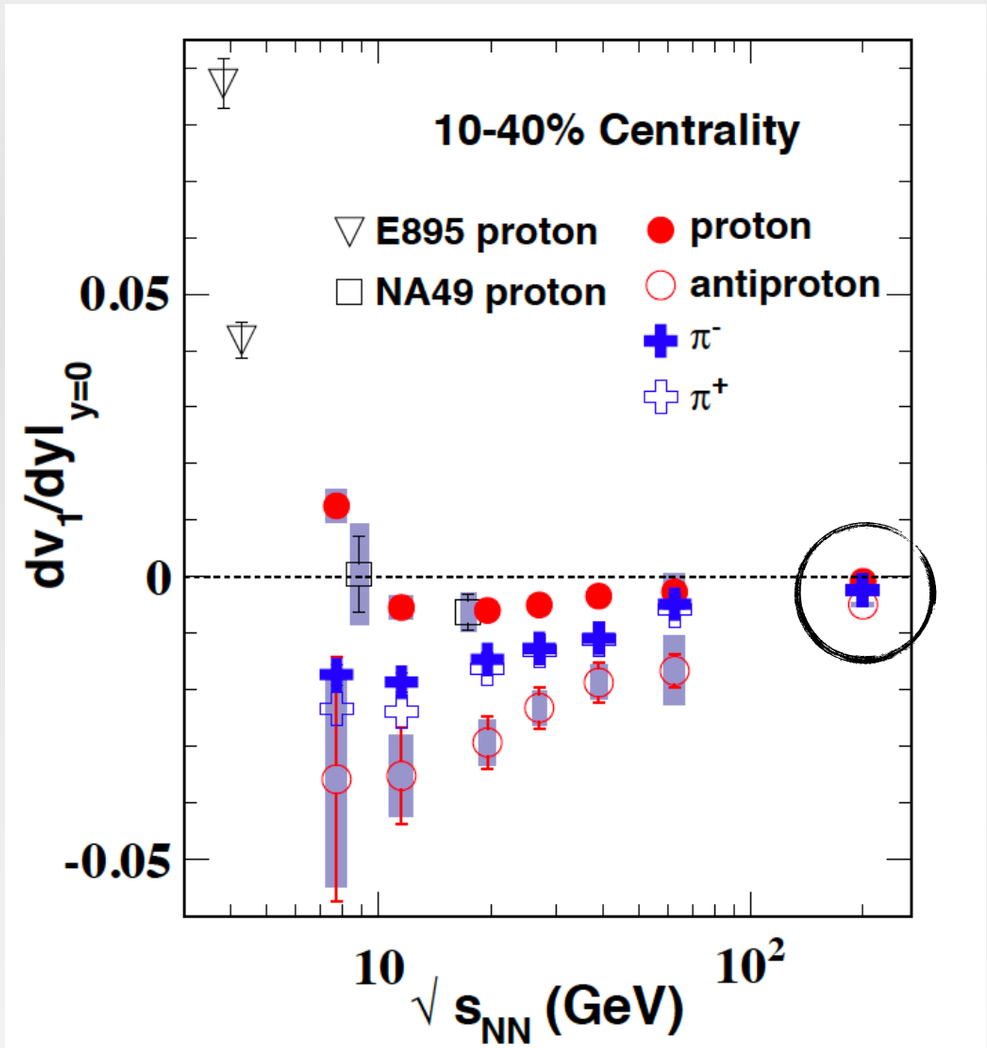
⇨ **1 order of magnitude bigger**: long-lived magnetic field? early thermalization?

⇨ **opposite sign**: dominance of Lorentz force?

# Charge-dependent $v_1$ with BES




STAR: Phys.Rev.Lett. 112 (2014) no.16, 162301




- ⇨ proton stopping seems important at low RHIC energies and the importance decrease with increasing energy
- ⇨ Is the effect observed at LHC related to possible baryon stopping?
  **At LHC $\mu_B \sim 0$, look at identified particle!**

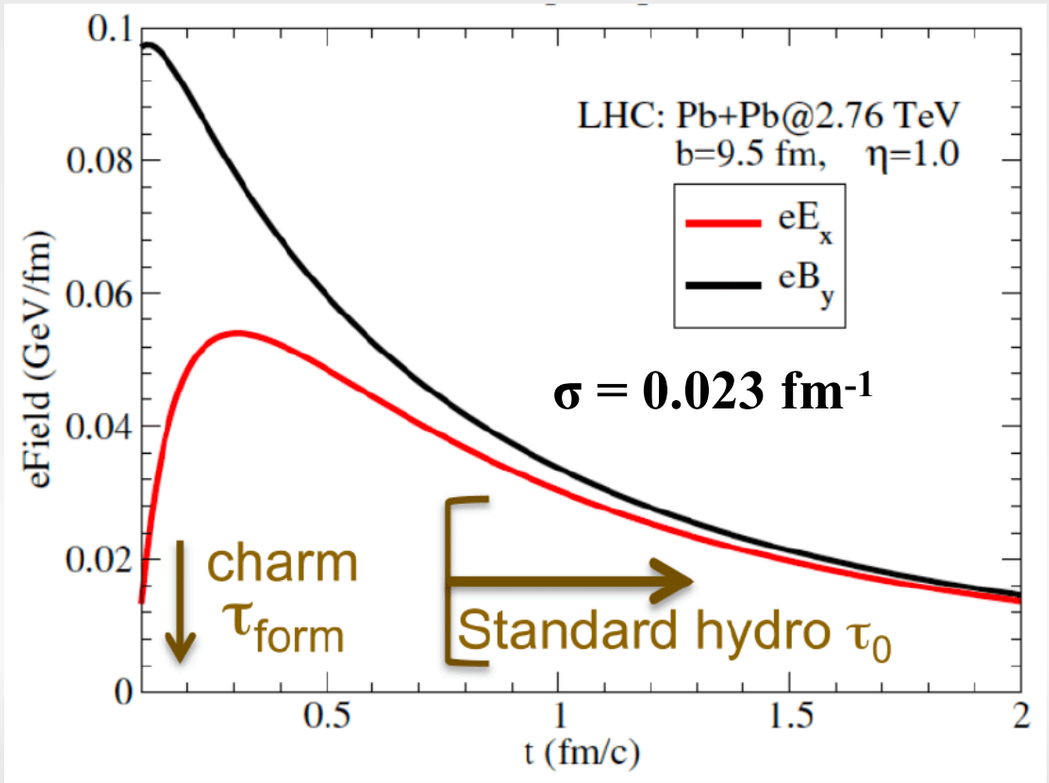
# Can we do something more?

# Can we do something more?

⇨ **Look at open heavy-flavour particles — charm**

# Why open heavy-flavour?

⇨ **formation time ~** 0.1 fm/c → comparable to the time scale **when B is maximum**

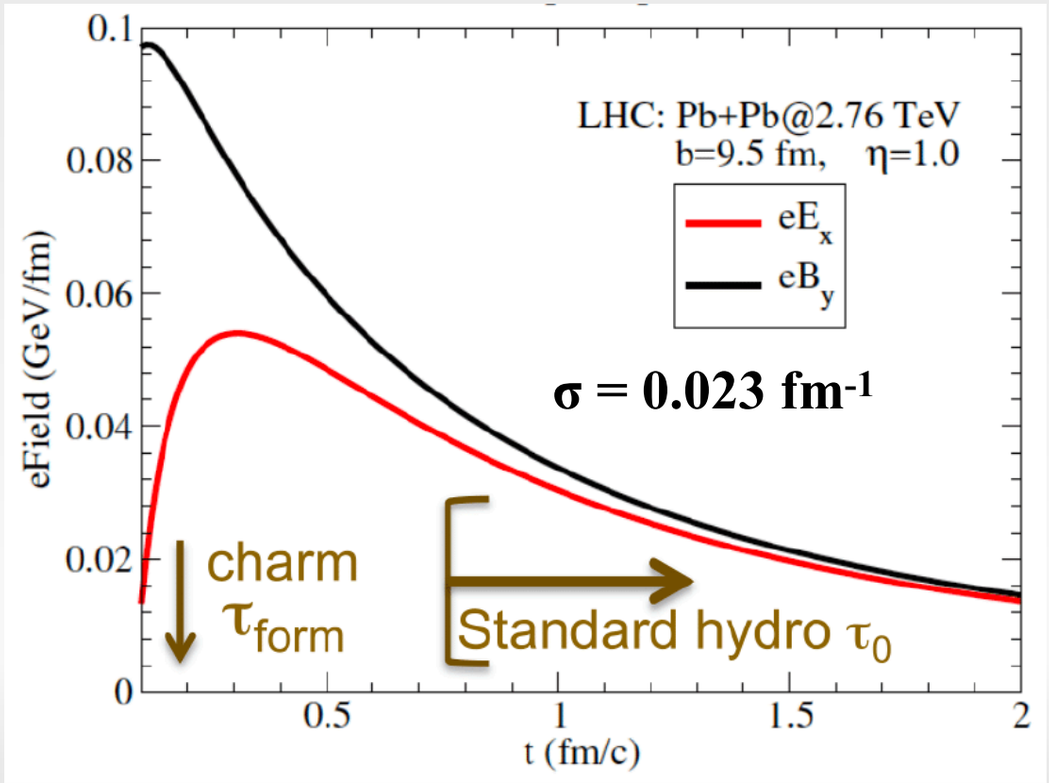


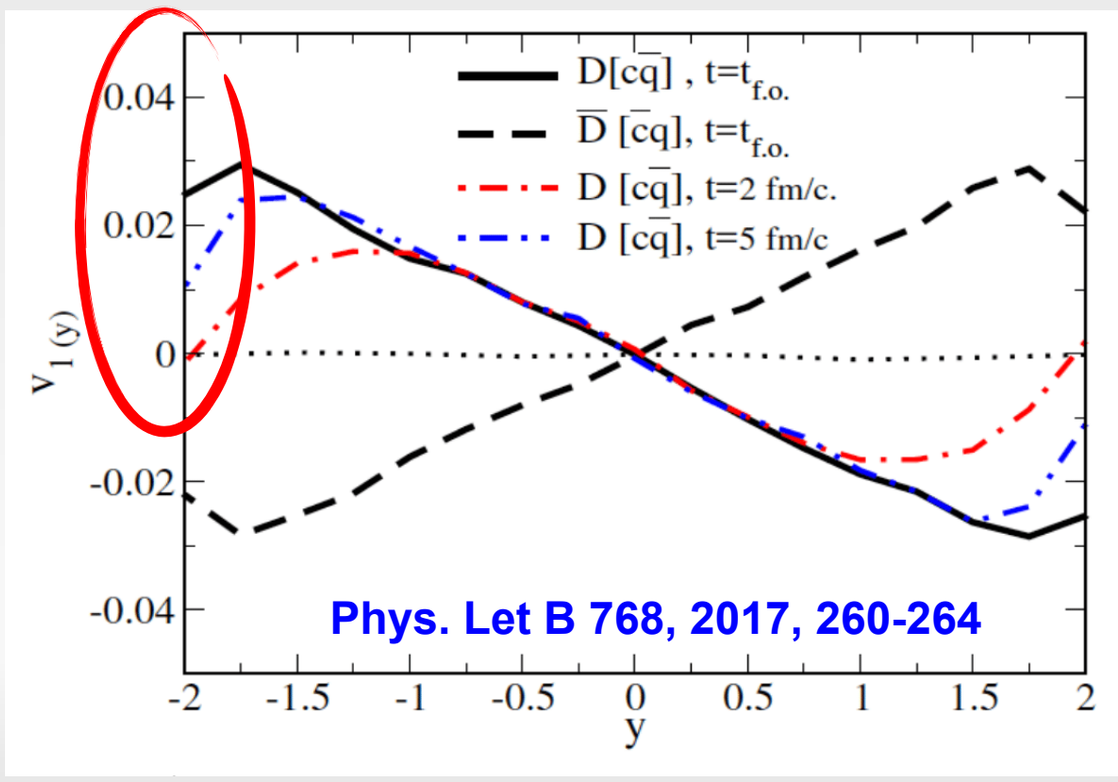
# Why open heavy-flavour?

⇨ **formation time** ~ 0.1 fm/c → comparable to the time scale **when B is maximum**

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

EM: $v_1^{avg} = 0,\ v_1^{diff} \neq 0;$



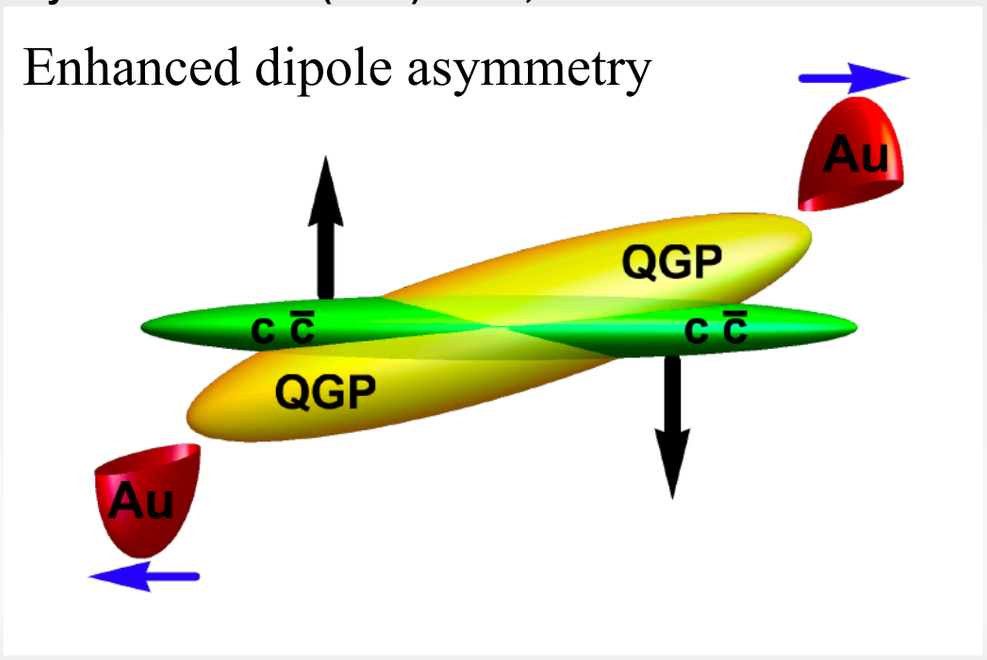



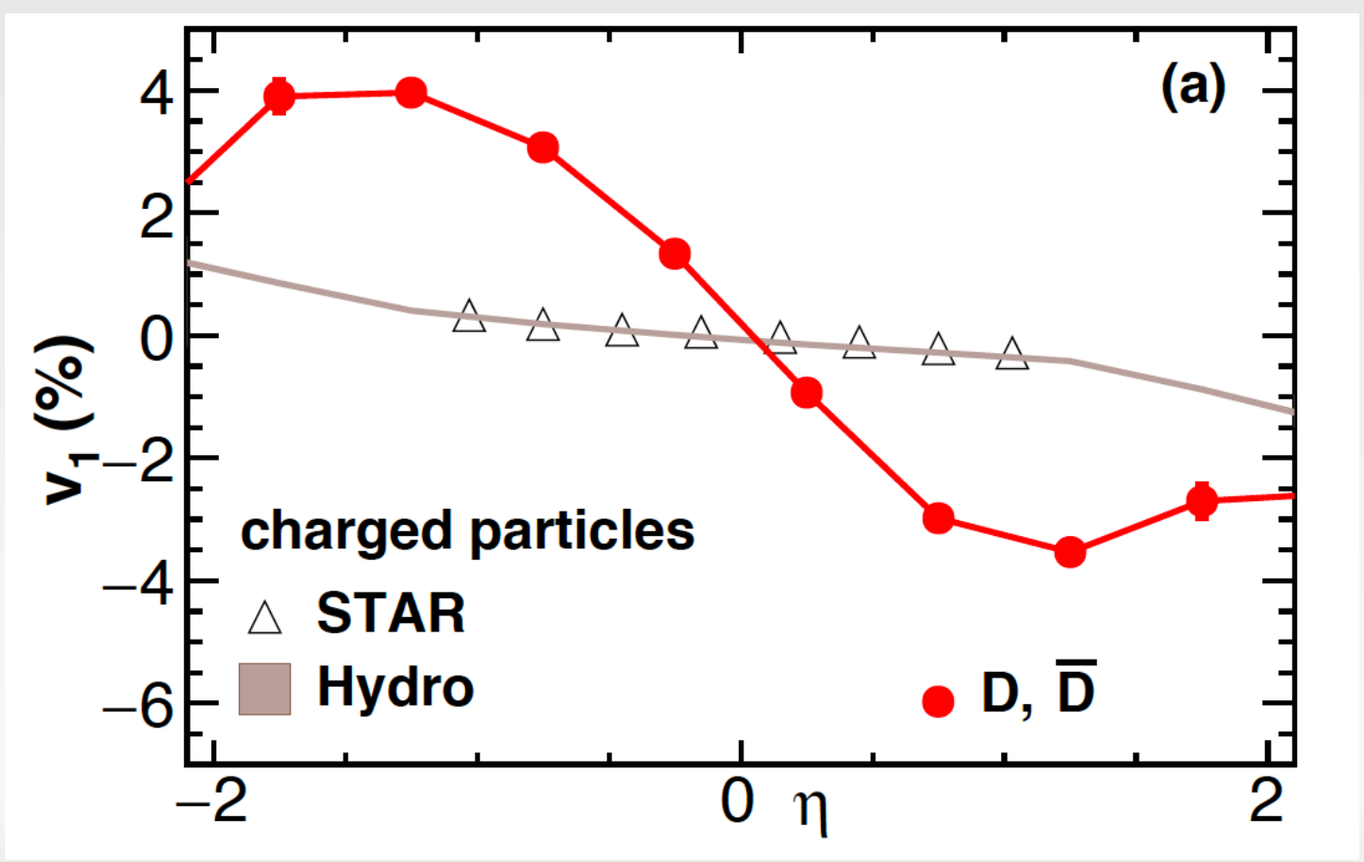
# EM field + tilting of the system

⇨ **Charm quark** is produced early, **shifted from the bulk**
→ larger directed flow of heavy-flavour mesons.

⇨ Heavy-flavour can be used as a probe of initial state longitudinal profile of matter distribution

**arXiv:1804.04893**
**Phys.Rev.Lett. 120 (2018) no.19, 192301**



# EM field + tilting of the system

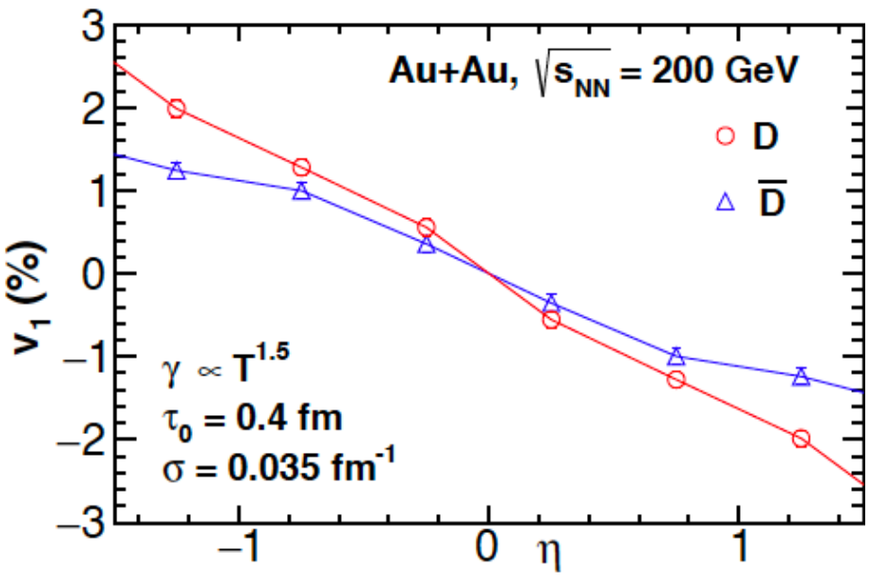
⇨ Electromagnetic field introduce a separation between charm and anti-charm

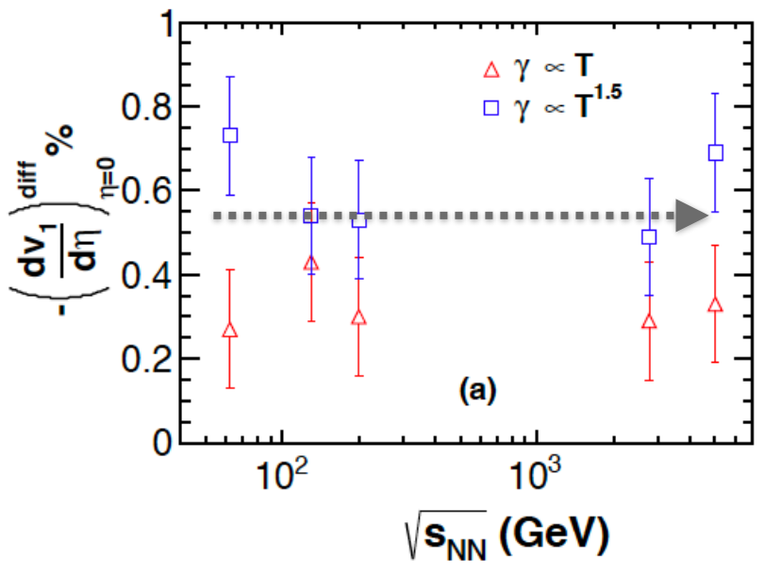
⇨ **Beam energy dependence:**

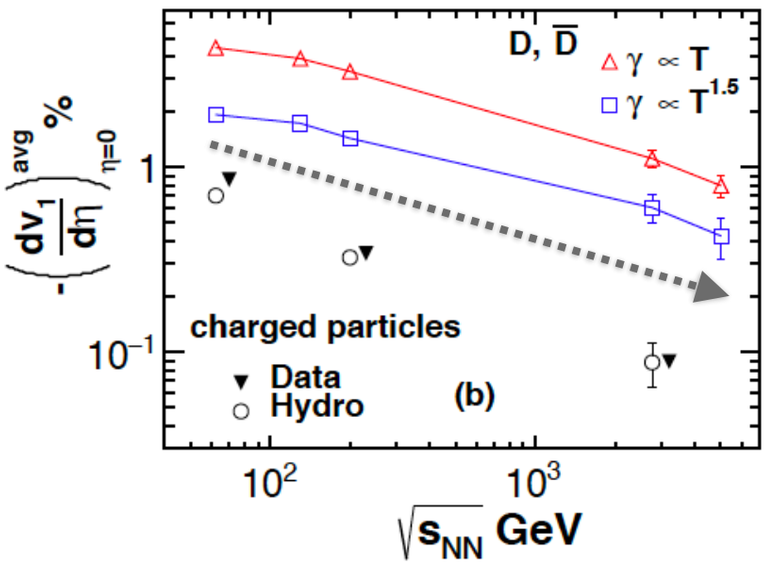
→ constant $v_1^{diff}$ and decreasing $v_1^{avg}$ due to decreasing tilting with increasing energy

**arXiv:1804.04893**
**Phys.Rev.Lett. 120 (2018) no.19, 192301**

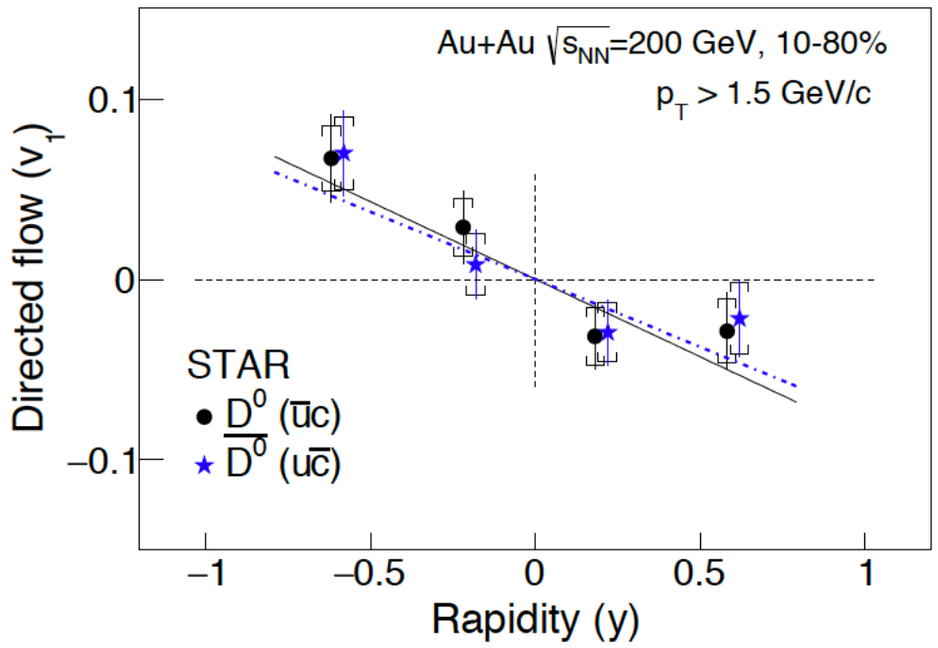
$$v_1^{avg} \neq 0,\ v_1^{diff} \neq 0$$



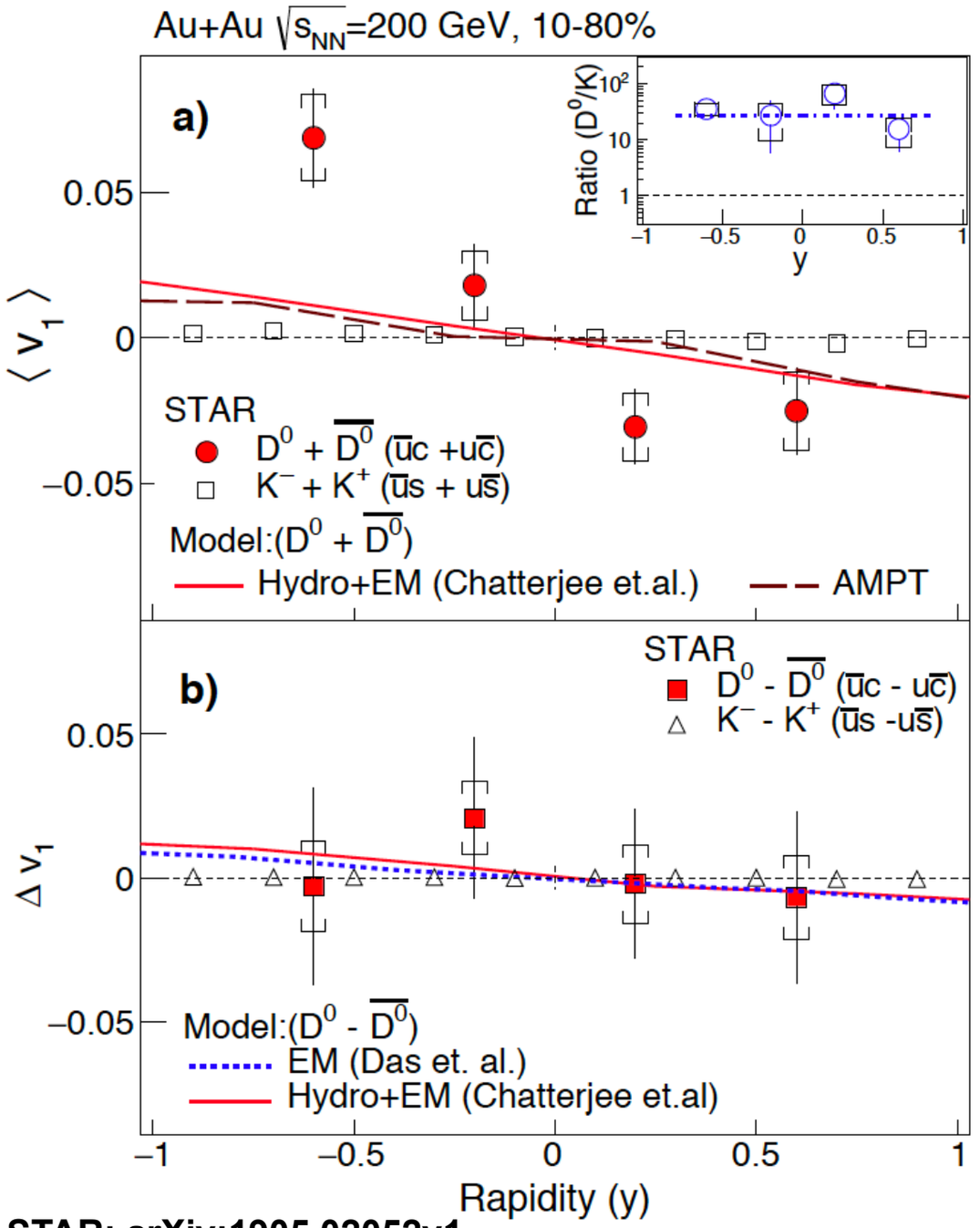
# STAR results in Au-Au




⇨ Observed negative slopes for both **D⁰** and **anti-D⁰ - Tilt imprinting**

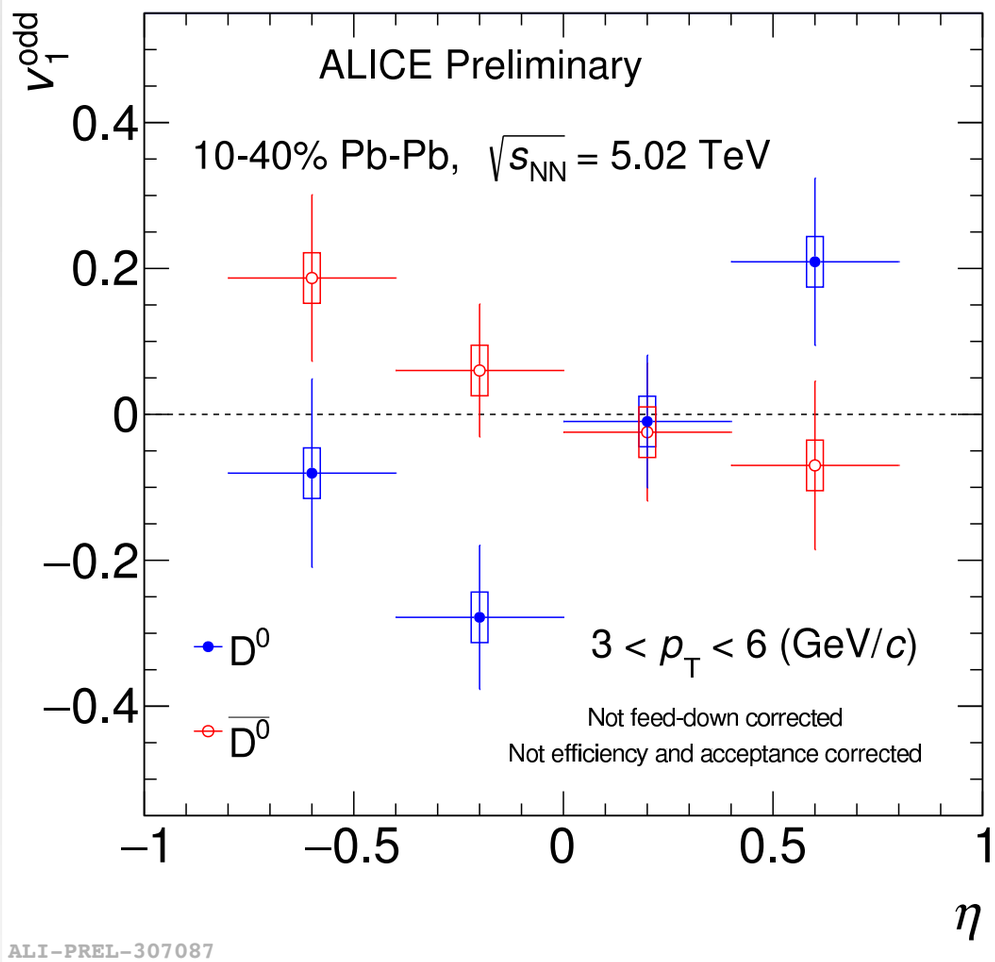
⇨ Charge-integrated $v_1$ for charmed hadrons is 25 times larger than kaons (**3.4σ significance**)

⇨ predicted signal of the charge-dependent $v_1$ of D meson is smaller than precision achieved




**STAR: arXiv:1905.02052v1**

# ALICE results




⇨ Despite the large uncertainties
→ hint of a positive slope for **D⁰**
and negative for **anti-D⁰**

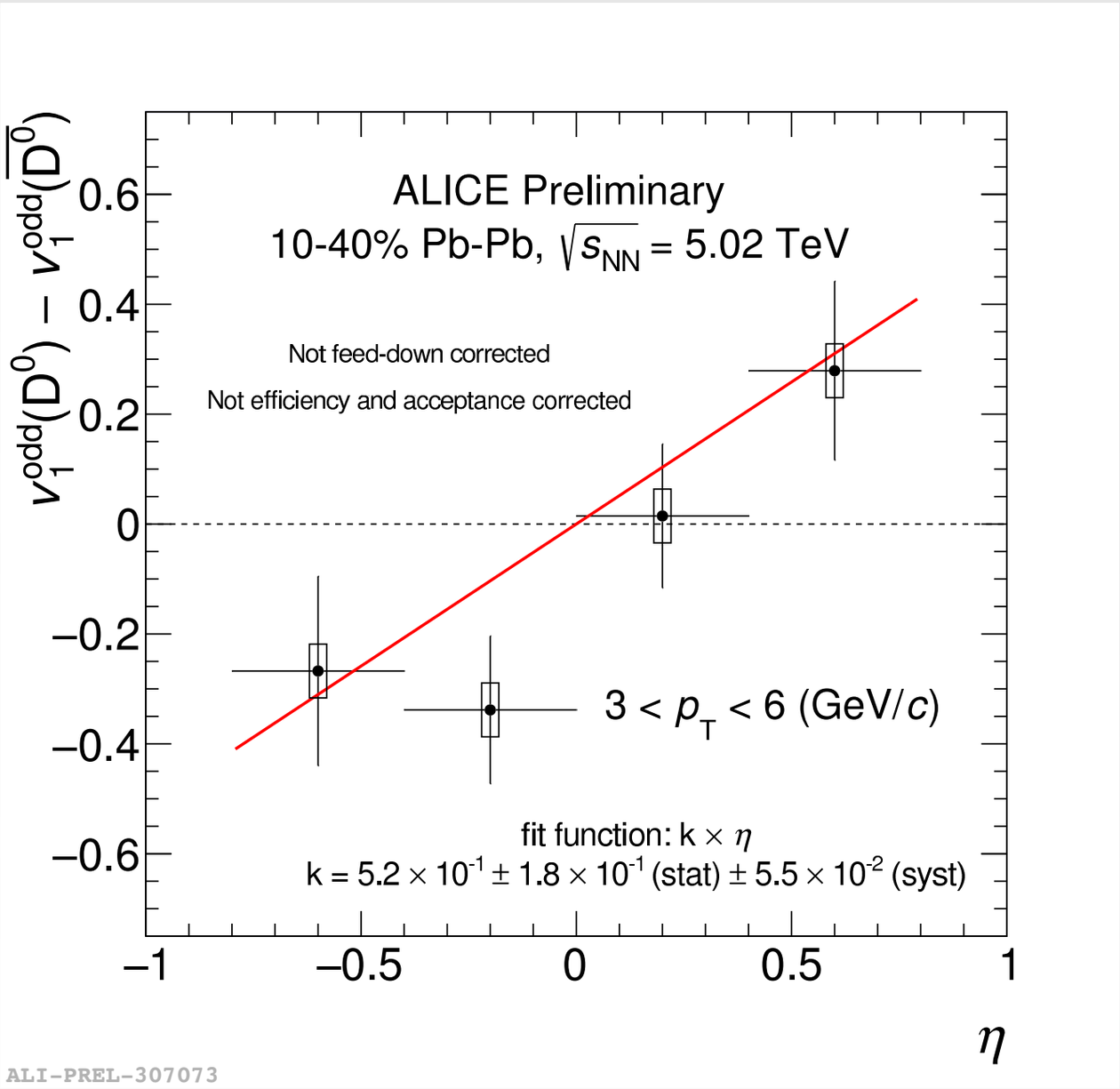
⇨ **Hint: signal factor 10 higher** then prediction: Phys. Let B 768, 2017, 260-264
→ long-lived magnetic field?
→ early thermalisation?

⇨ **Opposite trend** of **D⁰** and **anti-D⁰** w.r.t prediction: Phys. Let B 768, 2017, 260-264
→ dominance of Lorentz force?

⇨ Do we see the effect of the electro-magnetic field only?

# ALICE results

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



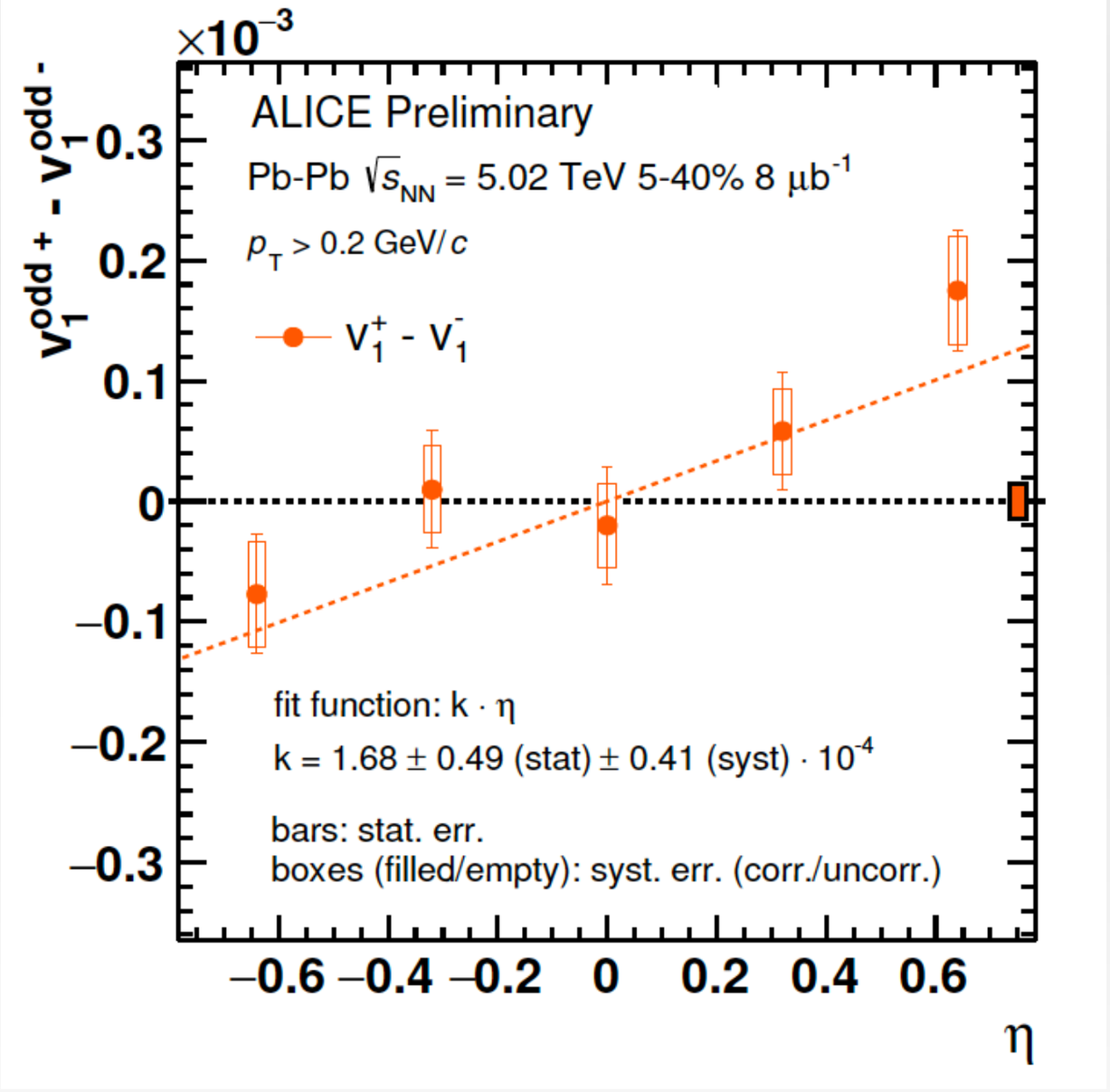

⇨ rapidity dependence of the charge difference $\Delta v_1$ is fitted using a linear function with slope k

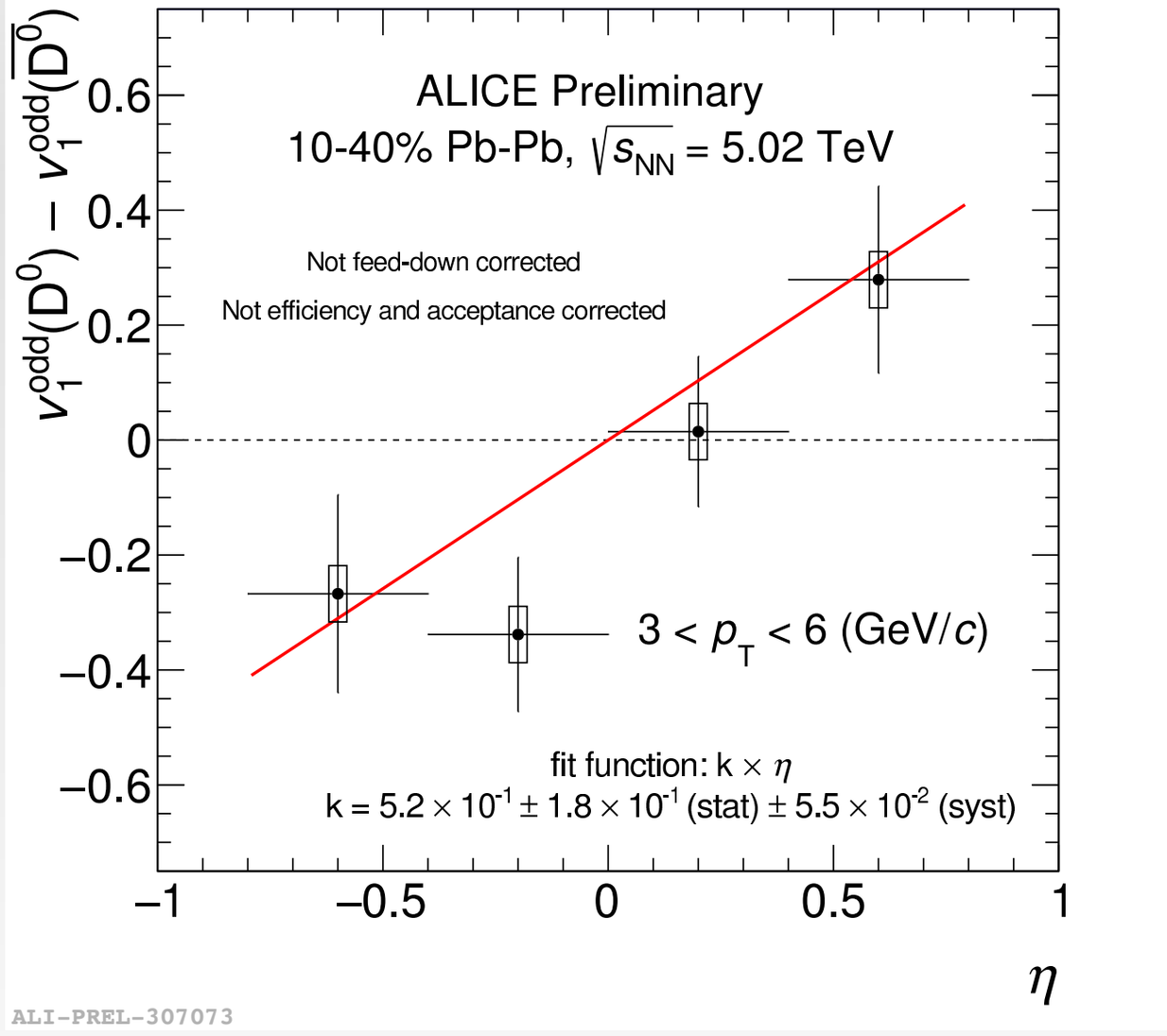
*k = 0.52 +/- 0.18 (stat) +/- 0.06 (syst)*

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

⇨ Hint of an **opposite slope** w.r.t theory calculations

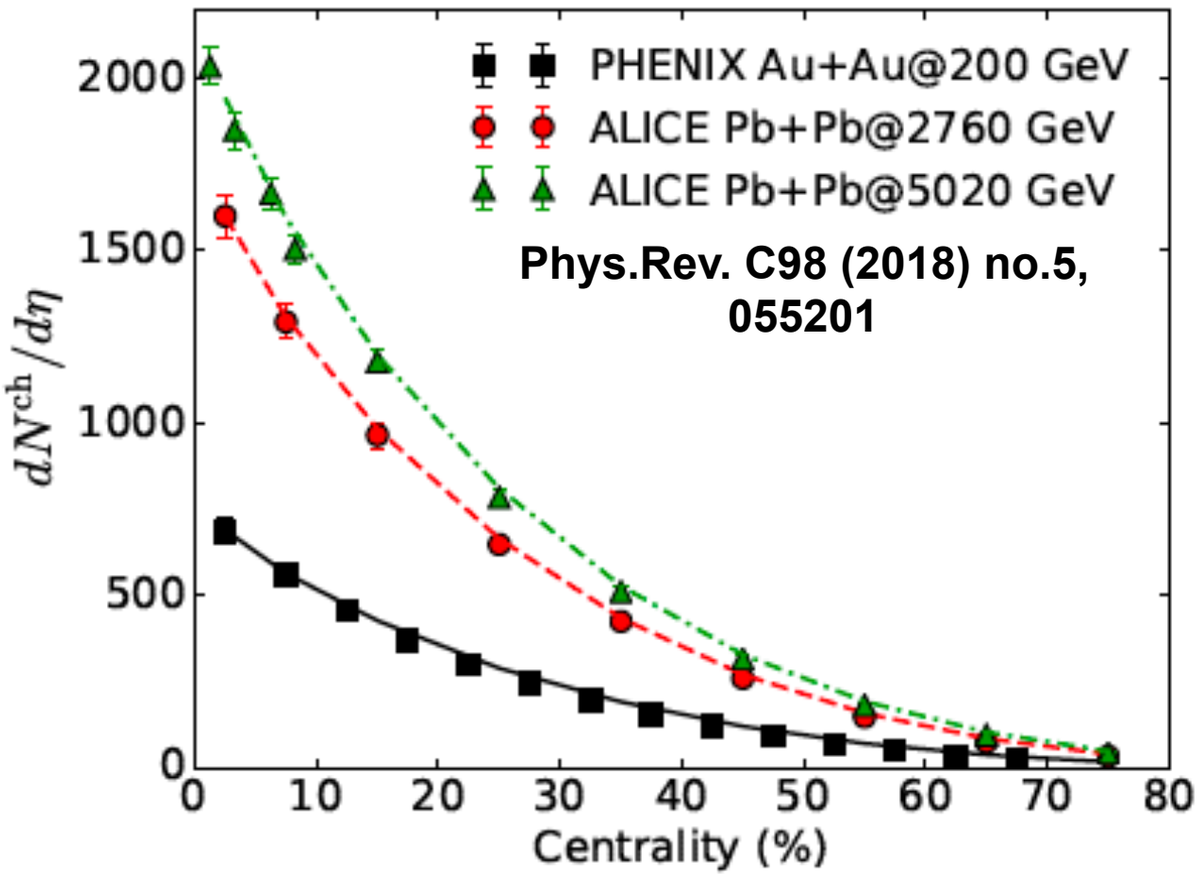
# Charged partivle vs heavy-flavour

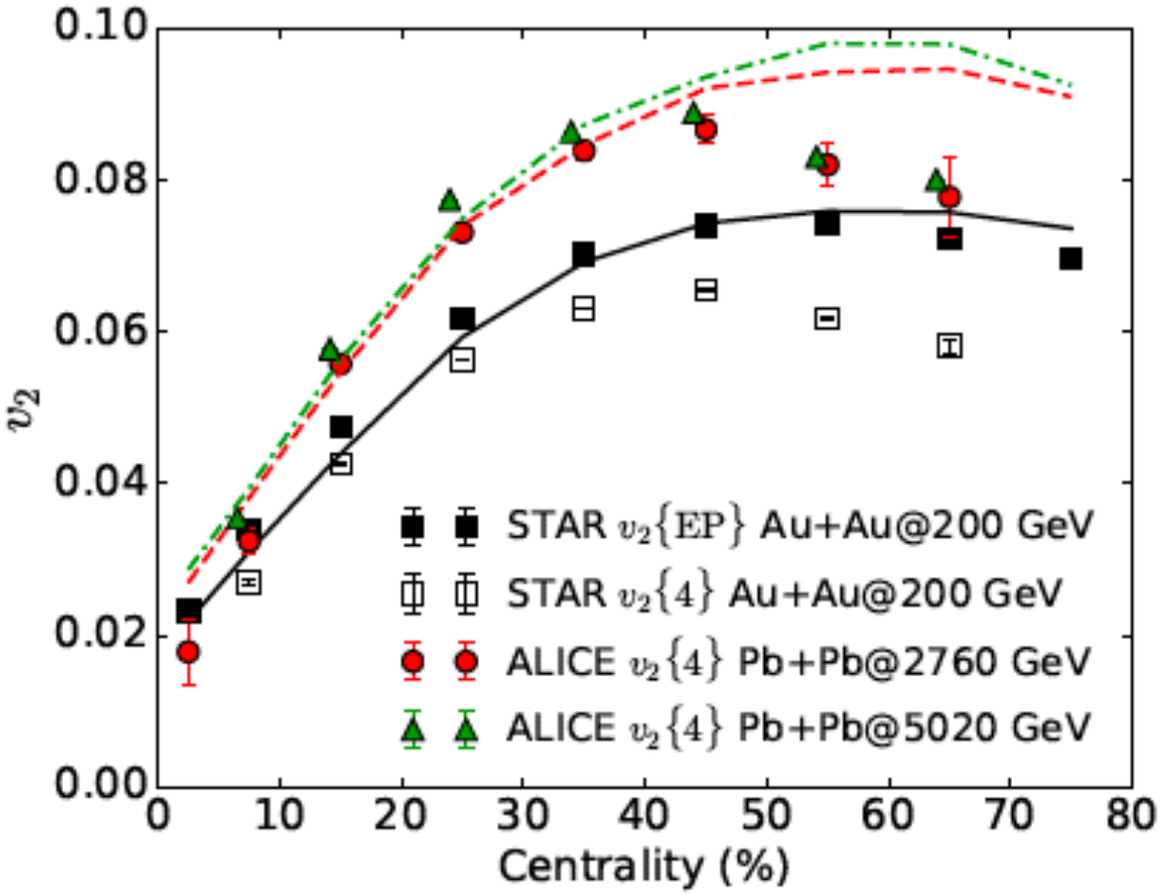



⇨ The **3 orders of magnitude difference** between charged-particle and heavy-flavour predicted by theory will be **experimentally accessible**

# New from theory!



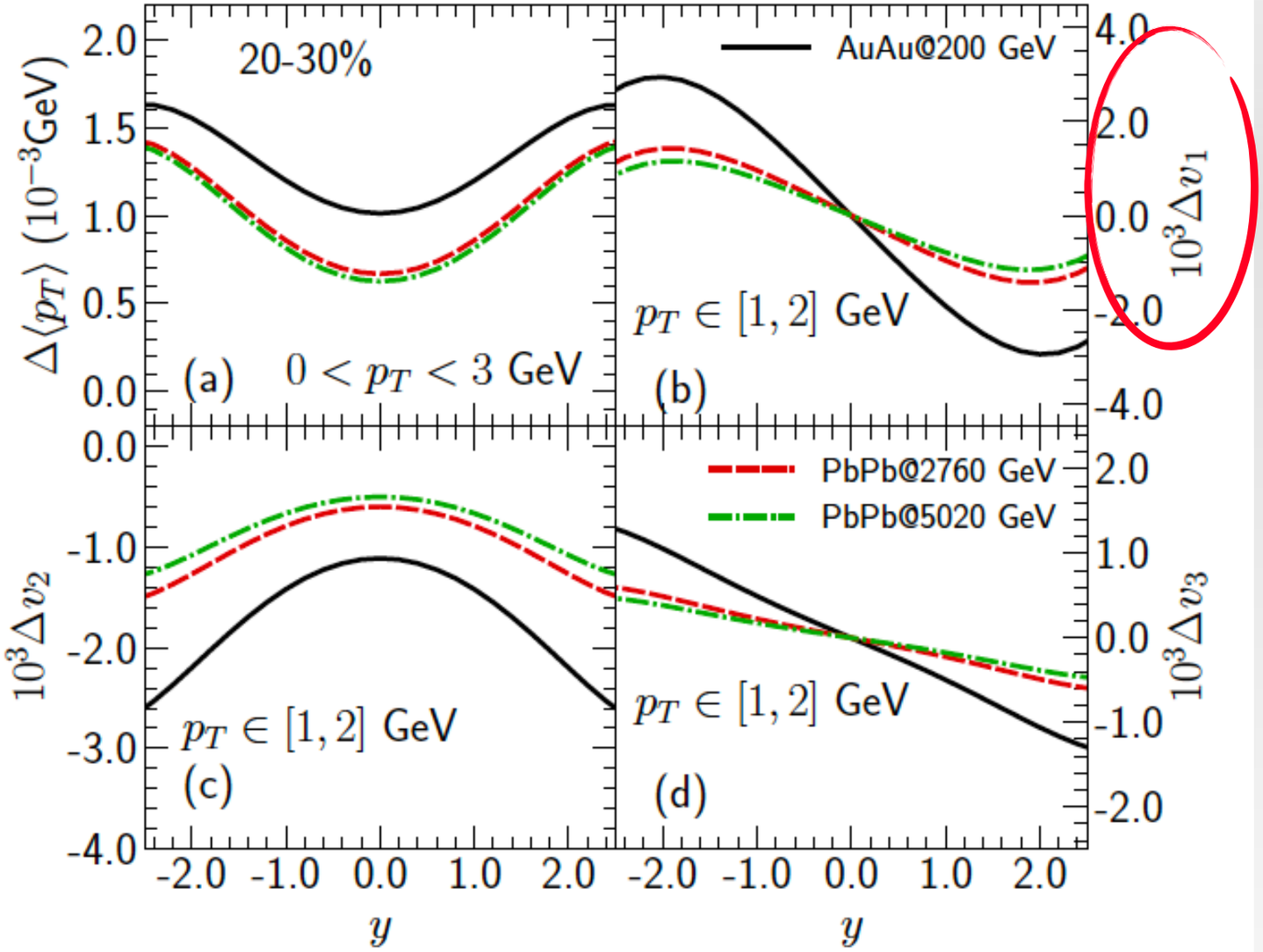




⇨ Simulate the evolution of the expanding QGP hydro-dynamically, using the iEBE-VISHNU framework, and add the magnetic and electric fields as well as the generated currents

⇨ Simulations well describe charged particle multiplicity and elliptic flow coefficients

# New from theory!

Phys.Rev. C98 (2018) no.5, 055201




- ⇨ **Similar order of magnitude w.r.t to measurements** (~$10^{-3}$)
- ⇨ Found a **charge-odd $v_3$** also odd in rapidity and that has a similar physical origin
- ⇨ The electric field produced by the net charge density of the plasma drives **rapidity-even charge-dependent $\langle p_T \rangle$ and elliptic flow $v_2$**

# Summary

1) **Charge-integrated** directed flow gives **unique insight into the initial tilt** of the produced matter. Probe of initial state longitudinal profile of matter distribution

⇨ **From RHIC to LHC a decrease of the $v_1$** as a function of rapidity
- suggest a **smaller tilt** of the system at higher energies

⇨ **charm is produced early**
- shifted from the bulk and a **larger $v_1$ w.r.t light quark is measured**

2) **Charge-dependent directed flow** used to **investigate the magnetic field** created in the initial stages of heavy-ion collisions

⇨ At **RHIC**: predicted **signal** of the charge-dependent $v_1$ of D meson is **smaller than precision achieved**

⇨ At **LHC**: Not yet high **significance** of the measurements **(2.7σ)**
- Hint for a **signal factor 10 higher and with an opposite trend** then prediction

# Backup

# Analysis strategy

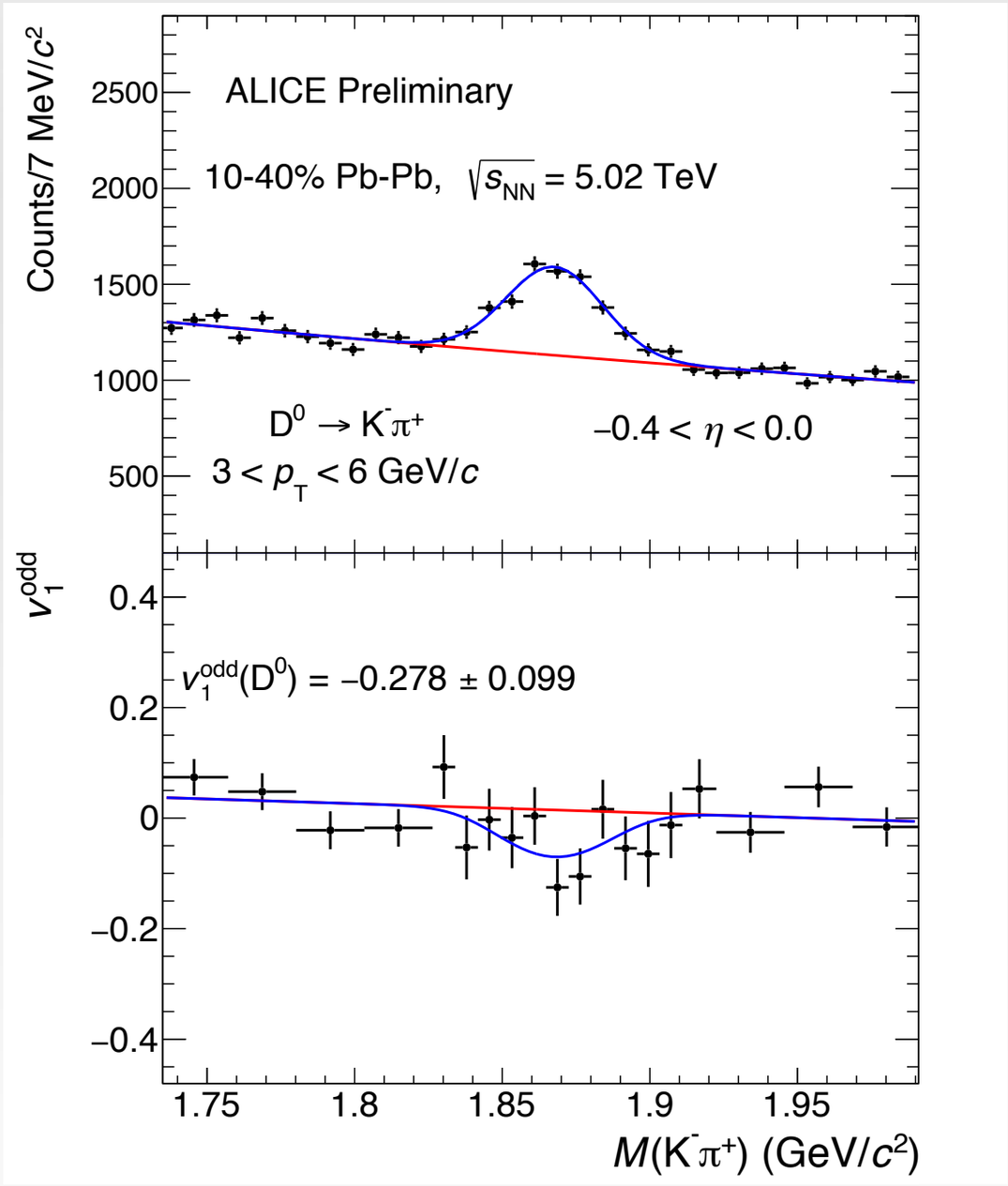
⇨ SP in which the Q vector is reconstructed from the spectator at beam rapidity

⇨ Analysis performed as a function of the invariant mass

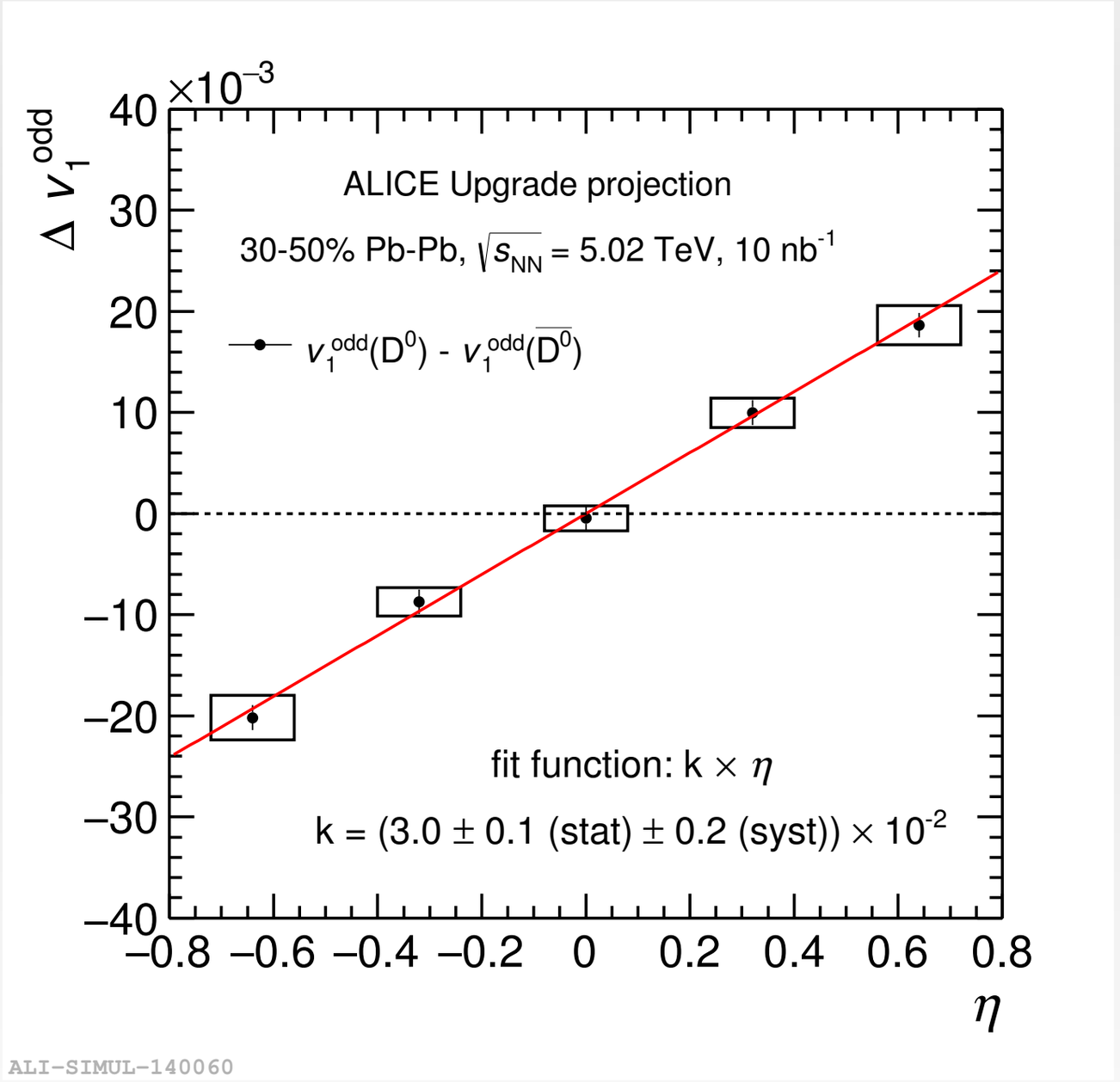
$$v_1(M) = \frac{S(M)}{S(M)+B(M)} * v_1^S + \frac{B(M)}{S(M)+B(M)} * v_B^1(M).$$

⇨ Assumption of directed flow for the background

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



# Projection for Run3/4




Extremely good significance is expected in Run3/4
Simulations done according to the values predicted by theory