# Measurement of rapidity-odd directed flow for $D^0$ and $\overline{D}^0$ mesons using the STAR detector at RHIC

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STAR

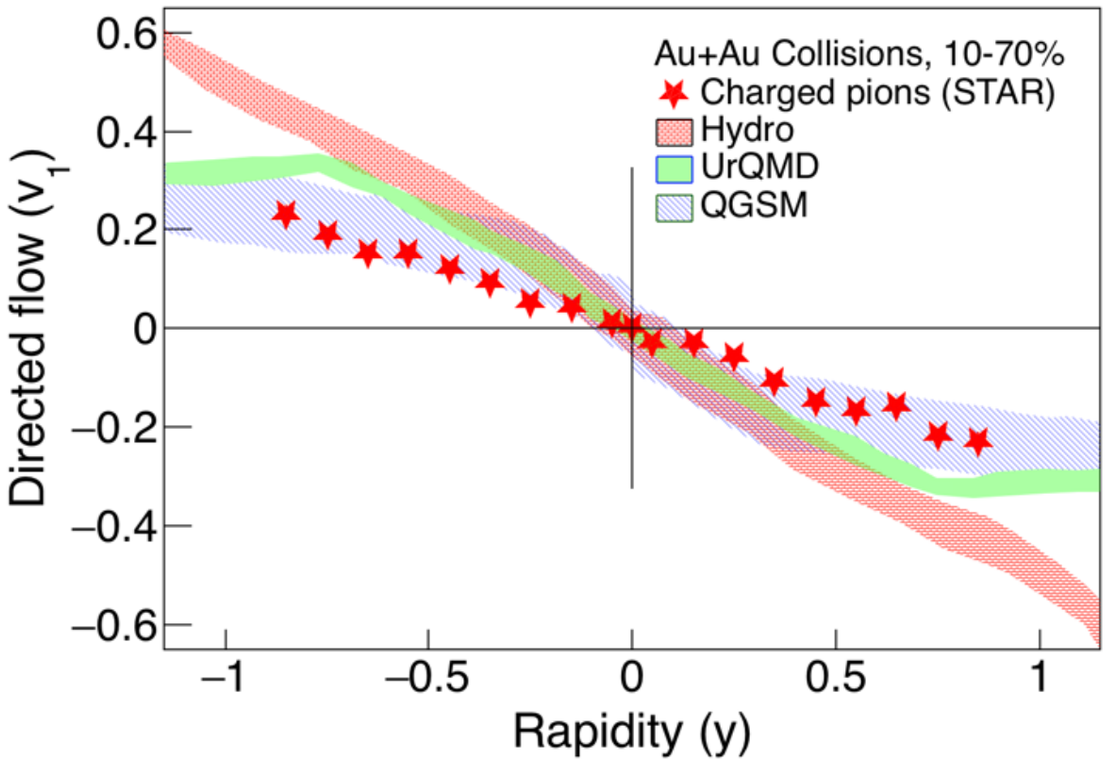
KENT STATE UNIVERSITY

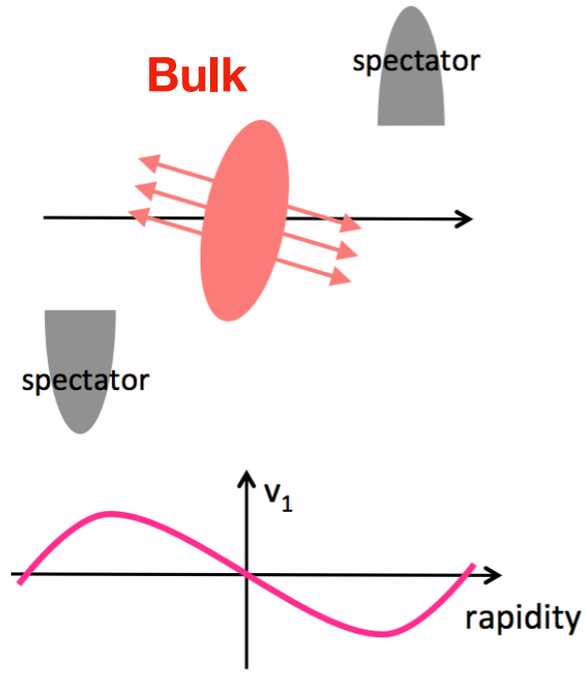
U.S. DEPARTMENT OF ENERGY | Office of Science

# Directed flow in heavy-ion collisions

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}[1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos 2(\phi - \Psi_R) + ...]$$

Directed flow $v_1 \sim \langle\cos(\varphi - \Psi_R)\rangle$



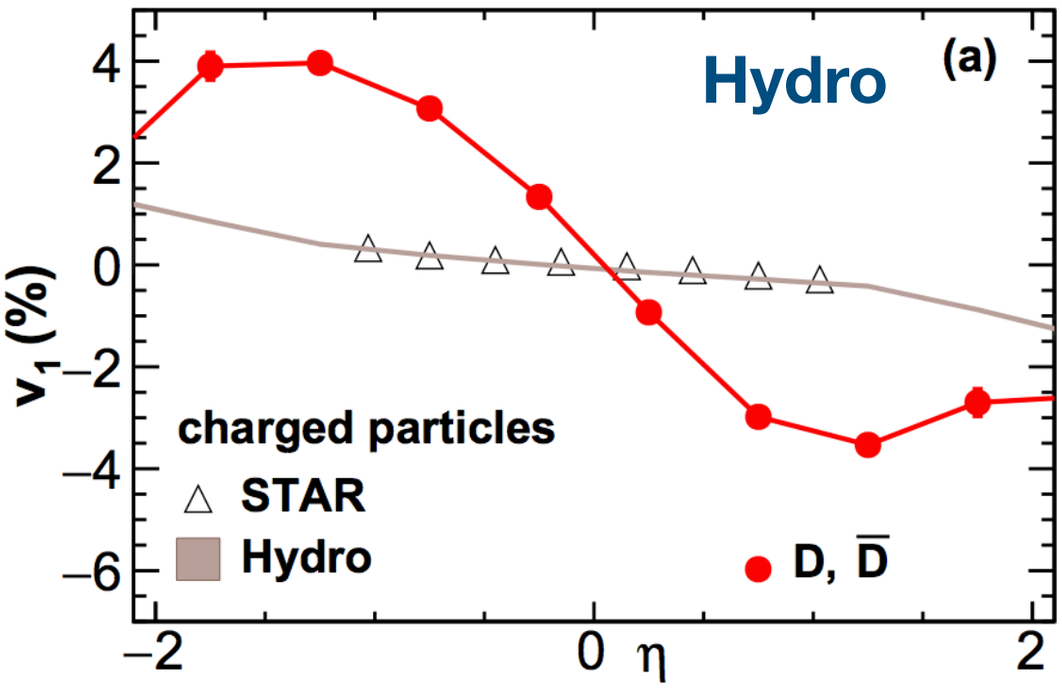



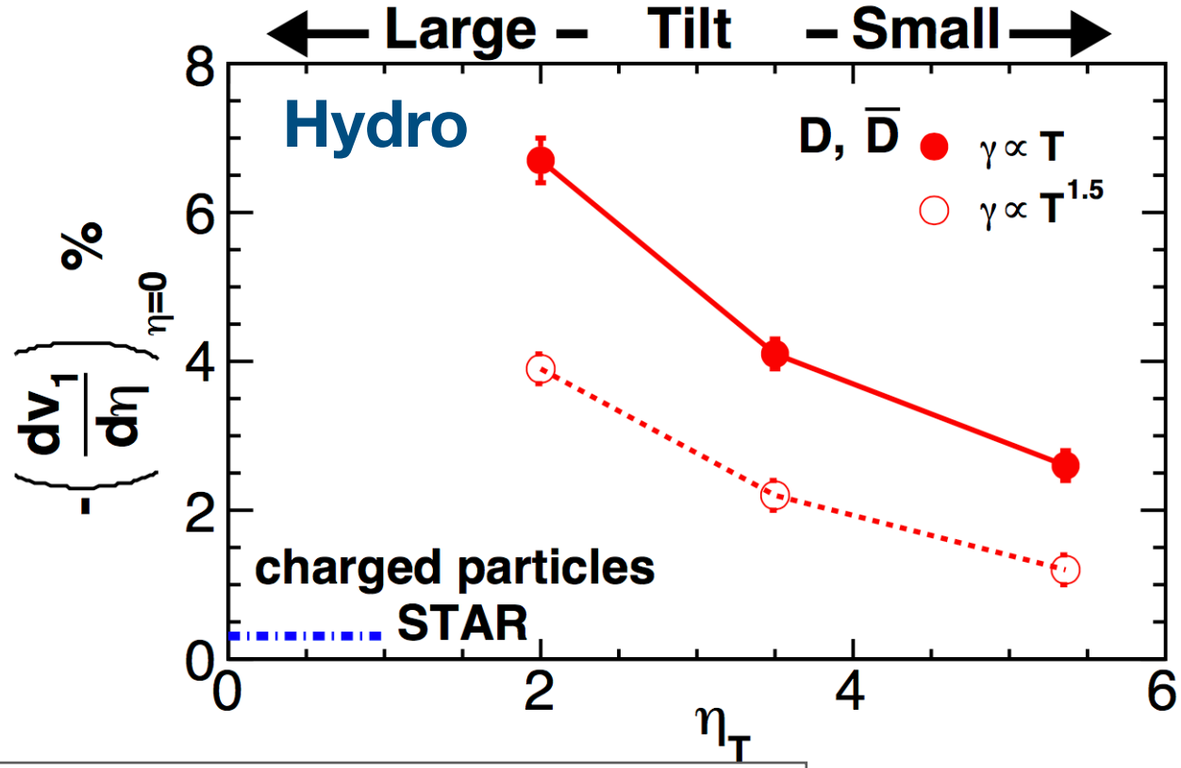

*L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 108, 202301 (2012)*
*Hydro: P. Bozek, I. Wyskiel, Phys Rev. C. 81, 054902 (2010)*
*UrQMD: H. Peterson et al, Phys Rev. C. 74, 064908 (2006)*
*QGSM: J. Beibel et al, Phys Rev. C. 76, 024912 (2007)*
*Transport: R. Snellings, et al, Phys Rev. Lett. 84, 2803 (2000)*

- Charged pions exhibit negative $v_1$ slope ("anti-flow") near mid-rapidity
- Models with hadronic physics or with baryon stopping and space momentum correlation can qualitatively explain "anti-flow" shape
- In hydro calculations with initially tilted bulk, the "anti-flow" shape is reproduced
- However, the sensitivity of the charged particle $v_1(y)$ to the tilt parameter is not very strong

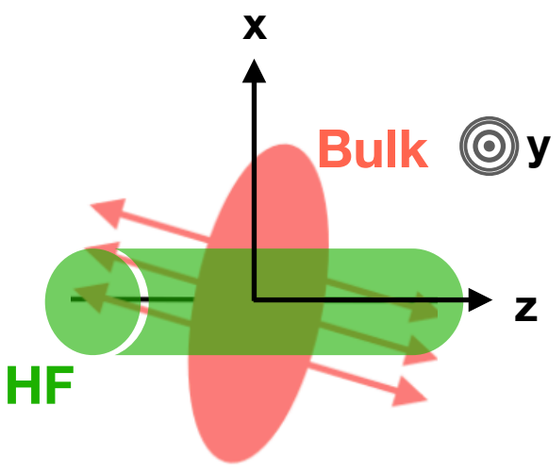
# Heavy quark $v_1$ from Hydro

*Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)*



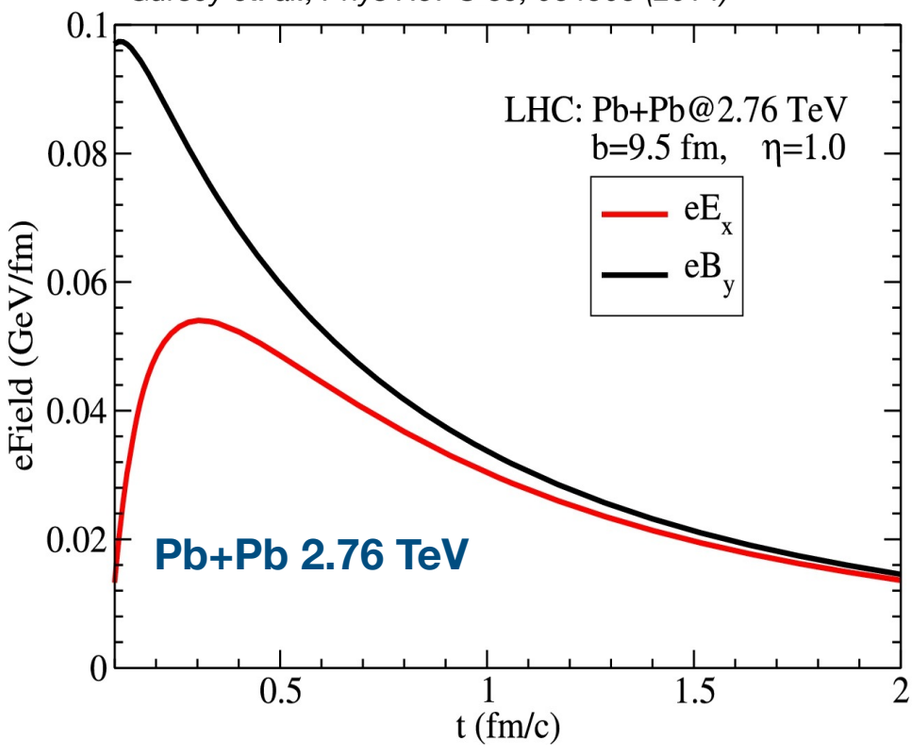

- Heavy quarks (HQ) are produced according to binary collision density profile, which is symmetric in rapidity
- At non-zero rapidity, the HQ production points are shifted in the transverse plane with respect to the bulk of the matter causing an enhanced dipole asymmetry in HQ flow pattern
- Additionally, drag by the titled bulk can induce large $v_1$ for charm quarks
- Heavy flavor (HF) $v_1$ has strong sensitivity towards the initial tilt of the source




$D^0$ $v_1$ can probe initial bulk matter distribution

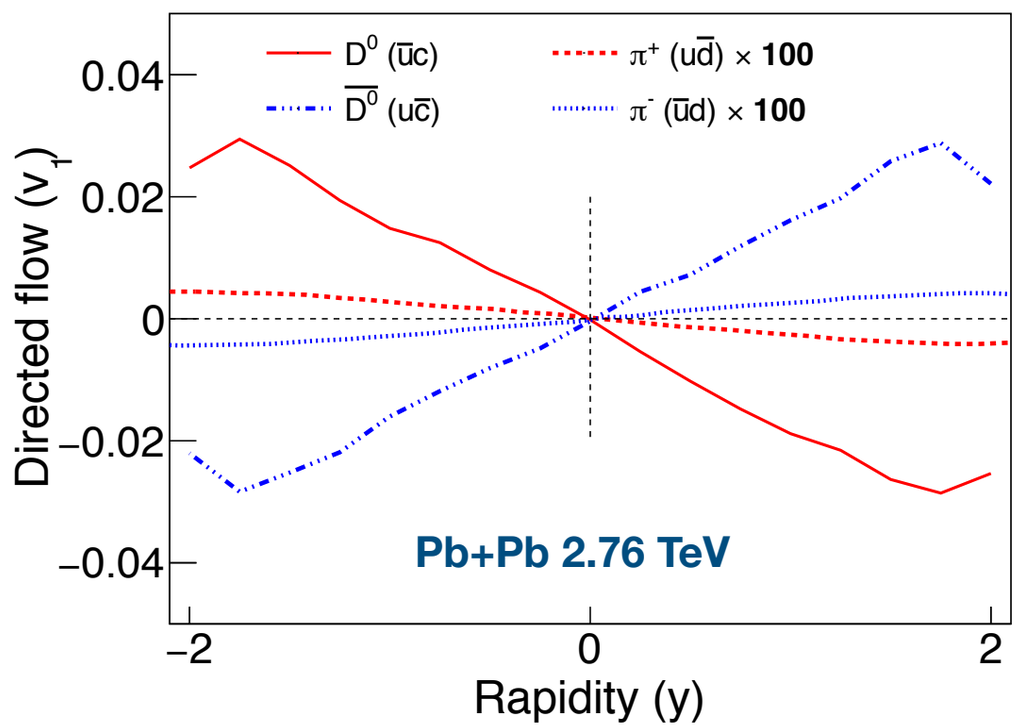
# Heavy quark $v_1$ from EM field

*Gursoy et. al., Phys Rev C 89, 054905 (2014)*

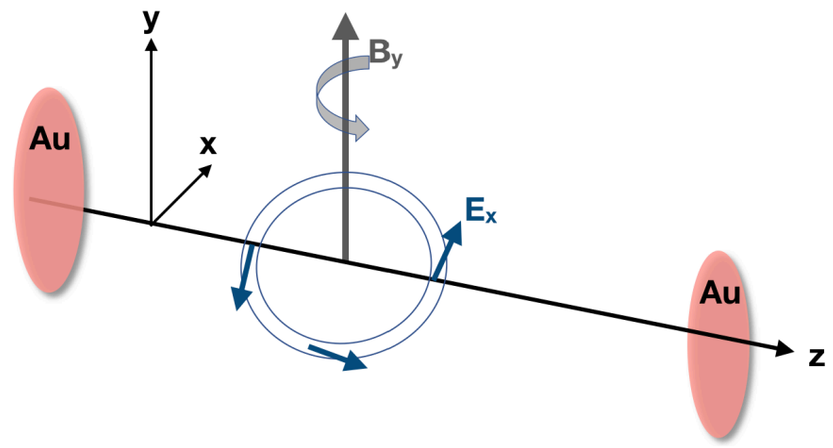



*Das et. al., Phys Lett B 768, 260 (2017)*

**EM**

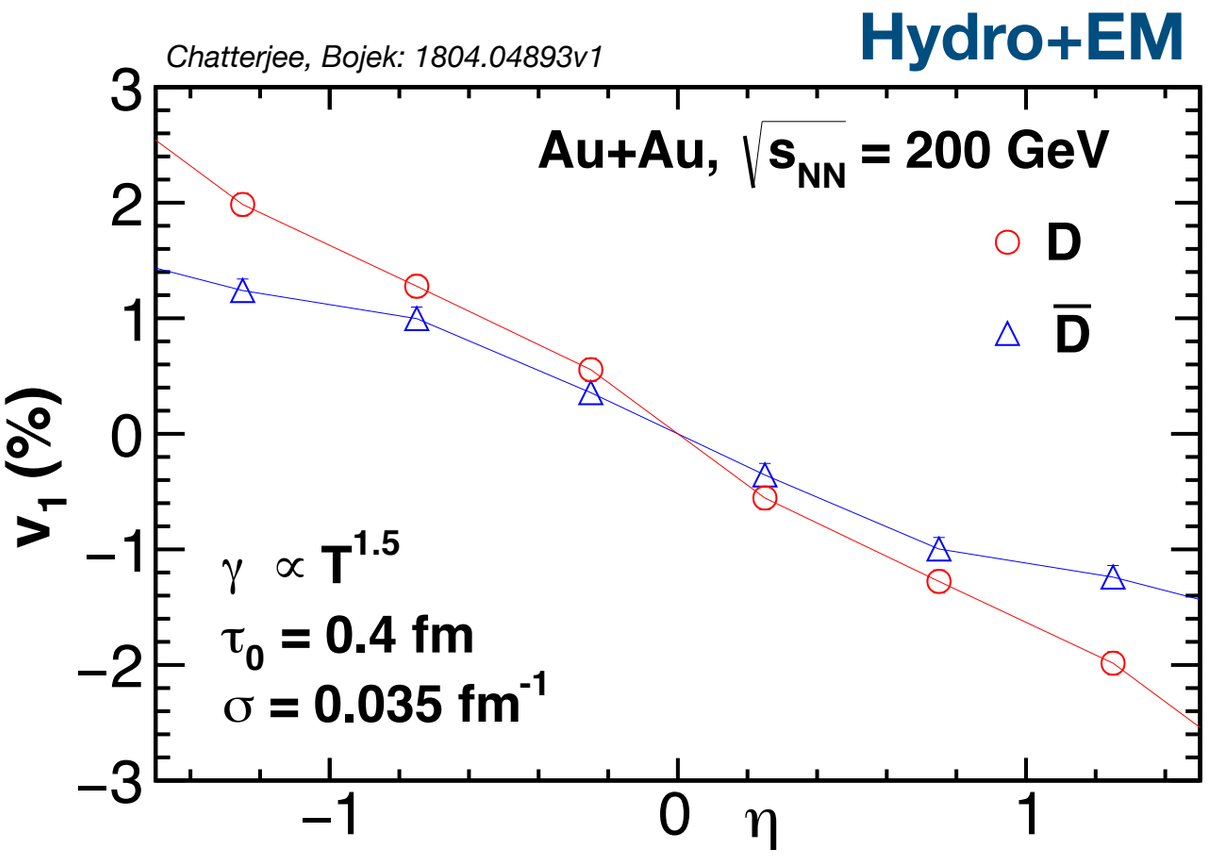


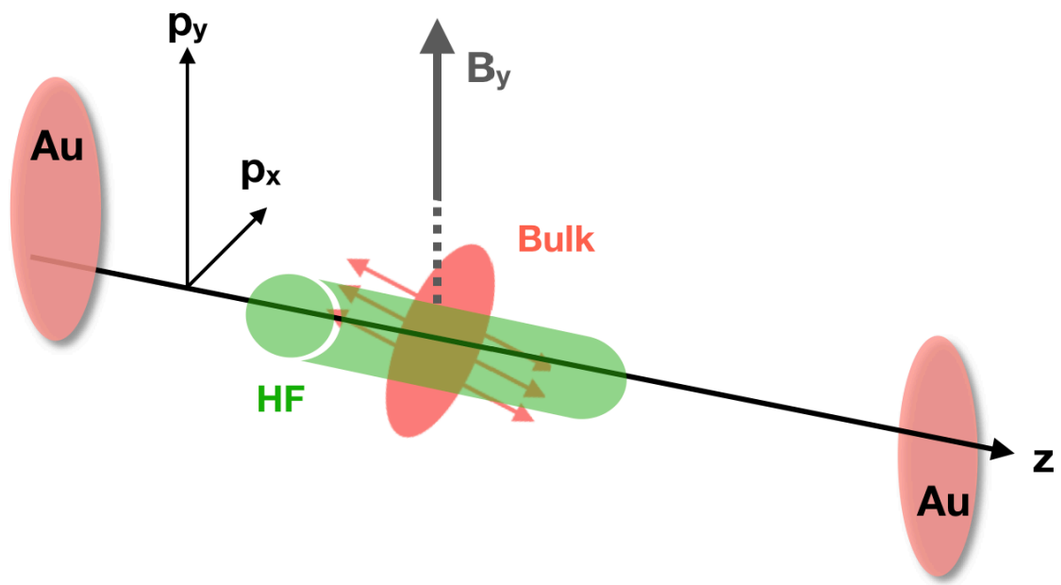

- Incoming charged particles can produce an enormously large EM field
- Due to early production of heavy quarks ($\tau_{CQ}$~0.1 fm/c), positive and negative charm quarks can get deflected by the initial EM force
- Model calculation demonstrates that such initial EM field can induce opposite $v_1$ for charm and anti-charm quarks
- The magnitude of induced $v_1$ of charm hadrons can be order of magnitude larger than that of the light flavor hadrons




$D^0$ and $\bar{D}^0$ $v_1$ can offer insight into the early time EM fields

# Heavy quark $v_1$ from Hydro+EM field



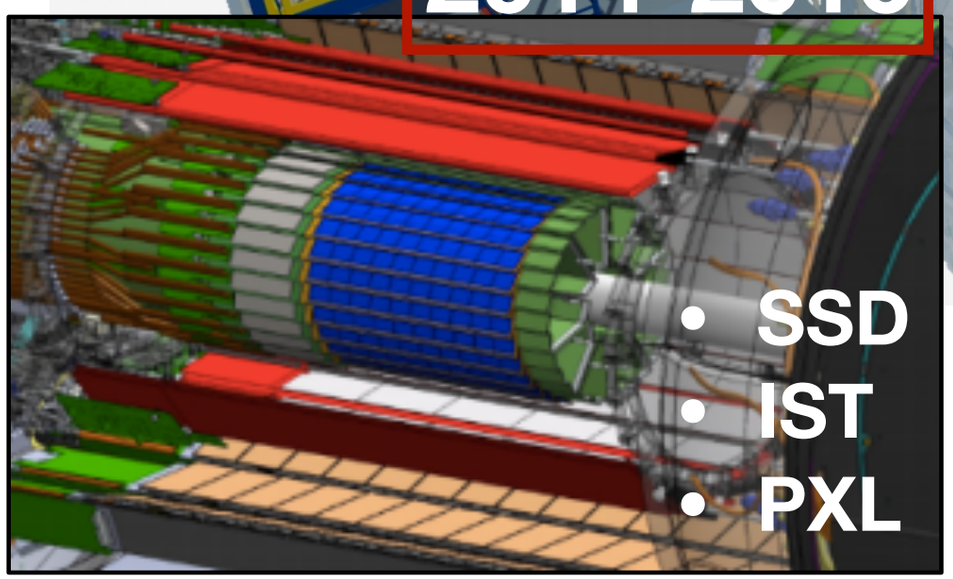

- Recent hydro model combined with initial EM field predicts a $v_1$ split between D and $\overline{D}$ mesons
- Predicted $v_1$ of D meson is greater than that of $\overline{D}$ meson
- Predicted difference in $v_1$ is about 10 times smaller than the average $v_1$

# STAR detector

TPC

TOF

HFT
2014-2016

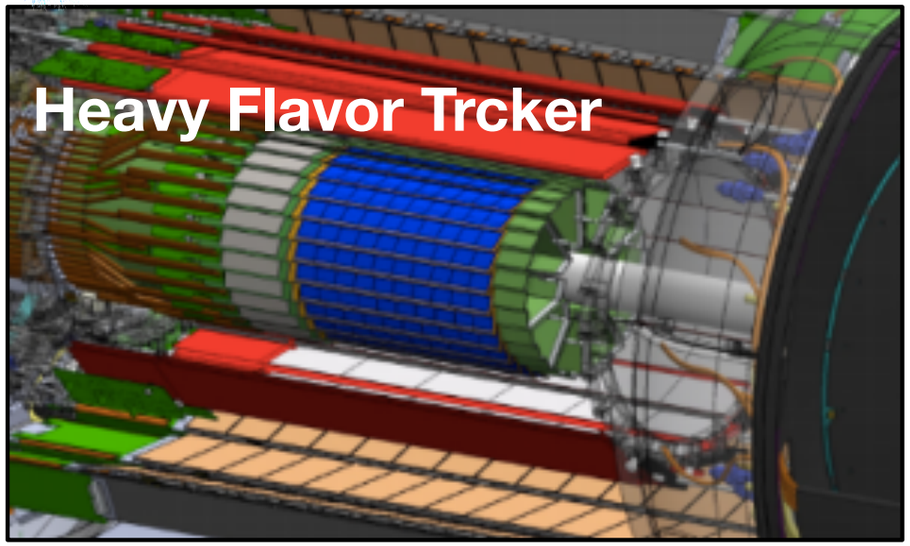


- SSD
- IST
- PXL

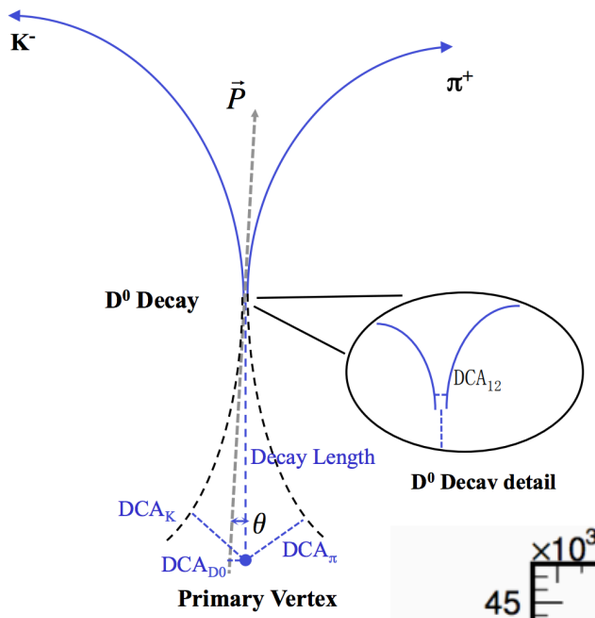
ZDC-SMD

- Full azimuthal coverage (0,2π)
- Excellent PID capabilities

# D⁰ reconstruction with HFT

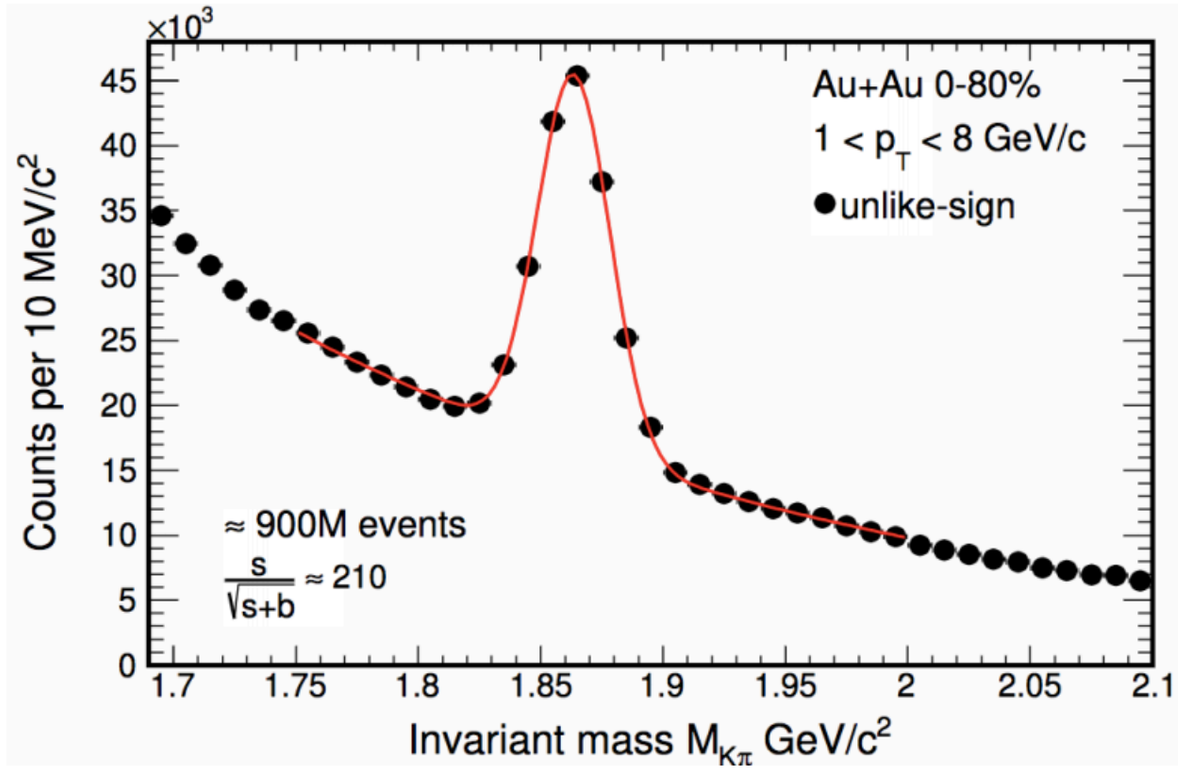


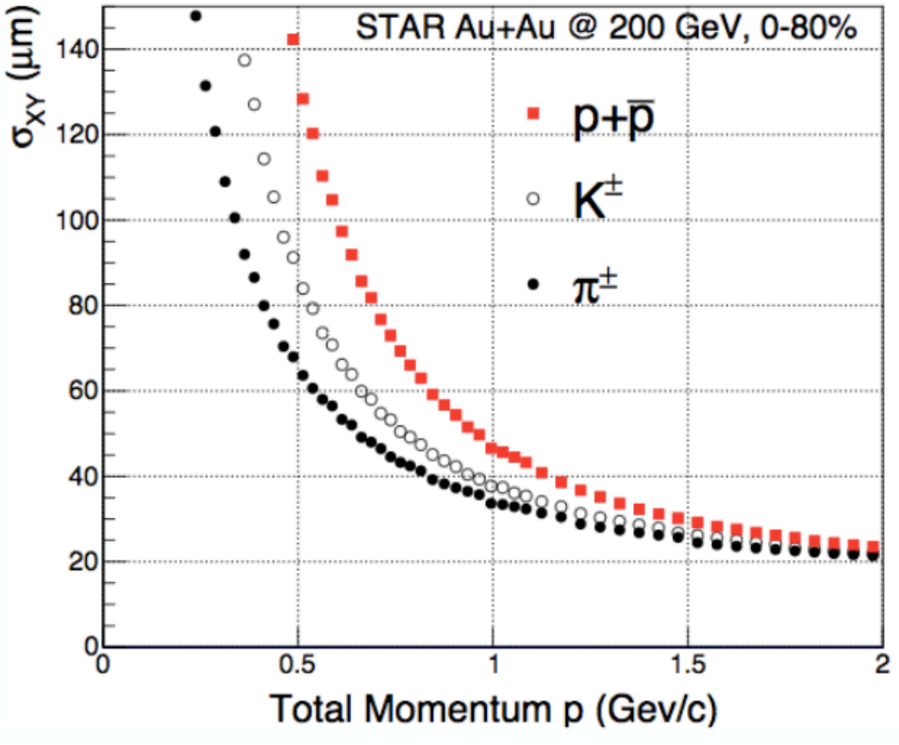

- Pseudorapidity (|η|<1)
- Azimuthal coverage (0,2π)
- Excellent track pointing resolution
- Allows topological reconstruction for heavy flavor particles




## D⁰ meson

Quark content: $D^0$ ($\bar{u}c$), $\overline{D}^0$ ($u\bar{c}$),
Decay channel: $D^0 \rightarrow K^-\pi^+$
$\overline{D}^0 \rightarrow K^+\pi^-$
Decay length (cτ): 120 μm
Mass: 1864.84 +/- 0.18 MeV/c²
Branching ratio: 3.89%

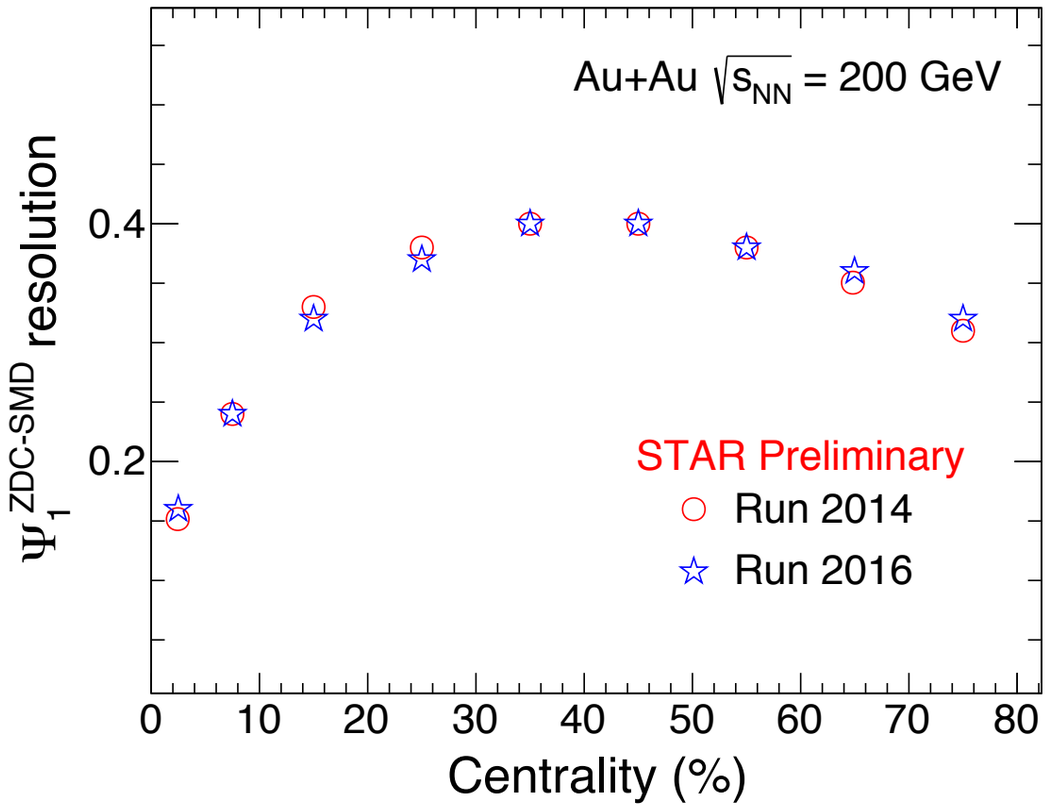



- HFT data from 2014 and 2016 runs
- Total ~ 2 billion good events
- Significance improved by a factor of 15, compared to reconstruction without HFT

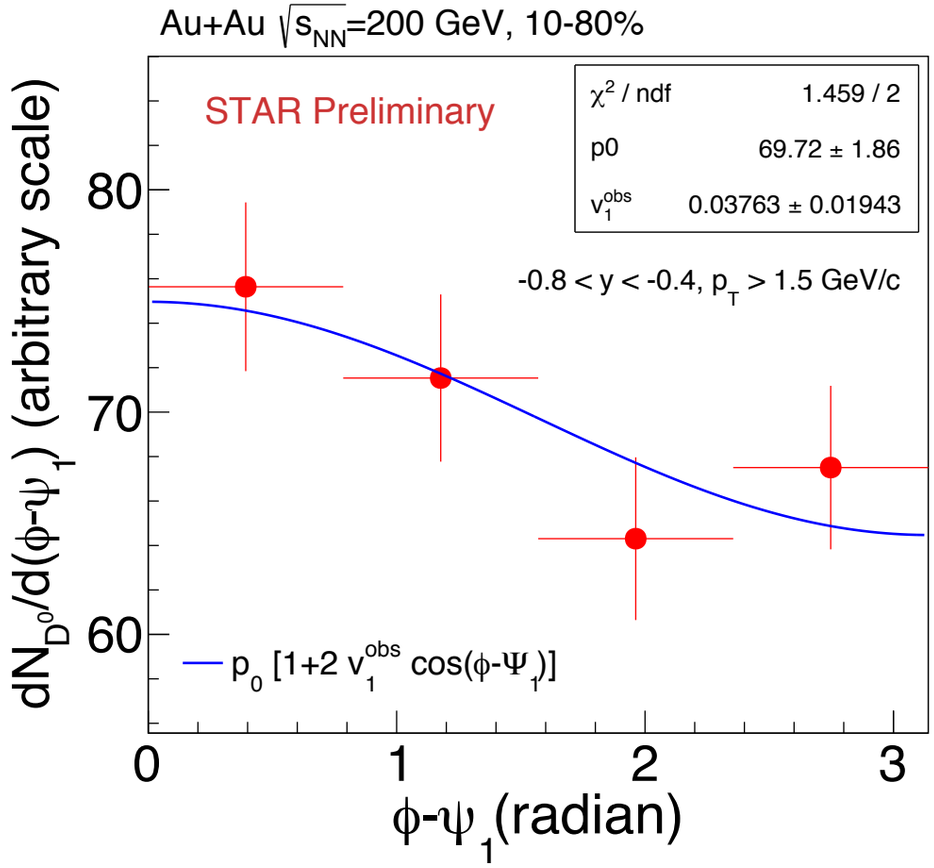
# $D^0$ $v_1$ from event plane method

## ZDC-SMD Event plane resolution:




- The first-order event plane measured using ZDC-SMD (|η|>6.4)
- $v_1$ signal is significant at forward rapidity
  Better $\psi_1$ resolution than mid-rapidity detectors
- Large η-gap significantly reduces non-flow contribution

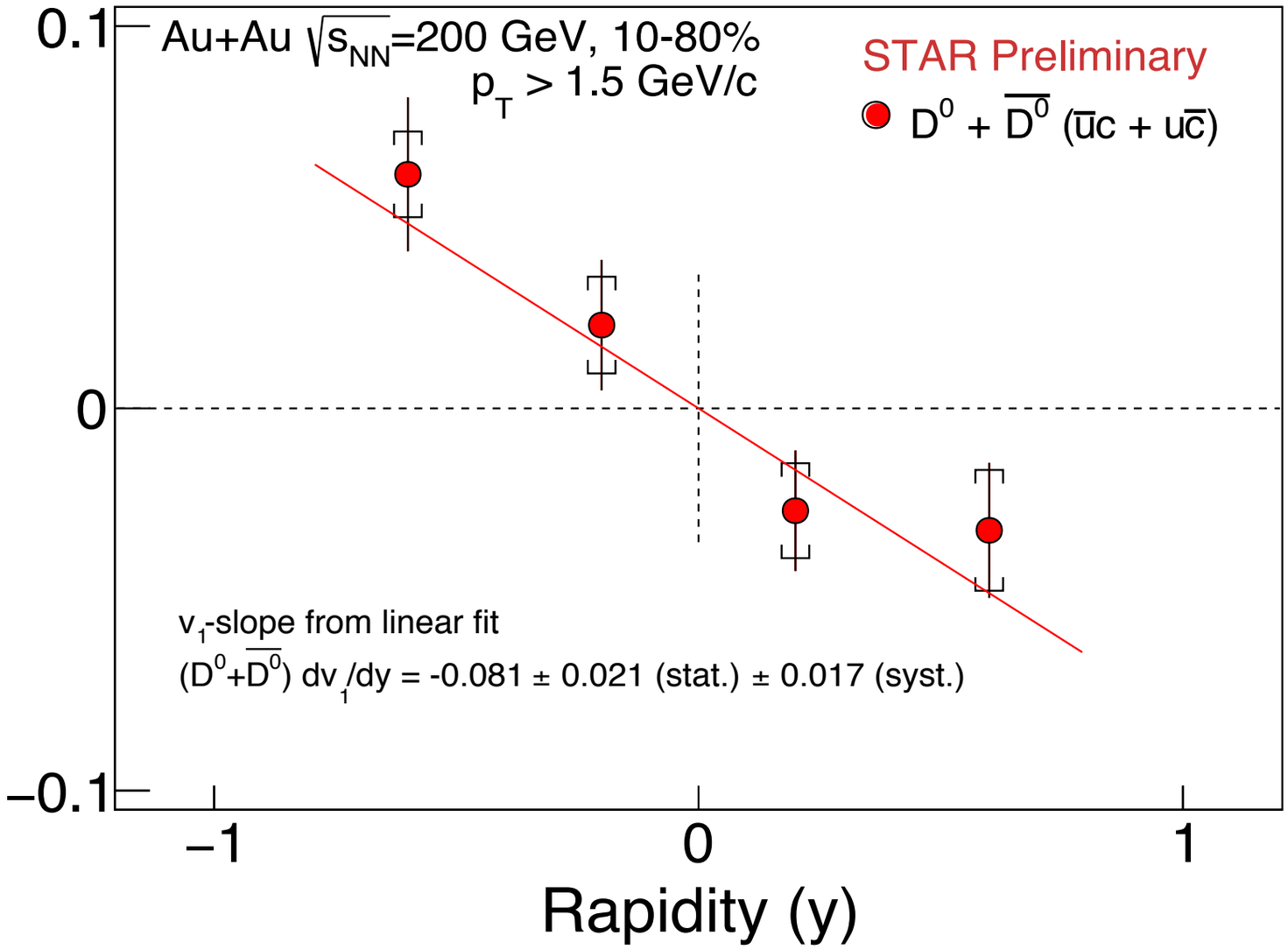
## $D^0$ $v_1$:




$$v_1 \sim \frac{\langle \cos(\phi - \psi_1) \rangle}{\psi_1 \text{ res.}} \sim \frac{v_1^{\text{obs}}}{\psi_1 \text{ res.}}$$

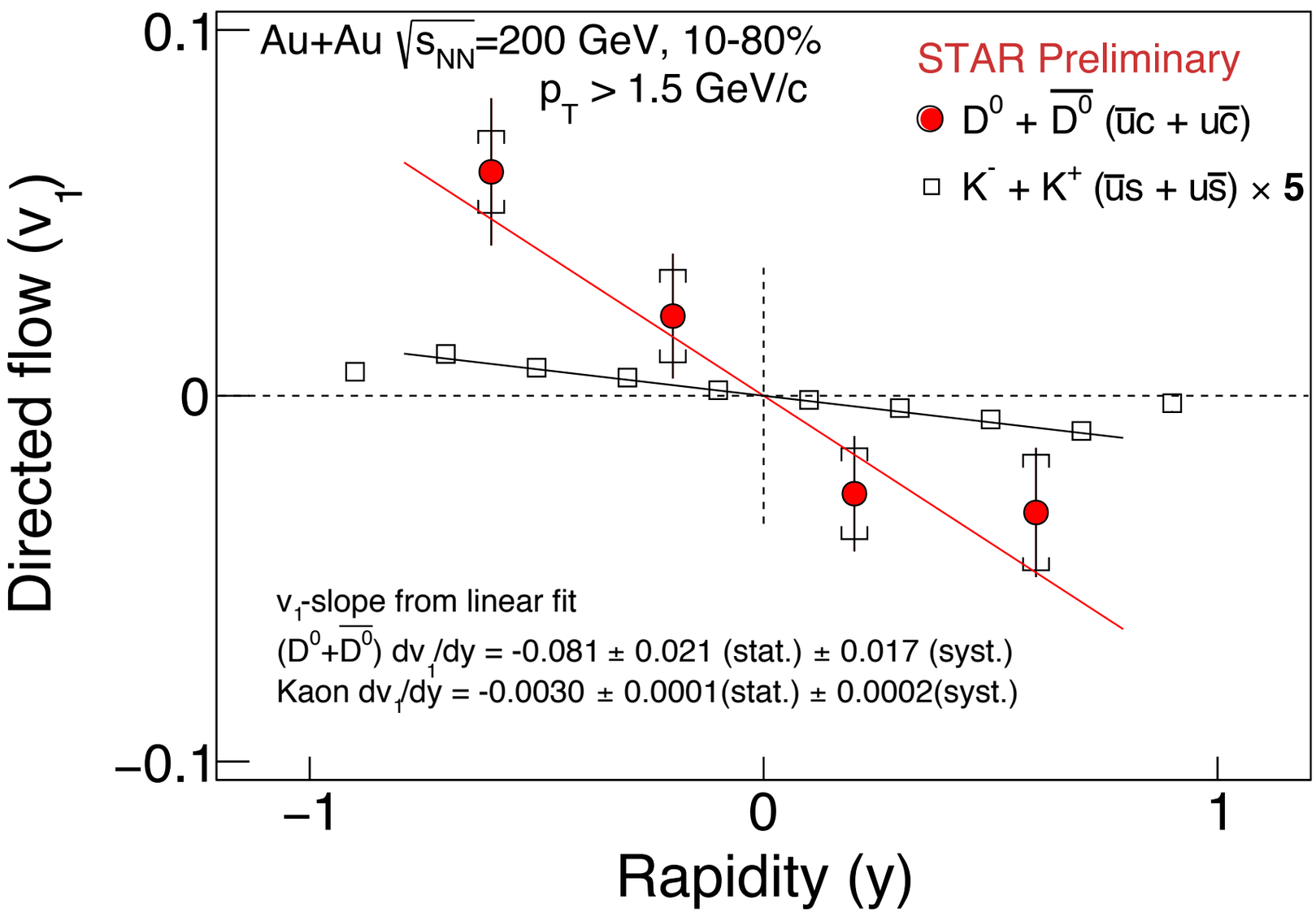
- $D^0$ $v_1$ measured using ϕ-$\psi_1$ method
- Results are corrected for event-plane resolution

# $D^0$ directed flow ($v_1$)




- First evidence of non-zero $D^0$ $v_1$

# $D^0$ vs. kaons $v_1$

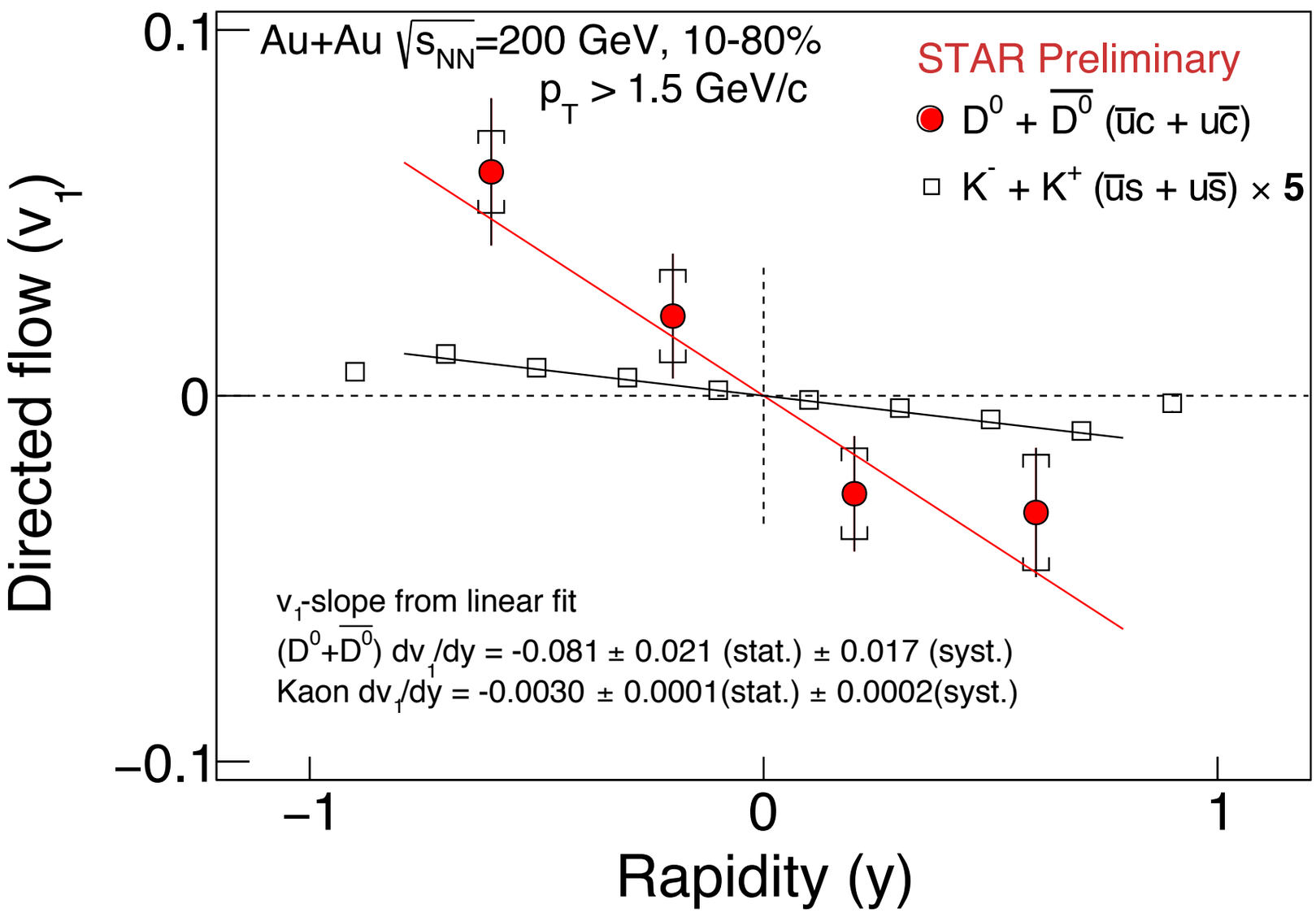



*Charged Kaons:*
*L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 120, 62301 (2018)*

- First evidence of non-zero $D^0$ $v_1$
- $v_1$ of $D^0$ is about 20 times larger than that of the kaons, with ~3σ significance

**Charm $v_1$ slope > Light flavor $v_1$ slope**

# $D^0$ vs. kaons $v_1$

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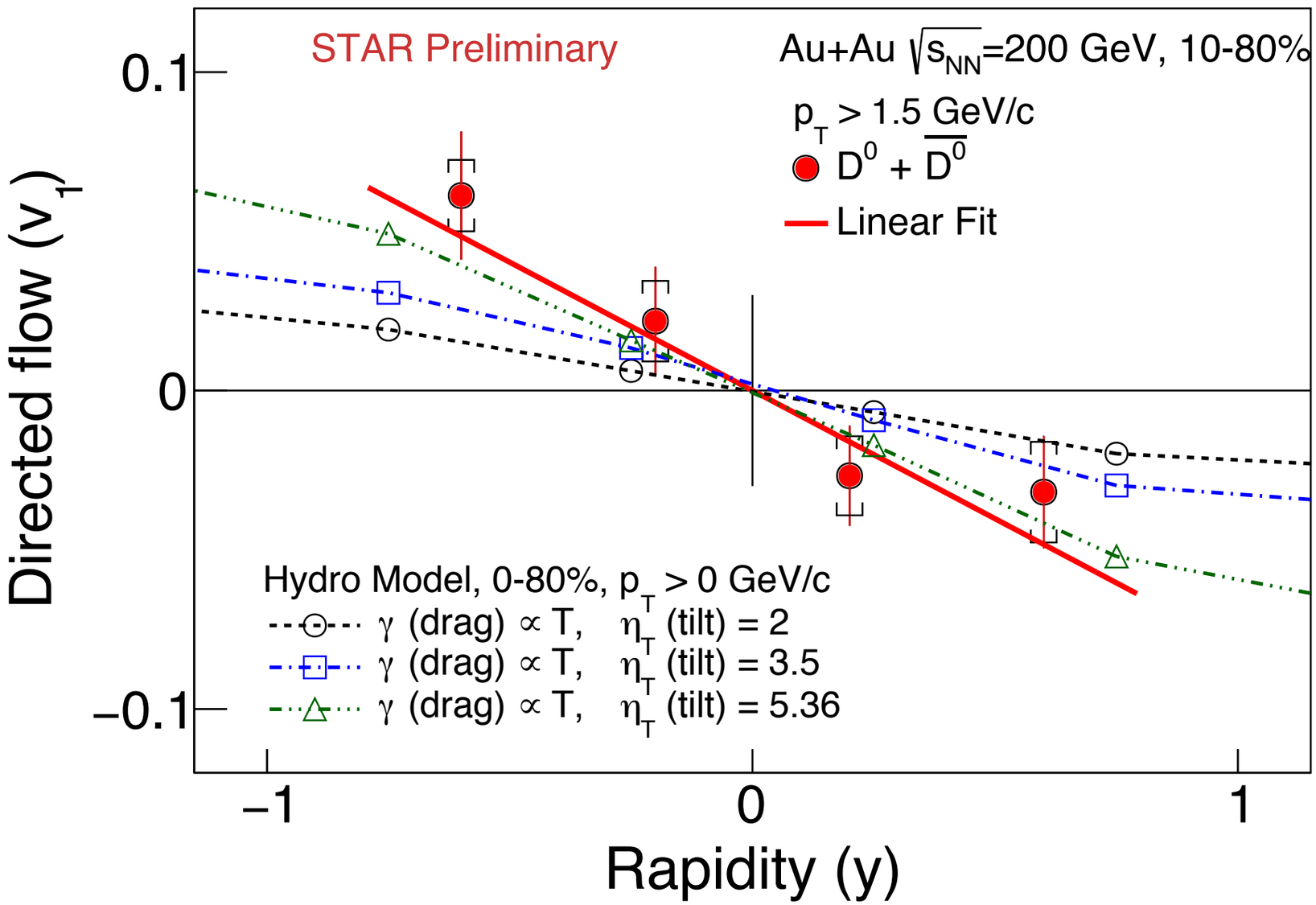
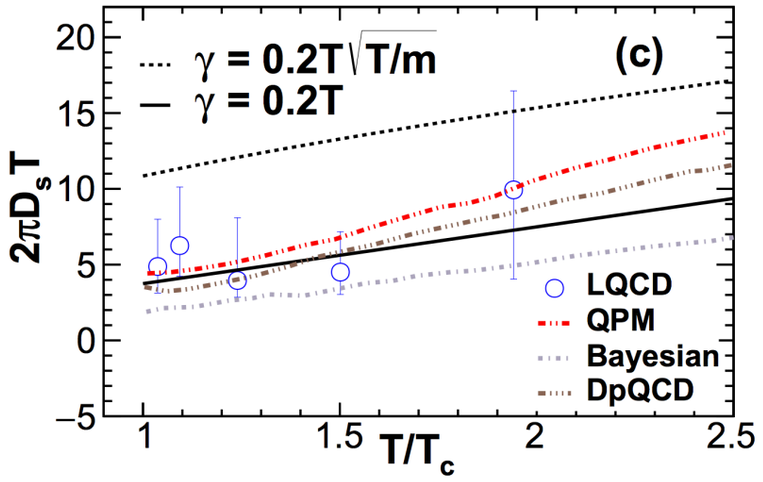
**Charm $v_1$ slope > Light flavor $v_1$ slope**

So far the largest $v_1$ slope measured at mid-rapidity at 200 GeV

# $D^0$ $v_1$ : data vs. hydro

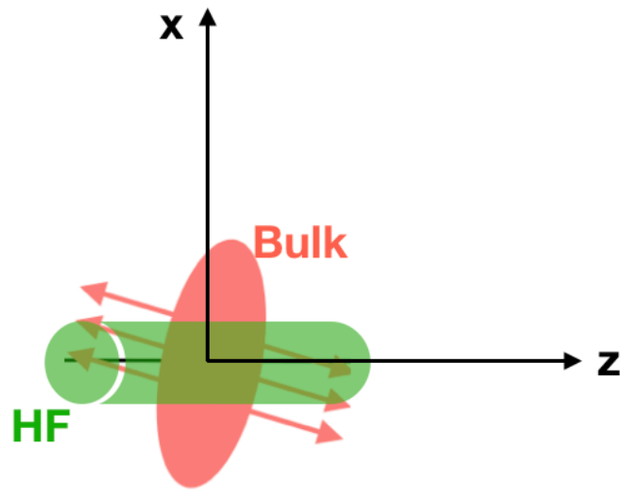



*Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)*



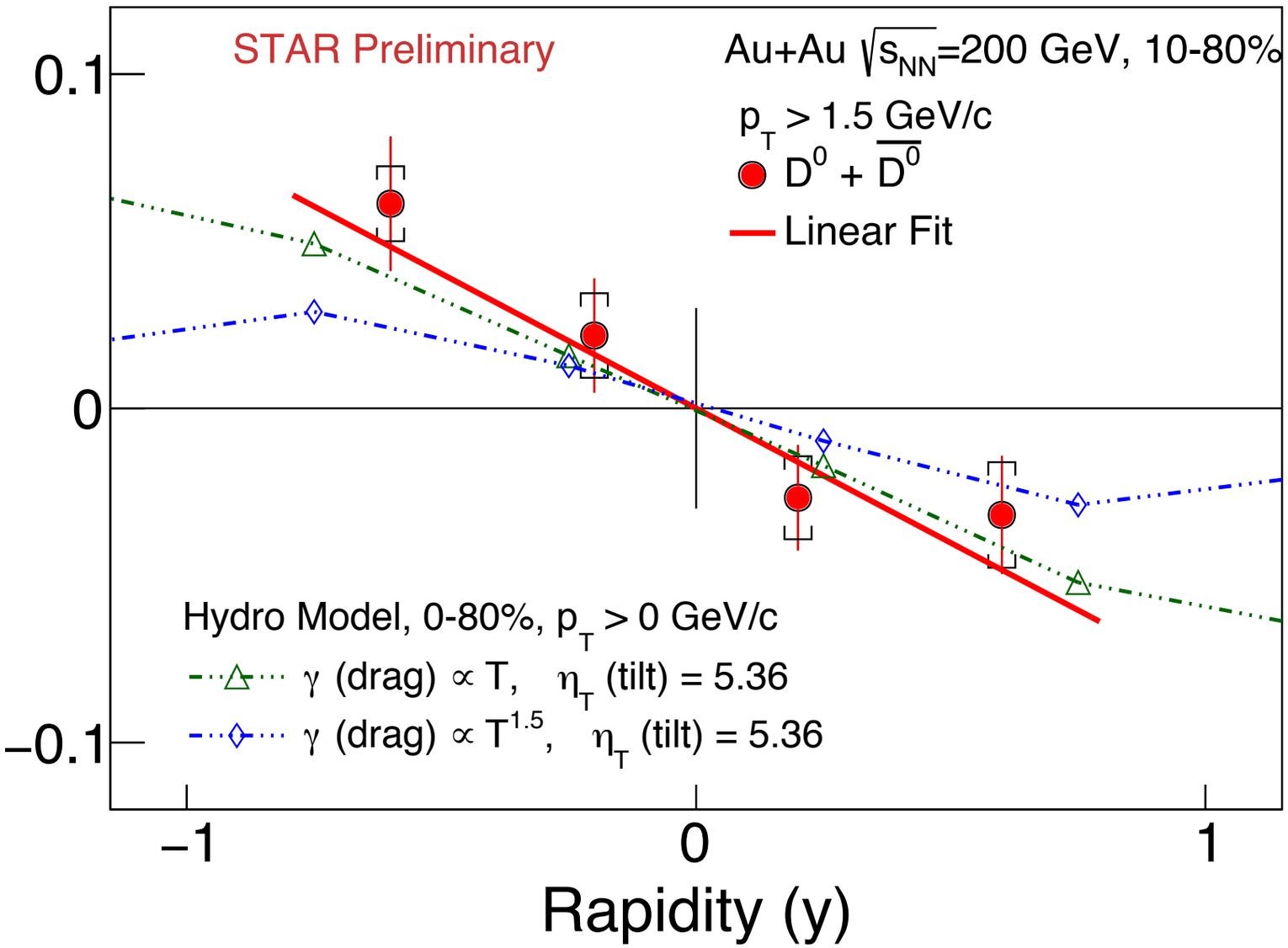

← **Smaller tilt**

← **Larger tilt**




- In hydro model, $D^0$ $v_1$ is sensitive to the initially tilted source
- Our data can help constrain model parameter

# $D^0$ $v_1$ : data vs. hydro

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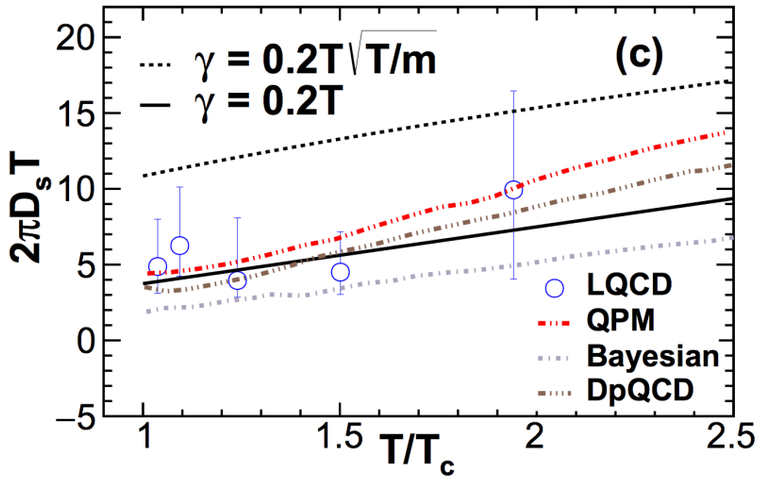


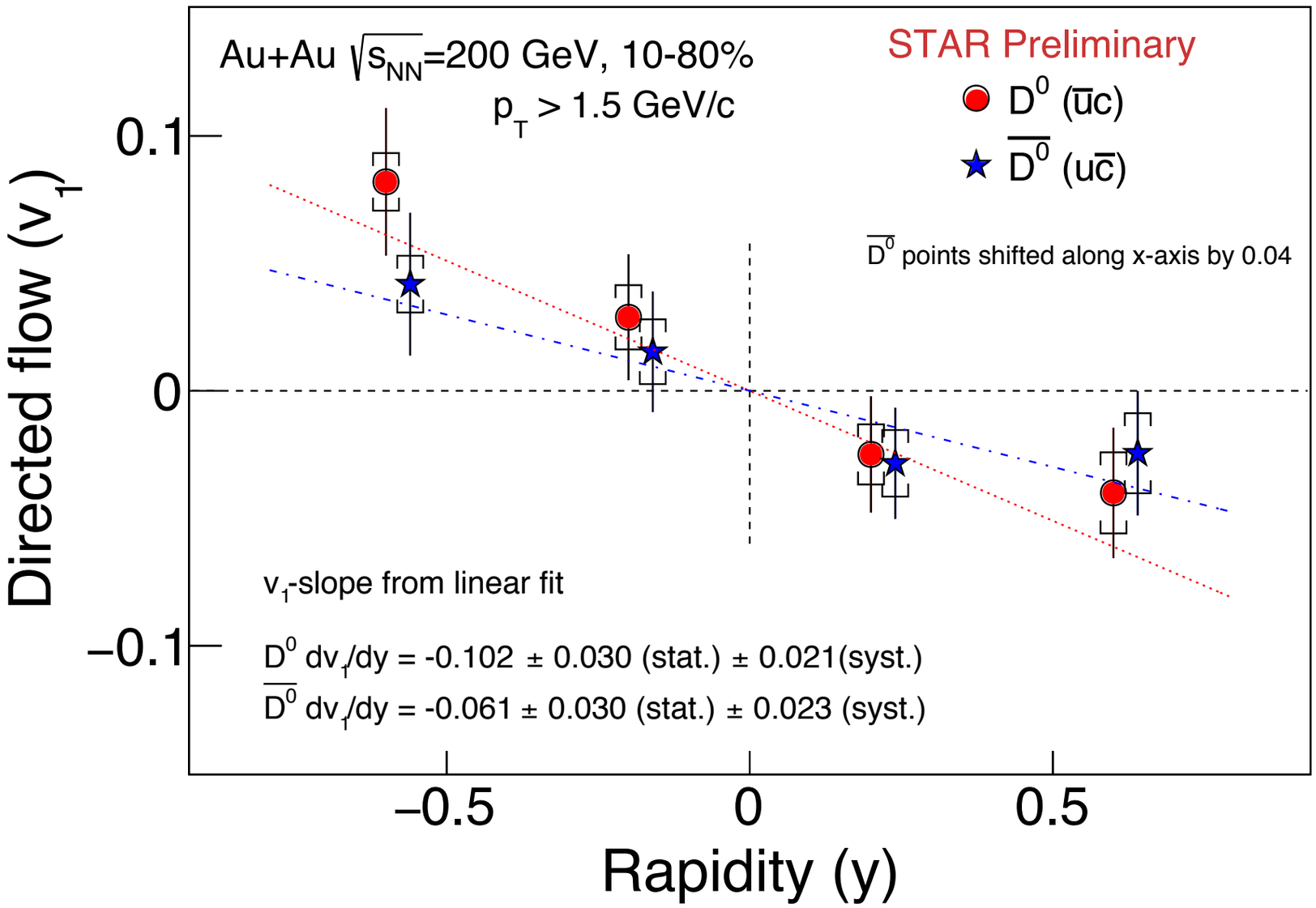

← Larger drag

← Smaller drag

- In hydro model,
- $D^0$ $v_1$ is sensitive to the initially tilted source
- $D^0$ $v_1$ is also sensitive to the temperature dependence of drag coefficient

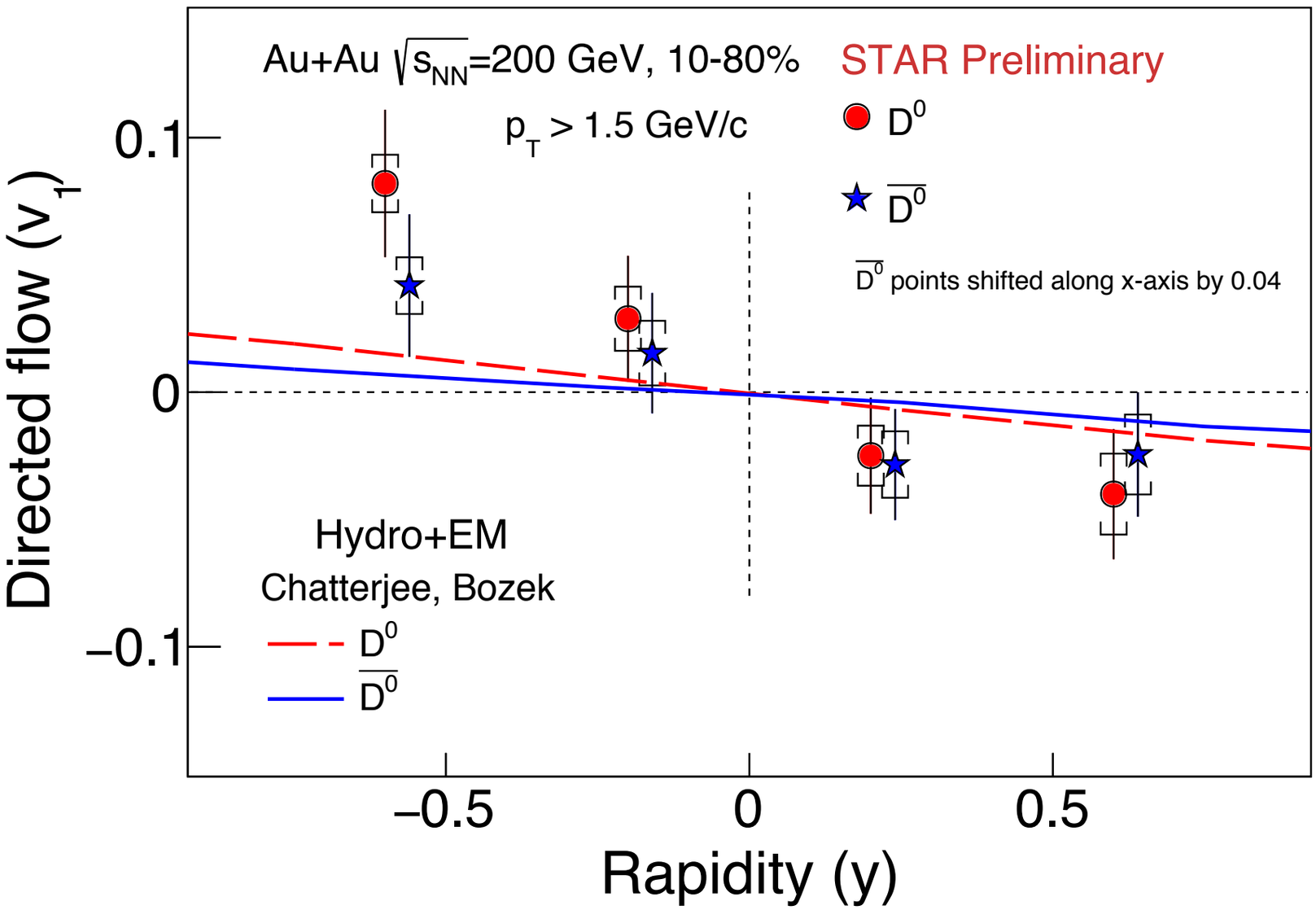
Simultaneous description of D meson $R_{AA}$, $v_2$ and $v_1$ can provide constraint on the drag coefficient

# $D^0$ and $\overline{D}^0$ $v_1$




- Both $D^0$ and $\overline{D}^0$ $v_1$ show a negative slope at mid-rapidity

# $D^0$ and $\overline{D}^0$ $v_1$



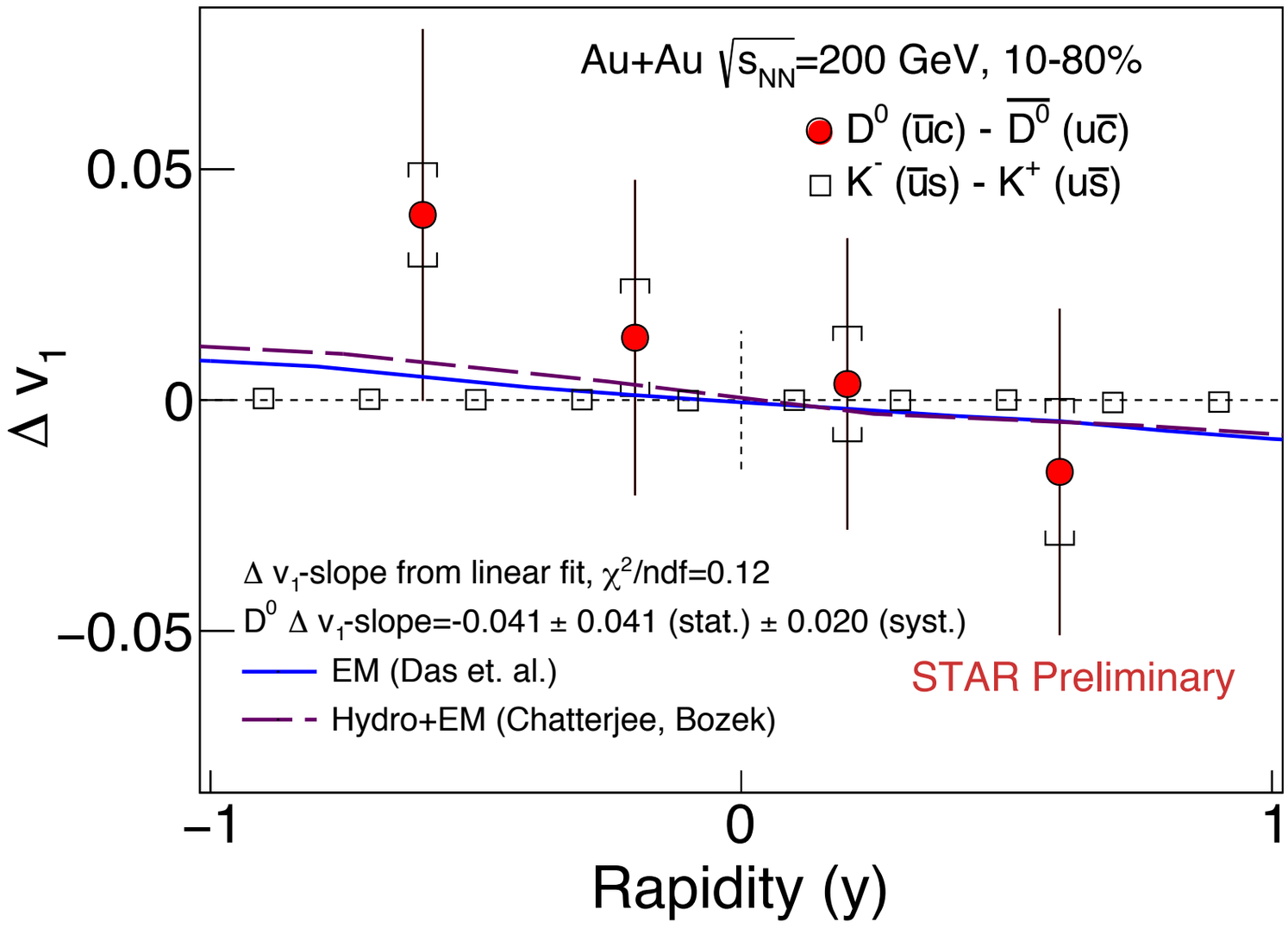

**Hydro+EM**

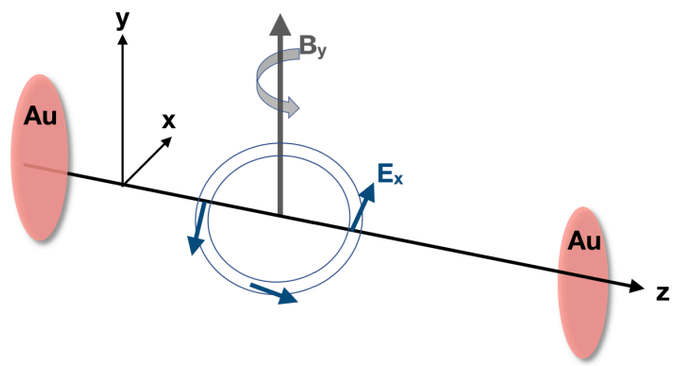
*Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)*
*Chatterjee, Bojek: 1804.04893v1*

- Both $D^0$ and $\overline{D}^0$ $v_1$ show a negative slope at mid-rapidity
- Hydro model combined with EM field predicts the correct sign of $v_1$
- The magnitude of $v_1$ depends on the tilt and drag parameter in model

# $(D^0 - \bar{D}^0)$ vs. $(K^- - K^+)$ $v_1$

## Difference between $D^0$ $v_1$ and $\bar{D}^0$ $v_1$:




*Hydro+EM:*
*Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)*
*Chatterjee, Bojek: 1804.04893v1*
*EM:*
*Das et. al., Phys Lett B 768, 260 (2017)*

- Expected difference between $D^0$ and $\bar{D}^0$ $v_1$ is a few percent
- Current precision does not allow to draw firm conclusion on magnetic field induced $v_1$ splitting

# Summary

- First evidence of non-zero directed flow for heavy flavor

- Both $D^0$ and $\bar{D}^0$ show negative $v_1$ slope near mid-rapidity
- Heavy flavor $v_1$ > light flavor $v_1$

  Data can be used to constrain the initial tilt in the distribution of the matter

  Data can constrain drag coefficients in conjunction with $v_2$ and $R_{AA}$ measurements

- Current precision is not sufficient to draw conclusion on magnetic field induced charge separation of heavy quarks