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

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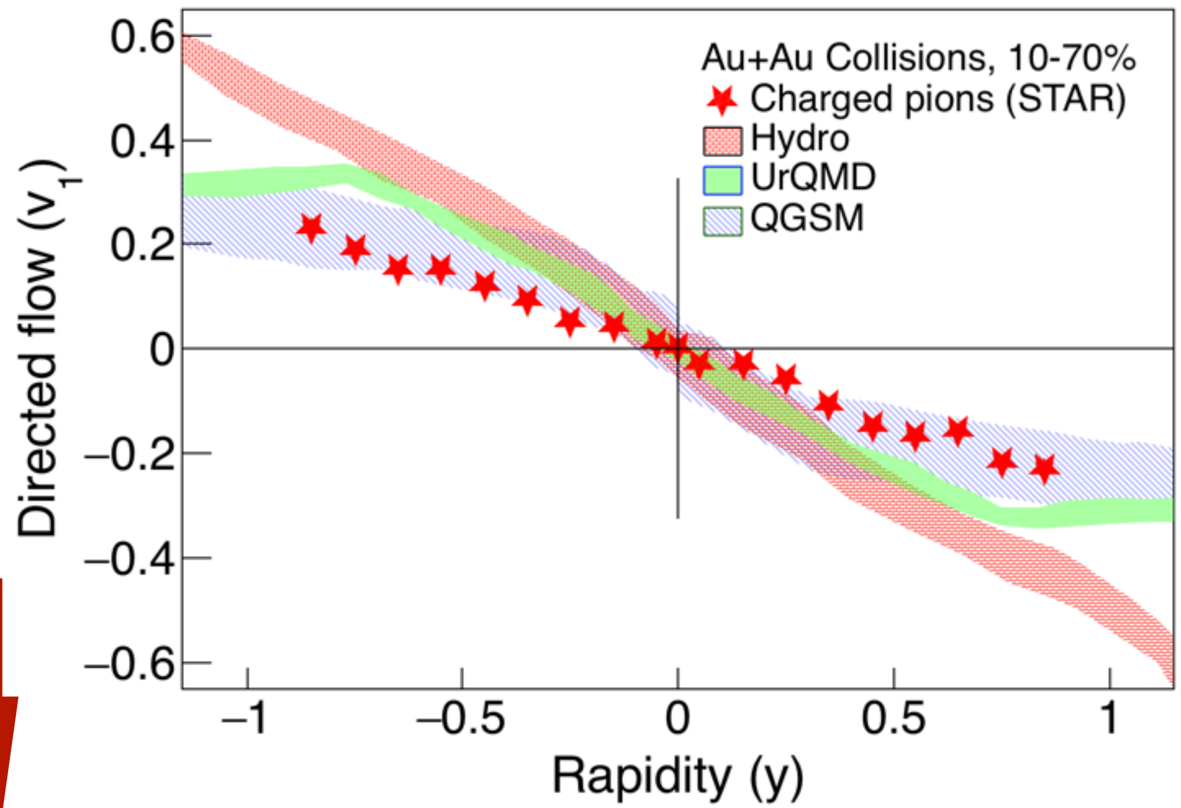
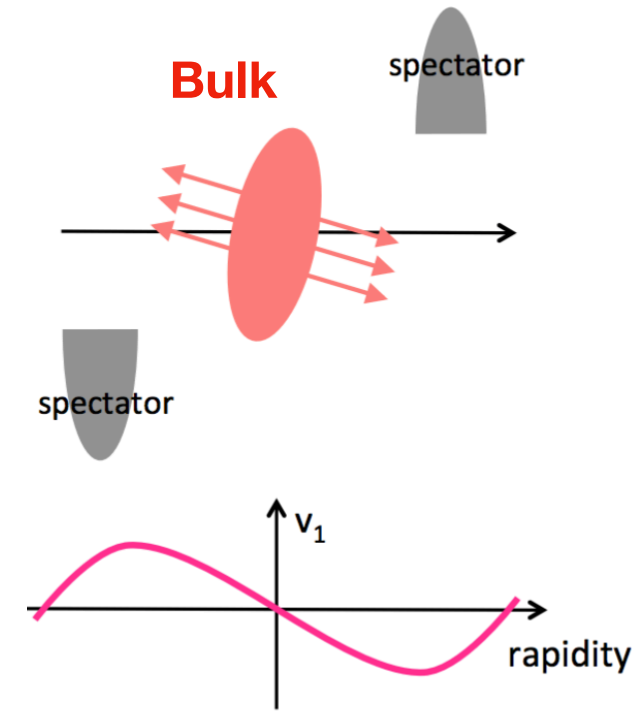
Directed flow in heavy-ion collisions

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

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



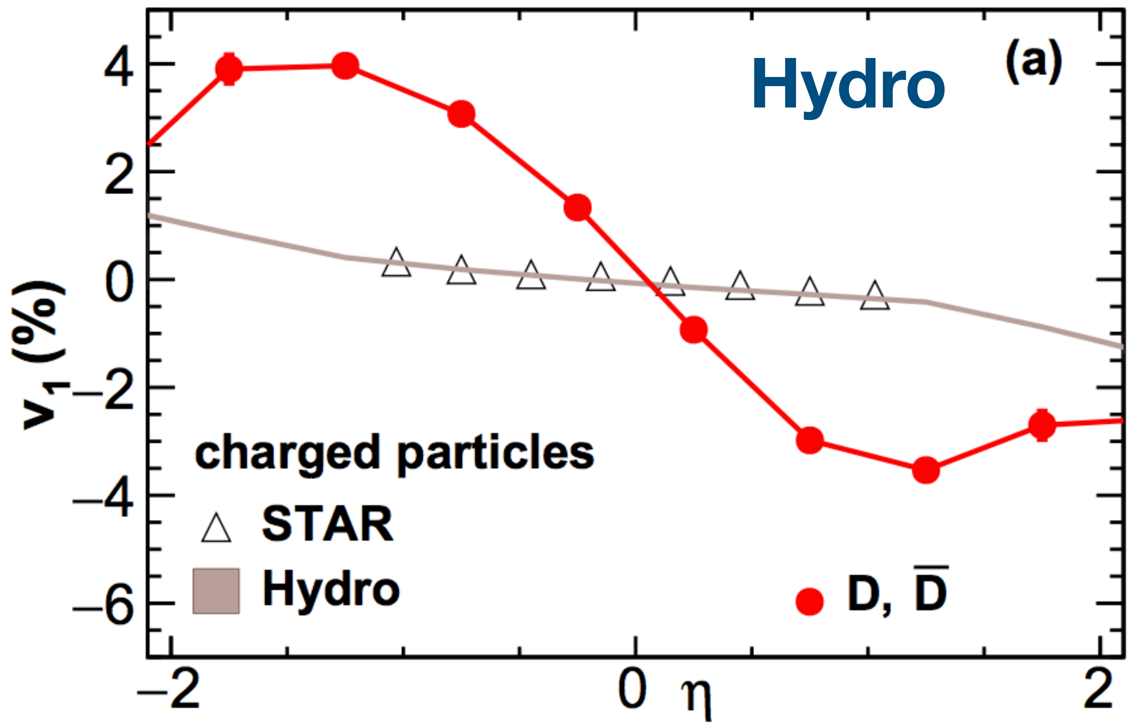


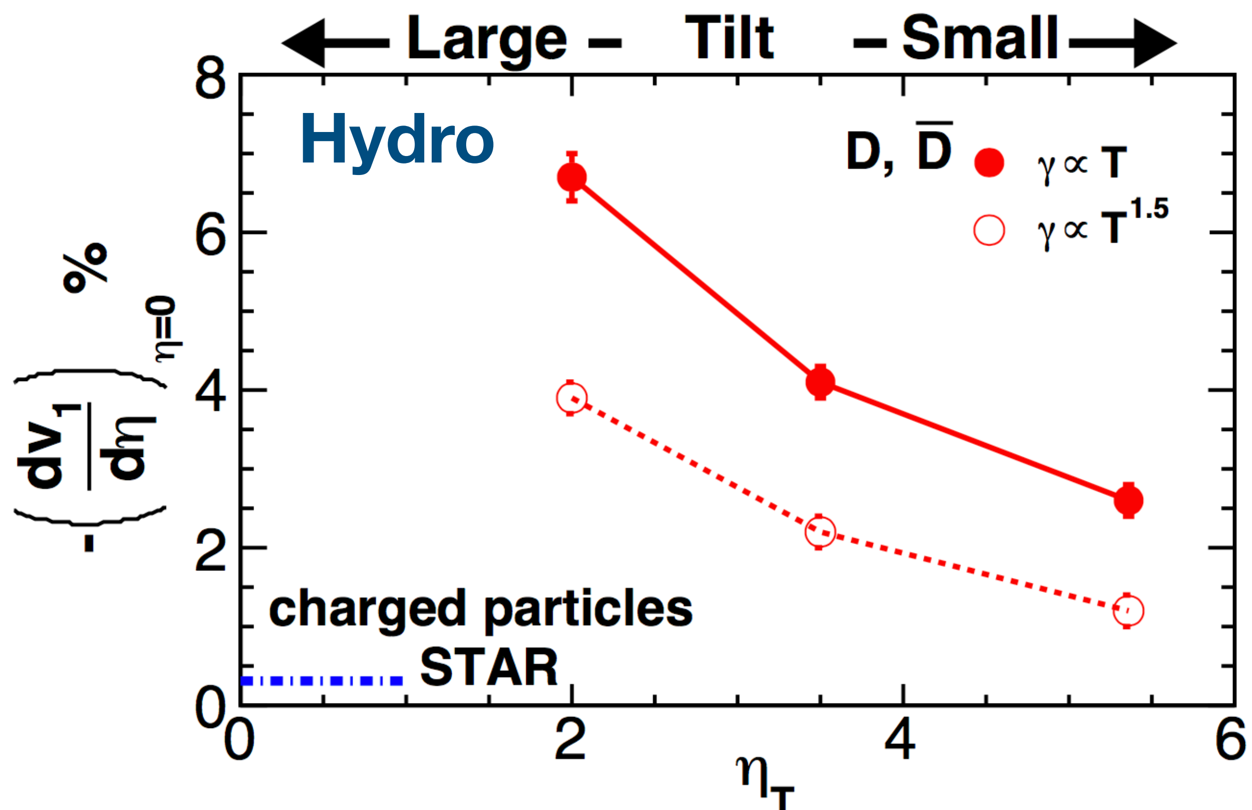
L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 108, 202301 (2012)
Hydro: P. Bozek, I. Wyskiel, Phys Rev. C. 81, 054902 (2010)
UrQMD: H. Peterson et al, Phys Rev. C. 74, 064908 (2006)
QGSM: J. Beibel et al, Phys Rev. C. 76, 024912 (2007)
Transport: R. Snellings, et al, Phys Rev. Lett. 84, 2803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

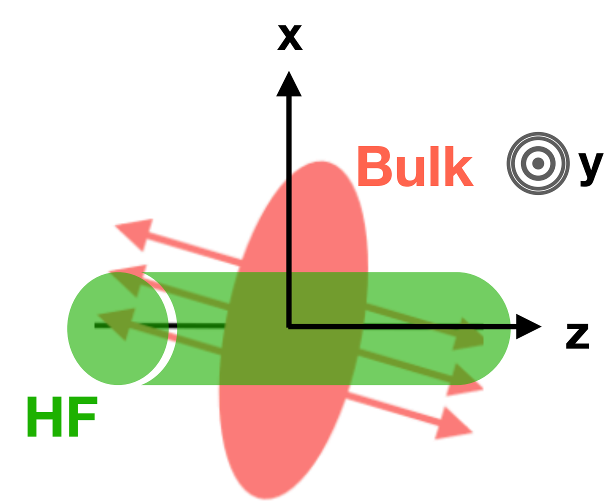
Heavy quark v_1 from Hydro

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





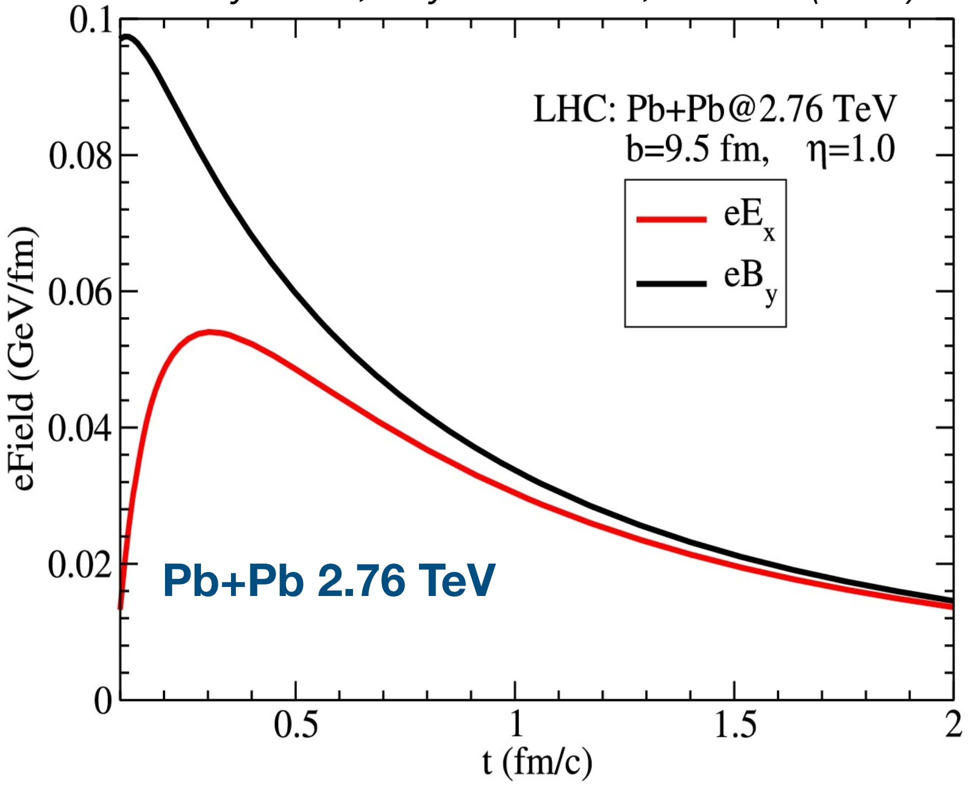
- Heavy quarks (HQ) are produced according to binary collision density profile, which is symmetric in rapidity
- At non-zero rapidity, the HQ production points are shifted in the transverse plane with respect to the bulk of the matter causing an enhanced dipole asymmetry in HQ flow pattern
- Additionally, 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

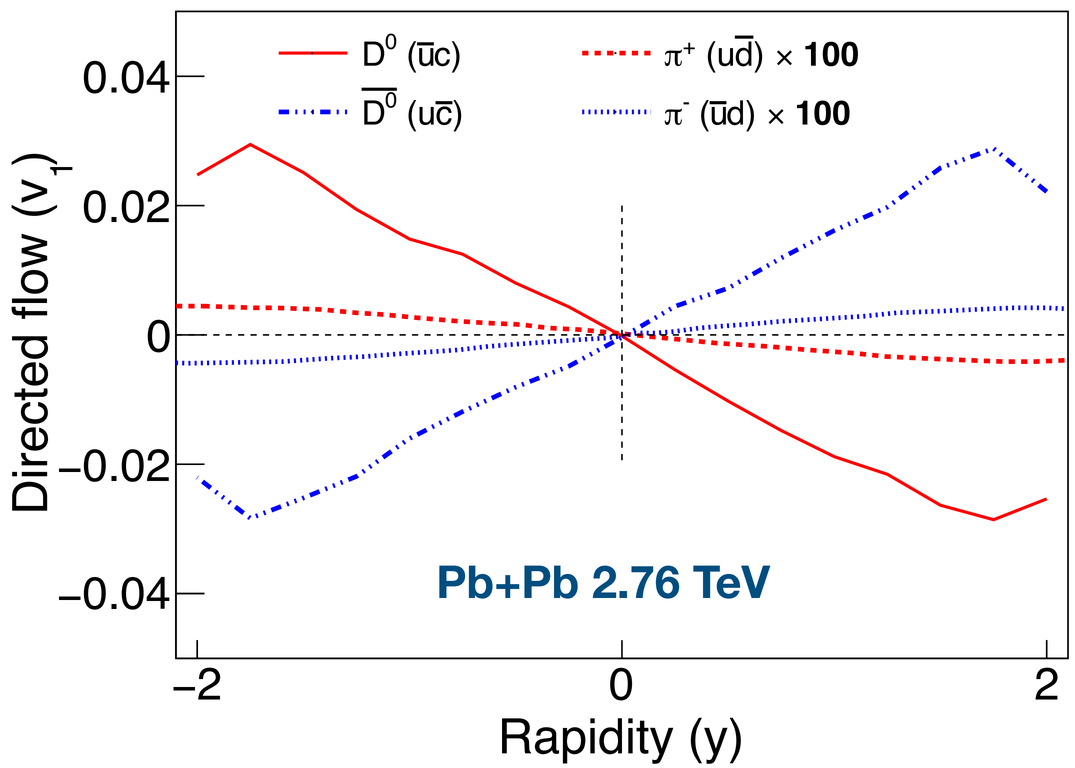
Heavy quark v_1 from EM field

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

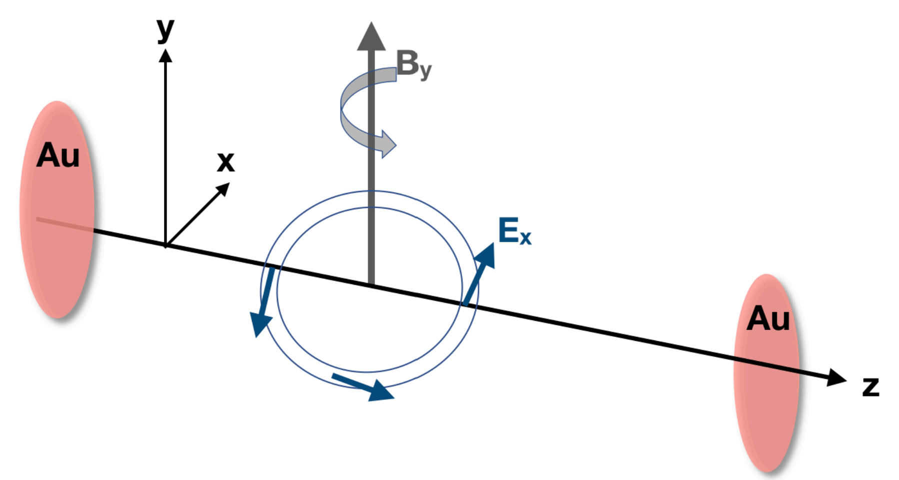


Das et. al., Phys Lett B 768, 260 (2017)

EM

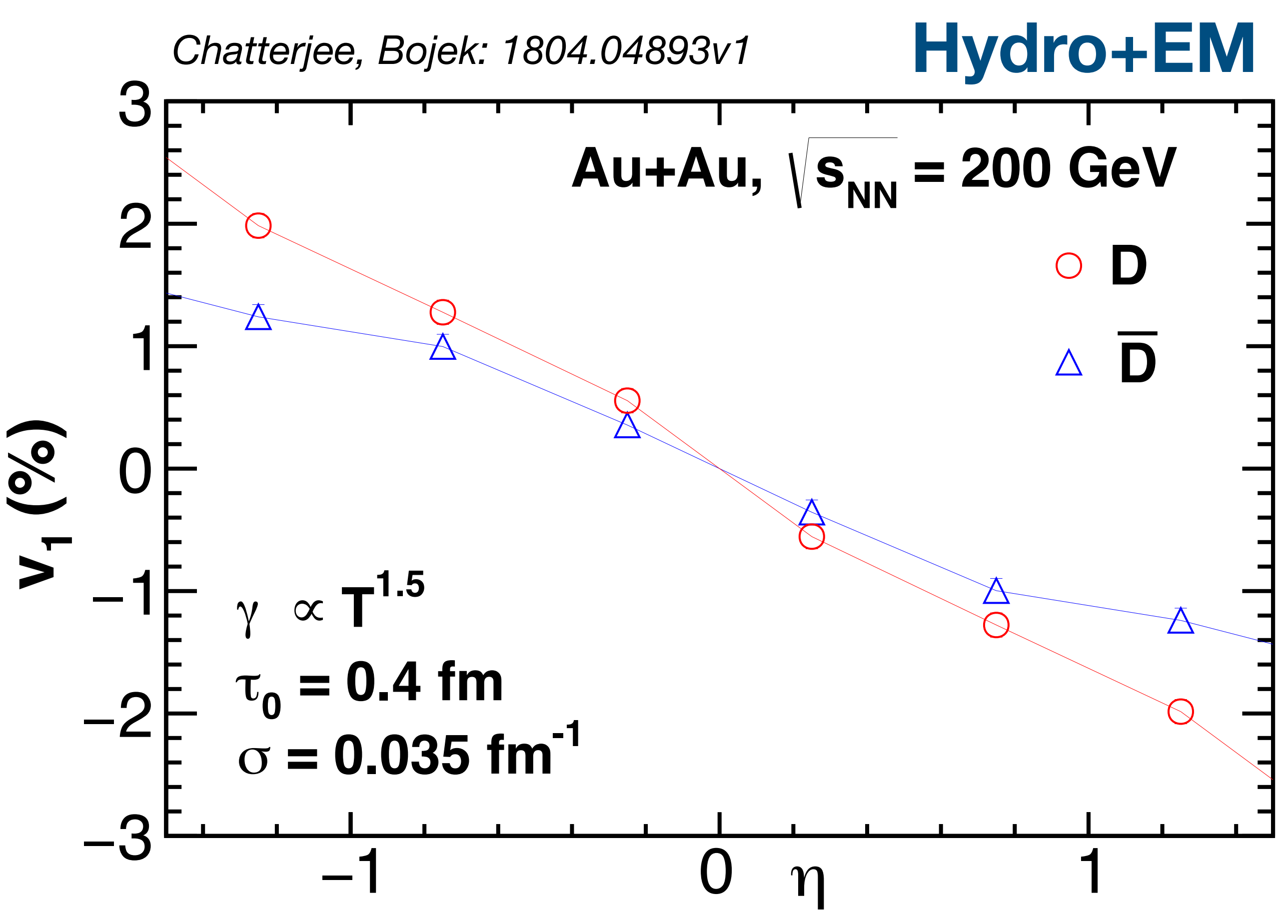


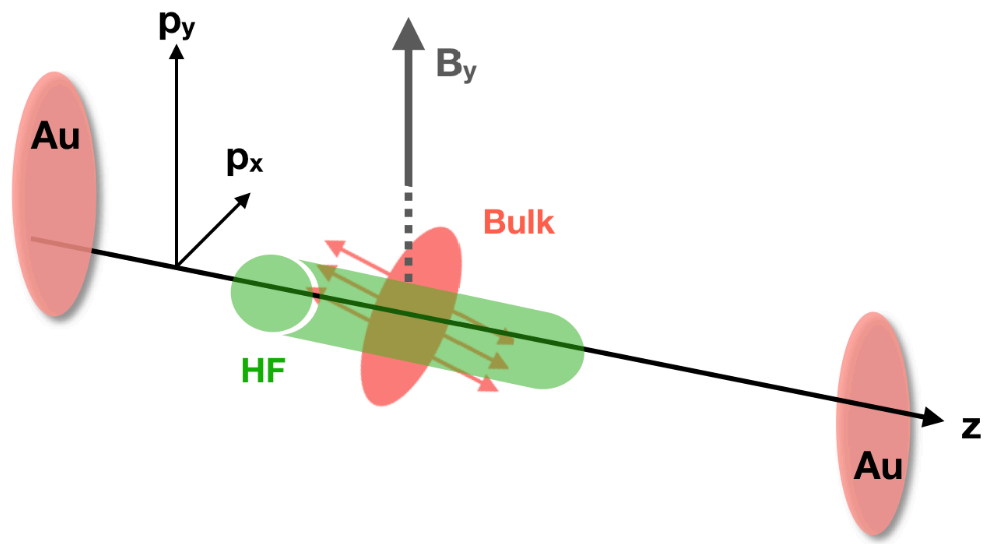
- Incoming charged particles can produce an enormously large EM field
- Due to early production of heavy quarks (τ_{CQ}~0.1 fm/c), positive and negative charm quarks can get deflected by the initial EM force
- Model calculation demonstrates that such initial EM field can induce opposite v_1 for charm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



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

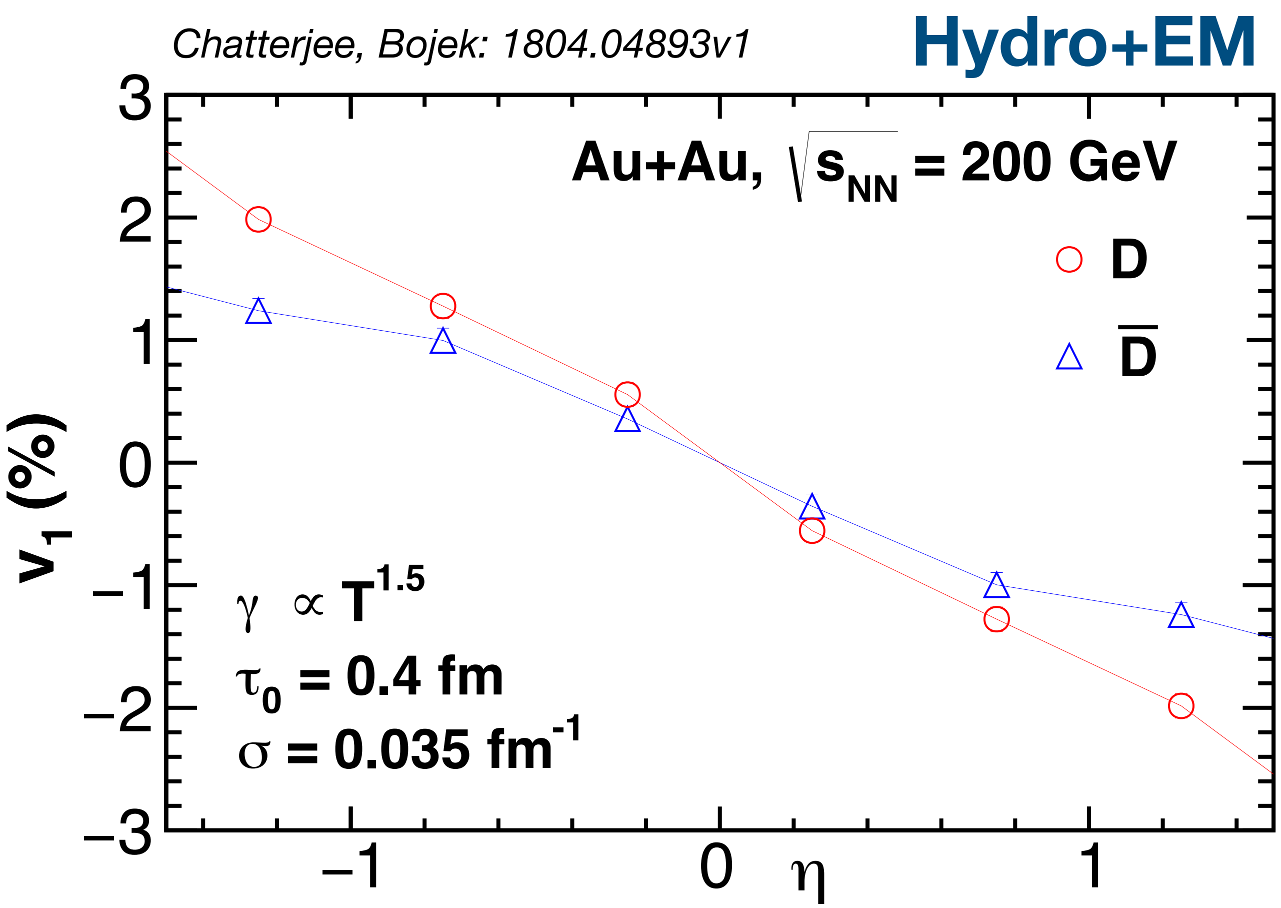
Heavy quark v_1 from Hydro+EM field

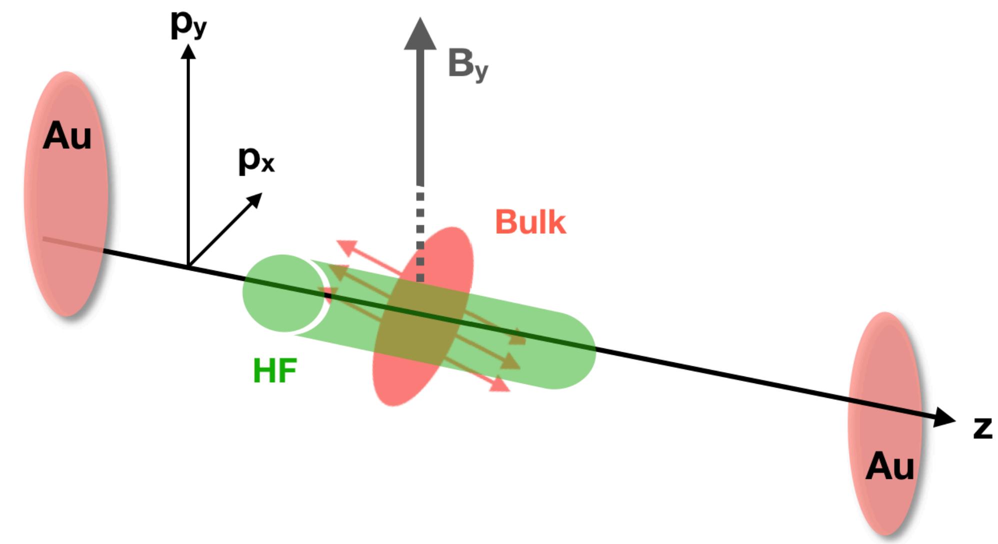




- Recent hydro model combined with initial EM field predicts a v_1 split between D and $\overline{D}$ mesons
- Predicted v_1 of D meson is greater than that of $\overline{D}$ meson
- Predicted difference in v_1 is about 10 times smaller than the average v_1

Heavy quark v_1 from Hydro+EM field





Summarizing v_1 expectation from models

D^0 and $\overline{D^0}$	Average	Difference
Hydro	≠ 0	= 0
EM	= 0	≠ 0
Hydro+EM	≠ 0	≠ 0

- Recent hydro model combined with initial EM field predicts a v_1 split between D and $\overline{D}$ mesons
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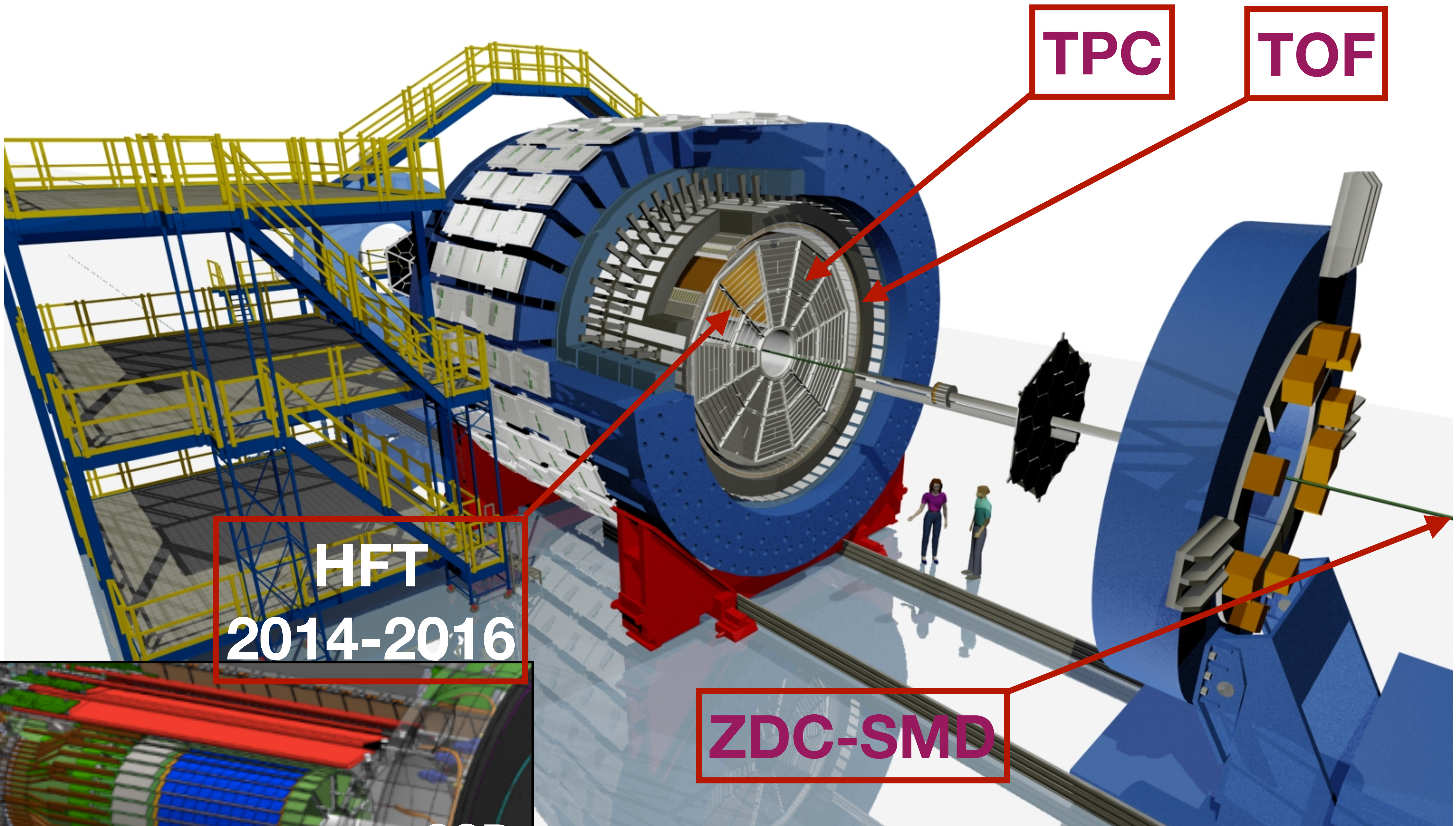
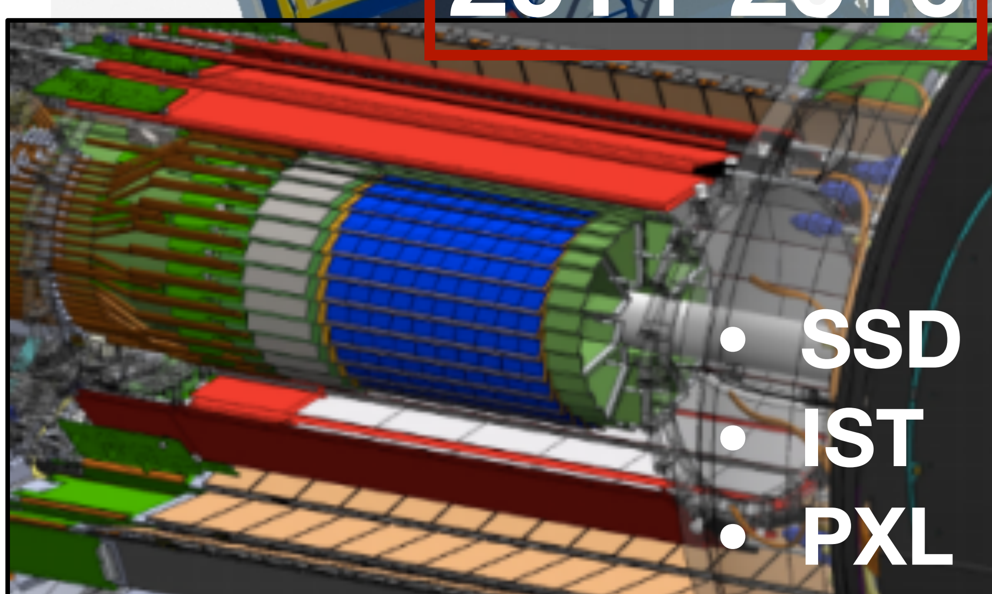
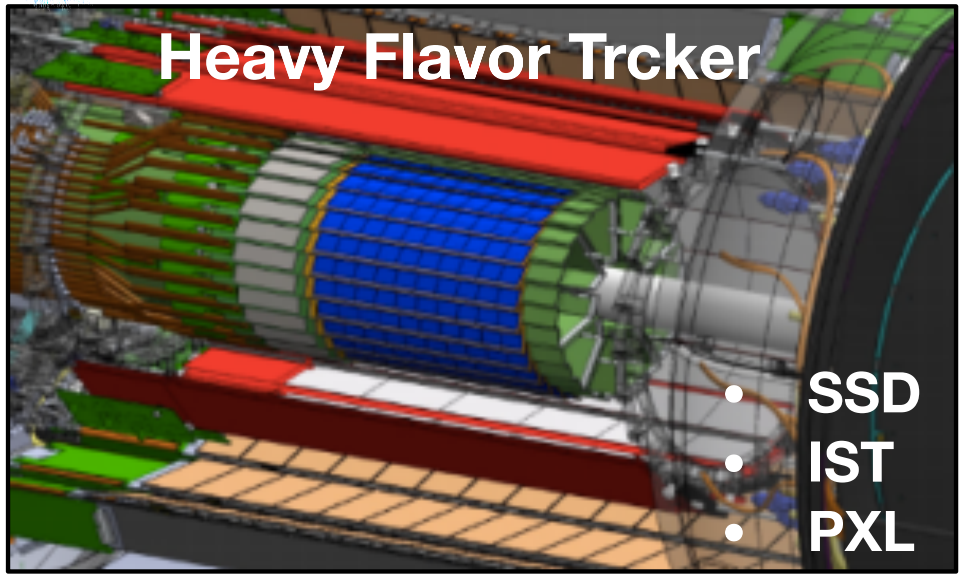
STAR detector



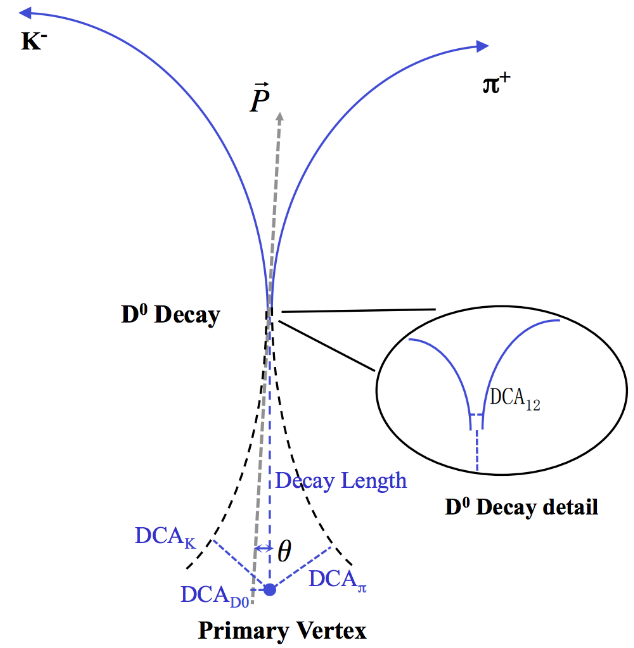


- **Full azimuthal coverage (0,2π)**
- **Excellent PID capabilities**

D^0 reconstruction with HFT

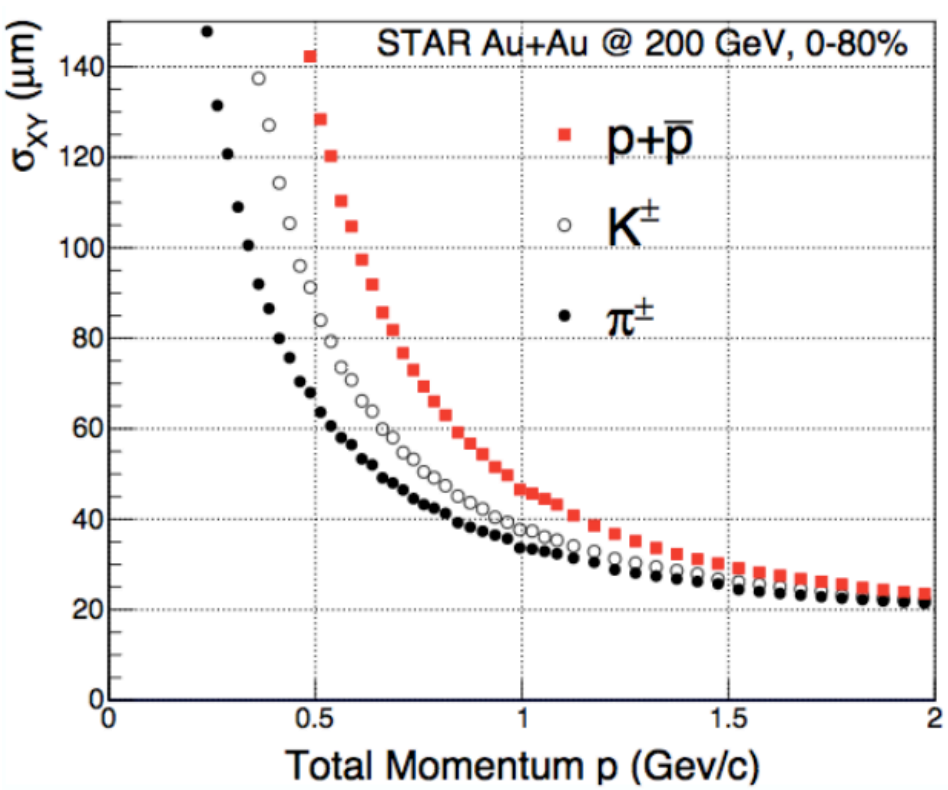


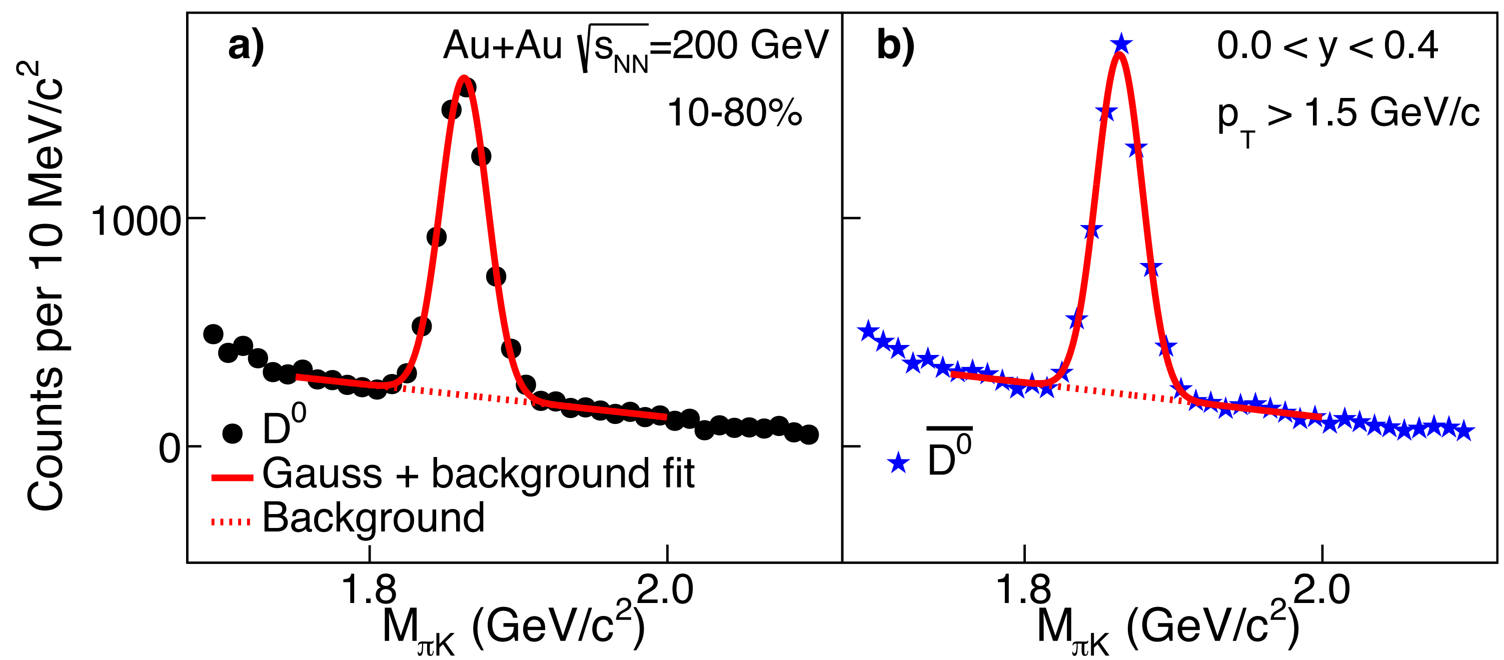
- Pseudorapidity (|η|<1)
- Azimuthal coverage (0,2π)
- Excellent track pointing resolution
- Allows topological reconstruction for heavy-flavor particles



D⁰ meson

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

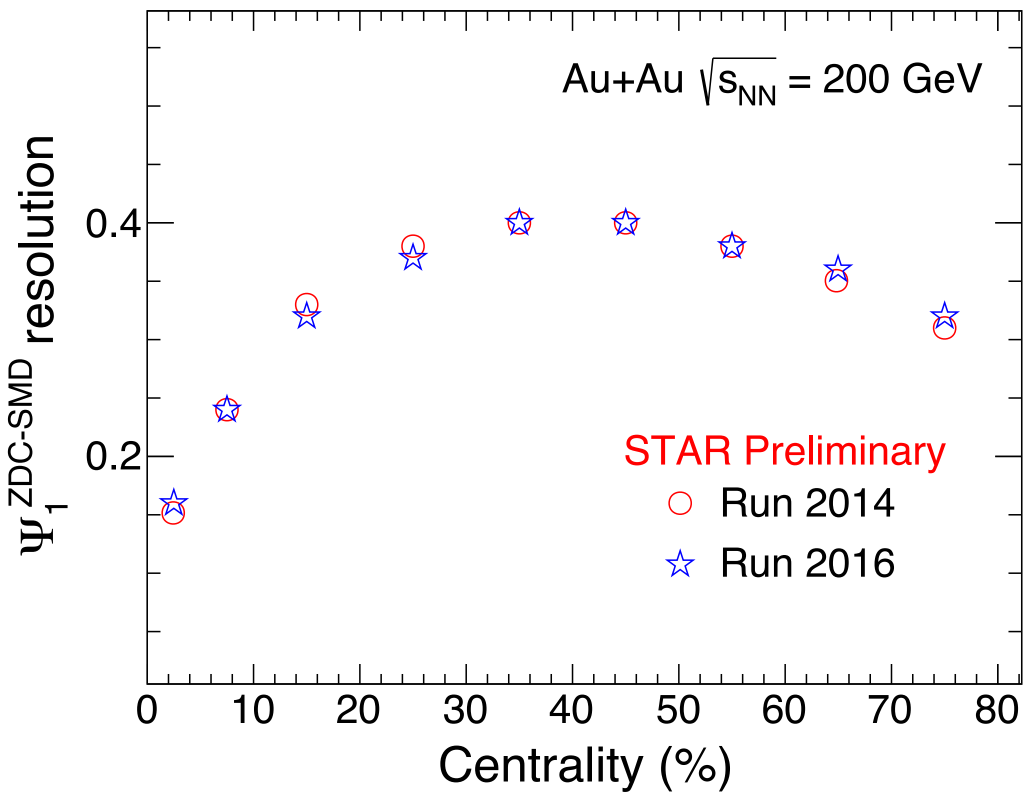




- HFT data from 2014 and 2016 runs
- Total ~ 2 billion good events
- Significance improved by a factor of 15, compared to reconstruction without HFT

D^0 v_1 from event plane method

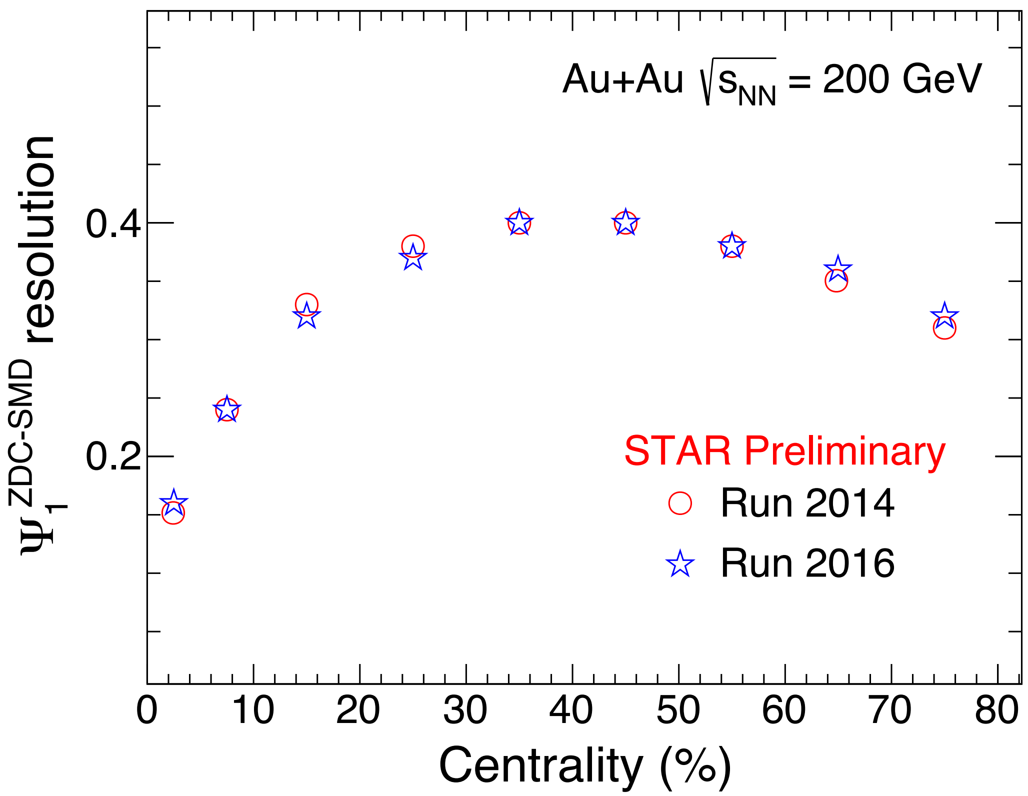
ZDC-SMD Event plane resolution:



- The first-order event plane measured using ZDC-SMD (|η|>6.4)
- v_1 signal is significant at forward rapidity
  Better ψ_1 resolution than mid-rapidity detectors
- Large η-gap significantly reduces non-flow contribution

D^0 v_1 from event plane method

ZDC-SMD Event plane resolution:



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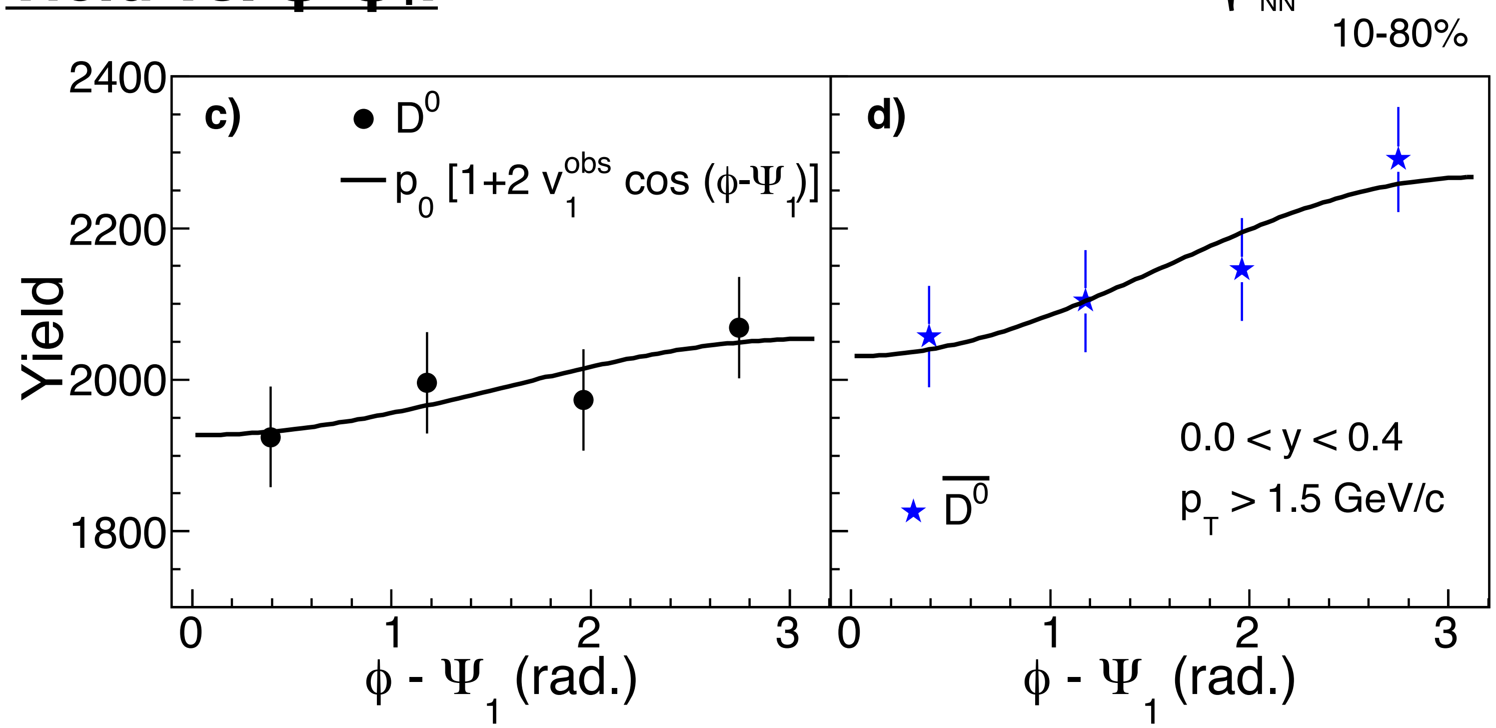
Yield vs. ϕ-ψ_1:

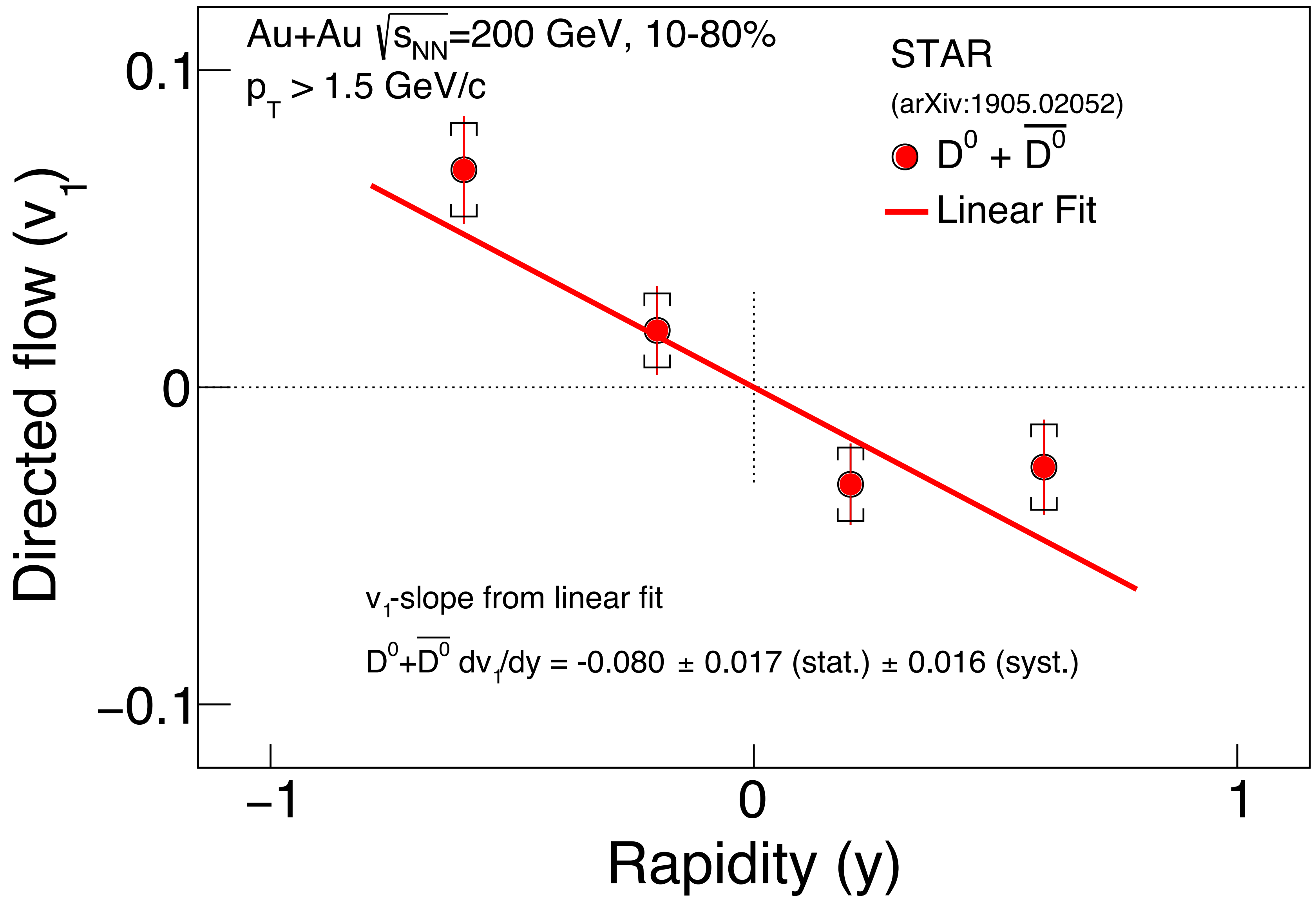


- D^0 v_1 measured using ϕ-ψ_1 method
- Results are corrected for event-plane resolution

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

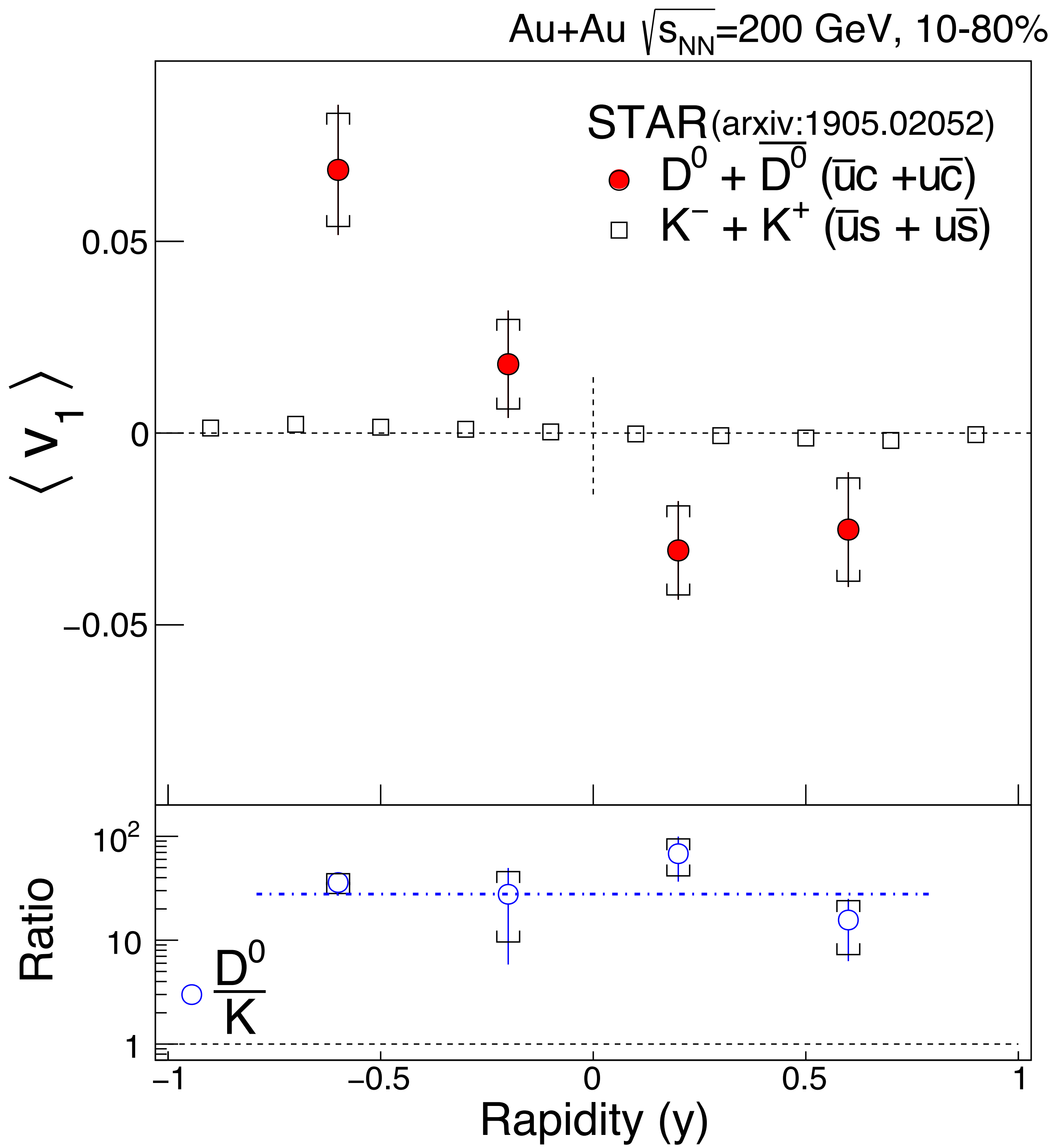
D^0 directed flow (v_1)

J Adam et. al. (STAR Collaboration), arXiv 1905.02052



- 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)

D^0:
J Adam et. al. (STAR Collaboration), arXiv 1905.02052

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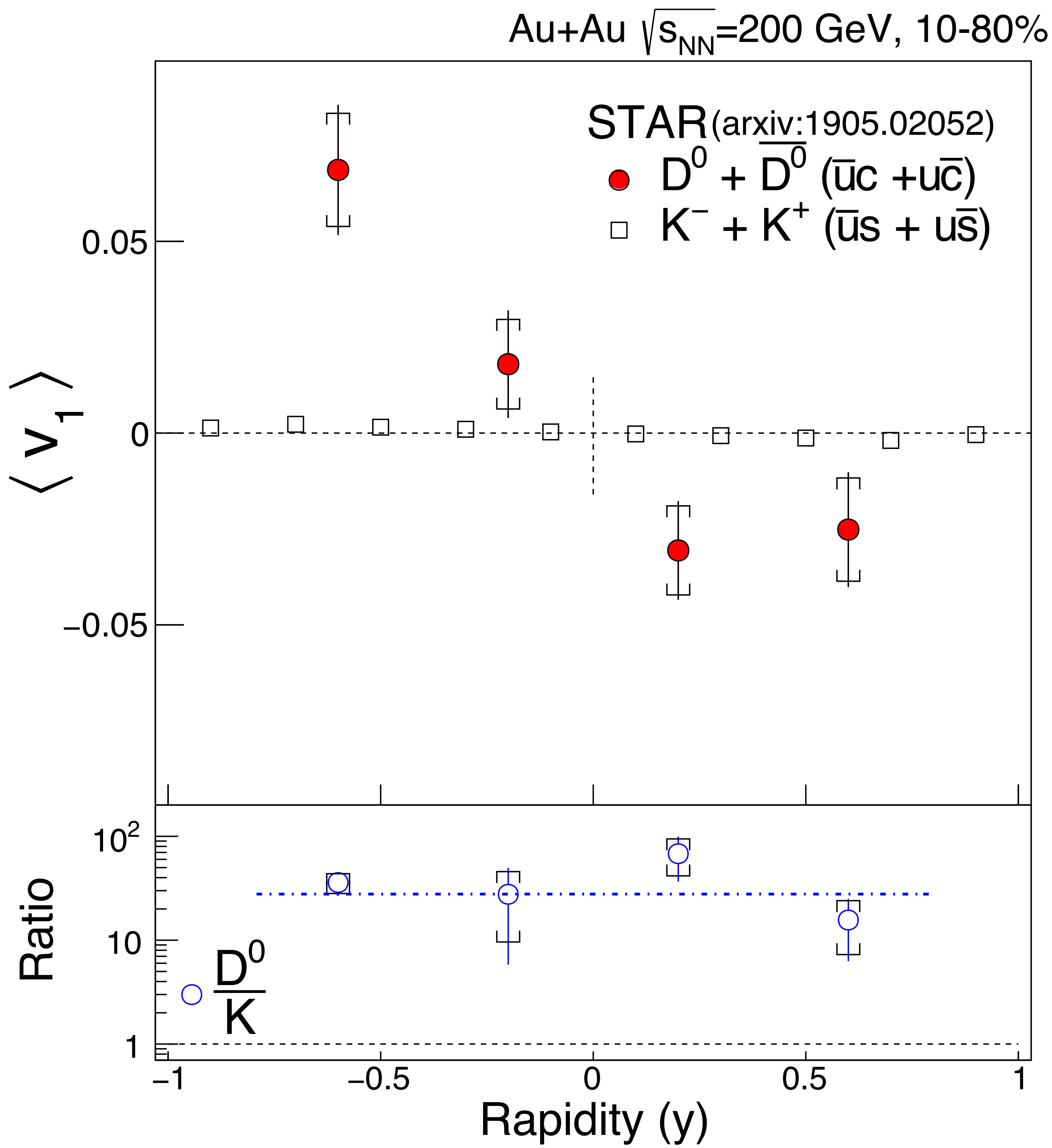

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L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 120, 62301 (2018)

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<u>v_1 slope</u>

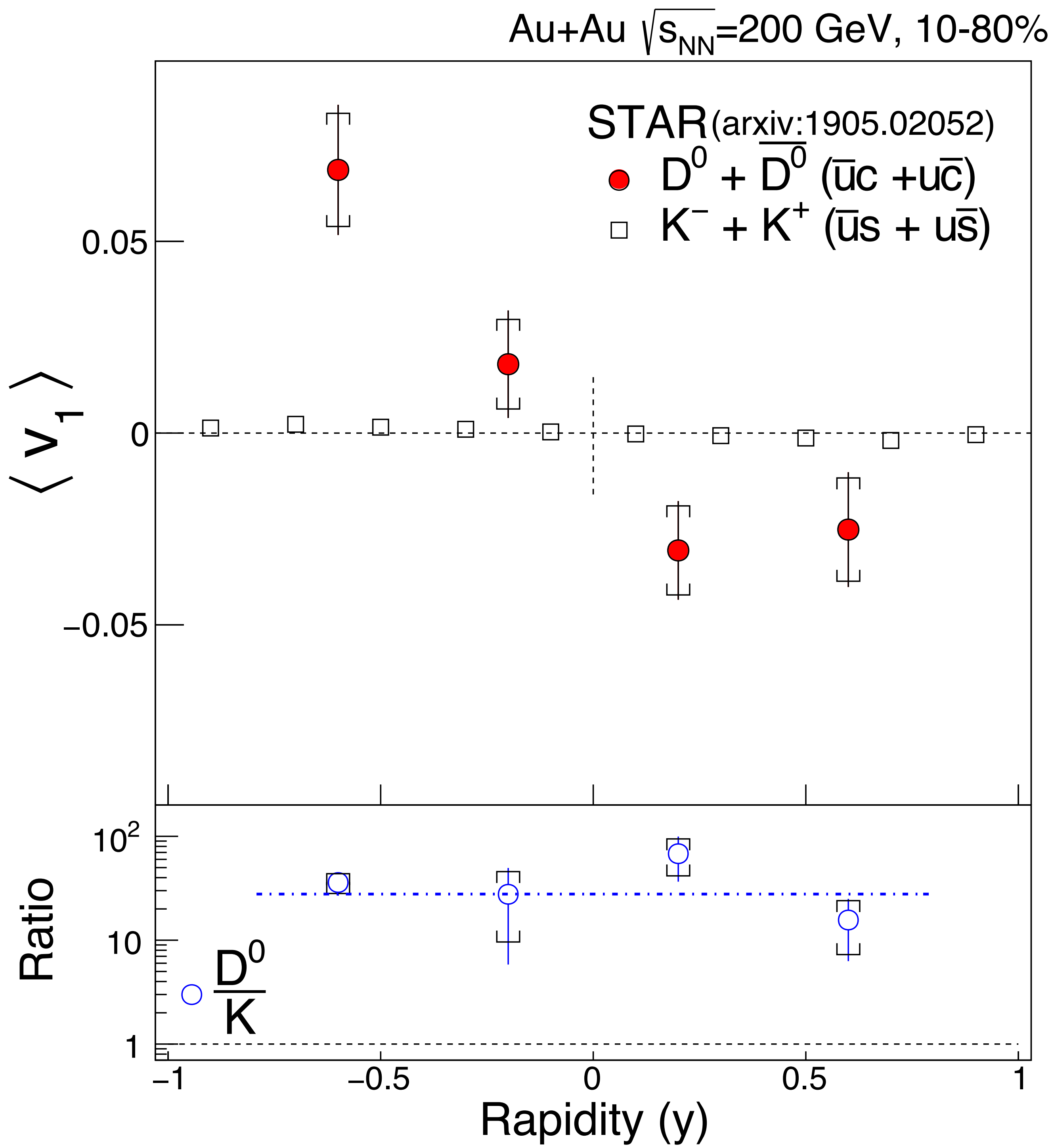
$D^0 : -0.080 \pm 0.017 \pm 0.016$

$\text{Kaon} : -0.003 \pm 0.0001 \pm 0.0002$

Charm v_1 slope > Light-flavor v_1 slope

- First evidence of non-zero D^0 v_1
- v_1 slope of D^0 is about 25 times larger than that of the kaons, with ~3.4σ significance

D^0 vs. kaons v_1



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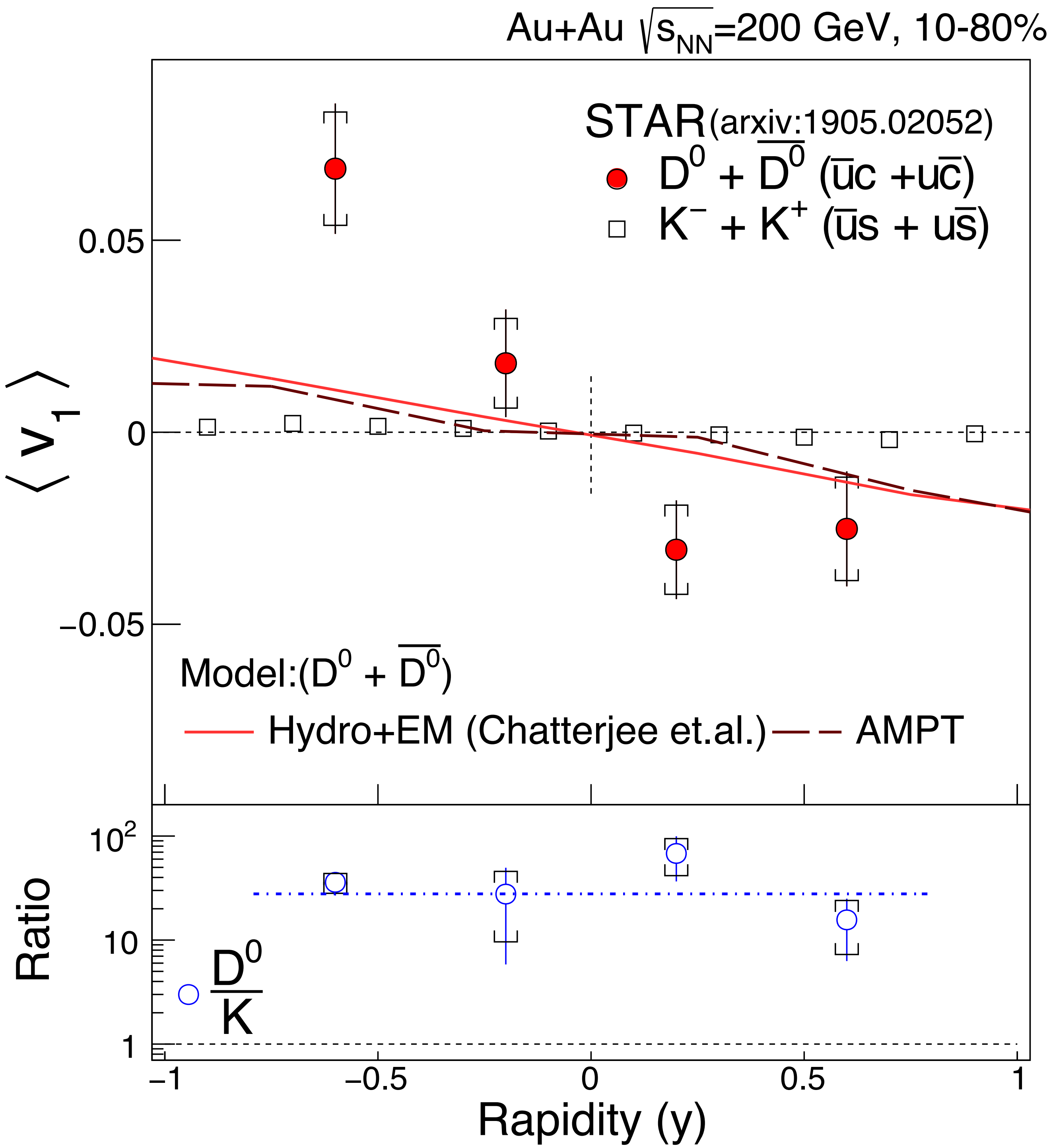
- v_1 slope of D^0 is about 25 times larger than that of the kaons, with ~3.4σ significance

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

D^0 v_1 : data vs. model



- Both Hydro+EM and AMPT model predicts the correct sign of v_1 of D^0 with magnitude larger than light-flavor hadrons, but under-predict data

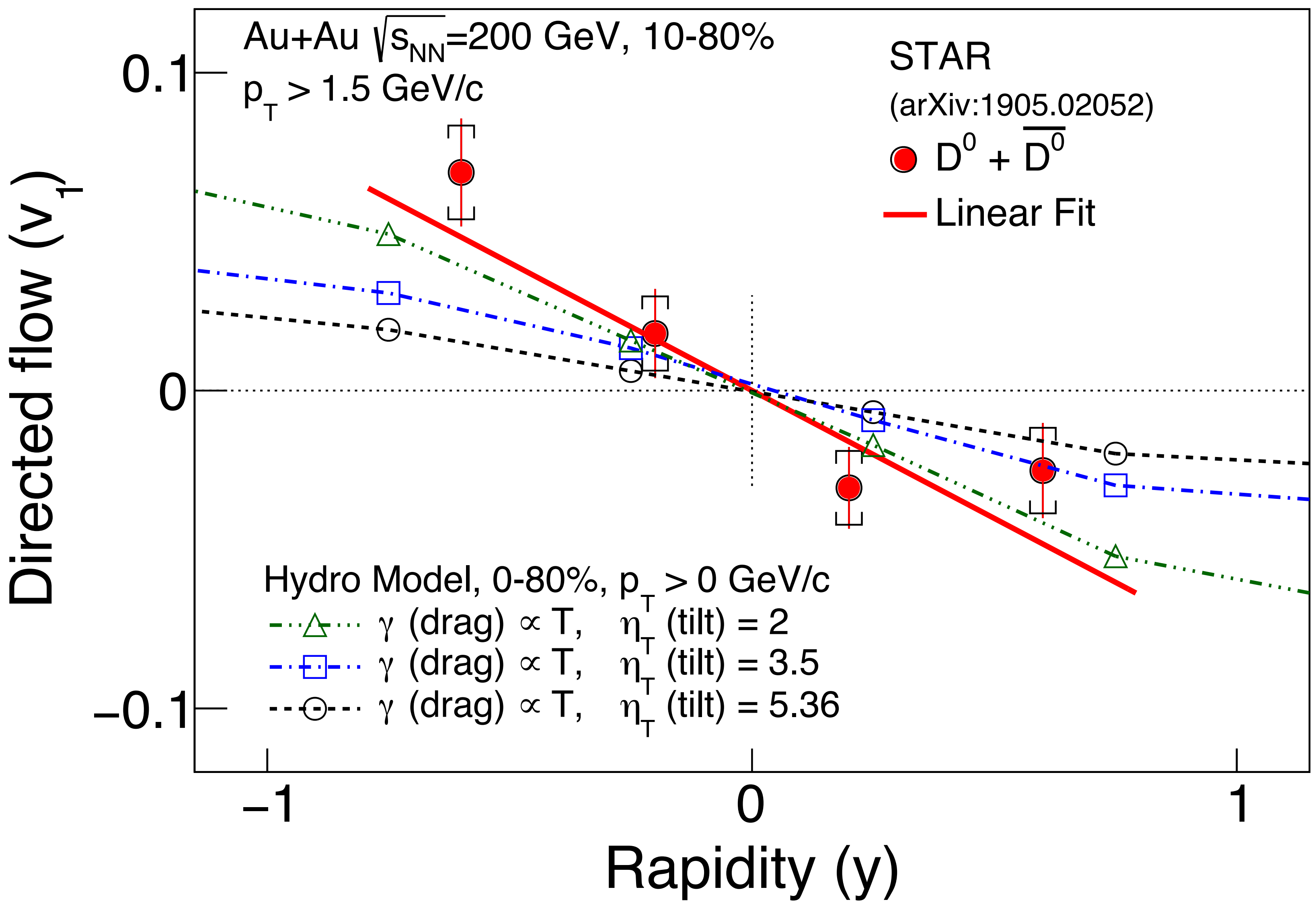
- Our data can help constrain model parameters

Hydro+EM:
Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)
Chatterjee, Bozek: 1804.04893v1

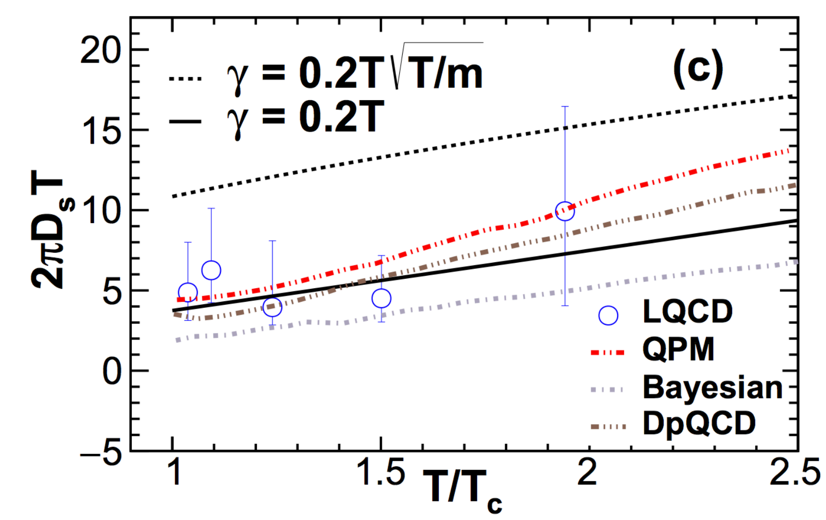
AMPT:
Singha, Nasim: Phys Rev C 97, 064917 (2018)

D^0 v_1 : data vs. hydro

J Adam et. al. (STAR Collaboration), arXiv 1905.02052

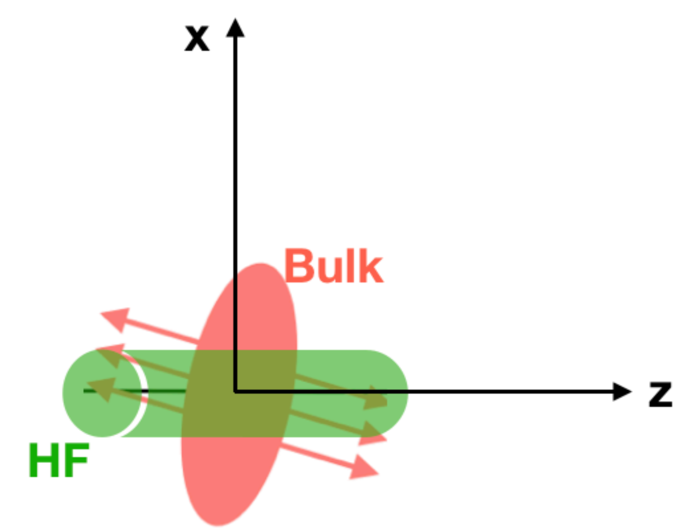


Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)



Smaller tilt

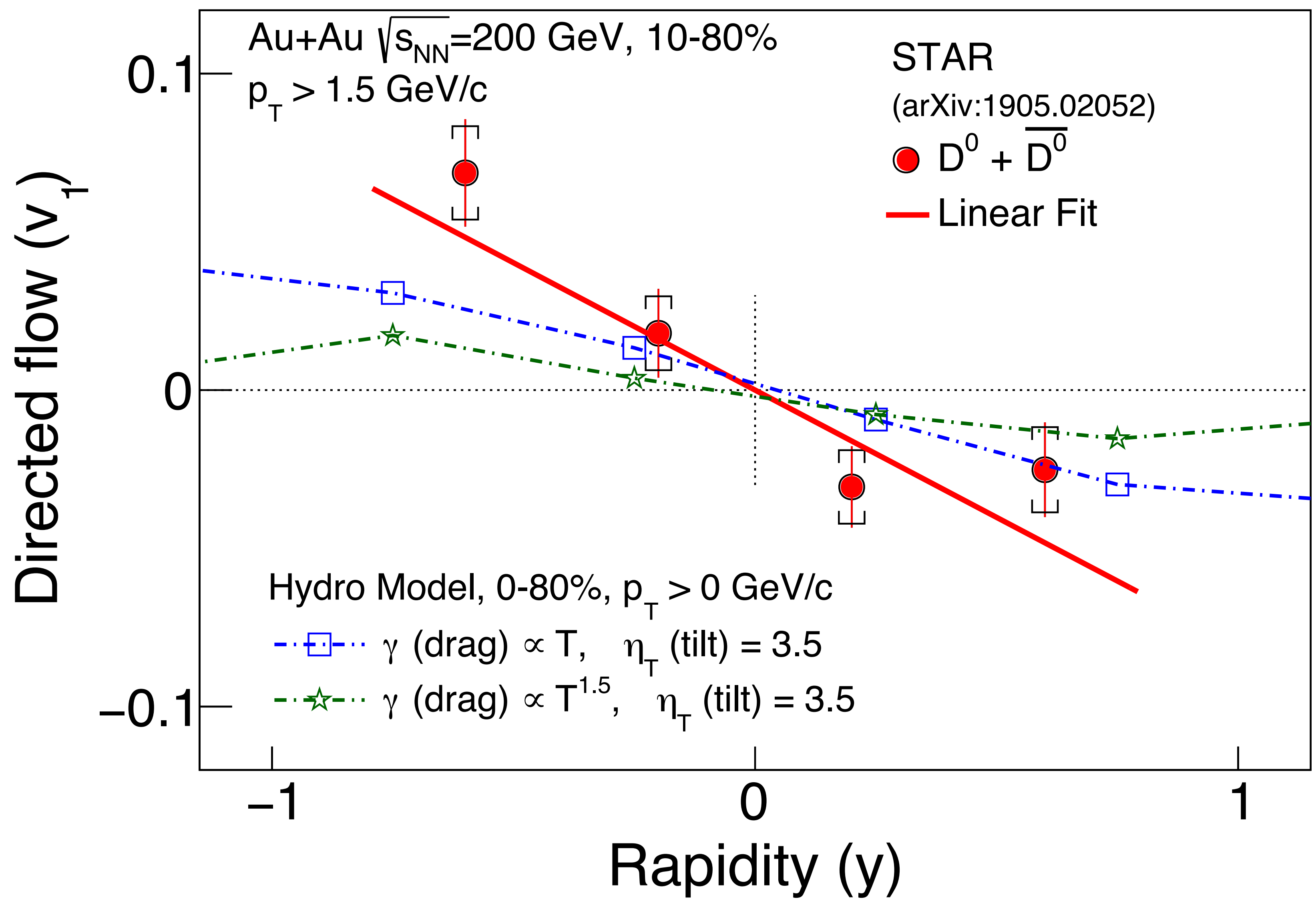
Larger tilt



- 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

J Adam et. al. (STAR Collaboration), arXiv 1905.02052



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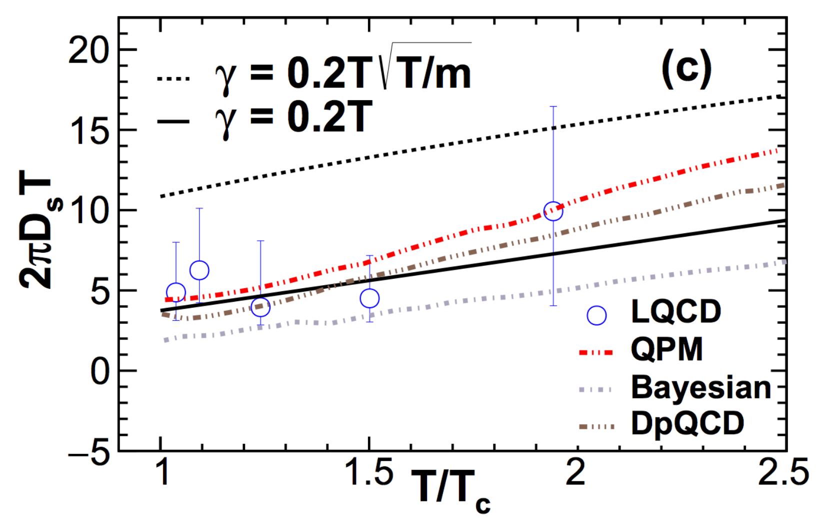


Larger drag coefficient

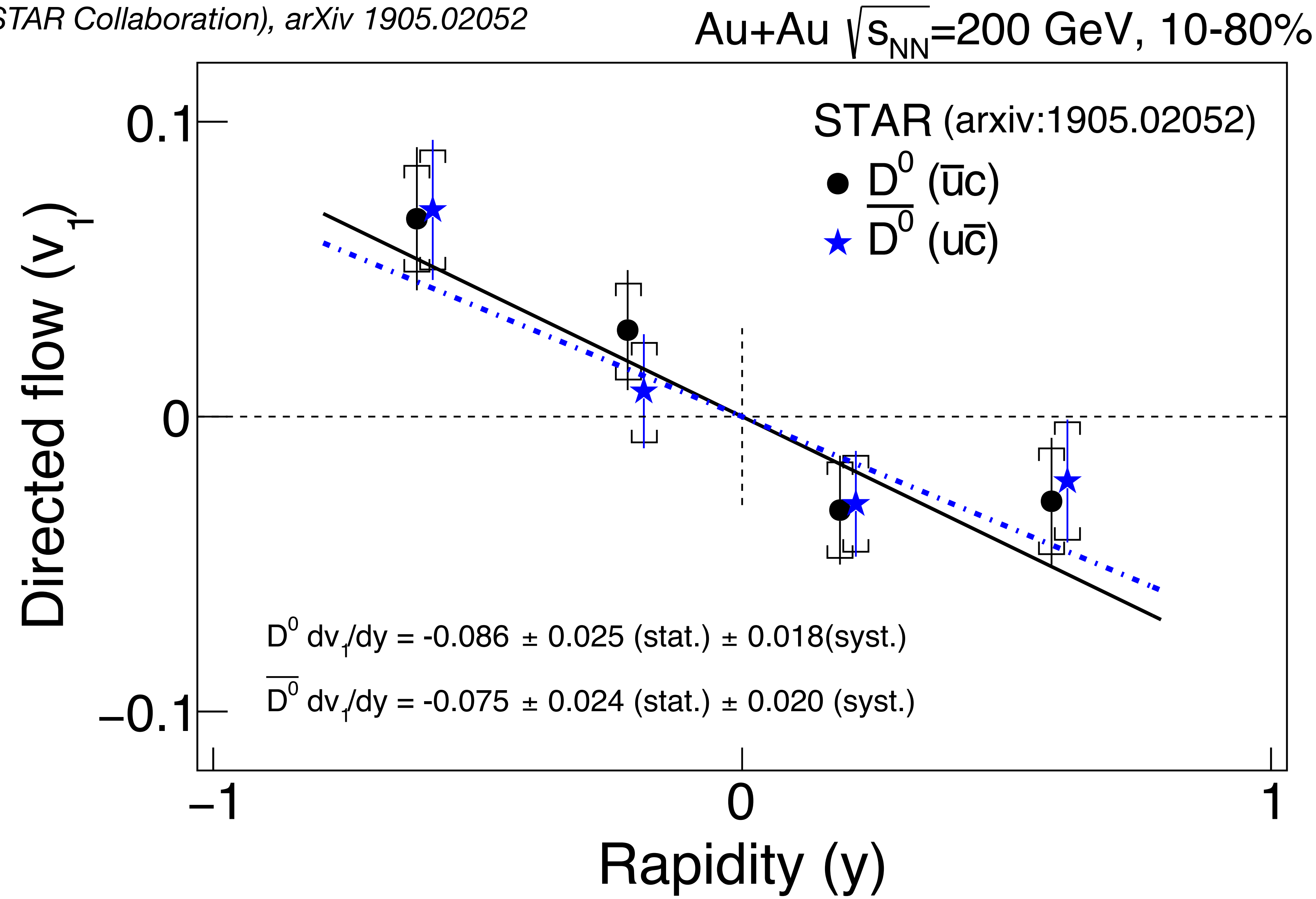
Smaller drag coefficient

- 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

J Adam et. al. (STAR Collaboration), arXiv 1905.02052

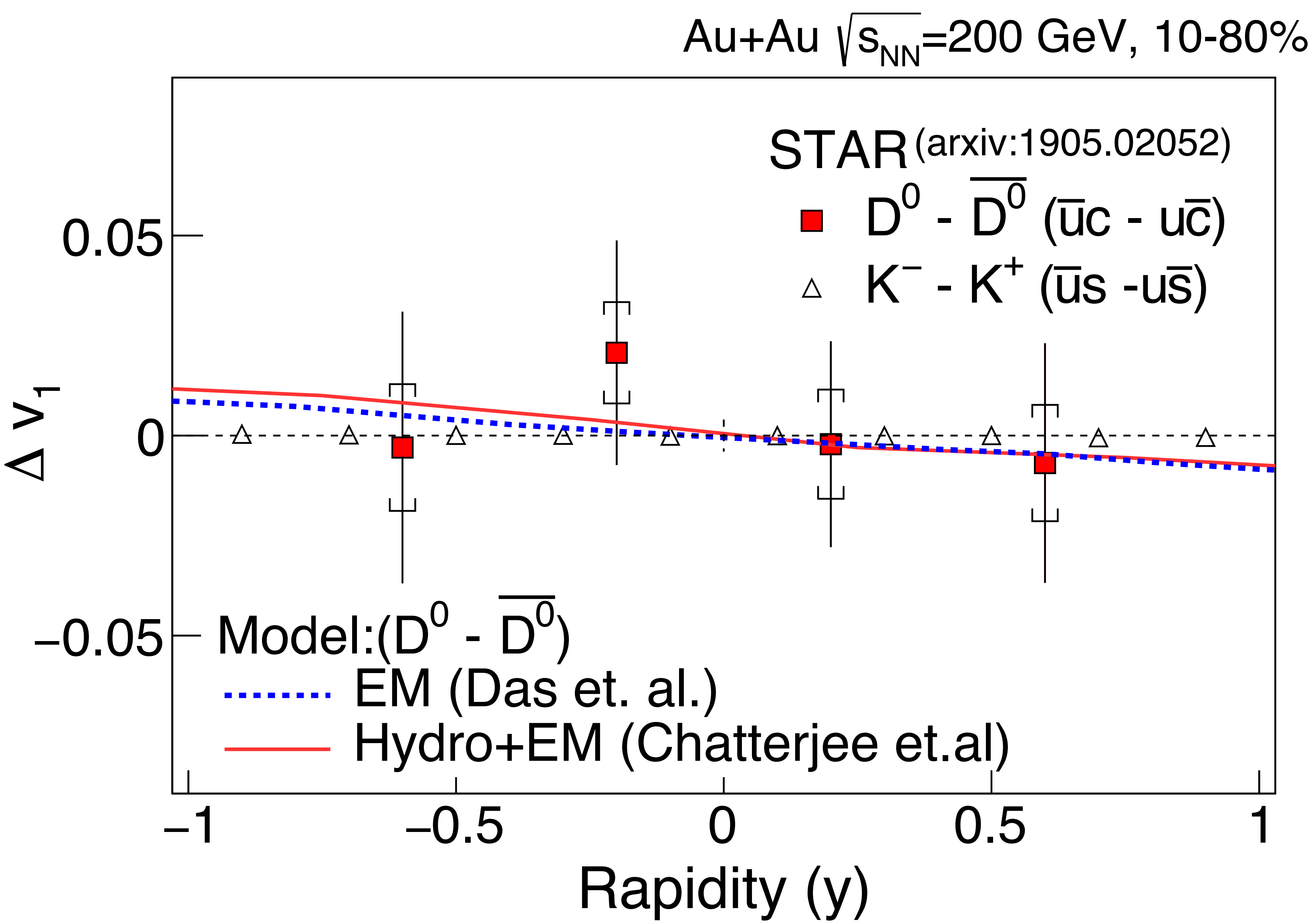


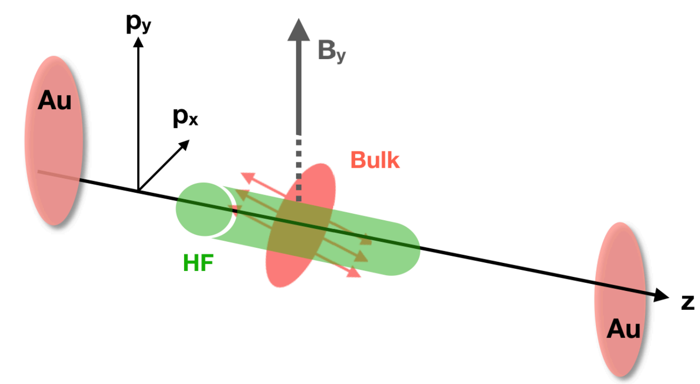
- Both D^0 and $\overline{D}^0$ v_1 show a negative slope at mid-rapidity

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

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

J Adam et. al. (STAR Collaboration), arXiv 1905.02052





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 $\overline{D}^0$ v_1 is a few percent
- Within current precision no v_1 splitting is observed

Summary

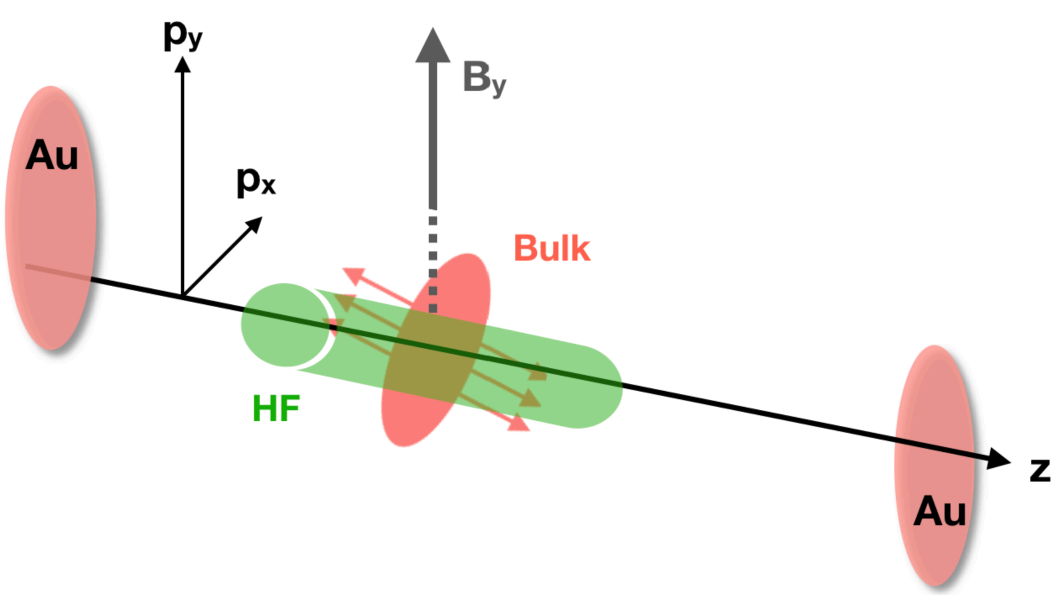
- First evidence of non-zero directed flow for heavy-flavor

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

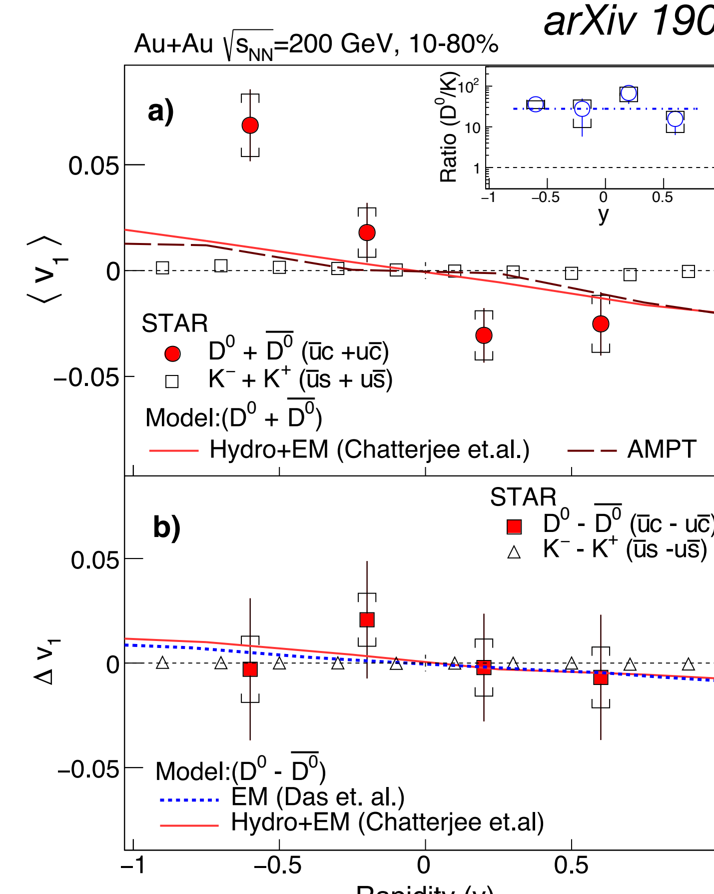
  Data can be used to constrain the initial tilt in the distribution of the matter

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

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



arXiv 1905.02052



Subhash Singha, IS 2019