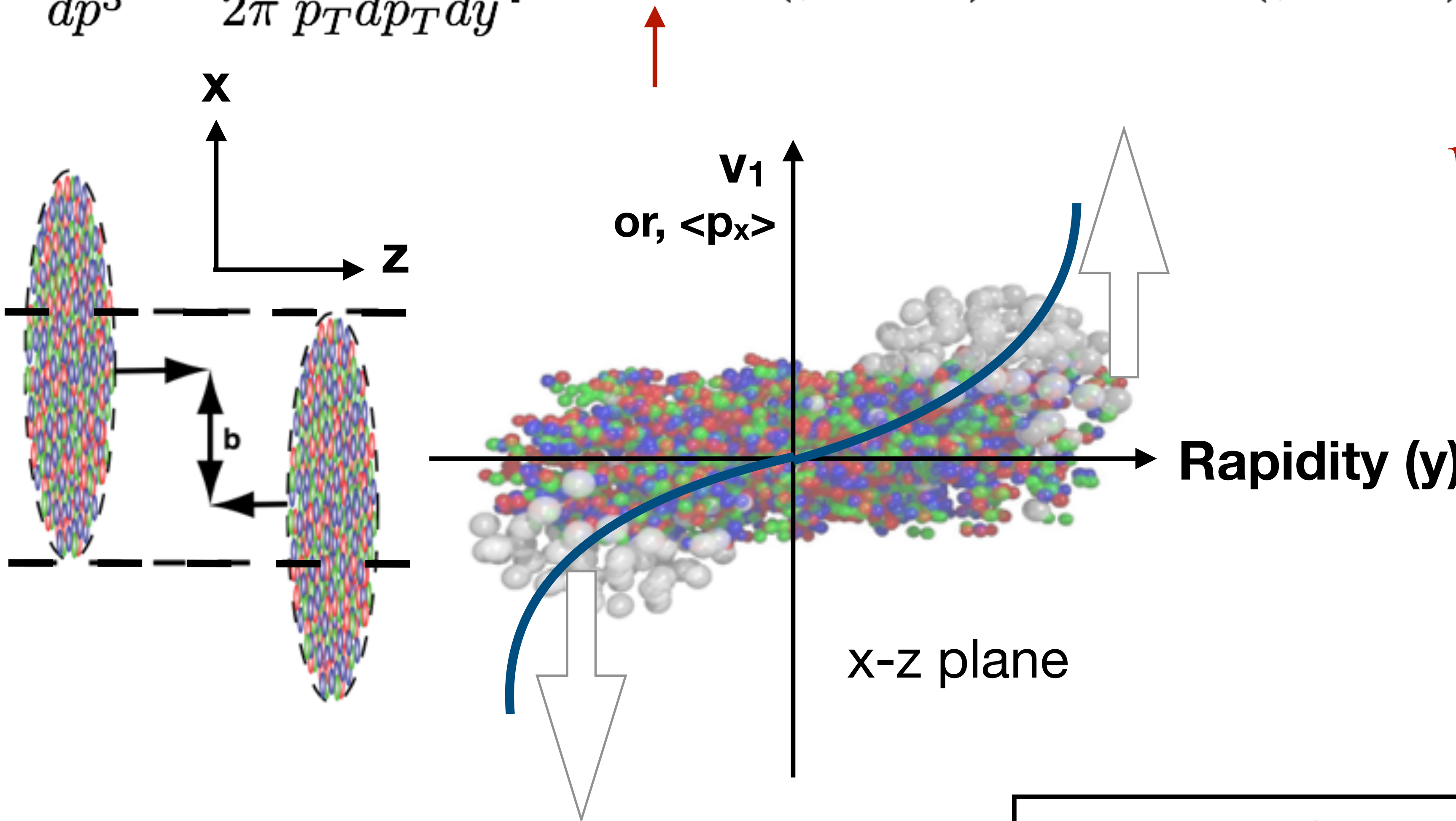
First observation of the directed flow of D^0 and $\overline{D^0}$ in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Subhash Singha
Kent State University
(for the STAR Collaboration)

Directed flow in heavy-ion collisions

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



$$v_1 \sim \langle \cos(\phi - \Psi) \rangle$$

ϕ is azimuthal angle of produced particles,

Ψ is the reaction plane angle

- Directed flow is the sideward collective motion of the produced particles within the reaction plane (x-z plane)
- Directed flow developed early in the collisions around time scale 2R/γ ~ 0.1 fm/c
- Probe of early stage of collisions

Rischke et. al. Heavy Ion Physics 1, 309 (1995)
Herrmann et. al. Annu. Rev. Nul Part Sci 49, 581 (1999)
Snellings et. al. hys Rev Lett 84, 2803 (2000)
Stocker et. al. Nucl Phys A 750, 121 (2005)

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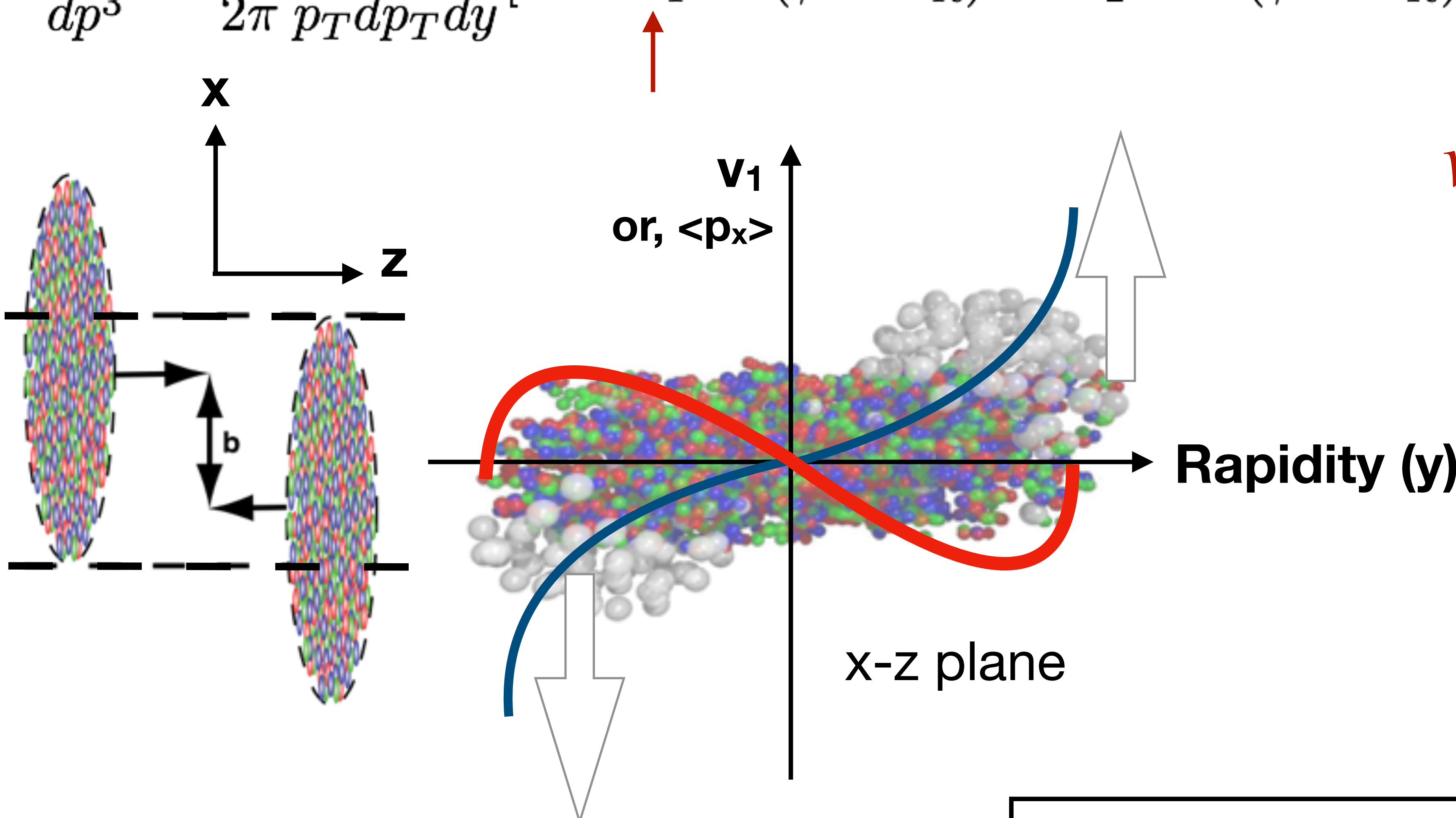

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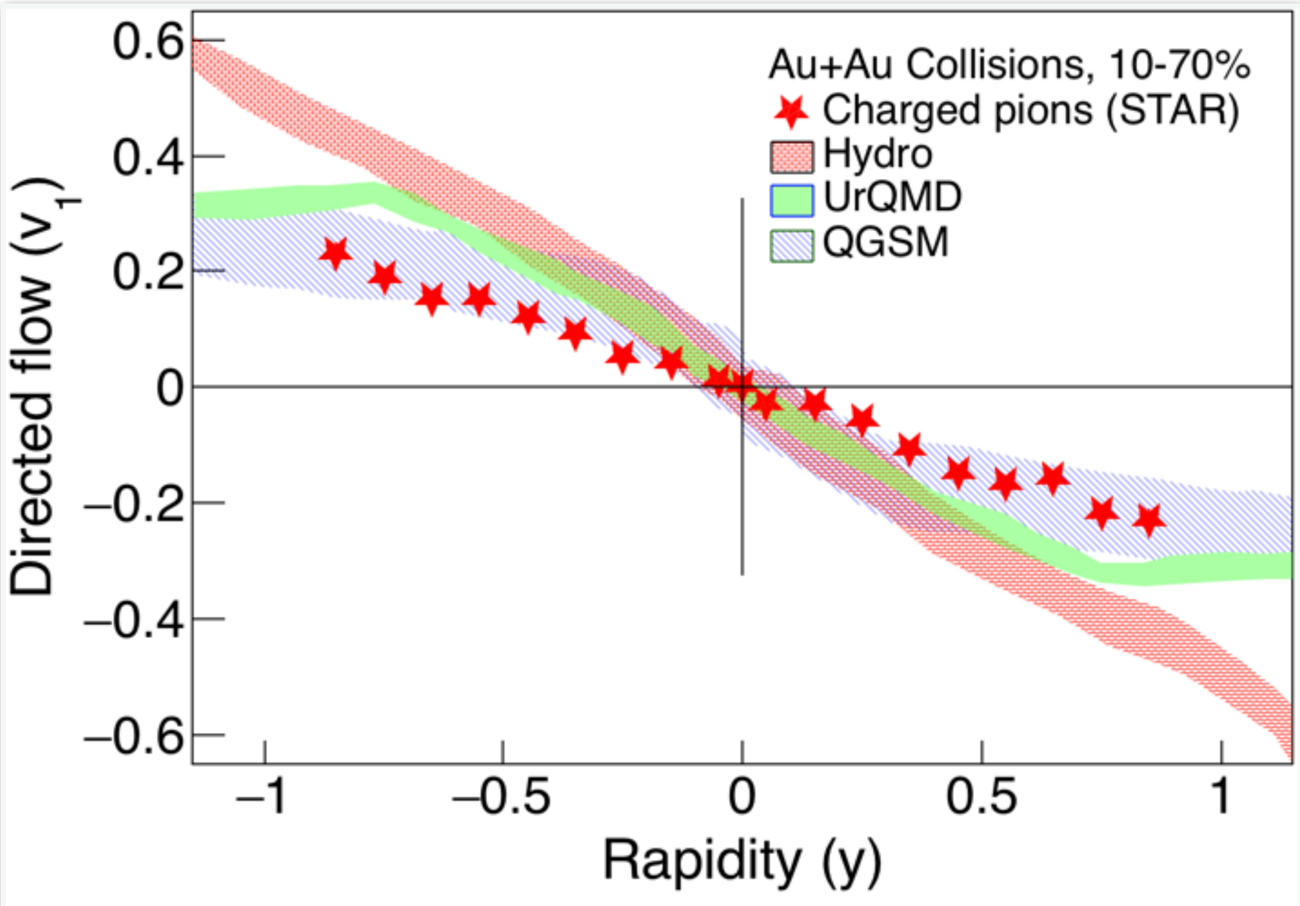
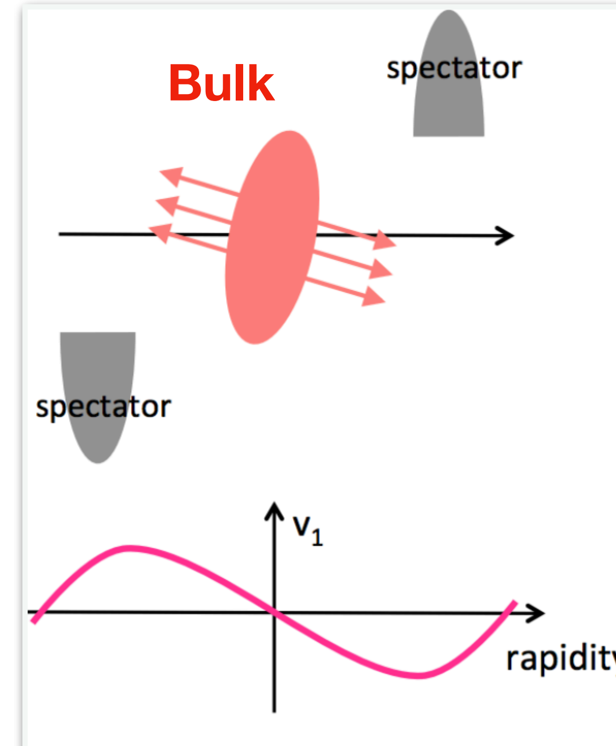
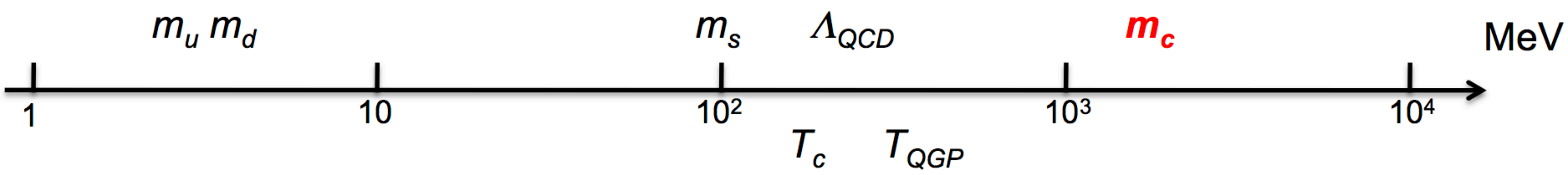




L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 108, 202301 (2012)
Hydro: P. Bozek, I. Wyskiel, Phys Rev. C. 81, 054902 (2010)
UrQMD: H. Peterson et al, Phys Rev. C. 74, 064908 (2006)
QGSM: J. Beibel et al, Phys Rev. C. 76, 024912 (2007)
Transport: R. Snellings, et al, Phys Rev. Lett. 84, 2803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

Uniqueness of heavy quarks



- $m_c >> T_{QGP}$ Heavy quarks are predominantly created from initial hard scatterings
- Due to early production, they can witness the entire evolution of the matter
- Heavy quarks relaxation time ~ lifetime of QGP

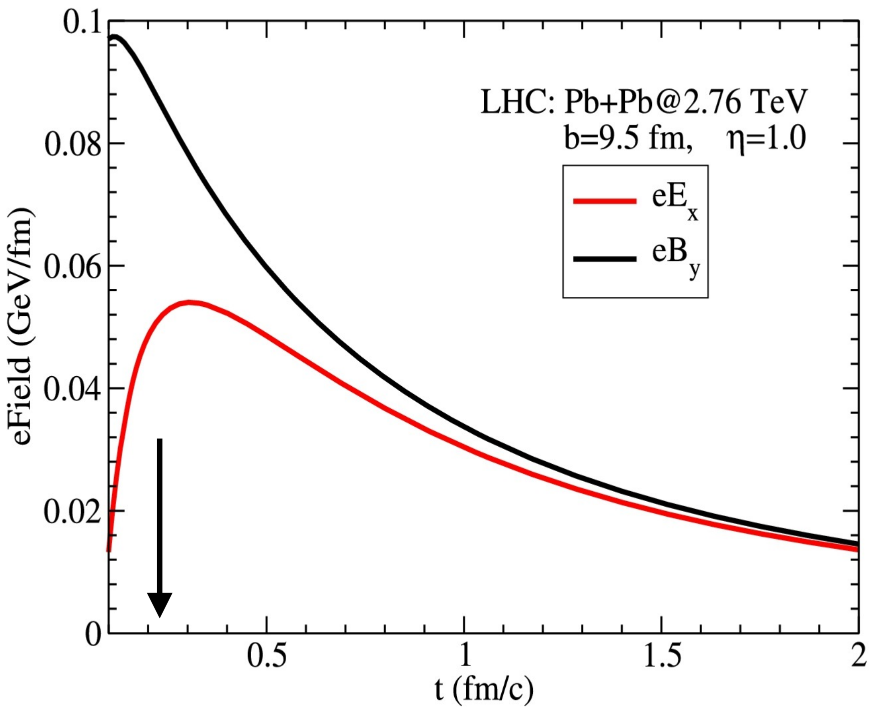
Ideal probe to study medium effects

Probe various aspect of QGP and its evolution through heavy quarks

- Initial state conditions (v_1)
- Transport (v_1, v_2, v_3)
- Energy loss (R_{AA}, R_{CP})
- Hadronization (particle ratios)

Heavy quarks with Initial EM field

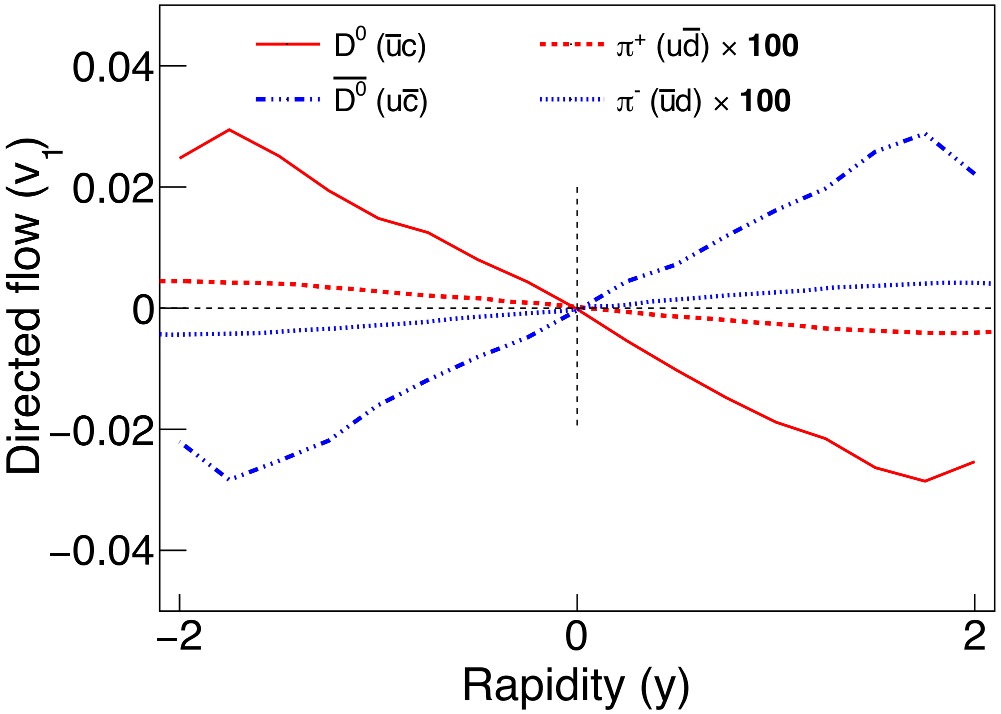
Gursoy et. al., Phys Rev C 89, 054905 (2014)



Induce charge dependent opposite signed v_1 for particles and ant-particles

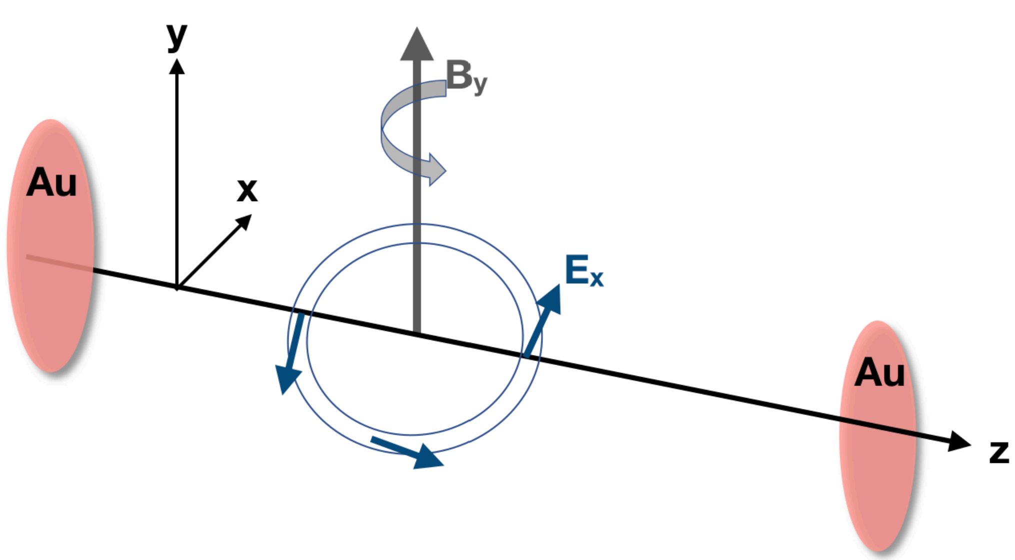
Das et. al., Phys Lett B 768, 260 (2017)

EM



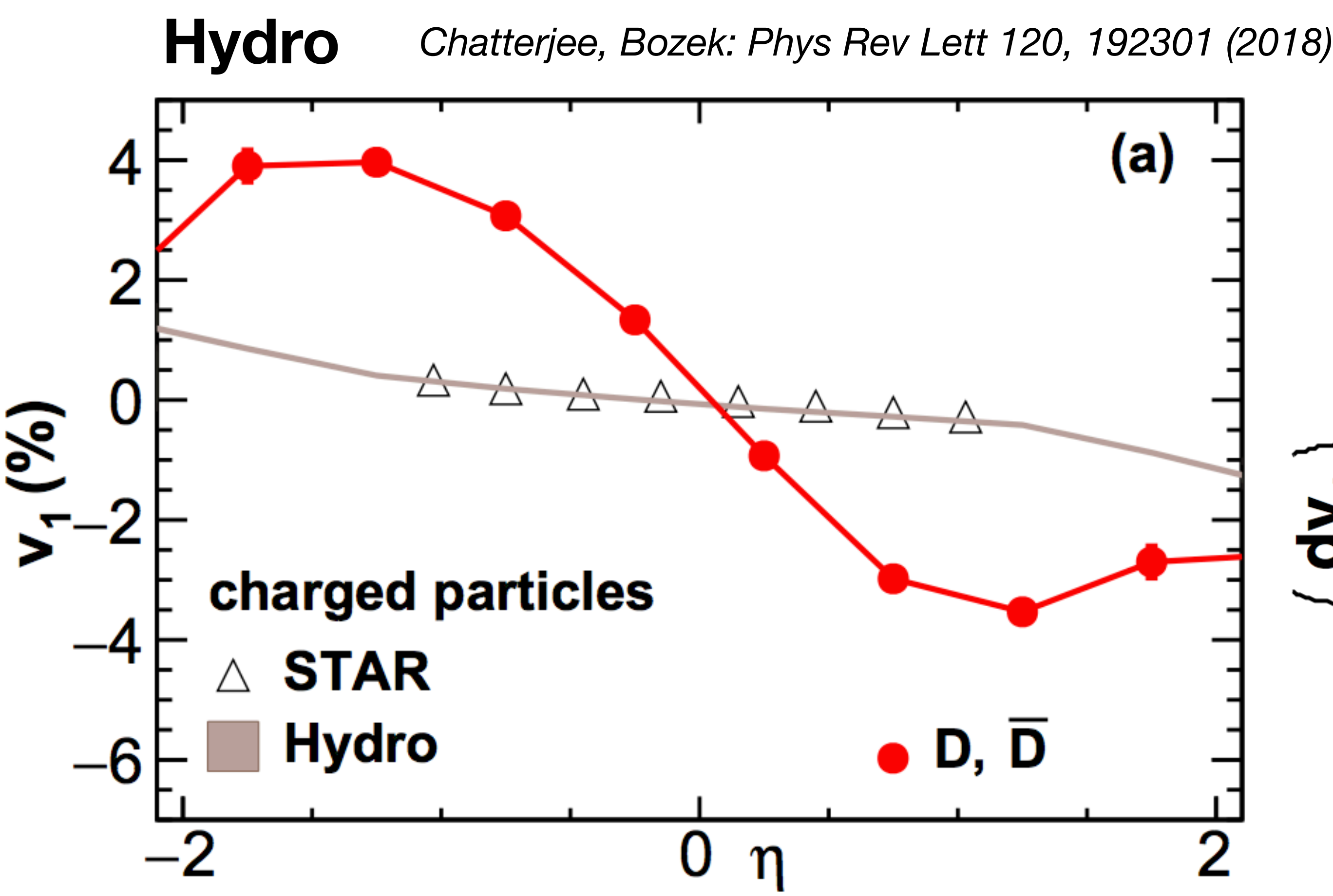
Das et. al., Phys Lett B 768, 260 (2017)

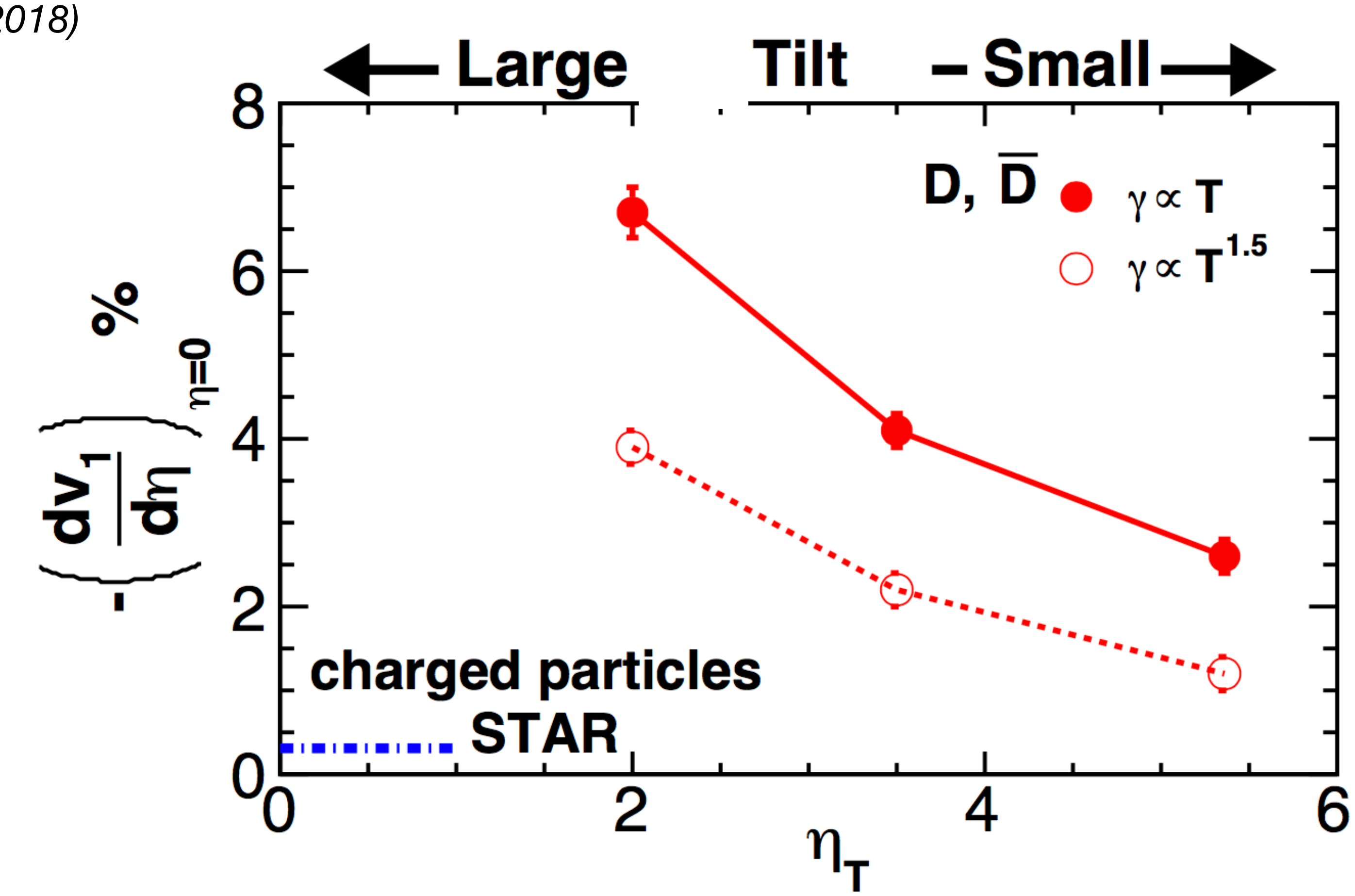
- Incoming charge particle can produce very strong electromagnetic (EM) field



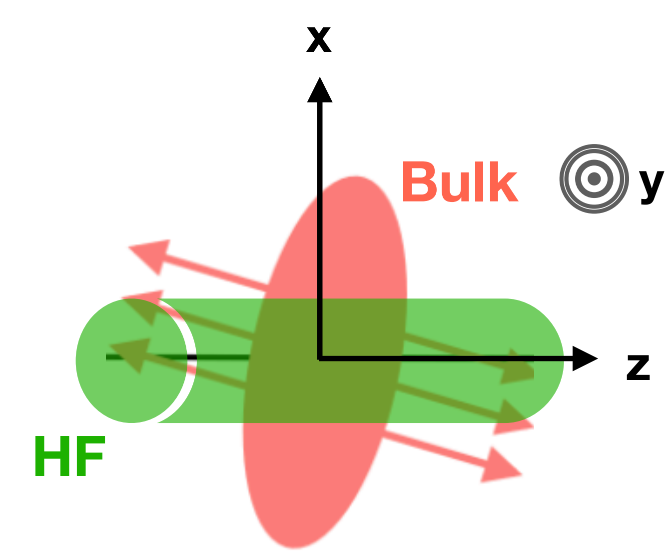
Ideal probe to study initial stage effects

Heavy quarks with hydro evolution



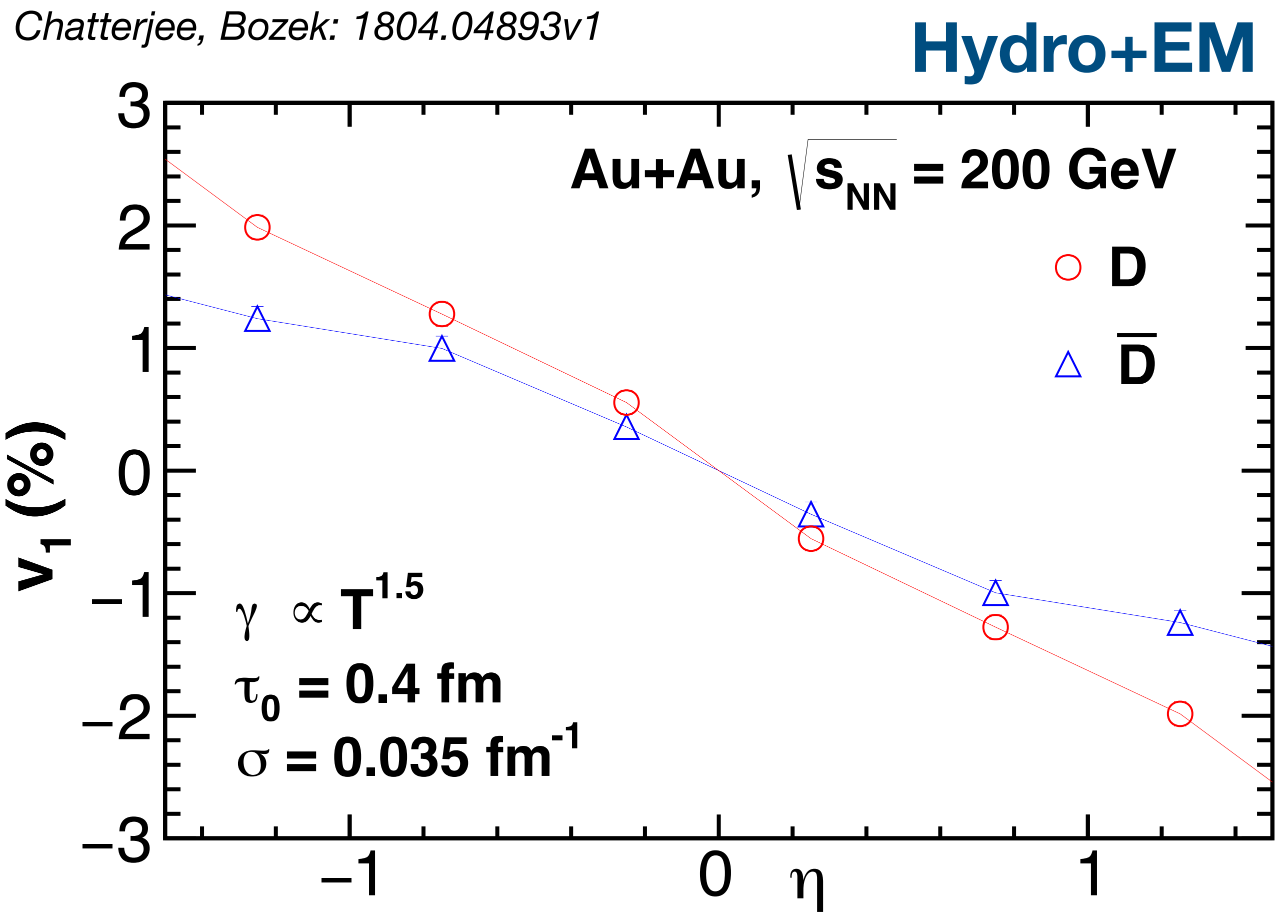


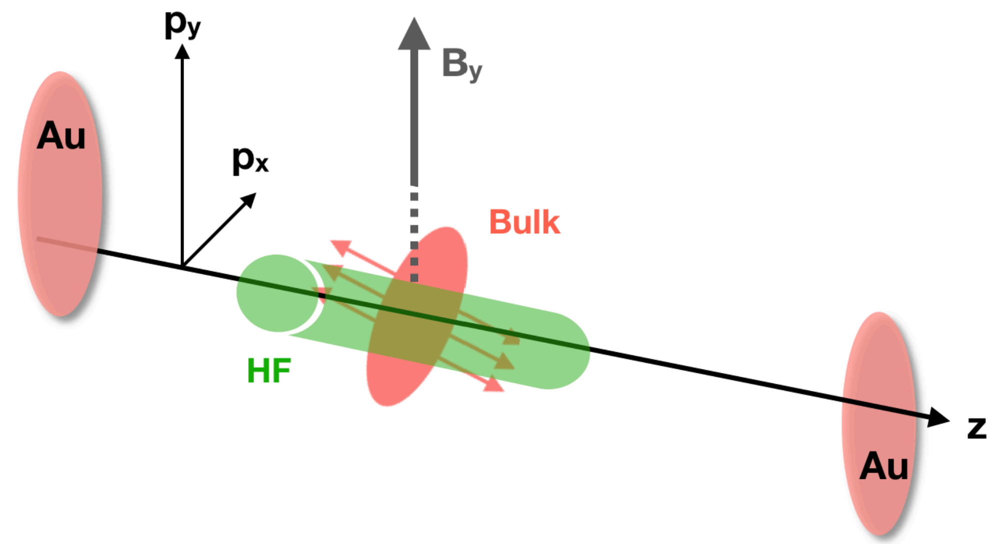
- Heavy quarks follow binary collision density profile, symmetric in rapidity
- Bulk medium may be tilted wrt to z-axis
- Drag by the tilted initial source can induce enhanced directed flow in heavy quarks



D^0 v_1 can probe initial bulk matter distribution

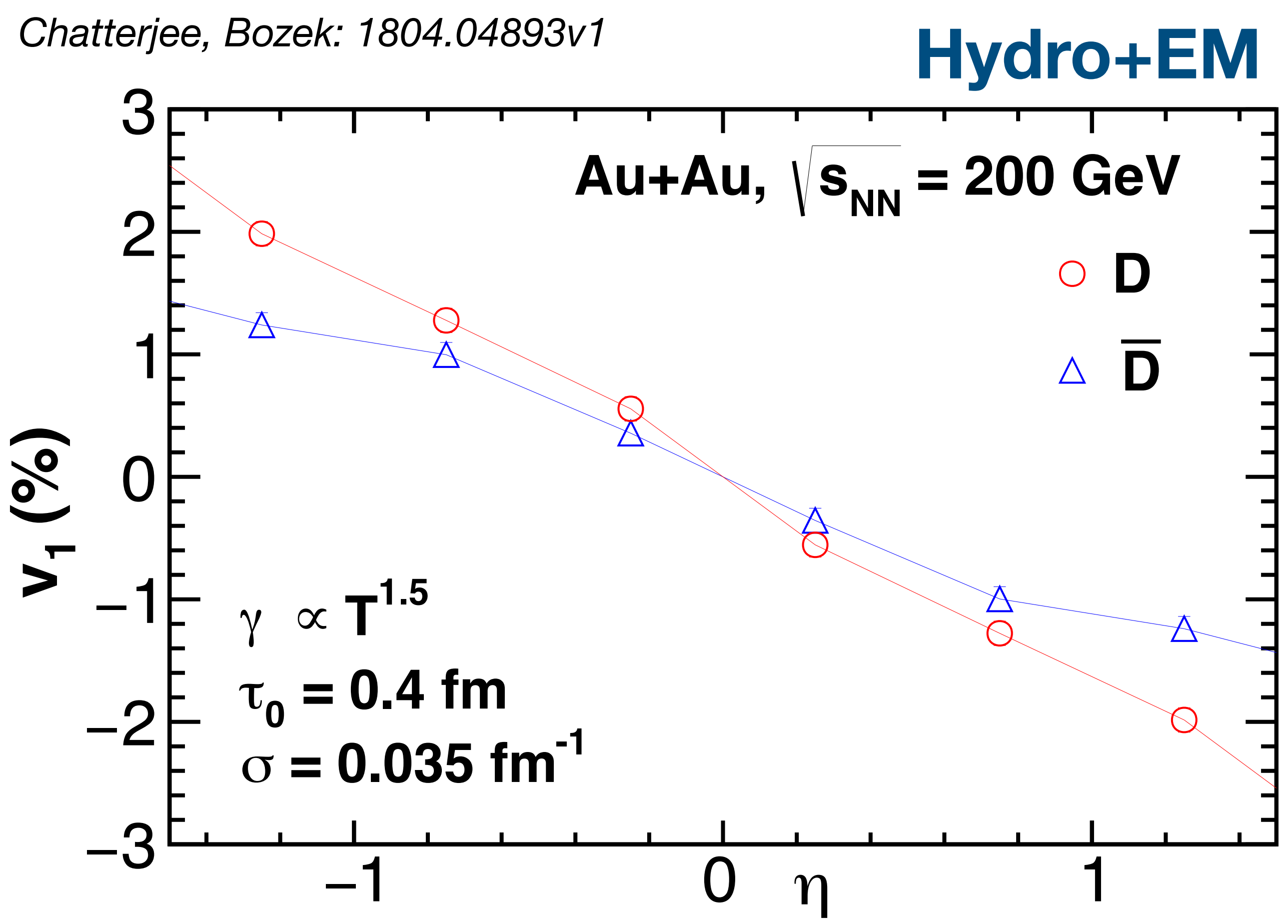
Heavy quark v_1 from Hydro+EM field

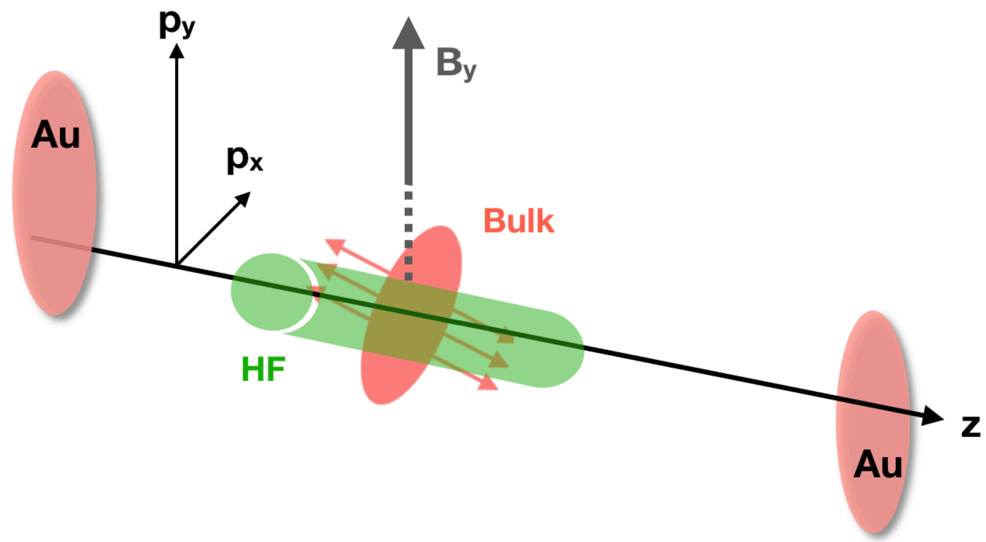




- Predicted v_1 of D meson is greater than that of $\overline{D}$ meson
- Predicted difference in v_1 is about 10 times smaller than the average v_1

Heavy quark v_1 from Hydro+EM field

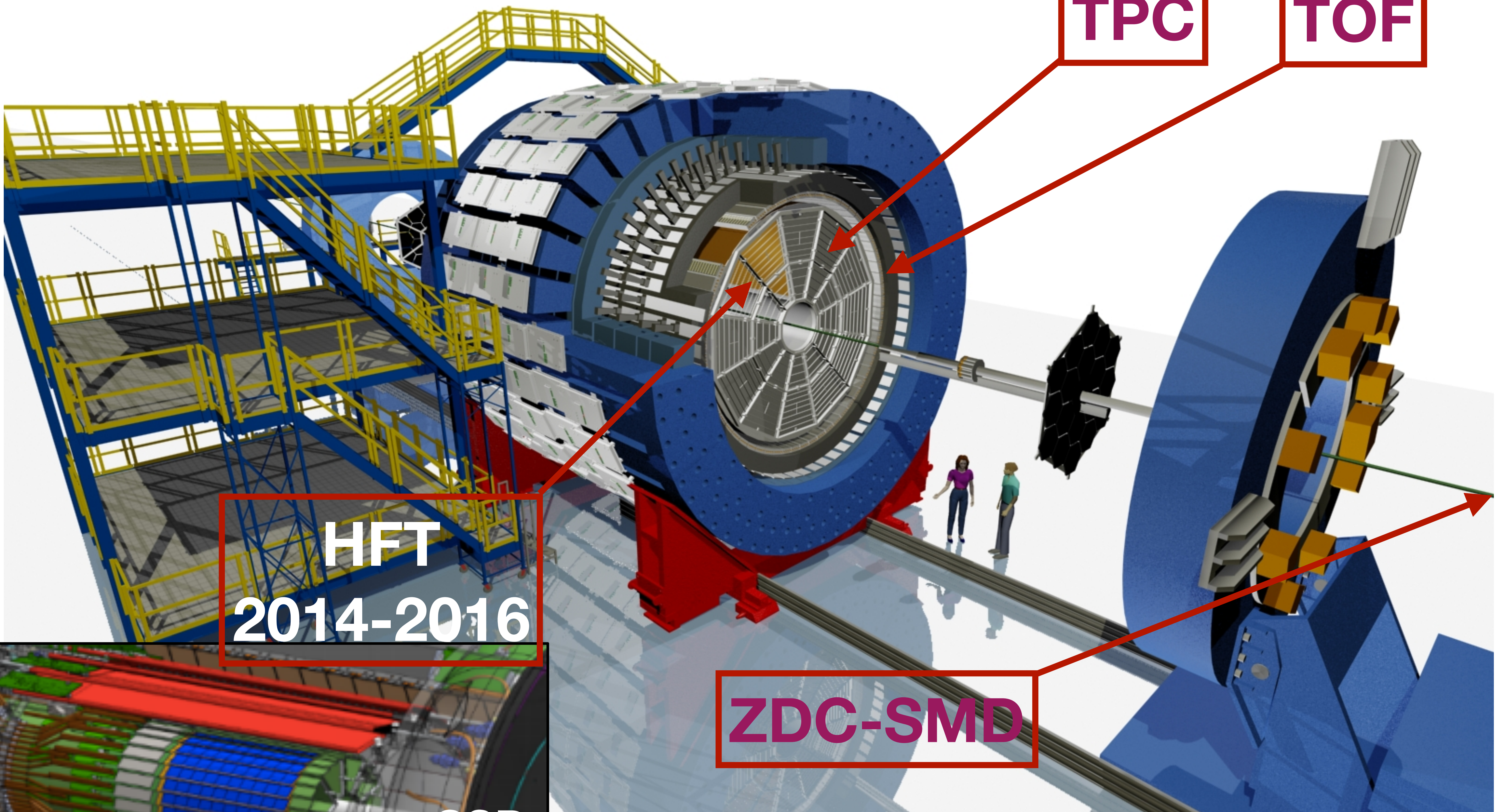


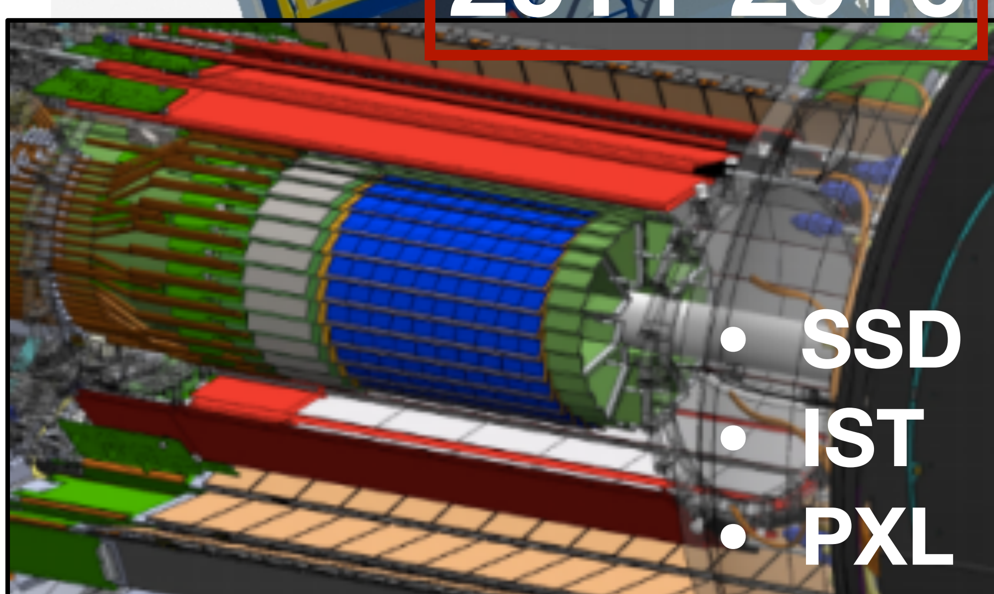


Summarizing v_1 expectation from models

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

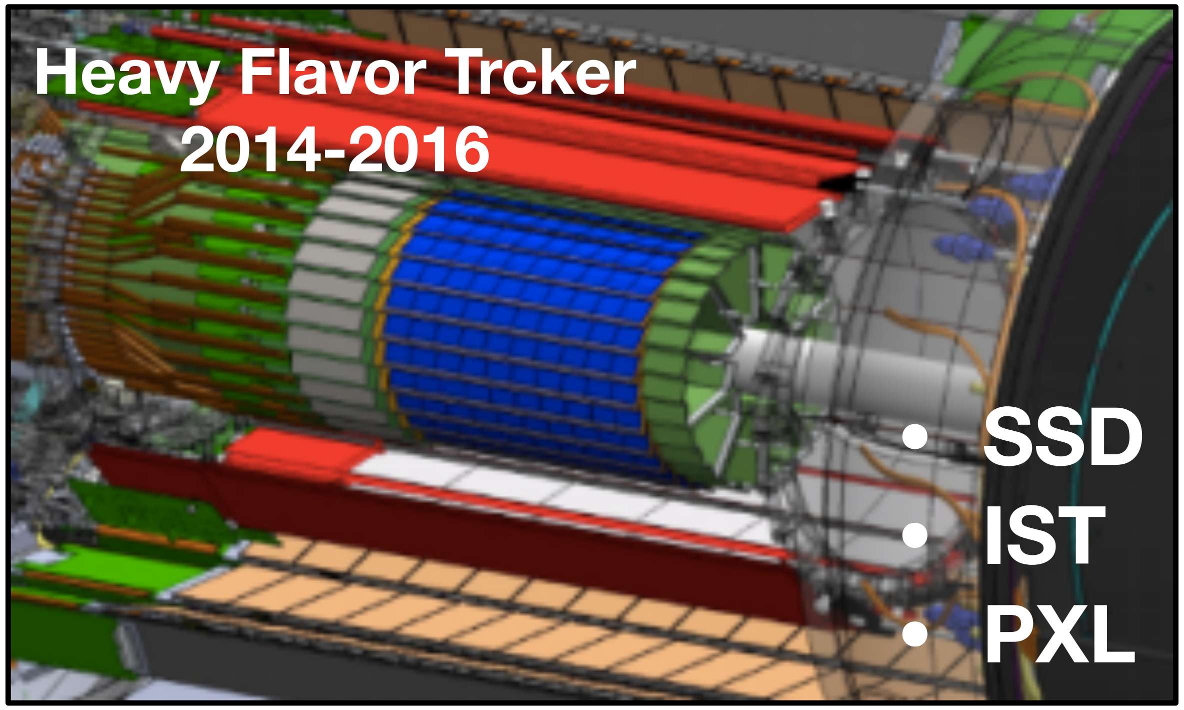
STAR detector



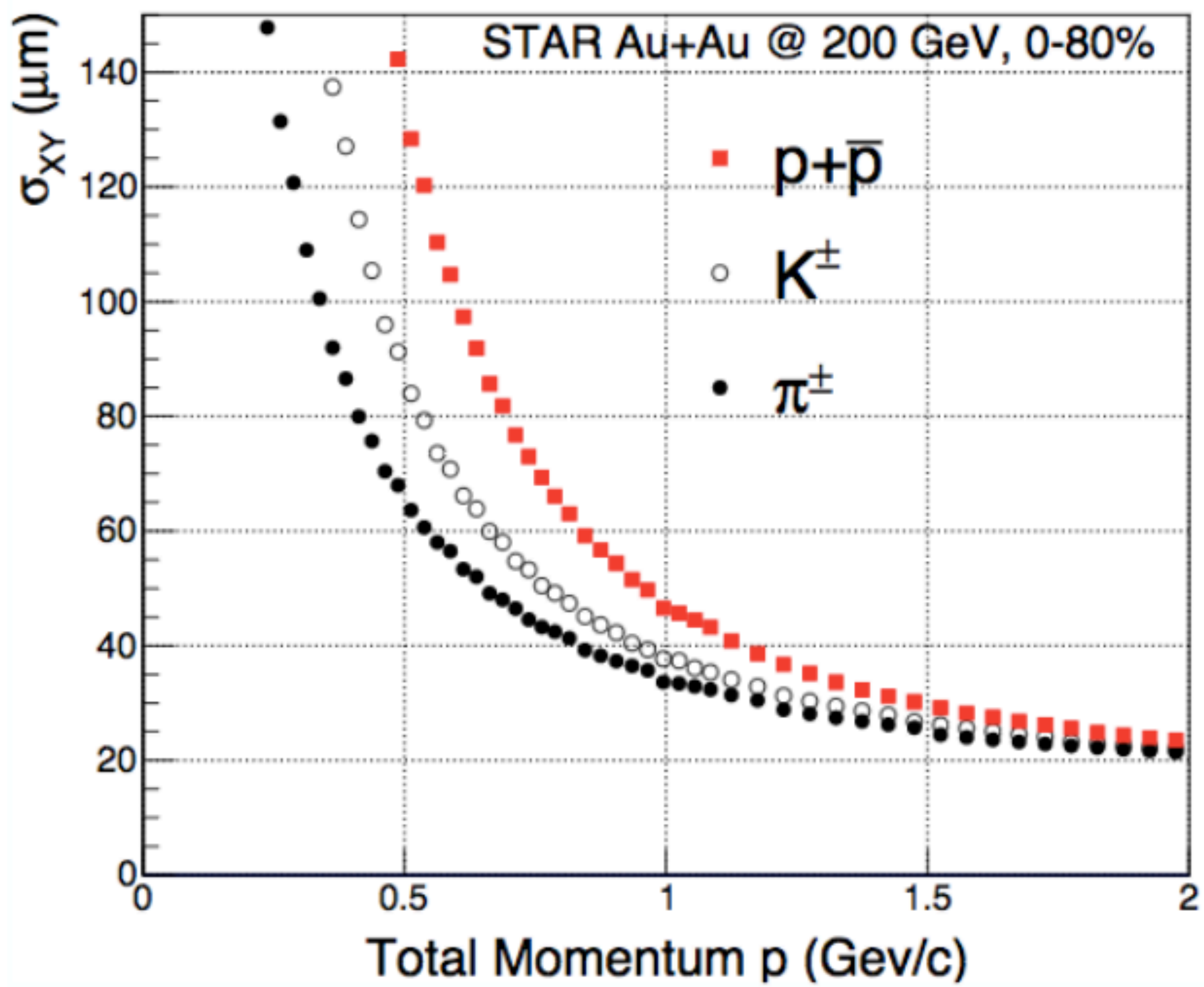


- Full azimuthal coverage (0,2π)
- Excellent PID capabilities

D^0 reconstruction with HFT



DCA$_{XY}$ resolution:

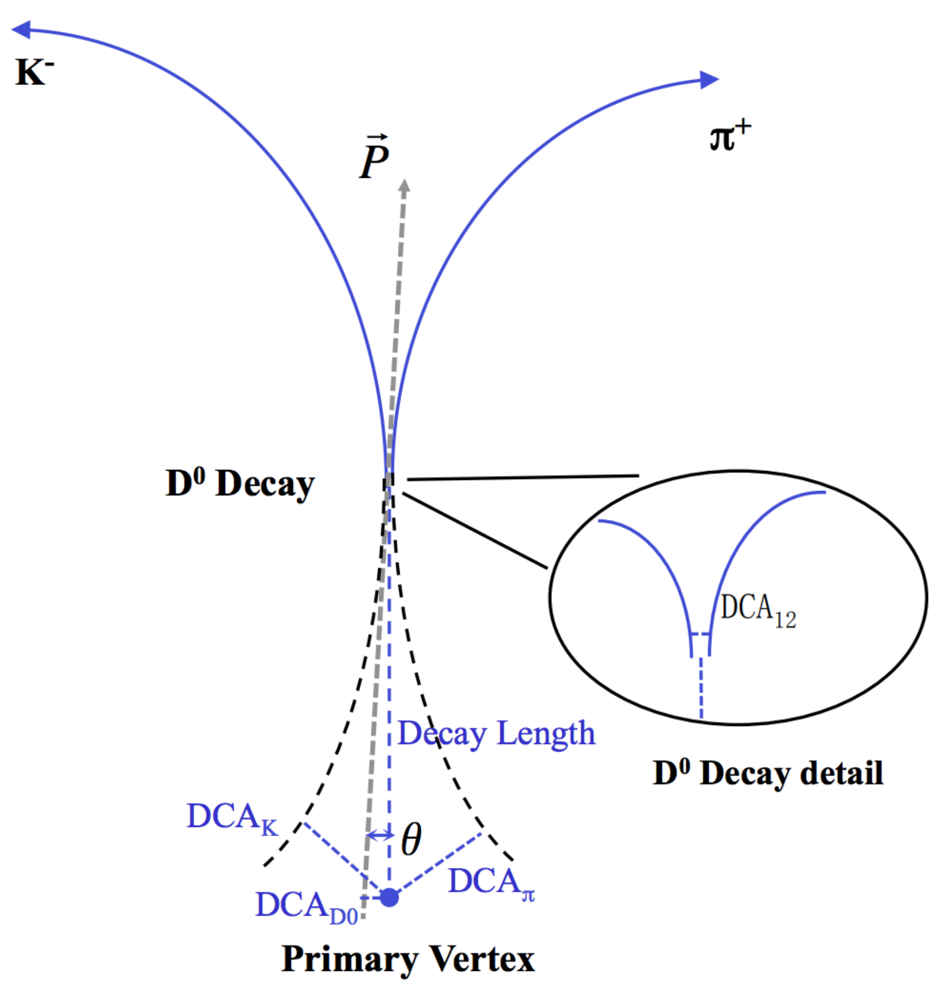


- Pseudorapidity (|η|<1)
- Azimuthal coverage (0,2π)
- Excellent track pointing resolution
- Allows topological reconstruction for heavy-flavor particles
- Greatly reduce combinatorial backgrounds

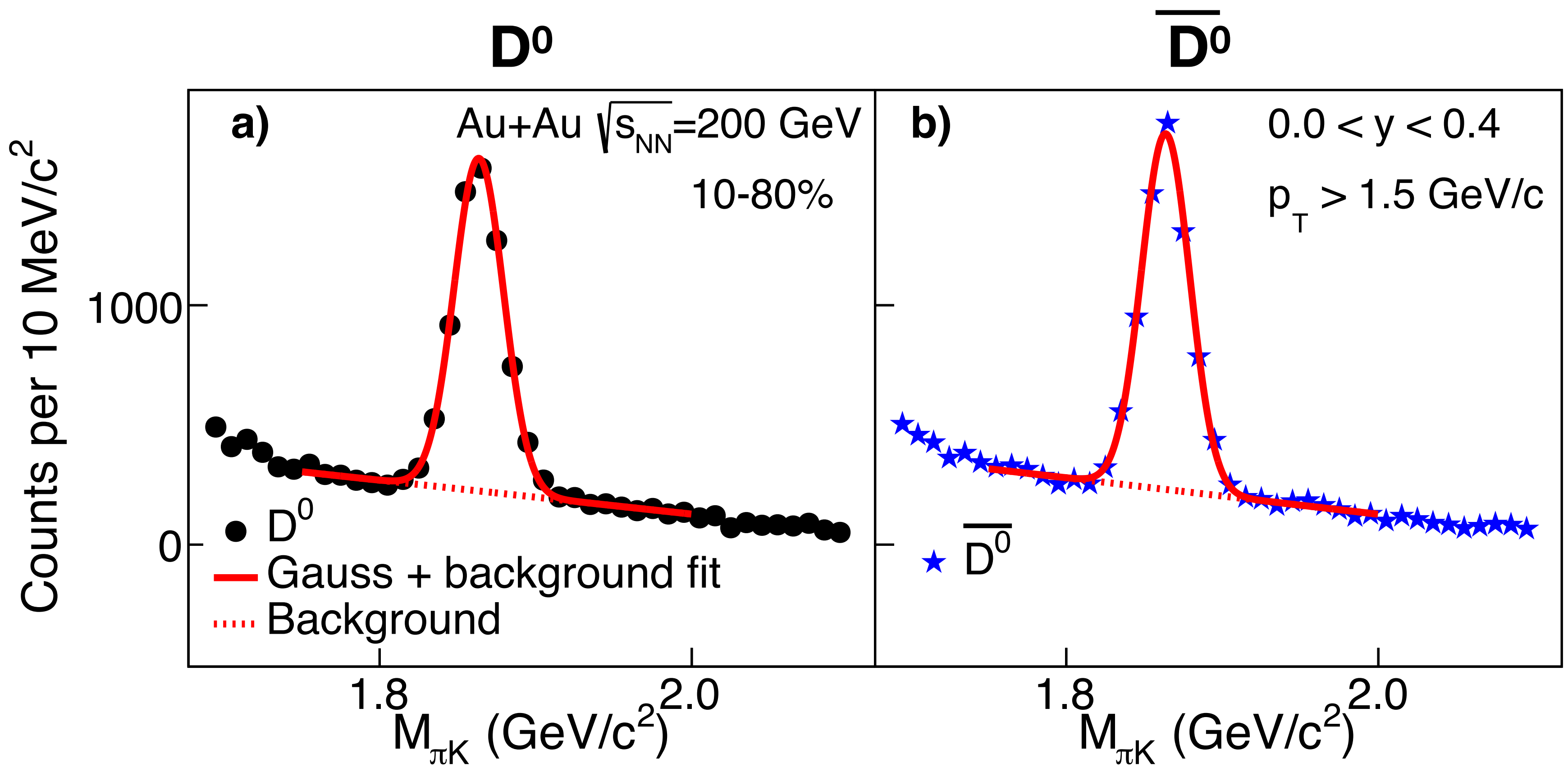
D^0 reconstruction with HFT

D^0 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 ($c\tau$): 120 μm
Mass: 1864.84 +/- 0.18 MeV/c^2
Branching ratio: 3.89%



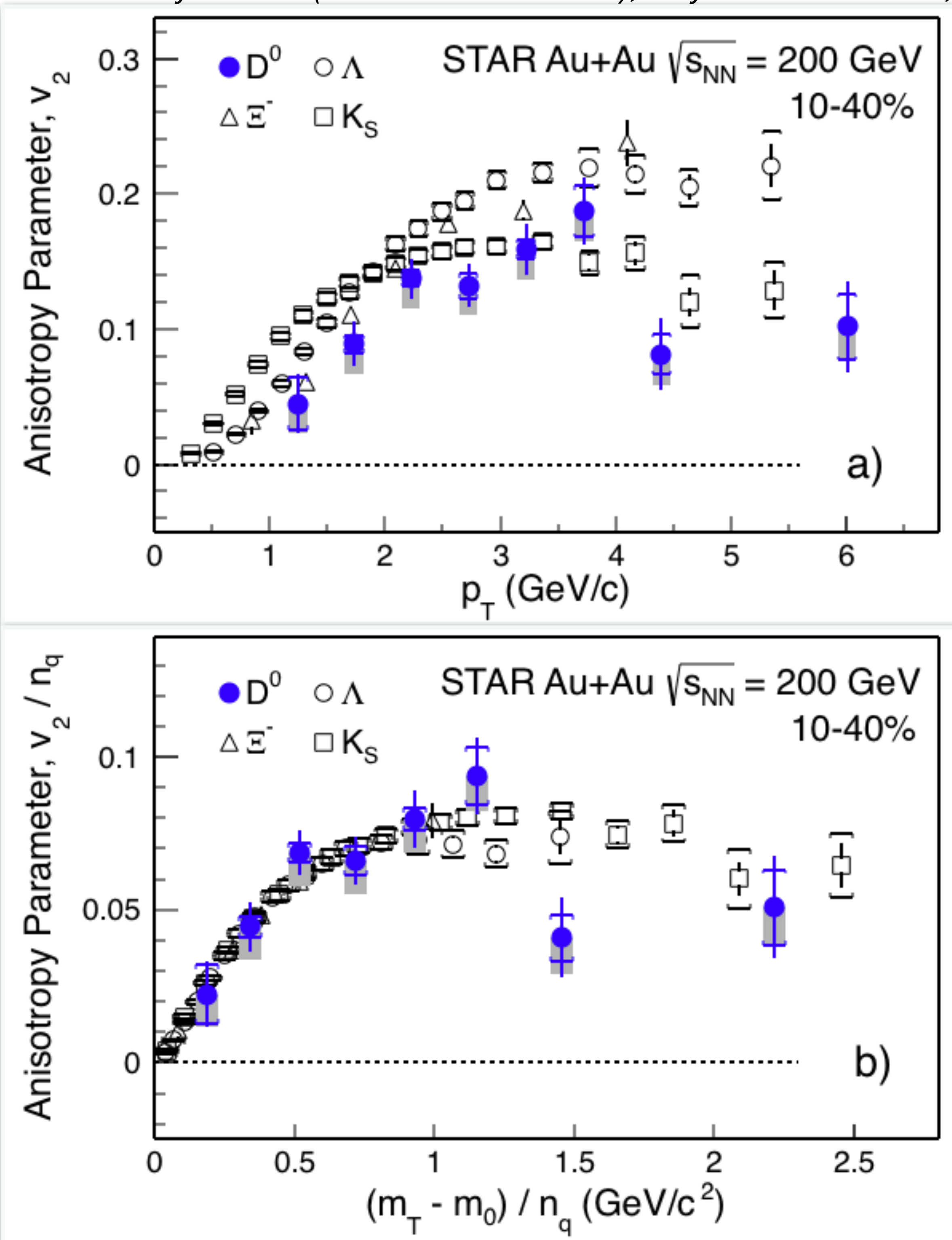
Topological reconstruction



- 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 elliptic flow (v_2) with HFT

L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 118, 212301 (2017)

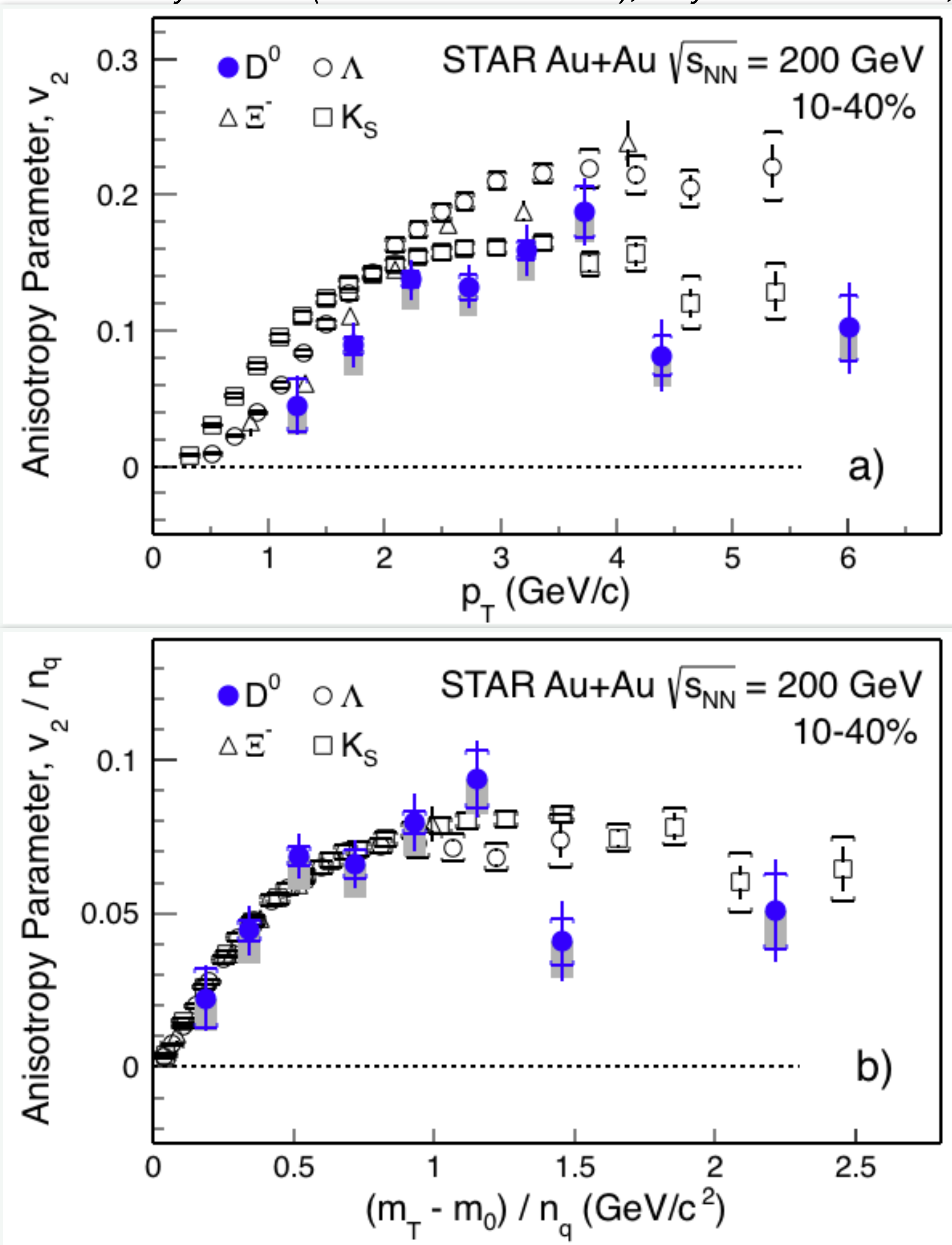


- D^0 flow magnitude comparable to light flavor hadrons
- D^0 flow magnitude consistent with NCQ scaling

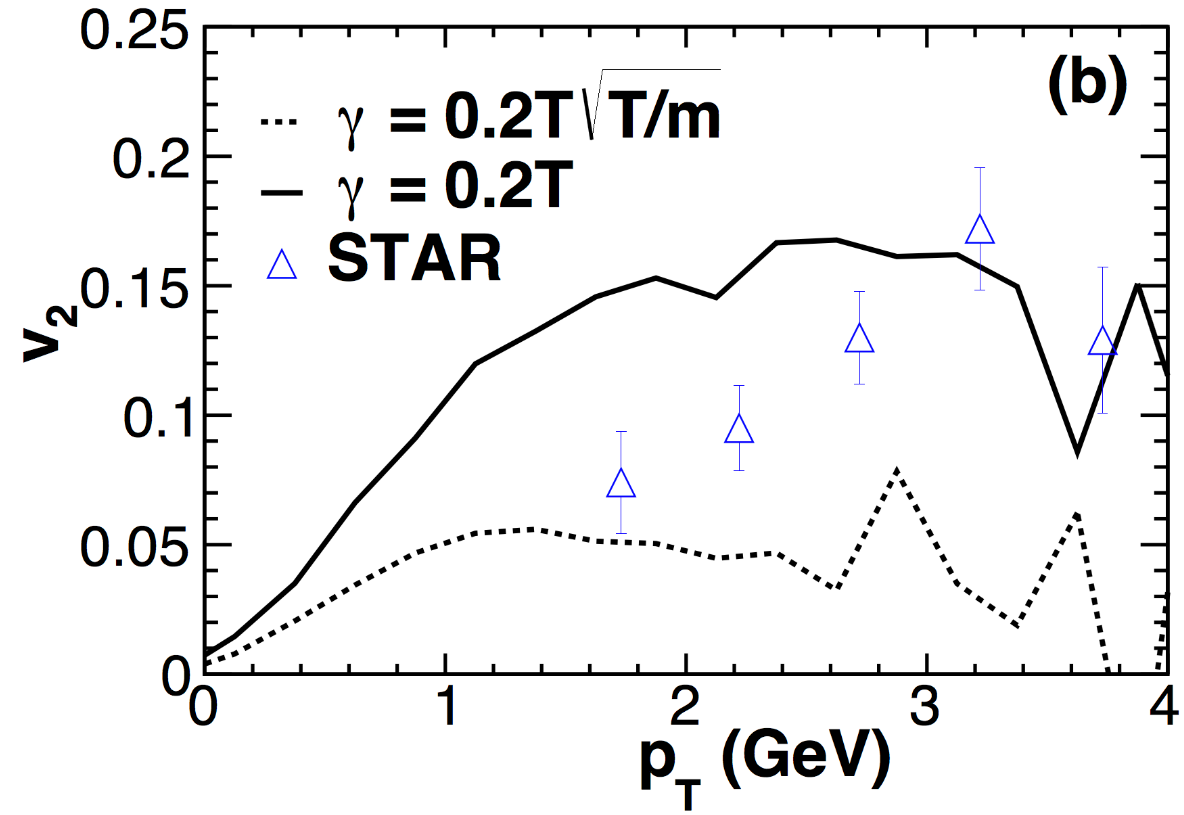
D^0 v_2 result suggests charm quarks achieve a thermal equilibrium with the medium

D^0 elliptic flow (v_2) with HFT

L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 118, 212301 (2017)



Hydro

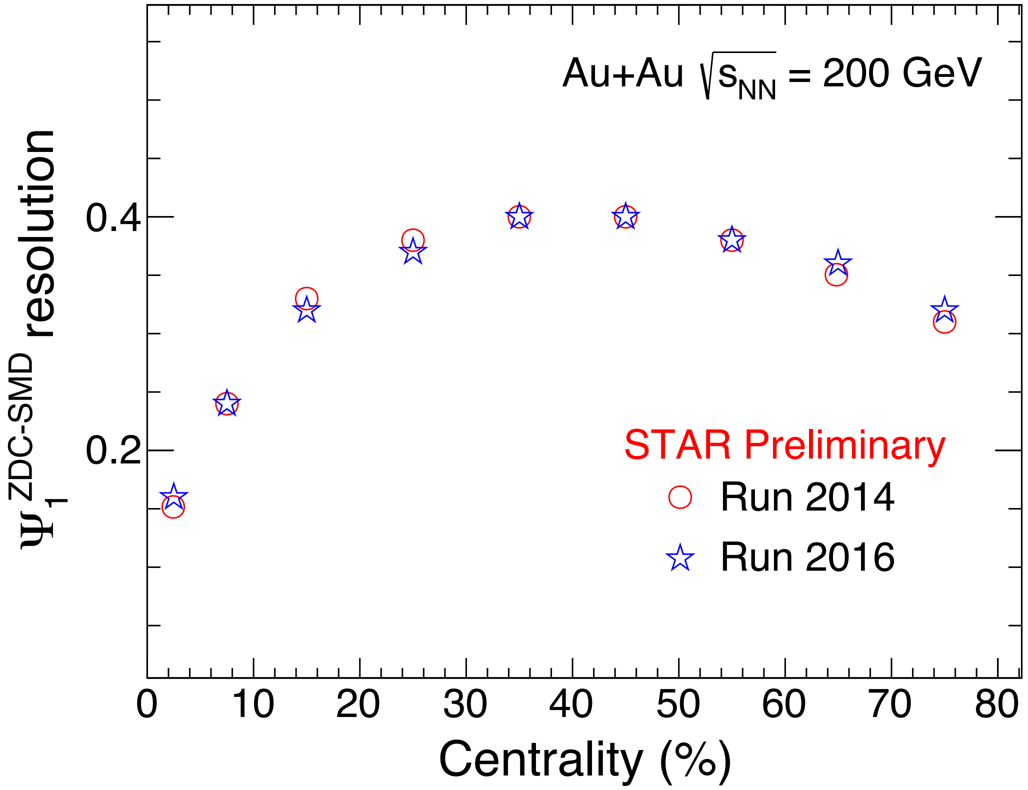


Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)

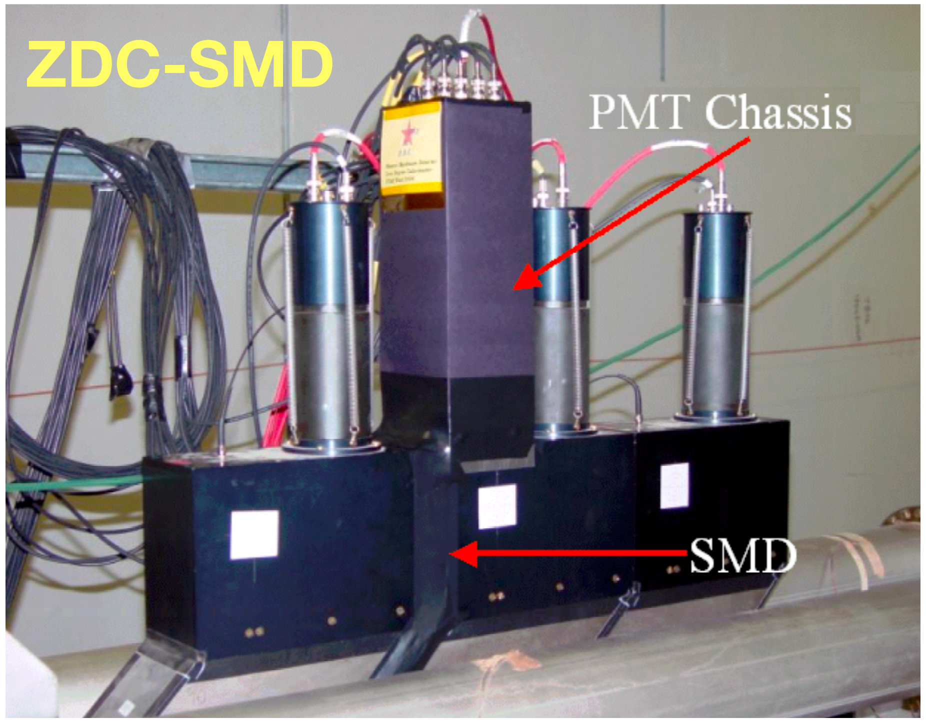
- Hydro predicted D^0 flow magnitude comparable to data
- Data can be used to calibrate model parameters (drag)

Event plane from ZDC-SMD

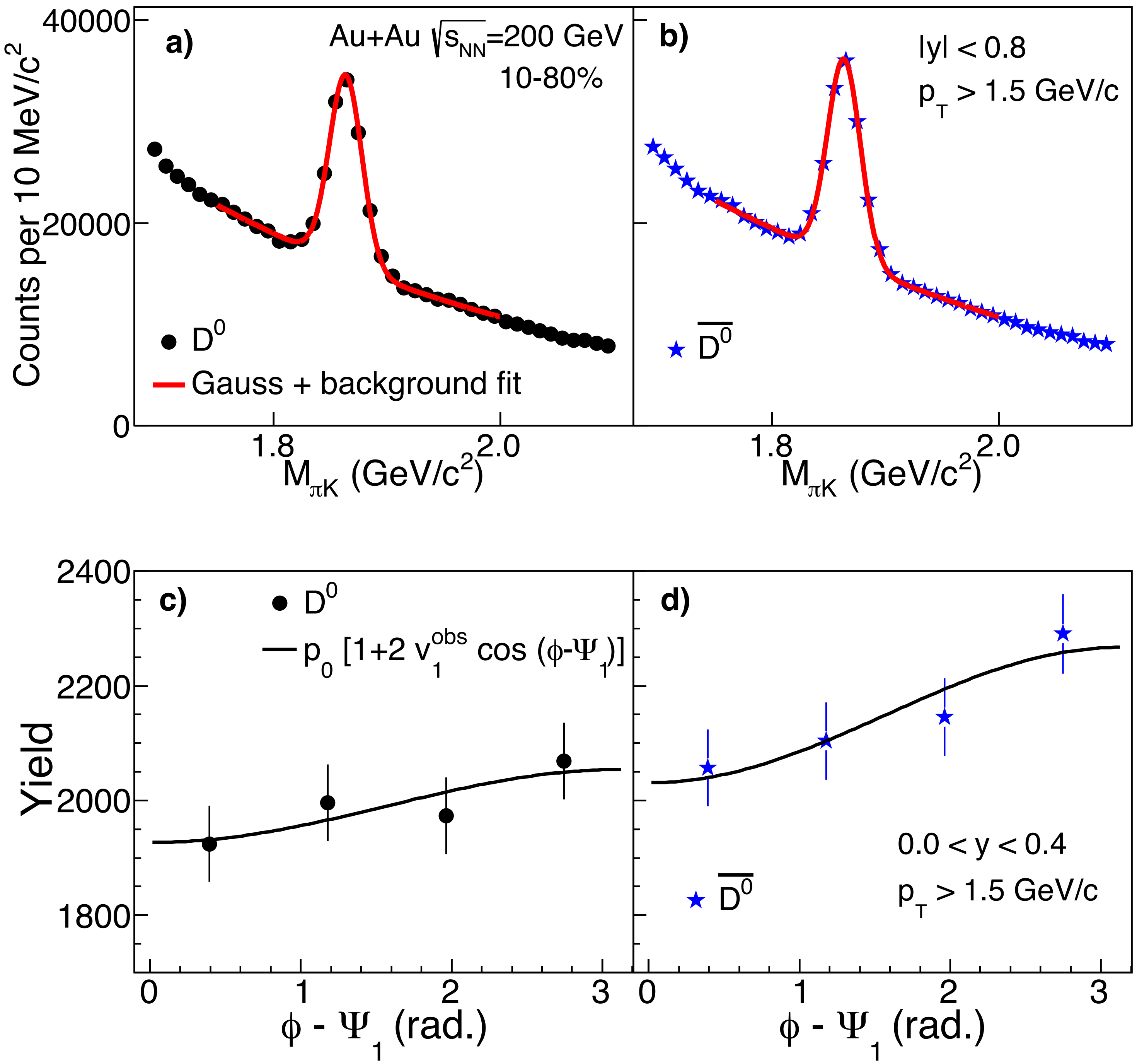
ZDC-SMD event plane resolution:



- The first-order event plane (ψ_1) measured using ZDC-SMD ($|\eta|$>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

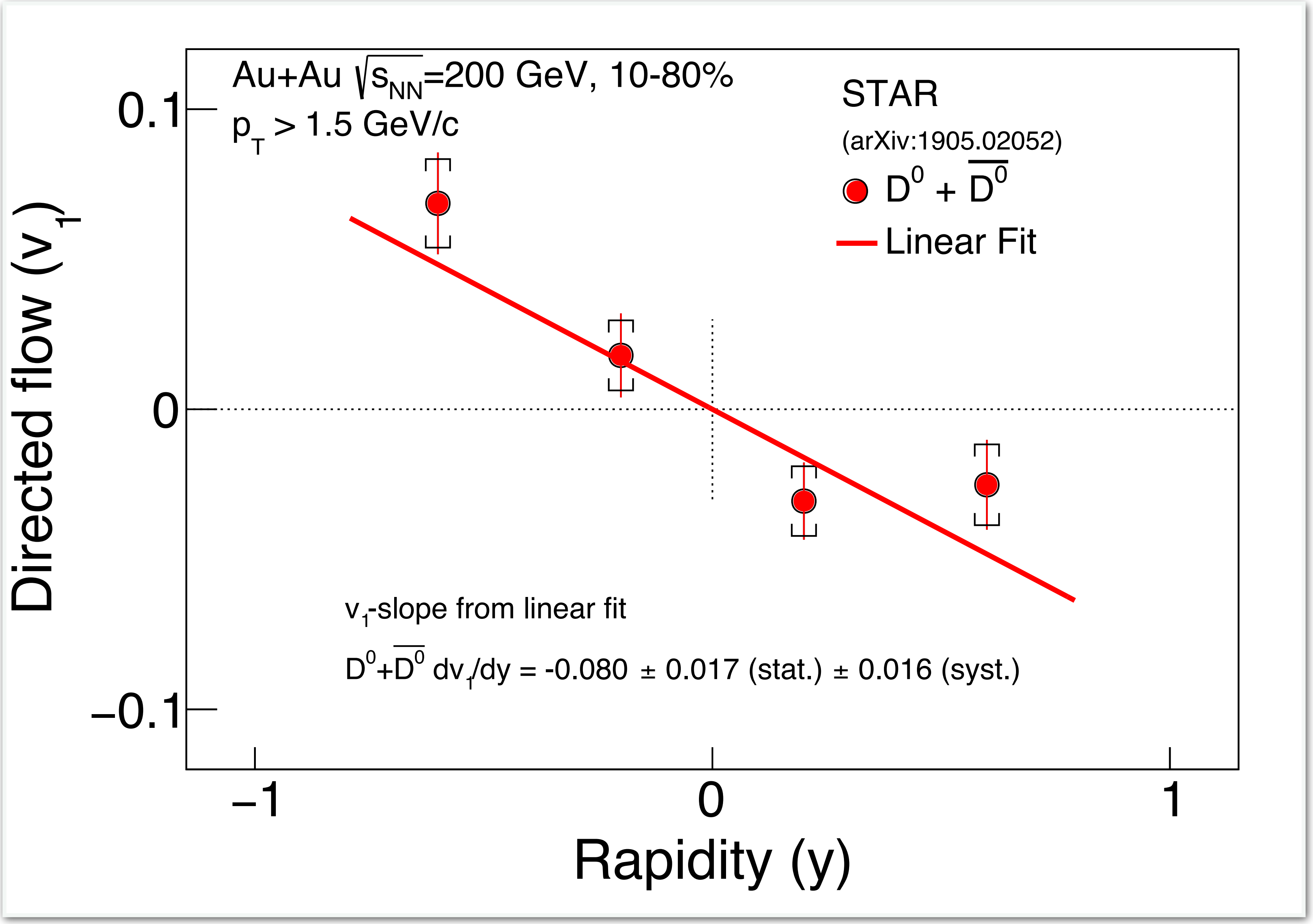


- D^0 v_1 measured using ϕ-ψ_1 method
- Results are corrected for event-plane resolution

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

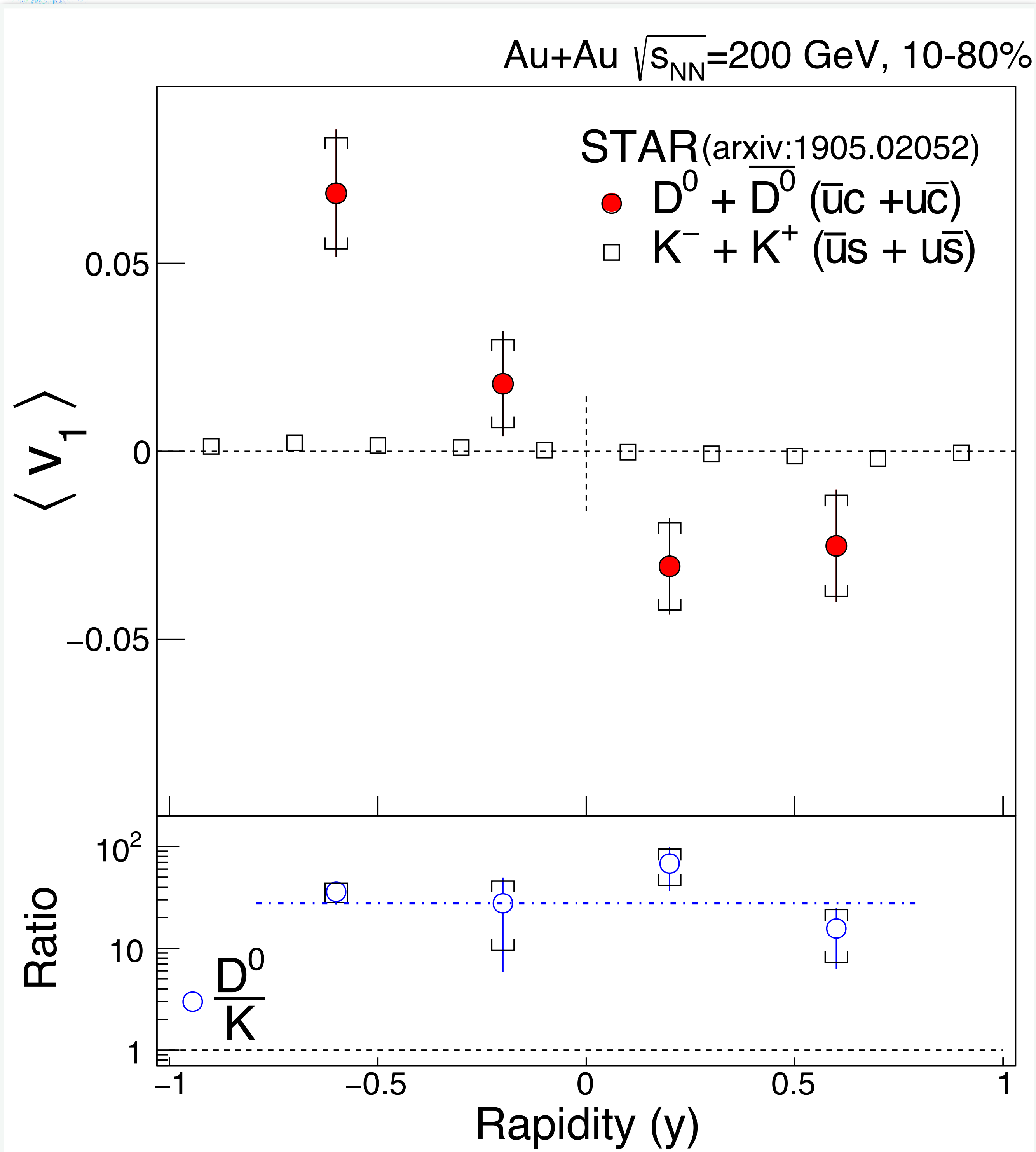
D^0 directed flow (v_1)

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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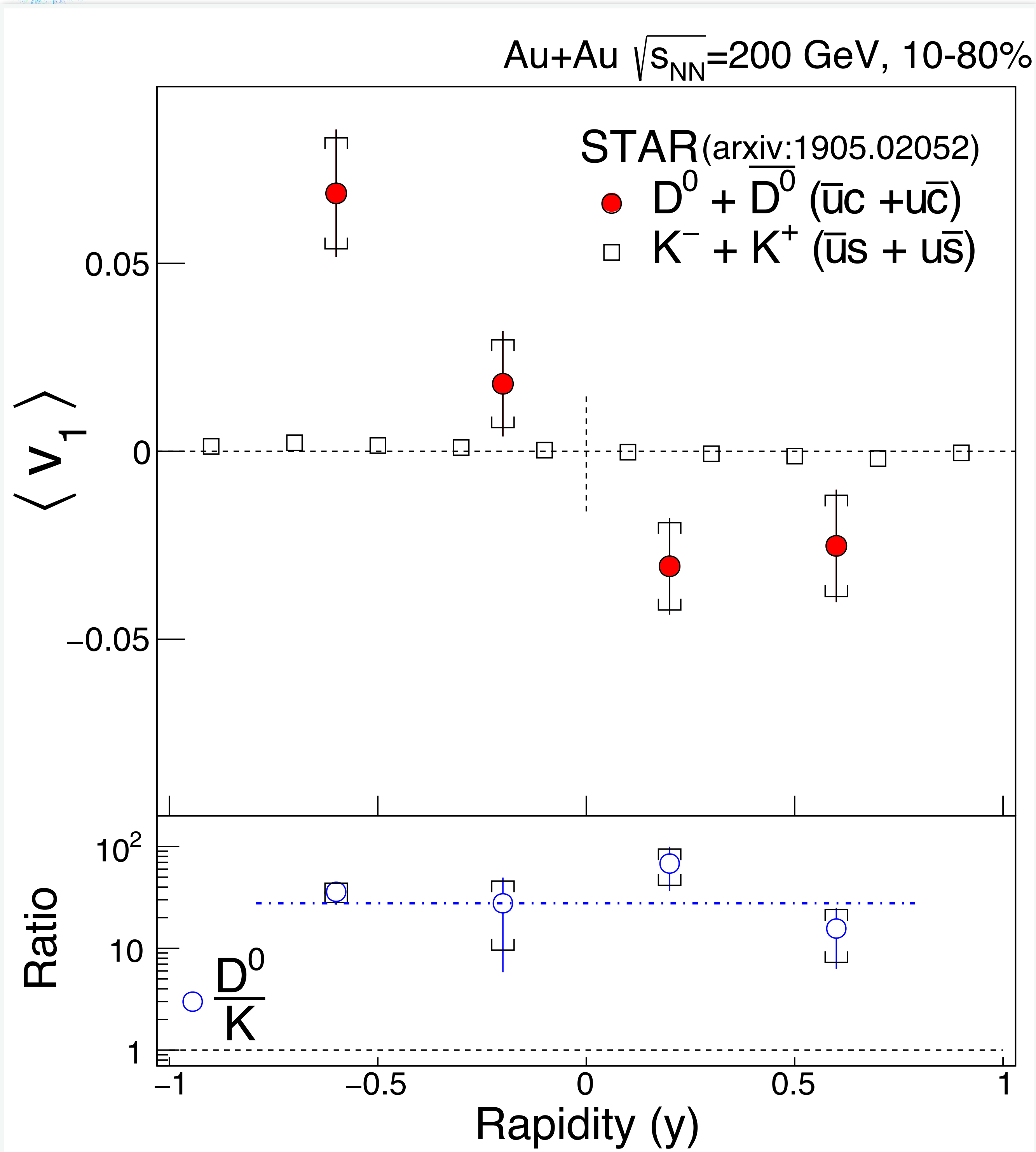


Charged Kaons:
L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 120, 62301 (2018)

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

v_1 slope

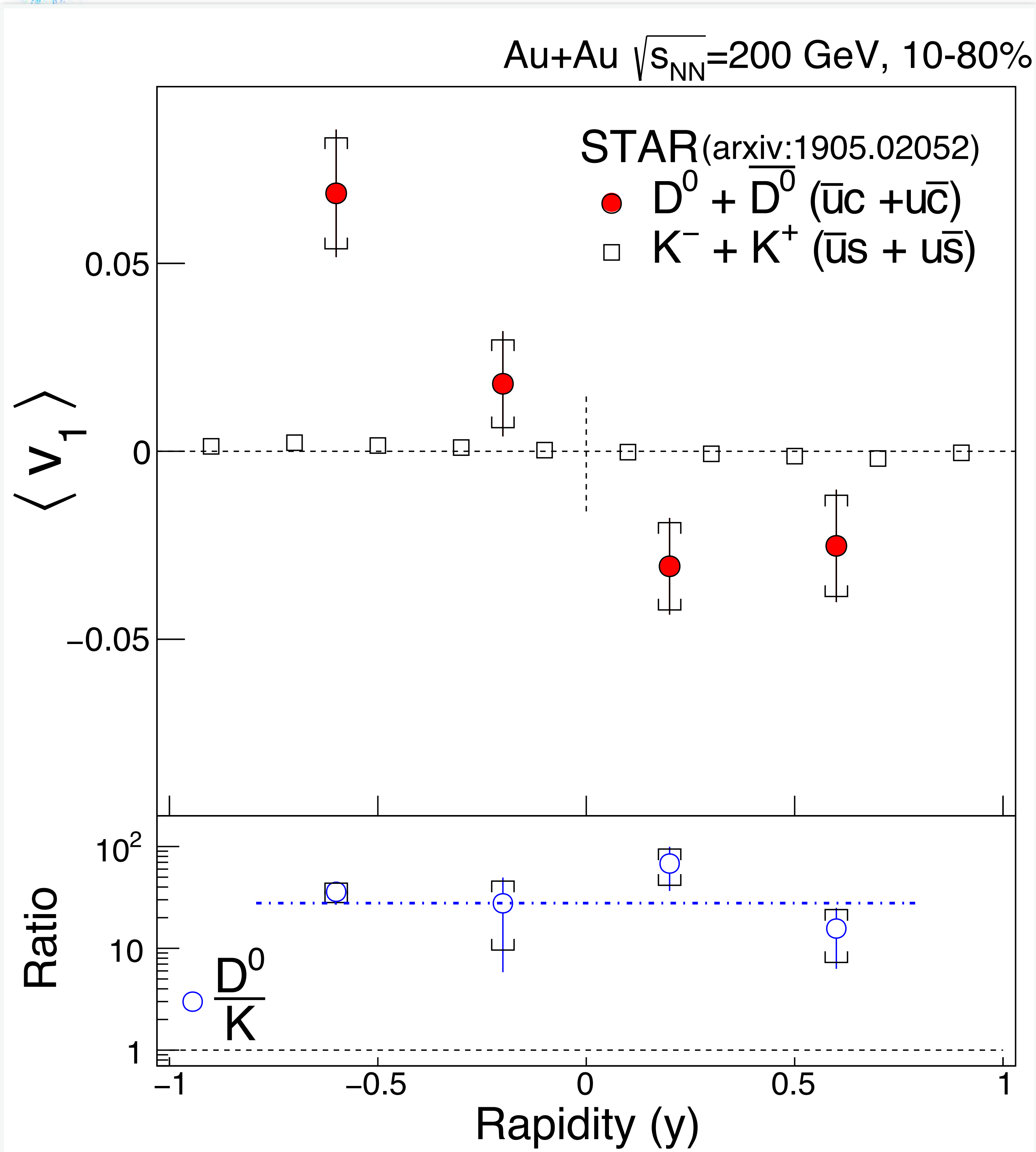
$D^0 : -0.080 \pm 0.017 \pm 0.016$

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

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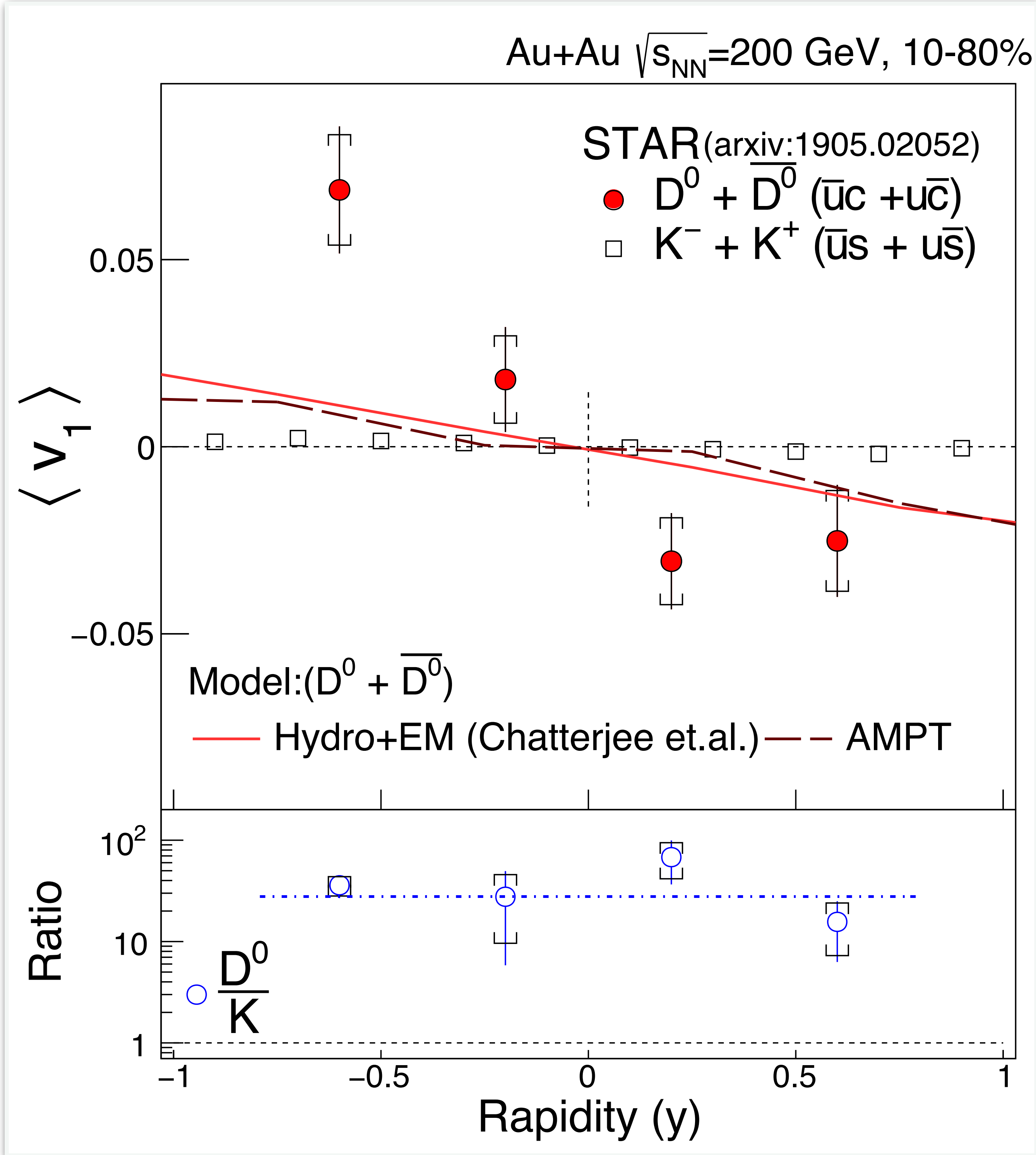
- v_1 slope of D^0 is about 25 times larger than that of the kaons, with ~3.4σ significance

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

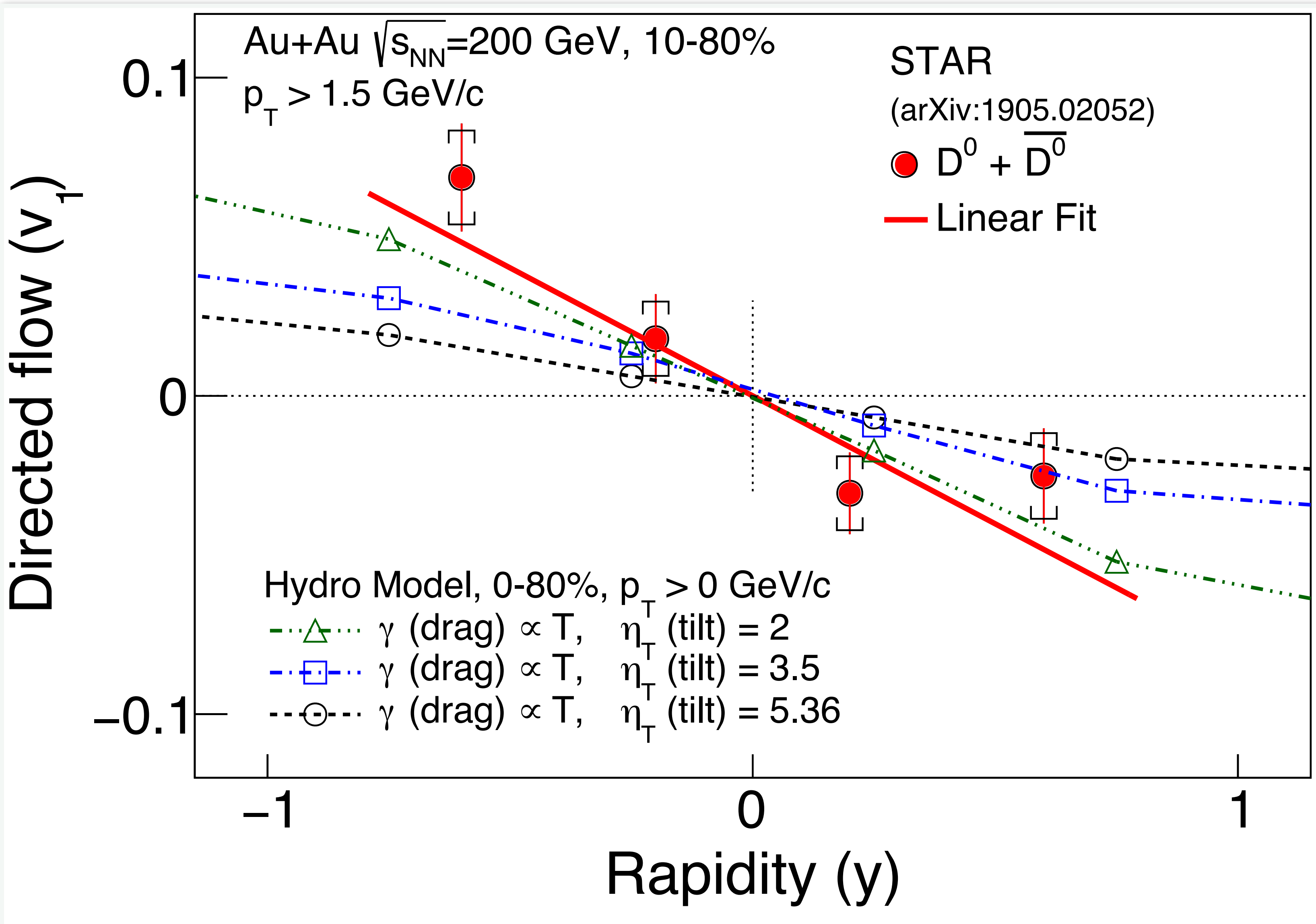
- Our data can help constrain model parameters

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

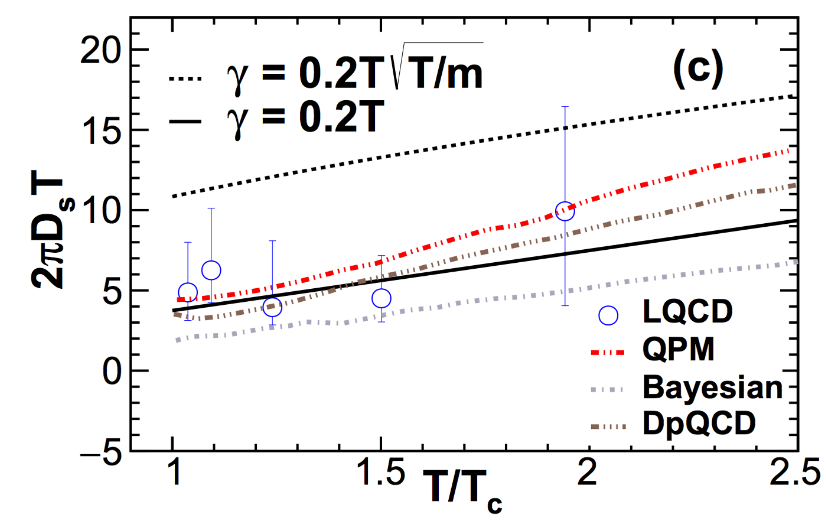
AMPT:
Singha, Nasim: Phys Rev C 97, 064917 (2018)

D^0 v_1 : data vs. hydro

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

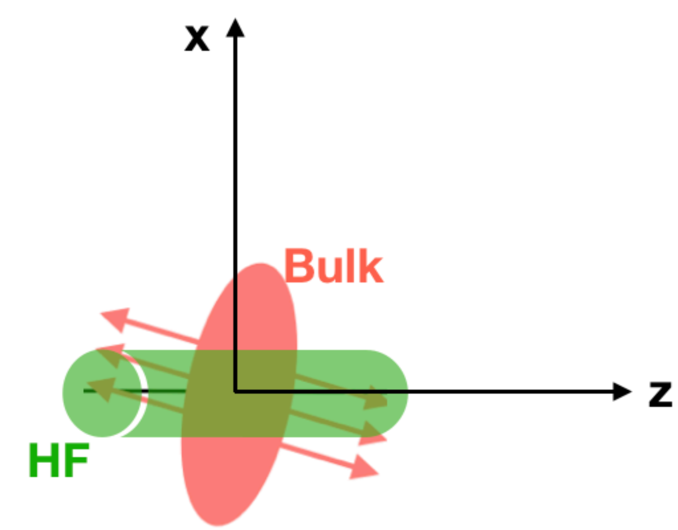


Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)



Smaller tilt

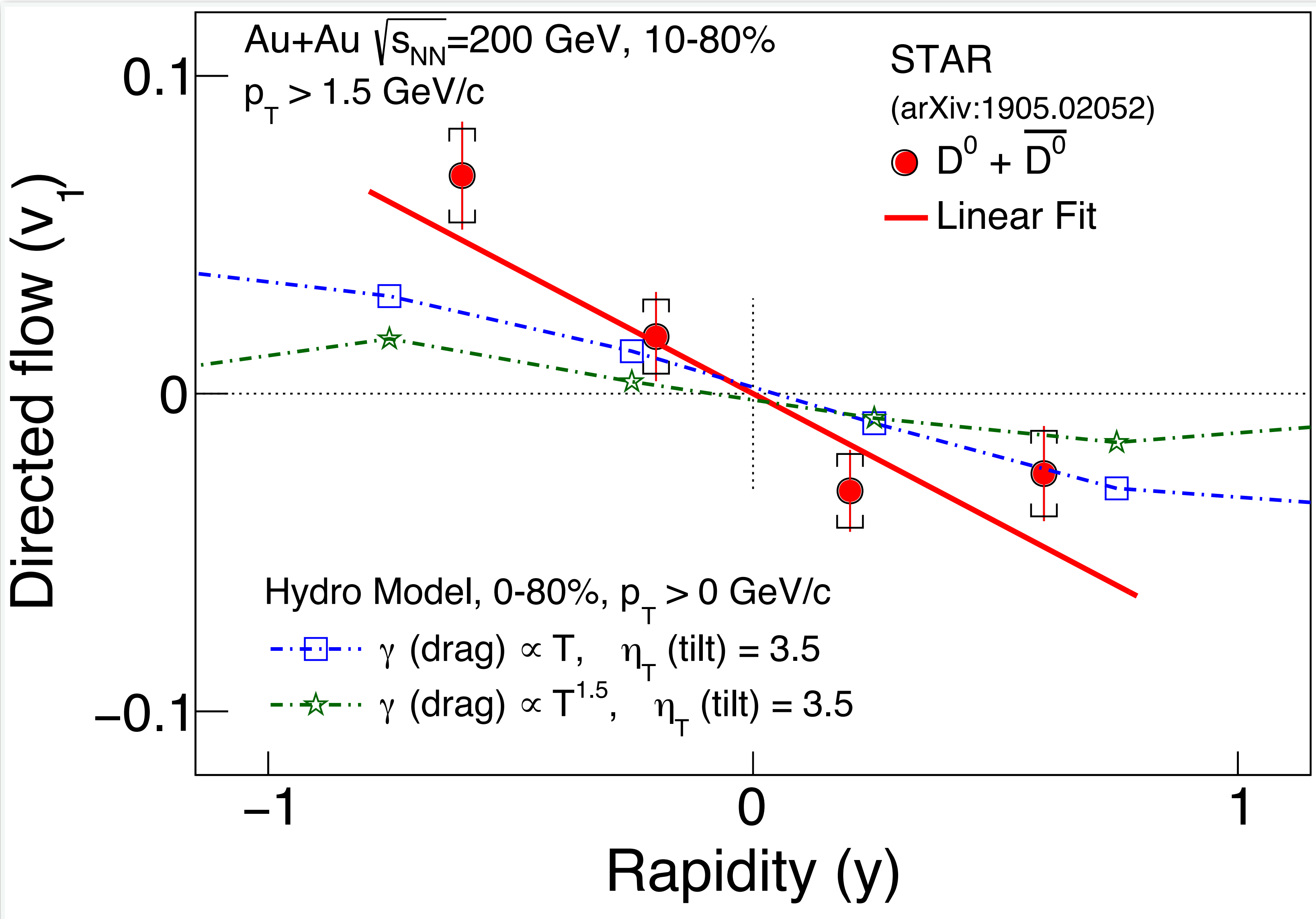
Larger tilt



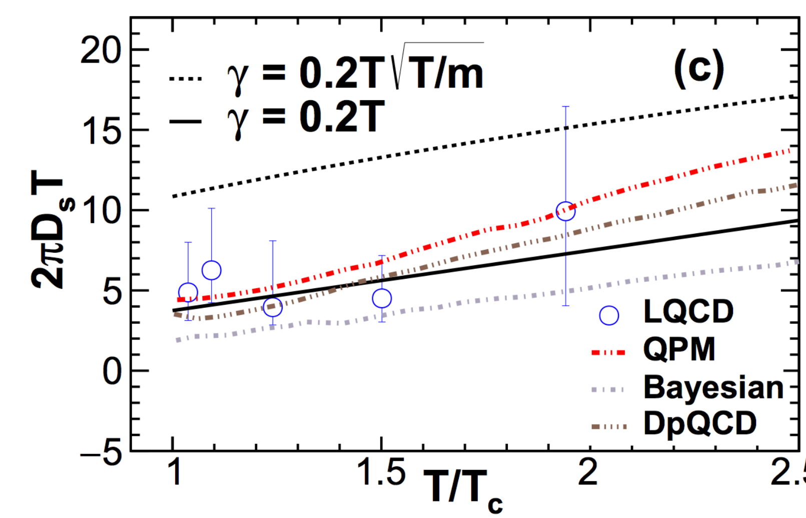
- In hydro model, D^0 v_1 is sensitive to the initially tilted source
- Our data can help constrain model parameter

D^0 v_1 : data vs. hydro

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



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



Larger drag coefficient

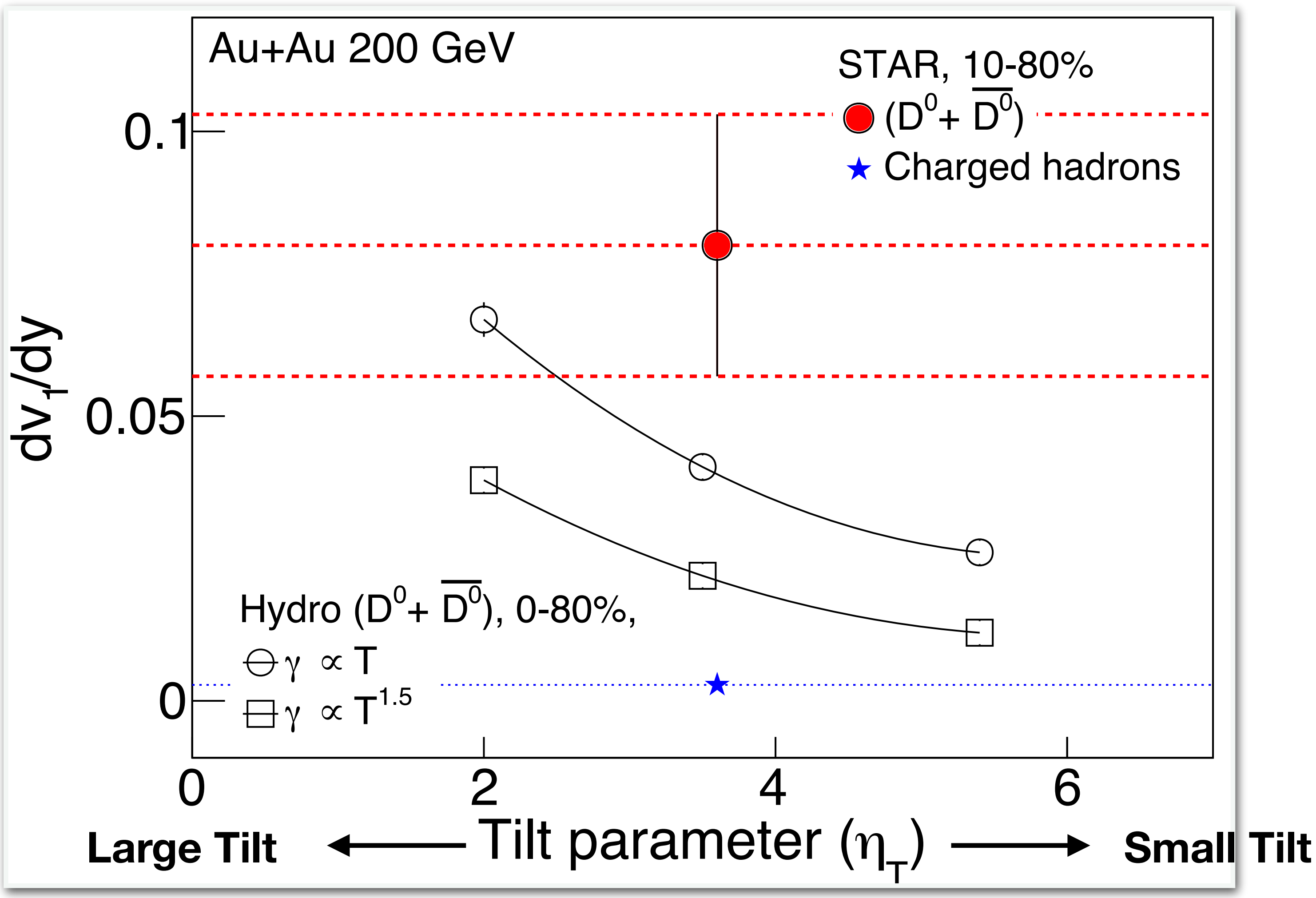
Smaller drag coefficient

- 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

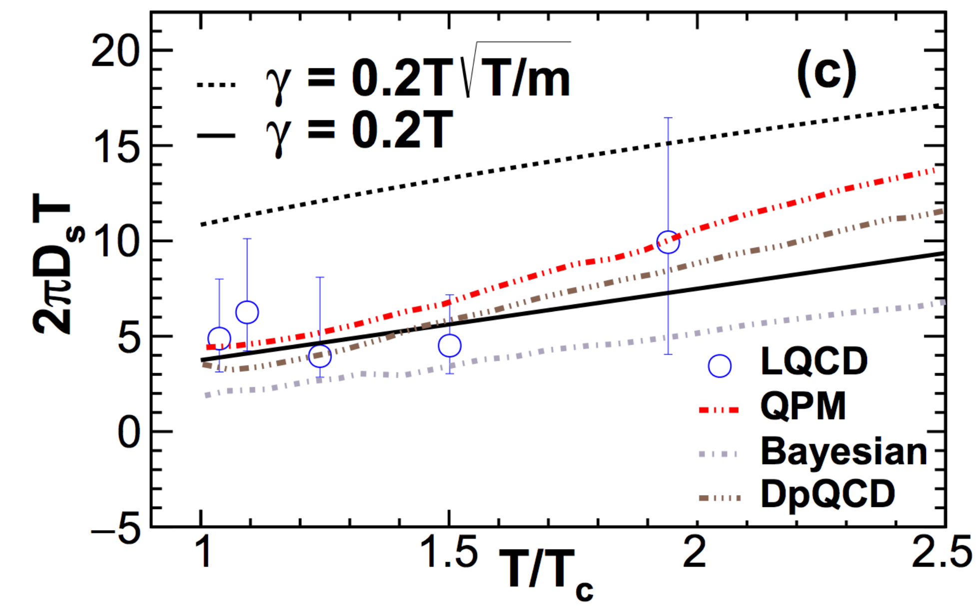
D^0 v_1 : data vs. hydro

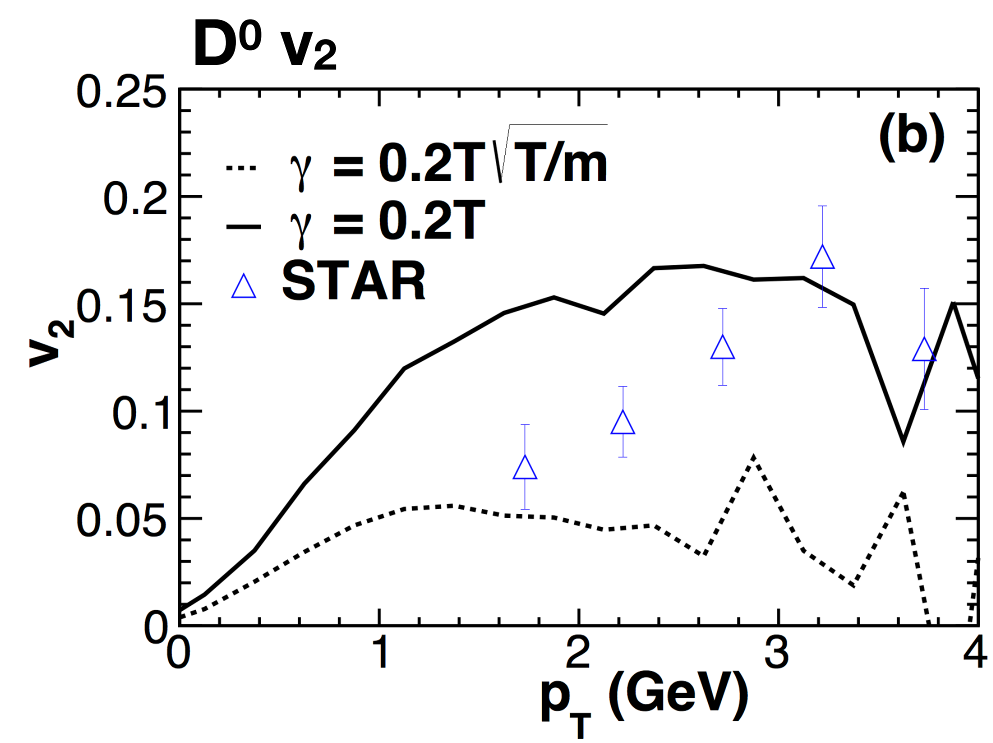
D^0 v_1

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



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

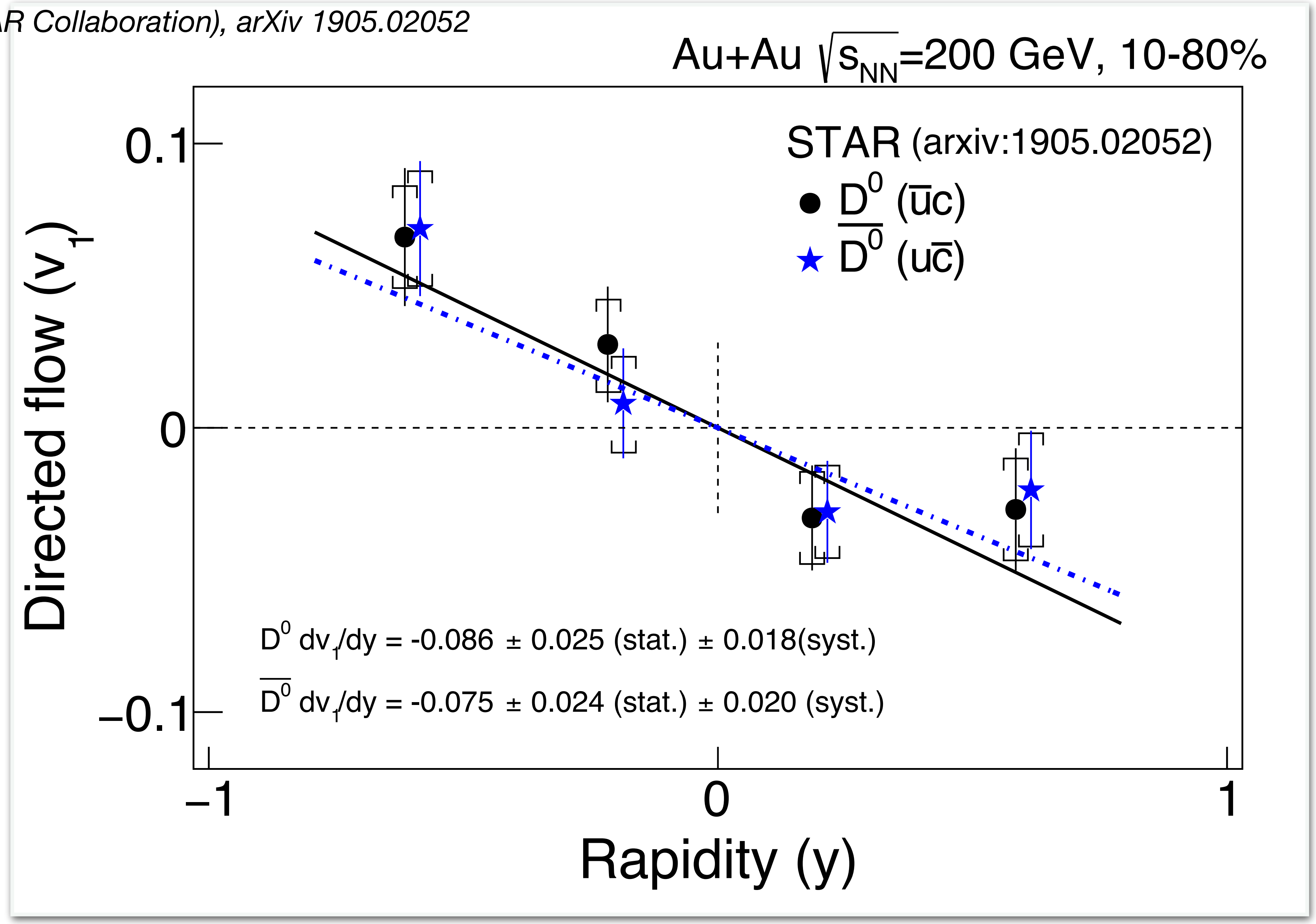




Simultaneous description of D meson v_1 and v_2 can provide constraint on the drag coefficient

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

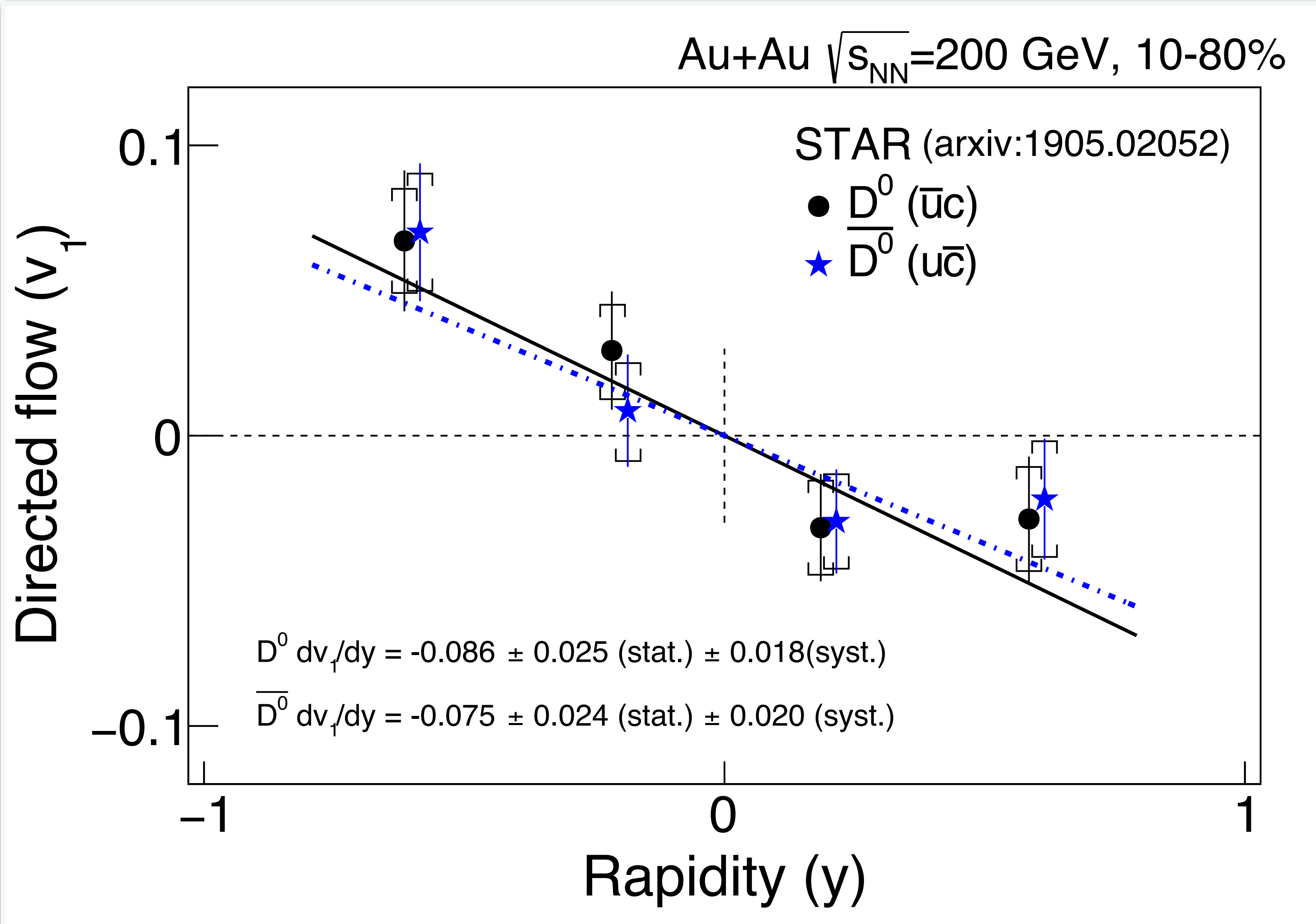
J Adam et. al. (STAR Collaboration), arXiv 1905.02052



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

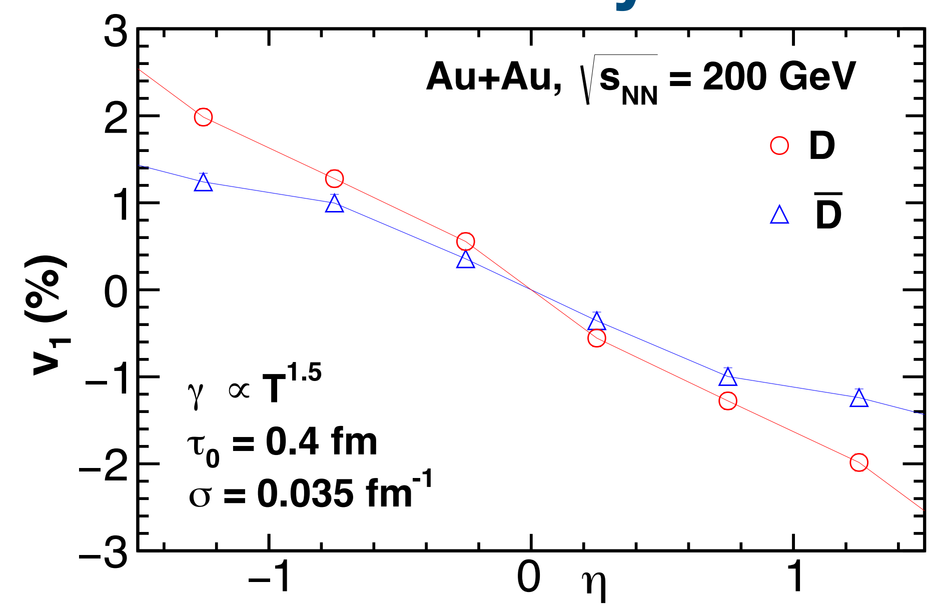
D^0 and $\overline{D}^0$ v_1

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



Chatterjee, Bozek: 1804.04893v1

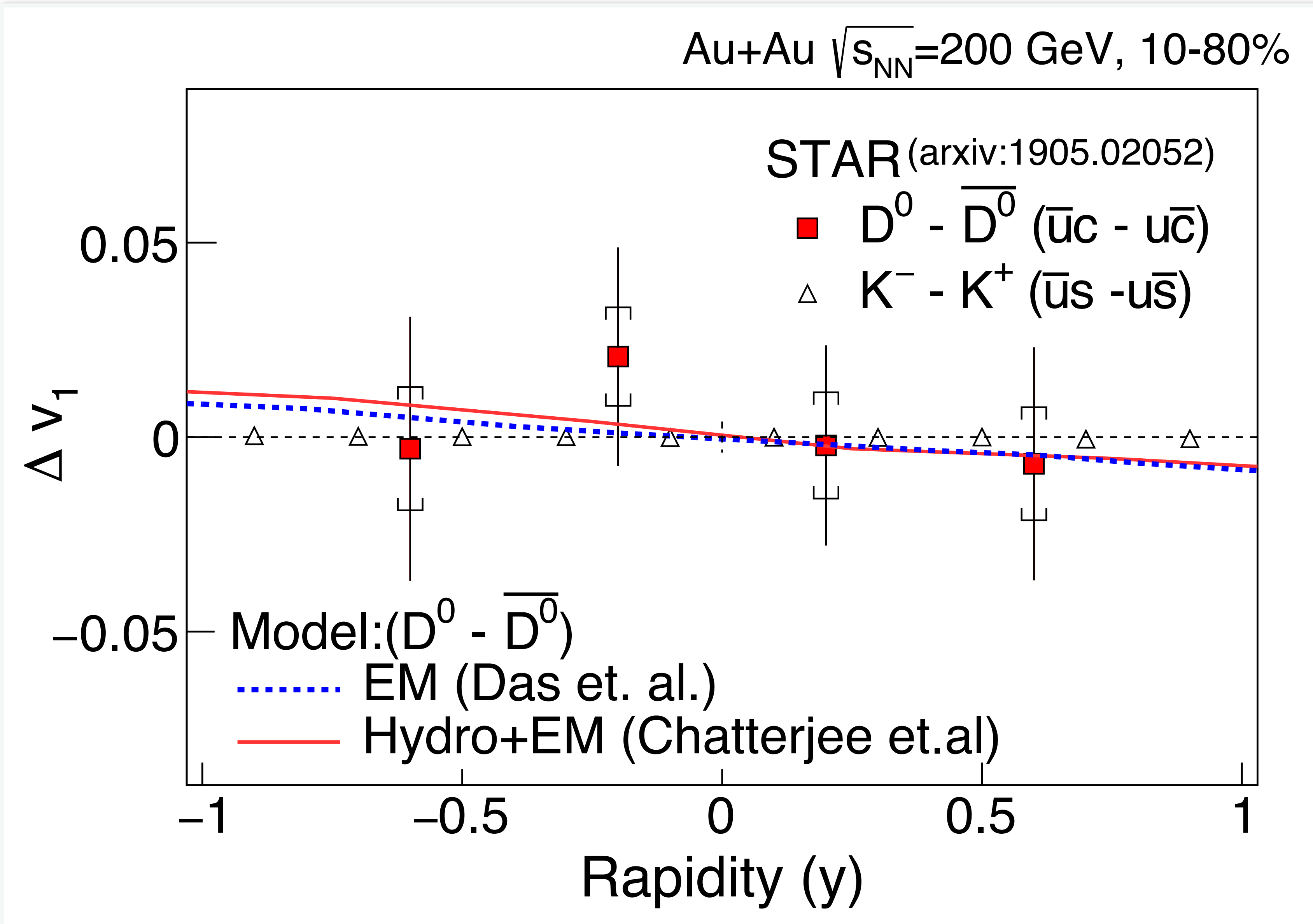
Hydro+EM

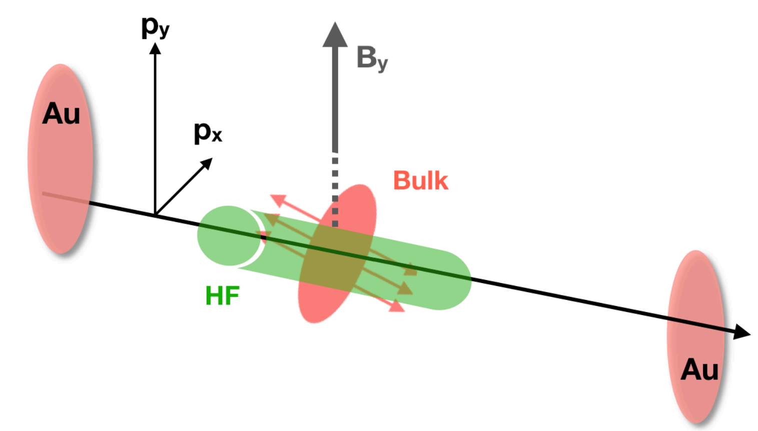


- Both D^0 and $\overline{D}^0$ v_1 show a negative slope at mid-rapidity
- Hydro+EM predict the correct sign for both of them

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

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





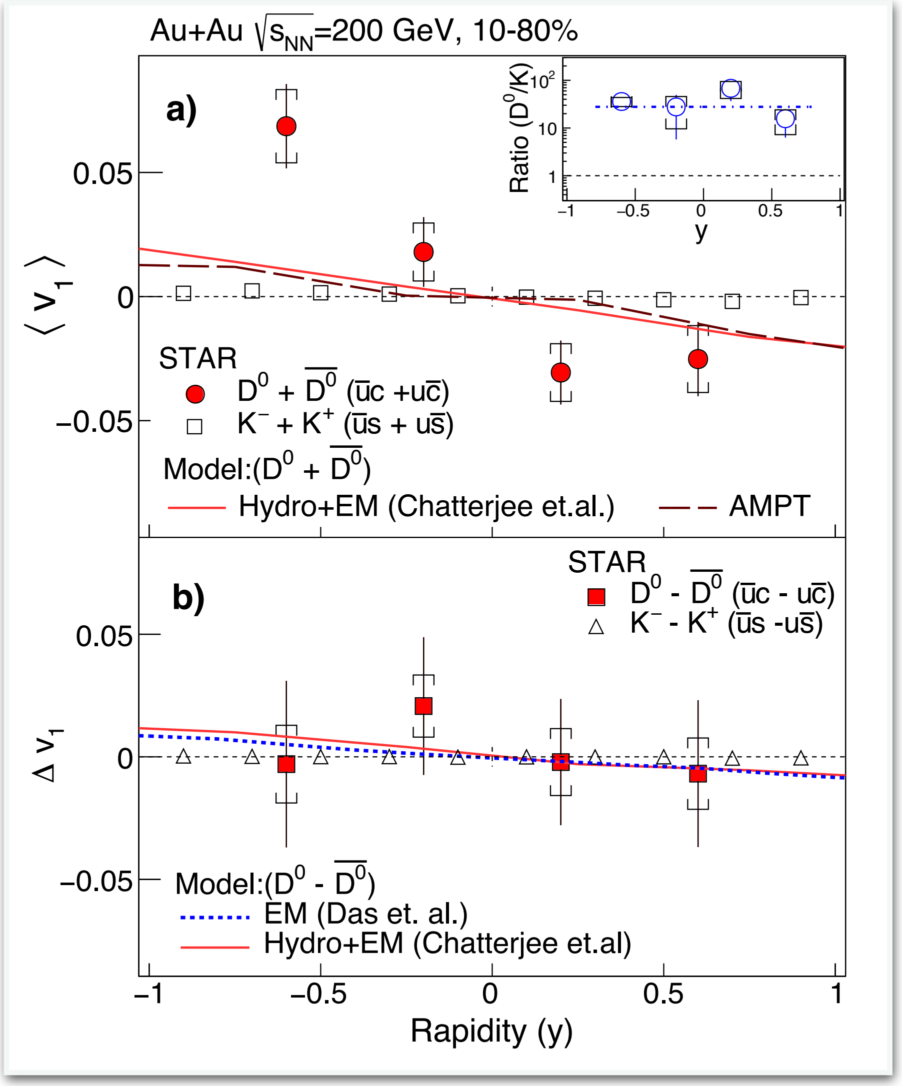
Hydro+EM:
Chatterjee, Bozek: Phys Rev Lett 120, 192301 (2018)
Chatterjee, Bozek: 1804.04893v1
EM:
Das et. al., Phys Lett B 768, 260 (2017)

- 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 and outlook

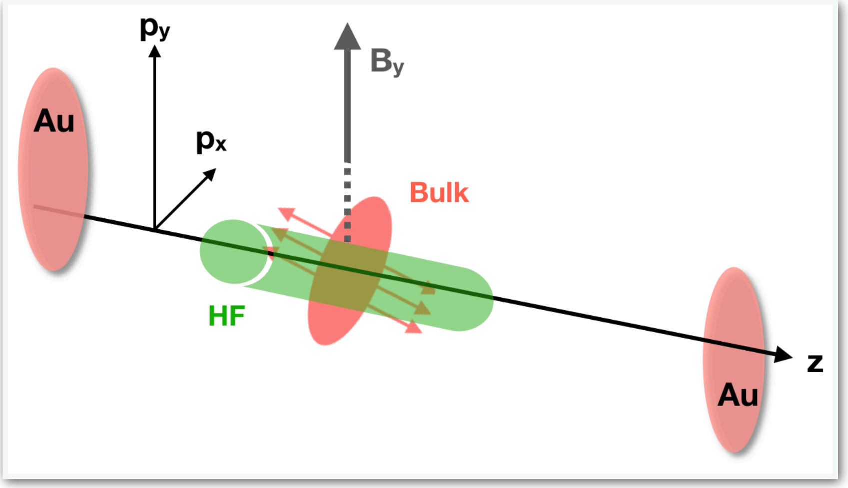
Summary:

- 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 provide constraints on the initial geometry and the transport properties of the medium
- Current precision is not sufficient to conclude on magnetic field induced charge separation of heavy quarks



Outlook:

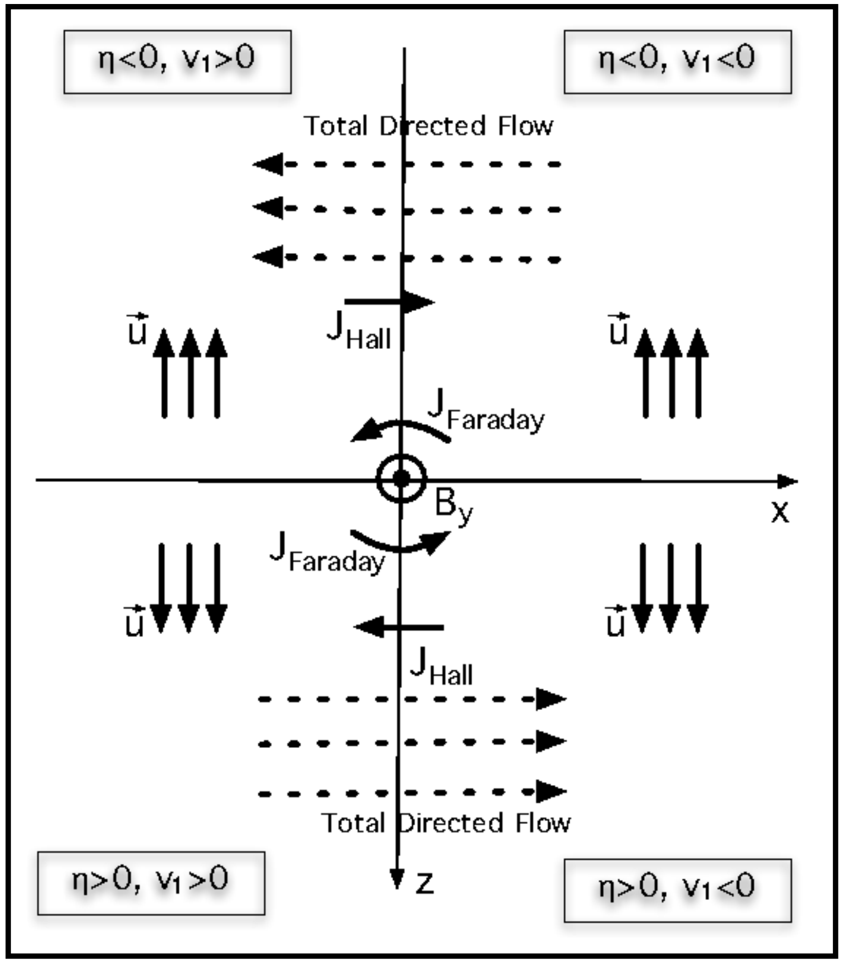
- Precision measurement heavy-flavor directed flow
- Ongoing activities KFParticle algorithm (enhance S/B ratio)
- Extend measurement to other heavy-flavor species (J/Ψ, D^0, $D^{+/-}$) (better understanding of charm dynamics)



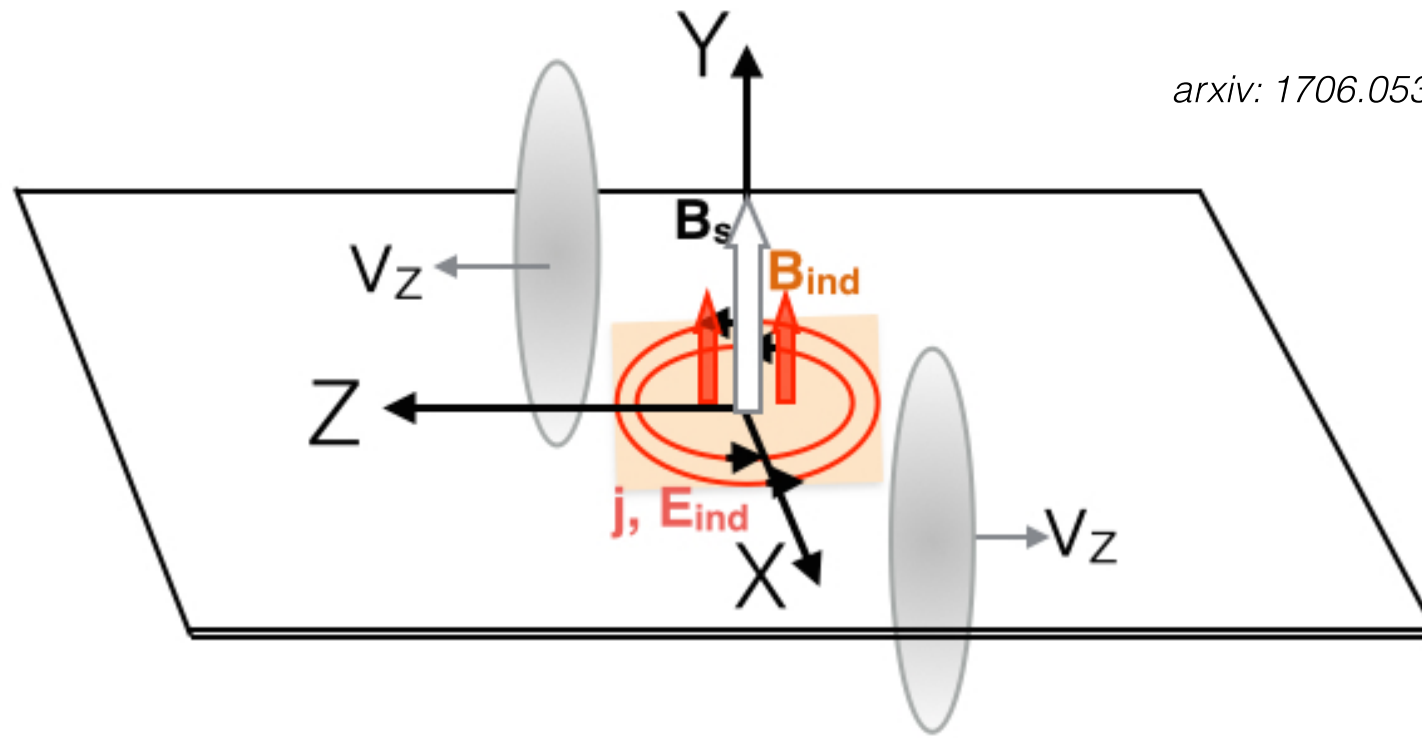
Backup slides

Directed flow from magnetic field

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



arxiv: 1706.05326



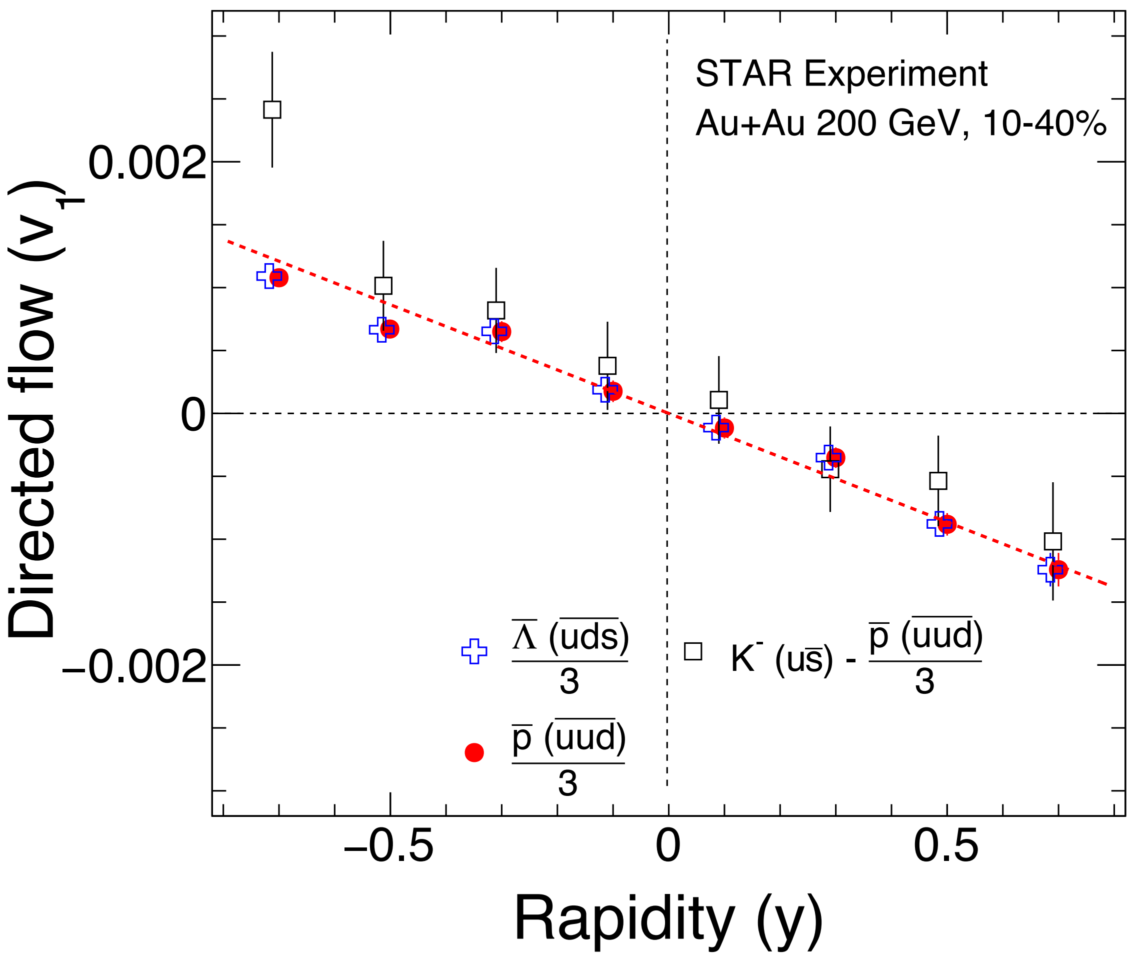
- The moving spectators can produce enormously large **B** field (eB ~10^{18} G)
- There could be two competitive effects
- <u>Hall effect:</u> $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$

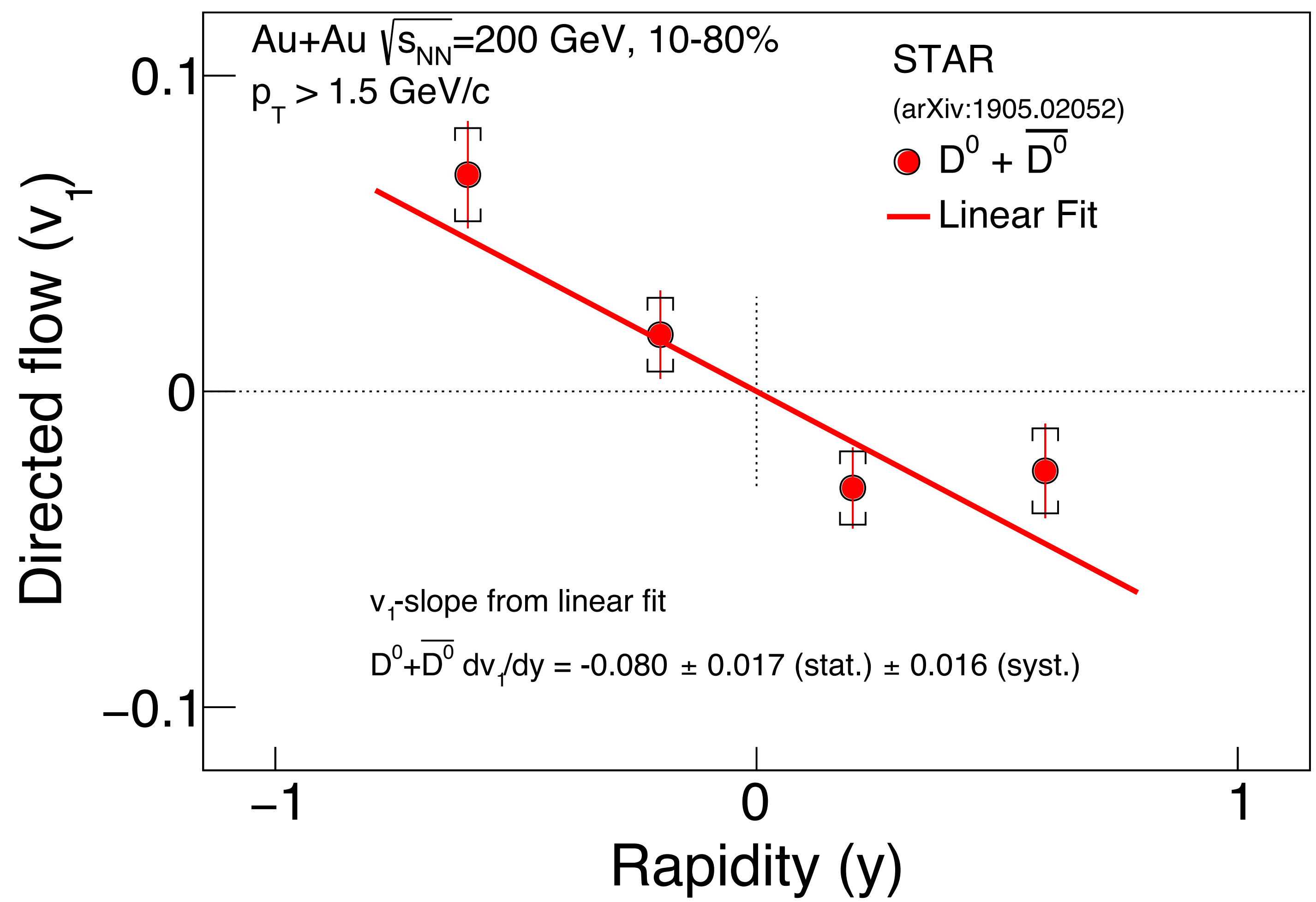
  Lorentz force directed along -ve X-direction in +ve rapidity and vice-versa
- <u>Faraday effect:</u> $\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$

  Time dependent **B** field generates a large **E** field

  Induced Faraday current will oppose the drift due to **B** field

Light flavor vs. heavy flavor v_1





First prediction of charm directed flow

PHYSICAL REVIEW C 71, 044901 (2005)

Collective flow of open and hidden charm in Au + Au collisions at $\sqrt{s} = 200$ GeV

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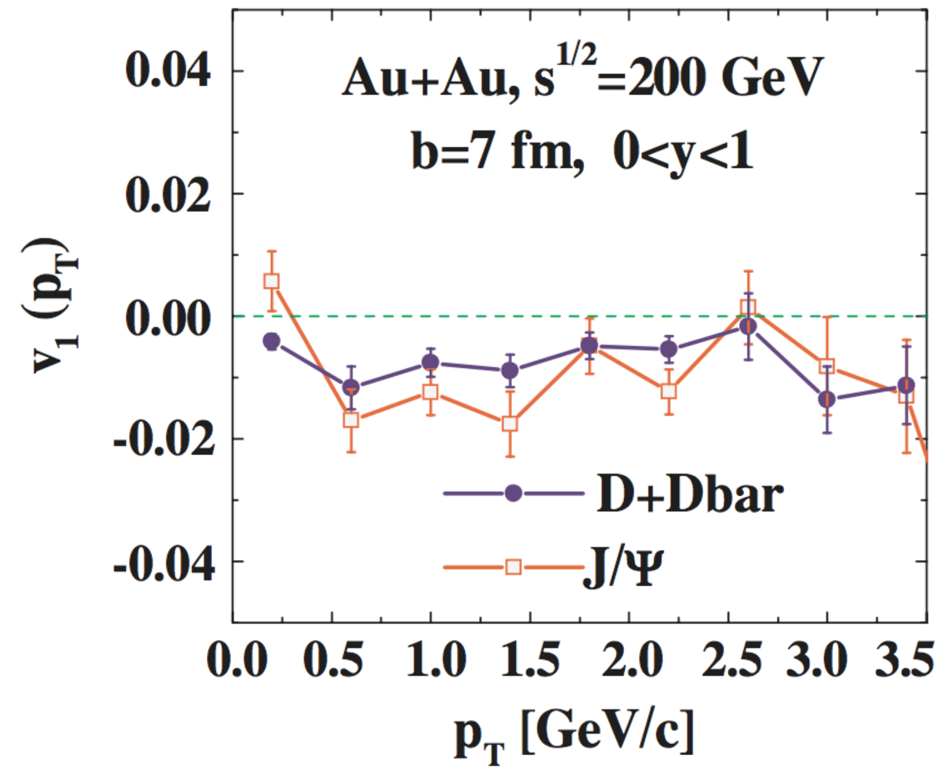
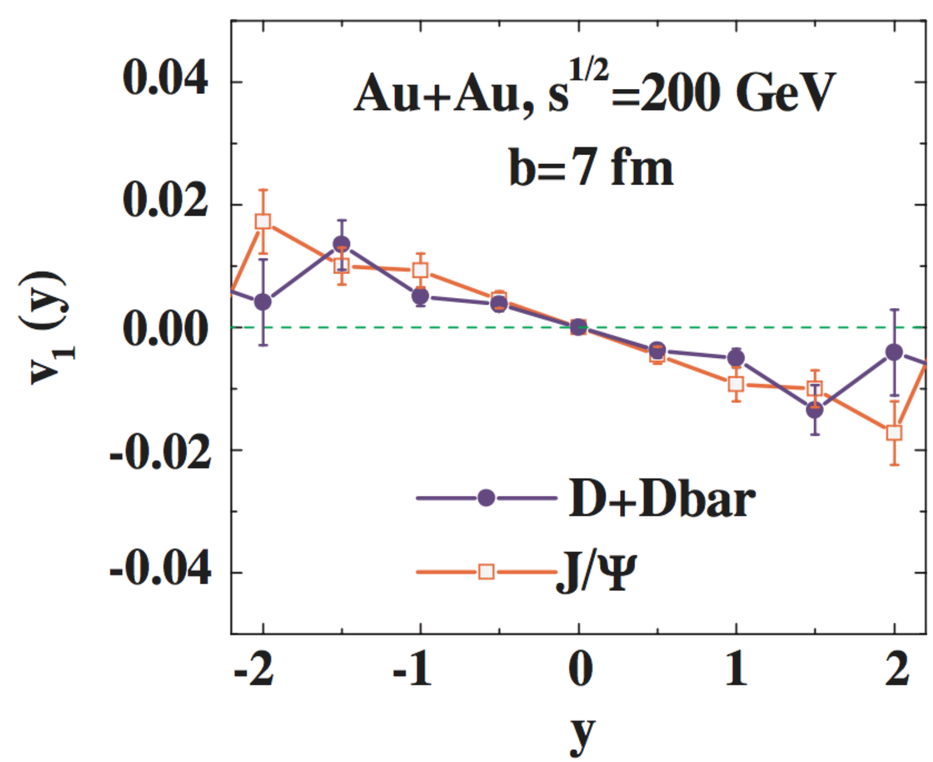
We study the collective flow of open charm mesons and charmonia in Au + Au collisions at $\sqrt{s} = 200$ GeV within the hadron-string-dynamics (HSD) transport approach. The detailed studies show that the coupling of $D, \bar{D}$ mesons to the light hadrons leads to comparable directed and elliptic flow as for the light mesons. This also holds approximately for J/Ψ mesons since more than 50% of the final charmonia for central and midcentral collisions stem from $D + \bar{D}$ induced reactions in the transport calculations. The transverse momentum spectra of $D, \bar{D}$ mesons and J/Ψ's are only very moderately changed by the (pre-)hadronic interactions in HSD, which can be traced back to the collective flow generated by elastic interactions with the light hadrons.

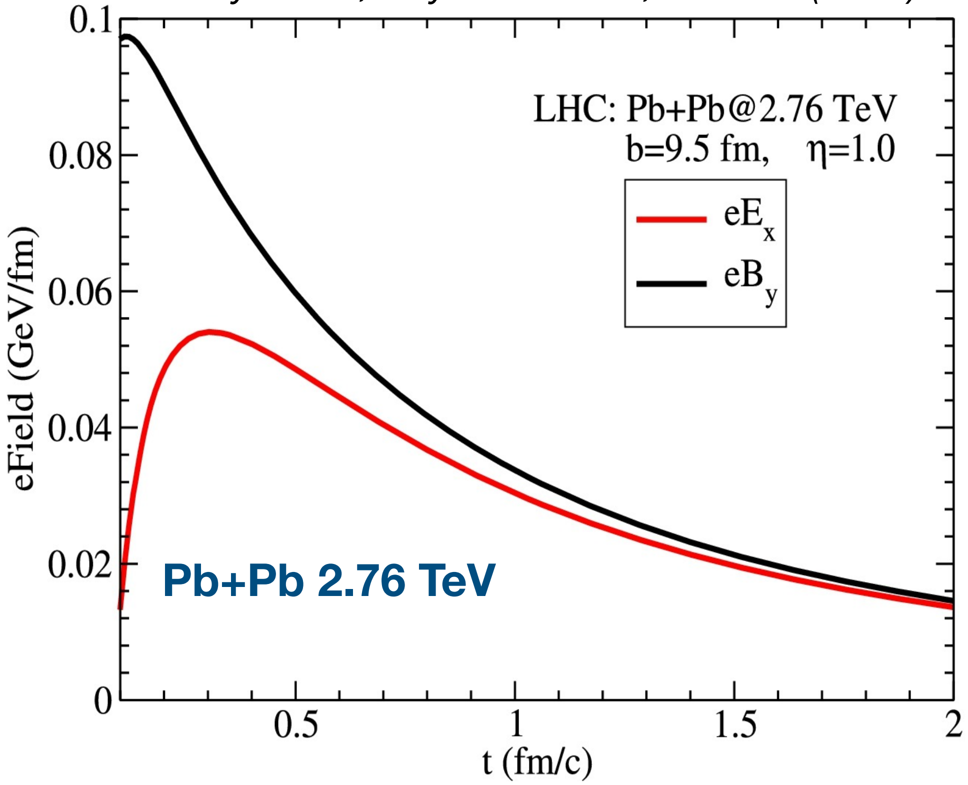




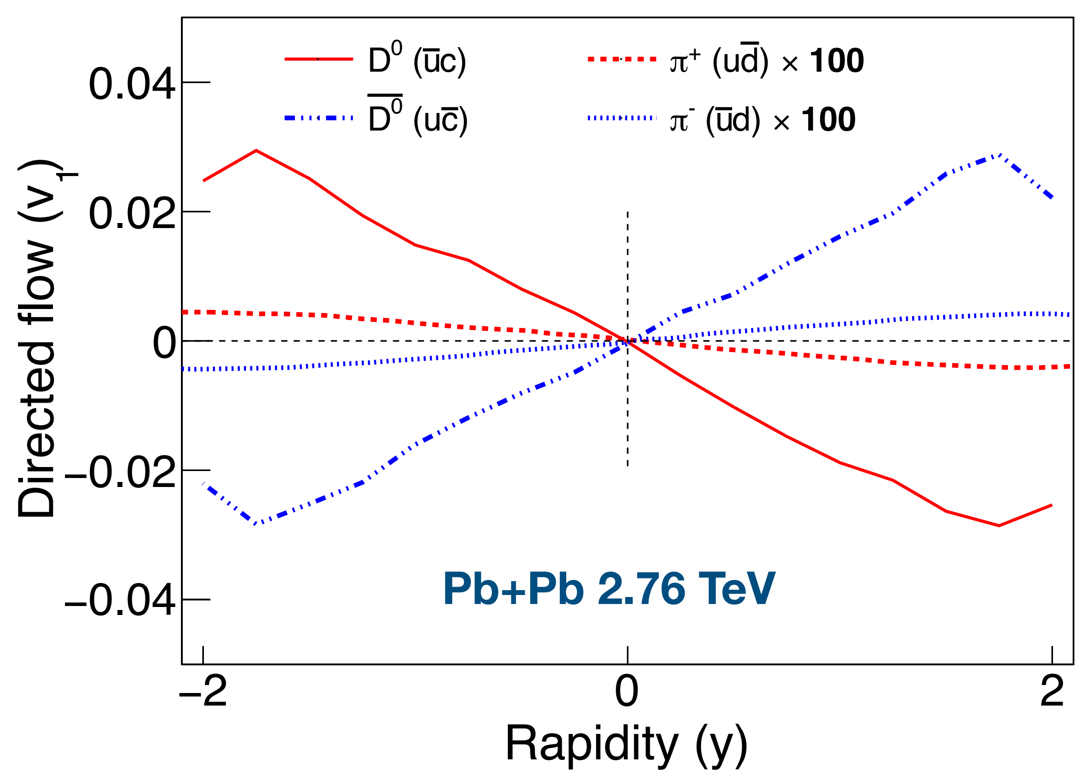
- D^0, J/Ψ v_1 show a negative slope
- D^0 v_1 comparable to light flavor

Heavy quark v_1 from initial EM field

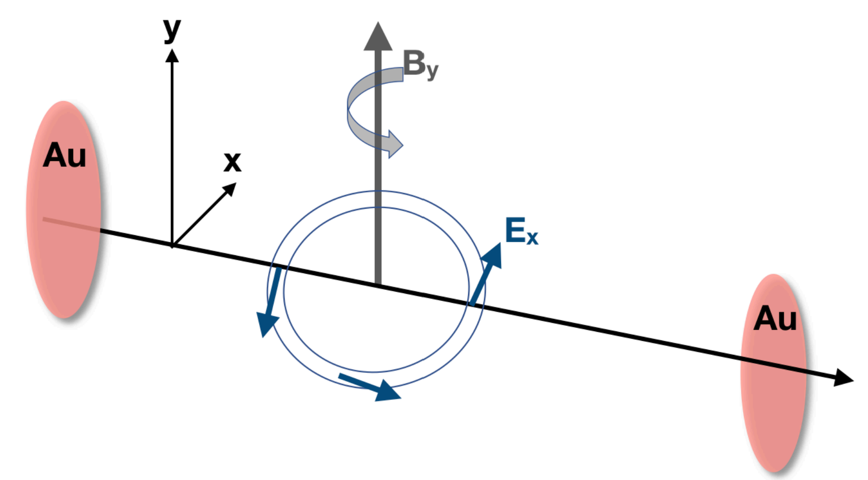
Gursoy et. al., Phys Rev C 89, 054905 (2014)



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

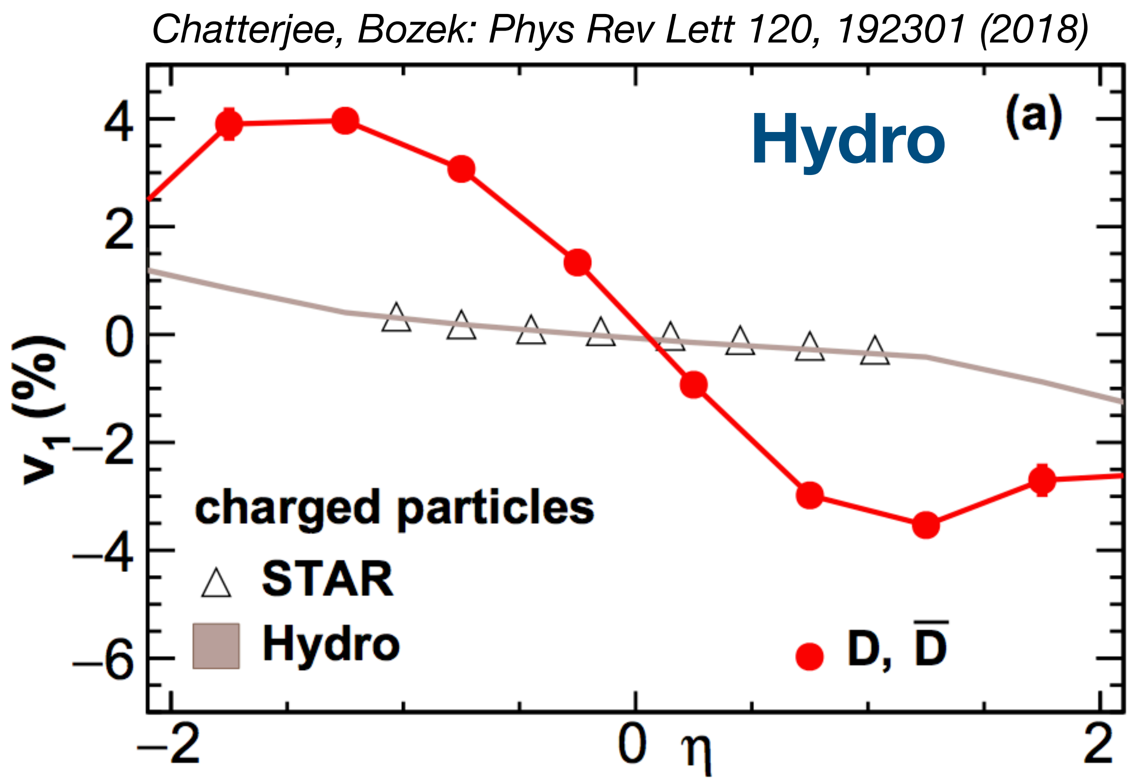


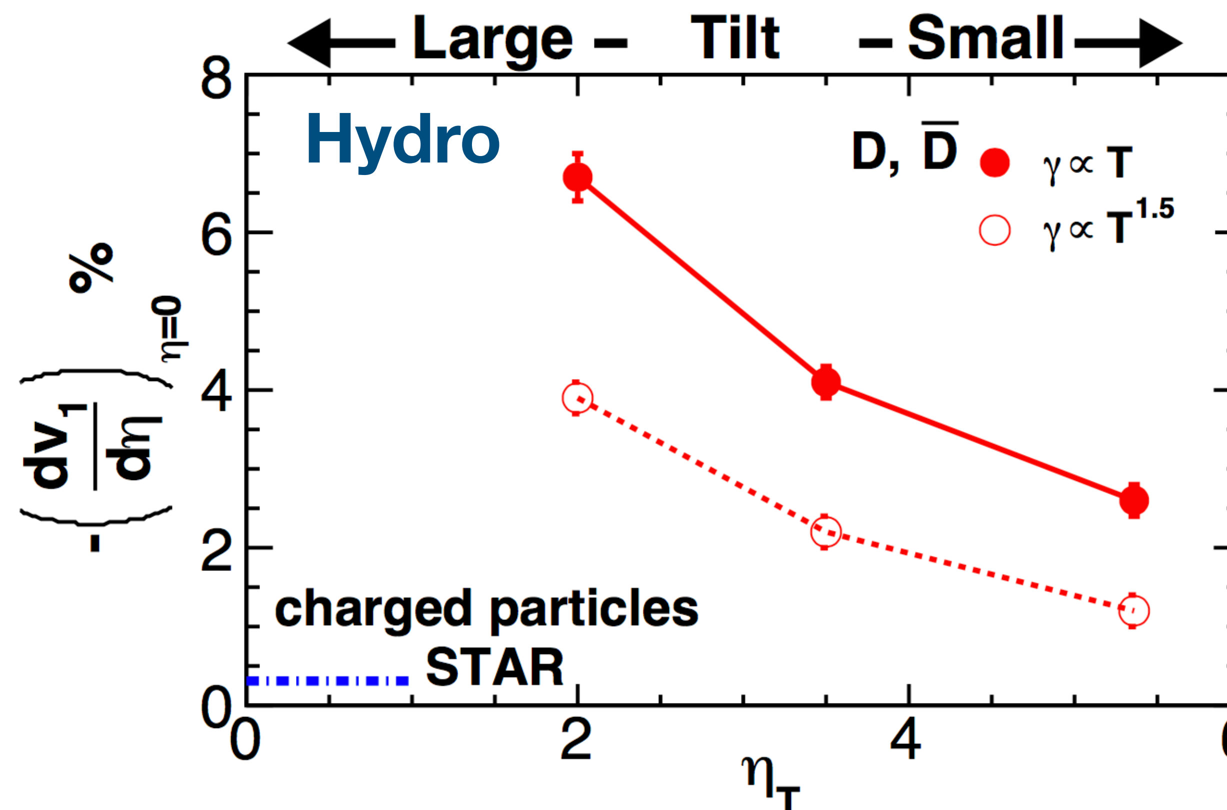
- Incoming charged particles can produce an enormously large EM field
- Due to early production of heavy quarks (τ_{CQ}~0.1 fm/c), positive and negative charm quarks can get deflected by the initial EM force
- Model calculation demonstrates that such initial EM field can induce opposite v_1 for charm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



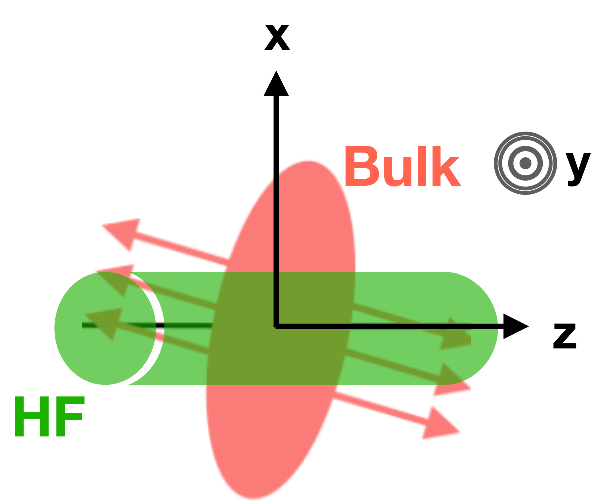
D^0 and $\overline{D}^0$ v_1 can offer insight into the early time EM fields

Heavy quark v_1 from Hydro





- 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