Measurements of directed and elliptic flow for D^0 and $\overline{D}^0$ mesons using the STAR detector at RHIC

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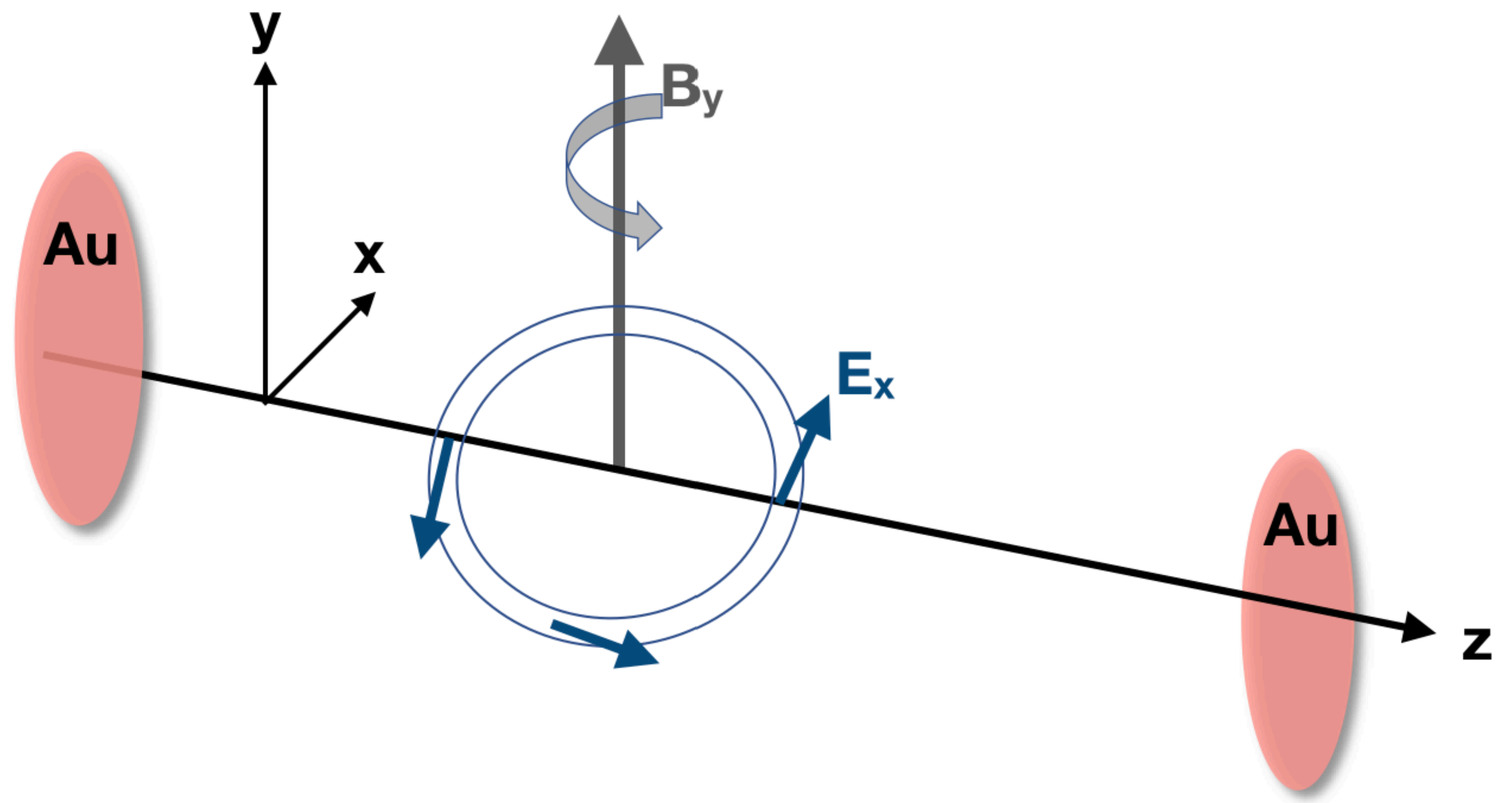
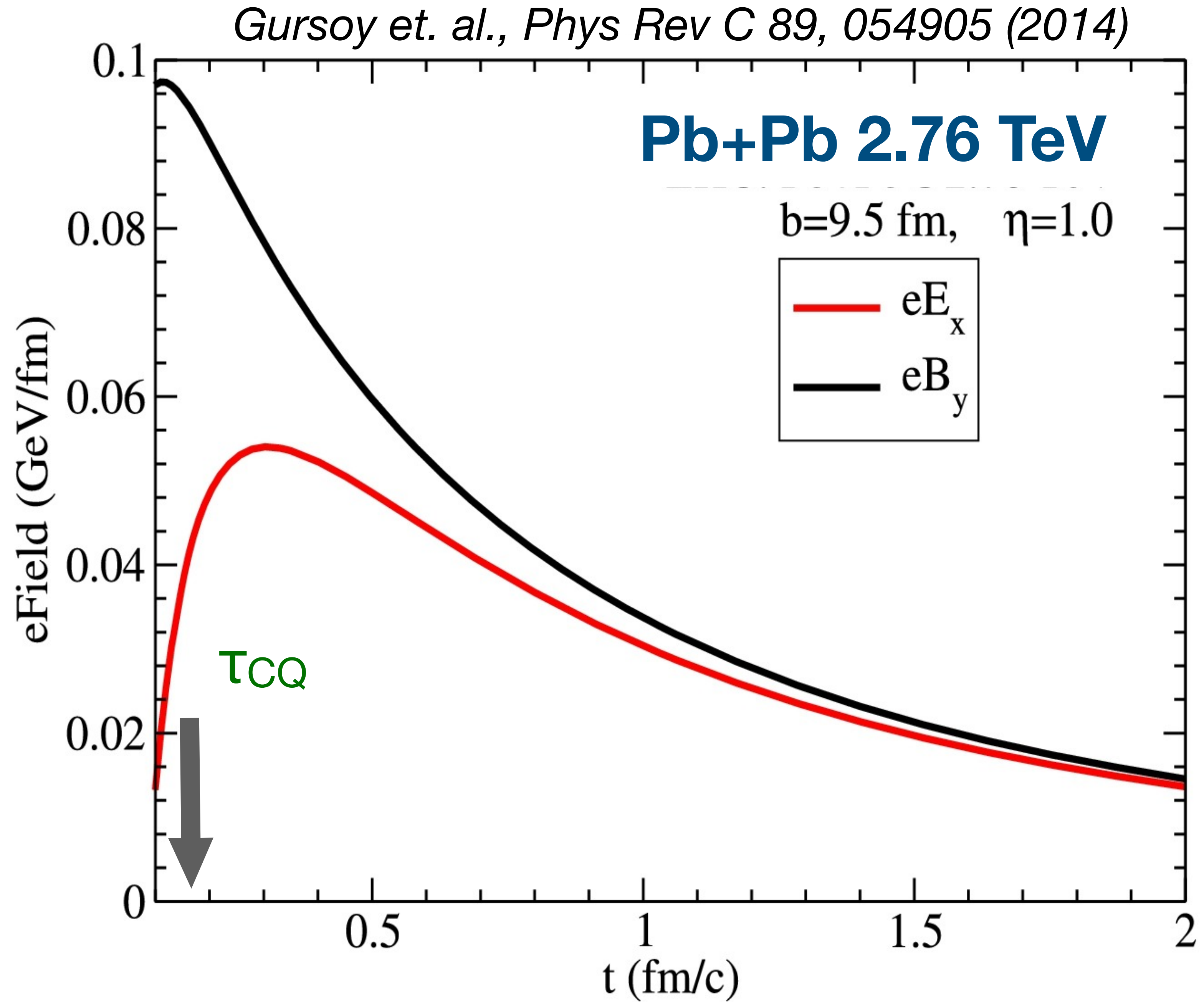
Outline

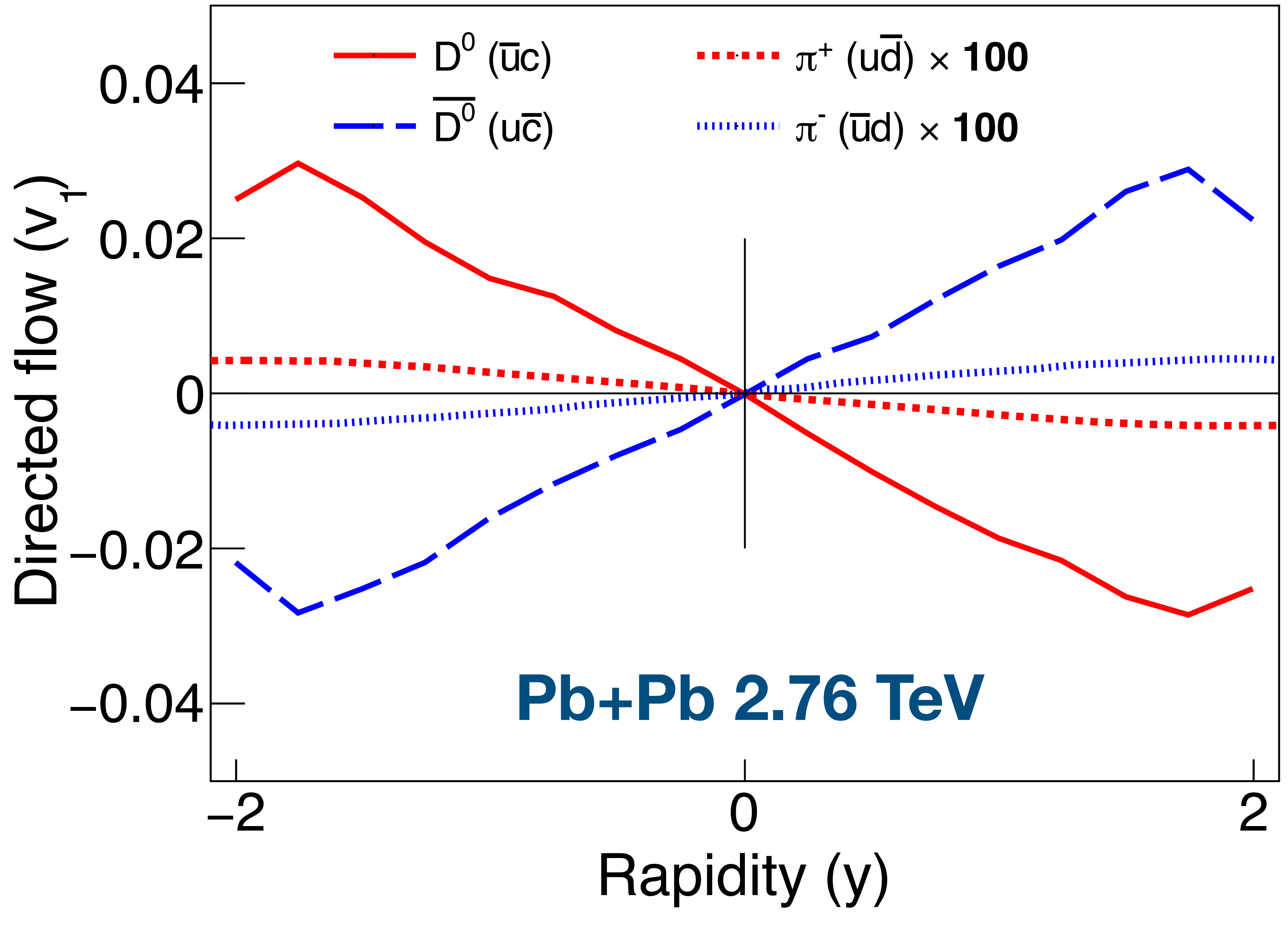
- ★ Motivation
- ★ STAR detector
- ★ Analysis details
- ★ Results:
  - $D^0/\overline{D}^0$ directed (v_1) and ($D^0+\overline{D}^0$) elliptic flow (v_2)
  - Comparison to light flavor hadrons and model calculations
- ★ Summary

Directed flow (v_1) for heavy quarks due to EM fields





- The moving spectators can produce enormously large electromagnetic field ($eB \sim 10^{18}$ G at RHIC)
- Due to early production of heavy quarks ($\tau_{CQ} \sim 0.1$ fm/c) positive and negative charm quarks (CQs) can get deflected by the initial EM force



- Model predicts opposite v_1 for charm and anti-charm quarks induced by this initial EM field

  This induced v_1 depends on the balance between E and B fields

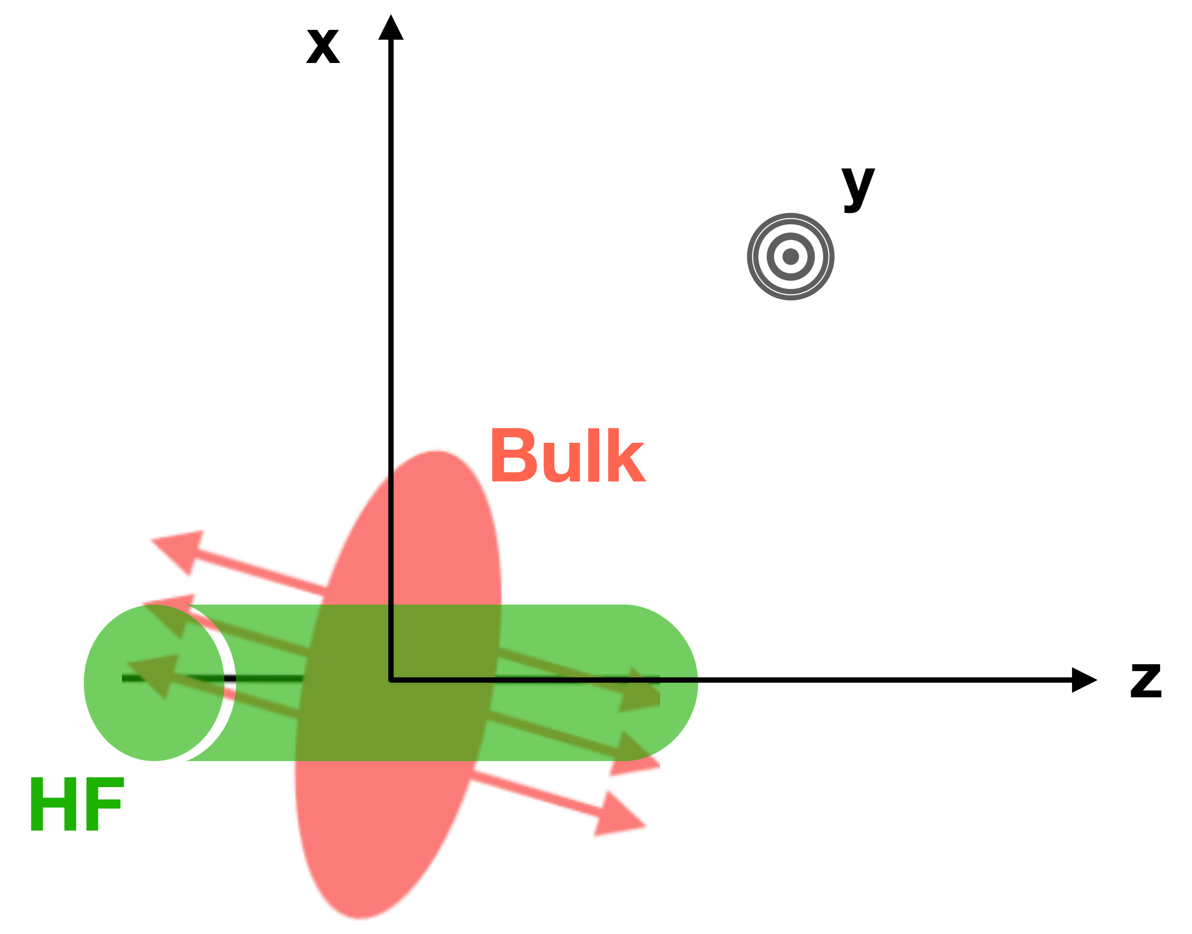
  The magnitude of such induced v_1 for heavy quarks is much larger than the light quarks

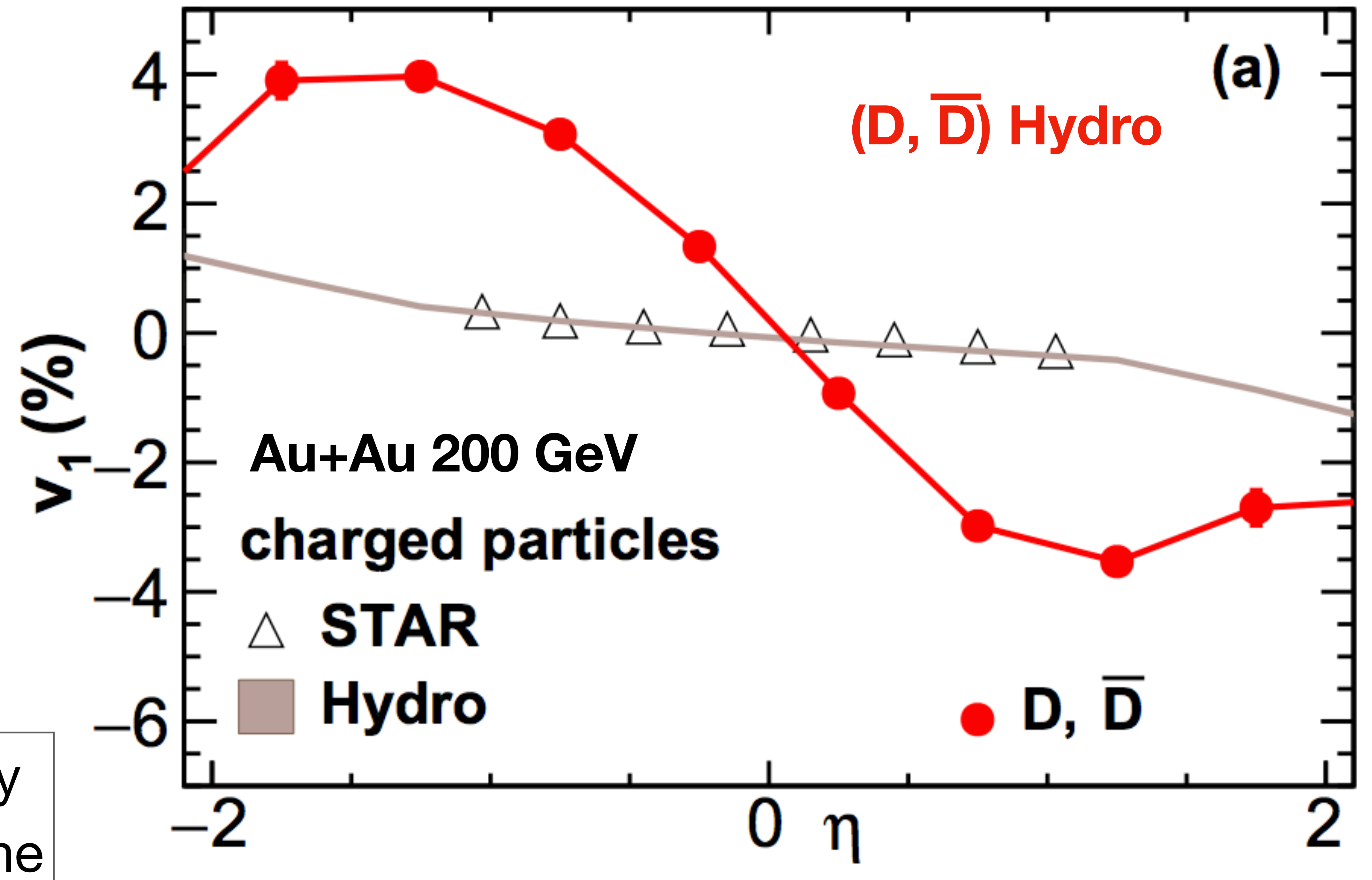
D^0 and $\overline{D^0}$ v_1 can offer insight into the early time EM fields

→ Provide constraint for CME related physics

Directed flow (v_1) for heavy quarks from hydro

Drag between the tilted bulk and the HFs





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

- Heavy quarks are produced according to N_{coll} density: symmetric in rapidity
- At non-zero rapidity, charm quarks production points are shifted from the bulk
- This can induce larger v_1 in charm quarks than light flavors
- Magnitude of charm quark v_1 depends on the drag parameter used in this model

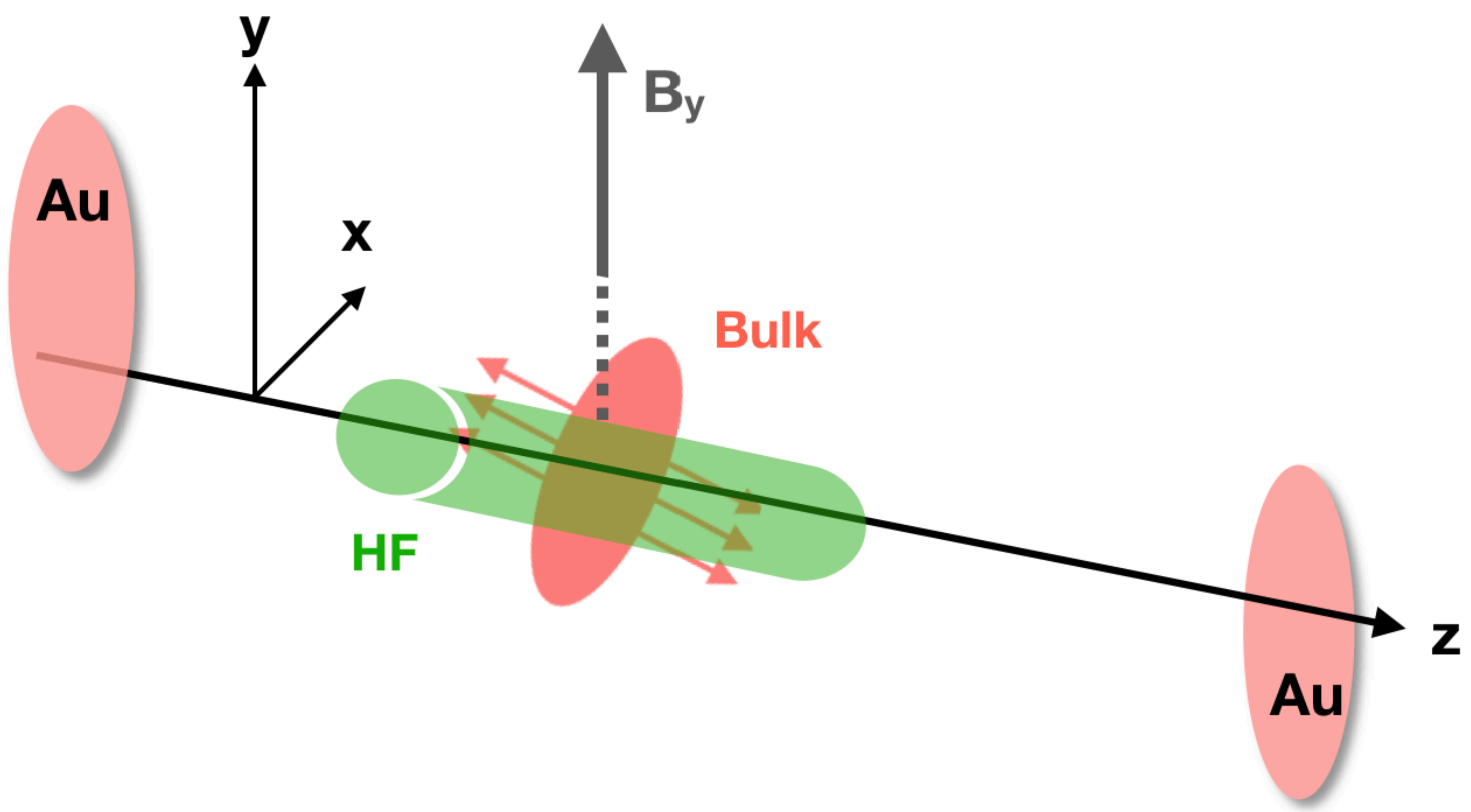
We can probe the longitudinal profile of the initial matter distribution through heavy flavor v_1

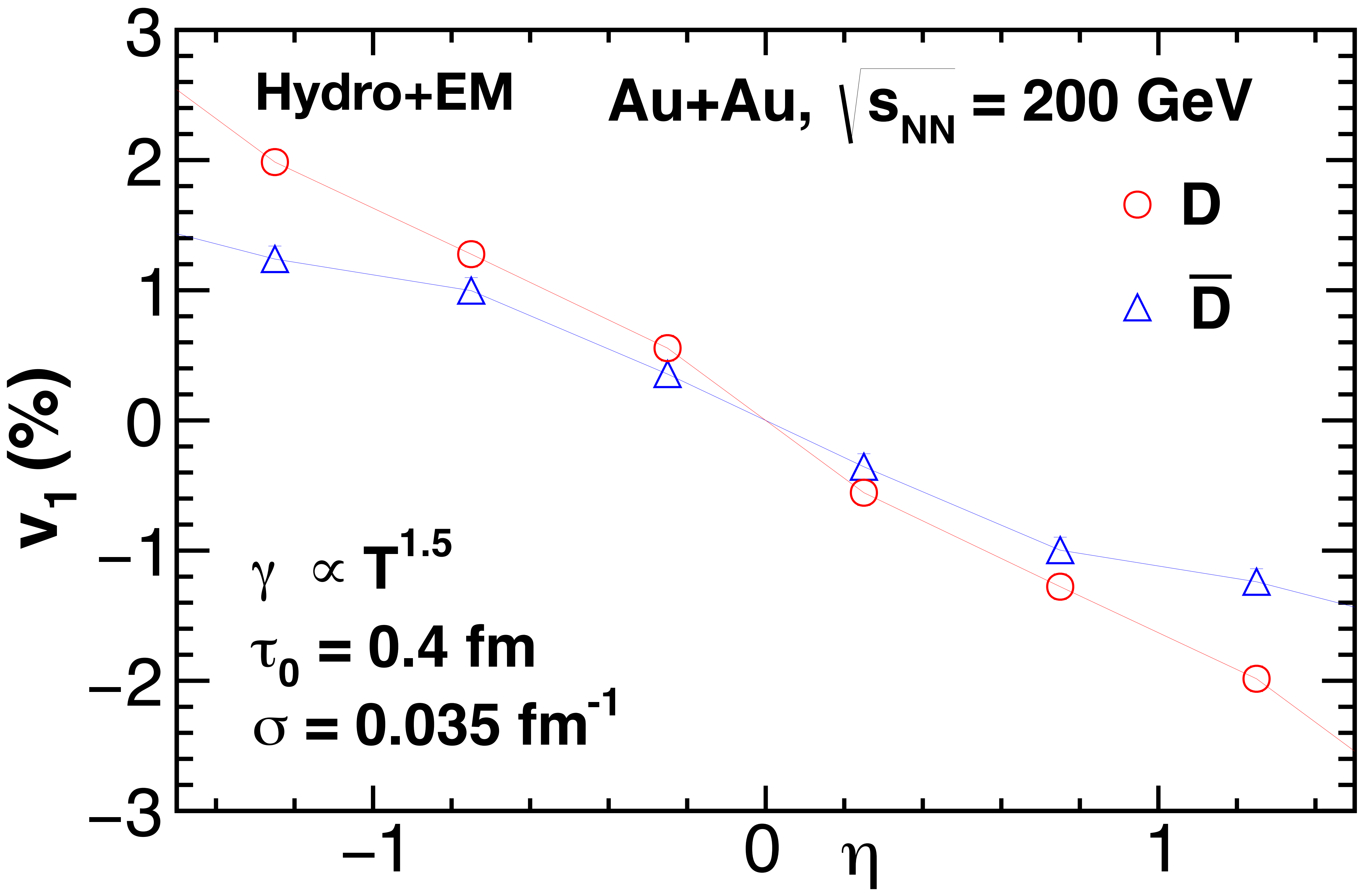
$(v_1\text{-slope})_{\text{Charm-Quark}} >> (v_1\text{-slope})_{\text{Light-Quark}}$ → Charm quarks much more sensitive to the initial tilt than the charged hadrons

D^0 ($\overline{D^0}$) v_1 can be used to constrain drag coefficients in conjunction with v_2 and R_{AA}

Directed flow (v_1) for heavy quarks from hydro + EM field

Interplay between the drag by tilted bulk and the EM field

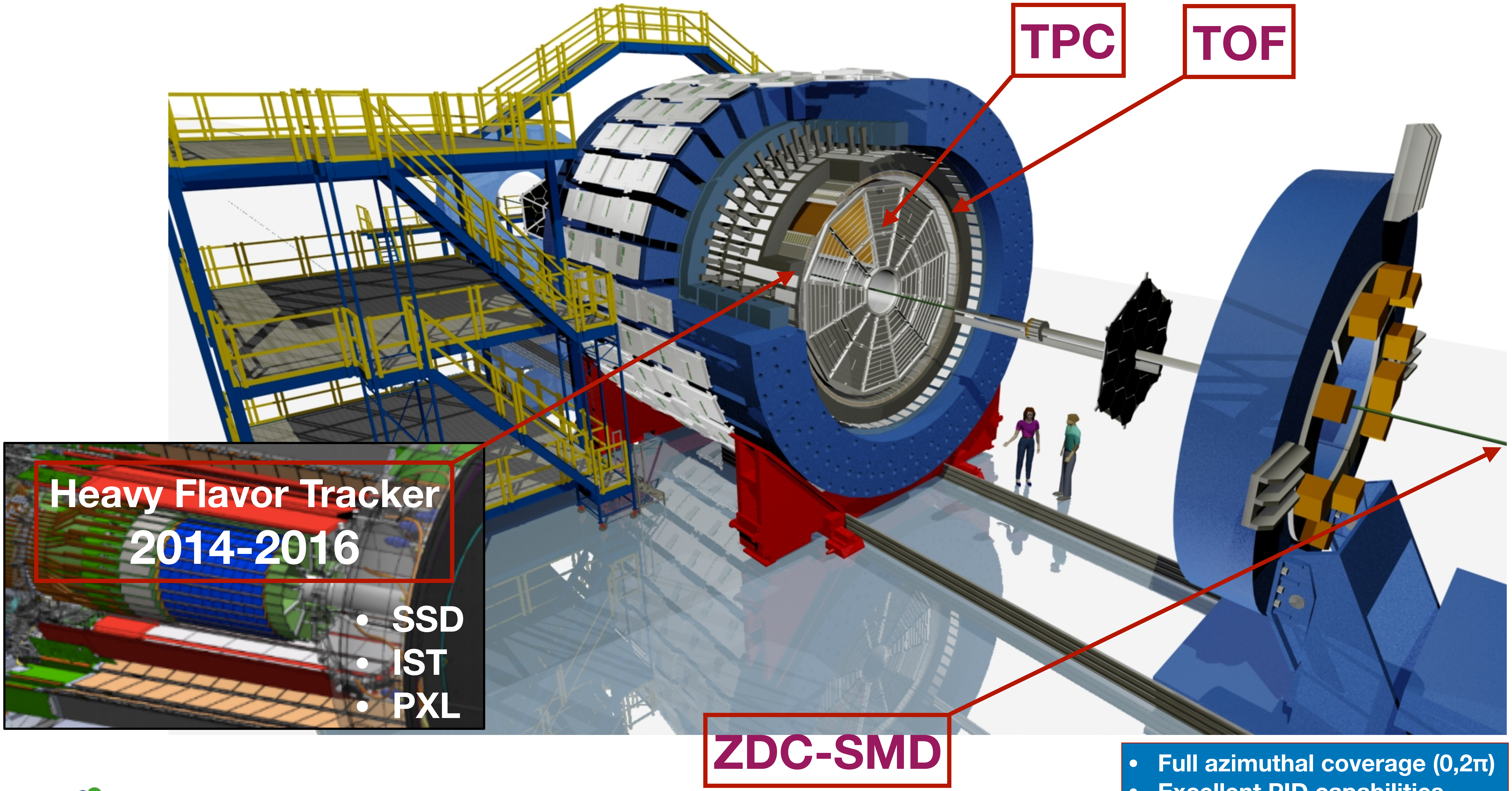




Chatterjee, Bozek: 1804.04893v1

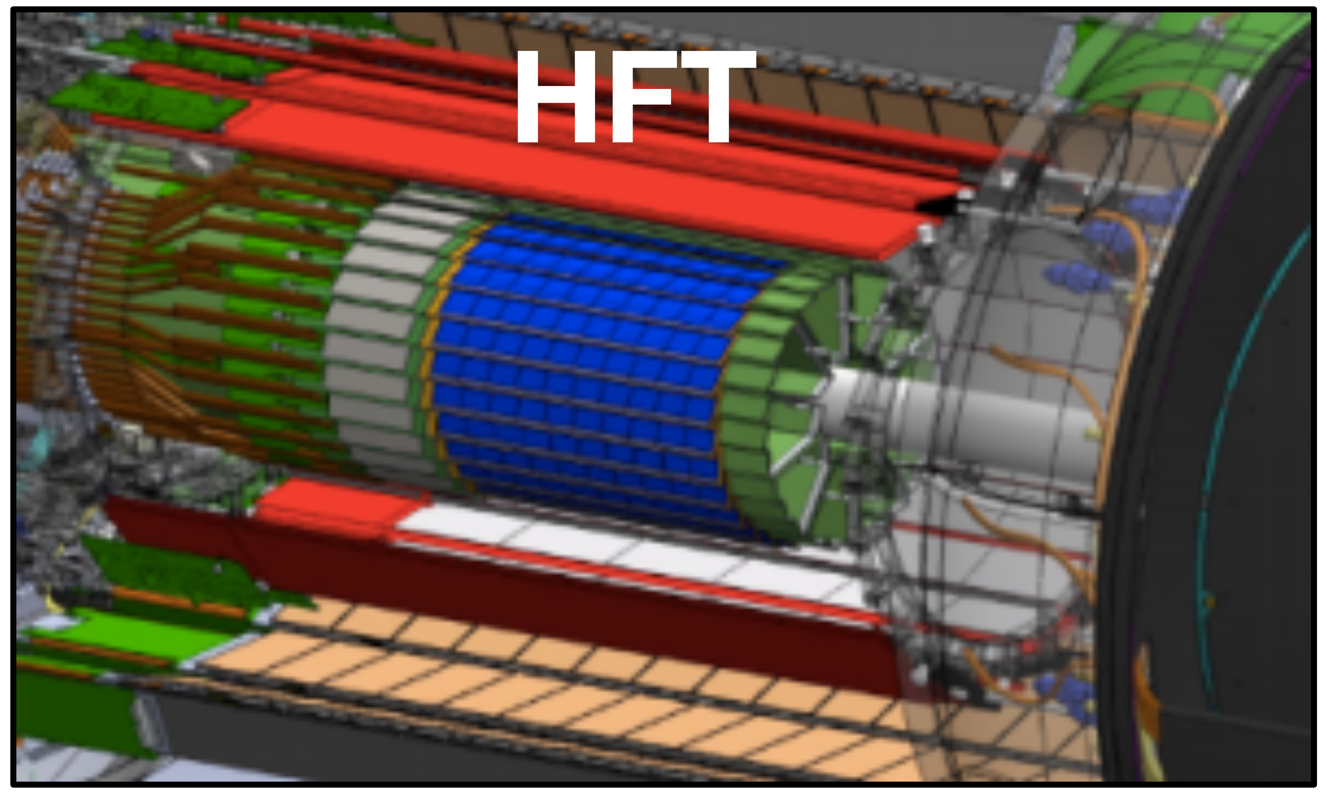
- Recent hydro model with initial EM field predicts v_1-split between the D and $\overline{D}$ meson
- D meson v_1 greater than the $\overline{D}$
- Predicted difference in v_1 is about 10 times smaller than the average v_1

The STAR detector

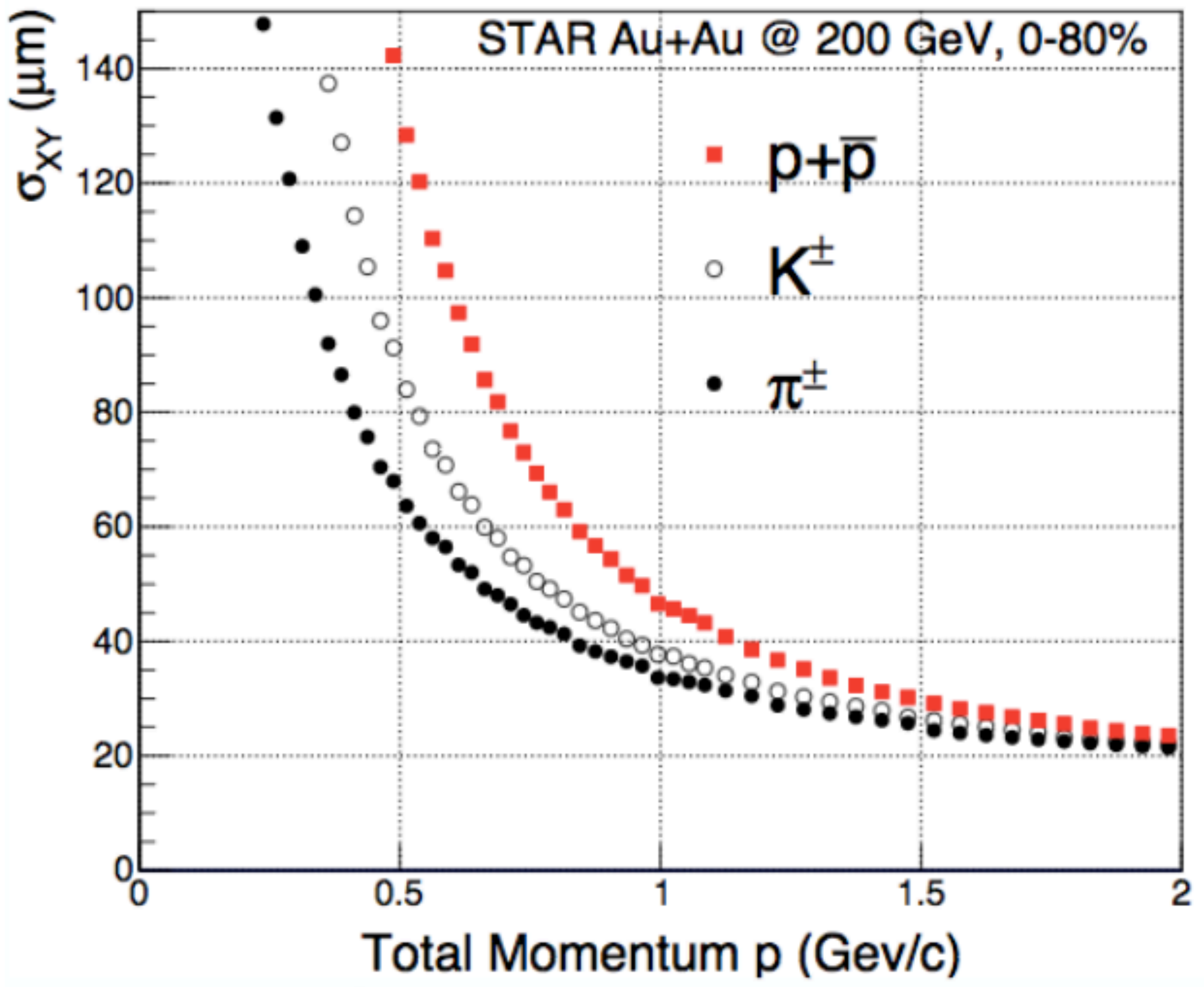


- Full azimuthal coverage (0,2π)
- Excellent PID capabilities

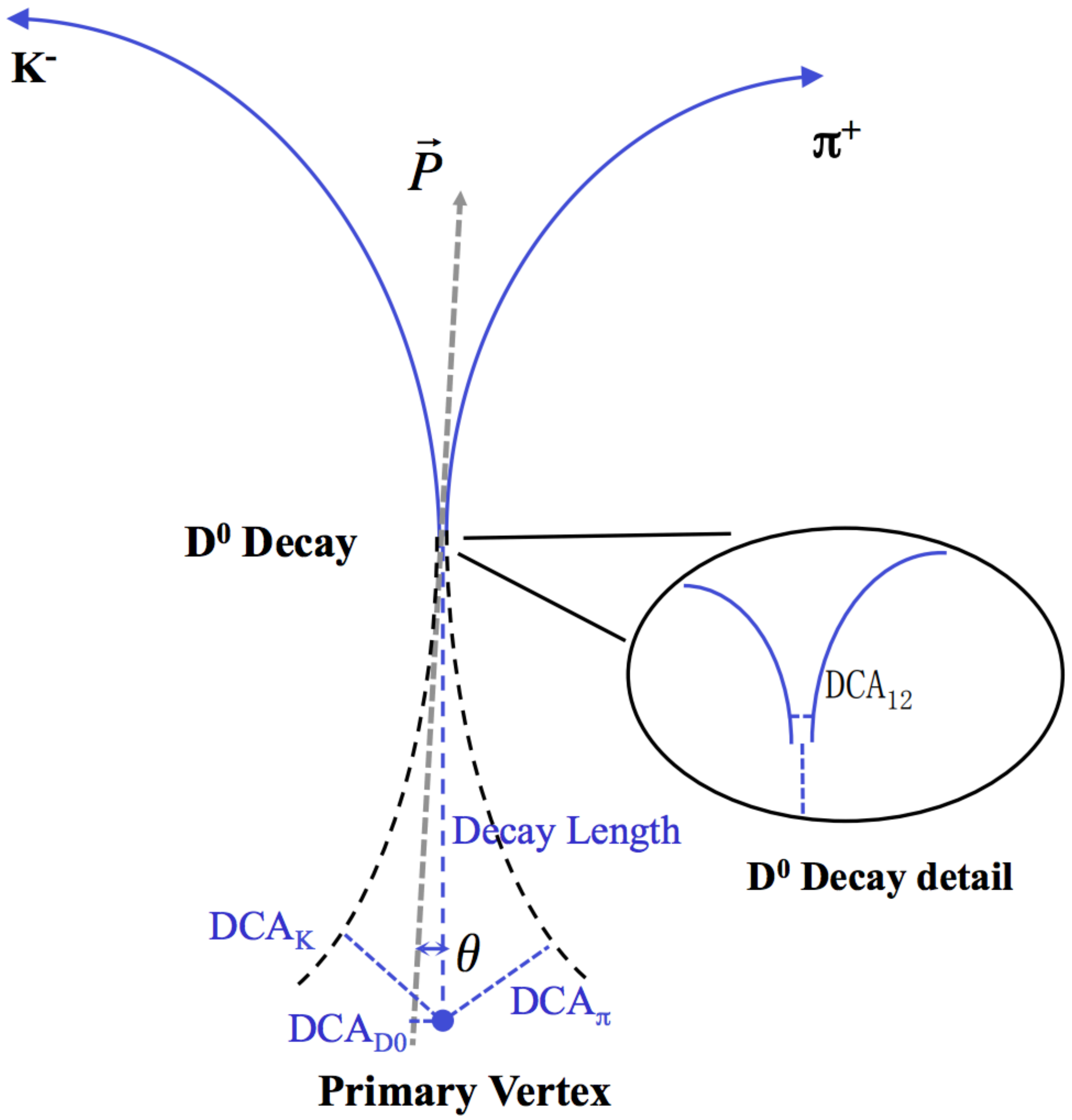
D^0 reconstruction with HFT



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

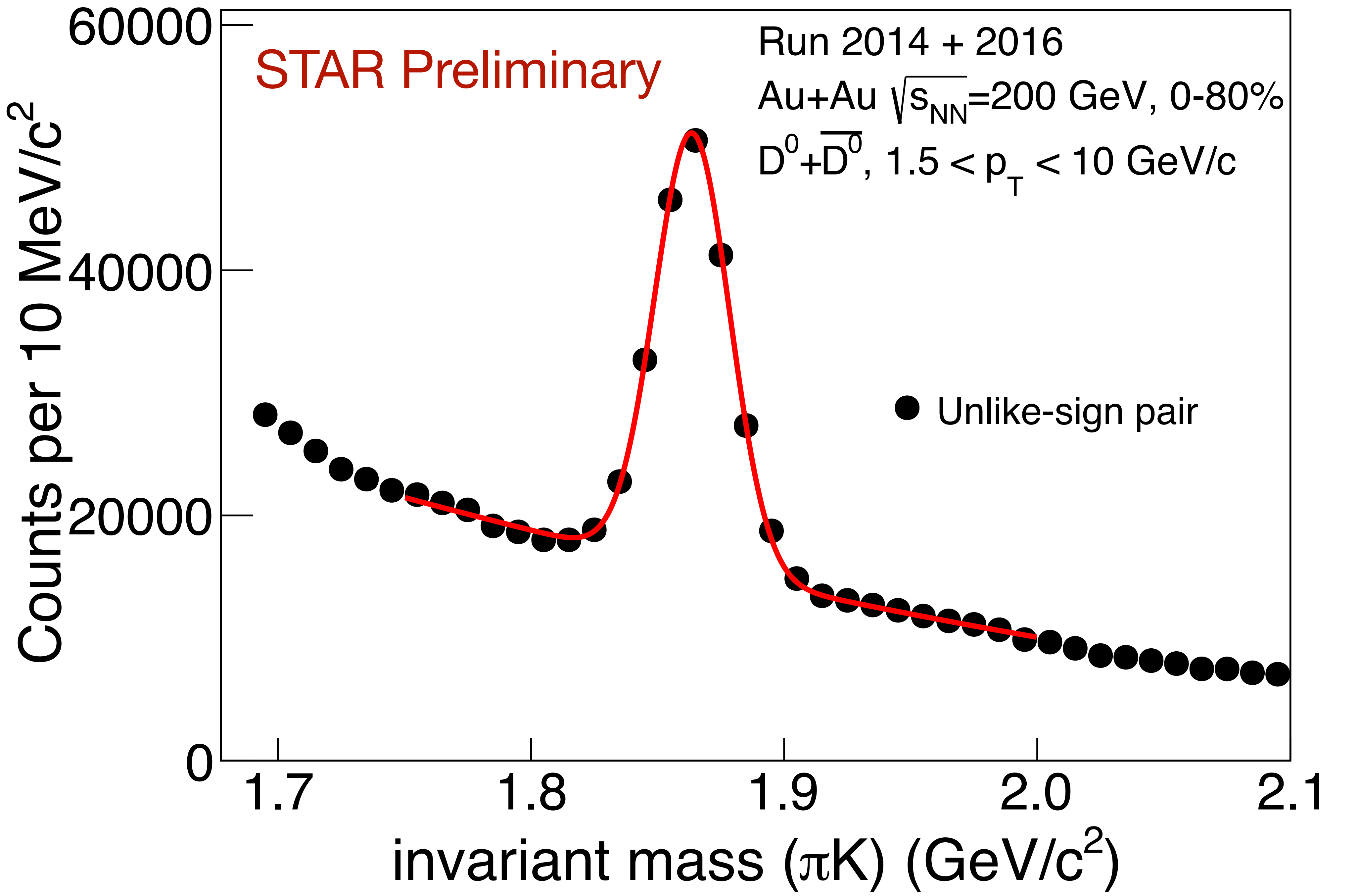


D^0 decay topology:



D^0 meson

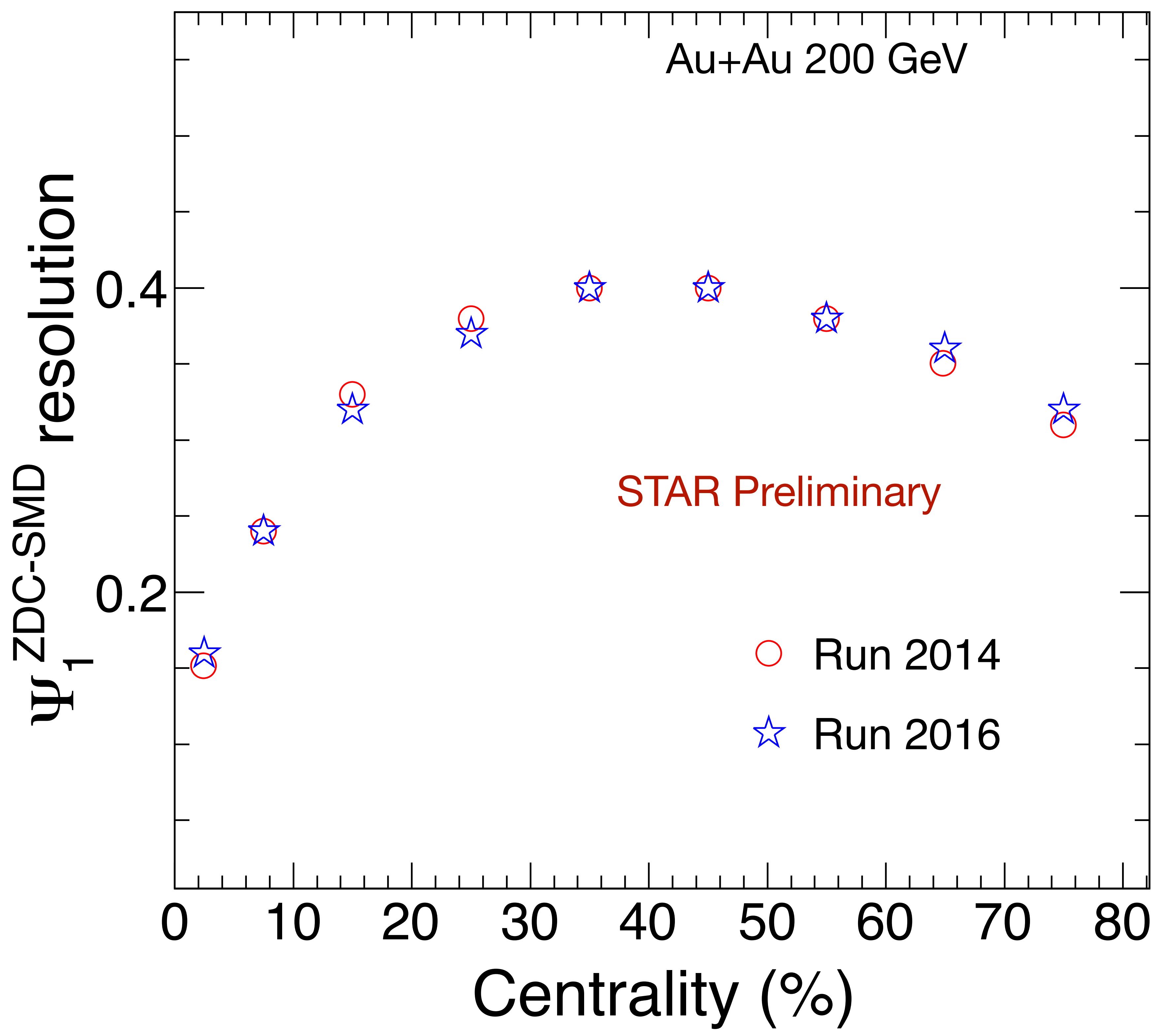
Quark content: D^0 ($\bar{u}c$), $\overline{D^0}$ ($u\bar{c}$),
Decay channel: $D^0 \rightarrow K^-\pi^+$
$\overline{D^0} \rightarrow K^+\pi^-$
cτ: 120 μm
Mass: 1864.84 +/- 0.18 MeV/c^2
Branching ratio: 3.89%



- HFT data from 2014 and 2016 runs
- Total ~ 2 billion events

D^0 v_1 from event plane method

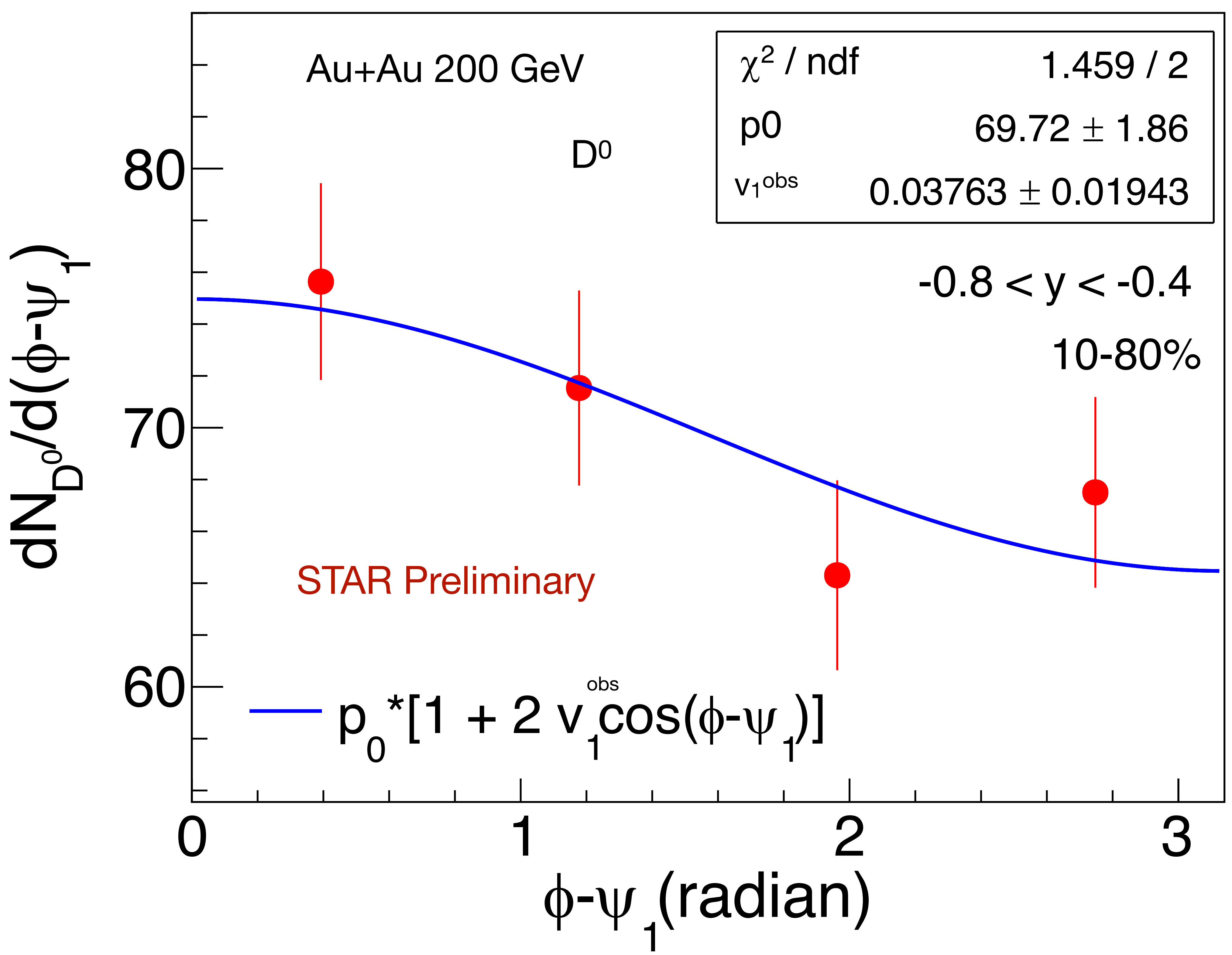
ZDC-SMD event plane resolution



- 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:

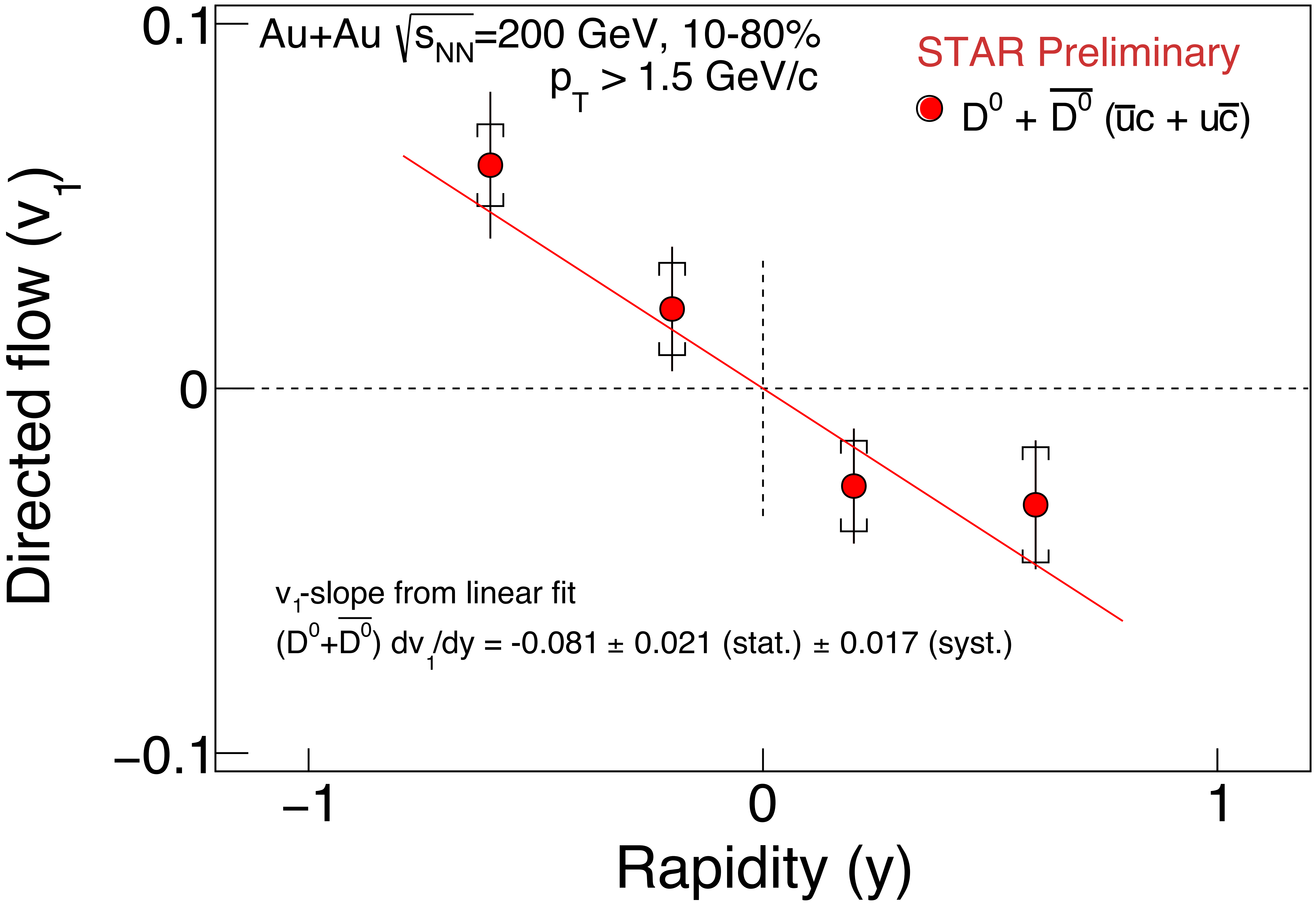
$p_T > 1.5$ GeV/c



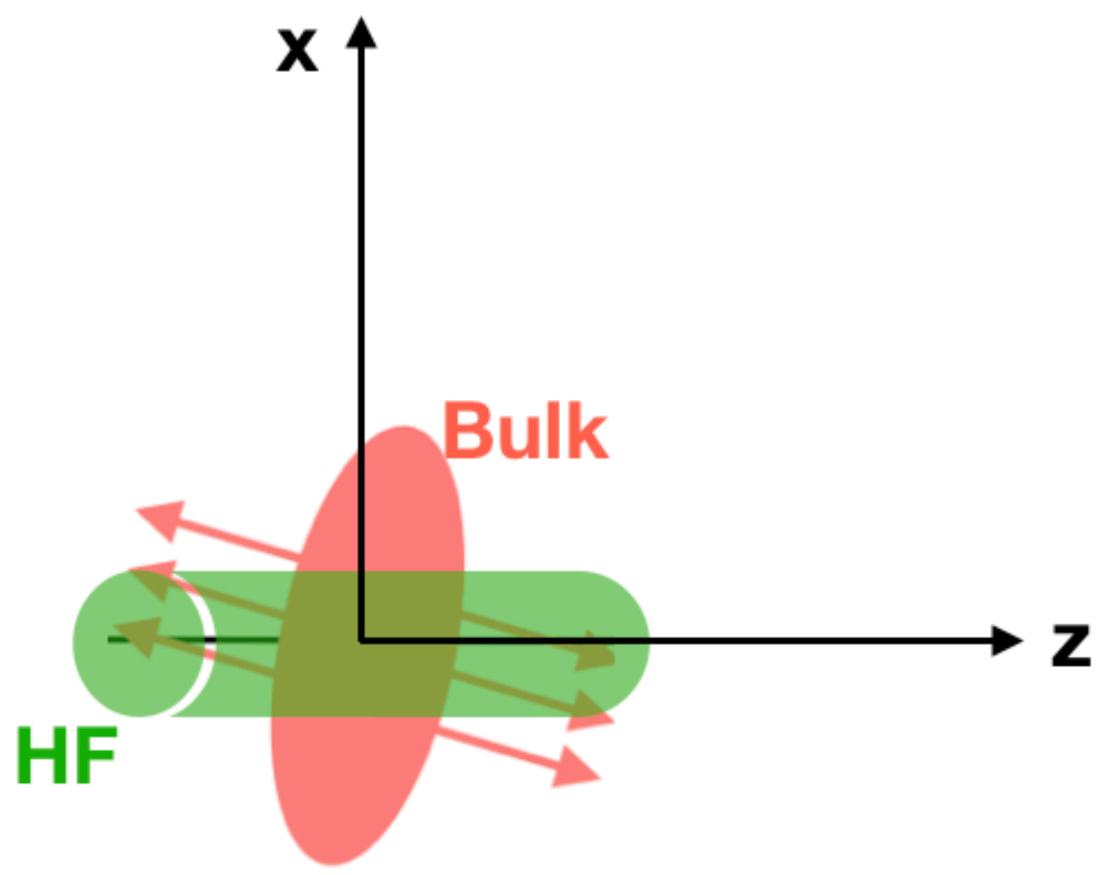
$$v_1 \sim \frac{\langle \cos(\phi - \psi_1) \rangle}{\psi_1 \text{ res.}} \sim \frac{v_1^{\text{obs}}}{\psi_1 \text{ res.}}$$

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

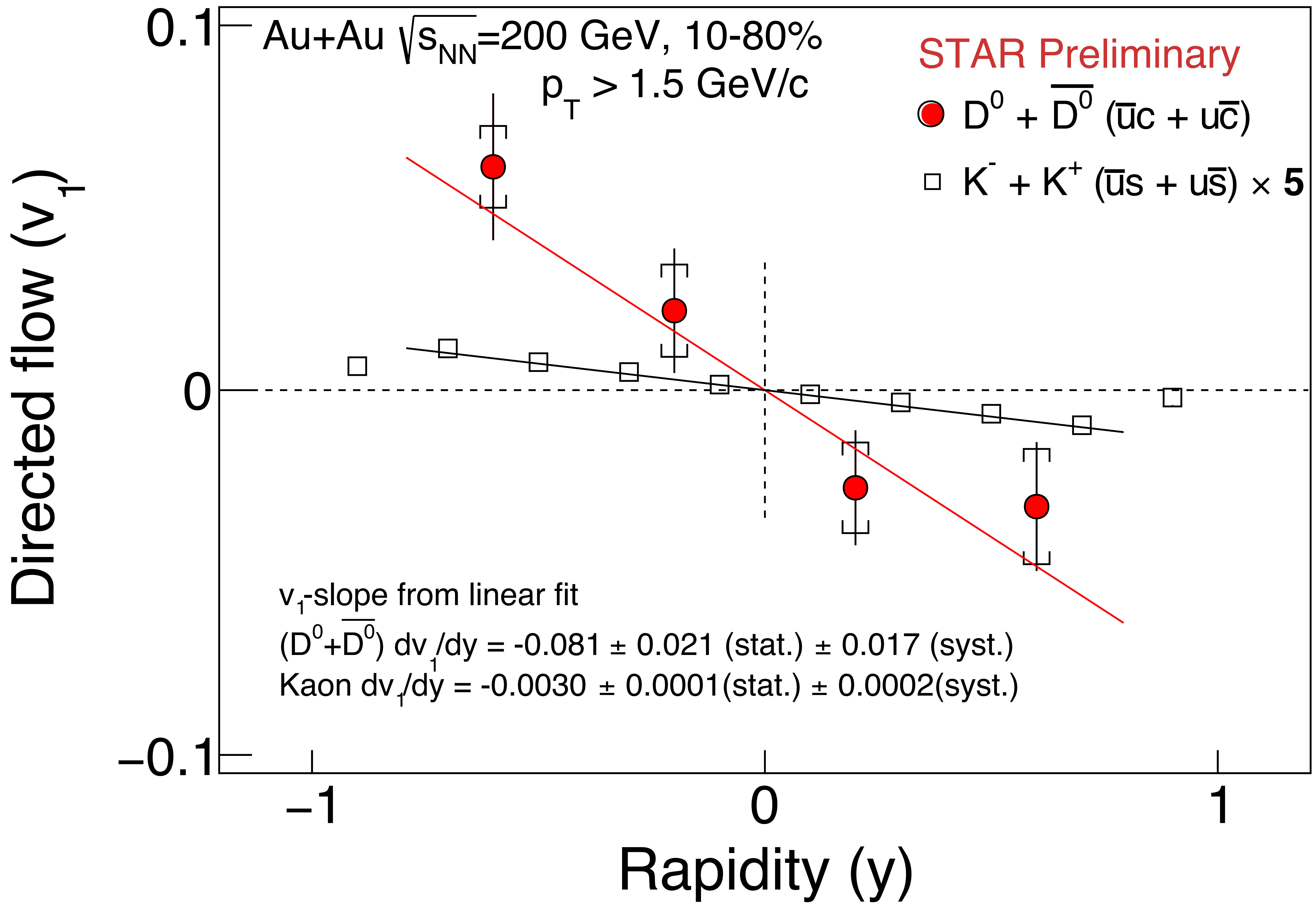
v_1 comparison: D^0 vs. kaon



- First observation of non-zero D^0 v_1

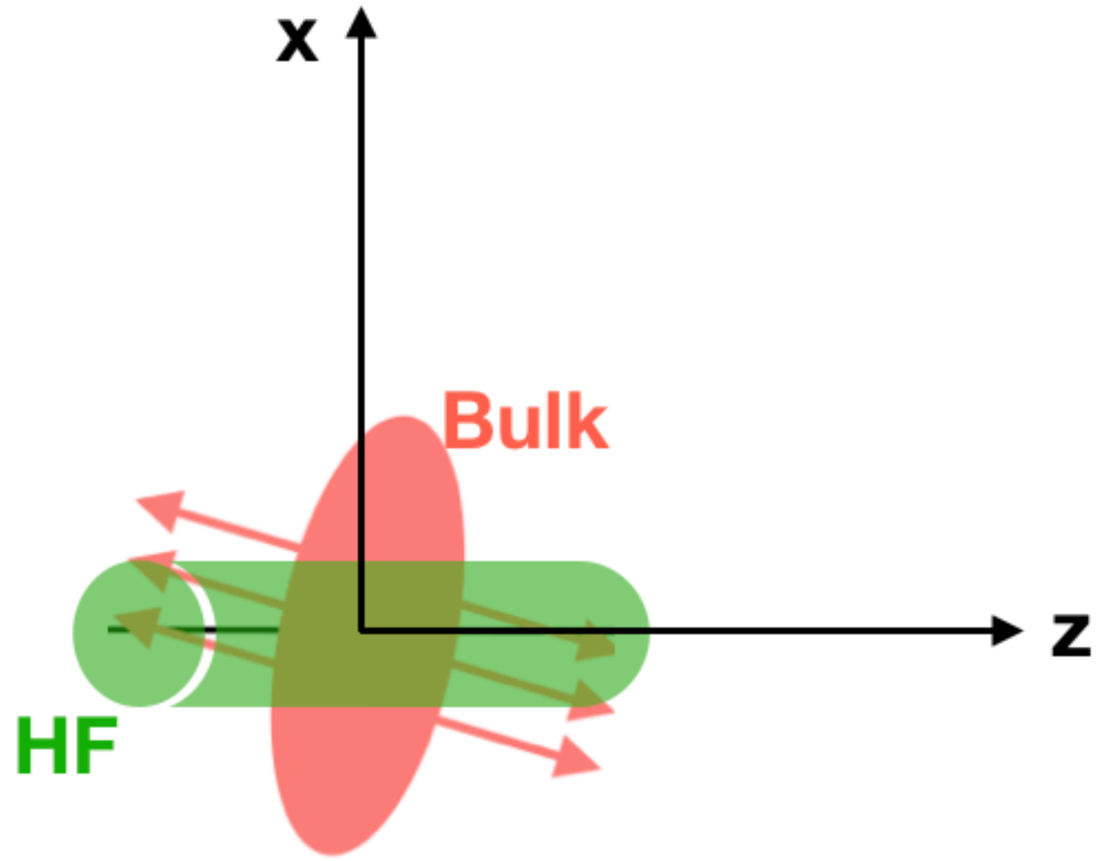


v_1 comparison: D^0 vs. kaon



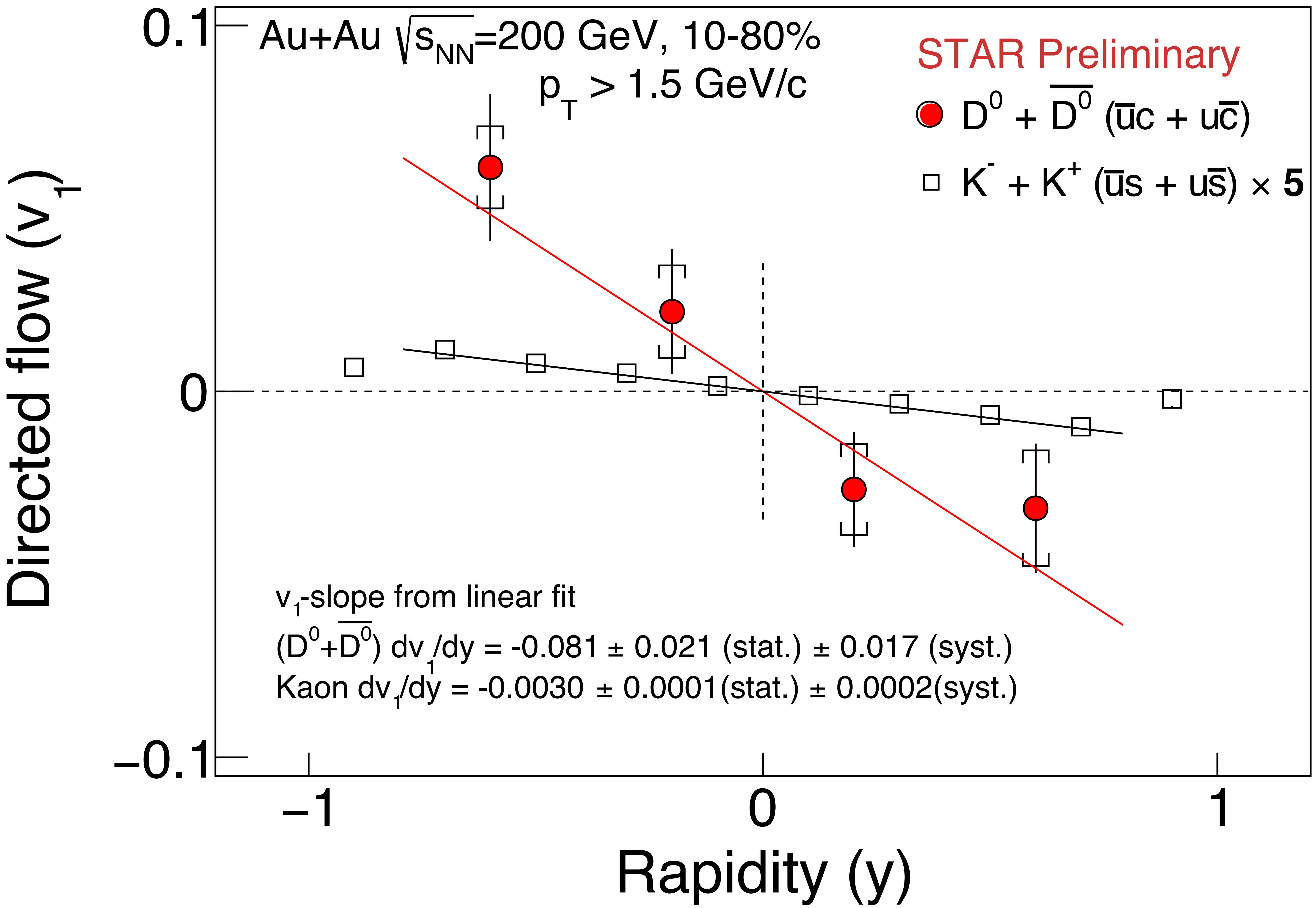
Charged Kaons:
L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 120, 62301 (2018)

- First observation of non-zero D^0 v_1
- D^0 v_1-slope much larger than that of kaons



Charm v_1-slope > light flavor v_1-slope

v_1 comparison: D^0 vs. kaon

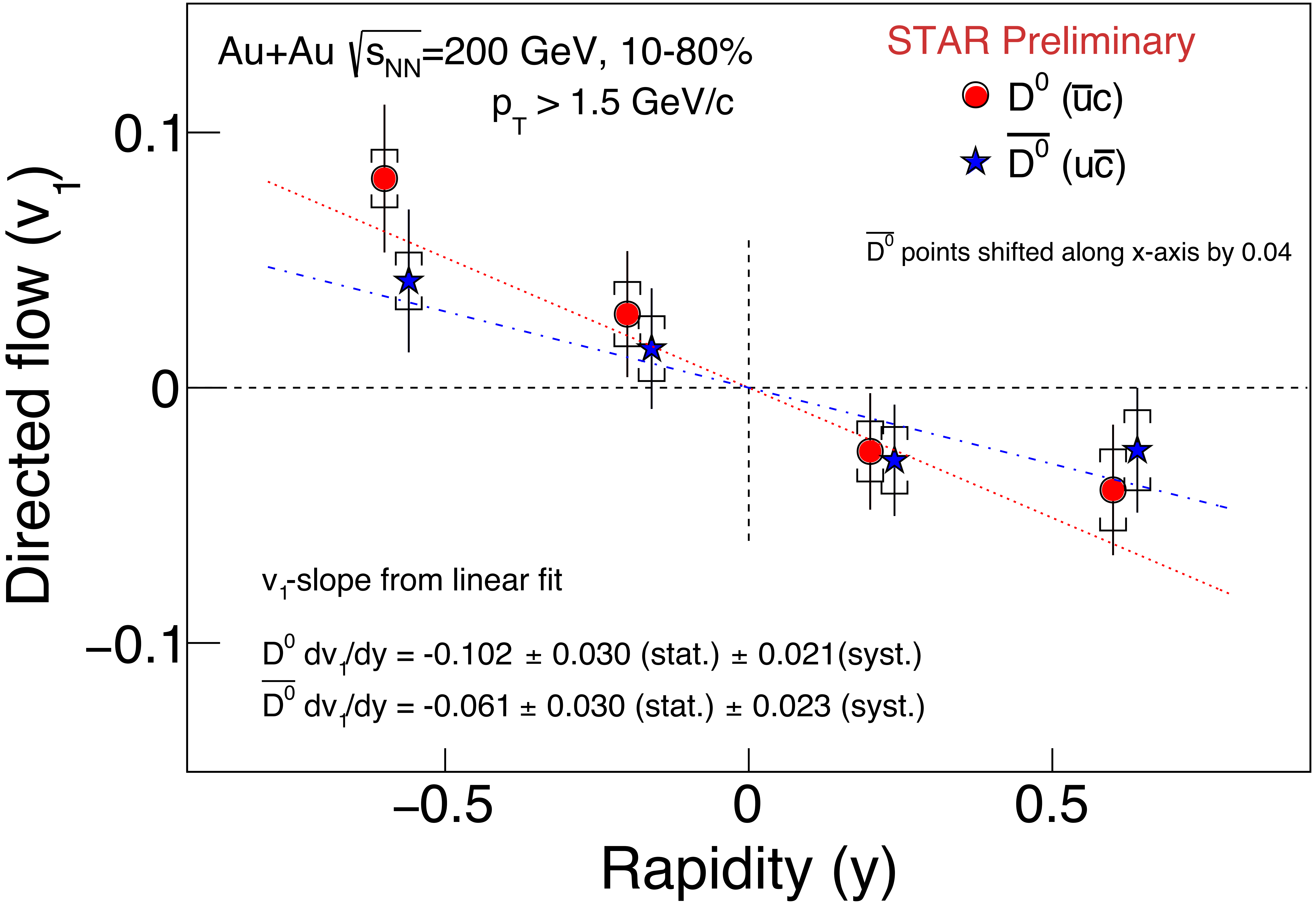


- First observation of non-zero D^0 v_1
- D^0 v_1-slope much larger than that of kaons

Charm v_1-slope > light flavor v_1-slope

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

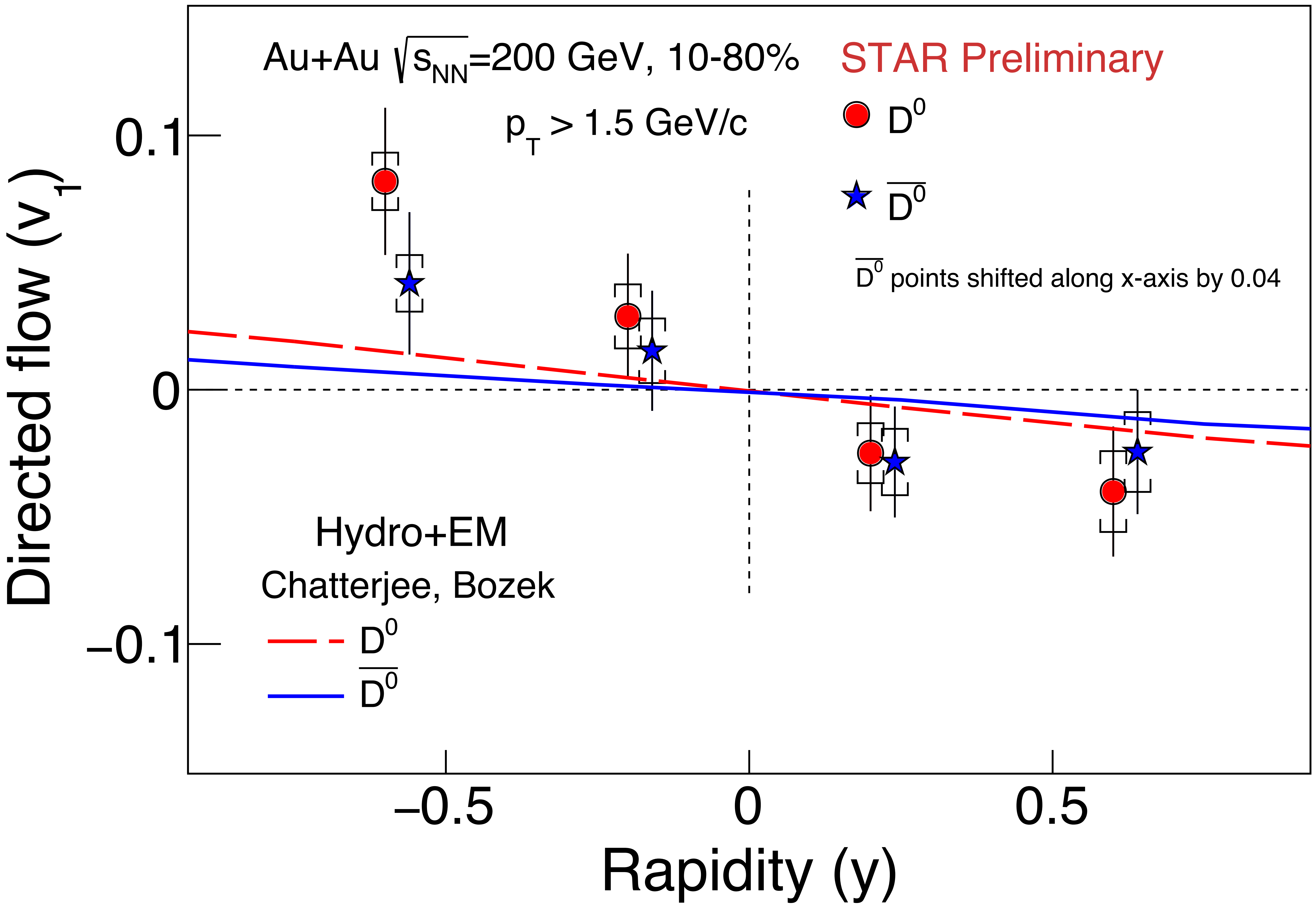
D^0 and $\overline{D^0}$ v_1

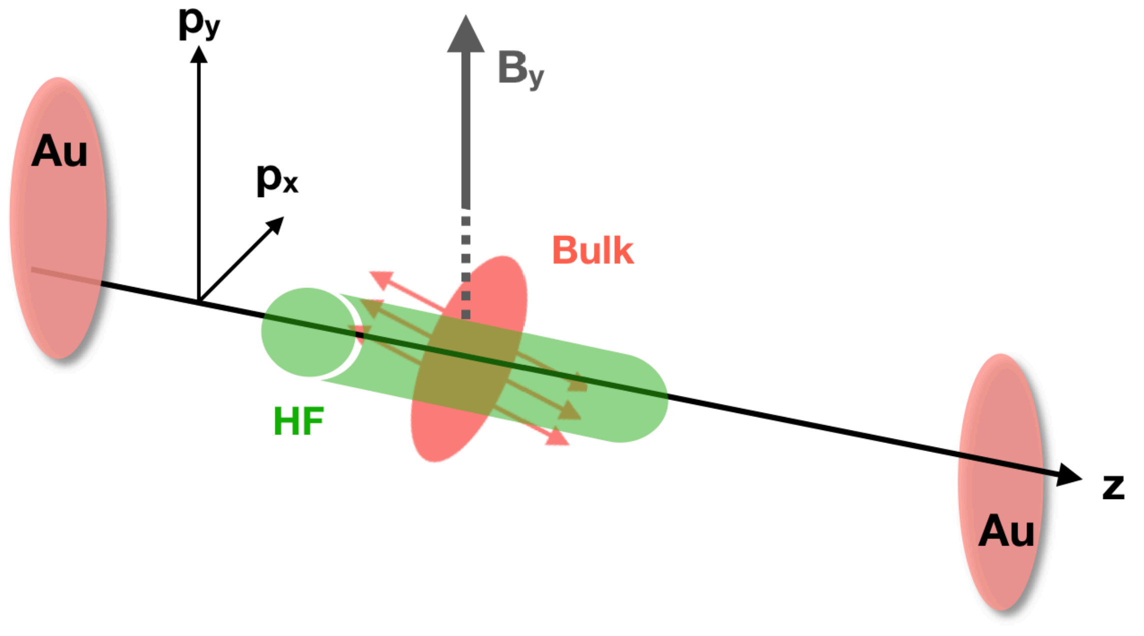


- First observation of non-zero D^0 v_1
- Both D^0 and $\overline{D^0}$ v_1 show a negative slope at mid-rapidity

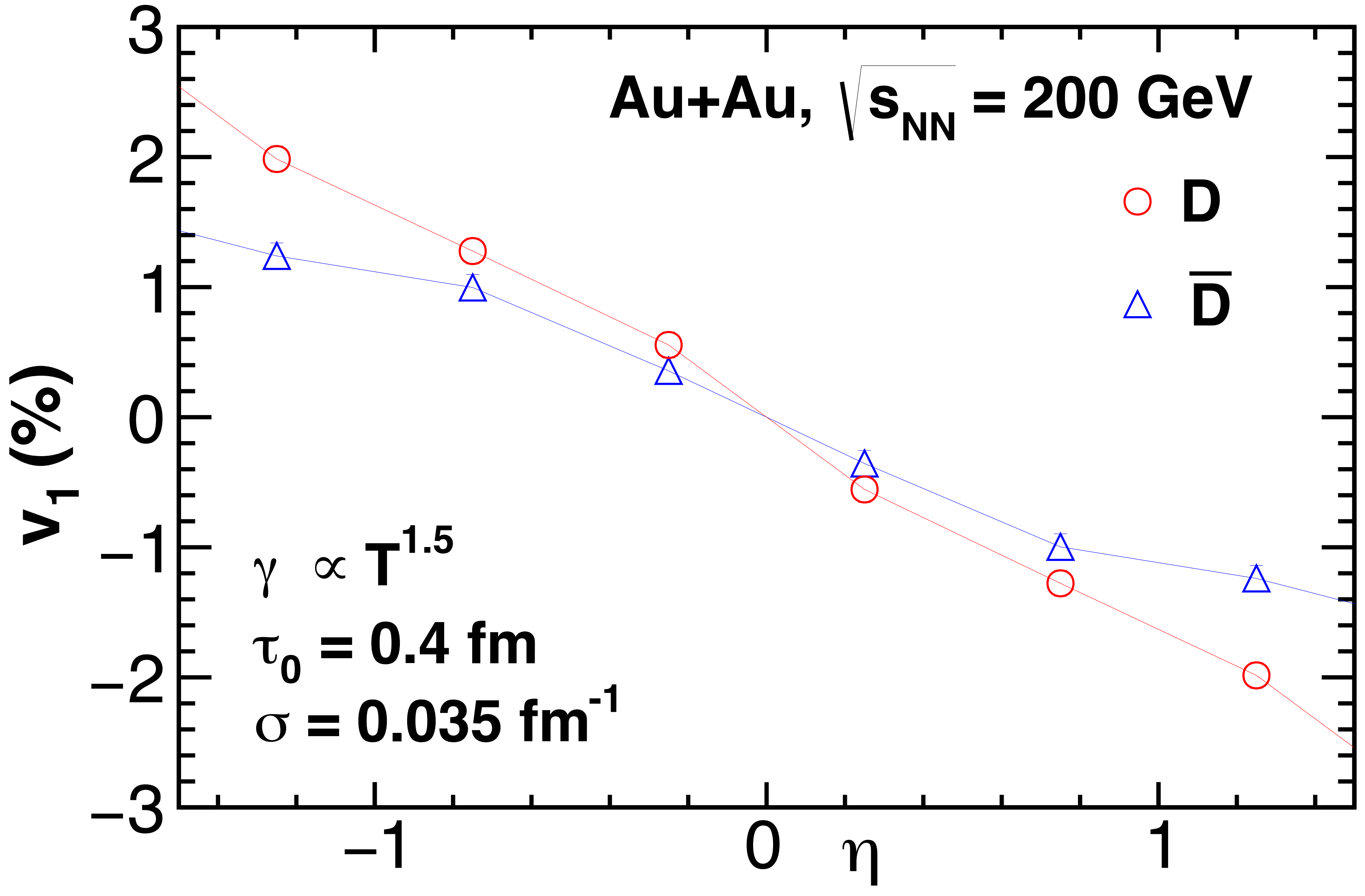
$$D^0 \; dv_1/dy = -0.102 \pm 0.030 \pm 0.021$$
$$\overline{D^0} \; dv_1/dy = -0.061 \pm 0.030 \pm 0.023$$

D^0 v_1: data vs. hydro + EM





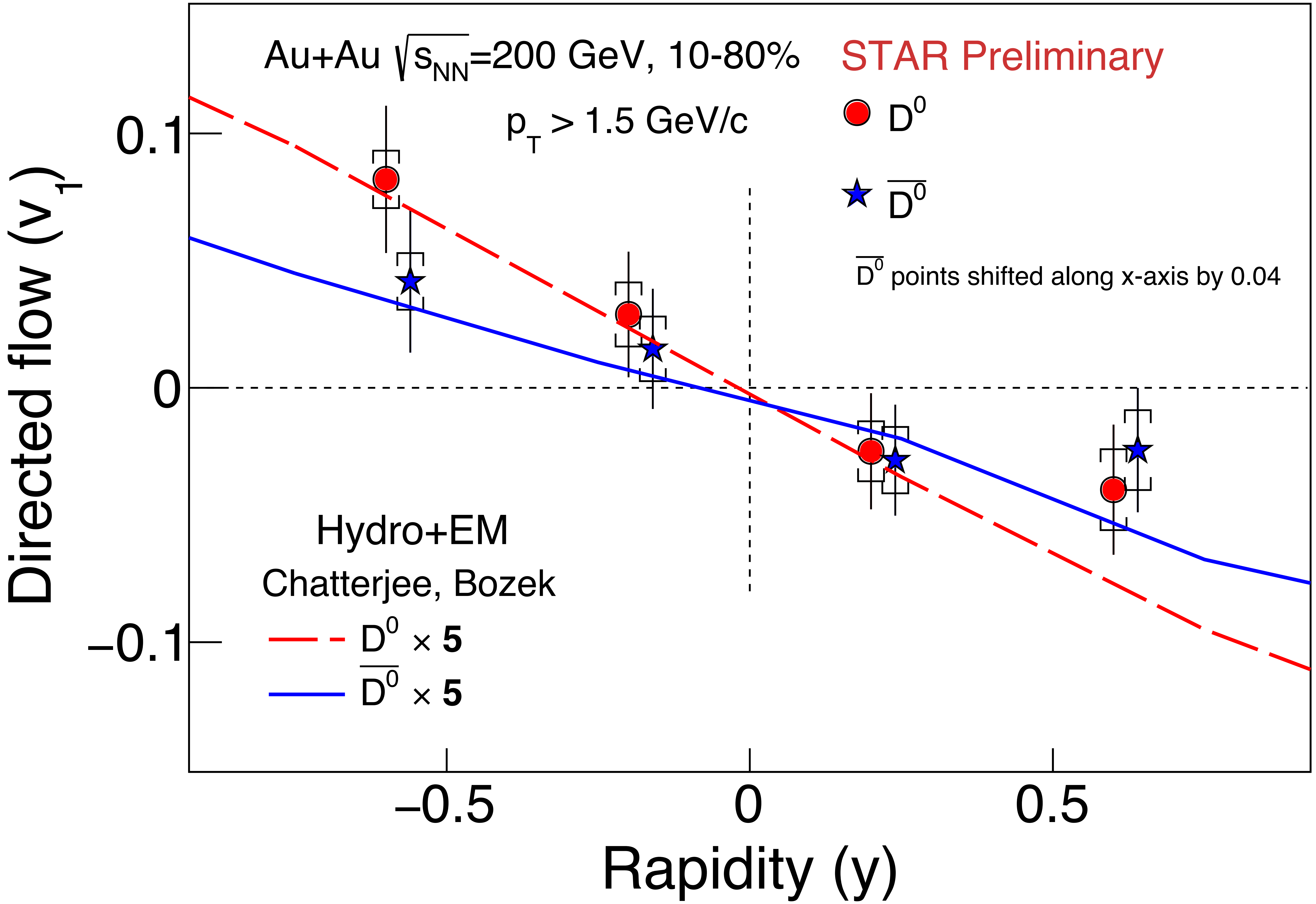
Expected v_1 from Hydro+EM field

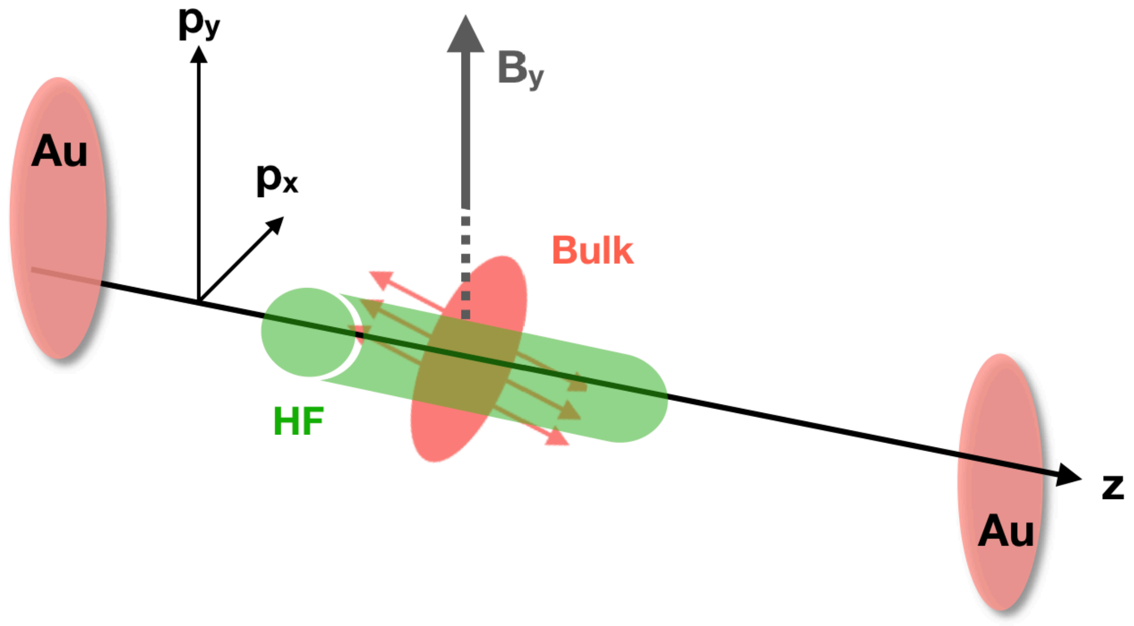


Chatterjee, Bozek: 1804.04893v1

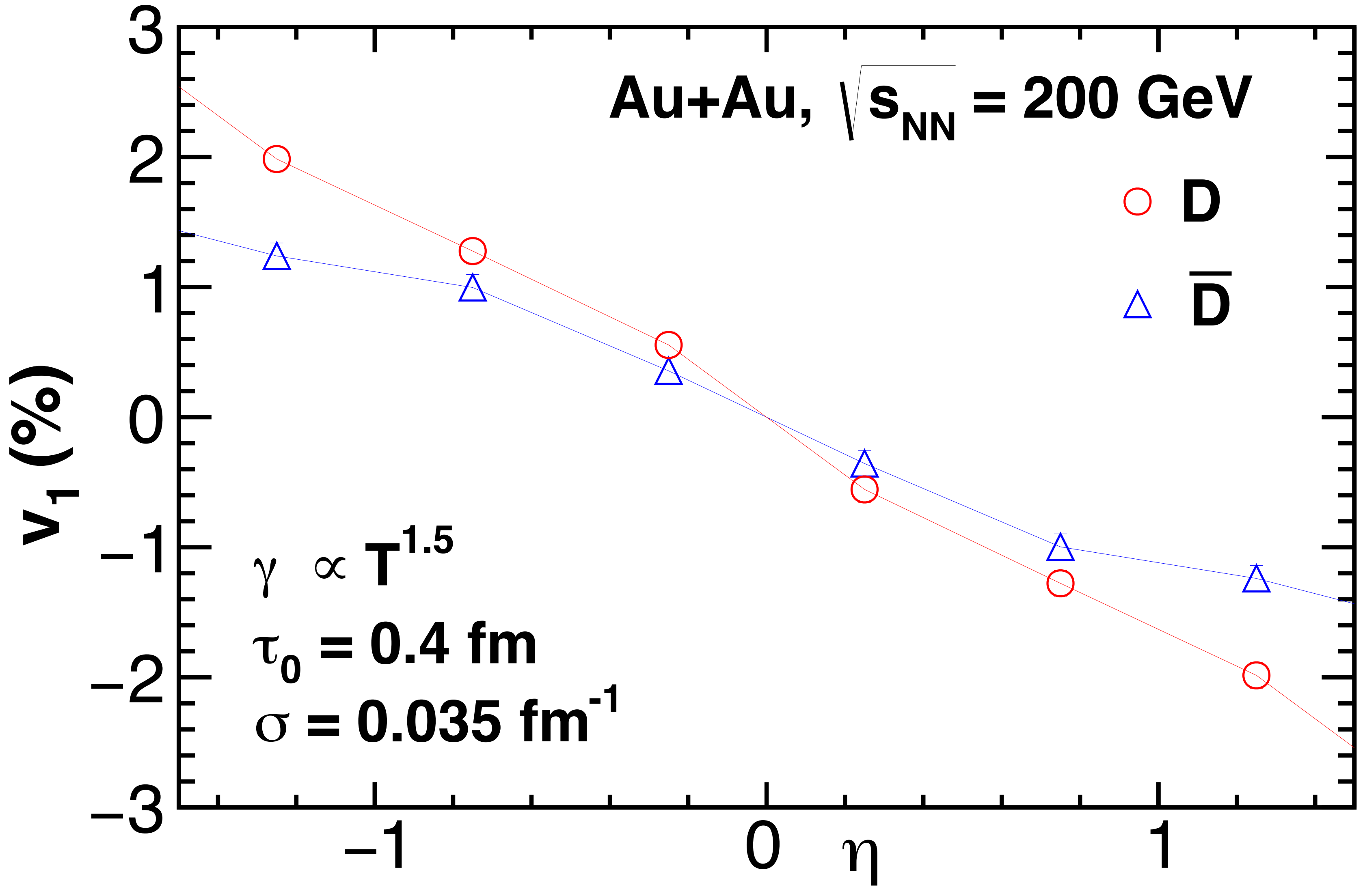
- The model predicts correct sign of v_1-slope for D^0 and $\overline{D^0}$ but wrong magnitude

D^0 v_1: data vs. hydro + EM





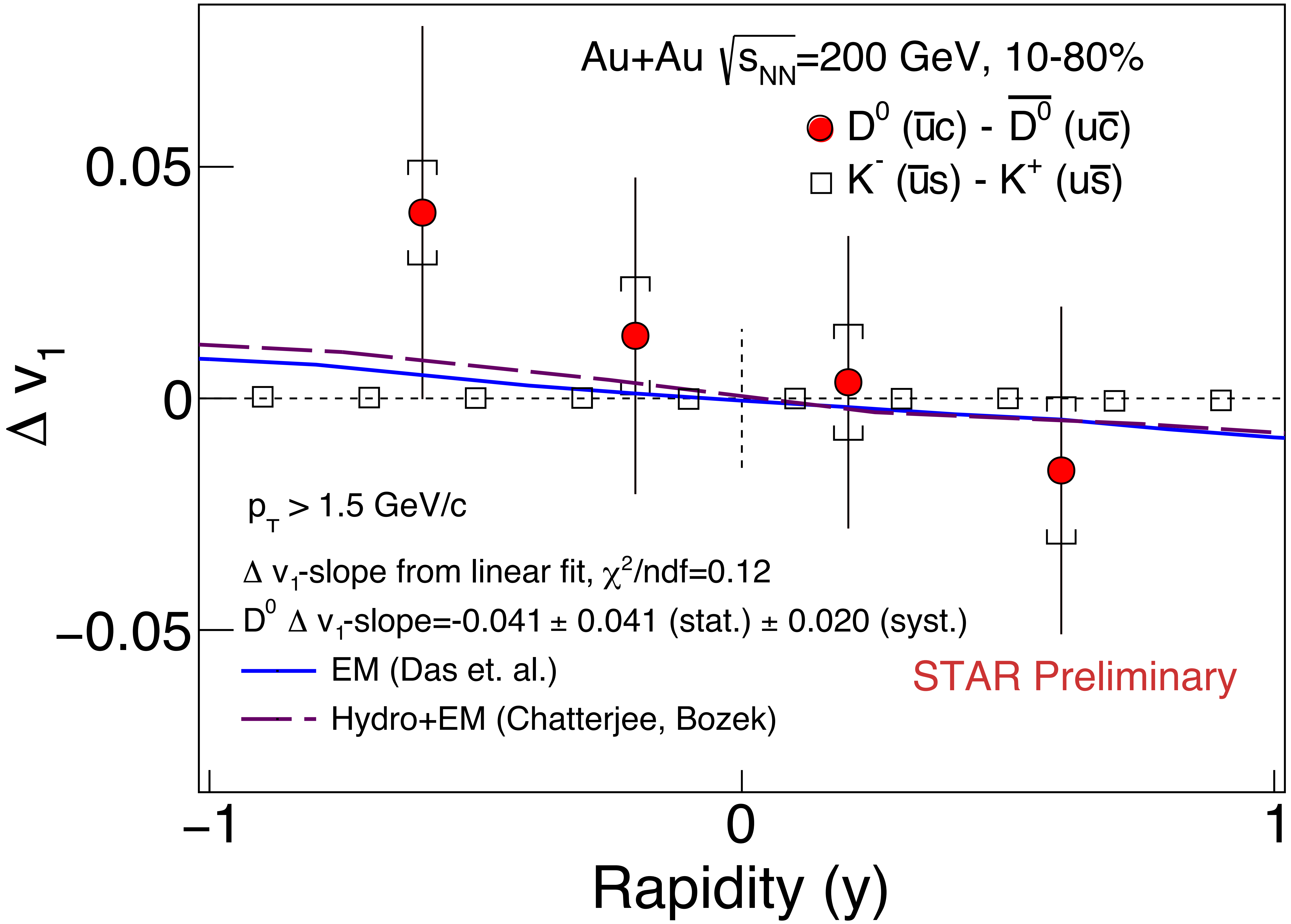
Expected v_1 from Hydro+EM field



Chatterjee, Bozek: 1804.04893v1

- The model predicts correct sign of v_1-slope for D^0 and $\overline{D^0}$ but wrong magnitude
- Our data will help to constrain model parameters (tilt and drag parameters)

Δv_1: data vs. models

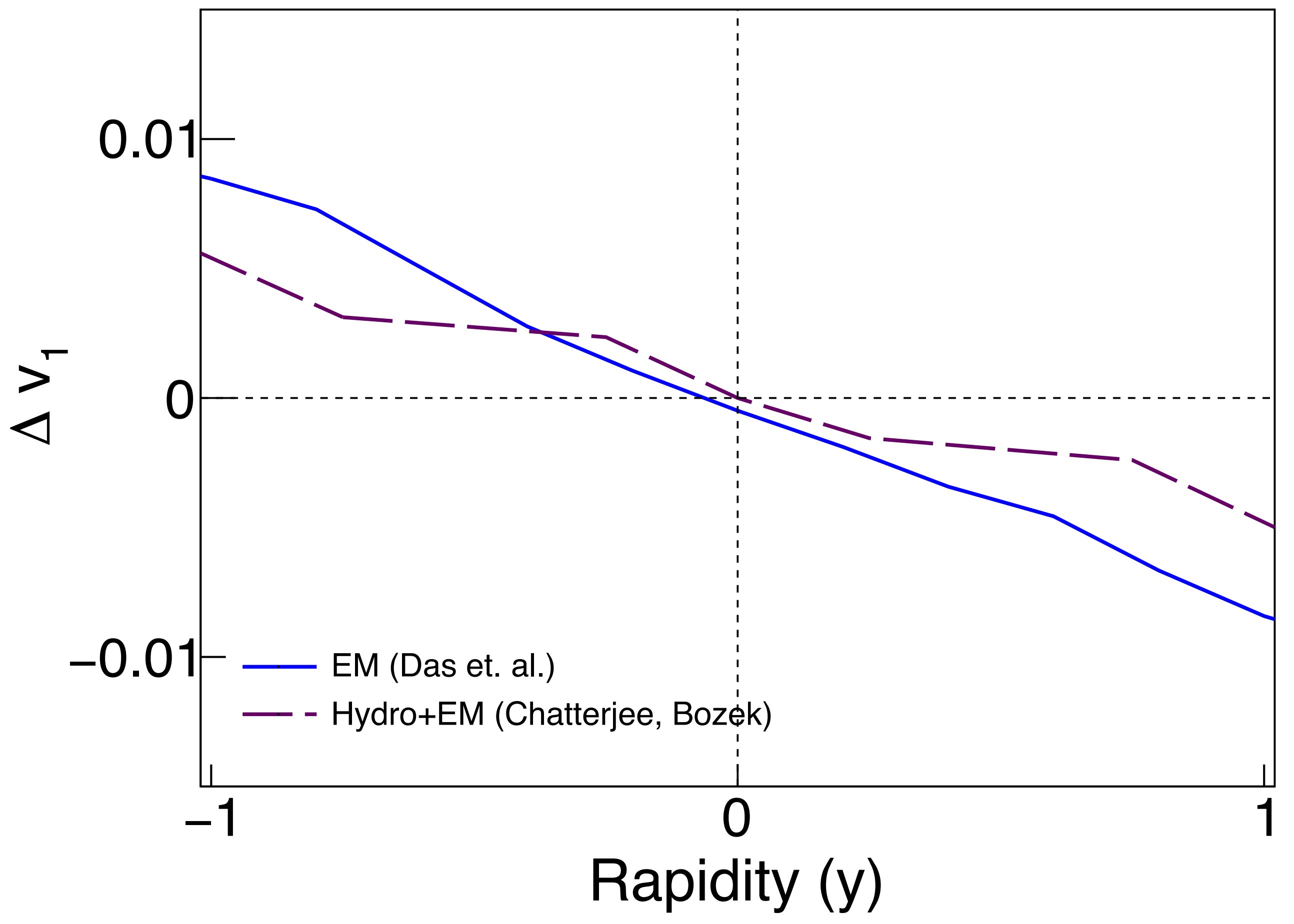


- Predicted ΔD^0 v_1-slope range between -0.008 to -0.004
- Current precision does not allow to draw firm conclusion on magnetic field induced v_1 splitting

Predicted Δv_1 from models

D^0 Δv_1-slope from EM: -0.008

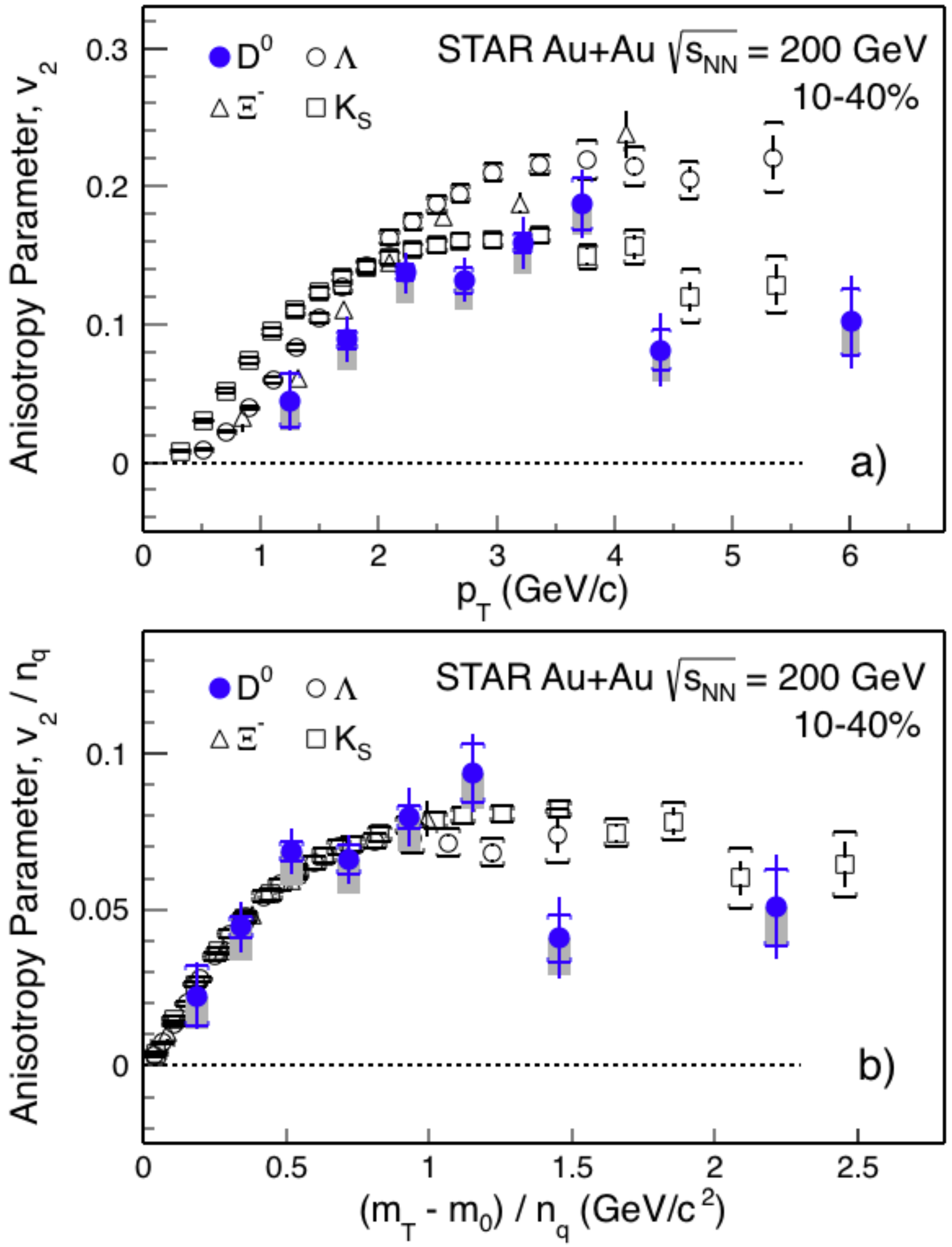
D^0 Δv_1-slope from Hydro+EM: -0.004



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

Recent D^0 elliptic flow (v_2) results from STAR

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

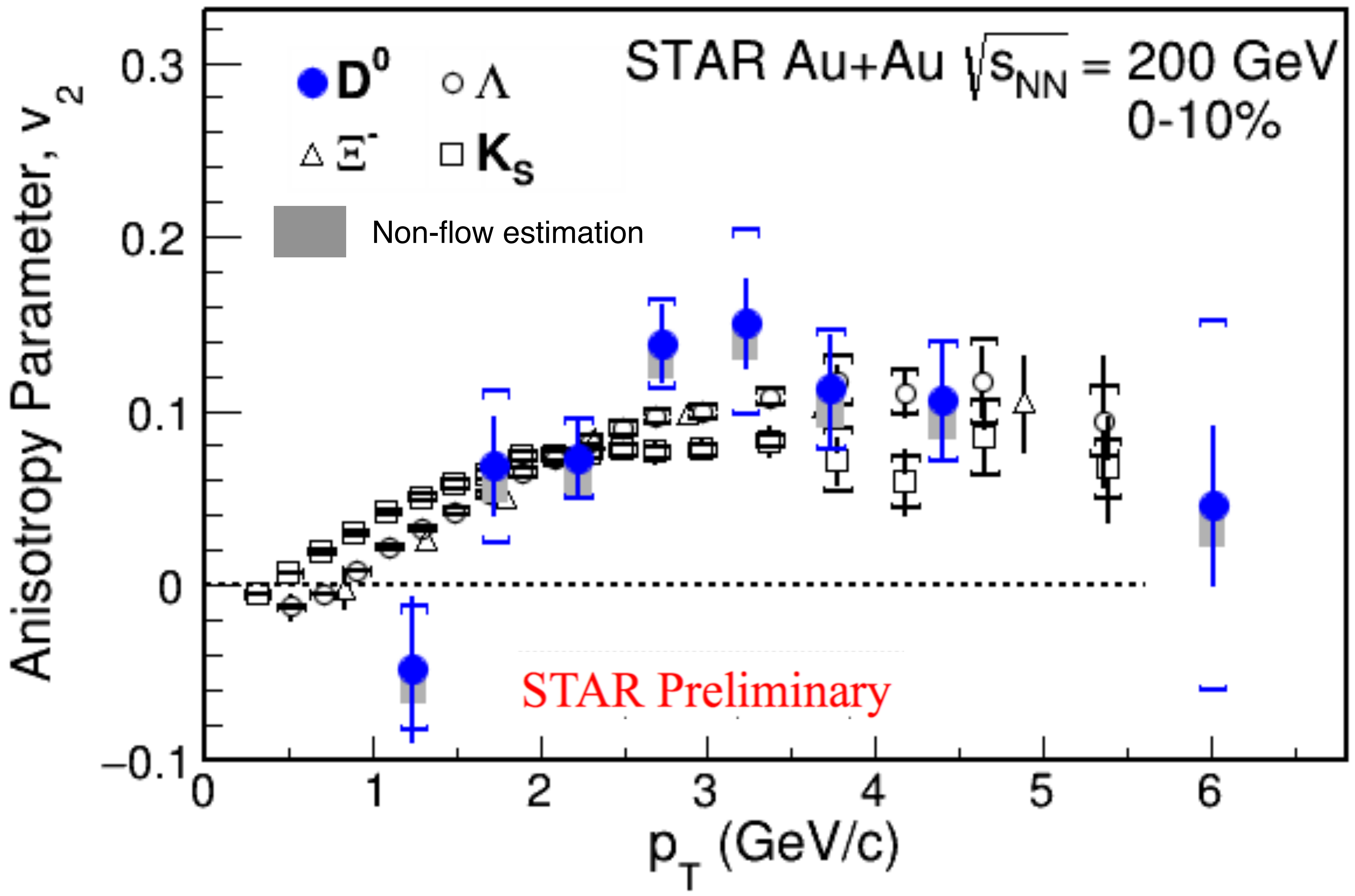


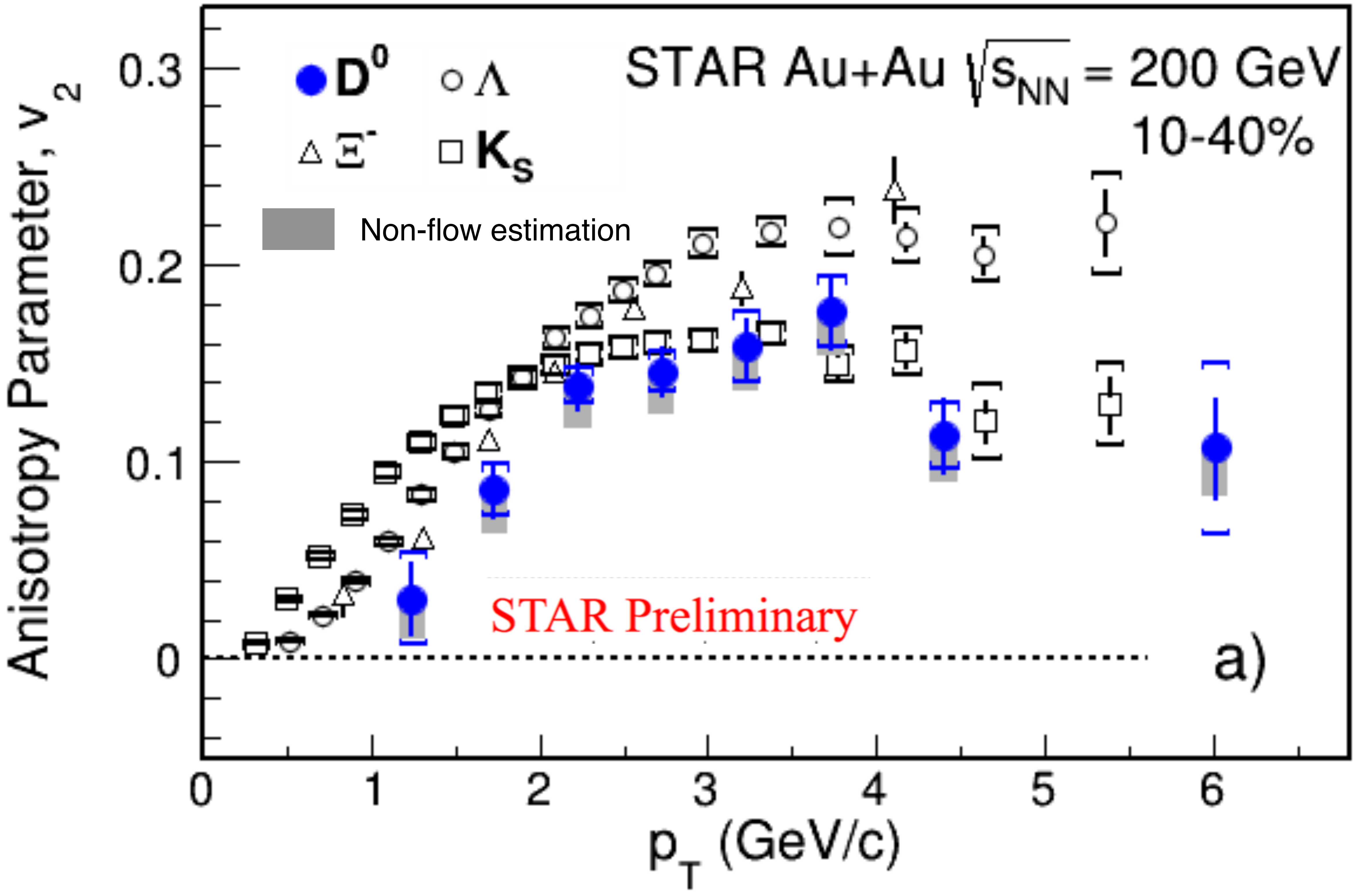
- STAR published D^0 v_2 from data taken during 2014 run
- D^0 flow magnitude consistent with NCQ scaling in minimum bias and mid-central collisions.
- High statistics 2016 run data allow to improve precision of the charm flow measurements at RHIC energy
- The 2016 data also allow us to extend NCQ scaling test to finer centrality bins

Precise D^0 v_2 measurement can allow:

→ Quantitative studies of QGP properties (transport coefficients)

D^0 v_2 comparison to light hadrons

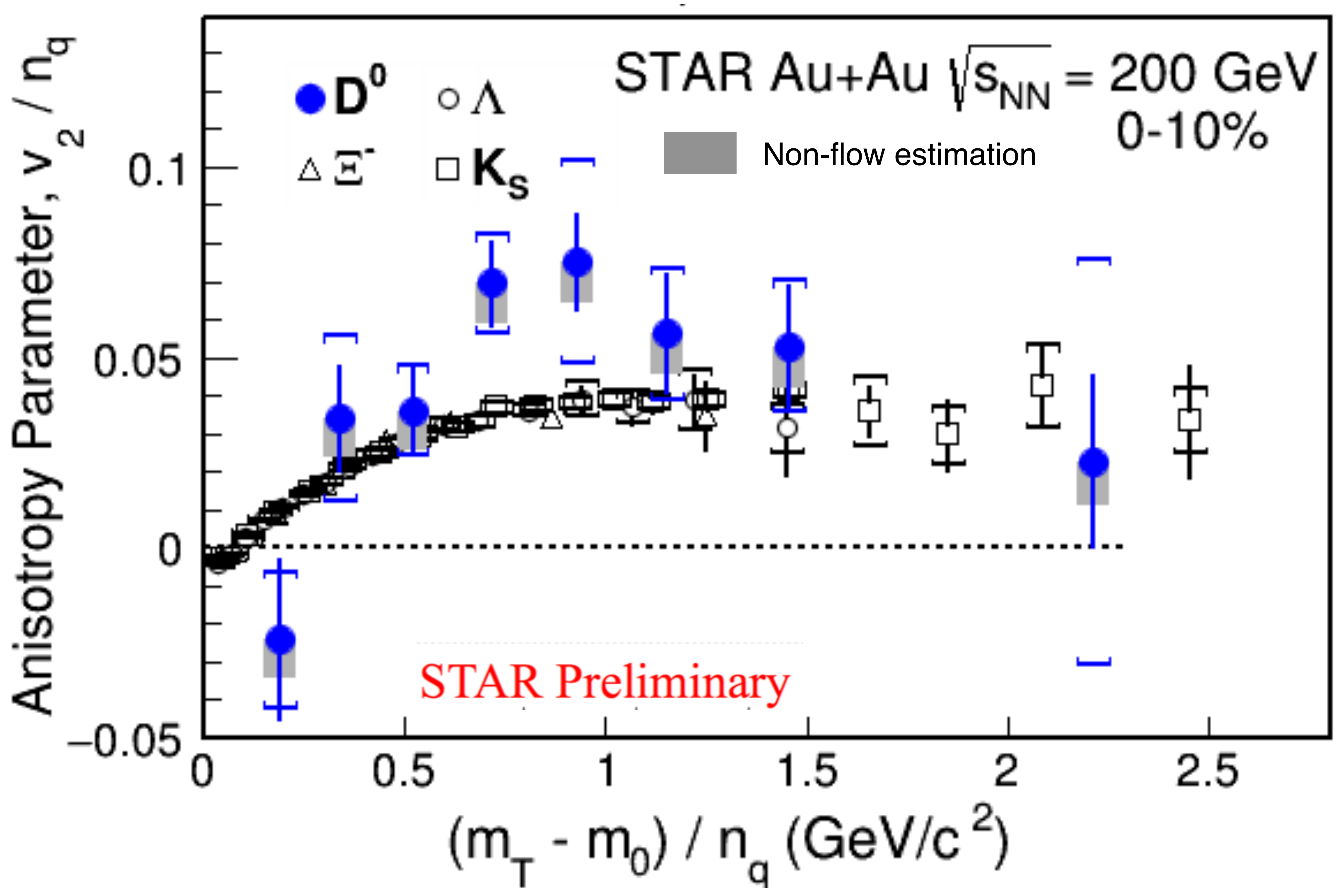


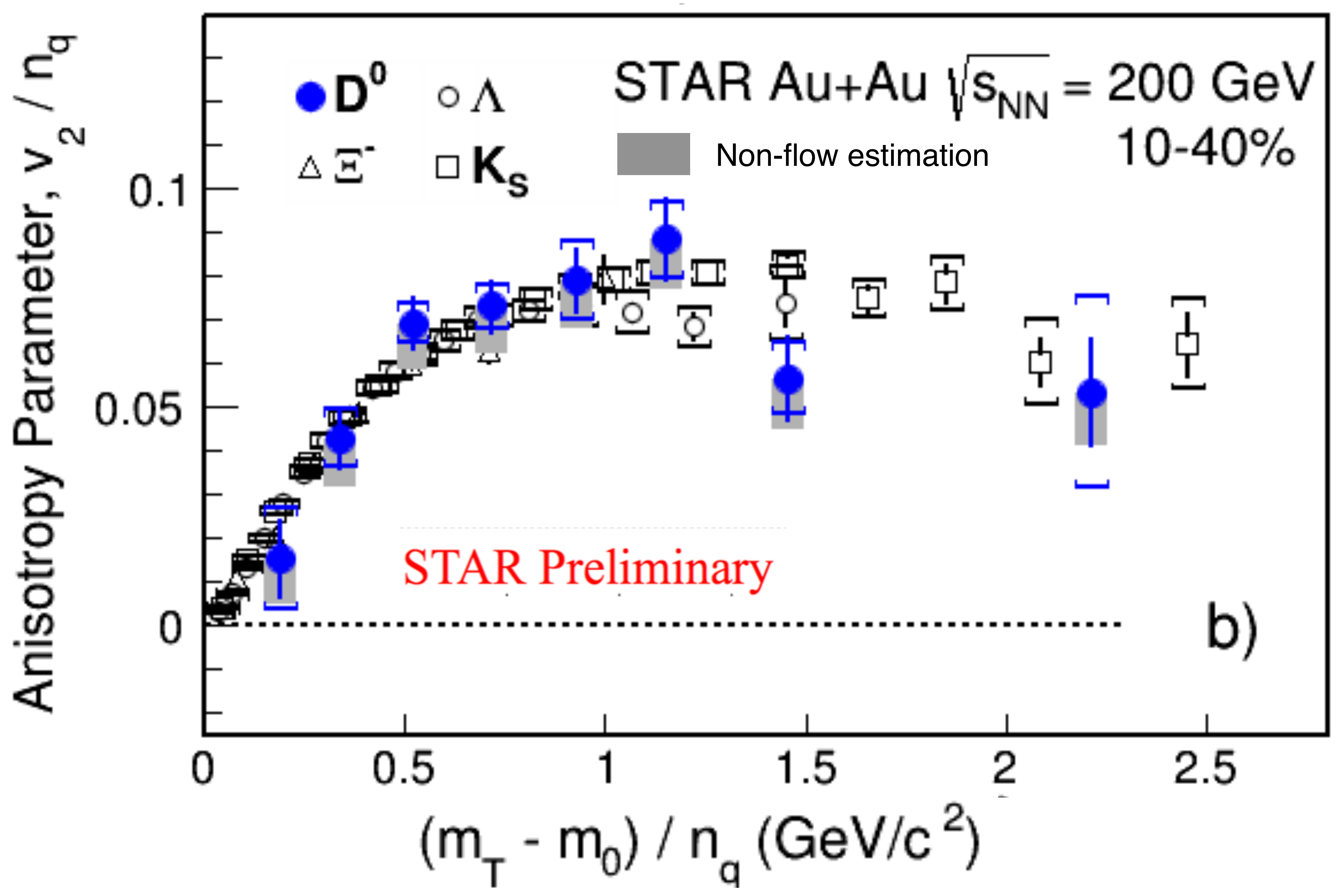


- D^0 v_2 results from combined data from 2014 and 2016 runs
- D^0 v_2 measurement extended to 0-10% centrality
- Clear mass ordering for p_T < 2 GeV/c in 10-40% centrality
- D^0 v_2 for p_T > 2 GeV/c in 10-40% centrality follows the mesons

Poster: Yue Liang
Id: 124

D^0 v_2 comparison to light hadrons



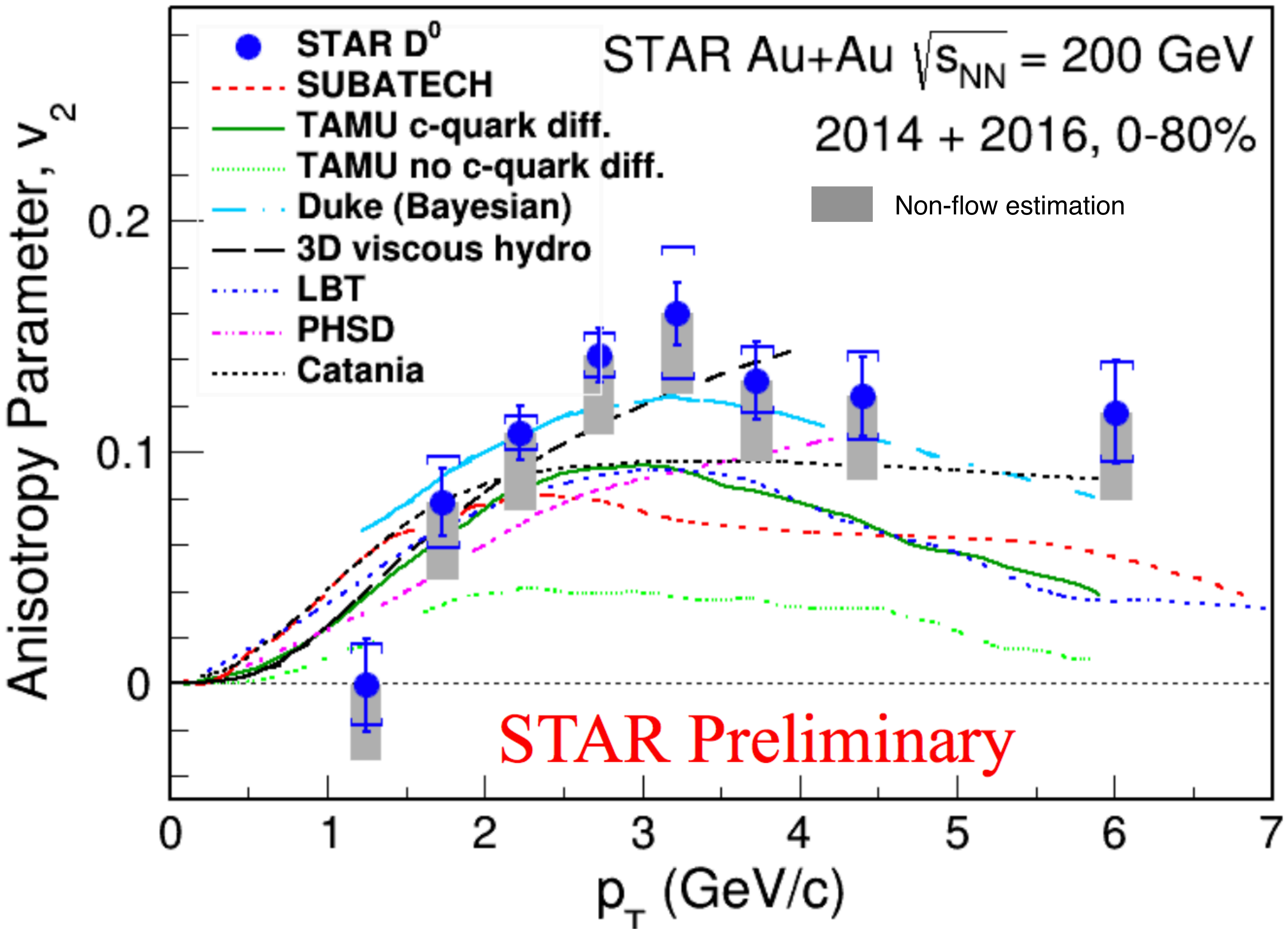


- NCQ scaling test with improved precision in D^0 v_2 measurement
- NCQ-scaled D^0 v_2 consistent with light hadrons for $(m_T-m_0)/n_q < 2.5$ GeV/c^2 in 10-40%
- Evidence of charm quarks flowing with the medium

Charm quark may achieve thermal equilibrium

Poster: Yue Liang
Id: 124

D^0 v_2: data vs. models



Compared Models	x2/NDF	p-value
SUBATECH [1]	17.3/8	0.026
TAMU c quark diff. [2]	12.0/8	0.15
TAMU no c quark diff. [2]	33.7/8	4.5×10^{-5}
Duke (Bayesian) [3]	8.5/8	0.39
3D viscous hydro [4]	3.7/6	0.71
LBT [5]	13.3/8	0.10
PHSD [6]	8.7/7	0.27
Catania [7]	9.7/8	0.29

[1] **SUBATECH:** *Phys Rev C 90, 054909 (2014), Phys Rev C 92, 014910 (2015)*
[2] **TAMU:** *Phys Rev C 86, 014903 (2012), Phys Rev Lett 110, 112301 (2013)*
[3] **Duke:** *Phys Rev C 92, 024907 (2015)*
[4] **3D viscous hydro:** *Phys Rev C 86, 024911 (2012)*
[5] **LBT:** *Phys Rev C 94, 014909 (2016)*
[6] **PHSD:** *Phys ReV 90, 051901 (2014), Phys ReV 90, 051901 (2014)*
[7] **Catania:** *Phys ReV 96, 044905 (2017)*

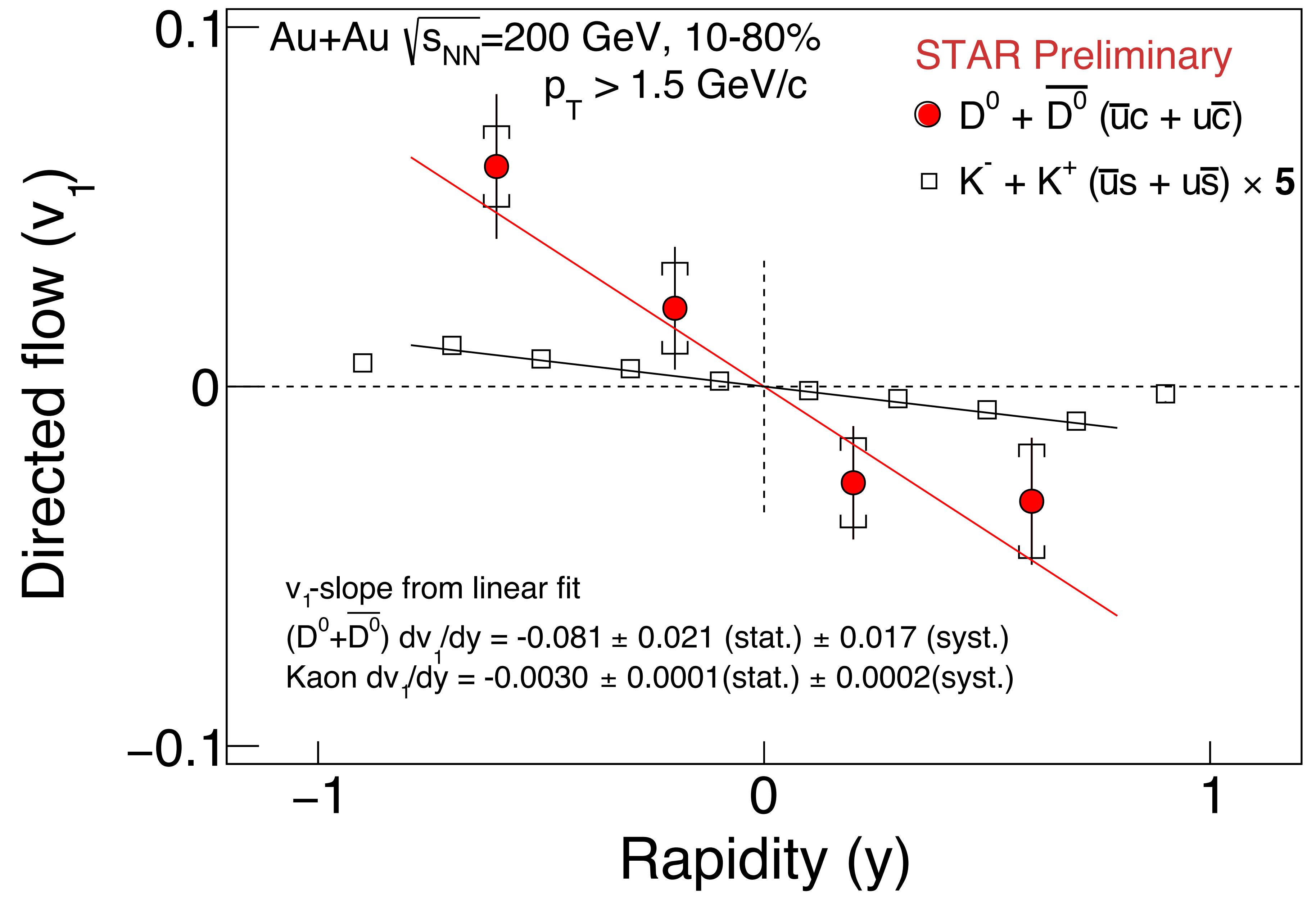
- D^0 v_2 results from combined data using 2014 and 2016 runs
- Improved precision to constrain the models

Poster: Yue Liang
Id: 124

Summary

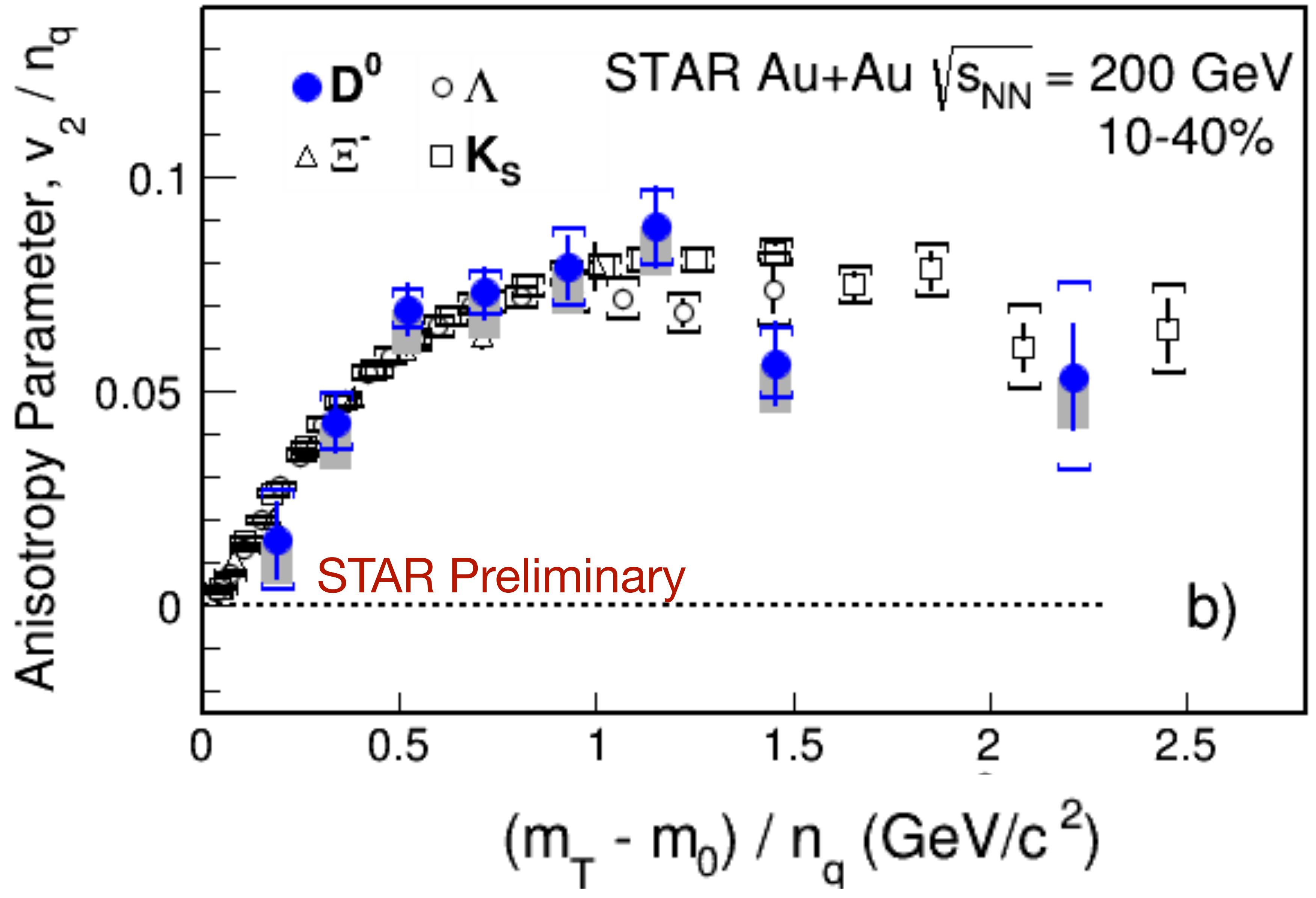
Directed flow

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



Elliptic flow

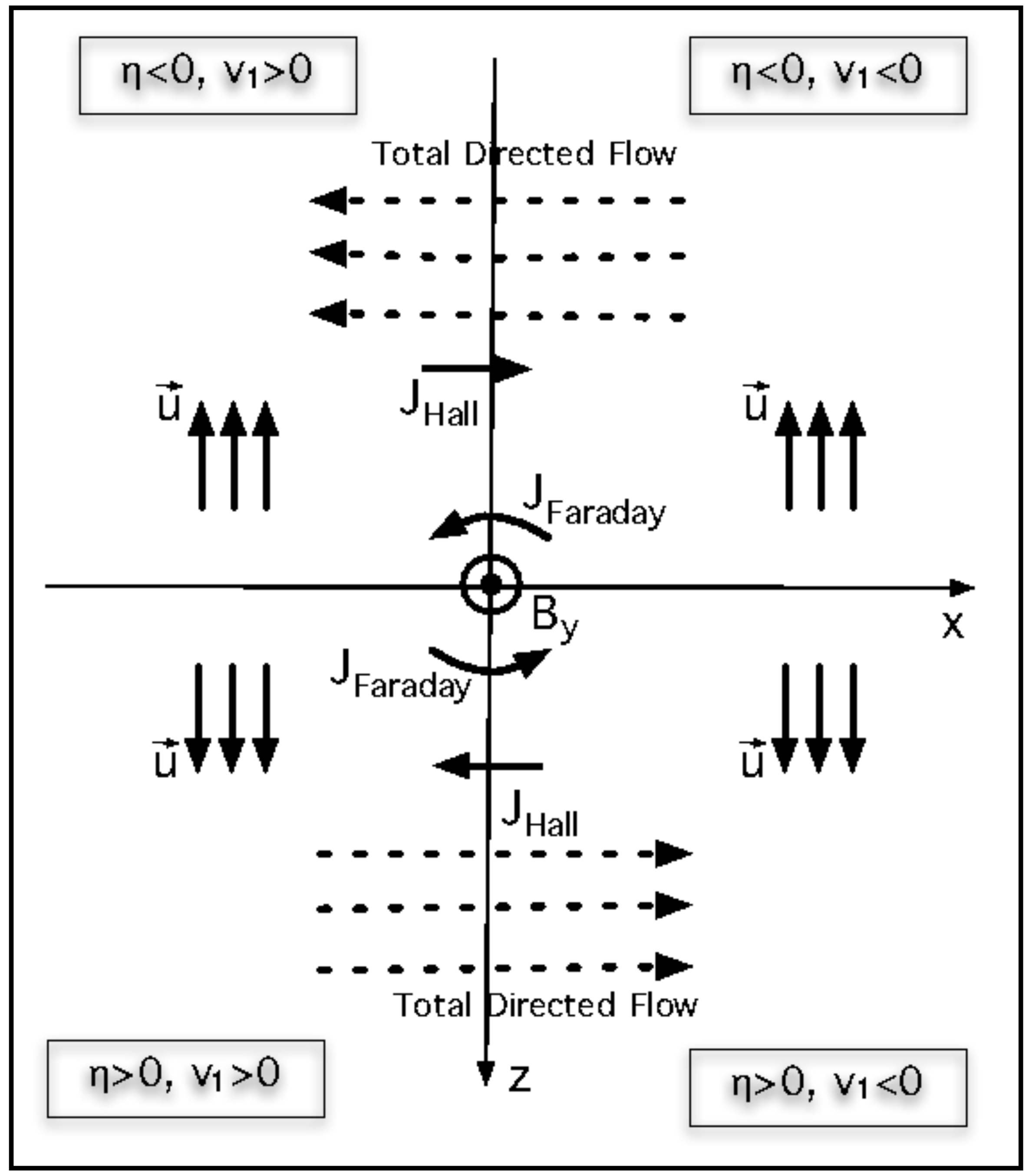
- Improved precision of D^0 v_2 results with combined 2014 and 2016 data
- D^0 v_2 result suggests charm quarks achieve a thermal equilibrium with the medium
- Precise D^0 v_2 measurements can further constrain model calculations

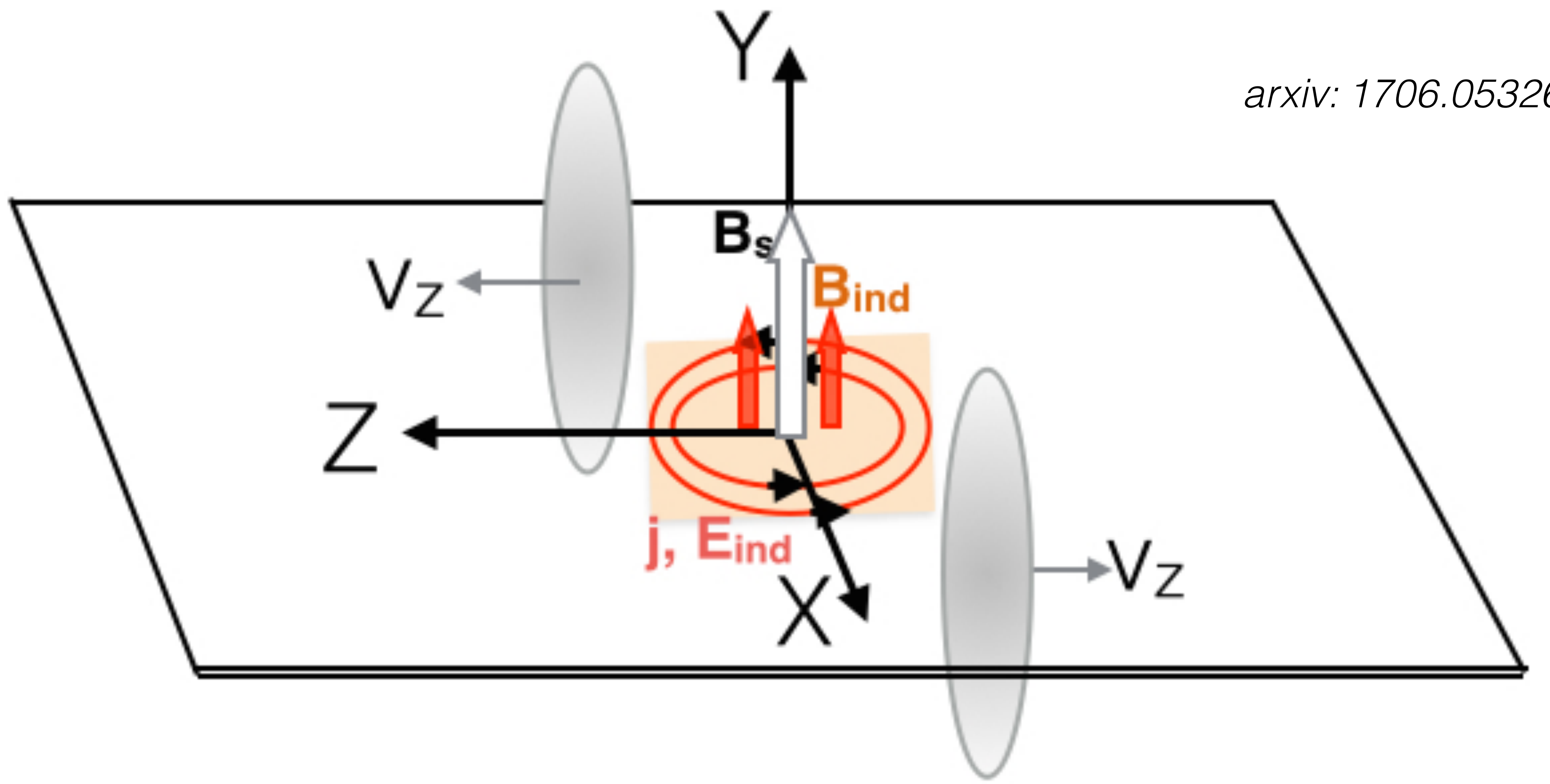


Backup slides

Directed flow from magnetic field

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





arxiv: 1706.05326

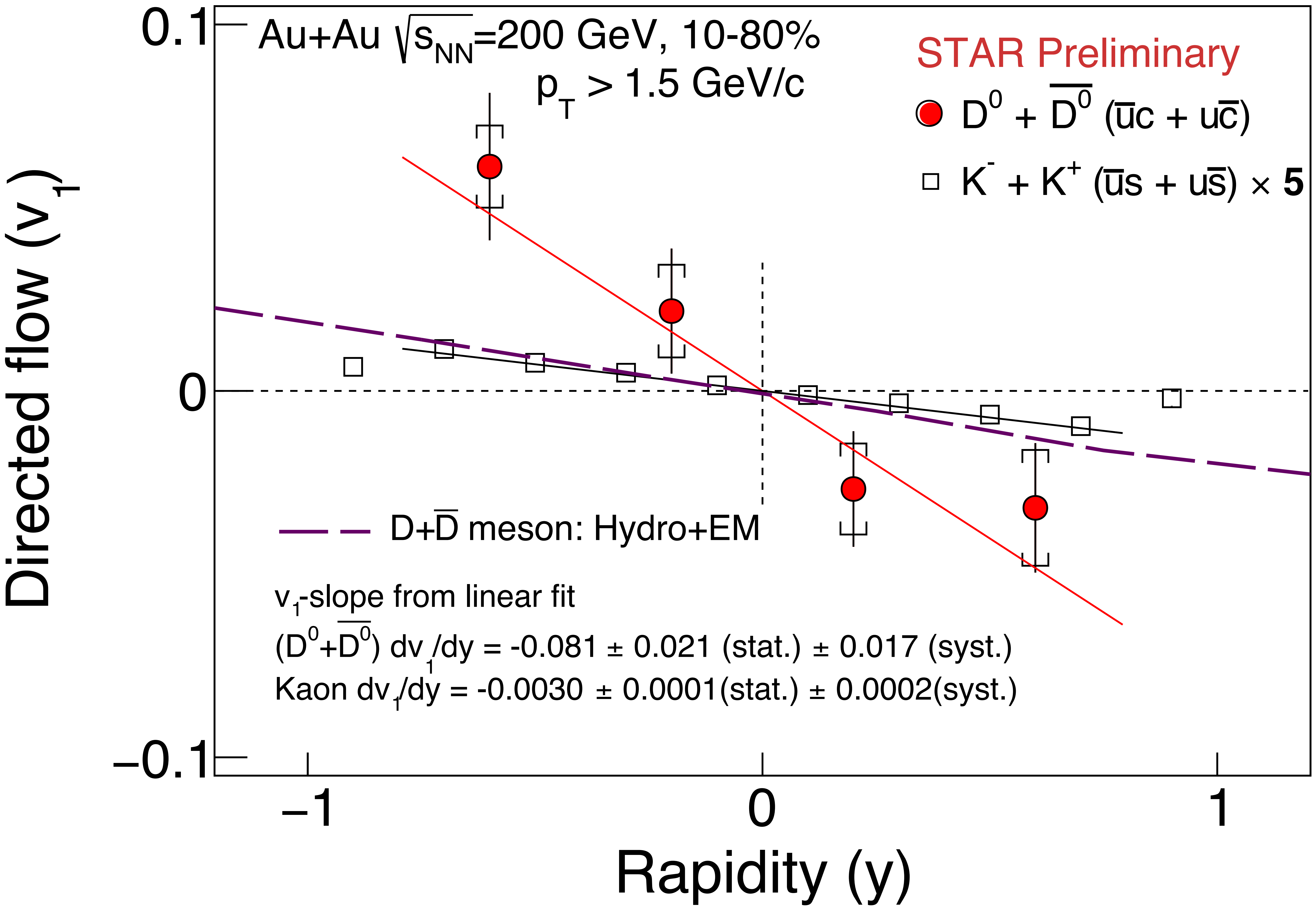
- The moving spectators can produce enormously large **B** field (eB ~10^{18} G)
- There could be two competing effects
- Hall effect: $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$

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

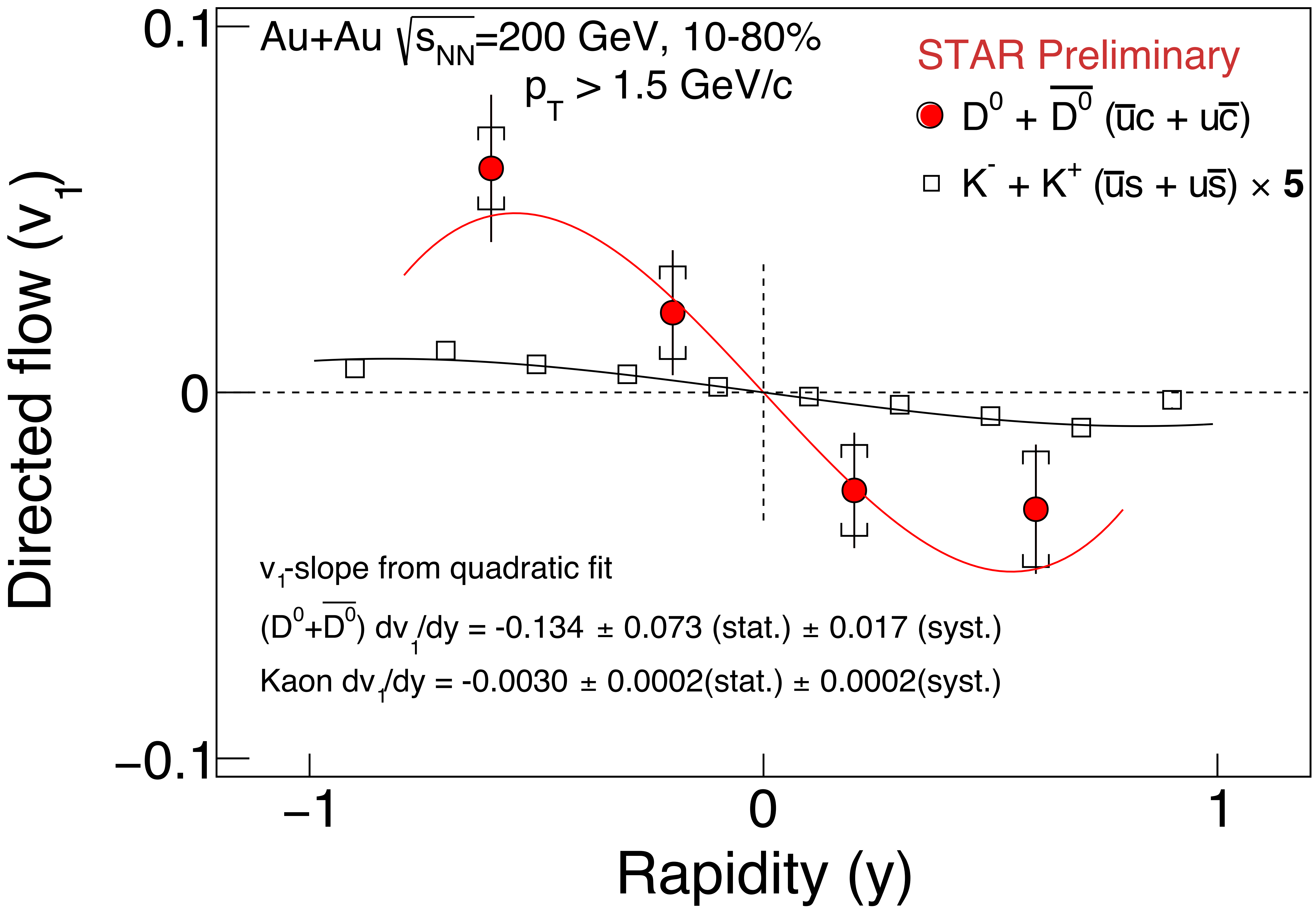
  Time dependent **B** field generates a large **E** field

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

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



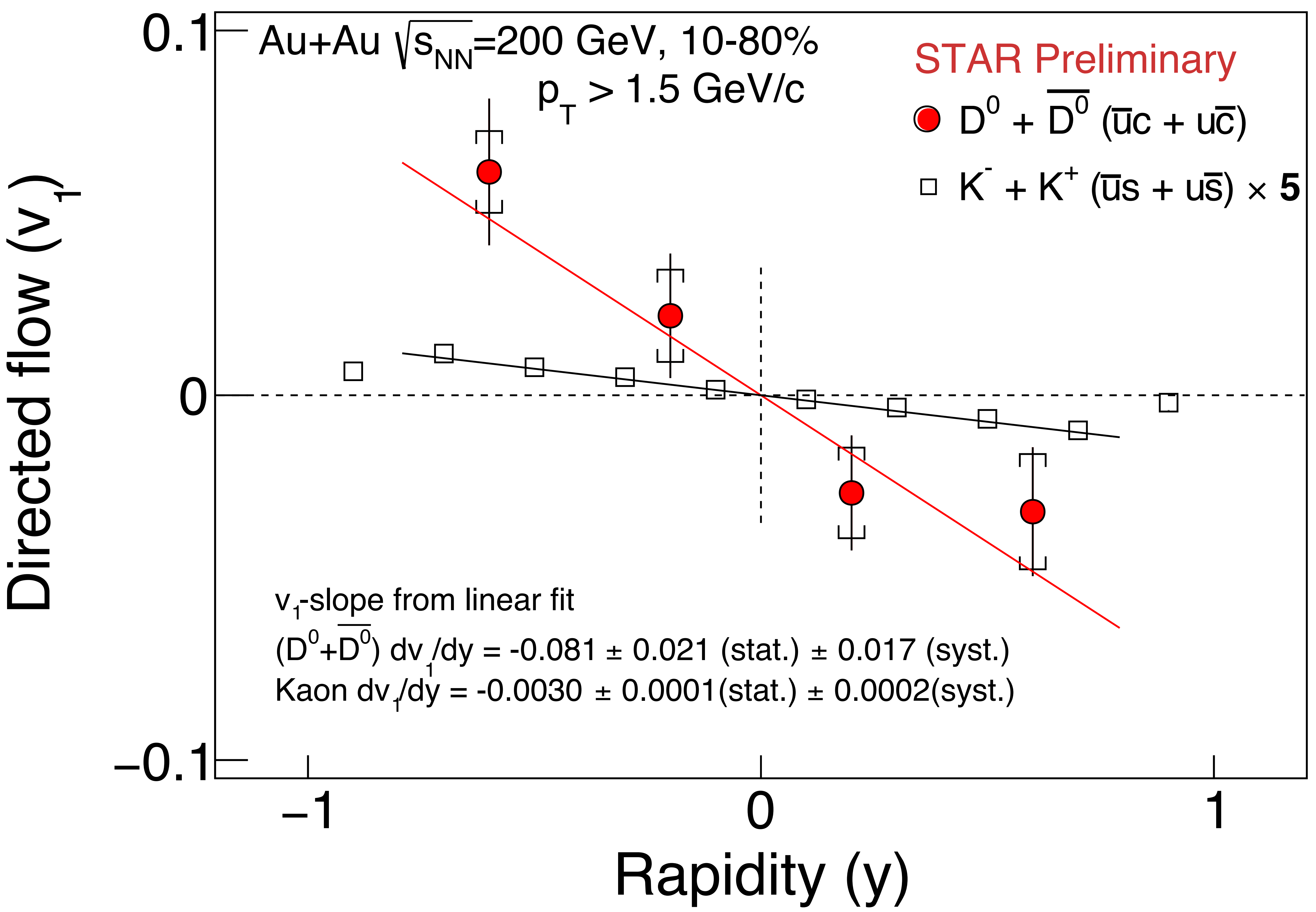
D^0 and $\overline{D^0}$ v_1 with kaons

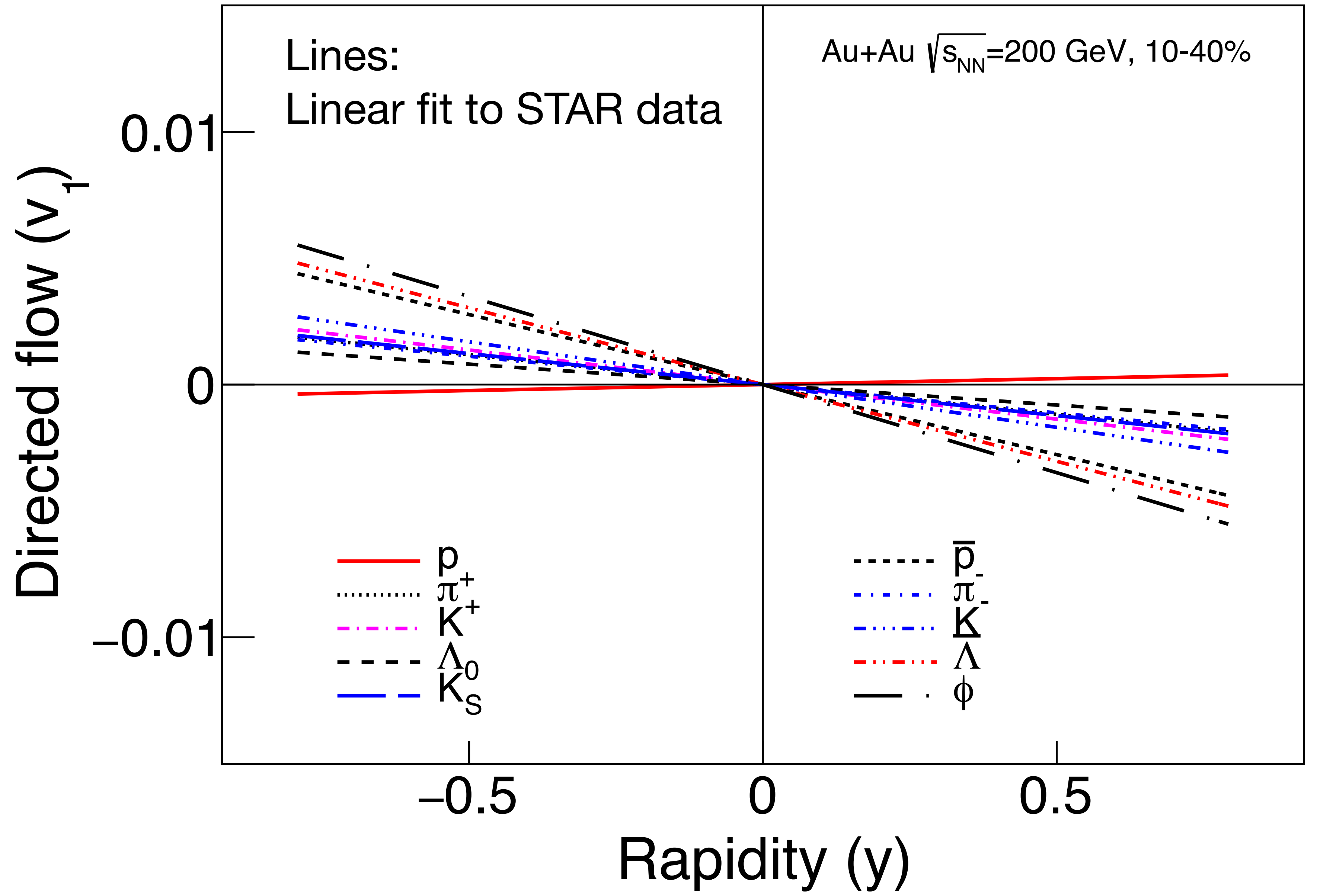


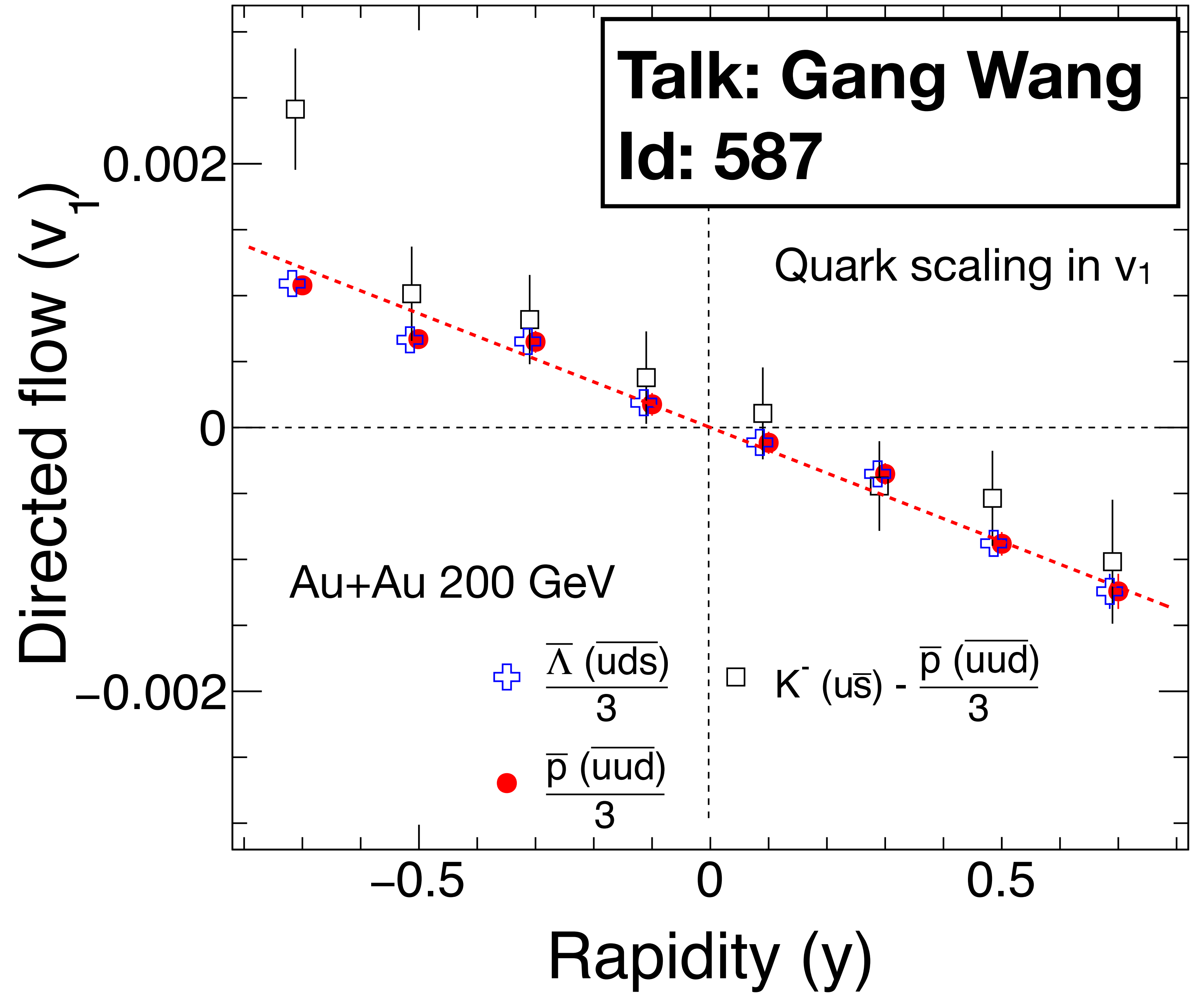
quadratic function: $p_0 y + p_1 y^3$

Light flavor vs. heavy flavor v_1

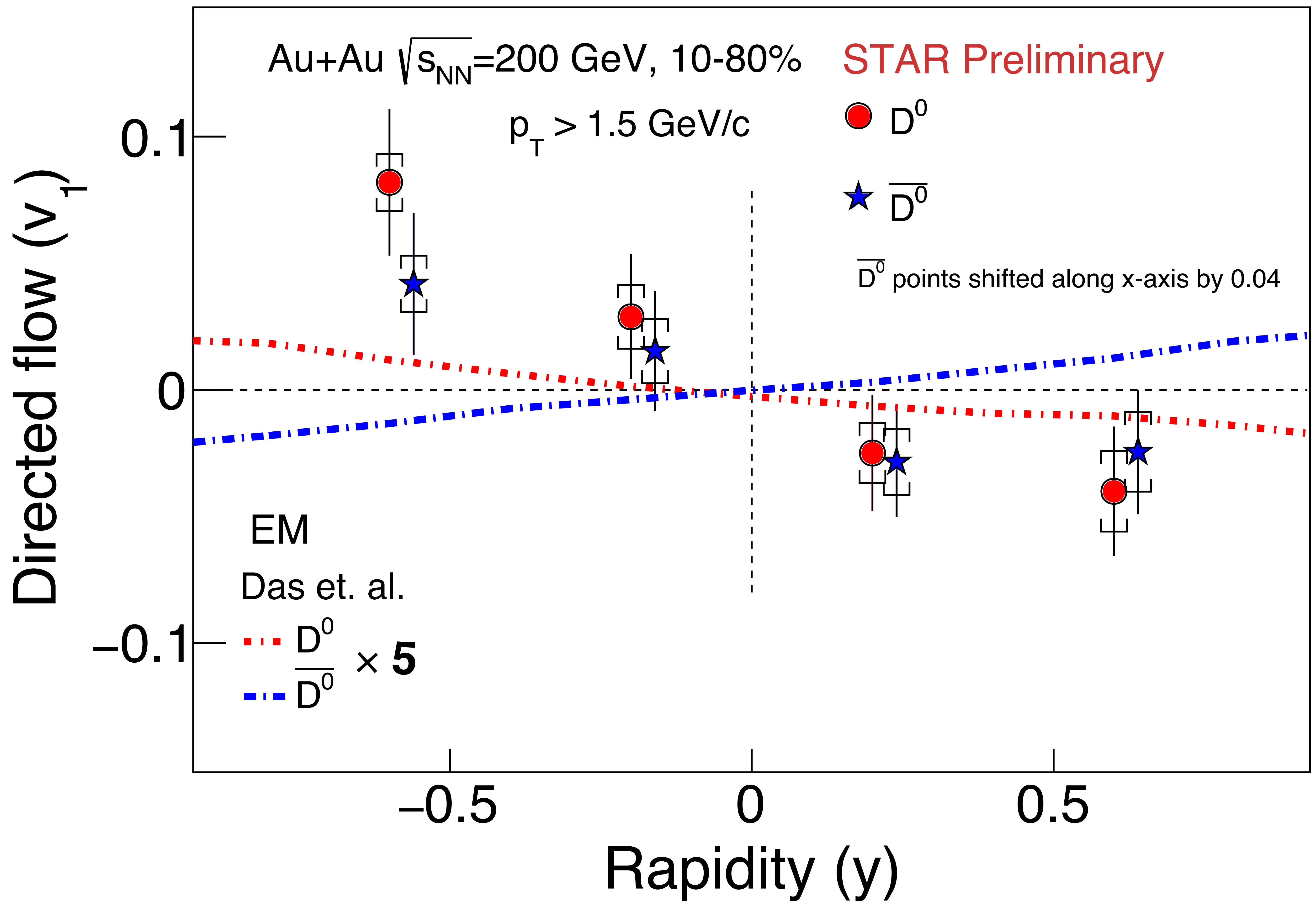
L Adamczyk et. al. (STAR Collaboration), Phys Rev. Lett. 120, 62301 (2018)

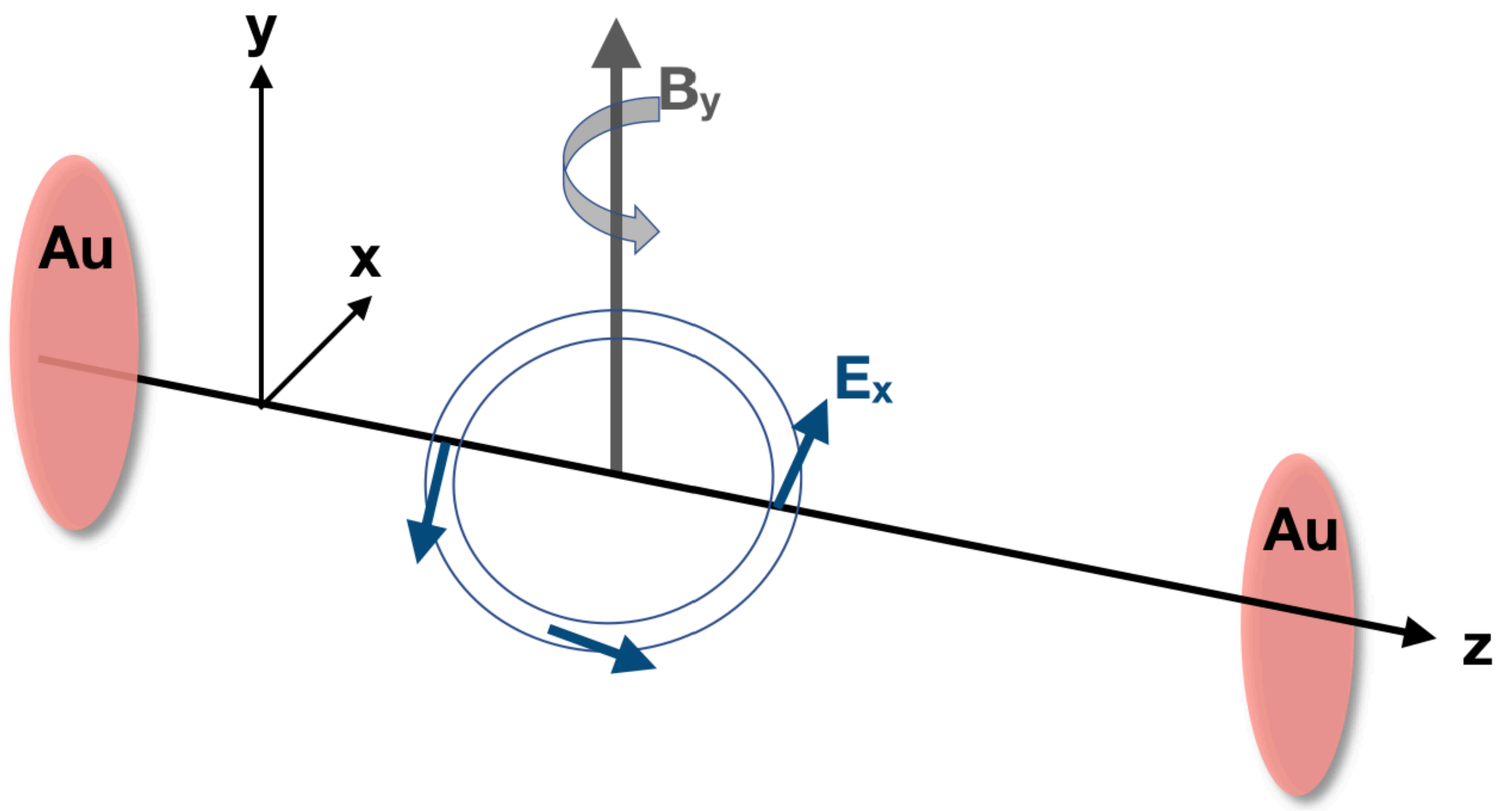




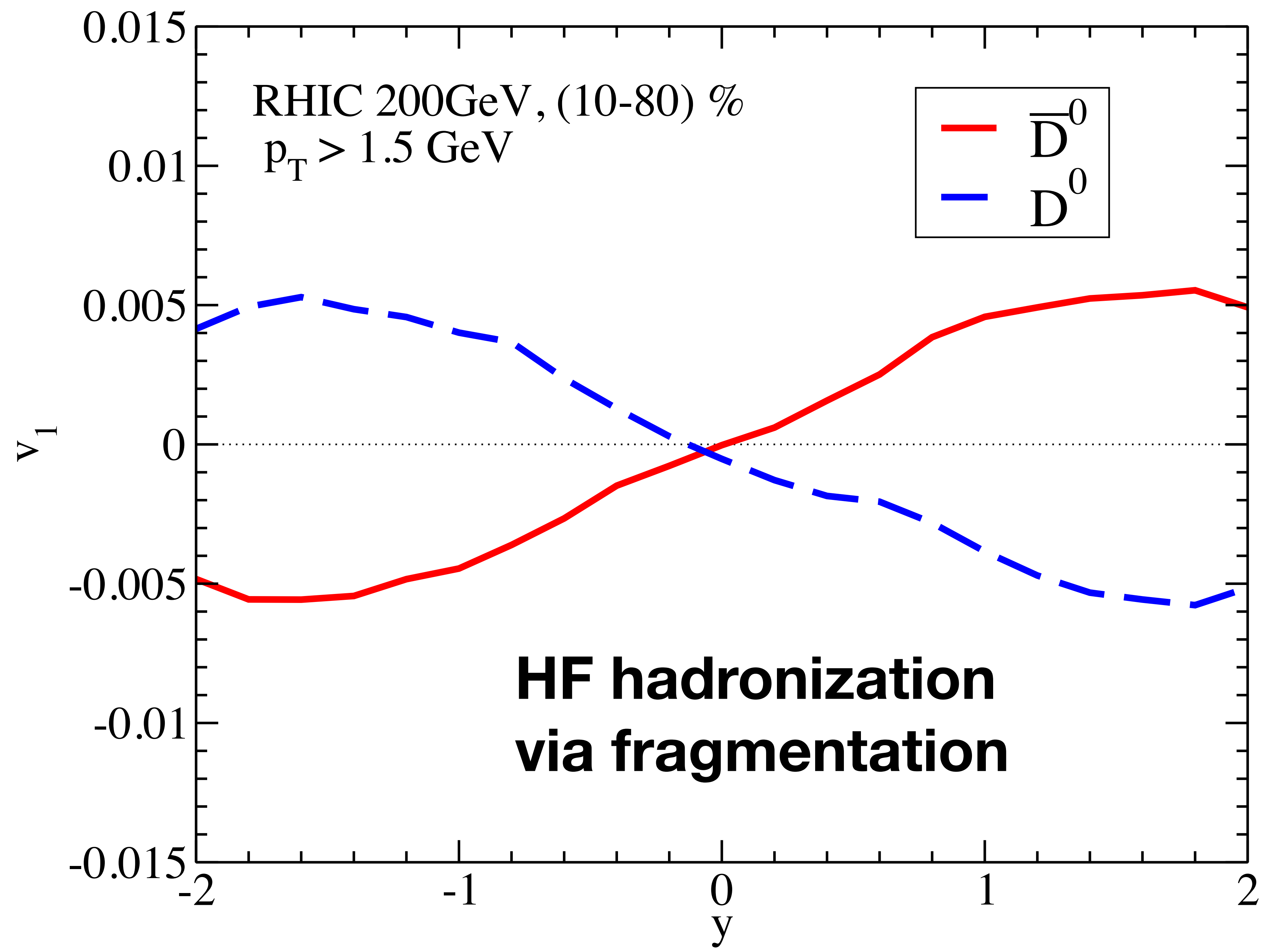


D^0 and $\overline{D^0}$ v_1 with recent model



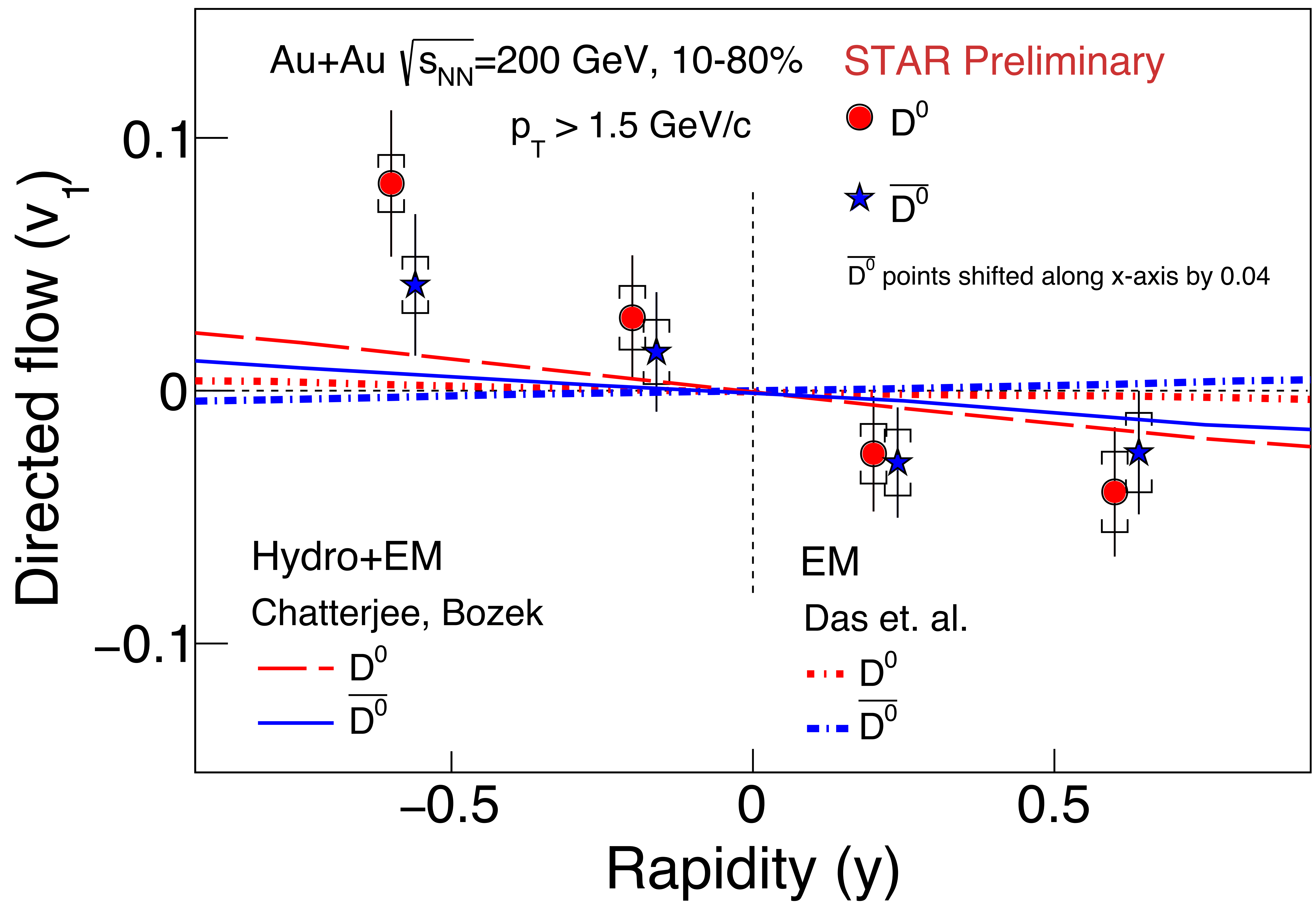


Expected v_1 from EM field

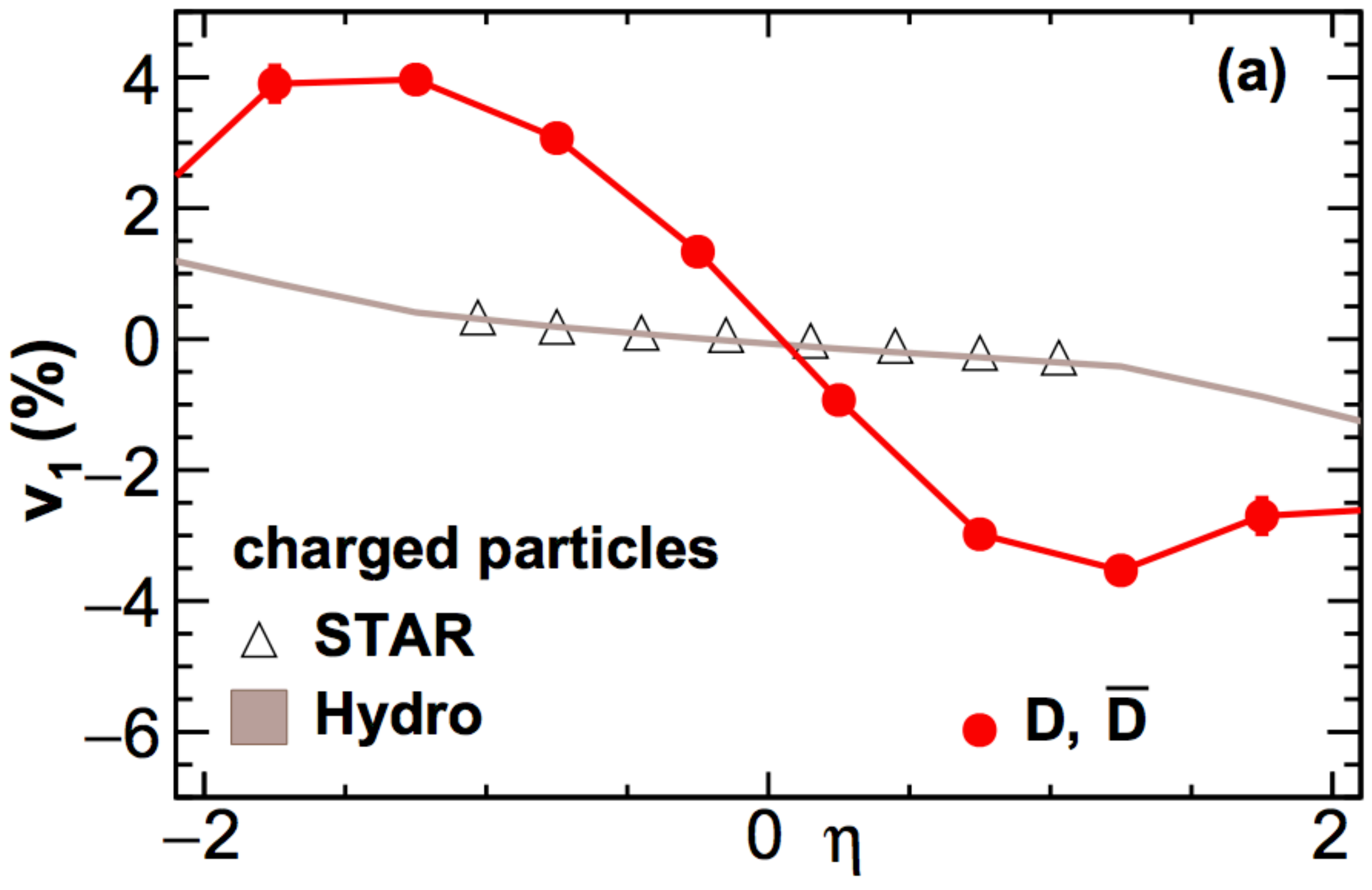


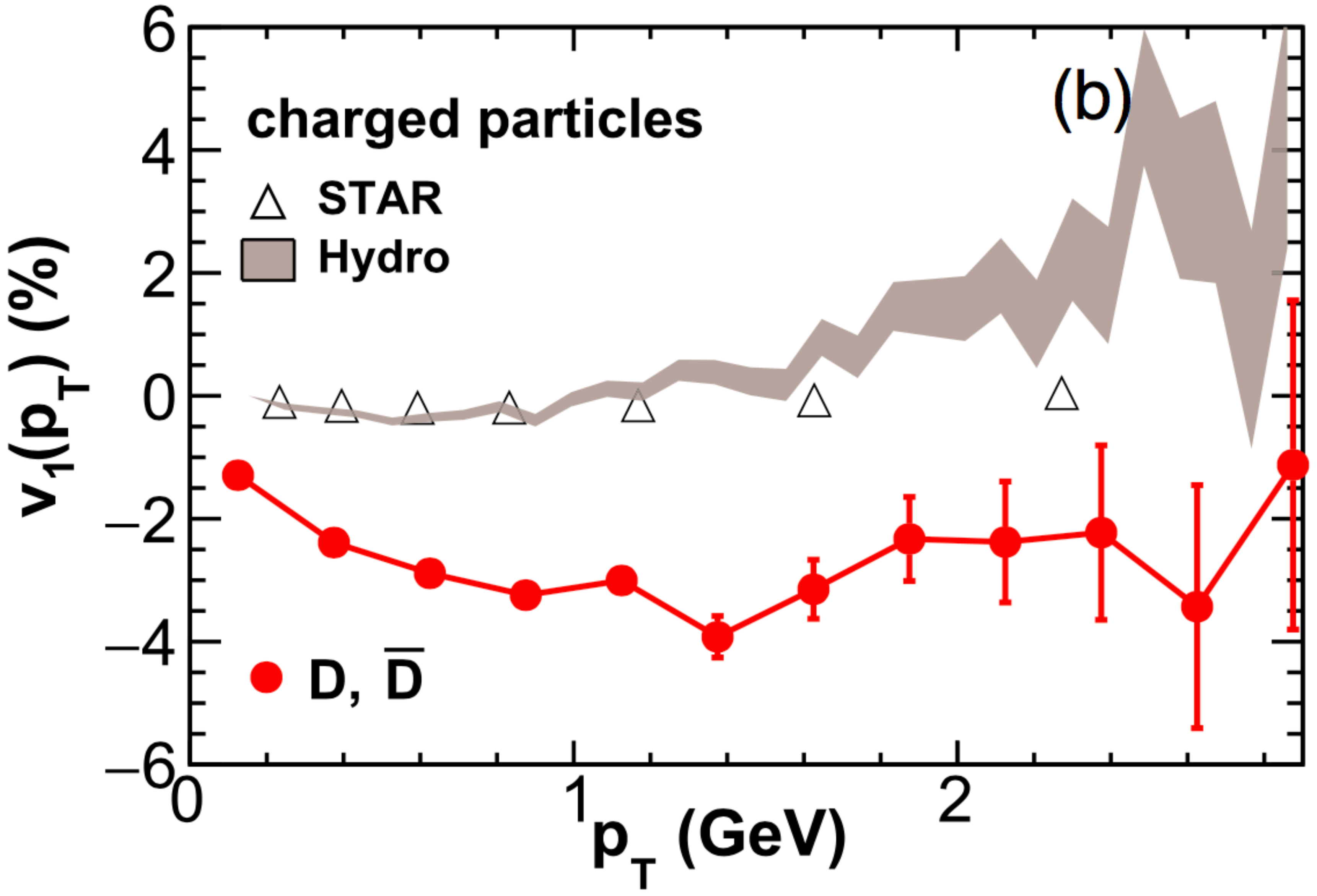
Das et. al., Phys Lett B 768, 260 (2017)

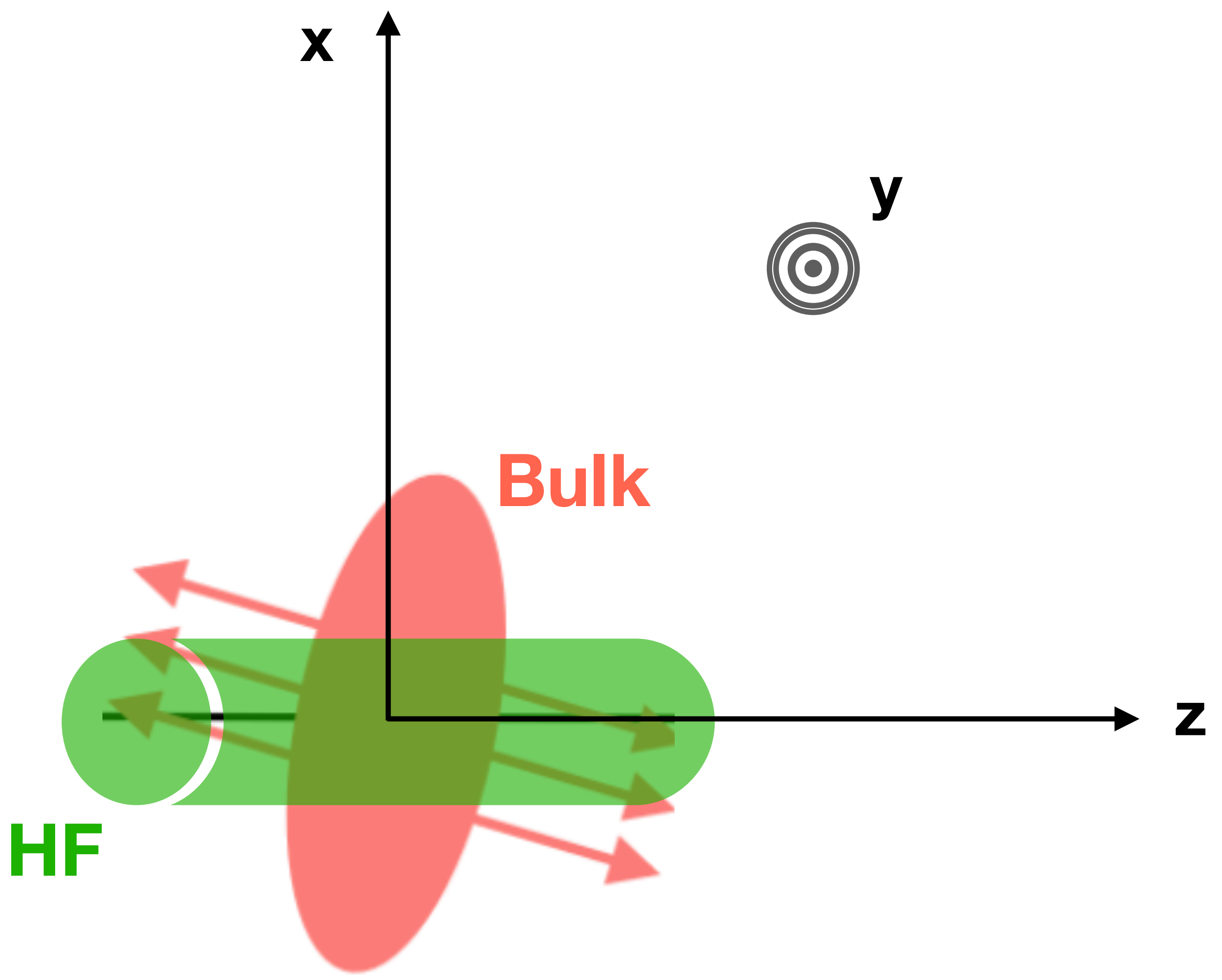
D^0 and $\overline{D^0}$ v_1 with recent models



D^0 v_1 from hydro model

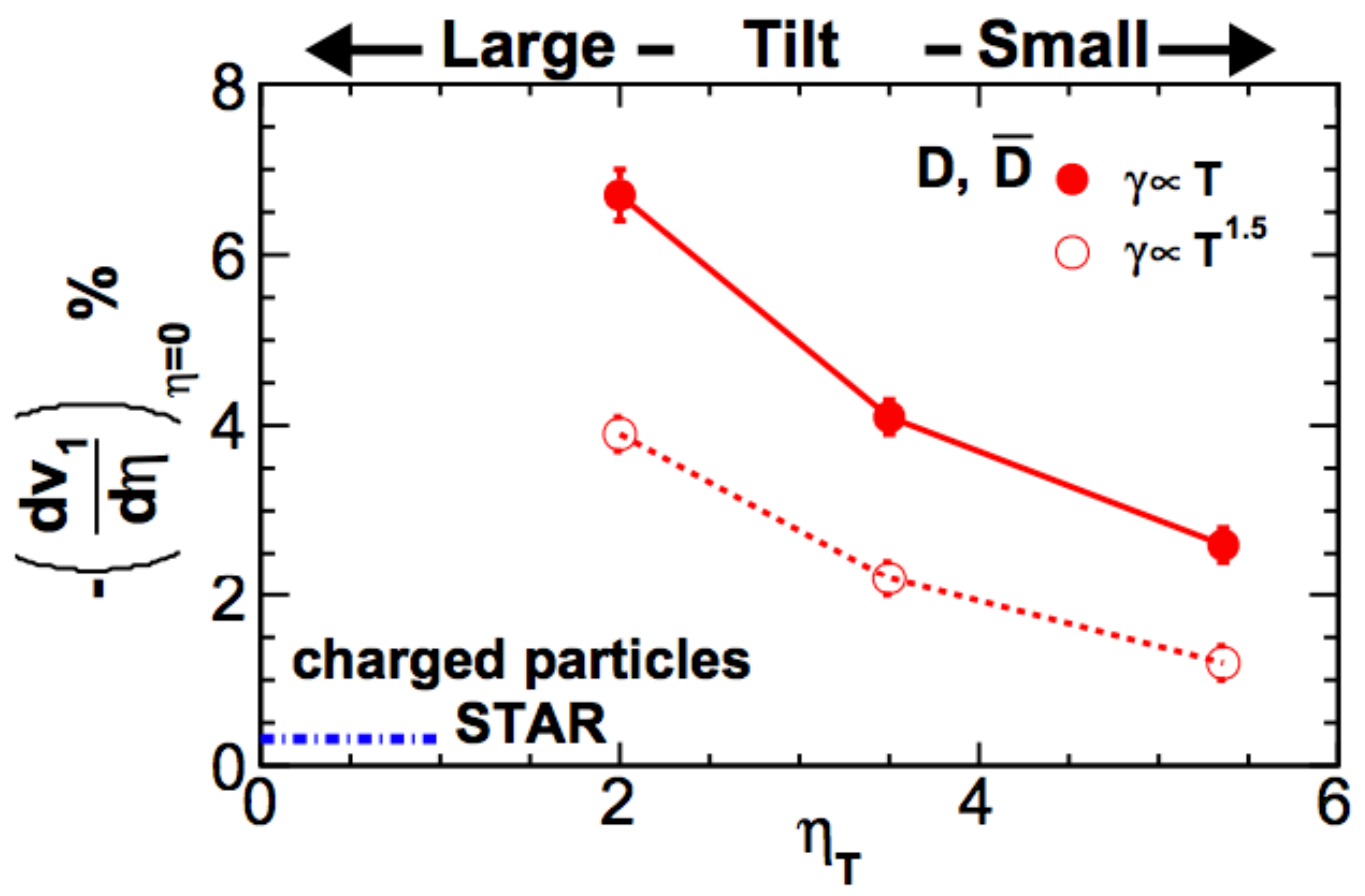






Bulk: Hydro
HF: Langevin

HF hadronization via fragmentation



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