Heavy probes of initial conditions
&
novel observables

Sandeep Chatterjee
IISER Berhampur

Hard Probes in non-equilibrium QCD matter,
16-27 March, 2026
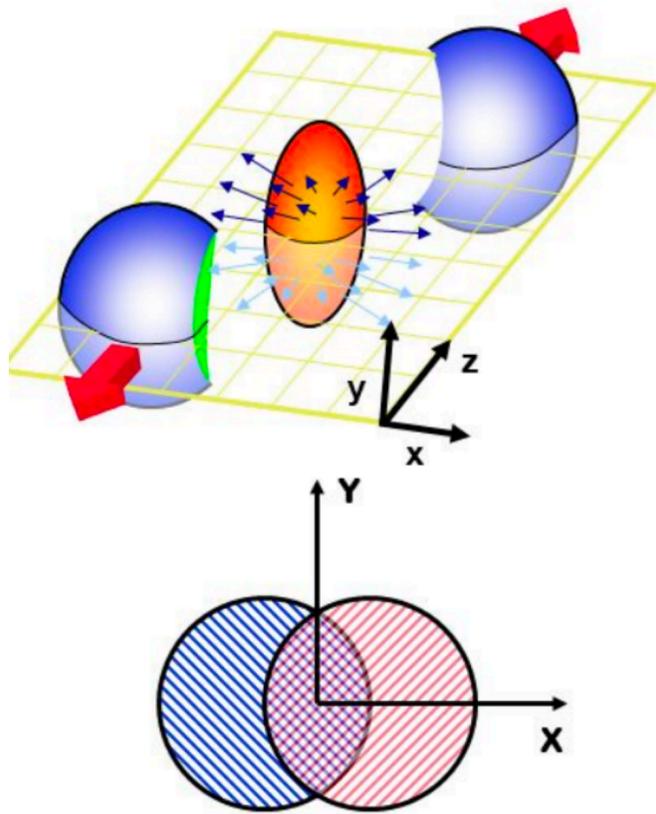ICTS Bengaluru

Heavy probes of initial geometry, EM fields
&
novel observables
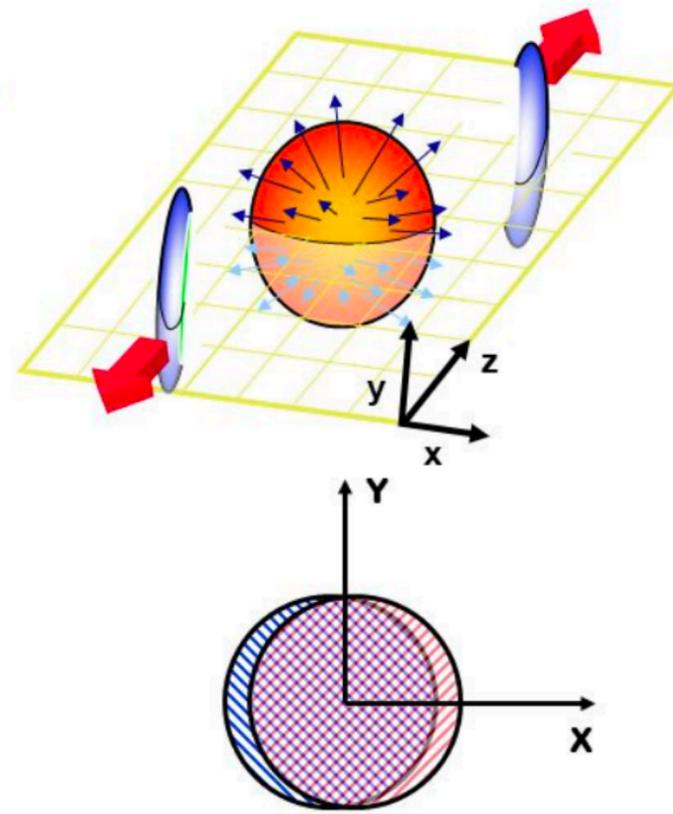
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Initial Collision Geometry

Peripheral Collision

(near) Central Collision

y

Ellipsoid-shaped volume

p_y

x

Spatial anisotropy

Azimuthal momentum sp

xy

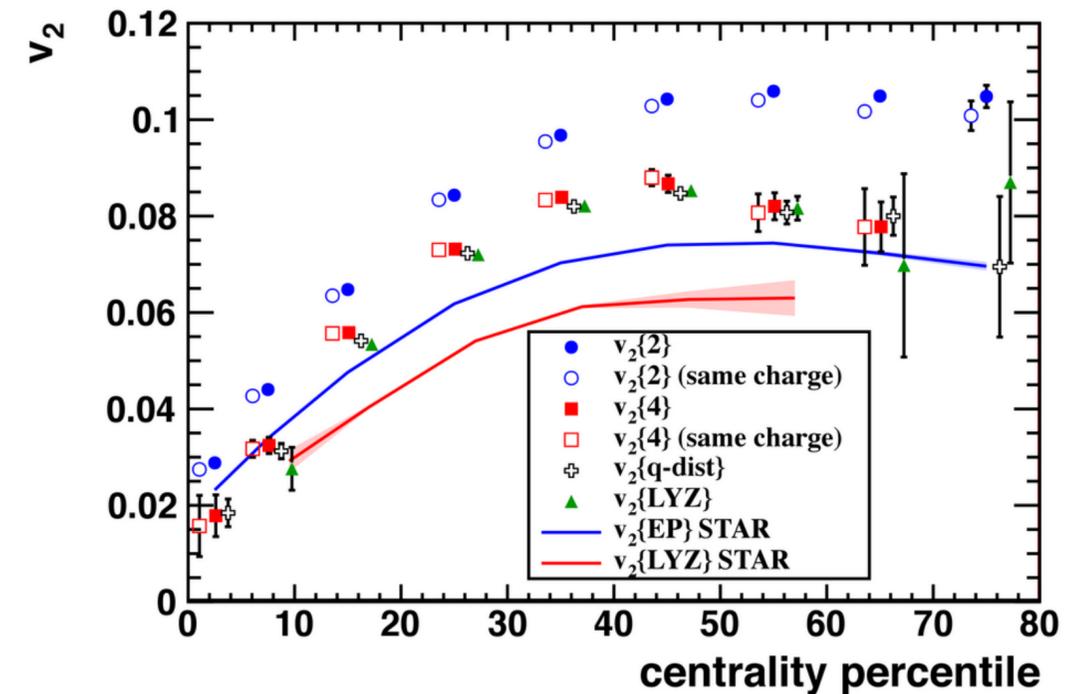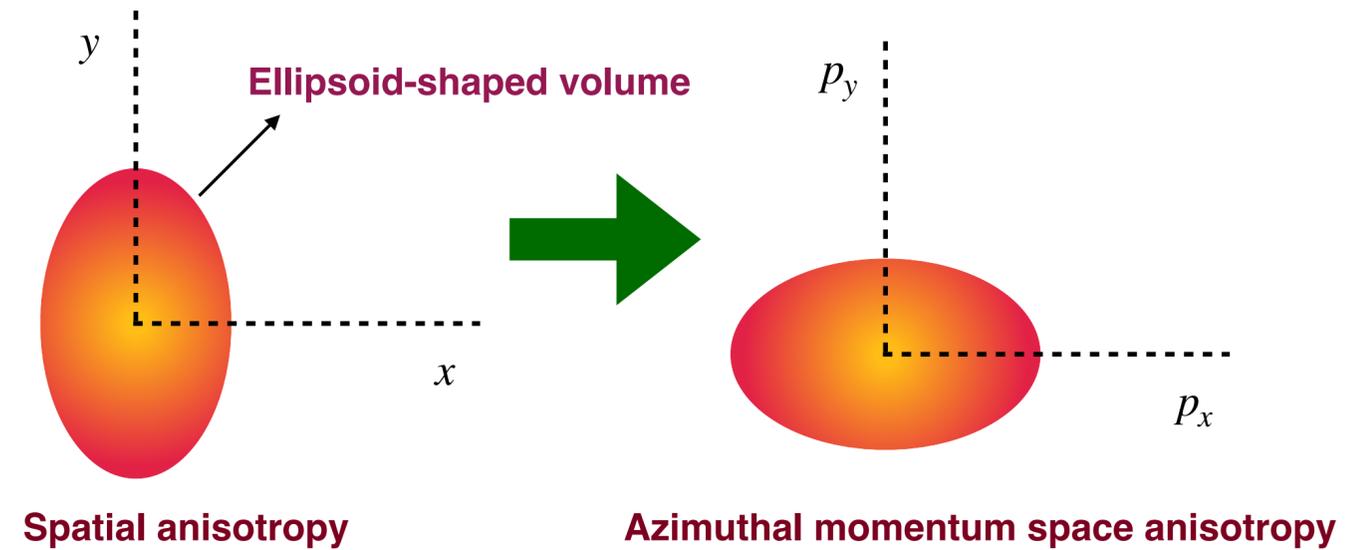v_2

0.12

0.1

0.08

0.06

Initial Collision Geometry - elliptic flow
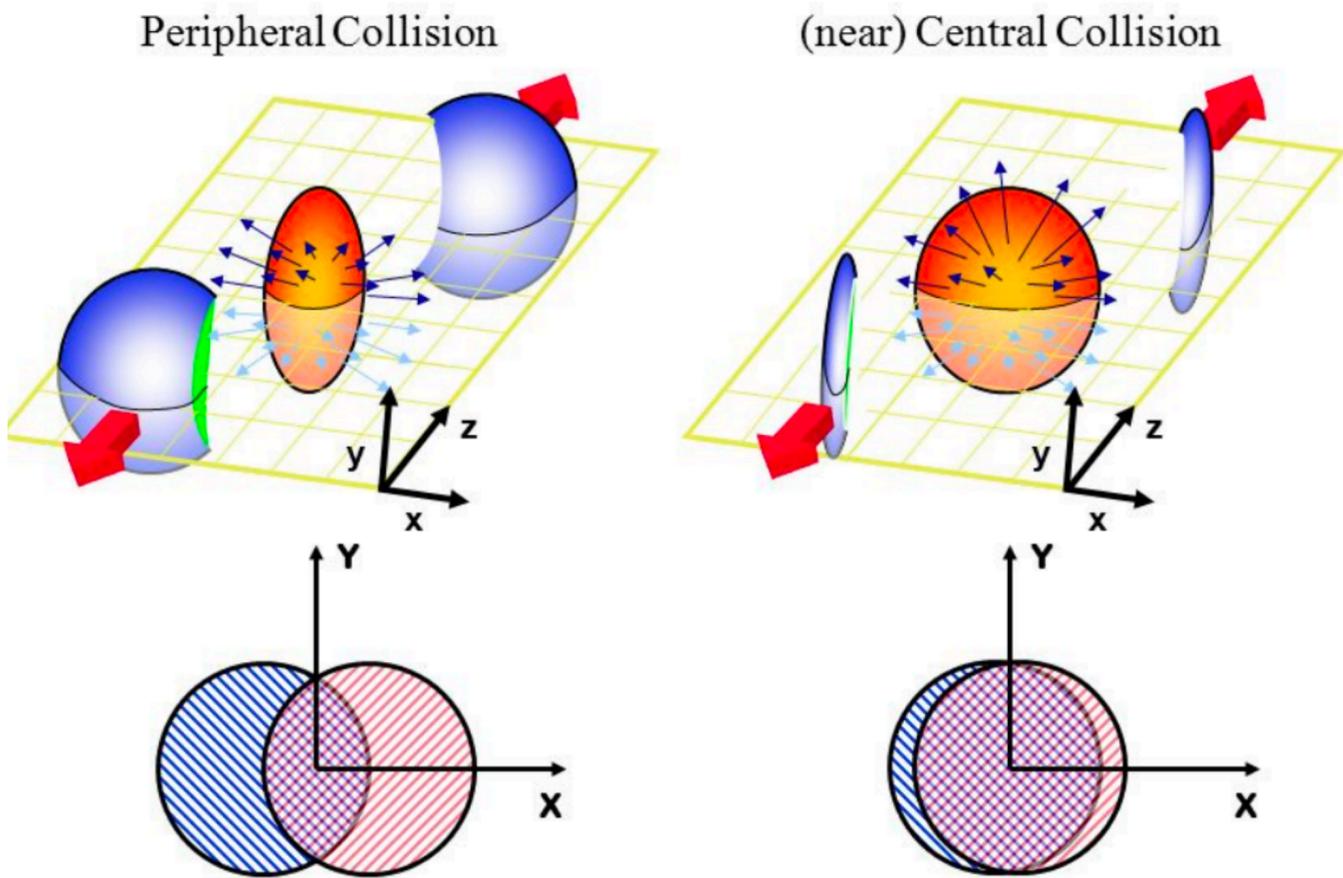
Peripheral Collision

(near) Central Collision

Ellipsoid-shaped volume

Spatial anisotropy

Azimuthal momentum space anisotropy

$$E\frac{d^3N}{dp^3} = \frac{d^3N}{p_T dp_T dy d\phi} = \frac{d^2N}{p_T dp_T dy}\frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n)]\right)$$

$$v_n(p_T, y) = \langle\cos(n(\phi - \psi_n))\rangle$$
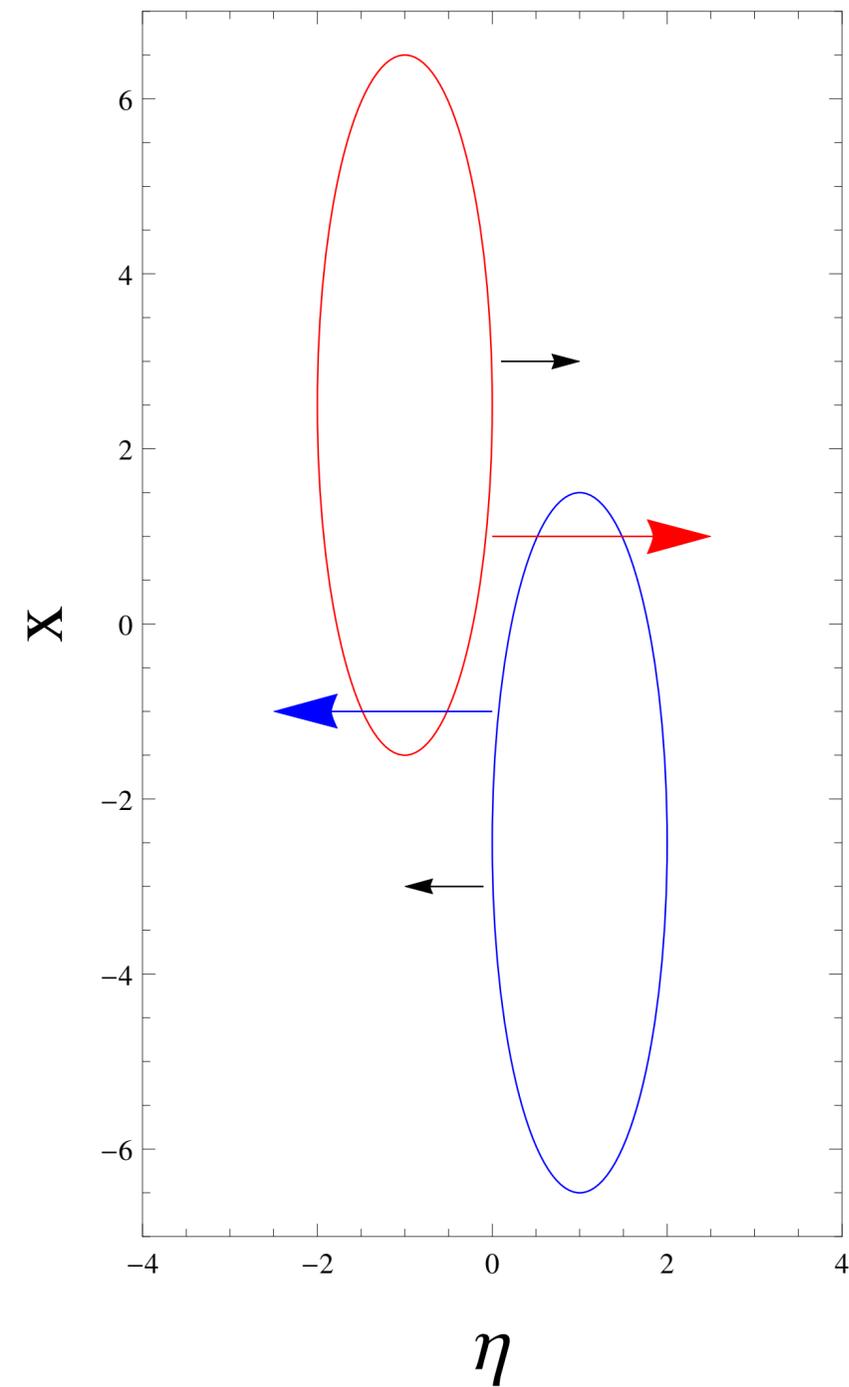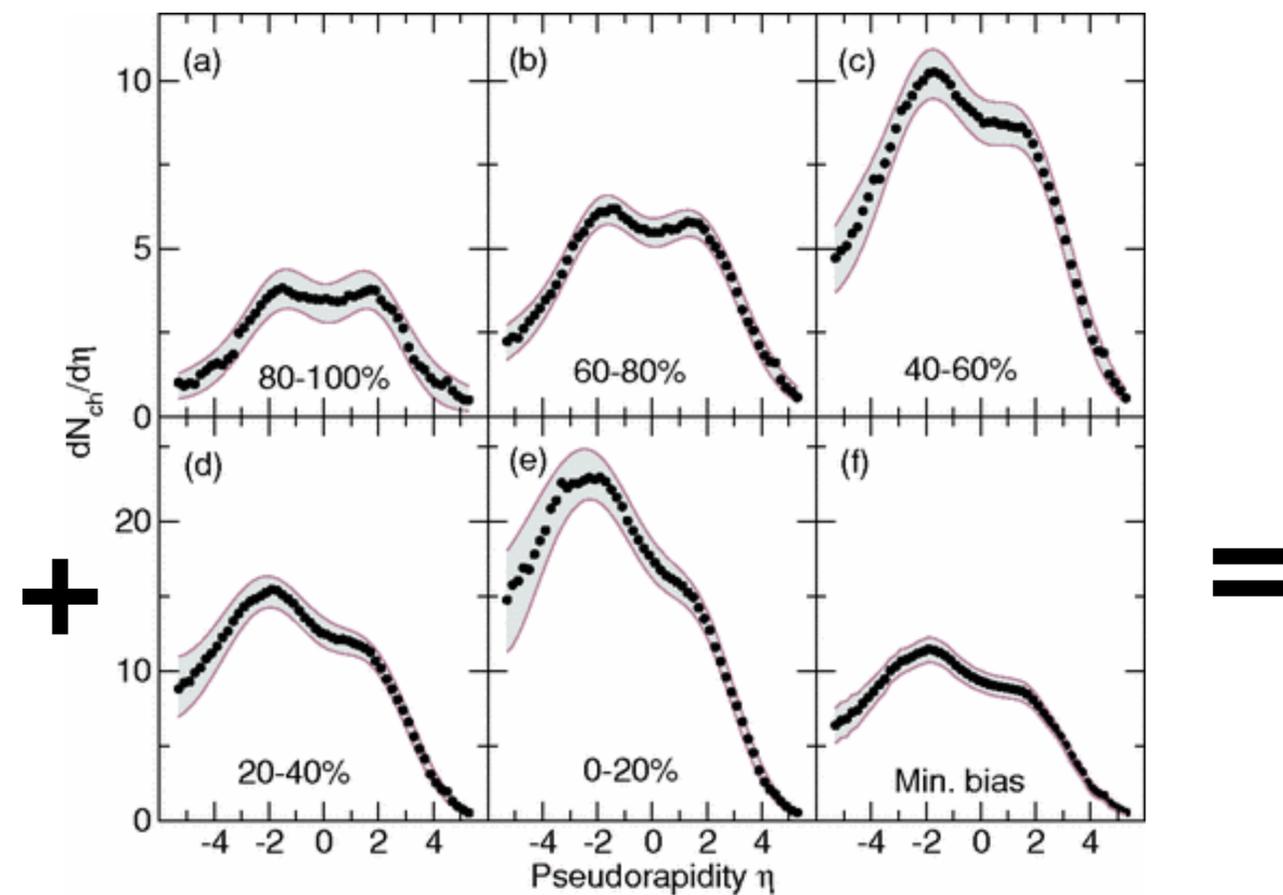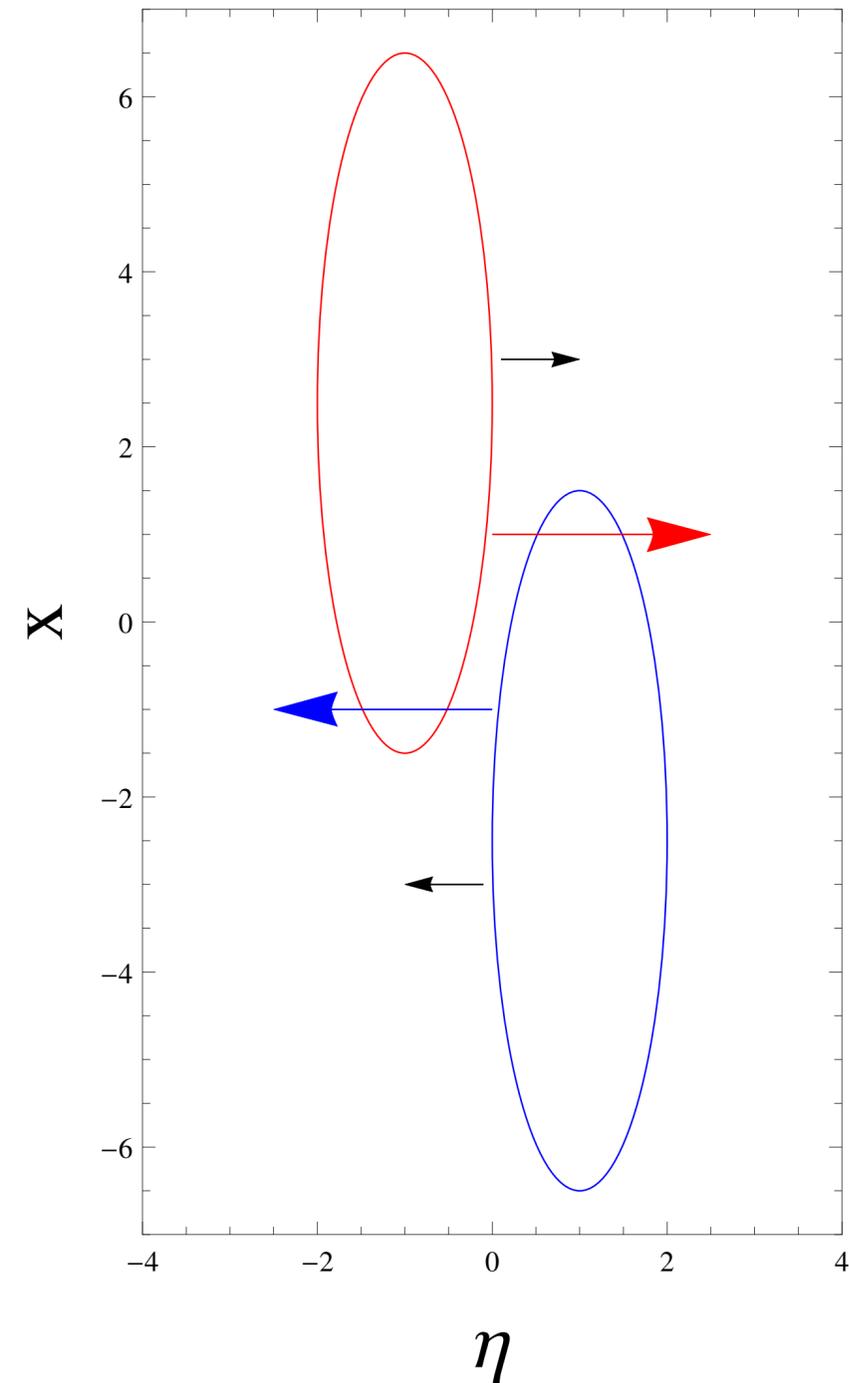
v_1, v_2, v_3

Initial Collision Geometry - directed flow

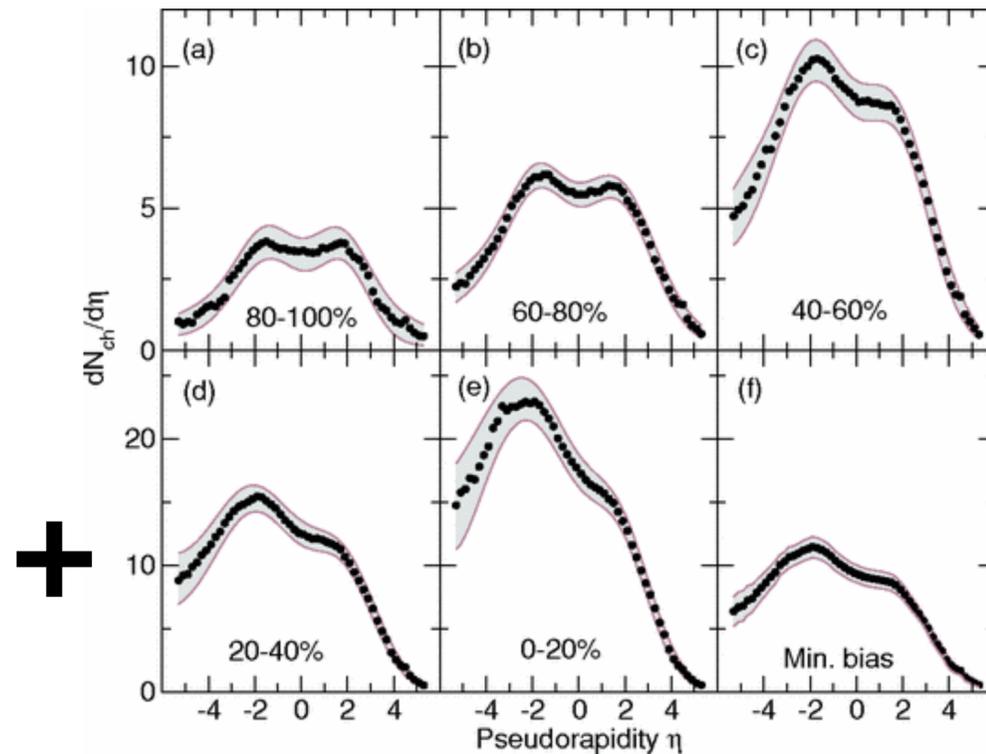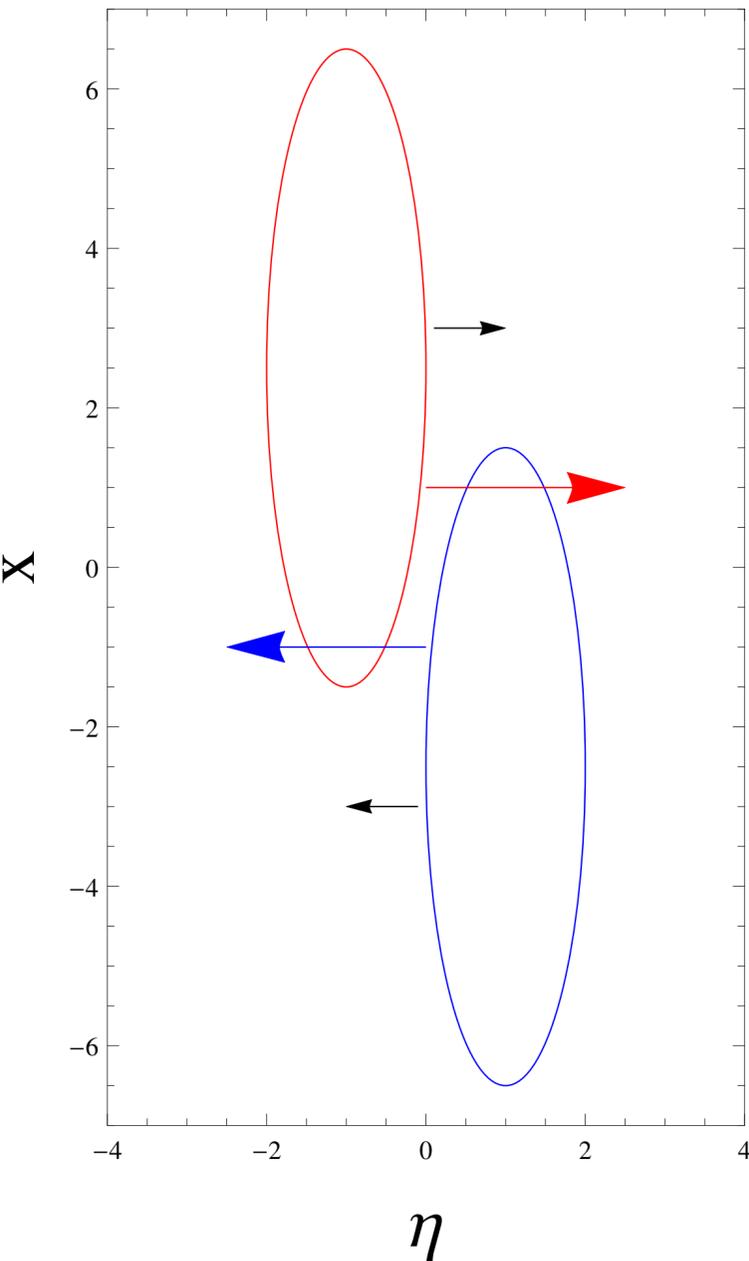# Initial Collision Geometry - directed flow

+

Initial Collision Geometry - directed flow

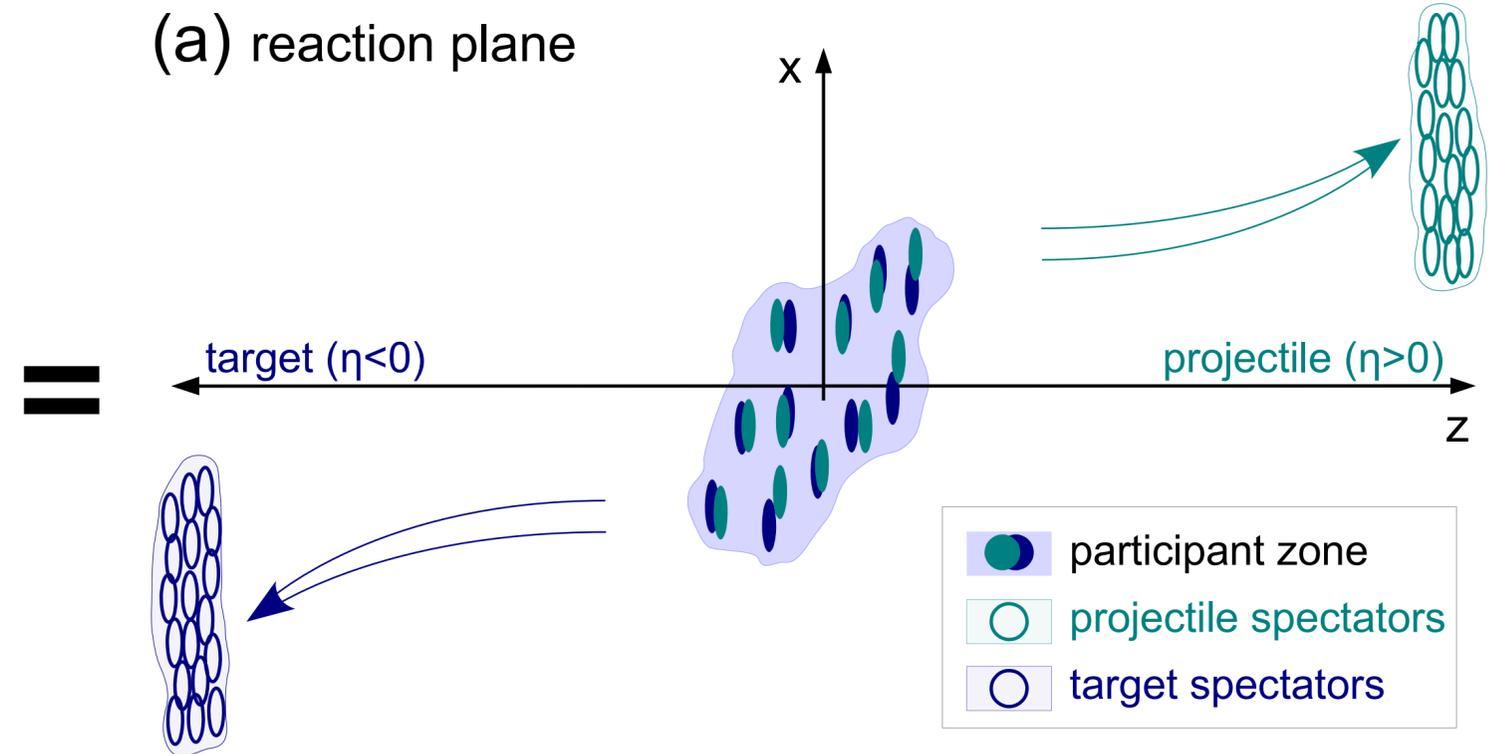d+Au at $\sqrt{s_{NN}} = 200$ GeV (PHOBOS 2011)

FB asymmetric deposition by a participant source

Initial Collision Geometry - directed flow
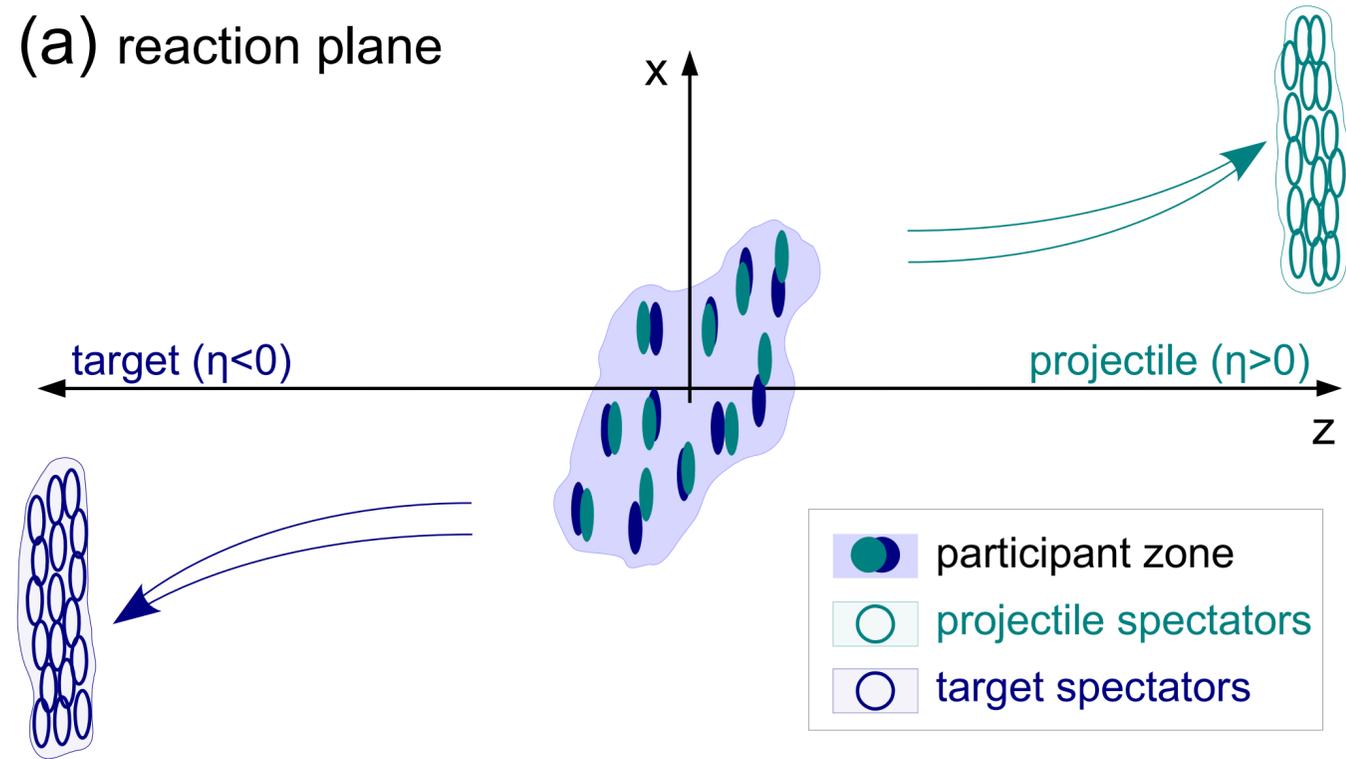

d+Au at $\sqrt{s_{NN}} = 200$ GeV (PHOBOS 2011)

FB asymmetric deposition by a participant source

(a) reaction plane

target ($\eta<0$)

projectile ($\eta>0$)

participant zone

projectile spectators

target spectators

Tilted fireball !!

Initial Collision Geometry - directed flow

(a) reaction plane

target ($\eta < 0$)

projectile ($\eta > 0$)

x

z

participant zone

projectile spectators

target spectators

Tilted fireball !!

v_1 (%)

- 0 - 5%
- 5 - 40%
- 40 - 80%
- PHOBOS: 6 - 40%
- $\langle p_x \rangle / \langle p_t \rangle$: 0 - 5%

η
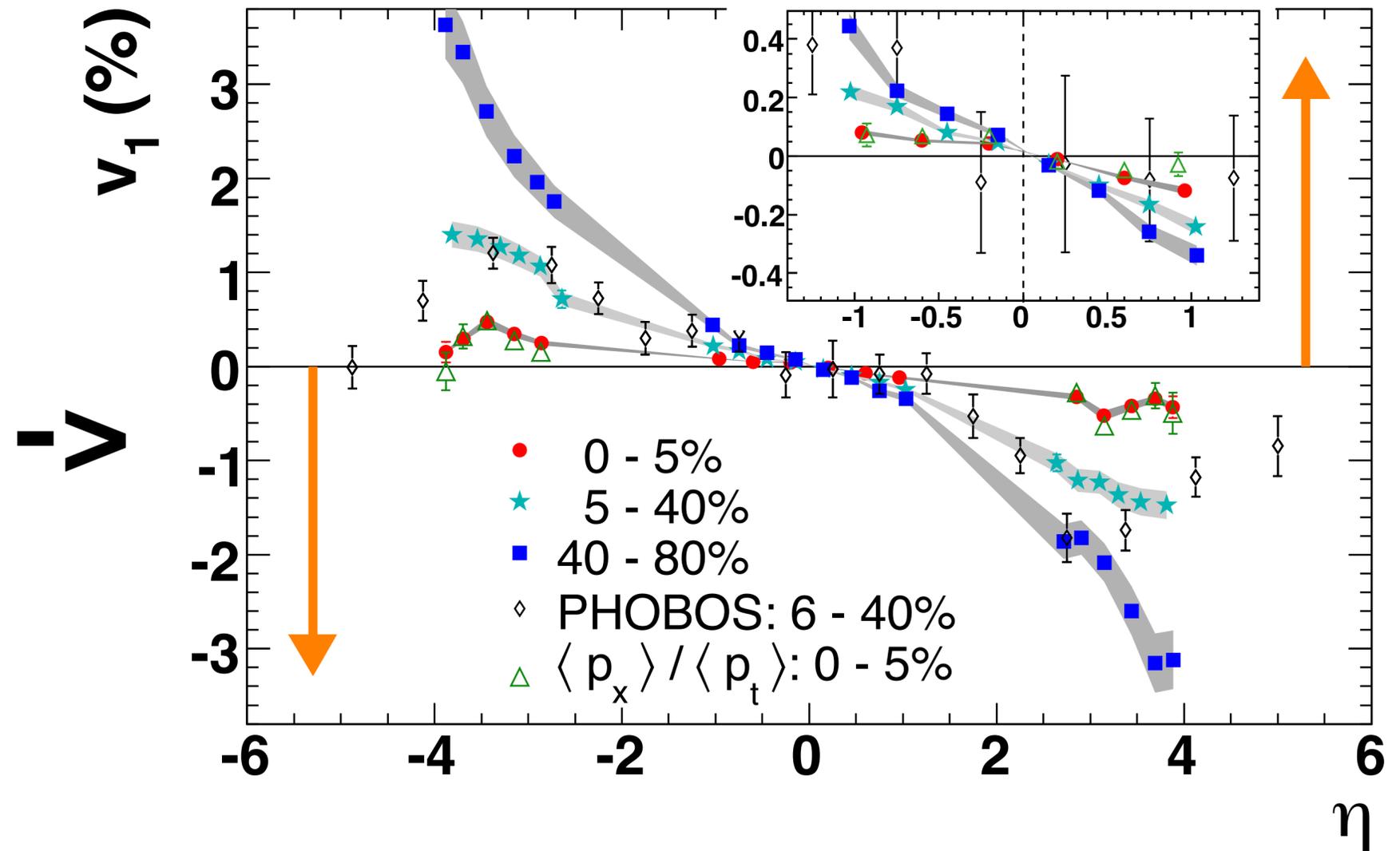
Au+Au at $\sqrt{s_{NN}} = 200$ GeV (STAR 2009)

Initial Collision Geometry - directed flow

(a) reaction plane

x

target (η<0)   projectile (η>0)

z

participant zone
projectile spectators
target spectators

->

Tilted fireball !!

(%)   STAR Data Au-Au √s=200 GeV c=5-40%
v_1 2   PHOBOS Au-Au c=0-40%

τ_0= 0.25 fm/c
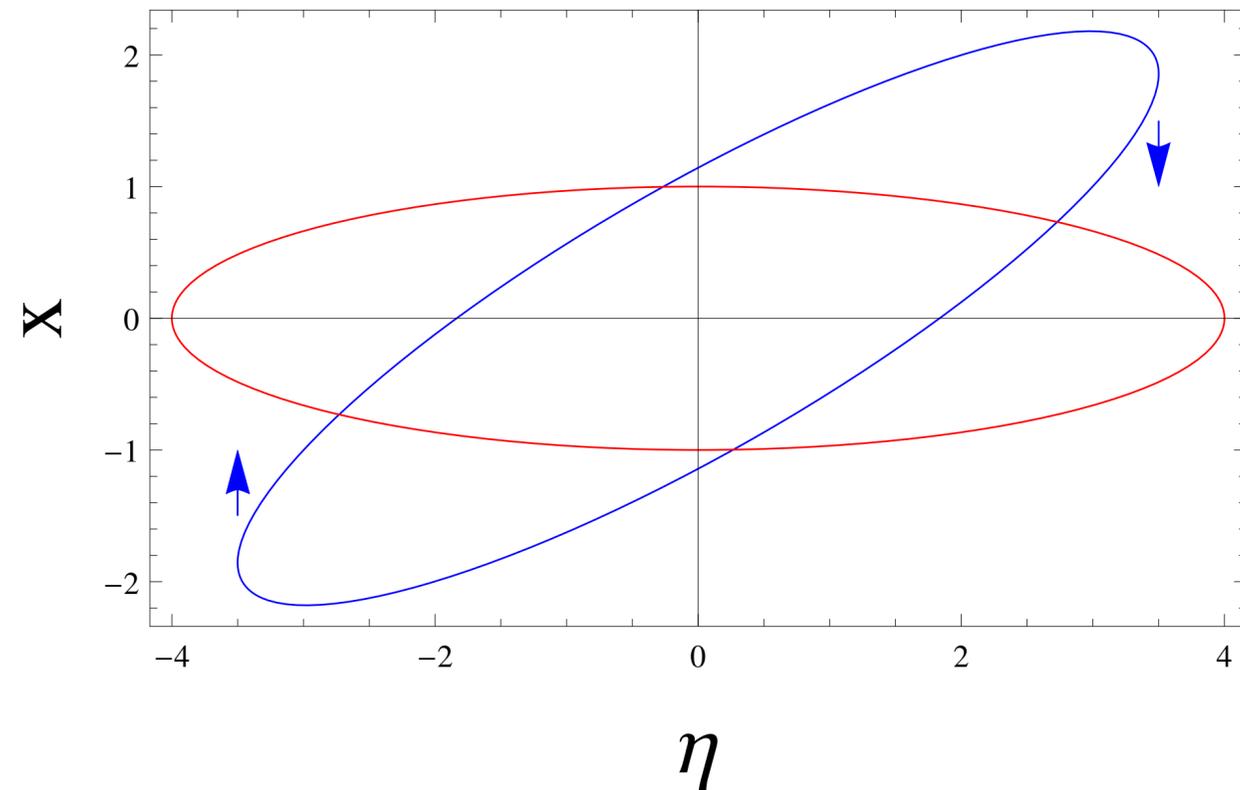τ_0= 1 fm/c
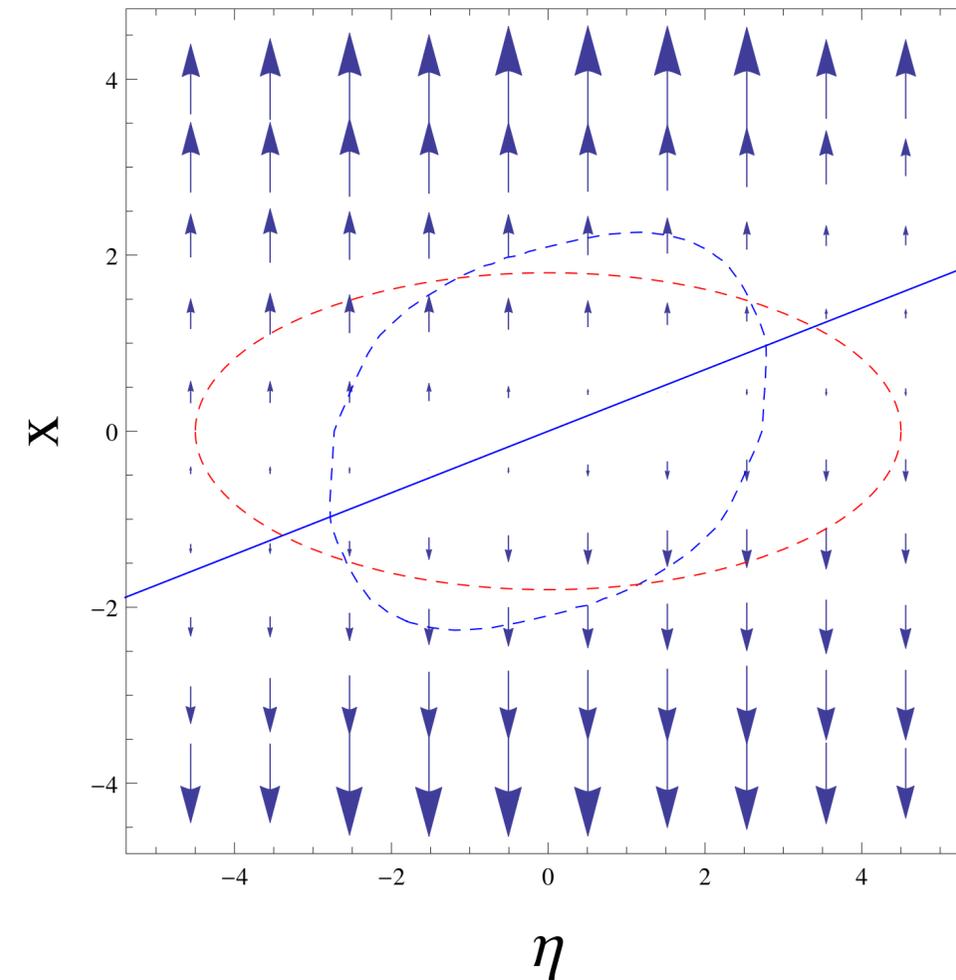η_m= y_b
entropy scaled

η
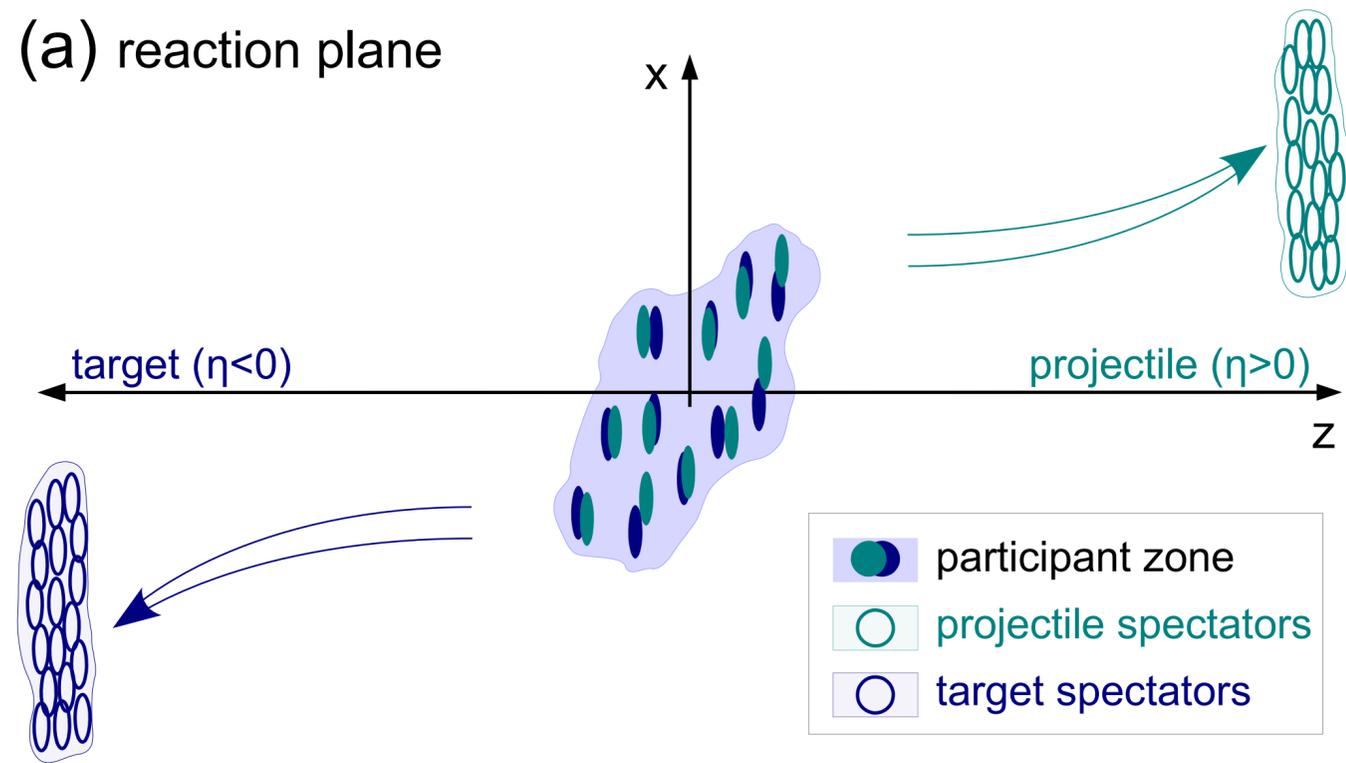
Bozek, Wyskiel 2010

Heavy probe of Initial Tilt

HQ from hard processes → FB-symmetric
Rapidity-even HQ dragged by Rapidity-odd bulk

Bulk vs heavy flavor

charm, anti-charm stronger probes of the tilt than the light flavor

Heavy probe of Initial Tilt

need to calibrate

- the tilt of the bulk: constrained by charged particle v_1, Bożek, Wyskiel 2010

- drag between the bulk and heavy flavor: constrained by heavy flavor R_{AA} and v_2 at mid-rapidity, we use an ansatz
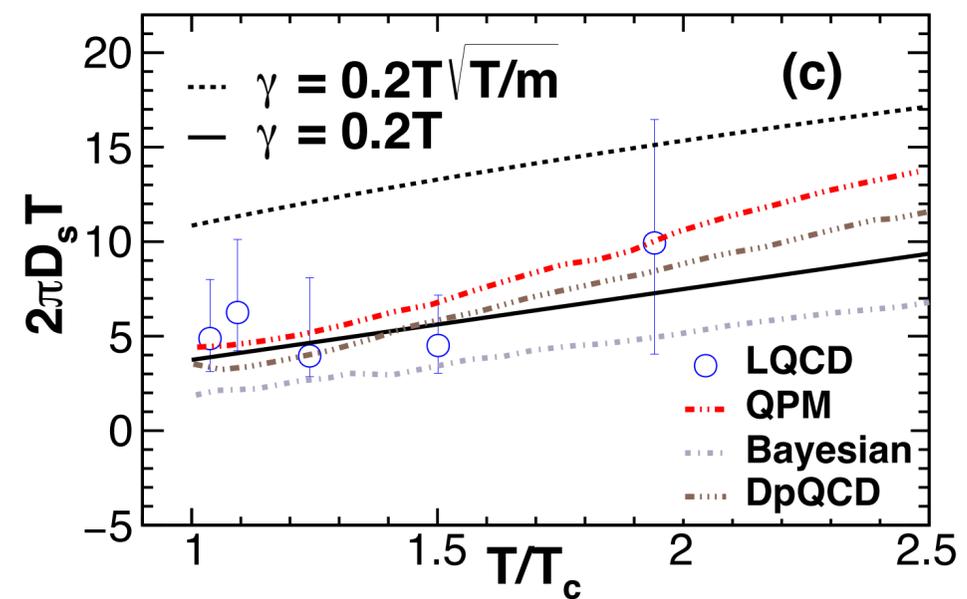 $\gamma = \gamma_0 T \left(\frac{T}{m}\right)^x$

Heavy probe of Initial Tilt - Calibrating the drag

Heavy probe of initial tilt:
10 times larger v_1 than light flavor!!

SC, Bozek 2018

Heavy probe of initial tilt:
10 times larger v_1 than light flavor!!
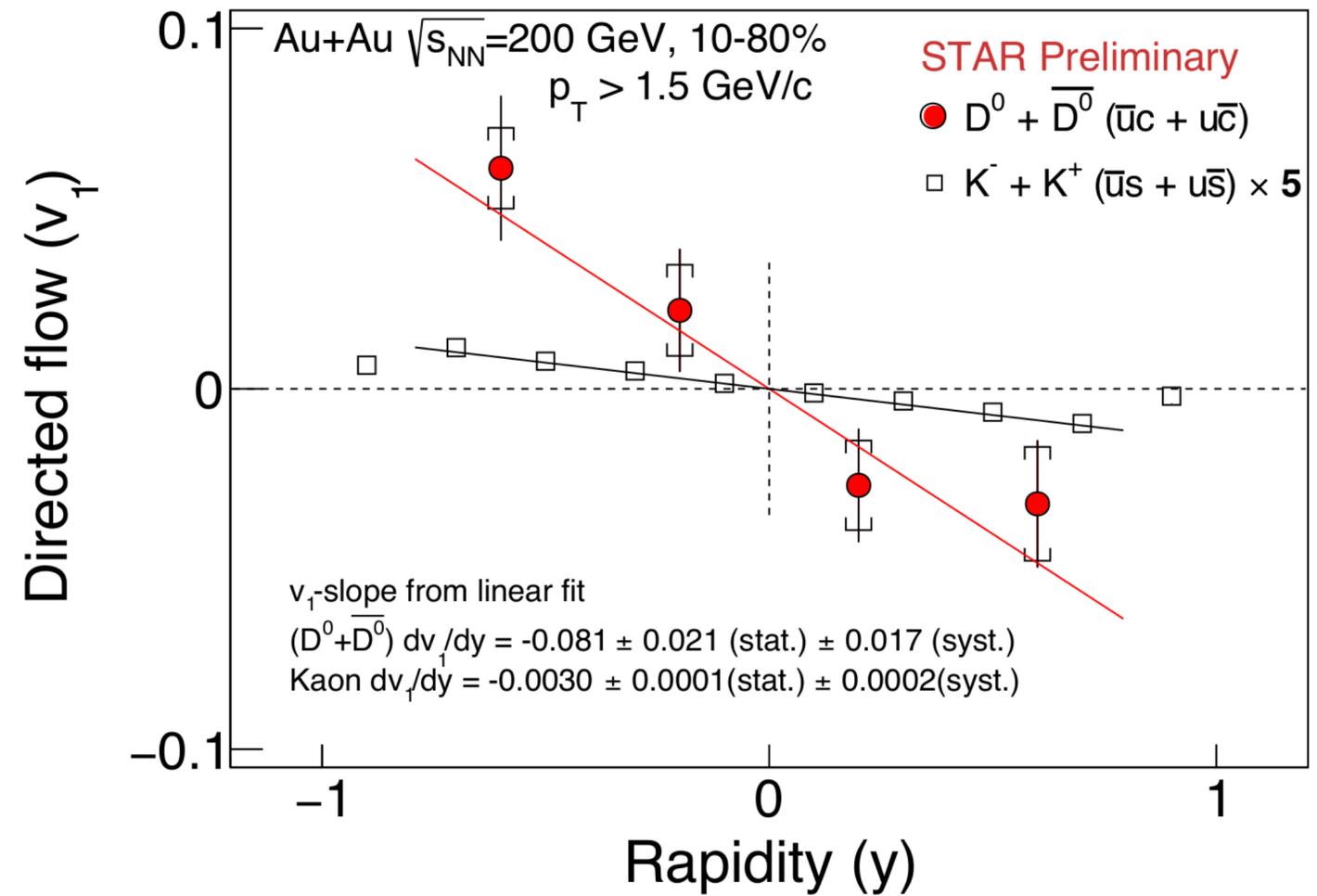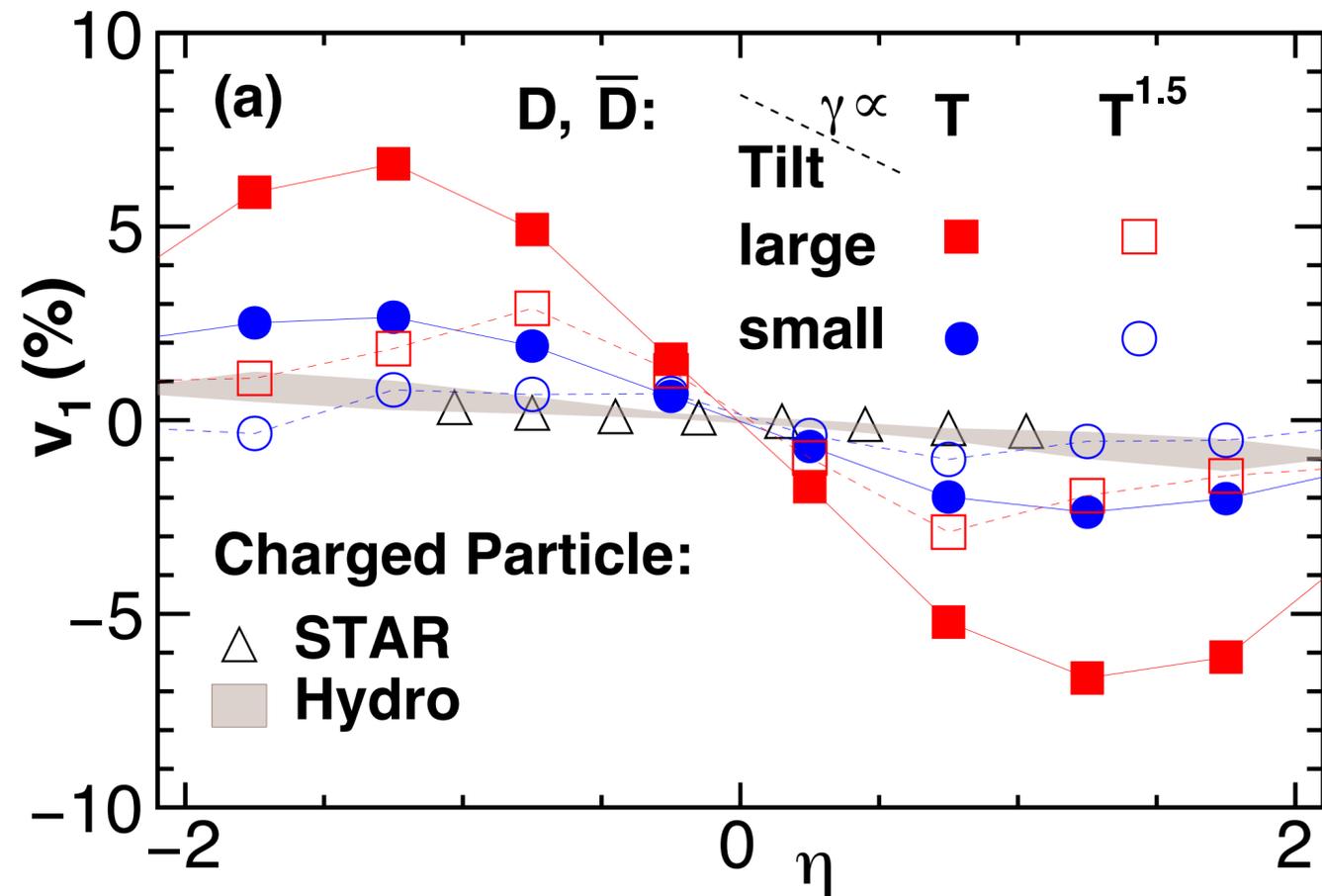
SC, Bozek 2018

Heavy probe of initial tilt:
10 times larger v_1 than light flavor!!

SC, Bozek 2018

Tilt ~ Angular Momentum -> Heavy probe of the Initial Angular momentum:
Refer to Amaresh's Talk

Initial Electromagnetic field
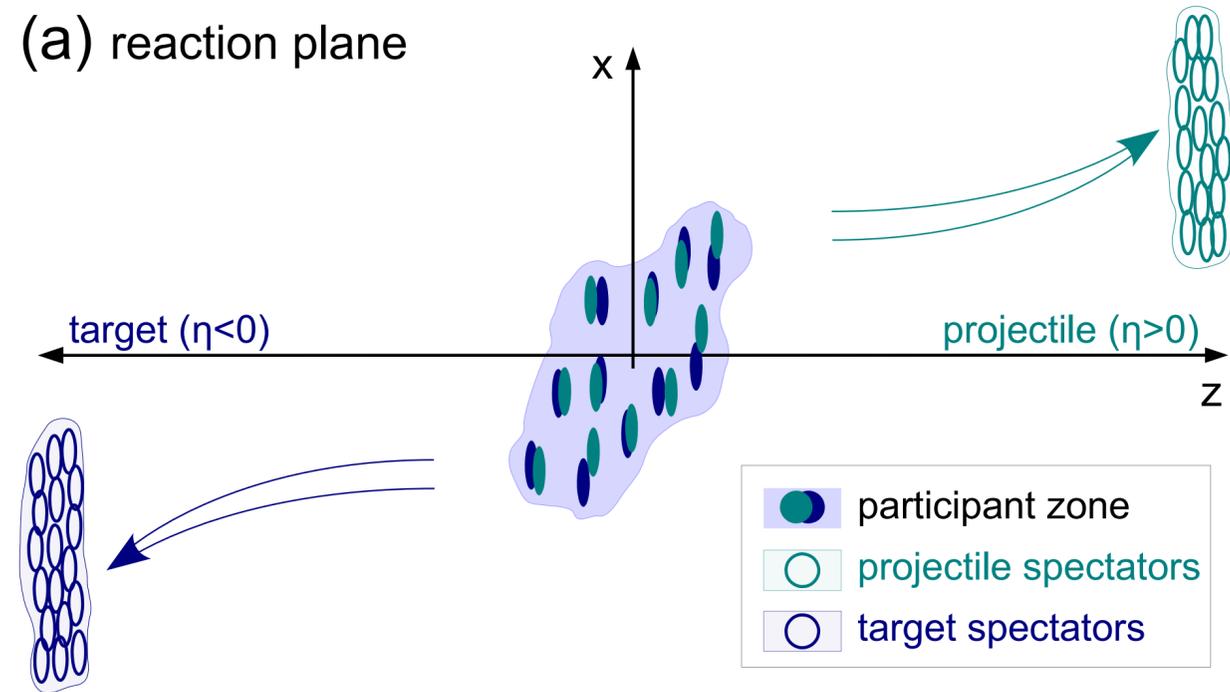
(a) reaction plane

- **B** $= -B\ \hat{y}$, B decreases as the spectators recede. For non-zero conductivity σ of the medium, this gives rise to a clock-wise **E** in the above reaction plane

- A positive charge at $\eta > 0$ experiences **B** force along $\hat{x}$ while **E** force along $-\hat{x}$, the net force resulting in a directed flow v_1

Light probe of Initial Electromagnetic field

v_1 split between positive and negative charged particles due to EM field
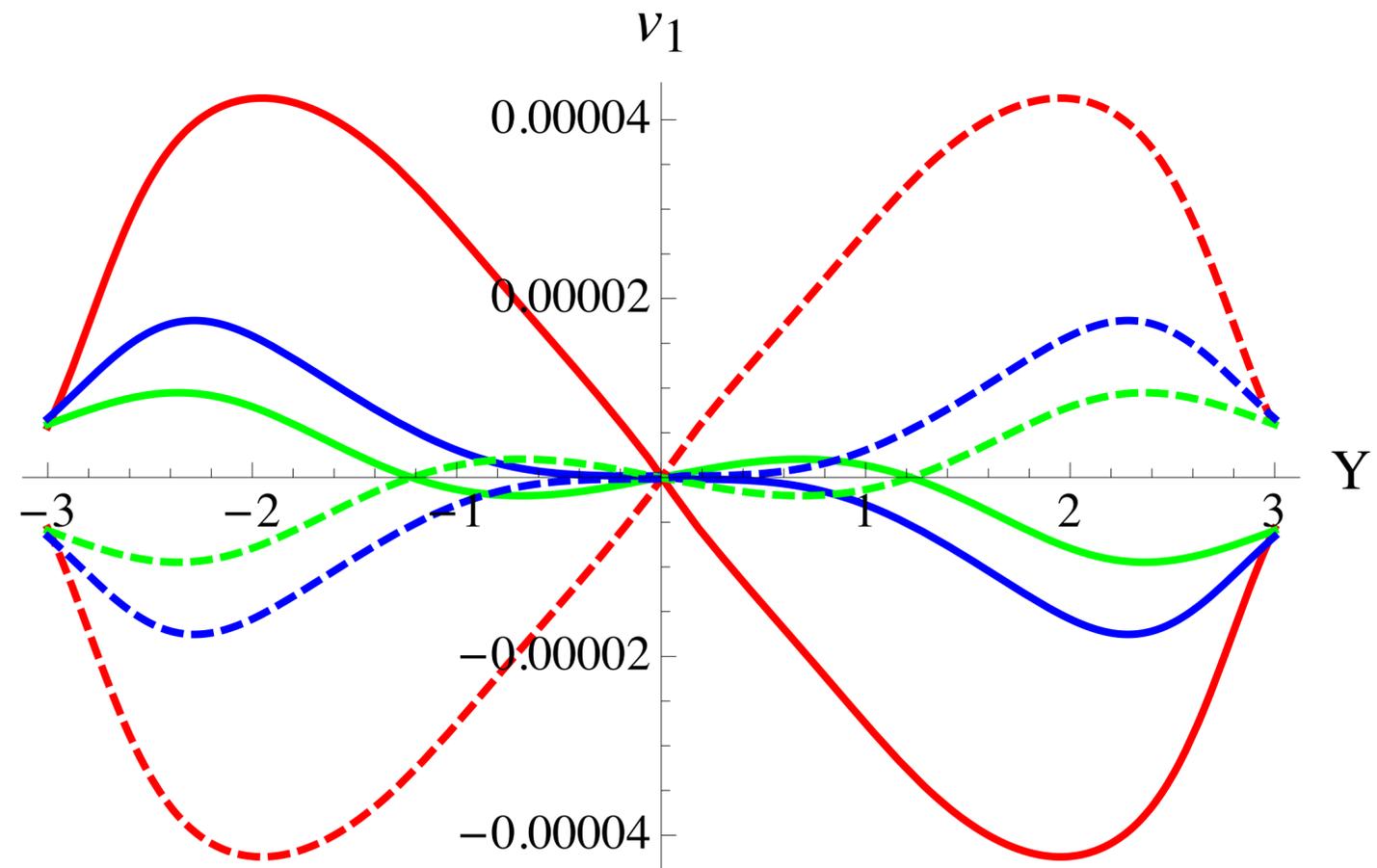
Gursoy, Kharzeev, Rajagopal 2014

Heavy probe of Initial Electromagnetic field

1000 times stronger effect on heavy flavor !!
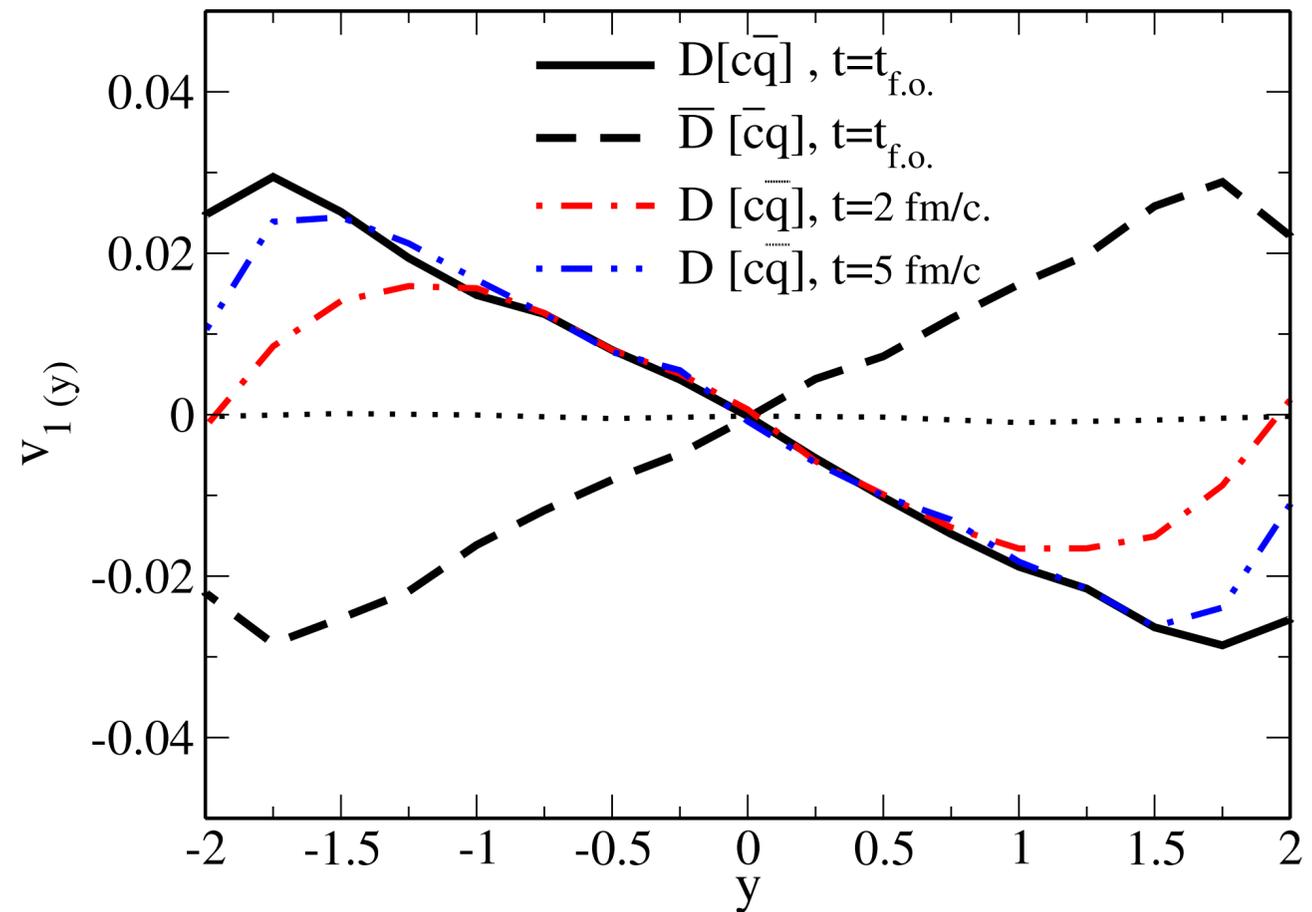
Das, Plumari, SC, Alam, Scardina, Greco 2016

Heavy probe of initial Electromagnetic field

Au+Au $\sqrt{s_{NN}}$=200 GeV, 10-80%

a)

Ratio (D^0/K)

$\langle v_1 \rangle$

STAR
- $D^0 + \overline{D^0}$ ($\overline{u}c + u\overline{c}$)
- $K^- + K^+$ ($\overline{u}s + u\overline{s}$)

Model:($D^0 + \overline{D^0}$)
- Hydro+EM (Chatterjee et.al.)
- AMPT

b)

STAR
- $D^0 - \overline{D^0}$ ($\overline{u}c - u\overline{c}$)
- $K^- - K^+$ ($\overline{u}s - u\overline{s}$)

Δv_1

Model:($D^0 - \overline{D^0}$)
- EM (Das et. al.)
- Hydro+EM (Chatterjee et.al)

Rapidity (y)

Pb+Pb @ LHC 5.02 TeV   ALICE

(a)
$p_T > 0.2$ GeV
5-40%

v_1

- $h^+ \times 10^3$
- $h^- \times 10^3$

(b)
$3 < p_T < 6$ GeV
10-40%

- D^0
- $\overline{D^0}$

(c)
- $(h^+ - h^-) \times 10^3$

Δv_1

5-40%
$p_T > 0.2$ GeV

(d)
- $D^0 - \overline{D^0}$

10-40%
$3 < p_T < 6$ GeV

η
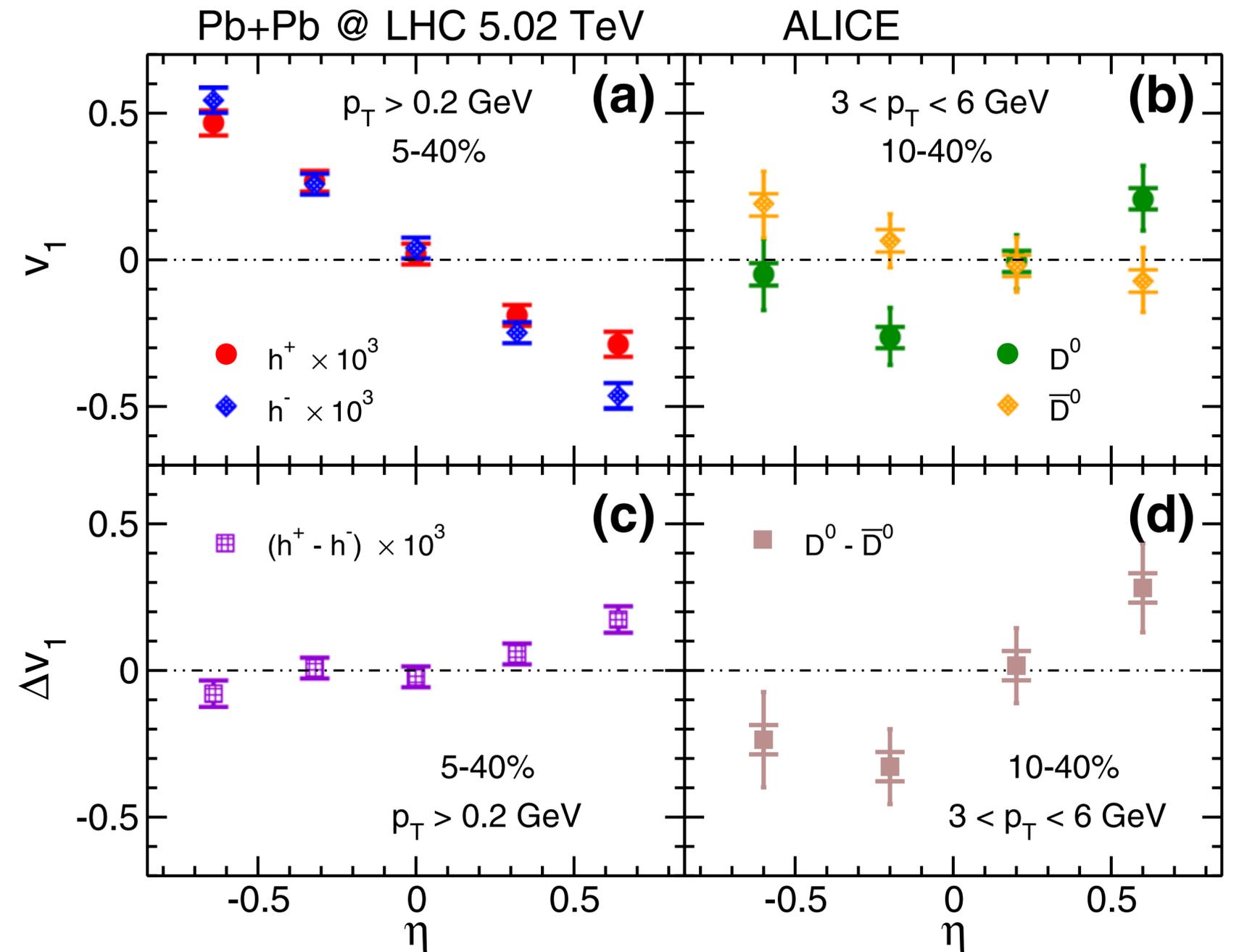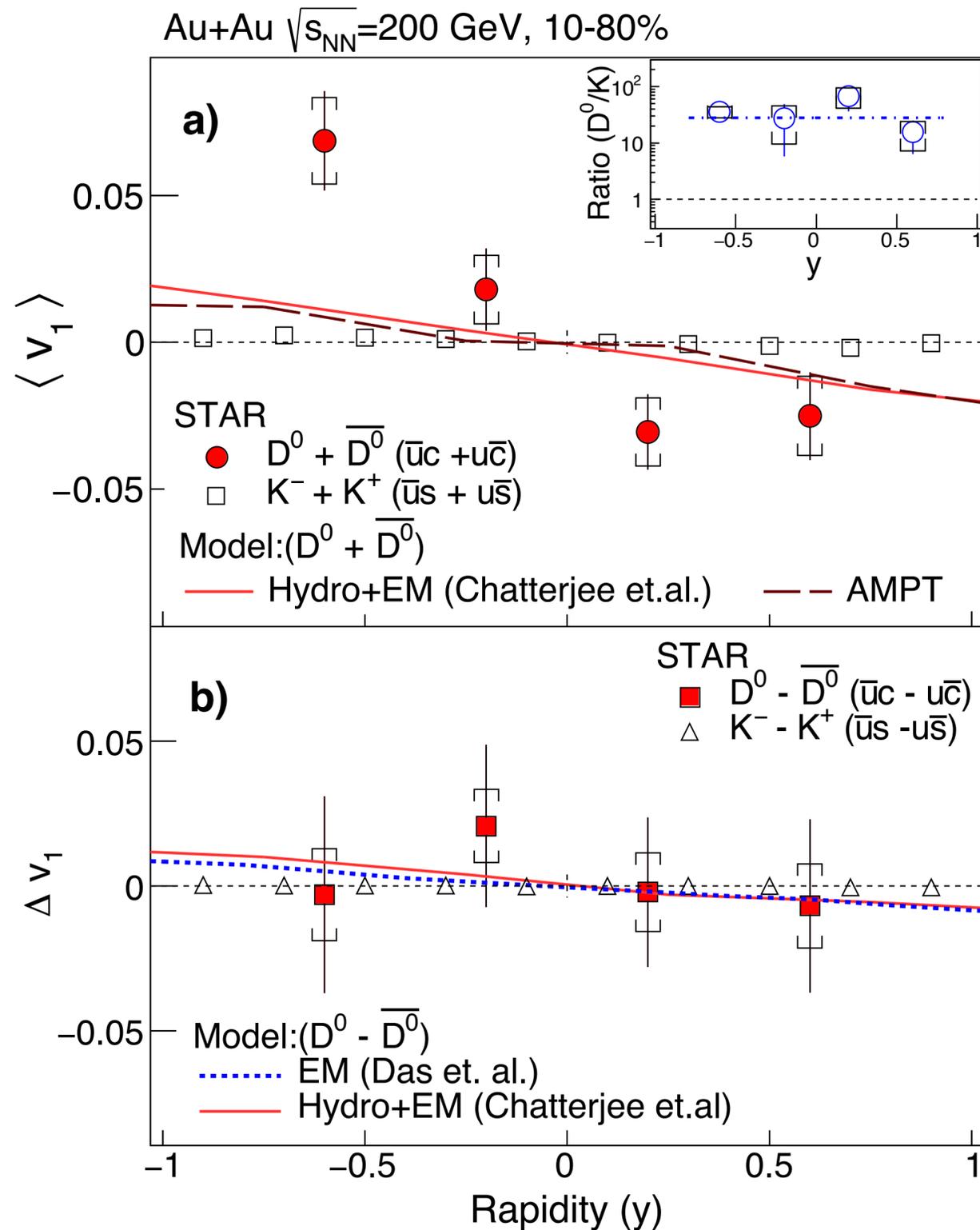
Alice measurements hints at disagreement

Heavy probes of initial geometry, EM fields
&
novel observables

With Kaiser Shafi, Tribhuban Parida, *in preparation*

Motivation

need to calibrate

- the tilt of the bulk: constrained by charged particle v_1, Bożek, Wyskiel 2010

- drag between the bulk and heavy flavor: constrained by heavy flavor R_{AA} and v_2 at mid-rapidity, we use an ansatz
  $\gamma = \gamma_0 T \left(\frac{T}{m}\right)^x$ **x is not well constrained**

Phase space of hadrons in the final state

- In the lab frame: (p_x, p_y, p_z)

- For most observables,
region of interest: mid-rapidity, i.e. $p_z \sim 0$
(transverse spectra,
elliptic flow)

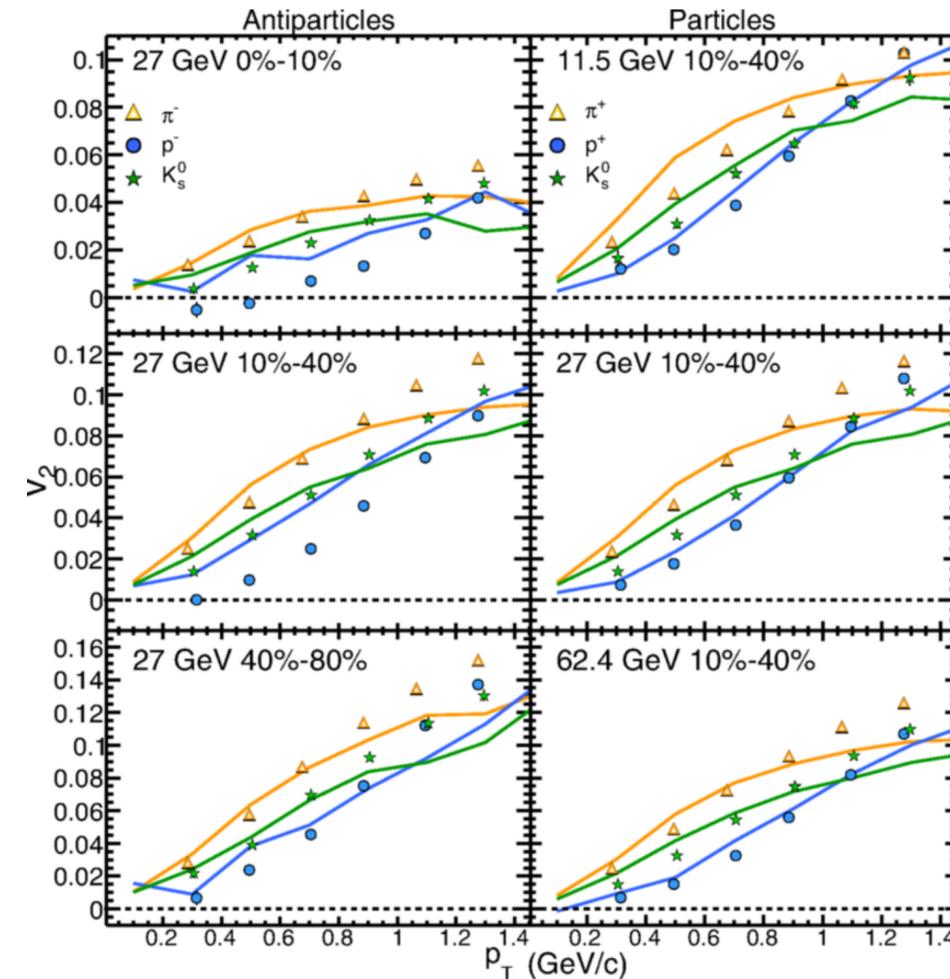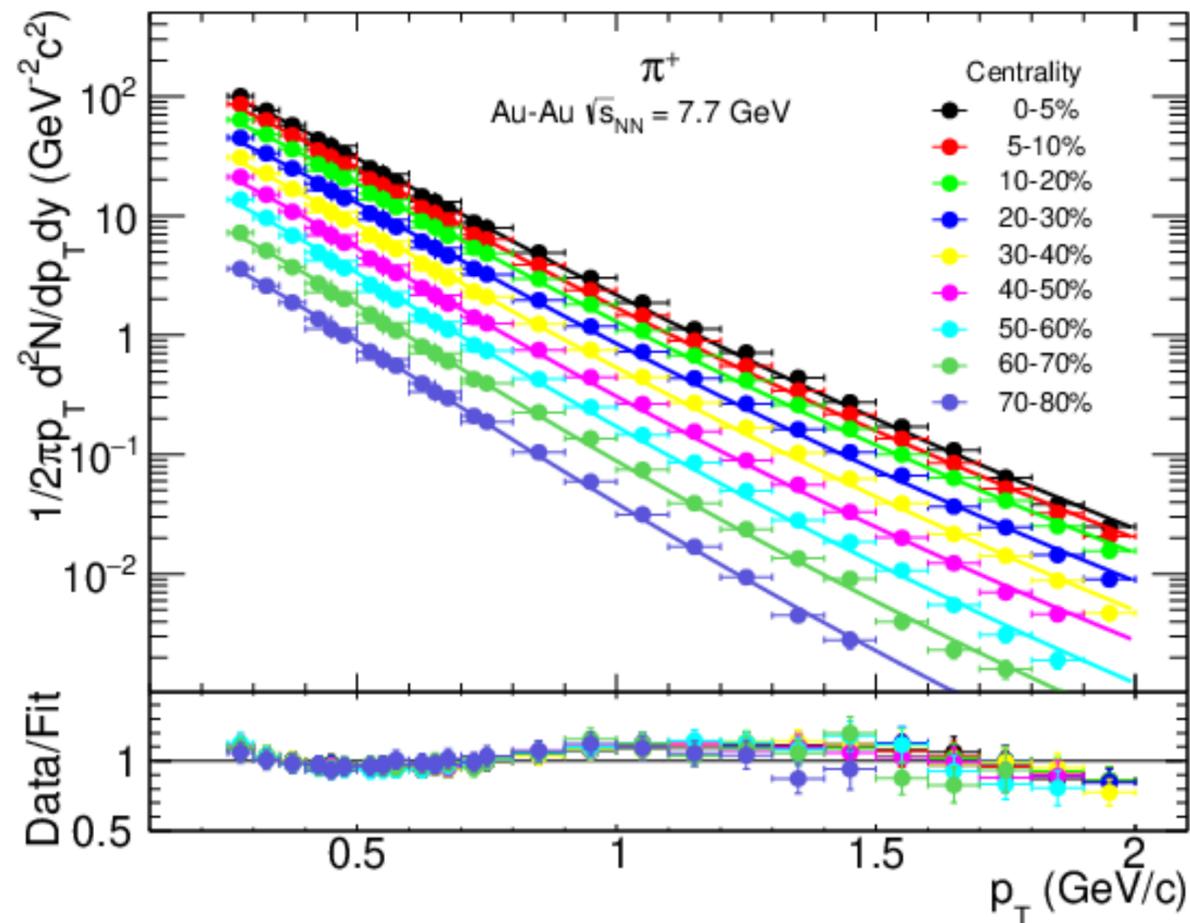- Resulting 2-D phase space: (p_x, p_y) -> (p_T, ϕ)

thus, we talk of 'p_T' dependence and 'azimuthal dependence'

Azimuthal dependence

Periodicity in ϕ provides a natural basis (Fourier expansion):

$N(\phi) = N_0 + v_1\cos(\phi) + \ldots.$ with $v_n \ll 1$;

p_T dependence

- p_T dependence by eye comparison!
  Are we missing important physics here?

Motivates us to revisit the p_T dependence

2-D mode decomposition: Fourier-Bessel Basis

$\Phi_{m,n}(r)$ plotted against r

Legend:
- $\Phi_{0,1}(r)$ (red solid), $\Phi_{0,5}(r)$ (red dashed)
- $\Phi_{2,1}(r)$ (blue solid), $\Phi_{2,5}(r)$ (blue dashed)
- $\Phi_{3,1}(r)$ (green solid), $\Phi_{3,5}(r)$ (green dashed)
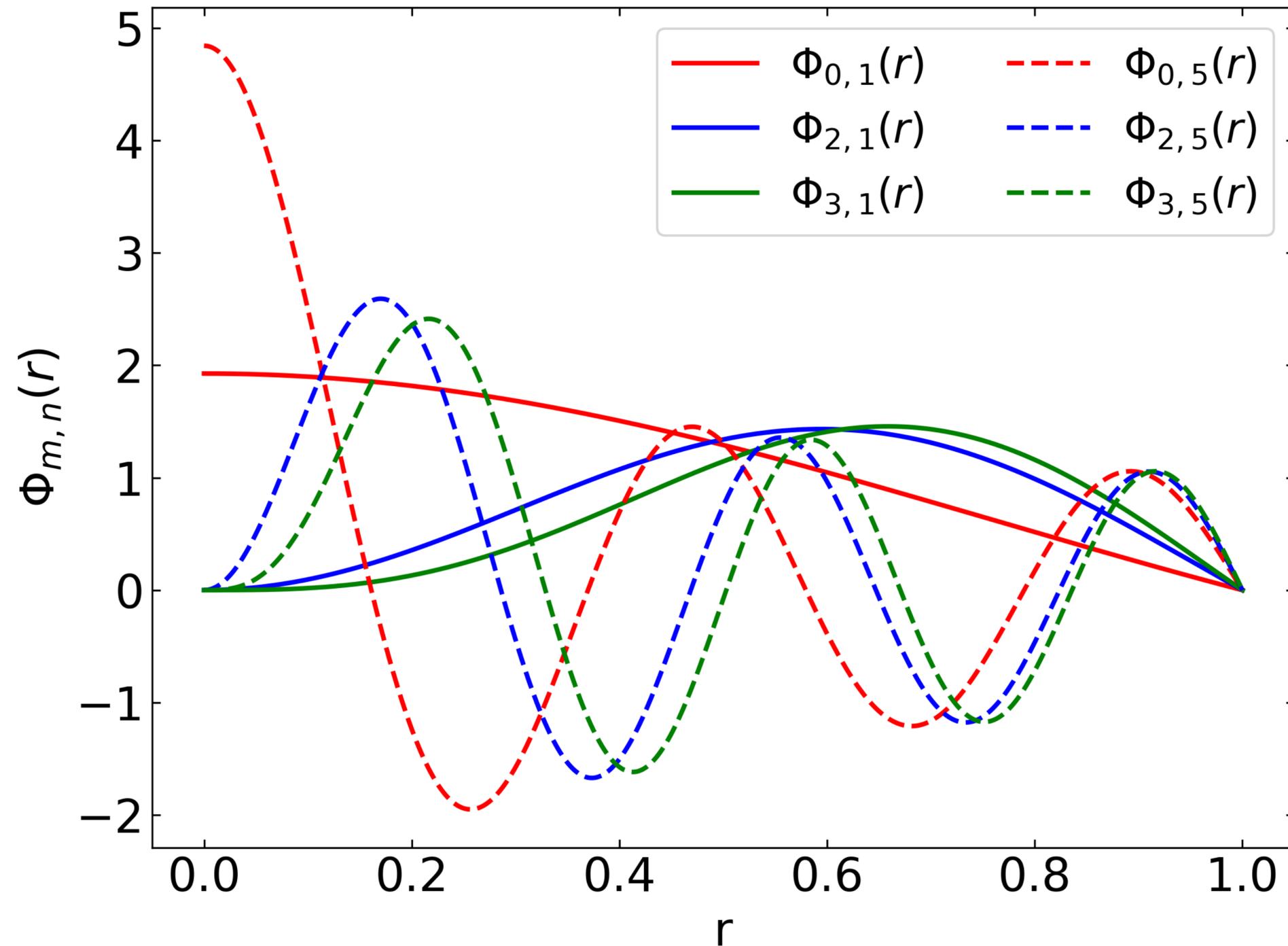
p_T basis functions

Bessel functions: eigenfunctions of Laplacian on disc -> provides a natural basis for the p_T dependence

$$\phi_{m,n}(r,\theta) := \frac{1}{J_{|m|+1}(\lambda_{m,n})} J_m\left(\frac{r}{r_0}\lambda_{m,n}\right) e^{im\theta}$$

J -> Bessel function of first kind

$$f(r,\theta) = \sum_{m,n} A_{m,n}\phi_{m,n}(r,\theta)$$

- 2-D mode expansion

Drag coefficient $\gamma = \gamma_0 T (T/m)^x$
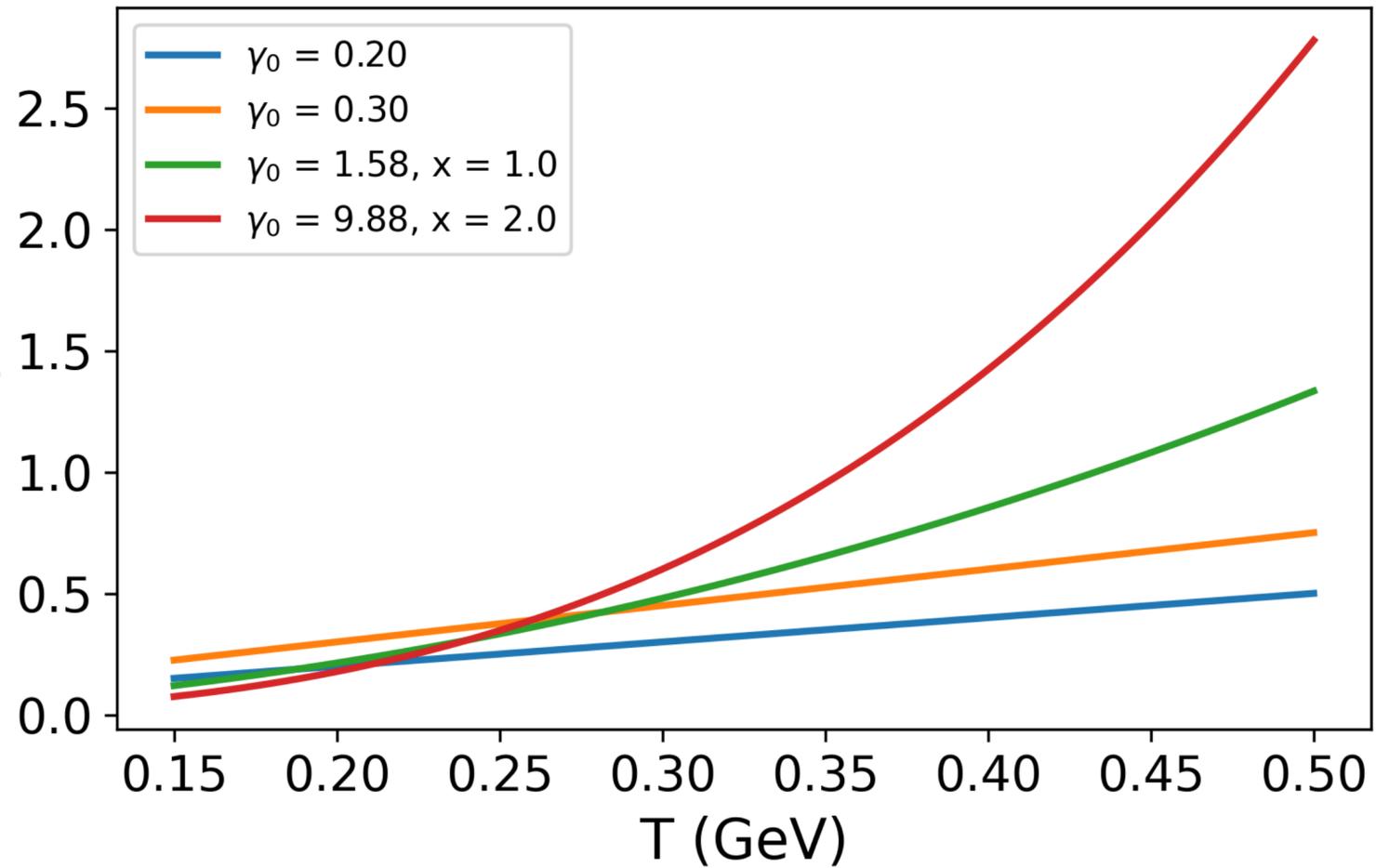
p_T mode decomposition of v_2

Pb+Pb 5.02 TeV, D_0: Glauber+MUSIC+Langevin, 20-30%, (p_T, ϕ)

Legend:
- $\gamma_0 = 0.20$
- $\gamma_0 = 0.30$
- $\gamma_0 = 1.58, x = 1.0$
- $\gamma_0 = 9.88, x = 2.0$
- $D_0 : Hydro$

Y-axis: $|F_{2n}| \div |F_{21}|$

X-axis: n
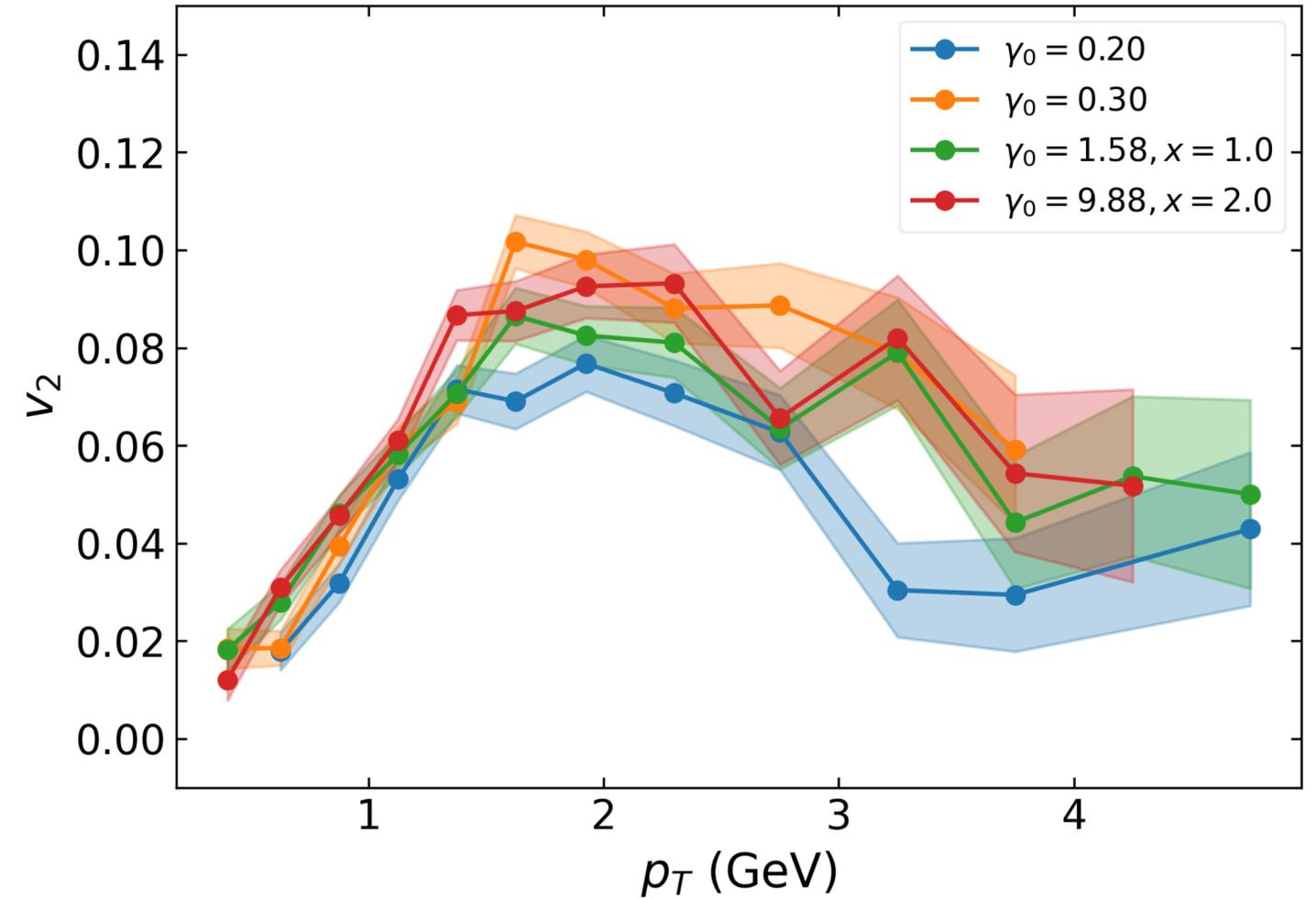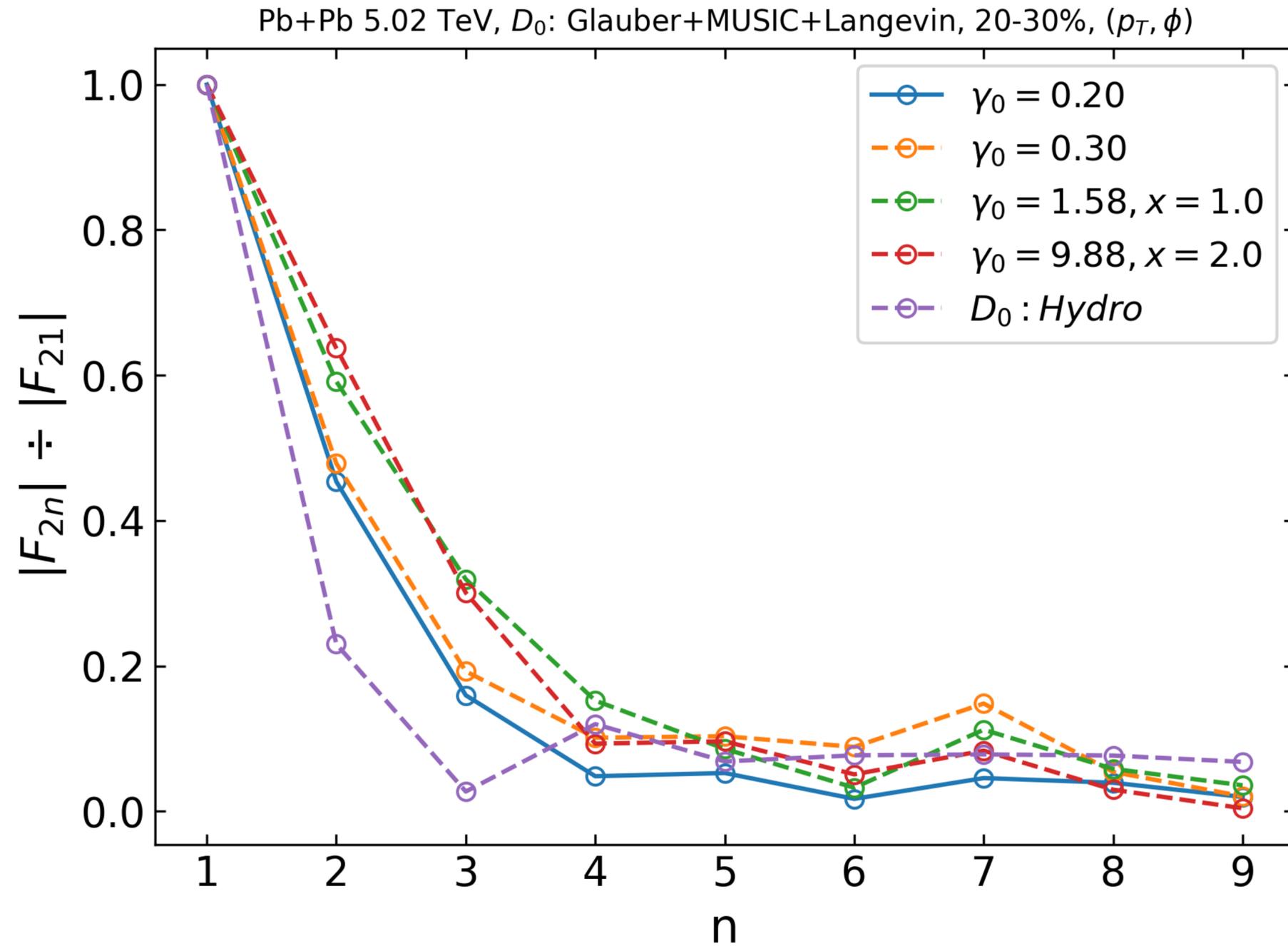
T dependence is revealed !!

p_T mode decomposition of v_2

Pb+Pb 5.02 TeV, D_0: Glauber+MUSIC+Langevin, 20-30%, $(p_T/\langle p_T \rangle, \phi)$

Legend:
- $\gamma_0 = 0.20$
- $\gamma_0 = 0.30$
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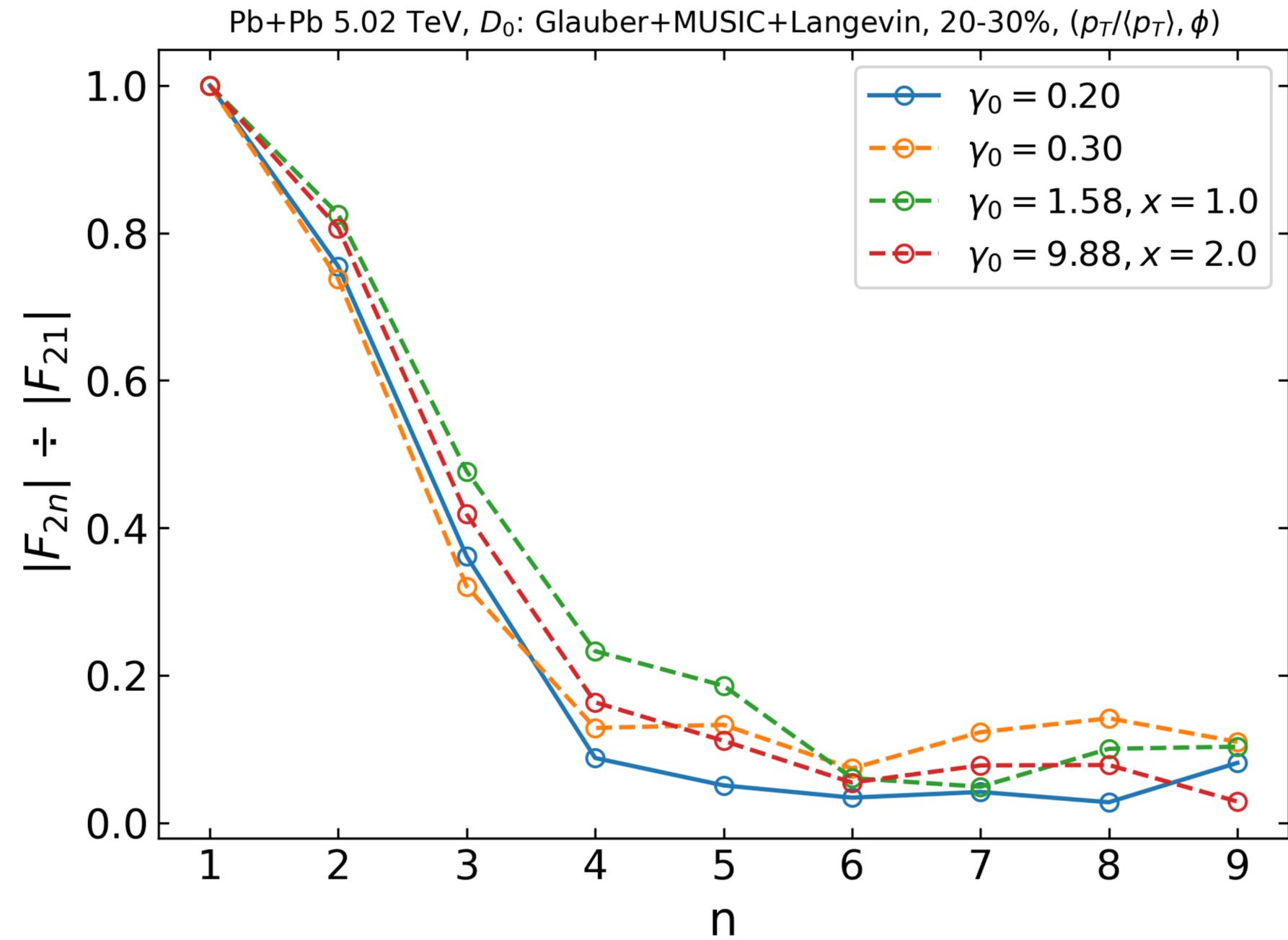
T dependence is revealed !!

Summarising..

Heavy flavor offers unique sensitive probes to understand the initial

- **3 dimensional distribution of the fireball**

- **Electromagnetic fields**

Au+Au $\sqrt{s_{NN}}$=200 GeV, 10-80%

a)

Ratio (D^0/K)

$\langle v_1 \rangle$

STAR
- $D^0 + \overline{D^0}$ ($\overline{u}c + u\overline{c}$)
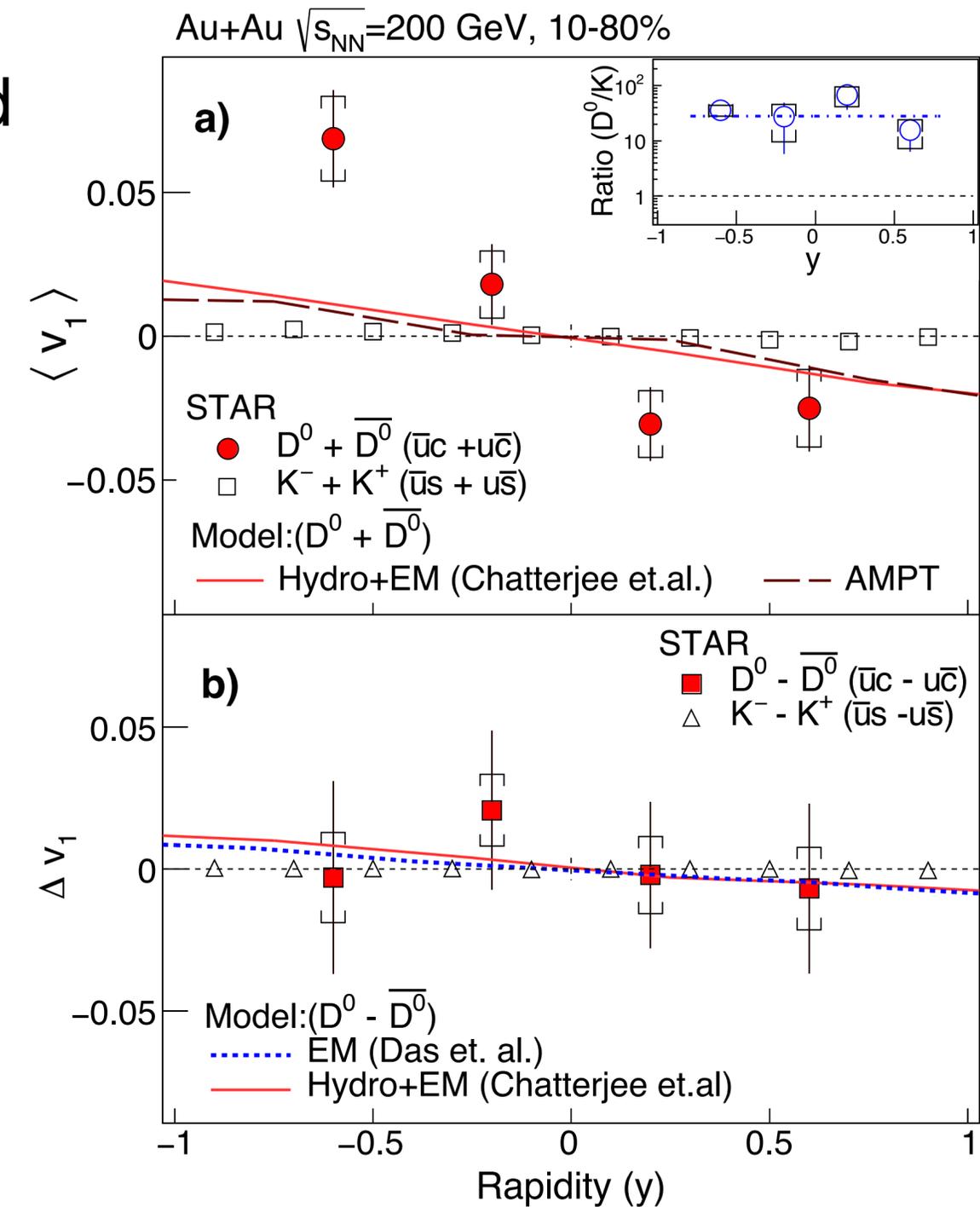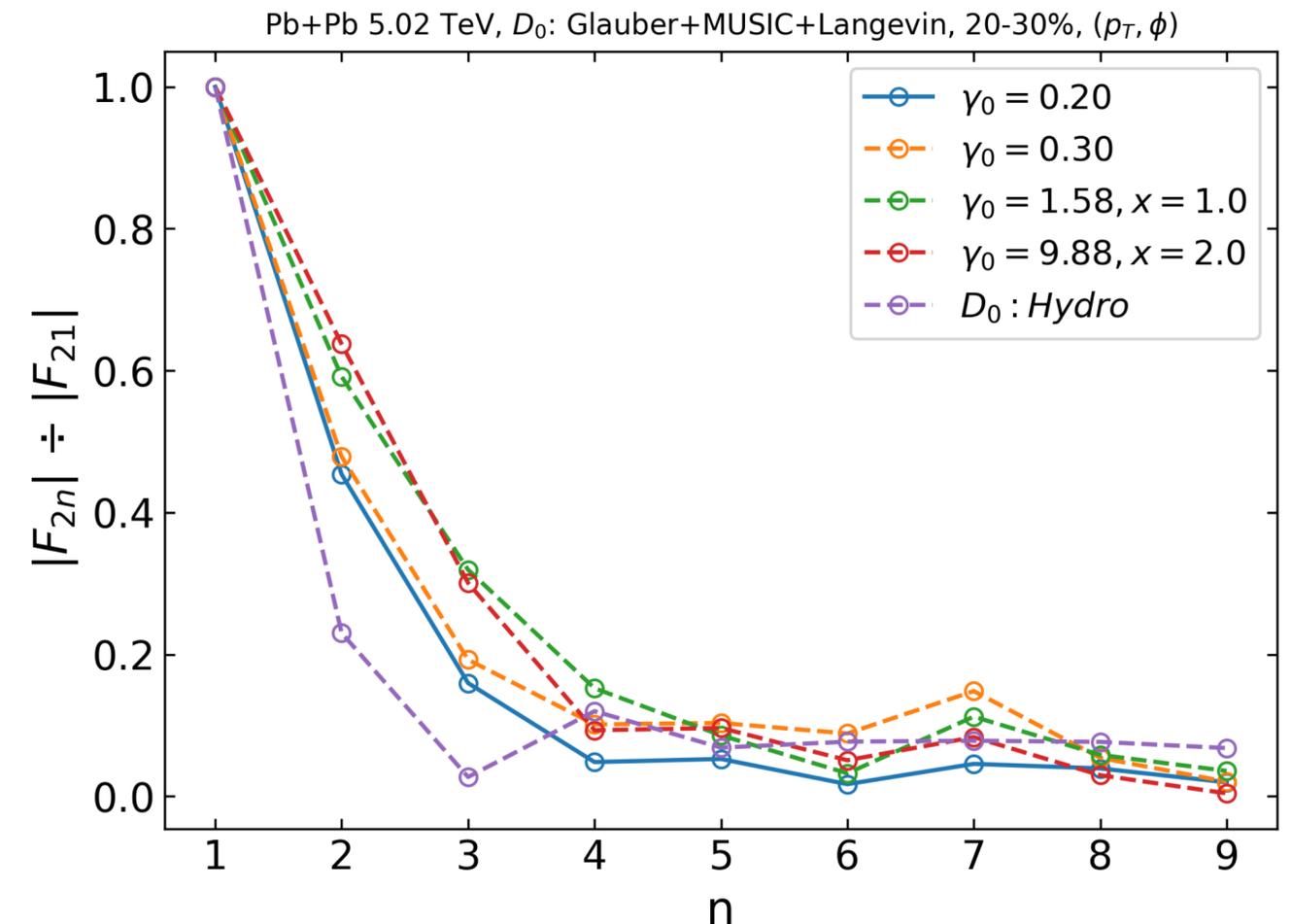- $K^- + K^+$ ($\overline{u}s + u\overline{s}$)

Model:($D^0 + \overline{D^0}$)
— Hydro+EM (Chatterjee et.al.)   — — AMPT

b)

STAR
- $D^0 - \overline{D^0}$ ($\overline{u}c - u\overline{c}$)
- $K^- - K^+$ ($\overline{u}s - u\overline{s}$)

Δv_1

Model:($D^0 - \overline{D^0}$)
······ EM (Das et. al.)
— Hydro+EM (Chatterjee et.al)

−1   −0.5   0   0.5   1

Rapidity (y)

Summarising..

Introduced a set of novel observables that provides a complete 2-D decomposition of the transverse phase space distribution - demonstrated their utility in extracting the temperature dependence of the heavy quark drag coefficient

Pb+Pb 5.02 TeV, D_0: Glauber+MUSIC+Langevin, 20-30%, (p_T, ϕ)

Thank You