# Constraining initial matter distribution using pT differential directed flow.

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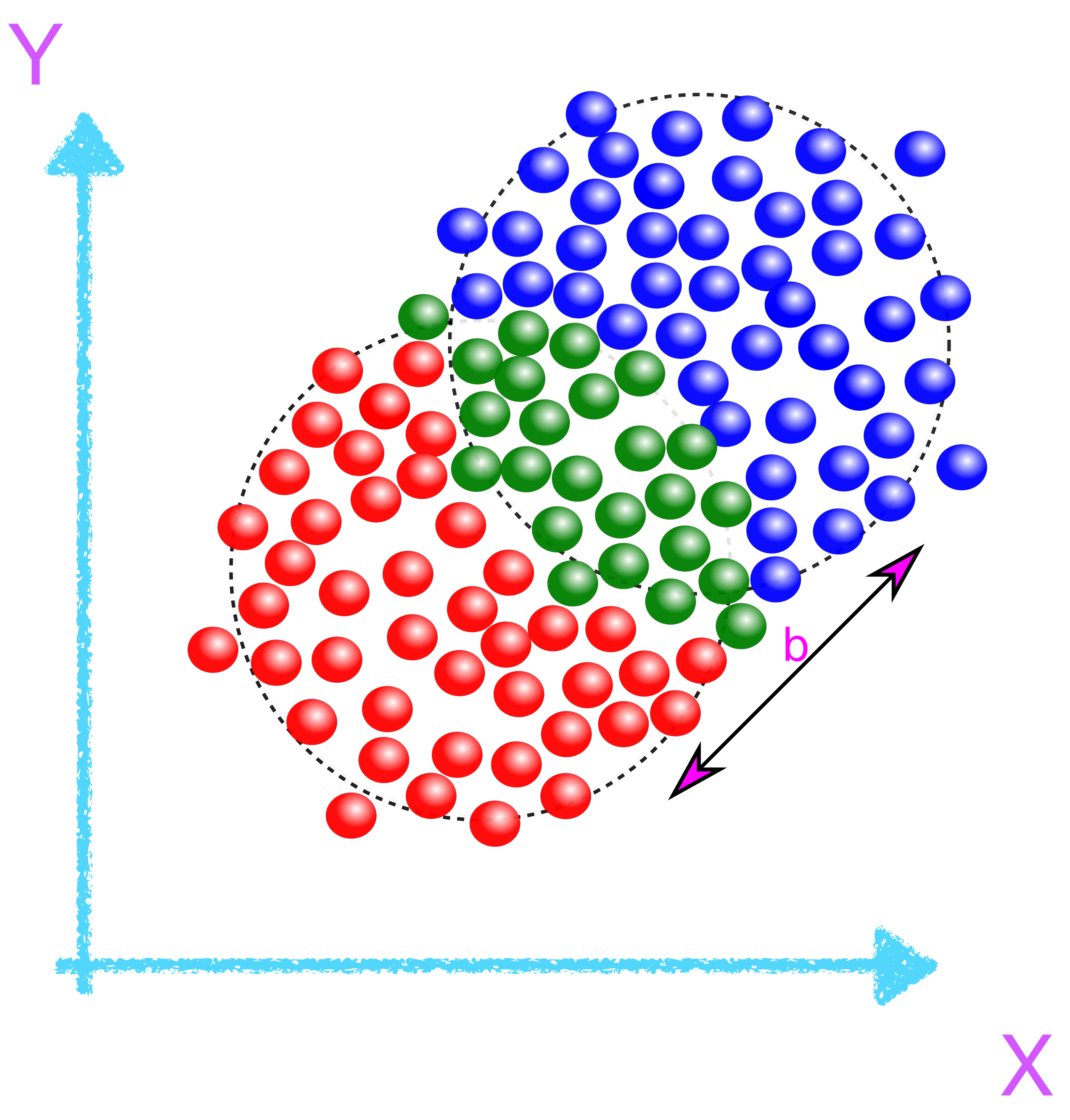
# Directed Flow

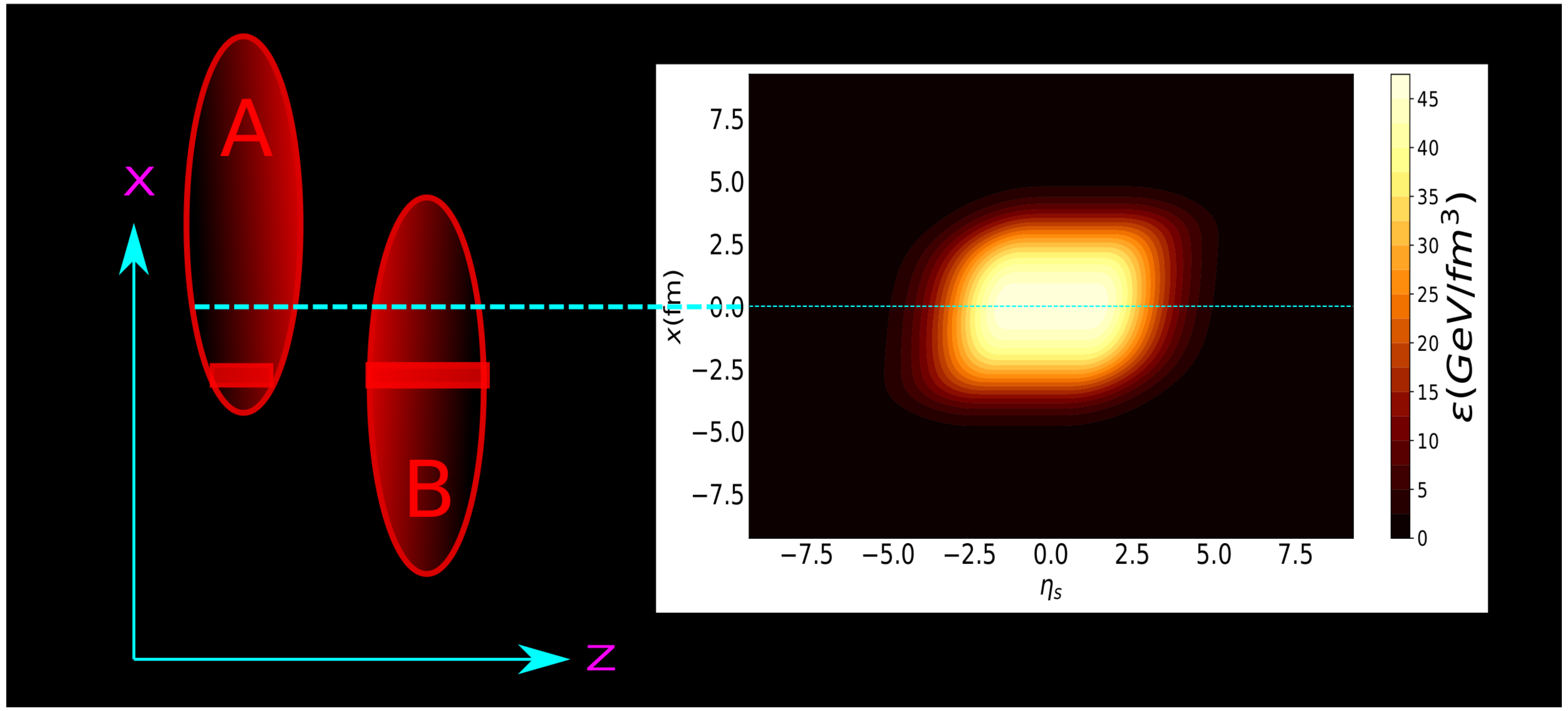
$$E\frac{dN}{d^3p} = \frac{dN}{p_T dp_T dy}\left[1 + v_1(p_T, y)\cos(\phi - \Psi_{RP}) + \ldots\right]$$

$v_1^{even}(y)$

$v_1^{odd}(y)$

Early stages of heavy ion collisions




(Shifted Fireball)

# Tilted Fireball

*P. Bozek and I. Wyskiel, Phys. Rev. C* 81, 054902 (2010)

Participant nucleon deposits more energy/entropy along it's direction of motion.

$$\epsilon(x,y,\eta_s) = \epsilon_0 \left[ \left( N_+(x,y) f_+(\eta_s) + N_-(x,y) f_-(\eta_s) \right) (1-\alpha) + N_{coll}(x,y)\epsilon_{\eta_s}(\eta_s)\alpha \right]$$

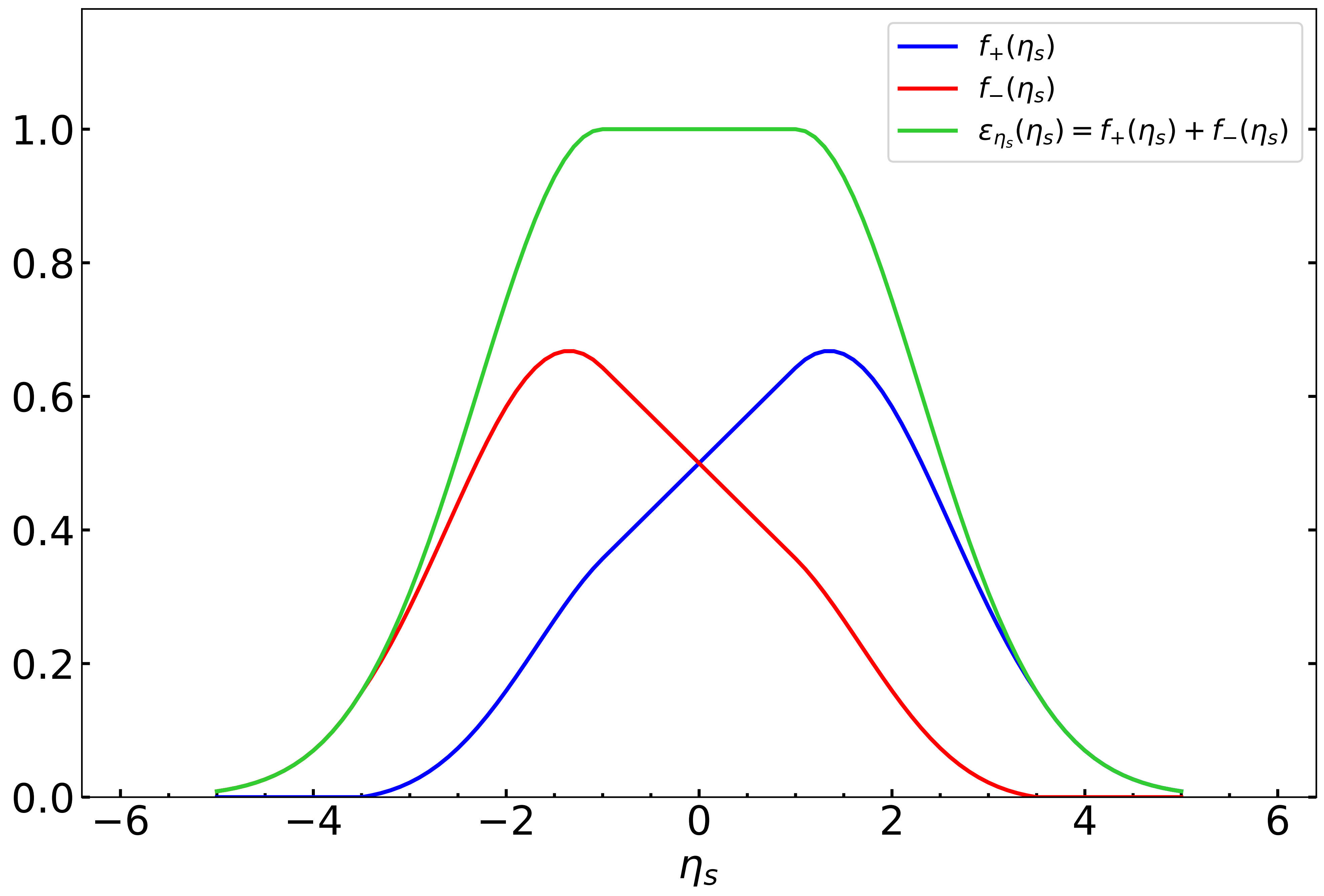
Free parameter

$$f_+(\eta_s) = \frac{\eta_s + \eta_m}{2\eta_m}\epsilon_{\eta_s}(\eta_s) \quad (-\eta_m < \eta_s < \eta_m)$$

$$f_-(\eta_s) = f_+(-\eta_s)$$

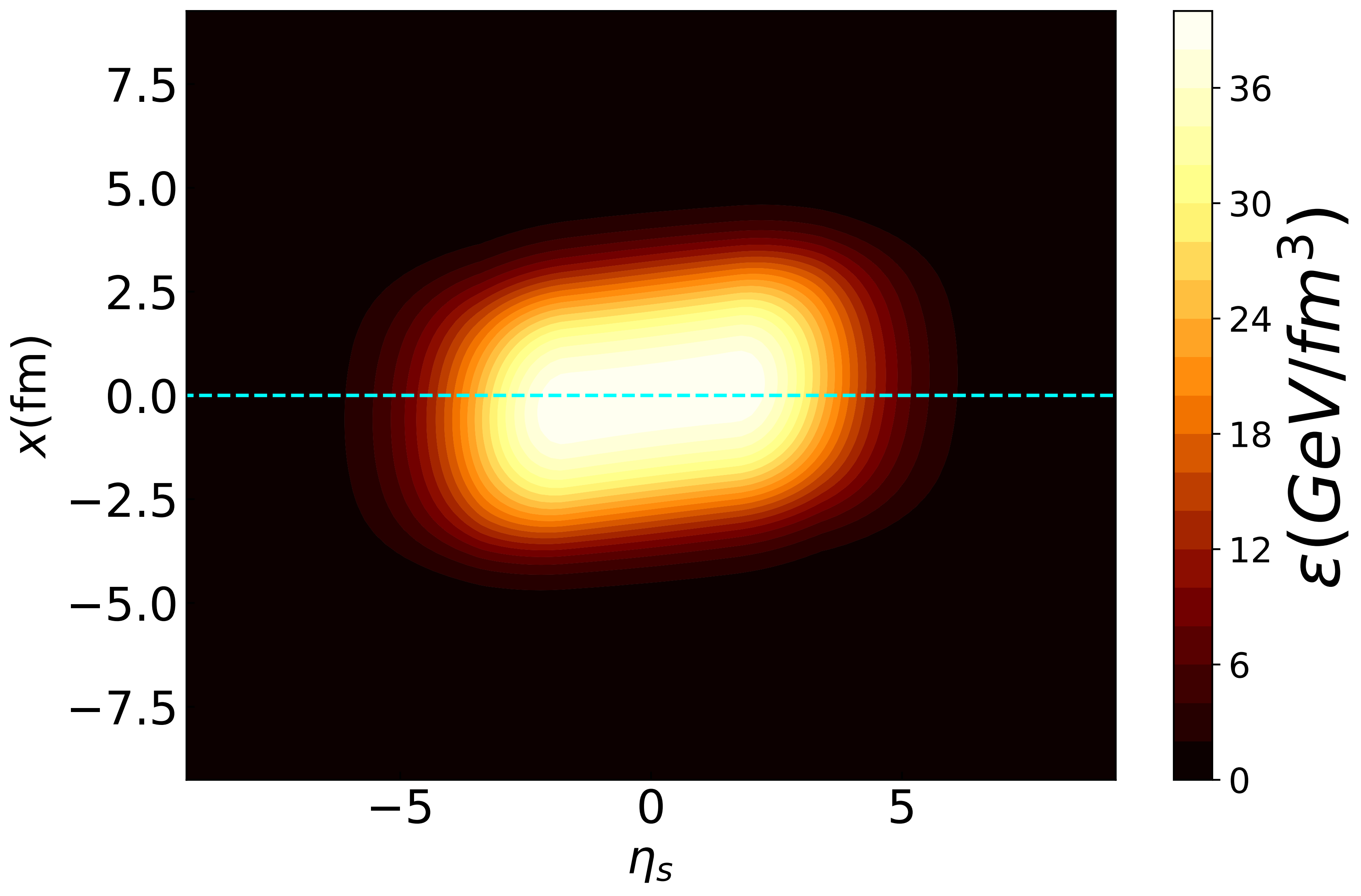
The asymmetry of deposited matter between froward and backward moving participants is linear around mid-rapidity region.

Bozek-Wyskiel(BW) model



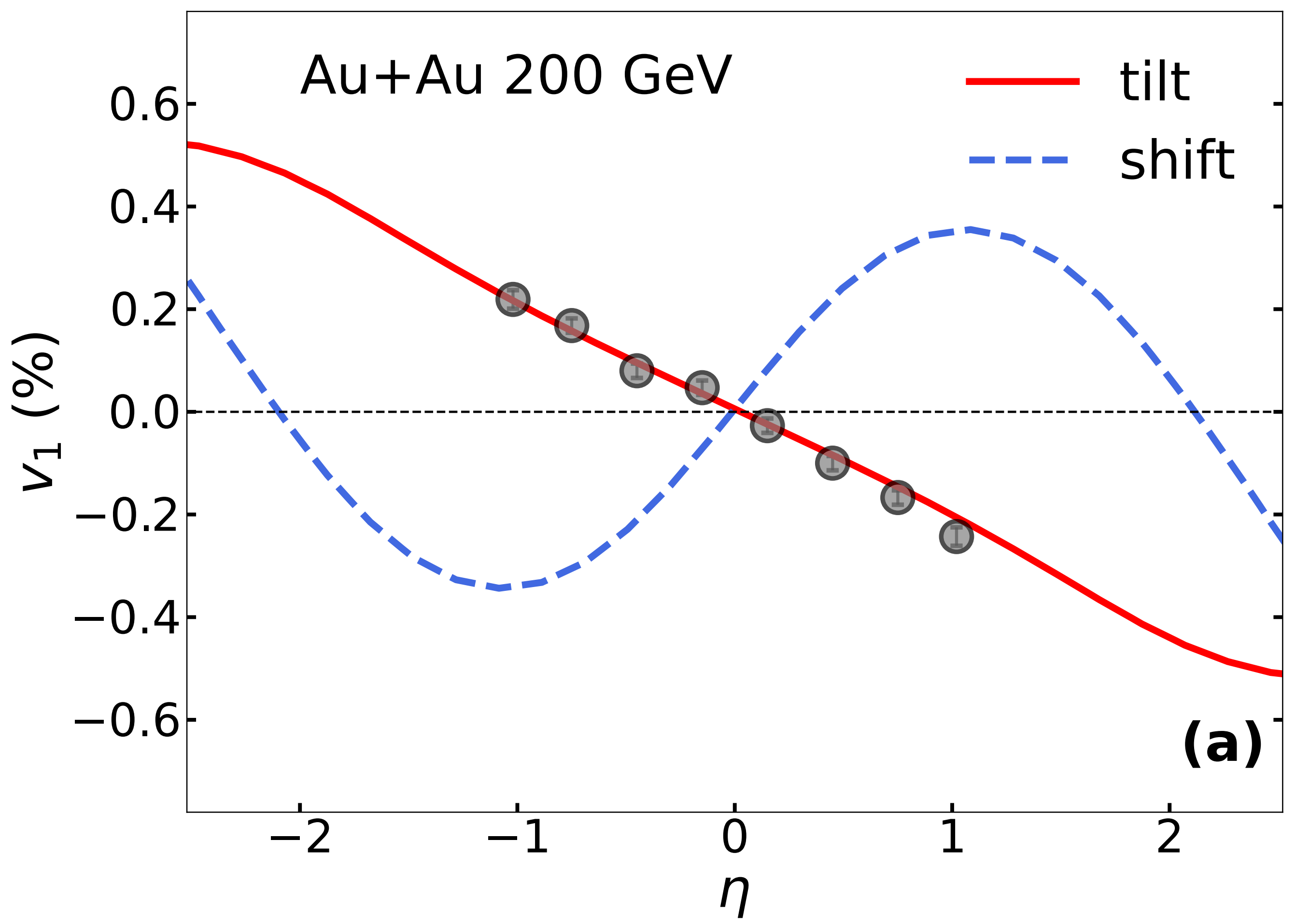
# Tilted Fireball (BW)

*P. Bozek and I. Wyskiel, Phys. Rev. C* 81, 054902 (2010)
*T. Parida and S. Chatterjee, Phys. Rev. C* 106, 044907 (2022)

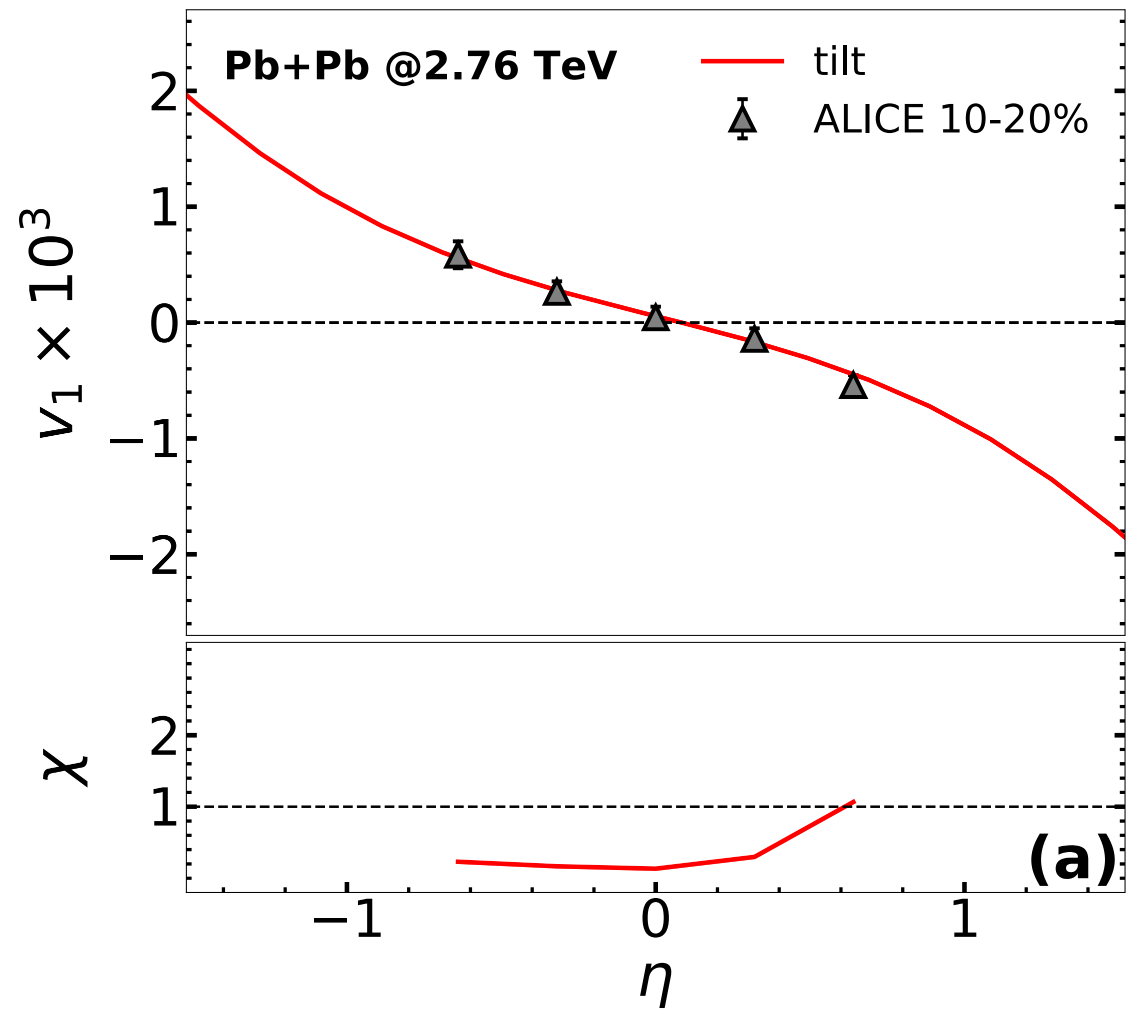



## Bozek-Wyskiel(BW) model

### Au+Au @200 GeV




### Pb+Pb @2.76 TeV



# Tilted Fireball (JYP)

*Z. F. Jiang, C. B. Yang and Q. Peng Phys. Rev. C* 104, 064903 (2021)

PHYSICAL REVIEW C **104**, 064903 (2021)

**Directed flow of charged particles within idealized viscous hydrodynamics at energies available at the BNL Relativistic Heavy Ion Collider and at the CERN Large Hadron Collider**

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Following the Bożek-Wyskiel parametrization tilted initial condition, an alternative way to construct a longitudinal tilted fireball based on the Glauber collision geometry is presented. This longitudinal tilted initial condition combined with the Ideal-CLVisc $(3+1)$D hydrodynamic model, a nonvanishing directed flow coefficient $v_1$ in a wide range is observed. After comparing the model's results with experimentally observed data of directed flow coefficient $v_1(\eta)$ from $\sqrt{s_{NN}} = 200$ GeV Cu + Cu, Au + Au collisions at RHIC energy to $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV Pb + Pb collisions at the LHC energy. One finds that directed flow measurements in heavy-ion collisions can set strong constraints on the imbalance of forward and backward incoming nuclei and on the magnitude asymmetry of pressure gradients along the $x$ direction.

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# Tilted Fireball (JYP)

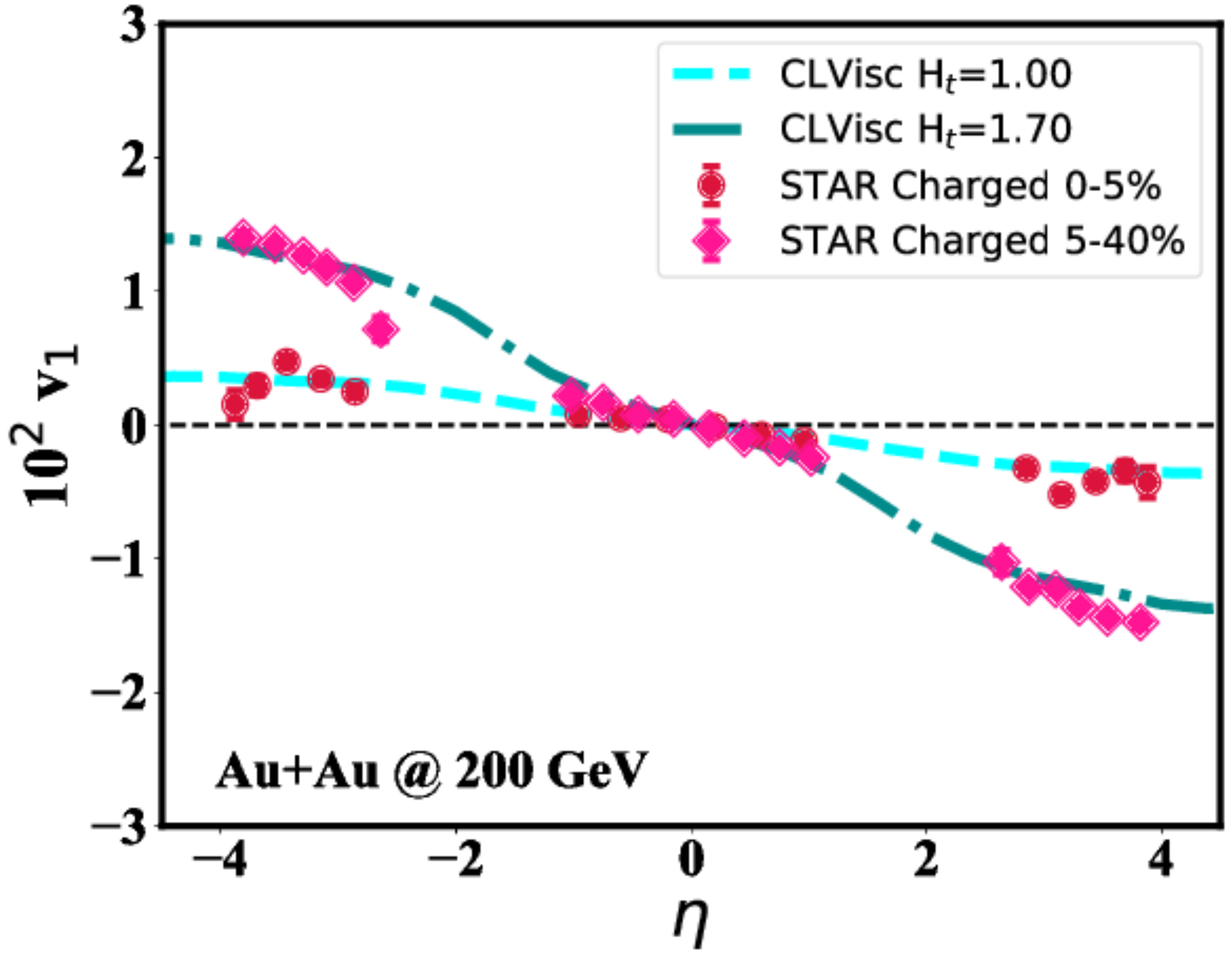
$Z.F.Jiang, C.B.Yang\ and\ Q.Peng\ Phys.Rev.C$ 104, 064903 (2021)

Jiang-Yang-Peng (JYP) model

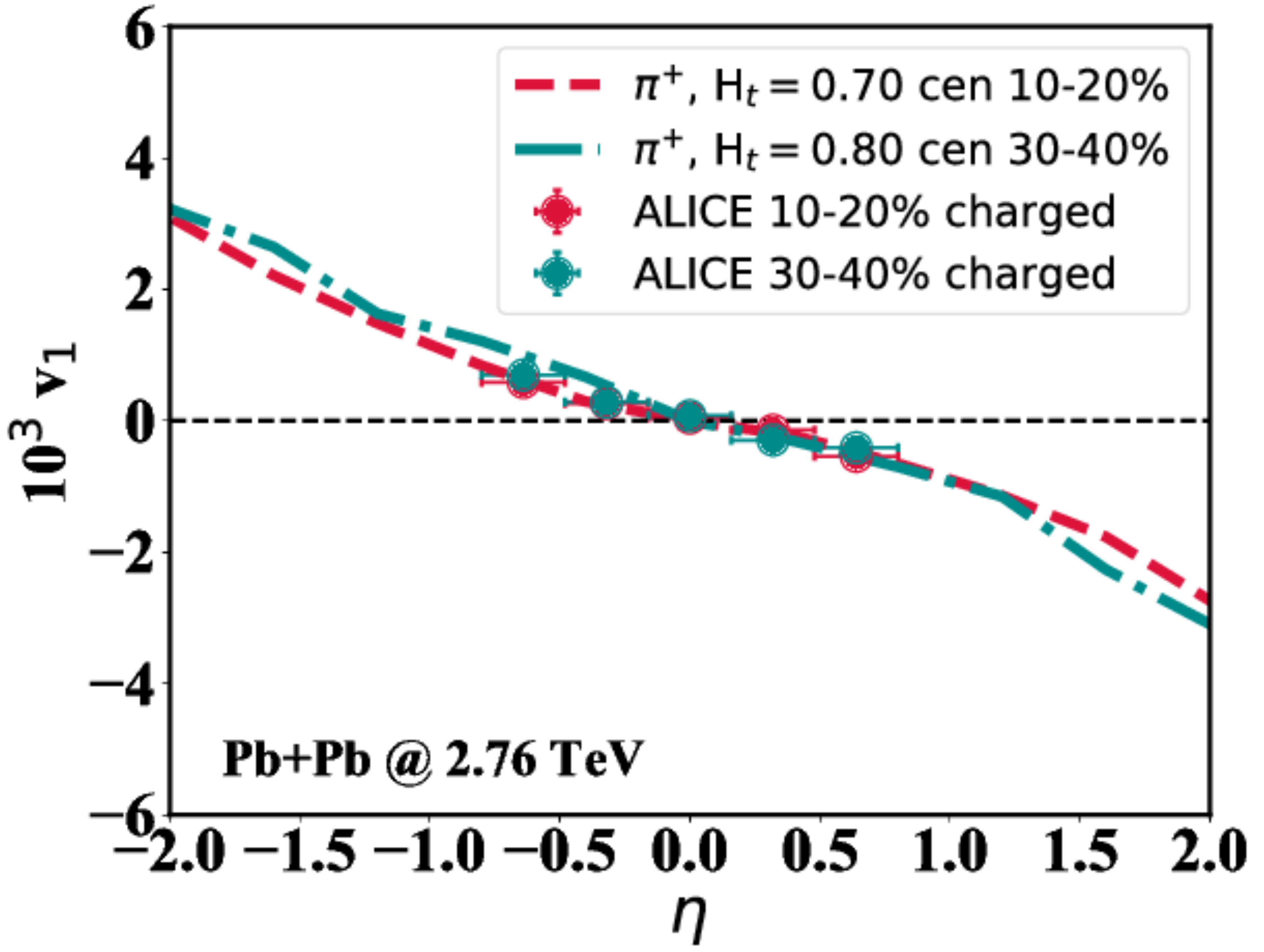
$$\epsilon(x,y,\eta_s) = \epsilon_0\left[(N_+(x,y)+N_-(x,y))(1-\alpha) + \left(N_+(x,y)-N_-(x,y)\right)H_t \tan\left(\frac{\eta_s}{\eta_t}\right)(1-\alpha) + N_{coll}(x,y)\alpha\right]\epsilon_{\eta_s}(\eta_s)$$

Free parameter

$$\eta_t = 8$$




$Z.F.Jiang\ et.al.\ Phys.Rev.C$ 105 (2022) 5, 054907
$Z.F.Jiang\ et.al.\ Phys.Rev.C$ 105 (2022) 3, 034901
$Z.F.Jiang\ et.al.\ Chin.Phys.C$ 47 (2023) 2, 024107




$Z.F.Jiang, et.al.\ arxiv:$ 2301.02960 (2023)
$Z.F.Jiang, et.al.\ arxiv:$ 2208.00155 (2023)

# Hydrodynamic Model calculation

Initial condition BW JYP

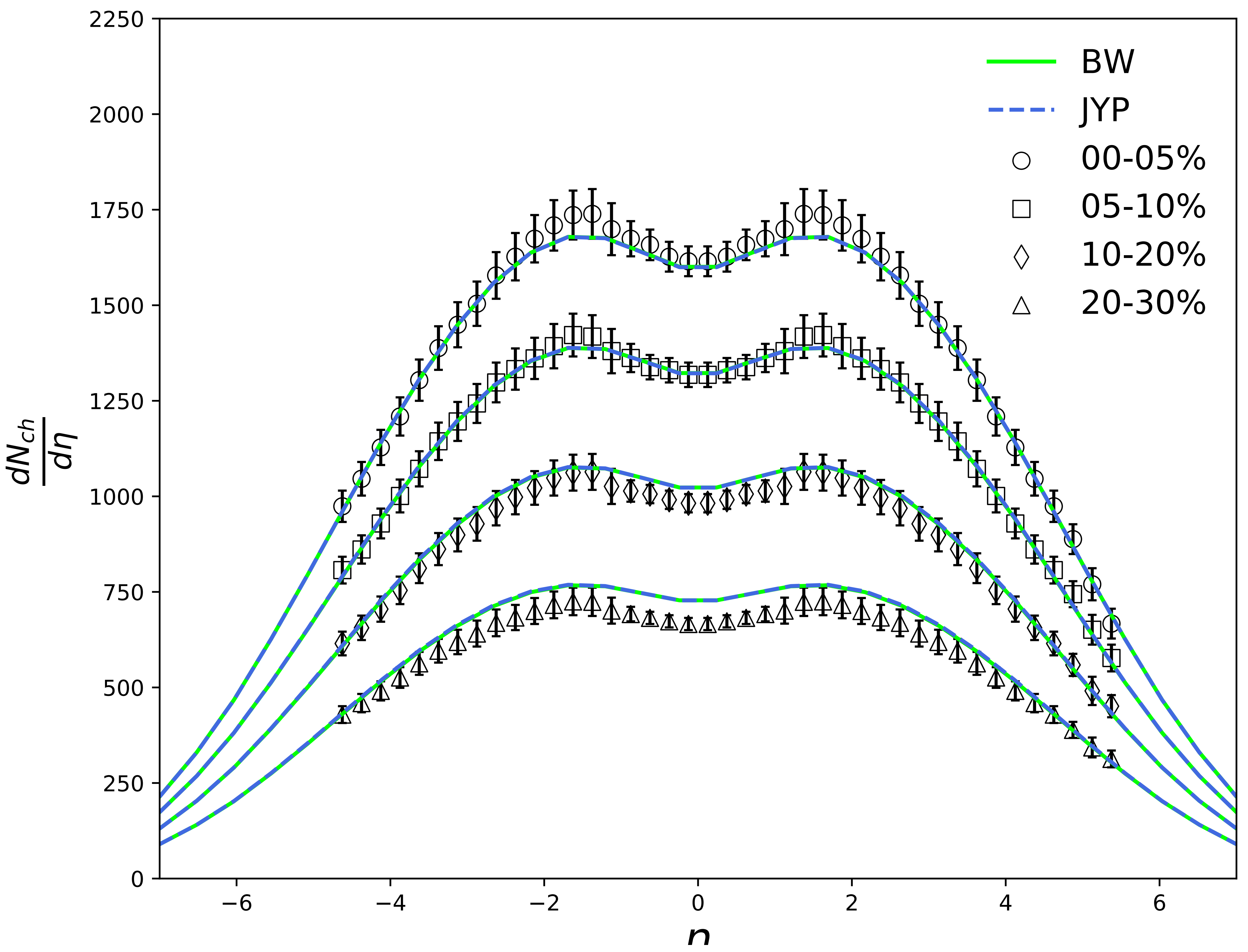
$$\tau_0 = 0.4\ fm$$

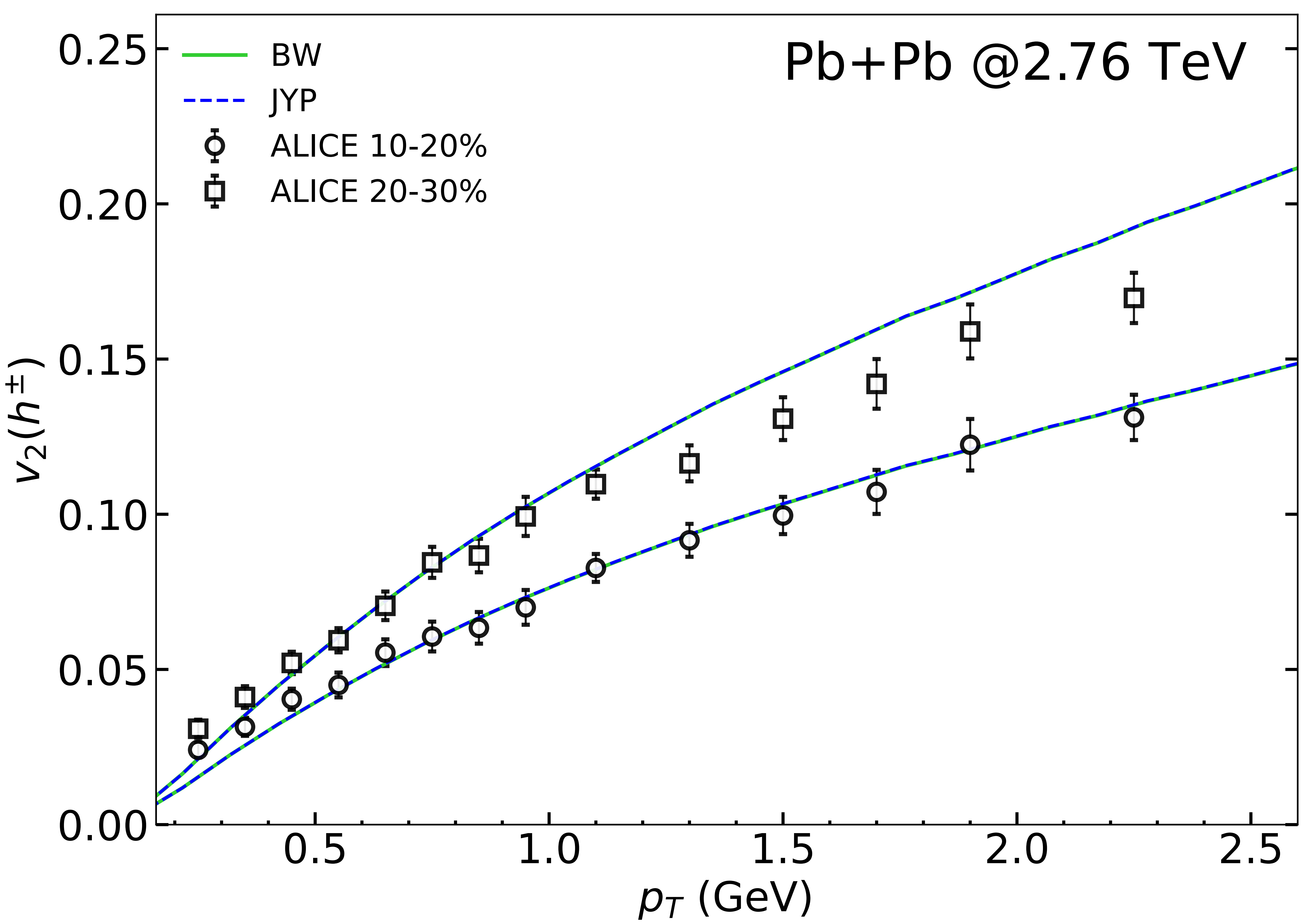
$$\eta/s = 0.08$$

$$\zeta/s = 0$$

$$T_f = 150\ MeV$$

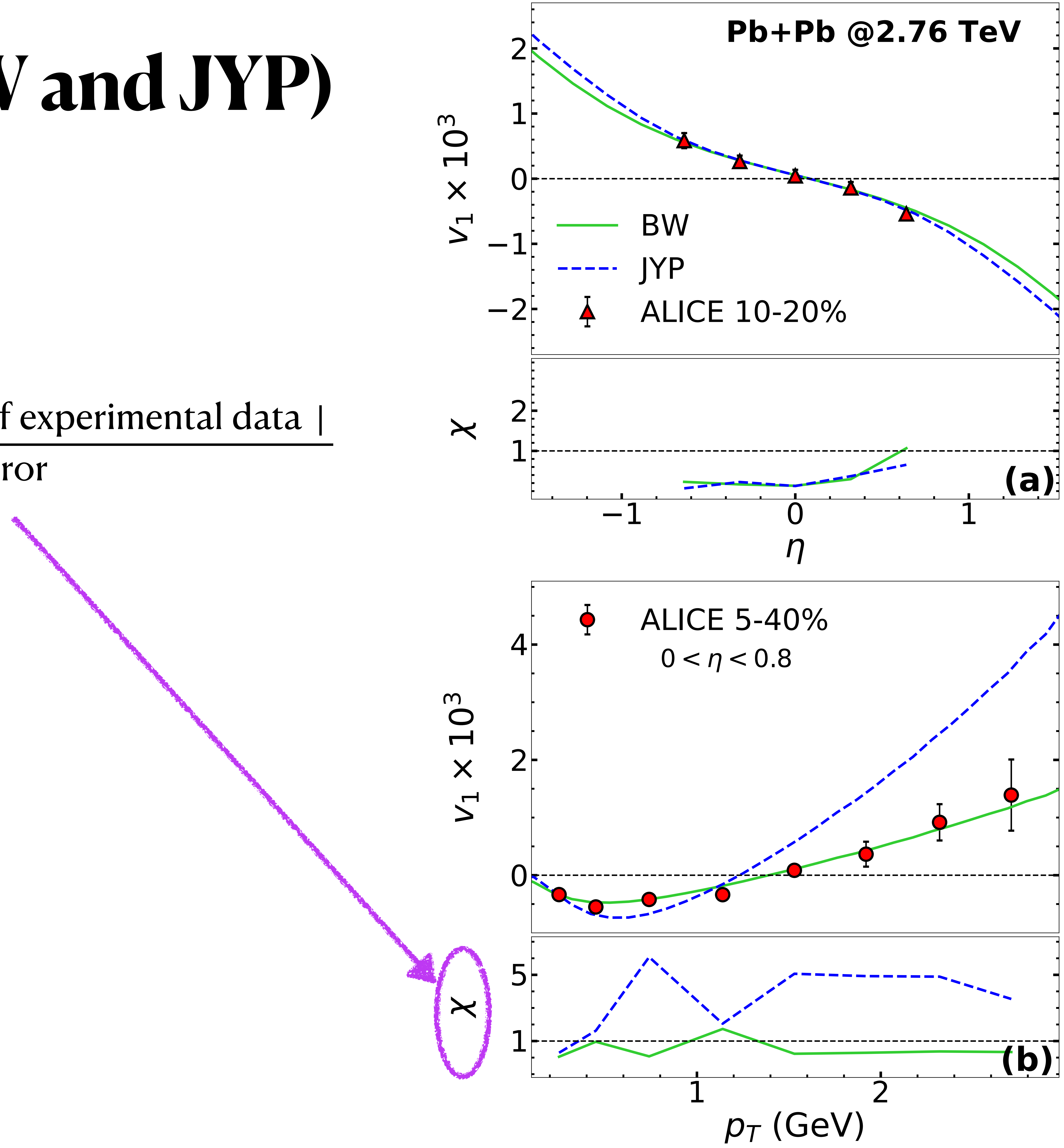
# Tilted Fireball (BW and JYP)



# Tilted Fireball (BW and JYP)

$$\chi = \frac{|\text{Model calculation - Mean value of experimental data }|}{\text{Experimental Error}}$$



# Tilted Fireball (BW and JYP)

$$\epsilon(x,y,\eta_s)^{BW} = \epsilon_0 \left[ (N_+(x,y) + N_-(x,y)) \ldots + \left(N_+(x,y) - N_-(x,y)\right) \left(\frac{\eta_s}{\eta_m}\right) \ldots + N_{coll}(x,y) \ldots \right] \epsilon_{\eta_s}(\eta_s)$$

$$\epsilon(x,y,\eta_s)^{JYP} = \epsilon_0 \left[ (N_+(x,y) + N_-(x,y)) \ldots + \left(N_+(x,y) - N_-(x,y)\right) H_t \tan\left(\frac{\eta_s}{\eta_t}\right) \ldots + N_{coll}(x,y) \ldots \right] \epsilon_{\eta_s}(\eta_s)$$

$$\frac{H_t}{\eta_t}\left(1 + \left(\frac{\eta_s}{\eta_t}\right)^2 + \ldots\right)\eta_s = \frac{H_t}{\eta_t}\eta_s \quad \text{if} \quad \eta_t >> |\eta_s|$$

For large $\eta_t$ → BW = JYP → $\frac{H_t}{\eta_t} = \frac{1}{\eta_m}$

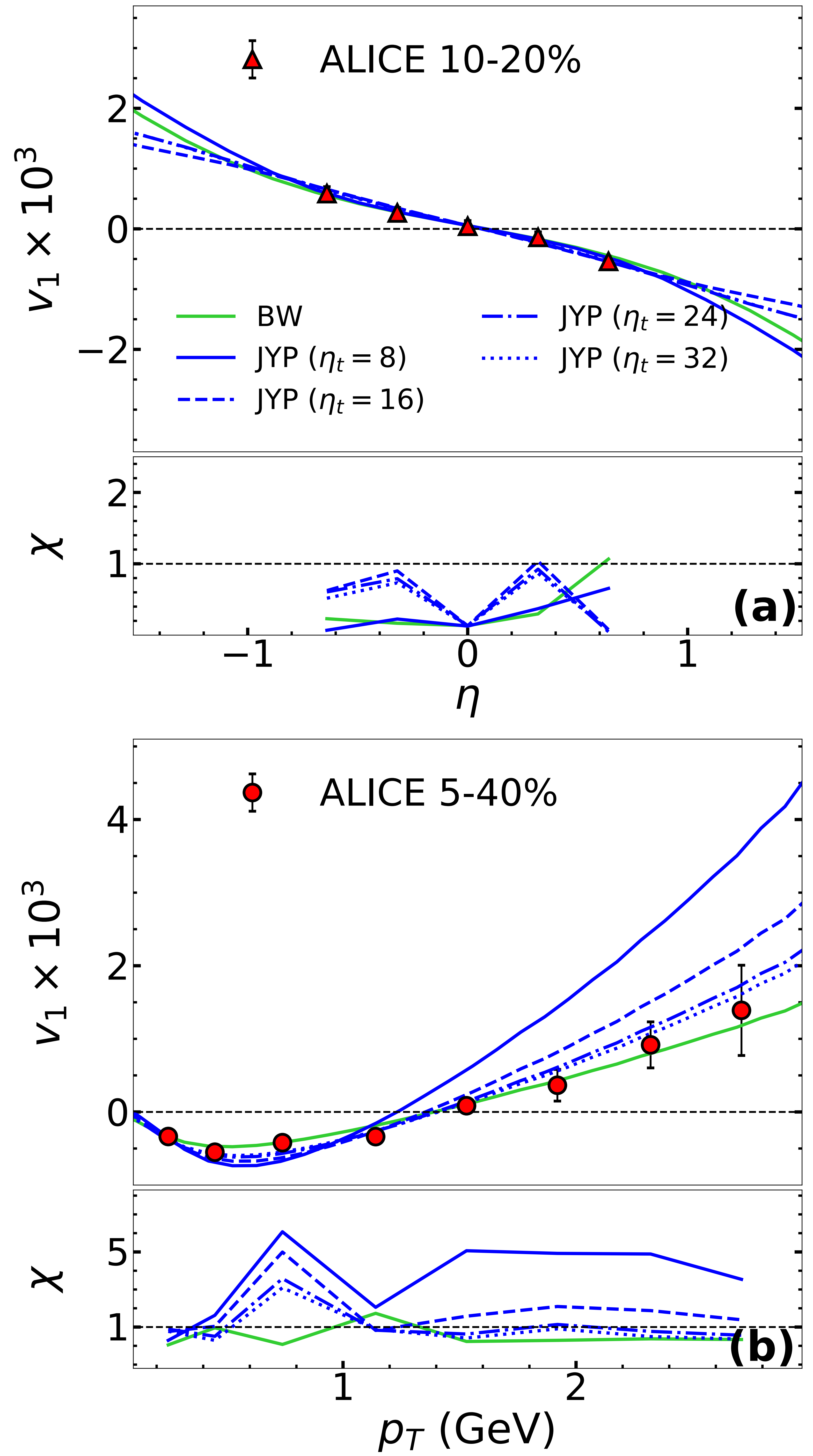
# Tilted Fireball (BW and JYP)

JYP model is a generalisation of BW model.

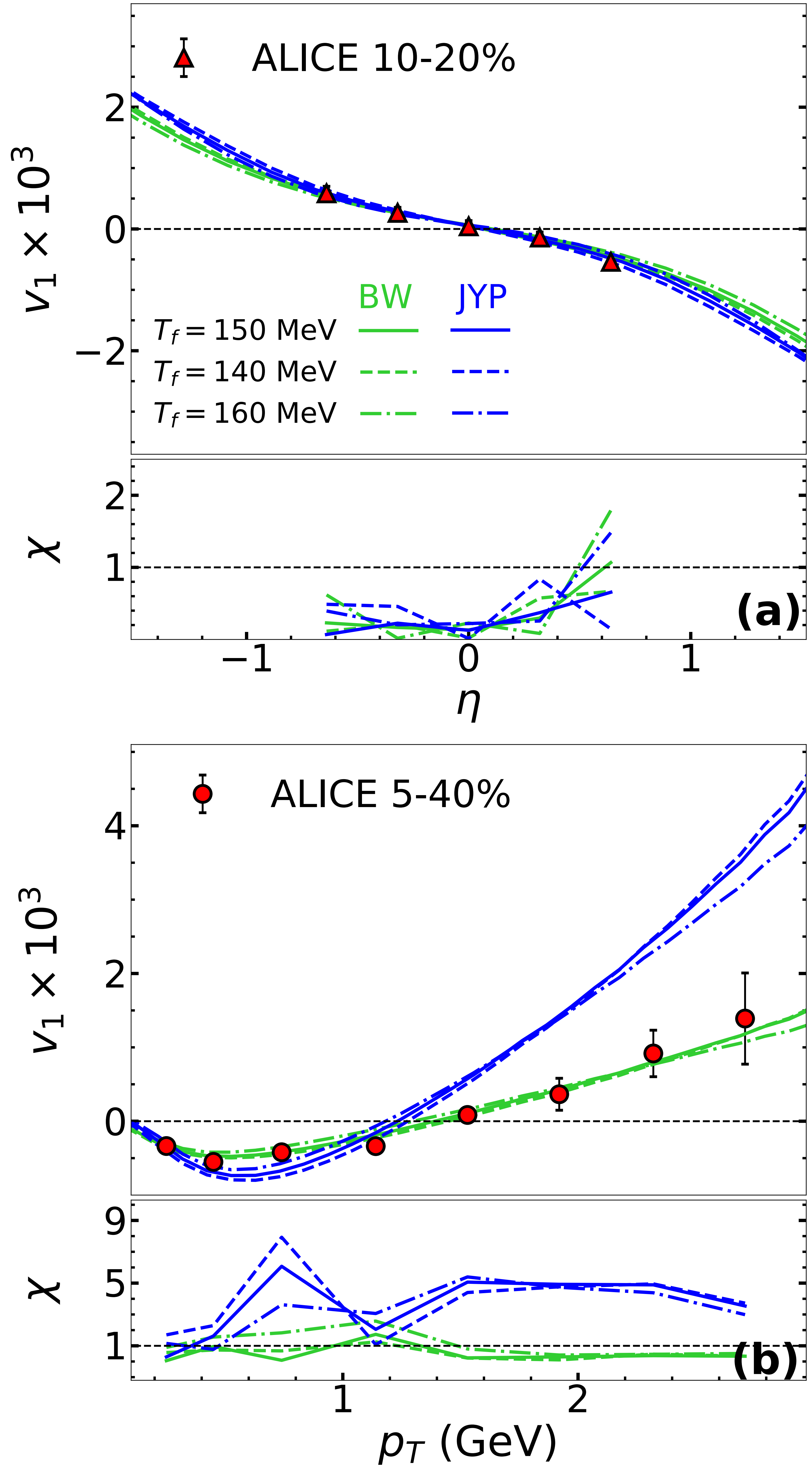
With a specific set of model parameter, and hydrodynamic evolution, we have shown that pT differential v1 is well described by an initial profile which assumes linear longitudinal gradient of matter deposition around mid rapidity by the participating nucleons.

Still it is difficult to discriminate different initial profiles as there is uncertainty in the evolution stage ( presence of free parameters in hydrodynamic calculations) .

Hence, it is important to study the effect of hydrodynamic model parameters on v1(pT).

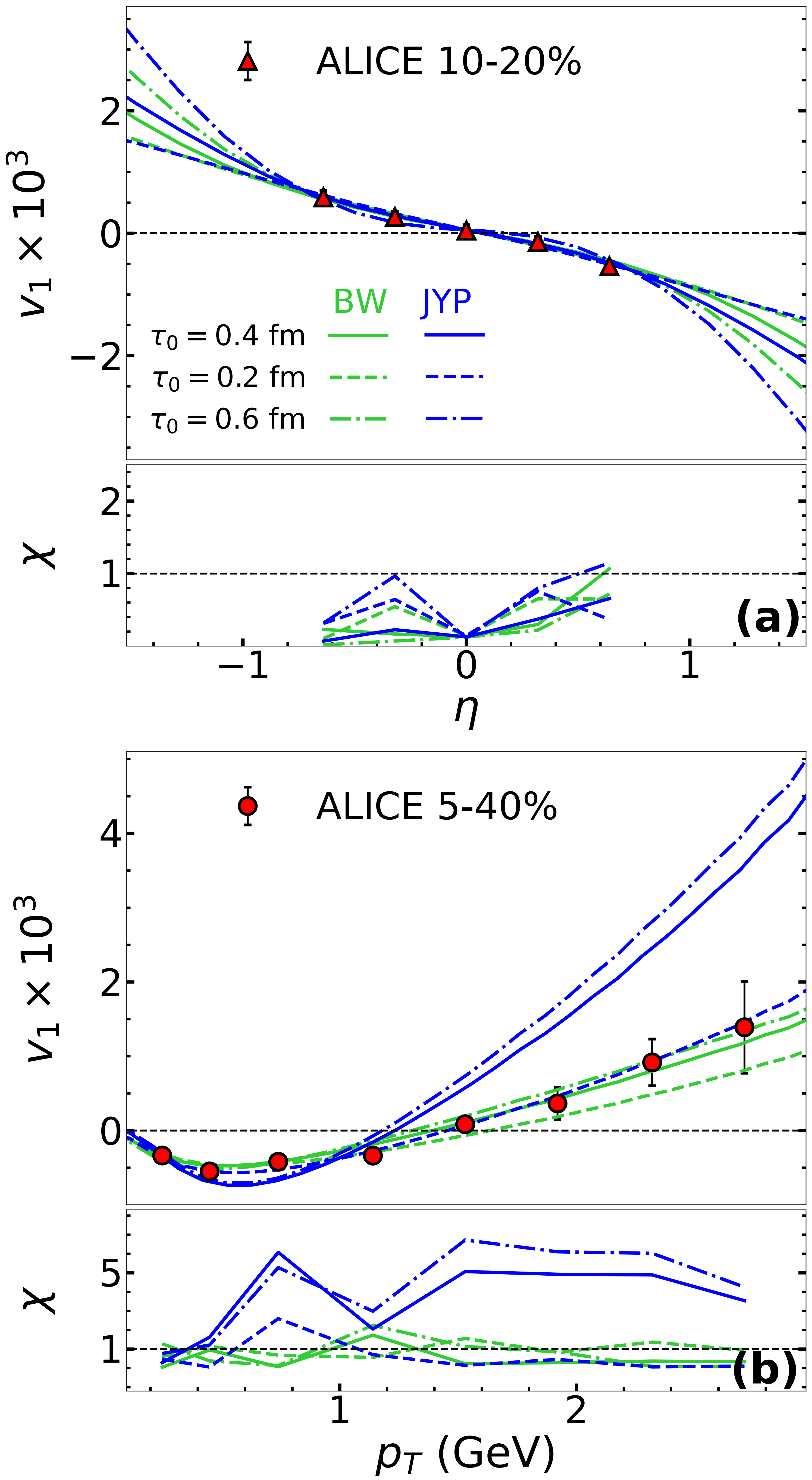


# Effect of $T_f$




V1(pT) is insensitive to freeze out temperature.

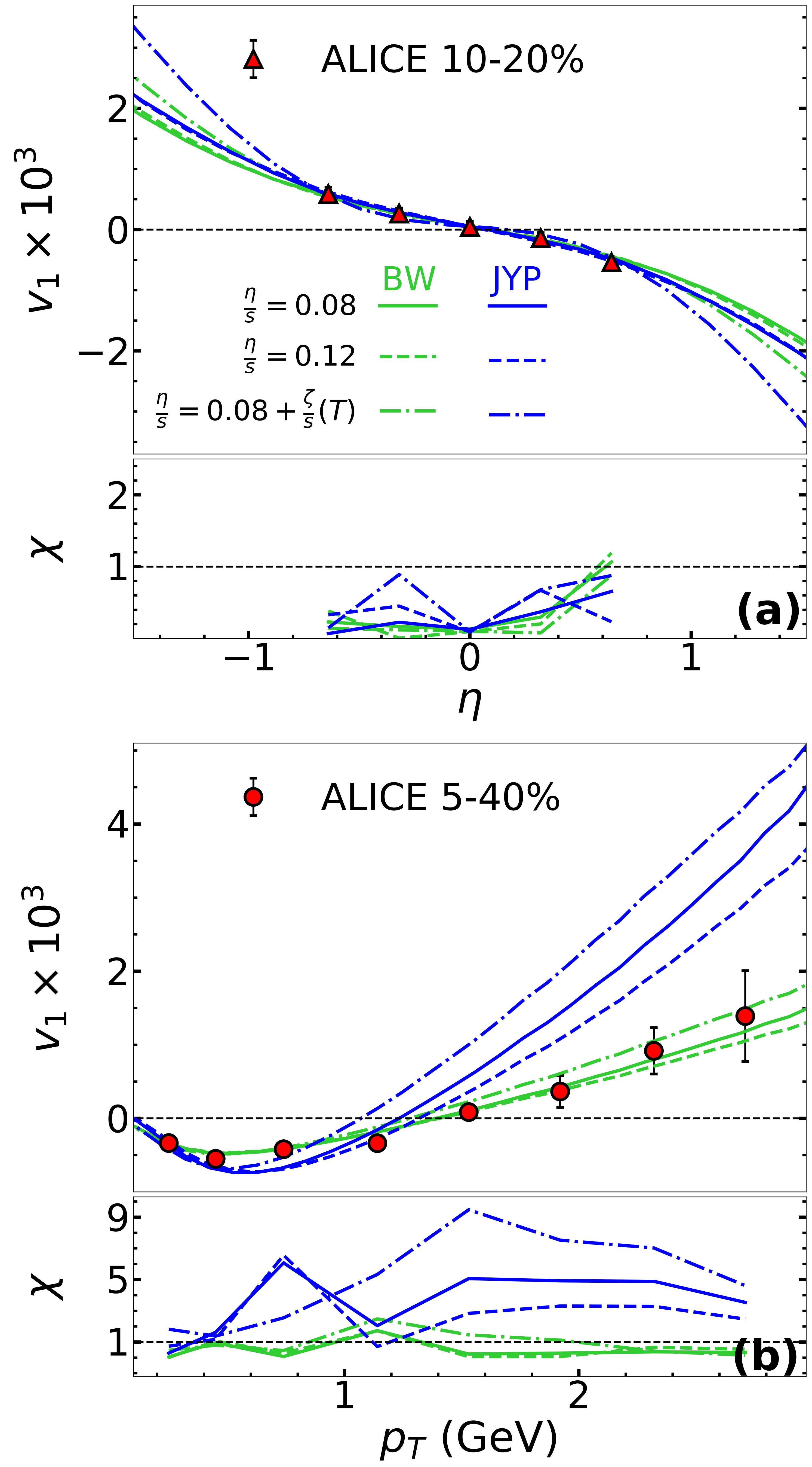
# Effect of $\tau_0$




JYP prefers very early initialisation of hydrodynamics.

Taking such small $\tau_0$ could substantially increase the <pT>.

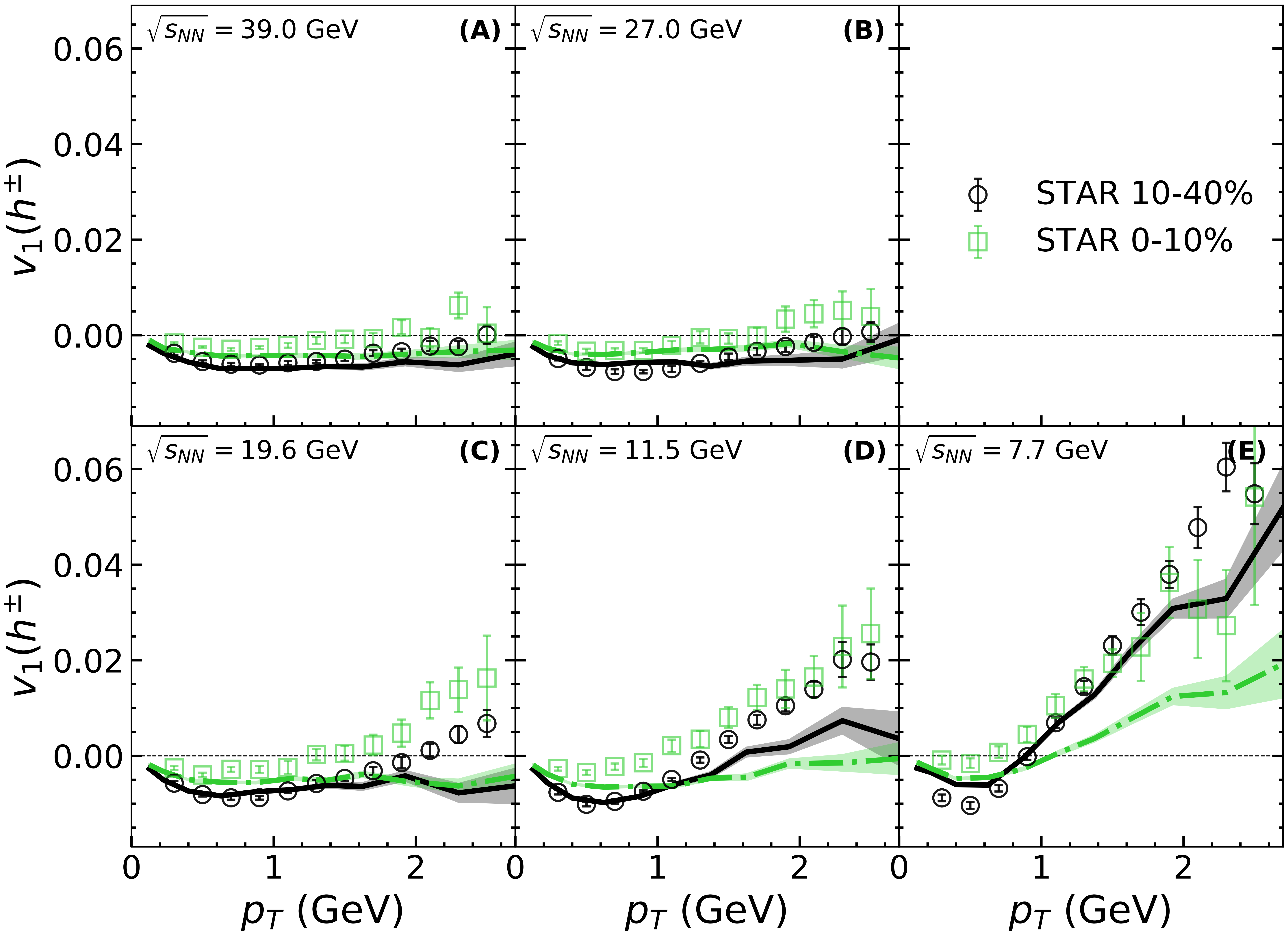
# Effect of transport coefficients




We expect a better description of v1(pT) data at large shear viscosity but on the other hand, model calculation of v2(pT) will deviate more from the experimental measurements.

Need of Bayesian analysis to discriminate models of initial matter deposition.

# V1(pT) at RHIC :

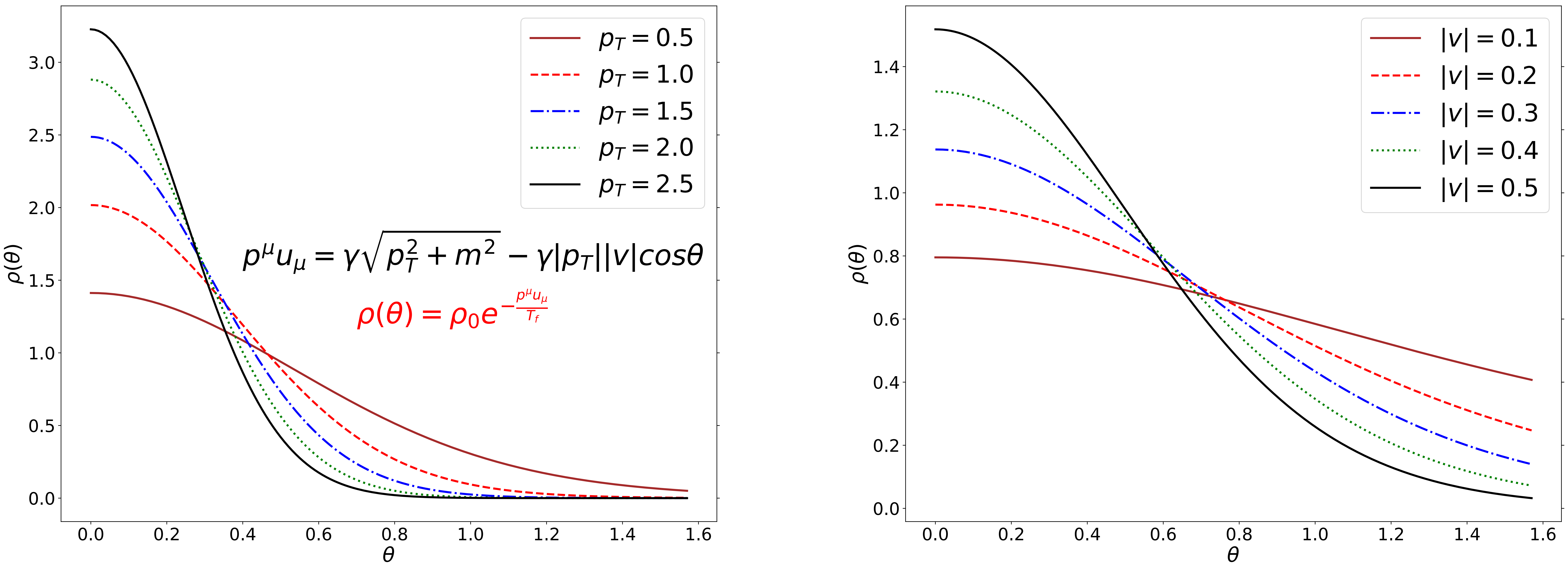

$\sqrt{s_{NN}}$ = 39.0 GeV
(A)
$\sqrt{s_{NN}}$ = 27.0 GeV
(B)
STAR 10-40%
STAR 0-10%
$\sqrt{s_{NN}}$ = 19.6 GeV
(C)
$\sqrt{s_{NN}}$ = 11.5 GeV
(D)
$\sqrt{s_{NN}}$ = 7.7 GeV
(E)
$v_1(h^{\pm})$
0.06
0.04
0.02
0.00
0
1
2
$p_T$ (GeV)

# Summary

1. V1(pT) is very sensitive to initial longitudinal gradient of matter deposition. Model to data comparison of pT differential v1 along with rapidity differential v1 puts additional constraint on the initial condition.

2. As v1(pT) is affected by the transport coefficients of hydro evolution, it can be useful to constrain the initial condition models and transport coefficients simultaneously by Bayesian analysis.

# Backup


$p_T = 0.5$
$p_T = 1.0$
$p_T = 1.5$
$p_T = 2.0$
$p_T = 2.5$
$p^\mu u_\mu = \gamma\sqrt{p_T^2 + m^2} - \gamma|p_T||v|cos\theta$
$\rho(\theta) = \rho_0 e^{-\frac{p^\mu u_\mu}{T_f}}$
$\rho(\theta)$
$\theta$
$|v| = 0.1$
$|v| = 0.2$
$|v| = 0.3$
$|v| = 0.4$
$|v| = 0.5$
$\rho(\theta)$
$\theta$