# Interplay between bulk medium evolution and covariant (D)GLV energy loss


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U.S. DEPARTMENT OF ENERGY
Office of Science

JET Collaboration

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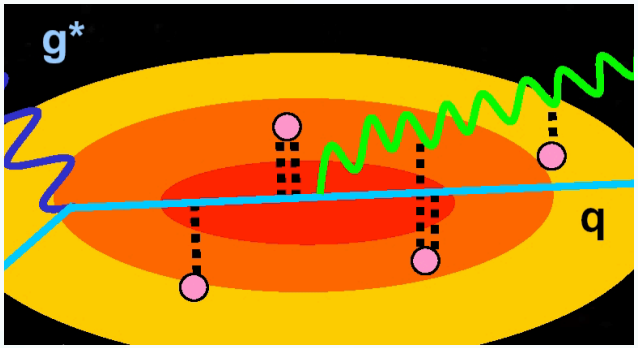
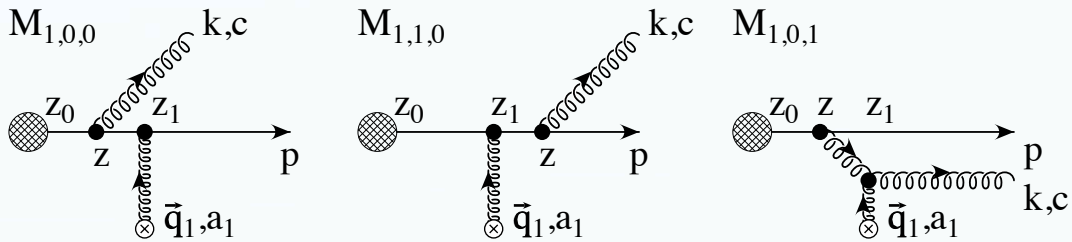
# Outline

- Motivation
- Covariant formulation
  - Light quark
  - Heavy quark
  - The effect of running coupling
- Summary

# DGLV – Opacity Expansion




Gyulassy, Levai, Vitev NPB594('00)
Djordjevic PRC 74('6)
Buzzatti & Gyulassy, PRL108('12)




$$x_E \frac{dN_g^{n=1}(L)}{dx_E d\mathbf{k}} = \frac{C_R \alpha_s}{\pi^2} \chi \int \frac{d\mathbf{q}}{\pi} \frac{\mu^2}{q^2\left(q^2+\mu^2\right)} \frac{2Q}{Q^2+X}\left(\frac{Q}{Q^2+X} - \frac{k}{k^2+X}\right)\left(1-\cos\omega L\right)\frac{x_E}{x_+} J\left(x_+\left(x_E\right)\right)$$

Where, $\omega = \dfrac{Q^2+X}{2x_+E}$ $\quad \mathbf{Q} = \mathbf{k} - \mathbf{q}$ $\quad X = M^2 x_+^2 + m_g^2(z)(1-x_+)$

We therefore use $\left\langle \Delta E^{(1)} \right\rangle = \int dL \rho\left(\tau, \mathbf{x}_{T,0} + \mathbf{L}\right) \sigma_{gg\to gg} \chi^{-1} dx dk E x_E \dfrac{dN_g^{n=1}}{dx_E dk}$

With finite energy & kinematics: $|k| \le xE \quad |q| \le \sqrt{6ET} \quad xE \ge \mu$

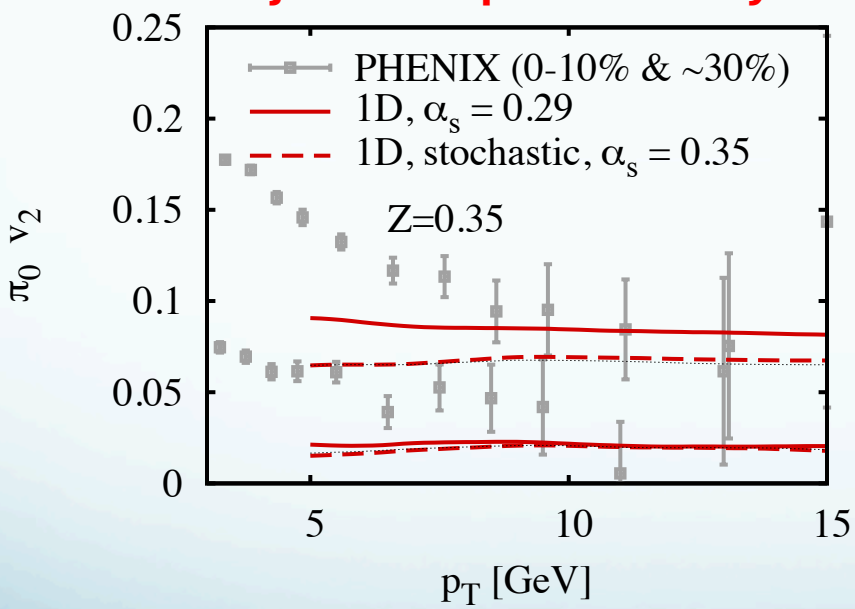
# Motivation

**Transverse expansion results in much smaller $v_2$ in GLV**

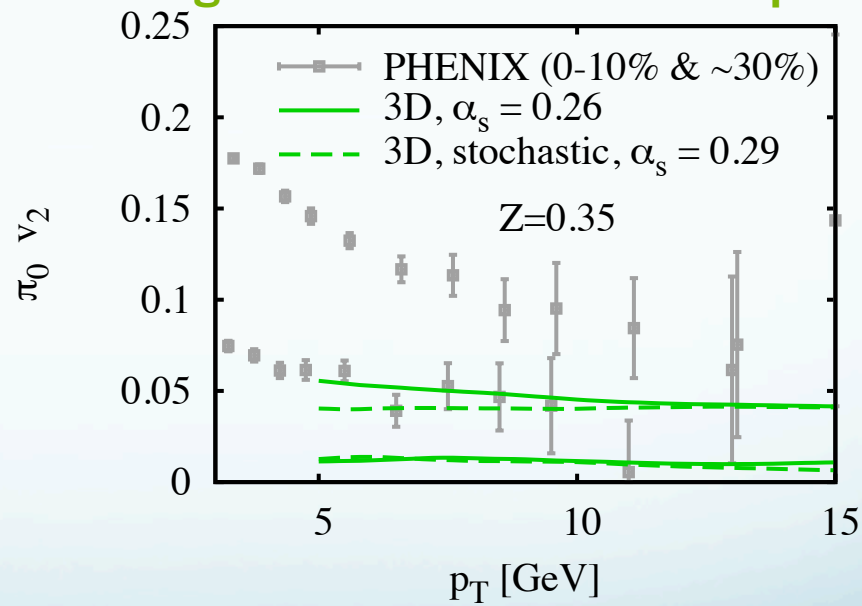
D. Molnar, D. Sun, arXiv:1305.1046

Au+Au at RHIC

**Bjorken expansion only**




**Longitudinal + transverse expansion**



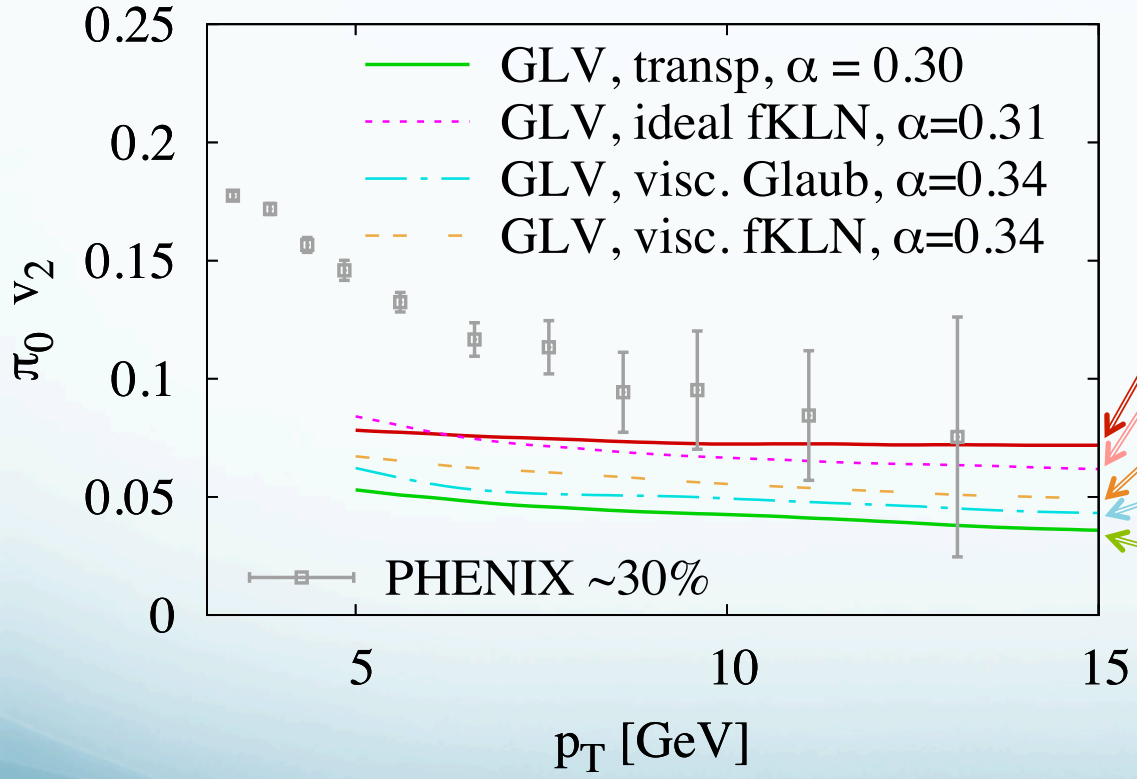

Due to the fact that GLV biases for late scattering

# Motivation

**Hydro medium gives larger $v_2$ than transport medium**

D. Molnar, D. Sun, arXiv:1405.4848

Au+Au, RHIC, b~8fm




1D

ideal fKLN $\eta = 0$

Song, Heinz, Moreland et al
arXiv:0709.0742, 0712.3715, 0805.1756;

visc. fKLN, $\frac{\eta}{s} \sim 0.08$

Shen et al, arXiv:1010.1856;
Renk et al, arXiv:1010.1635

visc. Glaub, $\frac{\eta}{s} \sim 0.08$

3D parton transport

D. Molnar ('12)

# Covariant formulation – light parton

**But energy loss in GLV is not covariant**

$$\Delta E = \frac{C_R \alpha_s}{\pi^2} \int dL \rho \sigma_{gg \to gg} \times E \times I\left(\frac{\mu^2 L}{E}, \frac{E}{\mu}, \frac{M}{\mu}\right)$$

**Suppose holds in fluid rest frame, then**

$$E_{LR} = E\gamma_F \left(1 - \mathbf{v} \bullet \mathbf{v_F}\right)$$

$$L_{LR} = L\gamma_F \left(1 - \mathbf{v} \bullet \mathbf{v_F}\right)$$

Massless particle

$$\Delta E_{LR} = \Delta E\gamma_F \left(1 - \mathbf{v} \bullet \mathbf{v_F}\right)$$

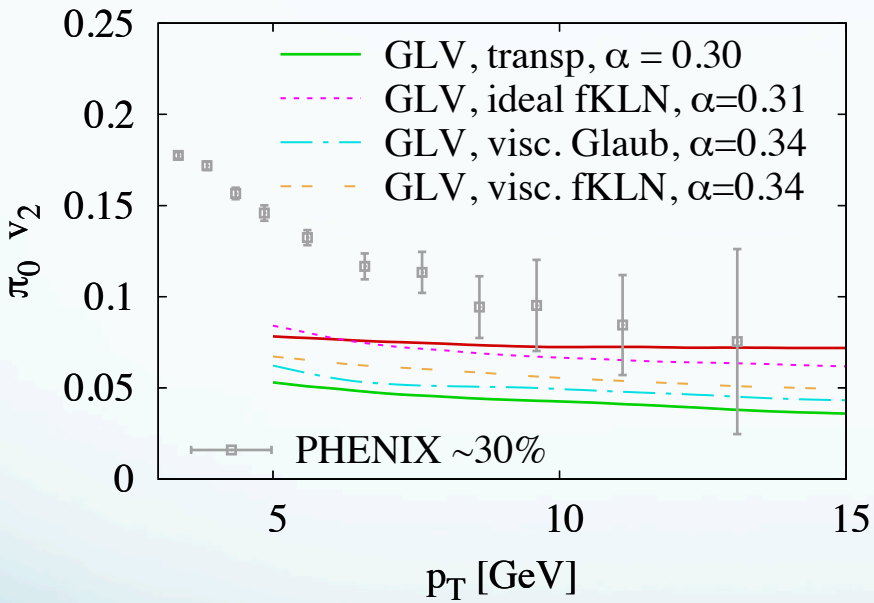
$$\Delta L_{LR} = \Delta L\gamma_F \left(1 - \mathbf{v} \bullet \mathbf{v_F}\right)$$

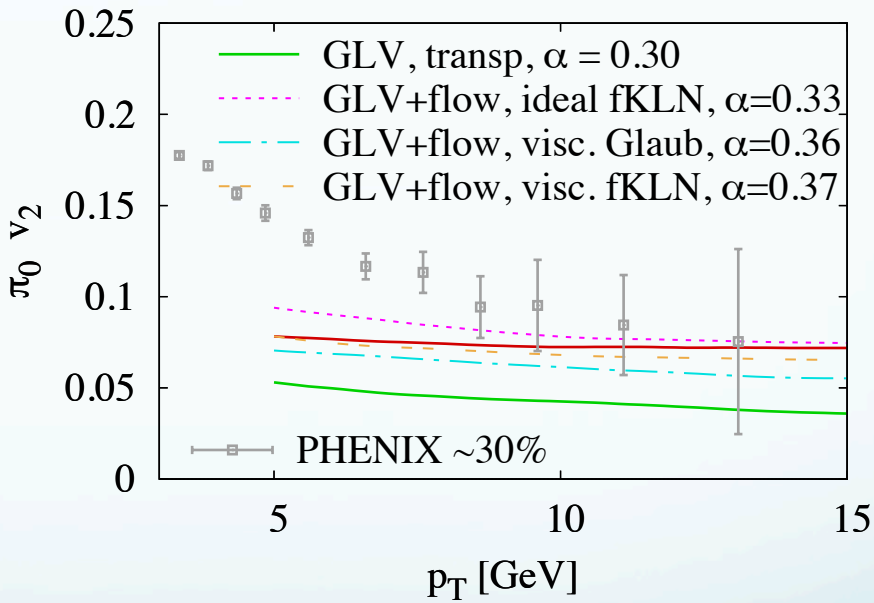
$$dL_{LR}\rho_{LR}\sigma = dL\rho_{LR}\sigma\gamma_F \left(1 - \mathbf{v} \bullet \mathbf{v_F}\right) = dL\rho\sigma\left(1 - \mathbf{v} \bullet \mathbf{v_F}\right)$$

# Results - Pion

**Covariance results in additional $v_2$ increase (~30%)**

**Original GLV** Au+Au, RHIC, b~8fm *Covariant GLV*




Covariance leads to an interplay between jet propagation direction and medium flow, causing an enhanced in-plane versus out-of-plane energy loss difference

# Covariant formulation – heavy quark

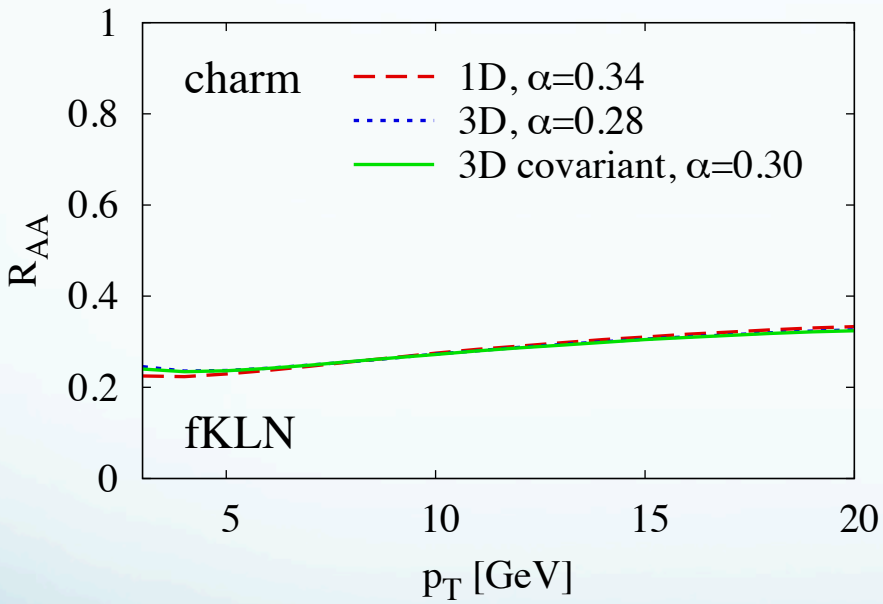
$$\Delta E^{(1)} = \int dx\, dk E x_E \frac{dN_g^{n=1}}{dx_E dk}$$

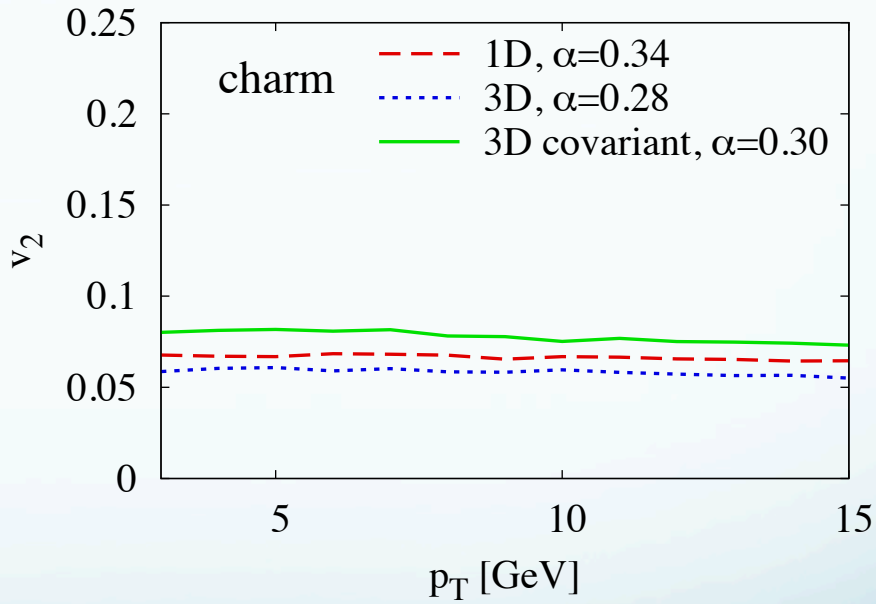
$$\Rightarrow \quad \left\langle \Delta E^{(1)} \right\rangle = \int dL \rho\left(\tau, \mathbf{x}_{T,0} + \mathbf{L}\right) \sigma_{gg\to gg} \chi^{-1} dx dk E x_E \frac{dN_g^{n=1}}{dx_E dk}$$

(x, p) 4 momentum LAB $\xrightarrow{\text{boost}}$ (x, p) LOCAL REST $\xrightarrow{\text{DGLV}}$ (x, pf) LOCAL REST $\xrightarrow{\text{boost}}$ (x, pf) LAB $\longrightarrow$ $\Delta E^{(1)}$ LAB $\longrightarrow$ $\left\langle \Delta E^{(1)} \right\rangle$ LAB

# Charm

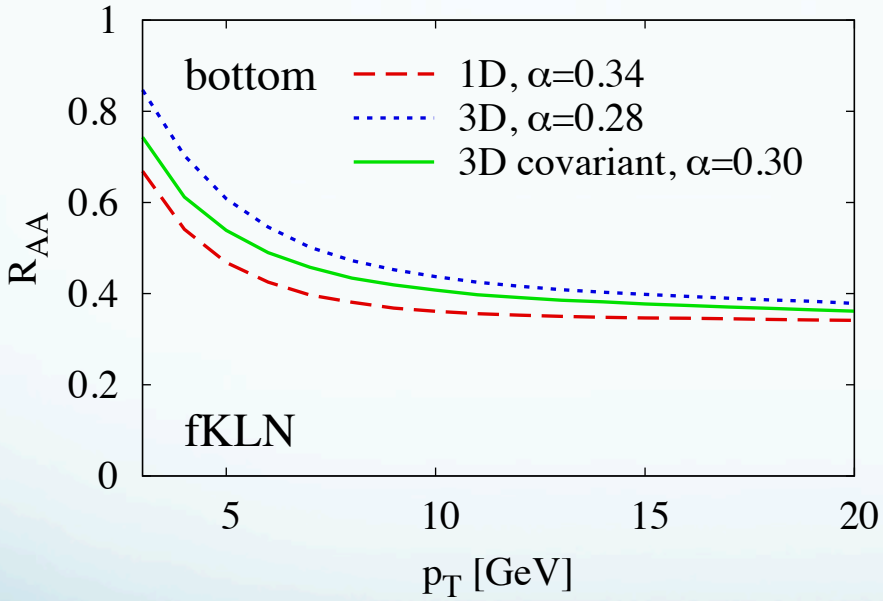
Au+Au, RHIC, b~8fm

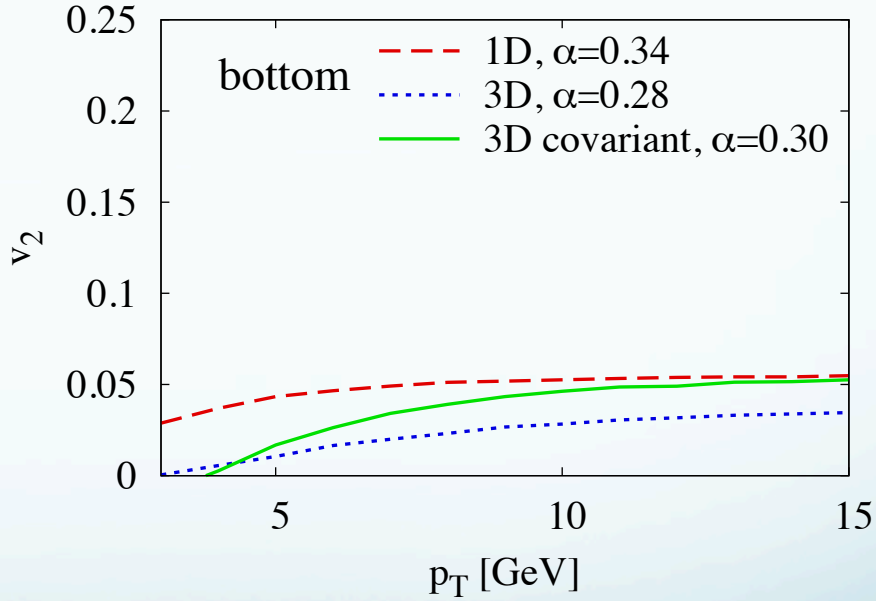


# Bottom

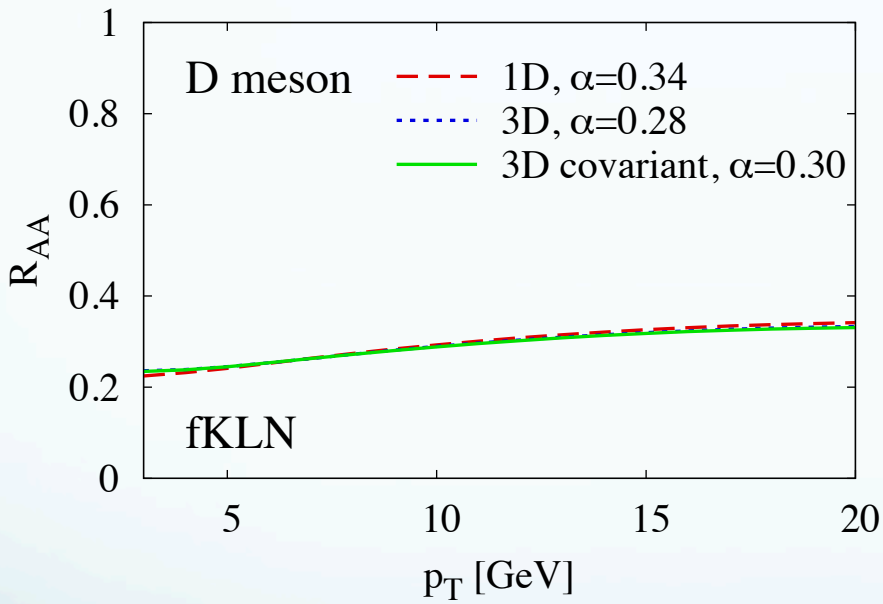
Au+Au, RHIC, b~8fm

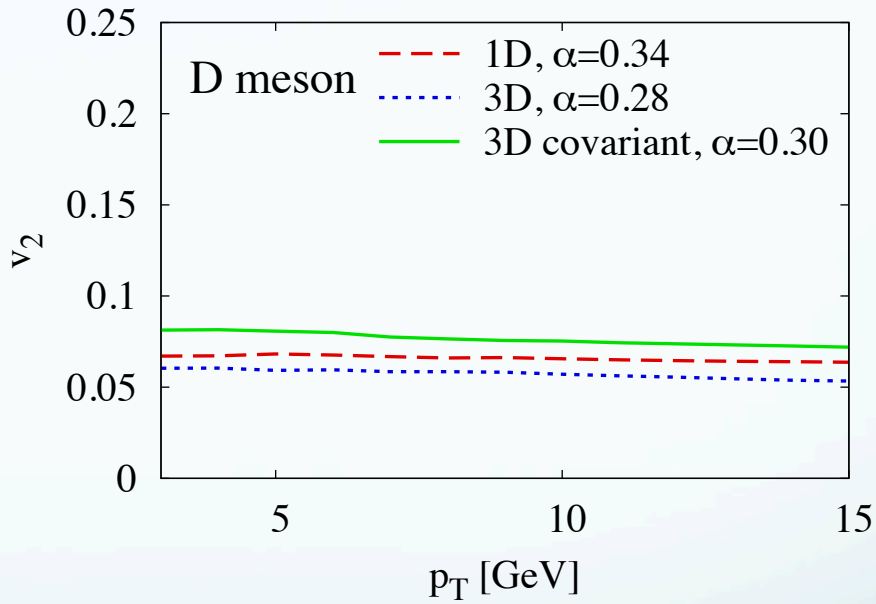


# D meson

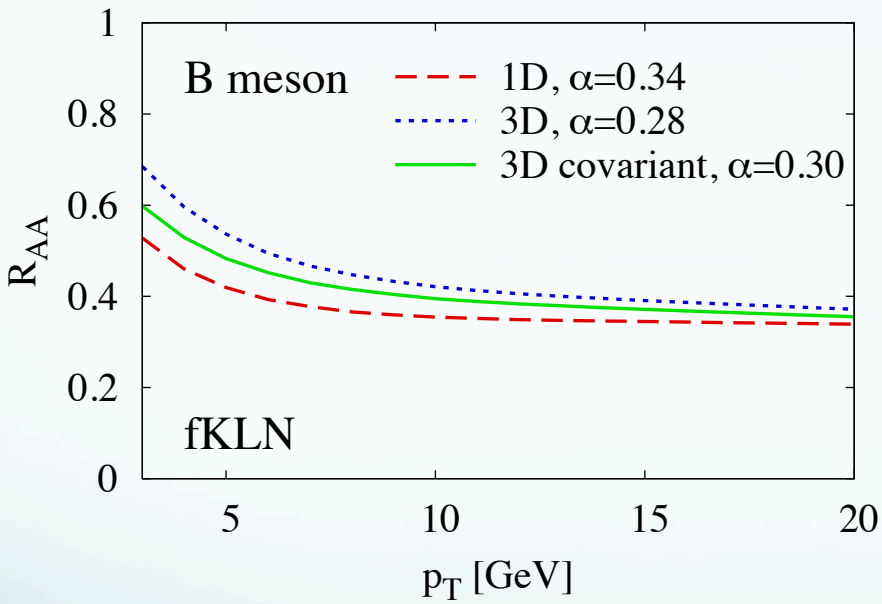
Au+Au, RHIC, b~8fm

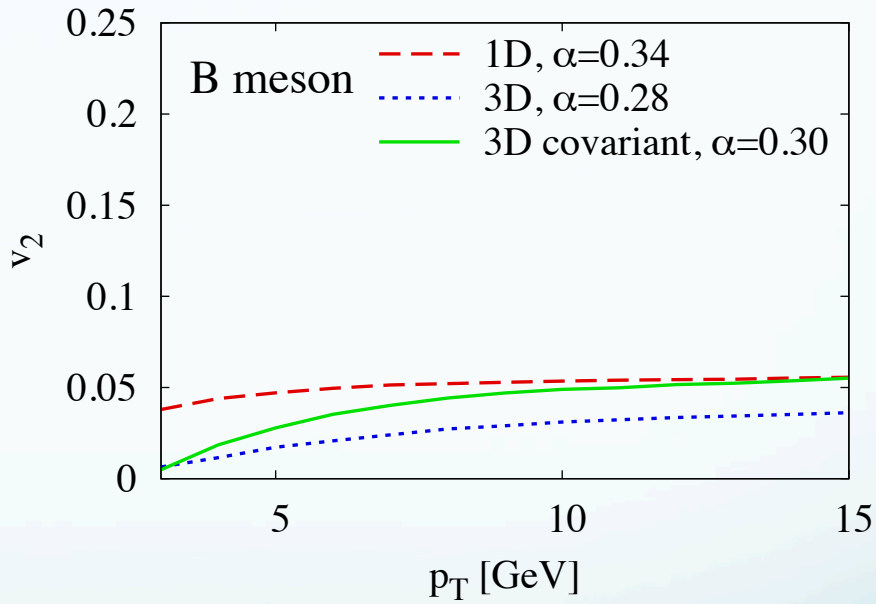


# B meson

Au+Au, RHIC, b~8fm




Covariant formulation results in a significantly larger v2 for all cases

# Running coupling

J. Xu et al, JHEP 1408 (2014) 063

$$\alpha_s \to \alpha_s\left(Q^2\right) = \begin{cases} \alpha_{\max} & \text{if } Q \le Q_{\min} \\ \dfrac{2\pi}{9\log(Q/\Lambda_{QCD})} & \text{if } Q > Q_{\min} \end{cases}$$

$$\Delta E = \frac{C_R}{\pi^2}\int dLE \times \rho\sigma_{gg\to gg}\alpha_s I\left(\frac{\mu^2 L}{E}, \frac{E}{\mu}, \frac{M}{\mu}\right)$$

$\alpha_s^2\left(Q_2^2\right)$ with $Q_2^2 = q^2$

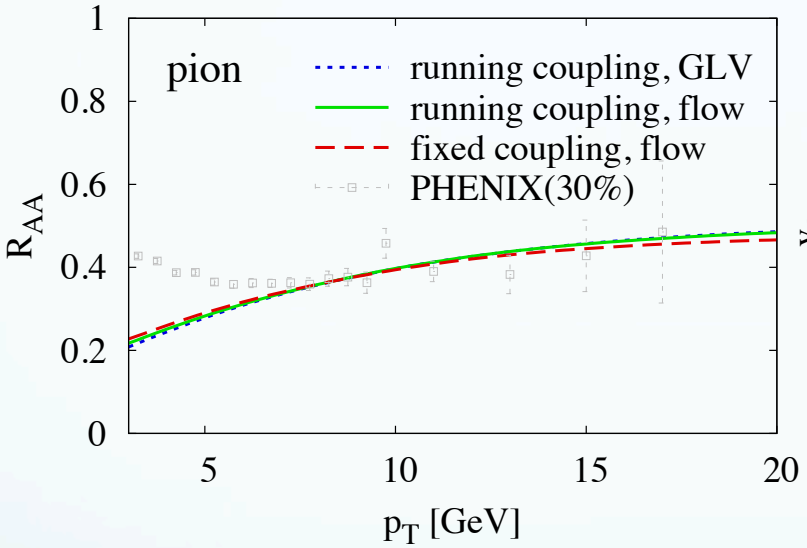
Jet-medium vertices

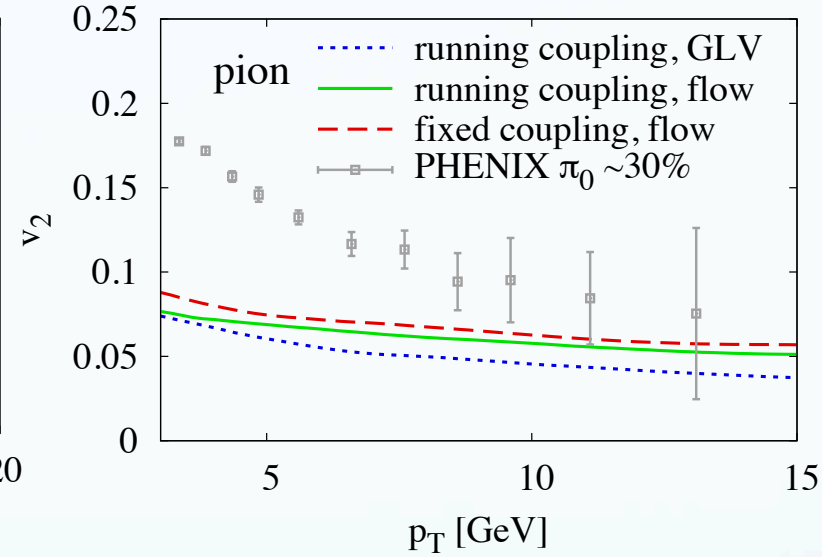
$\alpha_s\left(Q_1^2\right)$ with $Q_1^2 \approx \dfrac{k^2}{x_+\left(1-x_+\right)}$

Radiated gluon vertex

# Running Coupling - Pion

Au+Au, RHIC, b~8fm



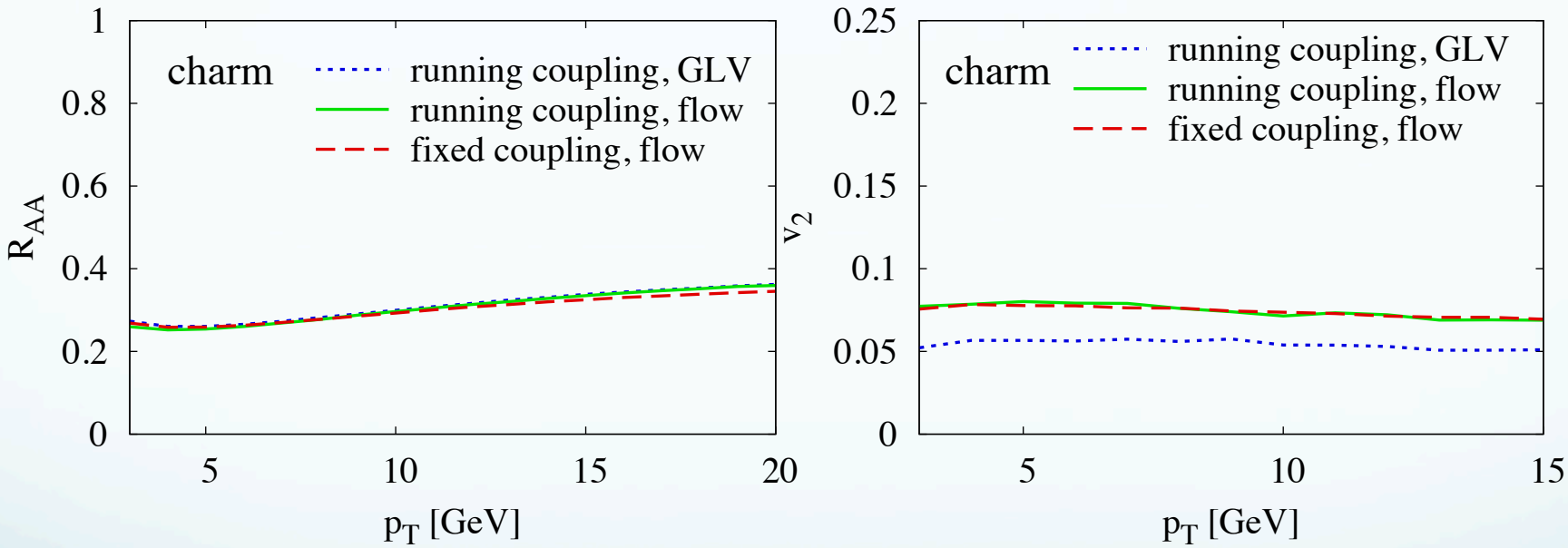




1. With running coupling added in, almost no effect on R_AA(after tuning). The effect on v2 is not significant, compared with statistical fluctuation.

2. Covariance increases v2 clearly.

# Charm quark

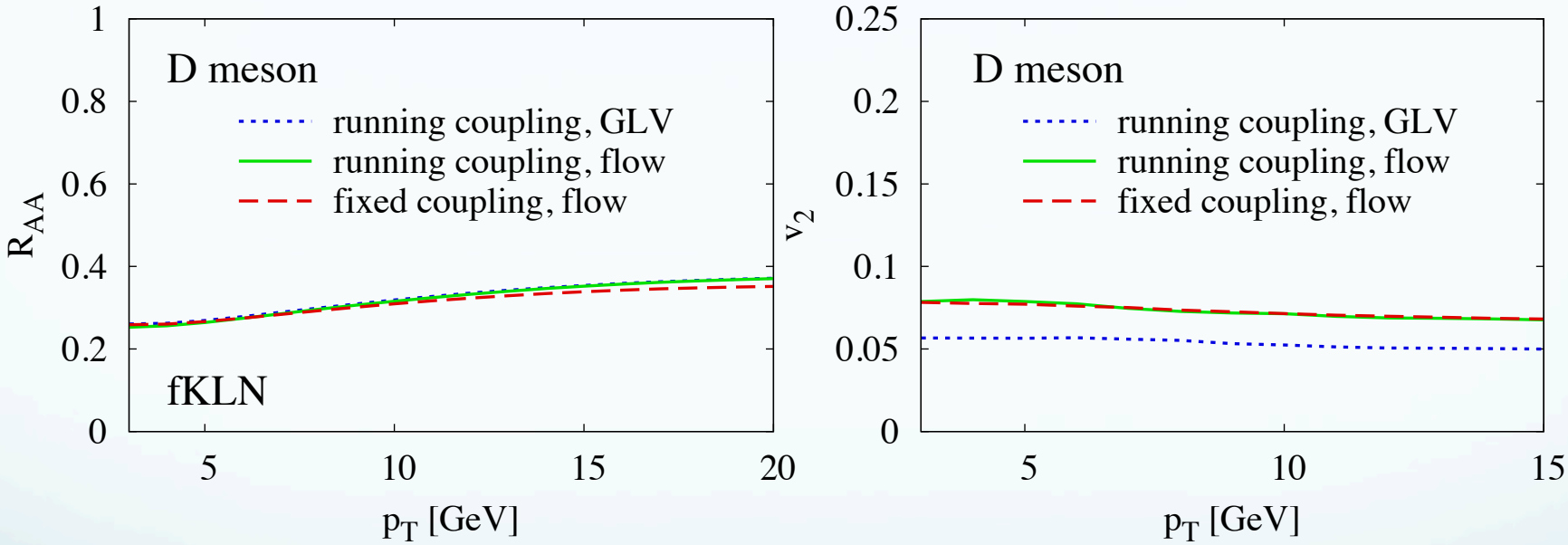
Au+Au, RHIC, b~8fm




No obvious effect due to running coupling

# D meson

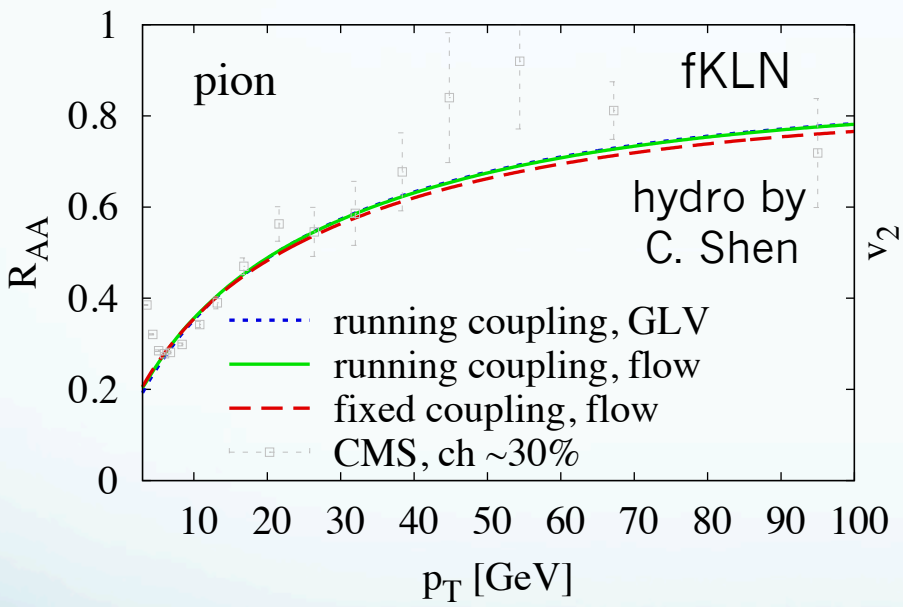
Au+Au, RHIC, b~8fm

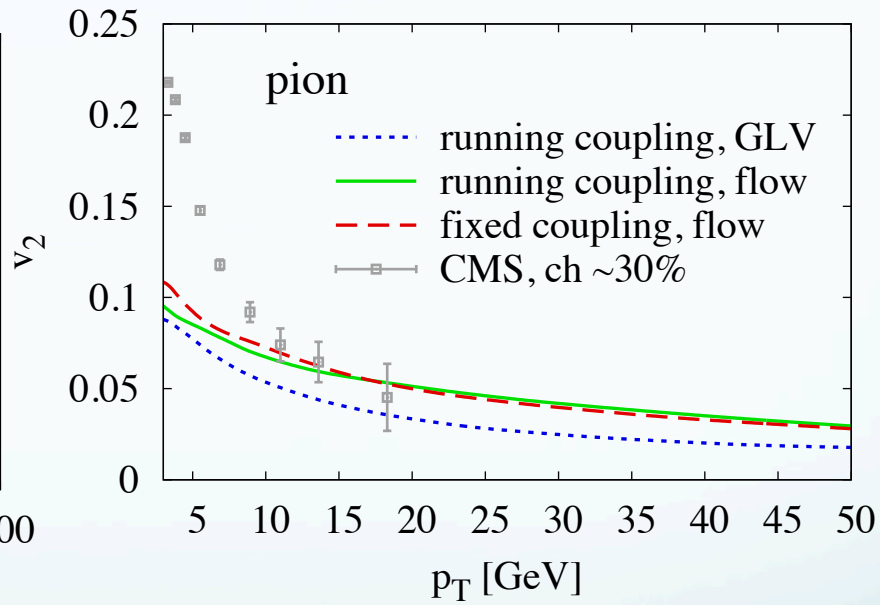



Same on D meson – no obvious effect due to running coupling

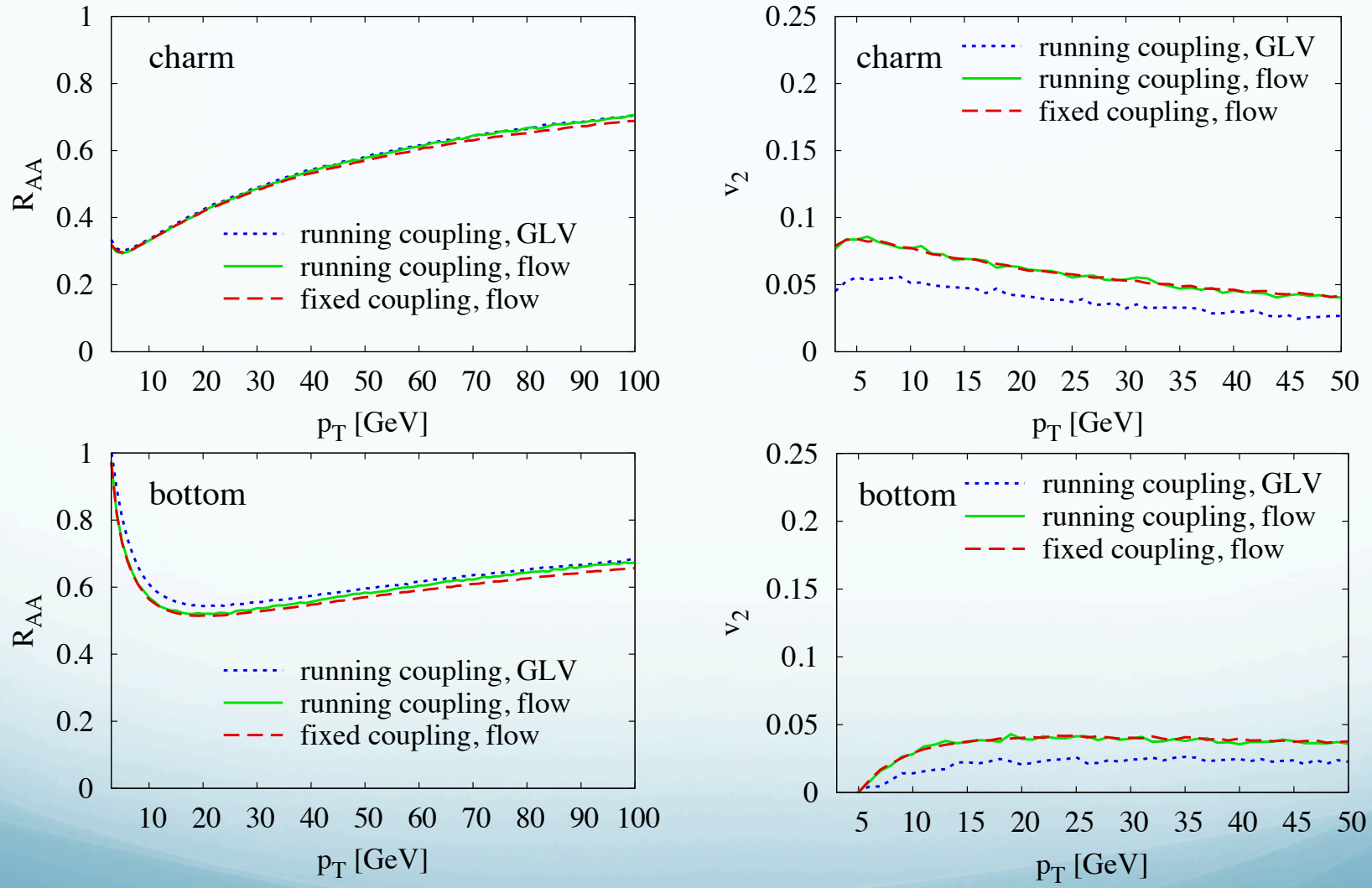
# Running coupling - LHC

Pb+Pb at 2.76TeV, b~8fm

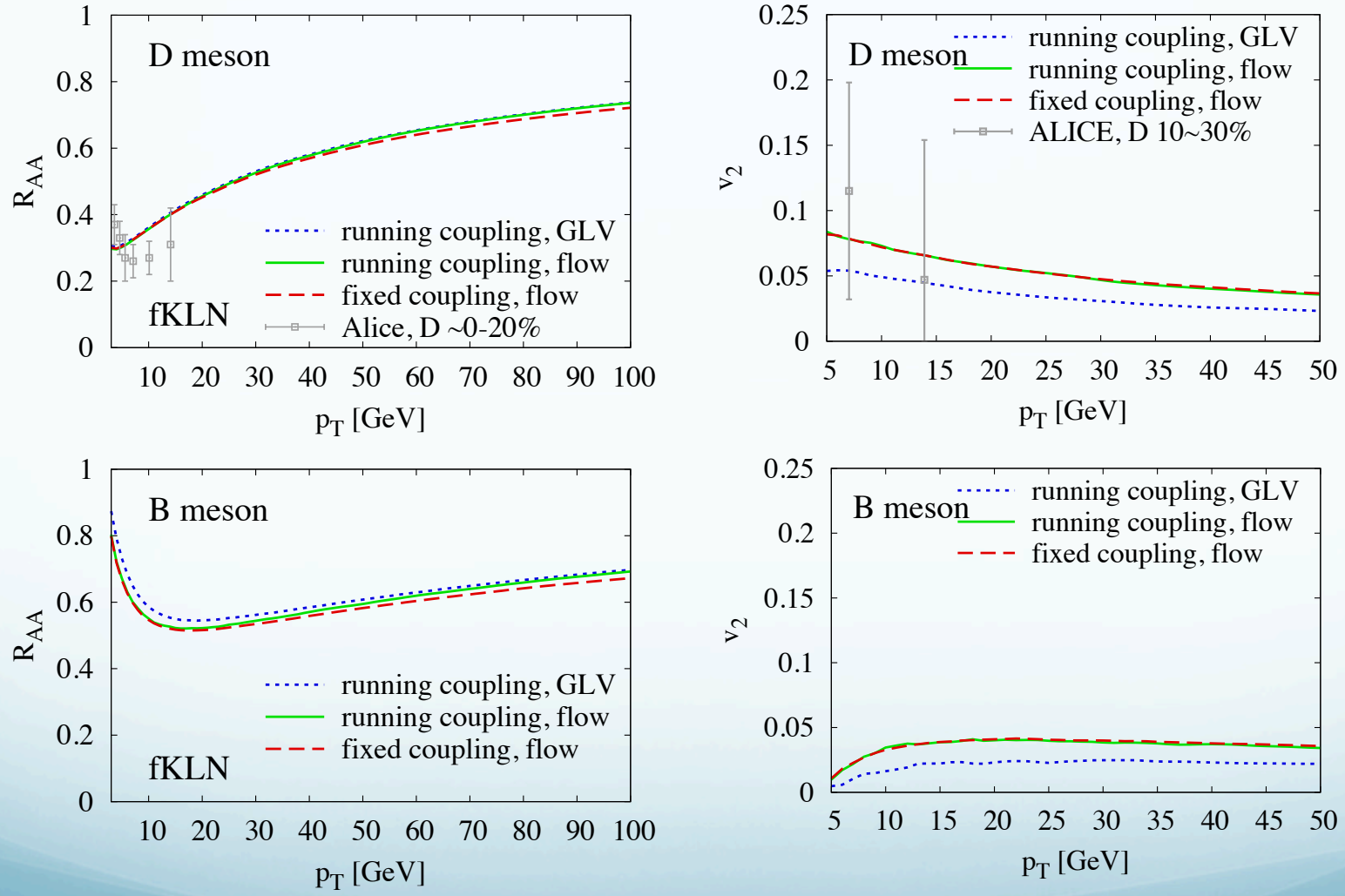


# Running coupling - LHC



# Running coupling - LHC



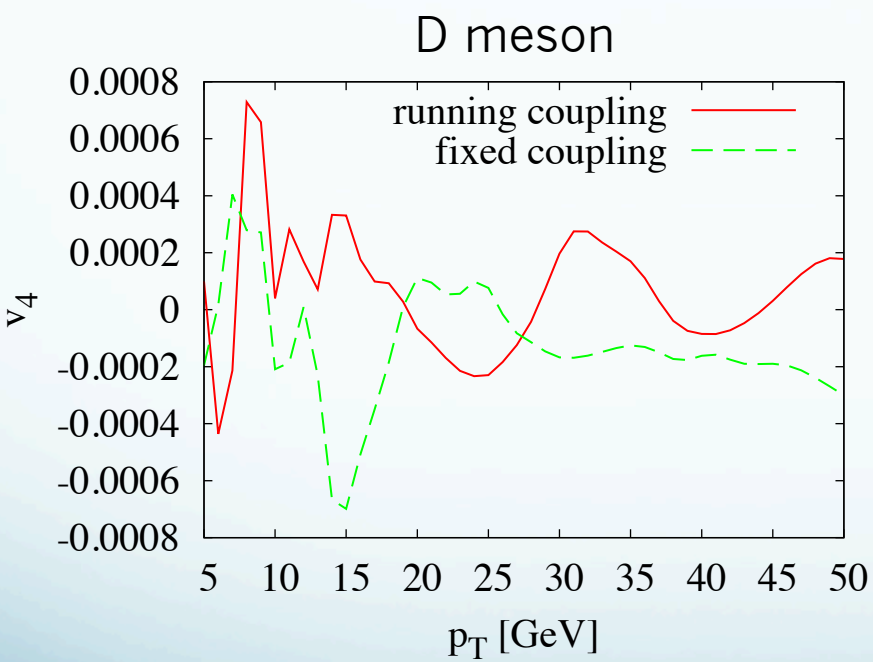
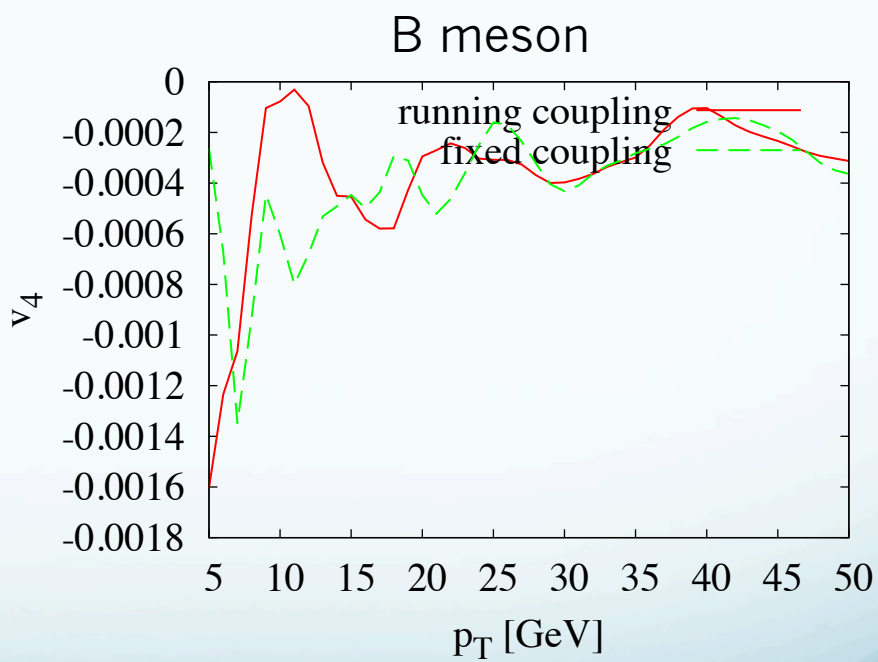
# Summary

- We studied (D)GLV radiative energy loss with various bulk medium models at both RHIC and LHC energies.
- Due to the bias of (D)GLV energy loss for later scattering, realistic transverse expansion suppresses elliptic flow($v_2$) significantly
- However, a covariant frame-independent treatment of (D)GLV energy loss increases $v_2$ for both light and heavy quarks. This comes from the interplay between collective medium flow and jet propagation direction.

Next steps:

- Elastic energy loss + radiative energy loss
- Other centralities

# Thanks!

# Other flow coefficients

Pb+Pb at 2.76 TeV, b~8fm