Covariant (D)GLV energy loss in proton-lead collisions at the LHC [†]

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Abstract

In $A+A$ reactions we have shown [1] that, compared to the original (Djordjevic-)Gyulassy-Levai-Vitev [2, 3] energy loss formulation, a frame-independent (D)GLV approach results in about 50% higher v_2 for pions, and also D and B mesons. This is due to an interplay between jet propagation direction and collective flow of the medium. Recently we have extended that calculation to include running strong coupling but have found surprisingly small effect on the nuclear suppression factor R_{AA} and elliptic flow v_2. With the assumption that QGP is produced in nearly central $p+Pb$ reactions at the LHC, we here use our covariant (D)GLV energy loss approach to calculate R_{pA} and harmonic flow coefficients v_n. This is especially interesting because hydrodynamics requires high opacities, which should then be manifested in energy loss. We find non-negligible v_2, as well as an R_{pA} slightly below unity, suggesting that the combination of hydrodynamics and (D)GLV energy loss is perhaps reasonable, compared to experimental measurements.

Covariant DGLV energy loss

In the Djordjevic-Gyulassy-Levai-Vitev (DGLV) formalism[2, 3] of parton energy loss, to first order in opacity χ, the medium-induced radiated gluon spectrum off a fast parton of mass M that scatters at distance L is

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

Here E is the jet parton energy, x_E and x_+ are the fractional energy and fractional lightcone momentum of the radiated gluon, μ is the local Debye screening mass, $X = x_+^2 M^2 + m_g^2(1-x_+)$, $\omega \equiv \frac{\mathbf{Q}^2+X}{2Ex_+}$, and $\mathbf{Q} = \mathbf{k}+\mathbf{q}$. As in [4] we average the energy loss along the jet path as

$$\langle \Delta E^{(1)} \rangle = E \int_0^\infty dL\, \rho(\vec{x}_0 + \hat{v}L, L/v)\, \sigma_{gg}(L) \int dx_E\, d^2\mathbf{k}\, x_E \frac{dN^{(1)}(L)}{dx_E\, d^2\mathbf{k}}\ , \quad (2)$$

using $\sigma_{gg} = 9\pi\alpha_s^2/2\mu^2$ for the scattering cross section in the medium for gluons, and observing finite energy and kinematic bounds ($|k| \lesssim x_E E$, $|q| \lesssim \sqrt{6ET}$, $x_E E \gtrsim \mu$). We set $\mu \approx 2T$, and approximate $X \approx x_+^2 M^2$ so that the massless limit recovers ordinary GLV energy loss (except for one unscreened "dynamical" $1/q^2$ term).

To define a **Lorentz covariant** approach, we calculate energy loss in the LR frame where the fluid is **at rest** at the point of scattering. This implies[1] a replacement $dL\,\rho\,\sigma_{gg} \to dL\,\rho\,\sigma_{gg}(1-\vec{v}\vec{v}_F)$, where $\vec{v}_F$ is the local three-velocity of fluid flow. Kinematic bounds are also evaluated in the LR frame. Covariance thus leads to an interplay between jet motion and medium flow, similarly to the approach in Ref. [5].

Effect of covariance in $A+A$

Figure 1 shows the influence of covariant energy loss on **neutral pion** observables in $Au+Au$ at $\sqrt{s_{NN}} =$ 200 GeV with impact parameter $b = 7.5$ fm. We employ LO pQCD jets with binary collision profile, together with bulk medium from 2+1D boost-invariant viscous hydrodynamics [6] with fKLN initial profile and lattice QCD equation of state (available from the TECHQM Collaboration [7]). Three cases are contrasted: i) "vanilla" GLV energy loss with running coupling ("running coupling, GLV"); ii) frame independent GLV energy loss with running coupling ("running coupling, flow"); and iii) frame independent energy loss with fixed coupling ("fixed coupling, flow"). All three are scaled to give the same R_{AA} at $p_T \sim 8GeV$ by adjusting α_s (fixed coupling case) or the maximum value of α_s (running coupling case, as in Ref. [8]).

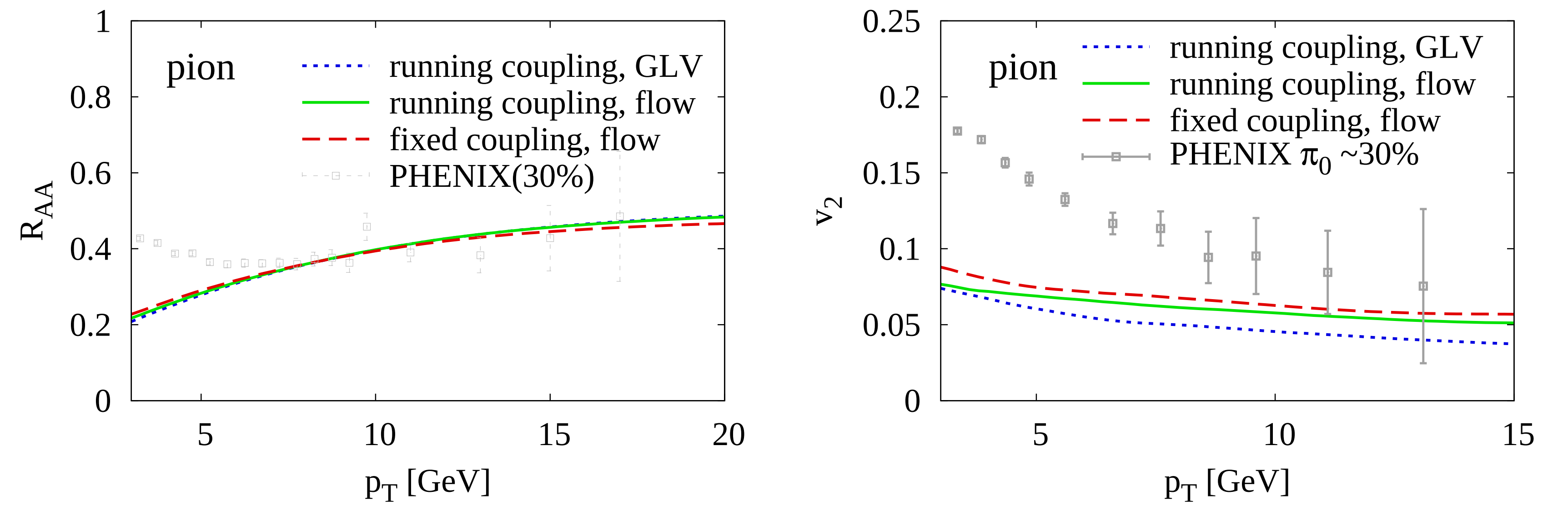

FIGURE 1: Neutral pion R_{AA} and v_2 in $Au+Au$ collision at $\sqrt{s_{NN}} = 200$ GeV with impact parameter $b = 7.5$ fm.

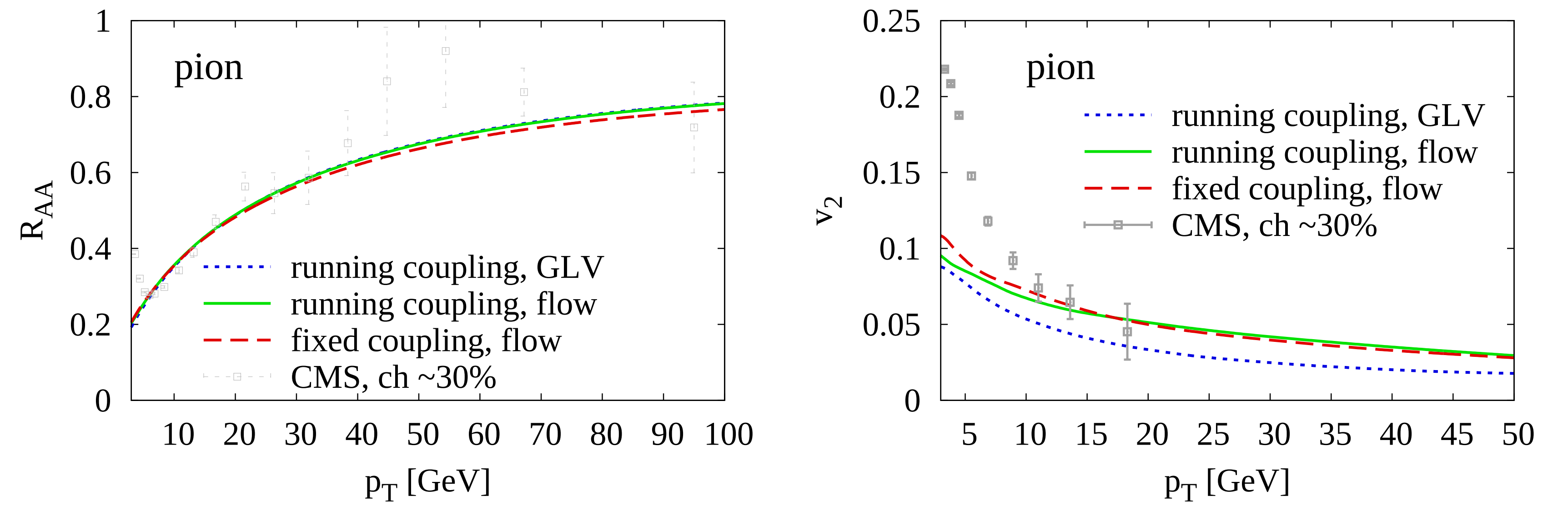

FIGURE 2: Neutral pion R_{AA} and v_2, same as in Fig. 1, except for $Pb+Pb$ at $\sqrt{s_{NN}} = 2760$ GeV.

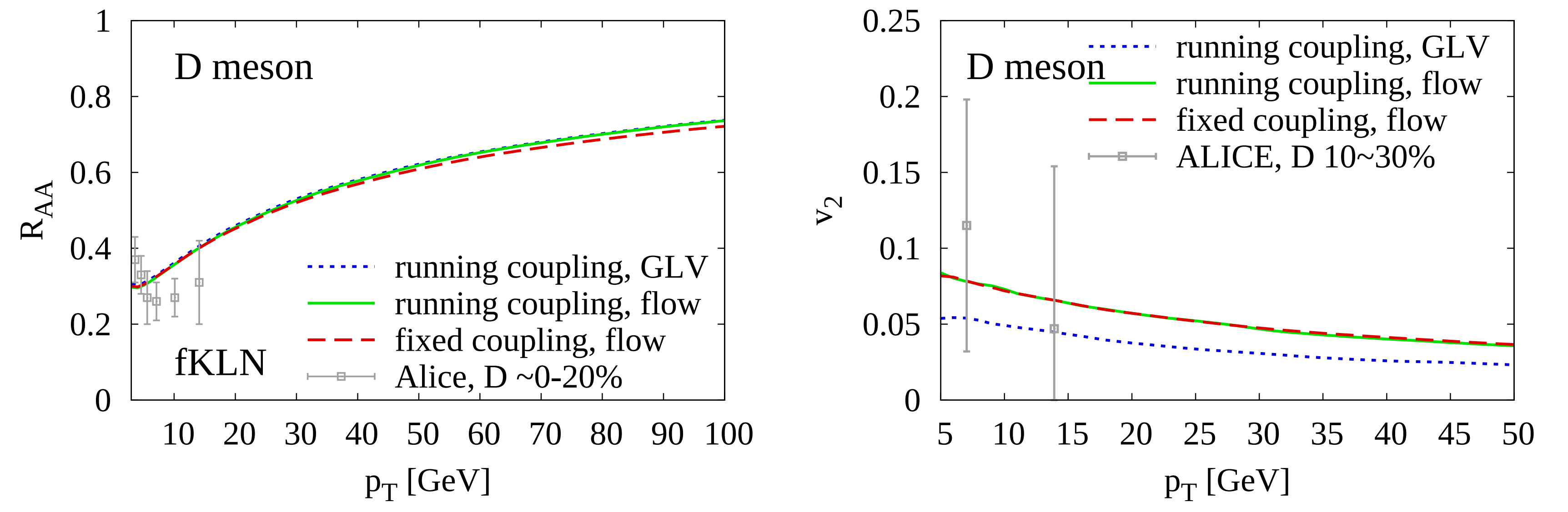

FIGURE 3: D meson R_{AA} and v_2 in $Pb+Pb$ collision at $\sqrt{s_{NN}} = 2760$ GeV.

The increase in elliptic flow due to jet-medium flow coupling from covariant treatment of energy loss is robust, as seen in the right plot. However, the influence of running coupling seems rather small.

Figures 2 and 3 show neutral pion and D meson results for $Pb+Pb$ at the LHC with $\sqrt{s_{NN}} = 2760$ GeV. Bulk medium evolution from viscous hydrodynamics with $\eta/s = 0.2$ was provided by Chun Shen. D mesons were obtained via independent fragmentation using the Peterson parameterization (with identical parameters to those in Ref. [8]). The conclusions about covariance and running coupling are the same as at RHIC energy (Figure 1).

Covariant GLV energy loss in $p+Pb$

Now we turn to $p+Pb$ interactions at the LHC with $\sqrt{s_{NN}} = 5.02$ TeV, top 3.4% centrality. We used GLISSANDO to generate initial conditions, and then applied 2+1D (boost invariant) ideal hydrodynamics using the MPC/Hydro code [9] to model the bulk medium evolution. Figure 4 shows neutral pion R_{pA} and v_n for a single event("Event 1"). Statistical errors are shown based on ten million simulated jets. We find an R_{pA} that is about $5-10\%$ below unity for $10 < p_T < 40$ GeV, and a non-negligible v_2 on the order of 1%. The magnitudes of v_3 and v_4 are reduced by about half compared to v_2.

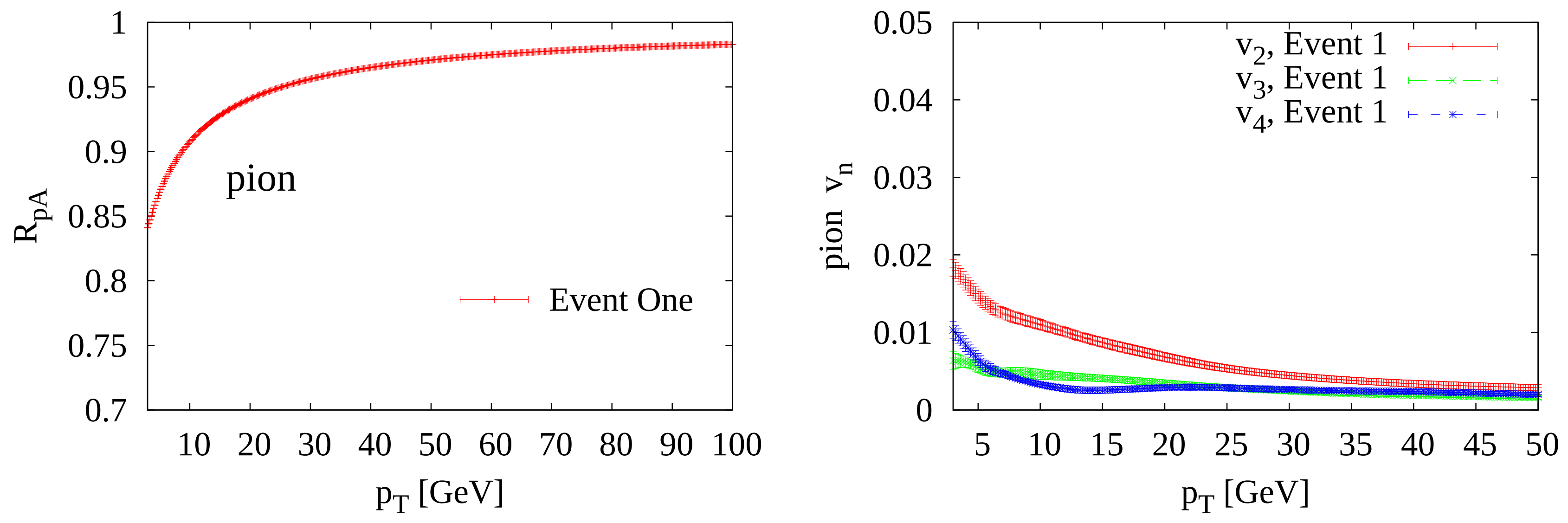

FIGURE 4: Neutral pion results for a single $p+Pb$ event at $\sqrt{s_{NN}} = 5.02$ TeV

Figure 5 shows event-by-event fluctuations for R_{pA} and v_n, obtained form 50 $p+Pb$ events. Intervals shown correspond to $\pm 1\sigma$ around the event average. Variations in initial geometry have significant effect on harmonic flow coefficients v_n. Taking into account the fluctuations, we can see that radiative energy loss alone could generate a v_2 as much as 2% at $p_T \sim 10GeV$. Besides, v_3 and v_4 have similar falling shapes vs p_T as v_2, but their magnitudes are about half of that of v_2. In view of experimental data indicating R_{pA} of about unity at high p_T and significant v_2 at modest p_T, we do not see an immediate contradiction with GLV energy loss and hydrodynamics. However, more complete calculations together with more precise measurements of R_{pA} and v_n at high p_T would provide stringent cross checks of (D)GLV energy loss and the hydrodynamic paradigm because all parameters in this calculation are fixed by R_{AA} measurements in $Pb+Pb$ reactions.

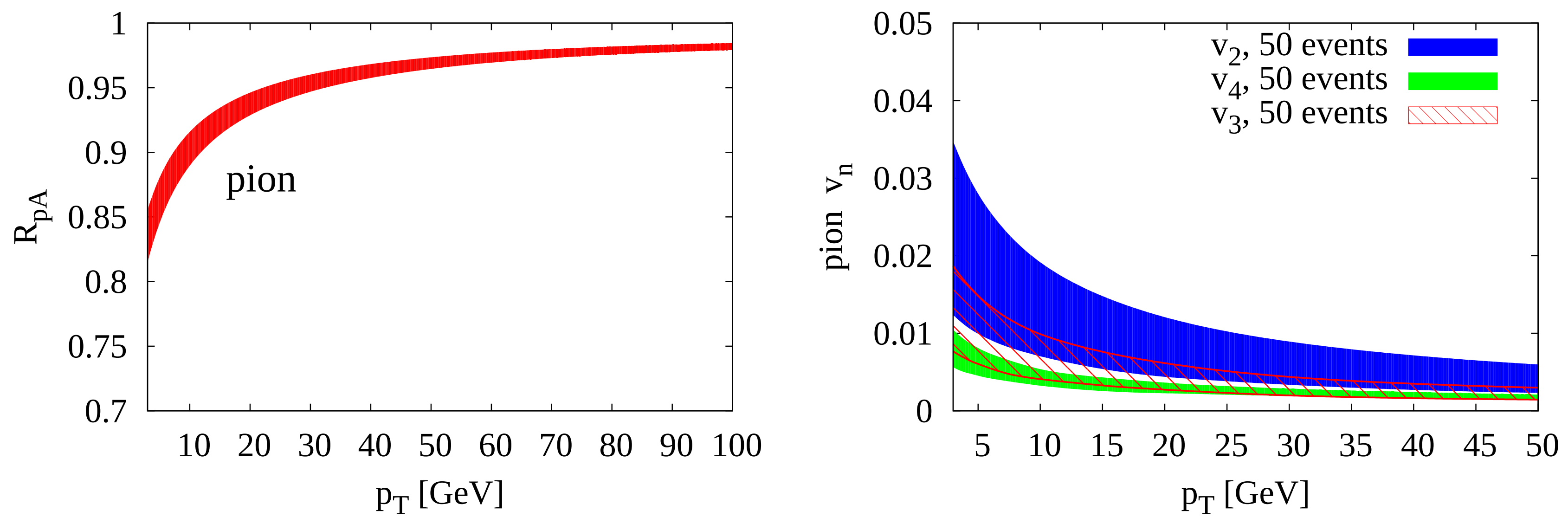

FIGURE 5: Event-by-event fluctuations for 3.4% most central $p+Pb$ events at $\sqrt{s_{NN}} = 5.02$ TeV.

Conclusions:

- **Covariant** (D)GLV formulation causes smaller energy loss for jets moving in the same direction as the medium flow. The reduction is larger the higher the flow velocity, which leads to an enhancement of the in-plane vs out-of-plane difference in energy loss ⇒ larger elliptic flow.
- With the assumption of hydrodynamic medium evolution in $p+Pb$, our (D)GLV calculations show a small reduction of R_{pA} below unity and nonnegligible $v_2 \sim 1\%$, $v_3, v_4 \sim 0.5\%$, which should be cross checked against experiment.

References:

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[†] This work was supported by the US DOE under grant DE-PS02-09ER41665, and the JET Collaboration (DOE grant DE-AC02-05CH11231).