Modification of Hard Probes of the QGP due to Flow-Induced Jet Drift

arXiv preprint coming soon…

Supported in part by DoE Grant (DE-SC0024560)
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INT
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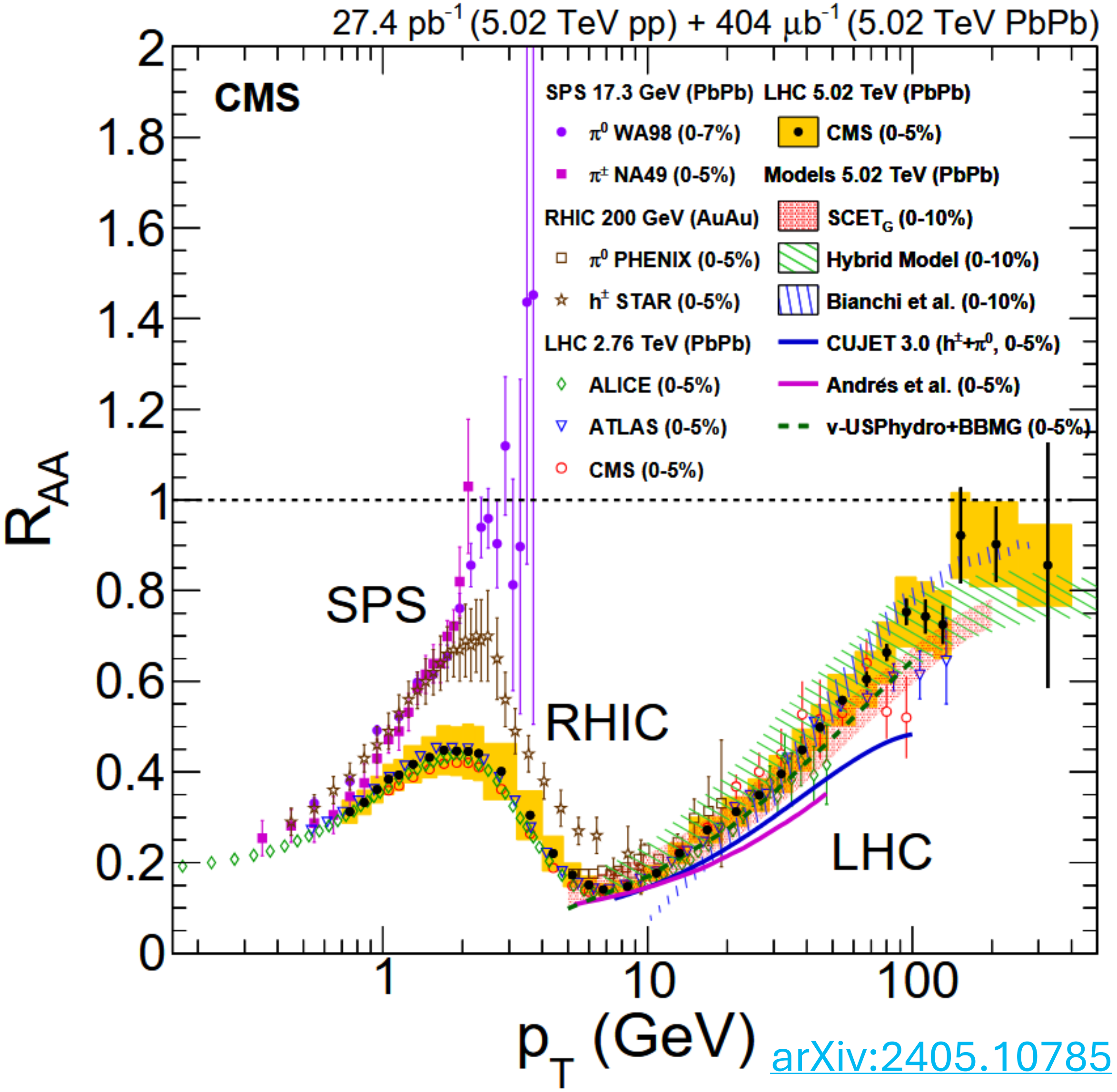
In collaboration with
Hasan Rahman, Matthew Sievert,
and Ivan Vitev

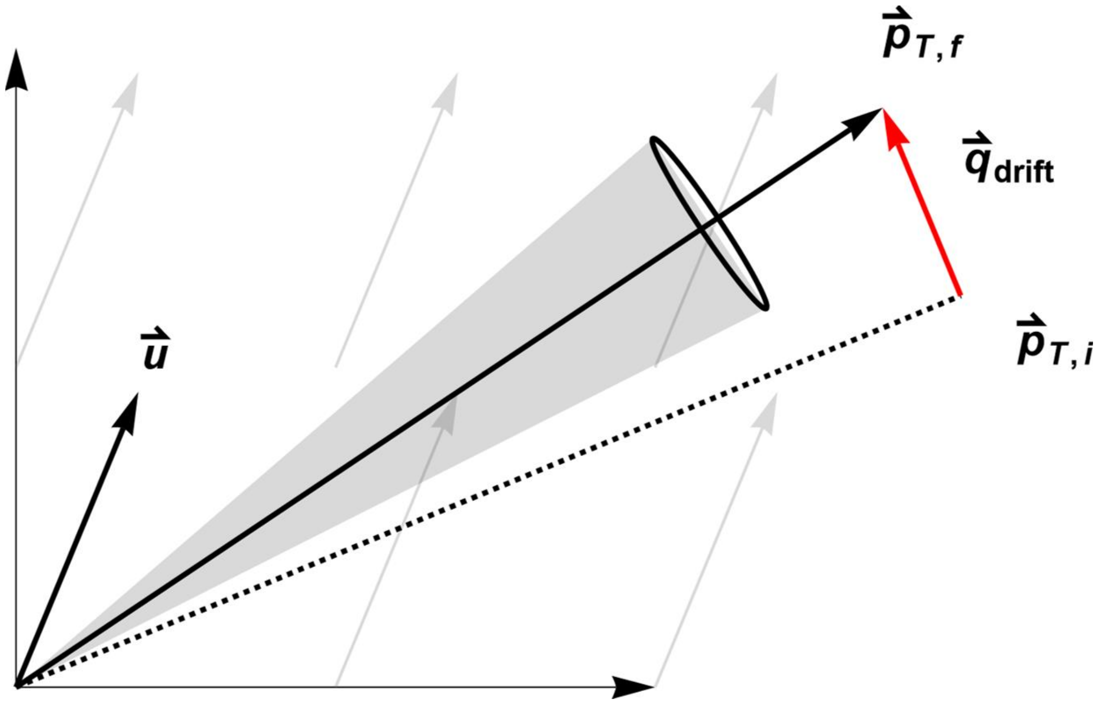
The Specialness of Anisotropic Effects

- Isotropic modifications of hard probes are not strongly model-descriminate
  - Compete with many sources of background
  - Many microscopic models obtain results similar to data (e.g. ch. had. R_AA)
- Few, if any, effects can mimic the coupling of hard particles to anisotropies in the medium
  - Few vector directions: Collective Flow & Gradients



arXiv:2405.10785

Anisotropic Jet Broadening: "Jet Drift"



- Part of a "New" class of pQCD effects: asymmetric / anisotropic
- Preferential broadening in direction of medium flow

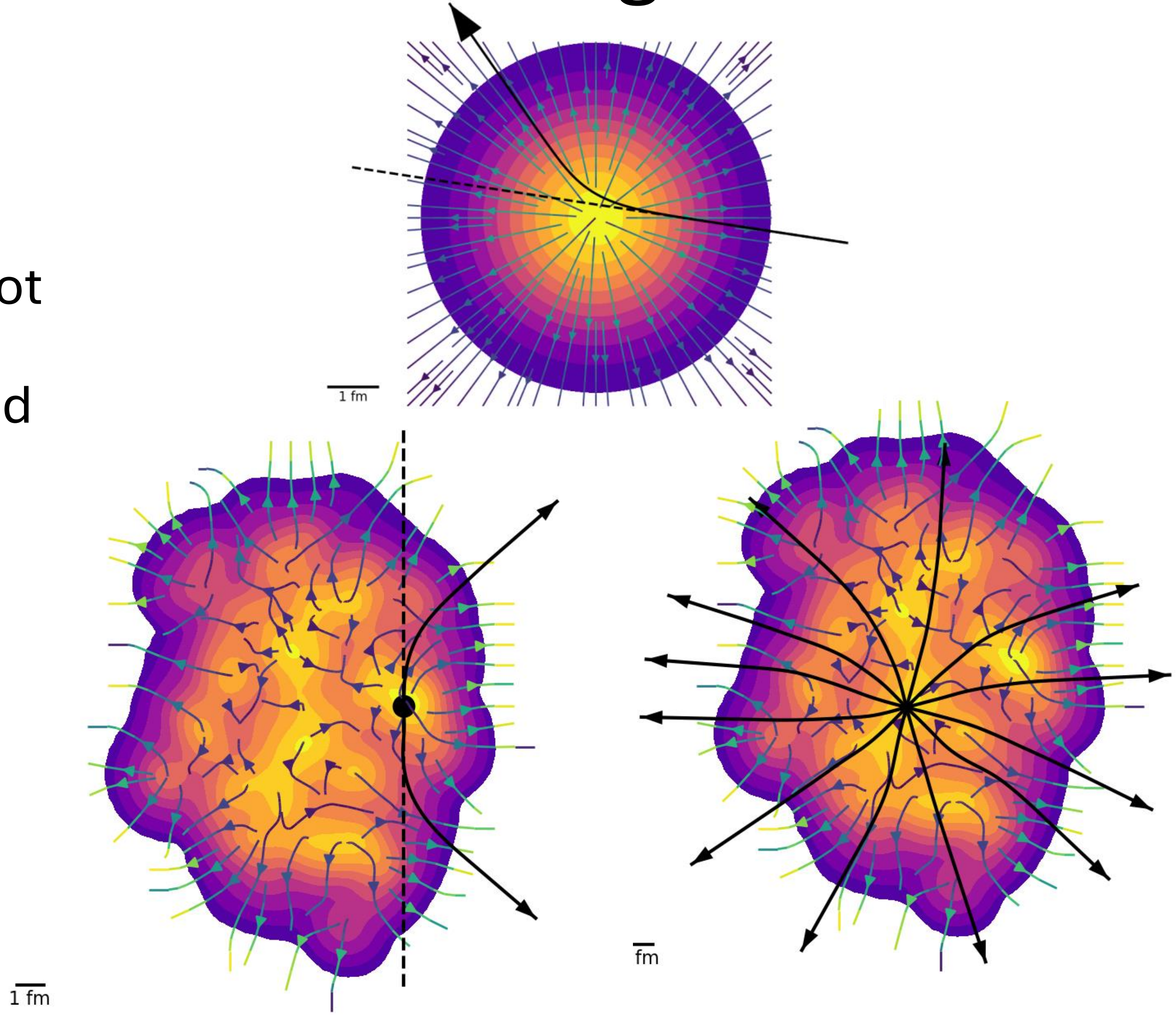
$$\langle \vec{q}_{drift} \rangle = \hat{e}_\perp \int d\tau \frac{3}{\underbrace{\boxed{E(\tau)}}_{\text{Energy suppressed}}} \underbrace{\boxed{\frac{\mu^2(\tau)}{\lambda(\tau)} \ln \frac{E(\tau)}{\mu(\tau)}}}_{\text{Temperature/Density Enhanced}} \overbrace{\boxed{\frac{u_\perp(\tau)}{1 - u_\parallel(\tau)}}}^{\text{Flow enhanced and flow direction controlled}}$$

$$\frac{1}{\lambda} = \sigma\rho$$
$$\rho \propto T^3$$
$$\mu \propto T$$

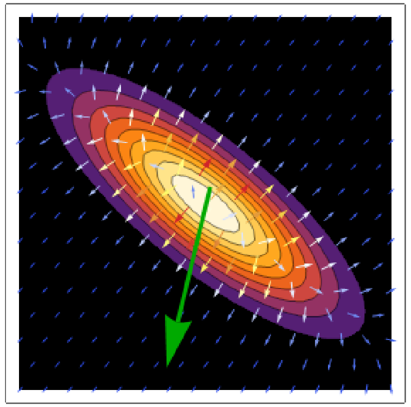
A. V. Sadofyev, I. Vitev, & M. D. Sievert
Phys.Rev.D 104 (2021)
(arXiv:2104.09513)

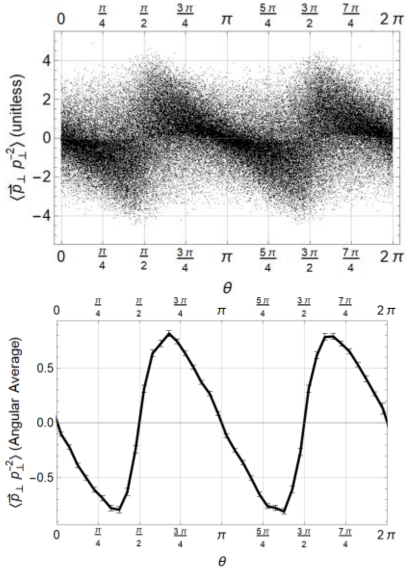
Possible Signatures of Jet Drift in Leading Hadrons

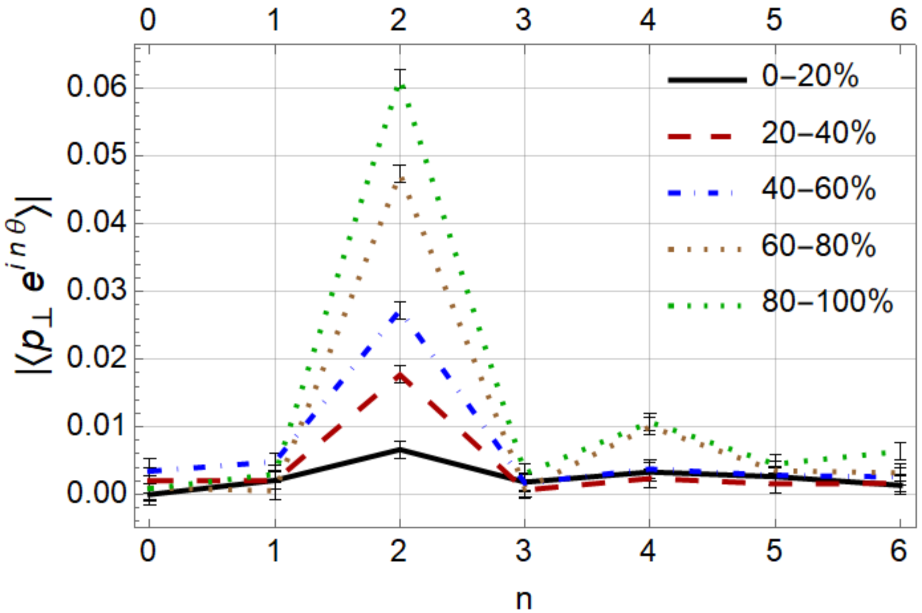
- Modification of suppression
    - Deflecting away from flowing hot spots
    - Particle sees reduced integrated density
- Anisotropic flow modification
    - Particles couple to soft anisotropic flow
- Acoplanarity enhancements
    - Particles couple to same "attractor" in the medium



Does Drift Survive Event Averaging?







- Naively, one might expect cancellation via event averaging
- Coupling to event anisotropic flow shown in glauber elliptic geometry to preserve effect
  - Fluctuating event plane, centrality
  - L. Antiporda, J. Bahder, H. Rahman & M. D. Sievert Phys.Rev.D 105 (2022) (arXiv: 2110.03590)
- What about in realistic heavy ion collisions?

APE: A Monte Carlo to Study Drift

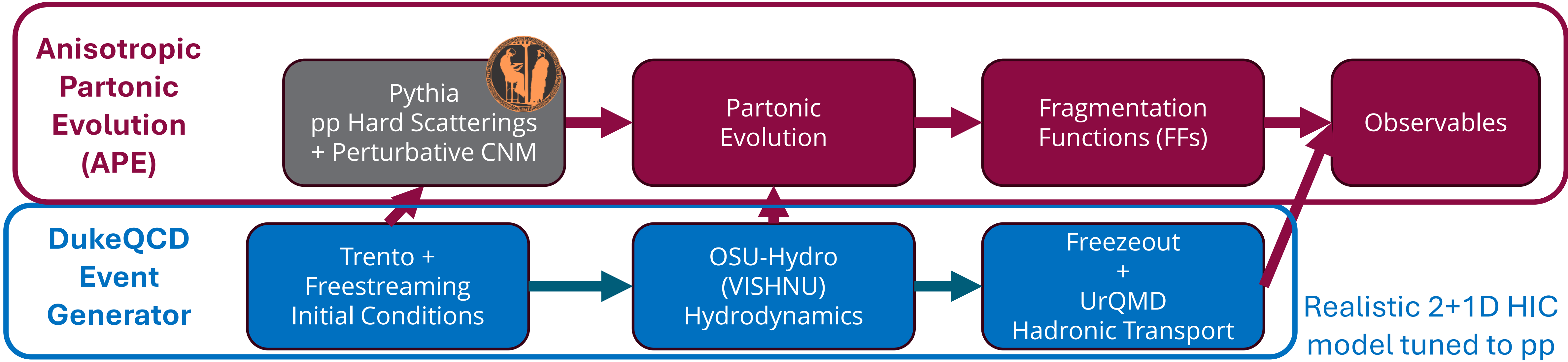
Test effect of addition of jet drift to realistic event-by-event jet-medium simulations on hard probes of heavy ion collisions

Pert. Cronin Effect, Nuclear Shadowing, & Iso-spin Effects
(arXiv:0201078)
(arXiv:0309094)

Highly Tuned pp Hard Scatterings
(arXiv:2203.11601)

Perturbative Partonic Evolution

Perturbative Fragmentation



Anisotropic Partonic Evolution (APE)

Pythia
pp Hard Scatterings
+ Perturbative CNM

Partonic Evolution

Fragmentation Functions (FFs)

Observables

DukeQCD Event Generator

Trento + Freestreaming Initial Conditions

OSU-Hydro (VISHNU) Hydrodynamics

Freezeout
+
UrQMD
Hadronic Transport

(arXiv:1808.02106)

Realistic 2+1D HIC model tuned to pp & PbPb data

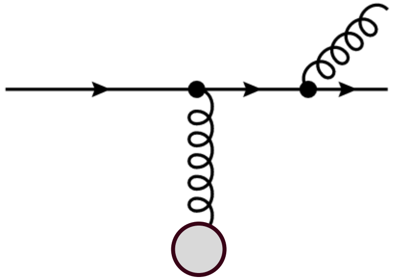
Energy Loss Effects

Radiative

$$\frac{dE}{d\ell} = -\frac{d}{dL}\left(\frac{2C_R\alpha_s}{\pi}\frac{L}{\lambda}E\int_{k_{max}}^{k_{max}}\frac{dk}{k}\int_0^{q_{max}} dq\, q\int_0^{2\pi} d\phi\right.$$
$$\left.\times\frac{\mu^2}{\pi(q^2+\mu^2)^2}\frac{2\mathbf{k}\cdot\mathbf{q}\,(\mathbf{k}-\mathbf{q})^2L^2}{16x^2E^2+(\mathbf{k}-\mathbf{q})^4L^2}\right)_{L=\ell}$$

- Single Emission GLV @ 1st order in opacity w/ finite kinematic bounds (q, k)
- Interpolated tabulated results
- Gyulassy, Levai, Vitev (2000) (arXiv:0006010)

E.g.

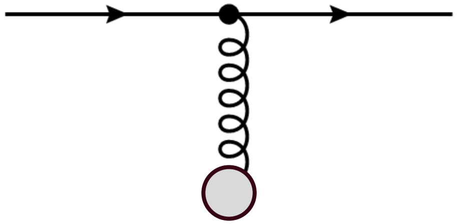


Collisional

$$\frac{dE}{d\ell} = -C_R\frac{1}{2}\mu^2\ln\left(2^{\frac{N_f}{2(6+N_f)}}0.920\frac{\sqrt{3ET}}{\mu}\right)$$

- Braaten & Thoma (1991) (iNSPIRE:317898)
- Light quarks: E >> m^2/T regime
- Gluons: CA/CF = 9/4 (arXiv:2305.13182)

E.g.

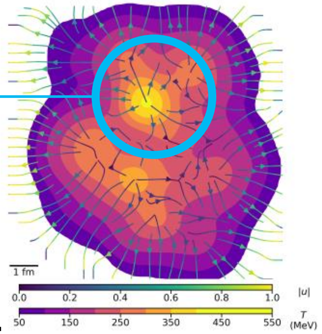


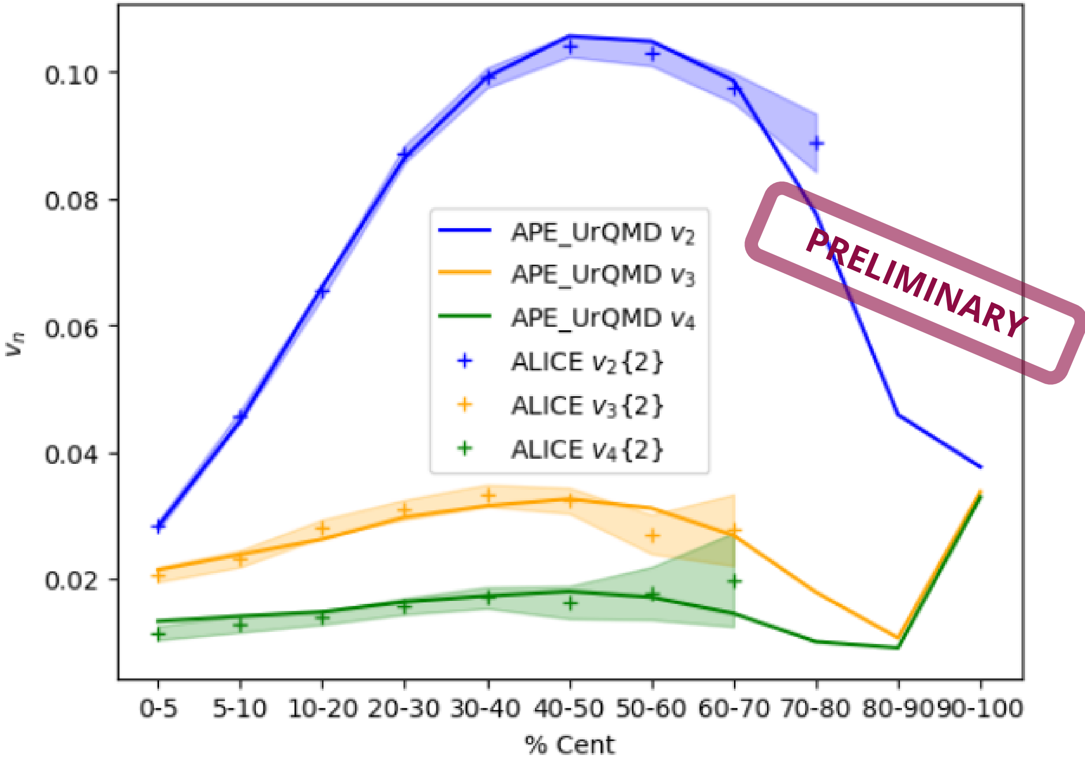
DukeQCD's HIC Event Generator

$$\langle \vec{q}_{drift} \rangle = \hat{e}_{\perp} \int d\tau \frac{3}{\boxed{E(\tau)}} \frac{\mu^2(\tau)}{\lambda(\tau)} \ln \frac{E(\tau)}{\mu(\tau)} \frac{u_{\perp}(\tau)}{1 - u_{\parallel}(\tau)}$$

Energy suppressed

- Highly tuned to soft sector observables
  - Reliable picture of final state
  - Not necessarily good description of intermediate dynamics – drift distinguishes
- Large event-by-event fluctuations
  - Nucleon substructure fluctuations included
  - Maximizes disruption of event-correlated drift

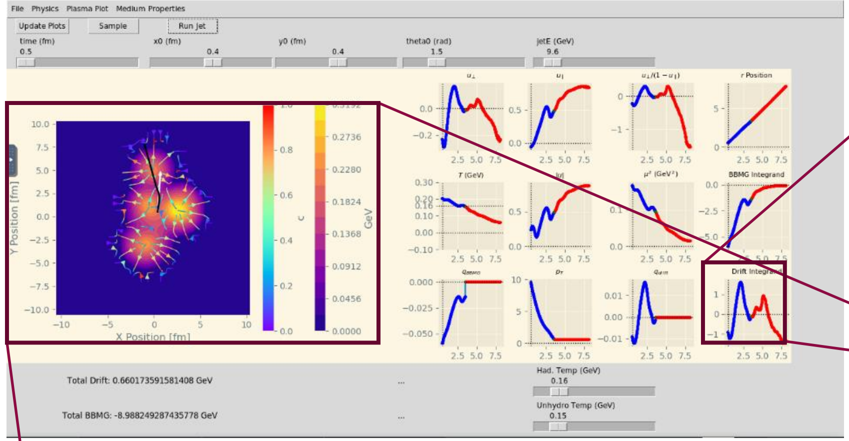




See also multiplicities, mean pT, pT fluctuation, etc.: (arXiv:1808.02106)

Ape Trajectories

- Approx. Binary collision density weighting of production points
- Computed within QGP phase of hydro backgrounds
  - EL & Drift cut off at T < 155 MeV
  - Cuts off highest flow region!!!
- Dynamic trajectories respond to medium flow
  - Deflections, zigzags, weirdness

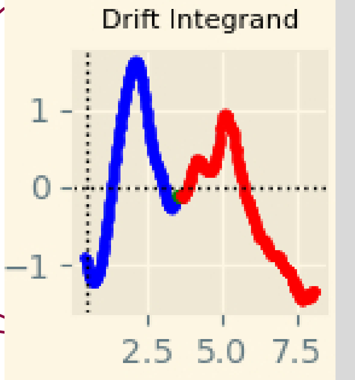


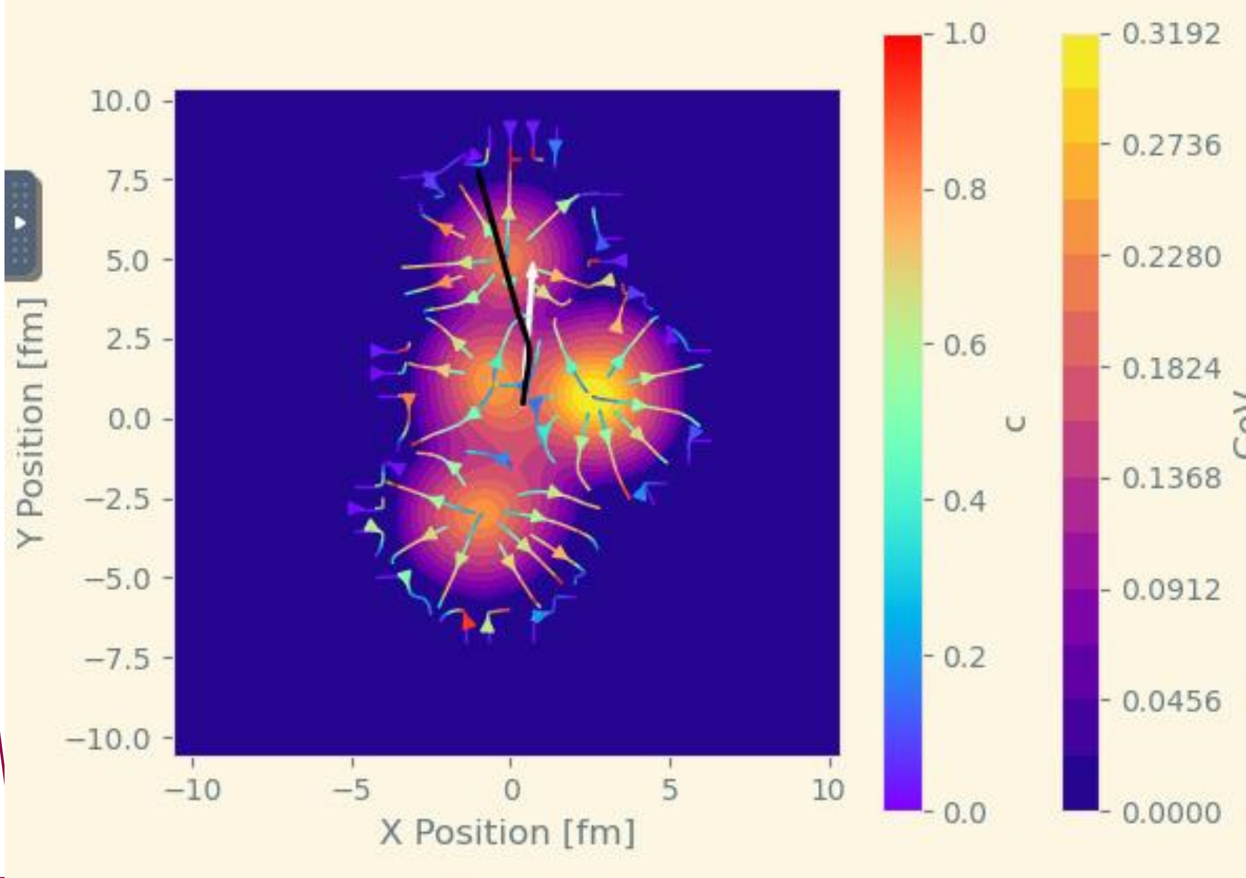
time (fm) 0.5
x0 (fm) 0.4
y0 (fm) 0.4
theta0 (rad) 1.5
jetE (GeV) 9.6

Total Drift: 0.660173591581408 GeV ...

Total BBMG: -8.988249287435778 GeV ...

Had. Temp (GeV) 0.16
Unhydro Temp (GeV) 0.15





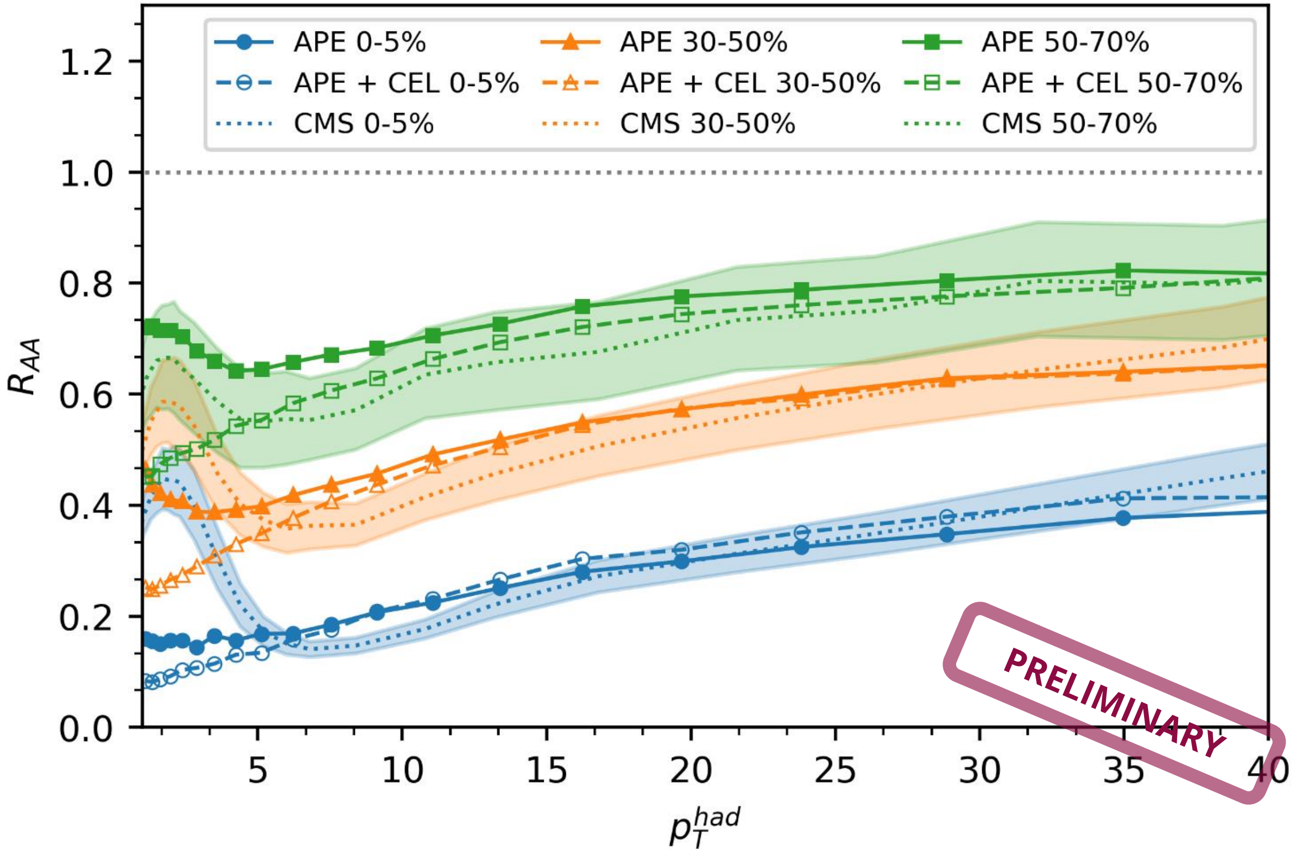
Parameter Fits & Model Choices

- Coupling
  - Tuned to high-pT RAA
- Jet Spectra
  - Constrained by Pythia pp tune
- Fragmentation Functions
  - JAM20 Fits
- Medium Model
  - Fixed by DukeQCD Tune

- DukeQCD "hic-eventgen" medium model parameters set by Bayesian parameter estimation (arXiv:1804.06469)
- Pythia input + pCNM determines partonic spectra
- Coupling from high pT RAA (30-50%)
- Choice of fragmentation function fits
  - Large change to scale of results!

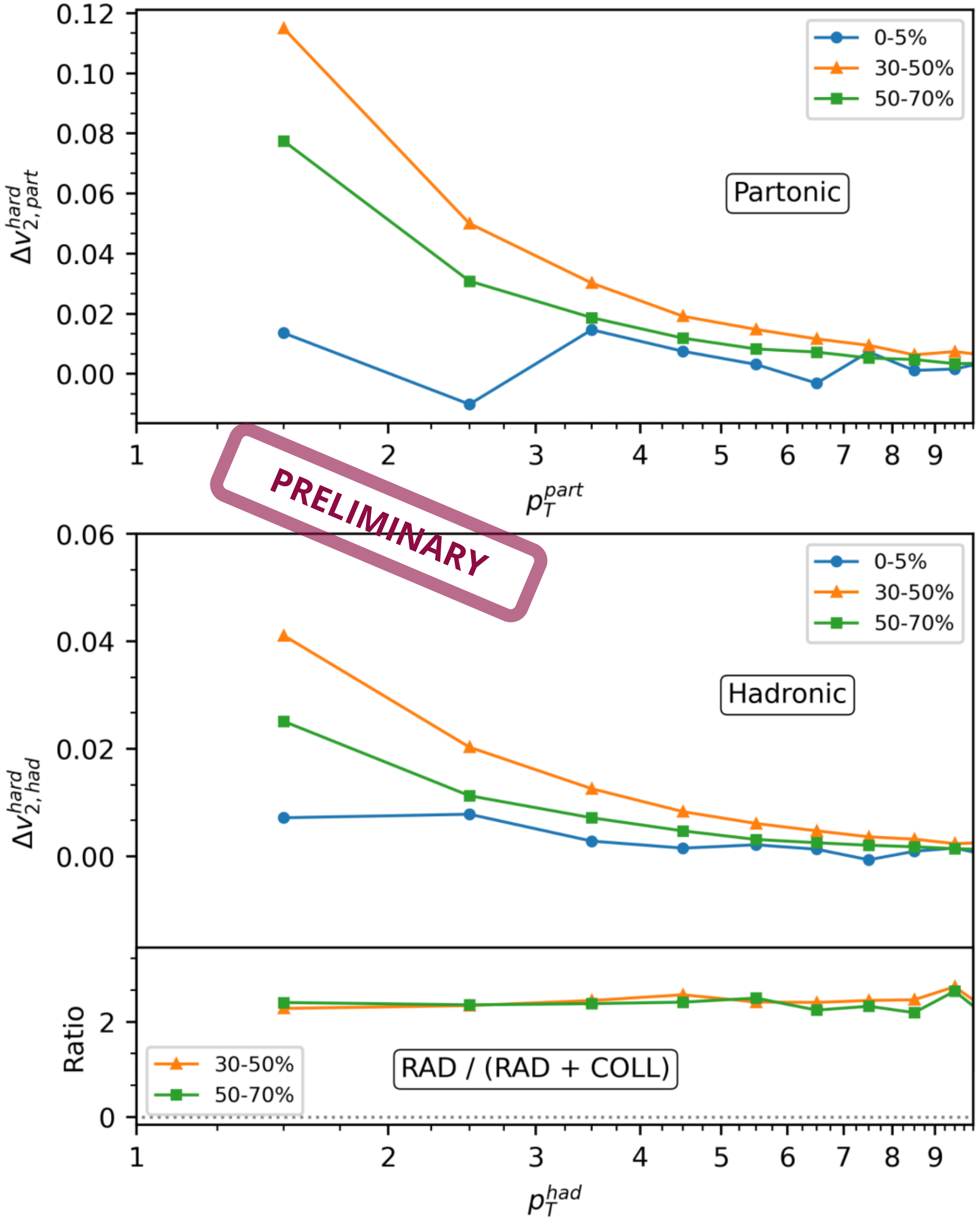
R_AA Tunes Coupling

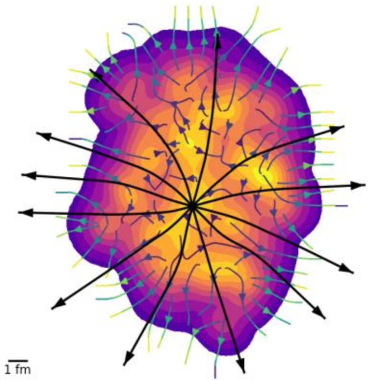
- Drift does not measurably modify R_AA(p_T)
  - Very useful – can tune coupling
  - Rad: g=2.0, Rad + Coll: g=1.6
- Additional sources of high-pT energy loss reduce effective drift coupling
- Better performance at low-pT can only enhance drift



V2 is Enhanced by Drift

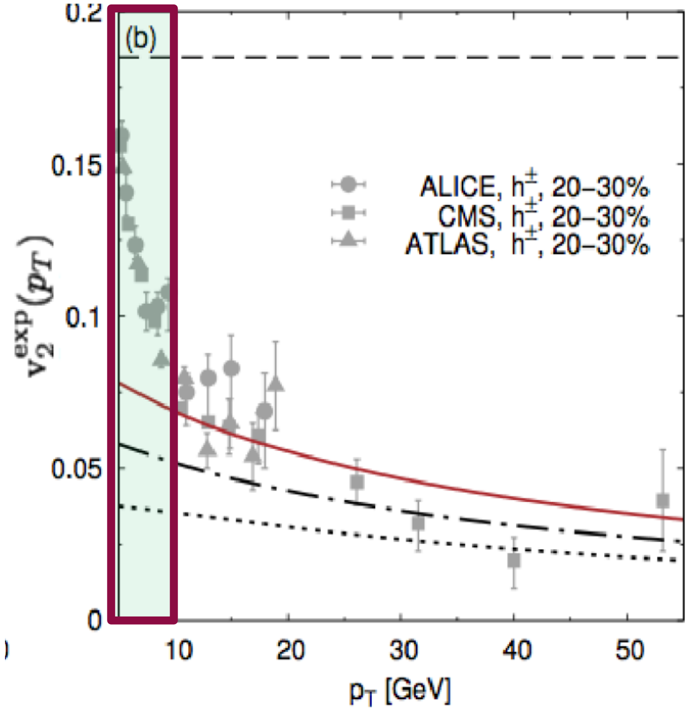
- Large surviving v_2 modulation at low-pT
  - Compare to: +/- 1% exp. uncertainty
- Conservative estimate of drift
  - Low temp cutoff removes large drift region
  - CNM effects + Coll. Energy loss reduce relative strength
  - No coalescence-type effects





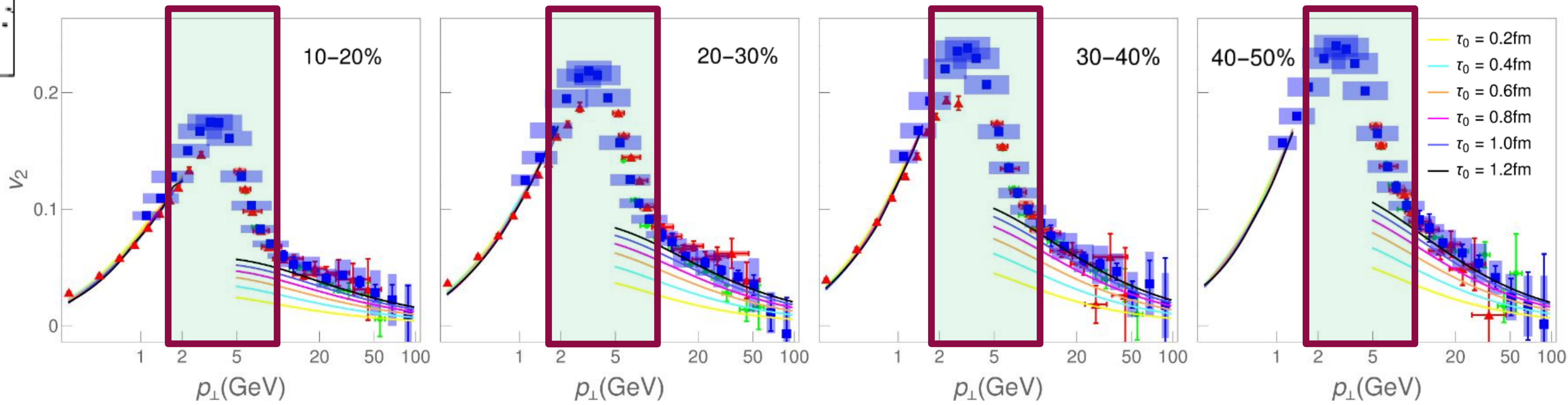
Importance for the R_AA x v_2 Puzzle

Drift produces measurable elliptic modulation at low pT that qualitatively matches elliptic flow missing in perturbative & similar calculations!

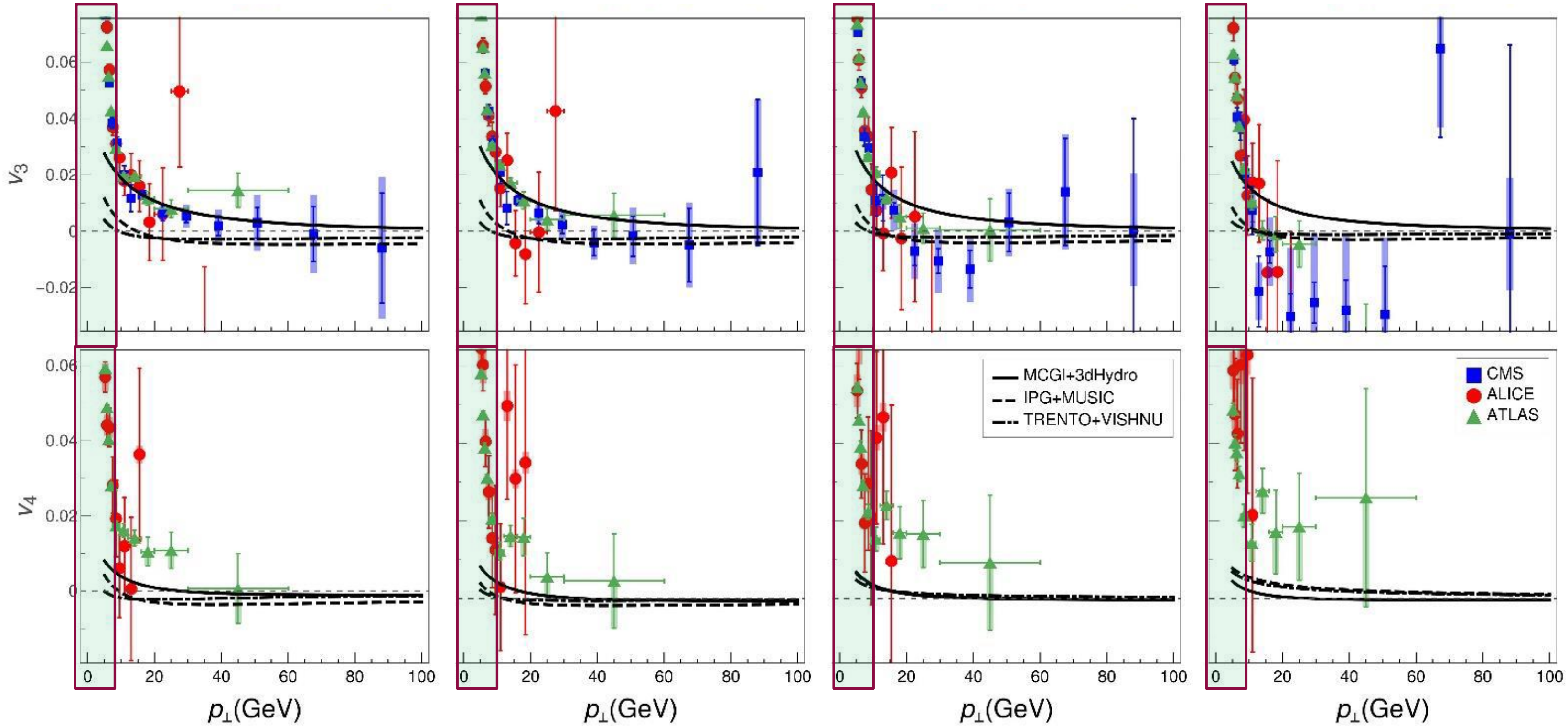


Parametric Energy Loss
Noronha-Hostler et al:
[(arXiv: 1602.03788)](https://arxiv.org/abs/1602.03788)

DREENA-A Ch. Had.
LHC PbPb
sqrt(s) = 5.02 TeV
Perturbative Energy Loss
Stojku et al.
(iNSPIRE:2640923)



Modulation not Limited to Elliptic Harmonics



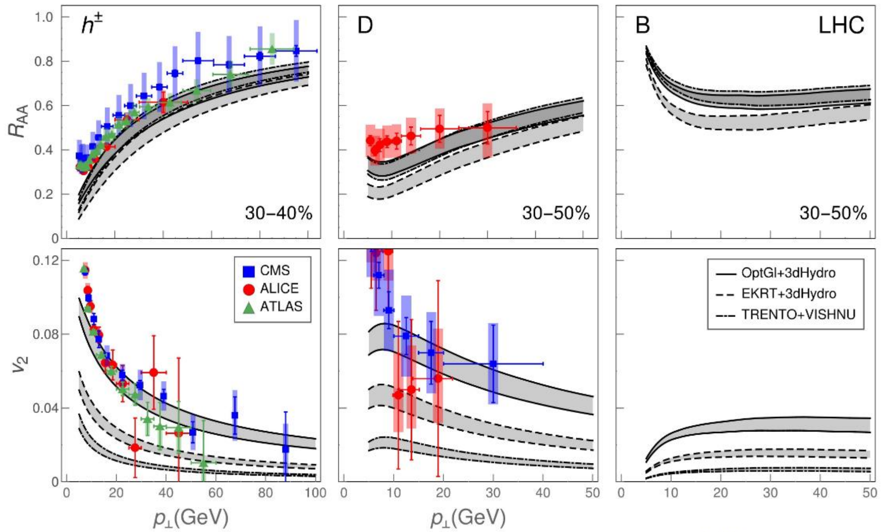
(arXiv:2208.09886)

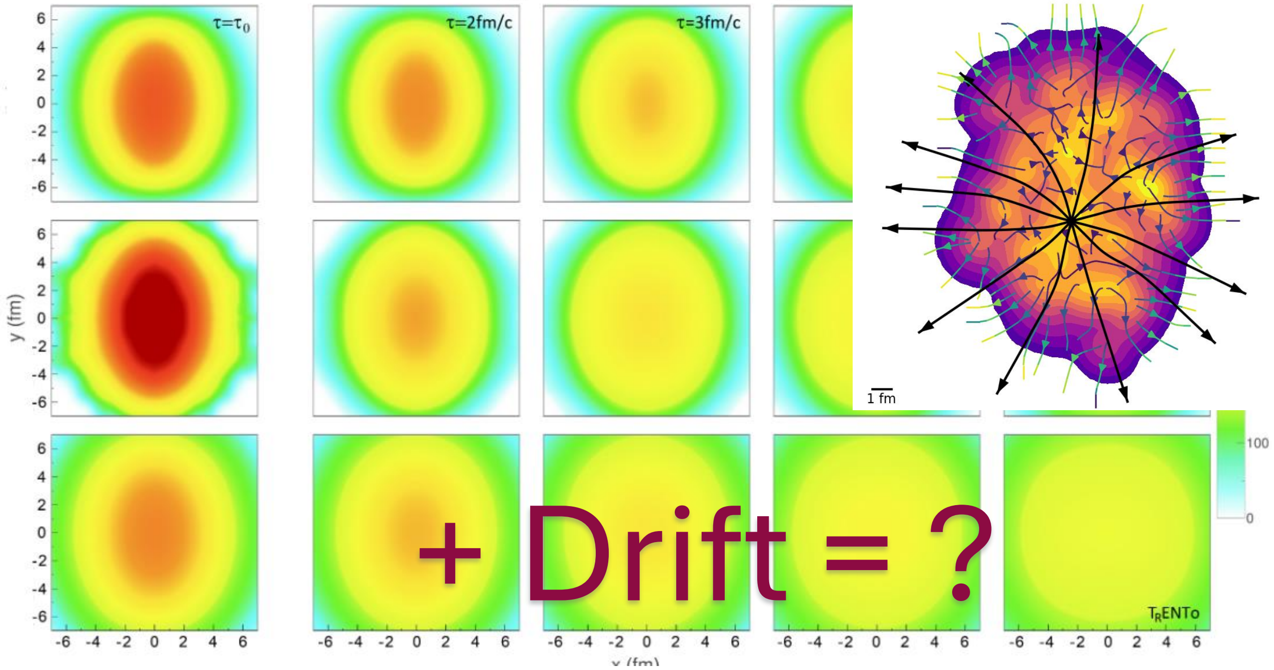
- Higher harmonic coupling works, too
- Possible importance to v_3 & v_4
- Difficult to couple to small anisotropies with energy loss alone
- Drift produces no substantial v_3 or v_4 enhancement in our model
  - Possibly needs better sampling
  - Large in later-time eccentricities

Drift v_n sensitive to pathlength ordered internal medium props.

(iNSPIRE:2606181)

- Drift distinguishes between high anisotropy at early times vs at late times via interplay with energy loss
  - Powerful additional constraint on evolution dynamics!!!
- How would a Bayesian parameter extraction like Magdalena's differ with the inclusion of drift?
  - Possibly selects on slightly smaller anisotropy, likely changes story of free streaming parameters

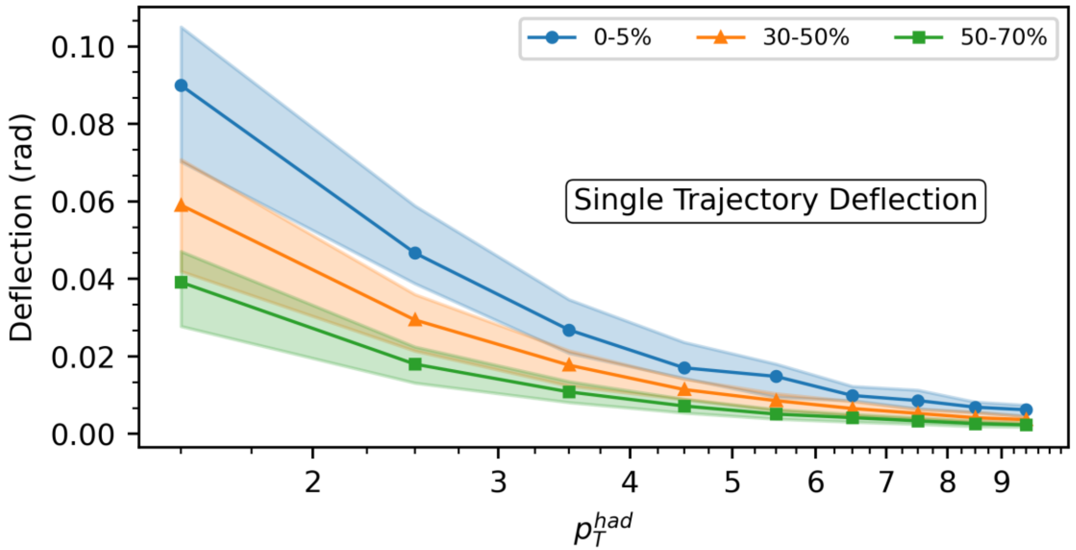


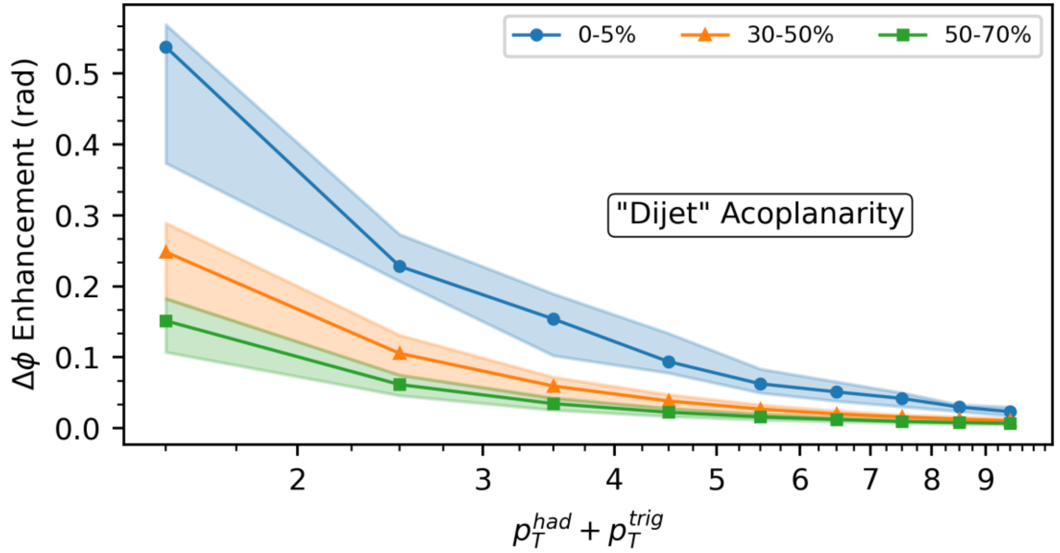


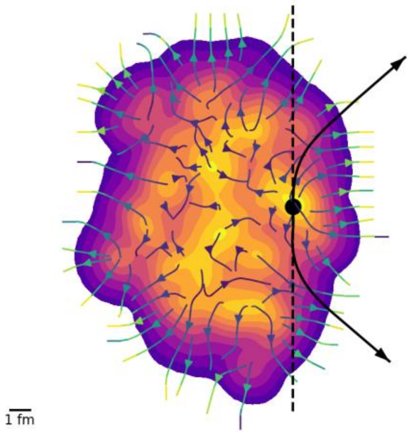
+ Drift = ?

Acoplanarity Enhancement RAD + CEL v. RAD

- Note centrality reversal
  - V_2 correlated to event plane
  - Acoplanarities access absolute deflections
- Initial acoplanarity fluctuation will change magnitude
  - Currently tree-level scattering: coplanar “dijets”

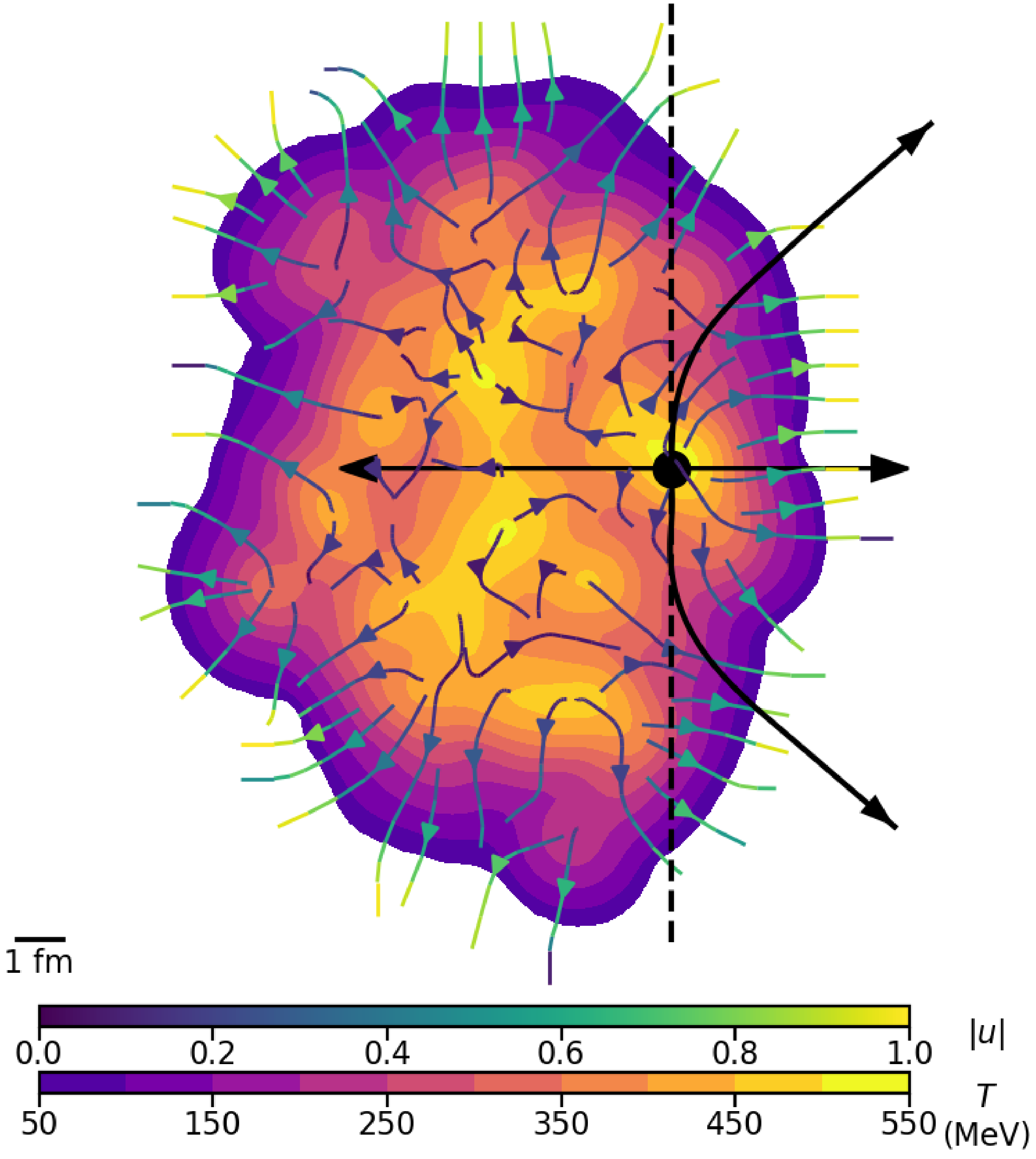






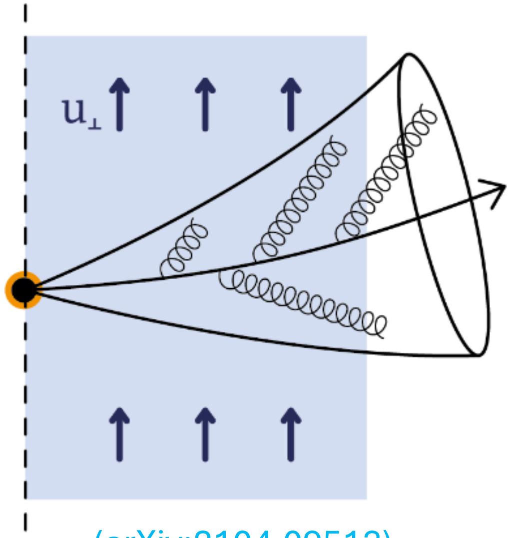
Acoplanarity Cuts

- Acoplanarity modulation still tied to event plane
  - Possible selection cuts for velocity tomography
  - Difficult to measure independent of pathlength effects
- Collimation effect possible along event plane

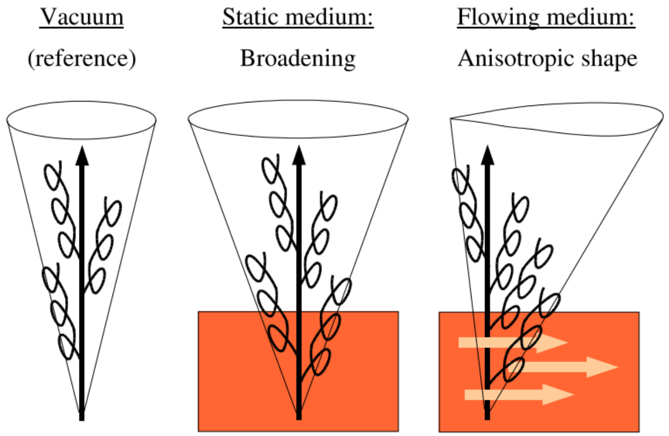


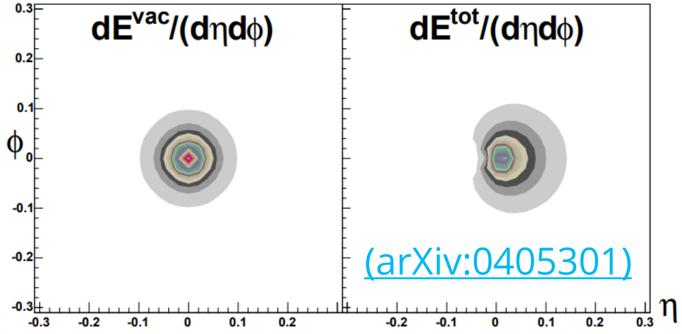
Anisotropic Jet Substructure

- People have been thinking about anisotropic radiation distribution for some time
  - Armesto, Salgado, & Wiedemann (2004)
    Flow anisotropy as Lorentz boost:
    https://inspirehep.net/literature/651342
  - Sievert, Sadofyev, Vitev (2021)
    Perturbative scalar calculation of radiation:
    https://inspirehep.net/literature/1859289
  - Barata, Milhano, & Sadofyev:
    Jet substructure harmonics:
    https://inspirehep.net/literature/2684595
  - Kuzmin & López
    Perturbative real gluon calculation of radiation:
    https://inspirehep.net/literature/2801226
- Drift of jet particles is also likely important!

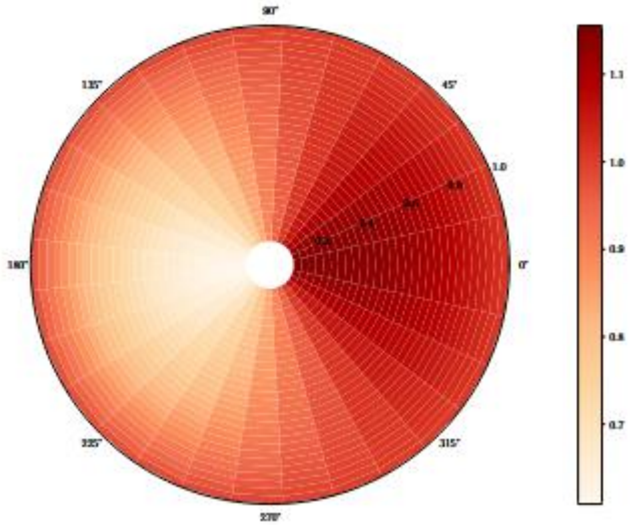


(arXiv:2104.09513)





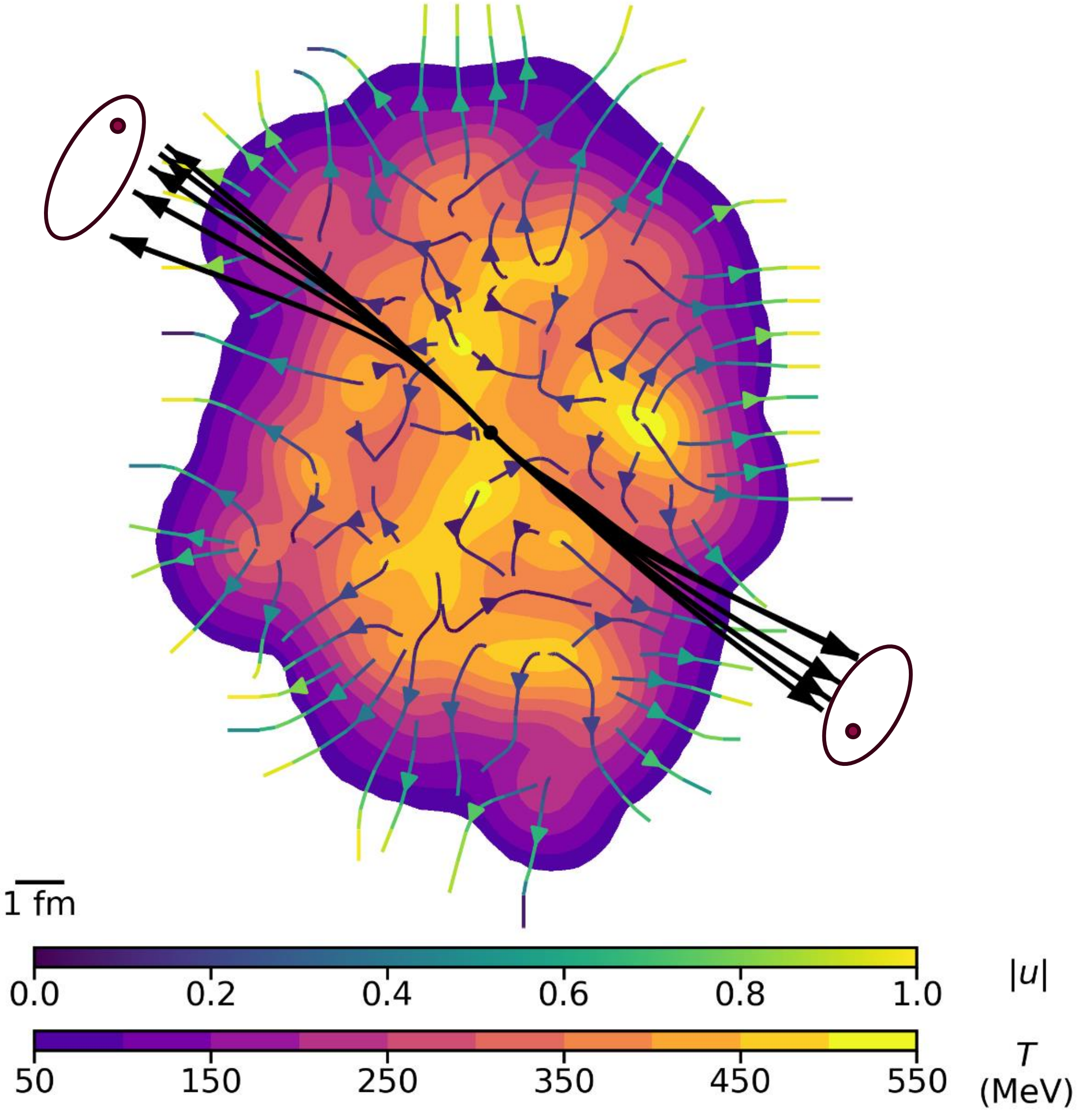
(arXiv:0405301)



(arXiv:2308.01294)

Drift of Ensemble of Particles

- Energy suppression naturally produces dispersion of hard and soft particles within jet
- Sub-eikonal property a detriment for inclusive measurements, but well suited for jet substructure modification

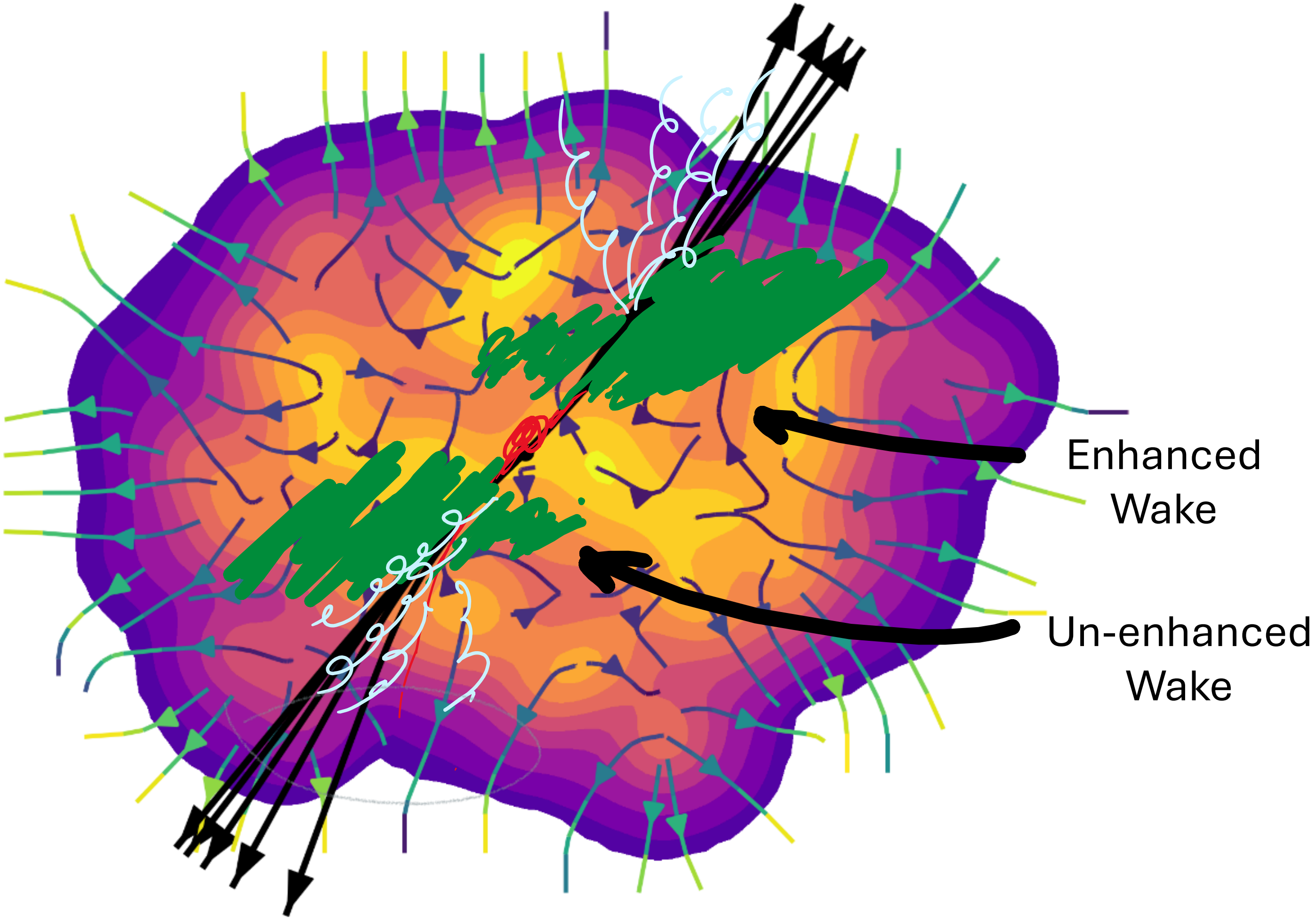


$$\langle \vec{q}_{drift} \rangle = \hat{e}_\perp \int d\tau \frac{3}{\boxed{E(\tau)}} \frac{\mu^2(\tau)}{\lambda(\tau)} \ln \frac{E(\tau)}{\mu(\tau)} \frac{u_\perp(\tau)}{1-u_\parallel(\tau)}$$

Energy suppressed

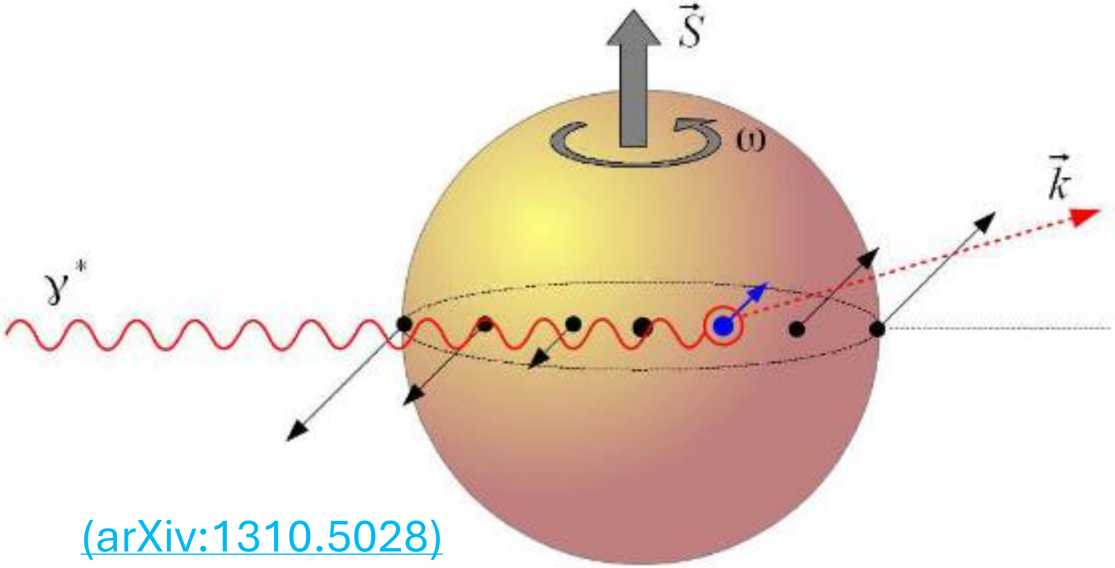
Anisotropic Jet Wake

- Conservation of momentum – should be anisotropic wake
  - Constructive with induced radiation anisotropy
- How does this interplay with jet substructure anisotropies?
  - Possible anisotropic background contamination of jet substructure observables



Drift at the EIC

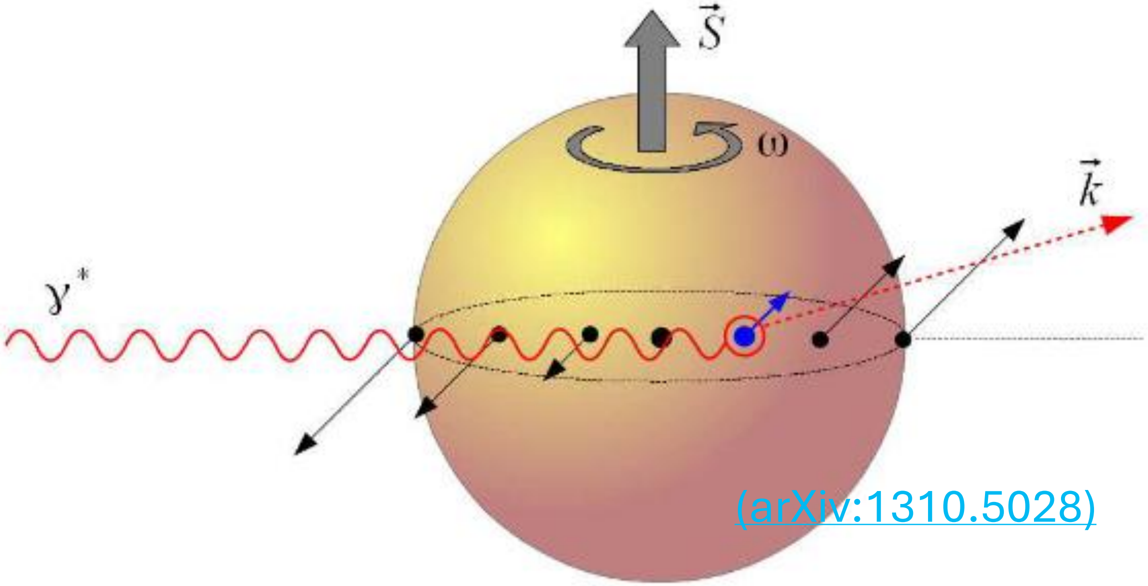
- Cold nuclear matter anisotropies can couple similarly to QGP flow
  - "Spin flow", gradients, etc.
- Possible distinction between pre-equilibrium and equilibrium anisotropy
  - Could provide constraints on pre-equilibrium qhat
- Possible large impact on tomographic parameter extraction via hard probes
- Comparative laboratory for jet substructure dispersion



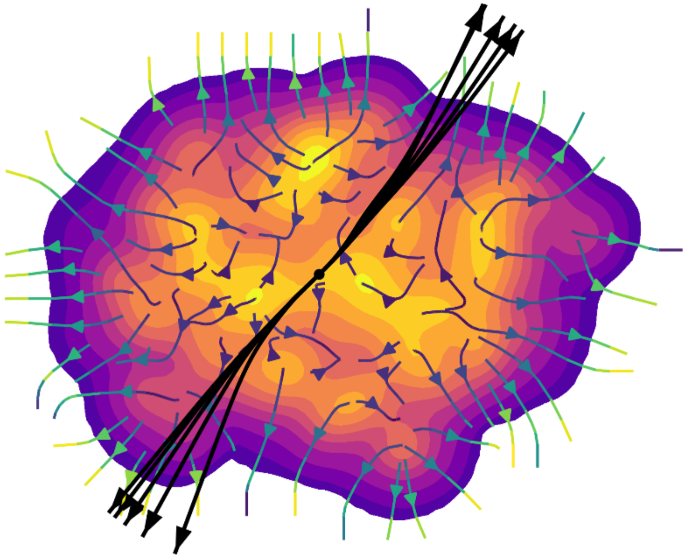
(arXiv:1310.5028)

Next Steps for Drift investigations

- CNM drift investigations
  - Drift due to polarized nuclei
  - Nicholas Baldonado, Alex Garcia, & Matt Sievert
- Jet Substructure
  - Drift-dispersion + flow-induced radiation => jet substructure anisotropy
  - Jo Bahder, Hasan Rahman, Matt Sievert, & Ivan Vitev

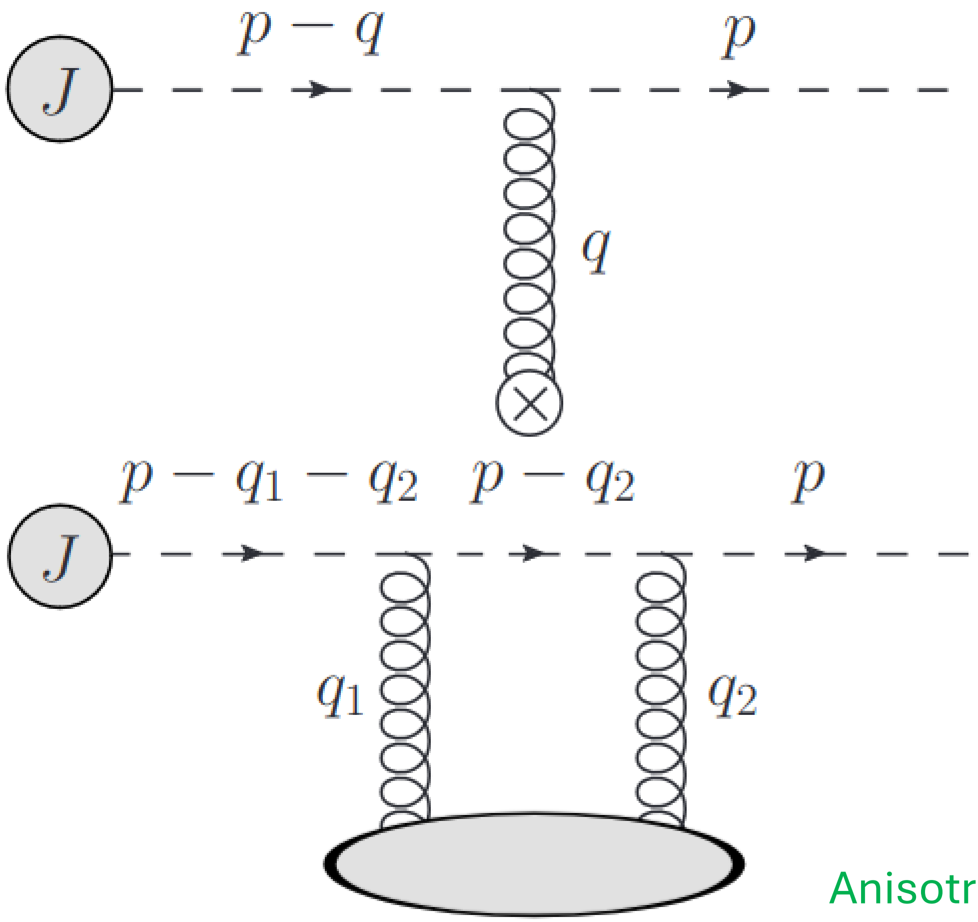


(arXiv:1310.5028)



Discussion!

Jet Broadening – Isotropic vs Anisotropic

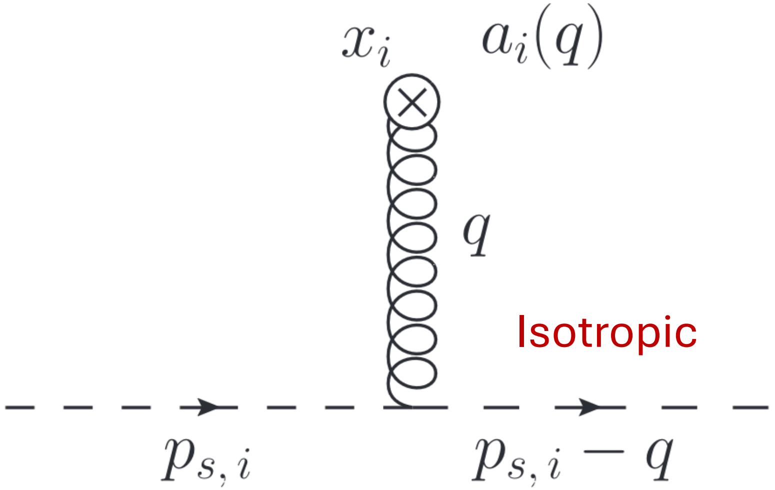


Anisotropic

$$g\, a_i^{\mu a}(q) = t_i^a\, u_i^\mu\, v_i(q)\, (2\pi)\, \delta\left(q^0 - \boxed{\boldsymbol{u}_i \cdot \boldsymbol{q}}\right)$$

Preferred direction!

A. V. Sadofyev, I. Vitev,
& M. D. Sievert
Phys.Rev.D 104 (2021)
(arXiv:2104.09513)



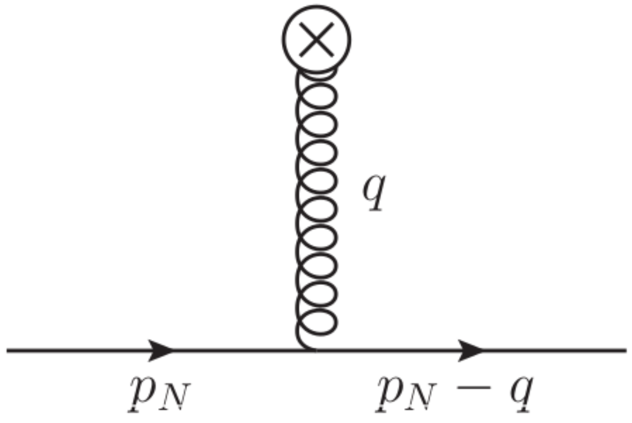
Isotropic

$$a_i^{\mu\, a}(q) = g^{\mu +}(t^a)_i \left[2\pi \boxed{\delta(q^+)}\right] \left[\frac{-g_{eff}}{q_T^2}\right]$$

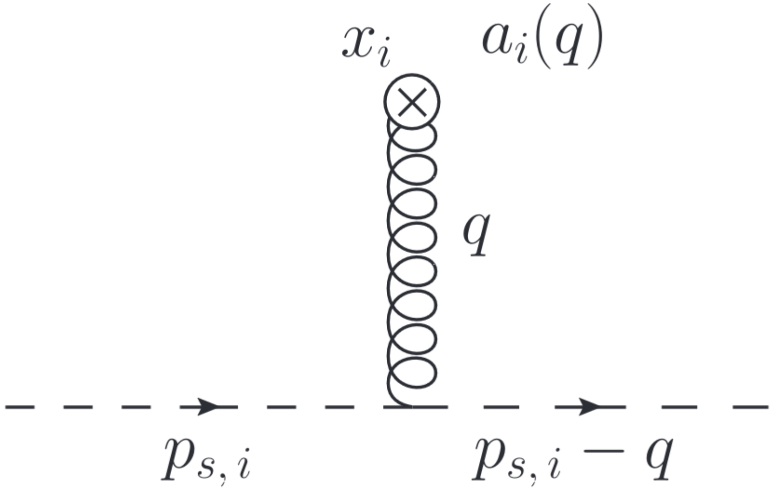
No vector info

- Difference in setup – constraints on external gluon field
- Isotropic
  - Jet quark moves lightcone (+), medium quark moves lightcone (-)
- Anisotropic
  - Jet quark moves lightcone (+), medium quark moves with medium flow
- Two vector directions associated with the medium
  - Flow
  - Gradients

Medium Gluon Field Potentials



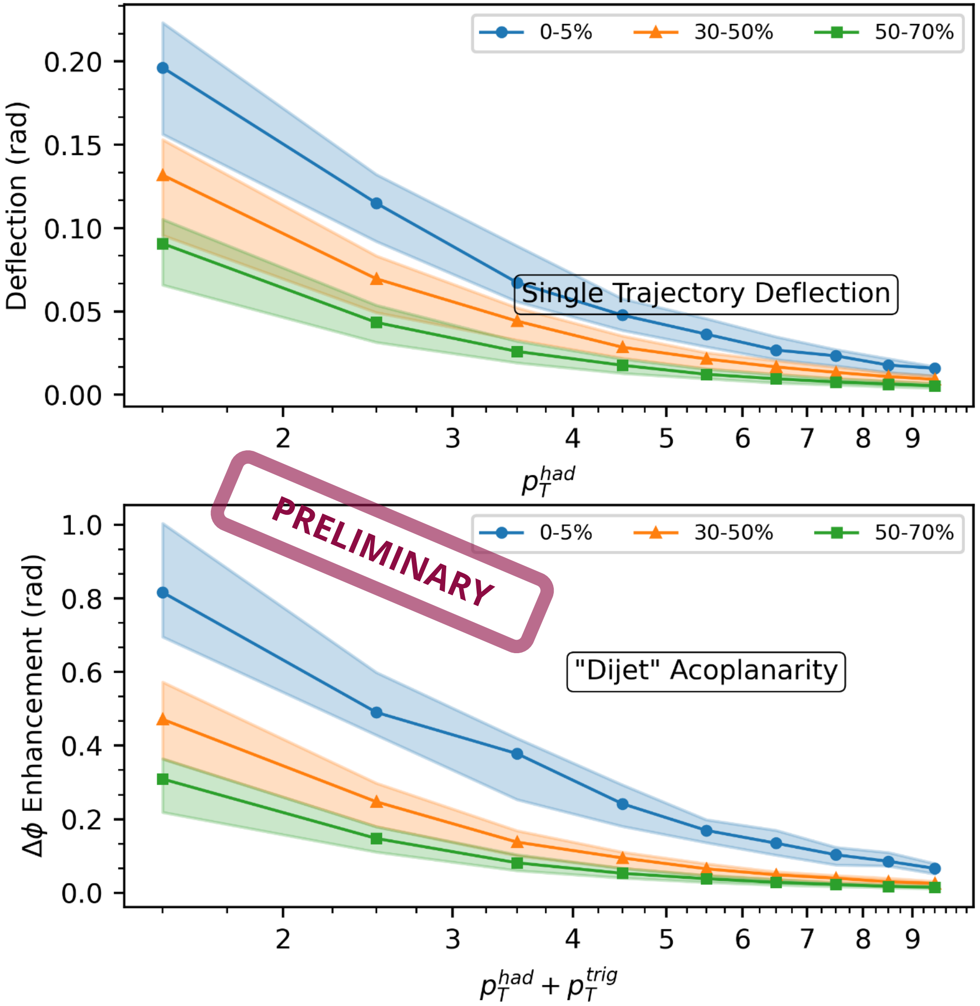
$$a_i^{\mu\, a}(q) = g^{\mu +}(t^a)_i \; \underbrace{\left[2\pi\delta(q^+)\right]}_{\substack{\text{Eikonal}\\ \text{delta function}\\ \text{(antiparallel)}}} \; \underbrace{\left[\frac{-g_{eff}}{q_T^2}\right]}_{\substack{\text{v(q)}\\ \text{Isotropic}\\ \text{scattering}\\ \text{centers}}}$$

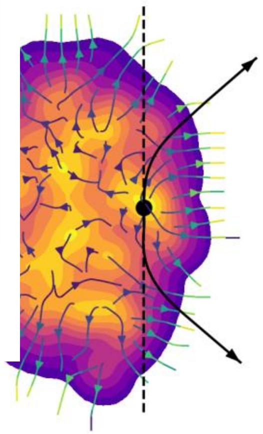


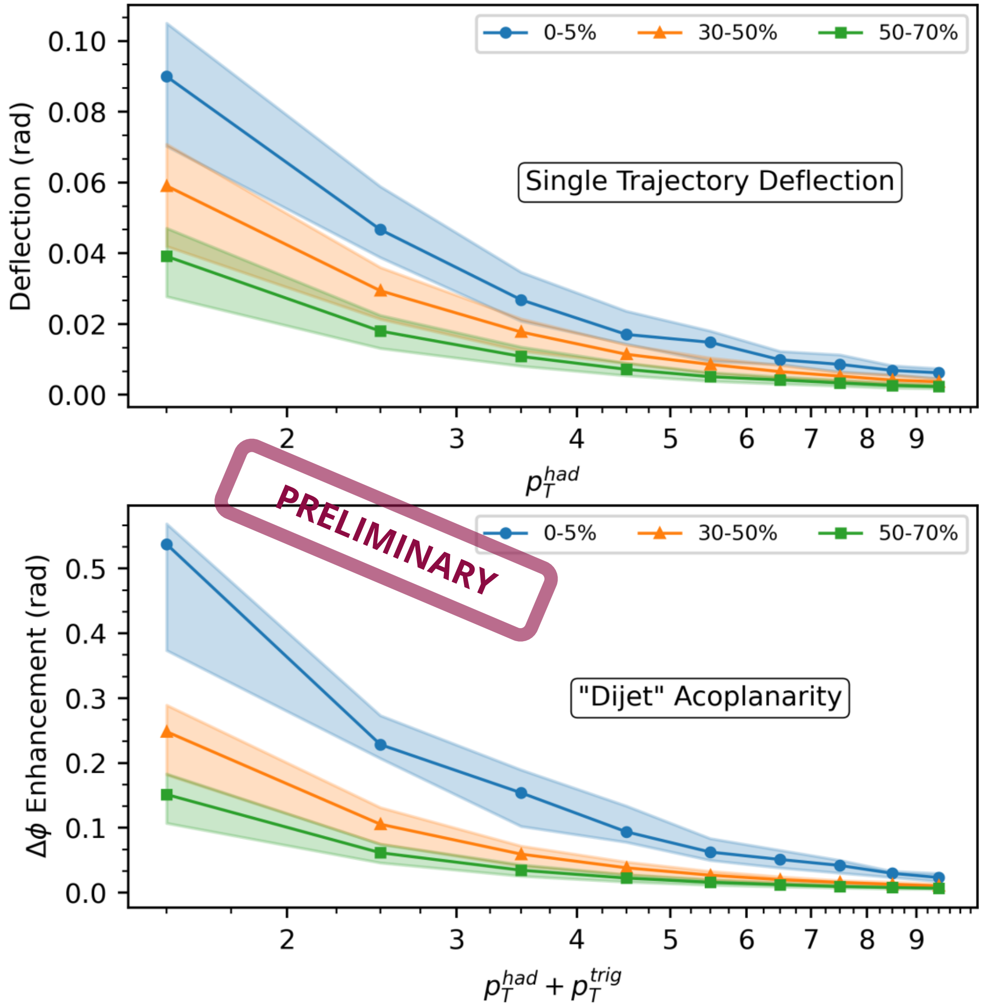
$$\left. g\, a_i^{\mu a}(q) = t_i^a\, u_i^\mu\, v_i(q)\, (2\pi)\, \delta\left(q^0 - \boldsymbol{u}_i \cdot \boldsymbol{q}\right) \right\} \text{Quark moves with medium}$$

$$v_i(q) \equiv v_i\left(\boldsymbol{q}^2 - (\boldsymbol{u}_i \cdot \boldsymbol{q})^2\right) \equiv \frac{-g^2}{\underbrace{\boldsymbol{q}^2 + \mu_i^2 - (\boldsymbol{u}_i \cdot \boldsymbol{q})^2 - i\epsilon}_{\substack{\text{v(q)}\\ \text{Directional}\\ \text{scattering}\\ \text{centers}}}}$$

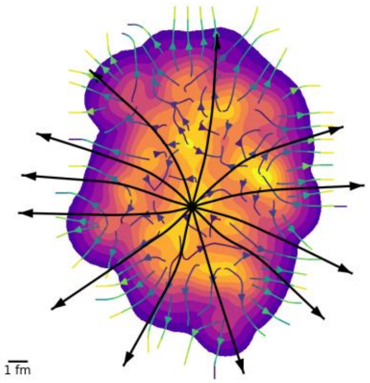
Acoplanarity Enhancement RAD + CEL v. RAD

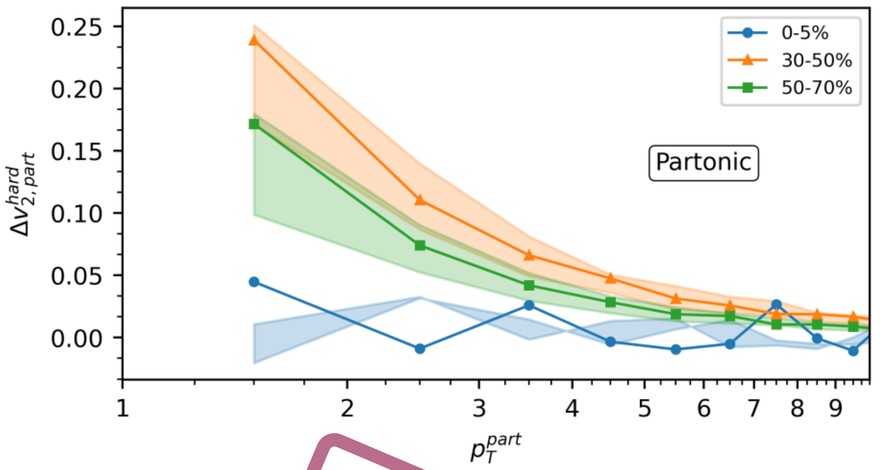


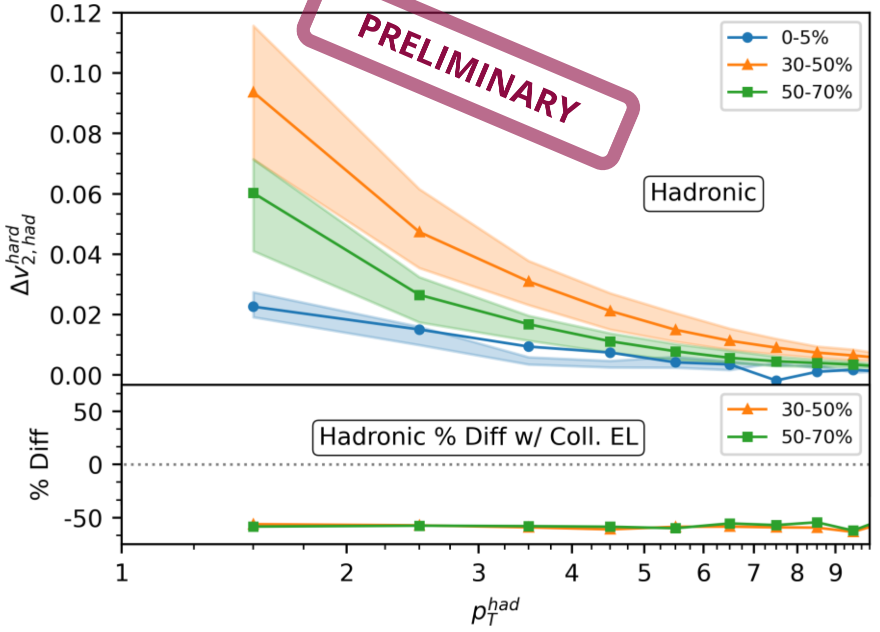


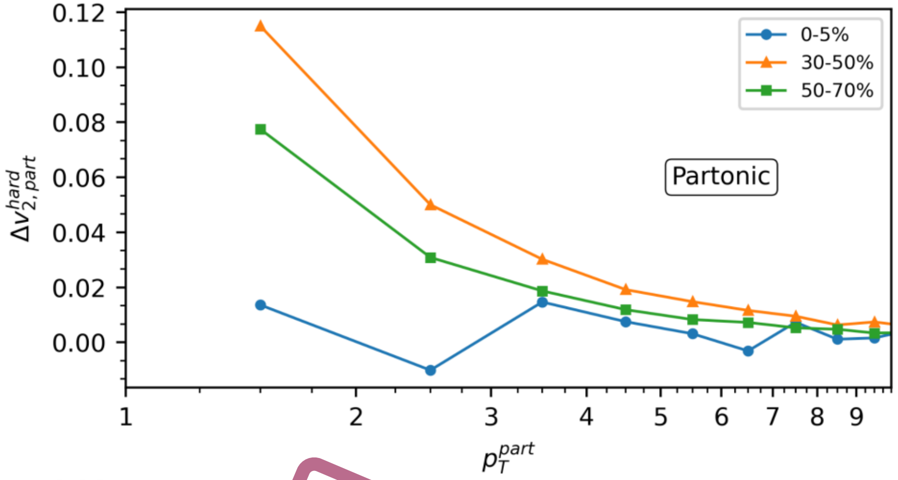


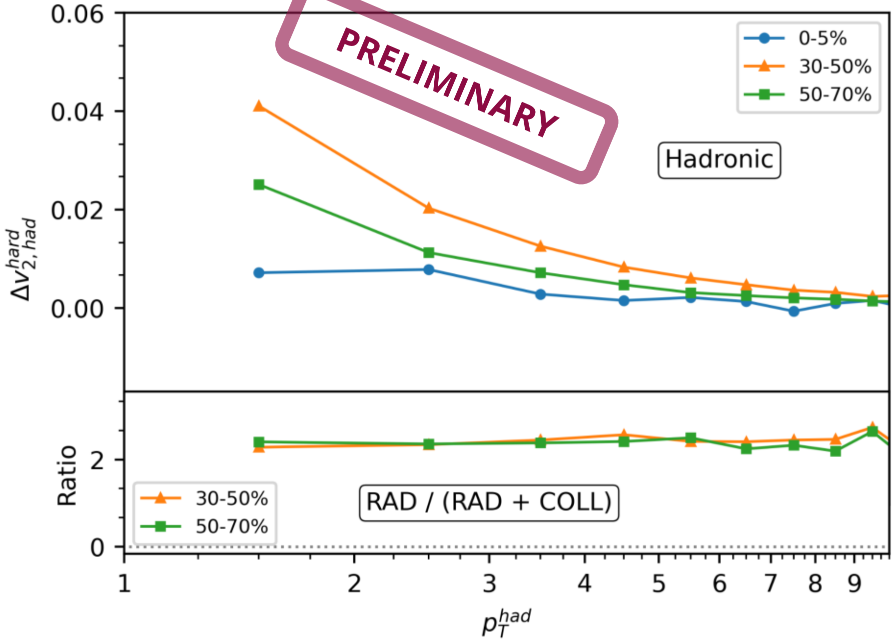
v2 Enhancement RAD + CEL v. RAD











CNM Effects

Implemented as in (arXiv:0209161)
Sans energy los

$$R_{BA}(p_T) = \begin{cases} \frac{d\sigma^{dA}}{dyd^2\mathbf{p}_T}\Big/\frac{2A\, d\sigma^{pp}}{dyd^2\mathbf{p}_T} & \text{in } \ d+A \\ \frac{dN^{AA}(b)}{dyd^2\mathbf{p}_T}\Big/\frac{T_{AA}(b)\, d\sigma^{pp}}{dyd^2\mathbf{p}_T} & \text{in } \ A+A \end{cases} , \qquad (1)$$

Compute CNM R_{AA} – Reweight distribution of hard processes

$$\left.\begin{array}{r} \frac{1}{2A}\frac{d\sigma^{dA}}{dyd^2\mathbf{p}_T} \\ \frac{1}{T_{AA}(b)}\frac{dN^{AA}(b)}{dyd^2\mathbf{p}_T} \end{array}\right\} = K\sum_{abcd}\int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b \, g(\mathbf{k}_a) g(\mathbf{k}_b)$$

$$\boxed{\times \, S_A(x_a, Q_a^2) S_B(x_b, Q_b^2)}$$

Shadowing Function

PDFs

$$\times \boxed{f_{a/A}(x_a, Q_a^2) f_{b/B}(x_b, Q_b^2)} \frac{d\sigma^{ab\to cd}}{d\hat{t}}$$

CNM Energy Loss Prob. (Not Used)

$$\boxed{\times \int_0^1 d\epsilon \, P(\epsilon)} \frac{z_c^*}{z_c} \boxed{\frac{D_{h/c}(z_c^*, Q_c^2)}{\pi z_c}} . \qquad (2)$$

FFs