Phenomenology of Jet Drift in Heavy Ion Collisions

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Hard Probes 2024
24th September, 2024

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In collaboration with
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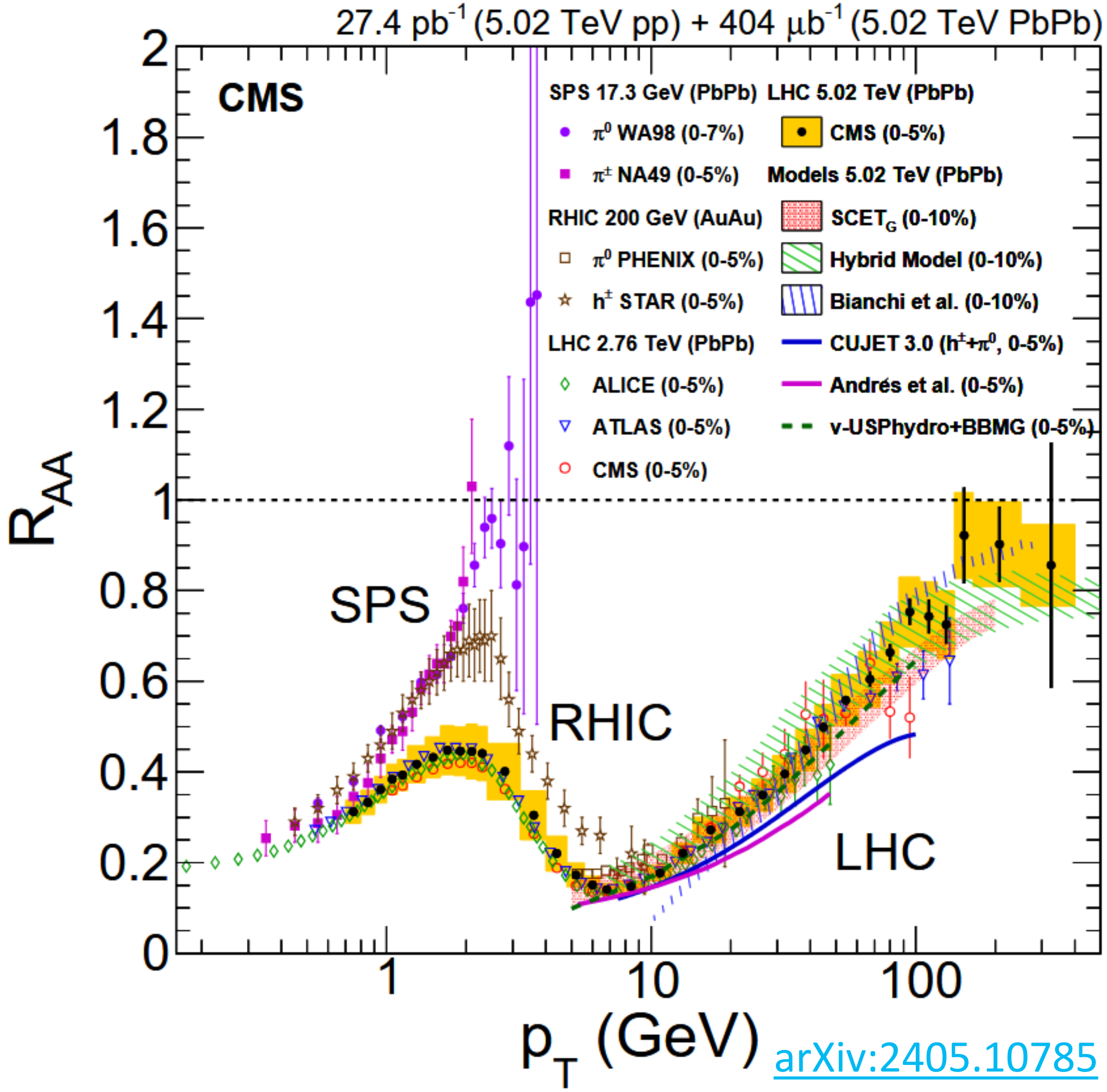
and Ivan Vitev

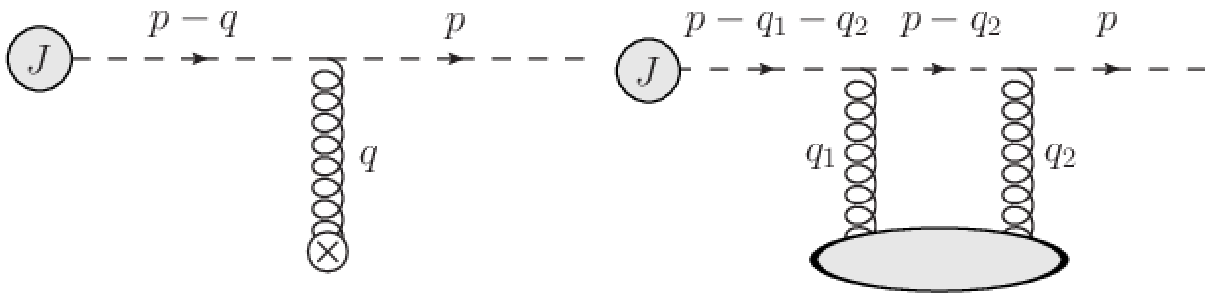
The State of Hard Probe Tomography

- Delivery of hard probe tomography lackluster
  - Many microscopic models obtain results similar to data (e.g. ch. had. R_AA)
- Two options for successful hard probe tomography
  - New observables (EECs & jet substructure)
  - Regions of phase space where hard probes interact in more discriminating ways (e.g. < 10 GeV)
- Both require new precision perturbative calculations, e.g. $\mathcal{O}\left(\frac{\mu}{E}\right)$ corrections & precise calculation inputs



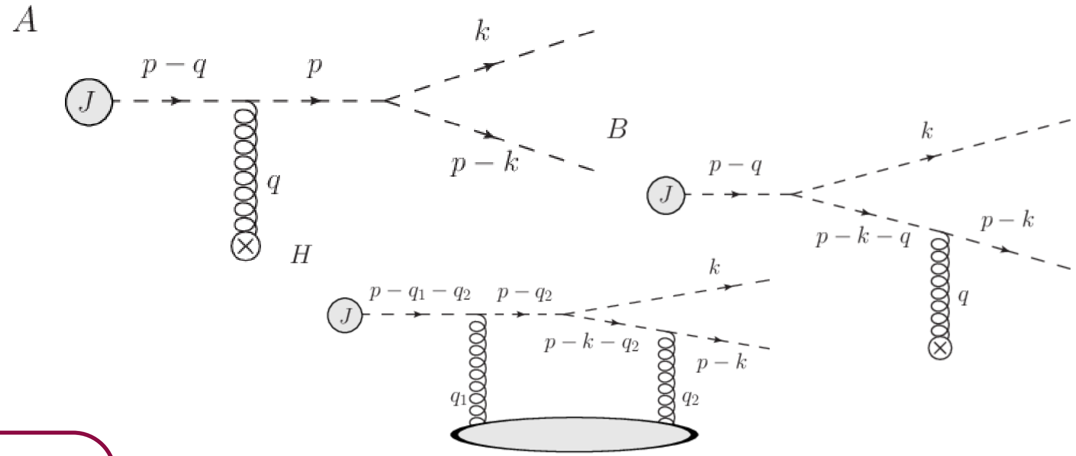
arXiv:2405.10785

Momentum Broadening & Radiation in the Presence of Flow

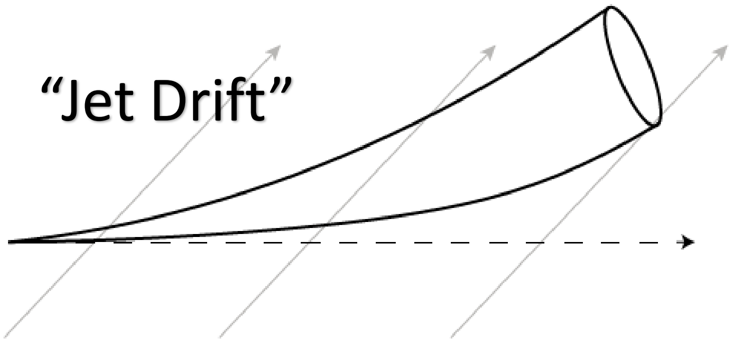


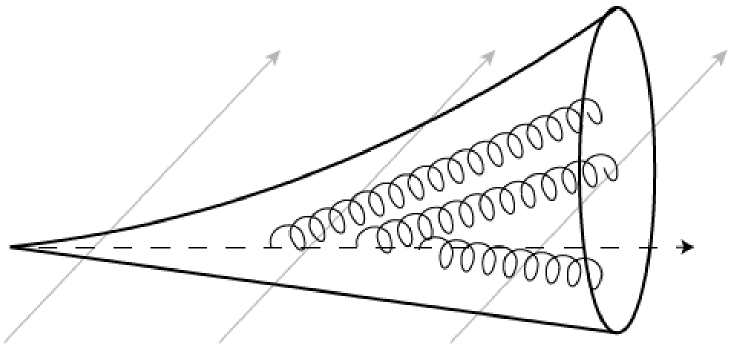
Born & Double-Born Momentum Broadening Diagrams

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



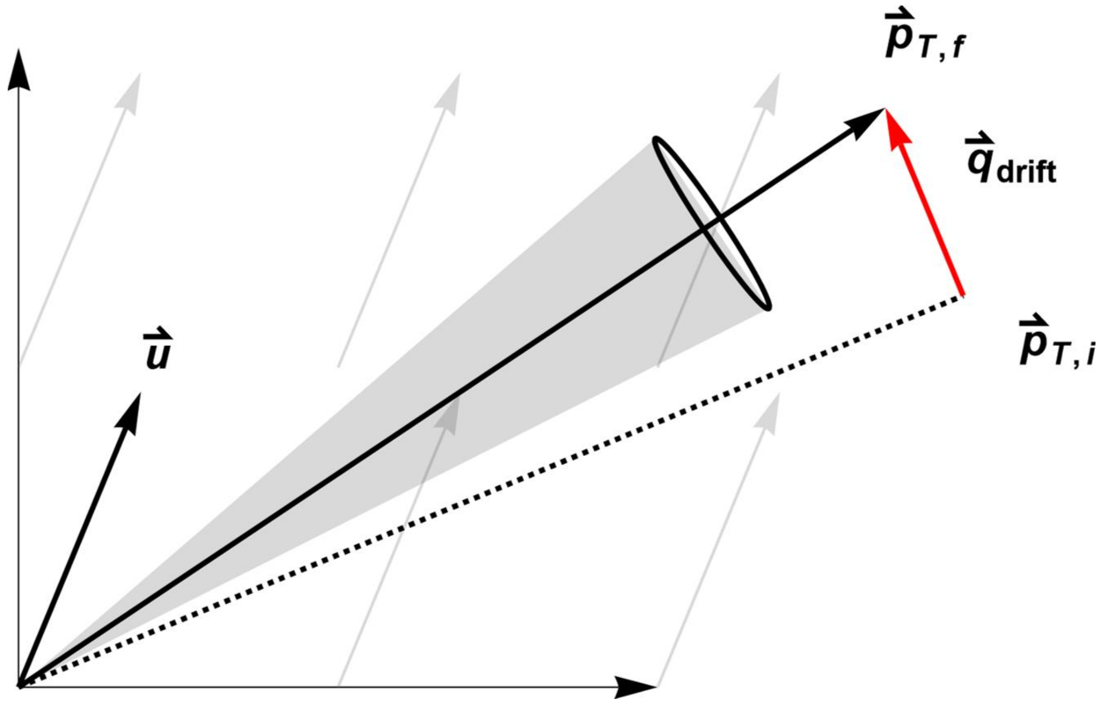
E.G. Born & Double-Born Radiation Diagrams





New systematic behavior at $\mathcal{O}\left(\frac{\mu}{E}\right)$

Anisotropic Jet Broadening: Jet Drift



- "Jet Drift": Preferential broadening in direction of medium flow
- Part of a "New" class of $\mathcal{O}\left(\frac{\mu}{E}\right)$ pQCD effects: asymmetric / anisotropic

Flow enhanced and flow direction controlled

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

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

Energy suppressed

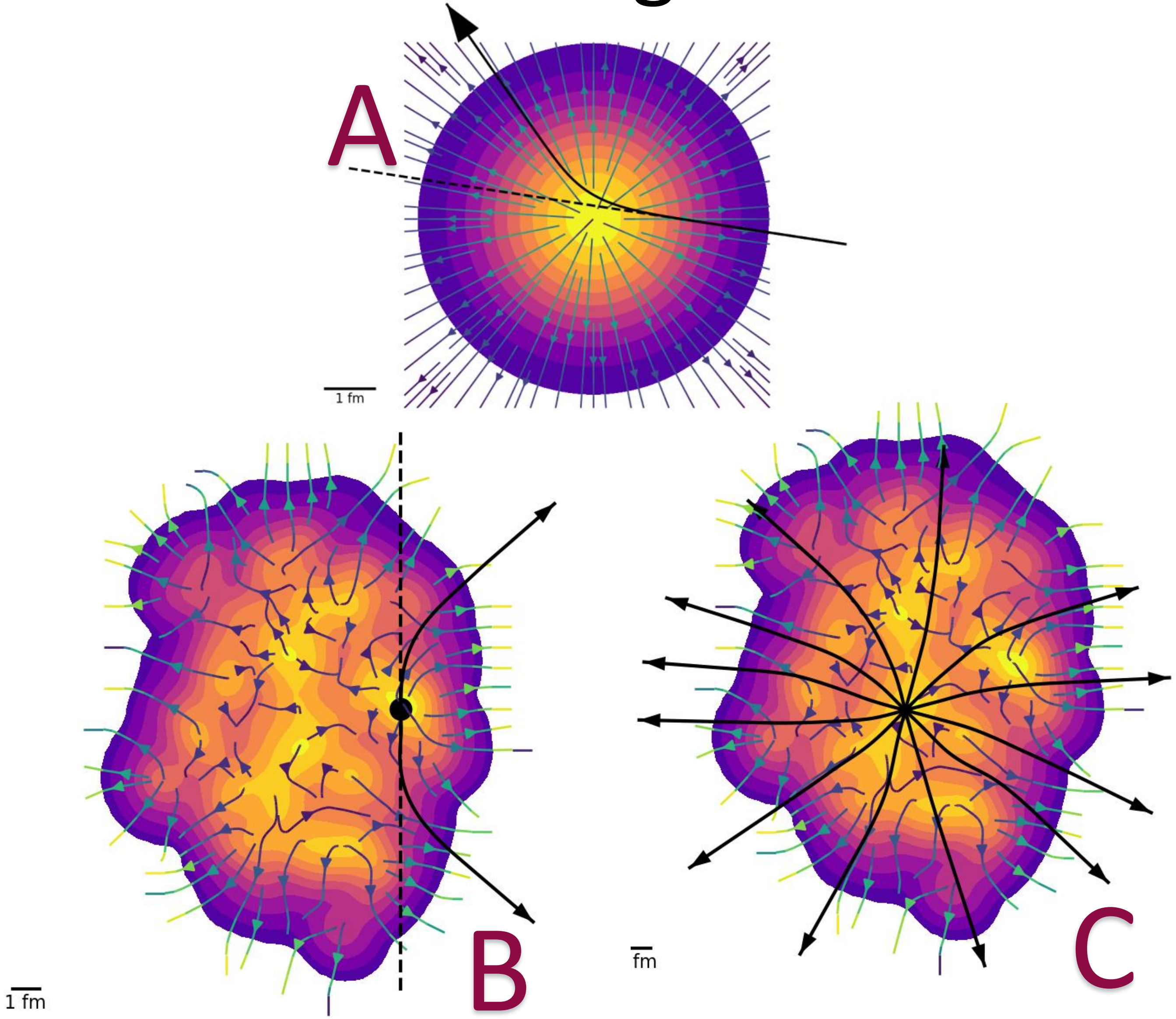
Temperature/Density Enhanced

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

Analytic Pheno.
L. Antiporda, J. Bahder, H. Rahman & M. D. Sievert
Phys.Rev.D 105 (2022)
(arXiv: 2110.03590)

Possible Signatures of Jet Drift in Leading Hadrons

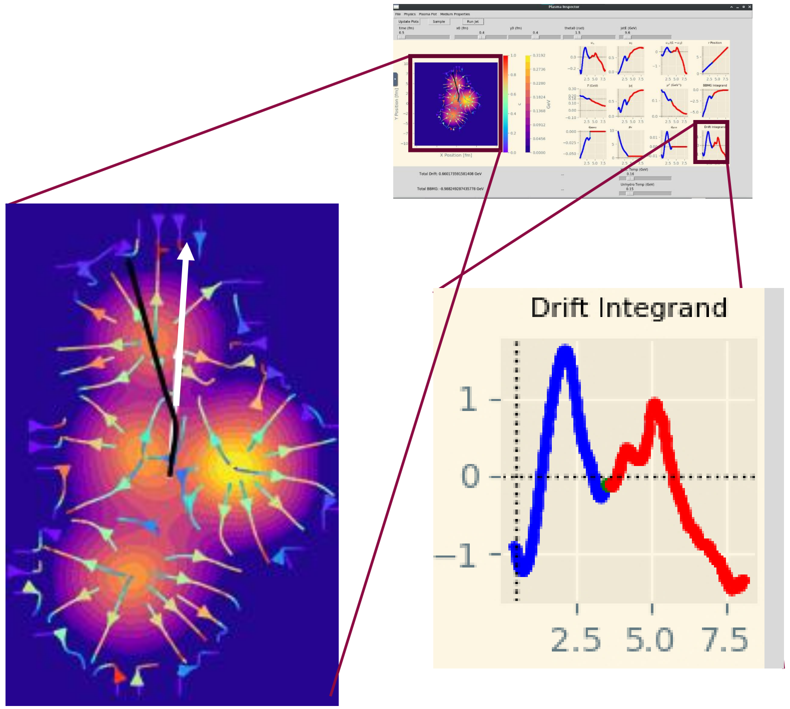
- Modification of suppression (A)
  - Deflecting away from flowing hot spots
  - Particle sees reduced integrated density
- Dihadron/dijet acoplanarity enhancements (B)
  - Particles couple to same “attractor” in the medium
- Anisotropic flow modification (C)
  - Particles couple to soft anisotropic flow



APE: A Primitive Monte Carlo

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

Study in $\sqrt{s}$ =5.02 TeV PbPb



Hard Particles (APE Workflow)

- Perturbative Tree Level Scatterings: Pythia pp Hard Scatterings + Perturbative CNM
- Perturbative Partonic Evolution: Anisotropic Partonic Evolution (APE)
- Perturbative Fragmentation: Fragmentation Functions (FFs)
- Observables

Soft Particles (DukeQCD Event Generator)

- Trento + Freestreaming Initial Conditions
- OSU-Hydro (VISHNU) Hydrodynamics
- Cooper-Frye Freezeout + UrQMD Hadronic Transport

(arXiv:1808.02106)

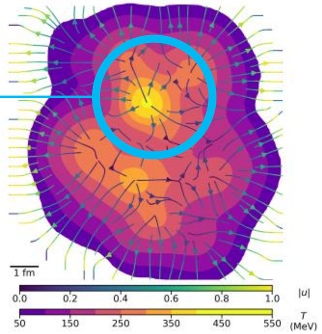
Realistic 2+1D soft HIC model tuned to pPb & PbPb data

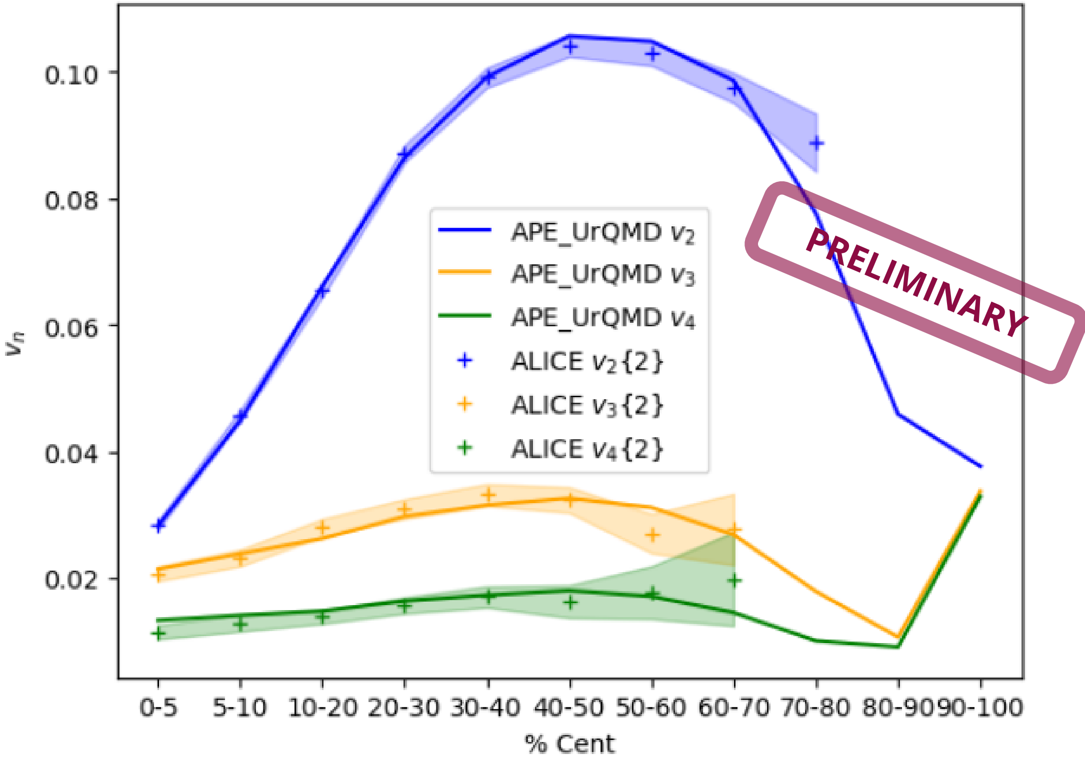
DukeQCD's HIC Event Generator

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

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
  - Maximizes disruption of event-correlated drift

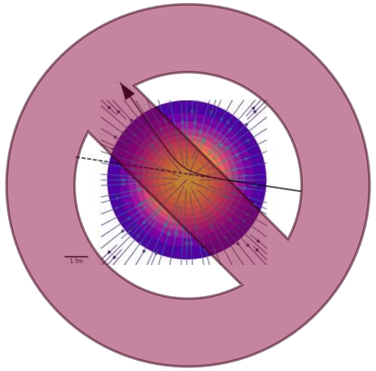




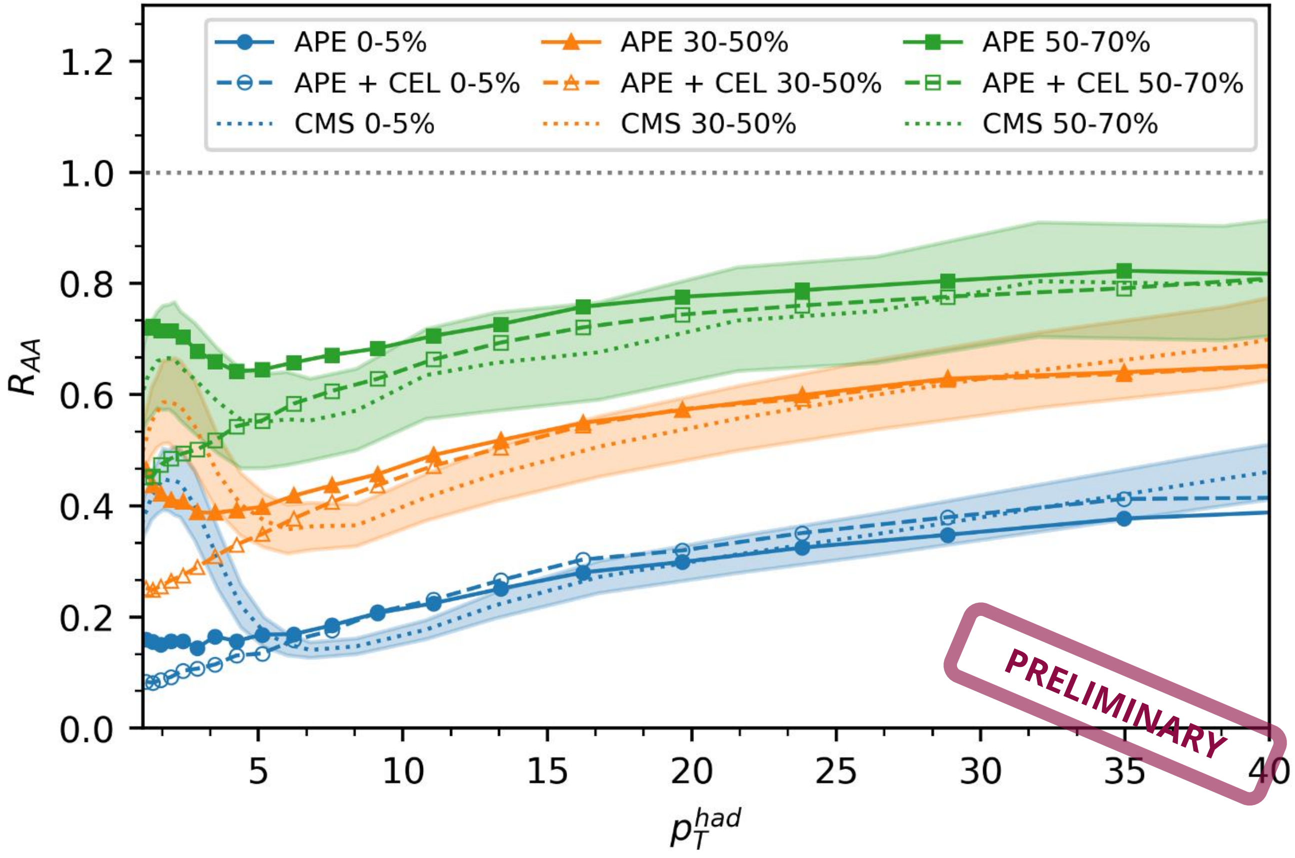
Target: Lower Bound of Drift

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

No Suppression Reduction

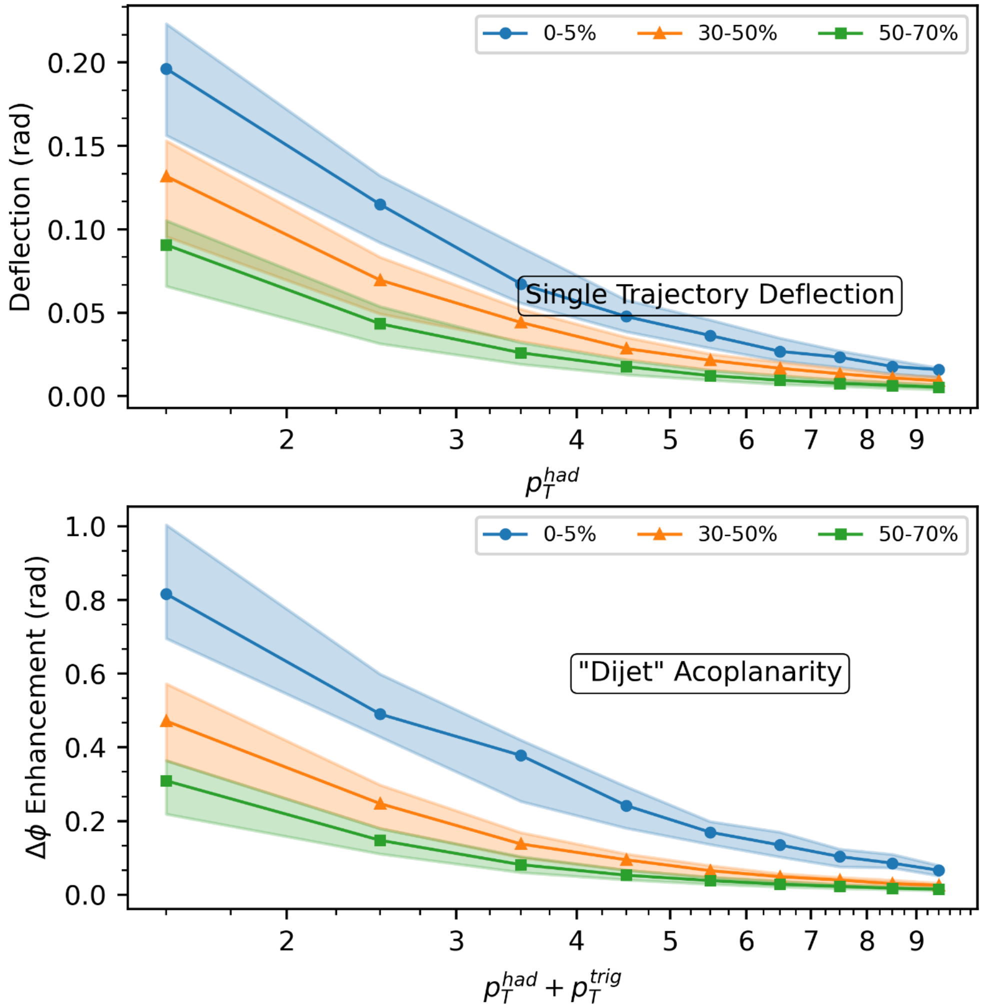


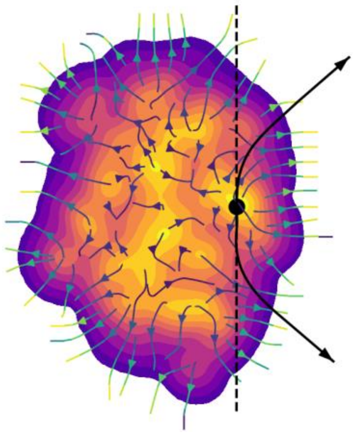
- Drift does not measurably modify R_AA(p_T)
  - Very useful – can tune coupling
  - Rad: g=2.0, Rad + Coll: g=1.6
- Additional sources of high-pT energy loss reduce effective drift coupling
- Better performance at low-pT can only enhance drift



Deflection Size & Acoplanarity Enhancement

- 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”

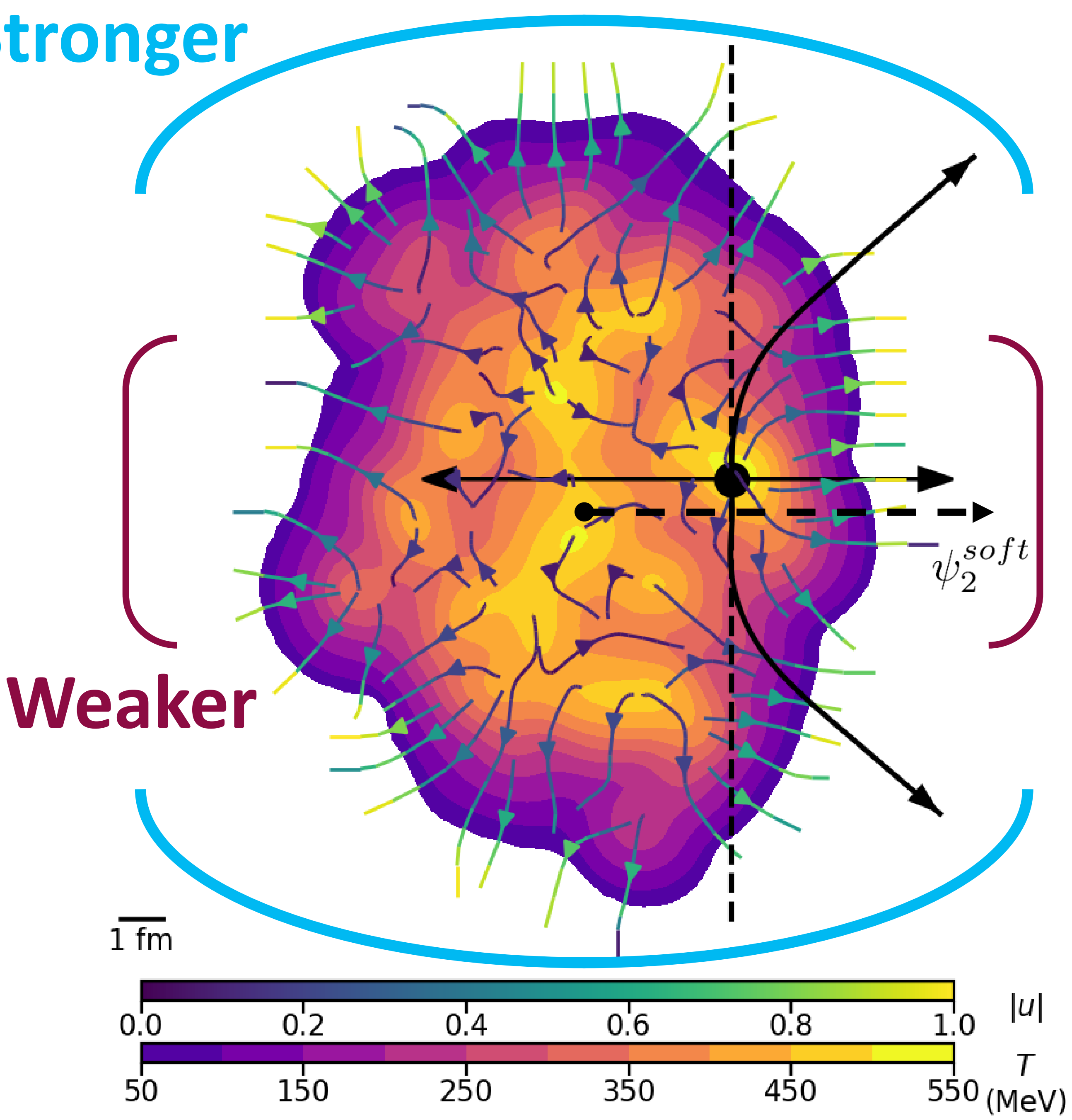




Colored band: drift +/- 25 % strength

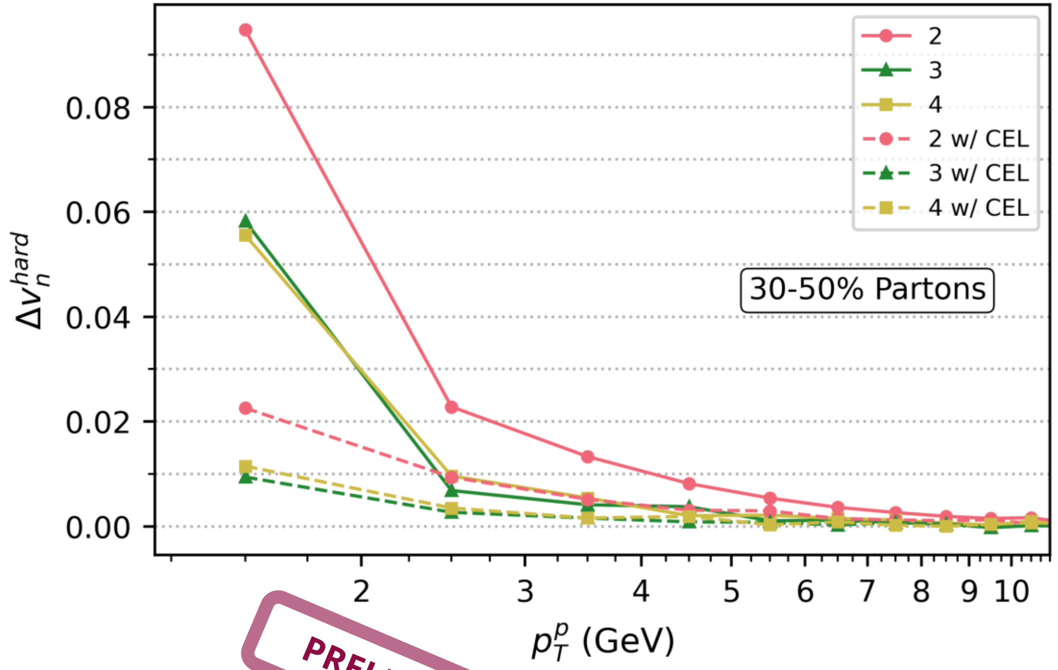
Acoplanarity Cuts

- 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

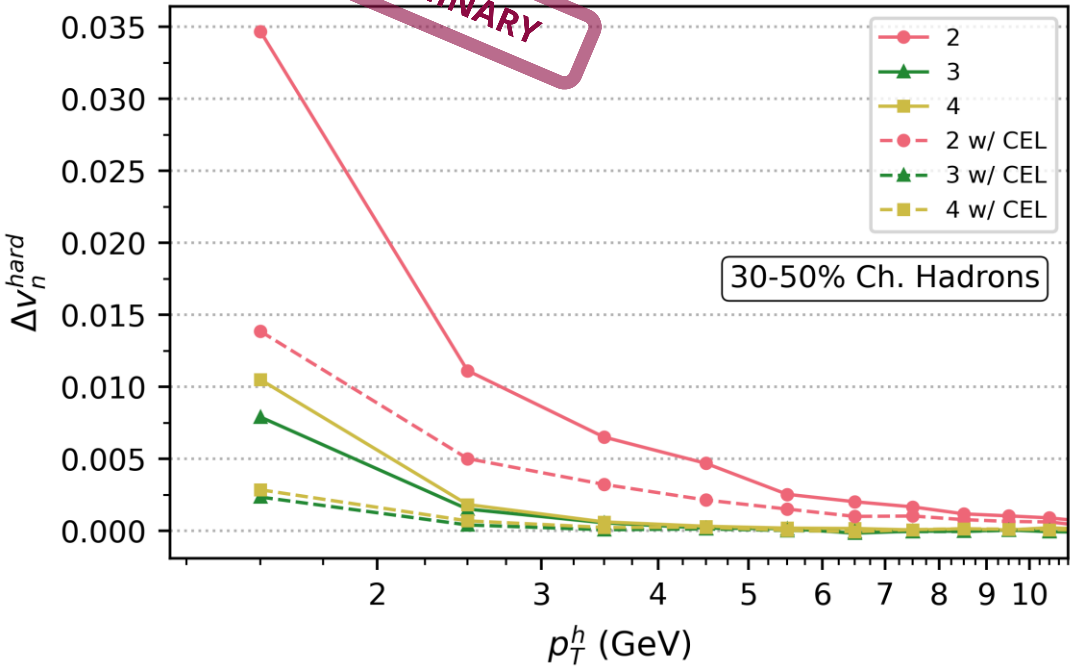


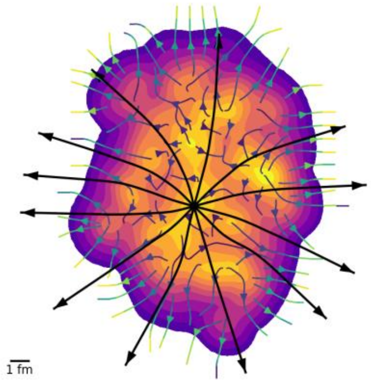
Vn is Enhanced by Drift

- Large surviving v_2 modulation at low-pT
  - Compare to: +/- 0.005 exp. uncertainty
- Conservative estimate of drift
  - Low temp cutoff removes large drift region
  - CNM effects + Coll. Energy loss reduce relative strength



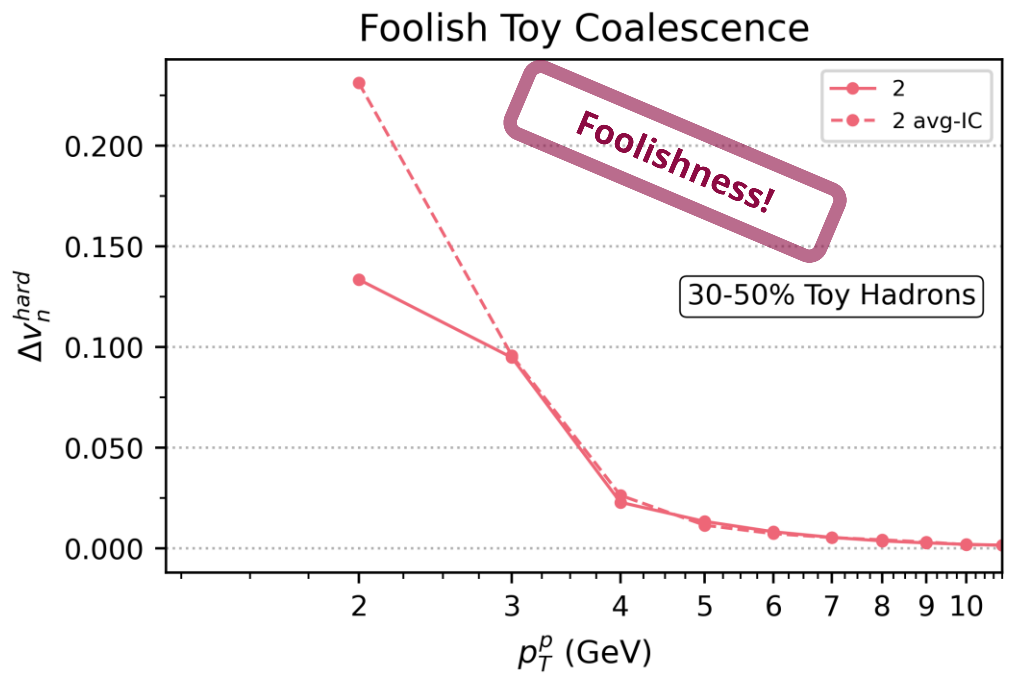
PRELIMINARY

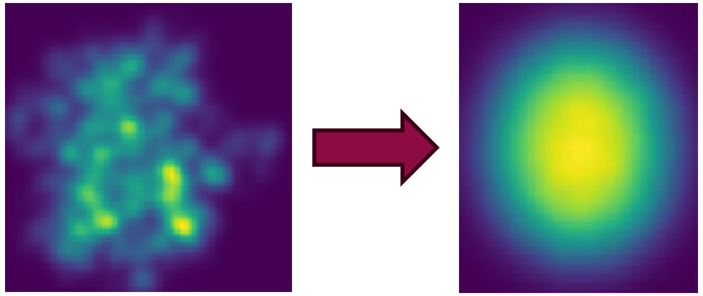


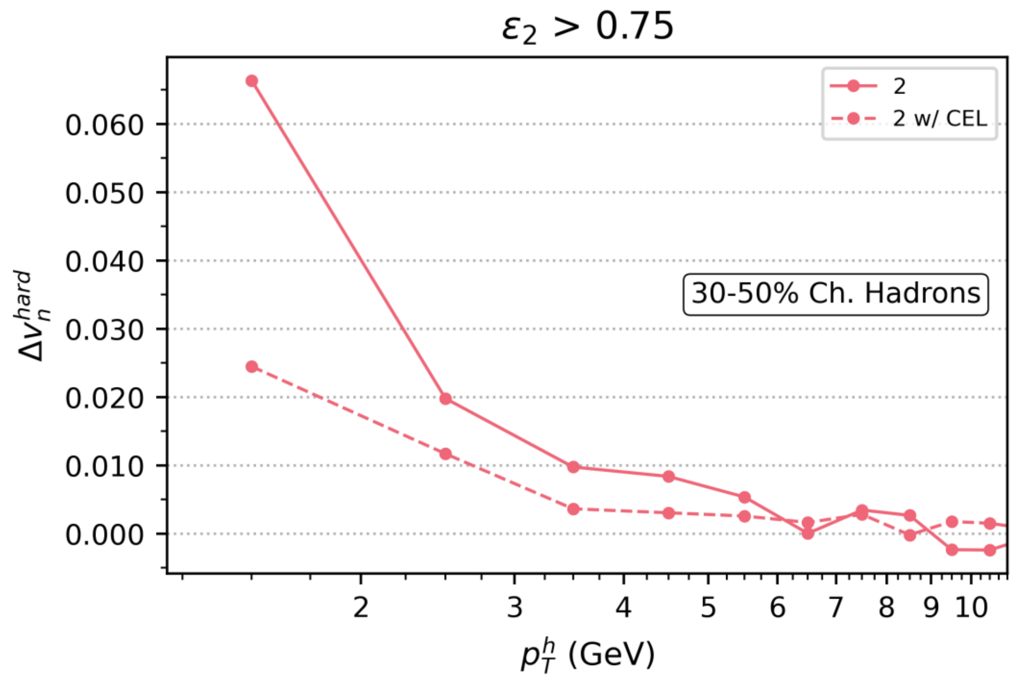


Effect too Small for You? Many Choices to Enhance!

- Take toy coalescence model
  - Say partons pick up collinear 1.5 GeV medium particle, on average
- Fluctuating drift & EL can result in much larger enhancements
- Effect may be large in tuned medium models
  - E.g. enhancement in smoothed events
- Consider cuts on event geometry (ϵ_2, or soft v_2)
  - E.g. $\epsilon_2 > 0.75$

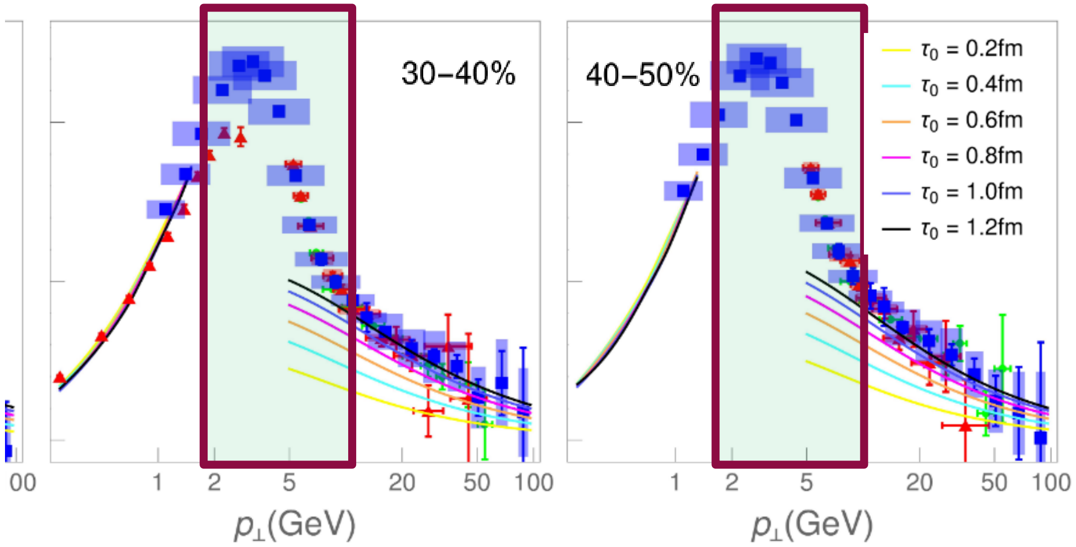




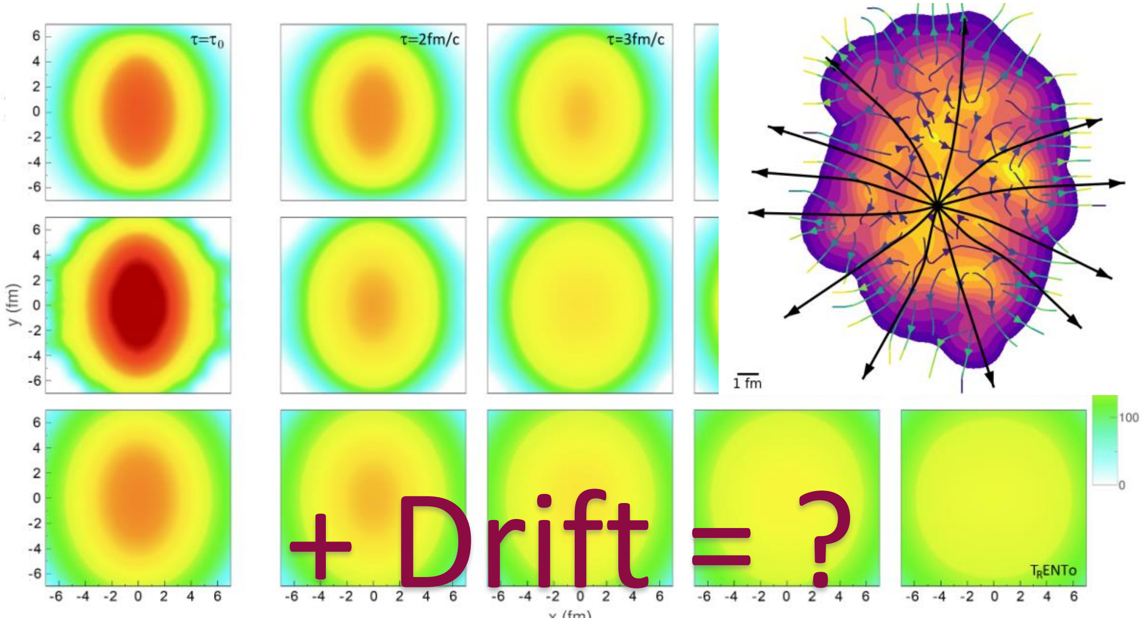


Drift v_n sensitive to pathlength ordered internal medium props.

(iNSPIRE:2640923)



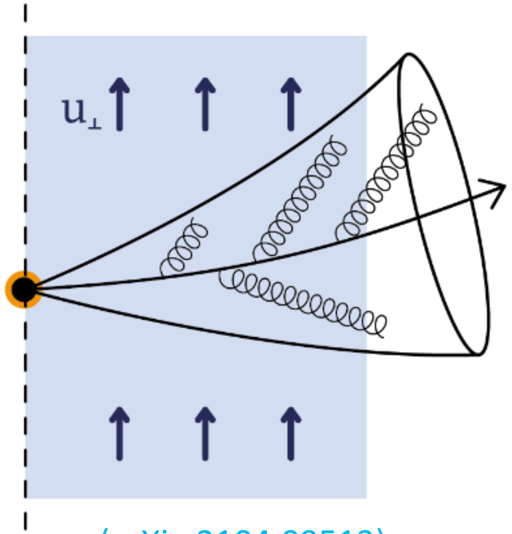
- Drift distinguishes between high anisotropy at early times vs at late times via interplay with energy loss
  - Powerful additional constraint on evolution dynamics!!!
- How would a hard + soft Bayesian parameter extraction like Magdalena's differ with the inclusion of drift?
  - Possibly selects on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



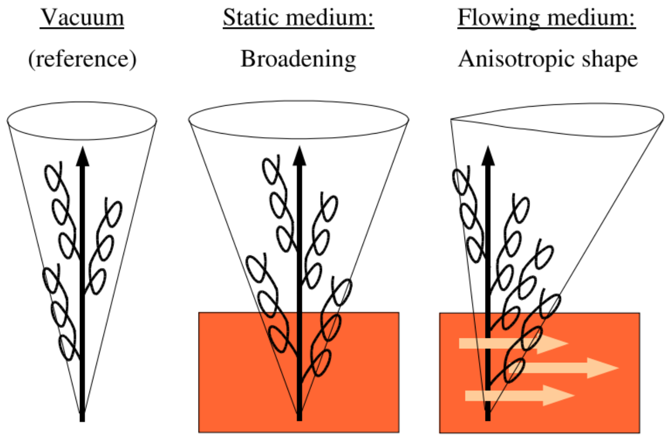
(iNSPIRE:2606181)

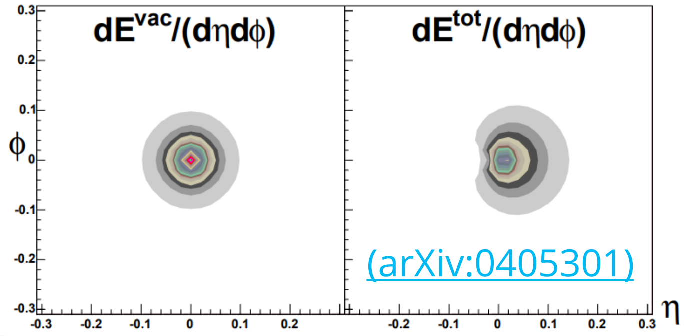
Anisotropic Jet Substructure

- 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!

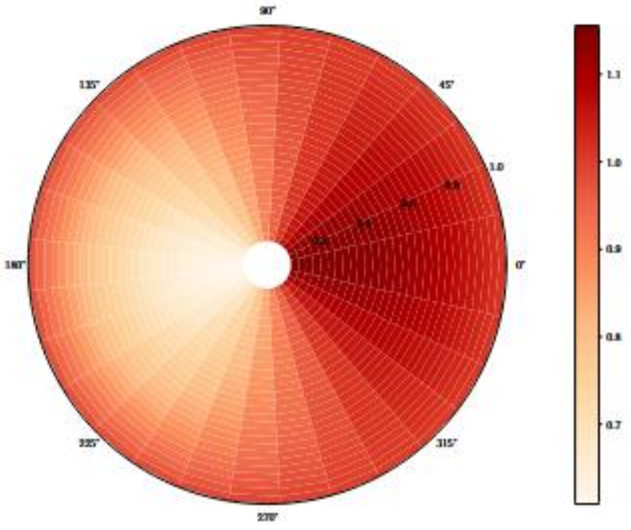


(arXiv:2104.09513)





(arXiv:0405301)

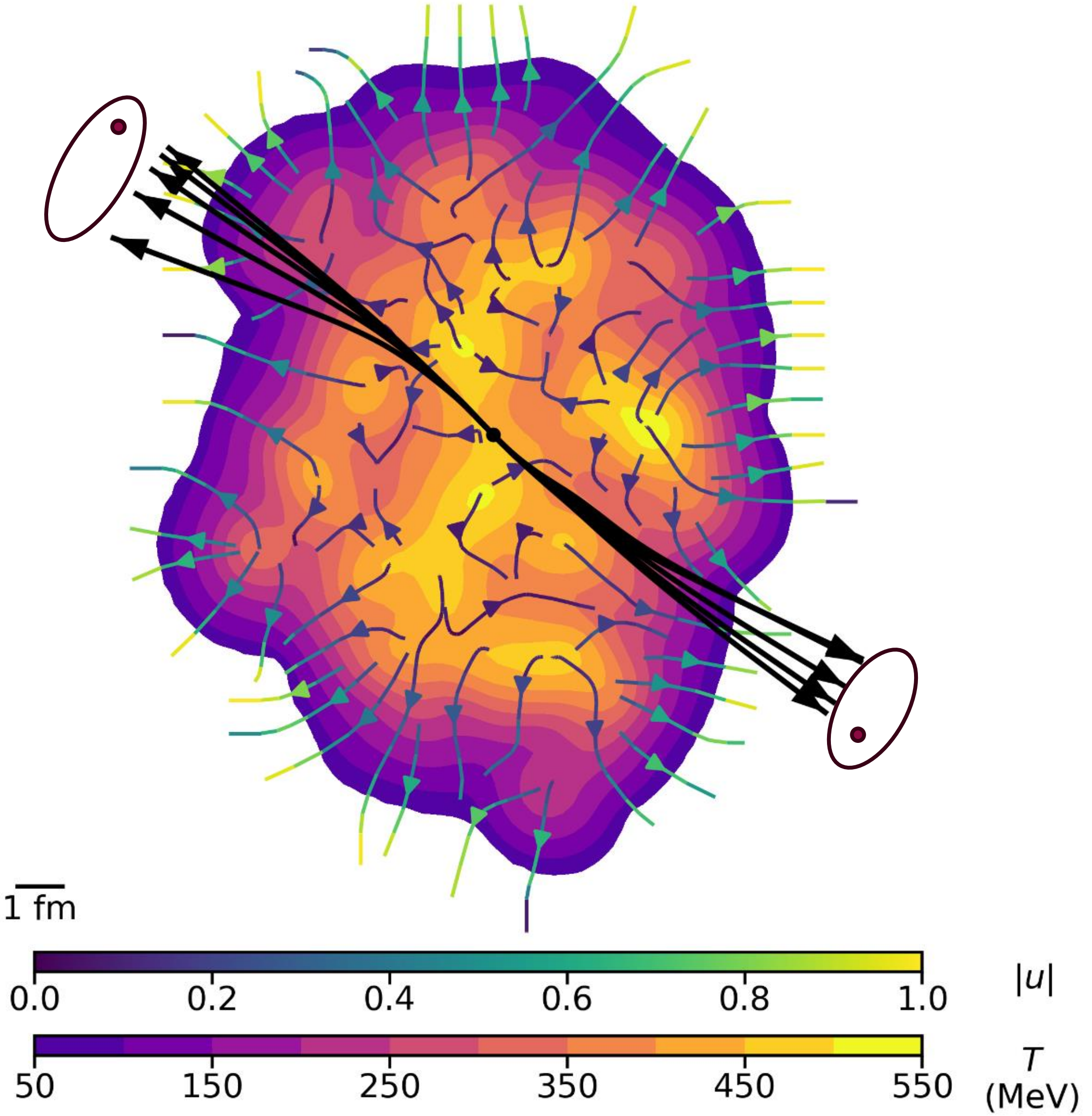


(arXiv:2308.01294)

Drift of Ensemble of Particles

$\Delta j, \mathrm{v_n}$ of substructure

- 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



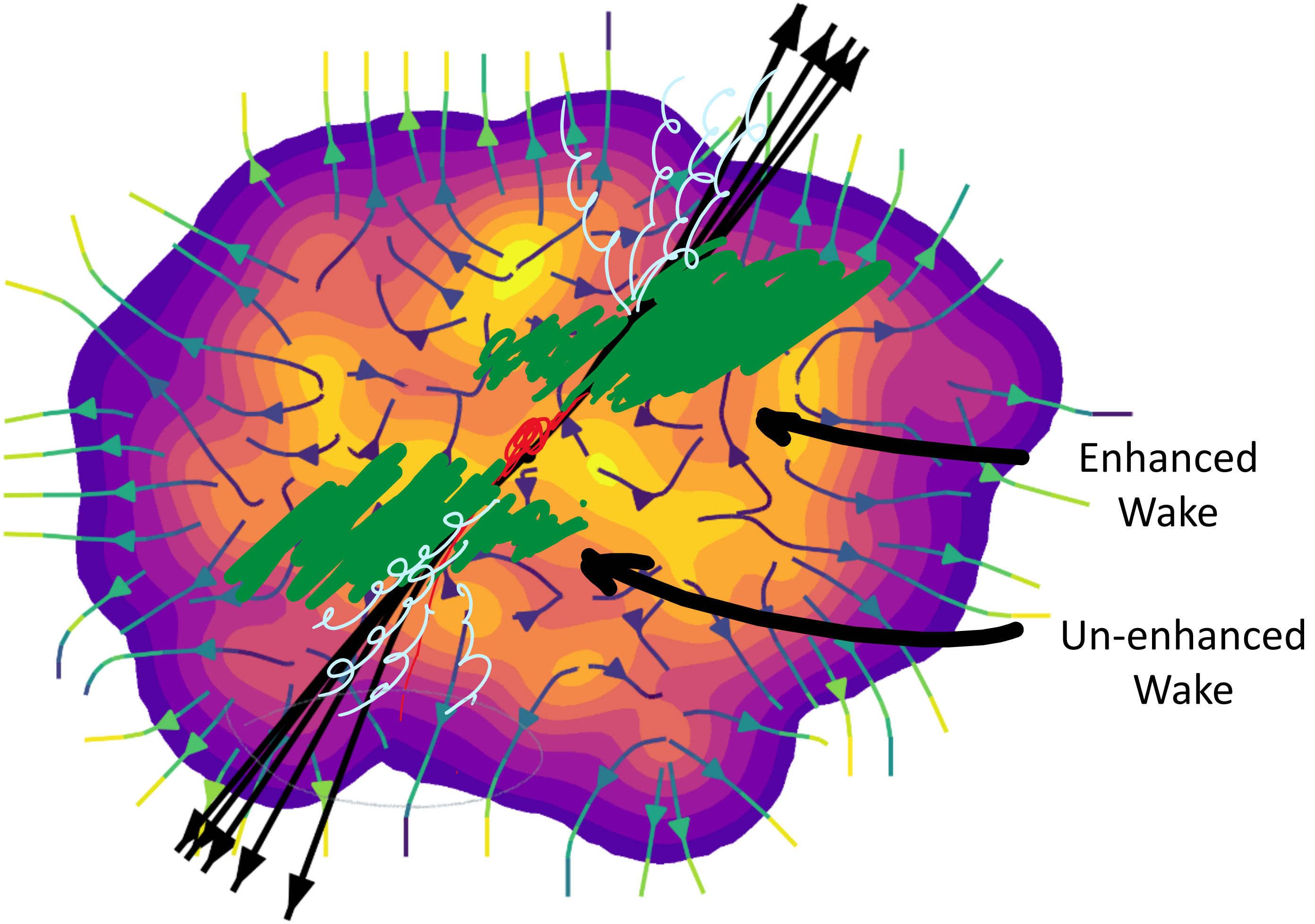
$$\langle \vec{q}_{drift} \rangle = \hat{e}_\perp \int d\tau \frac{3}{\boxed{E(\tau)}} \frac{\mu^2(\tau)}{\lambda(\tau)} \ln \frac{E(\tau)}{\mu(\tau)} \frac{u_\perp(\tau)}{1 - u_\parallel(\tau)}$$

Energy suppressed

Anisotropic Jet Wake

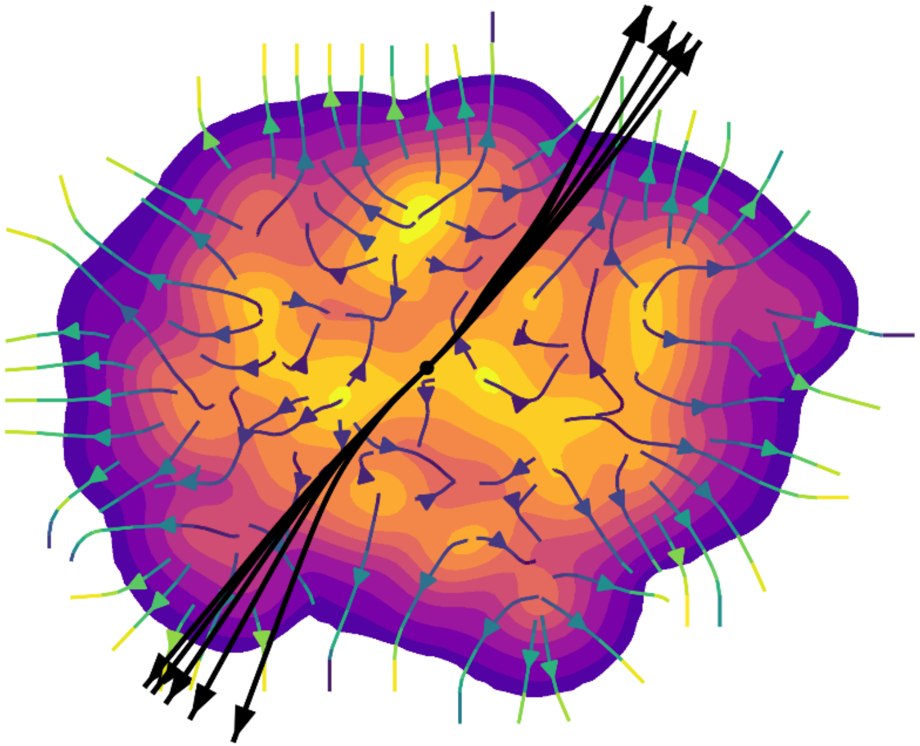
Does Z^0 wake measurement show anisotropy relative to event plane at any scale???

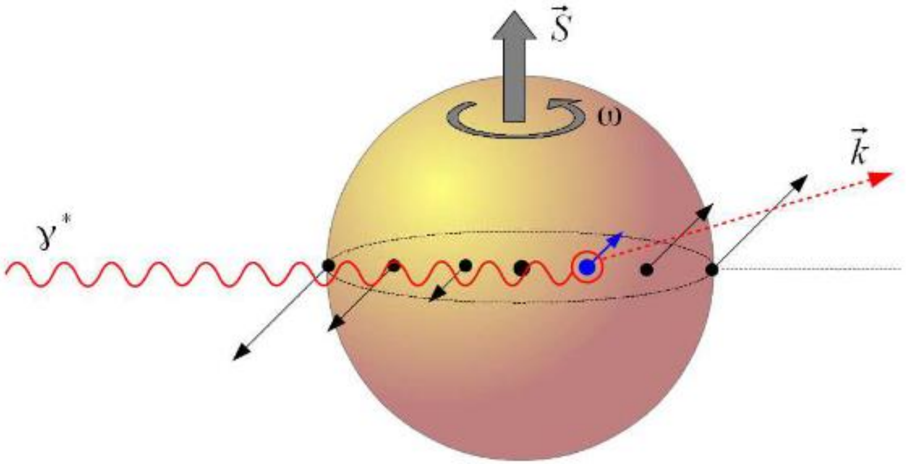
- Conservation of momentum – should be anisotropic wake
  - Constructive with induced radiation anisotropy
- How does this interplay with jet substructure anisotropies?
  - Possible anisotropic background contamination of jet substructure observables



Next Steps:

- Jet Substructure
  - Drift-dispersion + flow-induced radiation => jet substructure anisotropy
  - Jo Bahder, Hasan Rahman, Matt Sievert, & Ivan Vitev
- CNM drift investigations
  - Drift due to polarized nuclei
  - Nicholas Baldonado, Alex Garcia, & Matt Sievert
  - Add to APE MC for estimate
- Complete survey of important interactions to $\mathcal{O}\left(\frac{\mu}{E}\right)$



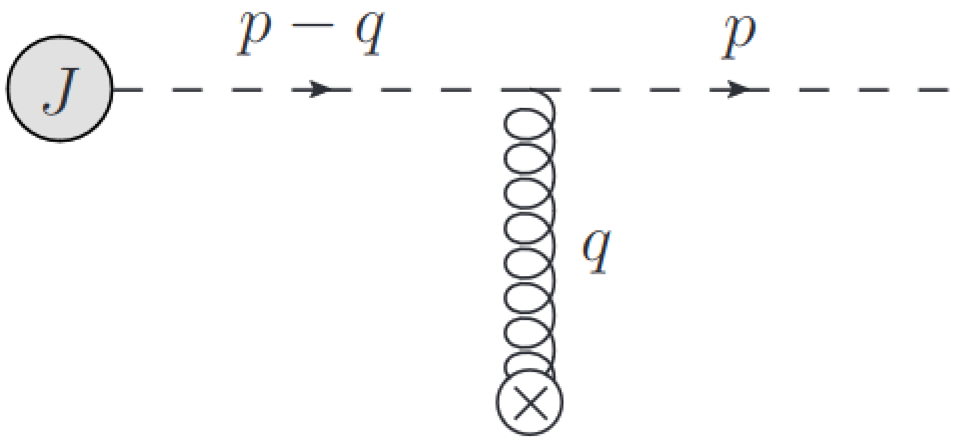


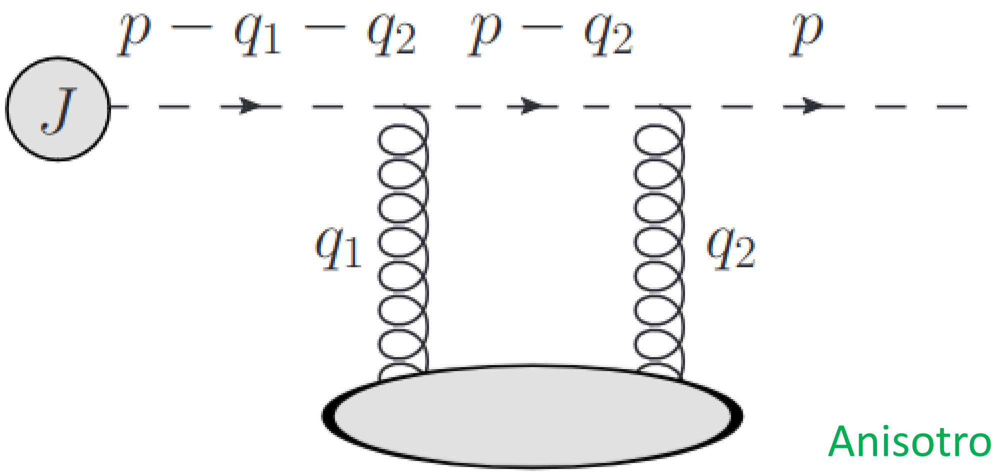
(arXiv:1310.5028)

Please Watch Out for the Paper in the Coming Weeks!

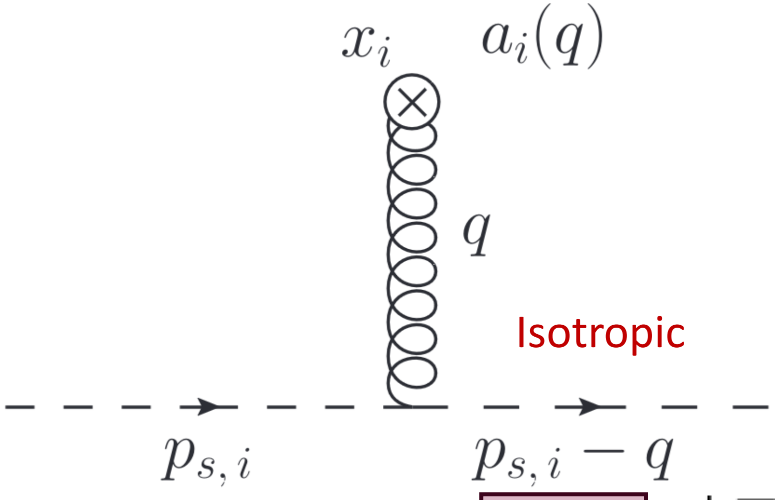
See Hasan Rahman's Talk at SoftJet Satellite meeting for investigation of drift correlations to medium properties!

Jet Broadening – Isotropic vs Anisotropic





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



Isotropic

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

No vector info

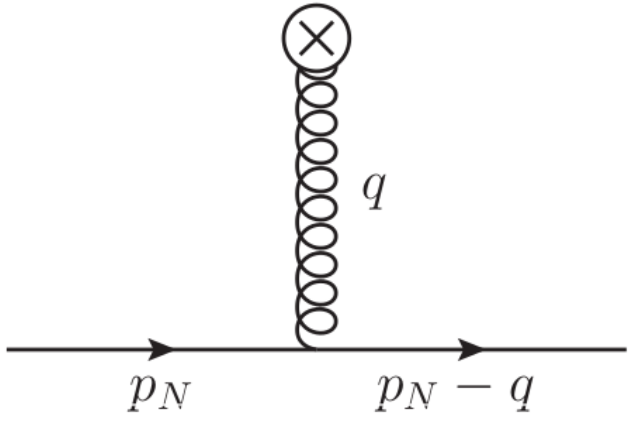
- Difference in setup – constraints on external gluon field
- Isotropic
  - Jet quark moves lightcone (+), medium quark moves lightcone (-)
- Anisotropic
  - Jet quark moves lightcone (+), medium quark moves with medium flow
- Two vector directions associated with the medium
  - Flow
  - Gradients

Anisotropic

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

Preferred direction!

Medium Gluon Field Potentials

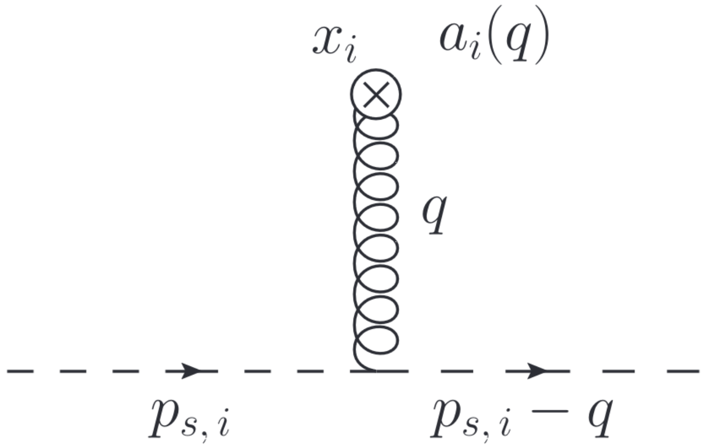


$$a_i^{\mu\,a}(q) = g^{\mu +}(t^a)_i \; [2\pi\delta(q^+)] \left[\frac{-g_{eff}}{q_T^2}\right]$$

$[2\pi\delta(q^+)]$: Eikonal delta function (antiparallel)

$\left[\frac{-g_{eff}}{q_T^2}\right]$: v(q) Isotropic scattering centers

Simple Isotropic Potential



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

Quark moves with medium

$$v_i(q) \equiv v_i\left(\boldsymbol{q}^2 - (\boldsymbol{u}_i \cdot \boldsymbol{q})^2\right) \equiv \frac{-g^2}{\boldsymbol{q}^2 + \mu_i^2 - (\boldsymbol{u}_i \cdot \boldsymbol{q})^2 - i\epsilon}$$

Denominator: v(q) Directional scattering centers

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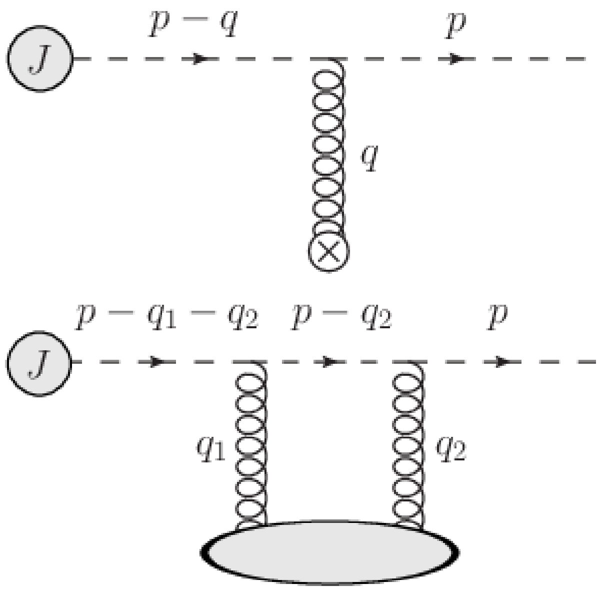
(arXiv:2104.09513)

Anisotropic Flow Potential
Regge Kinematics

NM STATE

All Diagrams



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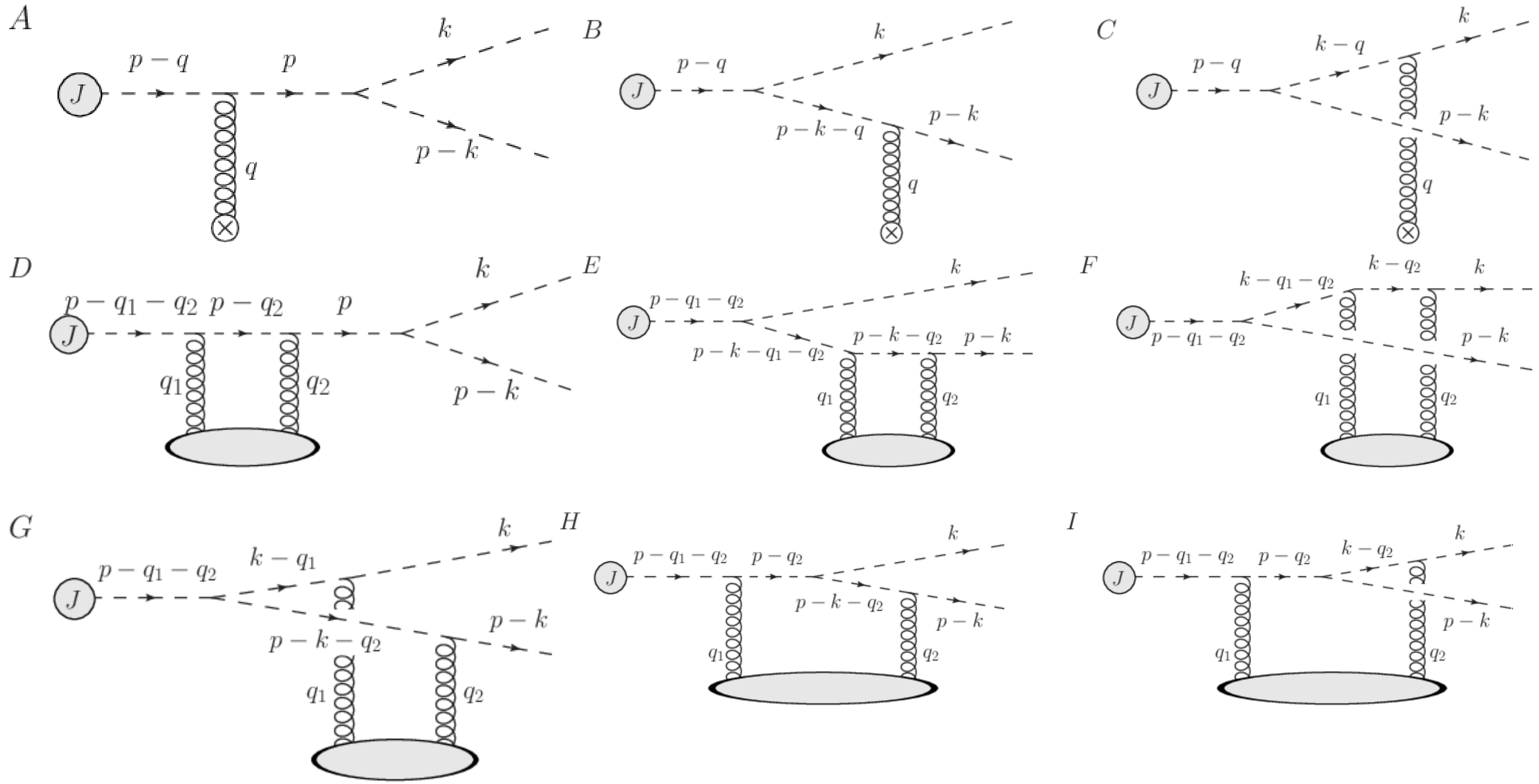
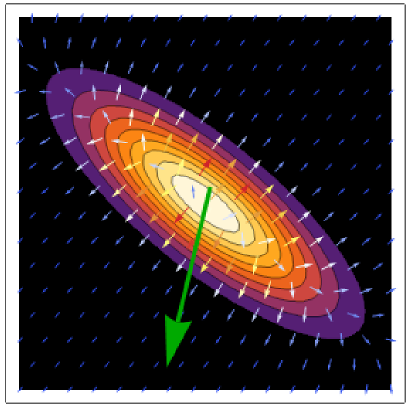
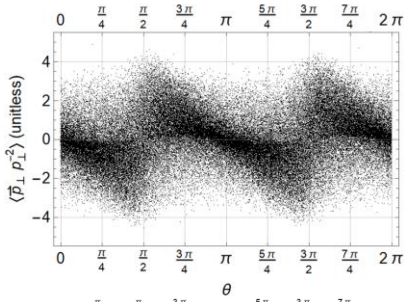


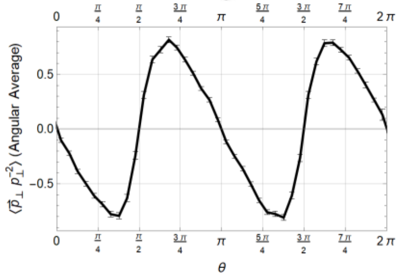
Born & Double-Born Radiation Diagrams

Does Drift Survive Event Averaging?

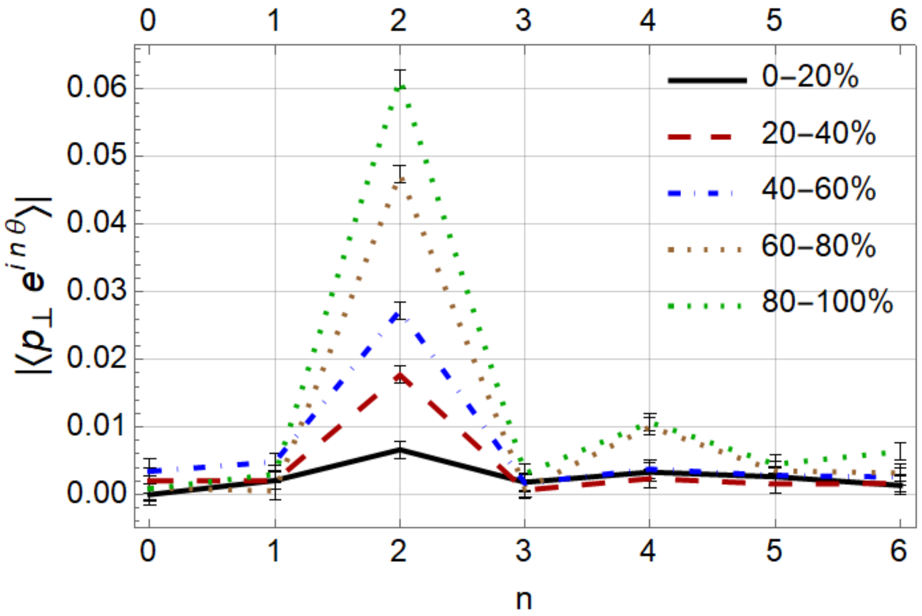
L. Antiporda, J. Bahder,
H. Rahman
& M. D. Sievert
Phys.Rev.D 105 (2022)
(arXiv: 2110.03590)







Harmonic Analogous to v_n^{hard}



- 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
- What about in realistic heavy ion collisions?

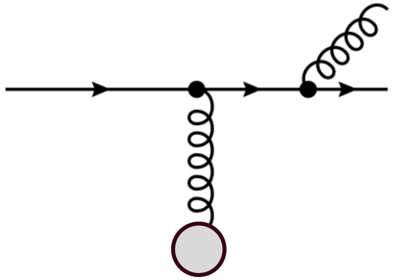
Energy Loss Effects

Radiative

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

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

E.g.

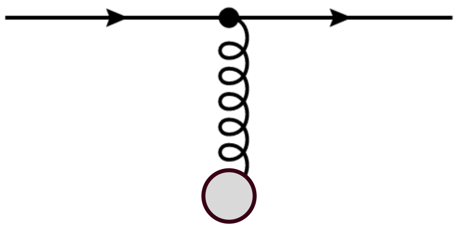


Collisional

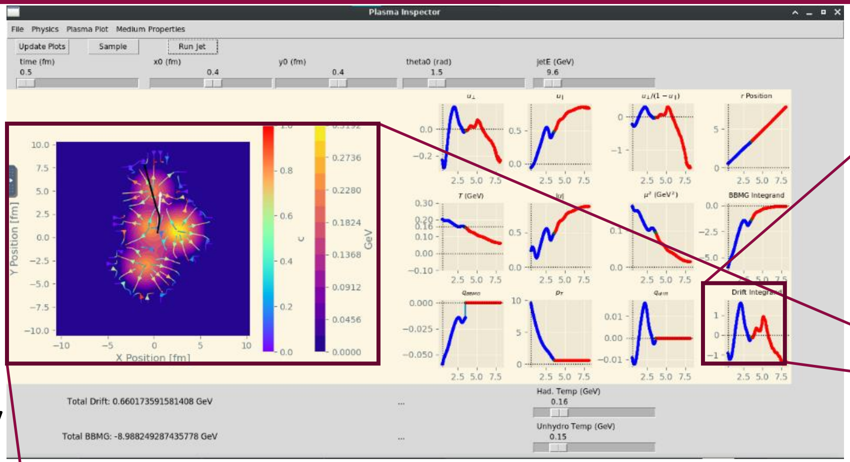
$$\frac{dE}{d\ell} = -C_R\frac{1}{2}\mu^2\ln\left(2^{\frac{N_f}{2(6+N_f)}}0.920\frac{\sqrt{3ET}}{\mu}\right)$$

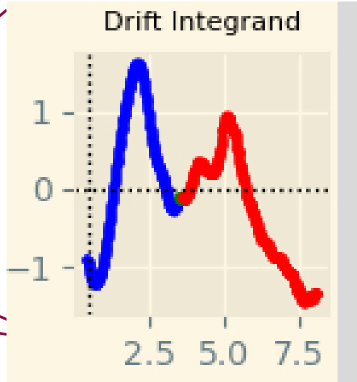
- Braaten & Thoma (1991) (iNSPIRE:317898)
- Light quarks: E >> m^2/T regime
- Gluons: CA/CF = 9/4 (arXiv:2305.13182)

E.g.

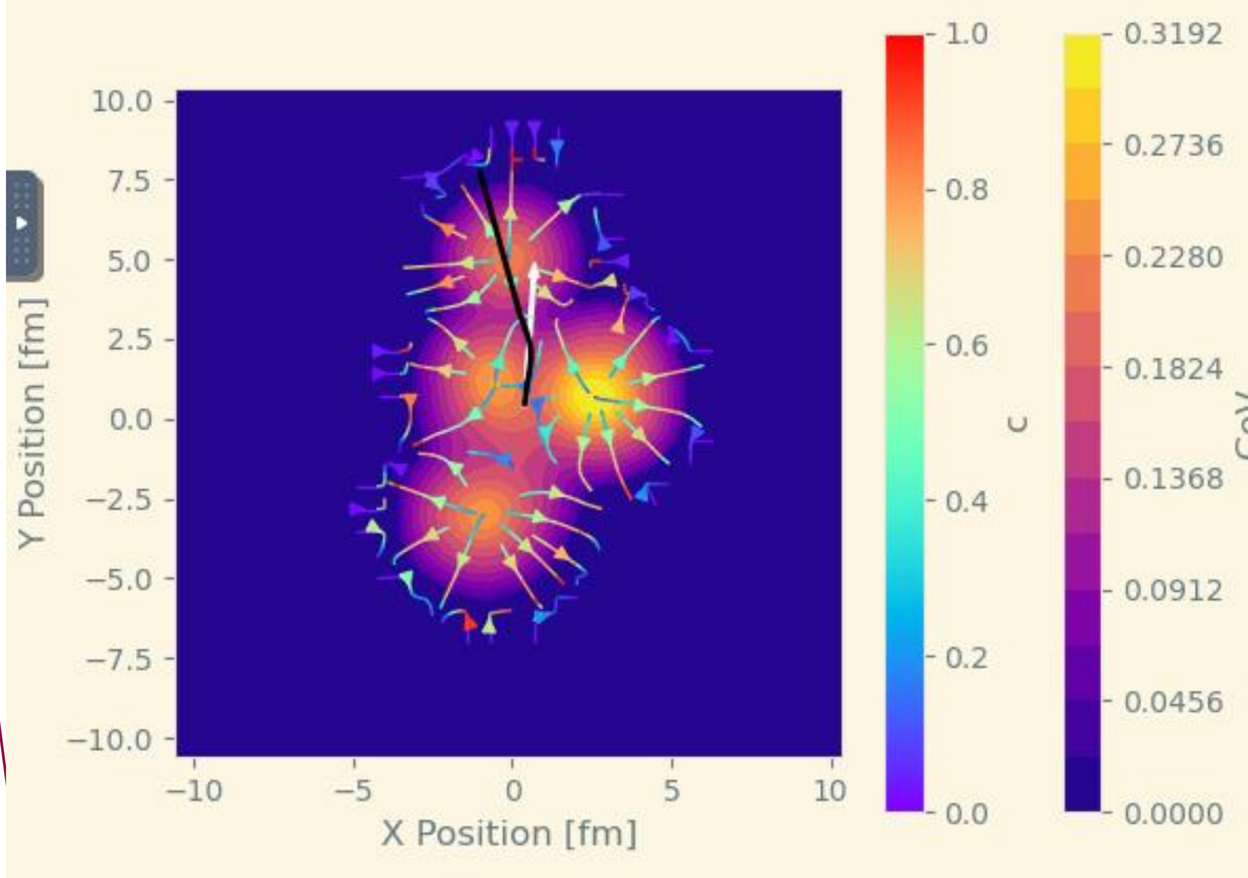


Ape Trajectories

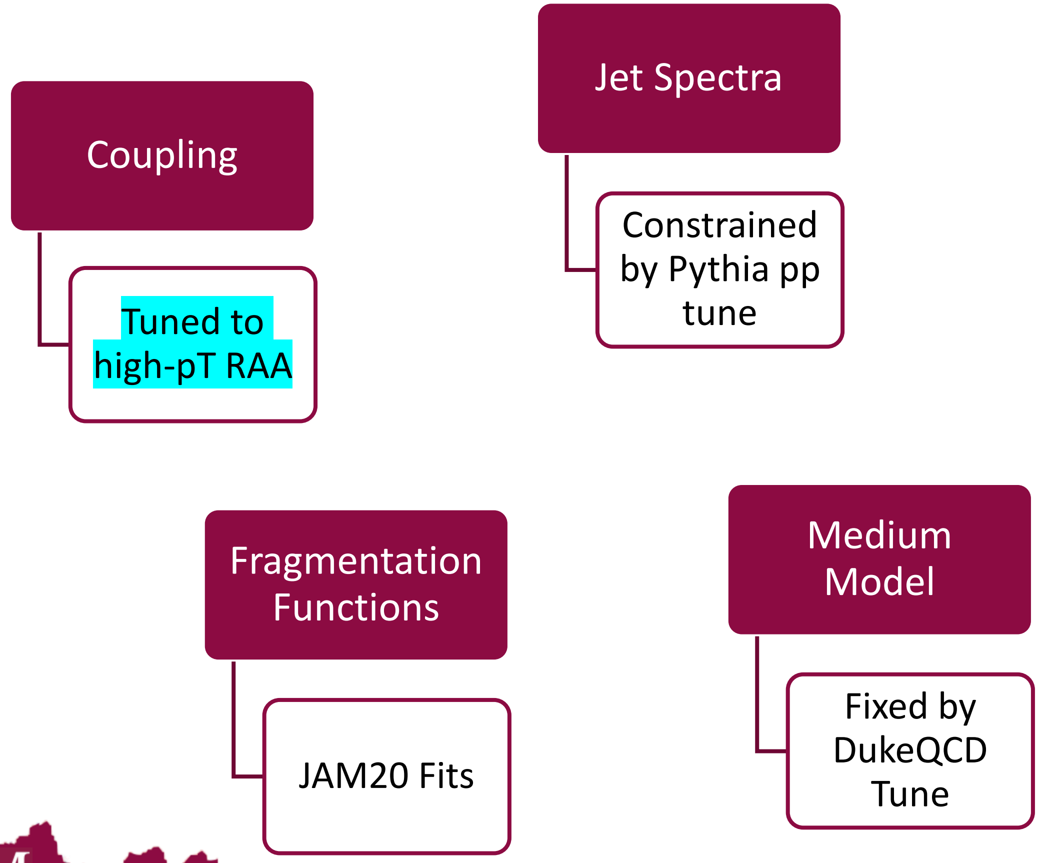




- Approx. Binary collision density weighting of production points
- Computed within QGP phase of hydro backgrounds
  - EL & Drift cut off at T < 155 MeV
  - Cuts off highest flow region!!!
- Dynamic trajectories respond to medium flow
  - Deflections, zigzags, weirdness



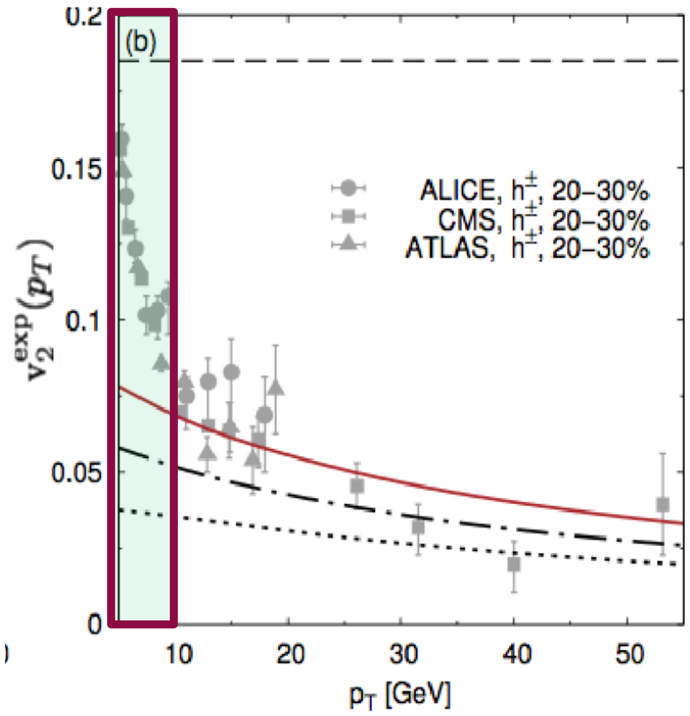
Parameter Fits & Model Choices



- 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!

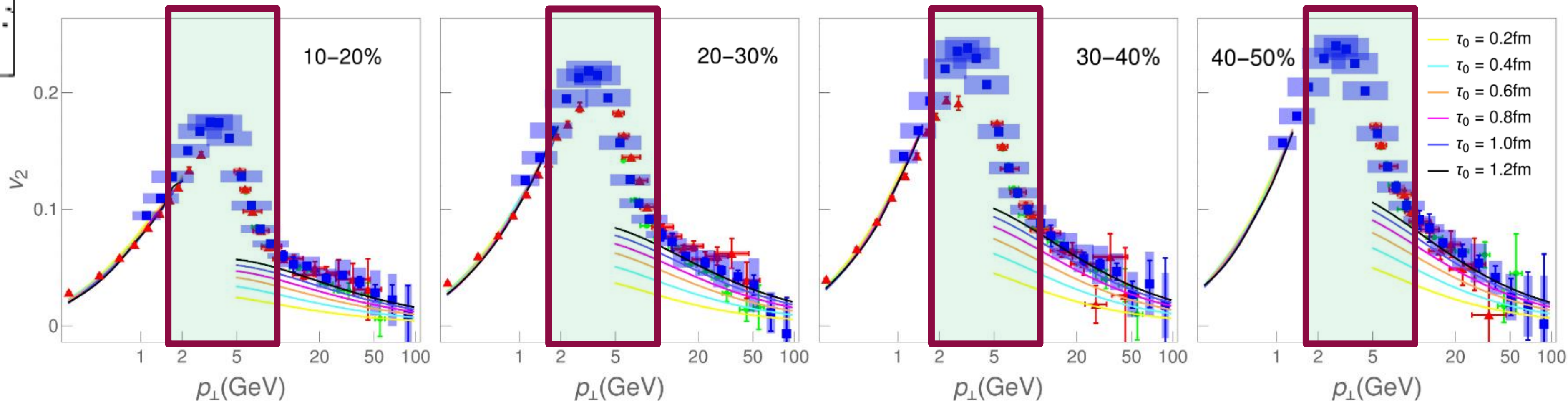
Importance for the R_AA x v_2 Puzzle

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

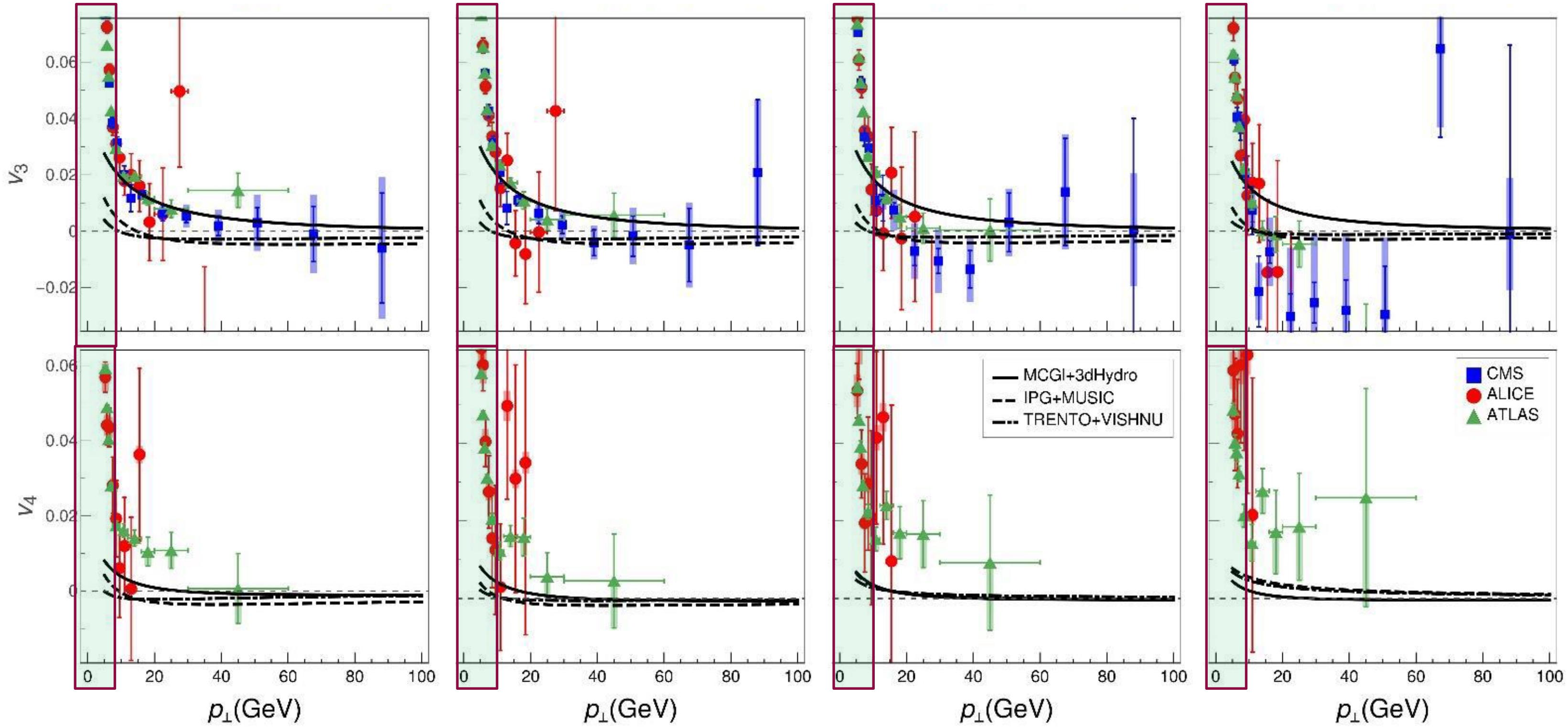


Parametric Energy Loss
Noronha-Hostler et al:
(arXiv: 1602.03788)

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



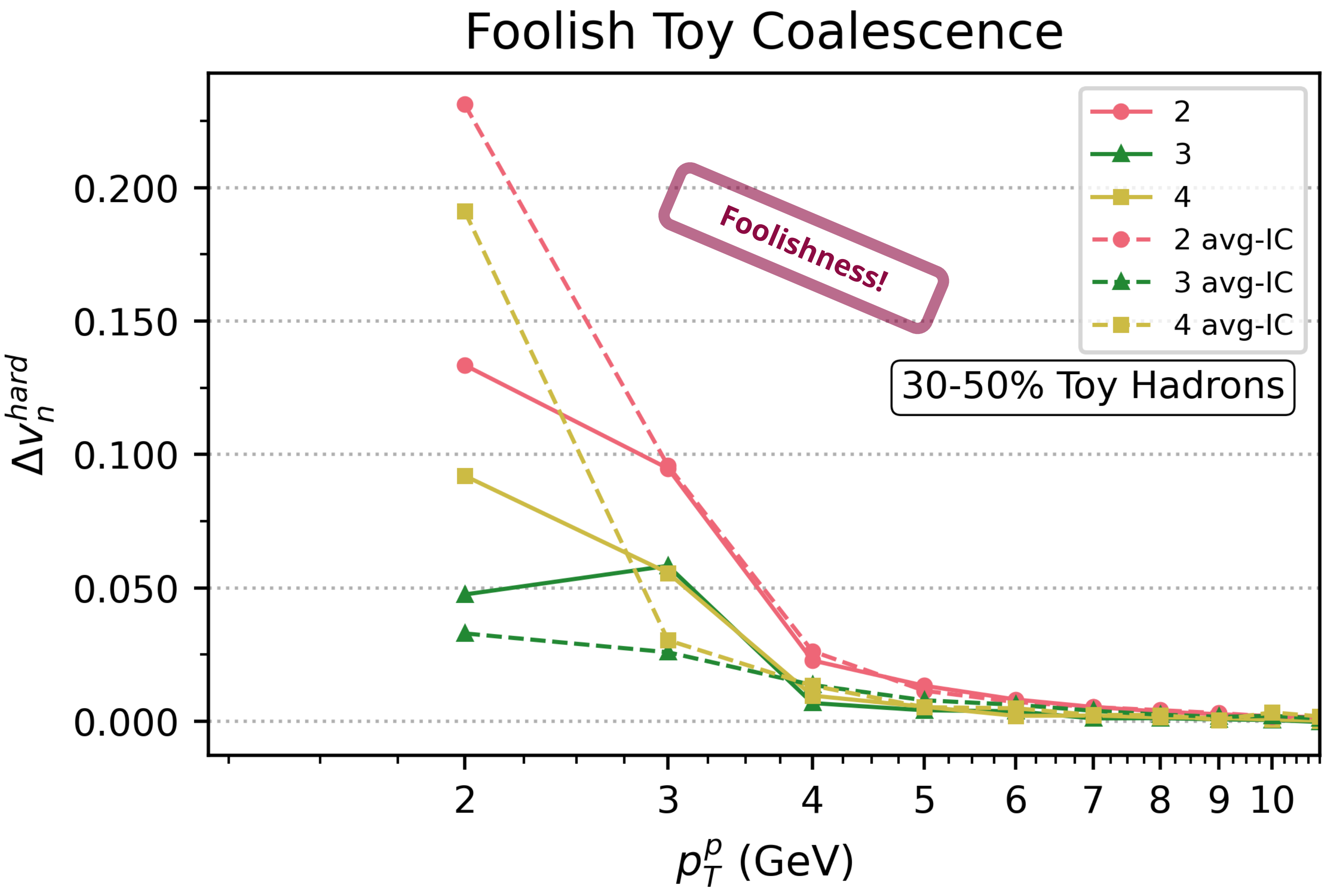
v3 & v4 from Perturbative Energy Loss



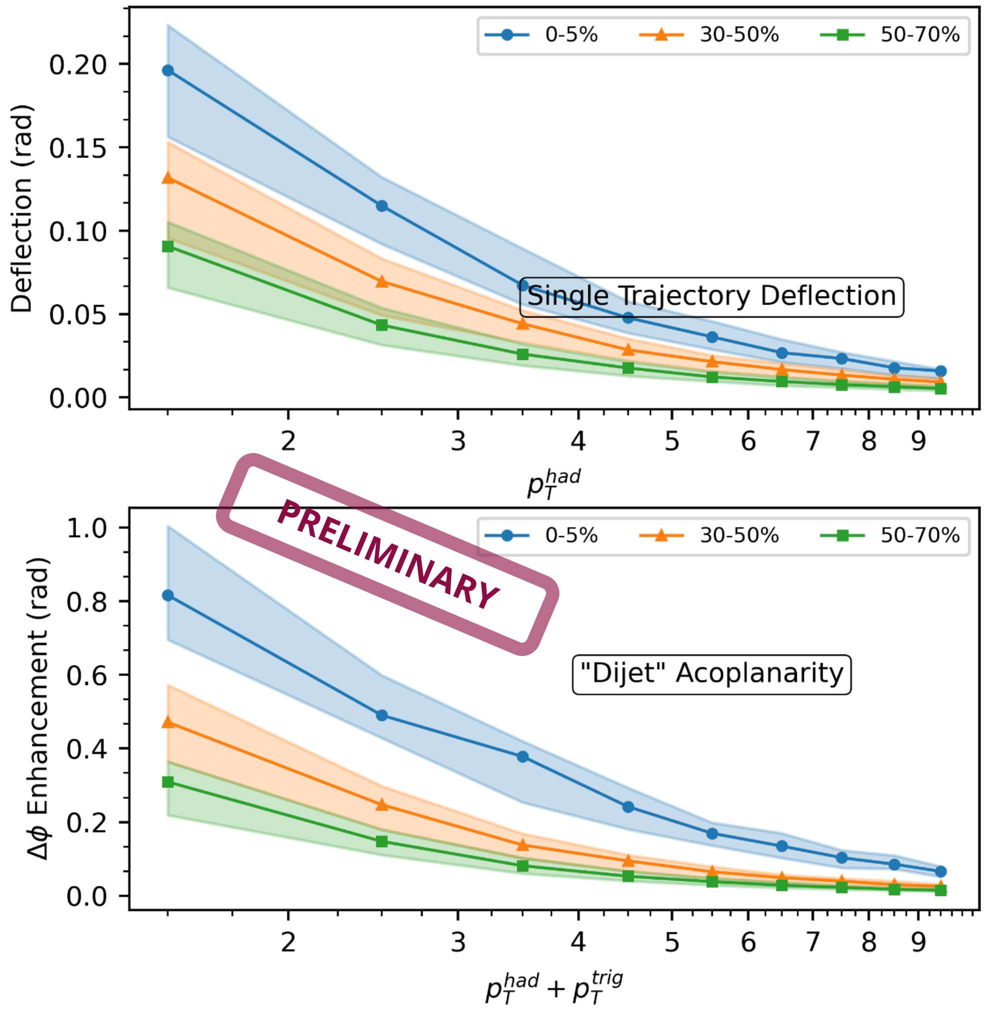
(arXiv:2208.09886)

- Drift produces higher harmonic coupling
- Possible importance to v_3 & v_4
- Difficult to couple to small anisotropies with energy loss alone

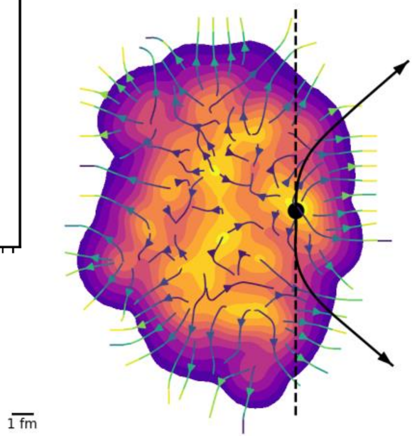
Toy Coalescence with v3 & v4

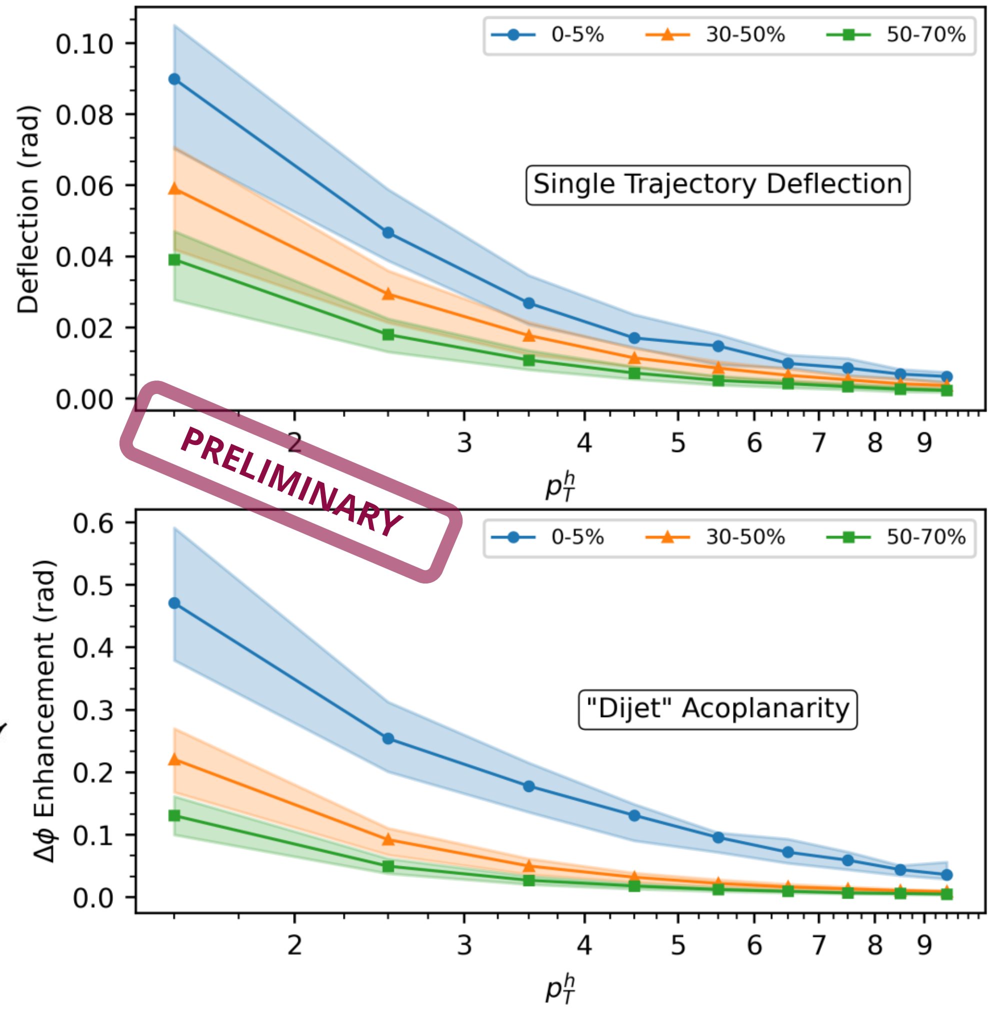


Acoplanarity Enhancement RAD + CEL v. RAD



Rad. EL + Drift

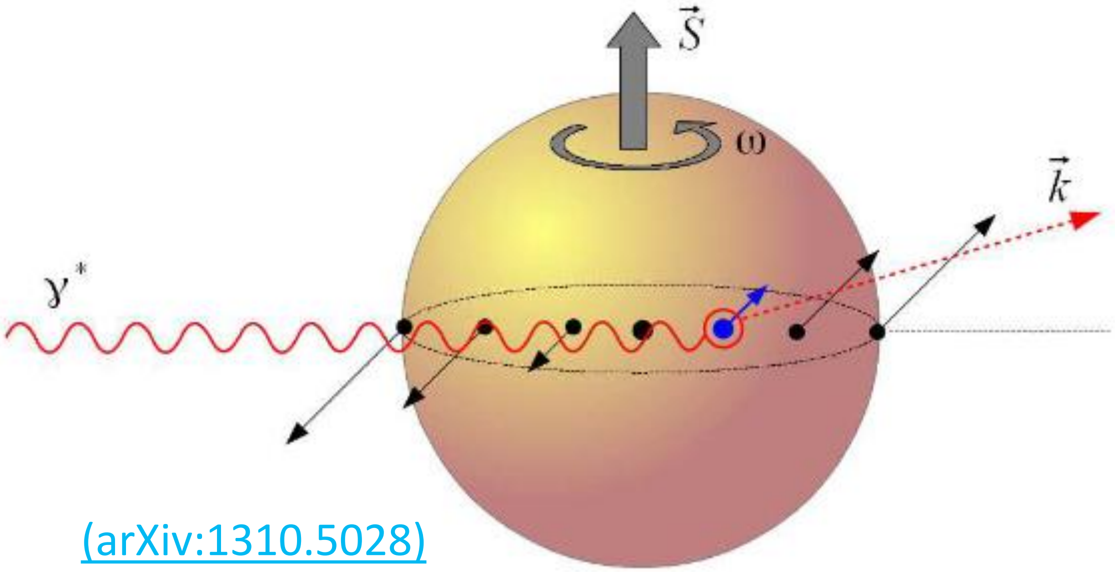




Rad. EL + Coll. EL + Drift

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)