Phenomenology of Jet Drift in Heavy Ion Collisions

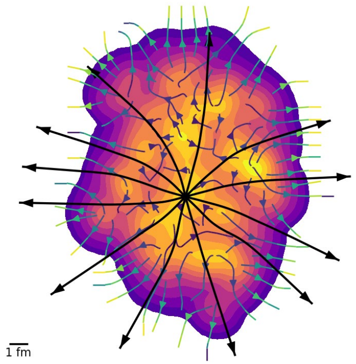
(arXiv: 2110.03590) & (arXiv:2412.05474)

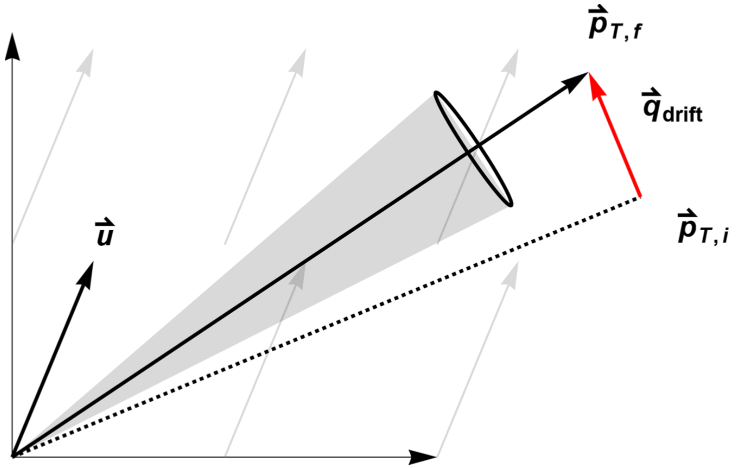
*Supported in part by DoE Grant (*DE-SC0024560*)*
Supported in part by a start-up grand from NMSU

Hot Jets (UIUC) 2025
9th January, 2025

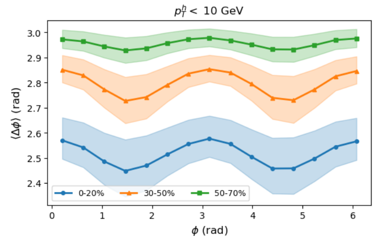
Jo Bahder

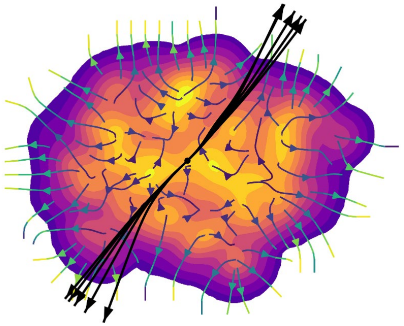
In collaboration with
Hasan Rahman, Matthew Sievert,
and Ivan Vitev





Outline

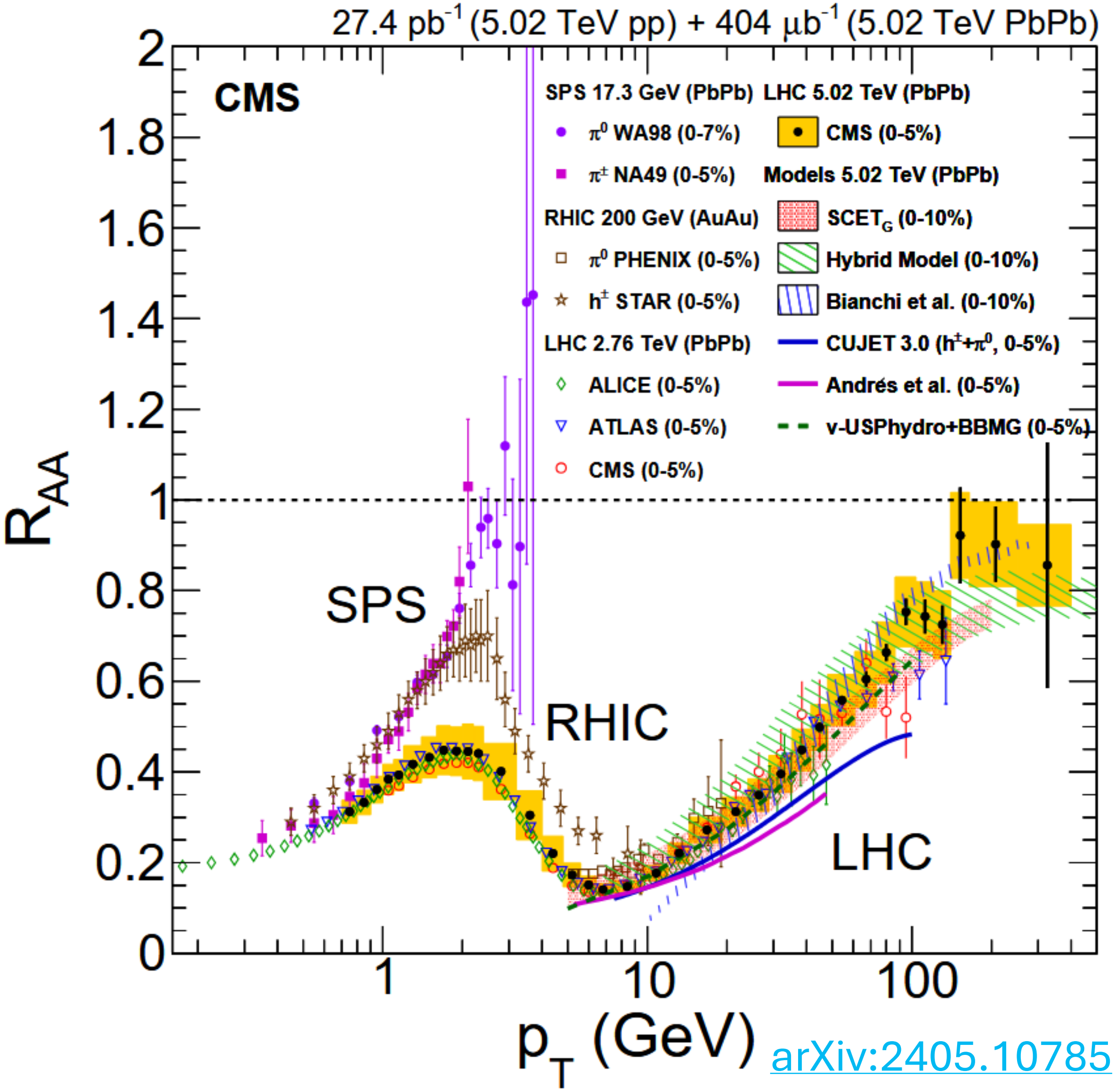




1. Motivation, Reminder of Jet Drift, & Possible Signatures
2. Introduction of Anisotropic Parton Evolution (APE)
3. Selected APE Results
4. Discussion of Implications

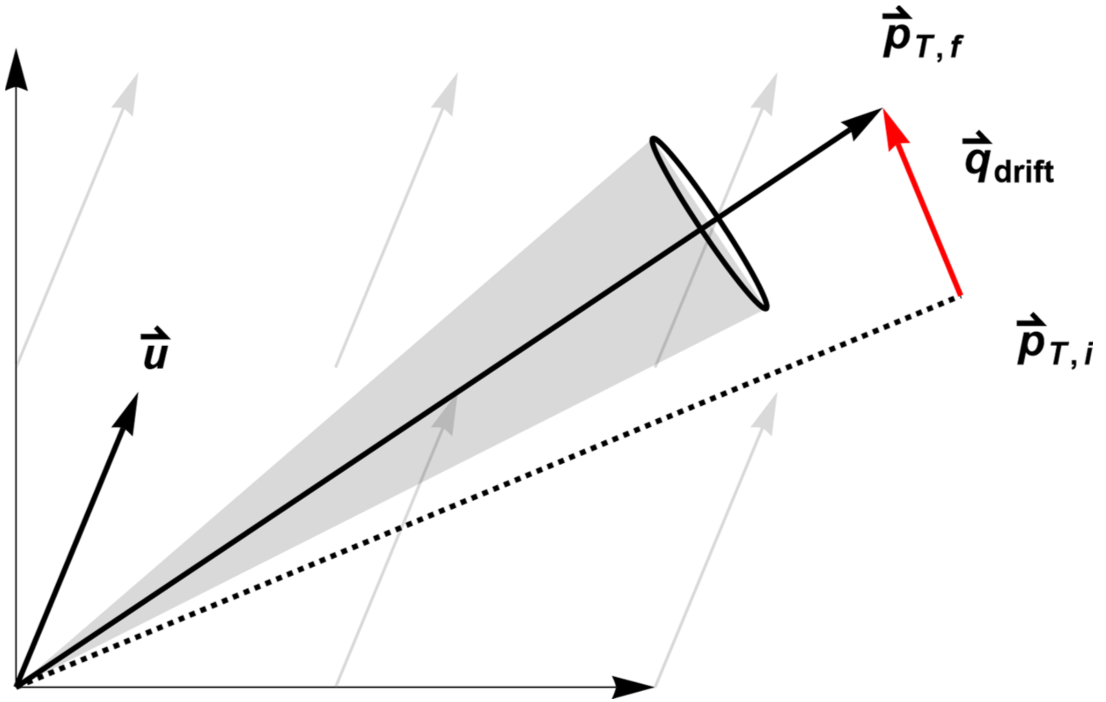
The State of Hard Probe Tomography

- 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
  - More discriminating observables (EECs?, jet substructure?)
  - More discriminating regions of phase space (e.g. < 10 GeV)
- Both require new precision perturbative calculations



arXiv:2405.10785

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

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

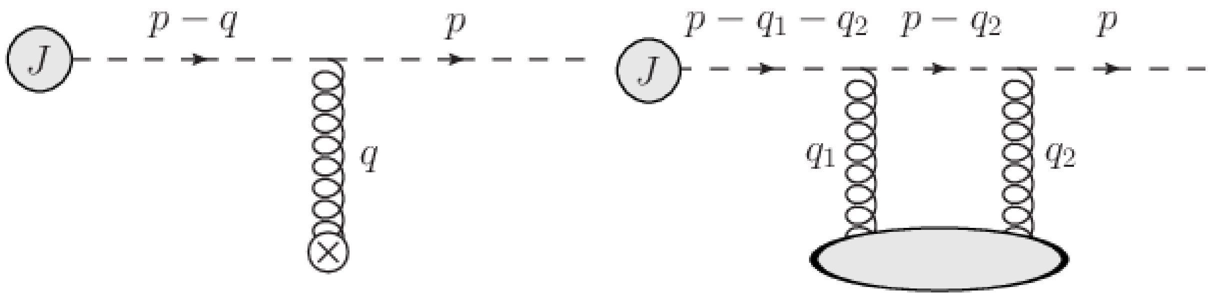
$$\langle \vec{q}_{drift} \rangle = \hat{e}_\perp \int d\tau \frac{3}{\boxed{E(\tau)}} \boxed{\frac{\mu^2(\tau)}{\lambda(\tau)} \ln \frac{E(\tau)}{\mu(\tau)}} \boxed{\frac{u_\perp(\tau)}{1 - u_\parallel(\tau)}}$$

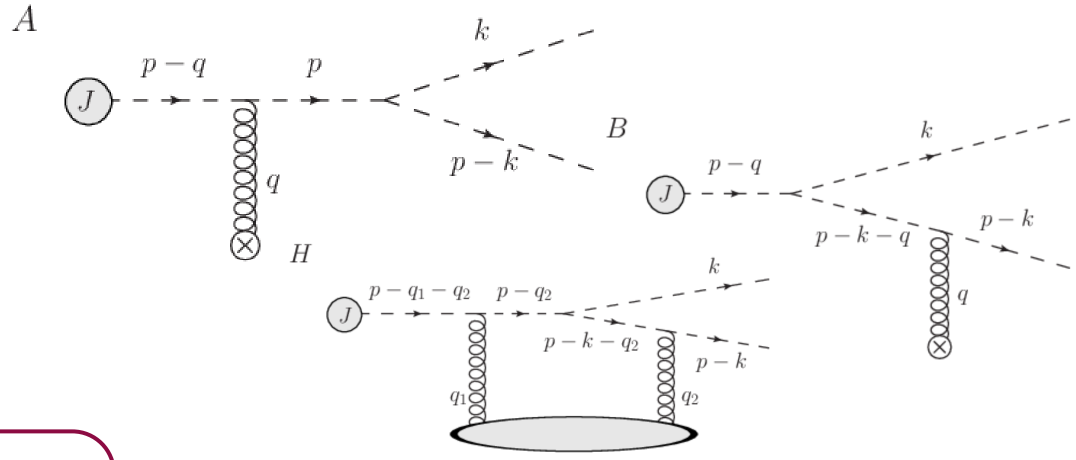
Energy suppressed

Temperature/Density Enhanced

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

Momentum Broadening & Radiation in the Presence of Flow

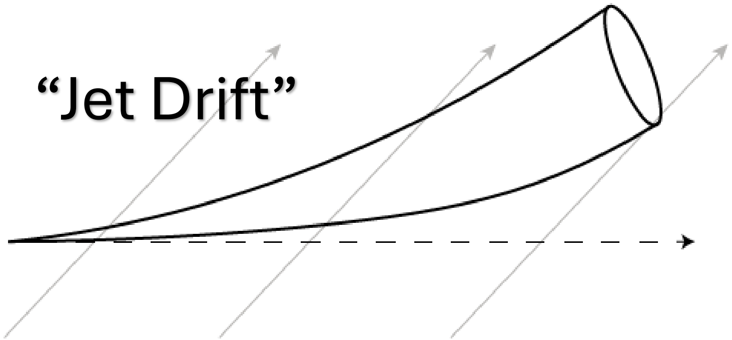


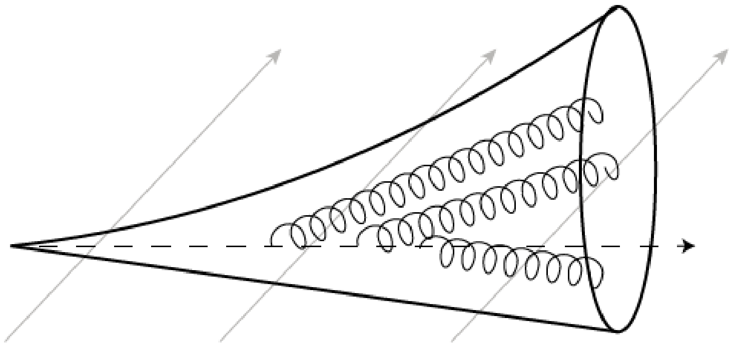


Born & Double-Born Momentum Broadening Diagrams

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

E.G. Born & Double-Born Radiation Diagrams

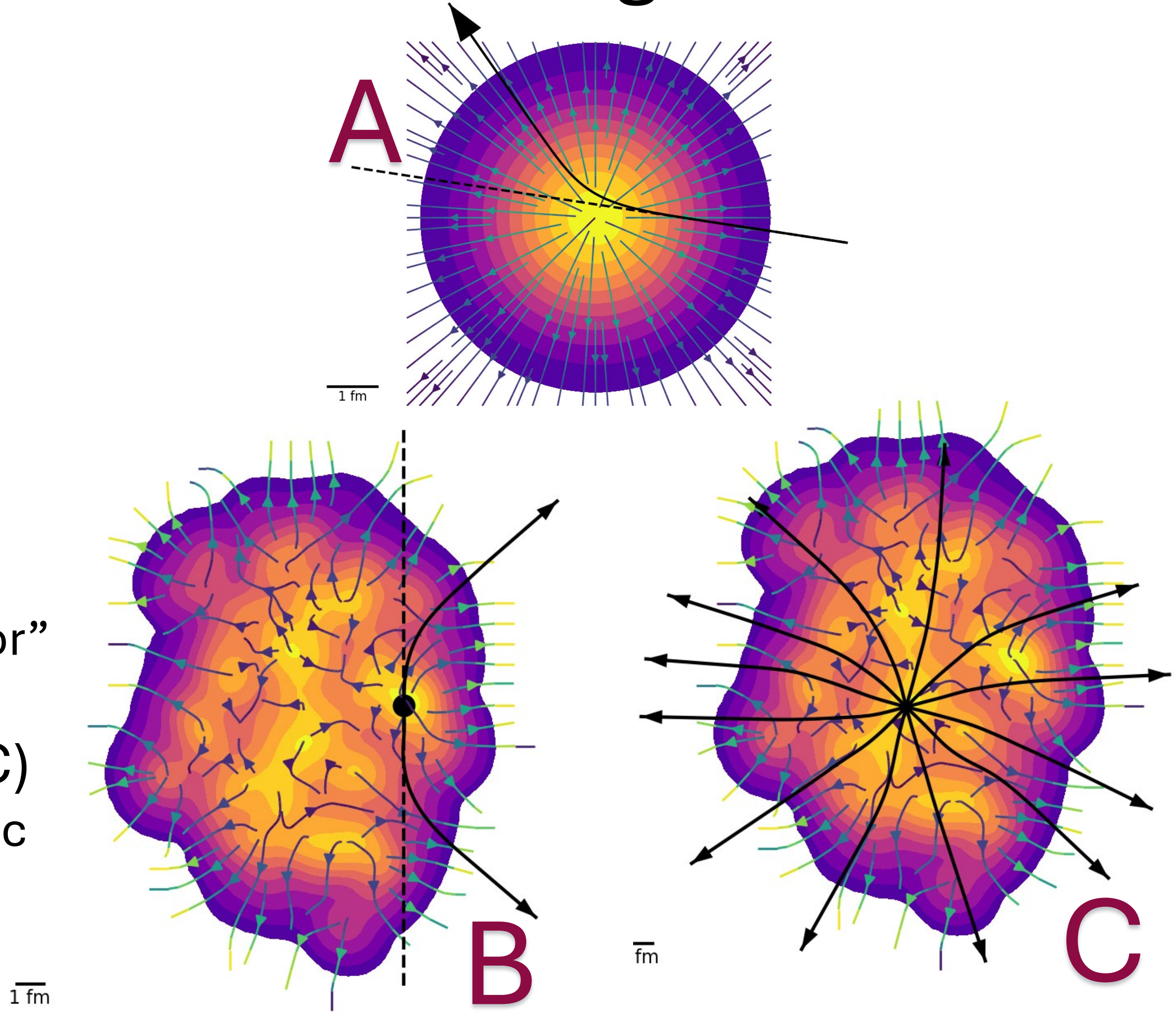




New systematic behavior at $\mathcal{O}\left(\frac{\mu}{E}\right)$

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

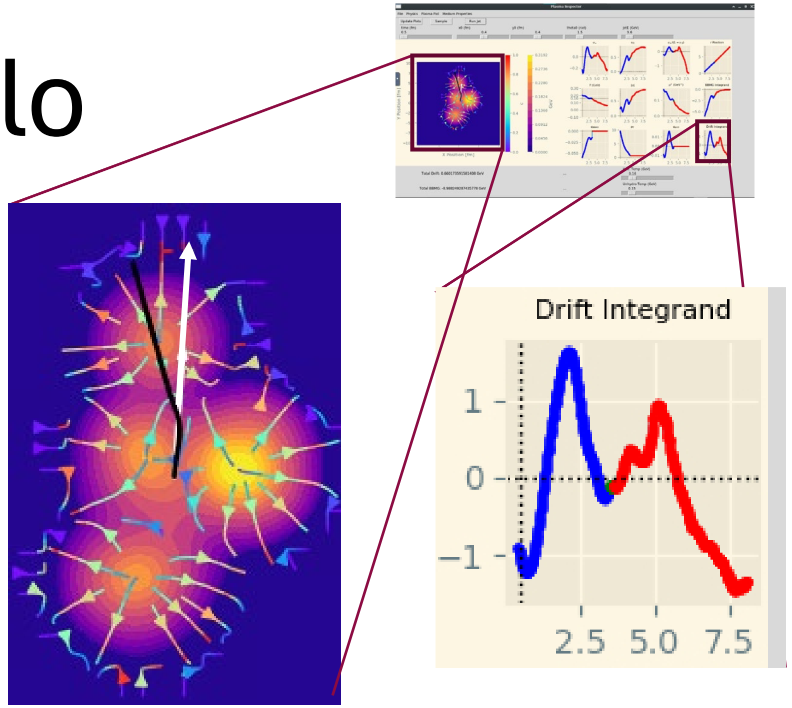


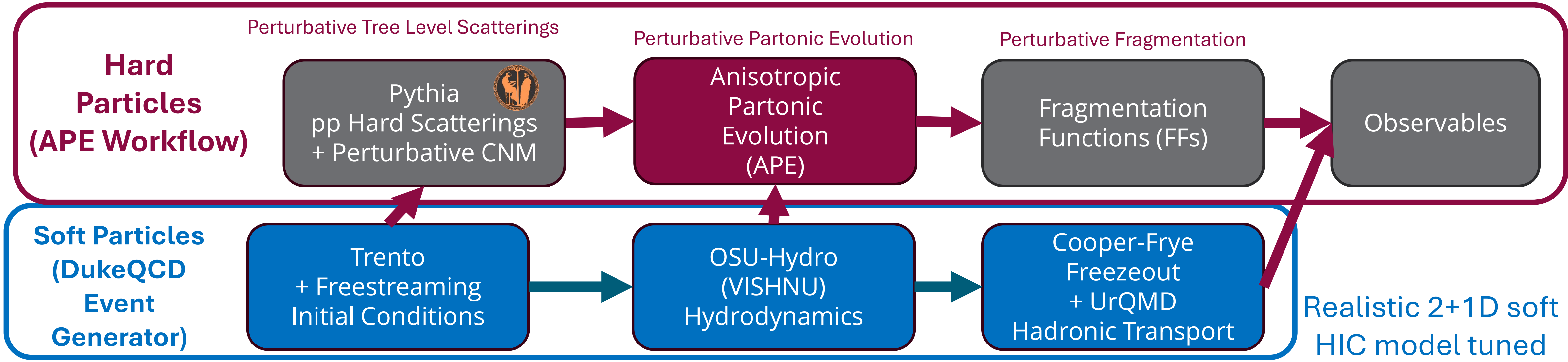
APE: A Primitive Man’s Monte Carlo

APE & Drift Pheno.
J. Bahder, H. Rahman,
M. D. Sievert, & I. Vitev
Preprint
(arXiv:2412.05474)

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

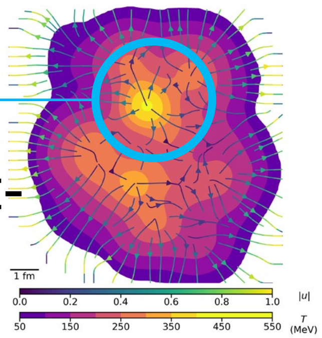
Realistic 2+1D soft HIC model tuned to pPb & PbPb data

(arXiv:1808.02106)

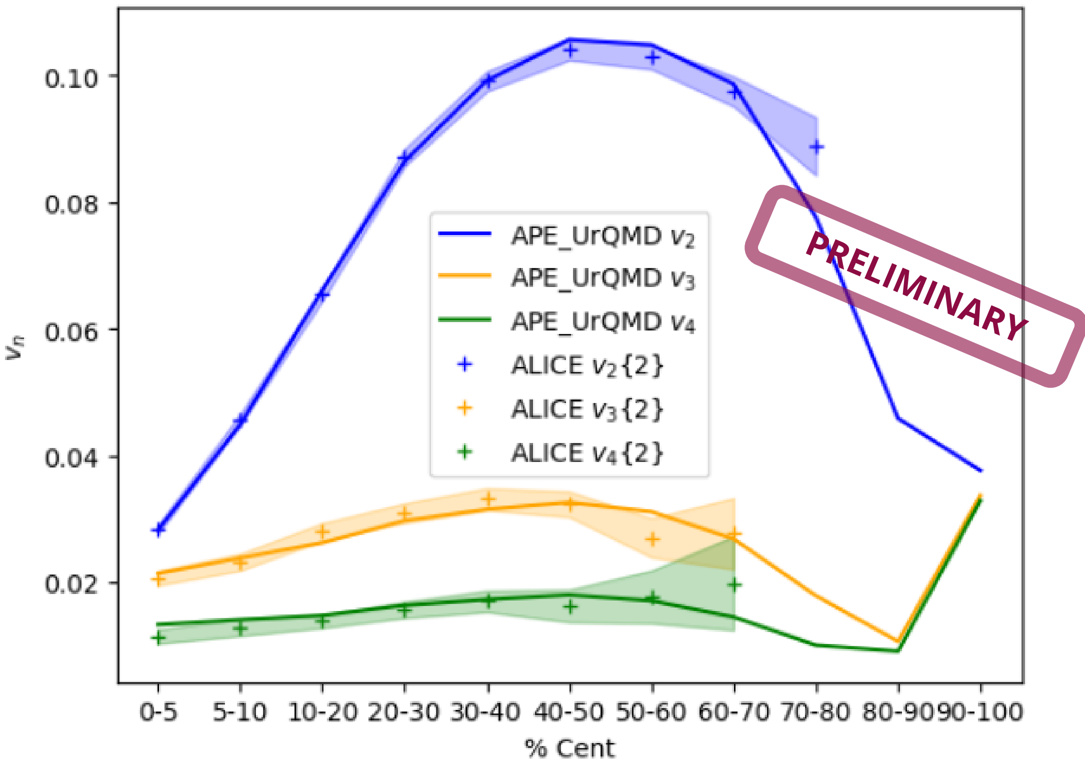
DukeQCD’s HIC Event Generator

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

- 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



Energy suppressed



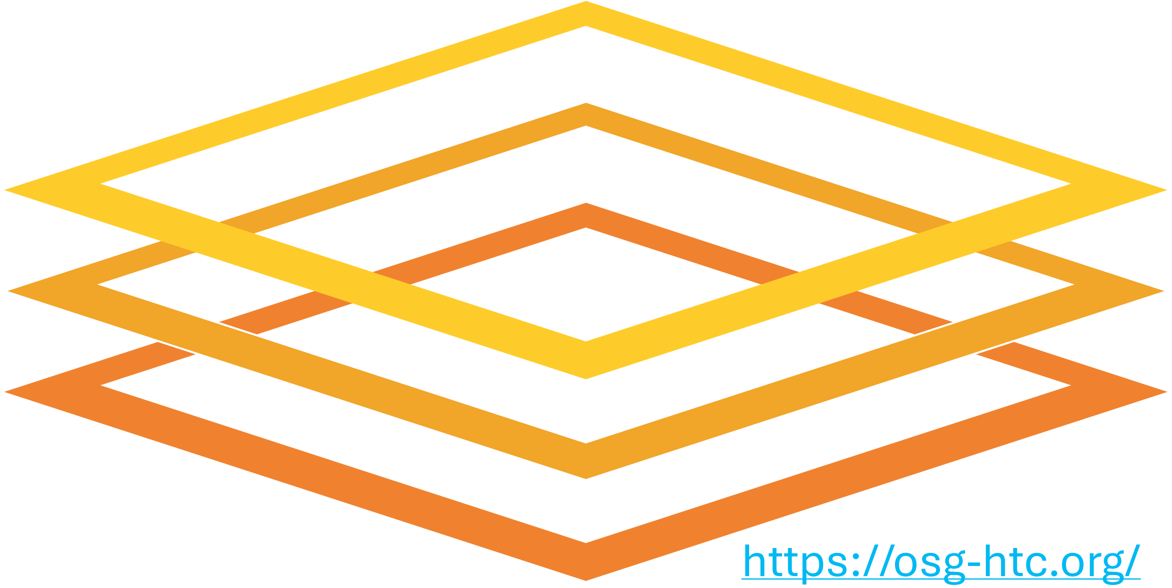
Target: Lower Bound of Drift

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

The Wonders of the Open Science Grid

- Do you have high throughput computing needs?
- Do you work for a US institution?

Check out the
Open Science Pool!



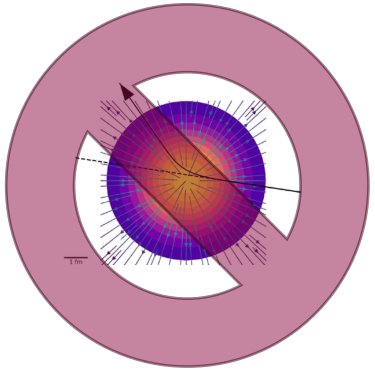
https://osg-htc.org/

Total core hours this project has used to date:

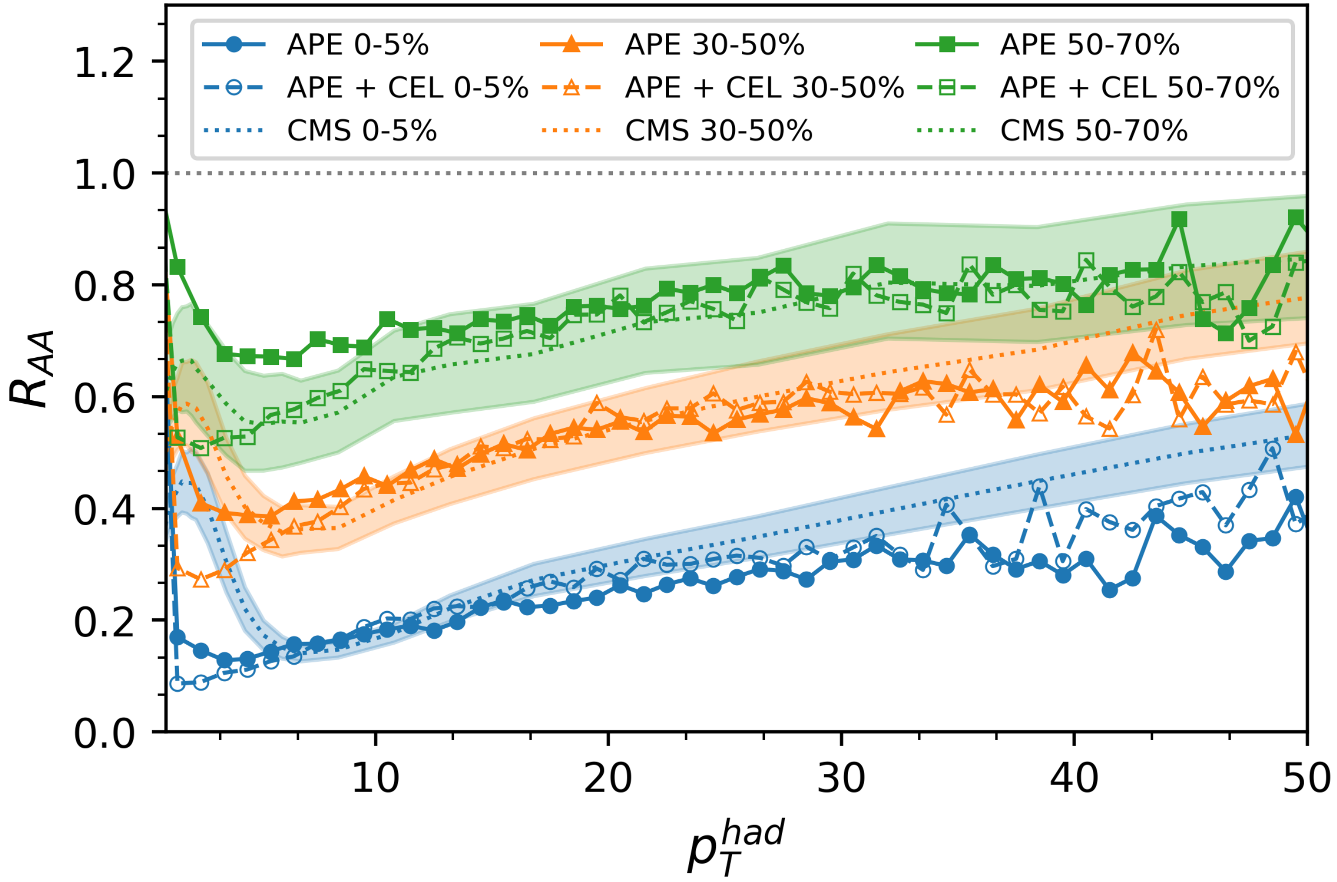
~1.589 MILLION
core hours

Or… 181 core *Years*

No Suppression Reduction

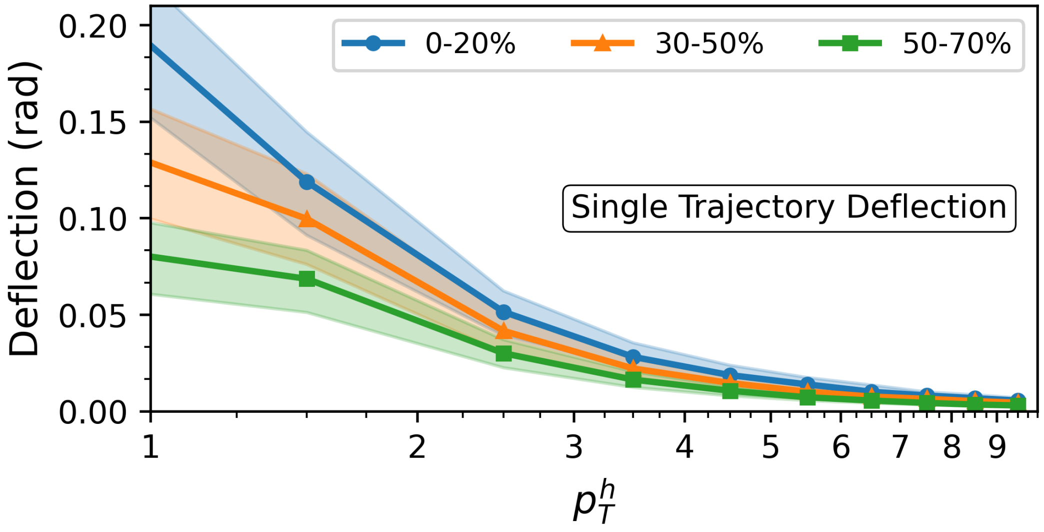


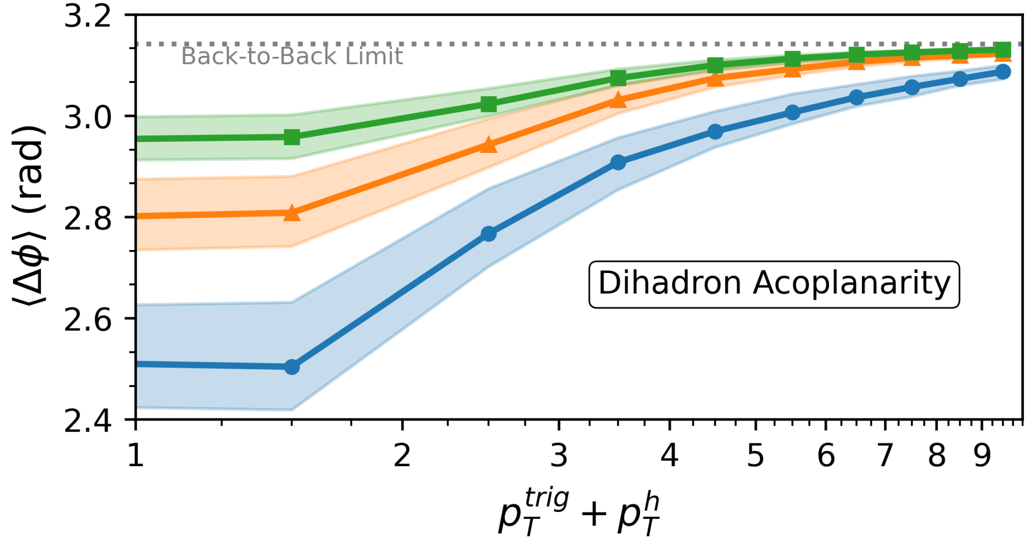
- Drift does not measurably modify R_AA(p_T)
  - Very useful – can tune coupling
  - Rad: g=2.0, Rad + Coll: g=1.6
- Additional sources of high-pT energy loss reduce effective drift coupling
- Better performance at low-pT can only enhance drift

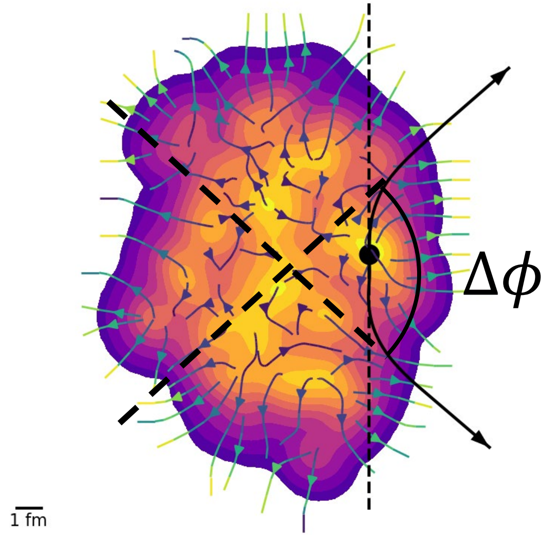


Deflection Size & Acoplanarity Enhancement

- 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"

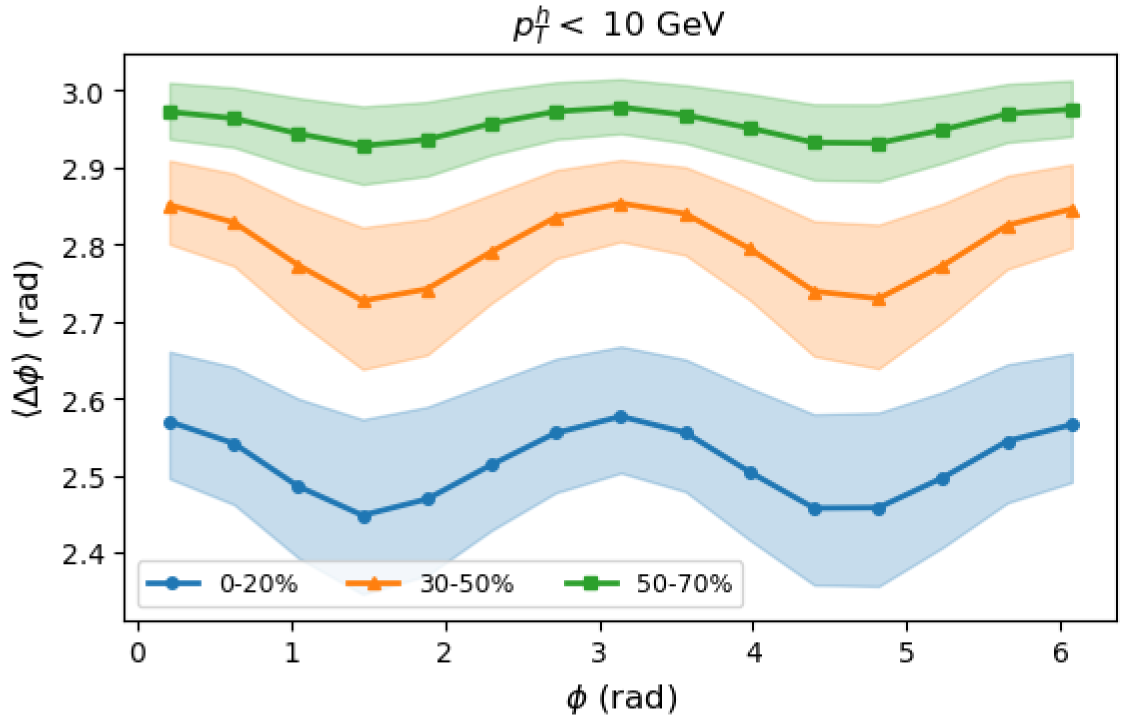


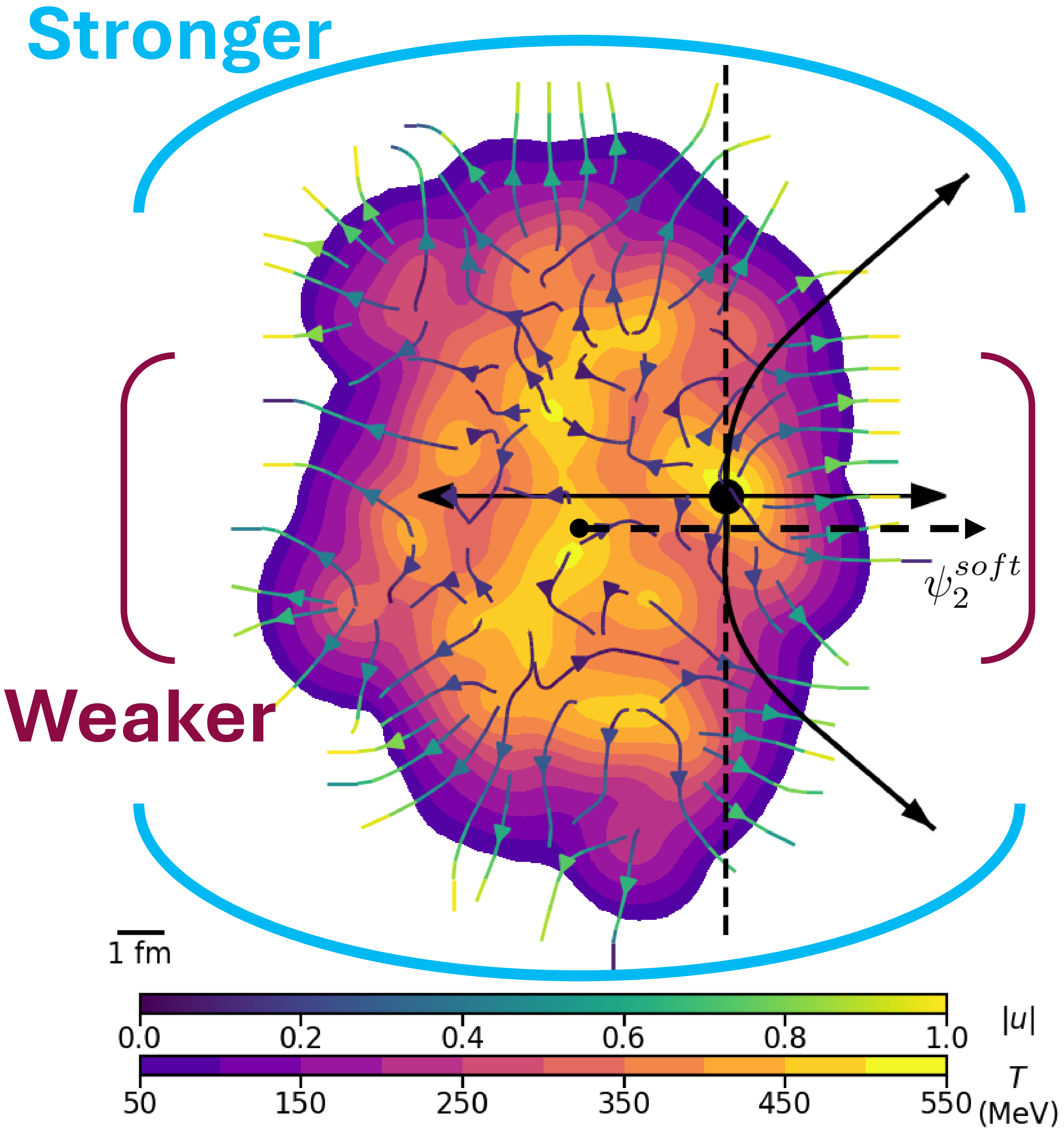




Colored band: drift +/- 25 % strength

Acoplanarity ϕ-dep.



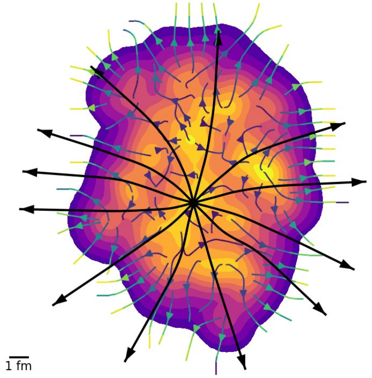


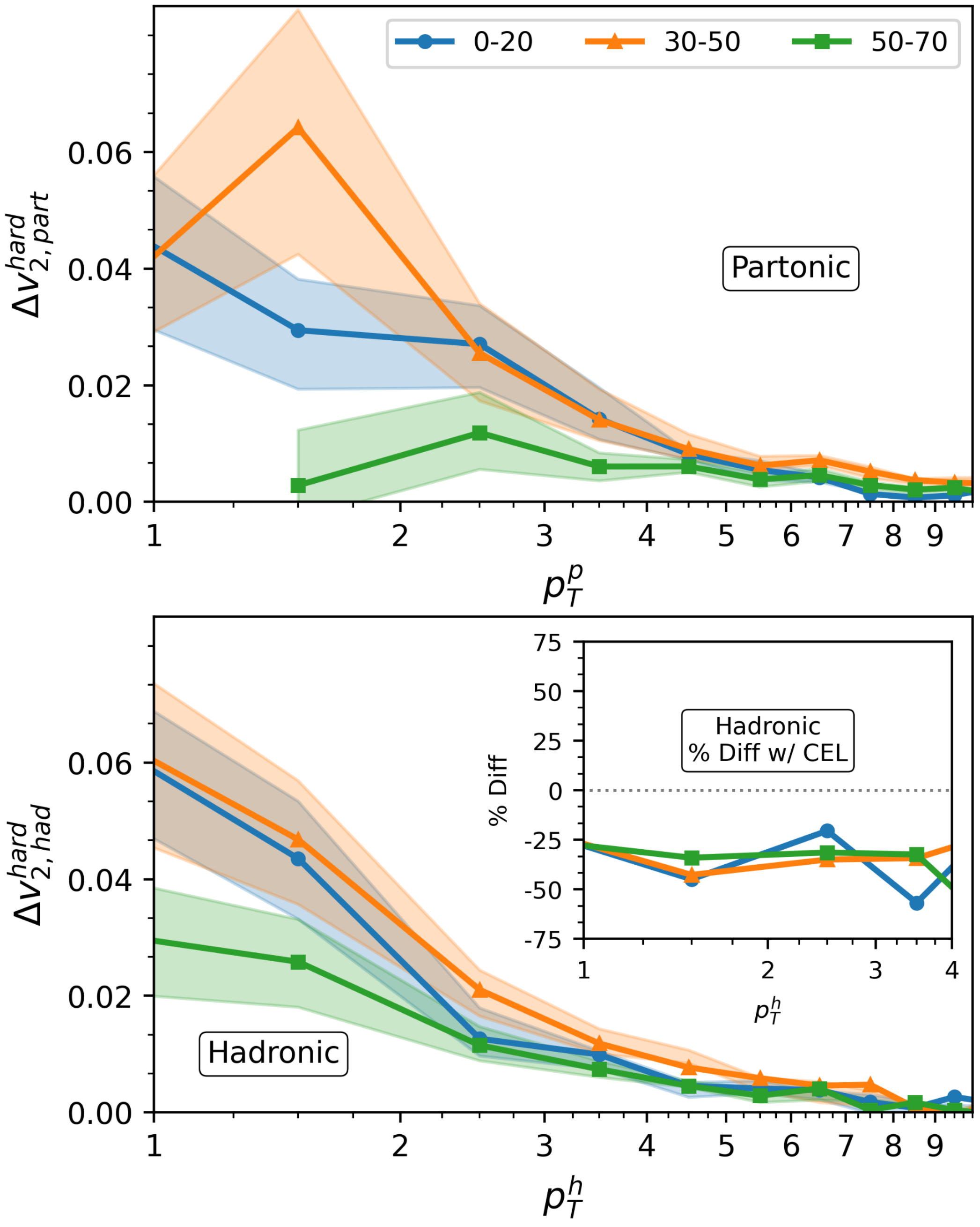
- Acoplanarity modulation is still tied to event plane
  - Possible selection cuts for velocity tomography
  - Difficult to measure independent of pathlength effects
- Collimation effect possible along event plane

Colored band: drift +/- 25 % strength

V_2 is Enhanced by Drift

- Large surviving v_2 modulation at low-p_T
  - 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

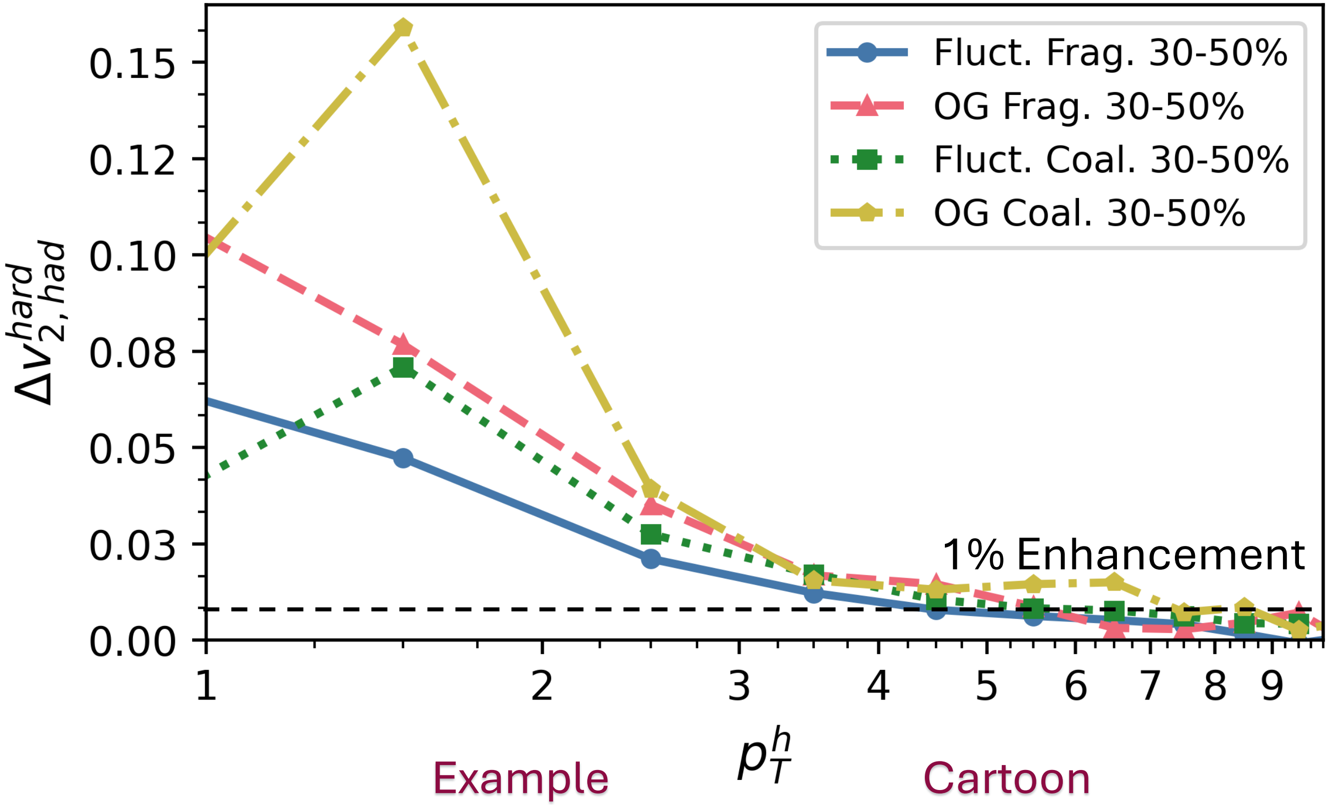


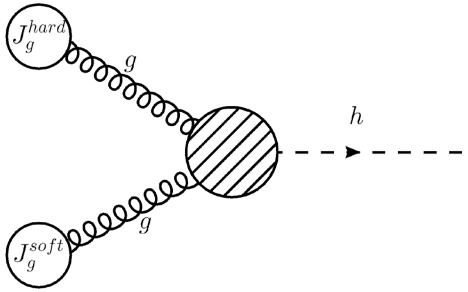


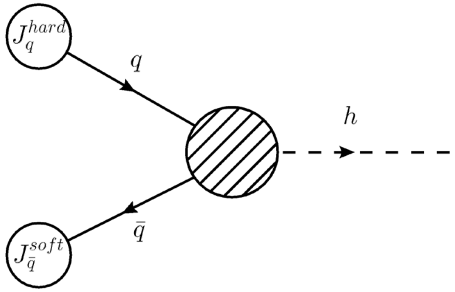
Colored band: drift +/- 25 % strength

Effect too Small for You?
Many Choices to Enhance!

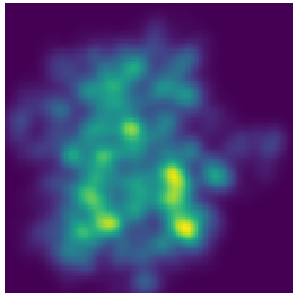
- Hadronization variation
  - E.g. “uniform Wigner Distribution” coalescence model (arxiv:nucl-th/0301093)
- Effect may be large in varied medium models
  - E.g. enhancement in optical Glauber initial conditions



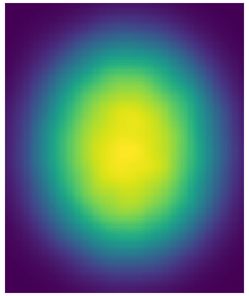




Example “Fluct.”

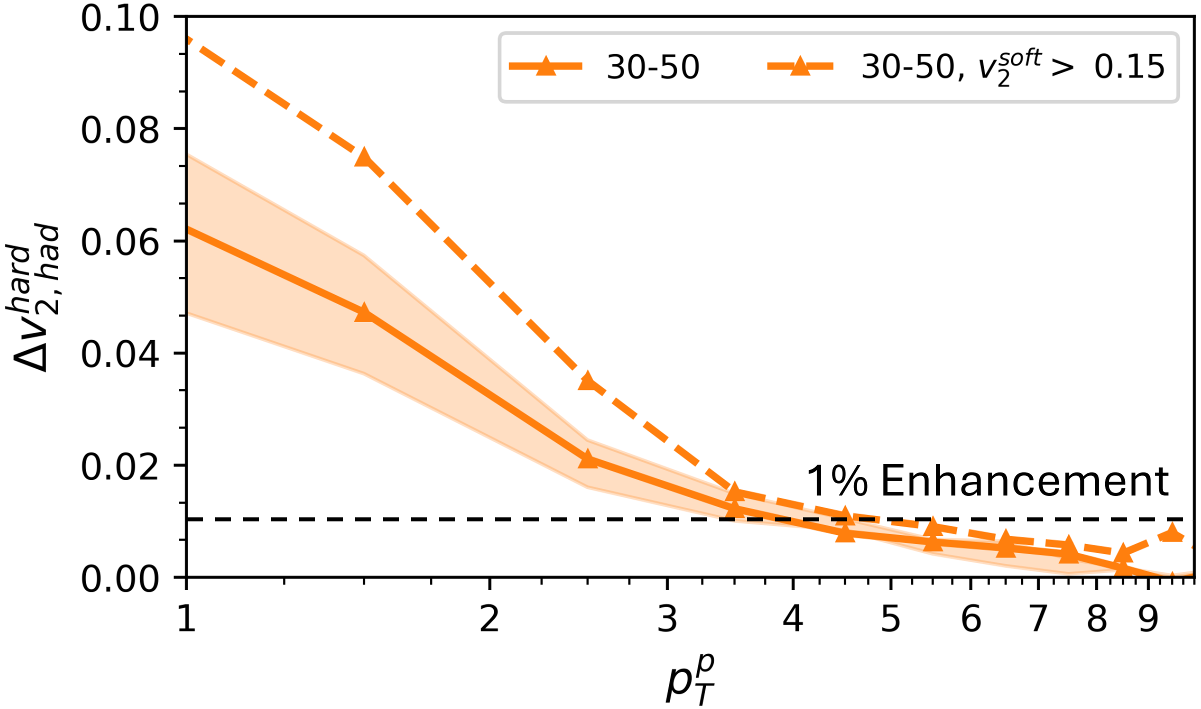


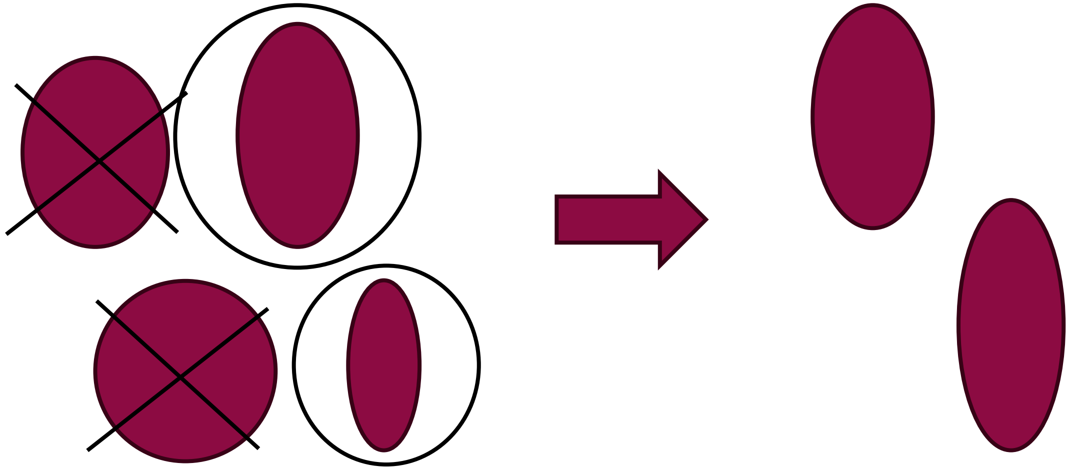
Cartoon “OG”



Effect too Small for You?
Make selection cuts!

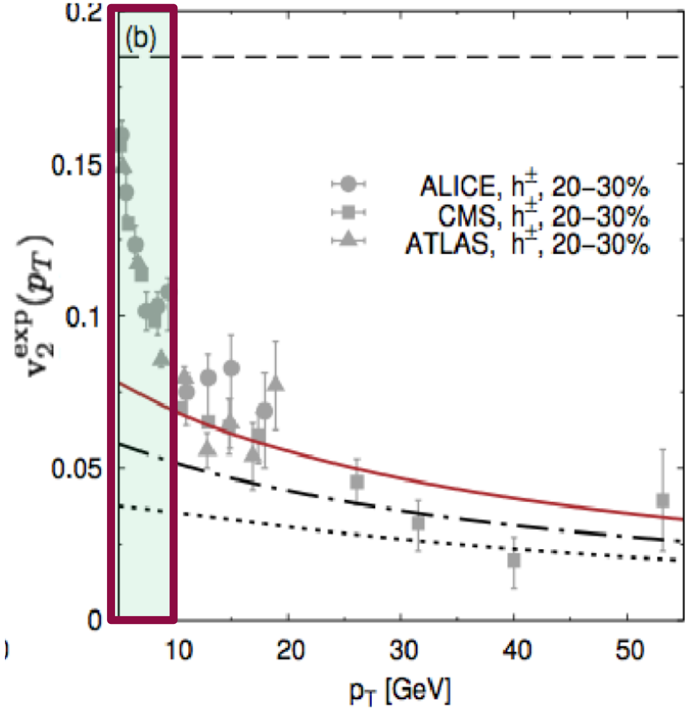
- Consider cuts on event geometry (ϵ_2, or soft v_2) or other collision systems
  - E.g. $v_2 > 0.15$
  - More in Hasan's talk
- Fluctuating drift & EL can result in much larger enhancements on avg.





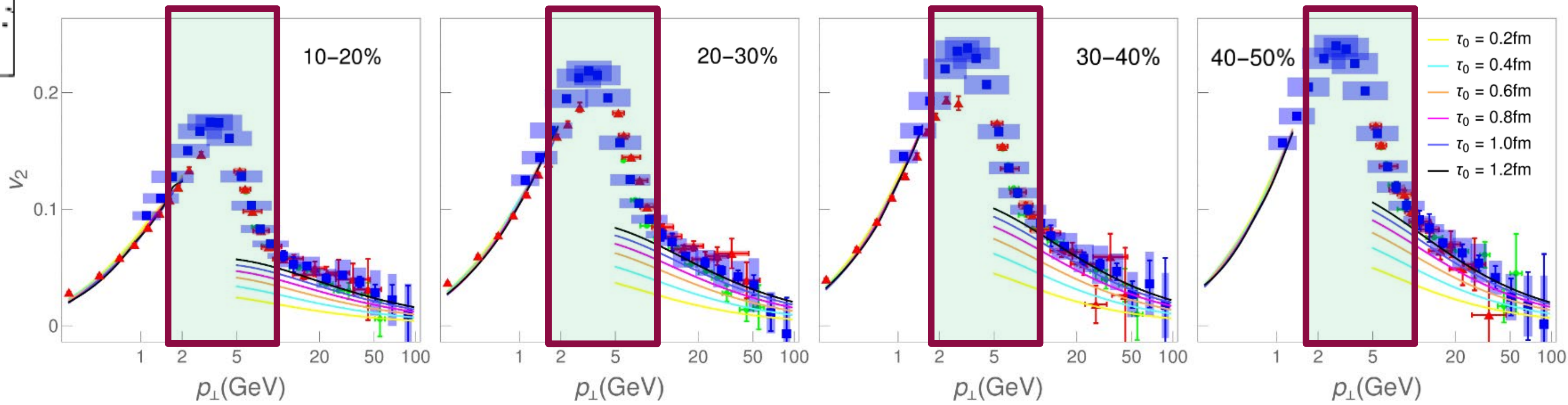
Importance for the R_AA x v_2 Puzzle

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

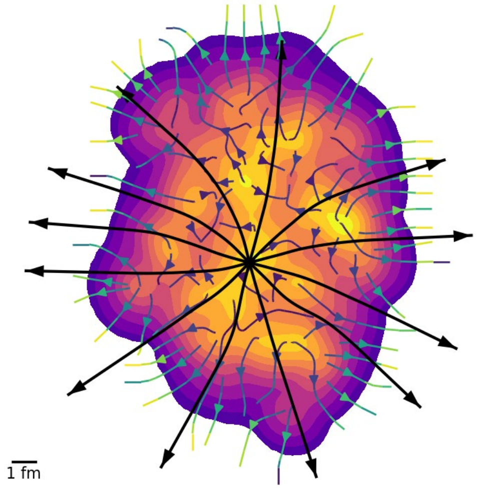


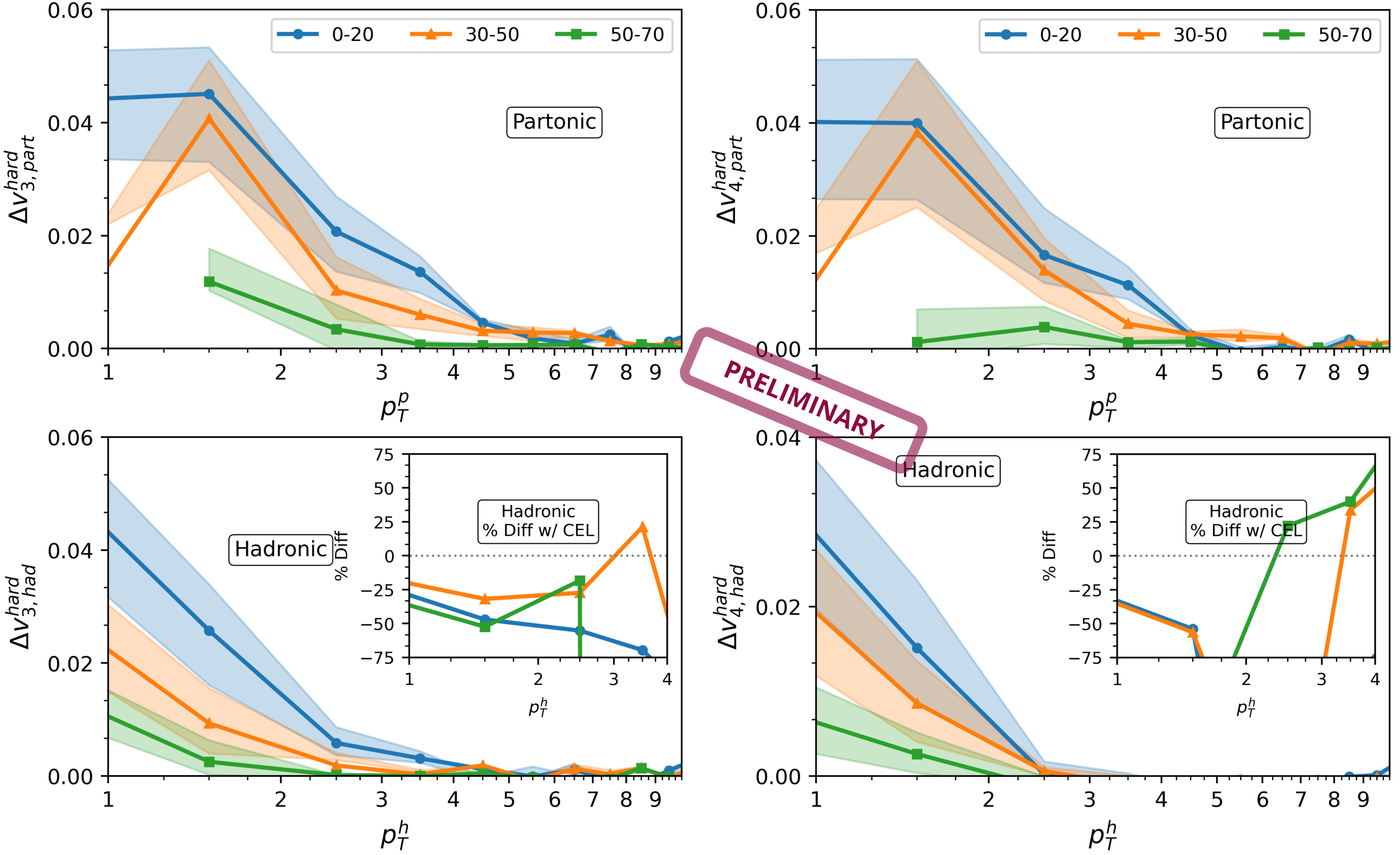
Parametric Energy Loss
Noronha-Hostler et al:
(arXiv: 1602.03788)

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



Higher Harmonic V_n's are Enhanced by Drift

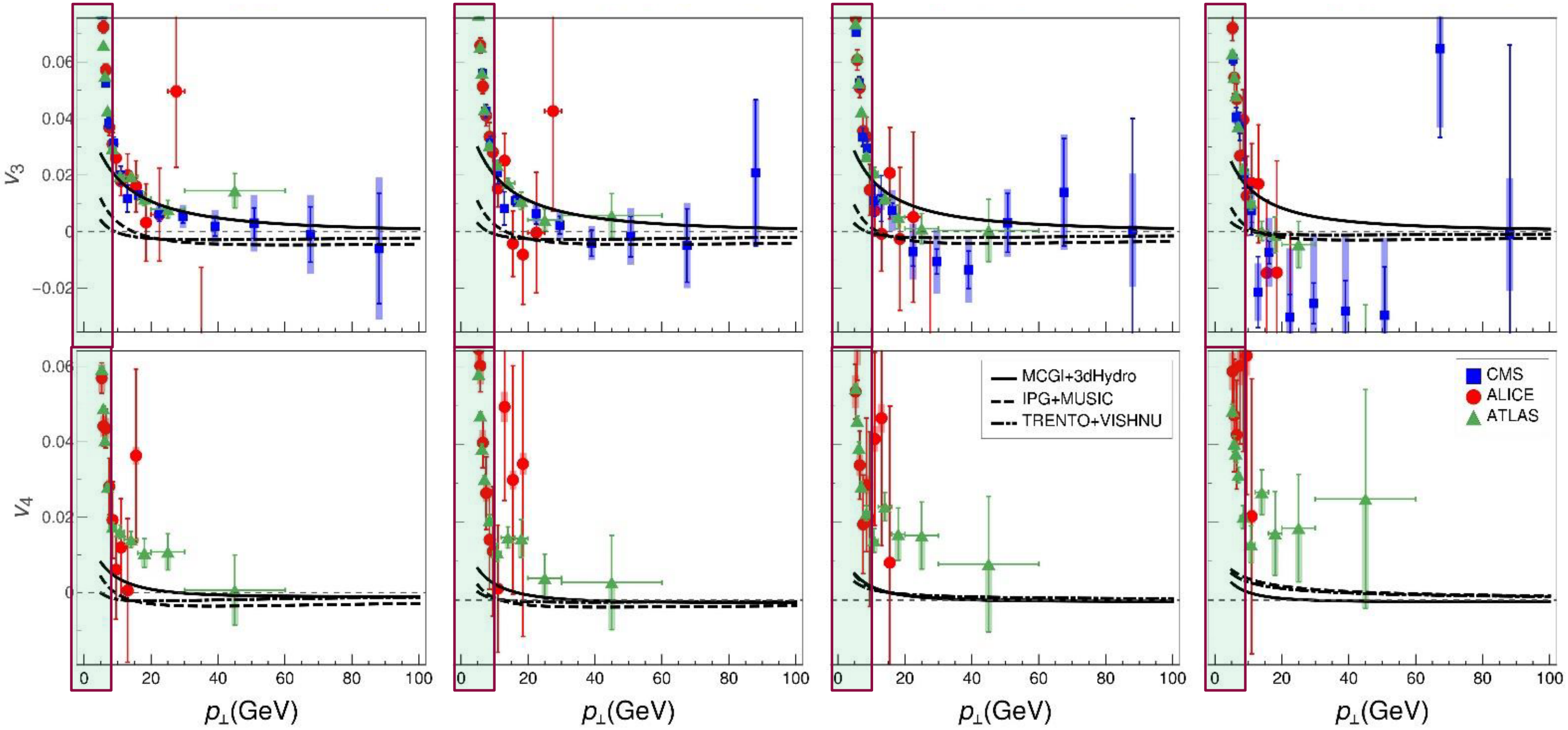




PRELIMINARY

v3 & v4 from Perturbative Energy Loss

E.g. DREENA results:



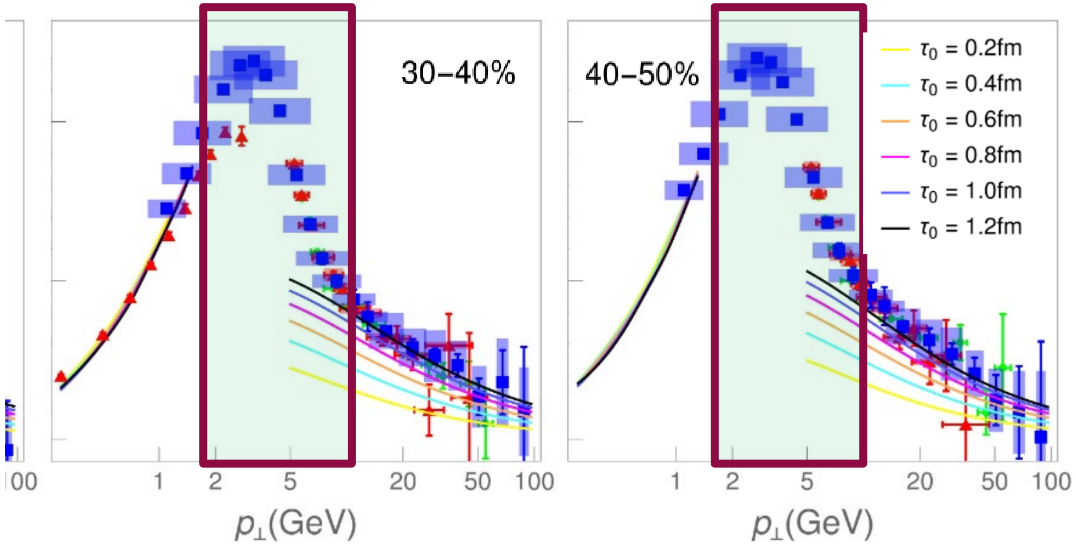
(arXiv:2208.09886)

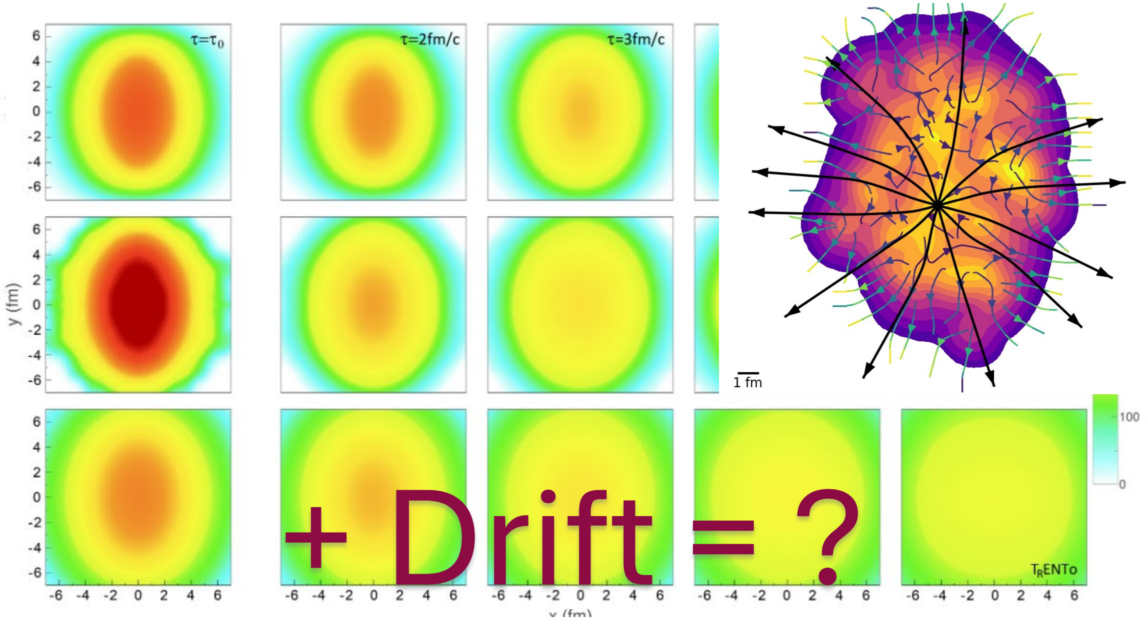
- Drift produces higher harmonic coupling
- Possible importance to v_3 & v_4 puzzle
- Difficult to couple to small anisotropies with energy loss alone

Drift v_n sensitive to pathlength ordered internal medium props.

- 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 Bayes-DREENA differ with the inclusion of drift?
  - Possibly selects on slightly smaller anisotropy, likely changes story of free streaming parameters

(iNSPIRE:2640923)



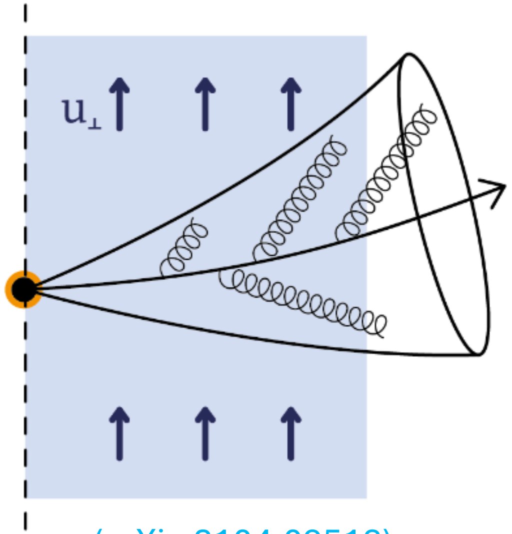


+ Drift = ?

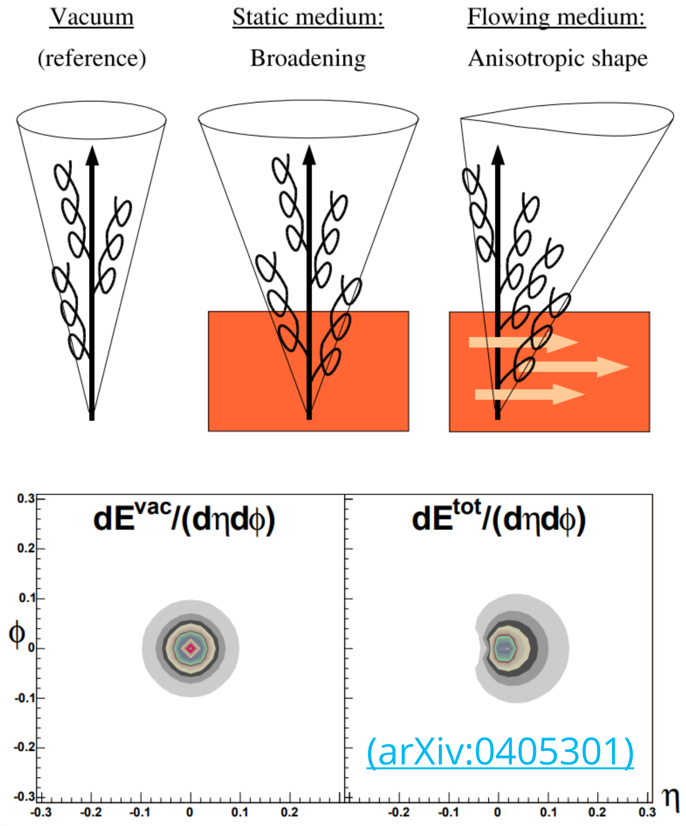
(iNSPIRE:2606181)

Anisotropic Jet Substructure

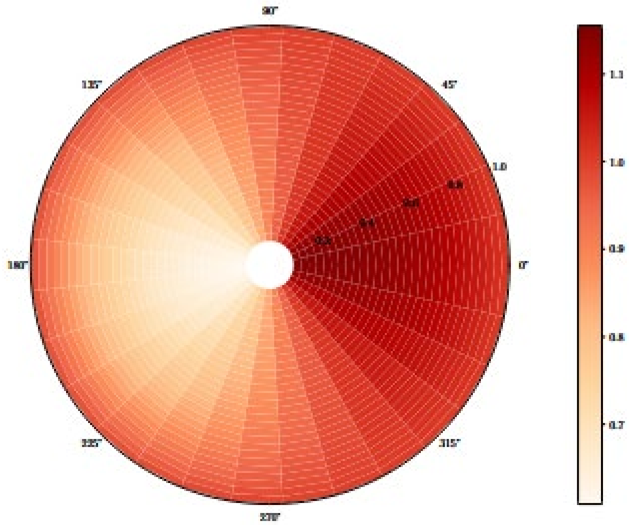
- People have been thinking about anisotropic radiation distribution for some time
    - Flow anisotropy as Lorentz boost (Armesto, Salgado, & Wiedemann)
    - Perturbative scalar calculation of radiation (Sievert, Sadofyev, Vitev)
    - Jet substructure harmonics (Barata, Milhano, & Sadofyev)
    - Perturbative real gluon calculation of radiation (Kuzmin & López)
- Drift of jet particles is also likely important!



(arXiv:2104.09513)



(arXiv:0405301)

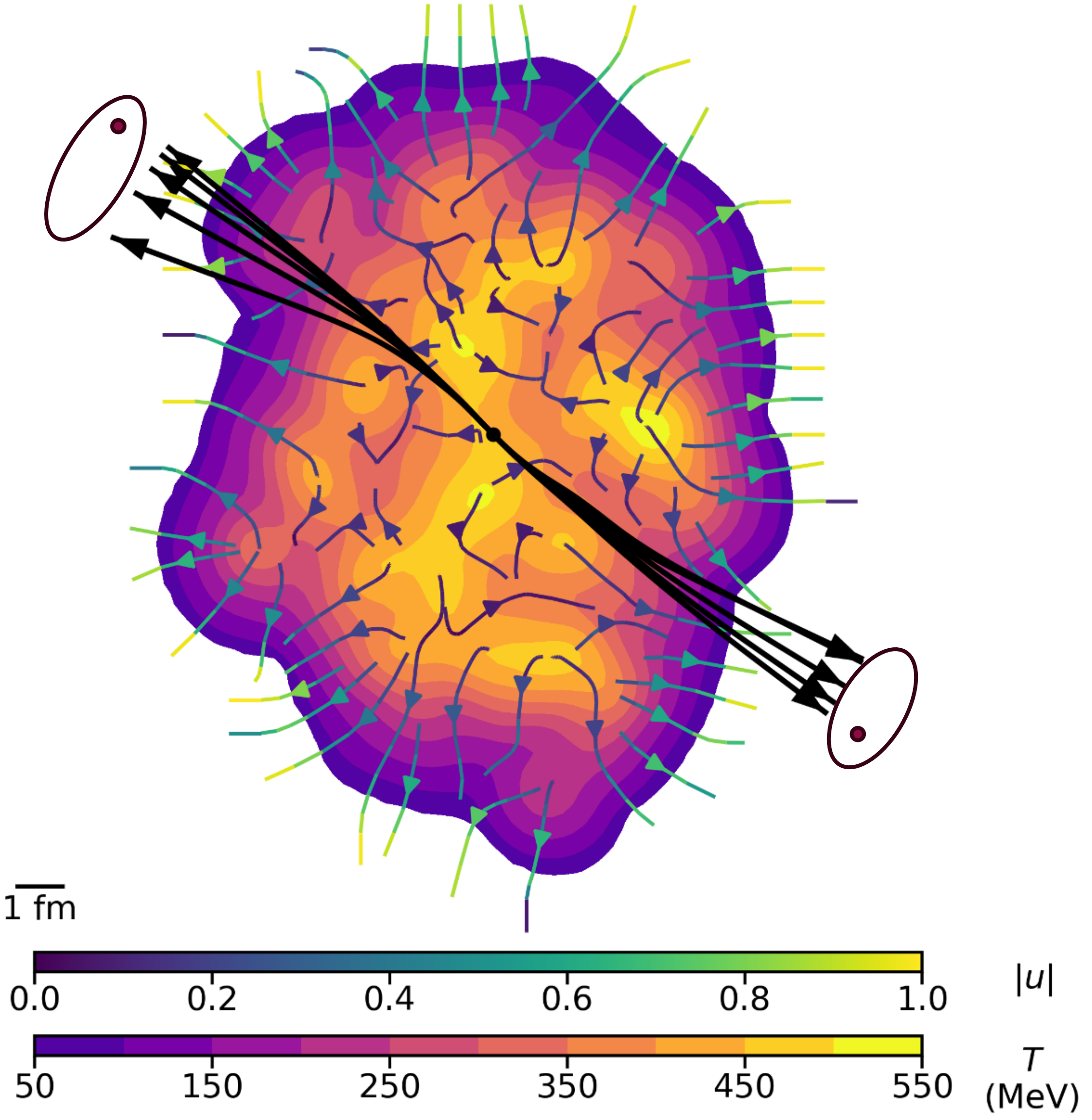


(arXiv:2308.01294)

$\Delta j, v_n$ of substructure

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



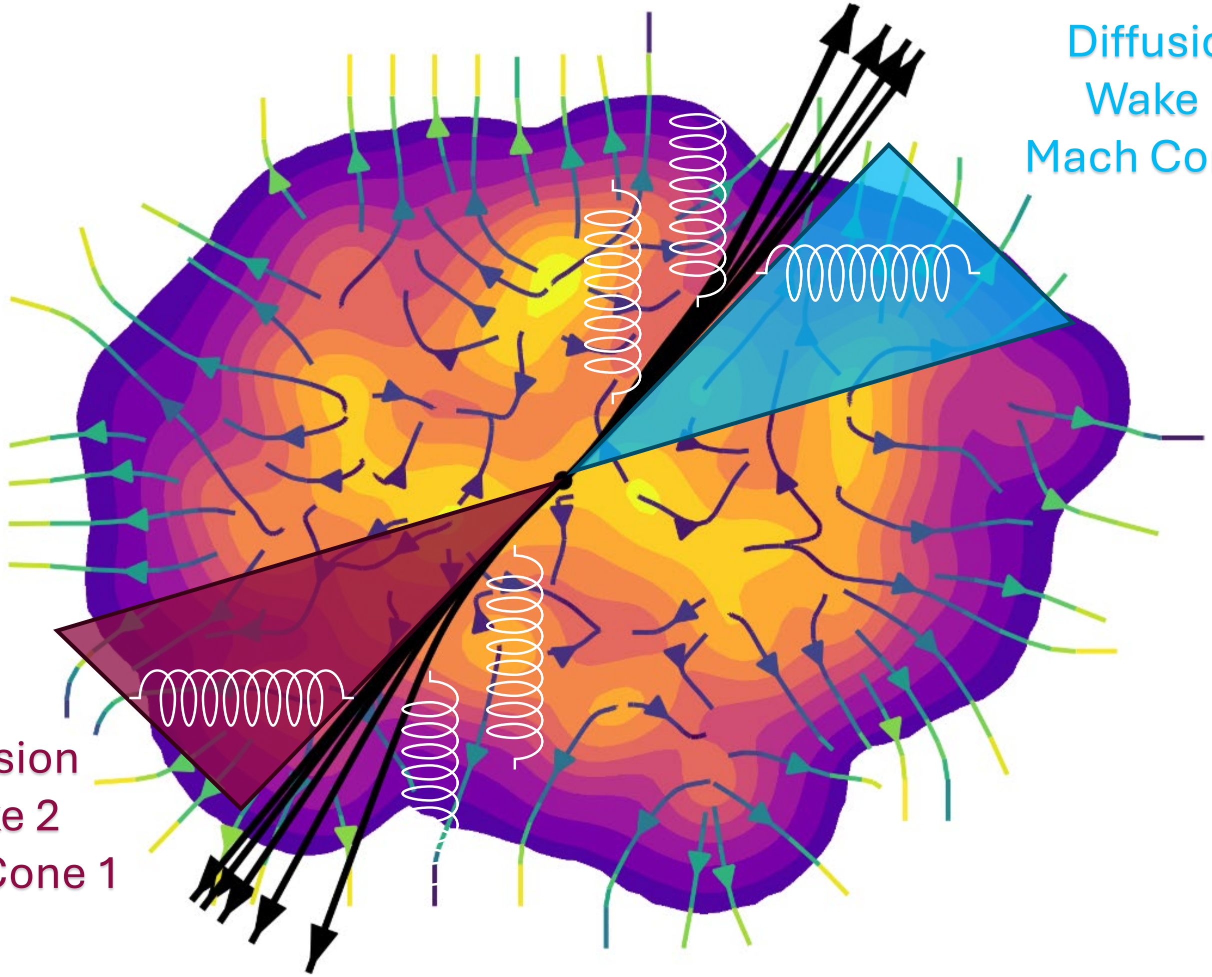
$$\langle \vec{q}_{drift}\rangle = \hat{e}_\perp \int d\tau \frac{3}{\boxed{E(\tau)}} \frac{\mu^2(\tau)}{\lambda(\tau)} \ln\frac{E(\tau)}{\mu(\tau)} \frac{u_\perp(\tau)}{1-u_\parallel(\tau)}$$

Energy suppressed

Anisotropic Jet Wake

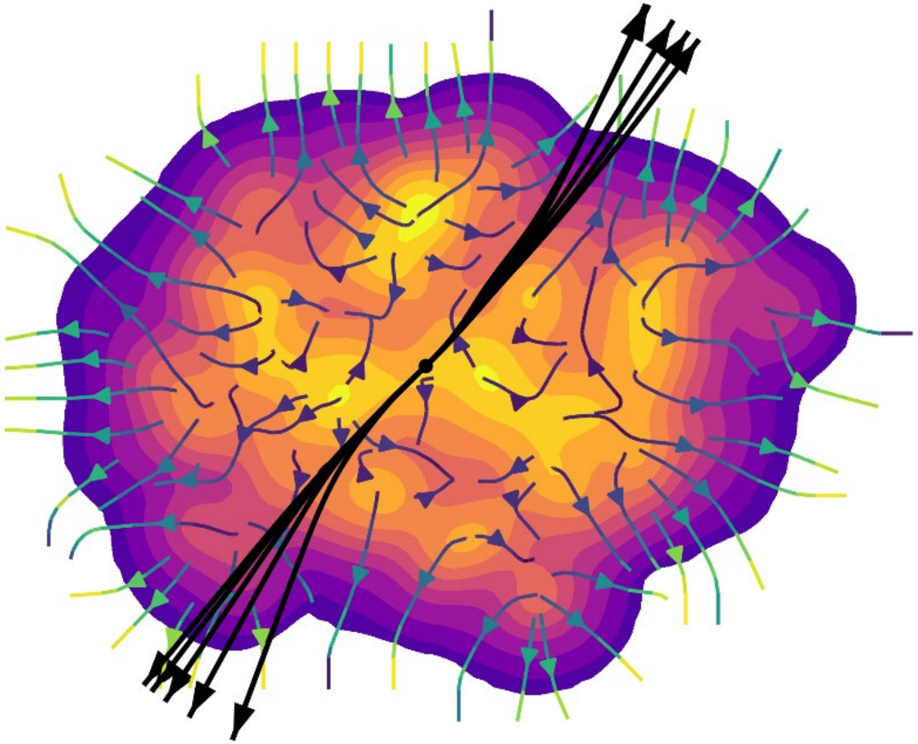
Signed Z^0 wake measurement could reveal anisotropy relative to event plane

- 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



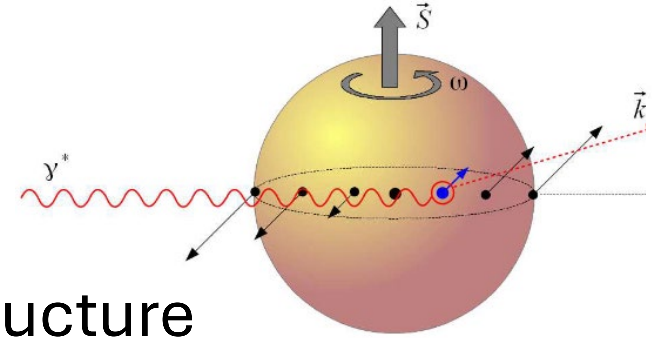
The Elephant in the Room…

- Is this even a perturbative regime?
- How seriously should you take these results?

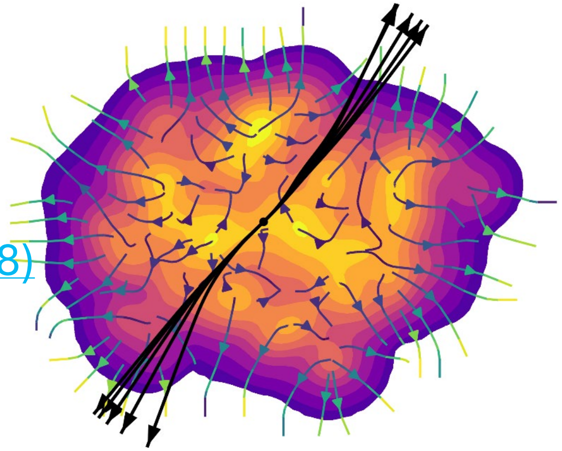


These results are manifestly incomplete, but they show that drift has robust signatures that are nonzero in even the most conservative estimate.

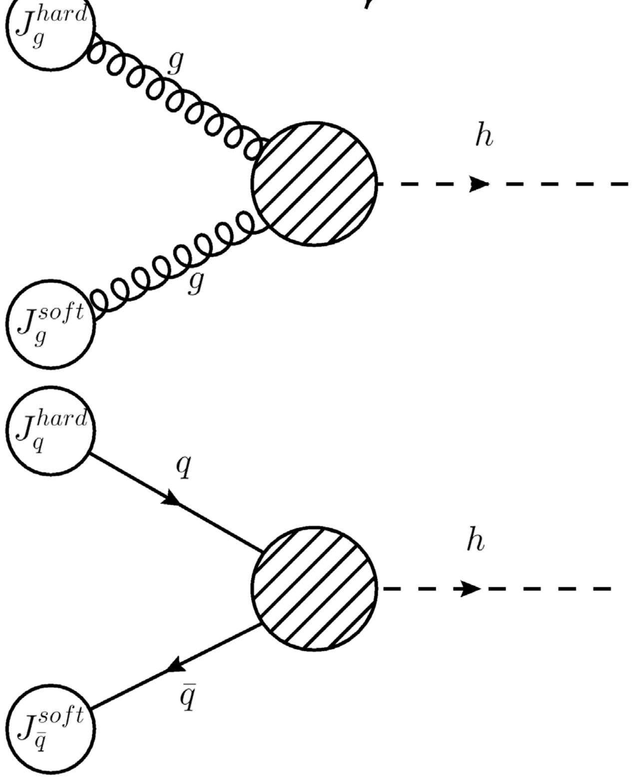
Next Steps:



(arXiv:1310.5028)



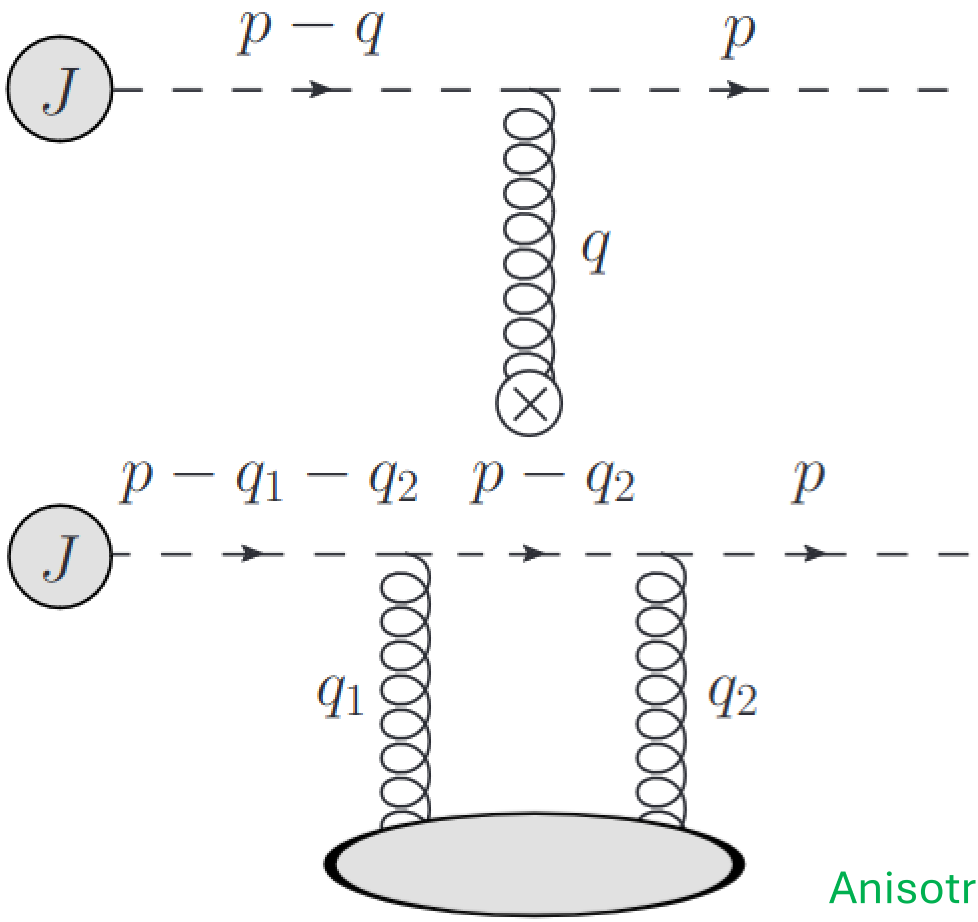
- Fluctuating Drift & Energy Loss, Jet Substructure
  - Drift-dispersion + flow-induced radiation => jet substructure anisotropy
  - Jo Bahder, Hasan Rahman, Matt Sievert, & Ivan Vitev
- CNM drift investigations
  - Drift due to polarized nuclei
  - Nicholas Baldonado, Alex Garcia, & Matt Sievert
- Complete survey of important interactions to $\mathcal{O}\left(\frac{\mu}{E}\right)$
  - Improve low-E hadronization formalisms
  - Better treatment of gradients & new diagrams



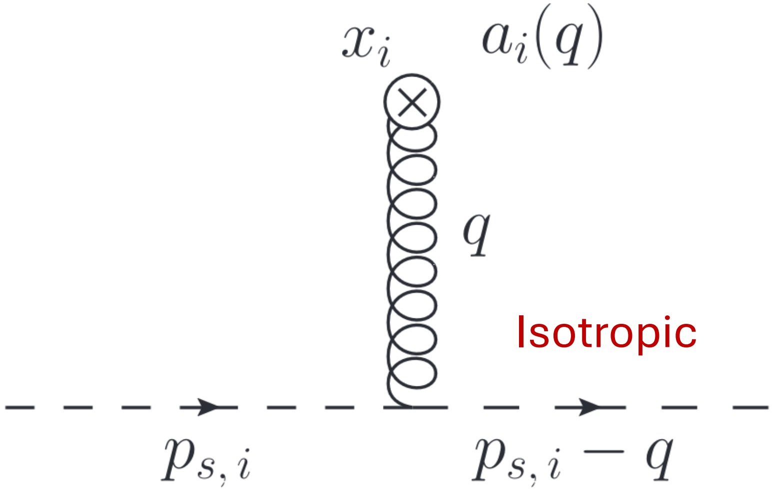
Thanks a Bunch!
See more details:
(arXiv:2412.05474)

Also see Hasan Rahman's talk in mere moments!!!

Jet Broadening – Isotropic vs Anisotropic



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



Isotropic

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

No vector info

Anisotropic

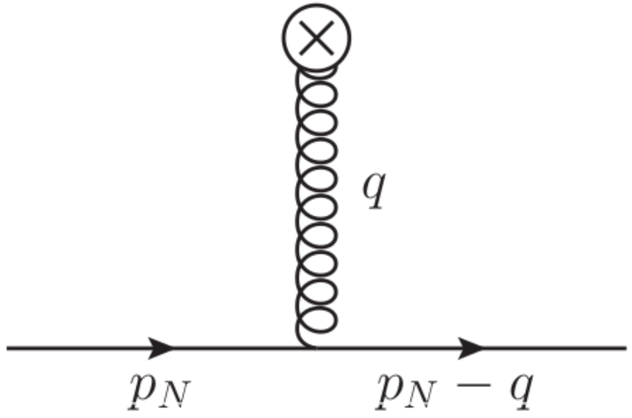
$$g\, a_i^{\mu a}(q) = t_i^a\, u_i^\mu\, v_i(q)\,(2\pi)\,\delta\left(q^0 - \boxed{\boldsymbol{u}_i\cdot\boldsymbol{q}}\right)$$

Preferred direction!

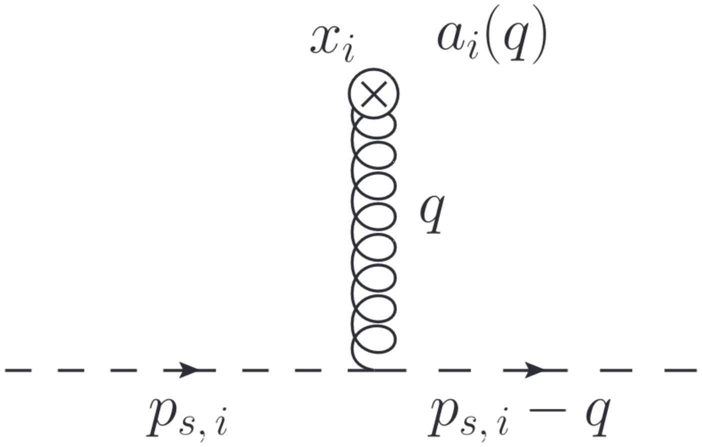
- Difference in setup – constraints on external gluon field
- Isotropic
  - Jet quark moves lightcone (+), medium quark moves lightcone (-)
- Anisotropic
  - Jet quark moves lightcone (+), medium quark moves with medium flow
- Two vector directions associated with the medium
  - Flow
  - Gradients

Medium Gluon Field Potentials

Simple
Isotropic
Potential



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



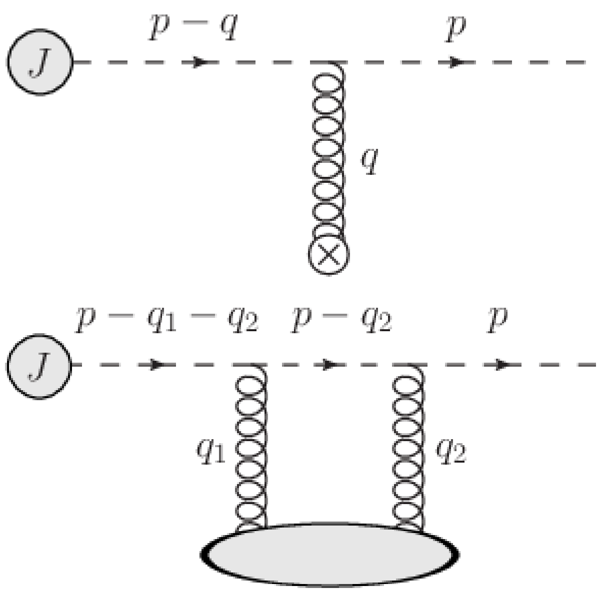
$$\left. g\, a_i^{\mu a}(q) = t_i^a\, u_i^\mu\, v_i(q)\, (2\pi)\, \delta\left(q^0 - \boldsymbol{u}_i \cdot \boldsymbol{q}\right) \right\} \text{Quark moves with medium}$$

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

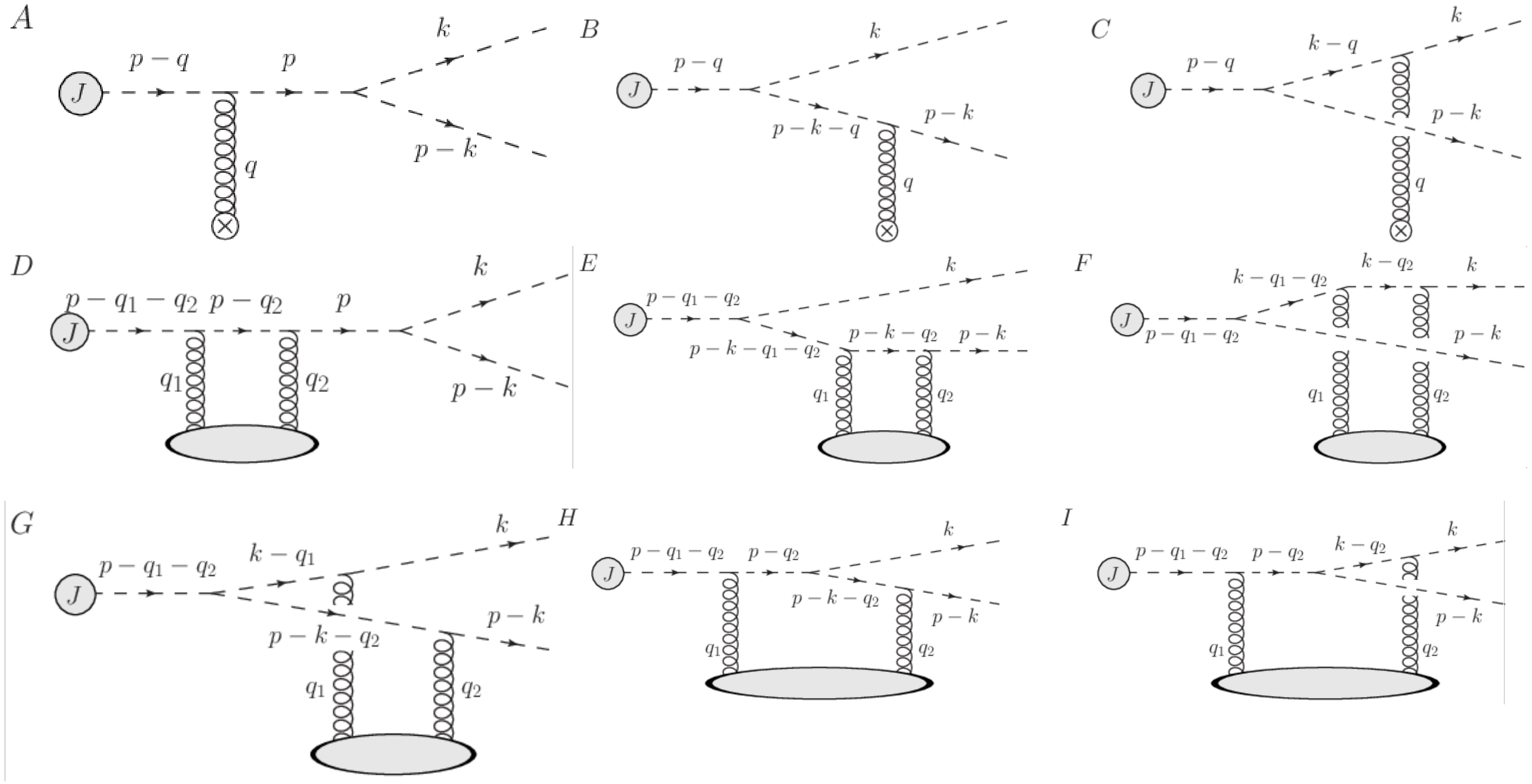
Anisotropic Flow
Potential
Regge Kinematics

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

All Diagrams



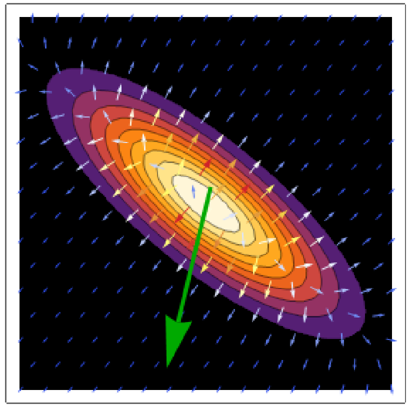
Born & Double-Born Momentum Broadening Diagrams

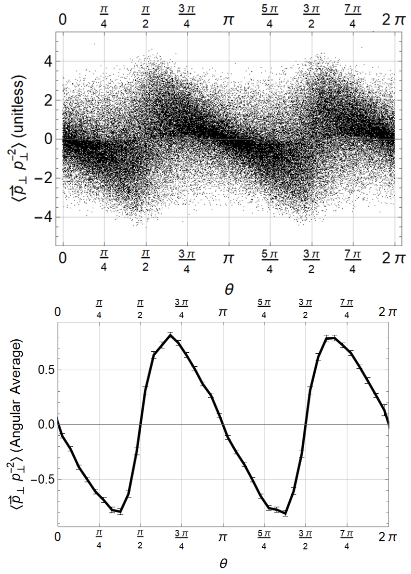


Born & Double-Born Radiation Diagrams

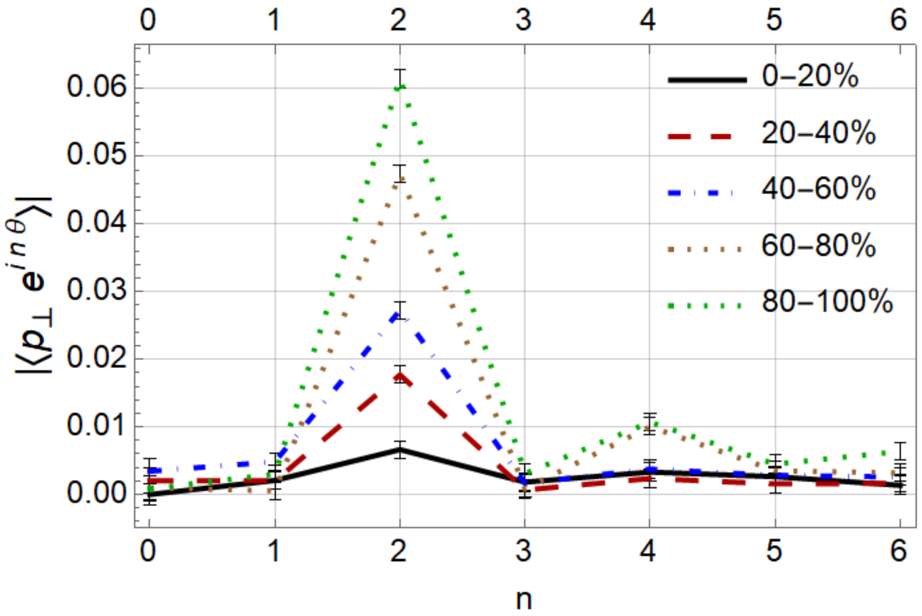
Does Drift Survive Event Averaging?

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

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

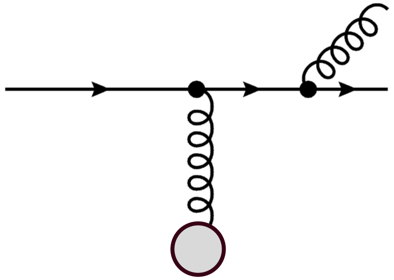
Collisional

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

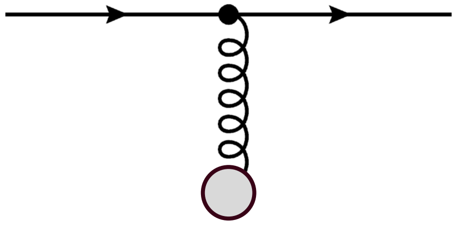
- Single Emission GLV @ 1st order in opacity w/ finite kinematic bounds (q, k)
- Interpolated tabulated results
- Gyulassy, Levai, Vitev (2000) (arXiv:0006010)

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

E.g.

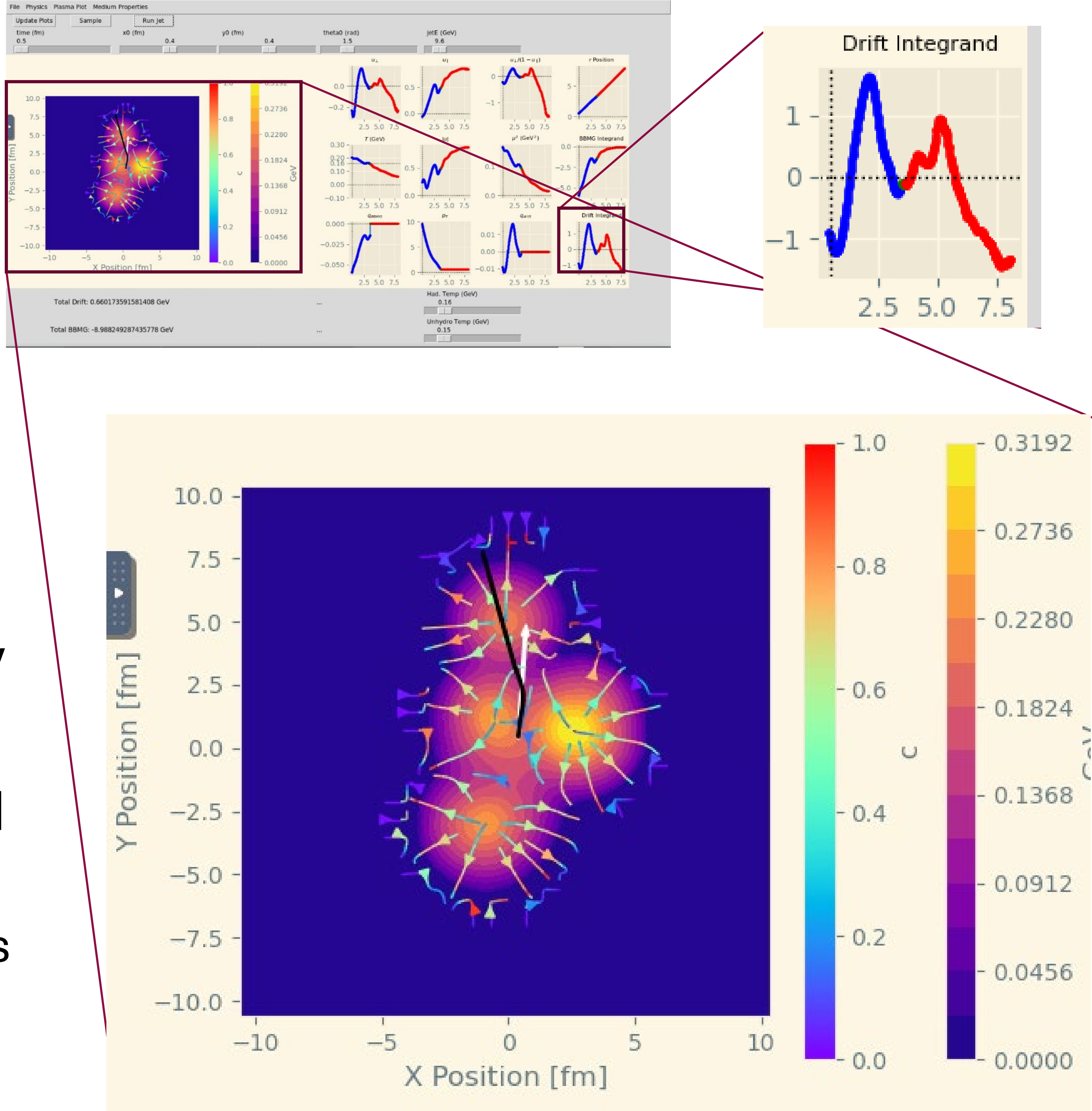


E.g.



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



Total Drift: 0.660173591581408 GeV

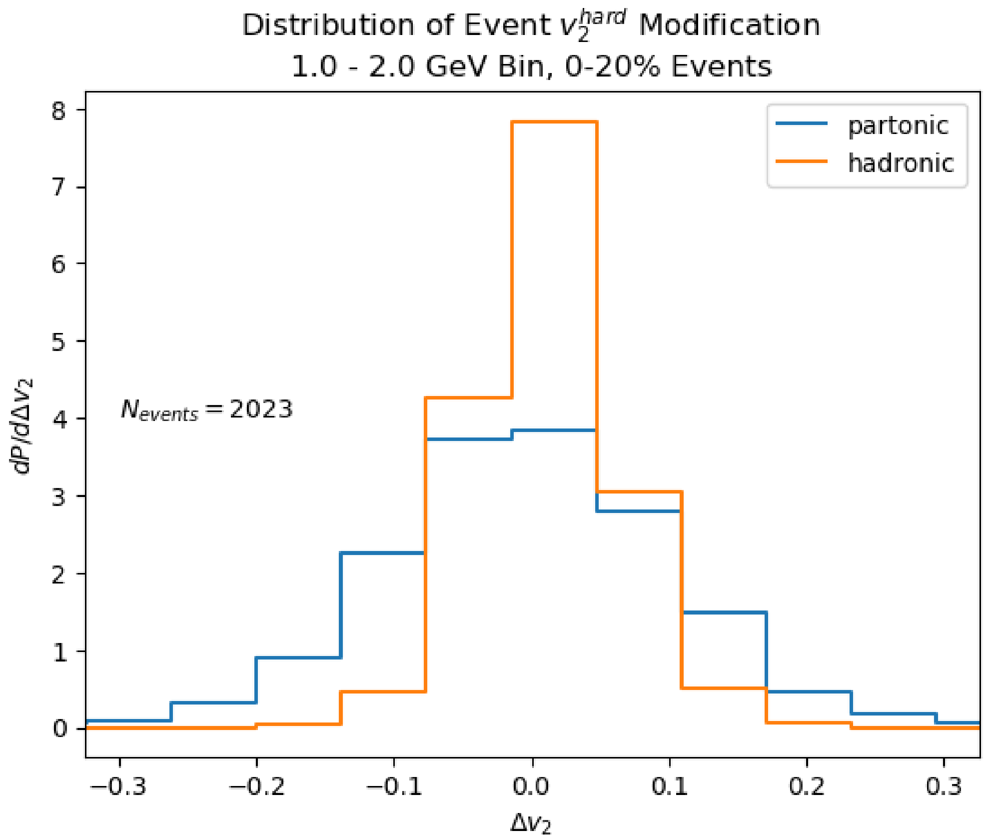
Total BBMG: -8.988249287435778 GeV

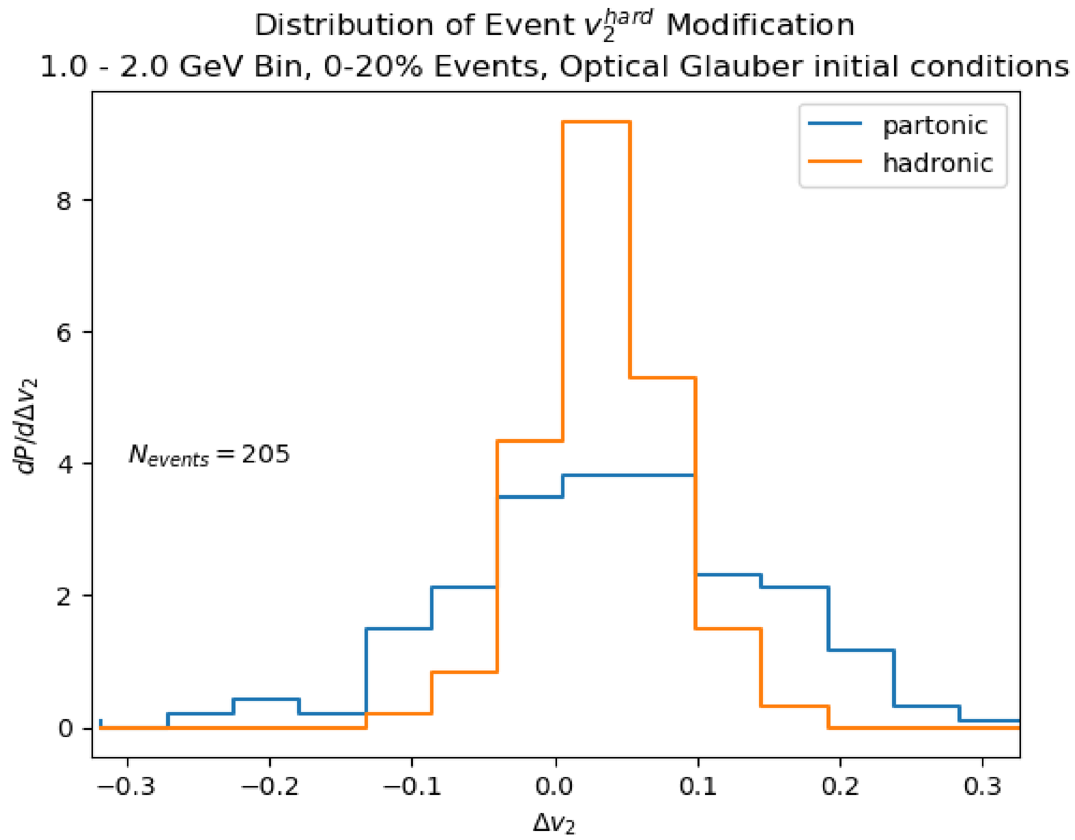
Parameter Fits & Model Choices

- **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!

How can delta v_n increase after fragmentation?

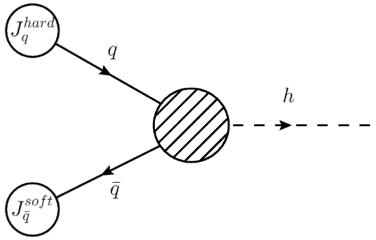

Distribution of Event v_2^{hard} Modification
1.0 - 2.0 GeV Bin, 0-20% Events


Distribution of Event v_2^{hard} Modification
1.0 - 2.0 GeV Bin, 0-20% Events, Optical Glauber initial conditions

- Deflections increase v_2 on average, but some deflections decrease v_2 (relative to energy loss alone)

- Fragmentation increases the relative correlation of deflections to flow, despite decreasing the average magnitude

Uniform Wigner Coalescence



$$|\mathcal{M}_{q\bar{q}\to h}|^2 = \int d^3\left(p_q, p_{\bar{q}}, p'_q, p'_{\bar{q}}\right)\left[\Psi_{h\to q\bar{q}}(p'_q,;p_h)\Psi^*_{h\to q\bar{q}}(p_q,;p_h)\right]\left[J^*_q(p'_q)J_q(p_q)\right]\left[J^*_{\bar{q}}(p'_{\bar{q}})J_{\bar{q}}(p_{\bar{q}})\right]$$

$$\times\,\delta^3(\vec{p}_h - \vec{p}_q - \vec{p}_{\bar{q}})\delta^3(\vec{p}_h - \vec{p}'_q - \vec{p}'_{\bar{q}})$$

$$\frac{dN_h}{d^3p_h} = \int d^3\left(p_q, p_{\bar{q}}, x_q, x_{\bar{q}}\right) W_{h\to q\bar{q}}(p_q, x_q - x_{\bar{q}})W_q(p_q, x_q)\, W_{\bar{q}}(p_{\bar{q}}, x_{\bar{q}})\;\; \delta^3(\vec{p}_h - p_q - p_{\bar{q}})$$

Choose uniform Wigner distribution

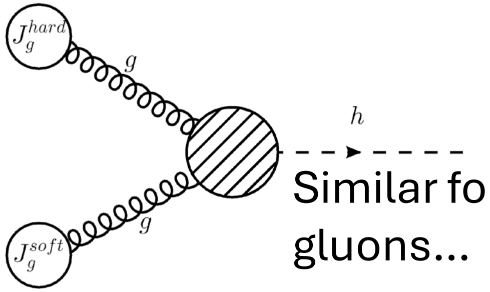
Fermi / Bose Dist.

$$\frac{1}{e^{E/k_bT} \pm 1}$$

$$\frac{dN_h}{dp_h d\phi_h} = g_\pi \frac{6\pi^2}{V\Delta_p^3}\int dp_1 d\phi_1\, dp_2 d\phi_2$$

$$\times\,\frac{dN_{hard}}{dp_1 d\phi_1}\frac{dN_{thermal}}{dp_2 d\phi_2}\,\delta^3(\vec{p}_h - \vec{p}_1 - \vec{p}_2)$$

$$\times\,\Theta(\Delta_p - |p_{T,1} - p_{T,2}|/2)$$

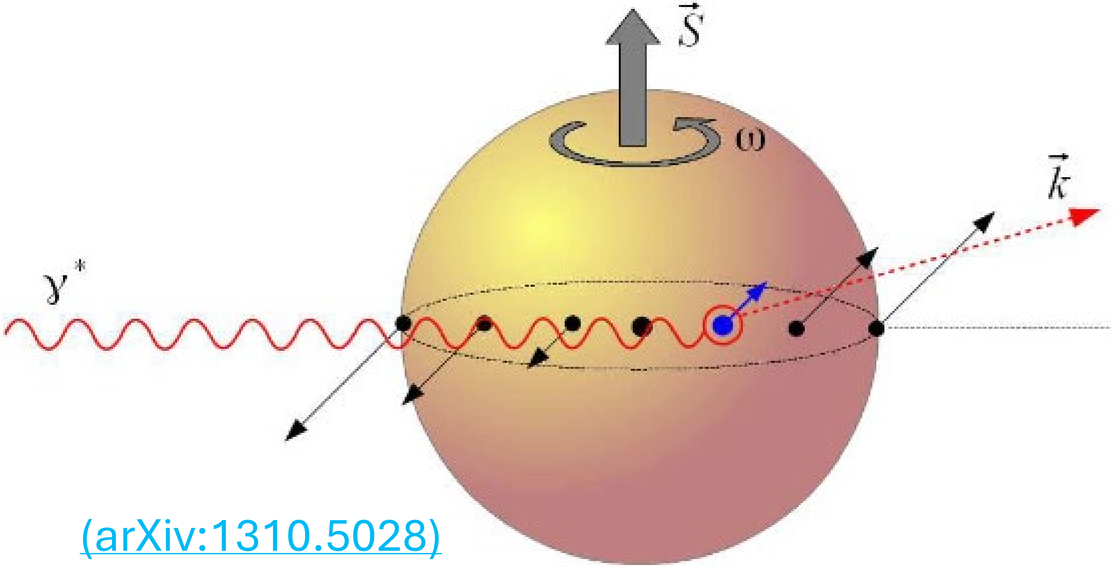


Similar for gluons...

(arxiv:nucl-th/0301093)

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)