# Flow Effects on Jet Substructure in Monte Carlo Approach

EMMI: Probing the Initial Stages with Jets

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GSI – Darmstadt, Germany
13h July, 2026

# Outline

I. Introducing Flow Effects

II. Implementation of Radiation Effects

III. Toy Phenomenology

# Introducing Flow Effects

# Flow Treatment

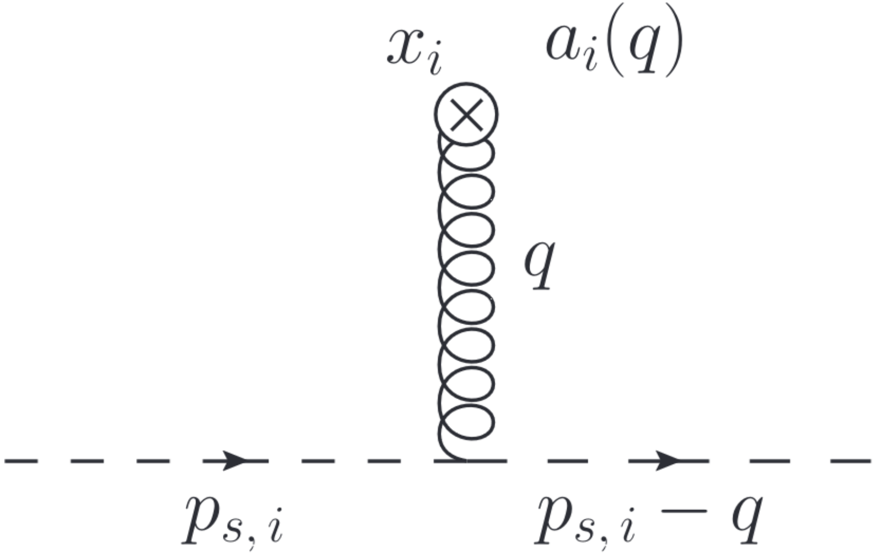
$$v_i(q) \equiv v_i\left(\boldsymbol{q}^2 - (\boldsymbol{u}_i \cdot \boldsymbol{q})^2\right) \equiv \frac{-g^2}{\boldsymbol{q}^2 + \mu_i^2 - (\boldsymbol{u}_i \cdot \boldsymbol{q})^2 - i\epsilon}$$

Directional scattering centers

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

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

$$A_{ext}^{\mu a}(q) = \sum_i e^{iq\cdot x_i} a_i^{\mu a}(q)$$

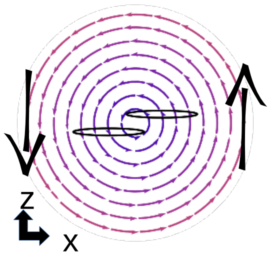


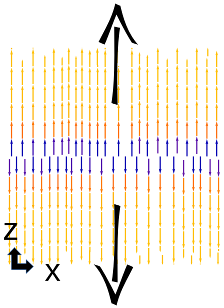

**Individual scattering centers have spatially varying velocity profile!**

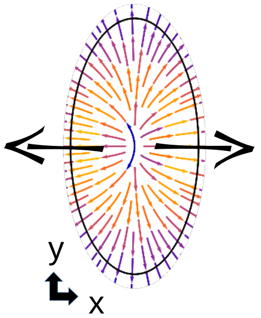
# Flow-Induced Anisotropic Broadening (“Drift”)

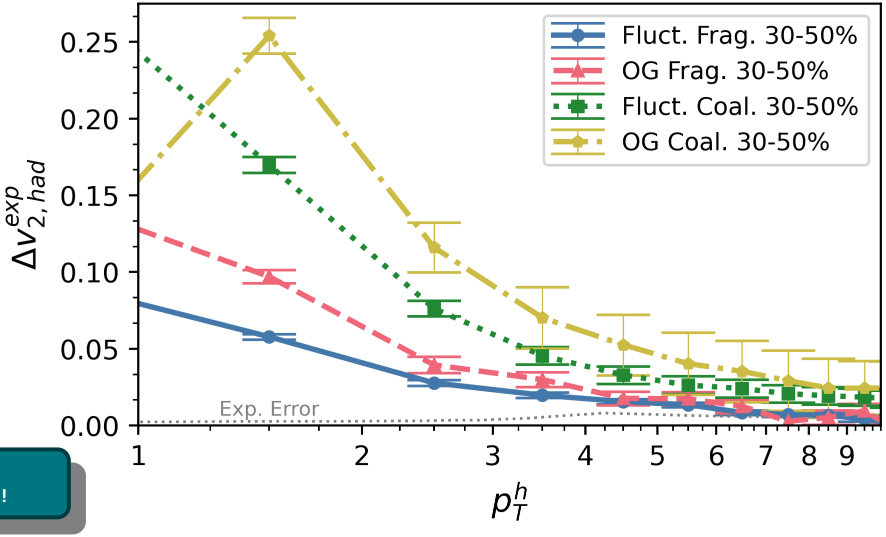
**APE MC & Realistic Pheno.**
J. Bahder, H. Rahman,
M. D. Sievert, & I. Vitev
*PRR (2026)*
(arXiv:2412.05474)

- Hard particles preferentially deflect in direction of medium flow
- Couple to flow structure of collision geometry
  - Event plane (azimuthal)
  - Expansion & Vorticity (rapidity)



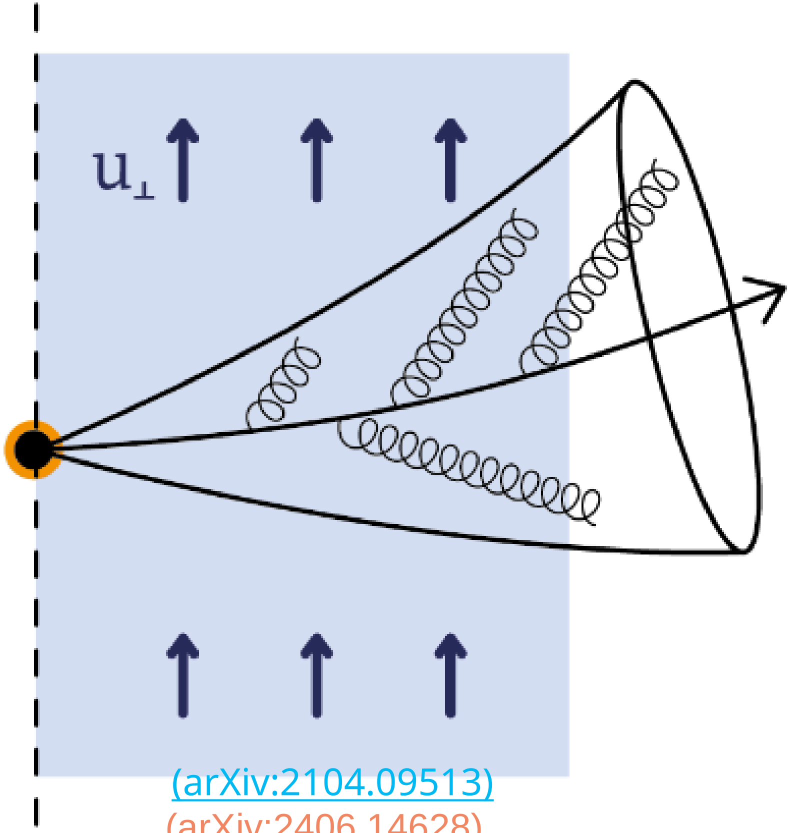




See Hasan Rahman’s
talk just after this for flow effect pheno.!

# Flow-Induced Anisotropic Radiation

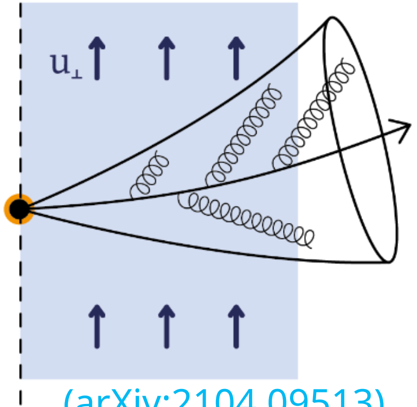



(arXiv:2104.09513)
(arXiv:2406.14628)

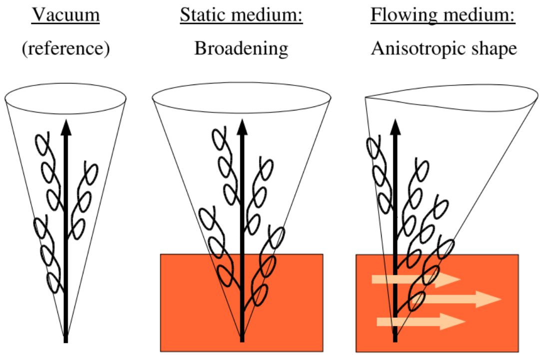
- Hard particles preferentially **radiate** in direction of medium flow
- Couple to same flow structures of collision geometry
- No phenomenology in state of the art media exists for the perturbatively calculated effect!

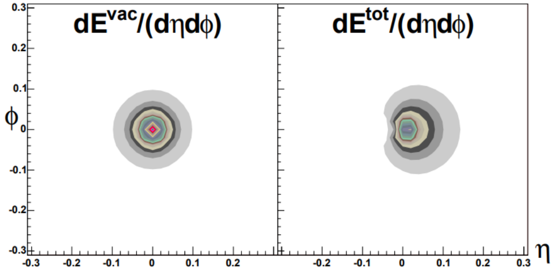
# Many Thoughts on Flow Affecting Substructure

- 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)

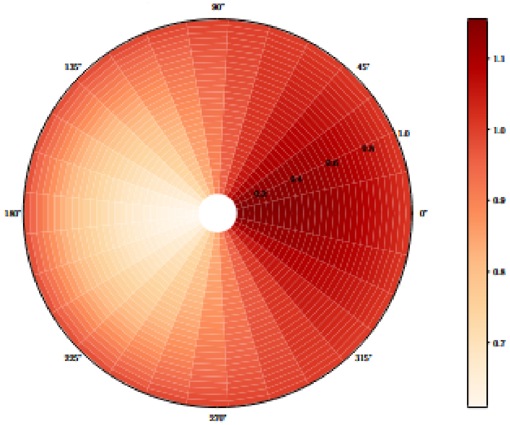



(arXiv:2104.09513)




(arXiv:0405301)



(arXiv:2308.01294)

...

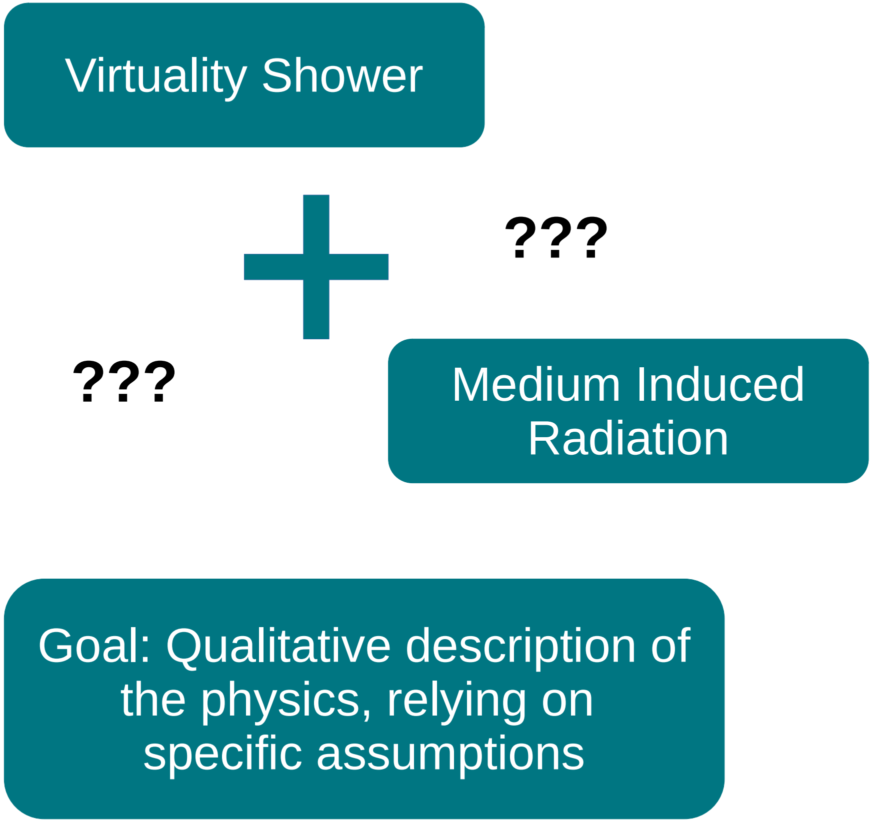
No Monte Carlo implementation exists…
**Let's give it a whirl!!!**

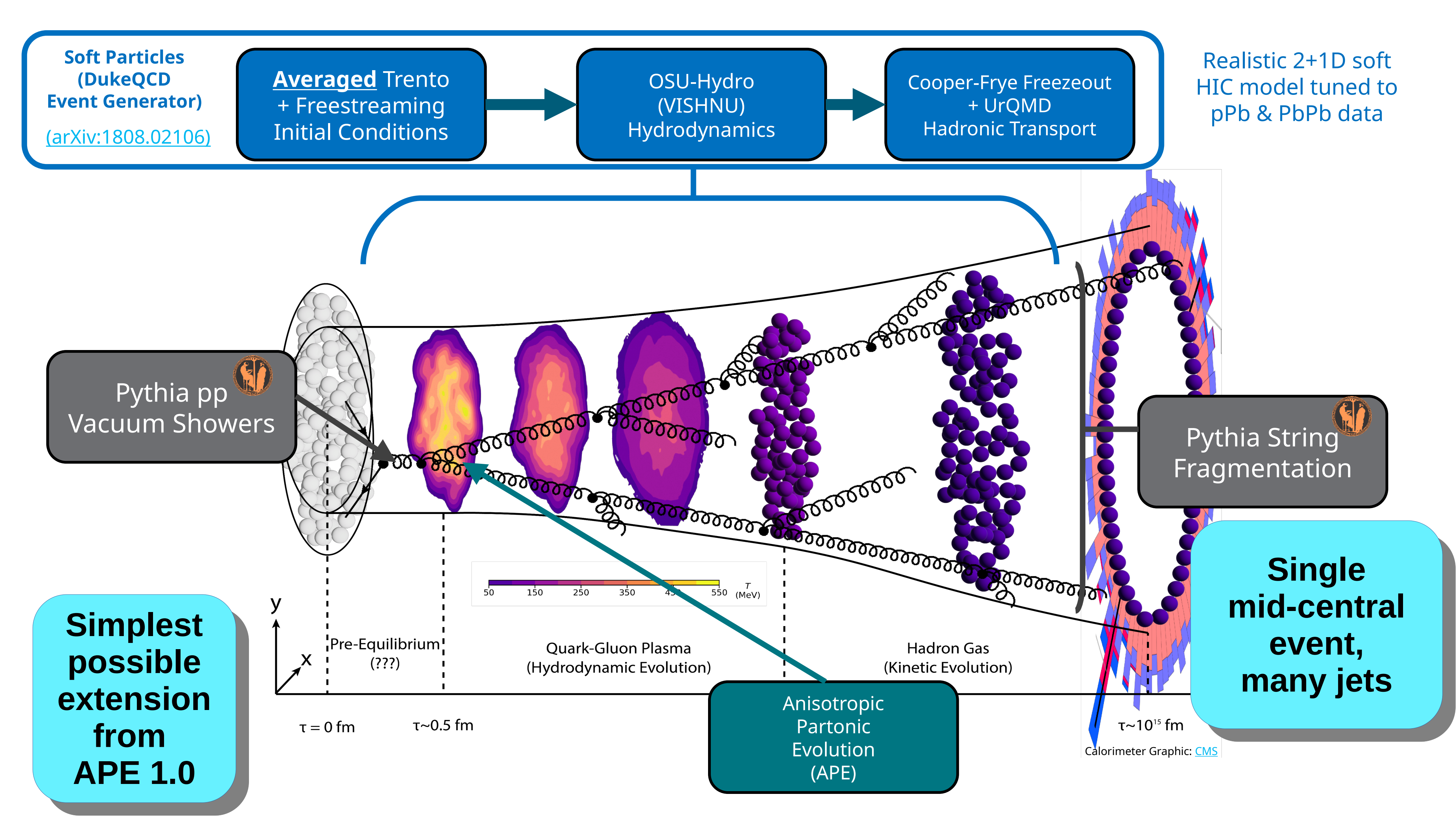
+ Many others!

# Implementing Radiation Effects

# Rigorous Jets are Hard for MCs

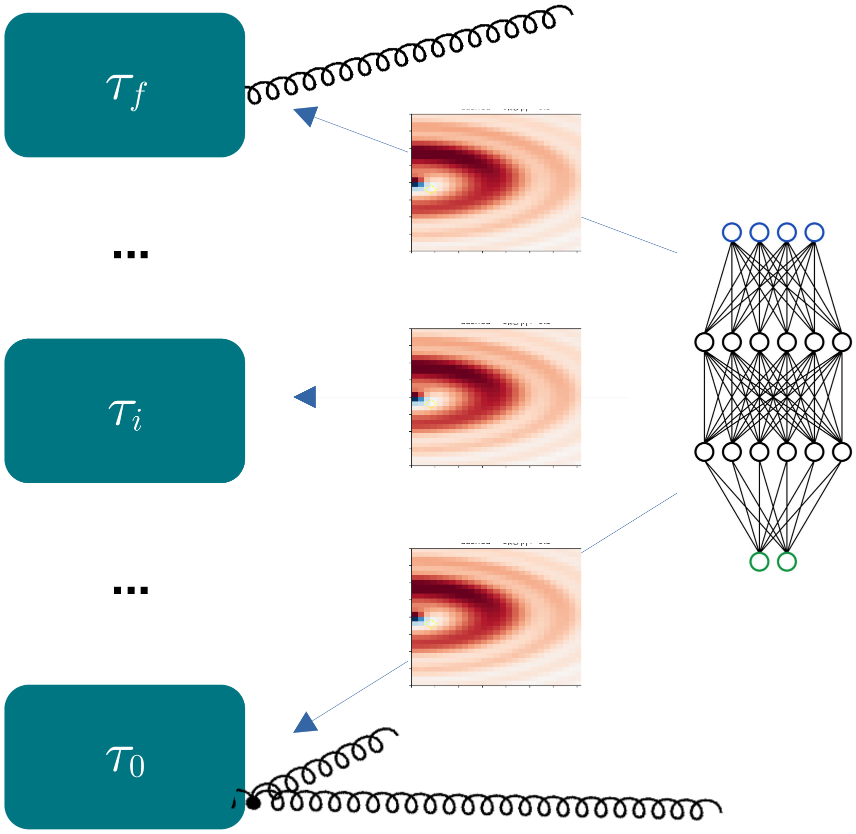
- Connection to virtuality shower unclear
- Opacity expansion calculation of radiation distribution not intuitively applicable for MCs
  - Integration over scattering centers vs spacetime evolution
  - Substantial negative intensity region
- Radiation -- expensive numerical integration




Soft Particles
(DukeQCD
Event Generator)
(arXiv:1808.02106)
Averaged 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
Pythia pp
Vacuum Showers
Pythia String
Fragmentation
50
150
250
350
550
T
(MeV)
y
x
Pre-Equilibrium
(???)
Quark-Gluon Plasma
(Hydrodynamic Evolution)
Hadron Gas
(Kinetic Evolution)
τ = 0 fm
τ~0.5 fm
τ~10^15 fm
Calorimeter Graphic: CMS
Anisotropic
Partonic
Evolution
(APE)
Simplest
possible
extension
from
APE 1.0
Single
mid-central
event,
many jets

# Radiation Scheme

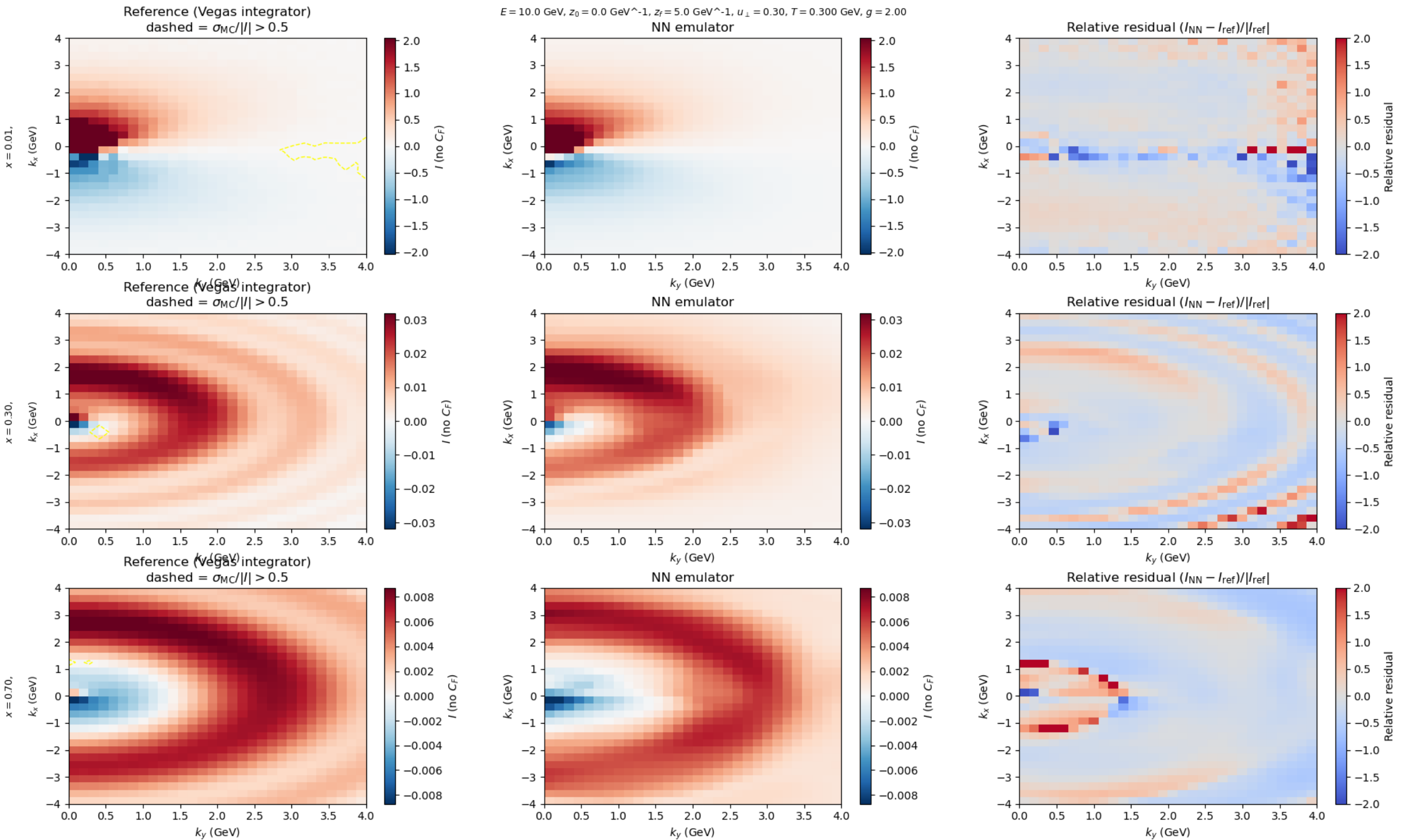
- Pythia vacuum shower
  - Complete – no “virtuality pause” as in some other MCs
- Medium evolution
  - Expensive numerical integration required
  - NN for numerical integration + Poisson sampling over short timesteps
  - Treat negativity as zero, use negative phase space to subtract from total probability of emission



# NN Performance – Short Pathlengths ~< 5 fm

Performance admirable...

Suffers from spectral bias at large x

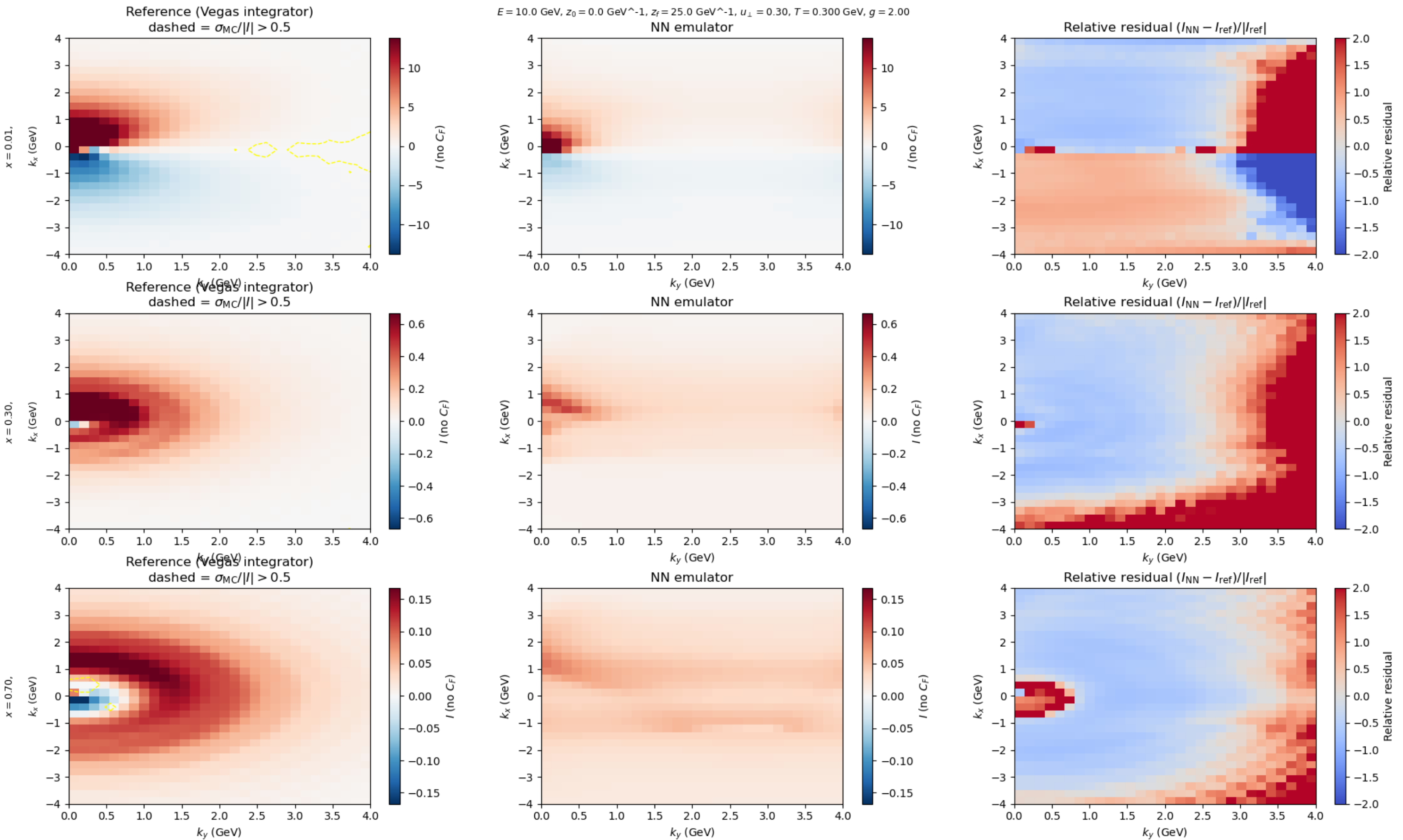


# NN Performance – Long Pathlengths ~> 5 fm

Performance abysmal...

Qualitative directional bias preserved, but overall norm underpredicted

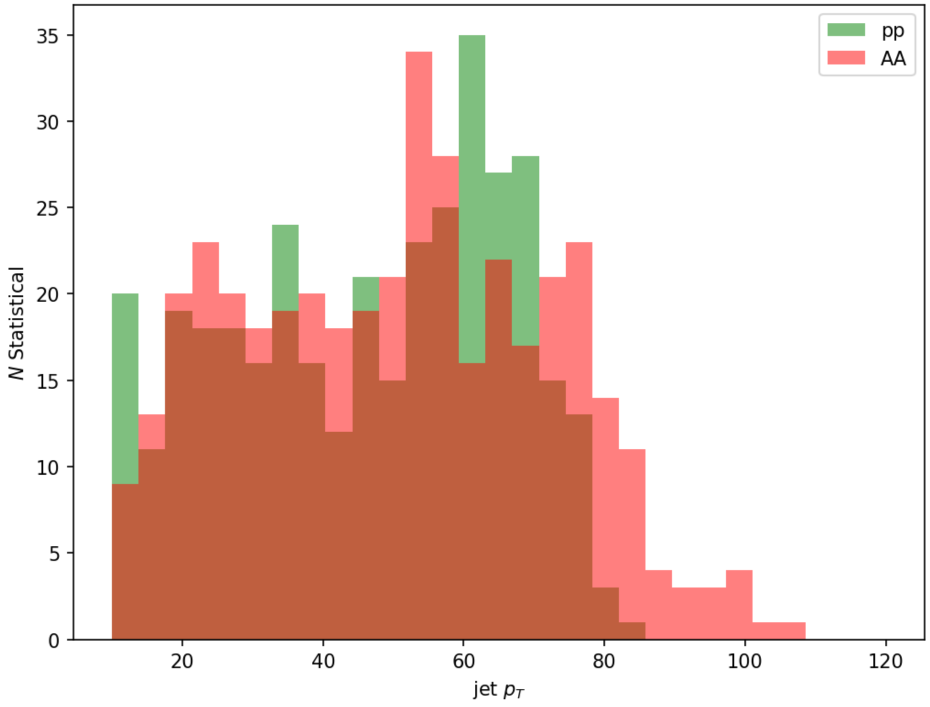
For now...
Fix w/ analytic isotropic norm!



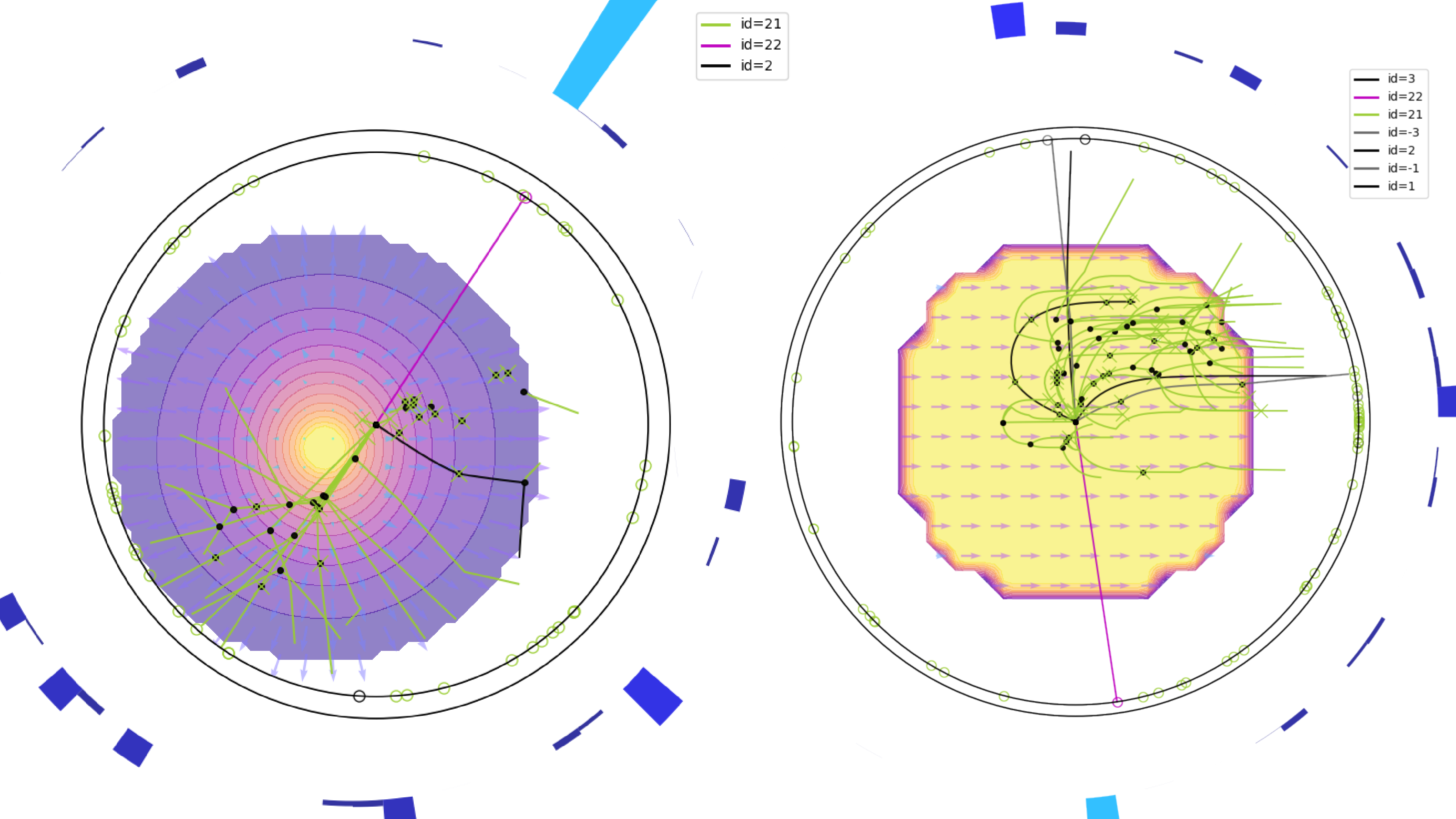
# Toy Jet Substructure Phenomenology

Goal:
Investigate the qualitative influence of soft event flow structure on substructure

# Sample Information



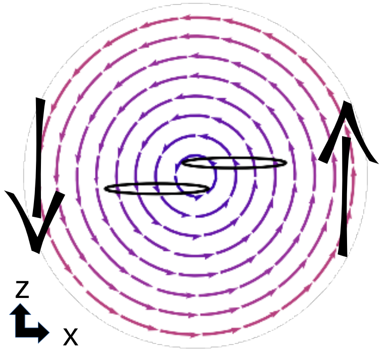

- O(1000) gamma-jet Hard scatterings 80 < pThat < 120 GeV
- Hard scattering |Yhat| < 0.1
- Fastjet anti-kT, WTA-pT axis
  - ArXiv:1111:6097
  - Jet results shown at R=1.0
- Single event geometry – averaged Duke event generator IC @ 200 GeV AuAu, b=10fm

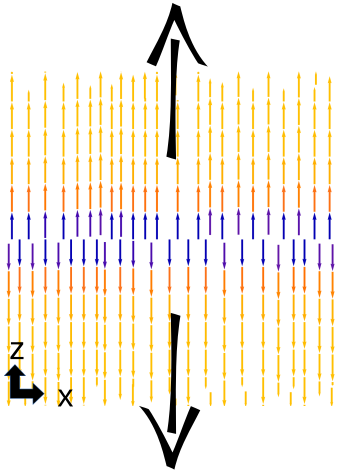


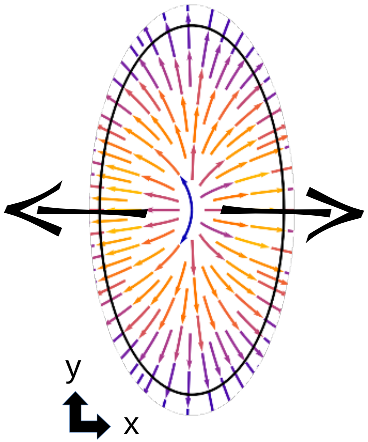
id=21
id=22
id=2
id=3
id=22
id=21
id=-3
id=2
id=-1
id=1

# What Flow do We Couple to? What are the Observables?

- Longitudinal Flow
  - Expansion flow
  - Vorticity flow (neglected here)
- Transverse Plane Flow
  - Elliptic flow towards soft event plane



# Coupling Vectors

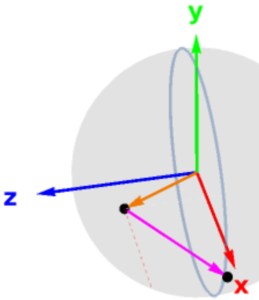
Focus on "$\alpha_x$" and "$\alpha_z$"
– the "rejection defined angles"

"Towards the flow attractor" often ambiguous...

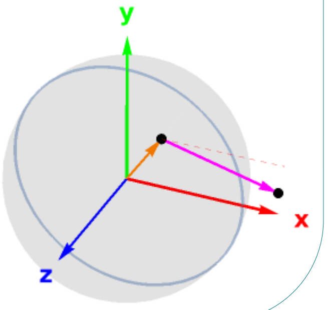
## Transverse Plane Flow:

$$\vec{\alpha}_x = \text{sign}(p_{jet,\,x})\,(\hat{x} - (\hat{x}\cdot\hat{p}_{jet})\hat{p}_{jet})$$

$$\alpha_{x2} = \text{sign}(p_x^{jet}p_y^{jet})(\hat{p}_{jet}\times\hat{z})$$

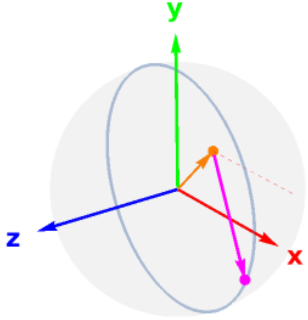


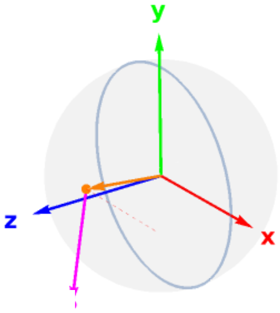

Must be near mid-rapidity and far from $\psi_2$ or $\psi_2 + \pi/2$

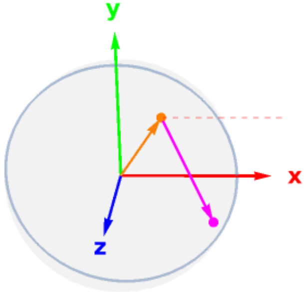



## "Total" flow vector:

$$\alpha_{total} = \text{sign}(p_y)\,((\hat{y}\cdot\hat{p}_{jet})\hat{p}_{jet} - \hat{y})$$



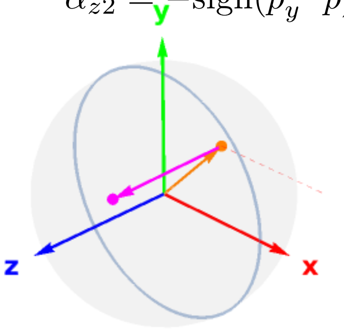



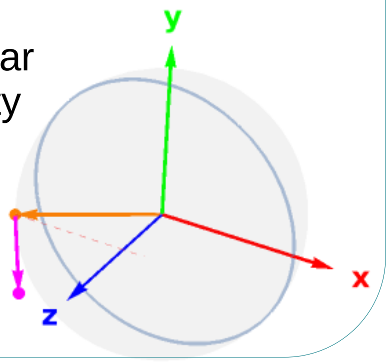

## Longitudinal Plane Flow:

$$\vec{\alpha}_z = \text{sign}(p_{jet,\,z})\,(\hat{z} - (\hat{z}\cdot\hat{p}_{jet})\hat{p}_{jet})$$

$$\alpha_{z2} = -\text{sign}(p_y^{jet}p_z^{jet})(\hat{p}_{jet}\times\hat{x})$$



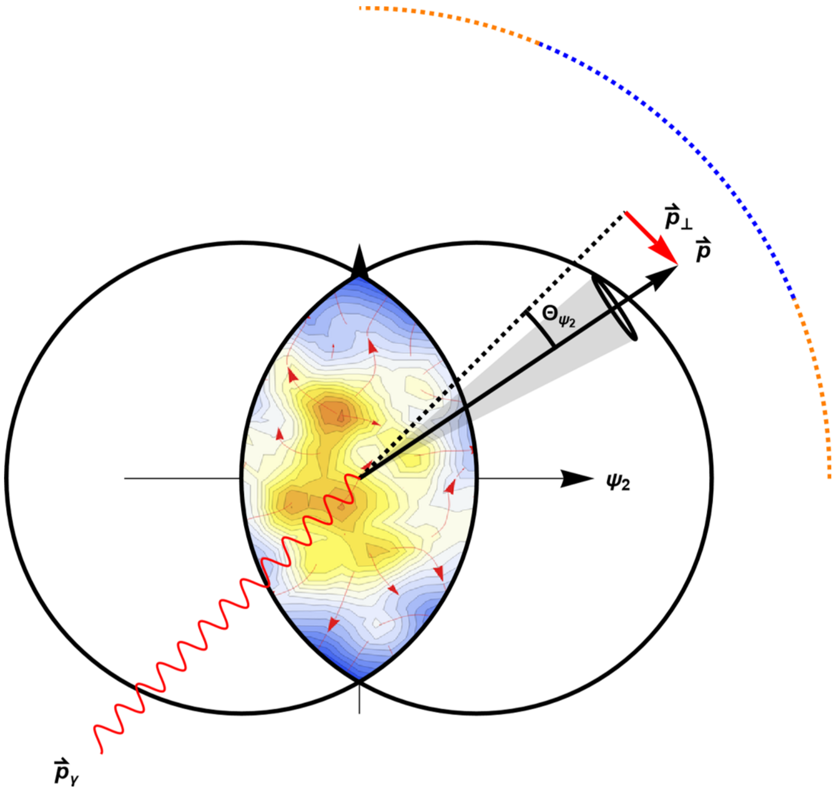

Must be near mid-rapidity



Unsigned version from
STAR: Photon-jet acoplanarity

# Signed Jet Deflection Ratio

- Sensitive to absolute deflections towards the event plane
  - Can form similar measure for jet constituents
  - Most direct measurement of flow **deflections**
- Requires **azimuthal fencing**
- Rapidity difference for longitudinal flow coupling

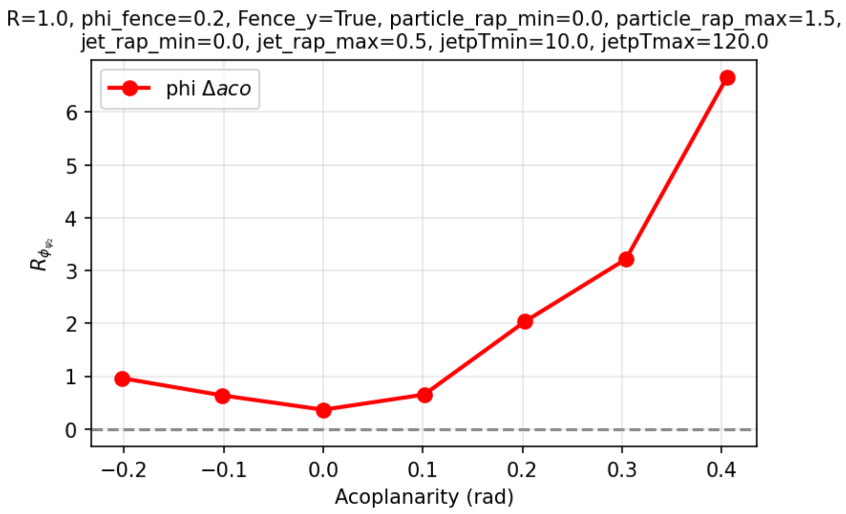


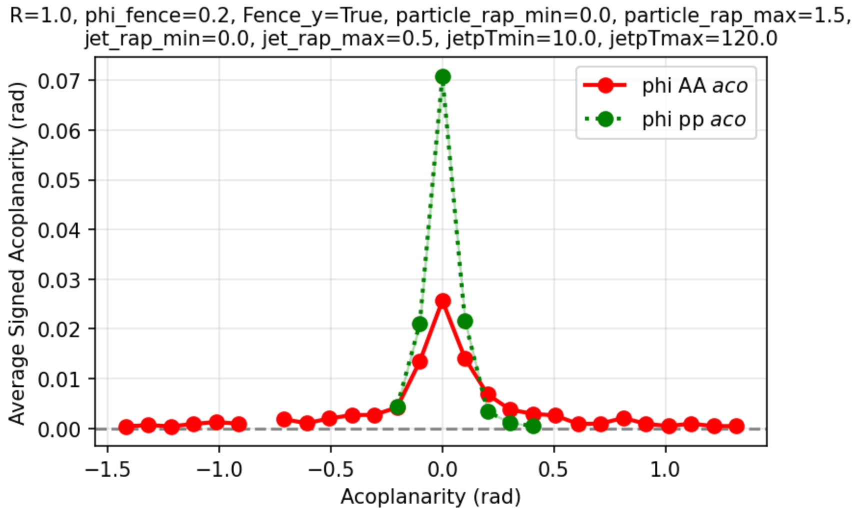

$$R_{\theta_{\psi_2}} = \frac{\frac{dN^{AA}}{d\Theta_{\psi_2}}}{\langle N_{coll}\rangle \frac{dN^{pp}}{d\Theta_{\psi_2}}}$$

For $x$-axis event plane

$$\Theta_{\psi_2} = (\mathrm{mod}(\phi_\gamma, \pi/2) - \mathrm{mod}(\phi_{jet}, \pi/2)) \begin{cases} +1, & \text{Quadrants I \& III} \\ -1, & \text{Quadrants II \& IV} \end{cases}$$

# Signed Jet Deflection Ratio Result

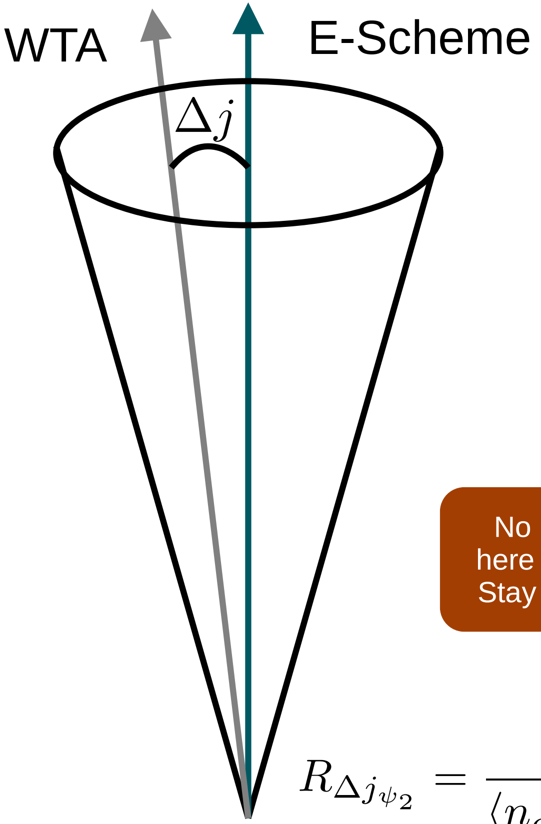



- Clear signal for artificial jet sample
- Needs exploration in minimum bias sample!
- Negligible Bootstrap error does not capture full sampling uncertainty...

# Signed Jet Axis Difference

Unsigned versions from
CMS: Dijets & Photon Tagged Jets
ALICE: D0 Tagged Jets




**E-Scheme:**
Four-vector sum of momenta at each step
- Sensitive to many deflected soft particles

**Winner-Take-All (WTA):**
Follows hardest prong at each step
- Sensitive to hard undeflected core of jet

No results here today… Stay tuned!!!

$$\Delta j = \sqrt{(\eta_{WTA} - \eta_{E-scheme})^2 + (\phi_{WTA} - \phi_{E-scheme})^2}$$

$$R_{\Delta j_{\psi_2}} = \frac{\frac{dN^{AA}}{d\Delta j_{\psi_2}}}{\langle n_{coll} \rangle \frac{dN^{pp}}{d\Delta j_{\psi_2}}}$$

$$\Delta j_{\psi_2} = (\phi_{WTA} - \phi_{E-scheme}) \begin{cases} +1, & \text{Quadrants I \& III} \\ -1, & \text{Quadrants II \& IV} \end{cases}$$

For $x$-axis event plane

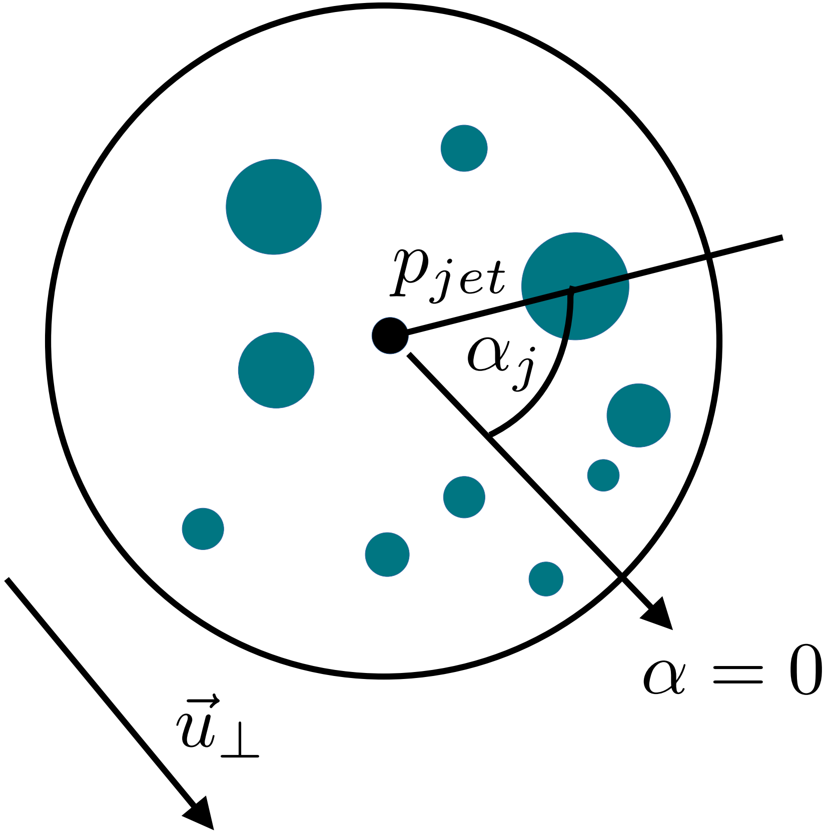
# Jet Substructure Harmonics

- Phase alignment with flow coupling direction
- Measures azimuthal distortion towards flow
- Highly dependent on your jet algorithm
  - E.g. anti-kT, enforces a circular jet on $y\phi$ cylinder
- We'll focus on this one for the moment...

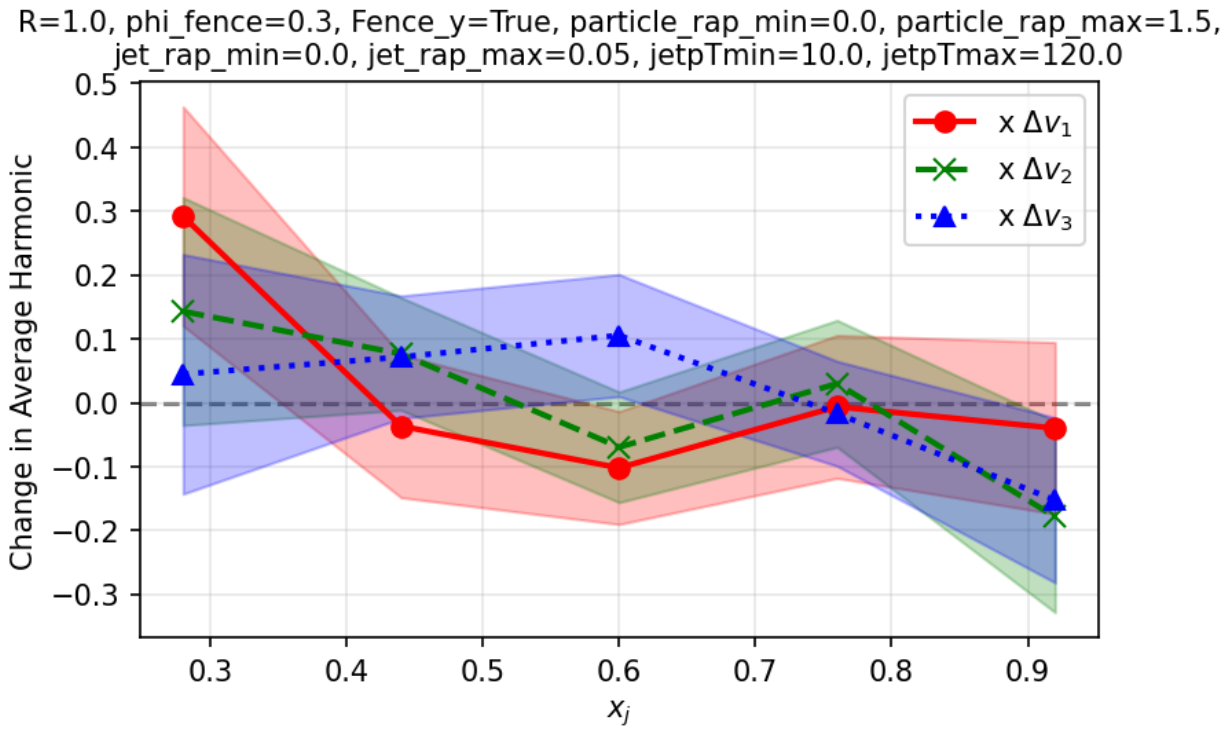
$$v_n(E) = \left\langle \frac{\sum_j \cos(n\alpha_j)}{\sum_j} \right\rangle_{events}$$

To eliminate contribution from pp dist. in small sample:

$$\Delta v_n(E) = v_n^{AA}(E) - v_n^{pp}(E)$$

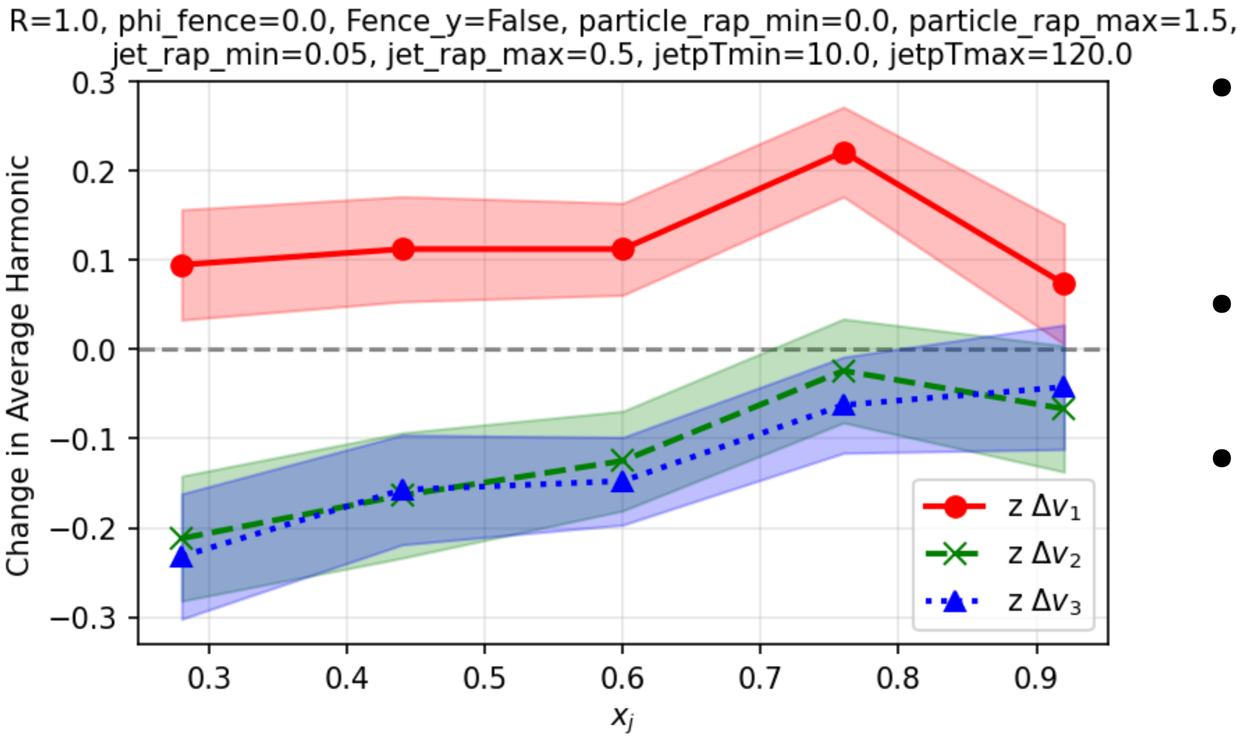


# Transverse Coupling




- Consistent with zero, neglecting sketchy ultralow x…
- Puzzling, but potentially explained by competition of elastic scatterings and radiation
- Full scale EBE runs required to write off the observable

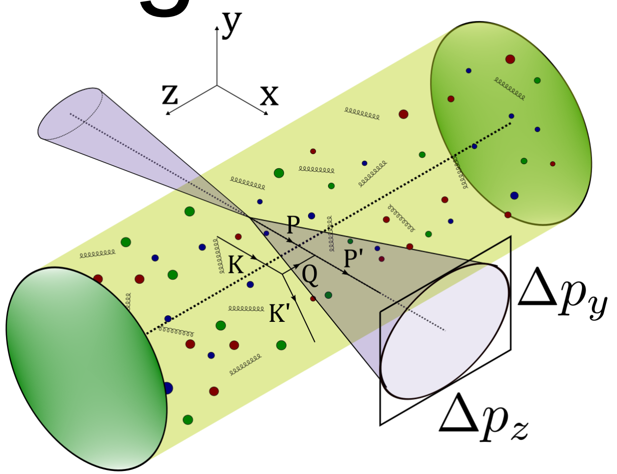
# Longitudinal Coupling



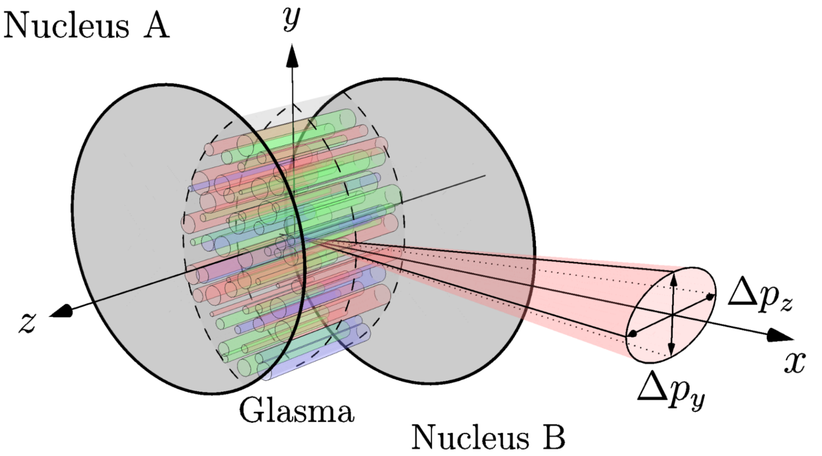

- Clear, unambiguous signal of v1 enhancement
- Expected enhancement at large x appears
- Systematics with event geometry and unfolded jet kinematics via large EBE runs are next steps

# Connecting to Early Stages

- Broadening calculations in EKT show geometry-correlated anisotropy
- Broadening and radiation calculations in glasma show geometry-correlated anisotropy
- Understanding anisotropic shapes from QGP phase is the first step towards potentially identifying asymmetries arising from the early stages
- Want feedback from early stages community – how can this work connect to early stages work to tease out meaningful information from substructure anisotropy?




Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron [2303.12520] [2303.12595] [2312.00447]




Ipp, Müller, Schuh [2009.14206]

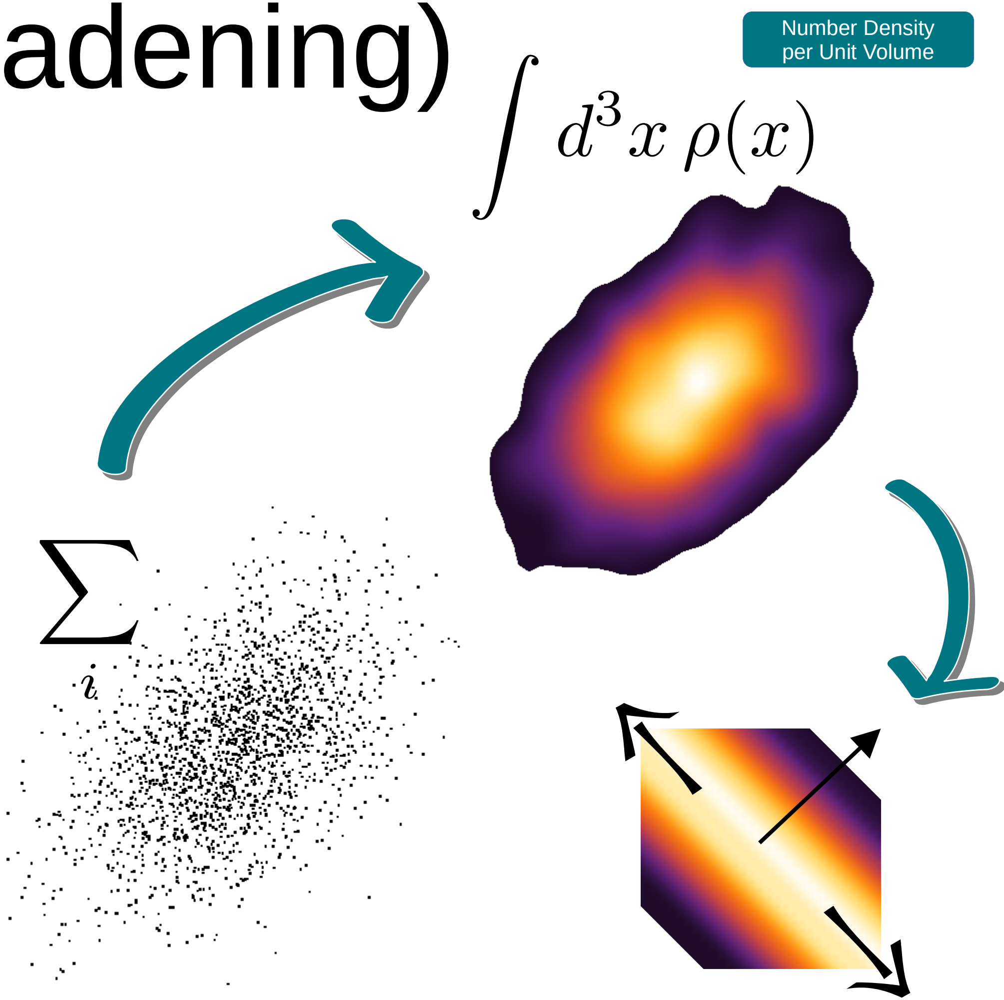
Glasma Radiation
Barata, Hauksson, Lopez, Sadofyev [2406.07615]

# Thanks a bunch!

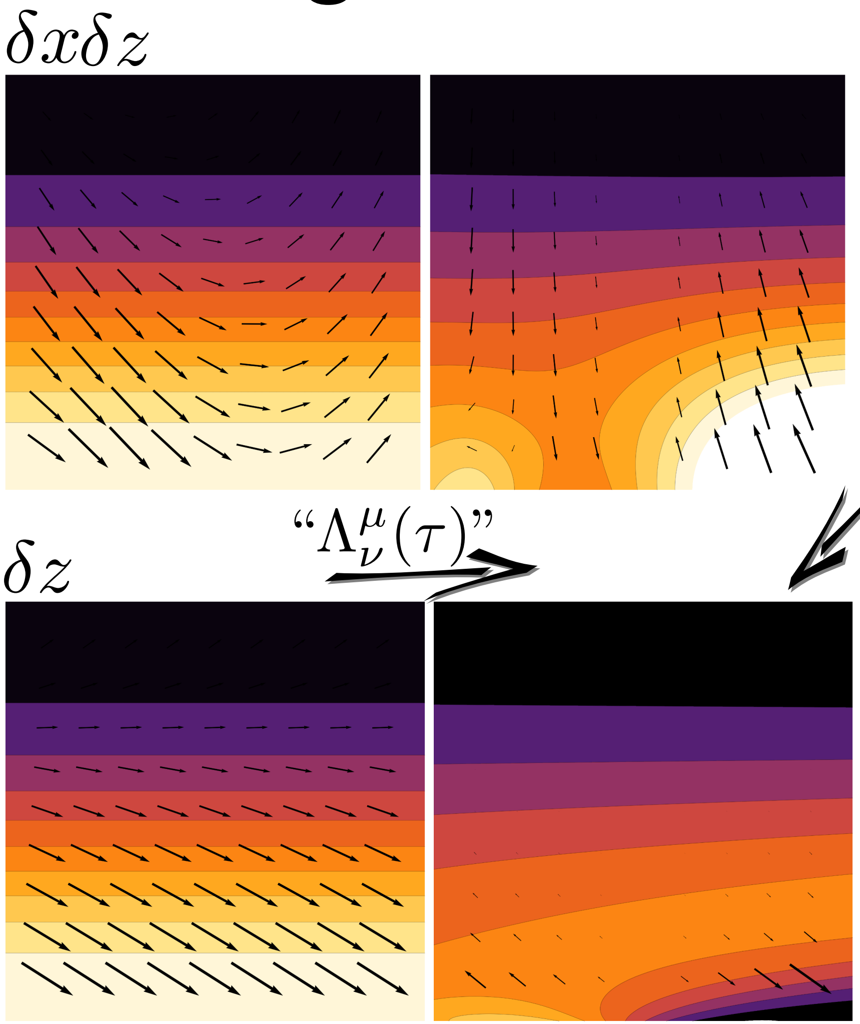
See APE Phenomenology:
(arXiv:2412.05474)

# Review of Scattering Center Treatment (Iso. Broadening)

- Summation over scattering centers to spatial integral over density
  - ***All*** scattering centers contribute to amplitude!
- Traditionally, **transverse variation is neglected**
- Longitudinal integration alone is analytically (simple models) or computationally (e.g. hydro) tractable
- **Can we consistently introduce flow to our scattering center distributions with a global boost?**



# Long. & Trans. Mixing – On Boosts

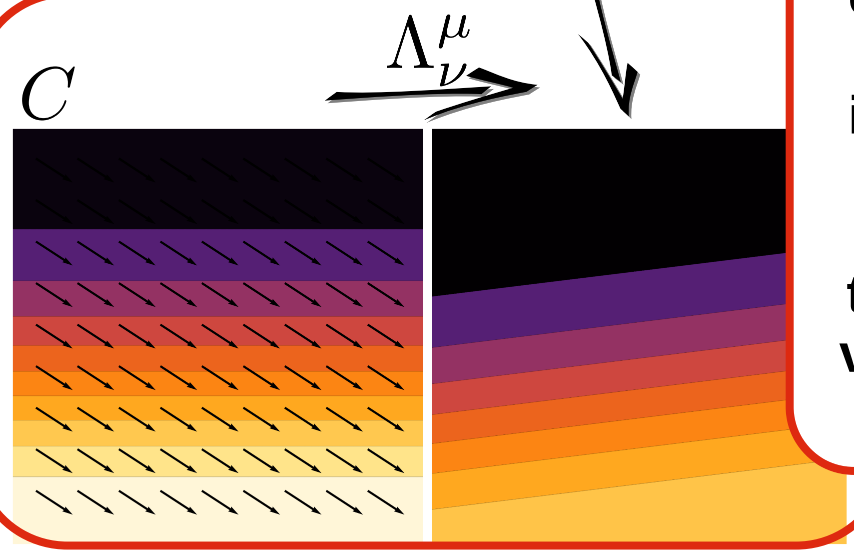



$u$ transforms as part of 4-velocity

$\rho$ transforms as $J^0$ of scattering center current

Even transversely invariant flow velocity leaves flow remnant

Cooling and **transverse variation** appear, even in constant flow




**No consistent way to implement without treating transverse variation in density**

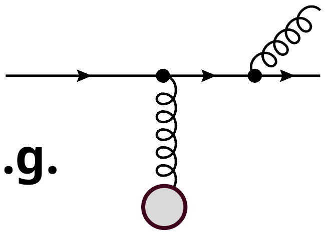
# Additional Model Choices

- Jet-jet particle hadronization only
  - Partons color is unchanged by medium – use Pythia color connections in hadronization
- Perfect background subtraction
- Vacuum shower completed before medium interaction
- No medium response
  - No wake, etc.
- Do not evolve particles $y > 1.0$
- Hard Particles “thermalize” at 2.00 GeV

# Radiative Energy Loss

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

**E.g.**



- Gyulassy, Levai, Vitev (2000) (arXiv:0006010)
- Single Emission GLV @ 1st order in opacity
  - APE 1.0: w/ finite kinematic bounds (q, k)
  - APE 2.0: Currently infinite kinematic bounds
    - Plans to implement energy set from NN

# Drift Deflection

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

# Competition of Transverse Plane Broadening Effects

- Use new APE to investigate mid-rapidity 2-to-2 hard scattering events
  - Gradients of $u_\perp$ partially cancel flow effect
  - No accident – origin of terms is in the same pole structure
- Events selected to demo cancellation… Full picture of magnitude requires full accounting of gradient effects & survey of geometries
  - Grads. of e.g. $u_z$ frequently has unlike sign & similar magnitude
  - Differing pathlength dependence shifts relative weight of flow and gradients in larger and smaller events