

# Response of Jets to Collective Flow in Heavy-Ion Collisions

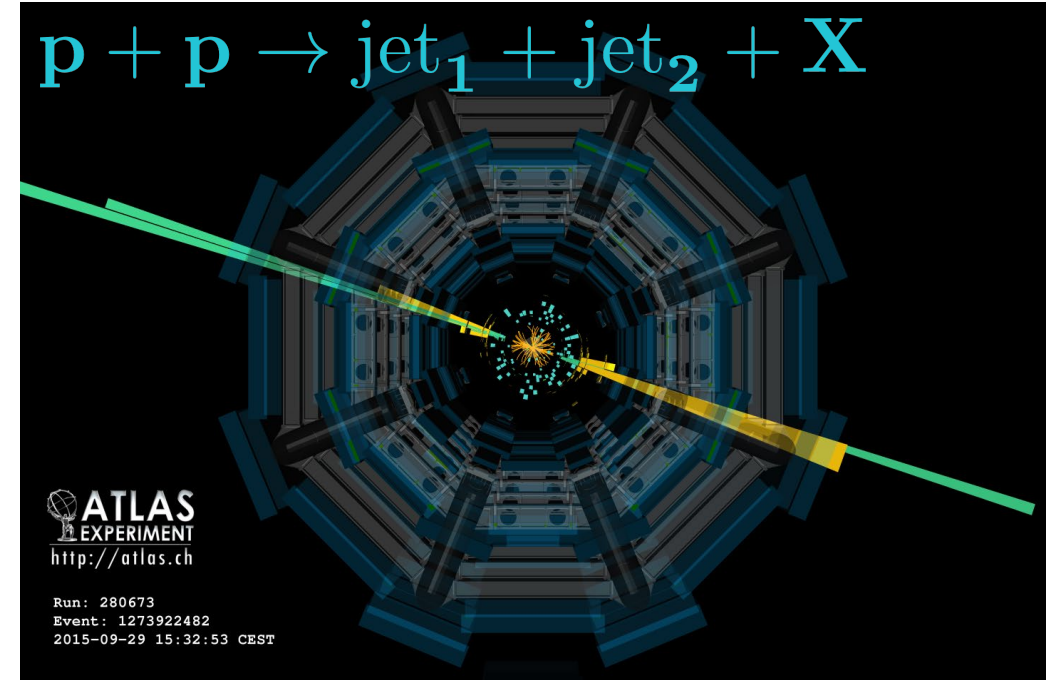
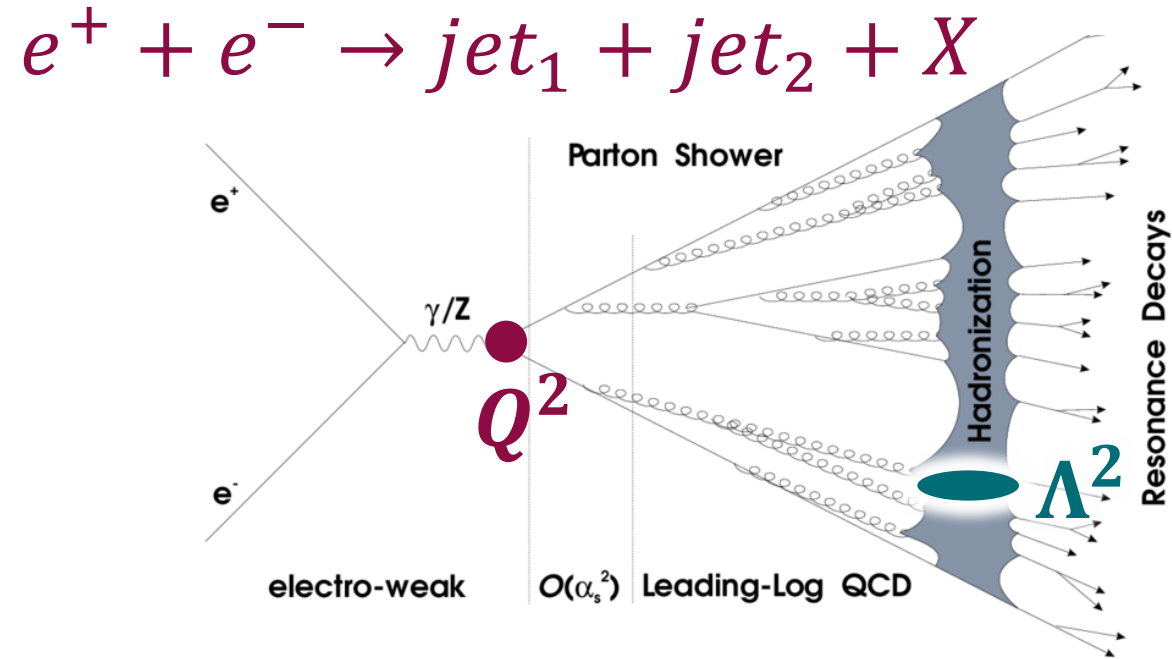
Matthew D. Sievert



*Hot Jets 2025*

*1/8/2025*

# Jets in Vacuum: a Microcosm of QCD

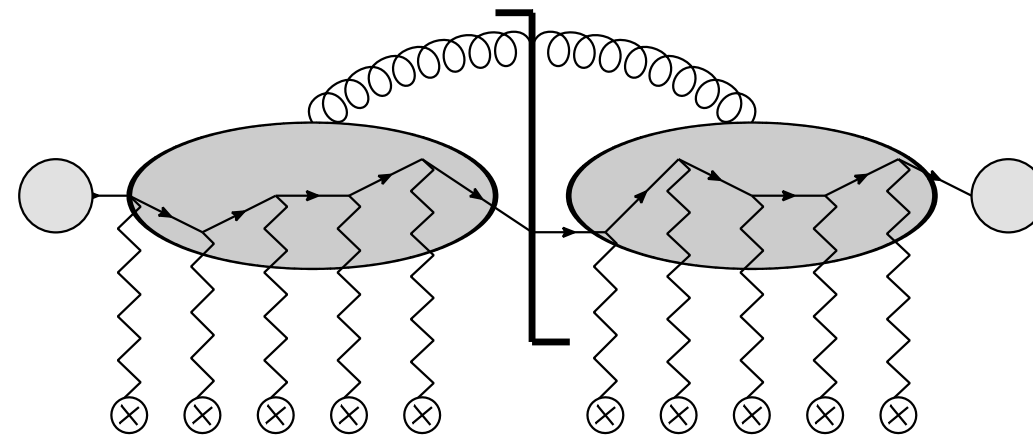


- Basic **jet production: hard parton-parton scattering** at high virtuality  $Q^2$
- **Cascade of radiation** falling in virtuality down from  $Q^2$  to the **hadronization scale**  $\Lambda^2$
- Jets and substructure: **radiative QCD evolution** from perturbative to nonperturbative

# Jets in Medium: Multi-Scale Probes

- At high  $p_T$ , jets lose energy primarily by **radiating** a shower of soft gluons
  - In vacuum: **Sudakov factor**
  - In medium: **LPM effect**
- The **interference pattern** of the shower carries information about the **medium**
  - **Position-space** information:  $\rho(\vec{x})$
  - **Momentum space** information:  $v(\vec{q})$

**Induced Radiation**  
+ accompanying  $p_T$  broadening



*Landau, Pomeranchuk, Dokl. Akad. Nauk Ser. Fiz 92 (1953)*

*Migdal, Phys. Rev. 103 (1956)*

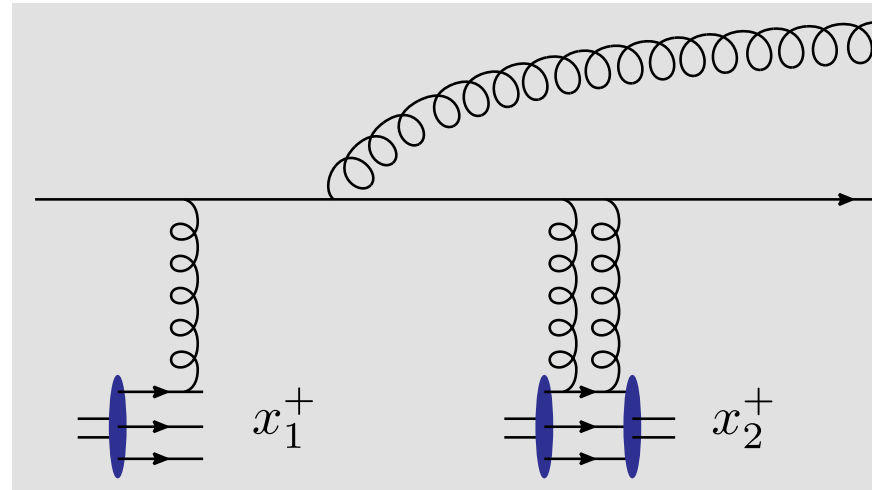
# Jets as Interferometers for Medium-Induced Radiation

➤ **Edge phases** of the emission region

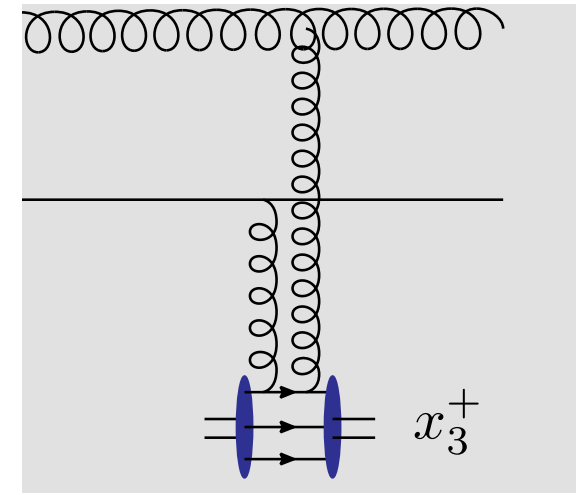
➤ **Phase slip** from scattering

## Formation Time

$$\frac{1}{\ell_f} = \frac{(\vec{k}_\perp - x\vec{p}_\perp)^2 + x^2 m^2}{2x(1-x)E}$$

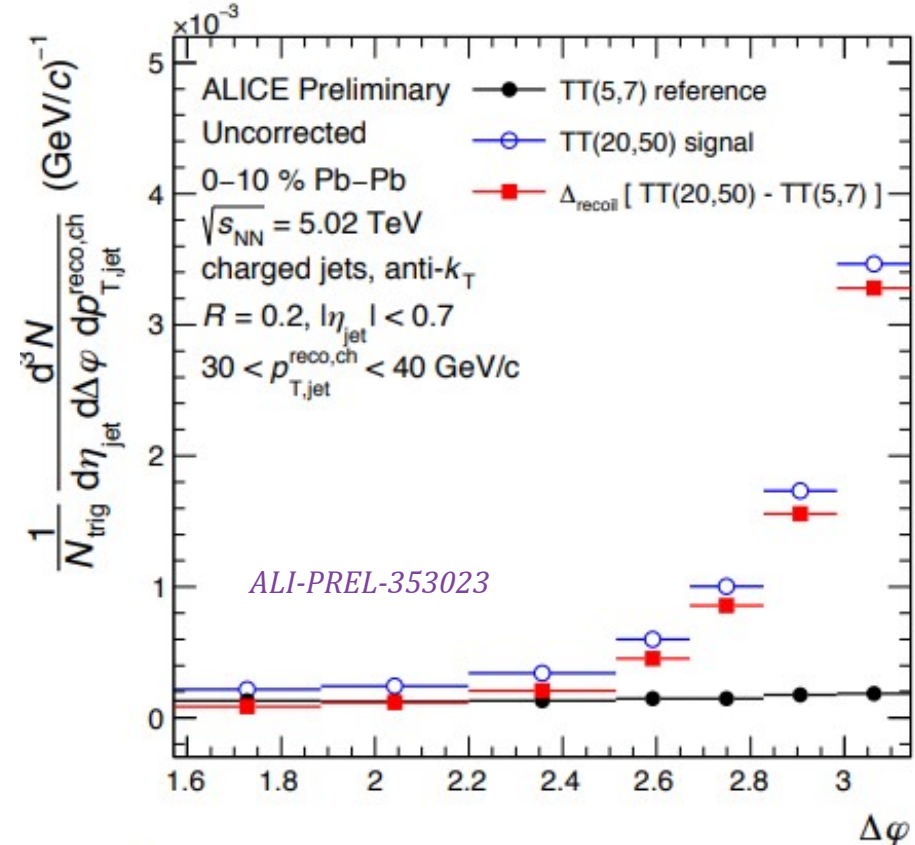
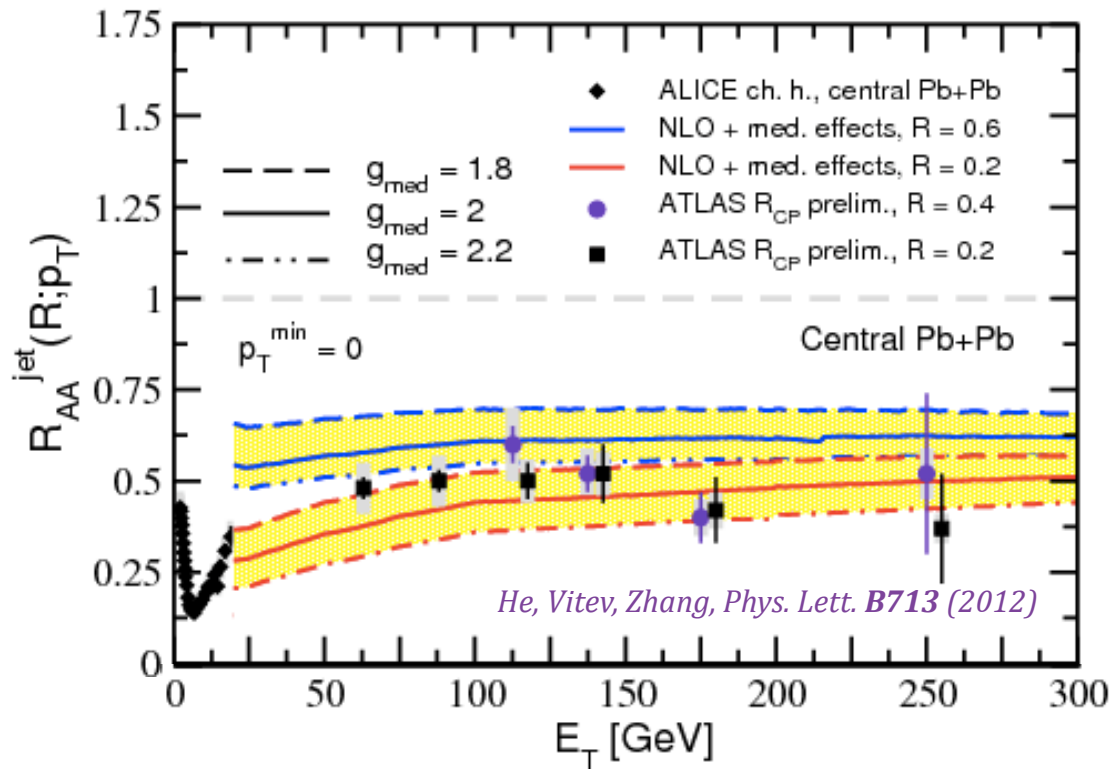


$$e^{i(z_1 / \ell_f)} - e^{i(z_2 / \ell_f)}$$



$$e^{i z_3 (1 / \ell'_f - 1 / \ell_f)}$$

# Canonical Signatures of Medium Modification



## ❖ Energy Loss

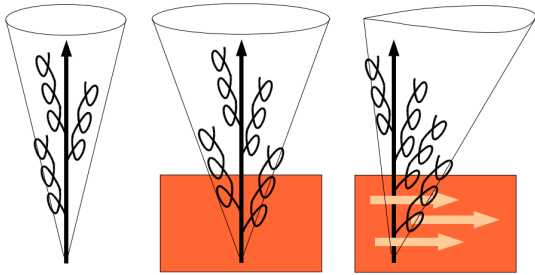
➤ Jet quenching,  $\gamma$ +jet imbalance ...

## ❖ Transverse Momentum Broadening

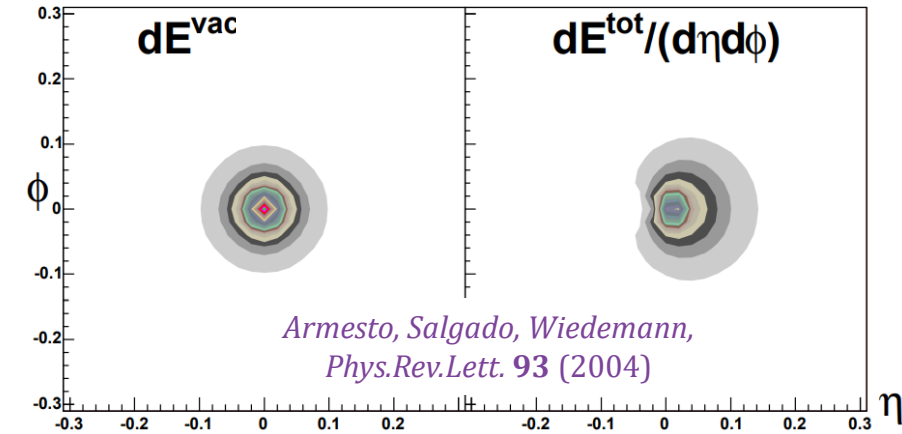
➤ Dijet /  $\gamma$ +jet acoplanarities ...

# Asymmetric Measures of Medium Modification

- Model employing **shifted potentials** to mimic **boosted fluid flow**.



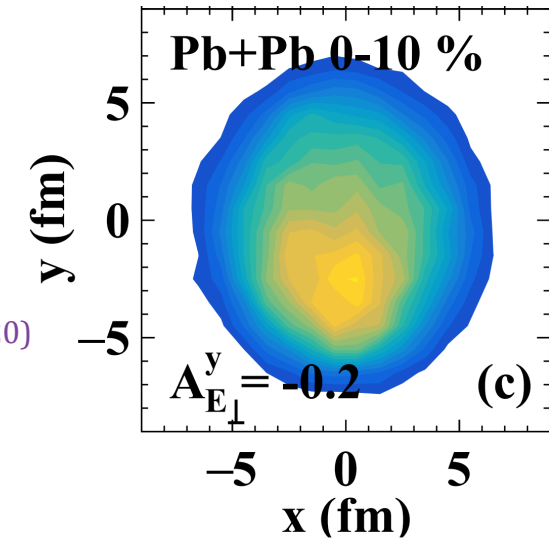
$$|a(\mathbf{q})|^2 = \frac{\mu^2}{\pi [(\mathbf{q} - \mathbf{q}_0)^2 + \mu^2]^2}$$



- Linearized Boltzmann Transport calculation of **jet asymmetries** induced by **gradients**

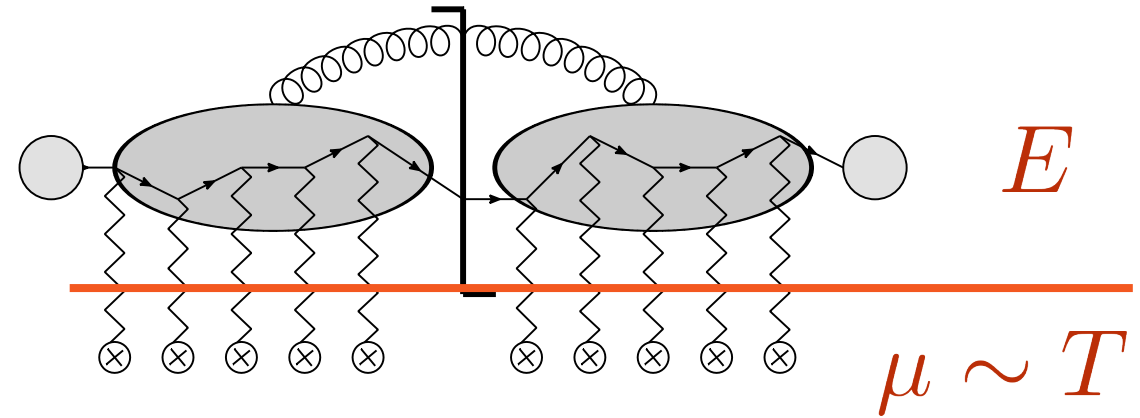
$$A_{N\vec{n}} = \frac{\int d^3r d^3k f_a(\vec{k}, \vec{r}) \text{Sign}(\vec{k} \cdot \vec{n})}{\int d^3r d^3k f_a(\vec{k}, \vec{r})}$$

He, Pang, Wang  
*Phys.Rev.Lett.* 125 (2020)



# Coupling to Collective Flow: Leading Power

- All versions of jet quenching theory assume a **separation of scales** between the jet and the medium ( $\frac{\mu}{E} \ll 1$ )



- At **leading (eikonal) power** in the jet energy, the medium is **effectively static**:

$$(p \cdot u) \approx E u^0 + \dots$$

- Can be written as a **frame-independent result** ( $p \cdot u$ ), but the calculation is valid **only to leading power**.

*e.g., Xiao et al, Phys. Rev. C109 (2024)*

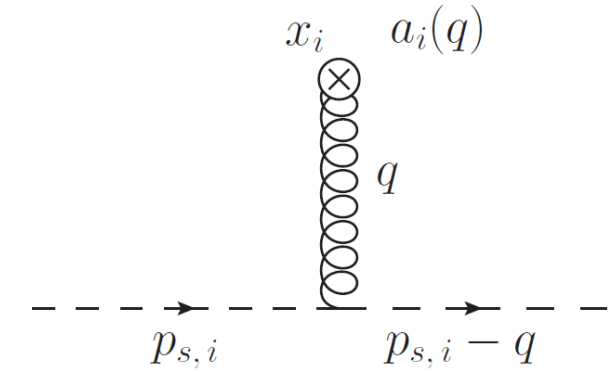
$$\frac{dN_g^a}{dz dk_{\perp}^2 d\tau} = \frac{6\alpha_s P_a(z) k_{\perp}^4}{\pi(k_{\perp}^2 + z^2 m^2)^4} \frac{p \cdot u}{p_0} \hat{q}_a(x) \sin^2 \frac{\tau - \tau_i}{2\tau_f}$$



# Coupling to Collective Flow: Sub-Leading Power

$$g A_{\text{ext}}^{\mu a}(q) = \sum_i e^{iq \cdot x_i} t_i^a u^\mu(\vec{x}_i) v(\vec{x}_i, \vec{q}) (2\pi) \delta(q^0 - \vec{u}(\vec{x}_i) \cdot \vec{q})$$

Sadofyev, MDS, Vitev, *Phys. Rev. D* **104** (2021)



❖ GW: Target masses assumed to be heavy (neglects medium recoil)

## Fully relativistic velocity Velocity-dependent potential

$$p_s^\mu = \gamma M (1, \vec{u})^\mu$$

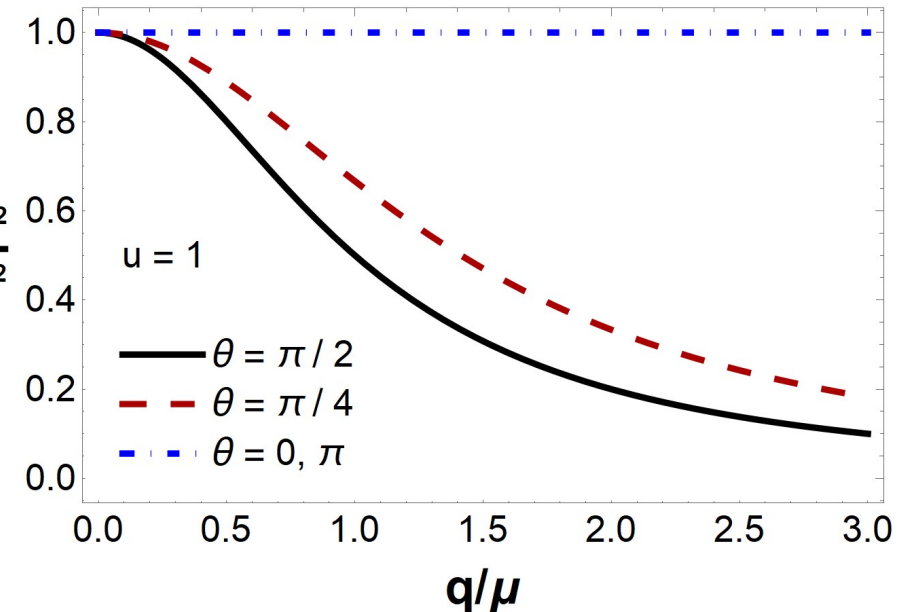
$$v(\vec{x}_i, \vec{q}) = \frac{-g^2}{\vec{q}^2 + \mu^2 - (\vec{u}(\vec{x}_i) \cdot \vec{q})^2 - i\epsilon}$$

- Propagate the **sub-eikonal, velocity-dependent corrections** to the Gyulassy-Wang potential

Gyulassy, Wang, *Nucl. Phys. B* **420** (1994)

- **Enhanced collinear scattering** with the flow
- Correlated **collisional energy transfer**

$$|v| \frac{\mu^2}{g^2}$$

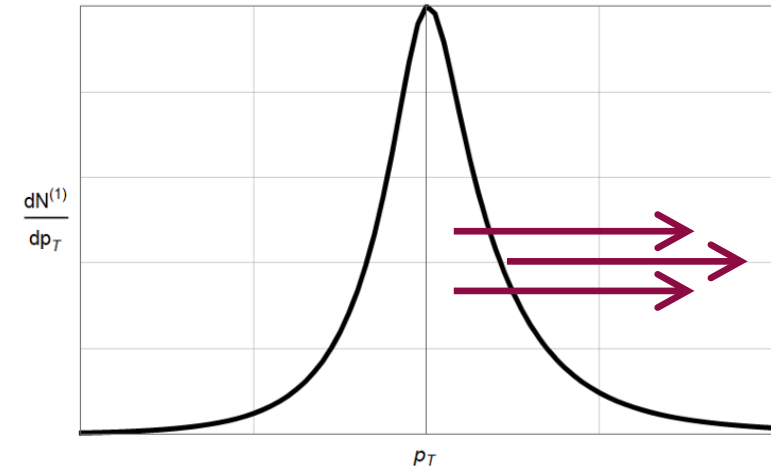




# Jet Drift: Skewed Momentum Broadening

$$E \frac{dN^{(1)}}{d^3p} = \int \frac{dt}{\lambda(t)} \int d^2q_{\perp} \bar{\sigma}(q_{\perp}, t) \left[ E \frac{dN^{(0)}}{d^3(p-q)} \left( 1 + \vec{u}_{\perp}(t) \cdot \vec{\Gamma}_{\perp}(t, \vec{q}_{\perp}) \right) - E \frac{dN^{(0)}}{d^3p} \left( 1 + \vec{u}_{\perp}(t) \cdot \vec{\Gamma}_{DB, \perp}(t, \vec{q}_{\perp}) \right) \right]$$

Sadofyev, *MDS*, Vitev, *Phys. Rev. D* **104** (2021)



- The leading (linear) flow-dependent correction **skews the jet distribution** preferentially **along the direction of the flow velocity**.

Sub-eikonal vertex

Shifted potential

Energy Shift

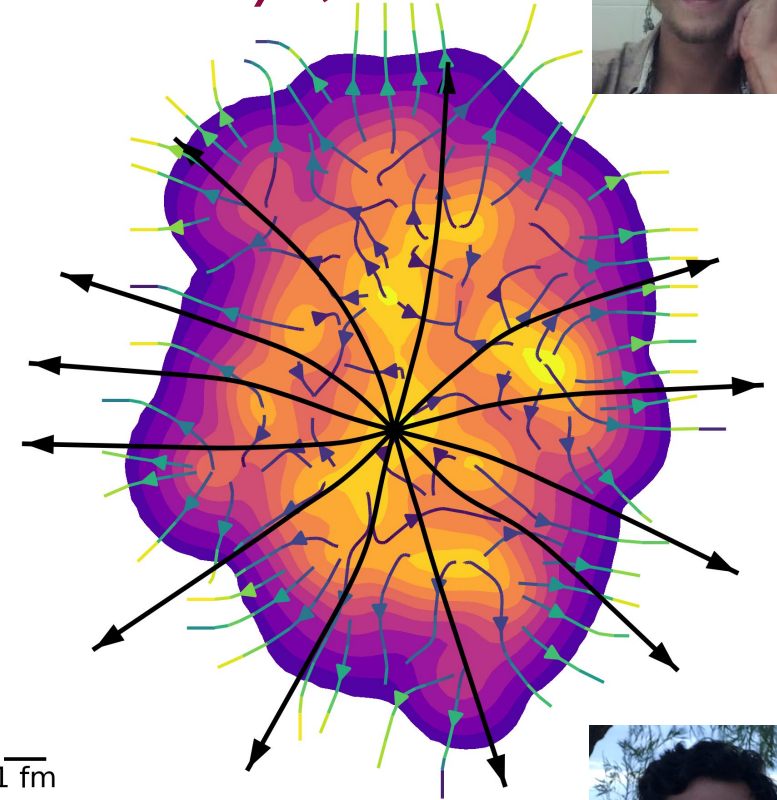
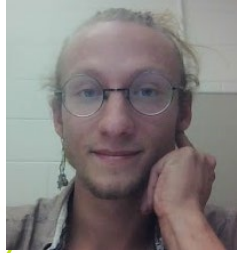
$$\Gamma(\mathbf{q}_{\perp}) = -2 \frac{\mathbf{p}_{\perp} - \mathbf{q}_{\perp}}{(1 - u_{iz})E} + \frac{\mathbf{q}_{\perp}}{(1 - u_{iz})E} \left( \frac{(p - q)_{\perp}^2 - p_{\perp}^2}{\bar{\sigma}(q_{\perp}^2)} \right) \frac{\partial \bar{\sigma}}{\partial q_{\perp}^2} - \frac{\mathbf{q}_{\perp}}{1 - u_z} \left( \frac{1}{\bar{N}_0(E, \mathbf{p}_{\perp} - \mathbf{q}_{\perp})} \frac{\partial \bar{N}_0}{\partial E} \right)$$

# Jet Drift: Skewed Momentum Broadening

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

- Simplest implementation: the **net transverse deflection** due to the preferred direction.
  - **Jets inherit the correlation to geometry** embedded in the collective flow  $u(x)$
  - Geometry coupling **above and beyond path-length dependence.**
  - Jet drift **influences many observables**

*Jo Bahder,  
Thurs 1/9, 10am*



*Hasan Rahman,  
Thurs 1/9, 11am*

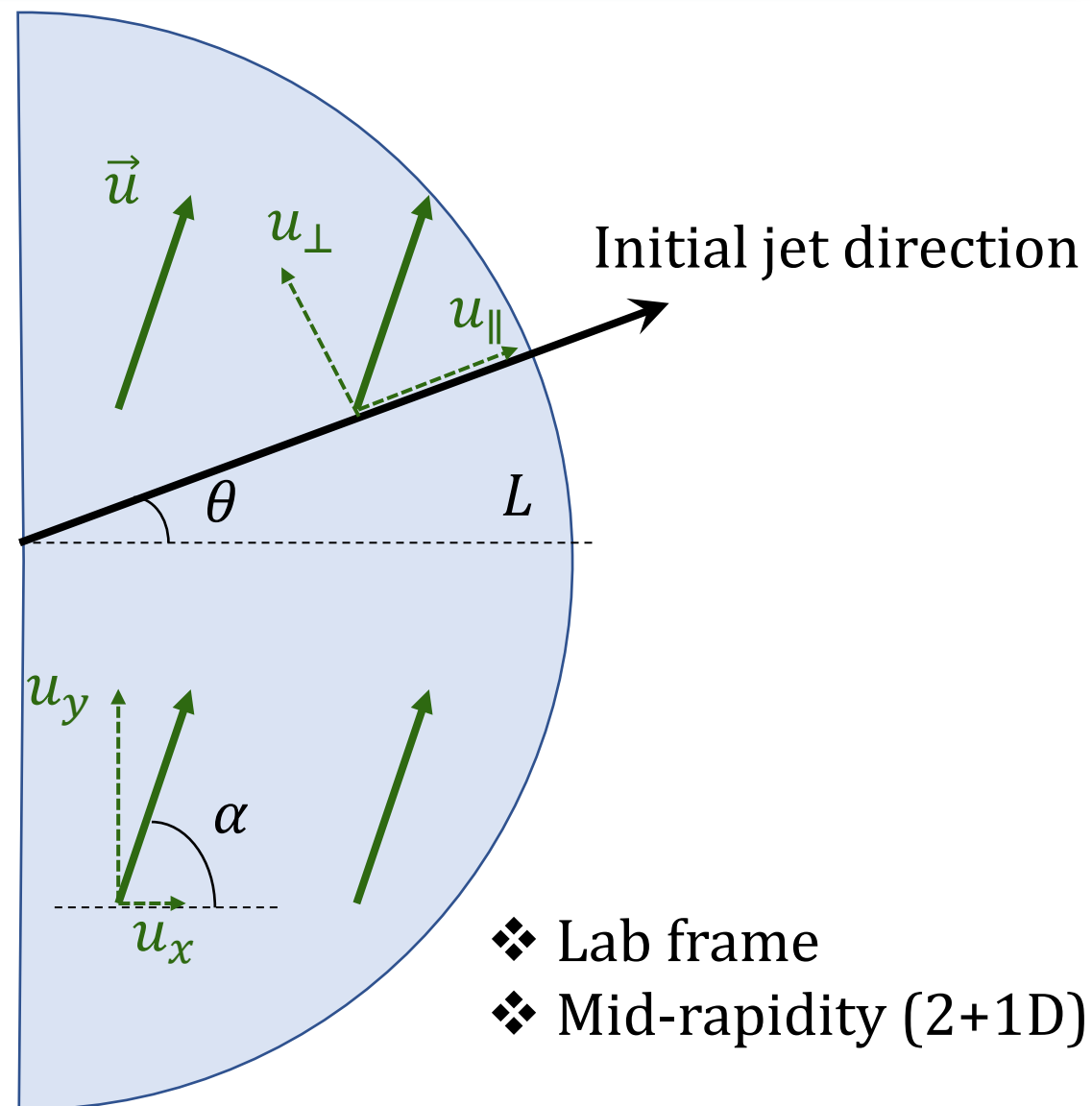


# What We Can We Learn from Jet Drift – The Constant Slab

Antiporda, Bahder, Rahman, *MDS, Phys. Rev. D105 (2022)*

$$\langle \vec{q}_{\text{drift}} \rangle = \hat{e}_{\perp} \frac{3L}{E} \frac{\mu^2}{\lambda} \ln \frac{E}{\mu} \frac{u \sin(\theta - \alpha)}{1 - u \cos(\theta - \alpha)}$$

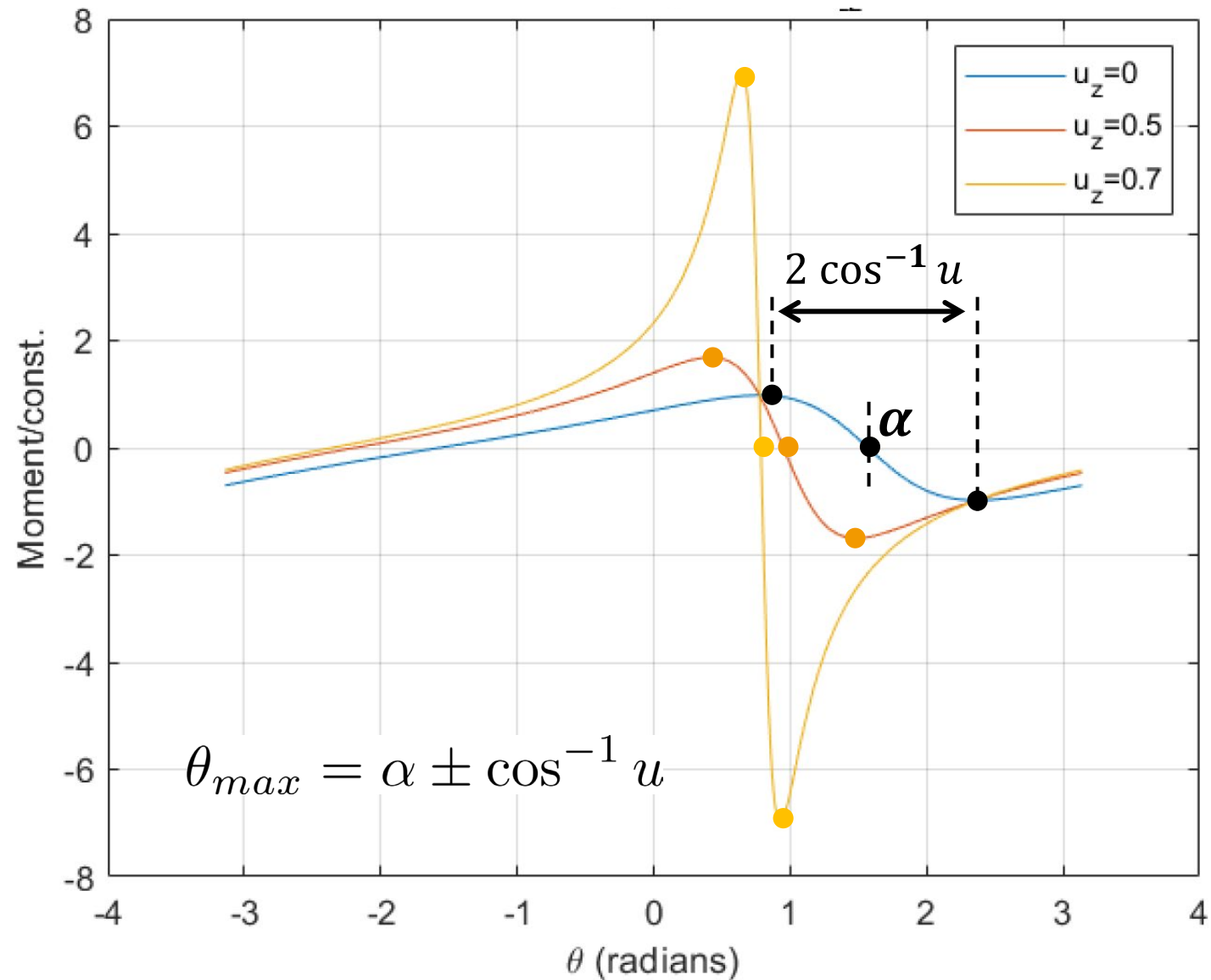
- Consider a **“brick”** with constant flow velocity  $u$  (a **“constant slab”** of flowing plasma)
- Flow velocity has **magnitude  $u$  and angle  $\alpha$**  (medium CMS rest frame), while the jet moves at an angle  $\theta$ .



# What We Can We Learn from Jet Drift – The Constant Slab

*Antiporda, Bahder, Rahman, MDS, Phys. Rev. D105 (2022)*

- Deflection encodes **tomographic information about the flow**:
  - **Zero crossing** when  $\theta = \alpha$
  - **Two extrema** centered about  $\alpha$  with total **width**  $2 \cos^{-1} u$
  - Entire peak / zero / peak structure becomes **narrower** and **larger** as  $u \rightarrow 1$ .



# What We Can We Learn from Jet Drift – The Constant Slab

- The **flow direction**  $\vec{u}$  is an **attractor** of the jet trajectories.

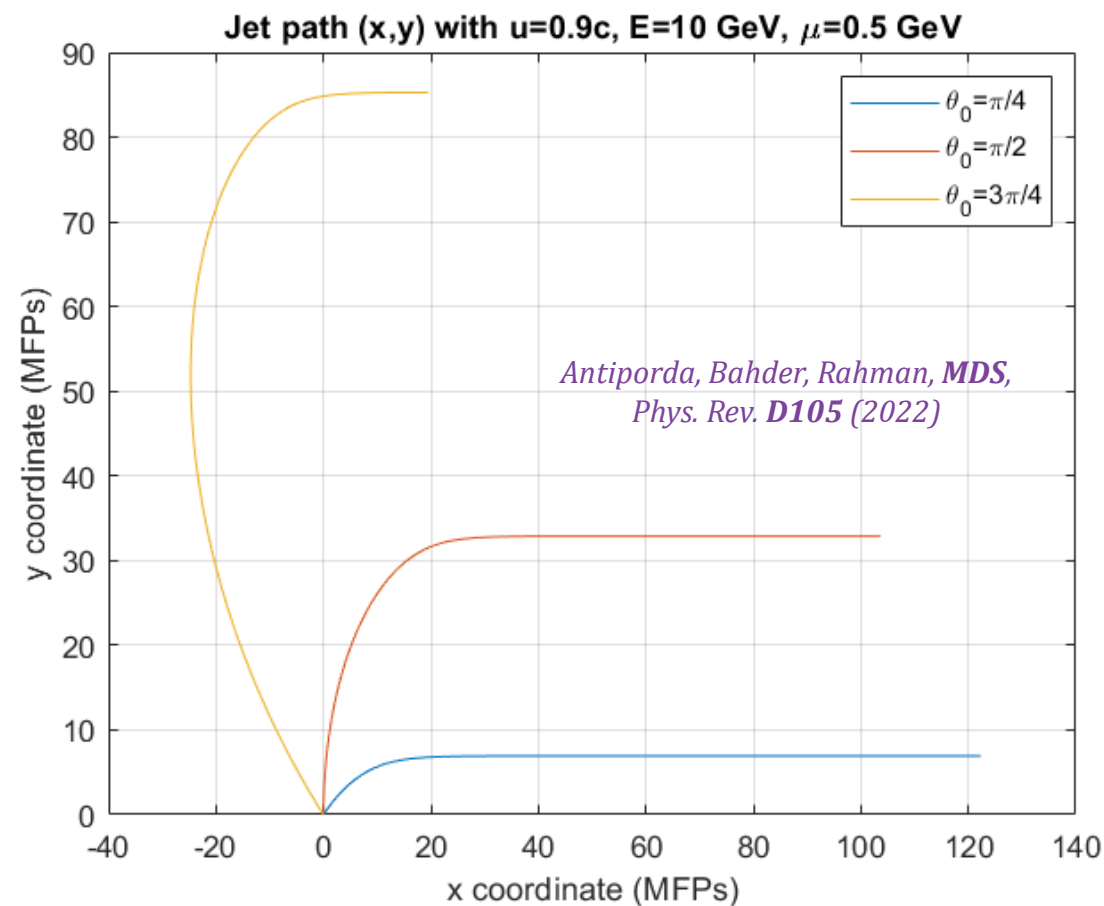
$$\frac{d\langle\theta\rangle}{dt} = \frac{3}{\lambda} \frac{u \sin(\langle\theta\rangle - \alpha)}{1 - u \cos(\langle\theta\rangle - \alpha)} \frac{\mu^2}{E^2} \ln \frac{E}{\mu}$$

- **Preferential kick towards  $\vec{u}$**  no matter the original direction
- Given enough time, **jet trajectories converge to the flow direction**
- The **time constants** carry information about the **fluid speed**.

$$\theta - \alpha \sim e^{-t/\tau_{attr}}$$

$$(\alpha + \pi) - \theta \sim e^{+t/\tau_{rep}}$$

$$\frac{\tau_{rep}}{\tau_{attr}} = \frac{1 + u}{1 - u}$$



# What We Can Learn from Jet Drift: Fluctuating Gaussian

- Consider **Gaussian ellipse toy model**, with the geometry and flow determined from a fluctuating impact parameter

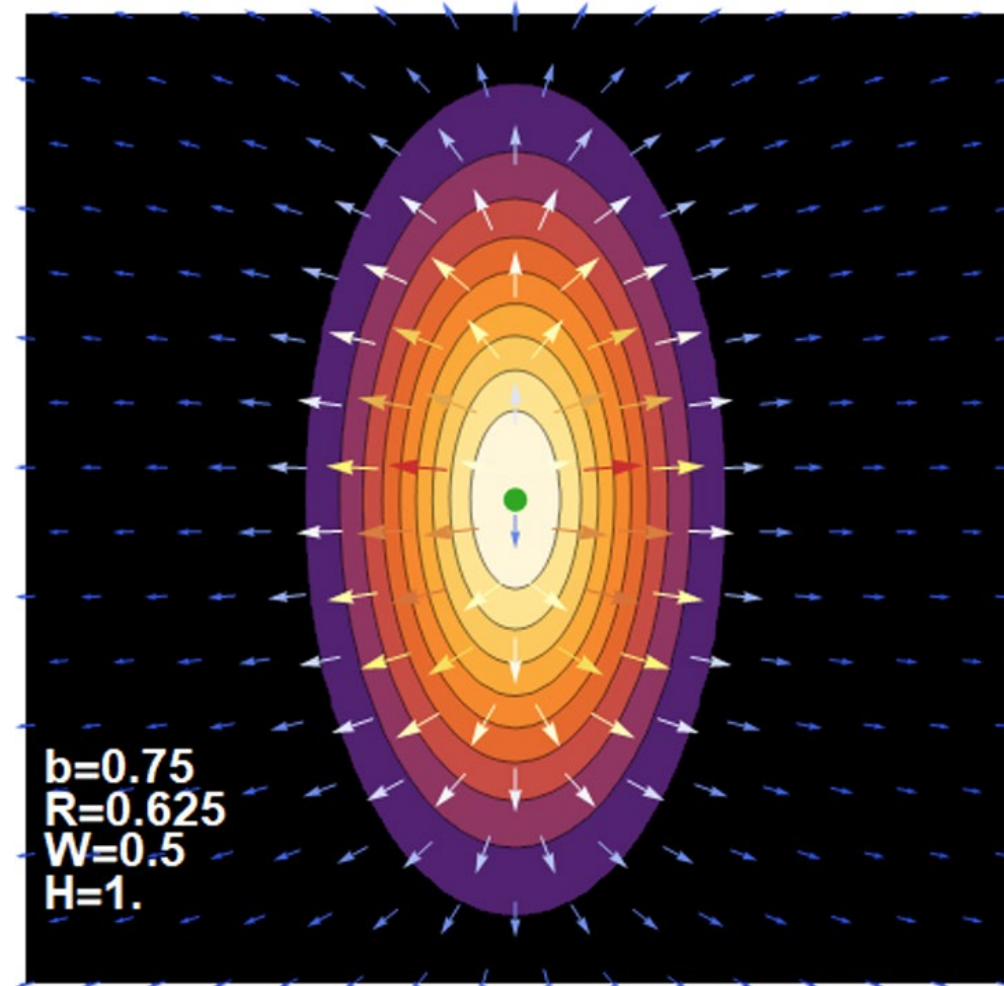
$$W = 2R - b$$

$$H = (4R^2 - b^2)^{1/2}$$

- Flow is assumed to be **proportional to the gradients**  $-\overrightarrow{\nabla T}$

$$T(x, y) = T_0 \exp\left(-\frac{x^2}{2W^2}\right) \exp\left(-\frac{y^2}{2H^2}\right)$$

$$\vec{u}(x, y) = u_0 \sqrt{HW} \left( \frac{x}{W^2} \hat{i} + \frac{y}{H^2} \hat{j} \right) \exp\left(-\frac{x^2}{2W^2}\right) \exp\left(-\frac{y^2}{2H^2}\right)$$



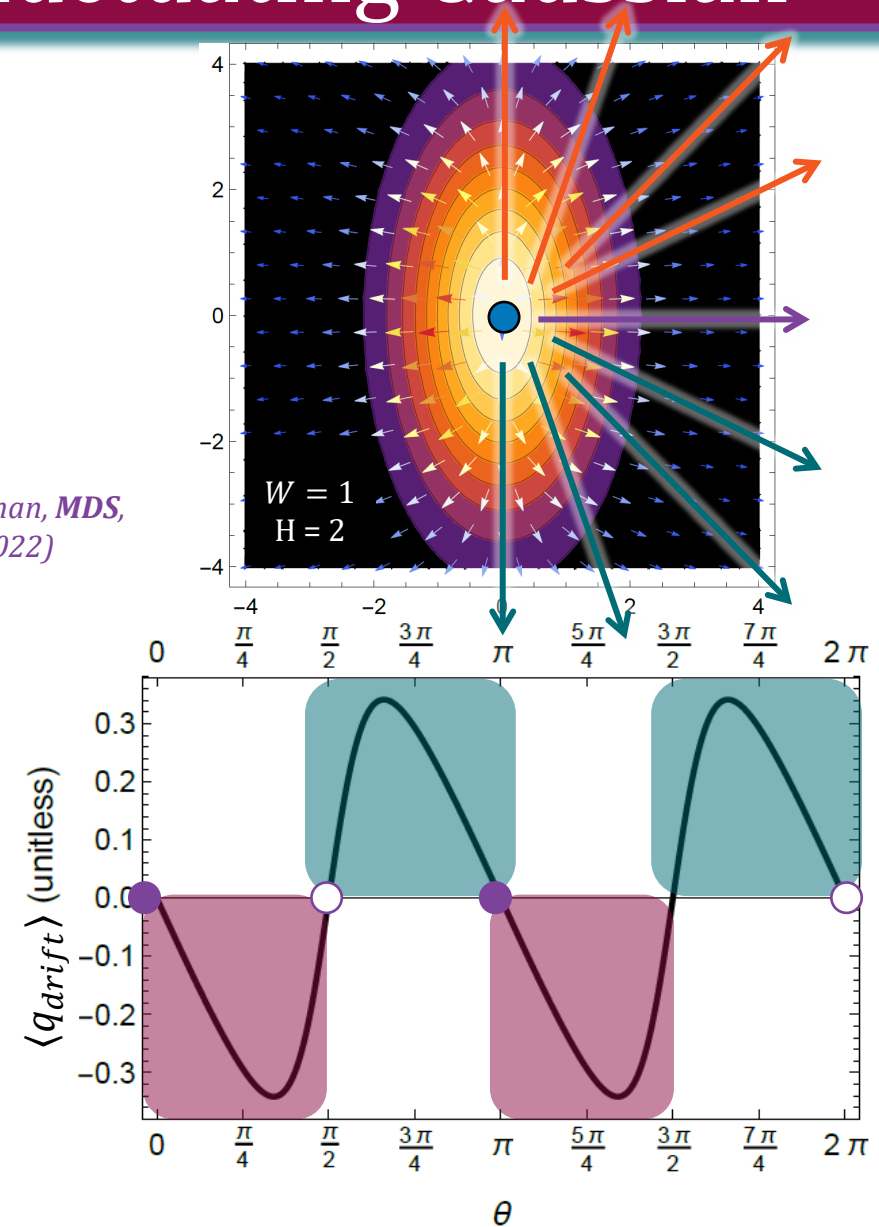
Antiporda, Bahder, Rahman, *MDS*,  
*Phys. Rev. D* **105** (2022)



# What We Can Learn from Jet Drift: Fluctuating Gaussian

- Folding jet drift with the event geometry converts what is locally a **directed flow** (“v1 of jets”) into a global **elliptic flow** (v2).
  - Local  $\cos \phi \rightarrow$  global  $\cos 2 \phi$
- Simplest picture for jets produced at the center:
  - The **event plane (minor axis)** becomes the **attractor** for jet trajectories
  - The **perpendicular direction (major axis)** becomes a **repulsor** for jet trajectories

*Antiporda, Bahder, Rahman, MDS,  
Phys. Rev. D105 (2022)*

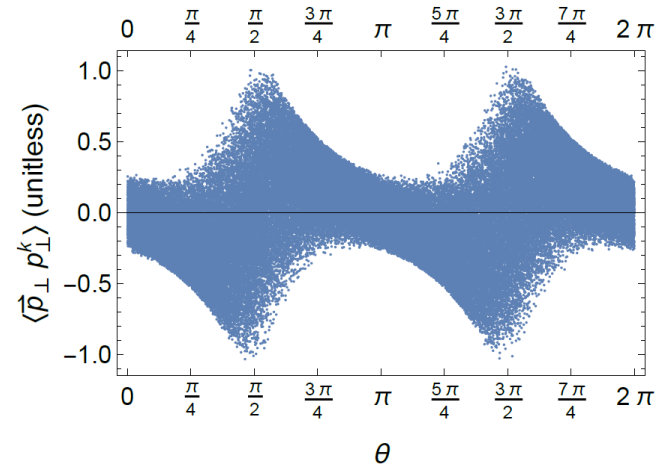




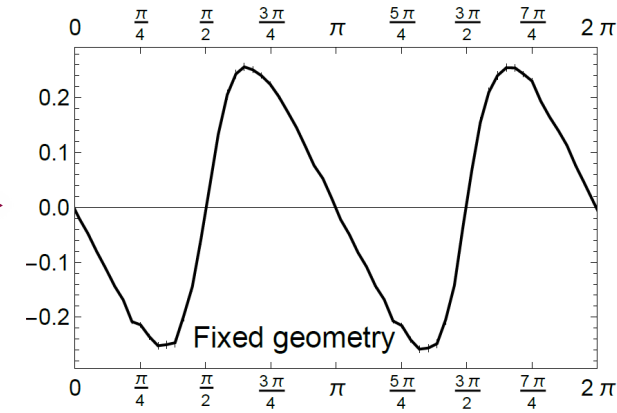
# What We Can Learn from Jet Drift: Fluctuating Gaussian

- The conclusions are **robust** and survive the inclusion of **fluctuations**:

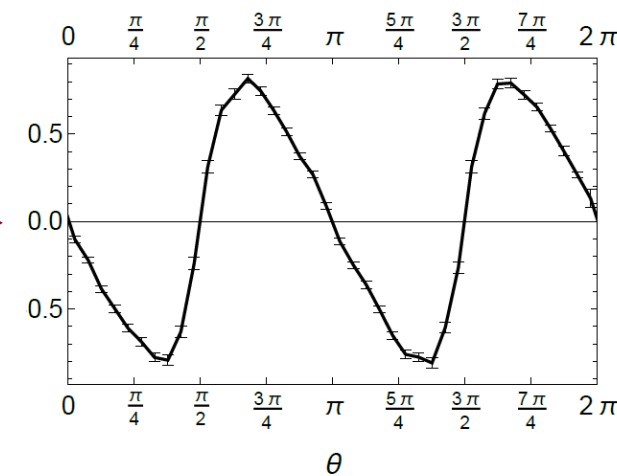
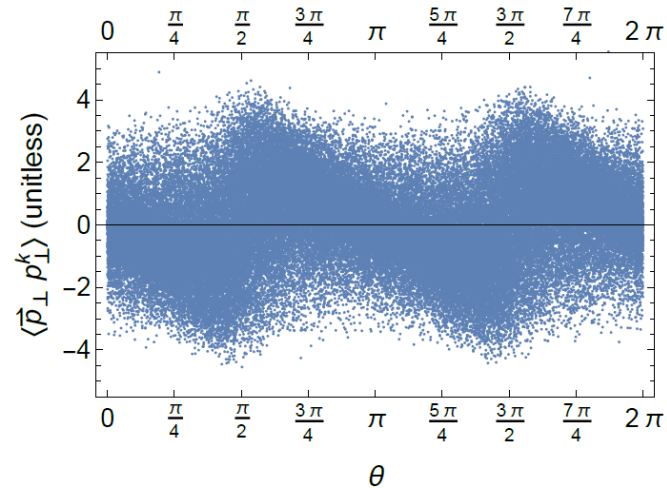
➤ **Production point** fluctuations (binary collision sampling)



*Antiporda, Bahder, Rahman, MDS, Phys. Rev. D105 (2022)*



➤ **Impact parameter** fluctuations



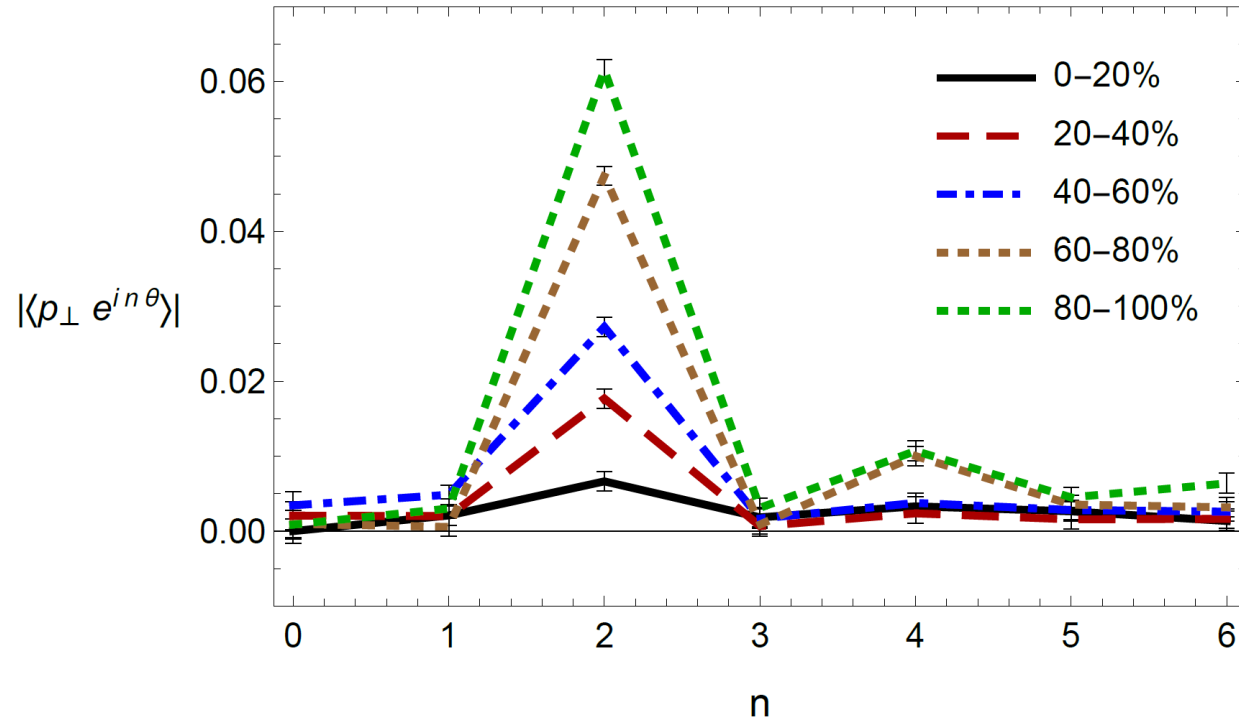
# Implications: Jet Drift and Elliptic Flow

- Through folding with the event geometry, jet drift (a locally “v1 type” effect) is converted into elliptic flow (a “v2 type” correlation with the event plane).

➤ **Some features are specific to this model** (e.g.,  $v_3 = 0$ )

➤ Some features are **generic: systematic enhancement of  $v_2$**  (and other even harmonics?)

*Antiporda, Bahder, Rahman, MDS,  
Phys. Rev. D105 (2022)*



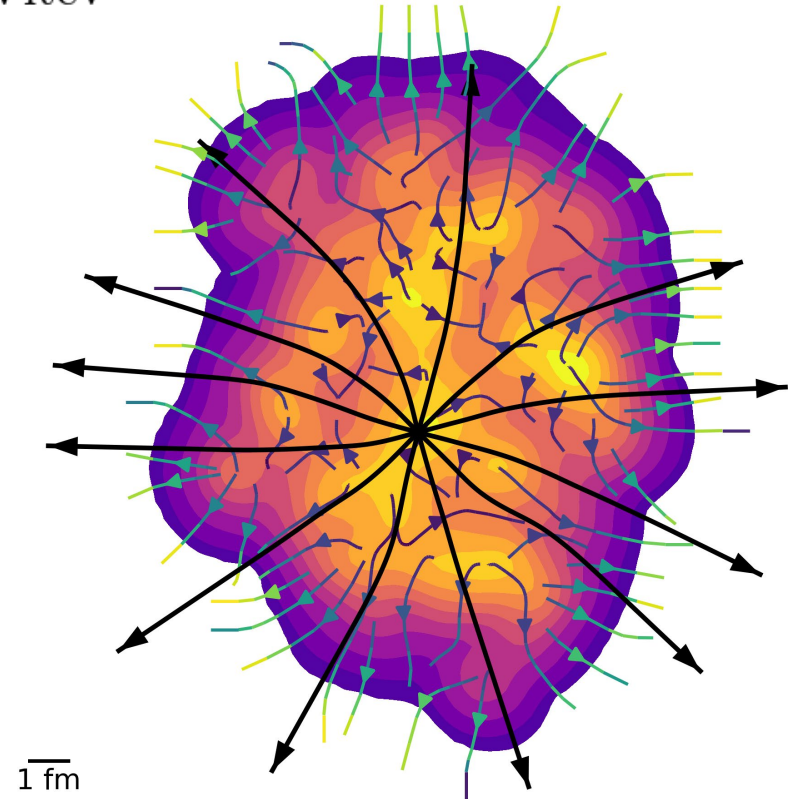
# The Next Frontier: Jet Drift in EBE Heavy-Ion Collisions

## Signatures of Jet Drift in QGP Hard Probe Observables

Joseph Bahder,<sup>1,\*</sup> Hasan Rahman,<sup>1,†</sup> Matthew D. Sievert,<sup>1,‡</sup> and Ivan Vitev<sup>2,§</sup>

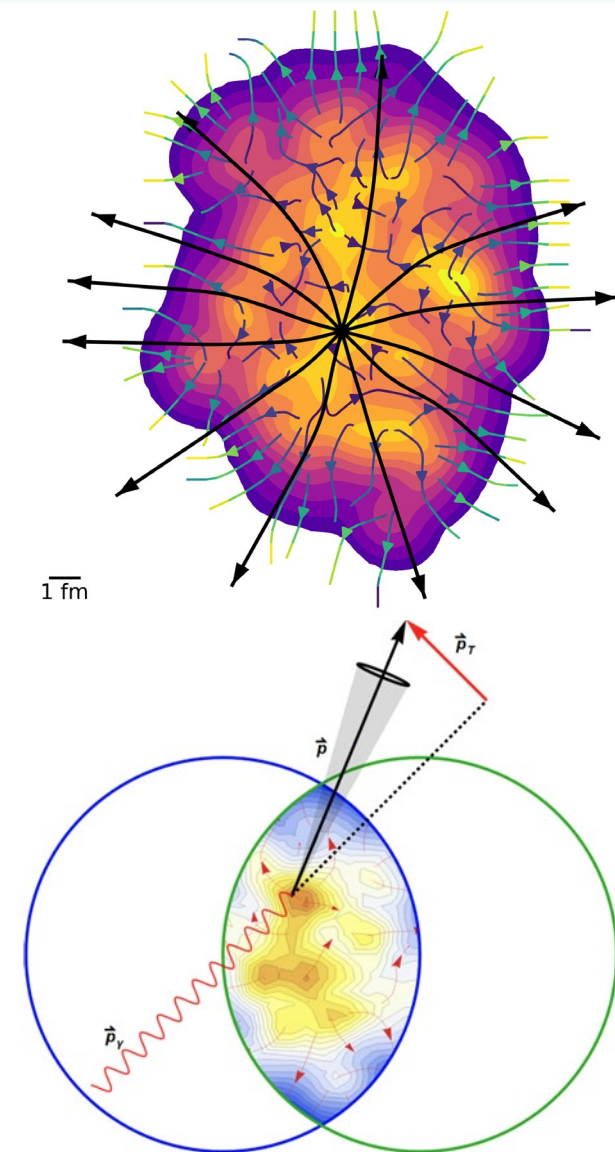
[arXiv: 2412.05474](https://arxiv.org/abs/2412.05474)

- Studies jet drift in **event-by-event viscous hydrodynamics simulations**.
- **Quantitative enhancement to  $v_2$**  of jets, especially at lower  $p_T$  (sub-eikonal effect)
- **Competes with conventional mechanisms** (path-length-dependent energy loss) for  $v_2$ .



# Searching for “Designer” Observables

- Although “low hanging fruit,” the **enhancement** of  $v_2$  due to drift is **not unique to drift**.
  - Natural **missing element** of the “ $R_{AA}$  to  $v_2$  Puzzle”
  - **Larger impact on the deflection magnitudes** (acoplanarities) although not correlated to the event plane.
  - Look for **3-point correlations?** (e.g.  $\gamma + jet$  correlated with the reaction plane)



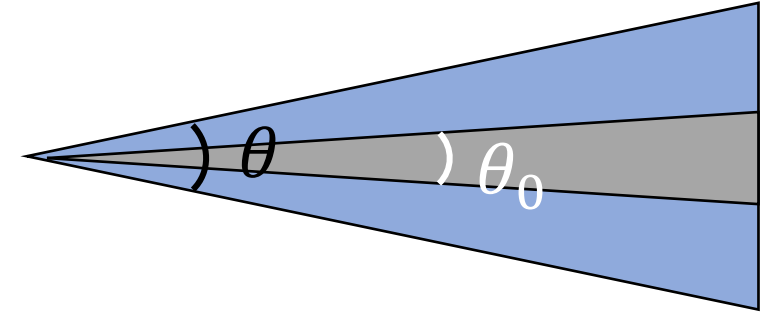
# A New Industry: Asymmetric Measures of Jets

- A representative selection: (note that groups overlap)

➤ Wang et al:	<a href="#"><u>2001.08273</u></a>	<a href="#"><u>2204.05323</u></a>	<a href="#"><u>2210.06519</u></a>	<a href="#"><u>2402.00264</u></a>
➤ Sievert et al:	<a href="#"><u>2104.09513</u></a>	<a href="#"><u>2110.03590</u></a>	<a href="#"><u>2207.07679</u></a>	<a href="#"><u>2412.05474</u></a>
➤ Sadofyev et al:	<a href="#"><u>2202.08847</u></a>	<a href="#"><u>2207.07141</u></a>	<a href="#"><u>2304.03712</u></a>	<a href="#"><u>2309.00683</u></a>
➤ Vitev et al:	<a href="#"><u>2412.12250</u></a>			

# Lesson: Power of Antisymmetry

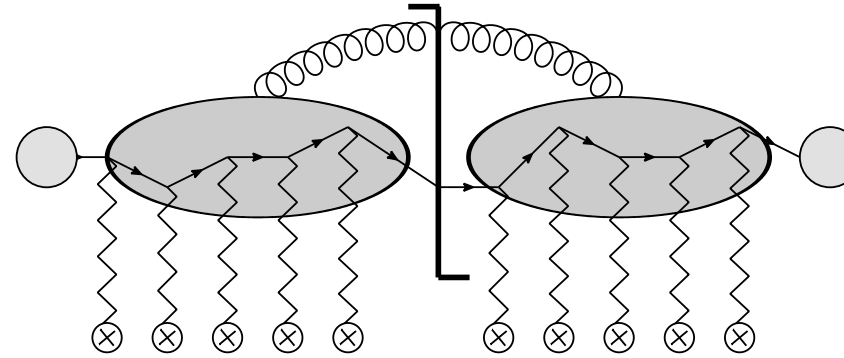
- Bread & butter jet quenching observables are driven by **isotropic** processes: energy loss ( $R_{AA}$ ),  $p_T$  broadening
- Even locally, there are **many competing “backgrounds”**: vacuum Sudakov shower, gluon saturation, cold nuclear matter effects, etc
- ❖ **Antisymmetric** observables can select on **different microscopic channels** which have **fewer backgrounds** than the symmetric ones
  - **Cold QCD: transverse spin asymmetries, parity-violating asymmetries, etc.**
  - **Hot QCD: preferred deflection of jets**
- ❖ **Power-suppressed effects** introduce **new quantum numbers** to the process (flow)



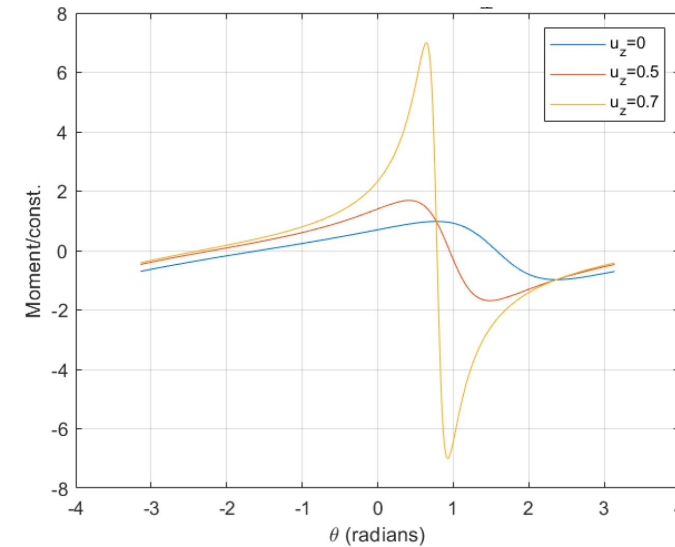


# Conclusions

- The radiation emitted by a hard parton is a sensitive **interferometer** to details of the nuclear medium.



- As an **antisymmetric** interaction with the medium, **jet drift** is “locally v1 type” resulting in a  $\langle \cos \phi \rangle$  correlation with the flow direction.



- Event geometry converts this into a global  $\langle \cos 2\phi \rangle$  correlation, **enhancing the elliptic flow** (among other effects).

