Response of Jets to Collective Flow in Heavy-Ion Collisions

Matthew D. Sievert

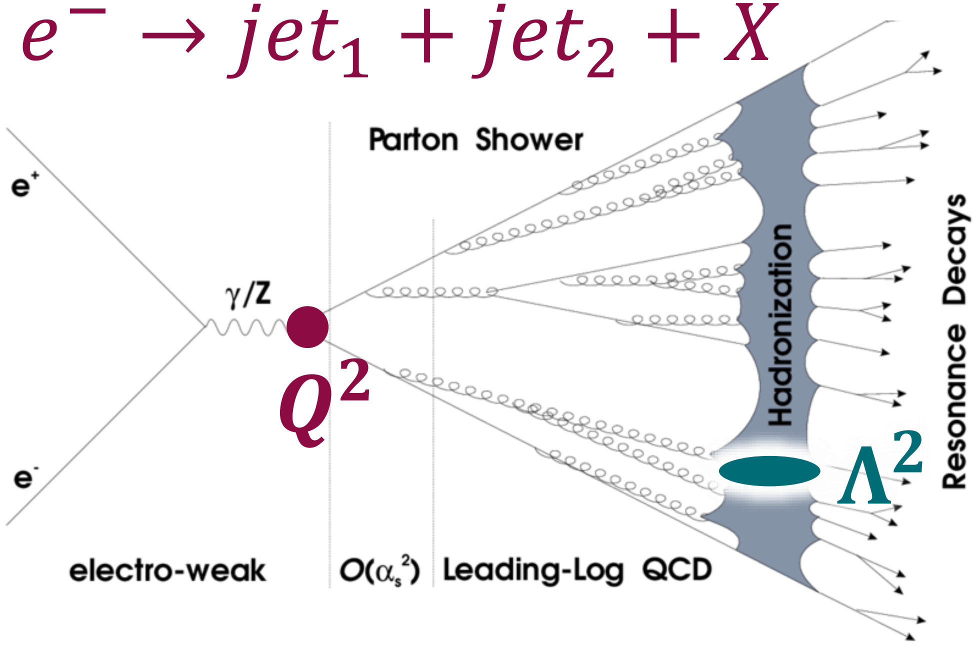
NM STATE

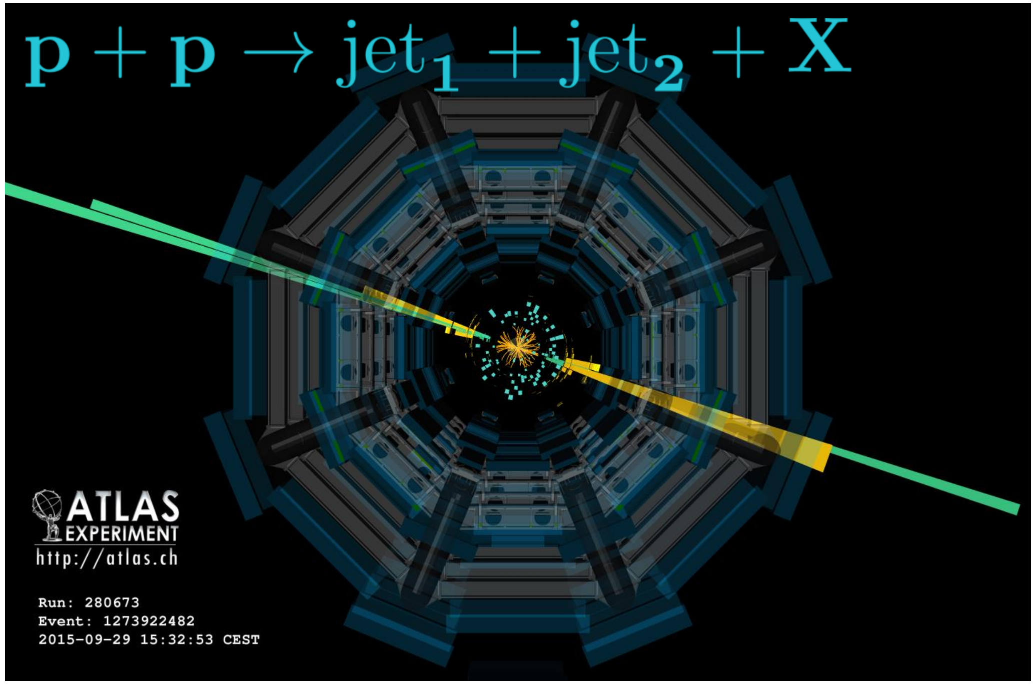
Hot Jets 2025

1/8/2025

Jets in Vacuum: a Microcosm of QCD

$$e^+ + e^- \rightarrow jet_1 + jet_2 + X$$





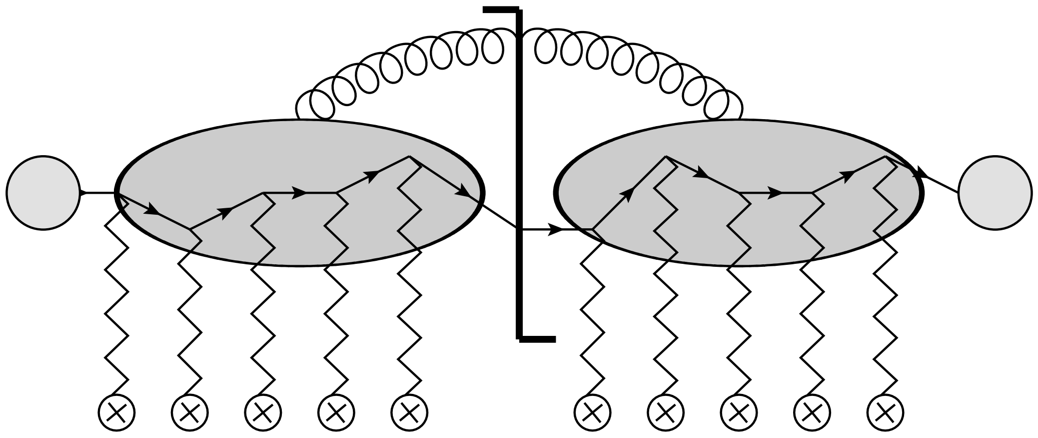
- Basic **jet production: hard parton-parton scattering** at high virtuality Q^2
- **Cascade of radiation** falling in virtuality down from Q^2 to the **hadronization scale** Λ^2
- Jets and substructure: **radiative QCD evolution** from perturbative to nonperturbative

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 $\boldsymbol{p_T}$ ***broadening***



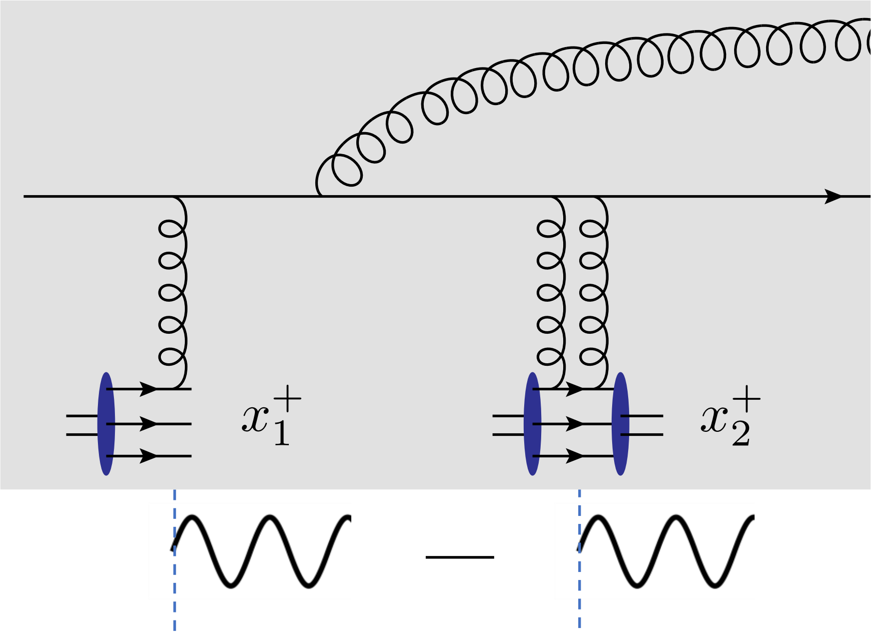
Landau, Pomeranchuk, Dokl. Akad. Nauk Ser. Fiz ***92*** *(1953)*

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

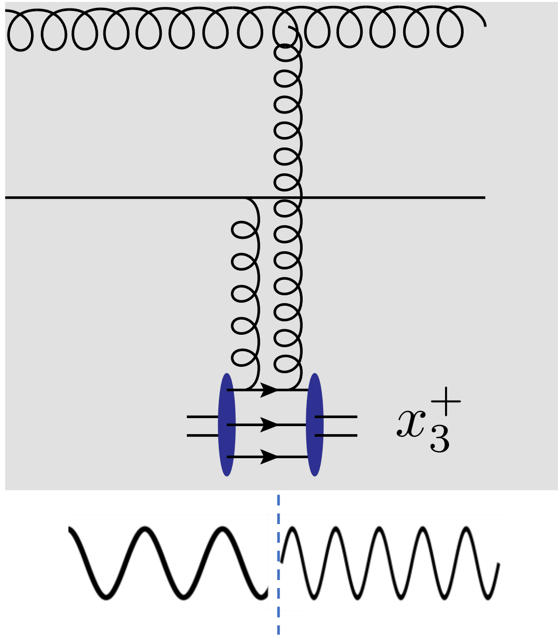
- **Edge phases** of the emission region
- **Phase slip** from scattering

Formation Time

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

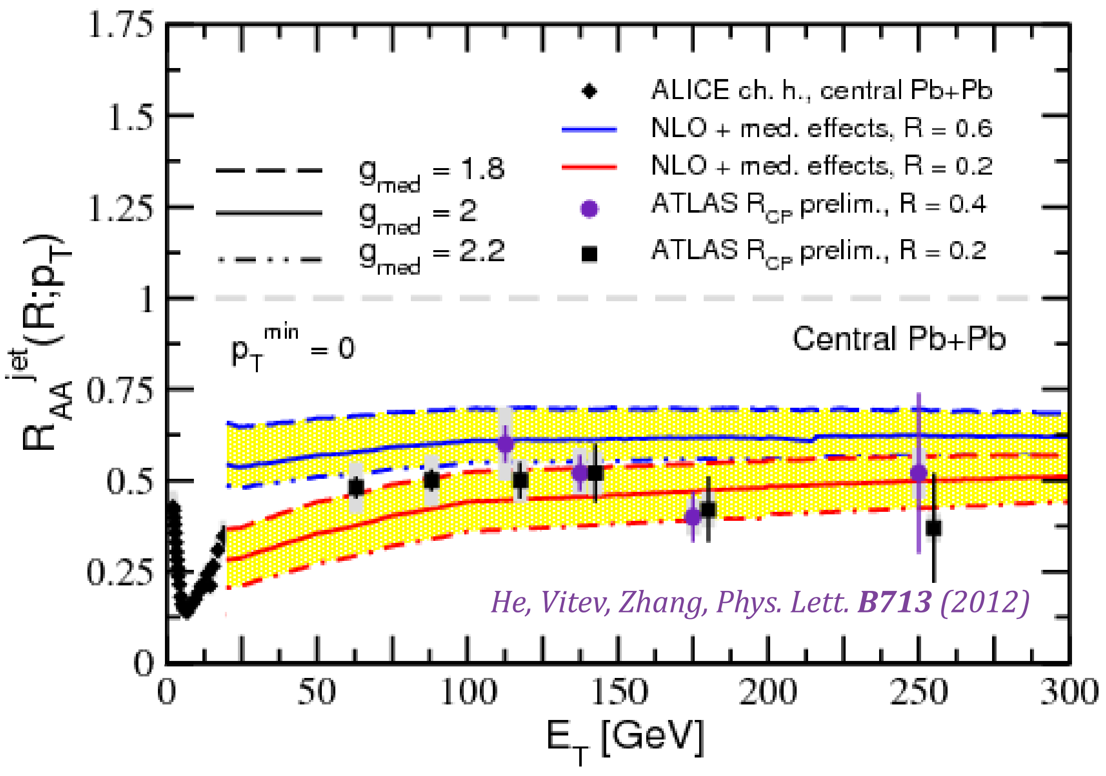


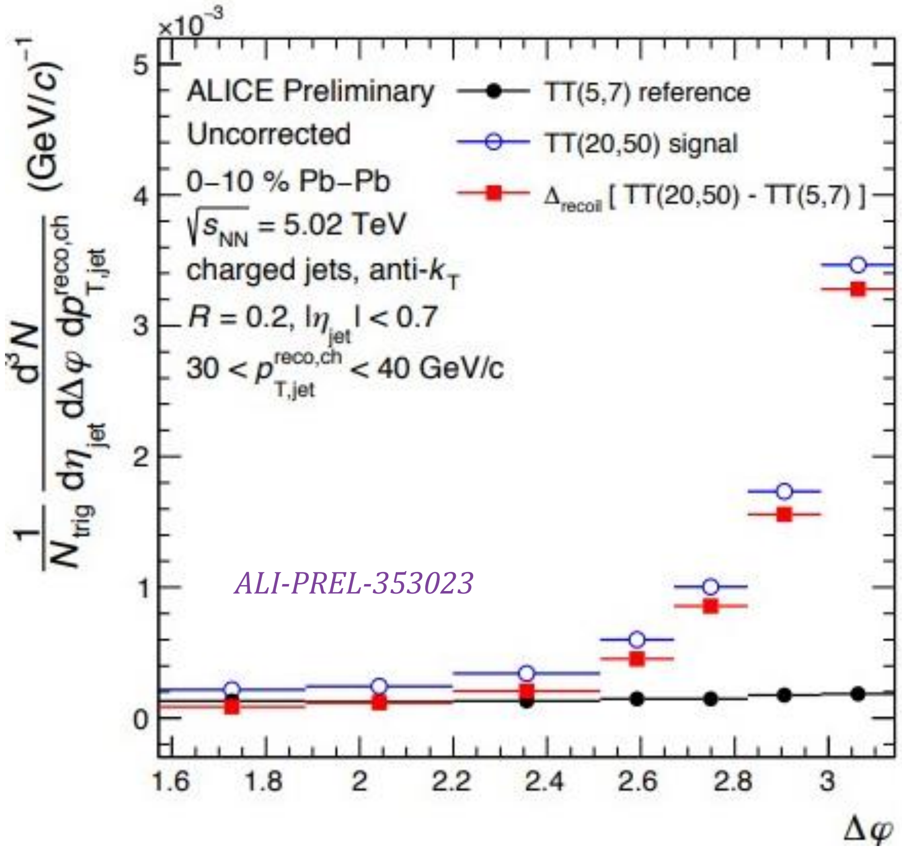
$$e^{i(z_1 / \ell_f)} - e^{i(z_2 / \ell_f)}$$



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

Canonical Signatures of Medium Modification





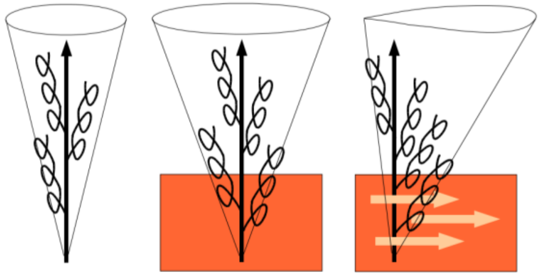
❖ **Energy Loss**

➢ Jet quenching, γ+jet imbalance …

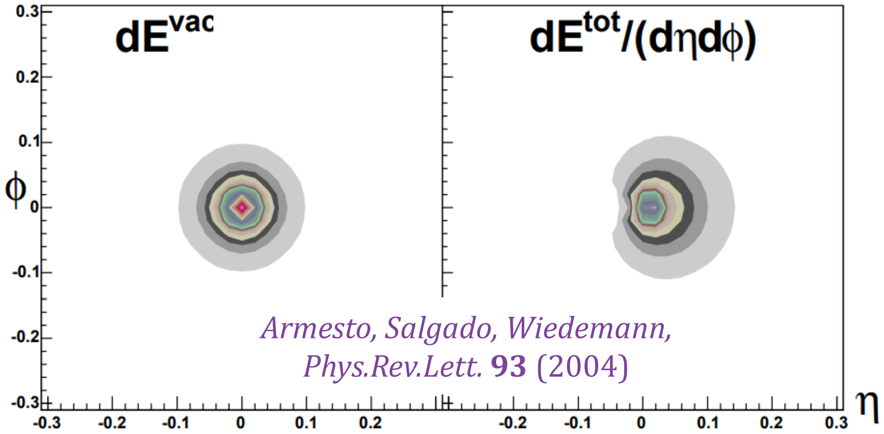
❖ **Transverse Momentum Broadening**

➢ Dijet / γ+jet acoplanarities …

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



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

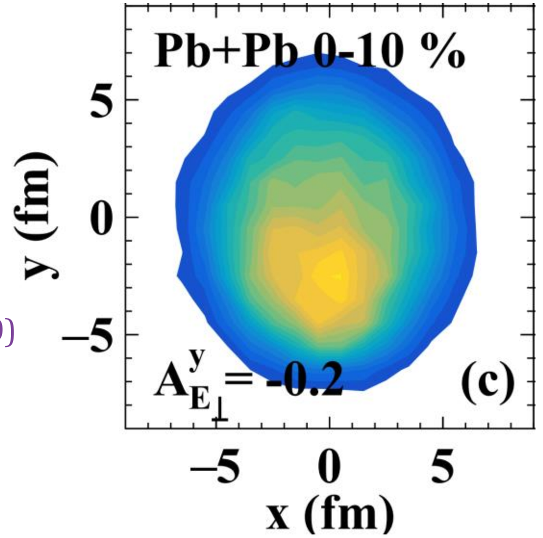


Armesto, Salgado, Wiedemann, Phys.Rev.Lett. **93** (2004)

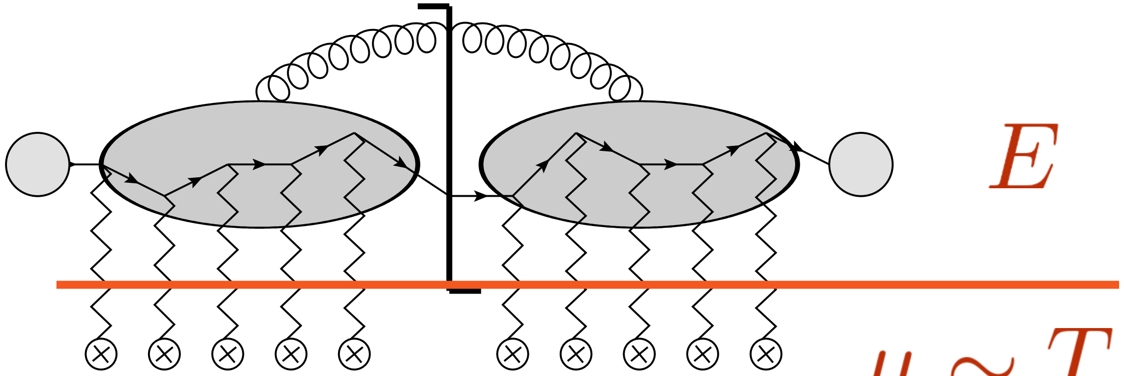
- Linearized Boltzmann Transport calculation of of **jet asymmetries** induced by **gradients**

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

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



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



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

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

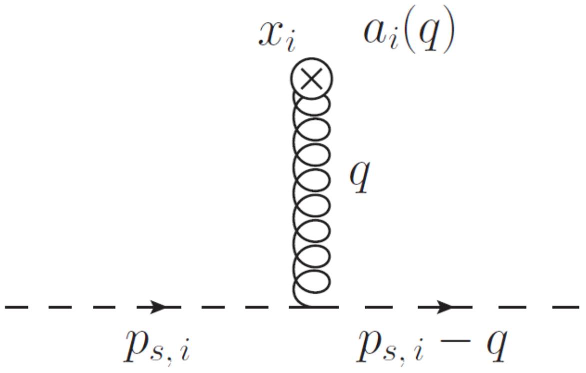
- Can be written as a **frame-independent result** $(p \cdot u)$, but the calculation is valid **only to leading power**.

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

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

$$g\, A^{\mu a}_{\text{ext}}(q) = \sum_i e^{iq\cdot x_i} t^a_i \; u^\mu(\vec{x}_i) \; v(\vec{x}_i,\vec{q}) \; (2\pi)\,\delta\left(q^0 - \vec{u}(\vec{x}_i)\cdot\vec{q}\right)$$

*Sadofyev, **MDS**, Vitev, Phys. Rev. **D104** (2021)*



Fully relativistic velocity

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

Velocity-dependent potential

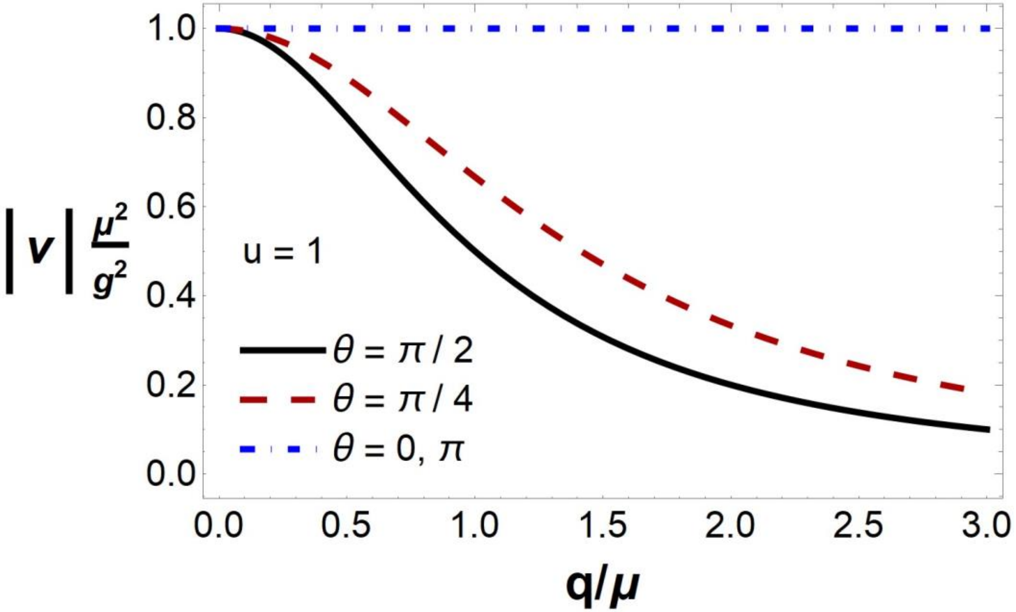
$$v(\vec{x}_i,\vec{q}) = \frac{-g^2}{\vec{q}^2 + \mu^2 - \left(\vec{u}(\vec{x}_i)\cdot\vec{q}\right)^2 - i\epsilon}$$

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

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

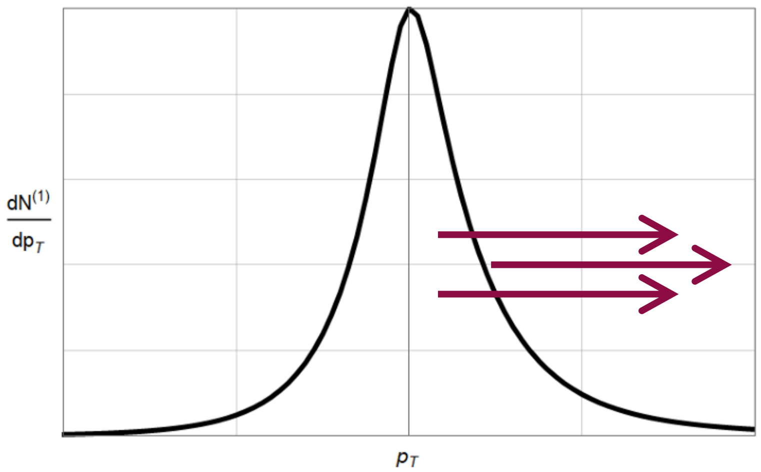
*Gyulassy, Wang, Nucl. Phys. **B420** (1994)*

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



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

*Sadofyev, **MDS**, Vitev, Phys. Rev. **D104** (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

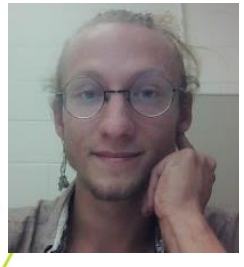
$$\mathbf{\Gamma}(\boldsymbol{q}_\perp) = -2\frac{\boldsymbol{p}_\perp - \boldsymbol{q}_\perp}{(1-u_{i\,z})E} + \frac{\boldsymbol{q}_\perp}{(1-u_{i\,z})E} \left(\frac{(p-q)^2_\perp - p^2_\perp}{\bar{\sigma}(q^2_\perp)} \right) \frac{\partial \bar{\sigma}}{\partial q^2_\perp} - \frac{\boldsymbol{q}_\perp}{1-u_z}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

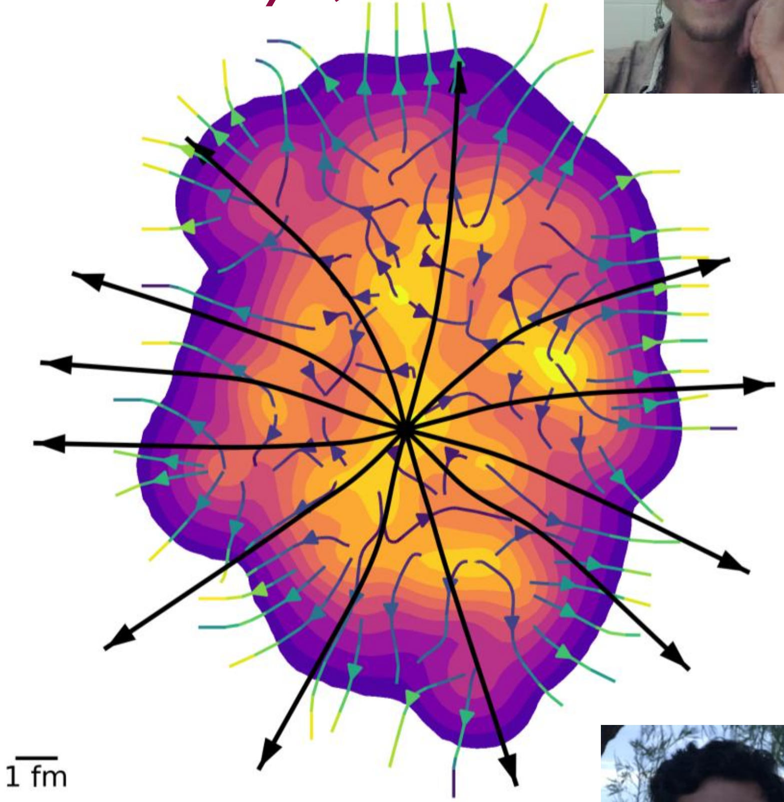
Jet Drift: Skewed Momentum Broadening

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

- 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

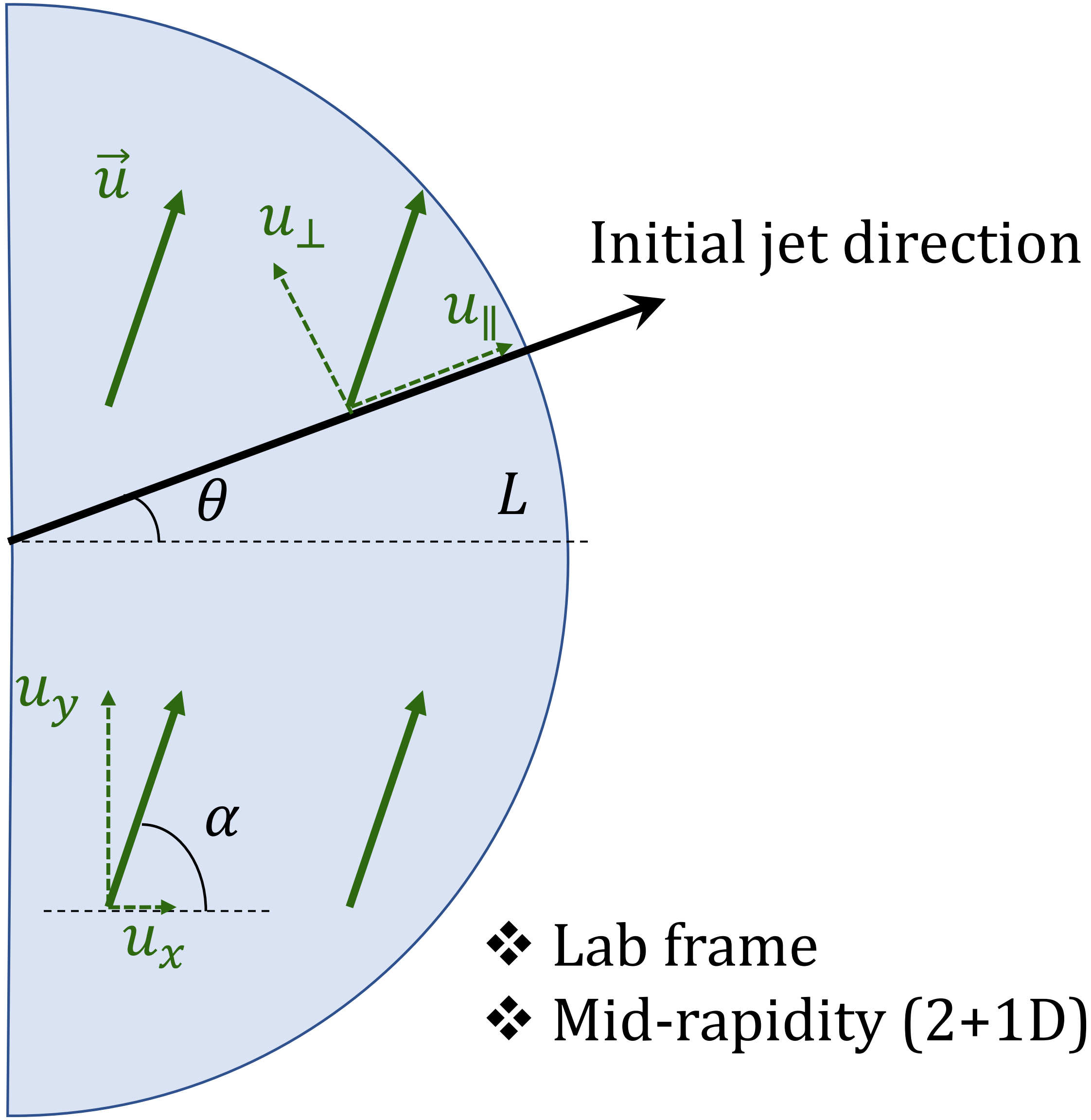
What We Can We Learn from Jet Drift – The Constant Slab

*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 α** (medium CMS rest frame), while the jet moves at an angle θ.



- Lab frame
- Mid-rapidity (2+1D)

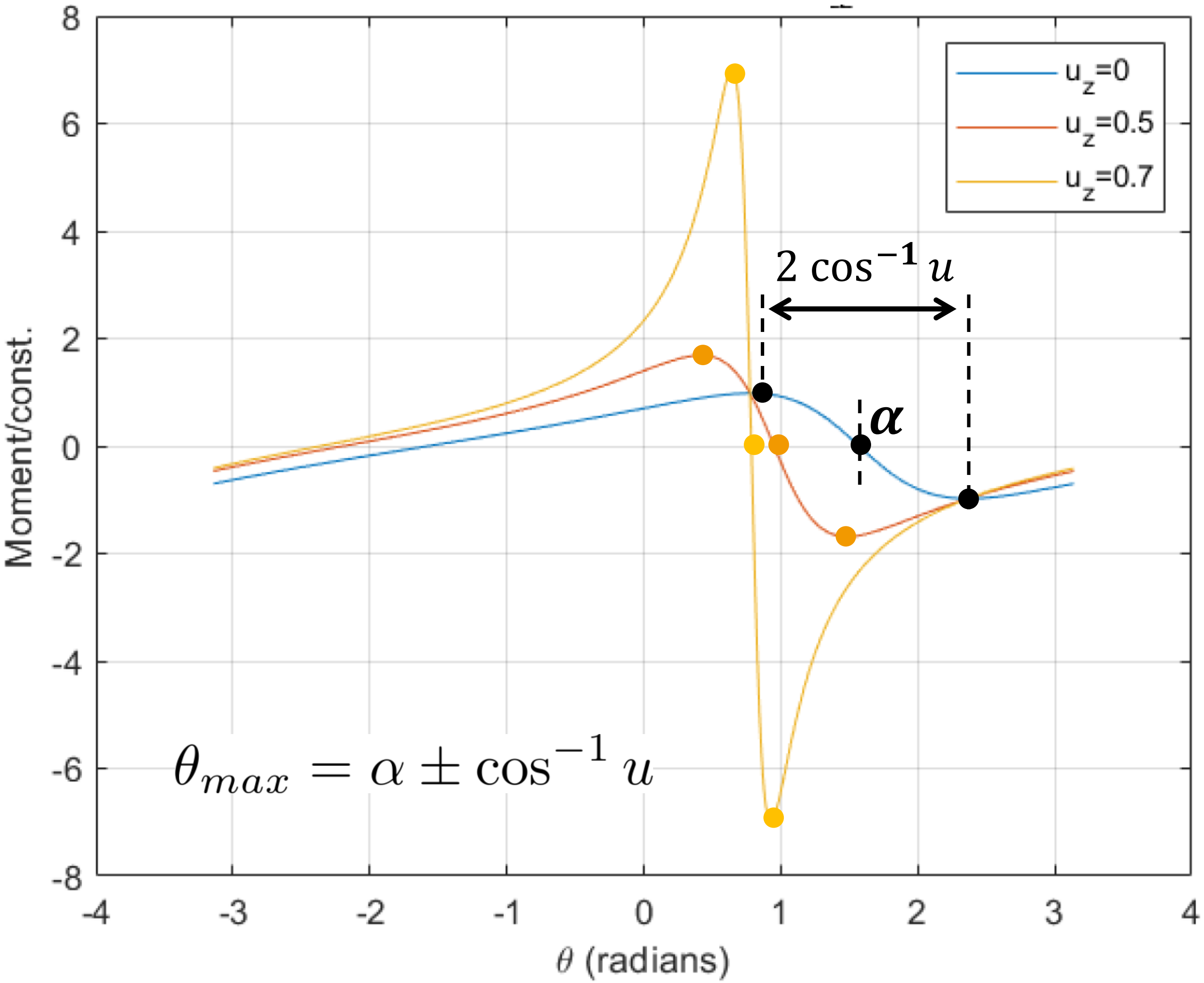
*Antiporda, Bahder, Rahman, **MDS**, Phys. Rev. **D105** (2022)*

- Deflection encodes **tomographic information about the flow**:

➢ **Zero crossing** when $\boldsymbol{\theta = \alpha}$

➢ **Two extrema** centered about α with total **width** $\mathbf{2\cos^{-1} u}$

➢ Entire peak / zero / peak structure becomes **narrower** and **larger** as $\boldsymbol{u \to 1}$.

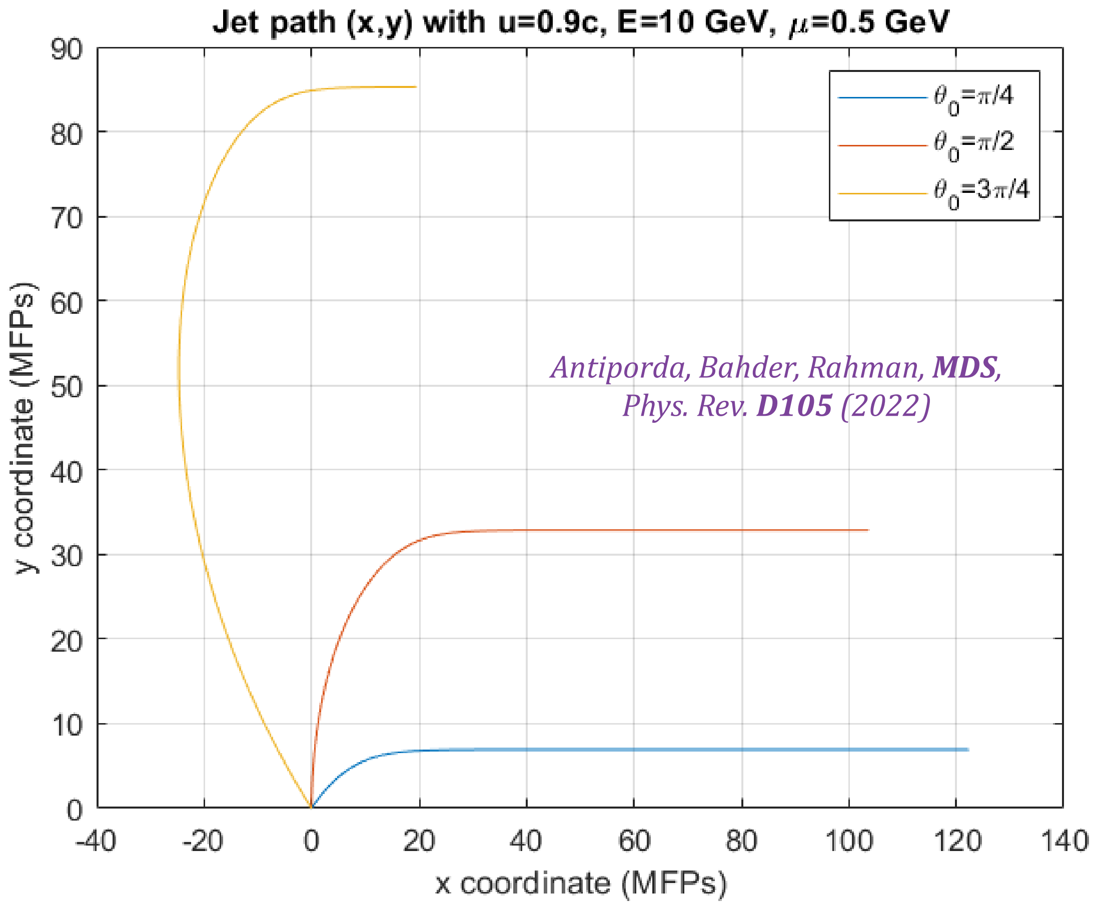


What We Can We Learn from Jet Drift – The Constant Slab

- 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**.



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

$$\theta - \alpha \sim e^{-t/\tau_{attr}} \qquad (\alpha + \pi) - \theta \sim e^{+t/\tau_{rep}} \qquad \frac{\tau_{rep}}{\tau_{attr}} = \frac{1+u}{1-u}$$

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

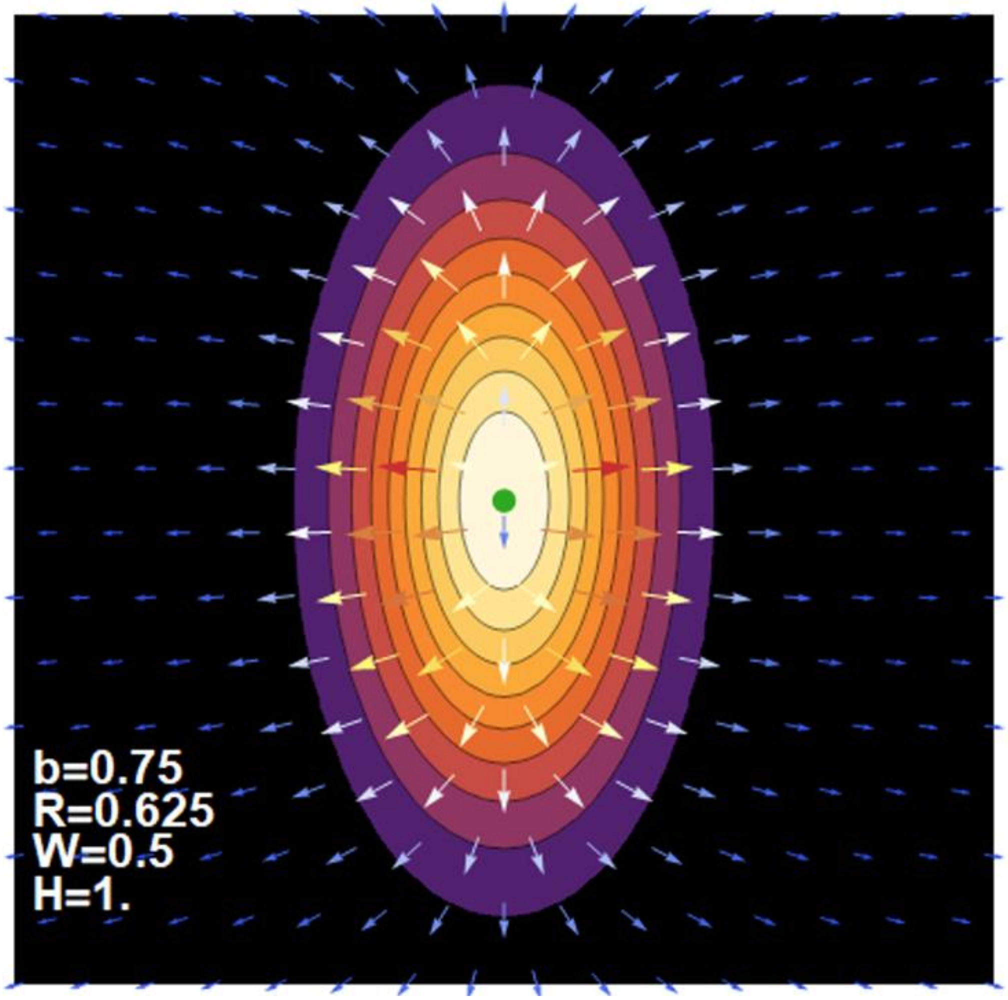
$$W = 2R - b$$

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

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

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

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



*Antiporda, Bahder, Rahman, **MDS**, Phys. Rev. **D105** (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 $\cos\phi$ → global $\cos 2\phi$

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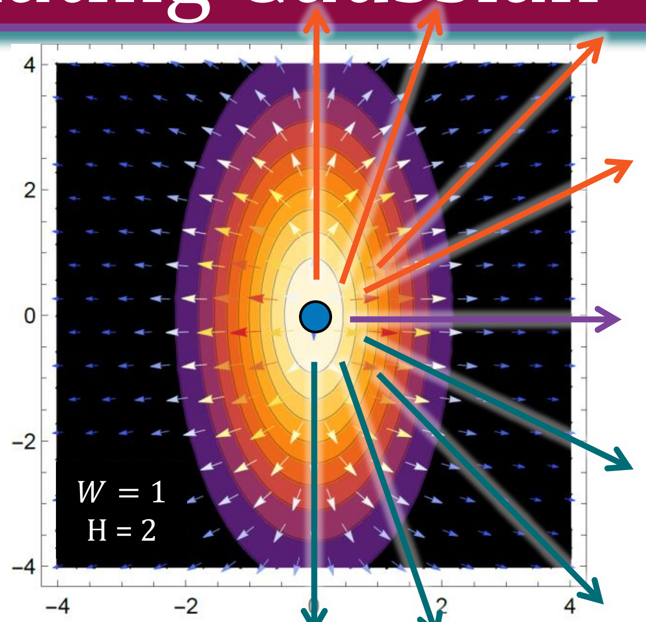
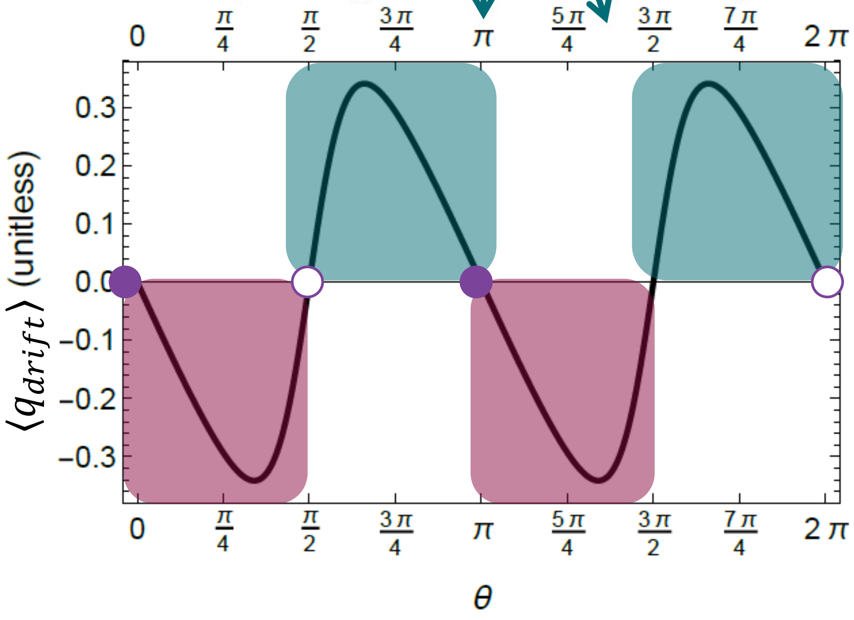


- Simplest picture for jets produced at the center:

  - The **event plane (minor axis)** becomes the **attractor** for jet trajectories

  - The **perpendicular direction (major axis)** becomes a **repulsor** for jet trajectories

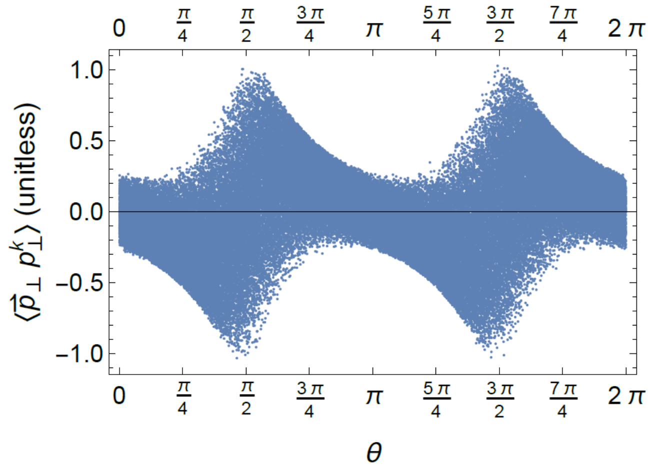


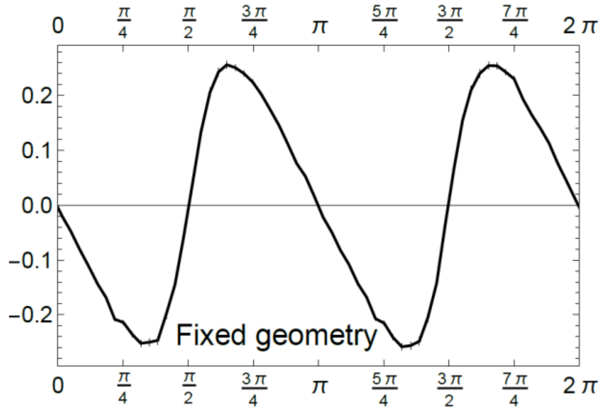
What We Can Learn from Jet Drift: Fluctuating Gaussian

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

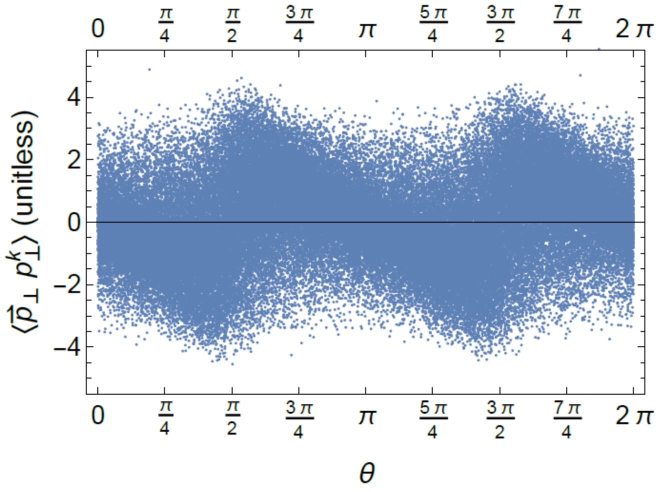
*Antiporda, Bahder, Rahman, **MDS**, Phys. Rev. **D105** (2022)*

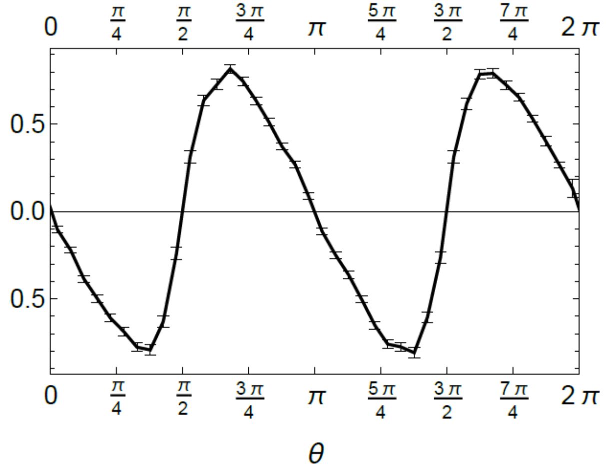
➢ **Production point** fluctuations (binary collision sampling)





➢ **Impact parameter** fluctuations





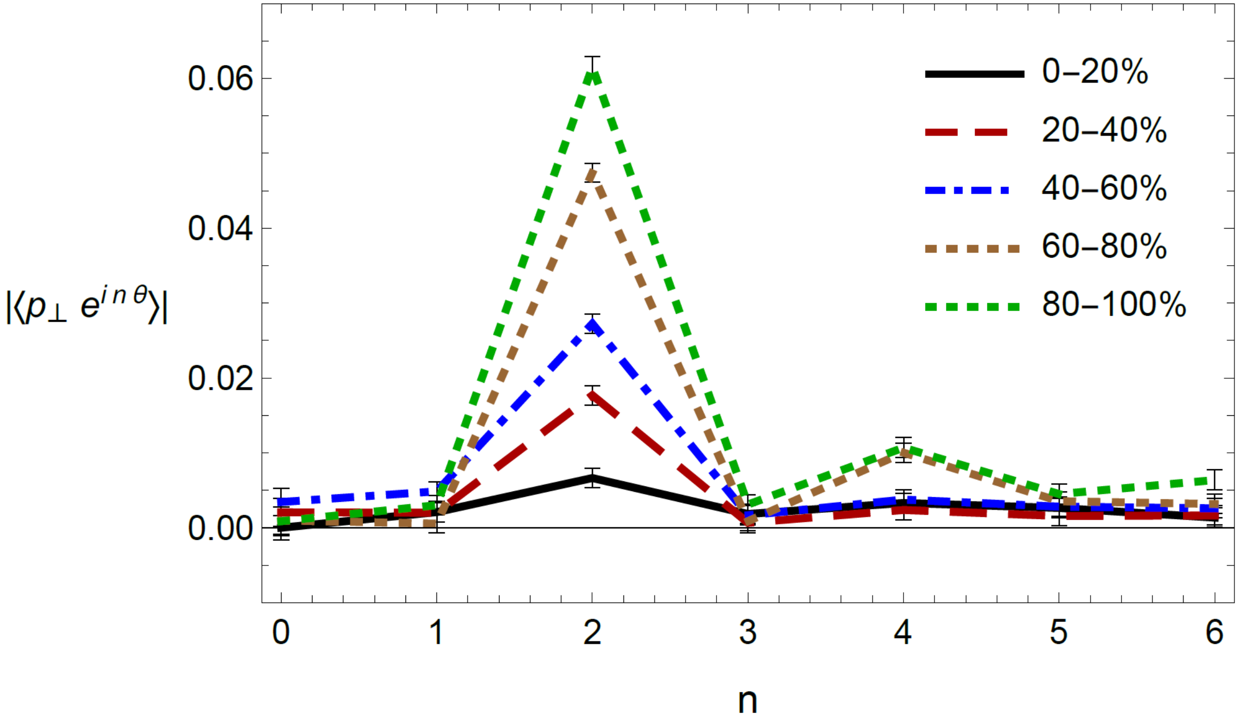
Implications: Jet Drift and Elliptic Flow

- 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)*



Signatures of Jet Drift in QGP Hard Probe Observables

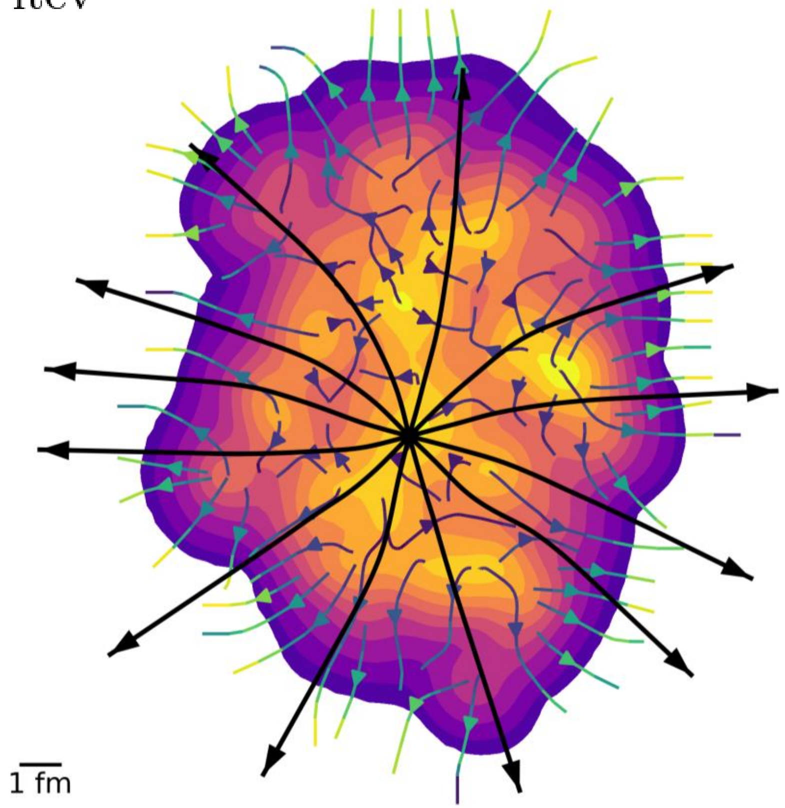
Joseph Bahder,[1,*] Hasan Rahman,[1,†] Matthew D. Sievert,[1,‡] and Ivan Vitev[2,§]

arXiv: 2412.05474

- Studies jet drift in **event-by-event viscous hydrodynamics simulations**.

- **Quantitative enhancement to v2** of jets, especially at lower pT (sub-eikonal effect)

- **Competes with conventional mechanisms** (path-length-dependent energy loss) for v2.



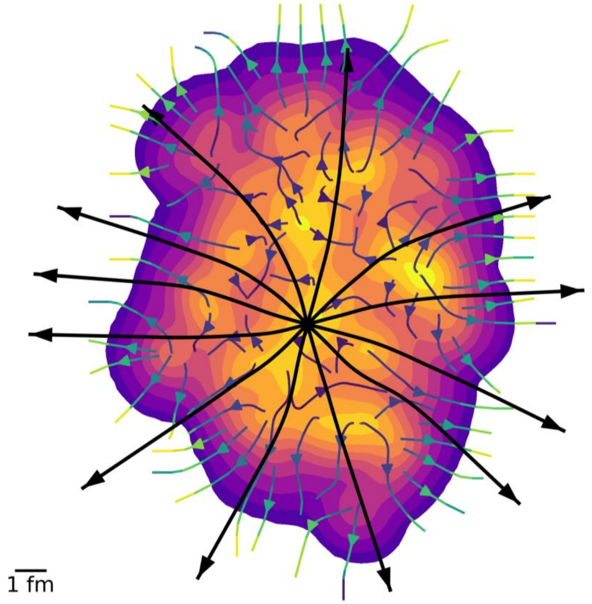
Searching for "Designer" Observables

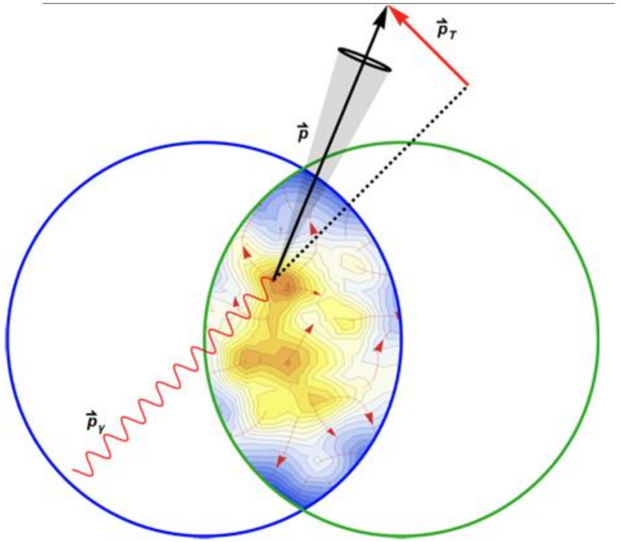
- Although "low hanging fruit," the **enhancement** of v2 due to drift is **not unique to drift**.

  - ➢ Natural **missing element** of the "R_{AA} to v2 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)



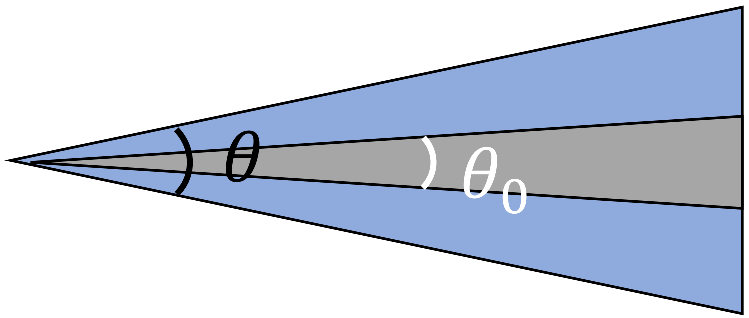


A New Industry: Asymmetric Measures of Jets

- A representative selection: (note that groups overlap)

➢ Wang et al:	2001.08273	2204.05323	2210.06519	2402.00264
➢ Sievert et al:	2104.09513	2110.03590	2207.07679	2412.05474
➢ Sadofyev et al:	2202.08847	2207.07141	2304.03712	2309.00683
➢ Vitev et al:	2412.12250			

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

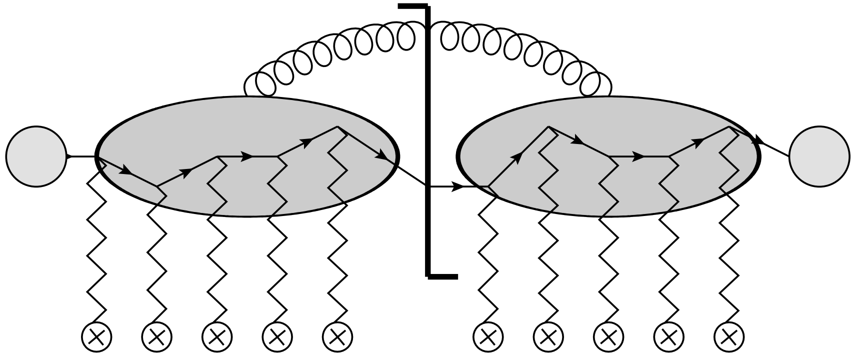
➢ **Cold QCD: transverse spin asymmetries, parity-violating asymmetries, etc.**

➢ **Hot QCD: preferred deflection of jets**

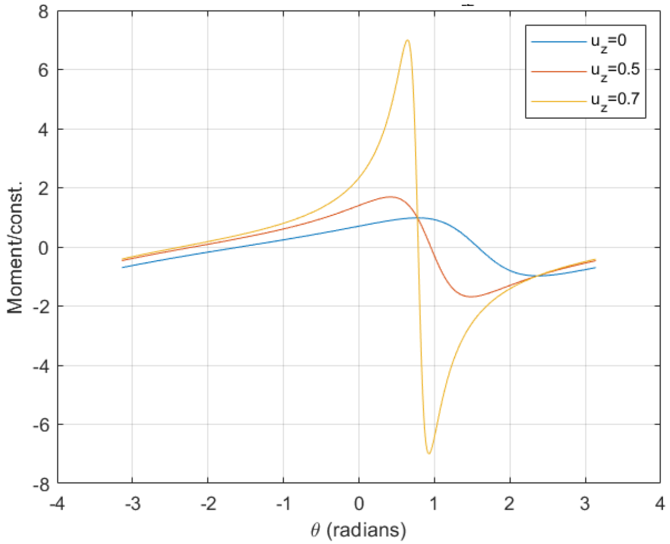
❖ **Power-suppressed effects** introduce **new quantum numbers** to the process (flow)

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).