Jet Drift in Event-by-Event Heavy-Ion Collisions

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RBRC Workshop:
Predictions for sPHENIX

7/21/2022

Key Papers for This Talk

- **Theoretical Calculation:** *Andrey Sadofyev, **MDS**, Ivan Vitev, Phys. Rev. **D104** (2021)*

Ab Initio Coupling of Jets to Collective Flow in the Opacity Expansion Approach

- **Model Phenomenology:** *Logan Antiporda, Joseph Bahder, Hasan Rahman, **MDS**, Phys. Rev. **D105** (2022)*

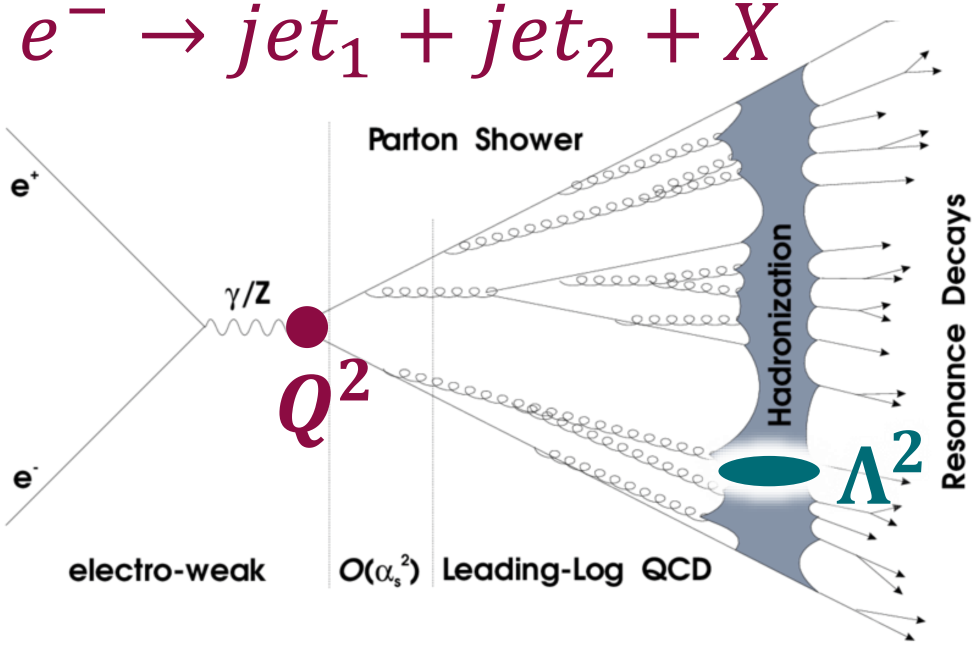
Jet Drift and Collective Flow in Heavy-Ion Collisions

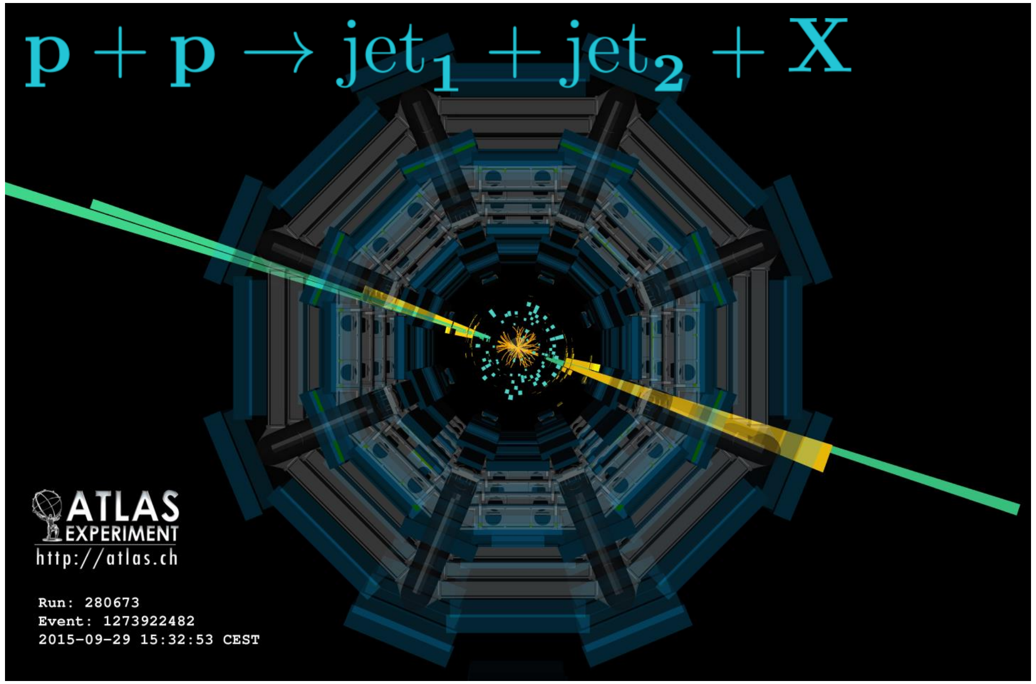
- **Hydro Phenomenology:** *Joseph Bahder, Logan Antiporda, Jorge Marquez Chavez, **MDS**, [in preparation]*

(In Preparation)

Jets in Vacuum: a Microcosm of QCD

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



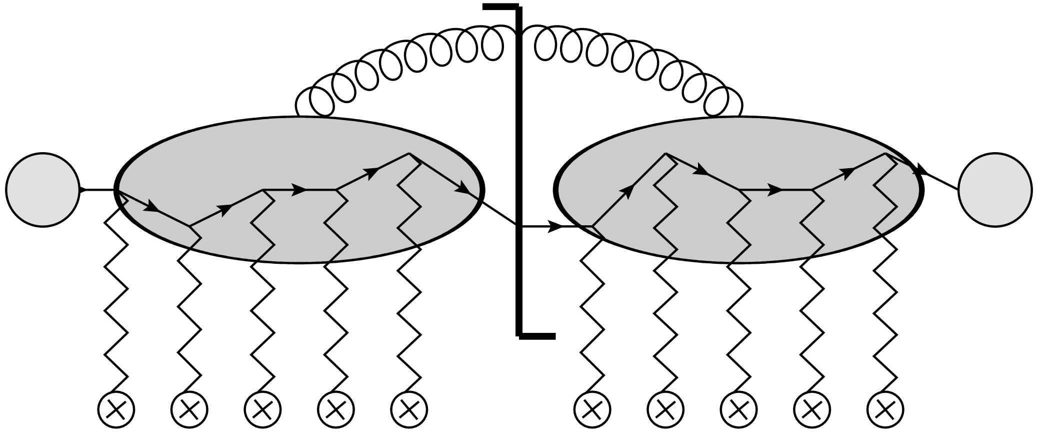


- Basic **jet production: hard parton-parton scattering** at high virtuality Q^2
- **Cascade of radiation** falling in virtuality down from Q^2 to the **hadronization scale** Λ^2
- Jets and substructure: **radiative QCD evolution** from perturbative to nonperturbative

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 ***p_T broadening***



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

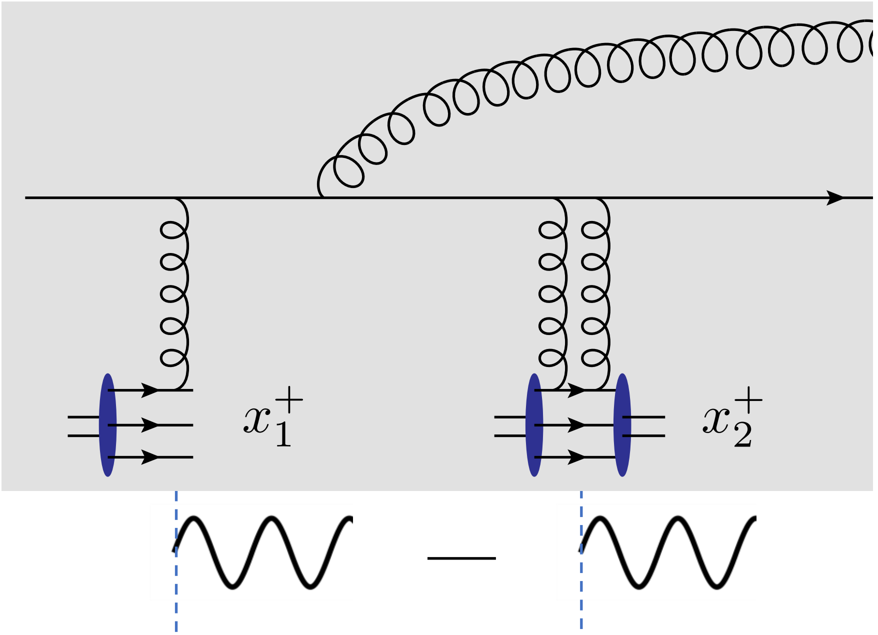
Migdal, Phys. Rev. ***103*** *(1956)*

Jets as Interferometers for Medium-Induced Radiation

Formation Time

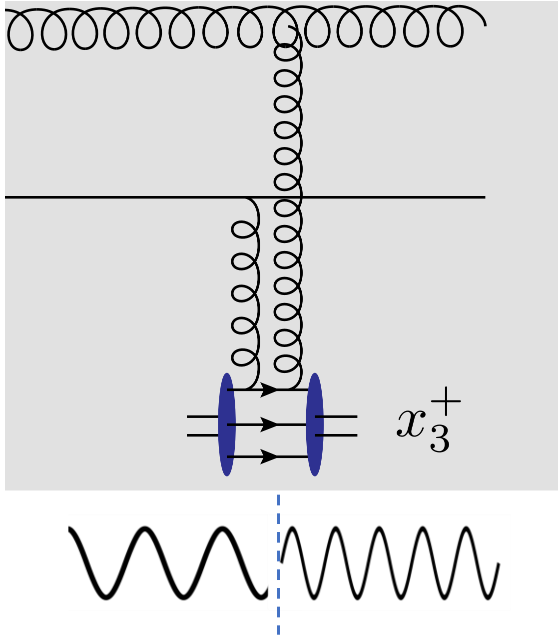
$$\frac{1}{\ell_f} = \frac{(\vec{k}_\perp - x\vec{p}_\perp)^2 + x^2 m^2}{2x(1-x)E}$$

- **Edge phases** of the emission region



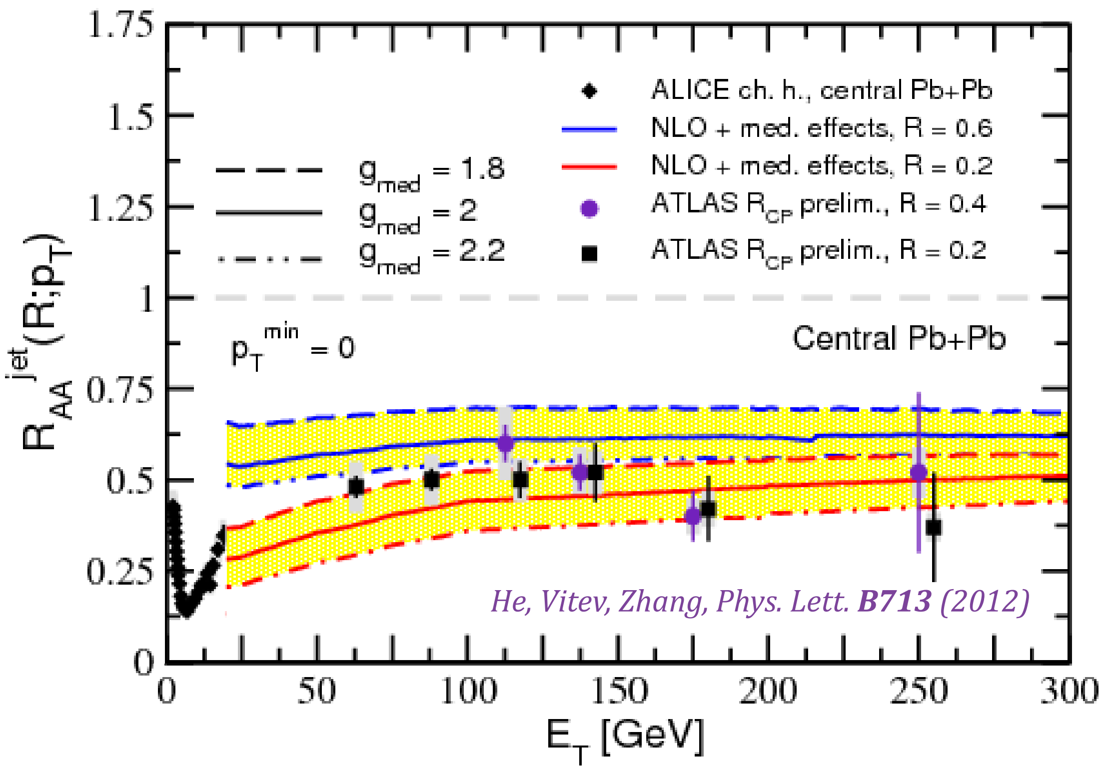
$$e^{i(z_1 / \ell_f)} - e^{i(z_2 / \ell_f)}$$

- **Phase slip** from scattering

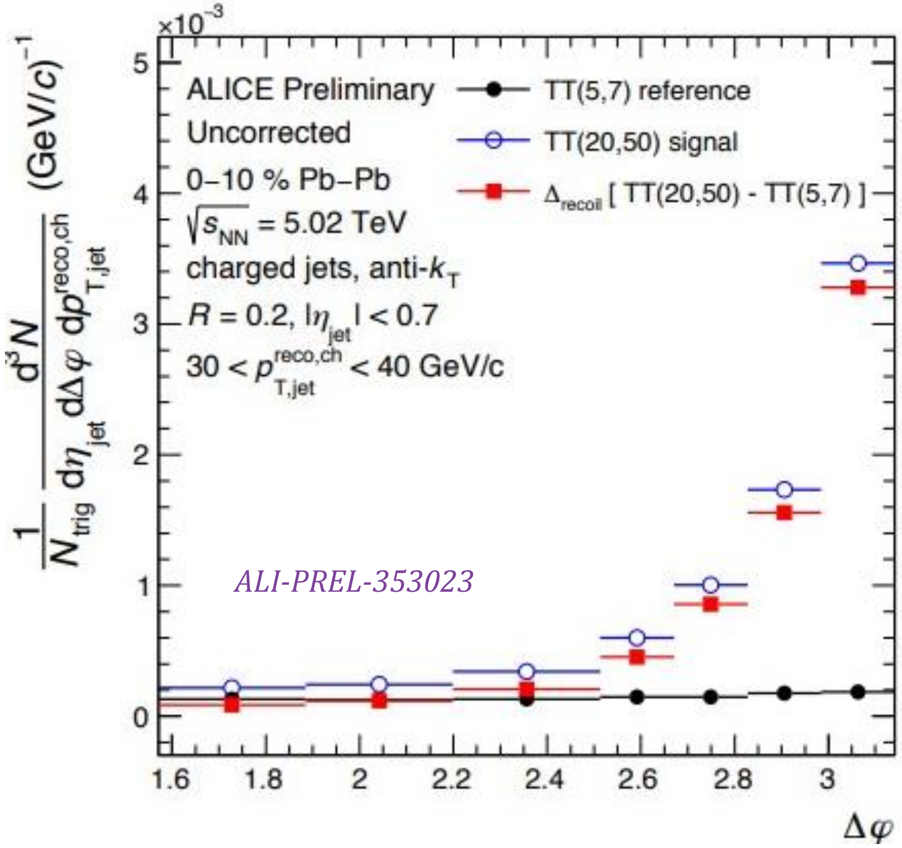


$$e^{i\, z_3\, (1 / \ell'_f - 1 / \ell_f)}$$

Canonical Signatures of Medium Modification



He, Vitev, Zhang, Phys. Lett. ***B713*** *(2012)*

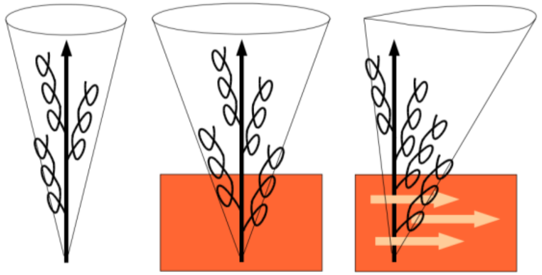


ALI-PREL-353023

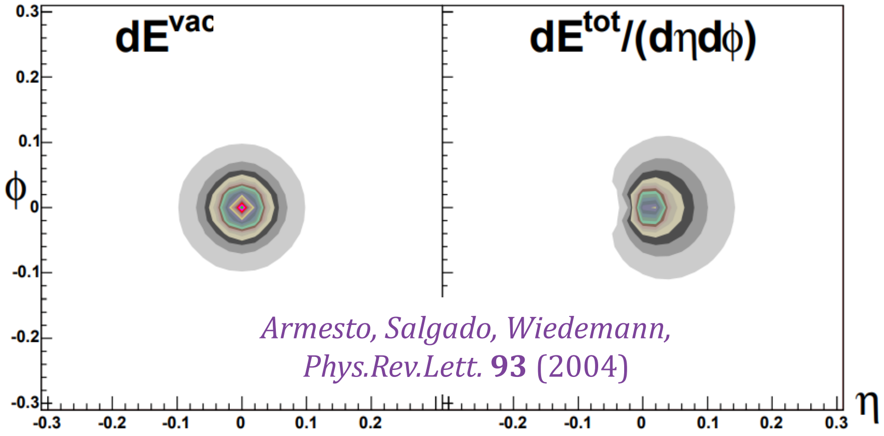
- **Energy Loss**
  - Jet quenching, γ+jet imbalance …
- **Transverse Momentum Broadening**
  - Dijet / γ+jet acoplanarities …

Asymmetric Measures of Medium Modification

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



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

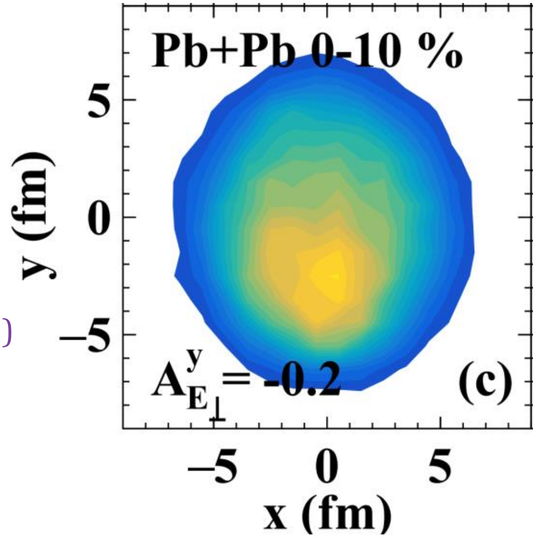


Armesto, Salgado, Wiedemann, Phys.Rev.Lett. **93** (2004)

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

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

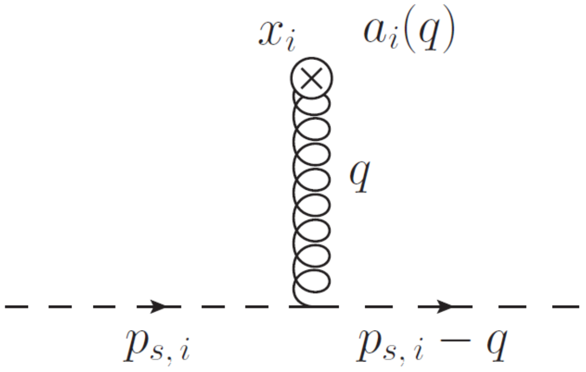
He, Pang, Wang Phys.Rev.Lett. **125** (2020)



Velocity Corrections in the Opacity Expansion

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

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



Fully relativistic velocity

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

Velocity-dependent potential

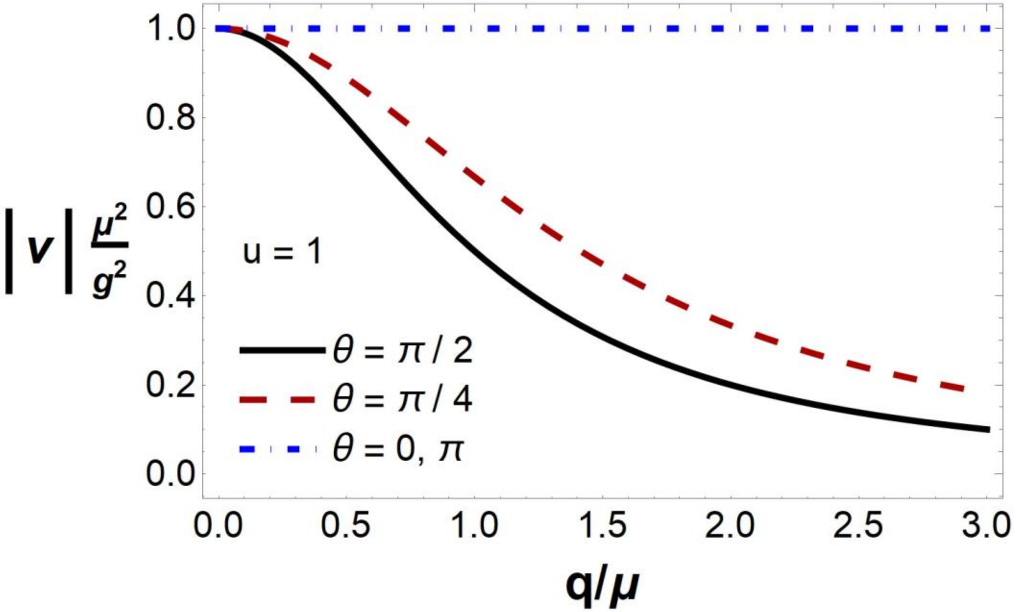
$$v(\vec{x}_i,\vec{q}) = \frac{-g^2}{\vec{q}^2 + \mu^2 - \left(\vec{u}(\vec{x}_i)\cdot\vec{q}\right)^2 - i\epsilon}$$

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

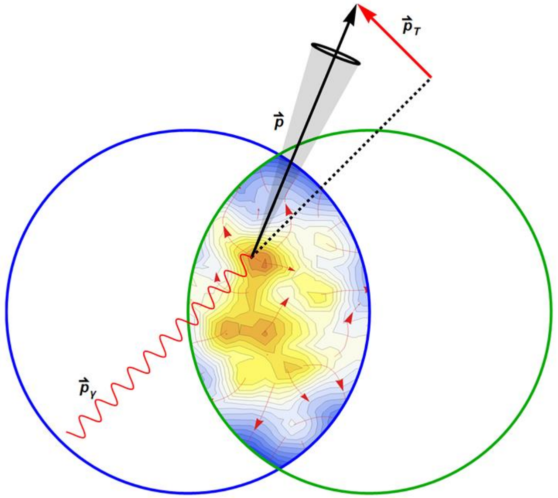
- Keep **sub-eikonal, velocity-dependent corrections** to the Gyulassy-Wang potential

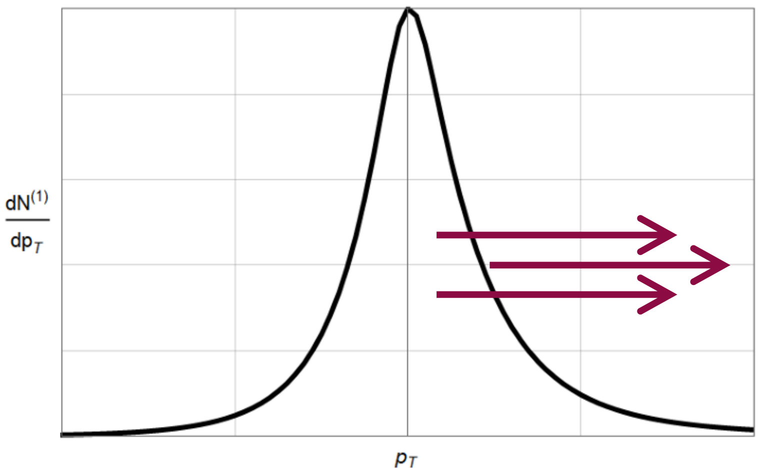
  *Gyulassy, Wang, Nucl. Phys. **B420** (1994)*

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



Jet Drift: Skewed Acoplanarities





$$\frac{dN^{(1)}}{d^3p_\gamma\, d^3p} = \int_0^L \frac{dt}{\lambda(t)} \int d^2q_T\, \hat{\sigma}(q_T^2, t)\left[\left(\frac{dN^{(0)}}{d^3p_\gamma\, d^2(p-q)_T\, dE}\right)\left(1+\vec{u}_T(t)\cdot\vec{\Gamma}(\vec{q}_T, t)\right) - \left(\frac{dN^{(0)}}{d^3p_\gamma\, d^2p_T\, dE}\right)\left(1+\vec{u}_T(t)\cdot\vec{\Gamma}_{DB}(\vec{q}_T, t)\right)\right]$$

Sub-eikonal vertex

Shifted potential

Energy Shift

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

Acoplanarities and Moments

- Assuming: Gyulassy-Wang potential, initial "pencil jet," LO initial distribution

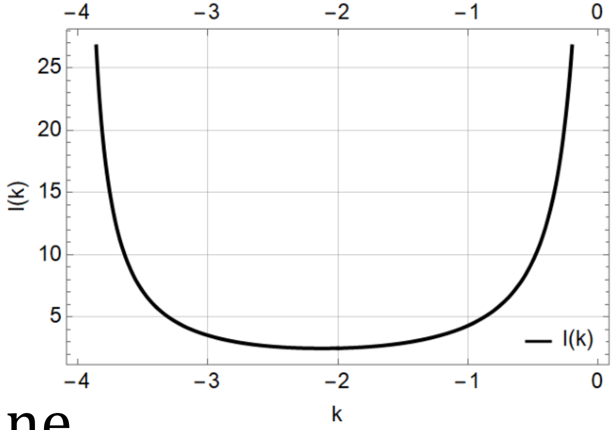
Jet drift: *sub-eikonal, antisymmetric*

$$\frac{dN^{(1)}}{d^2p_T} = \frac{1}{\pi} \int \frac{dt}{\lambda(t)} \frac{\mu^2(t)}{(p_T^2 + \mu^2(t))^2} \left[1 + \frac{\vec{u}_T(t) \cdot \vec{p}_T}{(1 - u_\parallel(t))\, E} \left(\frac{6p_T^2 + 4\mu^2(t)}{p_T^2 + \mu^2(t)} \right) \right]$$

- If the orientation of the **event plane is fixed (EPD)**, can measure the **net deflection of jets** relative to the event plane:

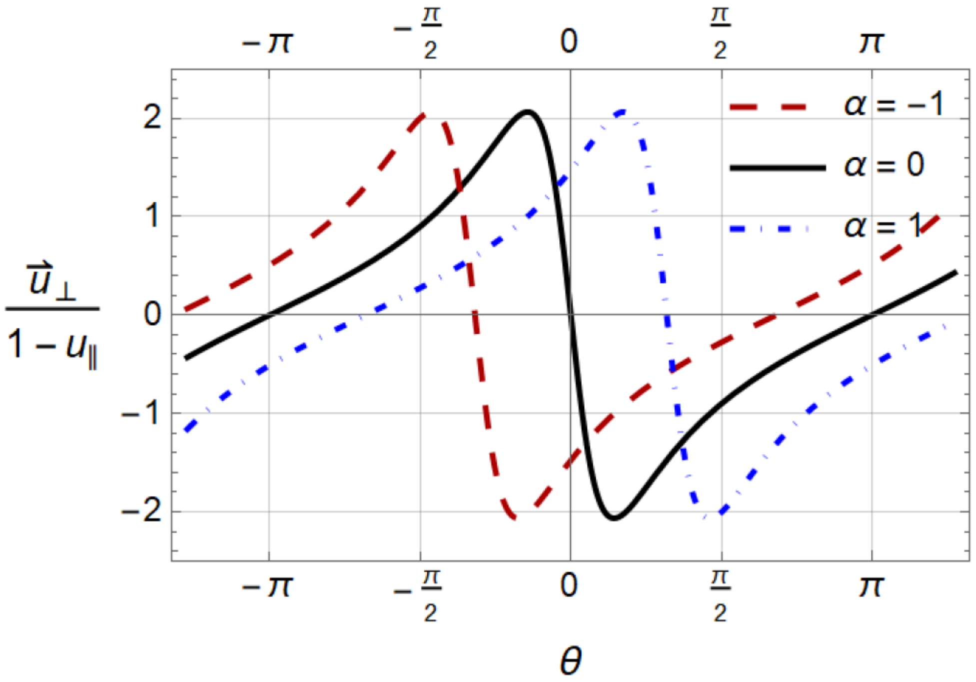
Antiporda, Bahder, Rahman, ***MDS****,*
Phys. Rev. ***D105*** *(2022)*

$$\langle \vec{p}_\perp \, p_\perp^k \rangle = \frac{I(k)}{E} \, \hat{e}_\perp \int \frac{dt}{\lambda(t)} \frac{u_\perp(t)}{1 - u_\parallel(t)} \mu^{k+2}(t)$$

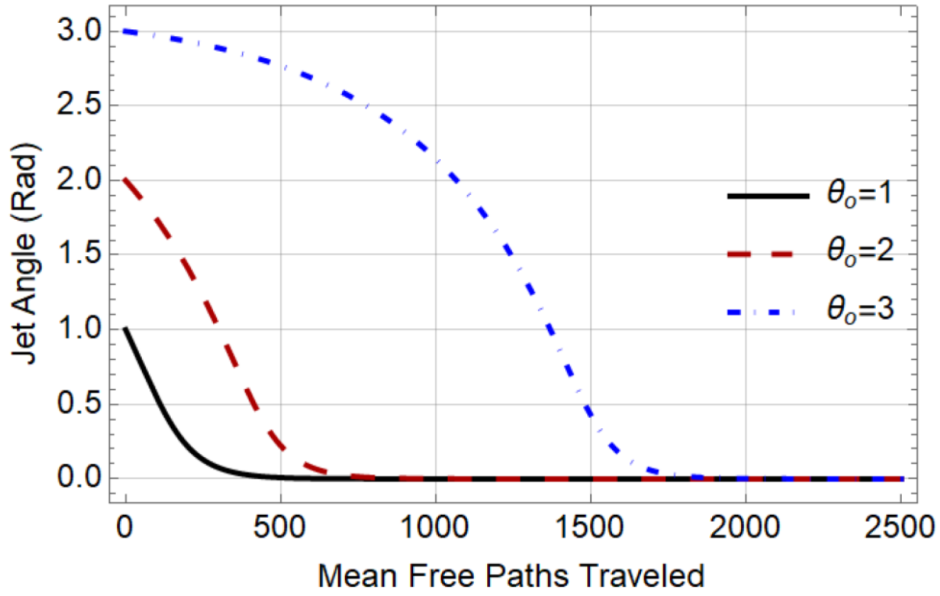


- Otherwise, look for **event-by-event correlations** with event plane

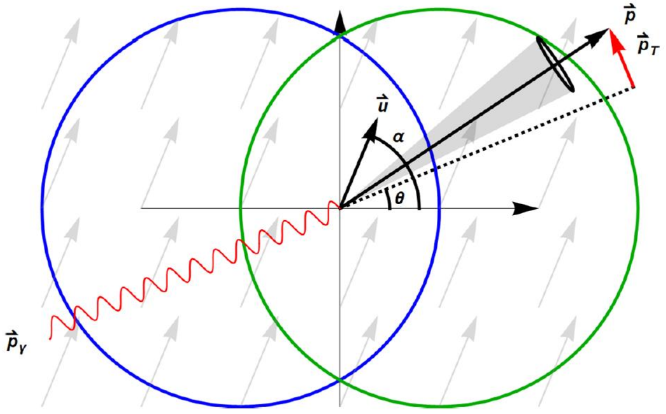
Simplest Case: The Constant Flowing Slab



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



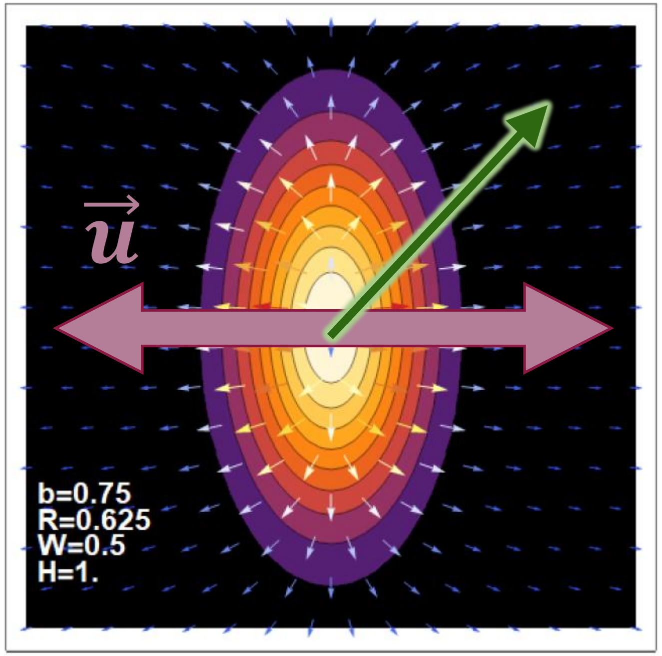
- Take all medium properties to be **constant** (“brick” / “slab”)
- Drift controlled by $u_\perp, u_\parallel$: detailed **tomographic information**
- Flow direction acts as an **attractor for jet trajectories**



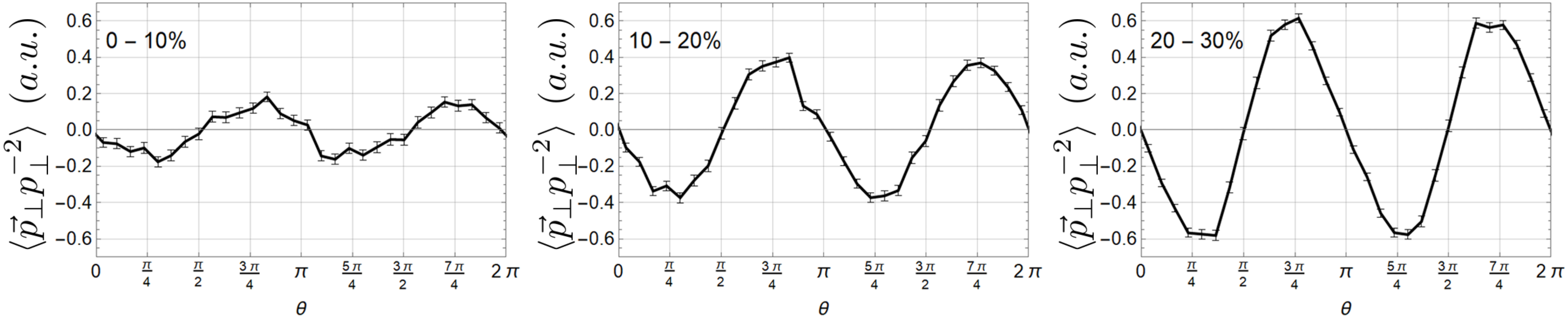
Gaussian Toy Model (Optical Glauber)

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

- Assume **Gaussian temperature profile**;
- **Shape fluctuates** with impact parameter;
- **Velocities** proportional to temperature **gradients**



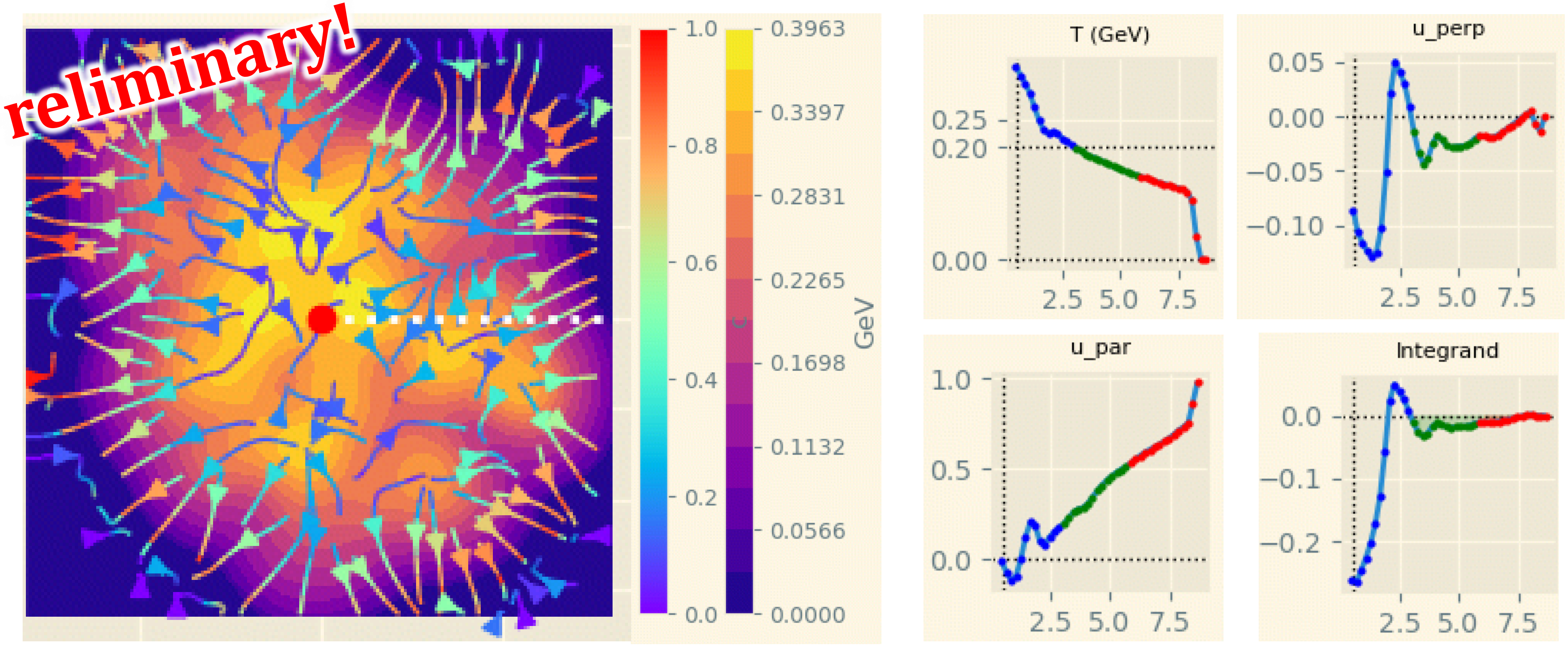
- **Elliptic flow** manifests **cos 2θ acoplanarity modulation**
- **Positive correlation** with **ellipticity ε_2** (centrality)
- **Robust event-plane correlation** despite fluctuations



2+1D Viscous Hydrodynamics

RHIC:
AuAu
200 GeV
0-10%

20 GeV jet



- Hydro backgrounds generated by Duke QCD event generator

  github.com/Duke-QCD/hic-eventgen

  - 2014 HotQCD lattice EOS

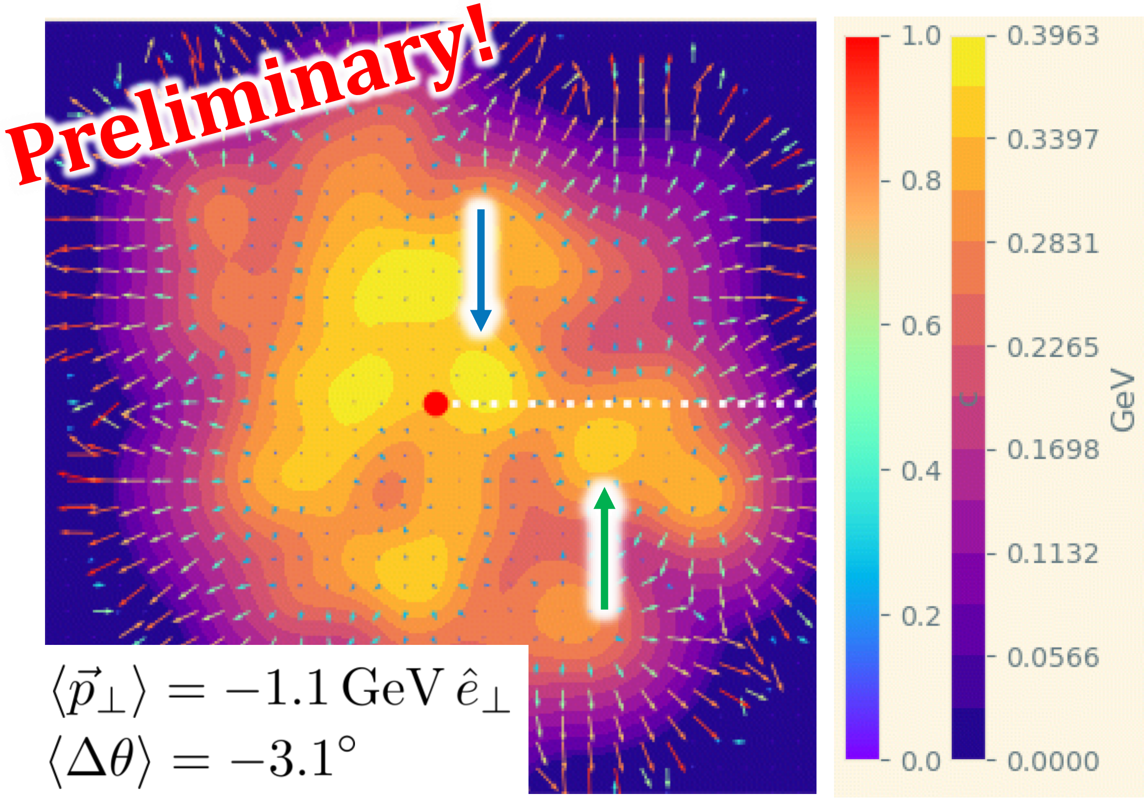
    Bazavov et al., Phys. Rev. ***D90*** *(2014)*

- Jets generated by binary collision sampling or by hand

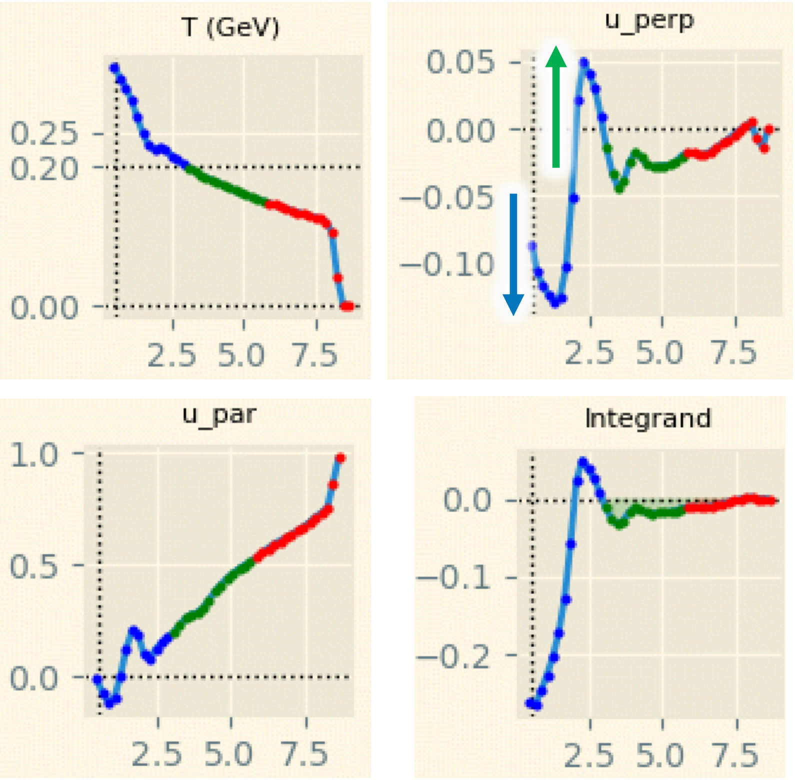
An Example: Radial Jet in a Central Event at RHIC

RHIC:
AuAu
200 GeV
0-10%

20 GeV jet



$$\langle \vec{p}_\perp \rangle = -1.1\,\mathrm{GeV}\,\hat{e}_\perp$$
$$\langle \Delta\theta \rangle = -3.1^\circ$$

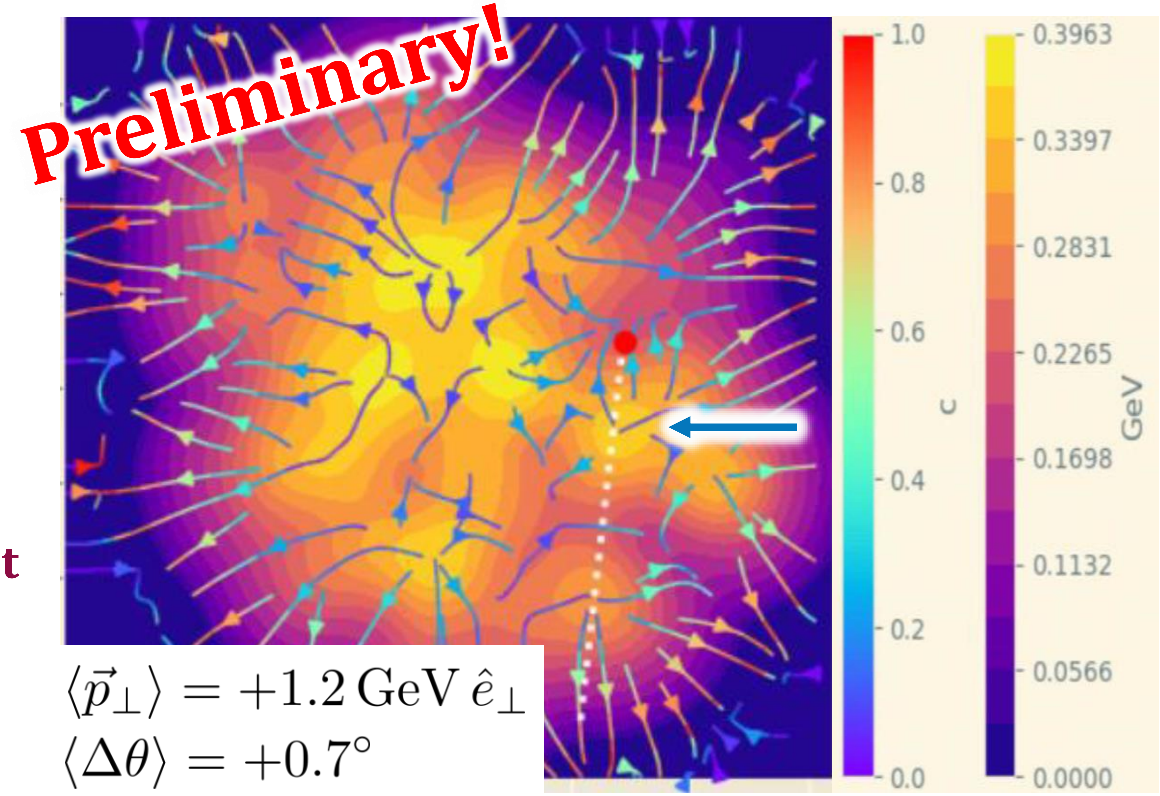


- Jet receives **transverse kicks** from passing **near hot spots**
- **No systematic drift** in either direction
- **Sizeable net deflections** ~several degrees for ~20 GeV jets

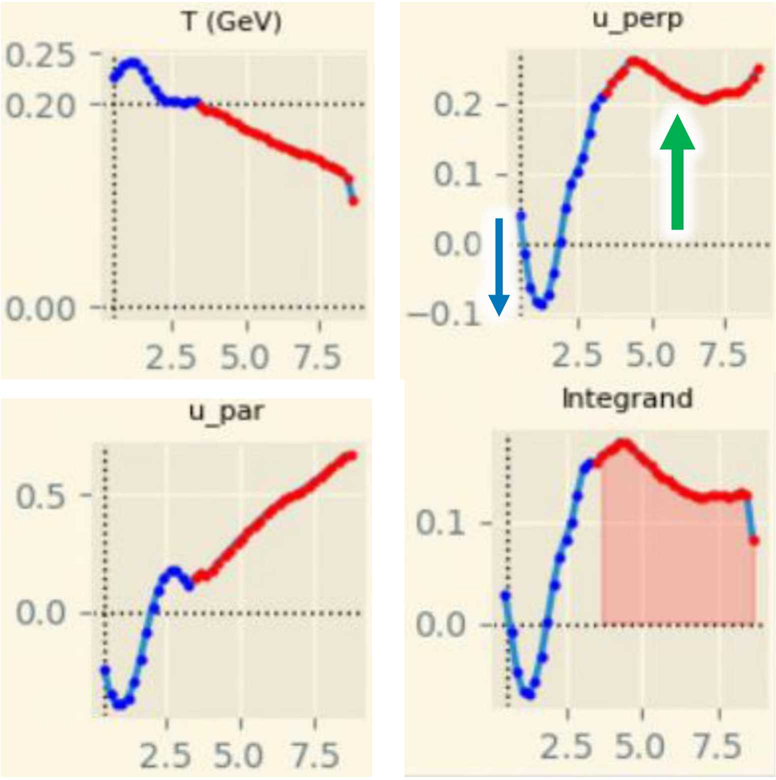
An Example: Tangent Jet in a Central Event at the LHC

LHC:
PbPb
5.02 TeV
0-10%

100 GeV jet

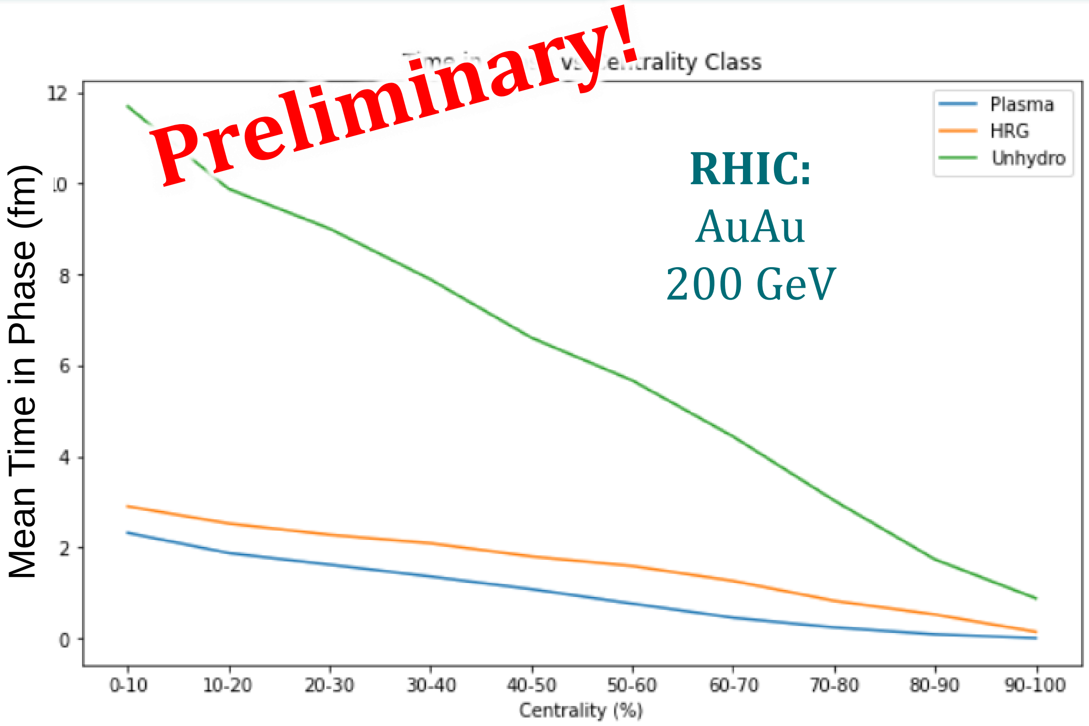


$$\langle \vec{p}_\perp \rangle = +1.2\,\mathrm{GeV}\,\hat{e}_\perp$$
$$\langle \Delta\theta \rangle = +0.7^\circ$$



- **Early** CW kick from **hot spot**; **late** systematic CCW drift from **radial flow**
- **Competition** between **falling temperature** and **rising velocities**
- **Tangent jets** which “surf the edge” of the plasma **benefit from both factors**

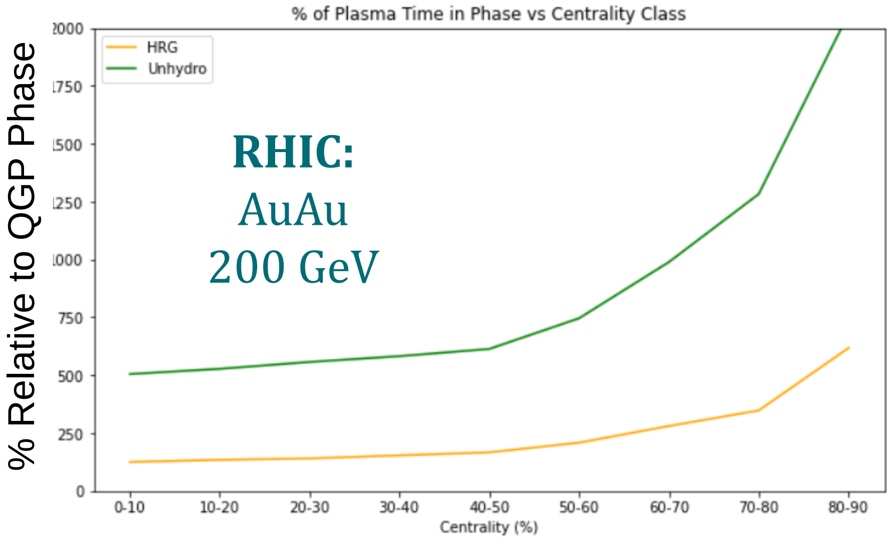
A Surprise…



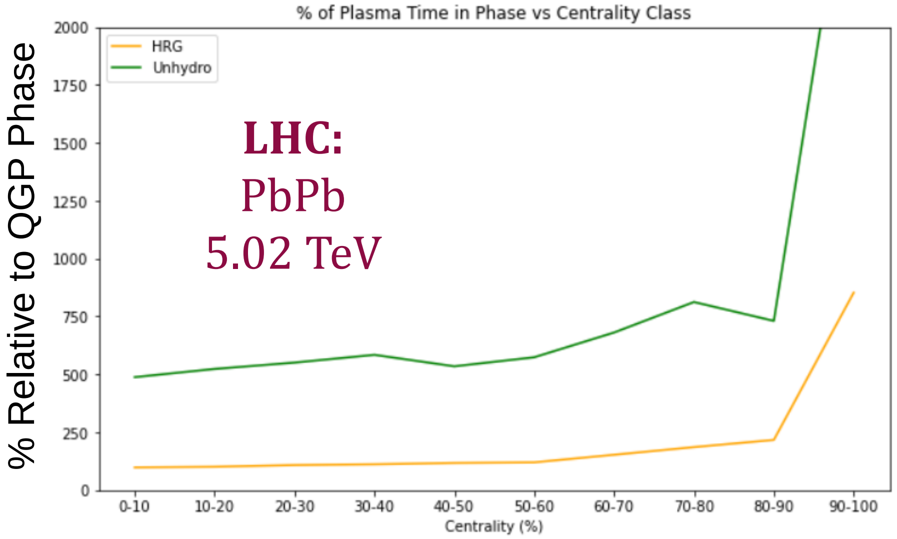
RHIC:
AuAu
200 GeV

- Jets spend **large amounts of time** in the **HRG phase** $T < T_c \sim 200\ MeV$ and in the **"unhydrodynamic" phase** $T < T_{FO} \sim 150\ MeV$

❖ **Comparable** lifetime **ratios** at RHIC and LHC!



RHIC:
AuAu
200 GeV



LHC:
PbPb
5.02 TeV

General Observations

Preliminary!

- For ~20GeV jets at RHIC, we observe **sizeable deflections** of up to ~**6°** from the **plasma phase alone**, $T > 200$ MeV
  - **Even larger contributions** if one extrapolates down into the **HRG or "unhydrodynamic" phases** (where the physics should greatly change)

- The jet drift effect appears to be **largest in central collisions** and **decreases with increasing centrality**
  - **Opposite** to what was observed for the Gaussian toy model
  - **Competing roles** of **temperature** and **ellipticity**
  - Disentangle with **selection cuts**?

Outlook: Much More to Come!

- Beginning a large-scale statistical analysis:
  - ➢ Initial acoplanarities from Pythia
  - ➢ Use of selection cuts (e.g., event-shape engineering) to maximize the jet drift signal and to disentangle competing effects (temperature vs. geometry)
  - ➢ Comparison of observables: γ+jet vs dijets, etc.

- Further theoretical developments:
  - ➢ Gradient treatment on the same footing
  - ➢ Fully reconstructed jets

Barata, Sadofyev, Salgado, Phys.Rev. **D105** (2022)

Andres, Dominguez, Sadofyev, Salgado, arXiv: 2207.07141

- The Future.... **JETSCAPE ?**