9th Conference
on Chirality, Vorticity
and Magnetic Fields
in Quantum Matter

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Λ Polarization as a Probe of Jet-Induced Vorticity

Cicero Muncinelli, G. Torrieri, J. Takahashi, M. Lisa

Acknowledgments:
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Outline

1. The objects of interest – QGP vorticity rings
2. Our hydrodynamic model
3. How to correlate vorticity and polarization?
4. How to measure Λ polarization experimentally?
5. Correlating polarization and vorticity rings – The Ring Observable
6. Understanding the observable
7. Probing medium properties

The object of interest

QGP vorticity ring

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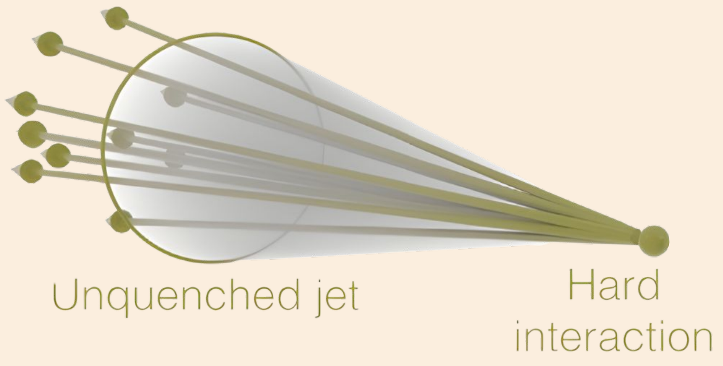
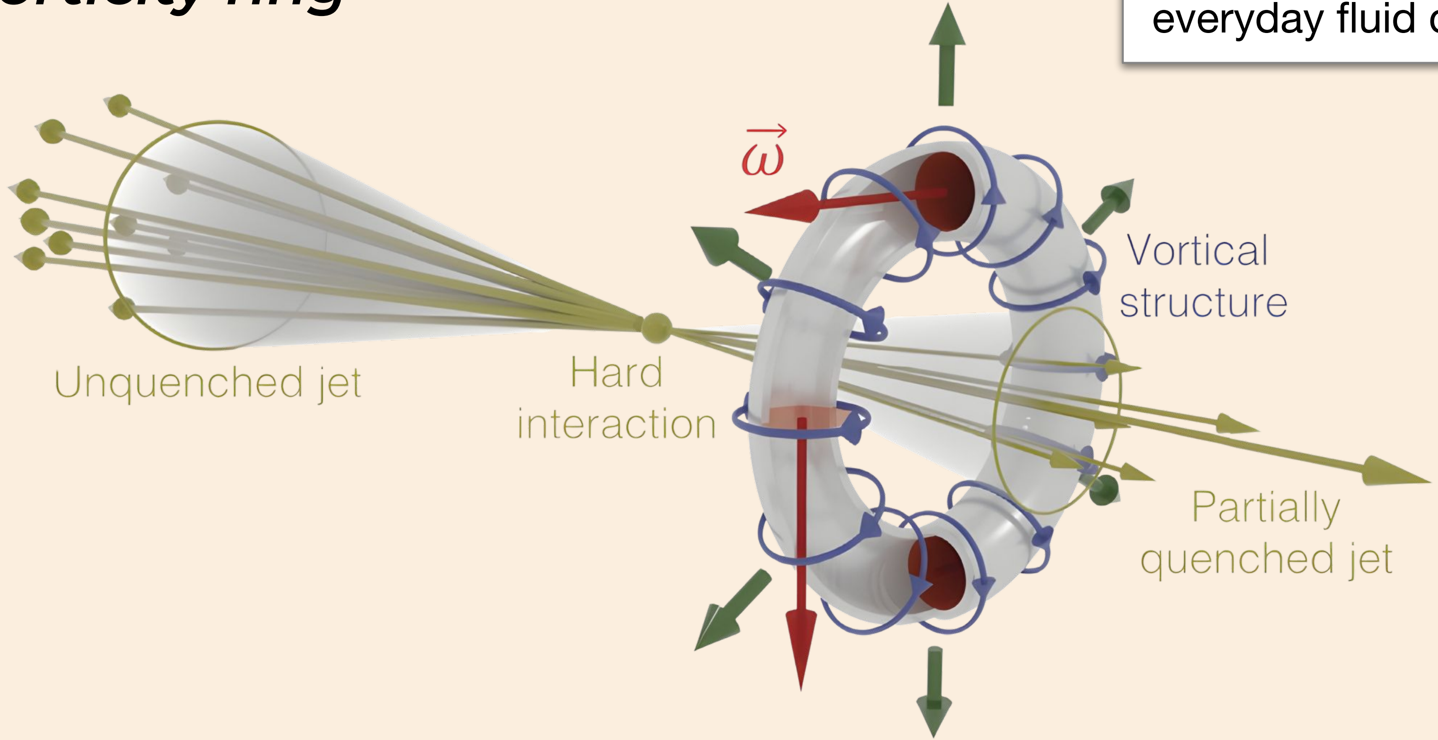


The object of interest
QGP vorticity ring

Formation of **toroidal "smoke rings"**, as in everyday fluid dynamics!



The tool

A hydrodynamic model

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TRENTo

- <u>**Initial condition**</u>
  generator (3D)

(PRC 92, 011901 (2015))

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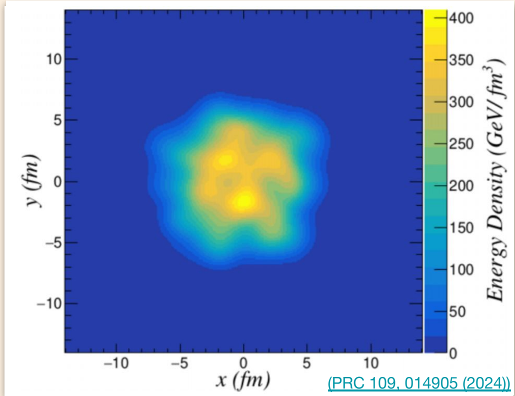

- Energy density for each IC (3D)

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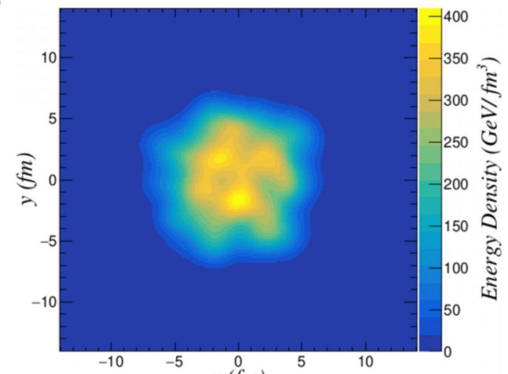

(PRC 109, 014905 (2024))

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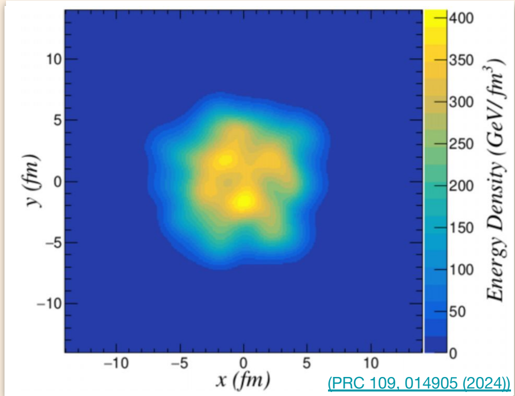

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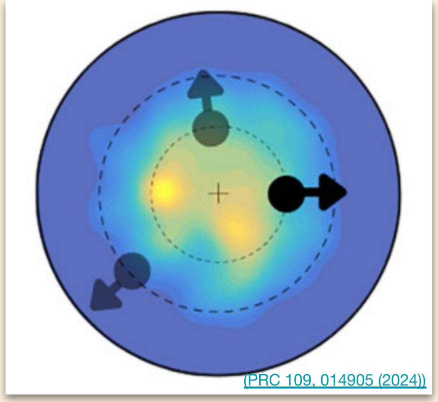
(PRC 82, 014903 (2010))



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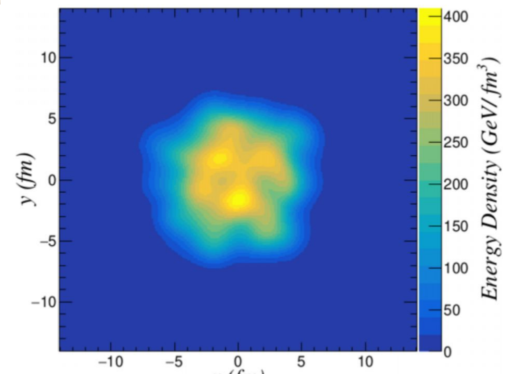

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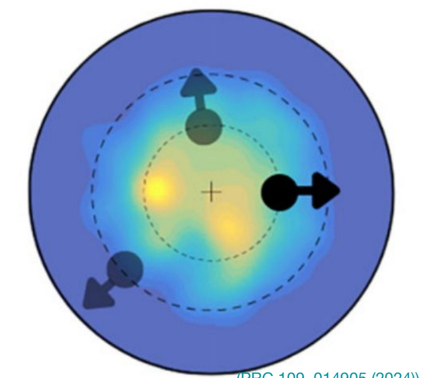

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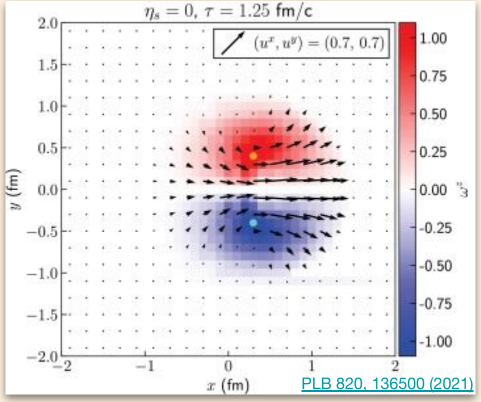

PLB 820, 136500 (2021)

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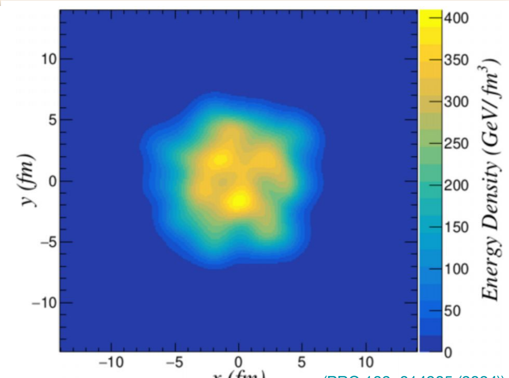
iSS

- **Hadronization**
- Vorticity-spin coupling

(CPC 199, 61(2016))



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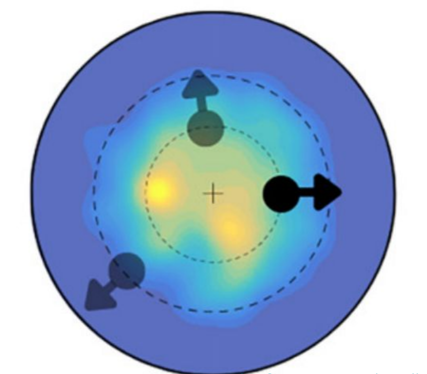
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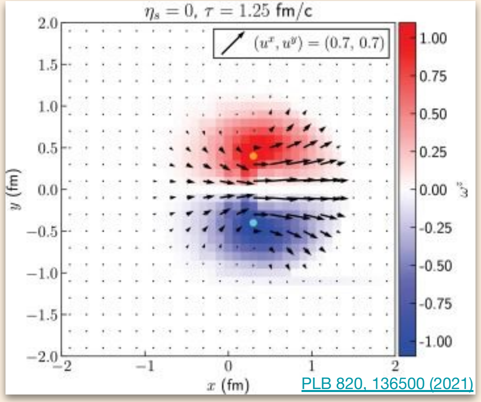

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Vorticity induces polarization

(Polarization carries vorticity information!)

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- Finally, the Λ polarization 4-vector is:

$$P^\mu_\Lambda(p) = \frac{S^\mu(p)}{\langle S\rangle}$$

with ⟨S⟩ = 1/2

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Measuring Λ Polarization

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Why use Λ?

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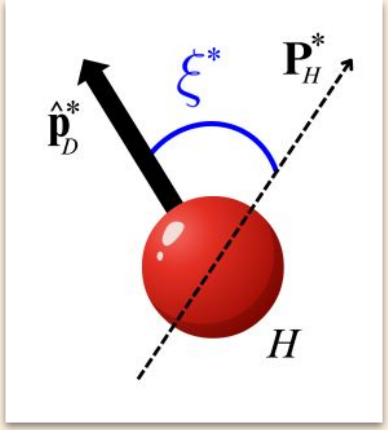

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- Parity violating weak-decay, with a daughter anisotropy:

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H P_H^* \cos\xi^*\right)$$

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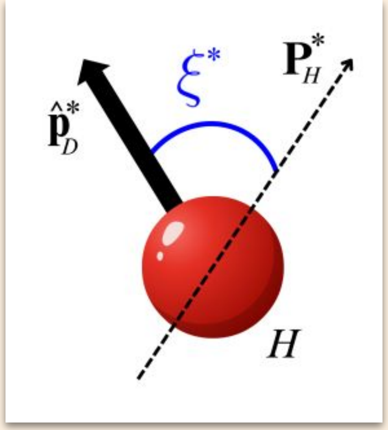

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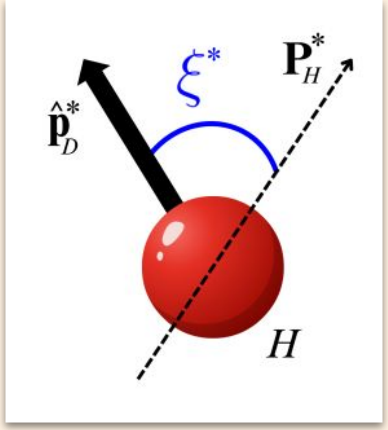

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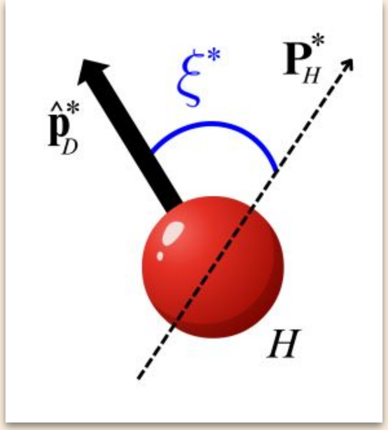
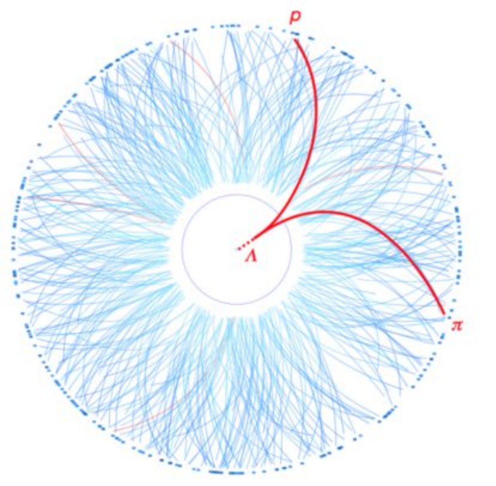
- Single decay vertex (easier to measure)





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- **For each particle**, the mean polarization along an arbitrary quantization axis ($\hat{n}$) is:

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$$P^\mu_{H,\mathrm{lab}} = \Lambda^\mu_{nu} \left(\langle p^\mu_\Lambda \rangle \right)\ P^\nu_{H,\mathrm{rest}}$$

where $\langle p_\Lambda^\mu \rangle$ is the mean 4-momentum of the Λ in the (p_T, y, ϕ, $\Delta\phi_J$) bin.

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$$\mathcal{R}^t_\Lambda \equiv \left\langle \frac{\vec{P}_\Lambda \cdot (\hat{t} \times \vec{p}_\Lambda)}{|\hat{t} \times \vec{p}_\Lambda|} \right\rangle_{p_T, y}$$

Where:

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Measures the component of polarization **circulating the jet**
(A signature of the "smoke ring")

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A simplistic bullet

$(x = y = \eta_s = 0;\ |y| < 0.5;\ \phi_J \in [0, 2\pi])$

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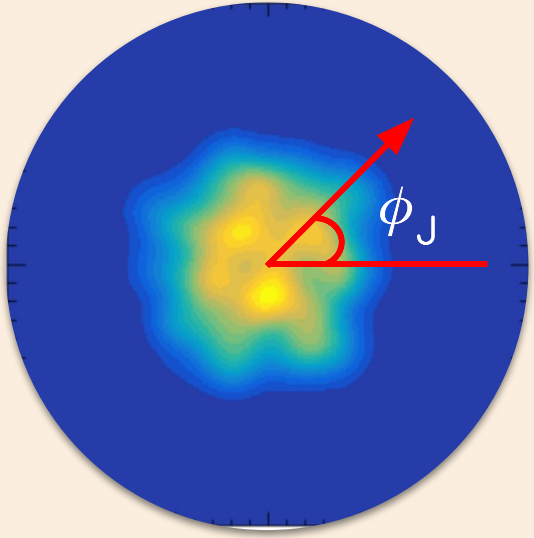
Uniformly distributed in ϕ



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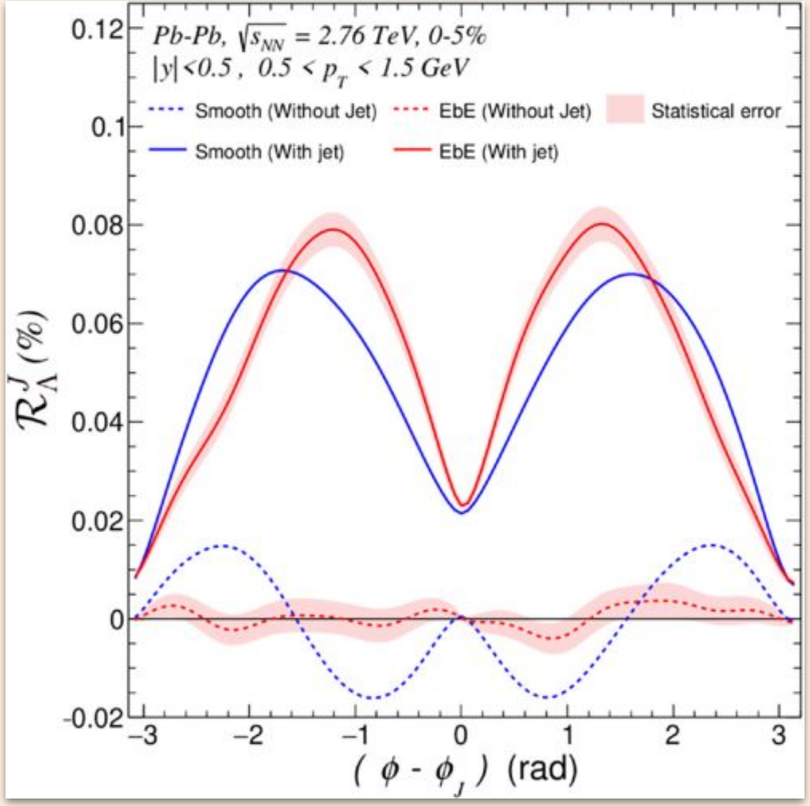

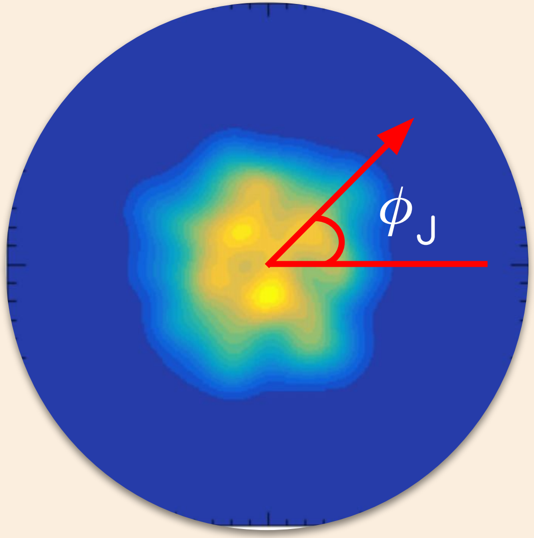

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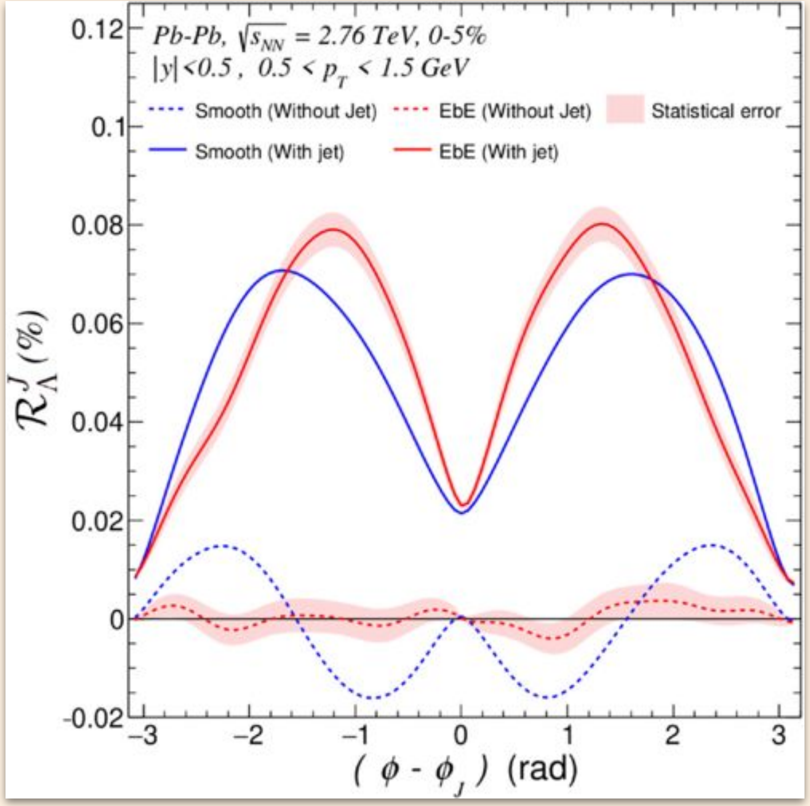

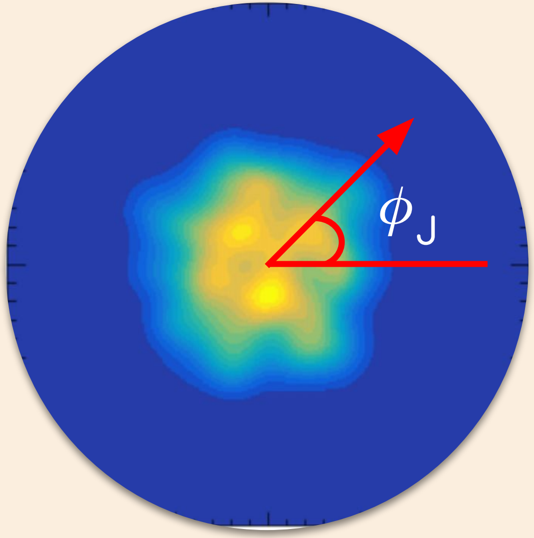

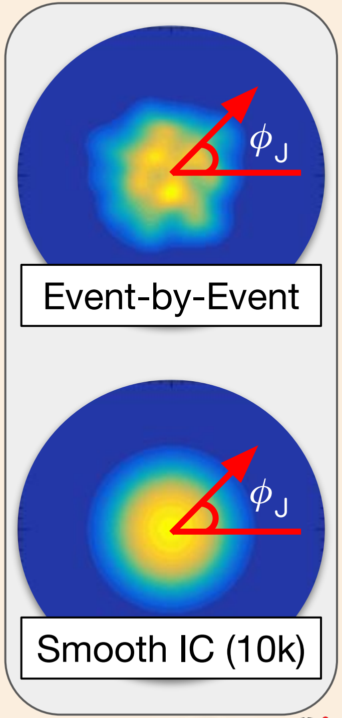

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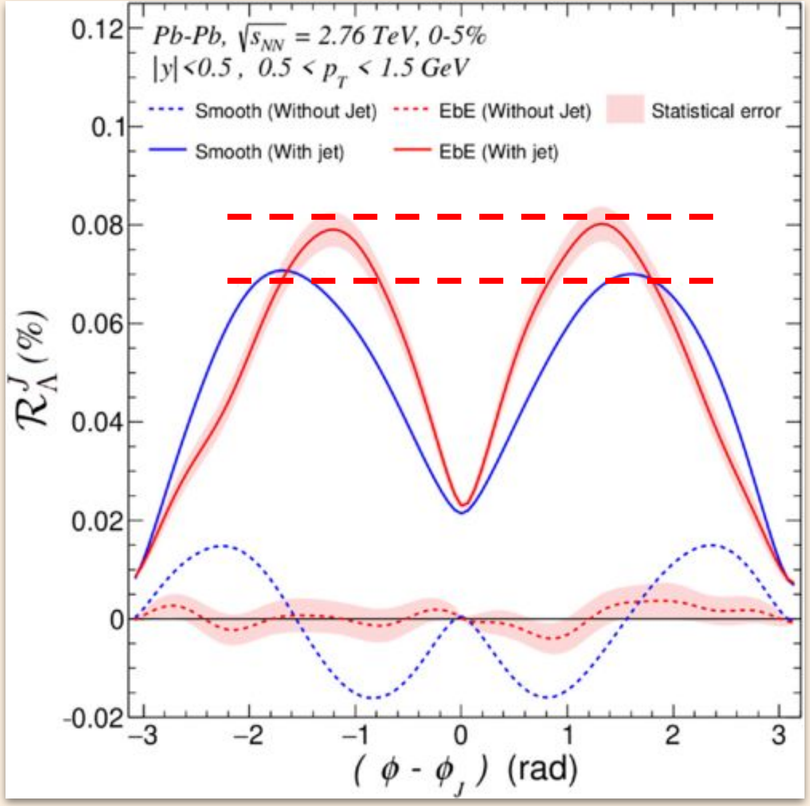
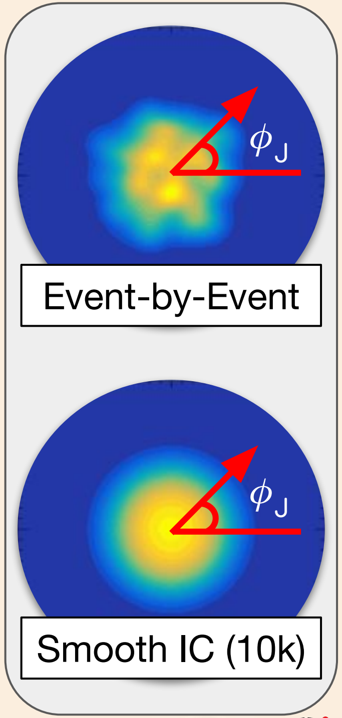


- **Smooth IC approximates well** (faster to compute!)



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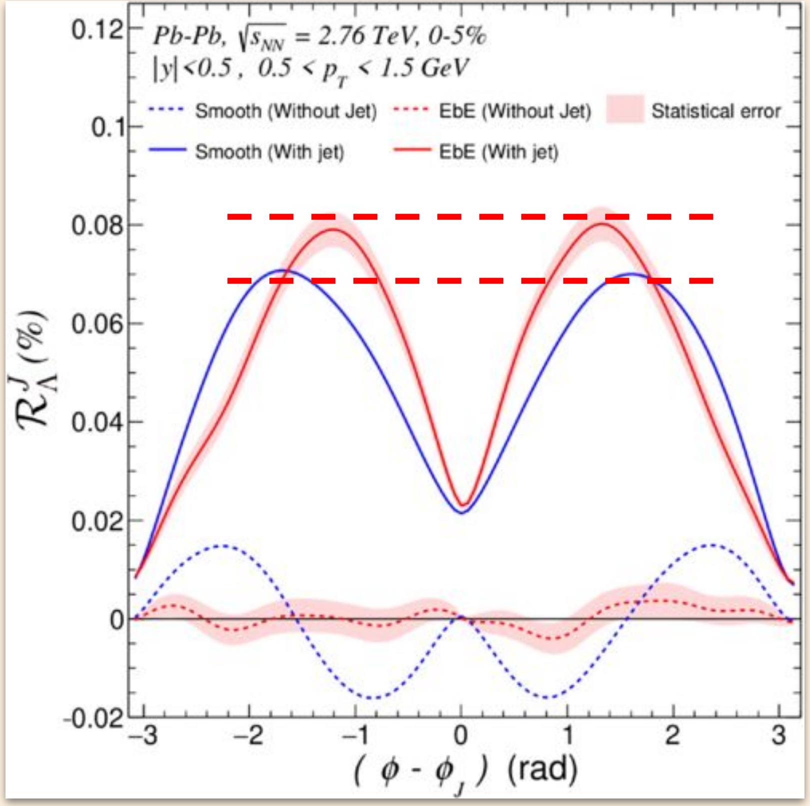

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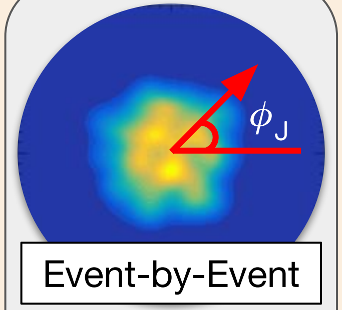

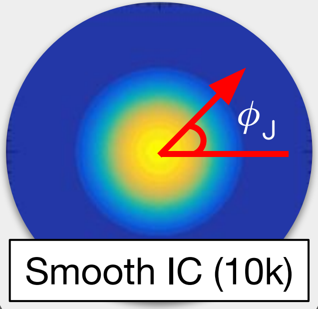

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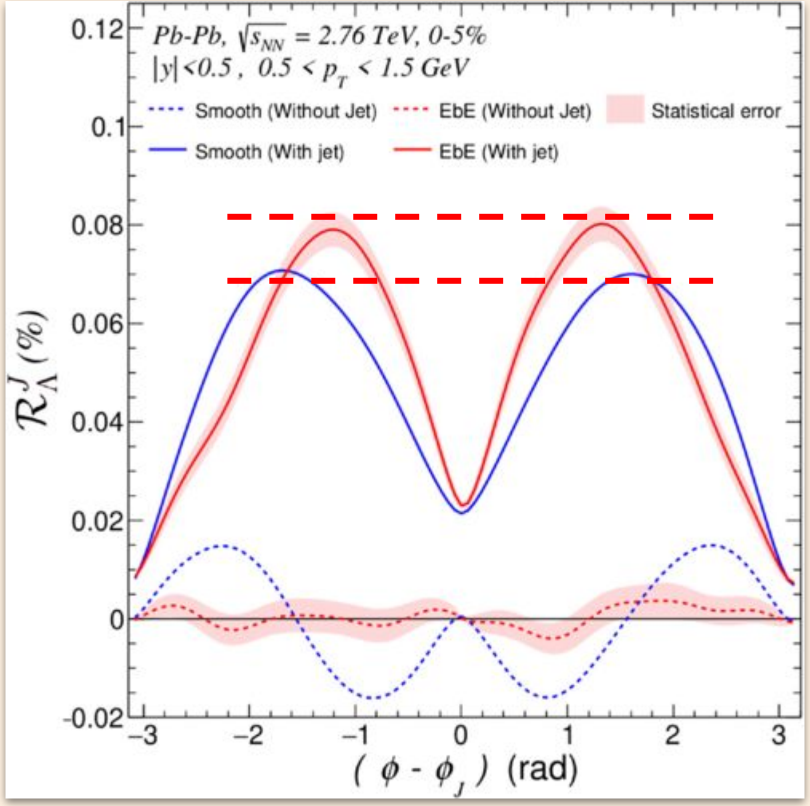

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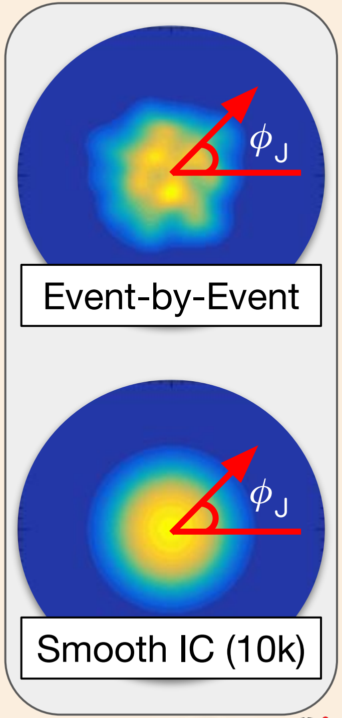
- **Clear distinction** between *With-jet* and *No-jet* events
- **Background signal integrates to zero** (polarization due to <u>RP expansion averages out</u> with the random ϕ_J trigger direction)



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(Free bullet radius)

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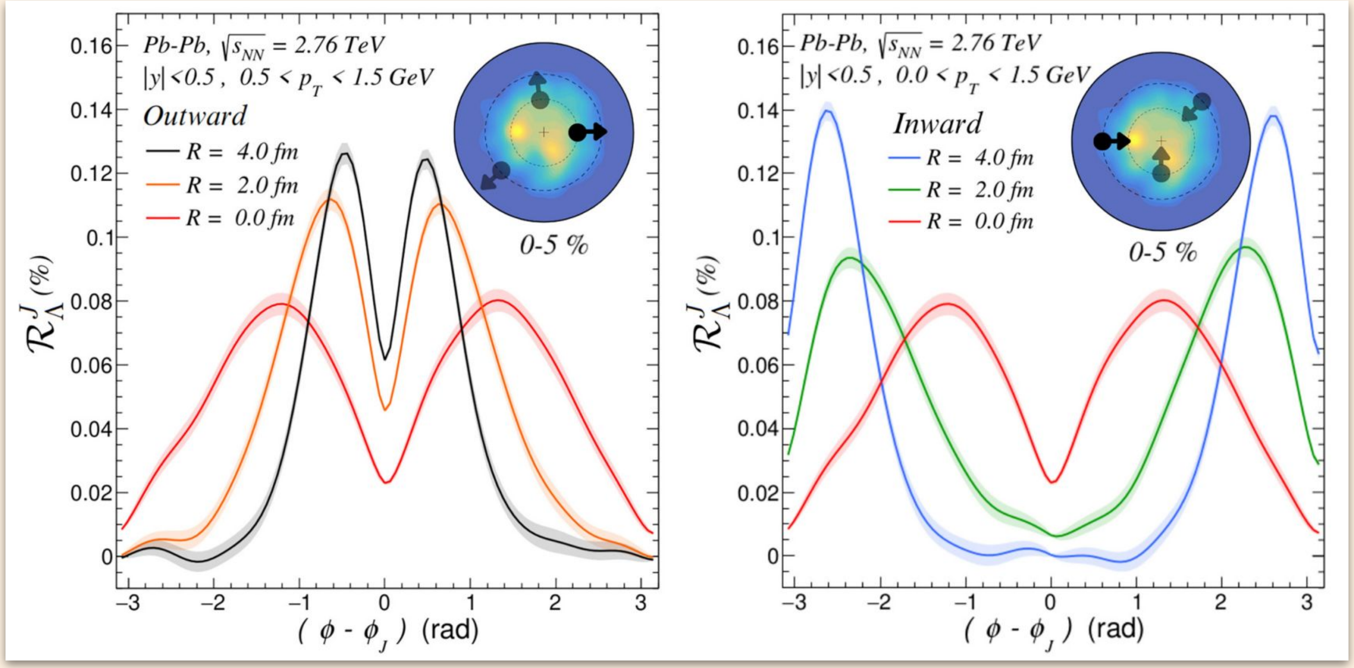

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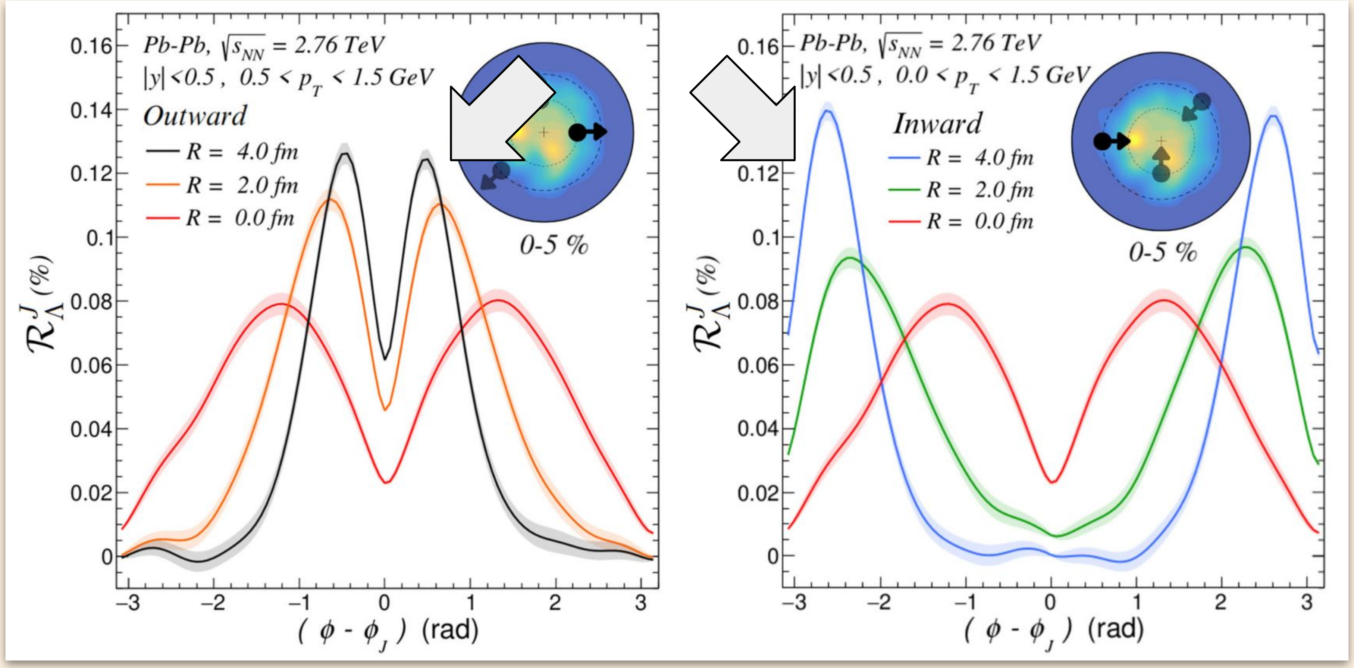

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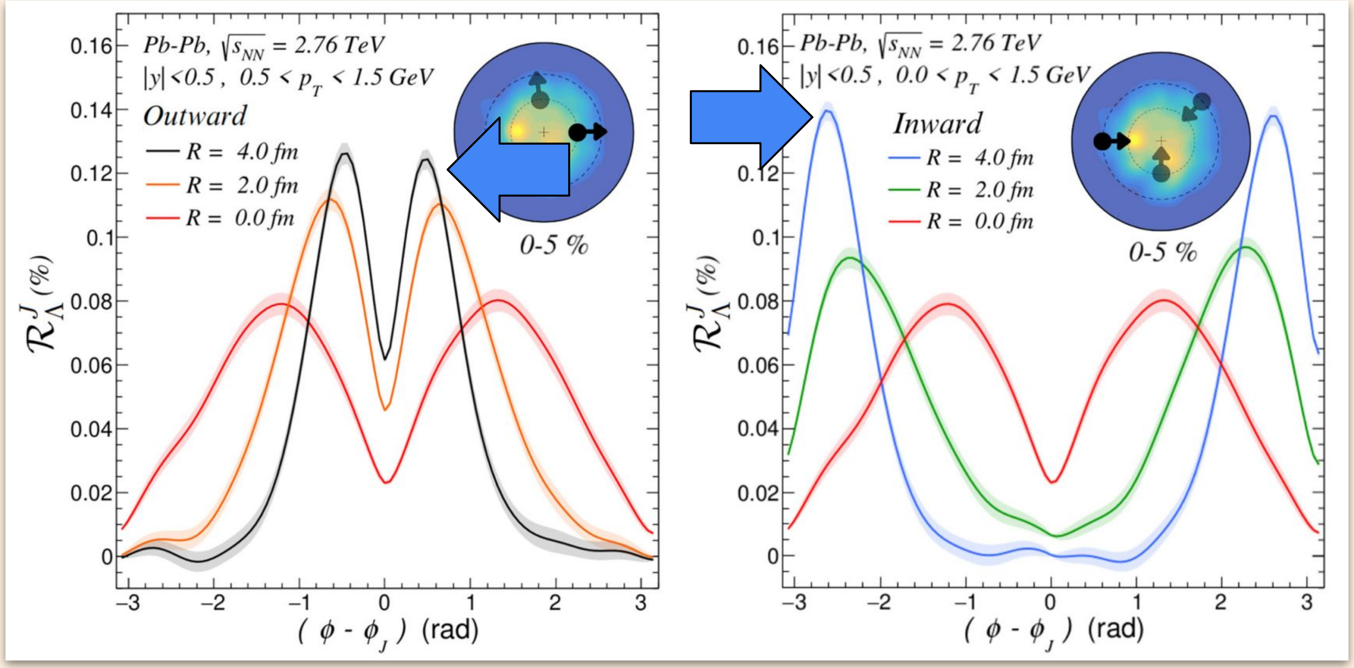

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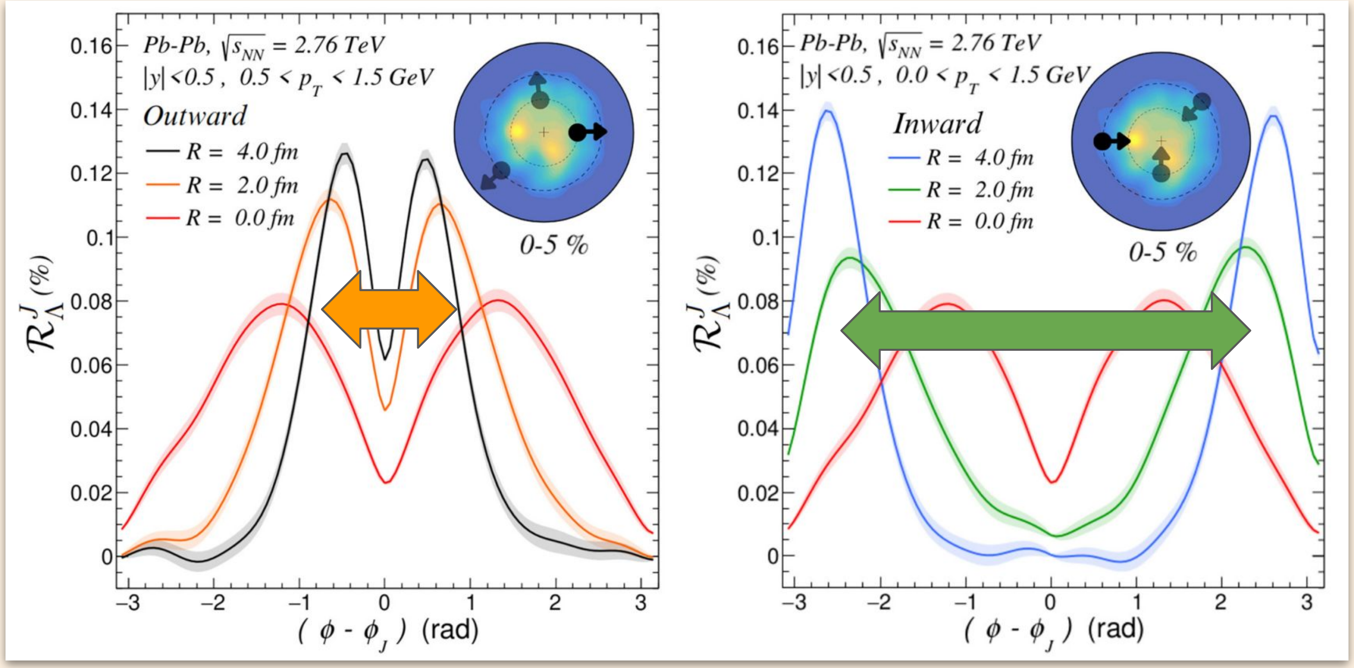

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- Deposition **against flow** leads to larger gradients and **larger polarization**
- **Angular aperture** is a proxy for **ring size**

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An even more realistic bullet

($|y| < 0.5; \phi_J = 0$)

(Free, mixed/unknown, bullet radii)

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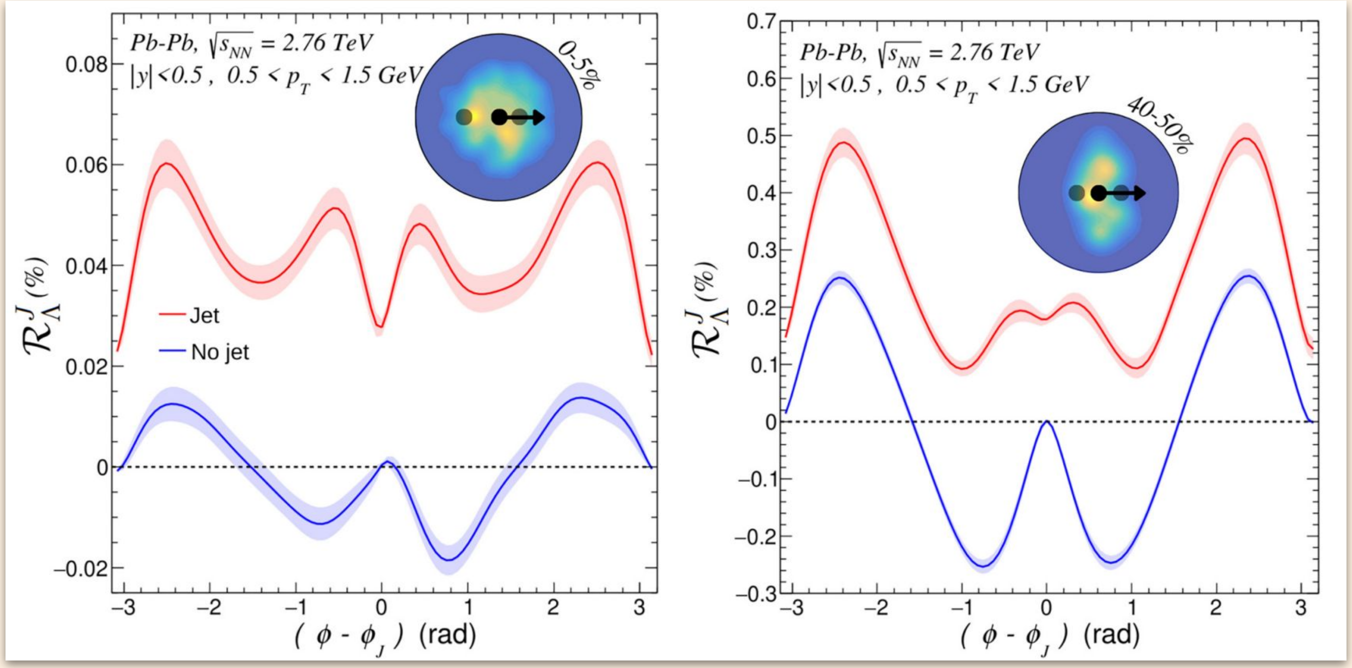

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An even more realistic bullet
(Free, <u>mixed/unknown</u>, bullet radii)

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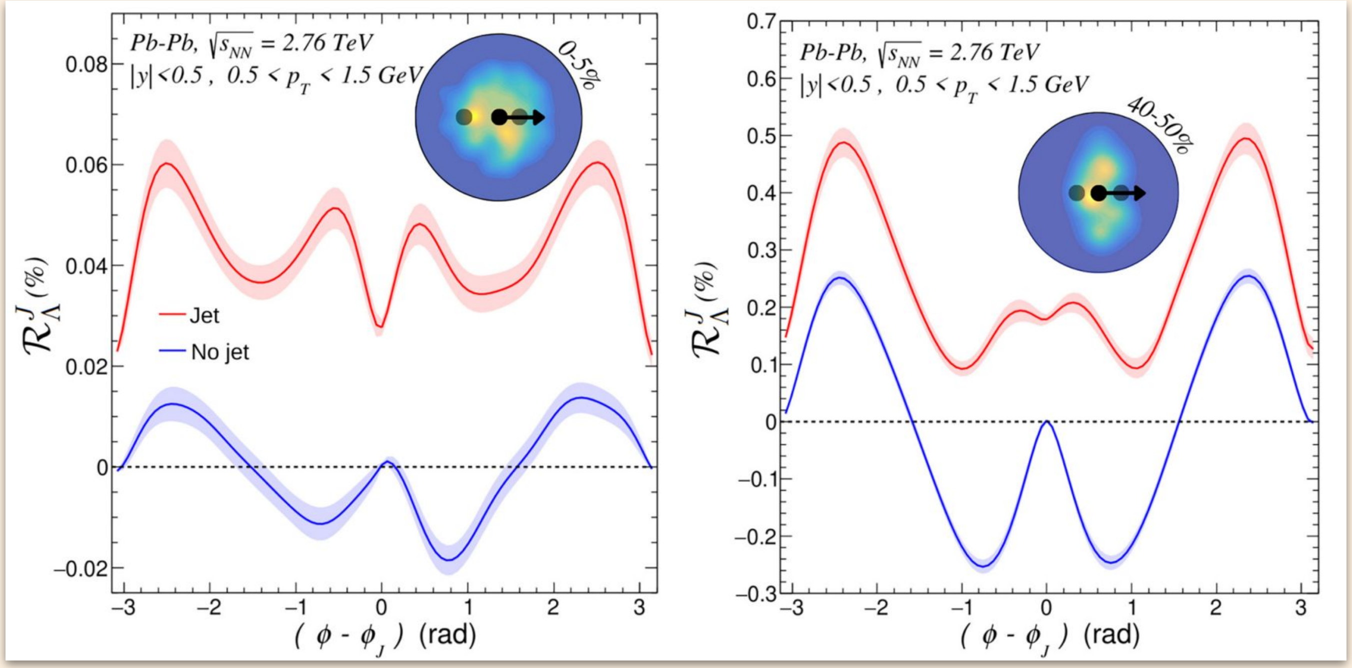

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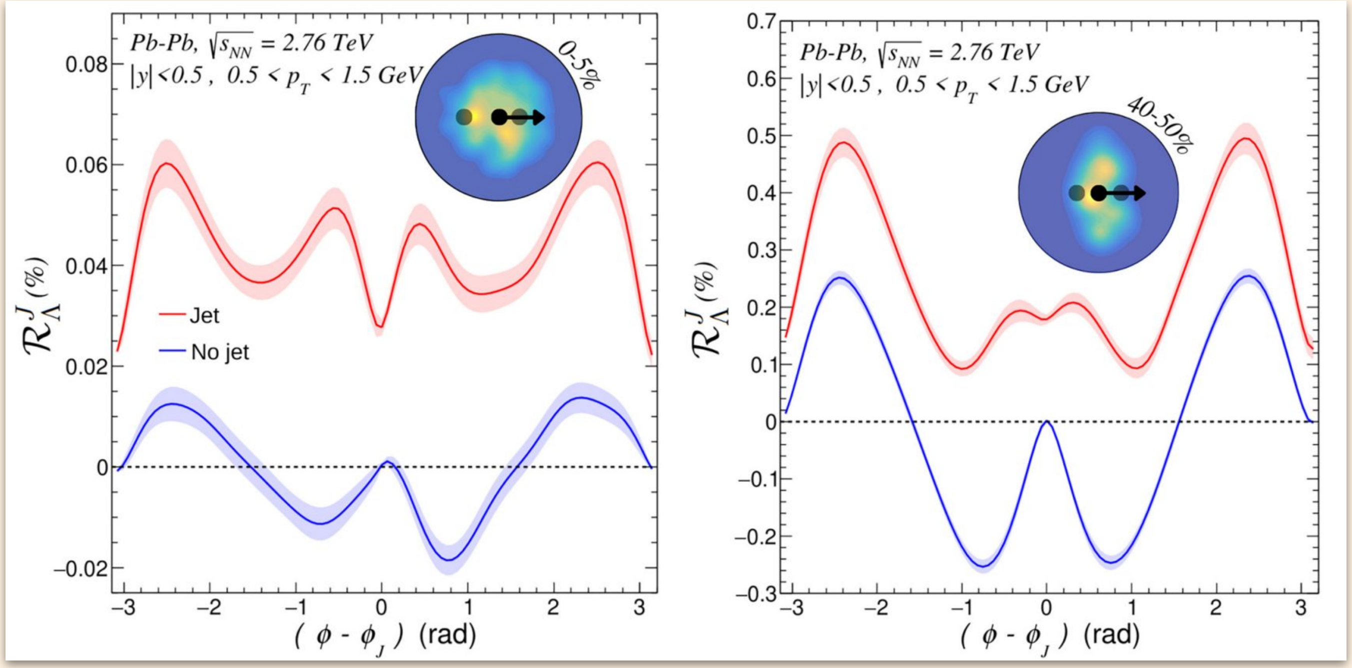

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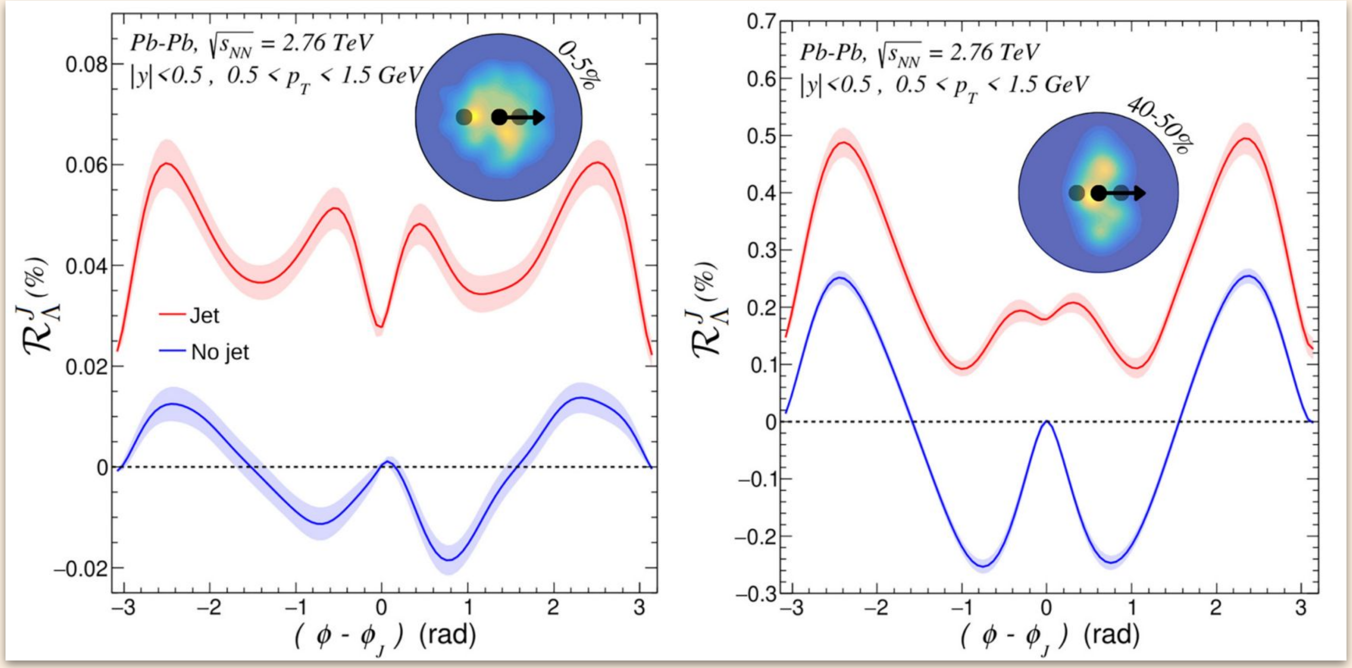

- Double peak signal is lost with the varying radii, but…
- **Integrated signal is consistently zero for background**, and **non-zero for jets**!
- Signal **increases with centrality** (shorter-lived fireball)

Probing QGP properties with polarization

(Integrated signal dependencies)

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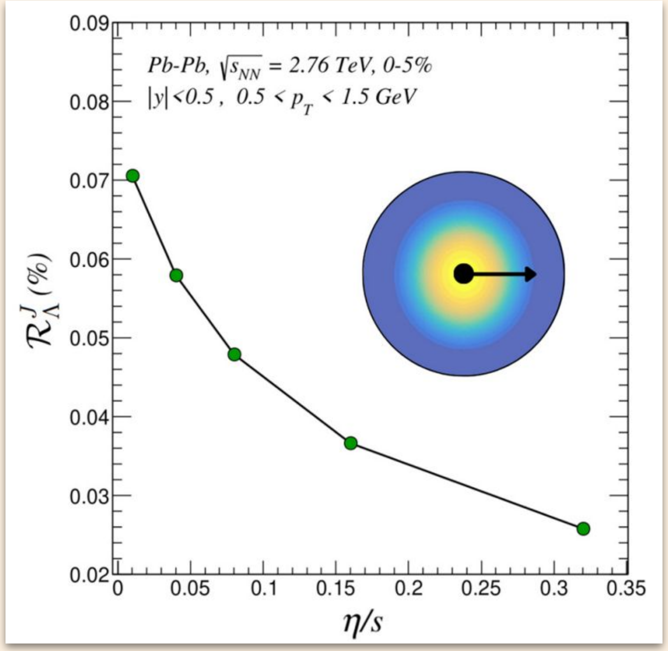
(Integrated signal dependencies)



Sensitiveness to **shear viscosity**:

- Stronger vortex-ring dissipation at higher viscosities

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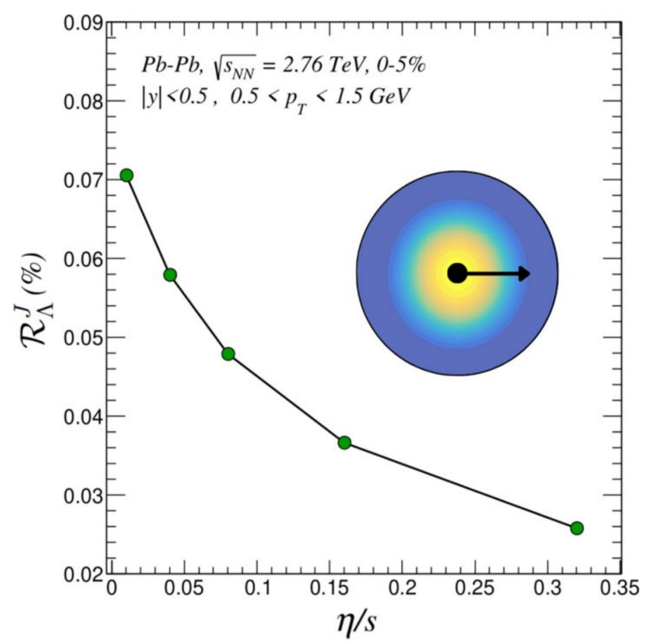
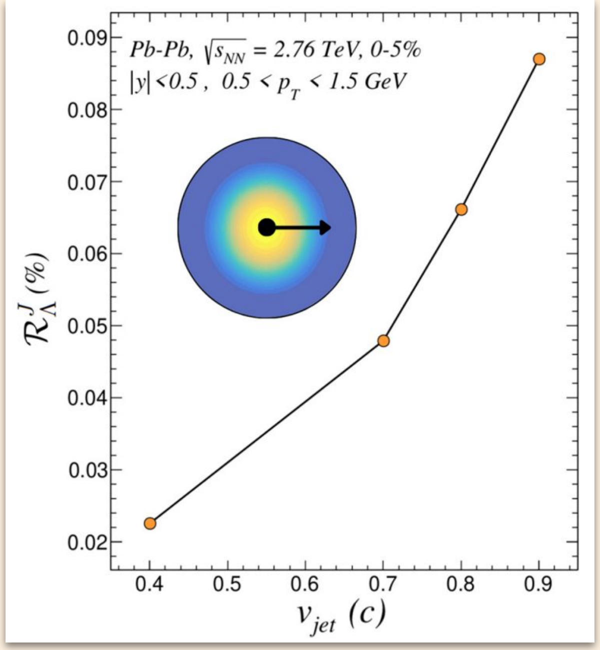


Sensitiveness to **shear viscosity**:

- Stronger vortex-ring dissipation at higher viscosities

Sensitiveness to **bullet velocity**:

- A possible guide to furthering jet-medium interaction models



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Summary and Outlook

- A new way of looking at **how the medium responds to thermalized jets**:

Vorticity rings!

- An observable that:
  - **Decouples anisotropic expansion** and **jet thermalization contributions**
  - Is **sensitive to medium properties**, such as the **specific shear-viscosity** of the QGP
  - Is **sensitive to jet properties** (position, alignment, velocity…)
- It is **possible to experimentally reconstruct** the 3D polarization vector
- Predicted signal is of the same order of magnitude as the global Λ polarization measured by STAR and ALICE, so it is <u>**feasible**</u>

Will be proposed to the ALICE collaboration soon, so…

…Stay tuned to a brand new vorticity measurement!

Acknowledgments:

FAPESP

FAPESP proc. 2025/01122-0
Thematic proj. 2023/13749-1

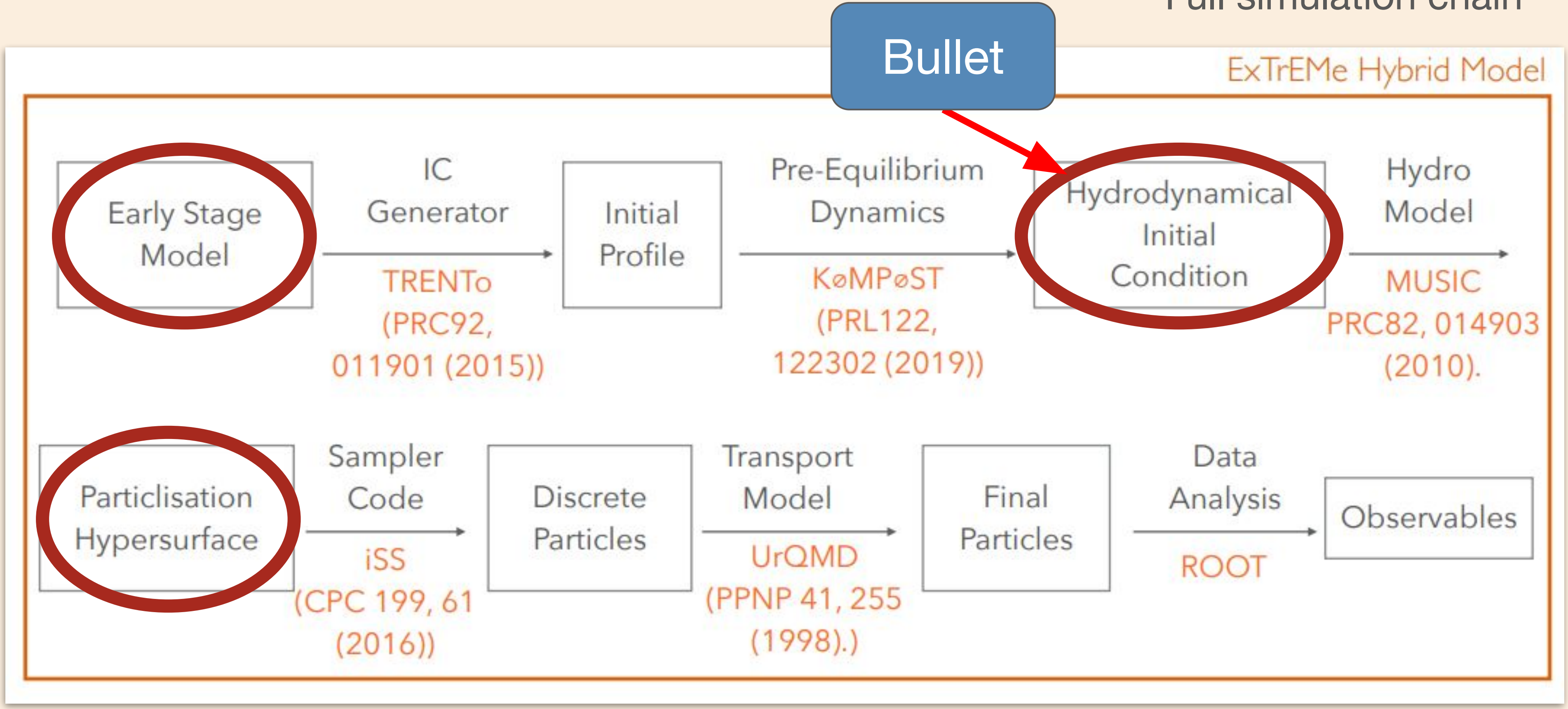
Thank you!

cicero.domenico.muncinelli@cern.ch

Backup

Cicero Muncinelli, G. Torrieri, J. Takahashi, M. Lisa

Full simulation chain



[Extreme Hydro workshop 2021]

Jet thermalization specifics

$\tau_0 = 0.25$ fm/c

$\tau_{th} = 1.0$ fm/c

- $\frac{\eta}{s} = 0.08, \frac{\zeta}{s} = 0$
- No baryonic density
- HotQCD EoS

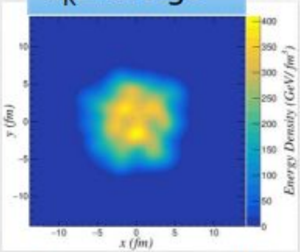
$\tau \cong 10$ fm/c

$T < 151$ MeV

τ [fm/c]

Relativistic Viscous Hydrodynamics (MUSIC)

T$_R$ENTo 3D



Slice at $\eta = 0$

$$j^\mu(\tau, x, y, \eta_s) = p^\mu_{th}\delta(\tau - \tau_{th})\theta\left(\frac{(x-x_0)^2+(y-y_0)^2}{R_{xy}} + \frac{(z-z_0)^2}{R_z}\right),$$
$$z = \tau \sinh \eta_s$$
$$z_0 = \tau \sinh \eta_0$$
$$R_z = \tau[\sinh(\eta_0 + R_\eta) - \sinh(\eta_0 - R_\eta)]$$

Instantaneous source term carrying total momentum p^μ_{th}, placed at time τ_{th}, position $\vec{x}_0$ and with an ellipsoidal shape

This is just **one <u>possible</u> realization of jet energy thermalization**, used to phenomenologically introduce a bullet! Others may be better!

[QM 2023: QGP vortex rings as a new probe for jet-induced medium response and longitudinal dynamics]()

Hydrodynamic Simulation

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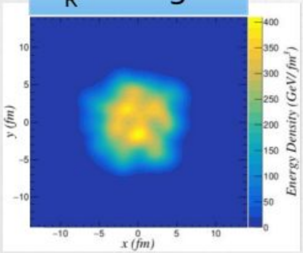

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$$R^t_\Lambda = \left\langle \frac{\vec{P}_\Lambda \cdot (\hat{t} \times \vec{p})}{|\hat{t} \times \vec{p}|} \right\rangle_{p_\perp, y}$$

$$\hat{t} = \frac{\vec{p}_{th}}{|\vec{p}_{th}|}$$

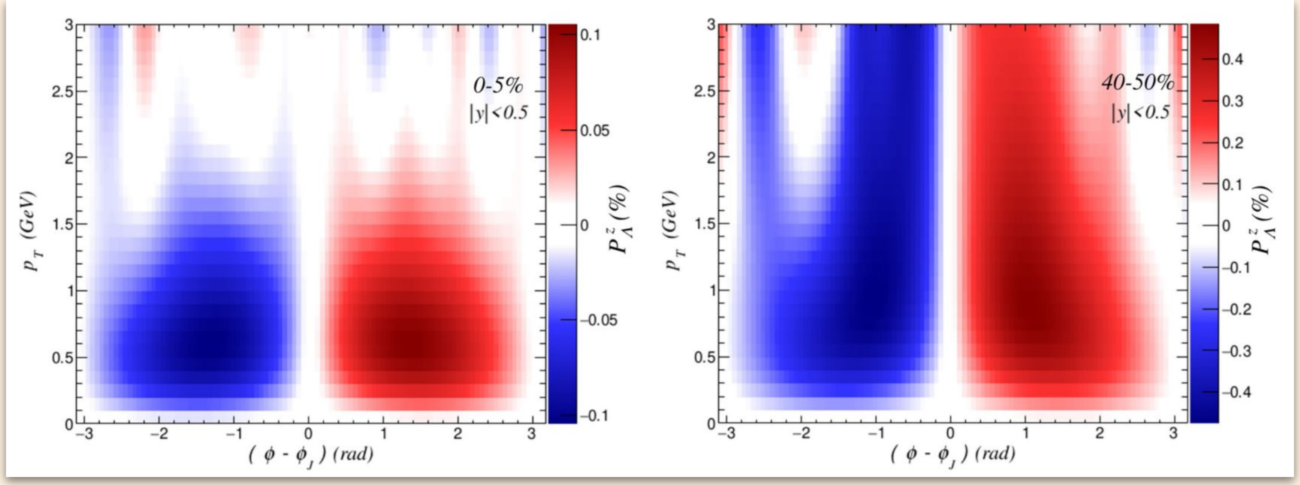
$$S^\mu = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int d\Sigma_\lambda p^\lambda n_f(1-n_f)\,\omega_{\rho\sigma}}{\int d\Sigma_\lambda p^\lambda n_f}$$

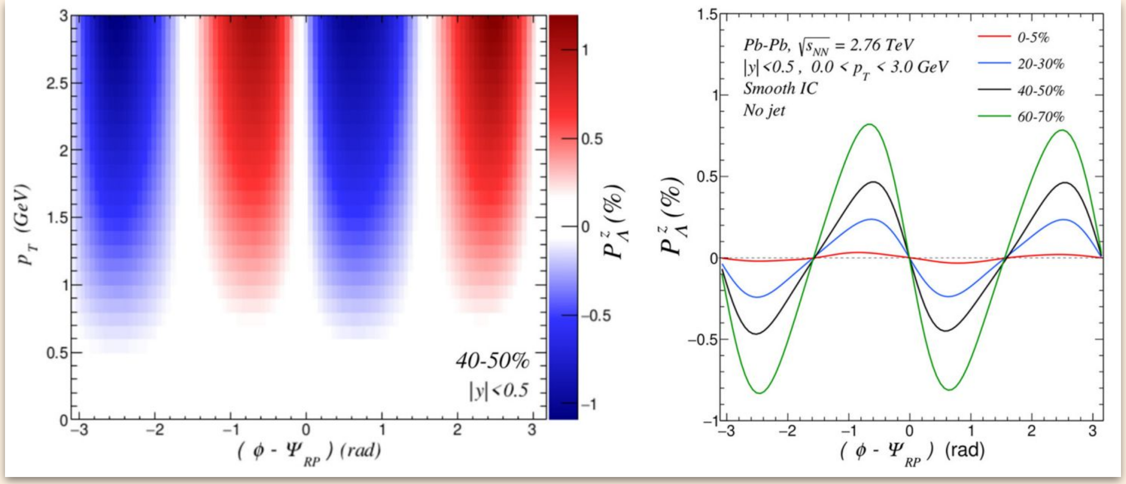
$$P^\mu = S^\mu/\langle S\rangle, \ \langle S\rangle = 1/2$$

Becattini *et. al.*, *Annals Phys.* 338 (2013)

QM 2023: QGP vortex rings as a new probe for jet-induced medium response and longitudinal dynamics

$P_z\ (p_T, \Delta\phi)$





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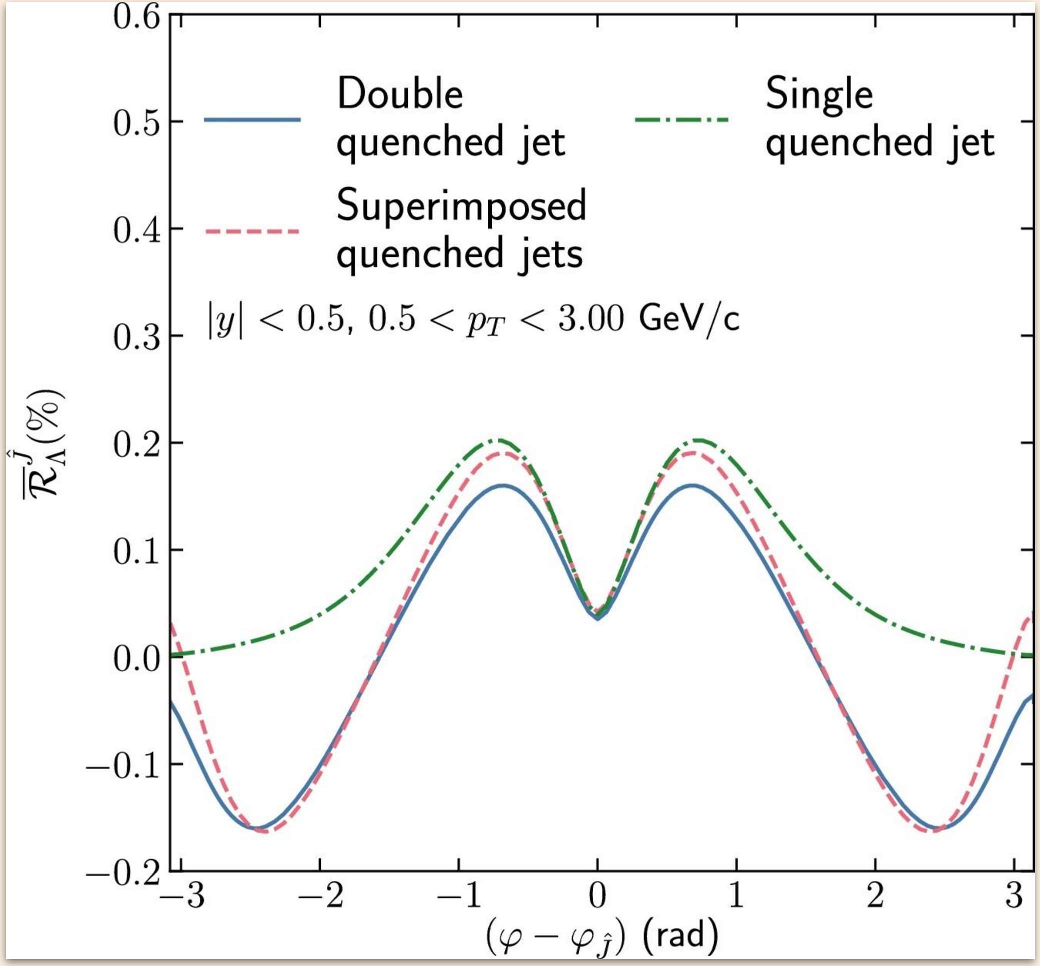
Dijet ring observable



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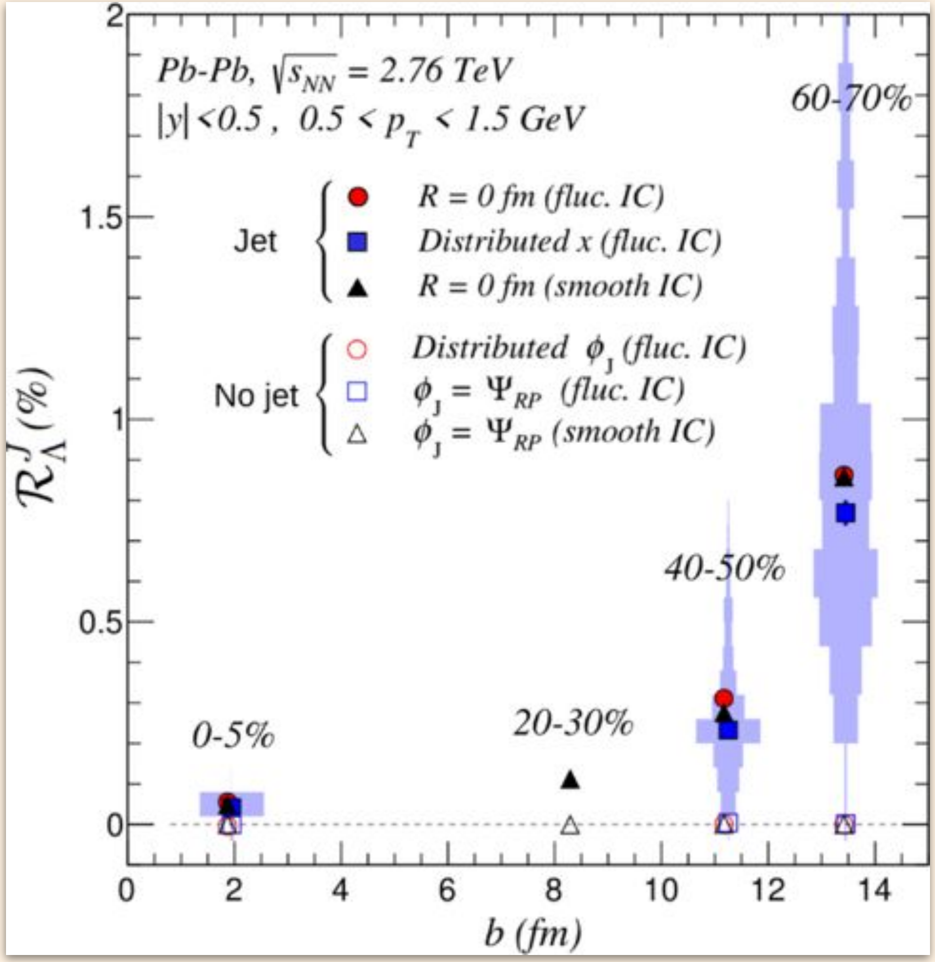
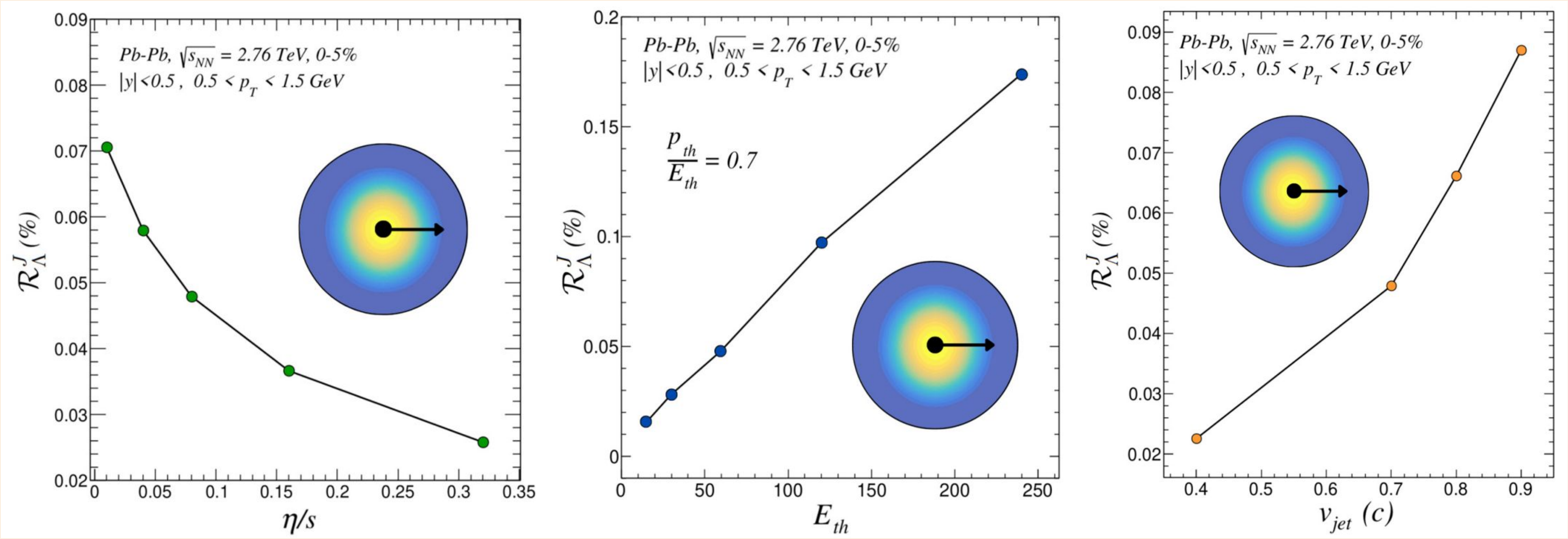
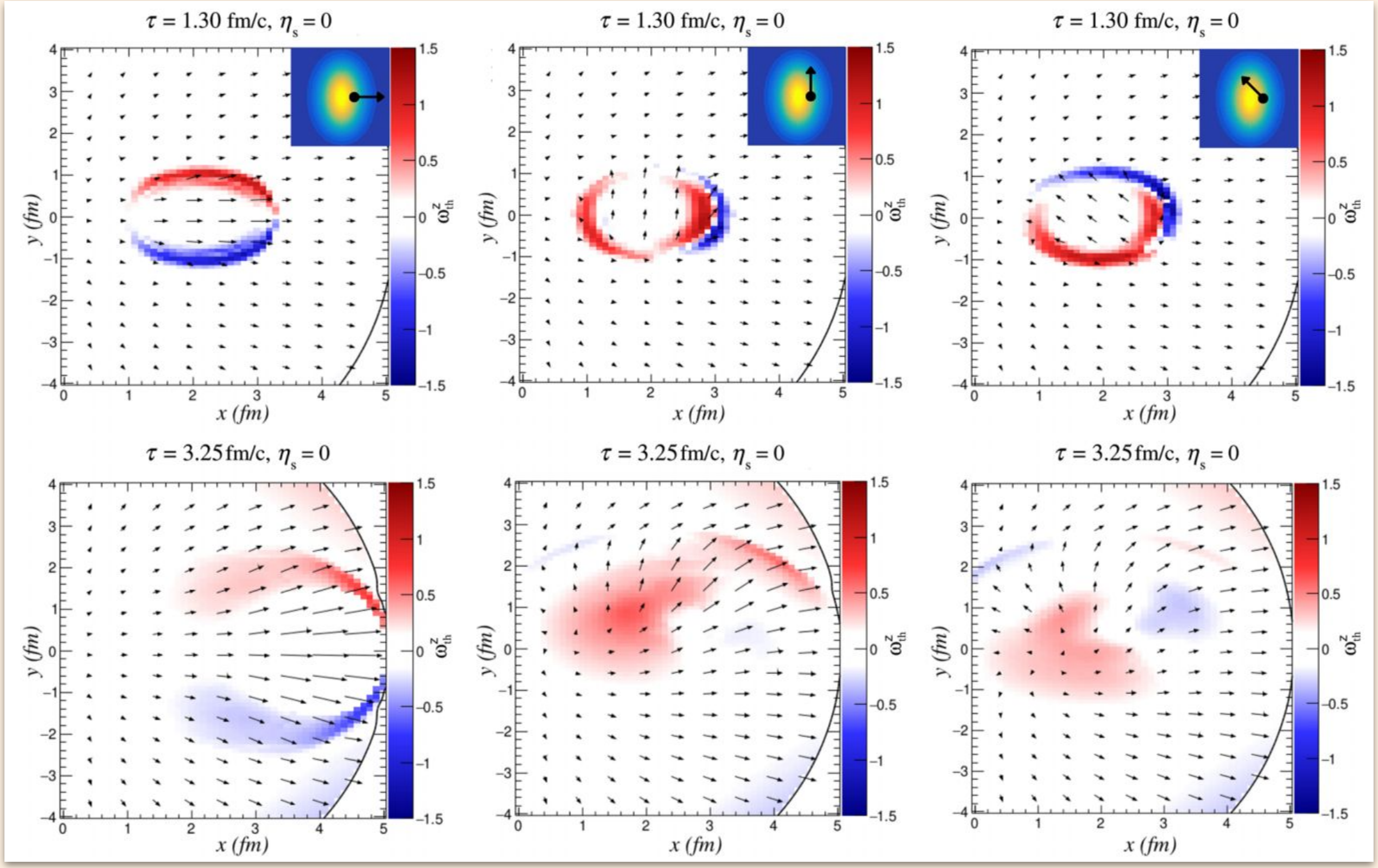
Centrality dependence
(integrated signal)



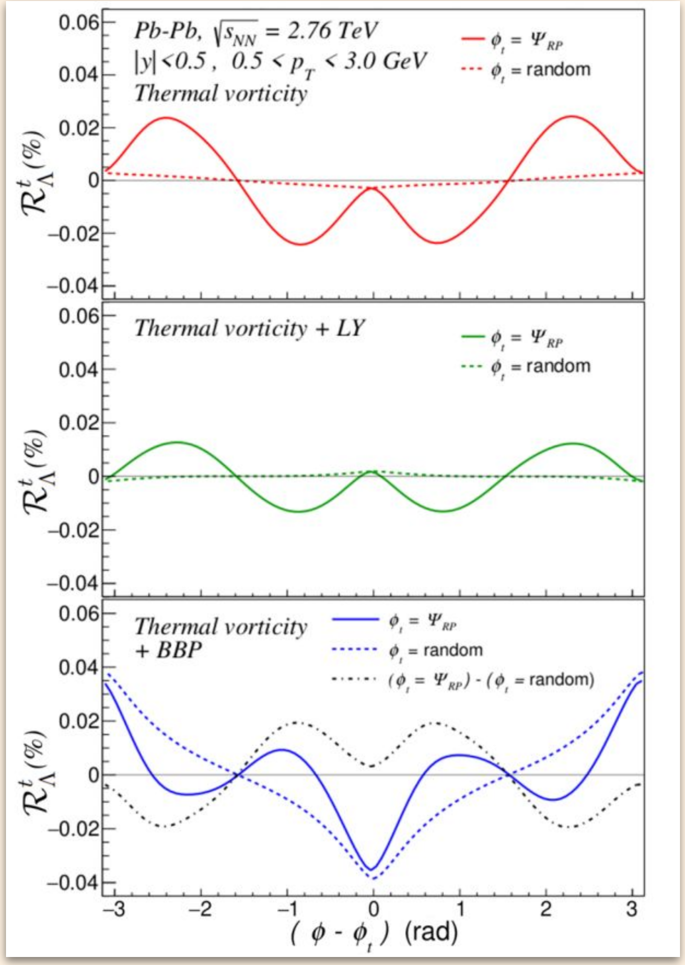
Smooth IC searches
$(x = y = \eta_s = 0)$





Realistic case: random jet direction and positions wrlt the expansion

Shear-induced polarization + Longitudinal expansion



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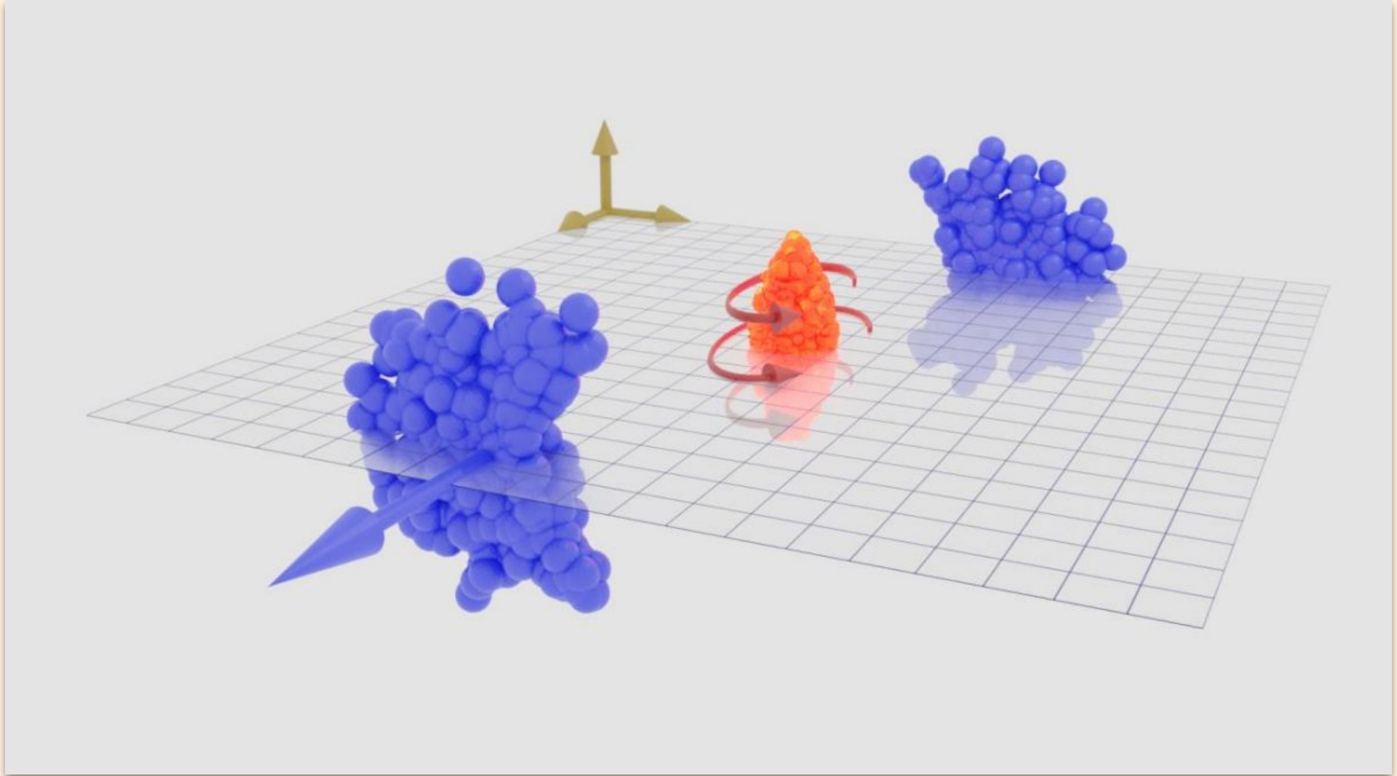
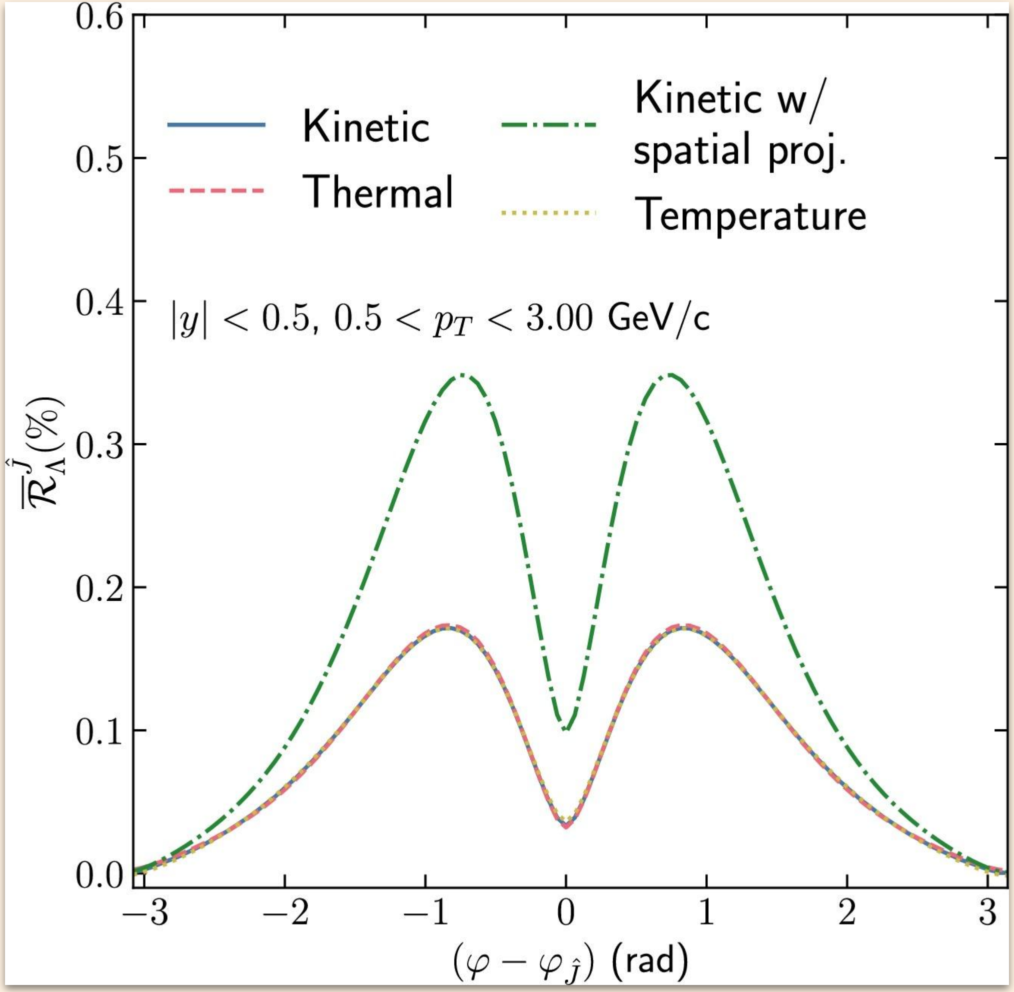


[QM 2023: QGP vortex rings as a new probe for jet-induced medium response and longitudinal dynamics]

Varying vorticity definitions



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