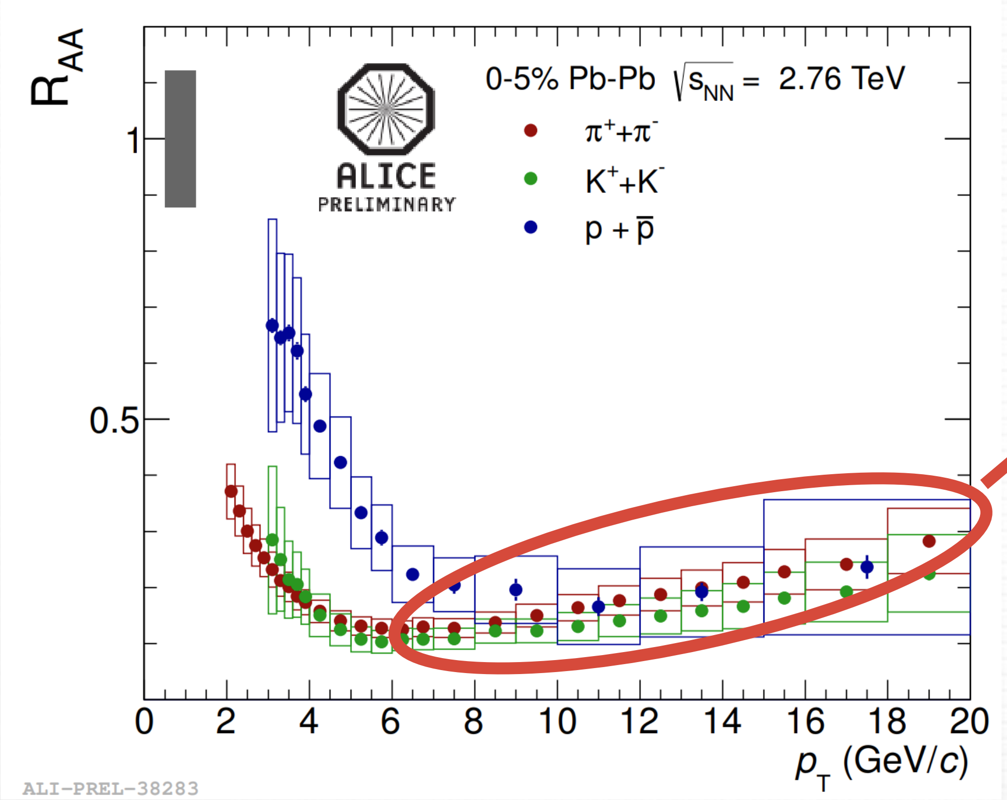
QGP vortex rings as a new probe for jet-induced medium response and longitudinal dynamics

Willian M. Serenone in collaboration with

V. H. Ribeiro, D. D. Chinellato, M. A. Lisa, C. Shen, J. Takahashi and G. Torrieri

Based on arXiv: **2305.02428** (submitted to Phys. Rev. C)

Where does the high momentum of jets goes?



arXiv:1301.5285

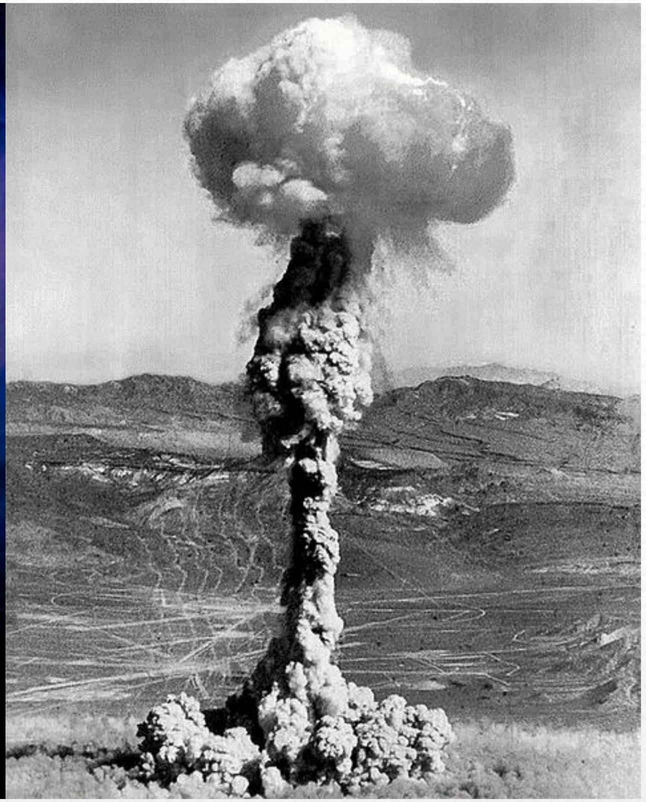
High momentum of p_T-spectra suppressed in heavy-ion collisions when compared to scaled pp spectra

Associated to a strongly-coupled medium.

Medium typically is described via Rel. Hydrodynamics

Vortex phenomena are ubiquitous in hydrodynamic-like systems

“Scary Barbie” Blackhole



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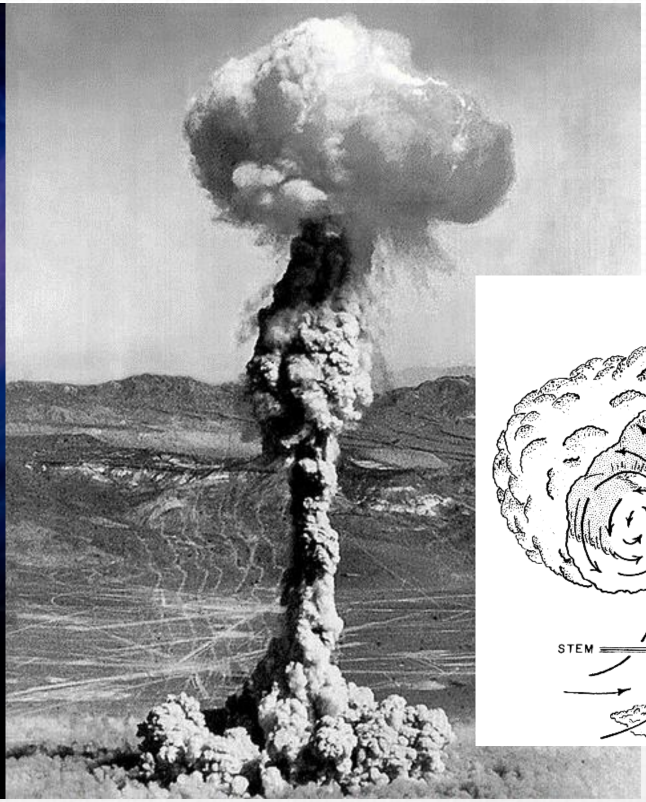
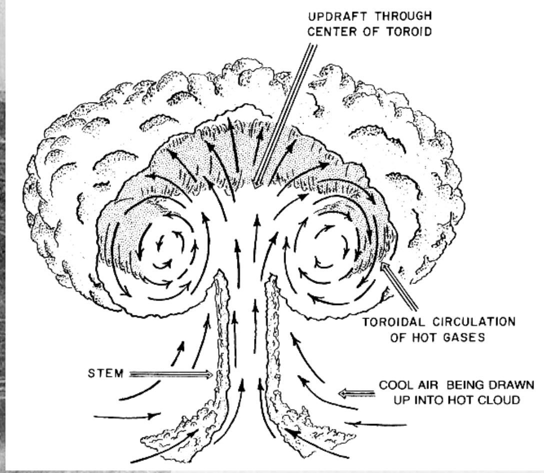
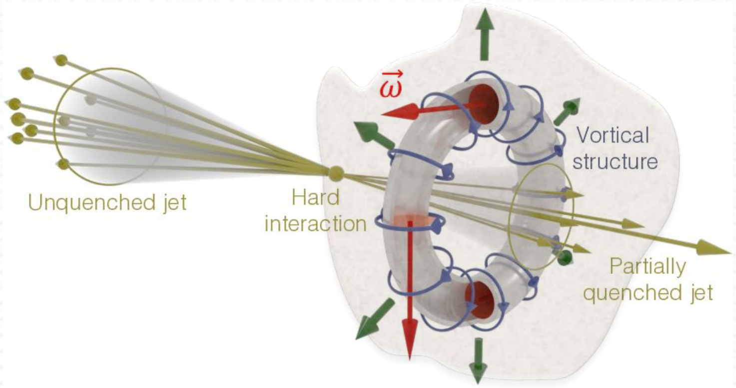
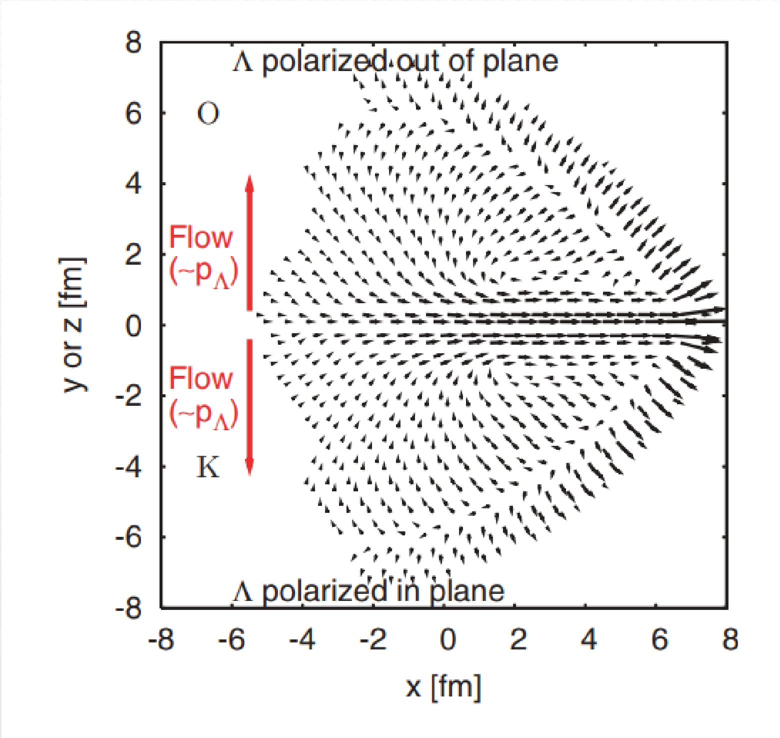


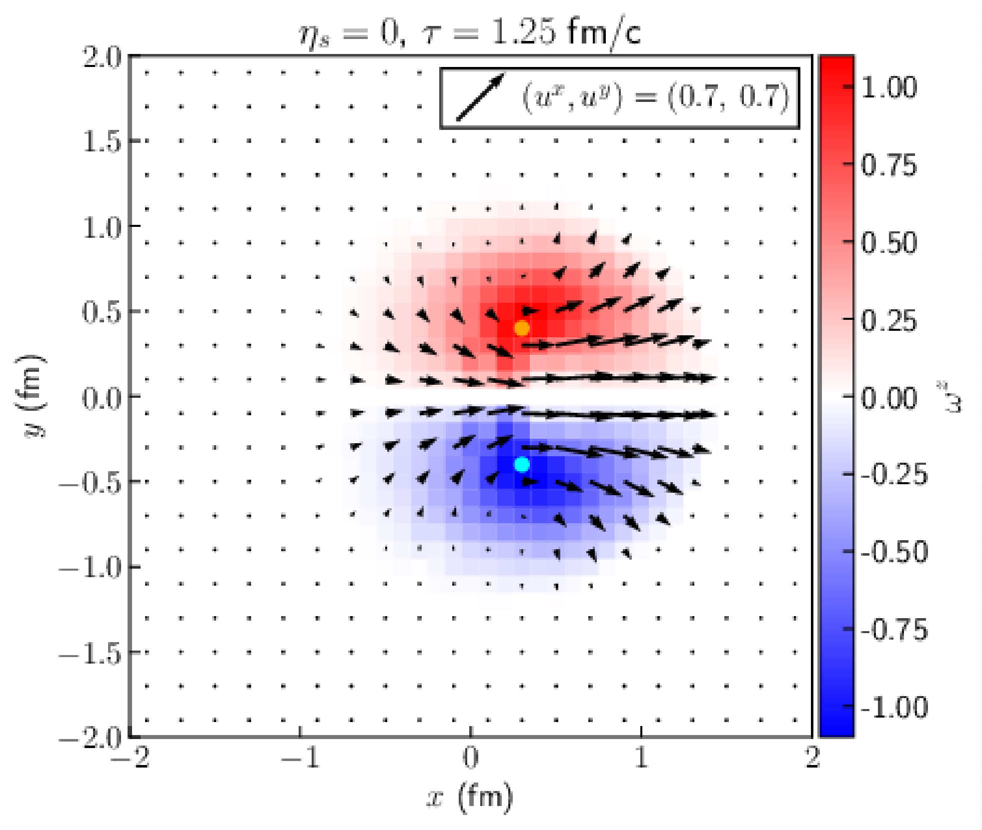


Vortex Rings in the QGP





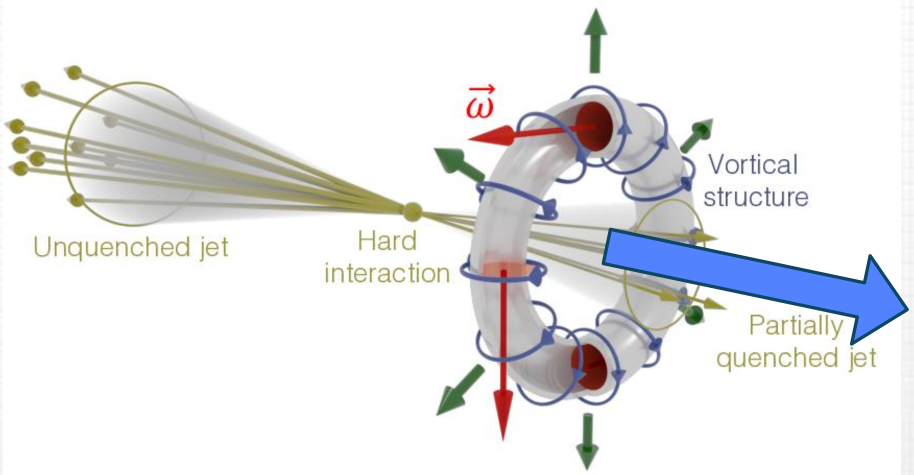
B. Betz *et. al.*, Phys. Rev. C **76**, 044901 (2007)



W. M. Serenone *et. al.*, Phys. Lett. B **820**, 136500 (2021)

Objectives

- Systematic phenomenological study with (3+1)D event-by-event simulations in central and peripheral **Pb+Pb** collisions at LHC energies ($\sqrt{s_{NN}} = \mathbf{2.76\ TeV}$)
- **Ring-observable** proposal: $R^t_\Lambda = \left\langle \frac{\vec{P}_\Lambda \cdot (\hat{t} \times \vec{p})}{|\hat{t} \times \vec{p}|} \right\rangle_{p_\perp, y}$

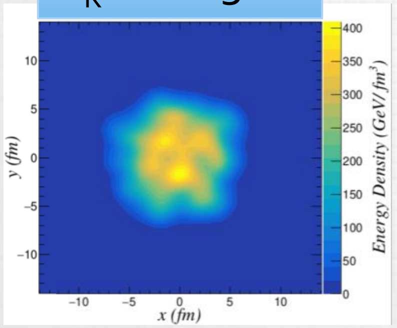


Hydrodynamic Simulation

$\tau_0 = 0.25$ fm/c

τ [fm/c]

T$_R$ENTo 3D



Slice at $\eta = 0$

Hydrodynamic Simulation

$\tau_0 = 0.25$ fm/c

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

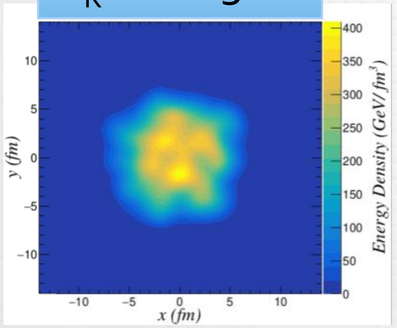
- HotQCD EoS

$\tau \cong 10$ fm/c
$T < 151$ MeV

τ [fm/c]

Relativistic Viscous Hydrodynamics (MUSIC)

T_RENTo 3D



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Hydrodynamic Simulation

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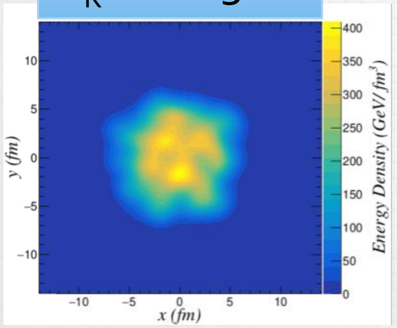

Slice at $\eta = 0$

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

$$z = \tau \sinh \eta_s$$

$$z_0 = \tau \sinh \eta_0$$

$$R_z = \tau[\sinh(\eta_0 + R_\eta) - \sinh(\eta_0 - R_\eta)]$$

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

Hydrodynamic Simulation

$\tau_0 = 0.25$ fm/c

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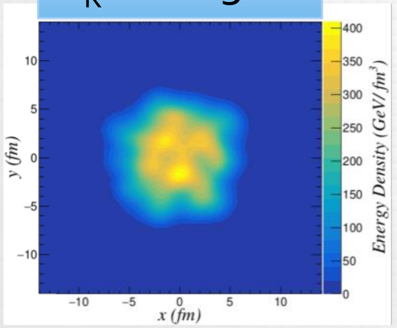

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Instantaneous source term carrying total momentum p^μ_{th}, placed at time τ_{th}, position $\vec{x}_0$ and with an ellipsoidal shape

$$S^\mu = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_\tau \frac{\int d\Sigma_\lambda p^\lambda n_f(1-n_f)\,\omega_{\rho\sigma}}{\int d\Sigma_\lambda p^\lambda n_f}$$
$$P^\mu = S^\mu/\langle S\rangle,\ \langle S\rangle = 1/2$$

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

Hydrodynamic Simulation

$\tau_0 = 0.25$ fm/c

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

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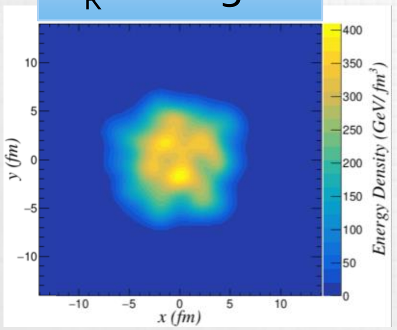
Relativistic Viscous Hydrodynamics (MUSIC)

$\mathrm{T_R ENTo}$ 3D



Slice at $\eta = 0$

$$j^\mu(\tau, x, y, \eta_s) = p^\mu_{th}\delta(\tau - \tau_{th})\theta\left(\frac{(x-x_0)^2+(y-y_0)^2}{R_{xy}} + \frac{(z-z_0)^2}{R_z}\right),$$
$$z = \tau \sinh \eta_s$$
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Instantaneous source term carrying total momentum p^μ_{th}, placed at time τ_{th}, position $\vec{x}_0$ and with an ellipsoidal shape

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

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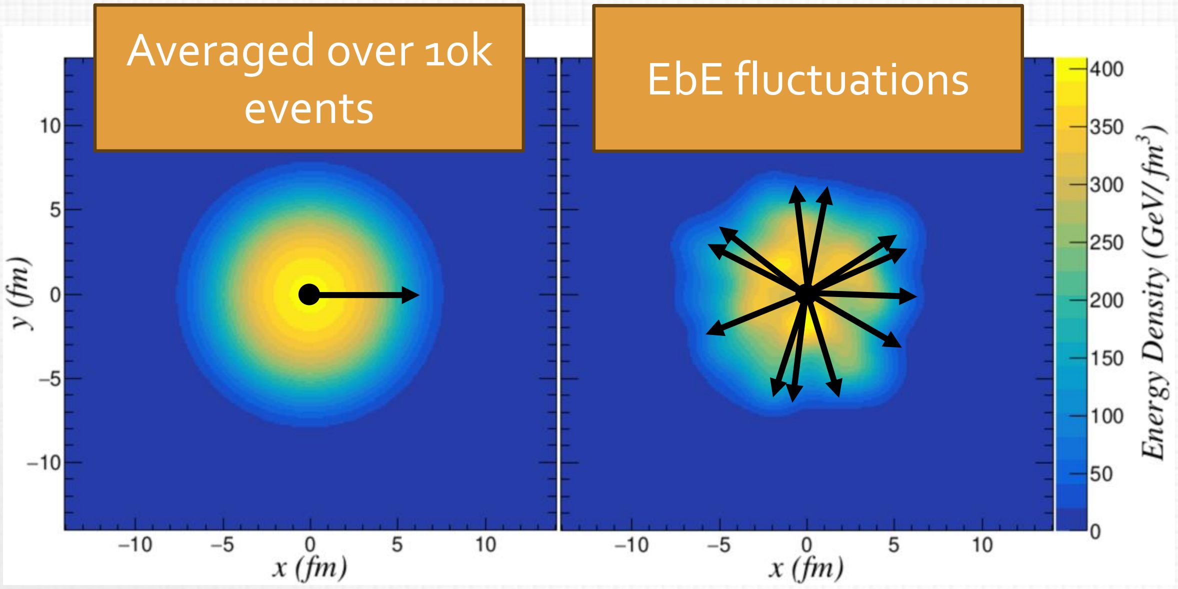
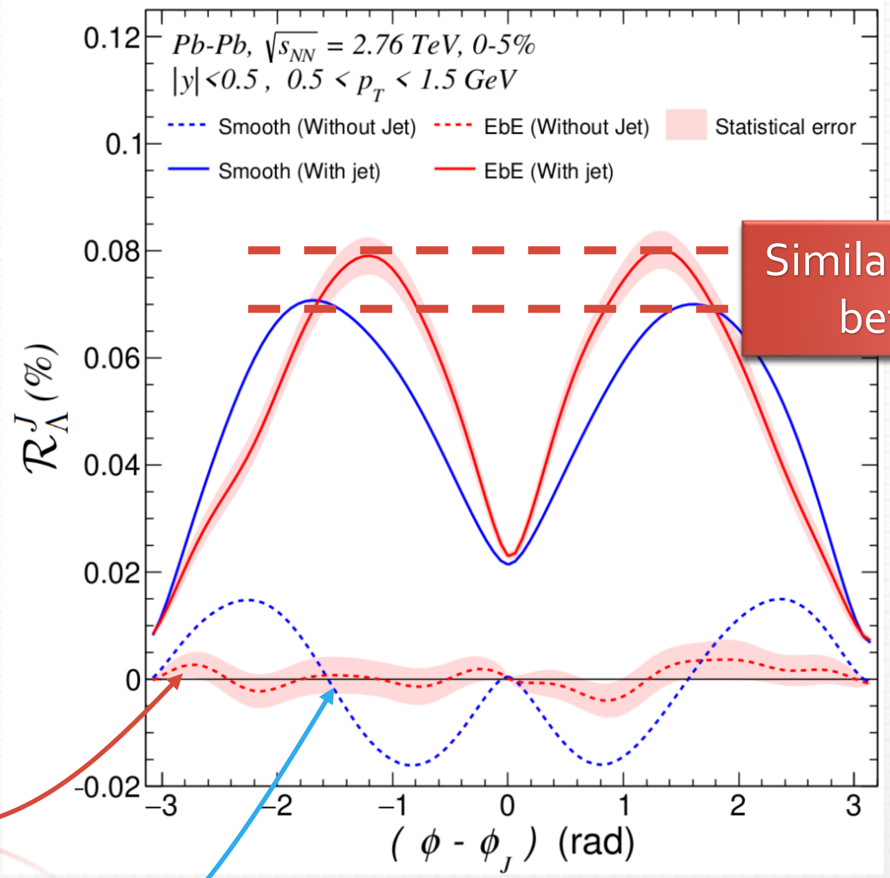
Becattini *et. al.*, *Annals Phys.* 338 (2013)

Averaged vs Fluctuating Initial Conditions



[Ribeiro *et. al.*, arXiv: 2305.02428](https://arxiv.org/abs/2305.02428)



Similar order of magnitude between both cases

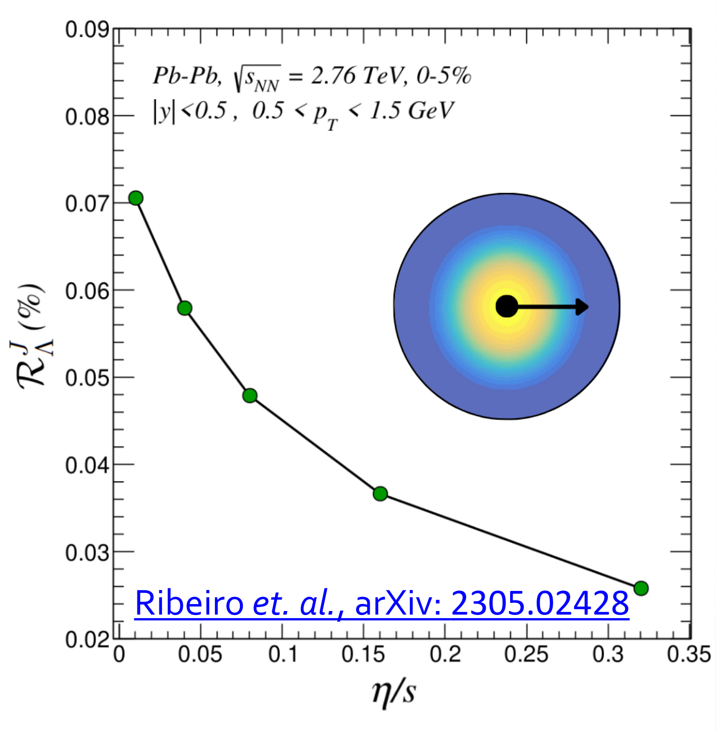
Random trigger direction supresses transverse expansion polarization

Residual effect of transverse expansion

[Ribeiro *et. al.*, arXiv: 2305.02428](https://arxiv.org/abs/2305.02428)

Polarization as QGP properties probe

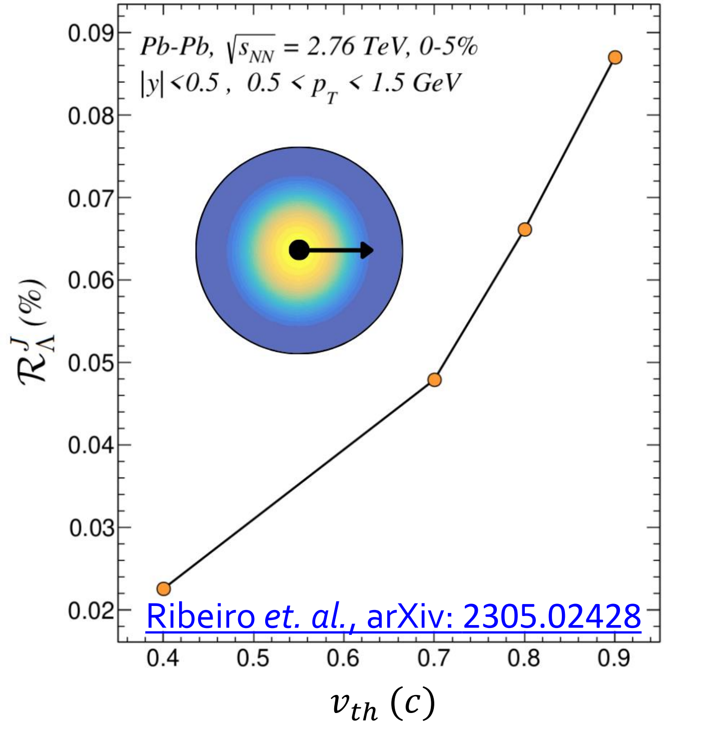
Sensitiveness to shear viscosity



- Stronger vortex-ring dissipation at higher viscosities
- Similar as seen in our previous work

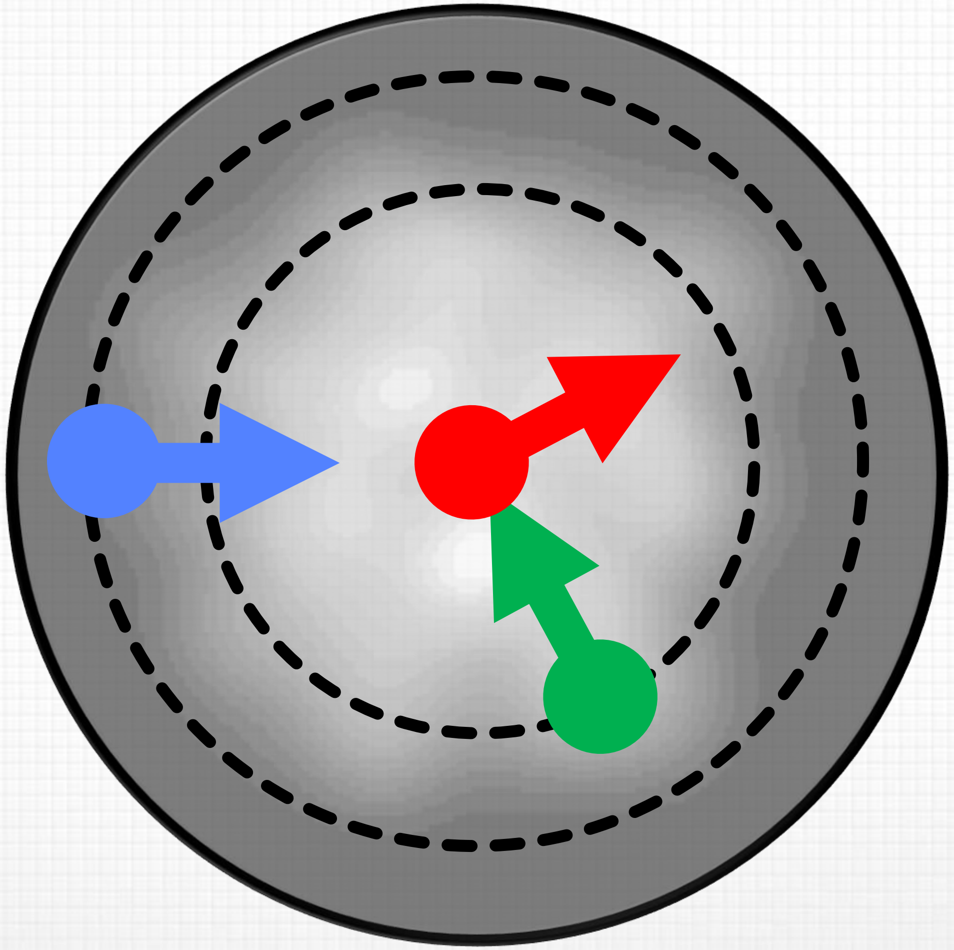
PLB **820**, 136500

Sensitiveness to source velocity

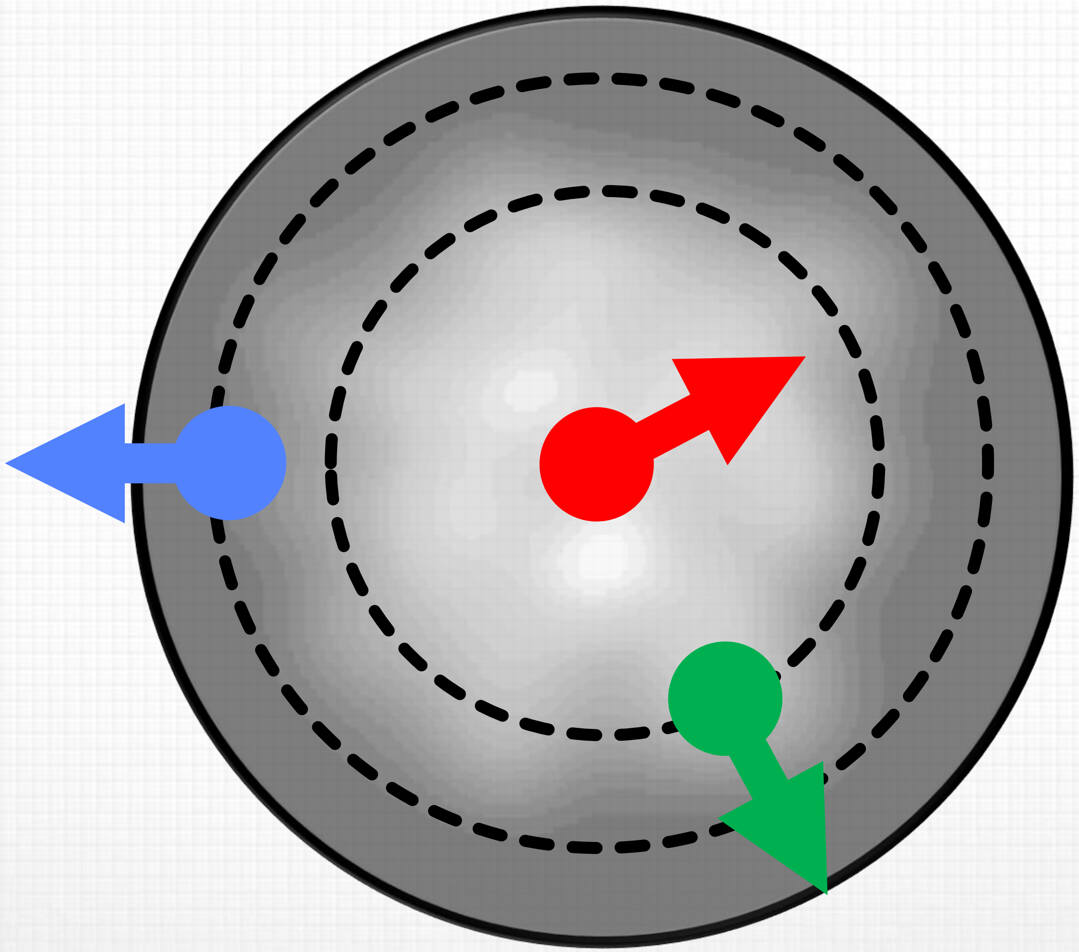


- $v_{th} = \frac{|\vec{p}_{th}|}{p^0_{th}}$
- $p^0_{th} = 59.6$ GeV fixed
- Velocity-driven phenomena
- Could be used as a guide to jet-medium interaction models

Dependence with **position** and orientation of source

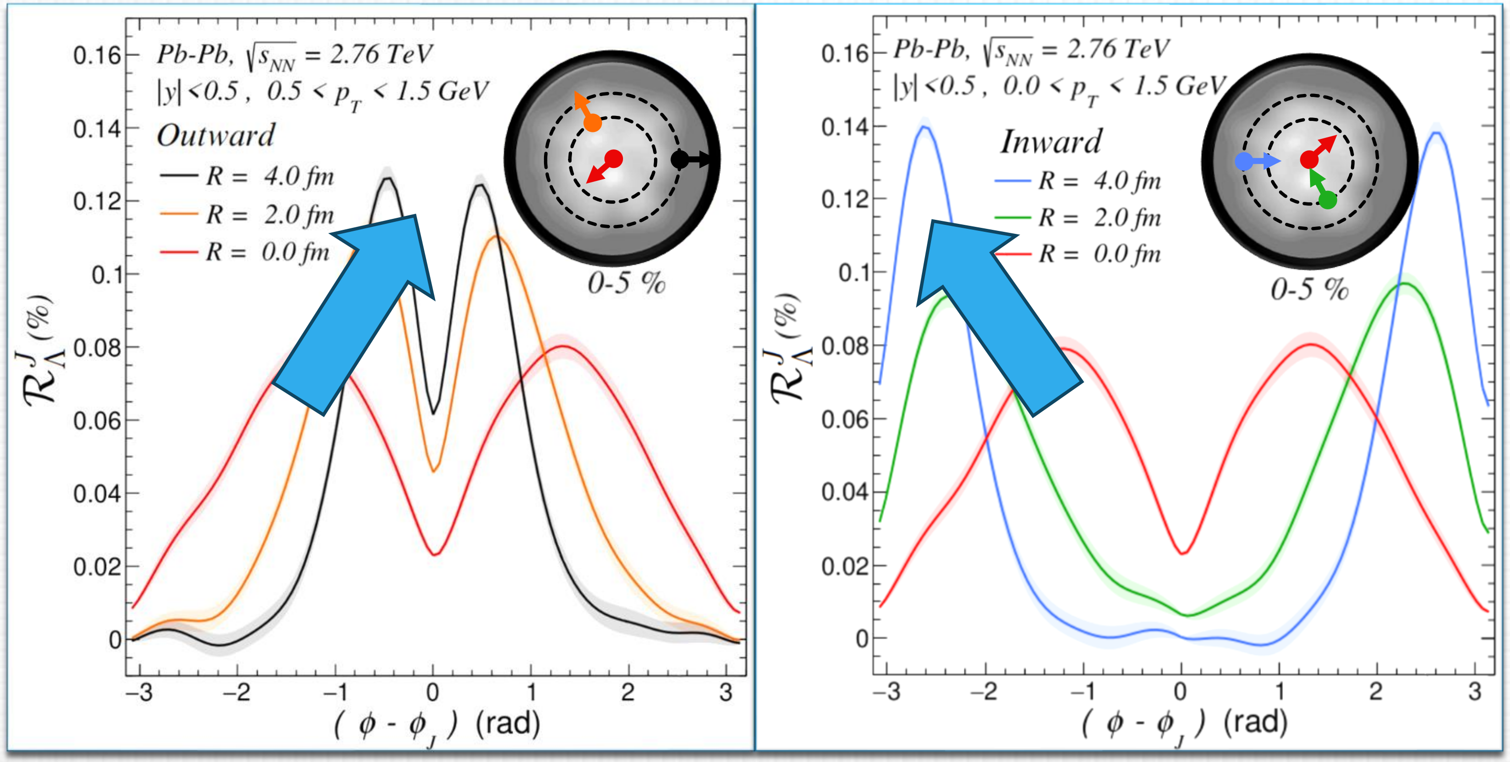


Dependence with position and **orientation** of source



Dependence with **position**

Ribeiro *et. al.*, arXiv: 2305.02428

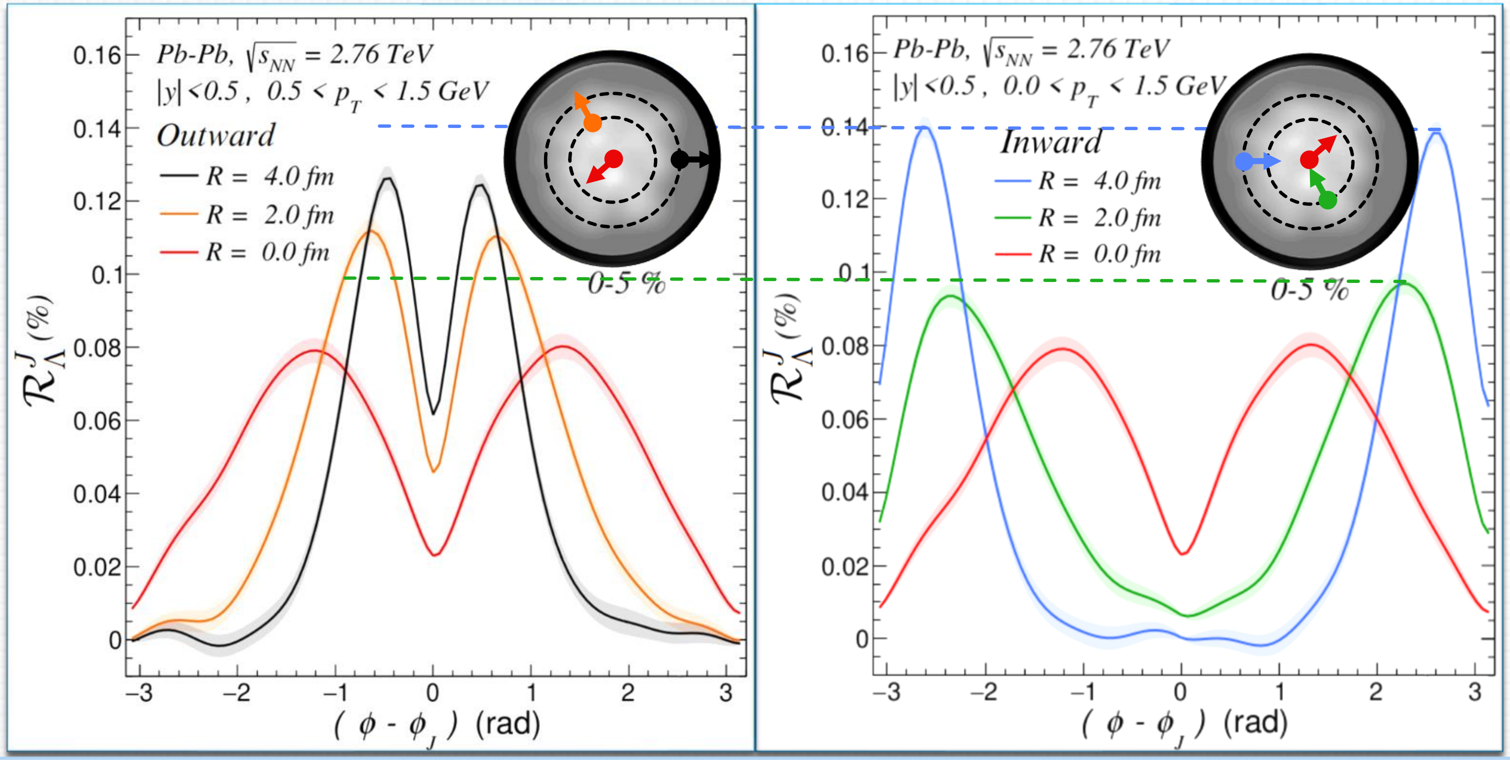


Deposition near event border

Less time to dissipate → Stronger rings

Dependence with **orientation**

Ribeiro *et. al.*, arXiv: 2305.02428



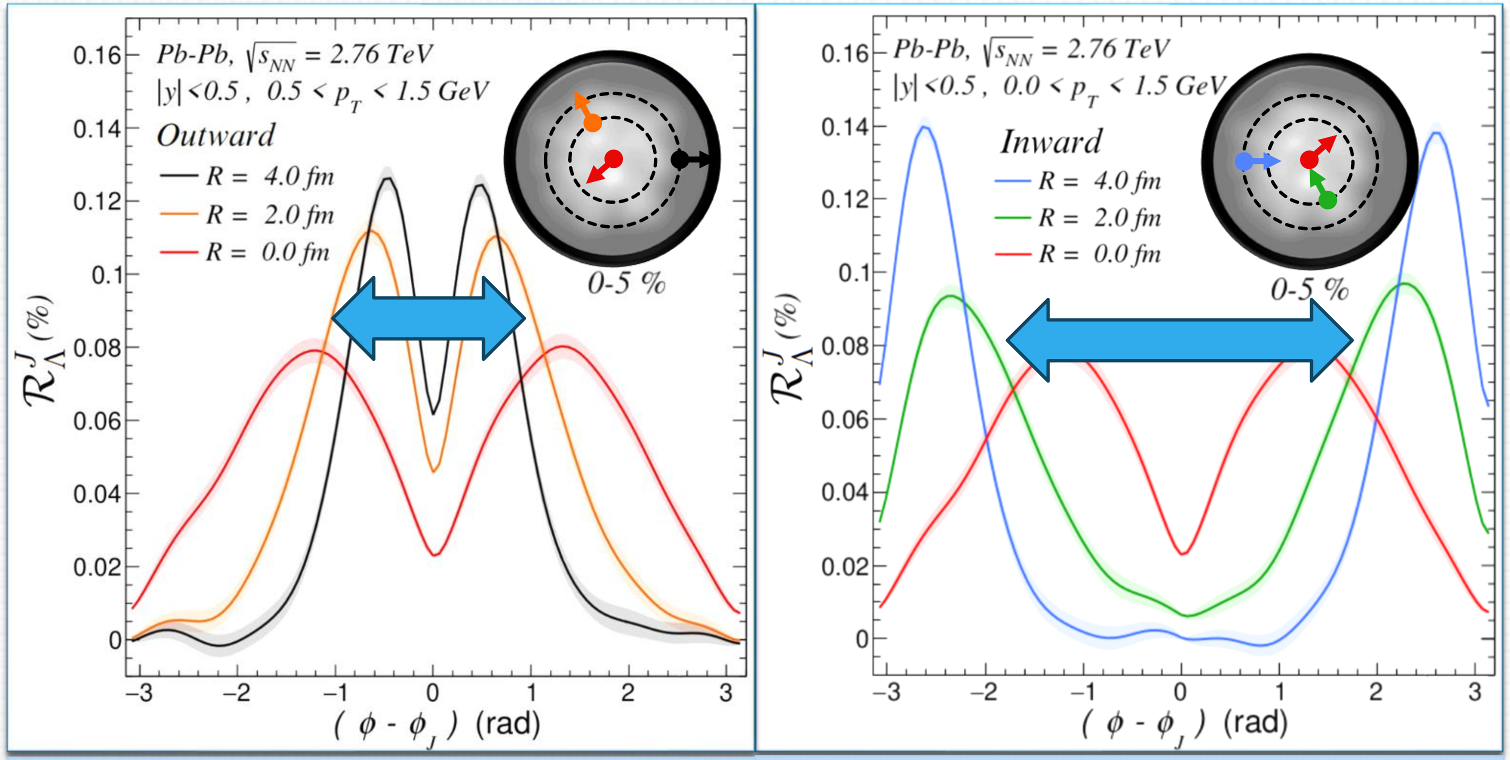
Inward vs Outward. Competing effects

Deposition against flow in inward case results in bigger vorticity

Vortex runs away from Particlization hypersurface, giving more time for dissipation

Fluctuation of position and orientation of thermal current

[Ribeiro *et. al.*, arXiv: 2305.02428]



Distance between peaks:

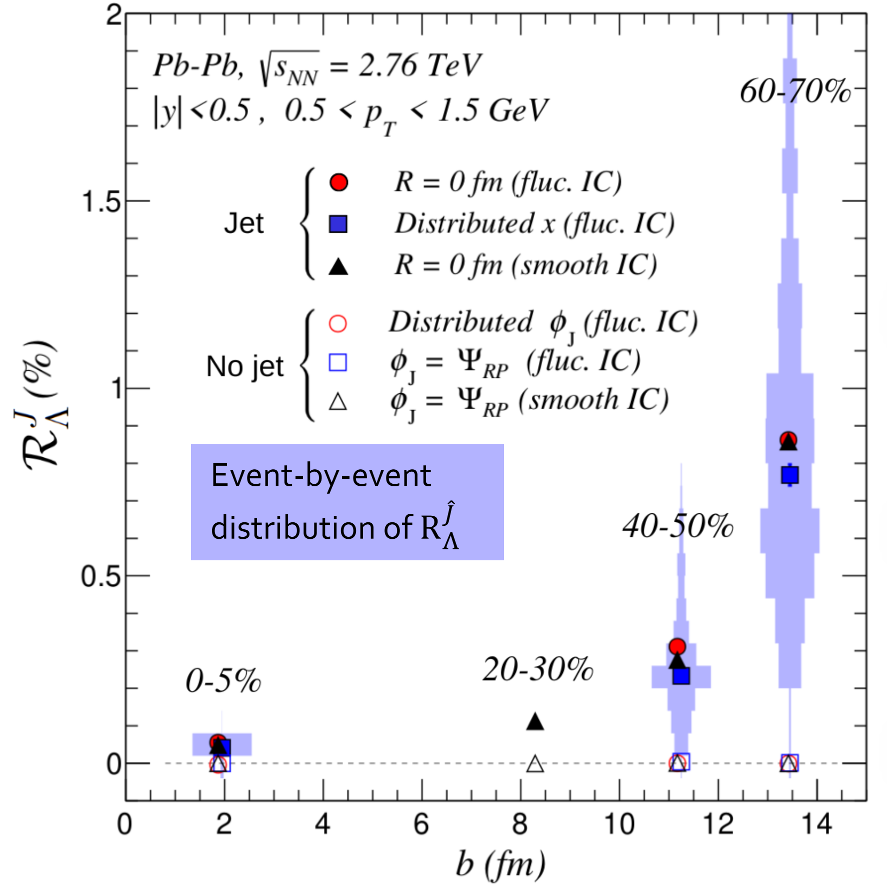
Proxy for vortex ring size

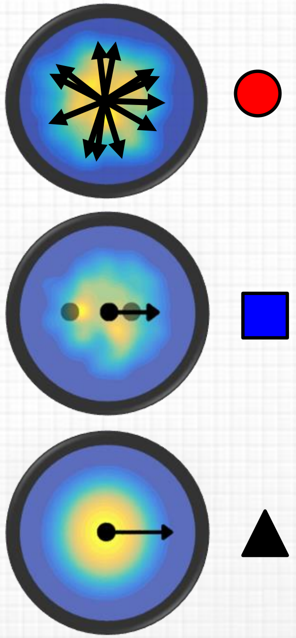
Peak position:

Proxy for vortex orientation with respect to particlization hypersurface

Ring observable averaged over azimuthal angle

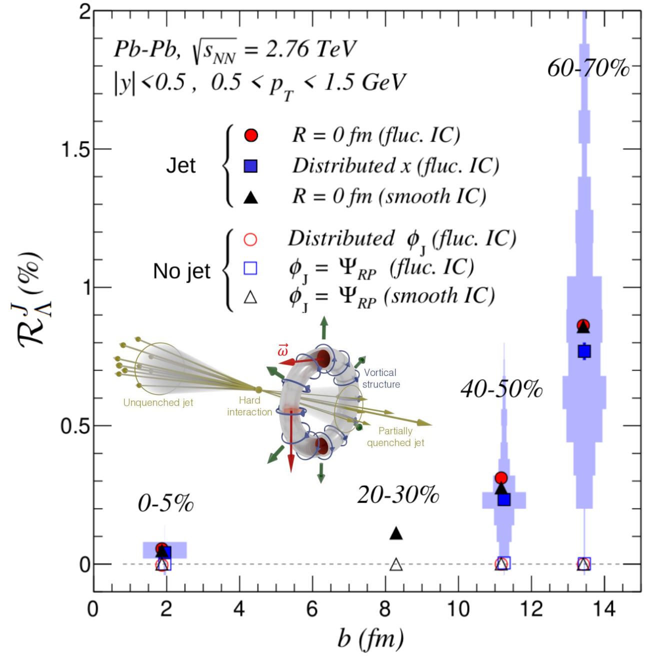
- Background is consistently zero
- Systematic increase of ring observable with centrality
  - Smaller fluid background causes fluid to develop larger velocity gradients
  - Smaller system causes particlization time to be reached earlier
- **Ring observable is a robust probe for jet-medium interaction**





[Ribeiro *et. al.*, arXiv: 2305.02428](https://arxiv.org/abs/2305.02428)

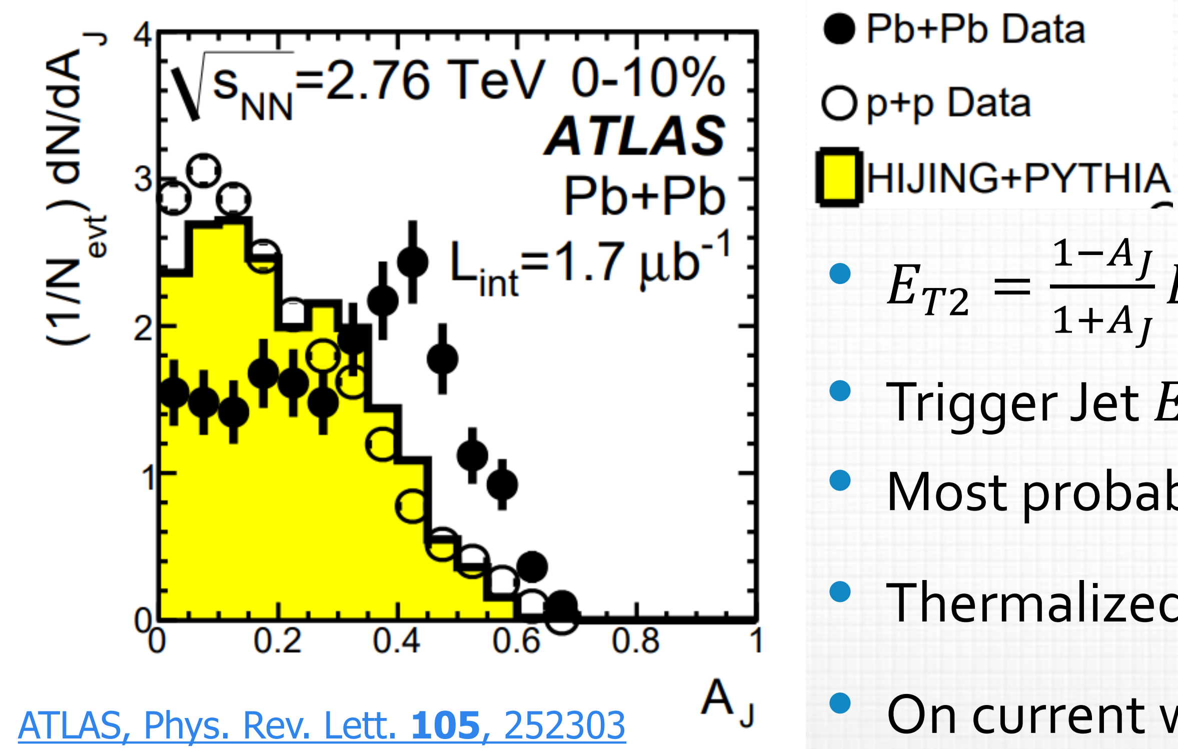
Conclusions



- Magnitude of ring observable reported in the present work is similar to what was reported by ALICE for global polarization.
  - Could be measured with on-tape data?
- Observable is robust even in EbE simulations
  - Random jet orientation should be enough to decouple vortices generated by system expansion and the ones from Jets
- Highly sensitive tool to probe the dynamics of the QGP and jet-medium interactions.
  - Medium properties: Shear viscosity and deposition model via magnitude of the deposited momentum
  - Location of medium-jet interaction
  - Jet orientation

Backup

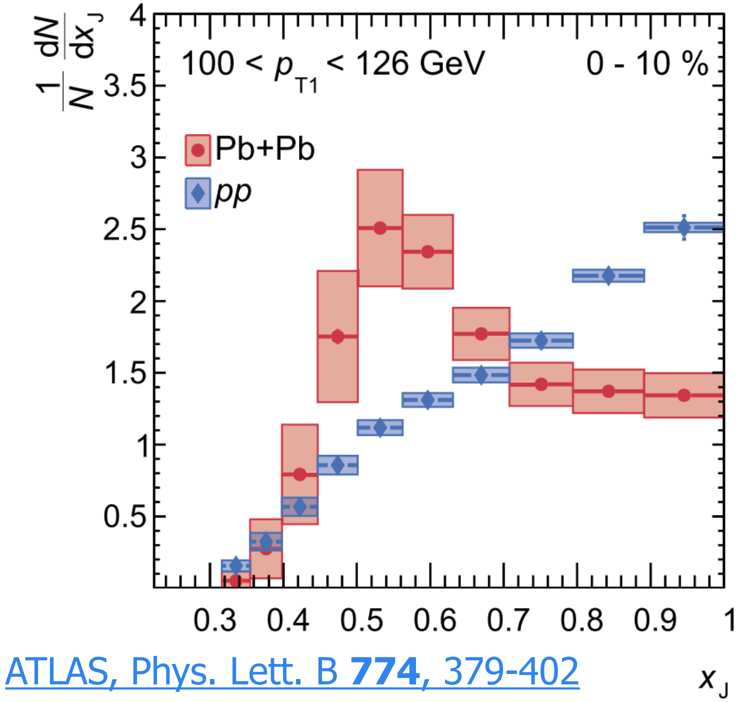
Energy and Momentum choice for source



ATLAS, Phys. Rev. Lett. **105**, 252303

- $E_{T2} = \frac{1-A_J}{1+A_J} E_{T1}$
- Trigger Jet $E_{T1} > 100$ GeV
- Most probable value for $A_J \sim 0.425$
- Thermalized energy: $E_{th} = \frac{2A_J}{1+A_J} E_{T1} \cong 0.596\, E_{T1} > 60$ GeV
- On current work, we use the minimum value, i.e. $E_{th} = 60$ GeV

Energy and Momentum choice for source



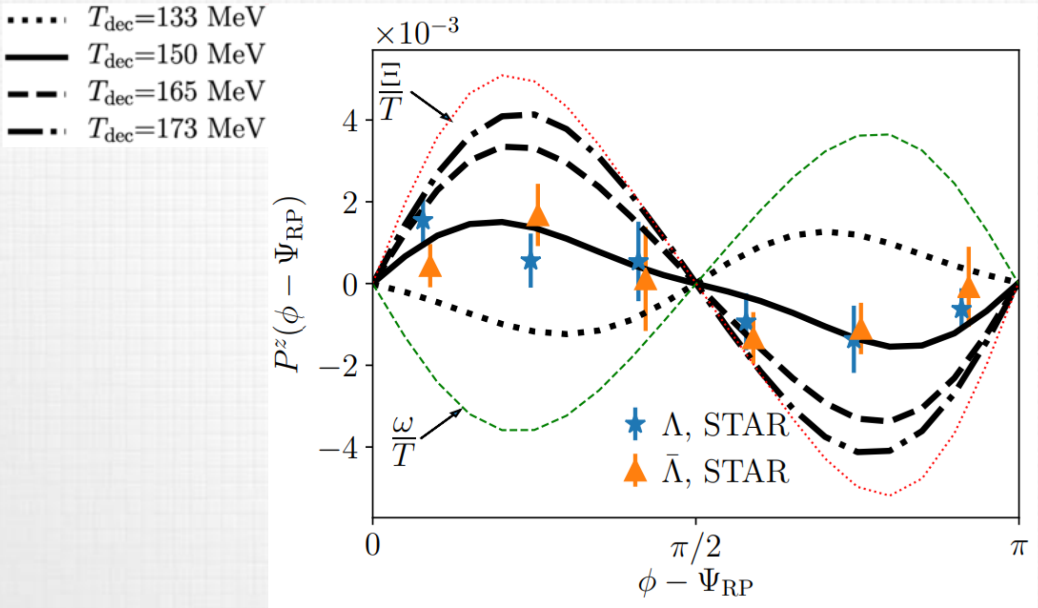
[ATLAS, Phys. Lett. B **774**, 379-402]

- $p_{T2} = x_J p_{T1}$
- $p_{th} = p_{T1} - p_{T2} = (1 - x_J) p_{T1}$
- Most probable value for $x_J \sim 0.5$ to $x_J \sim 0.6$
- $40.0 < p_{th} < 63$ GeV/c
- In this work, we use $p_{th} = 43$ GeV/c

$p_{T2} = x_J p$

Polarization sign problem

- Without jets, thermal vorticity generates longitudinal polarization with opposite sign



Becattini *et. al.* Phys. Rev. Lett. **127**, 272302

Polarization sign problem

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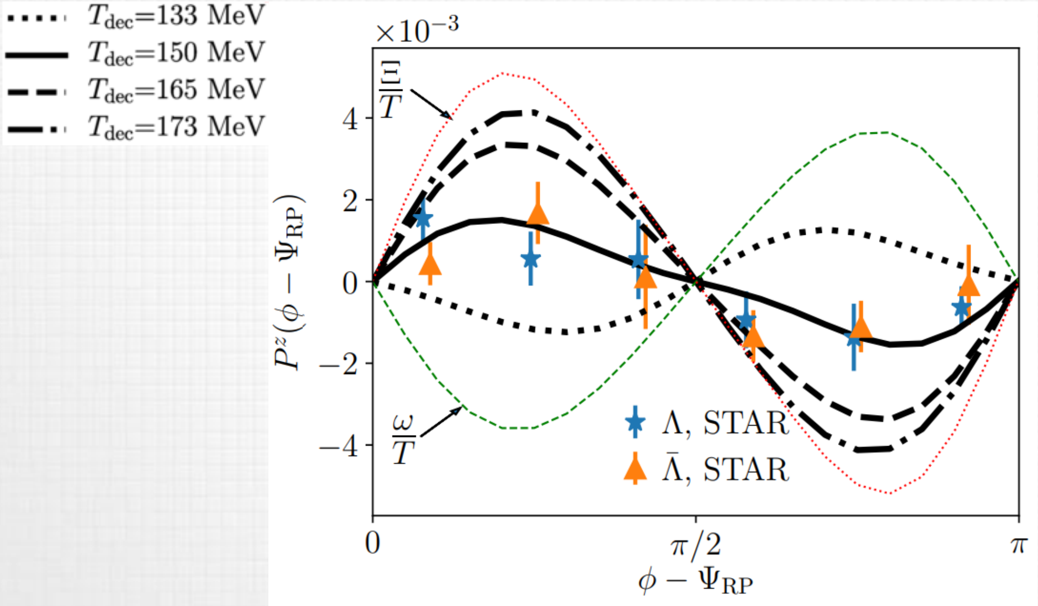


Becattini *et. al.* Phys. Rev. Lett. **127**, 272302

- 2021: Several groups proposed corrections mostly relying on correction due to shear tensor

$$S_\mu(p) = -\frac{1}{4m}\frac{\int_{d\Sigma} d\Sigma_\rho p^\rho n_f(1-n_f)A^\mu}{\int_{d\Sigma} d\Sigma_\rho p^\rho n_f}$$

$$A^\mu_{BBP} = \epsilon^{\mu\nu\sigma\tau}\left(\frac{\omega_{\nu\sigma}p_\tau}{2} + \frac{1}{E}\hat{t}_\nu \xi_{\sigma\lambda}p^\lambda p_\tau\right)$$

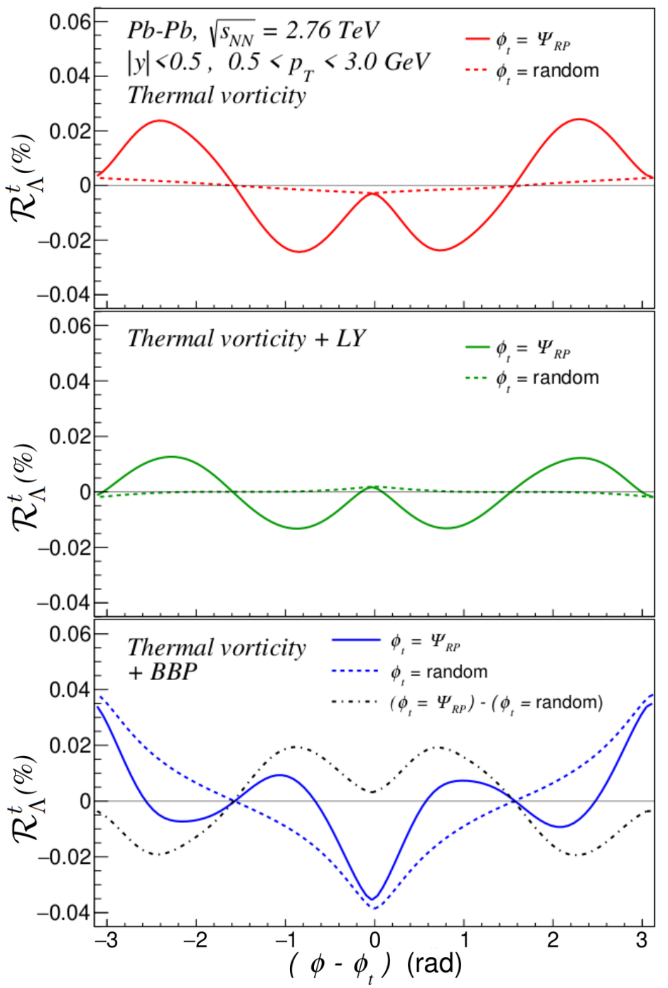
F. Beccatini, M. Buzzegoli, A. Palermo, Phys. Lett. B **820**, 136519 (2021)

$$A^\mu_{LY} = \epsilon^{\mu\nu\sigma\tau}\left(\frac{\omega_{\nu\sigma}p_\tau}{2} + \frac{1}{E}u_\nu \xi_{\sigma\lambda}p^\lambda_\perp p_\tau\right)$$

S. Y. F. Liu, Y. Yin; J. High Energy Phys. **2021**, 188 (2021)

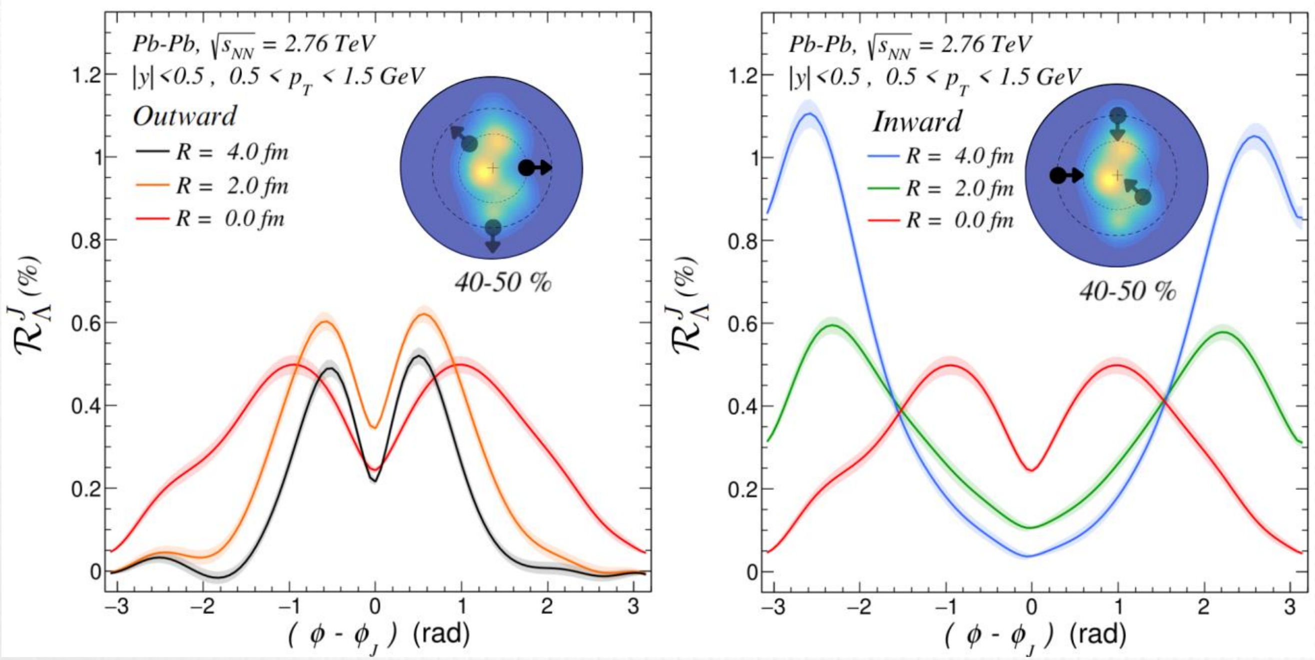
Polarization sign problem and the ring observable

- Longitudinal and transverse anisotropic expansion gives rise to ring-like structures
- Possible to filter out these contributions by selecting different trigger directions
- Averaging over random directions on the transverse plane allows for only longitudinal contributions to survive
  - For thermal only and LY shear-induced corrections, transverse polarization dominates
  - BBP shear-induced correction much more sensitive to longitudinal expansion



Ribeiro *et. al.*, arXiv: 2305.02428

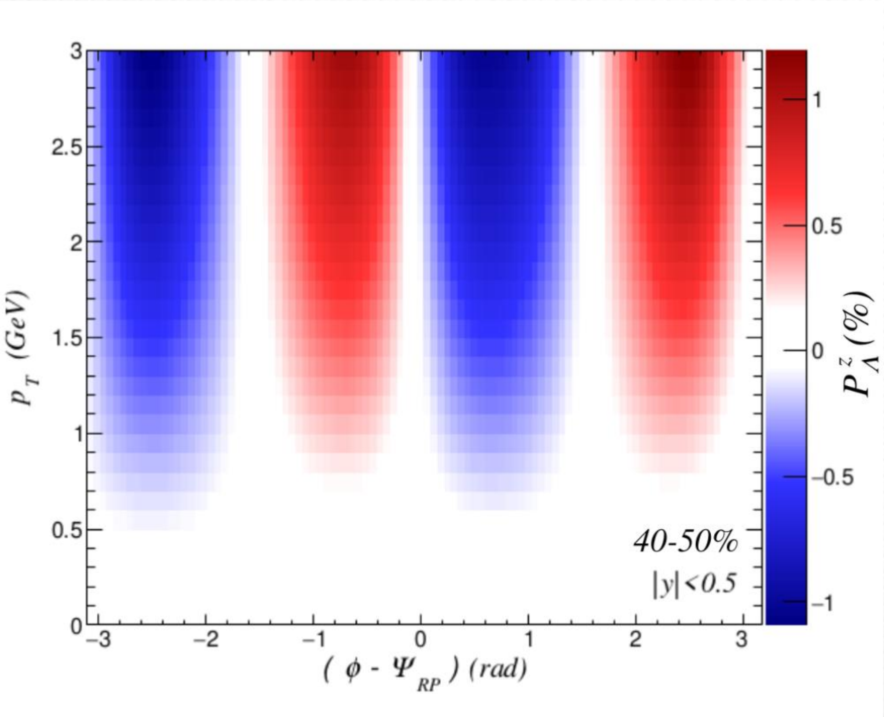
Fluctuation of position and orientation of thermal current



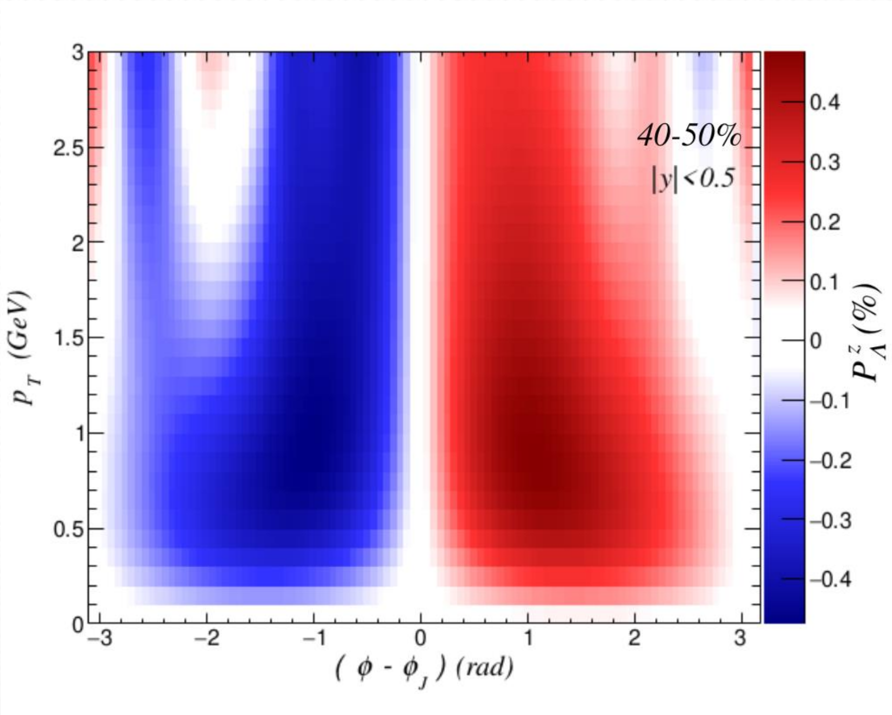
- Polarization magnitude increased in peripherical systems (6-10 factor)
  - Due to shorter evolution time (less time to dissipate jet) and smaller background
- Change of hierarchy between R = 4.0 fm and R = 2.0 fm in outward edge
  - Due to smaller interaction between source term and medium
- Otherwise, the qualitative behavior remains unchanged

Transverse momentum dependency of longitudinal polarization

Background event only



Background+Source term



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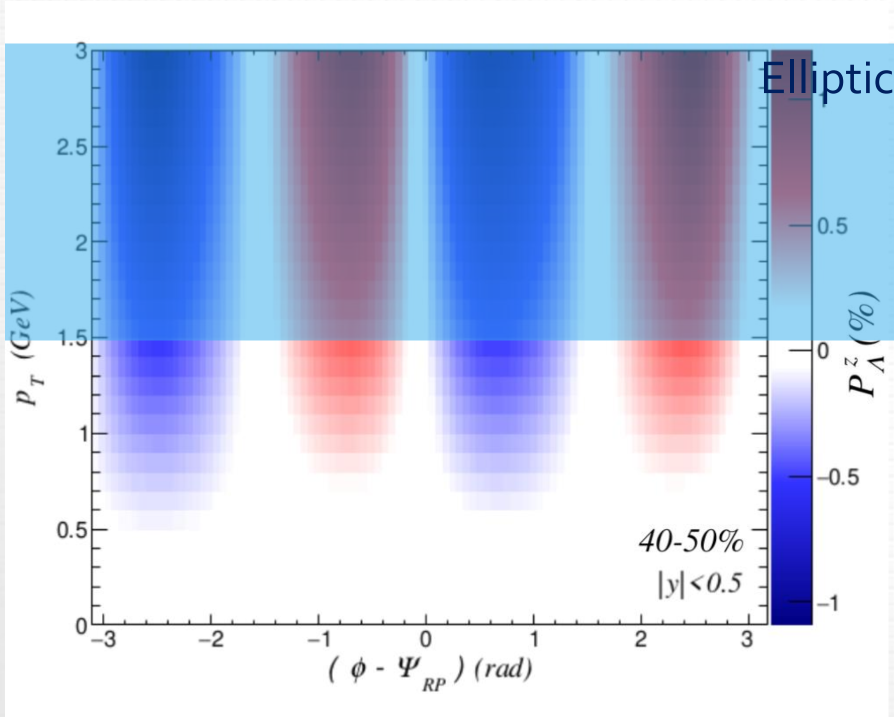
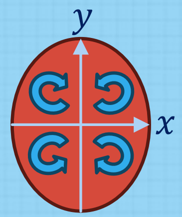
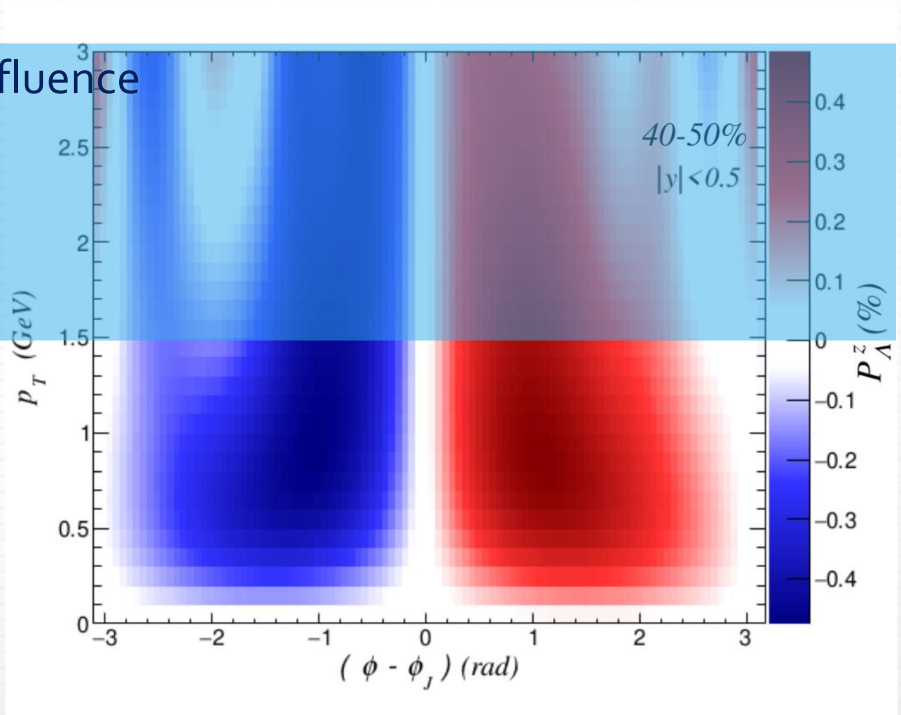


Elliptical flow Influence



Background+Source term



Transverse momentum dependency of longitudinal polarization

Background event only

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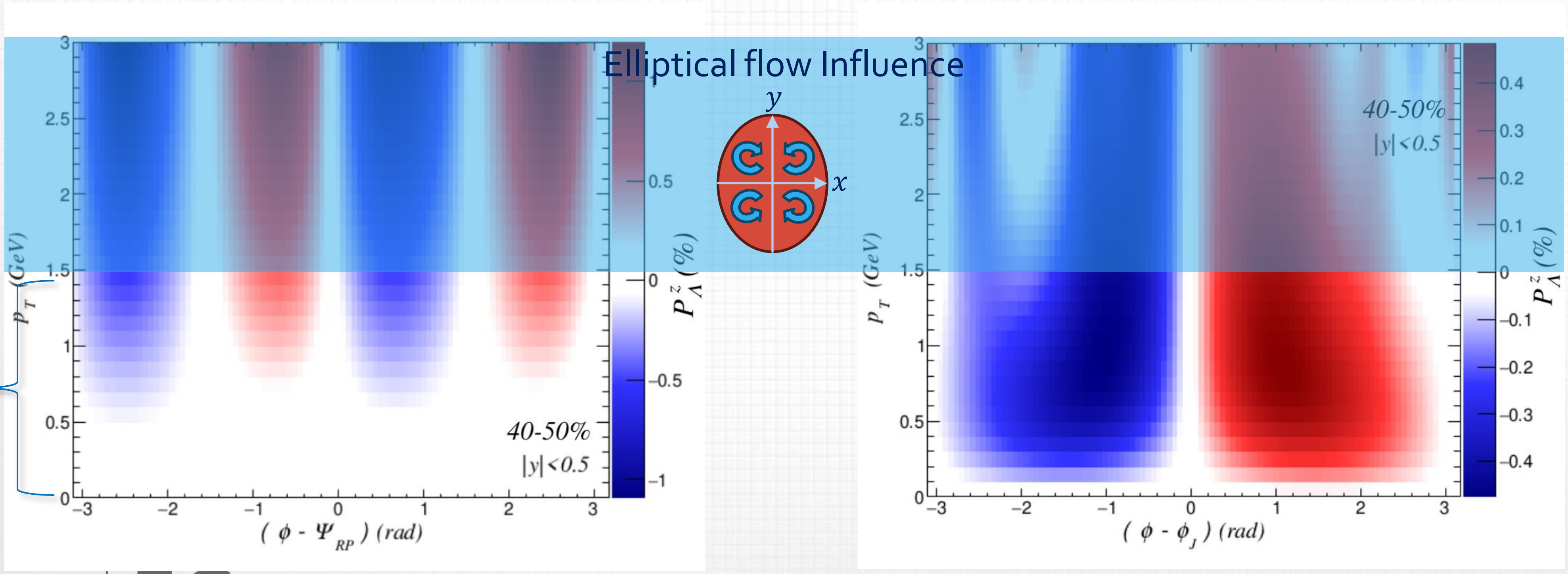
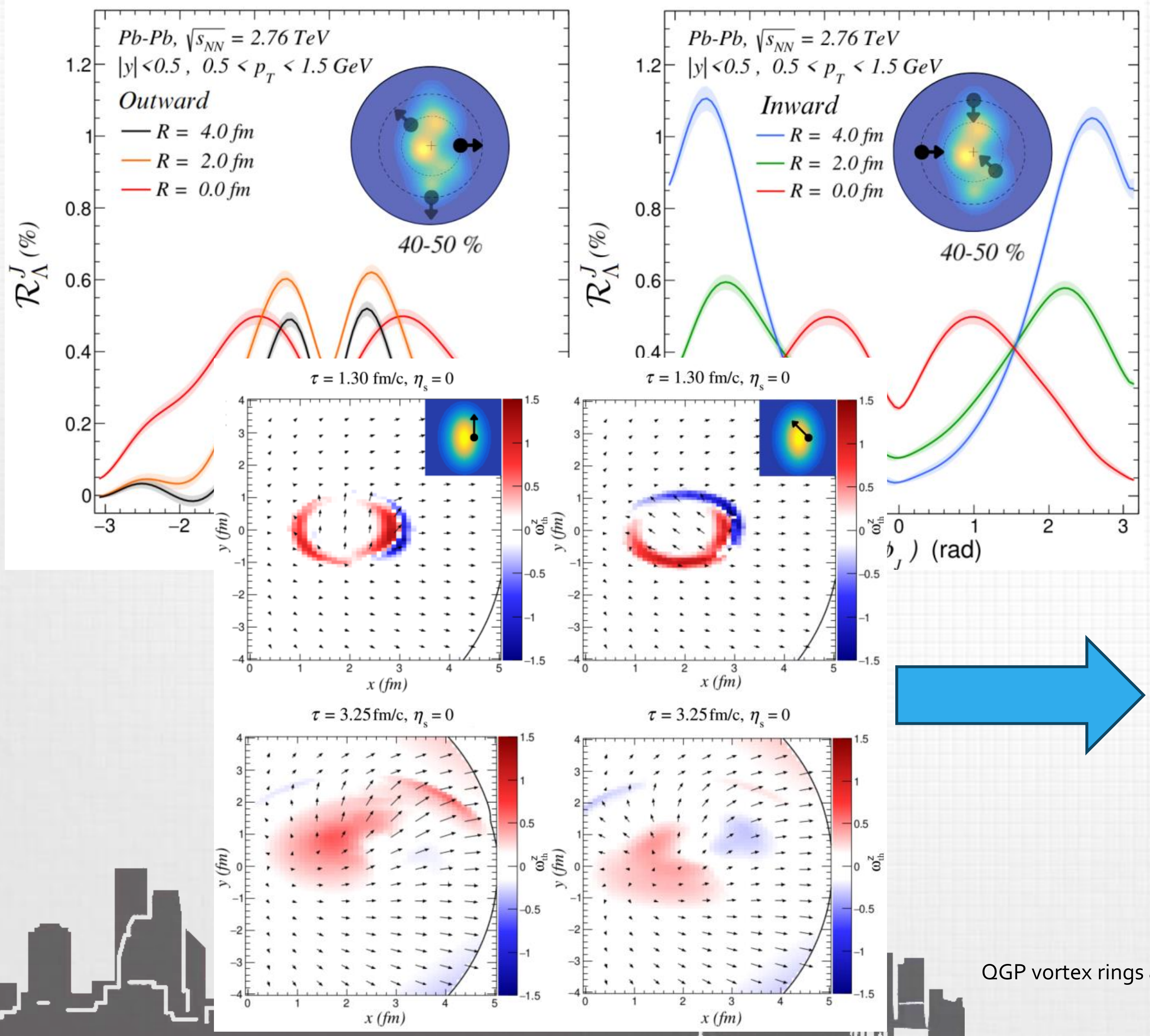


Motivates cut
$p_T < 1.5$ GeV/c

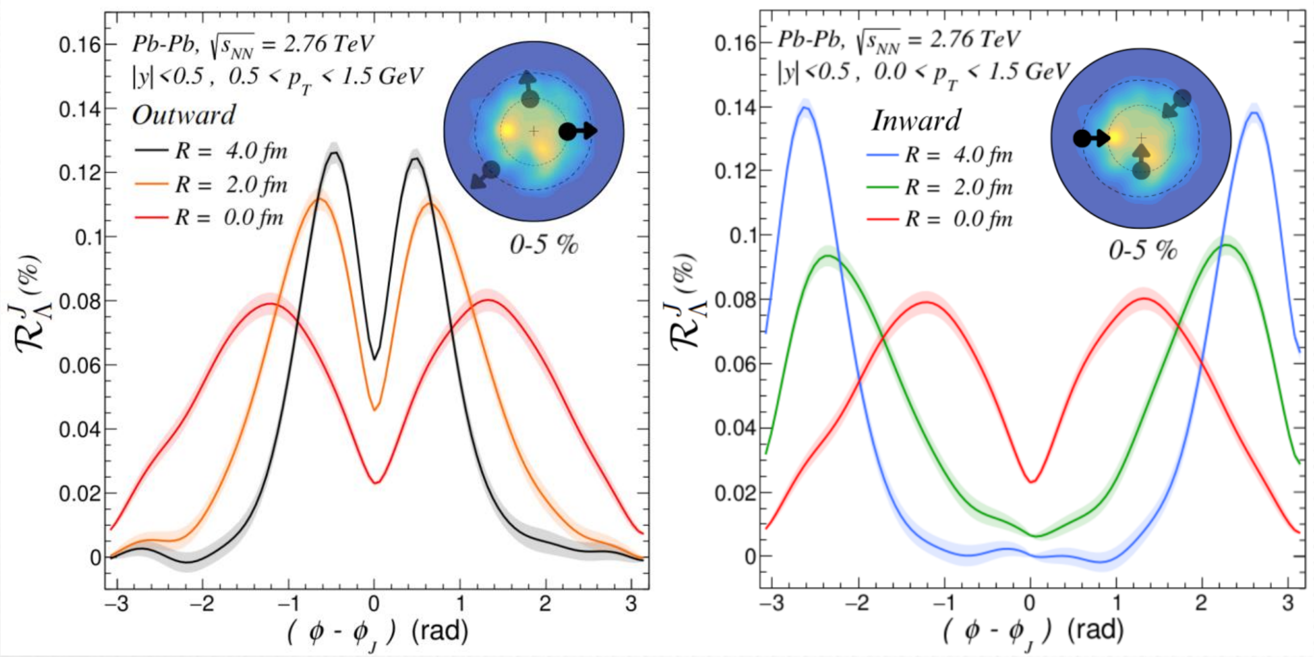
Fluctuation of position and orientation of thermal current



- Polarization magnitude increased in peripherical systems (6-10 factor)
  - Due to shorter evolution time (less time to dissipate jet)
- Change of hierarchy between R = 4.0 fm and R = 2.0 fm in outward edge
  - Due to smaller interaction between source term and medium
- Otherwise, the qualitative behavior remains unchanged

- Deposition in a direction transverse to flow deforms the vortex ring and significantly reduces the signal observed

Fluctuation of position and orientation of thermal current

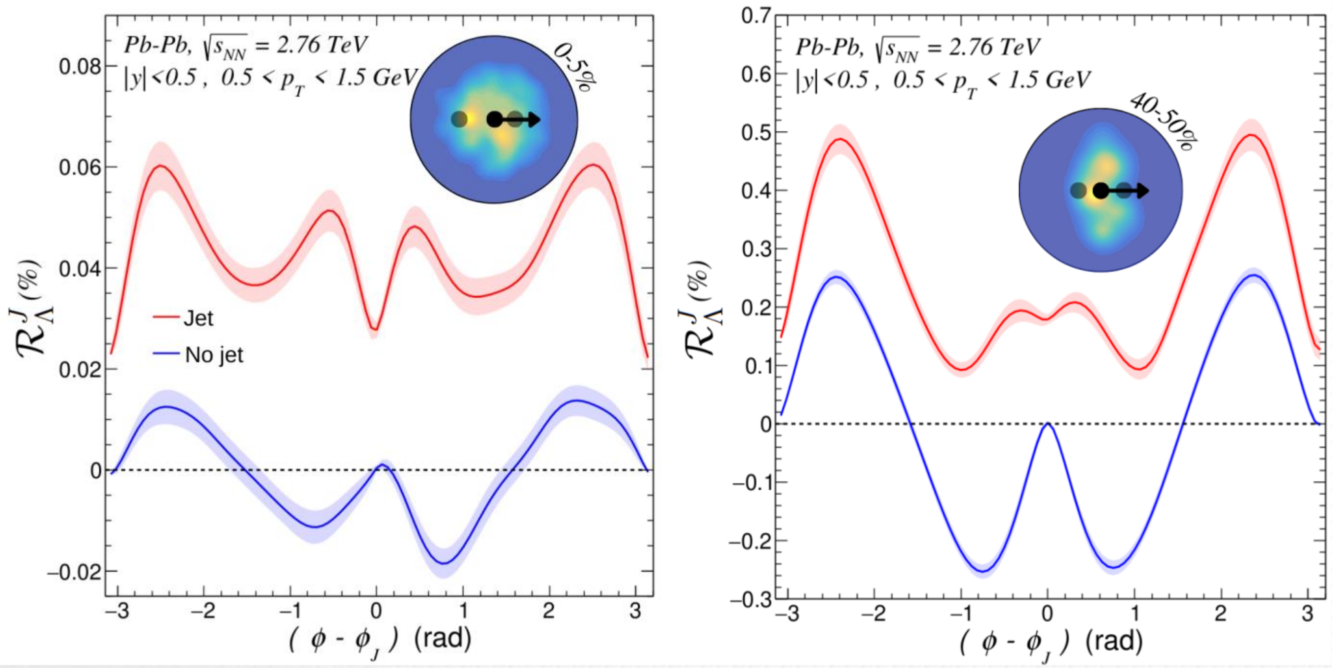


- Jets positioned in the outer layers generates stronger vorticity due to proximity with particlization surface.
- Competing effects:
  - Inward deposition generate larger gradients, hence larger polarization (blue vs black curve)
  - Meanwhile, particlization surface takes longer to reach it, giving more time to dissipation
  - Opposite is true to outward deposition

- Distance between peaks is proxy of vortex size
  - Jets "inside" the event are subject to system expansion longer and results in bigger vortices

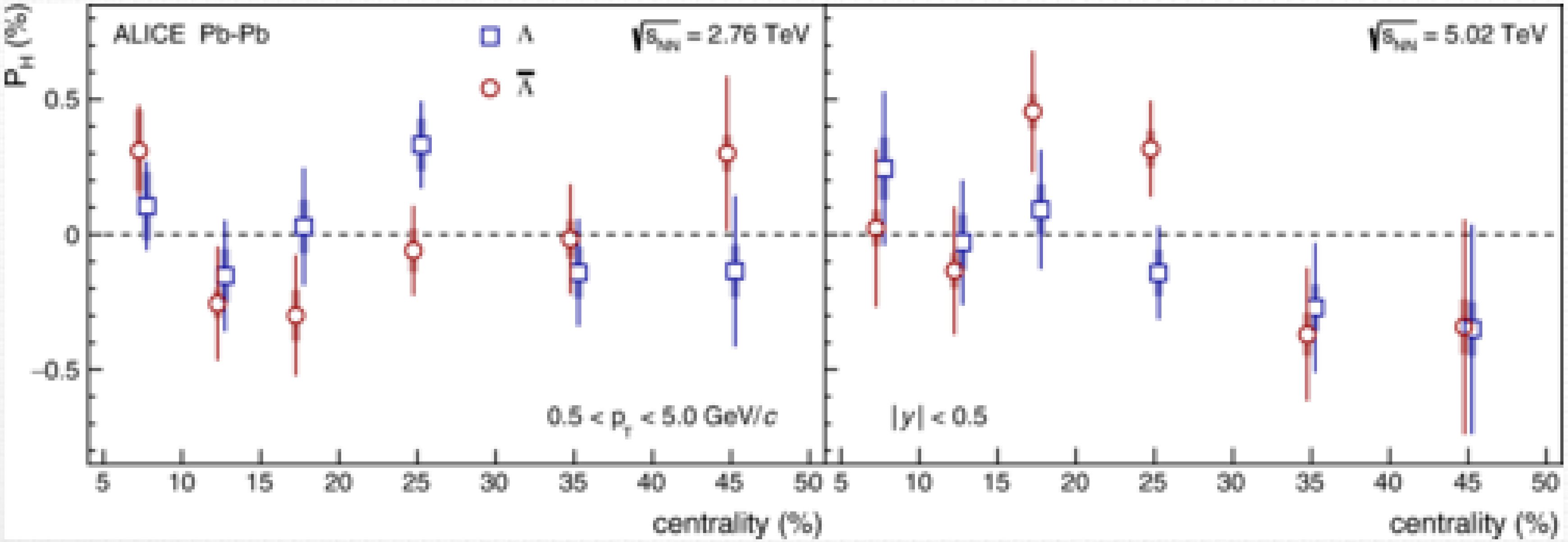
- Vortex is clustered around jet direction in outward scenario vs in its opposite direction due to angle between particlization surface and vortex ring

Fluctuation of position and orientation of thermal current



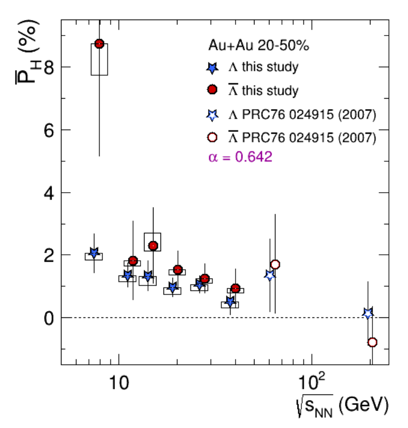
Approximately constant increase in the ring observable when compared to no jet events

ALICE Data on Polarization

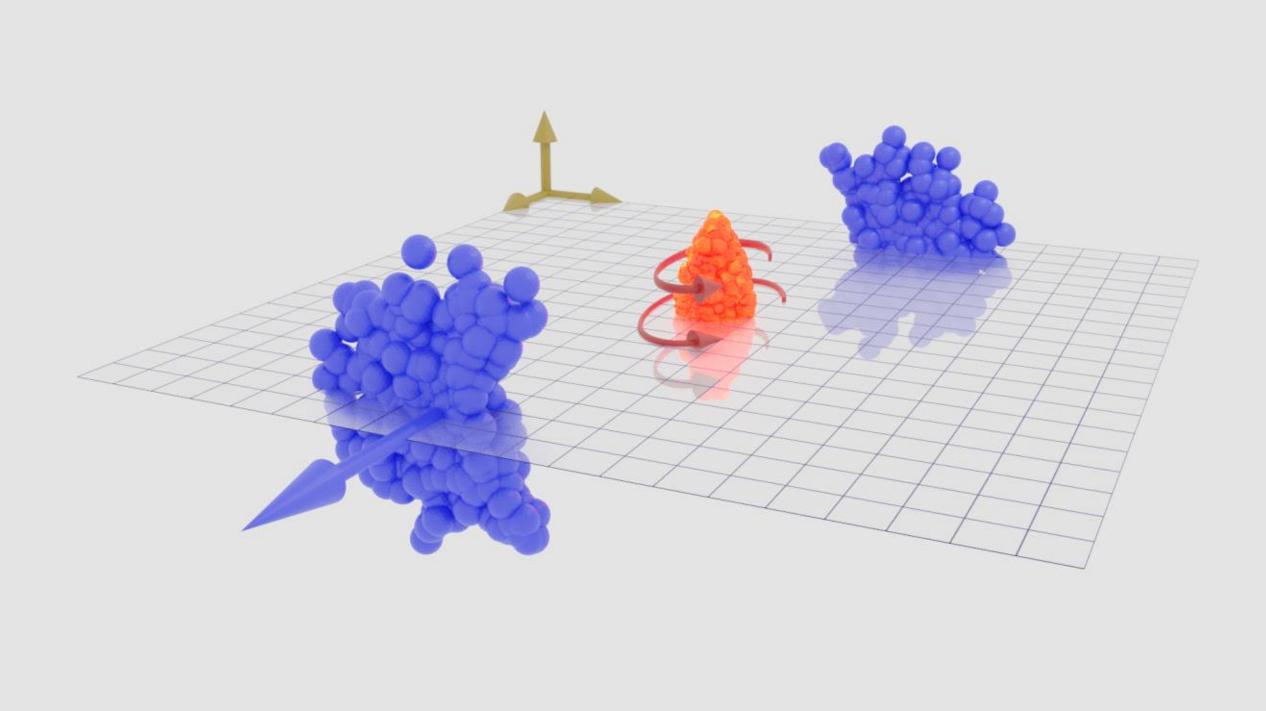


S. Acharya et al. (ALICE Collaboration) Phys. Rev. C **101**, 044611

Vorticity in the QGP



Nature 548 (2017) 62-65, 2017.



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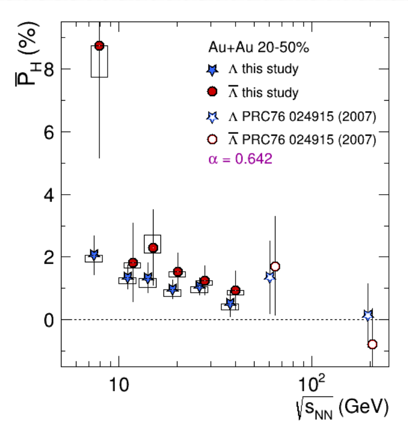
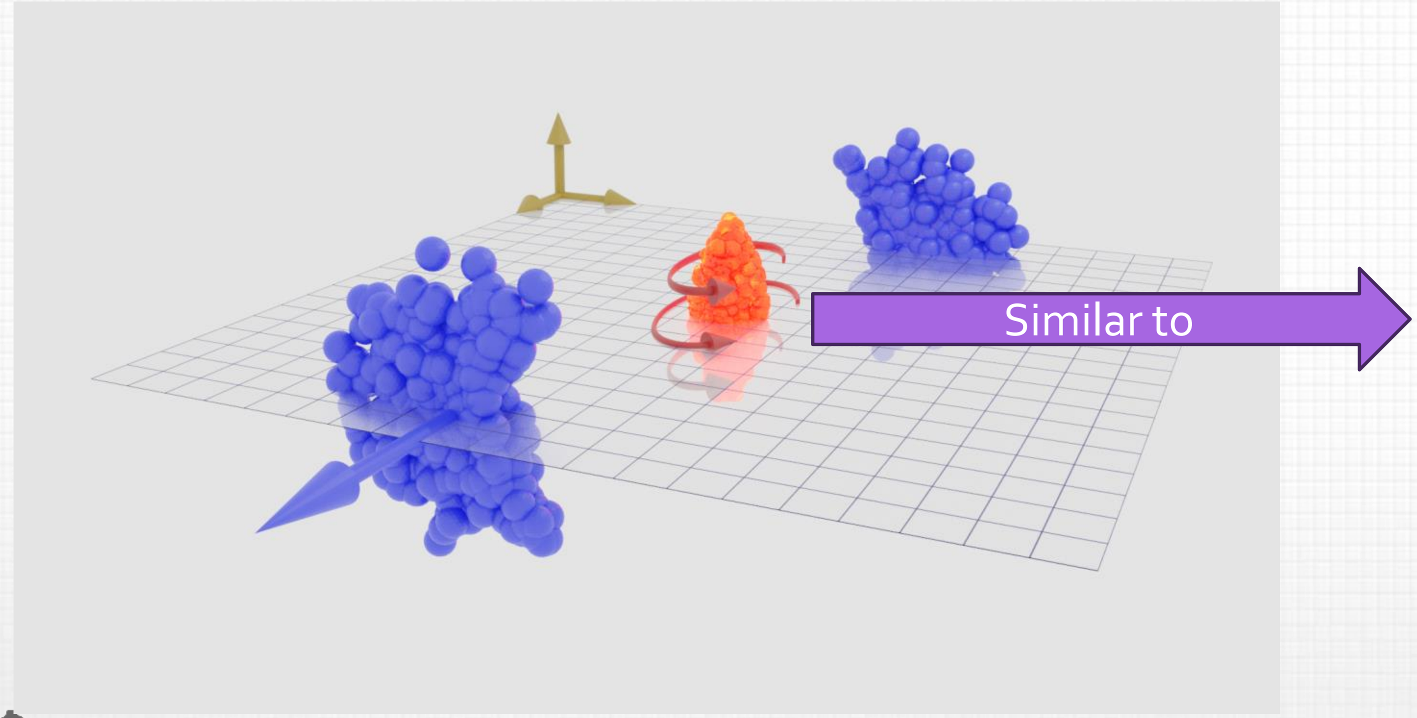


L. Adamczyck *et. al.* [STAR], Nature 548 (2017) 62-65, 2017.



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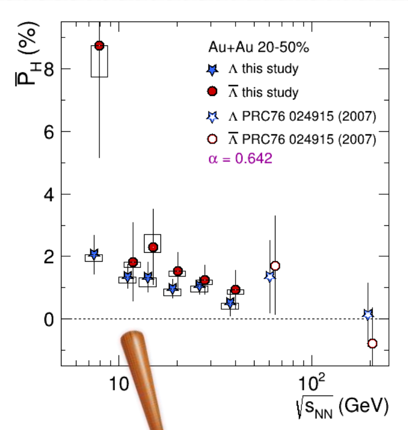
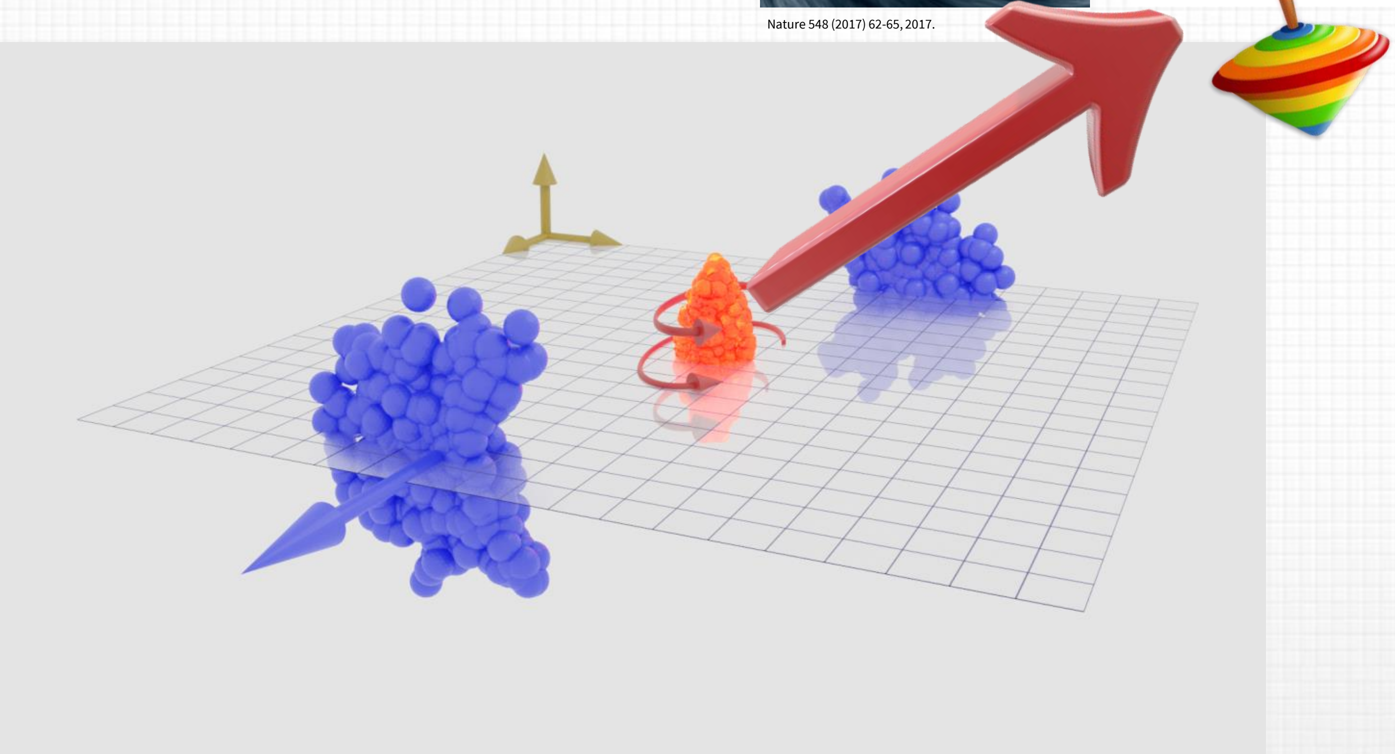




Vortex phenomena is ubiquitous in hydrodynamic-like systems

Vortex phenomena is ubiquitous in hydrodynamic-like systems


Author: NASA Goddard Space Flight Center from Greenbelt, MD, USA

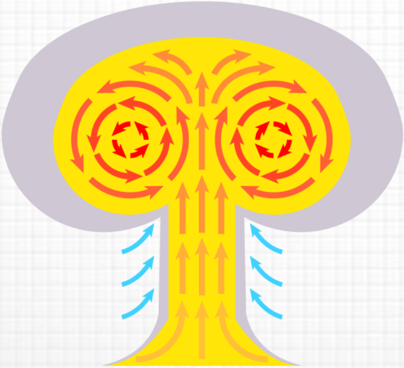

Source: NOAA Photo Library


https://commons.wikimedia.org/wiki/File:Delphinapterus_leucas_Bubble_Ring.JPG


https://en.wikipedia.org/wiki/File:DSC0856_(40742118092).jpg

Vortex phenomena is ubiquitous in hydrodynamic-like systems

Atomic blast Nevada Yucca 1951 (NNSA)



https://en.wikipedia.org/wiki/File:Mushroom_cloud.svg

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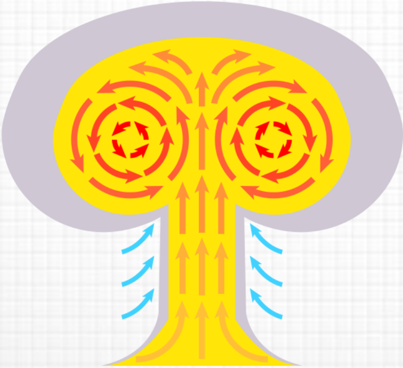

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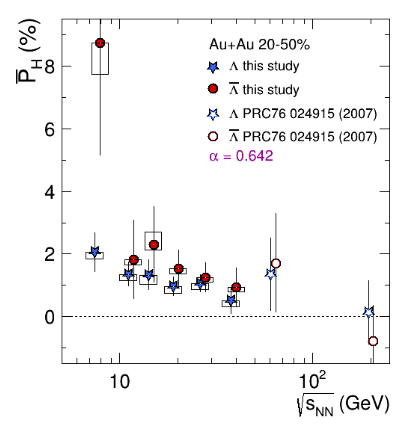

Nature 548 (2017) 62-65, 2017.