Toroidal vorticity in the QGP

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Phys. Rev. **C104** (2021) 1, 011901
Phys. Lett. **B820** (2021) 136500
arxiv:2305.02428 – submitted to PRC
arxiv:2309xxxx. – to be submitted to PRC

João Prado Barbon, David D. Chinellato, MAL, Vítor H. Ribeiro,
Willian M. Serenone, Chun Shen, Jun Takahashi, Giorgio Torrieri
(3C Collaboration)

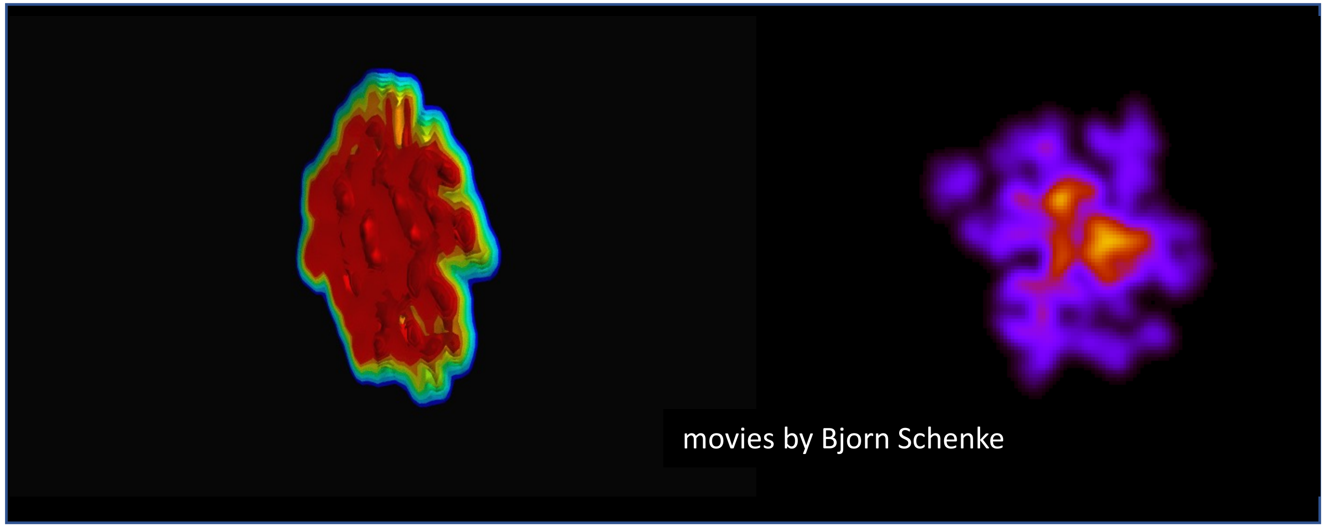
Outline

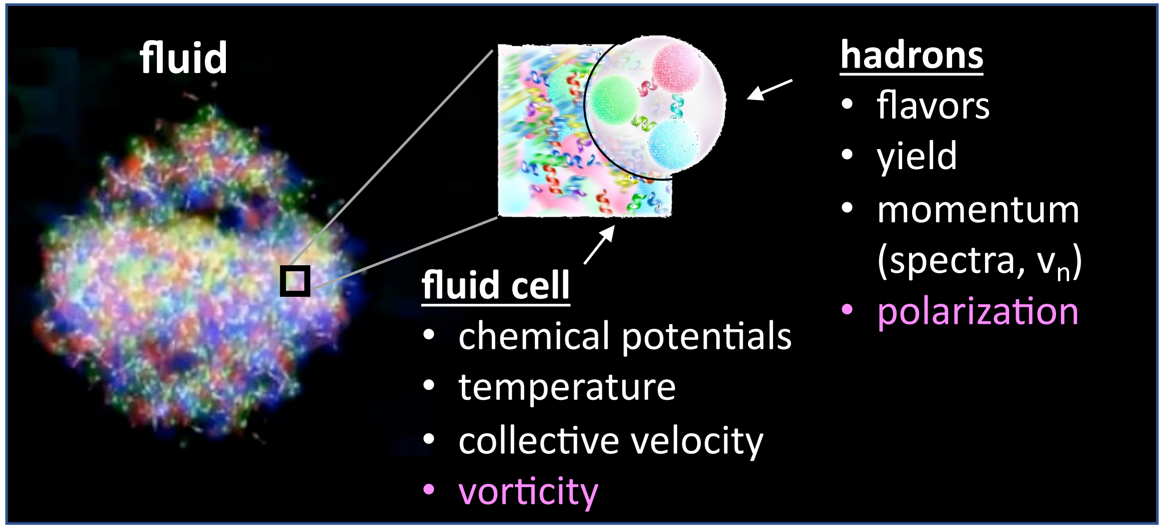
- Vorticity patterns in “undisturbed” hot QCD matter – seen and not-yet seen
  - global; longitudinal; circular

- Vortical toroids (“smoke rings”) around a disturbance
  - “jets” (bullet disturbances in fluid)
  - p+A

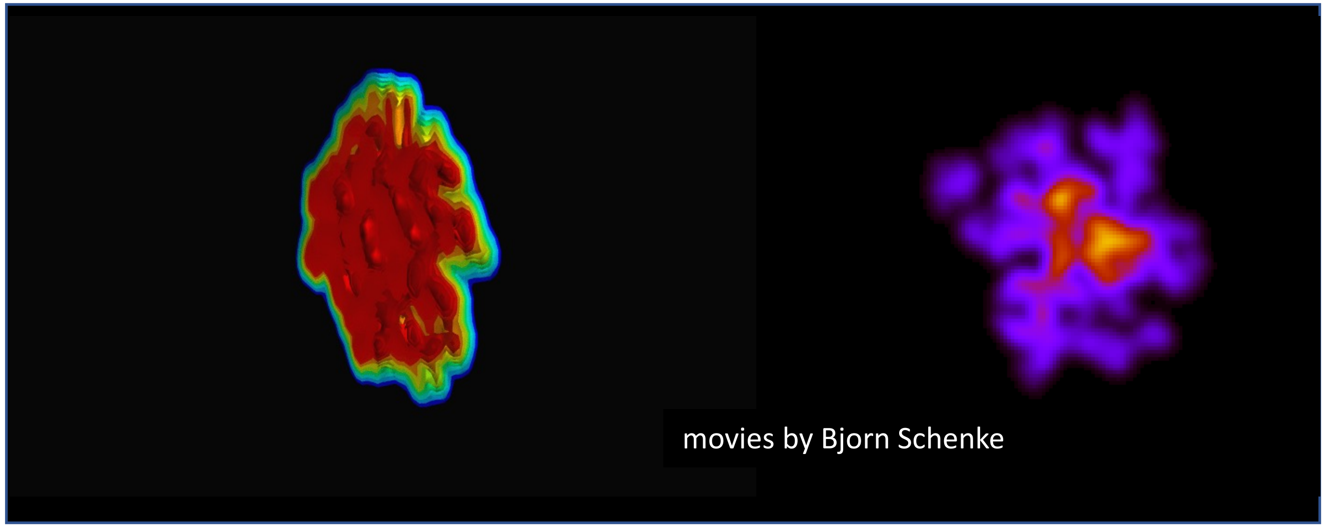
- Summary

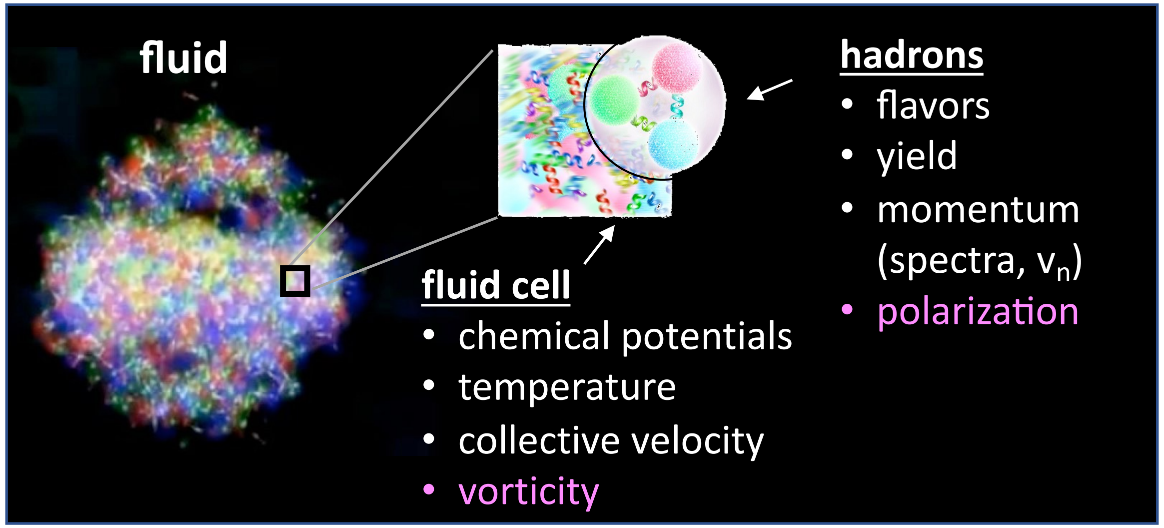
Hydrodynamic substructure imprinted upon hadrons

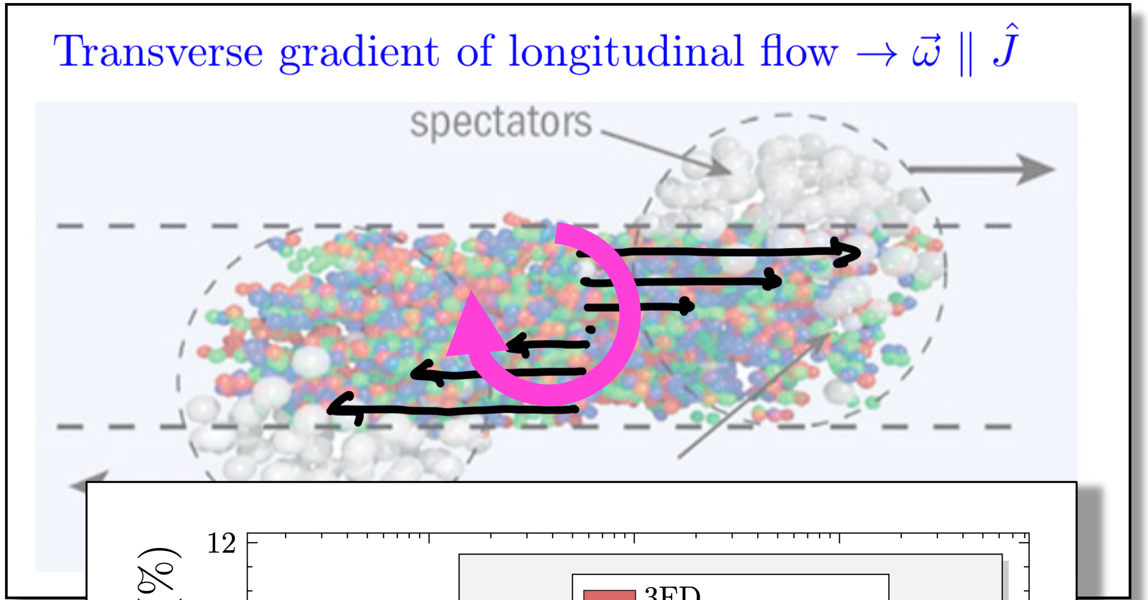


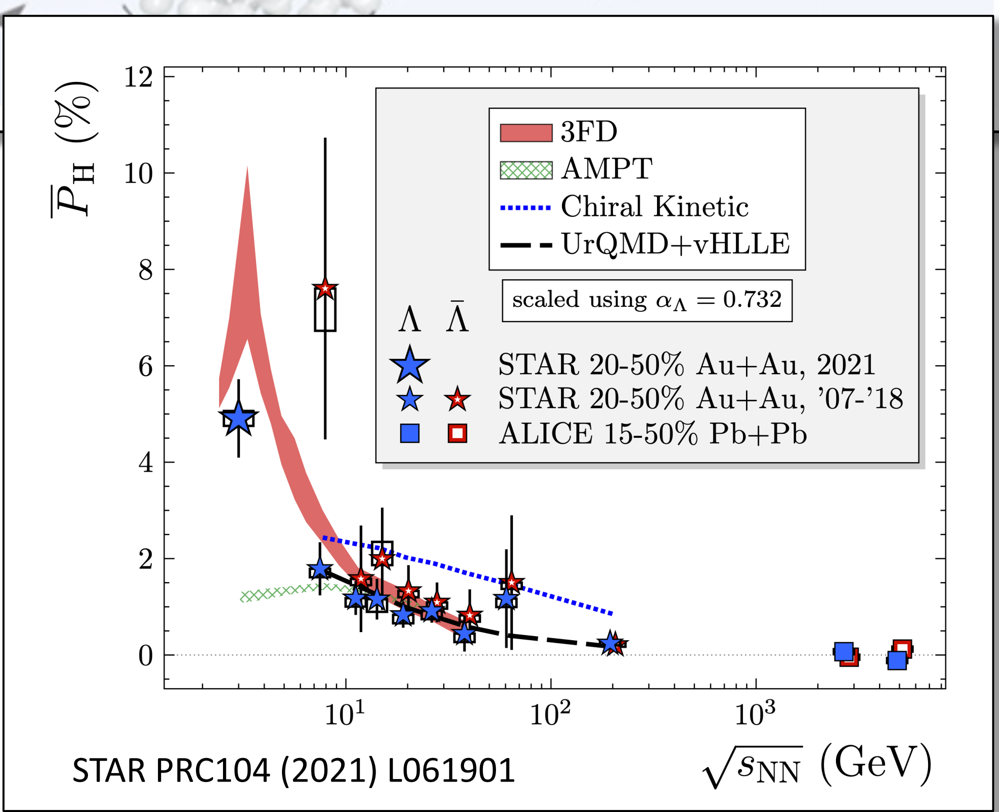


Polarization patterns in heavy ion collisions



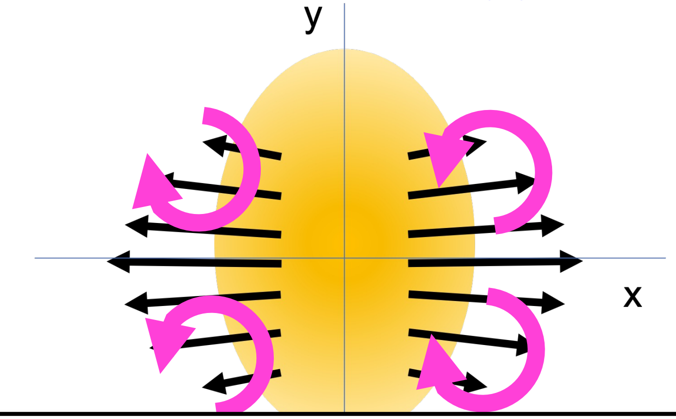


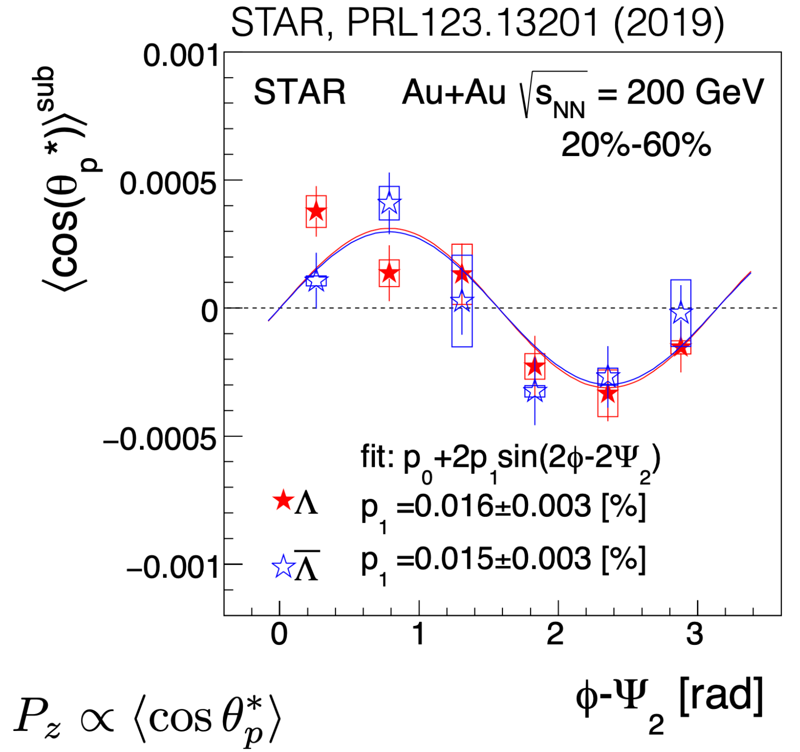




Polarization patterns in heavy ion collisions- seen

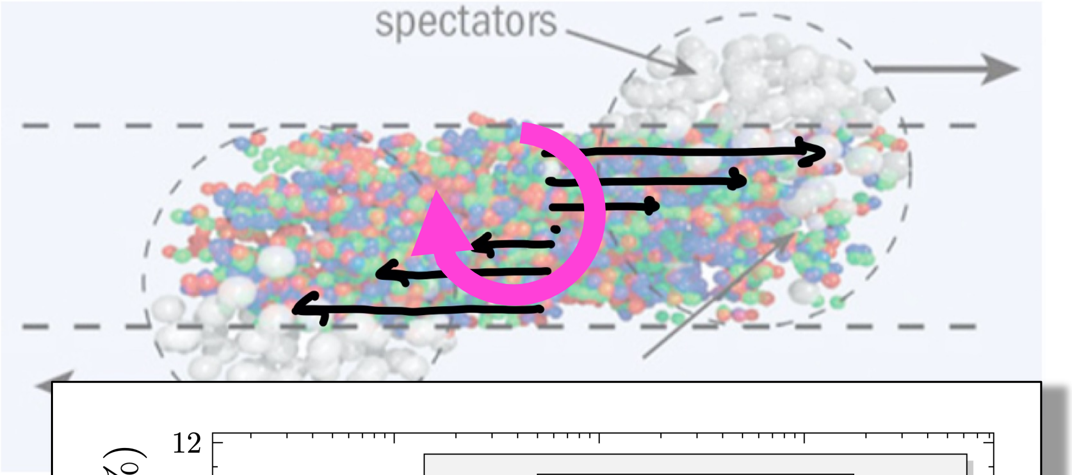
x (y) gradient of transverse-y (x) flow $\rightarrow \vec{\omega} \parallel \pm\hat{z}$

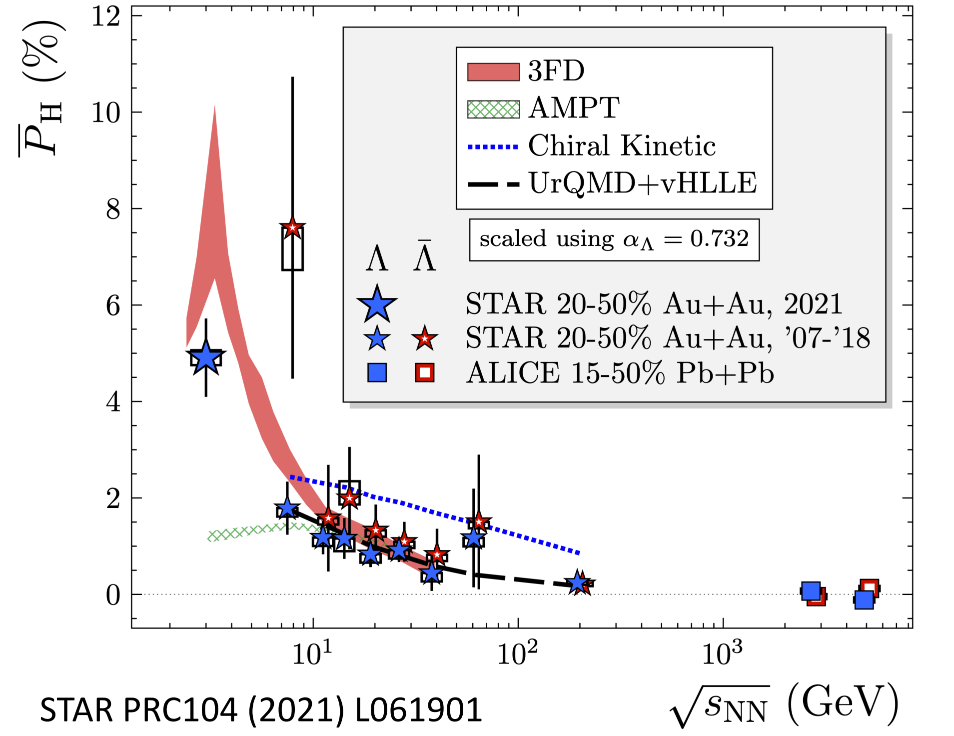




$P_z \propto \langle\cos\theta_p^*\rangle$

Transverse gradient of longitudinal flow $\rightarrow \vec{\omega} \parallel \hat{J}$

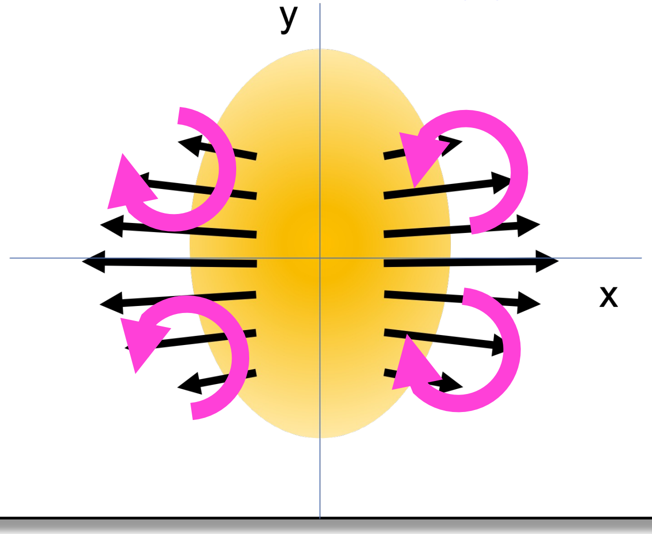




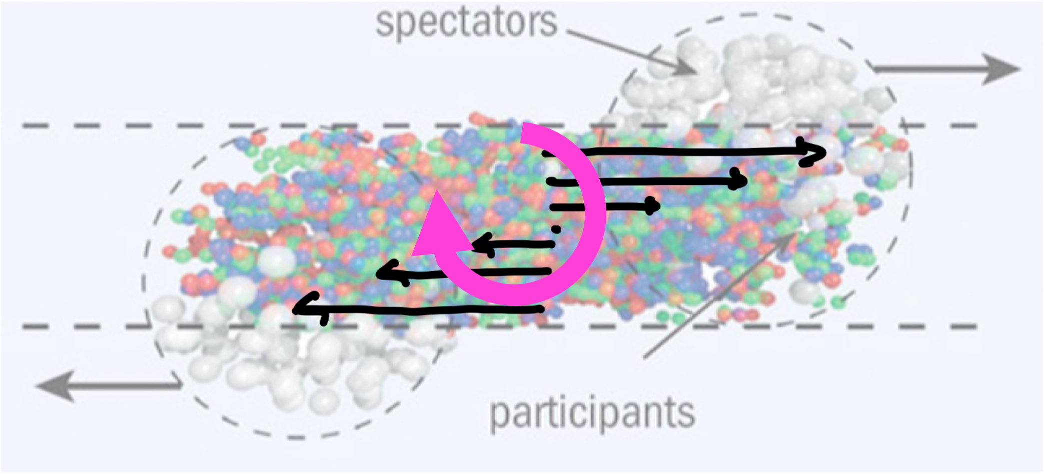
STAR PRC104 (2021) L061901

Polarization patterns in heavy ion collisions - seen & not yet seen

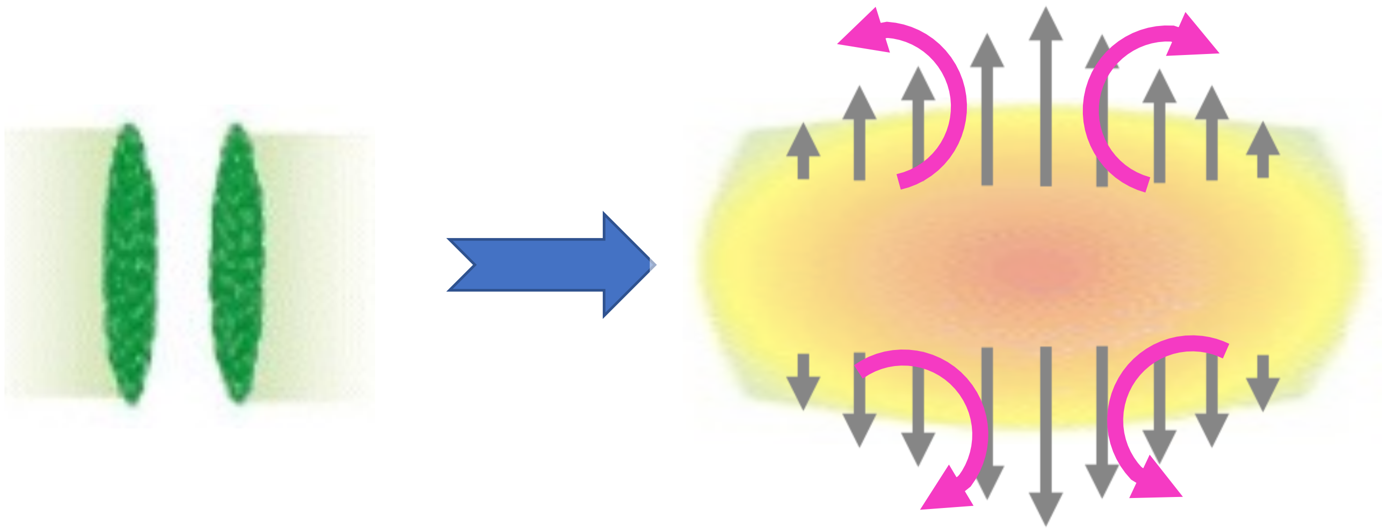
x (y) gradient of transverse-y (x) flow $\rightarrow \vec{\omega} \parallel \pm\hat{z}$



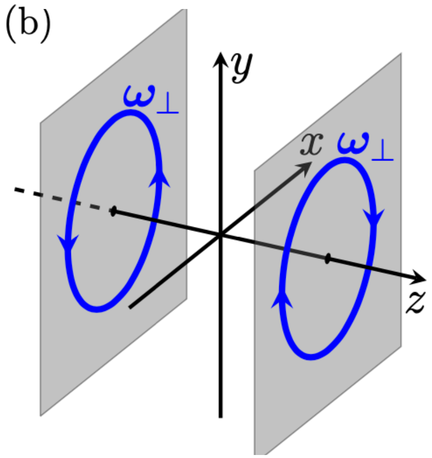
Transverse gradient of longitudinal flow $\rightarrow \vec{\omega} \parallel \hat{J}$



Longitudinal gradient of transverse flow (& temperature) $\rightarrow$ ring structure of $\vec{\omega}$

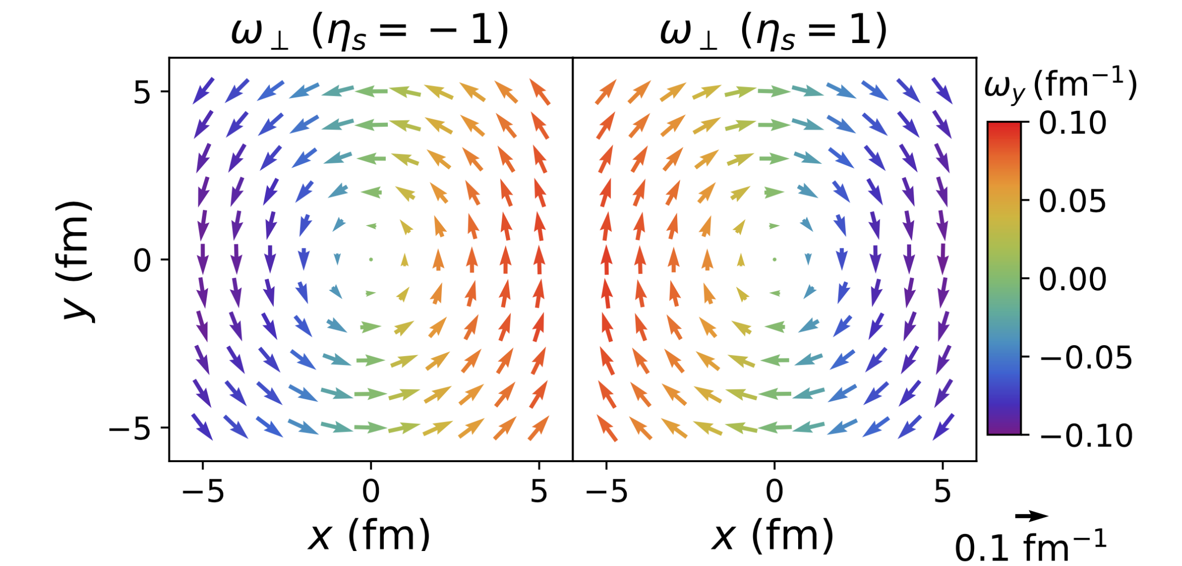


$\vec{\omega} \parallel \vec{p} \cdot \hat{z}\, (\vec{p} \times \hat{z})$



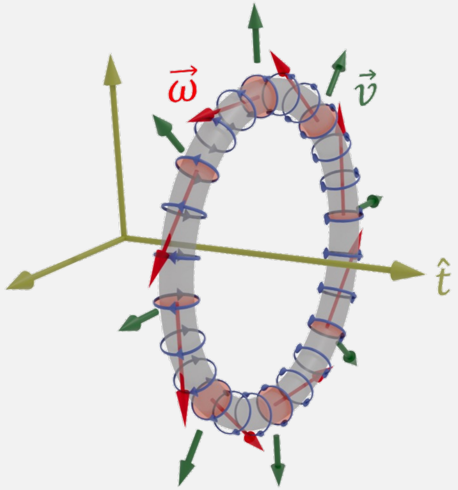
Xia, Li, Tang, Wang PRC 98, 024905 (2018)

Polarization patterns in heavy ion collisions- seen & not yet seen



Xia, Li, Tang, Wang PRC 98, 024905 (2018)

quantifying circular polarization structure

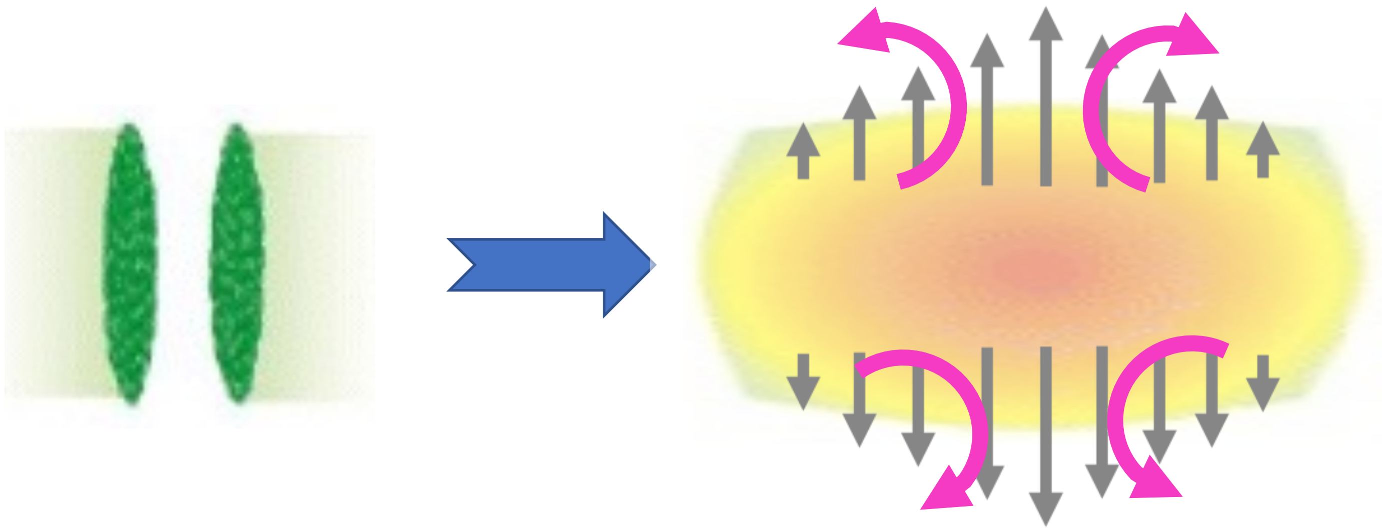


$$\overline{\mathcal{R}}^{\hat{t}}_{\rm NR} \equiv \left\langle \frac{\vec{\omega}_{\rm NR} \cdot (\hat{t} \times \vec{v}_{\rm cell})}{|\hat{t} \times \vec{v}_{\rm cell}|} \right\rangle_\phi$$

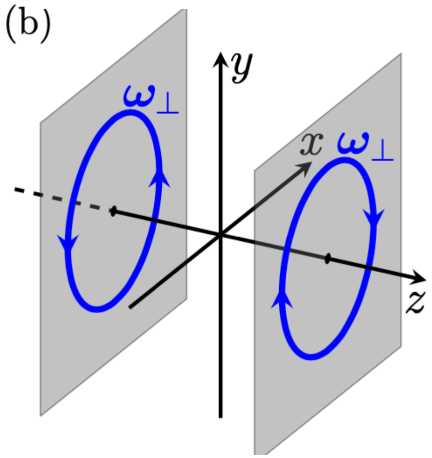
$$\mathcal{R}^{\hat{t}}_{\rm fluid} \equiv \frac{\epsilon^{\mu\nu\rho\sigma}\Omega_\mu n_\nu \hat{t}_\rho u_\sigma}{|\epsilon^{\mu\nu\rho\sigma} n_\nu \hat{t}_\rho u_\sigma|}$$

PRC104 (2021) 011901

Longitudinal gradient of transverse flow (& temperature) → ring structure of $\vec{\omega}$



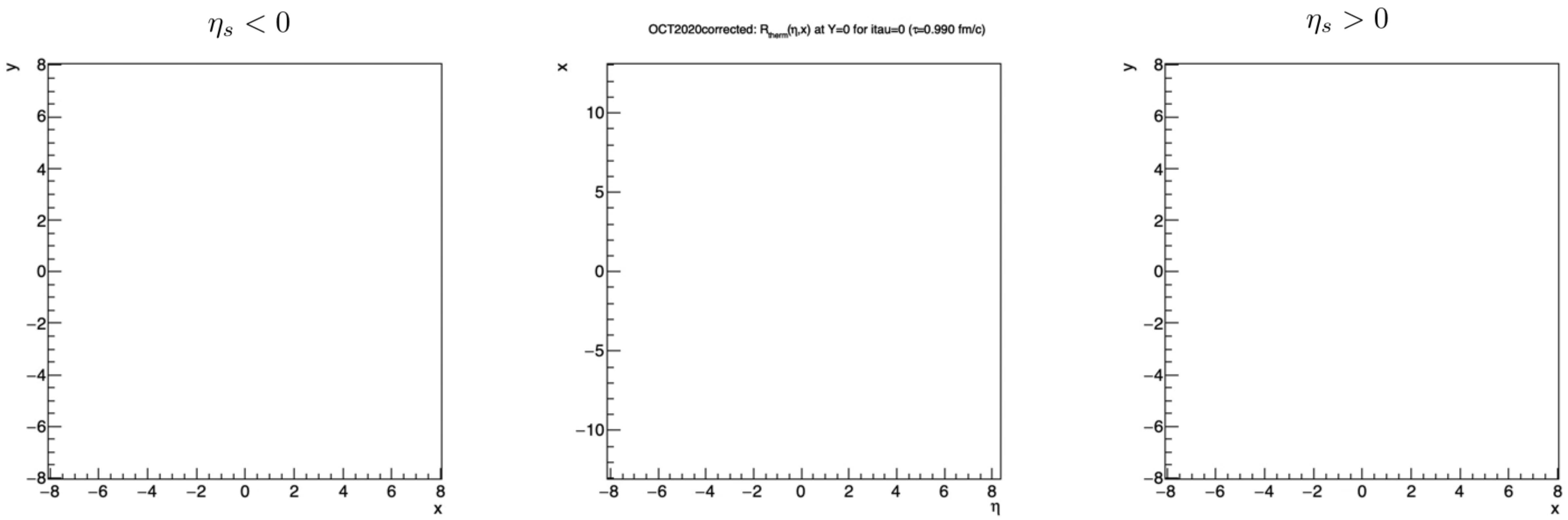
$\vec{\omega} \parallel \vec{p} \cdot \hat{z}\,(\vec{p} \times \hat{z})$



Xia, Li, Tang, Wang PRC 98, 024905 (2018)

Development of toroidal vorticity in MUSIC

Au+Au at 200 GeV Bjorken flow profile



$\vec{\omega}$ (red arrow) $\vec{u}_{\rm cell}$ (green arrow)

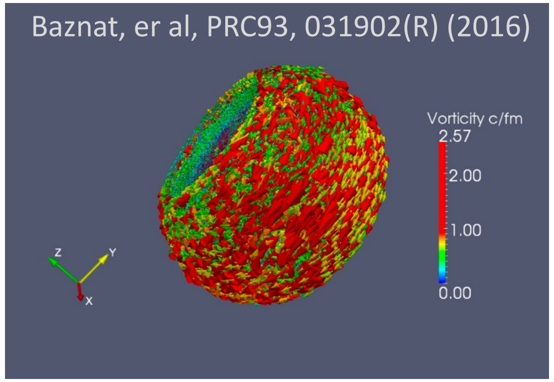
MUSIC hydrodynamics, with baryon currents
Schenke, Jeon, Gale PRC82 (2010) 014903
Schenke, Shen, Tribedy PRC102 (2020) 044905

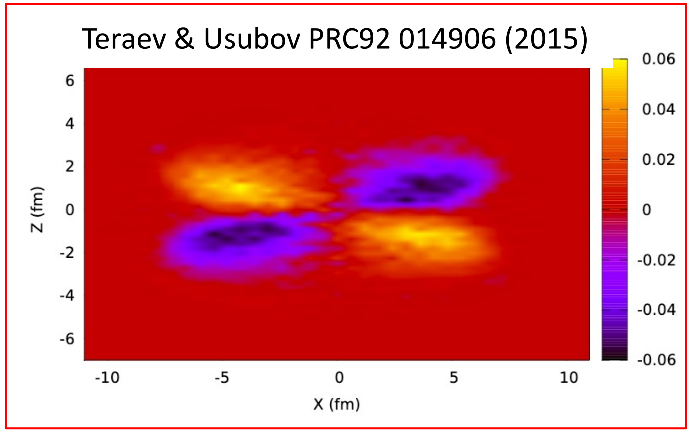
color axis: $\overline{\mathcal{R}}^{\hat{t}}_{\rm NR} \equiv \left\langle \frac{\vec{\omega}_{\rm NR} \cdot (\hat{t} \times \vec{v}_{\rm cell})}{|\hat{t} \times \vec{v}_{\rm cell}|} \right\rangle_\phi$ ➡ $\mathcal{R}^{\hat{t}}_{\rm fluid} \equiv \frac{\epsilon^{\mu\nu\rho\sigma}\Omega_\mu n_\nu \hat{t}_\rho u_\sigma}{|\epsilon^{\mu\nu\rho\sigma} n_\nu \hat{t}_\rho u_\sigma|}$

Rings predicted at all energies– can they be observed?

- This is a unique predicted structure! Observation would represent a compelling demonstration of fluid structure at the extremes of rapidity & energy

$\sqrt{s_{NN}} = 5 \text{ GeV} \rightarrow y_{\text{beam}} \approx 1.5$

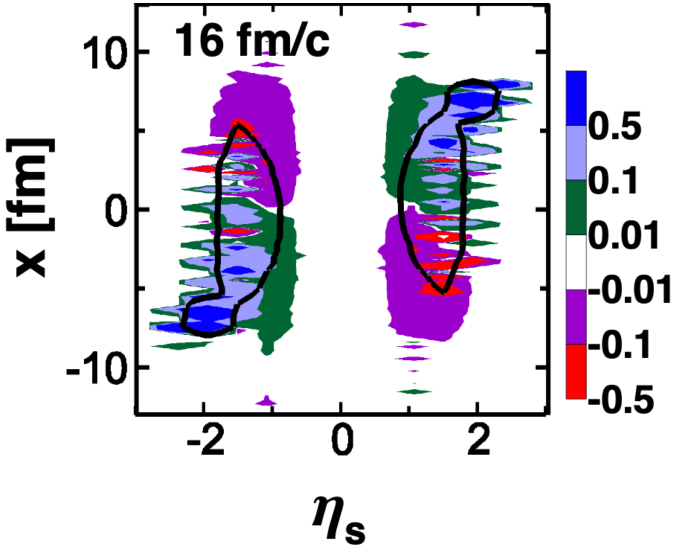




✓ Observable at HADES, STAR FXT (NICA??)

$\sqrt{s_{NN}} = 39 \text{ GeV} \rightarrow y_{\text{beam}} \approx 3.7$

Ivanov & Soldatov PRC97, 044915 (2018)

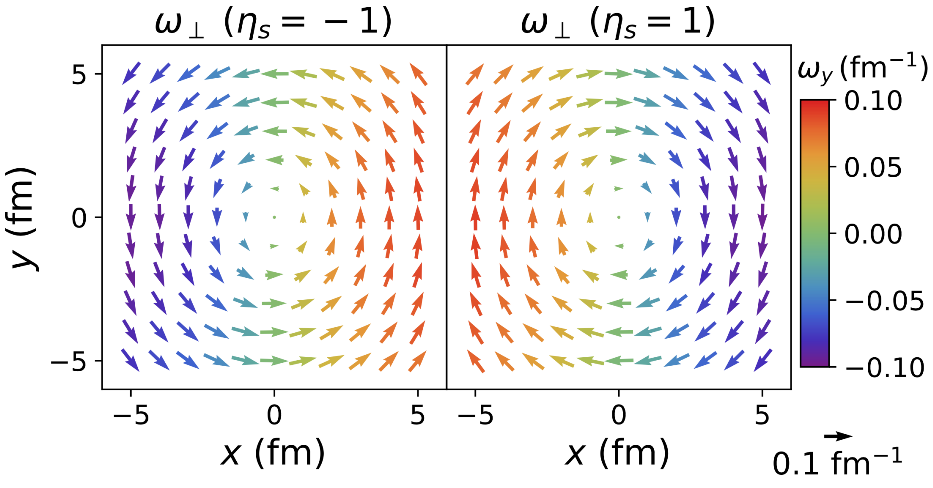


Focused forward

- in principle possible at STAR with forward tracking upgrade

$\sqrt{s_{NN}} = 200 \text{ GeV} \rightarrow y_{\text{beam}} \approx 5.4$

$\sqrt{s_{NN}} = 2700 \text{ GeV} \rightarrow y_{\text{beam}} \approx 8$



Xia, Li, Tang, Wang PRC98, 024905 (2018)

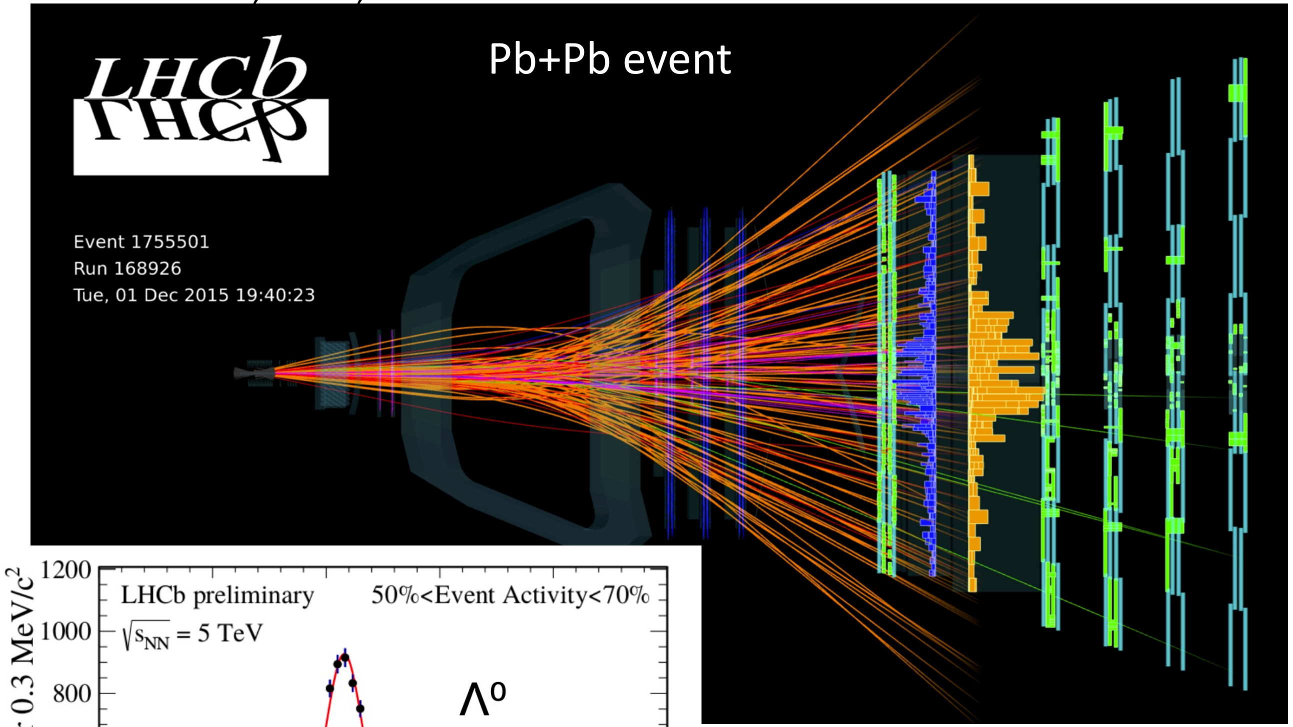
Focused forward

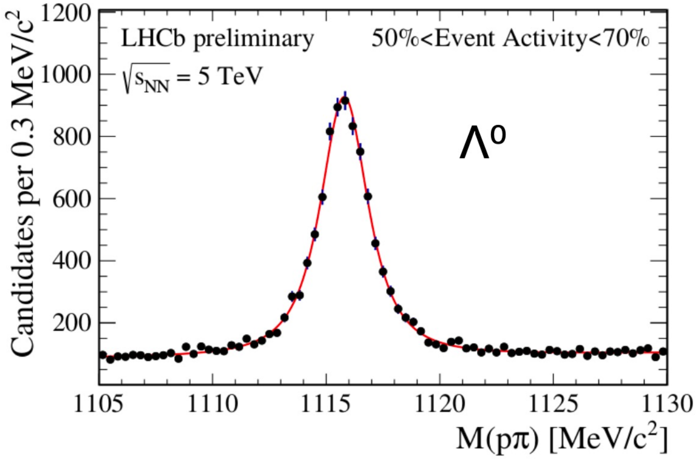
- difficult at STAR@RHIC or ATLAS/CMS/ALICE@LHC without forward tracking upgrade

Seeing the circular polarization

- This is a unique (& ubiquitous) predicted structure!
  Observation would represent a compelling demonstration of fluid structure at the extremes of rapidity & energy

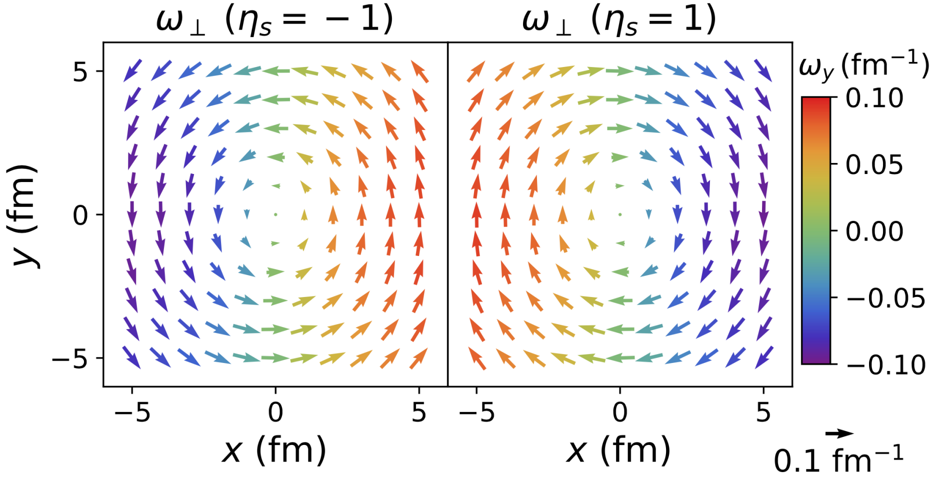
Michael Winn, ERICE, 2016





Note: No Event Plane Necessary!

$$\sqrt{s_{NN}} = 200\ \text{GeV} \rightarrow y_{\text{beam}} \approx 5.4$$
$$\sqrt{s_{NN}} = 2700\ \text{GeV} \rightarrow y_{\text{beam}} \approx 8$$



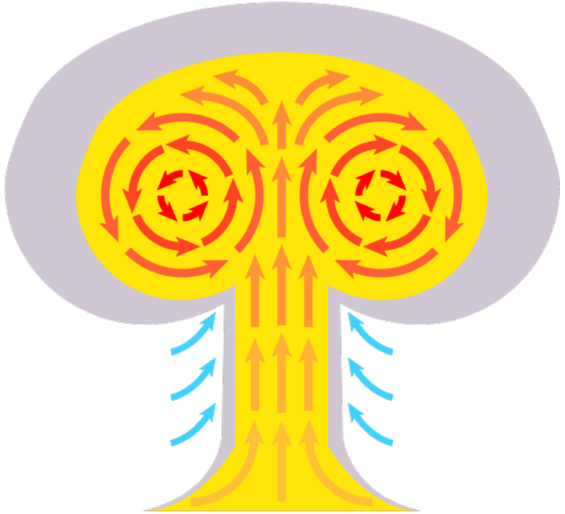
Focused forward

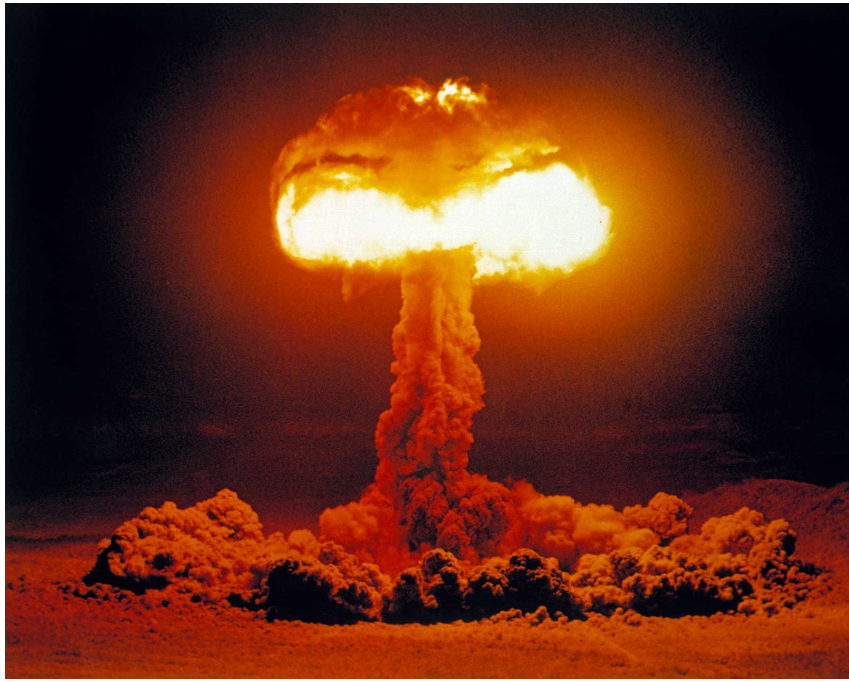
- Not possible at STAR@RHIC or ATLAS/CMS/ALICE@LHC without forward tracking upgrade

✓ LHCb ideal to observe this structure

observable: $R^z_\Lambda = \left\langle \frac{\vec{P}_\Lambda \cdot (\hat{z} \times \vec{p})}{|\hat{z} \times \vec{p}|} \right\rangle$

Polarization about a local disturbance





Helmholtz (1867): Persistent vortical toroids (smoke rings) are quintessential fluid behavior

Vortical Barbieheimer

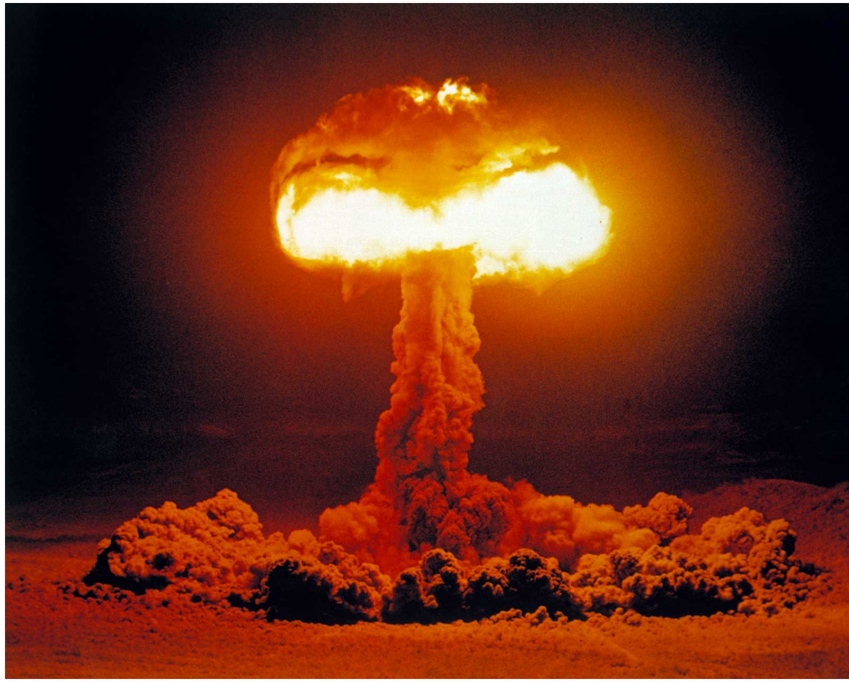
The Astrophysical Journal Letters, 948:L19 (11pp), 2023 May 10 https://doi.org/10.3847/2041-8213/accf1a

CrossMark

Scary Barbie: An Extremely Energetic, Long-duration Tidal Disruption Event Candidate without a Detected Host Galaxy at $z = 0.995$

Bhagya M. Subrayan[1], Dan Milisavljevic[1,2], Ryan Chornock[3], Raffaella Margutti[3], Kate D. Alexander[4], Vandana Ramakrishnan[1], Paul C. Duffell[1], Danielle A. Dickinson[1], Kyoung-Soo Lee[1], Dimitrios Giannios[1], Geoffery Lentner[1], Mark Linvill[1], Braden Garretson[1], Matthew J. Graham[5], Daniel Stern[6], Daniel Brethauer[3], Tien Duong[3], Wynn Jacobson-Galán[3], Natalie LeBaron[3], David Matthews[3], Huei Sears[7,8], and Padma Venkatraman[3]

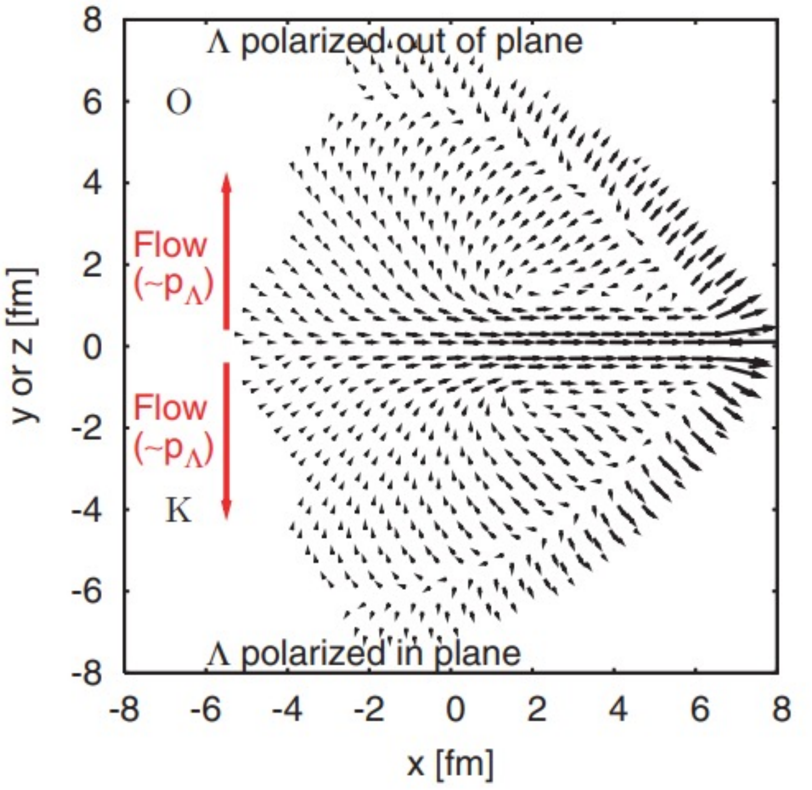
Thanks to Giorgio Torrieri for bringing Scary Barbie to my attention



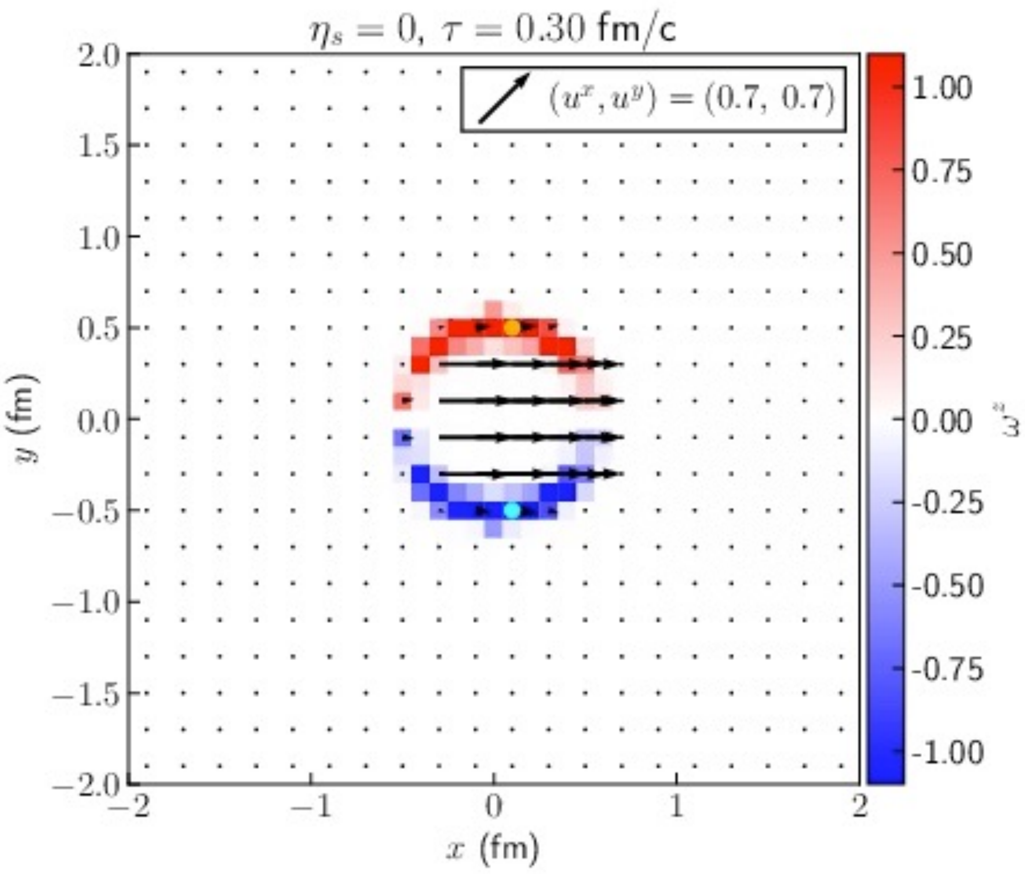
An artist's illustration of a black hole swallowing a star, the event that gave rise to Scary Barbie. (Image

Toroidal vortex structures around a "jet"

Local momentum density injected into QGP in HIC



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



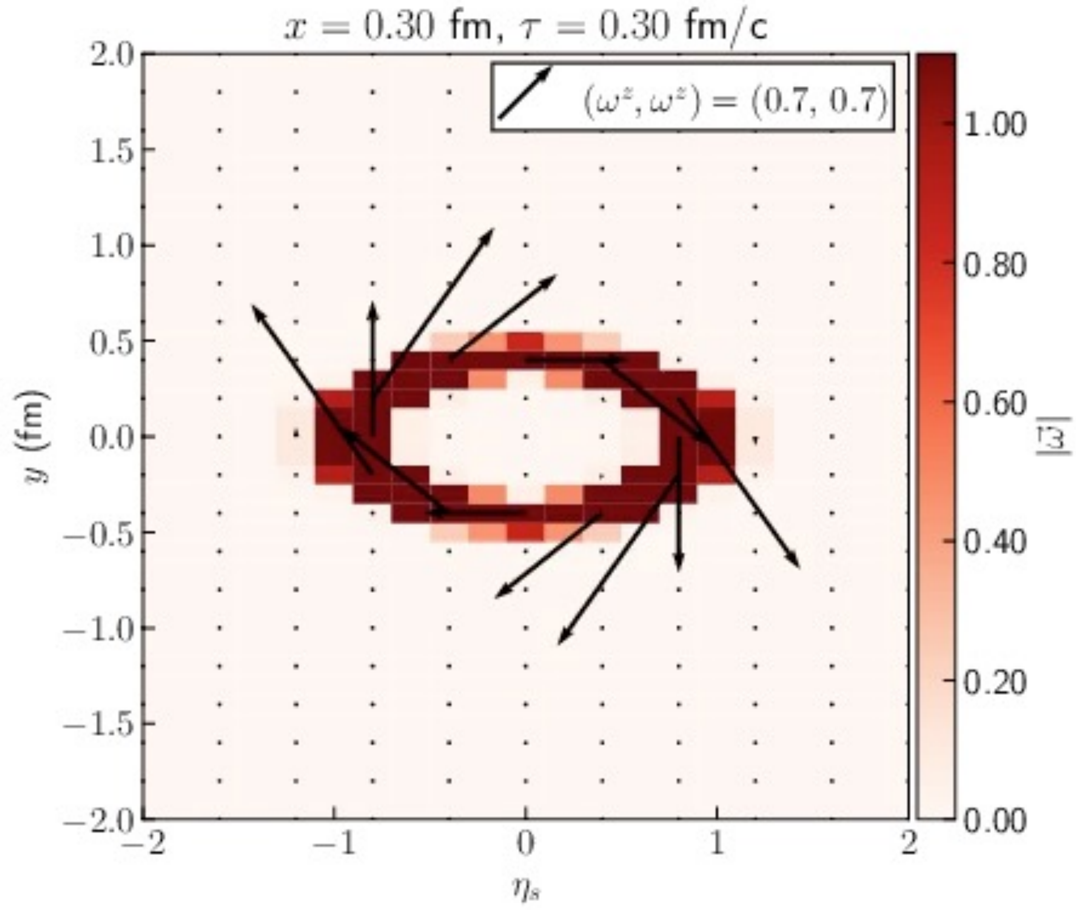
localized thrust to the right

Also: Tachibana/Hirano, NPA904-905 (2013) 1023c

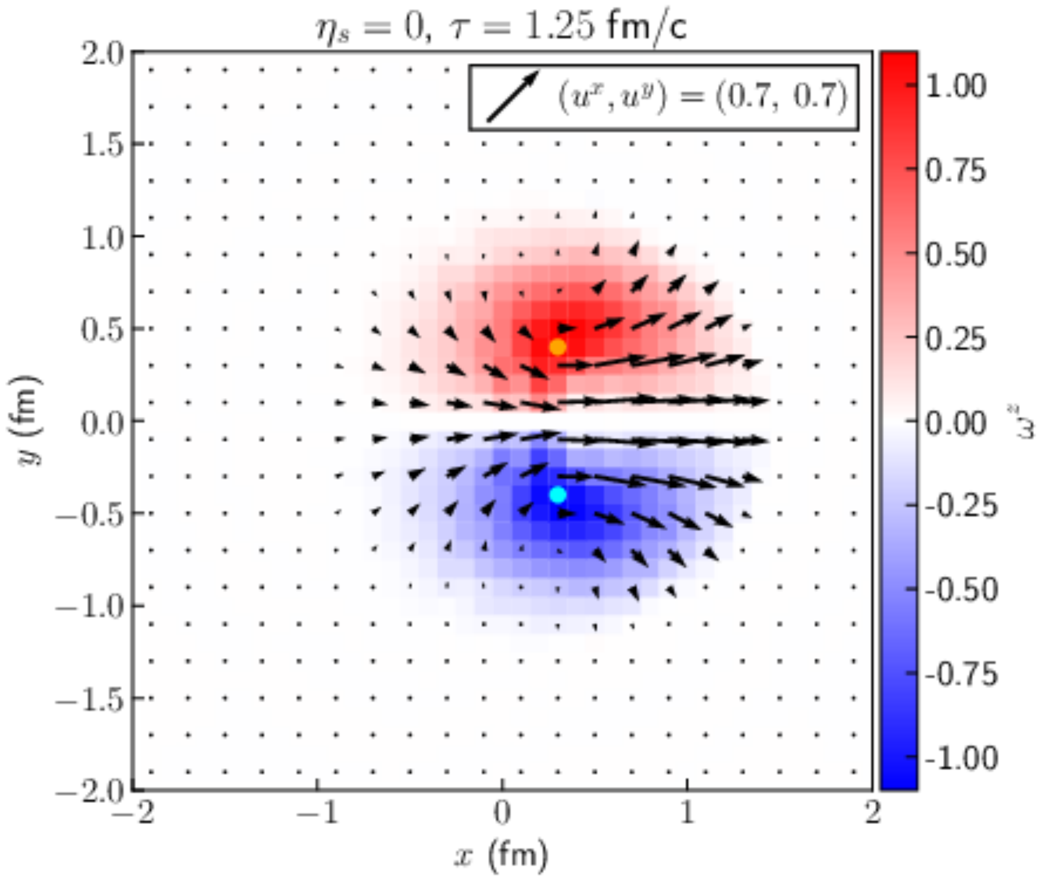
W. Matioli et al, PLB820 (2021) 136500

Toroidal vortex structures around a “jet”

Local momentum density injected into QGP in HIC



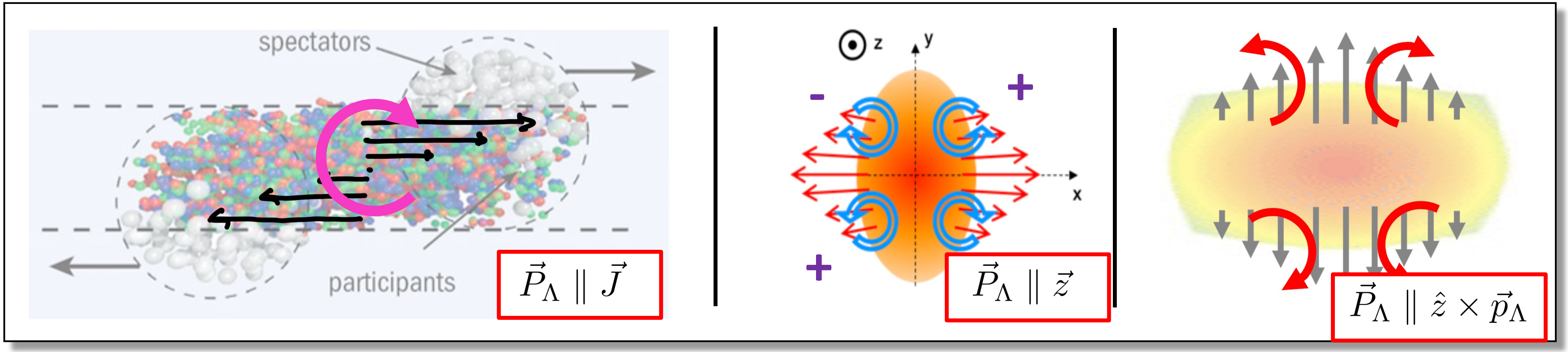
localized thrust out of the page

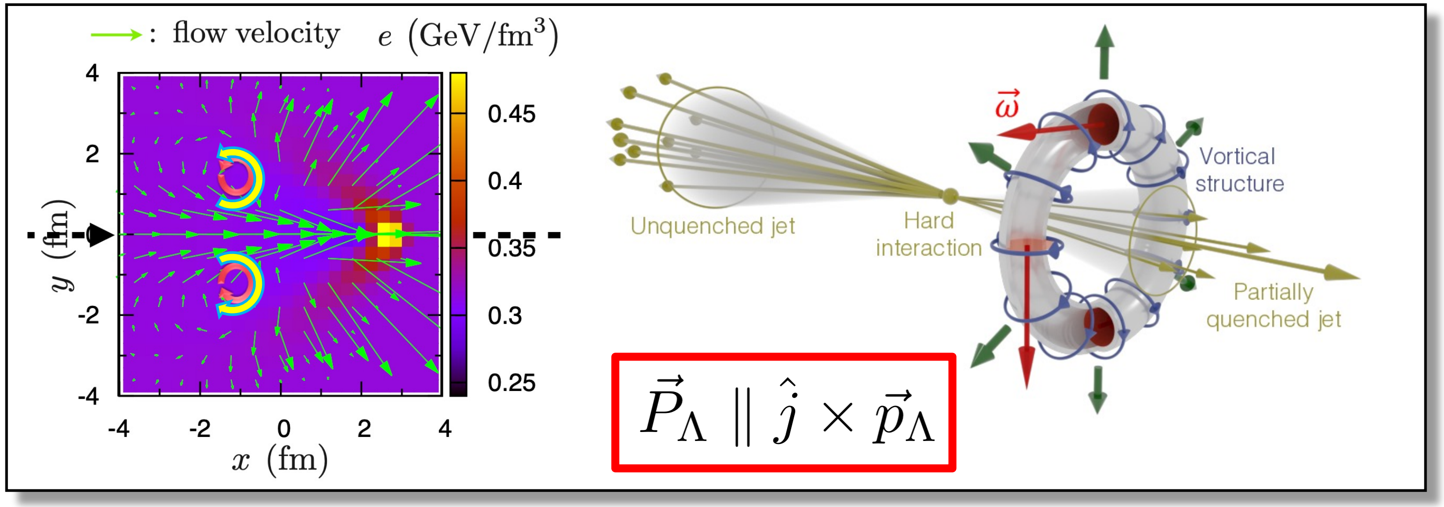


localized thrust to the right

W. Matioli et al, PLB820 (2021) 136500

Quantifying the vortex ring





Vortex Ring Observable about jet axis $\hat{t}$

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

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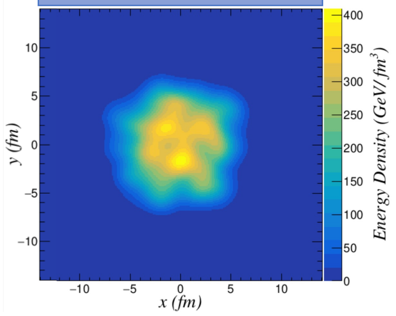
Phys. Lett. **B820** (2021) 136500

Hydrodynamic Simulation

$\tau_0 = 0.25$ fm/c

τ [fm/c]

T_RENTo 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

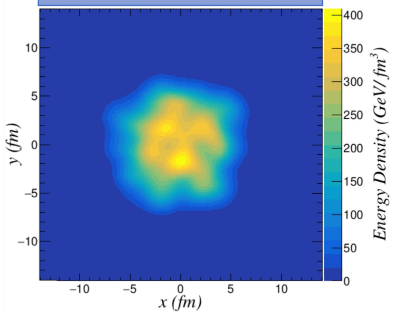
- HotQCD EoS

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

τ [fm/c]

Relativistic Viscous Hydrodynamics

T_RENTo 3D



Slice at $\eta = 0$

Hydrodynamic Simulation

$\tau_0 = 0.25$ fm/c

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

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

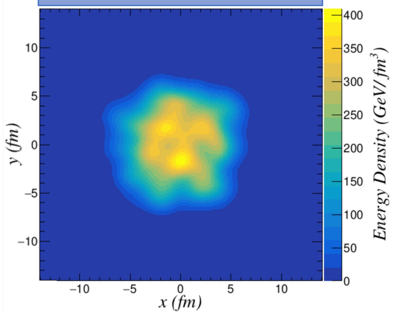
- HotQCD EoS

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

τ [fm/c]

Relativistic Viscous Hydrodynamics

T_RENTo 3D



Slice at $\eta = 0$

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

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

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

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

Hydrodynamic Simulation

$\tau_0 = 0.25$ fm/c

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

- $\frac{\eta}{s} = 0.08, \frac{\zeta}{s} = 0$
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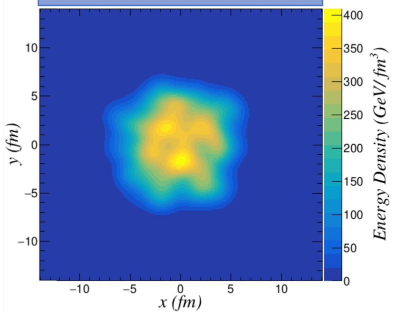
τ [fm/c]

Relativistic Viscous Hydrodynamics

T_RENTo 3D



Slice at $\eta = 0$

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

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

Hydrodynamic Simulation

$\tau_0 = 0.25$ fm/c

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

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

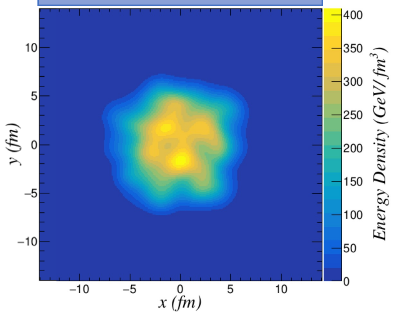
- HotQCD EoS

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

τ [fm/c]

Relativistic Viscous Hydrodynamics

T$_{\rm R}$ENTo 3D



Slice at $\eta = 0$

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

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

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

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

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

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

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

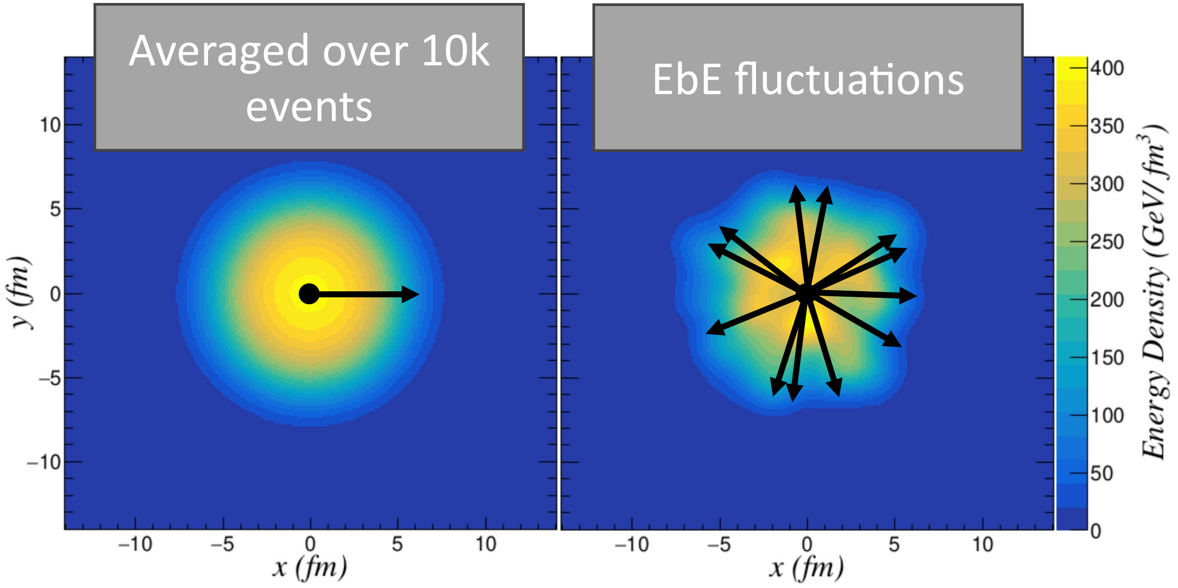
$$P^\mu = S^\mu / \langle S \rangle, \ \langle S \rangle = 1/2$$

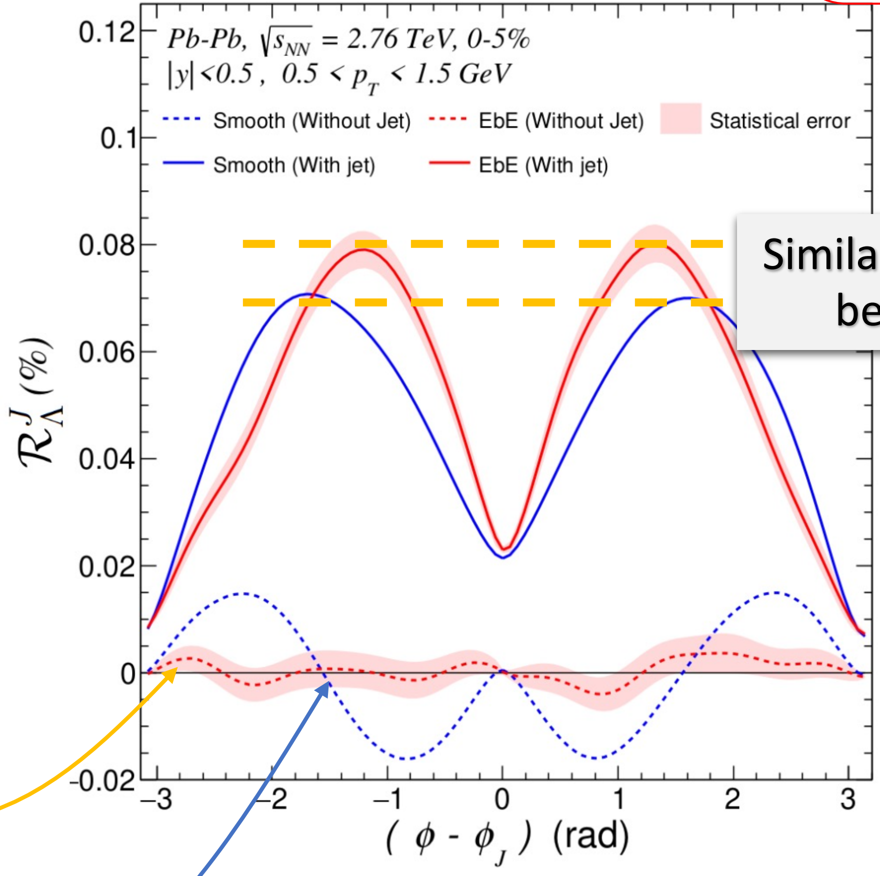
Effect of fluctuating initial conditions.

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

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

Phys. Lett. **B820** (2021)   arxiv:2305.02428



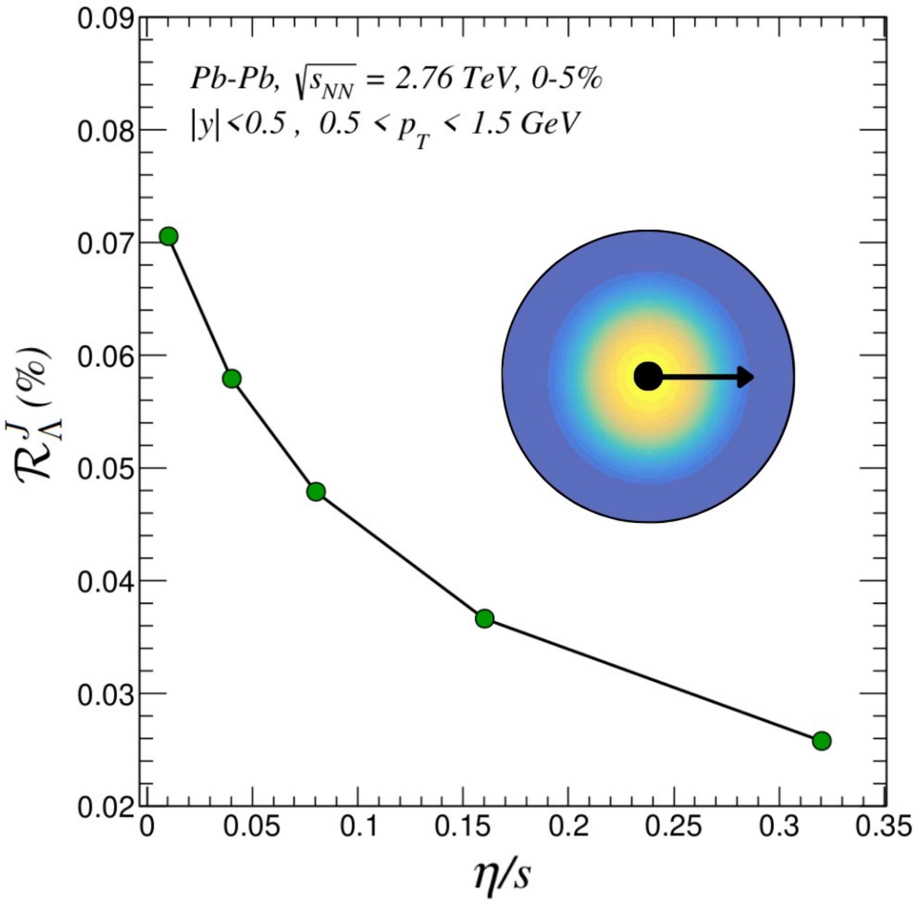


Similar order of magnitude between both cases

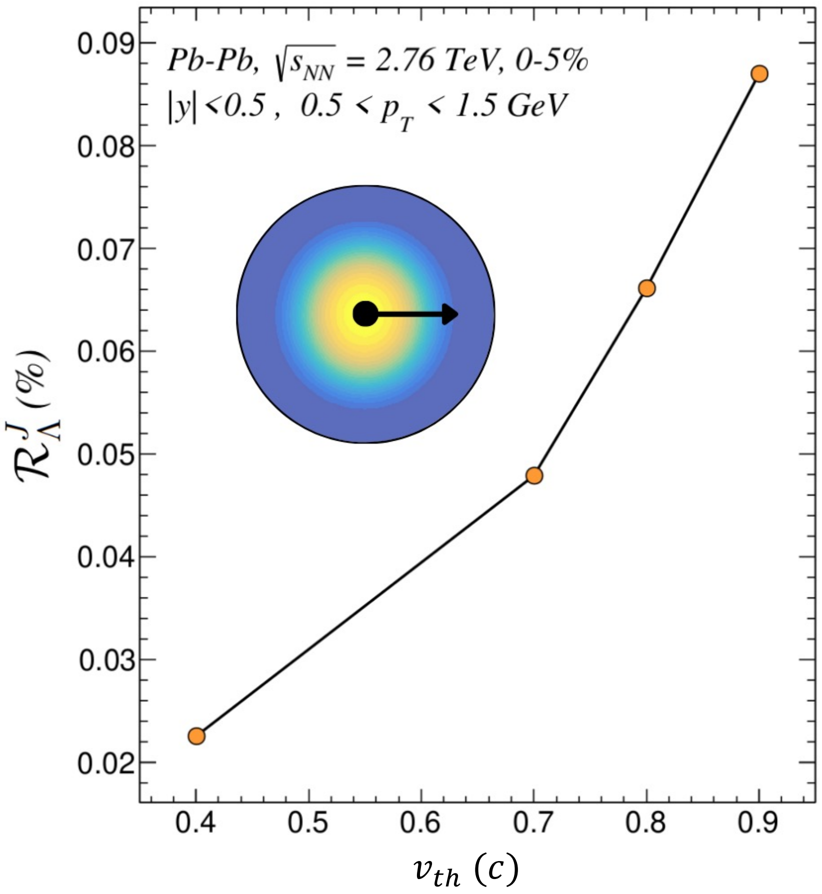
Random trigger direction supresses transverse expansion polarization

Residual effect of transverse expansion (v2)

Ring dependence on "bullet" and fluid properties



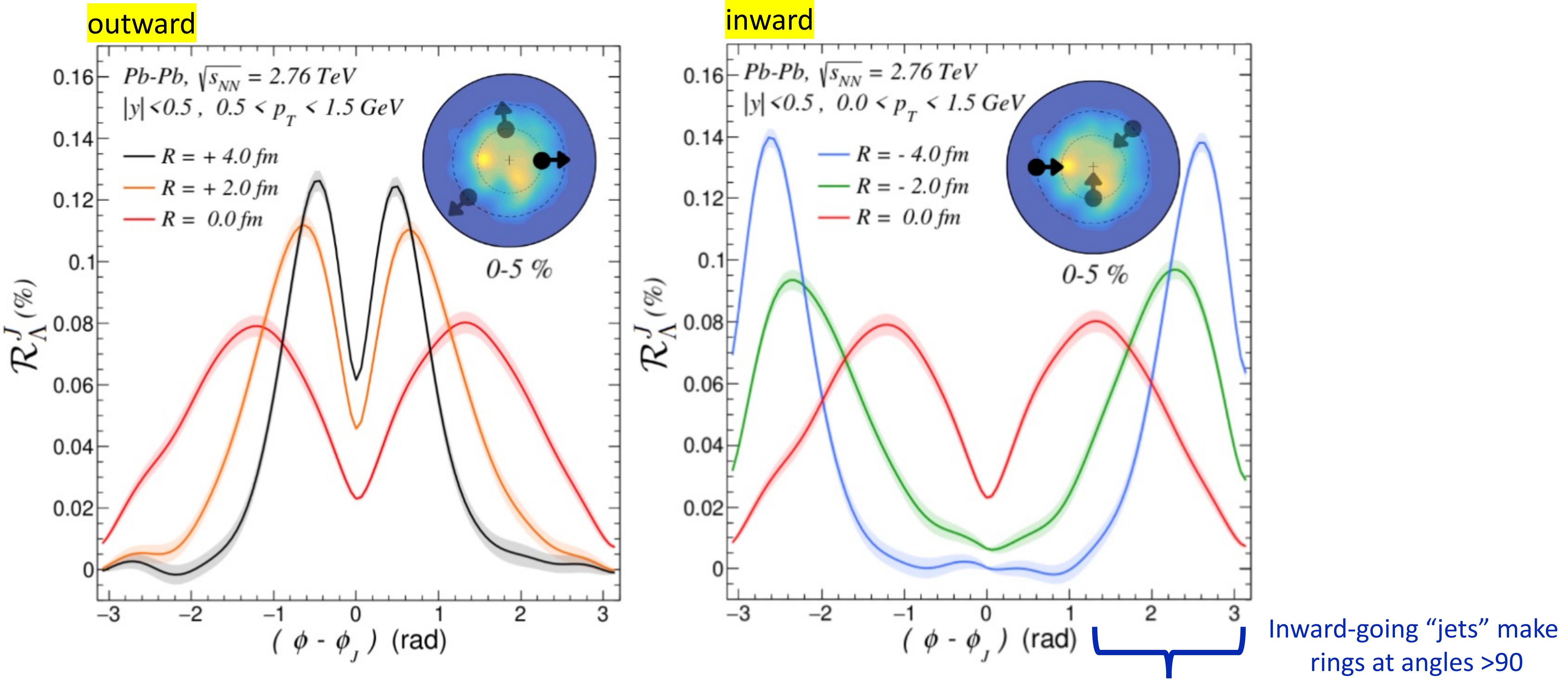
Vortex dissipation due to viscosity



- $v_{th} = \frac{|\vec{p}_{th}|}{p^0_{th}}$ (p^0_{th} = 59.6 GeV fixed here)
- may supplement quenching measurements

Phys. Lett. **B820** (2021)
arxiv:2305.02428

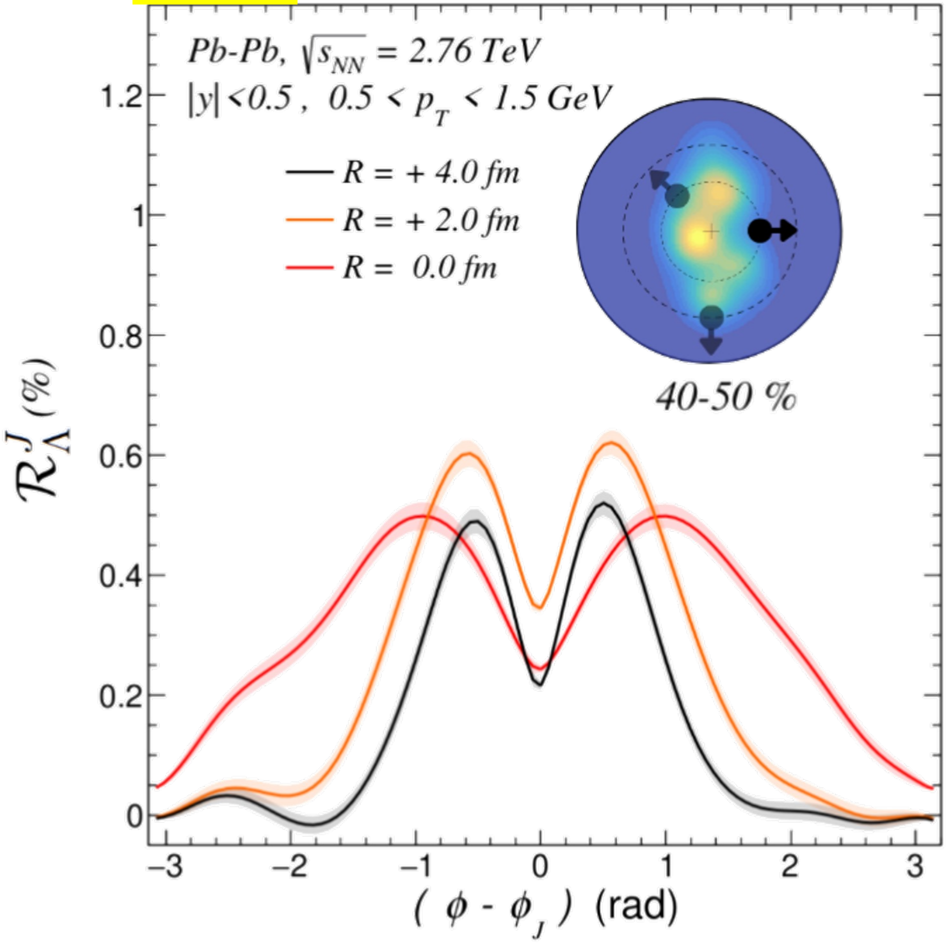
Dependence on bullet initial position and direction



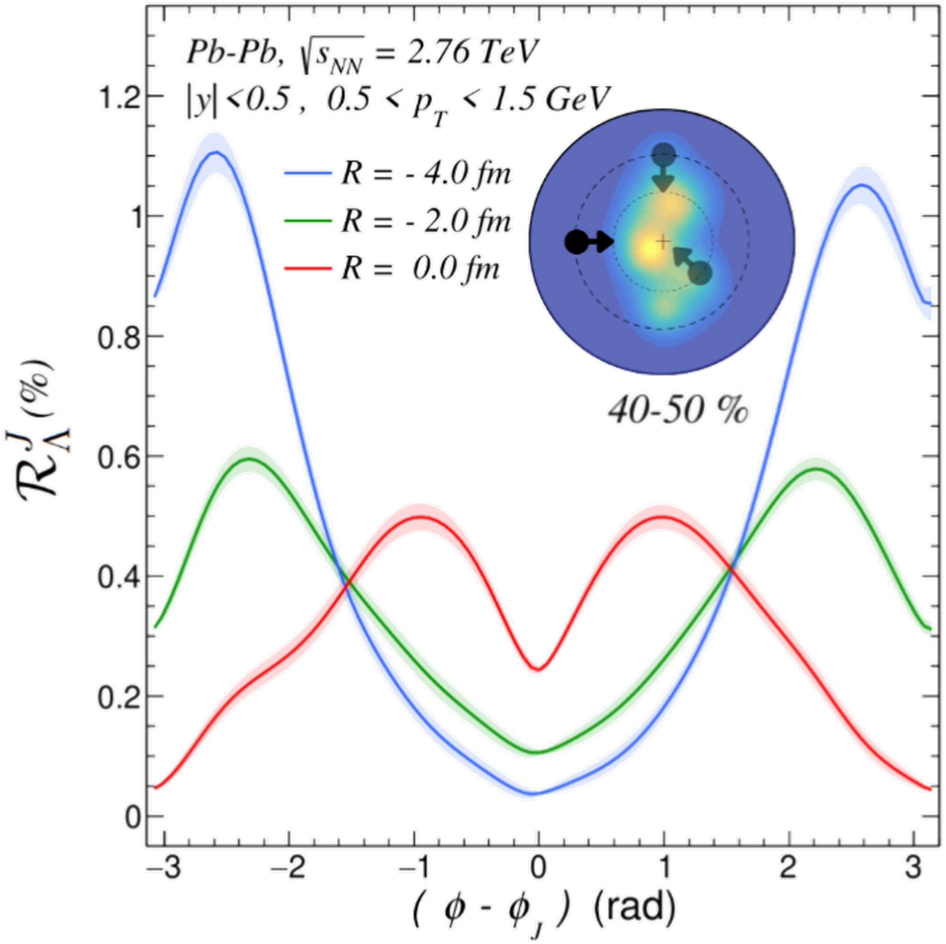
- production near the edge → less time for viscous dissipation → stronger rings
- ring size (peak positions) indicate closeness to edge (distance traveled)

Dependence on bullet initial position and direction- peripheral

outward



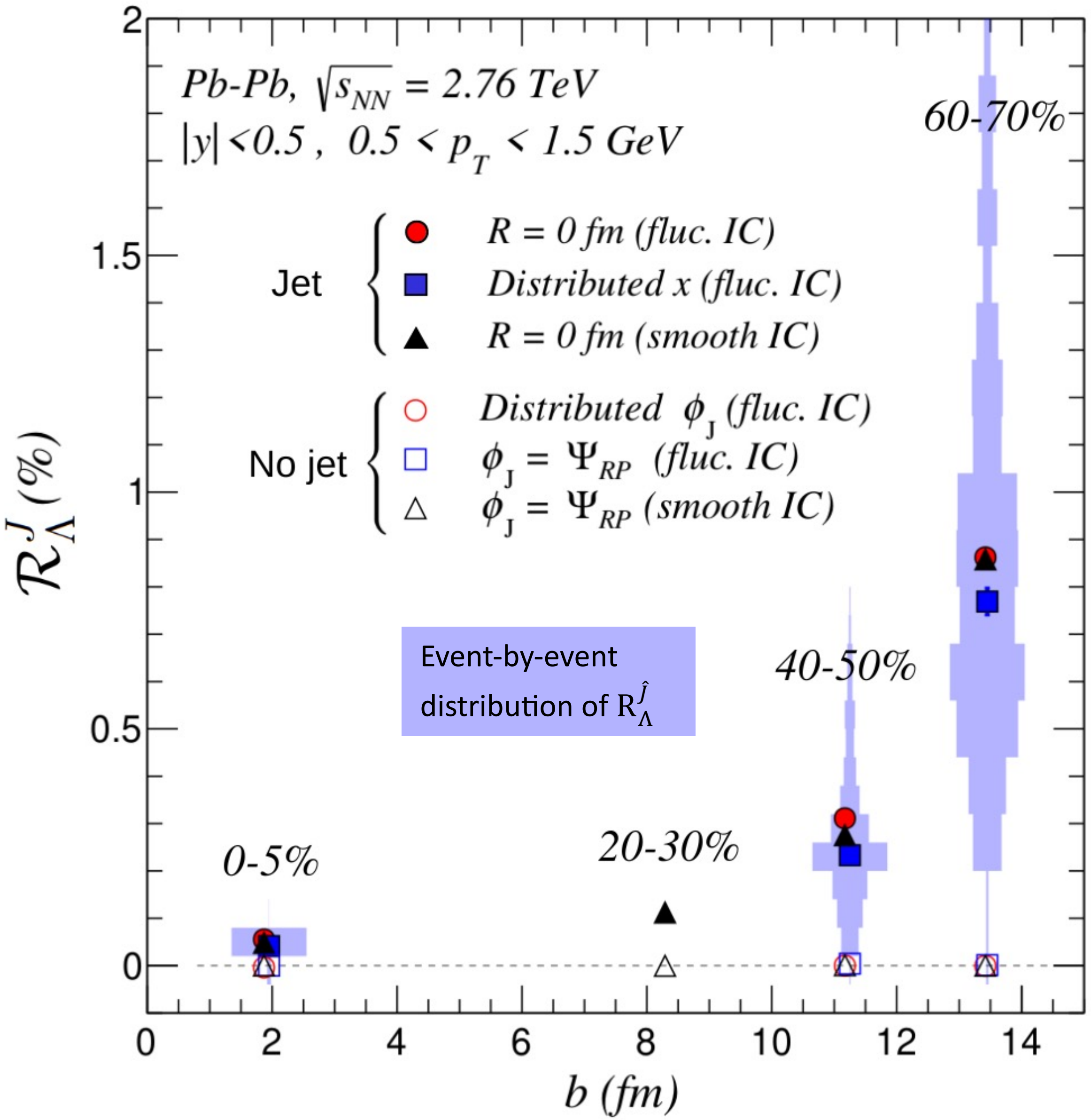
inward



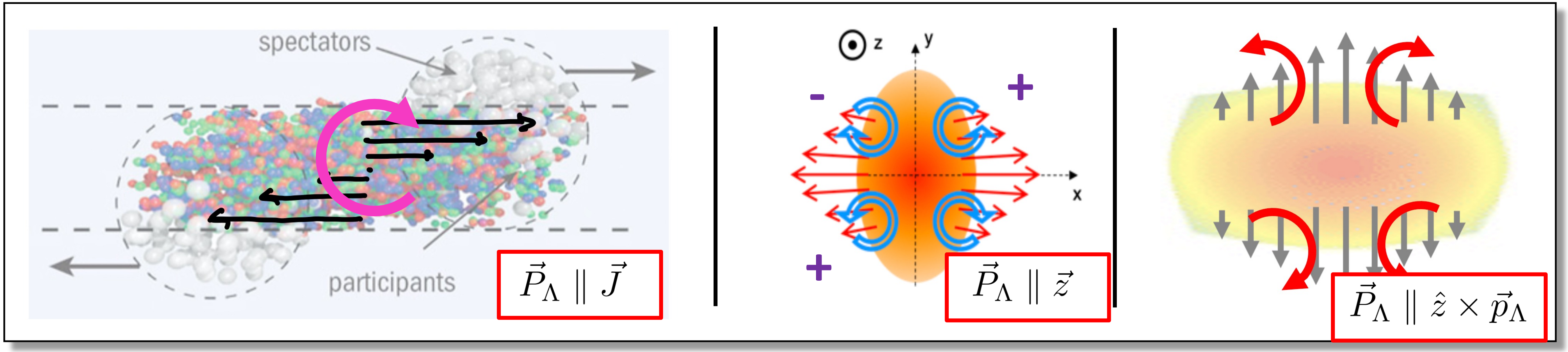
- production near the edge → less time for viscous dissipation → stronger rings (except if outside fluid!)
- ring size (peak positions) indicate closeness to edge (distance traveled)

Averaged over azimuthal angle, location

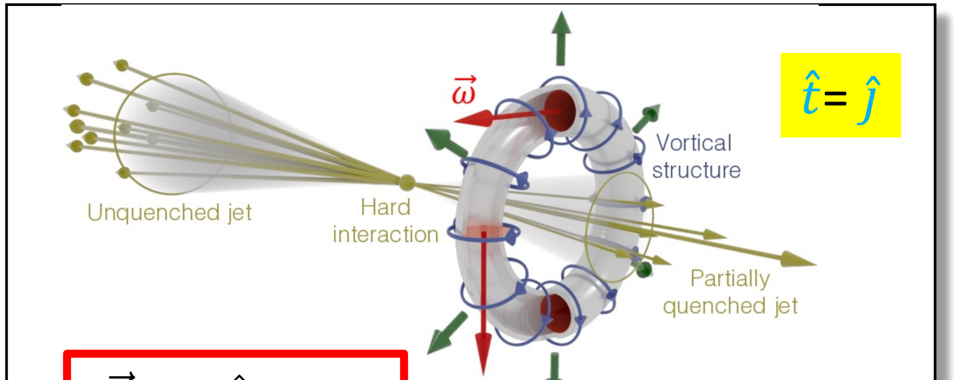
- Background is consistently zero
- Systematic increase of ring observable with *b*
  - Smaller fluid background causes fluid to develop larger velocity gradients
  - Smaller system causes particlization time to be reached earlier
- E-by-E fluctuations large, but means well-defined.
- **Ring observable is a robust probe for jet-medium interaction**



Polarization patterns in "undisturbed" fluid



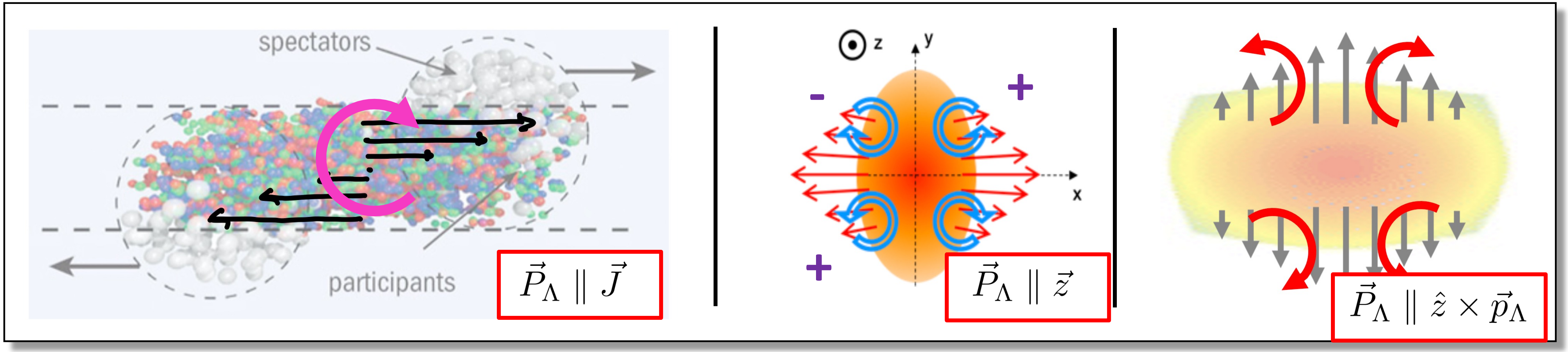
Polarization patterns in disturbed fluid – toroid about disturbance



Phys. Rev. **C104** (2021) 1, 011901
Phys. Lett. **B820** (2021) 136500

$$R_\Lambda^t = \left\langle \frac{\vec{P}_\Lambda \cdot (\hat{t} \times \vec{p})}{|\hat{t} \times \vec{p}|} \right\rangle$$

Polarization patterns in "undisturbed" fluid



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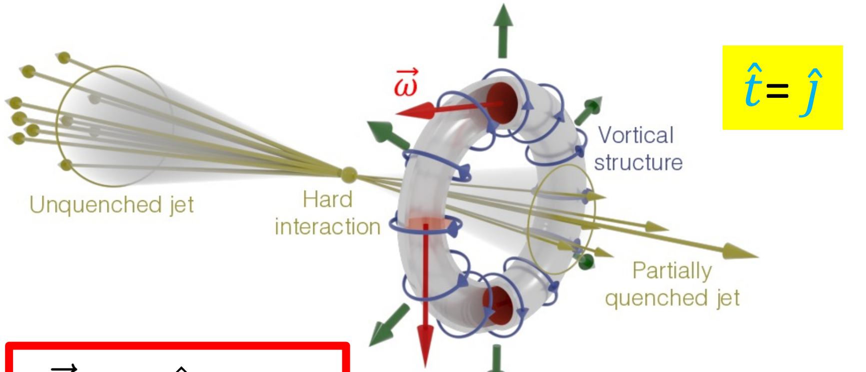

$\vec{P}_\Lambda \parallel \hat{j} \times \vec{p}_\Lambda$

Phys. Rev. **C104** (2021) 1, 011901
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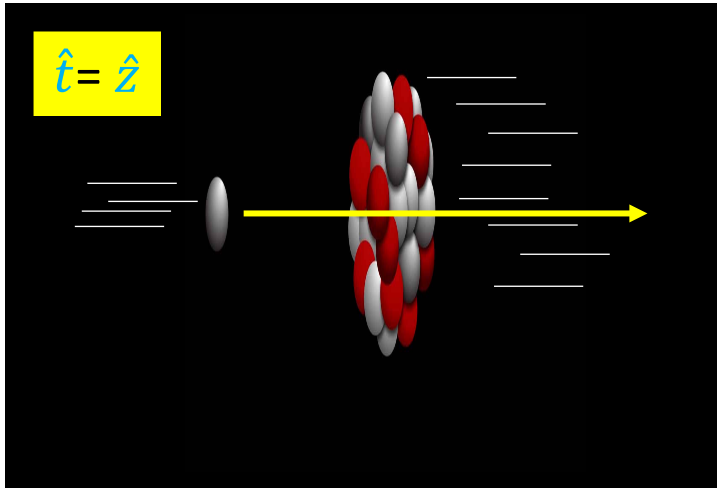
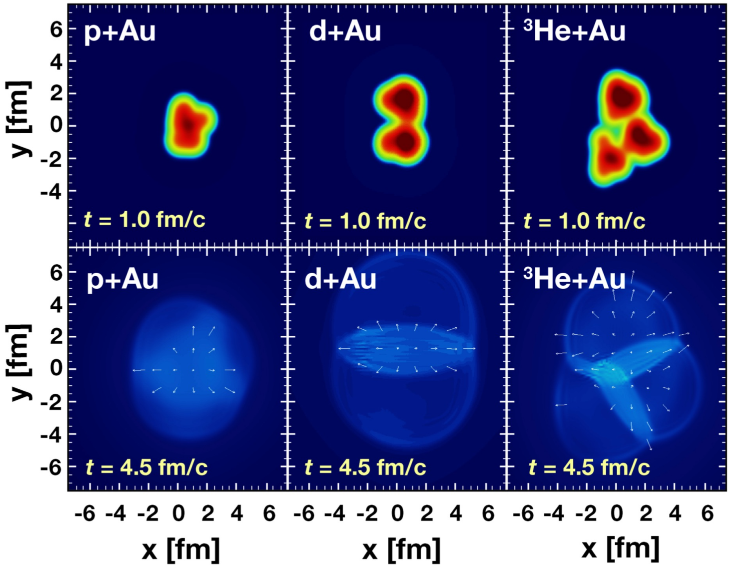
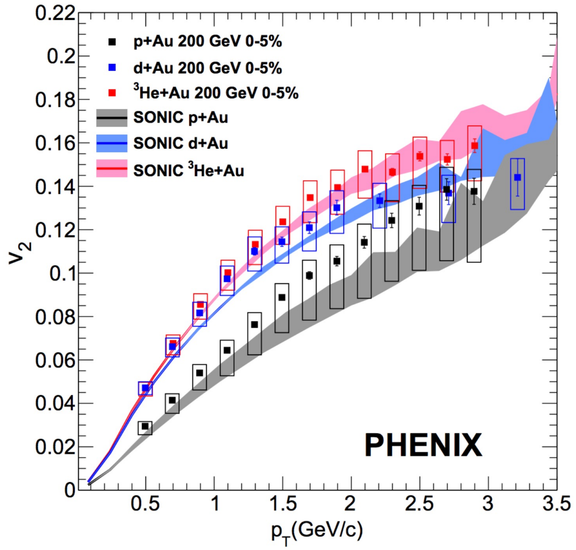
$$R^t_\Lambda = \left\langle \frac{\vec{P}_\Lambda \cdot (\hat{t} \times \vec{p})}{|\hat{t} \times \vec{p}|} \right\rangle$$

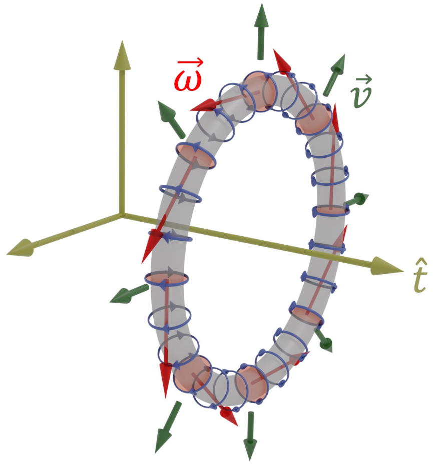


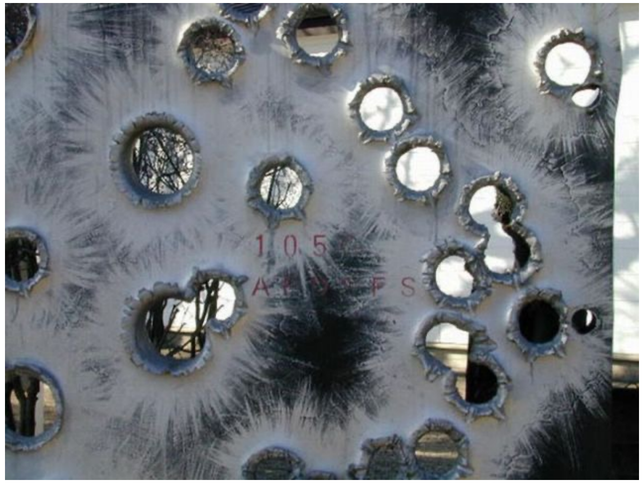
So crazy?

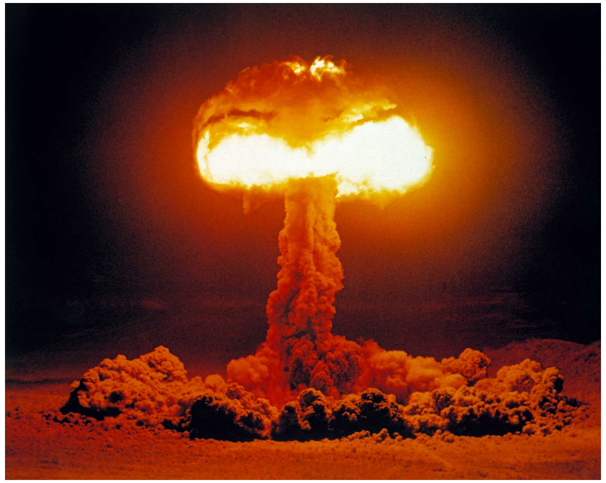




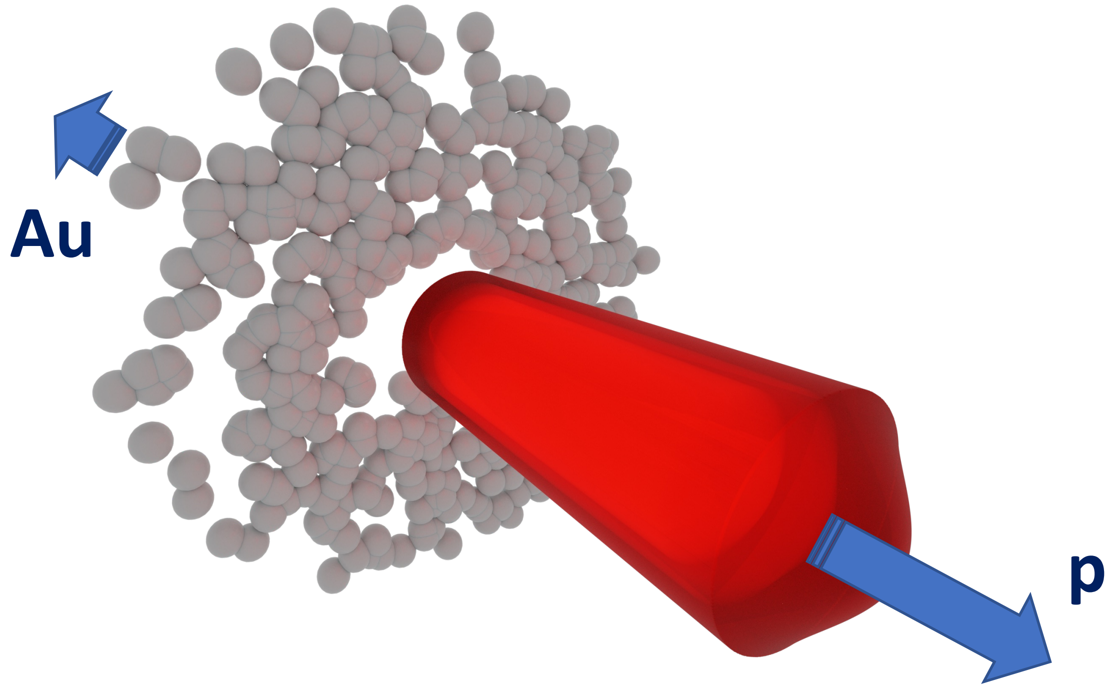
Maybe, but it could be a more robust test of the (not very) crazy claim of smallest QGP fluid, than v_n







What about p+A collisions…?



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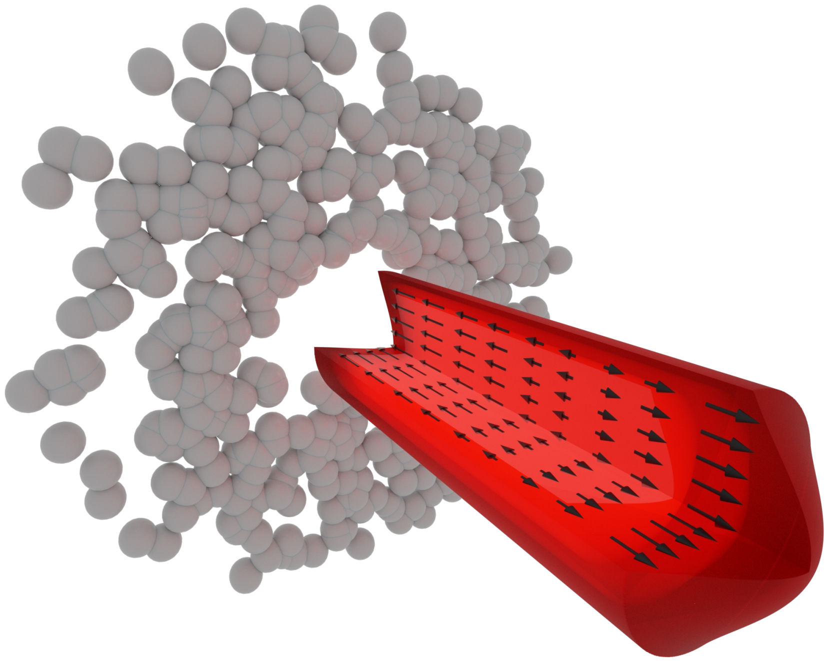
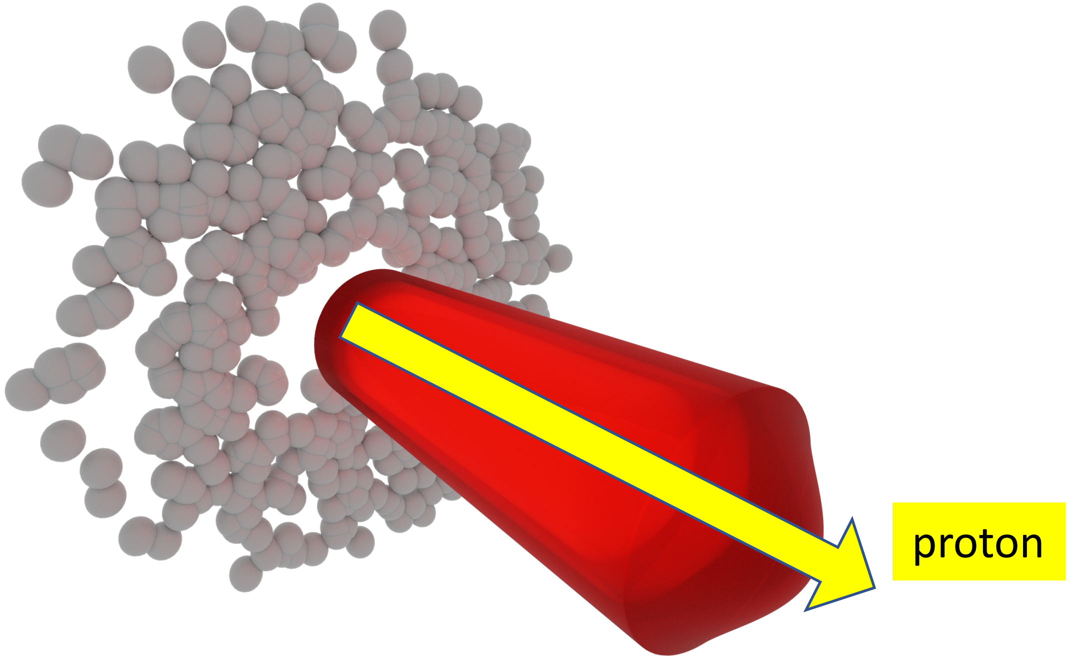


(a) Bjorken flow profile: $u_z = \eta_s$



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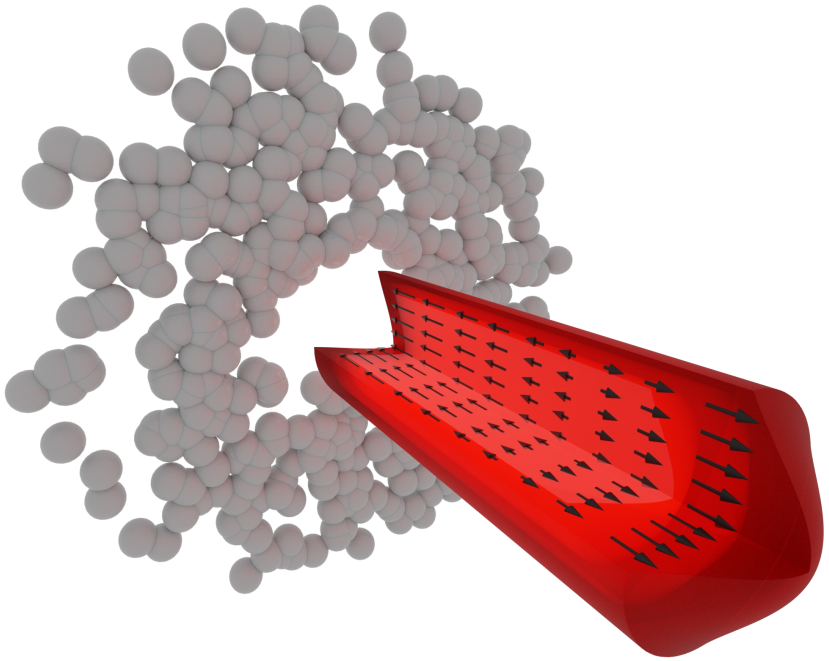

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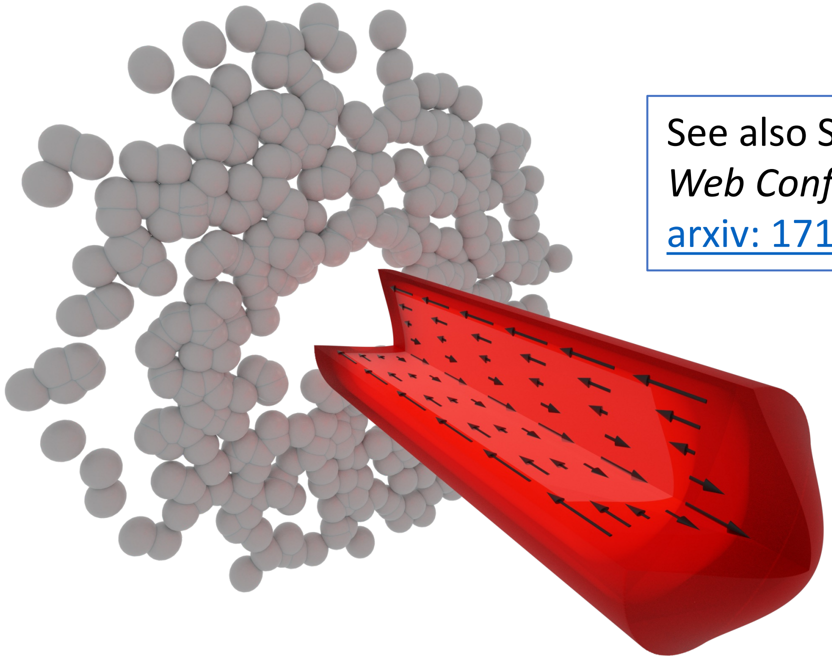


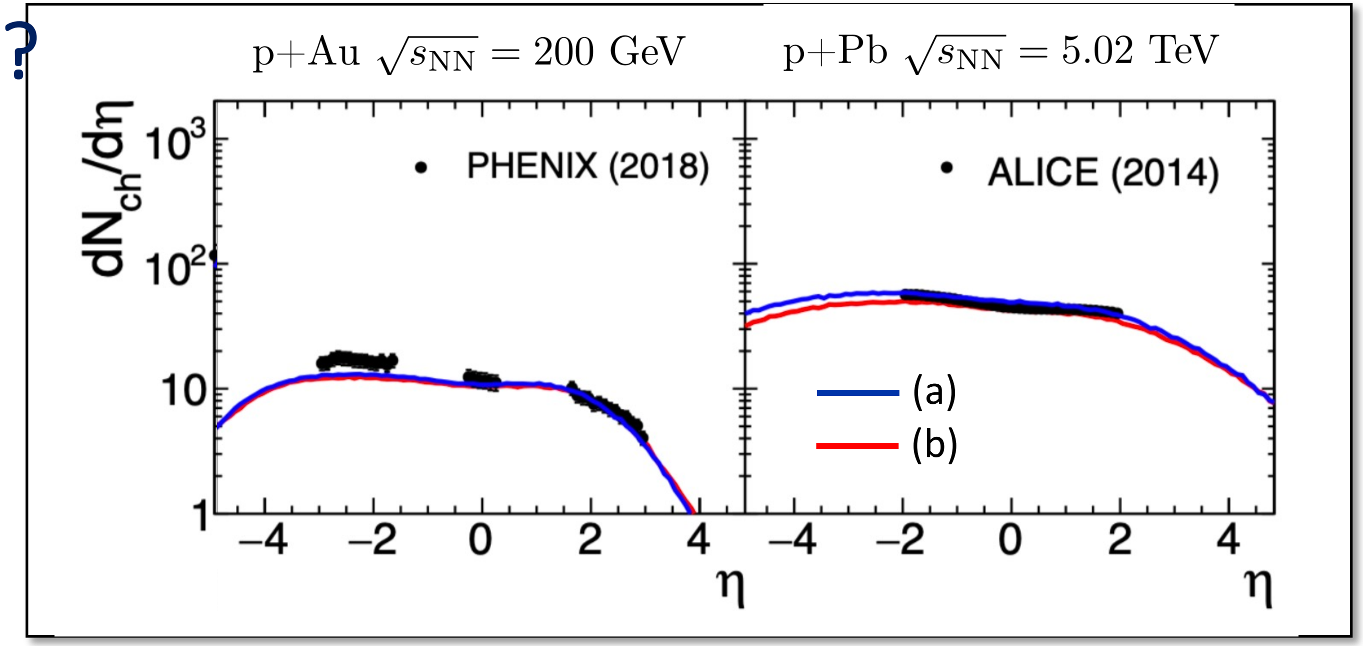
(b) Radial-gradient flow profile

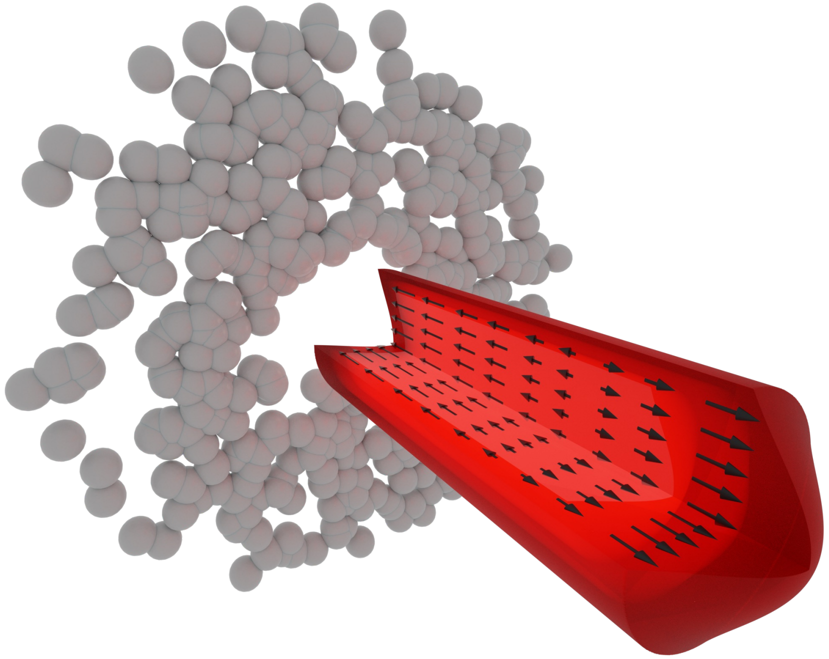
See also S. Voloshin, *EPJ Web Conf.* 171 (2018) 07002
arxiv: 1710.08934

PR**C104** (2021) 1, 011901

What about p+A collisions…?

- Basic observables are ~identical in these scenarios





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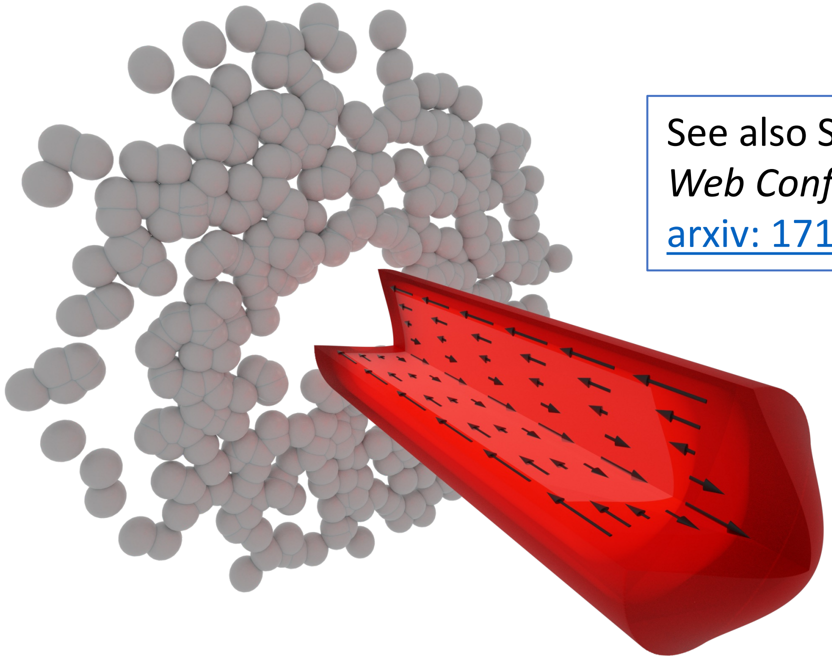

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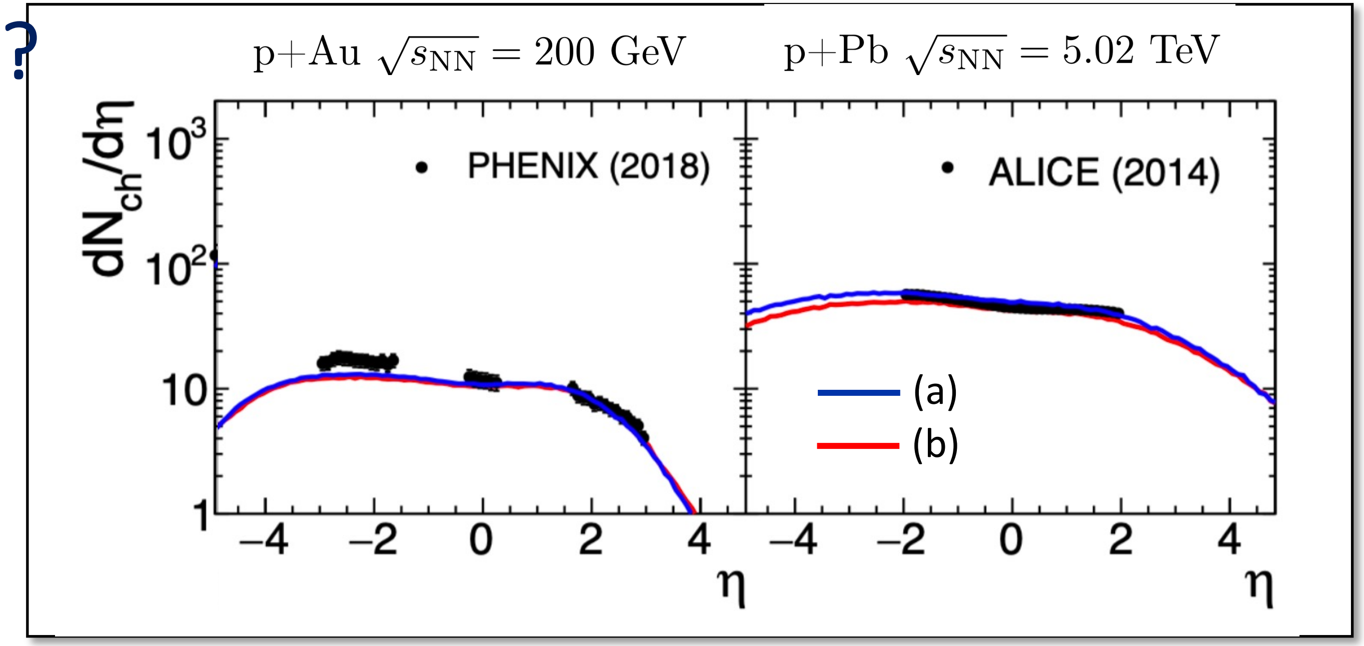
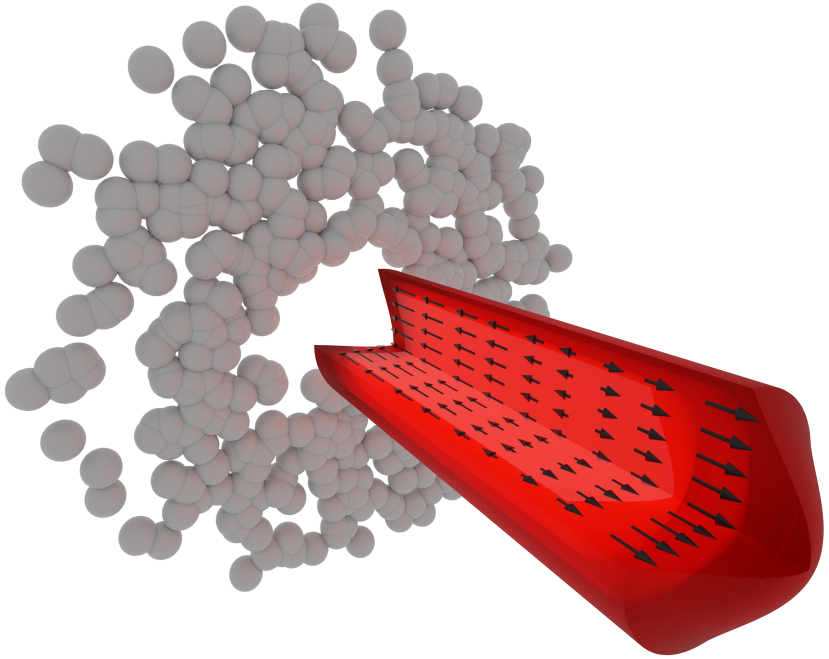
PR**C104** (2021) 1, 011901

What about p+A collisions…?

- Basic observables are ~identical in these scenarios
- **Vorticity is very different**





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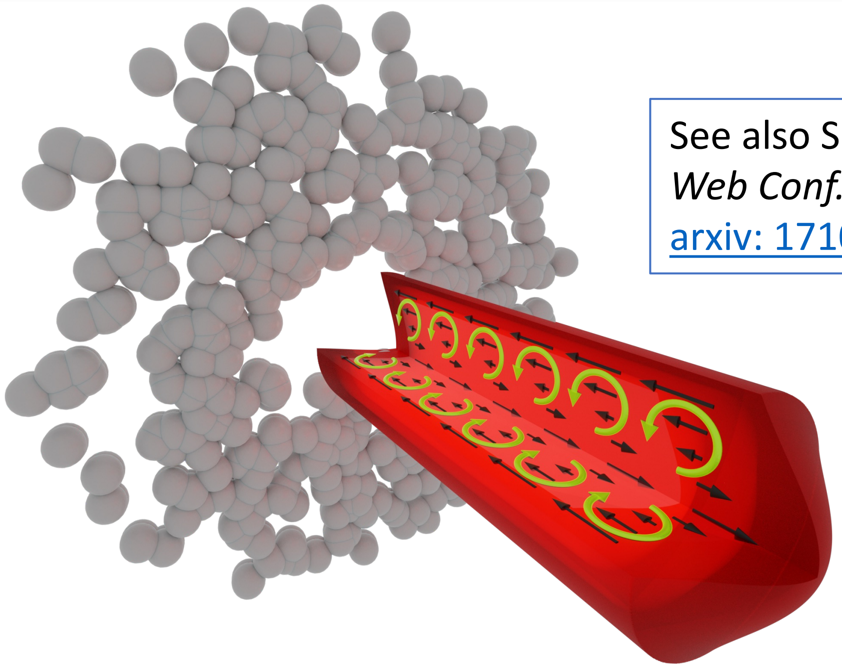

(b) Radial-gradient flow profile

See also S. Voloshin, *EPJ Web Conf.* 171 (2018) 07002 arxiv: 1710.08934

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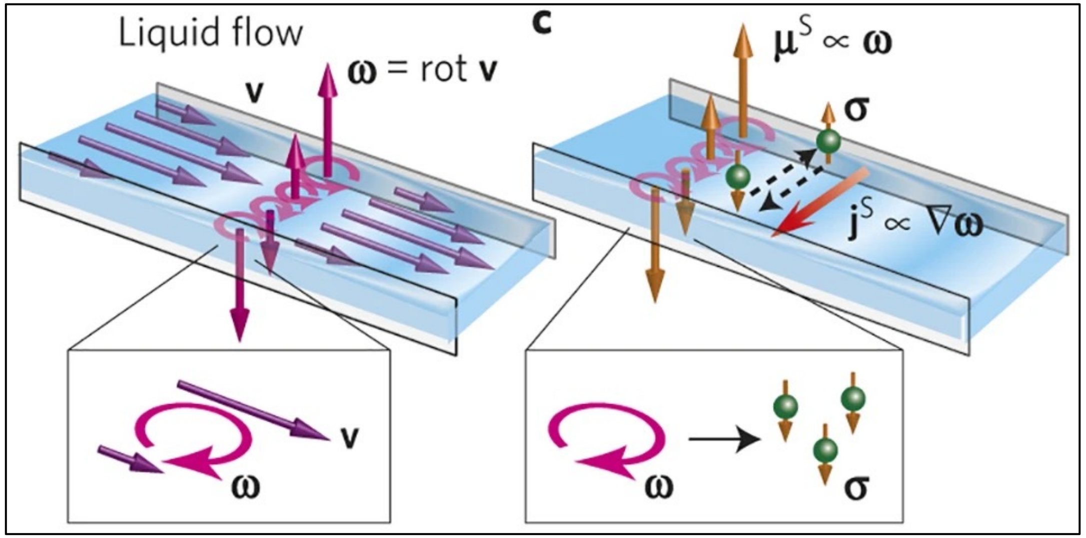
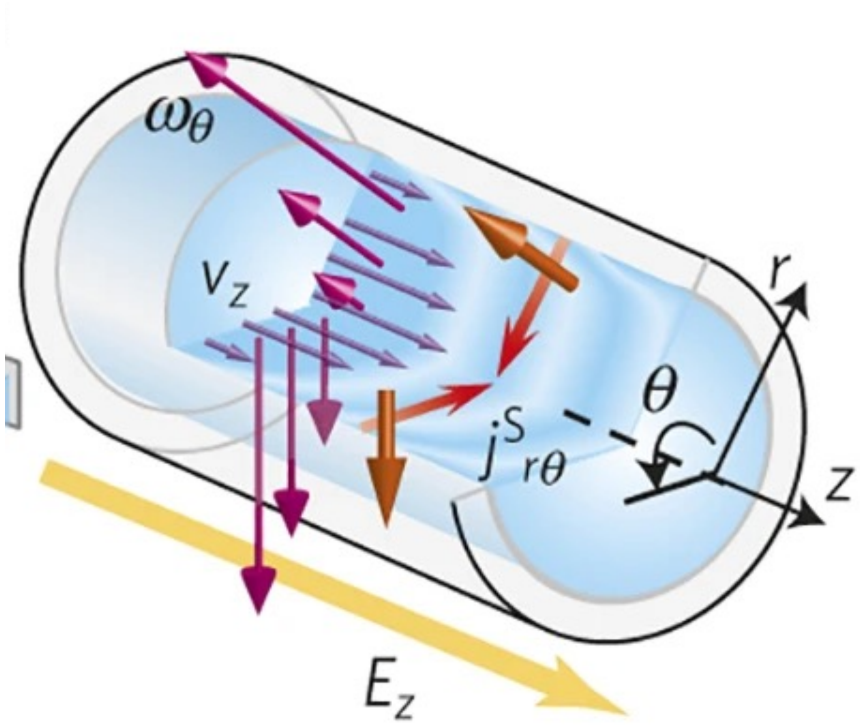
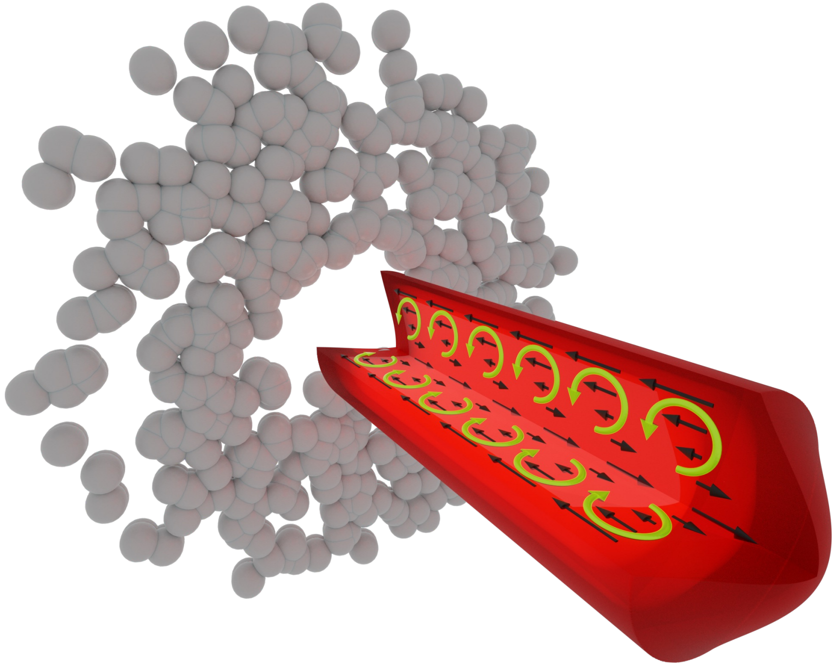
Relation to Takahashi geometry

The experimental geometry was not this



It was flow thru capillary tube:





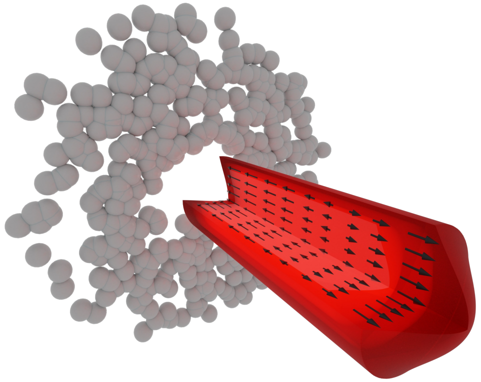
(b) Radial-gradient flow profile

PR**C104** (2021) 1, 011901

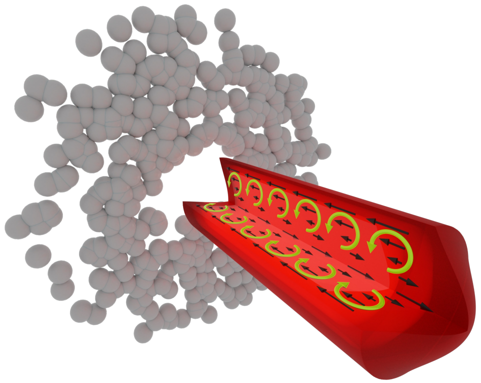
color axis: $\overline{\mathcal{R}}^{\hat{t}}_{\mathrm{NR}} \equiv \left\langle \frac{\vec{\omega}_{\mathrm{NR}} \cdot (\hat{t} \times \vec{v}_{\mathrm{cell}})}{|\hat{t} \times \vec{v}_{\mathrm{cell}}|} \right\rangle_\phi$ → $\mathcal{R}^{\hat{t}}_{\mathrm{fluid}} \equiv \frac{\epsilon^{\mu\nu\rho\sigma}\Omega_\mu n_\nu \hat{t}_\rho u_\sigma}{|\epsilon^{\mu\nu\rho\sigma} n_\nu \hat{t}_\rho u_\sigma|}$ | → $\vec{\omega}$ | → $\vec{u}_{\mathrm{cell}}$

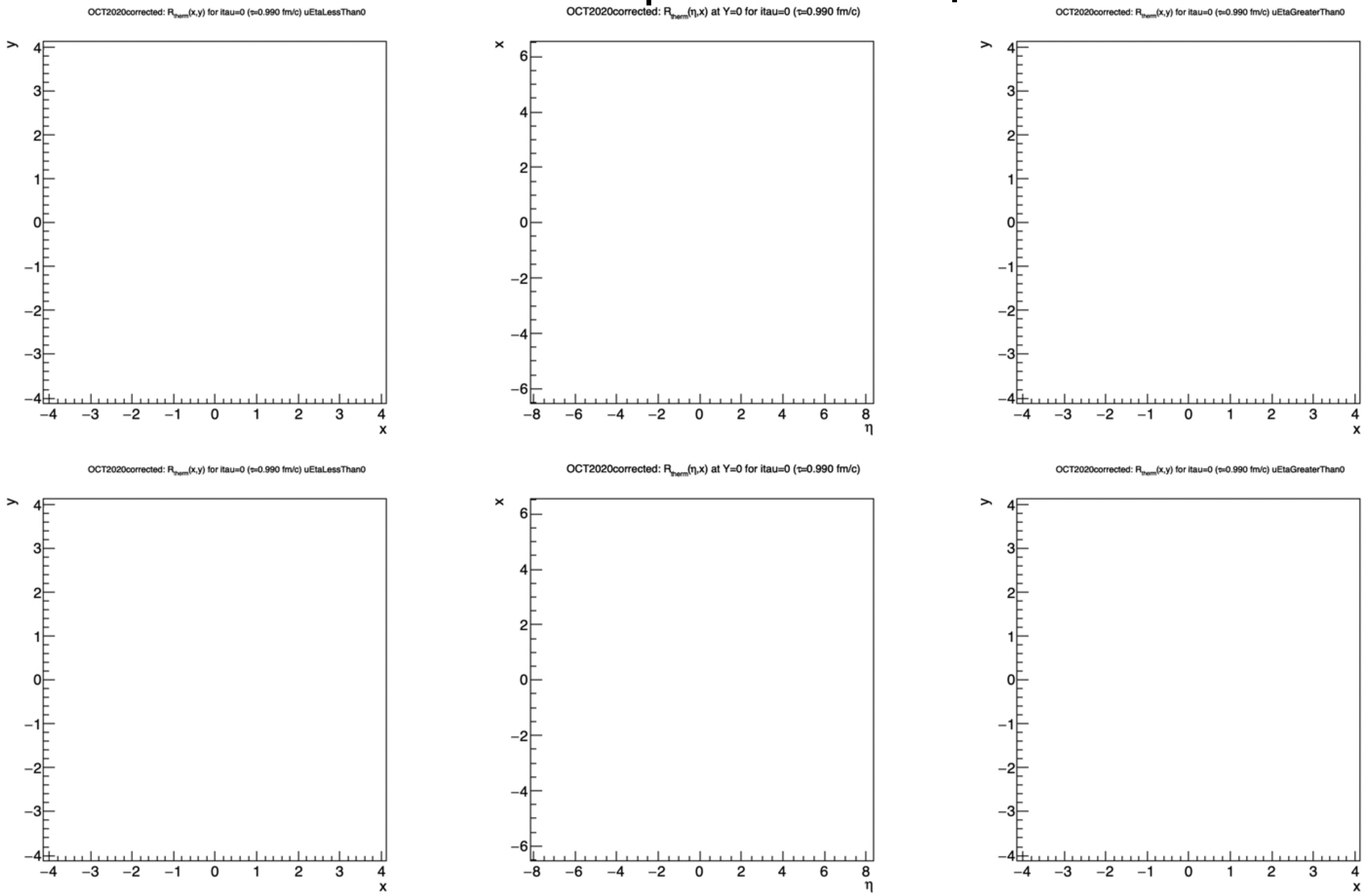
p+Au at 200 GeV

(a)



(b)





PR**C104** (2021) 1, 011901

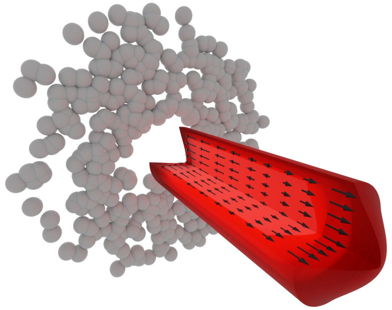
MUSIC hydrodynamics, with baryon currents

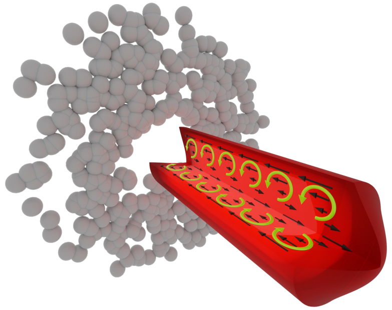
35

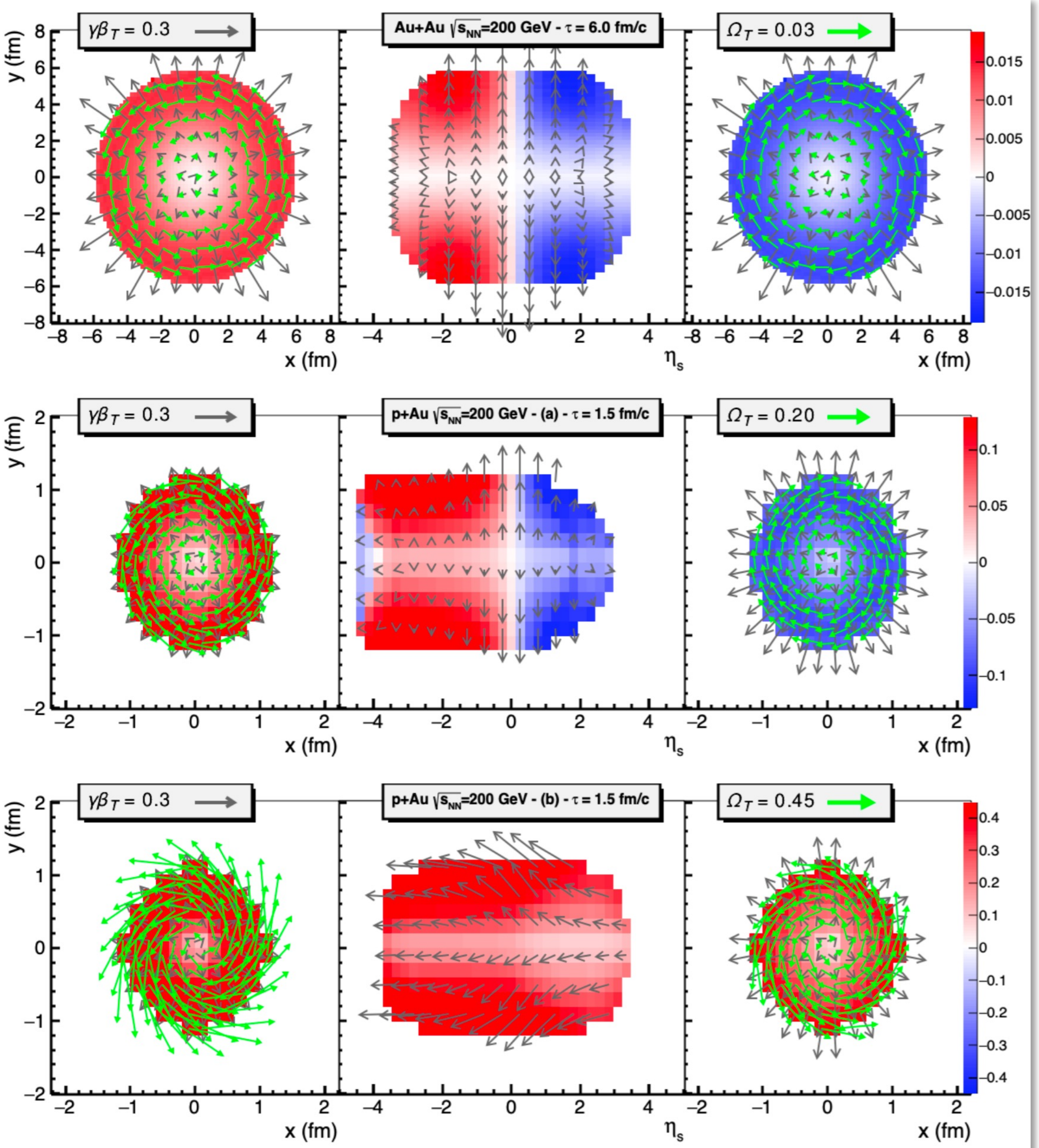
Snaphots

PRC104 (2021) 011901; arxiv: 2101.10872

smooth-on-smooth, b=0
collisions at RHIC



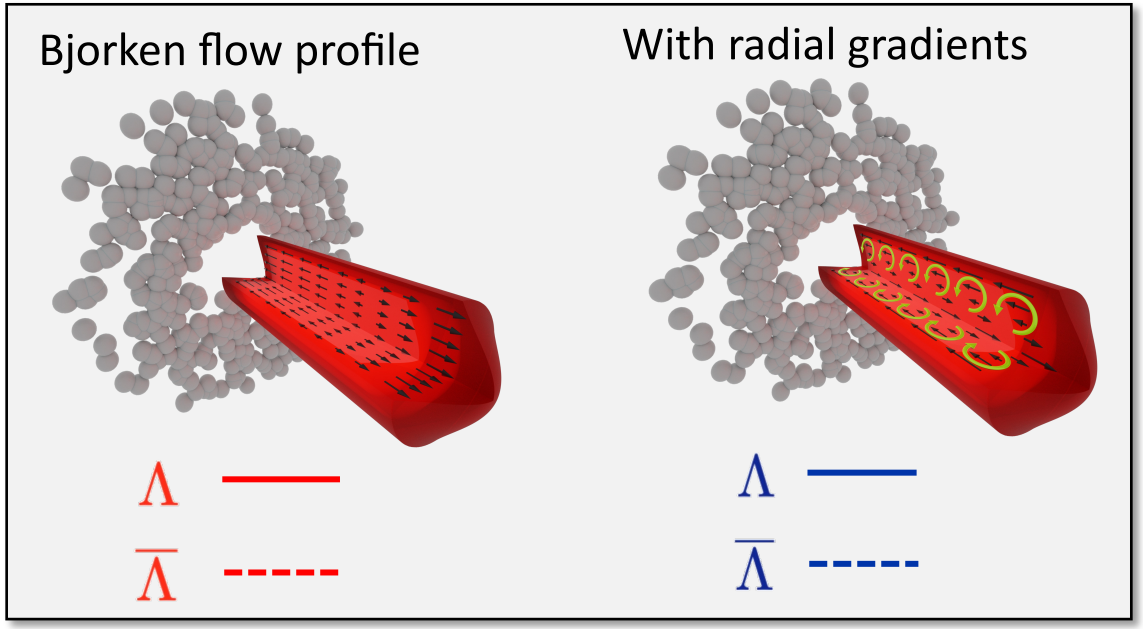




Observing the "smoke tubes"

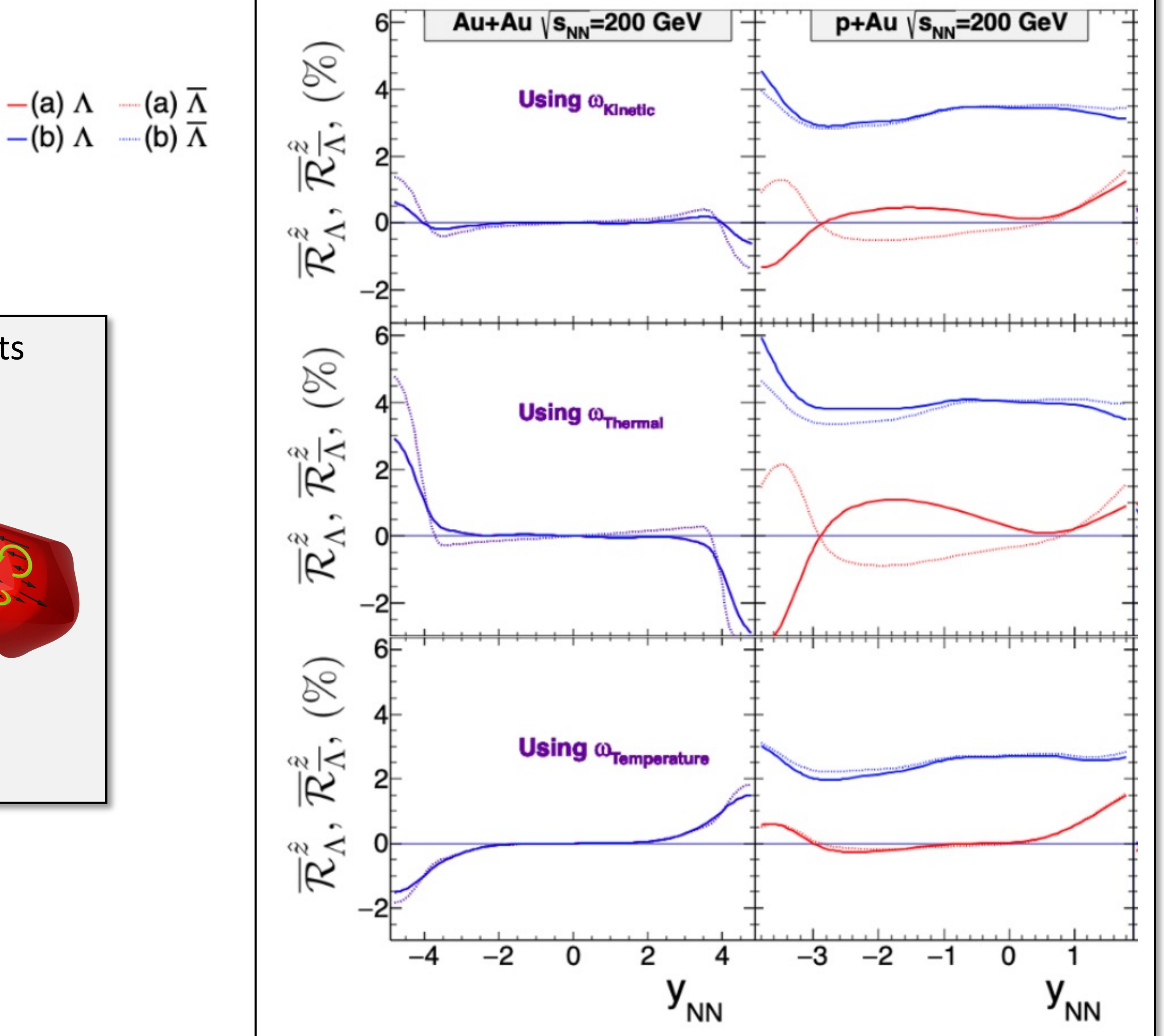
Ring vorticity observable

$$\overline{\mathcal{R}}^{\hat{z}}_{\Lambda} = 2\left\langle \frac{\vec{S}'_{\Lambda}\cdot\left(\hat{z}'\times\vec{p}_{\Lambda}'\right)}{\left|\hat{z}'\times\vec{p}_{\Lambda}'\right|}\right\rangle_{\phi}$$



- similar effect for all vorticity "flavors"
- **hyperon and anti-hyperon are similar**

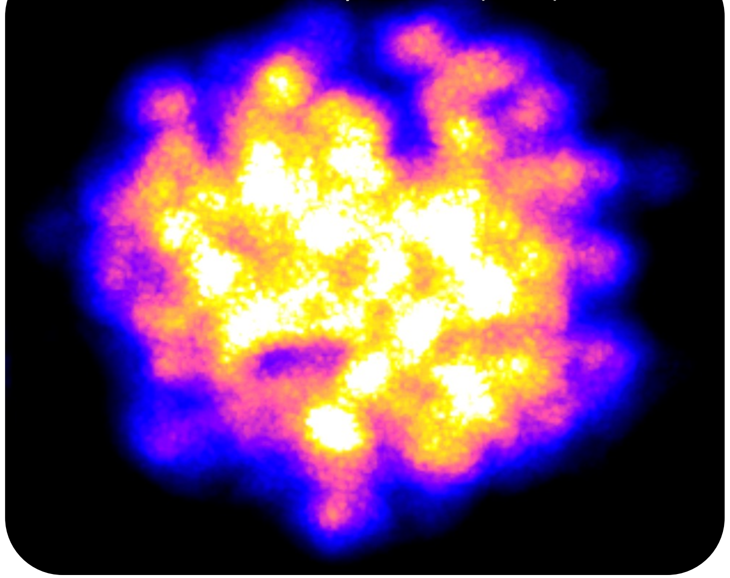
PRC104 (2021) 011901; arxiv: 2101.10872



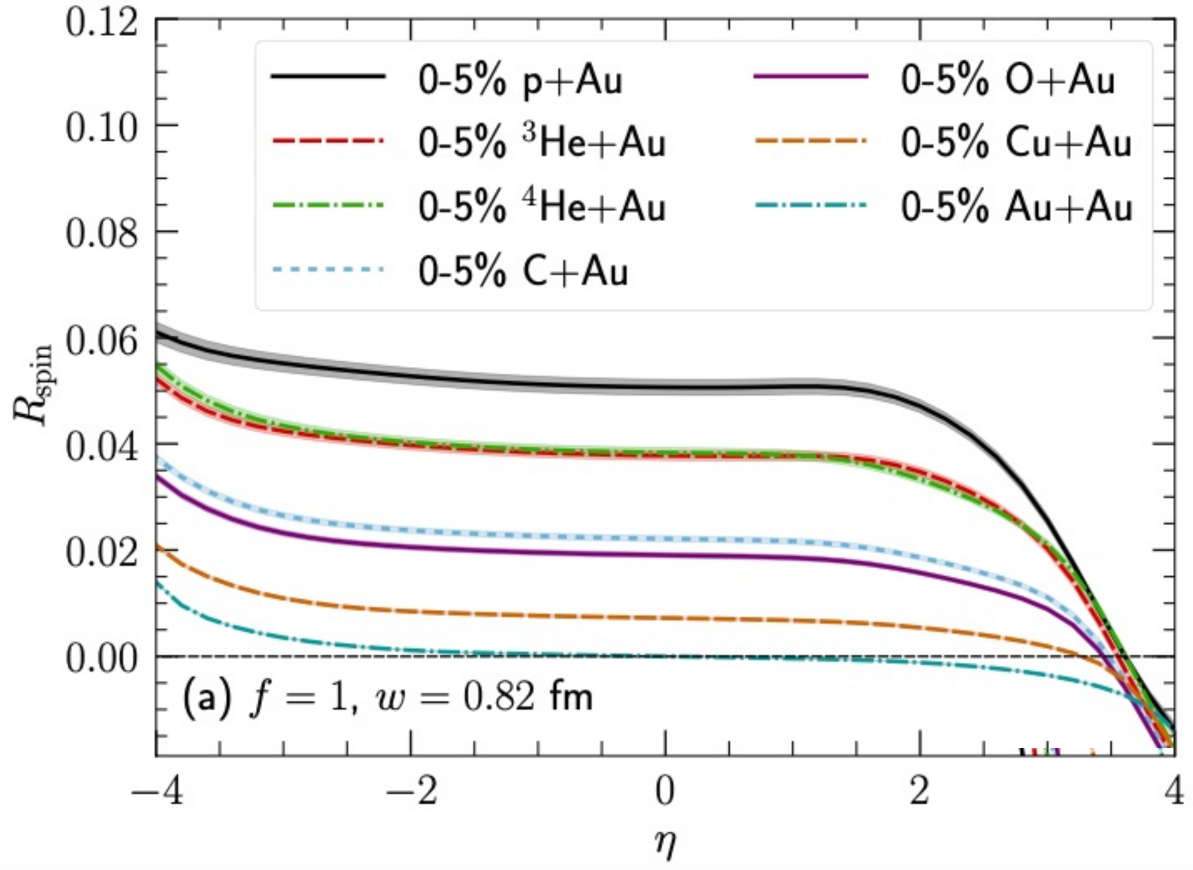
fluctuating initial conditions

- ✓ Event-by-event calculation with lumpy initial conditions, following prescription in [1]
  → little difference with smooth initial conditions
- ✓ reduced R_{spin} for more symmetric system

Schenke, Shen, Tribedy, PRC102 (2020) 044905



3C collaboration, in preparation arxiv:2309xxxx.



* note: p_T>500 MeV here, increasing R 0.04 → 0.06 in p+Au

[1] Shen, Alzhrani, PRC102 (2020) 014909 (2020)

system scan

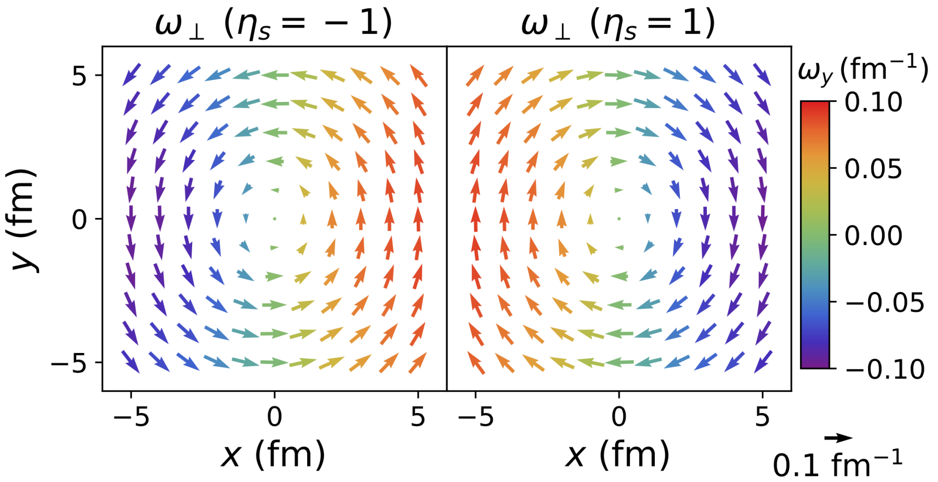
Suggests smaller systems produce larger signal

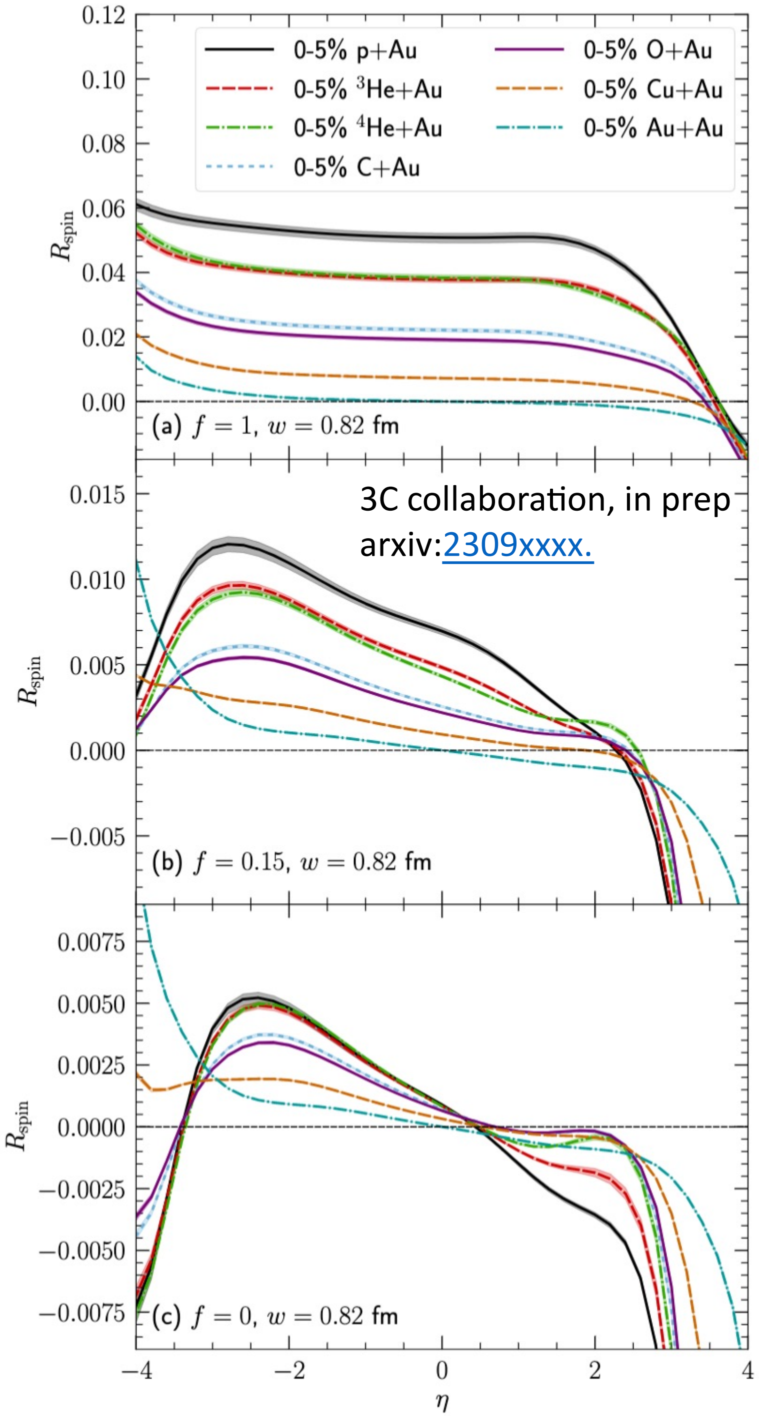
- higher gradients; less dissipation

However, amount of fluid may be reduced.

Fluctuating initial conditions underway.

Recall Au+Au



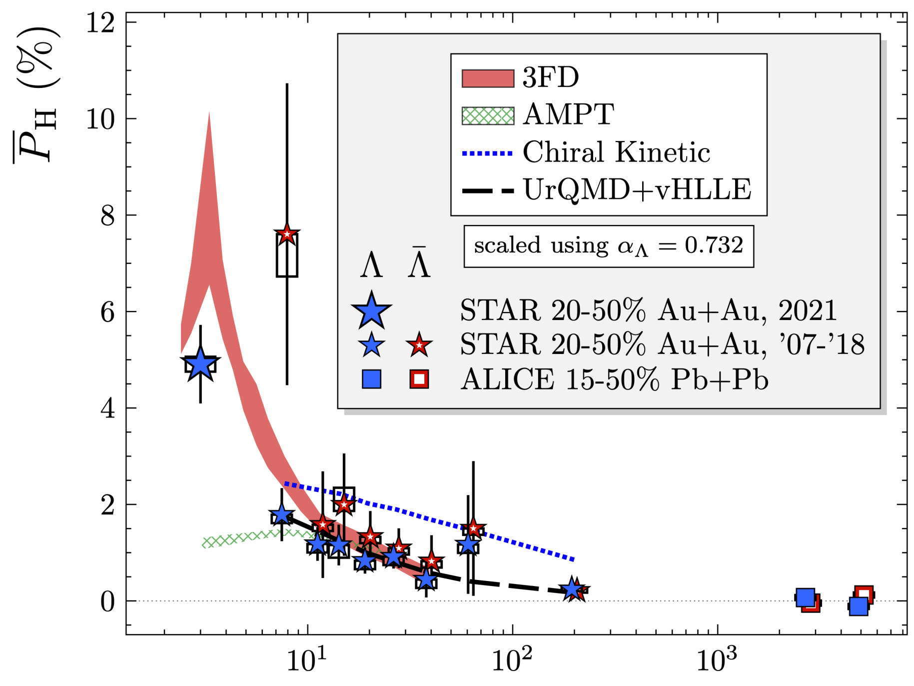


Experimental issues

$$\overline{\mathcal{R}}_{\Lambda}^{\hat{z}} = 2\left\langle \frac{\vec{S}_{\Lambda}' \cdot \left(\hat{z}' \times \vec{p}_{\Lambda}'\right)}{\left|\hat{z}' \times \vec{p}_{\Lambda}'\right|} \right\rangle_{\phi} = \frac{8}{\pi\alpha}\left\langle \sin\left(\phi_p - \phi_{\Lambda}\right)\right\rangle$$

Challenge: large topological dependence of efficiency

- artifacts *complicated* and ~10% (or more)
- will affect *any* tracking detector
- *must flip B-field* to cancel artifact



STAR PRC104 (2021) L061901

Advantage:

- no event plane needed!
  → measuring ~1% toroidal polarization is much easier than 1% global polarization (for same stats)

$$\overline{P}_H = -\frac{8}{\pi\alpha R_{\rm EP}^{(1)}}\left\langle \sin\left(\phi_p - \Phi_{EP,1}\right)\right\rangle_{\phi}$$

$$\delta_{\overline{P}_H} \propto (\#_{\Lambda})^{-1/2}\left(R_{\rm EP}^{(1)}\right)^{-1}$$

Summary

- **A+A / p+A collisions generate complex flow structures; probed by vorticity at small scale**
- **Circular vorticity pattern predicted for b=0 collisions at all energies**
  - LHCb – take a look!
- **Fluid system with localized disturbance – toroidal vortex structure forms**
  - Helmholtz (1867): Persistent vortical toroids (smoke rings) are quintessential fluid behavior
  - thermalized energy from jet quenching – sensitive to virtuality, fluid properties
  - p+A - would be a compelling evidence for hydro nature of the smallest system
- **Experimentally observable (*R*)**
  - distinct from hadronic processes by particle/antiparticle similarity, eta dependence
  - challenging to observe few % effect, but not daunting - flip B-field

João Prado Barbon, David Chinellato, Vítor H. Ribeiro, Willian Serenone, Jun Takahashi, Giorgio Torrieri

Universidade Estadual de Campinas (Unicamp)

UNICAMP

Chun Shen

Wayne State University

WAYNE STATE

Experimental issues

c/o Joey Adams

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STAR PRC104 (2021) L061901