QGP smoke rings in relativistic p+A collisions

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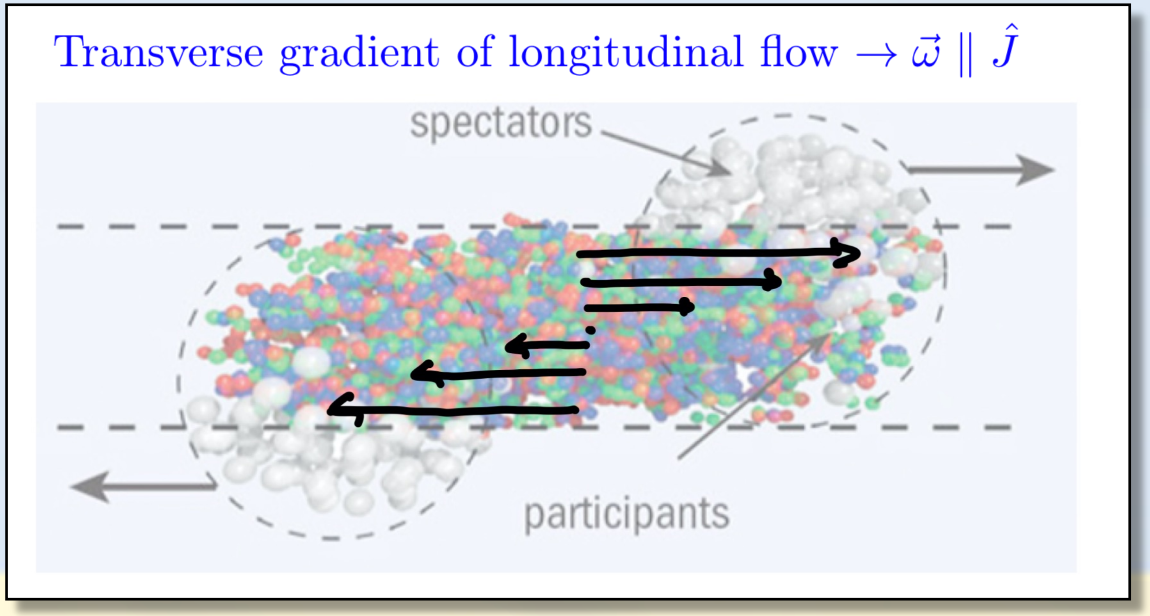
PRC104 (2021) 011901; arxiv: 2101.10872
PLB820 (2021) 136500; arxiv: 2102.11919

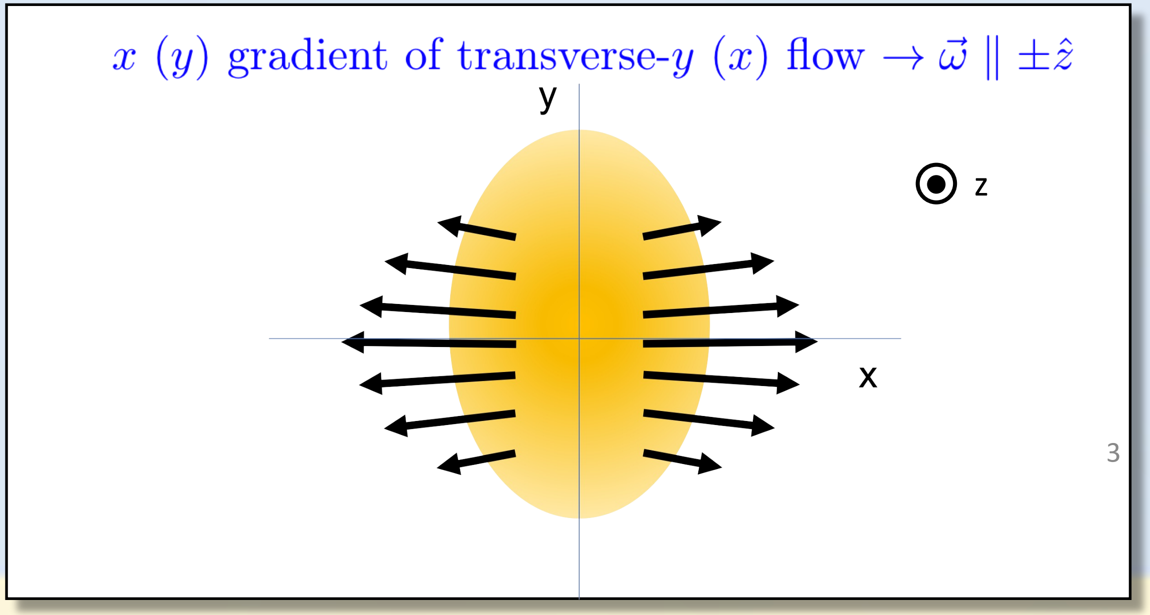
QUARK MATTER
KRAKÓW
2022

Outline

- Polarization/vorticity projections in A+A collisions:
  - Global, Longitudinal, Circular, Jet
- Toroidal vorticity in p+A collisions
  - motivation
  - calculations with 3D viscous hydro (with baryon currents)
- Polarization observable
  - effect of different vorticity definitions
  - effect of shear terms
  - effect of event-by-event fluctuations
- Experimental considerations
- Conclusion

Global and longitudinal **vorticity**

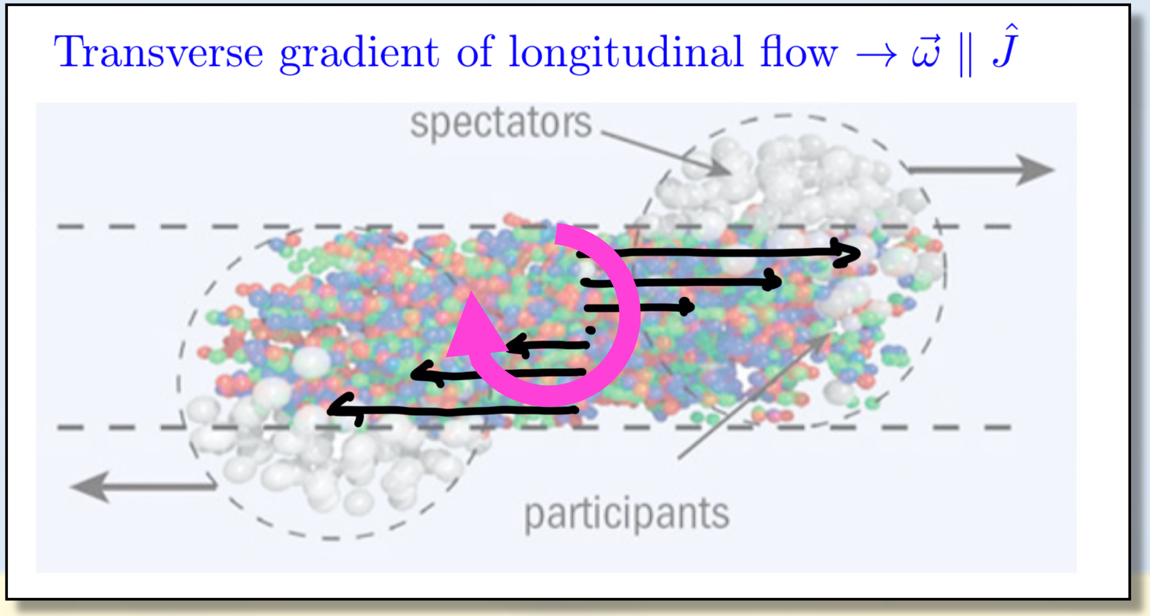


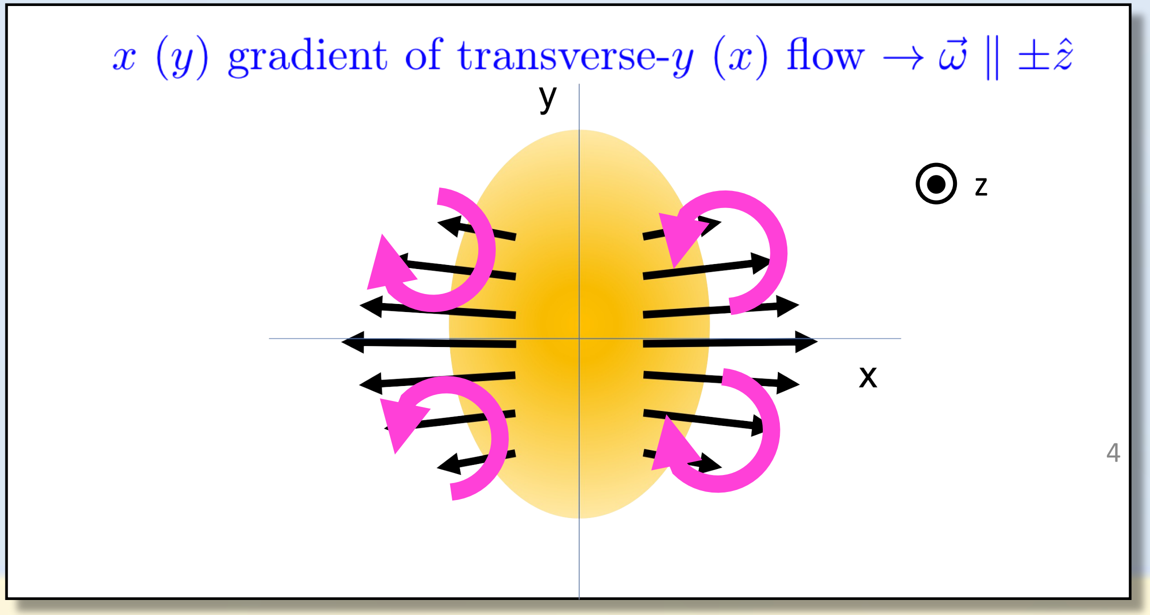


Reminder: vortical flow patterns in heavy ion collisions

- to first approximation and in NR limit, vorticity is a curl
- probe collective hydro behavior at finest scales

Global and longitudinal **vorticity**





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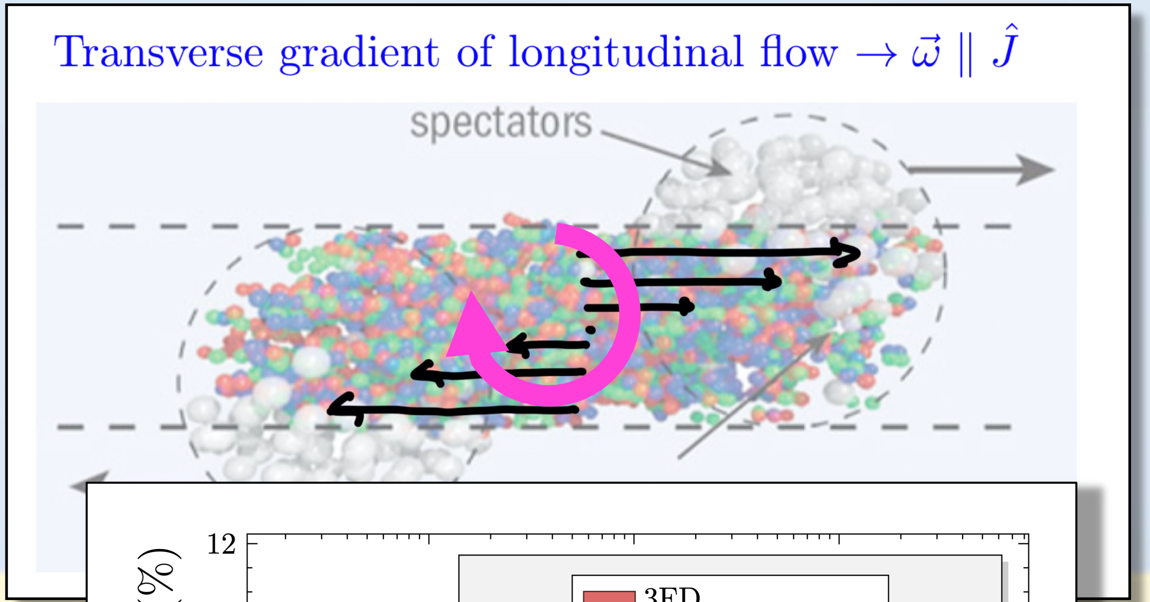
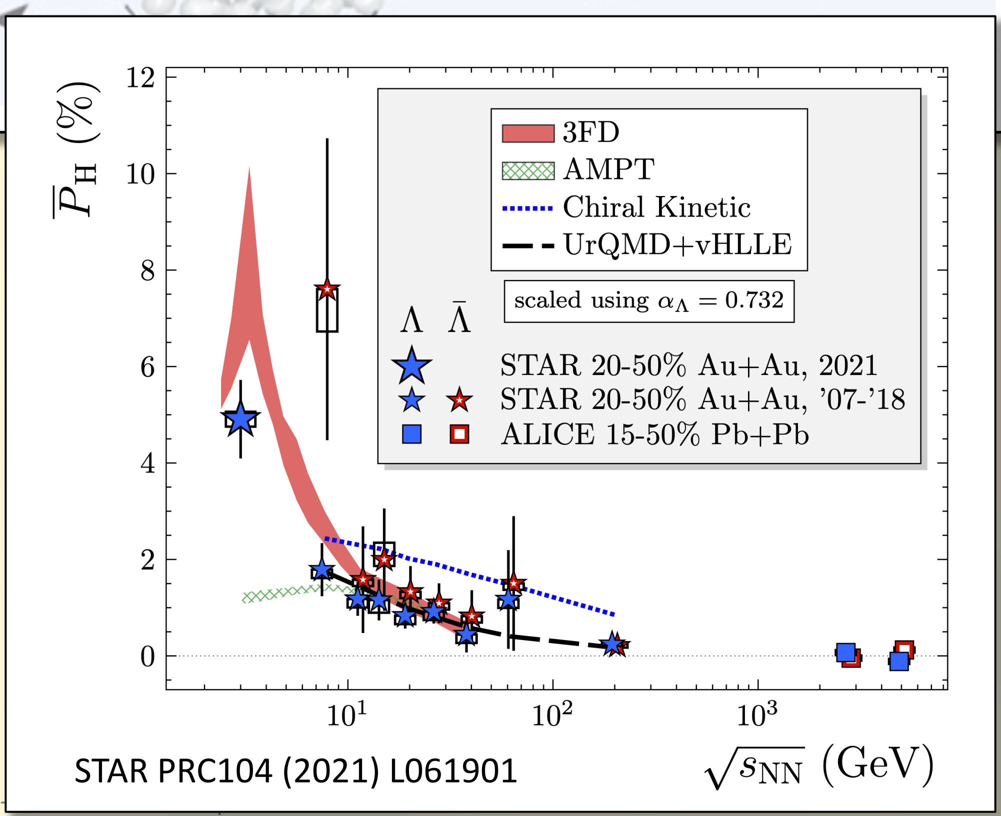
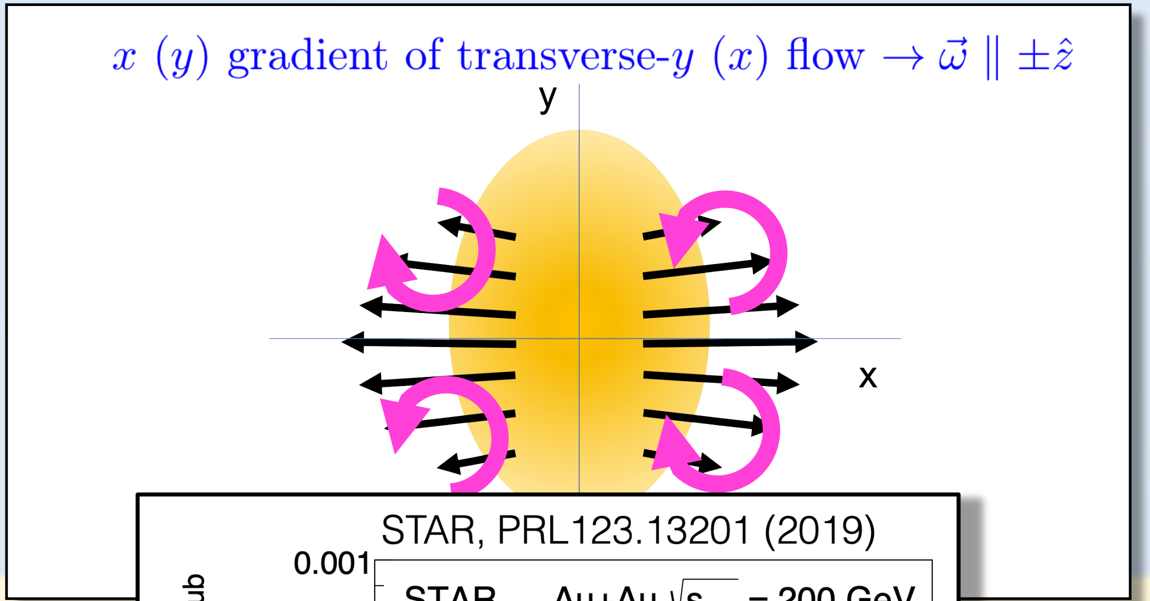
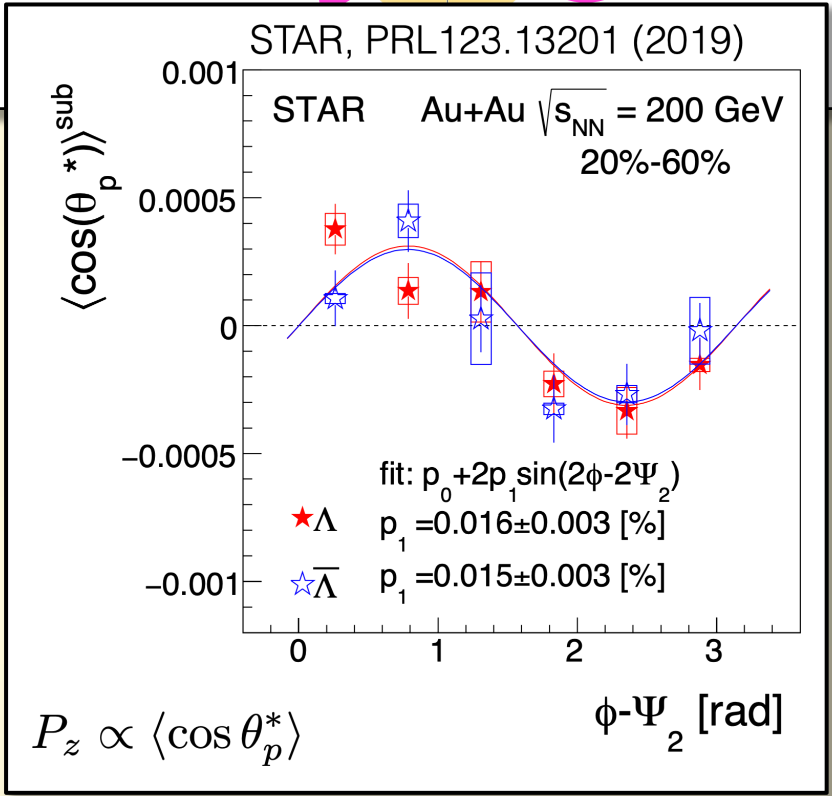
Global and longitudinal **vorticity** observed via **polarization**



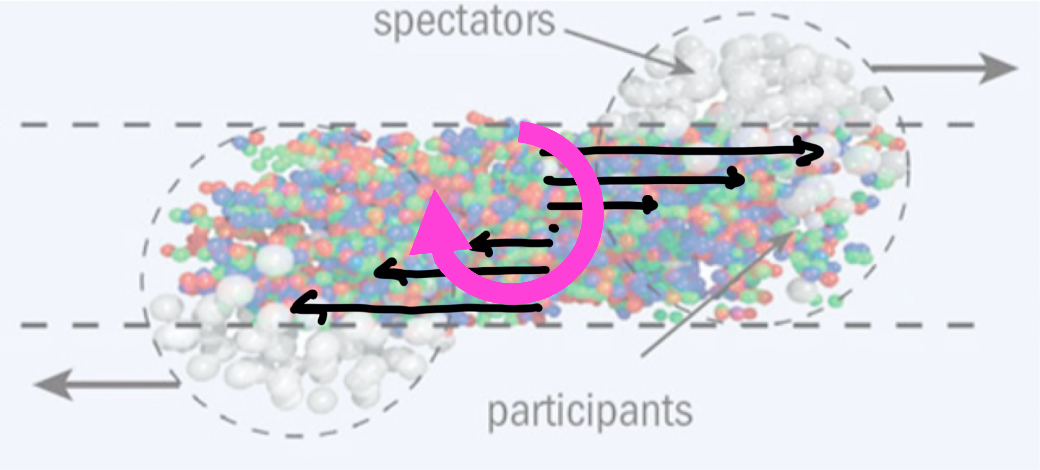




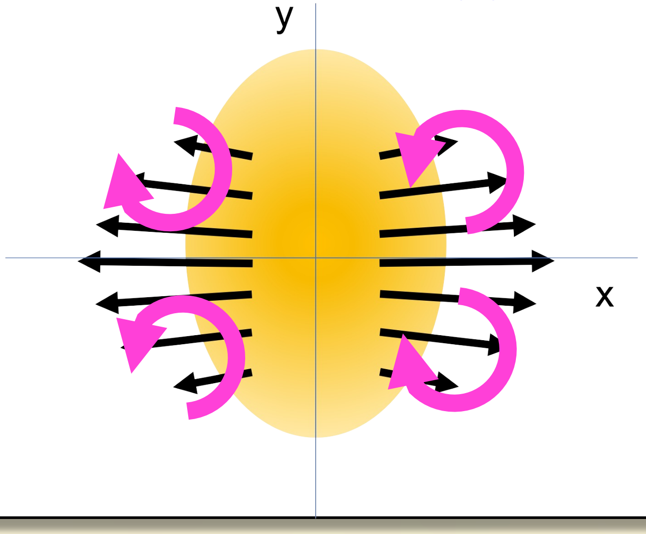


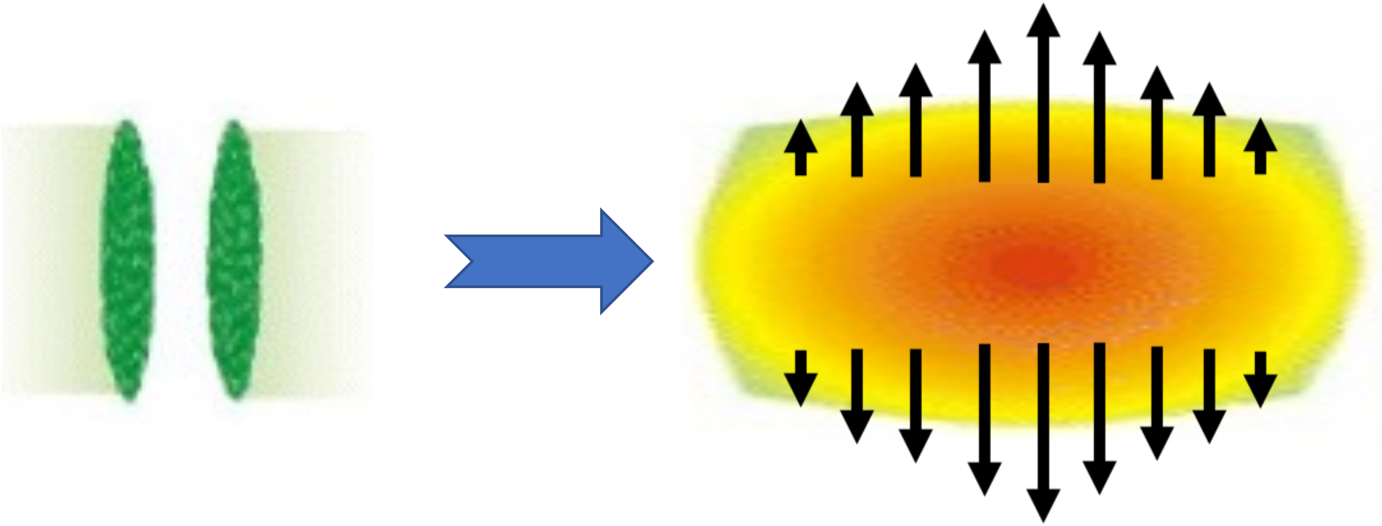
Circular polarization in central A+A

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



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





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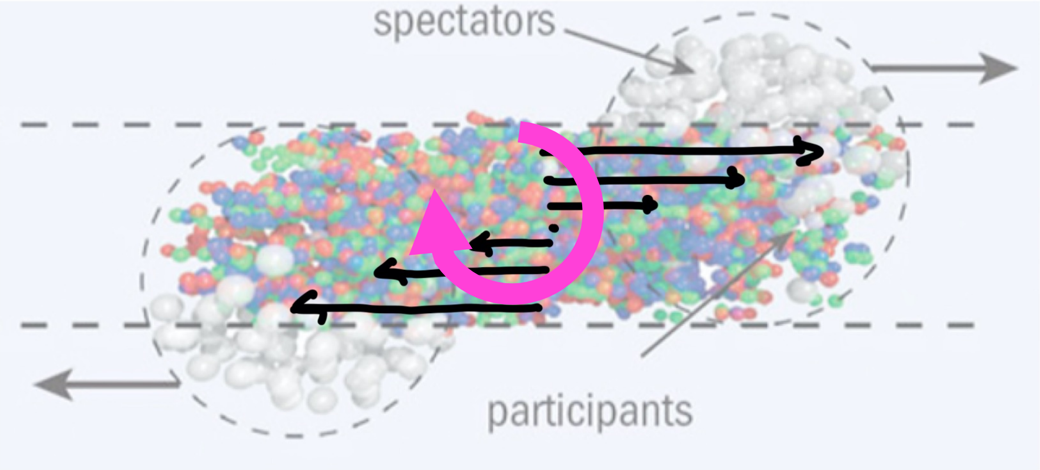

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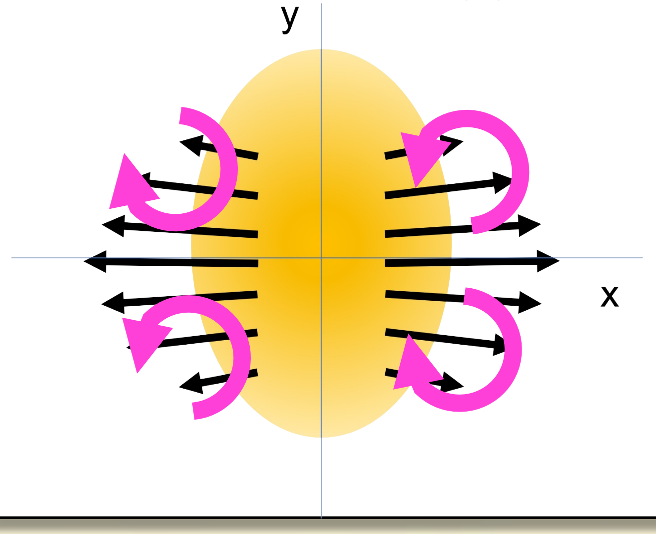
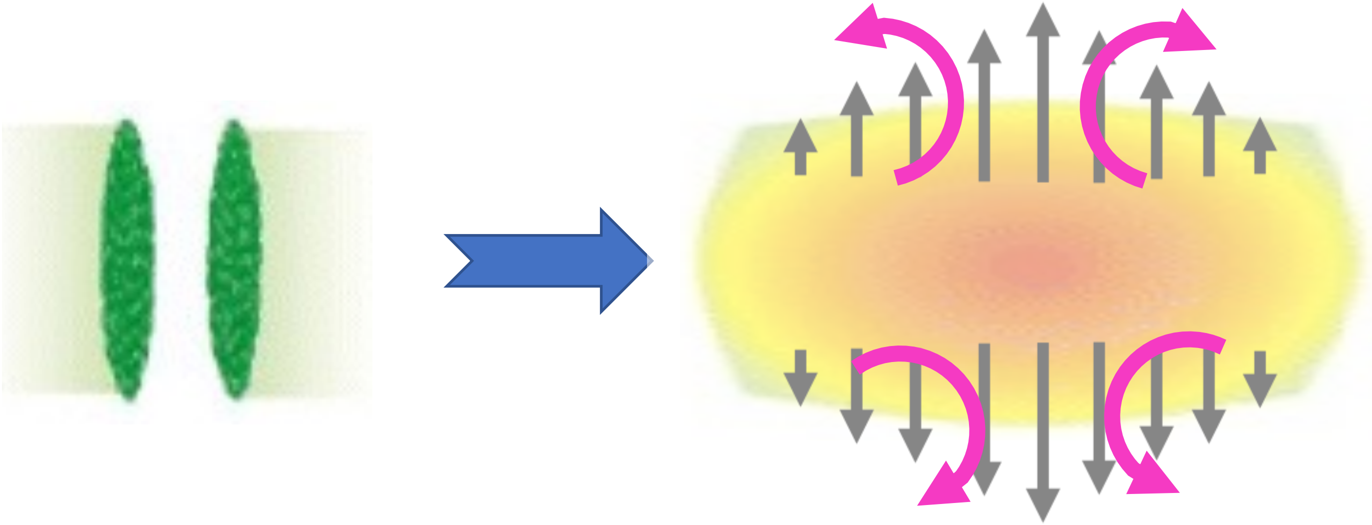
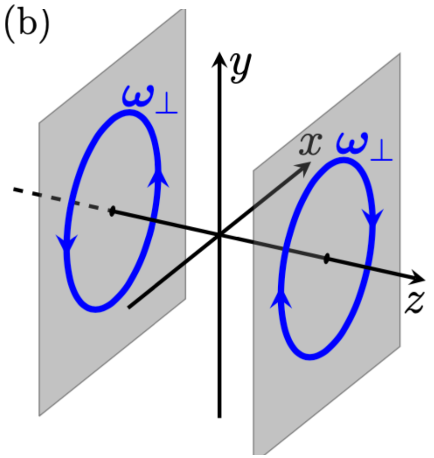


Longitudinal gradient of transverse flow (& temperature) $\rightarrow$ ring structure of $\vec{\omega}$



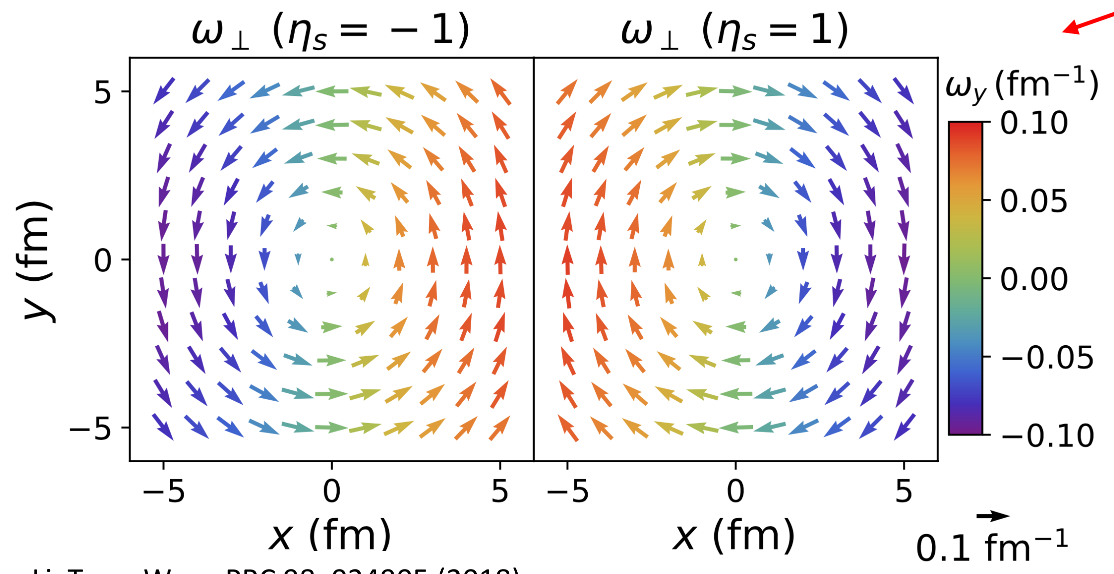
$\vec{\omega} \parallel \vec{p}\cdot\hat{z}\,(\vec{p}\times\hat{z})$



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

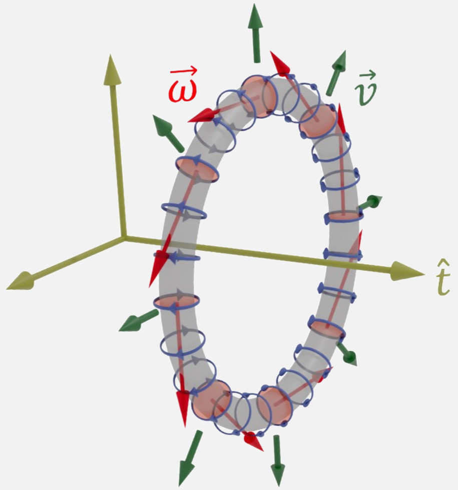
Circular polarization in central A+A

these are vorticity vectors, not flow velocities



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

quantifying smoke-ring structure

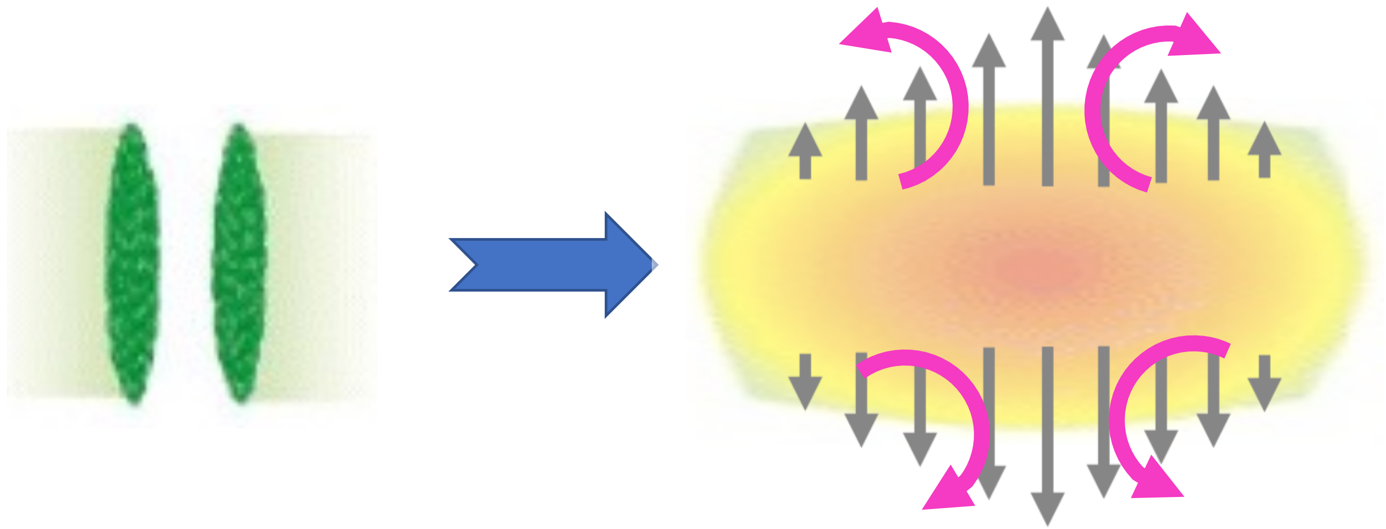


$$\mathcal{R}^{\hat{t}}_{\mathrm{NR}} \equiv \left\langle \frac{\vec{\omega}_{\mathrm{NR}} \cdot (\hat{t} \times \vec{v}_{\mathrm{cell}})}{|\hat{t} \times \vec{v}_{\mathrm{cell}}|} \right\rangle_\phi$$

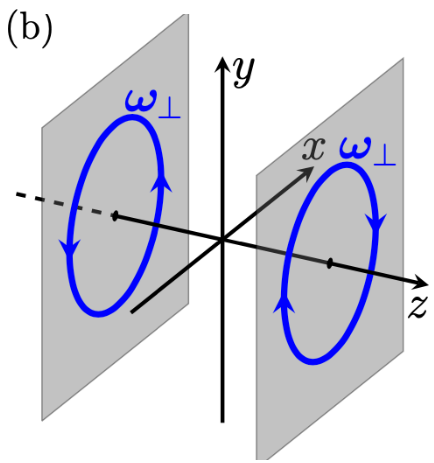
$$\mathcal{R}^{\hat{t}}_{\mathrm{fluid}} \equiv \frac{\epsilon^{\mu\nu\rho\sigma}\Omega_\mu n_\nu \hat{t}_\rho u_\sigma}{|\epsilon^{\mu\nu\rho\sigma} n_\nu \hat{t}_\rho u_\sigma|}$$

PRC104 (2021) 011901

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



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

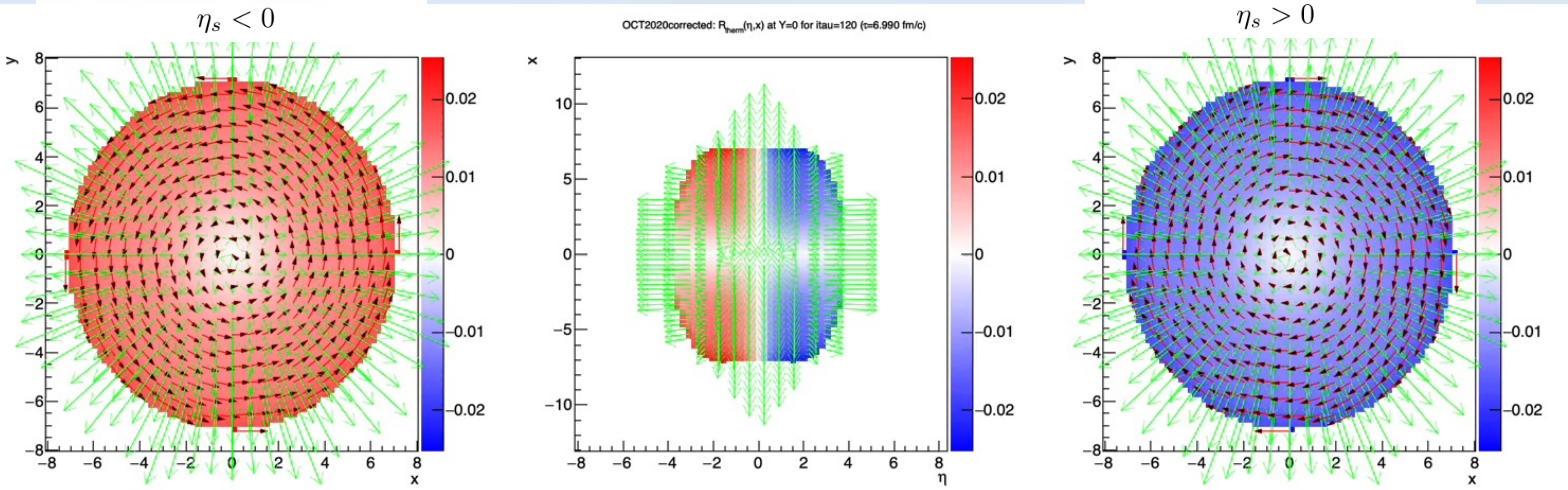


Xia, Li, Tang, Wang PRC 98, 024905 (2018)

Development of toroidal vorticity in MUSIC

PRC104 (2011) 011901

Au+Au at 200 GeV   Bjorken flow profile



→ $\vec{\omega}$ → $\vec{u}_{\rm cell}$

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

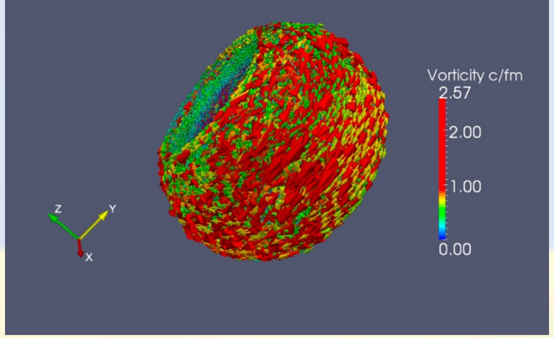
MUSIC hydrodynamics, with baryon currents
Schenke, Jeon, Gale PRC82 (2010) 014903
Schenke, Shen, Tribedy PRC102 (2020) 044905

Rings predicted at all energies– can they be observed?

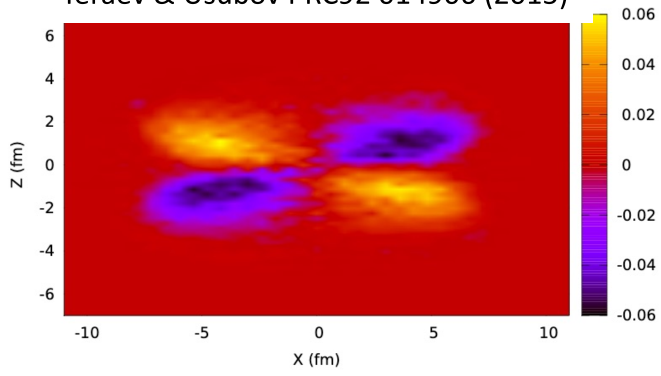
- This is a unique predicted structure! Observation would represent a compelling demonstration of fluid structure at the extremes of rapidity & energy

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

Baznat, er al, PRC93, 031902(R) (2016)



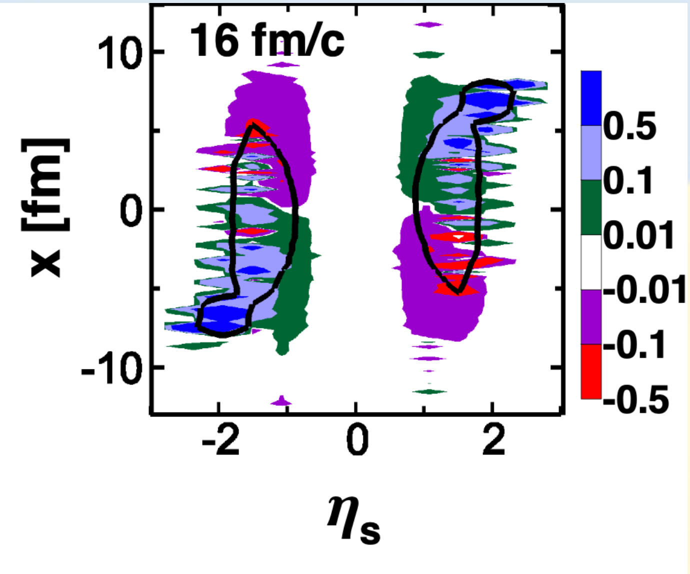
Teraev & Usubov PRC92 014906 (2015)



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

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

Ivanov & Soldatov PRC97, 044915 (2018)

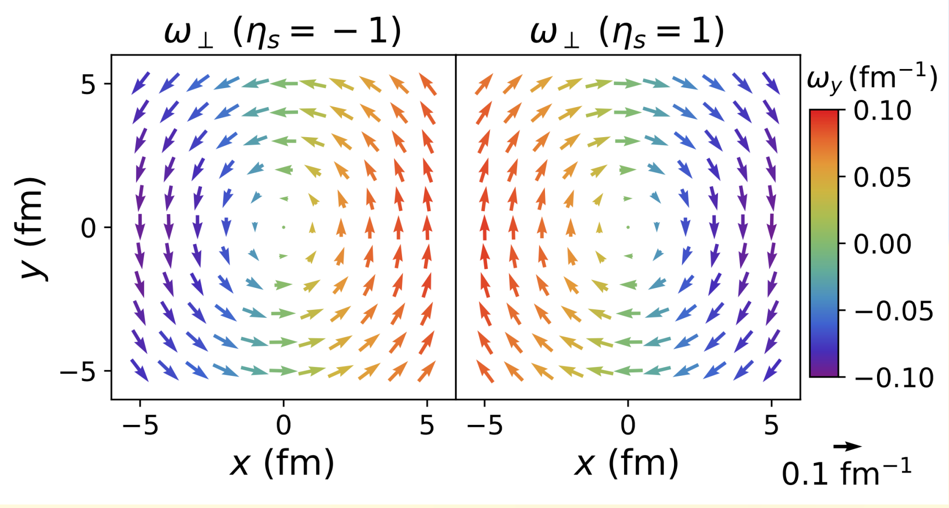


Focused forward

- 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)

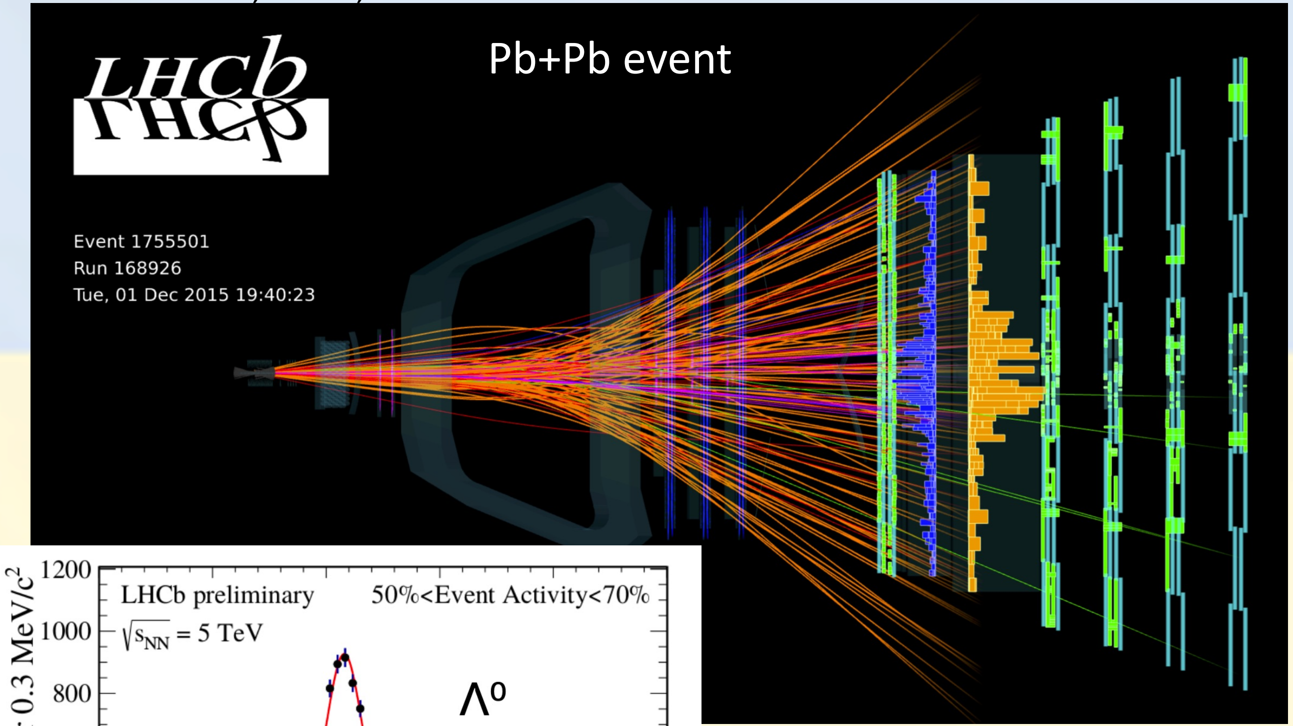
Focused forward

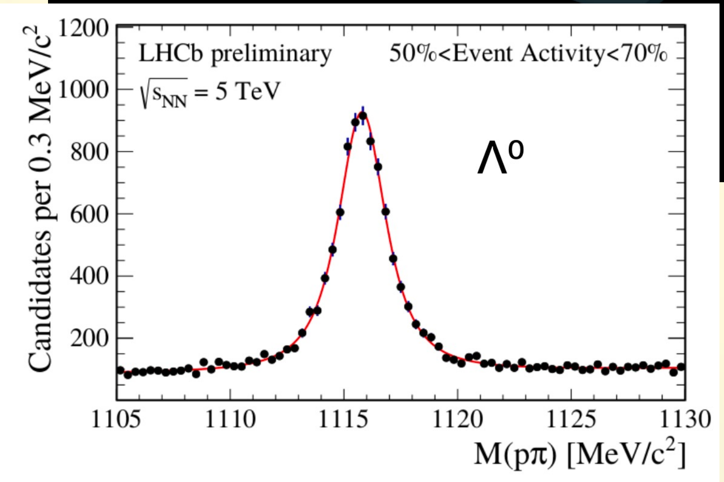
- difficult at STAR@RHIC or ATLAS/CMS/ALICE@LHC without forward tracking upgrade

Seeing the rings

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

Michael Winn, ERICE, 2016





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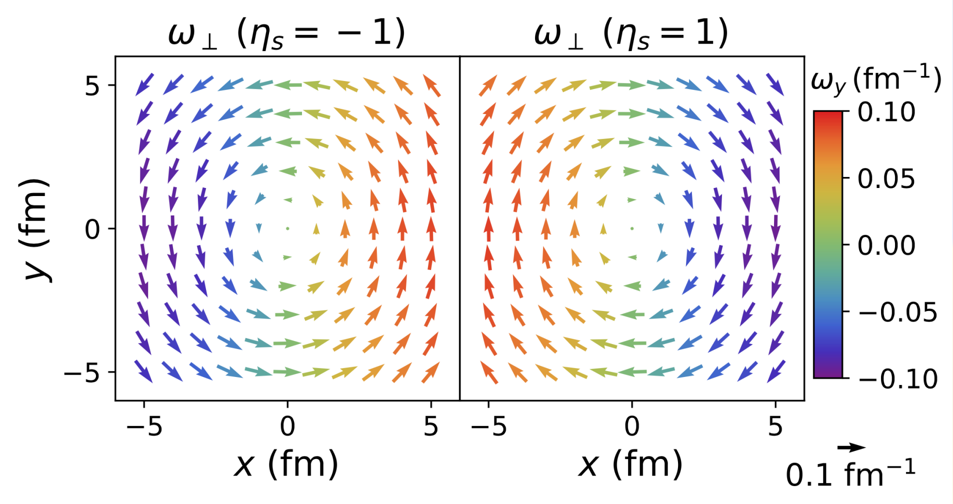


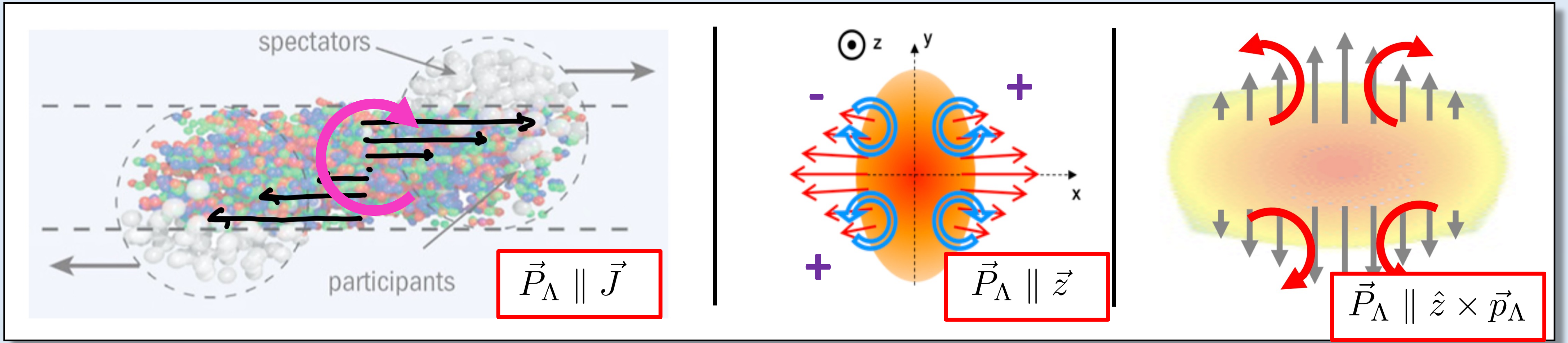
Note: No Event Plane Necessary!

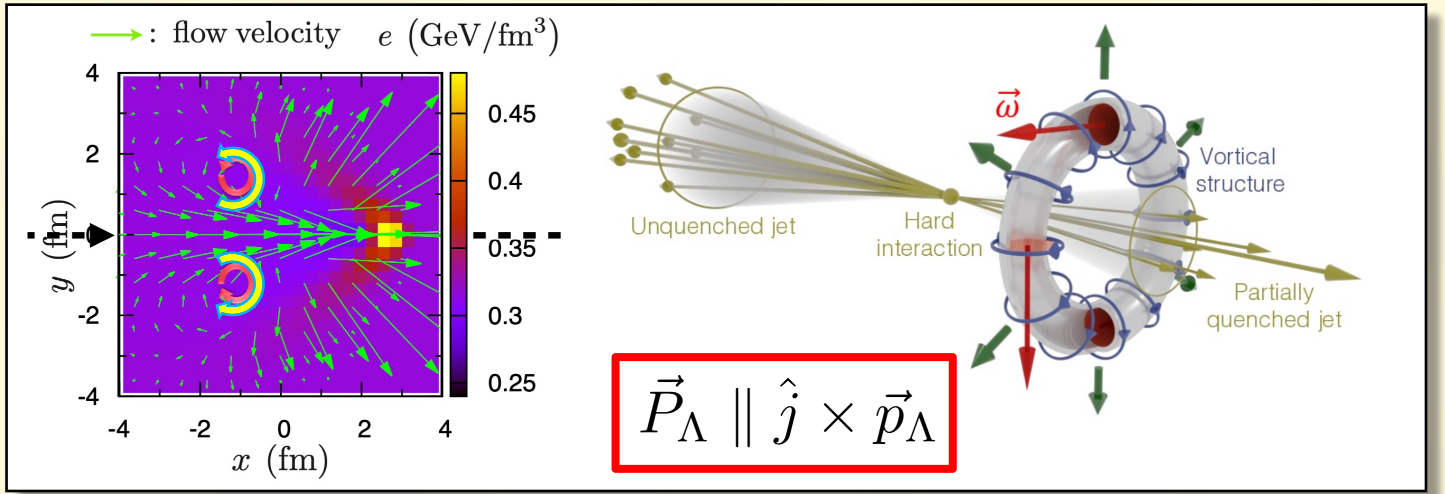
Focused forward

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

✓ LHCb ideal to observe this structure

Polarization about a local disturbance



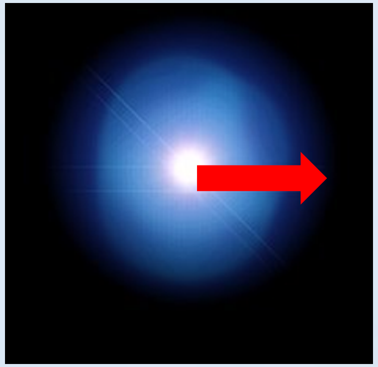


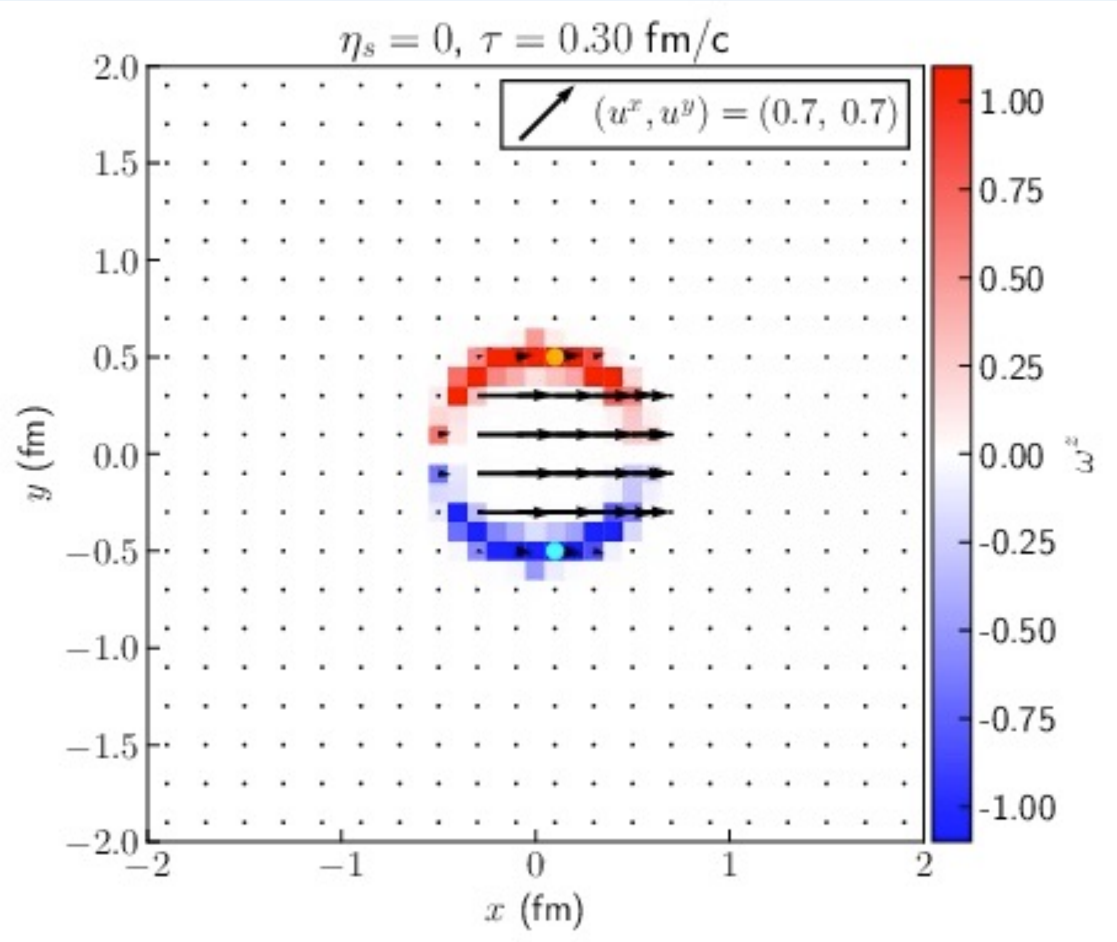
Helmholtz (1867): Persistent vortical toroids (smoke rings) are quintessential fluid behavior

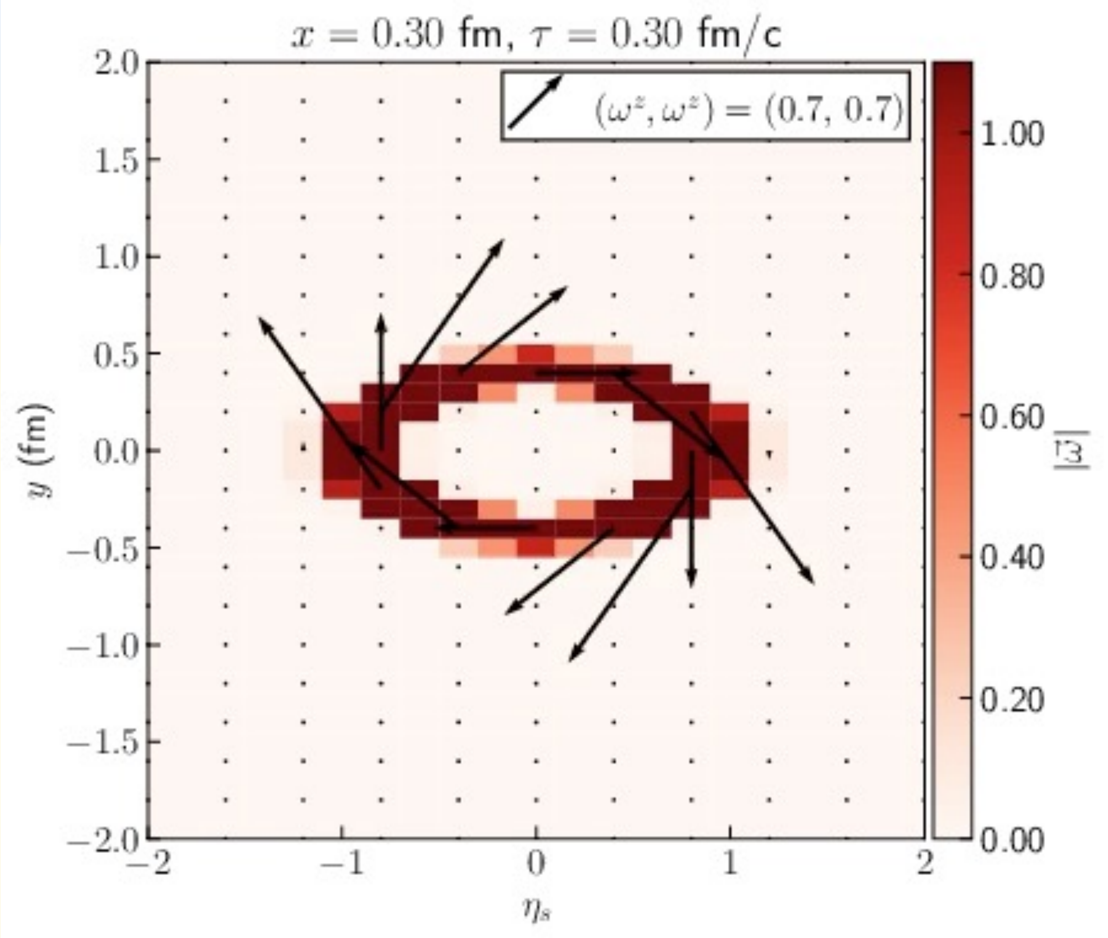
Vortex rings about the jet direction:

- Betz/Gyulassy/Torrieri, PRC76 (2007) 044901
- Tachibana/Hirano, NPA904-905 (2013) 1023c
- W. Matioli et al, PLB820 (2021) 136500

Jet-induced toroidal vorticity in MUSIC







Polarization about a local disturbance

Experimentally challenging, but potentially rich!

c.f. W. Matioli, Poster session 2 T02

- *early-stage* fluid behaviour?
- nature of energy loss in fluid
- sensitivity to transport coefficients

Toroidal vorticity
t = jet direction

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

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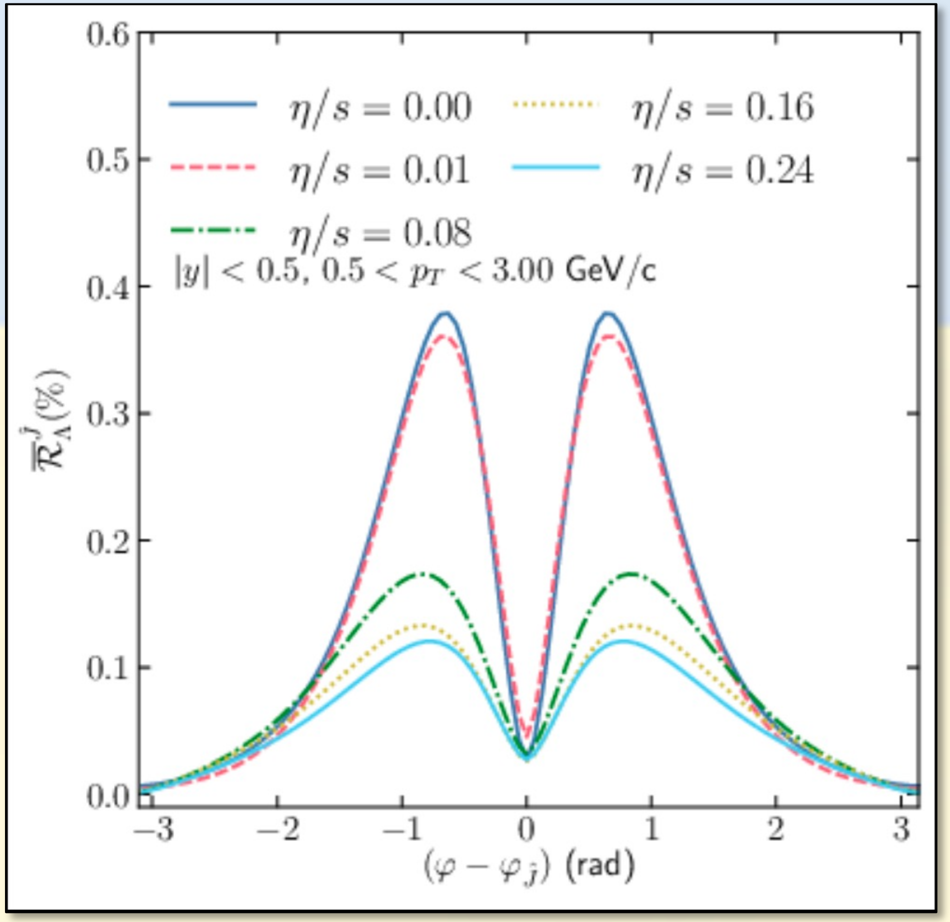
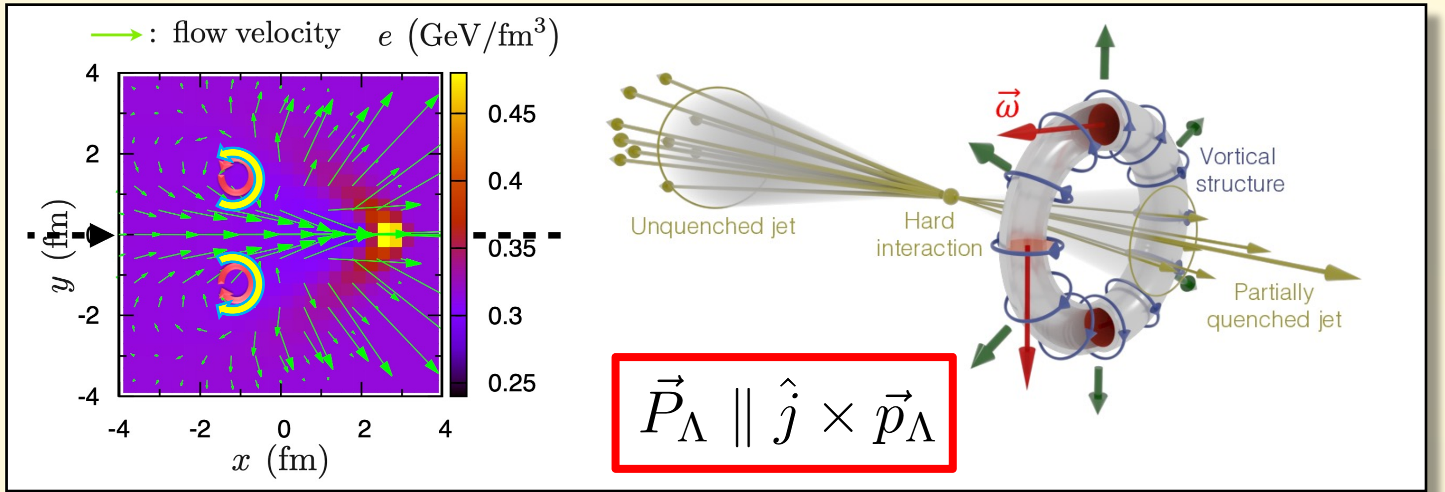
MUSIC hydro with embedded jet



W. Matioli et al, PLB820 (2021) 136500

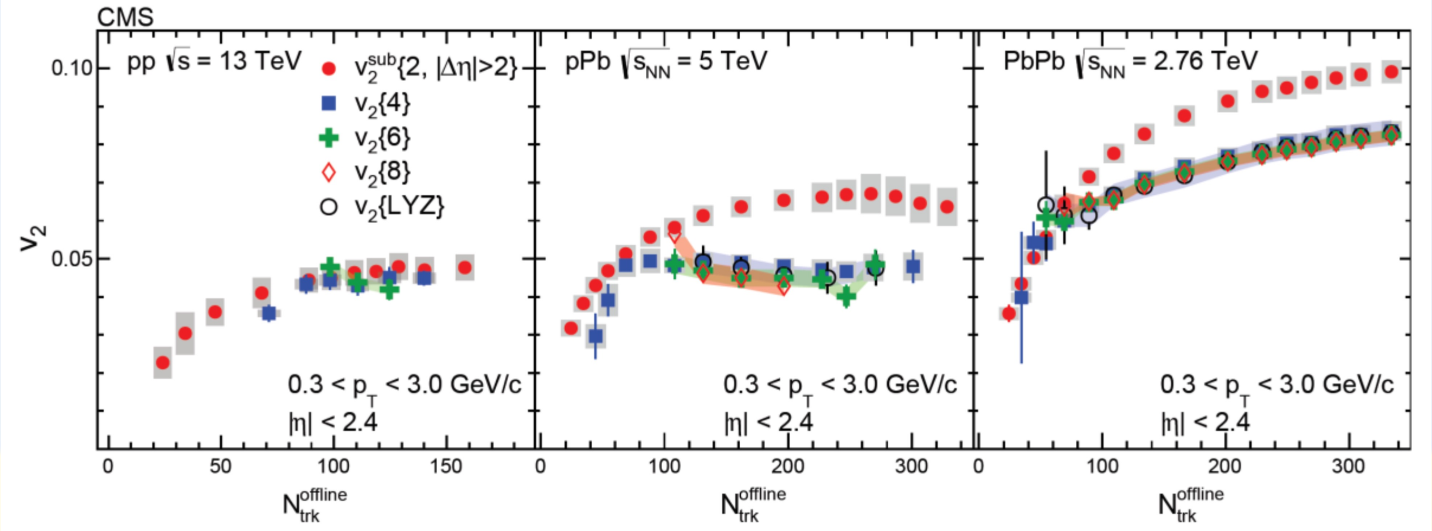


$$\vec{P}_\Lambda \parallel \hat{j} \times \vec{p}_\Lambda$$

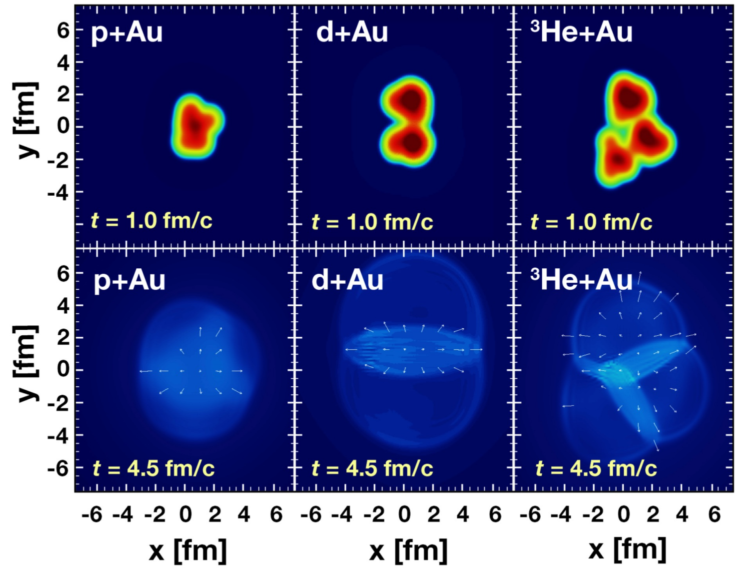
What about p+A collisions…?

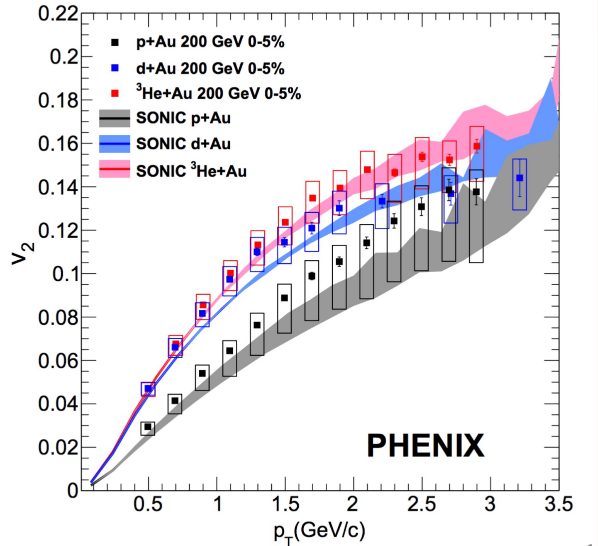
- Do such collisions really form "the smallest droplet of QGP?"

Nagle & Zajc, Ann.Rev.Nucl.Part.Sci. 68 (2018)



  - multi-particle correlation →
    though… not uniquely hydro prediction,
    e.g.: Dusling et al, PRD 97, 016014 (2018)





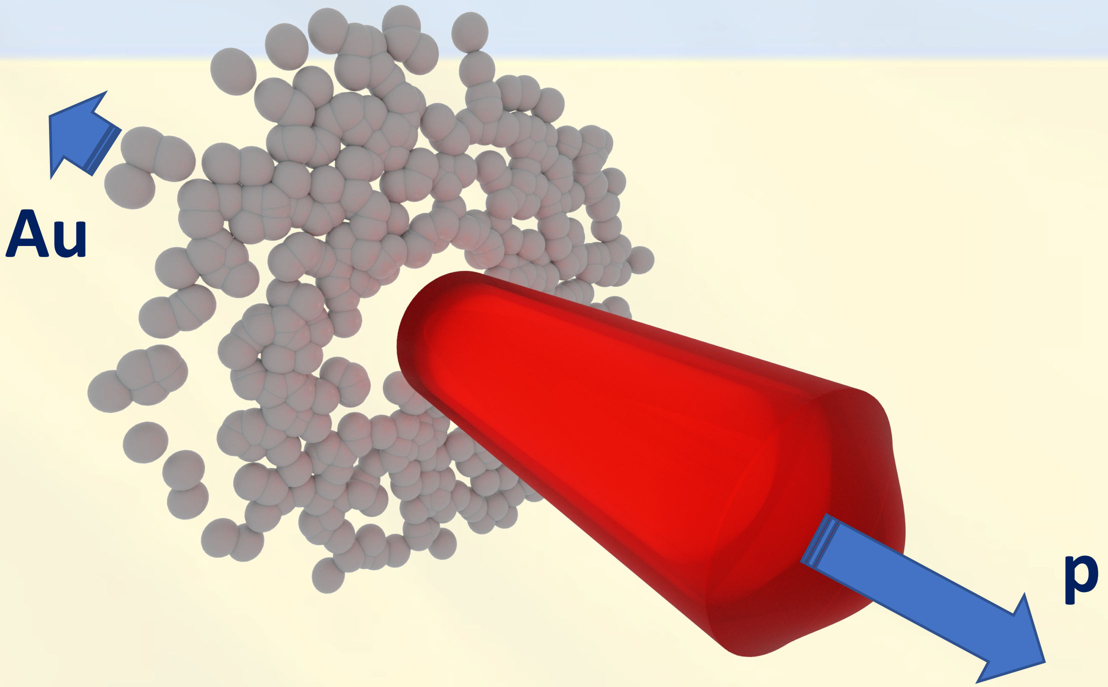
  - with well-chosen initial conditions and pre-equilibrium effects, hydro evolution seems to reproduce 2-particle anisotropy!

What about p+A collisions…?

- Do such collisions **really** form "the smallest droplet of QGP?"
  - if *everything* is hydro, are we confident that *anything* is hydro?
  - much of the supporting evidence comes from v_n… can we find a novel, hydro-characteristic test?

- "Every time you break a symmetry, you learn something"* (v2, v1, polarization!)
  - broken forward/backward symmetry → potentially interesting initial state

* Urs Wiedemann



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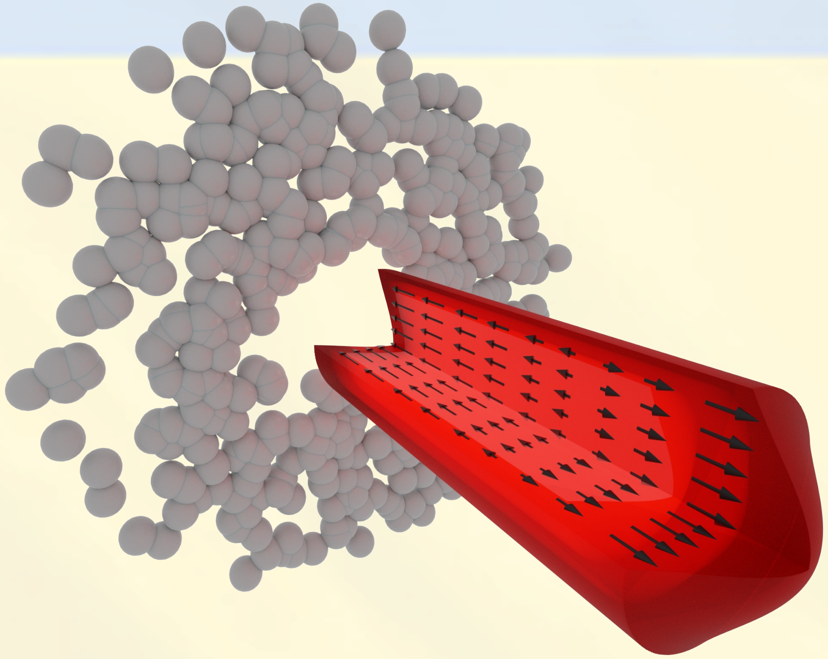
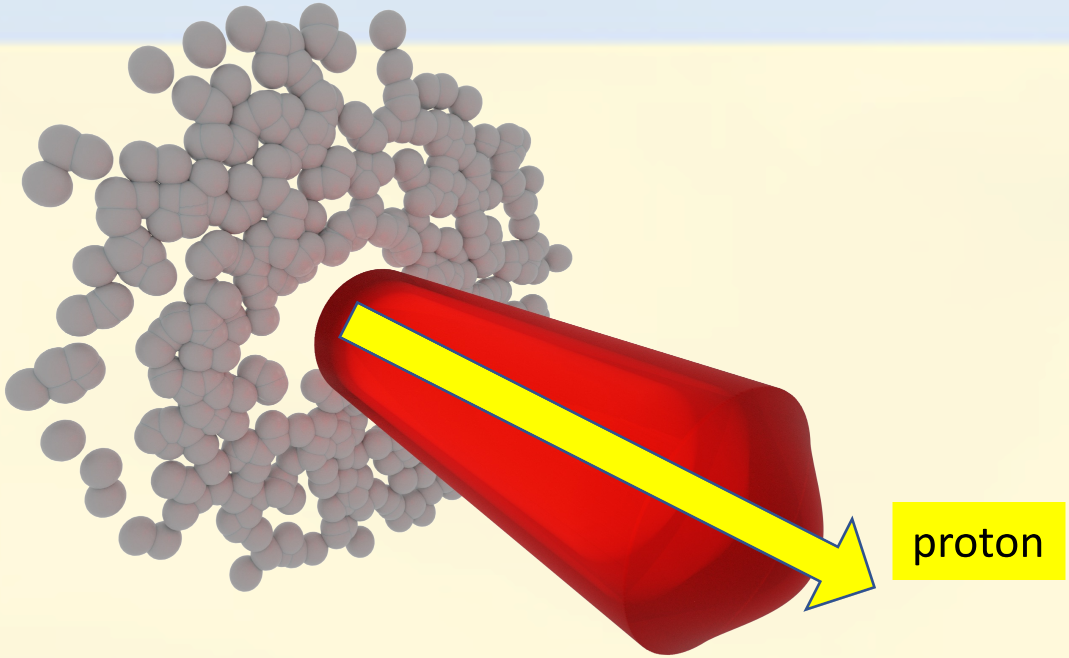


(a) Bjorken flow profile: $u_z = \eta_s$



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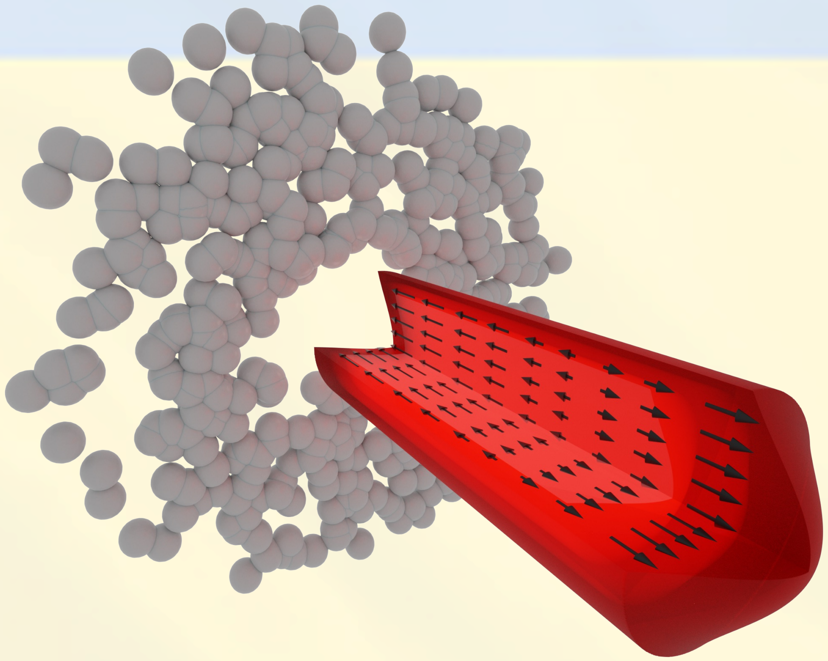

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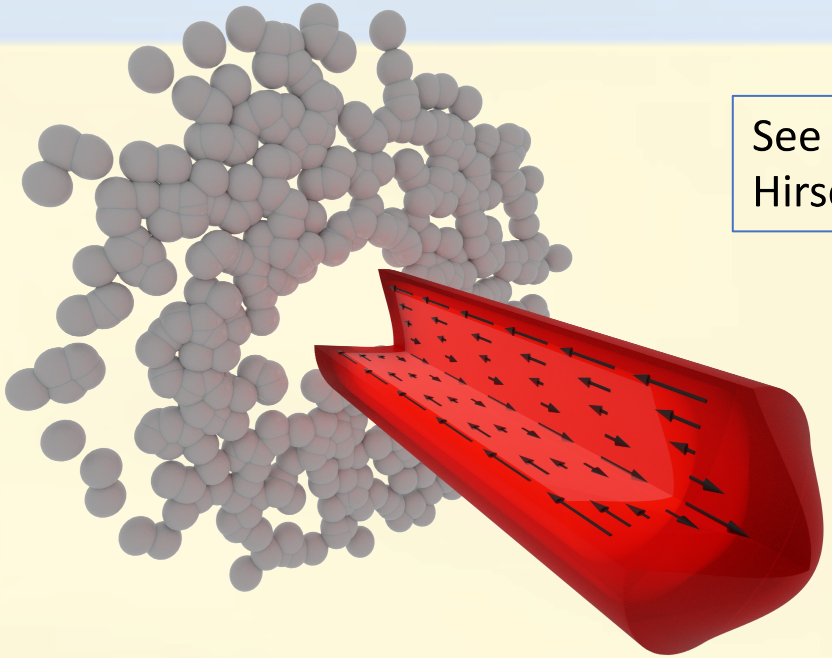
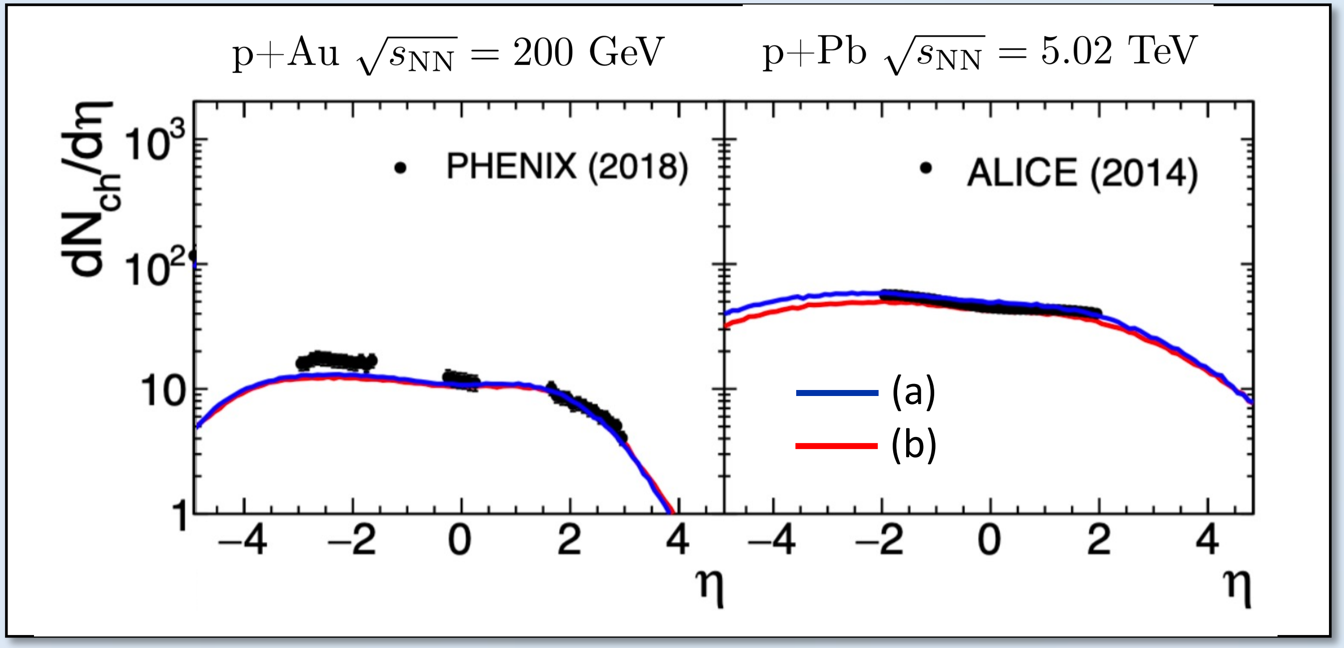


(b) Radial-gradient flow profile

See also S. Voloshin, Hirschegg 2017

What about p+A collisions...?

- Basic observables are ~identical in these scenarios



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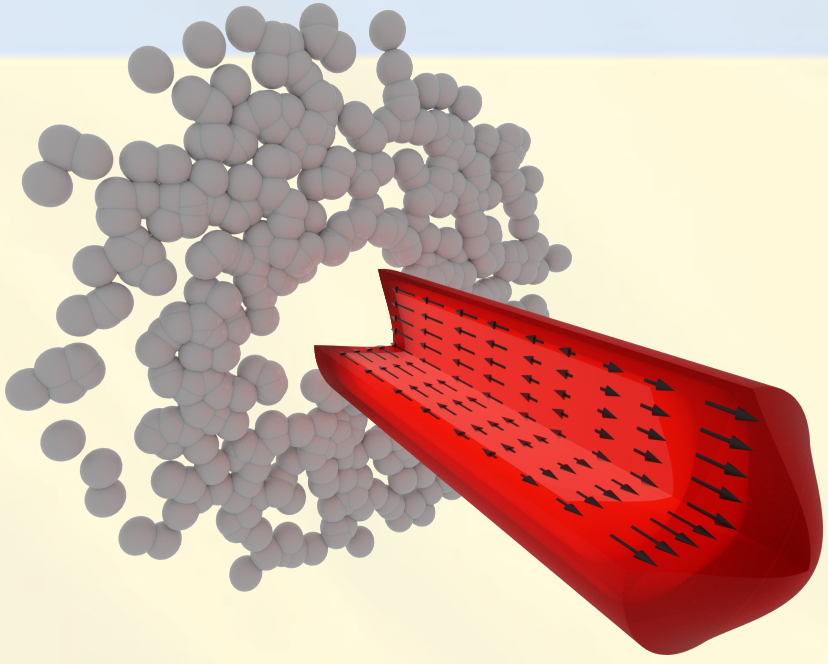

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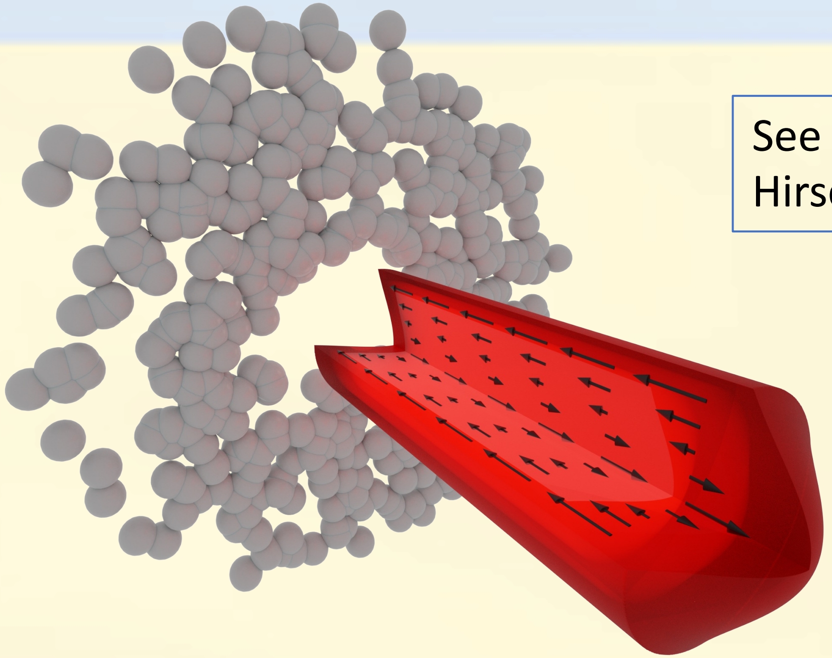
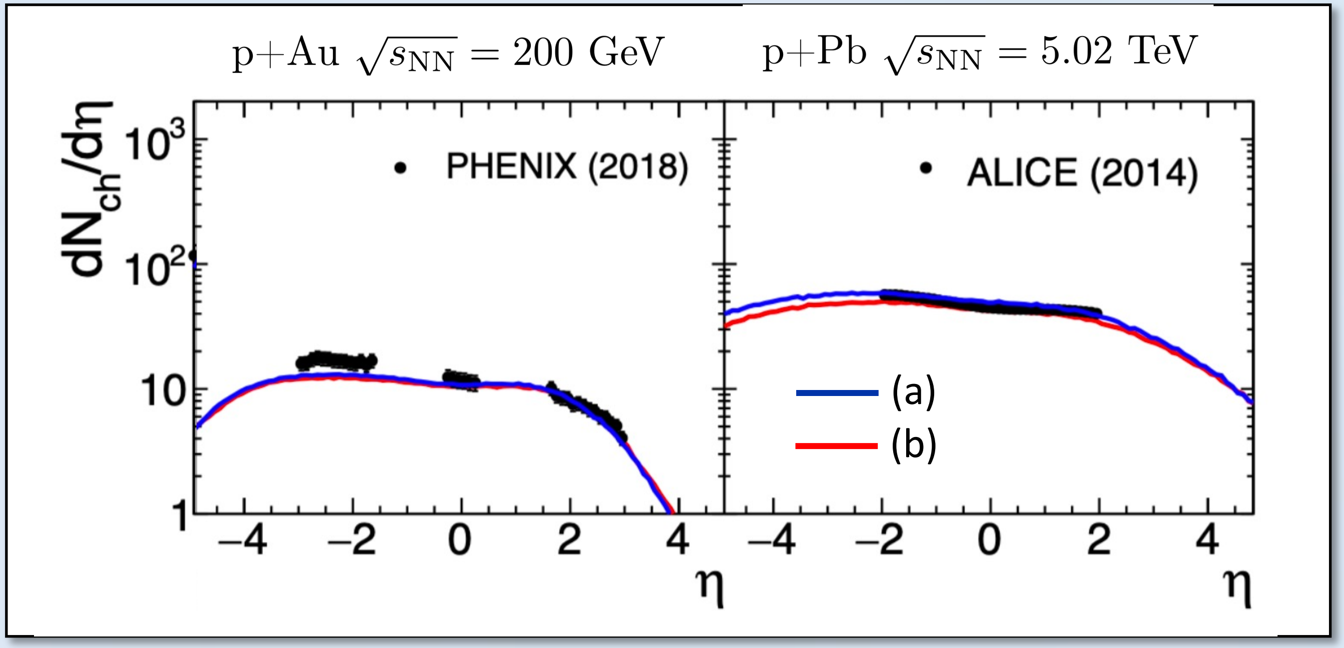


(b) Radial-gradient flow profile

What about p+A collisions…?

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



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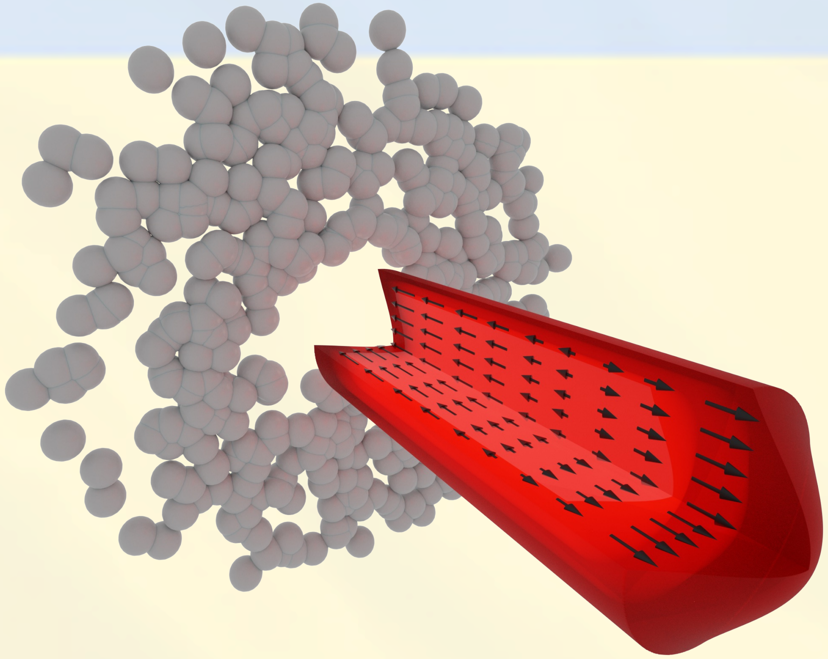

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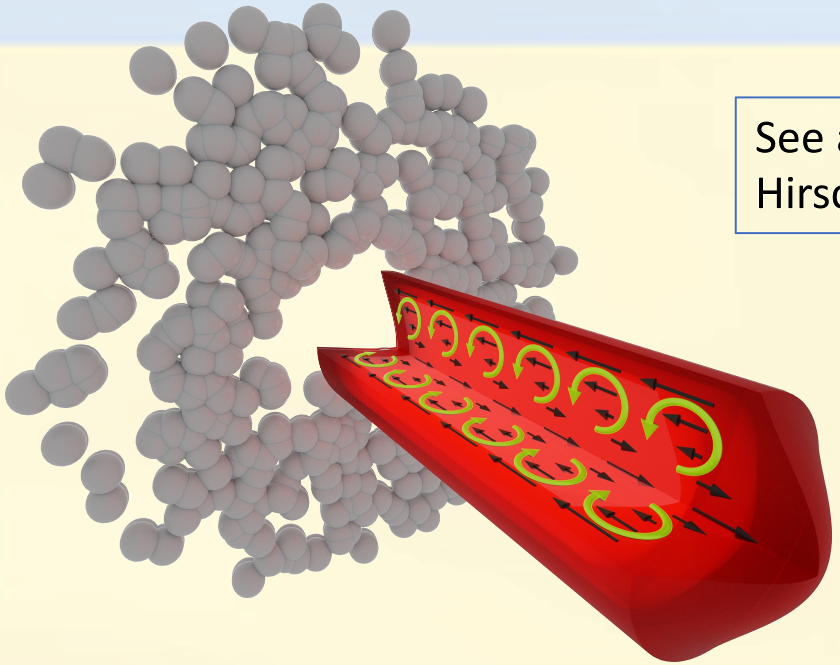
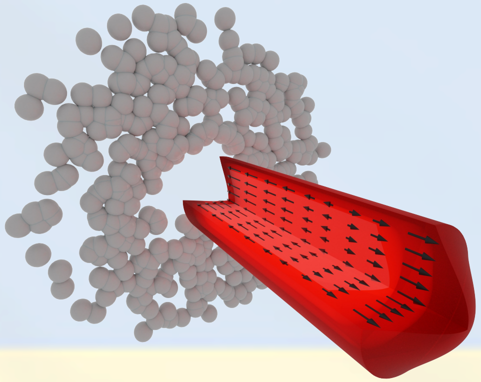


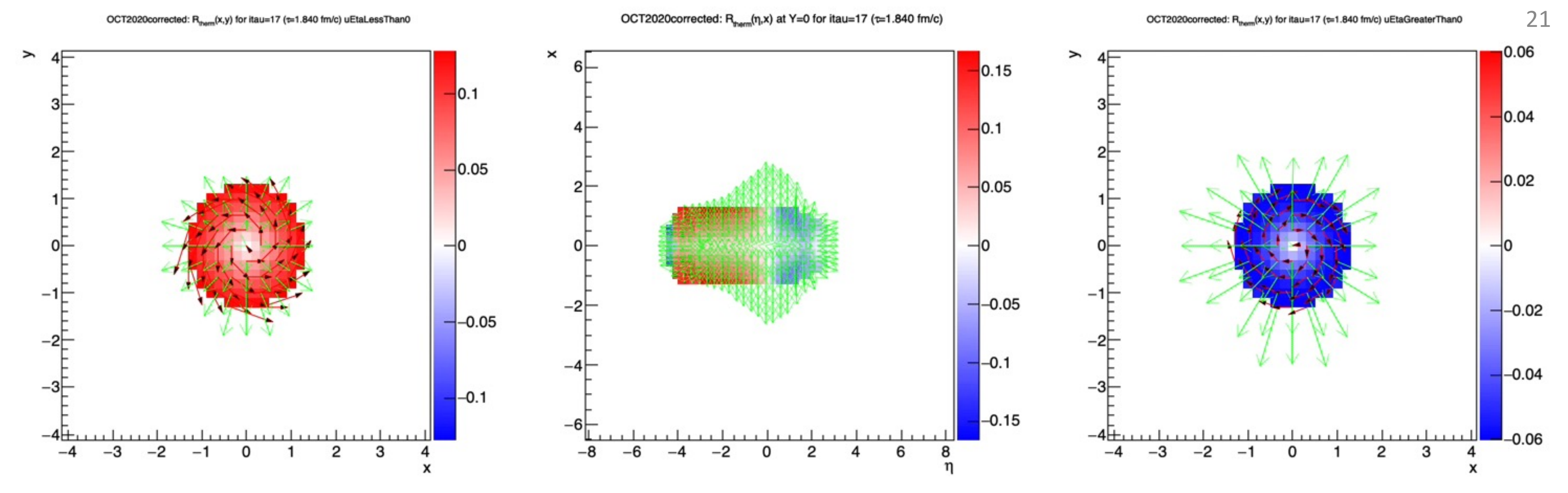
(b) Radial-gradient flow profile

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

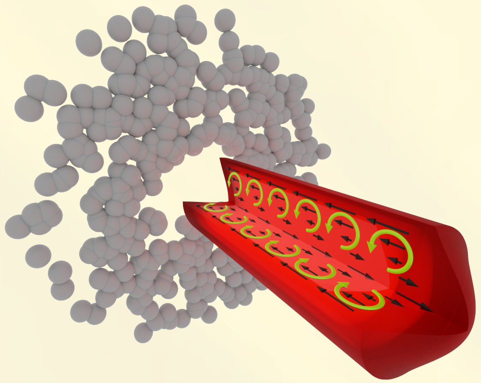
p+Au at 200 GeV

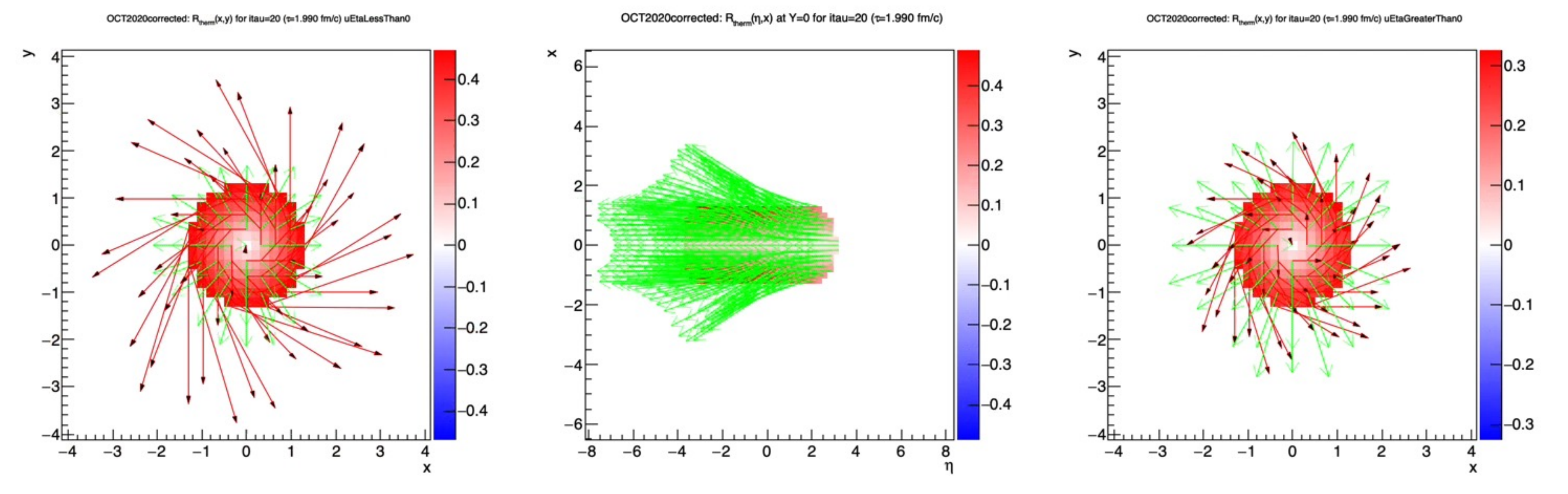
(a)





(b)

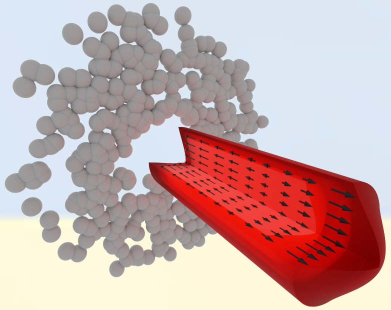


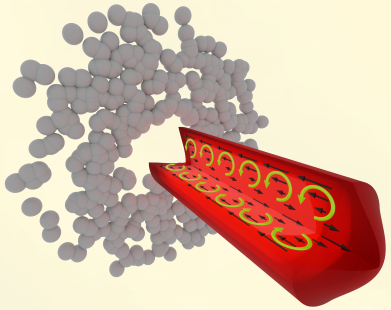


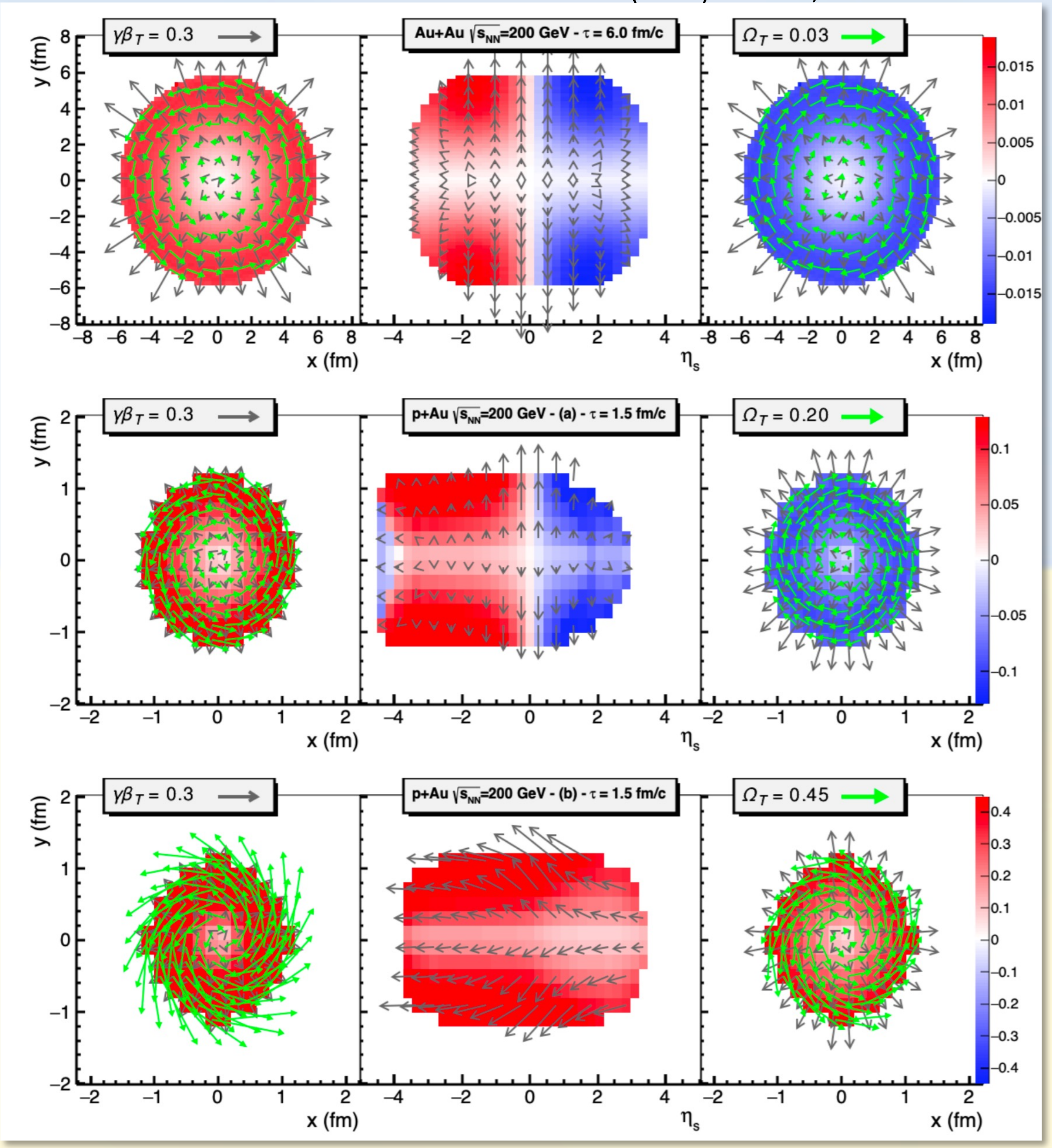
MUSIC hydrodynamics, with baryon currents

Snaphots

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

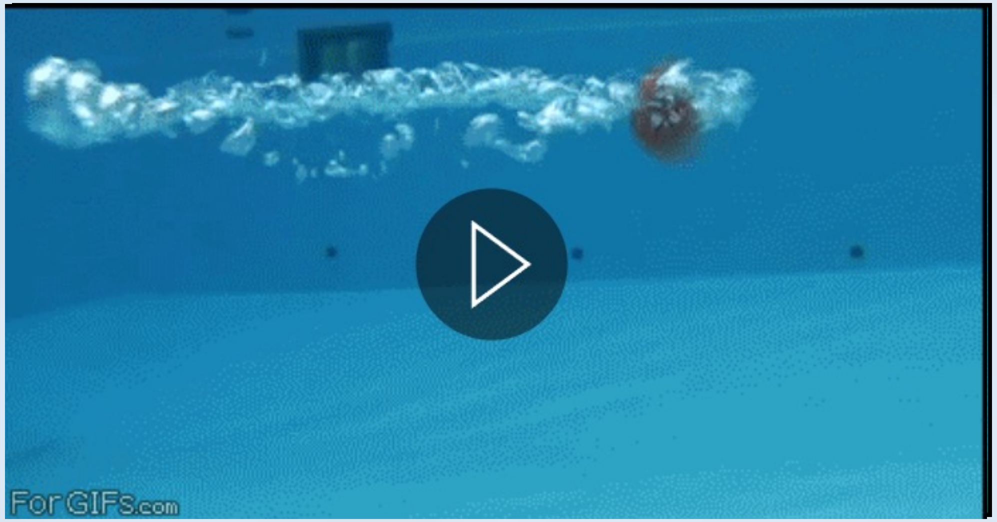


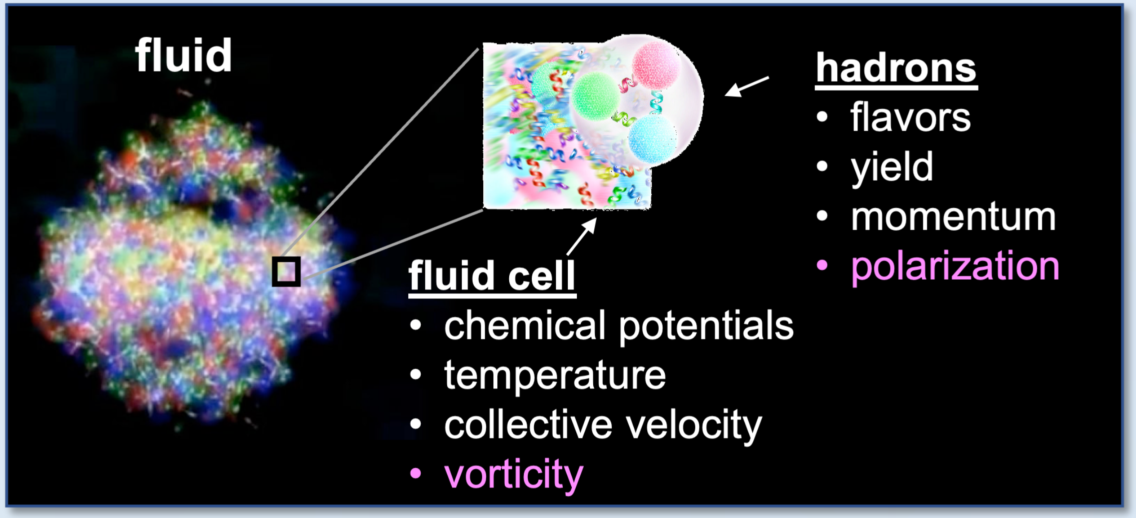




PRC104 (2021) 011901; arxiv: 2101.10872

Fluid ➞ particles (vorticity ➞ polarization)



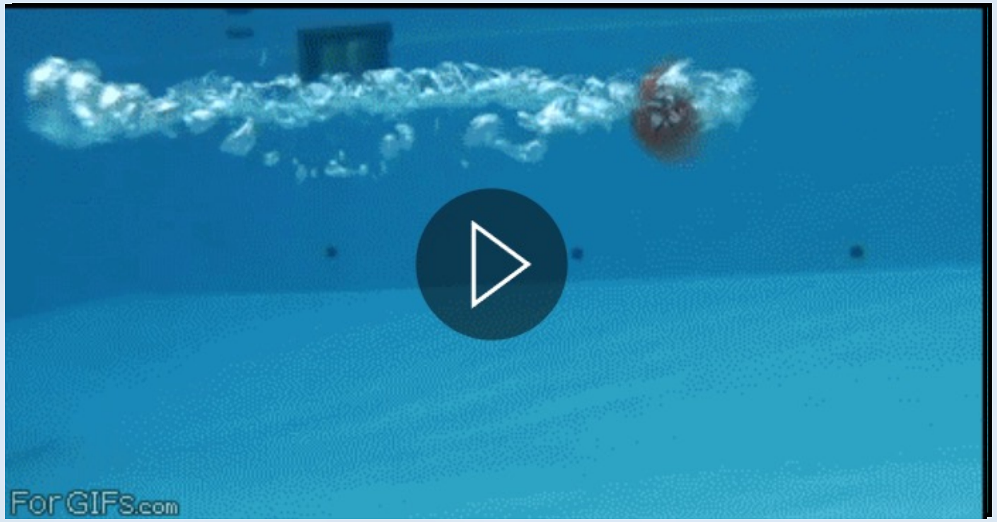


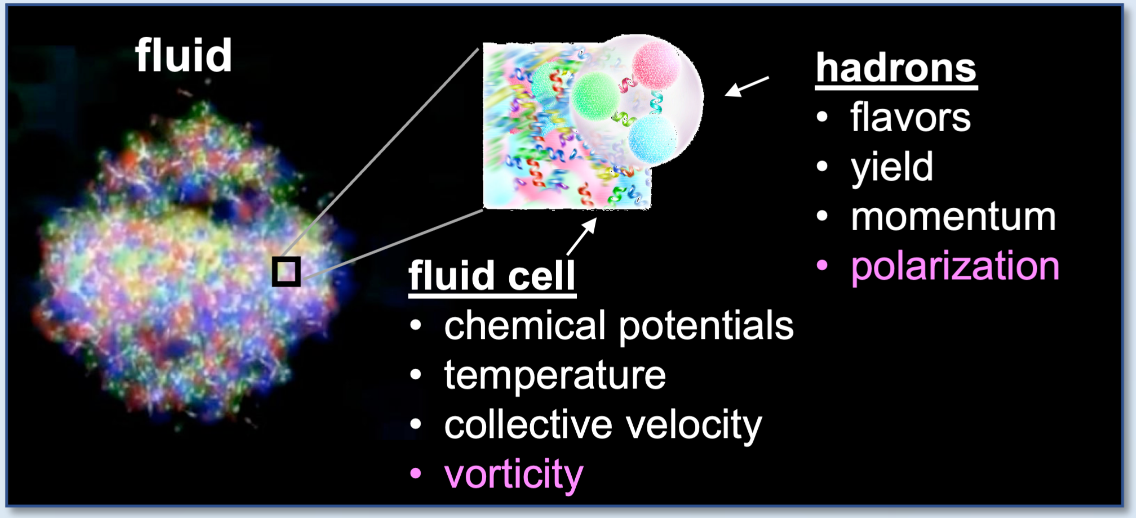
Cooper-Frye for spin

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

Becattini et al, Annal. Phys. 338 (2013) 32

Fluid ➞ particles (vorticity ➞ polarization)





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Becattini et al, Annal. Phys. 338 (2013) 32

alternative vorticities…

$$\omega^{(K)}_{\mu\nu} = -\tfrac{1}{2}\left(\partial_\mu u_\nu - \partial_\nu u_\mu\right)$$

$$\omega^{(T)}_{\mu\nu} = -\tfrac{1}{2}\left[\partial_\mu\left(Tu_\nu\right) - \partial_\nu\left(Tu_\mu\right)\right]$$

$$\omega^{(th)}_{\mu\nu} = -\tfrac{1}{2}\left[\partial_\mu\left(u_\nu/T\right) - \partial_\nu\left(u_\mu/T\right)\right]$$

non-vortical symmetric shear

$$\xi^{\mu\nu} \equiv \frac{1}{2}\left[\partial^\mu\left(\frac{u^\nu}{T}\right) + \partial^\nu\left(\frac{u^\mu}{T}\right)\right]$$

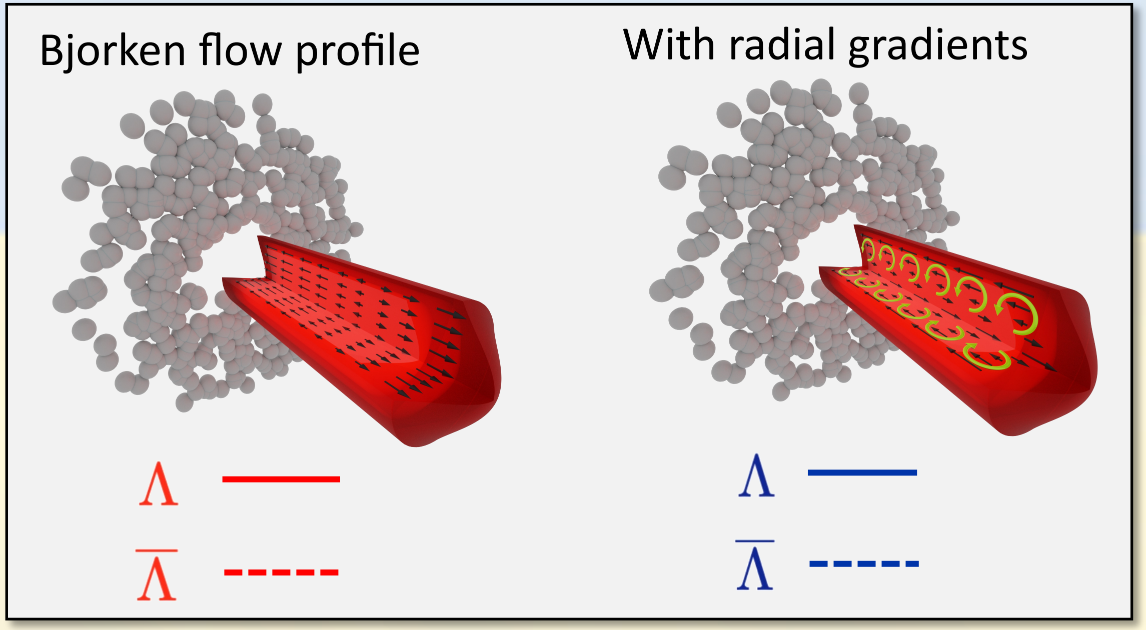
$$S_\mu \to S_\mu + \langle\mathcal{A}_\mu\rangle$$

$$\mathcal{A}_\mu = \frac{1}{E}\varepsilon^{\mu\rho\tau\sigma}p_\tau\xi_{\sigma\lambda} \times \begin{cases} \hat{t}_\rho p^\lambda & \leftarrow \text{Becattini et al (2021)} \\ u_\rho p^\lambda_\perp & \leftarrow \text{Liu \& Yin (2001)} \end{cases}$$

Observing the "smoke tubes"

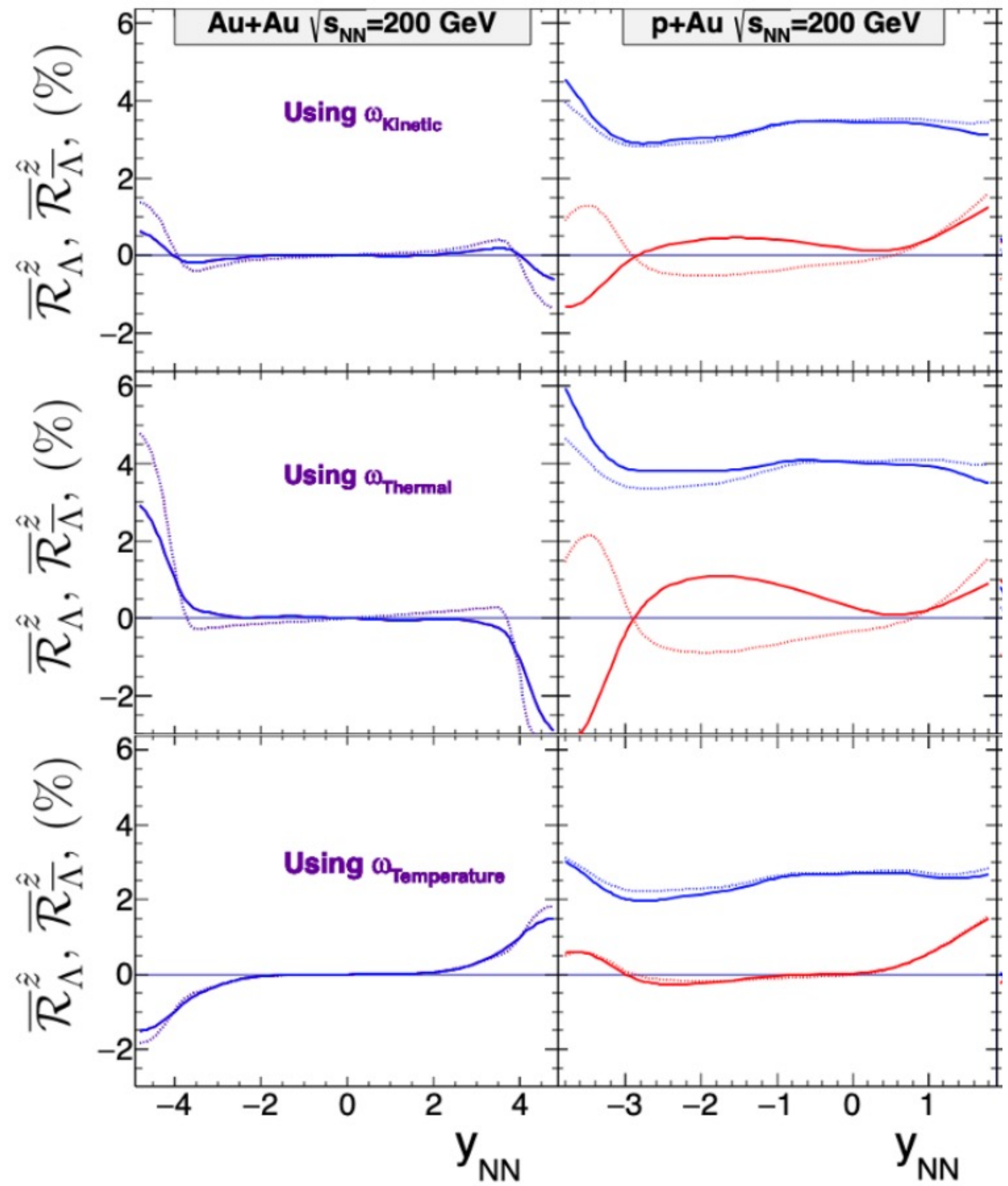
Ring vorticity observable

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



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

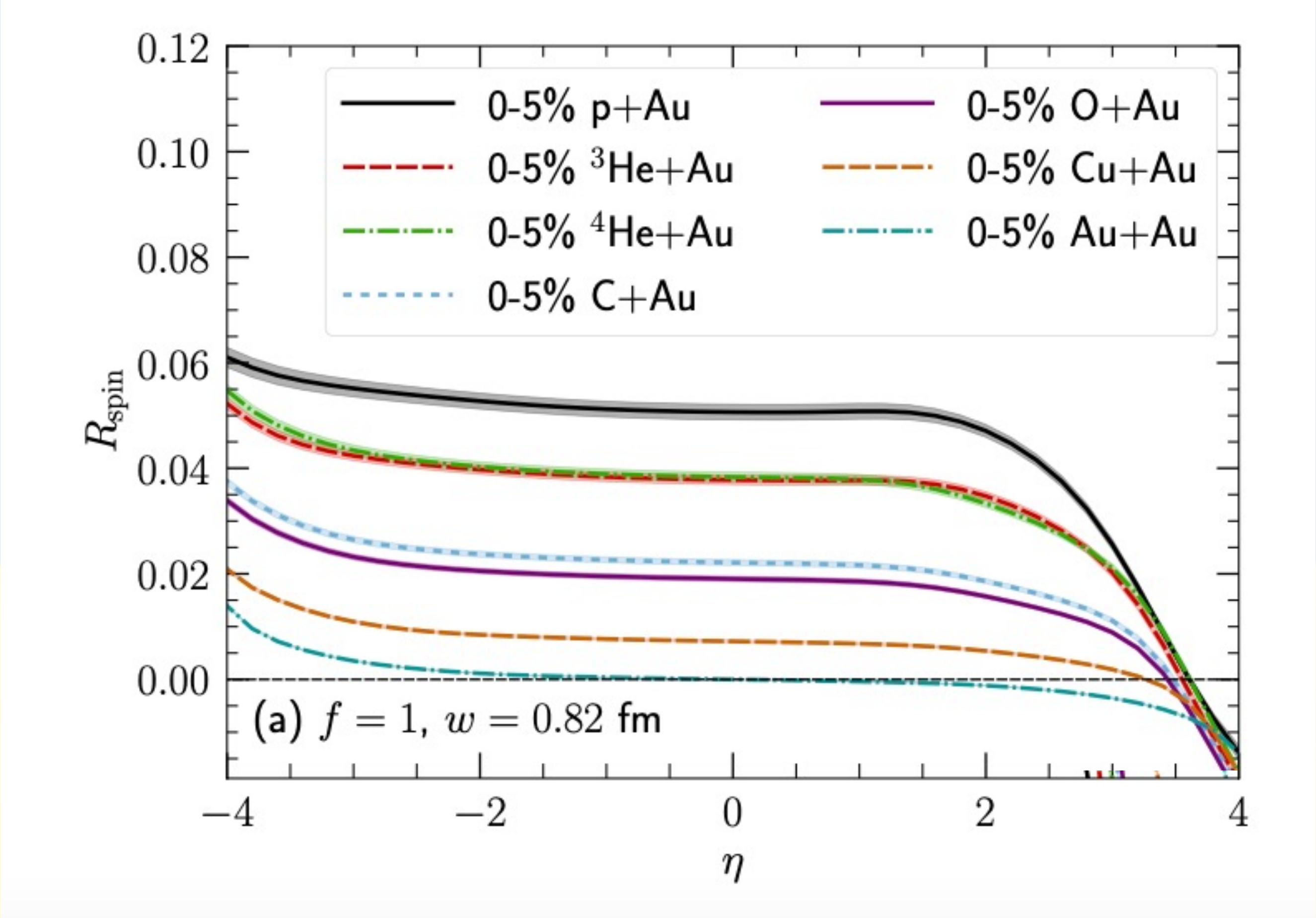
PRC104 (2021) 011901; arxiv: 2101.10872



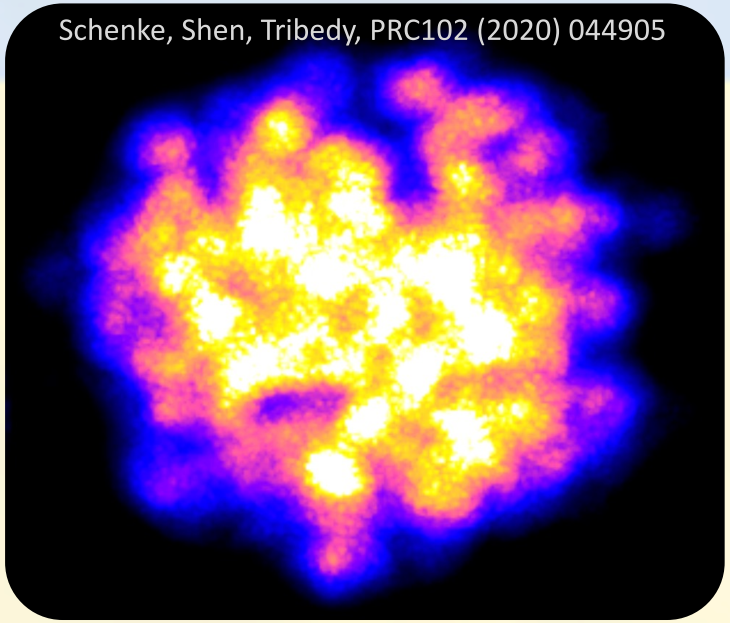
fluctuating initial conditions

Chinellato, MAL, Serenone, Shen, Takahashi, Torrieri in preparation

- ✓ 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



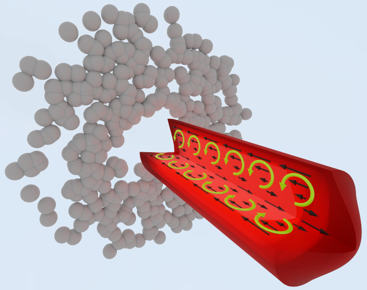
* note: p_T>500 MeV here, increasing R 0.04 → 0.06 in p+Au



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

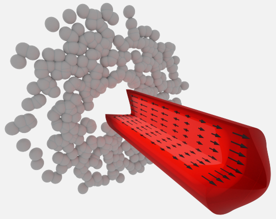
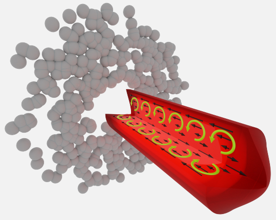
Interpolating between the scenarios

Reality may lie between the extremes…



f=100%

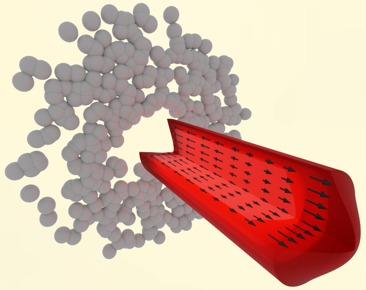
Dialing in the non-Bjorken flow. Schematically….

(1-f) ×  + f × 

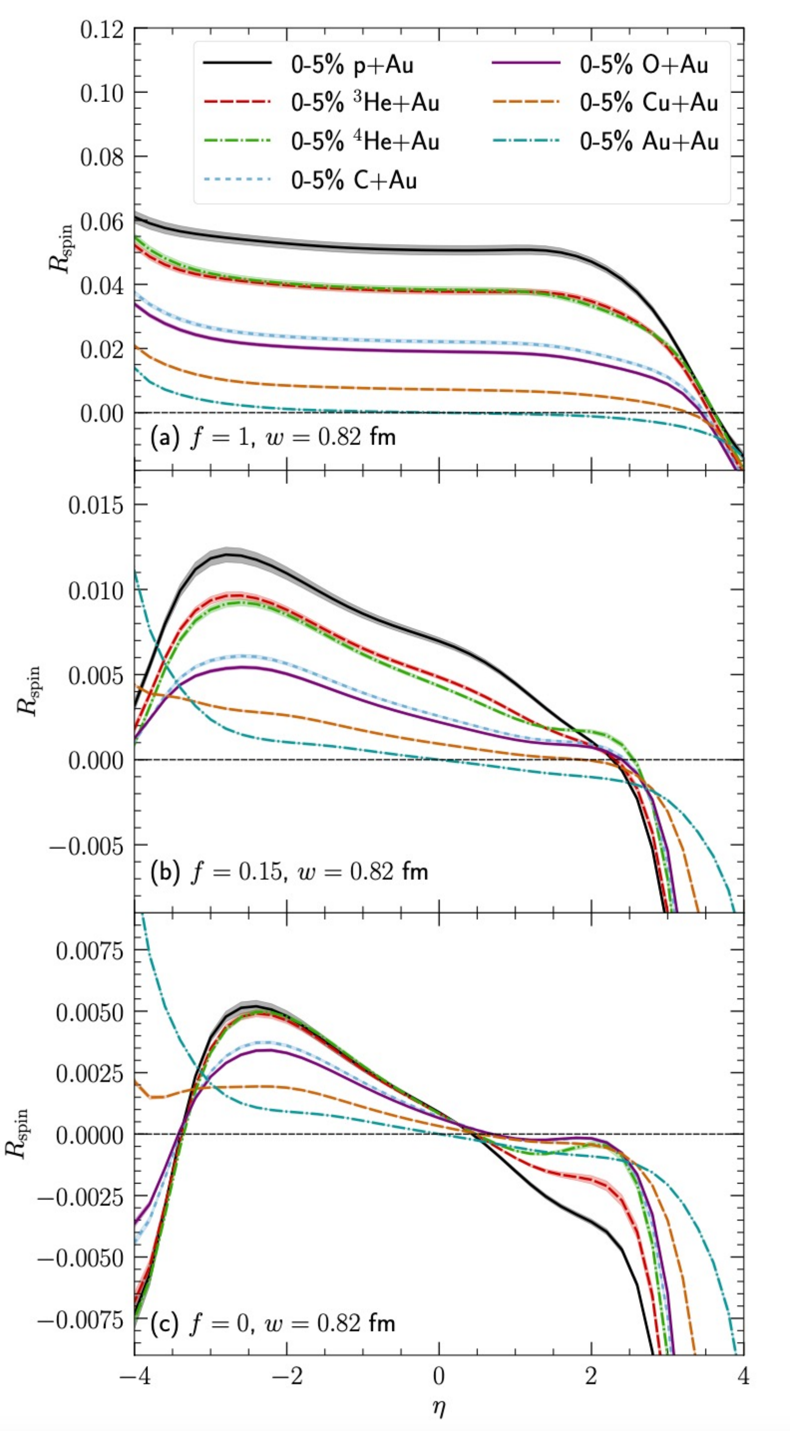
f=15%

- For *Au+Au* at 200 GeV (11 GeV), global polarization calls for f=15% (50%)
  - Ryu, Jupic, Shen: 2106.08125
- unclear whether this translates to p+A

- Even with low f, substantial signal

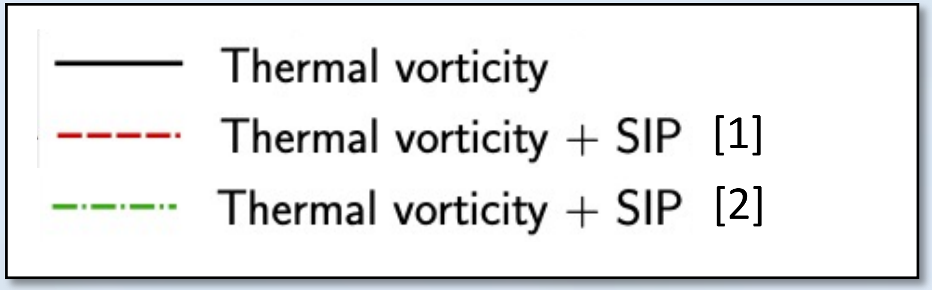


f=0%



Chinellato, MAL, Serenone, Shen, Takahashi, Torrieri in preparation

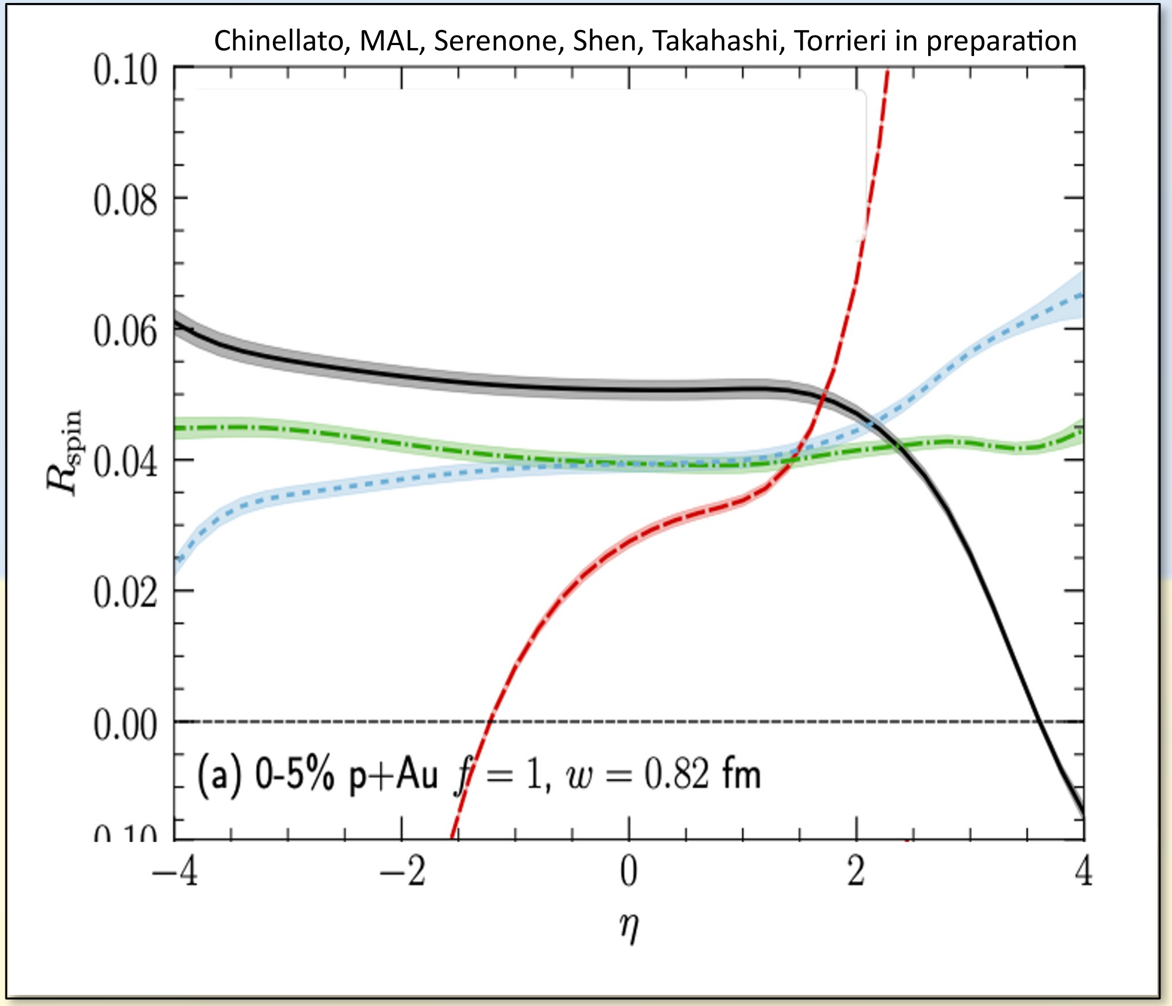
Effect of shear terms



[1] F. Becattini, M. Buzzegoli, and A. Palermo
Phys. Lett. B 820, 136519 (2021); arXiv:2103.10917

[2] Shuai Y. F. Liu and Yi Yin
JHEP 07, 188 (2021), arXiv:2103.09200

(c.f talks by Buzzegoli and Fu in session T02 Tuesday)



- Large difference in effects predicted by the two prescriptions
- Effect at midrapidity remains

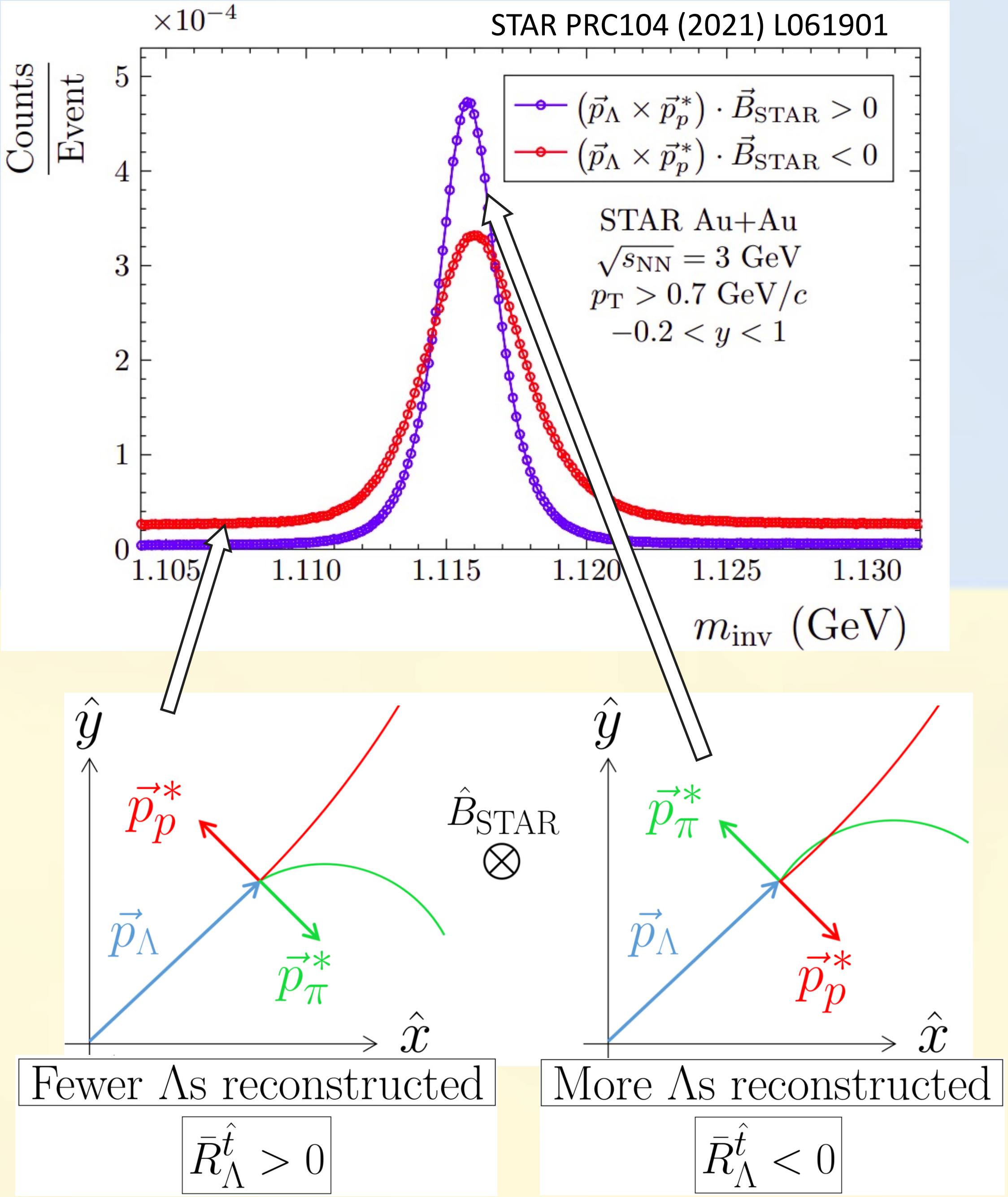
Experimental issues

c/o Joey Adams

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

Challenge: large topological dependence of efficiency

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



Experimental issues

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

Challenge: large topological dependence of efficiency

- artifacts *complicated* and ~10% (or more)
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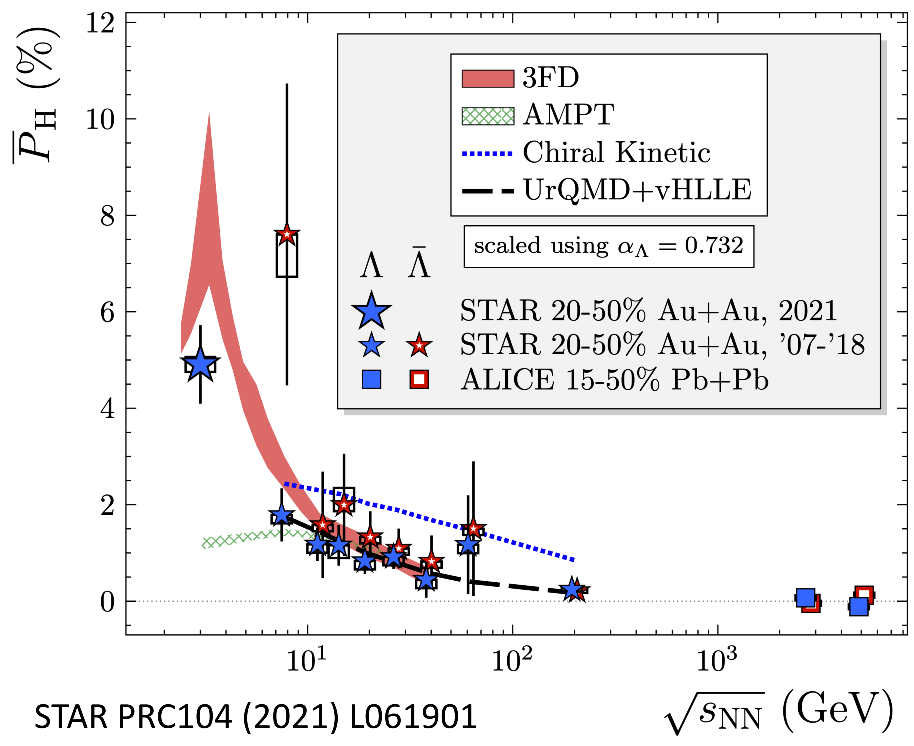


STAR PRC104 (2021) L061901

Advantage:

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

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

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

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!
- **A hydro system with p+A initial conditions could naturally generate a vortical toroid configuration**
  - similar to jet "blasting through"
  - Helmholtz (1867): Persistent vortical toroids (smoke rings) are quintessential fluid behavior
  - 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
- **We should explore this unique structure @ RHIC, LHC (while we can…)**

UNICAMP

João Prado Barbon, David Chinellato, Willian Serenone, Jun Takahashi, Giorgio Torrieri

University of Campinas (Unicamp)

Chun Shen

Wayne State University

WAYNE STATE

END

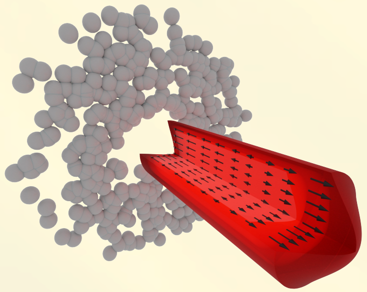
Two extreme cases

PRC104 (2021) 011901; arxiv: 2101.10872

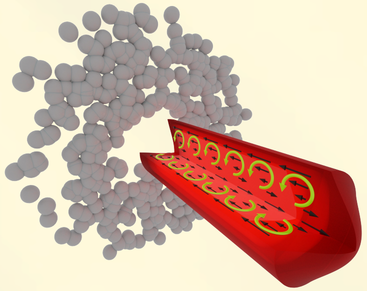
$$\overline{\mathcal{R}}_{\Lambda}^{\hat{z}} = 2 \left\langle \frac{\vec{S}'_{\Lambda} \cdot (\hat{z}' \times \vec{p}_{\Lambda}')}{|\hat{z}' \times \vec{p}_{\Lambda}'|} \right\rangle_{\phi}$$

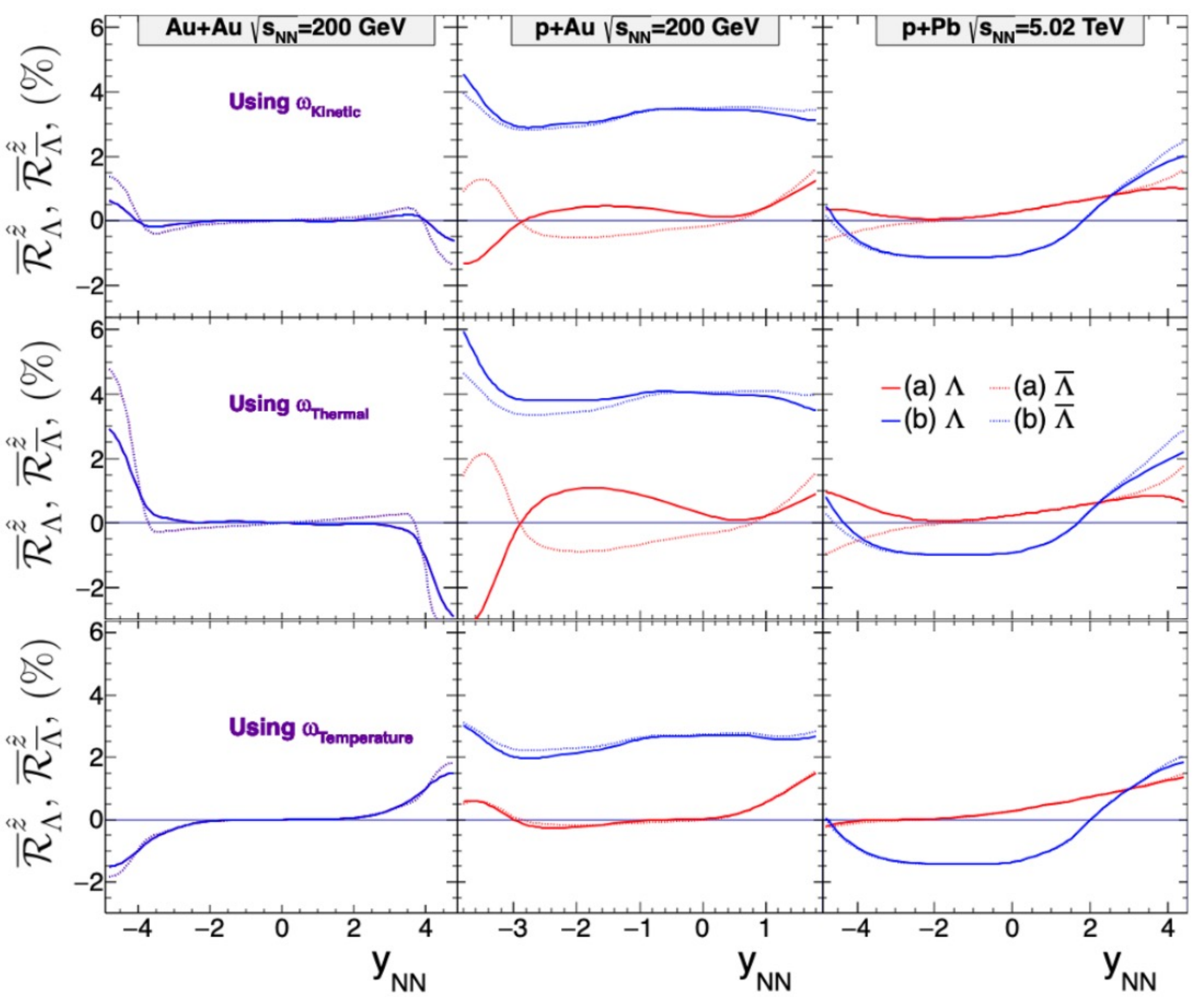
$$\omega_{\mu\nu}^{(K)} = -\tfrac{1}{2} \left(\partial_\mu u_\nu - \partial_\nu u_\mu \right)$$
$$\omega_{\mu\nu}^{(T)} = -\tfrac{1}{2} \left[\partial_\mu \left(T u_\nu \right) - \partial_\nu \left(T u_\mu \right) \right]$$
$$\omega_{\mu\nu}^{(th)} = -\tfrac{1}{2} \left[\partial_\mu \left(u_\nu / T \right) - \partial_\nu \left(u_\mu / T \right) \right]$$

(a)



(b)



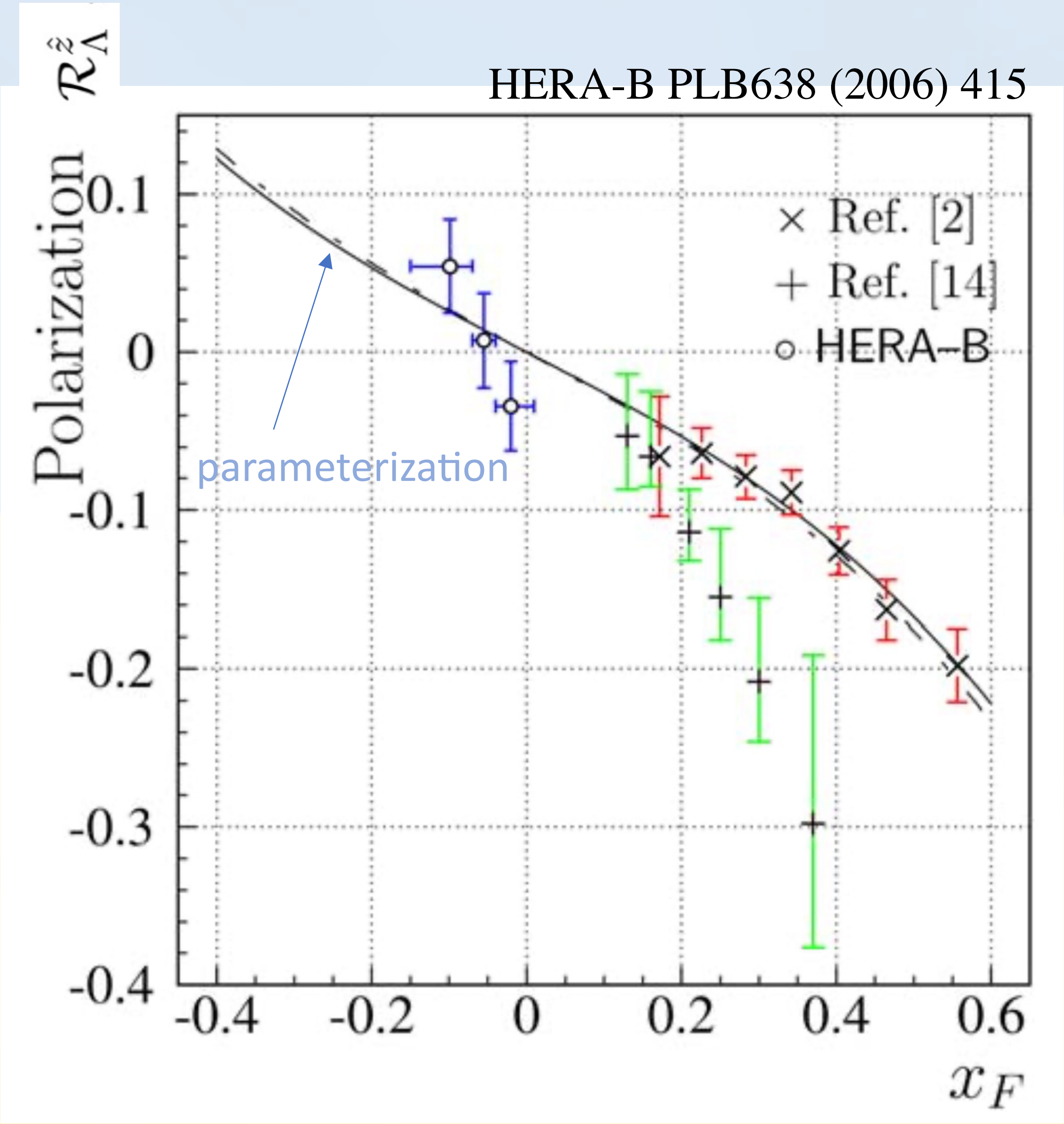


- similar effect for all vorticities
- **hyperon and anti-hyperon are similar**
- sign change at LHC energy

Reminder from 1970's (through 2010's)

production-plane polarization in p+A collisions.

- Same observable as ours!
- high-x signal
- ~independent of target (p, Be, C, Cu, W)
- ~independent of energy (only measured to ~40 GeV)
- odd in rapidity for p+p, but also p+A
- **no signal for anti-Lambdas**



+	NA48 p+N(?)	sqrt(sNN) = 29 GeV
x	E799 p+Be	sqrt(sNN) = 39 GeV
O	HERA-B p+W,C	sqrt(sNN) = 41.6 GeV

f parameter and *global* polarization

Ryu, Jupic, Shen: 2106.08125

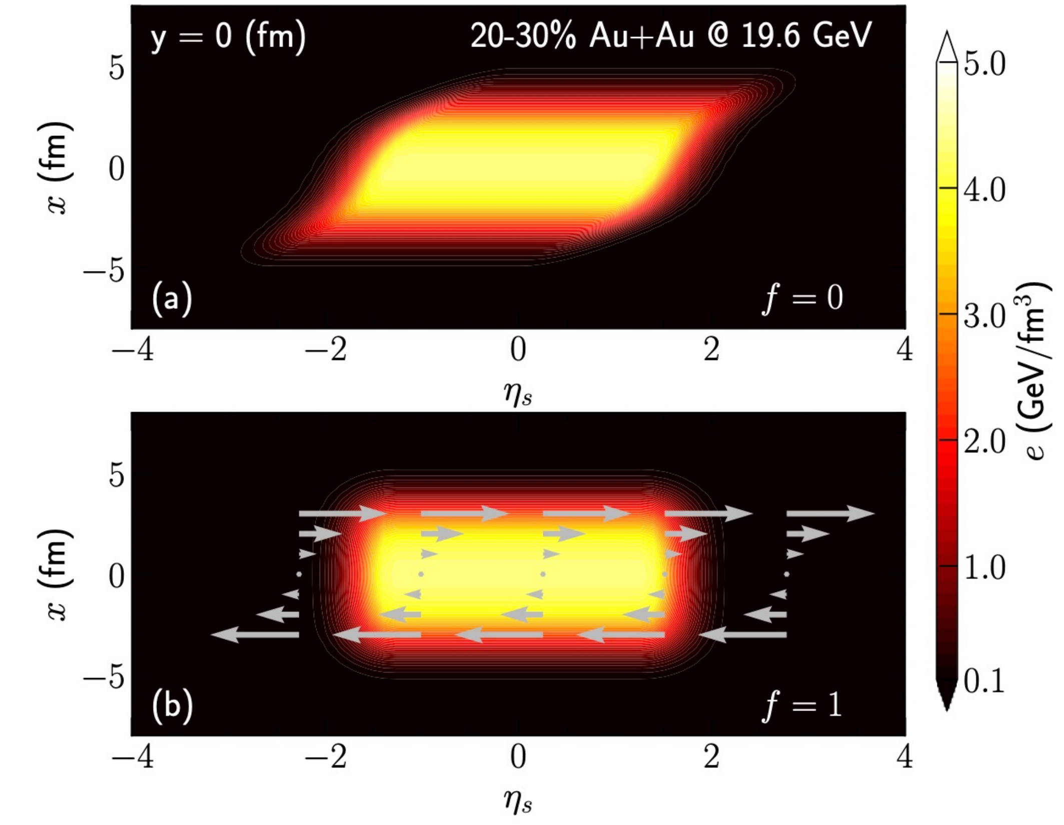
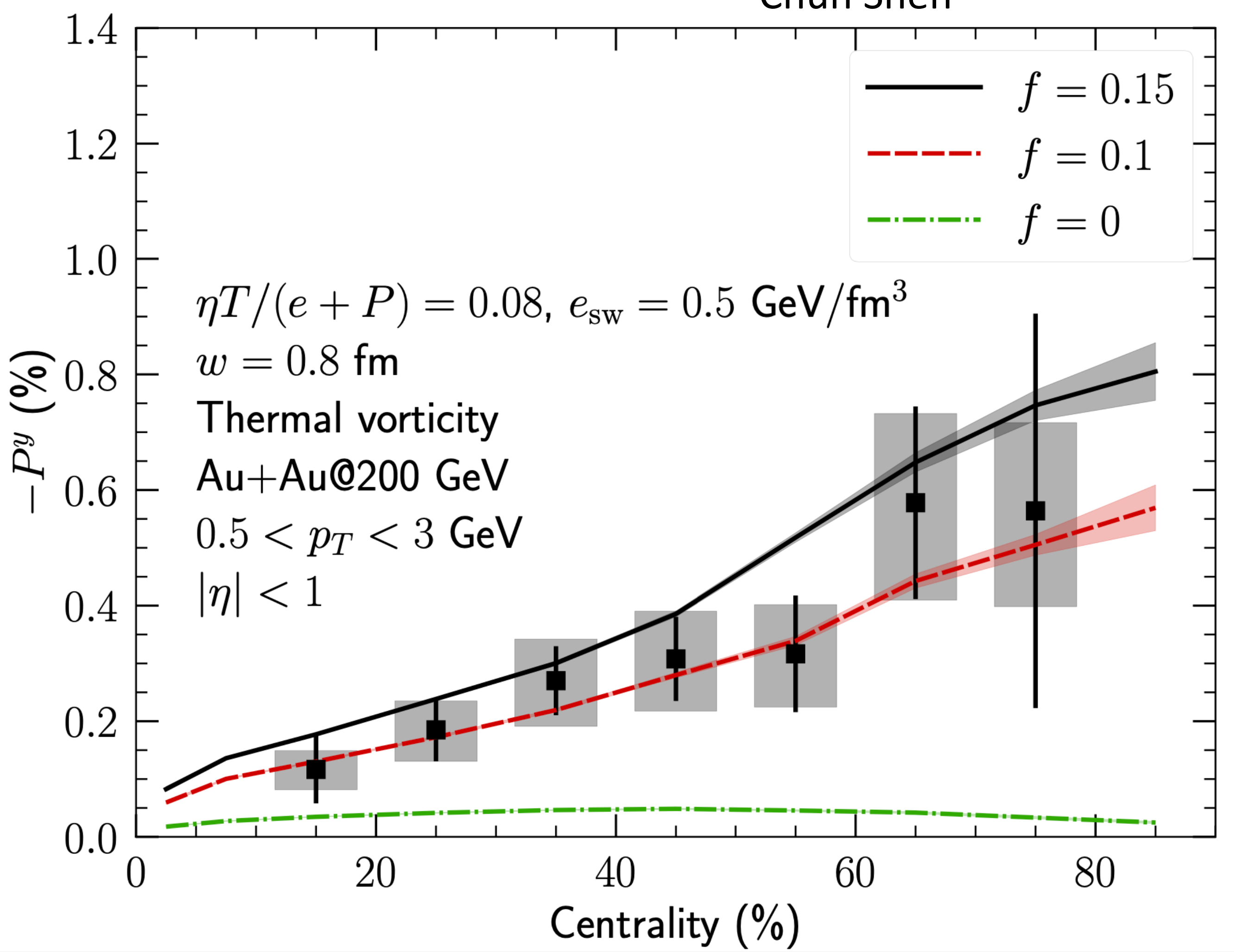


FIG. 1. Color contours show the initial energy density distributions in the $x - \eta_s$ plane for 20-30% Au+Au collisions at 19.6 GeV with the longitudinal rapidity fraction $f = 0$ (a) and $f = 1$ (b). The grey arrows in panel (b) indicate the non-zero initial longitudinal flow u^η with $y_L = y_{\rm CM}$ in Eqs. (13) and (14). $u^\eta = 0$ in panel (a).

Chun Shen



It is unclear to me that *f* will be the same in p+A