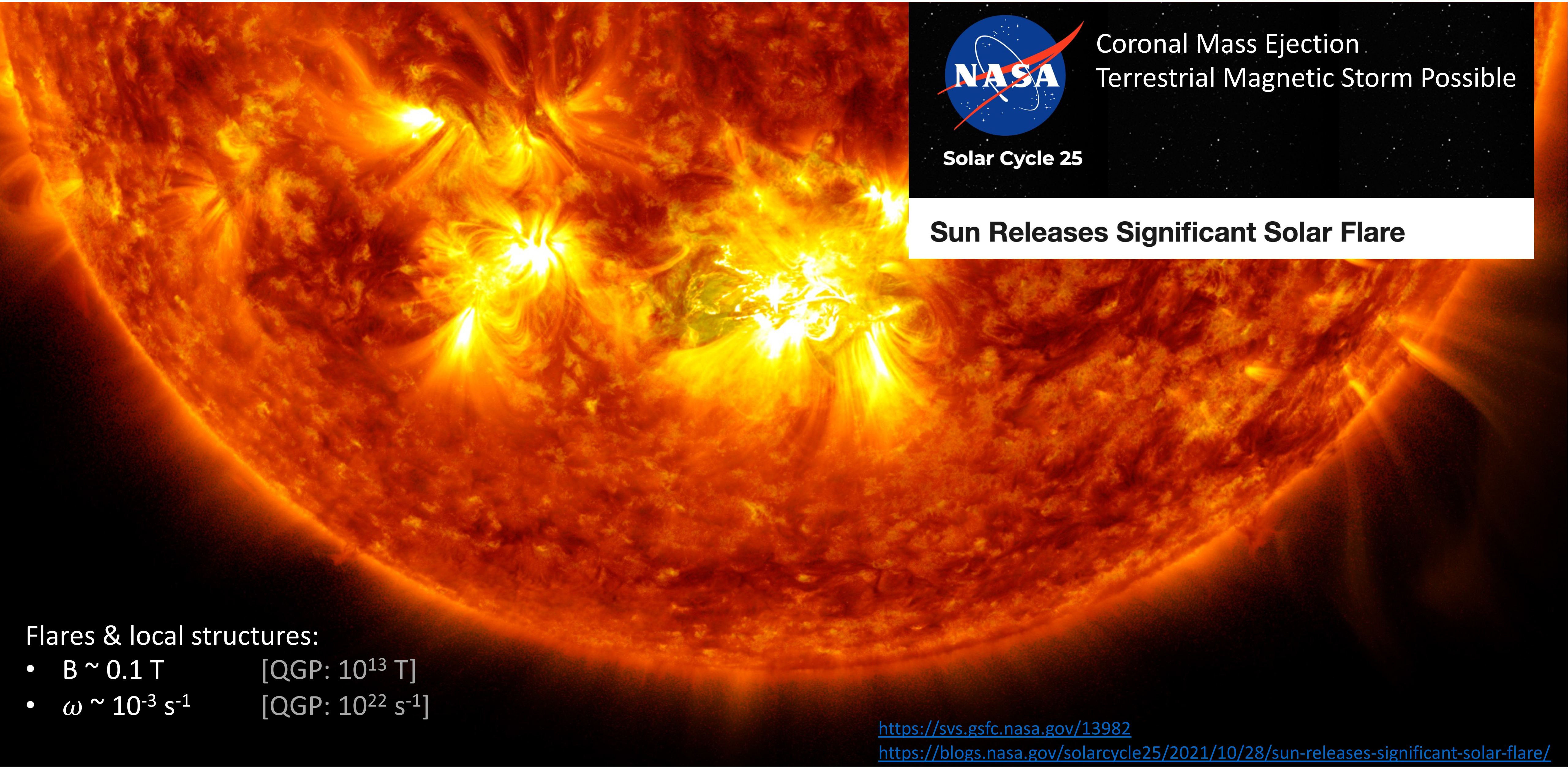
Experimental Overview of Hyperon Polarization and Vorticity

Mike Lisa
Ohio State University

28 Oct 2021 - CME Observed!



Flares & local structures:

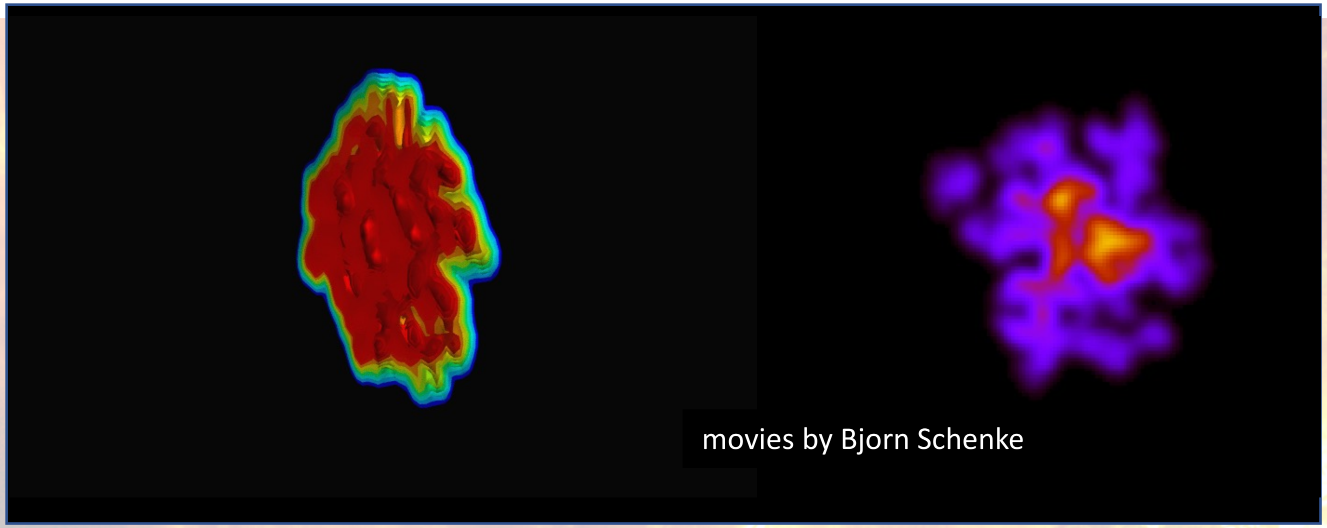
- B ~ 0.1 T [QGP: 10^{13} T]
- ω ~ 10^{-3} s^{-1} [QGP: 10^{22} s^{-1}]

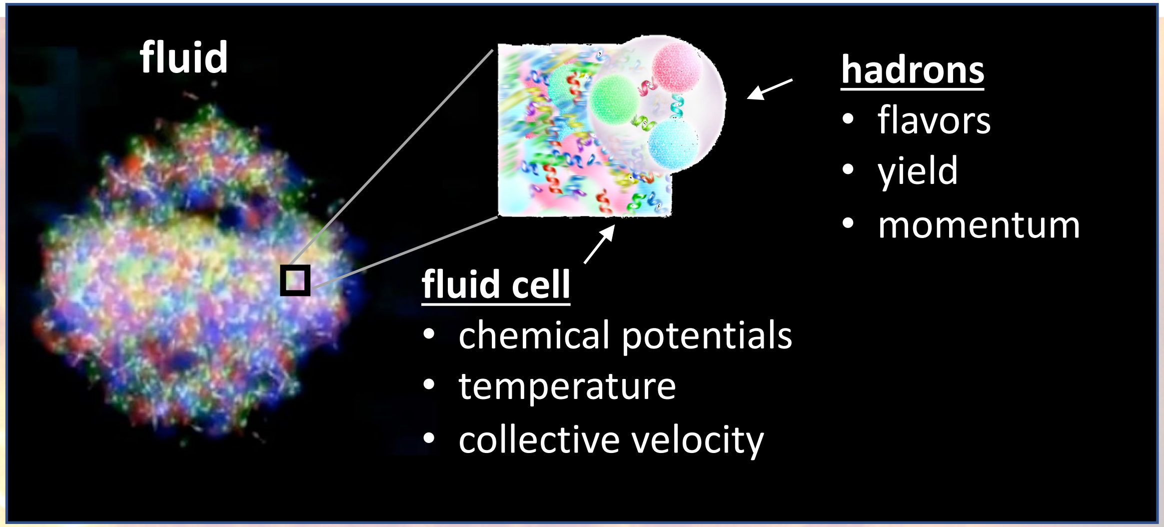
https://svs.gsfc.nasa.gov/13982
https://blogs.nasa.gov/solarcycle25/2021/10/28/sun-releases-significant-solar-flare/

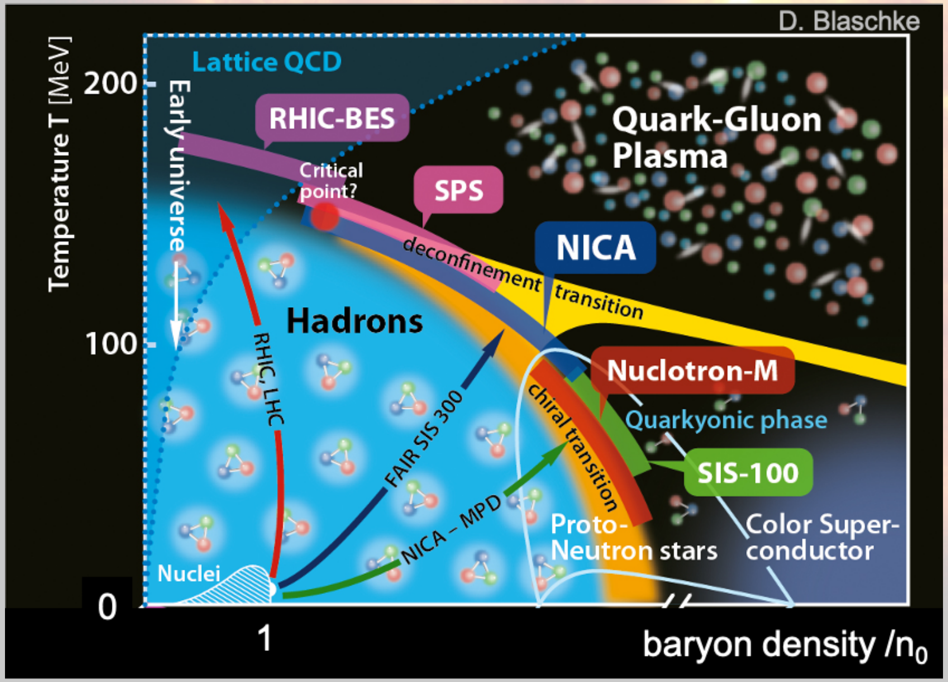
Outline

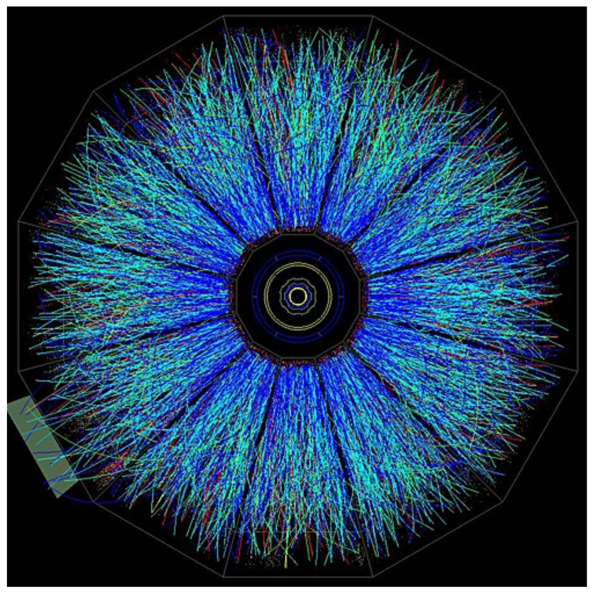
- Brief motivation & introduction
- Global polarization systematics & new “frontiers”
- Longitudinal polarization & new insights
- Future directions
- Summary

Standard model of H.I.C. : viscous hydrodynamics + Cooper-Frye



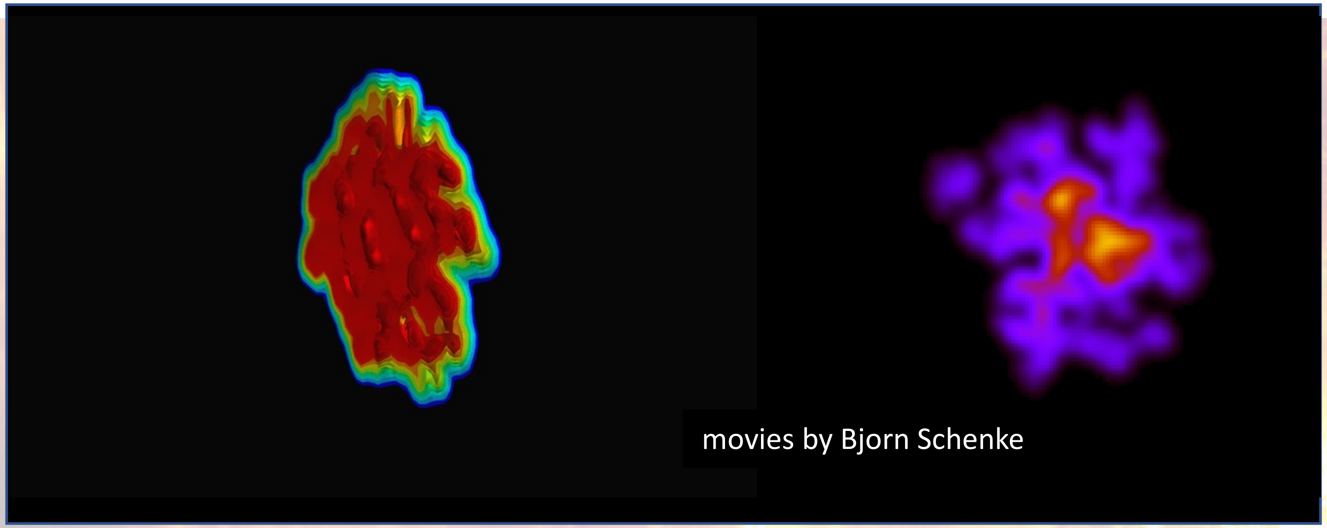


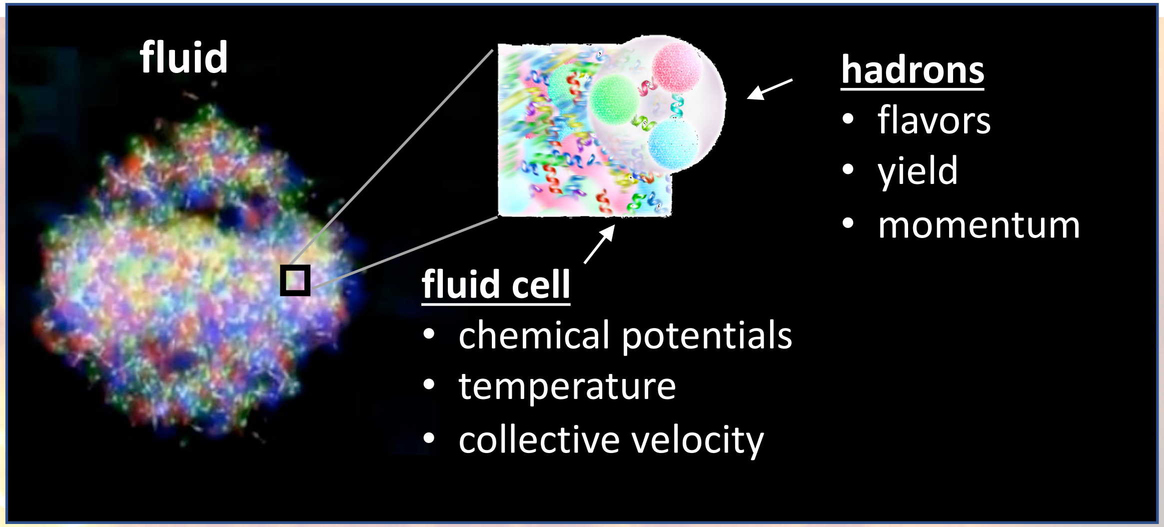


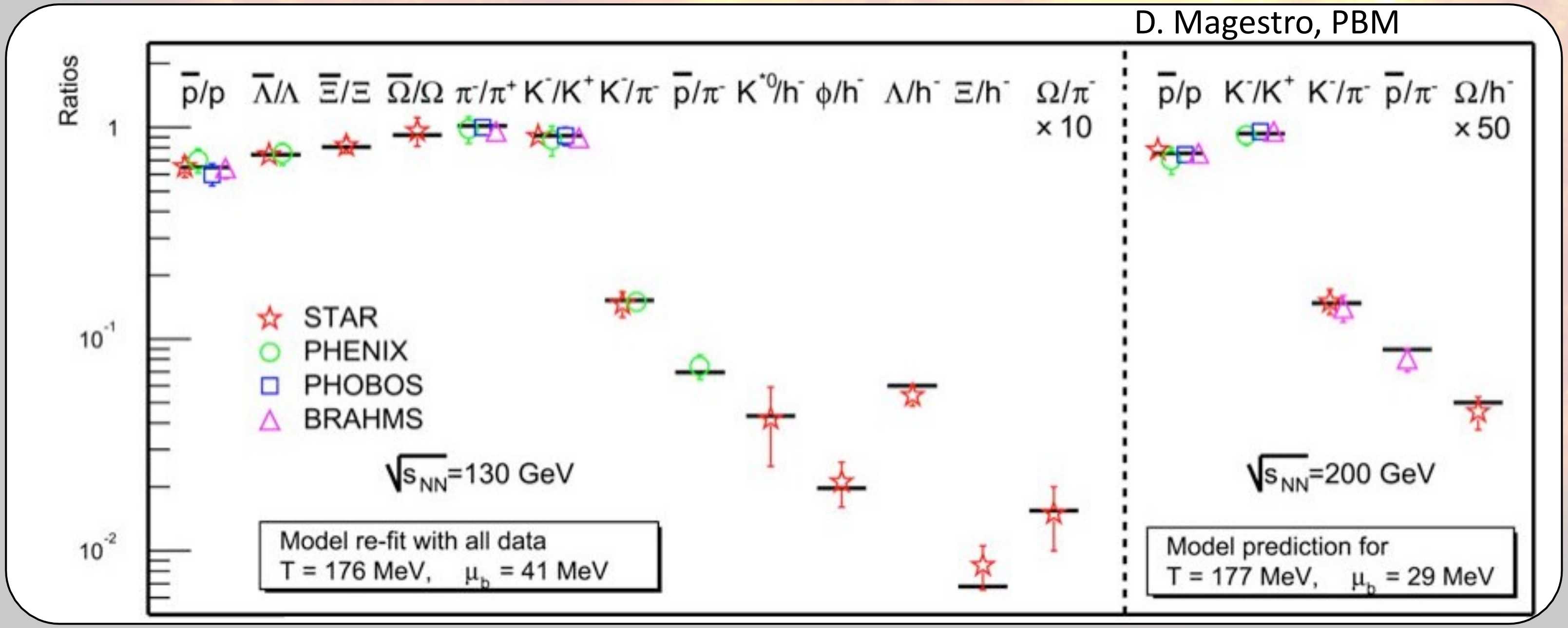


- Dynamic evolution of locally equilibrated matter
- Hadronization/freezeout driven by conservation laws
- emitted particles (*measurable!)* reflect properties of parent fluid cells

Standard model of H.I.C. : viscous hydrodynamics + Cooper-Frye







- Dynamic evolution of locally equilibrated matter
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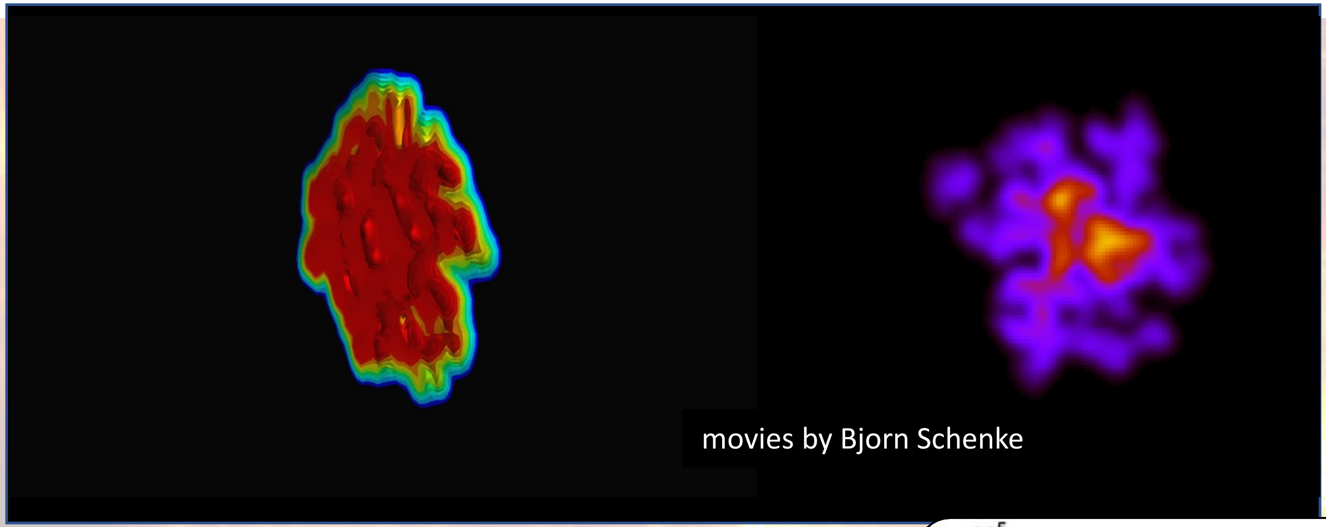
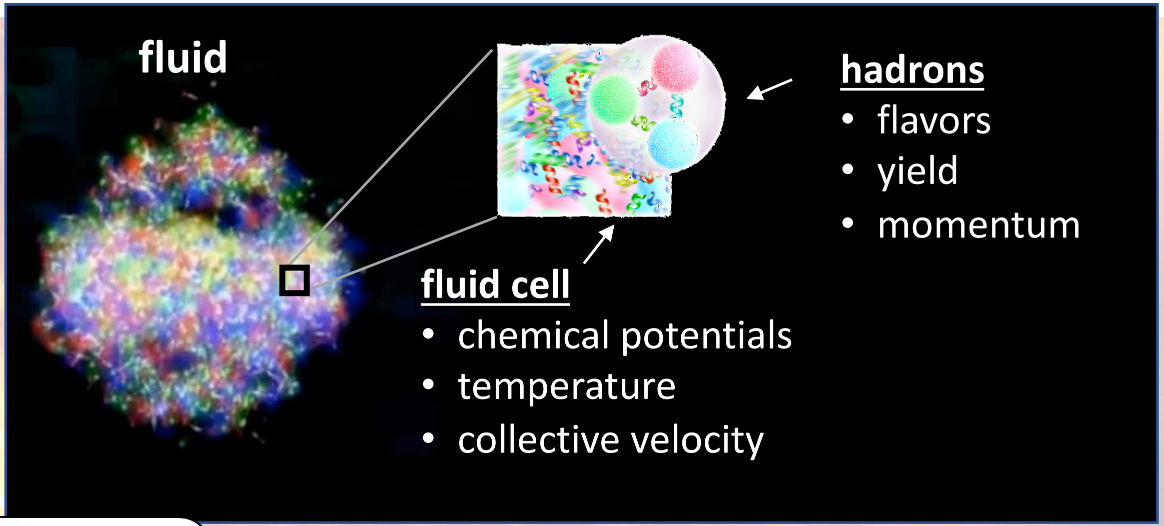
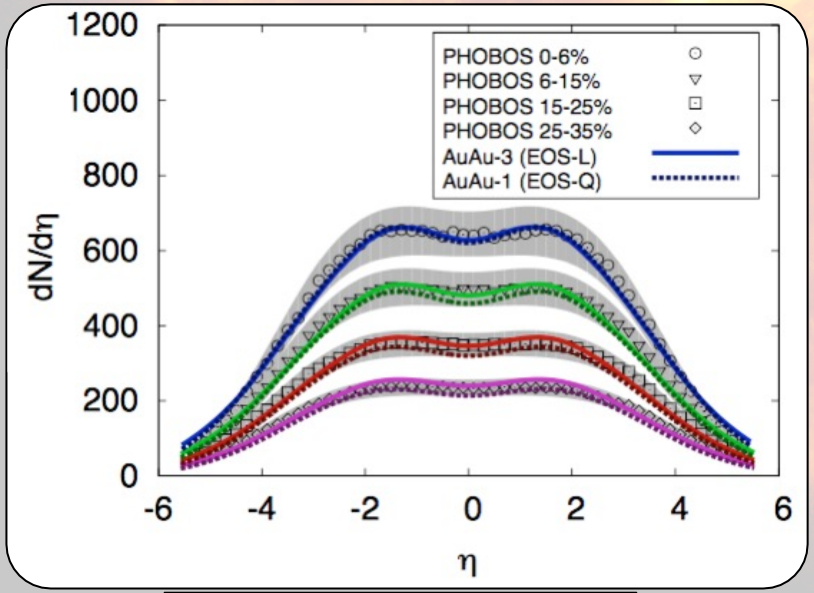
- Yields

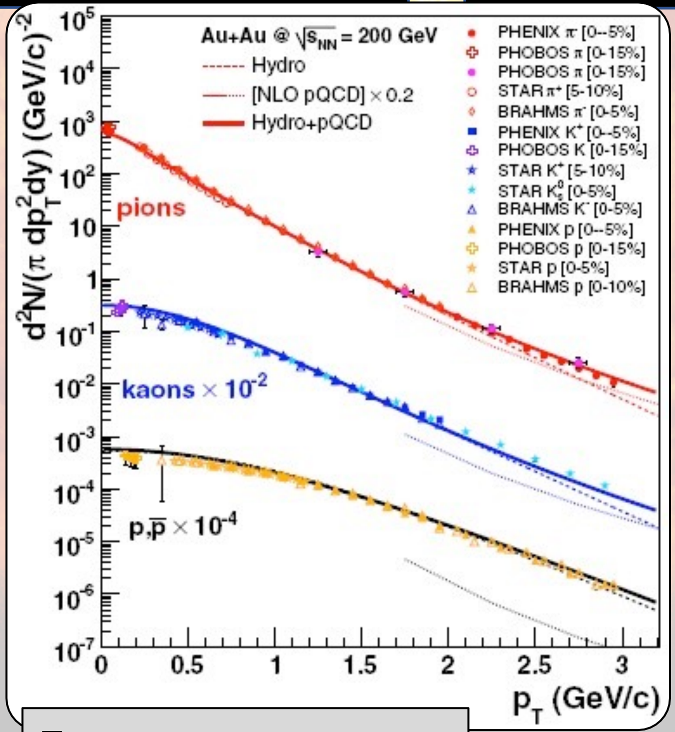
Standard model of H.I.C. : viscous hydrodynamics + Cooper-Frye







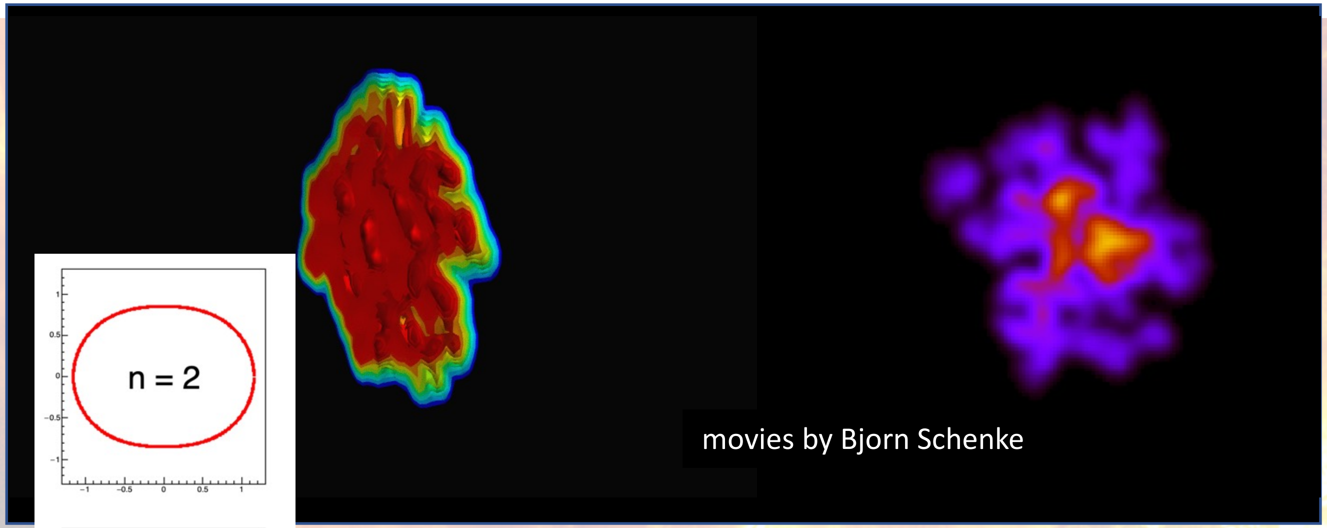
Longitudinal momentum

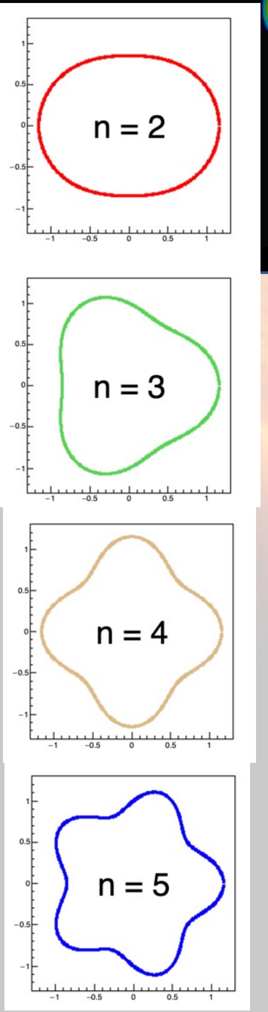


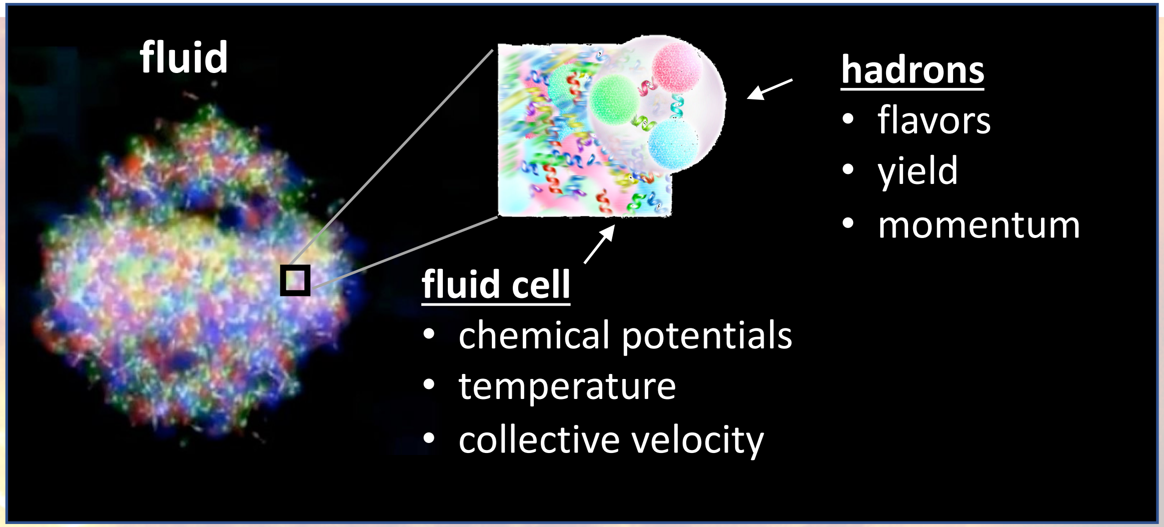
Transverse momentum

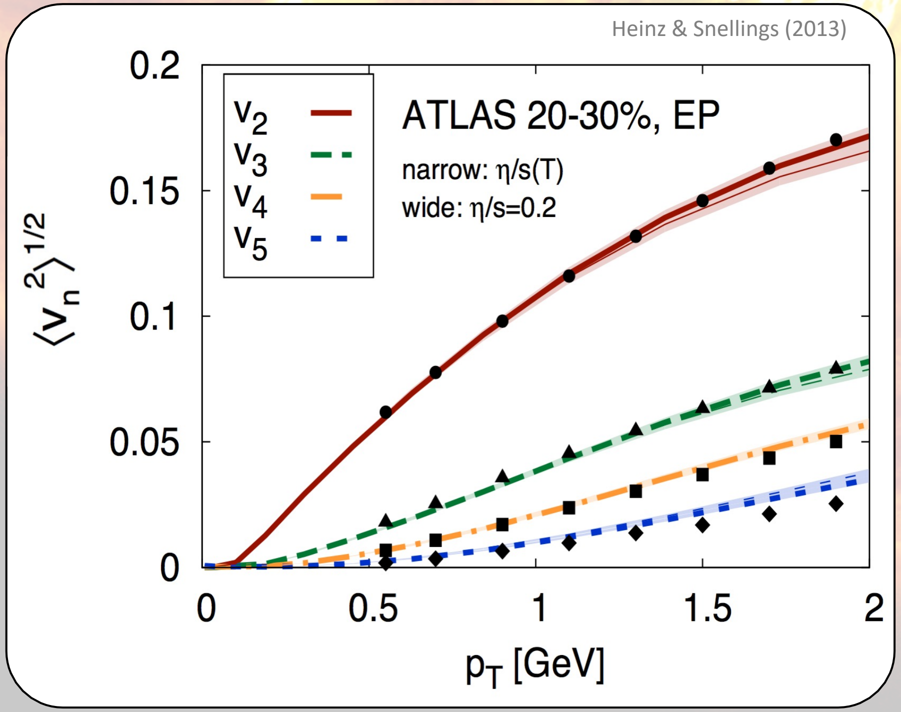
- Dynamic evolution of locally equilibrated matter
- Hadronization/freezeout driven by conservation laws
- emitted particles (*measurable!*) reflect properties of parent fluid cells
- Yields
- longitudinal, transverse distributions

Standard model of H.I.C. : viscous hydrodynamics + Cooper-Frye









- Dynamic evolution of locally equilibrated matter
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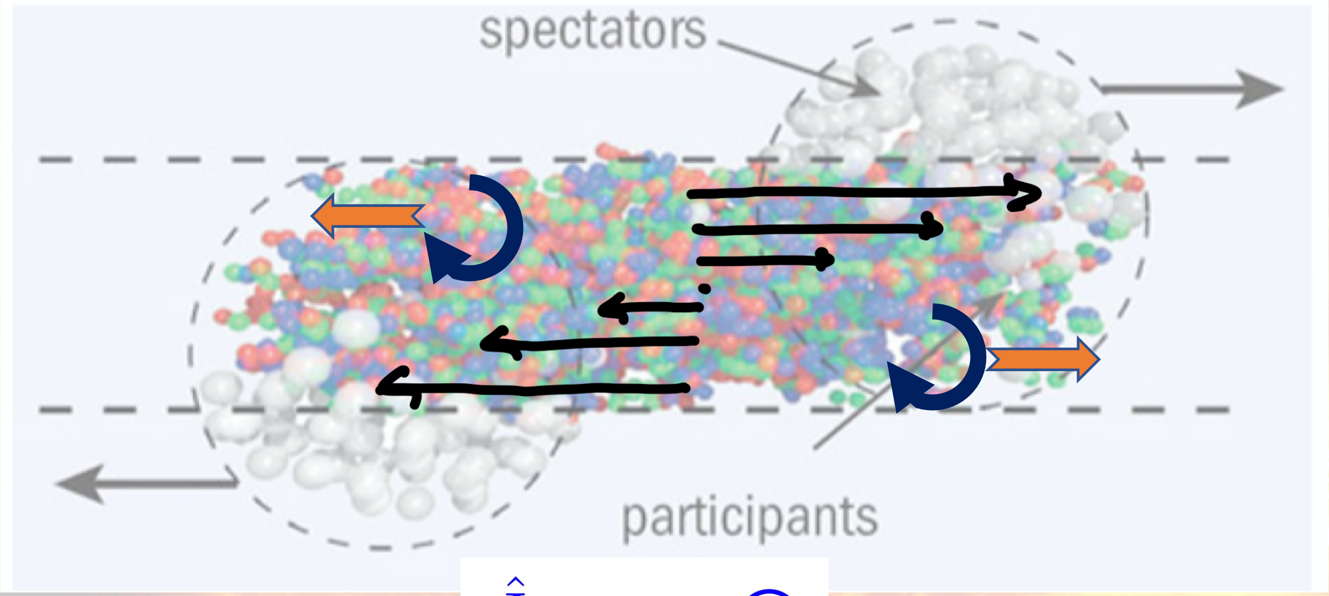
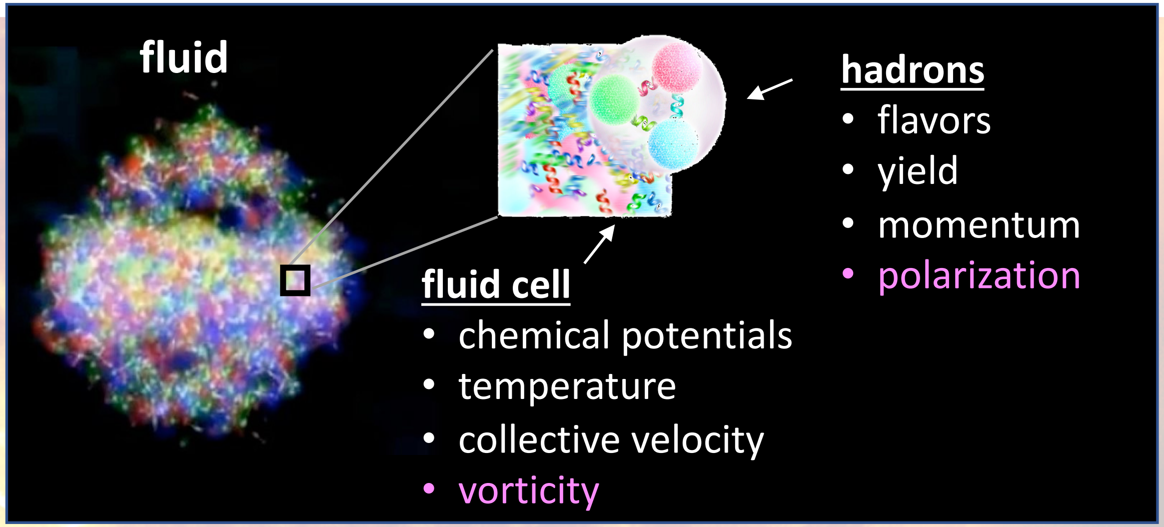
finer detail

- Yields
- longitudinal, transverse distributions
- azimuthal flow anisotropy

Rotational substructure of noncentral collisions



$\hat{J}_{\mathrm{global}}$ $\otimes$



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finer detail

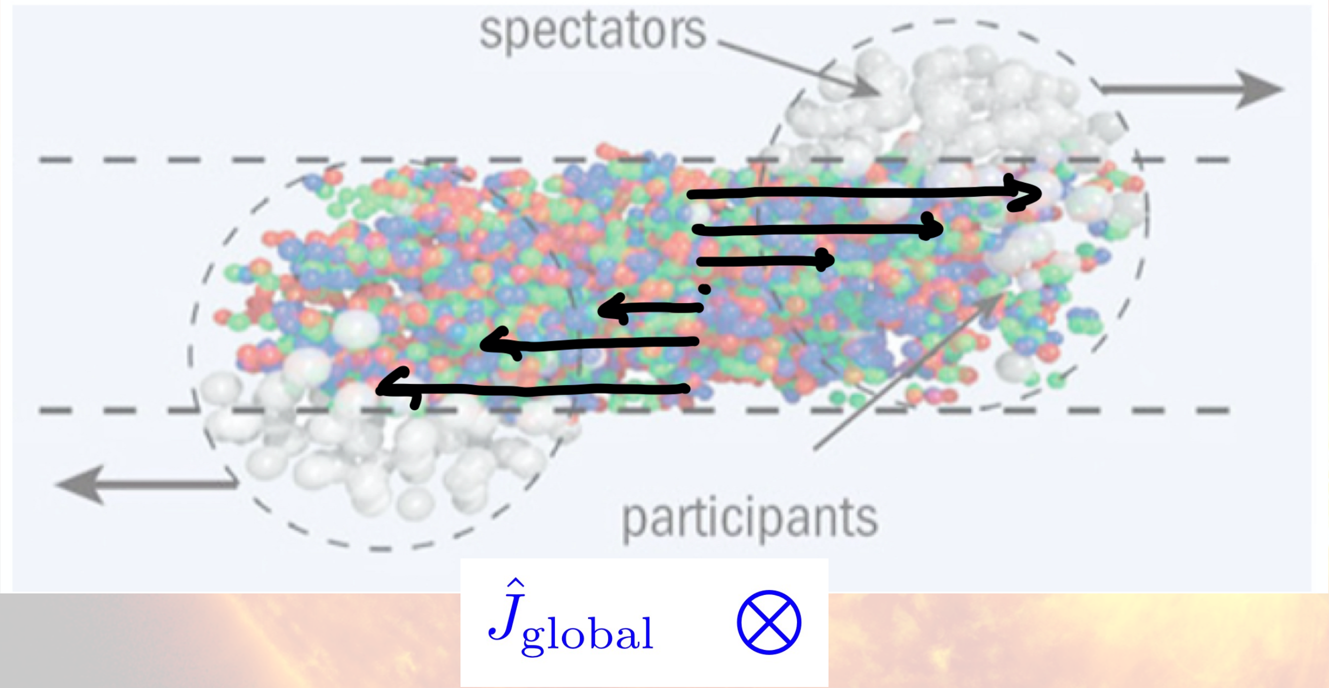
- Yields
- longitudinal, transverse distributions
- azimuthal flow anisotropy
- polarization

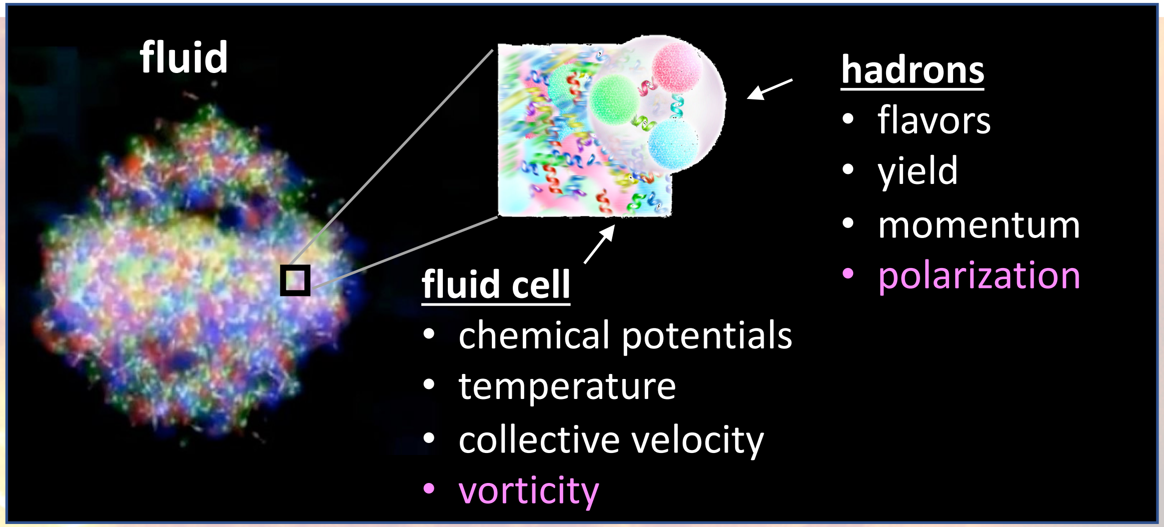
$$P \propto e^{-\left(E+\mu_B B+\mu_Q Q+\vec{\omega}\cdot\vec{S}\right)/T}$$

$$\boxed{\begin{array}{c}\text{Polarization}\\ \vec{P} \equiv \dfrac{\langle \vec{S} \rangle}{\left|\vec{S}\right|}\end{array}}$$

Becattini, Karpenko, MAL, Upsal, Voloshin, PRC 2017

Our job

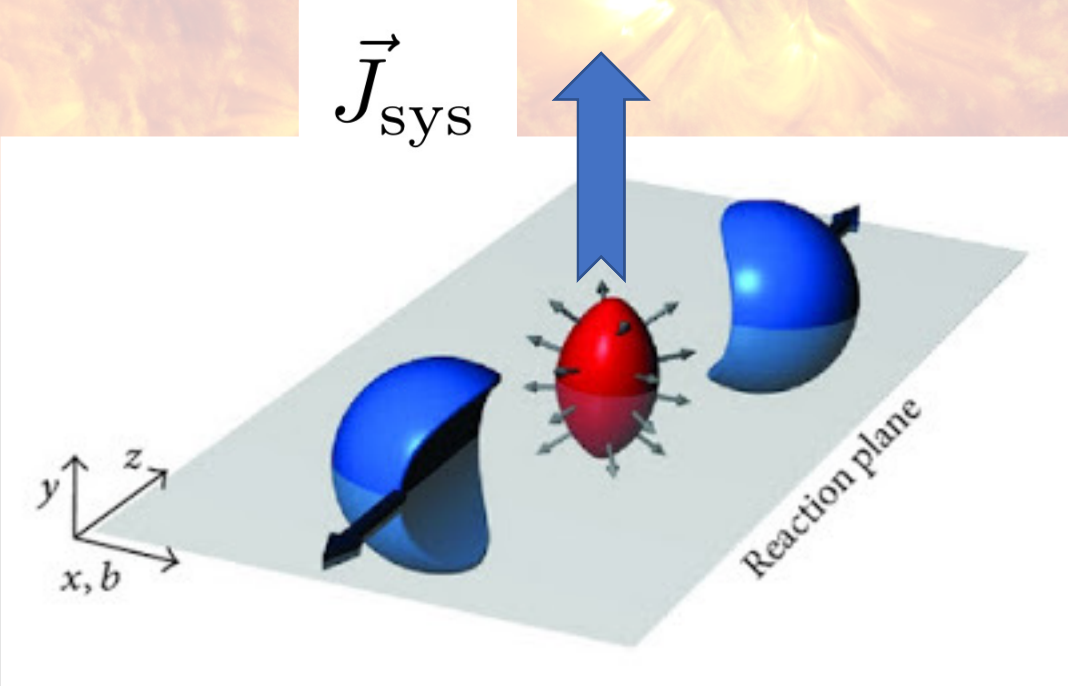


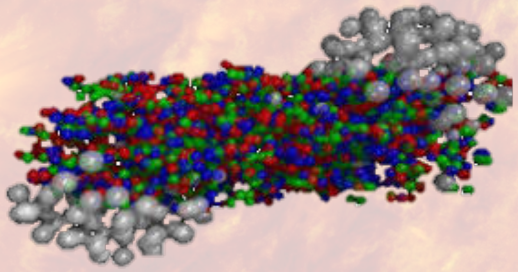


Correlate the angular momentum of the *system* with the (spin) angular momentum of emitted hadrons

$\underbrace{\text{angular momentum of the } \textit{system}}_{\text{Forward detectors}}$ $\underbrace{\text{(spin) angular momentum of emitted hadrons}}_{\text{midrapidity tracking \& weak decay}}$

Estimating direction of system angular momentum





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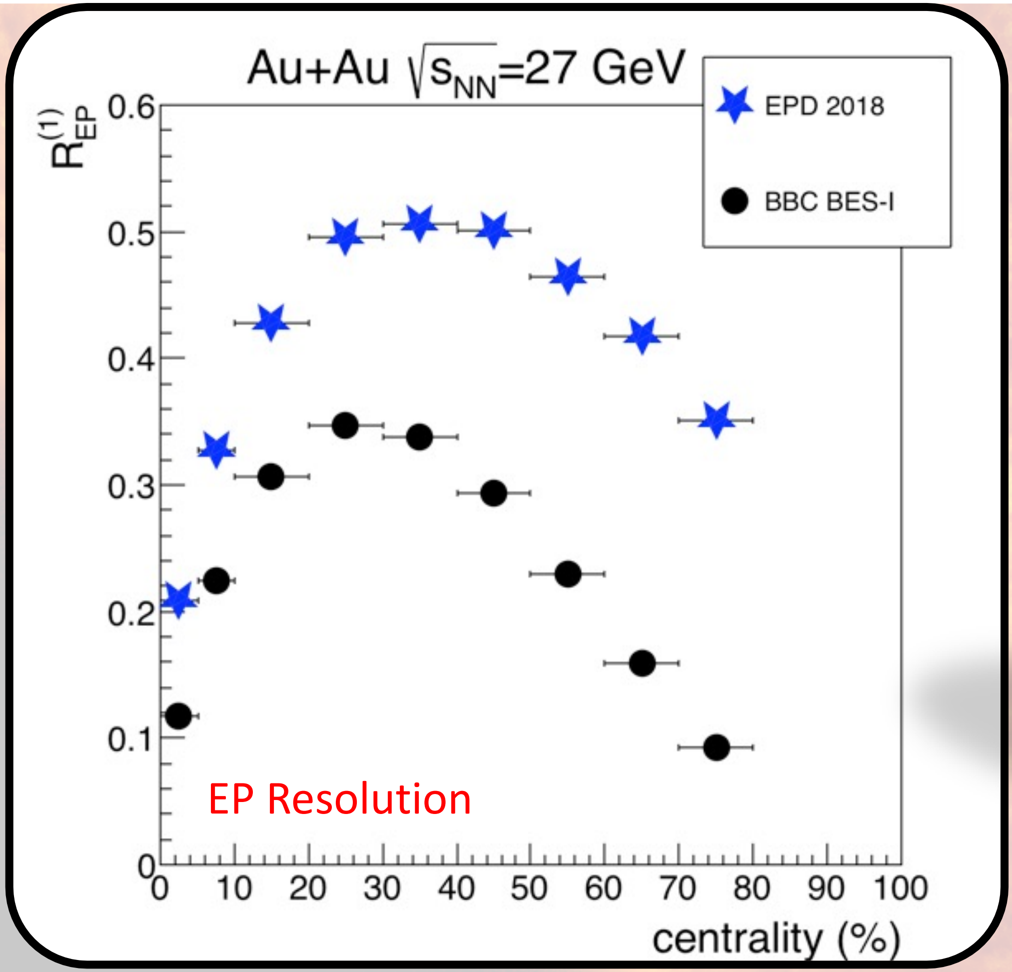
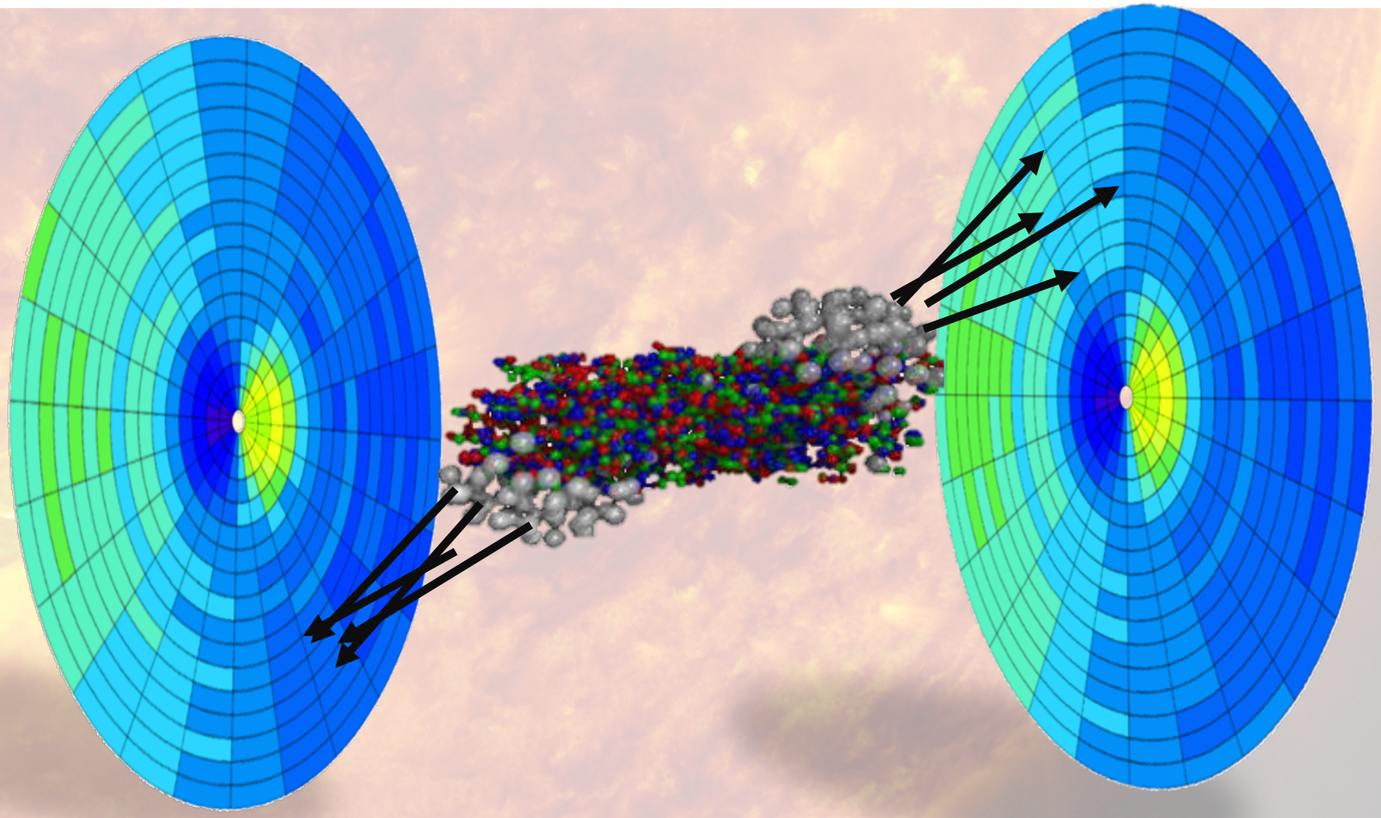
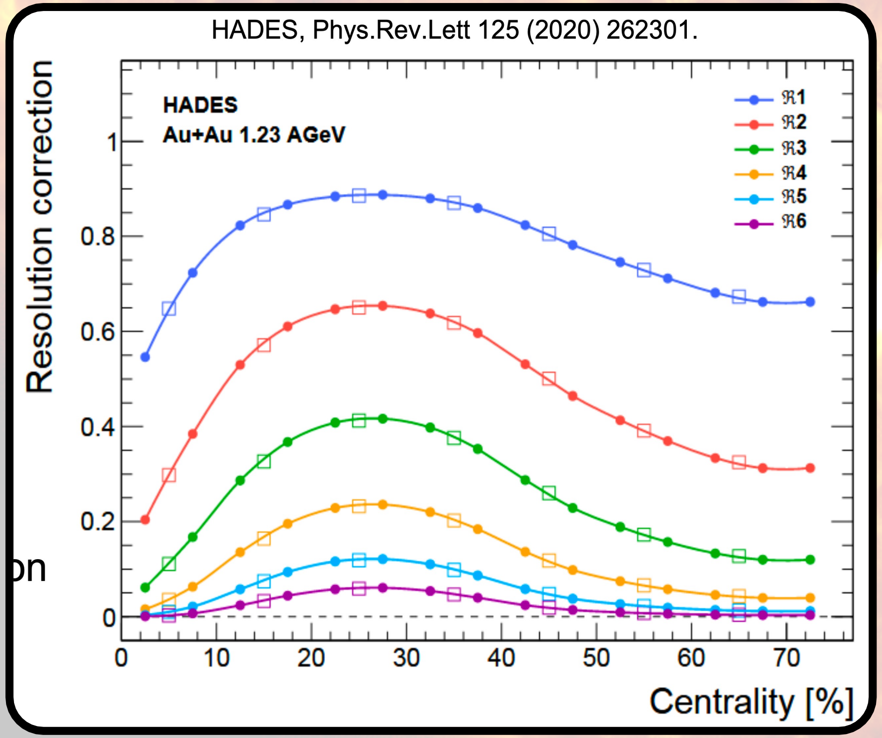
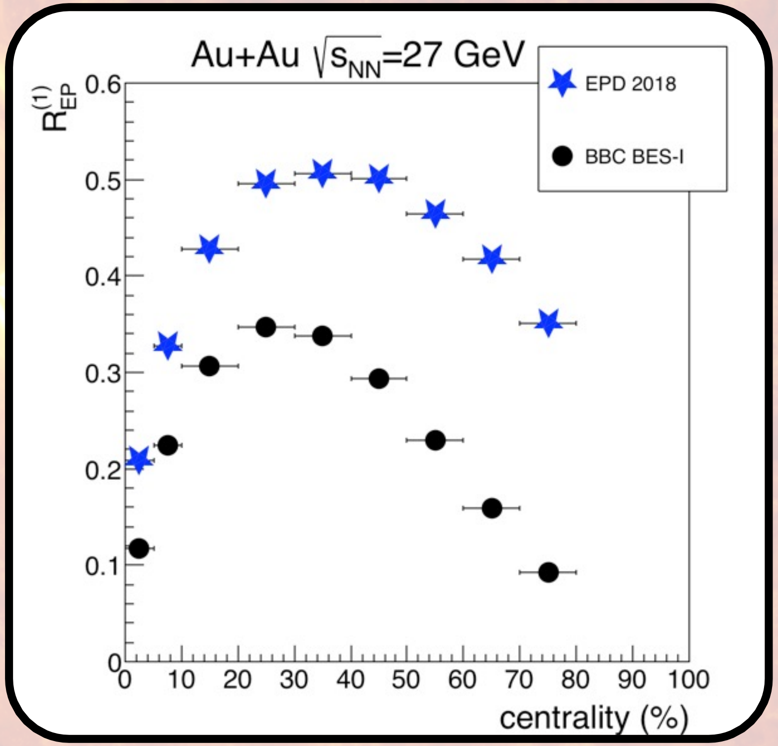


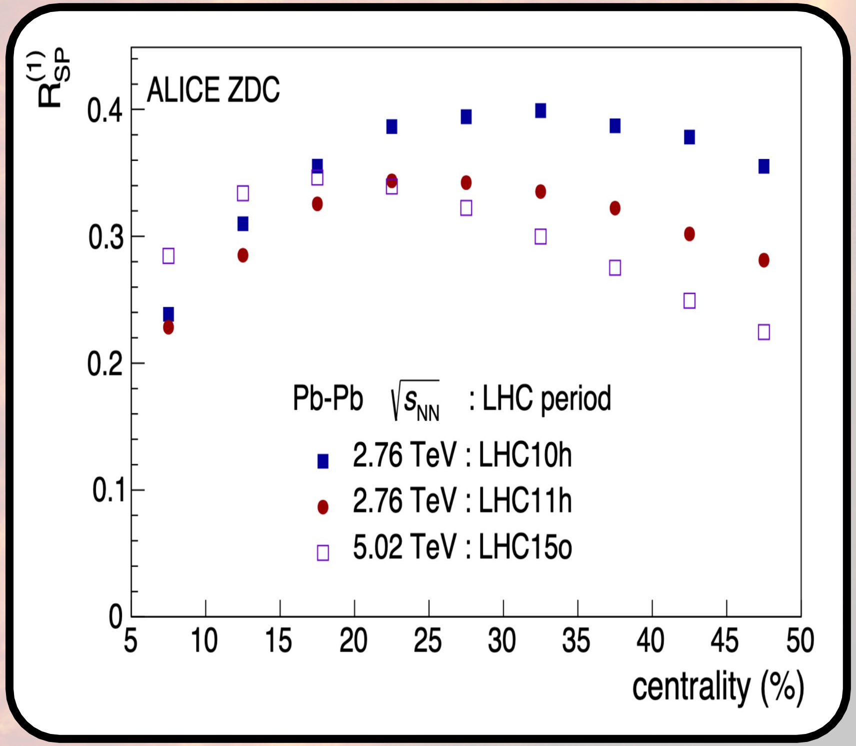


doubling resolution ⟷ four-fold increase in run length
(3 weeks required, instead of 3 months…)

Excellent EP[1] resolution over a huge energy range, worldwide



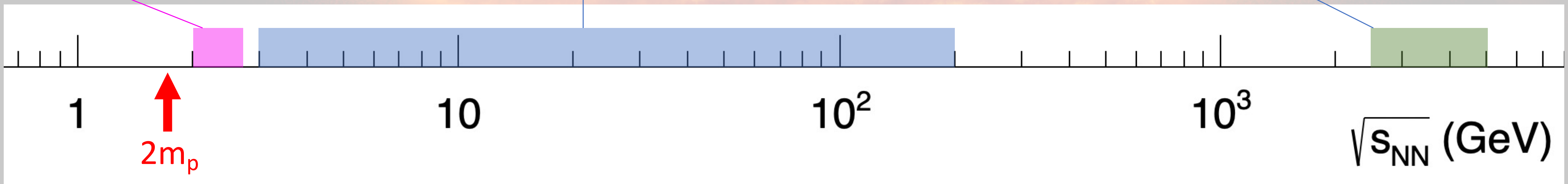




HADES @ SIS/GSI $\sqrt{s_{NN}}$=2.4 GeV

STAR @ RHIC/BNL $\sqrt{s_{NN}}$=27 GeV

ALICE @ LHC/CERN $\sqrt{s_{NN}}$=2.4 GeV



Measuring the spin of emitted particles

Lambdas are "self-analyzing"

- reveal polarization by preferentially emitting daughter proton in spin direction

all measurements must report the value used
comparisons must use appropriately scaled values

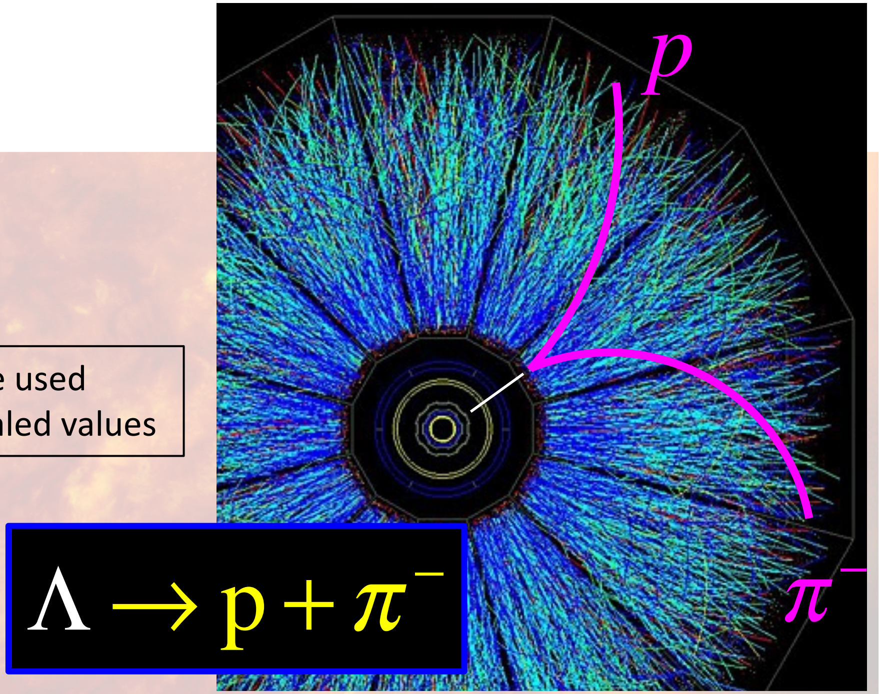
For an ensemble of Λs with polarization $\vec{P}$:

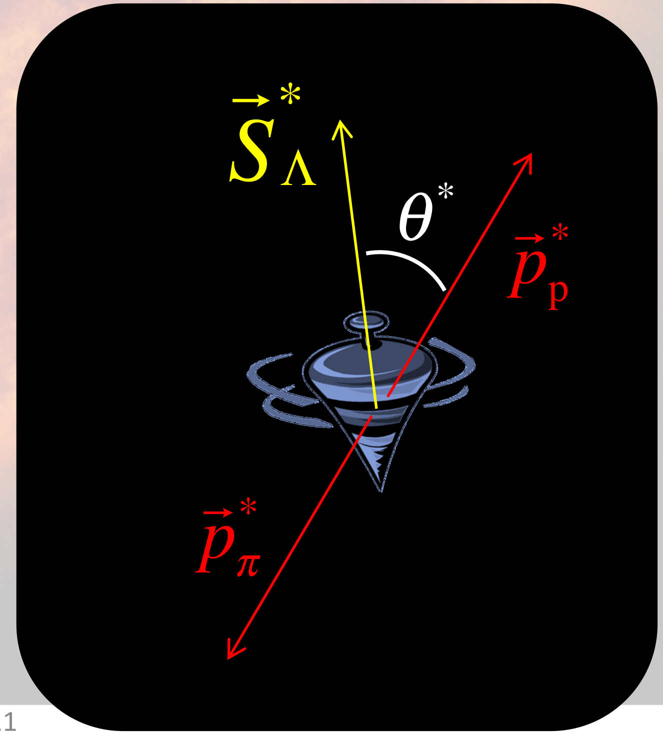
$$\frac{dW}{d\Omega^*} = \frac{1}{4\pi}\left(1+\alpha\vec{P}\cdot\hat{p}_p^*\right) = \frac{1}{4\pi}\left(1+\alpha P\cos\theta^*\right)$$

$\alpha = \cancel{0.642}$ PDG 2020 update! $\alpha_\Lambda = 0.732 \quad \rightarrow$ 14% reduction in $|\vec{P}_\Lambda|$

$\hat{p}_p^*$ is daughter proton momentum direction *in Λ frame*

$$0 < |\vec{P}| < 1: \qquad \vec{P} = \frac{3}{\alpha}\overline{\hat{p}_p^*}$$



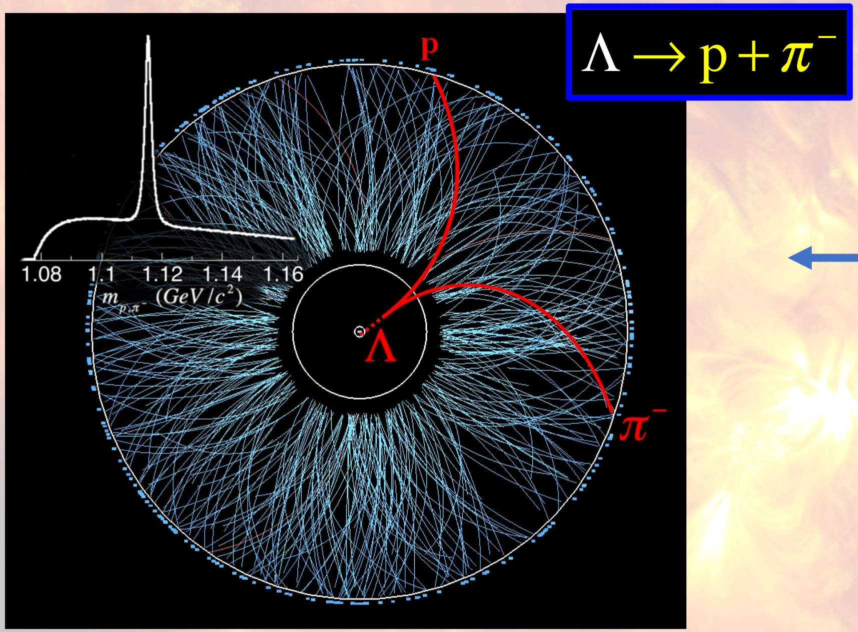


Note: The other particles are polarized, too!

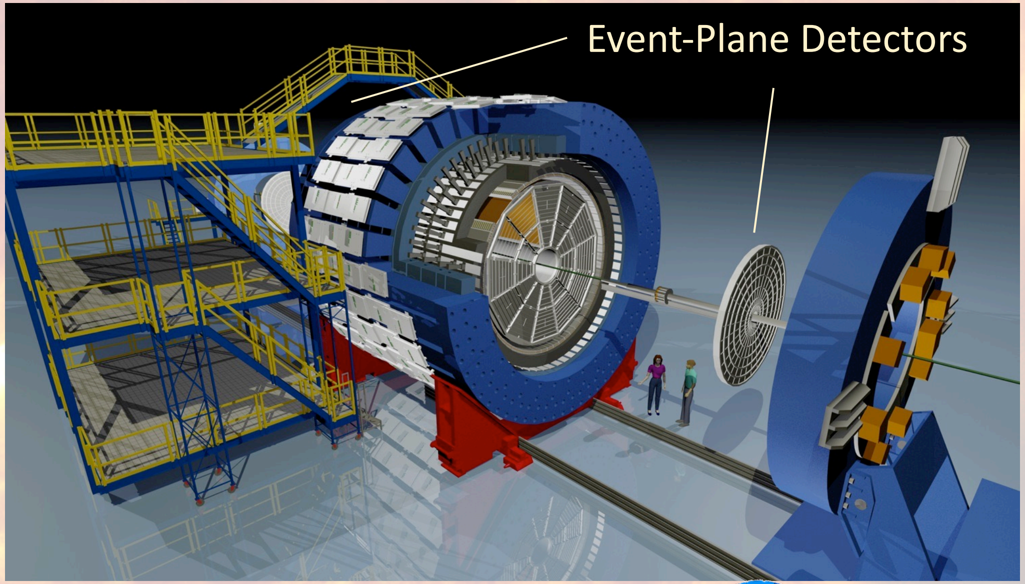
- only weakly-decaying particles reveal their spin this way (& there are few)
- their feed-down effect into Lambdas turns out to be small
  Becattini, Karpenko, MAL, Upsal, Voloshin PRC 95 (2017) 054902

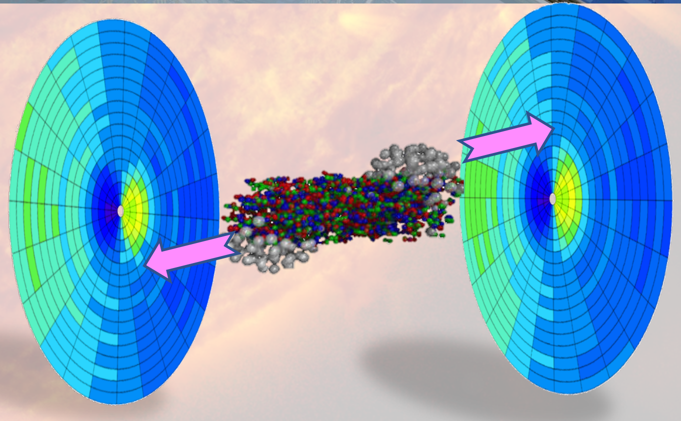
Measuring Polarization

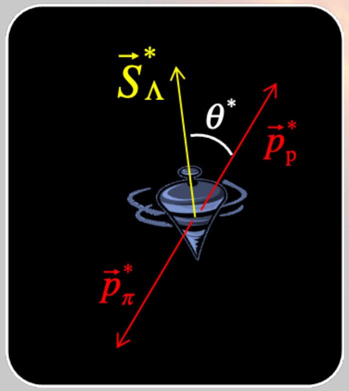
Measuring *Global* Polarization



Λ measured in midrapidity tracking detectors (TPC)







"Self-analyzing" decay: proton momentum aligns with Λ spin

$$\overline{P}_H = \frac{8}{\pi\alpha}\frac{\langle \sin(\Psi^{(1)}_{EP} - \phi^*_p)\rangle}{R^{(1)}_{EP}}$$

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_\Lambda \vec{P}_\Lambda \cdot \hat{p}^*_p\right)$$

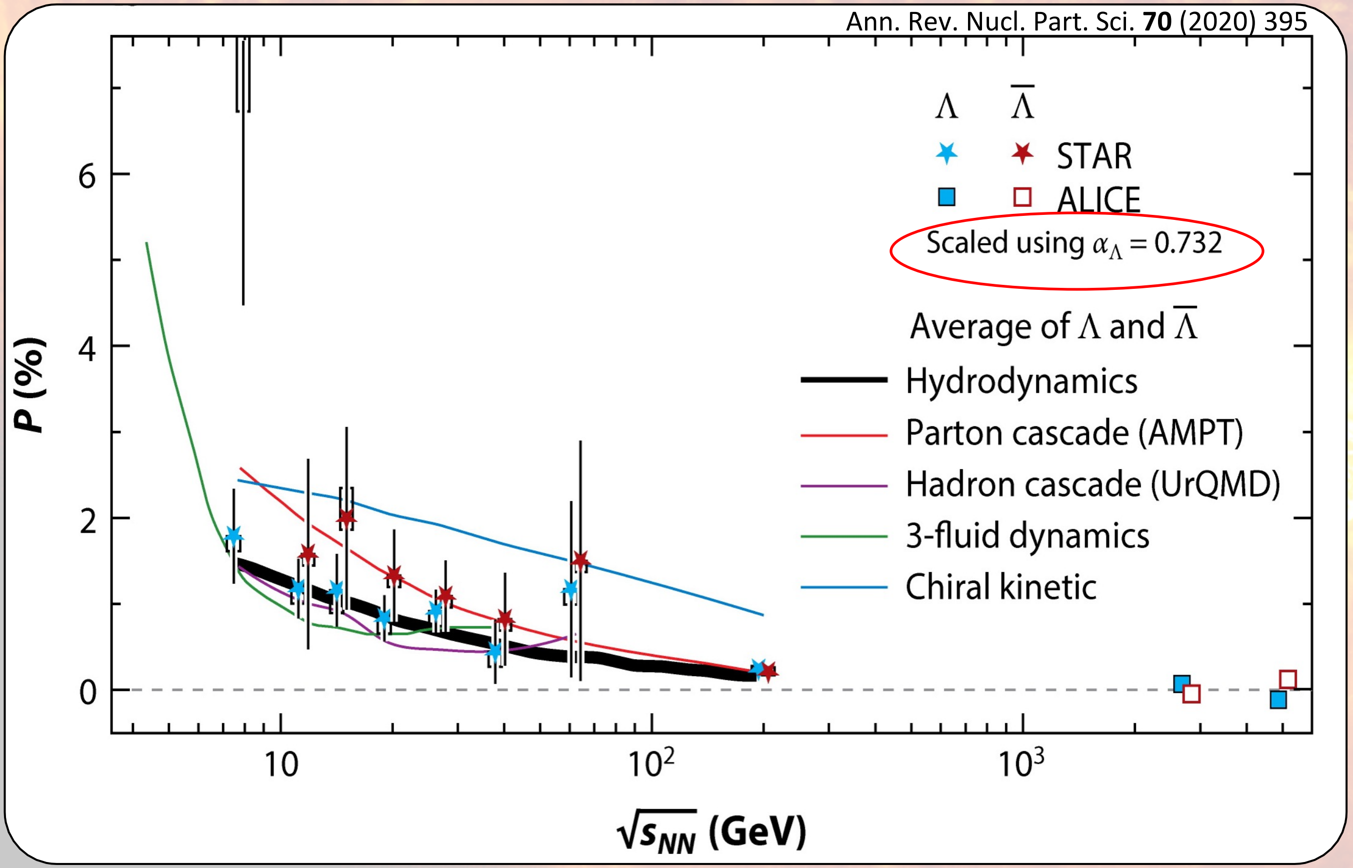
Both STAR (PRC 2007) and ALICE (PRC 2020)first global polarization results initially published with incorrect sign.

$$\cancel{P_H = \frac{8}{\pi\alpha_H}\langle \sin(\varphi^*_p - \Psi_{RP})\rangle}$$

Forward detectors measure $\hat{J}_{\text{global}}$ in terms of "event plane angle" $\Psi^{(1)}_{EP}$

Global Lambda Polarization

Lambda polarization is a well-understood/calibrated tool to access fluid substructure at the finest possible scale.

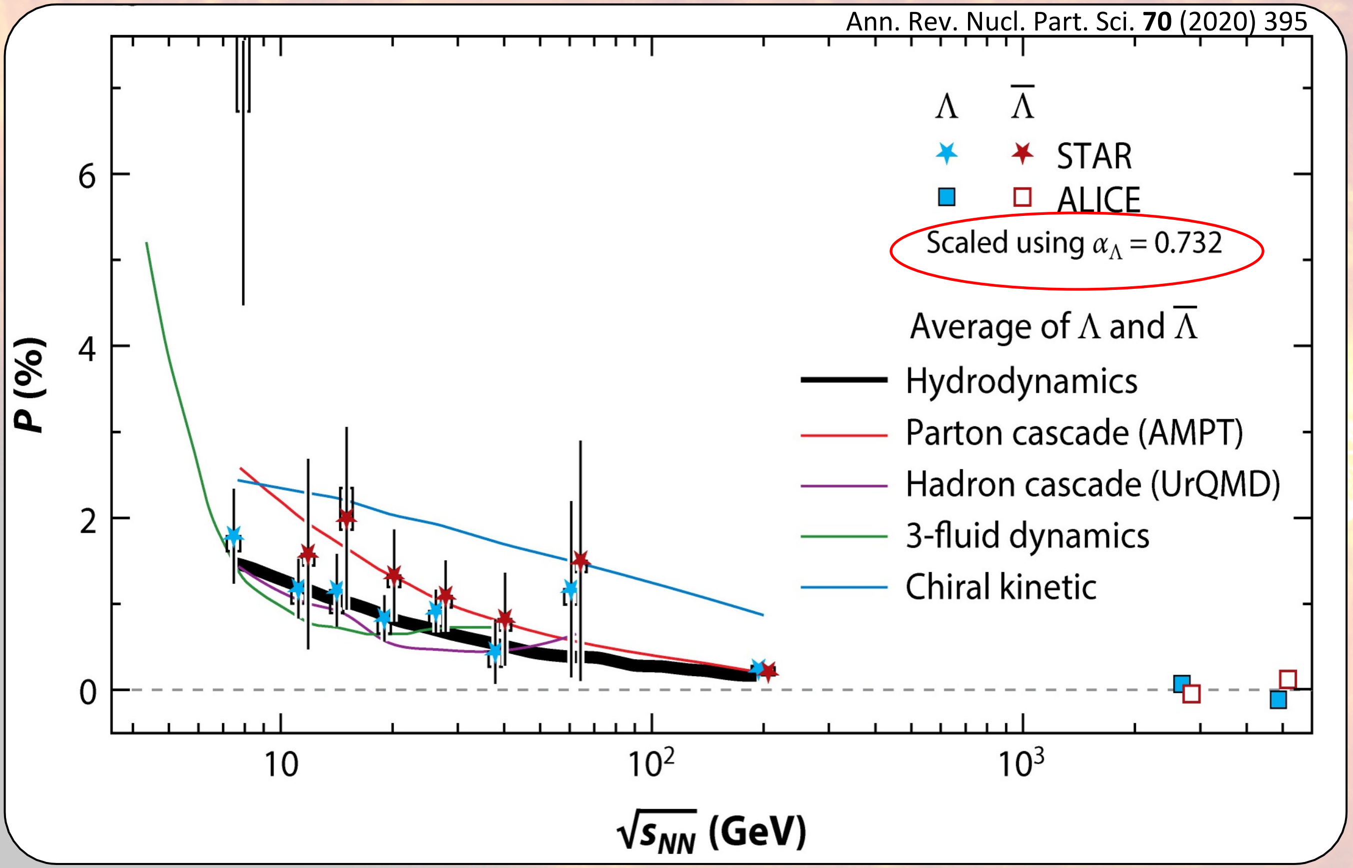


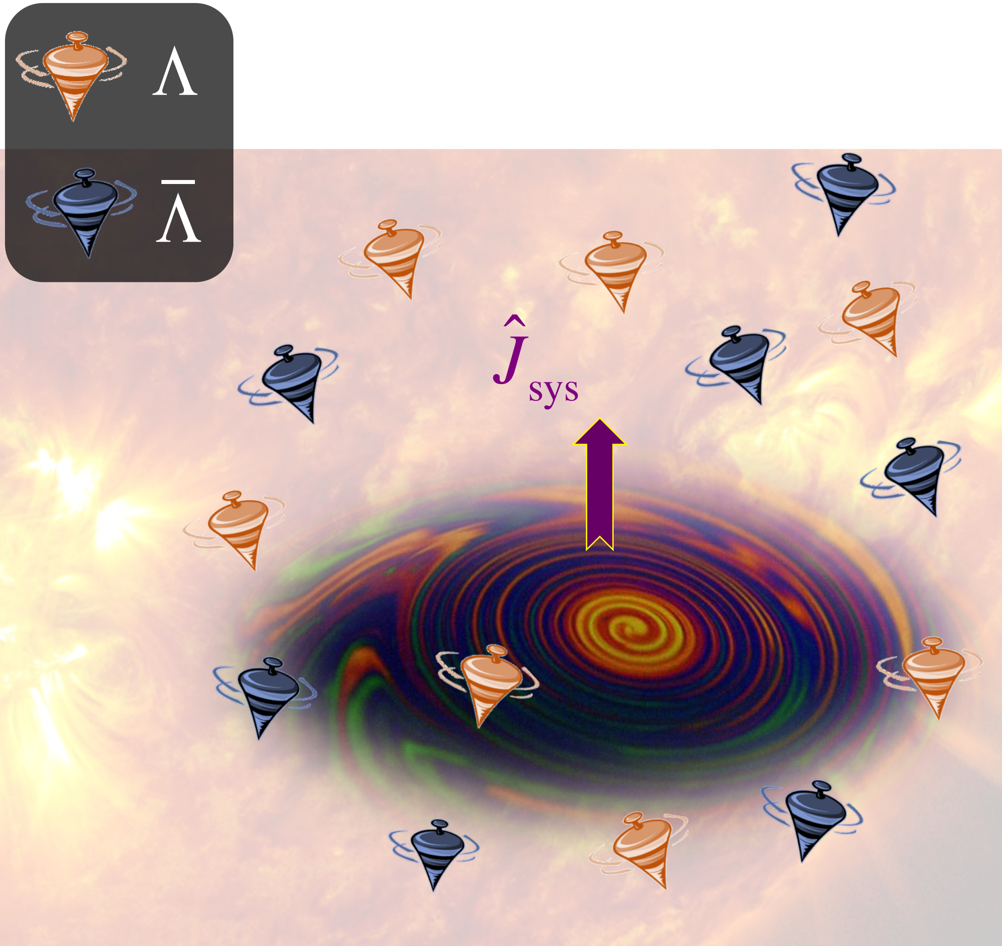
- Measured global polarization in good agreement with **standard** hydro predictions [1]
- Three-fluid hydro, especially important at low root(s) [2]
- Transport calculations (coarse-graining to calculate vorticity) [3,4] & kinetic+coalescence [5]

$$\overline{P}_H = \frac{8}{\pi\alpha} \frac{\langle \sin(\Psi_{EP}^{(1)} - \phi_p^*) \rangle}{R_{EP}^{(1)}}$$

[1] Karpenko I, Becattini F. Eur. Phys. J. C77:213 (2017)
[2] Ivanov YB, Toneev VD, Soldatov AA. Phys. Rev. C100:014908 (2019)
[3] Li H, Pang LG, Wang Q, Xia XL. Phys. Rev. C96:054908 (2017)
[4] Vitiuk O, Bravina LV, Zabrodin EE arXiv:1910.06292 [hep-ph] (2019)
[5] Sun Y, Ko CM. Phys. Rev. C96:024906 (2017)

Global Lambda Polarization

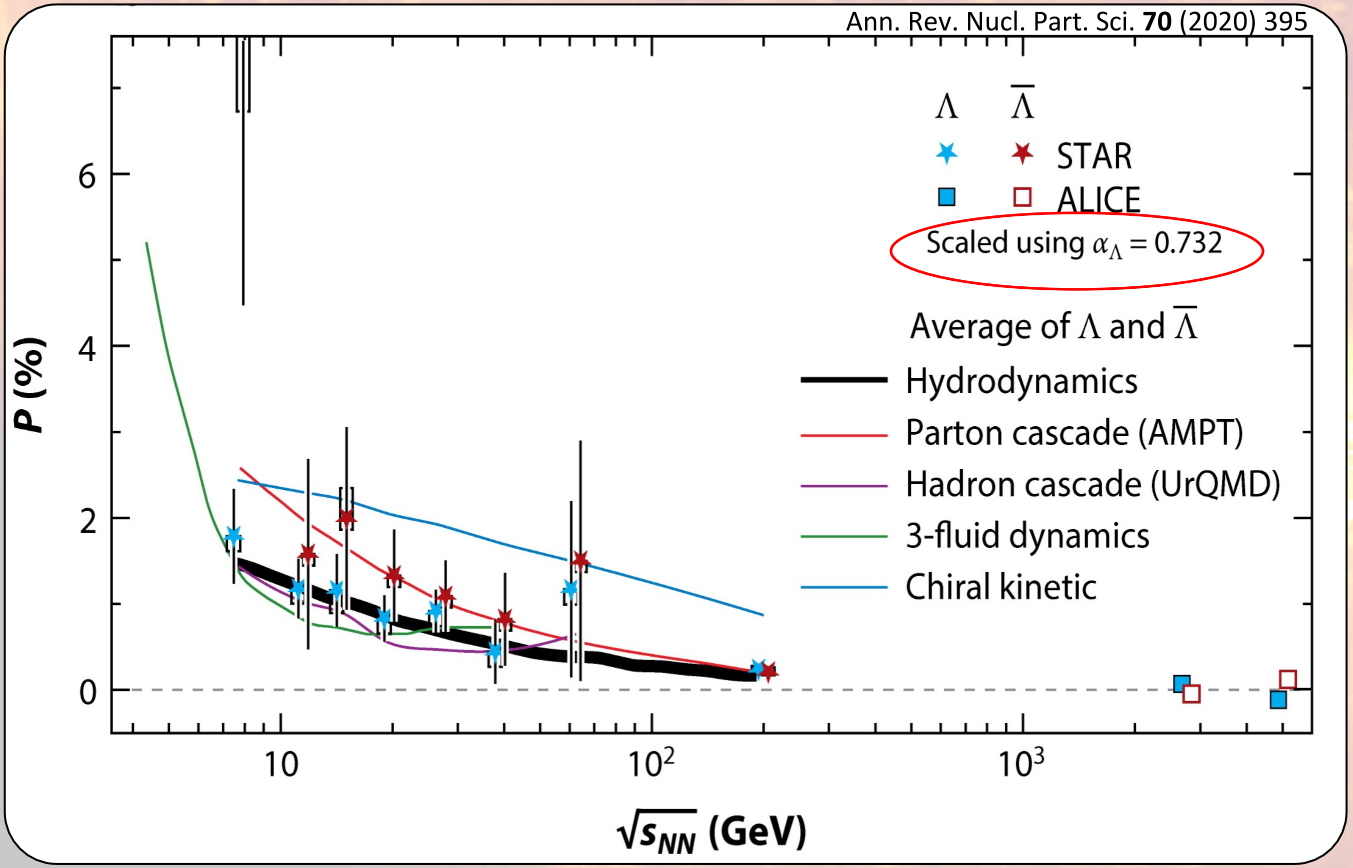


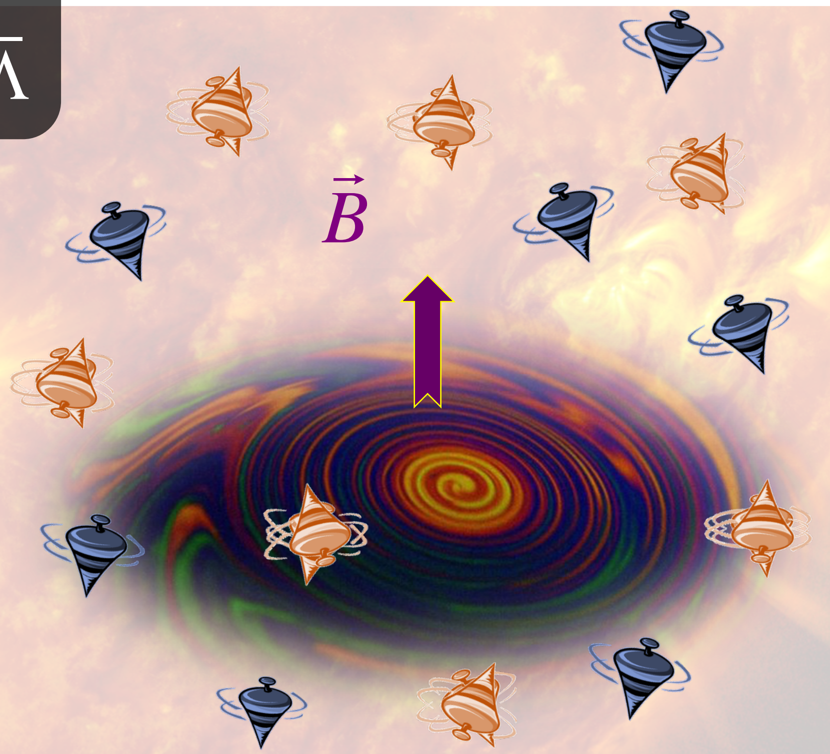


Vortical coupling: $P \propto \omega$

$\vec{\overline{P}}_\Lambda \parallel +\hat{J}_{sys}$ $\vec{\overline{P}}_{\overline{\Lambda}} \parallel +\hat{J}_{sys}$

Global Lambda Polarization





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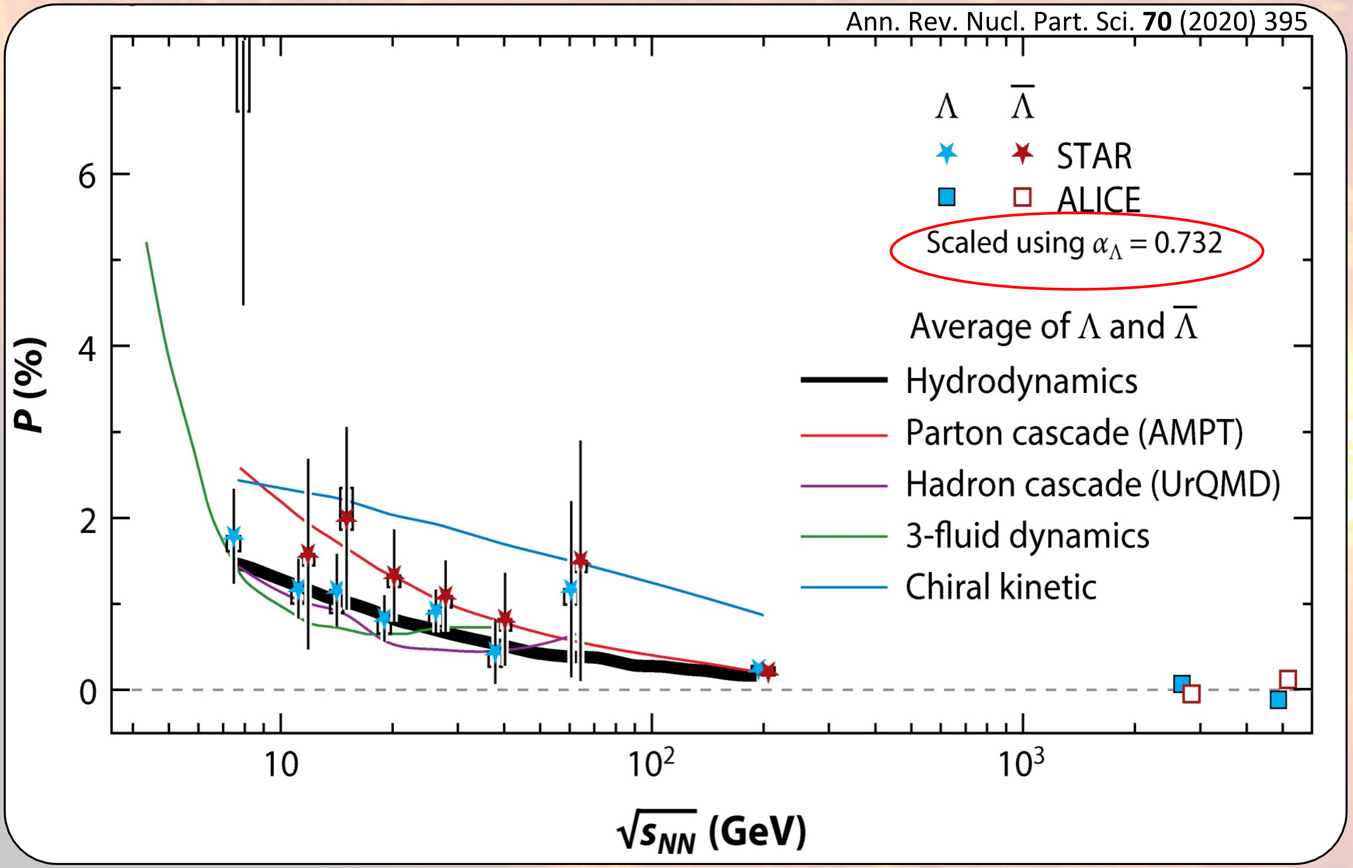
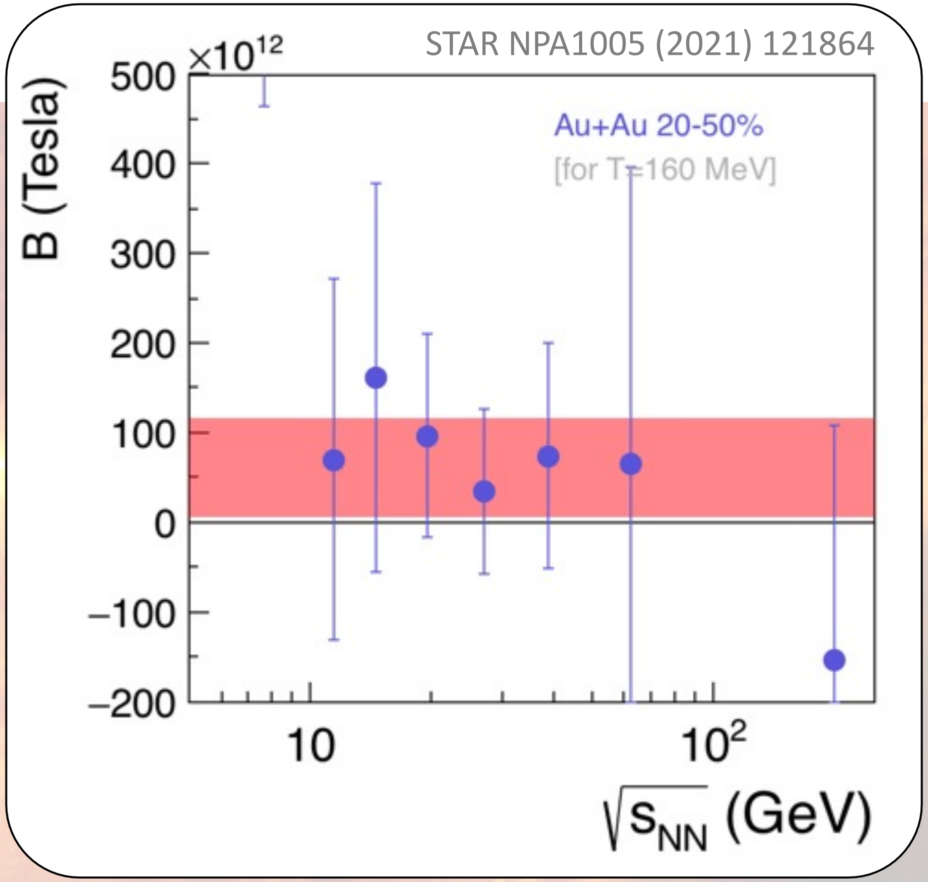
$\vec{\bar{P}}_{\Lambda} \parallel +\hat{J}_{sys}$ $\vec{\bar{P}}_{\bar{\Lambda}} \parallel +\hat{J}_{sys}$

Magnetic coupling: $P \propto \vec{\mu} \cdot \vec{B}$

$\vec{\bar{P}}_{\Lambda} \parallel -$ B $\vec{\bar{P}}_{\bar{\Lambda}} \parallel +$ B

B from Global Lambda Polarization?





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Magnetic coupling: $P \propto \vec{\mu} \cdot \vec{B}$

$\vec{P}_{\Lambda} \parallel -$ B $\quad$ $\vec{P}_{\bar{\Lambda}} \parallel +$ B

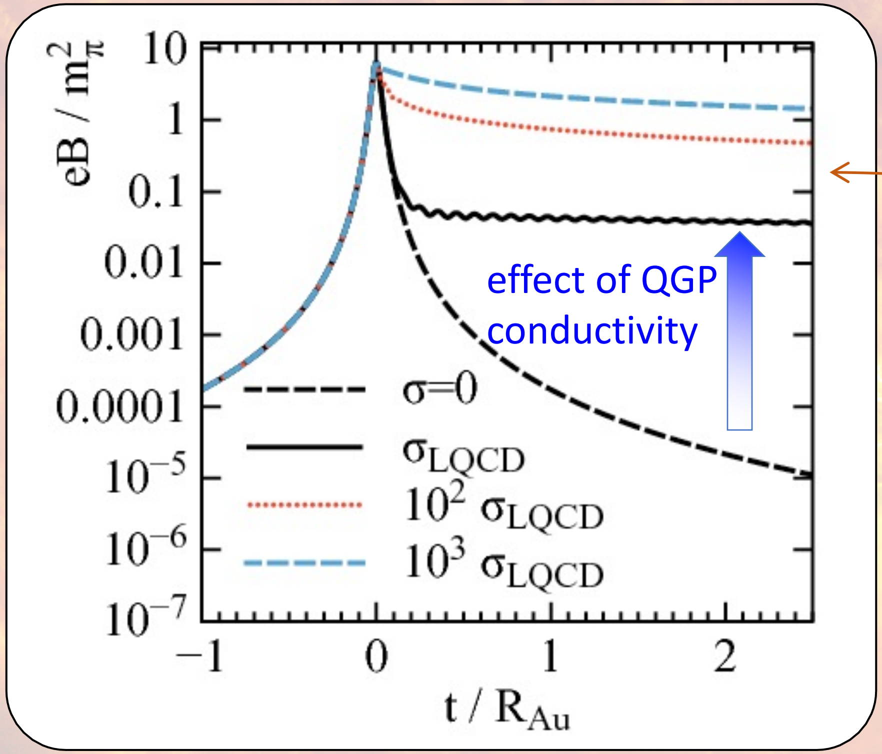
$$P_{\Lambda(\bar{\Lambda})} \simeq \frac{1}{2}\frac{\omega}{T} \pm \frac{\mu_\Lambda B}{T} \qquad \omega = (P_\Lambda + P_{\bar{\Lambda}})k_B T/\hbar \sim 10^{22}\mathrm{s}^{-1}$$

$$\langle B \rangle_{\sqrt{s}} = 6.0 \pm 5.5 \times 10^{13}\ \mathrm{T} \approx 0.6 \pm 5.5\ m_\pi^2$$

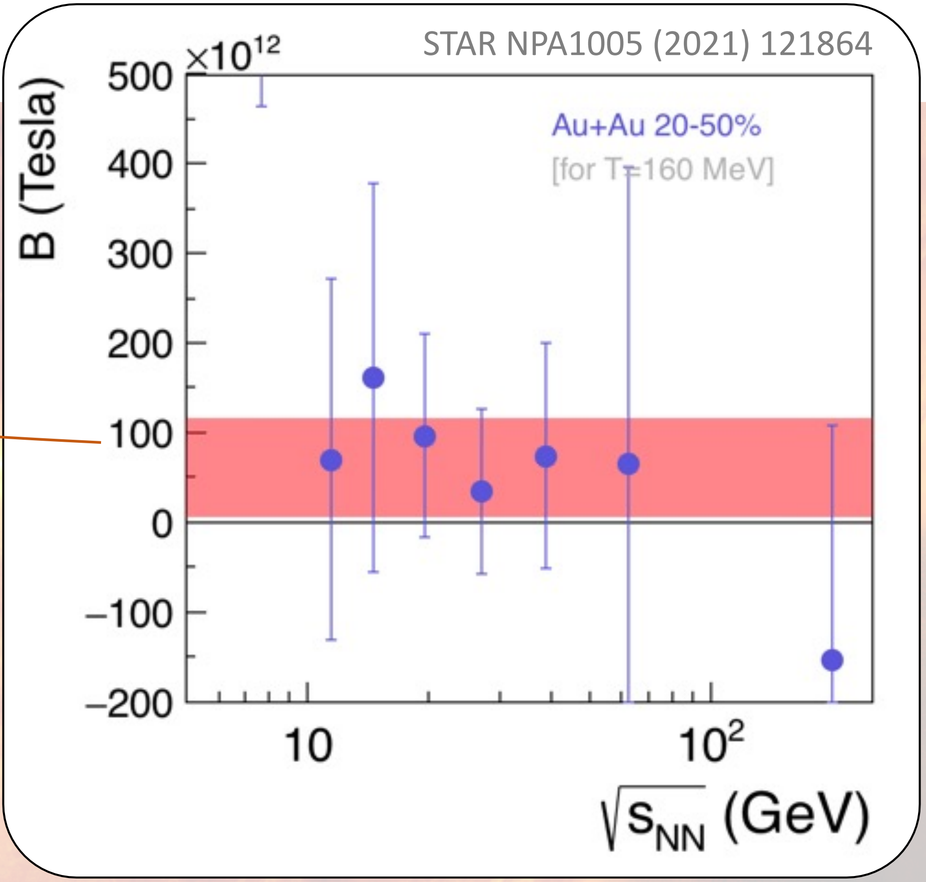
B from Global Lambda Polarization?

McLerran & Skokov NPA929 (2014) 184

$m_\pi^2 / e \approx 10^{14}$ T



STAR NPA1005 (2021) 121864



<u>Also:</u>
Skokov et al, Int J. Mod. Phys. E, 2009 **A24** 5925 – low energy fields live longer
M. Baznat et al., Phys. Rev. C 97, 041902 (2018) – chiral effects
Y. Fujimoto, K. Fukushima, Y. Hidaka, PLB816(2021)136184
Mueller B, Schaefer A.Phys. Rev.D98:071902 (2018) – upper limit
Guo Y, Shi S, Feng S, Liao J.Phys. Lett.B798:134929 (2019) – evolving B in transport
Guo X, Liao J, Wang E arXiv:1904.04704 [hep-ph] (2019) – “feedback”

<u>But</u> non-B-field splitting effects:
Vitiuk O, Bravina LV, Zabrodin EE arXiv:1910.06292
Csernai, Kapusta, Welle Phys. Rev.C99:021901 (2019)

19.6 GeV Au+Au data (RHIC run 2019) *may* reveal splitting. But there will be much to do, yet.

Global Lambda Polarization

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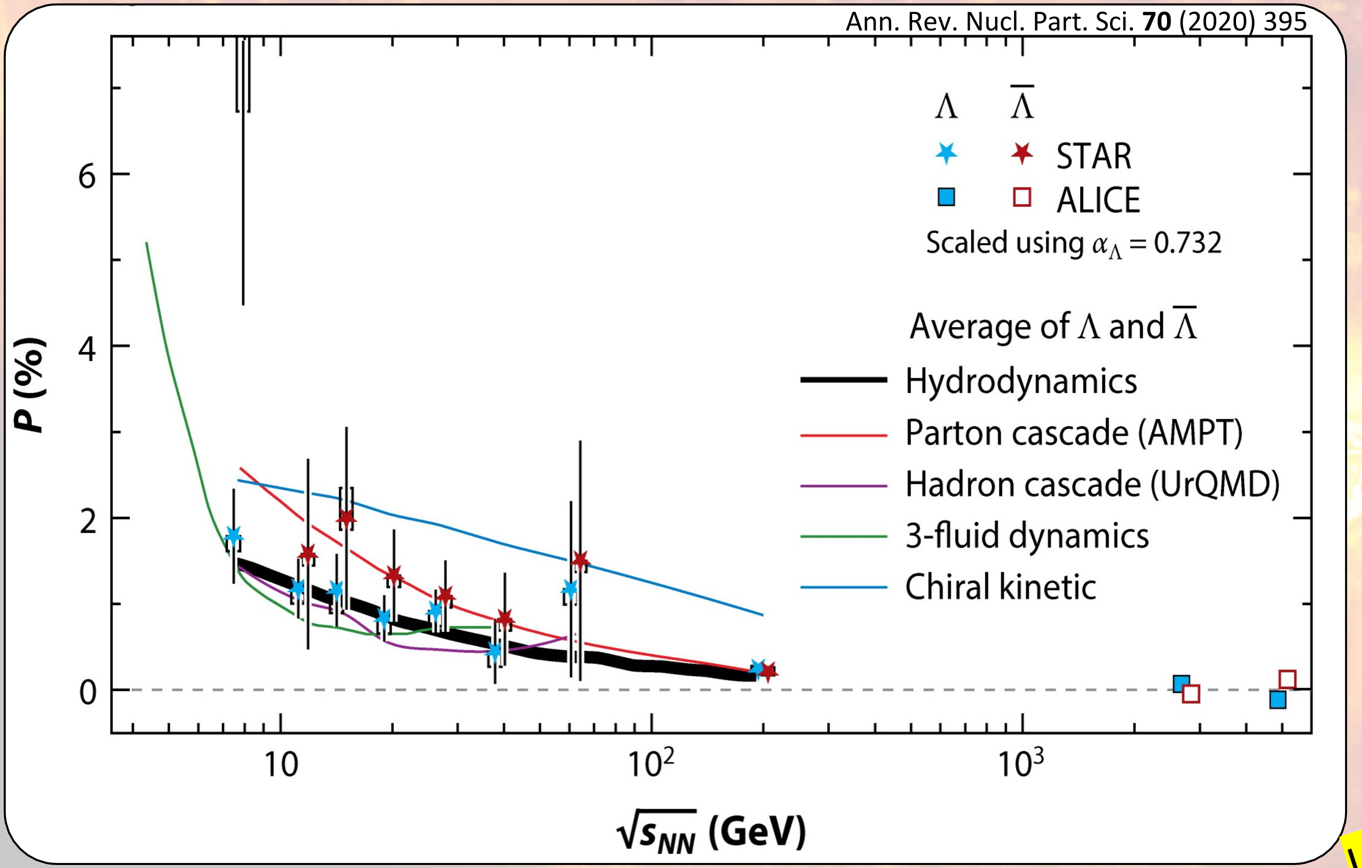

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Until/unless a splitting is observed, models are vorticity-driven

$$\overline{P}_H = \frac{8}{\pi\alpha} \frac{\langle \sin(\Psi_{EP}^{(1)} - \phi_p^*) \rangle}{R_{EP}^{(1)}}$$

[1] Karpenko I, Becattini F. Eur. Phys. J. C77:213 (2017)
[2] Ivanov YB, Toneev VD, Soldatov AA. Phys. Rev. C100:014908 (2019)
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Xi, Omega polarization

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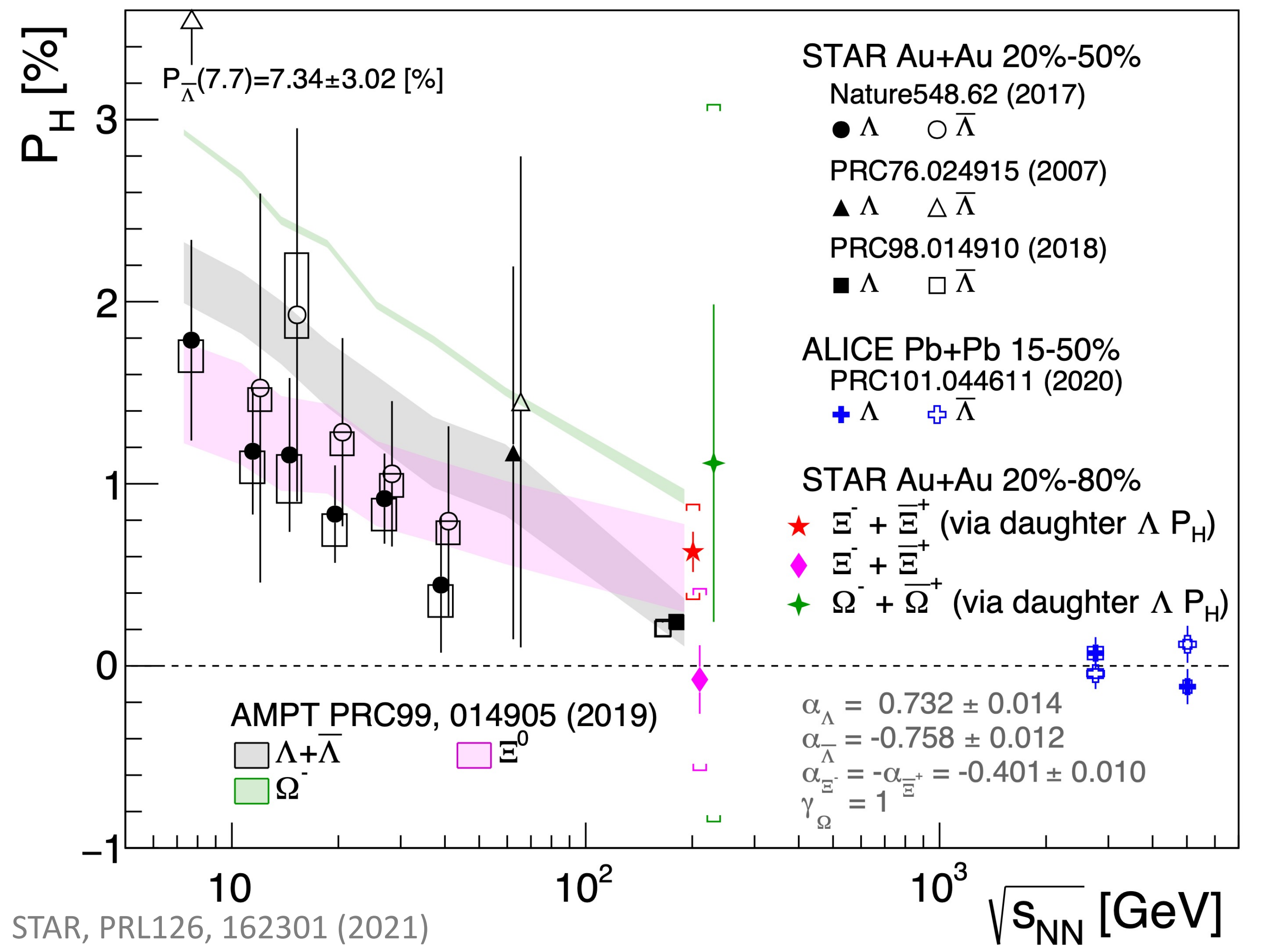


STAR, PRL126, 162301 (2021)

Extracting polarization of multistrange hyperons:

1. $\Xi \to \Lambda + \pi$ decay is self-analyzing (sim $\Lambda \to p + \pi$)

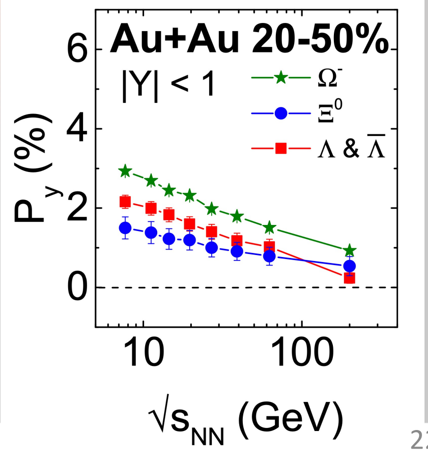
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_\Xi \vec{P}_\Xi \cdot \hat{p}^*_\Lambda\right)$$

2. Also, parent polarization can be extracted from polarization transferred to the daughter

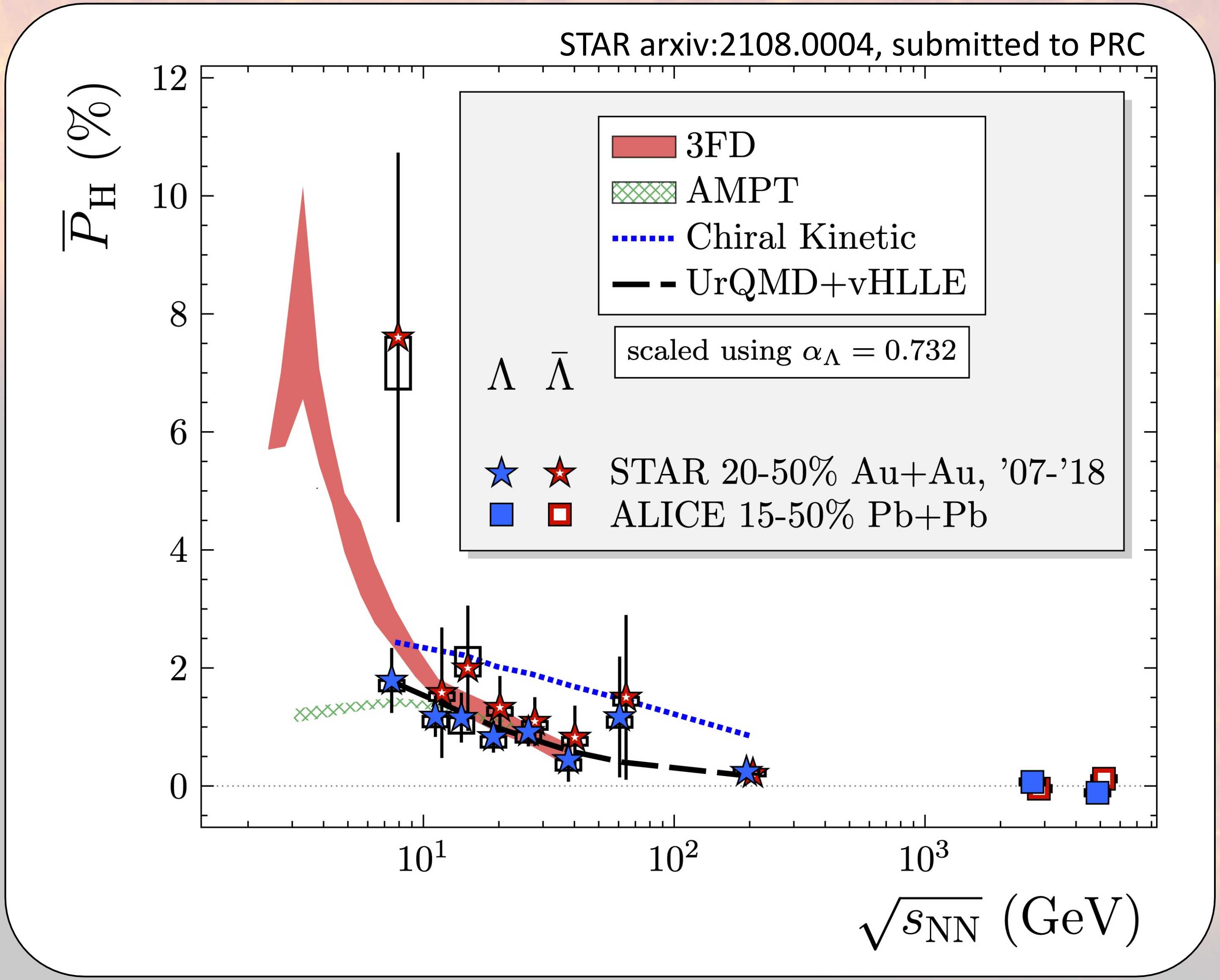
$$P_\Lambda = C_{\Xi-\Lambda} P_\Xi \quad , \quad P_\Lambda = C_{\Omega-\Lambda} P_\Omega$$

Consistent with common fluid vorticity

AMPT calculation
• mass & spin dependence
Wei, Deng, & Huang
PRC99 014905 (2019)



Global Lambda polarization – recent results

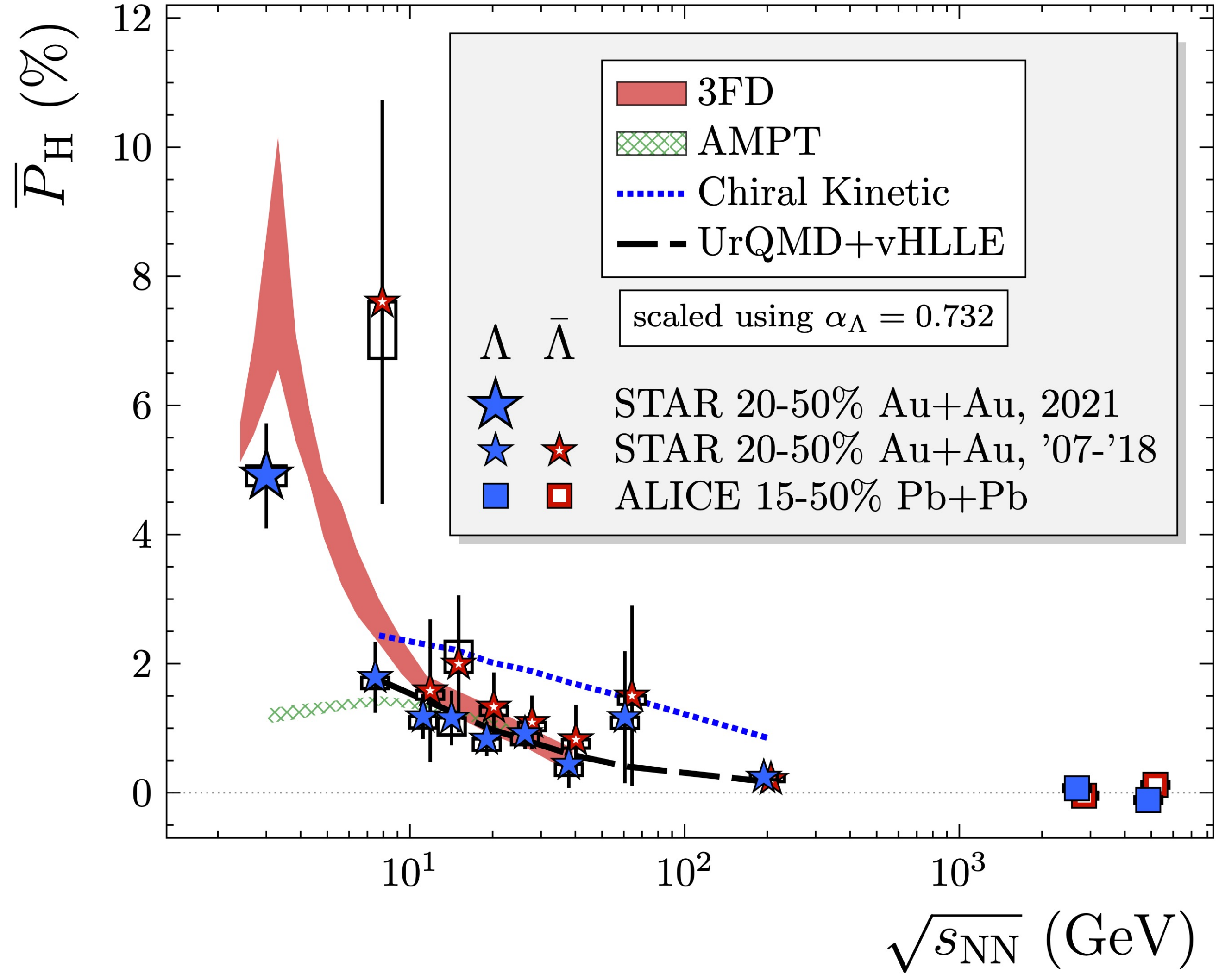


Finalized results

- ALICE 2.76, 5.02 TeV: PRC 2018
- STAR 200 GeV: PRC 2007, 2018
- STAR BES (7.7-32 GeV): Nature 2017

Global Lambda polarization – recent results

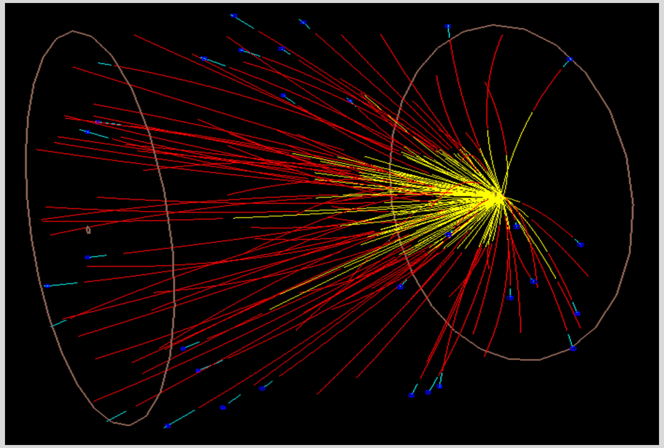
STAR arxiv:2108.0004, submitted to PRC



Finalized results

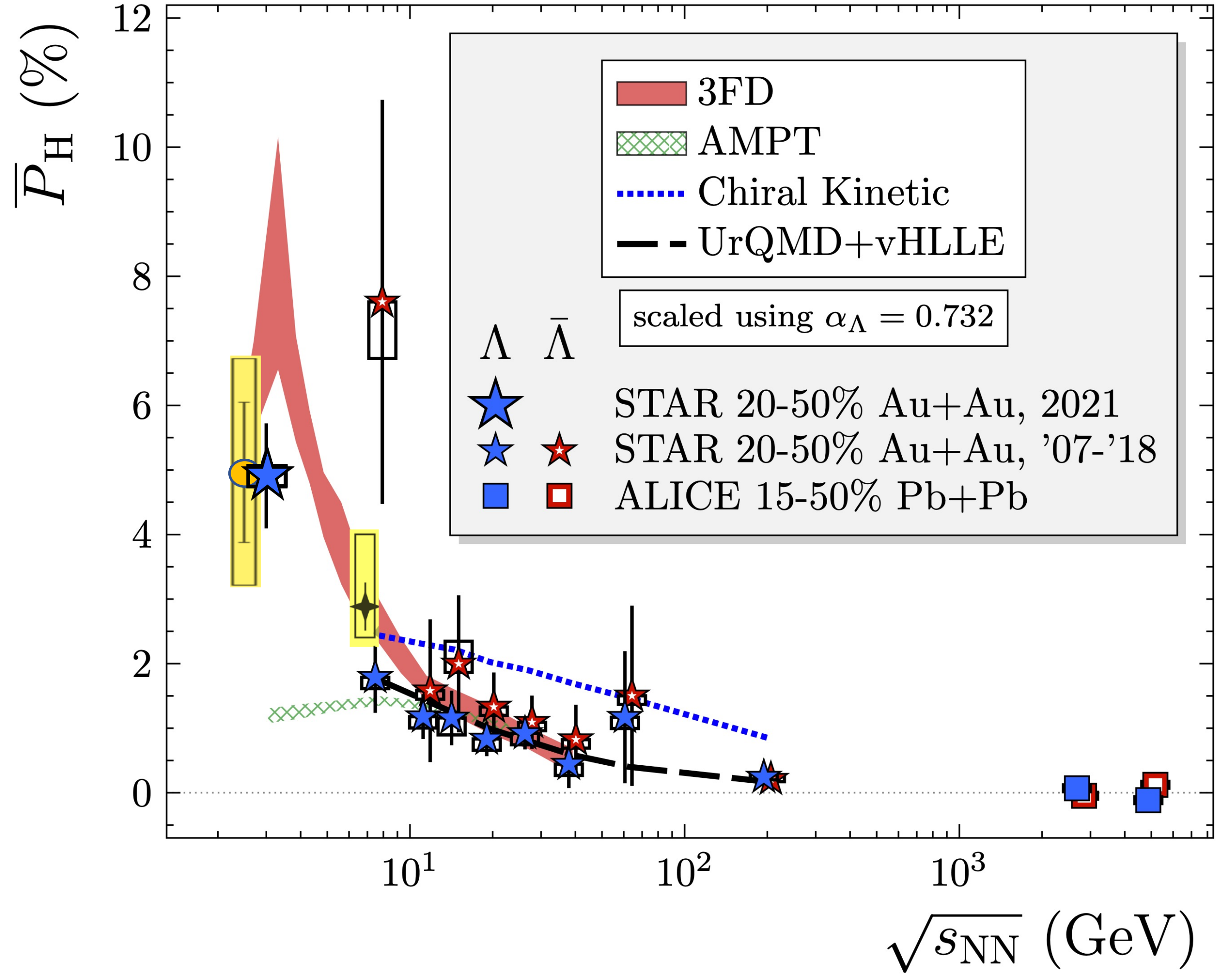
- ALICE 2.76, 5.02 TeV: PRC 2018
- STAR 200 GeV: PRC 2007, 2018
- STAR BES (7.7-32 GeV): Nature 2017
- STAR FXT (3 GeV): 2010.0004 (submitted)
    - see J. Adams talk today

- STAR fixed target program probes conditions where models do *not* agree
- maximum polarization! maximum vorticity?
- fluid treatment?



Global Lambda polarization – recent results

STAR arxiv:2108.0004, submitted to PRC



Finalized results

- ALICE 2.76, 5.02 TeV: PRC 2018
- STAR 200 GeV: PRC 2007, 2018
- STAR BES (7.7-32 GeV): Nature 2017
- STAR FXT (3 GeV): 2010.0004 (submitted)
    - see J. Adams talk today

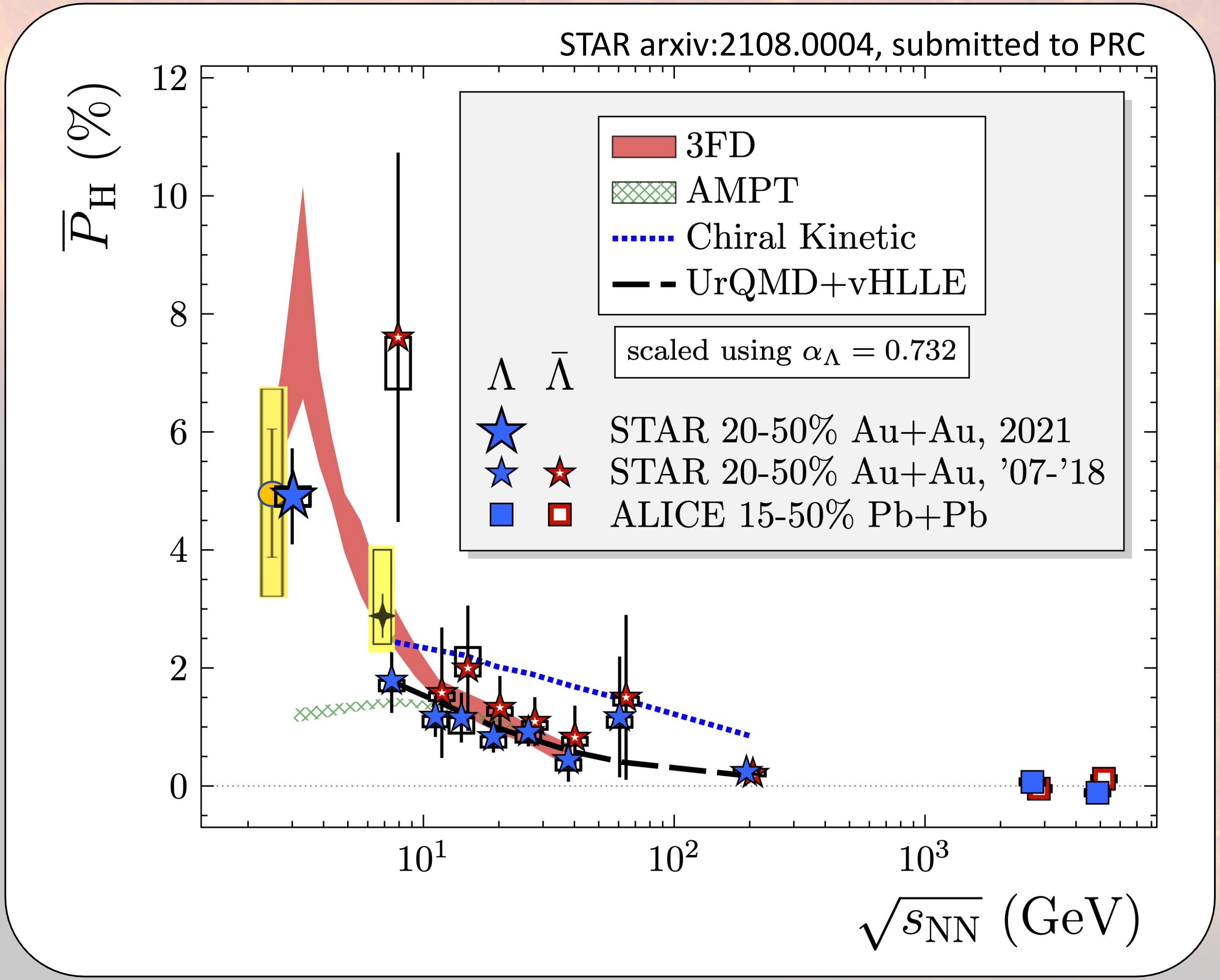
Preliminary results

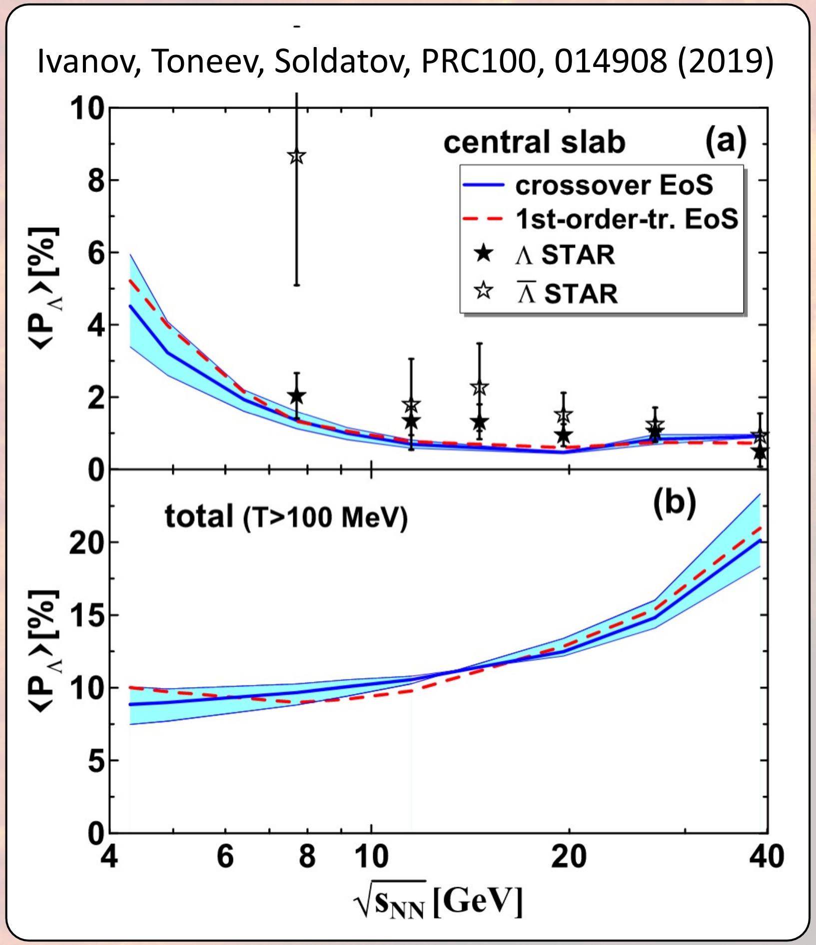
- STAR FXT (7.2 GeV): SQM2021
- HADES (2.4 GeV): SQM2021
    - see F. Kornas talk today

A consistent world systematics is shaping up

- across experiments/facilities/configurations
- across hyperon species
- across energies

Global Lambda polarization – recent results



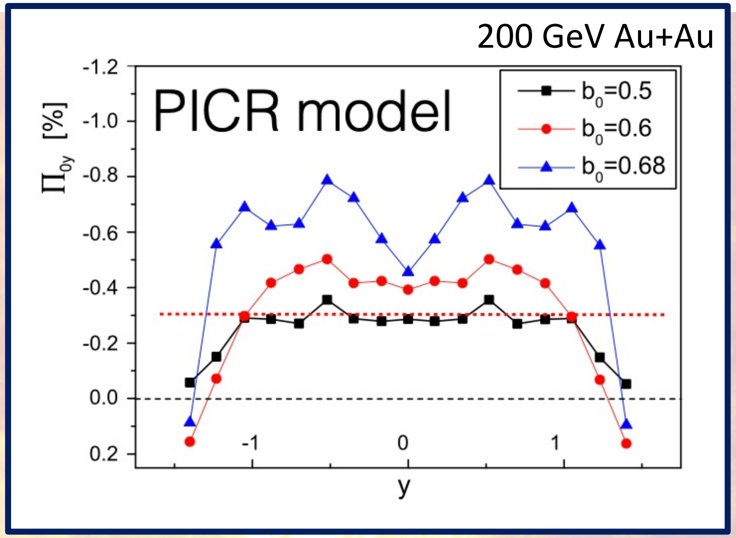


3FD calculations: energy dependence related to migration of vorticity to forward rapidity?

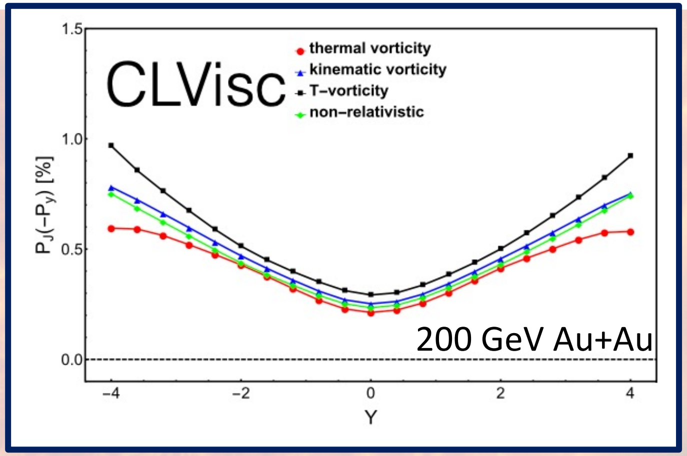
Rapidity dependence of global polarization

While most models reproduce midrapidity polarization well, *pre*dictions in unexplored kinematic regions vary significantly

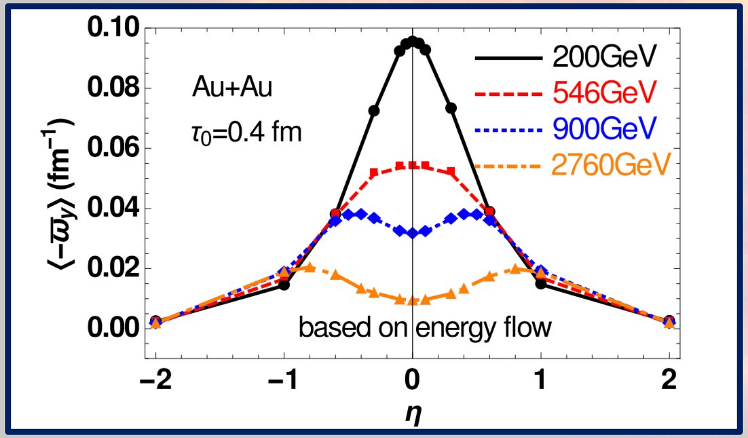
- may be related to √s evolution?
- stronger at low energy?



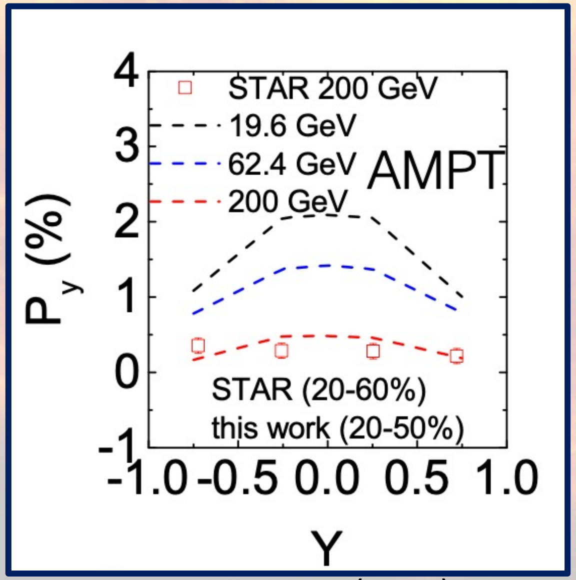
Xie, Wang, Csernei RPJ(2020)80:39



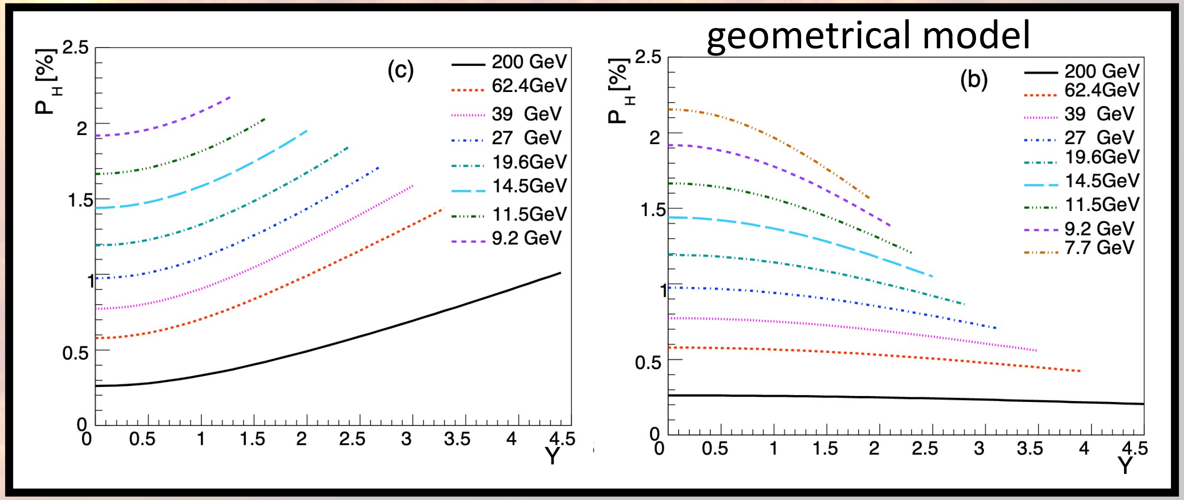
Wu et al, Phys. Rev. Res. 1 (2019) 033058



Feng, Huang PRC93(2016)064907

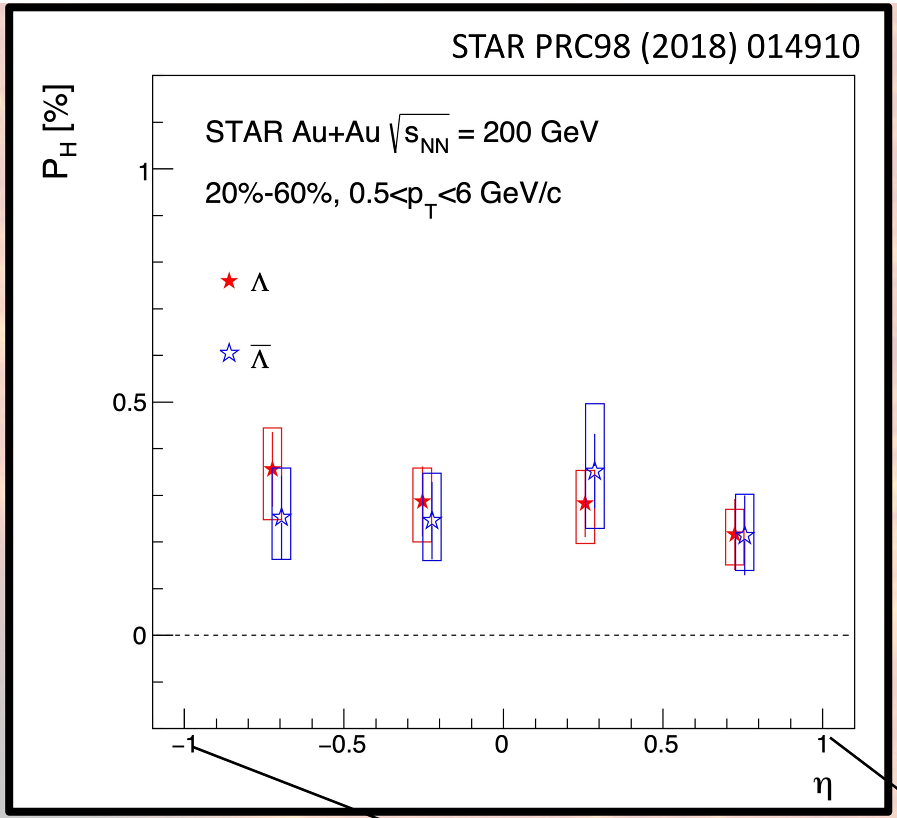


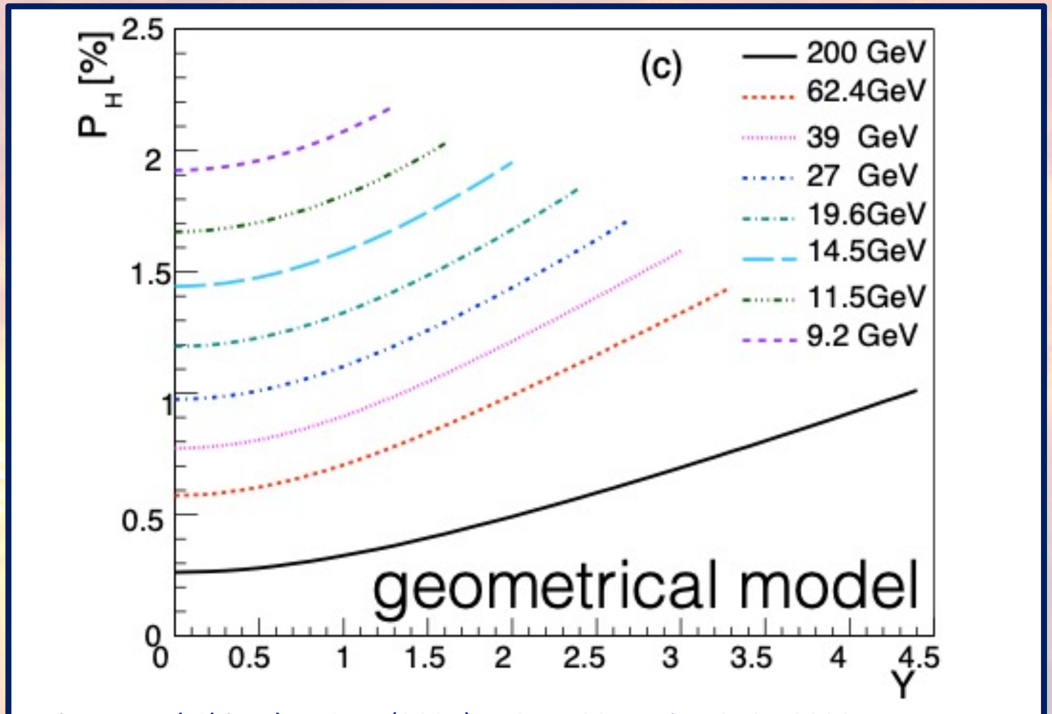
Wei,Deng,Huang PRC99(2019)014905



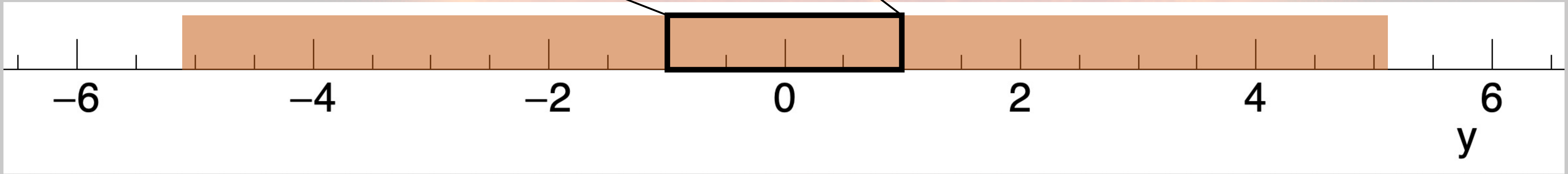
Liang, et al arXiv:1912.10223 Chin.Phys.C 45 (2021) 1, 014102

Measured rapidity dependence?

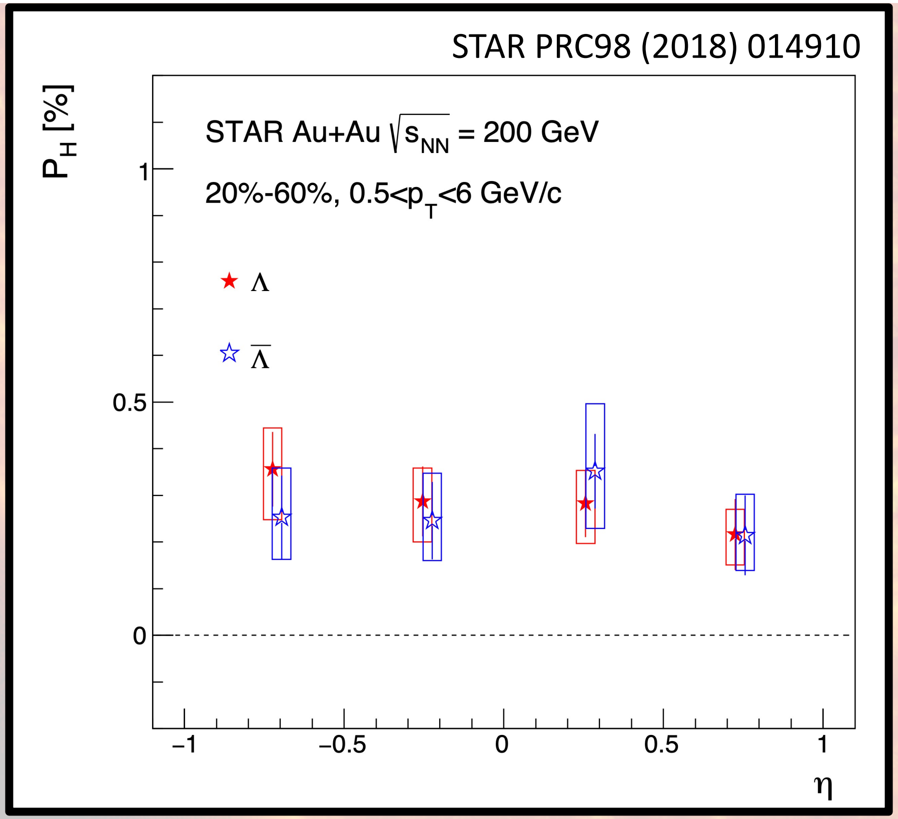


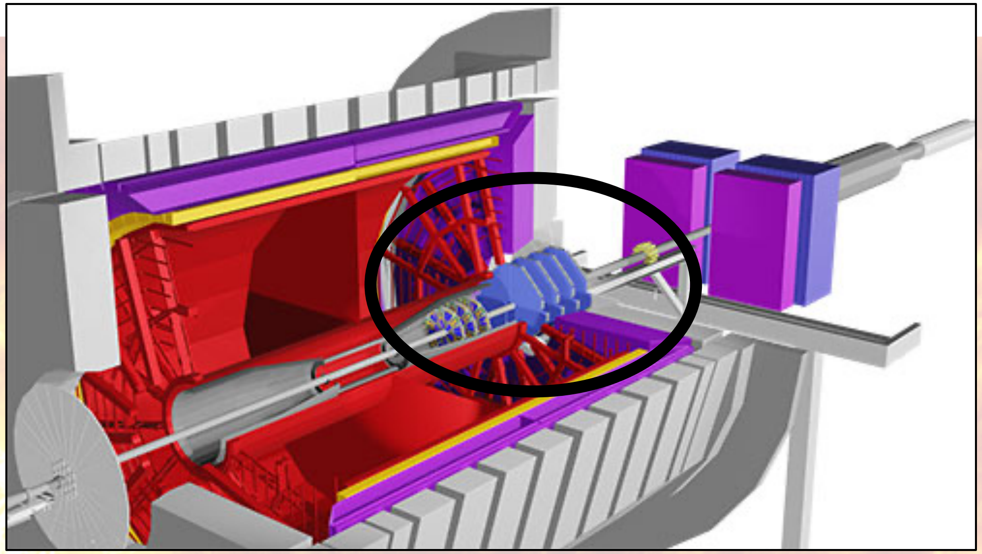


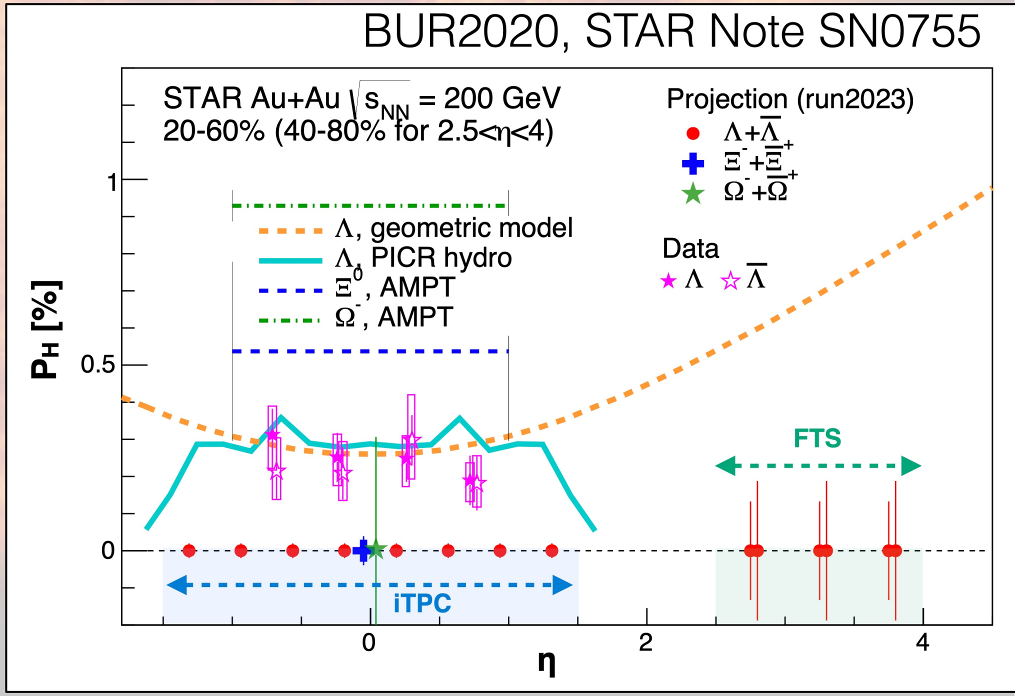
Liang, et al Chin.Phys.C 45 (2021) 1, 014102; arXiv:1912.10223



Measured rapidity dependence?

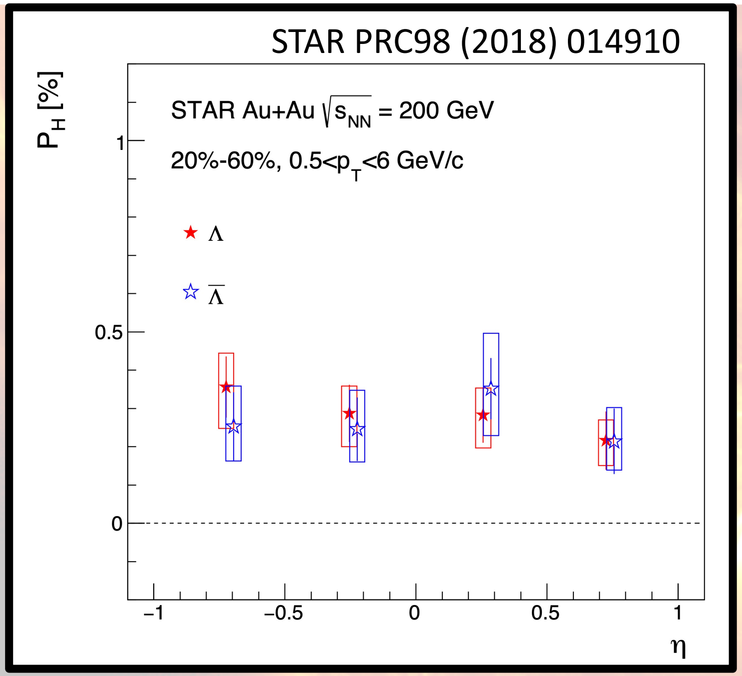


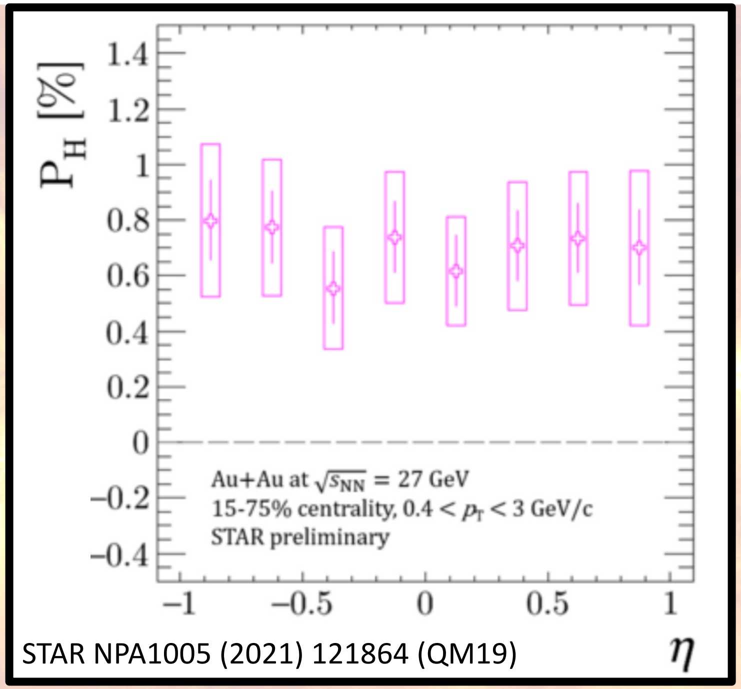


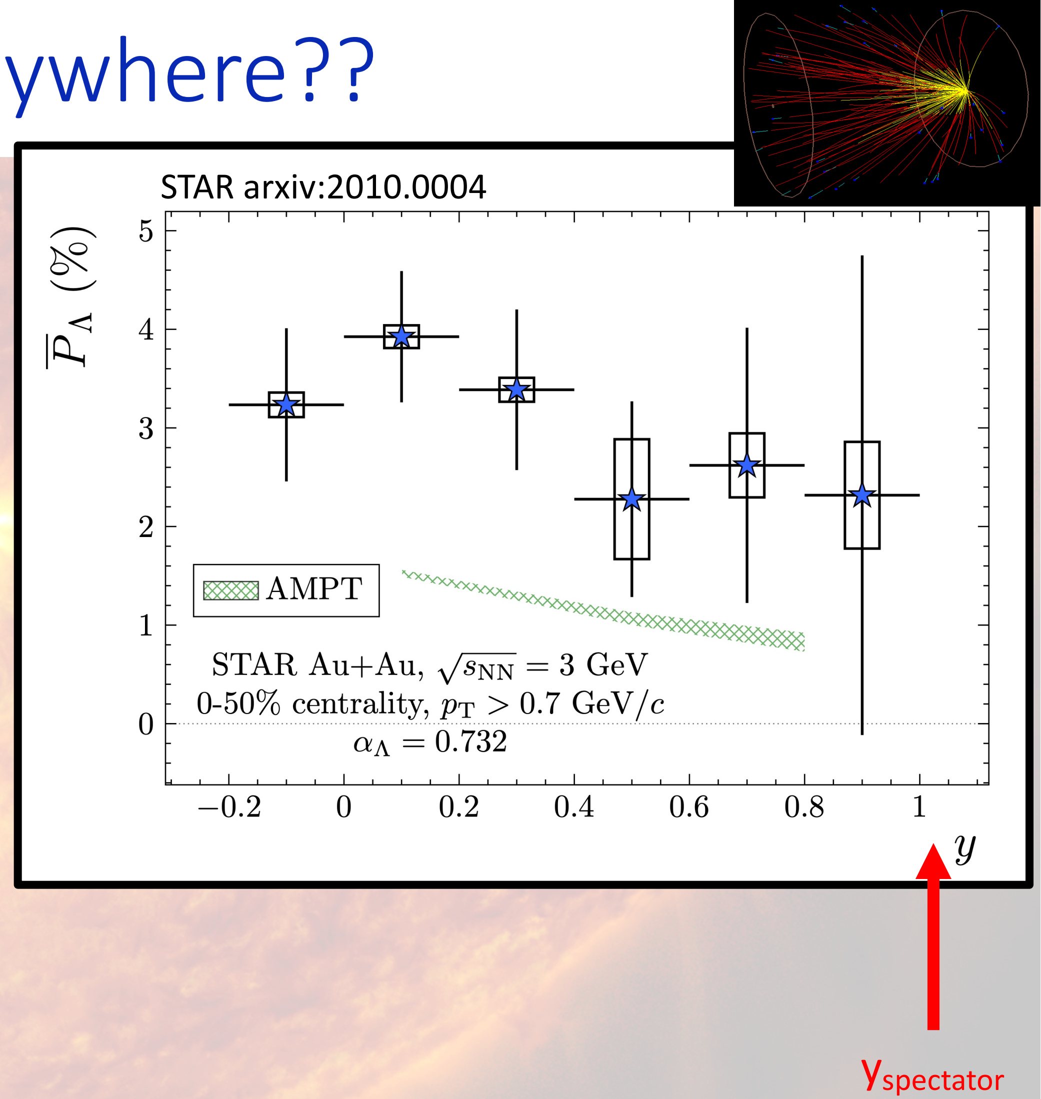


Meaningful reach at 200 GeV possible with STAR forward upgrade – 2023+

Measured rapidity dependence? – anywhere??







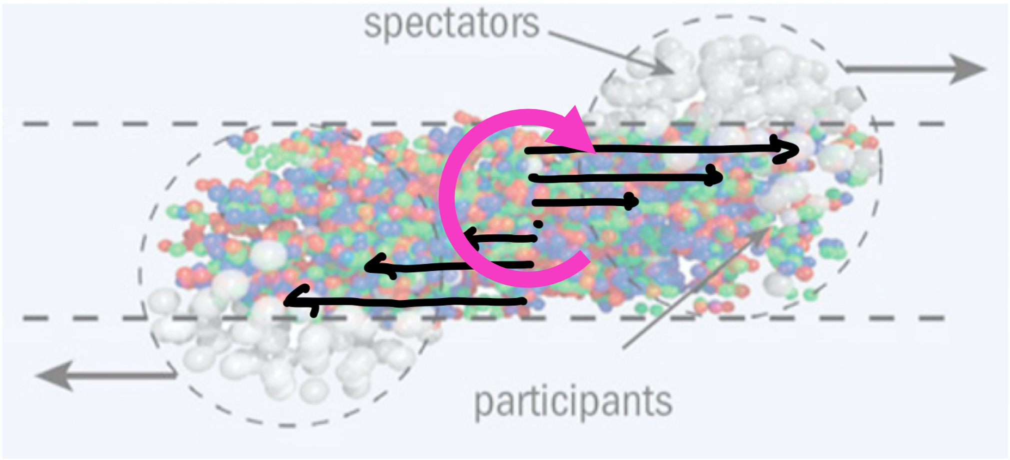
Meaningful reach at 200 GeV possible with STAR forward upgrade – 2023+

Within (rather large) uncertainties, no y-dependence over **entire kinematic range**, in 3 GeV collisions

- theory?
- c.f. J. Adams talk

In another direction – longitudinal polarization

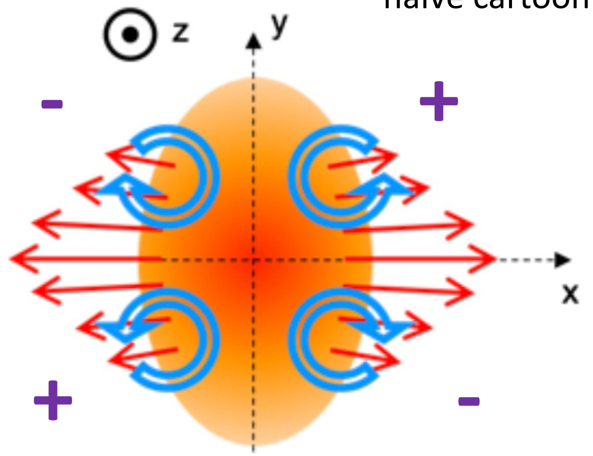
Transverse gradient of longitudinal flow $\rightarrow \vec{\omega} \parallel \hat{J}$



Natural analogy

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

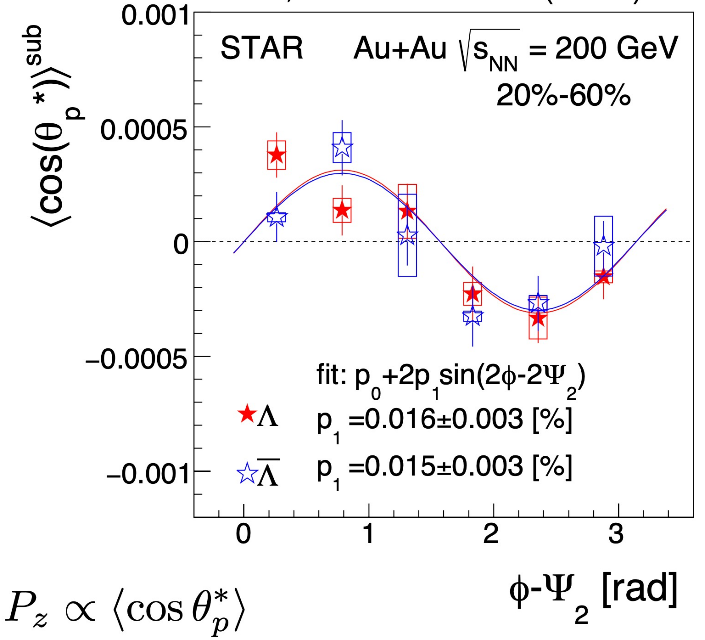
naïve cartoon



(By symmetry, must be quadrupole)

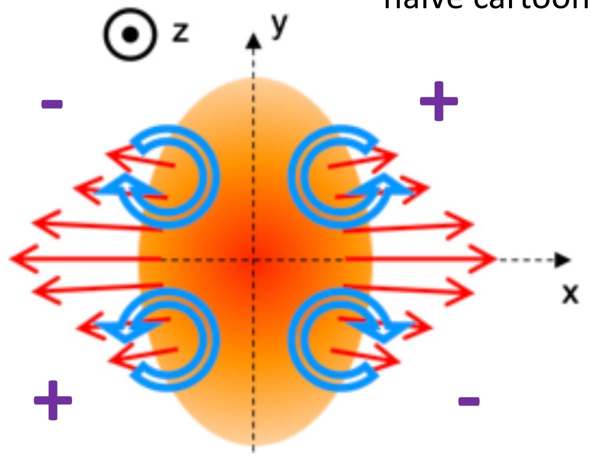
In another direction – longitudinal polarization

Toy Blast-wave works well



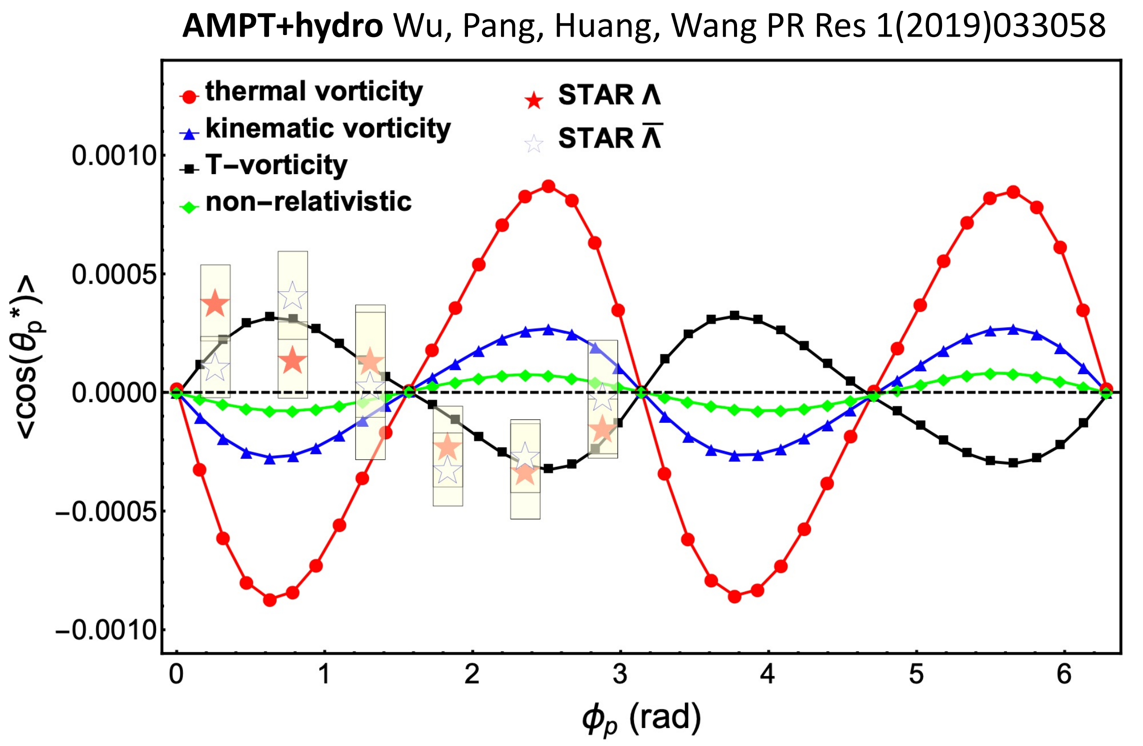
$P_z \propto \langle \cos\theta_p^* \rangle$

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

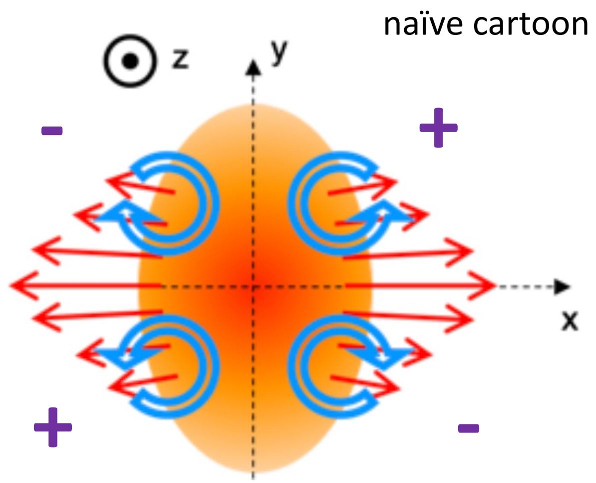


(By symmetry, must be quadrupole)

In another direction – longitudinal polarization



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



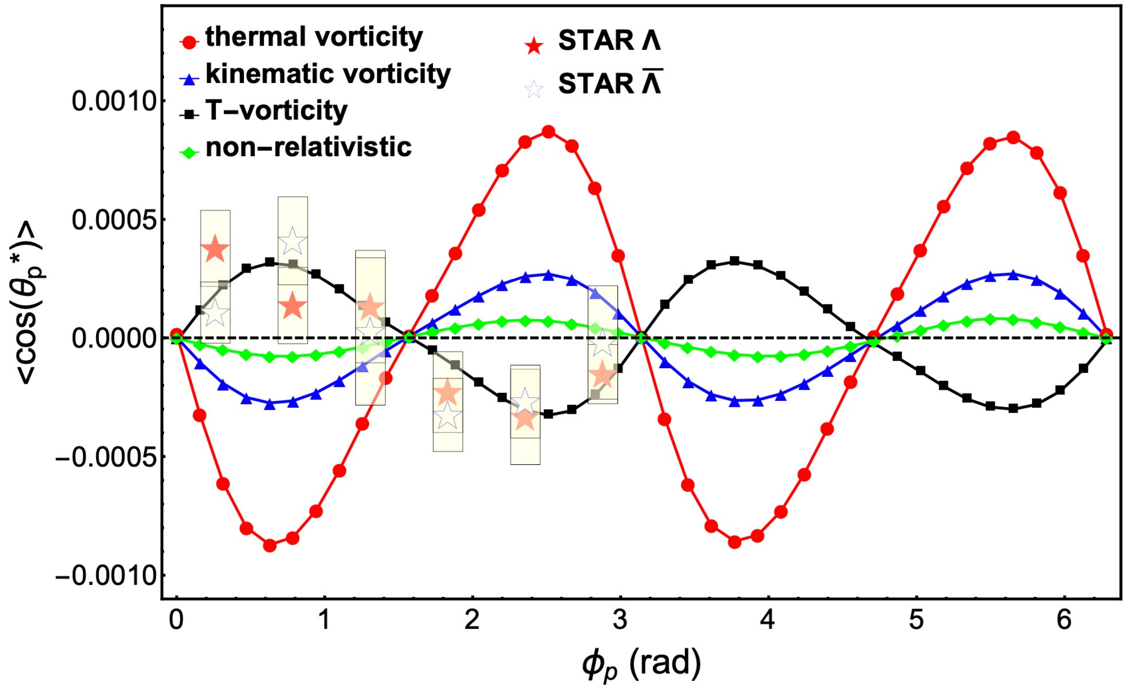
(By symmetry, must be quadrupole)

"Which kind of vorticity" to use? →

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

In another direction – longitudinal polarization

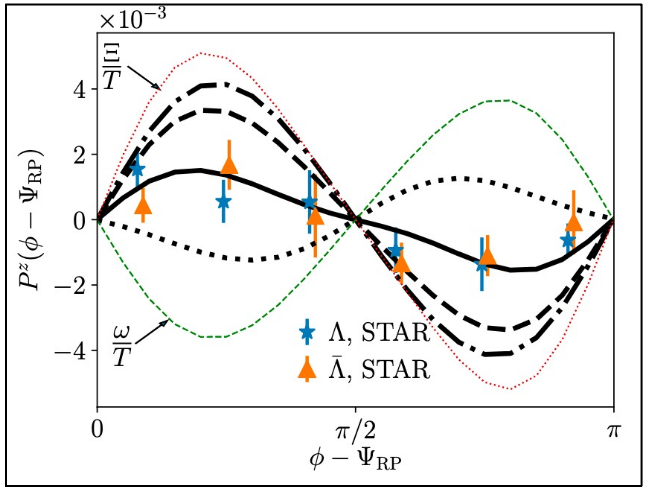
AMPT+hydro Wu, Pang, Huang, Wang PR Res 1(2019)033058

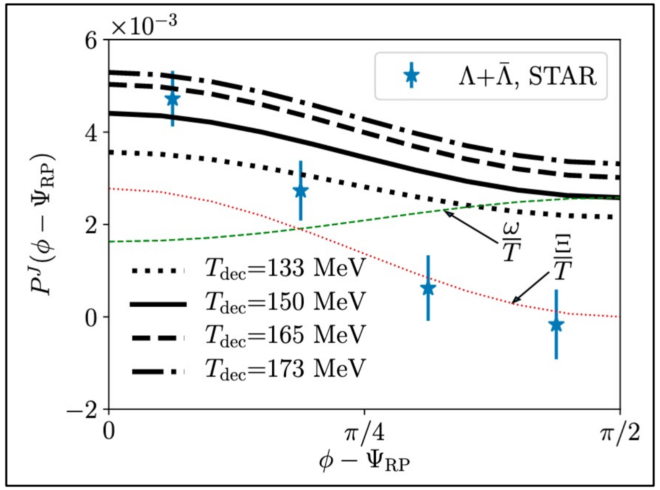


New important term realized

- kinematic shear

$$\Xi_{\rho\sigma} = \frac{1}{2}\left(\partial_\sigma u_\rho + \partial_\rho u_\sigma\right)$$





Fu, Liu, Pang, Song, Yin, PRL127, 142301 (2021); arXiv:2103.10403
Becattini, Buzzegoli, Palermo, Inghirami, Karpenko, arXiv:2103.14621
Liu and Yin, (2021), JHEP 07 (2021) 188; arXiv:2103.09200

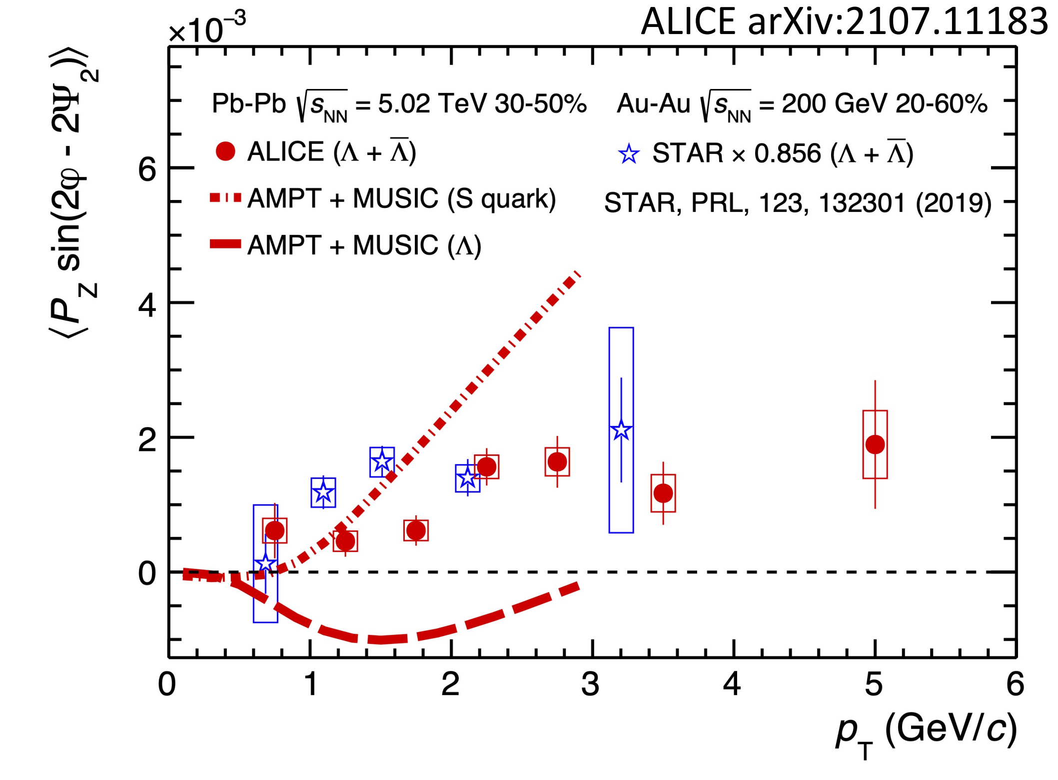
c.f. talk by Becattini

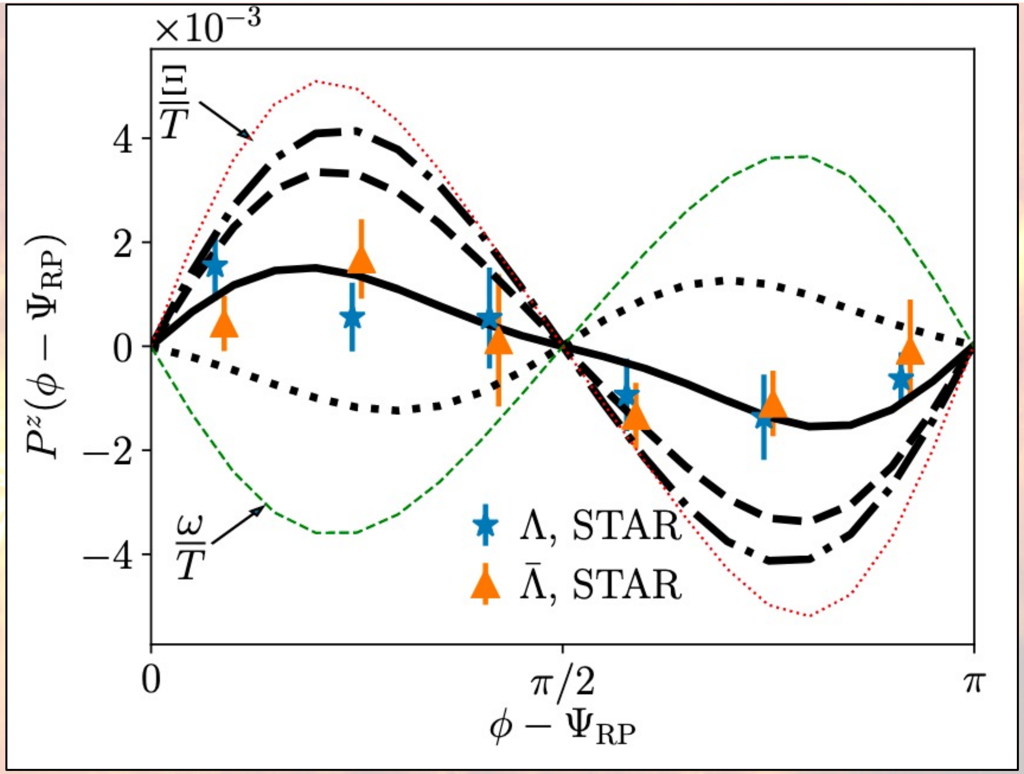
"Which kind of vorticity" to use? →

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

This is progress!

Which dominates?





✓ ALICE observes similar longitudinal flow pattern/magnitude as does STAR

c.f. talk by Becattini

2 extreme scenarios [1]

- all polarization derives from s-quark spin alignment → shear terms dominate
- polarization determined at hyperon freezeout, using Lambda mass → thermal vorticity dominates

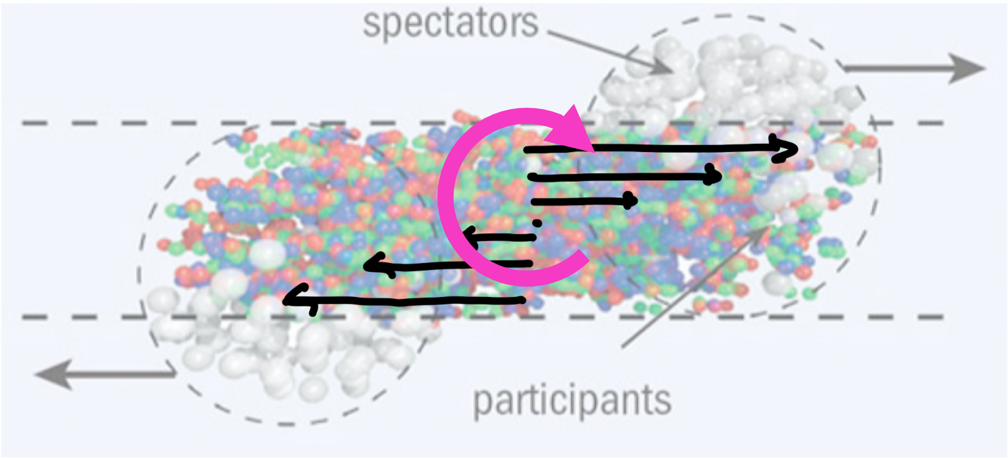
There is a lot to explore, here.

[1] Fu, Liu, Pang, Song, Yin, PRL127, 142301 (2021); arXiv:2103.10403

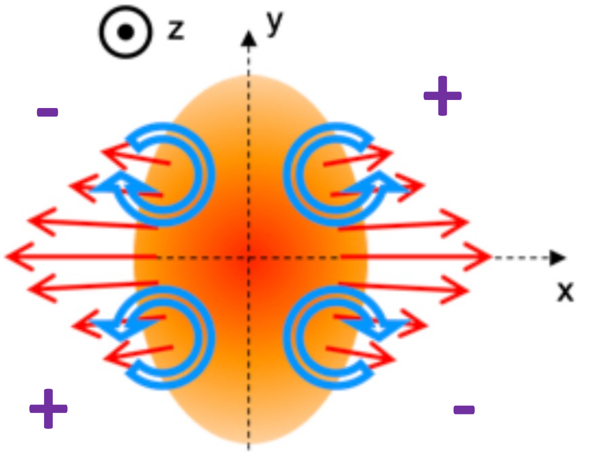
Much progress.
Some other directions we should explore

What about head-on collisions? (No anisotropic flow)

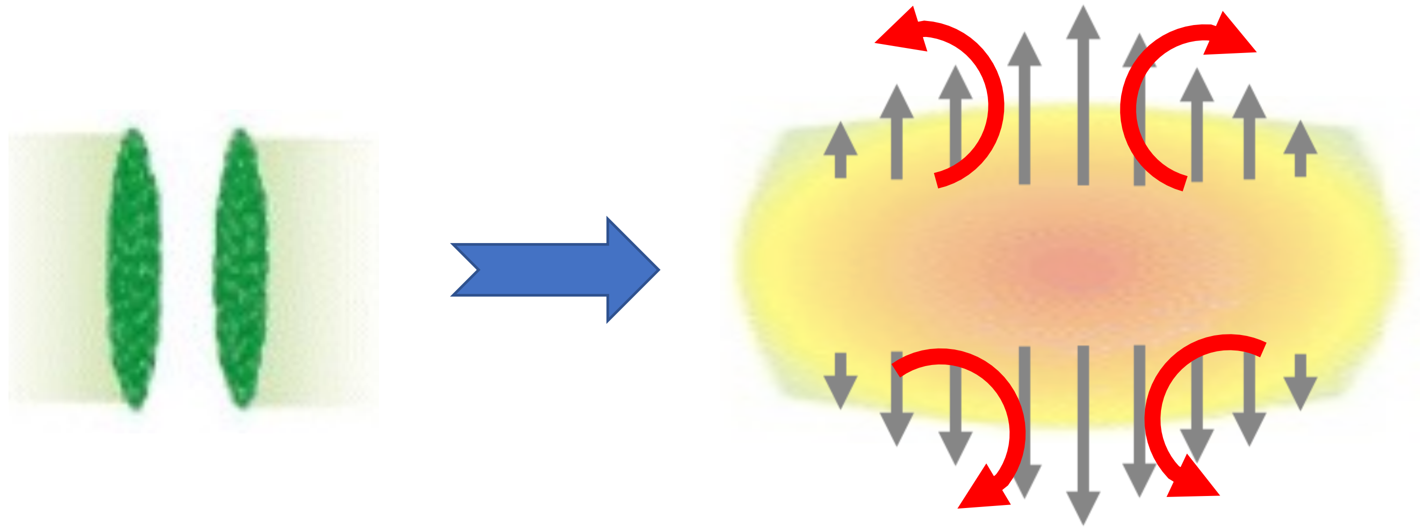
Transverse gradient of longitudinal flow $\rightarrow \vec{\omega} \parallel \hat{J}$

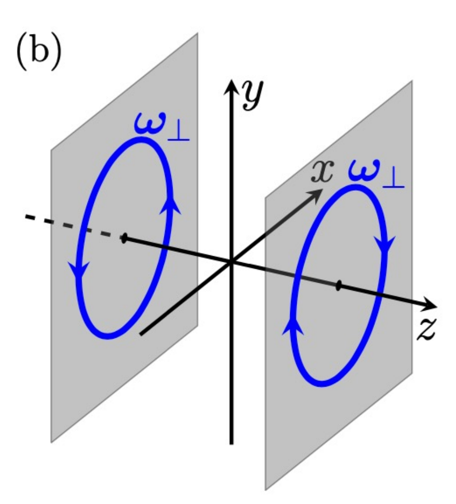


x (y) gradient of transverse-y (x) flow $\rightarrow \vec{\omega} \parallel \pm\hat{z}$



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



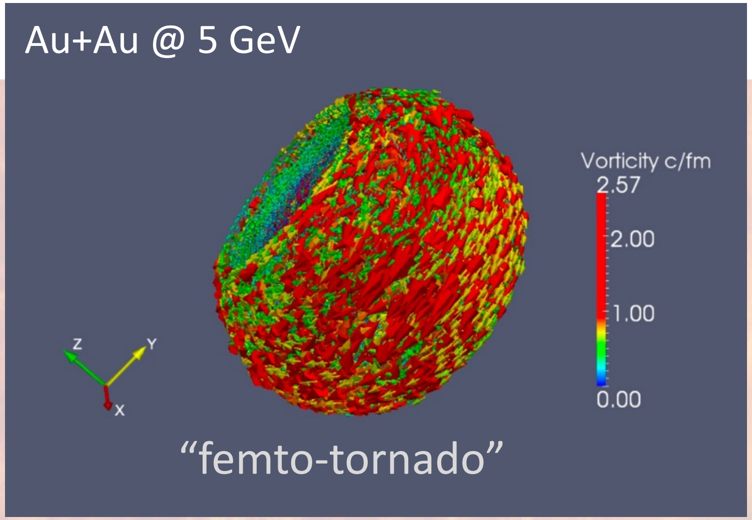


Xia, Li, Tang, Wang PRC 98, 024905 (2018)

Important: vanishes at y=0

Rings at NICA/FAIR/RHIC FXT energy

Baznat, Gudima, Sorin, Teryaev PRC93, 031902(R) (2016)



- Helicity separation in heavy-ion collisions (QGSM)
  Baznat, Gudima, Sorin, Teryaev PRC88, 061901(R) (2013)
- Vorticity and hydrodynamic helicity in heavy-ion collisions in the HSD model
  Teraev & Usubov PRC92 014906 (2015)
- Femto-vortex sheets and hyperon polarization in heavy-ion collisions (QGSM)
  Baznat, Gudima, Sorin, Teryaev PRC93, 031902(R) (2016)
- Vorticity in heavy-ion collisions at the JINR NICA (3FD)
  Ivanov & Soldatov, PRC **95**, 054915 (2017)
- Vortex rings in fragmentation regions in heavy-ion collisions at √sNN = 39 GeV (3FD)
  Ivanov & Soldatov PRC97, 044915 (2018)
- Vorticity structure and polarization of Λ hyperons in heavy-ion collisions (PHSD)
  Zinchenko, Sorin, Teryaev, Baznat DSPIN-2019 (2020)

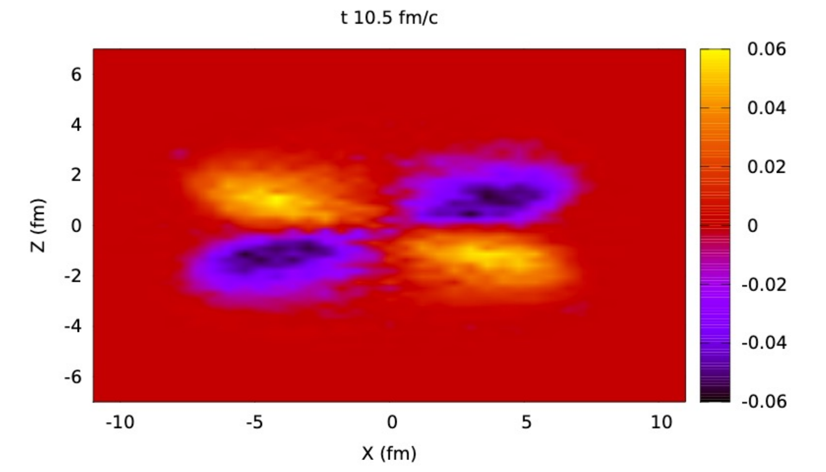


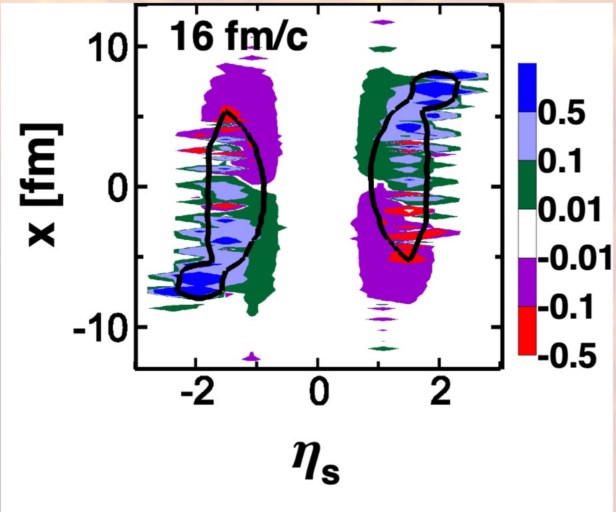
Figure 4. Weighted y-component of the vorticity (c/fm) averaged over all $x-z$ layers at $10.5 fm/c$, impact parameter $b = 0 fm$. Average value is $-1.2 \cdot 10^{-5} c/fm$.

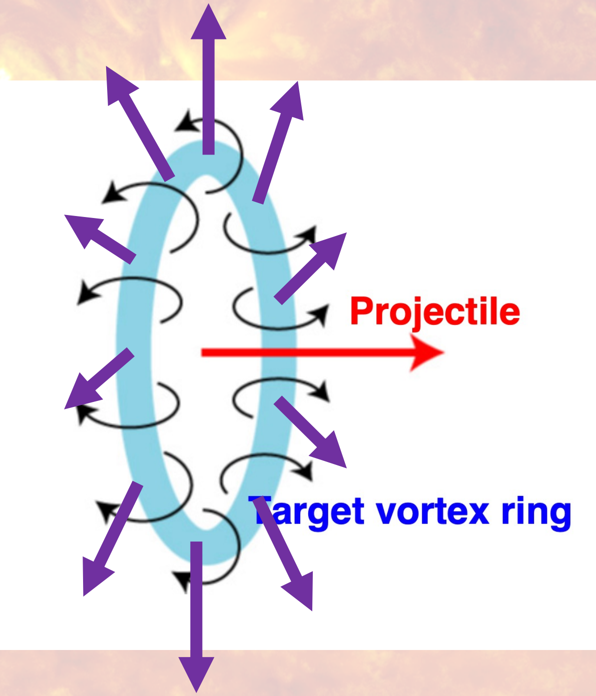
- Significant attention to structure in *space*
- Focus of observable implications seems to center on
  - identifying forward rapidity as important
  - convolution with directed flow affecting *global* polarization

Same observations at higher energy

<u>root(s) = 39 GeV</u>

Ivanov & Soldatov PRC97, 044915 (2018)





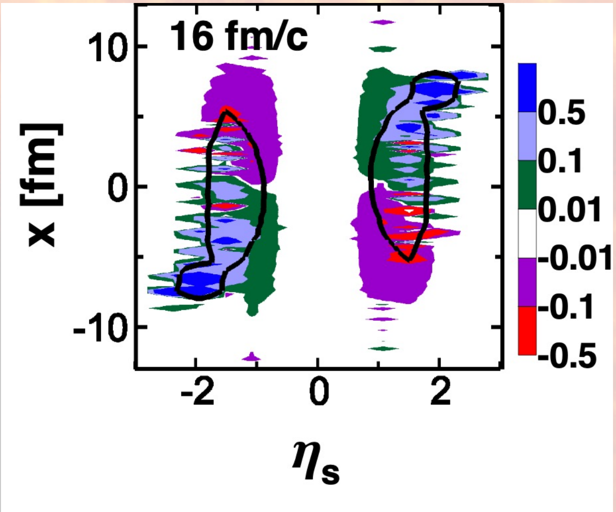
Transverse flow should render the vortex rings *themselves* visible!

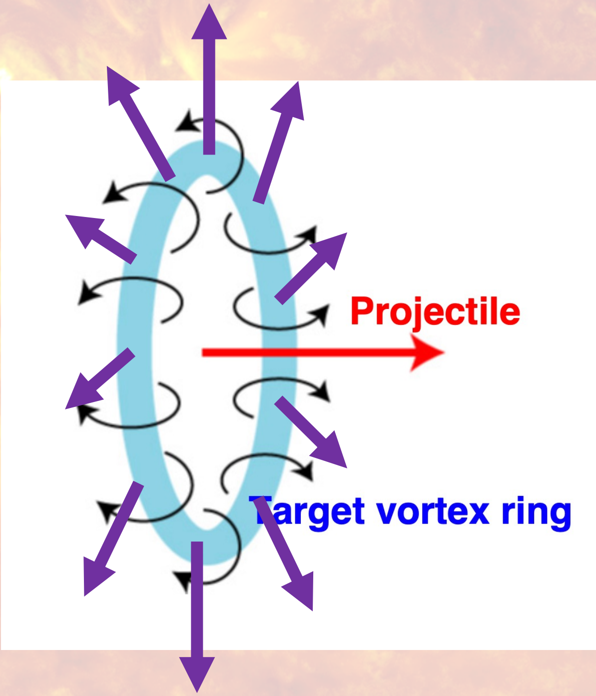
- don’t just worry about “accidental” effect on *global* polarization!

Same observations at higher energy

root(s) = 39 GeV

Ivanov & Soldatov PRC97, 044915 (2018)

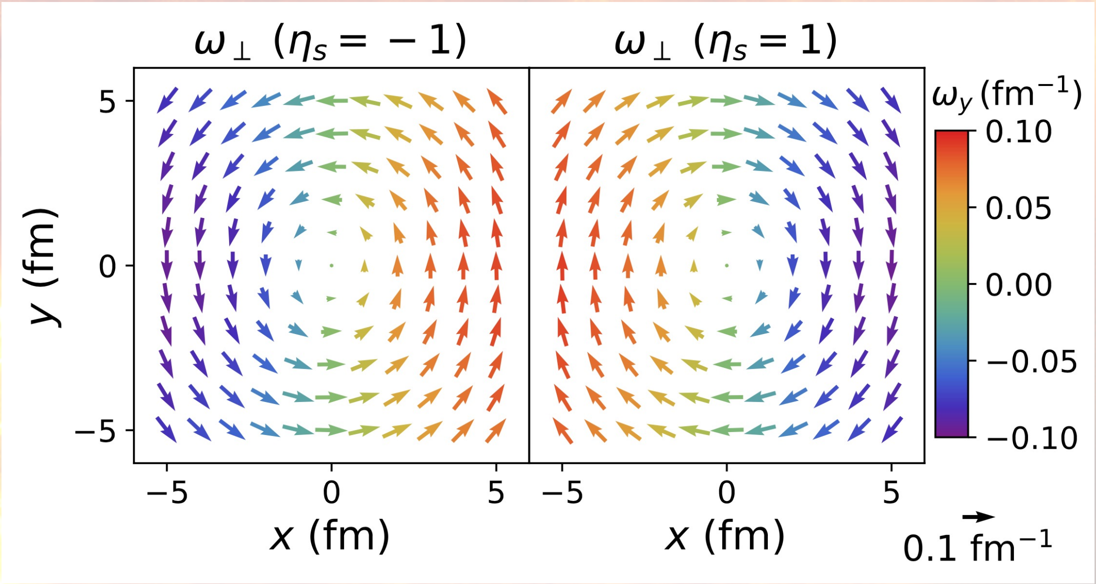


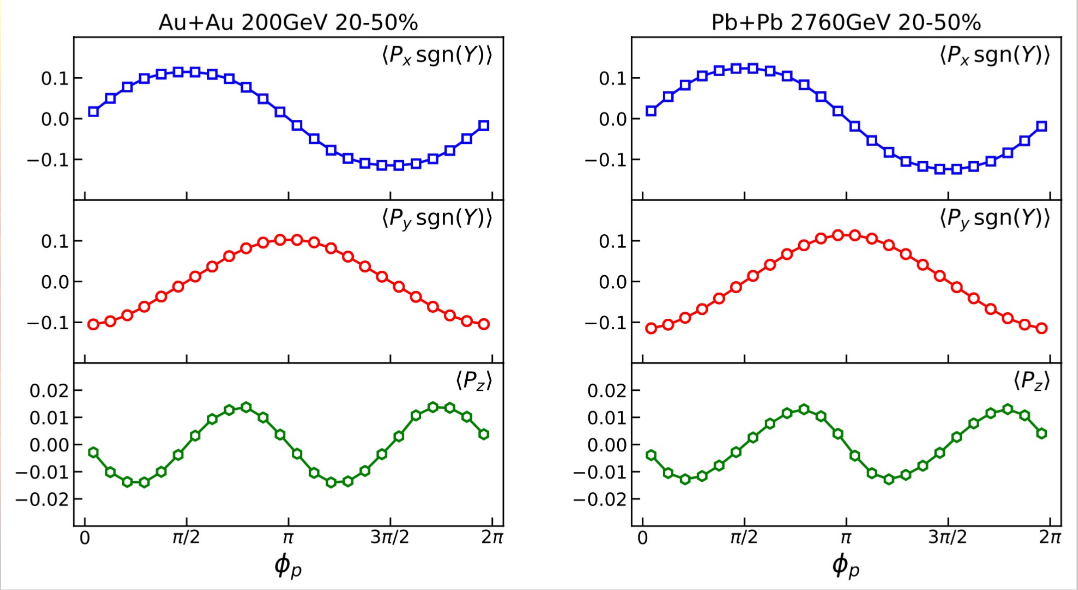


Transverse flow should render the vortex rings *themselves* visible!

- don't just worry about "accidental" effect on *global* polarization!

root(s) = 200, 2700 GeV



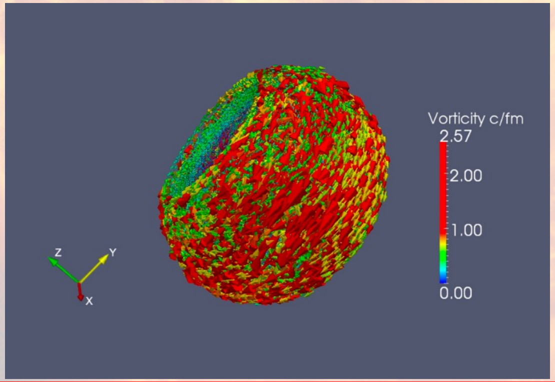


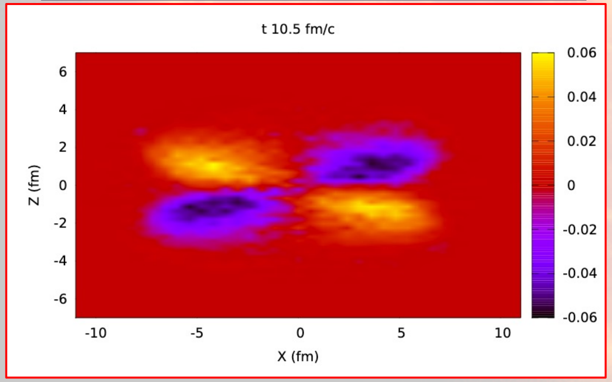
Xia, Li, Tang, Wang Phys. Rev. C 98, 024905 (2018)

Seeing the rings

- This is a unique predicted structure! Would represent a compelling demonstration of fluid structure at the extremes of rapidity

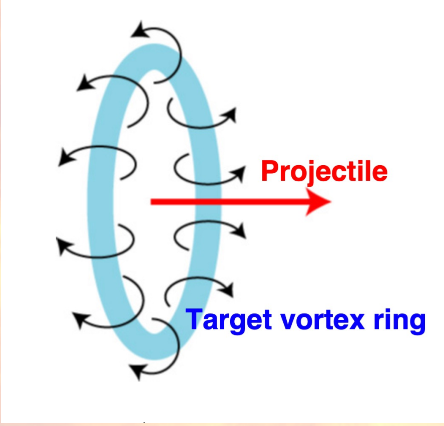
$\sqrt{s_{NN}} = 5\ \mathrm{GeV} \rightarrow y_{\mathrm{beam}} \approx 1.5$





✓ *In principle* observable at NICA, GSI, STAR FXT *

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

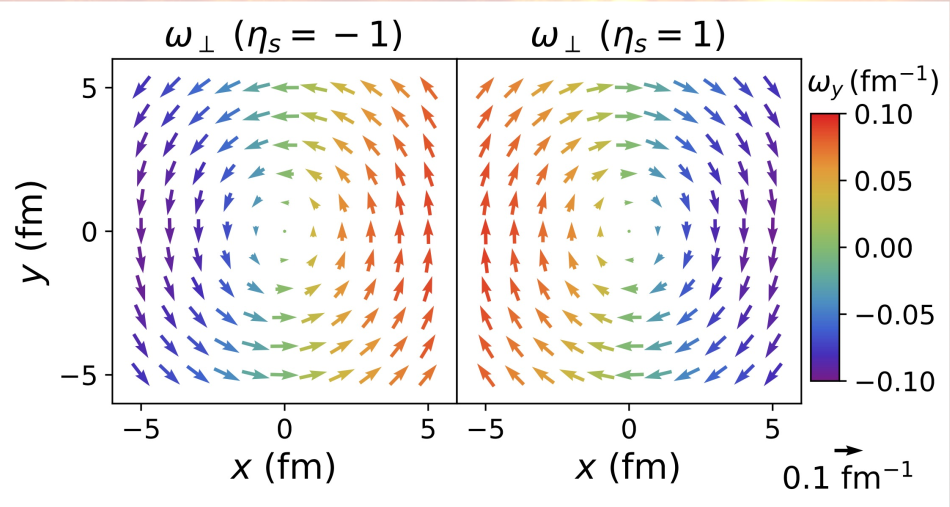


Focused forward

Not possible at STAR@RHIC without forward *tracking* upgrade

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

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



Focused forward

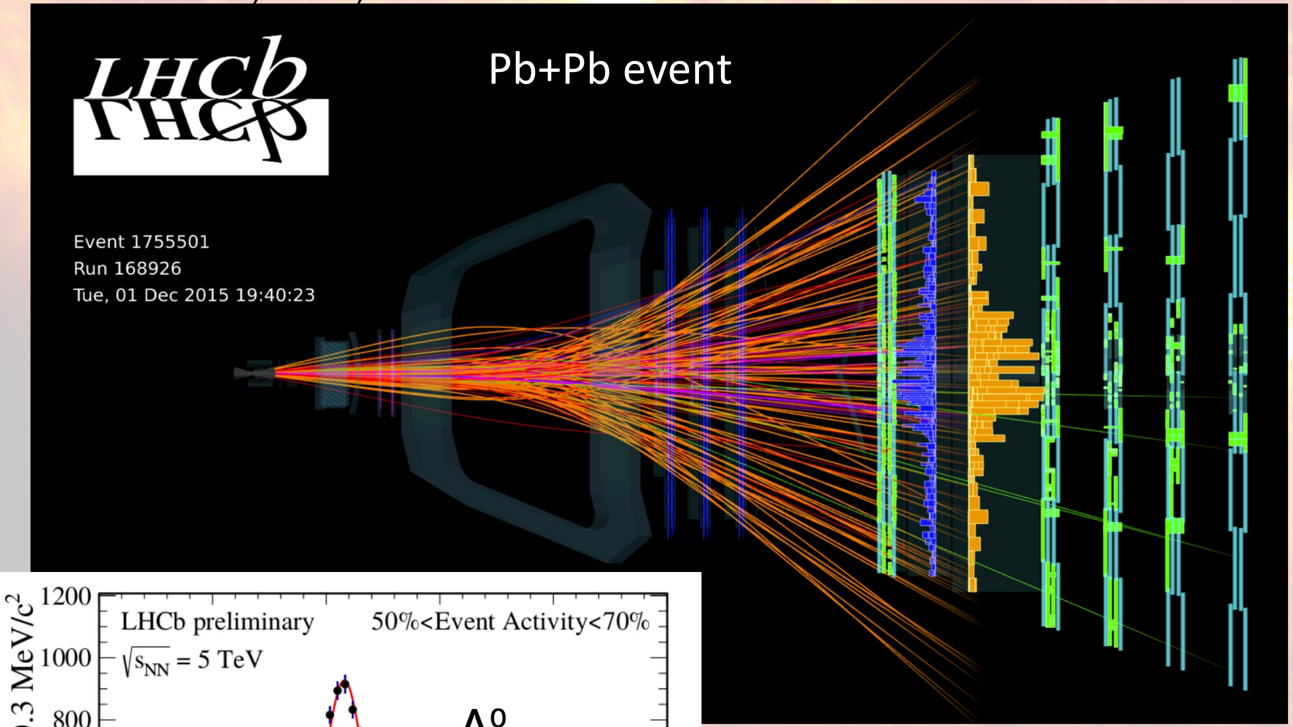
Not possible at STAR@RHIC or ATLAS/CMS/ALICE@LHC without forward tracking upgrade

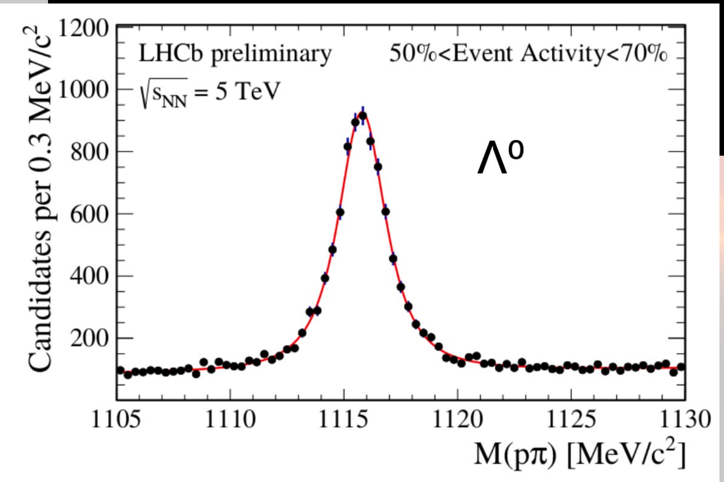
* in reality, detector effects strong and nontrivial

Seeing the rings

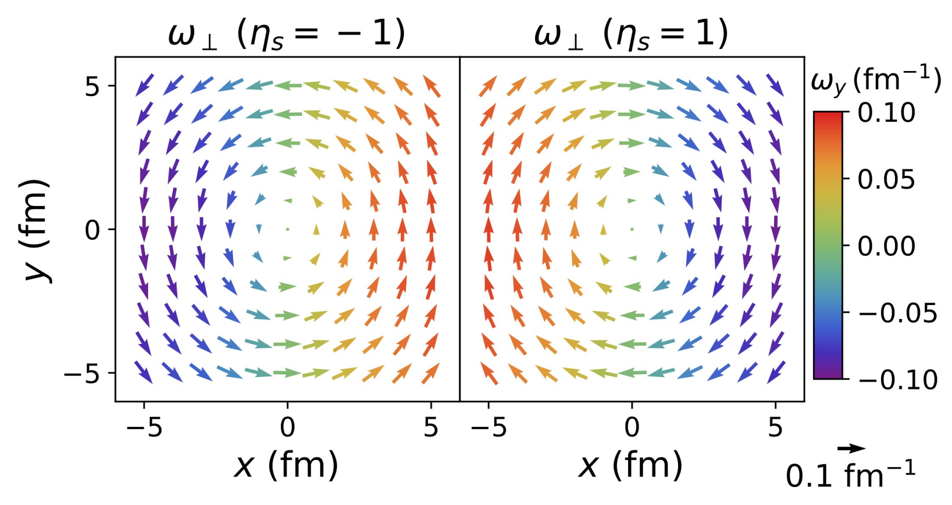
- This is a unique predicted structure! Would represent a compelling demonstration of fluid structure at the extremes of rapidity

Michael Winn, ERICE, 2016





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



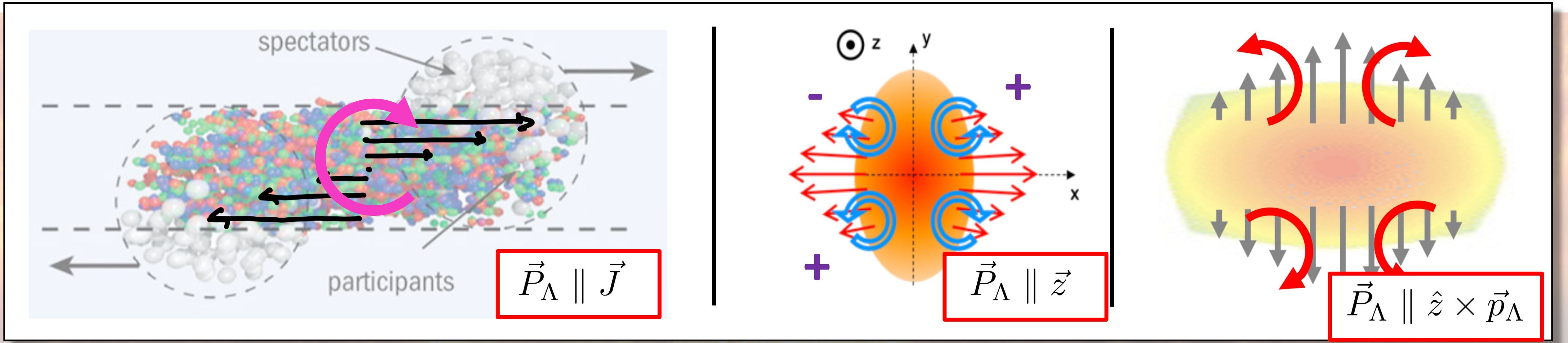
Note: No Event Plane Necessary!

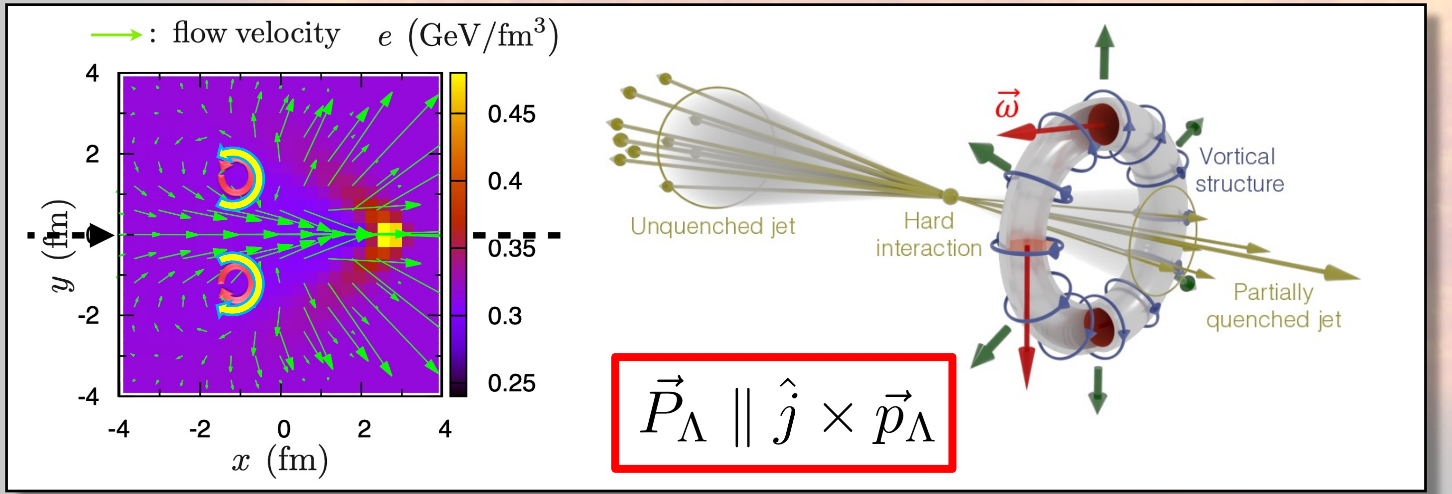
Focused forward

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



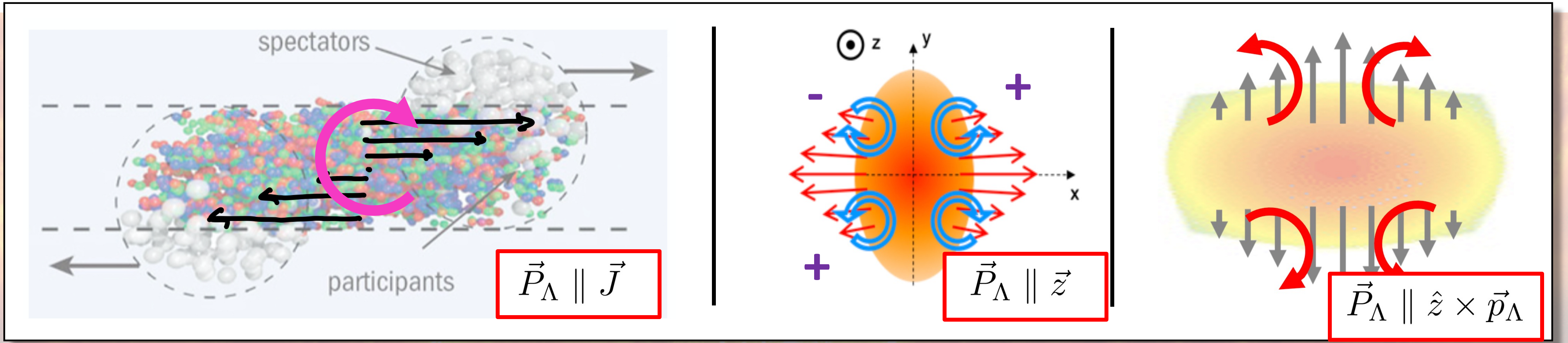


Vortex rings about the jet direction:

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

c.f. talk by Chun Shen

Polarization about a local disturbance



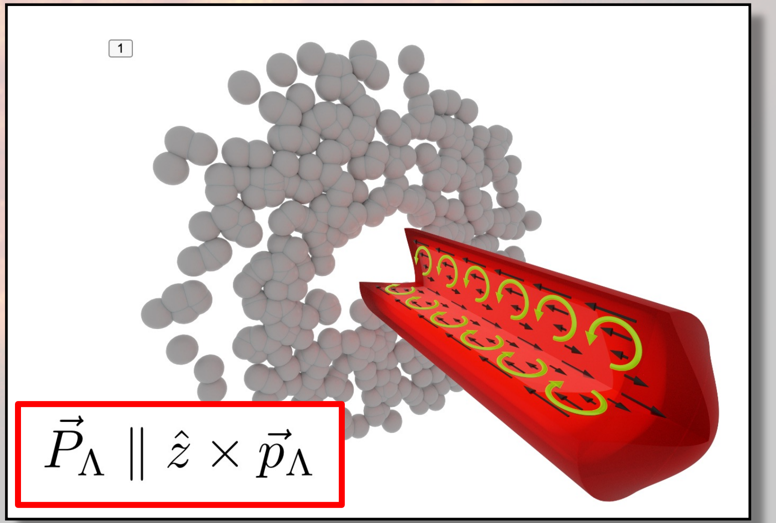
c.f. talk by Chun Shen

vortex rings at midrapidity in p+A collisions could probe unique hydro nature of smallest droplets of QGP

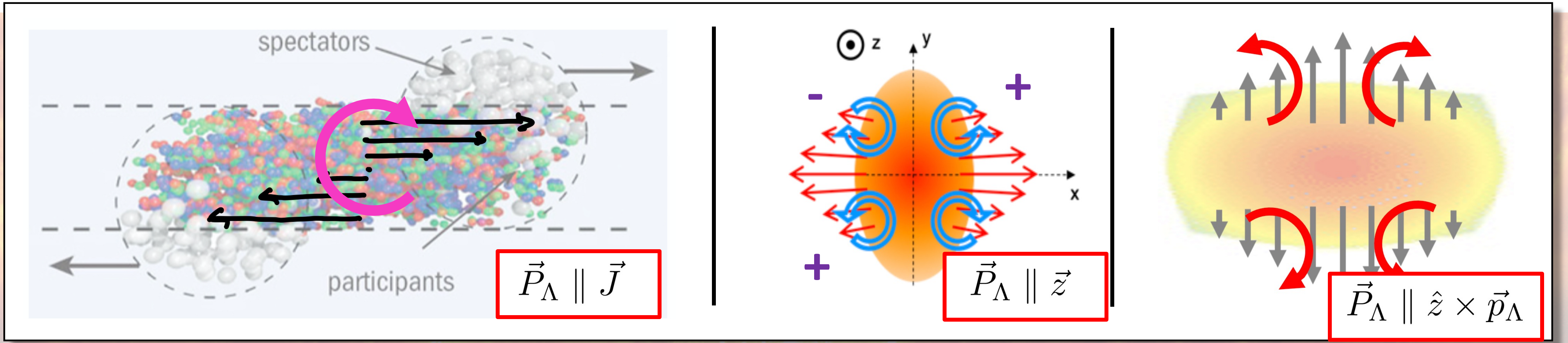
S. Voloshin, EPJ Web Conf.171, 07002 (2018)
M. Lisa et al, Phys. Rev. C 104, (2021) L011901

very strong and nontrivial detector effects to overcome

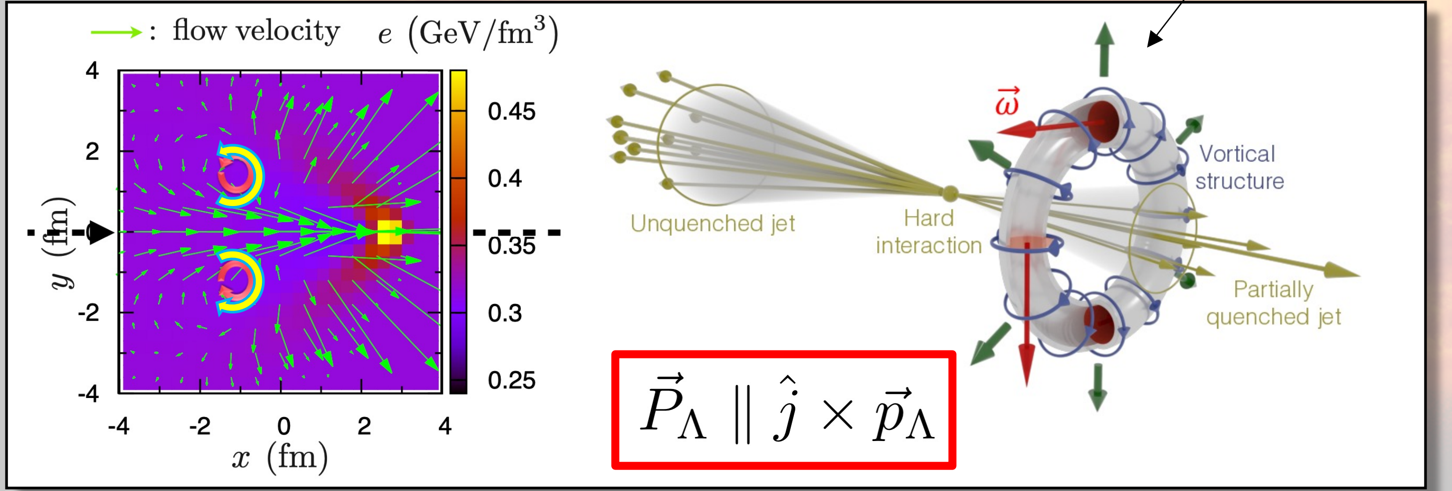
- ideally, flip magnetic field of detector

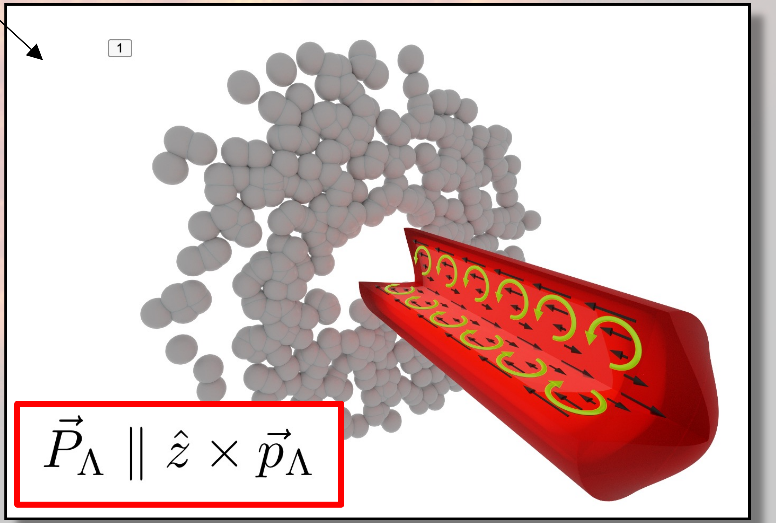


Polarization about a local disturbance

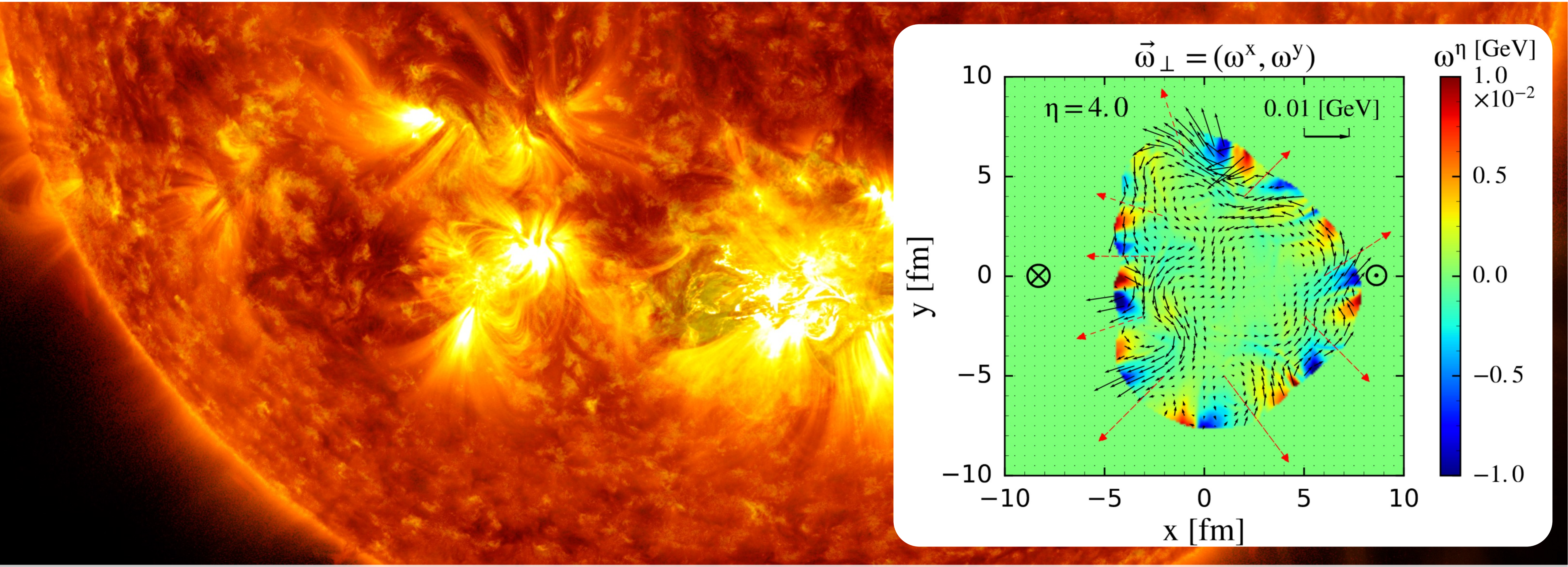


Small stuff blasting through big stuff





Complex system: It may be difficult to tag “vortical spots”



There will inevitably be “vortical spots” fluctuating in strength/position/orientation event-to-event

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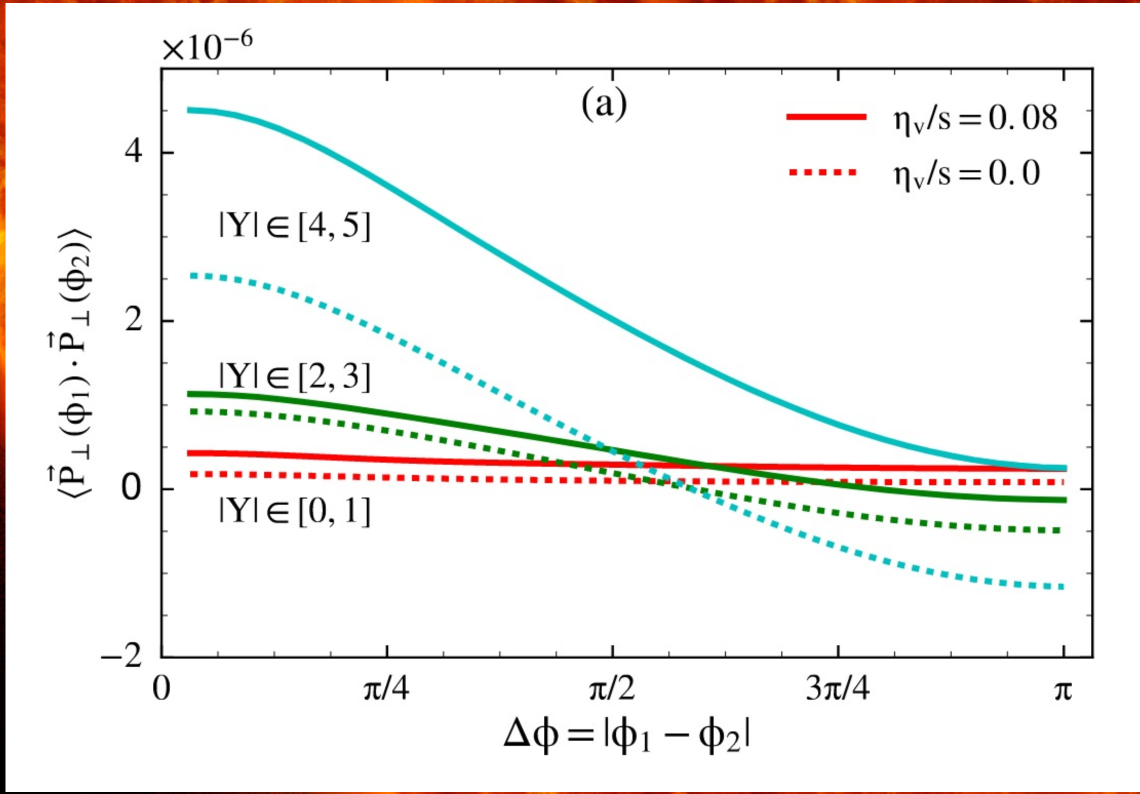
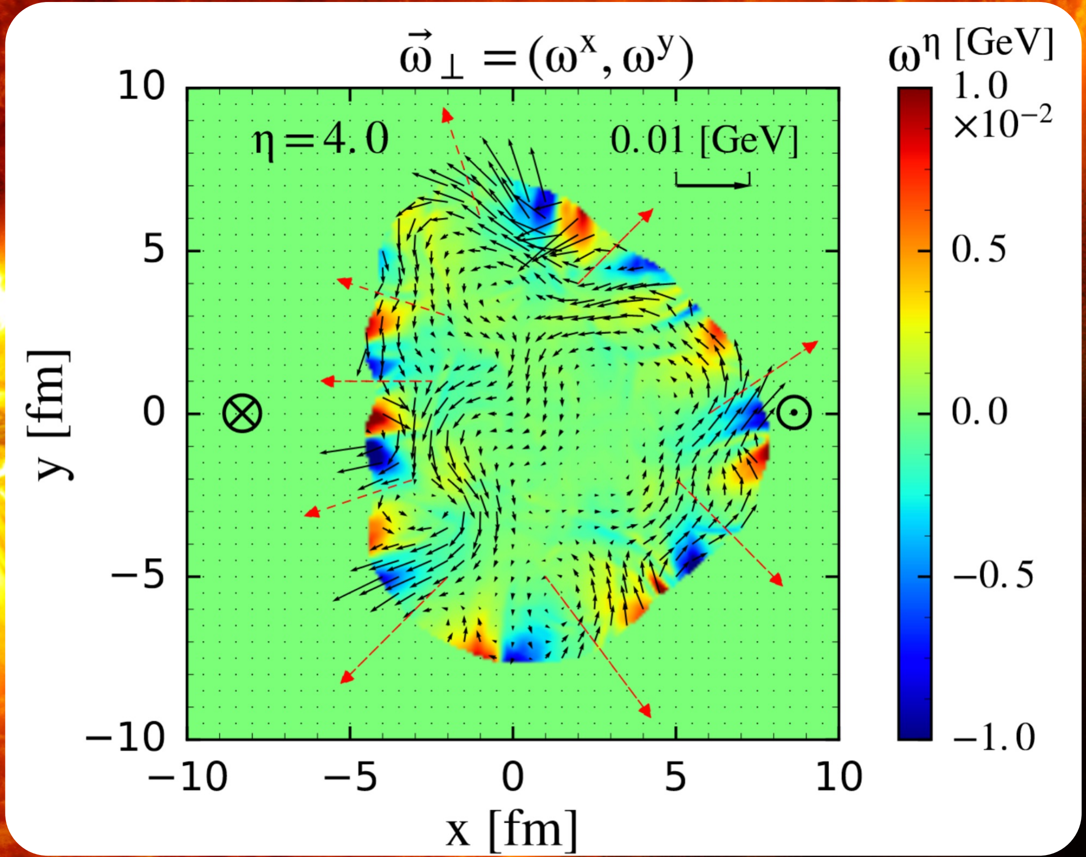
Complex system: It may be difficult to tag “vortical spots”





There will inevitably be “vortical spots” fluctuating in strength/position/orientation event-to-event

Measure spin-spin correlations in HBT-like analysis

- big artifacts and NOT easy!

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Summary

- Polarization probes the hydrodynamic system at finest level of detail
- Since first definitive report in 2016, tremendous degree of activity and burst of recent measurements
- World systematics of global hyperon polarization supports a consistent picture of vorticity dominance
  - for all hyperon species
  - 3 orders of magnitude in energy, at 3 experiments/facilities, including collider & fixed target configs
- Magnetic splitting $\langle \vec{P}_{\overline{\Lambda}} \cdot \hat{J} \rangle > \langle \vec{P}_{\Lambda} \cdot \hat{J} \rangle$ not yet reported. (Possible with STAR data on tape.)
- STAR/FXT and HADES have opened the ”low energy frontier”
  - maximum polarization ~ 3 GeV, quantitatively predicted by 3-fluid hydro (!?)
  - at this frontier, models diverge
- Polarization in the “forward frontier” may be intimately related to low √s and √s evolution
  - here also, models diverge
  - large η coverage needed:
    - STAR FXT – polarization flat over entire kinematic range at 3 GeV
    - higher √s needs forward detectors

Summary 2/2

- Longitudinal polarization
  - similar signals at 200 GeV (STAR) and 5.02 TeV (ALICE)
  - “sign problem” appears solved by realizing role of non-vortical shear (!)
    - not important for global polarization
    - relative influence sensitive to how polarization is “inherited” (!)
- Several other directions to explore
  - toroidal vorticity structures expected in *head-on* smooth-on-smooth collisions at all energies
    - HADES, STAR/FXT, MPD@NICA, CBM@FAIR..... kinematic reach is available, but detector effects can be hard
    - STAR/collider – possible with forward upgrade
    - at LHC….. LHCb!
  - vortex toroids produced by “disturbances”:
    - jets through QGP
    - proton through A (?)
  - spin-spin correlations can probe scale of vortical texture of the QGP
- We have only begun to map out the vortical terrain