Hyperon polarization as a probe of fluid behavior: Two interesting cases

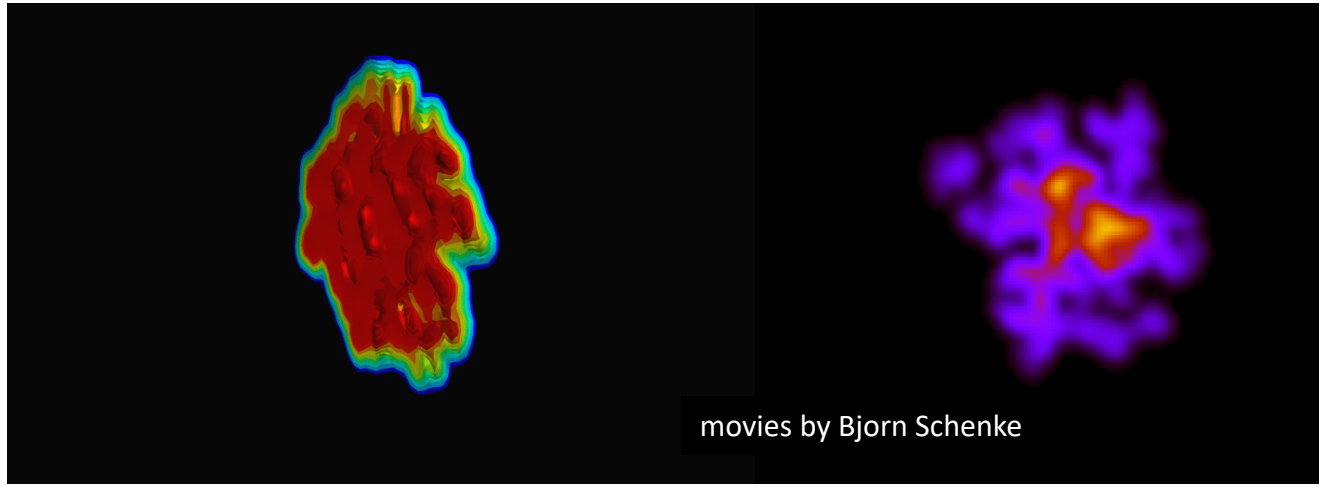
Mike Lisa

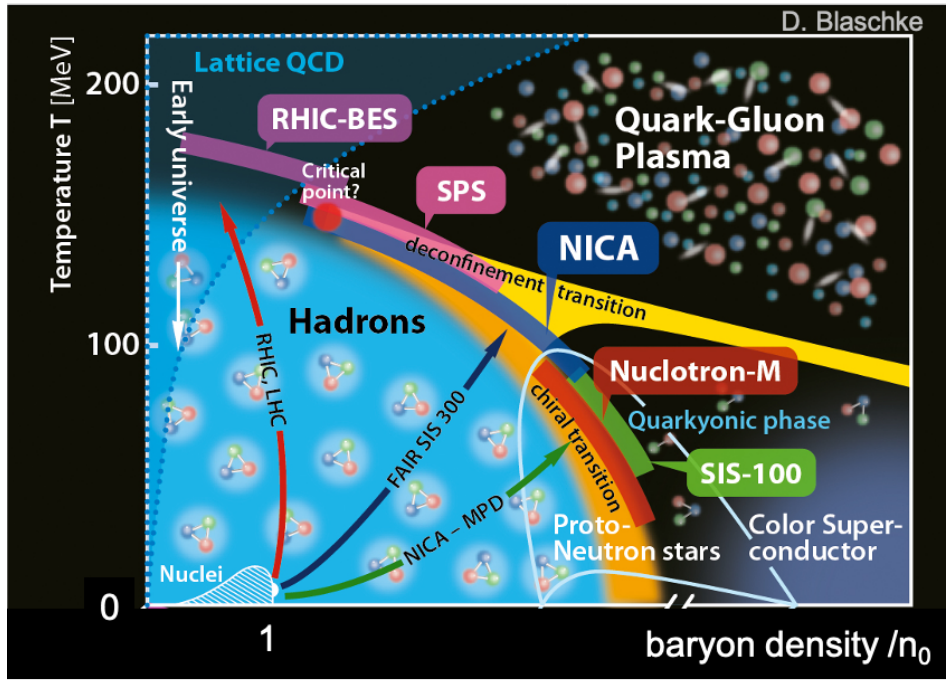
The Ohio State University

Outline

- Hyperon polarization as a probe of dynamic fluid substructure
- The low-energy frontier : NICA / FAIR / RHIC BES-II
- The forward frontier: NICA / FAIR / LHC
- Summary

Standard model of H.I.C. : viscous hydrodynamics



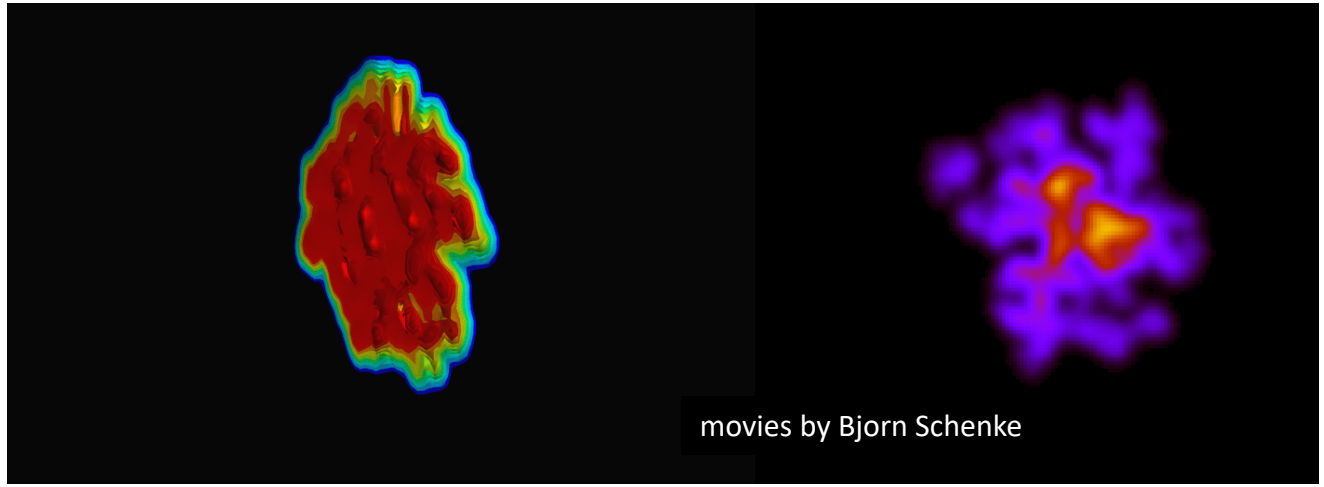


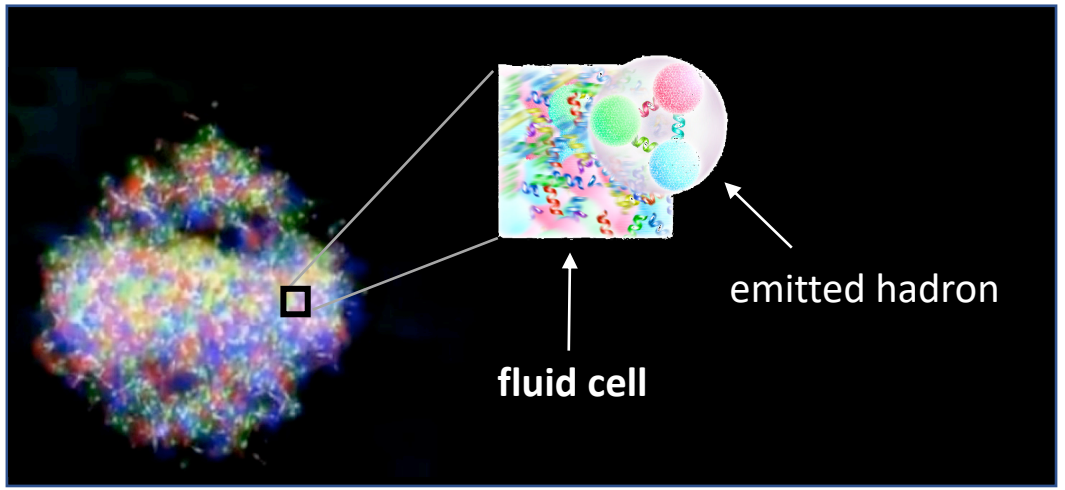
$$d_\mu T^{\mu\nu} = 0 \qquad T^{\mu,\nu} = e u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

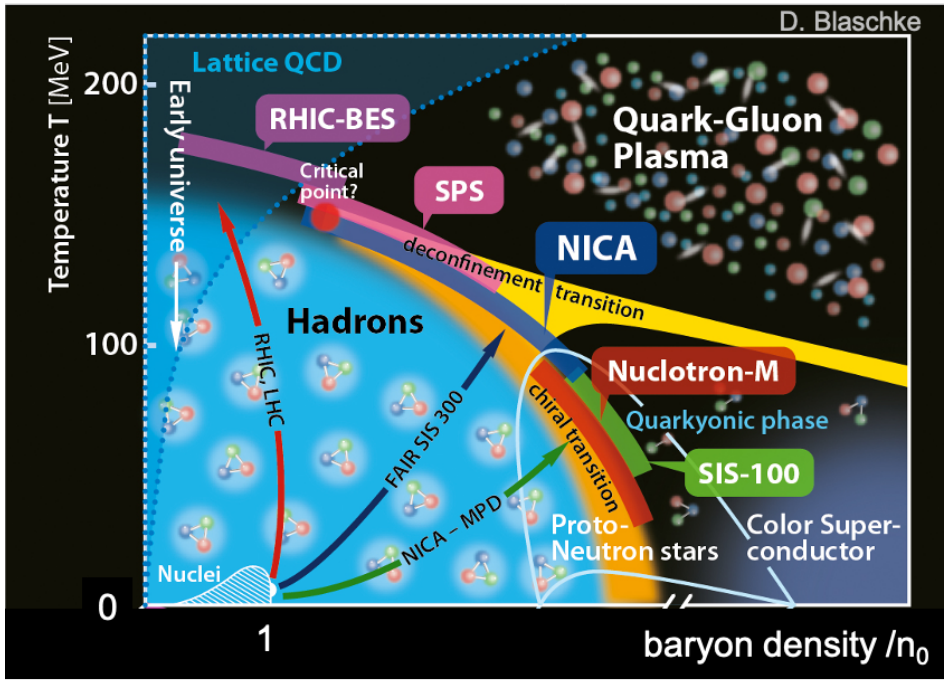
$$u^\mu d_\mu \Pi = -\frac{1}{\tau_\Pi}(\Pi + \zeta\theta) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi} d_\lambda\left(\frac{\tau_\Pi}{\zeta T} u^\lambda\right)$$

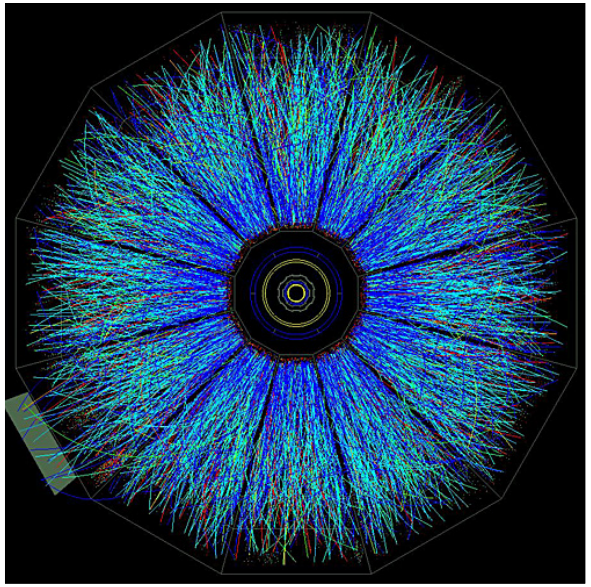
& many more terms...

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







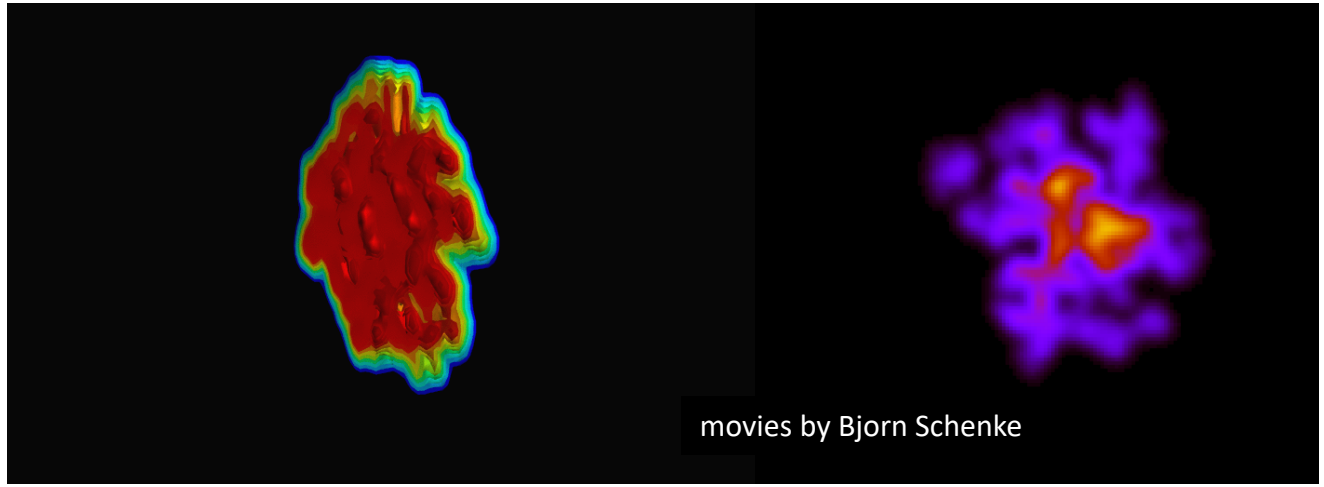


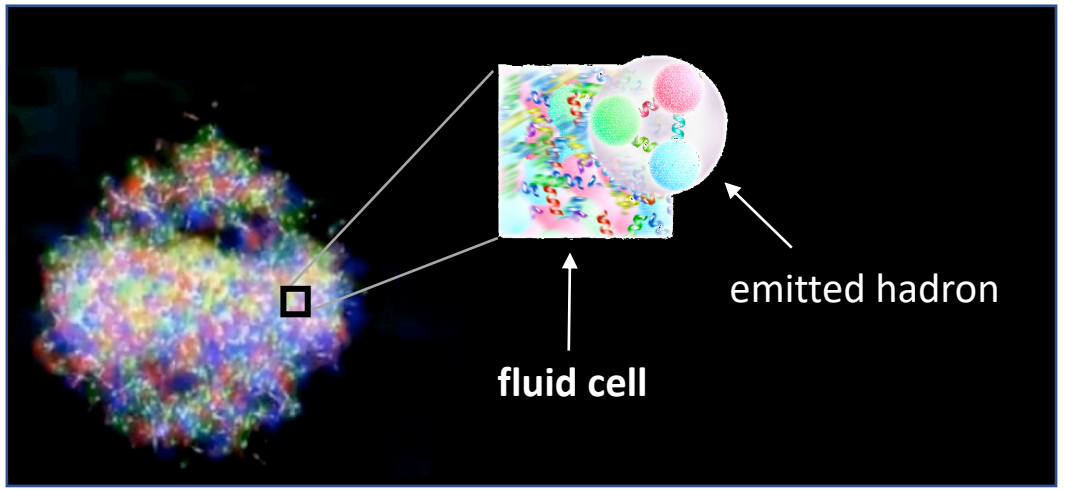
Hadronization & Freeze-out

- emitted particles reflect properties of parent fluid cells

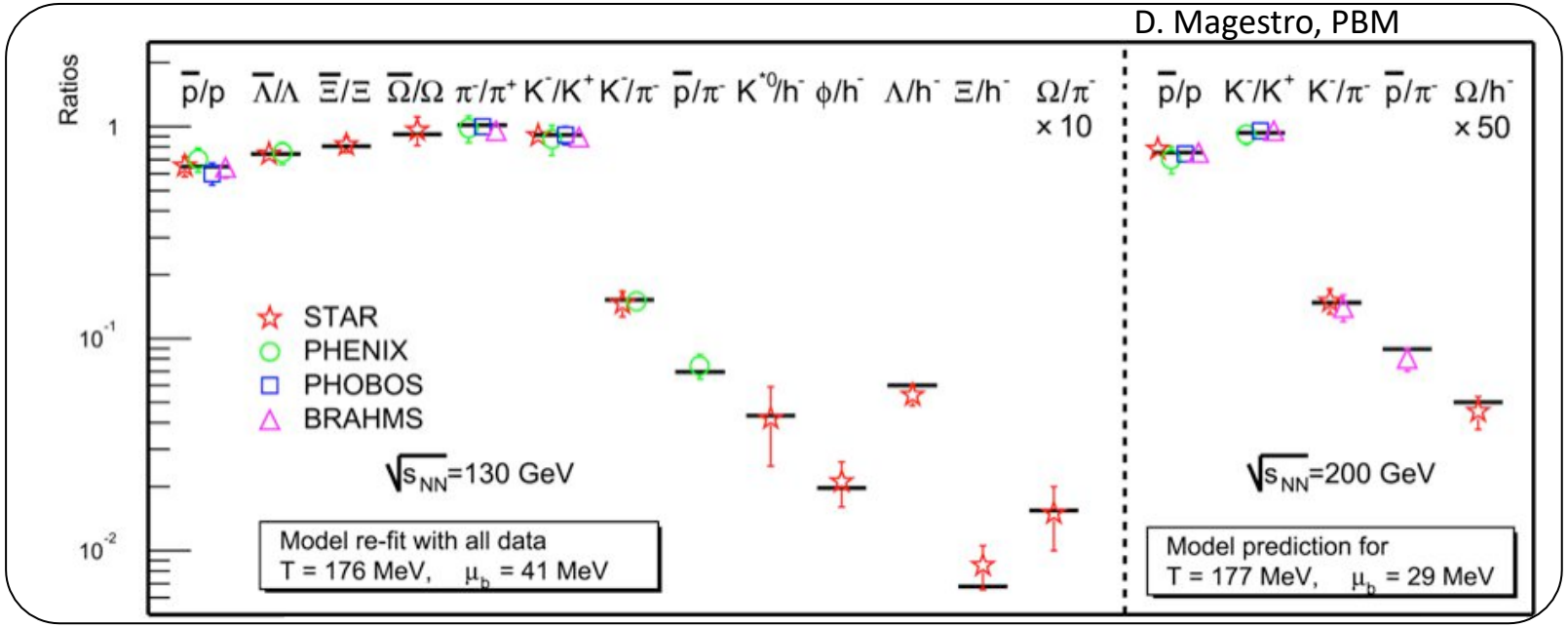
  Cooper-Frye (thermal)
  - chemical potentials
  - temperatures
  - collective velocities

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





D. Magestro, PBM



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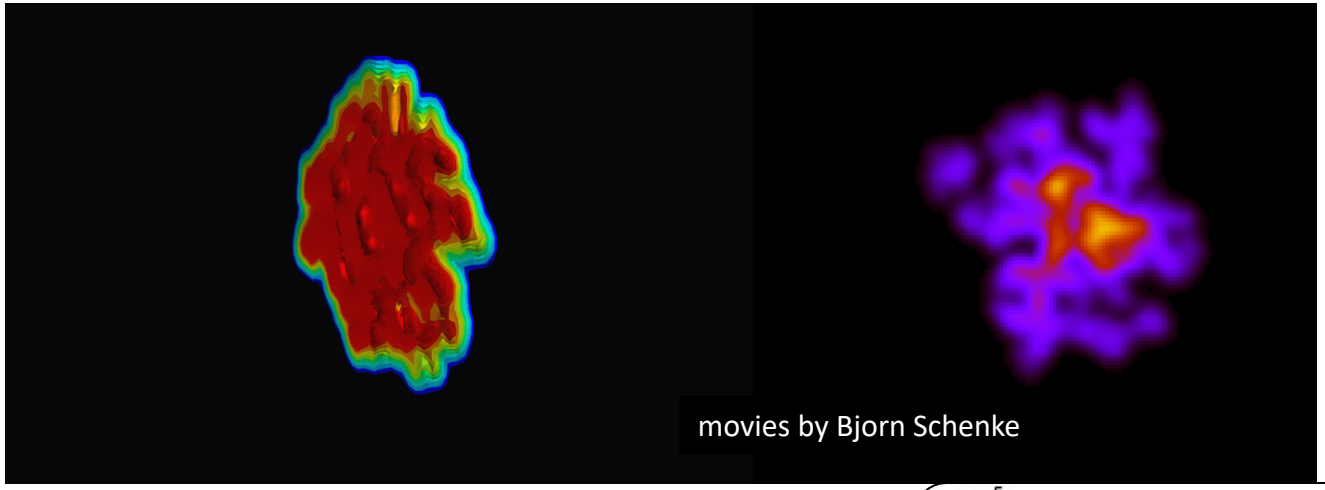
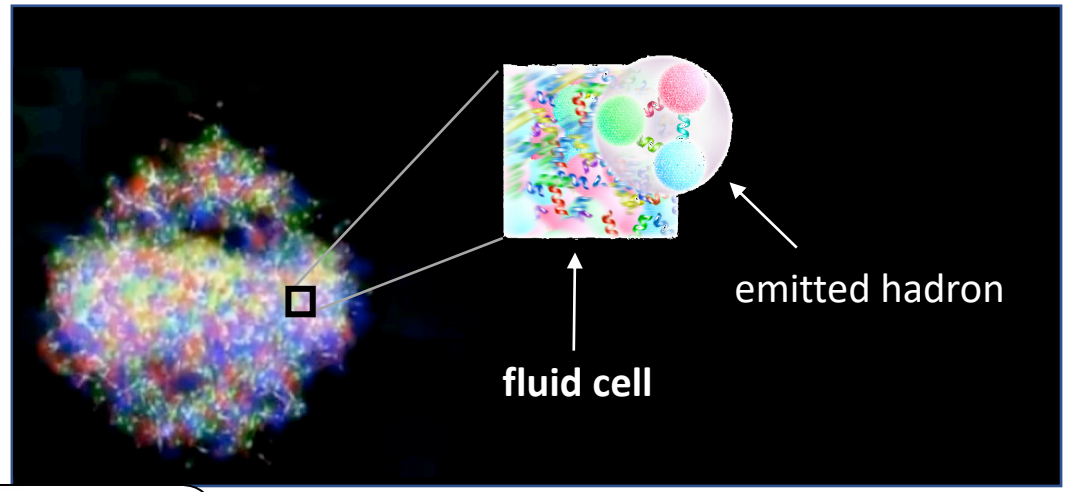
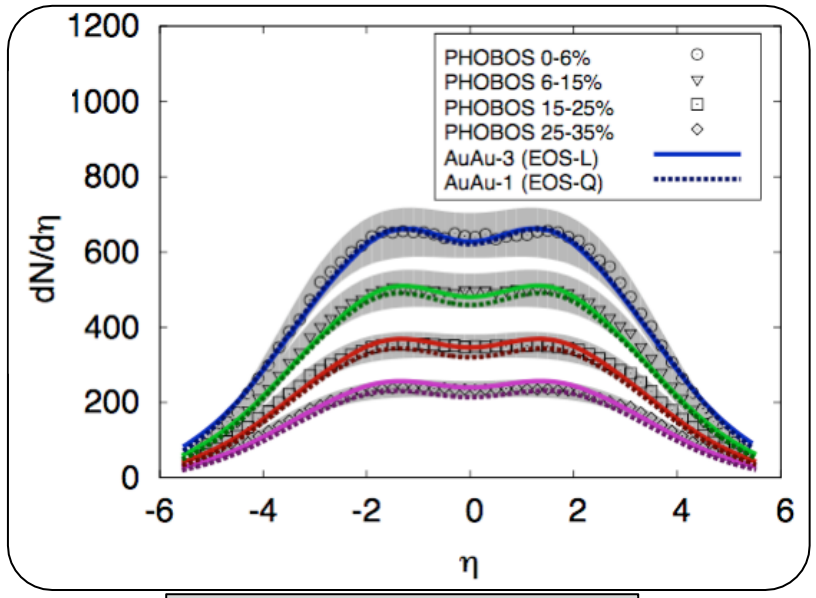
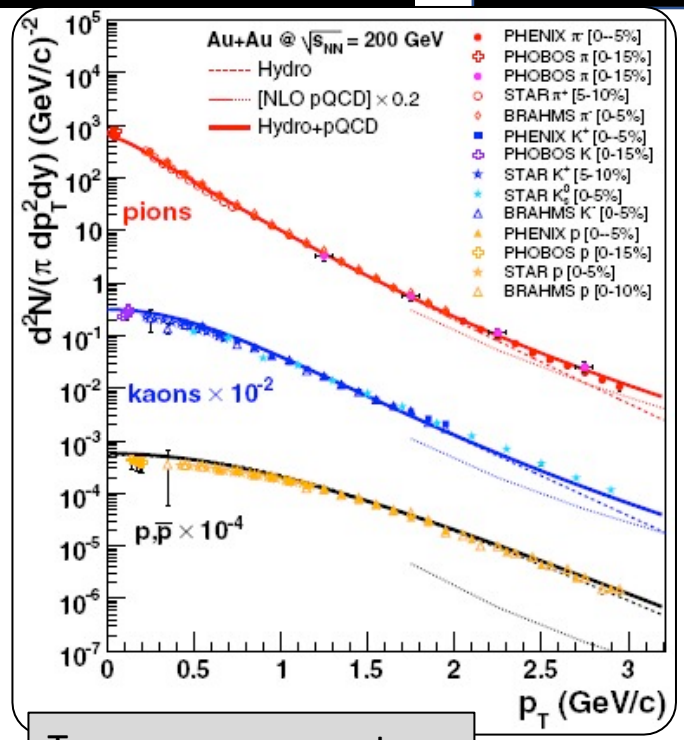






Longitudinal momentum



Transverse momentum

Hadronization & Freeze-out

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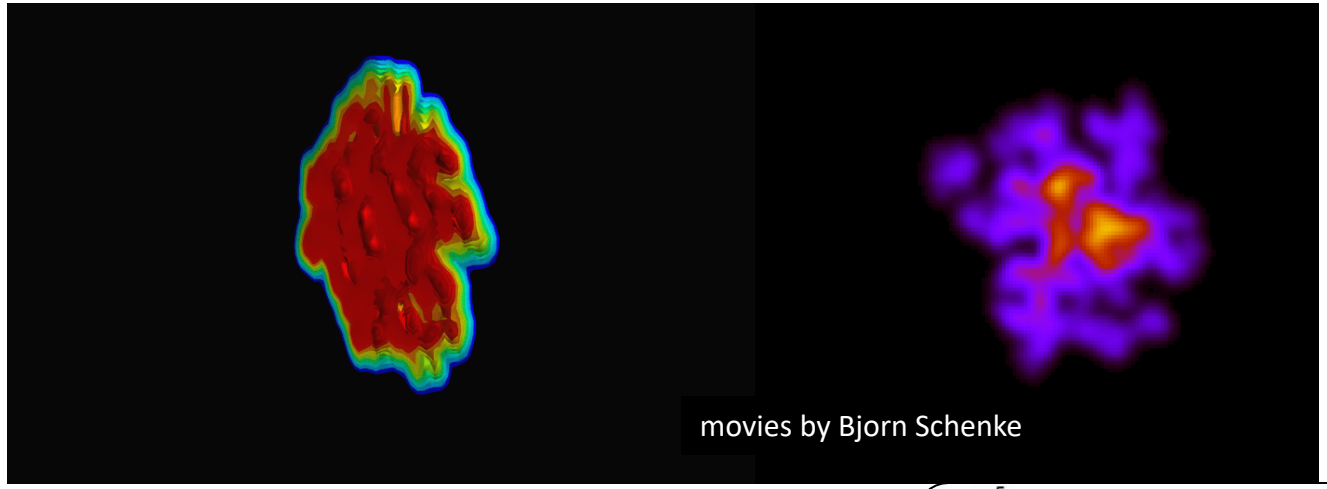
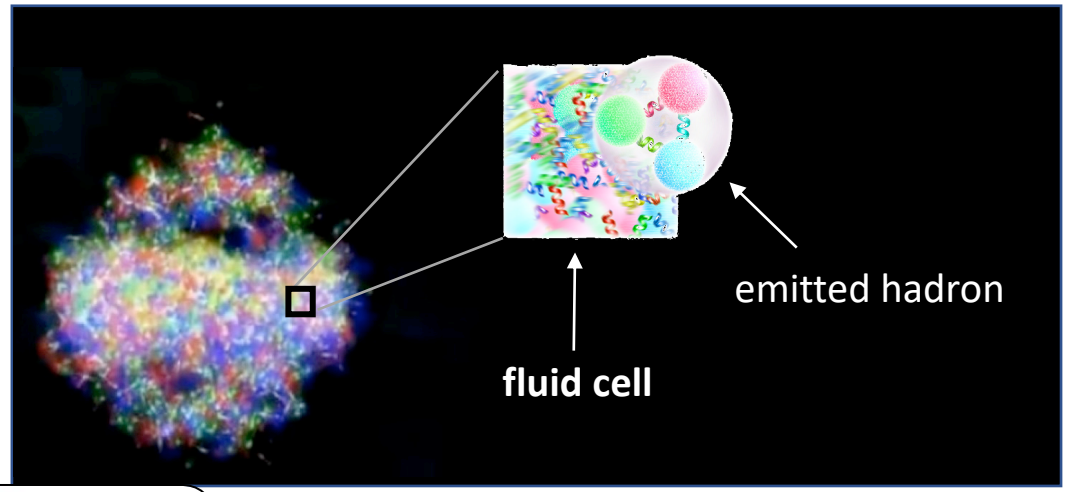
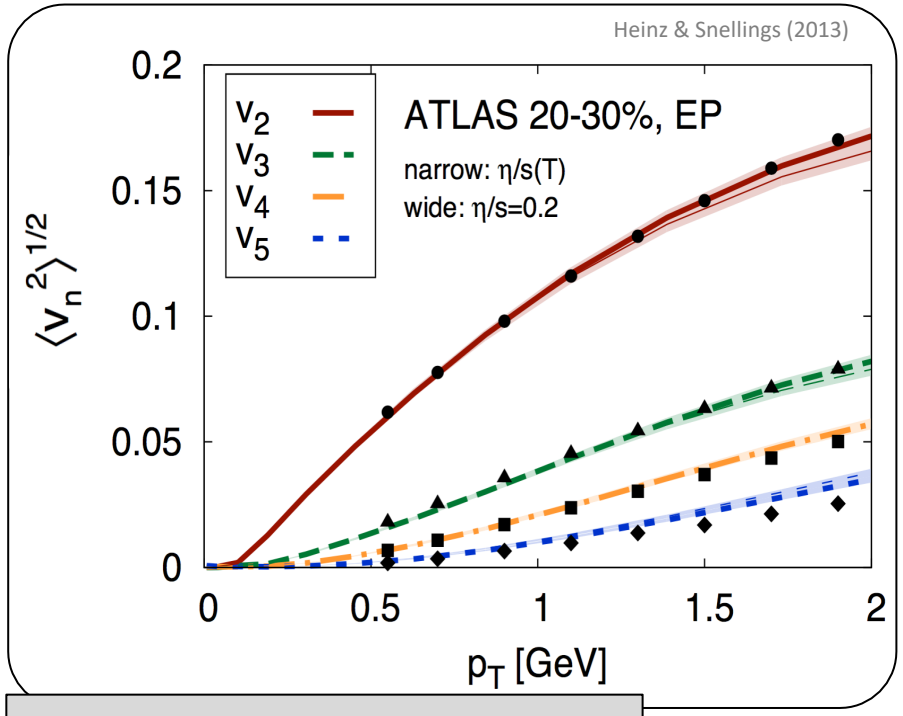
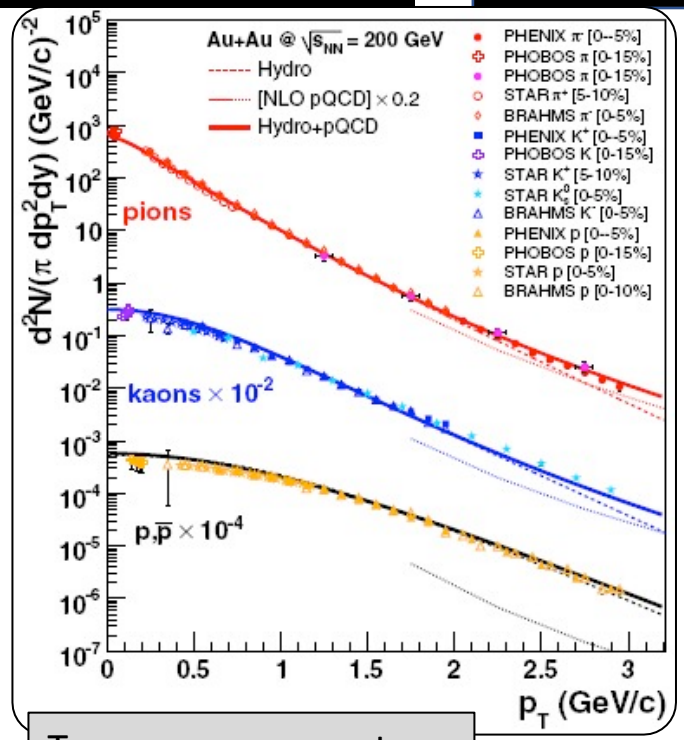






Transverse momentum anisotropy



Transverse momentum

Hadronization & Freeze-out

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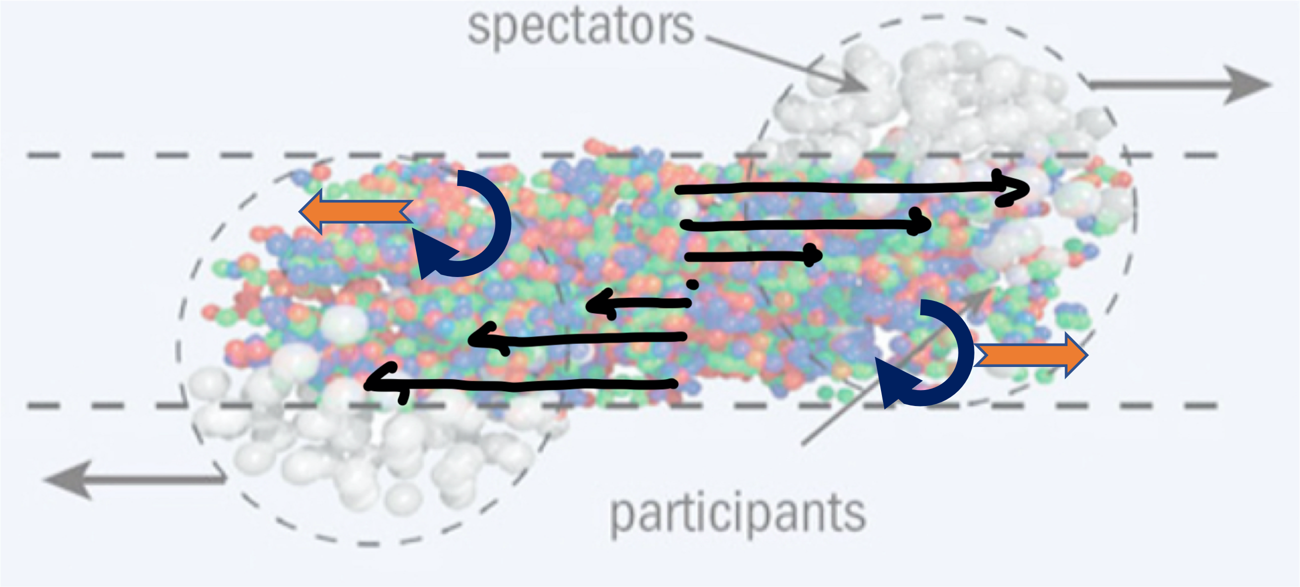
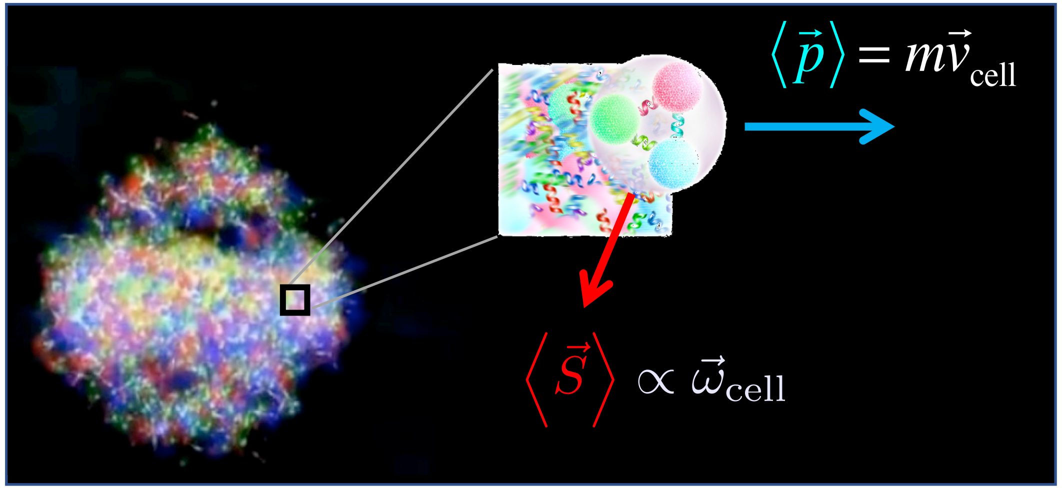
Rotational substructure of noncentral collisions





Hadronization & Freeze-out

- emitted particles reflect properties of parent fluid cells

  Cooper-Frye (thermal)
  - chemical potentials
  - temperatures
  - collective velocities
  - extend equilibrium F.O. to spin?

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

Polarization

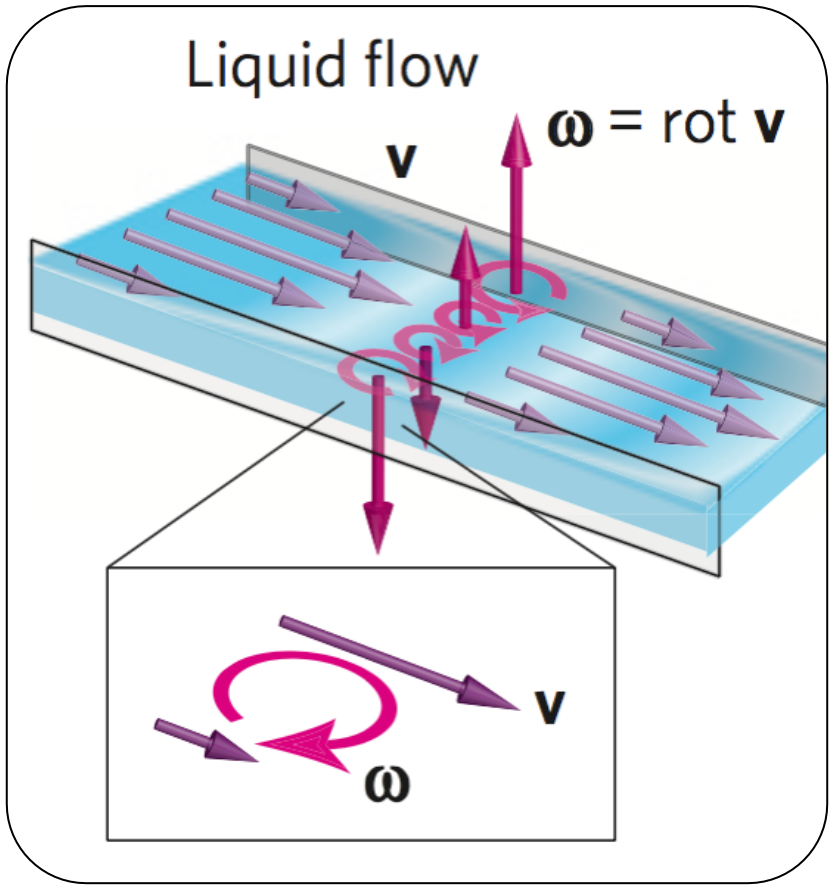
$$\vec{P} \equiv \frac{\langle \vec{S} \rangle}{\left|\vec{S}\right|}$$

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

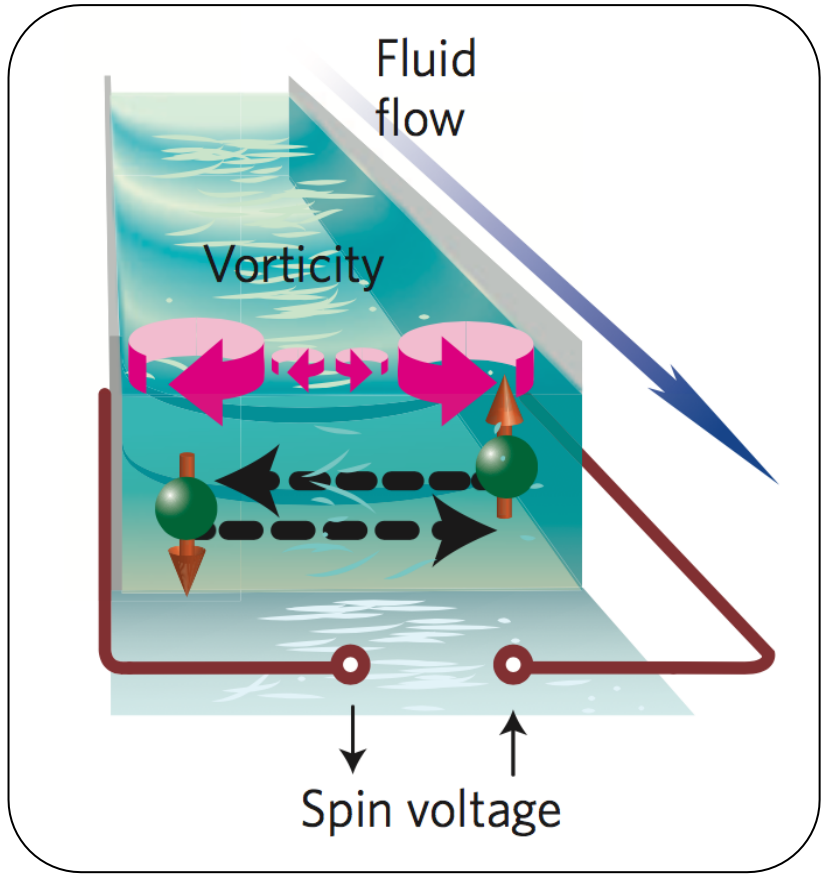
First observation of fluid vorticity-polarization coupling

"Spin hydrodynamic generation" Takahashi, *et al*. Nat. Phys. (2016)

"This opens a door to the new field of fluid spintronics"



Friction with walls induces vorticity



Vorticity of bulk → polarization of constituents (& spin voltage etc)

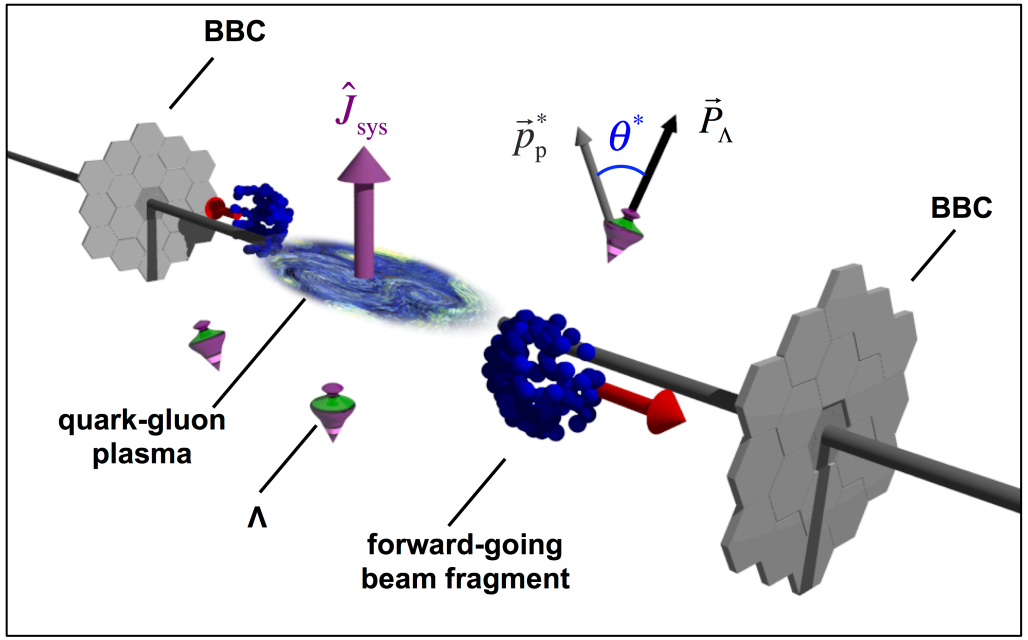
$$P\left(\vec{s}\right) \propto e^{-\vec{\omega}\cdot\vec{s}/k_B T}$$

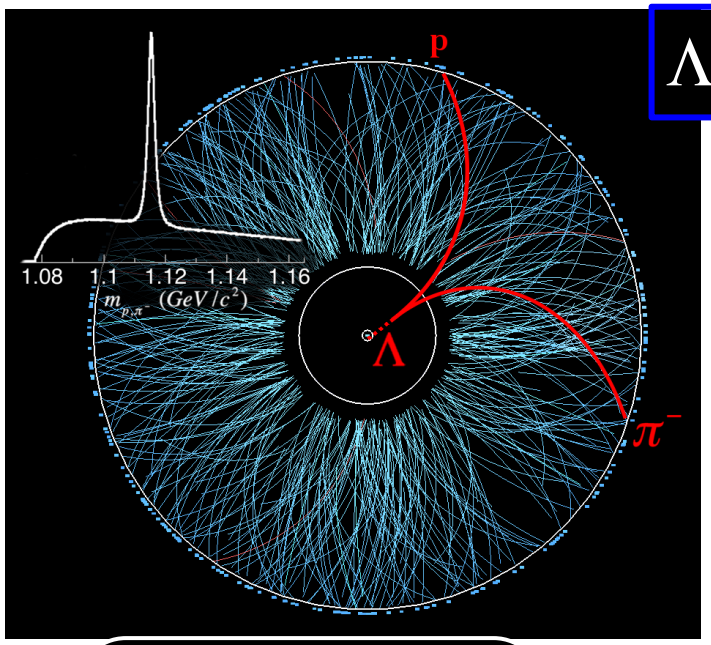
Takahashi could directly measure atomic alignment

Takahashi knew direction of angular momentum

Subatomic spintronics

"This opens a door to the new field of fluid spintronics"

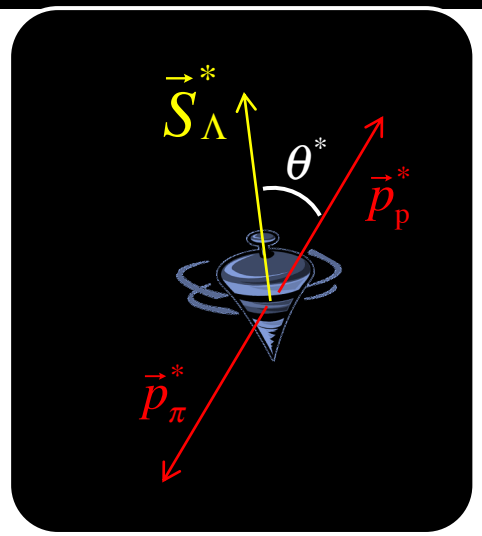




$$\Lambda \rightarrow p + \pi^-$$

Takahashi could directly measure atomic alignment

We use parity-violating decay of Lambda hyperons

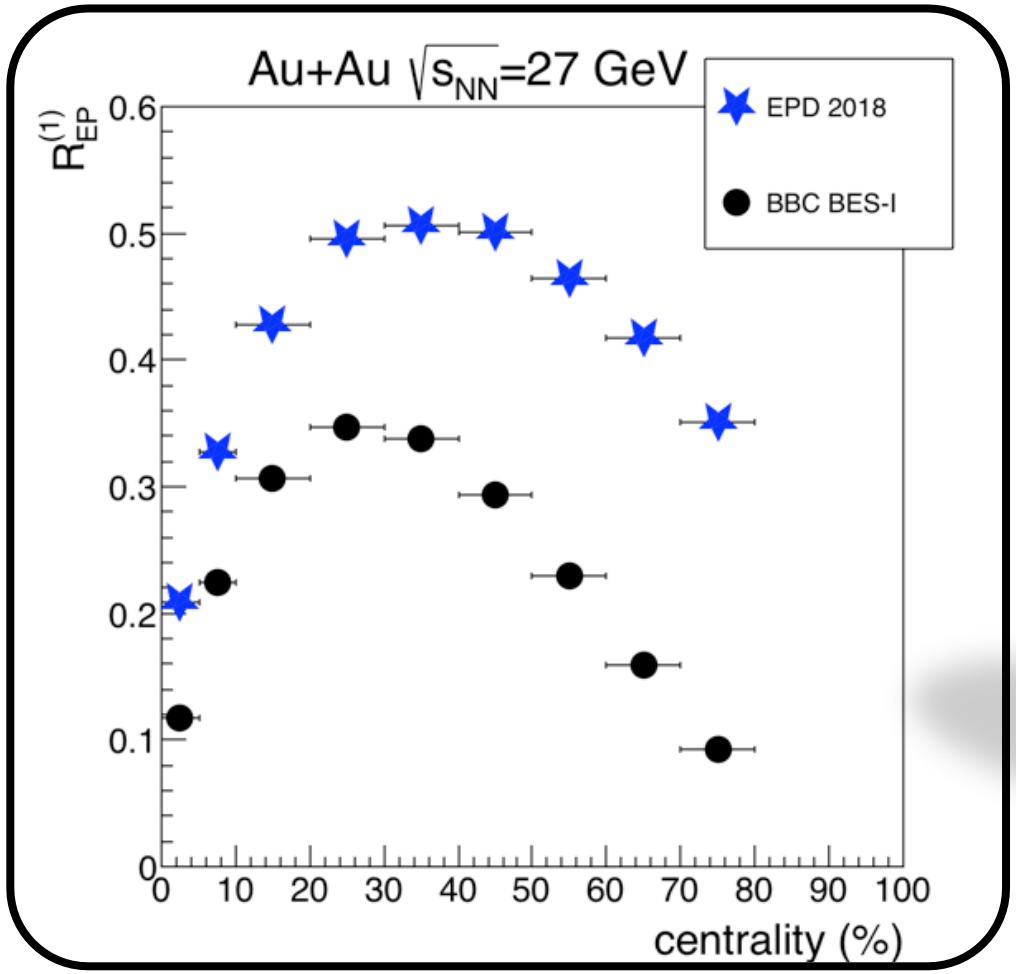


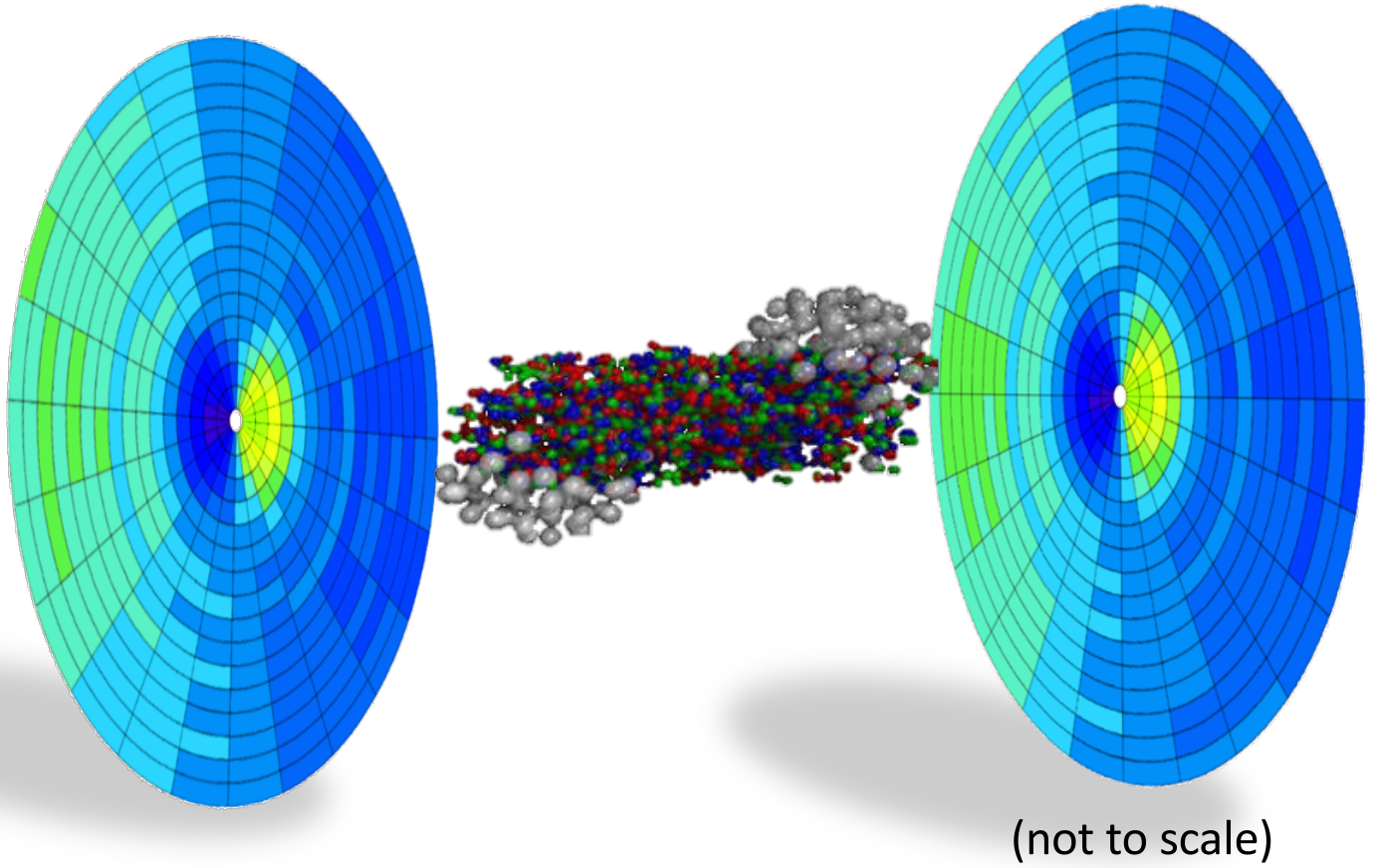
Takahashi knew direction of angular momentum

We estimate angular momentum direction via spectator deflection

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

Estimating direction of global vorticity at STAR





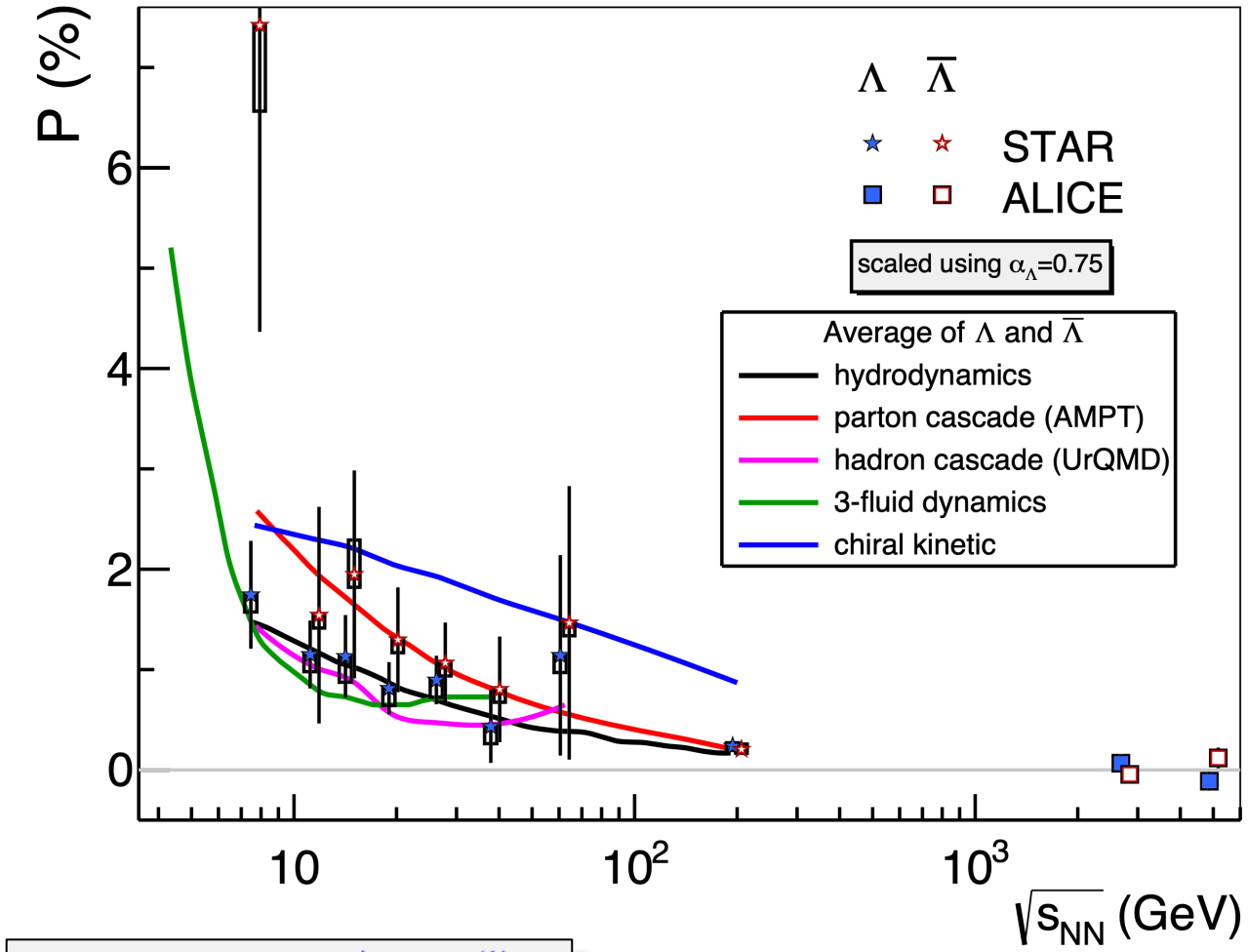
(not to scale)

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

Global Lambda Polarization

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

Becattini & MAL arXiv:2003.03640



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

- Global polarization observed at RHIC in quantitative agreement with standard hydro ***pre***dictions [1]
- Three-fluid hydro, especially important at low root(s) [2]
- Transport calculations (coarse-graining to calculate vorticity) [3,4] & kinetic+coalescence [5]

[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)

Lambda polarization

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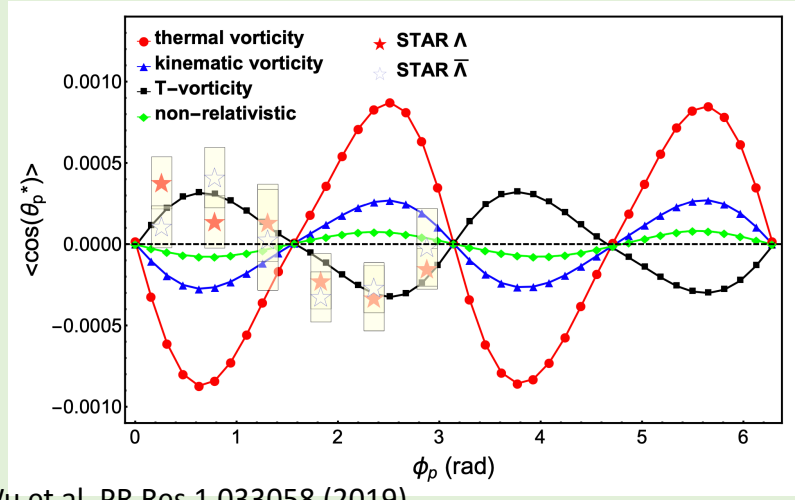
- the "usual" vorticity gives the wrong sign for longitudinal polarization



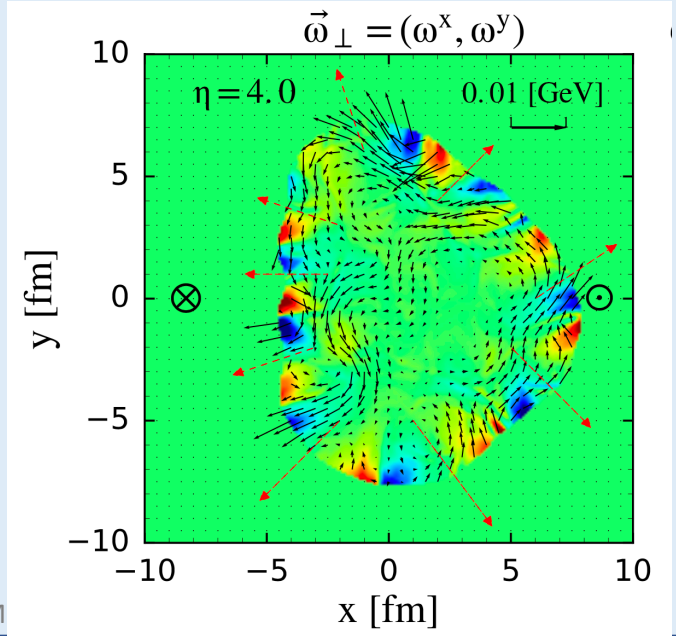
Wu et al, PR Res 1 033058 (2019)

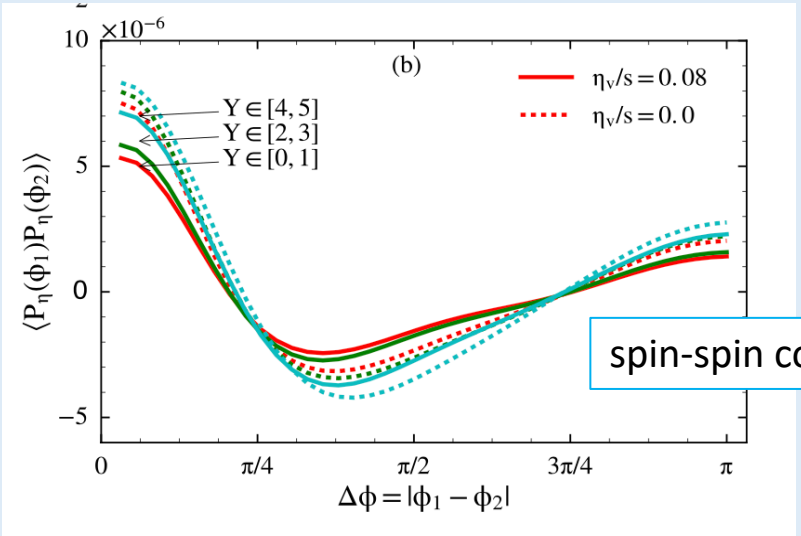
Quadrupolar structure of longitudinal polarization in the transverse momentum plane, as predicted. *Spectacular confirmation of hydro predictions... yet with a flipped sign!*

- Hydro initial conditions? (polarization is a sensitive probe of the initial flow)
- Incomplete local thermodynamic equilibrium for the spin degrees of freedom (spin kinetic theory)?
- Effect of spin dissipative transport coefficients?
- Effect of initial state fluctuations?
- Effect of decays?
- Error in the calculation

I. Karpenko, ECT* workshop, Oct 2020

Questions under intense theoretical investigation





spin-spin correlation!

Pang et al, PRL 117 (2016) 192301

Promising directions to be explored experimentally *(not easy!)*

Lambda polarization

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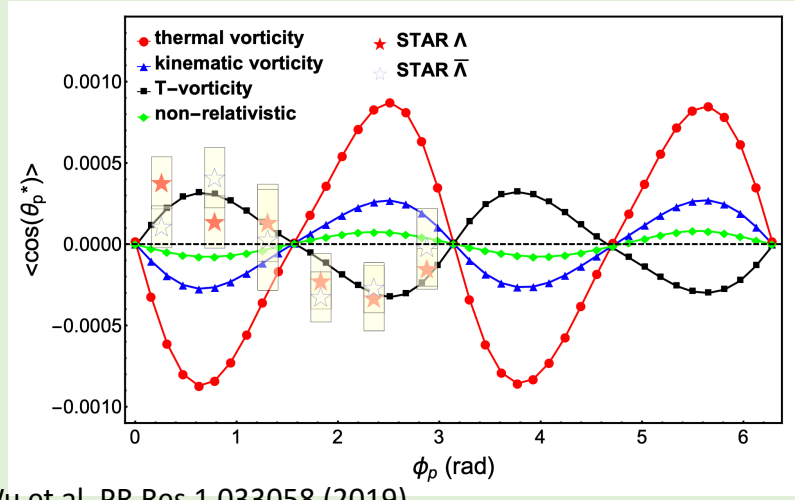

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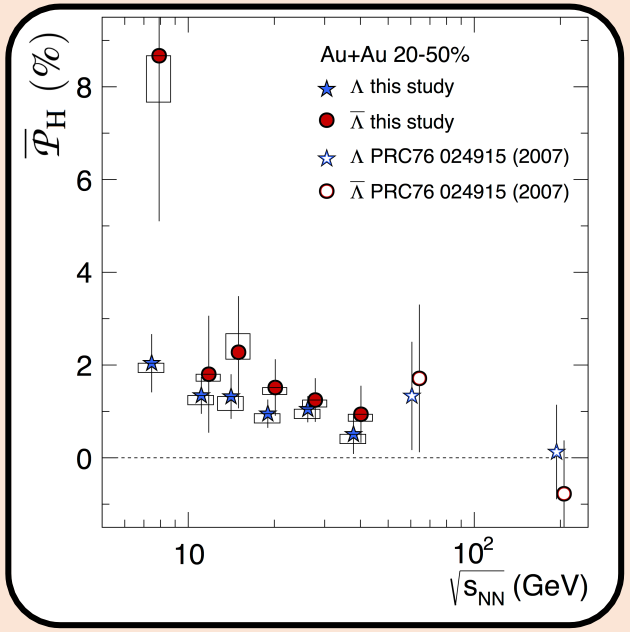
I. Karpenk

Questions under intense theoretical investigation

Theoretical *and* experimental pressing issue:
Splitting of Lambda / AntiLambda polarization

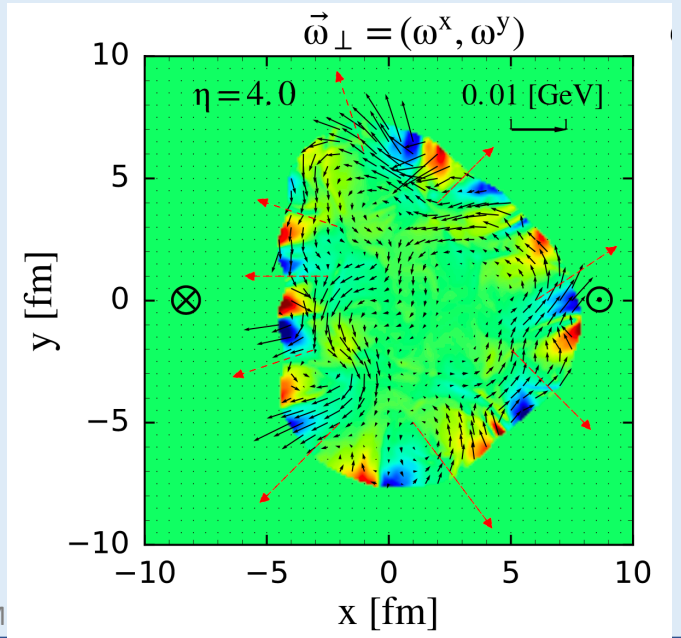


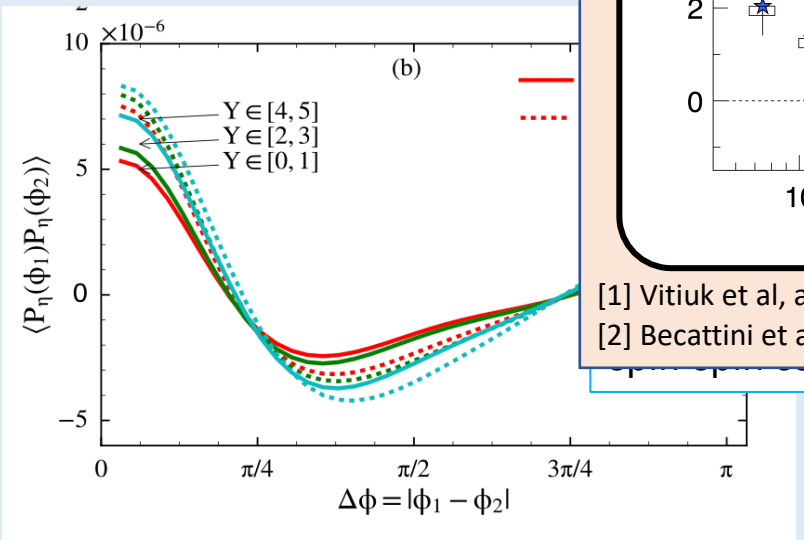
First… *is* there a split?

If so….

- diff freezeout? [1]
- magnetic field? [2]
- core-corona? [3]
- hadronic potential? [4]

[1] Vitiuk et al, arXiv:1910.06292
[2] Becattini et al, PRC95 (2017) 054902
[3] Ayala et al, arXiv:2003.13757
[4] Csernai et al, PRC99 (2019) 021901





Pang et al, PRL 117 (2016) 192301

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Lambda polarization

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

What are the next ”frontiers”?

1. at very low root(s) – NICA / FAIR / STAR FXT
   - do we still have a fluid substructure amenable to hydrodynamics?

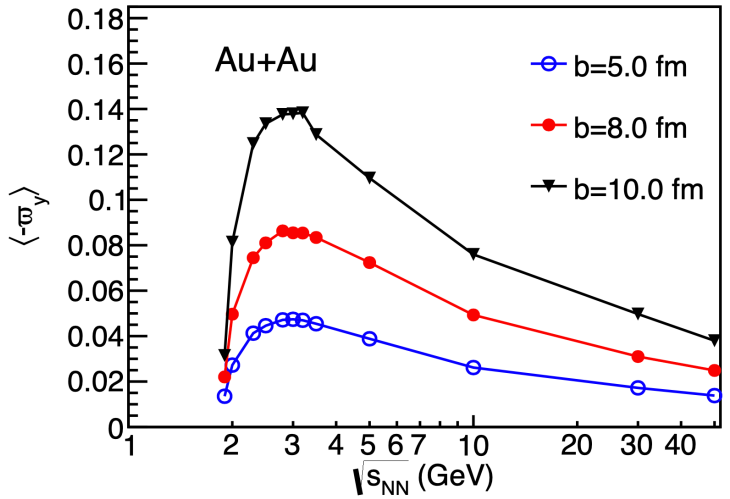
2. at very high energy – LHC / RHIC
   - the interesting structure at forward rapidity

Expectations at NICA / FAIR / STAR FXT / HADES@SIS -- sqrt(sNN) < 5 GeV

UrQMD with coarse-grained vorticity

Non-monotonic root(s) dependence – interplay with scales

- very low energy: angular momentum rises with sqrt(s)
- above root(s)~3 GeV, most of the angular momentum carried to forward direction

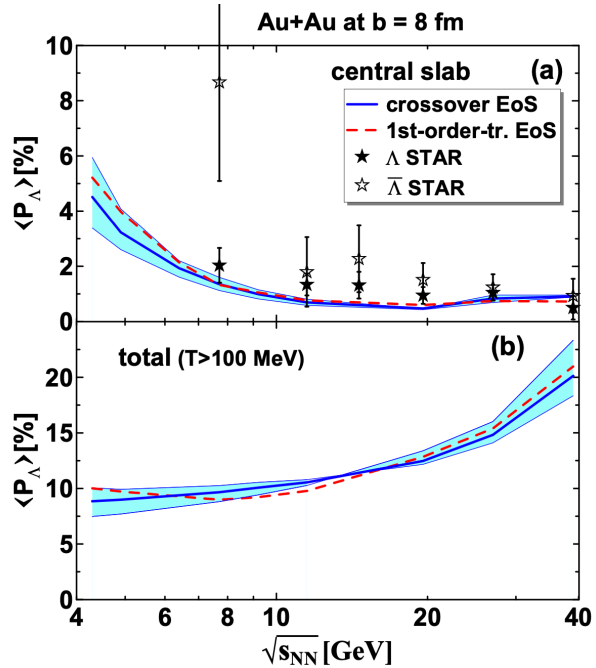


Deng, Huang, Ma, Zhang
PRC 101, 064908 (2020)

- rapidity dependence will be important!
- measure all the way to threshold!

3-fluid hydrodynamics

- steady rise with lowering root(s) *at midrapidity*, similar to above
  - can ”catch” all of the vorticity in NICA experiments?
- ?? what about even lower energy?



Ivanov, Toneev, Soldatov,
PRC100, 014908 (2019)

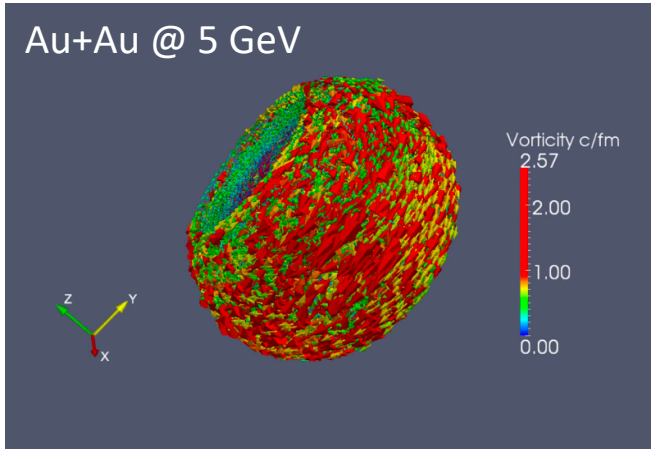
Also: Csernai, Xie and collaborators, PRC90 021 021904(R) (2014);
PRC94 054907 (2016) – hydro @ FAIR & NICA similar low RHIC

Speaking of forward rapidity…

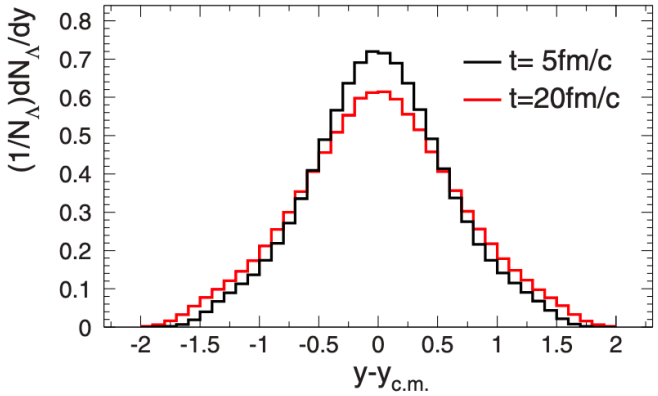
Baznat, Gudima, Sorin, Teryaev PRC93, 031902(R) (2016)
"femto-cyclones" on arxiv → "vortex sheet" in journal ☺

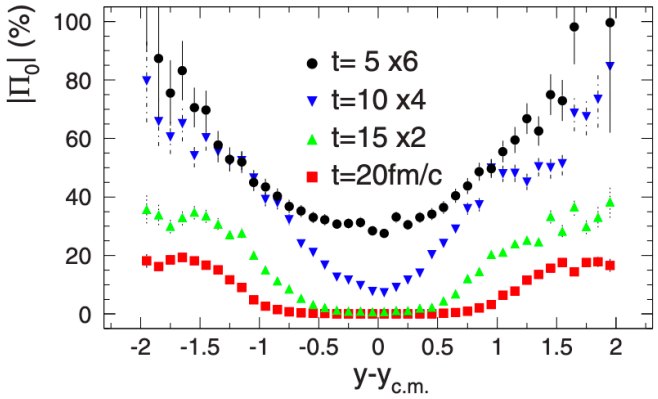
Several papers/groups using a variety of models:

- vorticity is dominated by the surface layer between participants & spectators --> importance of forward rapidity
- vortex rings or sheets



- 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 Nuclotron-based Ion Collider fAcility (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)





Rings – observable consequences…

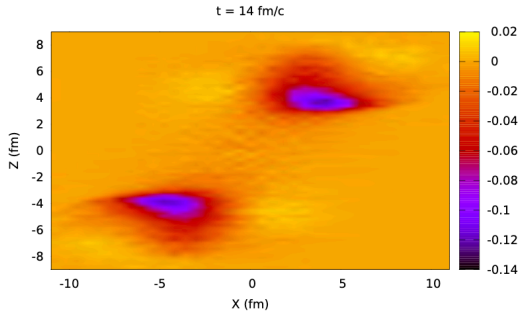


Figure 3. Weighted y-component of the vorticity (c/fm) averaged over all $x-z$ layers at $14fm/c$, impact parameter $b=8fm$. Average value is $-1.2452\cdot10^{-2}c/fm$.

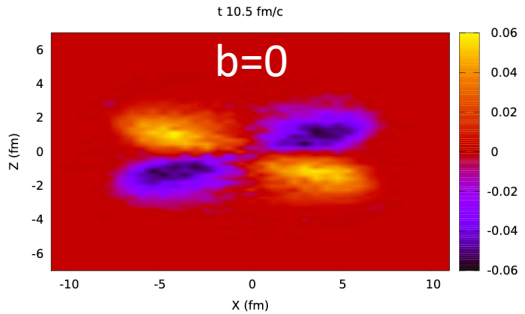
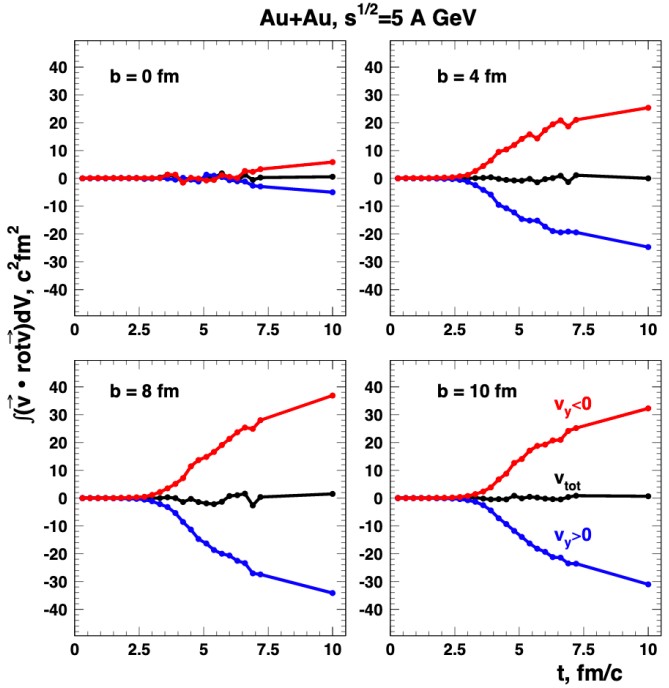


Figure 4. Weighted y-component of the vorticity (c/fm) averaged over all $x-z$ layers at $10.5fm/c$, impact parameter $b=0fm$. Average value is $-1.2\cdot10^{-5}c/fm$.

Teraev & Usubov PRC92 014906 (2015)



Zinchenko, Sorin, Teryaev, Baznat DSPIN-2019 (2020)

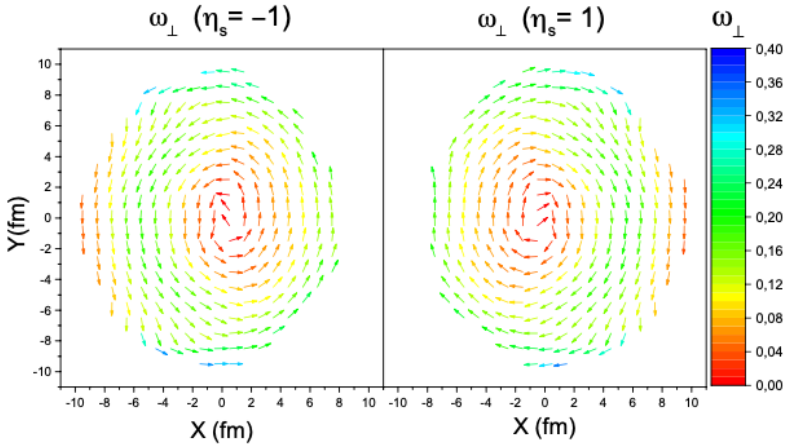


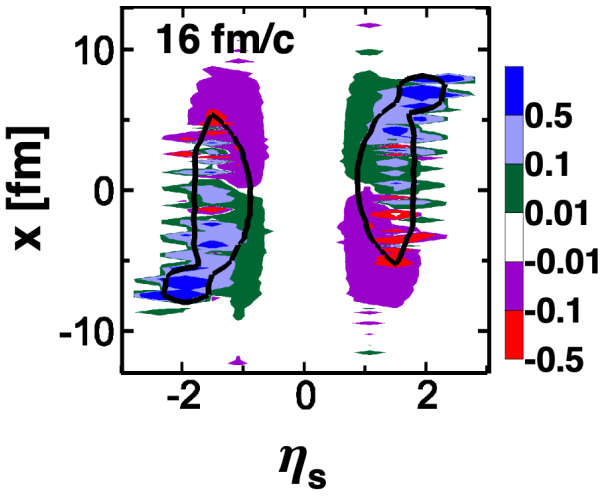
Figure 5. The distribution of the transverse vorticity $\vec{\omega}_\perp$ in the transverse plane at longitudinal position $\eta_s=-1$ (left) and $\eta_s=1$ (right) at time $t=9.5$ fm/c, b= 5 fm.

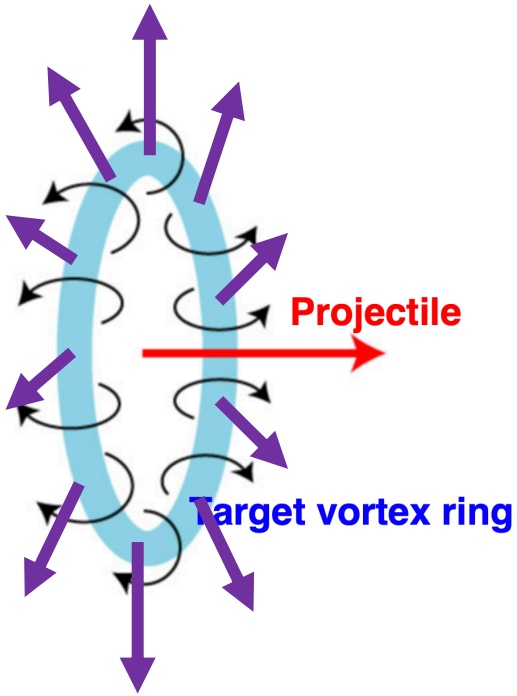
- Significant attention to structure in *space*
- Focus of observable implications seems to center on
  - identifying forward rapidity as important
  - convolution with directed flow affecting *global* polarization

Same observations at higher energy

root(s) = 39 GeV

Ivanov & Soldatov PRC97, 044915 (2018)





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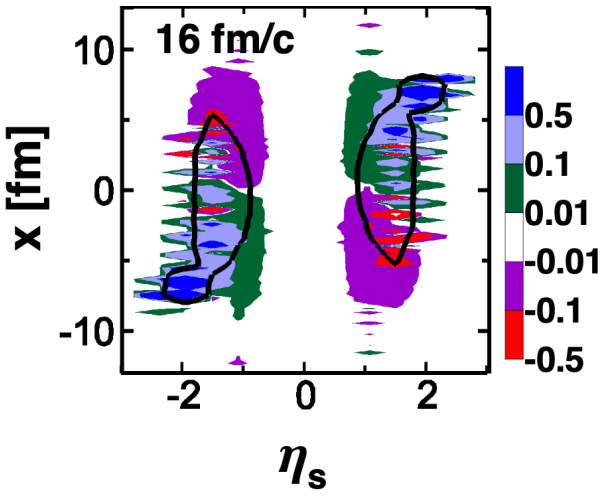

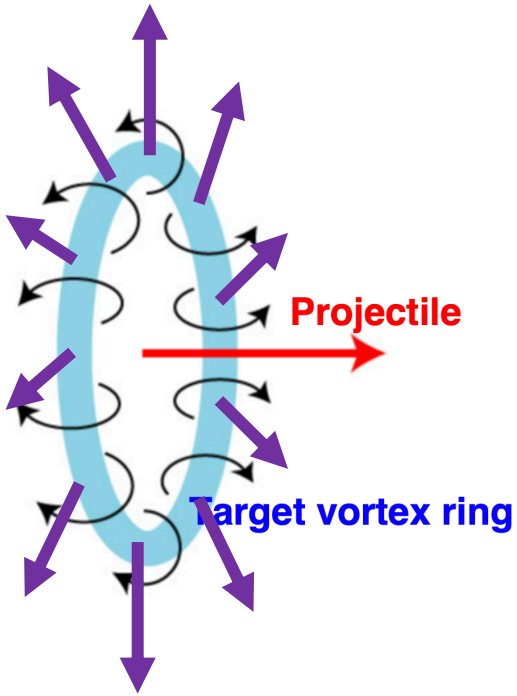

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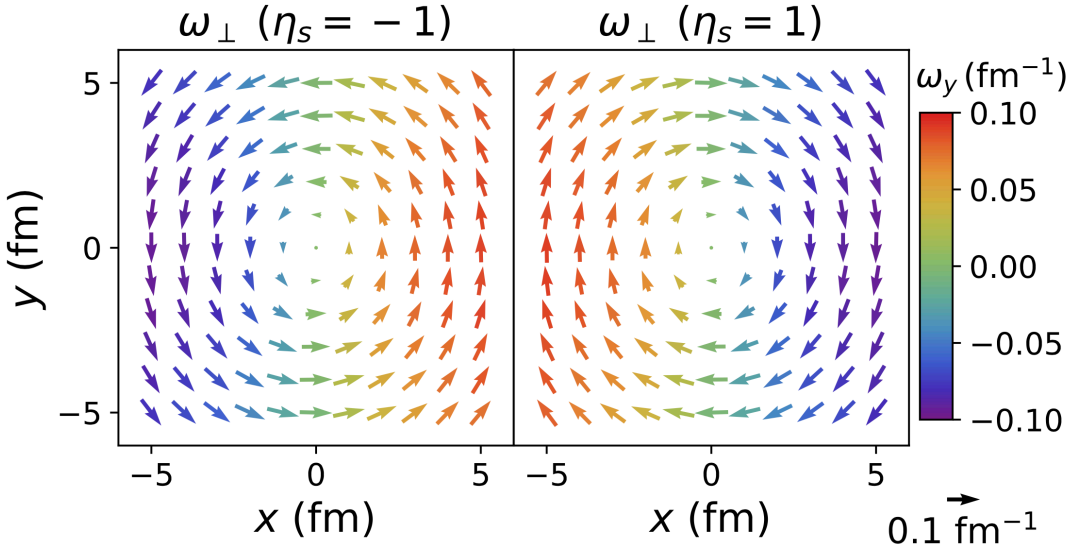
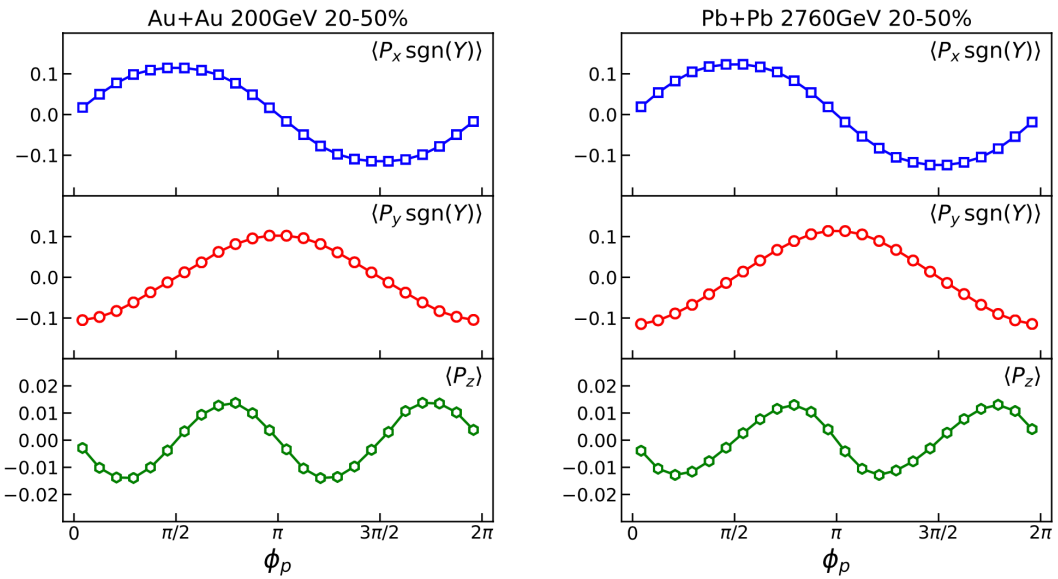
root(s) = 200, 2700 GeV



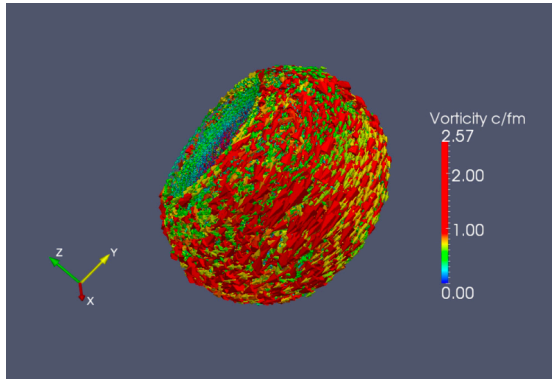


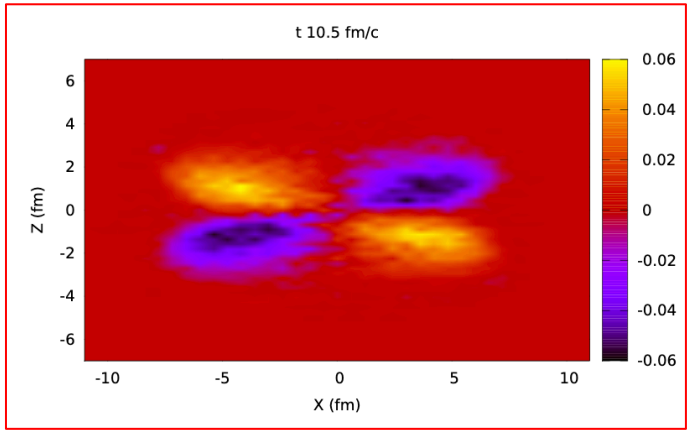
Xia, Li, Tang, Wang Phys. Rev. C 98, 024905 (2018)

Seeing the rings

- This is a unique predicted structure! Would represent a compelling demonstration of fluid structure at the extremes of rapidity and (low) energy

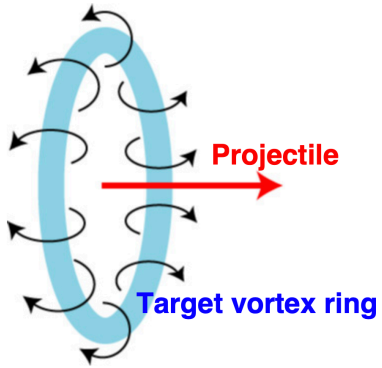
$\sqrt{s_{NN}} = 5$ GeV $\rightarrow y_{\mathrm{beam}} \approx 1.5$





✓ Observable at NICA

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

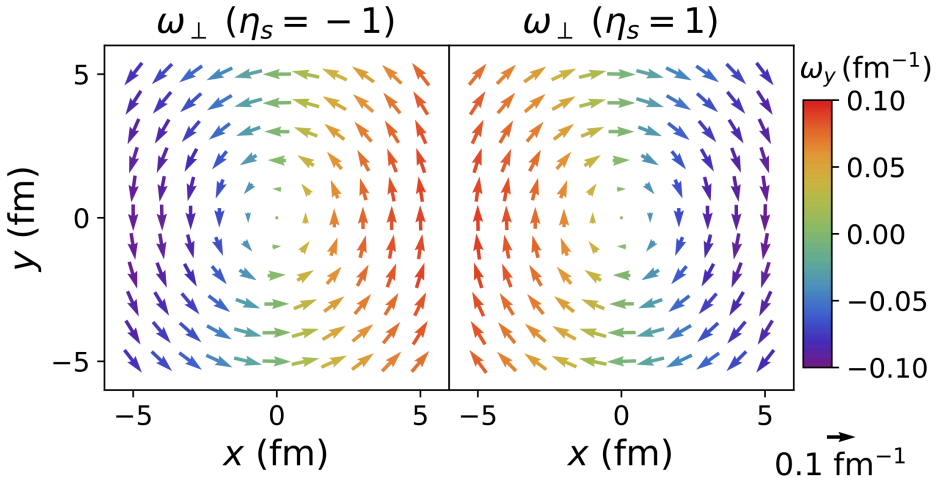


Focused forward

Not possible at STAR@RHIC without forward tracking upgrade

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

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



Focused forward

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

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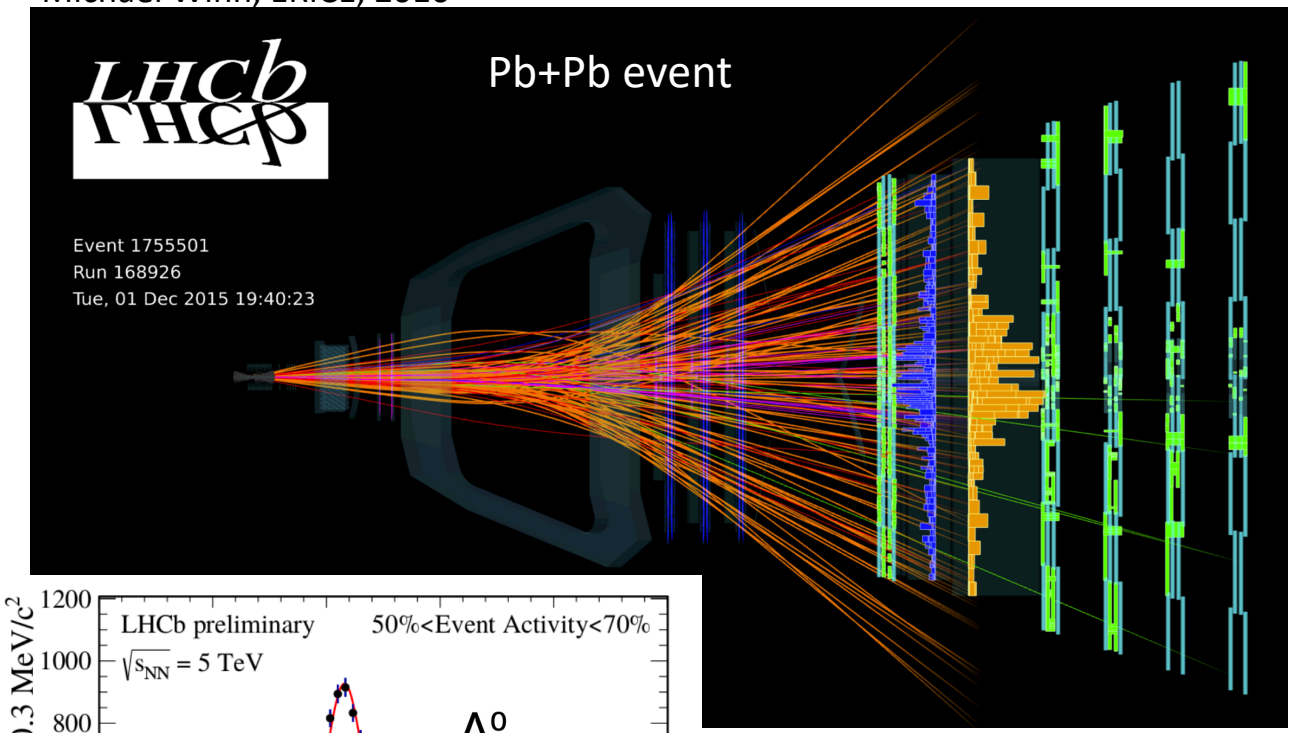
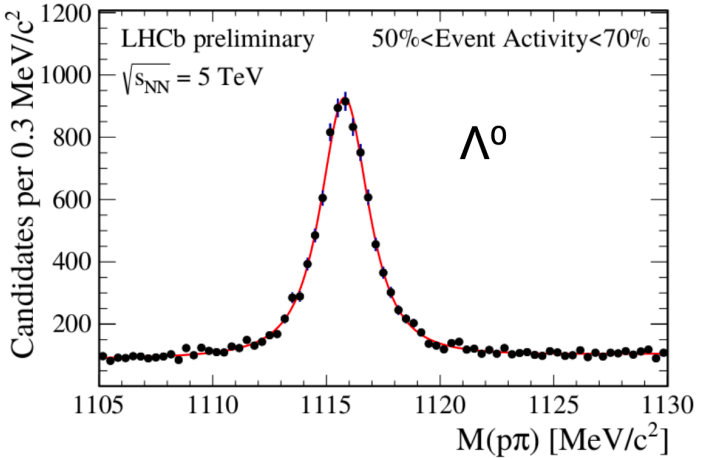
Michael Winn, ERICE, 2016





Note: No Event Plane Necessary!

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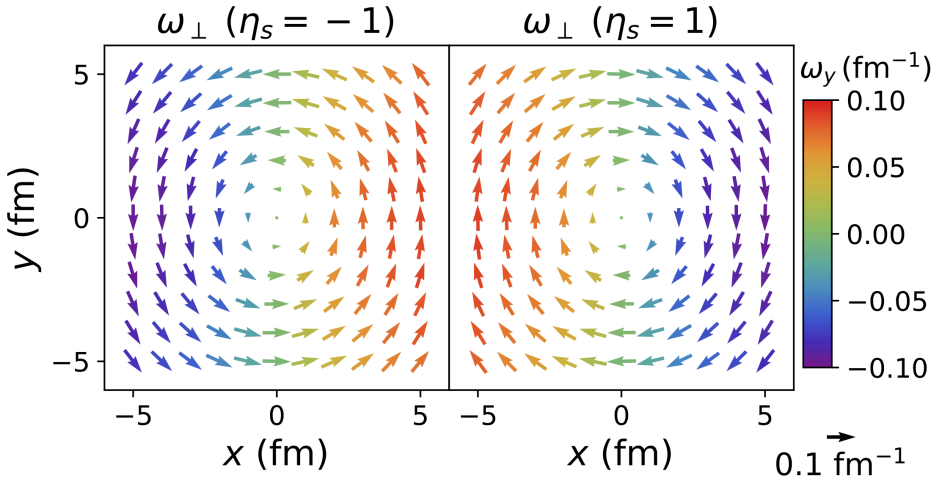

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✓ LHCb ideal to observe this structure

Summary

- Hyperon polarization is a sensitive probe of the fine substructure of the fluid
  - new direction in a mature field
  - important open questions, but seems well understood
- Energy dependence of global polarization?
  - can we understand collisions at NICA/FAIR in hydrodynamic terms?
  - important to capture forward polarization, as stopping competes with increased |J|

Summary

- Hyperon polarization is a sensitive probe of the fine substructure of the fluid
  - new direction in a mature field
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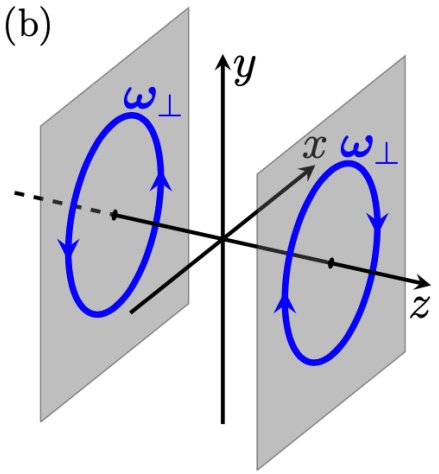
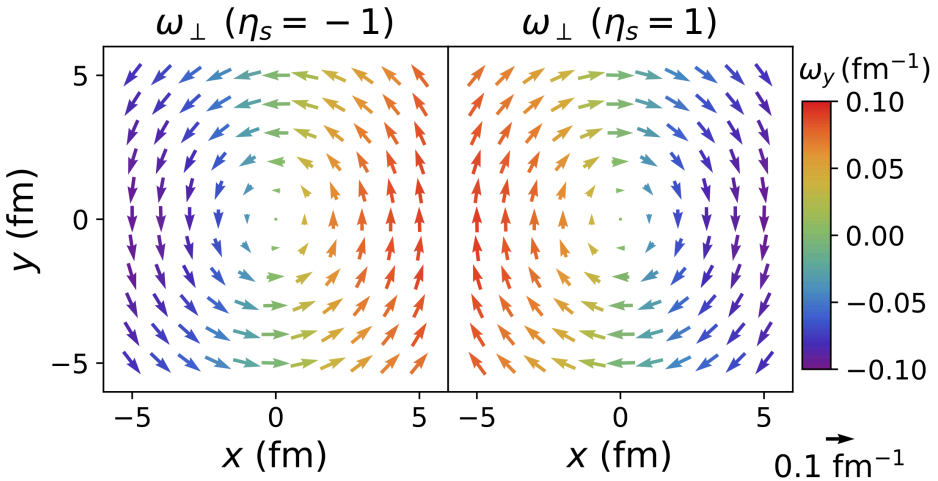
- Energy dependence of global polarization?
  - can we understand collisions at NICA/FAIR in hydrodynamic terms?
  - important to capture forward polarization, as stopping competes with increased |J|
- In addition to global (along total ang. mom) and longitudinal (along beam) polarization is a potential ring-like structure
  - first noted for low root(s)
  - observable at NICA…. and LHC?
  - design analyses to observe this dramatic fluid vortical signal
- This new tool is still shiny in our toolbox



can be *completely central*



благодарю вас