Global and local Λ polarization in heavy-ion collisions

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2018,06,22 at CHEP2018, Shanghai

Contents

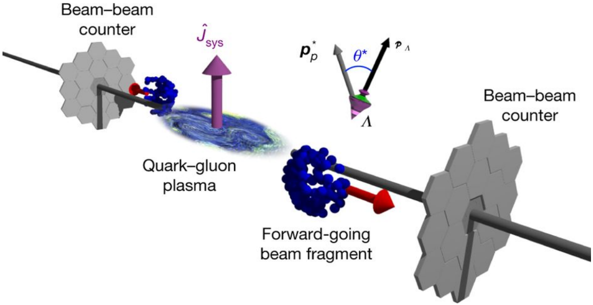
- Λ global polarization
  - why global polarization **decreases** with **increasing** $\sqrt{s_{NN}}$.
- Λ local polarization
  - rich information for local vorticity field.
- Summary

Li, Pang, Wang, XLX, Phys. Rev. C 96, no. 5, 054908 (2017)
XLX, Li, Tang, Wang, arXiv:1803.00867

Λ global polarization

Brief history of Λ global polarization

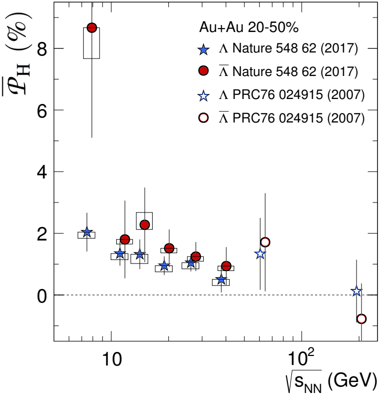
- **Liang, Wang 2004, Voloshin 2004**
  Orbital angular momentum in non-central collisions, spin-orbital coupling $\Rightarrow$ **global polarization**.



global polarization: average effect of $\boldsymbol{\omega}$ field on hyper-surface (**net vorticity**)

Brief history of Λ global polarization

- **Liang, Wang 2004, Voloshin 2004**
  global polarization is proposed.
- **STAR 2017**



Λ polarization probes ω and B

- Statistical-hydro model

  Becattini etal 2008, 2013

  Fang, Pang, Wang, Wang 2016

- For small fields

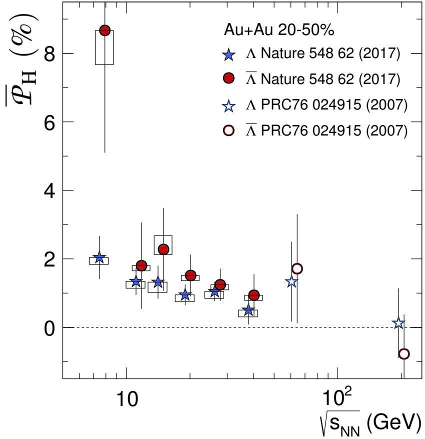
$$\mathbf{P}_\Lambda \simeq \frac{\boldsymbol{\omega}}{2T} + \frac{\mu_\Lambda \mathbf{B}}{T}$$
$$\mathbf{P}_{\bar{\Lambda}} \simeq \frac{\boldsymbol{\omega}}{2T} - \frac{\mu_\Lambda \mathbf{B}}{T}$$

  Becattini, Karpenko, Lisa, Upsal, Voloshin 2017

- Important inputs for studies on effects of $\boldsymbol{\omega}$ and $\mathbf{B}$:
  - CME/CVE/CMW ...
  - effects on QCD phase diagram.
  - ...

I focus on ω-induced Λ polarization in this talk.

STAR result 2017



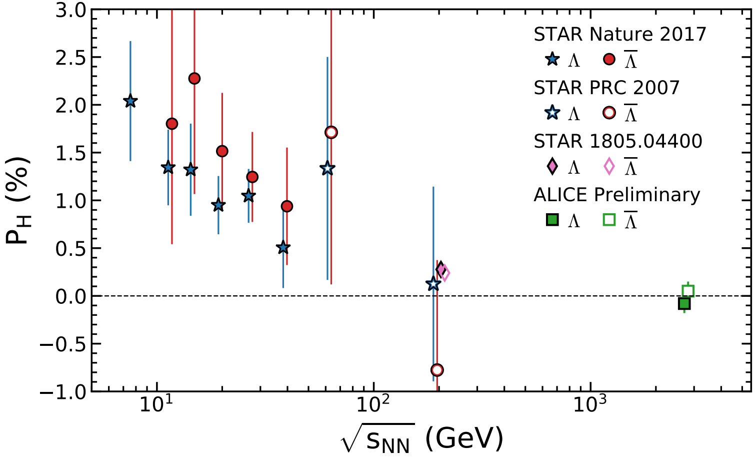
- **global polarization**: effect of **net vorticity**
- the most vortical fluid:

$$\langle \omega_y \rangle \sim 0.01\,\mathrm{fm}^{-1} \sim 10^{21}\,\mathrm{s}^{-1}$$

$$\mathbf{P}_\Lambda \simeq \frac{\boldsymbol{\omega}}{2T} + \frac{\mu_\Lambda \mathbf{B}}{T}$$

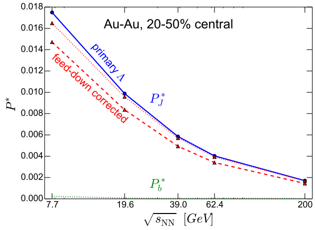
$$\mathbf{P}_{\bar{\Lambda}} \simeq \frac{\boldsymbol{\omega}}{2T} - \frac{\mu_\Lambda \mathbf{B}}{T}$$

Λ global polarization vs $\sqrt{s_{NN}}$

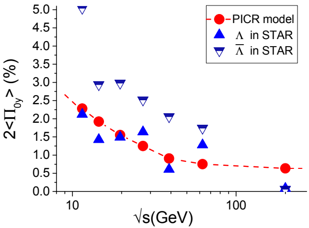


- Λ global polarization **decreases** with **increasing** $\sqrt{s_{NN}}$.
- In contrast to total angular momentum vs $\sqrt{s_{NN}}$.

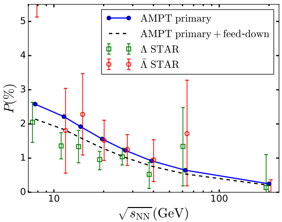
Λ global polarization in varied models



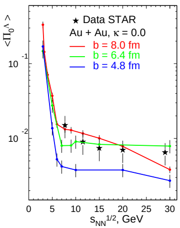
Karpenko, Becattini 2016



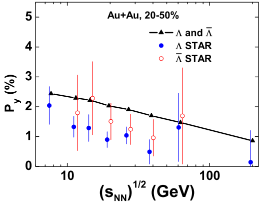
Xie, Wang, Csernai 2016



Li, Pang, Wang, Xia 2017

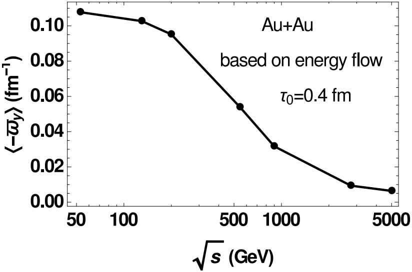


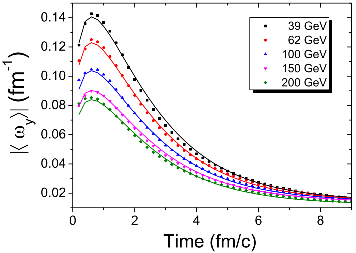
Baznat etal 2017



Sun, Ko 2017

Consistent with $\langle\omega_y\rangle(\sqrt{s_{NN}})$



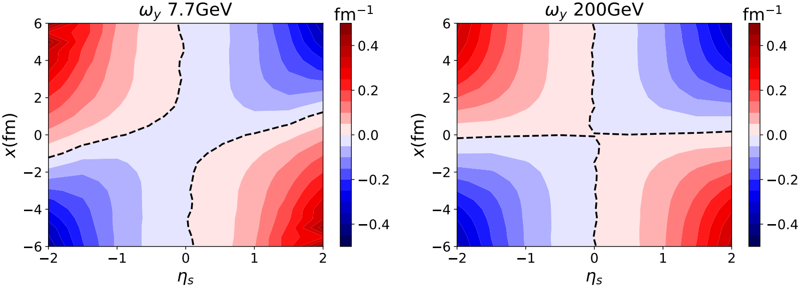


Deng, Huang 2016, HIJING **Jiang, Lin, Liao 2016, AMPT**

- $\langle\omega_y\rangle$: averaged vorticity, weighted by matter or energy density (**net vorticity**)
- $\langle\omega_y\rangle$ decreases with $\sqrt{s_{NN}}$.

Vorticity distribution

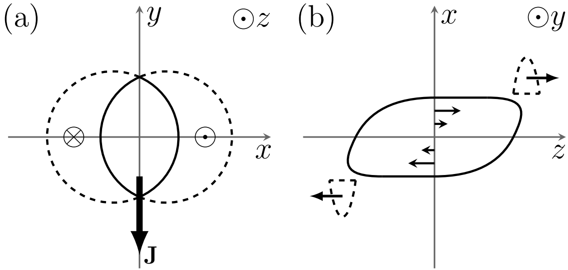
ω_y on *zx* plane at $t = 5\text{fm}/c$ in 20-30% Au+Au collisions:



- **Net vorticity** $\langle \omega_y \rangle$ is larger at lower $\sqrt{s_{\text{NN}}}$.
- Quadrupole pattern: **local vorticity** (see next section).

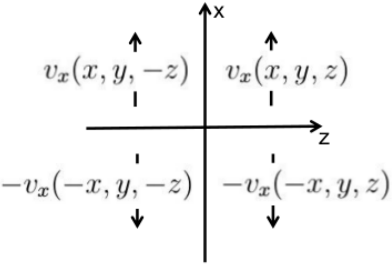
How to understand?

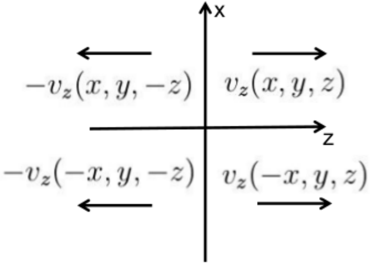
- **Net vorticity** and **global polarization** are generated from the fireball's *titled shape* on the reaction plane.



Central vs non-central collisions

- In central collisions, **net vorticity** vanishes due to the reflection symmetry $x \to -x$ and $z \to -z$.





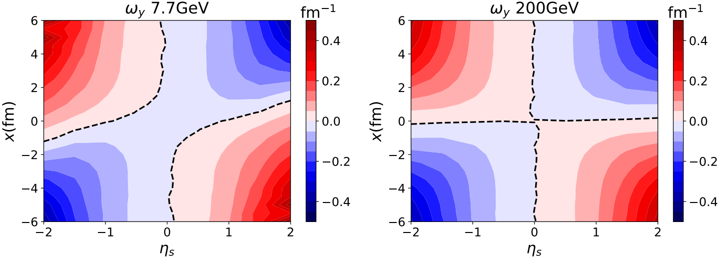
	$x \to -x$	$z \to -z$
v_x	odd	even
v_z	even	odd
ω_y	odd	odd

$$\omega_y = \frac{1}{2}(\partial_z v_x - \partial_x v_z)$$

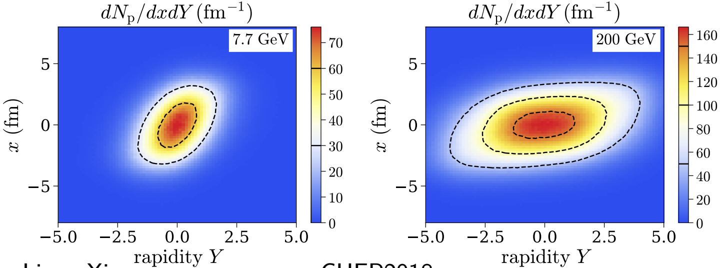
- In non-central collisions, the reflection symmetry breaks $\langle \omega_y \rangle \neq 0$

Vorticity and matter distribution

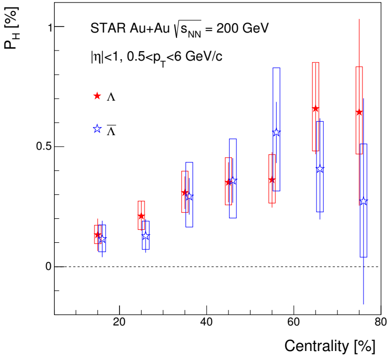
ω_y on zx plane at $t = 5\text{fm}/c$ in 20-30% Au+Au collisions:



Initial parton distribution:



Λ global polarization vs centrality

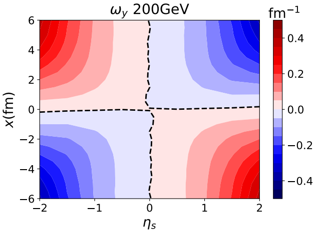


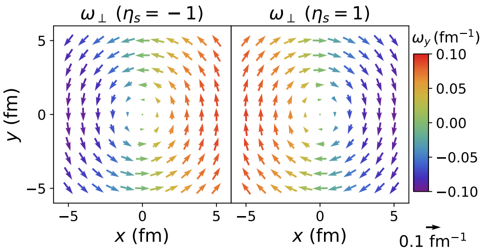
STAR 1805.04400

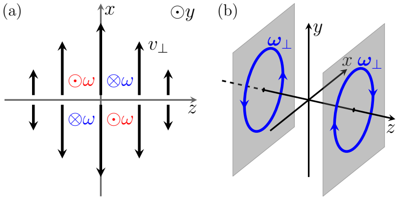
- Λ global polarization increases with centrality,
- consistent to the tilted shape scenario.

Local vorticity and Λ local polarization

Circular transverse vorticity $\boldsymbol{\omega}_\perp = (\omega_x, \omega_y)$







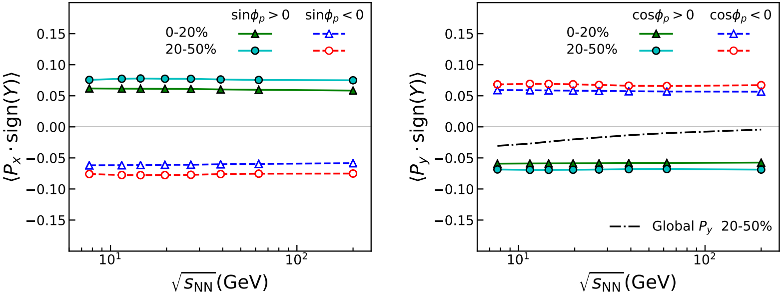
On xz plane: quadrupole ω_y
In 3D view: circular $\boldsymbol{\omega}_\perp$

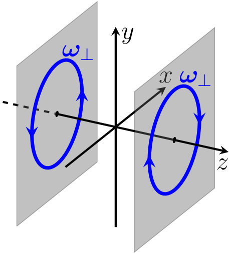
$$\mathbf{v}_\perp = v_\perp(z)\mathbf{e}_r$$

$$\boldsymbol{\omega}_\perp \equiv \frac{1}{2}(\nabla \times \mathbf{v})_\perp = \frac{1}{2}\partial_z v_\perp(z)\mathbf{e}_\phi$$

$\partial v_\perp / \partial |z| < 0.$

Circular transverse polarization $\mathbf{P}_\perp = (P_x, P_y)$



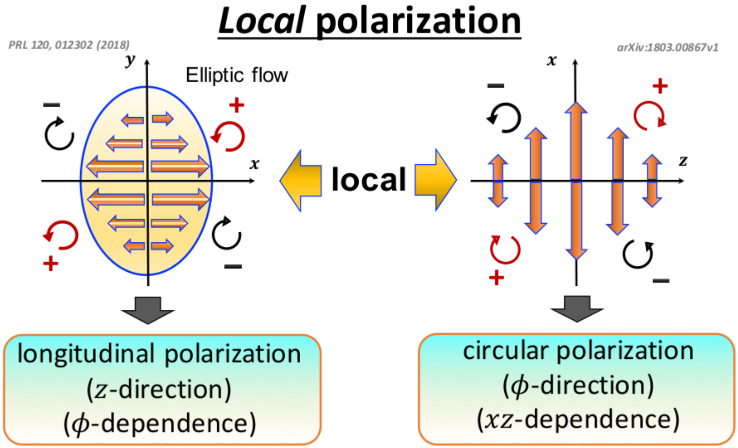


$$\langle \mathbf{P}_\perp \cdot \mathrm{sign}(Y)\rangle = \frac{\mathbf{P}_\perp(\phi_p, Y>0) - \mathbf{P}_\perp(\phi_p, Y<0)}{2}, \quad |Y| < 1$$

ϕ_p: azimuthal angle of Λ's momentum.

Y: Λ's rapidity.

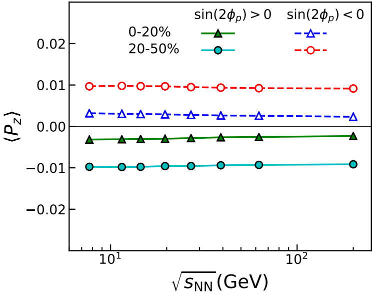
- insensitive with $\sqrt{s_{NN}}$,
  can be tested at 200 GeV and LHC energy.



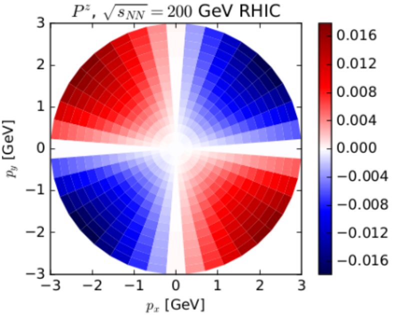
- quadrupole P_z from $\partial_\phi v_\perp$
  Becattini, Karpenko 2017
  Voloshin 2017
- circular $\mathbf{P}_\perp$ from $\partial_z v_\perp$
  XLX, Li, Tang, Wang 2018

above slide from Zhoudunming Tu's talk at QM2018

Quadrupole pattern of P_z



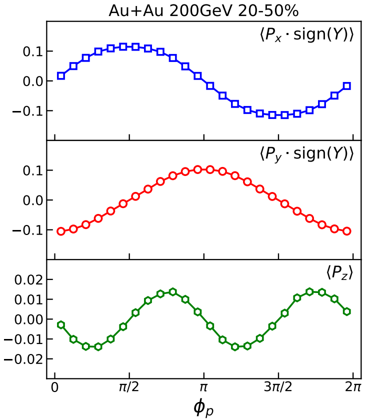
XLX, Li, Tang, Wang 2018
AMPT

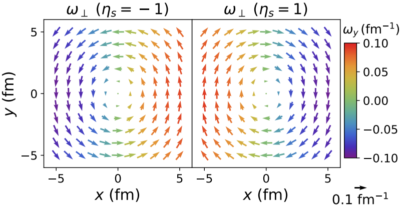


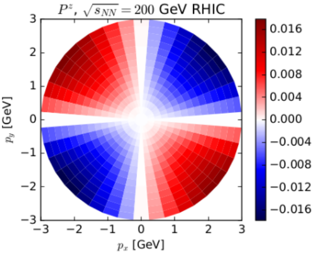
Becattini, Karpenko 2017
hydro+UrQMD

- consistent with Becattini and Karpenko's result.

Local polarization, harmonic behaviors

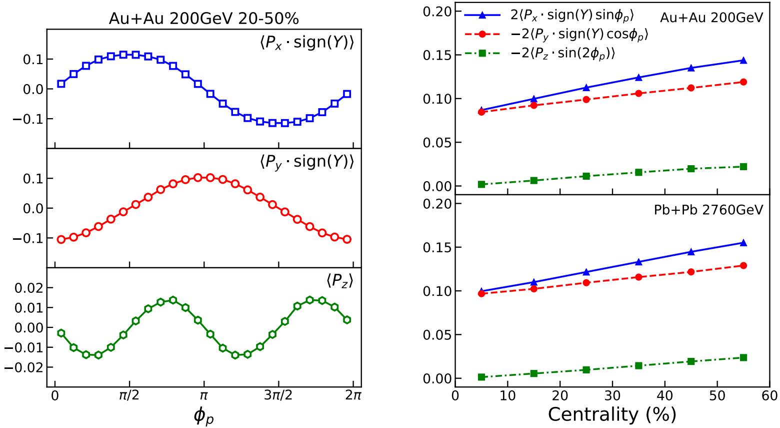






- $(P_x, P_y) \cdot \mathrm{sign}(Y) \sim -\mathbf{e}_\phi \sim (\sin\phi_p, -\cos\phi_p)$;
- $P_z \sim -\sin(2\phi_p)$

Local polarization, Fourier coefficients



- Local polarization is sizable,
  c.f. global polarization < 0.003 at 200 GeV and smaller at LHC energies.
- P_z and $|P_x - P_y|$ increases with centrality: elliptic flow.

Summary

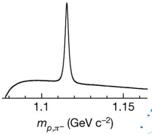
- The **net vorticity** and **global polarization** are from the fireball's *titled shape* on reaction plane.
  - Decreases with $\sqrt{s_{\mathrm{NN}}}$ in mid-rapidity;
  - Increases with centrality.
- **Local vorticity** and **local polarization**:
  - circular structure of $\boldsymbol{\omega}_\perp$ and $\mathbf{P}_\perp$, from $\partial_z v_\perp$.
  - quadrupole pattern of ω_z and P_z, from $\partial_\phi v_\perp$.
- **Local polarization** is sizable at 200 GeV and LHC energies, can be tested.

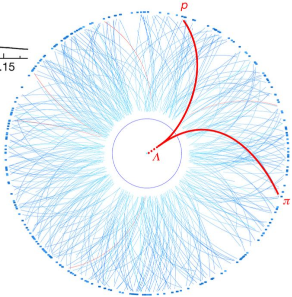
Thanks for listening

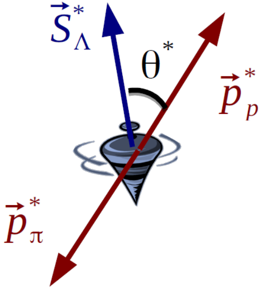
Backup

How to measure Λ polarization?

- Λ is "self-analyzing"







Weak decay $\Lambda \to p + \pi^-$

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H |\mathbf{P}_H| \cos\theta^*)$$

$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$

Λ polarization induced by ω and $\mathbf{B}$

- Polarization from $\boldsymbol{\omega}$ and $\mathbf{B}$

$$\rho \sim \exp\left(\frac{\boldsymbol{\omega}\cdot\widehat{\mathbf{S}} + \mathbf{B}\cdot\mu_\Lambda\widehat{\mathbf{S}}/S}{T}\right)$$

$$\mathbf{P} \equiv \langle\mathbf{S}\rangle/S = \mathrm{tr}(\rho\widehat{\mathbf{S}})/S$$

- For small fields

$$\mathbf{P}_\Lambda \simeq \frac{\boldsymbol{\omega}}{2T} + \frac{\mu_\Lambda\mathbf{B}}{T}$$
$$\mathbf{P}_{\bar{\Lambda}} \simeq \frac{\boldsymbol{\omega}}{2T} - \frac{\mu_\Lambda\mathbf{B}}{T}$$

$$\mu_\Lambda = -\mu_{\bar{\Lambda}} = -0.6138\mu_N$$

- $\boldsymbol{\omega}$-induced $\Lambda/\bar{\Lambda}$ polarizations are along $\boldsymbol{\omega}$;
- $\mathbf{B}$-induced $\Lambda/\bar{\Lambda}$ polarizations are along $\mp\mathbf{B}$.

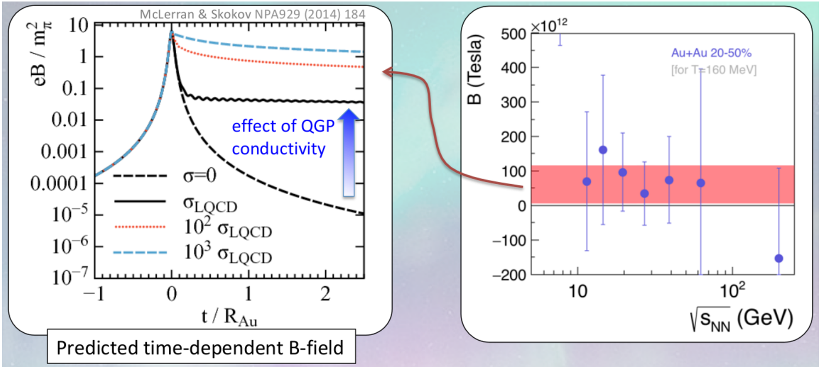
$$\boldsymbol{\omega} = (\mathbf{P}_\Lambda + \mathbf{P}_{\bar{\Lambda}})T$$
$$\mathbf{B} = (\mathbf{P}_\Lambda - \mathbf{P}_{\bar{\Lambda}})T/(2\mu_\Lambda)$$

$\Lambda/\bar{\Lambda}$ polarization can be used to probe ω and $\mathbf{B}$.

Becattini, Karpenko, Lisa, Upsal, Voloshin 2017

B-field from Λ global polarization

$$\mathbf{B} = (\mathbf{P}_\Lambda - \mathbf{P}_{\bar{\Lambda}})T/(2\mu_\Lambda)$$



Predicted time-dependent B-field

above picture from Lisa's talk at Florence workshop, 2018

- Uncertainties on both experimental and theoretical sides.