Hyperon-type dependence of global polarization and feed-down effect in heavy-ion collisions

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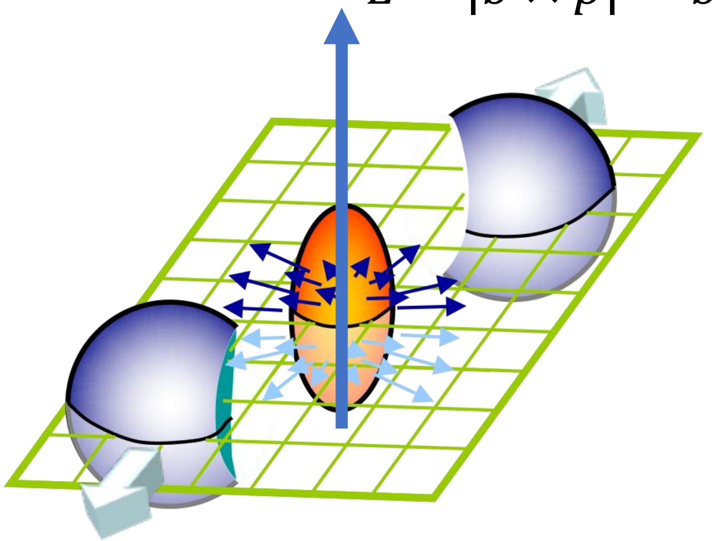
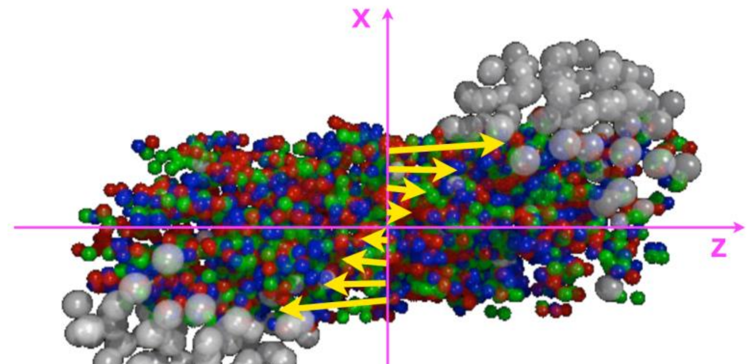
Angular momentum and vorticity

$$L = |\vec{b} \times \vec{p}| \simeq bA \frac{\sqrt{s_{\mathrm{NN}}}}{2}$$



RHIC: $L = 10^5\ \hbar$ @ 200 GeV & 7 fm
LHC: $L = 10^7\ \hbar$ @ 2760 GeV & 7 fm

Global angular momentum

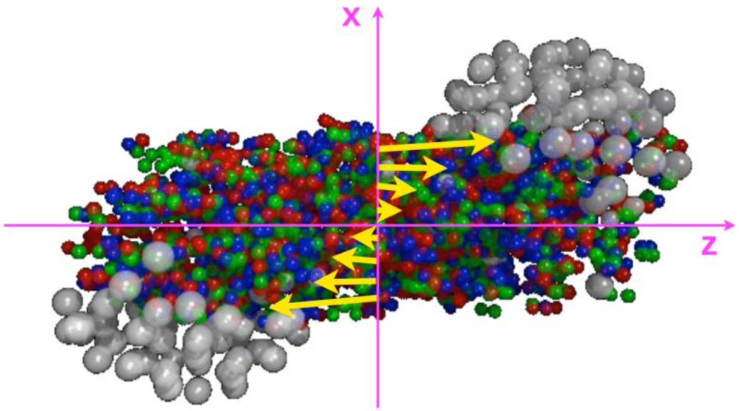


Picture from urqmd

$$\omega = \frac{1}{2} \nabla \times \mathrm{v}$$

Vorticity

Vorticity



Vorticity: $\omega = \frac{1}{2}\nabla \times \mathrm{v}$

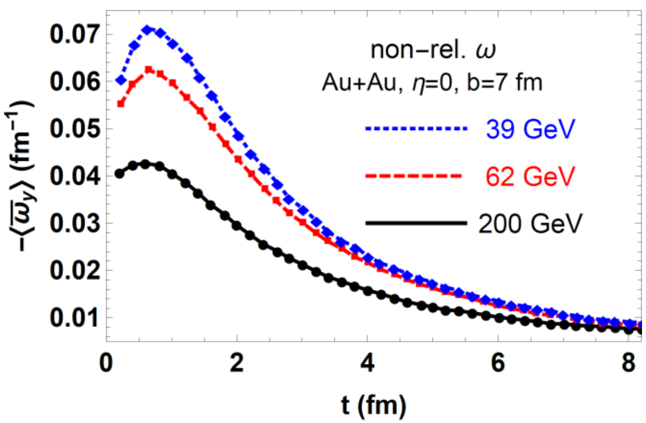
- **Estimation:**

$$\omega \sim \frac{\Delta v}{2\Delta x} \sim 10^{-2}\mathrm{c/fm} \sim 10^{21}\mathrm{s}^{-1}$$

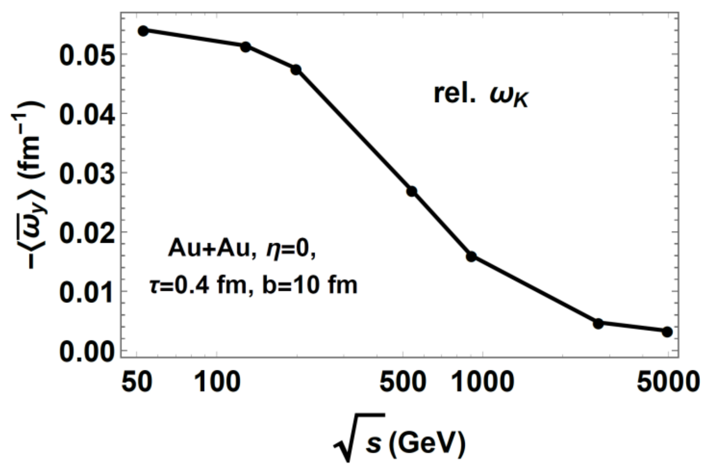
with $\Delta v \sim 10^{-1}$c and $\Delta x \sim 10$fm

- **Model calculation:**
  - ω decreases with the increase of energy at RHIC and LHC region.

AMPT, Jiang-Lin-Liao (2016)

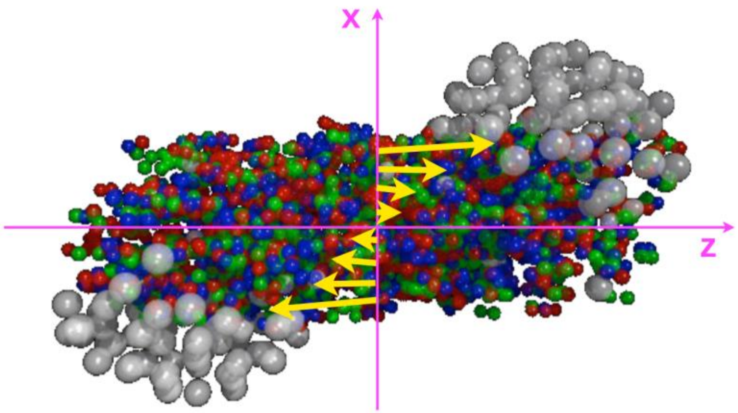


HIJING, Deng-Huang (2016)



Vorticity

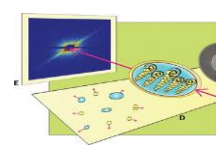
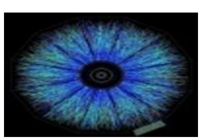
$$\omega \sim \frac{\Delta v}{2\Delta x} \sim 10^{-2} \mathrm{c/fm} \sim 10^{21} \mathrm{s}^{-1}$$



Vorticity: $\omega = \frac{1}{2} \nabla \times \mathrm{v}$

- **Vorticity of different scales:**
  - Great red spot of Jupiter: $10^{-4}\mathrm{s}^{-1}$
  - Supercell tornado core: $10^{-1}\mathrm{s}^{-1}$
  - Superfluid helium nanodroplet: $10^{7}\mathrm{s}^{-1}$
  - Heavy ion collision: $10^{21}\mathrm{s}^{-1}$
- **Physics:**
  - Spin polarization
  - Anomalous transport
  - Extended QCD diagram
  - Heavy flavor …



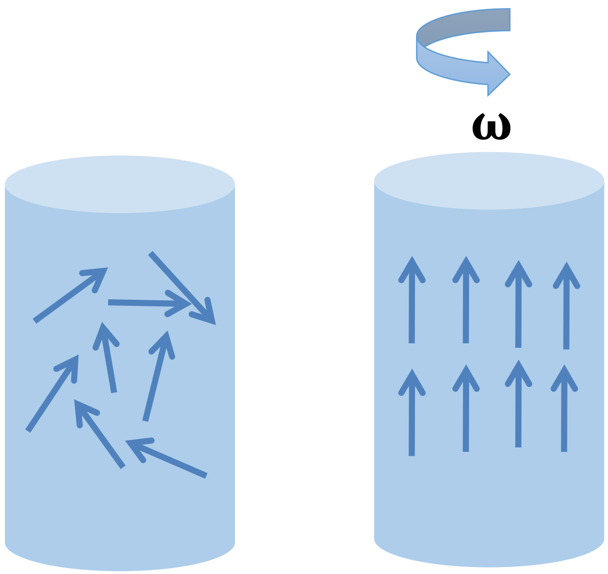
$10^{-16}\mathrm{s}^{-1}$ | $10^{-4}\mathrm{s}^{-1}$ | $10^{-1}\mathrm{s}^{-1}$ | $10^{7}\mathrm{s}^{-1}$ | $10^{21}\mathrm{s}^{-1}$

Global polarization

- Early idea on global polarization (based on in particle scattering):

  Liang-Wang, Phys. Rev. Lett. 94, 102301 (2005)

- Statistical description:



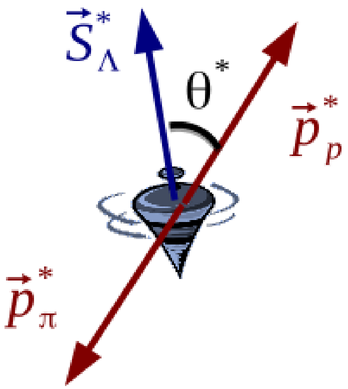
- Spin in rotating system: $\rho = \frac{1}{Z} e^{-(\hat{H}_0 - \boldsymbol{\omega}\cdot\hat{\mathbf{S}})/T}$
- For particles of spin S: $\mathbf{P} = \frac{\mathrm{tr}(\rho\hat{\mathbf{S}})}{S} \approx \frac{S+1}{3}\frac{\boldsymbol{\omega}}{T}$
- Relativistic case:

$$P^\mu = -\frac{S+1}{6m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_\nu\varpi_{\rho\sigma} + O(\varpi^2)$$

Becattini etal, Phys. Rev. C 77, 024906 (2008)
Becattini etal, Annals Phys. 338, 32 (2013)
Fang etal, Phys. Rev. C 94, 024904 (2016)
Florkowski etal, Phys. Rev. C 97, 041901 (2018)
Liu etal, Chin. Phys. C 44, 094101 (2020)
Weickgenannt etal, arXiv:2005.01506
....

Why polarization of hyperons?

- Parity-violating weak decay of a hyperon: $H \rightarrow D + X$



- By measure the angular distribution of decay products

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H P_H \cos\theta^*)$$

$\Lambda \rightarrow p\pi^-: \alpha = 0.732$

$\Xi^- \rightarrow \Lambda\pi^-: \alpha = -0.401$

The daughter momentum direction is associated with the parent spin.

- By measure the polarization of the daughter hyperon

$$P_D = C P_H$$

$\Xi^- \rightarrow \Lambda\pi^-: C \approx 0.944$

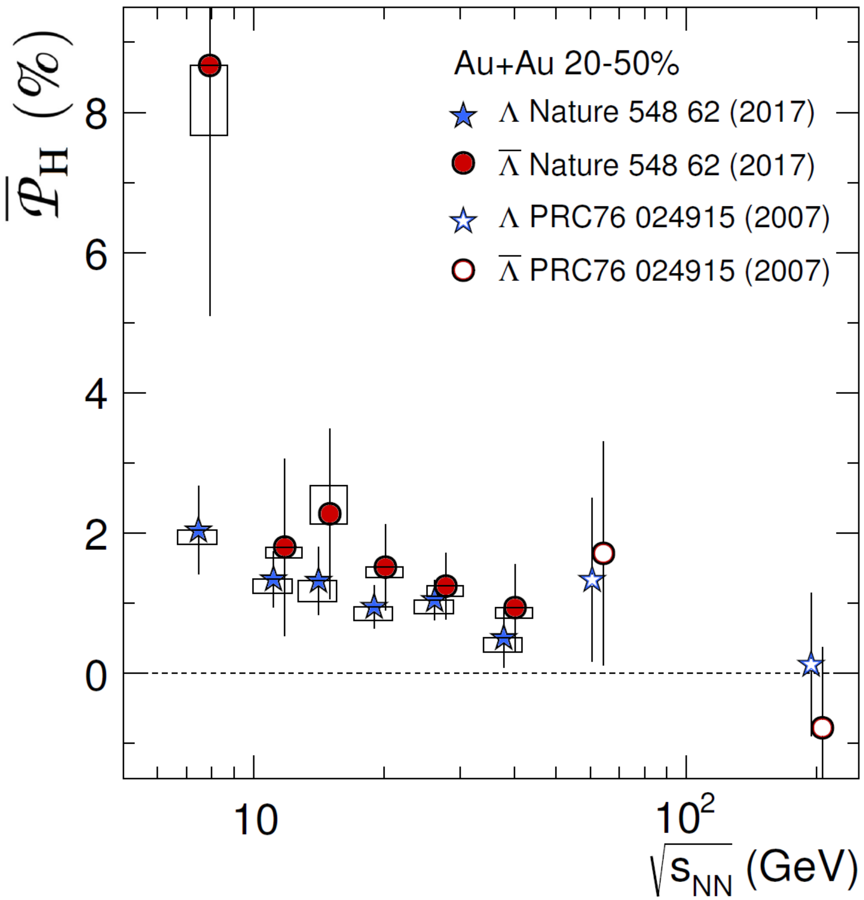
$\Omega^- \rightarrow \Lambda K^-: C \approx 1$ (assumed)

The daughter inherits part of the parent polarization.

See experiment talk by Niida on Thursday

Global Λ polarization

STAR, Nature 548 62 (2017)



- Global polarization:

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

- $\langle \omega_y \rangle = (9 \pm 1) \times 10^{21} \mathrm{s}^{-1}$

confirm QGP the most vortical fluid.

- $P_{\bar{\Lambda}} > P_\Lambda$:

Effect of magnetic field?

magnetic moment

$\mu_\Lambda = -0.613\mu_N$

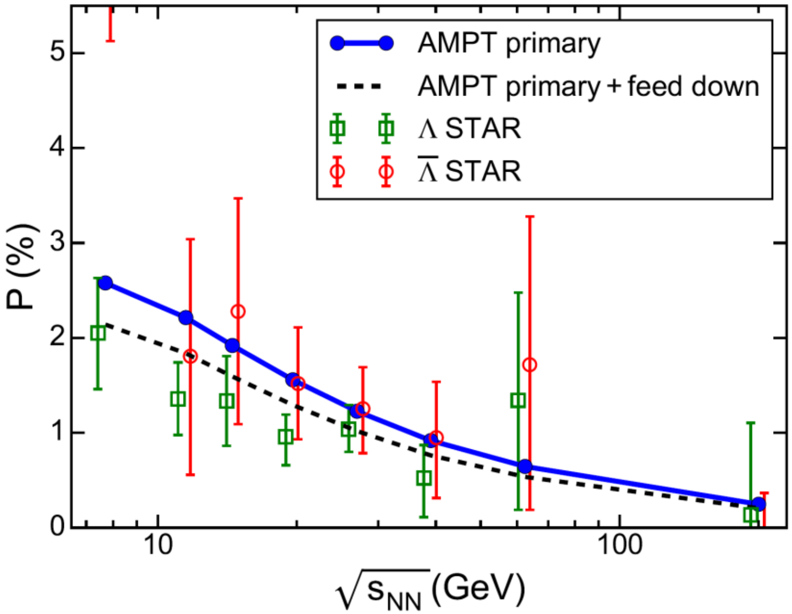
Different Λ and $\bar{\Lambda}$ space-time distribution?

Vitiuk, etal, Phys. Lett. B 803, 135298 (2020)
Ayala, etal, Phys. Lett. B 810, 135818 (2020)

Global Λ polarization

$$P^{\mu} = -\frac{S+1}{6m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_{\nu}\varpi_{\rho\sigma}$$

Li-Pang-Wang-XLX, PRC 96, 054908 (2017)



- Theory calculations agree with experiment.
- Support the vorticity interpretation of the global polarization

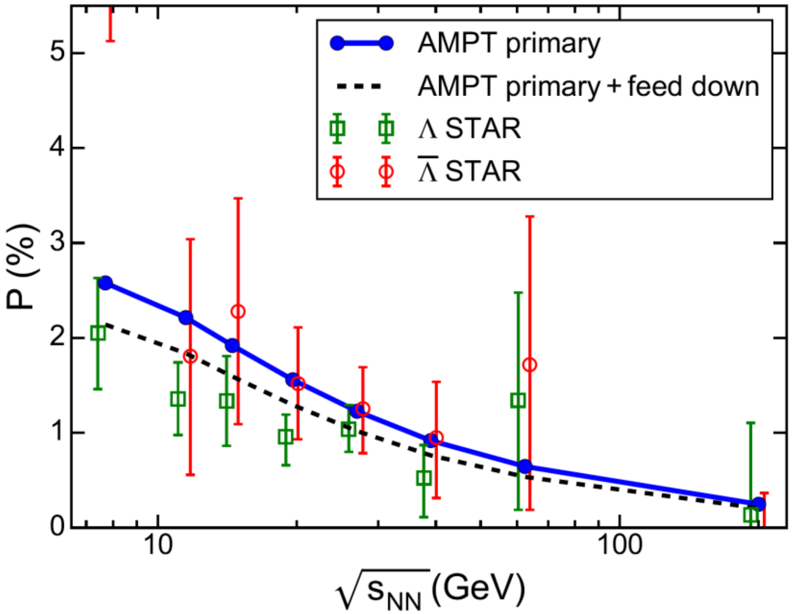
- See also:

  Hydro calculation:
  - Karpenko-Becattini 2017
  - Xie-Wang-Csernai 2017
  - Fu-Xu-Huang-Song 2020

  Transport model:
  - Shi-Li-Liao 2019
  - Wei-Deng-Huang 2019
  - Vitiuk-Bravina-Zabrodin 2020
  - …

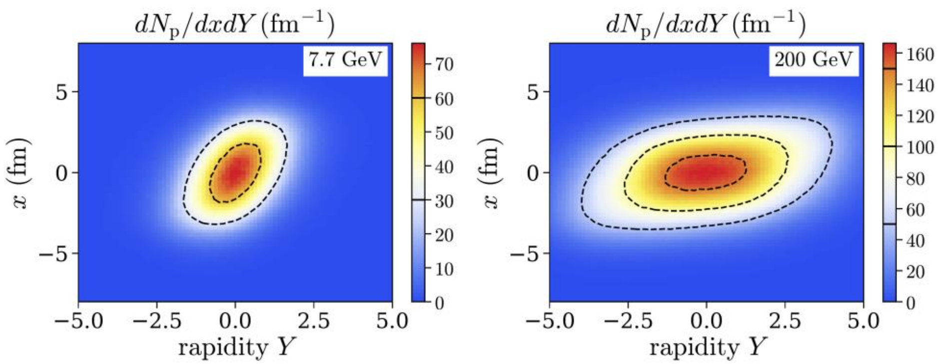
Global Λ polarization

Li-Pang-Wang-XLX, PRC 96, 054908 (2017)



$$P^{\mu} = -\frac{S+1}{6m}(1-n_F)\epsilon^{\mu\nu\rho\sigma}p_{\nu}\varpi_{\rho\sigma}$$

- P_{Λ} decreases with the increase of collision energy.
- More Bjorken-boost-invariant fluid produces smaller vorticity in mid-rapidity at higher energies.



Motivation

- The global Λ polarization has been well understood through the vorticity interpretation.

- To further test the vorticity interpretation, we can study the global polarization of other hyperons.

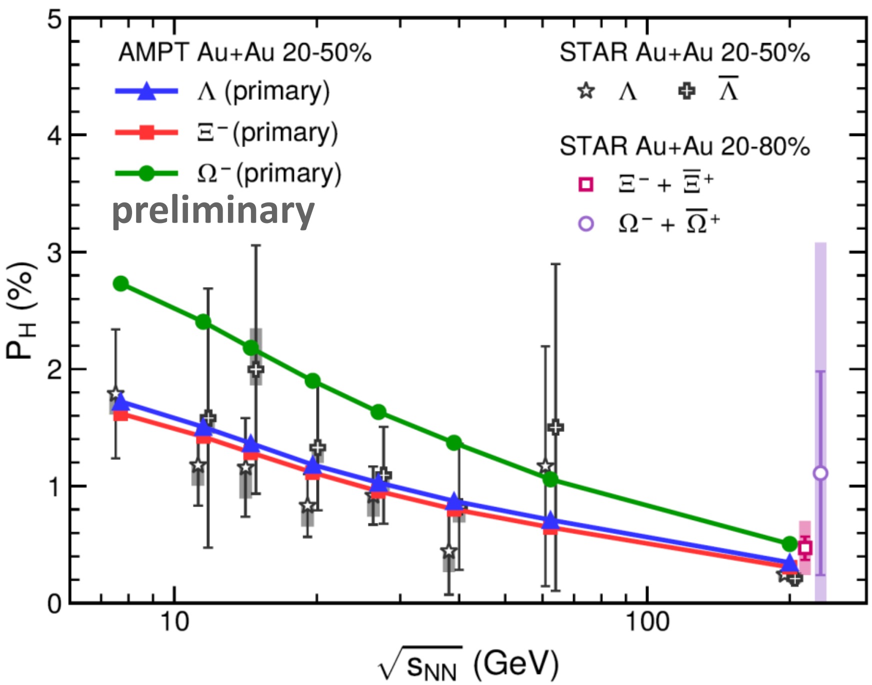
$$S_{\Lambda} = \frac{1}{2}, S_{\Xi^-} = \frac{1}{2}, S_{\Omega^-} = \frac{3}{2}$$

- To bridge the gap between theory and experiment, we also study the feed-down effect on their global polarizations.

Global polarization

Global polarization of primary Λ, Ξ^-, and Ω^-

Li-Xia-Huang-Huang, to appear



Consistent with the hydrodynamics calculation:

Fu-Xu-Huang-Song, Phys. Rev. C 103, 024903 (2021)

- P_Λ, P_{Ξ^-}, and P_{Ω^-} all decrease with the increase of collision energy.
- Primary global polarization ordering:

$$P_{\Omega^-} > P_\Lambda \simeq P_{\Xi^-}$$

- P_H depends on the spin number, energy-momentum, mass and space-time coordinates.

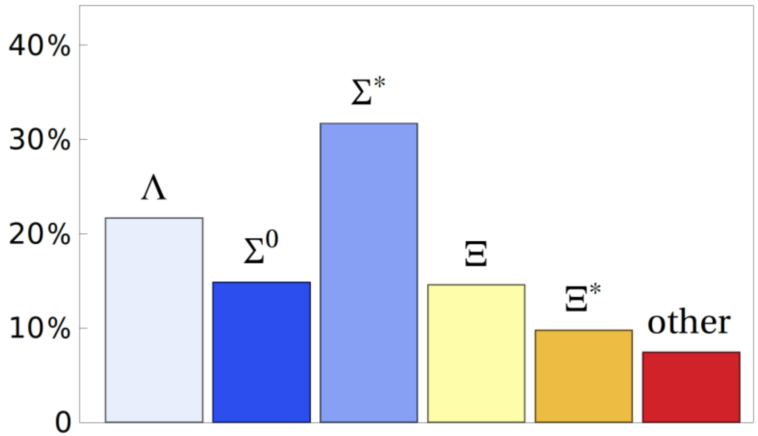
$$P^\mu \approx -\frac{S+1}{6}\epsilon^{\mu\nu\rho\sigma}\frac{p_\nu}{m}\varpi_{\rho\sigma}(x)$$

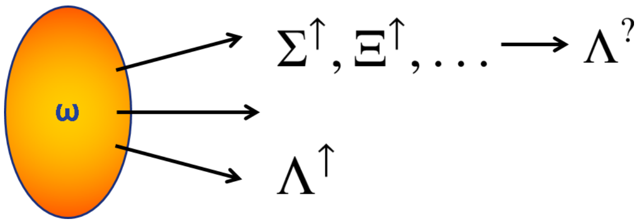
- $S_\Lambda = \frac{1}{2}, S_{\Xi^-} = \frac{1}{2}, S_{\Omega^-} = \frac{3}{2}$:

$$P_{\Omega^-} \simeq \frac{5}{3}P_\Lambda \simeq \frac{5}{3}P_{\Xi^-}$$

Feed-down effect

- The **primary** global polarizations are of the thermal particles produced from QGP.
- However, about 80% of final Λ's are produced by decay of heavier particles.





- All particles with spin are polarized and the spin can transfer to daughter:

$$\langle \mathbf{P}_D \rangle = C\mathbf{P}_P$$

Becattini-Karpenko-Lisa-Upsal-Voloshin, Phys. Rev. D 95, 054902 (2017)
Xia-Li-Huang-Huang, Phys. Rev. C 100, 014913 (2019)
Becattini-Cao-Speranza, Eur. Phys. J. C 79, 741 (2019)

Feed-down effect

- Spin transfer in decay $\langle \mathbf{P}_D \rangle = C\mathbf{P}_P$:

Decay	Spin and parity	C
Strong decay	$1/2^+ \to 1/2^+ 0^-$	-1/3
Strong decay	$1/2^- \to 1/2^+ 0^-$	1
Strong decay	$3/2^+ \to 1/2^+ 0^-$	1
Strong decay	$3/2^- \to 1/2^+ 0^-$	-3/5
Electromagnetic decay	$\Sigma^0 \to \Lambda\gamma$	-1/3
Weak decay	$\Xi^- \to \Lambda\pi^-$	$(1+2\gamma)/3 \approx 0.994$
Weak decay	$\Xi^0 \to \Lambda\pi^0$	$(1+2\gamma)/3 \approx 0.915$

- Apply the above rules to decays of $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$, Σ^0, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$, Ξ, $\Xi(1530)$.

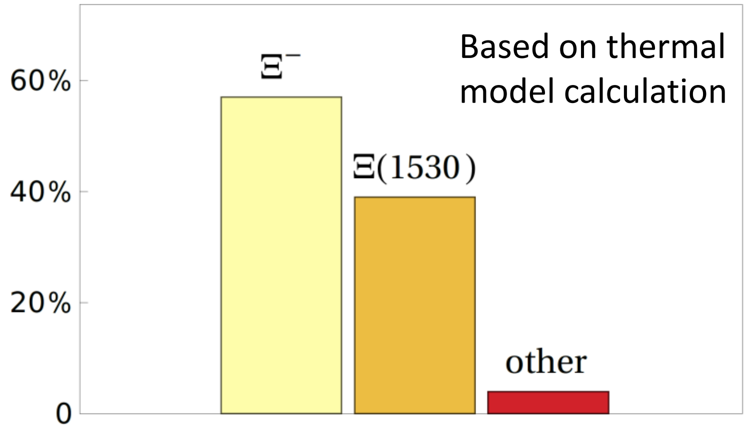
- The global polarization of Λ is reduced by $\sim 10\%$.

- The main contribution is $\Sigma^0 \to \Lambda\gamma$ with $C = -1/3$.

Becattini-Karpenko-Lisa-Upsal-Voloshin, Phys. Rev. D 95, 054902 (2017)
Xia-Li-Huang-Huang, Phys. Rev. C 100, 014913 (2019)
Becattini-Cao-Speranza, Eur. Phys. J. C 79, 741 (2019)

Feed-down effect on Ξ^- polarization

- About 60% of final Ξ^- are primary, and about 40% are from $\Xi(1530) \rightarrow \Xi^-\pi$



- In the decay $\Xi(1530) \rightarrow \Xi^-\pi$: $(3/2^+ \rightarrow 1/2^+ 0^-)$

(1) Spin transfer factor $C = 1$

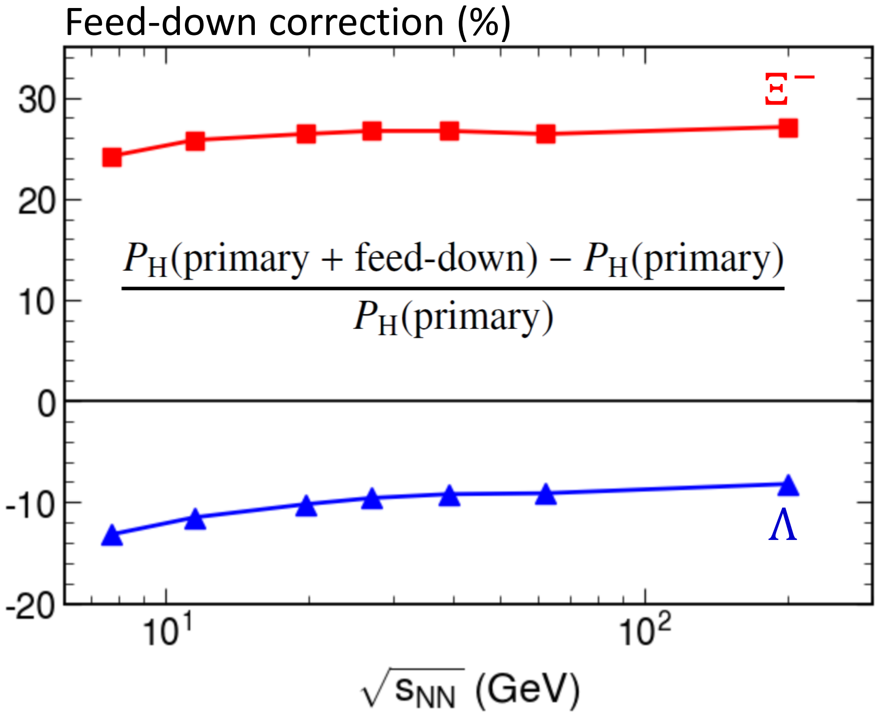
(2) Assume $P_{\Xi(1530)}^{\text{prim}} = \frac{5}{3} P_{\Xi^-}^{\text{prim}}$

$$P_{\Xi^-}(\text{primary+feed-down}) = \frac{N_{\Xi^-} + \frac{5}{3} N_{\Xi(1530)\rightarrow\Xi^-}}{N_{\Xi^-} + N_{\Xi(1530)\rightarrow\Xi^-}} P_{\Xi^-}(\text{primary})$$

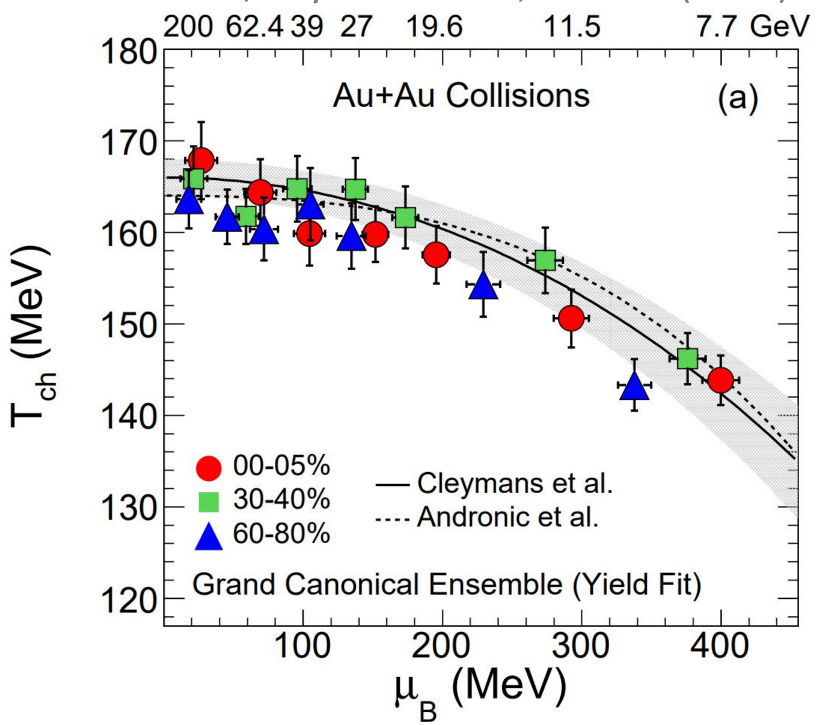
- The global polarization of Ξ^- is enhanced by $\sim$25%.

Feed-down effect

Li-Xia-Huang-Huang, to appear



STAR, Phys. Rev. C 96, 044904 (2017)

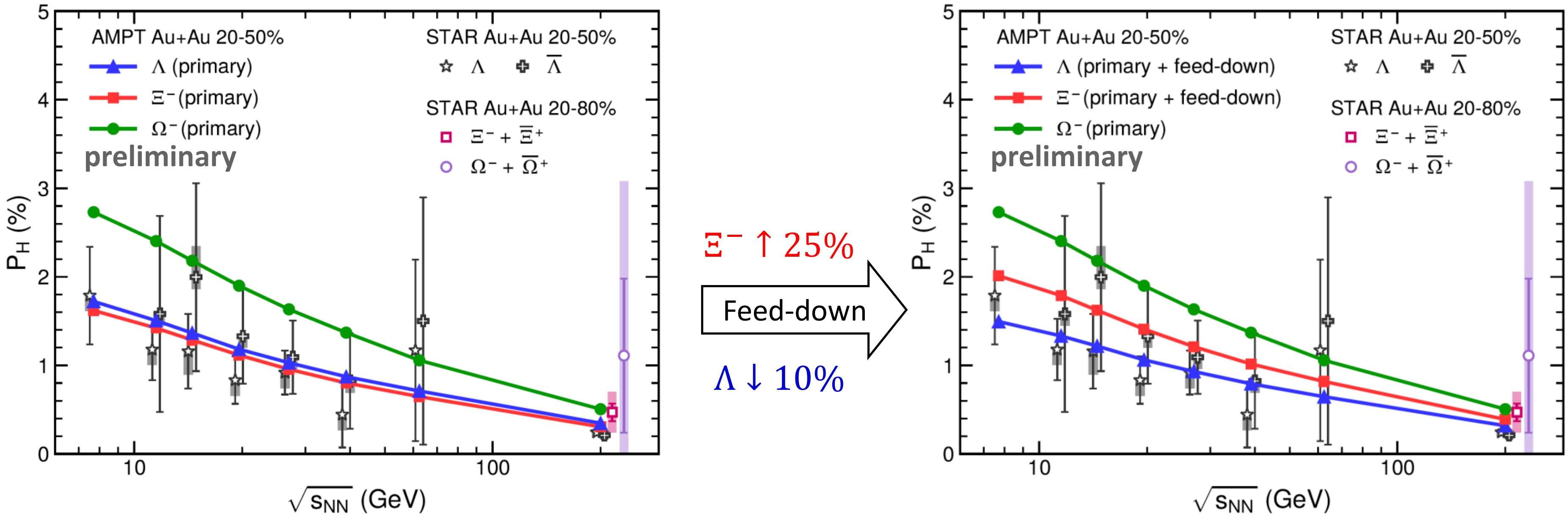


- 24–27% enhancement to the global polarization of primary Ξ^-.
- 8-13% reduction to the global polarization of primary Λ.
- The feed-down corrections slightly depend on energy due to different freeze-out parameters.

- Rare particles decay to Ω^-. Its feed-down effect is negligibly small.

Feed-down corrected global polarization

Li-Xia-Huang-Huang, to appear



- The **primary** global polarization fulfills $P_{\Lambda} \simeq P_{\Xi^-}$.
- With the **feed-down correction**, P_{Λ} and P_{Ξ^-} are separated. ☺
- Final global-polarization ordering:

$$P_{\Omega^-} > P_{\Xi^-} > P_{\Lambda}$$

Summary

- The global polarization of different hyperons provides a way to further test the vorticity interpretation of the global polarization.

- The **primary** global polarization fulfills $P_{\Omega^-} > P_{\Lambda} \simeq P_{\Xi^-}$.

- The **feed-down corrected** global polarization are in the ordering:

$$P_{\Omega^-} > P_{\Xi^-} > P_{\Lambda}$$

  - $P_{\Omega^-} > P_{\Lambda}$ and $P_{\Omega^-} > P_{\Xi^-}$ are due to the spin number.
  - $P_{\Xi^-} > P_{\Lambda}$ is because of the feed-down effect.

- The feed-down effect is crucial in interpreting the recent and future measurements of the global hyperon polarization.

Thank you for attention!