Λ polarization in heavy ion collisions

Haesom Sung, Su Houng Lee, Che Ming Ko

Yonsei University
Texas A&M University

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- **Λ+π cross section**
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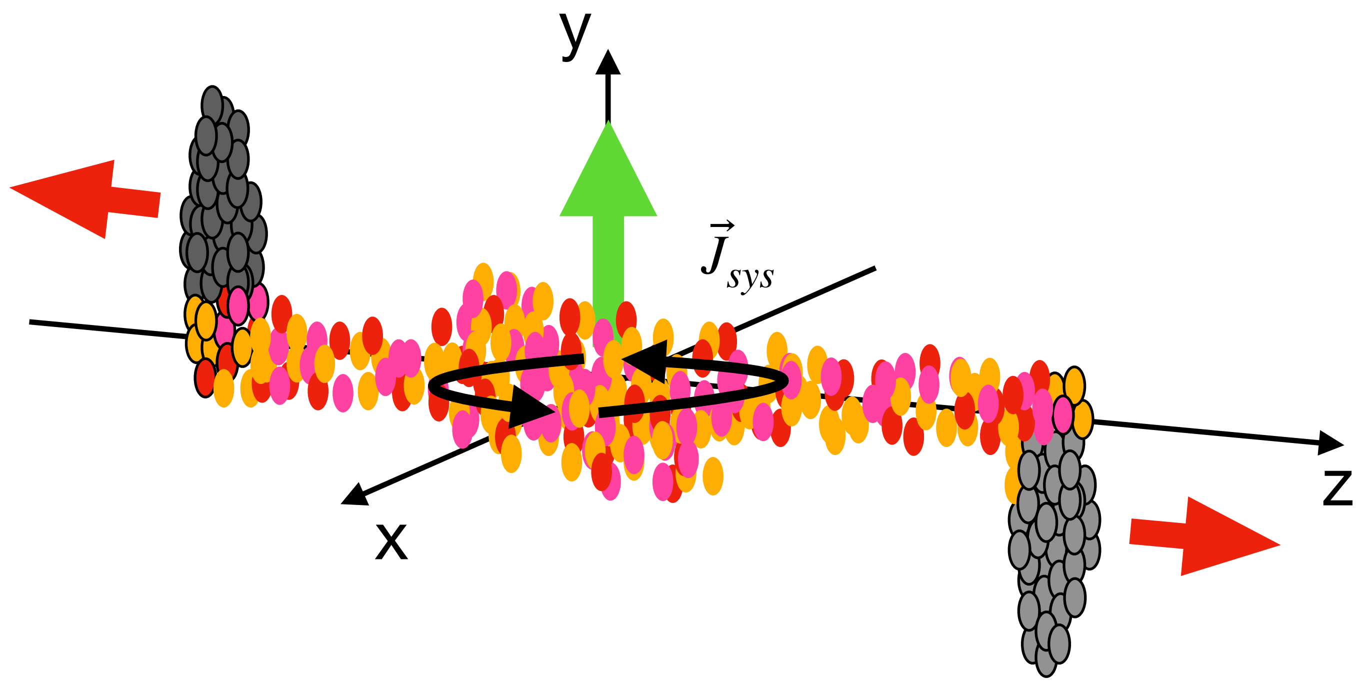
Introduction

Global and local polarization



- The vorticity ω represents local mechanical rotation of a fluid.
- The vorticity acts as a spin-current source.

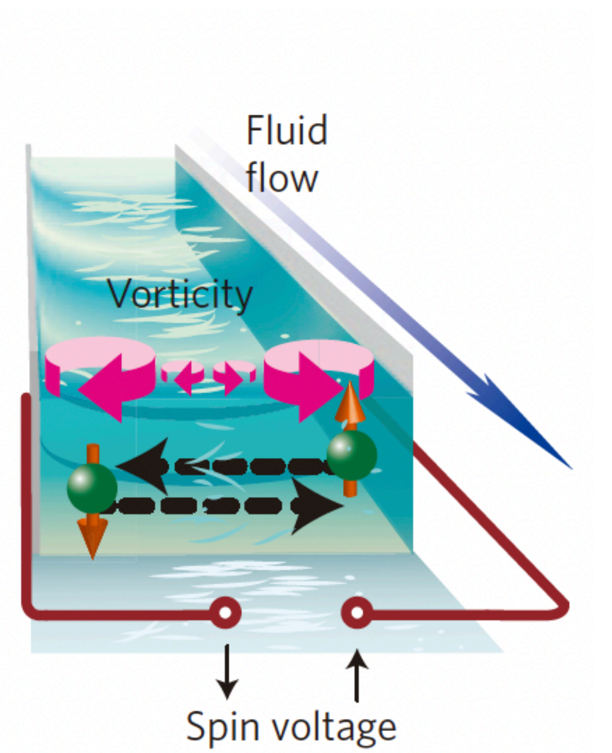
Takahashi. R, *et al.* Spin hydrodynamic generation. *Nature Phys* **12**, 52–56 (2016).

$$\nabla^2 \boldsymbol{\mu}^S = \frac{1}{\lambda^2}\boldsymbol{\mu}^S - \frac{4e^2}{\sigma_0 \hbar}\xi\boldsymbol{\omega}$$

$$\mu_s = \mu_\uparrow - \mu_\downarrow$$

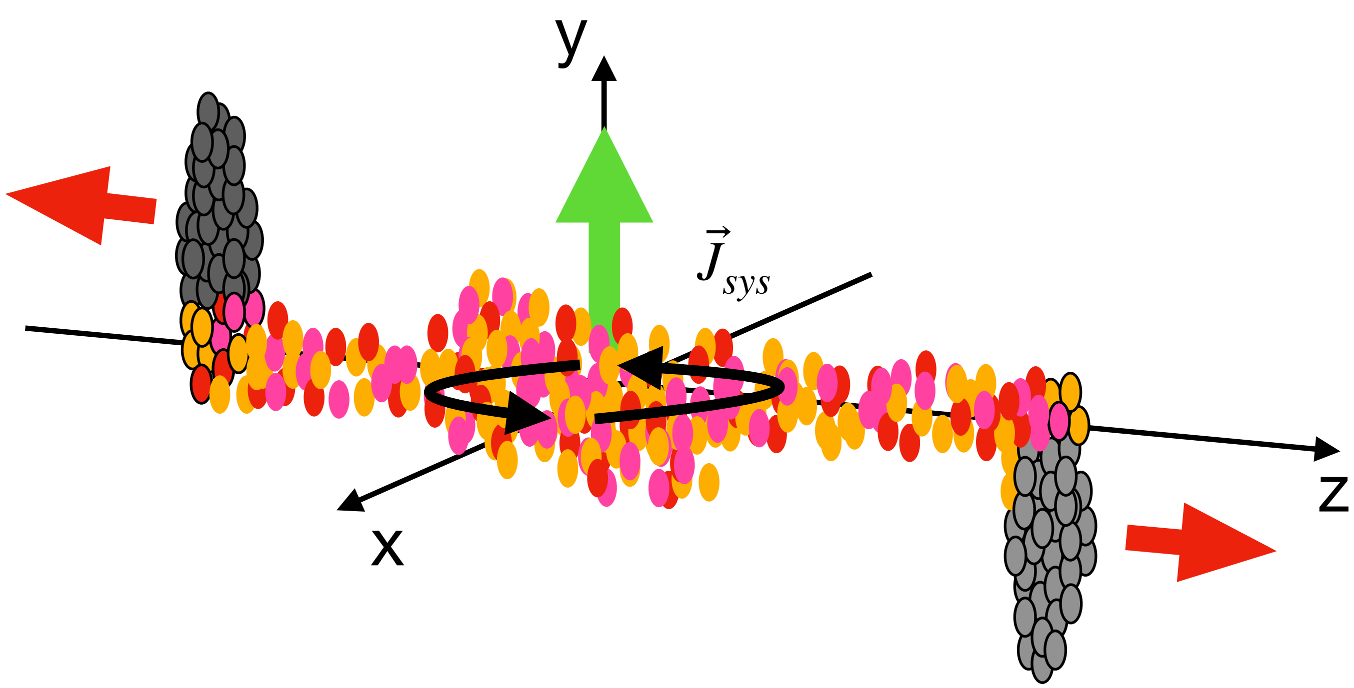
vorticity $\omega = \dfrac{1}{2}\nabla \times v$

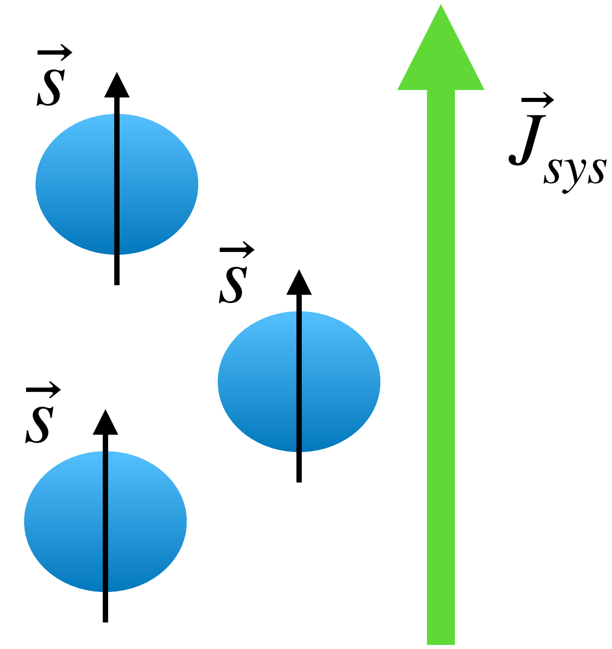
v: fluid velocity



Introduction

Global and local polarization





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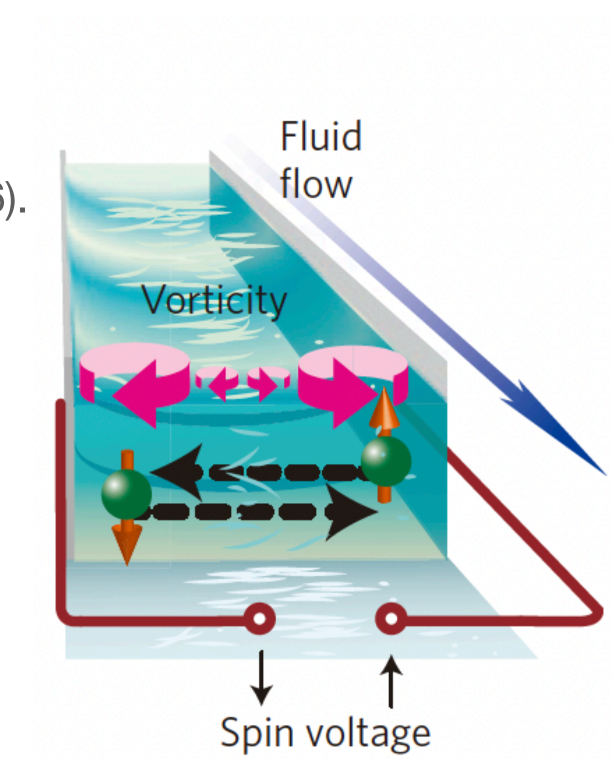
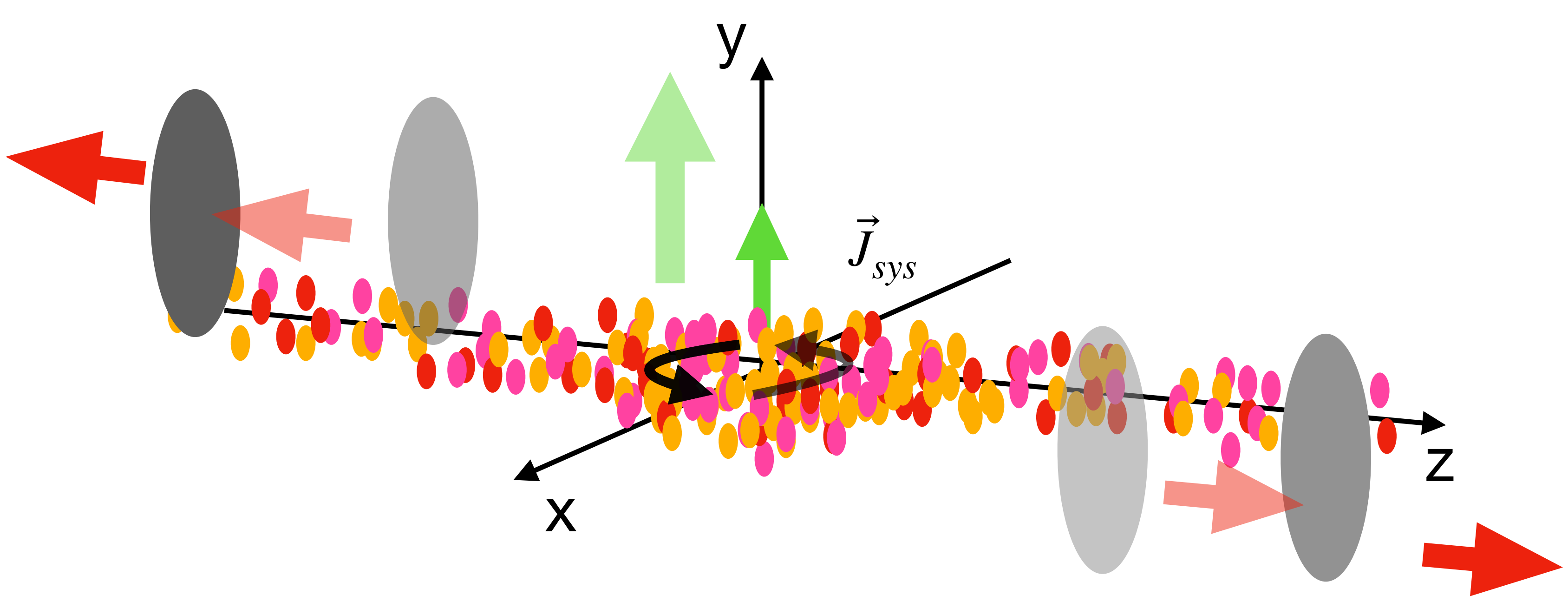
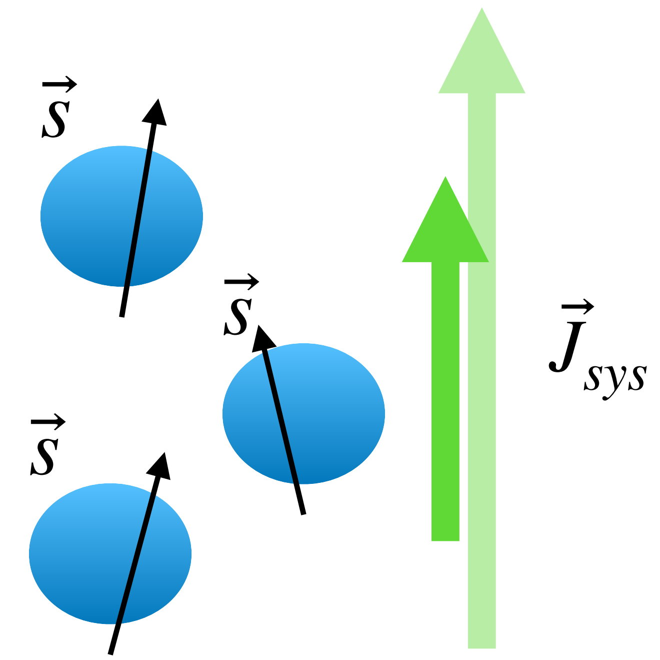


Introduction

Global and local polarization



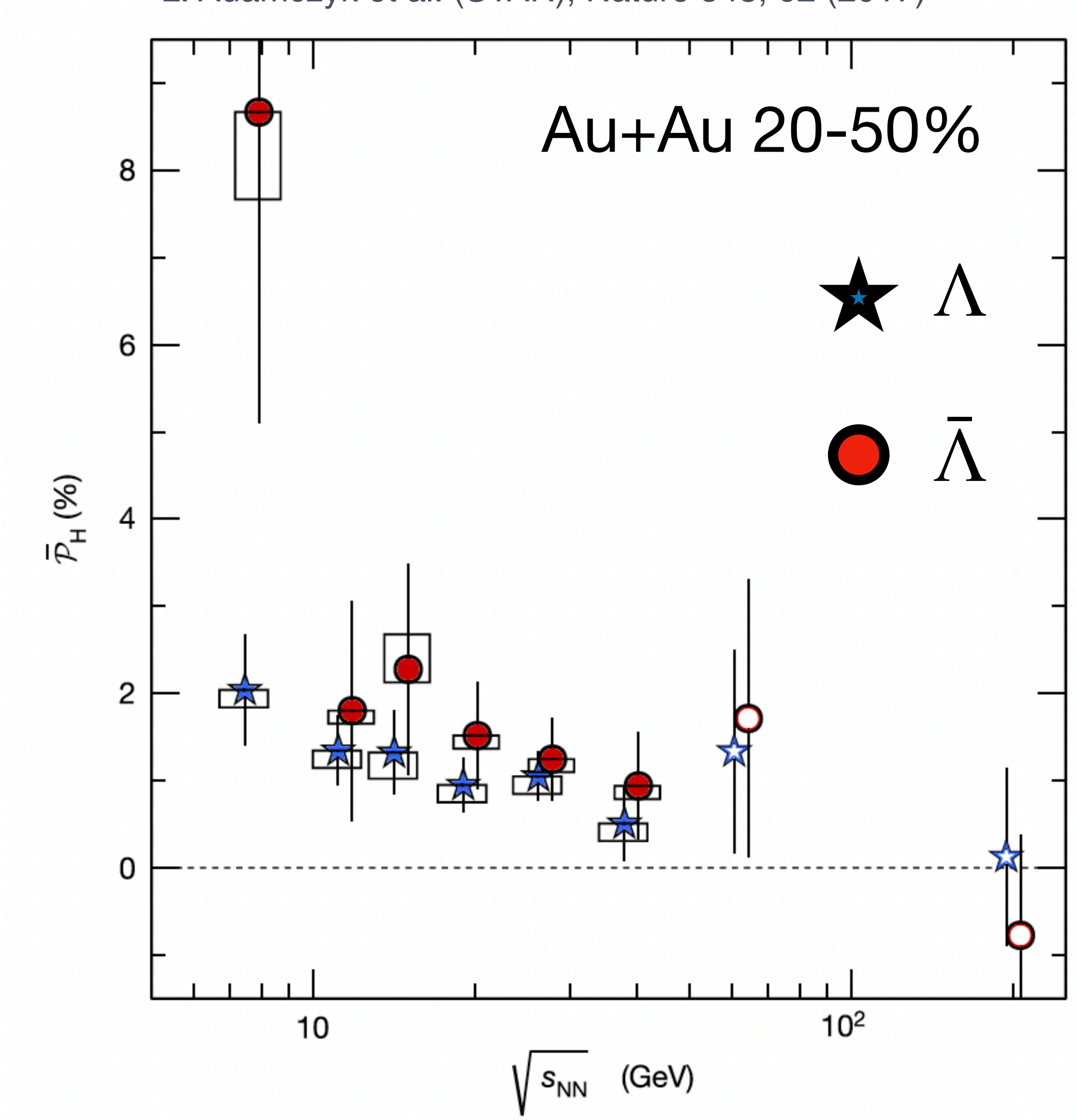


- Vorticity is getting weak with expanding of system
- We thought that collisions with other hadrons in the hadronic phase make the initial polarization to disappear.
- We expected that initial alignment of particle disappear in the final state.

Introduction

Global and local polarization

L. Adamczyk et al. (STAR), Nature 548, 62 (2017)

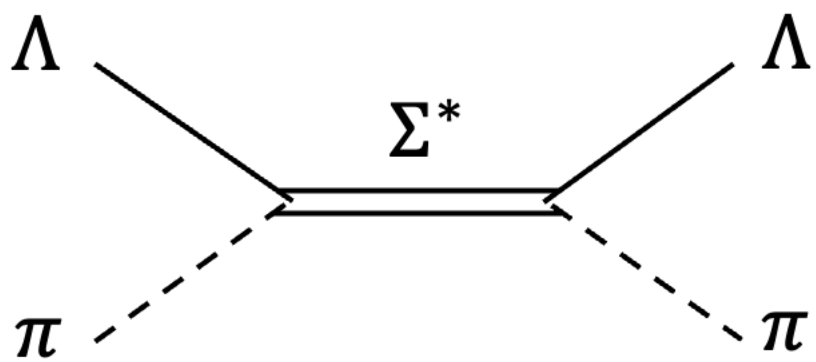


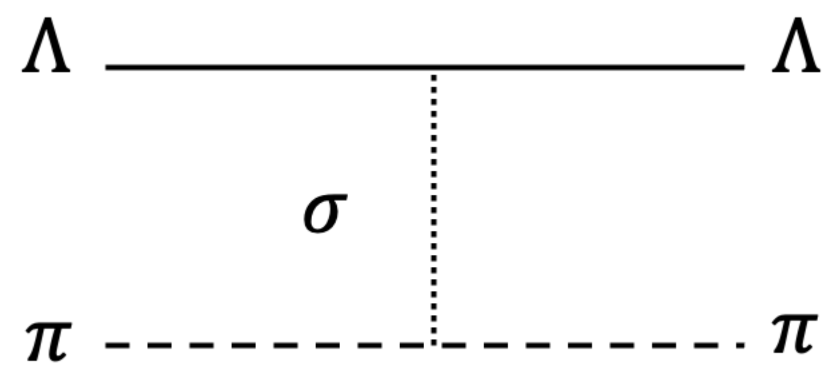
Non-zero global Λ polarization in Au+Au collisions

- Lambda polarization in early stage of system remains after scattering during hadron phase
- Estimate the Λ polarization during hadron phase

Kinetic equation of Λ

Scattering channel





Kinetic equation

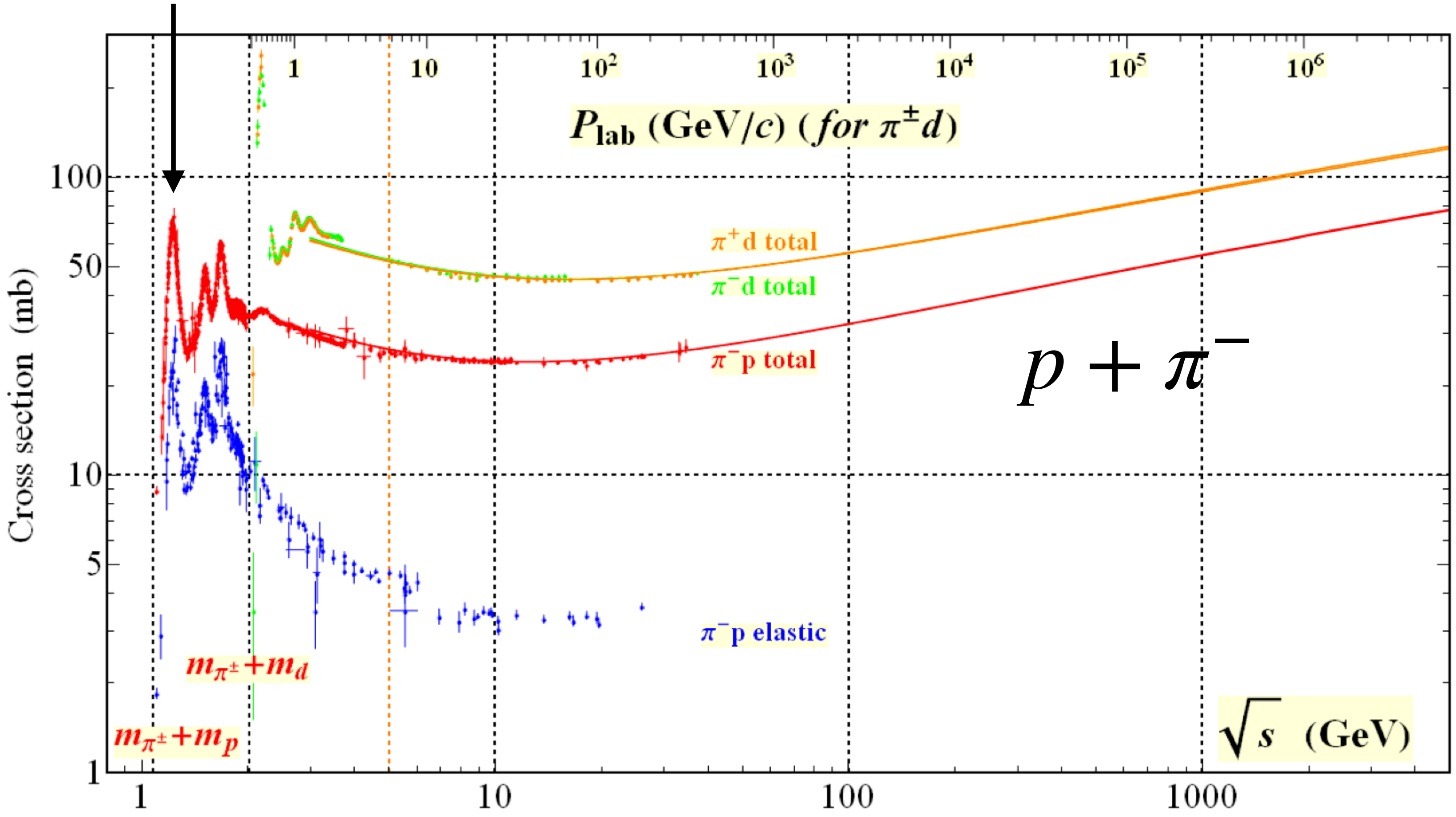
$$\frac{dN_{\Lambda_\uparrow}}{d\tau} = -\langle \sigma_{\Lambda_\uparrow \pi \to \Lambda_\downarrow \pi} v \rangle n_\pi N_{\Lambda_\uparrow} + \langle \sigma_{\Lambda_\downarrow \pi \to \Lambda_\uparrow \pi} v \rangle n_\pi N_{\Lambda_\downarrow}, \tag{20}$$

$$\frac{dN_{\Lambda_\downarrow}}{d\tau} = \langle \sigma_{\Lambda_\uparrow \pi \to \Lambda_\downarrow \pi} v \rangle n_\pi N_{\Lambda_\uparrow} - \langle \sigma_{\Lambda_\downarrow \pi \to \Lambda_\uparrow \pi} v \rangle n_\pi N_{\Lambda_\downarrow}, \tag{21}$$

Λ s-channel cross section

Σ^* resonance dominance

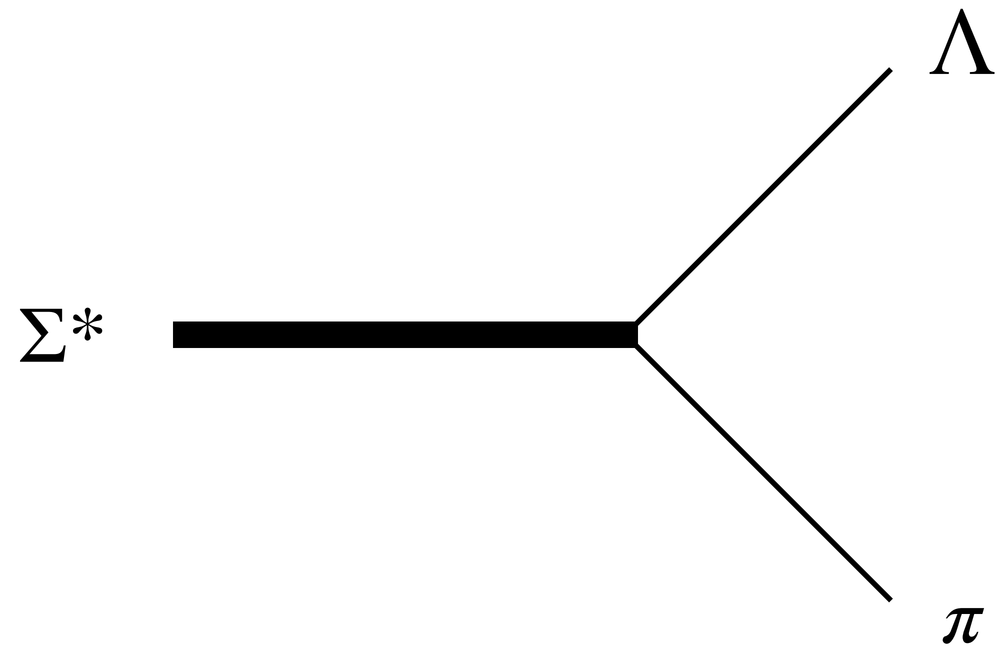
Δ resonance



- $p + \pi^-$ is p-wave, Δ(s=3/2) resonance is dominance
- => In the case of $\Lambda + \pi$, Σ^*(3/2) will be dominance

Λ s-channel cross section

Σ^* decay width and coupling constant



$$P^{\mu\nu} = -(\not{q} + M)\left[g_{\mu\nu} - \frac{\gamma_\mu\gamma_\nu}{3} - \frac{2q_\mu q_\nu}{3M^2} + \frac{q_\mu\gamma_\nu - q_\nu\gamma_\mu}{3M}\right]$$

$$i\mathscr{M} = \bar{u}_s(p_1)(ig)(ip_{2,\mu})u_r^\mu(k)$$

a ab

$$|\mathscr{M}|^2 = g^2 p_{2\mu}p_{2\nu}\bar{u}_s(p_1)u_r^\mu(k)\bar{u}_r^\nu(k)u_s(p_1)$$

a ab cd d

$$= g^2 p_{2\mu}p_{2\nu}\frac{1}{4}\sum_{r,s}[u_r^\mu(k)\bar{u}_r^\nu(k)]_{ad}[u_s(p_1)\bar{u}_s(p_1)]_{da}$$

$$|\mathscr{M}|^2 = -\frac{2}{3}g^2k^2(Mm_1 + \sqrt{k^2+m_1^2}\sqrt{k^2+m_2^2} + m_1^2 + k^2)$$

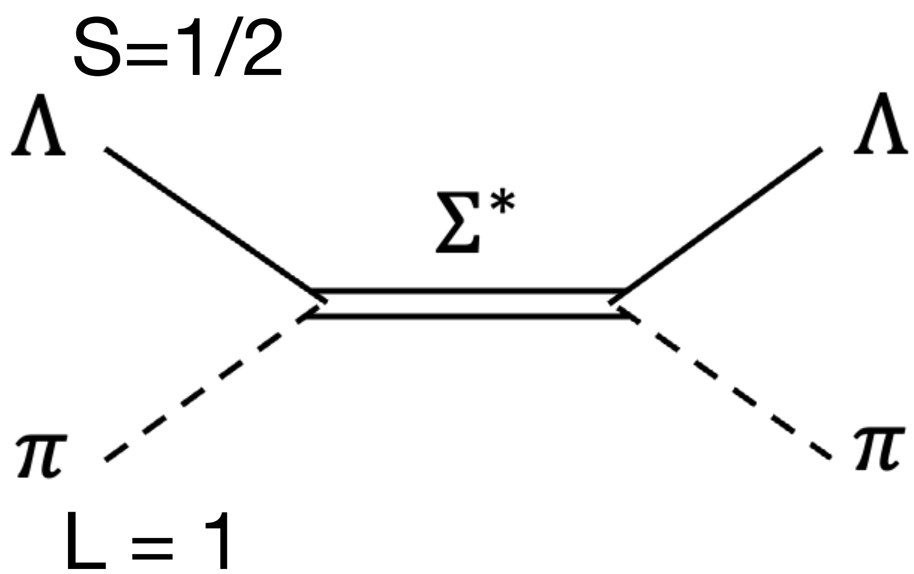
Decay width = 36MeV

=> $g_{\Sigma^*\Lambda\pi}$ = 9.83

Λ+π cross section

$$\sigma(s) = \frac{8\pi}{k^2}\frac{s\Gamma^2(s)}{(s-m_{\Sigma^*}^2)^2 + s\Gamma^2(s)}$$

Spin non-flip cross section



$$\langle j_1, m_1; j_2, m_2 | S | j_1, m_1; j_2, m_2 \rangle$$

$$\left\langle 1,1;\frac{1}{2},\frac{1}{2}|S|1,1;\frac{1}{2},\frac{1}{2}\right\rangle = a_{3/2},$$

$$\left\langle 1,1;\frac{1}{2},-\frac{1}{2}|S|1,0;\frac{1}{2},\frac{1}{2}\right\rangle = \frac{\sqrt{2}}{3}\left(a_{3/2}-a_{1/2}\right),$$

$$\left\langle 1,0;\frac{1}{2},\frac{1}{2}|S|1,0;\frac{1}{2},\frac{1}{2}\right\rangle = \frac{1}{3}\left(2a_{3/2}+a_{1/2}\right),$$

$$\left\langle 1,0;\frac{1}{2},-\frac{1}{2}|S|1,-1;\frac{1}{2},\frac{1}{2}\right\rangle = \frac{\sqrt{2}}{3}\left(a_{3/2}-a_{1/2}\right),$$

$$\left\langle 1,-1;\frac{1}{2},\frac{1}{2}|S|1,-1;\frac{1}{2},\frac{1}{2}\right\rangle = \frac{1}{3}\left(a_{3/2}+2a_{1/2}\right).$$

1. Spin non-flip cross section

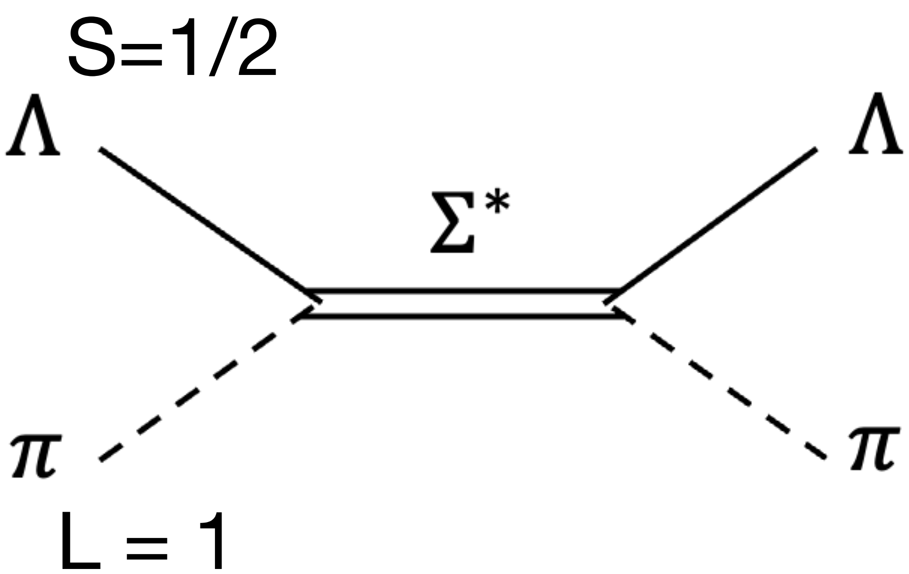
$$\sigma_{\uparrow\uparrow} = \bar{\sigma}\left(1+\left(\frac{2}{3}\right)^2+\left(\frac{1}{3}\right)^2\right) = \frac{14}{9}\bar{\sigma}$$

$$\begin{aligned}\sigma_{\uparrow\uparrow} &= \bar{\sigma}\sum_{m,M}\left|\left\langle \frac{1}{2}\frac{1}{2}1m\middle|\frac{3}{2}M\right\rangle\right|^4 \\ &= \bar{\sigma}\left[\left|\left\langle \frac{1}{2}\frac{1}{2}11\middle|\frac{3}{2}\frac{3}{2}\right\rangle\right|^4 + \left|\left\langle \frac{1}{2}\frac{1}{2}10\middle|\frac{3}{2}\frac{1}{2}\right\rangle\right|^4 \right.\\ &\quad \left. + \left|\left\langle \frac{1}{2}\frac{1}{2}1-1\middle|\frac{3}{2}-\frac{1}{2}\right\rangle\right|^4\right] \\ &= \bar{\sigma}\left[1+\left(\sqrt{\frac{2}{3}}\right)^4+\left(\sqrt{\frac{1}{3}}\right)^4\right] = \frac{14}{9}\bar{\sigma}.\end{aligned}$$

Λ+π cross section

Spin flip cross section

$$\sigma(s) = \frac{8\pi}{k^2}\frac{s\Gamma^2(s)}{(s - m_{\Sigma^*}^2)^2 + s\Gamma^2(s)}$$



$$\langle j_1, m_1; j_2, m_2 | S | j_1, m_1; j_2, m_2 \rangle$$

$$\left\langle 1,1;\frac{1}{2},\frac{1}{2}\,|\,S\,|\,1,1;\frac{1}{2},\frac{1}{2}\right\rangle = a_{3/2},$$

$$\left\langle 1,1;\frac{1}{2},-\frac{1}{2}\,|\,S\,|\,1,0;\frac{1}{2},\frac{1}{2}\right\rangle = \frac{\sqrt{2}}{3}\left(a_{3/2} - a_{1/2}\right),$$

$$\left\langle 1,0;\frac{1}{2},\frac{1}{2}\,|\,S\,|\,1,0;\frac{1}{2},\frac{1}{2}\right\rangle = \frac{1}{3}\left(2a_{3/2} + a_{1/2}\right),$$

$$\left\langle 1,0;\frac{1}{2},-\frac{1}{2}\,|\,S\,|\,1,-1;\frac{1}{2},\frac{1}{2}\right\rangle = \frac{\sqrt{2}}{3}\left(a_{3/2} - a_{1/2}\right),$$

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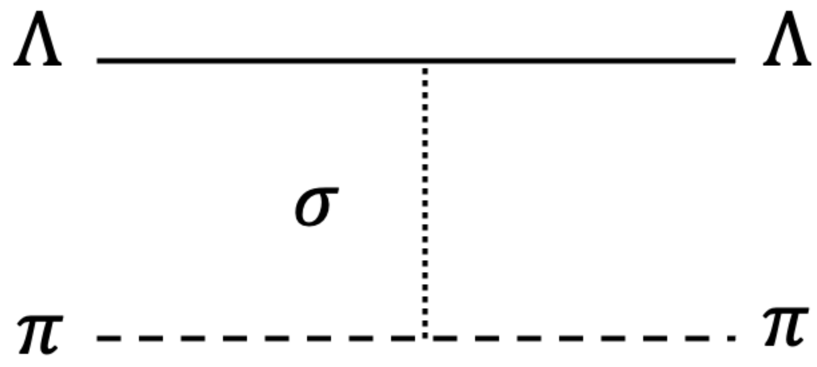
2. Spin flip cross section

$$\sigma_{\uparrow\downarrow} = \bar{\sigma}\left(\left(\frac{\sqrt{2}}{3}\right)^2 + \left(\frac{\sqrt{2}}{3}\right)^2\right) = \frac{4}{9}\bar{\sigma}$$

$$\begin{aligned}\sigma_{\uparrow\downarrow} &= \bar{\sigma}\sum_{m,M}\left|\left\langle \tfrac{1}{2} - \tfrac{1}{2} 1m \middle| \tfrac{3}{2} M\right\rangle \left\langle \tfrac{3}{2} M \middle| \tfrac{1}{2}\tfrac{1}{2} 1m\right\rangle\right|^2 \\ &= \bar{\sigma}\left[\left|\left\langle \tfrac{1}{2} - \tfrac{1}{2} 11 \middle| \tfrac{3}{2}\tfrac{1}{2}\right\rangle \left\langle \tfrac{3}{2}\tfrac{1}{2} \middle| \tfrac{1}{2}\tfrac{1}{2} 10\right\rangle\right|^2 \right. \\ &\quad \left. + \left|\left\langle \tfrac{1}{2} - \tfrac{1}{2} 10 \middle| \tfrac{3}{2} - \tfrac{1}{2}\right\rangle \left\langle \tfrac{3}{2} - \tfrac{1}{2} \middle| \tfrac{1}{2}\tfrac{1}{2} 1 - 1\right\rangle\right|^2\right] \\ &= \bar{\sigma}\left[\left(\sqrt{\tfrac{1}{3}}\sqrt{\tfrac{2}{3}}\right)^2 + \left(\sqrt{\tfrac{2}{3}}\sqrt{\tfrac{1}{3}}\right)^2\right] = \tfrac{4}{9}\bar{\sigma} \qquad (4)\end{aligned}$$

Λ+π cross section

t-channel with σ

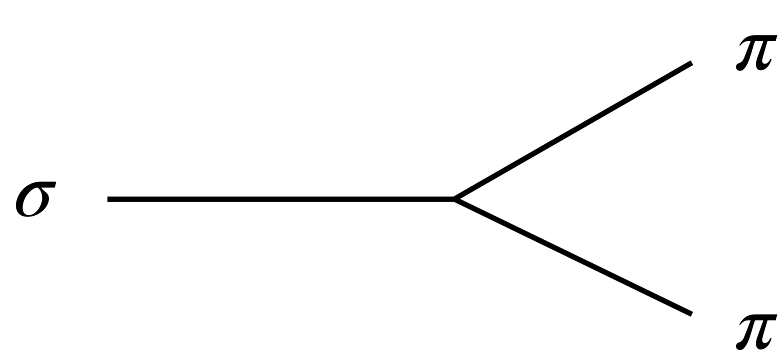


For quark counting rule,

$$g_{\Lambda\Lambda\sigma} = g_{NN\sigma} * 2/3 = 10.6 * 2/3 = 7.07$$

Advanced in Nuclear Physics Vol19, (p.226), Machleidt

σ decay width and coupling constant



$$i\mathscr{M} = ig_2$$

$$\mathcal{L}_{\sigma\Lambda\Lambda} = g_{\sigma\Lambda\Lambda}\bar{\Lambda}\Lambda\sigma$$

$$\mathcal{L}_{\sigma\pi\pi} = g_{\sigma\pi\pi}\sigma\pi\pi.$$

$$\Gamma = \frac{g_2^2}{8\pi s}|\vec{p}_{cm}|$$

$$= \frac{g_2^2}{8\pi s}\frac{[(s-(m_1+m_2)^2)(s-(m_1-m_2)^2)]^{1/2}}{2\sqrt{s}}$$

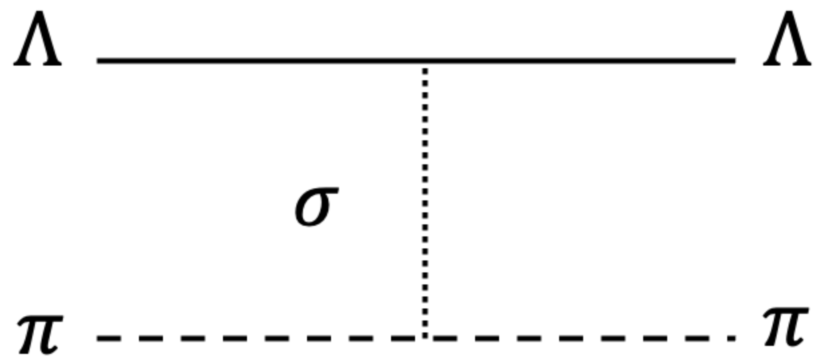
$$= \frac{g_2^2}{8\pi m_\sigma^2}\frac{\sqrt{m_\sigma^2-4m_\pi^2}}{2}$$

n Fig. 64.3 we read the range of pole positions for the $f_0(500)$, namely,

$$\sqrt{s^\sigma_{\rm Pole}} = (400-550) - i(200-350)\ \text{MeV}\ .$$

Λ+π cross section

Spin averaged t-channel cross section



$$\mathcal{L}_{\sigma\Lambda\Lambda} = g_{\sigma\Lambda\Lambda}\bar{\Lambda}\Lambda\sigma$$
$$\mathcal{L}_{\sigma\pi\pi} = g_{\sigma\pi\pi}\sigma\pi\pi.$$

$$F(q^2) = \frac{\Lambda^2 + t}{\Lambda^2 + m_\sigma^2},$$ with Λ = 1.8 GeV

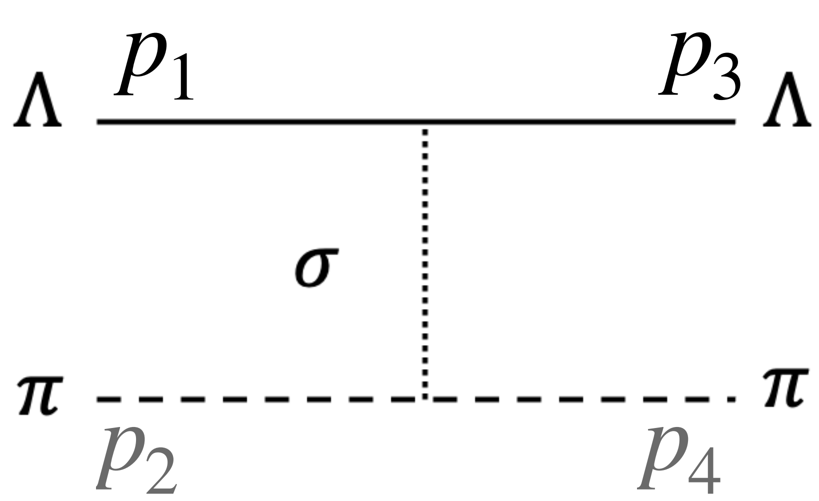
$$i\mathcal{M}_t = g_{\Lambda\Lambda\sigma} g_{\sigma\pi\pi} \bar{u}(p_3) \frac{i}{t - m_\sigma^2 + i m_\sigma \Gamma_\sigma(s)} u(p_1),$$

$$\begin{aligned}
|\overline{\mathcal{M}_t}|^2 &= \frac{g_{\Lambda\Lambda\sigma}^2 g_{\sigma\pi\pi}^2}{2} \frac{\mathrm{Tr}\left[(\not{p}_3 + m_\Lambda)(\not{p}_1 + m_\Lambda)\right]}{(t - m_\sigma^2)^2 + m_\sigma^2 \Gamma_\sigma(s)^2}, \\
&= 2 g_{\Lambda\Lambda\sigma}^2 g_{\sigma\pi\pi}^2 \frac{p_1 \cdot p_3 + m_\Lambda^2}{(t - m_\sigma^2)^2 + m_\sigma^2 \Gamma_\sigma(s)^2}, \\
&= g_{\Lambda\Lambda\sigma}^2 g_{\sigma\pi\pi}^2 \frac{4 m_\Lambda^2 - t}{(t - m_\sigma^2)^2 + m_\sigma^2 \Gamma_\sigma(s)^2}.
\end{aligned}$$

$$\Rightarrow \quad \boxed{\frac{d\sigma}{d\Omega} = \frac{1}{63\pi^2 s} \overline{|\mathcal{M}_t|^2} F^4(t).}$$

Λ+π cross section

spin flip & non-flip cross section



$$i\mathcal{M}_t = g_{\Lambda\Lambda\sigma} g_{\sigma\pi\pi} \bar{u}(p_3) \frac{i}{t - m_\sigma^2 + i m_\sigma \Gamma_\sigma(s)} u(p_1),$$

1. Spin non-flip cross section

$$\begin{aligned} \bar{u}_{s_f}(p_3) u_{s_i}(p_1) &= (E_\Lambda + m_\Lambda) \left(\chi_{s_f}^\dagger, \chi_{s_f}^\dagger \frac{\mathbf{p}_3 \cdot \boldsymbol{\sigma}}{E_\Lambda + m}\right) \\ &\times \begin{pmatrix} \chi_{s_i} \\ -\frac{\mathbf{p}_1 \cdot \boldsymbol{\sigma}}{E_\Lambda + m_\Lambda} \chi_{s_i} \end{pmatrix} \\ &= (E_\Lambda + m_\Lambda) \left\{ \left[1 - \frac{\mathbf{p}_3 \cdot \mathbf{p}_1}{(E_\Lambda + m_\Lambda)^2} \right] \chi_{s_f}^\dagger \chi_{s_i} \right. \\ &\left. - i \frac{\mathbf{p}_3 \times \mathbf{p}_1}{(E_\Lambda + m_\Lambda)^2} \chi_{s_f}^\dagger \boldsymbol{\sigma} \chi_{s_i} \right\}. \end{aligned} \quad (13)$$

$$\chi_+ = \begin{pmatrix} \cos\frac{\theta}{2} \\ e^{i\phi} \sin\frac{\theta}{2} \end{pmatrix}, \ \chi_- = \begin{pmatrix} \sin\frac{\theta}{2} \\ -e^{i\phi} \cos\frac{\theta}{2} \end{pmatrix}.$$

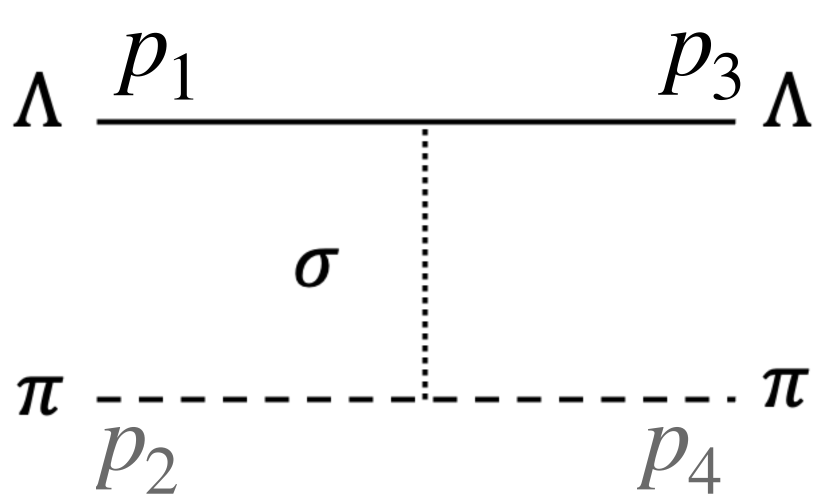
Using these expressions and $\sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$, one then has

$$\chi_+^\dagger \sigma_y \chi_+ = 0, \qquad \chi_-^\dagger \sigma_y \chi_+ = -ie^{i\phi}, \qquad (15)$$

$$\Rightarrow \quad \bar{u}_+(p_3) u_+(p_1) = (E_\Lambda + m_\Lambda) \left[1 - \frac{p^2 \cos\theta}{(E_\Lambda + m_\Lambda)^2} \right],$$

Λ+π cross section

spin flip & non-flip cross section



$$i\mathcal{M}_t = g_{\Lambda\Lambda\sigma} g_{\sigma\pi\pi} \bar{u}(p_3) \frac{i}{t - m_\sigma^2 + i m_\sigma \Gamma_\sigma(s)} u(p_1),$$

2. Spin flip cross section

$$\bar{u}_{s_f}(p_3) u_{s_i}(p_1) = (E_\Lambda + m_\Lambda) \left(\chi_{s_f}^\dagger, \chi_{s_f}^\dagger \frac{\mathbf{p}_3 \cdot \boldsymbol{\sigma}}{E_\Lambda + m}\right) \times \begin{pmatrix} \chi_{s_i} \\ -\frac{\mathbf{p}_1 \cdot \boldsymbol{\sigma}}{E_\Lambda + m_\Lambda} \chi_{s_i} \end{pmatrix}$$
$$= (E_\Lambda + m_\Lambda) \left\{ \left[1 - \frac{\mathbf{p}_3 \cdot \mathbf{p}_1}{(E_\Lambda + m_\Lambda)^2} \right] \chi_{s_f}^\dagger \chi_{s_i} - i \frac{\mathbf{p}_3 \times \mathbf{p}_1}{(E_\Lambda + m_\Lambda)^2} \cdot \chi_{s_f}^\dagger \boldsymbol{\sigma} \chi_{s_i} \right\}. \quad (13)$$

$$\chi_+ = \begin{pmatrix} \cos\frac{\theta}{2} \\ e^{i\phi} \sin\frac{\theta}{2} \end{pmatrix}, \quad \chi_- = \begin{pmatrix} \sin\frac{\theta}{2} \\ -e^{i\phi} \cos\frac{\theta}{2} \end{pmatrix}.$$

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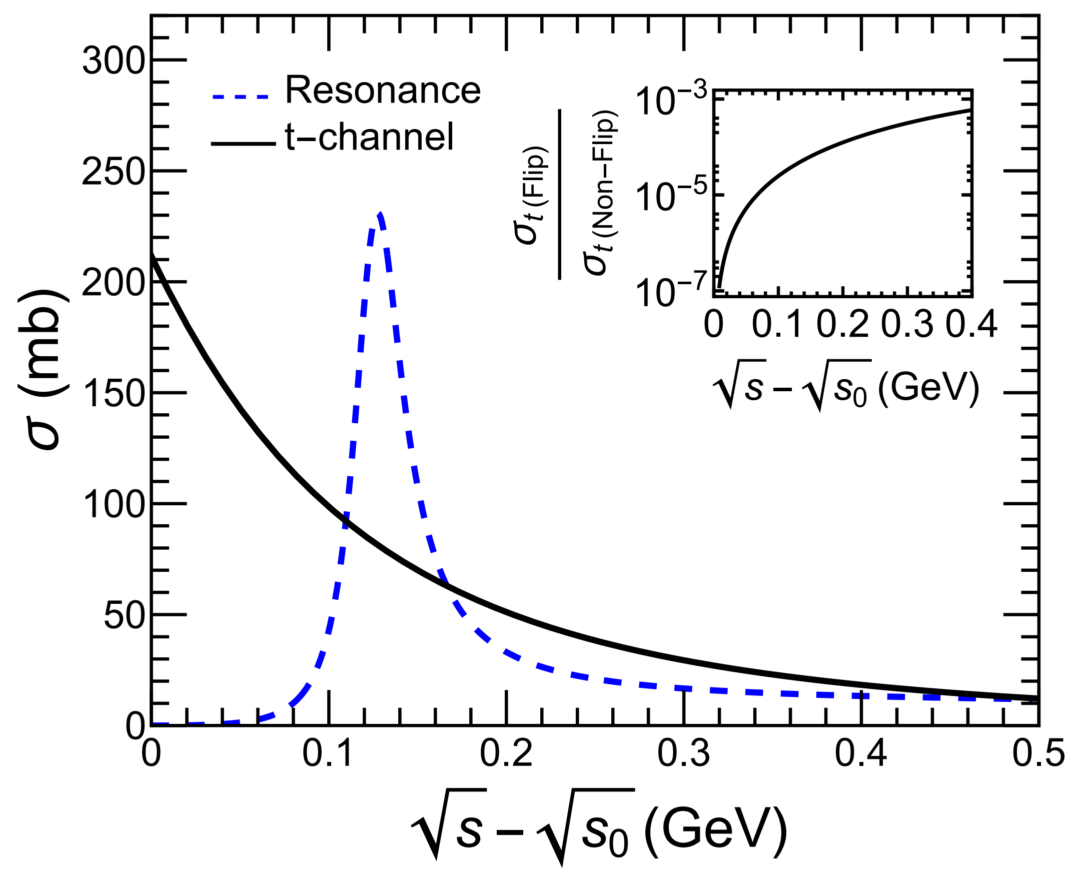
$$\Rightarrow \quad \bar{u}_-(p_3) u_+(p_1) = \frac{e^{i\phi} p^2 \sin\theta}{E_\Lambda + m_\Lambda}.$$

Λ+π cross section

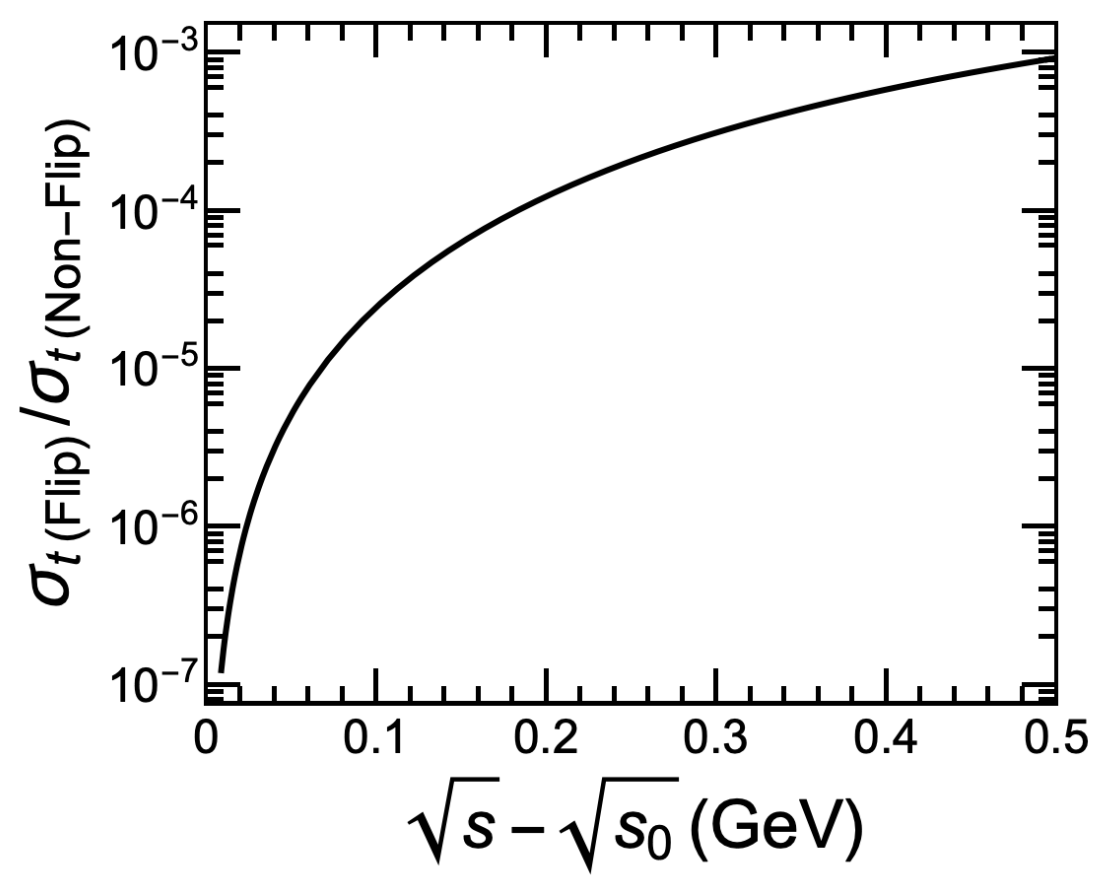
spin flip cross section of t-channel



Spin flip & non-flip amplitude

$$|\mathcal{M}_{t++}|^2 = \frac{g^2_{\Lambda\Lambda\sigma} g^2_{\sigma\pi\pi}}{(t - m^2_\sigma)^2 + m^2_\sigma \Gamma_\sigma(s)^2}, \times (E_\Lambda + m_\Lambda)^2 \left[1 - \frac{p^2 \cos\theta}{(E_\Lambda + m_\Lambda)^2}\right]^2 . \quad (17)$$

$$|\mathcal{M}_{t+-}|^2 = \frac{g^2_{\Lambda\Lambda\sigma} g^2_{\sigma\pi\pi}}{(t - m^2_\sigma)^2 + m^2_\sigma \Gamma_\sigma(s)^2} \frac{p^4 \sin^2\theta}{(E_\Lambda + m_\Lambda)^2} \quad (18)$$



Resonance cross section is the majority of Λ spin flip cross section.

t-channel is negligible for spin flip case

Result

Kinetic equation

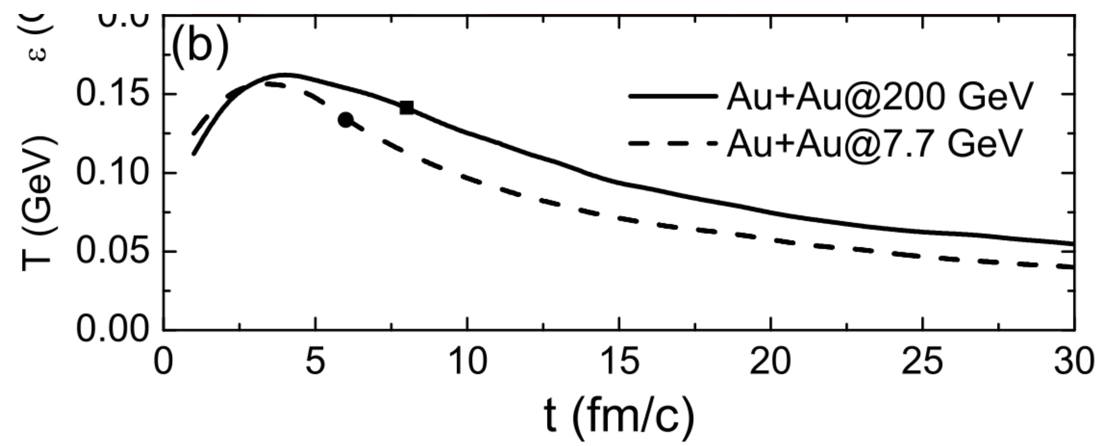
$$\frac{dN_{\Lambda_\uparrow}}{d\tau} = -\langle\sigma_{\Lambda_\uparrow\pi\to\Lambda_\downarrow\pi}v\rangle n_\pi N_{\Lambda_\uparrow} + \langle\sigma_{\Lambda_\downarrow\pi\to\Lambda_\uparrow\pi}v\rangle n_\pi N_{\Lambda_\downarrow}, \quad (20)$$

$$\frac{dN_{\Lambda_\downarrow}}{d\tau} = \langle\sigma_{\Lambda_\uparrow\pi\to\Lambda_\downarrow\pi}v\rangle n_\pi N_{\Lambda_\uparrow} - \langle\sigma_{\Lambda_\downarrow\pi\to\Lambda_\uparrow\pi}v\rangle n_\pi N_{\Lambda_\downarrow}, \quad (21)$$

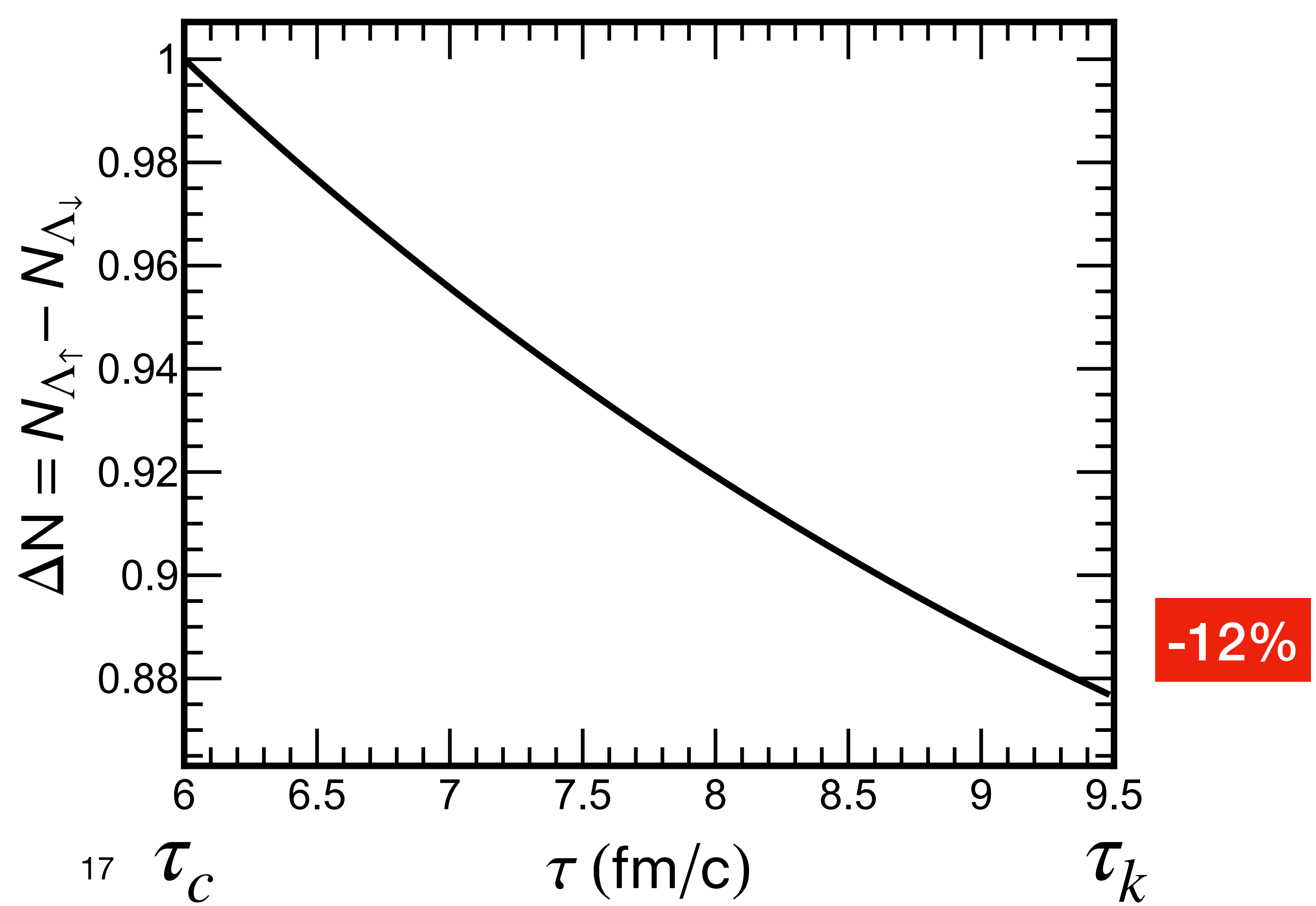
$$\Delta N(\tau) = N_{\Lambda\uparrow}(\tau) - N_{\Lambda\downarrow}(\tau)$$

$$\frac{d\Delta N}{d\tau} = -2 < \sigma v > \Delta N$$

J. Xu and C. M. Ko, Phys. Lett. B 772, 290 (2017), arXiv:1704.04934 [nucl-th]



Au+Au 7.7 GeV



Result show that Λ scattering during hadronic phase do not much affect to disappear the initial polarization

Summary

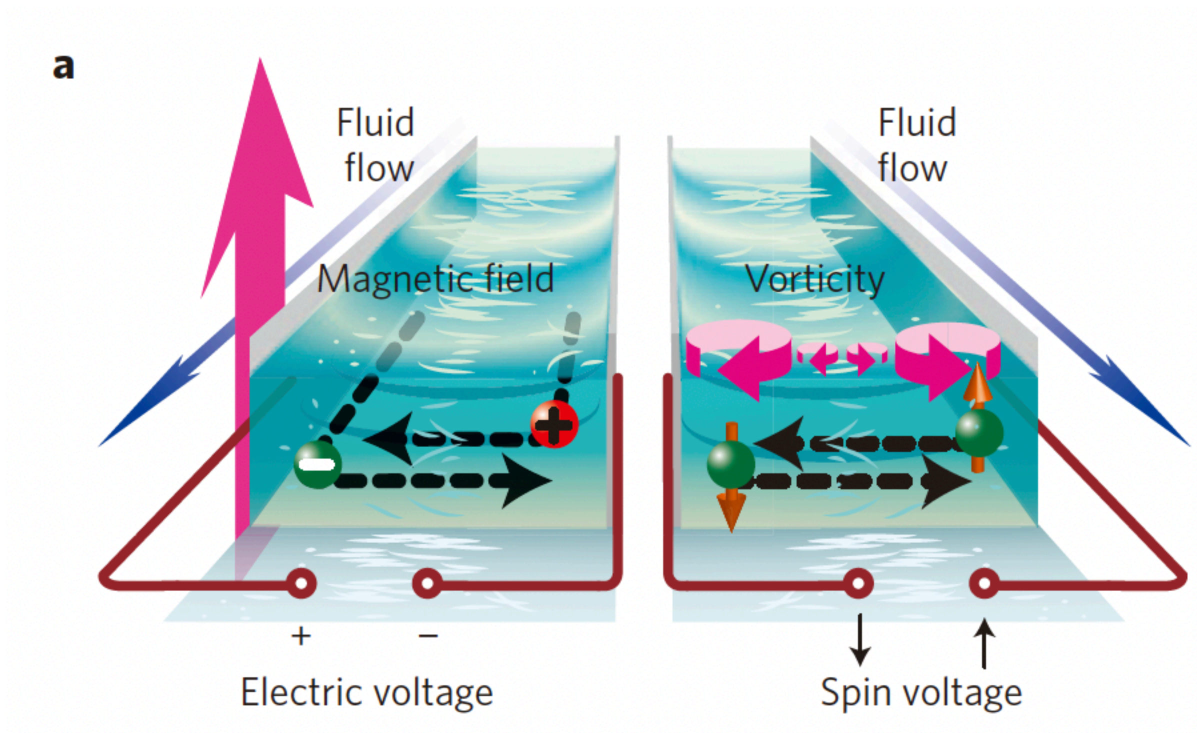
- Σ^* resonance cross section is important for estimating the spin non-flip Λ

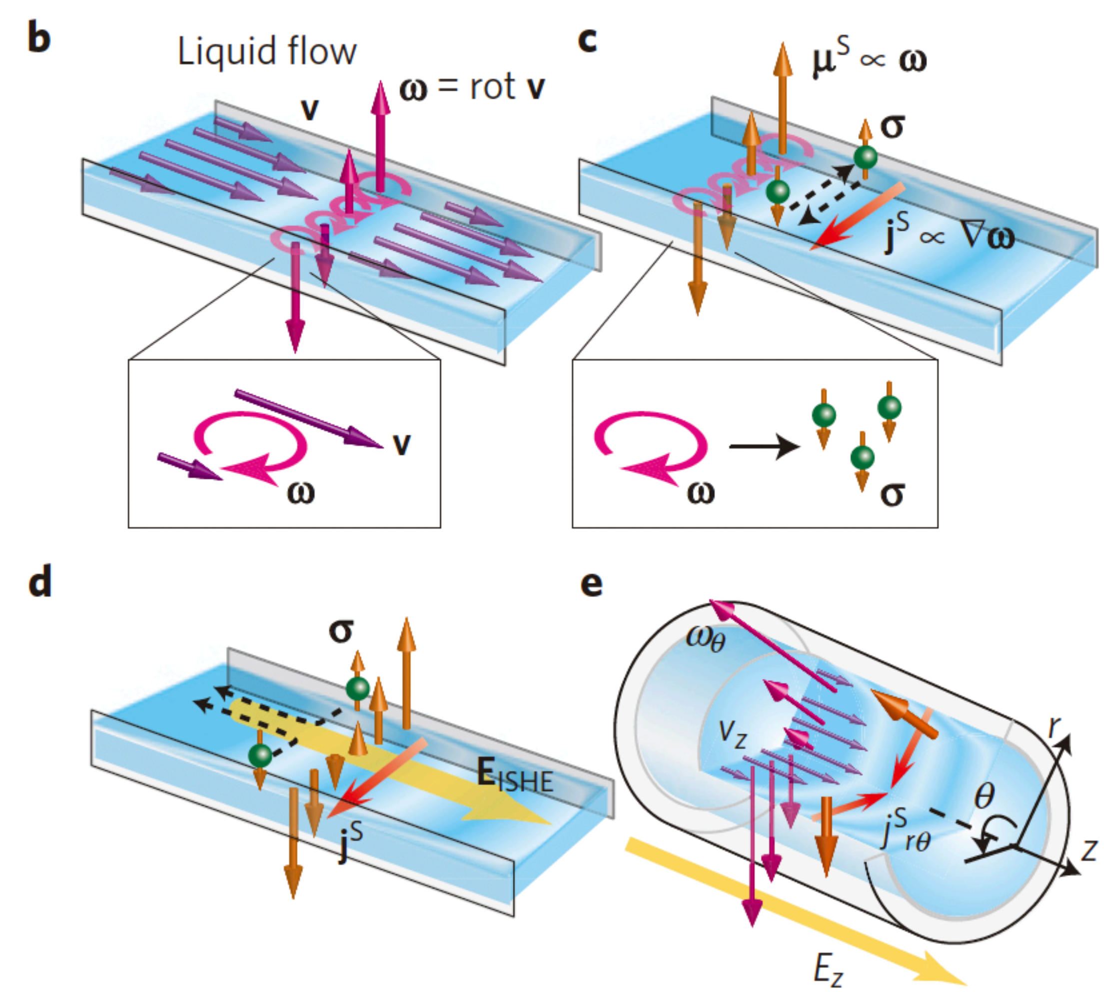
- The Λ spin polarization decrease by only about 12% during the hadronic stage of heavy ion collisions (Au+Au at $\sqrt{s} = 7.7$ GeV)

Appendix

Vorticity & Chiral Magnetic Effect

Takahashi, R., Matsuo, M., Ono, M. *et al.* Spin hydrodynamic generation. *Nature Phys* **12**, 52–56 (2016). https://doi.org/10.1038/nphys3526





$$\nabla^2 \boldsymbol{\mu}^S = \frac{1}{\lambda^2}\boldsymbol{\mu}^S - \frac{4e^2}{\sigma_0 \hbar}\xi\boldsymbol{\omega}$$

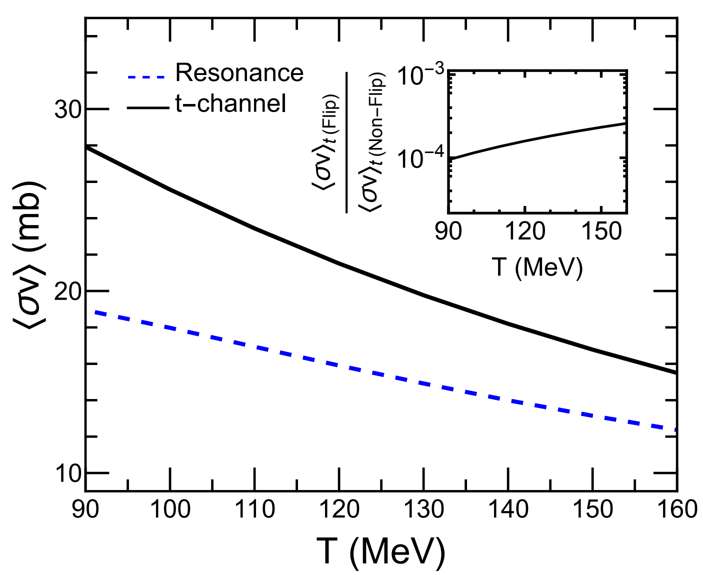
$$\mu_s = \mu_\uparrow - \mu_\downarrow$$

The vorticity ω = rot v represents local mechanical rotation of a fluid,

where v is the fluid velocity.

The vorticity acts as a spin-current source

- The effect of Λ scattering by nucleons, whose number is only about a factor of three smaller than the pion number in AuAu at 7.7 GeV



Spinor 1/2

1. Weyl representation(Peskin, Schwartz)

$$\gamma_0 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, u(0) = \sqrt{m}\begin{bmatrix} \xi \\ \xi \end{bmatrix}$$

$$u(p) = \begin{bmatrix} \sqrt{p\cdot\sigma}\xi \\ \sqrt{p\cdot\bar{\sigma}}\xi \end{bmatrix}$$

$$\sum_{s=1,2} u^s(p)\bar{u}^s(p) = \sum_s \begin{pmatrix} \sqrt{p\cdot\sigma}\xi^s \\ \sqrt{p\cdot\bar\sigma}\xi^s \end{pmatrix} \left(\xi^{s\dagger}\sqrt{p\cdot\bar\sigma}, \xi^{s\dagger}\sqrt{p\cdot\sigma}\right)$$

$$= \begin{pmatrix} \sqrt{p\cdot\sigma}\sqrt{p\cdot\bar\sigma} & \sqrt{p\cdot\sigma}\sqrt{p\cdot\sigma} \\ \sqrt{p\cdot\bar\sigma}\sqrt{p\cdot\bar\sigma} & \sqrt{p\cdot\bar\sigma}\sqrt{p\cdot\sigma} \end{pmatrix}$$

$$= \begin{pmatrix} m & p\cdot\sigma \\ p\cdot\bar\sigma & m \end{pmatrix}$$

$$= \gamma\cdot p + m$$

2. Dirac representation(Sakurai)

$$\gamma_0 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, u(0) = \begin{bmatrix} \xi \\ 0 \end{bmatrix}$$

$$u(p) = \sqrt{E+m}\begin{bmatrix} \xi \\ \dfrac{\vec{p}\cdot\vec{\sigma}}{E+m}\xi \end{bmatrix}$$

$$\sum_s u(p)\bar{u}^s(p) = \begin{pmatrix} \xi \\ \frac{\vec\sigma\cdot\vec p}{E+m}\xi \end{pmatrix} \left(\xi^\dagger, -\xi^\dagger\frac{\vec\sigma\cdot\vec p}{E+m}\right) \times (E+m)$$

$$= \begin{pmatrix} 1 & -\frac{\vec\sigma\cdot\vec p}{E+m} \\ \frac{\vec\sigma\cdot\vec p}{E+m} & -\frac{|\vec p|^2}{(E+m)^2} \end{pmatrix} \times (E+m) = \begin{pmatrix} E+m & -\vec\sigma\cdot\vec p \\ \vec\sigma\cdot\vec p & -\frac{|\vec p|^2}{(E+m)} \end{pmatrix}$$

$$= \begin{pmatrix} E+m & -\vec\sigma\cdot\vec p \\ \vec\sigma\cdot\vec p & -E+m \end{pmatrix}$$

$$= \gamma\cdot p + m$$

$$\gamma\cdot p + m := E\gamma^0 - \vec{p}\cdot\vec{\gamma} + m\mathbb{1} = \begin{pmatrix} E+m & -\vec p\cdot\vec\sigma \\ \vec p\cdot\vec\sigma & -E+m \end{pmatrix}$$

https://www.epj-conferences.org/articles/epjconf/pdf/2023/02/epjconf_sqm2022_03009.pdf

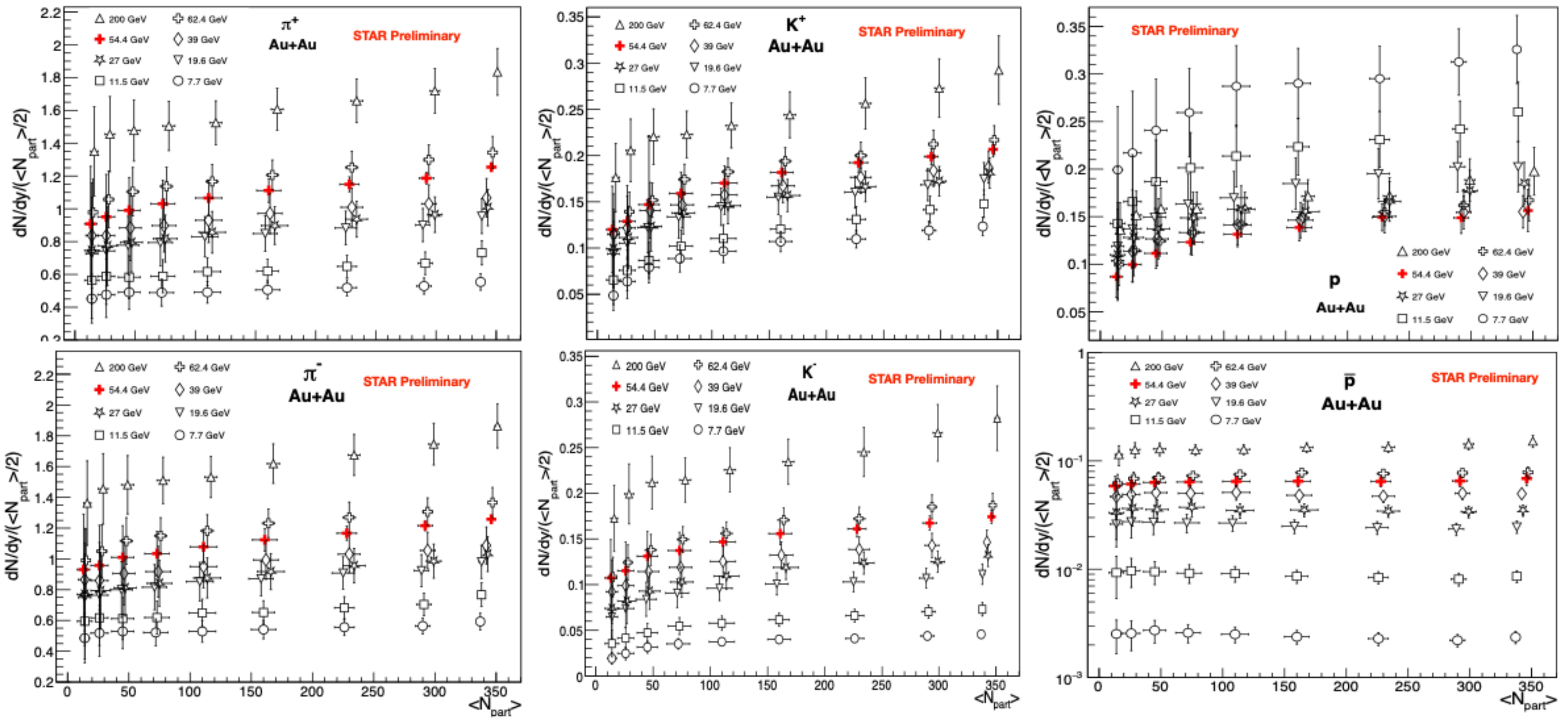


Figure 2. Centrality dependence of dN/dy normalized by $\langle N_{\text{part}}\rangle/2$ for $\pi^{\pm}$, $K^{\pm}$, and $p(\bar{p})$ at mid-rapidity ($|y| < 0.1$) in Au+Au collisions at $\sqrt{s_{NN}} = 54.4$ GeV. Errors shown are quadrature sums of statistical and systematic uncertainties.

Nature 548, 62 (2017)

Global Λ hyperon polarization in nuclear collision, STAR

- Heavy ion collisions in non-central collisions make fluid with strong vortical structure, which is needed to understand fluid properly.

- The vortical structure is also of particular interest because the **restoration of fundamental symmetries of quantum chromodynamics** is expected to produce novel **physical effects** in the presence of strong vorticity.

  - *No experimental indication of fluid vorticity in heavy ion collisions. Since **vorticity** represent **local rotational structure, S-L coupling** can lead to preferential orientation of paricle spins along the angular momentum.

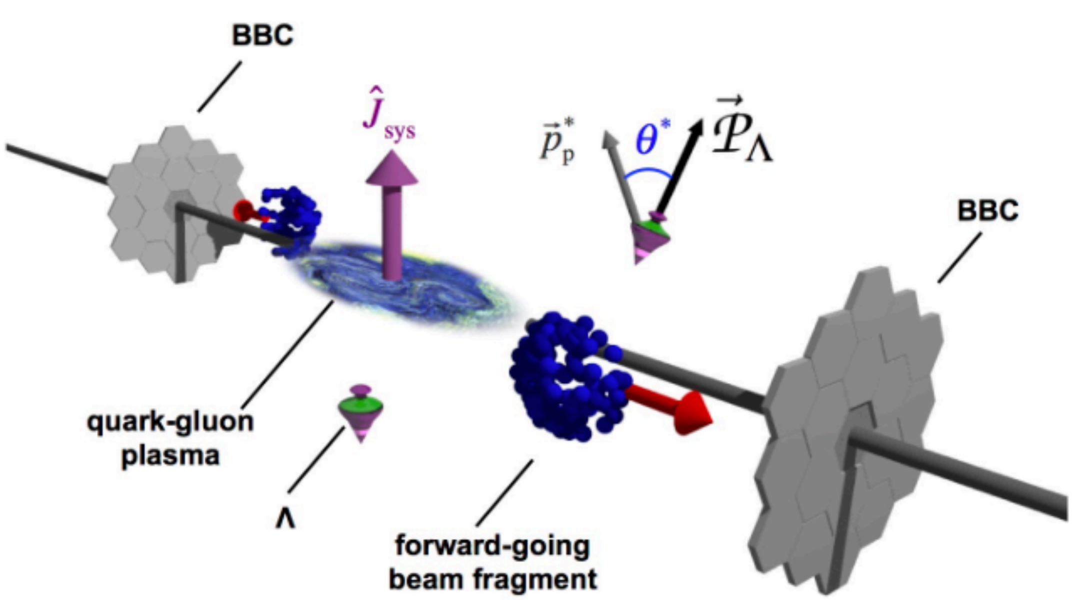
=> Measurement of an alignment between the global angular momentum and the spin of the emitted particles(Λ). => few cent of positive polarizatio

Global Λ polarization

L. Adamczyk et al. (STAR), Nature 548, 62 (2017)

https://www.star.bnl.gov/central/focus/LdbPola/

- Due to the parity-violating nature of their weak decay, **Lambdas reveal** the direction of their spin by preferentially **emitting the daughter proton** along that direction
- the polarization of emitted particles is directly related to the vorticity - the curl of the flow field - of the fluid
- The coupling between mechanical rotation of a system and quantum spin of a particle



Λ polarization:

new tool to study QGP and

relativistic Quantum fluid Vorticity

Nature 548, 62 (2017)

Global Λ hyperon polarization in nuclear collision, STAR

- fluid -> low viscosity -> hydrodynamic theory
- RHIC -> quark confinement, the origin of hadron mass
- *shear force introducing vorticity to the fluid
- The **vorticity** is a key ingredient in theories that predict observable effects associated with **chiral symmetry restoration**
- Spin-orbit coupling -> spin alignment along the vorticity in the local fluid cell, which, when averaged over the entire system, is parallel to $\hat{J}_{sys}$.
- **self-analyzing**: hyperon's decay process inherently contains information about its polarization. e.x. $\Lambda \rightarrow p + \pi^-$, the proton tends to be emitted along the spin direction of the parent Λ.

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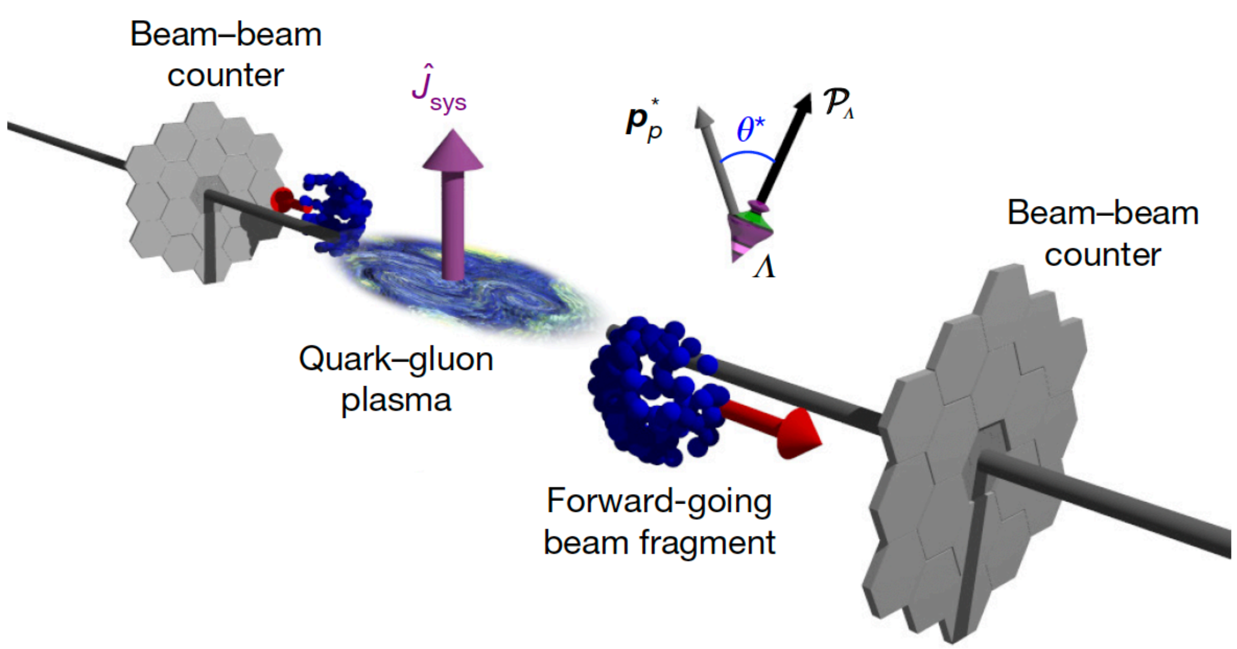
Global Λ hyperon polarization in nuclear collision, STAR



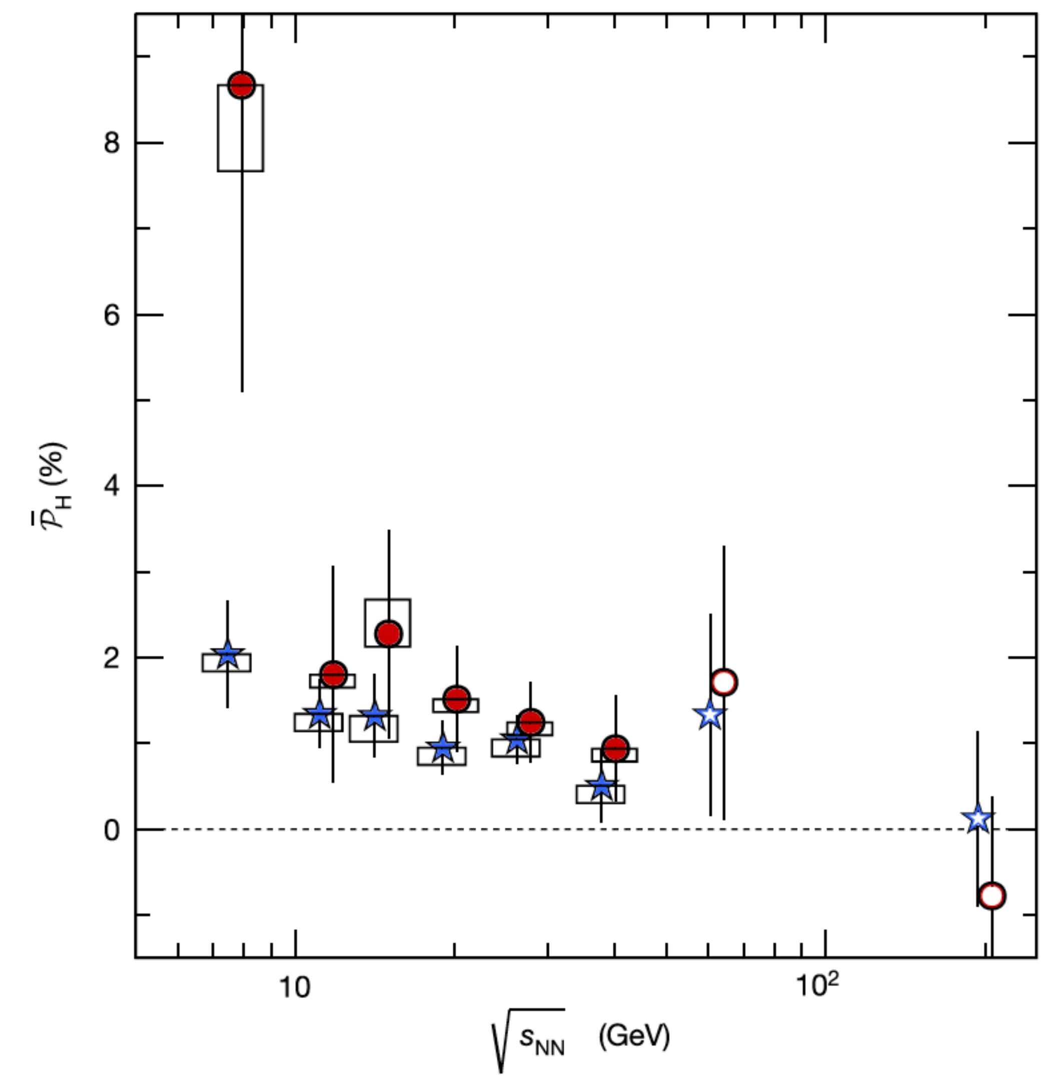


Figure 4 | The hyperon average polarization in Au + Au collisions. The average polarization for Λ (blue stars) and $\bar{\Lambda}$ (red circles) from 20–50% central collisions are plotted as a function of collision energy. Error bars represent statistical uncertainties only, while boxes represent systematic uncertainties. The results of the present study ($\sqrt{s_{NN}}$ < GeV), indicated by filled symbols, are shown together with those reported earlier[7] for 62.4 GeV and 200 GeV collisions, indicated by open symbols and for which only statistical errors are plotted.

the hyperon rest frame

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

$\mathscr{P}_H$: polarization vector, parallel to $\hat{J}_{sys}$

Nature 548, 62 (2017)

Global Λ hyperon polarization in nuclear collision, STAR

- $\Lambda^{'}, \bar{\Lambda}^{'}$: ‘primary’ hyperons emitted directly from the fluid
- However, most of Λ and $\bar{\Lambda}$ hyperons at these collisions arenot primary, but also decay products from heavier particles (e.x. $\Sigma^{*,+} \to \Lambda + \pi^{+}$), which themselves would be polarizaed by the fluid
- RHIC are expected to produce intense magnetic fields parallel to $\hat{J}_{sys}$. Coupling between the field and the intrinsic magnetic moments of emitted particles may induce a larger polarization for $\bar{\Lambda}$ than for Λ. This is not consistent with our observable.

Eur. Phys. J. C (2017) 77:213, Iu. Karpenko

Study of Λ polarization in relativistic nuclear collisions at $\sqrt{s}_{NN} = 7.7 - 200$ GeV

- Hydrodynamic theory

- abstract: UrQMD+vHLLE, the mean polarization of Λ in the out of plane direction is predicted to decrease rapidly with collision energy from a top value of about 2% at the lowest energy examined. polarization signal-thermal vorticity- estimate the feed-down contribution to Λ polarization due to the day of higher mass hyperons.

- polarized quarks -> polarized hadrons