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Role of $\Sigma^*(1385)$ in Λ hyperon polarization in relativistic heavy ion collisions

Haesom Sung, Che Ming Ko, Su Houng Lee

[1] Haesom Sung et al., *Phys.Lett.B* 858 (2024) 139004

[2] Haesom Sung et al., arXiv:2507.23238

2025.11.15

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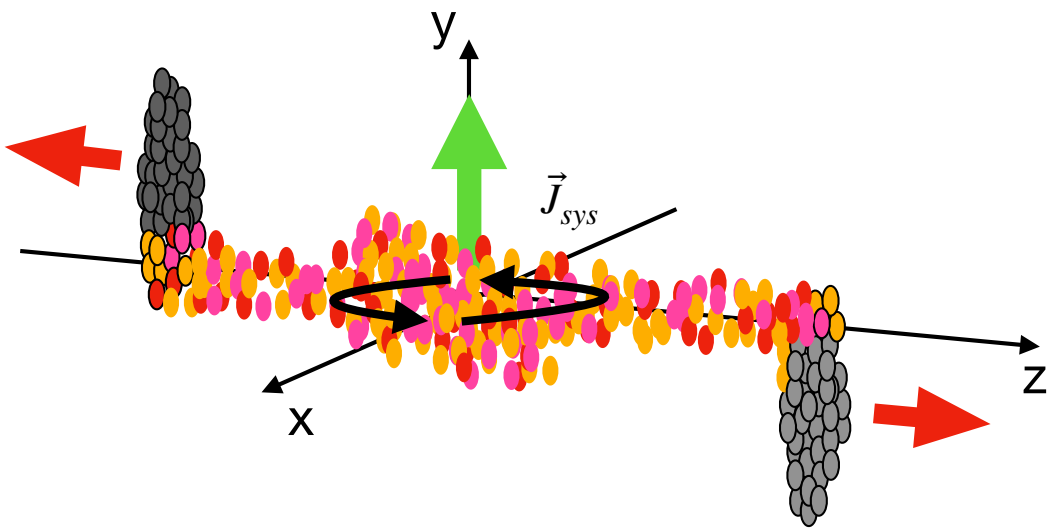
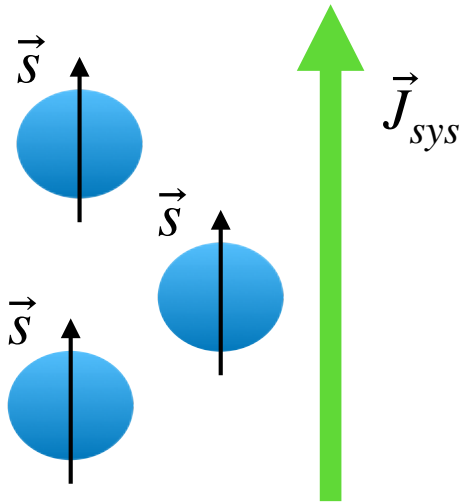
Introduction

Positive Global Λ Polarization in STAR experiment





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

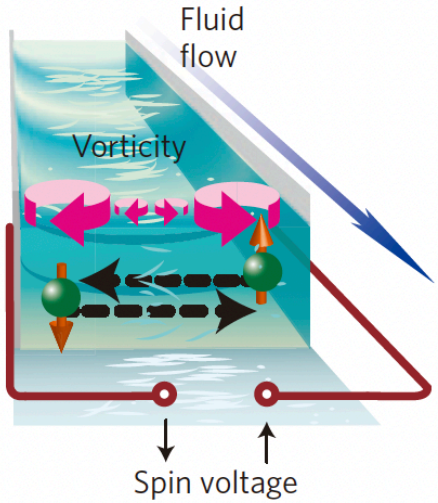
Takahashi. R, *et al.* Spin hydrodynami generation. *Nature Phys* **12**, 52–56 (201

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

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

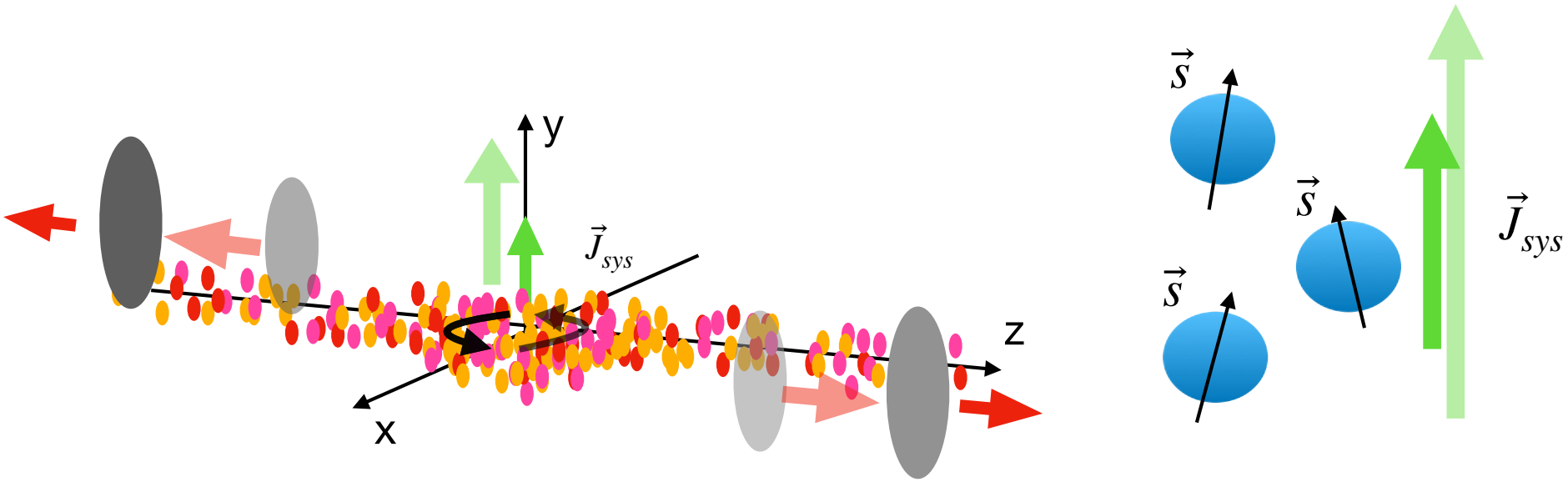
vorticity $\omega = \frac{1}{2}\nabla \times v$

v: fluid velocity



Motivation

Positive Global Λ Polarization in STAR experiment

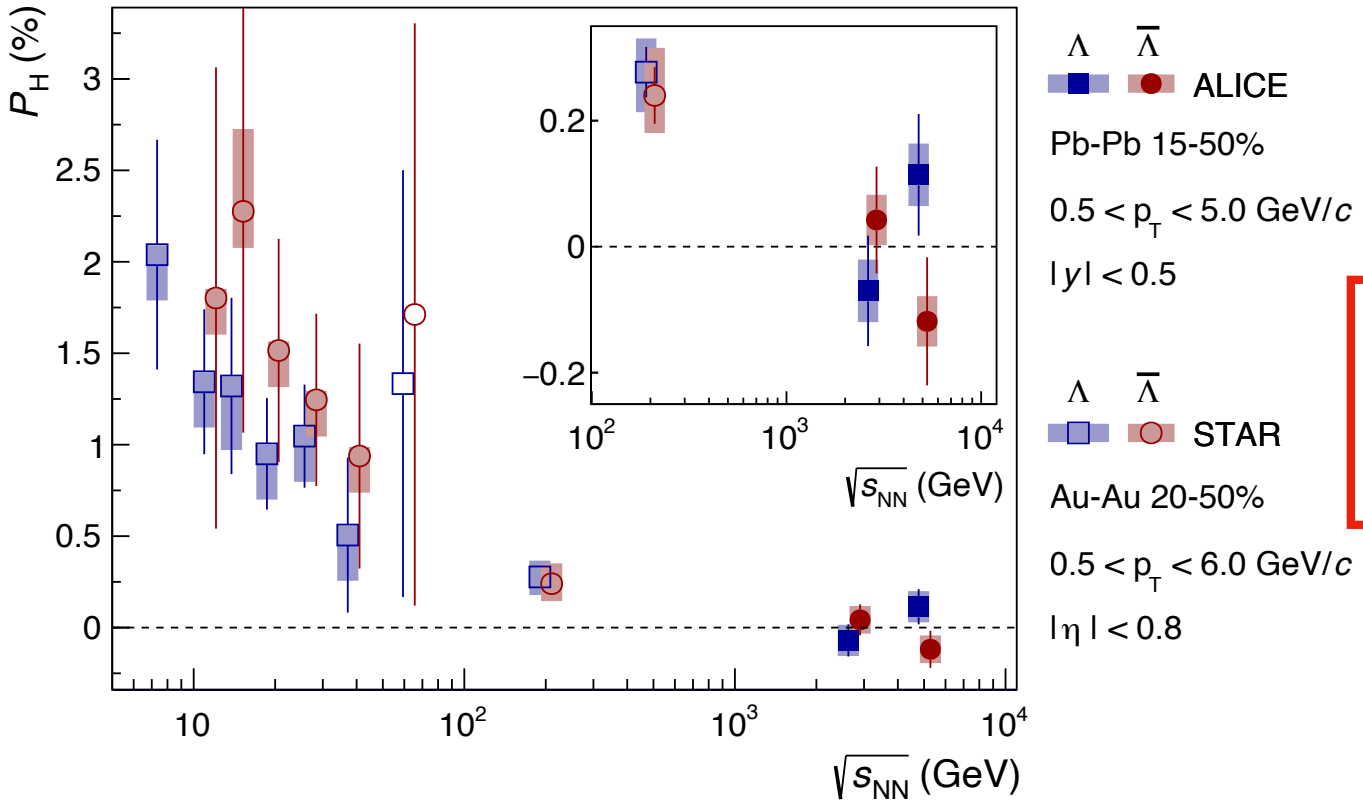


- Vorticity is getting weak with expanding of system
- We thought that collisions with other hadrons in the hadronic phase make the initial polarization to disappear.

Motivation

Positive Global Λ Polarization in STAR experiment

L. Adamczyk et al. (STAR), Nature 548, 62 (2017)
S. Acharya et al. (ALICE), Phys. Rev. C 101, 044611 (2020)



Λ $\overline{\Lambda}$ ALICE

Pb-Pb 15-50%

$0.5 < p_T < 5.0$ GeV/c

$|y| < 0.5$

Λ $\overline{\Lambda}$ STAR

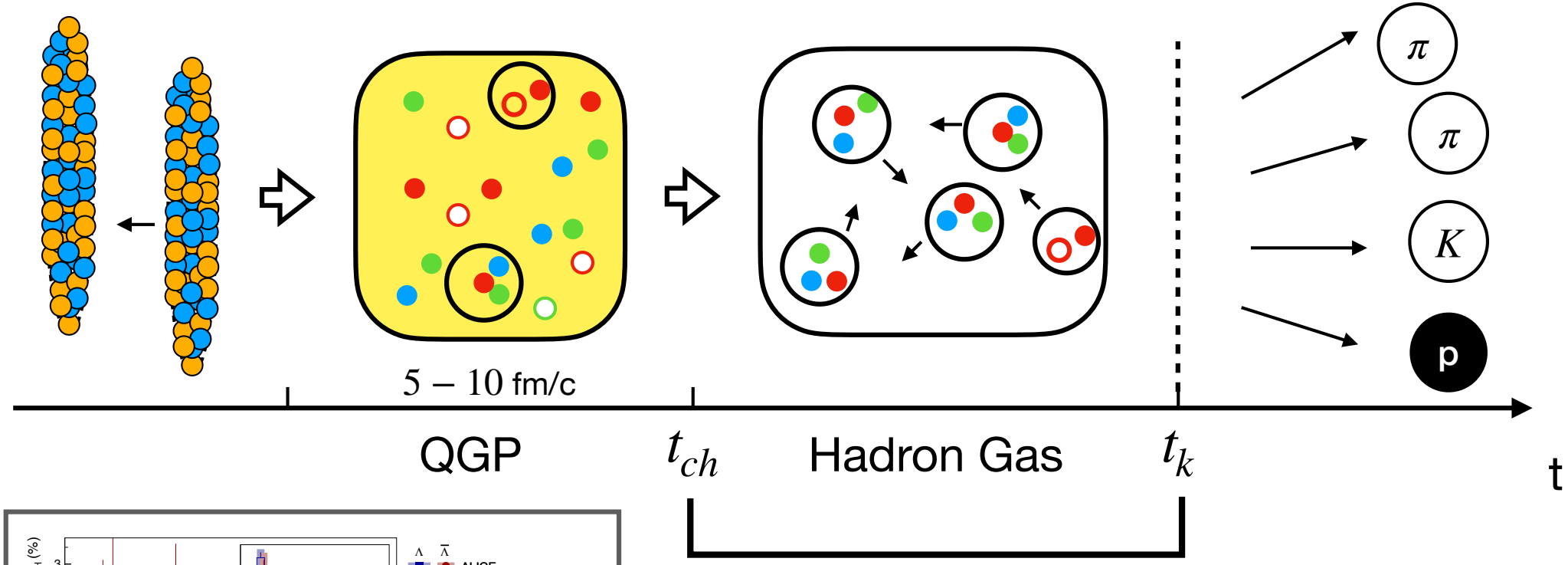
Au-Au 20-50%

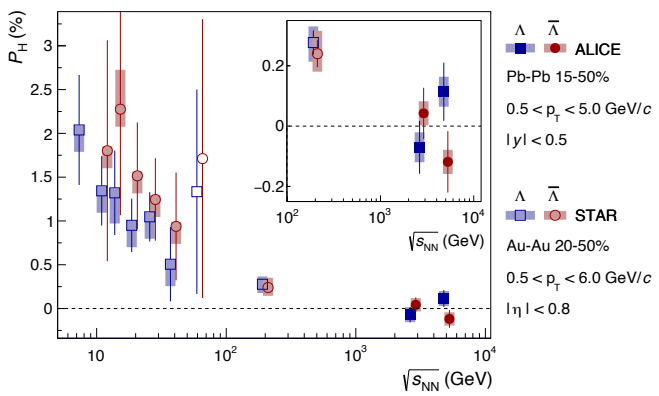
$0.5 < p_T < 6.0$ GeV/c

$|\eta| < 0.8$

Non-zero global Λ polarization in collision systems

Heavy ion collisions





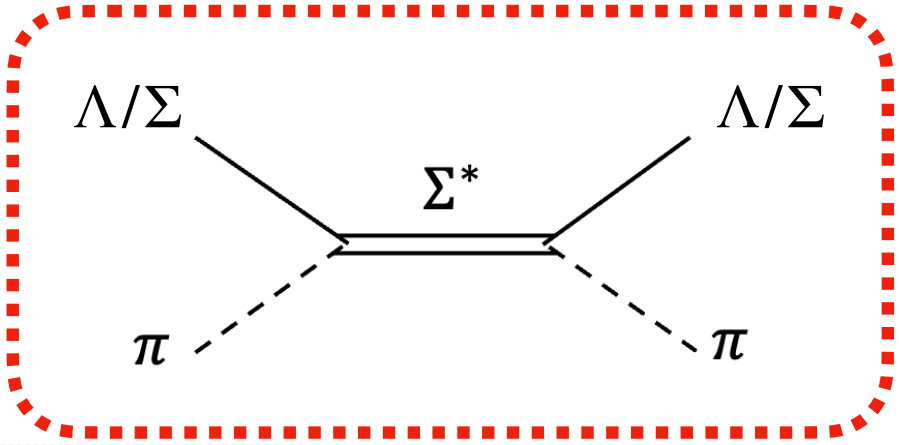
L. Adamczyk et al. (STAR), Nature 548, 62 (2017)
S. Acharya et al. (ALICE), Phys. Rev. C 101, 044611 (2020)

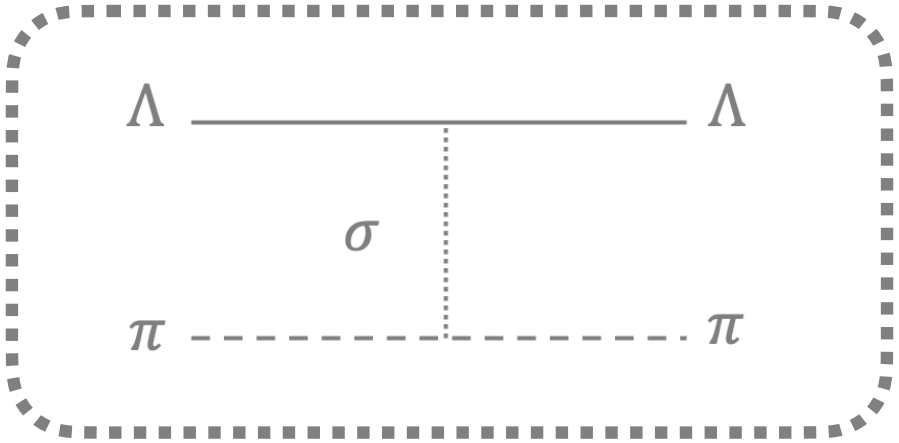
- The hadronic scattering effects in Lambda with Σ^* resonance
- Lambda polarization in early stage of system remains after scattering in hadron gas

$\Lambda+\pi$ cross section

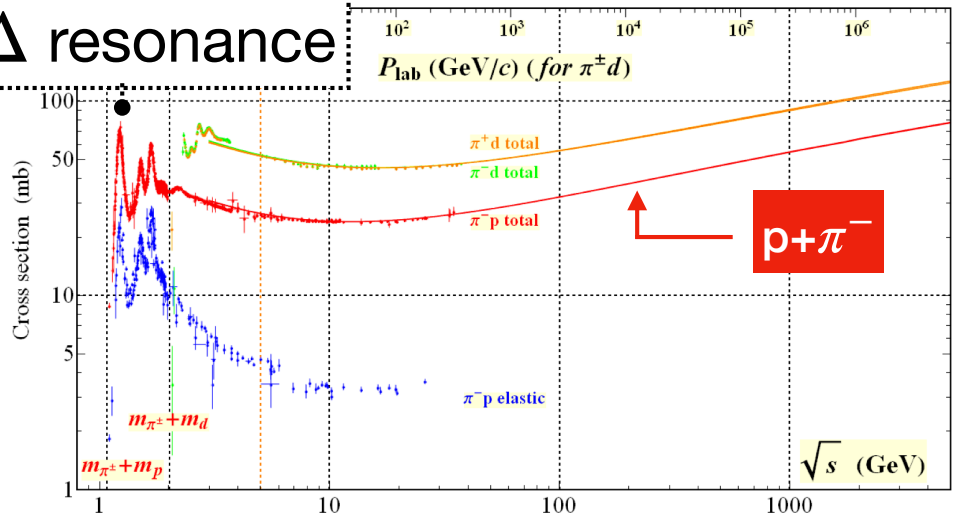
Σ^* resonance cross section

Scattering channel





Δ resonance



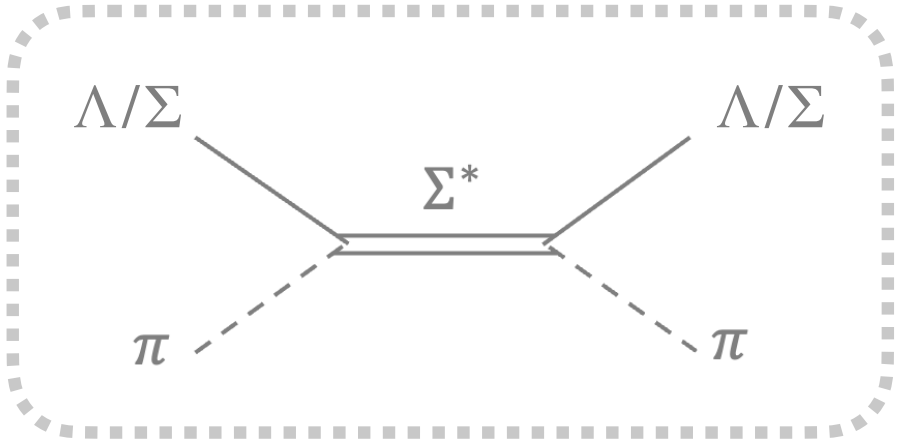
$p + \pi^-$ is p-wave, Δ(s=3/2) resonance is dominance

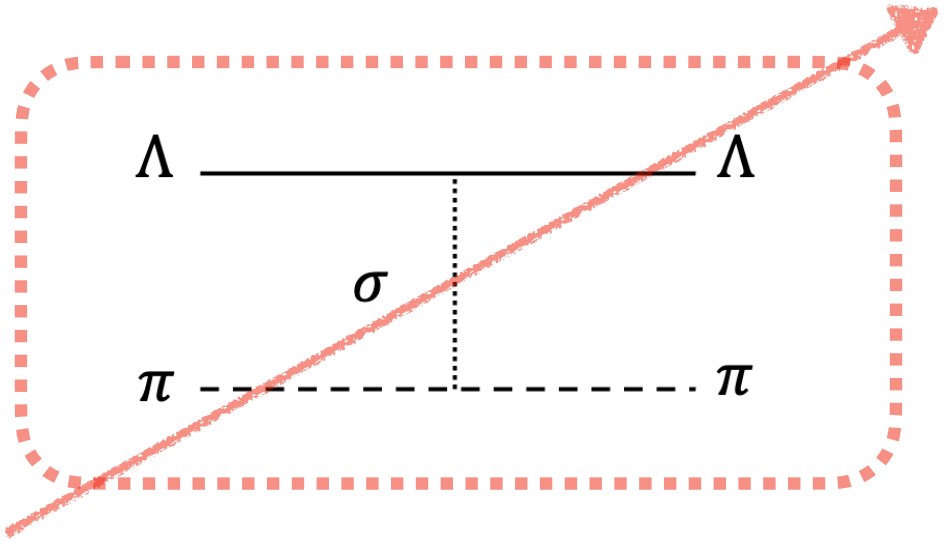
=> In the case of $\Lambda + \pi$, Σ^*(3/2) will be dominance

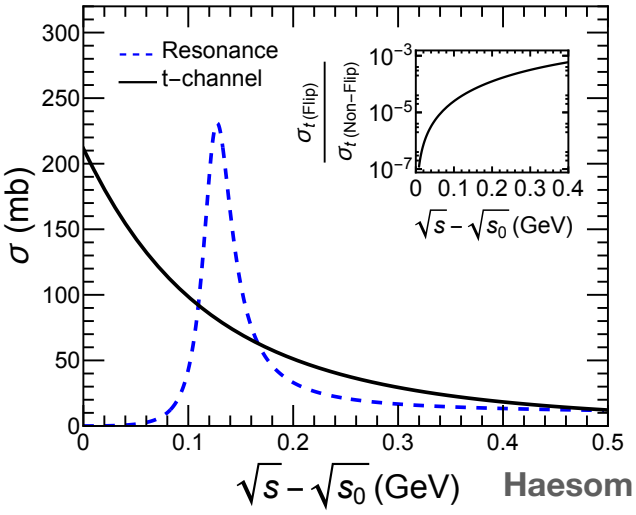
$\Lambda+\pi$ cross section

Negligible t-channel cross section

Scattering channel







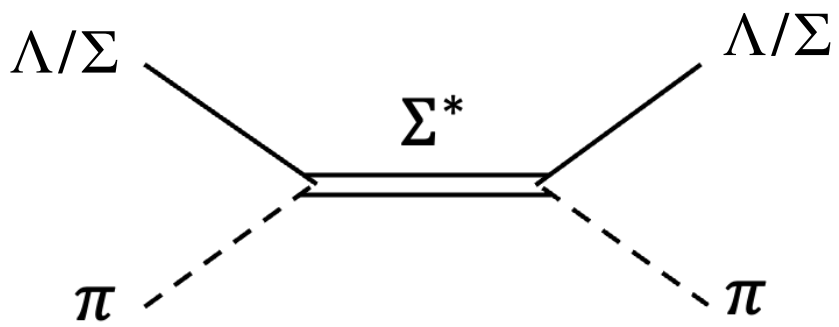
Resonance cross section is the majority of Λ spin flip cross section.

t-channel doesn't affect for changing Lambda polarization

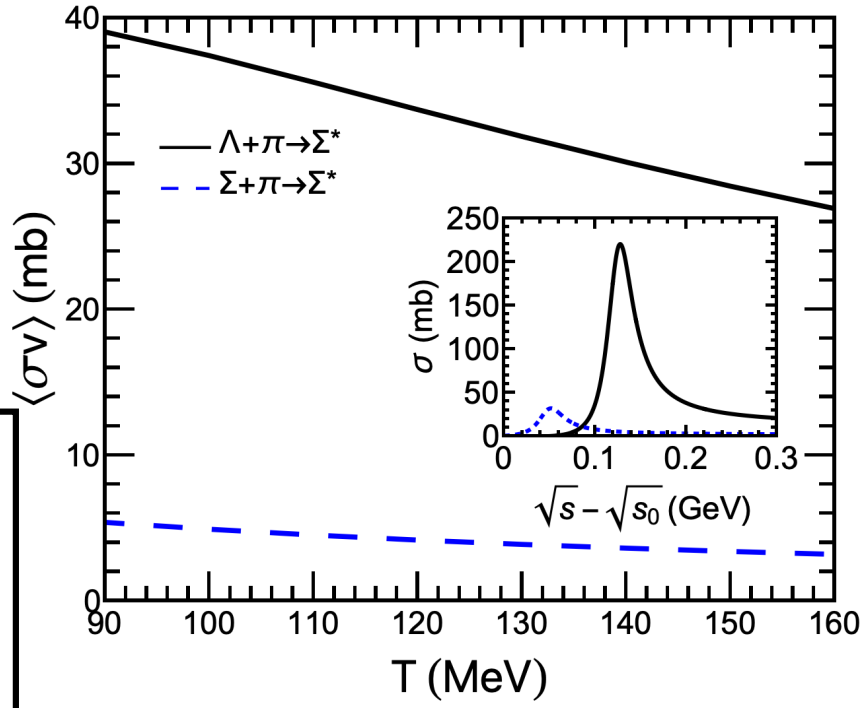
Haesom Sung et al., *Phys.Lett.B* 858 (2024) 139004

$\Lambda+\pi$ cross section

Σ^* resonance cross section



Haesom Sung et al., *arXiv:2507.23238*



* Resonance cross section

$$\sigma_{Y+\pi\to\Sigma^*}(s) = \frac{2s_{\Sigma^*}+1}{(2s_Y+1)(2s_\pi+1)}\frac{4\pi}{k^2}\frac{B_{\Sigma^*\to Y+\pi}s\Gamma^2_{\Sigma^*}(s)}{(s-m^2_{\Sigma^*})^2+s\Gamma^2_{\Sigma^*}(s)},$$

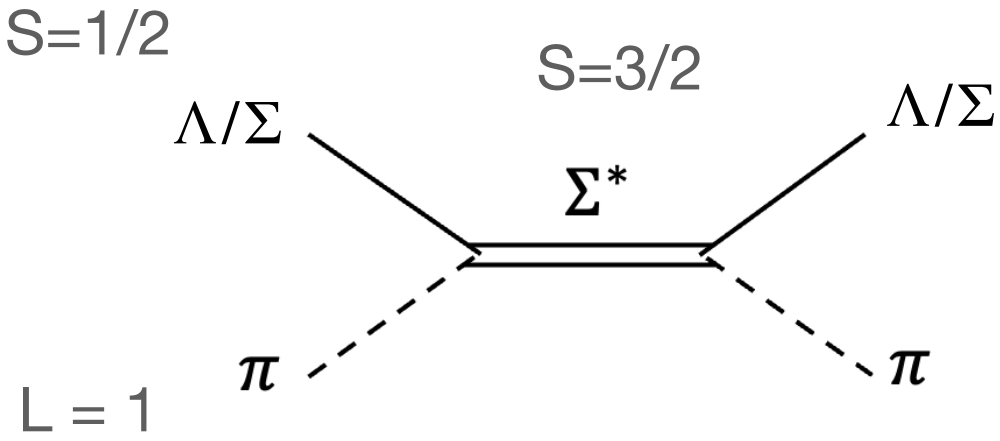
where $Y = \Lambda, \Sigma$.

* Thermal averaged cross section

$$\langle\sigma_{Y+\pi\to\Sigma^*}v\rangle = \frac{\int d^3\mathbf{p}_Y d^3\mathbf{p}_\pi f_Y(\mathbf{p}_Y) f_\pi(\mathbf{p}_\pi)\sigma_{Y+\pi\to\Sigma^*}v}{\int d^3\mathbf{p}_Y d^3\mathbf{p}_\pi f_Y(\mathbf{p}_Y) f_\pi(\mathbf{p}_\pi)}$$

$\Lambda+\pi$ cross section

Spin dependent Σ^* resonance cross section



Clebsch-Gordan Coefficients

$1 \times 1/2$

		3/2			
		+3/2	3/2	1/2	
+1	+1/2	1	+1/2	+1/2	
	+1	−1/2	1/3	2/3	3/2	1/2
	0	+1/2	2/3	−1/3	−1/2	−1/2
		0	−1/2	2/3	1/3	3/2
		−1	+1/2	1/3	−2/3	−3/2
				−1	−1/2	1

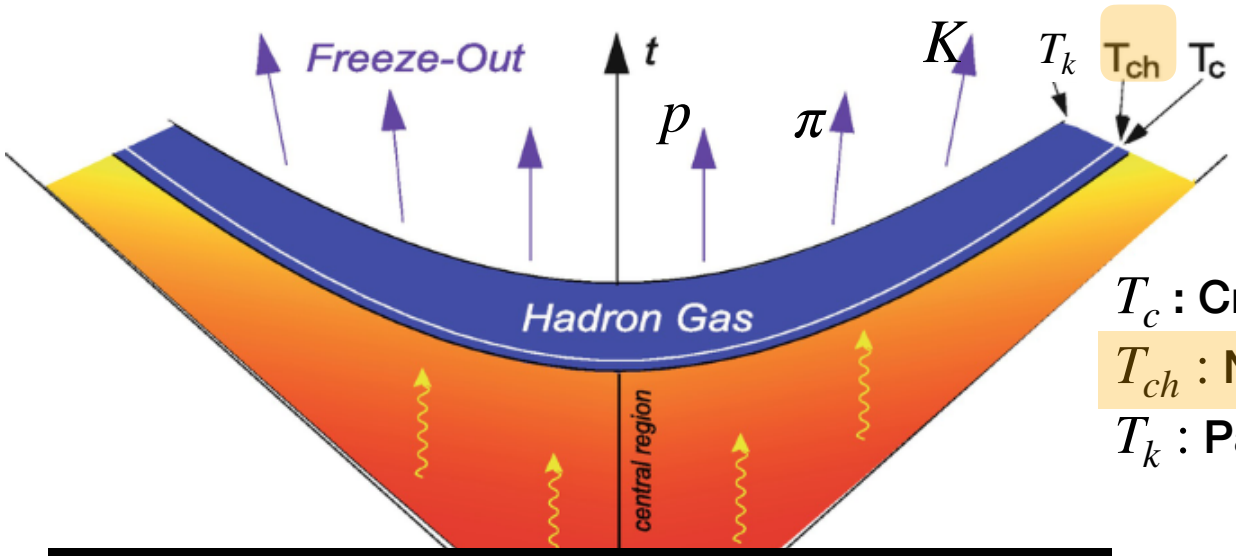
$$\sigma_{Y_{\pm1/2}+\pi\to\Sigma^*_{\pm3/2}} : \sigma_{Y_{\pm1/2}+\pi\to\Sigma^*_{\pm1/2}} : \sigma_{Y_{\pm1/2}+\pi\to\Sigma^*_{\mp1/2}} = 3 : 2 : 1$$

$$\Gamma_{\Sigma^*_{\pm3/2}\to Y_{\pm1/2}+\pi} : \Gamma_{\Sigma^*_{\pm1/2}\to Y_{\pm1/2}+\pi} : \Gamma_{\Sigma^*_{\mp1/2}\to Y_{\pm1/2}+\pi} = 3 : 2 : 1$$

where $Y = \Lambda, \Sigma$

Introduction

Chemical & Kinetic Freeze-out



T_c : Critical temperature for transition to QGP

T_{ch} : Number of each particle species is frozen

T_k : Particle momenta are frozen

* The abundance of hadrons are determined at chemical freeze-out temperature.

Andronic et al., *Nucl.Phys.A* 772 (2006) 167-199
Jun Xu, Che Ming Ko, *Phys.Lett.B* 772 (2017) 290-293

=> N_π, N_K, N_p are determined at T_{ch}

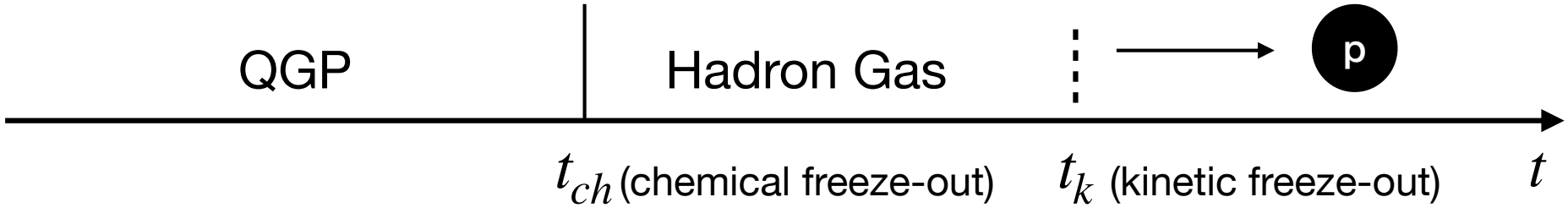
Statistical Model

$$N(T) = gV \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{1}{e^{\left(\sqrt{m^2+\mathbf{p}^2}\right)/T} \pm 1}$$

where +1 for fermion and -1 for boson.
g and V are the degeneracy factor and volume, respectively.

Fugacity

Considering the resonance decay in hadron gas



Jun Xu, Che Ming Ko, Physics Letters B 772 (2017) 290–293

- $S/A, \pi^{eff}, K^{eff}, N^{eff} \rightarrow V, Z_\pi, Z_K, Z_N$

$$S(T)/A(T) = S(T_c)/A(T_c),$$

$$N^{eff}_{\pi,k,n}(T) = N^{eff}_{\pi,k,n}(T_c),$$

where S is total entropy and A is total particle number.

$$N_\rho(T_c) \quad \rho \rightarrow 2\pi$$

$$N_{K^*}(T_c) \quad K^* \rightarrow K + \pi$$

$$N_{K_1}(T_c) \quad K_1 \rightarrow K + 2\pi$$

- Effective numbers

$$n_\pi^{\text{eff}}(T) = z_\pi n_\pi^T + z_\pi^2 n_\rho^T + z_\pi z_K n_{K^*}^T + z_\pi^2 z_K n_{K_1}^T + z_\pi z_N n_\Delta^T + \cdots,$$

$$n_K^{\text{eff}}(T) = z_K n_K^T + z_\pi z_K n_{K^*}^T + z_\pi^2 z_K n_{K_1}^T + z_K^2 n_\phi^T + \cdots,$$

$$n_N^{\text{eff}}(T) = z_N n_N^T + z_\pi z_N n_\Delta^T + \cdots.$$

$$n_Y^{(T)} = \frac{g_Y}{(2\pi)^3} \int d^3\mathbf{p} e^{-\left(\sqrt{m_Y^2 + \mathbf{p}^2} - \mu_Y\right)/T}$$

Fugacity

Considering the resonance decay in hadron gas

* Initial conditions

T_c= 146 MeV and V_c= 240 fm^3

* Chemical potential

μ_B= 376 MeV and μ_S= 88 MeV

L. Adamczyk et al. (STAR), Phys. Rev. C 96, 044904(2017), arXiv:1701.07065

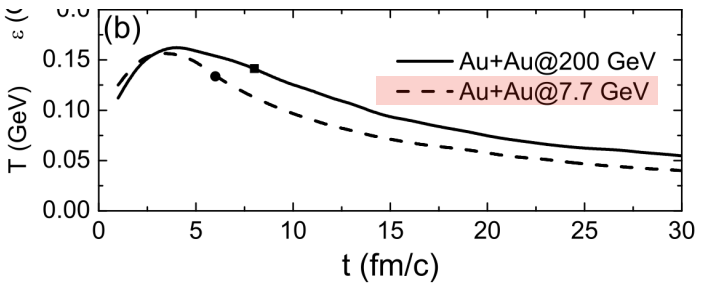
Boltzmann distribution

$$f_Y(\mathbf{p}_Y) = e^{-\left(\sqrt{m_Y^2 + \mathbf{p}_Y^2} - \mu_Y\right)/T}$$

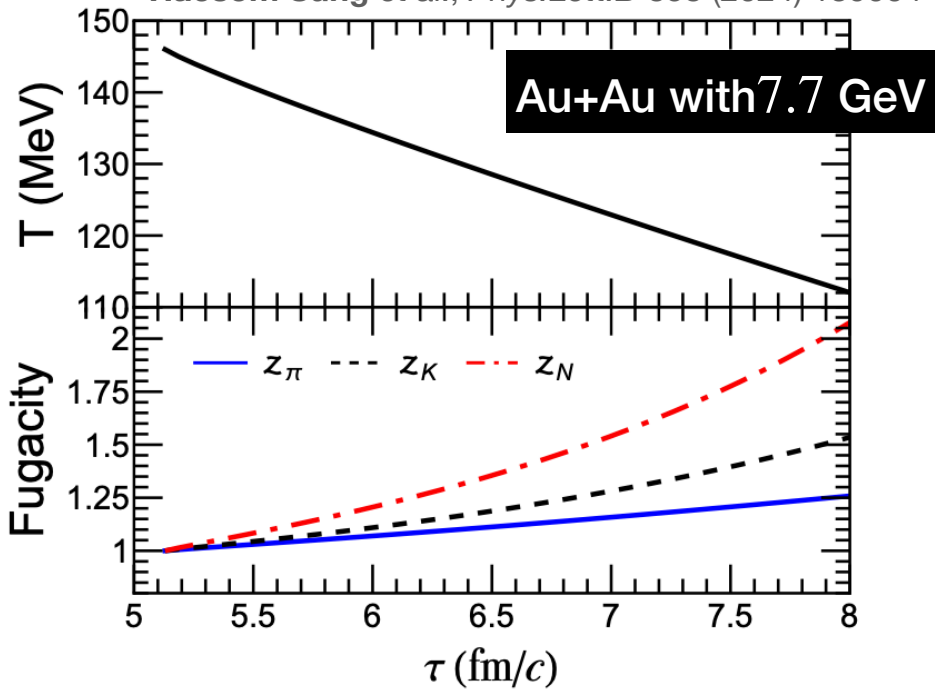
where $\mu_Y = B_Y\mu_B + S_Y\mu_S$

J. Xu and C. M. Ko, Phys. Lett. B 772, 290 (2017), arXiv:1704.04934

$T(t)$



Haesom Sung et al., *Phys.Lett.B* 858 (2024) 139004



Kinetic equation

Spin dependent Kinetic equation for Λ, Σ, and Σ^*

Spin-dependent Kinetic Equations

$$\frac{dN_{Y_{1/2}}}{d\tau} = \frac{1}{3}\langle\Gamma_{\Sigma^*\to Y+\pi}\rangle\left(3N_{\Sigma^*_{3/2}} + 2N_{\Sigma^*_{1/2}} + N_{\Sigma^*_{-1/2}}\right) - \langle\sigma_{Y+\pi\to\Sigma^*}v\rangle z_\pi^{(T)} n_\pi^{(T)} N_{Y_{1/2}}, \quad Y = \Lambda, \Sigma$$

$$\frac{dN_{Y_{-1/2}}}{d\tau} = \frac{1}{3}\langle\Gamma_{\Sigma^*\to Y+\pi}\rangle\left(N_{\Sigma^*_{1/2}} + 2N_{\Sigma^*_{-1/2}} + 3N_{\Sigma^*_{-3/2}}\right) - \langle\sigma_{Y+\pi\to\Sigma^*}v\rangle z_\pi^{(T)} n_\pi^{(T)} N_{Y_{-1/2}}, \quad Y = \Lambda, \Sigma$$

$$\frac{dN_{\Sigma^*_{3/2}}}{d\tau} = \frac{1}{2}\sum_{Y=\Lambda,\Sigma}\left[\langle\sigma_{Y+\pi\to\Sigma^*}v\rangle z_\pi^{(T)} n_\pi^{(T)} N_{Y_{1/2}} - \langle\Gamma_{\Sigma^*\to Y+\pi}\rangle N_{\Sigma^*_{3/2}}\right],$$

$$\frac{dN_{\Sigma^*_{1/2}}}{d\tau} = \frac{1}{6}\sum_{Y=\Lambda,\Sigma}\left[\langle\sigma_{Y+\pi\to\Sigma^*}v\rangle z_\pi^{(T)} n_\pi^{(T)} (2N_{Y_{1/2}} + N_{Y_{-1/2}}) - \langle\Gamma_{\Sigma^*\to Y+\pi}\rangle N_{\Sigma^*_{1/2}}\right],$$

$$\frac{dN_{\Sigma^*_{-1/2}}}{d\tau} = \frac{1}{6}\sum_{Y=\Lambda,\Sigma}\left[\langle\sigma_{Y+\pi\to\Sigma^*}v\rangle z_\pi^{(T)} n_\pi^{(T)} (N_{Y_{1/2}} + 2N_{Y_{-1/2}}) - \langle\Gamma_{\Sigma^*\to Y+\pi}\rangle N_{\Sigma^*_{-1/2}}\right],$$

$$\frac{dN_{\Sigma^*_{-3/2}}}{d\tau} = \frac{1}{2}\sum_{Y=\Lambda,\Sigma}\left[\langle\sigma_{Y+\pi\to\Sigma^*}v\rangle z_\pi^{(T)} n_\pi^{(T)} N_{Y_{-1/2}} - \langle\Gamma_{\Sigma^*\to Y+\pi}\rangle N_{\Sigma^*_{-3/2}}\right].$$

Polarization

$$P_Y = \frac{N_{Y_{1/2}} - N_{Y_{-1/2}}}{N_{Y_{1/2}} + N_{Y_{-1/2}}}, \quad Y = \Lambda, \Sigma$$

$$P_{\Sigma^*} = \frac{N_{\Sigma^*{}_{3/2}} + \frac{1}{3}N_{\Sigma^*{}_{1/2}} - \frac{1}{3}N_{\Sigma^*{}_{-1/2}} - N_{\Sigma^*{}_{-3/2}}}{N_{\Sigma^*{}_{3/2}} + N_{\Sigma^*{}_{1/2}} + N_{\Sigma^*{}_{-1/2}} + N_{\Sigma^*{}_{-3/2}}},$$

- Considering Σ^* resonance

$$N_Y^{(T)} = \frac{g_Y V}{(2\pi)^3}\int d^3\mathbf{p} e^{-(\sqrt{m_Y^2+\mathbf{p}^2}-\mu_Y)/T}\frac{g_Y V}{2\pi^2}m_Y^2 T K_2(m_Y/T)e^{\mu_Y/T}, \quad Y = \Lambda, \Sigma$$

$$N_{\Sigma^*_m}^{(T)} = \frac{A_{\Sigma^*}}{\pi}\int_{s_0}^{\infty} ds \frac{\sqrt{s}\Gamma_{\Sigma^*}(\sqrt{s})}{(s - m_{\Sigma^*}^2)^2 + s\Gamma_{\Sigma^*}^2(\sqrt{s})}\frac{g_{\Sigma^*}V}{(2\pi)^3}\int d^3\mathbf{p} e^{-(\sqrt{s+\mathbf{p}^2}-\mu_{\Sigma^*})/T},$$

- Detailed balance

$$\langle\Gamma_{\Sigma^*\to Y+\pi}\rangle = \frac{\langle\sigma_{Y+\pi\to\Sigma^*}v\rangle n_\pi^{(T)} N_Y^{(T)}}{N_{\Sigma^*}^{(T)}}$$

Polarization during Hadron phase

Spin dependent Kinetic equation for Λ, Σ, and Σ^*

Numbers

$$\frac{dN_Y}{d\tau} = \langle \sigma_{Y+\pi\to\Sigma^*} v \rangle z_\pi^{(T)} n_\pi^{(T)} \left(\frac{N_Y^{(T)}}{z_\pi^{(T)} N_{\Sigma^*}^{(T)}} N_{\Sigma^*} - N_Y \right), \qquad Y = \Lambda, \Sigma$$

$$\frac{dN_{\Sigma^*}}{d\tau} = \sum_{Y=\Lambda,\Sigma} \langle \sigma_{Y+\pi\to\Sigma^*} v \rangle z_\pi^{(T)} n_\pi^{(T)} \left(N_Y - \frac{N_Y^{(T)}}{z_\pi^{(T)} N_{\Sigma^*}^{(T)}} N_{\Sigma^*} \right),$$

Polarization

$$\frac{dP_Y}{d\tau} = \langle \sigma_{Y+\pi\to\Sigma^*} v \rangle n_\pi^{(T)} \frac{N_Y^{(T)} N_{\Sigma^*}}{N_{\Sigma^*}^{(T)} N_Y} (P_{\Sigma^*} - P_Y), \qquad Y = \Lambda, \Sigma$$

$$\frac{dP_{\Sigma^*}}{d\tau} = \sum_{Y=\Lambda,\Sigma} \langle \sigma_{Y+\pi\to\Sigma^*} v \rangle z_\pi^{(T)} n_\pi^{(T)} \frac{N_Y}{N_{\Sigma^*}} \left(\frac{5}{9} P_Y - P_{\Sigma^*} \right)$$

Initial conditions

$$P_\Lambda^{(0)} = 0.025$$

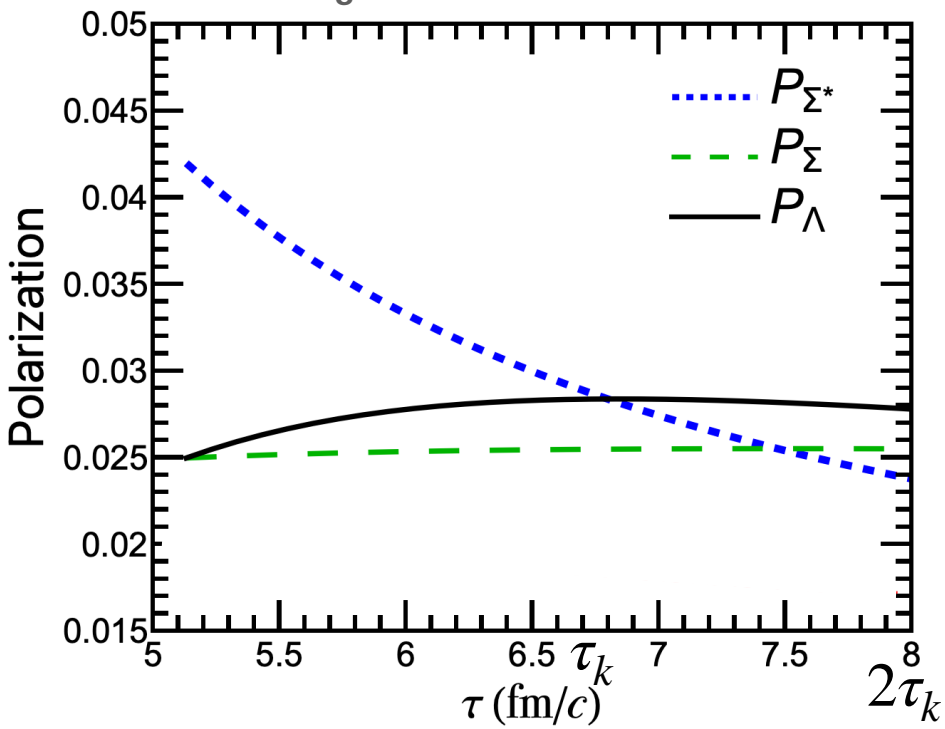
$$P_{\Sigma^*}^{(0)} = 5/3 P_\Lambda^{(0)} = 0.042$$

AMPT model

Hui Li, et al., Phys. Rev. C 96, 054908

F. Becattini, et al, Phys. Rev. C 95, 054902

Haesom Sung et al. arXiv:2507.23238



$$\mathbf{S} \simeq \frac{S(S+1)}{3} \frac{\omega}{T},$$

$$\mathbf{P}_{1/2} = 2\mathbf{S}_{1/2} = \frac{1}{2} \frac{\omega}{T}, \quad \rightarrow \quad P_{3/2} = 5/3 P_{1/2}$$

$$\mathbf{P}_{3/2} = \frac{2}{3} \mathbf{S}_{3/2} = \frac{5}{6} \frac{\omega}{T}.$$

Feed down contribution

Transfer Coefficients	value	
C_Λ	1	
C_{Σ^0}	-1/3	$\Sigma^0 \to \Lambda + \gamma$
$C^{\Sigma^{*0}}$	0.88	$\Sigma^{*0} \to \Lambda + \pi^0, \Sigma^{\pm} + \pi^{\mp}$
$C^{\Sigma^{*\pm}}$	0.86	$\Sigma^{*\pm} \to \Lambda + \pi^{\pm}, \Sigma^0 + \pi^{\pm}, \Sigma^{\pm} + \pi^0$
C^{Ξ^0}	0.9	$\Xi^0 \to \Lambda + \pi^0$
C^{Ξ^-}	0.927	$\Xi^- \to \Lambda + \pi^-$

F. Becattini, et al, Phys. Rev. C 95, 054902 (2017), arXiv:1610.02506 [nucl-th].

$$P_\Lambda^{\mathrm{FD}} = \frac{\sum_{Y=\Lambda,\Sigma^0,\Sigma^{*+},\Sigma^{*0},\Sigma^{*-},\Xi^0,\Xi^-} C_Y P_Y N_Y}{\sum_{Y=\Lambda,\Sigma^0,\Sigma^{*+},\Sigma^{*0},\Sigma^{*-},\Xi^0,\Xi^-} N_Y},$$

C_Y : Polarization transfer factor

P_Y : Polarization

N_Y : Number of particle

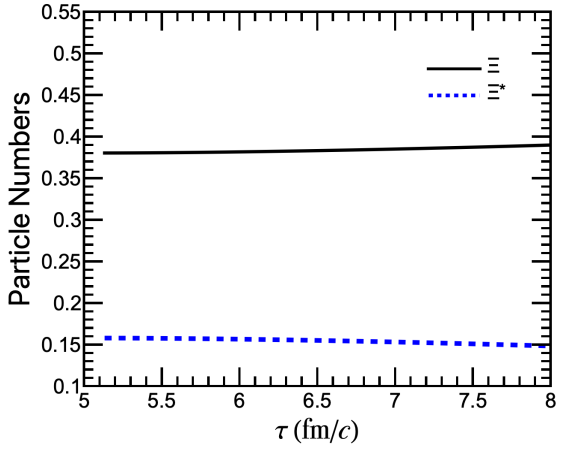
Kinetic equation for Ξ^* and Ξ

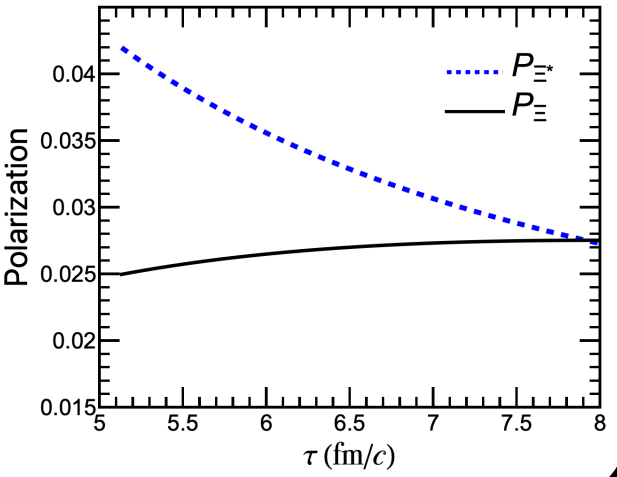
$$\frac{dN_\Xi}{d\tau} = \langle \sigma_{\Xi+\pi\to\Xi^*} v \rangle z_\pi^{(T)} n_\pi^{(T)} \left(\frac{N_\Xi^{(T)}}{z_\pi^{(T)} N_{\Xi^*}^{(T)}} N_{\Xi^*} - N_\Xi \right),$$

$$\frac{dN_{\Xi^*}}{d\tau} = \langle \bar{\sigma}_{\Xi+\pi\to\Xi^*} v \rangle z_\pi^{(T)} n_\pi^{(T)} \times \left(N_\Xi - \frac{N_\Xi^{(T)}}{z_\pi^{(T)} N_{\Xi^*}^{(T)}} N_{\Xi^*} \right),$$

$$\frac{dP_\Xi}{d\tau} = \langle \sigma_{\Xi+\pi\to\Xi^*} v \rangle n_\pi^{(T)} \frac{N_\Xi^{(T)} N_{\Xi^*}}{N_\Xi N_{\Xi^*}^{(T)}} (P_{\Xi^*} - P_\Xi),$$

$$\frac{dP_{\Xi^*}}{d\tau} = \langle \sigma_{\Xi+\pi\to\Xi^*} v \rangle z_\pi^{(T)} n_\pi^{(T)} \frac{N_\Xi}{N_\Xi^*} \left(\frac{5}{9} P_\Xi - P_{\Xi^*} \right). \quad (13)$$





Result

Spin dependent Kinetic equation for Λ, Σ, and Σ^*

Numbers

$$\frac{dN_Y}{d\tau} = \langle \sigma_{Y+\pi\to\Sigma^* v}\rangle z_\pi^{(T)} n_\pi^{(T)} \left(\frac{N_Y^{(T)}}{z_\pi^{(T)} N_{\Sigma^*}^{(T)}} N_{\Sigma^*} - N_Y \right), \qquad Y = \Lambda, \Sigma$$

$$\frac{dN_{\Sigma^*}}{d\tau} = \sum_{Y=\Lambda,\Sigma} \langle \sigma_{Y+\pi\to\Sigma^* v}\rangle z_\pi^{(T)} n_\pi^{(T)} \left(N_Y - \frac{N_Y^{(T)}}{z_\pi^{(T)} N_{\Sigma^*}^{(T)}} N_{\Sigma^*} \right),$$

Polarization

$$\frac{dP_Y}{d\tau} = \langle \sigma_{Y+\pi\to\Sigma^* v}\rangle n_\pi^{(T)} \frac{N_Y^{(T)} N_{\Sigma^*}}{N_{\Sigma^*}^{(T)} N_Y} (P_{\Sigma^*} - P_Y), \qquad Y = \Lambda, \Sigma$$

$$\frac{dP_{\Sigma^*}}{d\tau} = \sum_{Y=\Lambda,\Sigma} \langle \sigma_{Y+\pi\to\Sigma^* v}\rangle z_\pi^{(T)} n_\pi^{(T)} \frac{N_Y}{N_{\Sigma^*}} \left(\frac{5}{9} P_Y - P_{\Sigma^*} \right)$$

$$P_\Lambda^{\mathrm{FD}} = \frac{\sum_{Y=\Lambda,\Sigma^0,\Sigma^{*+},\Sigma^{*0},\Sigma^{*-},\Xi^0,\Xi^-} C_Y P_Y N_Y}{\sum_{Y=\Lambda,\Sigma^0,\Sigma^{*+},\Sigma^{*0},\Sigma^{*-},\Xi^0,\Xi^-} N_Y},$$

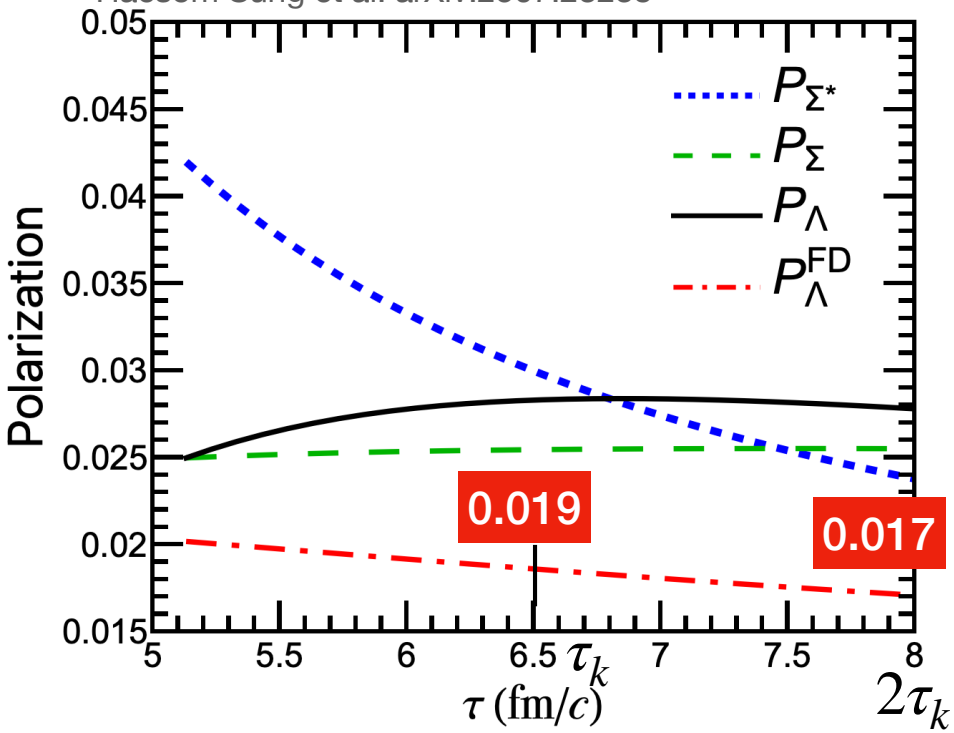
Initial conditions

AMPT model
Hui Li, et al., Phys. Rev. C 96, 054908
F. Becattini, et al, Phys. Rev. C 95, 054902

$$P_\Lambda^{(0)} = 0.025$$

$$P_{\Sigma^*}^{(0)} = 5/3 P_\Lambda^{(0)} = 0.042$$

Haesom Sung et al. arXiv:2507.23238



Summary

- Including the $\Sigma^*(1385)$ resonance effect, the Λ hyperon polarization **slightly increase** during hadronic stage of heavy ion collisions
- With feed-down contribution, Λ polarization shows **10-15% decrease** at kinetic freeze out time
- Confirming that **the Λ spin effectively freezes out at chemical freeze-out** rather than evolving significantly during the hadronic phase.

Thank you