The 5th Workshop on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

Effect of resonance decay on Λ polarization

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Content

- **Introduction**
- **Spin transfer in resonance decay**
- **Monte Carlo simulation**
  - Effect of the resonance decay on Λ polarization
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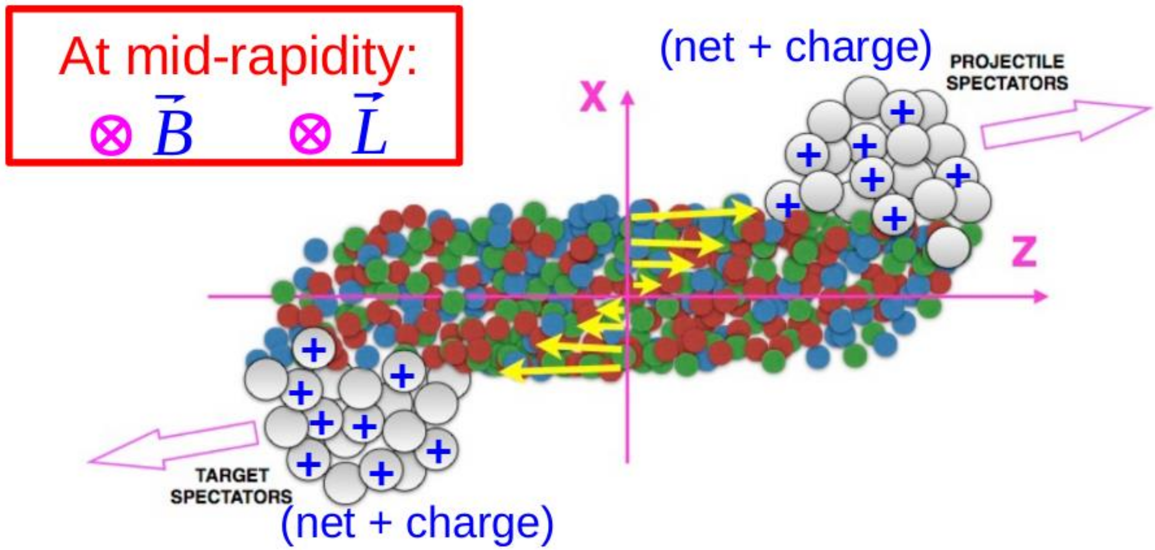
Introduction



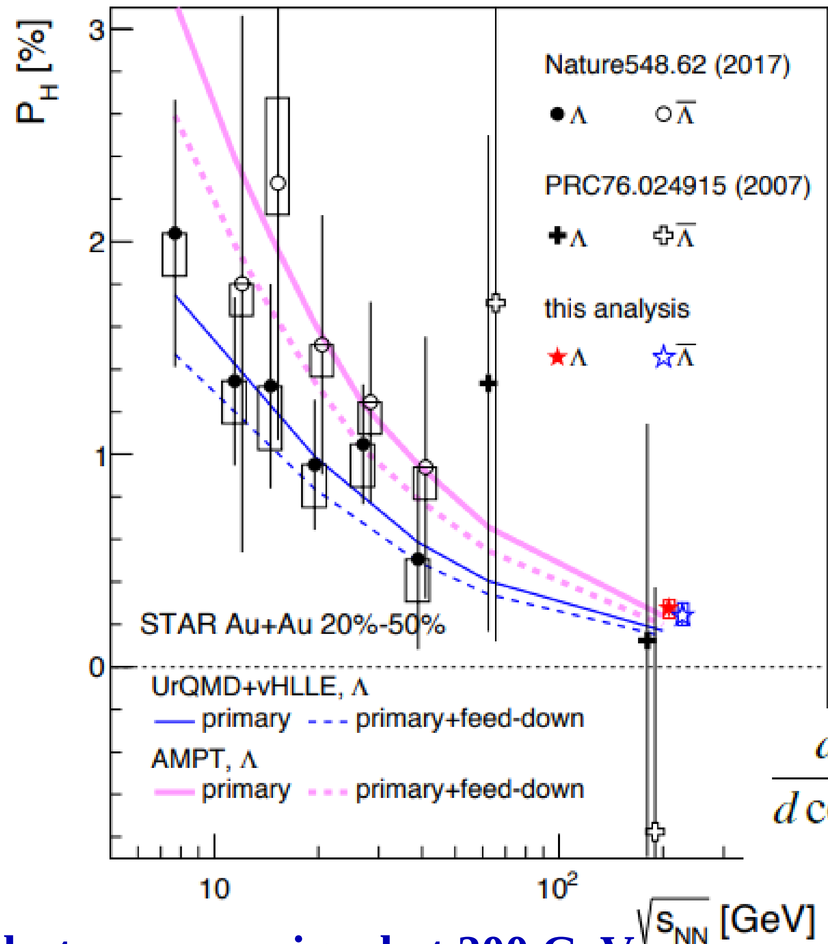
polarization of quarks & anti- ⇨ polarization of hyperons

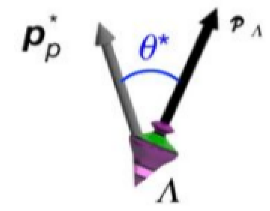
Λ Polarization provide us perfect probe for the magnetic and vorticity structure of QGP.

CME, CVE …

Z. T. Liang, X. N. Wang, Phys. Rev. Lett. 94, 102301
F. Becattini, F.Piccinini and J. Rizzo, Phys. Rev.C 76, 044901

Global Λ polarization



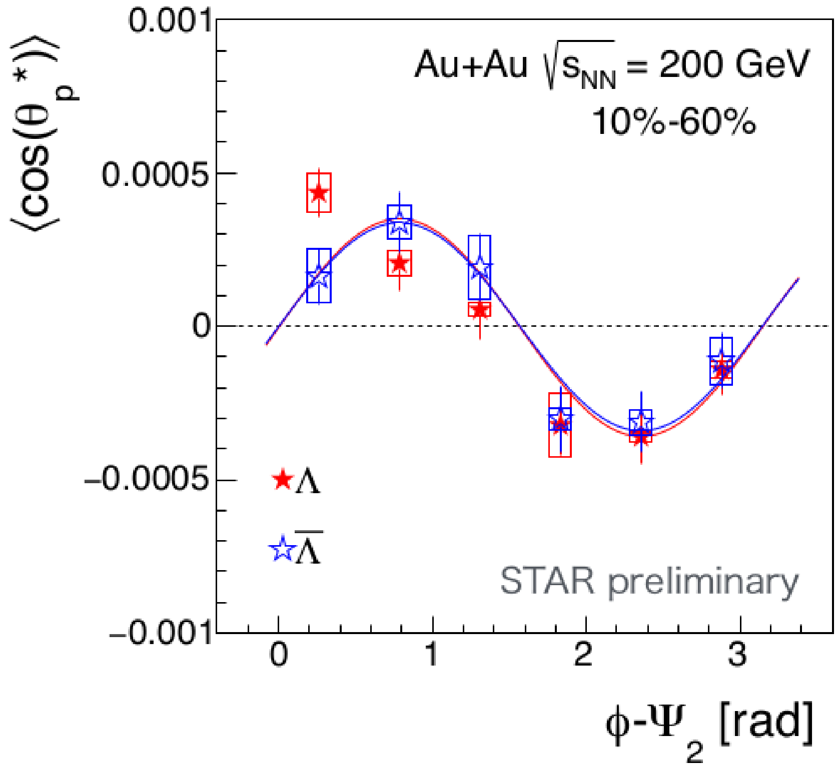


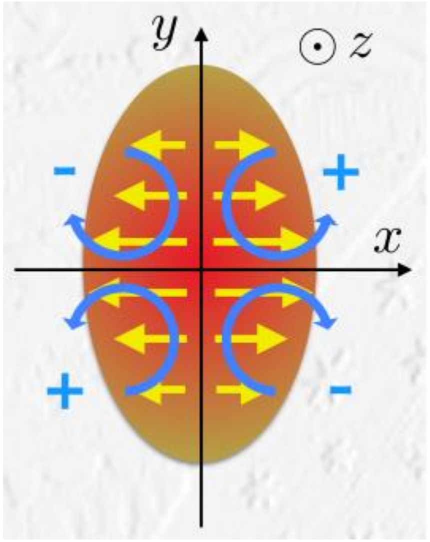
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right).$$

⇨ **Small but non zero signal at 200 GeV**

STAR Phys. Rev. C 98, 014910 2018
STAR Nature 548, 62
I. Karpenko, F. Becattini, Y. L. Xie, D. J. Wang, L. Csernai, H. Li, L.G. Pang, Q. Wang, X. L. Xia, C. M. Ko, Y. F. Sun, K. L. Li, S. Z. Shi, J. F. Liao, W. D. Xian, W. T. Deng, X.G. Huang …

Local Λ Polarization





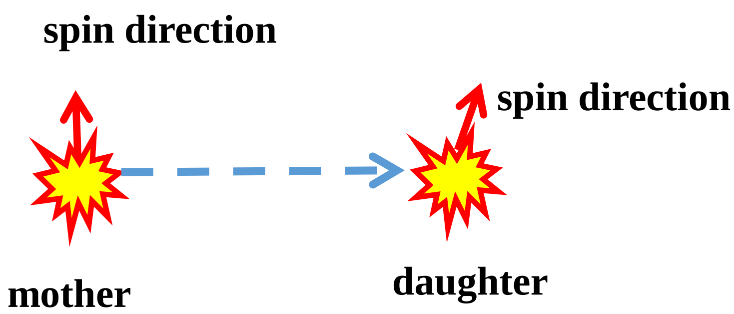
Voloshin at QM 2018

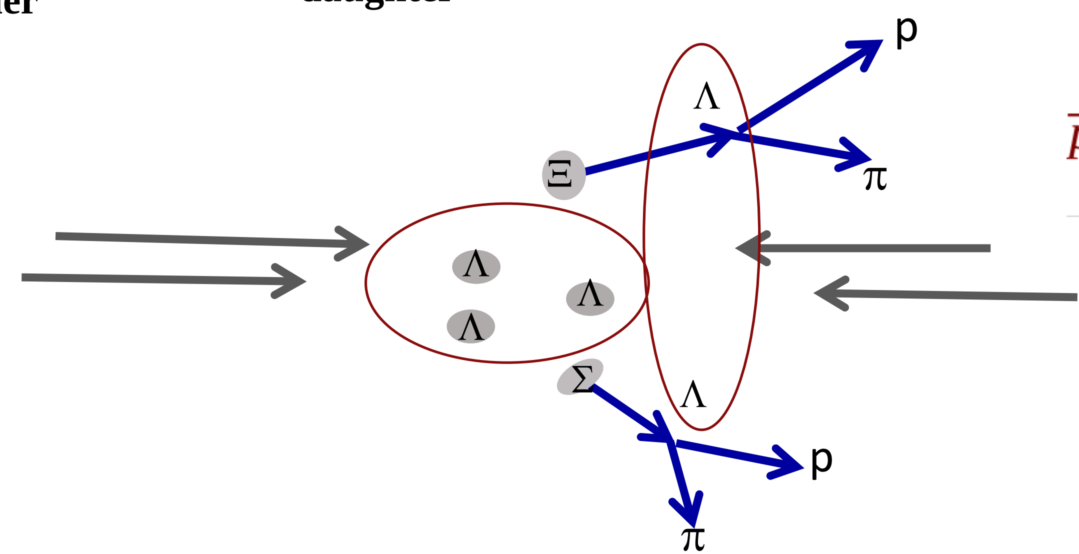
- Local velocity gradients due to elliptic flow may produce vorticity along beam direction (See Takafumi Niida's talk)
- Signal qualitatively disagrees with hydro and transport model

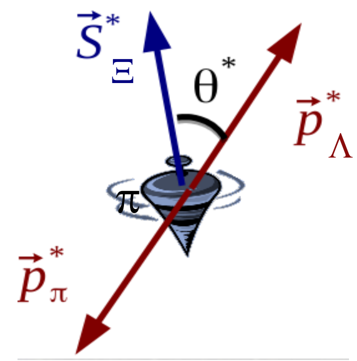
Takafumi Niida, Nuclear Physics A 00 (2018)
F. B., I. Karpenko, Phys. Rev. Lett. 120 ,012302(2018)
S. Voloshin, EPJ Conf. Ser. 17 (2018) 10700
X. L. Xia, H. Li, Z.-B. Tang, and Q. Wang, Phys. Rev. C98, 024905 (2018)

□ Spin transfer in resonance decay

Resonance decay







- Resonances produced at chemical freeze-out stage， Σ, $\Sigma(1385)$, $\Lambda(1405)$, Ξ ......
- Polarization of resonances can be transfered to Λ.
- For a polarized particle, what is the angular distribution and polarization vector of the decay daughter?

See G. Q. Cao's talk

Two body decay

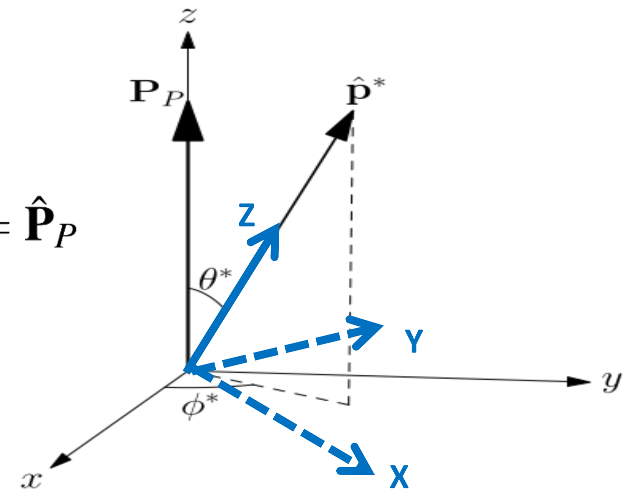
Decay problem $P \to D + X$

(spin dependent) $|S_P M_P\rangle\ S_D \lambda_D\rangle\ |S_X \lambda_X\rangle$

Based on the helicity formalism

z axis is set to be along the polarization vector of P $\hat{\mathbf{z}} = \hat{\mathbf{P}}_P$

a new quantization direction $\hat{\mathbf{Z}} = \hat{\mathbf{p}}^*$



Resonance Decay

- Spin Density-Matrix

- initial state: $|i\rangle = |S_P M_P\rangle$ $\quad \rho^i_{M_P;M'_P} = \langle S_P M_P | \rho^i | S_P M'_P\rangle$

- final state: $|f\rangle = |\theta^* \phi^* \lambda_D \lambda_X\rangle$ $\quad \rho^f_{\lambda_D\lambda_X;\lambda'_D\lambda'_X}(\theta^*,\phi^*) = \langle \theta^* \phi^* \lambda_D \lambda_X | \rho^f | \theta^* \phi^* \lambda'_D \lambda'_X\rangle$

$$\rho^f = T^\dagger \rho^i T \qquad T = \sqrt{\frac{2S_p+1}{4\pi}} D^{S_P *}_{M_p;\lambda_D-\lambda_X}(\phi^*,\theta^*,0) A_{\lambda_D;\lambda_X}$$

combination of **Wigner D function** and **Decay amplitude**

- Polarization $\quad \mathbf{P}_D = \mathrm{tr}(\hat{\mathbf{P}}\rho^f)/\mathrm{tr}(\rho^f) \qquad \mathrm{tr}(\rho^f) = \frac{1}{N}\frac{dN}{d\Omega^*}$

M. Jacob and G. C. Wick, (1959)

S. U. Chung, (1971) Spin Formalisms

J. D. Richman, (1984) An Experimenter's Guide to the Helicity Formalism

Ex1: Polarization vector and angular distribution

Strong decay $1/2^{\pm} \to 1/2^{+}0^{-}$

$\Sigma(1660) \to \Lambda\pi$ $\quad \frac{1}{2}^{+} \to \frac{1}{2}^{+}0^{-}$

$\Lambda(1405) \to \Sigma^{0}\pi$ $\quad \frac{1}{2}^{-} \to \frac{1}{2}^{+}0^{-}$

Matrix element is $T = \sqrt{\frac{2S_p+1}{4\pi}} D^{S_P *}_{M_p;\lambda_D-\lambda_X}(\phi^*,\theta^*,0) A_{\lambda_D;\lambda_X}$

$\rho^f = T^\dagger \rho^i T$

combination of **Wigner D function** and **Decay amplitude**

$$\rho^i_{M_P;M_P'} = \mathrm{diag}\left(\frac{1+P_P}{2}, \frac{1-P_P}{2}\right) \qquad \rho^D_{\lambda_D;\lambda_D'} = \frac{1}{4\pi}\begin{pmatrix} |A_{1/2}|^2(1+P_P\cos\theta^*) & -A_{1/2}A^*_{-1/2}P_P\sin\theta^* \\ -A^*_{1/2}A_{-1/2}P_P\sin\theta^* & |A_{-1/2}|^2(1-P_P\cos\theta^*) \end{pmatrix}$$

Since parity is conserved, amplitude is constrained by

$$A_{\lambda_D;\lambda_X} = \pi_P\pi_D\pi_X(-1)^{S_P-S_D-S_X}A_{-\lambda_D;-\lambda_X}$$

$$\rho^D_{\lambda_D;\lambda_D'} = \frac{1}{8\pi}\begin{pmatrix} 1+P_P\cos\theta^* & \pm P_P\sin\theta^* \\ \pm P_P\sin\theta^* & 1-P_P\cos\theta^* \end{pmatrix} \Longrightarrow \frac{1}{N}\frac{dN}{d\Omega^*} = \frac{1}{4\pi}$$

$$\begin{aligned} P_X(\theta^*,\phi^*) &= \pm P_P\sin\theta^*, \\ P_Y(\theta^*,\phi^*) &= 0, \\ P_Z(\theta^*,\phi^*) &= P_P\cos\theta^*. \end{aligned} \Longrightarrow$$

$\frac{1}{2}^{+} \to \frac{1}{2}^{+}0^{-}$ $\quad \mathbf{P}_D = 2(\mathbf{P}_P\cdot\hat{\mathbf{p}}^*)\hat{\mathbf{p}}^* - \mathbf{P}_P$

$\frac{1}{2}^{-} \to \frac{1}{2}^{+}0^{-}$ $\quad \mathbf{P}_D = \mathbf{P}_P$

Ex2: Polarization vector and angular distribution

Weak decay $1/2 \to 1/2\ 0$

$$\Xi \to \Lambda\pi$$

$$\frac{1}{2}^{+} \to \frac{1}{2}^{+} 0^{-}$$

$$\rho^{i}_{M_P;M'_P} = \mathrm{diag}\left(\frac{1+P_P}{2}, \frac{1-P_P}{2}\right) \qquad \rho^{D}_{\lambda_D;\lambda'_D} = \frac{1}{4\pi}\begin{pmatrix} |A_{1/2}|^2(1+P_P\cos\theta^*) & -A_{1/2}A^*_{-1/2}P_P\sin\theta^* \\ -A^*_{1/2}A_{-1/2}P_P\sin\theta^* & |A_{-1/2}|^2(1-P_P\cos\theta^*) \end{pmatrix}$$

parity is not conserved, amplitude can be decomposed as parrity odd and parity even

$$A_{\pm 1/2} = \frac{A_s \pm A_p}{\sqrt{2(|A_s|^2+|A_p|^2)}}$$

Lee-Yang formula

$$\mathbf{P}_D = \frac{(\alpha + \mathbf{P}_P\cdot\hat{\mathbf{p}}^*)\hat{\mathbf{p}}^* + \beta(\mathbf{P}_P\times\hat{\mathbf{p}}^*) + \gamma\hat{\mathbf{p}}^*\times(\mathbf{P}_P\times\hat{\mathbf{p}}^*)}{1+\alpha\mathbf{P}_P\cdot\hat{\mathbf{p}}^*}$$

$$\frac{1}{N}\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1+\alpha P_P\cos\theta^*)$$

weak decay parameter

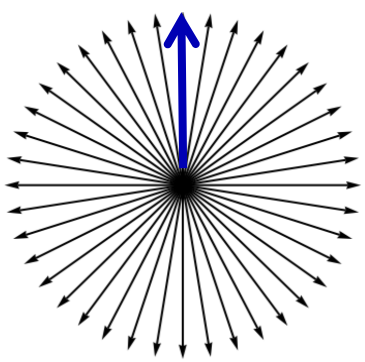
$$\begin{cases} \alpha = \dfrac{2\mathrm{Re}(A_s^*A_p)}{|A_s|^2+|A_p|^2}, \\ \beta = \dfrac{2\mathrm{Im}(A_s^*A_p)}{|A_s|^2+|A_p|^2}, \\ \gamma = \dfrac{|A_s|^2-|A_p|^2}{|A_s|^2+|A_p|^2}. \end{cases}$$

- $\alpha = 0, \beta = 0, \gamma = 1 \Rightarrow \mathbf{P}_D = \mathbf{P}_P$
- $\alpha = 0, \beta = 0, \gamma = -1 \Rightarrow \mathbf{P}_D = 2(\mathbf{P}_P\cdot\hat{\mathbf{p}}^*)\hat{\mathbf{p}}^* - \mathbf{P}_P$

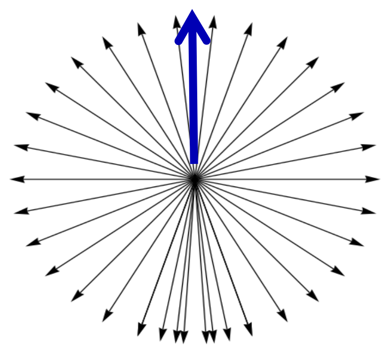
T. D. Lee and C.-N. Yang, Phys. Rev. 108, 1645 (1957)

Polarization vector and angular distribution

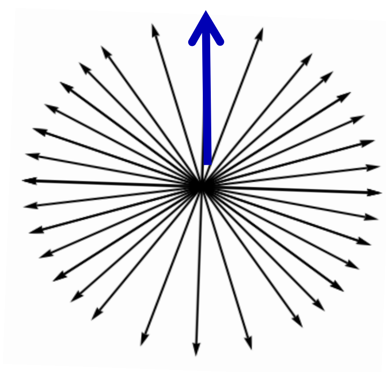
	spin and parity	$(1/N)dN/d\Omega^*$
strong decay	$1/2^+ \to 1/2^+0^-$	$1/(4\pi)$
strong decay	$1/2^- \to 1/2^+0^-$	$1/(4\pi)$
strong decay	$3/2^+ \to 1/2^+0^-$	$3\left[1-2\Delta/3-(1-2\Delta)\cos^2\theta^*\right]/(8\pi)$
strong decay	$3/2^- \to 1/2^+0^-$	$3\left[1-2\Delta/3-(1-2\Delta)\cos^2\theta^*\right]/(8\pi)$
weak decay	$1/2 \to 1/2\ \ 0$	$(1+\alpha P_P\cos\theta^*)/(4\pi)$
EM decay	$1/2^+ \to 1/2^+1^-$	$1/(4\pi)$



$$\frac{1}{N}\frac{dN}{d\Omega^*}=\frac{1}{4\pi}$$



$$\frac{1}{4\pi}\left(1+\alpha P_P\cos\theta^*\right)$$



$$\frac{3}{8\pi}\left[1-\frac{2}{3}\Delta-(1-2\Delta)\cos^2\theta^*\right]$$

$$\Delta=\rho_{\frac{1}{2}\frac{1}{2}}+\rho_{-\frac{1}{2}-\frac{1}{2}}$$

Polarization vector and angular distribution

	$\mathbf{P}_D$	$\langle \mathbf{P}_D \rangle / \mathbf{P}_P$
strong decay	$2\,(\mathbf{P}_P \cdot \hat{\mathbf{p}}^*)\,\hat{\mathbf{p}}^* - \mathbf{P}_P$	-1/3
strong decay	$\mathbf{P}_P$	1
strong decay	Seen in paper	1
strong decay	Seen in paper	-3/5
weak decay	$\frac{(\alpha+\mathbf{P}_P\cdot\hat{\mathbf{p}}^*)\hat{\mathbf{p}}^*+\beta(\mathbf{P}_P\times\hat{\mathbf{p}}^*)+\gamma\hat{\mathbf{p}}^*\times(\mathbf{P}_P\times\hat{\mathbf{p}}^*)}{1+\alpha\mathbf{P}_P\cdot\hat{\mathbf{p}}^*}$	$(2\gamma+1)/3$
EM decay	$-\,(\mathbf{P}_P \cdot \hat{\mathbf{p}}^*)\,\hat{\mathbf{p}}^*$	-1/3

Polarization transfer between mother and daughter are obtained.

After integral over the momentum, one can get $\mathbf{P}_D = C\mathbf{P}_P$

F. Becattini, I. Karpenko, M. Lisa, I. Upsal, S. Voloshin, Phys. Rev. C 95 054902 (2017)

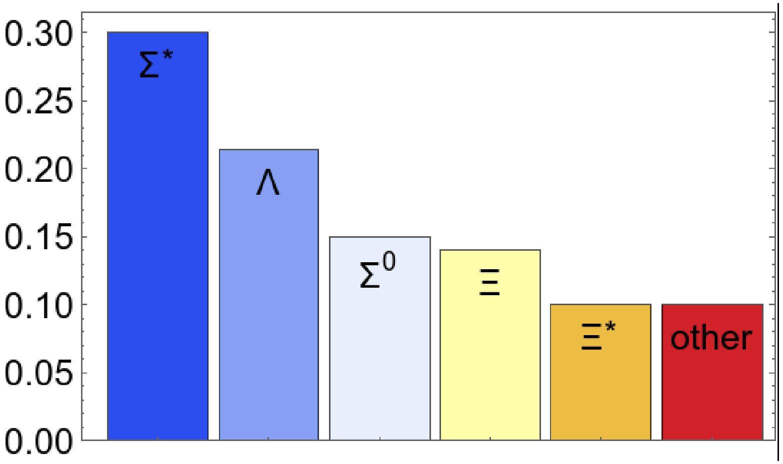
Monte Carlo simulation

- Effect of the decay on Λ polarization

Thermal model

16 species resonance state are considered

	spin and parity	decay channel
Λ	$1/2^+$	-
$\Lambda(1405)$	$1/2^-$	$\Sigma^0\pi$
$\Lambda(1520)$	$3/2^-$	$\Sigma^0\pi$
$\Lambda(1600)$	$1/2^+$	$\Sigma^0\pi$
$\Lambda(1670)$	$1/2^-$	$\Sigma^0\pi$, $\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	$\Sigma^0\pi$
Σ^0	$1/2^+$	$\Lambda\gamma$
Σ^{*0}	$3/2^+$	$\Lambda\pi$
Σ^{*+}	$3/2^+$	$\Lambda\pi$, $\Sigma^0\pi$
Σ^{*-}	$3/2^+$	$\Lambda\pi$, $\Sigma^0\pi$
$\Sigma(1660)$	$1/2^+$	$\Lambda\pi$, $\Sigma^0\pi$
$\Sigma(1670)$	$3/2^-$	$\Lambda\pi$, $\Sigma^0\pi$
Ξ^0	$1/2^+$	$\Lambda\pi$
Ξ^-	$1/2^+$	$\Lambda\pi$
Ξ^{*0}	$3/2^+$	$\Xi\pi$
Ξ^{*-}	$3/2^+$	$\Xi\pi$



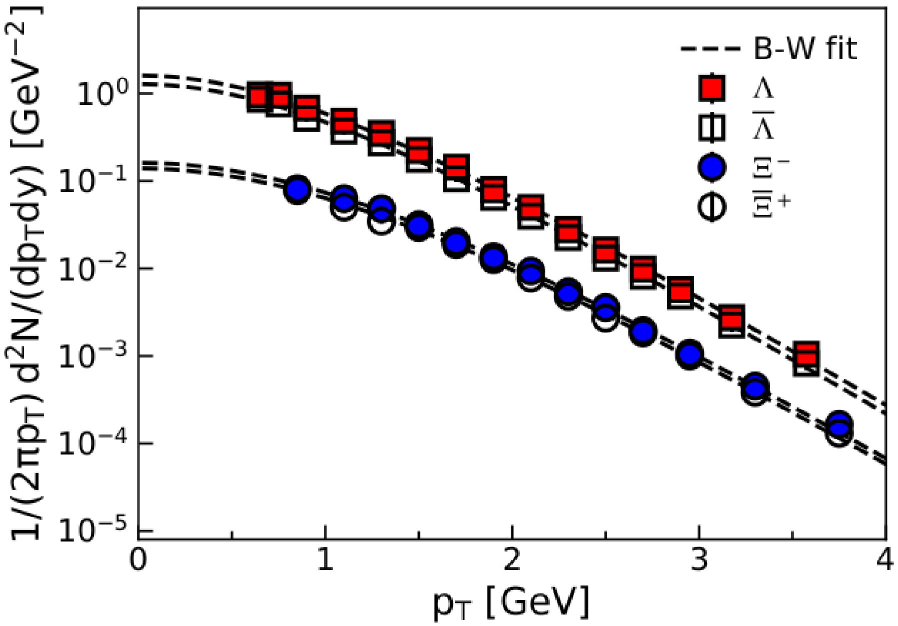
particle yields calculated by the THERMUS model

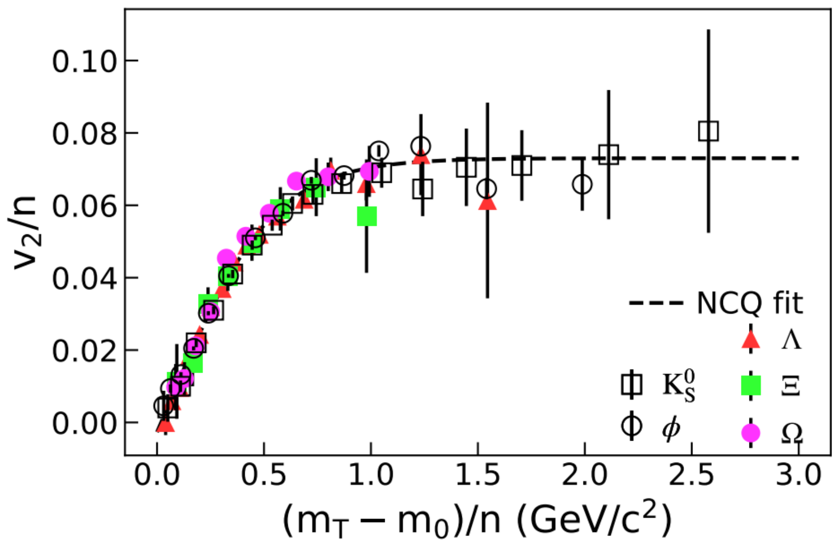
S. Wheaton and J. Cleymans, Comput. Phys. Commun., vol. 180, 2009

Transverse momentum spectrum and elliptic flow

$$\frac{d^2N}{p_T dp_T dy} \propto \int_0^1 \tilde{r} d\tilde{r} m_T I_0\left(\frac{p_T \sinh\rho}{T_{\text{kin}}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{\text{kin}}}\right)$$

$$v_2/n = \frac{a}{1+\exp\{-[(m_T - m_0)/n - b]/c\}} + d$$





Data taken from STAR

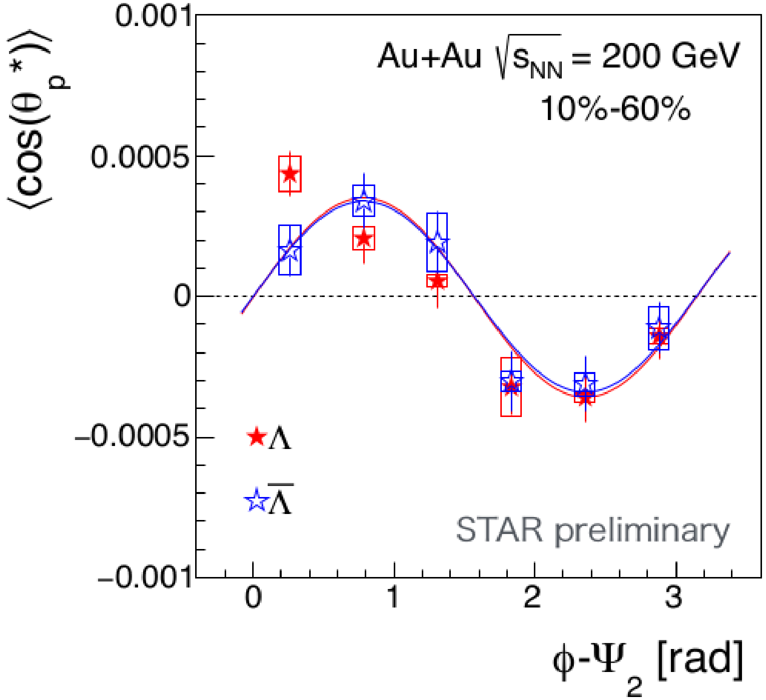
Phys. Rev. Lett, 116, 062301 (2016) , 98, 062301 (2007), 95, 122301 (2005), 92, 052302 (2004) …

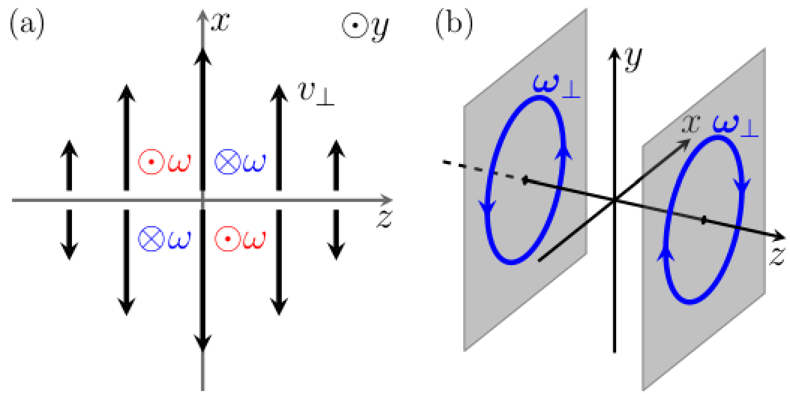
X. Dong, S. Esumi, P. Sorensen, N. Xu, and Z. Xu, Phys. Lett. B597, 328 (2004)

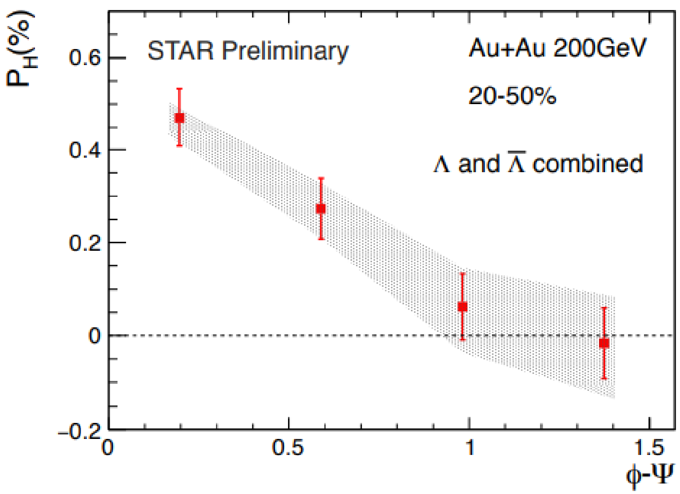
Input signal for primordial poalrization

General polarization form of the primordial particle

$$P_x(\phi) = F_{1x}\sin\phi,$$
$$P_y(\phi) = F_0 - F_{1y}\cos\phi + F_2\cos(2\phi),$$
$$P_z(\phi) = F_z\sin(2\phi),$$







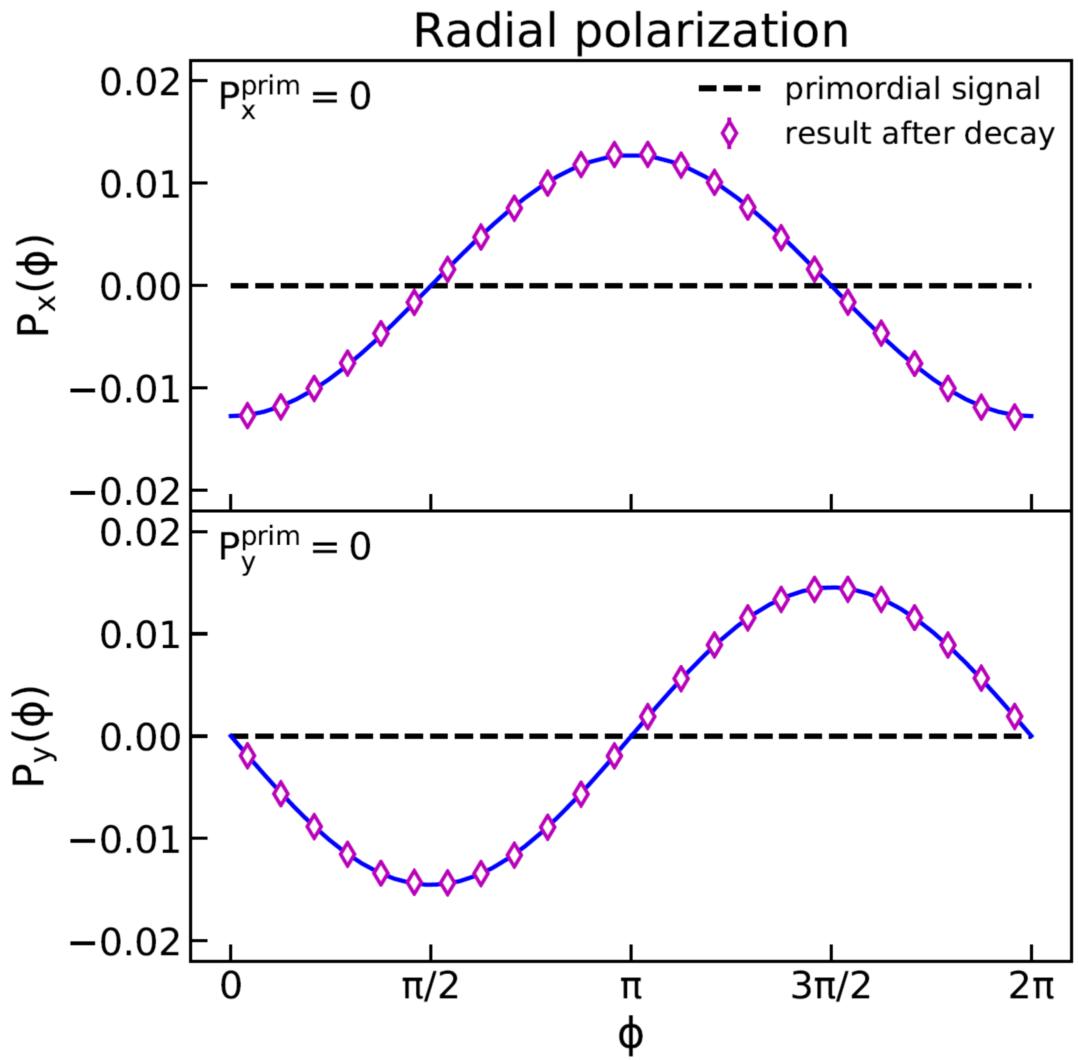
X. L. Xia, H. Li, Z.-B. Tang, and Q. Wang, Phys. Rev. C98, 024905 (2018)
Takafumi Niida, Nuclear Physics A 00 (2018) 1–4
QM talk of Biao Tu (2018)

Contribution from Ξ

$$\mathbf{P}_D = \frac{(\alpha + \mathbf{P}_P \cdot \hat{\mathbf{p}}^*)\,\hat{\mathbf{p}}^* + \beta\,(\mathbf{P}_P \times \hat{\mathbf{p}}^*) + \gamma \hat{\mathbf{p}}^* \times (\mathbf{P}_P \times \hat{\mathbf{p}}^*)}{1 + \alpha \mathbf{P}_P \cdot \hat{\mathbf{p}}^*}$$

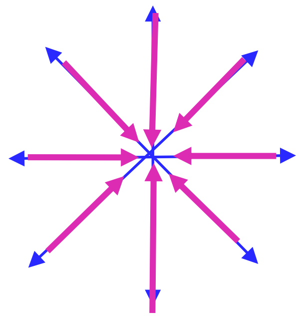
For $\mathbf{P}_P = (0,0,0)$ ⟹

$$\mathbf{P}_D = \alpha \hat{\mathbf{p}}^*$$



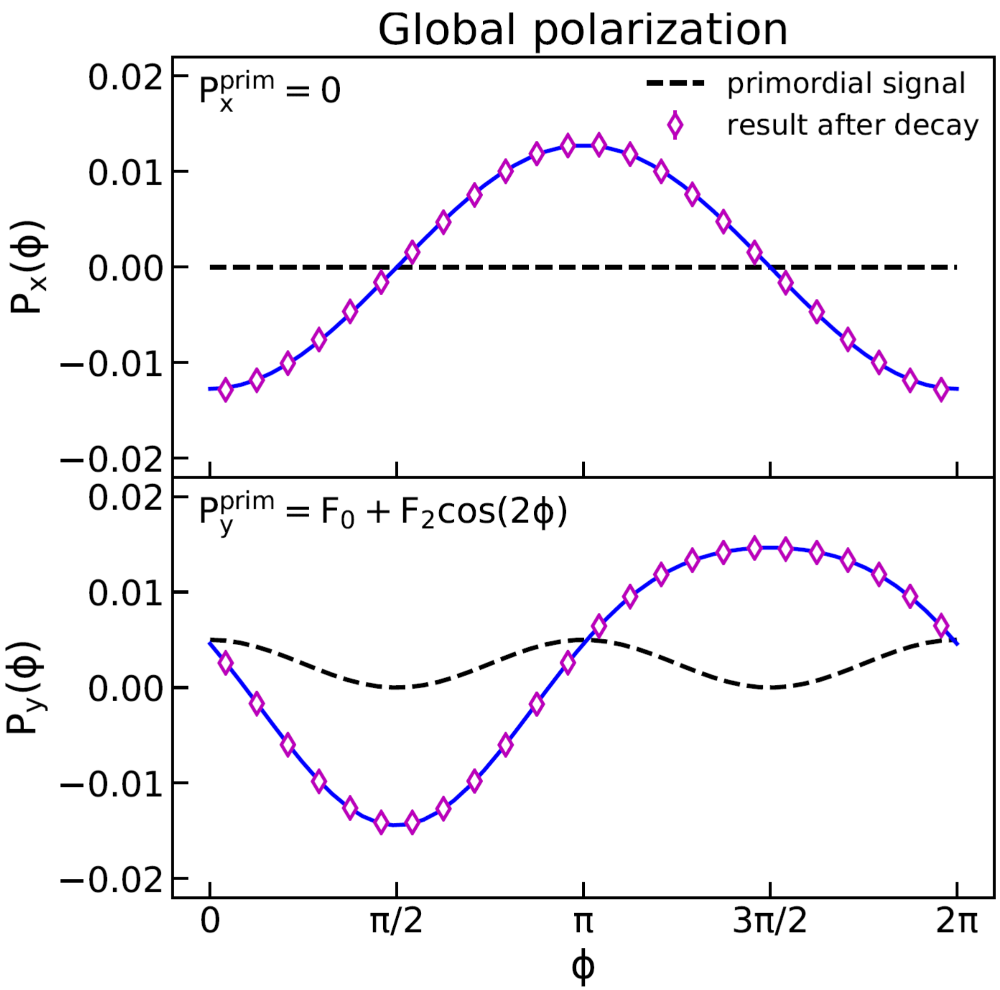
Ξ decay can contribute to the radial polarization. $\alpha_\Xi < 0$

$$\alpha_{\Xi^-} = -0.458$$

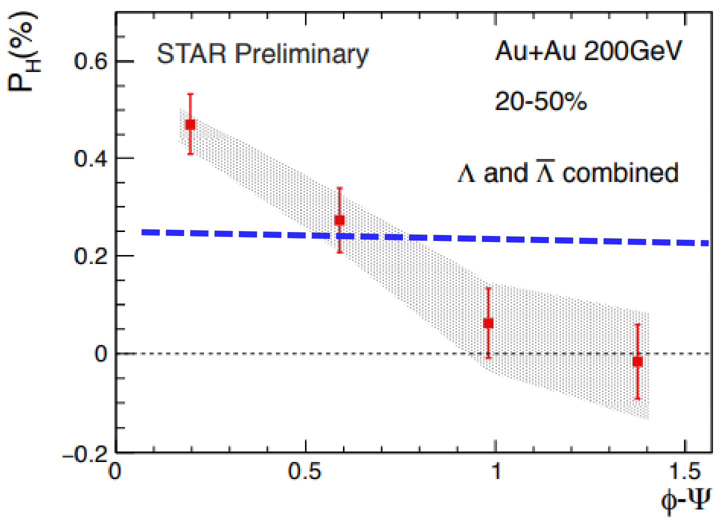


$$P_x(\phi) = K_{1x} \cos\phi\,,$$
$$P_y(\phi) = K_{1y} \sin\phi\,,$$

Simulation on global polarization

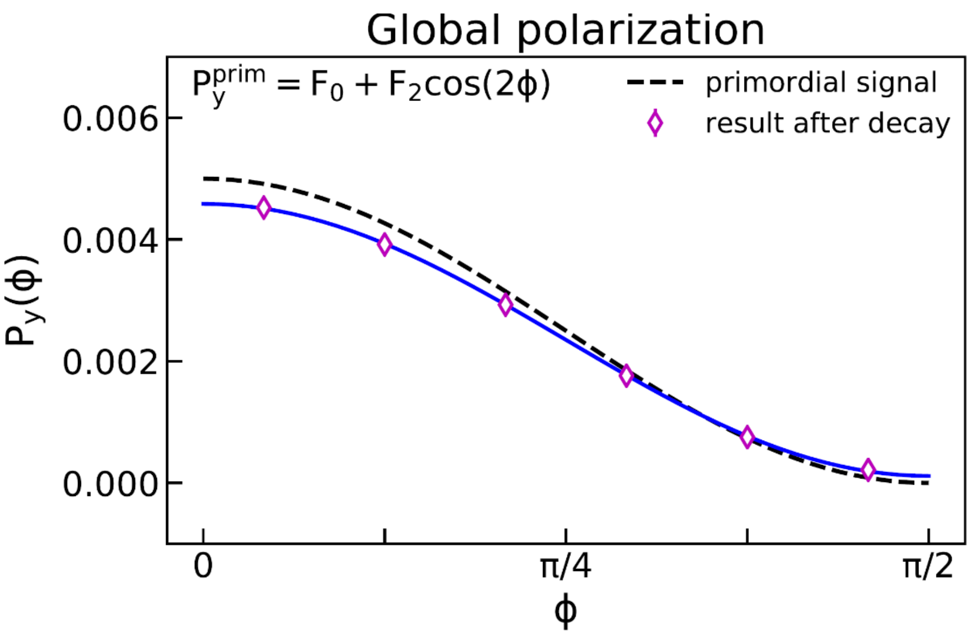


$$\mathbf{P}_P = (0, F_0 + F_2\cos(2\phi), 0)$$

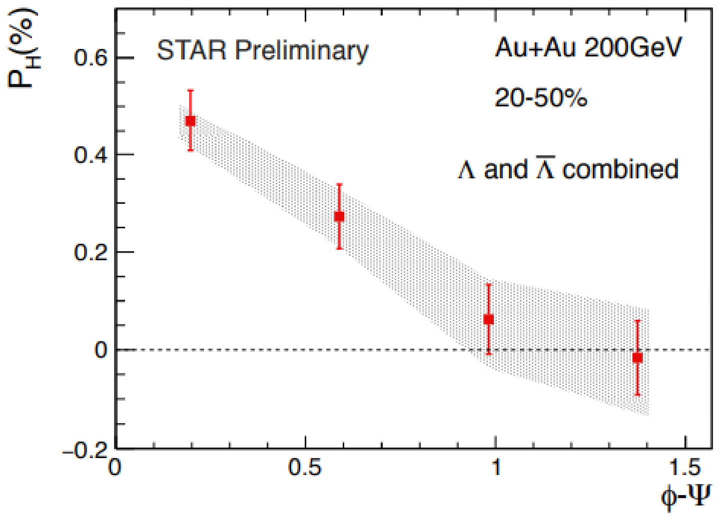


QM talk of Biao Tu (2018)

Simulation on the global polarization



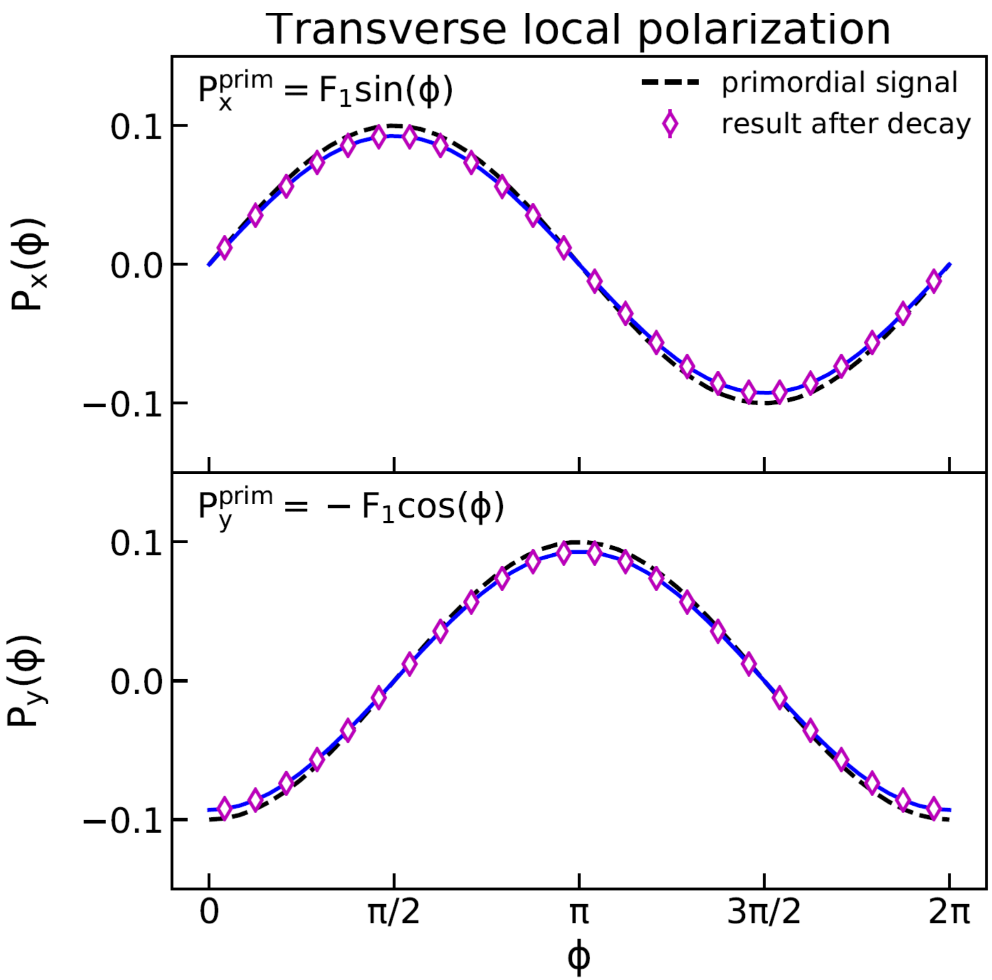
QM talk of Biao Tu (2018)



$$P_y(\phi) = F_0 + F_2 \cos(2\phi)$$

Simulation on transverse local polarization

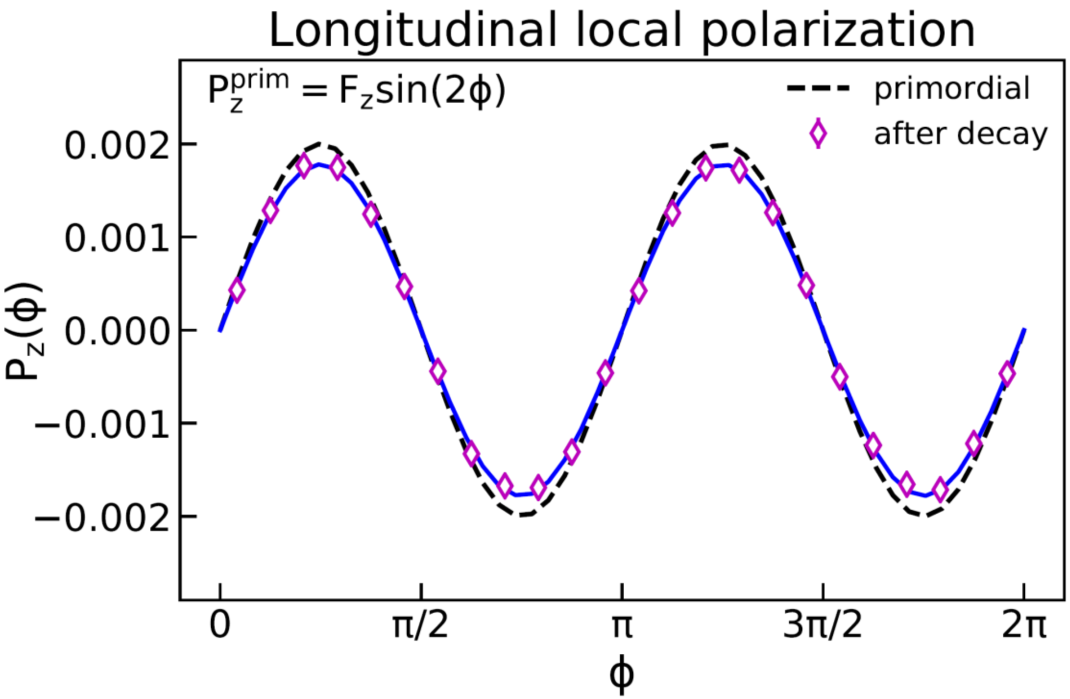
$$\mathbf{P}_P = (F_1 \sin\phi, -F_1 \cos\phi, 0)$$

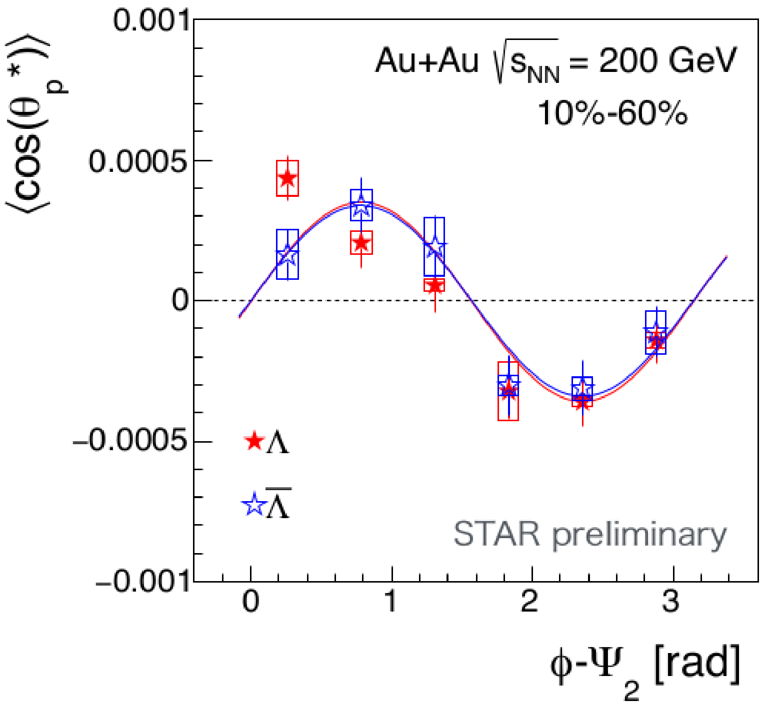


X.-L. Xia, H. Li, Z.-B. Tang, and Q. Wang, Phys. Rev. C98, 024905 (2018)

Simulation on longitudinal local polarization

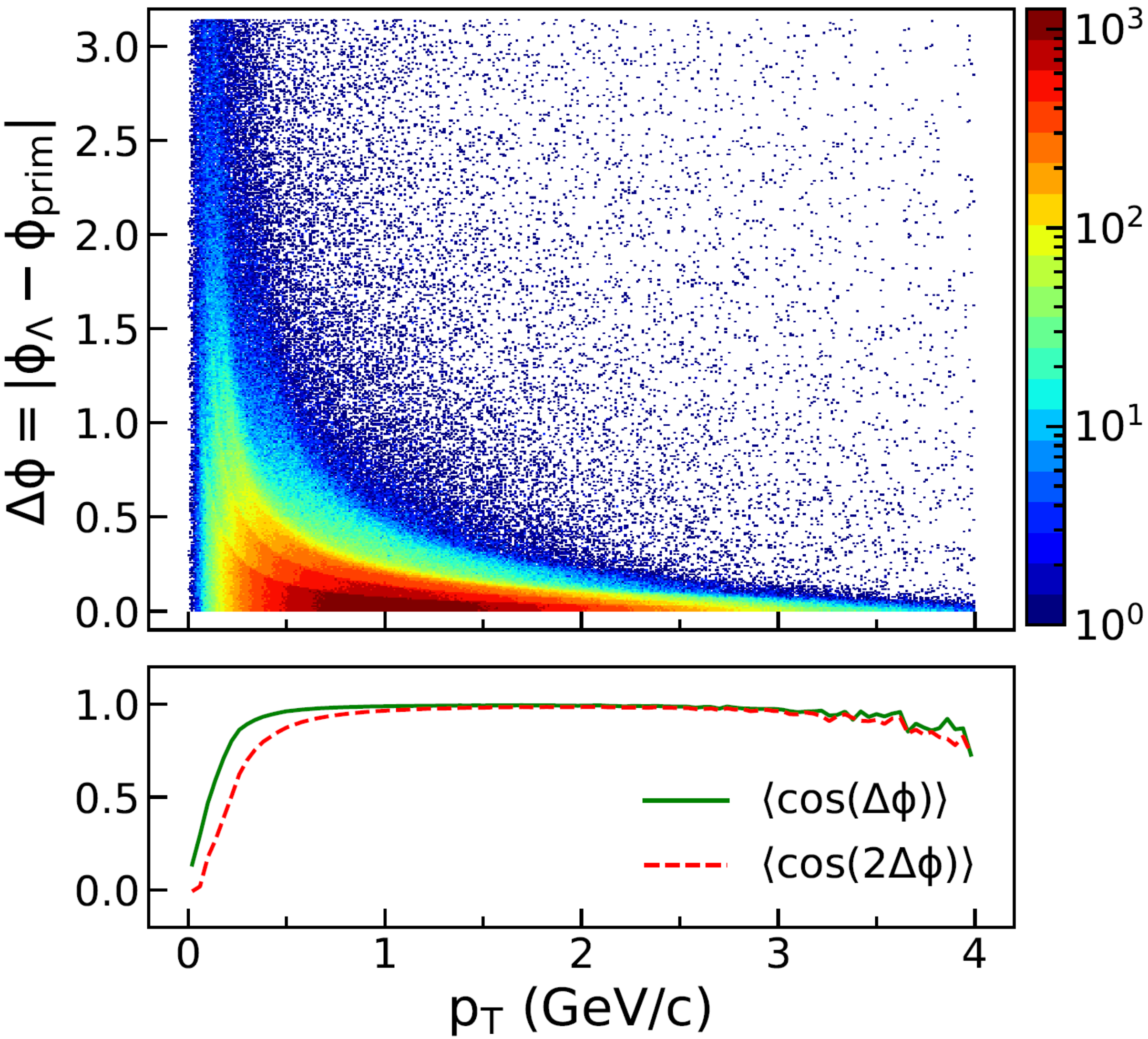
$$\mathbf{P}_P = (0, 0, F_z \sin(2\phi))$$

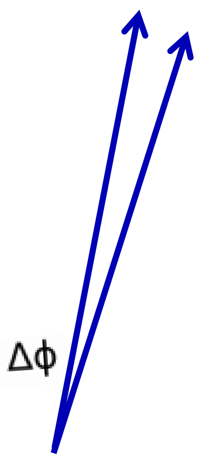




Takafumi Niida, Nuclear Physics A 00 (2018) 1–4

Azimuthal angle correlation of the daughter and mother





Summary

The polarization transfer between the mother and the daughter particle are obtained.

Monte Carlo simulation on the resonance decay on Λ polarization are performed.

- the effect of the resonance decay can suppress the primordial polarization (not significant).
- the Ξ weak decay can contribute a radial polarization to the Λ polarization.

Thanks for your attention!

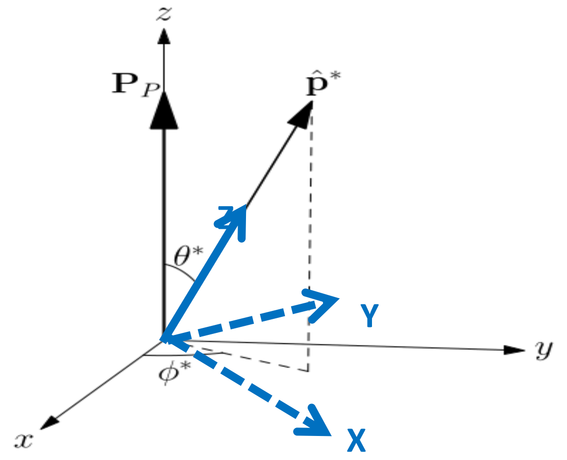
Helicity Frame

Which frame should be used?

$$\hat{\mathbf{X}} = \frac{\left(\hat{\mathbf{P}}_P \times \hat{\mathbf{p}}^*\right) \times \hat{\mathbf{p}}^*}{\sin\theta^*}$$

$$\hat{\mathbf{Y}} = \frac{\hat{\mathbf{P}}_P \times \hat{\mathbf{p}}^*}{\sin\theta^*},$$

$$\hat{\mathbf{Z}} = \hat{\mathbf{p}}^*,$$



Polarization vector

$$\mathbf{P} = P_x\hat{\mathbf{X}} + P_y\hat{\mathbf{Y}} + P_z\hat{\mathbf{Z}}$$

The z-axis is given by the momentum in the laboratory frame, chosen as the quantization axis in the helicity formalism

The y-axis is given by the direction of the vector product
Finally the x-axis is obtained