Spin-alignment of J/ψ meson: Dissociation mechanism of magnetic interaction

Zhishun Chen

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Under the supervision of Shu Lin,
Cooperate with Yun Guo, Min He

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03 **Scenario**
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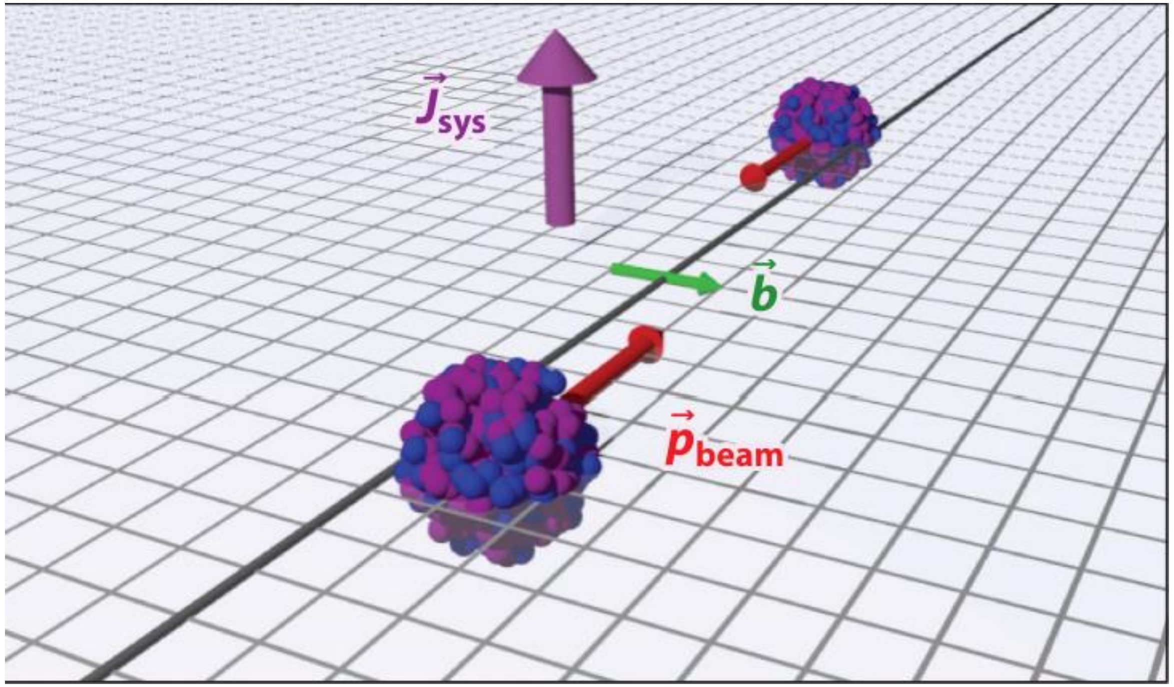


Figure from F. Becattini-Michael A. Lisa, AR 2020

- First idea in spin alignment

  Liang, Wang PRL 2005, PRB 2005

- Hyperon polarization can be nicely describe by hydrodynamic and transport-based calculations

- vector meson polarization still not clear...

  Vector meson field fluctuation
  Glasma field fluctuation
  Vorticity field
  EM field
  Fragmentation

01

Background

Spin density matrix

$$\rho = \sum_i P_i \, |\psi_i\rangle\langle\psi_i|$$

① $\rho = \rho^\dagger$

② $\mathrm{Tr}\rho = \sum_i P_i = 1$

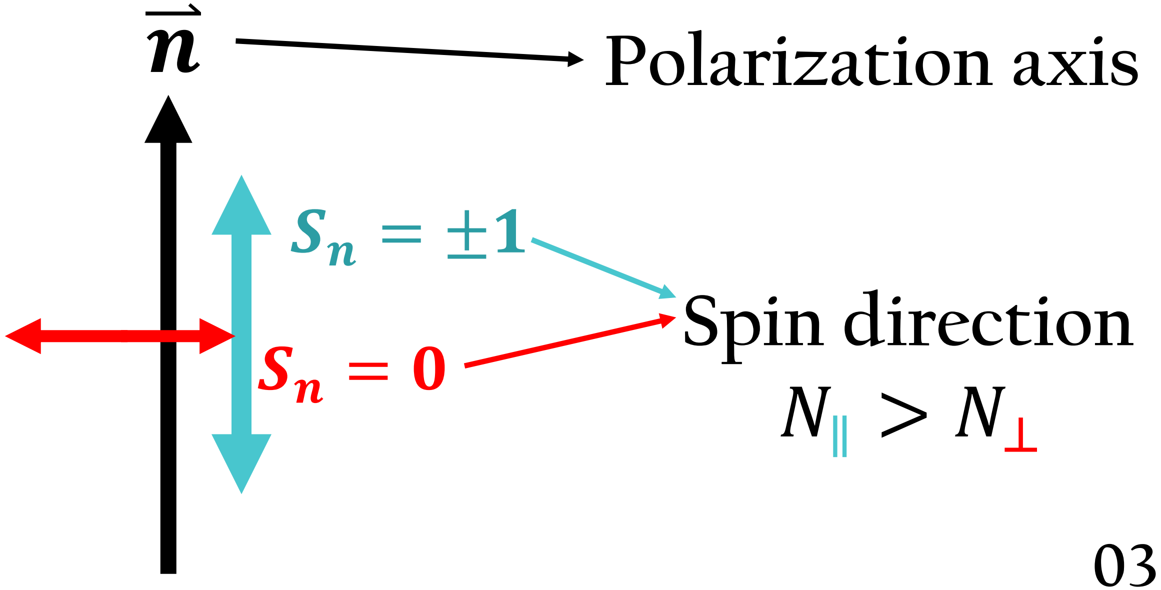
③ $\langle\varphi|\rho|\varphi\rangle \geq 0$

no polarization case:

$$\rho = \frac{1}{2S+1}\begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix}$$

$$\rho \overset{S=1}{\Longrightarrow} \frac{1}{3}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

If $\rho_{00} < 1/3$

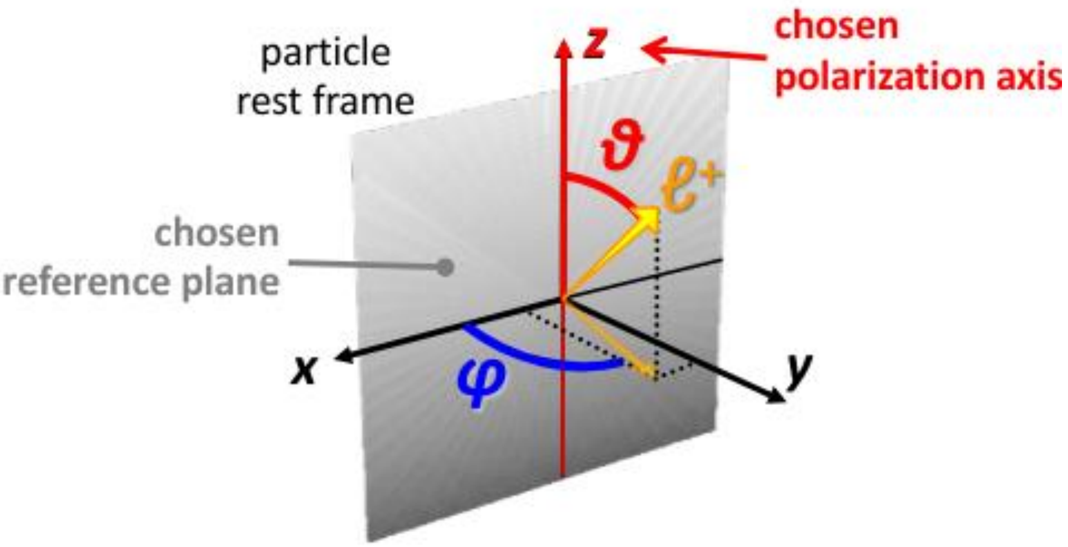


*Figures in this slide all from P. Faccioli-C.Lourenço, Particle Polarization in High Energy Physics

01

Background

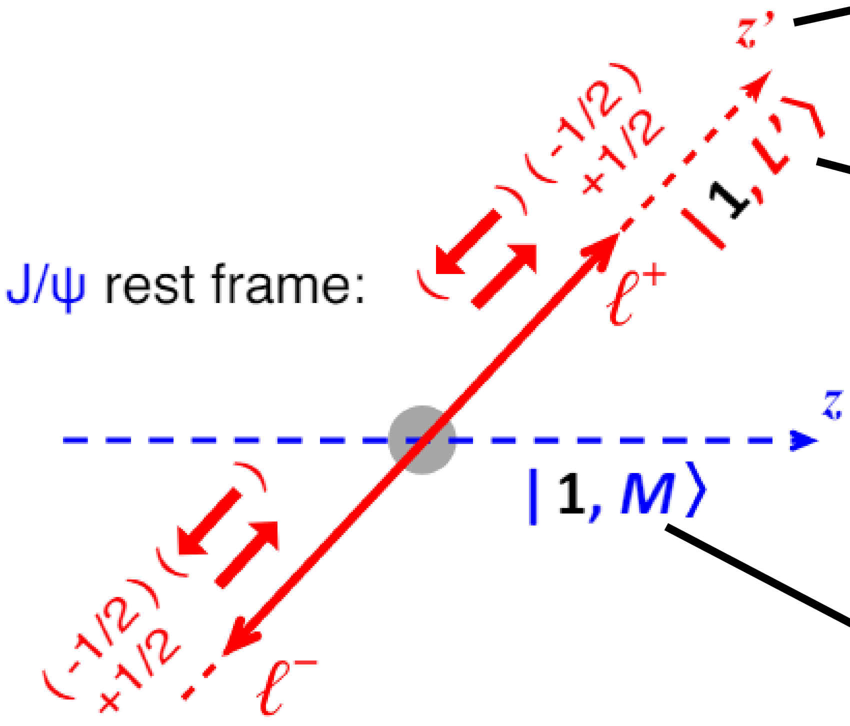
How to measure spin alignment in experiment



- J/ψ decay into lepton-antilepton pair
- (ϑ, φ) indicate positive lepton's direction
- Measurement of angular distribution

01 Background

How to measure spin alignment in experiment



emission axis

Total angular momentum component of the dilepton system along z'

Spin component of J/ψ along z

$$|J/\psi\rangle = \sum_{M=0,\pm 1} a_M \, |J/\psi; 1, M\rangle_z$$

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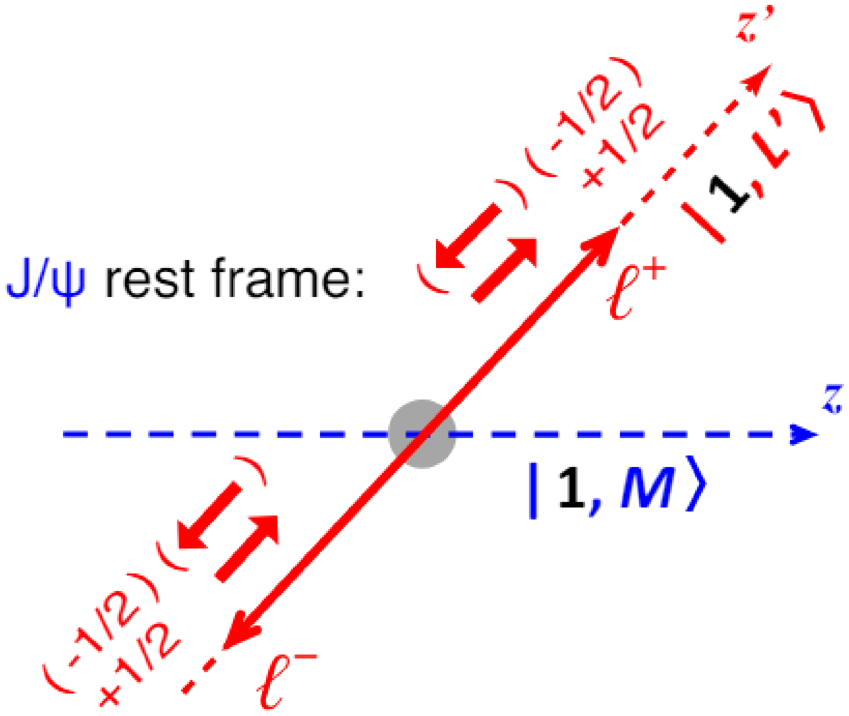
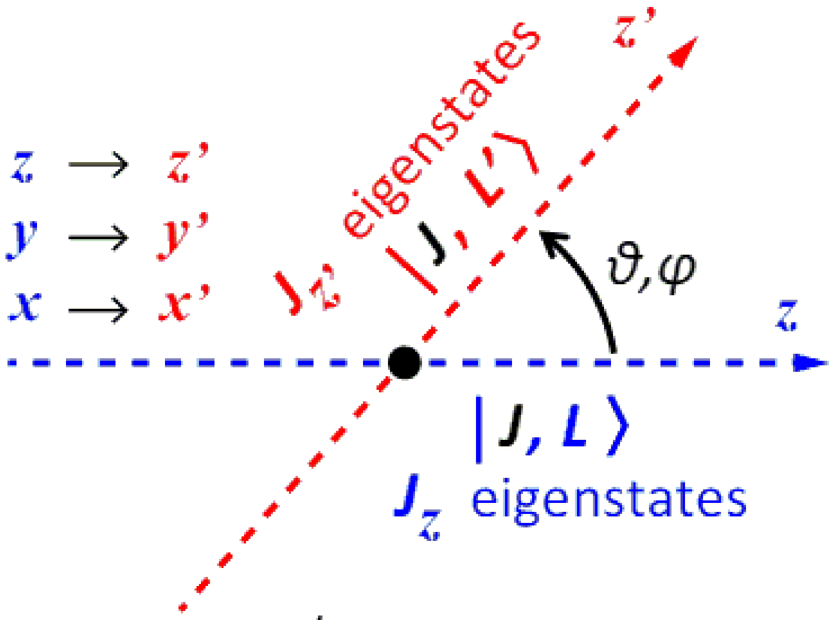
Background

How to measure spin alignment in experiment



$$|J/\psi\rangle = \sum_{M=0,\pm1} a_M\, |J/\psi; 1, M\rangle_z$$



$$|J, L'\rangle = \sum_{L=-J}^{+J} \mathcal{D}^{J}_{L L'}(\vartheta,\varphi)\, |J, L\rangle$$

Dilepton system

superposition of eigenstates of J_z

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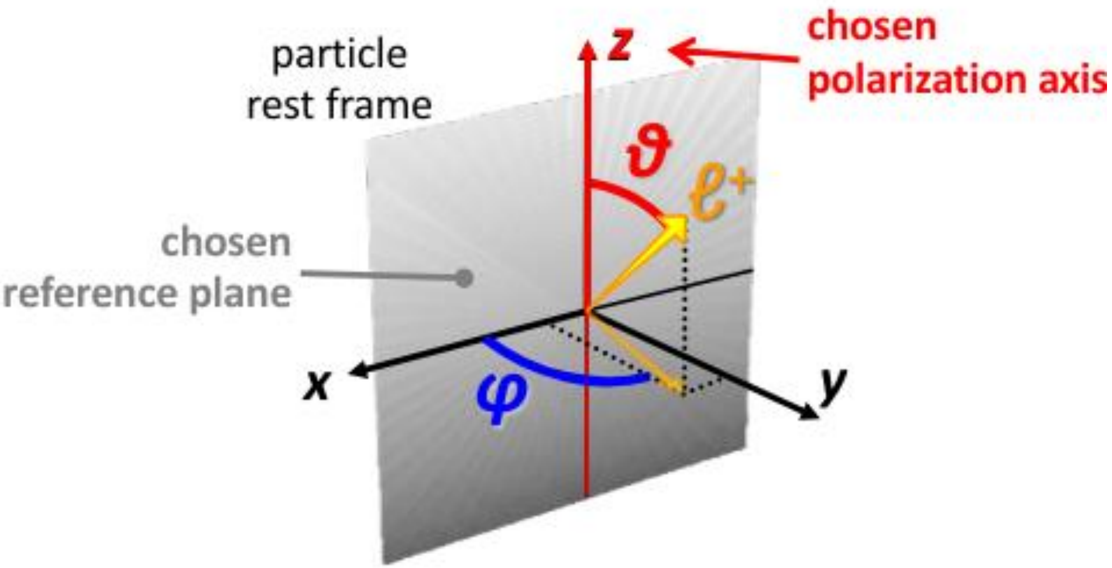
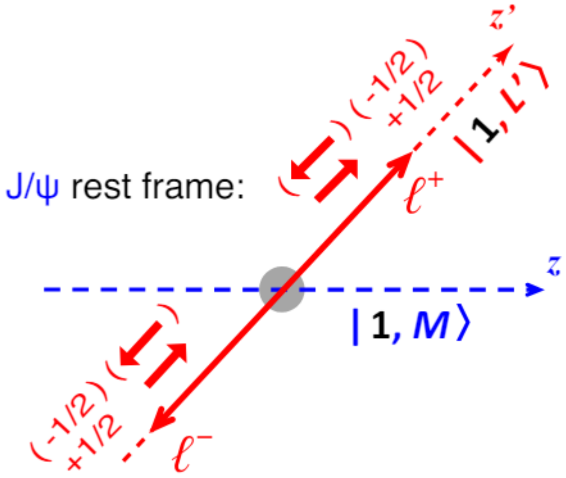
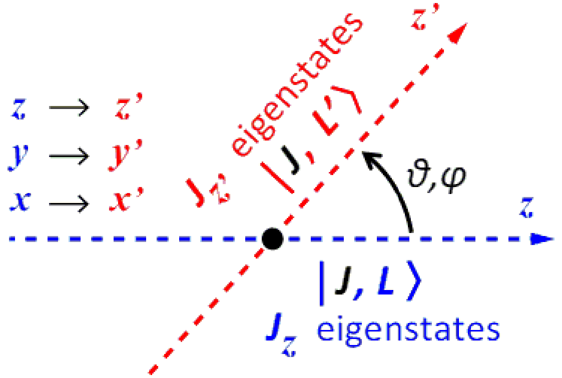




$$|J/\psi\rangle = \sum_{M=0,\pm1} a_M \, |J/\psi; 1, M\rangle_z$$



$$|J, L'\rangle = \sum_{L=-J}^{+J} \mathcal{D}^{J}_{L L'}(\vartheta,\varphi)\, |J, L\rangle$$

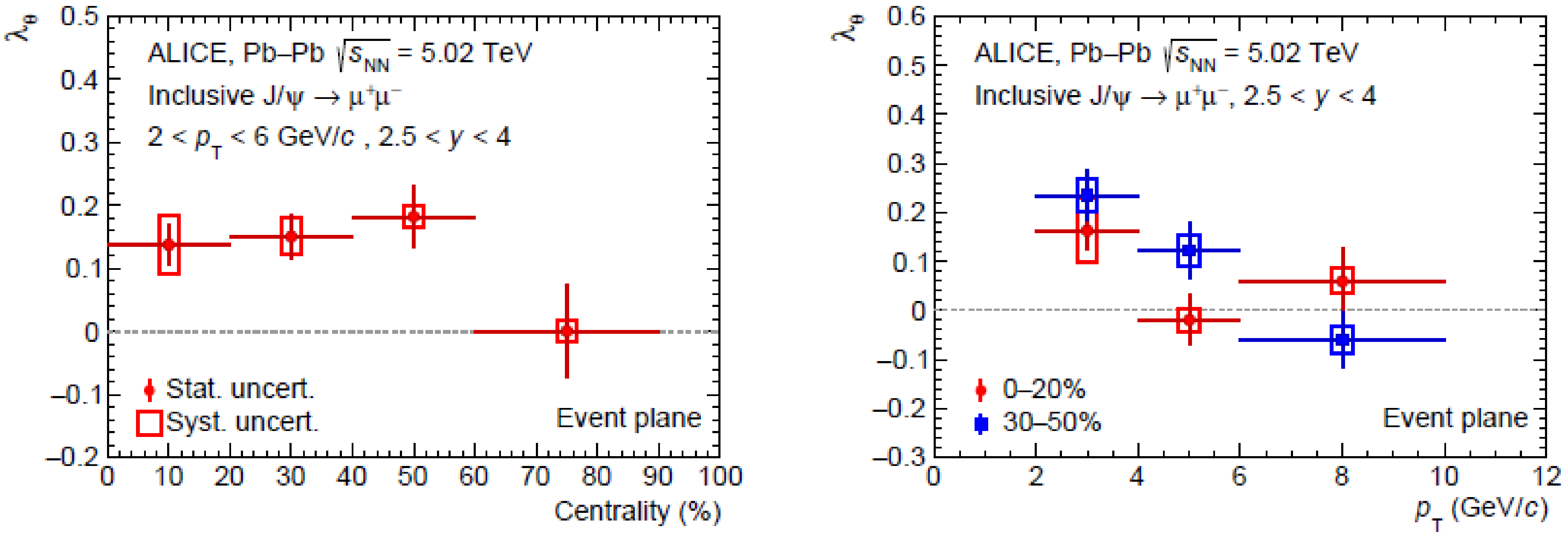
$$W(\vartheta) \propto \frac{1+\lambda_\vartheta \cos^2\vartheta}{3+\lambda_\vartheta}$$

$$\lambda_\vartheta = \frac{1-3|a_0|^2}{1+|a_0|^2}, \text{actually } |a_0|^2 = \rho_{00}$$

Background

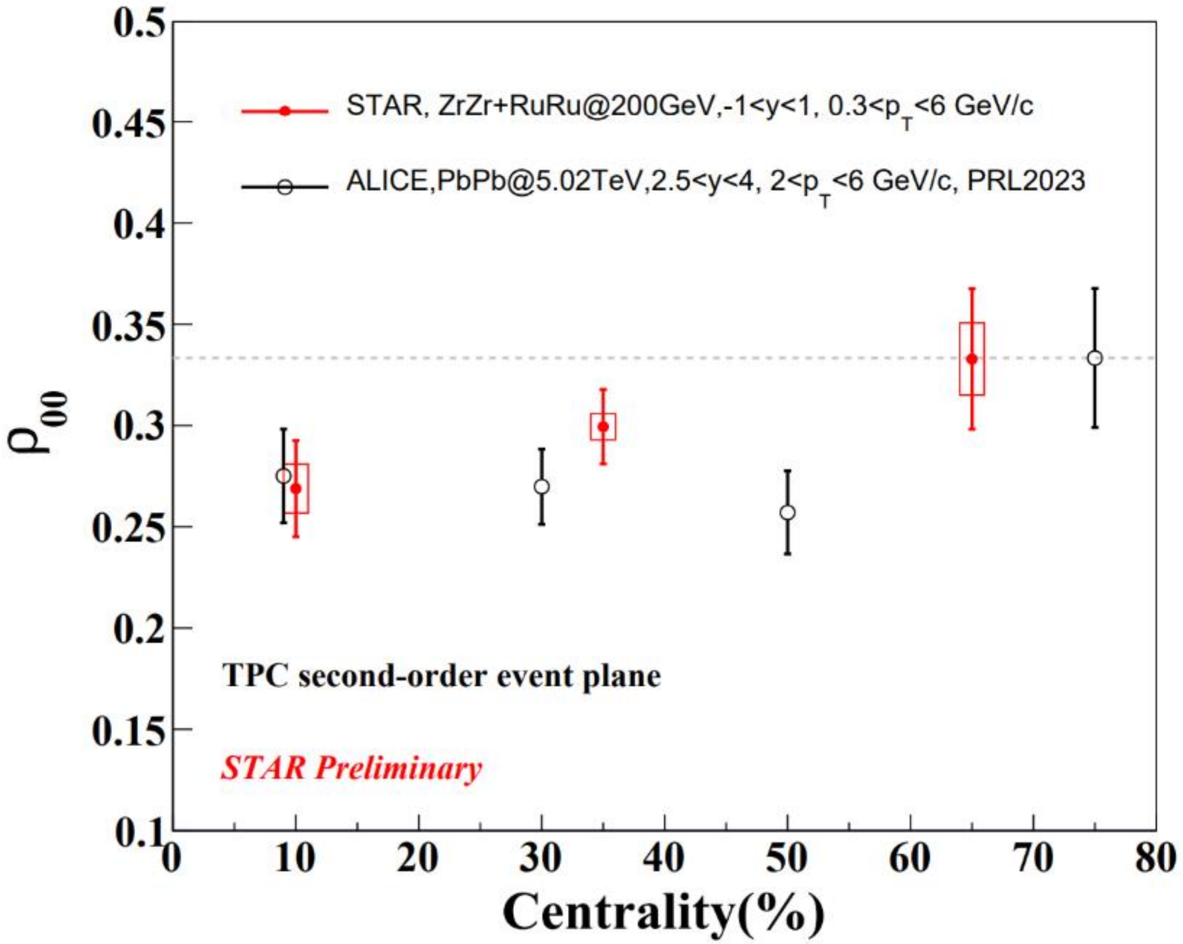
- The parameters of polar angle distribution are measured experimentally.

$$\lambda_\vartheta \propto (1-3\rho_{00})/(1+\rho_{00}) \qquad \rho_{00} < 1/3$$



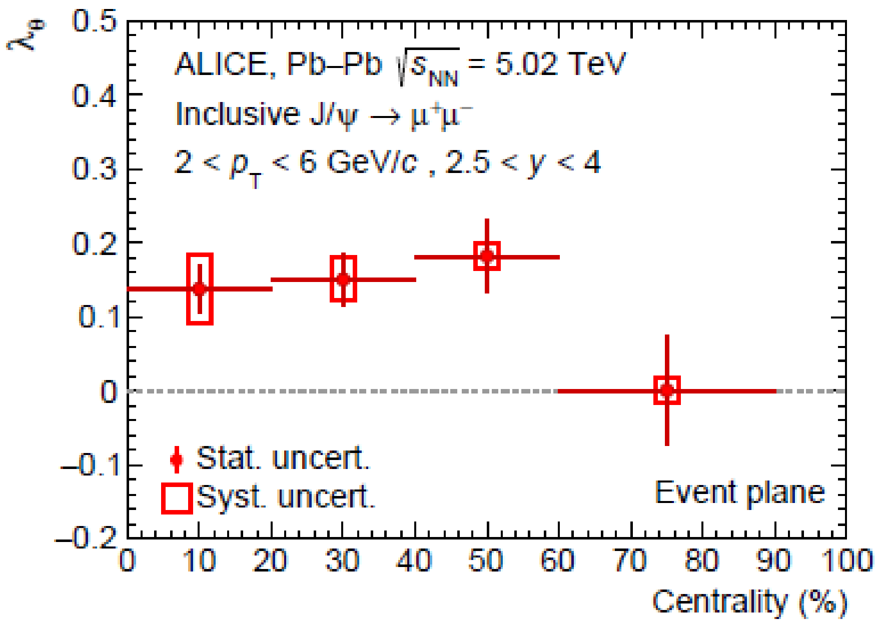
ALICE, PRL 2023

RHIC vs LHC

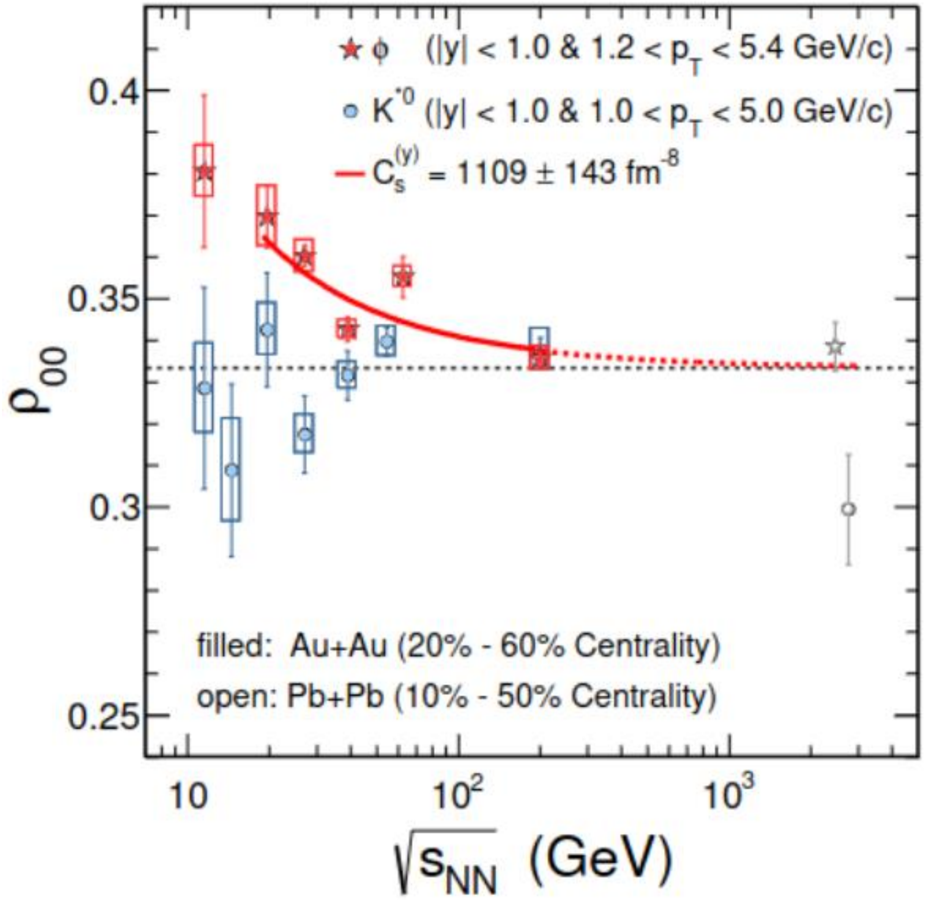


The $\boldsymbol{\rho_{00}}$ at RHIC energy has the same sign with that at LHC energy.

J/ψ vs ϕ



$\rho_{00} < 1/3$



Opposite to ϕ

Boltzmann equation

$$\boldsymbol{p^{\mu}\partial_{\mu}f^{i} = -C^{i}f^{i} + \cancel{D}^{i}}$$

$\boldsymbol{i = 0, \pm}$ represent spin triplet

Only consider the dissociation

$$\boldsymbol{\rho_{00} = \frac{f^{0}}{\sum_{i} f^{i}}}$$

Physical pictures

Boltzmann equation

$$p^{\mu}\partial_{\mu}f^{i} = -C^{i}f^{i} + D^{i}$$

$i = 0, \pm$ represent spin triplet

Only consider the dissociation

$$\rho_{00} = \frac{f^0}{\sum_i f^i} < \frac{1}{3} \quad \Rightarrow \quad C^0 > \frac{1}{3}(C^0 + C^+ + C^-)$$

Differences in spin-dependent damping rate may result in spin alignment

Zhu-Zhuang-Xu, PLB 2005

Frame-independent

$$p^{\mu}\partial_{\mu}f^{i} = -C^{i}f^{i}$$

$$C_{D} = \frac{1}{2}\int \frac{d^{3}k}{(2\pi)^{3}2E_{k}}\sigma_{D}4F_{g\psi}\, f_{g}(t,x,k)$$

Zhu-Zhuang-Xu, PLB 2005

Frame-independent

$$p^{\mu}\partial_{\mu}f^{i} = -C^{i}f^{i}$$

$$C_D = \frac{1}{2}\int \frac{d^3k}{(2\pi)^3 2E_k}\sigma_D 4F_{g\psi} f_g(t,x,k)$$

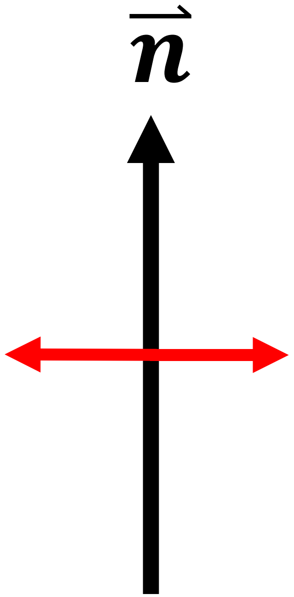
- k: Momentum of gluon
- σ_D: Cross section
- $4F_{g\psi}$: Flux factor
- $f_g(t,x,k)$: Distribution function of gluon

Dissociation coefficient C_D can be calculated in any frame

Gluon dissociation process: $g + J/\psi \to c + \bar{c}$

Expected result: $\rho_{00} < 1/3 \Rightarrow state(S_n = 0)less$

$\Rightarrow \Gamma(S_n = 0)larger$



Consider the spin sensitive interaction

$$H_{Q\bar{Q}} = H + H_I$$

$$H = \frac{\vec{p}^2}{m_Q} + V_1(|\vec{r}|) + \sum_a \frac{\lambda_a}{2}\frac{\bar{\lambda}_a}{2} V_2(|\vec{r}|)$$

$$H_I = Q^a A_0^a(t,\vec{0}) - \vec{d}^a \cdot \vec{E}^a(t,\vec{0}) - \vec{m}^a \cdot \vec{B}^a(t,\vec{0}) + \dots$$

Yan, PRD 1980;
Kuang-Yan, PRD 1981

$Q\bar{Q}$ potential arise from gluon exchange with
color singlet & color octet

$$H_{Q\bar{Q}} = H + H_I$$

$$H = \frac{\vec{p}^2}{m_Q} + V_1(|\vec{r}|) + \sum_a \frac{\lambda_a}{2}\frac{\bar{\lambda}_a}{2} V_2(|\vec{r}|)$$

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Yan, PRD 1980;
Kuang-Yan, PRD 1981

J/ψ rest frame

$$H_{Q\bar{Q}} = H + H_I$$

Yan, PRD 1980;
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$$H = \frac{\vec{p}^2}{m_Q} + V_1(|\vec{r}|) + \sum_a \frac{\lambda_a}{2}\frac{\bar{\lambda}_a}{2} V_2(|\vec{r}|)$$

J/ψ rest frame

$$H_I = Q^a A_0^a(t,\vec{0}) - \vec{d}^a \cdot \vec{E}^a(t,\vec{0}) - \vec{m}^a \cdot \vec{B}^a(t,\vec{0}) + \ldots$$

Spin-independent

$$Q_a = g_s\left(\frac{\lambda_a}{2} + \frac{\bar{\lambda}_a}{2}\right)$$

monopole

$$\vec{d}_a = \frac{g_s}{2}\vec{r}\left(\frac{\lambda_a}{2} - \frac{\bar{\lambda}_a}{2}\right)$$

electric dipole

Spin-dependent

$$\vec{m}^a = \frac{g_s}{2m_Q}\left(\frac{\lambda^a}{2} - \frac{\bar{\lambda}^a}{2}\right)\left(\frac{\vec{\sigma}}{2} - \frac{\vec{\sigma}'}{2}\right)$$

magnetic dipole

$$H_{M1} = -\frac{g_s}{2m_Q}\left(\frac{\lambda^a}{2} - \frac{\bar{\lambda}^a}{2}\right)\left(\frac{\vec{\sigma}}{2} - \frac{\vec{\sigma}'}{2}\right) \cdot \nabla \times \vec{A}^a$$

Chen-He, PRC 2017

Suppressed by
heavy quark's mass

$$\mathcal{M}_{M1} \propto \left\langle (c\bar{c})_8 \middle| \left(\frac{\vec{\sigma}}{2} - \frac{\vec{\sigma}'}{2}\right) \cdot \vec{B} \middle| J/\psi \right\rangle$$

$$H_{M1} = -\frac{g_s}{2m_Q}\left(\frac{\lambda^a}{2} - \frac{\bar{\lambda}^a}{2}\right)\left(\frac{\vec{\sigma}}{2} - \frac{\vec{\sigma}'}{2}\right) \cdot \nabla \times \vec{A}^a$$

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Spin average over the initial state

$$\sigma_{M1,Coulomb}^{g+J/\psi \to C+\bar{C}}(E_g) = \frac{2^3}{3} g_s^2 \frac{\epsilon_B^{5/2}}{m_Q^2} \frac{(E_g - \epsilon_B)^{1/2}}{E_g^3} \propto |\mathcal{M}_{M1}|^2$$

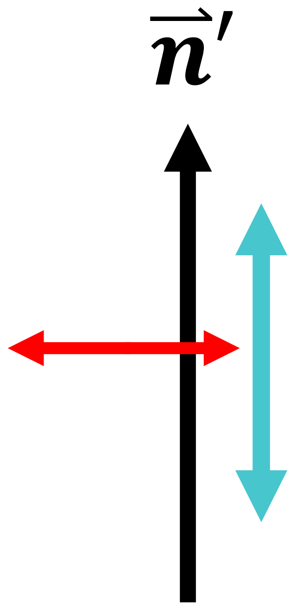
Energy of gluon (E_g) Binding energy (ϵ_B)

$$\mathcal{M}_{M1} \propto \frac{1}{2} \langle (c\bar{c})_8 | (\vec{\sigma} - \vec{\sigma}') \cdot \vec{B} | J/\psi \rangle$$

$$|(c\bar{c})\rangle = \frac{1}{\sqrt{2}} |\uparrow\downarrow - \downarrow\uparrow\rangle$$

$$|J/\psi\rangle = \begin{cases} |\uparrow\uparrow\rangle, & S_{n'} = 1 \\ \frac{1}{\sqrt{2}} |\uparrow\downarrow + \downarrow\uparrow\rangle, & S_{n'} = 0 \\ |\downarrow\downarrow\rangle, & S_{n'} = -1 \end{cases}$$

Choose $\vec{n}'$ as quantization axis in J/ψ rest frame



Physical pictures

$$\mathcal{M}_{M1} \propto \frac{1}{2} \langle (c\bar{c})_8 | (\vec{\sigma} - \vec{\sigma}') \cdot \vec{B} | J/\psi \rangle$$

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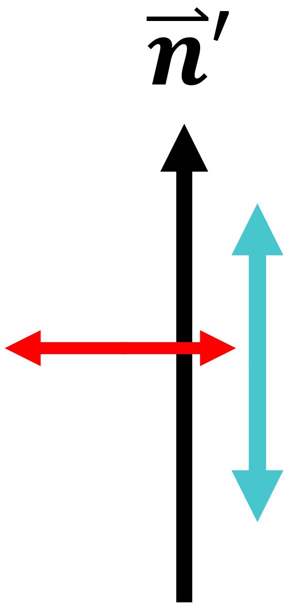
Choose $\vec{n}'$ as quantization axis in J/ψ rest frame

Calculate in different spin initial state



$$|\mathcal{M}_1|^2 = |\mathcal{M}_{-1}|^2 = {B_{n'\perp}}^2/2$$

$$|\mathcal{M}_0|^2 = {B_{n'}}^2 = k'^i k'^j (\delta_{ij} - n'_i n'_j)$$

03

Scenario

Boltzmann equation in Bjorken flow

$$\left[\partial_\tau + \frac{1}{\tau} tanh(Y-\eta)\,\partial_\eta\right] f^i = -\frac{1}{\tau_R} f^i$$

$$C^i = C^E(\tau, p) + C_B^i(\tau, p, n)$$

Proper time

Selected quantization axis

Momentum of J/ψ

Boltzmann equation in Bjorken flow

$$[\partial_\tau + \frac{1}{\tau} tanh(Y - \eta)\, \partial_\eta] f^i = -\frac{1}{\tau_R} f^i$$

$$f(\tau, \eta, Y, p_T) = \frac{\tau_0}{\tau} \bar{f}\,(\tau, Y, p_T)\, \delta(\eta - Y)$$

Zhu-Zhuang-Xu, PRB 2005

All J/ψ are produced at t=y=0

$$\partial_\tau \bar{f}^i(\tau, Y, p_T) = -\frac{1}{\tau_R} \bar{f}^i(\tau, Y, p_T)$$

$$\bar{f}^{i}(\tau, Y, p_T) = exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C^E}{p \cdot u}\right] exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C_B^i}{p \cdot u}\right] \bar{f}_0\,(\tau_0, Y, p_T)$$

$$\rho_{00} - \frac{1}{3} = \frac{f^0}{\sum_i f^i} - \frac{1}{3}$$

$$\bar{f}^i(\tau, Y, p_T) = exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C^E}{p \cdot u}\right] exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C_B^i}{p \cdot u}\right] \bar{f}_0\,(\tau_0, Y, p_T)$$

$$\rho_{00} - \frac{1}{3} \cong -\frac{1}{3}\int_{\tau_0}^{\tau} d\tau' \frac{C_B^0}{p \cdot u} + \frac{1}{3}\int_{\tau_0}^{\tau} d\tau' \frac{\bar{C}_B}{p \cdot u}$$

In rest frame

$$\Delta\tau \sim 0.59\, fm$$
$$\sigma_{M1} < 1mb$$
$$p' \cdot u' = m_\psi = 3.1\, GeV$$

The integral is quite small, we take the first order of Taylor expansion

03 Scenario

$$\bar{f}^i(\tau, Y, p_T) = exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C^E}{p\cdot u}\right] exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C_B^i}{p\cdot u}\right] \bar{f}_0(\tau_0, Y, p_T)$$

$$\rho_{00} - \frac{1}{3} \cong -\frac{1}{3}\int_{\tau_0}^{\tau} d\tau' \frac{C_B^0}{p\cdot u} + \frac{1}{3}\int_{\tau_0}^{\tau} d\tau' \frac{\bar{C}_B}{p\cdot u}$$

Quantization axis-dependent

$$C_B^i(\tau, p, \boldsymbol{n})$$

$$C_B^0 \propto k'^i k'^j (\delta_{ij} - n'_i n'_j)$$

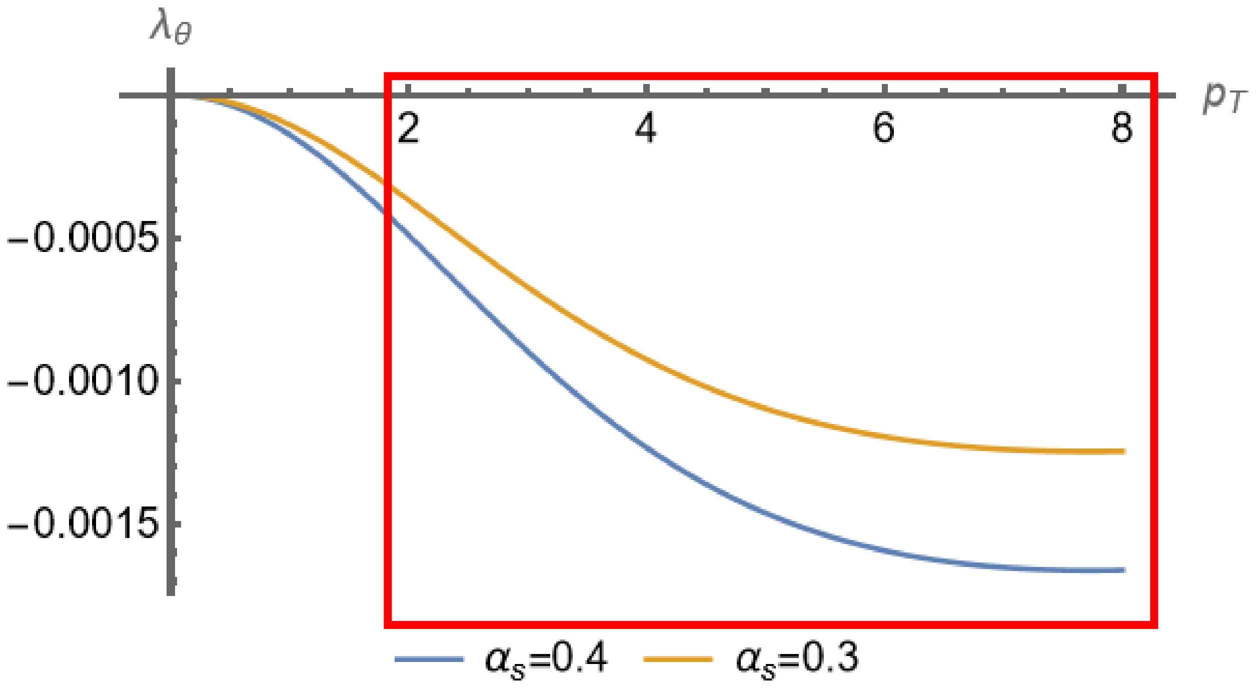
$$3\bar{C}_B = C_B^0 + C_B^+ + C_B^- \propto 2k'^2$$

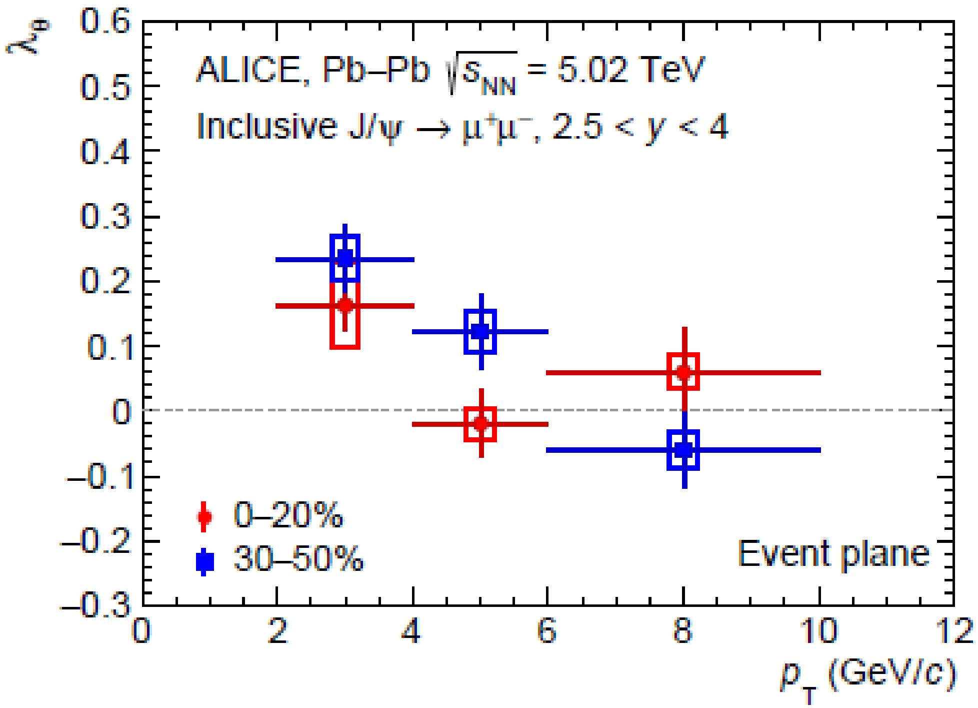
$$C_B^0 = \frac{1}{2}\int \frac{d^3k}{(2\pi)^3 2E_k} \frac{\sigma_{M1}}{2k'^2/3} k'^i k'^j (\delta_{ij} - n'_i n'_j) 4F_{g\psi} f_g(t, x, k)$$

Express in lab frame

$$\rho_{00}-\frac{1}{3}=\frac{1}{3}\boxed{A}\left[\frac{1}{3}+\frac{\left(-u\cdot n+\frac{p\cdot u}{m_\psi}\frac{p\cdot n}{m_\psi}\right)^2}{\left(\frac{p\cdot n}{m_\psi}\right)^2+1}-\frac{1}{3}\left(\frac{p\cdot u}{m_\psi}\right)^2\right]$$

Parameter of integral





Dissociation only gives $\rho_{00} > 1/3$

NLO may gives more contribution

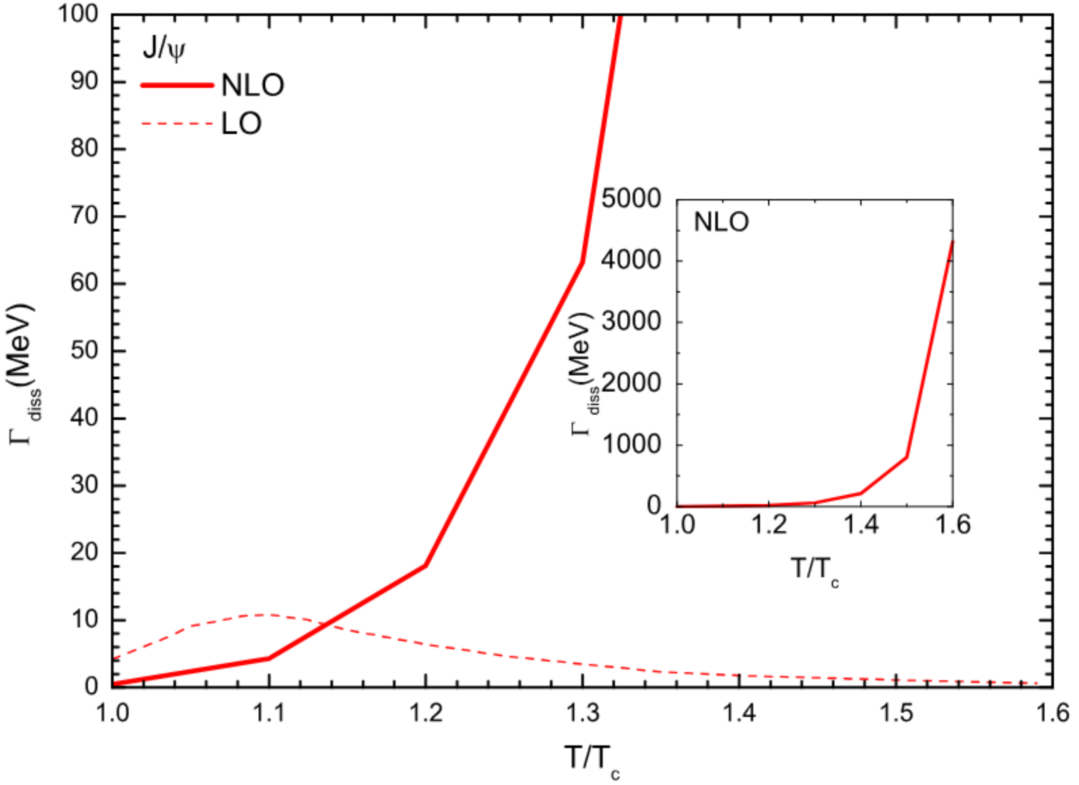
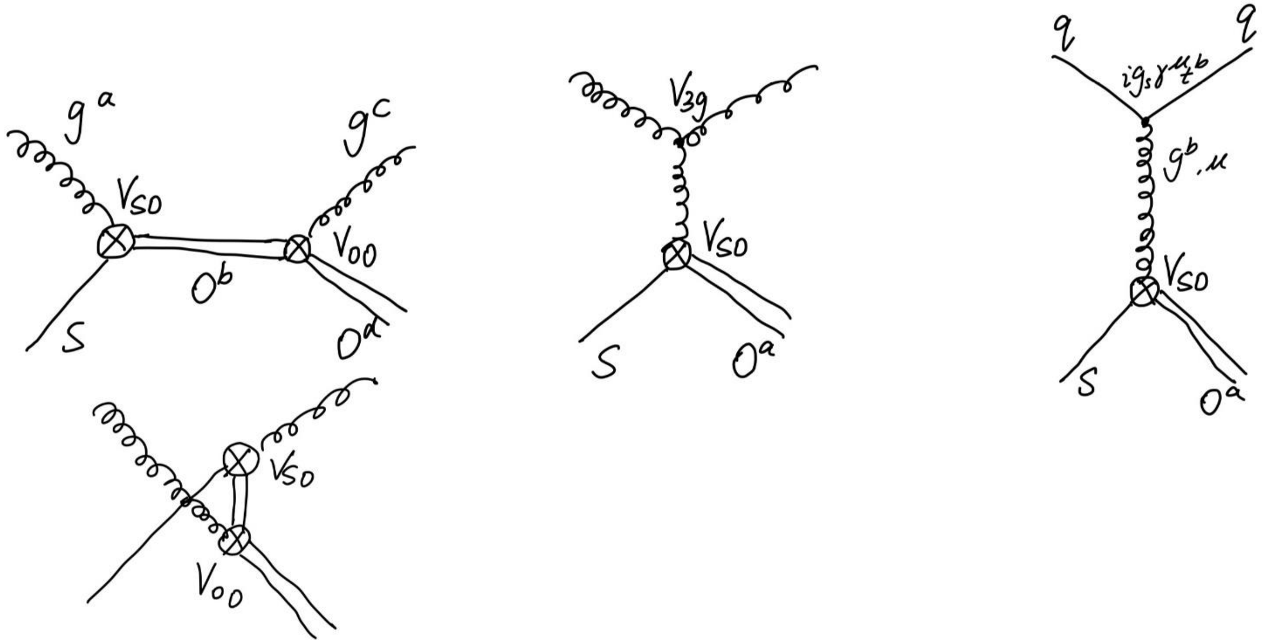


Figure from Chen-He, PLB 2018



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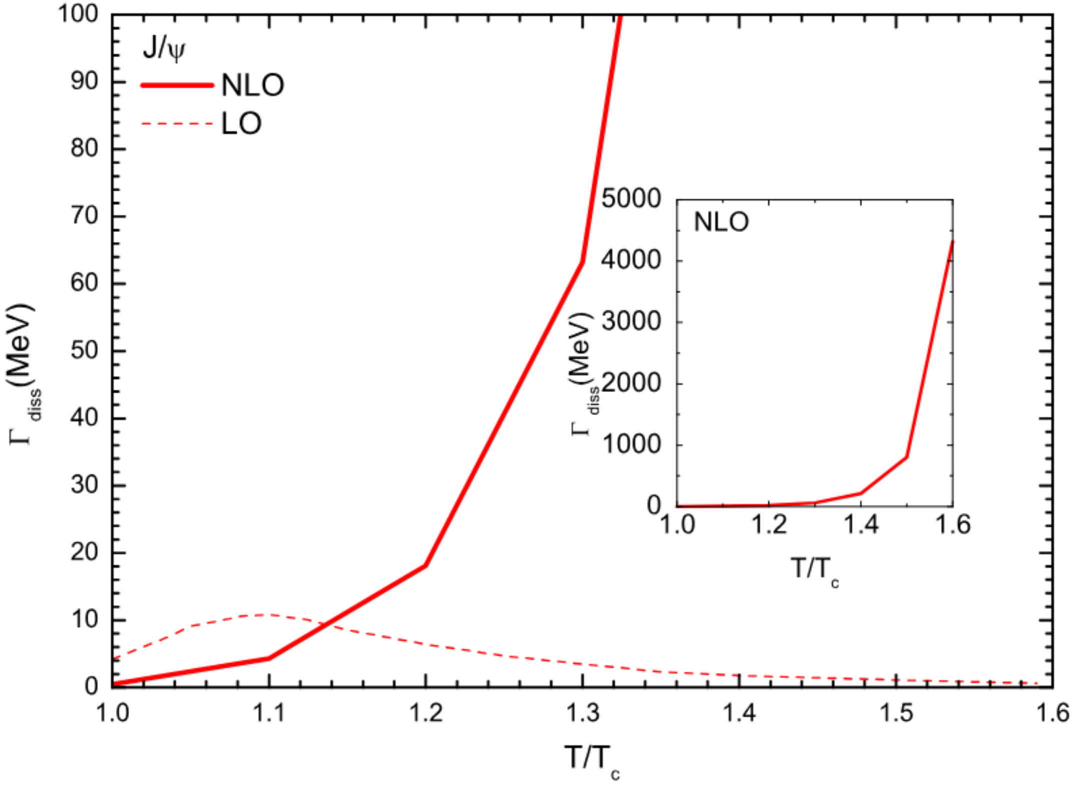
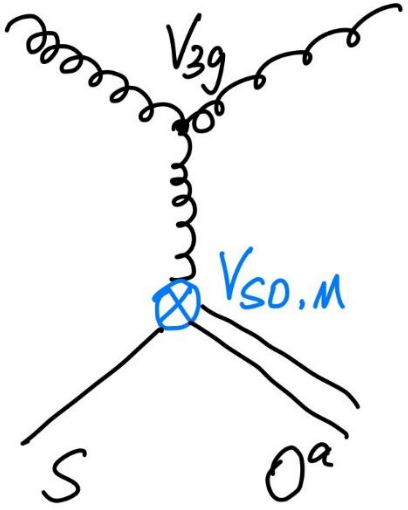
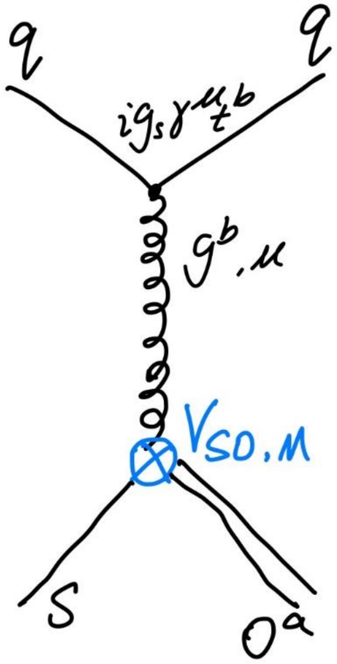


Figure from Chen-He, PLB 2018





Conclusion and outlook

conclusion

- A possible mechanism about spin alignment.
- Numerical simulation gives negative sign.

outlook

- Regeneration may gives the right sign.
- NLO process may gives more contribution.

SYSU

Thanks for listening!

Zhishun Chen

Date: 2024/5/18