Spin-alignment of Moving Quarkonium from Spin Chromomagnetic Coupling

Zhishun Chen

Date: 2024/11/17

Under the supervision of Shu Lin

Background

research status

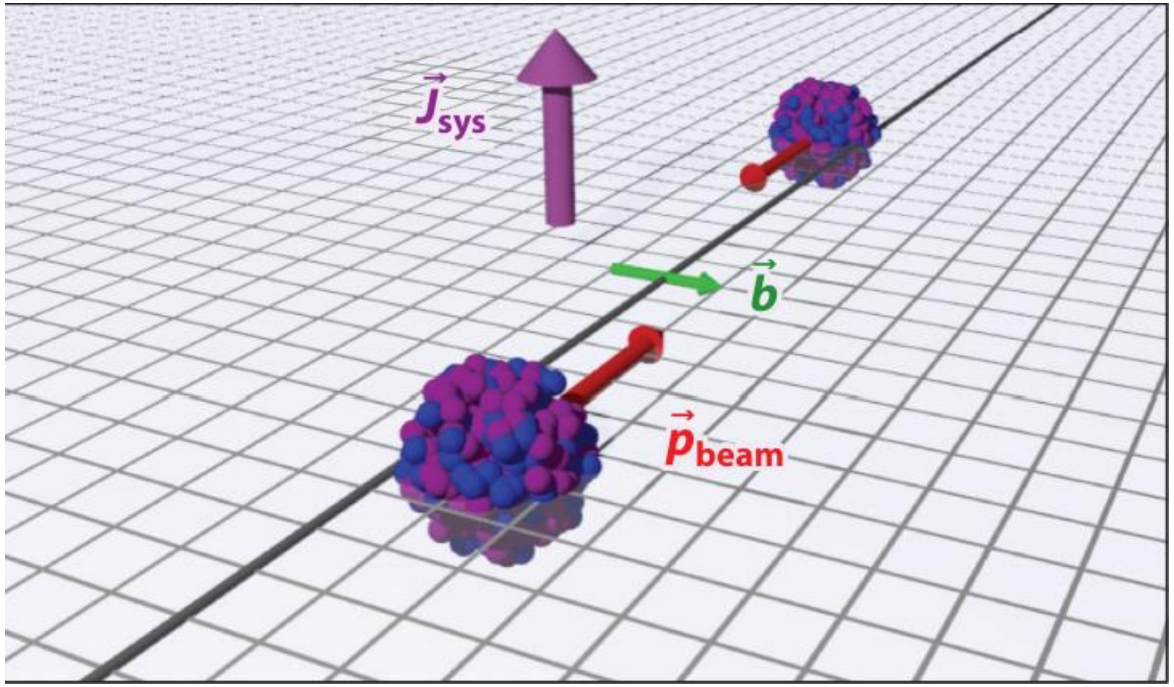


Figure from F. Becattini-Michael A. Lisa, AR 2020

- 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 $\mathrm{Tr}\rho = \sum_i P_i = 1$

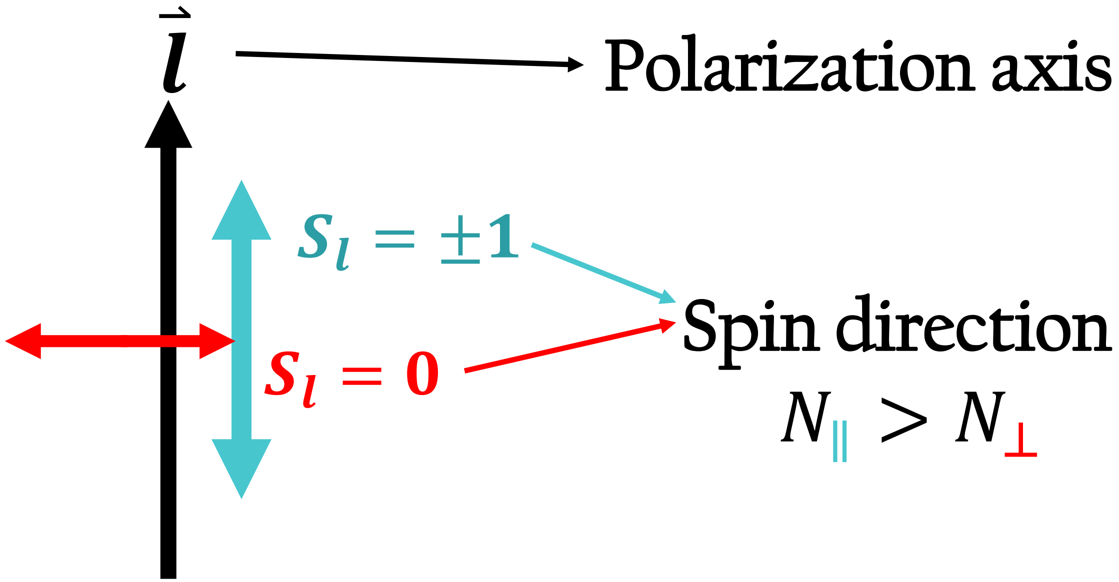
③ $\langle\varphi|\rho|\varphi\rangle \geq 0$

no polarization case:

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

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

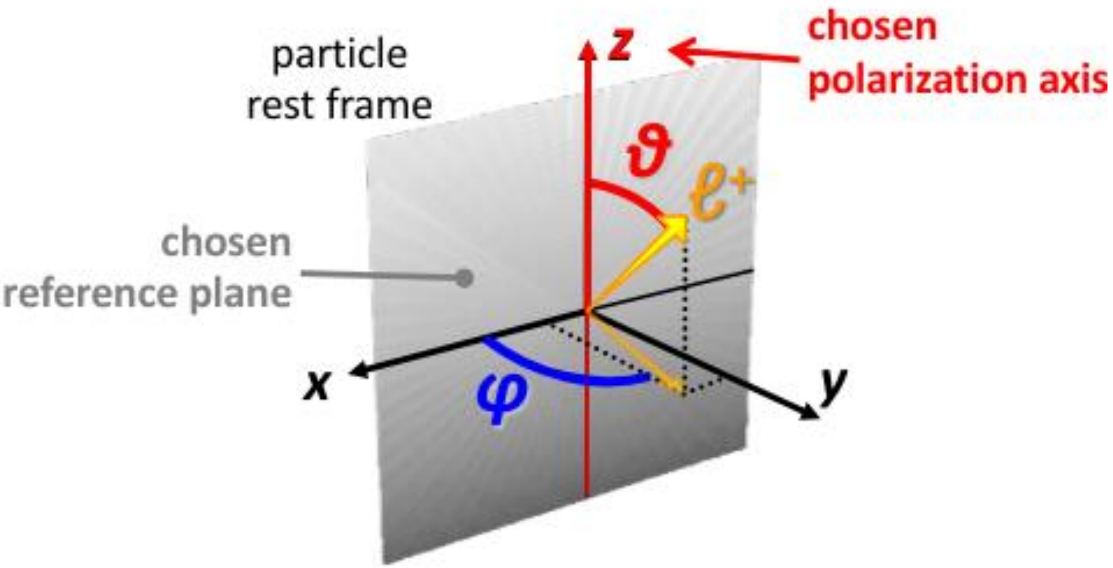
If $\rho_{00} < 1/3$

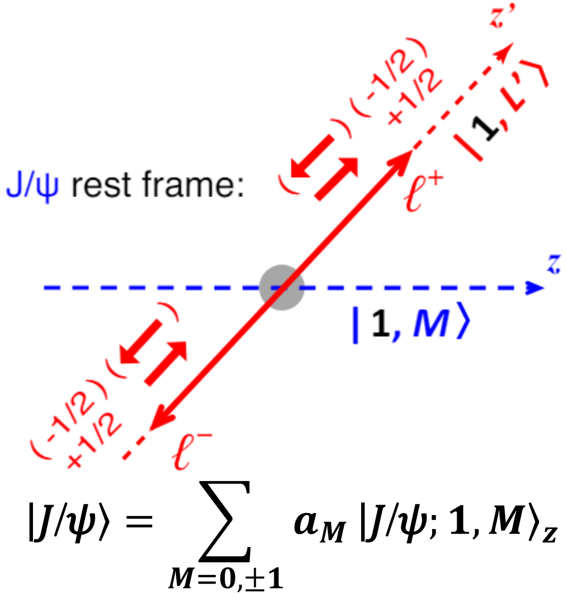


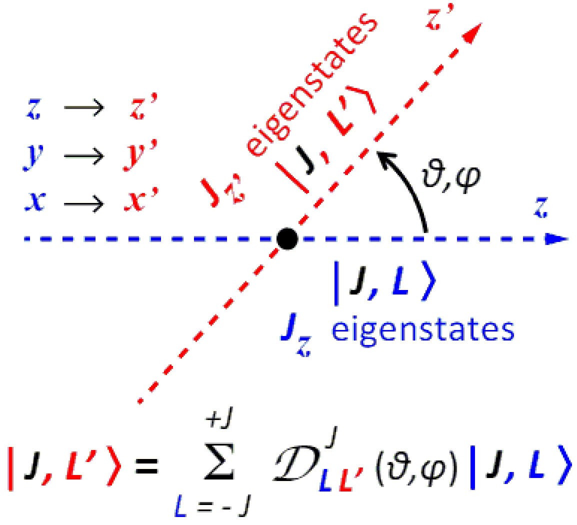
*Figures in this slide all from P. Faccioli-C.Lourenço, Particle Polarization in High Energy Physics

01 Background

How to measure spin alignment in experiment







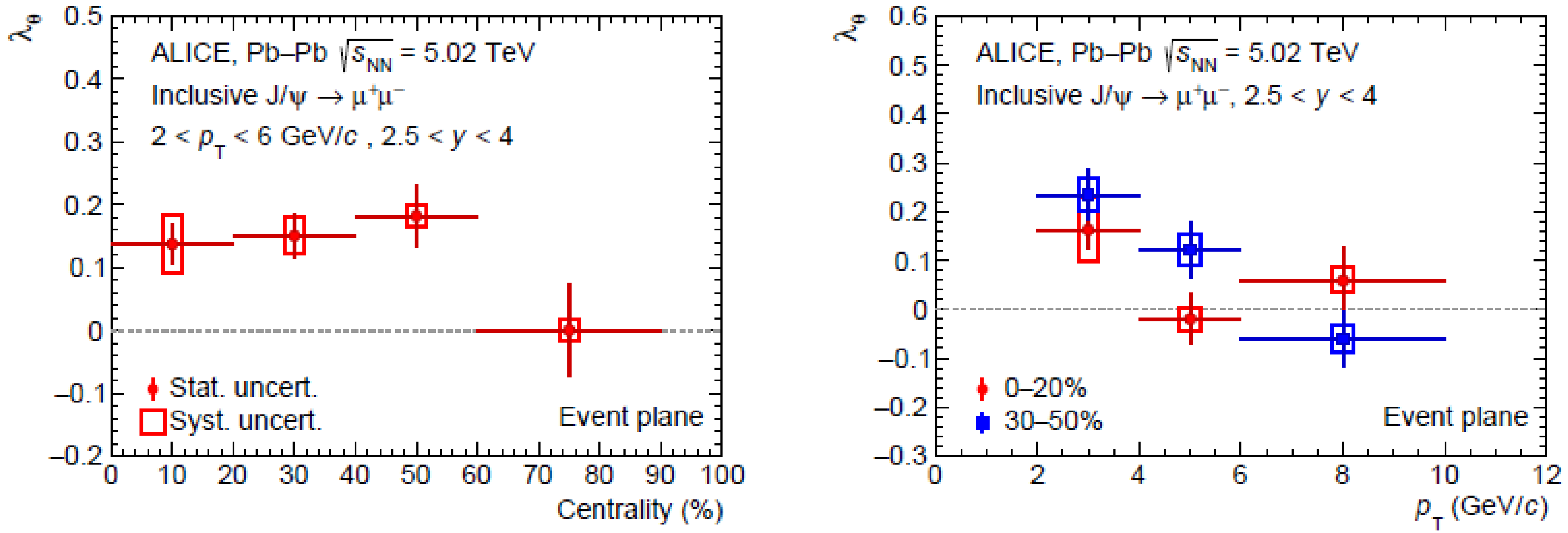
$$W(\vartheta) \propto \frac{1 + \lambda_\vartheta \cos^2 \vartheta}{3 + \lambda_\vartheta}$$

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

01 Background

- The parameters of polar angle distribution are measured experimentally.

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

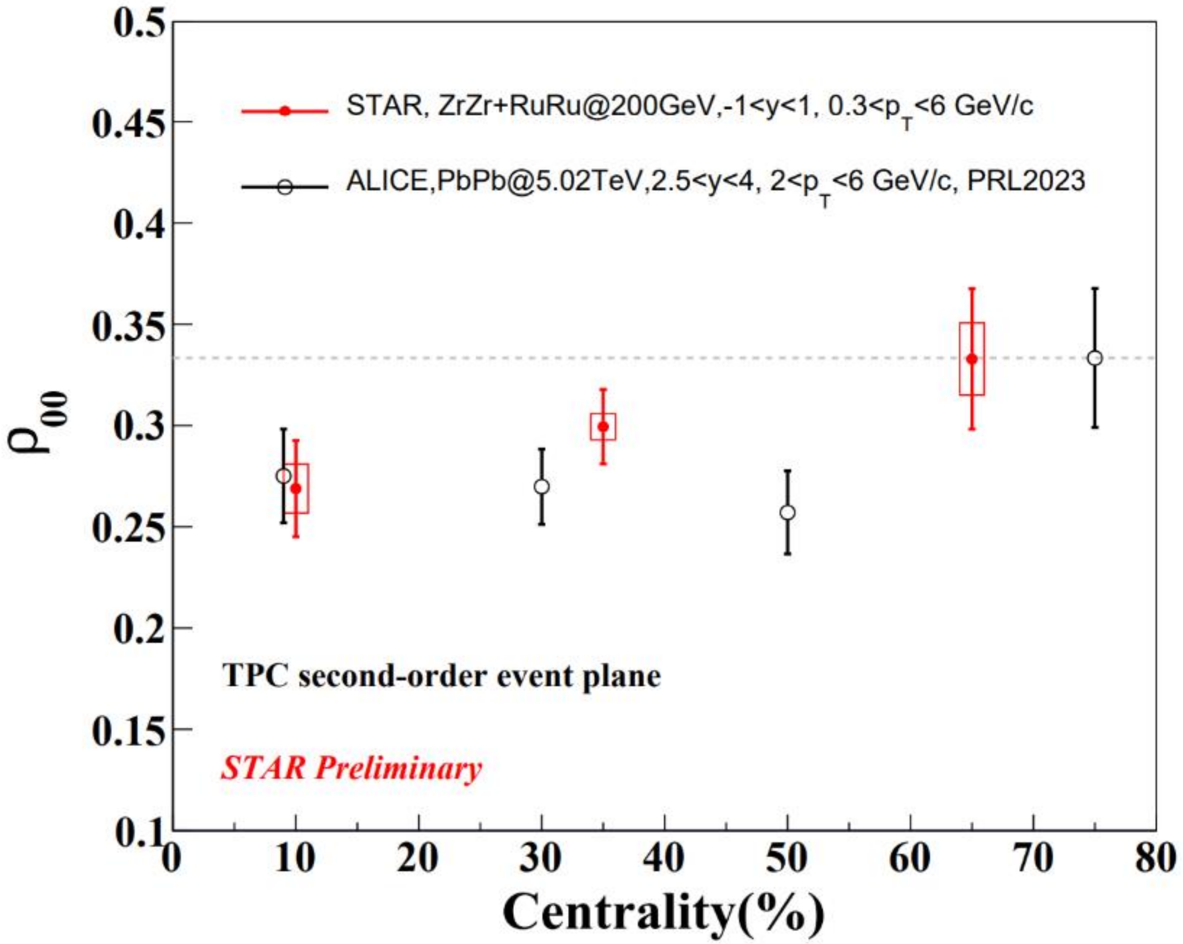


ALICE, PRL 2023

01 Background

Other measurement about spin alignment

RHIC vs LHC

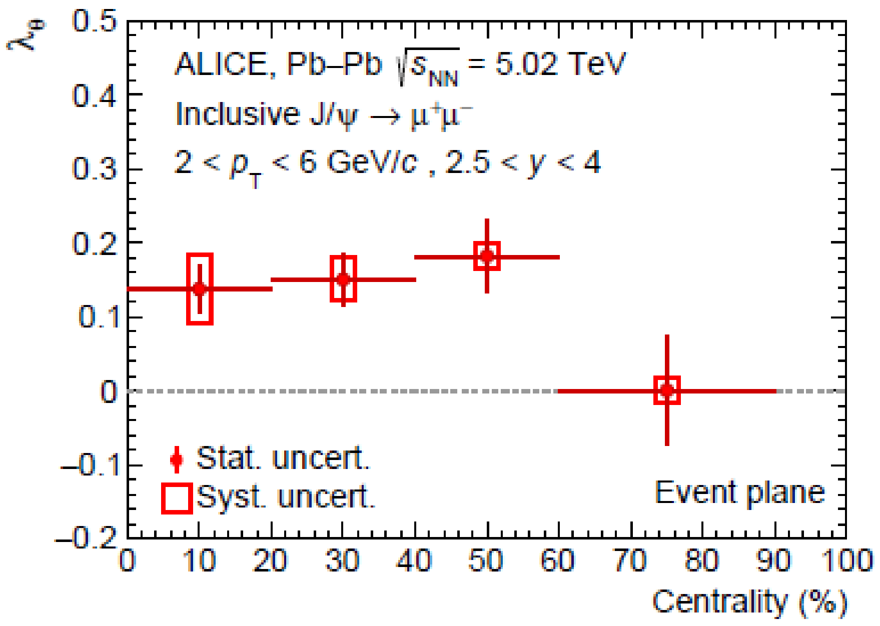


The ρ_{00} at RHIC energy has the same sign with that at LHC energy.

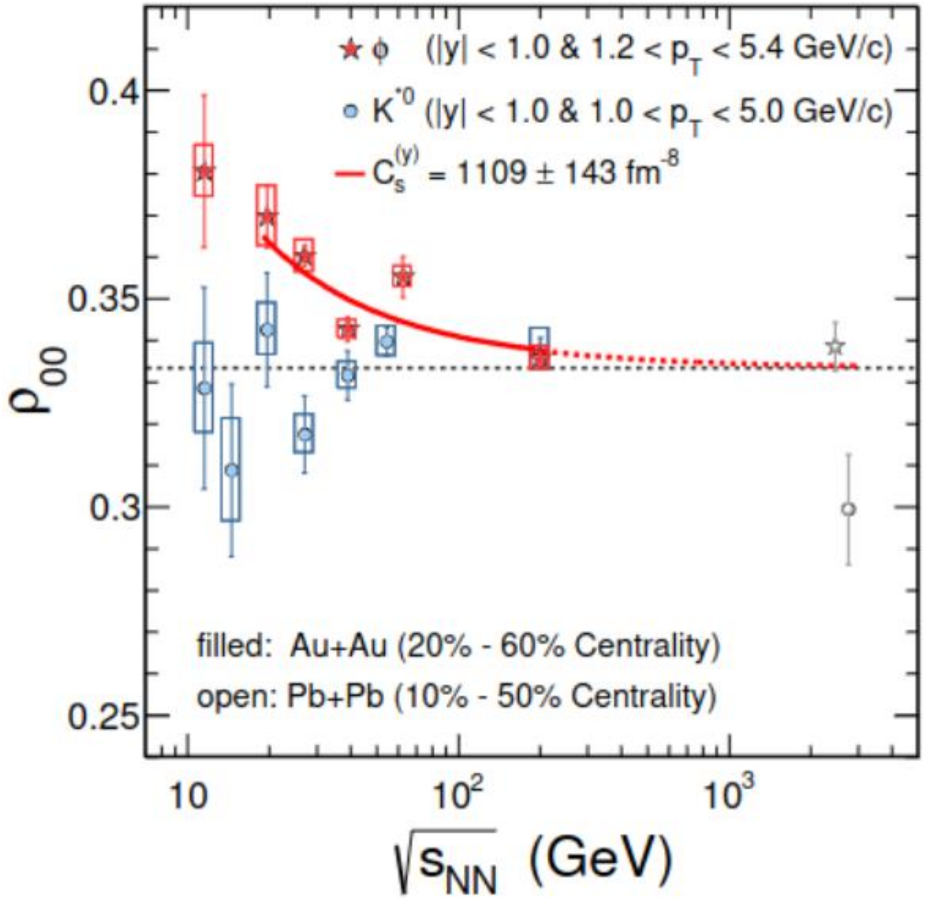
Background

Other measurement about spin alignment

J/ψ vs ϕ

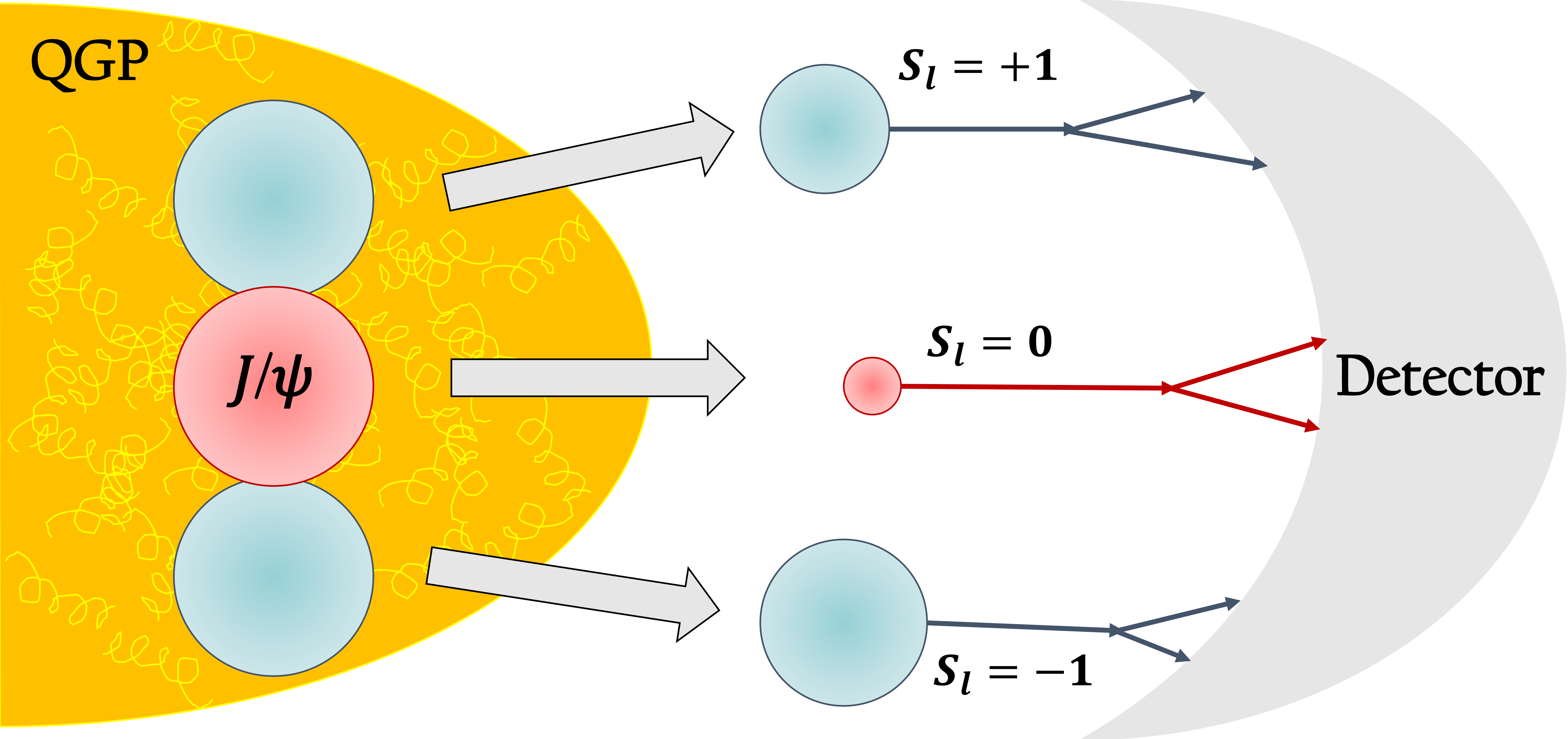


$\rho_{00} < 1/3$



Opposite to ϕ

02 Physical pictures



Boltzmann equation

$$P^\mu \partial_\mu f^i = -C^i f^i + \cancel{D}^i \qquad i = 0, \pm \text{ represent spin triplet}$$

Dissociation dominant case

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

02 Physical pictures

Boltzmann equation

$$P^\mu \partial_\mu f^i = -C^i f^i + D^i$$

$i = 0, \pm$ represent spin triplet

Dissociation dominant case

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

Differences in spin-dependent damping rate result in spin alignment

Physical pictures

Boltzmann equation in Bjorken flow

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

$$C^i = C^{non}(\boxed{\tau}, \boxed{P}) + C^{spin,i}(\tau, P, \boxed{l})$$

Proper time

Momentum of J/ψ

Selected quantization axis

Boltzmann equation in Bjorken flow

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

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

Zhu-Zhuang-Xu, PRB 2005

All J/ψ are produced at t=z=0

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

Physical pictures

$$\tilde{f}^i(\tau, Y, p_T) = exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C^{non}}{P\cdot u}\right] exp\left[-\int_{\tau_0}^{\tau} d\tau' \frac{C^{spin,i}}{P\cdot u}\right] \tilde{f}_0\,(\tau_0, Y, p_T)$$

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

Zhu-Zhuang-Xu, PLB 2005

Frame-independent

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

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

Zhu-Zhuang-Xu, PLB 2005

Frame-independent

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

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

Momentum of gluon

Cross section

Flux factor

Distribution function of gluon

Dissociation coefficient C_D can be calculated in any frame

02 Physical pictures

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

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

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

Yan, PRD 1980;
Kuang-Yan, PRD 1981

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

Physical pictures

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

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

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

Yan, PRD 1980;
Kuang-Yan, PRD 1981

J/ψ rest frame

02 Physical pictures

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

Yan, PRD 1980;
Kuang-Yan, PRD 1981

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

J/ψ rest frame

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

Spin-independent

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

Chromo-monopole

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

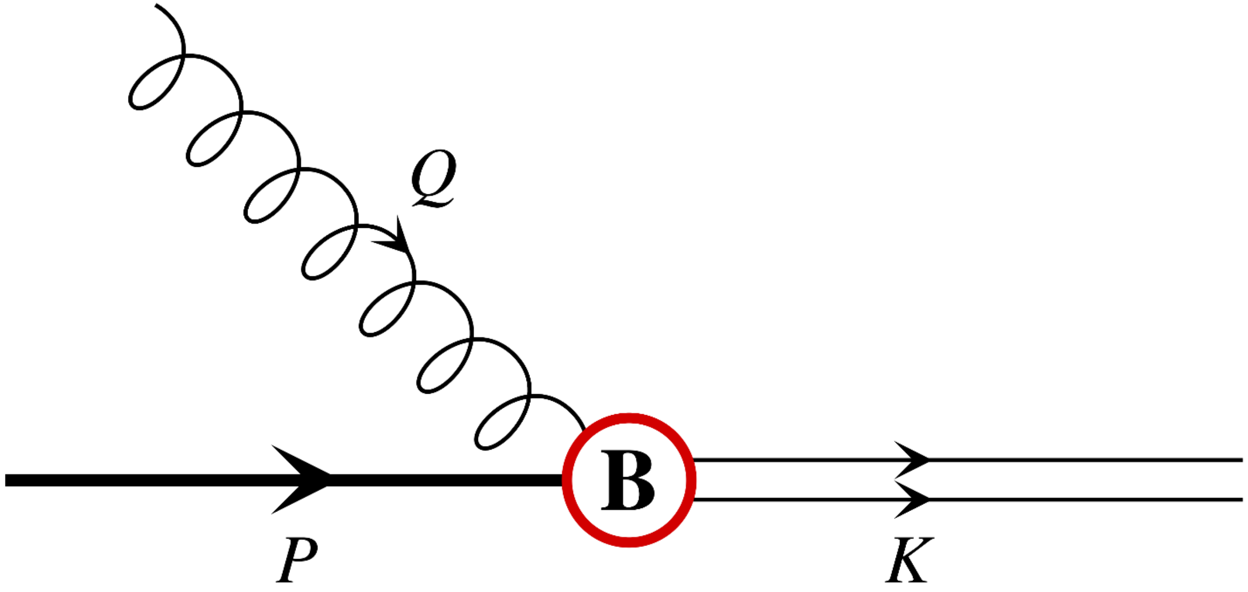
Chromoelectric dipole

Spin-dependent

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

Chromomagnetic dipole

Physical pictures

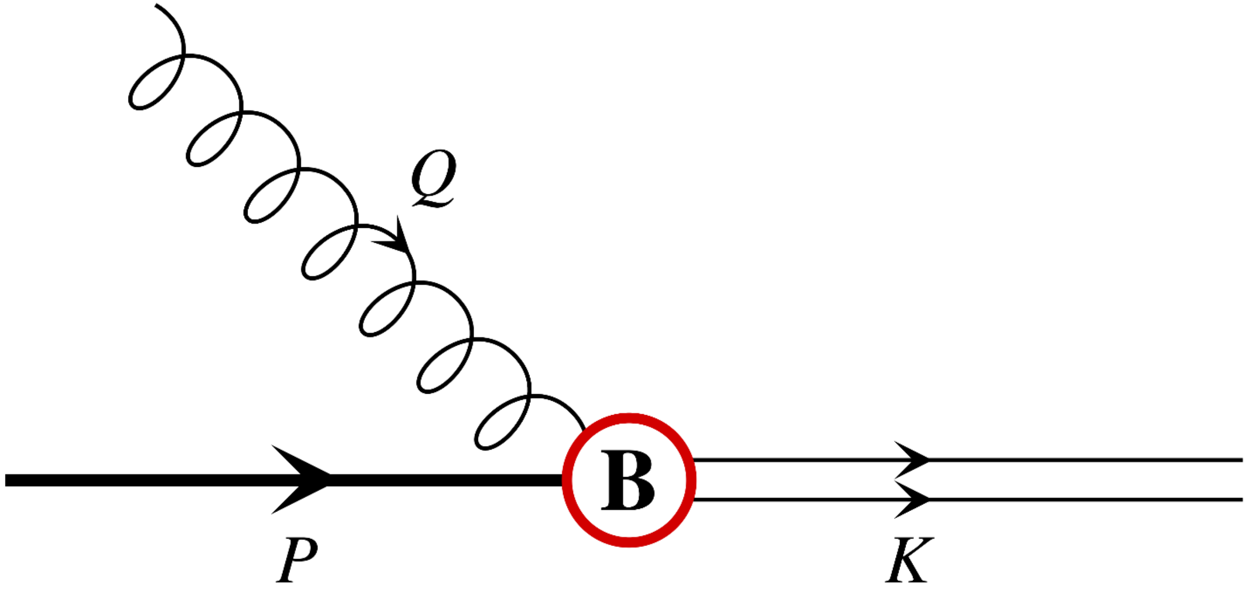


Chen-He, PRC 2017

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

Suppressed by heavy quark's mass

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



Chen-He, PRC 2017

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

Suppressed by heavy quark's mass

Spin average over the initial state

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

Energy of gluon

Binding energy

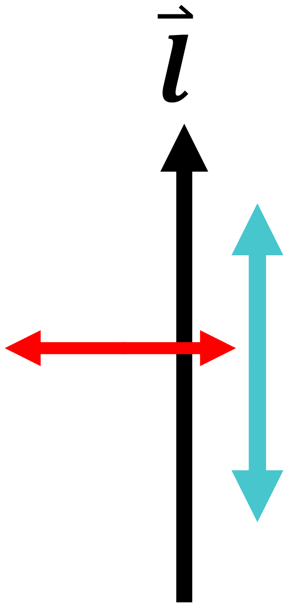
Physical pictures

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

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

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

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



Physical pictures

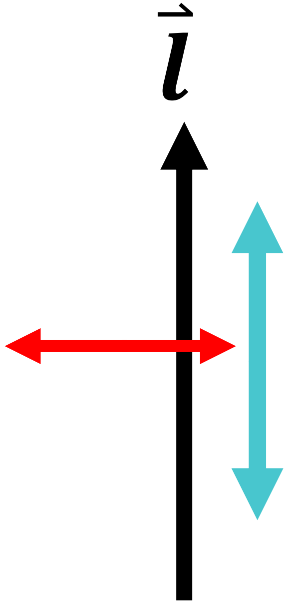
$$\mathcal{M}_{M1} \propto \frac{1}{2} \langle (c\bar{c})_8 | (\vec{\sigma} - \vec{\sigma}') \cdot \vec{B} | J/\psi \rangle$$

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

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

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

Calculate in different spin initial state



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

$$|\mathcal{M}_0|^2 = {B_l}^2 = q^i q^j (\delta_{ij} - l_i l_j)$$

02 Physical pictures

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

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

$$\Delta\tau \sim 0.56\, fm = \frac{0.56}{197}\; MeV^{-1}$$

In rest frame $\sigma_{M1} < 1mb \sim \frac{0.1}{197^2} MeV^{-2}$

$$P\cdot u = M_\psi u_0 > 3.1\, GeV$$

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

Physical pictures

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

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

Quantization axis-dependent

$$C_B^i(\tau, P, l)$$

$$C_B^0 \propto q^i q^j (\delta_{ij} - l_i l_j)$$

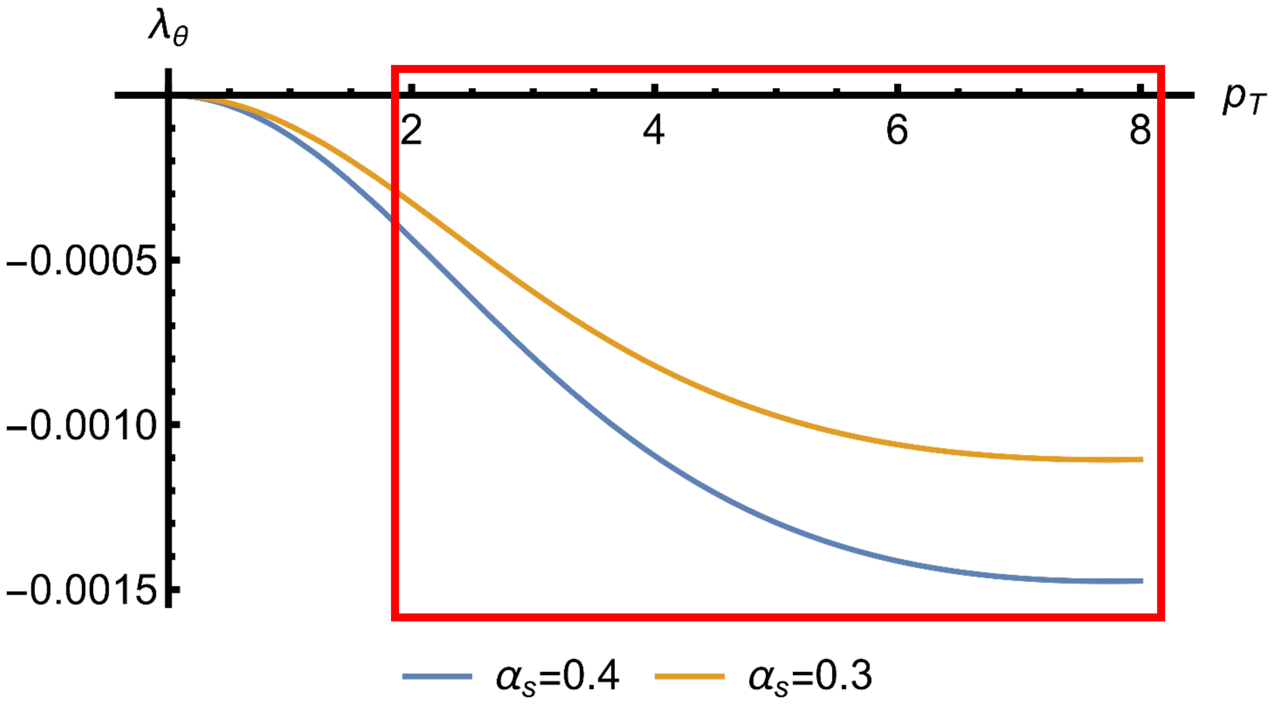
$$3\overline{C}_B = C_B^0 + C_B^+ + C_B^- \propto 2q^2$$

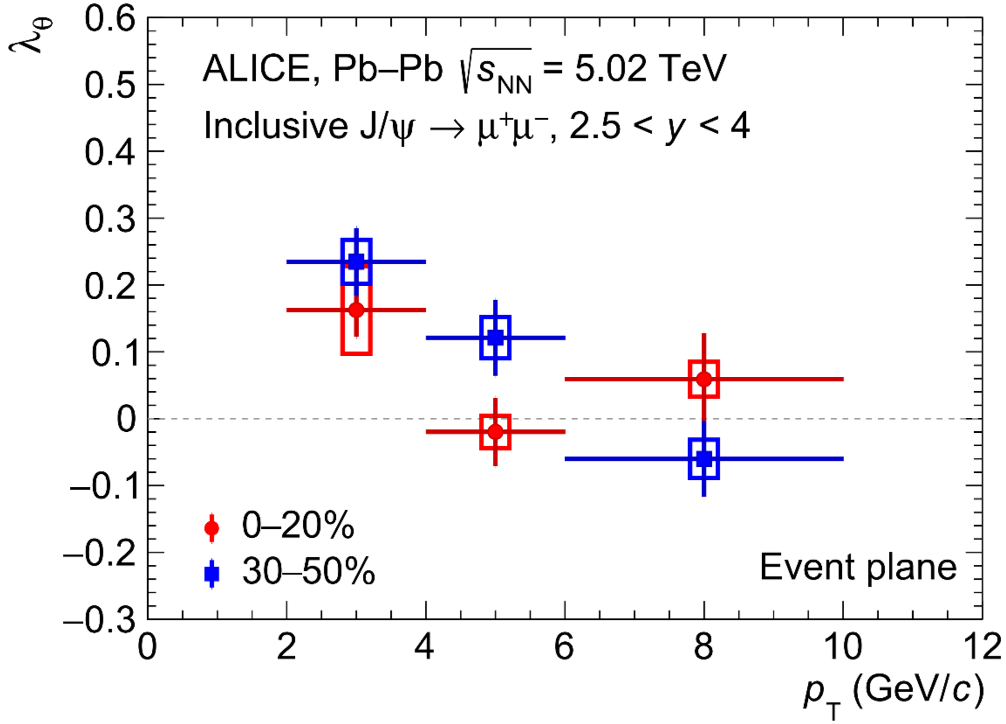
$$C_B^0 = \frac{1}{2}\int \frac{d^3q}{(2\pi)^3 2E_q} \frac{\sigma_{M1}}{2q^2/3} q^i q^j (\delta_{ij} - l_i l_j) 4F_{g\psi} f_g(t, x, q)$$

Express in lab frame

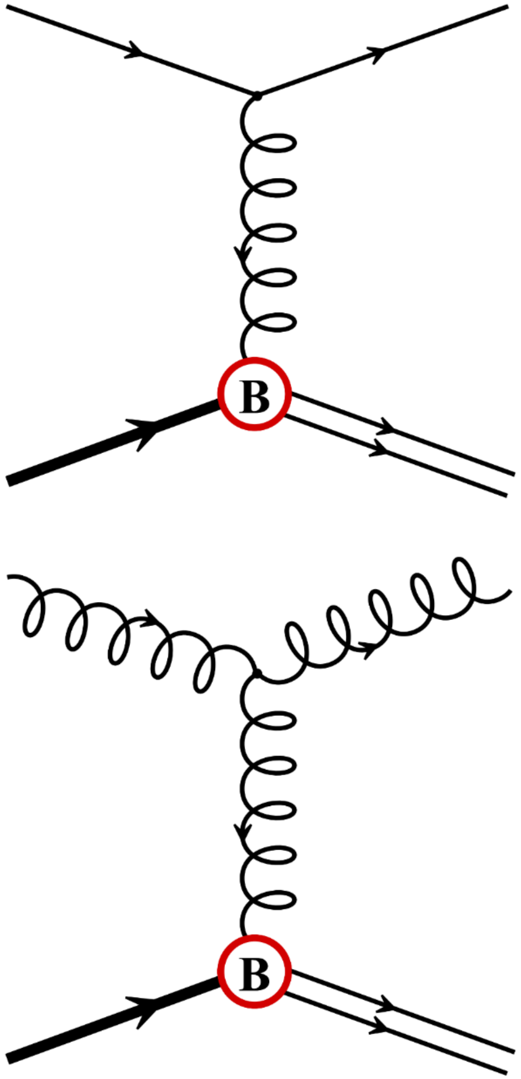
$$\rho_{00}-\frac{1}{3}=\frac{1}{3}\boxed{A}\left[\frac{1}{3}+\frac{\left(-u\cdot l+\frac{P\cdot u}{M_\psi}\frac{P\cdot l}{M_\psi}\right)^2}{\left(\frac{P\cdot l}{M_\psi}\right)^2+1}-\frac{1}{3}\left(\frac{P\cdot u}{M_\psi}\right)^2\right]$$

Parameter of integral

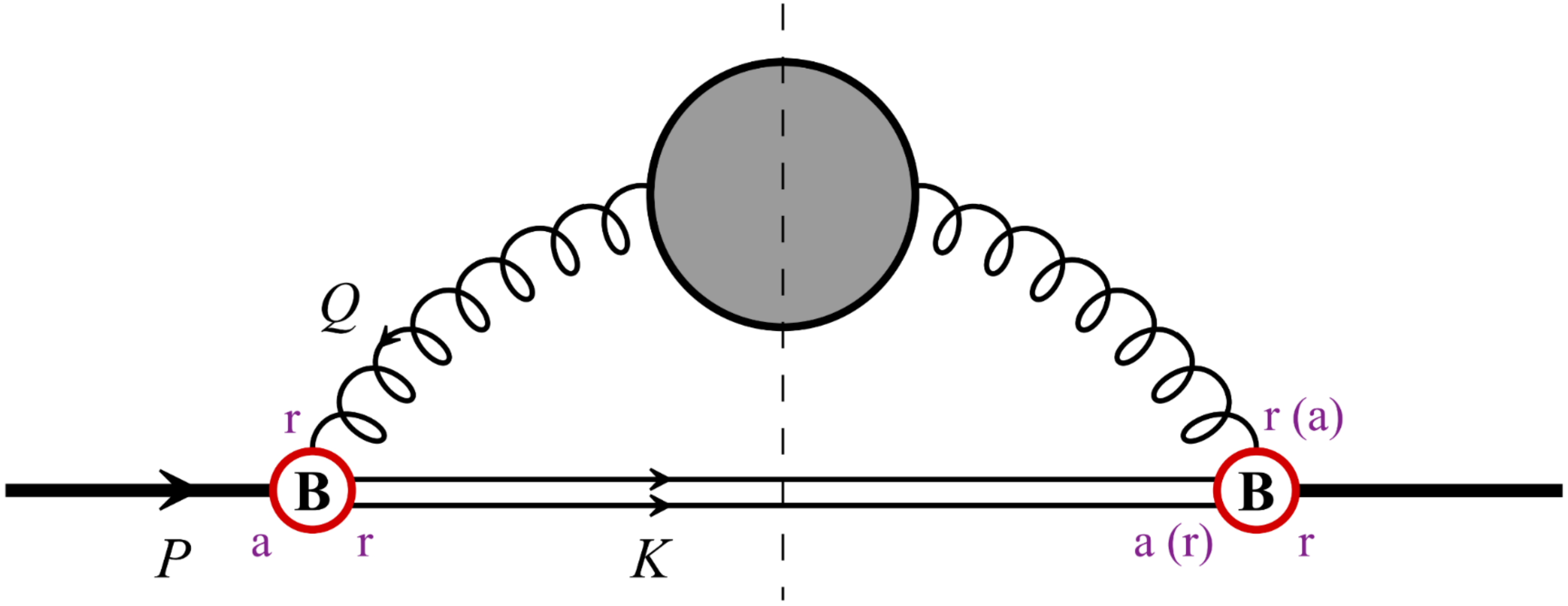




Dissociation only gives $\rho_{00} > 1/3$

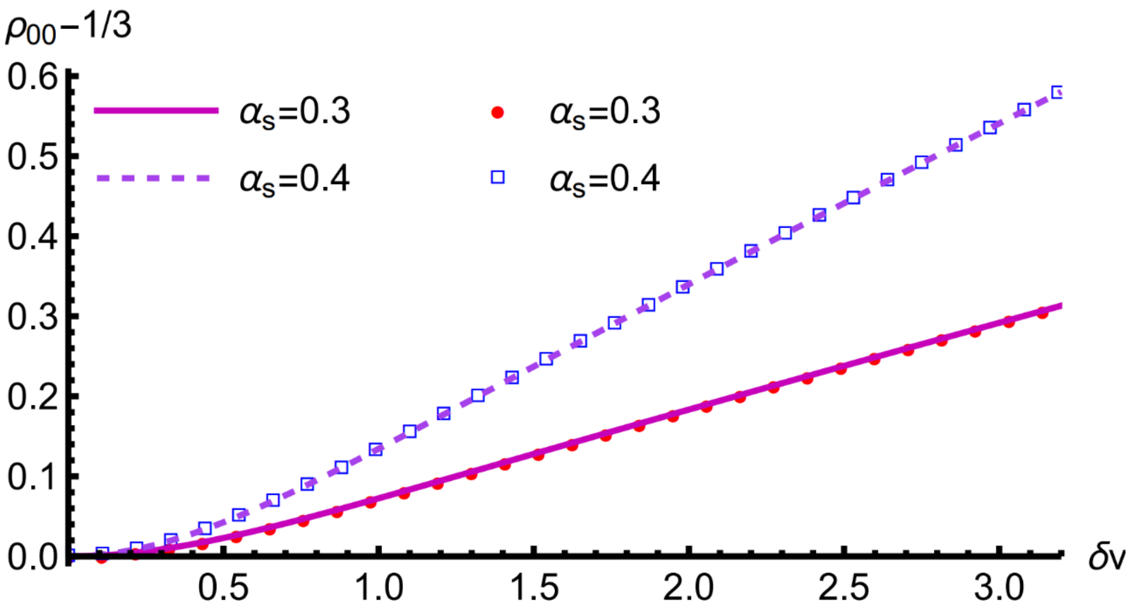


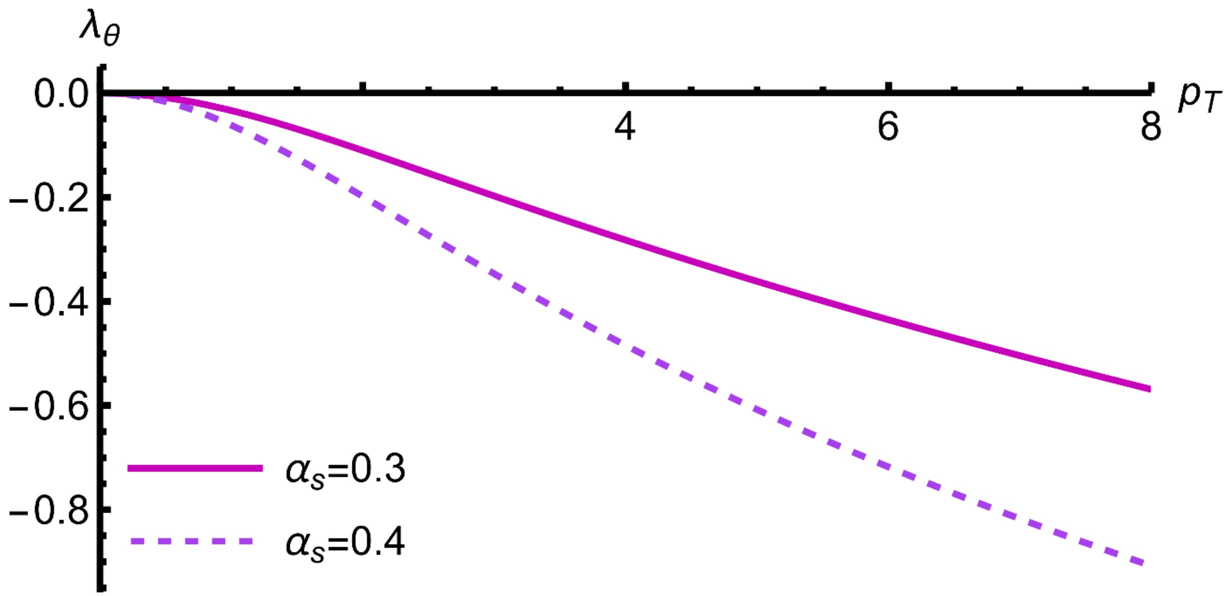
Inelastic scattering (NLO)



$$\delta\Pi = \Pi(u) - \Pi\left(\frac{P}{M_\psi}\right) \to \mathcal{O}(\delta v^2)$$

NLO gives more contribution

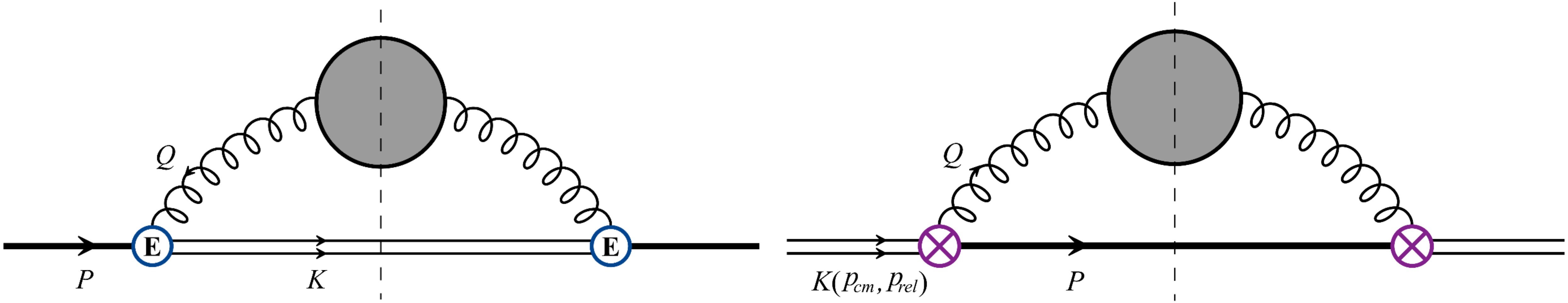




Regeneration Dominant case

$$P^\mu \partial_\mu f^i = -C^i f^i + D^i$$

$$\rho_{00} - \frac{1}{3} \cong \frac{\int_{\tau_0}^{\tau} d\tau' \frac{D_B^0 - \bar{D}_B}{P\cdot u} exp\left[-\int_{\tau'}^{\tau} d\tau'' \frac{C^E}{P\cdot u}\right]}{3\int_{\tau_0}^{\tau} d\tau' \frac{D_E}{P\cdot u} exp\left[-\int_{\tau'}^{\tau} d\tau'' \frac{C^E}{P\cdot u}\right]}$$



Regeneration will gives the right sign

Conclusion and outlook

conclusion

- A possible mechanism about spin alignment.
- Numerical simulation gives opposite sign.
- NLO process gives more contribution.

outlook

- Regeneration gives the right sign.

Thanks for listening!

Zhishun Chen

Date: 2024/11/17