J/psi spin alignment from polarized damping rate

Shu Lin

Sun Yat-Sen University

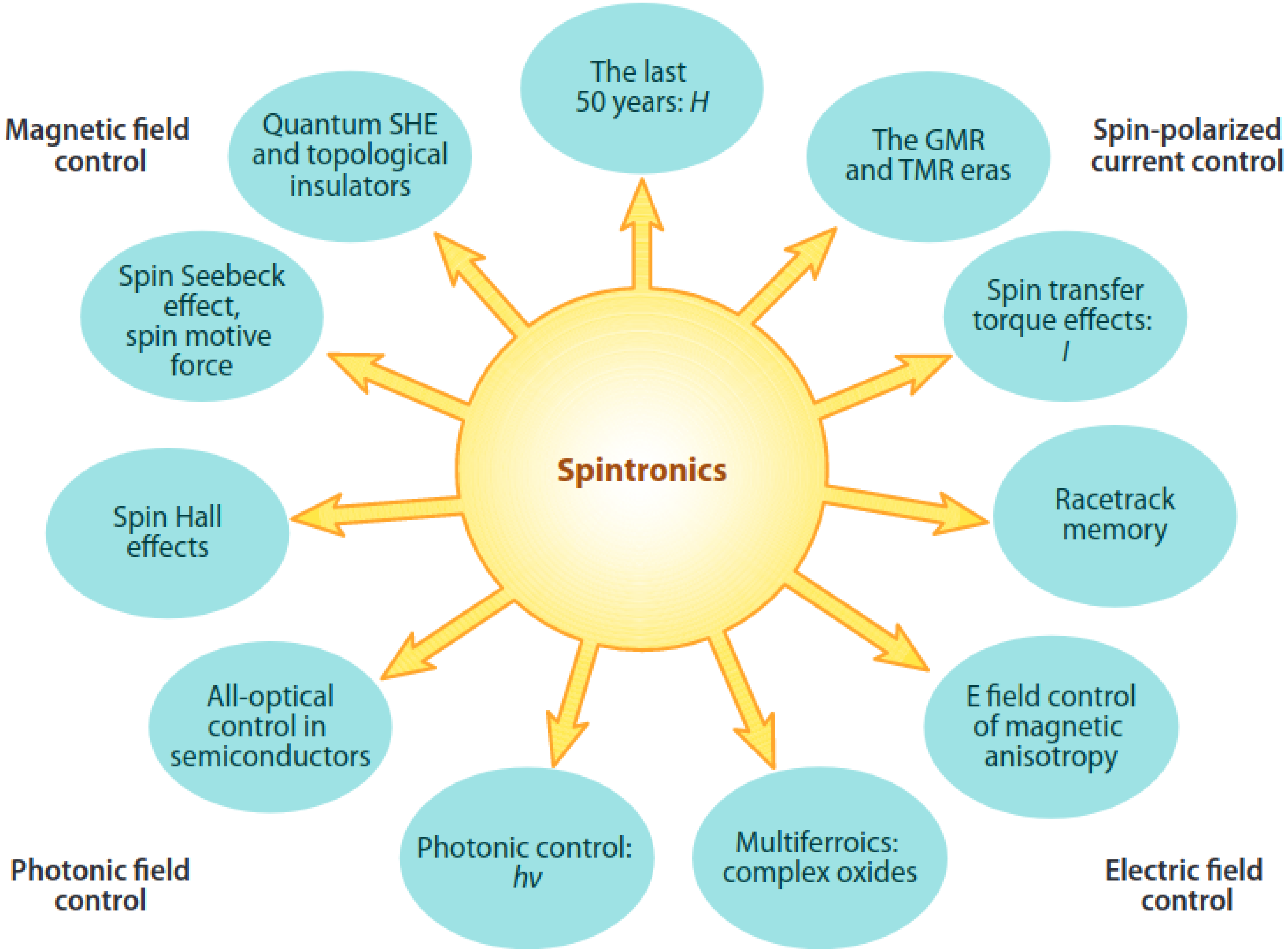
ExHIC-p workshop on polarization phenomena in nuclear collisions,
Academia Sinica, Taipei, March 14-17, 2024

Z. Chen, Y. Guo, M. He, SL, to appear

Outline

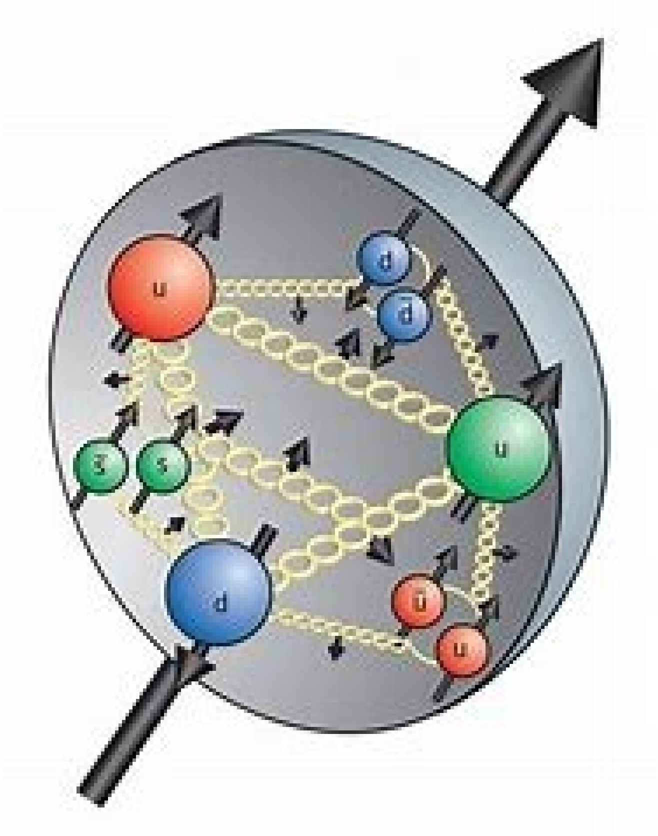
- Uniqueness of spin physics in heavy ion collisions
- Difference between spin polarization and spin alignment
- Spin alignment of ϕ and J/Ψ
- Effective theory of charmonium
- Spin dependent damping rate
- Heavy ion phenomenology
- Conclusion and outlook

Spintronics in condensed matter physics



Bader+Parkin
ARCMP 2010

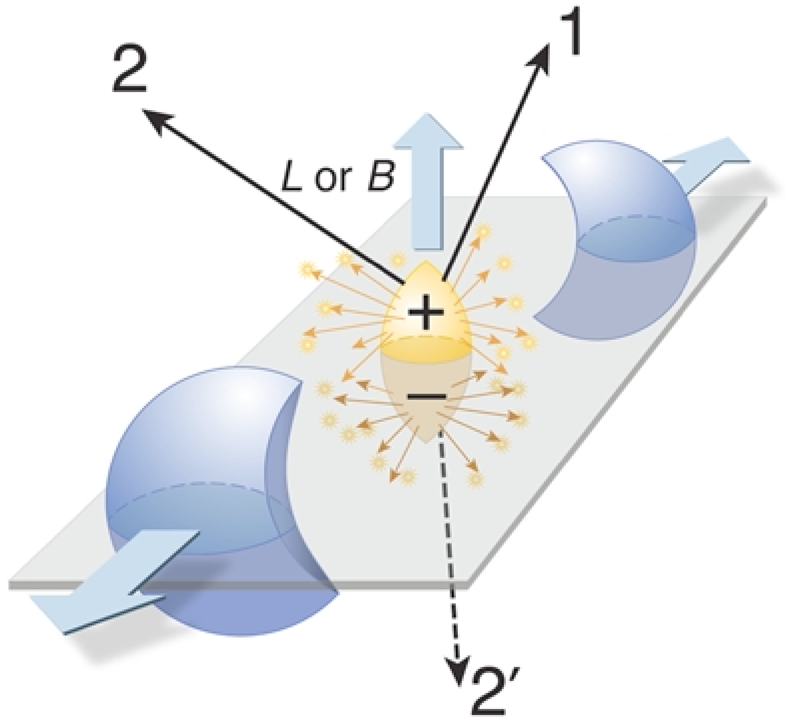
Spin in particle physics



Proton spin composition (1988-now)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

Spin polarization (alignment) in HIC



$$L_{ini} \sim 10^5 \hbar \rightarrow S_{final}$$

Liang, Wang, PRL 2005, PLB 2005

Spin polarization observed in multiple final particles (Λ, ϕ , J/Ψ) as messengers, probe different apsects of the QCD medium

Explorations of spin polarization (alignment) in HIC just begin!

Talks by A.-h. Tang, S. Lim

Difference between spin polarization and alignment

Spin polarization: approx conserved, sum of parton polarization from medium, insensitive to interaction

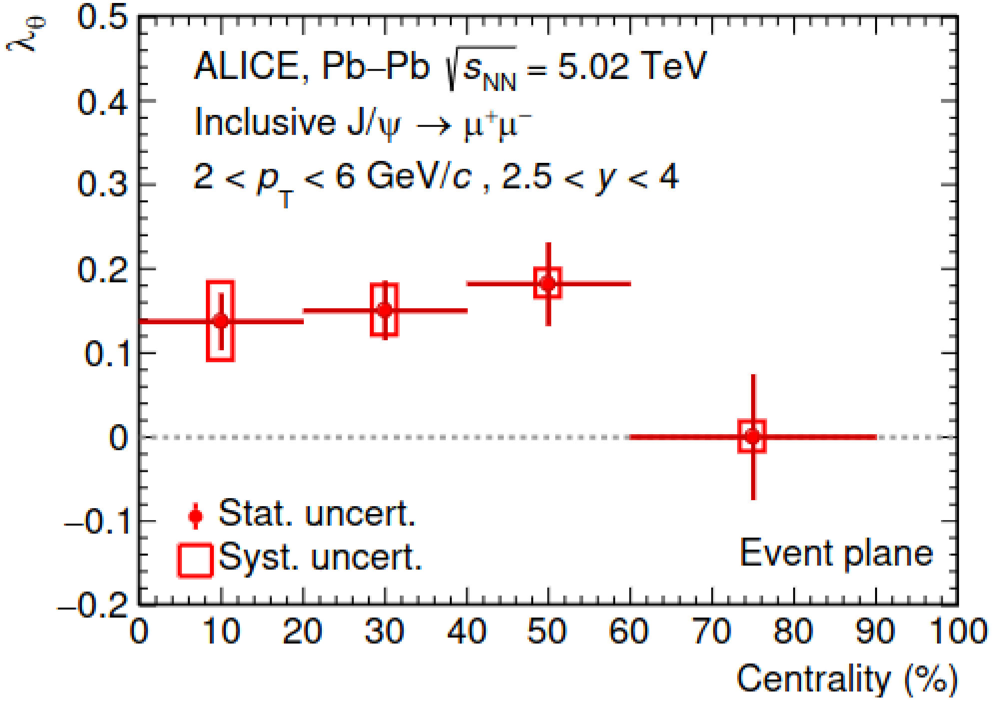
Vorticity field
EM field
Other hydro gradient field

Spin alignment: not conserved, origin complicated, sensitive to interaction

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

Talks by Q. Wang, X.-L. Sheng, L. Oliva, K. Avdhesh, H. Kim

Spin alignment of J/Ψ vs ϕ

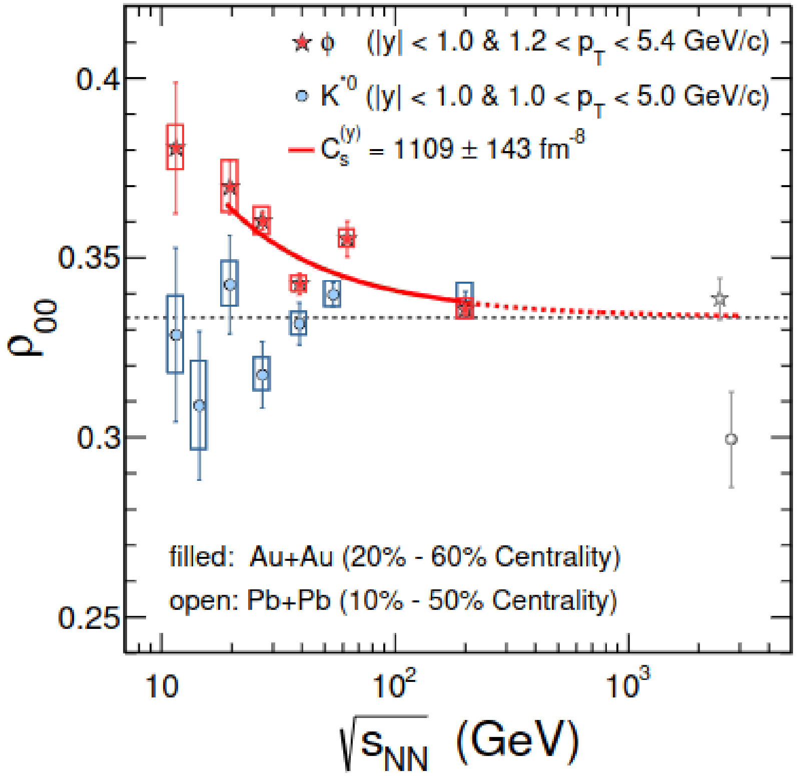


$$\rho_{00} < \frac{1}{3}$$

opposite to ϕ

ALICE, PRL 2023

STAR, Nature 2023



$$J/\Psi + g \longleftrightarrow c + \bar{c}$$

$$B \to J/\Psi + X$$

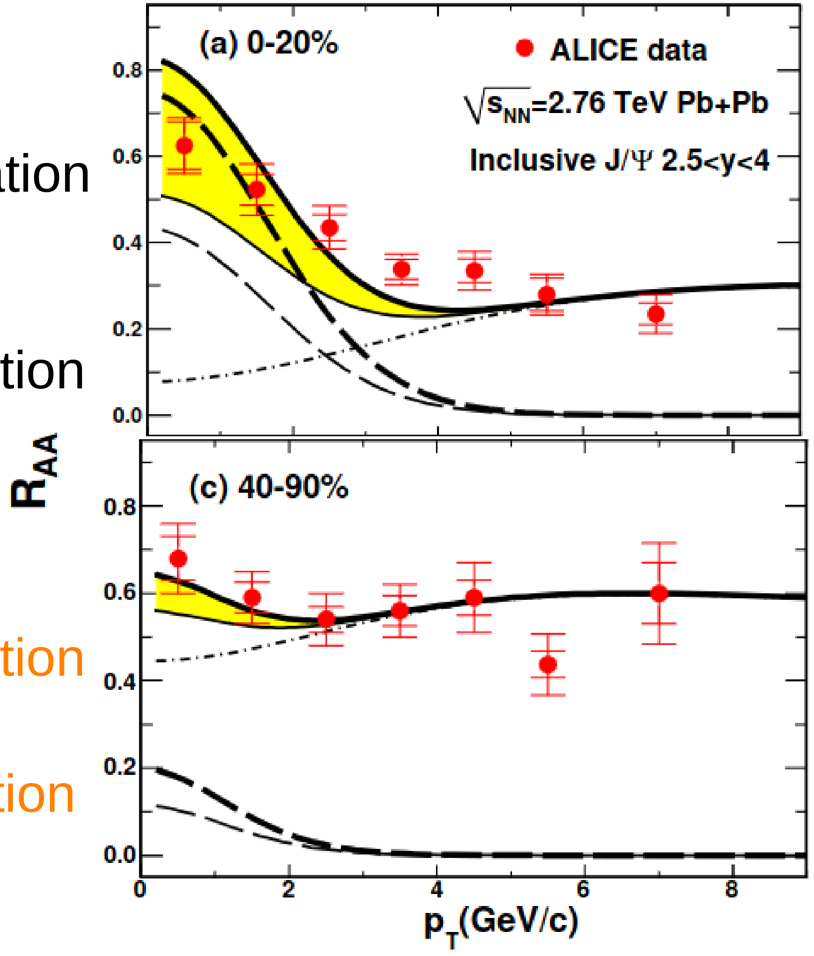
$$s + \bar{s} \to \phi$$

Talks by A.-h. Tang, S. Lim

J/Ψ production mechanism at forward rapidity

regeneration

dissociation



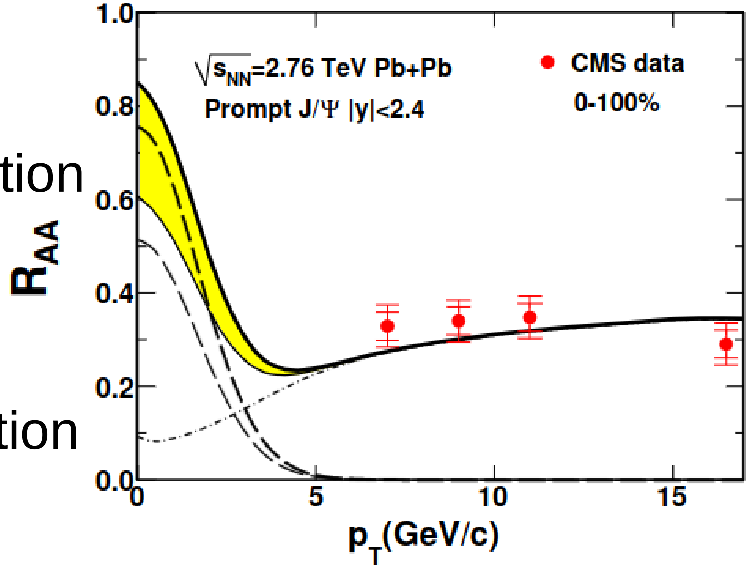
dissociation

regeneration

K. Zhou et al, PLB 2014

regeneration

dissociation



At LHC energy, regeneration important at central collision, less so at peripheral collision, dissociation significant

J/Ψ spin alignment from polarized damping

Focus on dissociation of charmonium produced in hard scattering

J/Ψ S-wave spin triplet $S = 1, L = 0$

$$p^\mu \partial_\mu f_i = -C_i f_i + D_i$$ i: spin triplet label

disso regen

Spin dependent (polarized) damping rate leads to spin alignment

$\rho_{00} < \frac{1}{3}$ requires $C_0 > \frac{1}{3}(C_0 + C_+ + C_-)$

Quantum mechanical desciption of charmonium

$$H_{\rm eff} = H_0 + H_I,$$

$$H_0 = \frac{\vec{p}^2}{m_Q} + V_1(|\vec{r}|) + \sum_a \frac{\lambda^a}{2}\frac{\bar{\lambda}^a}{2} V_2(|\vec{r}|),$$

color singlet

color octet

Yan, PRD 1980, Kuang-Yan, PRD 1981

rest frame of J/Ψ

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

Spin dependent interaction

$$\vec{d}^a = \frac{1}{2} g_s \vec{r} \left(\frac{\lambda^a}{2} - \frac{\bar{\lambda}^a}{2} \right),$$

chromo-electric dipole moment

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

chromo-magnetic dipole moment

Cross sections from chromo-electric interaction

$$\sigma_{E_1,\text{Coulomb}}^{g+J/\psi\to c+\bar{c}}(E_g) = \frac{2^7}{9} g_s^2 \frac{\epsilon_B^{5/2}}{m_Q} \frac{(E_g - \epsilon_B)^{3/2}}{E_g^5},$$

$$\propto |\langle (c\bar{c})_8, \vec{p} | \vec{r} | J/\psi \rangle|^2$$

Spin independent interaction

$c\,\bar{c} \qquad S = 1, L = 1$

Peskin, NPB 1979, Bhanot-Peskin, NPB 1979
Chen-He, PRC 2017

Cross sections from chromo-magnetic interaction

$$\sigma^{g+J/\psi\to c+\bar{c}}_{M_1,\mathrm{Coulomb}}(E_g) = \frac{2^3}{3} g_s^2 \frac{\epsilon_B^{5/2}}{m_Q^2} \frac{(E_g-\epsilon_B)^{1/2}}{E_g^3}.$$

$$\propto \ |\langle (c\bar{c})_8| \left(\frac{\vec{\sigma}}{2} - \frac{\vec{\sigma}'}{2}\right) \cdot (\vec{k}\times\vec{\epsilon}_{k\lambda})|J/\psi\rangle|^2$$

$c\bar{c} \qquad S=0, L=0$

Peskin, NPB 1979, Bhanot-Peskin, NPB 1979
Chen-He, PRC 2017

Spin dependent interaction

$$\left|\langle\frac{\uparrow\downarrow-\downarrow\uparrow}{\sqrt{2}}\right|\left(\frac{\vec{\sigma}}{2}-\frac{\vec{\sigma}'}{2}\right)\cdot\vec{B}\left|\uparrow\uparrow\rangle\right|^2 = \left|\langle\frac{\uparrow\downarrow-\downarrow\uparrow}{\sqrt{2}}\right|\left(\frac{\vec{\sigma}}{2}-\frac{\vec{\sigma}'}{2}\right)\cdot\vec{B}\left|\downarrow\downarrow\rangle\right|^2 = \frac{B_\perp^2}{2}$$

$$\left|\langle\frac{\uparrow\downarrow-\downarrow\uparrow}{\sqrt{2}}\right|\left(\frac{\vec{\sigma}}{2}-\frac{\vec{\sigma}'}{2}\right)\cdot\vec{B}\left|\frac{\uparrow\downarrow-\downarrow\uparrow}{\sqrt{2}}\rangle\right|^2 = B_\parallel^2$$

$\parallel, \perp$ defined w.r.t quantization axis n

$$B_n^2 \sim \sum_\lambda |\left(\vec{k}'\times\vec{\epsilon}_{k'\lambda}\right)\cdot\hat{n}'|^2 = k_i' k_j'(\delta_{ij}-n_i' n_j')$$

Assumptions and simplifications

- Evolution of J/Ψ only
- Initial condition : unpolarized J/Ψ produced by hard scattering
- Ignore regeneration, only dissociation
- Spin dependent damping rate in QGP leads to spin alignment

from particle effect

Vector meson field fluctuation
Glasma field fluctuation

from field fluctuation

Vorticity field
EM field
Fragmentation

from mean field

Boltzmann equation in Bjorken flow

$$p^\mu \partial_\mu f_i = -C_i f_i \qquad C_i = C^E + C_i^B$$

In Bjorken flow $C^E = C^E(\tau, p), \quad C_i^B = C_i^B(\tau, p, n)$

Approx boost invariant solution $E \to \infty$

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

Zhu-Zhuang-Xu, PLB 2005

J/Ψ produced at collision point

dissociation changes number, not momentum

$$\bar{f}(\tau, y, p_T) = \exp\left(-\int_{\tau_0}^{\tau} \frac{\mathrm{d}\tau'}{\tau_R^i(\tau')}\right) \bar{f}_0(\tau_0, y, p_T) \qquad \frac{1}{\tau_R^i} = \frac{C^E}{p \cdot u} + \frac{C_i^B}{p \cdot u}$$

Spin alignment

$$f^i(\tau, y, p_T) \simeq \exp\left(-\int_{\tau_0}^{\tau} d\tau' \frac{C^E}{p\cdot u}\right) \exp\left(-\int_{\tau_0}^{\tau} d\tau' \frac{C_i^B}{p\cdot u}\right) \bar{f}_0(\tau_0, y, p_T)$$

$$\rho_{00} - \frac{1}{3} = \frac{f^0}{f^0 + f^- + f^+} - \frac{1}{3} \simeq -\frac{1}{3}\int_{\tau_0}^{\tau} \frac{C_0^B d\tau'}{p\cdot u} + \frac{1}{3}\int_{\tau_0}^{\tau} \frac{d\tau' \bar{C}^B}{p\cdot u}$$

Only chromo-magnetic damping factor survives

$$C_0^B \propto k_i' k_j' \left(\delta_{ij} - n_i' n_j'\right)$$

$$C_0^B + C_+^B + C_-^B \propto 2k'^2$$

isotropic $k_i' k_j' \to \frac{1}{3} k'^2 \delta_{ij}$

alignment: anisotropic collision geometry

Spin dependent damping: limit 1

$$p^\mu \partial_\mu f_i = -C_i f_i$$

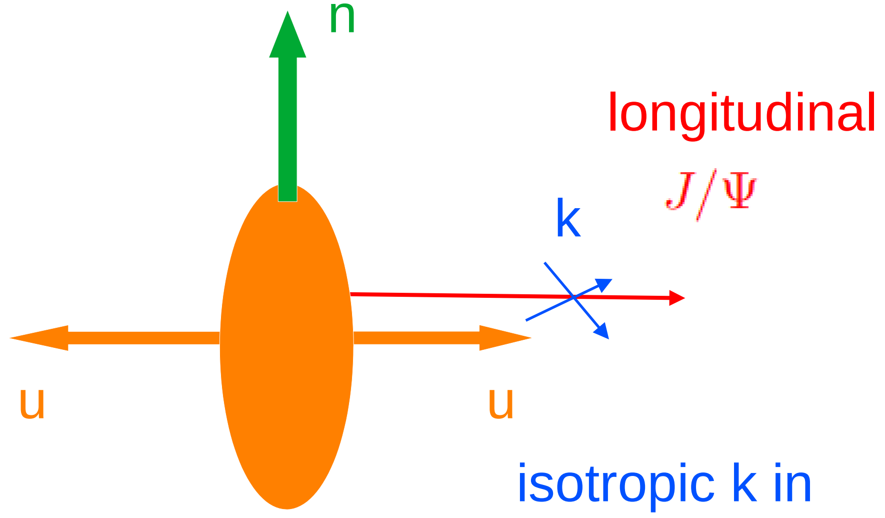
$$C_0^B \propto k'_i k'_j \left(\delta_{ij} - n'_i n'_j\right)$$

$$C_0^B + C_+^B + C_-^B \propto 2k'^2$$

$p_T \to 0$

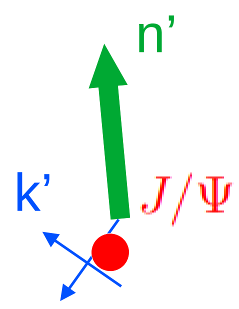
No boost

lab frame



isotropic k in fluid LRF

J/Ψ rest frame



isotropic k in J/psi LRF

$$k'_i k'_j \to \frac{1}{3} k'^2 \delta_{ij}$$

$$C_0^B \to \bar{C}^B$$

$$\rho_{00} \to \frac{1}{3}$$

Spin dependent damping: limit 2

$$p^\mu \partial_\mu f_i = -C_i f_i$$

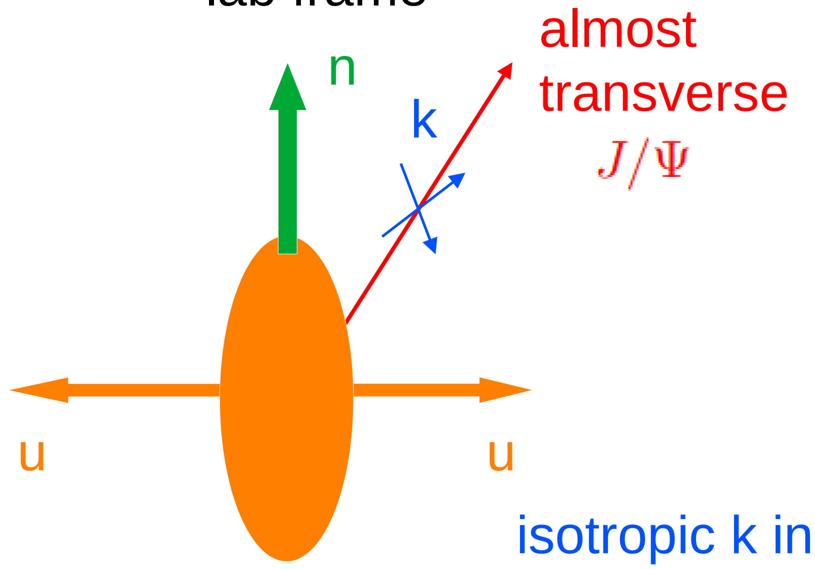
$$C_0^B \propto k'_i k'_j \left(\delta_{ij} - n'_i n'_j\right)$$

$$C_0^B + C_+^B + C_-^B \propto 2k'^2$$

$p_T \to \infty$

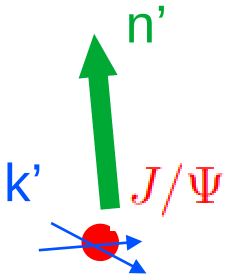
transverse boost

lab frame



isotropic k in
fluid LRF

J/Ψ rest frame



$$\langle k'_i k'_j \rangle_{\hat{p}} \to \frac{1}{2} k'^2 \delta_{ij}$$

$$C_0^B < \bar{C}^B$$

$$\rho_{00} > \frac{1}{3}$$

k approx transverse
in J/psi LRF

Frame & quantization axis

$$p^\mu \partial_\mu f_i = -C_i f_i$$

Lorentz invariant

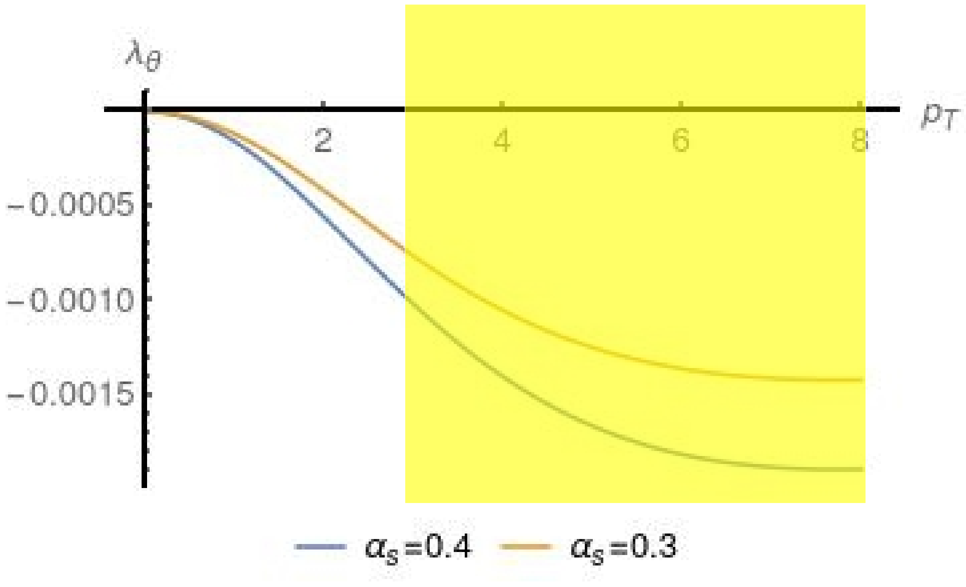
$$\rho_{00} - \frac{1}{3} = \frac{f^0}{f^0 + f^- + f^+} - \frac{1}{3}$$

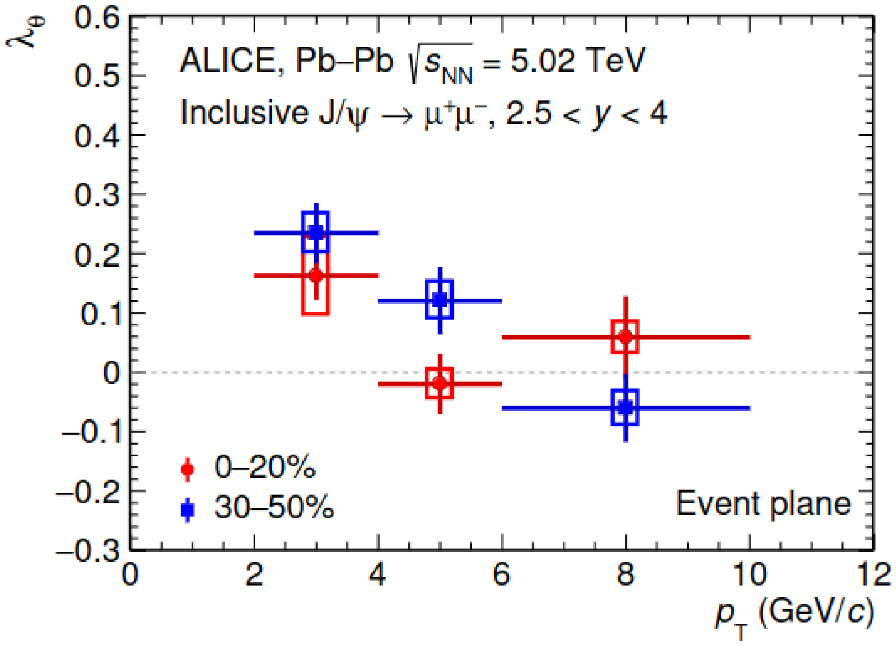
frame independent
quantization axis dependent

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

expressed in lab frame

Spin alignment





- ➢non-monotonic p_T dependence
- ➢rapidity independent
- ➢Coulombic binding

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

$$\frac{g^2 T_0^{1/2} \epsilon_B^{5/2}}{m_Q^2}$$

Conclusion

- Possible mechanism of J/Ψ spin alignment from particle effect
- Interplay of spin-chromo-magnetic coupling and anisotropic flow leads to spin dependent damping
- Dissociation only gives $\rho_{00} > \frac{1}{3}$

Outlook

- J/Ψ regeneration to give non-trivial momentum dependence
- QGP effect on formation of J/Ψ
- Feed down from excited states

Thank you!