Spin alignments of vector mesons - new frontier of spin dynamics

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Outline

- Introduction
- Global polarization of hyperons in HIC
- Global spin alignment of vector mesons in HIC
- Relativistic Spin Boltzmann Equation (for spin alignments of vector mesons) in Closed-Time-Path formalism (CTP) from Kadanoff-Baym equation (KBE)
- Questions and discussions

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Global polarization of hyperons in HIC

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STAR results: Hyperon Polarization



parity-violating decay of hyperons

In case of Λ 's decay, daughter proton preferentially decays in the direction of Λ 's spin (opposite for anti- Λ)

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha \mathbf{P}_{\mathbf{\Lambda}} \cdot \mathbf{p}_{\mathbf{p}}^*)$$

 $\begin{array}{c} \alpha: \ \Lambda \ \text{decay parameter (=0.642\pm0.013)} \\ P_{\Lambda}: \ \Lambda \ \text{polarization} \\ p_{P}: \ \text{proton momentum in } \ \Lambda \ \text{rest frame} \\ \\ \hline \\ \alpha_{\Lambda} = 0.7519 \pm 0.0036 \pm 0.0024 \\ \alpha_{\overline{\Lambda}} = - \ 0.7559 \pm 0.0036 \pm 0.0030 \\ \end{array}$



 $\Lambda \rightarrow p + \pi^+$ (BR: 63.9%, c τ ~7.9 cm)

BES III, PRL129, 131801 (2022)

$\omega = (9 \pm 1)x10^{21}/s$, the largest angular velocity that has ever been observed in any system

Liang, Wang, PRL (2005) Betz, Gyulassy, Torrieri, PRC (2007) Becattini, Piccinini, Rizzo, PRC (2008) Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017) Fang, Pang, Q. Wang, X. Wang, PRC (2016)

Global polarization in HIC: model calculation



Karpenko, Becattini, EPJC(2017)



Li, Pang, Wang, Xia PRC(2017)



Xie, Wang, Csernai, PRC(2017)





Shi, Li, Liao, PLB(2018)



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Global polarization in HIC: model calculation



B.C. Fu, K. Xu, X.G. Huang, H.C. Song, Phys. Rev. C 103, 024903 (2021)

S. Ryu, V. Jupic, C. Shen, arXiv:2106.08125 Y.X. Wu, C. Yi, G.Y. Qin, S.Pu, arXiv:2204.02218

Spin polarization from QKT

• The polarization vector is connected to the axial current in phase space by (modified) Cooper-Frye formula [Becattini et al., Annal Phys. (2013); Fang, Pang, et al., PRC (2016)]

$$\mathcal{S}^{\mu}(\mathbf{p}) = rac{\int d\Sigma \cdot p \mathcal{J}^{\mu}_5(p,X)}{2m_\Lambda \int d\Sigma \cdot \mathcal{N}(p,X)},$$

• All possible contributions to the polarization vector [Hidaka, Pu, Yang, PRD (2018); Yi, Pu, Yang, PRC(2021); Yi, Pu, Gao, Yang, PRC (2022)]

$$\begin{split} \mathcal{S}_{\text{thermal}}^{\mu}(\mathbf{p}) &= \frac{\hbar}{8m_{\Lambda}N} \int d\Sigma^{\sigma} p_{\sigma} f_{V}^{(0)} (1 - f_{V}^{(0)}) \epsilon^{\mu\nu\alpha\beta} p_{\nu}\partial_{\alpha} \frac{u_{\beta}}{T} & \text{Thermal vorticity} \\ \mathcal{S}_{\text{shear}}^{\mu}(\mathbf{p}) &= -\frac{\hbar}{4m_{\Lambda}N} \int d\Sigma \cdot p f_{V}^{(0)} (1 - f_{V}^{(0)}) \frac{\epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta}}{(u \cdot p)T} \frac{1}{2} \left\{ p^{\sigma} (\partial_{\sigma} u_{\nu} + \partial_{\nu} u_{\sigma}) - D u_{\nu} \right\} & \text{Shear viscous} \\ \mathcal{S}_{\text{accT}}^{\mu}(\mathbf{p}) &= -\frac{\hbar}{8m_{\Lambda}N} \int d\Sigma \cdot p f_{V}^{(0)} (1 - f_{V}^{(0)}) \frac{1}{T} \epsilon^{\mu\nu\alpha\beta} p_{\nu} u_{\alpha} (D u_{\beta} - \frac{1}{T} \partial_{\beta}T), & \text{Fluid acceleration} \\ \mathcal{S}_{\text{chemical}}^{\mu}(\mathbf{p}) &= \frac{\hbar}{4m_{\Lambda}N} \int d\Sigma \cdot p f_{V}^{(0)} (1 - f_{V}^{(0)}) \frac{1}{(u \cdot p)} \epsilon^{\mu\nu\alpha\beta} p_{\alpha} u_{\beta} \partial_{\nu} \frac{\mu}{T}, & \text{Gradient of chemical potential} \end{split}$$

• Other approaches: Fu, et al., JHEP2021, PRL 2021; Becattini et al., PRD 2021, PRL 2021;

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Spin alignment of vector mesons

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Vector meson spin alignment: strong decays

• Vector mesons K^{*0} and ϕ decay mainly through strong interaction (parity is conserved), the polarization cannot be measured

$$\begin{array}{rcccc} K^{*0} & \to & K^+ + \pi^-, & (\sim 100\%) & & \mbox{Kaons and pions are} \\ \phi & \to & K^+ + K^-, & (\sim 49\%) & & \mbox{(pseudo)scalar mesons} \end{array}$$

• These decays are in p-wave (L=1). For ϕ meson the decay amplitude has the form

$$\left\langle K^{+}, K^{-} \right| \mathscr{S} \left| \phi; \underline{S_{z}} \right\rangle = Y_{1,S_{z}}(\theta, \varphi)$$
 angles of one particular kaon $S_{z} = -1, 0, 1$

• Angular distribution of decay products $Y_{10} = \sqrt{\frac{3}{4\pi}} \cos \theta, \quad Y_{1,\pm 1} = \mp \sqrt{\frac{3}{8\pi}} \sin \theta e^{\pm i\varphi}$ $\frac{dN}{d\Omega} = \left| \left\langle K^+, K^- \right| \mathscr{S} \left| \phi; S_z \right\rangle \right|^2 = \underline{|Y_{1,S_z}(\theta, \varphi)|^2}$ symmetric for $\theta \to \pi$.

symmetric for $\theta \rightarrow \pi - \theta$

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Vector meson polarization: strong decays

• The spin ensemble of ϕ vector meson is described by spin density matrix ρ (3 × 3 complex Hermitian matrix). The angular distribution of one decay product (kaon) is

$$\begin{split} \frac{dN}{d\Omega} &= \sum_{S_z} \rho_{S_z} \left| \left\langle K^+, K^- \right| \mathscr{S} \left| \phi; S_z \right\rangle \right|^2 & \text{8 real indep. variables } \operatorname{Tr}(\rho) = 1 \\ &= \sum_{S_z} \left\langle K^+, K^- \right| \mathscr{S} \left| \phi; S_z \right\rangle \rho_{S_z} \left\langle \phi; S_z \right| \mathscr{S} \left| K^+, K^- \right\rangle & \begin{pmatrix} \rho_{-1,-1} & \rho_{-1,0} & \rho_{-1,1} \\ \rho_{-1,0}^* & \rho_{00} & \rho_{01} \\ \rho_{-1,1}^* & \rho_{01}^* & \rho_{11} \end{pmatrix} \\ &\to \sum_{S_{z1}, S_{z2}} \left\langle K^+, K^- \right| \mathscr{S} \left| \phi; S_{z1} \right\rangle \rho_{S_{z1}S_{z2}} \left\langle \phi; S_{z2} \right| \mathscr{S} \left| K^+, K^- \right\rangle & \text{5 real variables } \\ &= \sum_{S_{z1}, S_{z2}} \frac{\rho_{S_{z1}S_{z2}}Y_{1,S_{z1}}(\theta, \varphi)Y_{1,S_{z2}}^*(\theta, \varphi)}{\rho_{00} & \rho_{-1,1} & (\rho_{-1,0} - \rho_{01})} \end{split}$$

 The polarization of vector meson is related to some elements (not all) of spin density matrix.

$$\vec{\mathcal{P}} = [\mathcal{P}_1, \mathcal{P}_3, \mathcal{P}_3] \qquad \qquad \textbf{3 real variables} \\ = \left[\sqrt{2} \operatorname{Re}\left(\rho_{-1,0} + \rho_{01}\right), \sqrt{2} \operatorname{Im}\left(\rho_{-1,0} + \rho_{01}\right), (\rho_{11} - \rho_{-1,-1})\right] \qquad \qquad \textbf{Polarization in spin quantization direction}$$

Vector meson polarization: strong decays

• By integrating over φ , we get the polar angle distribution

$$\frac{dN}{d\cos\theta} = \int_0^{2\pi} d\varphi \frac{dN}{d\Omega} = \frac{3}{4} \left[(\underline{1-\rho_{00}}) + (\underline{3\rho_{00}-1})\cos^2\theta \right]$$
The angle between decay product and spin direction of the vector meson in its rest frame polar angle dependence is related to ρ_{00}

One cannot measure the polarization of vector mesons by strong decays. One can only know if vector mesons are polarized or not (polar angle dependence disappears or not) by comparing ρ_{00} and



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STAR results on global spin alignments of vector mesons



STAR Collab., 2204.02302 [to appear in Nature]

"the global spin alignment for phi unexpectedly large, while that for K^{*0} is consistent with zero. The observed spin-alignment pattern and magnitude for the phi cannot be explained by conventional mechanisms, while a model with strong force fields [2,3] accommodates the current data. "

[2] Sheng, Oliva, QW
(2020, Erratum 2022)
[3] Sheng, QW, Wang (2020)

Possible contributions to ρ_{00}^{ϕ}



See Ai-Hong Tang's talk for more discussion

Polarization of strange quarks by ϕ vector fields (non-relativistic model)

- Like electric charges in motion can generate an EM field, s and s̄ quarks in motion can generate an effective φ vector field [Sheng, Oliva, QW (2020)].
- Similar to how EM field polarize (anti)quarks, the ϕ vector field can polarize s and \overline{s} , but with a large magnitude due to strong interaction.

$$egin{aligned} ec{\mathcal{P}}_{s/ar{s}} &=& rac{1}{2} oldsymbol{\omega} + rac{1}{2m_s} oldsymbol{arepsilon} imes \mathbf{p}_{s/ar{s}} \ &
onumber \ &
on$$

Sheng, Oliva, QW (2020)

Electric part of spin polarization corresponds to spin-orbit couplings (spin-Hall effects) not accessible via Λ polarization:

$$\underbrace{\mathbf{E} \times \mathbf{p}}_{\mathbf{F}} \sim -\frac{1}{r} \frac{d\Phi}{dr} (\mathbf{r} \times \mathbf{p})$$
Spin \longleftrightarrow Local OAM

ρ_{00}^{ϕ} from ϕ fields in non-relativistic coalescence model

• Assuming the spin quantization direction is y-direction (OAM), in a non-relativistic coalescence model [Greco, Ko, Levai (2003); Fries, Muller, Nonaka, Bass (2003); Hua, Yang (2003)], ρ_{00} has the form

$$\begin{split} \rho_{00}^{\phi}(t,\mathbf{x}) &\approx \frac{1}{3} - \frac{4}{9} \int \frac{d^3 \mathbf{p}}{(2\pi)^3} |\psi_{\phi}(\mathbf{p})|^2 & \phi \text{ meson's non-relativistic} \\ \text{in products} & \times \left\{ P_s^y(\mathbf{p}) P_s^y(-\mathbf{p}) - \frac{1}{2} \left[P_s^z(\mathbf{p}) P_s^z(-\mathbf{p}) + P_s^x(\mathbf{p}) P_s^x(-\mathbf{p}) \right] \right\} \\ \phi \text{ meson} & \times \left\{ \frac{1}{3} + \frac{g_{\phi}^2}{9m_s^2 T_{\text{eff}}^2} \left[\left\langle B_{\phi,y}^2 \right\rangle - \frac{1}{2} \left\langle B_{\phi,x}^2 + B_{\phi,z}^2 \right\rangle \right] \right\} \\ \approx \frac{1}{3} + \frac{g_{\phi}^2}{9m_s^2 T_{\text{eff}}^2} \left[\left\langle E_{\phi,y}^2 \right\rangle - \frac{1}{2} \left\langle E_{\phi,x}^2 + E_{\phi,z}^2 \right\rangle \right] \right\} \\ = \frac{1}{27m_s^2 T_{\text{eff}}^2} G_s^{(y)} \\ \text{Effective temperature} & \text{Sheng, Oliva, QW (2020)} \end{split}$$

Prediction for ρ_{00} from ϕ field (non-relativistic coalescence model)



Sheng, Oliva, QW (2020)

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Shortcomings of non-relativistic coalescence model for ρ_{00}^{ϕ}

- Spins are decoupled from momenta: too simple to account for spin dynamics. The sign of anti-quark's momentum is not easy to determine (easy to make a mistake)
- No Lorentz covariance, only valid for quasi-static ϕ mesons, cannot be applied to ϕ mesons with non-vanishing momenta with confidence
- It is not a model based on relativistic quantum field theory
- The deeper implication of ϕ field cannot be explored
- To solve above problems, it is necessary to develop a relativistic spin transport theory for ϕ mesons to describe the relativistic fusion process $s\overline{s} \rightarrow \phi$ with spin d.o.f.

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Relativistic spin Boltzmann equation for fusion process

A phenomenological approach to Relativistic Spin Boltzmann Equation (RSBE) for fusion process $\mathbf{k} - \mathbf{p}', r$

$$k \cdot \partial_{x} f_{\lambda}^{V}(x, \mathbf{k})$$

$$\sum_{r,s=\pm 1/2} \int \frac{d^{3}\mathbf{p}'}{E_{\mathbf{p}'}^{\overline{q}} E_{\mathbf{k}-\mathbf{p}'}^{q}} \delta\left(E_{\mathbf{k}}^{V} - E_{\mathbf{k}-\mathbf{p}'}^{\overline{q}} - E_{\mathbf{p}'}^{\overline{q}}\right)$$

$$\times |M(\mathbf{k} - \mathbf{p}', r; \mathbf{p}', s \to \mathbf{k}, \lambda)|^{2}$$

$$\times \left\{ f_{r}^{q}(\mathbf{k} - \mathbf{p}') f_{s}^{\overline{q}}(\mathbf{p}') \left[1 + f_{\lambda}^{V}(\mathbf{k})\right] - f_{\lambda}^{V}(\mathbf{k}) \left[1 - f_{r}^{q}(\mathbf{k} - \mathbf{p}')\right] \left[1 - f_{s}^{\overline{q}}(\mathbf{p}')\right] \right\}$$

$$\mathbf{Gain term} \qquad \mathbf{Loss term}$$

The rigorous way is to derive RSBE from CTP (SK) or KBE in ٠ terms of Matrix Valued Spin Dependent Distributions (MVSD) for quarks and vector mesons

$$\begin{array}{ccccccccc} f_r^q & \to & f_{r_1 r_2}^q & & \\ f_s^{\overline{q}} & \to & f_{s_1 s_2}^{\overline{q}} & & f_{\lambda}^V & \to & f_{\lambda_1 \lambda_2}^V \end{array}$$

MVSD: Sheng, Weickgenannt, Speranza, Rischke, QW (2021); Sheng, QW, Rischke (2022)

Spin density matrix: diagonal \implies diagonal + off-diagonal elements

Matrix Valued Spin Dependent Distributions (MVSD) for spin-1/2 fermions

- MVSD in phase space $p^{\mu} \equiv \frac{1}{2}(p_1^{\mu} + p_2^{\mu})$ $q^{\mu} \equiv p_1^{\mu} p_2^{\mu}$ $f_{rs}(x,p) \equiv \int \frac{d^4q}{2(2\pi)^3} \exp\left(-\frac{i}{\hbar}\vec{q}\cdot x\right)\delta(\vec{p}\cdot \vec{q}) \left\langle a^{\dagger}(\underline{s},\mathbf{p}_2)a(\underline{r},\mathbf{p}_1) \right\rangle$
- MVSD can be parameterized in terms un-polarized distributions and polarization distributions

$$\begin{split} f_{rs}^{(+)}(x,\mathbf{p}) &= \frac{1}{2} \underline{f_q(x,\mathbf{p})} \left[\delta_{rs} - \underline{P_{\mu}^q(x,\mathbf{p})} n_j^{(+)\mu}(\mathbf{p}) \tau_{rs}^j \right], \end{split} \begin{array}{l} \text{Pauli matrices} \\ \text{in spin space} \\ \text{in spin space} \\ \text{(rs-space)} \end{split} \\ f_{rs}^{(-)}(x,-\mathbf{p}) &= \frac{1}{2} \underline{f_{\overline{q}}(x,-\mathbf{p})} \left[\delta_{rs} - \underline{P_{\mu}^{\overline{q}}(x,-\mathbf{p})} n_j^{(-)\mu}(\mathbf{p}) \tau_{rs}^j \right], \end{split}$$

Polarization dist.

Un-polarized dist. MVSD: Sheng, Weickgenannt, et al. (2021); Sheng, QW, Rischke (2022) Four-vectors of three basis directions in rest frame of q and \overline{q} (one is the spin quantization direction)

RSBE in MVSD from CTP or KBE

 A general RSBE can be derived for fusion process in relativistic quantum field theory on CTP (KBE)

$$k \cdot \partial_{x} f_{\lambda_{1}\lambda_{2}}^{V}(x,\mathbf{k}) = \frac{1}{16} \sum_{\lambda_{1}',\lambda_{2}'} \left[\epsilon_{\mu}^{*}(\lambda_{1},\mathbf{k})\epsilon_{\nu}(\lambda_{1}',\mathbf{k})\delta_{\lambda_{2}\lambda_{2}'} \right] polarization vector for vector meson for vector$$

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Fusion and dissociation process

In the dilute gas limit ٠

 $f_{\lambda_1\lambda_2}^V \sim f_{rs}^q \sim f_{rs}^{\overline{q}} \ll 1$

 $k \cdot \partial_x f^V_{\lambda_1 \lambda_2}(x, \mathbf{k}) = \frac{1}{8} \left[\epsilon^*_{\mu}(\lambda_1, \mathbf{k}) \epsilon_{\nu}(\lambda_2, \mathbf{k}) \mathcal{C}^{\mu\nu}_{\text{coal}}(x, \mathbf{k}) \right]$

 $-\mathcal{C}_{\mathrm{diss}}(\mathbf{k})f^V_{\lambda_1\lambda_2}(x,\mathbf{k})$], Dissociation collision kernel

Sheng, Oliva, et al., 2205.15689, 2206.05868

RSBE for fusion (coalescence) and dissociation process $q\overline{q} \leftrightarrow$ ٠ V can be simplified as **Coalescence collision kernel**

 n_x , n_y , n_z are three basis directions in rest frame of vector meson

$$-\mathcal{C}_{\text{diss}}(\mathbf{k})f_{\lambda_{1}\lambda_{2}}^{V}(x,\mathbf{k})],$$

$$\epsilon_{0} = \mathbf{n}_{y}$$

$$\epsilon_{+1} = -\frac{1}{\sqrt{2}}(\mathbf{n}_{z} + i\mathbf{n}_{x})$$

$$\epsilon_{+1} = -\frac{1}{\sqrt{2}}(\mathbf{n}_{z} - i\mathbf{n}_{x})$$

$$\epsilon_{-1} = \frac{1}{\sqrt{2}}(\mathbf{n}_{z} - i\mathbf{n}_{x})$$

Polarization vector of vector meson

The coalescence part depends on MVSDs of q and \overline{q} , while the dissociation part does not.

MVSD or spin density matrix element for vector mesons

Forml solution to MVSD (spin density matrix) for vector mesons

$$f_{\lambda_1\lambda_2}^V(x,\mathbf{k}) \sim \frac{1}{\mathcal{C}_{\text{diss}}(\mathbf{k})} \left[1 - e^{-\mathcal{C}_{\text{diss}}(\mathbf{k})\Delta t} \right] \\ \times \epsilon_{\mu}^*(\lambda_1,\mathbf{k})\epsilon_{\nu}(\lambda_2,\mathbf{k})\mathcal{C}_{\text{coal}}^{\mu\nu}(x,\mathbf{k})$$

Sheng, Oliva, et al., 2205.15689, 2206.05868

• where the coalescence collision kernel $C_{coal}^{\mu\nu}$ is given by

$$\begin{aligned} \mathcal{C}_{\text{coal}}^{\mu\nu}(x,\mathbf{k}) &= \int \frac{d^3\mathbf{p}'}{(2\pi\hbar)^2} \frac{1}{E_{\mathbf{p}'}^{\overline{q}} E_{\mathbf{k}-\mathbf{p}'}^{q}} \delta\left(E_{\mathbf{k}}^{V} - E_{\mathbf{p}'}^{\overline{q}} - E_{\mathbf{k}-\mathbf{p}'}^{q}\right) \\ &\times \operatorname{Tr}\left\{\underline{\Gamma}^{\nu}\left(p'\cdot\gamma - m_{\overline{q}}\right)\left[1 + \gamma_{5}\gamma \cdot \underline{P}^{\overline{q}}(x,\mathbf{p}')\right]\right. \end{aligned} \qquad \begin{array}{l} \text{polarization} \\ \text{distributions} \\ \text{in phase space for} \\ \text{for vector} \\ \text{for vector} \\ \end{array} \\ &\times \frac{f_{\overline{q}}(x,\mathbf{p}')f_{q}(x,\mathbf{k}-\mathbf{p}'), \end{aligned}$$

un-polarized quark distribution functions

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Spin density matrix element for vector mesons

Spin density matrix (normalized MVSD) for vector mesons

$$f^V_{\lambda_1\lambda_2} \propto
ho^V_{\lambda_1\lambda_2} = rac{\epsilon^*_{\mu}(\lambda_1, \mathbf{k})\epsilon_{
u}(\lambda_2, \mathbf{k})\mathcal{C}^{\mu
u}_{\mathrm{coal}}}{\sum_{\lambda=0,\pm 1}\epsilon^*_{\mu}(\lambda, \mathbf{k})\epsilon_{
u}(\lambda, \mathbf{k})\mathcal{C}^{\mu
u}_{\mathrm{coal}}}$$

 Focus on φ meson, polarization distributions for s and s̄ appear in the collision kernel are in the form

$$\begin{split} P_s^{\mu}(x,\mathbf{p}) \approx &\frac{1}{4m_s} \epsilon^{\mu\nu\rho\sigma} \left(\omega_{\rho\sigma} + \frac{g_{\phi}}{(u \cdot p)T_{\text{eff}}} \frac{F_{\rho\sigma}^{\phi}}{\rho} \right) p_{\nu} \\ P_{\overline{s}}^{\mu}(x,\mathbf{p}) \approx &\frac{1}{4m_s} \epsilon^{\mu\nu\rho\sigma} \left(\omega_{\rho\sigma} - \frac{g_{\phi}}{(u \cdot p)T_{\text{eff}}} \frac{F_{\rho\sigma}^{\phi}}{\rho} \right) p_{\nu} \end{split}$$
 Field strength tensor of ϕ field

Sheng, Oliva, et al., 2205.15689, 2206.05868

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Spin density matrix element for vector mesons

• The fusion (coalescenece) collision kernel $C_{coal}^{\mu\nu}$ can be evaluated in the rest frame of ϕ meson, which gives ρ_{00}^{ϕ}

$$\begin{split} \rho_{00}(x,\mathbf{0}) \approx &\frac{1}{3} + C_1 \left[\frac{1}{3} \boldsymbol{\omega}' \cdot \boldsymbol{\omega}' - (\boldsymbol{\epsilon}_0 \cdot \boldsymbol{\omega}')^2 \right] & C_1 = \frac{8m_s^* + 16m_s^2 m_\phi^2 + 3m_\phi^4}{120m_s^2(m_\phi^2 + 2m_s^2)}, \\ & + C_2 \left[\frac{1}{3} \boldsymbol{\varepsilon}' \cdot \boldsymbol{\varepsilon}' - (\boldsymbol{\epsilon}_0 \cdot \boldsymbol{\varepsilon}')^2 \right] & C_2 = \frac{8m_s^4 - 14m_s^2 m_\phi^2 + 3m_\phi^4}{120m_s^2(m_\phi^2 + 2m_s^2)}. \\ & - \frac{4g_\phi^2}{m_\phi^2 T_{\text{eff}}^2} C_1 \left[\frac{1}{3} \mathbf{B}_{\phi}' \cdot \mathbf{B}_{\phi}' - \underline{(\boldsymbol{\epsilon}_0 \cdot \mathbf{B}_{\phi}')^2} \right] \\ & - \frac{4g_\phi^2}{m_\phi^2 T_{\text{eff}}^2} C_2 \left[\frac{1}{3} \mathbf{E}_{\phi}' \cdot \mathbf{E}_{\phi}' - \underline{(\boldsymbol{\epsilon}_0 \cdot \mathbf{E}_{\phi}')^2} \right], \end{split}$$
All fields with prime are defined in the rest frame of \$\phi\$ meson

spin quantization direction

• Features: (1) perfect factorization of x and p dependence; (2) perfect cancellation for mixing terms (protected by symmetry): all fields appear in squares, i.e. ρ_{00}^{ϕ} measures fluctuations of fields. Surprising results!

Lorentz transformation for ϕ fields

• We can express ρ_{00}^{ϕ} in terms of ϕ fields in the lab frame and obtain the dependence on momenta of ϕ mesons

$$\begin{aligned} \mathbf{B}_{\phi}' &= \gamma \mathbf{B}_{\phi} - \gamma \mathbf{v} \times \mathbf{E}_{\phi} + (1 - \gamma) \frac{\mathbf{v} \cdot \mathbf{B}_{\phi}}{v^2} \mathbf{v}, \\ \mathbf{E}_{\phi}' &= \gamma \mathbf{E}_{\phi} + \gamma \mathbf{v} \times \mathbf{B}_{\phi} + (1 - \gamma) \frac{\mathbf{v} \cdot \mathbf{E}_{\phi}}{v^2} \mathbf{v}, \end{aligned}$$

• where
$$\gamma = E_{\mathbf{k}}^{\phi}/m_{\phi}$$
 and $\mathbf{v} = \mathbf{k}/E_{\mathbf{k}}^{\phi}$

In terms of lab-frame fields we obtain (factorization of x and p)

Parameters and comparison with data

Two parameters (transverse and longitudinal field squares)

$$\left\langle (g_{\phi} \mathbf{B}_{x(y)}^{\phi})^{2} \right\rangle = \left\langle (g_{\phi} \mathbf{E}_{x(y)}^{\phi})^{2} \right\rangle = F^{2}$$
$$\left\langle (g_{\phi} \mathbf{B}_{z}^{\phi})^{2} \right\rangle = \left\langle (g_{\phi} \mathbf{E}_{z}^{\phi})^{2} \right\rangle = r_{z} F^{2} < F^{2}$$

Two sets of values for parameters give the same result

$$\begin{array}{l} F^2 = 0.45 m_\pi^4, \; m_s = 170 \, {\rm MeV} \\ F^2 = 5.02 m_\pi^4, \; m_s = 530 \, {\rm MeV} \end{array} \qquad r_z = 0.79 \end{array}$$

- The magnitude of electric field's contribution decreases with increasing m_s

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Collision energy dependence



Transverse momentum dependence



Figure 2. The ϕ meson's ρ_{00}^{y} as functions of transverse momenta at different collision energies.

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Centrality dependence



Figure 4. The ϕ meson's ρ_{00}^y as a function of centrality at 200 GeV. Red, green, and blue diamond points are our results for centrality ranges 0-5%, 10-40%, and 40-80%, respectively. The dashed line is the fitting curve using a second order polynomial.

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Take-home message: baryon spin vs vector meson spin



- Take-home message:
- P_{Λ} measures the mean fields (exerting on s quark)
- ${m
 ho}_{00}^{\phi}$ measures squares of fields (field fluctuations) (on s quark)

Questions for discussions

Questions to be answered in the future:

- What are particles? What are fields? Particle-field duality?
- What is the nature of vector meson fields? Are they real entities? Can we calculate field squares on Lattice?
- Any connection with QCD sum rules and QCD vacuum properties? Any connection with quark or gluon condensates (trace anomaly)?
- Any implication for J/Psi polarization (gluon fields)?
- Quantitative analysis of hydro contributions: how large is the contribution from shear tensor? (Speranza's talk)

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Some discussions

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Particles and fields

• Particles and fields are most fundamental forms of matter: particlelike matter, field-like matter

Particle-wave duality particle-field duality Quantization of fields: fields particle's quantum states Inverse mapping: particle's quantum states fields

 $\begin{array}{c} \underline{\Phi(x)} \Longrightarrow |\mathbf{p}\rangle = \sqrt{2E_p} a^{\dagger}(\mathbf{p}) |0\rangle \\ \text{field} \\ \text{particle's momentum} \\ \text{state} \\ \underline{|\Phi\rangle}, |\mathbf{p}\rangle \Longrightarrow \underline{\Phi(x)} = \int \frac{d^3 \mathbf{p}}{(2\pi)^3 2E_p} \langle \mathbf{p} |\Phi\rangle e^{-ip \cdot x} \\ \text{particle's state} \\ \text{as wave packet} \\ \end{array}$

- Which are more fundamental: particles and fields? "The reason that our field theories work so well is not that they are fundamental truths, but that any relativistic quantum theory will look like a field theory when applied to particles at sufficiently low energy"
 - -- Steven Weinberg

Particles and fields

- In analogy with electromagnetic fields Yukawa proposed in 1935 the existence of mesons that mediate nuclear forces to bind protons and neutrons into atomic nuclei [Nobel Prize 1949].
- π : Powell and Perkins, 1947 [Nobel prize 1950]
- ρ, ω : Alvarez et al, 1961 [Nobel prize 1968]
- Nuclear force or NN potential: one boson exchange potential (OBEP)
- In low-energy nuclear reactions other meson fields may exist which carry strangeness quantum number such as K, φ etc.



Chiral quark model

Nuclear Physics B234 (1984) 189-212 © North-Holland Publishing Company

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CHIRAL QUARKS AND THE NON-RELATIVISTIC QUARK MODEL*

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We study some of the consequences of an effective lagrangian for quarks, gluons and goldstone bosons in the region between the chiral symmetry breaking and confinement scales. This provides an understanding of many of the successes of the non-relativistic quark model. It also suggests a resolution to the puzzle of the hyperon non-leptonic decays.

Qun Wang (USTC), Spin alignments of vector mesons

Chiral quark model

Scale for strong interaction in dynamical process



• SU(3) Goldstone bosons by 3×3 matrix Σ and ξ ,

$$\begin{split} \Sigma &= \exp\left(i\frac{2\chi}{f}\right) \qquad \qquad \chi = \frac{1}{\sqrt{2}} \\ &= \exp\left(i\frac{\chi}{f}\right) \exp\left(i\frac{\chi}{f}\right) \qquad \qquad \left(\begin{array}{ccc} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ & K^- & \overline{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{array}\right) \end{split}$$

Chiral quark model

• Σ and ξ transform under $SU_L(3) \times SU_R(3)$ as

$$\Sigma \to L\Sigma R^{\dagger}, \qquad \xi \to L\xi U^{\dagger} = U\xi R^{\dagger}$$

• A set of color and flavor triplet quarks $\psi = \begin{pmatrix} u \\ d \\ c \end{pmatrix}$.

$$, \qquad \psi = U\psi$$

Lagrangian

$$\mathcal{L} = \overline{\psi} \left[i \gamma_{\mu} (\partial^{\mu} + i g G^{\mu}) + g_{V} \gamma_{\mu} V^{\mu} \right] + g_{A} \overline{\psi} \gamma_{\mu} A^{\mu} \psi + \frac{1}{4} f^{2} \operatorname{Tr} \left(\partial^{\mu} \Sigma^{\dagger} \partial_{\mu} \Sigma \right) - \frac{1}{2} \operatorname{Tr} F_{\mu\nu} F^{\mu\nu} V^{\mu} = \frac{1}{2} \left(\xi^{\dagger} \partial^{\mu} \xi + \xi \partial^{\mu} \xi^{\dagger} \right) \Longrightarrow \overset{\text{Vector field induced by}}{\text{Goldstone boson fields}} A^{\mu} = \frac{1}{2} i \left(\xi^{\dagger} \partial^{\mu} \xi - \xi \partial^{\mu} \xi^{\dagger} \right)$$

Scale anomaly in QCD

• The quantum effects (loop diagrams) modify the expression for the trace of the energy-momentum tensor

- Running coupling \rightarrow dimensional transmutation \rightarrow mass scale

$$\beta(g) = -b \frac{g^3}{16\pi^2} + ..., \ b = 9 - \frac{2}{3}n_h,$$
 Gross, Wilczek, Politzer (1973)

• At small momentum transfer, heavy quarks decouple:

$$\sum_{h} m_h \bar{Q_h} Q_h \to -\frac{2}{3} n_h \frac{g^2}{32\pi^2} G^{\alpha\beta a} G^a_{\alpha\beta} + \dots$$
Shifman (1978)

