介质中的形状因子

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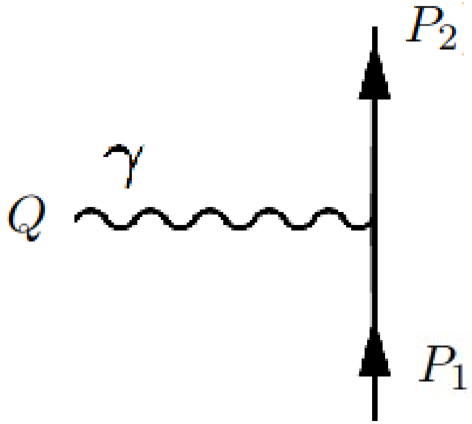
Outline

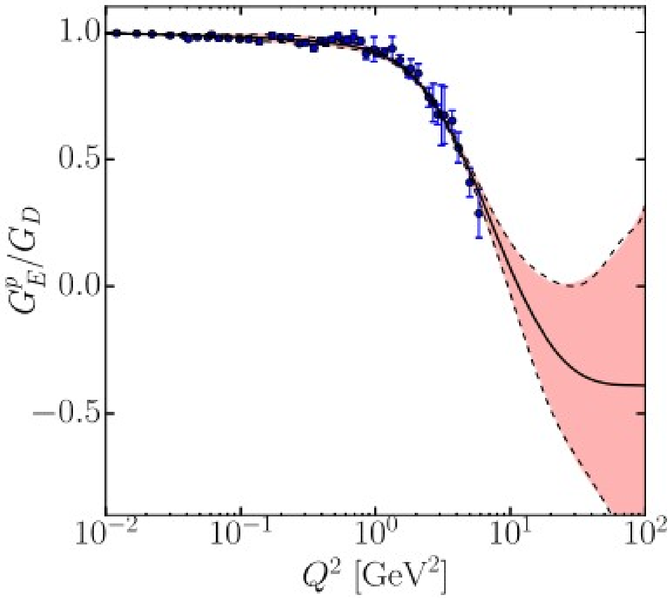
- Why form factors?
- Spin polarization in heavy ion collisions and form factors in medium
- Form factors description of spin couplings
- Electromagnetic form factors in vacuum and in medium
- Gravitational form factors in vacuum and in medium
- Summary

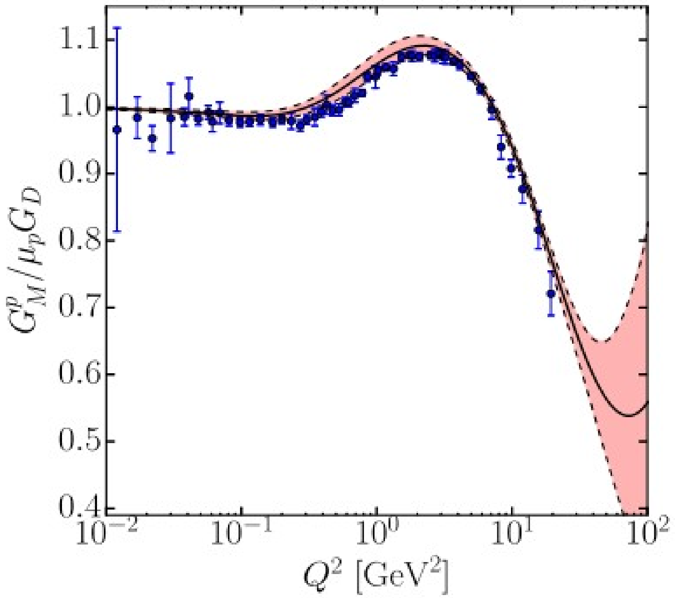
Electromagnetic form factors



$$Q = P_2 - P_1$$

$$P = \frac{1}{2}(P_1 + P_2)$$





PLB 2018,
Ye et al

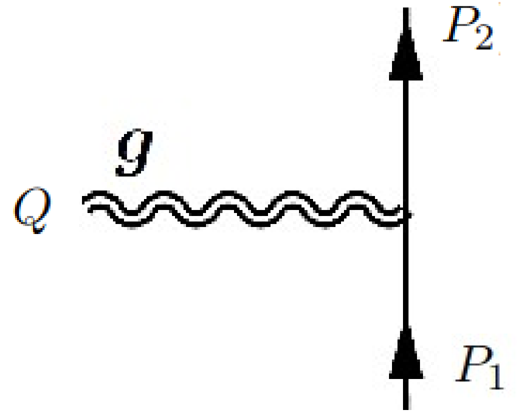
$$\langle P_2|J^\mu(Q)|P_1\rangle = \bar{u}(P_2)\left[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu}Q_\nu}{2m}F_2(Q^2)\right]u(P_1)$$

$$= \bar{u}(P_2)\left[\frac{P^\mu}{m}G_E(Q^2) + \frac{i\epsilon^{\mu\nu\rho\sigma}Q_\nu P_\rho \gamma_\sigma \gamma^5}{2m^2}G_M(Q^2)\right]u(P_1)$$

Form factors parameterize interaction based on symmetry

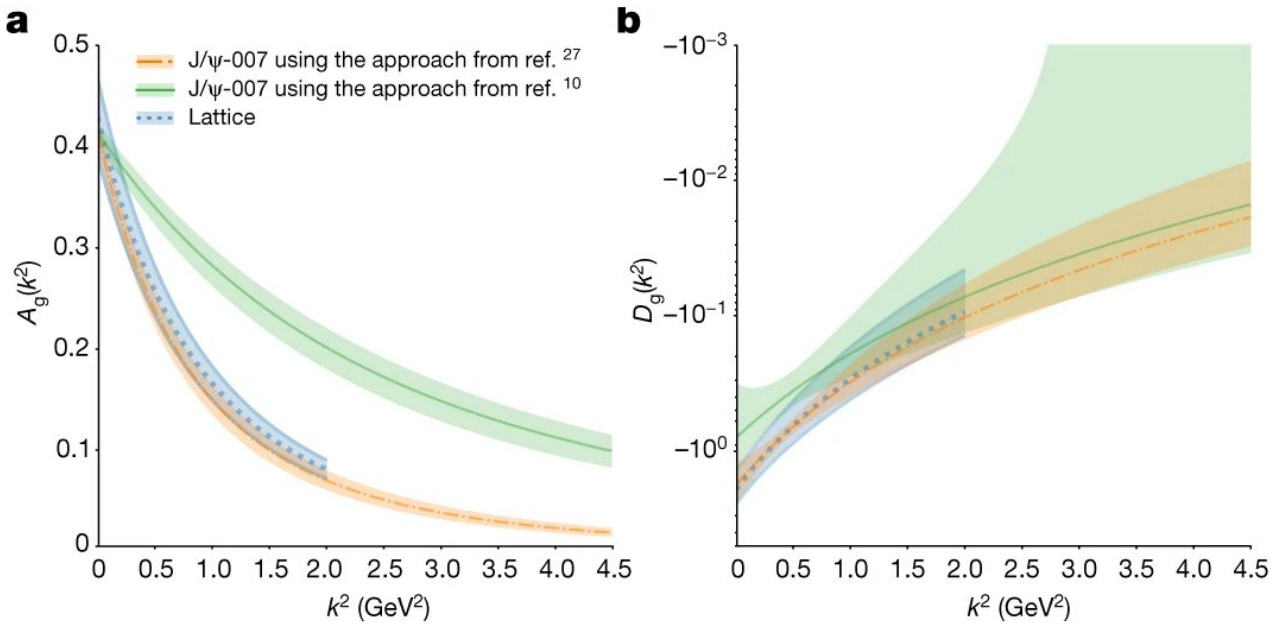
- accessible experimentally
- charge distribution, magentic moment

Gravitational form factors



$$Q = P_2 - P_1$$

$$P = \frac{1}{2}(P_1 + P_2)$$



Nature 2021, Meziani et al

$$\langle P_2|T^{\mu\nu}(Q)|P_1\rangle = \bar{u}(P_2)\left[\frac{P^\mu P^\nu}{m}A(Q^2) + \frac{iP^{\{\mu}\sigma^{\nu\}\rho}Q_\rho}{2m}J(Q^2) + \frac{Q^\mu Q^\nu - \eta^{\mu\nu}Q^2}{4m}D(Q^2)\right]u(P_1)$$

Form factors parameterize interaction based on symmetry

- accessible experimentally
- mass distribution, gravitomagnetic moment, internal structures

Gravitomagnetic moment

$$\langle P_2|T^{\mu\nu}(Q)|P_1\rangle = \bar{u}(P_2)\left[\frac{P^\mu P^\nu}{m}A(Q^2) + \frac{iP^{\{\mu}\sigma^{\nu\}\rho}Q_\rho}{2m}J(Q^2) + \frac{Q^\mu Q^\nu - \eta^{\mu\nu}Q^2}{4m}D(Q^2)\right]u(P_1)$$

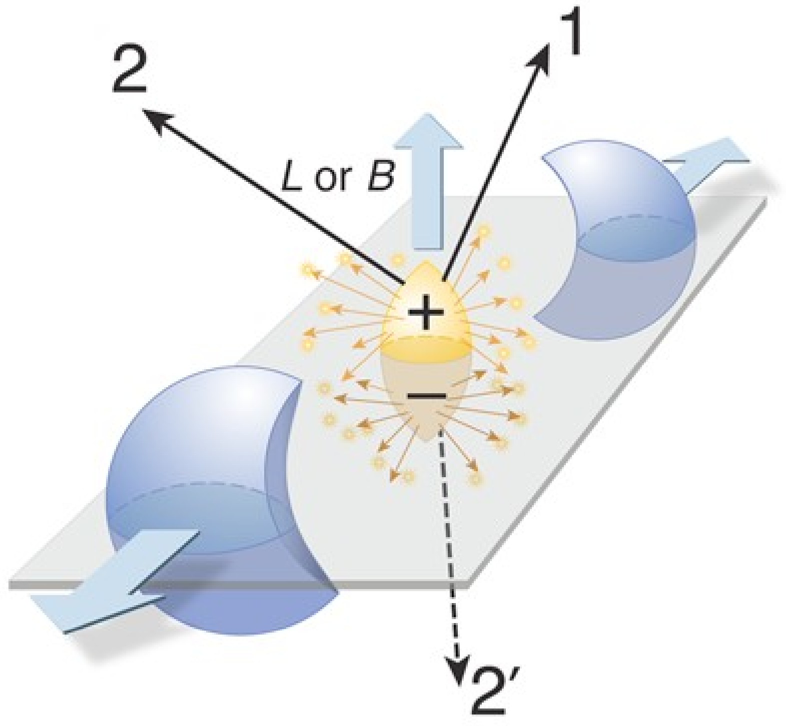
introduce metric perturbation $h_{0i}(t,x) = v_i(t,x)$.

$$i\mathcal{M} \sim \bar{u}(P)\sigma_k u(P) i\epsilon^{ijk} q_j v_i \sim \vec{S}\cdot\vec{\omega}$$

$\vec{S}$ spin $\vec{\omega}$ rotational angular velocity

$J(Q^2 \to 0)$ gravitomagnetic moment

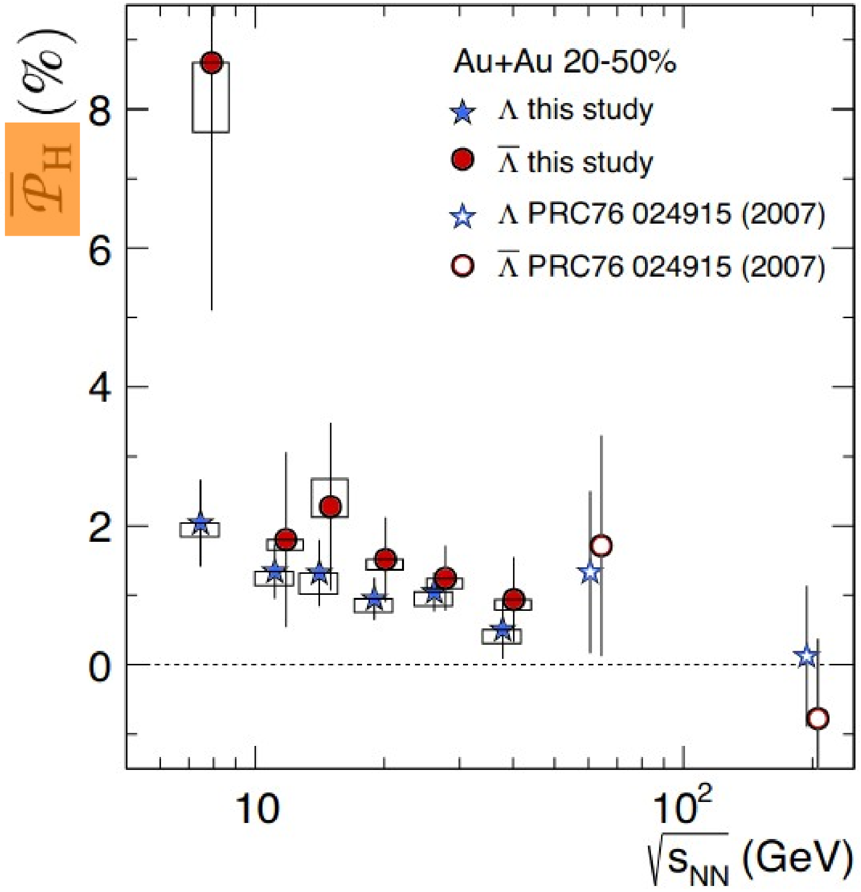
global spin polarization in heavy ion collisions



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

Liang, Wang, PRL 2005, PLB 2005

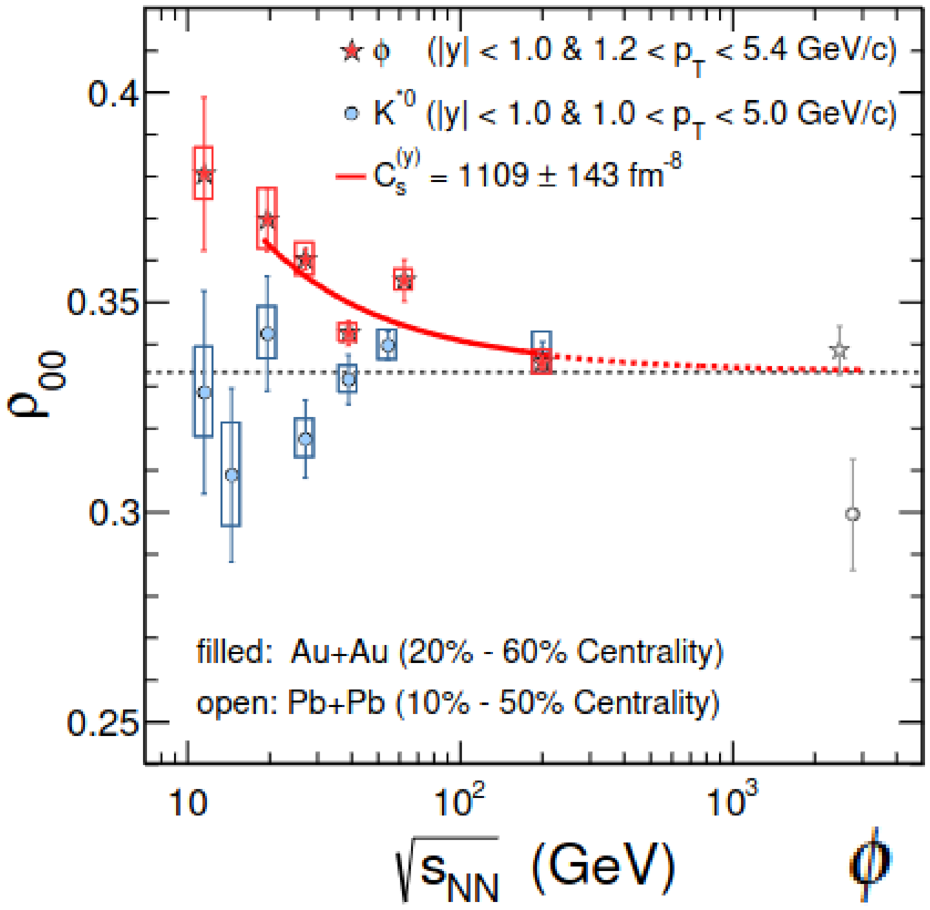
$$S = \frac{1}{2}$$



STAR collaboration, Nature 2017

$$e^{-\beta(H_0 - \mathbf{S}\cdot\omega)}$$

global spin alignment in heavy ion collisions



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STAR collaboration, Nature 2023

$S = 1$

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

vector mesons unpolarized

$\rho_{00} > 1/3$ vector mesons transversely polarized

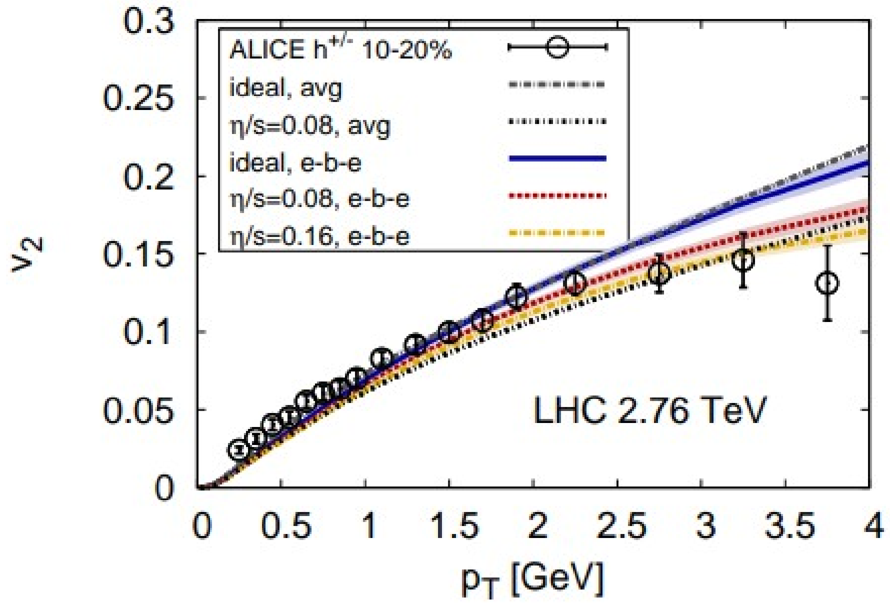
Quantum kinetic theory (QKT): pro and cons

QKT=Boltzmann+spin

Hidaka, Pu, Wang, Yang, PPNP 2022

Pro: systemtic treatment of spin transport

Cons: assumes medium weakly coupled, not well-justified for QGP



kinetic theory: $\frac{\eta}{s} \sim O\left(\frac{1}{g^4}\right) \sim 1.7$ for $\alpha_s = 0.3$

Arnold, Moore, Yaffe 2003

phenomenology $\frac{\eta}{s} \simeq 0.08$

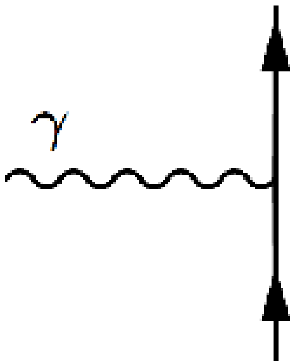
QGP medium might not be weakly coupled

Spin polarization in heavy ion collisions

for $S = \frac{1}{2}$ particle (consider high temperature limit, quark massless)

$$S_i \sim B_i$$

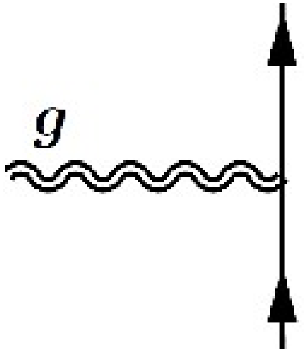
$$S_i \sim \epsilon^{ijk} \hat{p}_j E_k$$



particle in external EM fields

$$S_i \sim \omega_i$$

$$S_i \sim \epsilon^{ijk} \hat{p}_j \hat{p}_l \sigma_{kl}$$



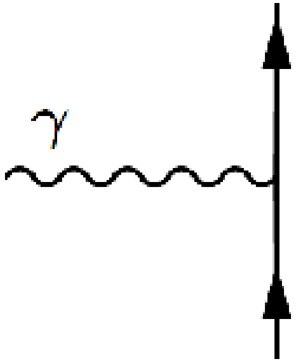
particle in off-equilbrium state: hydro gradient (mimicked by metric fields)

Spin polarization and correlation functions

Wigner function

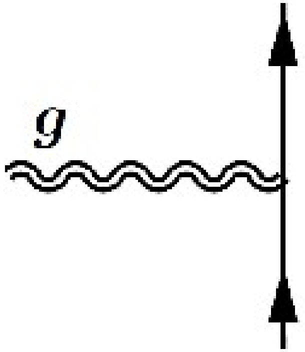
$$S^{<}_{\alpha\beta}(X = \frac{x+y}{2}, P) = \int d^4(x-y) e^{iP\cdot(x-y)/\hbar} \left(-\langle \bar{\psi}_\beta(y)\psi_\alpha(x)\rangle\right)$$

- particle in external EM fields



$$\langle S^{<}(X,P)\rangle_{\text{eq},A_\mu}$$

- particle in off-equilbrium state: hydro gradient



$$\langle S^{<}(X,P)\rangle_{\text{off-eq}} = \langle S^{<}(X,P)\rangle_{\text{eq},h_{\mu\nu}}$$

$A_\mu,\ h_{\mu\nu}$ slow-varying $\partial_X \ll P$

Spin polarization from chiral kinetic theory

right-handed fermion
in EM fields

$$S^<(X=\frac{x+y}{2},P)=\int d^4(x-y)e^{iP\cdot(x-y)/\hbar}U(y,x)\left(-\langle\psi^\dagger(y)\psi(x)\rangle\right)$$

gauge link $U(y,x)=\mathcal{P}\exp[-i\int_x^y dz^\mu A_\mu(z)]$

$$S^< \equiv \bar{\sigma}_\mu S^{<\mu}$$

$$S^{<0}=-2\pi\left[\delta(P^2)p_0 f(p_0)+\mathbf{p}\cdot\mathbf{B}\delta'(P^2)f(p_0)\right]$$

$$S^{<i}=-2\pi\left[\delta(P^2)p_i f(p_0)+\left(p_0B_i-\epsilon^{ijk}P_jE_k\right)\delta'(P^2)f(p_0)\right]$$

absorb e in E&B fields

O(∂^0)

E, B ~ O(∂)

spin-magnetic coupling

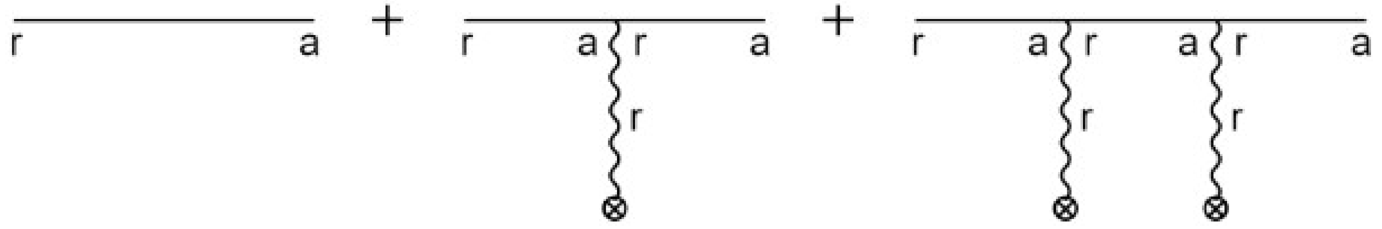
spin Hall effect

Hidaka, Pu, Yang, PRD 2018
Gao, Liang, Wang, PRD 2019

Spin polarization from field theory

$$S^{<\mu} = -(S^{\mu}_{ra} - S^{\mu}_{ar}) f(P_0)$$

$$S_{ra} =$$



$$q \sim \partial_X$$

resummation to all order in A, and up to O(q) reproduces the collisionless CKT results

Two lessons:

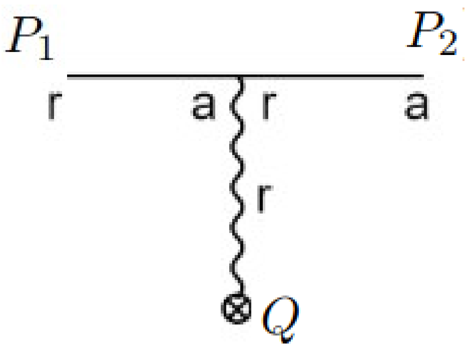
- CKT equivalent to the tree-level vertex (Lorentz invariant)
- Electric field can't do work to fermion (implicit in CKT)

no-work condition $E^{\mu} = F^{\mu\nu} n_{\nu}$ $\quad$ $Q \cdot n = 0$ static $\quad$ n^{μ} spin frame vector

$E \cdot P = 0 \longrightarrow P \cdot Q = 0$ orthogonal

SL, Tian, 2306.14811

EM form factors in vacuum



$$P^2 = 0$$

$$P \cdot Q = 0$$

$$\longrightarrow \quad P_{1,2}^2 \sim O(Q^2)$$

scattering of fermions on EM fields

$$P_i \cdot \bar{\sigma} = u(P_i) u(P_i)^\dagger$$ from massless propagators

$$u(P_2) u^\dagger(P_2) i\sigma^\mu u(P_1) u^\dagger(P_1) A_\mu$$

$$u^\dagger(P_2) i \left(n^\mu + \hat{p}^\mu + \frac{i\epsilon^{\mu\nu\rho\sigma} n_\nu P_\rho Q_\sigma}{2(P \cdot n)} \right) u(P_1)$$

$$Q \cdot n = 0$$

$$P \cdot Q = 0$$

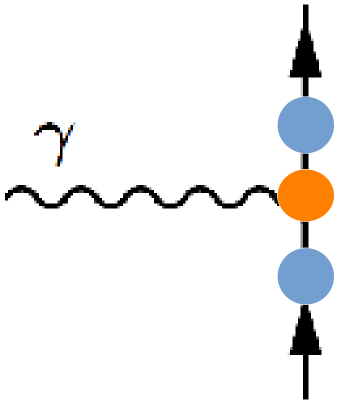
Ward identity satisfied by each structure,
three form factors degenerate

SL, Tian, 2306.14811

What to expect for FF in medium?

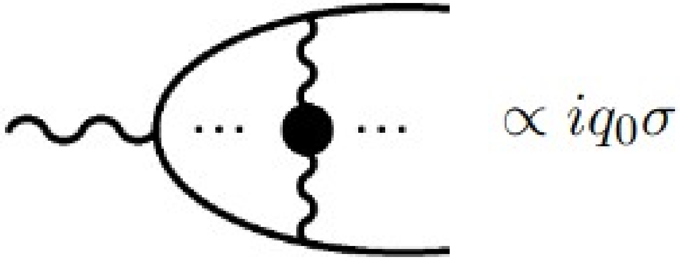
What is in-medium FF?

- parameterize scattering of medium with external fields in medium
- both vertex and fermion states corrected by the medium interaction



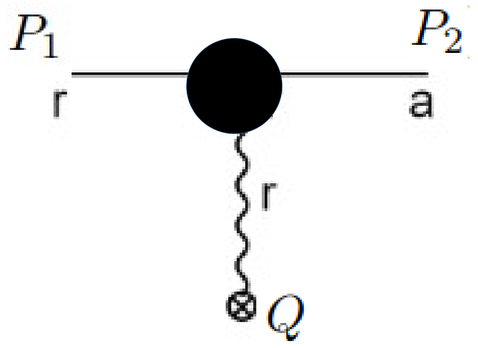
Difference from vacuum FF

- breaking of Lorentz invariance, more structures possible
- dissipation effect introduces non-hermiticity, complex form factors



EM form factors in medium

$n^\mu \to u^\mu$ medium frame vector



$$\Gamma^\mu = F_0 u^\mu + F_1 \hat{p}^\mu + F_2 \frac{i\epsilon^{\mu\nu\rho\sigma} u_\nu P_\rho Q_\sigma}{2(P\cdot u)^2}$$

$$S^{<0} = F_2 \left(\vec{p}\cdot\vec{B}\right) 2\pi\delta'(P^2) f(p_0)$$

$$S^{<i} = \left[F_0 \epsilon^{ijk} E_j p_k + F_1 \left(p_0 B^i - \left(\vec{B}\cdot\vec{p}\right)\hat{p}^i\right) + F_2 \left(\vec{B}\cdot\vec{p}\right)\hat{p}^i\right] 2\pi\delta'(P^2) f(p_0)$$

spin Hall effect

spin-perpendicular magnetic coupling

spin-parallel magnetic coupling

medium interaction can lift the degeneracy of form factors

SL, Tian, 2306.14811

Transformation under time-reversal

$$\Gamma^\mu = F_0 u^\mu + F_1 \hat{p}^\mu + F_2 \frac{i\epsilon^{\mu\nu\rho\sigma} u_\nu P_\rho Q_\sigma}{2(P \cdot u)^2}$$

Γ^0 T-even Γ^i T-odd

→ All form factors T-even

$$Q \cdot n = 0$$
$$P \cdot Q = 0$$

$F_i = F_i(p^2, q^2)$ → All form factors real

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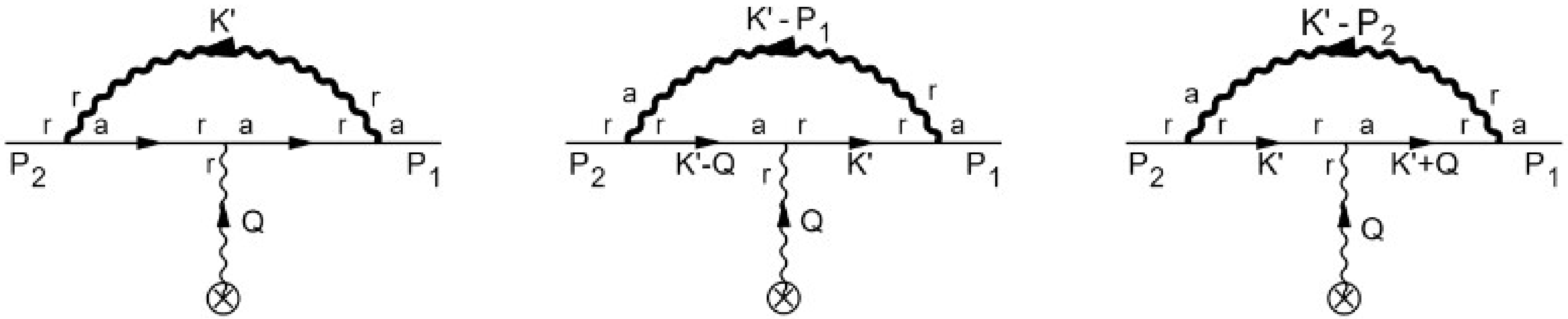
Example of medium correction to EMFF: vertex



$$-2im_f^2 A_\nu \sigma_\lambda \left(\hat{l}^\lambda \hat{l}^\nu \frac{1}{p^2} \ln\frac{2p}{q} + \hat{p}^\lambda \hat{p}^\nu \frac{1}{p^2} - \hat{p}^\lambda P^\nu \frac{1}{p^3} \ln\frac{2p}{q} \right)$$

$$m_f^2 = \frac{1}{8} g^2 T^2 C_F \qquad \hat{l}^i = \frac{1}{pq} \epsilon^{ijk} q_j p_k$$

simplificaitons

- medium contribution only (HTL)
- leading contributions as $q \to 0$

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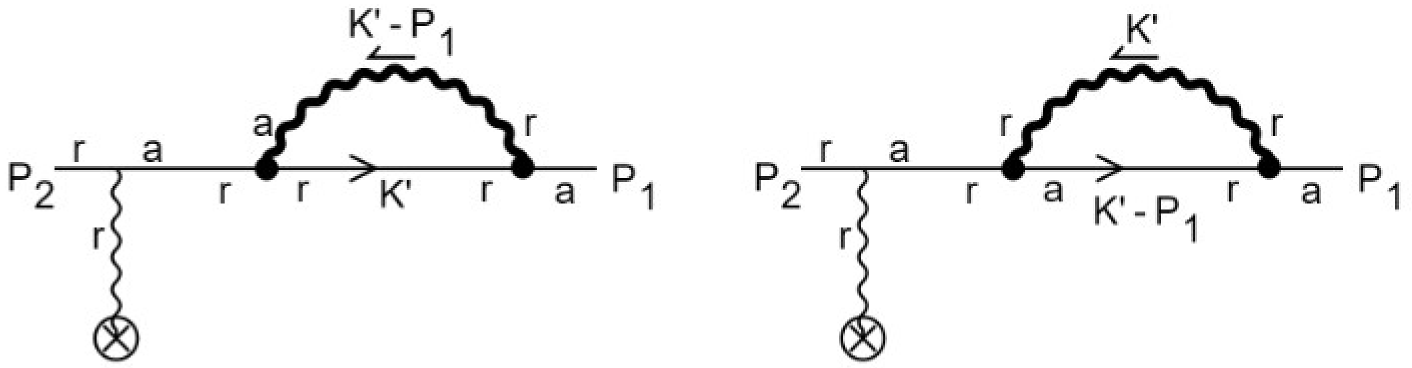
Example of medium correction to EMFF: self-energy



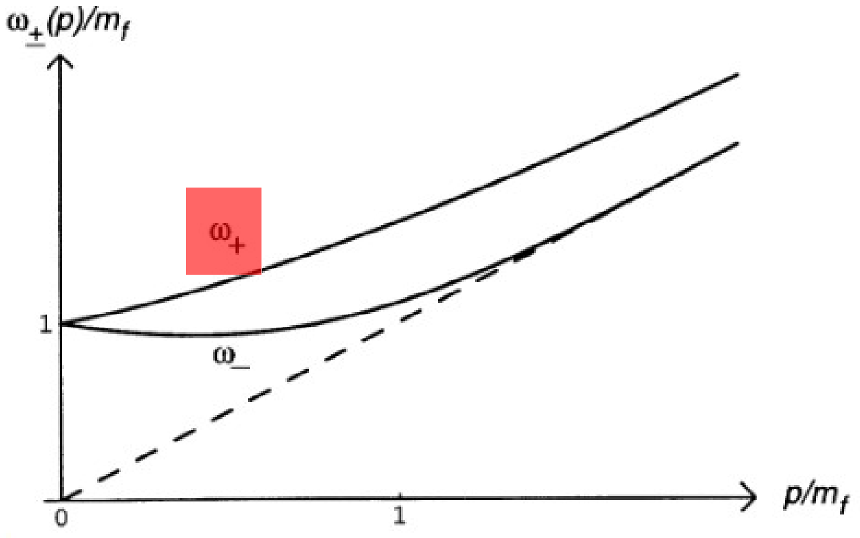
$$S^{ra}(P) = \frac{i}{2}\Delta_+(P)\left(\gamma^0 - \gamma\cdot\hat{p}\right) + \frac{i}{2}\Delta_-(P)\left(\gamma^0 + \gamma\cdot\hat{p}\right)$$

chiral symmetry remains

$$\delta\Gamma^\mu = \delta Z_+ \sigma^\mu$$

$p \gg m_f$:

$$\delta\Gamma^\nu_{self-energy} A_\nu = 2\frac{m_f^2}{2p^2}\left(1 - ln\frac{2p^2}{m_f^2}\right)\sigma^\nu A_\nu .$$



Le Bellac, thermal field theory

Example of medium correction to EMFF: sum

$$\delta F_0 = \frac{2m_f^2}{p^2} X + \frac{m_f^2}{p^2}\left(1 - ln\frac{2p^2}{m_f^2}\right),$$

spin Hall effect

$$\delta F_1 = \frac{2m_f^2}{p^2}(X - 1) + \frac{m_f^2}{p^2}\left(1 - ln\frac{2p^2}{m_f^2}\right),$$

spin-perpendicular magnetic coupling

$$\delta F_2 = \frac{2m_f^2}{p^2} X + \frac{m_f^2}{p^2}\left(1 - ln\frac{2p^2}{m_f^2}\right),$$

spin-parallel magnetic coupling

$$X = \frac{1}{6}\left(2\ln\left(\frac{pT}{m_f^2}\right) + \ln\left(\frac{2pT}{m_g^2}\right) - 36\ln(A) + \ln\left(16\pi^3\right) + 3\right)$$

- all form factors real
- partial lift of the degeneracy $\delta F_1 \neq \delta F_2 = \delta F_0$

Gravitational FF in vacuum

FF for massless case $Q \to 0$ ignore D-term

$$\langle P_2|T^{\mu\nu}(Q)|P_1\rangle = \bar{u}(P_2)\left[A(Q^2)\frac{P^\mu P^\nu}{P\cdot n} \pm B(Q^2)\frac{-iP^{\{\mu}\epsilon^{\nu\}\lambda\sigma\rho}\gamma_\lambda n_\sigma Q_\rho}{P\cdot n}\right]u(P_1)$$

compared to massive case

$$\langle P_2|T^{\mu\nu}(Q)|P_1\rangle = \bar{u}(P_2)[\frac{P^\mu P^\nu}{m}A(Q^2) + \frac{iP^{\{\mu}\sigma^{\nu\}\rho}Q_\rho}{2m}J(Q^2) + \frac{Q^\mu Q^\nu - \eta^{\mu\nu}Q^2}{4m}D(Q^2)]u(P_1)$$

tree-level $T^{\mu\nu} = \frac{i}{2}\bar{\psi}\left(\gamma^{\{\mu}\partial^{\nu\}} - \gamma^{\{\mu}\overleftarrow{\partial}^{\nu\}}\right)\psi$

$\longrightarrow$ $A = 1 \quad B = -\frac{1}{2}$

metric perturbation $h_{0i}(t,x) = v_i(t,x)$

$$i\mathcal{M} \sim \bar{u}(P)\sigma_k u(P) i\epsilon^{ijk}q_j v_i \sim \vec{S}\cdot\vec{\omega}$$

spin-vorticity coupling

SL, Tian, 2302.12450

Gravitational FF in medium

Einstein equivalence principle $B(Q^2=0) = -\frac{1}{2}$

spin-vorticity coupling non-renormalized?

medium breaks Lorentz invariance,
violating equivalence principle!

Donoghue et al 1984, 1985

Buzzegoli, Kharzeev, PRD 2021

SL, Tian, 2302.12450

$$\Gamma^{\mu\nu} = \gamma \cdot \hat{p} \left(F_0 u^\mu u^\nu + F_1 u^{\{\mu} \hat{p}^{\nu\}} + F_2 \hat{p}^\mu \hat{p}^\nu \right) + \gamma \cdot \hat{l} \left(F_3 \hat{p}^{\{\mu} \hat{l}^{\nu\}} + F_4 u^{\{\mu} \hat{l}^{\nu\}} \right)$$

$\hat{l}_i = \epsilon^{ijk} \hat{q}_j \hat{p}_k$ no-work condition $q_0 = 0$ $P \cdot Q = 0$

five structures, each satisfies energy-momentum conservation

Gravitational FF in medium: example

vertex correction

$$\delta\Gamma^{\mu\nu} = m_f^2\Big[-\gamma\cdot\hat{p}P^\mu P^\nu \frac{\ln\frac{2p}{q}}{p^3} - \gamma\cdot\hat{l}P^{\{\mu}\hat{l}^{\nu\}}\frac{\ln\frac{2p}{q}}{p^2} + \gamma\cdot\hat{p}\left(2u^\mu u^\nu + u^{\{\mu}\hat{p}^{\nu\}} + \hat{p}^\mu\hat{p}^\nu\right)\frac{1}{p} + 2\gamma\cdot\hat{l}\hat{l}^{\{\mu}\hat{p}^{\nu\}}\Big]$$

self-energy

$$\delta\Gamma^{\mu\nu} = \delta Z_+\gamma^{\{\mu}P^{\nu\}} \qquad \delta Z_+ = \frac{m_f^2}{2p^2}\left(1 - \ln\frac{2p^2}{m_f^2}\right)$$

Application: spin-vorticity coupling receives multiplicative renormalization

e.g. $p = 500\mathrm{MeV}$ $\quad T = 150\mathrm{MeV}$ $\quad \alpha_s = 0.3$

7% suppression of spin-vorticity coupling

SL, Tian, 2302.12450

Summary

- Spin polarization from CKT reproduced using tree-level field theory, and reformulated with form factors
- Form factors in vacuum generalized to form factors in medium
- In-medium electromagnetic FF lift degeneracy of spin magnetic coupling and spin Hall effect
- In-medium gravitational FF leads to suppression of spin-vorticity coupling

Outlook

- Dissipation effect: complex FF
- Applications to spin polarization in heavy ion collisions

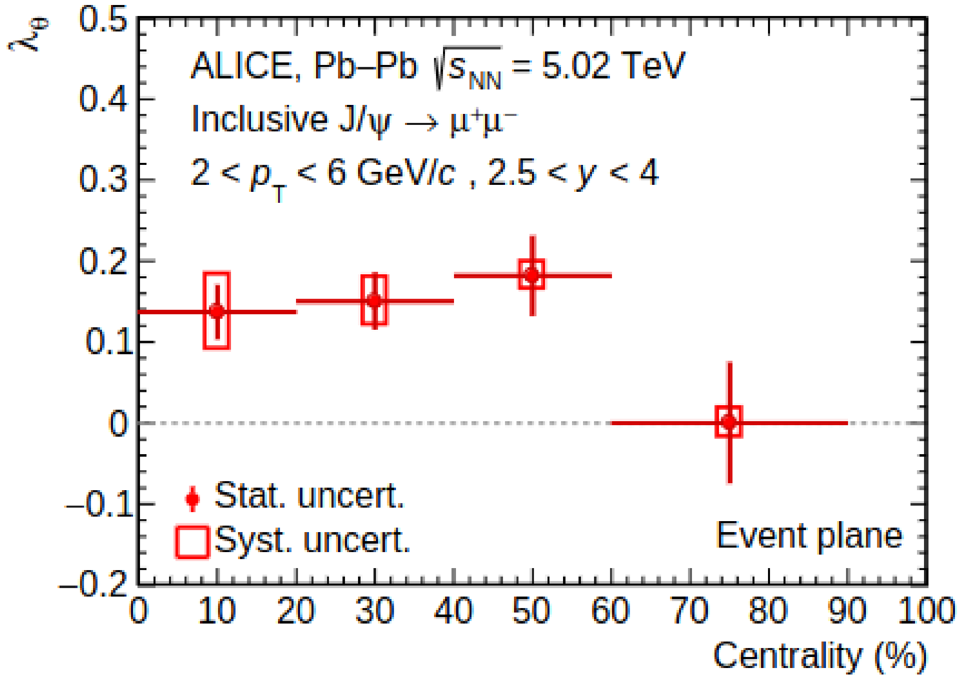
Thank you!

Spin Hall effect

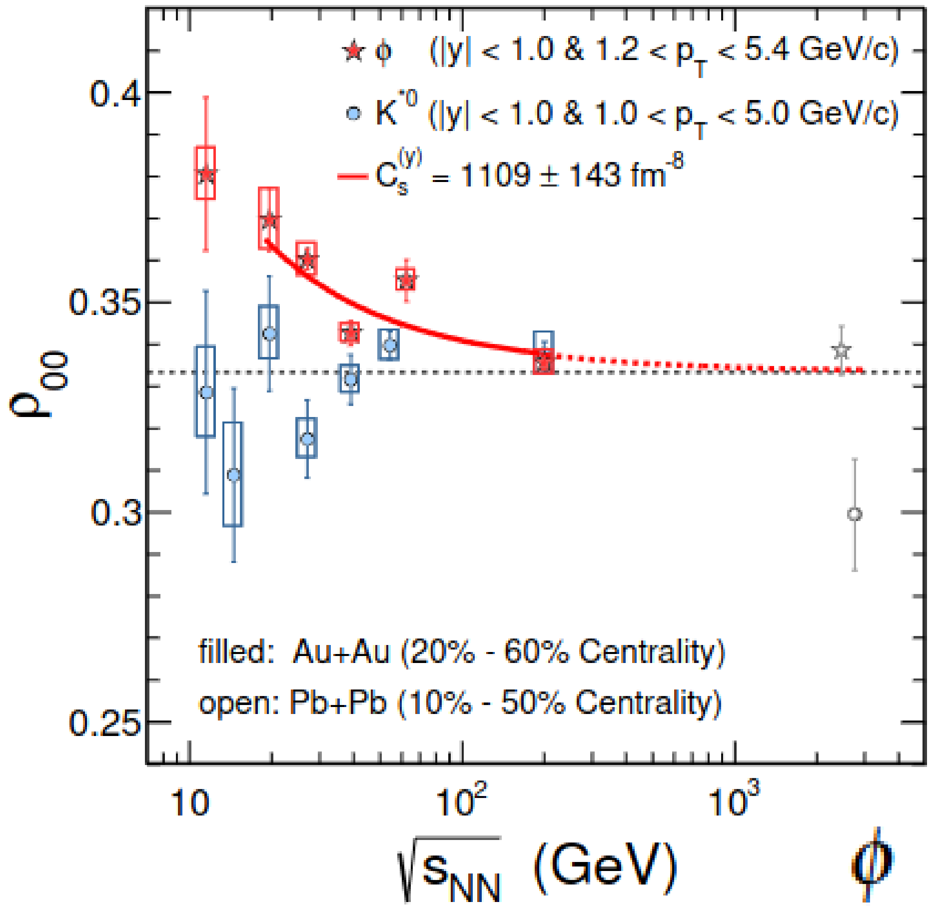
$$\dot{\boldsymbol{x}} = \hat{\boldsymbol{p}} + \dot{\boldsymbol{p}} \times \boldsymbol{b};$$

$$\dot{\boldsymbol{p}} = \boldsymbol{E} + \dot{\boldsymbol{x}} \times \boldsymbol{B}.$$

global spin alignment in heavy ion collisions



$S = 1$



ALICE colloration, PRL 2023 J/ψ

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$\lambda_\theta > 0$
$\rho_{00} > 1/3$
indicates vector mesons transversely polarized

STAR collaboration, Nature 2023