Spin alignment of the ϕ meson in the hadronic phase of the Quark Gluon Plasma

Based on v.C Phys.Re111 (2025) 1, 014914 and 25xx.xxxx

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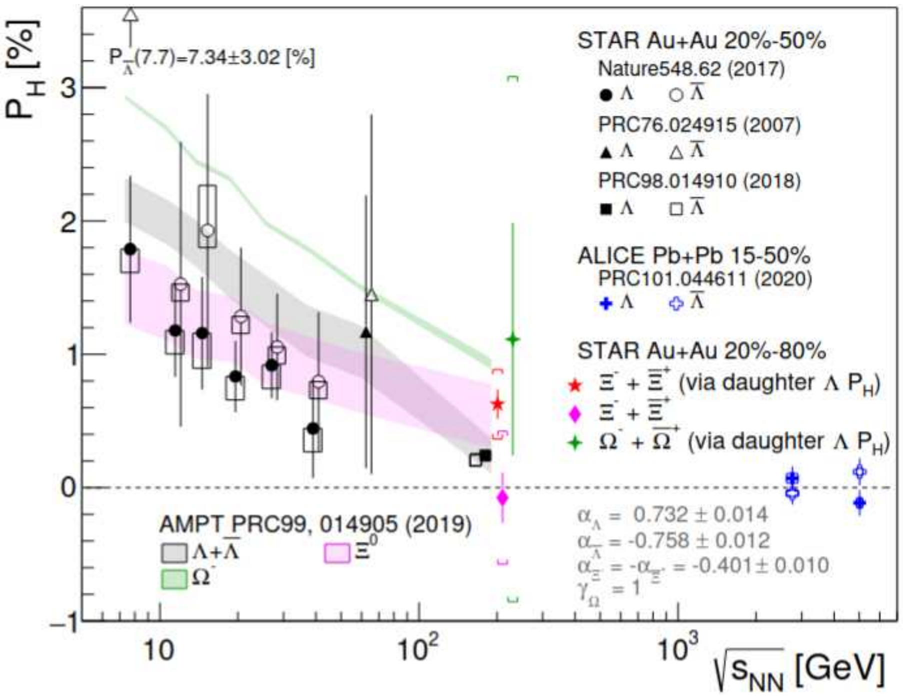
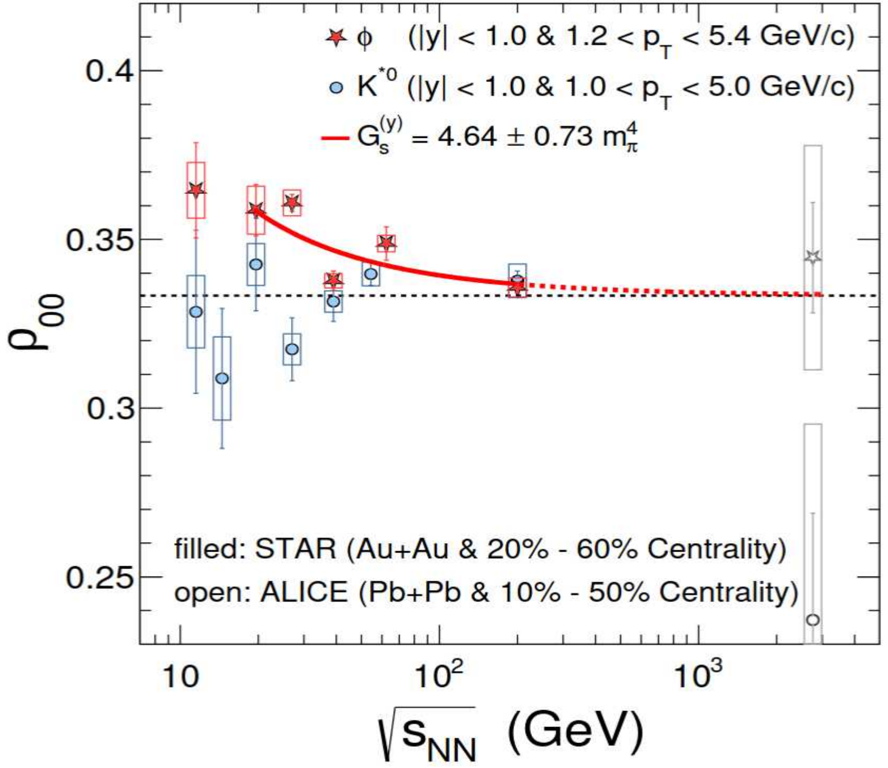
Motivation

Spin vector polarization



STAR Phys.Rev.Lett. 126 (2021) 16, 162301

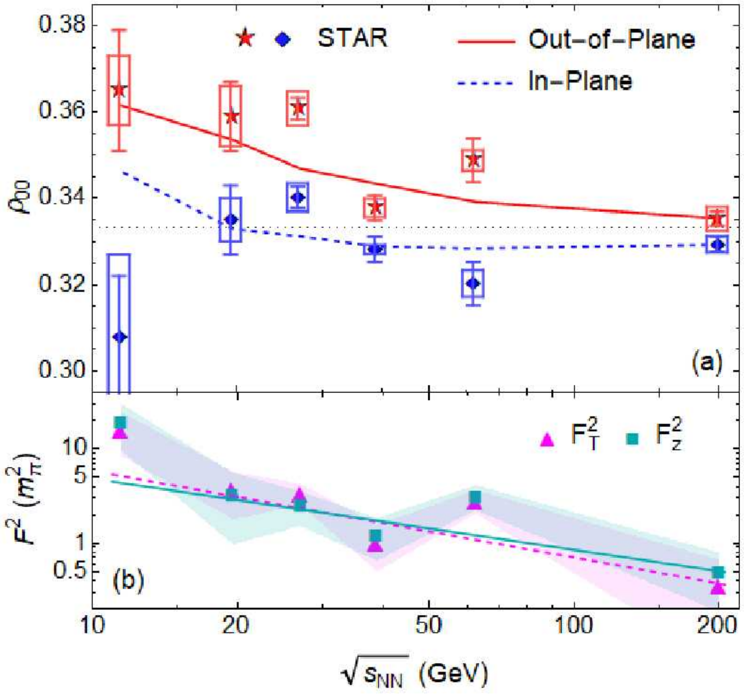
Alignment = spin tensor polarization

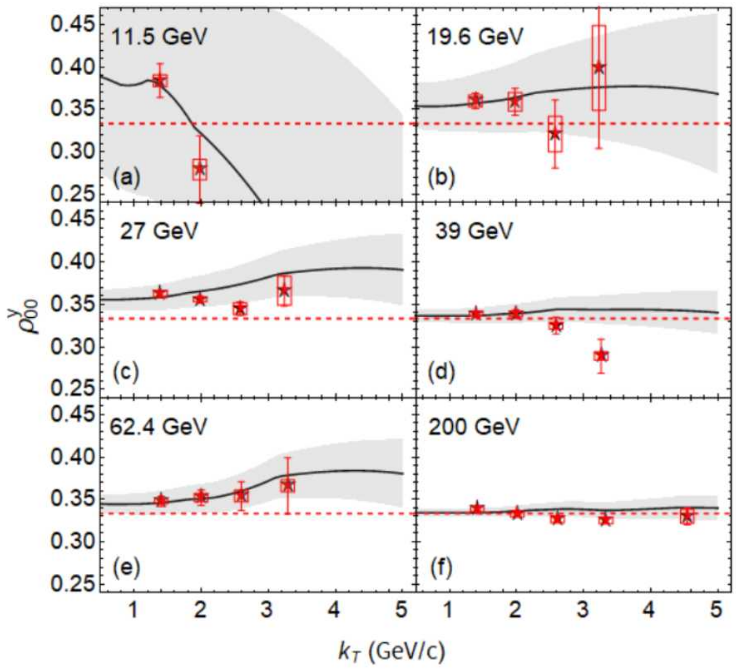


STAR, Nature 614 (2023) 7947

Leading theoretical model: strong force field fluctuations fitted from alignment data (first principle calculations are ongoing, see L. Oliva, QM2025).

Sheng, Oliva, Liang, Wang, Wang Phys.Rev.Lett. 131 (2023) 4, 042304; Phys.Rev.D 109 (2024) 3, 036004, Sheng, Pu, Wang Phys.Rev.C 108 (2023) 5, 054902





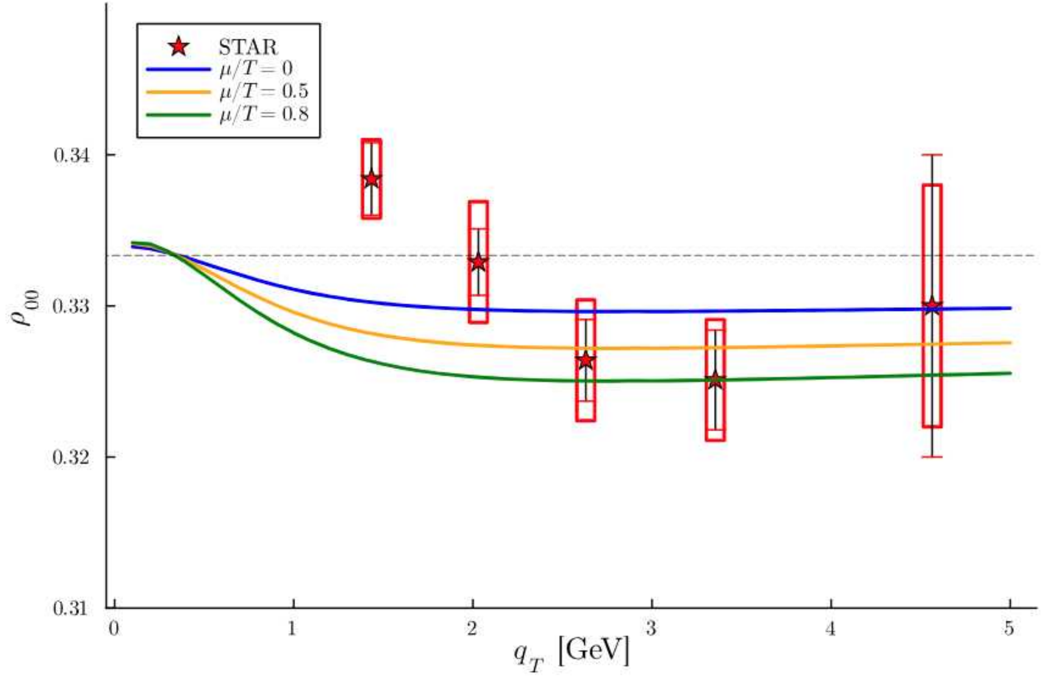
Hydrodynamic evolution of the medium is not taken into account. Independent probes would be desirable.

Results

We compute the polarized ϕ production rate in the hadronic phase, due to interactions with Kaons and dissipation.

We test the model in a Bjorken flow.

Then we take into account scatterings with baryons and the hydrodynamic evolution of the medium.



Grossi, AP, Zahed Phys.Rev.C 111 (2025) 1, 014914

ϕ meson production rate

The number of ϕ mesons produced in the hadronic phase is computed similarly to an electromagnetic rate

$$N_\phi = \sum_{I,F} |\mathcal{M}_{I,F}|^2 \times \frac{e^{-\beta E_I}}{Z} \times \frac{V d^3 q}{(2\pi)^3}$$

$$|\mathcal{M}_{I,F}|^2 = |\langle F\phi|\mathcal{S}|I\rangle|^2$$

With a vector meson-current interaction with strange quarks

$$\mathcal{S} = \int \mathrm{d}^4x \; G_V \phi_\mu \bar{\psi}_s \gamma^\mu \psi_s = \int \mathrm{d}^4x \; G_V \phi_\mu J_s^\mu$$

The meson state can be defined as

$$\langle \phi(q,\sigma)|J_s^\mu|0\rangle = \frac{f_\phi m_\phi \epsilon_\sigma^\mu(q)}{\sqrt{2\varepsilon_q V}}$$

And eventually the production rate reads

$$E_q \frac{\mathrm{d}R_{\sigma\sigma'}}{\mathrm{d}^3 q} = \frac{1}{e^{\beta\cdot q}+1}\frac{G_V^2 f_\phi^2 m_\phi^2}{(2\pi)^3}\epsilon_\sigma^\mu(q)\epsilon^{*\nu}_{\sigma'}(q)\mathrm{Im}\left(iW^F_{\phi\ \mu\nu}(q)\right)$$

With the Feynman propagator

$$W_F(k) = \int \mathrm{d}^4x\, e^{ik\cdot x}\langle T\phi(x)\phi(0)\rangle$$

To compute the thermal propagator, one can organize an expansion in the most abundant stable states.
Steele, Yamagishi, Zahed Phys.Lett.B 384 (1996) 255-262

Dealing with the ϕ meson, the most relevant one are Kaon states, and we consider baryon resonances that may become relevant at larger densities

$$
\begin{aligned}
W^F_{\mu\nu}(q) = &\int \mathrm{d}^4 x e^{iq\cdot x} \langle 0 | T(\phi_\mu(x)\phi_\nu(0)) | 0\rangle \\
&+ \sum_a \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \frac{n_K(k)}{2k^0} \int \mathrm{d}^4 x e^{iqx} \langle K^a(k) | T(\phi_\mu(x)\phi_\nu(0)) | K^a(k)\rangle_{\mathrm{conn.}} \\
&+ \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{n_N(p)}{2p^0} \int \mathrm{d}^4 x e^{iqx} \sum_{spin} \langle N(p,s) | T(\phi_\mu(x)\phi_\nu(0)) | N(p,s)\rangle_{\mathrm{conn.}} + \dots
\end{aligned}
$$

Leading contribution

$$iW_F^{\mu\nu}(q)_0 = i\langle 0|\phi^\mu(q)\phi^\nu(0)|0\rangle = \left(-q^2 g^{\mu\nu} + q^\mu q^\nu\right)\Pi_V^\phi(q)$$

$$E_q \frac{dR^0_{\sigma,\sigma'}}{d^3q} = \delta_{\sigma,\sigma'}\left[\frac{1}{e^{\beta E_q^\phi}+1} G_V^2 f_\phi^2 m_\phi^2 \frac{q^2}{(2\pi)^3} \mathrm{Im}\ \Pi_V^\phi(q)\right]_{q^2=m_\phi^2}$$

Then the spin density matrix is computed

$$\rho_{00}(q_T) = \frac{\int \mathrm{d}\phi \mathrm{d}\eta_q \mathrm{d}^4V\ E_q \frac{\mathrm{d}R_{00}}{\mathrm{d}^3q}}{\sum_{\sigma=-1}^{1} \int \mathrm{d}\phi \mathrm{d}\eta_q \mathrm{d}^4V\ E_q \frac{\mathrm{d}R_{\sigma\sigma}}{\mathrm{d}^3q}}$$

The vacuum spectral function yields an isotropic emission

$$\rho_{00} = 1/3$$

Kaon contribution

We use the reduction scheme developed in Yamagishi and Zahed, Annals Phys. 247, 292, Kamano Phys.Rev.D 81 (2010) 076004

It's based on algebraic properties of broken SU(3) flavor symmetry in QCD

It allows writing ϕ spectral functions on a Kaon state in terms of vacuum spectral functions.

$$\langle K(k)|\phi_\mu(q)\phi_\nu(0)|K(k)\rangle = \frac{G_V^2}{m_\phi^4}\langle K(k)|J^s_\mu(q)J^s_\nu(0)|K(k)\rangle =$$

$$= (g_{\mu\nu}q^2 - q_\mu q_\nu)\,\frac{4}{f_K^2}\,\mathrm{Im}\Pi_V^{88}(q) - (g_{\mu\nu}(k\pm q)^2 - (k\pm q)_\mu(k\pm q)_\nu)\frac{2}{f_K^2}\mathrm{Im}\Pi_A^U(k\pm q)$$

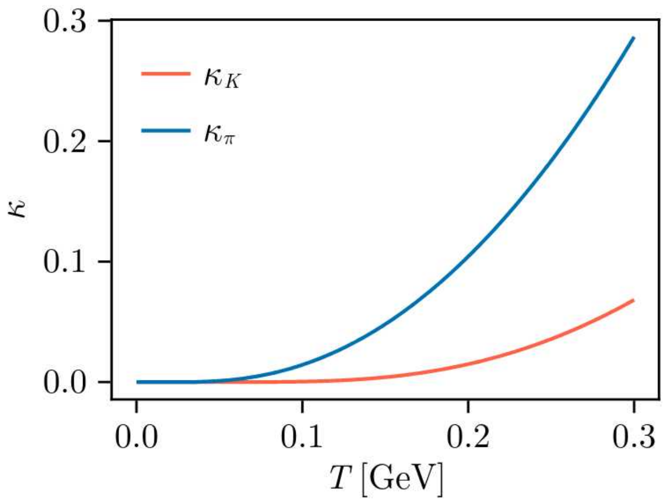
$$+ (2k_\mu + q_\mu)(-k_\nu q^2 + k\cdot q q_\nu)\frac{4}{f_K^2}\mathrm{Re}\Delta_R(k\pm q)\,\mathrm{Im}\Pi_V^{88}(q)$$

The Kaon contribution to the production rate reads

$$\frac{dR^1_{L,\perp}}{d^3q} = \frac{1}{e^{\beta E^\phi_q}+1}\,\frac{G_V^4 f_\phi^2}{m_\phi^2}\,\frac{1}{(2\pi)^3 E^\phi_q}\int \frac{d^3p}{(2\pi)^3}\,\frac{1}{2E^K_p}\,\frac{1}{e^{\beta E^K_p}-1}$$
$$\times\left[\frac{4q^2}{f_K^2}\,\mathrm{Im}\Pi^{88}_V(q) - \left((p\pm q)^2 - |\epsilon_{L,\perp}\cdot(p\pm q)|^2\right)\frac{2}{f_K^2}\,\mathrm{Im}\Pi^U_A((p\pm q))\right.$$
$$\left. - q^2|\epsilon_{L,\perp}\cdot p|^2\frac{8}{f_K^2}\,\mathrm{Re}\,\Delta_R(p\pm q)\,\mathrm{Im}\Pi^{88}_V(q)\right]_{q^2=m_\phi^2}$$

It is suppressed by a “diluteness” factor

$$\kappa = \frac{1}{f_K^2}\int\frac{\mathrm{d}^3k}{(2\pi)^3}\,\frac{1}{e^{\beta\cdot k}-1}$$



Dissipative corrections

Dissipative corrections can be computed in a Zubarev-like fashion

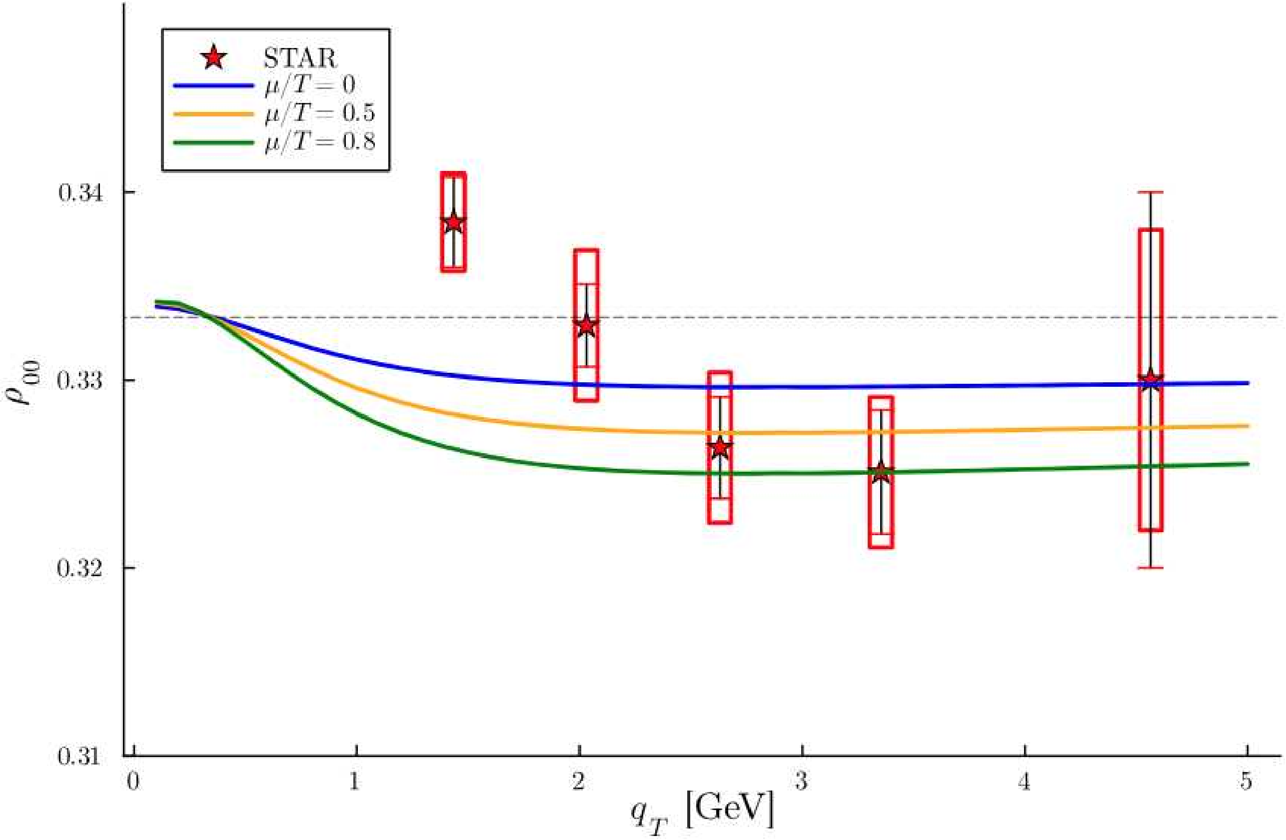
We follow Yiu, Zahed Phys.Rev.D 96 (2017) 11, 116021

$$\rho(t_0) \simeq \left(1 - \partial_\mu \beta_\nu \int_{t_0}^{t} \mathrm{d}t' \int_0^1 \mathrm{d}z \mathrm{d}^3 x T^{\mu\nu}(x, t' + iz\beta)\right) \rho(t)$$

$$\langle \widehat{J}^s_\mu \widehat{J}^s_\nu \rangle \simeq \langle \widehat{J}^s_\mu \widehat{J}^s_\nu \rangle_0 - \int_{t_0}^{t} \mathrm{d}t' \partial_\rho \beta_\sigma \langle \widehat{T}^{\rho\sigma} \widehat{J}^s_\mu \widehat{J}^s_\nu \rangle$$

$$\begin{aligned}\frac{dR^1_{L,\perp}}{d^3q} = & \frac{1}{e^{\beta E^\phi_q} + 1} \frac{G_V^4 f_\phi^2}{m_\phi^2} \frac{1}{(2\pi)^3 E^\phi_q T} \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \frac{1}{2E^K_p} \frac{e^{\beta p\cdot u}}{(e^{\beta p \cdot u} - 1)^2} \frac{p_\mu p_\nu (\frac{\eta}{s}\sigma^{\mu\nu} + \frac{1}{3}\frac{\zeta}{s}\theta\Delta^{\mu\nu})}{p\cdot u} \\ & \times \left[\frac{4q^2}{f_K^2} \mathrm{Im}\Pi^{88}_V(q) - ((p \pm q)^2 - |\epsilon_{L,\perp} \cdot (p \pm q)|^2) \frac{2}{f_K^2} \mathrm{Im}\Pi^U_A((p \pm q)) \right. \\ & \left. - q^2 |\epsilon_{L,\perp} \cdot p|^2 \frac{8}{f_K^2} \mathrm{Re}\,\Delta_R(p \pm q) \,\mathrm{Im}\Pi^{88}_V(q)\right]_{q^2 = m_\phi^2}\end{aligned}$$

Results in a Bjorken flow



The effect is rather small due to the small kaon diluteness.

If Kaons are out-of-equilibrium and there is a Kaon inbalance the effect is enhanced

Grossi, AP, Zahed Phys.Rev.C 111 (2025) 1, 014914, data from STAR, Nature 614 (2023) 7947

Nucleons and resonances

We account for effective interactions with spin ½ baryons

$$\mathcal{L} = -g\bar{\psi}\left(\gamma^\mu \phi_\mu - \frac{i\kappa\sigma^{\mu\nu}}{2m}\partial_\mu\phi_\nu\right)\psi$$

The rate is modified as:

$$E_q \frac{\mathrm{d}R^N_{\sigma\sigma'}}{d^3q} = -\frac{1}{e^{\beta E_q}+1}\frac{G_V^2 m_\phi^2 f_\phi^2}{(2\pi)^3} g^2\left(f(q)\delta_{\sigma\sigma'} + g_{\sigma\sigma'}(q)\right)$$

In the s-channel g vanishes for stable particles, not in the u channel though.

We consider protons, neutrons and N(1880) resonances.

Hydrodynamic Simulation

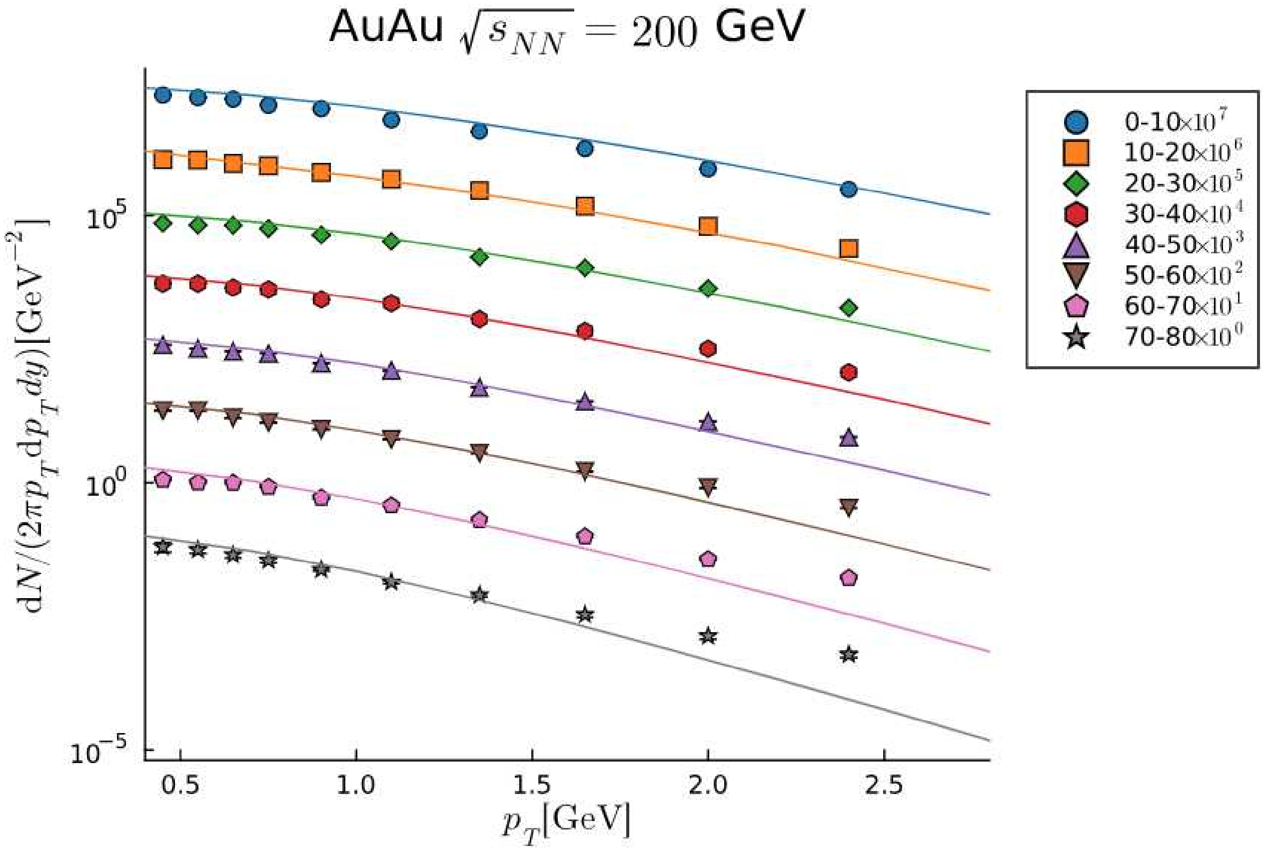
Preliminary results!

We use the code Fluidum, with Trento IC, in 2+1D.

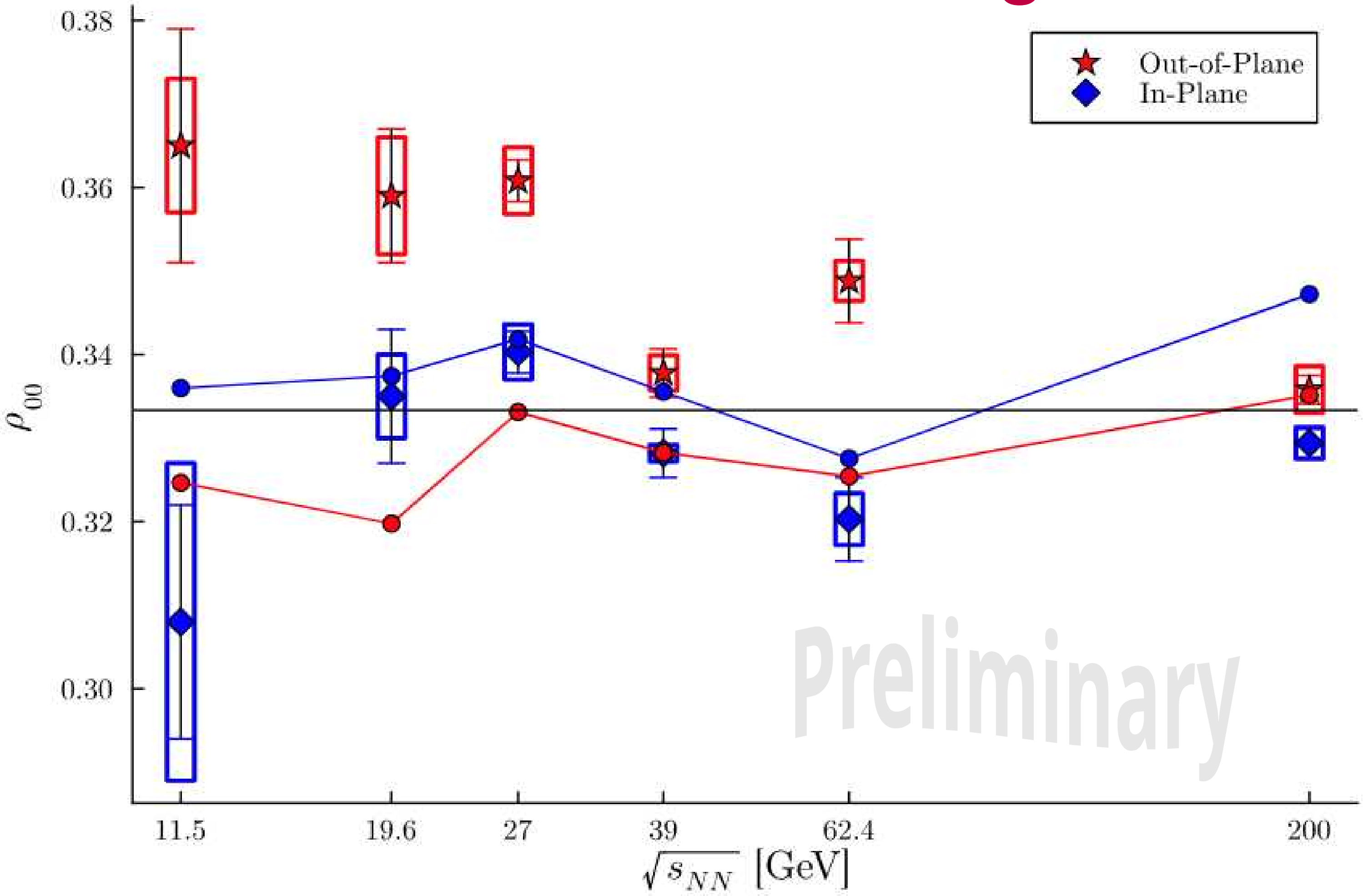
Hadronic phase is assumed to be between T=110 and T=170 MeV.

Integrals are computed over the entire fluid history via Monte Carlo methods.

Spectra are used to fix the coupling constant and the normalization of the initial state

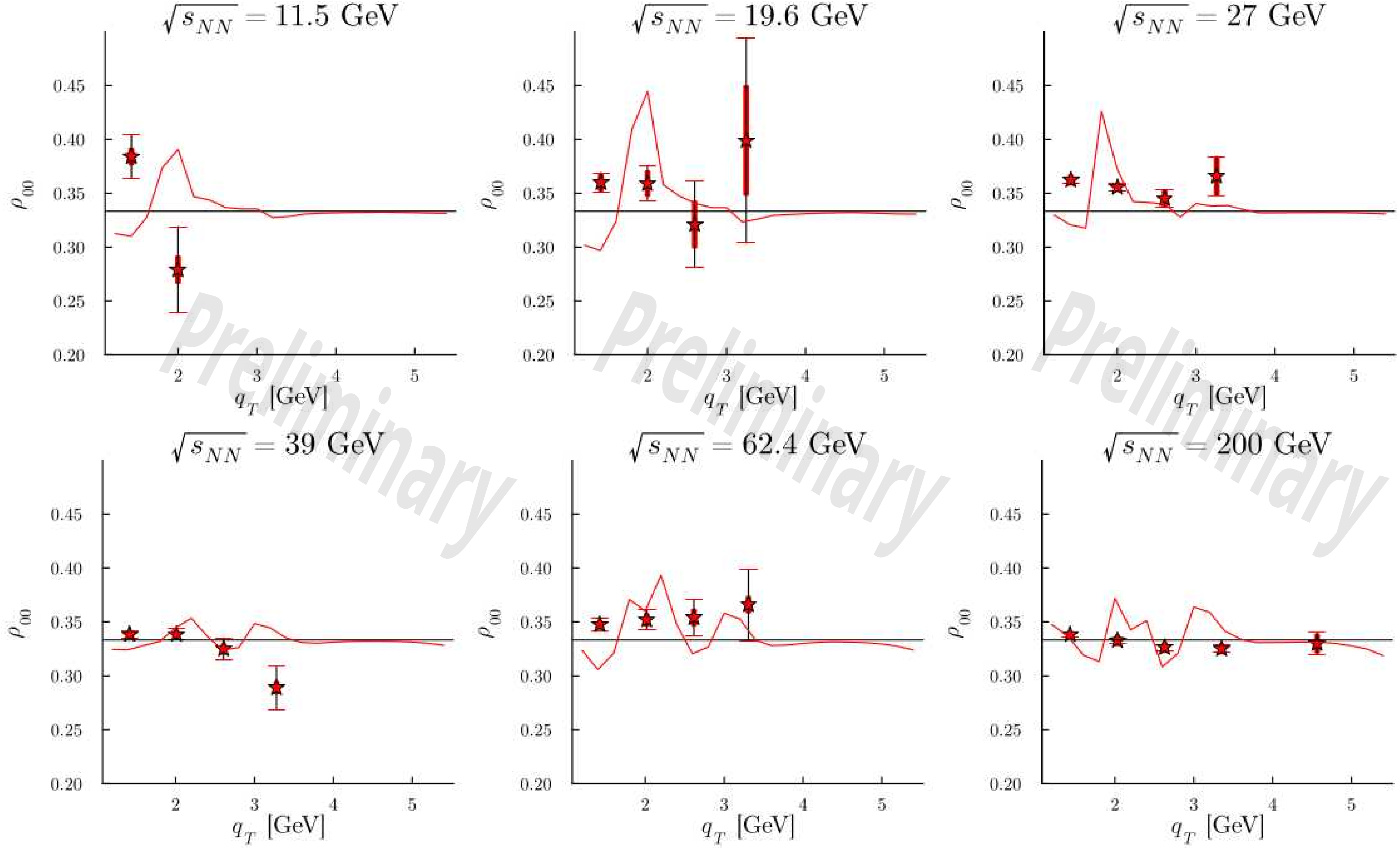


Global alignment



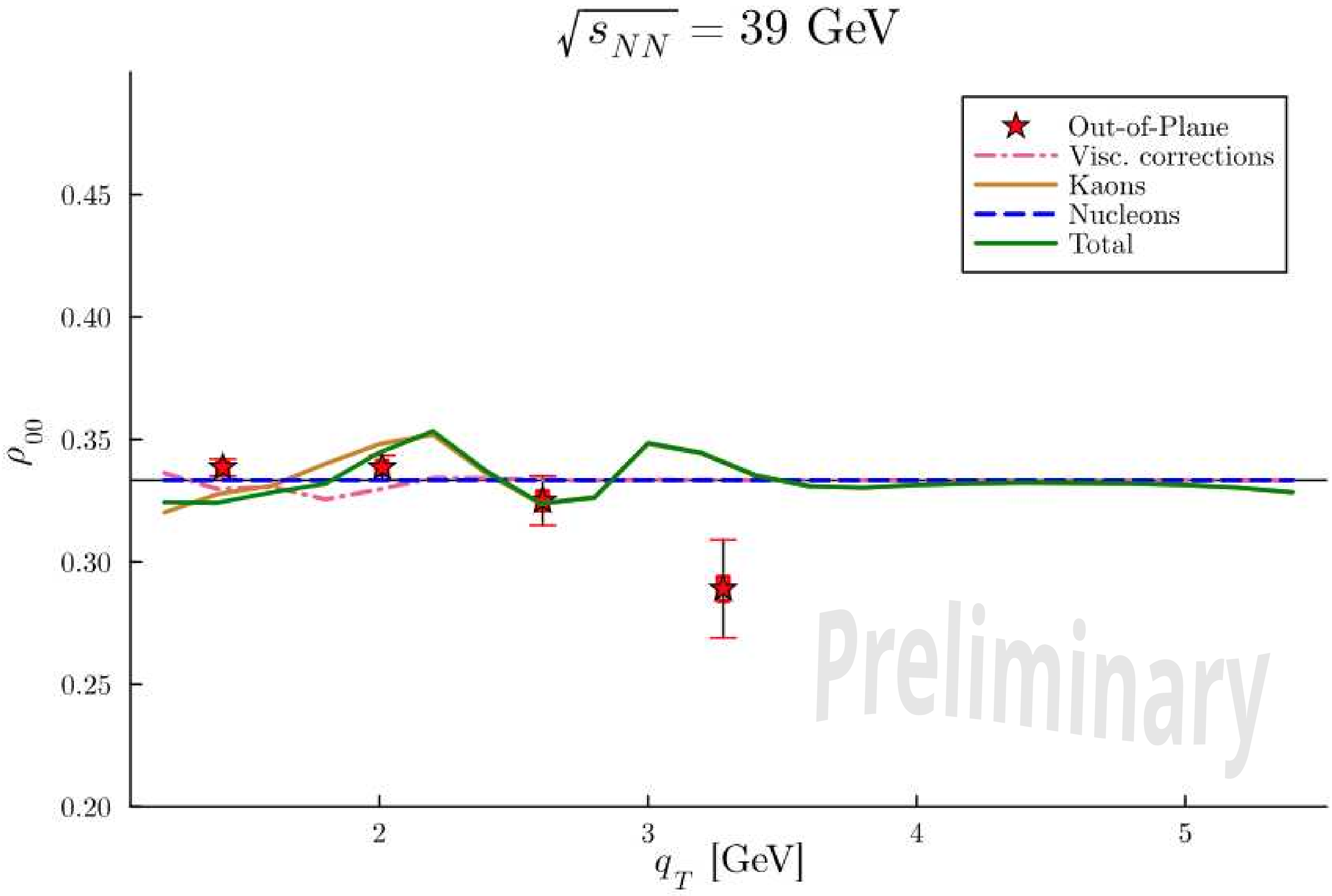
In-Plane alignment qualitatively in agreement.

The model doesn't capture the Out-of-Plane alignment: 3D hydrodynamic needed?


$\sqrt{s_{NN}} = 11.5$ GeV
$\sqrt{s_{NN}} = 19.6$ GeV
$\sqrt{s_{NN}} = 27$ GeV
$\sqrt{s_{NN}} = 39$ GeV
$\sqrt{s_{NN}} = 62.4$ GeV
$\sqrt{s_{NN}} = 200$ GeV
ρ_{00}
0.20
0.25
0.30
0.35
0.40
0.45
2
3
4
5
q_T [GeV]
Preliminary

The leading effect comes from interactions with Kaons

Scattering don't seem to play a significant role



Conclusions and outlook

Emission rate in the hadronic phase can be computed via chiral master formulae for SU(3) flavor symmetry breaking.

Rate are computed on top of 2+1D hydro evolution.

Scattering with nucleons are accounted for but their effect is negligible.

For the ρ meson the approximate flavor symmetry is more accurate. Can one describe its alignment with this method?

The results do not describe out of plane experimental data. Need for 3+1D hydro?

Thanks for the attention!

Backup

Spectral functions

$$\Pi_V^I(q^2) = \frac{f_V^2}{q^2}(\mathbf{F}_V(q^2) - 1) \qquad \Pi_A^I(q^2) = \frac{f_V^2}{m_V^2 - q^2 - im_V\Gamma(q^2)}$$

$$\mathbf{F}_V(q^2) = \frac{m_V^2}{m_V^2 - q^2 - im_V\Gamma(q^2)} \qquad \Gamma(q^2) = \theta(q^2 - M_{BR}^2)\Gamma_0 \frac{m_V}{\sqrt{q^2}}\left(\frac{q^2 - M_{BR}^2}{m_V^2 - M_{BR}^2}\right)^{\frac{3}{2}}$$

$$\Pi_V^{88} = \frac{1}{3}\Pi_V^\omega + \frac{2}{3}\Pi_V^\phi \qquad \Pi_A^U = \Pi_A^{K_1(1270)} + \Pi_A^{K_1(1400)}$$

$$\mathrm{Re}\,\Delta_R(p \pm q) = \frac{\mathrm{PP}}{(p+q)^2 - m_K^2} + \frac{\mathrm{PP}}{(p-q)^2 - m_K^2}$$