Spin alignment of vector mesons in heavy ion and proton - proton collisions

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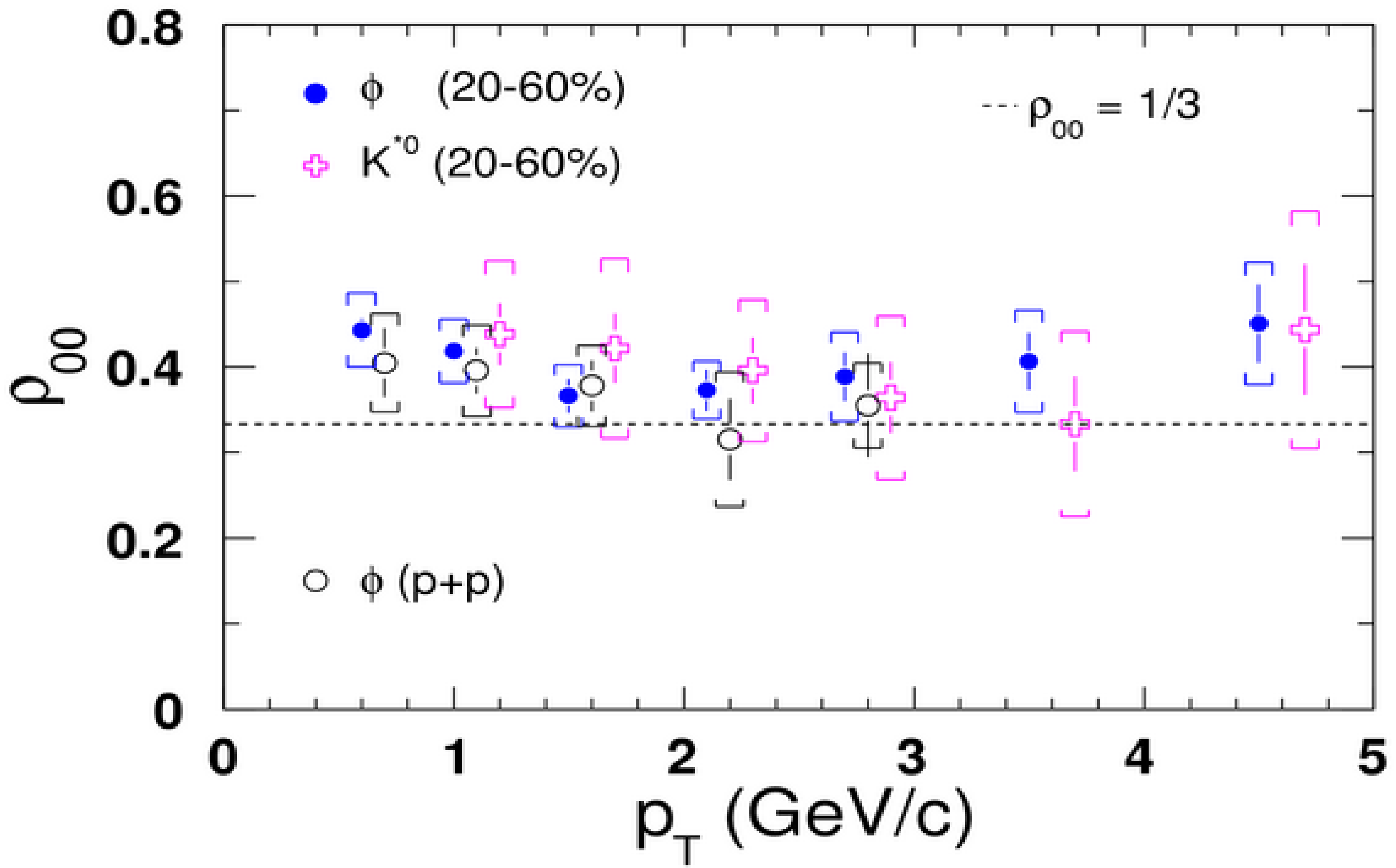
Motivation

Polarization measurements could become an important tool to identify the production of Quark-Gluon Plasma (QGP). Λ^0 *Polarization found at RHIC(Phys. Rev.C 76,024915 (2007): Global polarization measurement in Au+Au collisions)*

A change in polarization as a function of the centrality of the collision, compared to that observed in pp interactions, can be associated in a change in this hyperon's production mechanisms, from ordinary recombination-like processes to quark coalescence. *Same production processes, produce spin alignment of vector mesons like K^{*0}* ***Φ RHIC.***

ρ_{00} vs p_T



K^{*0} and Φ spin may be slightly aligned at low p_T w.r.t. production plane.

J. Phys.G34:s331-s336,(2007); J.Phys.G35:044068,(2008)

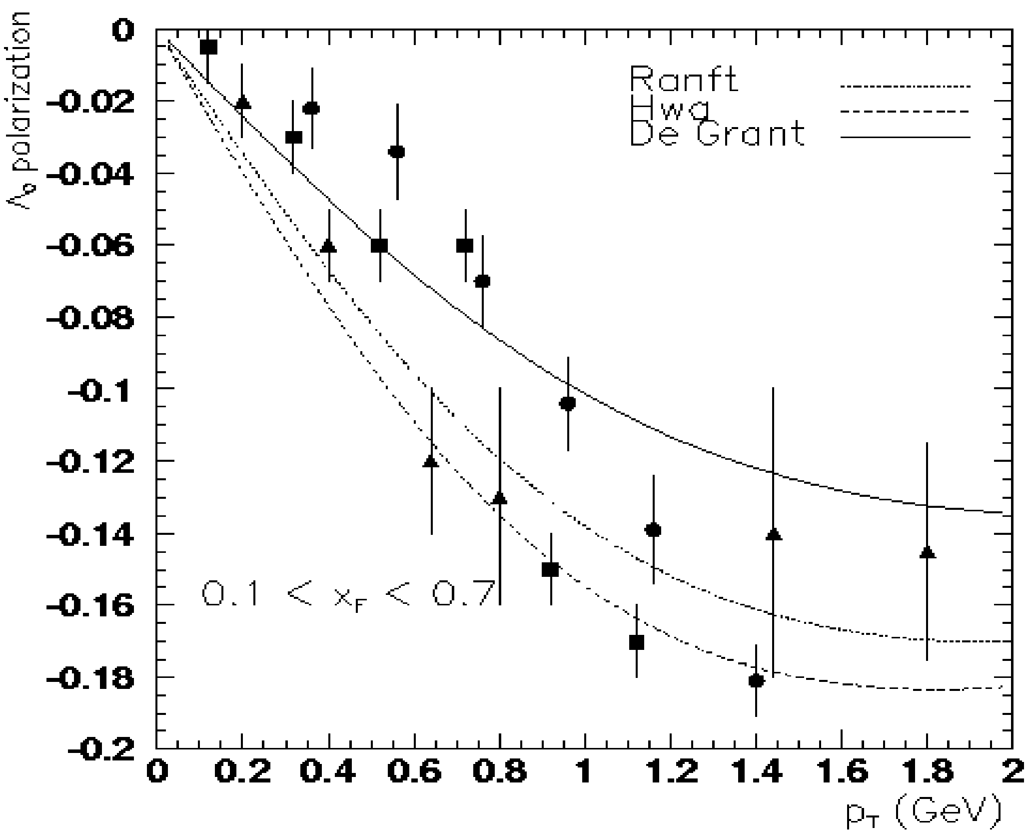
Phy.Rev.C77,061902 (2008)

Semiclassical model for Λ_o Polarization in pp collisions

In pp interactions, it is believed that Λ^o's are produced through the recombination of a sea s-quark and a proton valence diquark.
Models of recombination of quarks to form baryons and mesons at low p_T have been implemented successfully in the context of the parton model

$$\omega_T = \left(\frac{\gamma}{1+\gamma}\right) F x \beta$$

$$P^{s,f} = \pm \left| \frac{\omega_T^{s,f}}{\Delta E} \right|$$



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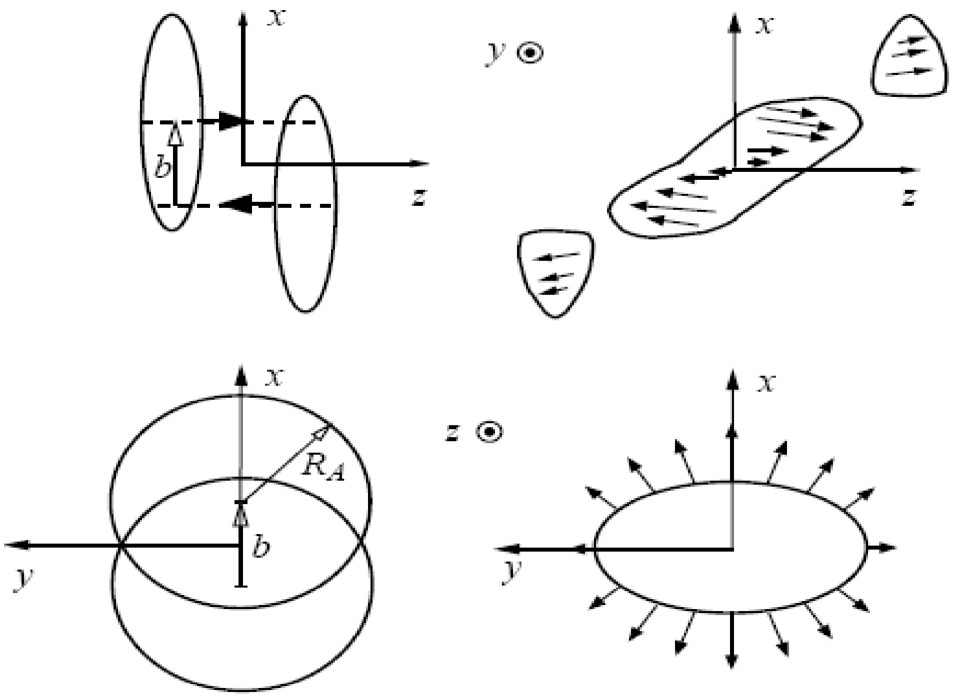
Introduction

- Spin alignment of vector mesons is a unique probe of particle production and dynamics[1,2]

  1. Orbital angular momentum → spin?
  2. Coalescence/Fragmentation of polarized quarks?
  3. Contributions to the significant collective flow observed at RHIC?



1. Z.T. Liang and X.N. Wang, PRL 94 102301 (05), PRL 96 039901 (06), PLB 629 (05) 20-26;
2. S.A. Voloshin nucl-th/0410089.

Spin Density Matrix

For a single s= ½ spin, there is a two dimesional spin state |+> and |-> therefore the spin matrix, given that it must be hermitian and normalized must have the form

$$\rho = \frac{1}{2}\begin{pmatrix} 1+\alpha_z & \alpha_x + i\alpha_y \\ \alpha_x - i\alpha_y & 1-\alpha_z \end{pmatrix}$$

In terms of the Pauli matrices:

$$\rho = \frac{١}{٢}\left(١ + \vec{\alpha}\cdot\vec{\sigma} \right)$$

With eigenvalues

$$1 \pm \frac{|\vec{\alpha}|}{2}$$

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For two quarks system we assume that quarks have an initial longitudinal polarization α, the normalized spin density matrix is:

$$\rho^{q} = \begin{pmatrix} 1+\alpha_{z} & 0 \\ 0 & 1-\alpha_{z} \end{pmatrix}$$

$$\rho^{\bar{q}} = \begin{pmatrix} 1+\alpha_{z}^{\bar{q}} & \alpha_{x}^{\bar{q}}+i\alpha_{y}^{\bar{q}} \\ \alpha_{x}^{\bar{q}}-i\alpha_{y}^{\bar{q}} & 1-\alpha_{z}^{\bar{q}} \end{pmatrix}$$

$$\rho^{q}\otimes\rho^{\bar{q}} = \begin{pmatrix} (1+\alpha_{z}^{q})(1+\alpha_{z}^{\bar{q}}) & (1+\alpha_{z}^{q})(\alpha_{x}^{\bar{q}}+i\alpha_{y}^{\bar{q}}) & 0 & 0 \\ (1+\alpha_{z}^{q})(\alpha_{x}^{\bar{q}}-i\alpha_{y}^{\bar{q}}) & (1+\alpha_{z}^{q})(1-\alpha_{z}^{\bar{q}}) & 0 & 0 \\ 0 & 0 & (1-\alpha_{z}^{q})(1+\alpha_{z}^{\bar{q}}) & (1-\alpha_{z}^{q})(\alpha_{x}^{\bar{q}}+i\alpha_{y}^{\bar{q}}) \\ 0 & 0 & (1-\alpha_{z}^{q})(\alpha_{x}^{\bar{q}}-i\alpha_{y}^{\bar{q}}) & (1-\alpha_{z}^{q})(1-\alpha_{z}^{\bar{q}}) \end{pmatrix}$$

Introduction

- Spin alignment of vector mesons is described by the spin density matrix:

$$\rho_{11} + \rho_{00} + \rho_{-1-1} = 1$$

$$\rho^V = \begin{vmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{vmatrix}$$

→ Any deviation of ρ_{00} from 1/3 manifests the spin alignment of the vector mesons

- We measure ρ_{00} through decayed products angular distribution in the rest frame of vector mesons:

$$\frac{dN}{d\cos\theta} = Norm \times \frac{3}{4} \times [(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta]$$

No need to determine the direction of the reaction plane

SPIN ALIGNMENT:

Three different hadronization scenario :

1) recombine polarized quark and polarized anti-quark;

$$\rho_{00}^{\rho(rec)} = \frac{1-P_q^2}{3+P_q^2} \quad \text{and} \quad \rho_{00}^{K^*(rec)} = \frac{1-P_q P_s}{3+P_q P_s} \quad < \quad 1/3$$

2) recombine polarized q/$\bar{q}$ with unpolarized $\bar{q}$/q;

3) fragmentation of a fast polarized quark/anti-quark.

$$P_q = 0 \text{ or } P_{\bar{q}} = 0, \text{ so } \rho_{00} = 1/3$$

$$\rho_{00}^{\rho(frag)} = \frac{1+\beta P_q^2}{3-\beta P_q^2}, \rho_{00}^{K^*(frag)} = \frac{f_s}{n_s+f_s}\frac{1+\beta P_q^2}{3-\beta P_q^2} + \frac{n_s}{n_s+f_s}\frac{1+\beta P_s^2}{3-\beta P_s^2} > 1/3$$

Our model of vector meson production.

The spin alignment with respect to the production plane is different of zero.
We show that this behavior can be understood in a simple model of vector meson production where the spin of their constituent quarks is oriented during hadronization as the result of Thomas precession.

For central rapidity → $P_{per} >> P_{par}$

$P_{per}^{f} \neq 0 \rightarrow P_{par}^{f} = 0$

$P_{par}^{s} \neq 0 \rightarrow P_{per}^{s} = 0$

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Semiclassical Polarization

In the scenario where the spin of a quark is oriented during the recombination processes. The semiclassical picture is the Thomas precession produced by the accelerating force that pulls a slow moving quark (q^s) to form a fast moving hadron. This mechanism also predict that if a quark is fast (q^f) and is decelerated to form the hadron, its polarization will be of opposite sign compared to the case when it is accelerated. The pulling force is required to not be parallel to the original quark velocity since the Thomas frequency is a vector formed by the cross product of force **F** and velocity β, and γ is the Lorentz factor

$$\omega_T = \left(\frac{\gamma}{1+\gamma}\right) F x \beta$$

And the polarization is given by:

$$P^{s,f} = \frac{\pm \omega_T^{s,f}}{\Delta E}$$

ΔE is the change of energy in the process of hadron formation and w is the Thomas precession frecuency for q^s and q^f

Pull force and Thomas frequency

It should move with an intermediate value of momentum between that of the q^s and q^f the fast quark should slow daown whereas the slow quark should speed up. The pulling force is equal to the change in the momentum ΔP of the given quark, in the interval of time Δt for the recombination process:

$$F = \frac{\Delta P}{\Delta t}$$

$$\omega^{s,f} = \frac{\Delta p^{s,f}}{\Delta t} \beta^{s,f} < \sin\theta >^{s,f} ¿$$

Where the angle is between the quark velocity vector and their corresponding change in momentum.

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Change in momentum of q^s

$$\Delta P^s = \sqrt{(p_{par}^{s/H} - p_{par}^{s})^{2} + (p_{per}^{s/H})^2}$$

To enhance the probability of recombination, the rapidity of q^s has to be within the hadron's one, so:

$$p_{par}^{s} = m_{per}^{s} \sinh(y^H) = \frac{m^s}{m_{per}^{H}} p_{par}^{H}$$

Where $m_{per}^{s} = m^s$ since $p_{pep}^{s} = 0$

$$\Delta p^s \simeq x_{per} \, p_{per}^{H}$$

$$x_{per} = \frac{p_{per}^{s/H}}{p_{per}^{H}}$$

Here we have neglected the longitudinal hadron momentum with respect to its transverse one

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Change in energy

It is common to both the accelerating q^s and the decelerating q^f:

$$\Delta E = p^f_{per}\left(1+\frac{(m^f)^2}{2(p^f_{per})^2}\right)+\sqrt{(p^s_{per})^2+(m^s)^2}-p^H_{per}\left(1+\frac{(m^H)^2}{2(p^H_{per})^2}\right)$$

$$\Delta E = \left(\frac{1-z}{z}\,p^H_{per}\right)+\left(\frac{z(m^f)^2-(m^H)^2}{2\,p^H_{per}}\right)+m\cosh y^H$$

Aproximation for ΔE is such that $p_{per} \geq m^H$ and for $z \leq 1$

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Polarization Φ(1020)

$$P^{s,f} = \pm \left| \frac{\omega_T^{s,f}}{\Delta E} \right|$$

ρ_{00} density matrix element given by

$$\rho_{..} = \frac{1 - P^f P^s}{3 + P^s P^f}$$

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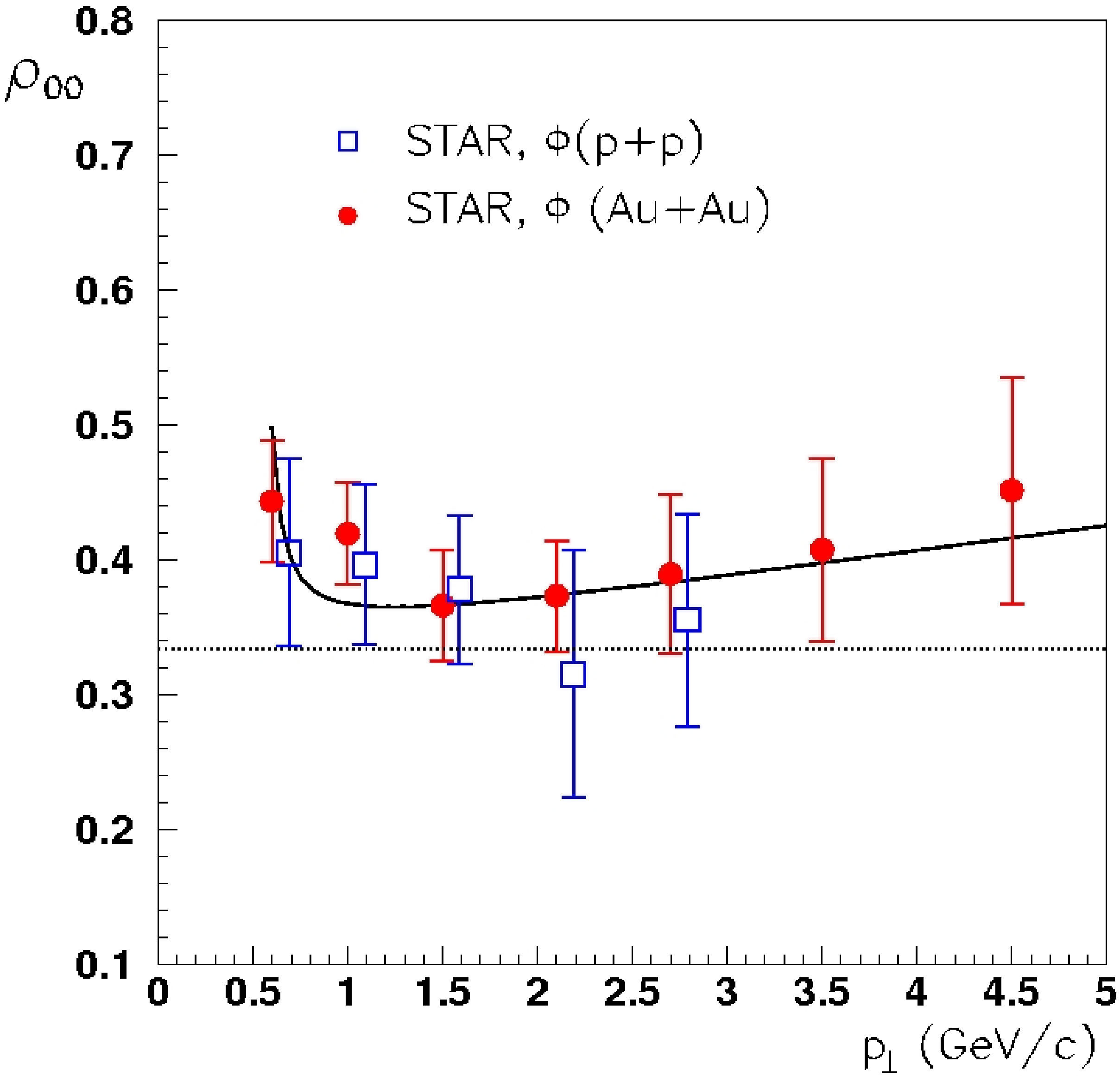
Spin alignment for Φ(1020): model versus STAR data



ρ_{00} as a function of pT for ϕ(1020) using the model, compared to data from STAR for p +p and Au + Au collisions at centrality 20-60 %, measured with respect to the production plane.

For clarity, the pT for p + p data has been displaced by 0.09 GeV with respect to the reported central value. The statistical and systematic errors have been added in quadrature.
For comparison, we also draw the constant value 1/3

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Polarization K^{*0}

$$P^{s,f} = \pm \left(\frac{\omega_T^{s,f}}{\Delta E} \right)$$

ρ_{00} density matrix element given by

$$\rho_{00}^{K*\text{¿}} = \frac{1}{2} \left(\rho_{00}^{f=s,s=d} + \rho_{00}^{f=d,s=S} \right)$$

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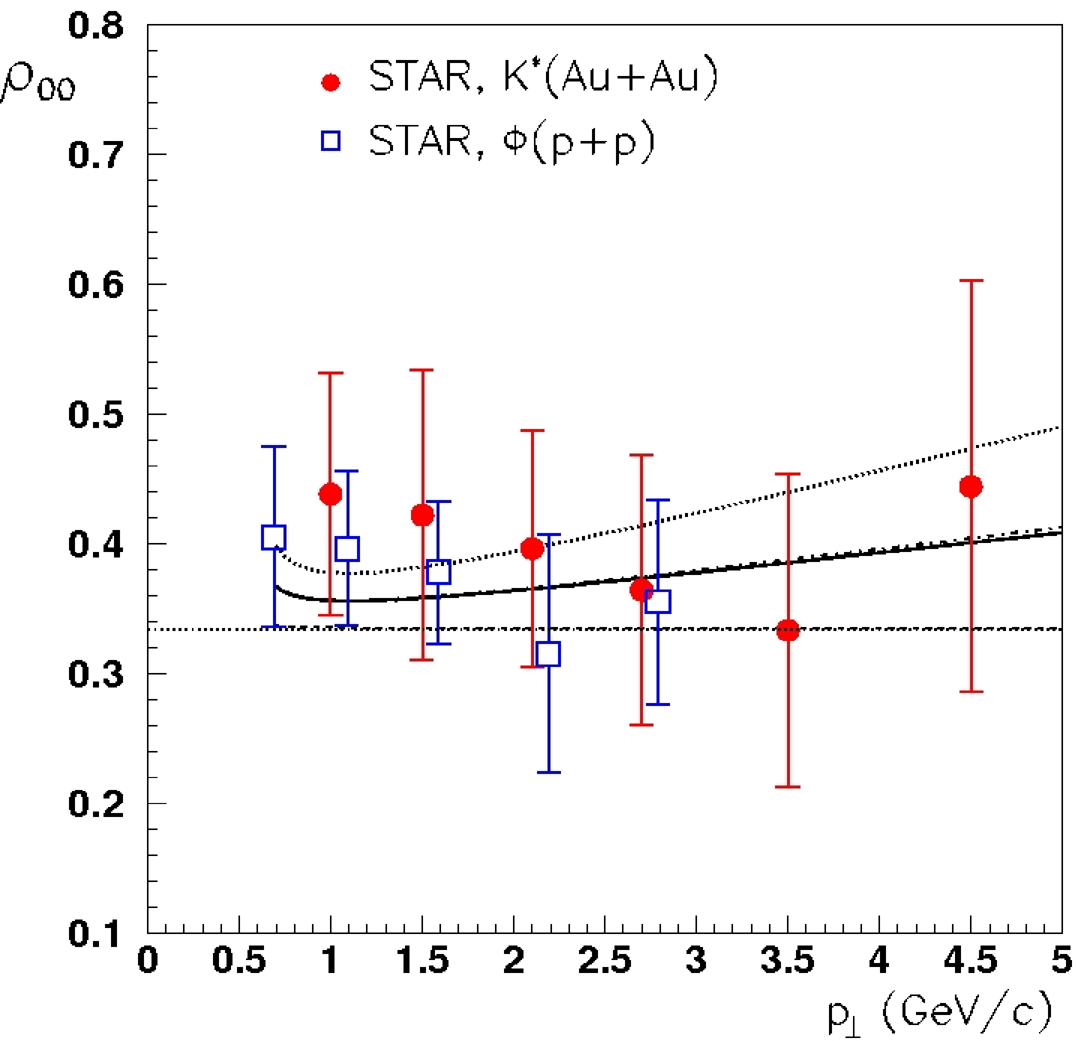
Spin alignment for K*: model versus STAR data.



ρ_{00} as a function of pt for K using the model, compared to data from STAR for p +p and Au + Au collisions at centrality 20-60 %, measured with respect to the production plane.

The upper dashed curve represents the case for ρoo^{f=s, s=d}

Lower dashed curve represents the case for ρoo^{f=d, s=S} . The intermediate solid curve represents ρoo^{K} as the algebraic average of the above.
The intermediate dotted curve represents the case ρoo is computed using the average product of polarizations.

For comparison, we also draw the constant value 1/3 that represents the absence of polarization.

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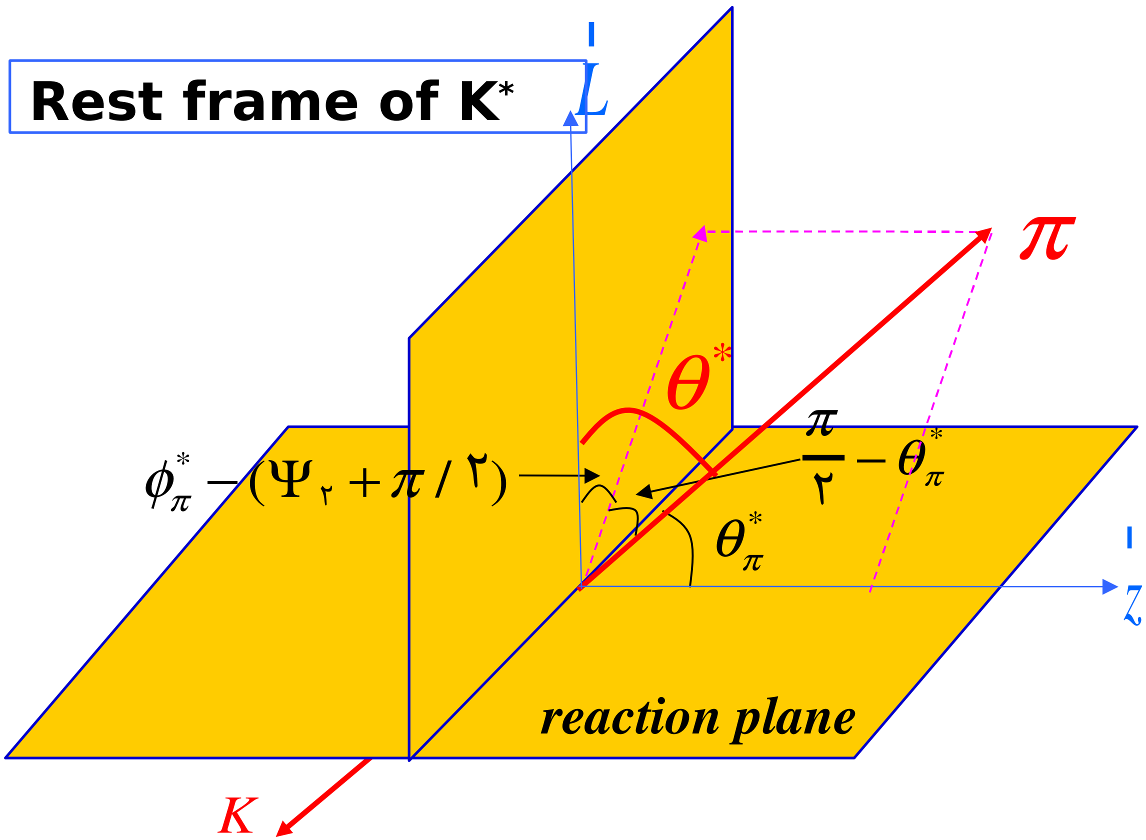
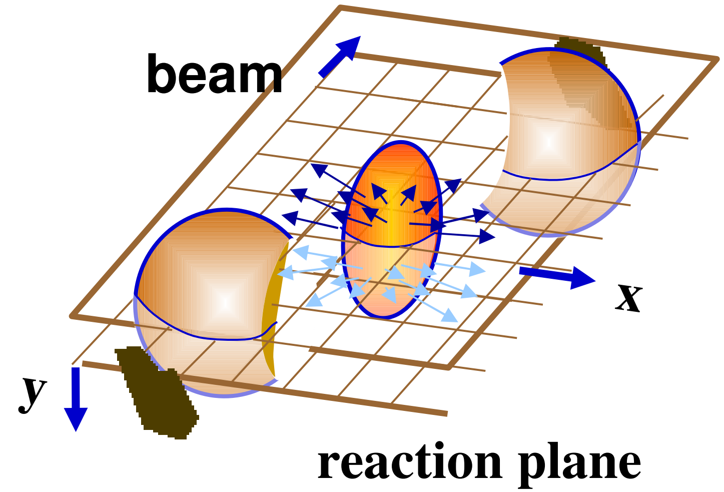
Angle definition





$$\cos\left(\theta^*\right) = \sin\left(\theta^*_\pi\right)\sin(\phi^*_\pi - \Psi_2)$$

$$W\left(\theta\right) = \frac{3}{4}\left[\left(1 - \rho_{00}\right) + (3\rho_{00} - 1)\cos^2\theta^*\right]$$