Single spin effects in collisions of hadrons and heavy ions at high energy

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Outline

- Introduction

- SSA & hadron polarization origin
- Experimental data regularities
- Model predictions
- Summary

Introduction

Spin is a fundamental quantum characteristic of particles, and, at the same time, a powerful tool to study their nature.

$A\uparrow + B \rightarrow C + X$ (study of single-spin asymmetry, $A_N(p_T, x_F, \sqrt{s})$).

$A + B \rightarrow C\uparrow + X$ (study of hadron C polarization, $P_N(p_T, x_F, \sqrt{s})$).

In perturbative QCD single spin effects are small: $A_N \approx \alpha_S m_Q/E_Q \leq 1\%$.

$\alpha_S \approx 0.2 - 0.5$; **current quark mass** $m_Q \approx$ **5-10 MeV;** $E_Q \approx P_T \approx 1$ **GeV/c.**

A new quasi-classical mechanism for the single spin effects is proposed, which is based on the massive constituent quark interaction with an effective chromomagnetic field of color flux tubes (strings). Quark spin precession in the color field is taken into account, which can be the reason of a specific dependence of the A_N **on kinematical variables:** $A_N(p_T, x_F, \sqrt{s})$.

Quark interaction with QCD string (flux tube) field

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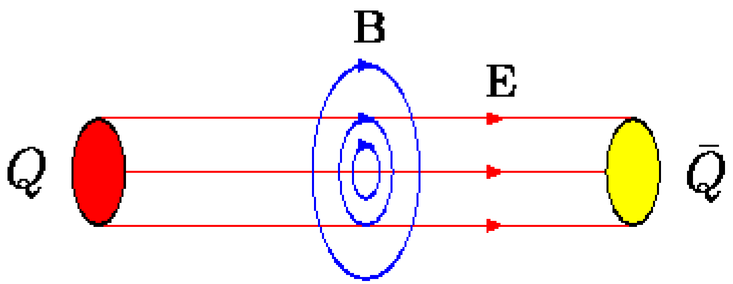
Longitudinal chromoelectric **E**ª and a circular chromomagnetic **B**ª fields of the QCD strings.



Color flux tube fields **B** *and* **E**.
A.B.Migdal, S.B.Khohlachev, 1985

JETP Lett. 41, 194 (1985).

$\mu = sgg_s/2M_Q$ – chromomagnetic constituent quark moment.

Field dependence on the distance *r* from the string axis:

$$E^{(3)}_Z = -2\alpha_s \nu / \rho^2 \exp(-r^2/\rho^2), \quad (1)$$

$$B^{(2)}_\varphi = -2\alpha_s \nu\, r/\rho^3 \exp(-r^2/\rho^2), \quad (2)$$

where ν – number of quarks, $\rho = 1.25 R_C \approx 2.08\ GeV^{-1}$, $R_C^{-1} \approx 0.6$ GeV, R_C – confinement radius, $\alpha_s = g_s^2/4\pi \approx 0.5$;

Stern-Gerlach-like forces act on a quark inside QCD string (flux tube)

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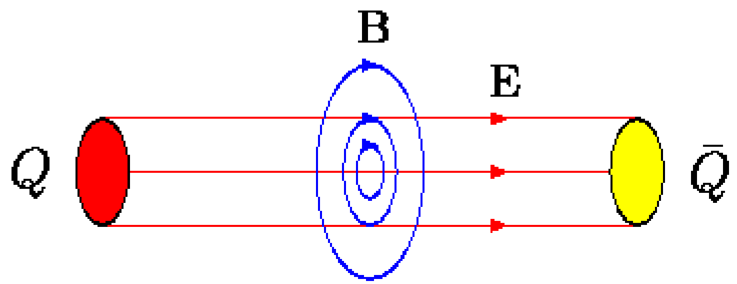
General case of interaction with electromagnetic field: M.Conte et al., ICFA Beam Dyn.Newslett. 24,66(2001).

We assume that similar equations are valid for chromomagnetic field $\mathbf{B}^a$ of the QCD strings:

$$\mathbf{f}_x \approx \boldsymbol{\mu}_x\, \partial \mathbf{B}_x/\partial x + \boldsymbol{\mu}_y\, \partial \mathbf{B}_y/\partial x \qquad (3)$$

$$\mathbf{f}_y \approx \boldsymbol{\mu}_x\, \partial \mathbf{B}_x/\partial y + \boldsymbol{\mu}_y\, \partial \mathbf{B}_y/\partial y \qquad (4)$$



Color flux tube fields **B** *and* **E**.
A.B.Migdal, S.B.Khohlachev, 1985

JETP Lett. 41, 194 (1985).

- **Effective Color Field is a superposition of fields, created by many spectator quarks and antiquarks which are not common with the quarks of the observed (detected) hadron.**

- **SSA is due to the Stern-Gerlach-like forces: (M.Ryskin, 1988)**

Sov. J. Nucl. Phys. 48, 708 (1988).

Quark spin precession in the effective color field of strings

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- **Quark spin ξ Larmore precession in the field $B_\varphi \approx 2\alpha_s vr/\rho^3$:**

$d\xi/dt \approx a[\xi\, B]$ **(BMT-equation, leading term only)** **(4)**

$a = g_s/2M_Q(g - 2 + 2M_Q/E_Q)$ **($M_U \approx M_D \approx 0.35$ GeV)** **(5)**

$\xi_y(S) = \xi_y^0\, [\cos(kS)(B_x/B)^2 + (B_y/B)^2]$, **(6)**

where S – quark path length, $k = aB/v$, $dS = v\,dt$, $v \approx c = 1$.

$\mu_a = (g-2)/2$ **(color anomalous dipole quark moment)** **(7)**

- **Instanton model: $\mu_a \approx -0.2$ (Kochelev); $\mu_a \approx -0.74$ (Diakonov)**

In QED $\mu_a \approx +\alpha/2\pi$; in pQCD $\mu_a \approx -\alpha_S/6\pi$ (non-abelian).

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Quark spin precession in the effective color field of strings

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Integration of Stern-Gerlach force over a quark trajectory length *S* and field volume gives additional spin-dependent transverse momentum P_T (spin precession eq. (6) is assumed):

$$\delta P_x \approx gv[1-\cos(kS)]/\{2\rho kS(g - 2 + 2M_Q/E_Q)\}, \qquad (8)$$

where $k = aB/v$, $a = g_s/2M_Q(g - 2 + 2M_Q/E_Q)$.

It is assumed also that the angle $kS = \omega_A x_A \equiv \omega_A(x_R + x_F)/2$ (9)

$$A_N \approx \delta P_x \, \partial/\partial p_T \ln(d^3\sigma/d^3p); \quad \text{(Ryskin, 1988)} \qquad (10)$$

In Ryskin's model $\delta P_x \approx 0.1$ GeV is a constant and A_N dependence on X_F is due to competition of spin-dependent and spin-independent processes with different X_F-dependences.

- In the effective color field model we have dynamical origin of A_N dependence on scaling variable x_A and on quantum numbers of quarks in hadrons A, B, C, in particular on g–factor and M_Q.

Polarization effects in the string field

Equations (8)-(10) are generalized to take into account the interchange A↔B symmetry consideration and suppression of spin effects at very low and very high P_T, as well as its threshold behavior as a function of kinematical variables:

V.V.Abramov, Eur.Phys.J.C 14, 427(2000); hep-ph/0111128; Physics of Atomic Nuclei 68, 385 (2005); Preprint IHEP 2006-23.

$$A_N \approx C(\sqrt{s})V(E_{cm})F(P_T,A)[G(y_A\omega_A) - \sigma(\theta_{cm})G(y_B\omega_B)]; \qquad (11)$$

$$G(X) = [1 - \cos(X)]/X; \quad \text{-due to spin precession and S-G force} \qquad (12)$$

$$y_A = x_A - (E_0/\sqrt{s} + f_A)[1 + \cos(\theta_{cm})] + a_0[1 - \cos(\theta_{cm})] \qquad (13)$$

$x_A = (x_R + x_F)/2$ – scaling variable 1

$$y_B = x_B - (E_0/\sqrt{s} + f_B)[1 - \cos(\theta_{cm})] + a_0[1 + \cos(\theta_{cm})] \qquad (14)$$

$x_B = (x_R - x_F)/2$ – scaling variable 2

Polarization effects in the string field

$$A_N \approx C(\sqrt{s})V(E_{cm})F(P_T,A)[G(y_A\omega_A) - \sigma(\theta_{cm})G(y_B\omega_B)\ ]; \qquad (11)$$

$$\sigma(\theta_{cm}) = \chi \sin(\theta_{cm}) + \varepsilon; \qquad (\sigma=1 \text{ for } A\equiv B) \qquad (15)$$

- $C(\sqrt{s}) = C_0/(1 - E_R/\sqrt{s}\ );$ $\quad (2M_Q/E_Q/(g\text{-}2) \sim E_R/\sqrt{s}\ );$ (16)

$V(E_{cm}) \approx \pm\,\Theta(E_{cm} - E_{cm}^{Th})$, where E_{cm} –hadron energy in c.m. (17)

$F(P_T,A) = \{1 - \exp[-(P_T/d_0)^3\ ]\}(1 - \eta \ln A)$ – P_T and A-dependence.

Phenomenological parameters **(N=12): ω_A, ω_B, a_0, E_0, C_0, E_R, χ, ε, η, f_A, f_B, d_0**. In case of **A≡B** we have **$\omega_A=\omega_B$, $f_A=f_B$, $\chi=0$, $\varepsilon = 1$.**

- Eq. (11) predicts oscillation of A_N or P_N as a function of scaling variable y_A (y_B) with frequency ω_A (ω_B) which depends on quantum numbers of hadrons A, B, C, and reaction energy $\sqrt{s}$. In the case of heavy ion collisions it depends also on a projectile A atomic number.

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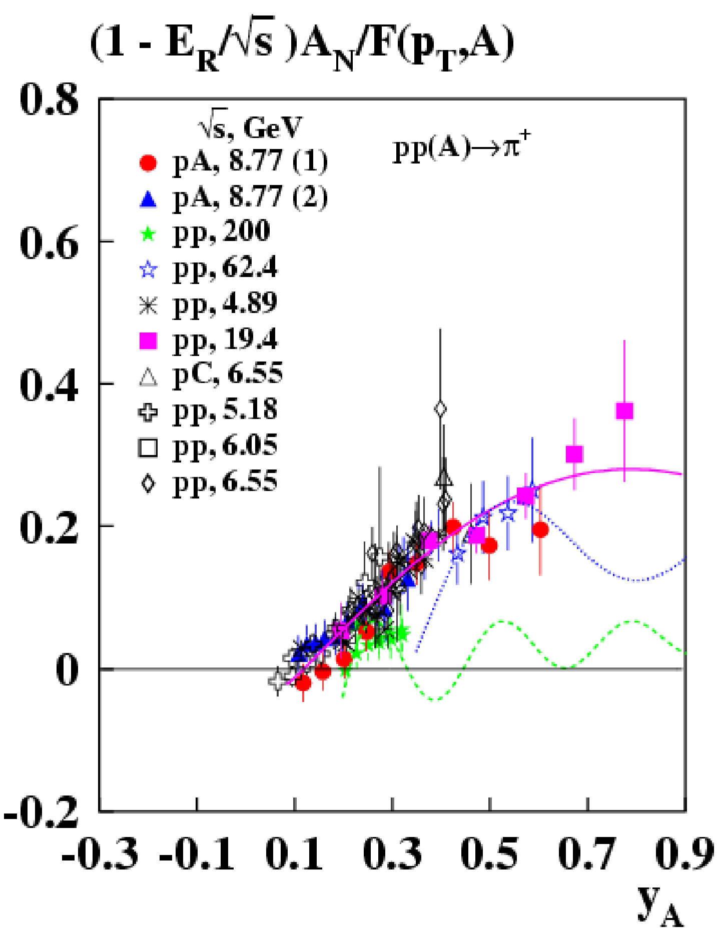
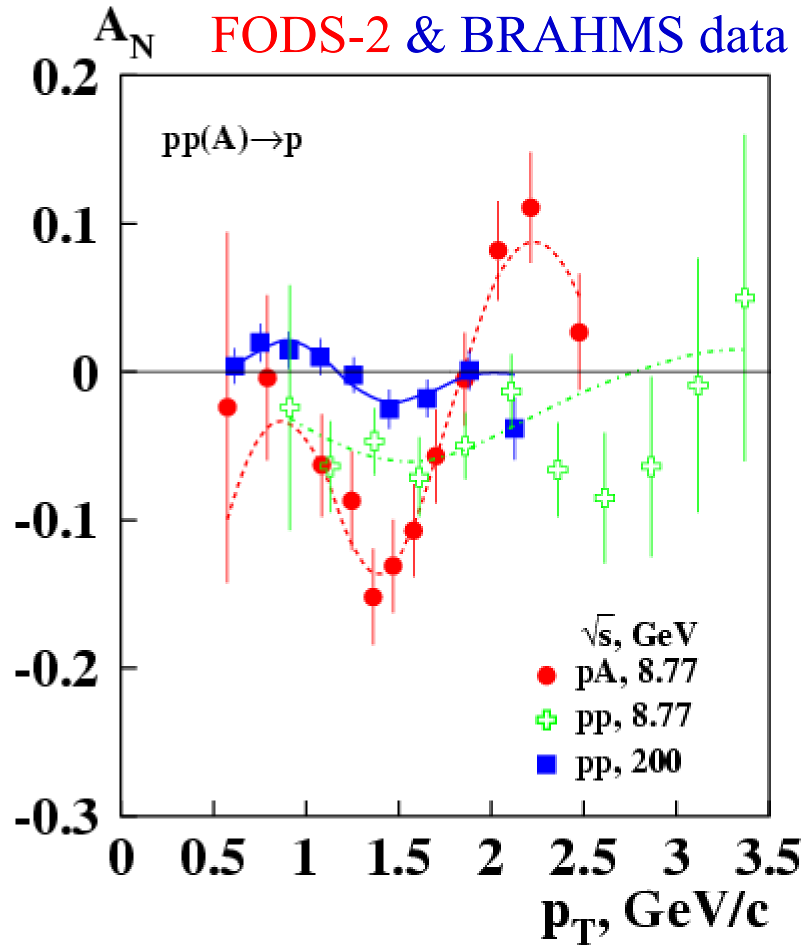
SSA Scaling for √s=5-200 GeV
Effective Color Field Model Predictions

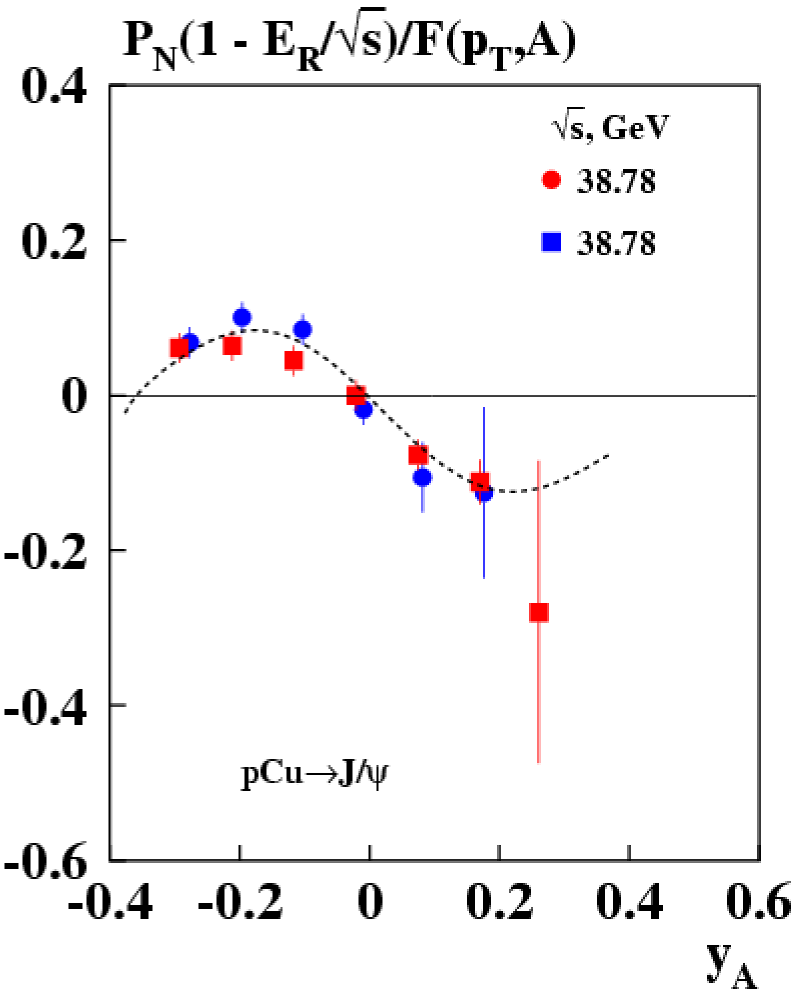


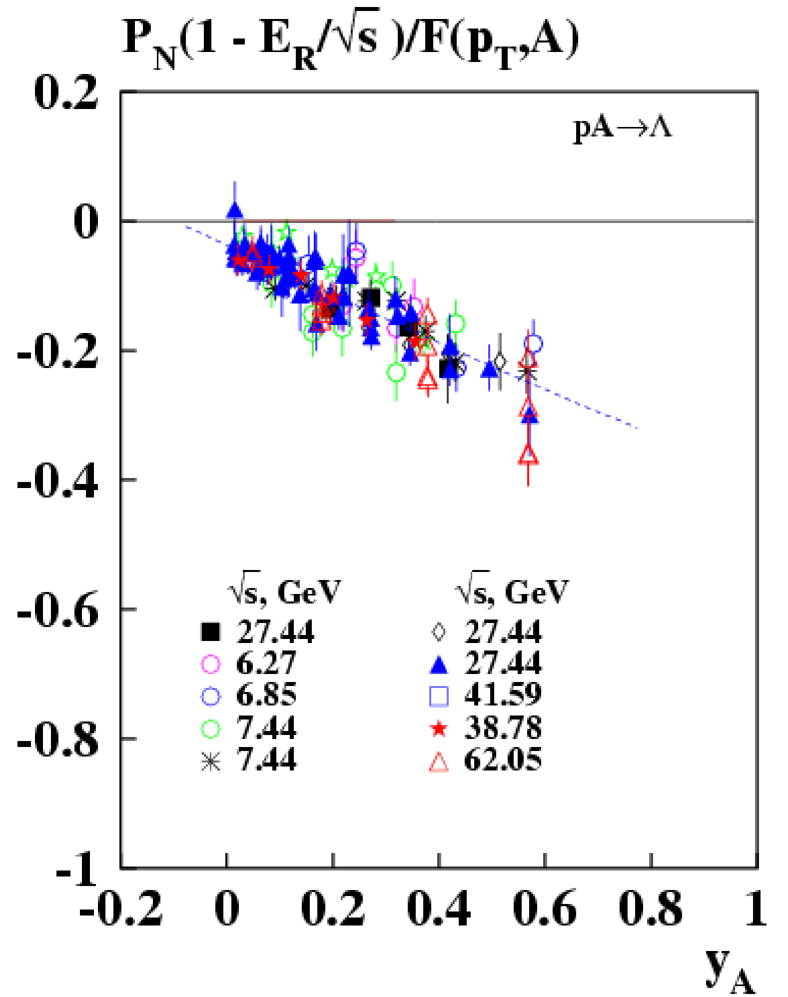


π^+: $\sqrt{s}<20$ GeV, $\omega_A=+2.7\pm0.7$; $\sqrt{s}=62$ GeV, $\omega_A=-11.5\pm1.0$; $\sqrt{s}=200$ GeV, $\omega_A=-23\pm4$.

pp(A) → p: $\sqrt{s}=8.77$ GeV, $\omega_A= -10.7\pm1.0$; $\sqrt{s}=200$ GeV, $\omega_A= -63.9\pm14.0$

Scaling and Polarization Oscillation
Effective Color Field Model Predictions





pA→J/ψ: $\sqrt{s}$=39 GeV, ω_A= -11.6±2.2;

pA→Λ : $\sqrt{s}$ <62 GeV, ω_A= -0.95±2.3

Scaling and Polarization Oscillation
Effective Color Field Model Predictions

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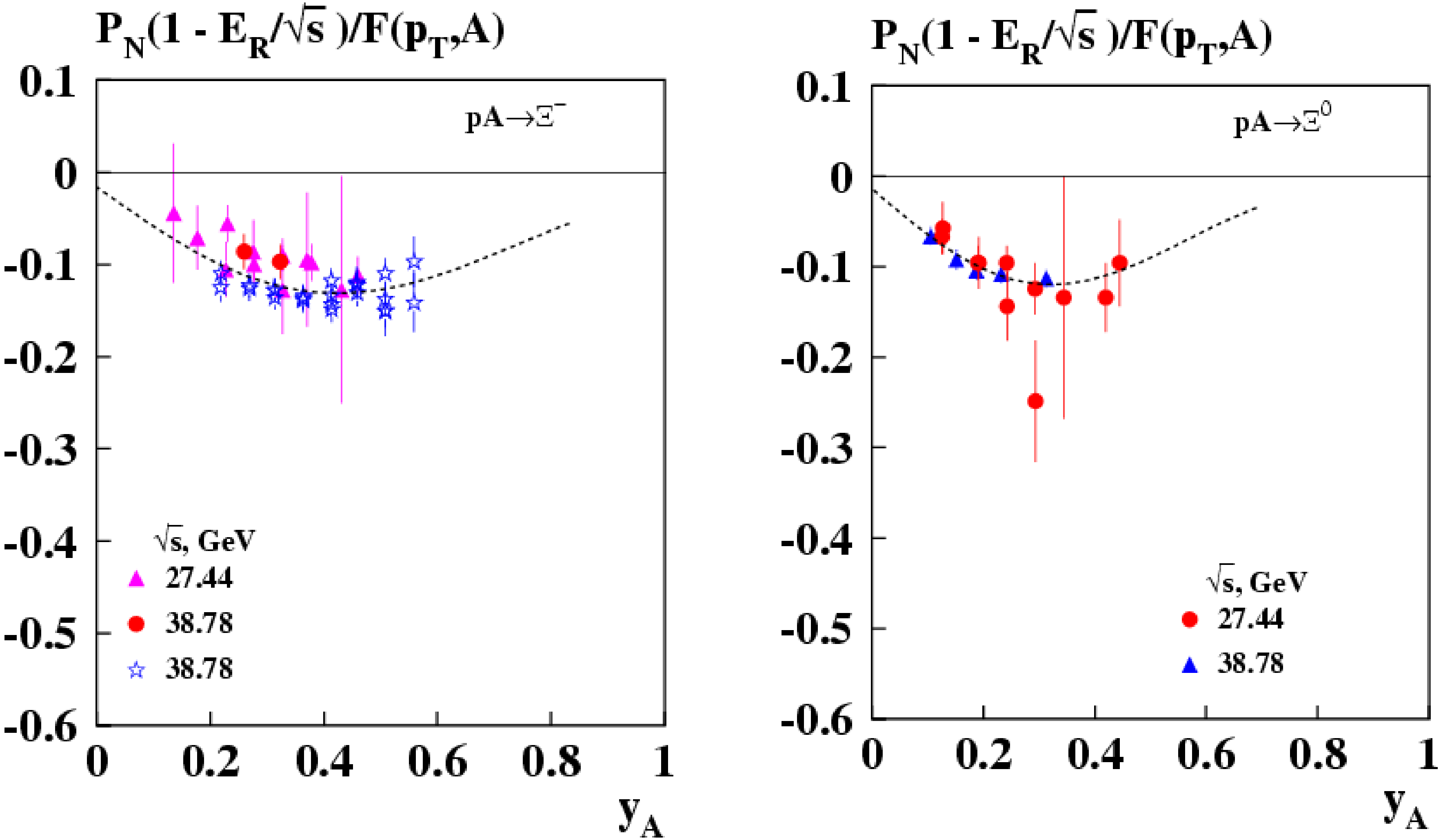
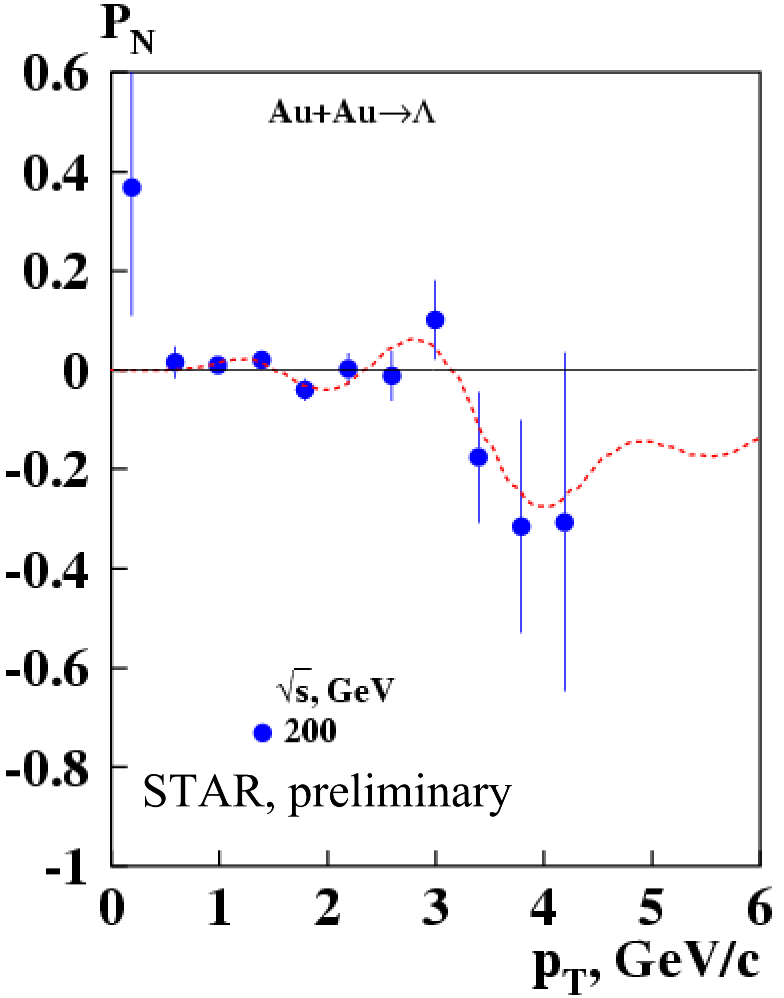
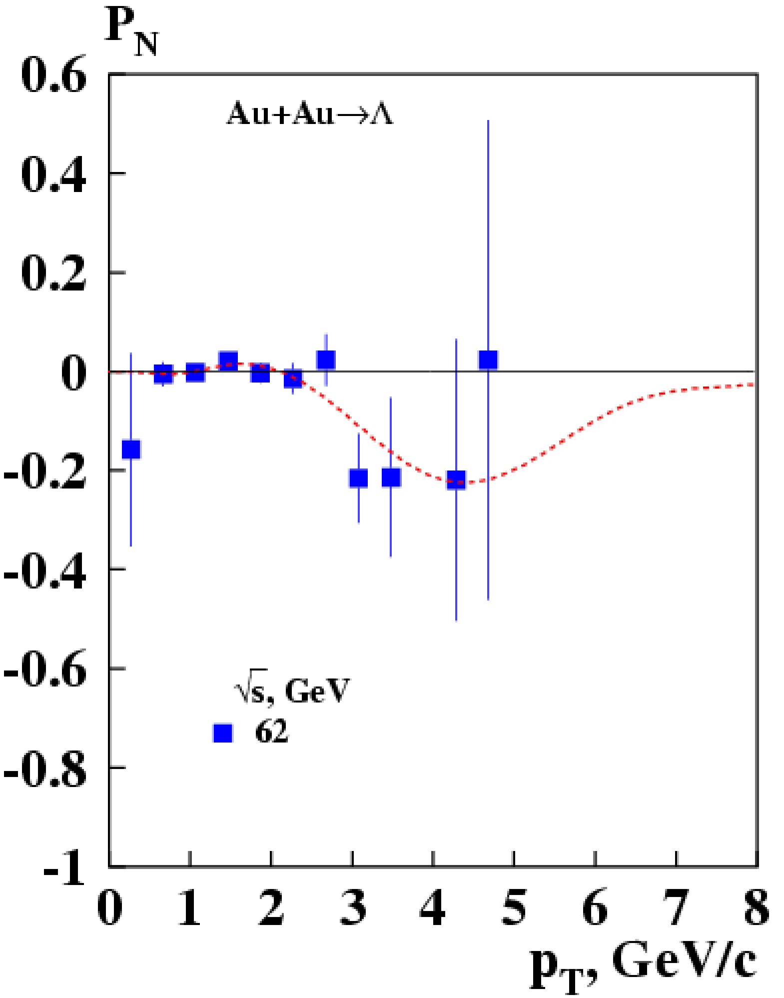


$pA \to \Xi^-$: $\sqrt{s}<39$ GeV, $\omega_A = -5.50\pm1.31$; $pA \to \Xi^0$: $\sqrt{s} < 39$ GeV, $\omega_A = -5.42\pm0.80$

Global Polarization for Au+Au Collisions
Effective Color Field Model Predictions

Color field B^a is high due to many new spectator quarks $N_Q \sim A^{1/3} \cdot \exp(-w/\sqrt{s})$

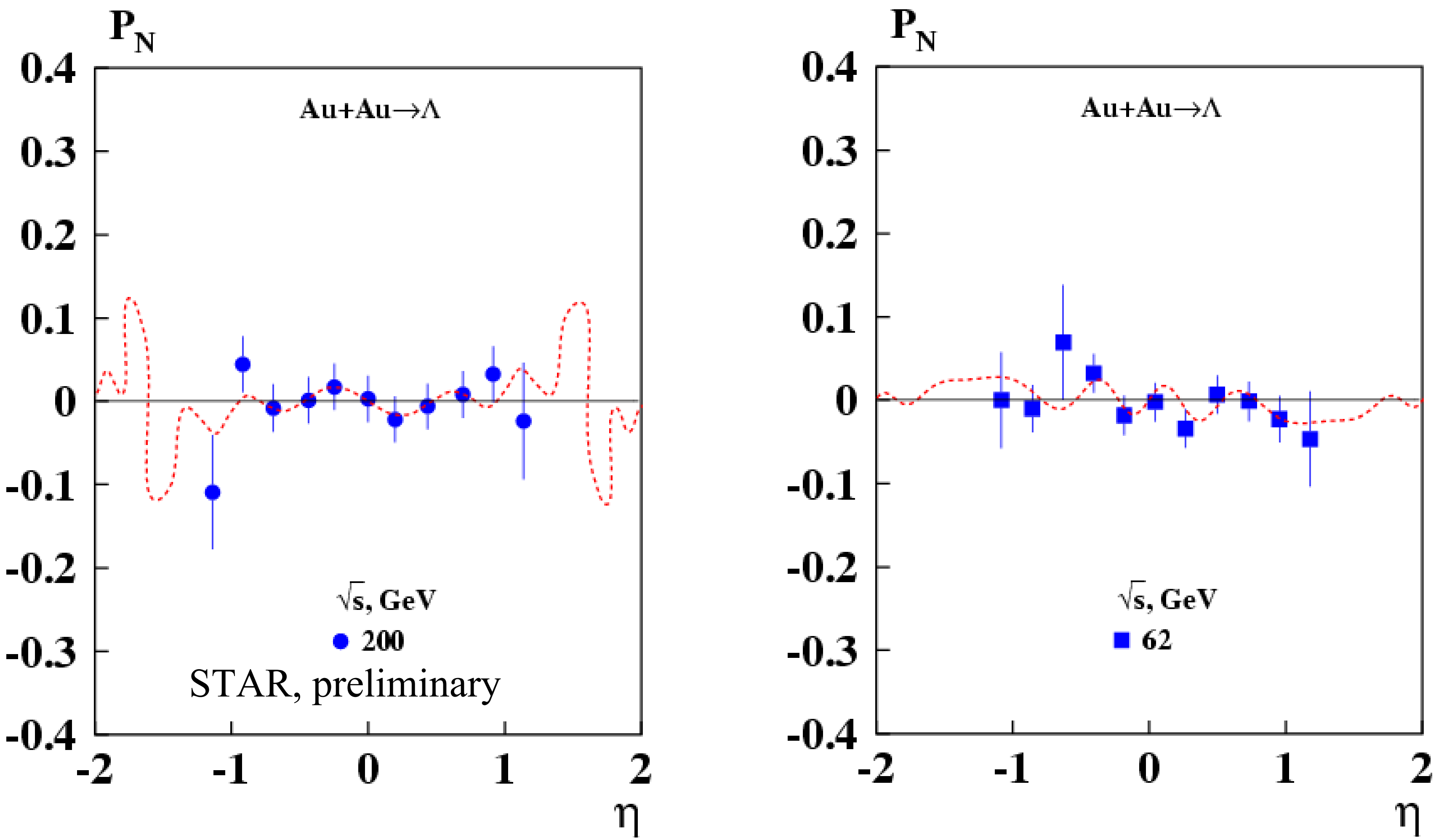




Au+Au→Λ: $\sqrt{s}$=200 GeV, ω_A= -374±51; Au+Au→Λ: $\sqrt{s}$ = 62 GeV, ω_A= -34±21

Global Polarization for Au+Au Collisions
Effective Color Field Model Predictions

Color field B^a is high due to many new spectator quarks $N_Q \sim A^{1/3} \cdot \exp(-w/\sqrt{s})$



Au+Au→Λ: $\sqrt{s}$=200 GeV, ω_A= -479±83; Au+Au→Λ: $\sqrt{s}$ = 62 GeV, ω_A= -40±6

Global Polarization for Au+Au Collisions
Effective Color Field Model Predictions

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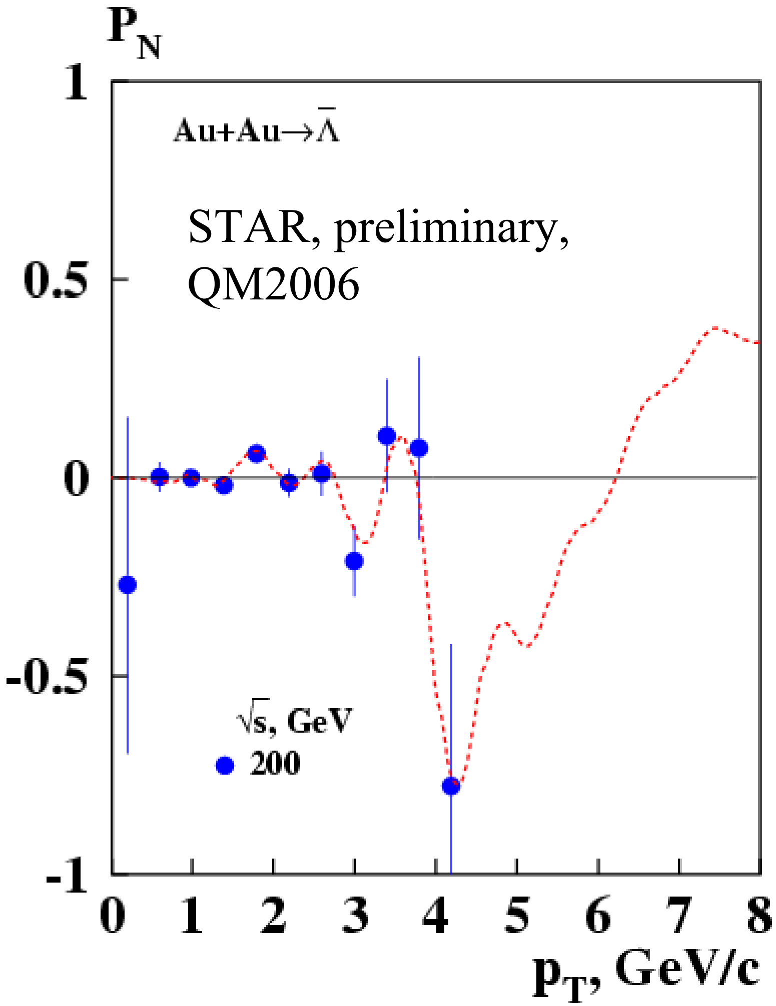
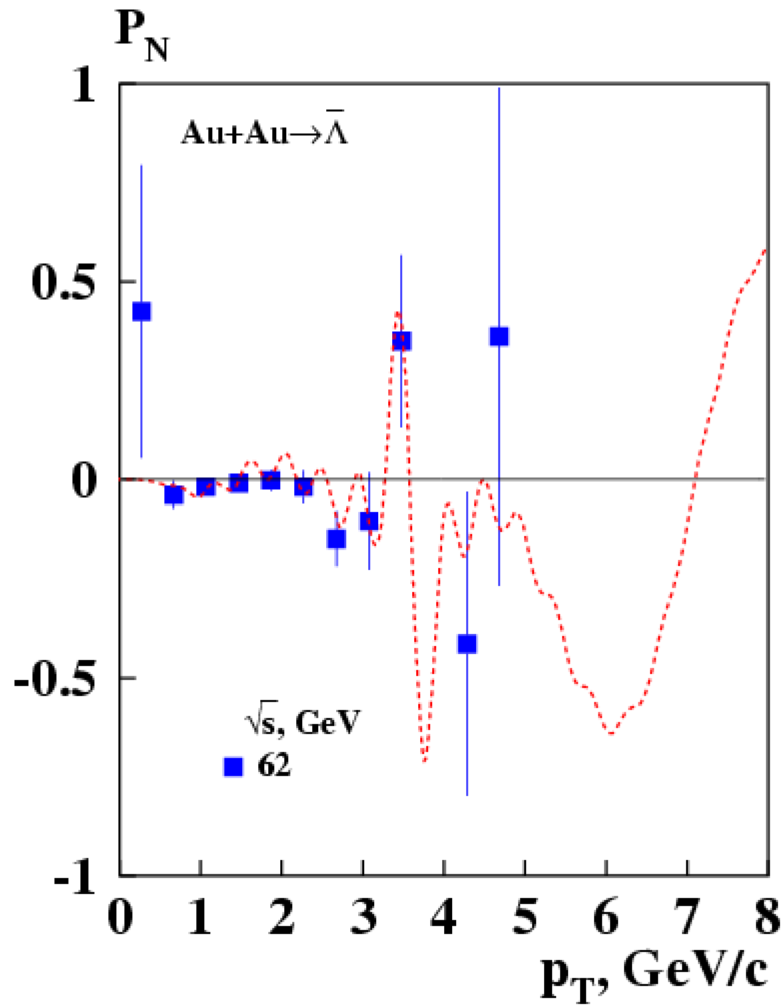
Color field B^a is high due to many new spectator quarks $N_Q \sim A^{1/3} \cdot \exp(-w/\sqrt{s})$





Au+Au→$\tilde{\Lambda}$: $\sqrt{s}$=200 GeV, ω_A= -648±46; Au+Au→$\tilde{\Lambda}$: $\sqrt{s}$ = 62 GeV, ω_A= -359±15

Global Polarization for Au+Au Collisions
Effective Color Field Model Predictions

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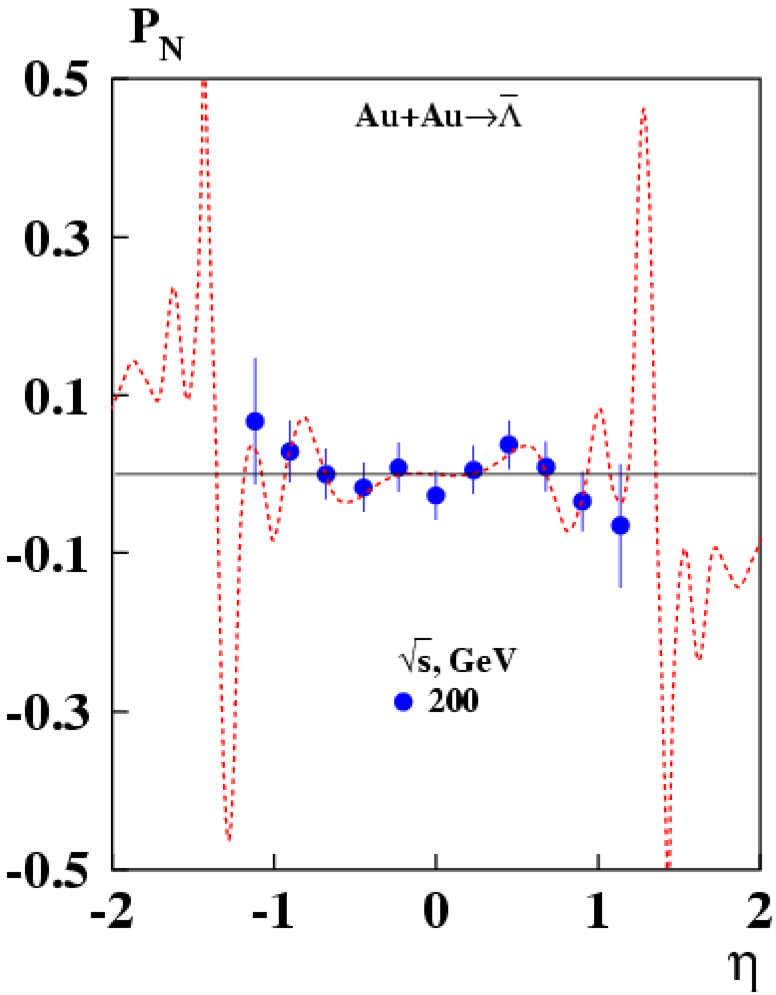
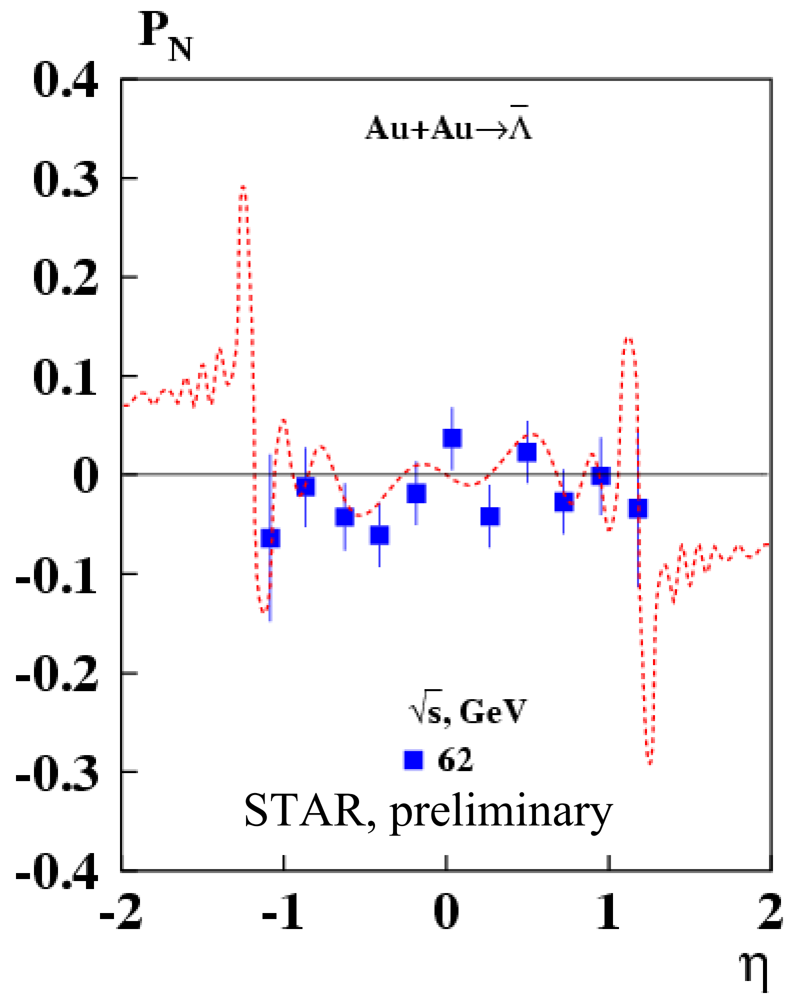
Color field B^a is high due to many new spectator quarks $N_Q \sim A^{1/3} \cdot \exp(-w/\sqrt{s})$





Au+Au→$\tilde{\Lambda}$: $\sqrt{s}$=200 GeV, ω_A= -585±18; Au+Au→$\tilde{\Lambda}$: $\sqrt{s}$ = 62 GeV, ω_A= -354±20

Λ Polarization for Au+Au Collisions at 5 GeV in E896. ECF Model Predictions

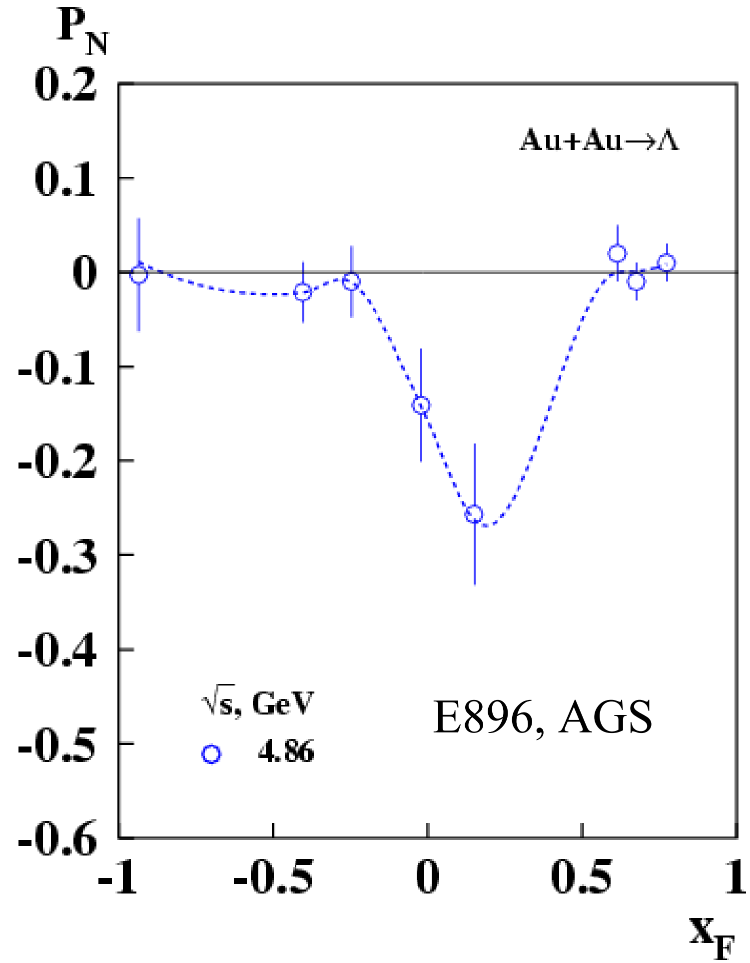
Color field B^a is high due to many new spectator quarks $N_Q \sim A^{1/3} \cdot \exp(-w/\sqrt{s})$

ECF Model predictions:

For low energy Au+Au collisions the model predicts positive $\omega_A = +18.69 \pm 2.99$;

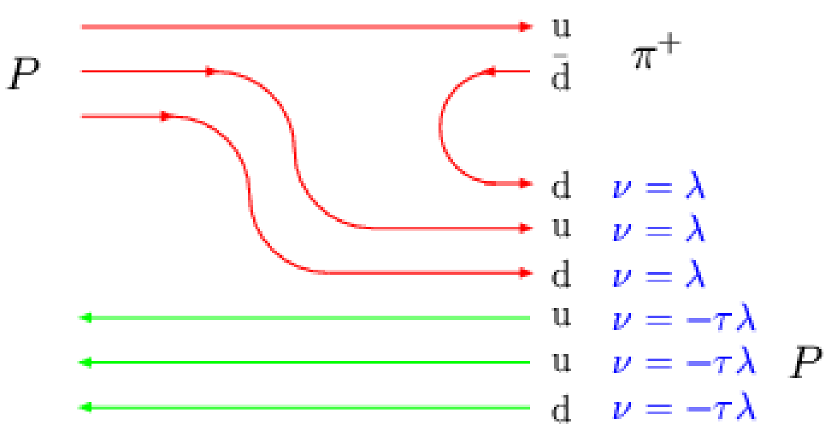
This is different from the case of pA collisions: $\omega_A = -2.81 \pm 0.33$;

and from high energy Au+Au case: $\omega_A = -387 \pm 58$; $\sqrt{s} = 200$ GeV.



Data: Au+Au→Λ +X: $\sqrt{s}$=4.86 GeV, $\omega_A = +18.61 \pm 0.54$; Model: $\omega_A = +18.69 \pm 2.99$;

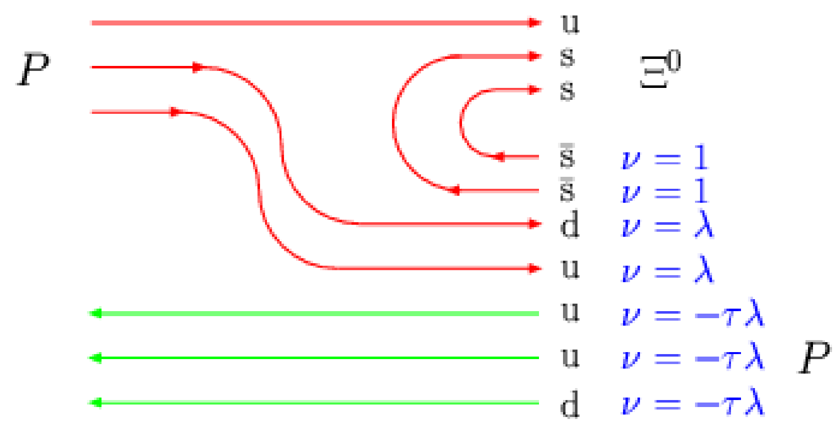
Quark counting rule for ω_A for processes $p + p \to \pi^+$ & $p + p \to \Xi^0$



$pp \to \pi^+ + X$ production quark diagram.

Color flux tube counting.

$$\omega^{pp}_{\pi^+} = \omega_0[3\lambda - 3\tau\lambda]R = +1.40 \pm 0.20,$$
$$\omega_{exp} = +2.67 \pm 0.65$$



$pp \to \Xi^0 + X$ production quark diagram.

Color flux tube counting.

$$\omega^{pp}_{\Xi} = \omega_0[2 + 2\lambda - 3\tau\lambda] = -5.83 \pm 0.61,$$
$$\omega_{exp} = -5.42 \pm 0.80$$

$$\omega^{q} = \omega_0 R_q\{\tilde{q}_{new} + \lambda q_{new} - \tilde{q}_{used} - \lambda q_{used} + \lambda q_A + \tilde{q}_A - \tau(\lambda q_B + \tilde{q}_B)\} \quad (18)$$

$$\omega^{\tilde{q}} = \omega_0 R_q\{\lambda\tilde{q}_{new} + q_{new} - \lambda\tilde{q}_{used} - q_{used} + q_A + \lambda\tilde{q}_A - \tau(q_B + \lambda\tilde{q}_B)\} \quad (19)$$

$R_q = (g-2)_q M_S/(g-2)_S M_q$; $\omega_0 = -3.32 \pm 0.34$; $\lambda = -0.091 \pm 0.015$; $\tau = -0.032 \pm 0.033$;

$R_U = 1.49 \pm 0.24$; $R_D = 2.05 \pm 0.41$; $R_S = 1$; $R_C = 0.64 \pm 0.27$;

Quark counting rule for ω_A for heavy ions collisions: $A + A \to \Lambda$

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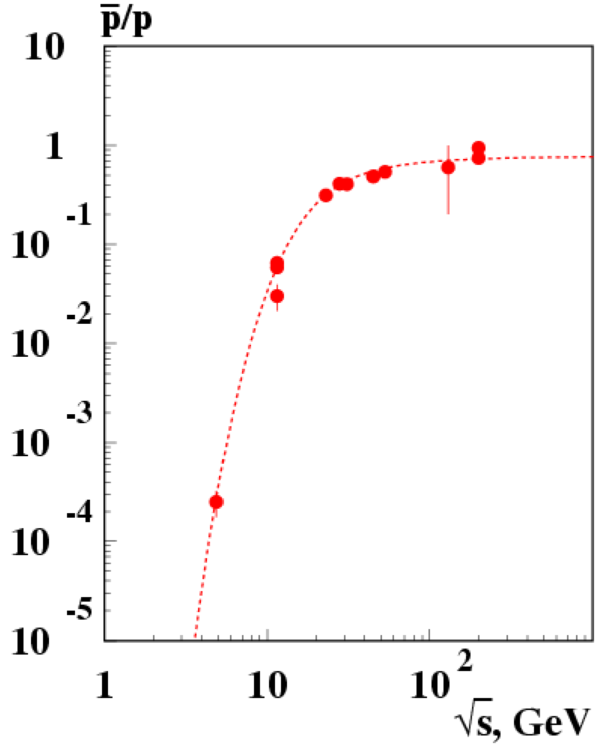
At high energies new quarks are produced which increase the color magnetic field.



In nucleus the effective number of quarks inside tube of radius R_C, creating strings:

$$q_A = 3(1+f_N)A_{eff} \sim 3(1+f_N)A^{1/3} \quad (20)$$

$$\tilde{q}_A = 3f_N A_{eff} \sim 3f_N A^{1/3} \quad (21)$$

Suppression of new quarks f_N at high P_T and x_F.

f_N is a function of $\sqrt{s}$, x_F, P_T. $f \sim A^{1/3}\exp(-w/\sqrt{s})(1-X_0)^n$, where for Au+Au collisions

$X_0 = [(P_T/P_0)^2 + x_F^2]^{1/2}$; $P_0 = 48$ GeV $-.028\sqrt{s}$; $n = 6.67 \pm .39$; $w = 119 \pm 19$ GeV

Quark counting rule for ω_A – oscillation frequency (prelim.)

Reaction	$<\sqrt{s}>$, GeV	Model	Data	Quark
$pA \to \pi^+$	10.30	$+1.40 \pm 0.20$	$+2.67 \pm 0.65$	u
$pp \to \pi^+$	200.0	-22.92 ± 2.80	-22.60 ± 3.70	u
$pA \to \pi^-$	9.367	$+1.91 \pm 0.33$	$+1.58 \pm 0.38$	d
$pp \to \pi^-$	200.0	-28.36 ± 6.03	-43.07 ± 6.23	d
$pA \to p$	8.77	-8.56 ± 1.08	-10.74 ± 1.04	u
$pp \to p$	200.00	-28.74 ± 3.85	-63.9 ± 14.0	u
$pA \to \Lambda$	26.15	-2.81 ± 0.33	-0.95 ± 2.29	s
$pA \to \Xi^-$	35.20	-5.83 ± 0.61	-5.50 ± 1.31	s
$pA \to \Xi^0$	30.99	-5.83 ± 0.61	-5.42 ± 0.80	s
$pA \to J/\psi$	38.78	-11.56 ± 3.13	-11.58 ± 2.23	$\tilde{c}$
$nC \to K^*(892)^-$	10.50	-23.22 ± 5.41	-26.91 ± 5.67	$\tilde{u}$
$Au+Au \to \Lambda$	200.00	-389 ± 58	-374 ± 51	s
$Au+Au \to \tilde{\Lambda}$	200.0	-665 ± 60	-648 ± 46	$\tilde{s}$

Physical meaning of E_0 and preliminary estimate of $(g\text{-}2)_Q$

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Model phenomenological parameters depends on g_Q and M_Q.

E_0 is related with threshold energy in c.m. (where A_N or P_N =0).

$E_0 \approx 2M_Q[1 + 2/(2 - g)]$, where $M_U \approx M_D \approx 0.35$ GeV; (22)

Data fit: **$E_0 = 2.02 \pm 0.21$ GeV** (π^-) and **$E_0 = 1.640 \pm 0.040$ GeV** (π^+);

$\mu_a = (g\text{-}2)_d/2 \approx -0.53^{+0.10}_{-0.07}$; $\mu_a = (g\text{-}2)_u/2 \approx -0.745 \pm 0.033$;

These model dependent estimations of $\mu_a=(g\text{-}2)/2$ are in the range of the existing instanton model predictions:

$\mu_a = -0.2$ (N.Kochelev) and $\mu_a = -0.74$ (D.Diakonov)

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Summary and outlook

- The analyzing power (A_N) and hadron polarization (P_N) reveal scaling dependence on kinematical variables: $A_N \approx G(p_T, y_A)/(1 - E_R/\sqrt{s})$, as expected in the effective color field model.

- P_N and A_N oscillation due to the quark spin precession in the effective color field is predicted and confirmed for proton, Λ, $\tilde{\Lambda}$, J/ψ, $K^*(892)^-$, Ξ^0, Ξ^- production.

- Oscillation frequencies ω_A obey the quark counting rule and rise with $\sqrt{s}$ and projectile atomic number.

- Spin precession mechanism allows to estimate $\mu_a=(g-2)/2$: $(g-2)_u/2 \approx -0.75 \pm 0.03(\mathrm{stat})$; $(g-2)_d/2 \approx -0.53 \pm 0.10(\mathrm{stat})$, which are consistent with the instanton model predictions.

Summary and outlook

- The dependence of the model parameters on dynamical quark mass and its anomalous chromomagnetic moment allows to estimate these very interesting physical values which give insight into the realm of non-pertubative QCD.

- The results of this study indicate an important role of massive constituent quarks in hadron interaction. The properties of these quasi-particles can be studied in single-spin processes in general and in heavy ion collisions in particular.