Spin Physics in QCD: from Spin-Orbit in Atoms to EMC Spin Crisis to Transversity at FAIR

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Lectures at CGSWHP

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Georgia

Contents:

- Two perfect reasons for spin physics to die out at $E \to \infty$
- DIS off $D\uparrow$: long life to tensor asymmetry at $E \to \infty$. HERMES
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- ★ Transversity in $p\uparrow$: Terra Incognita
- Why has not been measured?
- Collins & Sivers functions. 1st evidence from HERMES
- Breight future: $\bar{p}\uparrow$ at HESR PAX will do that!
- Why not RHIC?

Merani by N. Baratashwili

გასწი, მერანო, შენს ჭენებას

არ აქვს სამძღვარი.

Ты скачи, мой Мерани,

до грядущей, неведомой грани

(Н. Баазов)

Keep your gallop, Merani,

till you carry me on through the horizon

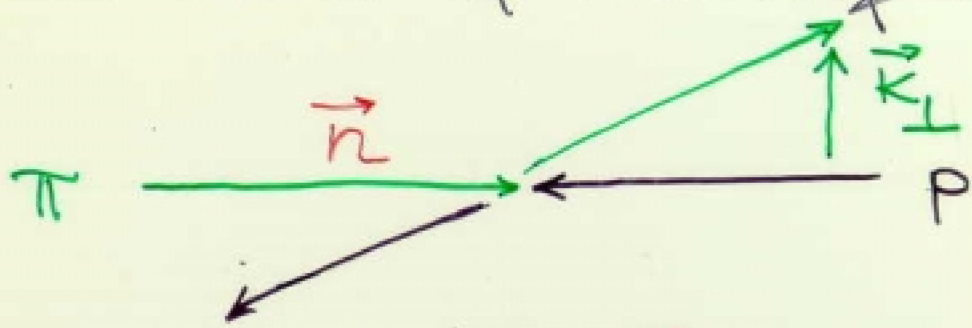
Spin-Orbit Interaction

$$V_{LS}(r)\ \vec{L}\cdot\vec{S}$$

Atomic fine structure ⇒

Conception of Quantum Theory

$\rho - \gamma$ analogy: spin-orbit interaction of nucleons & hadrons



$$\mathcal{A} = f + ig\,\vec{\sigma}\cdot[\vec{n}\,\vec{k}_\perp]$$

- Left-right asymmetry on p↑
- Normal polarization of the scattered proton
- More spin amplitudes in NN
- Still more in ND

"Ich habe bemerkt" sagte Herr K.,
"daß wir viele abschreken von unserer
Lehre dadurch, daß wir auf alles
eine Antwort wissen. Könnten wir
nicht im Interesse der Propaganda
eine Liste der Fragen aufstellen,
die uns ganz ungelöst erscheinen?"

Bertolt Brecht.

Geschichten vom Herrn Keuner.

Two perfect reasons for spin phenomena to vanish at high energies

★ Partial waves & Absorption

$$A \propto \sum_\ell (2\ell+1) P_\ell(\cos\theta)[1-\exp(2i\delta_\ell)]$$

- $\sigma_{in} \propto \sum_\ell (2\ell+1)[1-|\exp(2i\delta_\ell)|^2]$

Absorption $\Rightarrow$ complex δ_ℓ

$$\exp(2i\delta_\ell) \Rightarrow 0$$

★ πN partial waves:

$$j = \ell \pm \frac{1}{2} \Rightarrow \delta_\ell^\pm$$

- Central amplitude

$$f_\ell = (\ell+1)[1-\exp[2i\delta_\ell^+]] + \ell\cdot[1-\exp[2i\delta_\ell^-]]$$

$$\xrightarrow{\text{Absorption}} 2\ell+1$$

- Spin-flip

$$g_\ell = \exp[2i\delta_\ell^+] - \exp[2i\delta_\ell^-]$$

$$\xrightarrow{\text{Absorption}} 0 \; !$$

Chirality & Quark Helicity Conservation in QCD

$$\psi_{R,L} = \frac{1}{2}(1 \pm \gamma_5)\psi$$

- Kinetic term & Interaction

$$G^a_\mu \bar{\psi} t^a \gamma_\mu \psi \Rightarrow$$

$$\Rightarrow \bar{\psi}_L \gamma_\mu \psi_L + \bar{\psi}_R \gamma_\mu \psi_R$$

- Chirality conservation broken by quark masses

$$m_q \bar{\psi}\psi = m_q \{ \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L \}$$

$\Rightarrow$ Ignore at high energy, EXACT conservation of quark chirality (= helicity)

★ QED/QCD spin-orbit simply keeps the spin tuned to the momentum

The tensor spin structure function of the deuteron $b_2(x, Q^2)$

- Deep inelastic scattering $\Leftrightarrow$ measure total virtual photoabsorption cross sections $\sigma_{tot}(\gamma^* h)$, $h = p, D \ldots$, $Q^2 =$ photon virtuality, $x = Q^2/(W^2 + Q^2)$, $W = \gamma^* h$–cms energy.

- Structure functions $\Leftrightarrow$ total cross sections.
  e.g.: $F_2(x, Q^2) \simeq \frac{4\pi^2 \alpha_{em}}{Q^2} \sigma_{tot}(\gamma^* h)$

- Tensor spin structure function b_2:

$$b_2(x, Q^2) = 2F_{2D}^{(0)}(x, Q^2) - F_{2D}^{(+)}(x, Q^2) - F_{2D}^{(-)}(x, Q^2)$$

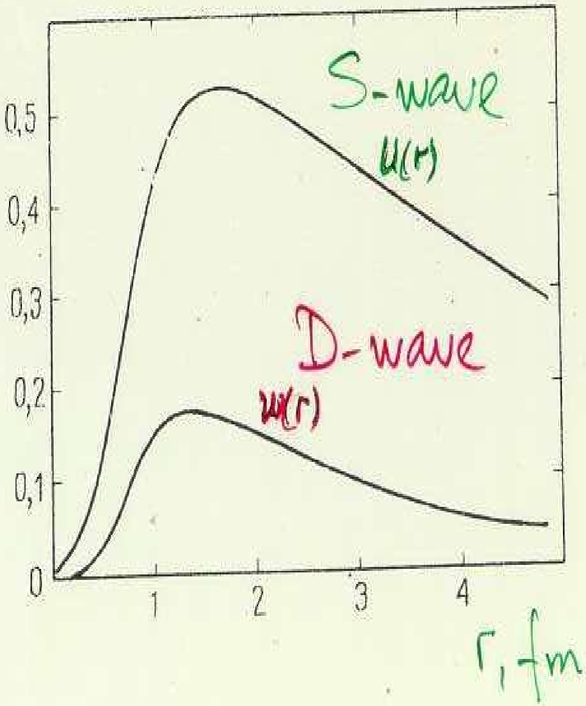
  ⋆ Hoodbhoy, Jaffe, Manohar ('89)

- Early considerations in impulse approximation by Hoodbhoy et al. suggest a vanishing effect as $x \to 0$ ($W \to \infty$).

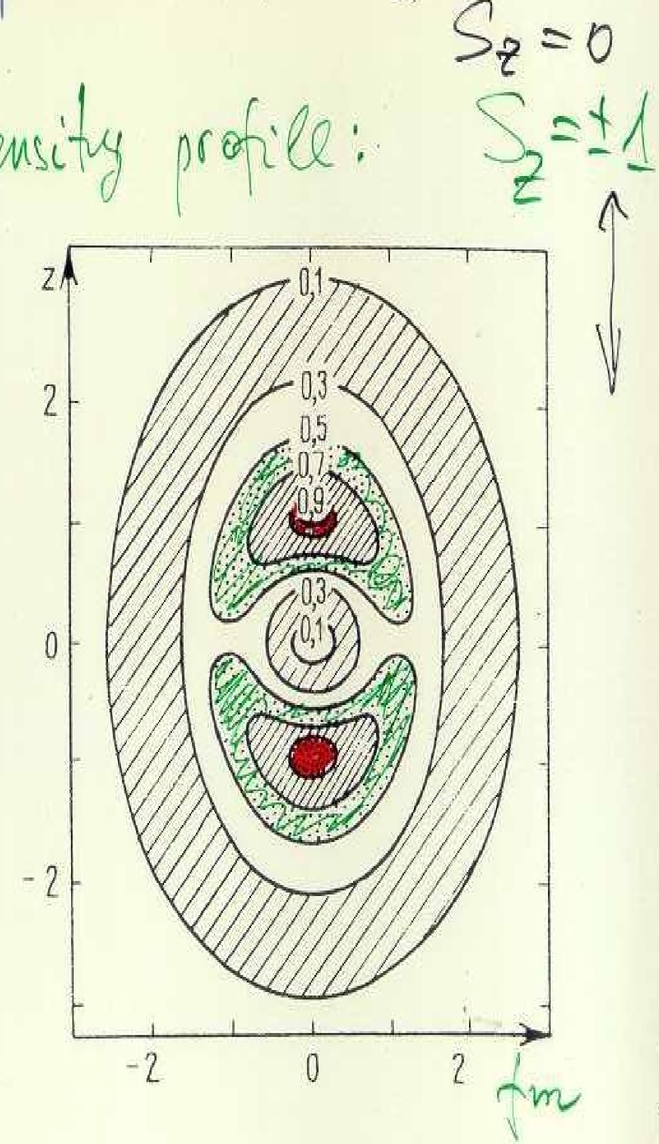
- Inelastic shadowing contribution dominates b_2 at small x, and leads to an alignment effect rising with energy!

S-D mixing & quadrupole deformation

Radial WF's



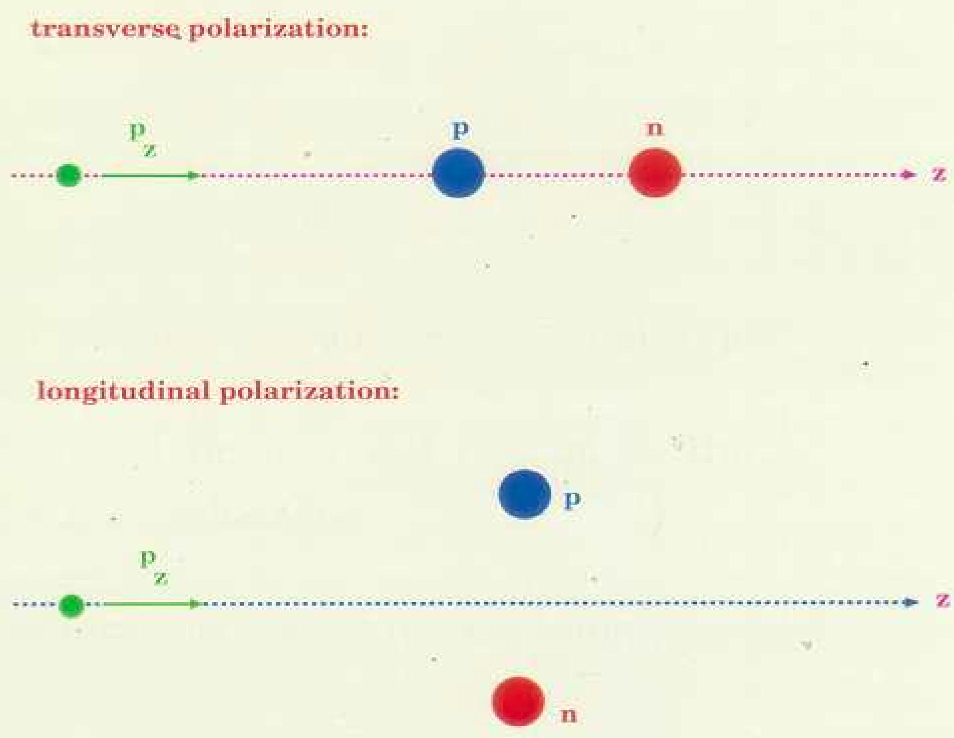
Density profile:



The Glauber shadowing/screening/eclipse effect:

- Imagine proton and neutron as two absorbing discs with cross sections σ_N
  $\star$ proton and neutron will overlap in the impact parameter plane with a probability $w \sim \langle \frac{\sigma_N}{4\pi R_D^2} \rangle$.

  $\Rightarrow$ total cross section of the deuteron:
  $\sigma_D = 2\sigma_N - w \cdot \sigma_N = 2\sigma_N - \langle \frac{\sigma_N^2}{4\pi R_D^2} \rangle$
- The shape of the deuteron in the impact parameter plane depends on its polarization state:



Physics Letters B 398 (1997) 245–251

Nonvanishing tensor polarization of sea quarks in polarized deuterons

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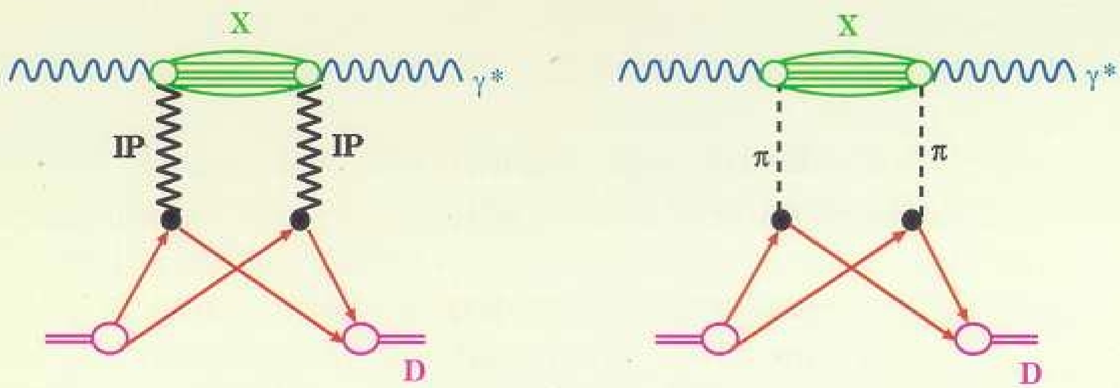
hep-ph/9611460 , 28 Nov. 1996

Abstract

We show how the dependence of the diffractive nuclear shadowing and of the nuclear excess of pions on the deuteron spin alignment leads to a substantial tensor polarization of sea partons in the deuteron. The corresponding tensor structure function $b_2(x,Q^2)$ rises towards small x and we predict the about one per cent tensor asymmetry $A_2(x,Q^2) = b_2(x,Q^2)/F_{2d}(x,Q^2)$ which by almost two orders in magnitude exceeds the effect evaluated earlier in the impulse approximation. We show that the integral $\int_0^1 dx\, b_1(x,Q^2)$ diverges, which implies that the sum rule $\int_0^1 dx\, b_1(x,Q^2) = 0$ suggested by Close and Kumano does not exist. We comment on the impact of tensor polarization on the determination of the vector spin structure function $g_{1d}(x,Q^2)$ for the deuteron.

Inelastic shadowing contributions



- Both mechanisms constrained by HERA–DESY data:
- IP-exchange $\Longleftrightarrow$ diffractive structure functions,
  - ⋆ predominantly imaginary amplitude,
  - ⋆ $d\sigma/dtdM^2 \approx$ const. with energy,
  - ⋆ contribution to b_2 driven through s/d-wave interference.
  - ⋆ a NON-perturbative mechanism
- π–exchange $\Longleftrightarrow$ production of forward neutrons (ZEUS/H1 forward spectrometers)
  - ⋆ real amplitude
  - ⋆ at fixed M^2: $d\sigma/dtdM^2 \approx 1/(\text{energy})^2$, but finite after M^2–integration.
  - ⋆ Spin–flip coupling to the nucleon $\propto (\vec{\sigma} \cdot \vec{k}_\pi)$ $\Longrightarrow$ highly nontrivial contribution to b_2.
- Nuclear modification of the pion cloud of the bound nucleon – a NON-perturbative mechanism

Z. Phys. A 357, 129–131 (1997)

Short note

Polarized deuteron structure functions at small $x^{\star}$

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Received: 17 December 1996

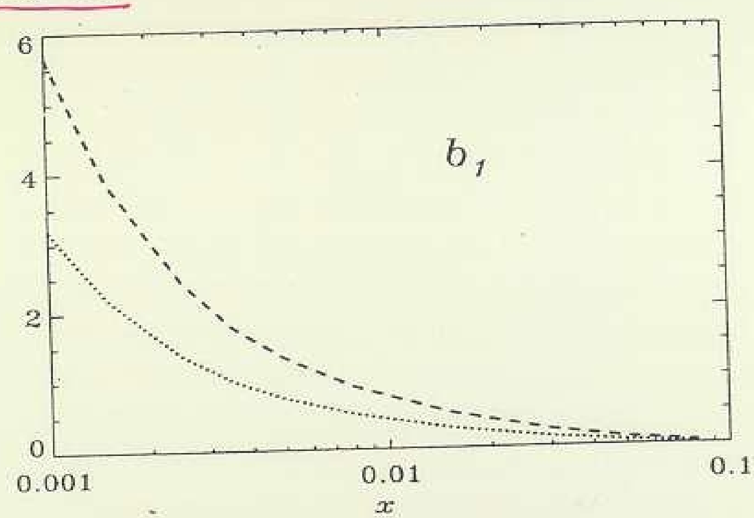

Fig. 2. Double scattering contribution to b_1 from (14). The *dashed* and *dotted curves* correspond to the Paris [10] and Bonn [11] potential respectively

$$\frac{b_1}{F_1^N} = \mathscr{R}_{b_1} \frac{\delta F_2}{F_2^N},$$

$$\mathscr{R}_{b_1} = -1.03 \text{ (Paris potential)}$$

$$\mathscr{R}_{b_1} = -0.58 \text{ (Bonn potential)}$$

Overestimated by the factor ~3.

High Energy Physics - Phenomenology, abstract
hep-ph/9711323 version 1

The Double Scattering Contribution to \$b_1(x,Q^2)\$ in the Deuteron

Authors: K. Bora, R.L. Jaffe

We study the tensor structure function \$b_1\xq\$ i deep inelastic scattering (DIS) of an electron from a polarized deuteron target. We model the electron-nucleon cross section at the starting point for \$Q^2\$ evolution by vector-meson-dominance (VMD). Shadowing due to the double-scattering of vector mesons, along with the presence of a d-state admixture in ground state deuteron wave function gives rise to a non-vanishing contribution to \$b_1\xq\$. Although significant at large Bjorken \$x\$, the restoration of rotational symmetry for small \$x\$ (\$\leq10^{-3}\$) requires that \$b_1^{(2)}\xq\$ approach zero as \$x\to 0\$ in this model. If the model is valid, it should apply within the range of present fixed target experiments.

PHYSICAL REVIEW D VOLUME 57, NUMBER 11 1 JUNE 1998

Double-scattering contribution to $b_1(x,Q^2)$ in the deuteron

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(Received 30 December 1997; published 8 May 1998)

We study the tensor structure function $b_1(x,Q^2)$ in deep inelastic scattering of an electron from a polarized deuteron target. We model the electron-nucleon cross section at the starting point for Q^2 evolution by vector-meson dominance. Shadowing due to the double scattering of vector mesons, along with the presence of a d-state admixture in a ground-state deuteron wave function gives rise to a nonvanishing contribution to $b_1(x,Q^2)$. We find a large enhancement at low x in qualitative agreement with other recent estimates of double-scattering contributions to $b_1(x,Q^2)$. If the model is valid, it should apply within the range of present fixed-target experiments. [S0556-2821(98)06111-6]

PACS number(s): 13.60.Hb, 12.40.Vv, 13.75.Cs, 13.88.+e

Is there any thing
whereof it may be said,
See, this is new?
it hath been already
of old time, which was
before us.

Ecclesiastes - 1:10.

SCATTERING OF NEUTRONS BY ORIENTED NONSPHERICAL NUCLEI

G. L. VISOTSKIĬ, E. V. INOPIN, and A. A. KRESNIN
Physico-Technical Institute, Ukrainian S.S.R.
J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 574-580 (February, 1959)

The effects due to nonsphericity increase if the targets employed are oriented nuclei. Actually, we consider, for example, a black nucleus in the shape of an ellipsoid of revolution with semi-axes a and b (a is the major semi-axis, directed along the axial symmetry axis of the nucleus). If the nuclei are now oriented so that the symmetry axis of the nucleus coincides with the direction of the incident beam of neutrons, we obtain for the total cross section $\sigma_t^{\parallel} = 2\pi b^2$, but if the symmetry axis is directed perpendicular to the incident beam, we get $\sigma_t^{\perp} = 2\pi ab$. Thus $\sigma_t^{\perp}/\sigma_t^{\parallel} = a/b$. We can thus determine directly whether the nucleus is prolate or oblate. In the former case $\sigma_t^{\perp}/\sigma_t^{\parallel} > 1$, and in the latter $\sigma_t^{\perp}/\sigma_t^{\parallel} < 1$. For the nonsphericities observed experimentally, a typical ratio of the semi-axis is $1.3 - 1.4$ and the estimate made here shows that the nonsphericity effects may reach 30 or 40%.

Volume 59B, number 4 PHYSICS LETTERS 24 November 1975

ALIGNMENT EFFECTS IN DEUTERON TOTAL CROSS SECTIONS

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Since the deuteron is cigar-shaped, it clearly makes difference to the total cross section whether it is pointing along the beam direction or across it.

This alignment term is comparable in size with the average eclipse contribution because it is linear in the D-state *amplitude*. Because the nucleon has spin $\frac{1}{2}$, there is no contribution to Δ in impulse approximation, so that this cross section difference must involve the interaction with both nucleons.

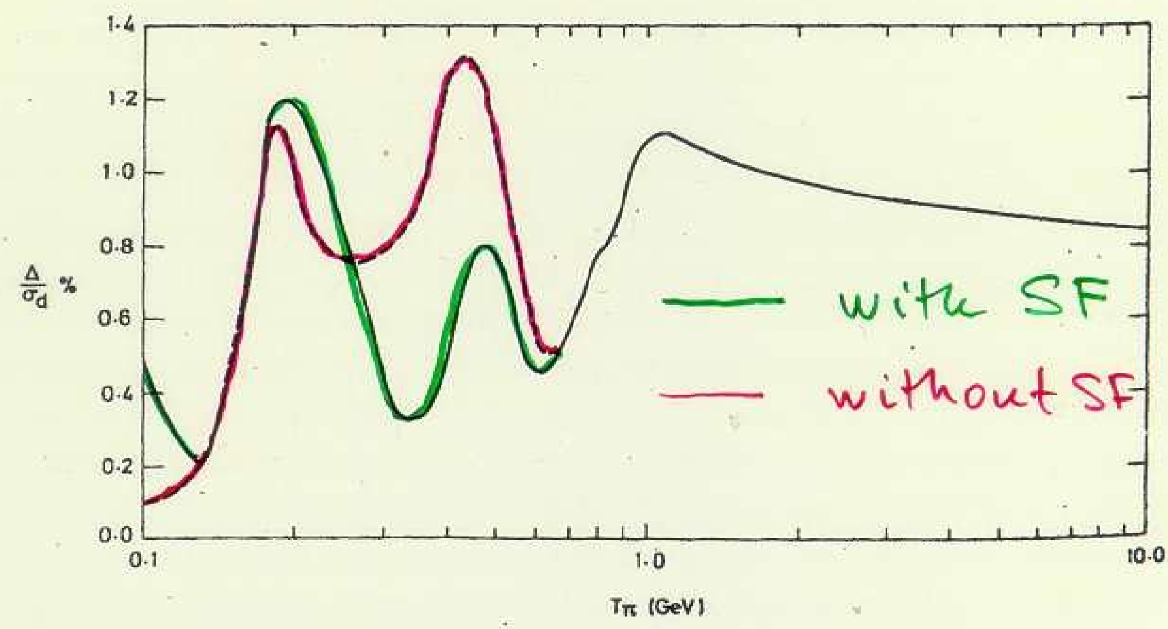
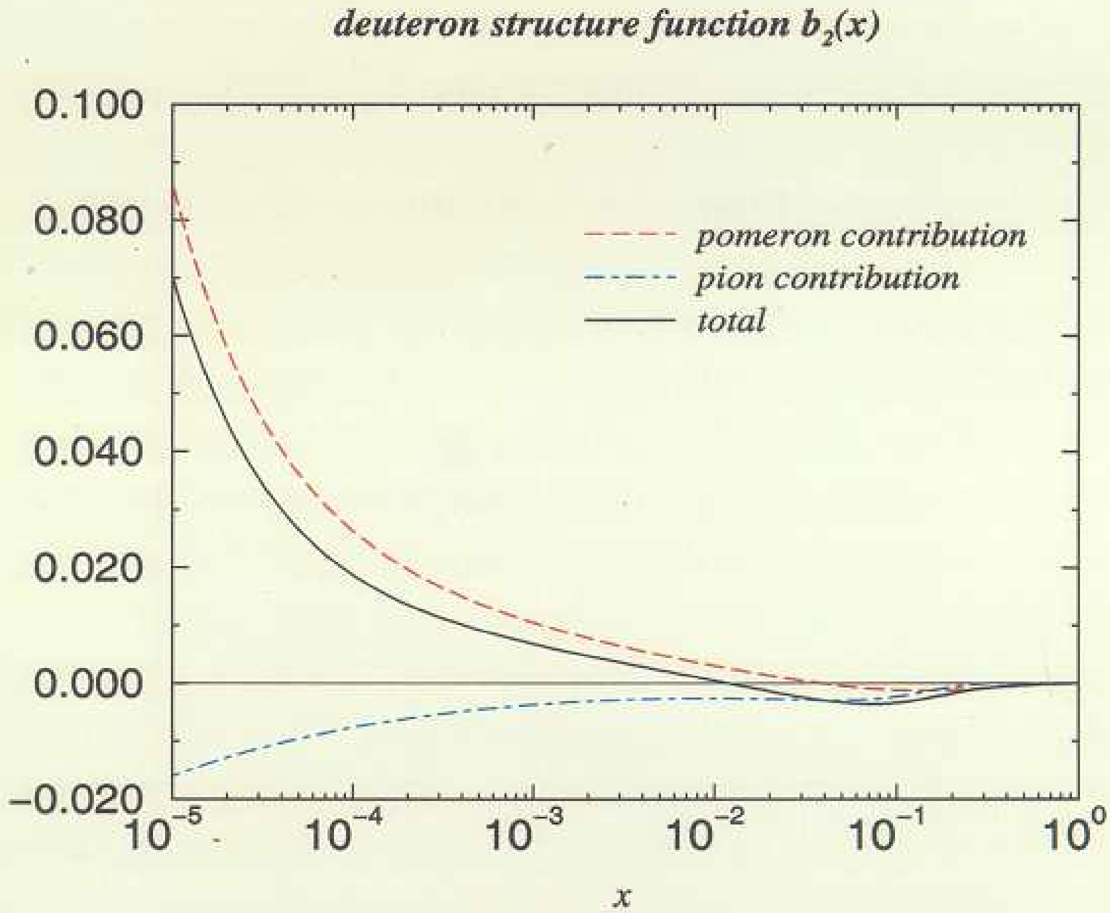


Fig. 1. Predicted fractional difference in the pion total cross section of aligned deuterons with (solid curve) and without (dashed curve) the effect of the double spin flip. Below 1 GeV the pion-nucleon amplitudes were taken from phase shifts [6], above from a Regge parameterisation [7].

Numerical results



- N.Nikolaev, W.S., PLB 398 (245), 1997.
- an asymmetry on the percent level, is measurable, and data have been taken by HERMES-DESY collaboration.
- possible significance for neutron spin structure function determinations.
- a strong violation (divergence !) of the Close–Kumano sum rule

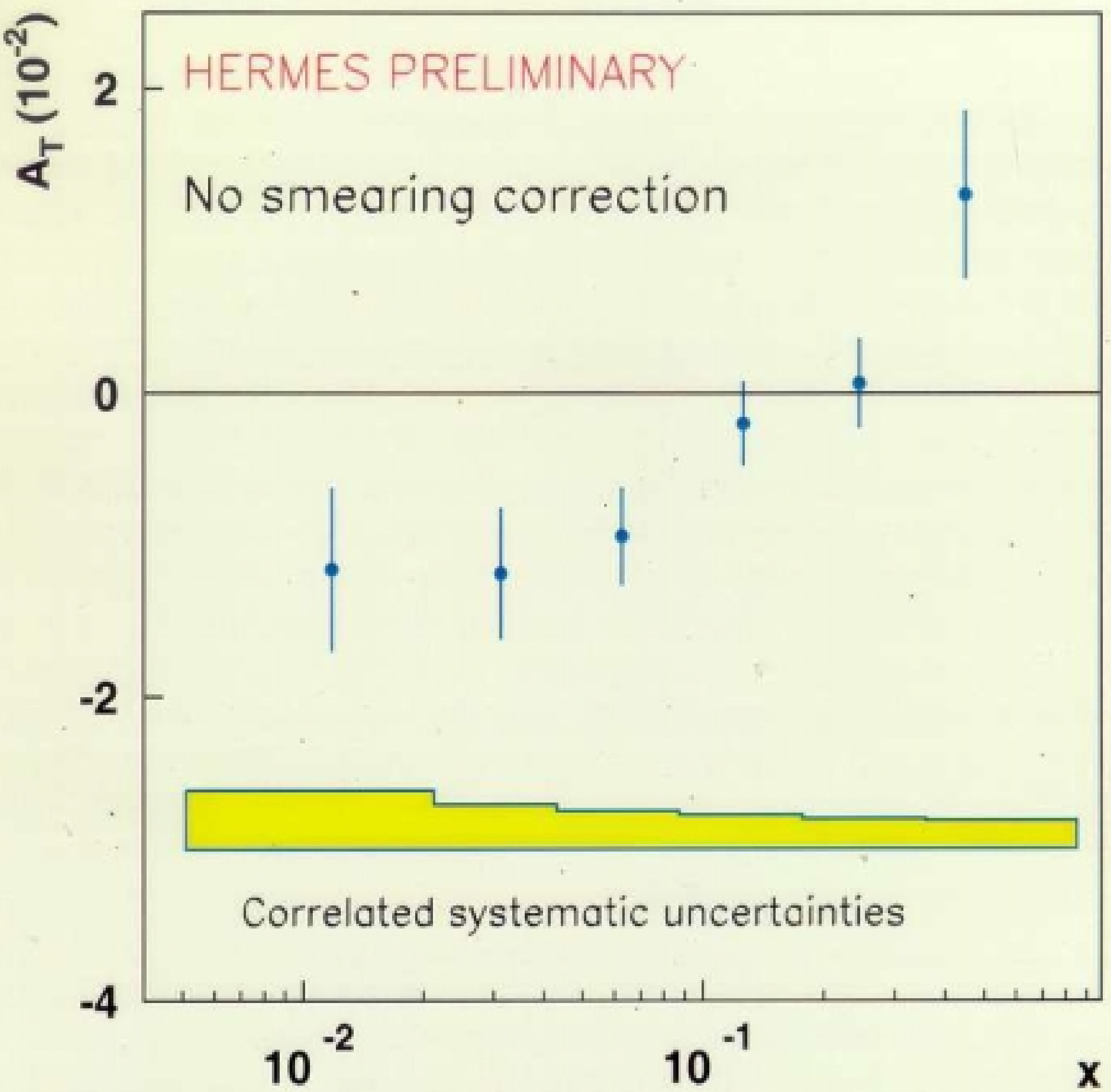
$$\int_0^1 \frac{dx}{x} b_2(x) = 0.$$

DIS off aligned deuterons:
diffractive DIS & DS

→ tensor polarization of the parton density of the D

Theory: NNN, W. Schäfer
Piller et al..

Dedicated run by HERMES



The first chiral-even quark distrbution: unpolarized DIS

$$F_2(x) = x \sum_q e_q^2 q(x)$$

Unpolarized distribution function $q(x, Q^2)$ = the quark momentum distribution at infinite momentum.

The first moment measures the quark vector charge

$$\langle PS|\overline{\psi}\gamma^{\mu}\psi|PS\rangle = \int_0^1 dx(q(x) - \overline{q}(x))$$

Very fast growth towards small x:

⋆ quarks readily radiate soft gluons,

⋆ gluons still more readily radiate still softer gluons,

⋆ gluons split into sea

$$g \to q\bar{q}$$

Was anticipated theoretically and confirmed at HERA

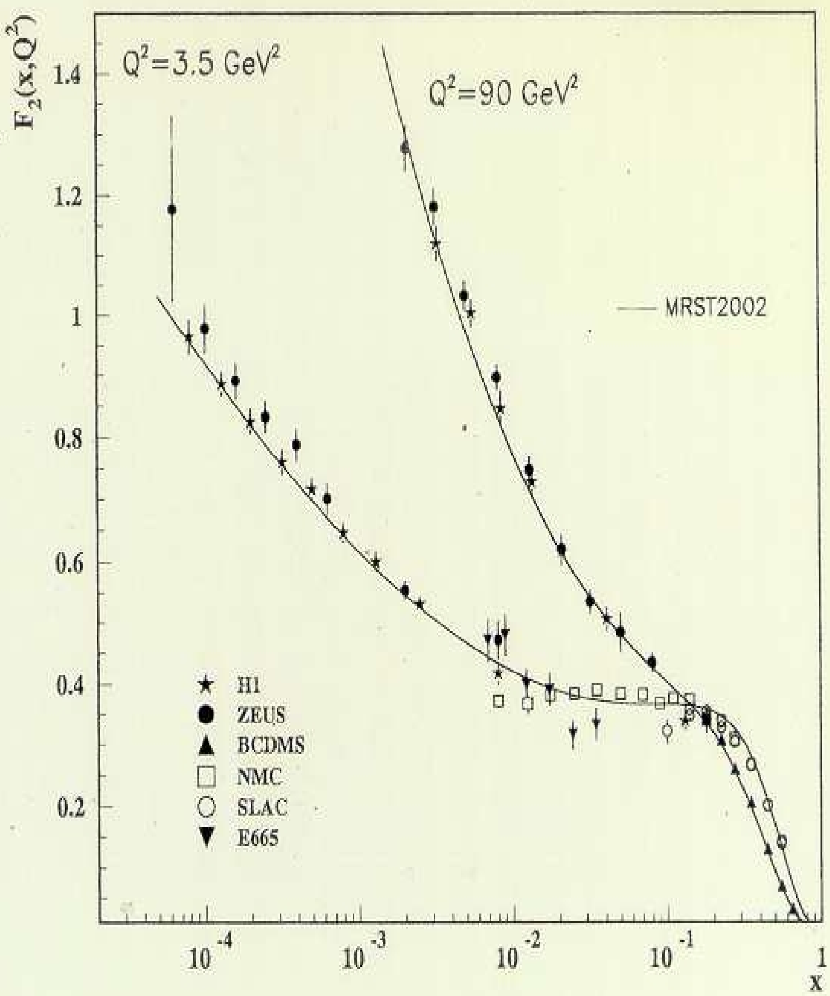


Figure 16.2: The proton structure function F_2^p given at two Q^2 values (3.5 GeV^2 and 90 GeV^2), which exhibit scaling at the 'pivot' point $x \sim 0.14$. See the caption in Fig. 16.6 for the references of the data. Also shown is the MRST2002 parameterization [13] given at the same scales.

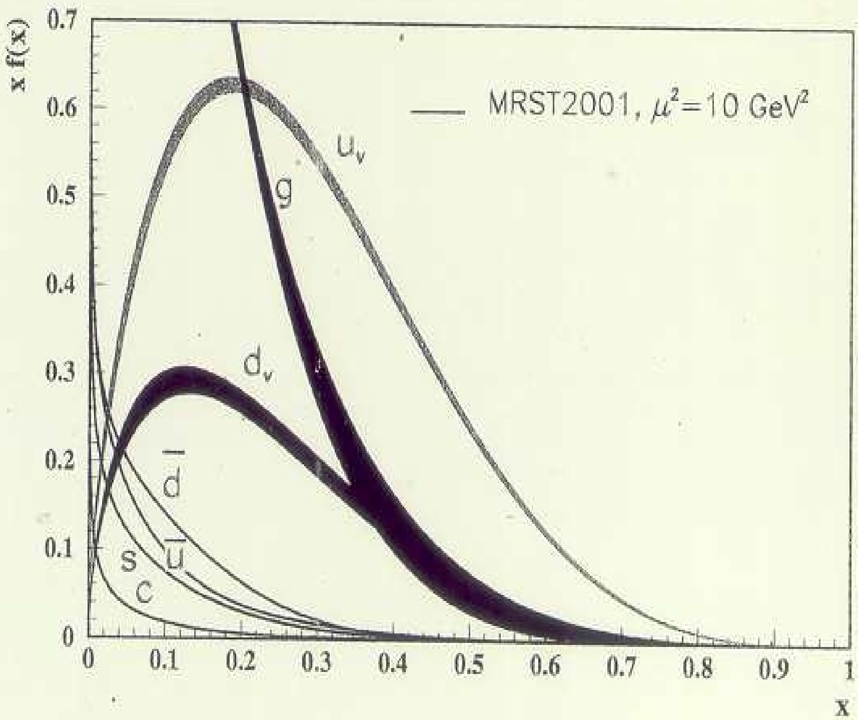


Figure 16.4: Distributions of x times the unpolarized parton distributions $f(x)$ (where $f = u_v, d_v, \overline{u}, \overline{d}, s, c, g$) using the MRST2001 parameterization [29,13](with uncertainties for u_v, d_v, and g) at a scale $\mu^2 = 10$ GeV^2.

The second chiral-even quark distrbution:

Double longitudinal spin asymmetry in polarized DIS

The polarized proton structure function

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta(x, Q^2)$$

The helicity distribution $\Delta q(x, Q^2)$ of the quarks in a proton polarized parallel to its momentum.

The first moment measures the *axial* charge of the quarks

$$\begin{aligned}\Delta\Sigma &= \langle PS|\overline{\psi}\gamma^\mu\gamma_5\psi|PS\rangle \\ &= \int_0^1 dx(\Delta q(x) + \Delta\overline{q}(x))\end{aligned}$$

Can be identified with the quark spin contribution to the nucleon spin.

QCD evolution properties of helicity distribution:

Large x, valence quarks: very weak Q^2 dependence of the asymmetry

Very SLOW growth towards small x:

$\star$ polarized quarks readily radiate soft gluons but soft gluons are unpolarized.

$$A_{LL} = A_1 \text{ vanishes as } x \to 0.$$

$\star$ within collinear factorization a perturbative splitting of polarized gluons

$$g \to q\bar{q}$$

does not transfer polarization to (anti)quarks.

$\star$ Collinear factorization fails: very important contribution from the axial anomaly:

$$\Delta\Sigma \Longrightarrow \Delta\Sigma - \frac{3}{2\pi}\alpha_S(Q^2)\Delta g(Q^2)$$

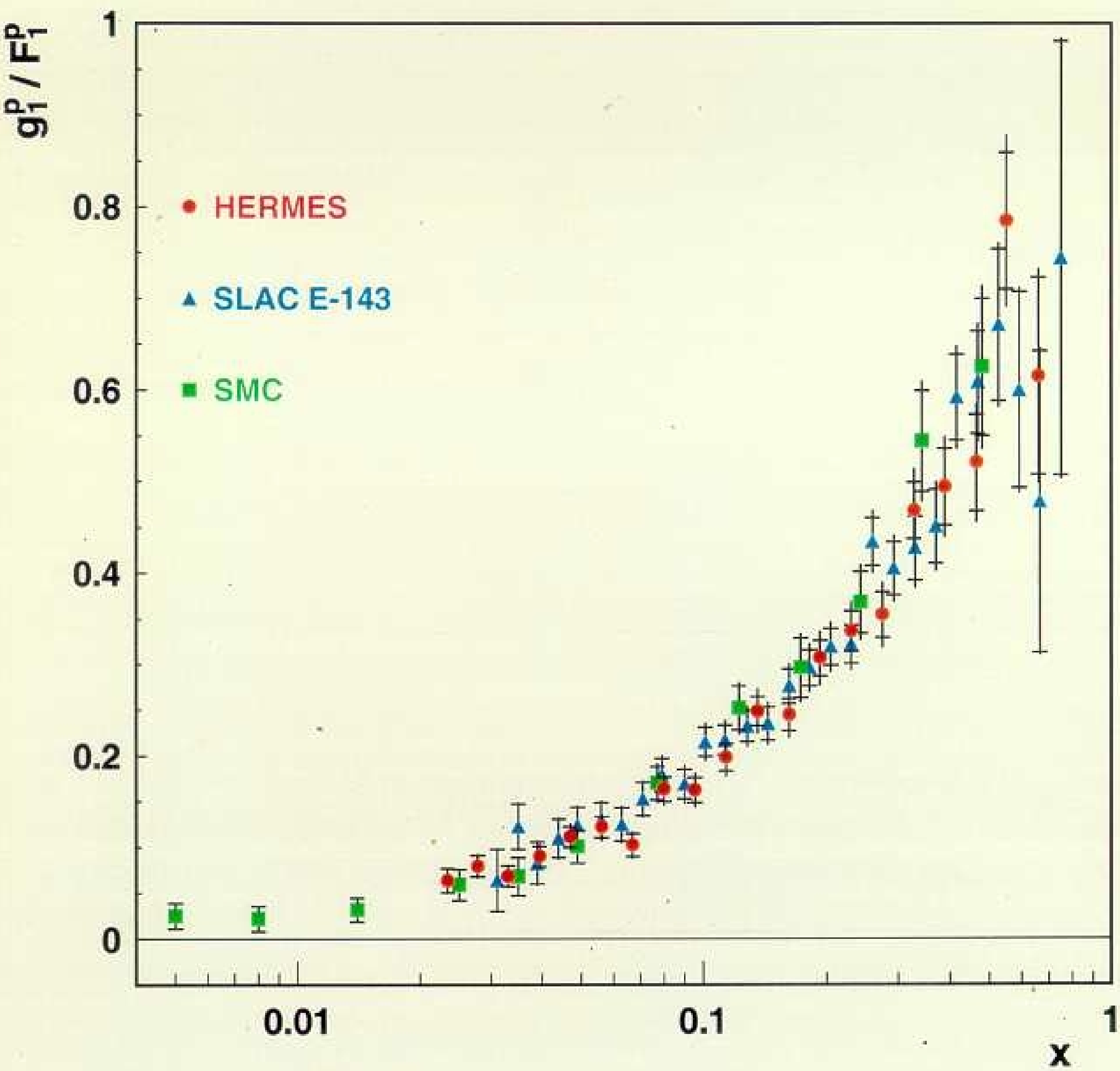


Fig. 7: Double longitudinal spin asymmetry in polarized DIS shown as the ratio of polarized to unpolarized proton structure function from the SMC, E143 and HERMES experiments.

The weighting by e_q^2; invoke SU(3) and axial constants from hyperon decays. The no-glue phenomenology:

$$\Delta u + \Delta\bar{u} = 0.76 \pm 0.03$$

$$\Delta d + \Delta\bar{d} = -0.48 \pm 0.03$$

$$\Delta s + \Delta\bar{s} = -0.14 \pm 0.03$$

The EMC spin crisis:

$$\Delta\Sigma = 0.16 \pm 0.08 \ll 1$$

Typical fits to DIS + semi-inclusive data with allowance for polarized glue:

$$\Delta g(Q^2) \sim 1$$

boosts $\Delta\Sigma$ to $\Delta\Sigma \approx 0.4$

The quest for polarized glue $\Delta g(Q^2)$ is the prime task of COMPASS & RHIC.

How much of the proton spin has gone to the orbital angular momentum of quarks & gluons ????????

Orbital angular momentum

$\gamma^*_T, V_T \qquad \lambda + \bar{\lambda} = \begin{cases} \pm 1 \otimes L_z = 0 \\ 0 \otimes L_z = \pm 1 \end{cases}$

$\gamma^*_L, V_L \qquad \lambda + \bar{\lambda} = 0$

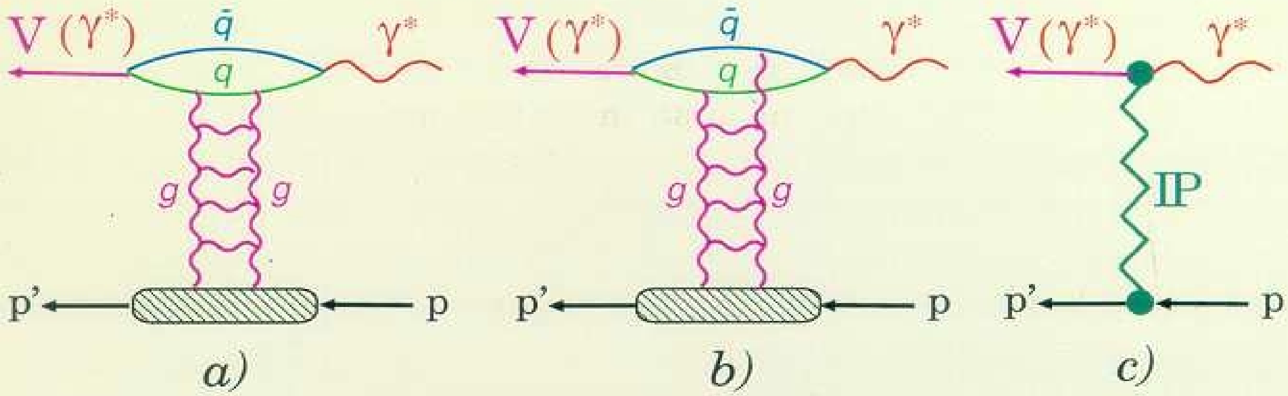


Fig. 6: (a,b) The subset of two-gluon tower pQCD diagrams for the Pomeron exchange contribution (c) to the Compton scattering (DIS) and diffractive vector meson production. Not shown are two more diagrams with $q \leftrightarrow \bar{q}$.

Exact conservation of $\lambda, \bar{\lambda}$

$\gamma_L \rightarrow (\bar{q}q)_{\lambda+\bar{\lambda}=0} \rightarrow V_T$

Helicity flip is entirely from orbital momentum

ρ spin density matrix

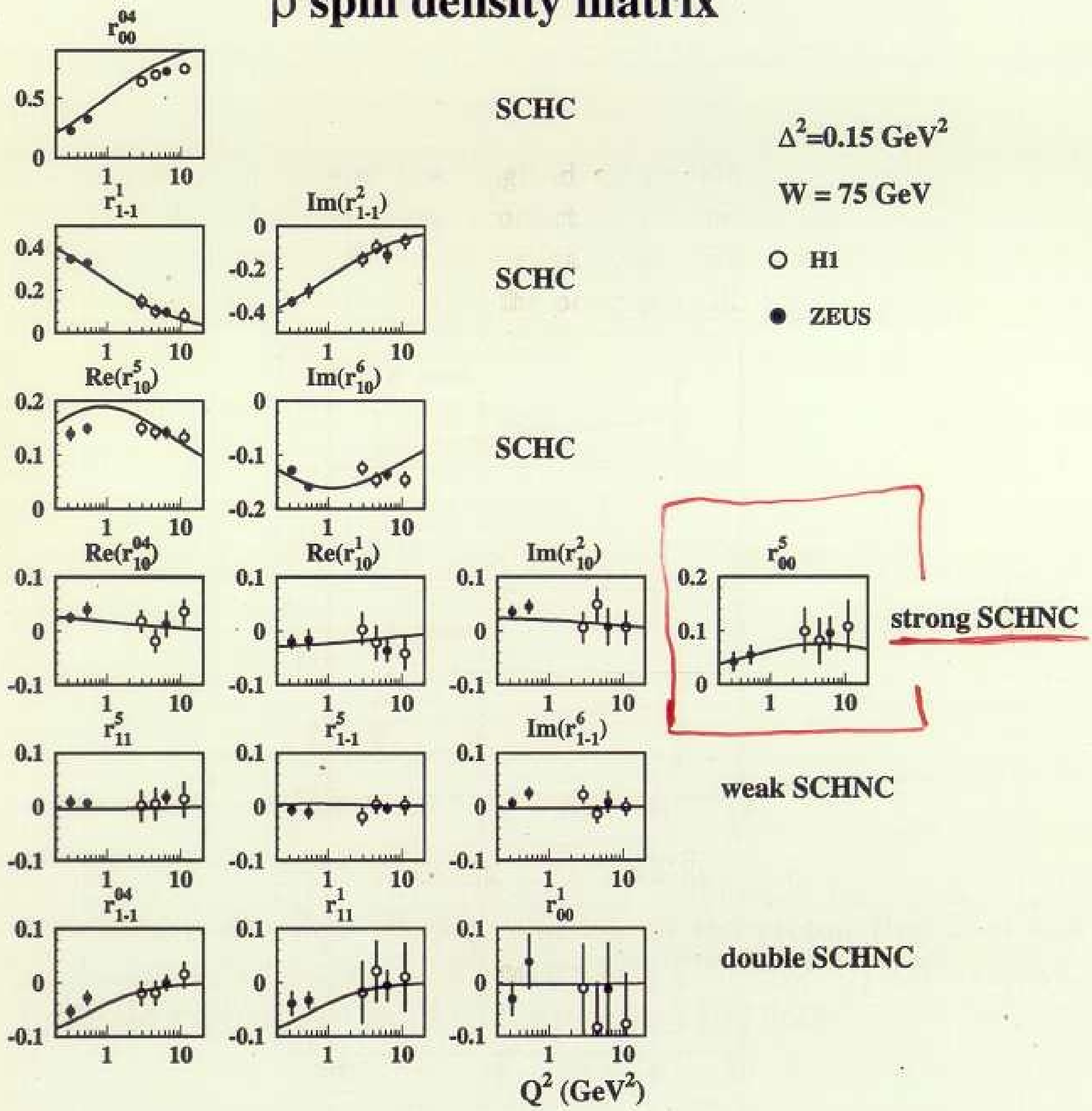
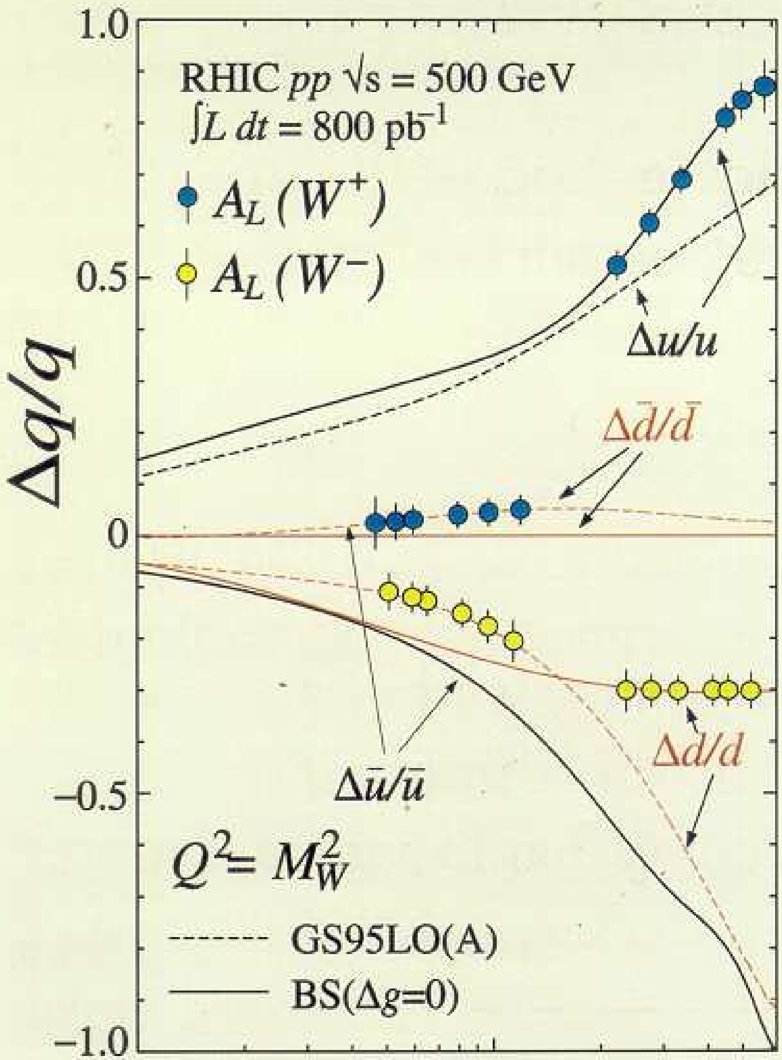


Fig. 9: The spin-density matrix elements measured in the reaction $\gamma^* p \to \rho p$ as a function of Q^2. The first three rows are the same as in Fig. ?? and show the SCHC matrix elements. The full symbols present the ZEUS [?] and the open points the H1 [?] results. The curves represent the k_t-factorization calculations [?, ?].

Double longitudinal spin asymmetries in jet and open charm production at RHIC.

Take advantage of parity violation in $pp \to W^{\pm}X$ at RHIC.



Expected sensitivity to the parton polarizations at RHIC

The *third* leading twist structure function: the chiral-odd quark distribution:

The transversity $h_1(x, Q^2)$ measures the quark transverse spin distribution in a proton polarized perpendicular to the proton momemtum at infinite momentum.

Is related to the quark tensor charge through its first moment

$$\langle PS|\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS\rangle = \int_0^1 dx(\delta q_1(x)+\delta\overline{q}_1(x))$$

Until now its properties remain completely unknown.

The nonrelativistic intuition: the both axial-vector and axial-tensor currents describe the same Gamow-Teller transitions but with important distnction:

$$\gamma^\mu \gamma_5 \Longrightarrow S_z = \sigma_3$$

Only chiral-even nonvanishing matrix elements between

$$\Psi_L \quad and \quad \Psi_L, \qquad or \quad \Psi_R \quad and \quad \Psi_R$$

$$\sigma^{\mu\nu} \gamma_5 \Longrightarrow S_\pm = \sigma_\pm$$

Only chiral-odd nonvanishing matrix elements between

$$\Psi_L \quad and \quad \Psi_R, \qquad or \quad \Psi_R \quad and \quad \Psi_L$$

Nonrelativistically, for massive quarks, the transversity and helicity matrix elements are related by rotations.

Not true relativistically: in hard QCD the chiral-even helicity distribution is trivial, the chiral-odd transversity probes the chiral-symmetr breaking in hard domain!!!!

Poor man's approximation:$h_1 \approx g_1$

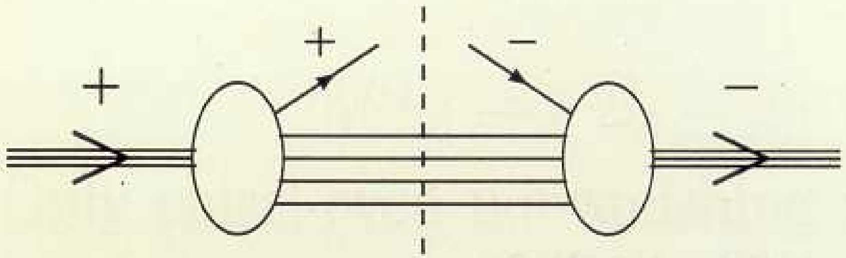


Figure 1: *Transversity in helicity basis.*

Precludes a gluon transversity distribution at leading twist - mismatch of the gluon and nucleon helicity flip!
Hard QCD and electroweak processes conserve chirality!!!
Transversity decouples from DIS unless coupled to a second chiral-odd function:
(a) Drell-Yan with transverse polarized beam and target: transversity of the beam couples to transversity of the target. Double transverse spin asymmetry.
(b) Knock-out of transversly polarizied quark coupled to *(unknown)* chiral-odd fragmentation as poor man's polarimeter of transversity.

Chiral-odd fragmentation: where from?

⋆ Make use of the transverse momentum which the pion produced in fragmentation may have with respect to the momentum of the transversely polarized fragmenting parent quark.

A correlation of the form

$$i\vec{S}_T \cdot (\vec{P}_\pi \times \vec{k}_\perp)$$

⋆ Almost deja vue: recall elastic scattering!

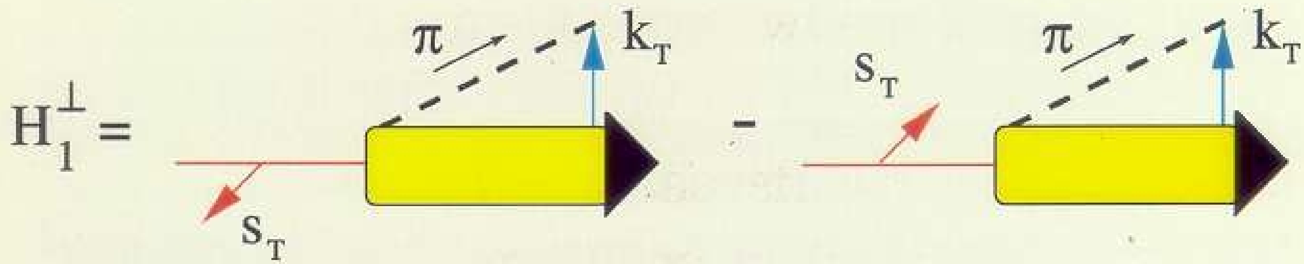


Figure 2: *The Collins function.*

Looks T-odd: requires a phase induced by final-state interactions.

Is the $k_\perp$ of the parton in the initial state relevant as well?
Sivers: the $k_\perp$ distribution could have an azimuthal asymmetry,

$$\vec{S}_T \cdot (\vec{P} \times \vec{k}_\perp)$$

times the unpolarized fragmentation. Contains

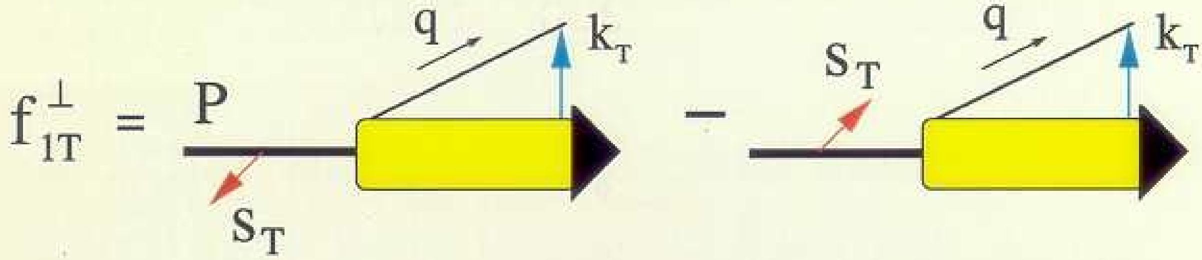


Figure 3: *The Sivers function.*

information on the parton angular momentum distributions.
For more than a decade was argued *(erroneously)* to vanish by time-reversal arguments: the final state interaction caused phases believed to be of no help for initial state asymmetries.

Single *transverse* spin effects: azimuthal asymmetry of produced hadrons (pions) & transverse polarization of hyperons (Λ's)

⋆ SSA is large!

⋆ Seen in all reactions at all energies from COSY to KEK to FNAL to RHIC to ....

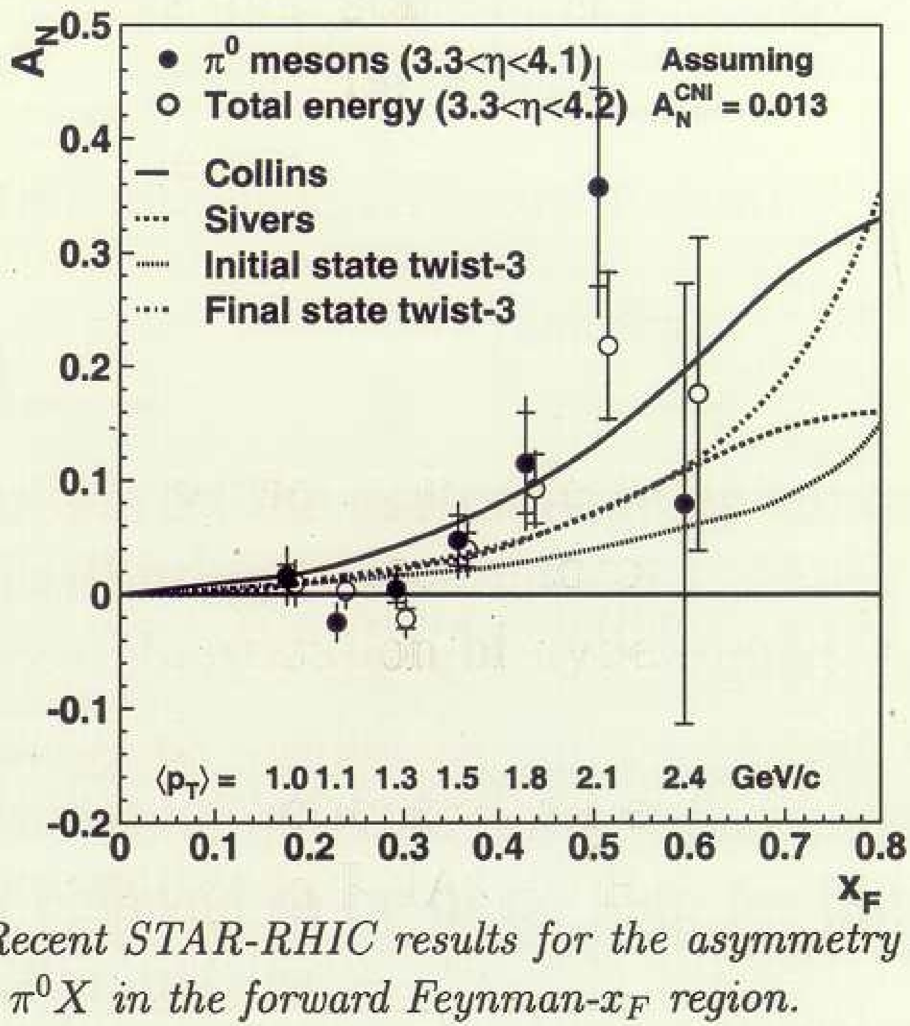


Figure 4: *Recent STAR-RHIC results for the asymmetry* A_N *in* $pp \to \pi^0 X$ *in the forward Feynman-*x_F *region.*

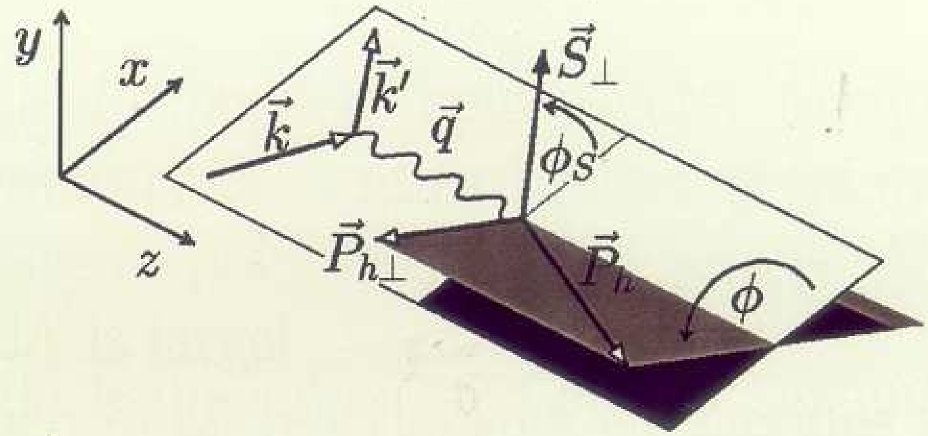


Figure 5: *Azimuthal angles of the hadron production plane and the target spin, relative to the lepton scattering plane.*

Collins vs. Sivers in semi-inclusivd DIS:

The observable: single-spin asymmetry $A_\perp$ in the reaction $ep^\uparrow \to e'\pi X$:

$\star$ Collins:

$$A_\perp \propto |\vec{S}_T| \sin(\phi+\phi_S) \sum_q e_q^2 h_1(x)\ H_1^{\perp,q}(z)\ ,$$

$\star$ Sivers:

$$A_\perp \propto |\vec{S}_T| \sin(\phi-\phi_S)\ \sum_q e_q^2\ f_{1T}^{\perp,q}(x)\ D_q^\pi(z)$$

Separable from Collins by the azimuthal angular dependence.

HERMES

Both Collins and Sivers are at work:

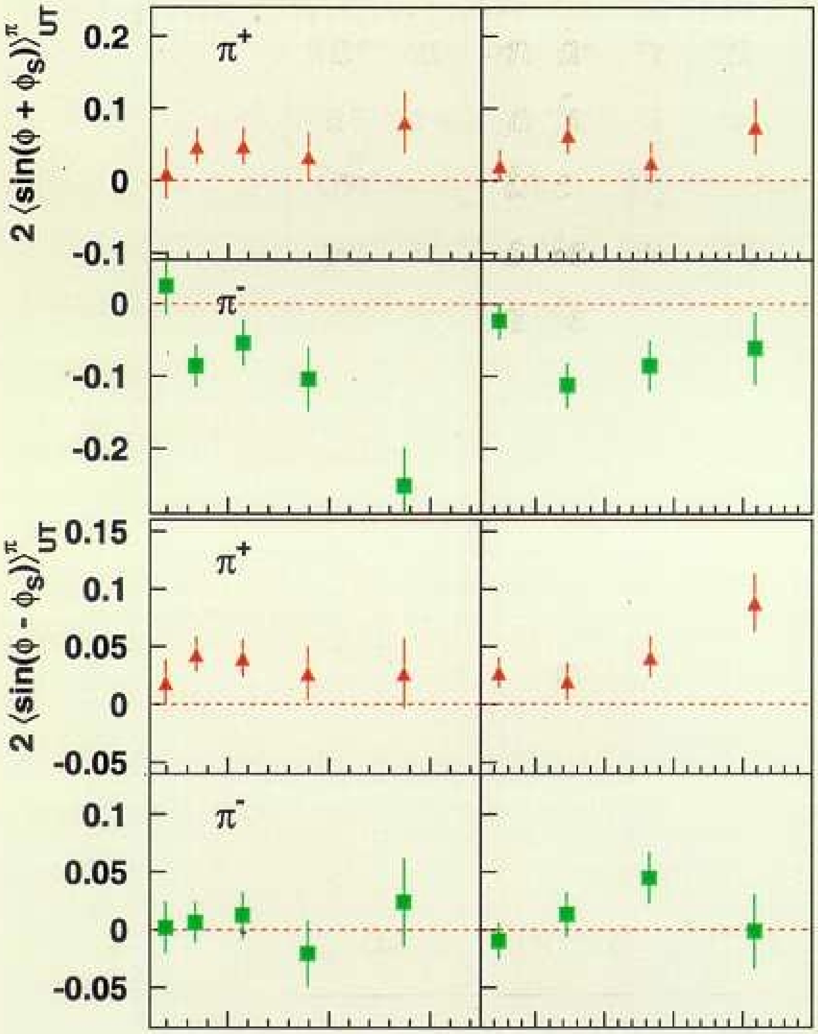


Figure 7: *DIS Collins (Sivers) moments for charged pions as a function of x and z.*

Double transverse polarized Drell-Yan production at HESR: $p^{\uparrow}\bar{p}^{\uparrow} \to e^+e^- X$.

The pQCD subprocess

$$q^{\uparrow}(x_1)\,\bar{q}^{\uparrow}(x_2) \to e^+e^-$$

The observable: the azimuthal asymmetry

$$\hat{a}_{TT}(\theta,\varphi) = \frac{\sin^2\theta}{1+\cos^2\theta}\,\cos(2\varphi)\,, \qquad (1)$$

θ = the polar angle of the lepton pair wrt to the collision axis,
φ = azimuthal angle of the lepton wrt to the polarization axis.

Has been measured at e^+e^- colliders: natural transverse polarization of beam by the Sokolov-Ternov effect. The first ever evidence for hadronic jets from the observation of $a_{TT}(\theta,\varphi)$

Kinematics & dynamics of Drell-Yan:
the mass of the pair M:

$$M^2 = x_1 x_2 s$$

the longitudinal momentum

$$x_F = x_1 - x_2$$

The total cross section

$$\frac{d\sigma}{dM^2\, dx_F} = \frac{4\pi\alpha^2}{9\, M^2 s\, (x_1 + x_2)}$$
$$\sum_q e_q^2 \, [q(x_1)\, \bar{q}(x_2) + (1 \leftrightarrow 2)]$$

The transversity signal is a chiral-even observable:

$$A_{TT}^{pp} = \hat{a}_{TT}$$
$$\times \sum_q e_q^2 \left[h_1^q(x_1, M^2)\, h_1^{\bar{q}}(x_2, M^2) + (1 \leftrightarrow 2)\right] /$$
$$\sum_q e_q^2 \left[q(x_1, M^2)\, \bar{q}(x_2, M^2) + (1 \leftrightarrow 2)\right] ,$$

QCD evolution of transversity:

$\star$ Gluons don't like to carry transversity: the helicity mismatch:

$$\Delta\lambda_N = \pm 1 \neq \Delta\lambda_g = \pm 2$$

$\Longrightarrow$ very poor transfer of transversity from the valence quarks to the sea.

$\star$ RHIC: valence quark of one proton has to annihilate with the sea antiquark from another proton and vice versa, it is hard to predict the transversity of the sea.

$\Longrightarrow$ very small A_{TT}^{pp} at RHIC, at the best a few per cent effect.

Drell-Yan with PAX at HESR:

⋆ The dominant pQCD subprocess: annihilation of the valence quark in the proton with the valence anti quark in the antiproton.

⋆ Poor man's *but still realistic* estimate: transversity of valence quarks ∼ helicity distribution of valence quarks.

e_q^2 favours u-quarks, helicity density for d quarks is small

$$\frac{A_{TT}^{p\bar{p}}}{\hat{a}_{TT}} \simeq \frac{h_1^u(x_1, M^2)\, h_1^u(x_2, M^2)}{u(x_1, M^2)\, u(x_2, M^2)} \simeq A_1(x_1, M^2) A_1(x_2, M^2) \quad (2)$$

HESR: $x_{1,2} \sim$ 0.3 0.5 $\div$ 0.7, gigantic $A_{TT}^{p\bar{p}} \sim 30\%$. Weak variation over the phase space. Admits simple theoretical interpretation. Still larger asymmetries are predicted by chiral soliton models.

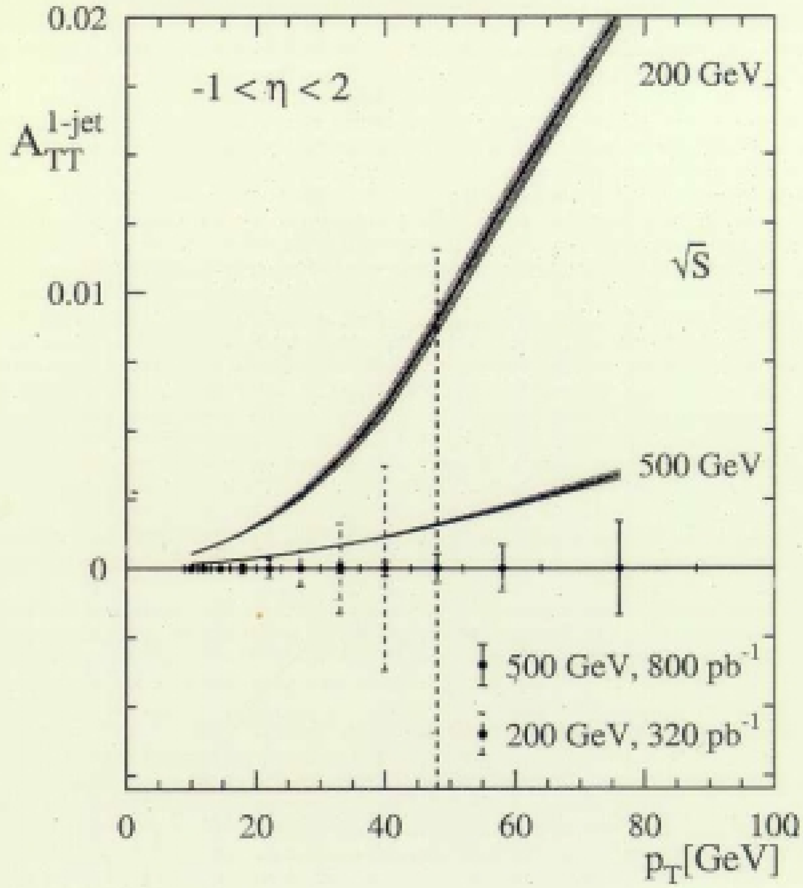


Figure 1: "Maximally possible" A_{TT} for single-inclusive jet production at RHIC c.m.s. energies of 200 GeV and 500 GeV as a function of p_T. Jet rapidities are integrated over the detector acceptance ($-1 \leq \eta \leq 2$). The shaded bands represent the theoretical uncertainty in A_{TT} if μ_F is varied in the range $p_T/2 \leq \mu_F \leq 2p_T$. Also indicated as "error bars" is the expected statistical accuracy for certain bins in p_T.

Not so high energy of HESR is not a problem!

$s = 30\ \text{GeV}^2 \quad \Rightarrow M \lesssim 5.5\ \text{GeV}$

The standard DY studies focus on $M > 4$ GeV to kill the $J/\Psi, \Psi'$ background.

The J/Ψ is not a background for the transversity studies!

The dominant pQCD subprocess at HESR:

$$q\bar{q} \rightarrow J/\Psi \rightarrow e^+e^-$$

J/Ψ is spin-1 particle, the same asymmetry as in

$$q\bar{q} \rightarrow \gamma^* \rightarrow e^+e^-$$

$\Longrightarrow$ one can safely extend the A_{TT} studies to $M < 3$ GeV. NLO pQCD corrections have little impact on asymmetries.

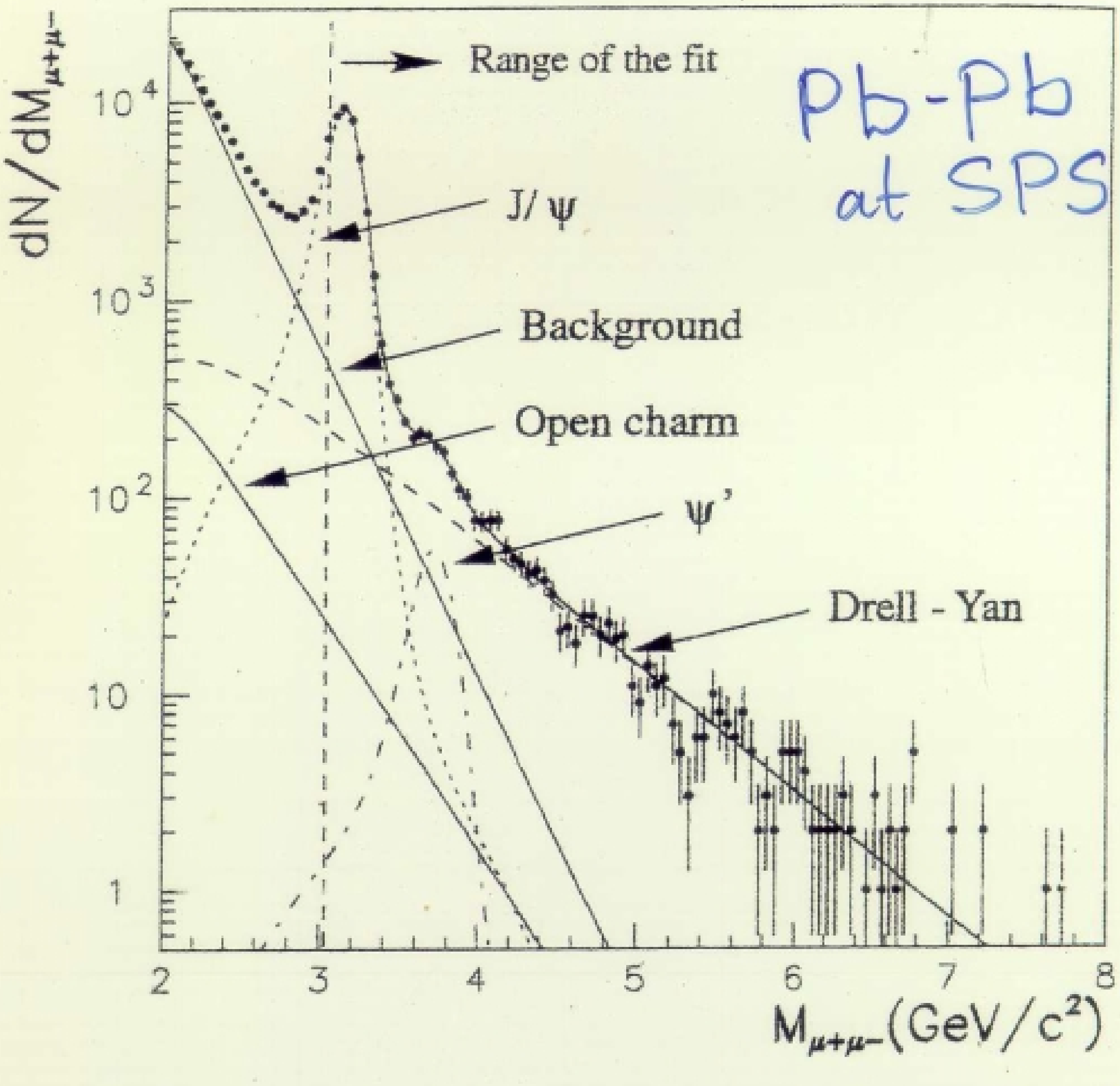


Figure 8 Mass distribution of $\mu^+\mu^-$ pairs in Pb-Pb collisions. From Reference 57 with permission.

Summary & Outlook

- ~40 years of unpolarized DIS
- ~30 years of unpolarized Drell-Yan
- ~20 years of helicity in DIS

The Future:

★ Transversity in $\bar{p}^{\uparrow} p^{\uparrow}$ at PAX-HESR

- Ideal Kinematical conditions to explore the valence region
- Large asymmetry A_{TT}, easy interpretation

! PAX-HESR is better than RHIC