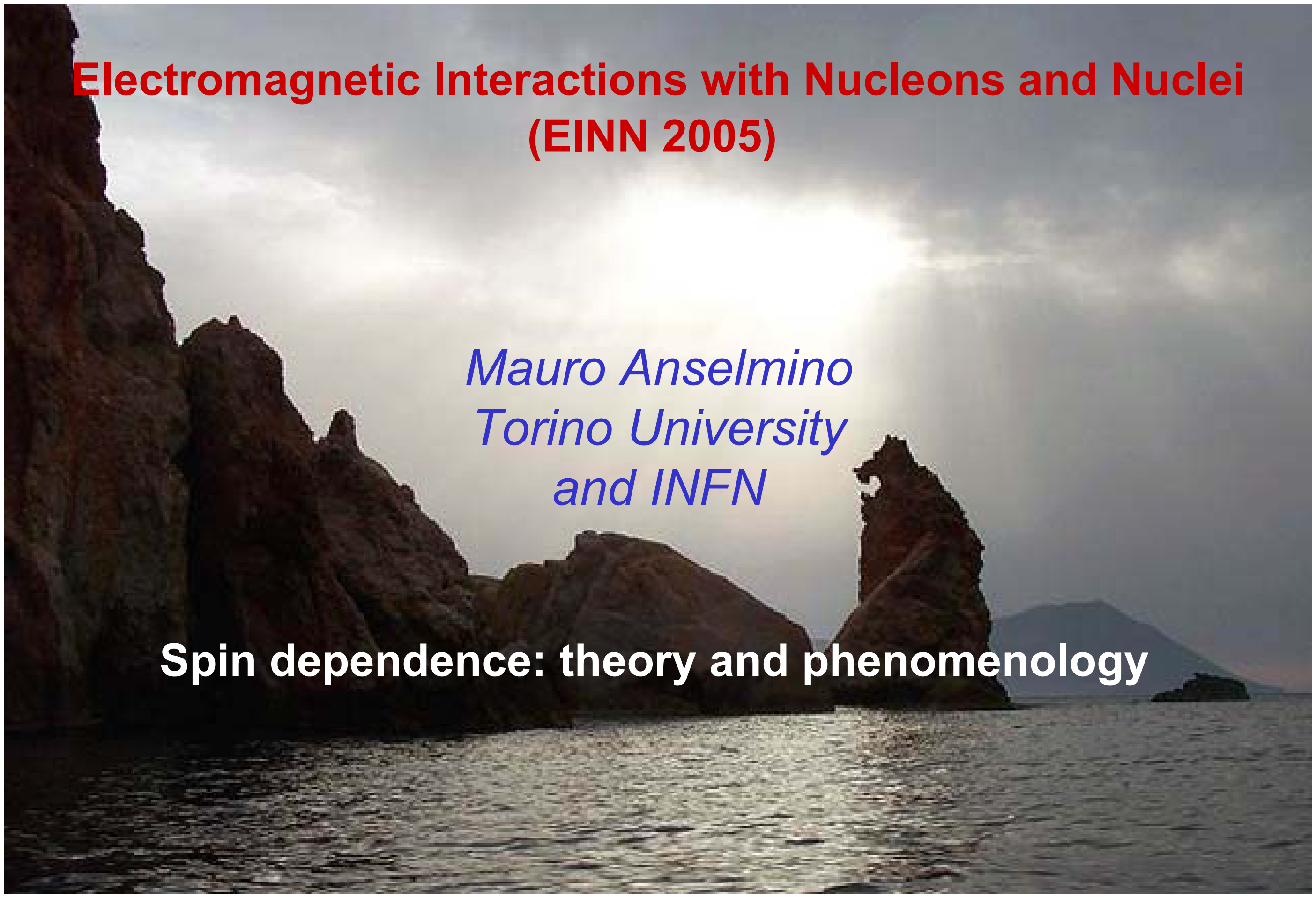
6th European Research Conference
September 21-24, 2005 - Milos, Greece



Electromagnetic Interactions with Nucleons and Nuclei (EINN 2005)

Mauro Anselmino
Torino University
and INFN

Spin dependence: theory and phenomenology

"Partonic spin cases"

Polarized DIS and helicity distributions,
spin carried by quarks and gluons?

Transversity distributions, unknown

Spin dependent, $k_\perp$ unintegrated parton distributions:
fundamental spin-$k_\perp$ correlations?

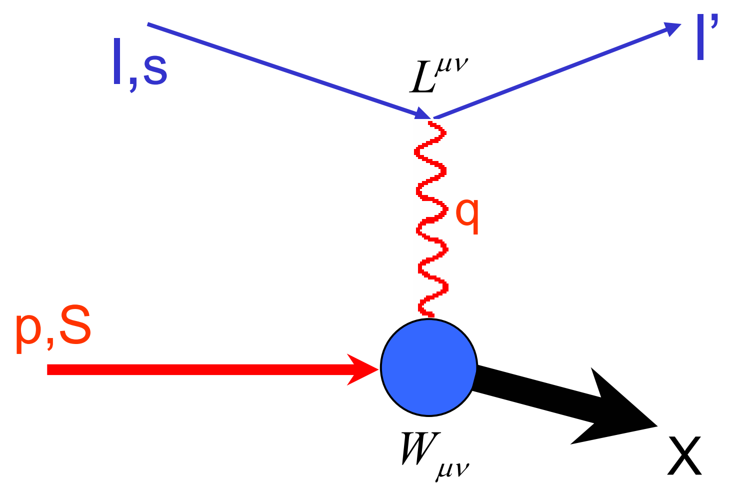
$f_{a,s/p,S}(x,\vec{k}_\perp,Q^2)$ ⇔ Transverse single spin asymmetries

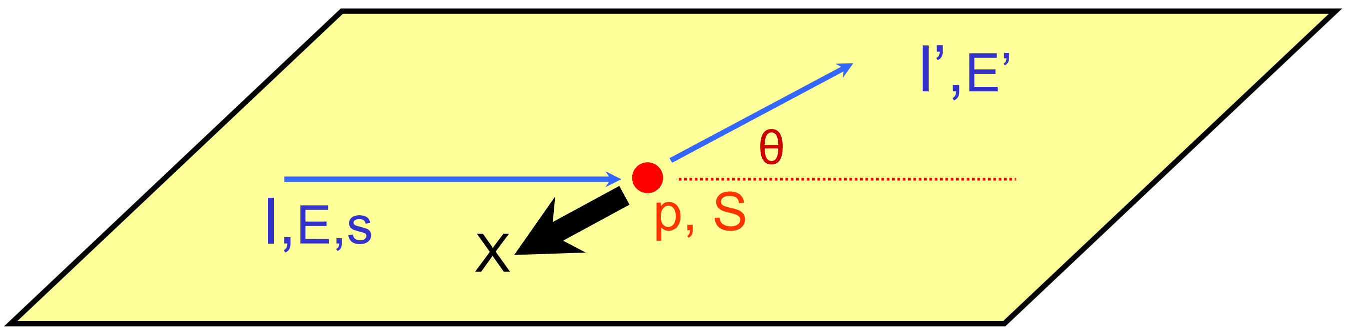
Polarized fragmentation functions $D_{h,S/a,s}(z,\vec{p}_\perp,Q^2)$

What do we know, and how, about the proton structure?

Main source of information is DIS

$$\frac{d\sigma}{d\Omega\, dE'} = \frac{\alpha^2}{2Mq^4}\frac{E'}{E} L^{\mu\nu} W_{\mu\nu}$$





parity conserving case (one photon exchange)

$$L^{\mu\nu}(l,l',s) = 2\left(l^{\mu}l'^{\nu} + l'^{\mu}l^{\nu} - g^{\mu\nu}l\cdot l'\right) + 2im\varepsilon_{\mu\nu\alpha\beta}s^{\alpha}(l-l')^{\beta}$$

$$W_{\mu\nu}(p,q,S) = \left(-g_{\mu\nu} + \frac{q_{\mu}q_{\nu}}{q^2}\right)F_1(x,Q^2) + \frac{\hat{p}_{\mu}\hat{p}_{\nu}}{p\cdot q}F_2(x,Q^2) +$$

$$-i\varepsilon_{\mu\nu\alpha\beta}\,q^{\alpha}\left[\frac{S^{\beta}}{p\cdot q}g_1(x,Q^2) + \frac{p\cdot q\,S^{\beta} - S\cdot q\,p^{\beta})}{(p\cdot q)^2}g_2(x,Q^2)\right]$$

measuring $d\sigma$ one extracts information on the structure functions F_1, F_2, g_1 and g_2

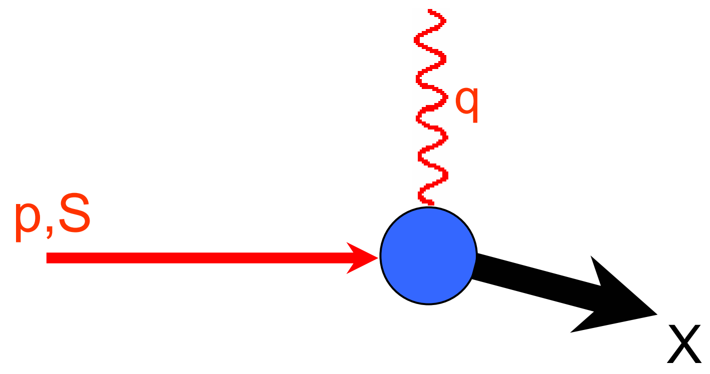
$$x = \frac{Q^2}{2p\cdot q} \qquad \hat{p}_{\mu} = p_{\mu} - \frac{p\cdot q}{q^2}q_{\mu}$$

$F_{1,2}$ related to $q(x,Q^2)$, $g(x,Q^2)$ quark, gluon distributions

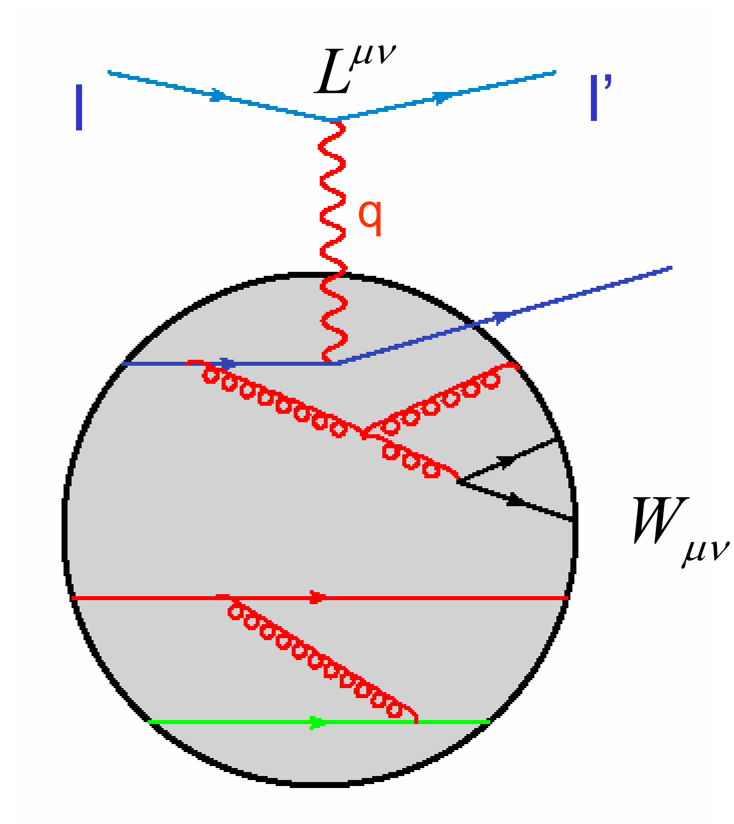
g_1 related to $\Delta q(x,Q^2)$, $\Delta g(x,Q^2)$ quark, gluon helicity distributions

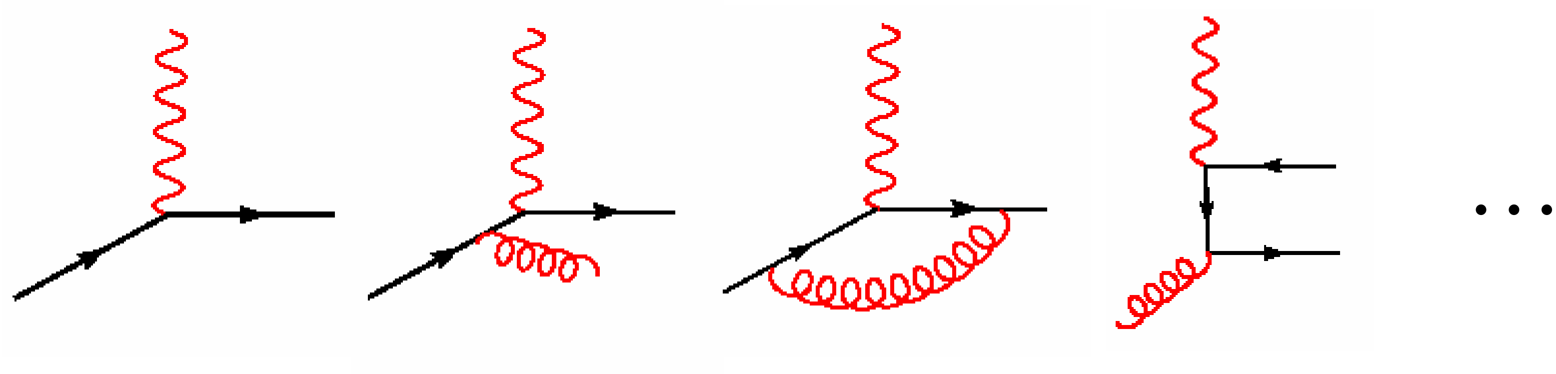
$$q = q_{+} + q_{-} \qquad \Delta q = q_{+} - q_{-} \qquad g = g_{+} + g_{-} \qquad \Delta g = g_{+} - g_{-}$$

QCD parton model



$\Rightarrow$





$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \left\{ \Delta C_q \otimes [\Delta q + \Delta\bar{q}] + \frac{1}{N_f} \Delta C_g \otimes \Delta g \right\}$$

$$C \otimes q \equiv \int_x^1 \frac{\mathrm{d}y}{y} C\left(\frac{x}{y}, \alpha_s\right) q(y,Q^2)$$

$$\Delta C_i(x,\alpha_s) = \Delta C_i^0(x) + \frac{\alpha_s(Q^2)}{2\pi} \Delta C_i^{(1)}(x) + \ldots$$

coefficient functions

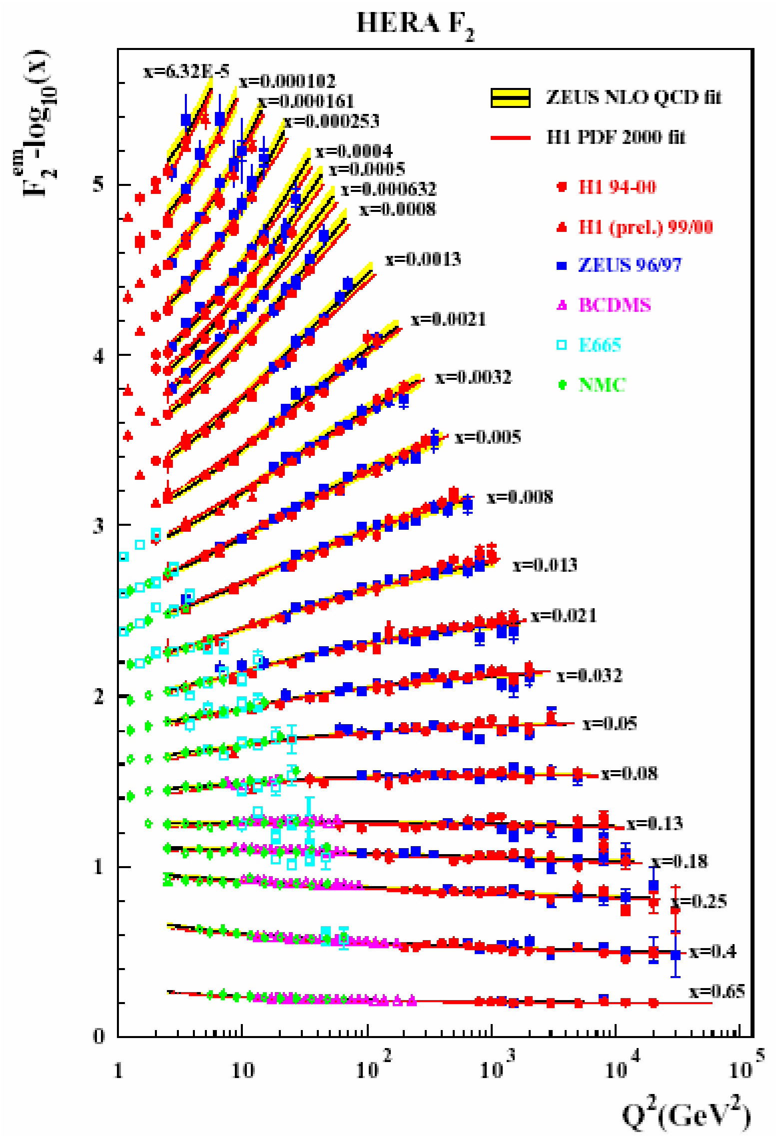
$$P_{ij}(x,\alpha_s) = P_{ij}^0(x) + \frac{\alpha_s(Q^2)}{2\pi} P_{ij}^{(1)}(x) + \ldots$$

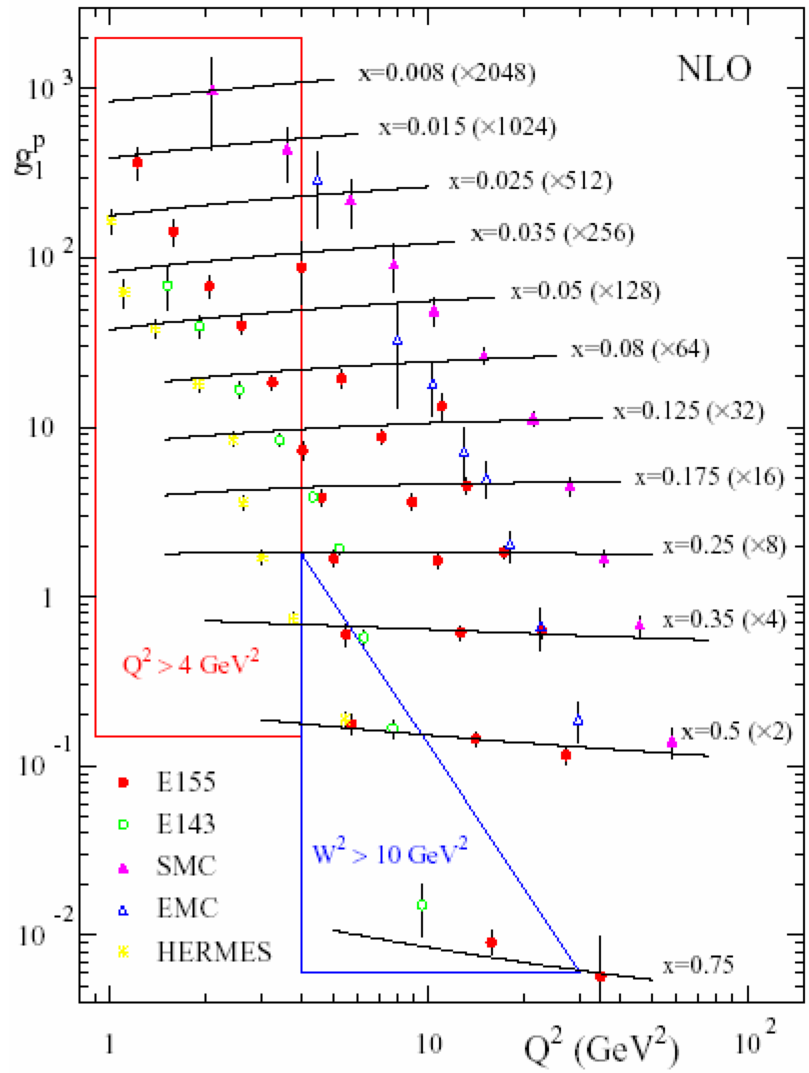
splitting functions

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2} \begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi} \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix}$$

QCD evolution

$$\left(\Delta\Sigma = \sum_q [\Delta q + \Delta\bar{q}] \right)$$


HERA F_2
F_2^{em}-$\log_{10}(x)$
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
ZEUS NLO QCD fit
H1 PDF 2000 fit
H1 94-00
H1 (prel.) 99/00
ZEUS 96/97
BCDMS
E665
NMC
Q^2(GeV^2)


g_1^p
NLO
x=0.008 (×2048)
x=0.015 (×1024)
x=0.025 (×512)
x=0.035 (×256)
x=0.05 (×128)
x=0.08 (×64)
x=0.125 (×32)
x=0.175 (×16)
x=0.25 (×8)
x=0.35 (×4)
x=0.5 (×2)
x=0.75
Q^2 > 4 GeV^2
W^2 > 10 GeV^2
E155
E143
SMC
EMC
HERMES
Q^2 (GeV^2)

de Florian, Navarro, Sassot

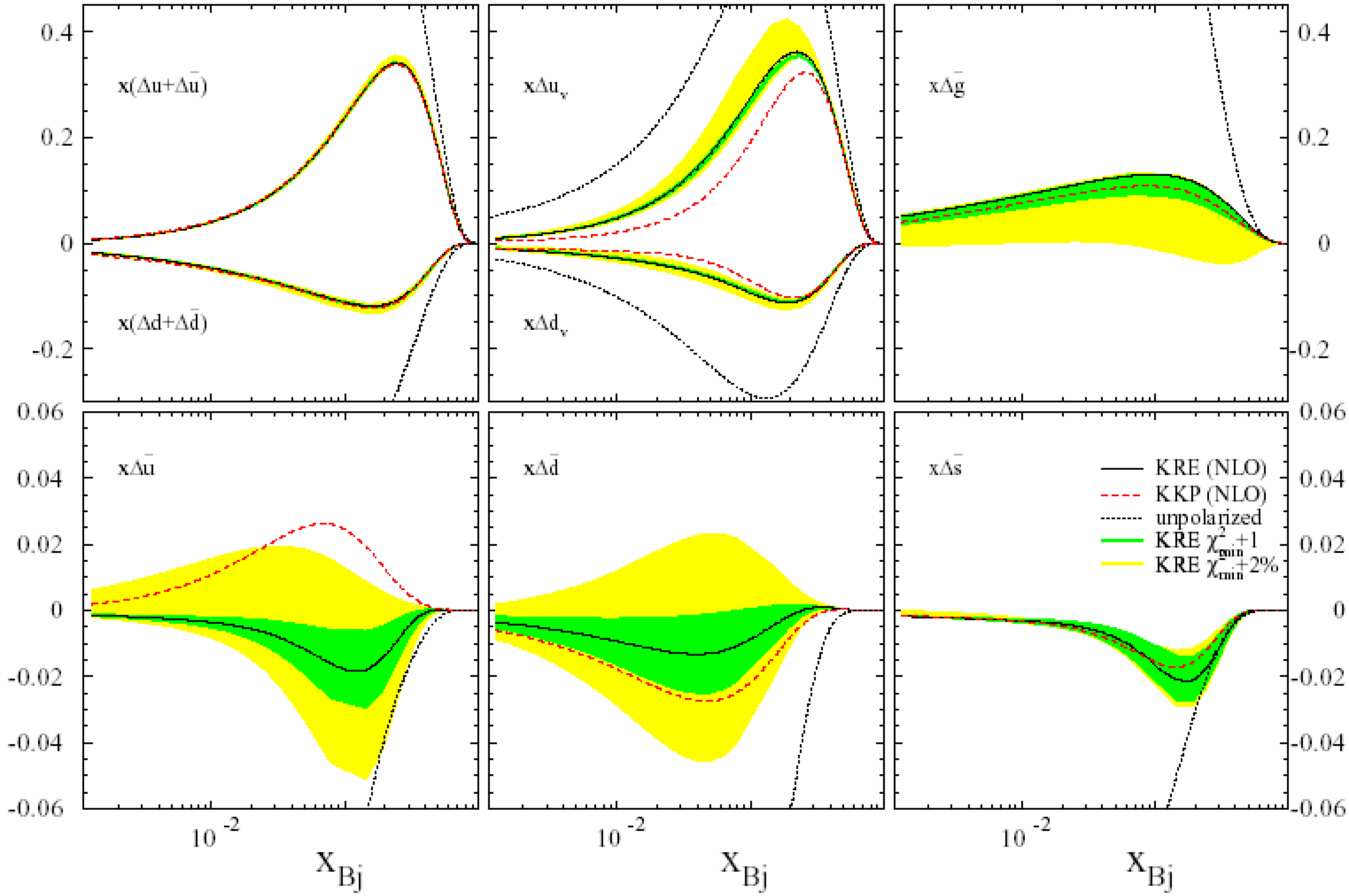


FIGURE 2. Parton densities at $Q^2 = 10$ GeV^2, and the uncertainty bands corresponding to $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 2\%$

Research Plan for Spin Physics at RHIC
February 11, 2005

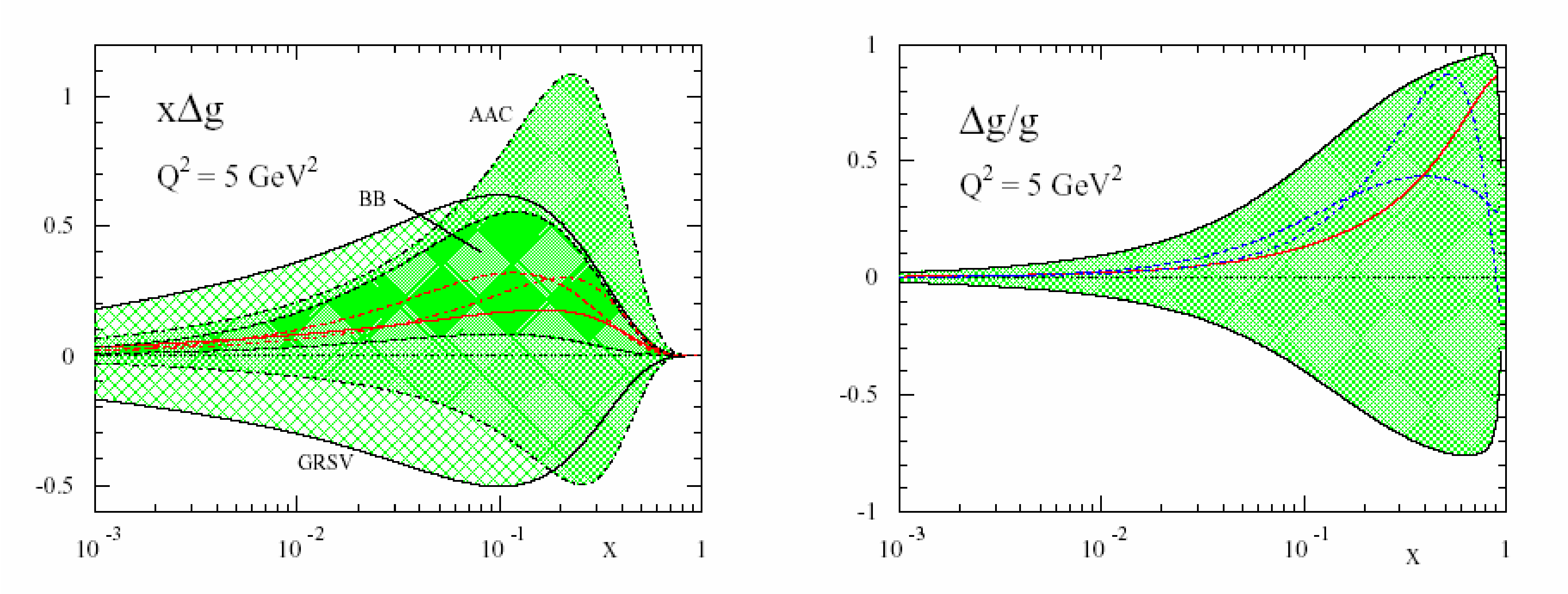


Figure 11: *Left: results for* Δg(x,Q^2 = 5GeV^2) *from recent NLO analyses [1, 2, 36] of polarized DIS. The various bands indicate ranges in* Δg *that were deemed consistent with the scaling violations in polarized DIS in these analyses. The rather large differences among these bands partly result from differing theoretical assumptions in the extraction, for example, regarding the shape of* Δg(x) *at the initial scale. Note that we show* xΔg *as a function of* log(x), *in order to display the contributions from various* x*-regions to the integral of* Δg. *Right: the "net gluon polarization"* Δg(x,Q^2)/g(x,Q^2) *at* Q^2 = 5 *GeV*^{2}*, using* Δg *of [2] and its associated band, and the unpolarized gluon distribution of [82].*

$$\langle S_q \rangle = \frac{1}{2}\int_0^1 \Delta\Sigma(x,Q^2)\,\mathrm{d}x \cong 0.1$$

$$\frac{1}{2} = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle$$

longitudinal spin sum rule, not the whole story…

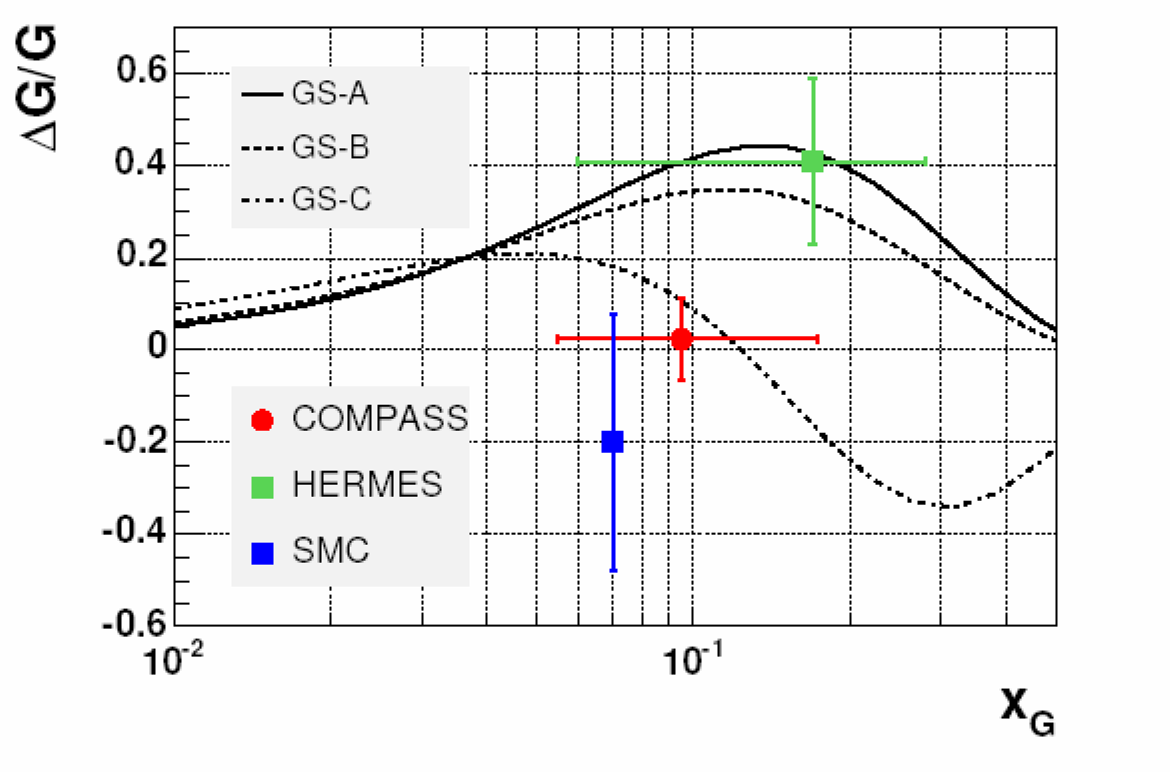
$$\left(\Delta\Sigma = \sum\nolimits_q (\Delta q + \Delta\overline{q}) \qquad \langle S_g \rangle(Q^2) = \int_0^1 \Delta g(x,Q^2)\,\mathrm{d}x \right)$$

Direct measure of Δg needed

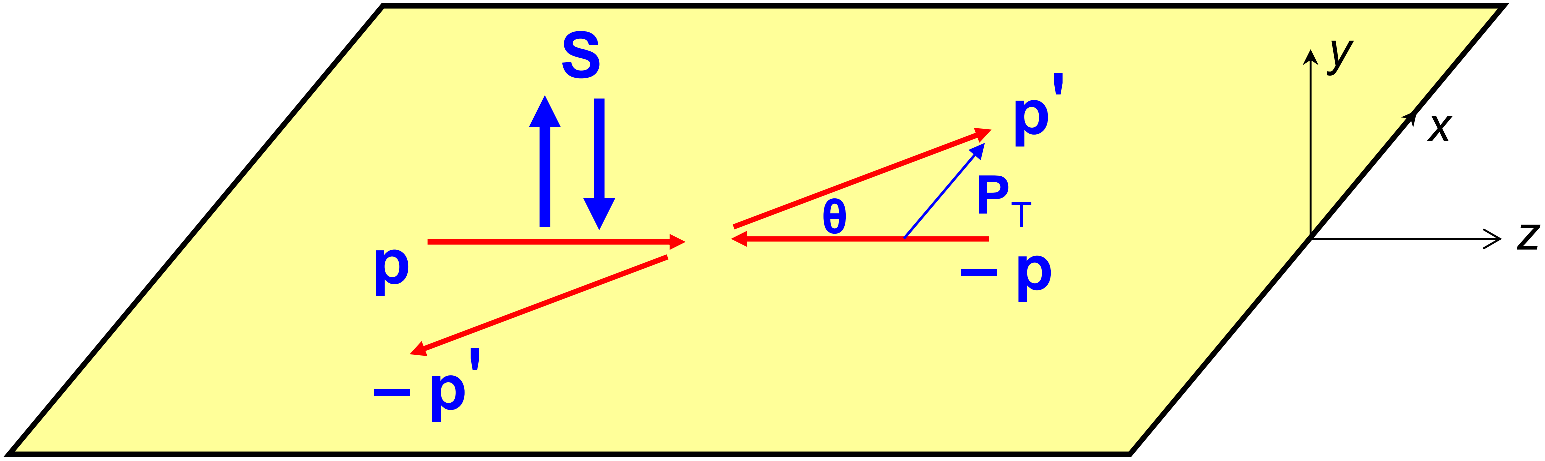
- large p_T di-hadron production in SIDIS, $\gamma^* g \to q\overline{q}$ — F. Tessarotto
- high p_T pions and jets at RHIC, $gg \to gg,\ qg \to qg$
- direct photon production at RHIC, $qg \to q\gamma$
- charm production at RHIC, $gg \to c\overline{c}$

Small and large x behaviours, flavour decompositions, …. — R. De Vita

large p_T di-hadron production in SIDIS



Transverse single spin asymmetries in elastic scattering



$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto \vec{\mathrm{S}} \cdot \left(\vec{\mathrm{p}} \times \vec{\mathrm{P}}_{\mathrm{T}} \right) \propto \sin\theta$$

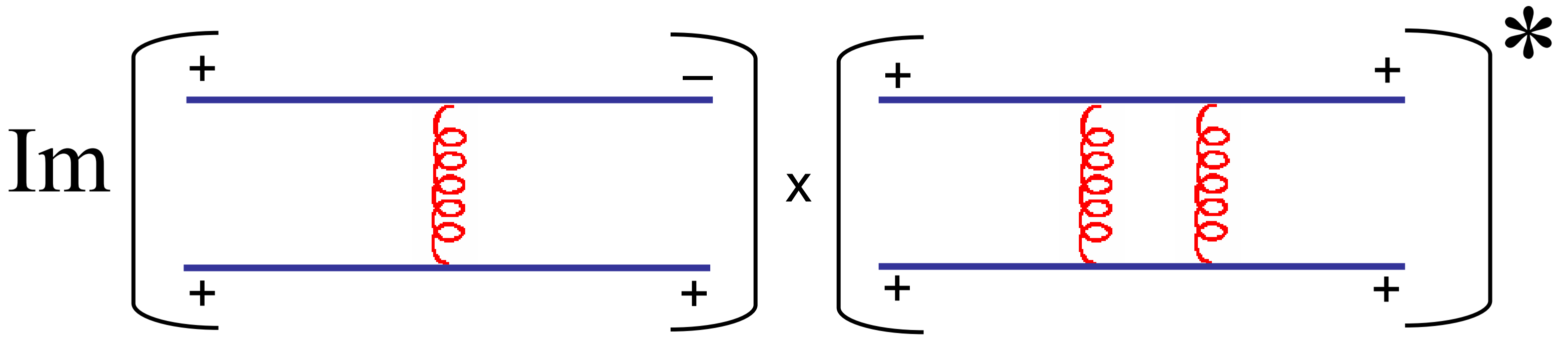
Example: $pp \to pp$

$$M_{++;++} \equiv \Phi_1$$
$$M_{--;++} \equiv \Phi_2$$
$$M_{+-;+-} \equiv \Phi_3$$
$$M_{-+;+-} \equiv \Phi_4$$
$$M_{-+;++} \equiv \Phi_5$$

5 independent helicity amplitudes

$$A_N \propto \mathrm{Im}\left[\Phi_5 (\Phi_1 + \Phi_2 + \Phi_3 - \Phi_4)^* \right]$$

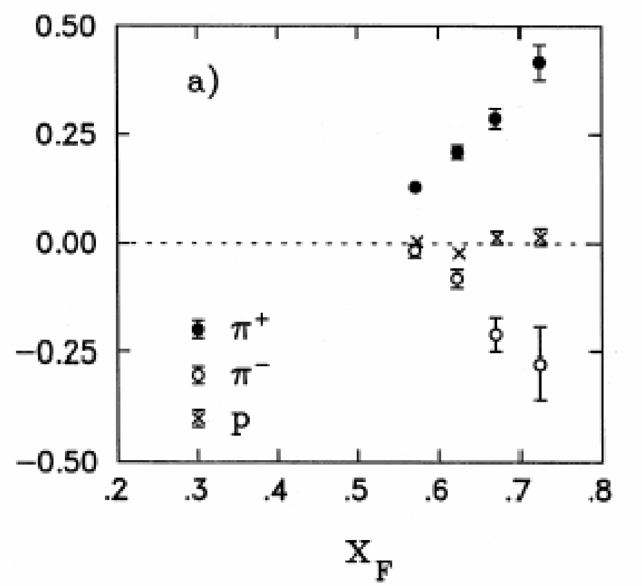
$A_N \neq 0$ needs helicity flip + relative phase



QED and QCD interactions conserve helicity, up to corrections $O(m_q / E)$

$$\Rightarrow \quad A_N \propto \frac{m_q}{E} \alpha_s$$ at quark level

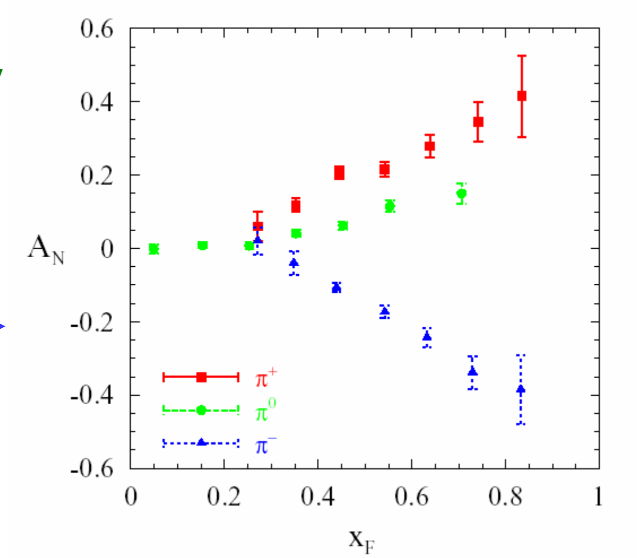
but large SSA observed at hadron level!

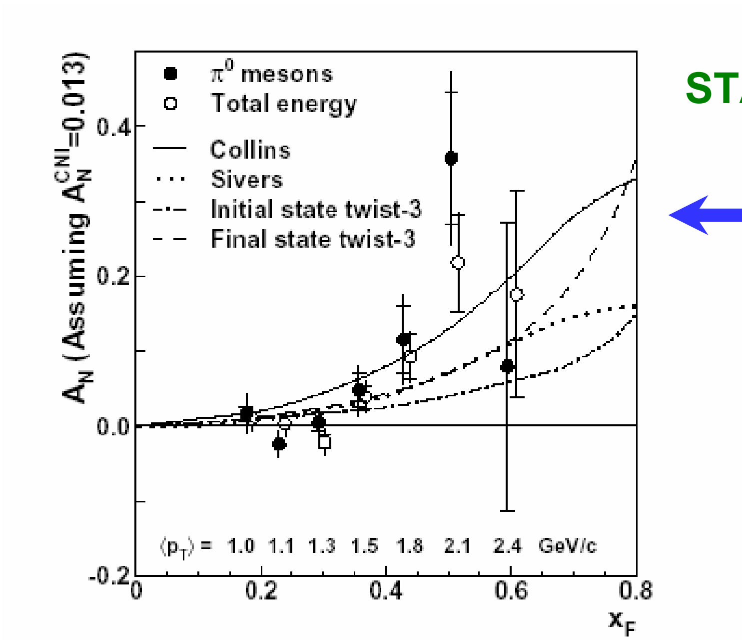


BNL-AGS $\sqrt{s}$ = 6.6 GeV
0.6 < p_T < 1.2

$$p^{\uparrow} p \rightarrow \pi X$$

E704 $\sqrt{s}$ = 20 GeV
0.7 < p_T < 2.0



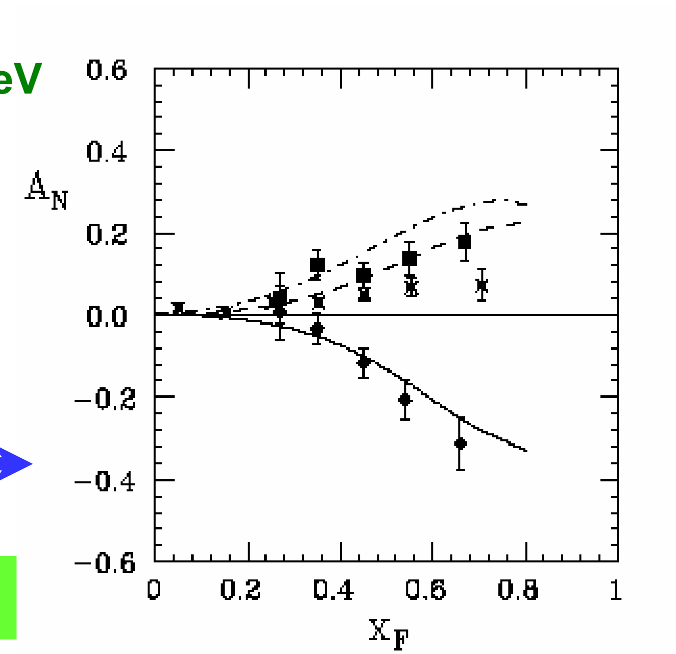


STAR-RHIC $\sqrt{s}$ = 200 GeV
1.1 < p_T < 2.5

$$p^{\uparrow} p \rightarrow \pi^0 X$$

E704 $\sqrt{s}$ = 20 GeV
0.7 < p_T < 2.0

$$\bar{p}^{\uparrow} p \rightarrow \pi X$$



SSA, pp → πX

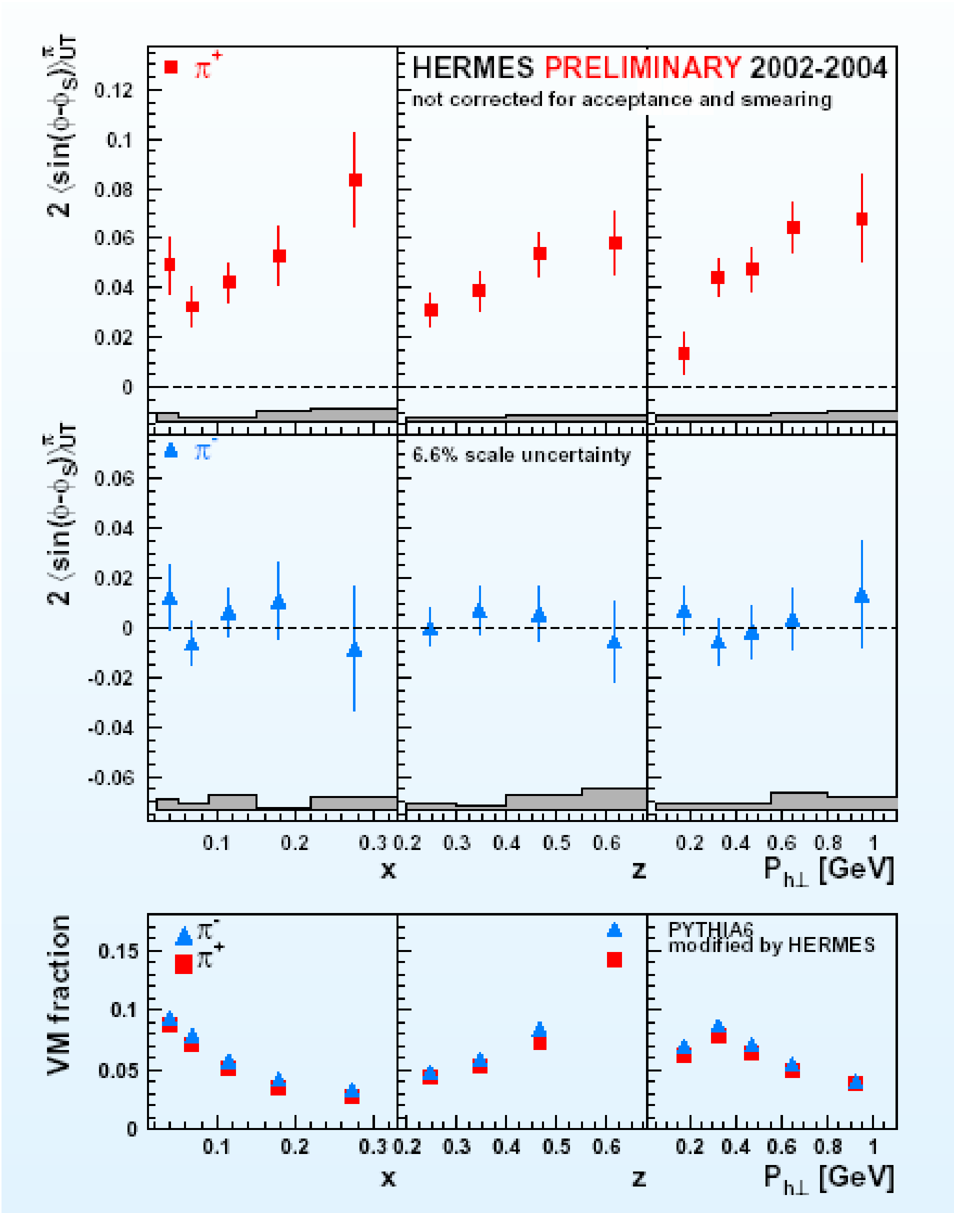
$$l\,N^{\uparrow} \to l\,\pi\,X$$

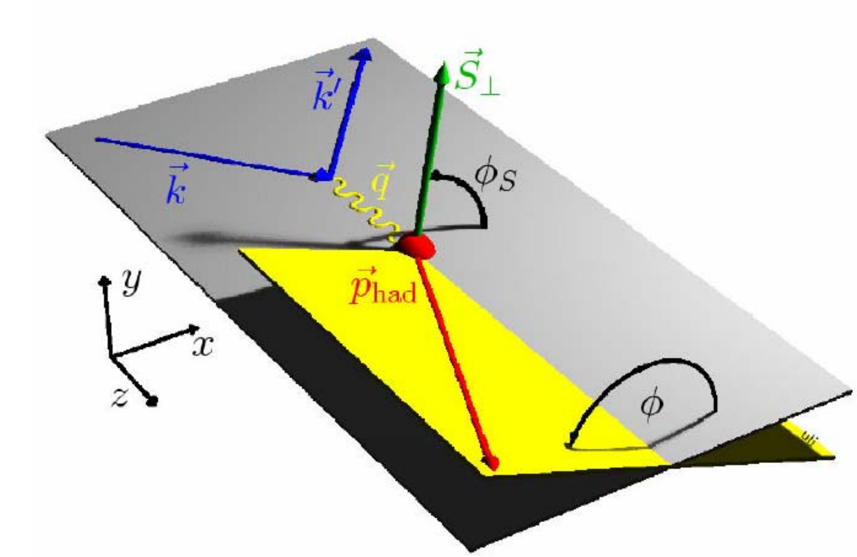
"Sivers moment"

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$2\langle \sin(\Phi - \Phi_S) \rangle = A_{UT}^{\sin(\Phi-\Phi_S)}$$

$$\equiv 2\,\frac{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} - d\sigma^{\downarrow}) \sin(\Phi - \Phi_S)}{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} + d\sigma^{\downarrow})}$$





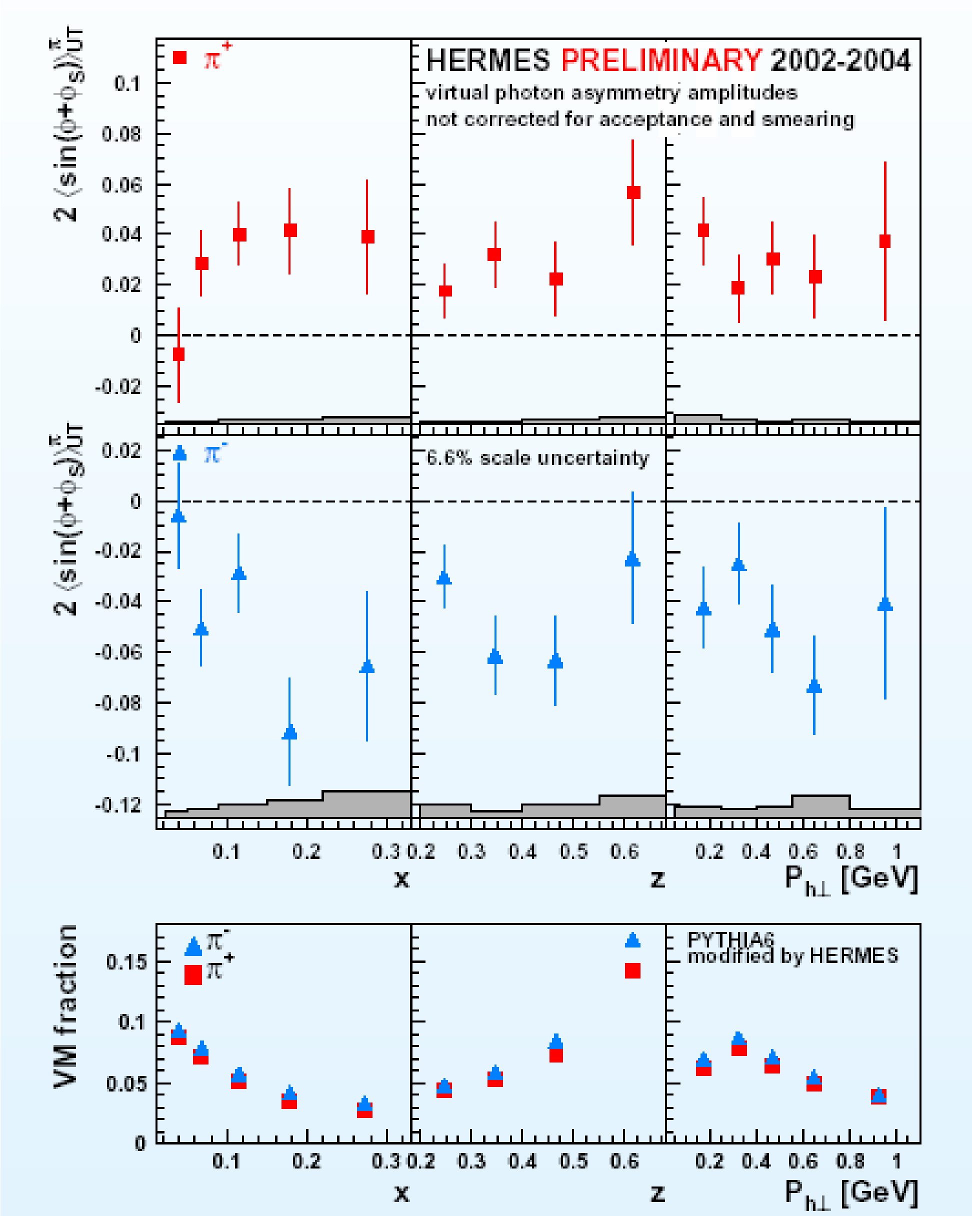
$$l\,N^{\uparrow} \rightarrow l\,\pi\,X$$

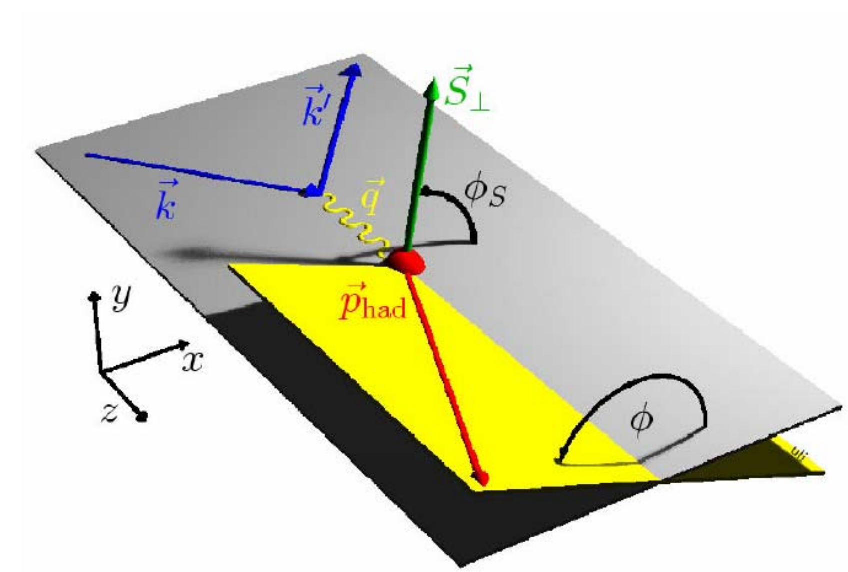
"Collins moment"

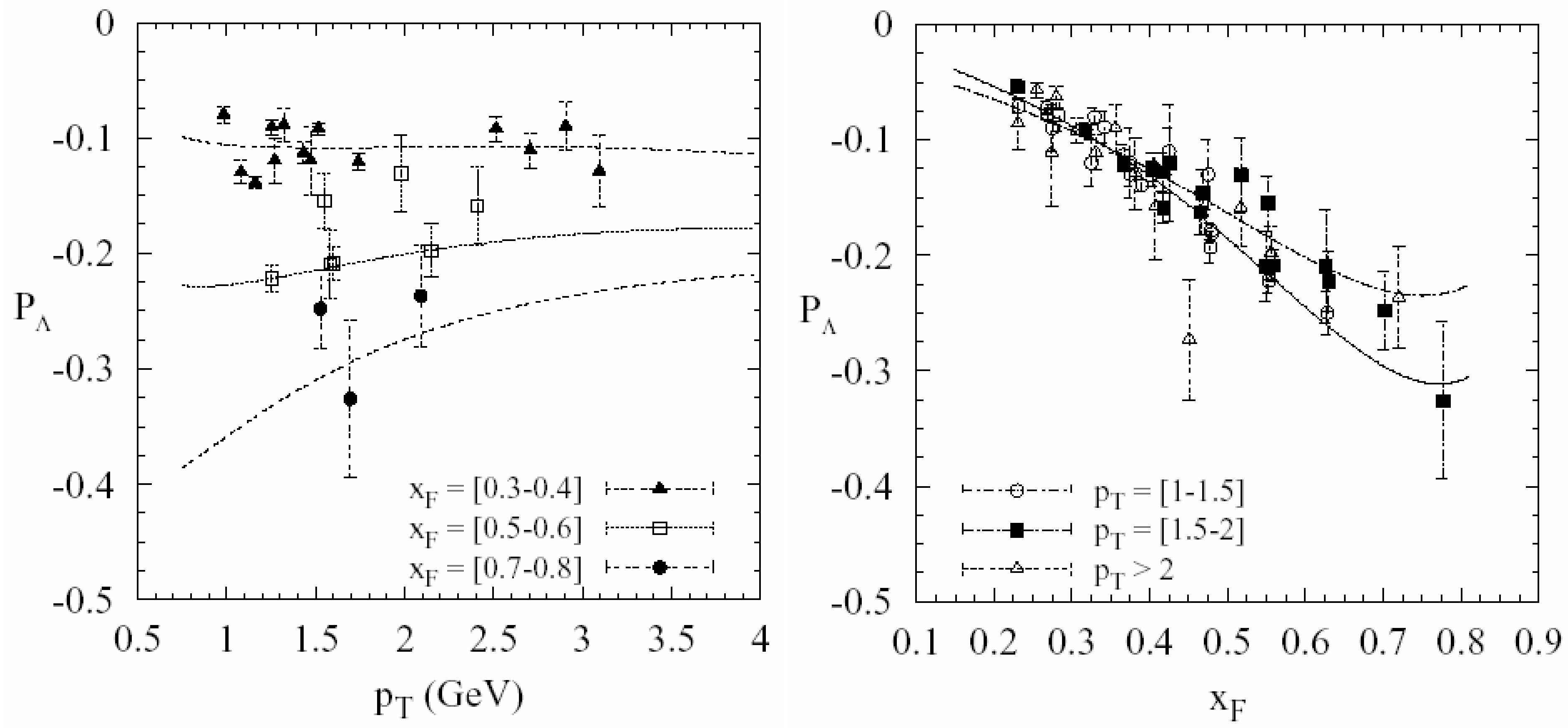
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$2\langle \sin(\Phi + \Phi_S) \rangle = A_{UT}^{\sin(\Phi+\Phi_S)}$$

$$\equiv 2\,\frac{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} - d\sigma^{\downarrow}) \sin(\Phi + \Phi_S)}{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} + d\sigma^{\downarrow})}$$







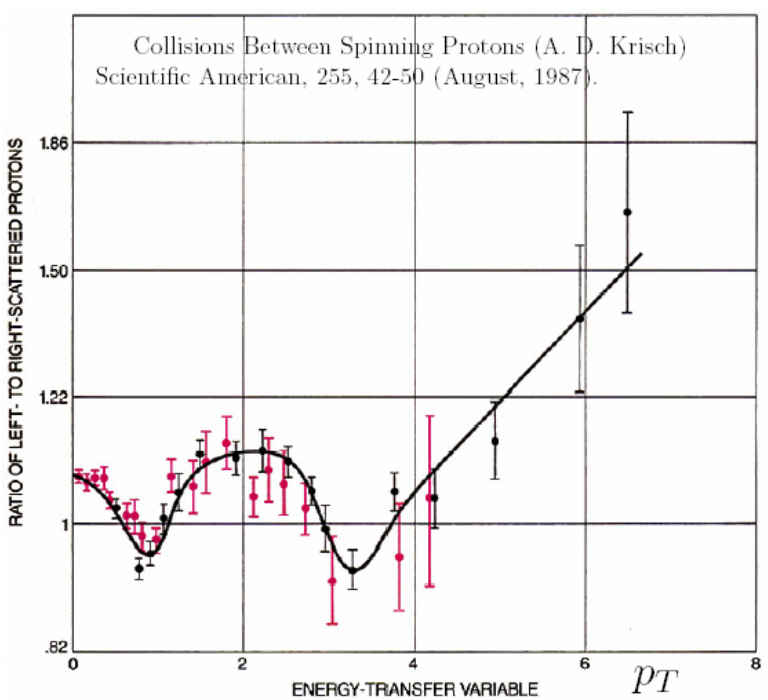
Transverse Λ polarization in unpolarized p-Be scattering at Fermilab

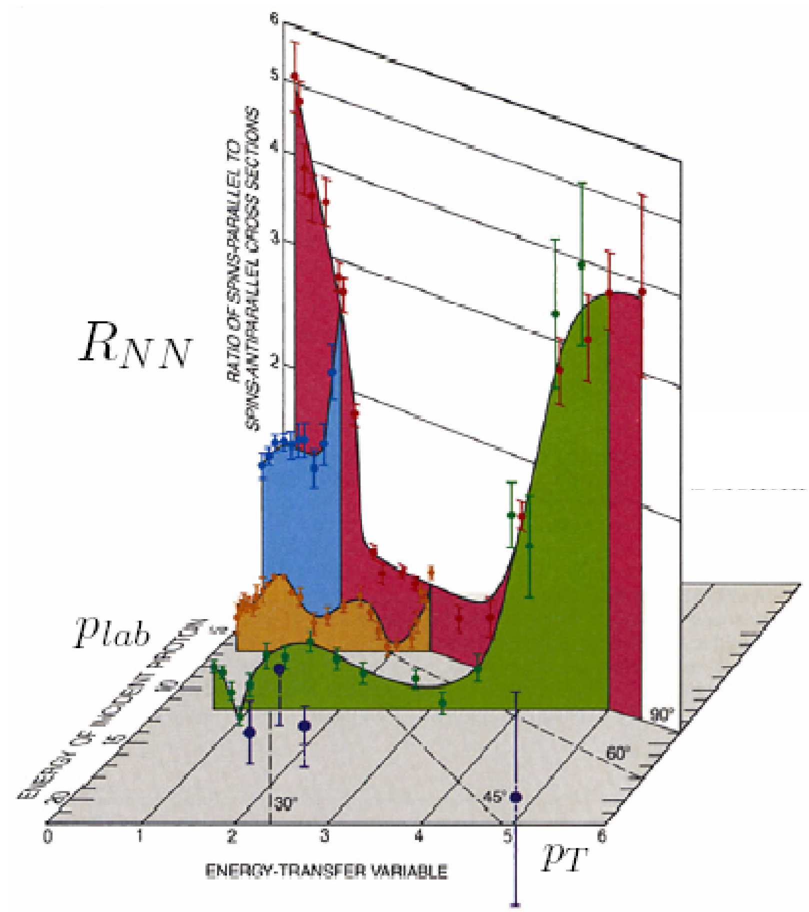
$$p\,N \rightarrow \Lambda^{\uparrow}\,X$$

"The largest spin effect ever seen by any human", S. Brodsky, Como 2005

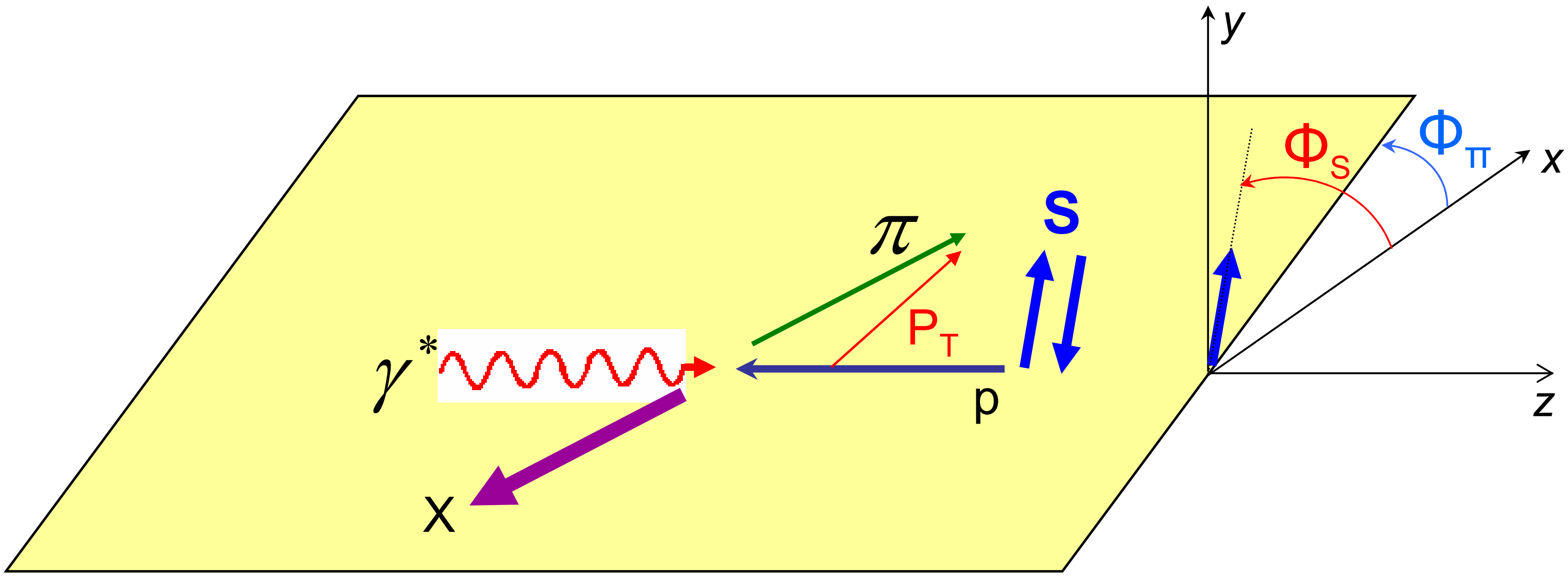
$p^{\uparrow} p \to p\ p$

$p^{\uparrow} p^{\uparrow} \to p\ p$





Transverse single spin asymmetries in SIDIS



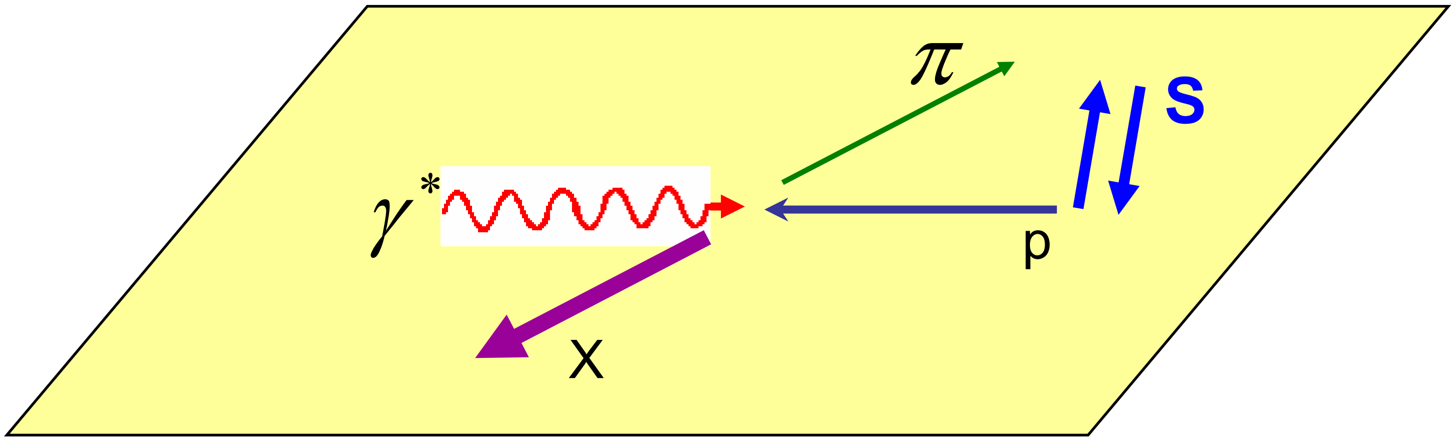
$$A_N \propto \vec{S} \cdot \left(\vec{p} \times \vec{P}_T\right) \propto P_T \sin(\Phi_\pi - \Phi_S)$$

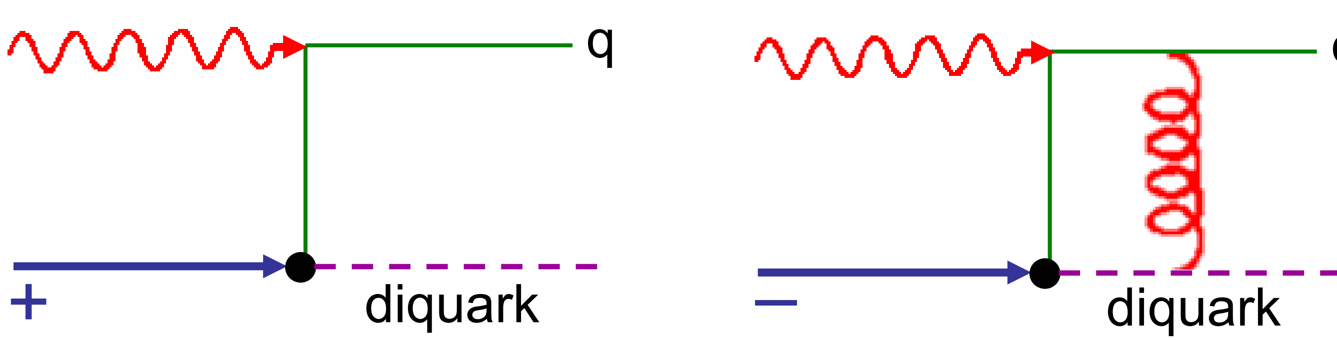
need $k_\perp$ dependent quark distribution in $p^\uparrow$ ➡ Sivers mechanism

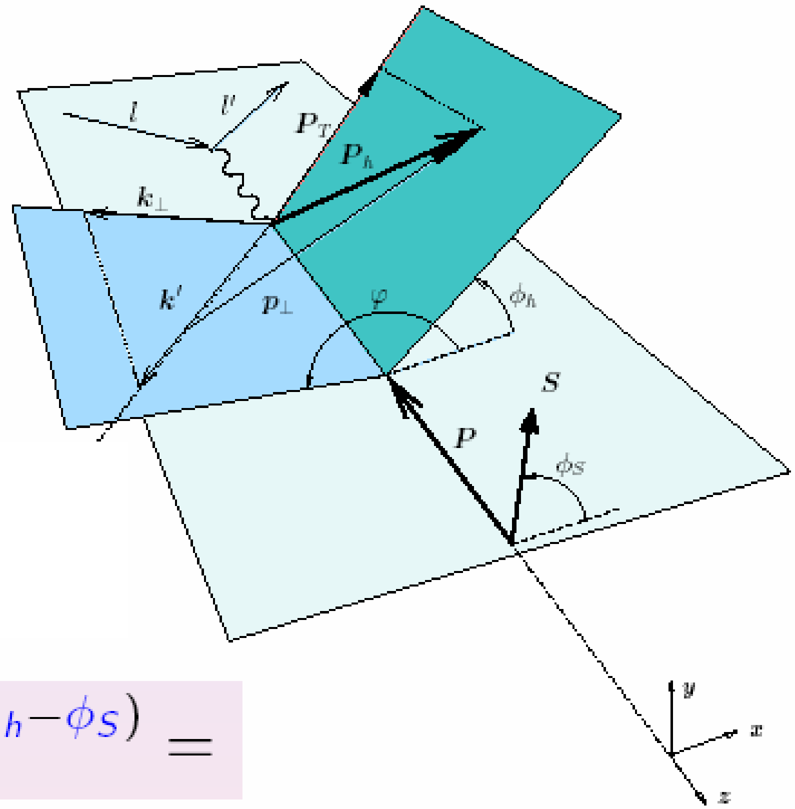
or $p_\perp$ dependent fragmentation of polarized quark ➡ Collins mechanism

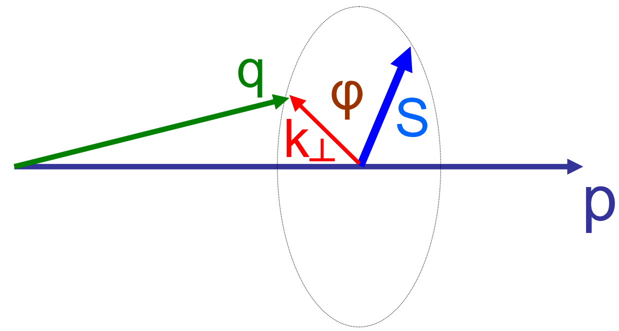
(talk by G. Schnell)

Brodsky, Hwang, Schmidt model for Sivers function









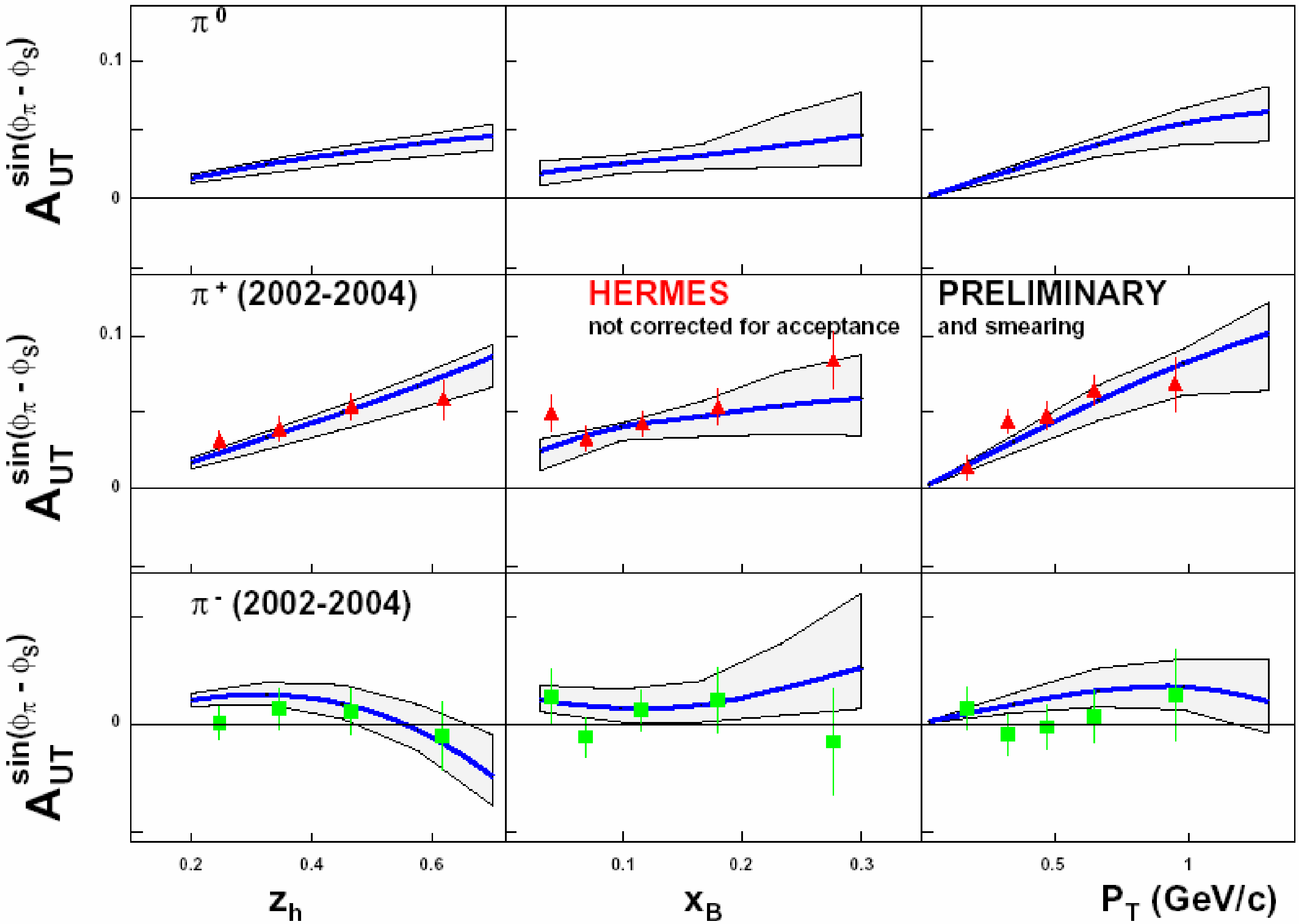
$$f_{q/p^\uparrow}(x,\vec{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\vec{S}\cdot(\hat{p}\times\hat{k}_\perp)$$

Sivers asymmetry in SIDIS

$$p_\perp = P_T - z\,k_\perp + O(k_\perp^2/Q^2)$$

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{\sum_q \int d\{\phi_h \phi_S \boldsymbol{k}_\perp\}\,\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\sin(\varphi-\phi_S)\,\frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2}\,J\,\frac{z}{z_h}\,D_q^h(z,\boldsymbol{p}_\perp)\,\sin(\phi_h-\phi_S)}{2\pi\sum_q \int d\phi_h\, d^2\boldsymbol{k}_\perp\; f_q(x,\boldsymbol{k}_\perp)\,\frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2}\,J\,\frac{z}{z_h}\,D_q^h(z,\boldsymbol{p}_\perp)}$$

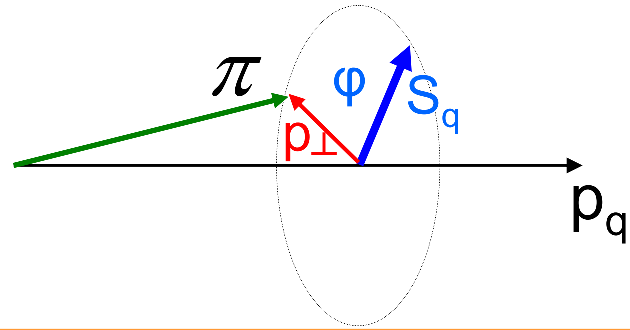
M.A, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin
hep-ph/0501196 (PRD 71, 074006) and hep-ph/0507181

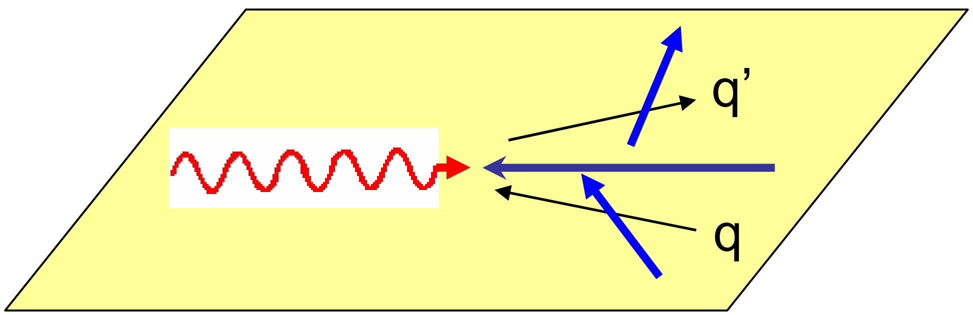


Collins mechanism for SSA

Asymmetry in the fragmentation of a transversely polarized quark

(Fundamental QCD property? D. Sivers)

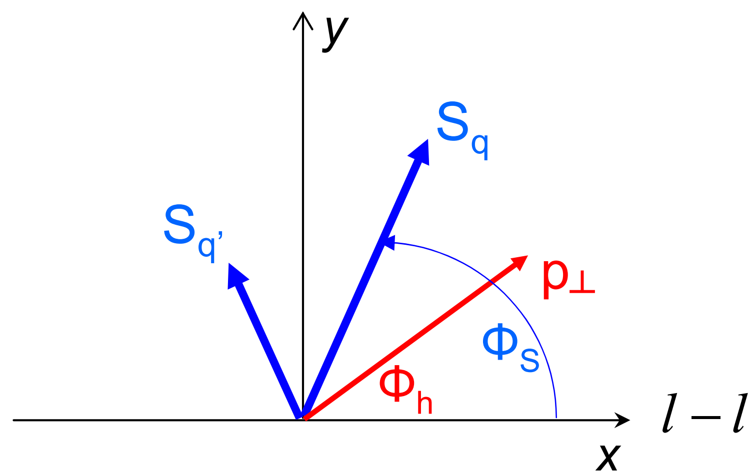




$$D_{h/q^{\uparrow}}(z,\vec{p}_{\perp}) = D_{h/q}(z,p_{\perp}) \; + \frac{1}{2}\Delta^{N}D_{h/q^{\uparrow}}(z,p_{\perp})\,\vec{S}_{q}\cdot(\hat{p}_{q}\times\hat{p}_{\perp})$$

initial q spin is transferred to final q', which fragments

$$\vec{S}_{q'}\cdot(\hat{p}_{q'}\times\hat{p}_{\perp}) \propto \sin(\Phi_{h}+\Phi_{S})$$



neglecting intrinsic motion in partonic distributions:

$$A_N^h = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{\sum_q \int e_q^2\, h_{1q}(x)\,(1-y)/(xy^2)\,\Delta^N D_{h/q^\uparrow}(z, p_\perp)}{\sum_q \int e_q^2\, f_{q/p}(x)\,[1+(1-y)^2]/(xy^2) D_{q/p}(z, p_\perp)} \sin(\Phi_h + \Phi_S)$$

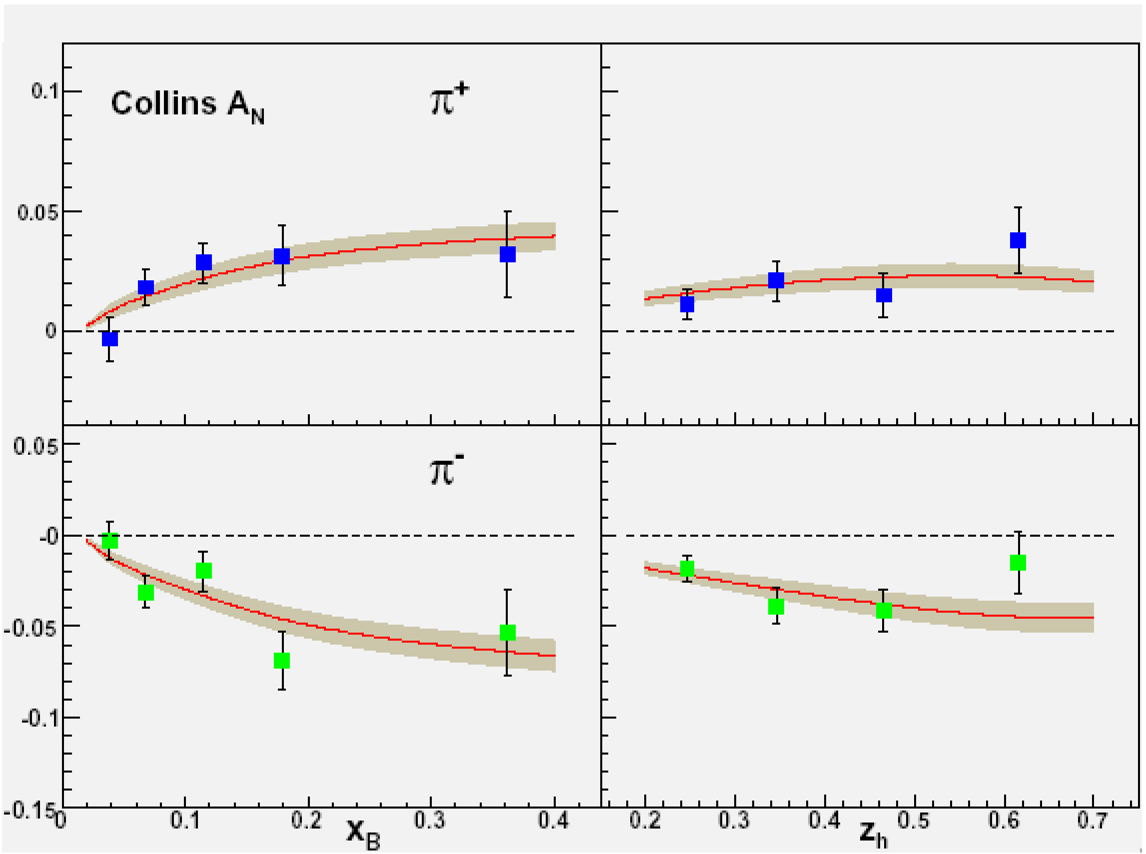
transversity

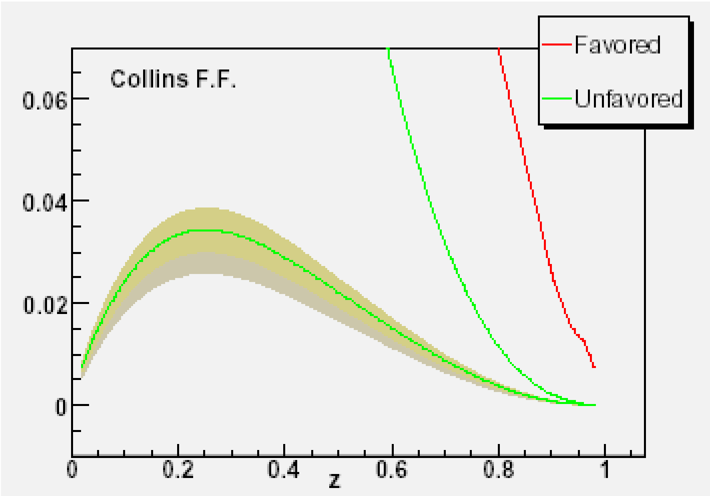
Collins function

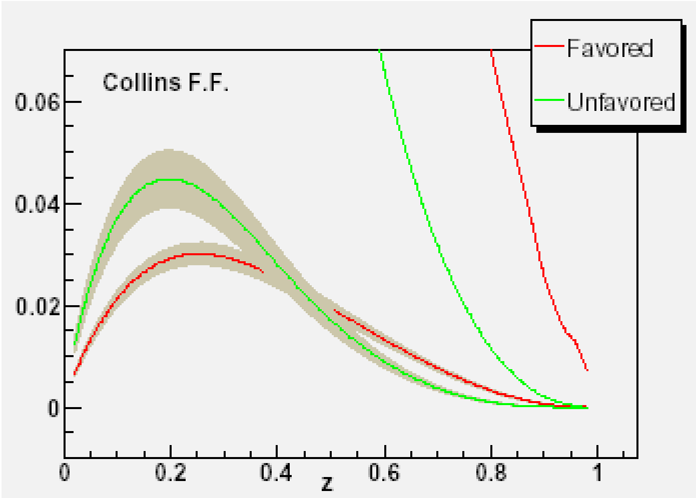
$$A_{UT}^{\sin(\Phi_h+\Phi_S)} \equiv 2\,\frac{\int d\Phi_h d\Phi_S [d\sigma^\uparrow - d\sigma^\downarrow] \sin(\Phi_h + \Phi_S)}{\int d\Phi_h d\Phi_S [d\sigma^\uparrow + d\sigma^\downarrow]}$$

First extraction of Collins functions from HERMES data:
W. Vogelsang and F. Yuan (assuming Soffer-saturated h_1)

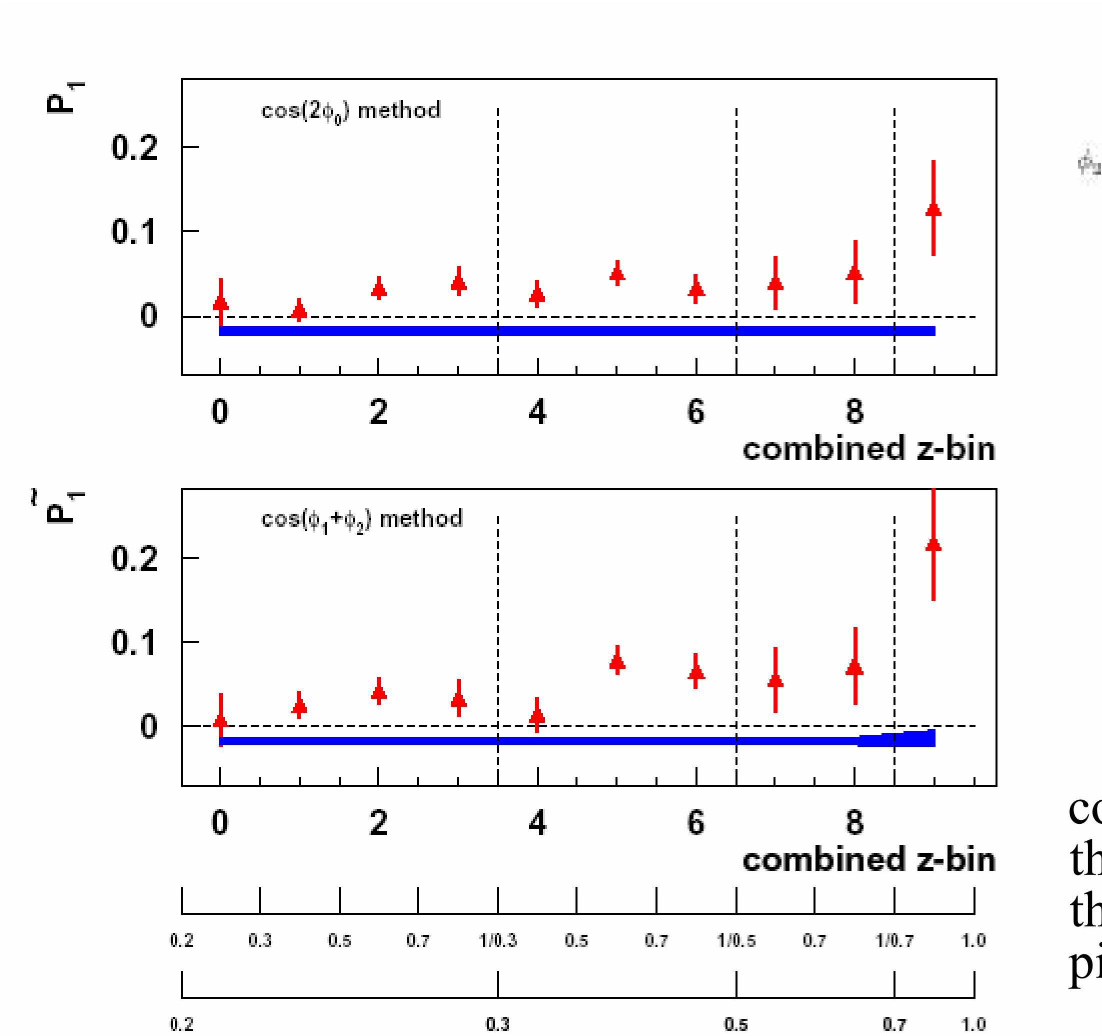
fit to HERMES data on $A_{UT}^{\sin(\Phi_h+\Phi_S)}$

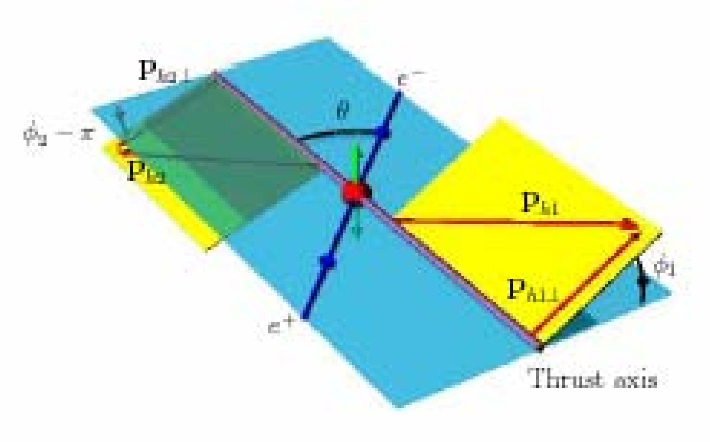






Extraction of Collins functions from HERMES + BELLE data



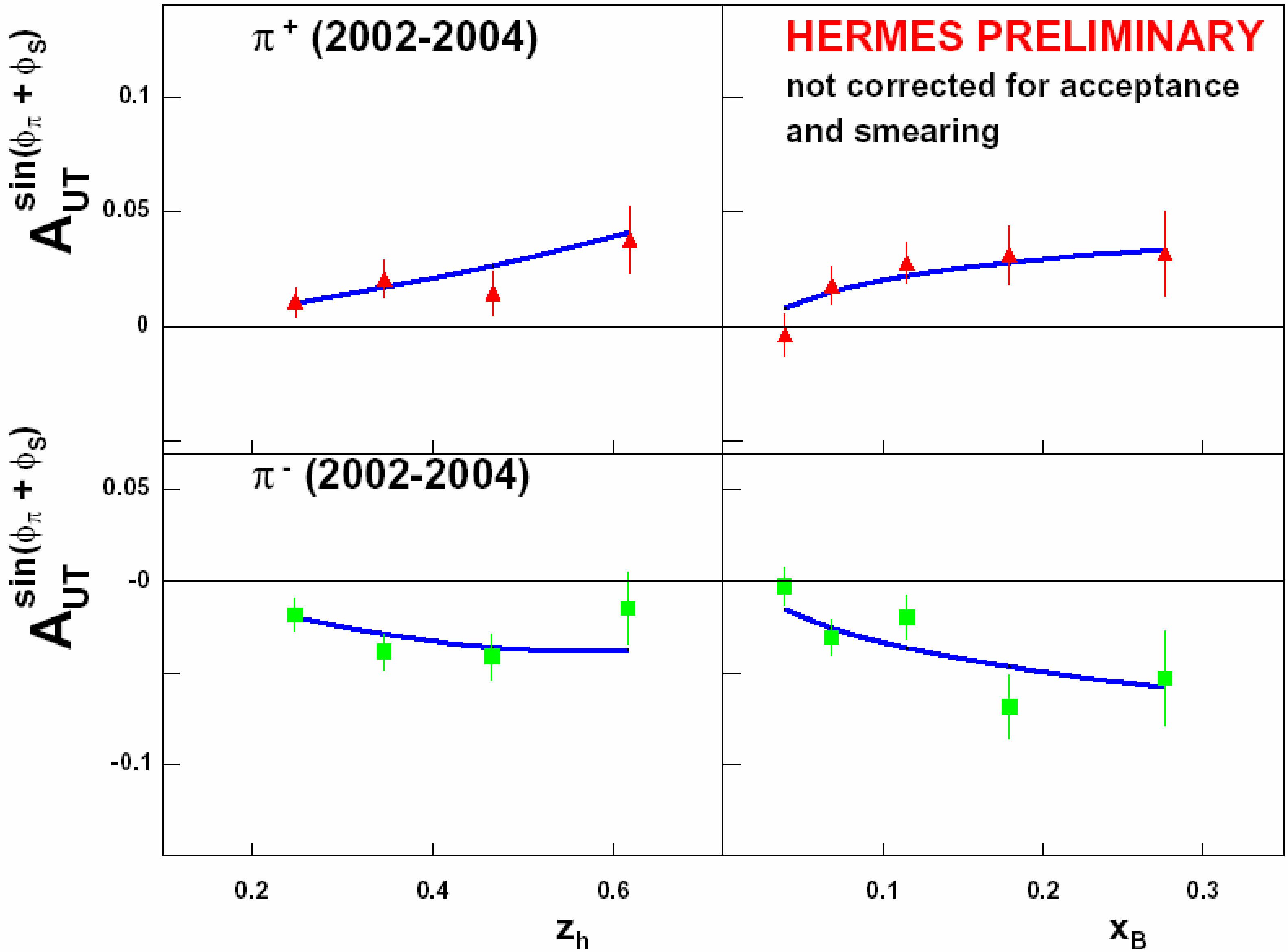


P$_1$ depends on

$$\frac{\Delta_N D^{(1)}(z_1)\,\Delta_N D^{(1)}(z_2)}{D(z_1)\,D(z_2)}$$

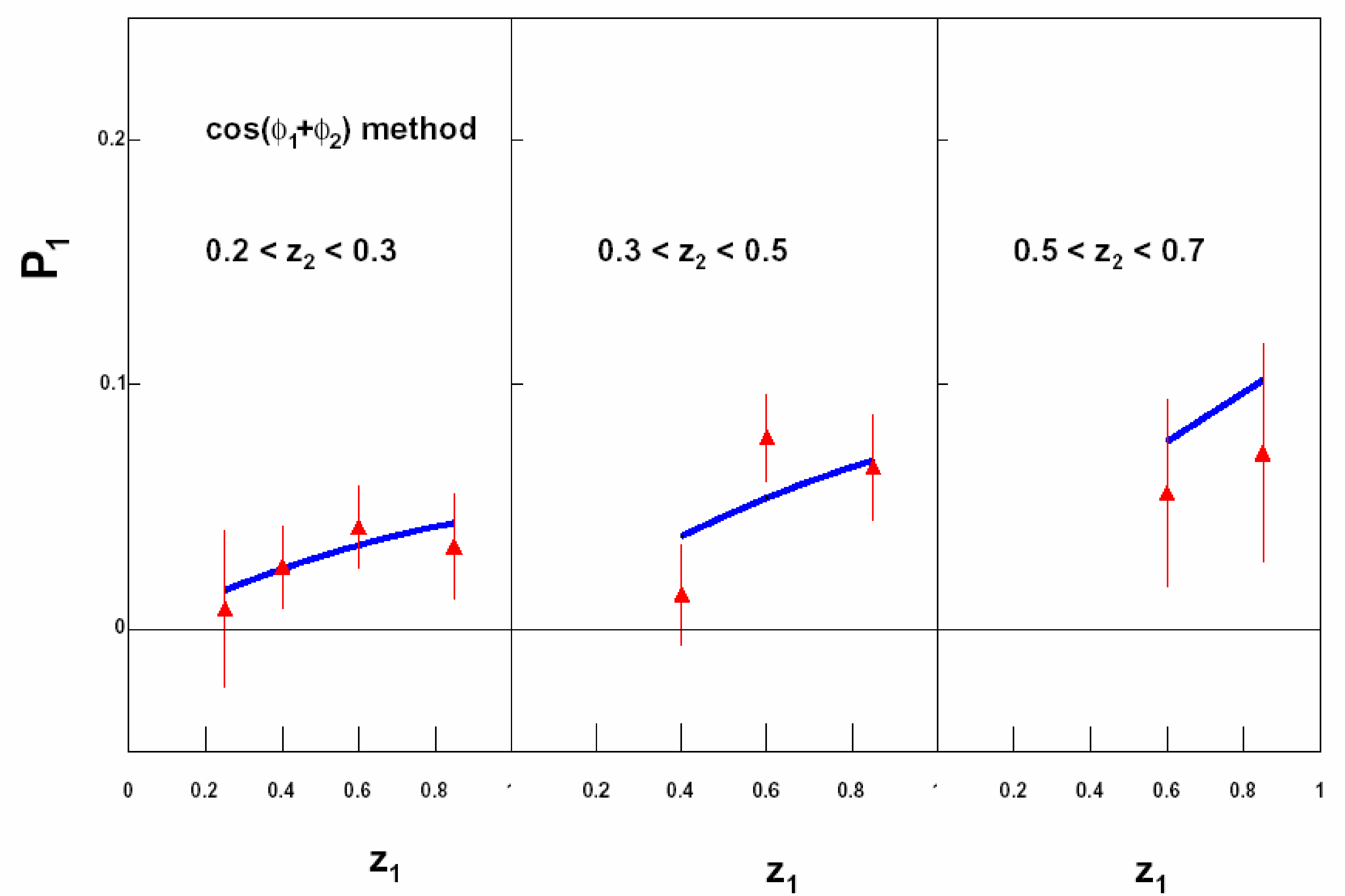
correlation, event by event, between the spin of q and $\overline{q}$, that is between the two azimuthal distributions of pions inside the jets

Fits to HERMES Collins data, preliminary results

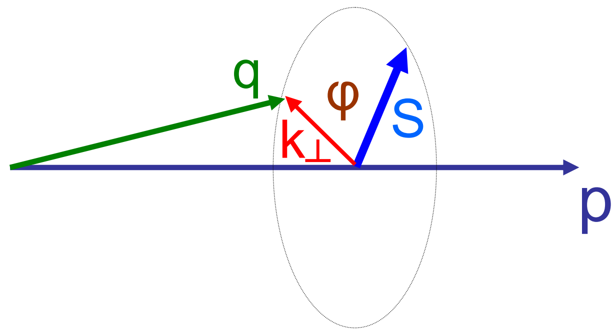


Fits to BELLE Collins data, preliminary results

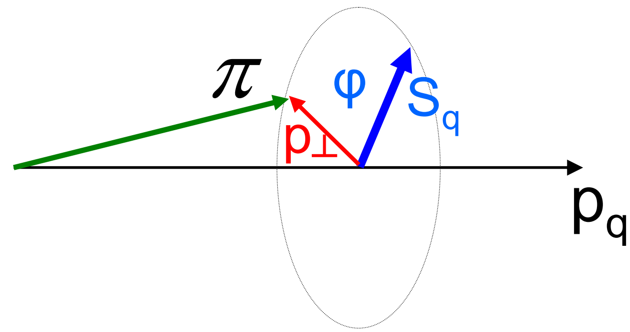
M.A, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin, in preparation



spin-$k_\perp$ correlations – Trento conventions



Sivers function



Collins function

$$f_{q/p^\uparrow}(x,\vec{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\vec{S}\cdot(\hat{p}\times\hat{k}_\perp)$$

$$D_{h/q^\uparrow}(z,\vec{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\vec{S}_q\cdot(\hat{p}_q\times\hat{p}_\perp)$$

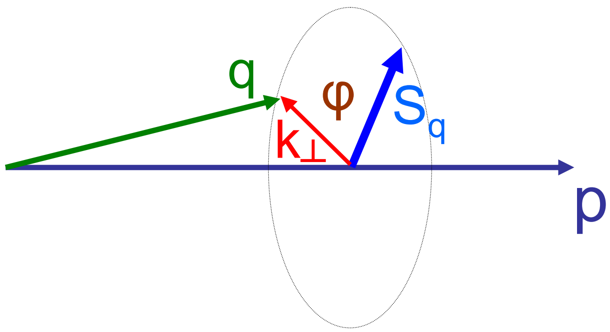
Amsterdam group notations

$$\Delta^N f_{q/p^\uparrow} = -\frac{2k_\perp}{M} f_{1T}^{\perp q}$$

$$\Delta^N D_{h/q^\uparrow} = 2\frac{p_\perp}{z\,M_h} H_1^{\perp q}$$

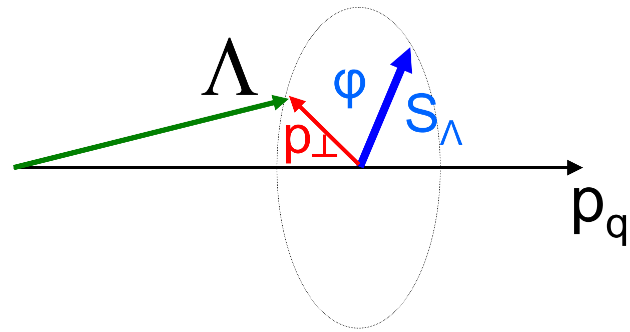
$$f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$$

spin-$k_\perp$ correlations



Boer-Mulders function

$$f_{q^\uparrow/p}(x,\vec{k}_\perp) = \frac{1}{2} f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q^\uparrow/p}(x,k_\perp)\, \vec{S}_q \cdot (\hat{p} \times \hat{k}_\perp)$$



polarizing f.f.

$$D_{\Lambda^\uparrow/q}(z,\vec{p}_\perp) = \frac{1}{2} D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{\Lambda^\uparrow/q}(z,p_\perp)\, \vec{S}_\Lambda \cdot (\hat{p}_q \times \hat{p}_\perp)$$

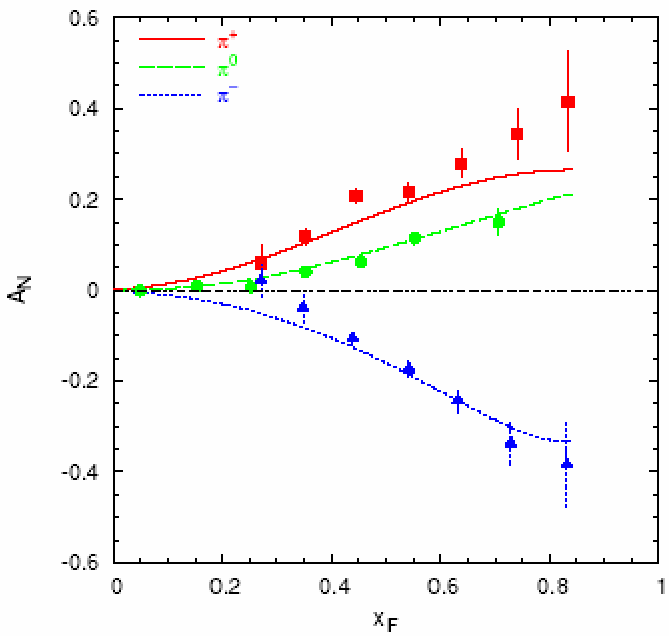
Amsterdam group notations

$$\Delta^N f_{q^\uparrow/p} = -\frac{k_\perp}{M} h_1^{\perp q} \qquad\qquad \Delta^N D_{\Lambda^\uparrow/q} = \frac{p_\perp}{z\, M_\Lambda} D_{1T}^{\perp q}$$

SSA in $p^{\uparrow}p \to \pi X$

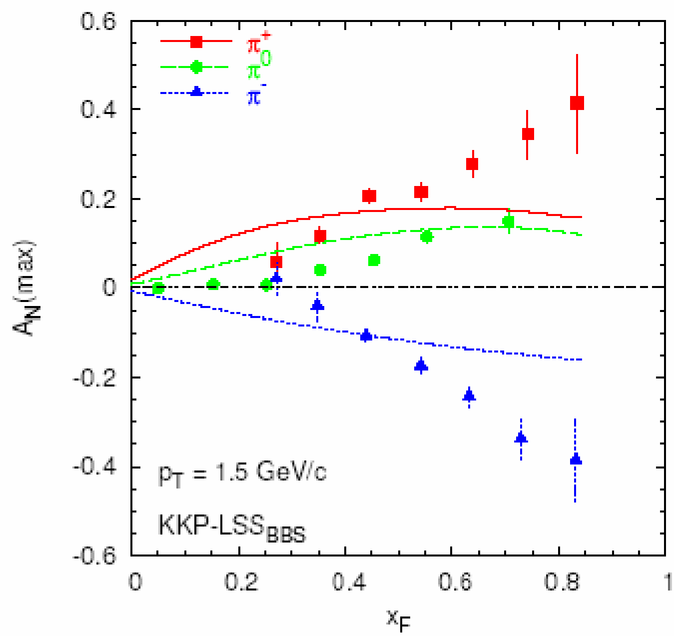
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \simeq \Delta^N f_{a/p^{\uparrow}} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c} \quad \text{“Sivers effect”}$$
$$+ \; h_{1a} \otimes f_{b/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{\pi/c^{\uparrow}} \quad \text{“Collins effect”}$$

E704 data, E = 200 GeV



fit to A_N with Sivers effects alone

U. D’Alesio, F. Murgia



maximized value of A_N with Collins effects alone

M.A, M. Boglione, U. D’Alesio, E. Leader, F. Murgia

Parton distributions

$q, \Delta q$ and h_1 (or $\delta q, \Delta_T q$) are fundamental leading-twist quark distributions

$q = q_+ + q_-$ quark distribution – well known

$\Delta q = q_+ - q_-$ quark helicity distribution – known

$\Delta_T q = q_\uparrow - q_\downarrow$ transversity distribution – unknown

$g = g_+ + g_-$ gluon distribution ~ known

$\Delta g = g_+ - g_-$ gluon helicity distribution – poorly known

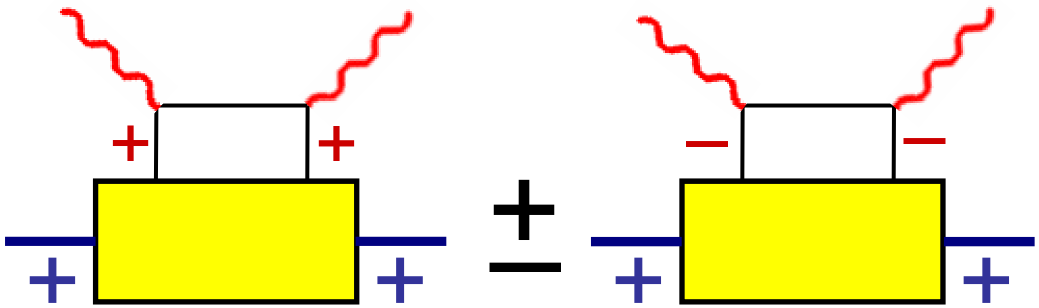
all equally important

Δq related to $\bar{q}\gamma^\mu \gamma_5 q$ ➡ chiral-even

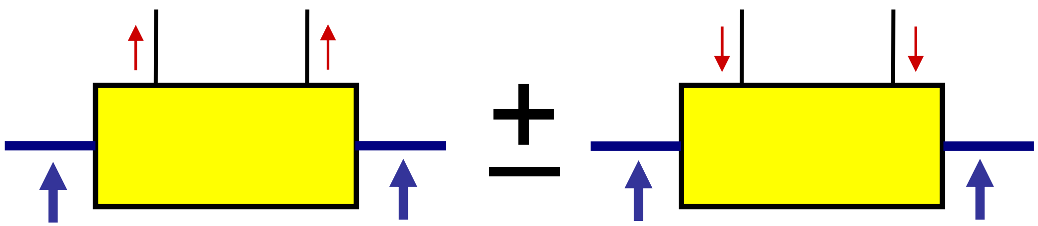
$\Delta_T q$ related to $\bar{q}\sigma^{\mu\nu}\gamma_5 q$ ➡ chiral-odd

$$2\,|\Delta_T q| \leq q + \Delta q$$

positivity bound



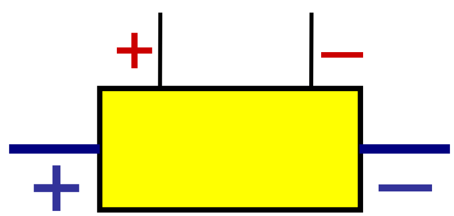
$= \begin{matrix} q(x,Q^2) \\ \Delta q(x,Q^2) \end{matrix}$



$= \begin{matrix} q(x,Q^2) \\ \Delta_T q(x,Q^2) \end{matrix}$

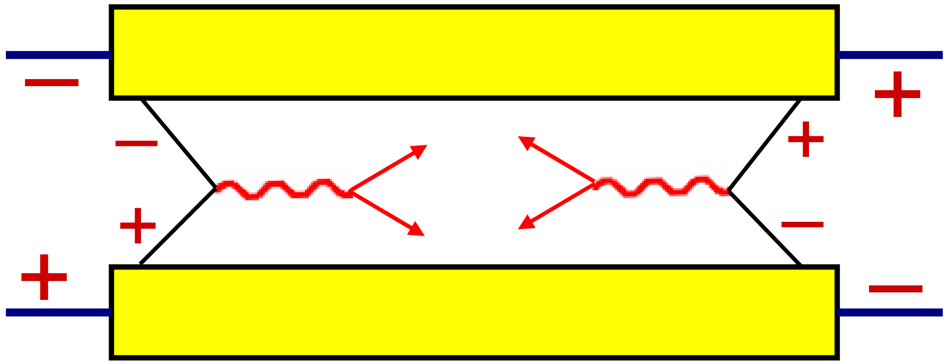
in helicity basis $\quad \uparrow\downarrow = \frac{1}{\sqrt{2}}\left(|+\rangle \pm i\,|-\rangle \right)$

$\Rightarrow \quad h_1(x,Q^2) =$



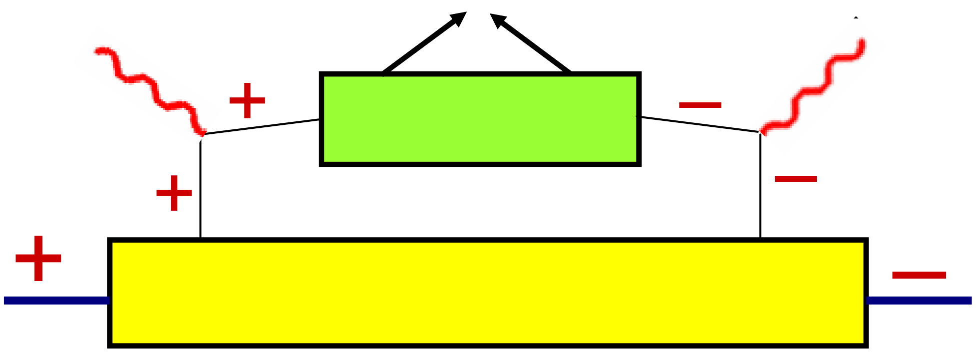
decouples from DIS
(no quark helicity flip)

h_1 must couple to another chiral-odd function. For example: D-Y, $pp \rightarrow l^+l^- X$, and SIDIS, $l\,p \rightarrow l\,\pi\,X$, processes



$h_1 \times h_1$

J. Ralston and D.Soper, 1979
J. Cortes, B. Pire, J. Ralston, 1992

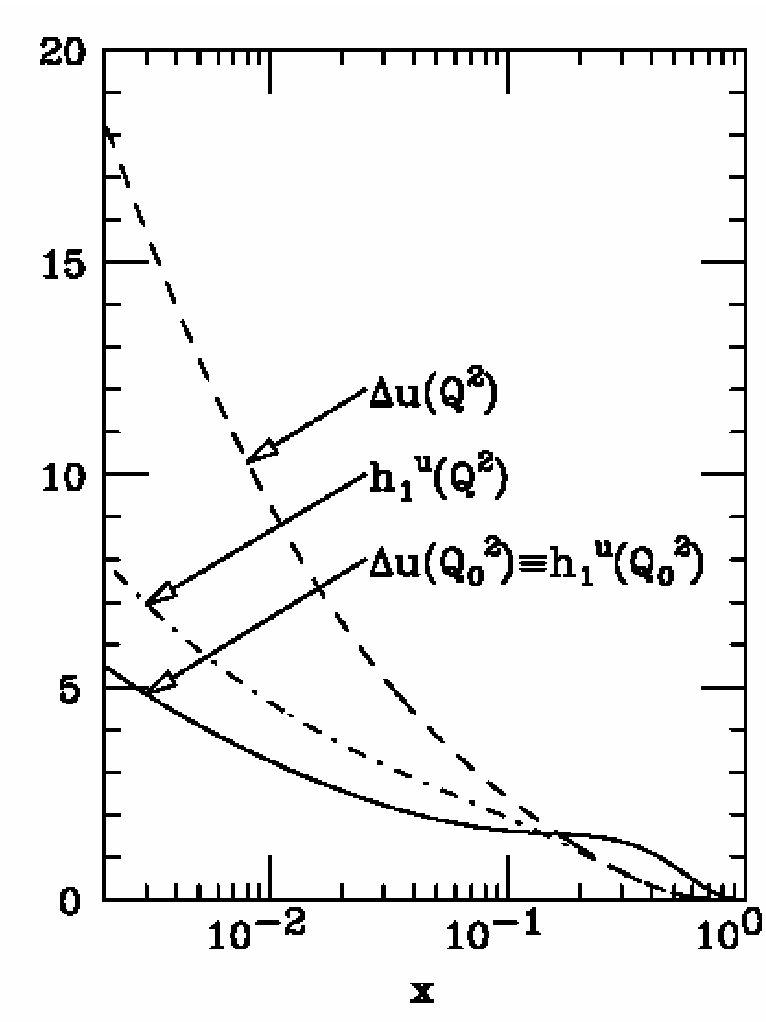


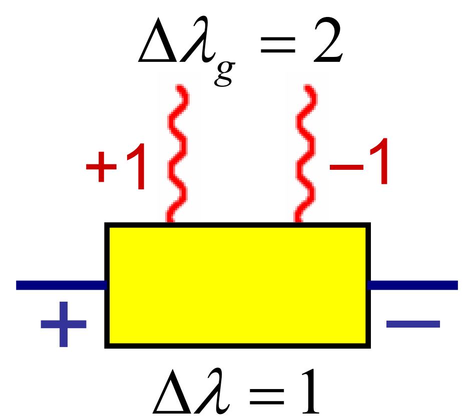
h_1 x *Collins function*

J. Collins, 1993

No gluon contribution to h_1

⇨ simple Q^2 evolution



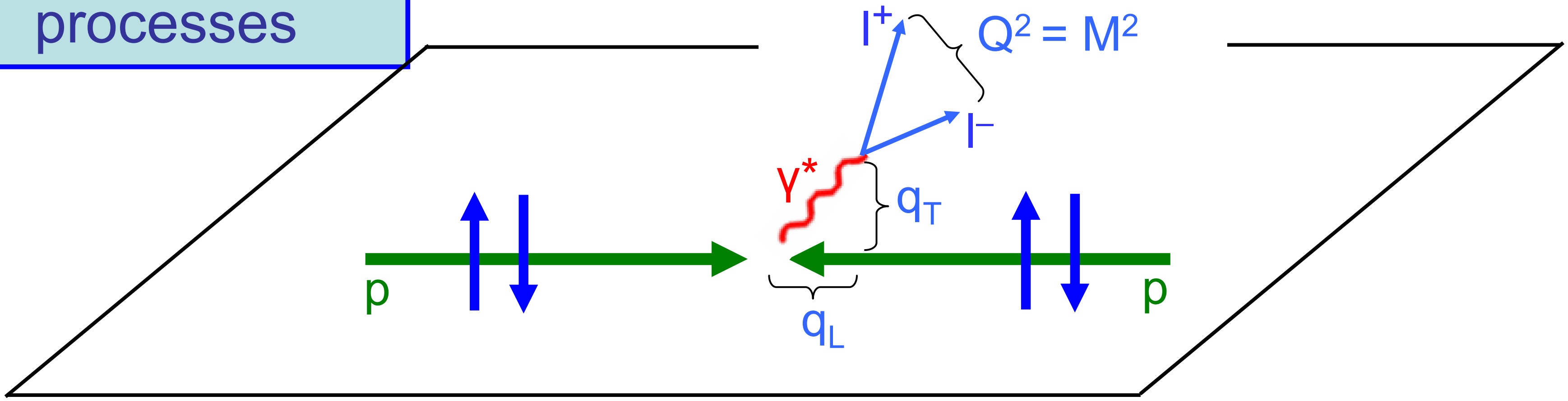


$Q^2 = 25\ GeV^2$

$Q_0{}^2 = 0.23\ GeV^2$

V. Barone, T. Calarco, A. Drago

h_1 in Drell-Yan processes



Elementary LO interaction: $q\bar{q} \to \gamma^* \to l^+ l^-$

$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\pi\alpha^2}{9M^2 s}\frac{1}{x_1+x_2}\sum_a e_a^2\left[q_a(x_1)\,\bar{q}_a(x_2) + \bar{q}_a(x_1)\,q_a(x_2)\right]$$

$$x_F = x_1 - x_2 \qquad x_1\,x_2 = M^2/s \equiv \tau \qquad x_F = 2q_L/\sqrt{s}$$

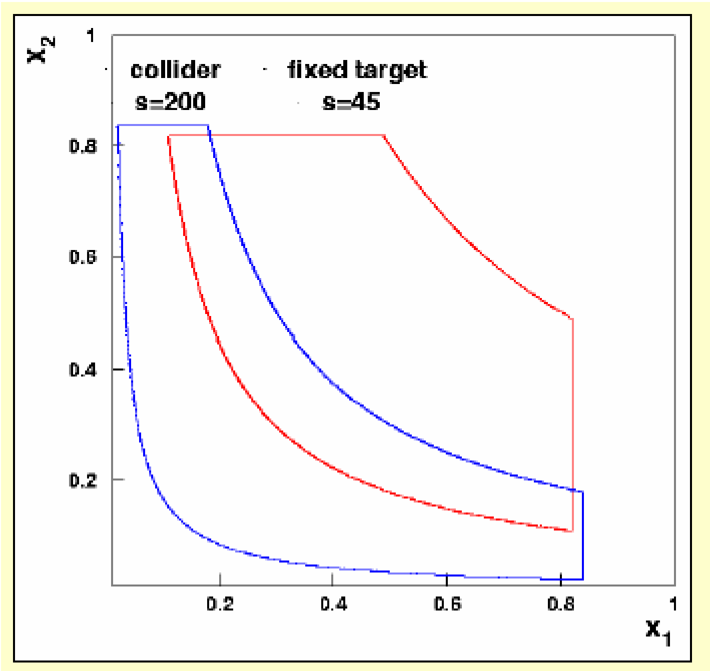
3 planes: plane ⊥ polarization vectors, p-γ* plane, l^+l^- γ* plane ⇒ plenty of spin effects

h_1 from $p^{\uparrow}\bar{p}^{\uparrow} \to l^+ l^- X$ at GSI

$$A_{TT} = \hat{a}_{TT} \frac{\sum_q e_q^2 \left[h_{1q}(x_1)h_{1q}(x_2) + h_{1\bar{q}}(x_1)h_{1\bar{q}}(x_2)\right]}{\sum_q e_q^2 \left[q(x_1)q(x_2) + \bar{q}(x_1)\bar{q}(x_2)\right]} \approx \hat{a}_{TT} \frac{h_{1u}(x_1)h_{1u}(x_2)}{u(x_1)u(x_2)}$$

large x_1,x_2

GSI energies: $s = 30 - 210\ \text{GeV}^2 \qquad M \geq 2\ \text{GeV}^2$

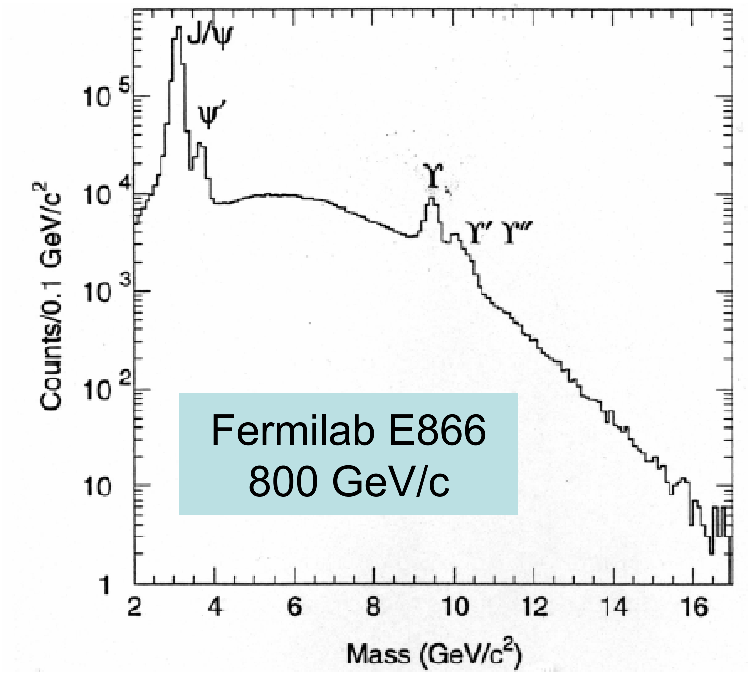


one measures h_1 in the quark valence region: A_{TT} is estimated to be large, between 0.2 and 0.4

PAX proposal: hep-ex/0505054

s = 210 GeV² is best energy (talk by P. Reimer at workshop)

Energy for Drell-Yan processes



"safe region": $M \geq M_{J/\Psi}$

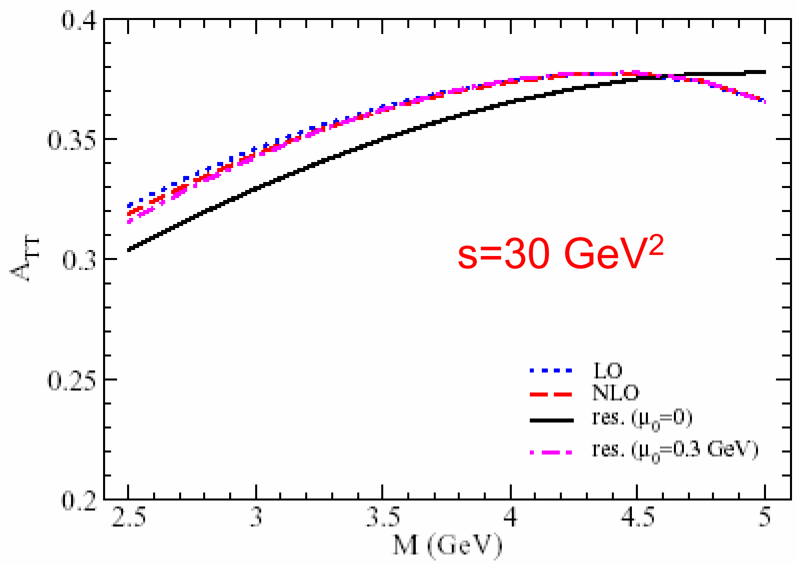
$$\Rightarrow \quad \tau \geq \frac{M^2_{J/\Psi}}{s}$$

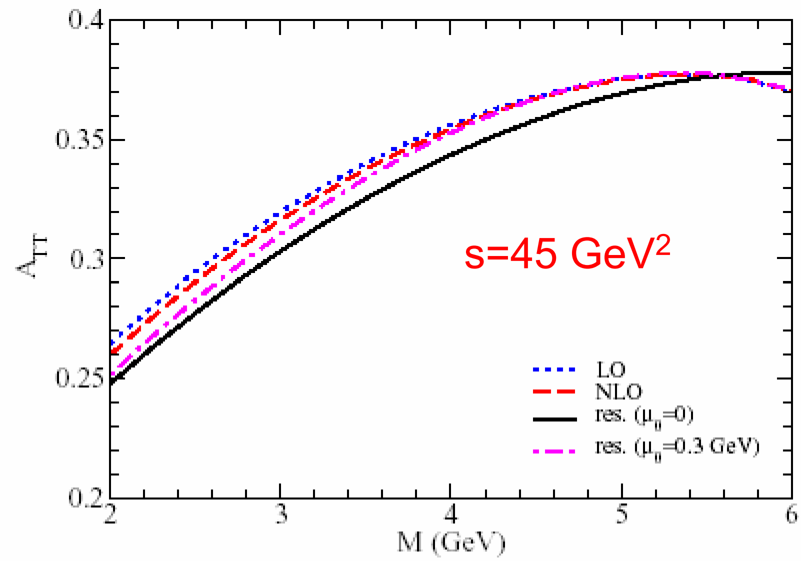
QCD corrections might be very large at smaller values of *M*:

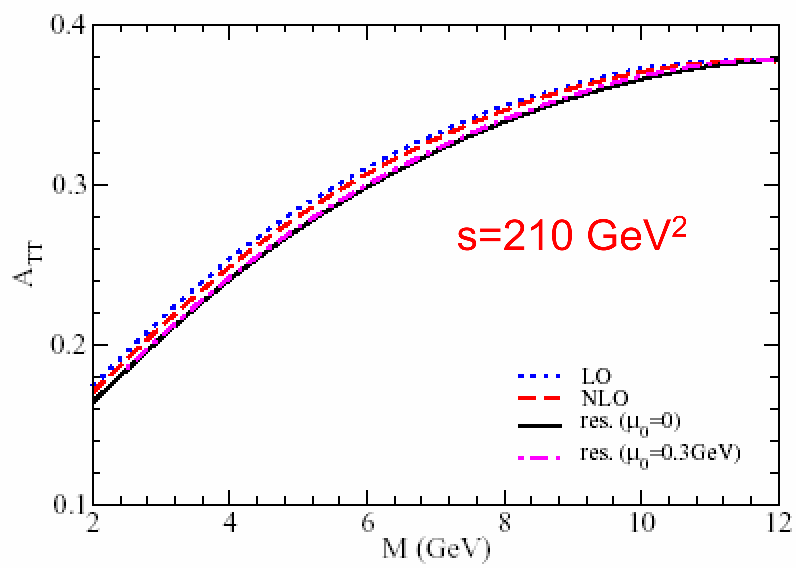
yes, for cross-sections, not for A_{TT}
K-factor almost spin-independent

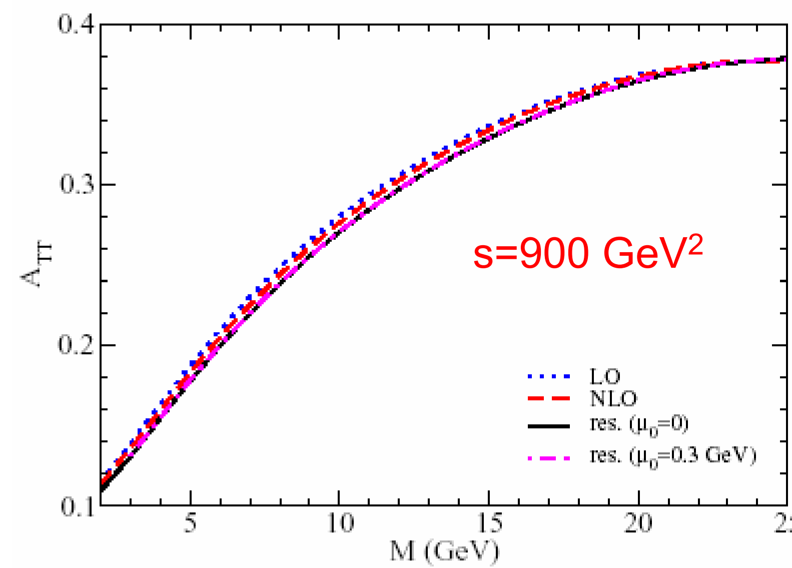
H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya, hep-ph/0503270

V. Barone et al., in preparation


s=30 GeV^2
A_{TT}
M (GeV)
LO
NLO
res. (μ_0=0)
res. (μ_0=0.3 GeV)


s=45 GeV^2
A_{TT}
M (GeV)
LO
NLO
res. (μ_0=0)
res. (μ_0=0.3 GeV)


s=210 GeV^2
A_{TT}
M (GeV)
LO
NLO
res. (μ_0=0)
res. (μ_0=0.3GeV)


s=900 GeV^2
A_{TT}
M (GeV)
LO
NLO
res. (μ_0=0)
res. (μ_0=0.3 GeV)

Alternative accesses to transversity

Inclusive Λ production and measure of Λ polarization

$$P_\Lambda \propto h_1(x) \otimes \Delta_T D(z)$$ (transverse fragmentation function)

Two pion production: l p↑ → π π X

$$\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow \propto h_1(x) \otimes \delta q_I(z, p_\perp)$$ (interference fragmentation function)

Vector meson production: l p↑ → ρ X

$$\rho_{10}(V) \propto h_1(x) \otimes D_{1,0}^{+,-}(z, p_\perp)$$ (generalized fragmentation function)

Inclusive hadronic production: p p↑ → π X

$$\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow \propto h_1(x) \otimes \Delta^N D_{\pi/q^\uparrow}(z, p_\perp)$$ (problematic)

Single Spin Asymmetry in D-Y processes

$$\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow \propto h_1(x) \otimes h_1^\perp(z, p_\perp)$$ (Boer-Mulders function)

The spin story goes on ....

Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might just ban such measurements altogether out of self-protection.

J.D. Bjorken
St. Croix, 1987

Spin is one of the most fundamental concepts in physics, deeply rooted in Poincare invariance and hence in the structure of space-time itself. All elementary particles we know today carry spin, among them the particles that are subject to the strong interactions, the spin-1/2 quarks and the spin-1 gluons. Spin, therefore, plays a central role also in our theory of the strong interactions, Quantum Chromodynamics (QCD), and to understand spin phenomena in QCD will help to understand QCD itself.

RHIC proposal
2005