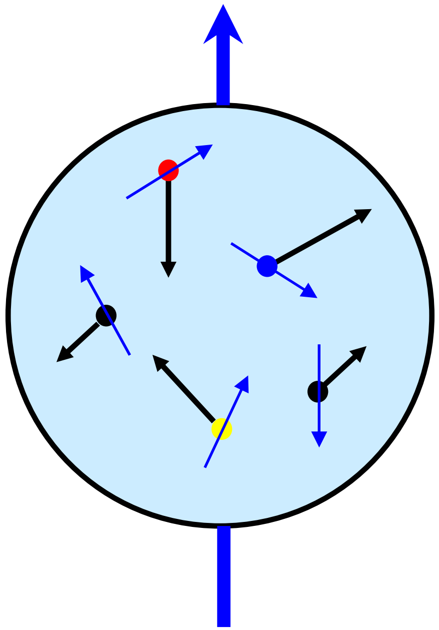
Transverse spin and $\boldsymbol{k}_\perp$ structure of the proton

- integrated partonic distributions
- the missing piece, transversity
- partonic intrinsic motion (TMD)
- spin and $\boldsymbol{k}_\perp$: transverse Single Spin Asymmetries
- SSA in SIDIS and pp, $p\bar{p}$ inclusive processes
- conclusions



Mauro Anselmino, Spin in Hadron Physics, Tbilisi, 05/09/2006

$K_\perp$ integrated parton distributions

$q, \Delta q$ and h_1 (or $\delta q, \Delta_T q$) are fundamental leading-twist quark distributions depending on longitudinal momentum fraction *x*

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

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

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

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

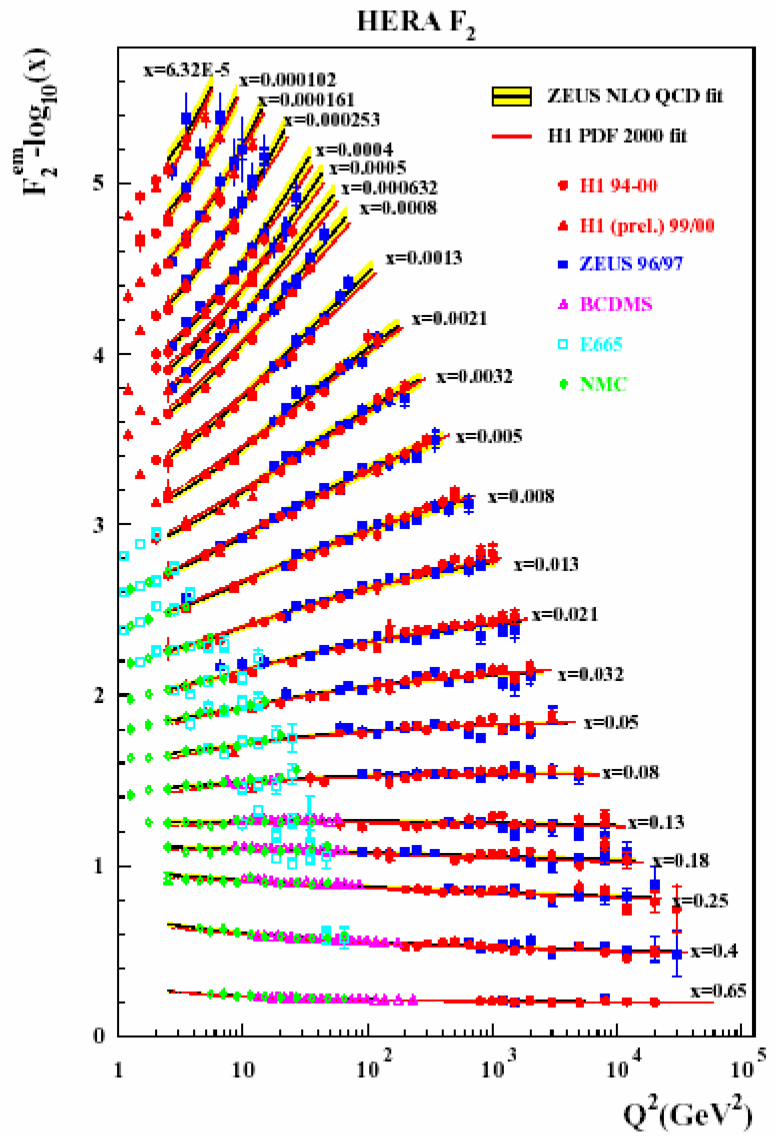
all equally important

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

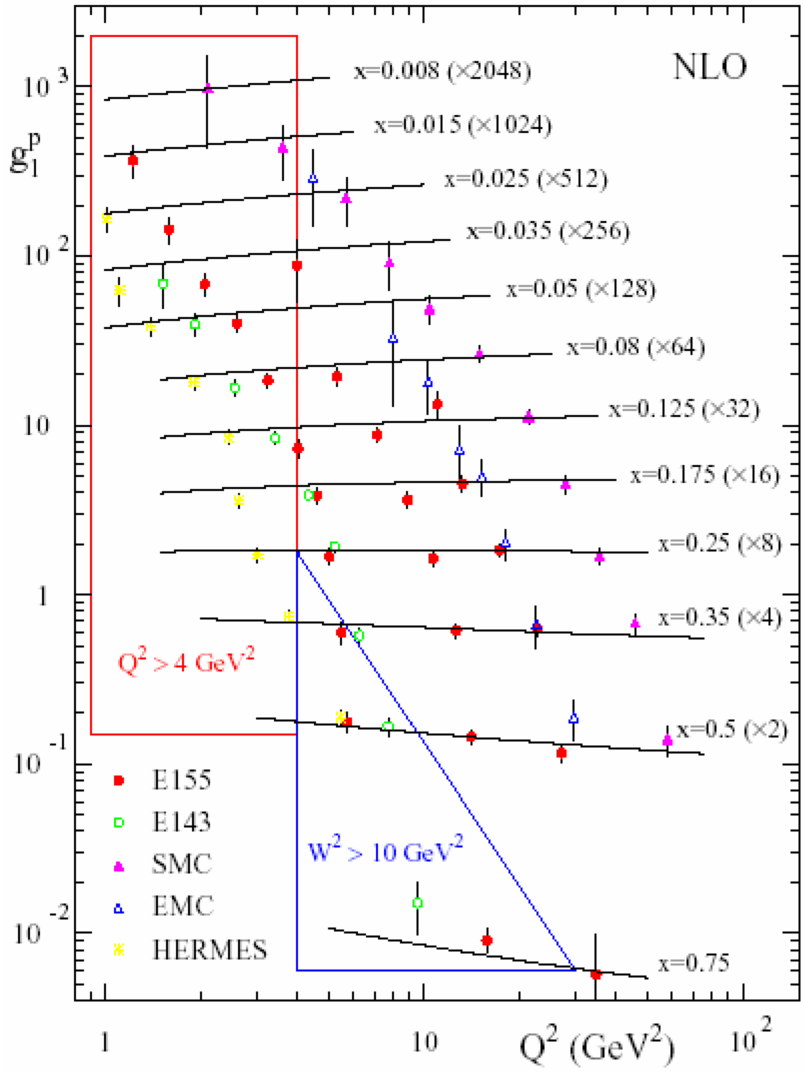
$\Delta_T q$ related to $\bar{q}\sigma^{\mu\nu}\gamma_5 q$ ➡ chiral-odd

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

positivity bound



$$\Rightarrow \quad q(x,Q^2)$$



$$\Rightarrow \quad \Delta q(x,Q^2)$$

de Florian, Navarro, Sassot

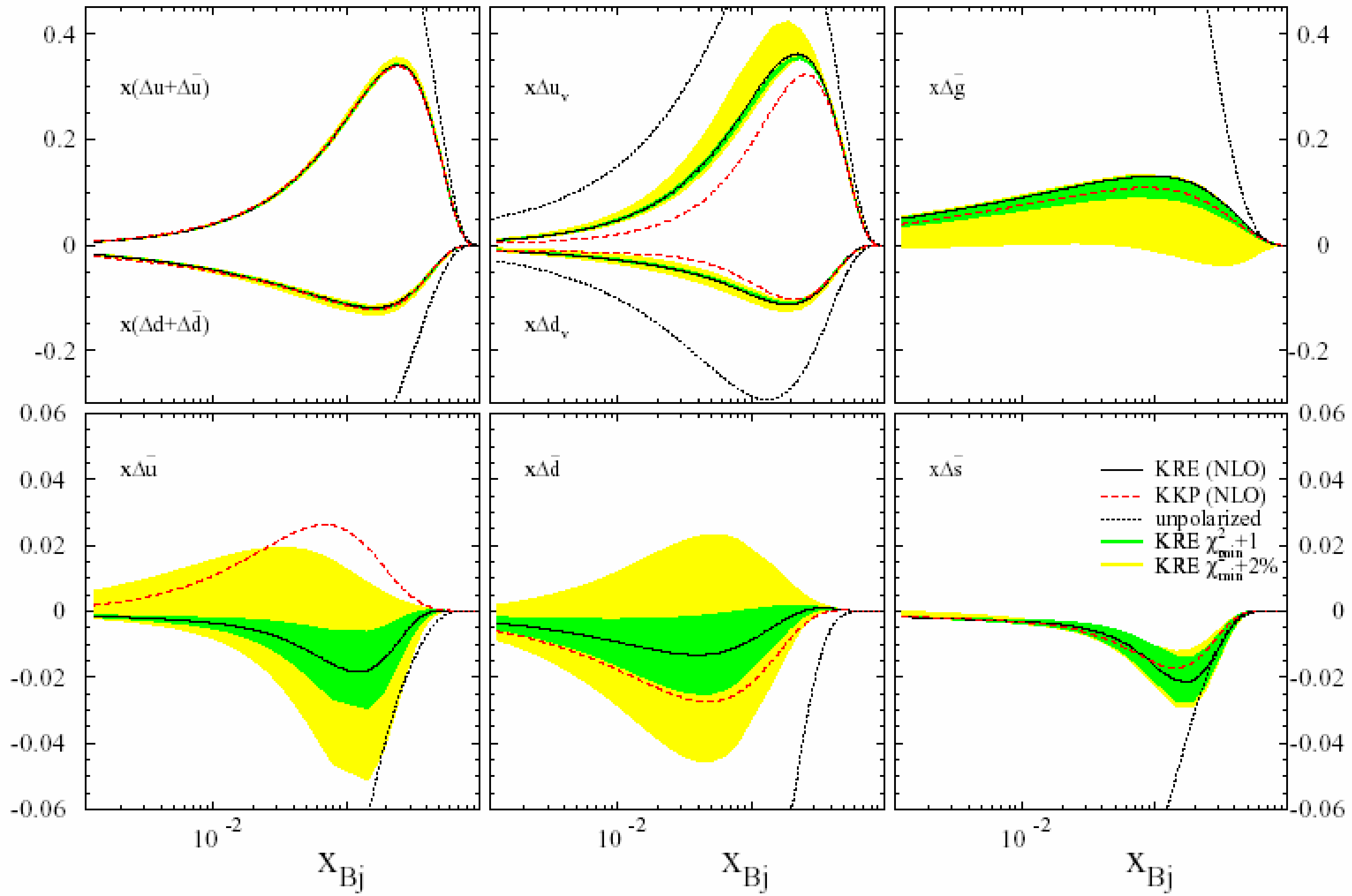


FIGURE 2. Parton densities at $Q^2 = 10$ GeV^2, and the uncertainty bands corresponding to $\Delta\chi^2 = 1$ and $\Delta\chi^2 = 2\%$

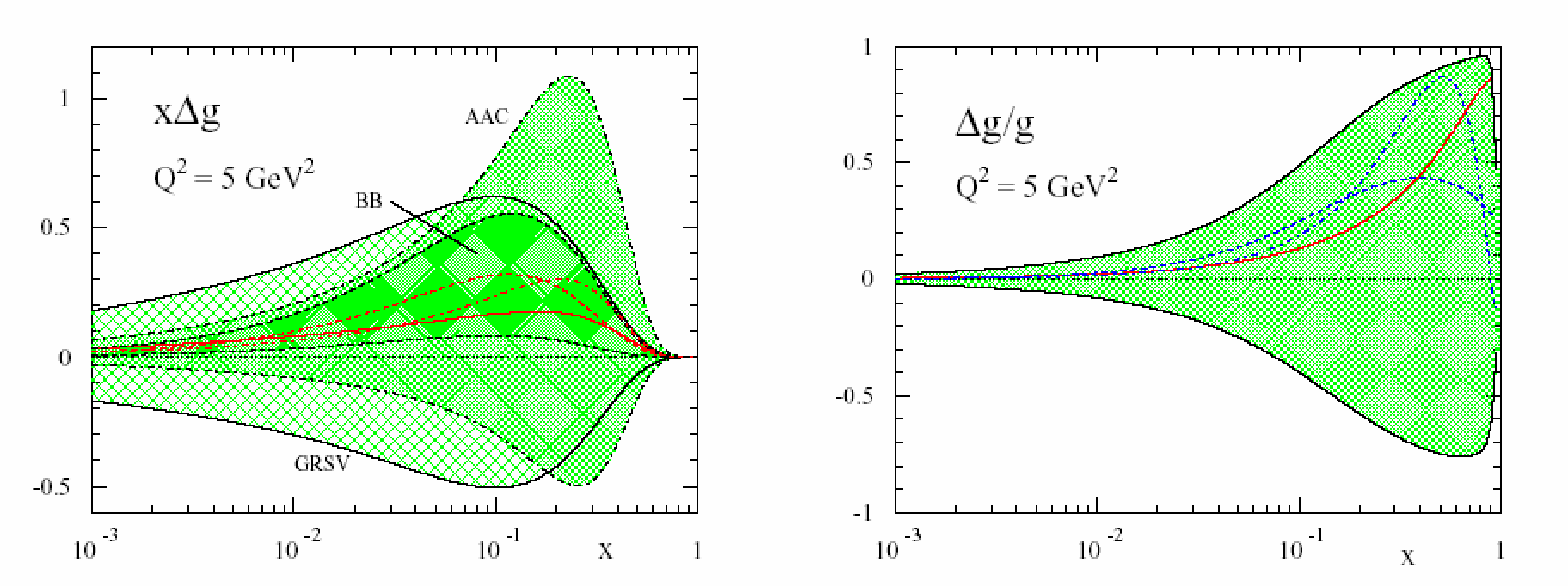
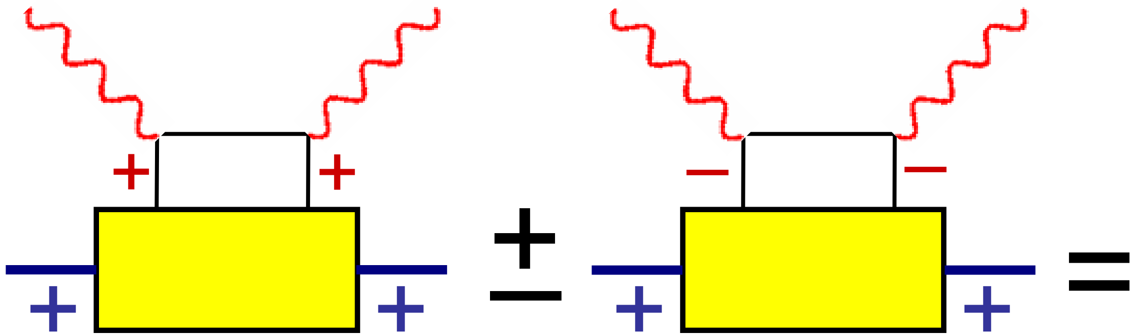
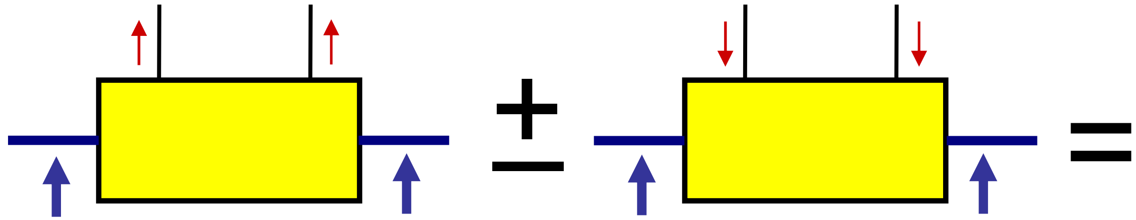


Figure 11: *Left: results for* Δg(x,Q^2 = 5GeV^2) *from recent NLO analyses [1, 2, 36] of polarized DIS. The various bands indicate ranges in* Δg *that were deemed consistent with the scaling violations in polarized DIS in these analyses. The rather large differences among these bands partly result from 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].*

The missing piece, transversity



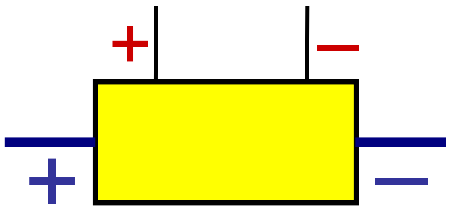
$$q(x,Q^2)$$
$$\Delta q(x,Q^2)$$



$$q(x,Q^2)$$
$$\Delta_T q(x,Q^2)$$

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

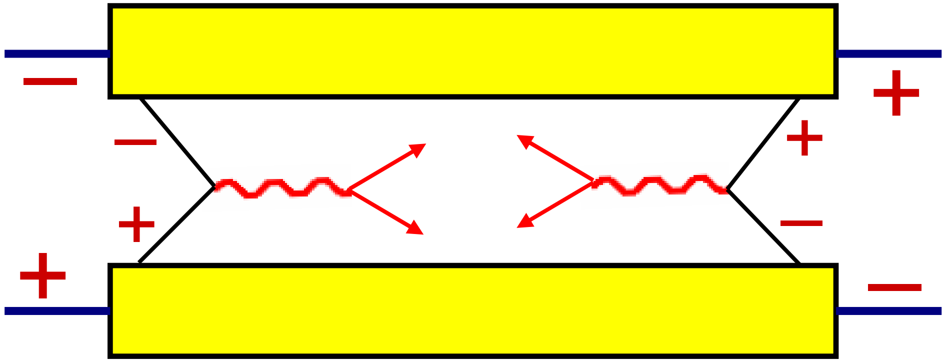
$$h_1(x,Q^2) =$$



decouples from DIS
(no quark helicity flip)

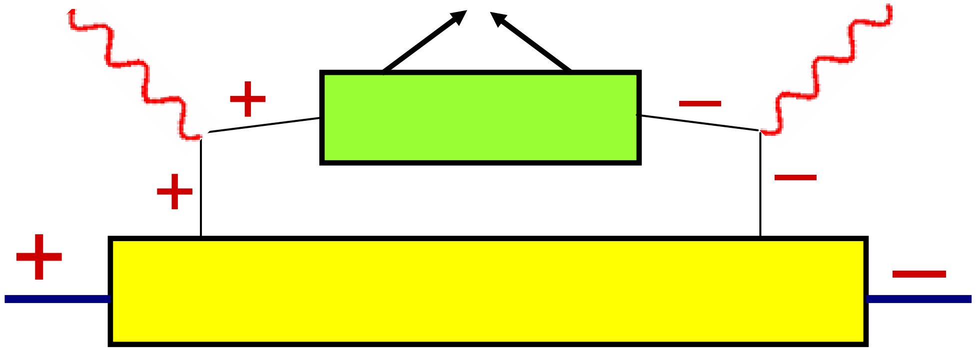
h_1 must couple to another chiral-odd function. For example

$$\mathrm{D-Y},\ p\,p \rightarrow l^+ l^- X, \text{and SIDIS}, l\,p \rightarrow l\,\pi\,X$$



h_1 x h_1

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

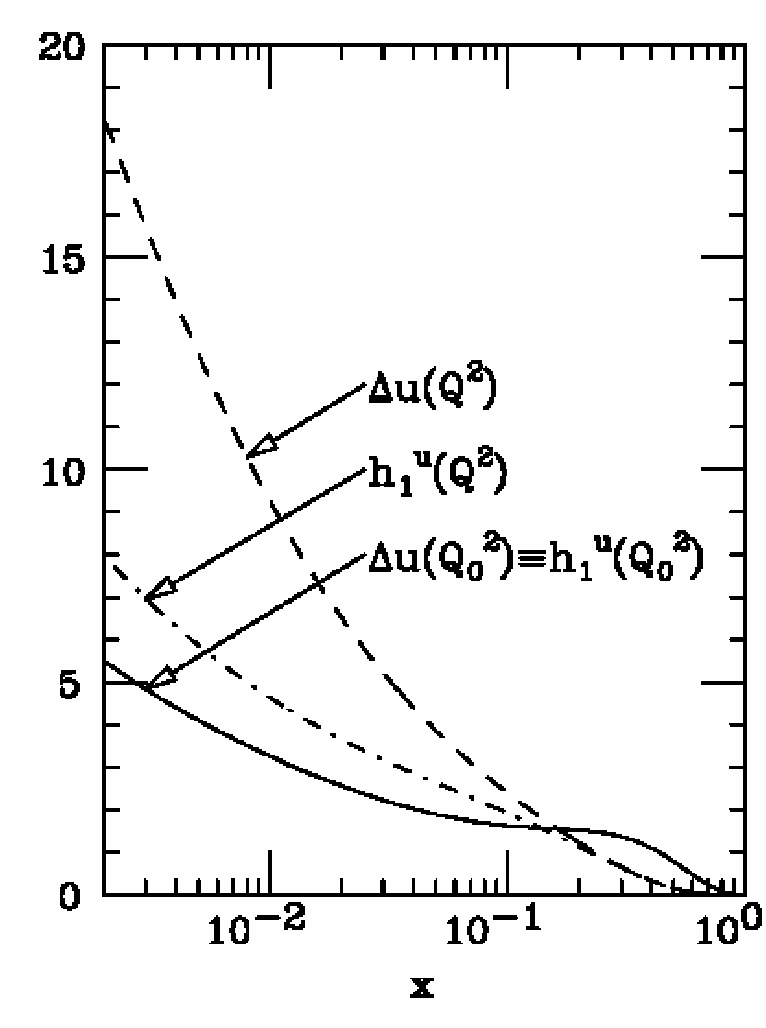


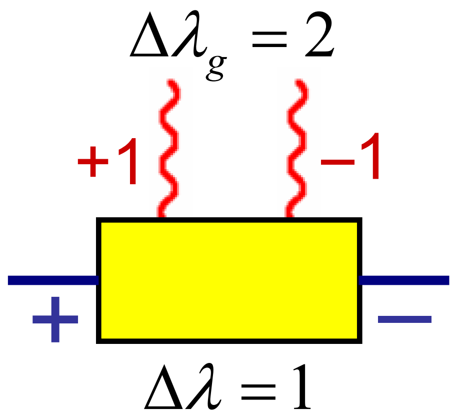
h_1 x *Collins function*

J. Collins, 1993

No gluon contribution to h_1

simple Q^2 evolution

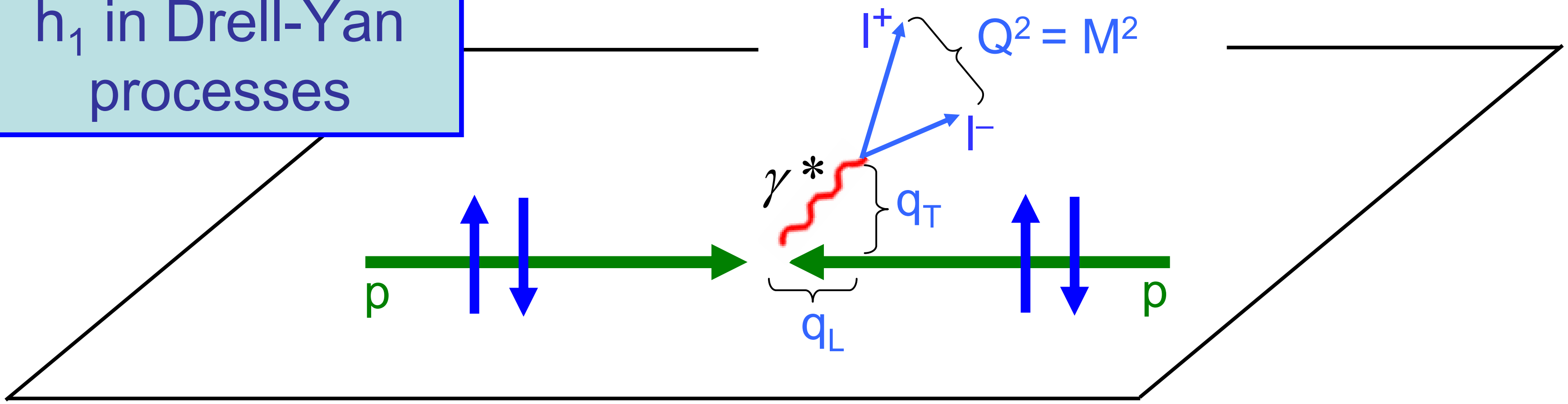




$Q^2 = 25\ GeV^2$
$Q_0^2 = 0.23\ GeV^2$

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 $\perp$ to polarization vectors,
$p - \gamma^*$ plane, $l^+ - l^-$ plane ⇨ plenty of spin effects

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

$$A_{TT} = \frac{\mathrm{d}\sigma^{\uparrow\uparrow} - \mathrm{d}\sigma^{\uparrow\downarrow}}{\mathrm{d}\sigma^{\uparrow\uparrow} + \mathrm{d}\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^{\,2}\left[h_{1q}(x_1)h_{1\bar{q}}(x_2) + h_{1\bar{q}}(x_1)h_{1q}(x_2)\right]}{\sum_q e_q^{\,2}\left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]}$$

$$\hat{a}_{TT} = \frac{\mathrm{d}\hat{\sigma}^{\uparrow\uparrow} - \mathrm{d}\hat{\sigma}^{\uparrow\downarrow}}{\mathrm{d}\hat{\sigma}^{\uparrow\uparrow} + \mathrm{d}\hat{\sigma}^{\uparrow\downarrow}} = \frac{\sin^2\vartheta}{1+\cos^2\vartheta}\cos(2\varphi)$$

RHIC energies: $\sqrt{s} = 200\,\mathrm{GeV} \quad M^2 \leq 100\ \mathrm{GeV}^2$

➡ $\tau \leq 2\cdot 10^{-3}$ small x_1 and/or x_2

$h_{1q}(x, Q^2)$ evolution much slower than $\Delta q(x, Q^2)$ and $q(x, Q^2)$ at small x

➡ A_{TT} at RHIC is very small
smaller s would help

Barone, Calarco, Drago

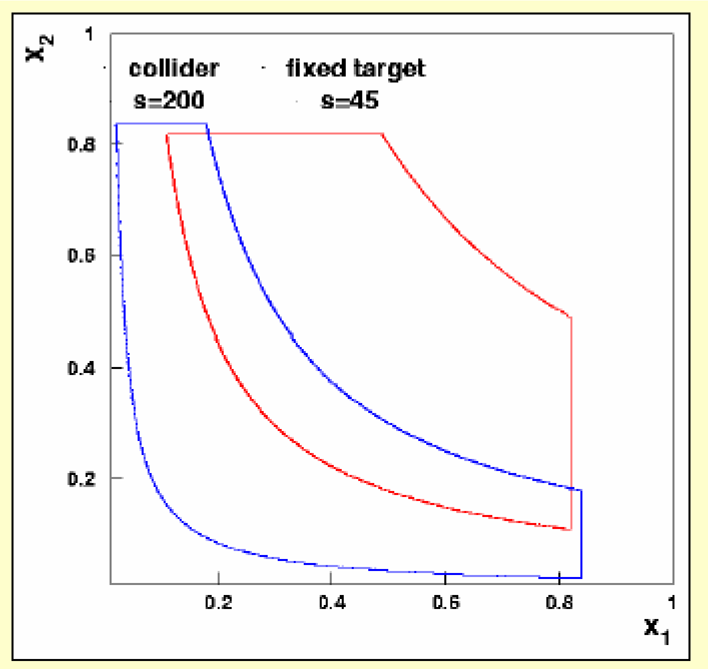
Martin, Schäfer, Stratmann, Vogelsang

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

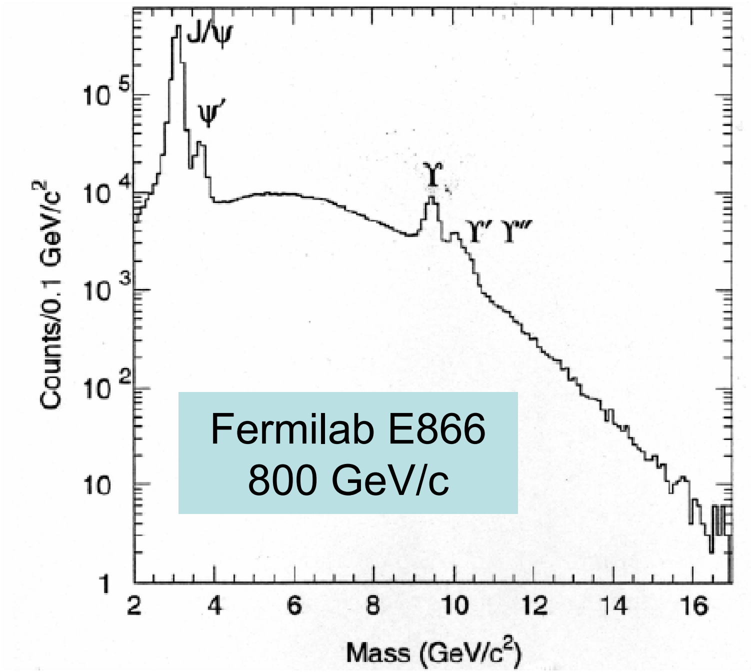
GSI energies: $s = 30 - 210\ \text{GeV}^2 \qquad M \geq 2\ \text{GeV}^2$



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

Energy for Drell-Yan processes



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

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

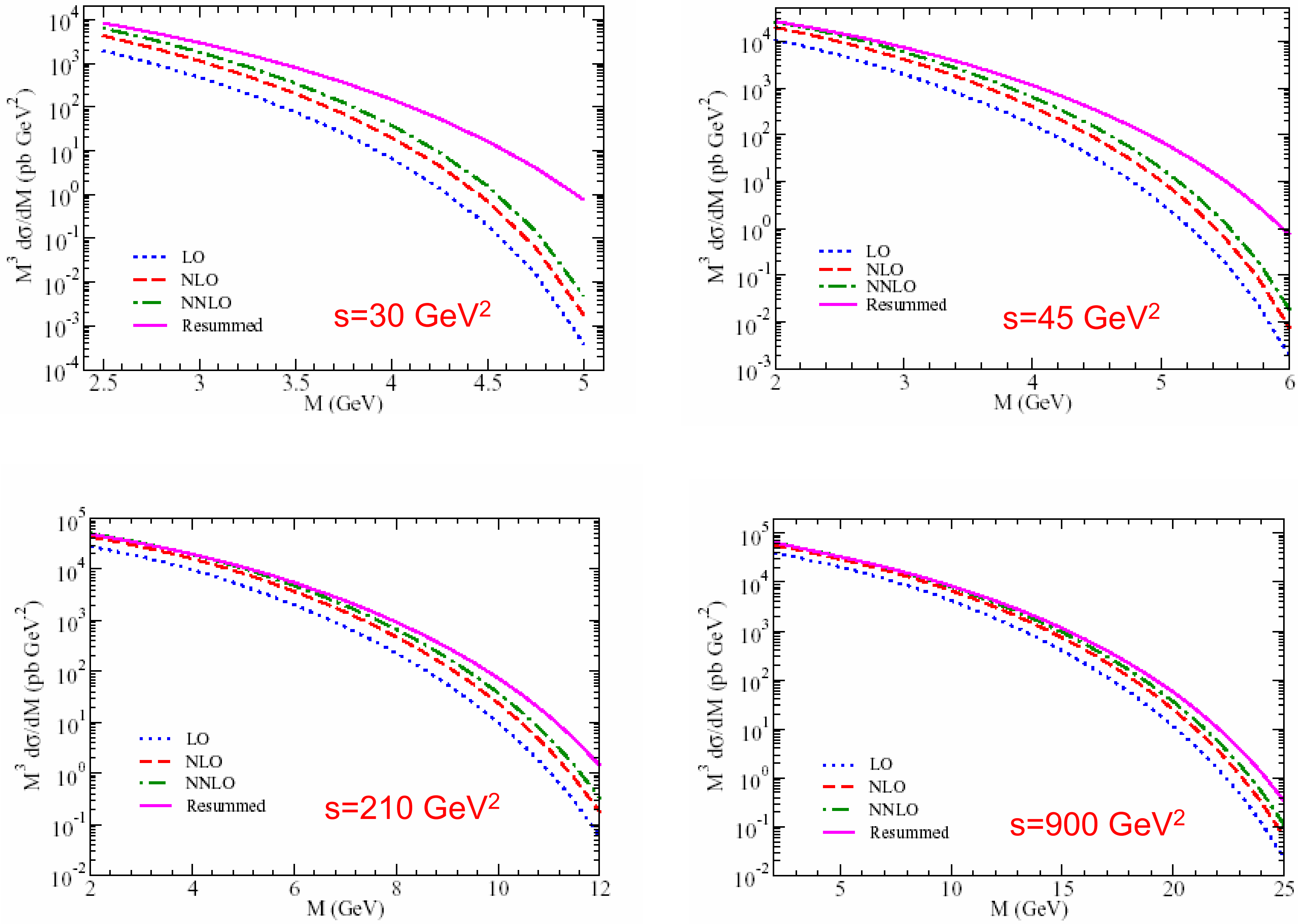
QCD corrections might be very large at smaller values of *M*:

yes, for cross-sections, not for A_{TT}

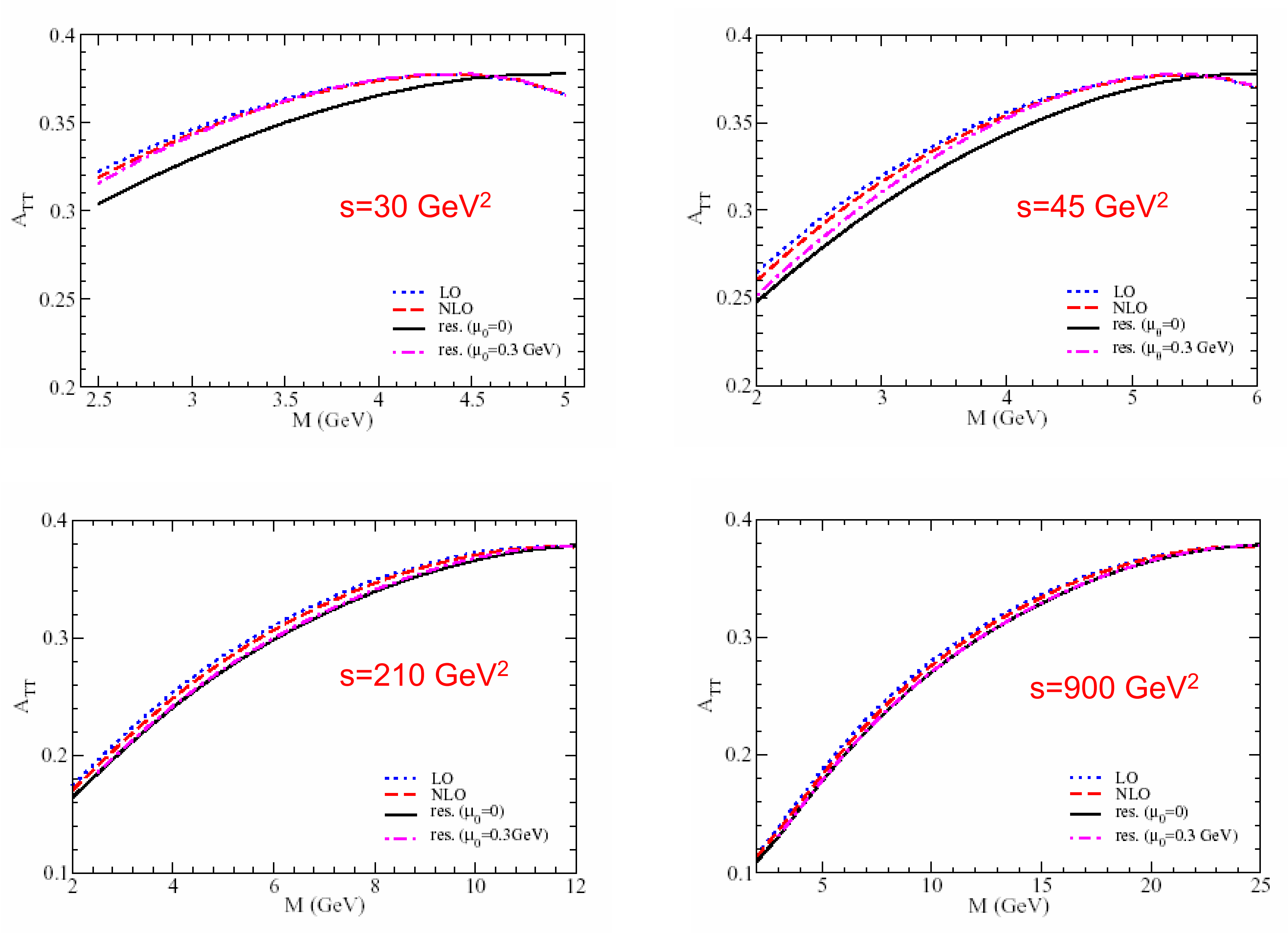
K-factor almost spin-independent

H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya

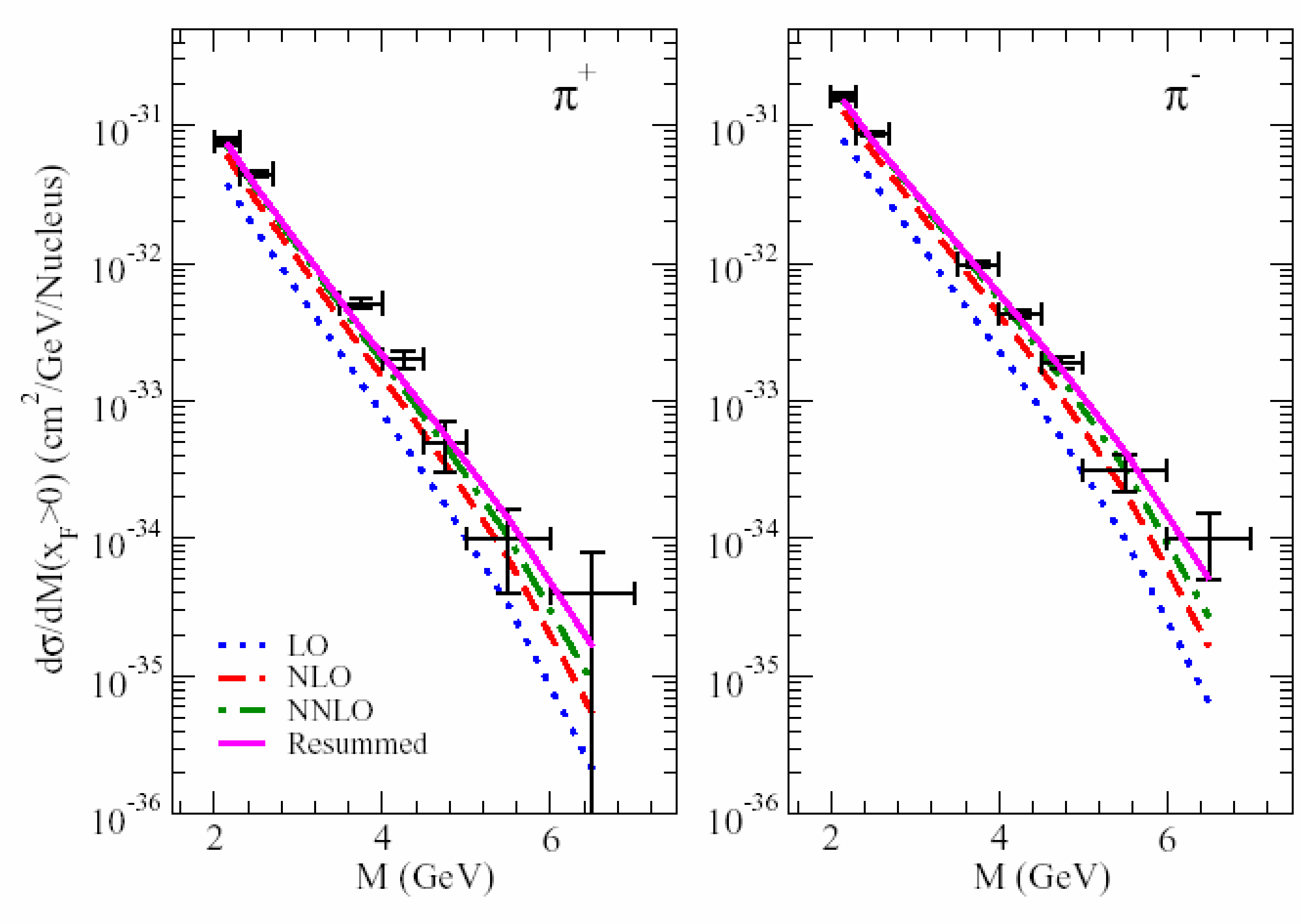
M. Guzzi, V. Barone, A. Cafarella, C. Corianò and P.G. Ratcliffe



M³ dσ/dM (pb GeV²)
M (GeV)
LO
NLO
NNLO
Resummed
s=30 GeV²
s=45 GeV²
s=210 GeV²
s=900 GeV²



s=30 GeV^2
s=45 GeV^2
s=210 GeV^2
s=900 GeV^2
A_{TT}
M (GeV)
LO
NLO
res. (μ_0=0)
res. (μ_0=0.3 GeV)



data from CERN WA39, π N processes, s = 80 GeV^2

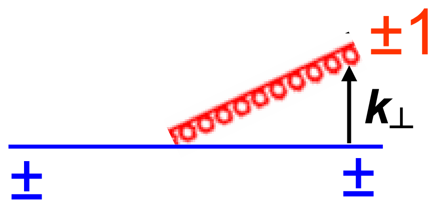
H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya

Partonic intrinsic motion

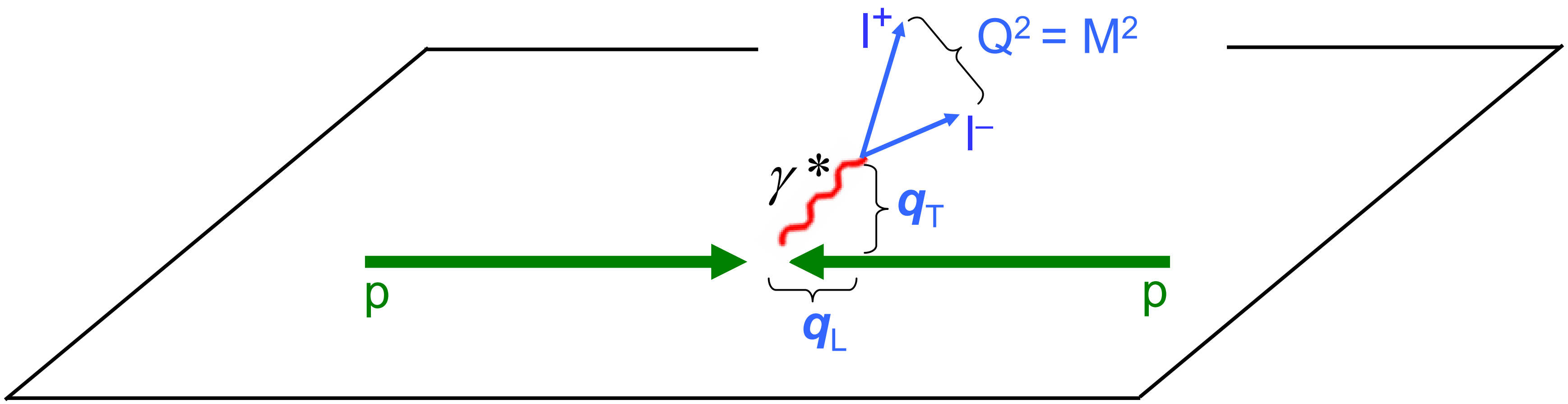
Plenty of theoretical and experimental evidence for transverse motion of partons within nucleons and of hadrons within fragmentation jets

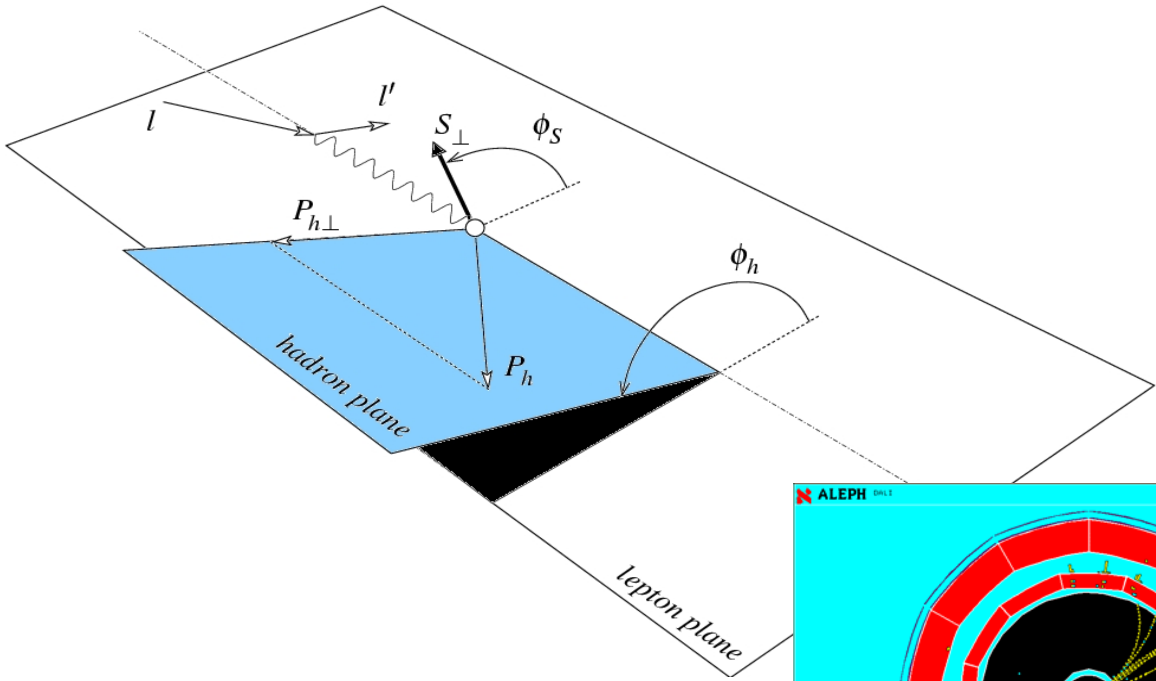
uncertainty principle $\Delta x \approx 1\,\text{fm} \Rightarrow \Delta p \approx 0.2\ \text{GeV/c}$

gluon radiation



q_T distribution of lepton pairs in D-Y processes

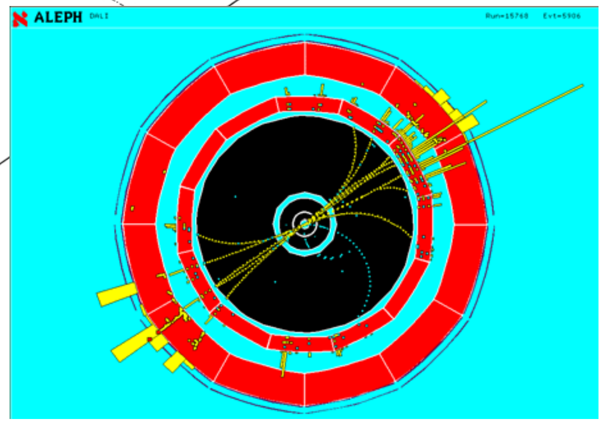




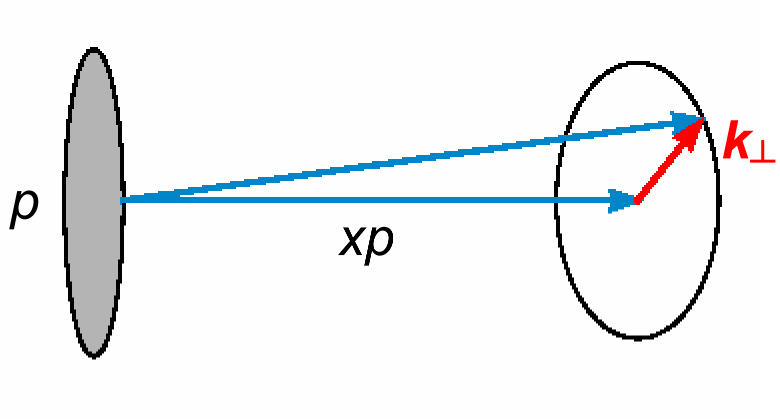
p_T distribution of hadrons in SIDIS

$$\gamma^* p \to h\, X$$

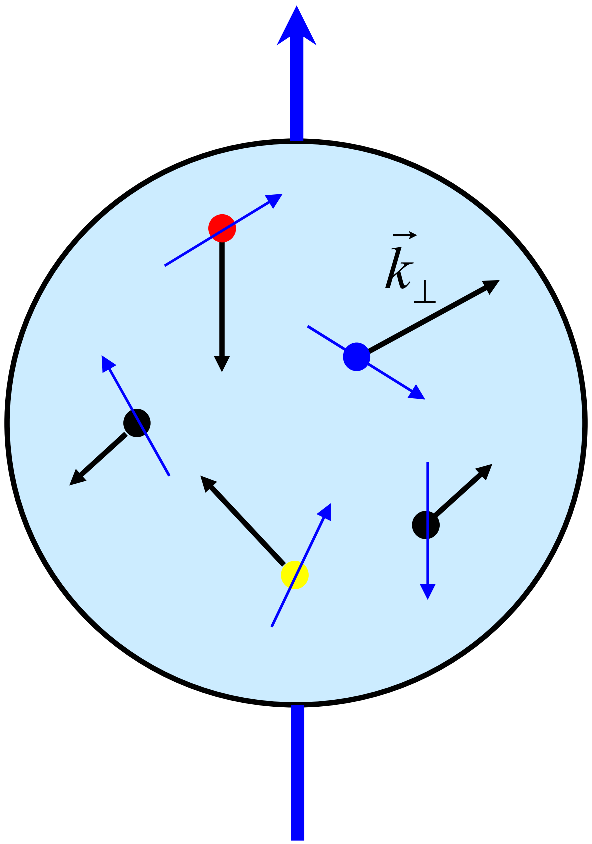
Hadron distribution in jets in e^+e^- processes



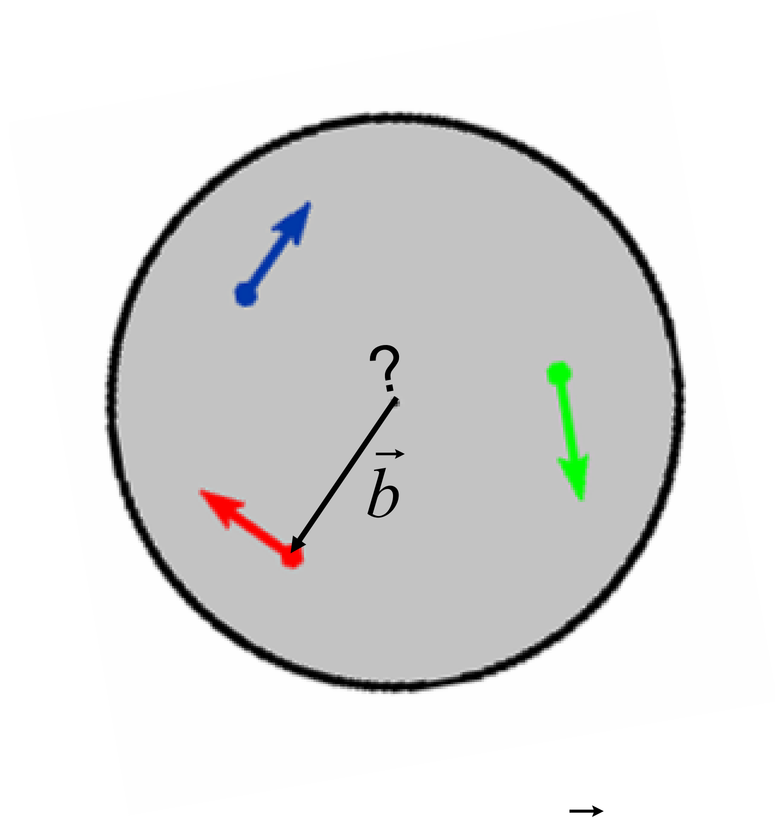
Large p_T particle production in $pN \to hX$



Transverse motion is usually integrated, but there might be important spin-$k_\perp$ correlations spin-$k_\perp$ correlations?



orbiting quarks?



Transverse Momentum Dependent distribution functions $q(x, \vec{k}_\perp)$

Space dependent distribution functions (GPD) $q(x, \vec{b})$

Unpolarized SIDIS, $[O(\alpha_s^0)]$

$$\mathrm{d}\sigma^{lp\to lhX} = \sum_q f_q(x,Q^2) \otimes \mathrm{d}\hat{\sigma}^{lq\to lq} \otimes D_q^h(z,Q^2)$$

in collinear parton model

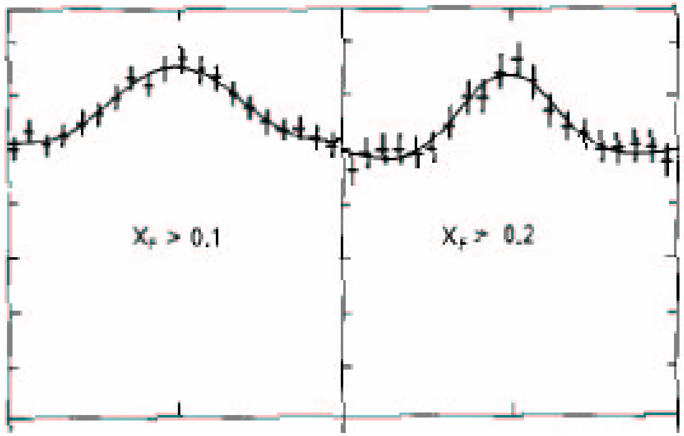
$$\mathrm{d}\hat{\sigma}^{lq\to lq} \propto \hat{s}^2 + \hat{u}^2 \propto 1 + (1-y)^2$$

$$x = \frac{Q^2}{2p\cdot q} \qquad Q^2 = -q^2 \qquad y = \frac{p\cdot q}{l\cdot p}$$

thus, no dependence on azimuthal angle Φ_h at zero-th order in pQCD

the experimental data reveal that

$$\mathrm{d}\hat{\sigma}^{lq\to lh^\pm X} / \mathrm{d}\Phi_h \propto A + B\cos\Phi_h + C\cos 2\Phi_h$$



M. Arneodo et al (EMC): Z. Phys. C 34 (1987) 277

Cahn: the observed azimuthal dependence is related to the intrinsic $k_\perp$ of quarks (at least for small P_T values)

$$\vec{k}_\perp = (k_\perp \cos\varphi, k_\perp \sin\varphi, 0)$$

$$\hat{s} = sx\left[1 - \frac{2k_\perp}{Q}\sqrt{1-y}\cos\varphi\right] + O\left(\frac{k_\perp^2}{Q^2}\right)$$

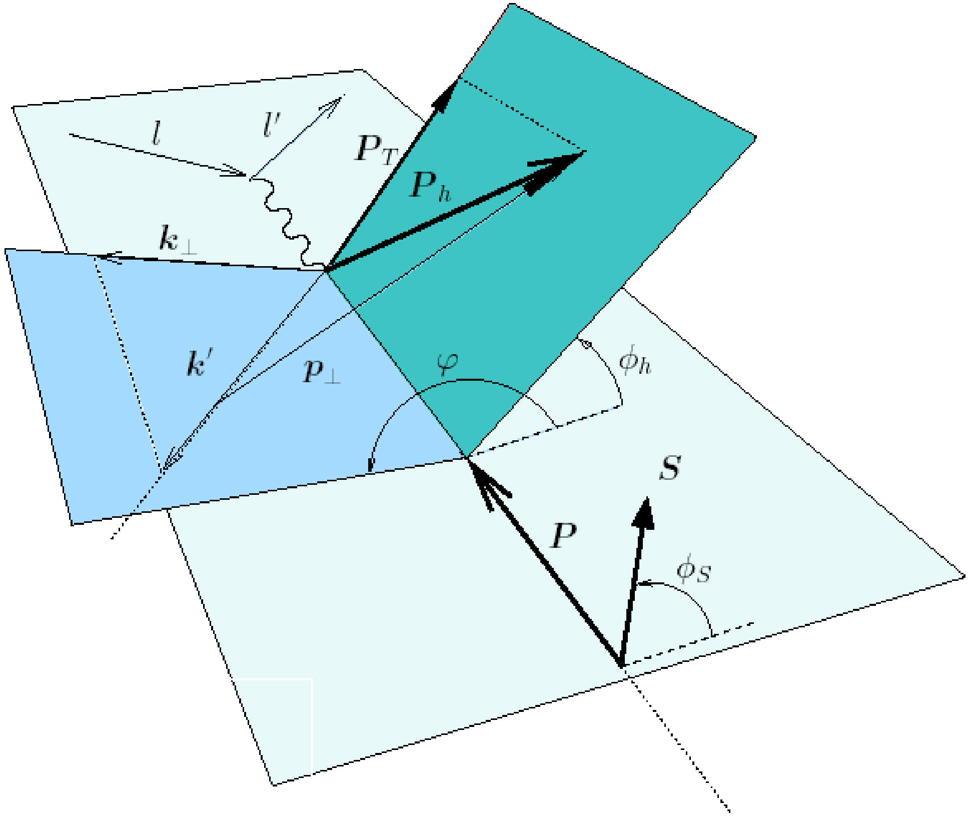
$$\hat{u} = s\,x\,(1-y)\left[1 - \frac{2k_\perp}{Q\sqrt{1-y}}\cos\varphi\right] + O\left(\frac{k_\perp^2}{Q^2}\right)$$

⇒ assuming collinear fragmentation, $\varphi = \Phi_h$

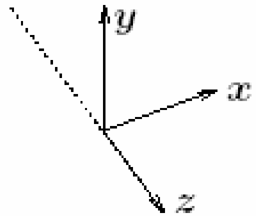
$$\frac{d\hat{\sigma}^{lq\to lhX}}{d\Phi_h} \propto \hat{s}^2 + \hat{u}^2 \propto A + B\cos\Phi_h + C\cos 2\Phi_h$$

These modulations of the cross section with azimuthal angle are denoted as "Cahn effect".

SIDIS with intrinsic $\boldsymbol{k}_\perp$

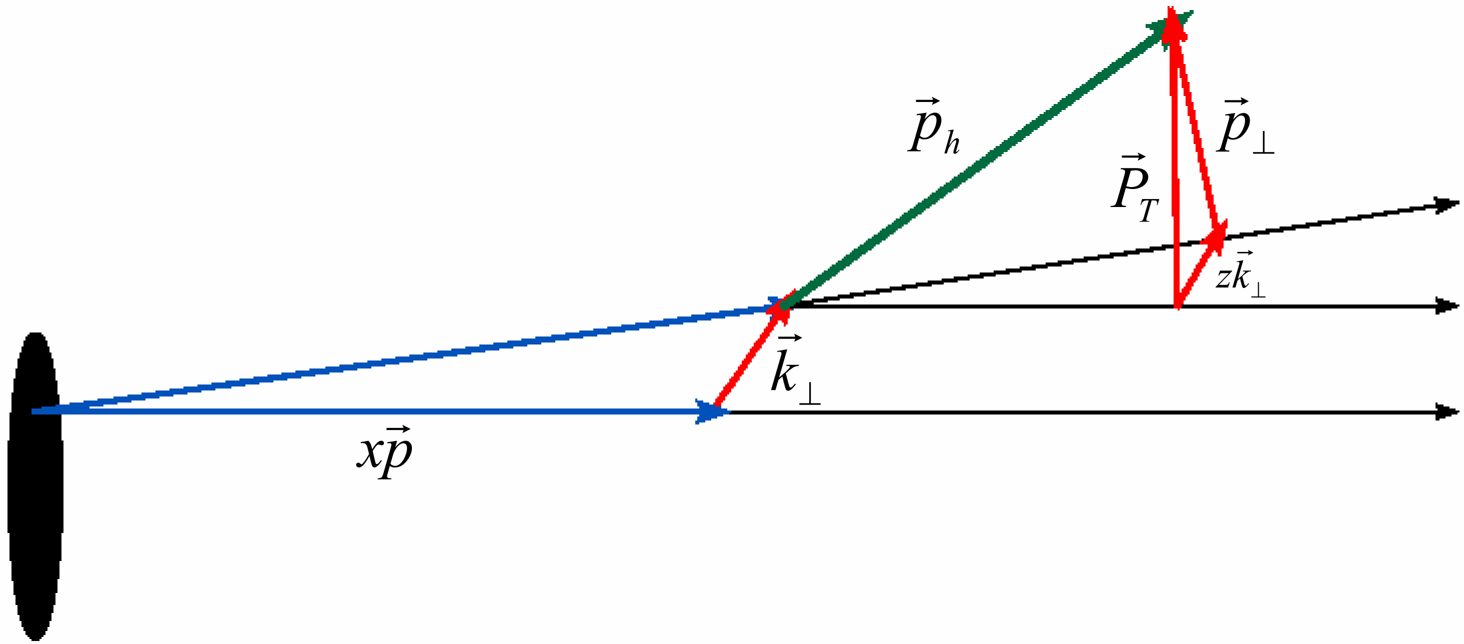


kinematics
according to Trento
conventions (2004)



factorization holds at large Q^2, and $P_T \approx k_\perp \approx \Lambda_{QCD}$ Ji, Ma, Yuan

$$\mathrm{d}\sigma^{lp\to lhX} = \sum_q f_q(x, k_\perp; Q^2) \otimes \mathrm{d}\hat{\sigma}^{lq\to lq}(y, \vec{k}_\perp; Q^2) \otimes D_q^h(z, p_\perp; Q^2)$$



The situation is more complicated as the produced hadron has also intrinsic transverse momentum with respect to the fragmenting parton

neglecting terms of order $(k_\perp / Q)$ one has

$$\vec{P}_T = \vec{p}_\perp + z\vec{k}_\perp$$

assuming:

$$\begin{cases} f_q(x, k_\perp) = f_q(x)\,\dfrac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle} \\[2ex] D_q^h(z, p_\perp) = D_q^h(z)\,\dfrac{1}{\pi\langle p_\perp^2\rangle}\,e^{-p_\perp^2/\langle p_\perp^2\rangle} \end{cases}$$

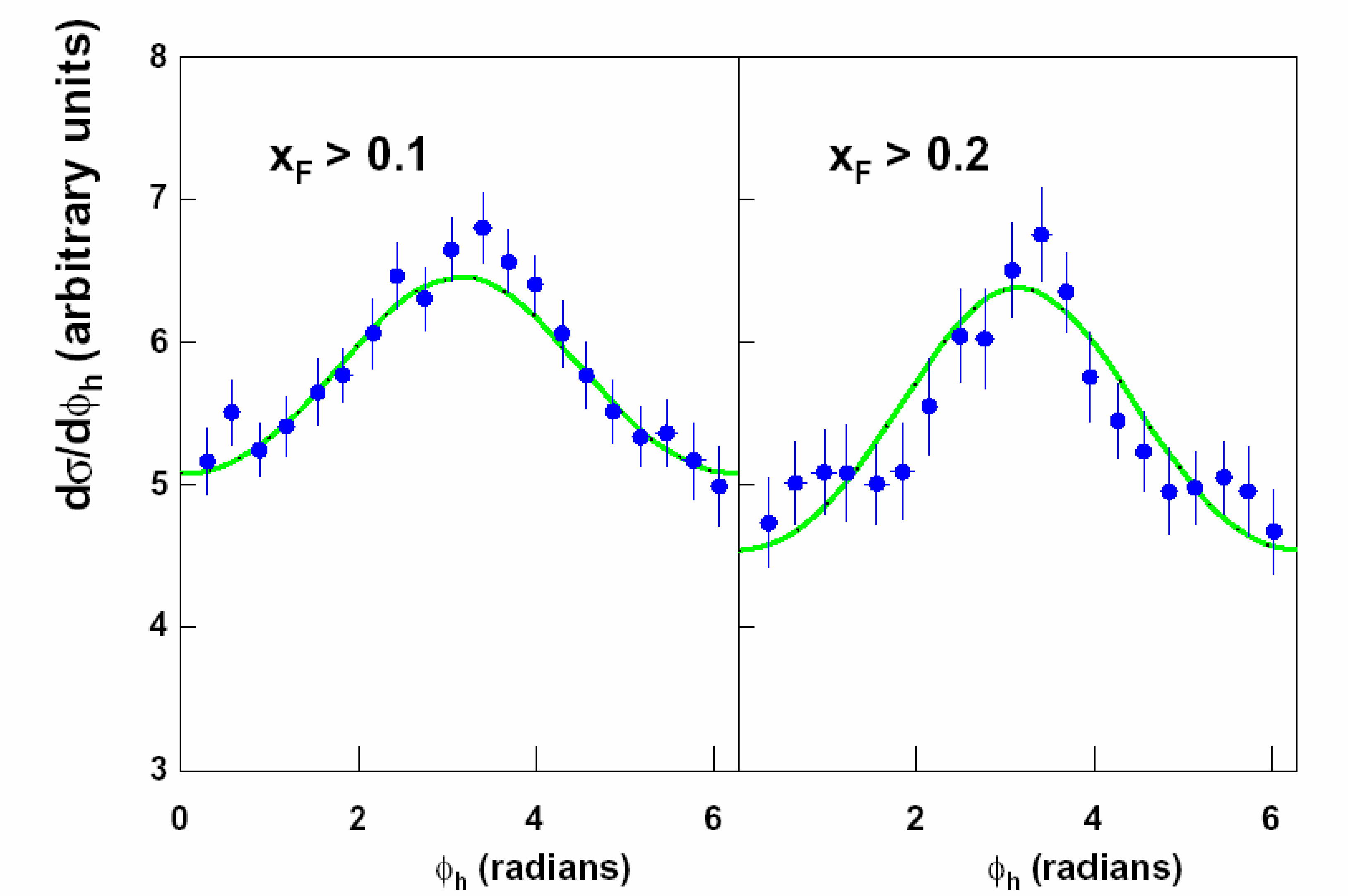
one finds:

$$\frac{d^5\sigma^{\ell p\to\ell hX}}{dx_B\,dQ^2\,dz_h\,d^2\boldsymbol{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4}\, f_q(x_B)\, D_q^h(z_h)\Big[1+(1-y)^2 - 4\,\frac{(2-y)\sqrt{1-y}\,\langle k_\perp^2\rangle\, z_h\, P_T}{\langle P_T^2\rangle\, Q}\,\cos\phi_h\Big]\frac{1}{\pi\langle P_T^2\rangle}\,e^{-P_T^2/\langle P_T^2\rangle}$$

with $\langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$ ➡

clear dependence on $\langle p_\perp^2\rangle$ and $\langle k_\perp^2\rangle$ (assumed to be constant)

Find best values by fitting data on Φ_h and P_T dependences

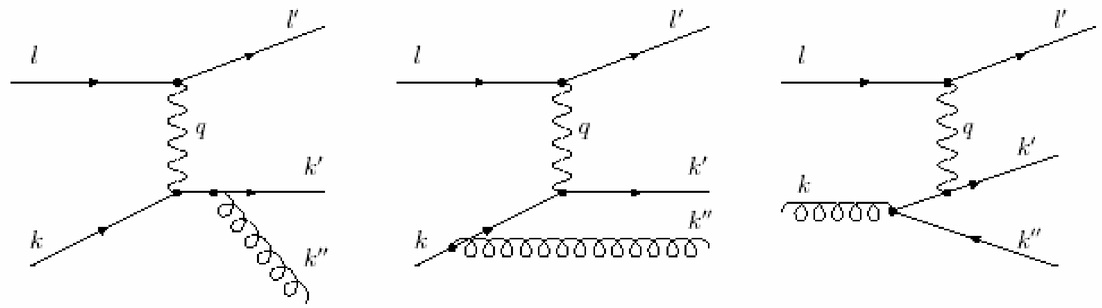


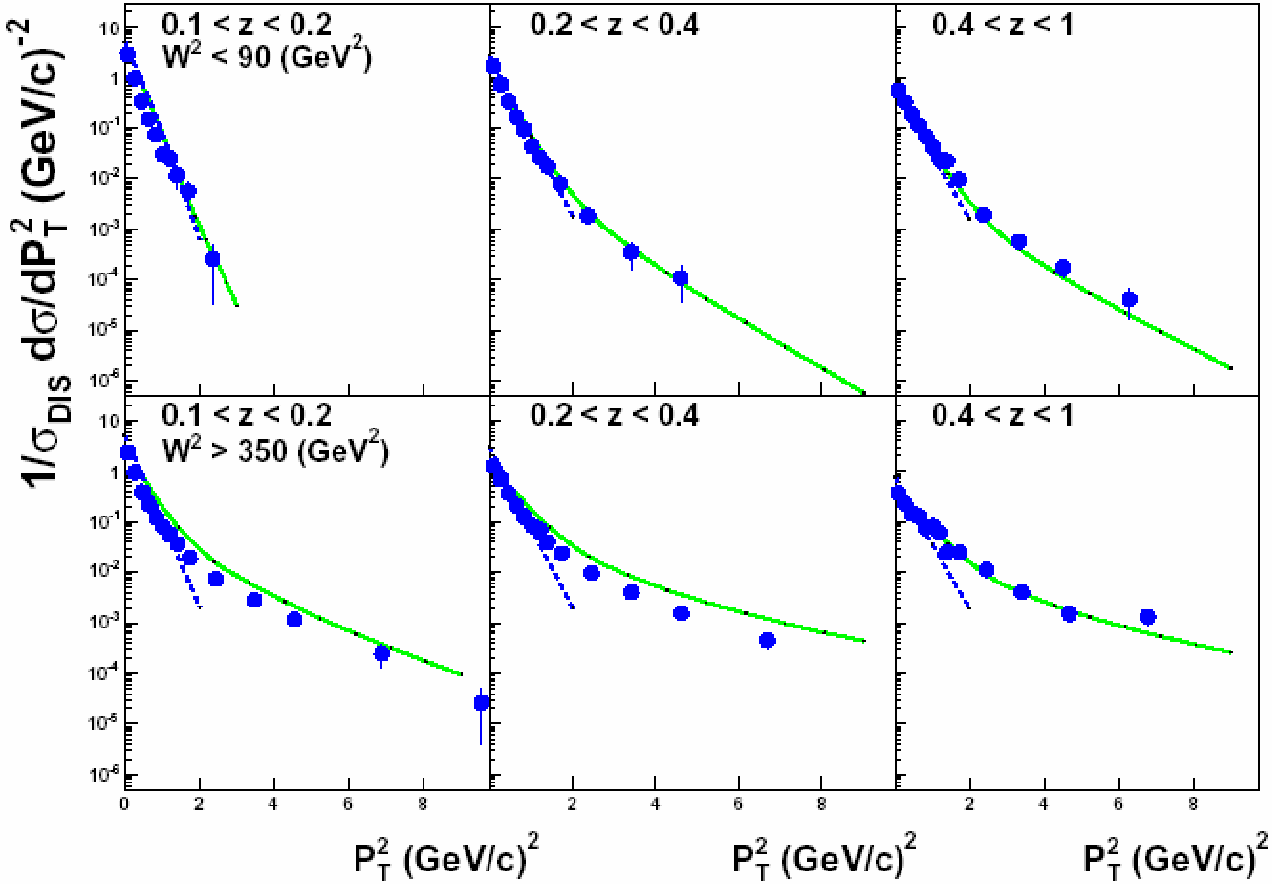
EMC data, μp and μd, *E* between 100 and 280 GeV

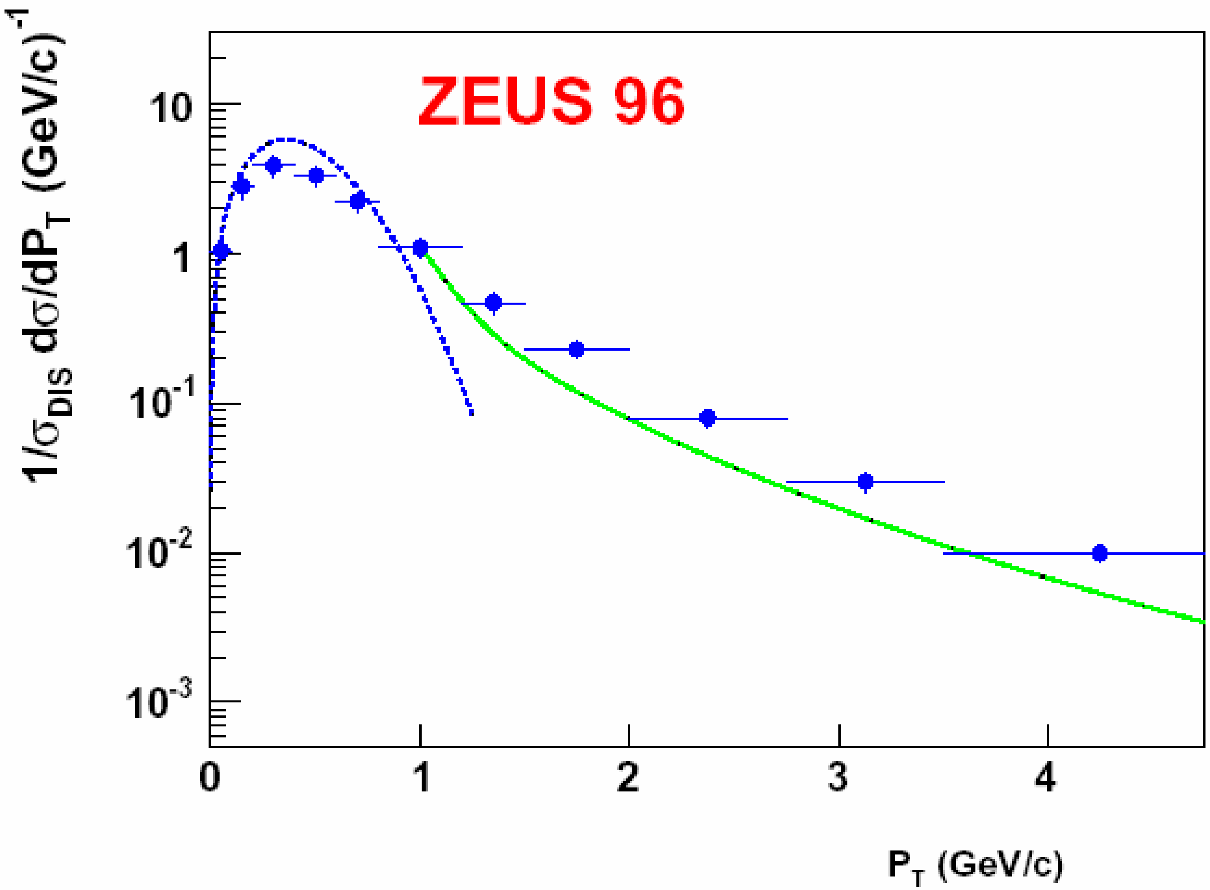
$$\langle k_\perp^2 \rangle = 0.28 \ (\mathrm{GeV})^2 \qquad \langle p_\perp^2 \rangle = 0.25 \ (\mathrm{GeV})^2$$

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

Large P_T data explained by NLO QCD corrections



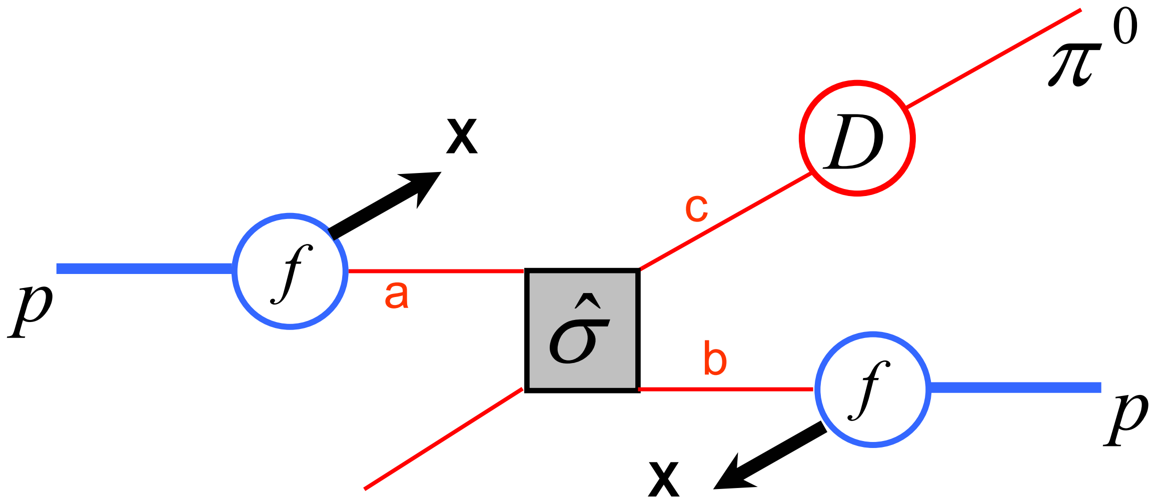




dashed line: parton model with unintegrated distribution and fragmentation functions
solid line: pQCD contributions at LO and a *K* factor (*K* = 1.5) to account for NLO effects

$p\,p \to \pi^0 X$ (collinear configurations)

factorization theorem



$$d\sigma = \sum_{a,b,c,d=q,\bar{q},g} \underbrace{f_{a/p} \otimes f_{b/p}}_{\text{PDF}} \otimes d\hat{\sigma}^{ab\to cd} \otimes \underbrace{D_{\pi/c}}_{\text{FF}}$$

PDF

pQCD elementary interactions

FF

The cross section

$$\frac{E_C\, d\sigma^{AB\to CX}}{d^3\mathbf{p}_C} = \sum_{a,b,c,d}\int dx_a\, dx_b\, dz\, f_{a/A}(x_a,Q^2)\, f_{b/B}(x_b,Q^2)$$

$$\times \frac{\hat{s}}{\pi z^2}\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\hat{s},\hat{t},\hat{u},x_a,x_b)\,\delta(\hat{s}+\hat{t}+\hat{u})\, D_{C/c}(z,Q^2)$$

$$= \sum_{a,b,c,d}\int dx_a\, dx_b\, f_{a/A}(x_a,Q^2)\, f_{b/B}(x_b,Q^2)$$

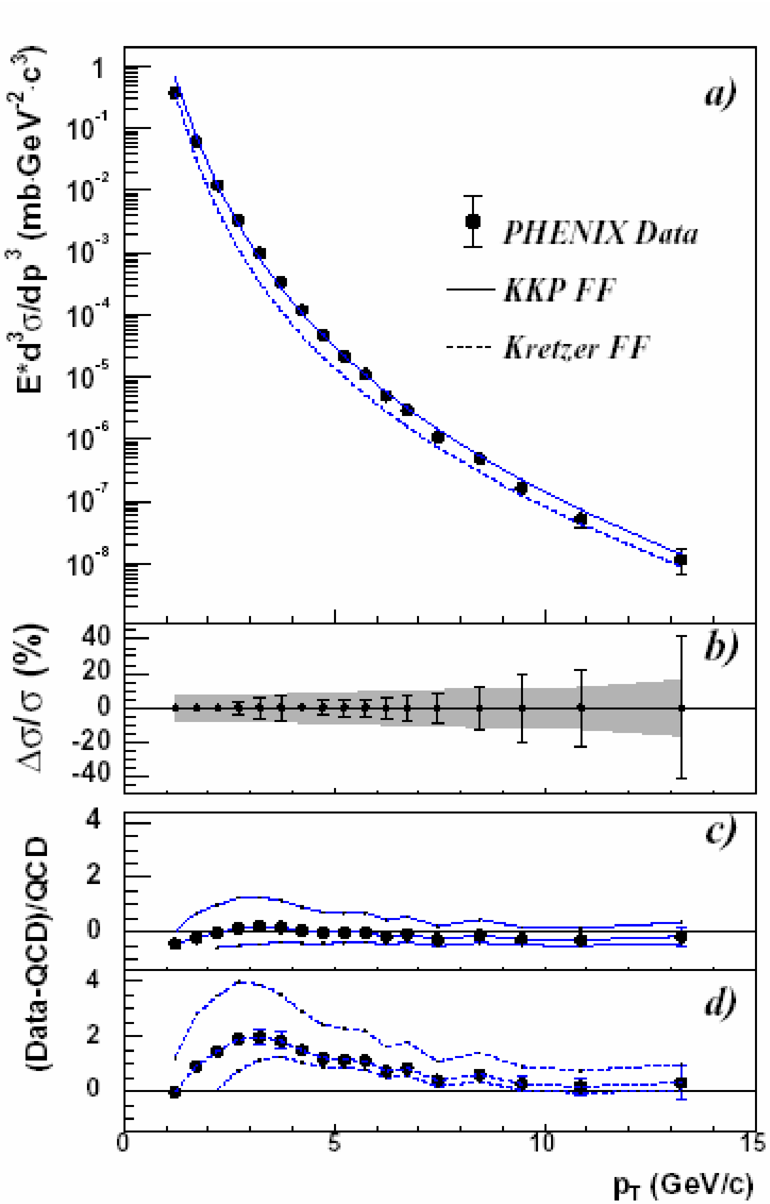
$$\times \frac{1}{\pi z}\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\hat{s},\hat{t},\hat{u},x_a,x_b)\, D_{C/c}(z,Q^2)\;,$$

$$x_a x_b z s = -x_a t - x_b u$$

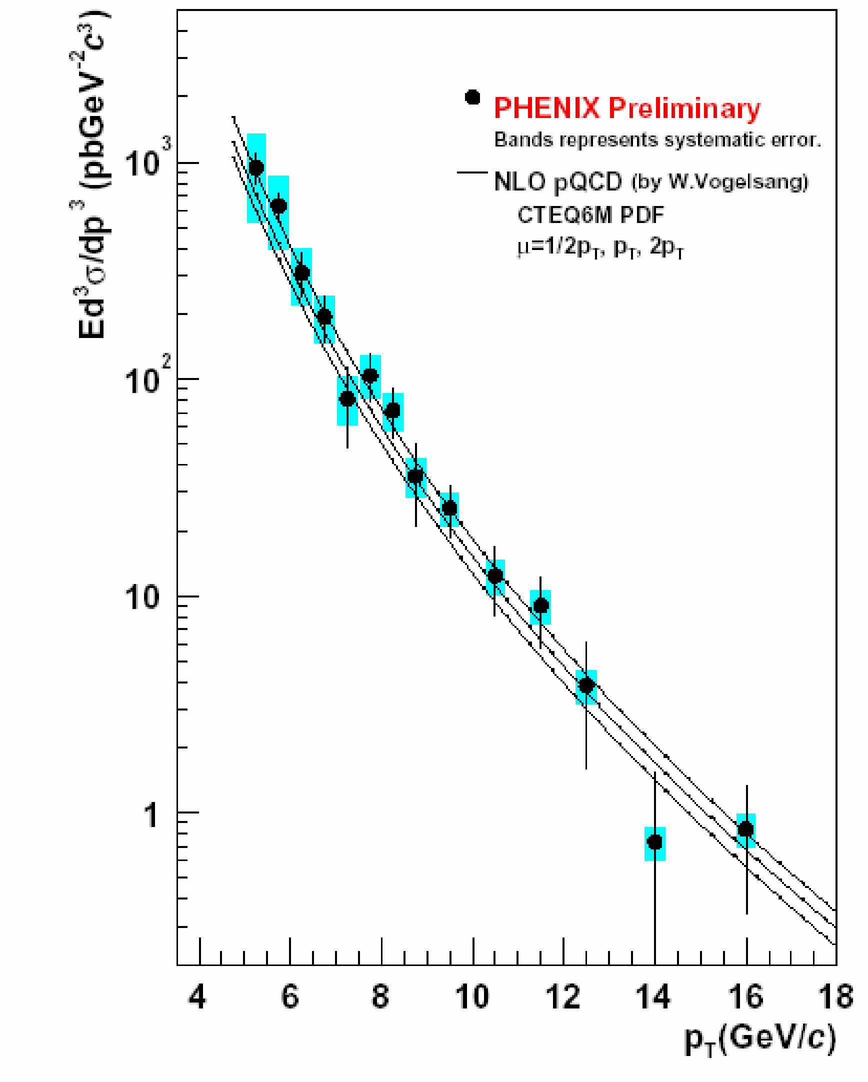
$\hat{s},\hat{t},\hat{u}$ elementary Mandelstam variables

s,t,u hadronic Mandelstam variables

RHIC data $\sqrt{s} = 200\ \text{GeV}$

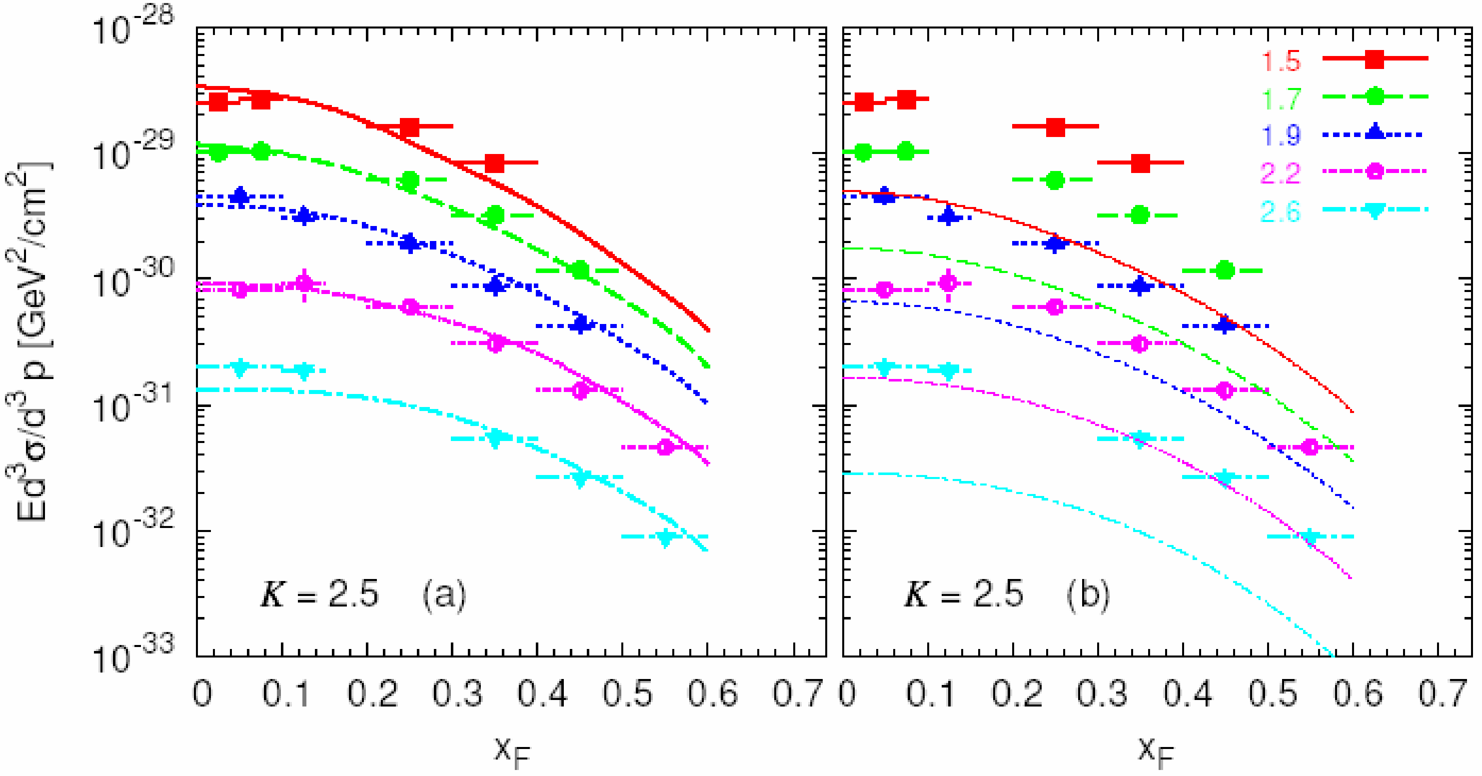


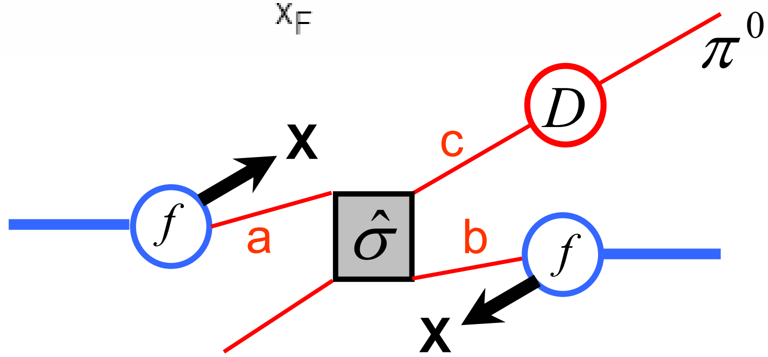
$p\ p \to \pi^0\ X$



$p\ p \to \gamma\ X$

$\langle k_\perp \rangle = 0.8\,\mathrm{GeV}$ no $\langle k_\perp \rangle$





F. Murgia, U. D'Alesio

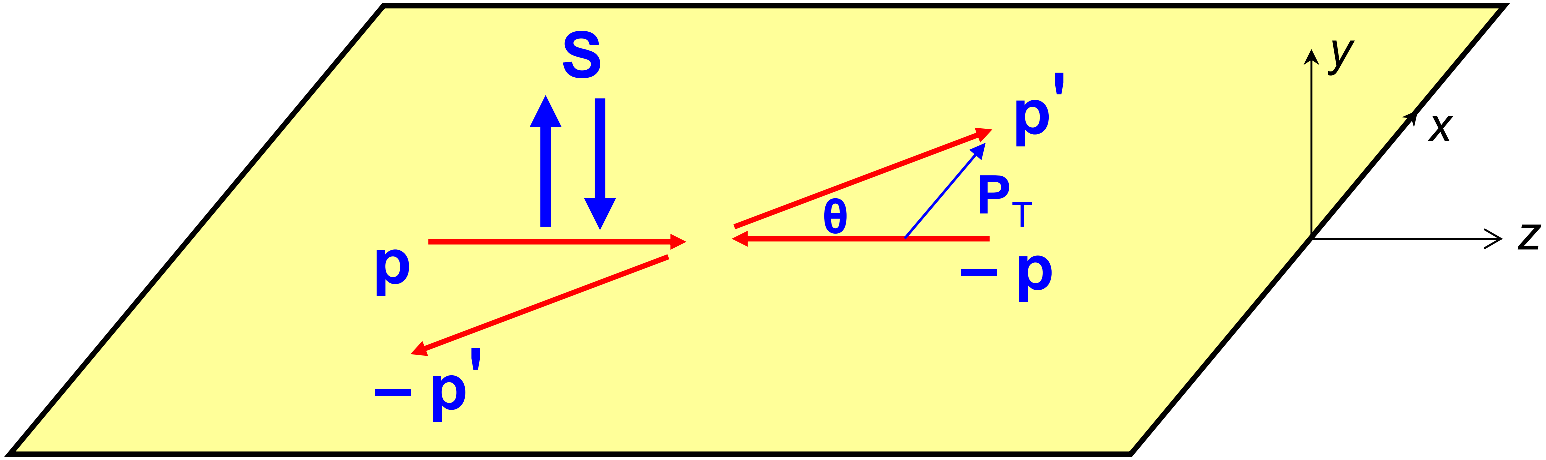
FNAL data, PLB 73 (1978)

$$p\,p \rightarrow \pi^0\,X \qquad \sqrt{s} \approx 20\ \mathrm{GeV}$$

original idea by Feynman-Field

non collinear configurations

Transverse single spin asymmetries: elastic scattering



$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \vec{S} \cdot \left(\vec{p} \times \vec{P}_T\right) \propto \sin\theta$$

Example: $pp \rightarrow pp$ ➡

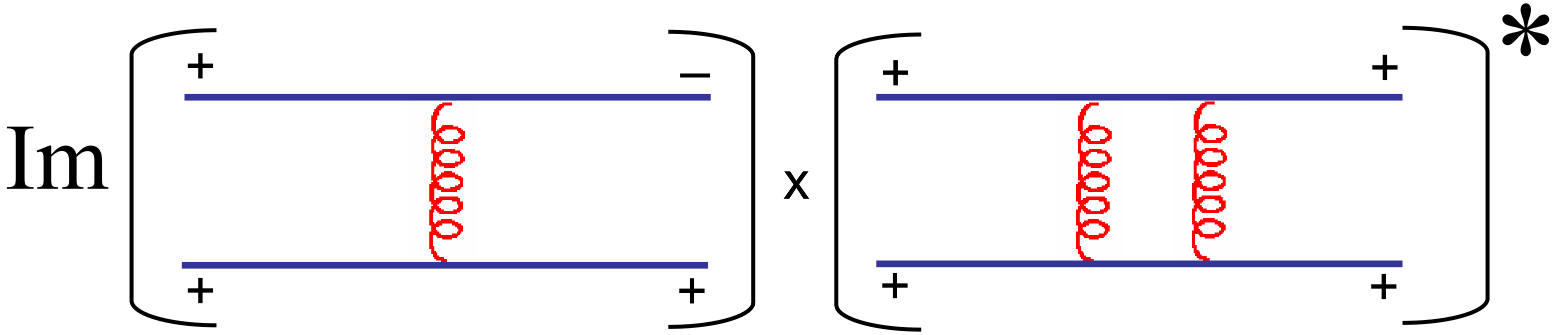
$$M_{++;++} \equiv \Phi_1$$
$$M_{--;++} \equiv \Phi_2$$
$$M_{+-;+-} \equiv \Phi_3$$
$$M_{-+;+-} \equiv \Phi_4$$
$$M_{-+;++} \equiv \Phi_5$$

5 independent helicity amplitudes

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

Single spin asymmetries at partonic level. Example: $qq' \to qq'$

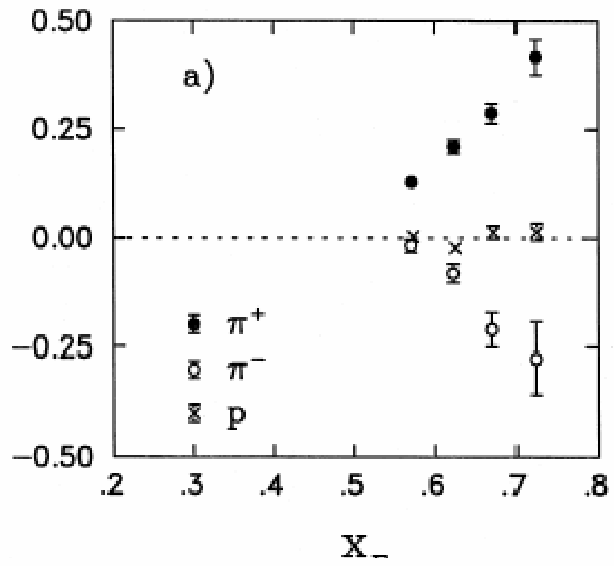
$A_N \neq 0$ needs helicity flip + relative phase



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

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

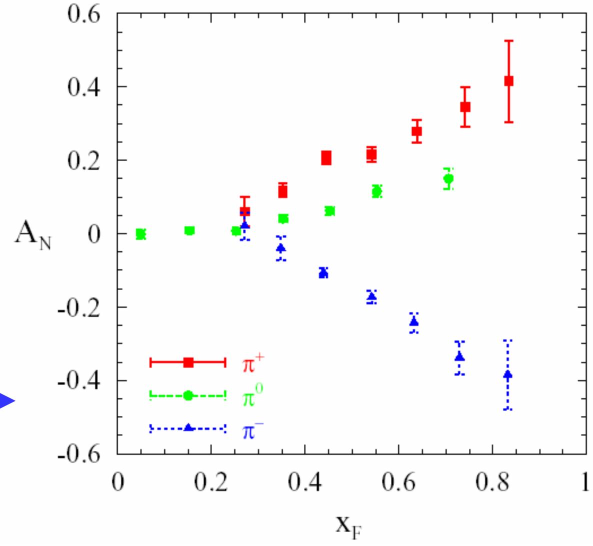
but large SSA observed at hadron level!

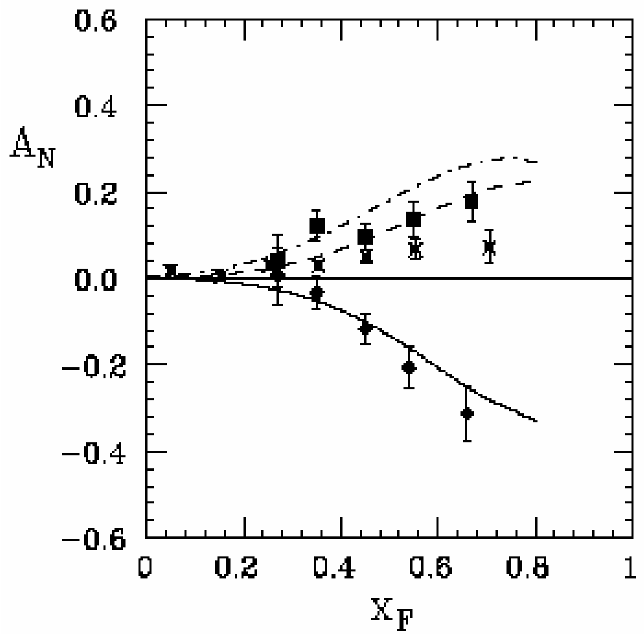


BNL-AGS $\sqrt{s}$ = 6.6 GeV
0.6 < p_T < 1.2

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

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





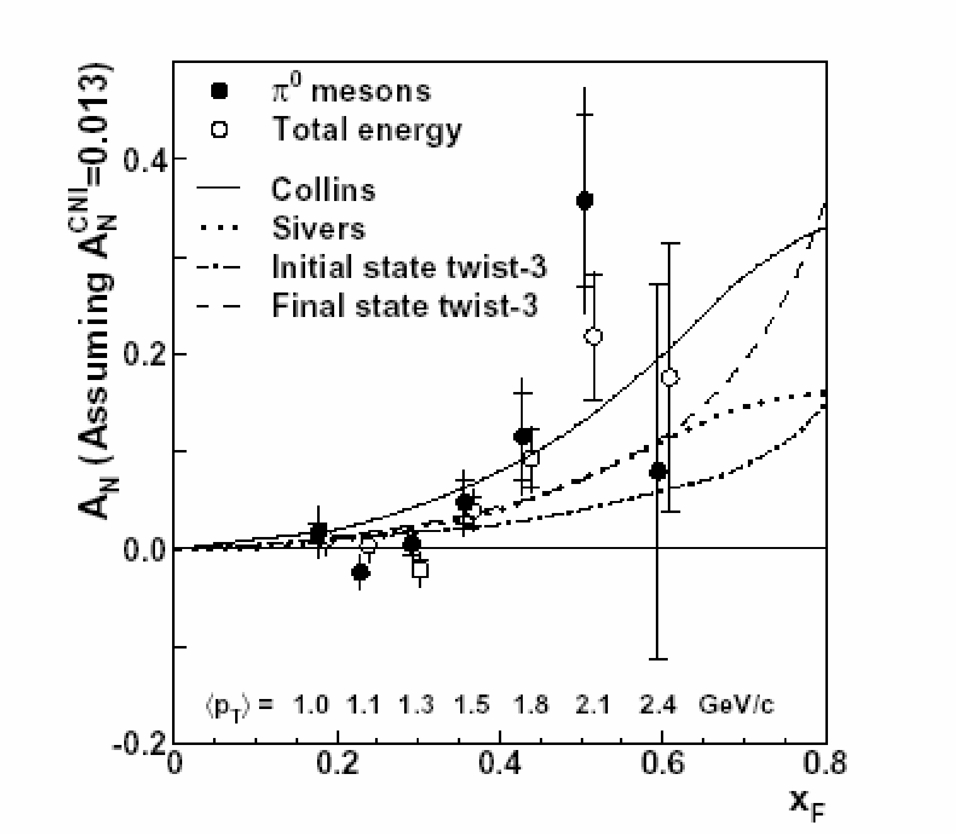
E704 $\sqrt{s}$ = 20 GeV
0.7 < p_T < 2.0

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

observed transverse Single Spin Asymmetries

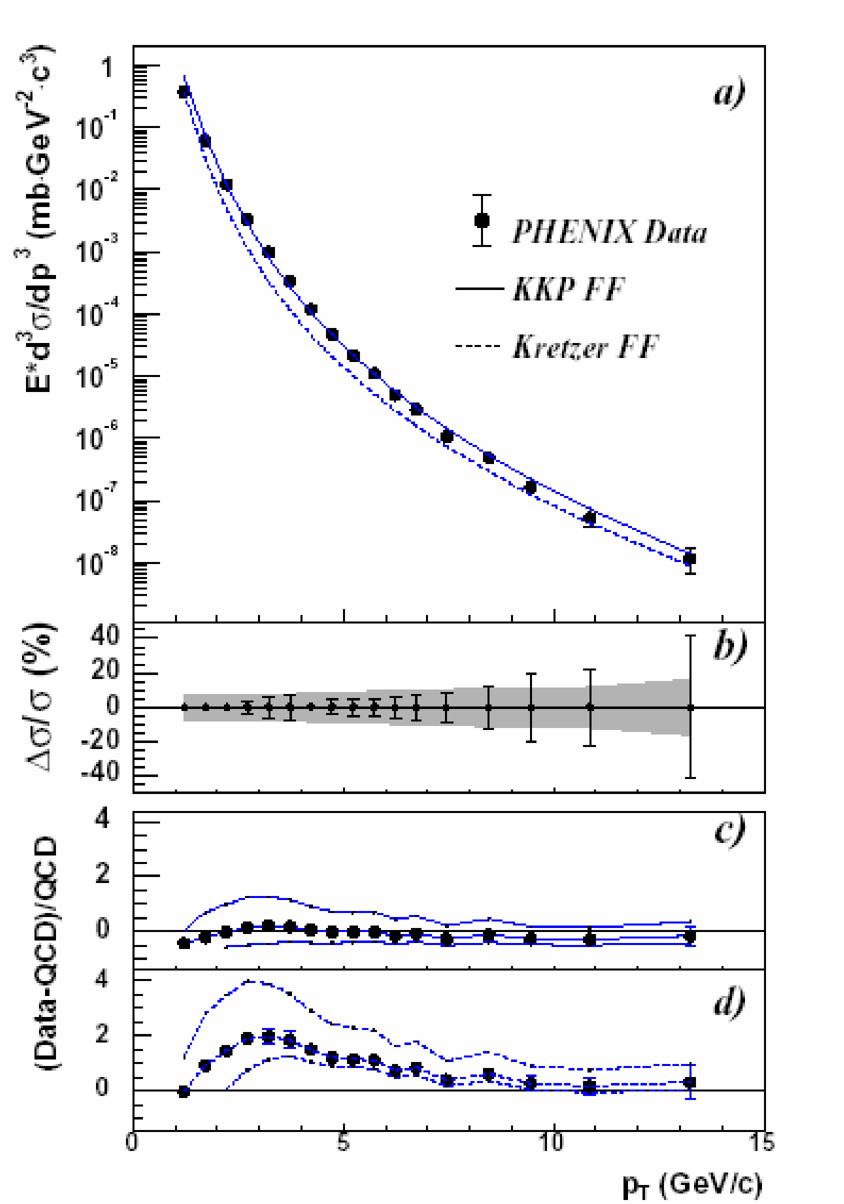
$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

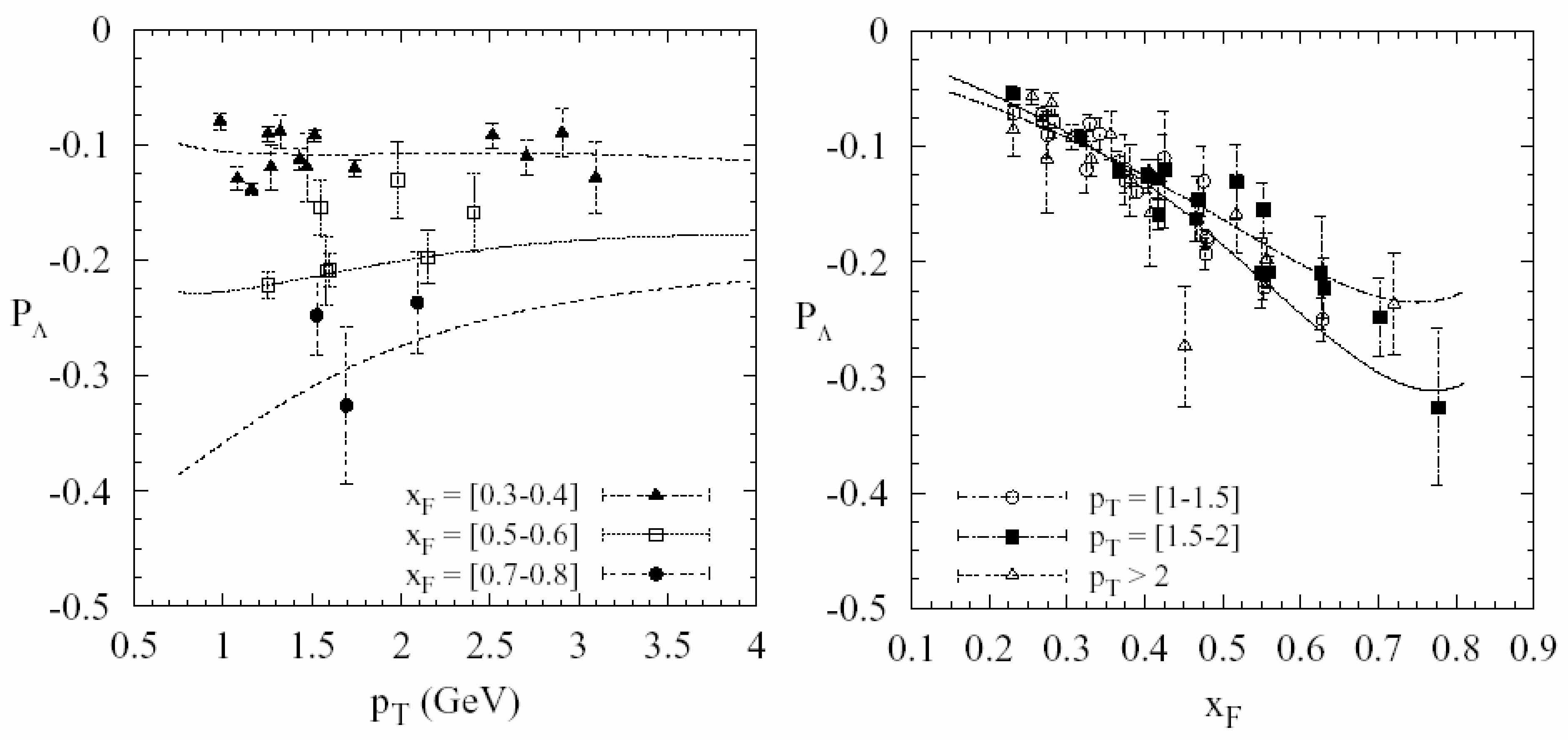
experimental data on SSA



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

A_N stays at high energies ….



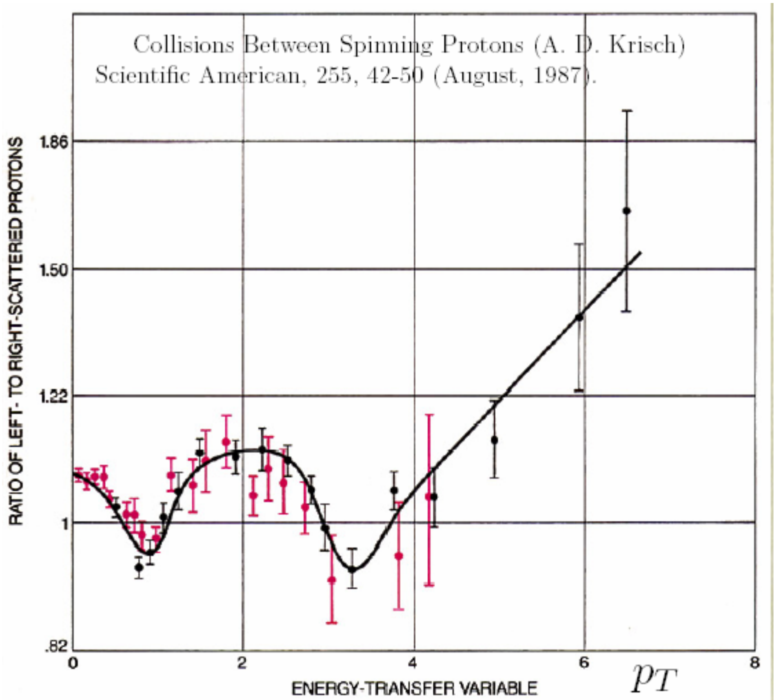


Transverse Λ polarization in unpolarized p-Be scattering at Fermilab

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

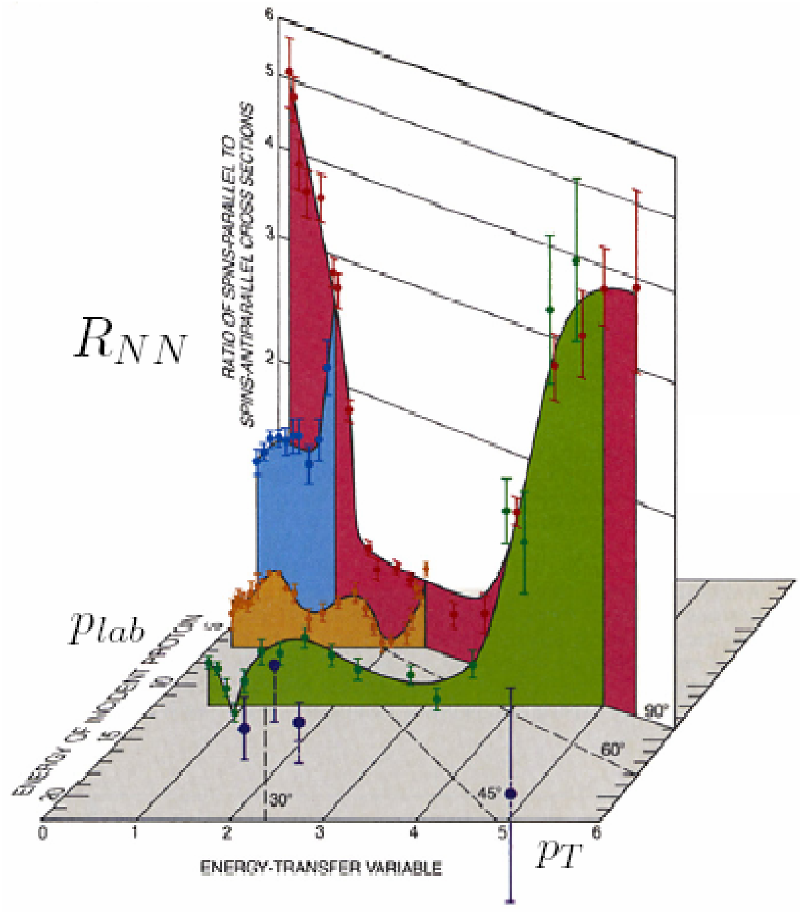
$$P_\Lambda = \frac{d\sigma^{\Lambda^{\uparrow}} - d\sigma^{\Lambda^{\downarrow}}}{d\sigma^{\Lambda^{\uparrow}} + d\sigma^{\Lambda^{\downarrow}}}$$

$$p^{\uparrow} p \rightarrow p \; p$$

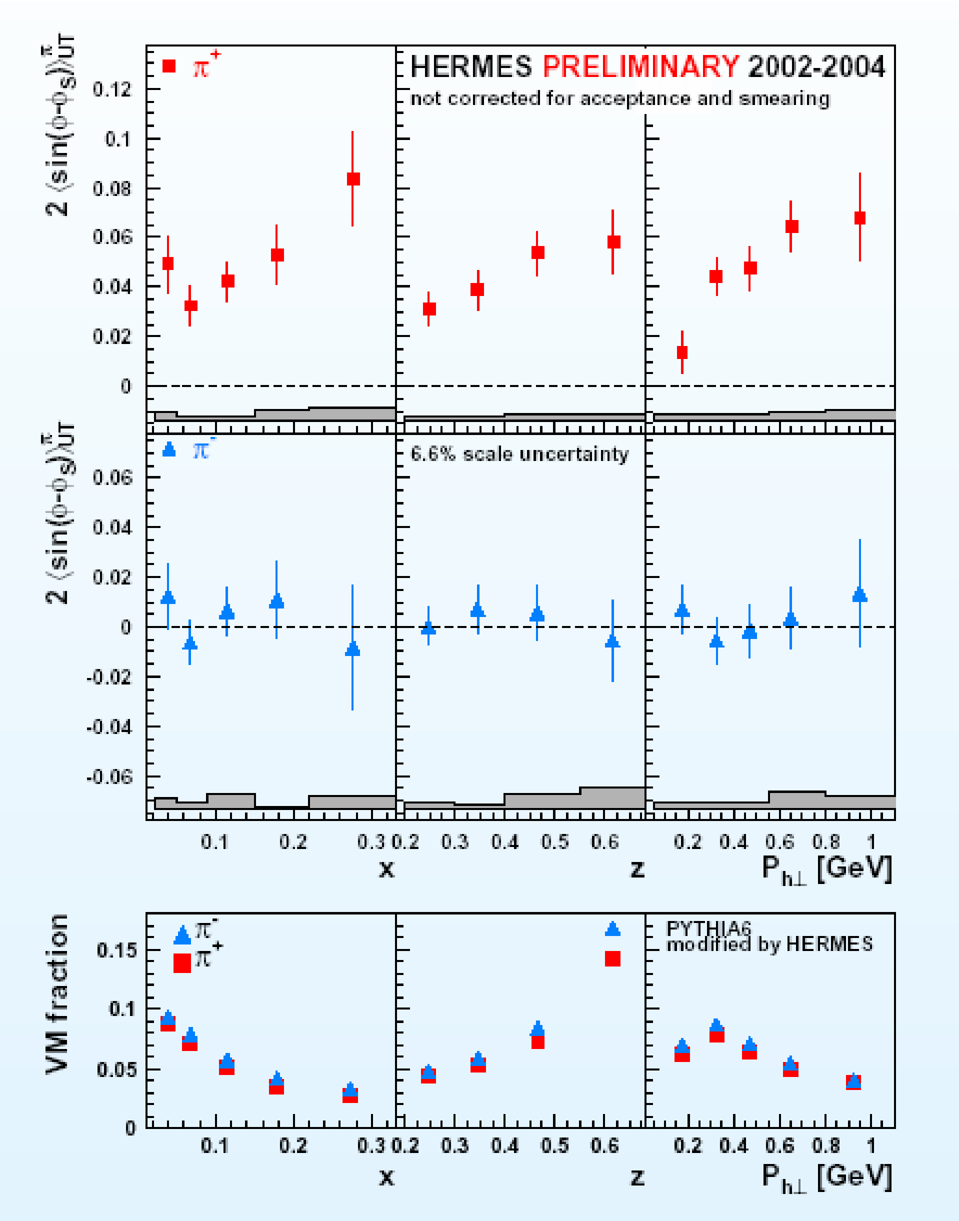


$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$p^{\uparrow} p^{\uparrow} \rightarrow p \; p$$



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



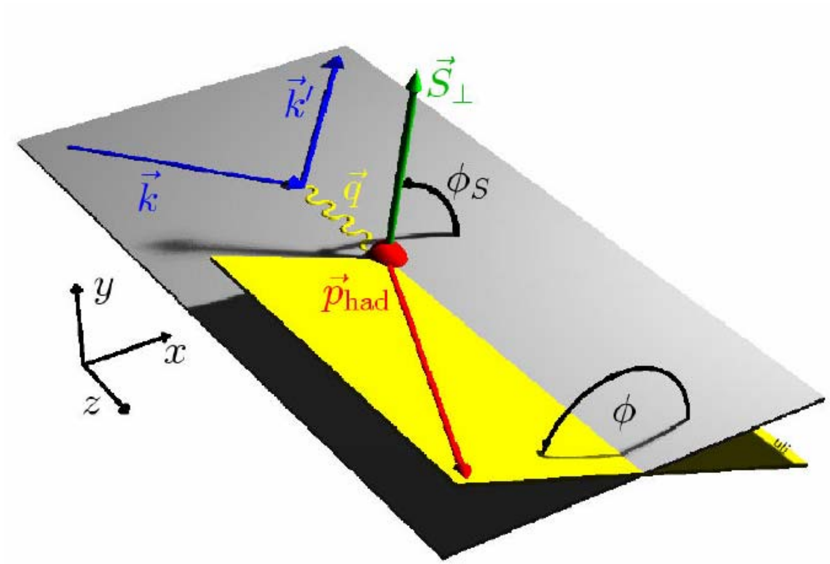
$$l\,N^{\uparrow} \rightarrow l\,\pi\,X$$

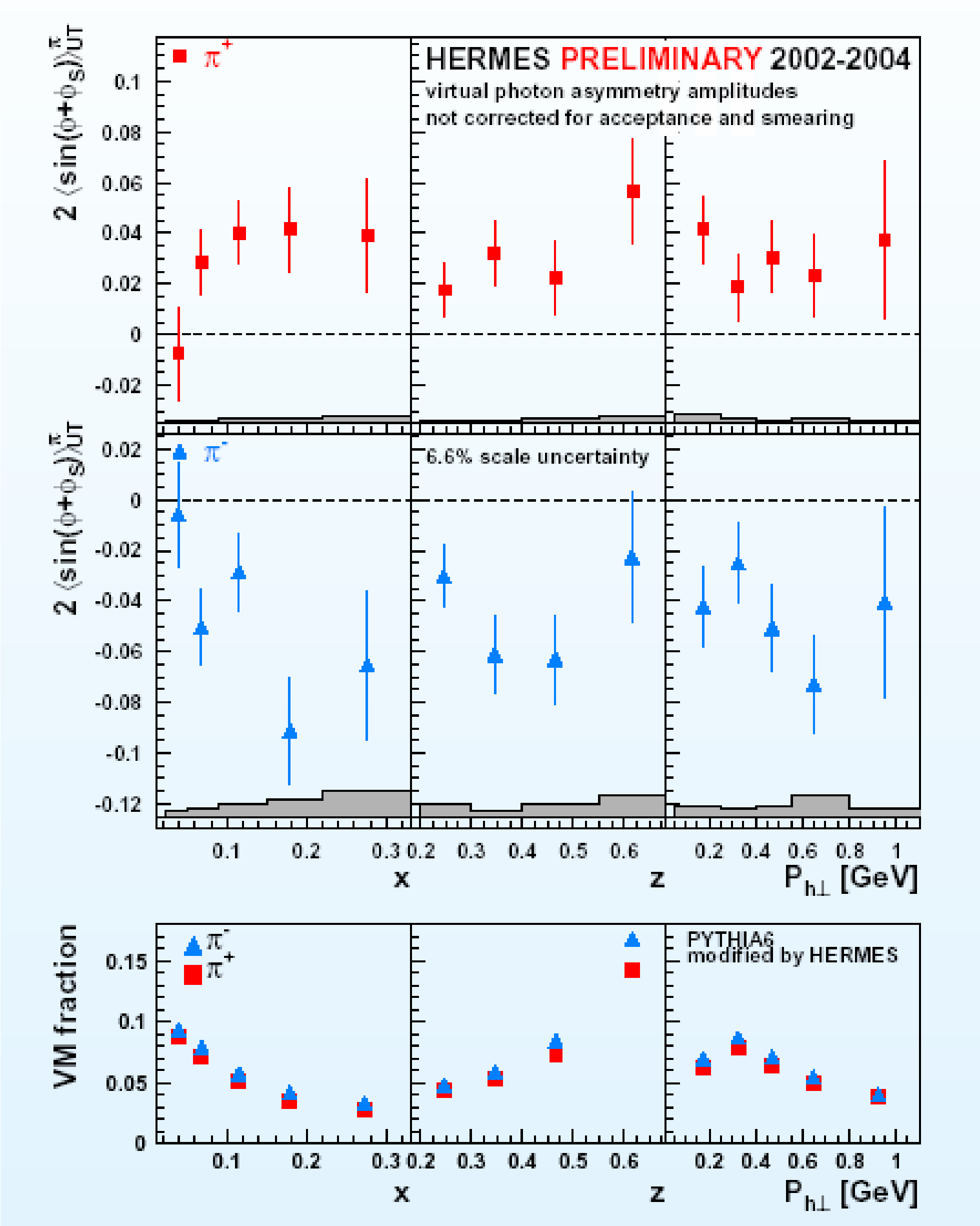
"Sivers moment"

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

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

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





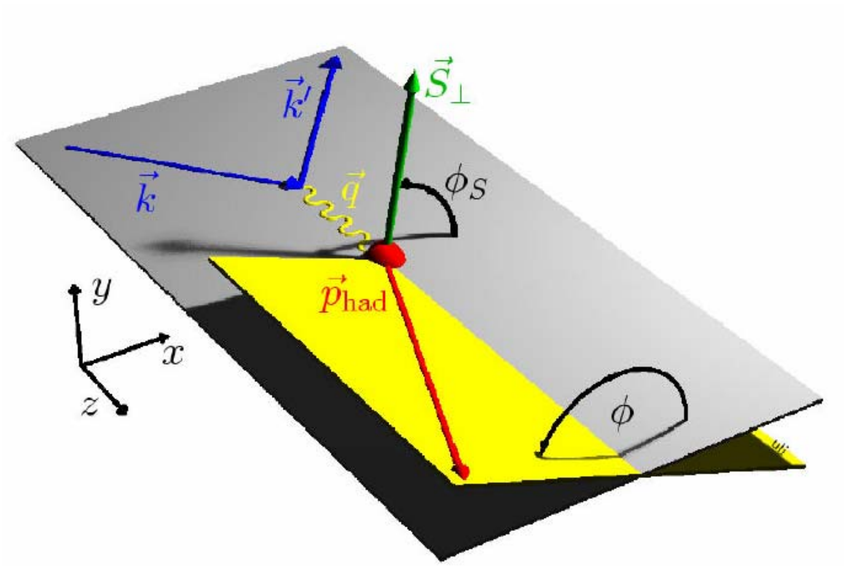
$$l\, N^{\uparrow} \rightarrow l\, \pi\, X$$

"Collins moment"

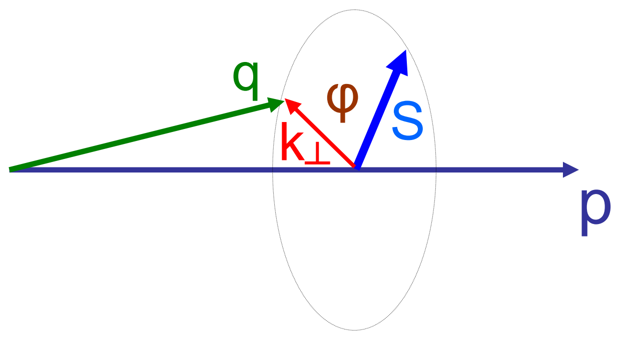
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

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

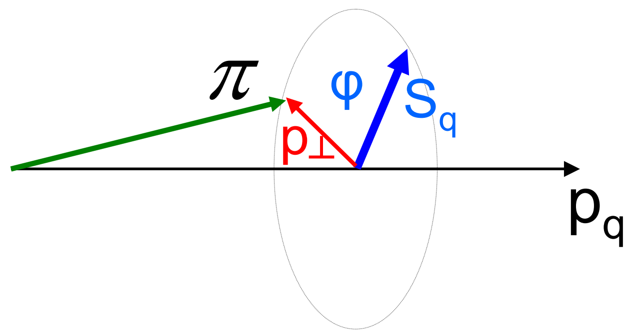
$$\equiv 2 \frac{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} - d\sigma^{\downarrow}) \sin(\Phi + \Phi_S)}{\int d\Phi\, d\Phi_S (d\sigma^{\uparrow} + d\sigma^{\downarrow})}$$



spin-$k_\perp$ correlations



Sivers function



Collins function

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

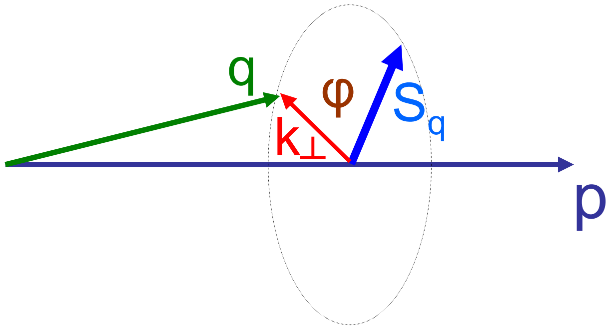
$$D_{h/q^\uparrow}(z,\vec{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\vec{S}_q\cdot(\hat{p}_q\times\hat{p}_\perp)$$

Amsterdam group notations

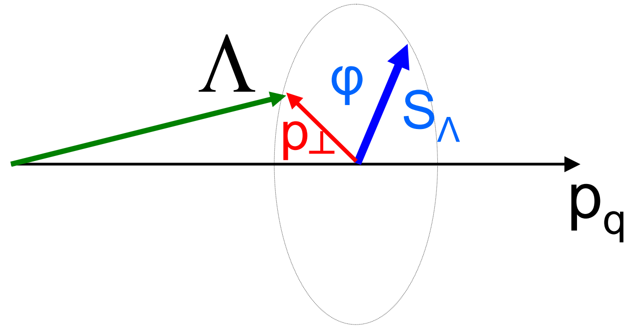
$$\Delta^N f_{q/p^\uparrow} = -\frac{2k_\perp}{M} f_{1T}^{\perp q}$$

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

spin-$k_\perp$ correlations



Boer-Mulders function



polarizing f.f.

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

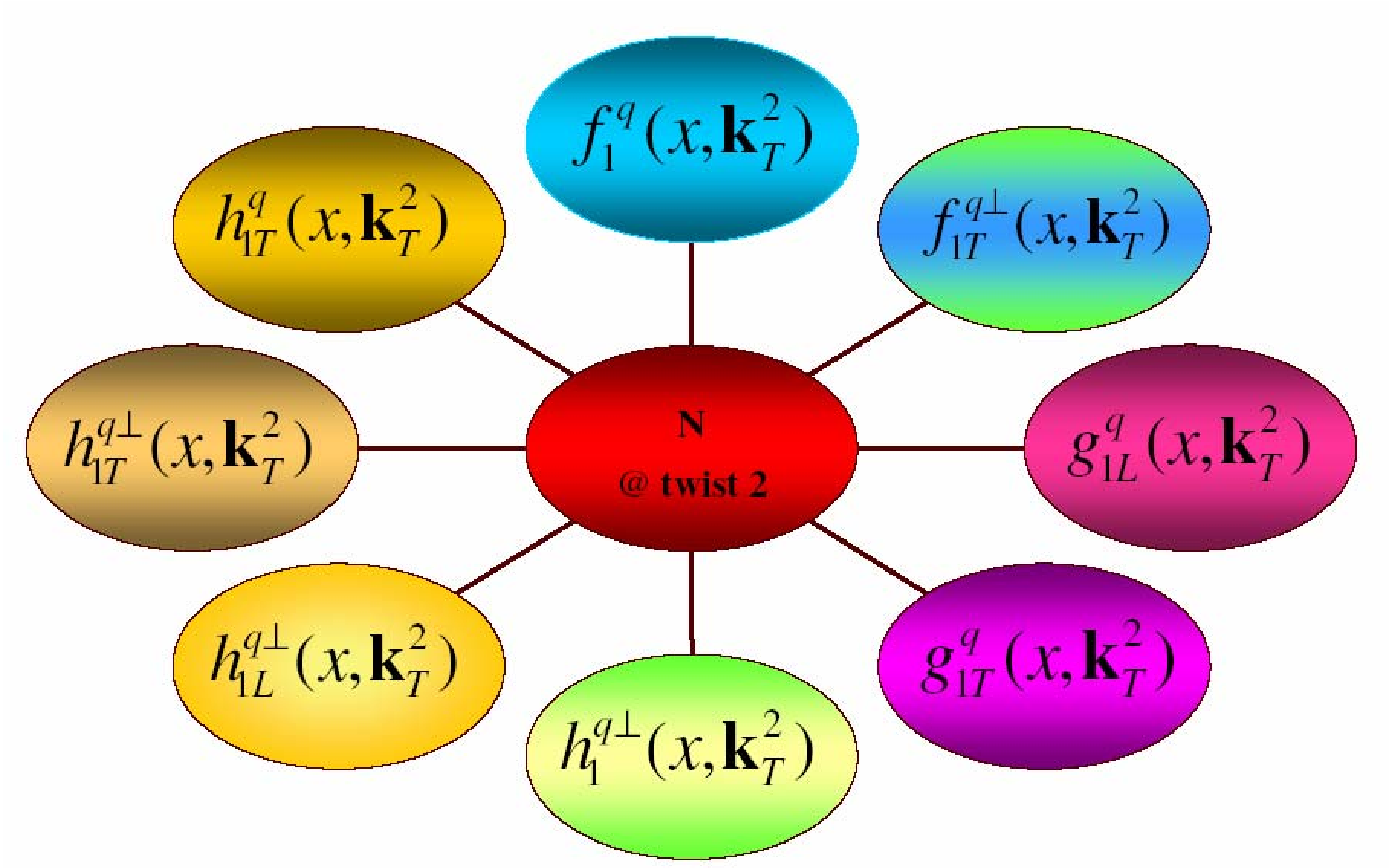
$$D_{\Lambda^\uparrow/q}(z,\vec{p}_\perp) = \frac{1}{2} D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{\Lambda^\uparrow/q}(z,p_\perp)\,\vec{S}_\Lambda\cdot(\hat{p}_q\times\hat{p}_\perp)$$

Amsterdam group notations

$$\Delta^N f_{q^\uparrow/p} = -\frac{k_\perp}{M} h_1^{\perp q}$$

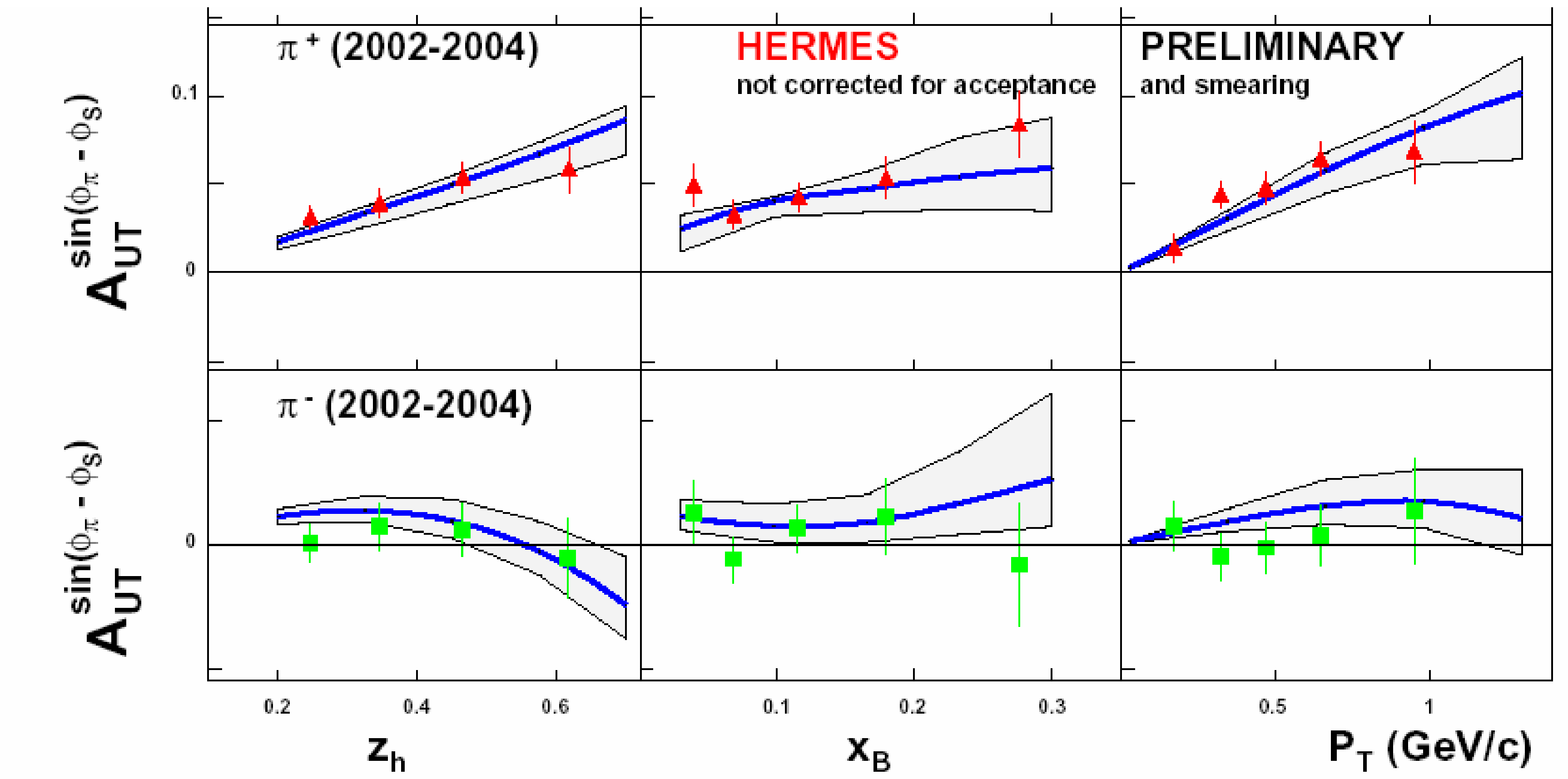
$$\Delta^N D_{\Lambda^\uparrow/q} = 2\frac{p_\perp}{z\,M_\Lambda} D_{1T}^{\perp q}$$

8 leading-twist spin-$k_\perp$ dependent distribution functions



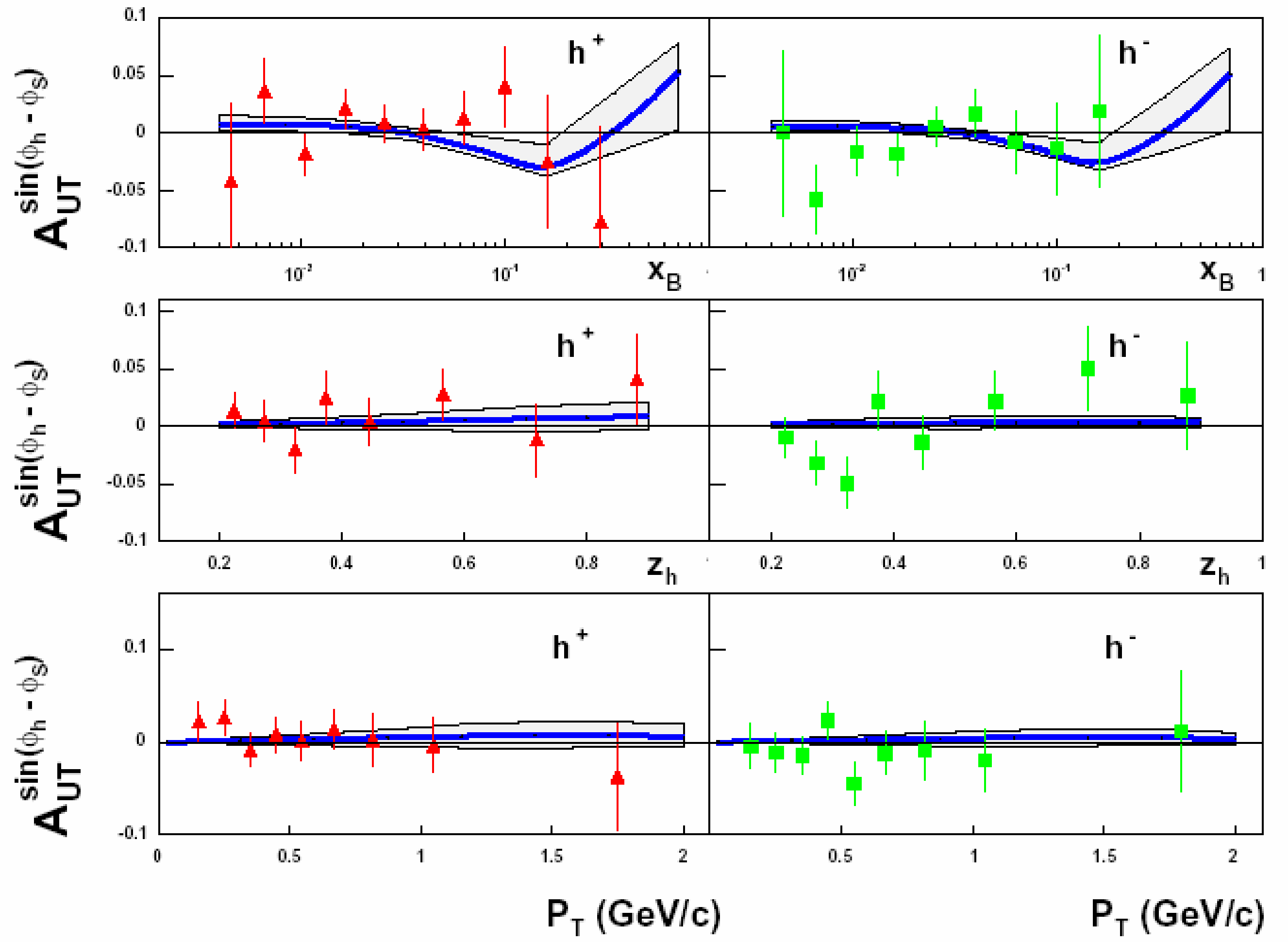
$A_{UT}^{\sin(\Phi-\Phi_S)}$ from Sivers mechanism

M.A., U.D'Alesio, M.Boglione, A.Kotzinian, A Prokudin

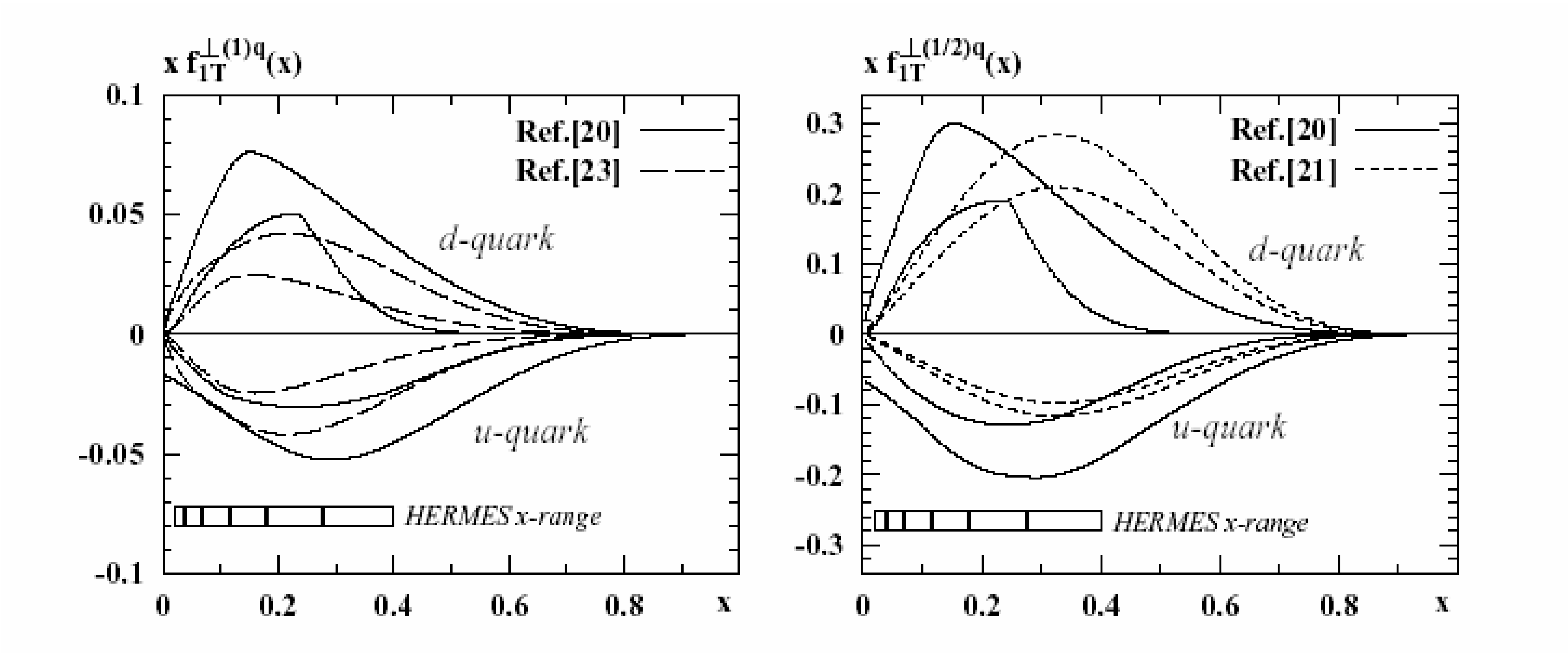


Deuteron target

$$A_{UT}^{\sin(\Phi_h - \Phi_S)} \propto \left(\Delta^N f_{u/p^\uparrow} + \Delta^N f_{d/p^\uparrow}\right)\left(4D_u^h + D_d^h\right)$$



M. Anselmino, M. Boglione, J.C. Collins, U. D'Alesio, A.V. Efremov, K. Goeke, A. Kotzinian, S. Menze, A. Metz, F. Murgia, A. Prokudin, P. Schweitzer, W. Vogelsang, F. Yuan



The first and 1/2-transverse moments of the Sivers quark distribution functions. The fits were constrained mainly (or solely) by the preliminary HERMES data in the indicated x-range. The curves indicate the 1-σ regions of the various parameterizations.

$$f_{1T}^{\perp(1)q} = \int d^2\vec{k}_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp q}(x,k_\perp) \qquad f_{1T}^{\perp(1/2)q}(x) = \int d^2\vec{k}_\perp \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)$$

What do we learn from Sivers distribution?

total amount of intrinsic momentum carried by partons of flavour a

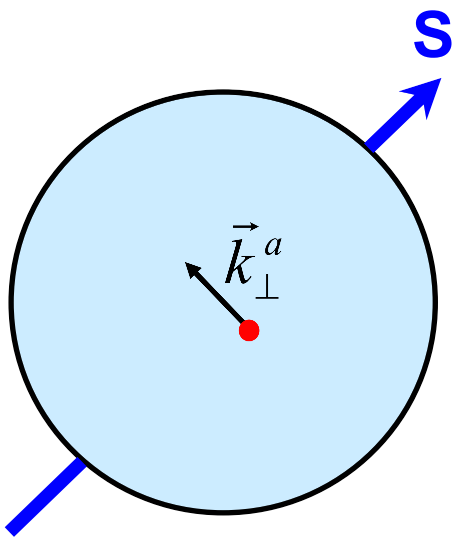
$$\vec{k}_\perp^{\,a} = \int dx\, d^2\vec{k}_\perp\, \vec{k}_\perp \left[\hat{f}_{a/p}(x,k_\perp) + \frac{1}{2}\Delta^N \hat{f}_{a/p^\uparrow}(x,k_\perp)\, \vec{S}\cdot(\hat{p}\times\hat{k}_\perp) \right]$$

$$= \left(\sin\Phi_S\, \hat{i} - \cos\Phi_S\, \hat{j}\right) \frac{\pi}{2} \int dx\, dk_\perp\, k_\perp^2\, \Delta^N \hat{f}_{a/p^\uparrow}(x,k_\perp)$$

for a proton moving along the +z-axis and polarization vector

$$\vec{S} = \left(\cos\Phi_S\, \hat{i} + \sin\Phi_S\, \hat{j}\right)$$

$$\vec{S}\cdot(\hat{p}\times\hat{k}_\perp) = \sin(\Phi_S - \varphi)$$



Numerical estimates from SIDIS data

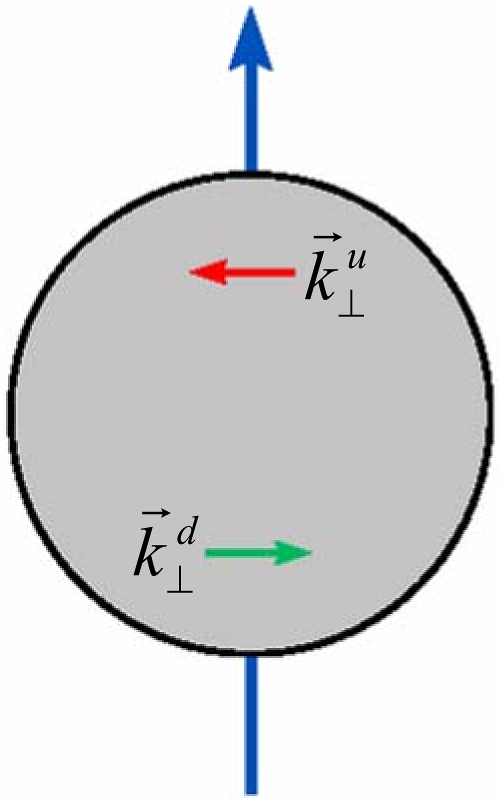
$$\vec{k}_\perp^{\,u} \cong +0.14^{+0.05}_{-0.06} \left(\cos\Phi_S\,\hat{i} + \sin\Phi_S\,\hat{j}\right) \qquad \text{GeV/c}$$

$$\vec{k}_\perp^{\,d} \cong -0.13^{+0.03}_{-0.02} \left(\cos\Phi_S\,\hat{i} + \sin\Phi_S\,\hat{j}\right) \qquad \text{GeV/c}$$

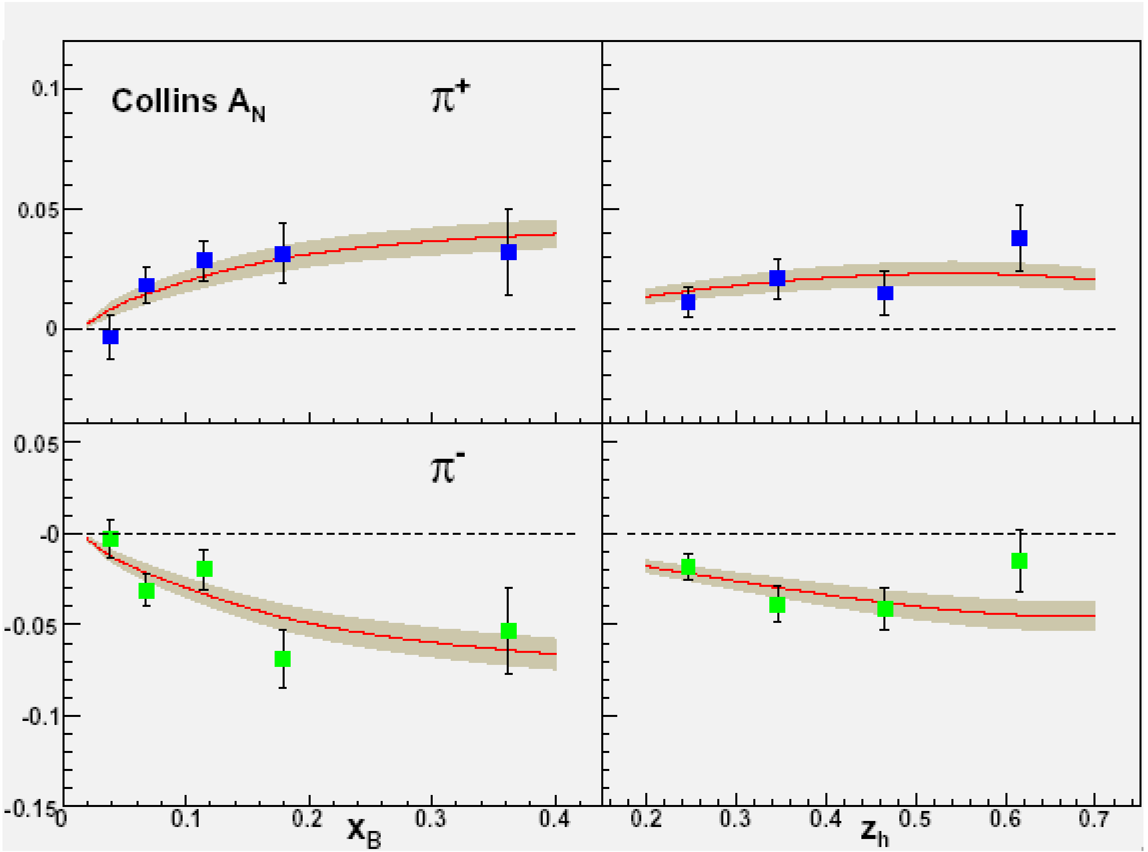
Sivers functions extracted from A_N data in $p\,p \to \pi\,X$ give also opposite results, with

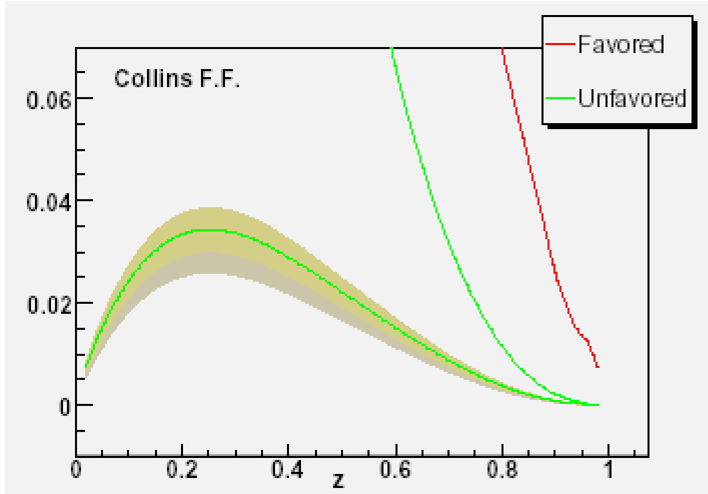
$$k_\perp^u \cong 0.032 \qquad k_\perp^d \cong -0.036$$

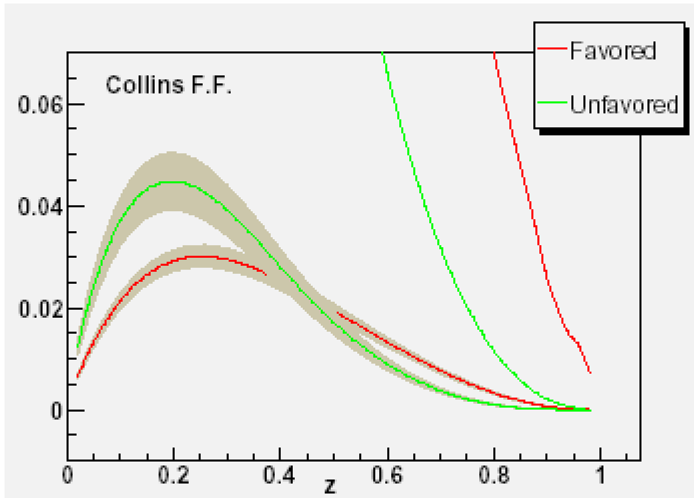
$$\vec{k}_\perp^{\,u} + \vec{k}_\perp^{\,d} \approx 0\,?$$



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







W. Vogelsang and F. Yuan

Hadronic processes: the cross section with intrinsic $\boldsymbol{k}_\perp$

$$\frac{E_C\, d\sigma^{AB\to CX}}{d^3\boldsymbol{p}_C} =$$

$$\sum_{a,b,c,d} \int dx_a\, dx_b\, dz\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{k}_{\perp C}\, \delta(\boldsymbol{k}_{\perp C}\cdot \hat{\boldsymbol{p}}_c)\, \hat{f}_{a/A}(x_a, \boldsymbol{k}_{\perp a}; Q^2)\, \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b}; Q^2)$$

$$\frac{\hat{s}^2}{\pi x_a x_b z^2 s}\, J(\boldsymbol{k}_{\perp C})\, \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(\hat{s}, \hat{t}, \hat{u}, x_a, x_b)\, \delta(\hat{s}+\hat{t}+\hat{u})\, \hat{D}_{C/c}(z, \boldsymbol{k}_{\perp C}; Q^2)\,,$$

intrinsic $\boldsymbol{k}_\perp$ in distribution and fragmentation functions
and in elementary interactions

factorization is assumed, not proven in general; some progress for Drell-Yan processes, two-jet production, Higgs production via gluon fusion (Ji, Ma, Yuan; Collins, Metz; Bacchetta, Bomhof, Mulders, Pijlman)

The polarized cross section with intrinsic $\boldsymbol{k}_\perp$

$$\frac{E_C\, d\sigma^{(A,S_A)+(B,S_B)\to C+X}}{d^3\boldsymbol{p}_C} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a\, dx_b\, dz}{16\pi^2 x_a x_b z^2 s}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{k}_{\perp C}\, \delta(\boldsymbol{k}_{\perp C}\cdot\hat{\boldsymbol{p}}_c)\, J(\boldsymbol{k}_{\perp C})$$

$$\times\ \rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\, \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a})\, \rho^{b/B,S_B}_{\lambda_b,\lambda'_b}\, \hat{f}_{b/B,S_B}(x_b,\boldsymbol{k}_{\perp b}) \qquad (1)$$

$$\times\ \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\, \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b}\, \delta(\hat{s}+\hat{t}+\hat{u})\, \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})\,,$$

$\rho^{a/A,S_A}_{\lambda_a\lambda'_a}$ — helicity density matrix of parton *a* inside polarized hadron *A*

$\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}$ — pQCD helicity amplitudes

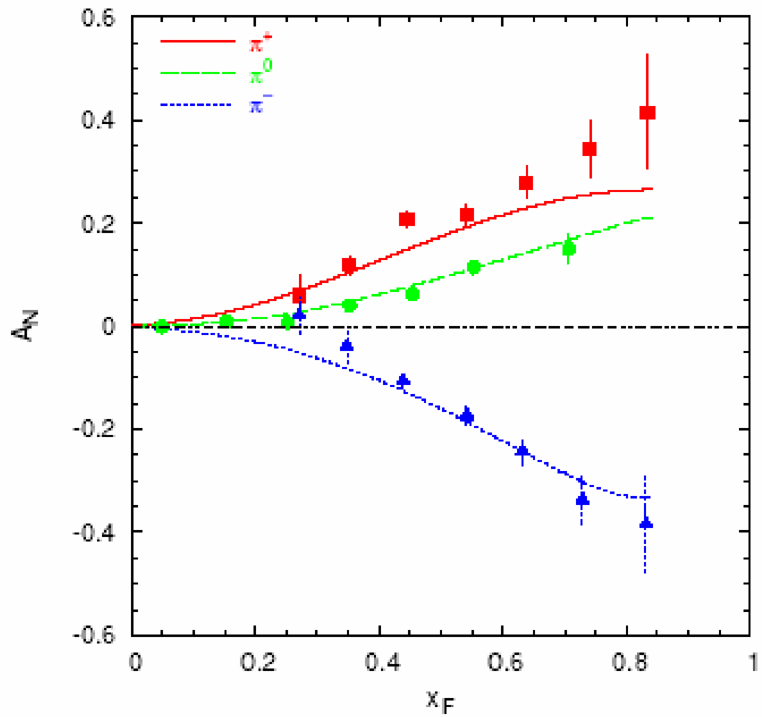
$D^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}$ — product of fragmentation amplitudes

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

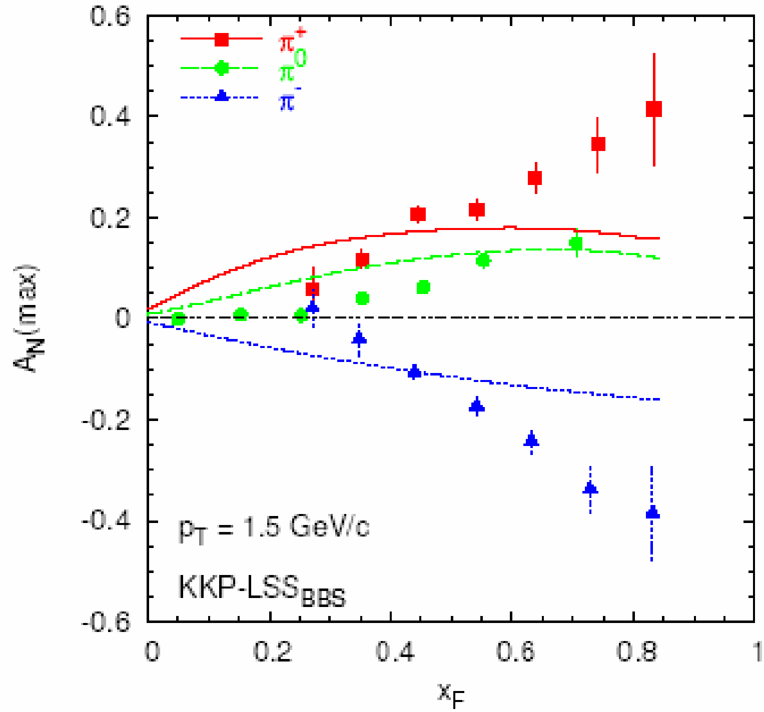
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \simeq \Delta^N f_{a/p^{\uparrow}} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c} \qquad \text{"Sivers effect"}$$

$$+ \; h_{1a} \otimes f_{b/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{\pi/c^{\uparrow}} \qquad \text{"Collins effect"}$$

E704 data, E = 200 GeV



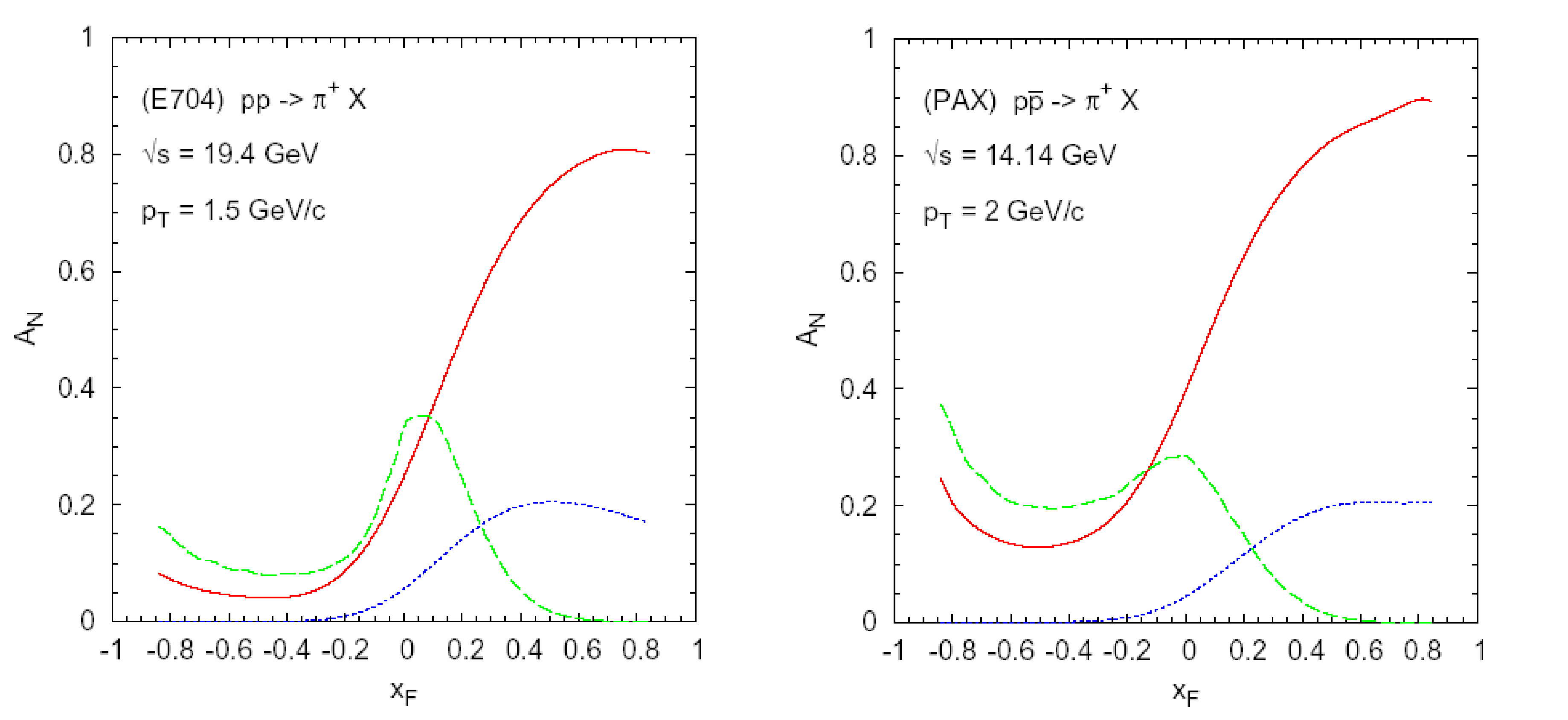
fit to A_N with Sivers effects alone



maximized value of A_N with Collins effects alone

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

Special channels available with antiprotons – Results from U. D'Alesio



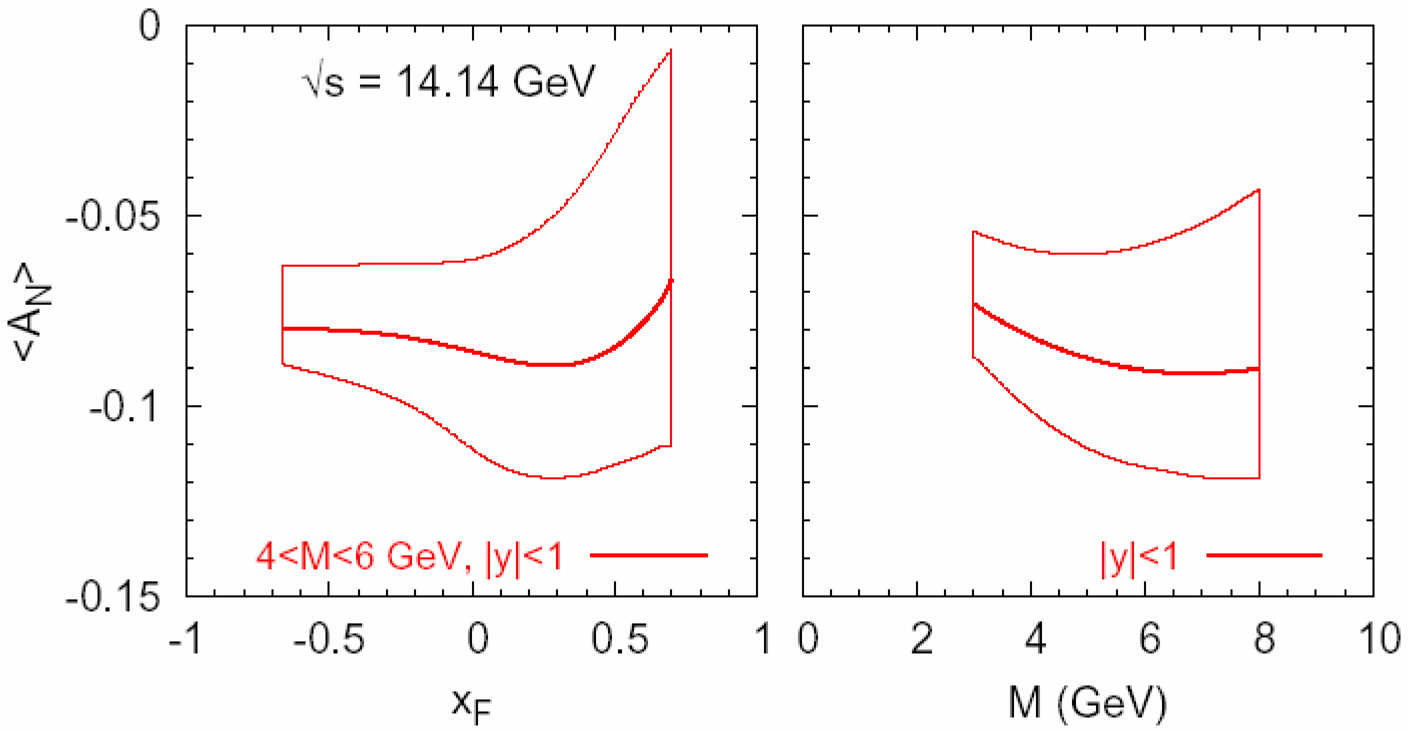
Maximised (i.e., saturating positivity bounds) contributions to A_N

- ——— quark Sivers contribution
- - - - - gluon Sivers contribution
- ········ Collins contribution

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

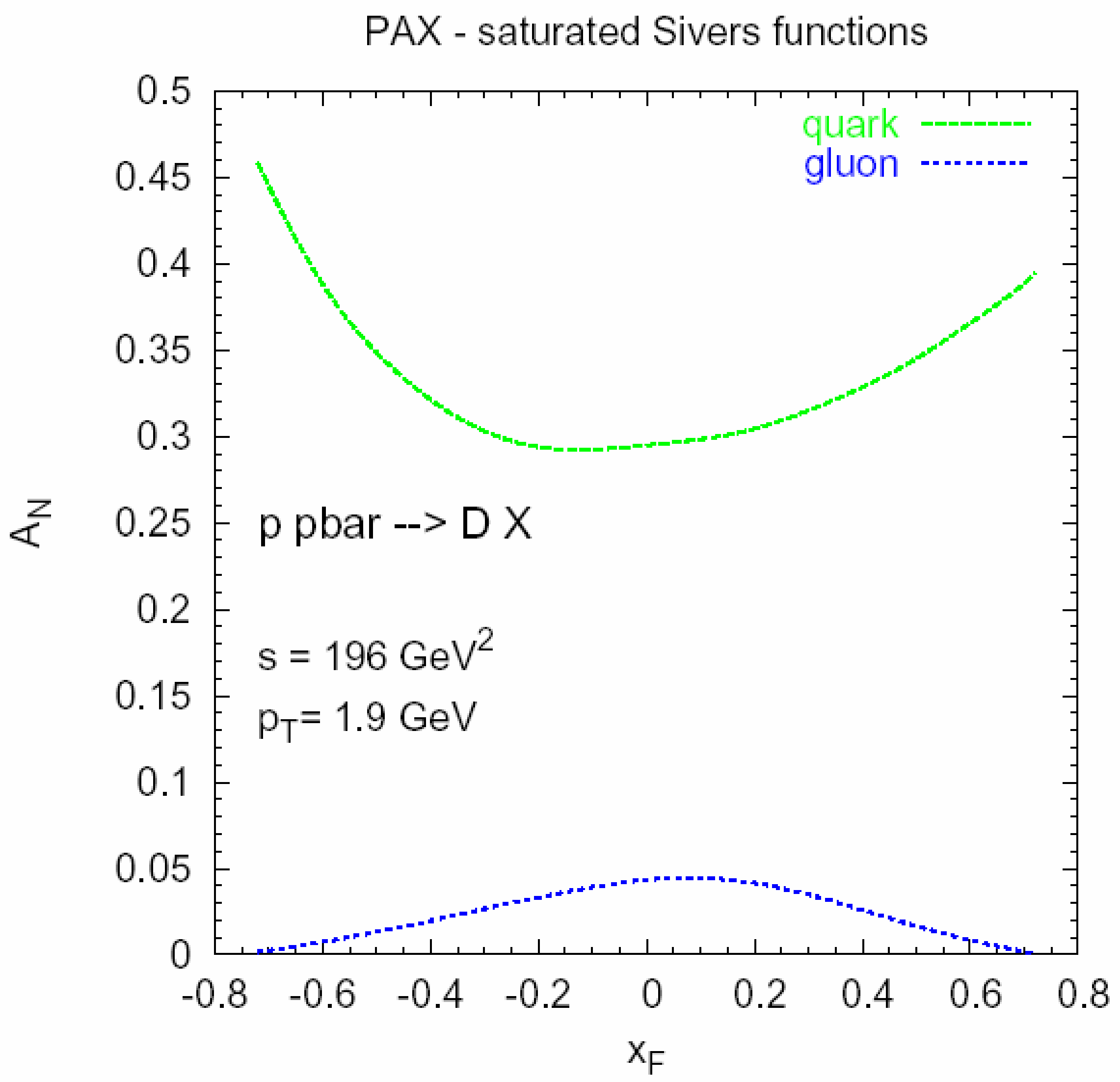
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

Predictions for A_N in D-Y processes



$$p^{\uparrow}\,\overline{p} \rightarrow l^{+}l^{-}\;X$$

Sivers function from SIDIS data, large asymmetry and cross section expected

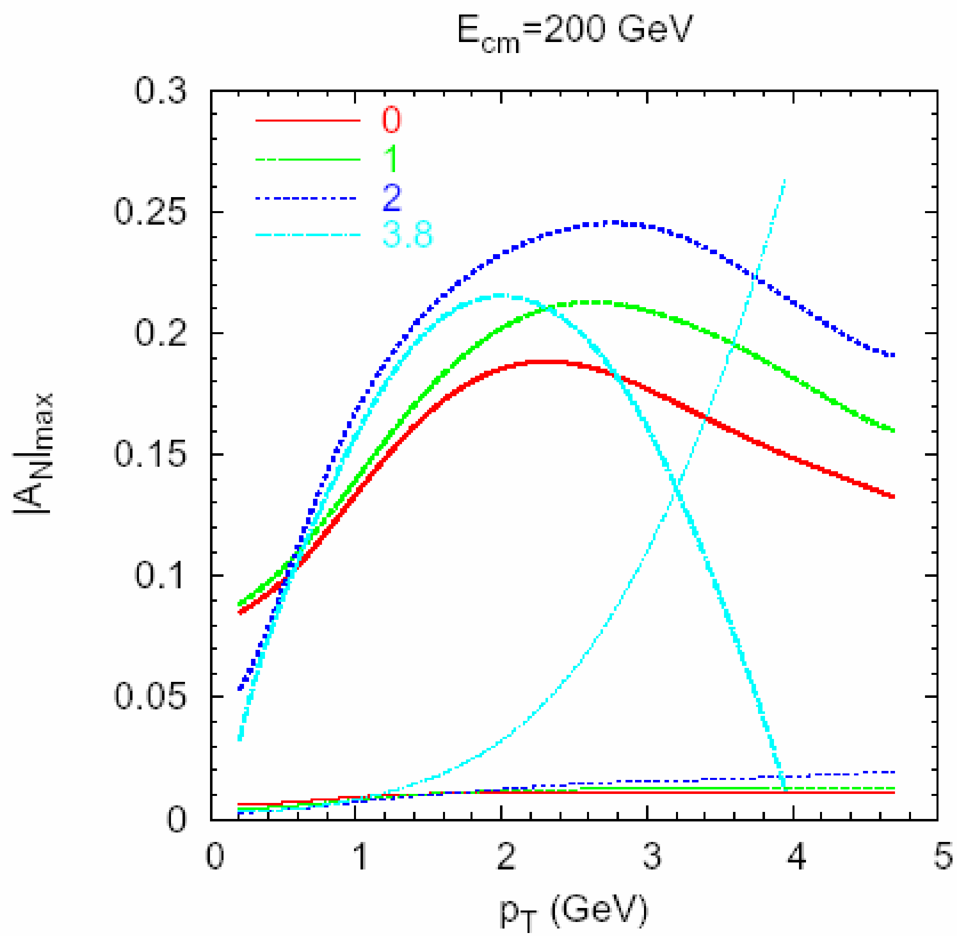


$$p^{\uparrow}\overline{p} \rightarrow D\ X$$

at PAX, contrary to RHIC, dominates the $q\overline{q} \rightarrow c\overline{c}$ channel:

SSA in p↑p → D X

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto \sum_q \Delta^N f_{q/p^{\uparrow}} \otimes f_{\bar{q}/p} \otimes d\hat{\sigma}^{q\bar{q}\to Q\bar{Q}} \otimes D_{D/Q}$$
$$+ \Delta^N f_{g/p^{\uparrow}} \otimes f_{g/p} \otimes d\hat{\sigma}^{gg\to Q\bar{Q}} \otimes D_{D/Q}$$



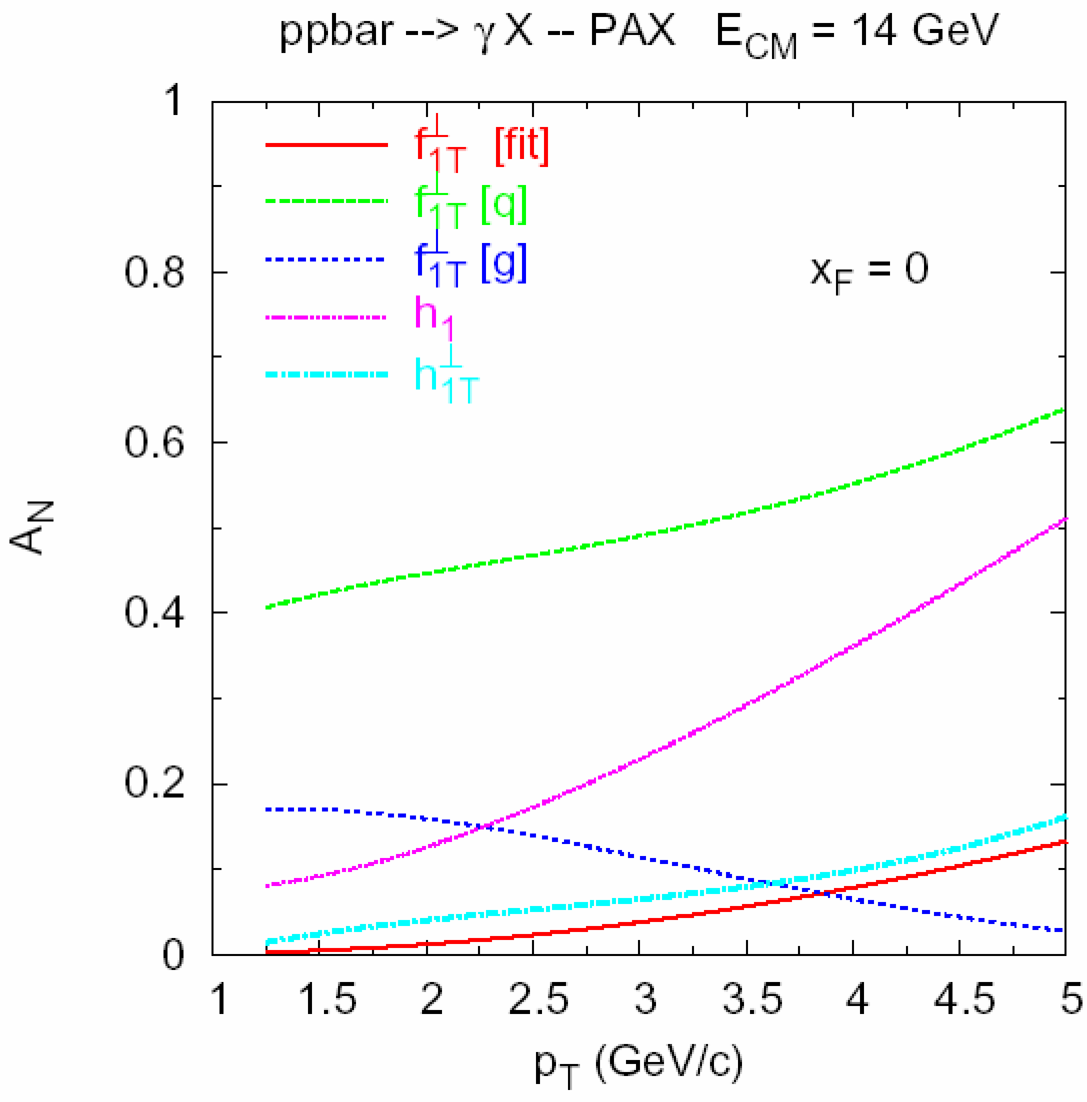
only Sivers effect: no transverse spin transfer in
$q\bar{q} \to Q\bar{Q}, \; gg \to Q\bar{Q}$

dominance of gluonic channel, access to gluon Sivers function

$|A_N|_{\max} =$ assuming saturated Sivers function

$$\Delta^N f_{a/p^{\uparrow}} = 2 f_{a/p}$$

(thick lines: $gg \to Q\bar{Q}$, thin lines: $q\bar{q} \to Q\bar{Q}$
0, 1, 2, 3.8 denote rapidities)



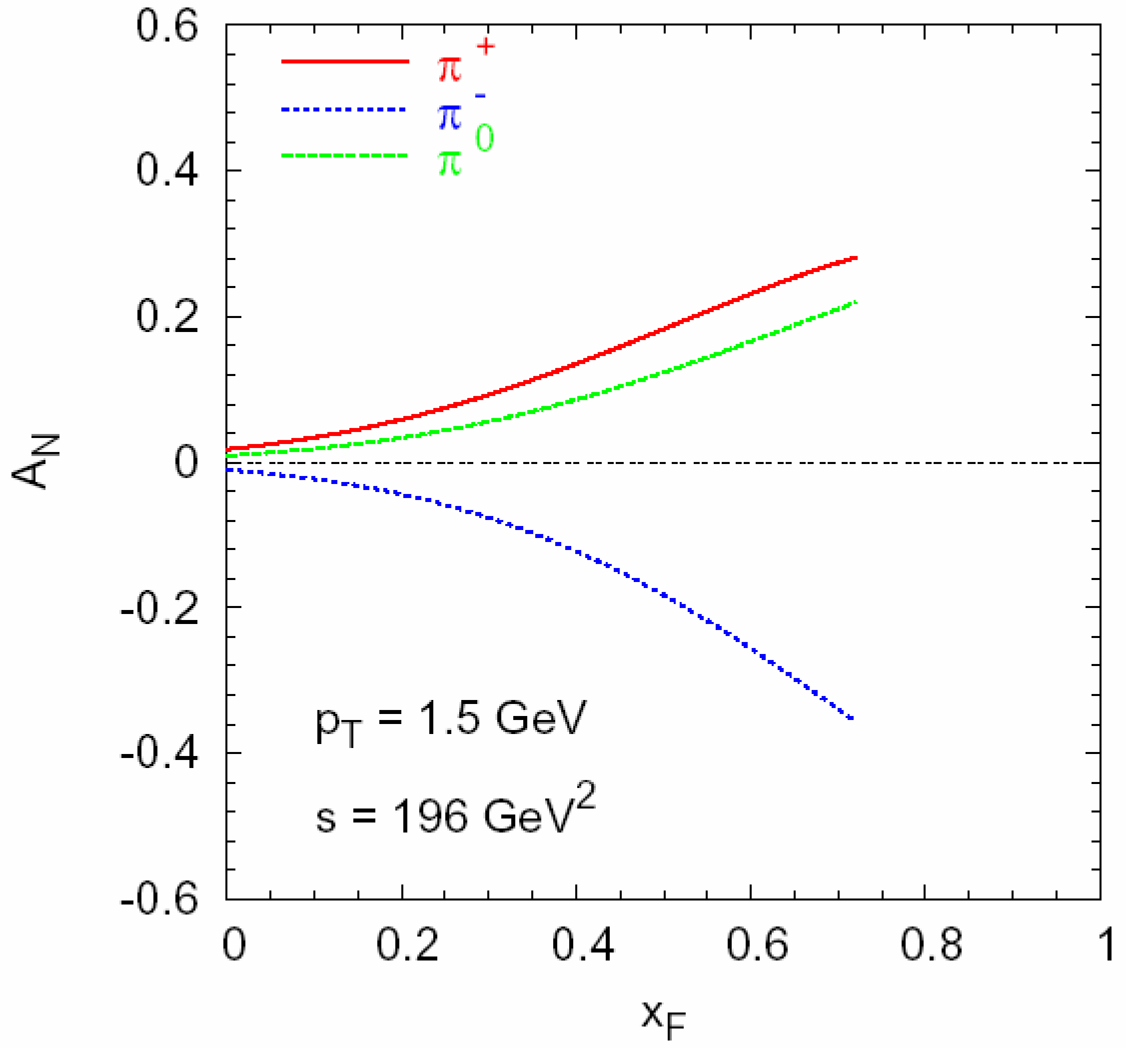
predictions based on Sivers functions extracted from fitting E704 data

maximised contributions from h_1 times B-M, not suppressed by phases

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

$$p^{\uparrow}\bar{p} \to \gamma\, X$$

$qg \to q\gamma$ and $q\bar{q} \to g\gamma$ dominating channels



predictions based on Sivers functions from E704 data

$$p^{\uparrow}\bar{p} \rightarrow \pi^{+,0,-}\ X$$

Conclusions

- Polarized antiprotons are the only way to access directly the transversity distribution: optimum energy at $s \approx 200$ GeV^2
- Unintegrated (TMD) distribution functions allow a much better description of QCD nucleon structure and hadronic interactions
- $\boldsymbol{k}_\perp$ is crucial to understand observed SSA in SIDIS and pp interactions; antiprotons will add new information and allow further test of our understanding
- Spin-$\boldsymbol{k}_\perp$ dependent distribution and fragmentation functions: towards a complete phenomenology of spin asymmetries
- Open issues: factorization, QCD evolution, universality, higher perturbative orders, …