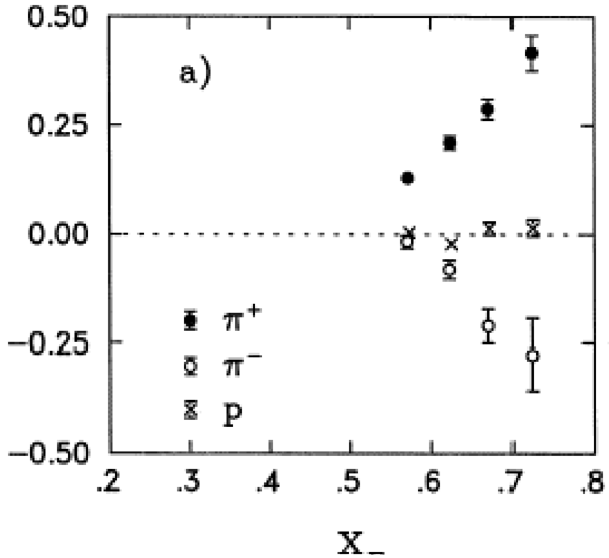
Spin is challenging ....

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.

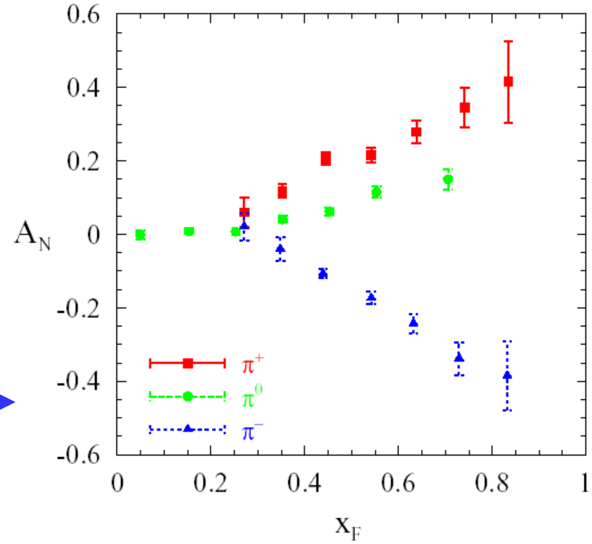
J.D. Bjorken
St. Croix, 1987

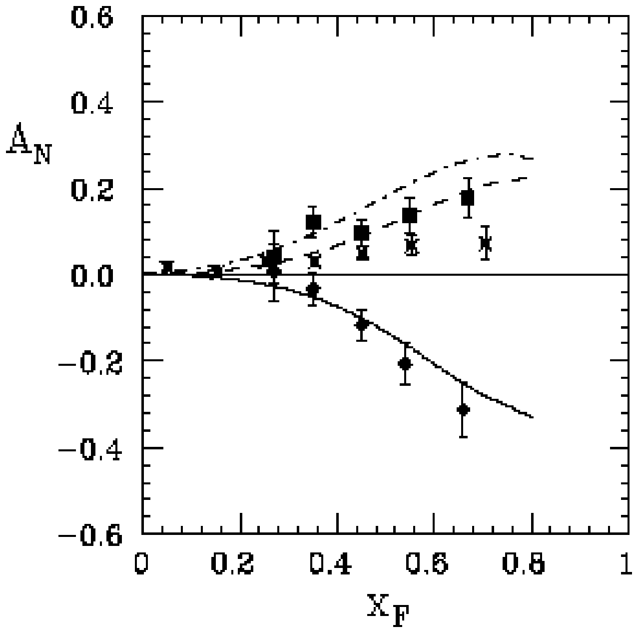


BNL-AGS $\sqrt{s}$ = 6.6 GeV
$0.6 < p_T < 1.2$

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

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





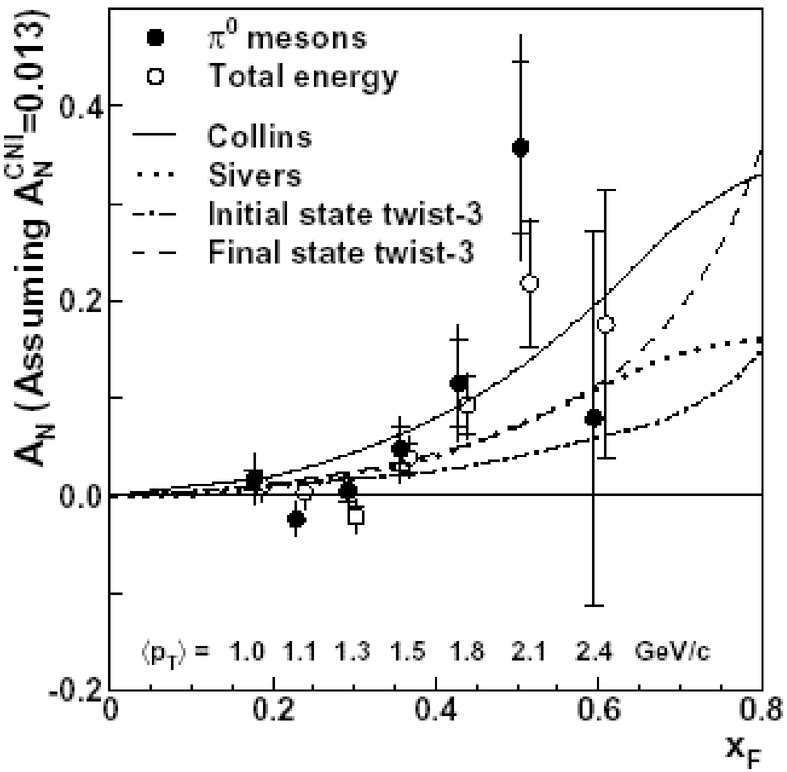
E704 $\sqrt{s}$ = 20 GeV
$0.7 < p_T < 2.0$

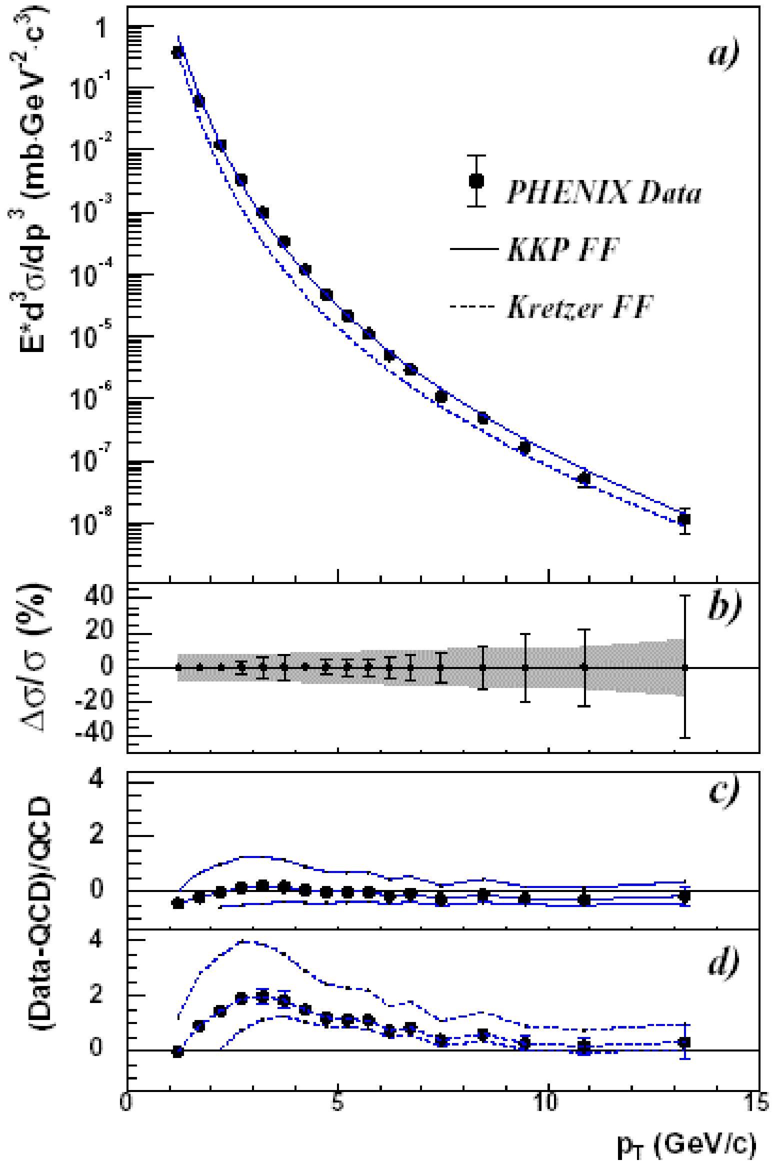
$$\bar{p}^{\uparrow} p \to \pi\ X$$

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 √s = 200 GeV
$1.1 < p_T < 2.5$

A_N stays at high energies ….

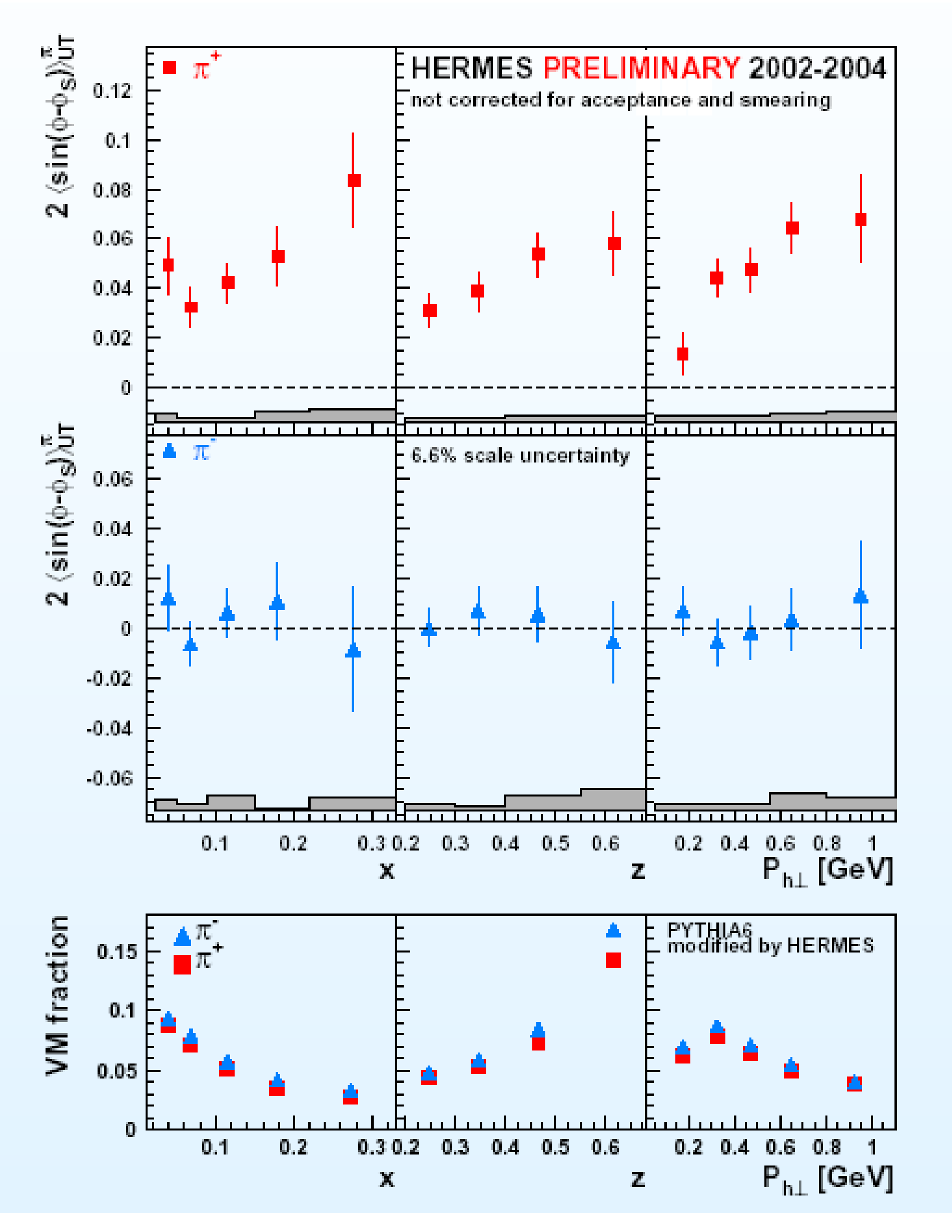
$$l\, N^{\uparrow} \rightarrow l\, \pi\, X$$

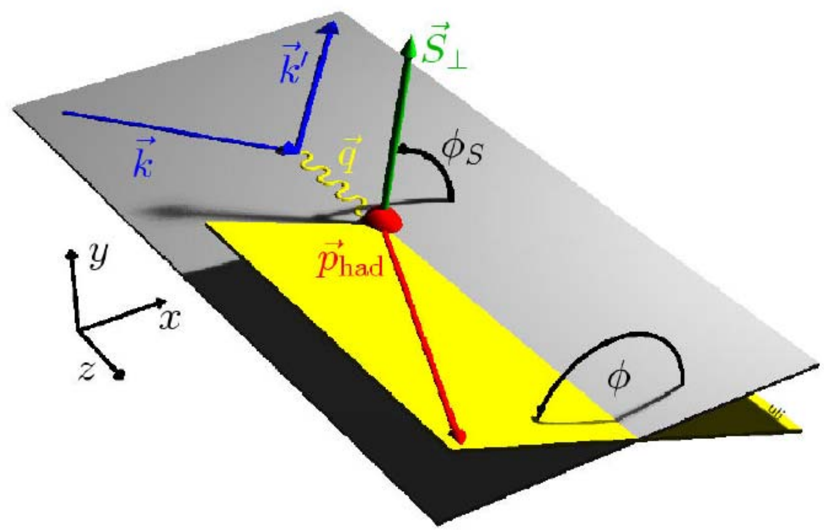
"Sivers moment"

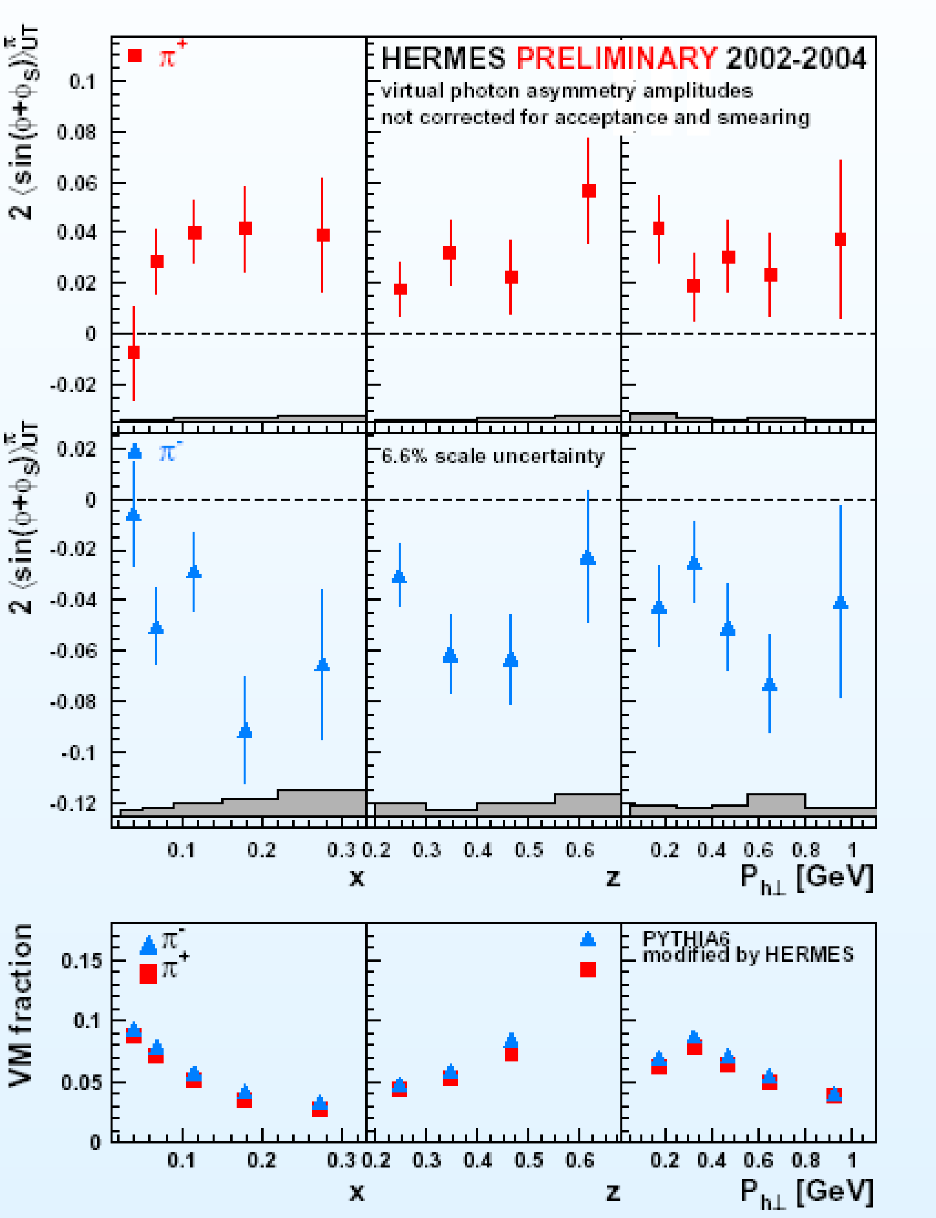
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

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

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







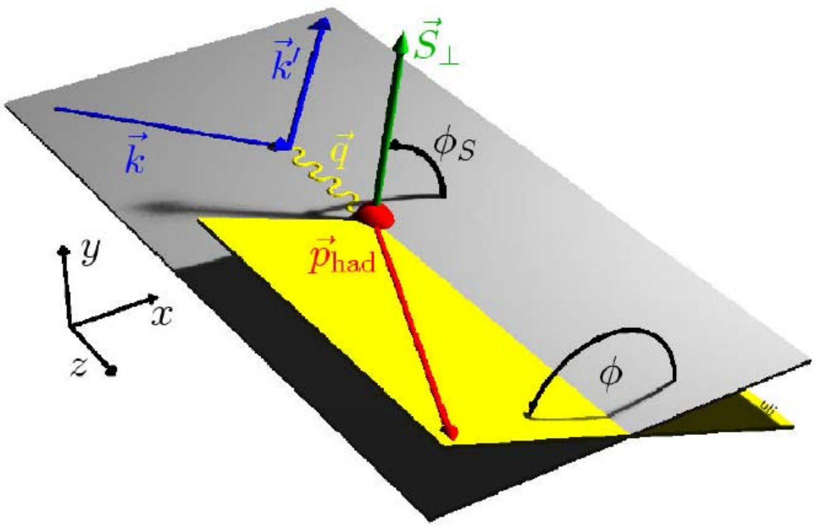
$$l\, N^{\uparrow} \rightarrow l\, \pi\, X$$

"Collins moment"

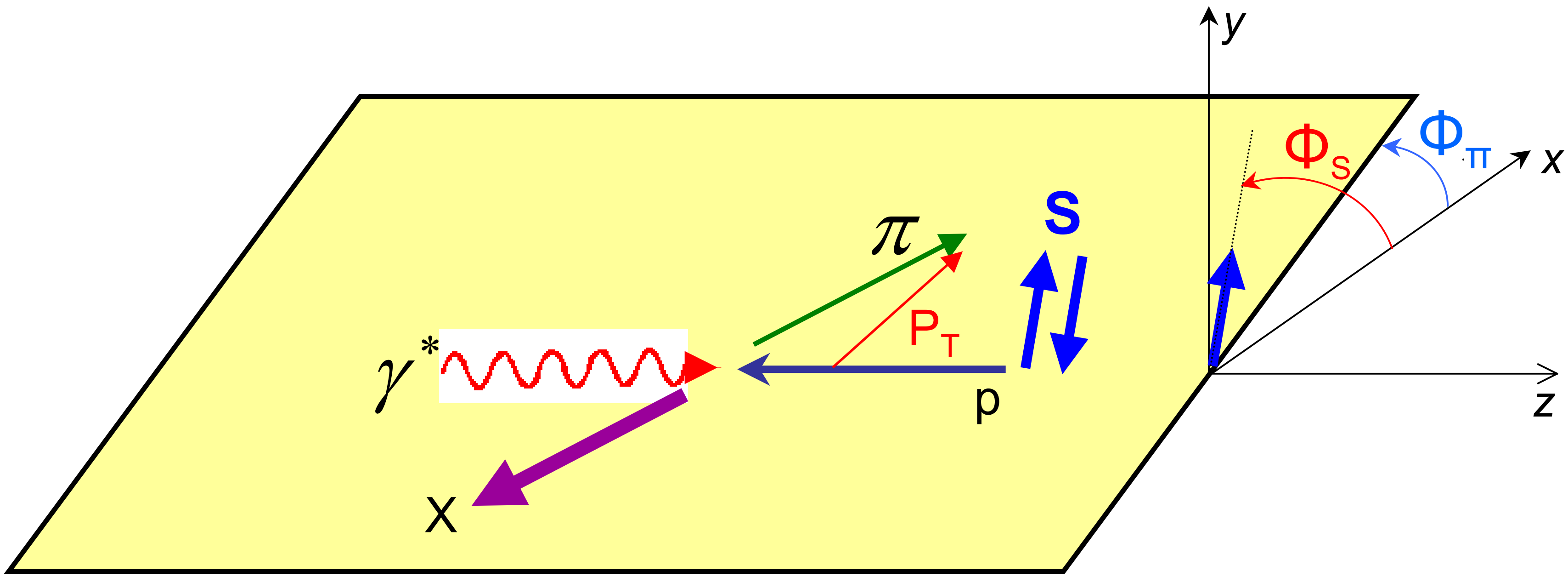
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

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

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



Transverse single spin asymmetries in SIDIS



$$A_N \propto \vec{S} \cdot \left(\vec{p} \times \vec{P}_T \right) \propto P_T \sin(\Phi_\pi - \Phi_S) \qquad \gamma^* - p \text{ c.m. frame}$$

if partons inside p are all collinear there cannot be (at LO) any P_T

needs $k_\perp$ dependent quark distribution in $p^\uparrow$ (Sivers mechanism) or
$p_\perp$ dependent fragmentation of polarized quark (Collins mechanism)

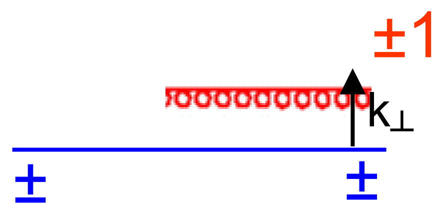
$k_\perp$ dependent parton distributions (TMD)

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

There must be a primordial intrinsic $k_\perp$ due to quark confinement:

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

There is intrinsic $k_\perp$ generated by QCD evolution



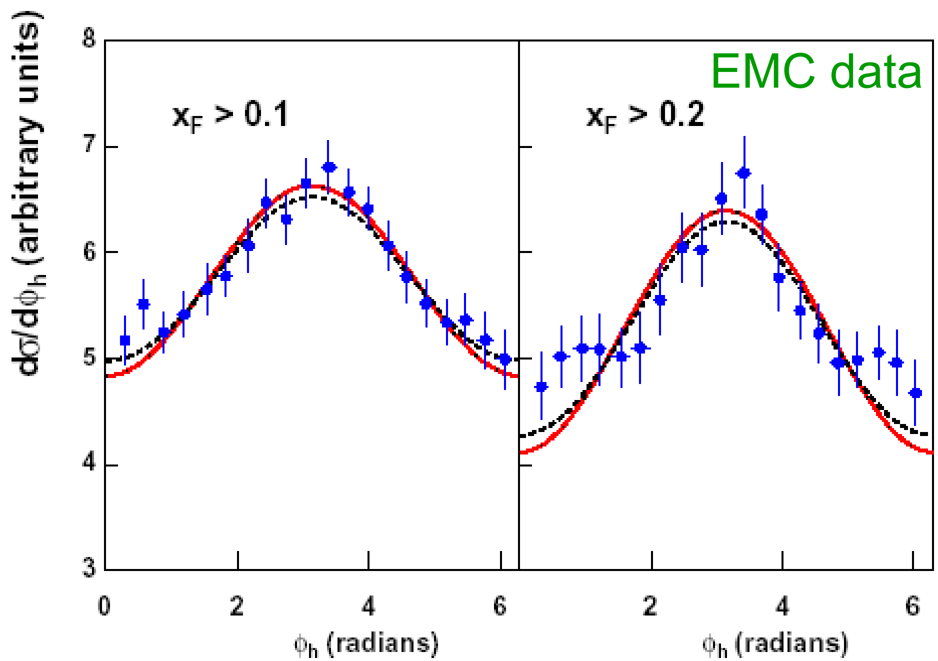
$$\mathrm{d}\sigma^{lp\to lhX} = \sum_q f_q(x, k_\perp, Q^2) \otimes \mathrm{d}\hat{\sigma}^{lq\to lq} \otimes D_q^h(z, p_\perp, Q^2)$$

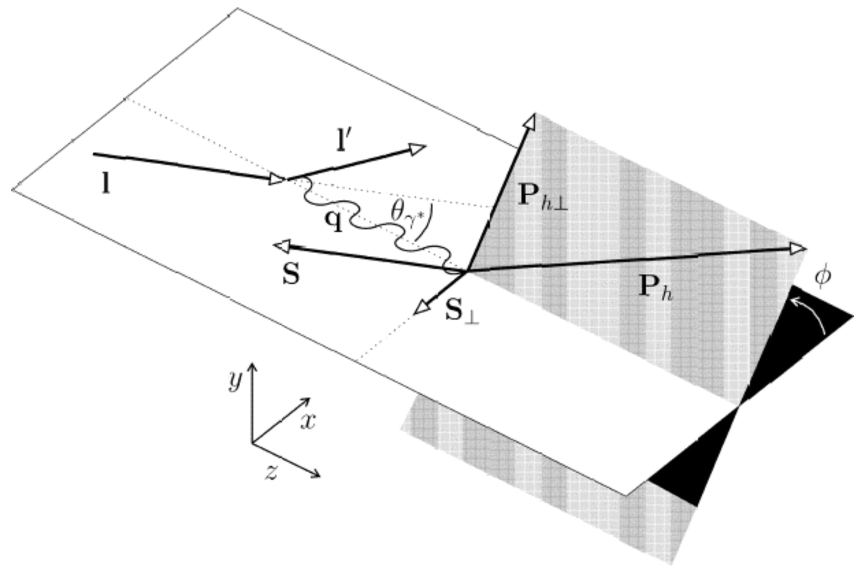
The elementary interaction depends on $\boldsymbol{k}_\perp = k_\perp(\cos\varphi, \sin\varphi, 0)$

$$\hat{s}^2 + \hat{u}^2 \simeq x_B^2 s^2 + (x_B s + Q^2)^2 - 4\boldsymbol{\ell}\cdot\boldsymbol{k}_\perp(2x_B s - Q^2) =$$

$$\frac{Q^4}{y^2}\left(1 + (1-y)^2 - 4\frac{k_\perp}{Q}(2-y)\sqrt{1-y}\cos\varphi\right) .$$

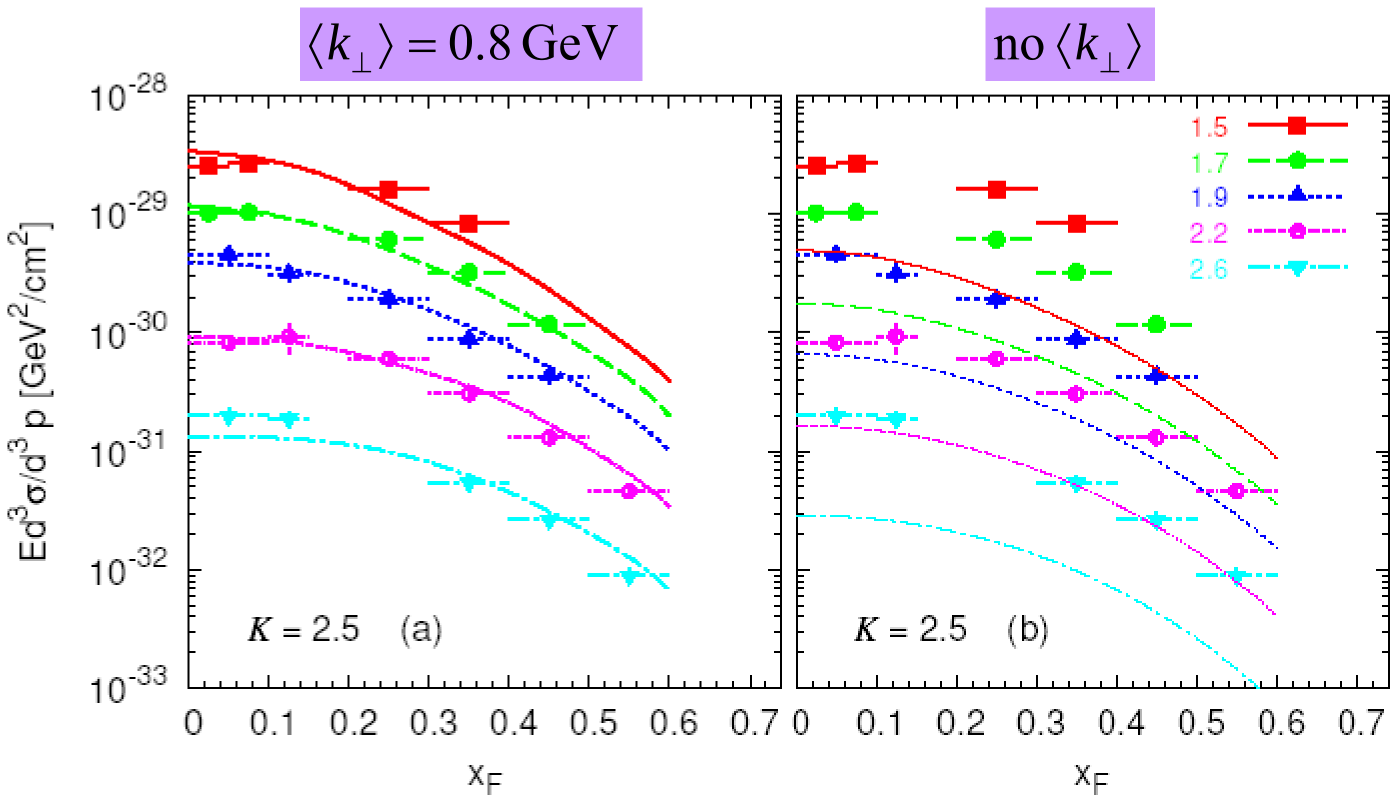
Azimuthal dependence in unpolarized SIDIS cross section (Cahn effect)





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

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

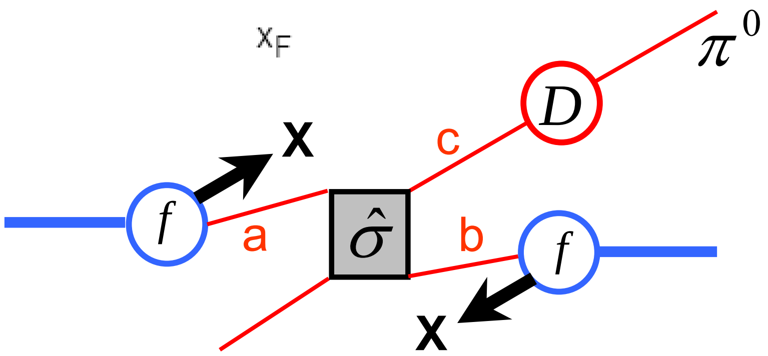


F. Murgia, U. D'Alesio

BNL data, PLB 73 (1978)

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

original idea from Feynman-Field



non collinear configurations

The cross section with intrinsic $k_\perp$

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

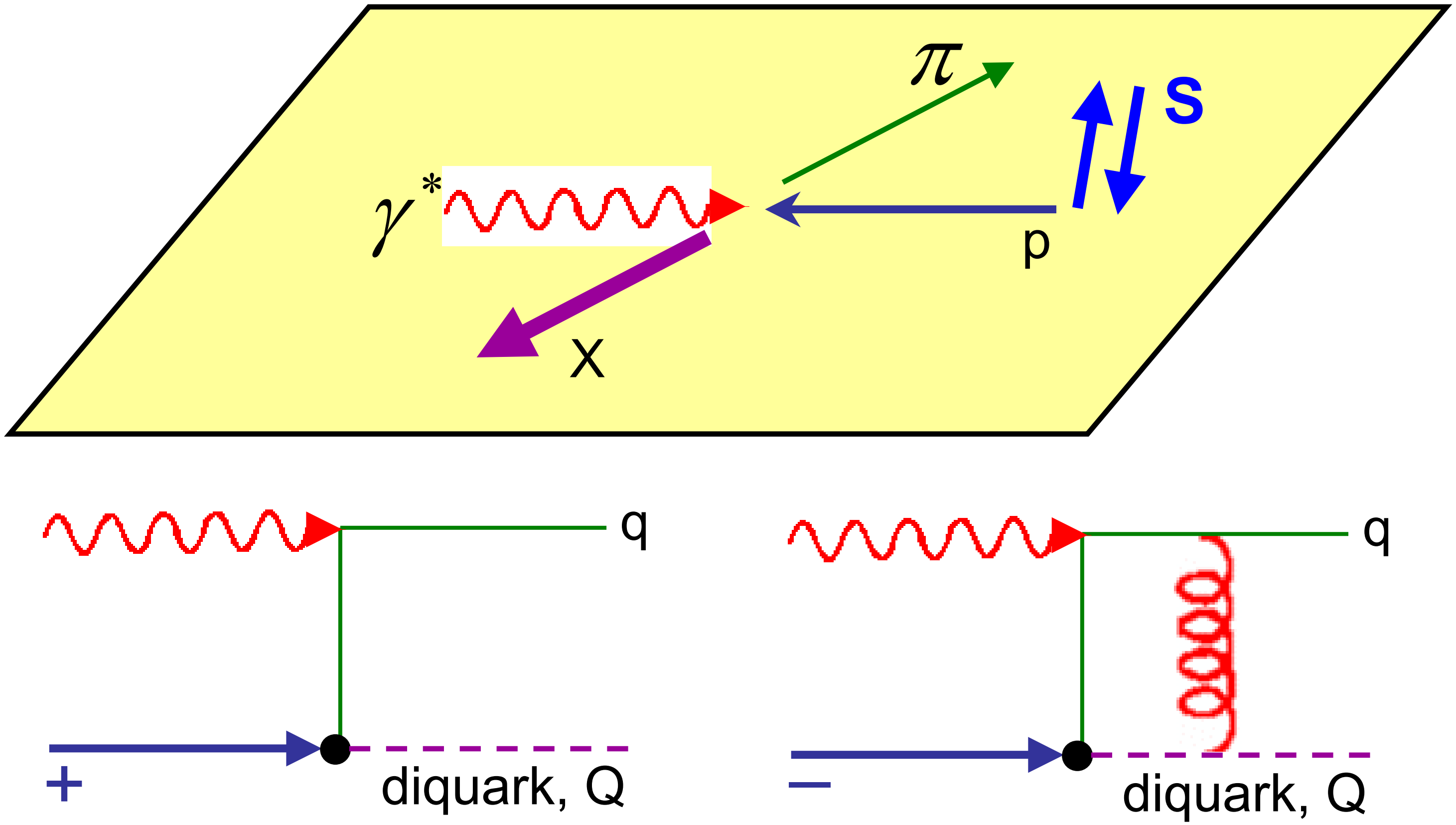
$$\sum_{a,b,c,d} \int dx_a\, dx_b\, dz\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b}\, d^3\boldsymbol{k}_{\perp C}\, \delta(\boldsymbol{k}_{\perp C}\cdot\hat{\boldsymbol{p}}_c)\, \hat{f}_{a/A}(x_a, \boldsymbol{k}_{\perp a}; Q^2)\, \hat{f}_{b/B}(x_b, \boldsymbol{k}_{\perp b}; Q^2)$$

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

factorization is assumed, not proved

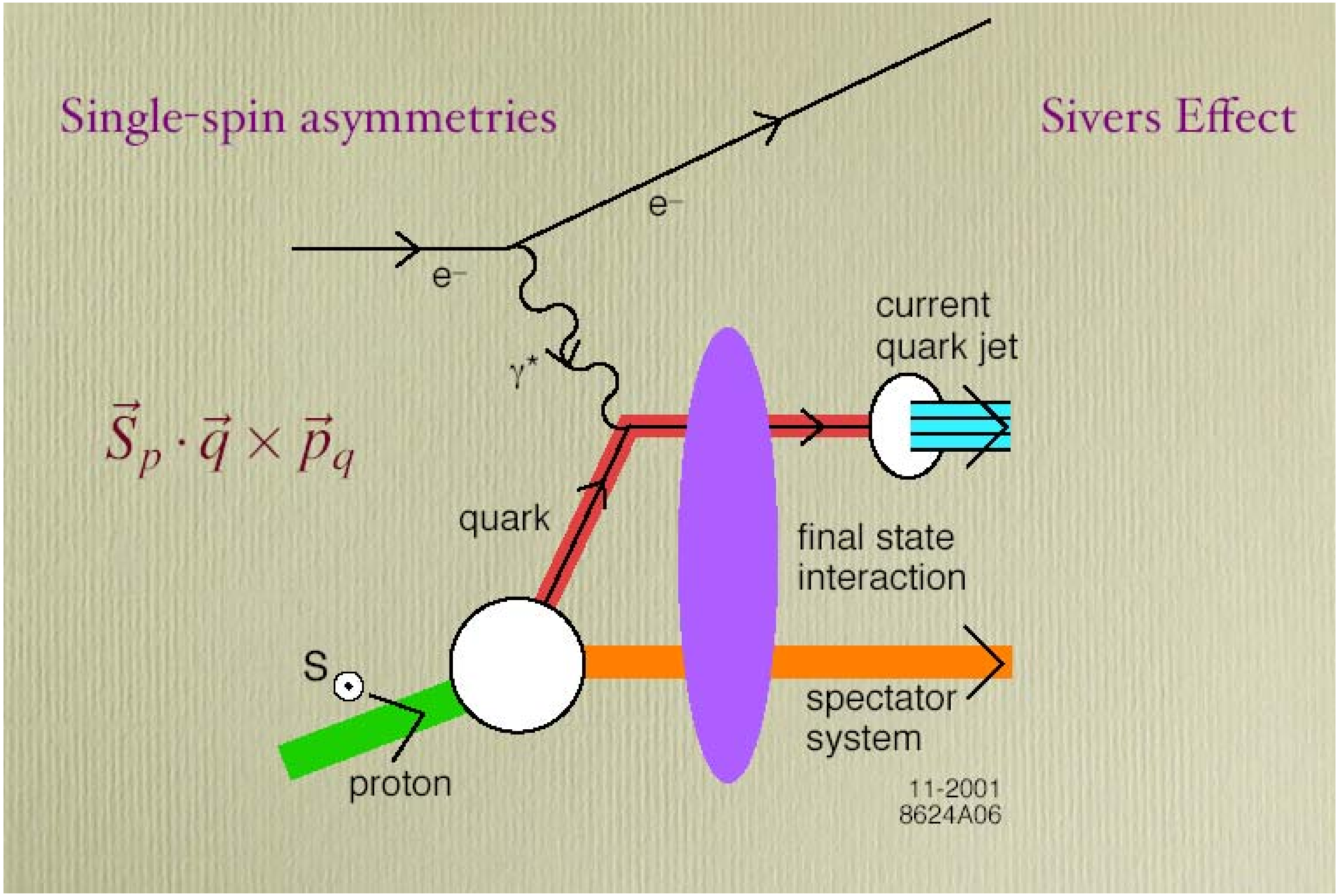
intrinsic $k_\perp$ in distribution and fragmentation functions and in elementary interactions

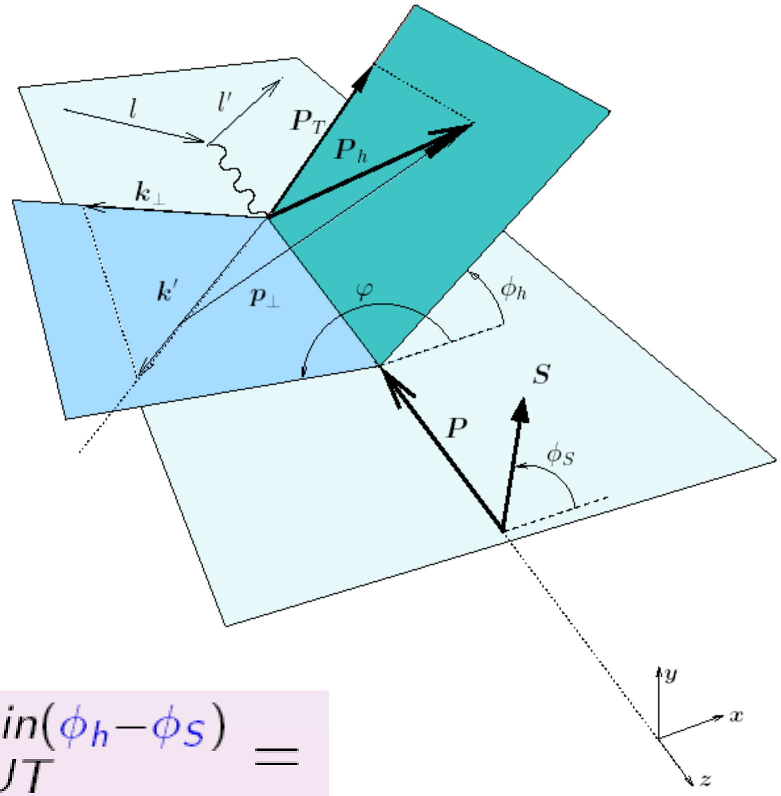
Brodsky, Hwang, Schmidt model for Sivers function



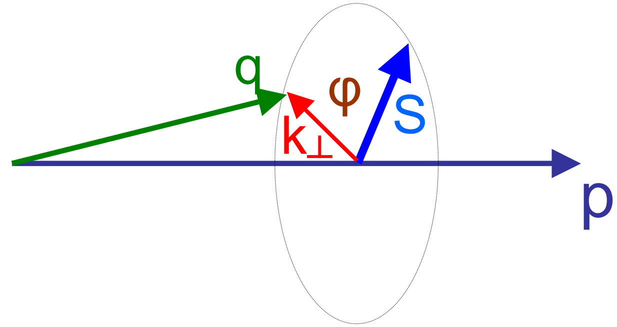
$\gamma^* p \to q\, Q$ cannot be forward in order to have a SSA

 intrinsic $k_\perp$ of quark


Single-spin asymmetries
Sivers Effect
$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$
e−
e−
γ*
current
quark jet
quark
final state
interaction
S
spectator
system
proton
11-2001
8624A06



Sivers mechanism in SIDIS



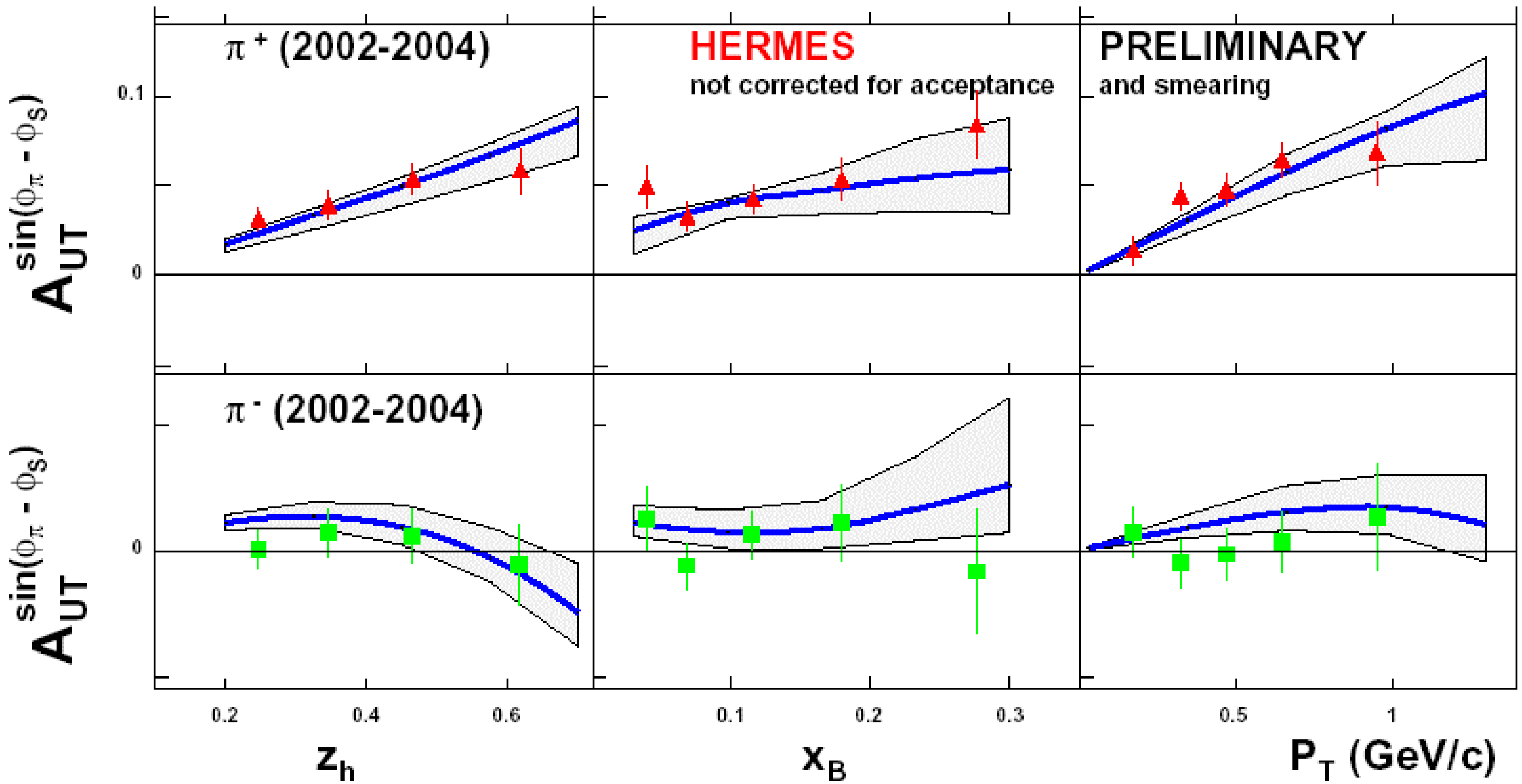
$$f_{q/p^\uparrow}(x,\vec{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\vec{S}\cdot(\hat{p}\times\hat{k}_\perp)$$

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

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

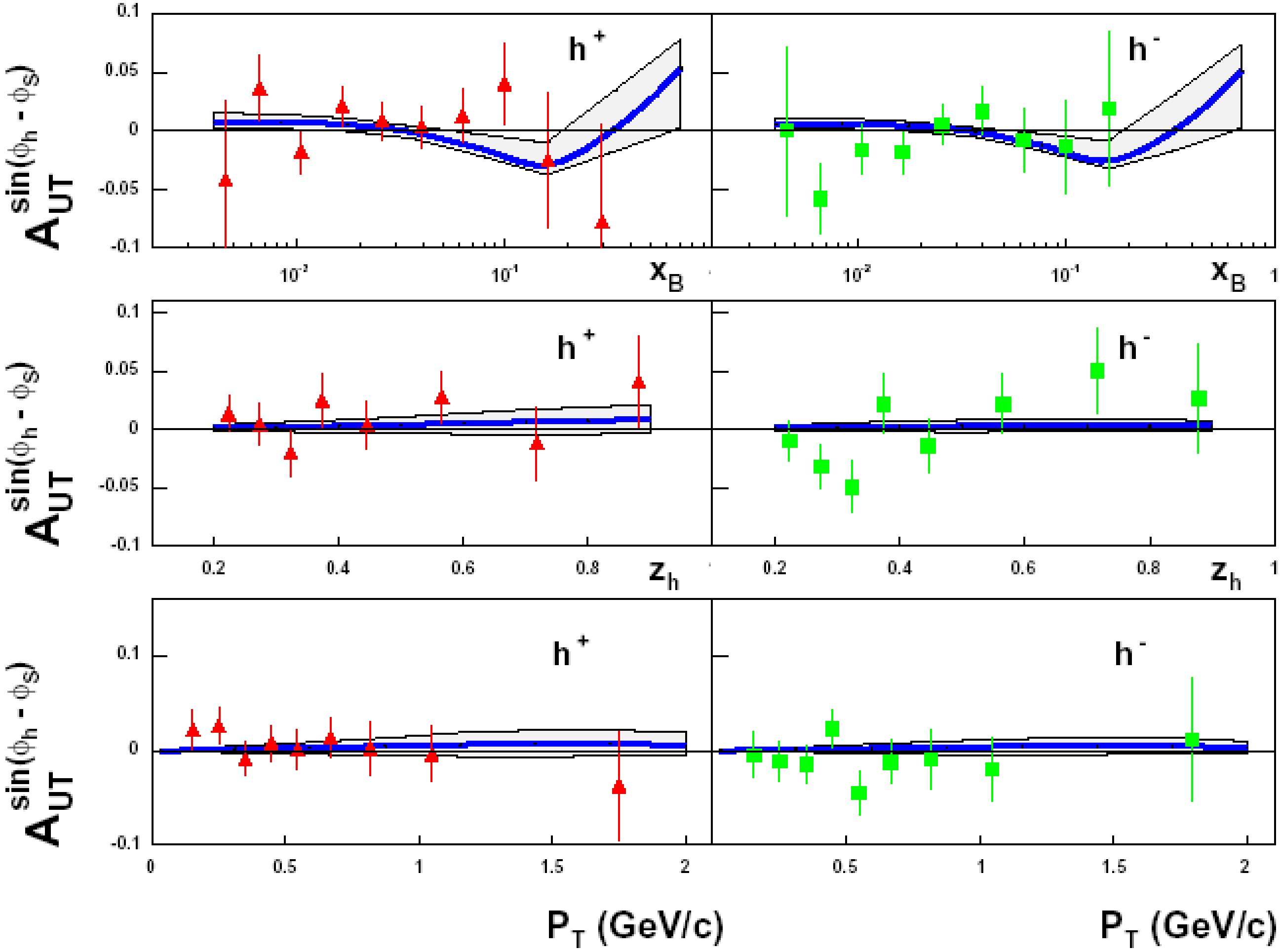
$A_{UT}^{\sin(\Phi-\Phi_S)}$ from Sivers mechanism

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

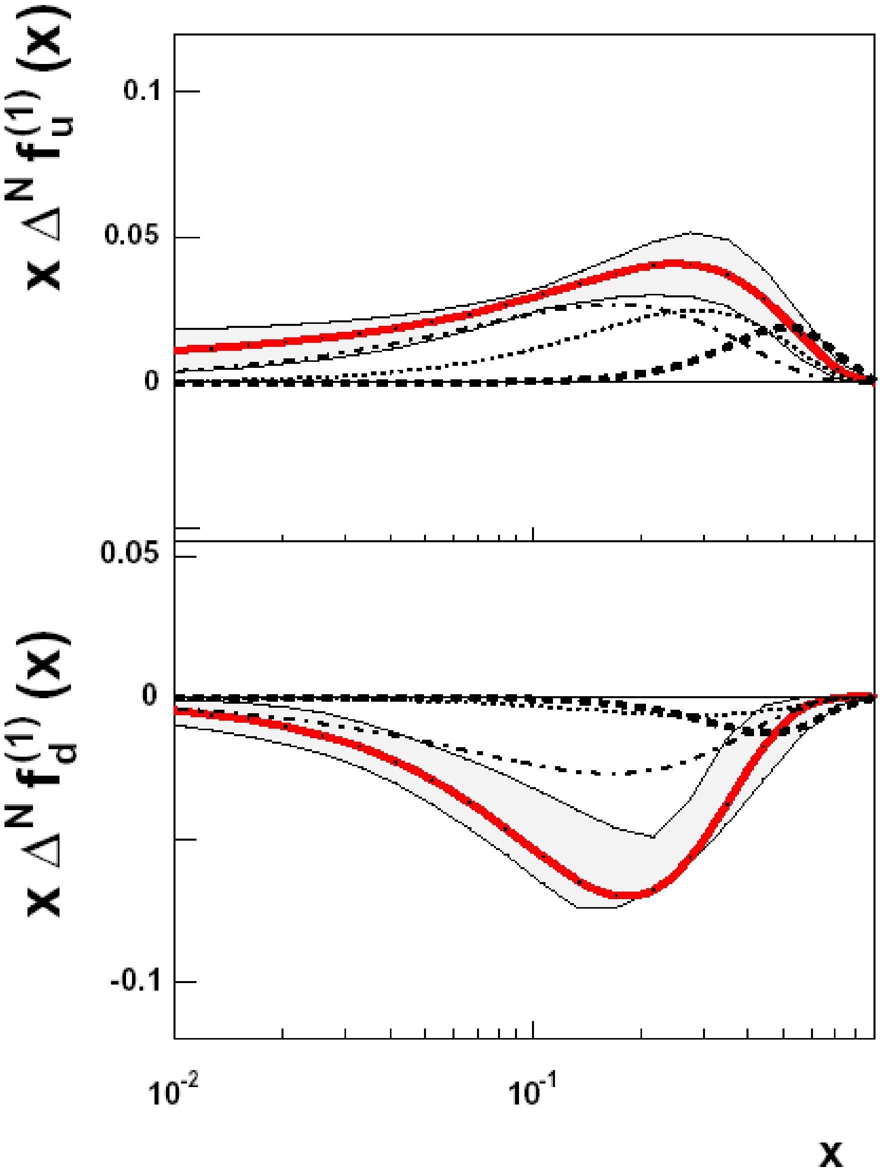


Deuteron target

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



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



First $p_\perp$ moments of extracted Sivers functions, compared with models

data from HERMES and COMPASS

$$\Delta^N f_q^{(1)}(x) \equiv \int d^2 k_\perp \frac{k_\perp}{4 m_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp)$$

HERMES + E704: Sivers function is not zero

→ Spin-$k_\perp$ partonic correlations in nucleons

Theory: not quite universal

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

J. Collins, a "QCD theorem"

Models: few, in fair agreement

$$f_{1T}^{\perp u} = - f_{1T}^{\perp d}$$

chiral models

$$f_{1T}^{\perp q} \propto \kappa^q$$

M. Burkardt

Other accesses to Sivers function

SSA in Drell-Yan processes (no fragmentation), $p^{\uparrow} p(\bar{p}) \to l^+ l^- X$

$$A_N^{\text{D-Y}} \propto \sum_q \Delta^N f_{q/p^{\uparrow}}(x_1, k_{1\perp}) \otimes f_{\bar{q}}(x_2)$$

Sivers function usual parton distribution

SSA in charm production (no spin transfer), $p^{\uparrow} p(\bar{p}) \to D\, X$

$$A_N^{p\bar{p}\to DX} \propto \sum_a \Delta^N f_{a/p^{\uparrow}}(x_1, k_{\perp 1}) \otimes f_b(x_2) \otimes D_c(z)$$

usual fragmentation function

elementary processes:

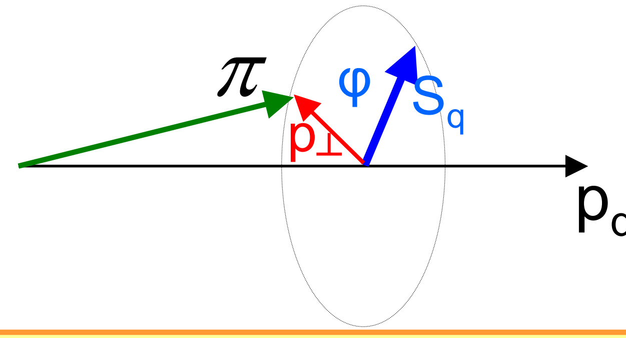
$q\bar{q} \to c\bar{c}$ GSI energies

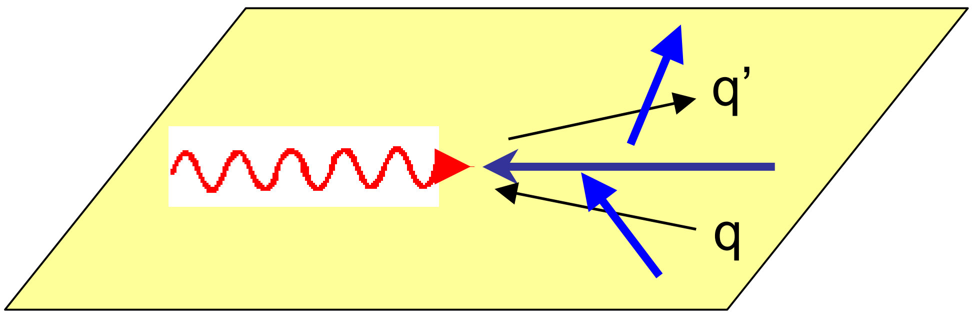
$gg \to c\bar{c}$ RHIC energies

Collins mechanism for SSA

Asymmetry in the fragmentation of a transversely polarized quark

(Fundamental QCD property? D. Sivers)

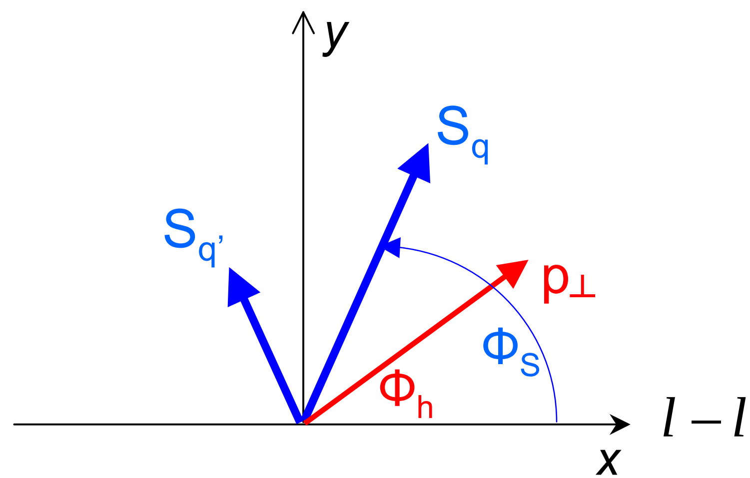




$$D_{h/q^{\uparrow}}(z,\vec{p}_{\perp}) = D_{h/q}(z,p_{\perp}) \ + \frac{1}{2}\Delta^{N} D_{h/q^{\uparrow}}(z,p_{\perp})\,\vec{S}_{q}\cdot(\hat{p}_{q}\times\hat{p}_{\perp})$$

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:

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

transversity

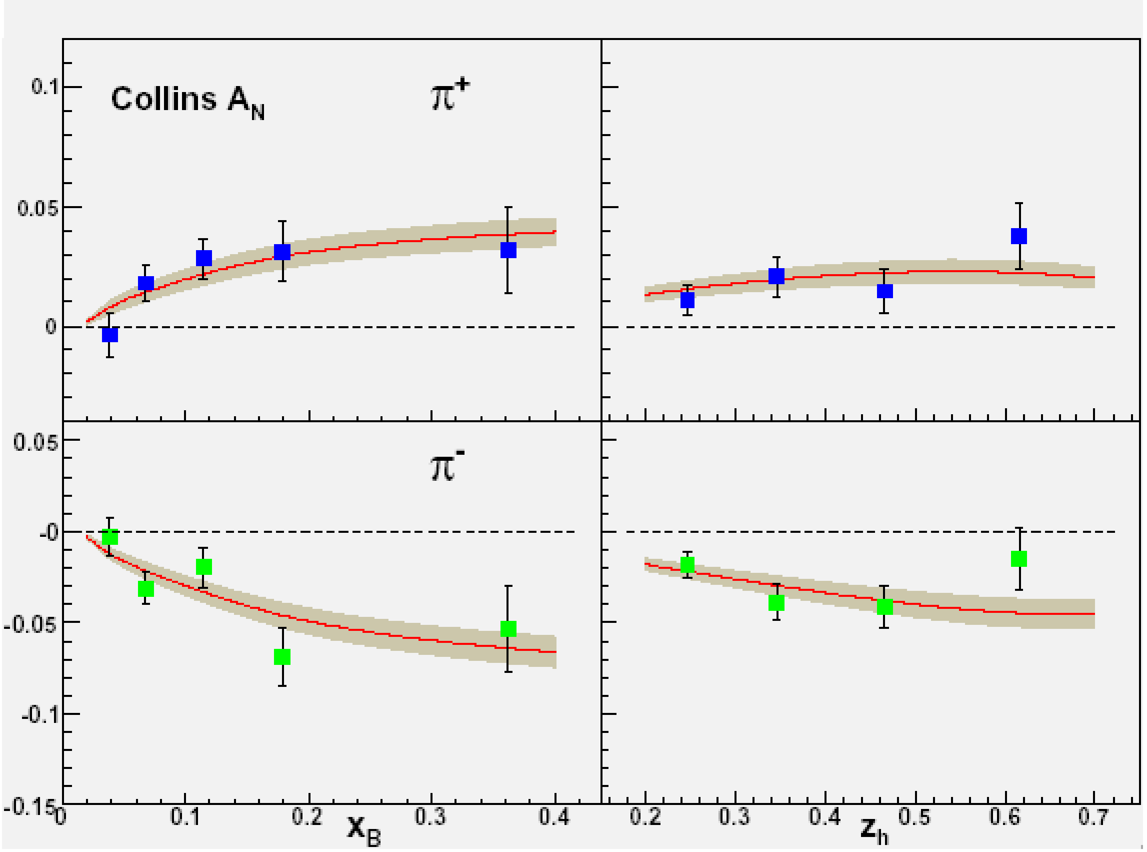
Collins function

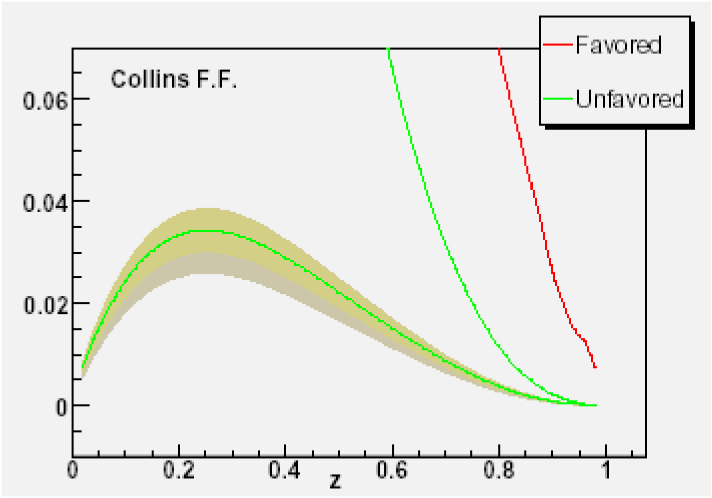
$$\frac{\sum_q \int e_q^2\, h_{1q}(x)\,(1-y)/(xy^2)\,\Delta^N D_{h/q^\uparrow}(z,p_\perp)}{\sum_q \int e_q^2\; f_{q/p}(x)\,[1+(1-y)^2]/(xy^2)\,D_{q/p}(z,p_\perp)}\;\sin(\Phi_h+\Phi_S)$$

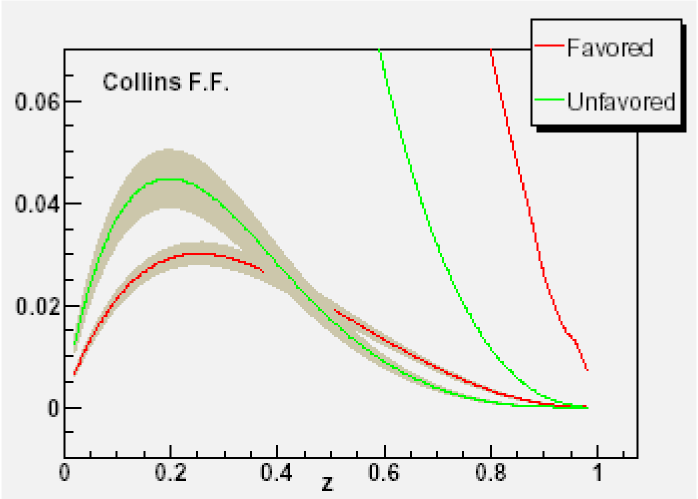
$$A_{UT}^{\sin(\Phi_h+\Phi_S)} \equiv 2\,\frac{\int \mathrm{d}\Phi_h \mathrm{d}\Phi_S [\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow]\sin(\Phi_h+\Phi_S)}{\int \mathrm{d}\Phi_h \mathrm{d}\Phi_S [\mathrm{d}\sigma^\uparrow + \mathrm{d}\sigma^\downarrow]}$$

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

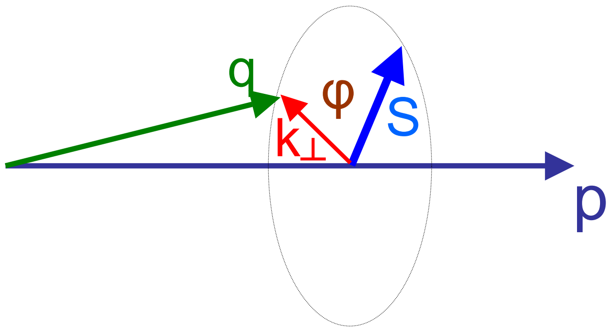
fit to HERMES data on $A_{UT}^{\sin(\Phi_h+\Phi_S)}$



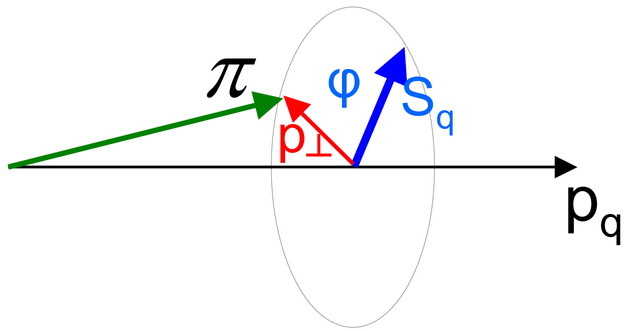




spin-$k_\perp$ correlations



Sivers function



Collins function

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

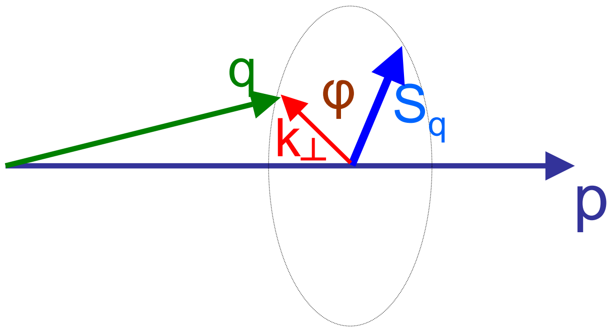
$$D_{h/q^\uparrow}(z,\vec{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\vec{S}_q\cdot(\hat{p}_q\times\hat{p}_\perp)$$

Amsterdam group notations

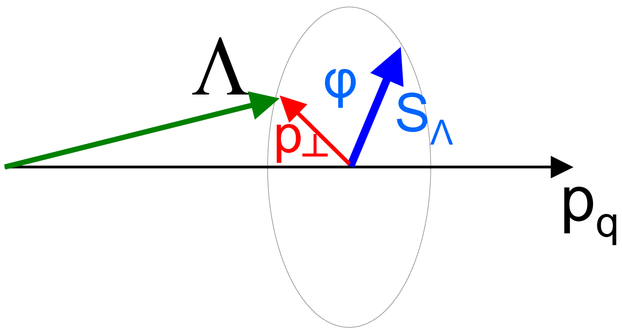
$$\Delta^N f_{q/p^\uparrow} = -\frac{2k_\perp}{M} f_{1T}^{\perp q}$$

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

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

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

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

The last missing piece of the proton structure: transversity

- The parton transverse spin distribution, h_1
- A partner for h_1
- Transversity in Drell-Yan processes
- Transversity in SIDIS processes
- Collins function from e^+e^- data
- Hunting strategies for h_1

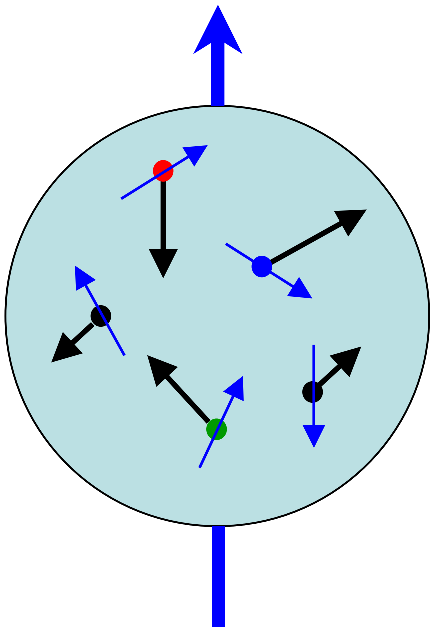
Transversity

(transverse spin and transverse motion)

(unravelling the spin-orbital motion of partons?)

Towards transversity distributions:
theory and experiments

Spin and $k_\perp$ dependent parton distributions (TMD)



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

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

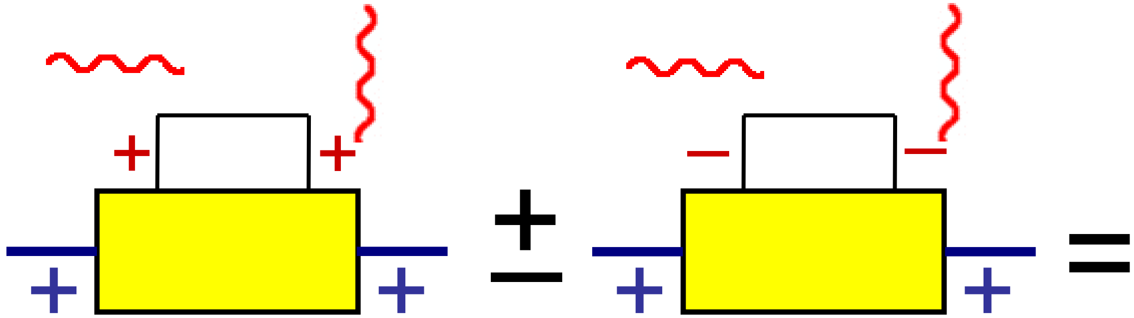
all equally important

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

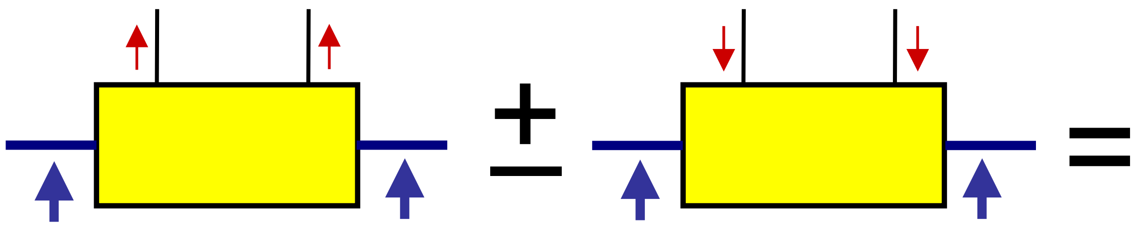
$\Delta_T q$ related to $\bar{q}\sigma^{\mu\nu}\gamma_5 q$ ➡ chiral-odd

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

positivity bound



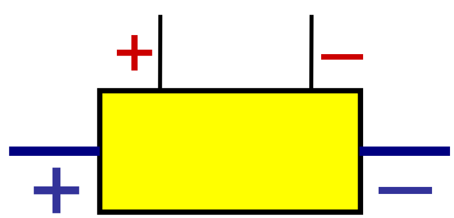
$$q(x,Q^2)$$
$$\Delta q(x,Q^2)$$



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

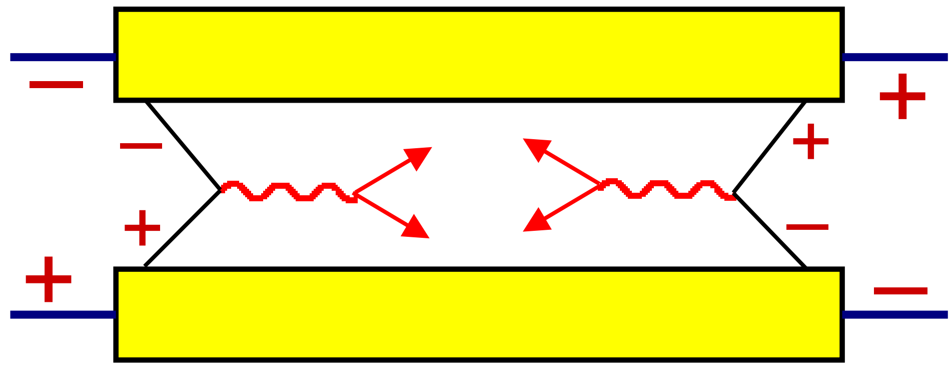
in helicity basis $\uparrow\downarrow = \frac{1}{\sqrt{2}}\left(|+\rangle \pm i\,|-\rangle\right)$

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



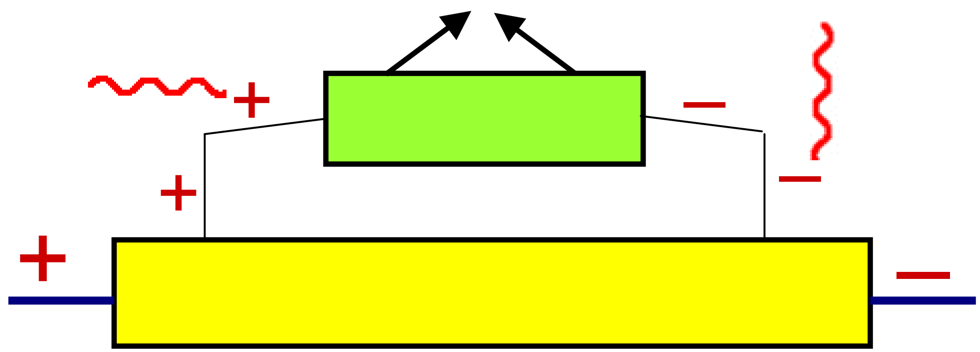
decouples from DIS
(no quark helicity flip)

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



$h_1 \times h_1$

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

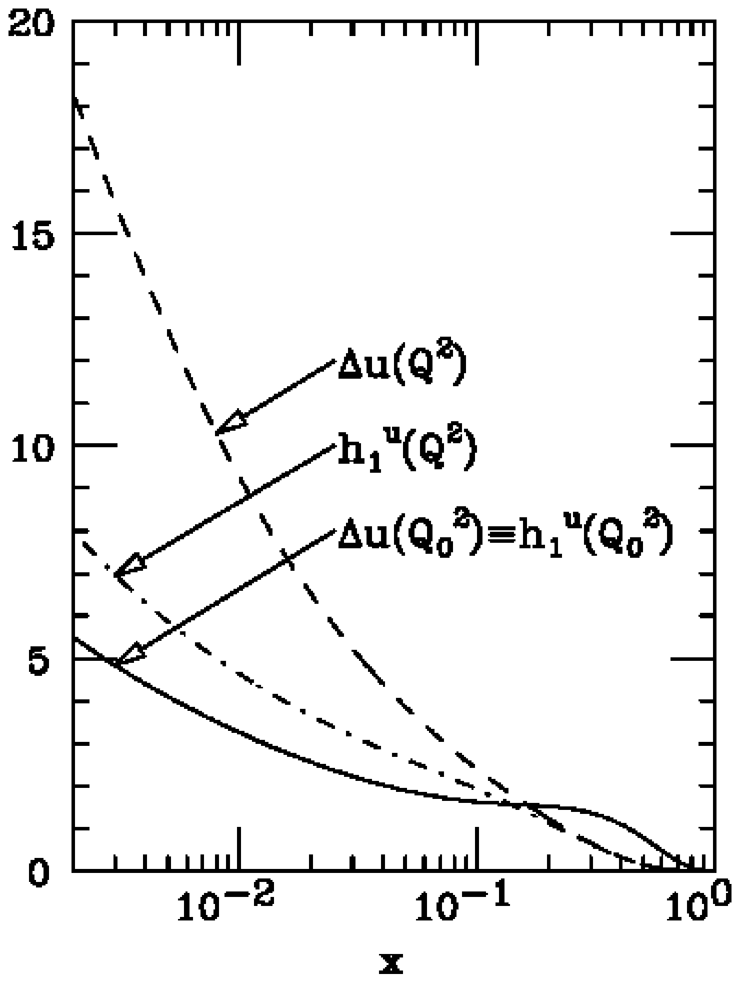


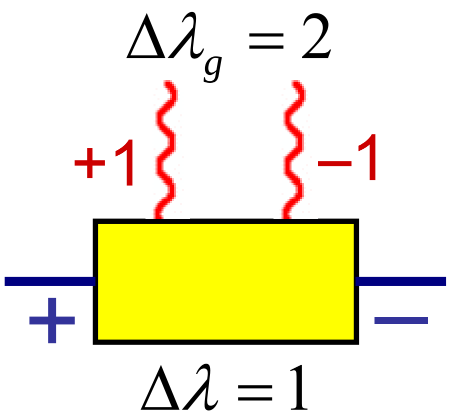
h_1 x Collins function

J. Collins, 1993

No gluon contribution to h_1

⇨ simple Q^2 evolution



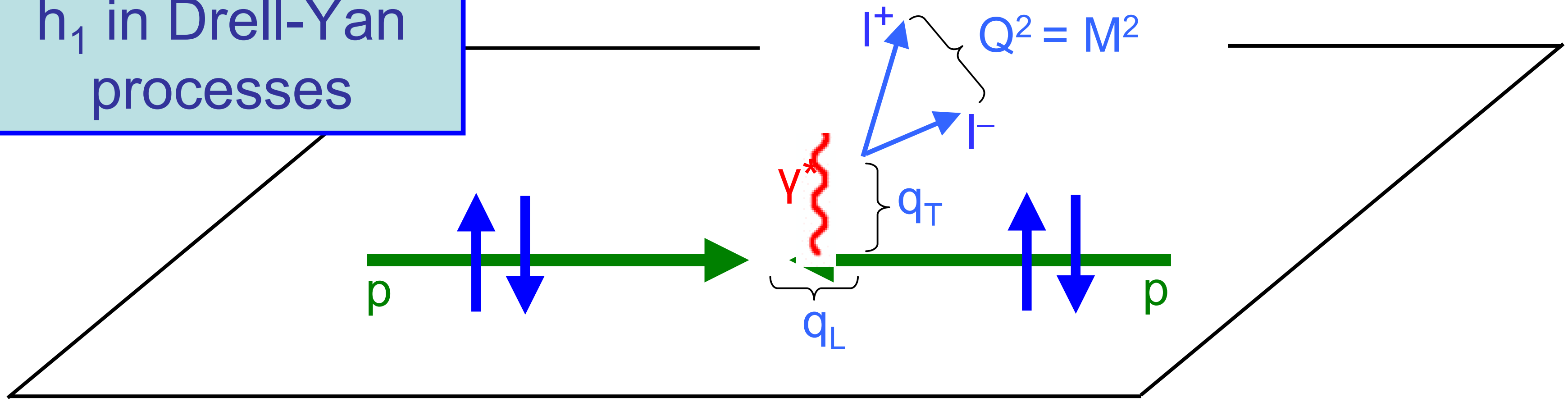


$Q^2 = 25\ \mathrm{GeV}^2$

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

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 $p^\uparrow p^\uparrow \to l^+ l^- X$ at RHIC

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

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

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

➡ $\tau \le 2 \cdot 10^{-3}$ 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

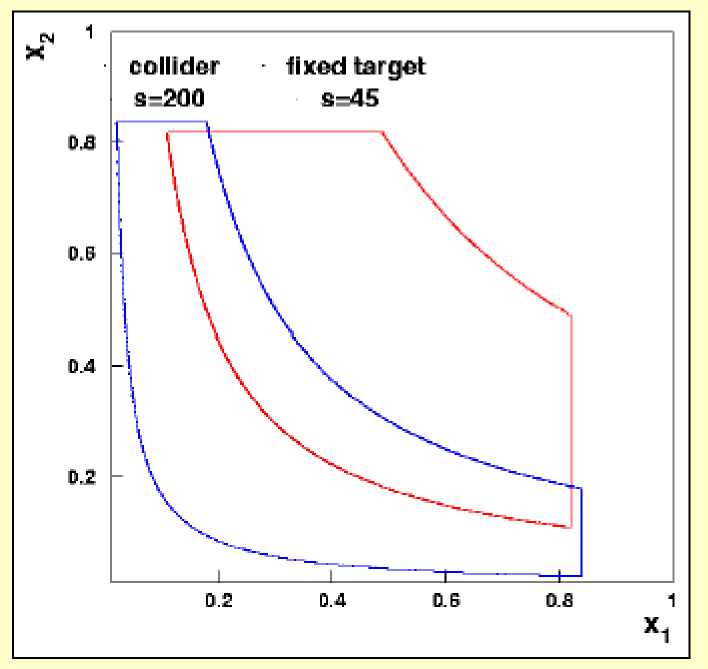
Barone, Calarco, Drago
Martin, Schäfer, Stratmann, Vogelsang

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

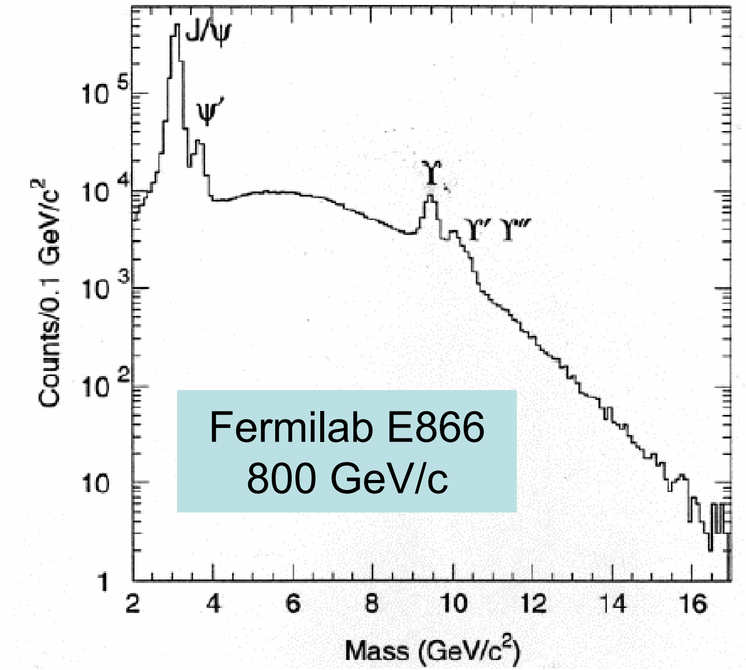


one measures h_1 in the quark valence region: A_{TT} is estimated to be large, between 0.2 and 0.4

PAX proposal: hep-ex/0505054

s = 210 GeV^2 is best energy

Energy for Drell-Yan processes



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

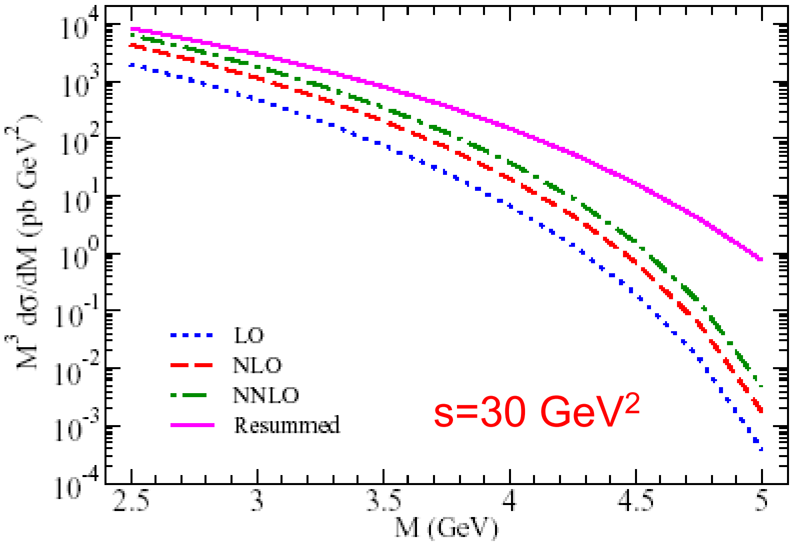
$$\Rightarrow \quad \tau \geq \frac{M^2_{J/\Psi}}{s}$$

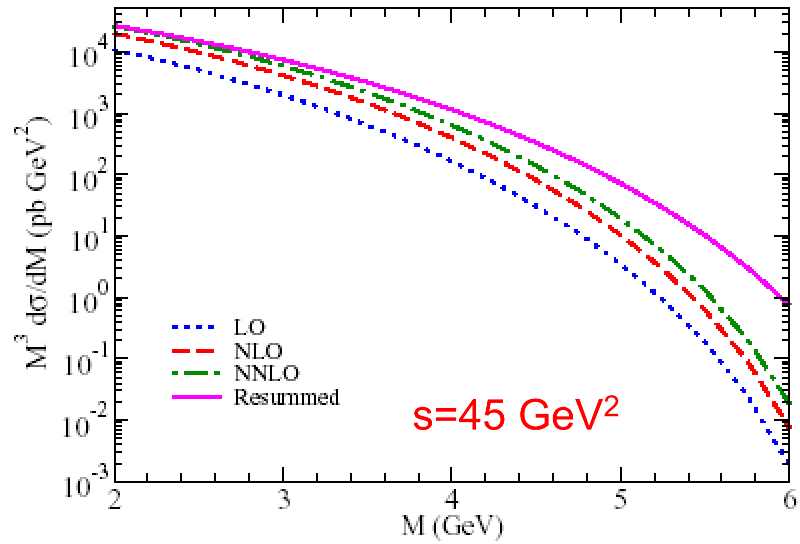
QCD corrections might be very large at smaller values of *M*:

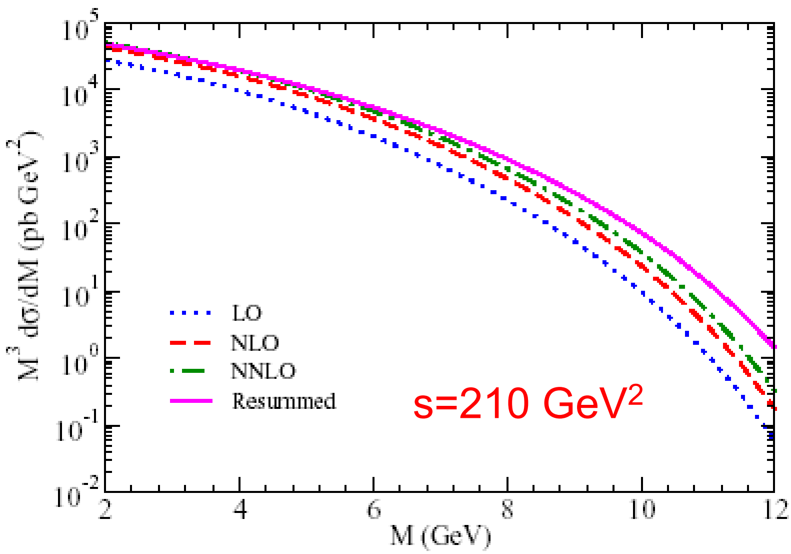
yes, for cross-sections, not for A_{TT}

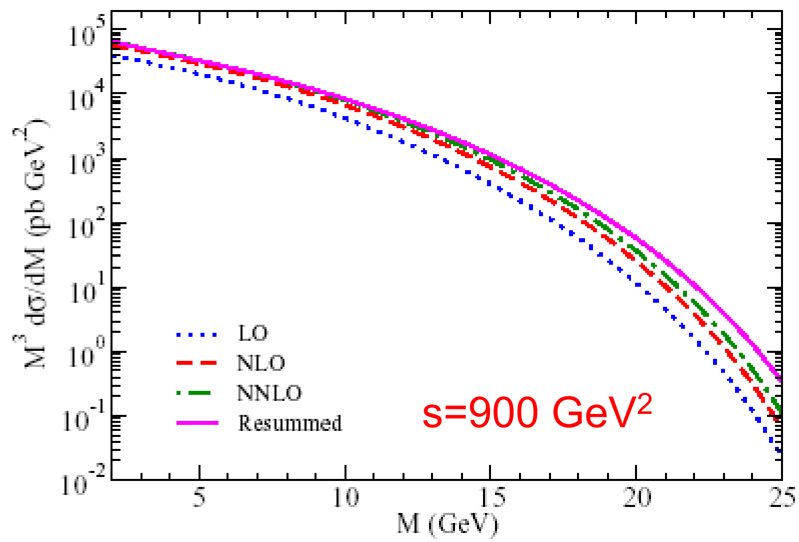
K-factor almost spin-independent

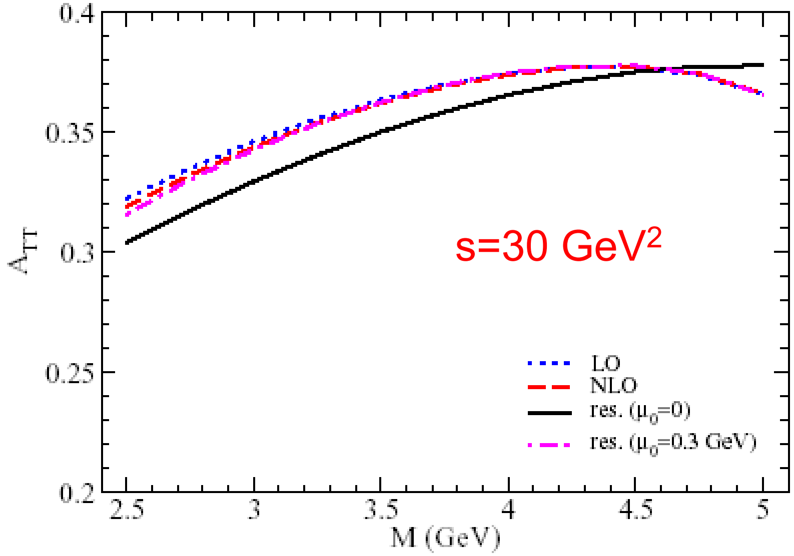
H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya, hep-ph/0503270

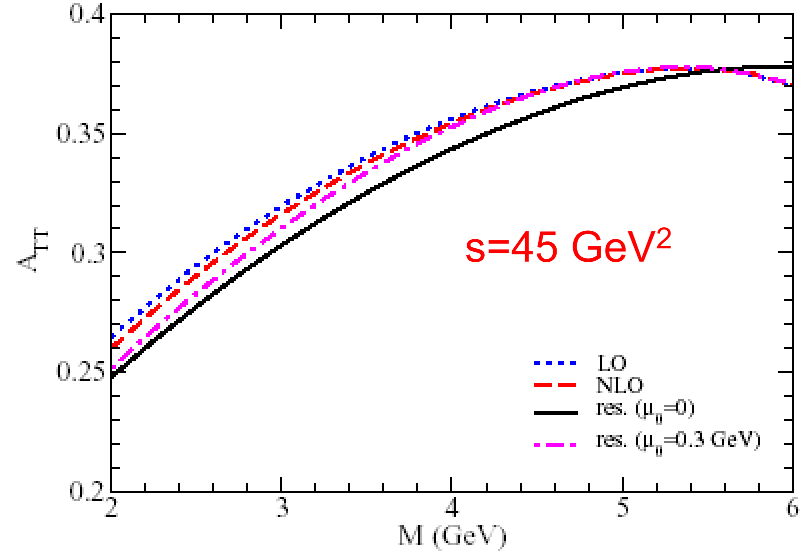

$M^3\, d\sigma/dM$ (pb GeV^2)
M (GeV)
LO
NLO
NNLO
Resummed
s=30 GeV^2

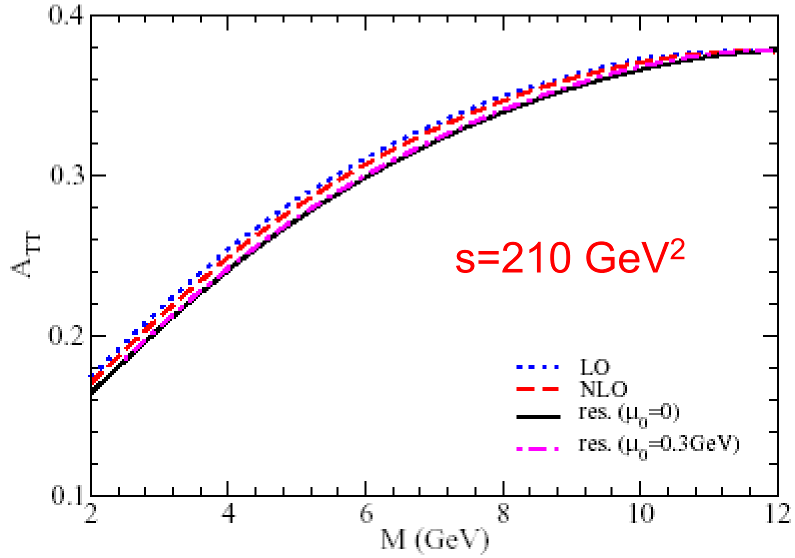

$M^3\, d\sigma/dM$ (pb GeV^2)
M (GeV)
LO
NLO
NNLO
Resummed
s=45 GeV^2

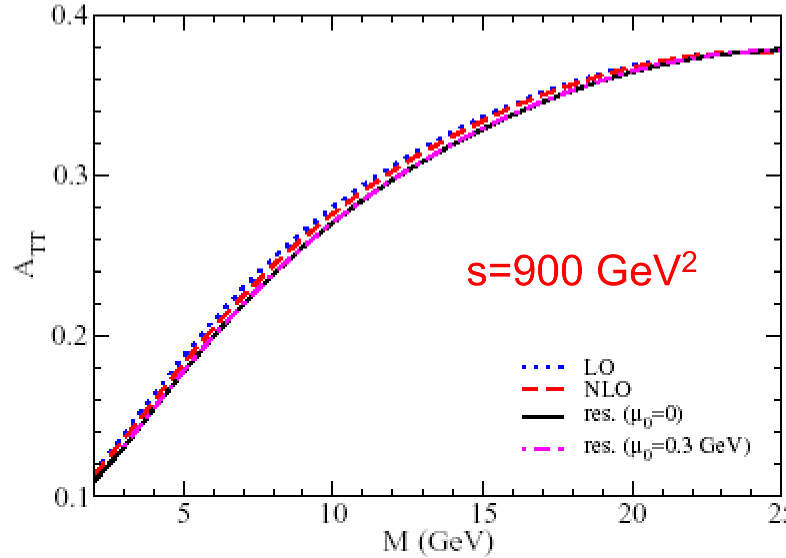

$M^3\, d\sigma/dM$ (pb GeV^2)
M (GeV)
LO
NLO
NNLO
Resummed
s=210 GeV^2

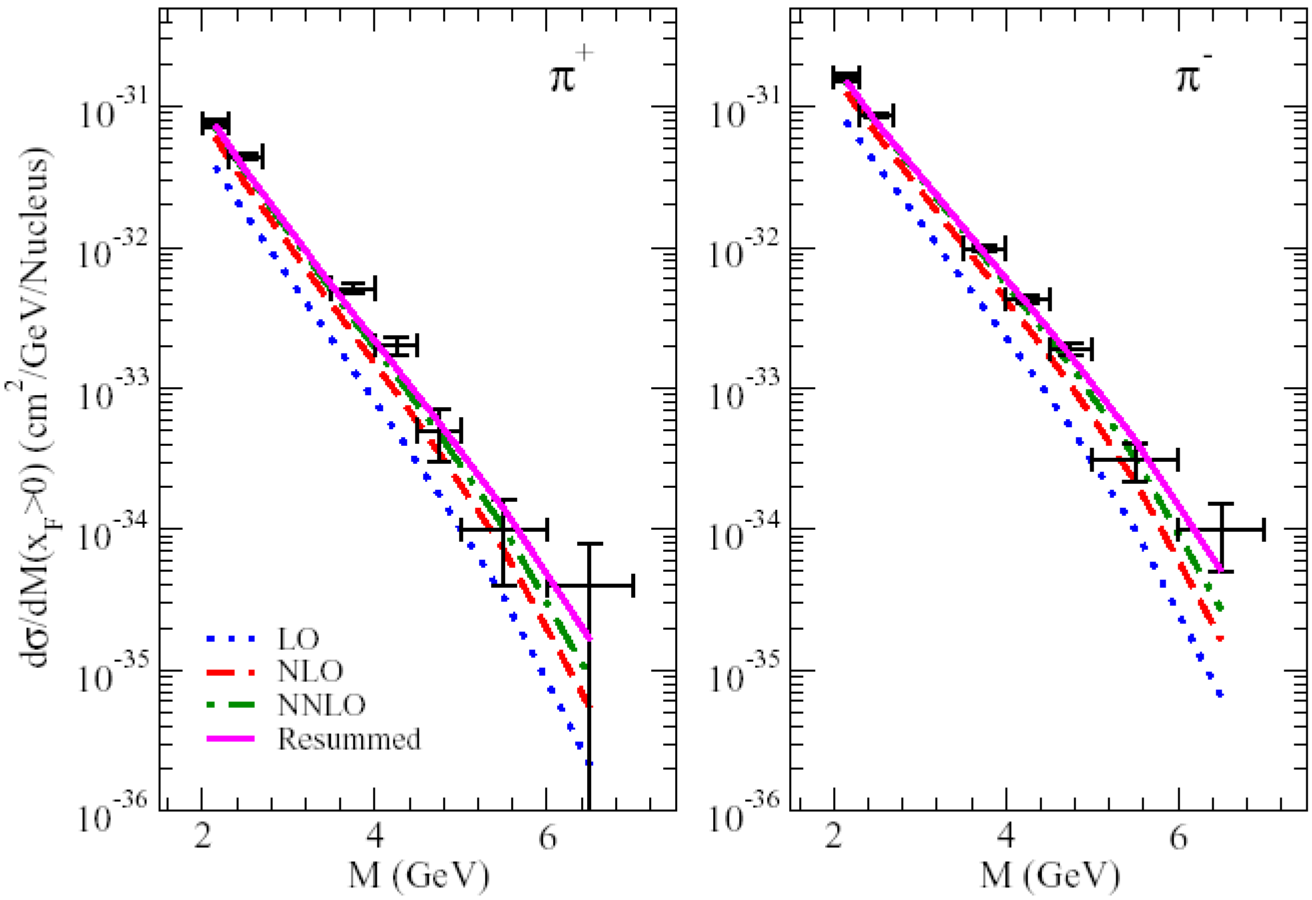

$M^3\, d\sigma/dM$ (pb GeV^2)
M (GeV)
LO
NLO
NNLO
Resummed
s=900 GeV^2


s=30 GeV²
A_TT
M (GeV)
LO
NLO
res. (μ0=0)
res. (μ0=0.3 GeV)


s=45 GeV²
A_TT
M (GeV)
LO
NLO
res. (μ0=0)
res. (μ0=0.3 GeV)


s=210 GeV²
A_TT
M (GeV)
LO
NLO
res. (μ0=0)
res. (μ0=0.3GeV)


s=900 GeV²
A_TT
M (GeV)
LO
NLO
res. (μ0=0)
res. (μ0=0.3 GeV)



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

h_1 x Collins from SIDIS processes

neglecting intrinsic motion in partonic distributions:

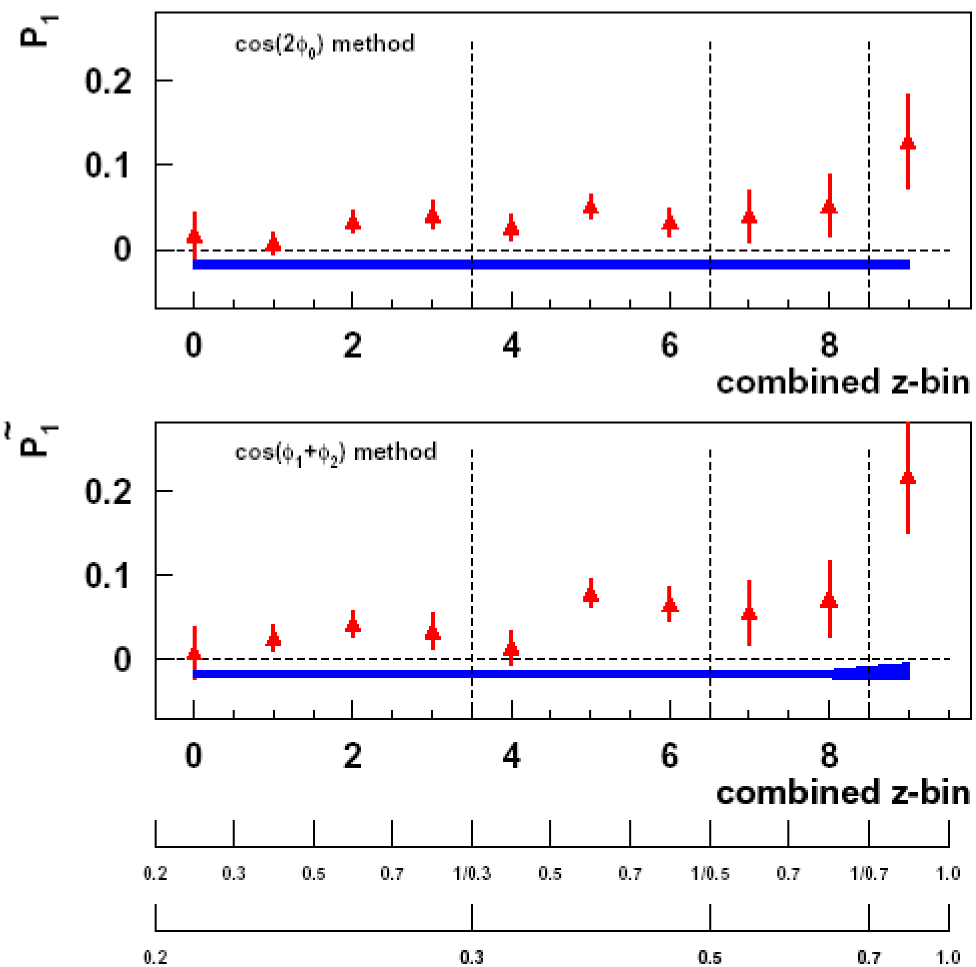
transversity

Collins function

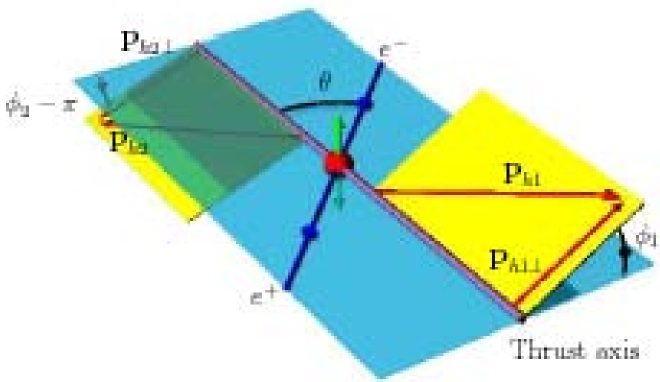
$$A_N^h = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{\sum_q \int e_q^2\, h_{1q}(x)\,(1-y)/(xy^2)\,\Delta^N D_{h/q^\uparrow}(z,p_\perp)}{\sum_q \int e_q^2\; f_{q/p}(x)\,[1+(1-y)^2]/(xy^2) D_{q/p}(z,p_\perp)} \sin(\Phi_h + \Phi_S)$$

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

Extraction of Collins functions from HERMES + BELLE data



$$e^+e^- \to h_1 h_2 X$$

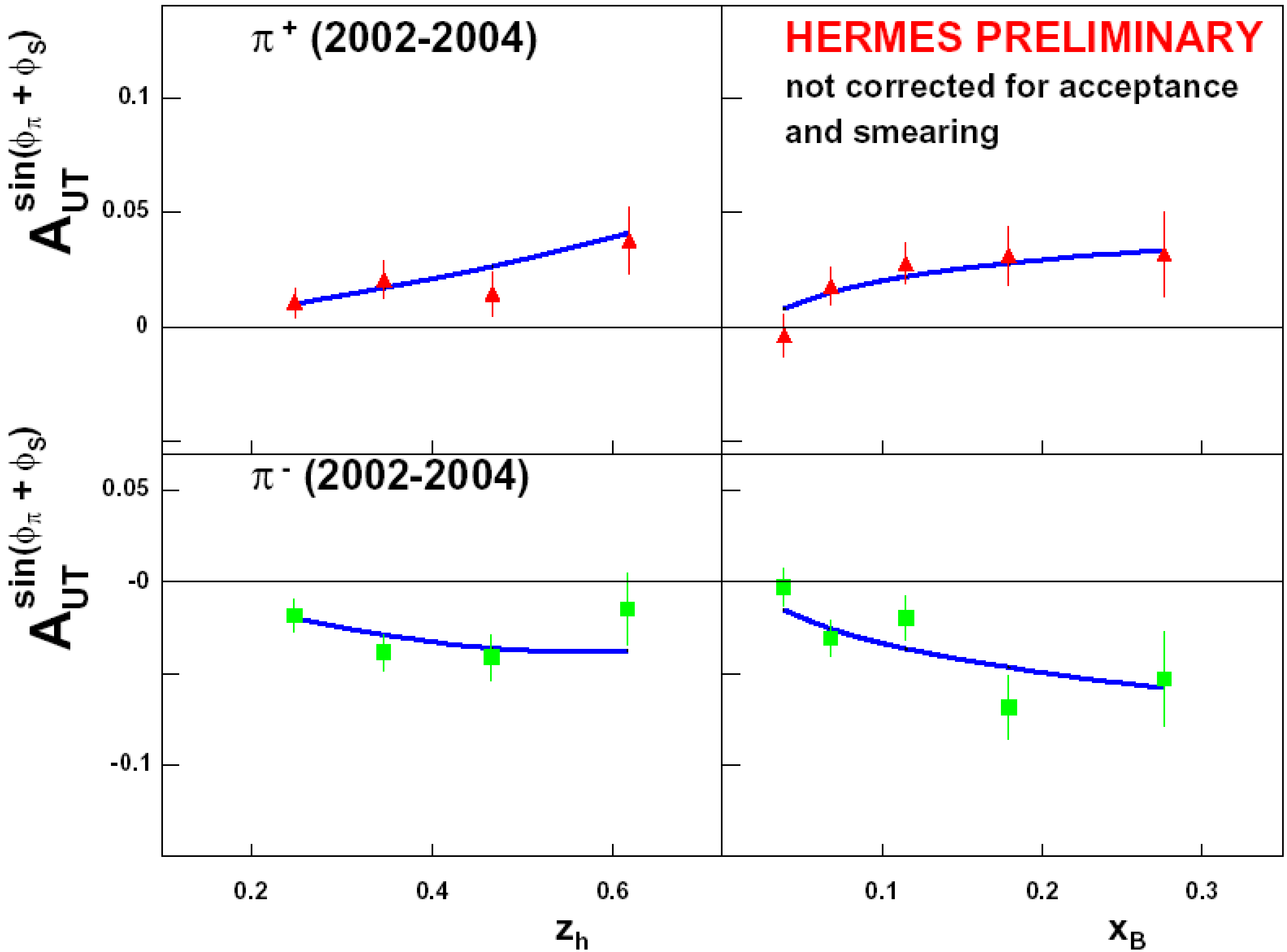


P_1 depends on

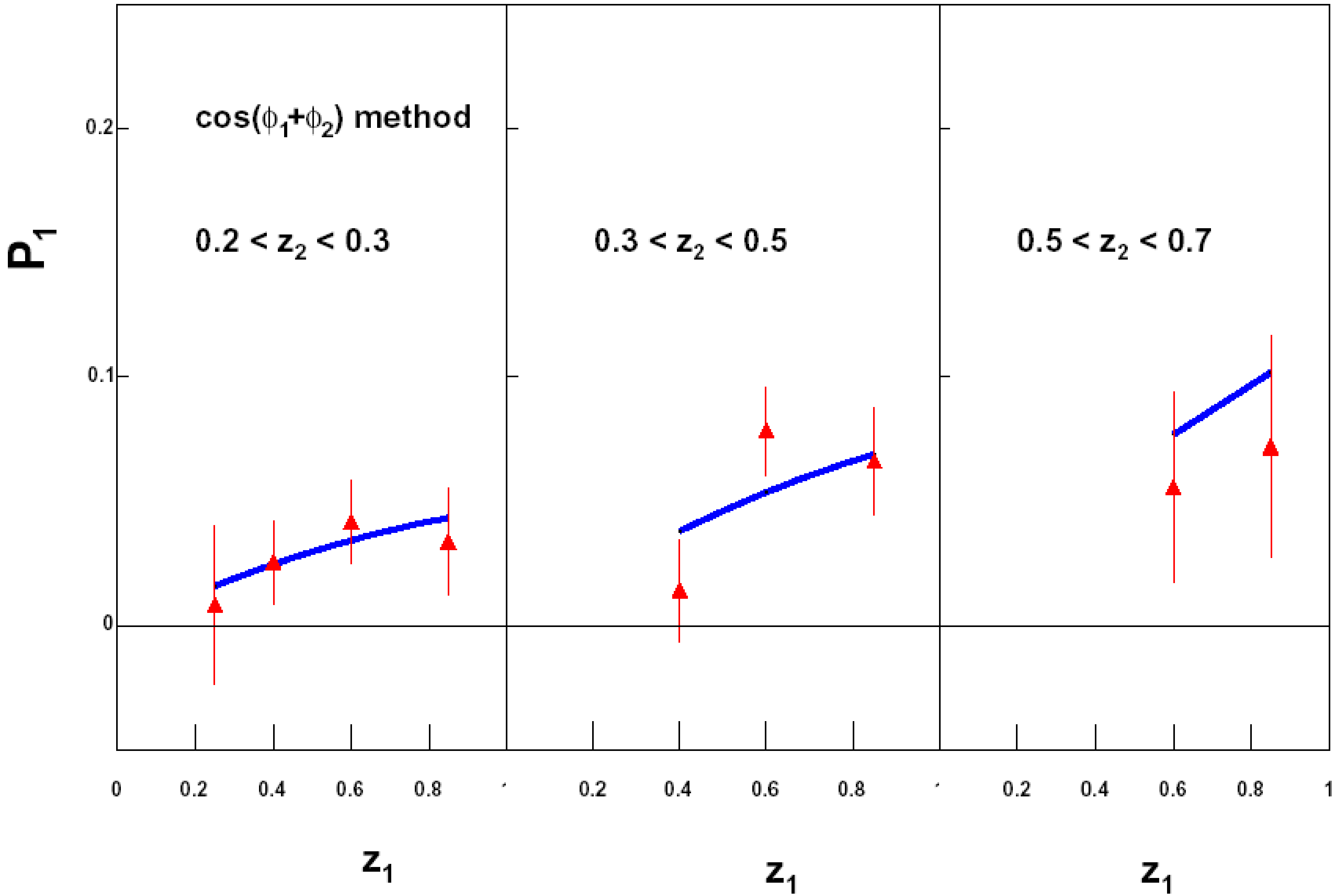
$$\frac{\Delta_N D_{h_1/q}(z_1)\,\Delta_N D_{h_2/\bar{q}}(z_2)}{D_{h_1/q}(z_1)\,D_{h_2/\bar{q}}(z_2)}$$

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

Fits to HERMES Collins data, preliminary results



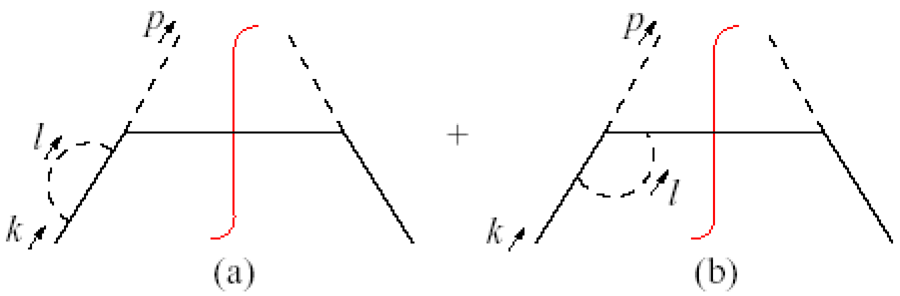
Fits to BELLE Collins data, preliminary results



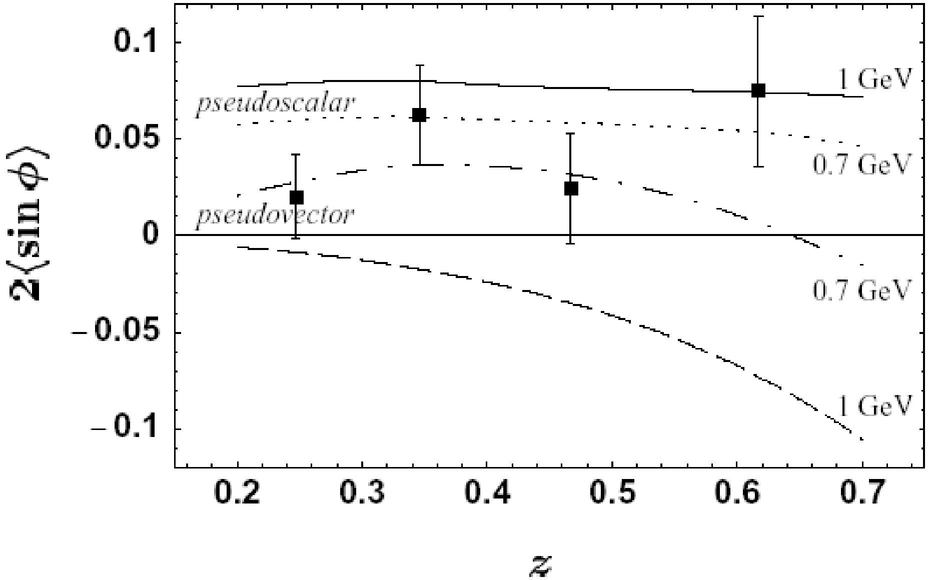
HERMES + BELLE: Collins function is not zero

Theory: probably universal Collins, Metz

Models: few, in disagreement



pion-quark vertex ?
loop?



assumes $h_1 = \Delta q$

disfavoured Collins functions = 0

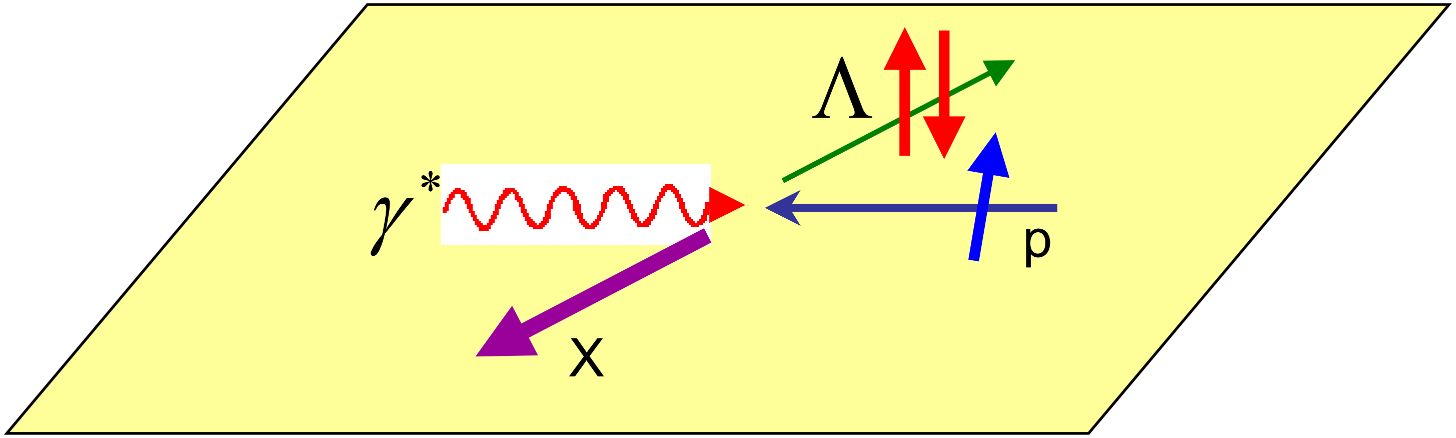
Alternative accesses to transversity

Inclusive Λ production and measure of Λ polarization

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

transverse fragmentation function

$$\Delta_T D = D_{q^\uparrow}^{\Lambda^\uparrow} - D_{q^\uparrow}^{\Lambda^\downarrow}$$

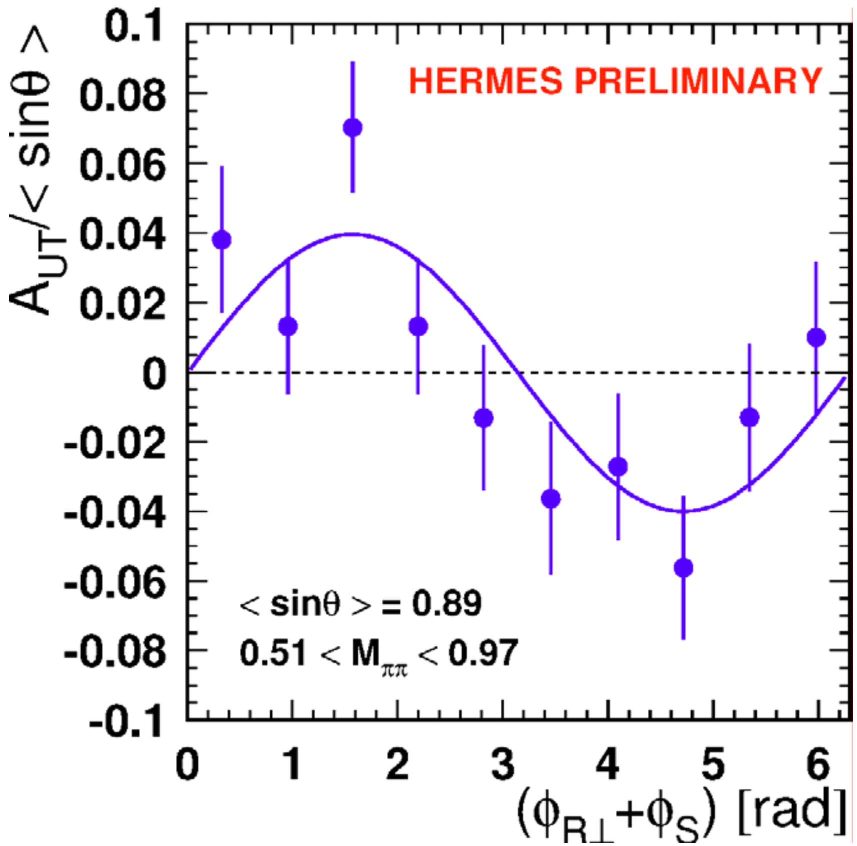


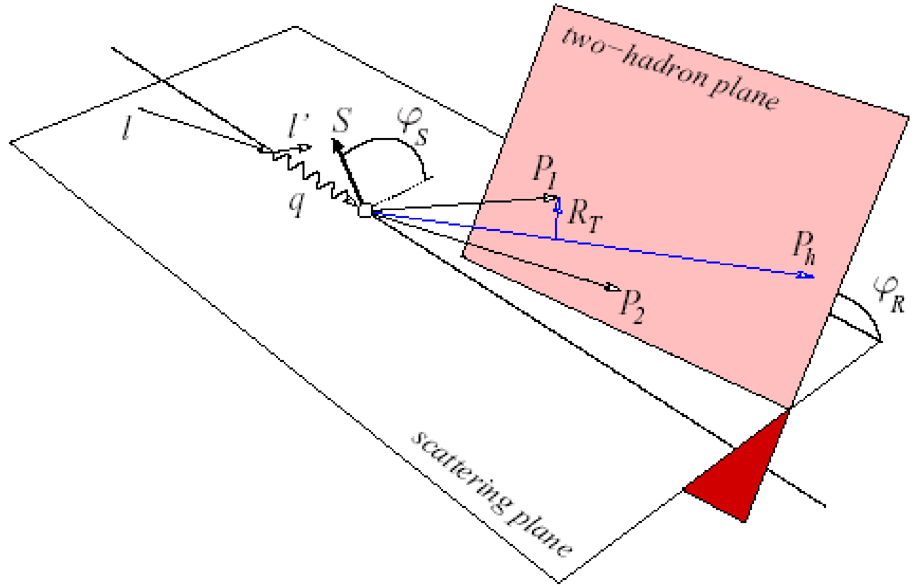
COMPASS analysis in progress

Two pion production: $l\ p^{\uparrow} \rightarrow \pi\ \pi\ X$

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

interference
fragmentation function





$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S)\, h_1\, \delta q_I$$

$$\delta q_I = H_1^{\sphericalangle}$$

Vector meson production: $l\, p^{\uparrow} \to \rho\, X$

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

(generalized fragmentation function)

Inclusive hadronic production: $p^{\uparrow}\, p \to \pi\, X$

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

Single Spin Asymmetry in D-Y processes

(Boer-Mulders distribution)

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

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

Single and no Spin Asymmetry in D-Y processes

$$d\sigma^{unp} \propto 1 + \cos^2\vartheta + \kappa \sin^2\vartheta \cos(2\varphi)$$

$$\kappa \propto h_1^{\perp}(x_1, k_{1\perp}) \otimes h_1^{\perp}(x_2, k_{2\perp})$$

Boer-Mulders functions

extract these unknown chiral-odd functions from unpolarized cross-section

$$A_N \propto \rho \sin^2\vartheta \sin(\varphi + \varphi_S)$$

$$\rho \propto h_1(x_1, k_{1\perp}) \otimes h_1^{\perp}(x_2, k_{2\perp})$$

combine above measurement with measurement of A_N to obtain information on h_1

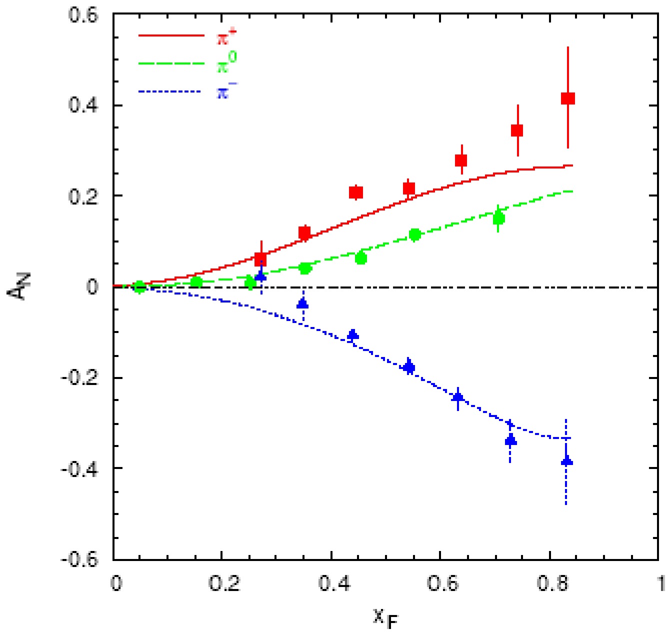
$\cos(2\varphi)$ asymmetry has been observed to be large in π N Drell-Yan processes

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

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

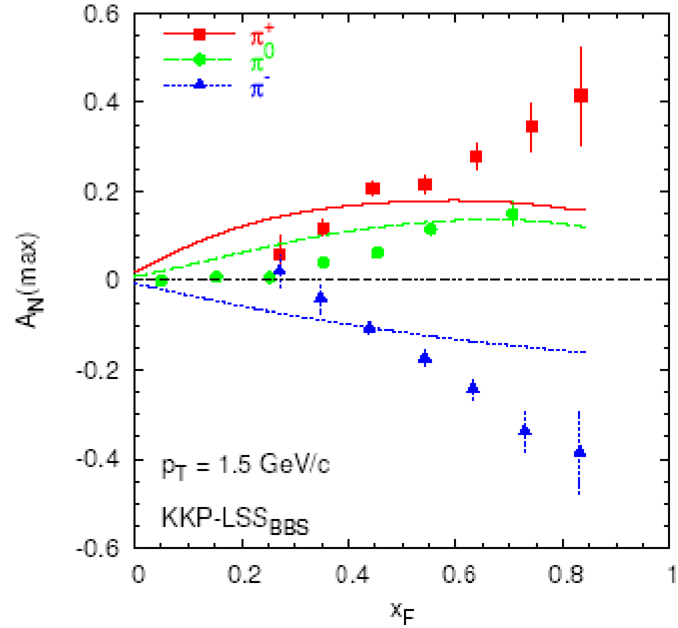
$$+ \; h_{1a} \otimes f_{b/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{\pi/c^{\uparrow}}$$ "Collins effect"

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

Conclusions

- plenty of intriguing spin data, many ongoing and planned experiments with polarized particles
- real challenge for any theory
- QCD spin dynamics is simple, hadron spin dynamics is not
- non perturbative nucleon structure must involve spin and transverse motion of partons
- phenomenology of SSA: extraction of spin-$k_\perp$ correlations and predictions
- the longitudinal spin is not the whole story; transverse spin adds new independent information
- parity non conserving processes (charged current DIS and W production in pp reactions) give access to new information on polarized quark distributions
- ......