

International Workshop on Structure and Spectroscopy

19-21 March 2007

University Freiburg

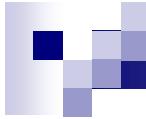
Nucleon Spin Structure with Hadronic Collisions at COMPASS

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In collaboration with:

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- F. Conti (Univ. Pavia)



Examples of unexplained asymmetry data

Single Spin Asymmetry (SSA)

SSA data 

$$\left. \begin{array}{l} h_1 \ h_2 \rightarrow H^\uparrow X \\ h_1 H^\uparrow \rightarrow h_2 X \end{array} \right\} \text{SSA} = \frac{d\sigma(H^\uparrow) - d\sigma(H^\downarrow)}{d\sigma(H^\uparrow) + d\sigma(H^\downarrow)}$$

Single Spin Asymmetry in Drell-Yan ?

Azimuthal Asymmetry in Drell-Yan

Drell-Yan 

Examples of large SSA

$$pp \rightarrow \Lambda^\uparrow X$$

$$s = (82)^2 \text{ GeV}^2$$

$$1 \leq p_T \leq 4 \text{ GeV}/c$$

Ex.: Heller *et al.*, P.R.L. **41** ('78) 607
but also other data for p-Be at higher s

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

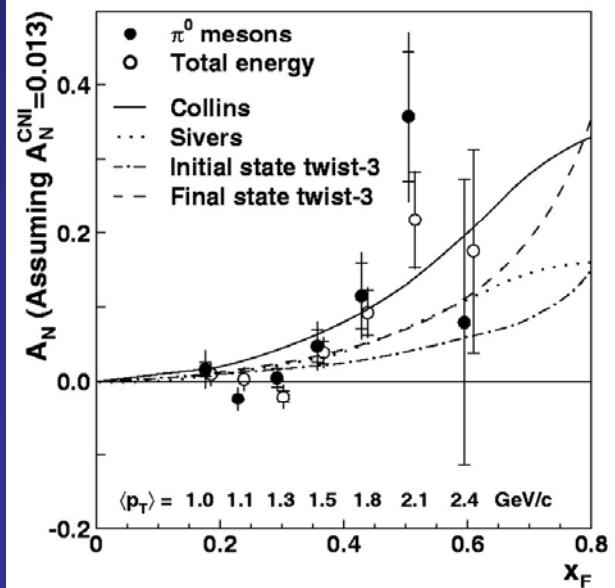
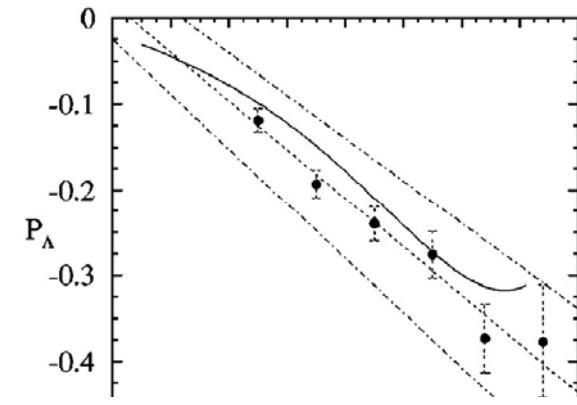
$$s = (200)^2 \text{ GeV}^2$$

$$3.4 < \eta < 4 \quad p_T > 1 \text{ GeV}/c$$

$$30 < E_\pi < 55 \text{ GeV}$$

Adams *et al.* (STAR), P.R.L. **92** ('04) 171801

$A_N \sim 20\%-40\%$ as for $s < (20)^2 \text{ GeV}^2$ experiments!



Chiral oddness of SSA

helicity basis $|\pm\rangle$ transverse basis

$$\begin{cases} |\uparrow\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle) \\ |\downarrow\rangle = \frac{i}{\sqrt{2}}(|+\rangle - |-\rangle) \end{cases}$$

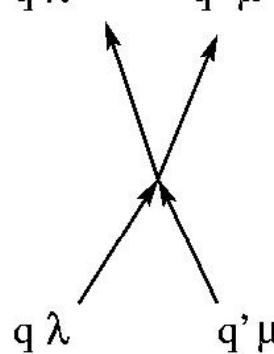
$$SSA \sim \langle \uparrow | \dots | \uparrow \rangle - \langle \downarrow | \dots | \downarrow \rangle = \langle + | \dots | - \rangle + \langle - | \dots | + \rangle \quad \text{helicity flip}$$

QCD : massless coll. partons + collinear fact. th.

$$d\sigma = \sum_{abc} \text{PDF}(x_a, Q^2) \otimes \text{PDF}(x_b, Q^2) \otimes d\hat{\sigma} \otimes \text{PFF}(z_c, Q^2)$$

several contributions to $d\hat{\sigma}$

Ex.: $q \lambda' \quad q' \mu'$



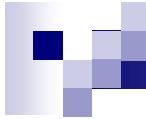
6 independent $M_{\lambda \mu}^{\lambda' \mu'}$

$$\begin{array}{lll} M_{++}^{++} = M_1 & M_{++}^{--} = M_2 & M_{+-}^{+-} = M_3 \\ M_{+-}^{-+} = M_4 & M_{++}^{-+} = M_5 & M_{+-}^{++} = M_6 \end{array}$$

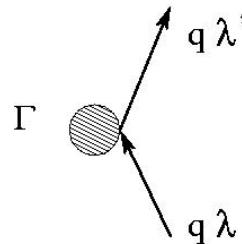
$$SSA = \frac{d\sigma(q^\uparrow) - d\sigma(q^\downarrow)}{d\sigma(q^\uparrow) + d\sigma(q^\downarrow)}$$

interference of amplitudes

$$\text{quark-quark elastic scattering} \propto \text{Im} [M_6(M_1 + M_3)^* - M_5(M_2 - M_4)^*]$$



Collinear massless quark spinors $\lambda = \pm 1$



$$\begin{aligned} M &\sim \bar{u}_{\lambda'} \Gamma u_{\lambda} \\ &\sim \bar{u}_{\lambda'} (1 - \lambda' \gamma_5) (1 - \lambda \gamma_5) \Gamma u_{\lambda} \\ &\sim \delta_{\lambda \lambda'} \bar{u}_{\lambda'} \Gamma u_{\lambda} + \text{order} \left(\frac{m_q}{E_q} \right) \end{aligned}$$

$$\frac{1 + \lambda \gamma_5}{2} u_{\lambda} = u_{\lambda}$$

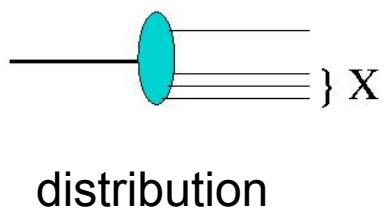
$$\bar{u}_{\lambda} \frac{1 - \lambda \gamma_5}{2} = \bar{u}_{\lambda}$$

pQCD: helicity flip suppressed
+ interfer. suppressed as loops } \Rightarrow SSA suppressed !

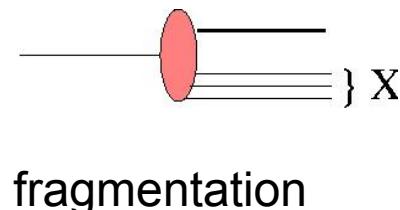
[Kane et al., P.R.L. 41 (78) 1689]

Moreover $d\sigma = \sum_{abc} \text{PDF}(x_a, Q^2) \otimes \text{PDF}(x_b, Q^2) \otimes d\hat{\sigma} \otimes \text{PFF}(z_c, Q^2)$

collinear partons



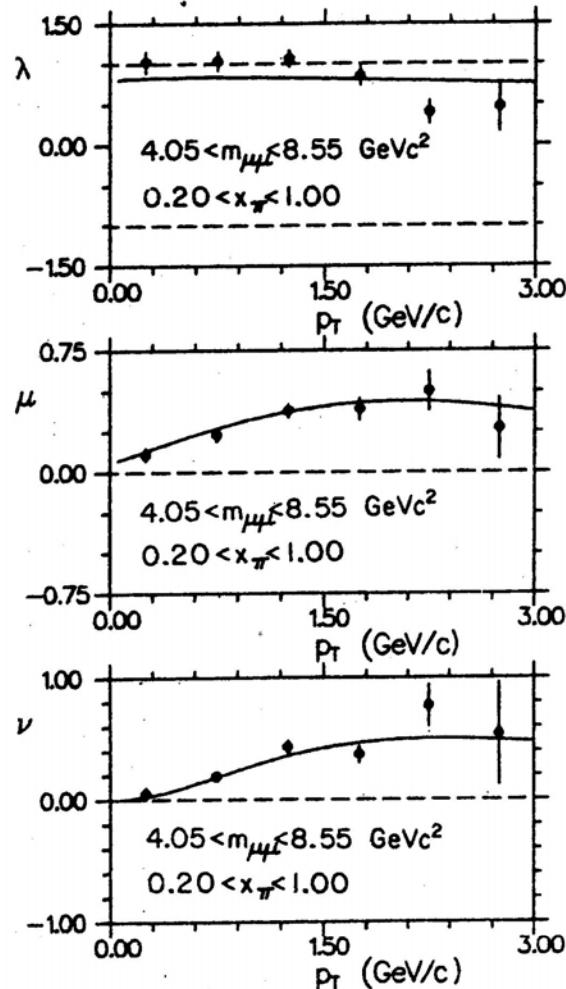
distribution



fragmentation

rotational invariance \rightarrow SSA ~ 0 !

NLO, higher twist, etc.. do not explain data ! Need **intrinsic parton p_T** ?



$$\pi^- A \rightarrow \mu^+ \mu^- X \quad A = d, W$$

Ex.: Conway *et al.* (E615), P.R. D39 ('89) 92
 fixed target with $E_\pi = 252 \text{ GeV}$
 (see also

NA10, Z. Phys. C31 ('86) 513 ; C37 ('88) 545
 with $140 \leq E_\pi \leq 286 \text{ GeV}$)

pQCD: massless collinear partons

\Rightarrow no ϕ dependence

$\Rightarrow \lambda \sim 1$ μ , $\nu \sim 0$

Lam-Tung sum rule (P.R. D21 (80) 2712)

$$1 - \lambda - 2\nu = 0$$

exp. $\Rightarrow \lambda \sim 1$ $\nu \sim 0.3$
 sum rule violated !

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left[1 + \lambda \cos^2 \theta + \mu \sin^2 \theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right] + o(\alpha_s)$$

on Structure &
 scopy

- observed **large SSA** in hadronic collisions with transverse polarization
⇒ **mix parton helicity** (=chirality at twist 2) and require ampl. interference
- but QCD with collinear massless partons preserves helicity and
interference is suppressed by loop contributions

↓

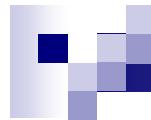
need **chiral-odd** nonperturbative mechanisms

- observed also **large azimuthal asymmetries** in unpolarized Drell-Yan
- QCD with collinear partons generates only radiative (=DGLAP) p_T parton distributions and small asymmetries
- need **intrinsic** (=non DGLAP) p_T parton distribution
- interaction between transverse polarization and **orbital motion** of partons

↓

need **(naïve) T-odd** nonperturbative mechanisms

$\left[\begin{array}{l} \text{SSA} = 0 \text{ for } p\bar{p} \rightarrow \pi X \text{ for years} \\ \text{because of T reversal invariance!} \end{array} \right]$



Drell-Yan kinematics

c.m. energy $s = (P_1 + P_2)^2$

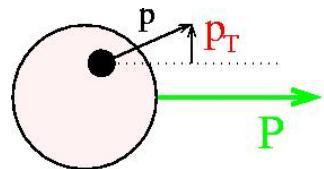
invariant mass $Q^2 \equiv M^2 = (l^+ + l^-)^2$

DIS regime $M^2, s \rightarrow \infty$
 $0 \leq \tau = \frac{M^2}{s} \leq 1$

factorization theorem

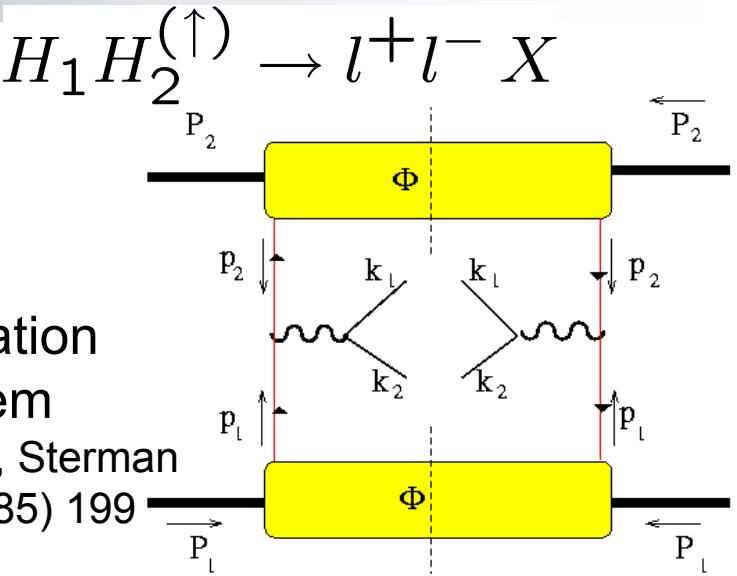
Collins, Soper, Sterman
 N.P. **B250** (85) 199

$$M^2 \rightarrow \infty \left\{ \begin{array}{l} P_1 \sim (0, P_1^+, 0_T) \quad x_1 = \frac{p_1^+}{P_1^+}, p_{1T} \\ P_2 \sim (P_2^-, 0, 0_T) \quad x_2 = \frac{p_2^-}{P_2^-}, p_{2T} \end{array} \right. \quad q_T = p_{1T} + p_{2T}$$

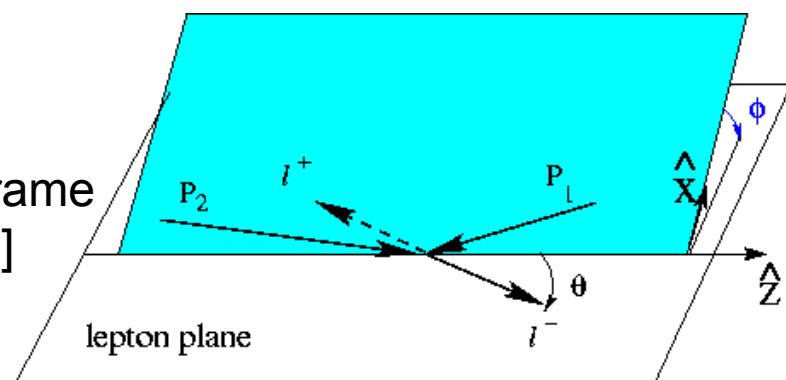


T momenta in $\hat{x}\hat{z}$ plane

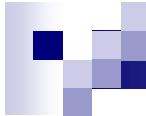
Collins-Soper frame
 [P.R. **D16** (77) 2219]



dominant contribution
 if $M \neq$ resonances



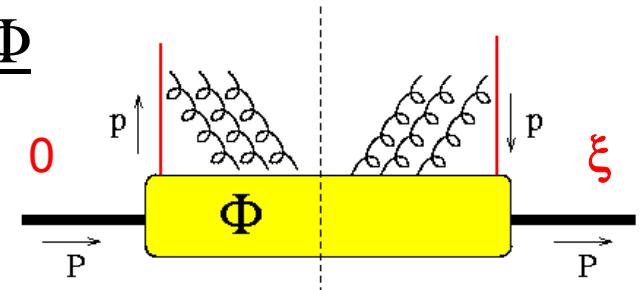
$$d\sigma \propto \overline{\sum_{S_1}} \text{Tr} [\bar{\Phi}(x_1; p_{1T}, S_1) \gamma^\mu \otimes \Phi(x_2; p_{2T}, S_2) \gamma^\nu] + \begin{pmatrix} q & \leftrightarrow & -q \\ \mu & \leftrightarrow & \nu \end{pmatrix}$$



parton-parton correlator Φ

$$S \equiv S_T = (0, 0, \mathbf{S}_T)$$

$$p \approx (0, xP^+, \mathbf{p}_T) \Rightarrow \xi = (\xi^-, 0, \xi_T)$$



$$\Phi(x, \mathbf{p}_T, S) = \int \frac{d^4 \xi}{(2\pi)^3} e^{-ip \cdot \xi} \langle P, S | \bar{\psi}(\xi) \underbrace{U_{[0,\xi]} \psi(0)}_{\text{gauge link}} | P, S \rangle$$

- decomposition of $\Phi(x, \mathbf{p}_T, S)$ upon $(\mathbb{1}, \gamma^\mu, \gamma_5, \gamma^\mu \gamma_5, \sigma^{\mu\nu}, \sigma^{\mu\nu} \gamma_5) \otimes (p^\mu, P^\mu, S^\mu)$
- hermiticity $\gamma^0 \Phi^\dagger(x, \mathbf{p}_T, S) \gamma^0 = \Phi(x, \mathbf{p}_T, S)$
- parity invariance $\gamma^0 \Phi(x, \tilde{\mathbf{p}}_T, \tilde{S}) \gamma^0 = \Phi(x, \mathbf{p}_T, S)$ $\tilde{a} = (a^0, -\mathbf{a})$
- ~~time-reversal~~ “ $(i\gamma^2 \Phi^\dagger(x, \tilde{\mathbf{p}}_T, \tilde{S}) i\gamma^2)^* = \Phi(x, \mathbf{p}_T, S)$ ”
project out only the leading-twist content of Φ
 \Rightarrow number density interpretation of parton distributions
how does Φ look like?

correlator Φ at leading twist including transverse momentum & polarization

$$\Phi(x, \mathbf{p}_T, S_T) = \frac{1}{2P^+} \left\{ f_1(x, \mathbf{p}_T) \not{P} + \int d\mathbf{p}_T - h_1(x, \mathbf{p}_T) i\sigma_{\mu\nu} S_T^\mu P^\nu \gamma_5 \right\}$$

number density of q^\uparrow in p^\uparrow

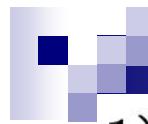
$$f_{q^\uparrow/p^\uparrow} = \frac{1}{2} \left(\Phi^{[\not{h}_-/2]} + \Phi^{[i\sigma_{\mu\nu} n_-^\mu s^\nu \gamma_5/2]} \right)$$

$$= \frac{1}{4} \left\{ f_1 - f_{1T}^\perp \frac{\hat{\mathbf{P}} \times \mathbf{p}_T \cdot \mathbf{S}_T}{M} - h_1^\perp \frac{\hat{\mathbf{P}} \times \mathbf{p}_T \cdot \mathbf{s}}{M} + h_1 \mathbf{S}_T \cdot \mathbf{s} + h_{1T}^\perp \left(\frac{\mathbf{p}_T \cdot \mathbf{S}_T}{M} \frac{\mathbf{p}_T \cdot \mathbf{s}}{M} - \frac{\mathbf{p}_T^2}{M^2} \mathbf{S}_T \cdot \mathbf{s} \right) \right\}$$

4 possible cases: $f_{q^\uparrow/p^\uparrow}$ $f_{q^\downarrow/p^\uparrow}$ $f_{q^\uparrow/p^\downarrow}$ $f_{q^\downarrow/p^\downarrow}$

def. : $\Phi^{[A]} \equiv \frac{1}{2} \text{Tr} [\Phi A]$
 $n_- = (1, 0, \mathbf{0}_T)$

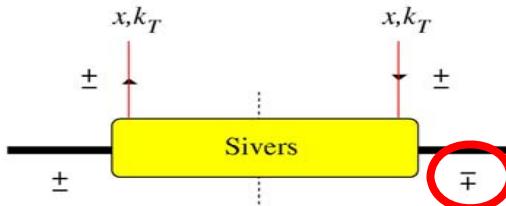
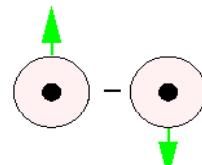
following Trento Conventions
[Bacchetta *et al.*, P.R. D70 (04) 117504]



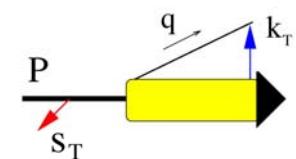
$$1) f_{q/p} = (f_{q^\uparrow/p^\uparrow} + f_{q^\downarrow/p^\uparrow}) + (f_{q^\uparrow/p^\downarrow} + f_{q^\downarrow/p^\downarrow}) \equiv f_1^q(x, \mathbf{p}_T)$$

$$f_1 = \text{circle with dot}$$

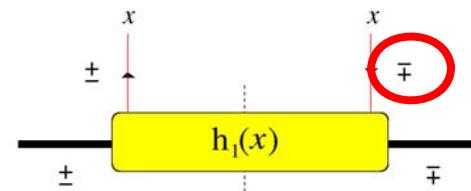
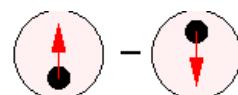
$$2) f_{q/p^\uparrow} - f_{q/p^\downarrow} = (f_{q^\uparrow/p^\uparrow} + f_{q^\downarrow/p^\uparrow}) - (f_{q^\uparrow/p^\downarrow} + f_{q^\downarrow/p^\downarrow}) \equiv -f_{1T}^{\perp q} \frac{\hat{\mathbf{P}} \times \mathbf{p}_T \cdot \mathbf{S}_T}{M}$$



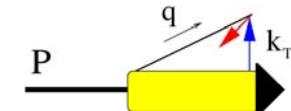
Sivers



$$3) f_{q^\uparrow/p} - f_{q^\downarrow/p} = (f_{q^\uparrow/p^\uparrow} + f_{q^\uparrow/p^\downarrow}) - (f_{q^\downarrow/p^\uparrow} + f_{q^\downarrow/p^\downarrow}) \equiv -h_{1T}^{\perp q} \frac{\hat{\mathbf{P}} \times \mathbf{p}_T \cdot \mathbf{s}}{M}$$



Boer-Mulders



$$4) " \delta f_{q^\uparrow/p^\uparrow} " = (f_{q^\uparrow/p^\uparrow} - f_{q^\uparrow/p^\downarrow}) - (f_{q^\downarrow/p^\uparrow} - f_{q^\downarrow/p^\downarrow}) \equiv h_1^q \mathbf{S}_T \cdot \mathbf{s}$$

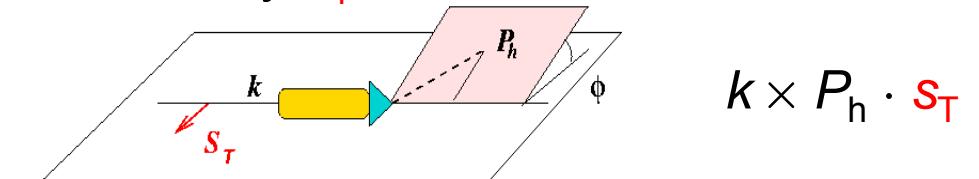
$$h_1 = \text{circle with dot} - \text{circle with dot}$$

$$h_{1T}^{\perp} = \text{circle with dot and up arrow} - \text{circle with dot and down arrow}$$

$$+ h_{1T}^{\perp q} \left(\frac{\mathbf{p}_T \cdot \mathbf{S}_T \mathbf{p}_T \cdot \mathbf{s}}{M^2} - \frac{\mathbf{p}_T^2}{M^2} \mathbf{S}_T \cdot \mathbf{s} \right)$$

transversity

transversity h_1 from Collins effect in SIDIS

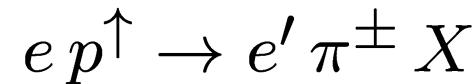
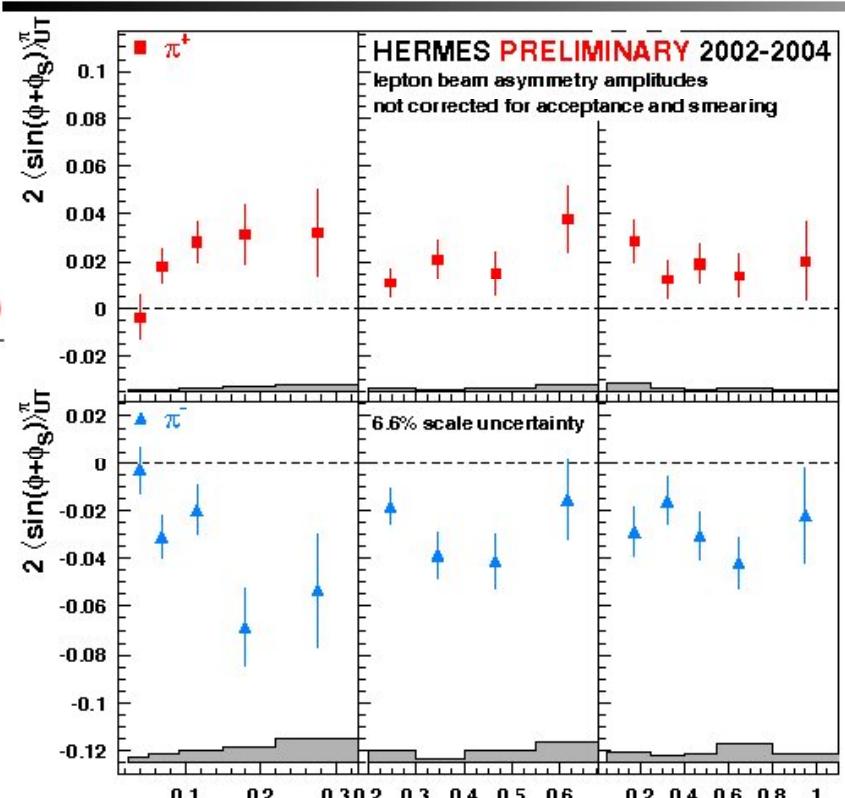
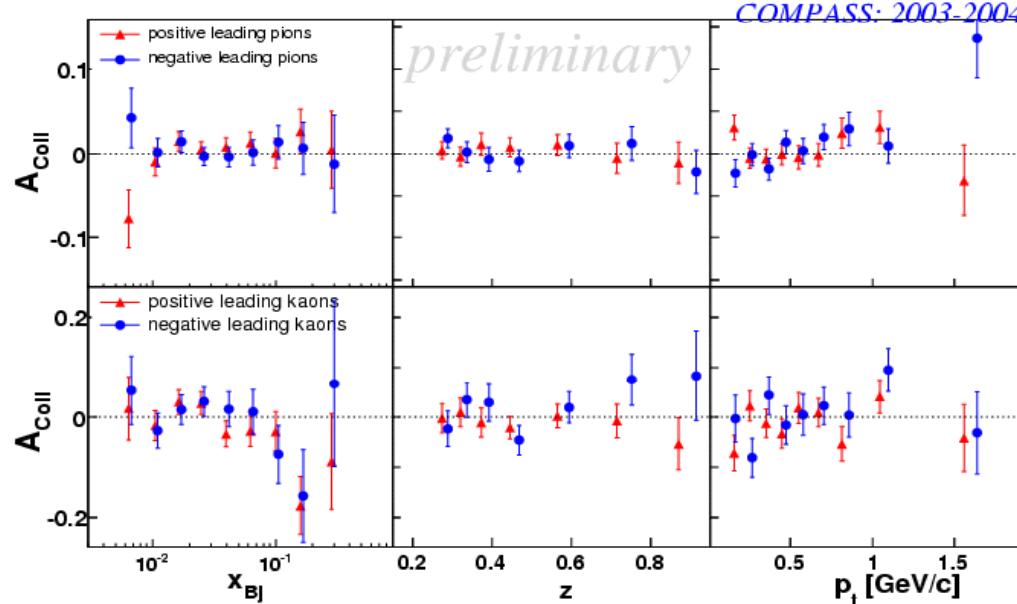


$$\frac{\langle |\mathbf{P}_{hT}| \sin(\phi + \phi_S) (d\sigma^\uparrow - d\sigma^\downarrow) \rangle}{\langle d\sigma^\uparrow + d\sigma^\downarrow \rangle} \propto \frac{\sum_{q\bar{q}} e_q^2 z h_1^q(x) H_1^{\perp q(1)}(z)}{\sum_{q\bar{q}} e_q^2 f_1^q(x) D_1^q(z)}$$

combine SIDIS and $e^+e^- \rightarrow$ parametrization of h_1

[Efremov *et al.*, P.R. D73 (06) 094025
Anselmino *et al.*, hep-ph/0701006]

Prokudin talk



Airapetian *et al.* (HERMES)
[P.R.L. 94 ('05) 012002]

μ on ${}^6\text{LiD}$

Magnon for COMPASS @ SPIN2006

Martin talk

list



Sivers funct. f_{1T}^{\perp} from Sivers effect in SIDIS

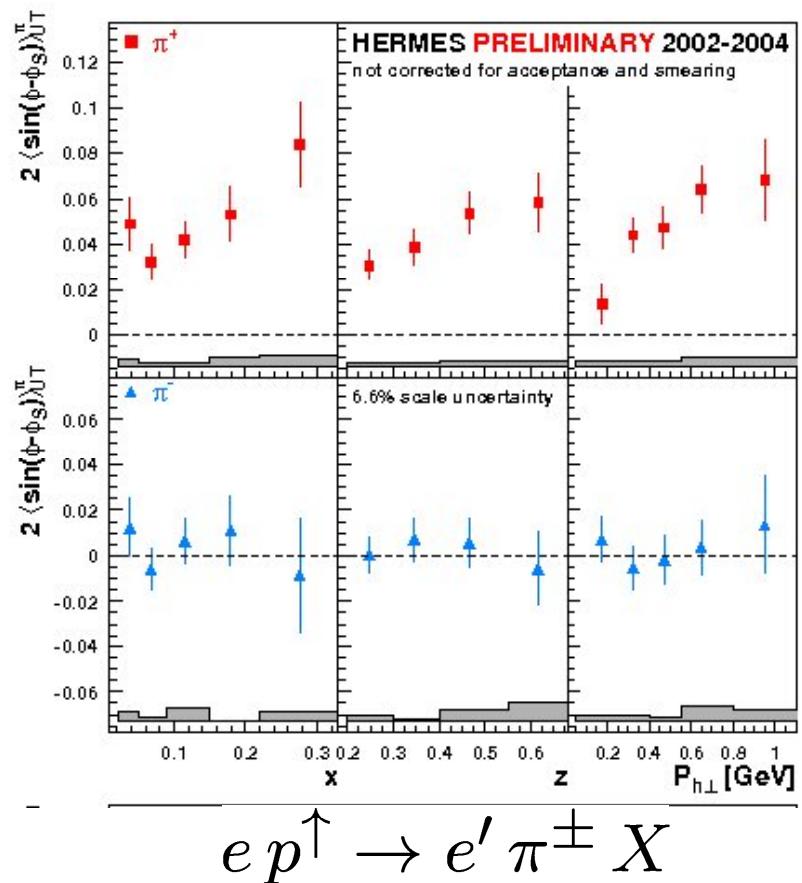
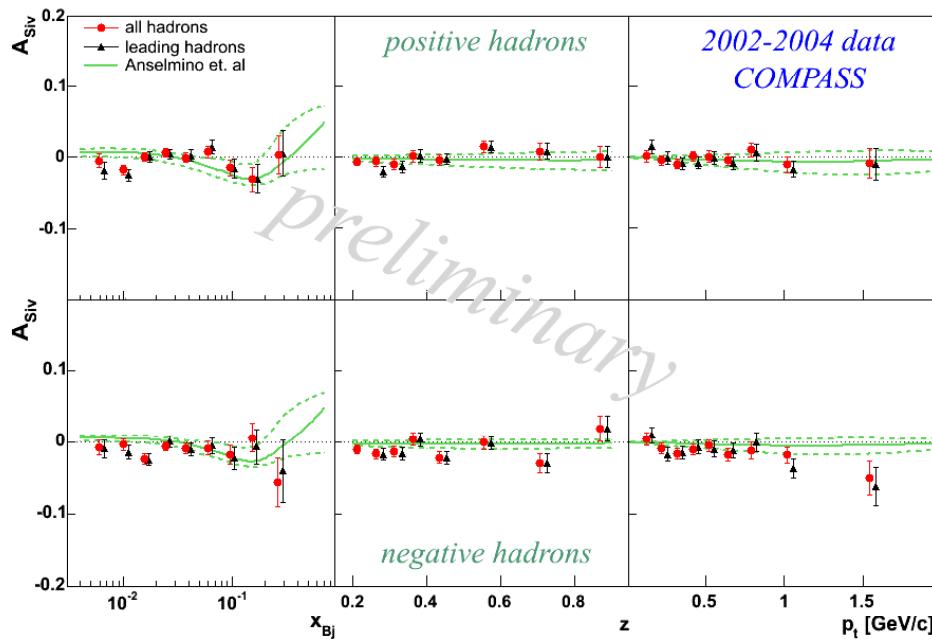
$$\frac{\langle |P_{h\perp}| \sin(\phi - \phi_S) (d\sigma^\uparrow - d\sigma^\downarrow) \rangle}{\langle d\sigma^\uparrow + d\sigma^\downarrow \rangle} \propto -\frac{\sum_{q\bar{q}} e_q^2 f_{1T}^{\perp q(1)}(x) D_1^q(z)}{\sum_{q\bar{q}} e_q^2 f_1^q(x) D_1^q(z)}$$

$S_T \neq 0 \rightarrow L_q \neq 0 \rightarrow$ asymmetric distribution of q
in transverse plane

[Burkardt, Phys. Rev. D66('02) 114005]

parametrizations: Anselmino et al., P.R. D72 (05) 094007

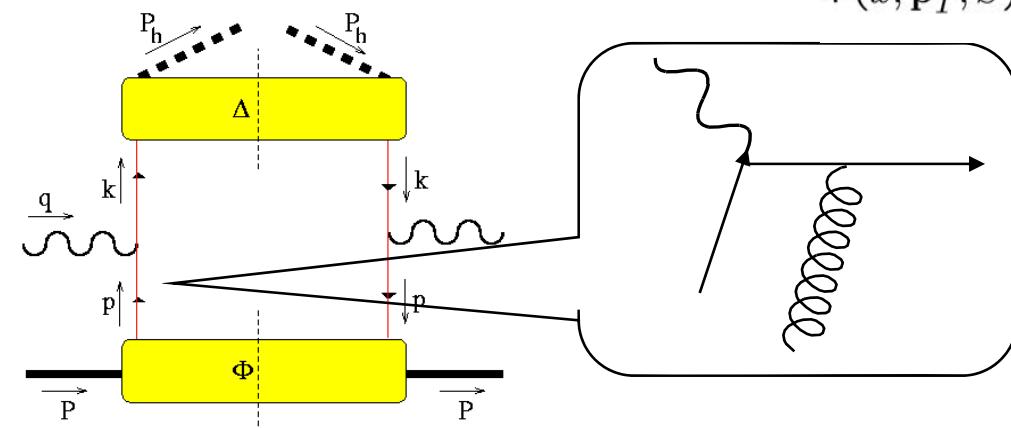
Prokudin talk



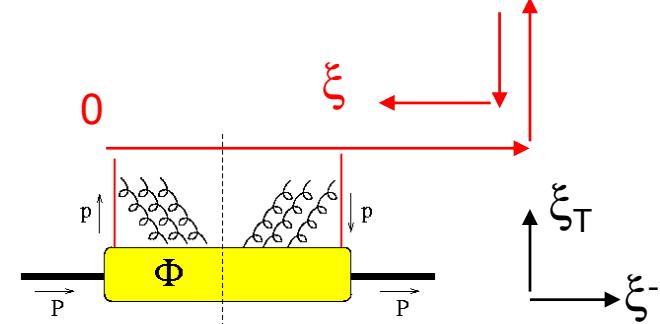
Airapetian et al. (HERMES)
[P.R.L. 94 ('05) 012002]

μ on ${}^6\text{LiD}$
Magnon for COMPASS @ SPIN2006
Martin talk

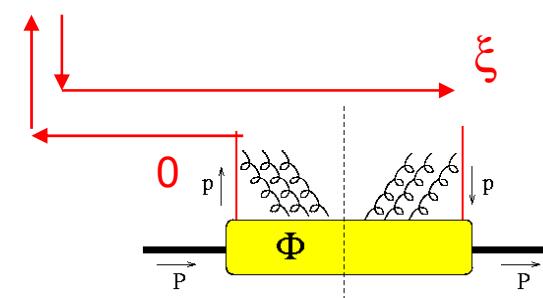
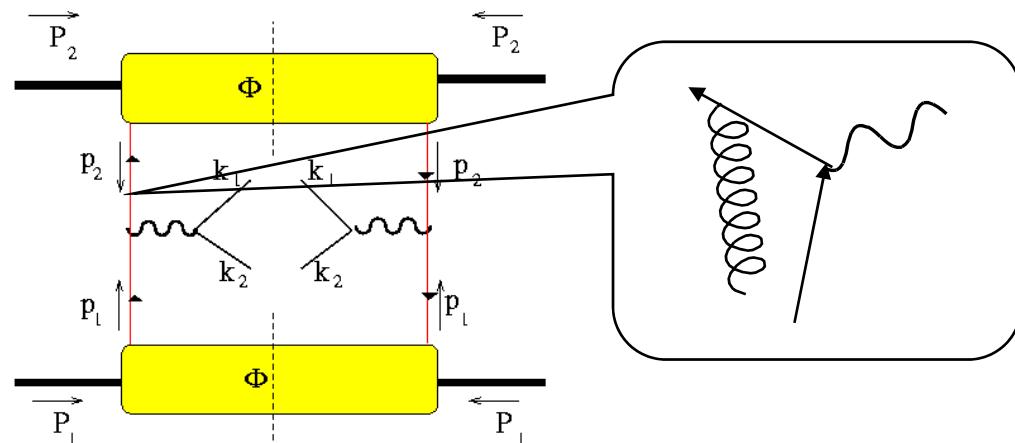
“universality” theorem for Sivers function



$$\Phi(x, p_T, S) = \int \frac{d^4\xi}{(2\pi)^3} e^{-ip\cdot\xi} \langle P, S | \bar{\psi}(\xi) U_{[0,\xi]} \psi(0) | P, S \rangle$$



future pointing gauge link

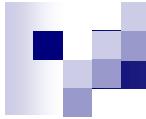


past pointing gauge link

list

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

Collins
P.L. B536 (02) 43



Drell-Yan cross section at leading twist

Boer, P.R. D**60** ('99) 014012
Tangermann & Mulders, P.R. D**51** ('95) 3357

$$\frac{d\sigma}{dx_1 dx_2 d\Omega d\mathbf{q}_T} = d\sigma^o + |\mathbf{S}_{2T}| d\Delta\sigma^\uparrow$$

$1-\lambda \neq 2v$ is hadronic effect?
Or as QCD vacuum pol.?

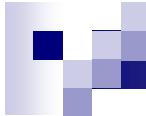
[Brandenburg *et al.*,
Z.P. C**60** (93) 697]

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda+3} \left[1 + \lambda \cos^2 \theta + \mu \sin^2 \theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right] + o(\alpha_s)$$

$$\begin{aligned} \propto \sum_q e_q^2 & \left\{ (1 + \cos^2 \theta) \mathcal{F} [\bar{f}_1^q f_1^q] + \sin^2 \theta \cos 2\phi \mathcal{F} [A(\mathbf{p}_{1T}, \mathbf{p}_{2T}) \bar{h}_1^{\perp q} h_1^{\perp q}] \right. \\ & + |\mathbf{S}_{2T}| (1 + \cos^2 \theta) \sin(\phi - \phi_{S2}) \mathcal{F} [\hat{\mathbf{h}} \cdot \mathbf{p}_{2T} \bar{f}_1^q f_{1T}^{\perp q}] \\ & \left. - |\mathbf{S}_{2T}| \sin^2 \theta \sin(\phi + \phi_{S2}) \mathcal{F} [\hat{\mathbf{h}} \cdot \mathbf{p}_{1T} \bar{h}_1^{\perp q} h_1^q] \dots \right\} \end{aligned}$$

$$\mathcal{F} [\bar{f}_1 f_1] = \int d\mathbf{p}_{1T} d\mathbf{p}_{2T} \delta(\mathbf{p}_{1T} + \mathbf{p}_{2T} - \mathbf{q}_T) [\bar{f}_1(x_1, \mathbf{p}_{1T}) f_1(x_2, \mathbf{p}_{2T}) + 1 \leftrightarrow 2] \quad \hat{\mathbf{h}} = \frac{\mathbf{q}_T}{|\mathbf{q}_T|}$$

$$d\sigma = \mathcal{F} [\bar{f}_1 f_1] \{1 + \dots\}$$



Monte-Carlo simulation

assume q_T dependence \rightarrow break convolution \mathcal{F}

$$\frac{d\sigma}{d\Omega dx_1 dx_2 dq_T} = K \frac{1}{s} \left[A(q_T, x_1 - x_2, M) F(x_1, x_2) \right] \left[1 + \sum_{i=1}^4 c_i(q_T, x_1, x_2) S_i(\theta, \phi, \phi_{S2}) \right]$$

$\propto d\sigma^o$ event distribution

LLA QCD corrections
 $\rightarrow f_1(x, \log Q^2)$

NLLA corrections (compensate in SSA?
see Kawamura *et al.*, hep-ph/0703079 NLL+LO
JPARC kin.: $s=100 \text{ GeV}^2$, $Q=2 \text{ GeV}$, $y=0$)

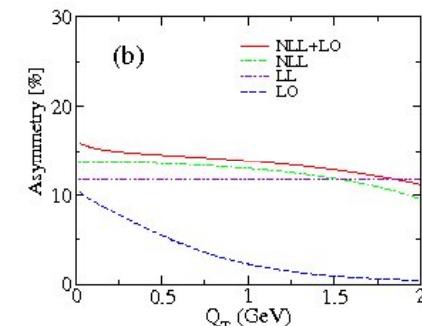
$$c_1 S_1 = \cos^2 \theta$$

$$c_2 S_2 = A_{UU}^{\cos 2\phi} = \frac{\sum_q e_q^2 \mathcal{F} [C_2(p_{1T}, p_{2T}) \bar{h}_1^{\perp q} h_1^{\perp q}]}{\sum_q e_q^2 \mathcal{F} [\bar{f}_1^q f_1^q]} \sin^2 \theta \cos 2\phi$$

$$c_3 S_3 = A_T^{\sin(\phi + \phi_S)} = -|\mathbf{S}_{2T}| \frac{\sum_q e_q^2 \mathcal{F} [\hat{\mathbf{h}} \cdot \mathbf{p}_{1T} \bar{h}_1^{\perp q} h_1^q]}{\sum_q e_q^2 \mathcal{F} [\bar{f}_1^q f_1^q]} \sin^2 \theta \sin(\phi + \phi_{2S})$$

$$c_4 S_4 = A_T^{\sin(\phi - \phi_S)} = |\mathbf{S}_{2T}| \frac{\sum_q e_q^2 \mathcal{F} [\hat{\mathbf{h}} \cdot \mathbf{p}_{2T} \bar{f}_1^q f_1^{\perp q}]}{\sum_q e_q^2 \mathcal{F} [\bar{f}_1^q f_1^q]} (1 + \cos^2 \theta) \sin(\phi - \phi_{2S})$$

[Conway *et al.* (E615),
P.R. D39 (89) 92 for π -A
Anassontzis *et al.* (E537),
P.R. D38 (88) 1377 for \bar{p} -A]



Generate the asymmetry

1. select the SSA $\rightarrow c_i S_i$ $i=2-4$ and model/parametrize it
2. generate events in $q_T, \theta, \phi, x_1, x_2$ at fixed ϕ_{S2} using $A F \sim d\sigma^0$
3. sum upon q_T, θ, x_1 (and also ϕ_{S2} for $i=2$) for some ϕ
4. for each x_2 accumulate events with

$$\left. \begin{array}{ll} F[\phi, \phi_{S2}] > 0 & \leftrightarrow U \\ F[\phi, \phi_{S2}] < 0 & \leftrightarrow D \end{array} \right\} \text{SSA}(x_2) = (U-D) / (U+D)$$

5. for each case, repeat simulation independently for 5-10 times
6. build mean value and variance of SSA for each x_2
7. only statistic errors

Monte Carlo kinematics and cuts

π (anti-p ?) beam on (polarized) NH₃

$E_\pi = 50 - 200$ GeV

$s \sim 2 M_p E_\pi = 100 - 400$ GeV²

$Q \equiv M$ range explored:

(J/ ψ & ψ') $4 \leq M \leq 9$ (Y) GeV

← avoid
resonances
& higher twists
 $\sim M_p / M$

$$q\bar{q} \rightarrow \gamma^*$$

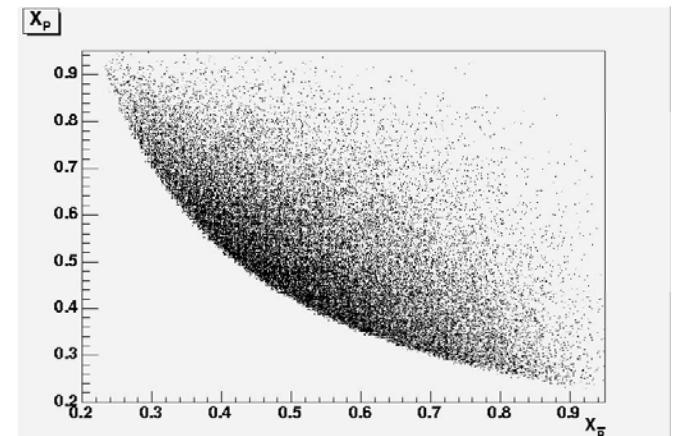
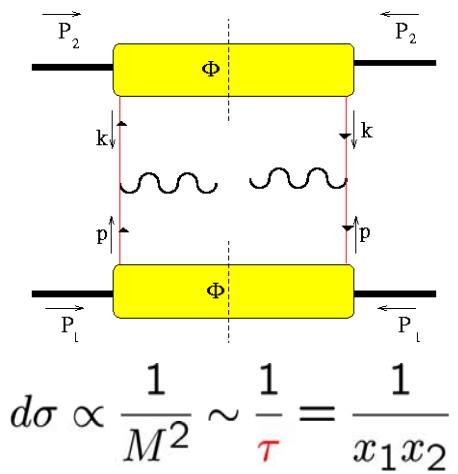
$$\tau = \frac{M^2}{s}$$

τ in “valence” region: $0.1 \leq x_{1/2} \leq 0.5$

Moreover:

$0.5 - 1 \leq q_T \leq 3$ GeV/c (loose 50% of data!)

$60^\circ \leq \theta \leq 120^\circ$ (only for $\sin^2\theta$ distributions)



target dilution factor:

(π -NH₃) collision $\sim 14/17$ (π -N) + $3/17$ (π -H $^\uparrow$) \rightarrow only 20% of polarized events!

Bianconi & Radici, P.R. D71 (05) 074014

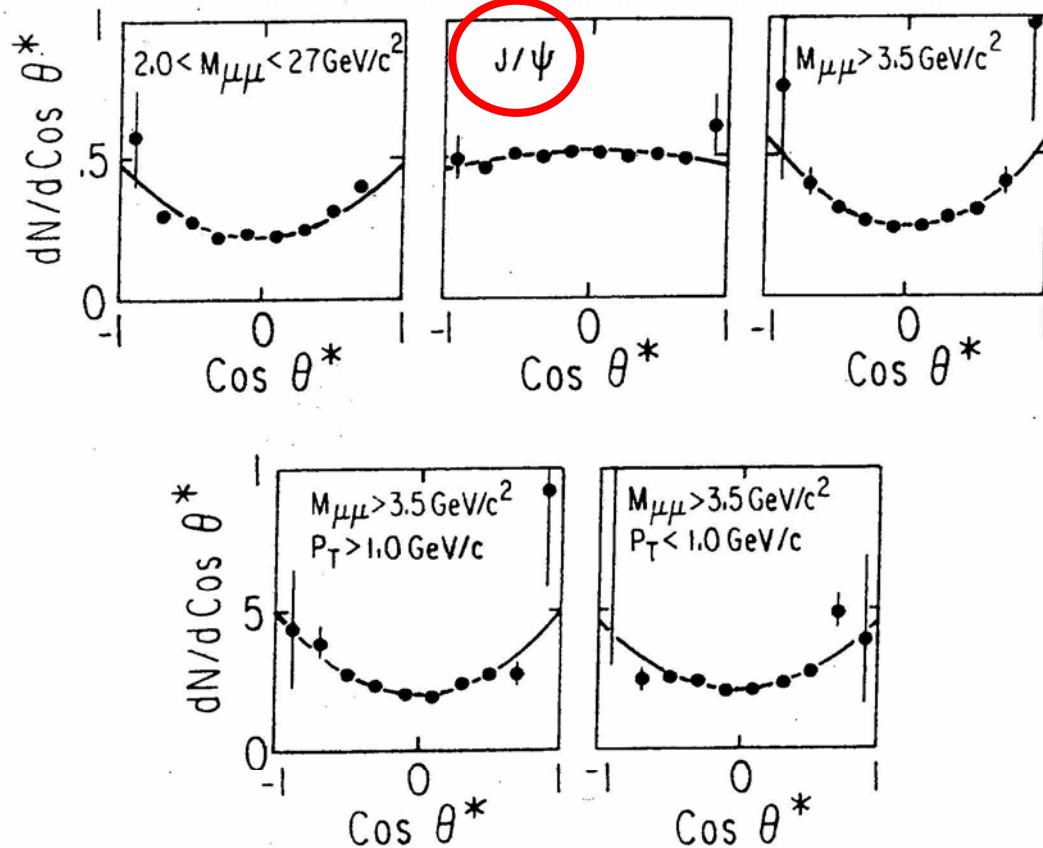
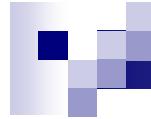


FIG. 3. Helicity angular distributions in three different mass intervals. The $M > 3.5 \text{ GeV}/c^2$ interval is also shown divided in two p_T intervals. The Collins-Soper angle (θ^*) is defined in the text.

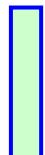
Hogan *et al.* (FNAL-E444)
Phys. Rev. Lett. **42** (79) 948

in Parton Model
angular distribution
 $\sim (1 + \cos^2 \theta)$
from elementary QED process
 $e^+e^- \rightarrow \mu^+\mu^-$
corresponds to
response function R_T
to transverse γ^*
does not work for J/ψ



SSA from the Sivers effect: param. #1

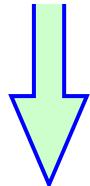
$$c_4 \text{ } S_4 = A_T^{\sin(\phi - \phi_S)} = |\mathbf{S}_{2T}| \frac{\sum_q e_q^2 \mathcal{F} [\hat{\mathbf{h}} \cdot \mathbf{p}_{2T} \bar{f}_1^q f_{1T}^{\perp q}]}{\sum_q e_q^2 \mathcal{F} [\bar{f}_1^q f_1^q]} (1 + \cos^2 \theta) \sin(\phi - \phi_{2S})$$



Anselmino et al.
P.R. D72 (05) 094007; D72 (05) 099903E

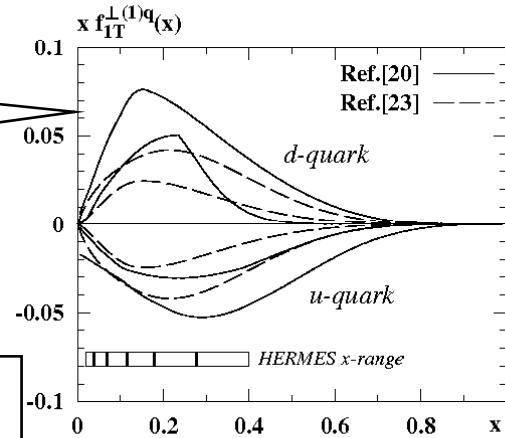
$$f_{1T}^{\perp q} = -N_q \frac{(\alpha_q + \beta_q)^{\alpha_q + \beta_q}}{\alpha_q^{\alpha_q} \beta_q^{\beta_q}} x^{\alpha_q} (1-x)^{\beta_q} \frac{2M_2 M_0}{\mathbf{p}_T^2 + M_0^2} f_1^q(x, \mathbf{p}_T)$$

$$f_1^q(x, \mathbf{p}_T) = \frac{1}{\pi \langle \mathbf{p}_T^2 \rangle} e^{-\mathbf{p}_T^2 / \langle \mathbf{p}_T^2 \rangle} f_1^q(x)$$



c_4

fit HERMES+COMPASS
SIDIS SSA data
 $\langle \mathbf{p}_T^2 \rangle = 0.25 \text{ (GeV/c)}^2$



$$c_4 \approx |\mathbf{S}_{2T}| \frac{4M_0 q_T}{q_T^2 + 4M_0^2} \sum_q e_q^2 N_q \frac{(\alpha_q + \beta_q)^{\alpha_q + \beta_q}}{\alpha_q^{\alpha_q} \beta_q^{\beta_q}} x_2^{\alpha_q} (1-x_2)^{\beta_q}$$

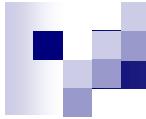
$$\int d\mathbf{q}_T d\cos\theta dx_1 A_T^{\sin(\phi - \phi_S)}$$

$$\begin{cases} \sin(\phi - \phi_S) > 0 \\ \sin(\phi - \phi_S) < 0 \end{cases}$$



results

N_u	0.32 ± 0.11	N_d	-1.0 ± 0.12
α_u	0.29 ± 0.35	α_d	1.16 ± 0.47
β_u	0.53 ± 3.58	β_d	3.77 ± 2.59
M_0^2	0.32 ± 0.25		



The flavor-average approximation

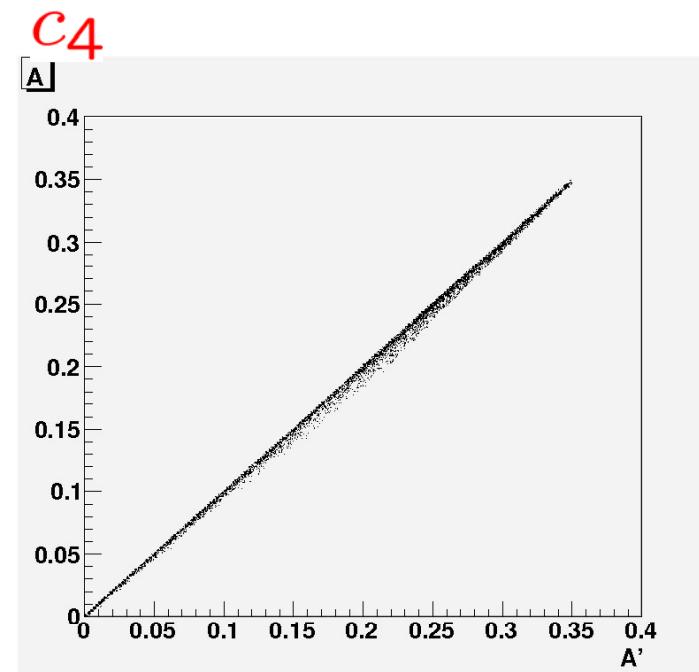
$$\begin{aligned} \textcolor{red}{c}_4 &= N(\mathbf{q}_T) \frac{e_u^2 \bar{u}(x_1) u_{Siv}(x_2) + e_d^2 \bar{d}(x_1) d_{Siv}(x_2)}{\left[e_u^2 \bar{u}(x_1) u(x_2) + e_d^2 \bar{d}(x_1) d(x_2) + e_s^2 \bar{s}(x_1) s(x_2) \right] + (1 \leftrightarrow 2)} \\ &\approx N(\mathbf{q}_T) \left[\textcolor{blue}{n}_u \frac{u_{Siv}(x_2)}{u(x_2)} + \textcolor{blue}{n}_d \frac{d_{Siv}^A(x_2)}{d(x_2)} \right] \equiv \bar{c}_4 \end{aligned}$$

$$N(\mathbf{q}_T) = |\mathbf{S}_{2T}| \frac{4M_0 q_T}{\mathbf{q}_T^2 + 4M_0^2}$$

neglect sea (anti)quarks + flavor average $\rightarrow \textcolor{blue}{n}_q$ statistical weight

consistent with
HERMES analysis
of Sivers effect

assume no strong
flavor dependence
of sea



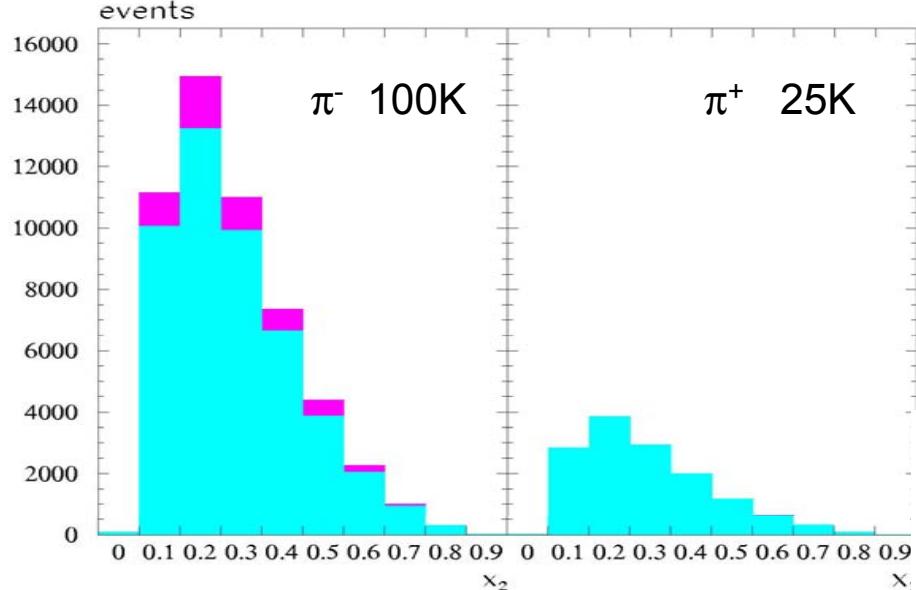
\bar{c}_4

Bianconi & Radici
hep-ph/0610317



Sivers


 $\pi^\pm p \uparrow \rightarrow \mu^+ \mu^- X$ 100K events (before dilut.) $E_\pi = 100 \text{ GeV}$ $s = 200 \text{ GeV}^2$
 $4 \leq M \leq 9 \text{ GeV}$ $0.5 \leq q_T \leq 2.5 \text{ GeV}/c$



$$\sin(\phi - \phi_{Sp}) > 0$$

$$\sin(\phi - \phi_{Sp}) < 0$$

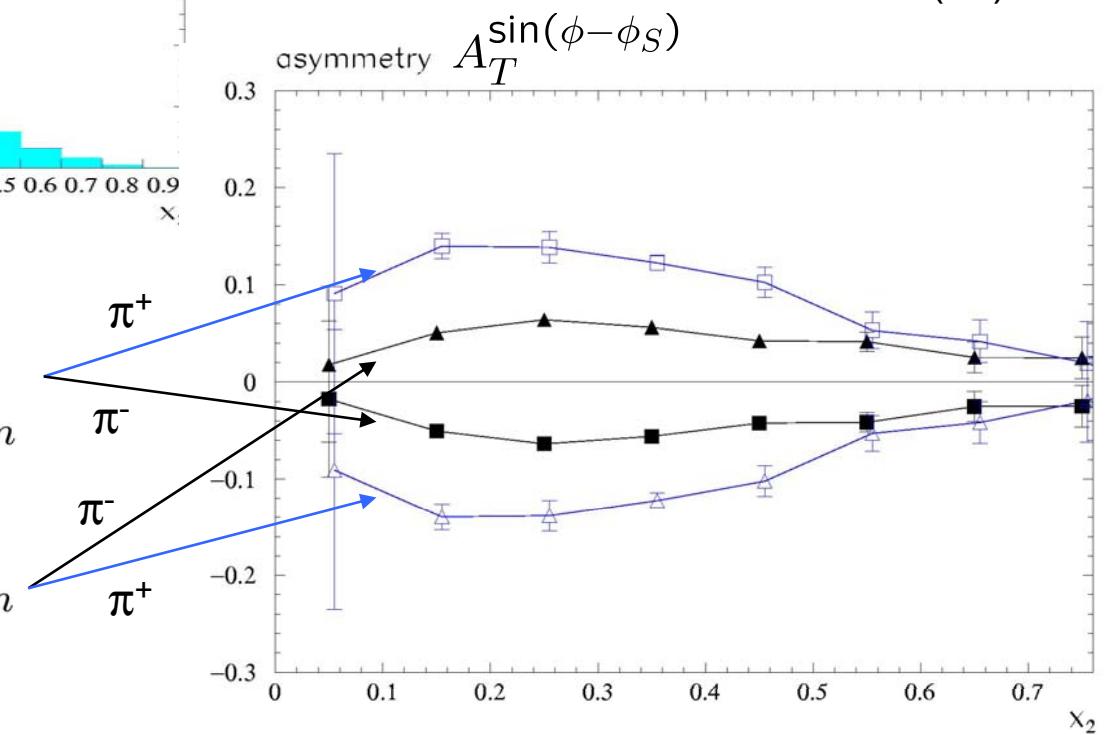
Bianconi & Radici
P.R. D73 (06) 114002

param. # 1

$$f_{1T}^{\perp q}|_{SIDIS} = + f_{1T}^{\perp q}|_{Drell-Yan}$$

$$f_{1T}^{\perp q}|_{SIDIS} = - f_{1T}^{\perp q}|_{Drell-Yan}$$

$$N_u = 0.32 \quad N_d = -1.0$$



Running time for Monte Carlo sample

Program → total σ for absorption of pions per nucleon producing Drell-Yan event in the selected kinematics

luminosity $L \times \sigma =$ # of “good” Drell-Yan events per nucleon and per sec.

s (GeV 2)	M (GeV)	σ_{tot} (nb/N)	events/month
200	2.5 – 4 (no J/ ψ)	0.5	52K
	4 - 9	0.25	26K
30	1.5 - 2.5	0.8	20K
	4 - 9	4×10^{-4}	10

COMPASS π beam
 $L=4 \times 10^{31} \text{ (cm}^{-2}\text{s}^{-1}\text{)}$
PRELIMINARY!
 (see Denisov talk)

PANDA
 $L \sim 10^{31} \text{ (cm}^{-2}\text{s}^{-1}\text{)}$

COMPASS	after cuts	dilution factor	polarized events
π^- beam	100K	0.2	20K

~ 40 days of running!

SSA from the Sivers effect: param. #2

$$c_4 S_4 = A_T^{\sin(\phi - \phi_S)} = |\mathbf{S}_{2T}| \frac{\sum_q e_q^2 \mathcal{F} [\hat{\mathbf{h}} \cdot \mathbf{p}_{2T} \bar{f}_1^q f_{1T}^{\perp q}]}{\sum_q e_q^2 \mathcal{F} [\bar{f}_1^q f_1^q]} (1 + \cos^2 \theta) \sin(\phi - \phi_{2S})$$

$$f_{1T}^{\perp q} = N_q x (1-x) \frac{M_2 p_0^2 p_T}{(\mathbf{p}_T^2 + \frac{p_0^2}{4})^2} f_1^q(x, \mathbf{p}_T)$$

Bianconi & Radici
P.R. D73 (06) 034018; D73 (06) 114002

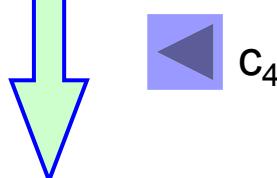
$$f_1^q(x, \mathbf{p}_T) = \frac{1}{\pi \langle \mathbf{p}_T^2 \rangle} e^{-\mathbf{p}_T^2 / \langle \mathbf{p}_T^2 \rangle} f_1^q(x)$$

$$\langle \mathbf{p}_T^2 \rangle = 0.25 \text{ (GeV/c)}^2$$

x dependence
 \mathbf{p}_T

$\text{pp}^\uparrow \rightarrow \pi^0 X$
SSA as
Sivers effect

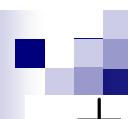
Vogelsang & Yuan,
P.R. D72 (05) 054028
Adler *et al.* (PHENIX),
P.R.L. 95 (05) 202001



$$c_4 \approx |\mathbf{S}_{2T}| \left(\frac{2p_0 q_T}{q_T^2 + p_0^2} \right)^2 \frac{8N_u + N_d}{9} x_2 (1 - x_2)$$

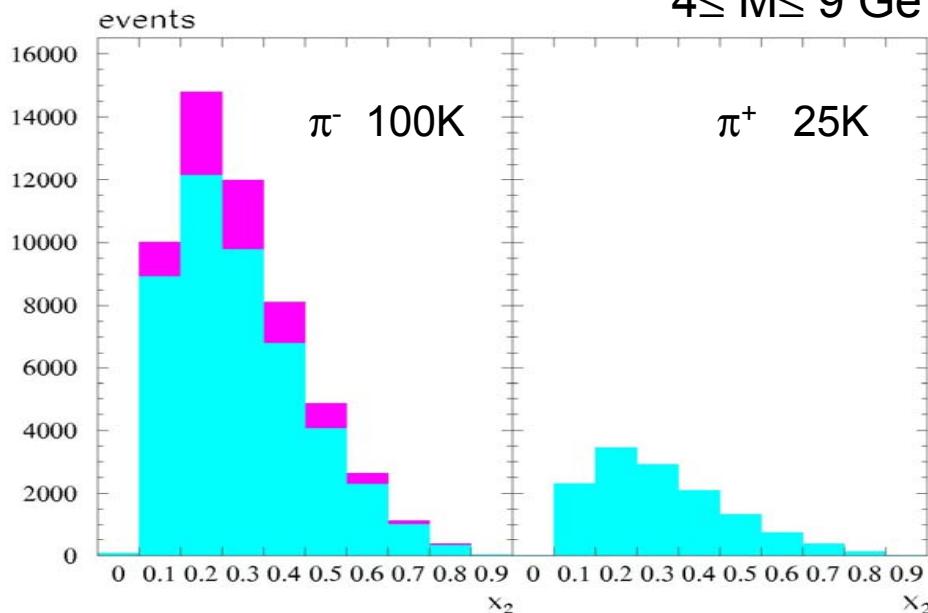
N_u	0.7	N_d	-0.7
p_0	2 GeV/c		

$$\int d\mathbf{q}_T d\cos\theta dx_1 A_T^{\sin(\phi - \phi_S)} \begin{cases} \sin(\phi - \phi_S) > 0 \\ \sin(\phi - \phi_S) < 0 \end{cases}$$



$$\pi^\pm p \uparrow \rightarrow \mu^+ \mu^- X$$

100K events (before dilut.) $E_\pi = 100 \text{ GeV}$ $s = 200 \text{ GeV}^2$
 $4 \leq M \leq 9 \text{ GeV}$ $0.5 \leq q_T \leq 2.5 \text{ GeV}/c$



$$\sin(\phi - \phi_{Sp}) > 0$$

$$\sin(\phi - \phi_{Sp}) < 0$$

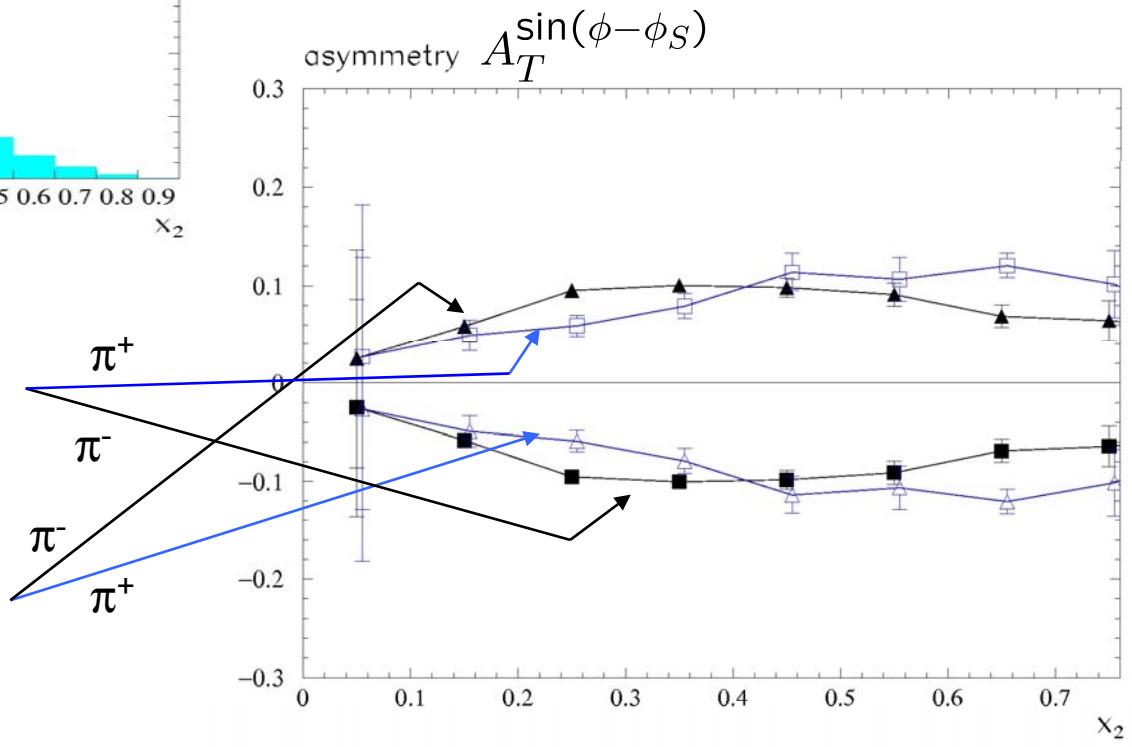
Bianconi & Radici
P.R. D73 (06) 114002

param. # 2

$$f_{1T}^{\perp q}|_{SIDIS} = + f_{1T}^{\perp q}|_{Drell-Yan}$$

$$f_{1T}^{\perp q}|_{SIDIS} = - f_{1T}^{\perp q}|_{Drell-Yan}$$

$$N_u = 0.7 \quad N_d = -0.7$$



Violation of Lam-Tung sum rule

$$\frac{\nu}{2} S_2 \propto c_2 S_2 = A_{UU}^{\cos 2\phi} = \frac{\sum_q e_q^2 \mathcal{F} [C_2(\mathbf{p}_{1T}, \mathbf{p}_{2T}) \bar{h}_1^{\perp q} h_1^{\perp q}]}{\sum_q e_q^2 \mathcal{F} [\bar{f}_1^q f_1^q]} \sin^2 \theta \cos 2\phi$$

| no parametrizations of h_1^{\perp} available, but:

0.3 $\leq x \leq 0.7$

Boer, P.R. D**60** ('99) 014012

fit $v(q_T)$ from NA10 exp. [Guanziroli et al., Z.P. C**37** (88) 545]

$$h_1^{\perp q}(x, p_T) = c^q \frac{M_C M}{p_T^2 + M_C^2} f_1^q(x, p_T)$$

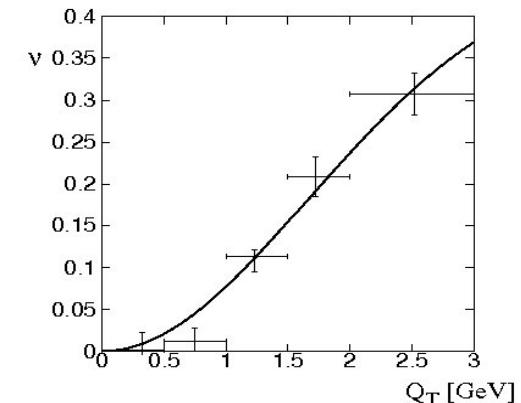
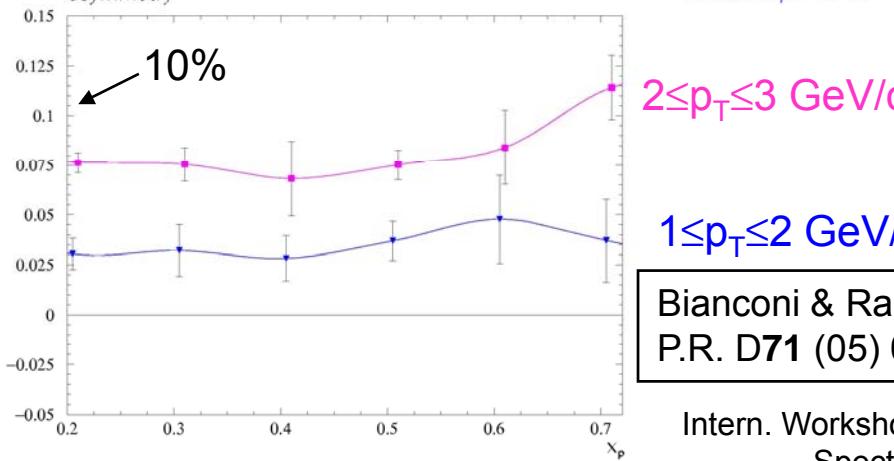
$$f_1^q(x, p_T) = \frac{\alpha_T}{\pi} e^{-\alpha_T p_T^2} f_1^q(x)$$

α_T	c^q	M_C
1 GeV ²	1	2.3 GeV

$$\frac{\nu}{2} = c_2 \approx c^{\langle q \rangle} c^{\langle \bar{q} \rangle} \frac{4M_C^2 q_T^2}{(q_T^2 + 4M_C^2)^2}$$

$$\int d\mathbf{q}_T d\cos \theta dx_1 A_{UU}^{\cos 2\phi}$$

$$\begin{cases} \cos 2\phi > 0 \\ \cos 2\phi < 0 \end{cases}$$



Models

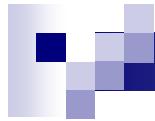
MIT [Yuan, P.L. B**575** (03) 45]

$1/N_c$ [Pobylitsa, hep-ph/0301236]

Diquark [Bacchetta et al., P.L. B**578** (04) 109]

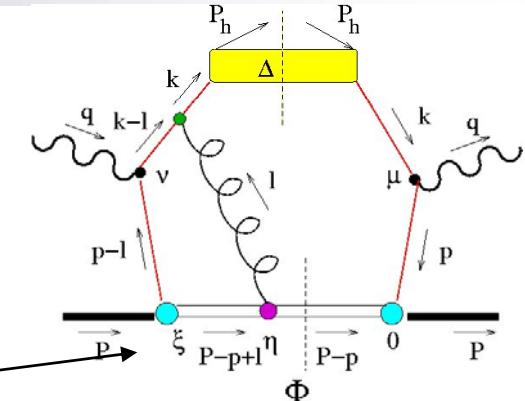
Lu & Ma, P.R. D**70** (04) 094044]

PYTHIA simulation [Sissakian et al., E.P.J. C**46** (06) 147]



Diquark-model-driven fit of v

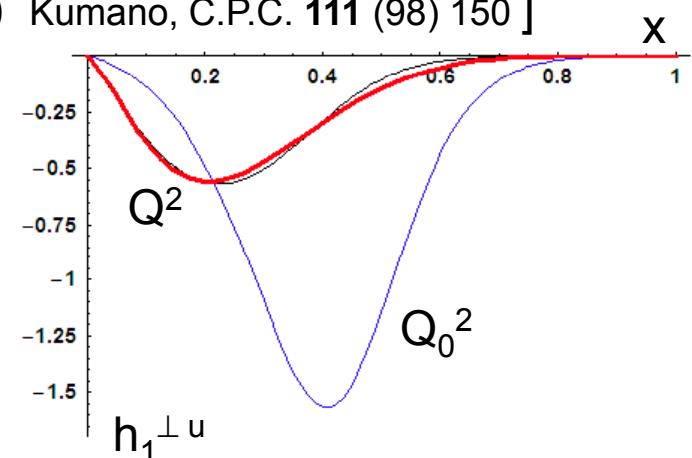
- one-gluon approx. of gauge link; in SIDIS, T-odd structure from interference diagram
- propagator of diquark in Light-Cone (LC) gauge
(only polarized states \perp to momentum;
consistent with LCwf of Brodsky [N.P. B593 (01) 311])
- exploration of several p-q-D form factors
- calculations of $f_{1T}^{\perp q}$ and $h_1^{\perp q}$; signs consistent with lattice

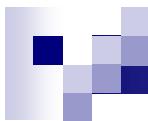


Conti, Bacchetta, Radici
in preparation
[Haegler (QCDSF/UKQCD), hep-ph/0612032]

Procedure:

- take $f_1(x, \mathbf{p}_T)$ from model at $Q_0^2 = 0.1 \text{ GeV}^2$; calculate $f_1(x) = \int d\mathbf{p}_T f_1(x, \mathbf{p}_T)$
- evolve $f_1(x)$ to $Q^2=16 \text{ GeV}^2$ [q evolution (f_1) Kumano, C.P.C. **94** (96) 185
 q^\perp evolution (h_1^{\perp} , $h_1^{\perp q}$) Kumano, C.P.C. **111** (98) 150]
- fit result with $N x^\alpha (1-x)^\beta$
- change sign in h_1^{\perp} from SIDIS to Drell-Yan
- add factorized \mathbf{q}_T dependence fitted to $v(\mathbf{q}_T)$ from NA10 data, i.e. c_2 of previous slide
- “consistency” of generated asymmetries
 $h_1^{\perp} \otimes h_1^{\perp}$ and $h_1^{\perp q} \otimes h_1^{\perp}$





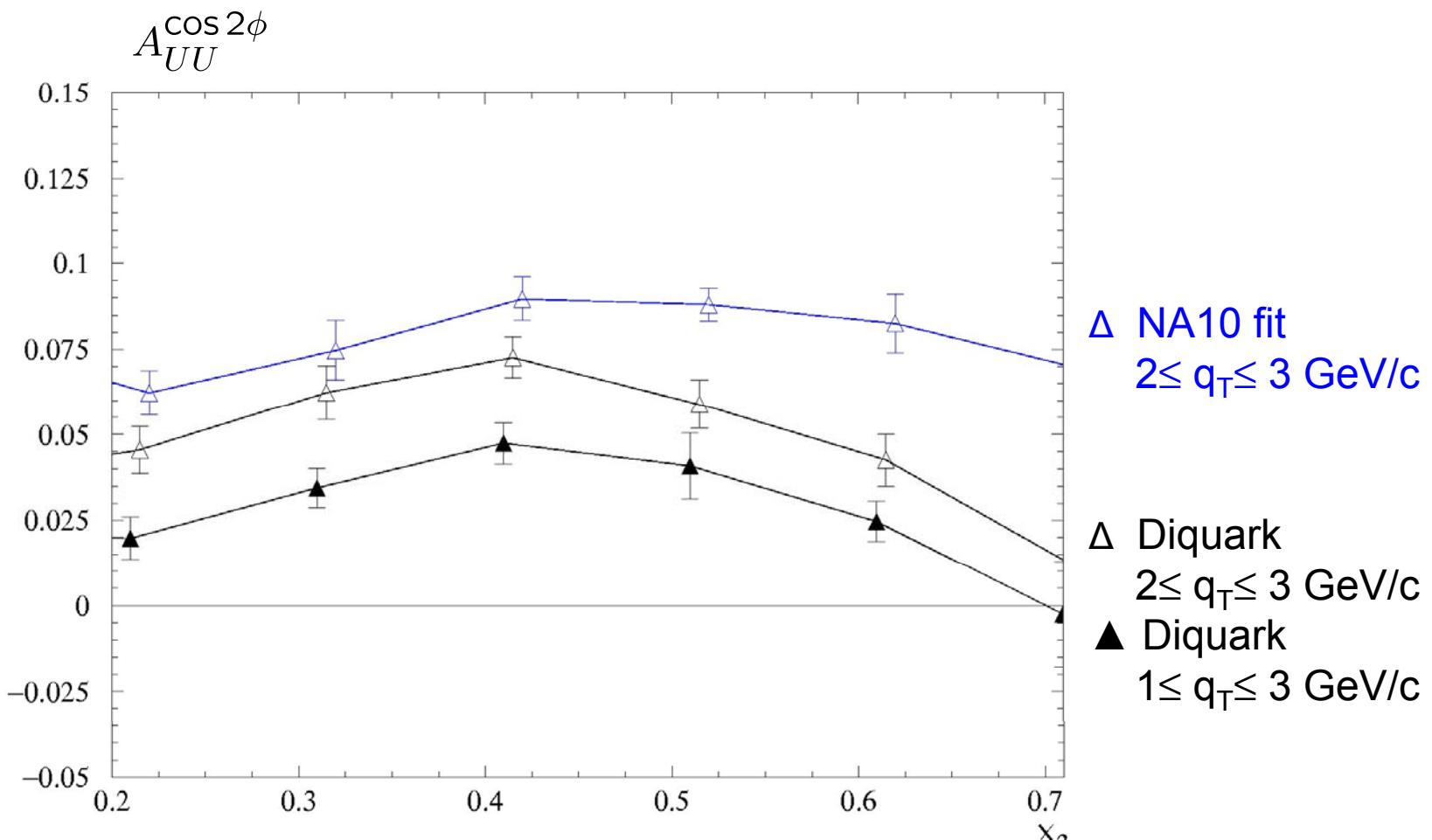
$\bar{p}p \rightarrow \mu^+ \mu^- X$

100K events (no dilut.)

$4 \leq M \leq 9 \text{ GeV}$

$E_{\text{beam}} = 100 \text{ GeV} \quad s = 200 \text{ GeV}^2$

$60^\circ \leq \theta \leq 120^\circ$



running time with anti-p beam?

see Denisov talk

SSA from the Boer-Mulders effect

$$c_3 S_3 = A_T^{\sin(\phi + \phi_S)} = -|\mathbf{S}_{2T}| \frac{\sum_q e_q^2 \mathcal{F} [\hat{\mathbf{h}} \cdot \mathbf{p}_{1T} \bar{h}_1^{\perp q} h_1^q]}{\sum_q e_q^2 \mathcal{F} [\bar{f}_1^q f_1^q]} \sin^2 \theta \sin(\phi + \phi_{2S})$$

$$h_1^{\perp q}(x, \mathbf{p}_T) = c^q \frac{M_C M}{\mathbf{p}_T^2 + M_C^2} f_1^q(x, \mathbf{p}_T)$$

$$h_1^q(x, \mathbf{p}_T) = \frac{\alpha_T}{\pi} e^{-\alpha_T \mathbf{p}_T^2} h_1^q(x)$$

$$f_1^q(x, \mathbf{p}_T) = \frac{\alpha_T}{\pi} e^{-\alpha_T \mathbf{p}_T^2} f_1^q(x)$$

$h_1^{\perp q}$, h_1^q , f_1^q from Diquark model
with factorized
evolved x dependence
and NA10-fitted \mathbf{q}_T dependence

α_T	c^q	M_C
1 GeV ²	1	2.3 GeV

$$c_3 \approx -|\mathbf{S}_{2T}| \frac{2M_C q_T}{q_T^2 + 4M_C^2} \frac{\langle h_1(x_2) \rangle}{\langle f_1(x_2) \rangle}$$

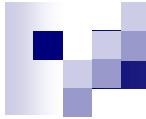
input $\frac{\langle h_1(x) \rangle}{\langle f_1(x) \rangle} = \begin{cases} \sqrt{x} \\ \sqrt{1-x} \end{cases}$ output SSA

Bianconi & Radici
P.R. D73 (06) 114002

$$\int d\mathbf{q}_T d\cos \theta dx_1 A_T^{\sin(\phi + \phi_S)}$$

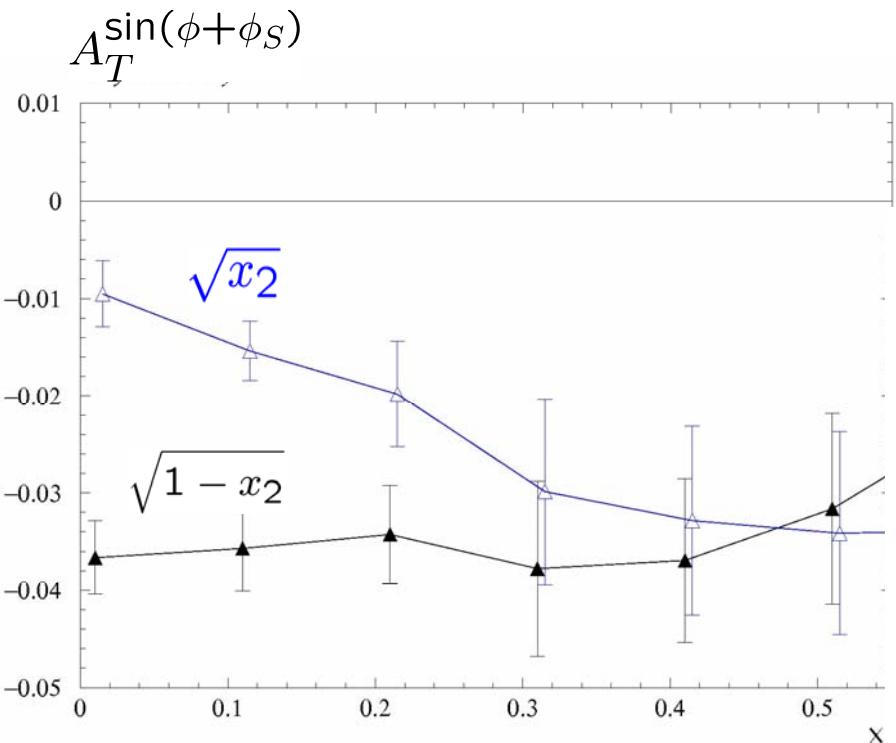
 $\sin(\phi + \phi_S) > 0$
 $\sin(\phi + \phi_S) < 0$

see also
PYTHIA simulation
[Sissakian *et al.*,
E.P.J. C46 (06) 147]



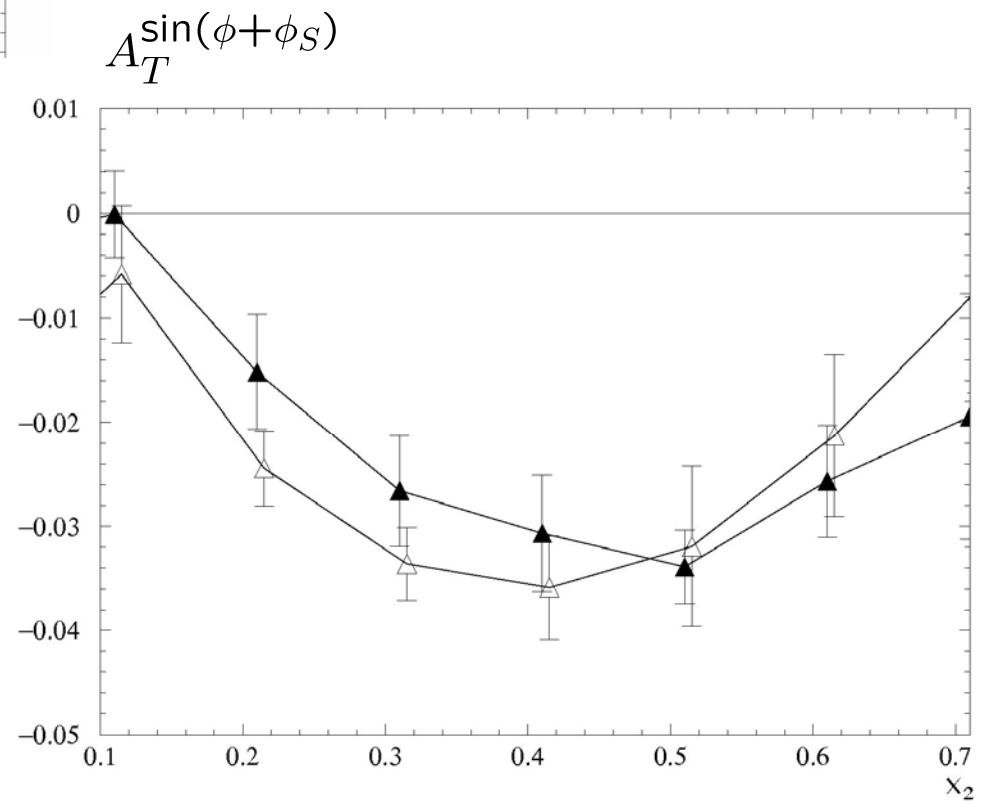
$$\pi^- p^\uparrow \rightarrow \mu^+ \mu^- X$$

200K events (dilut. factor 1/4) $s=100$ GeV 2
 $1.5 \leq M \leq 2.5$ GeV $60^\circ \leq \theta \leq 120^\circ$

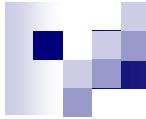


$$\bar{p}p^\uparrow \rightarrow \mu^+ \mu^- X$$

200K events $s=200$ GeV 2 $4 \leq M \leq 9$ GeV
 $\blacktriangle 1 \leq q_T \leq 3$ $\triangle 2 \leq q_T \leq 3$ GeV/c



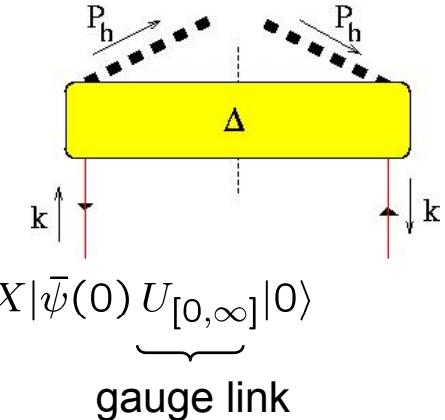
running time with
anti-p beam?
see Denisov talk



parton-parton correlator Δ

$$k \approx \left(\frac{P_h^-}{z}, 0, \mathbf{k}_T \right) \Rightarrow \zeta = (0, \zeta^+, \zeta_T)$$

$$\Delta(z, \mathbf{k}_T) = \sum_X \int \frac{d^4\zeta}{(2\pi)^4} e^{ik \cdot \zeta} \underbrace{\langle 0 | U_{[\infty, \zeta]}^\dagger}_{\text{gauge link}} \psi(\zeta) | P_h, X \rangle \langle P_h, X | \underbrace{\bar{\psi}(0) U_{[0, \infty]} | 0 \rangle}_{\text{gauge link}}$$



- decomposition of $\Delta(z, \mathbf{k}_T)$ upon $(\mathbf{1}, \gamma^\mu, \gamma_5, \gamma^\mu \gamma_5, \sigma^{\mu\nu}, \sigma^{\mu\nu} \gamma_5) \otimes (k^\mu, P_h^\mu)$

- hermiticity $\gamma^0 \Delta^\dagger(z, \mathbf{k}_T) \gamma^0 = \Delta(z, \mathbf{k}_T)$

- parity invariance $\gamma^0 \Delta(z, \tilde{\mathbf{k}}_T) \gamma^0 = \Delta(z, \mathbf{k}_T)$ $\tilde{a} = (a^0, -\mathbf{a})$

correlator Δ at leading twist including transverse momentum & no polarization

$$\int d\mathbf{k}_T \quad \Delta(x, \mathbf{k}_T) = \frac{1}{2P_h^-} \left\{ D_1 \not{P}_h \boxed{\text{---}} \right\}$$

number density of h in \mathbf{q}^\uparrow

$$\Delta^{[A]} \equiv \frac{1}{2} \text{Tr} [\Delta A]$$

$$n_+ = (0, 1, \mathbf{0}_T)$$

$$D_{h/q^\uparrow} = \frac{1}{2} \left(\Delta^{[\gamma_\mu n_+^\mu/2]} + \Delta^{[i\sigma_{\mu\nu} n_+^\mu s'^\nu \gamma_5/2]} \right) = \frac{1}{2} \left\{ D_1 + \textcolor{red}{H}_1^\perp \frac{\hat{\mathbf{k}} \times \mathbf{P}_{hT} \cdot \mathbf{s}'}{z M_h} \right\}$$

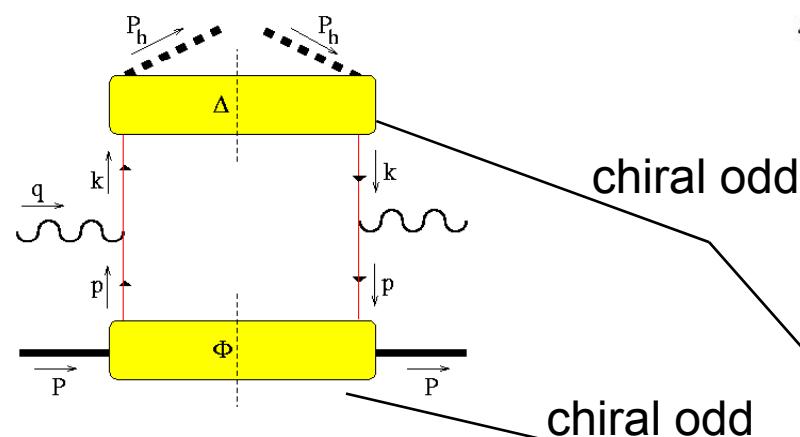
2 combinations: D_{h/q^\uparrow} D_{h/q^\downarrow}

$$1) D_{h/q} = D_{h/q\uparrow} + D_{h/q\downarrow} \equiv D_1^q(z, \mathbf{k}_T)$$

$$\mathbf{D}_1 = \bullet \longrightarrow \circ$$

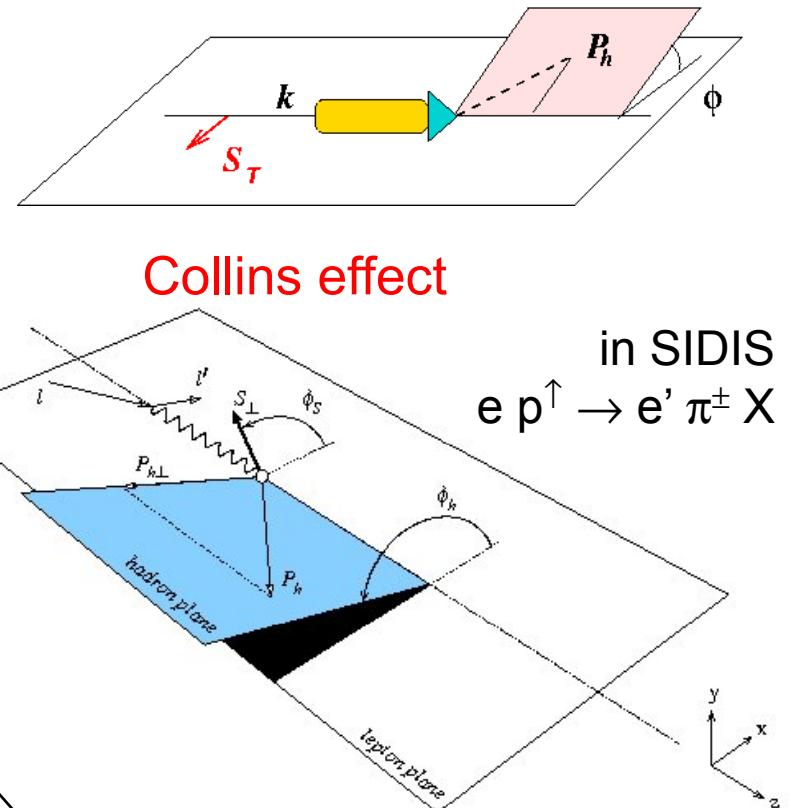
$$2) D_{h/q\uparrow} - D_{h/q\downarrow} \equiv H_1^{\perp q} \frac{\hat{\mathbf{k}} \times \mathbf{P}_{hT} \cdot \mathbf{s}'}{z M_h}$$

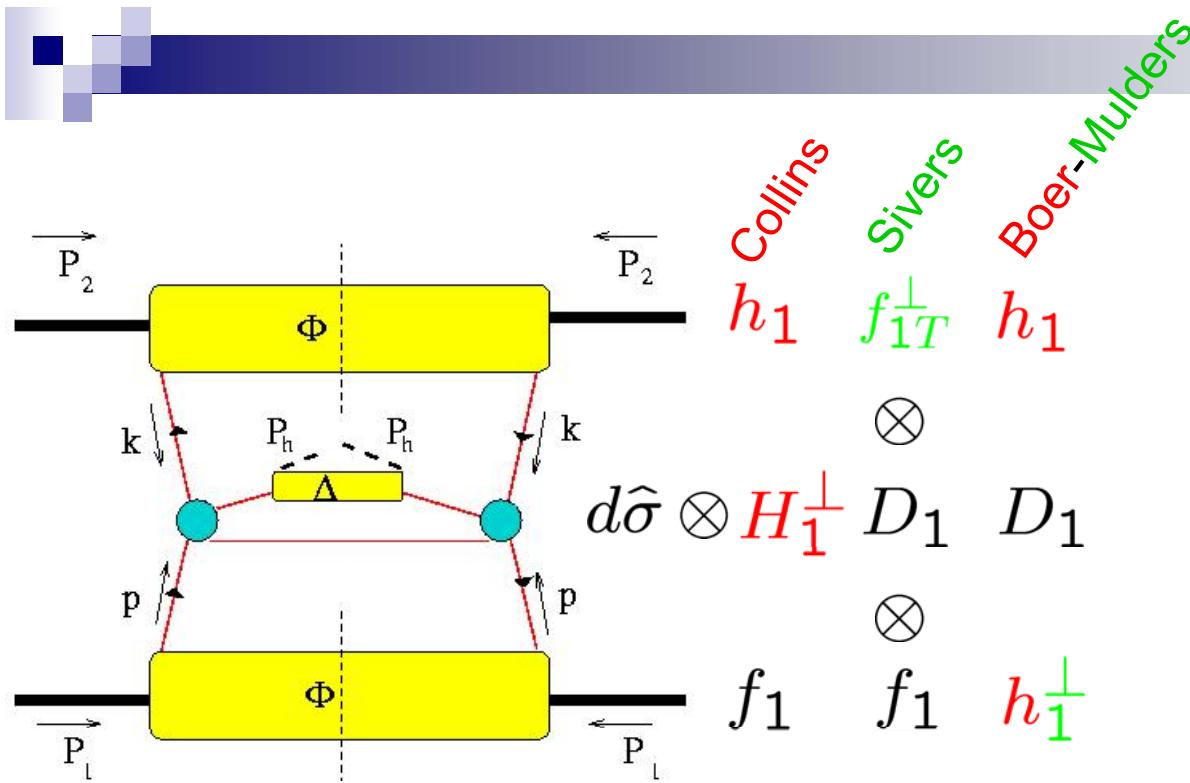
$$H_1^{\perp} = \left(\bullet \uparrow \longrightarrow \circ \right) - \left(\bullet \downarrow \longrightarrow \circ \right)$$



$$\frac{\langle |\mathbf{P}_{hT}| \sin(\phi + \phi_S) (d\sigma^\uparrow - d\sigma^\downarrow) \rangle}{\langle d\sigma^\uparrow + d\sigma^\downarrow \rangle} \propto \frac{\sum_{q\bar{q}} e_q^2 z h_1^q(x) H_1^{\perp q(1)}(z)}{\sum_{q\bar{q}} e_q^2 f_1^q(x) D_1^q(z)}$$

need knowledge
of $\mathbf{k}_T \sim -\mathbf{P}_{hT}/z$





but all rely on a factorization theorem for p_T -dependent PDF which has not yet been proven!

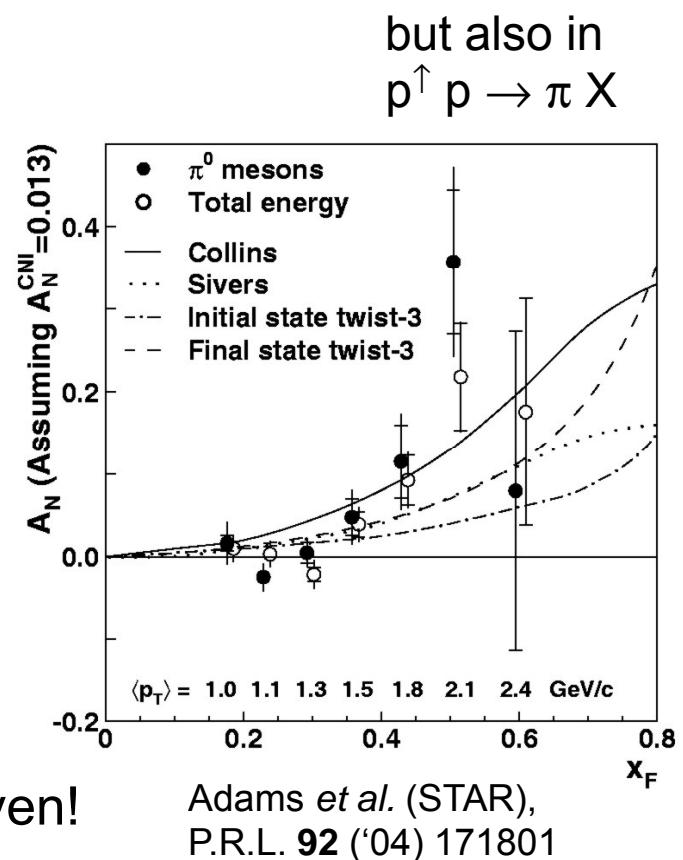
$d\sigma \sim 1/P_{hT}$ in pQCD with collinear approx. (q helicity flip and ampl. interference suppressed) \rightarrow more complicated elementary mechanism :

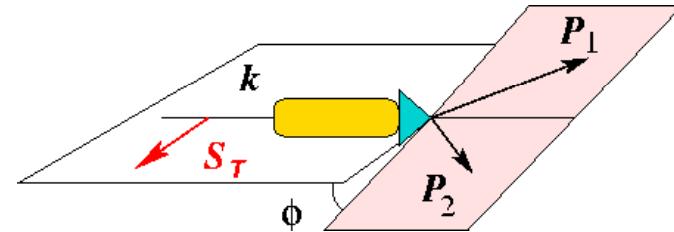
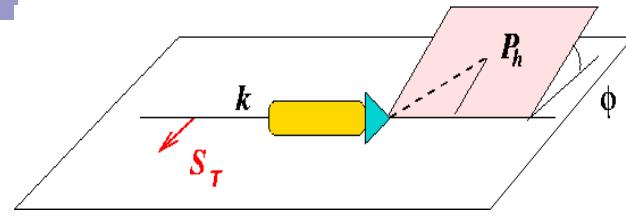
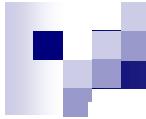
Qiu-Sterman (twist-3) effect ?
[Qiu & Sterman, P.R.L. 67 (91) 2264]

Kouvaris et al., P.R.D74 (06) 114013]

$$T_{qg} \otimes f_1 \otimes d\hat{\sigma}_{ijk}^{lm} \otimes D_1$$

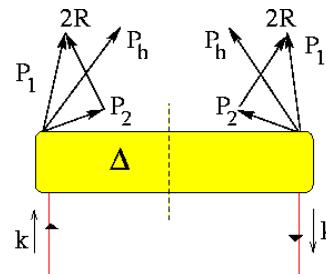
look for simpler situations!





Collins effect

$$\int d\mathbf{k}_T \dots \mathbf{k} \times \mathbf{P}_{hT} \cdot \mathbf{s}'_T \dots \rightarrow 0$$



survives $\int d\mathbf{k}_T$ $\left\{ \begin{array}{l} \mathbf{P}_h = \mathbf{P}_1 + \mathbf{P}_2 \\ R = \frac{1}{2}(\mathbf{P}_1 - \mathbf{P}_2) \end{array} \right. \rightarrow \mathbf{P}_h \times \mathbf{R} \cdot \mathbf{s}'_T$

$$k \approx \left(\frac{P_h^-}{z}, 0, \mathbf{k}_T \right) \Rightarrow \xi = (0, \xi^+, \xi_T) \quad \zeta = \frac{z_1 - z_2}{z} = \frac{2R^-}{P_h^-}$$

$$\Delta(z, \zeta, \mathbf{k}_T, R) = \sum_X \int \frac{d^4\xi}{(2\pi)^4} e^{+ik \cdot \xi} \langle 0 | \mathcal{U}_{(-\infty, \xi)}^\dagger \psi(\xi) | P_h, R; X \rangle \langle P_h, R; X | \bar{\psi}(0) \mathcal{U}_{(0, -\infty)} | 0 \rangle$$

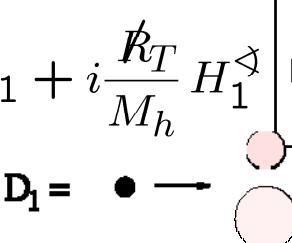
- decomposition of $\Delta(z, \zeta, \mathbf{k}_T, R)$ upon $(\mathbb{1}, \gamma^\mu, \gamma_5, \gamma^\mu \gamma_5, \sigma^{\mu\nu}, \sigma^{\mu\nu} \gamma_5) \otimes (k^\mu, P_h^\mu, R^\mu)$ with hermiticity and parity invariance

$$\int d\mathbf{k}_T \quad \Delta(z, \zeta, \mathbf{k}_T, M_h^2, \phi_R) = \frac{1}{2} \left\{ D_1 + i \frac{R_T}{M_h} H_1^\zeta \left[\left(\bullet \rightarrow \circlearrowleft \right) - \left(\bullet \rightarrow \circlearrowright \right) \right] \right\} \gamma^+$$

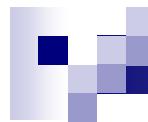
[twist 2 → Bianconi et al., P.R.D **62** (00) 034008

twist 3 → Bacchetta & Radici,

P.R.D **69** (04) 074026]



Intern. Workshop on Structure &
Spectroscopy



first suggestion [Konishi et al., P.L.B78 (78) 243]

SSA in $e p^\uparrow \rightarrow e' (h_1 h_2) X$

[Collins et al., N.P.B420 (94) 565
Jaffe et al., P.R.L. 80 (98) 1166
Radici et al., P.R.D65 (02) 074031]

at leading twist

$$A_{UT}^{\sin(\phi_R + \phi_S)}(x, y, z, M_h^2) \equiv \frac{1}{\sin(\phi_R + \phi_S)} \frac{d\sigma_{UT}}{d\sigma_{UU}} \\ = - \frac{B(y)/y^2}{A(y)/y^2} \frac{\pi |\vec{R}|}{4 M_h} \frac{\sum_q e_q^2 (\mathbf{h}_1^q(x)/x) H_{1,q}^\leftarrow(z, M_h^2)}{\sum_q e_q^2 (f_1^q(x)/x) D_{1,q}(z, M_h^2)}$$

H_1^\leftarrow from $e^+e^- \rightarrow (h_1 h_2) (h_1' h_2') X$ (BELLE)

Grosse-Perdekamp talk ?

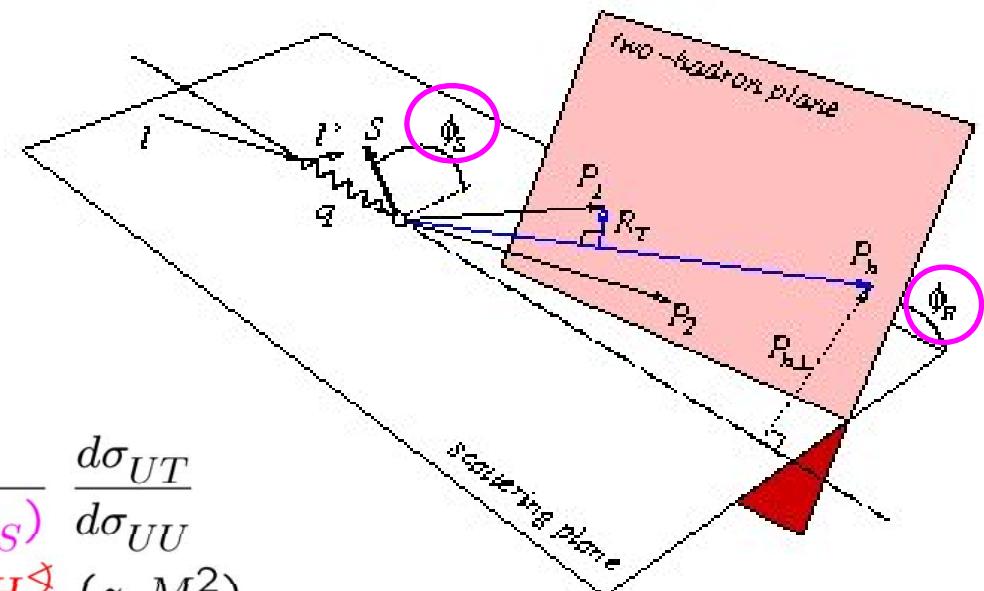
checked universality in SIDIS and e^+e^- at twist 2

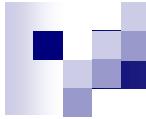
[Boer et al., P.R.D67 (03) 094003]

evolution equations with
explicit M_h dependence
just as simple as PDF
[Ceccopieri, Radici, Bacchetta,
in preparation]

or models !

$$\frac{d}{d \ln Q^2} D_1^{i \rightarrow h_1 h_2}(z_1, z_2, M_h^2, Q^2) \\ = \frac{\alpha_s(Q^2)}{2\pi} \int_{z_1+z_2}^1 \frac{du}{u^2} D_1^{j \rightarrow h_1 h_2} \left(\frac{z_1}{u}, \frac{z_2}{u}, M_h^2, Q^2 \right) P_{ji}(u)$$



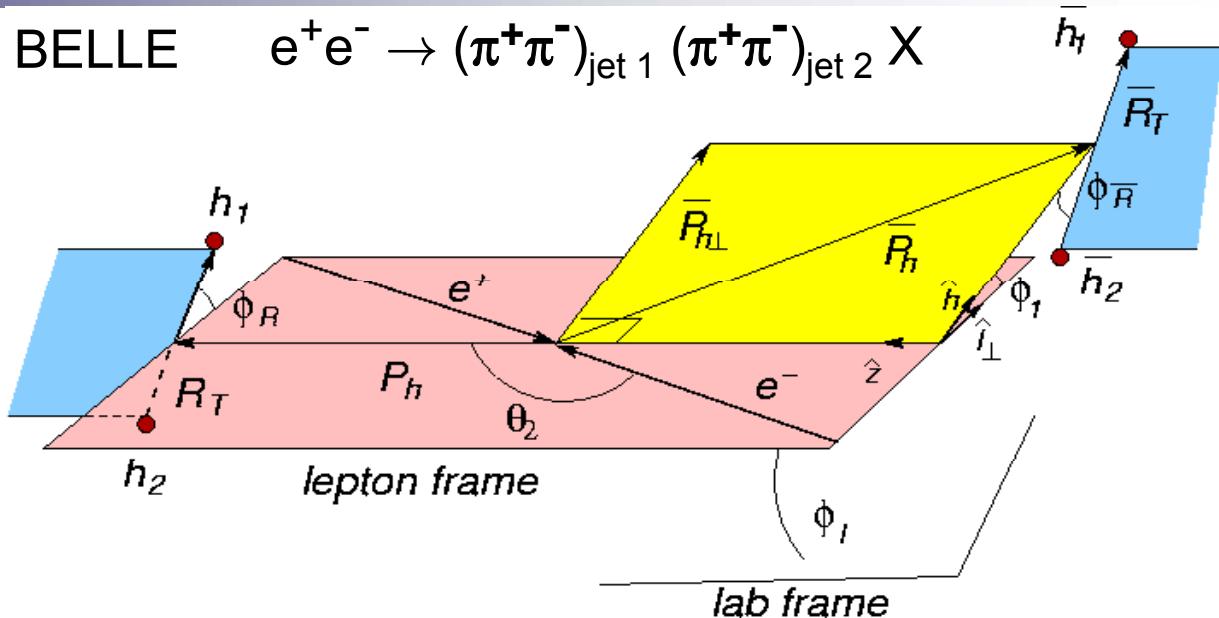


H_1^Δ

unknown from BELLE

(Boer, Jakob, Radici,
P.R. D67 (2003) 094003
also Artru, Collins,
Z. Phys. C69 ('96) 277)

$e^+e^- \rightarrow (\pi^+\pi^-)_{\text{jet } 1} (\pi^+\pi^-)_{\text{jet } 2} X$



leading twist

$$d\sigma = \frac{6\alpha^2}{Q^2} z^2 \bar{z}^2 \left\{ \dots + \cos(\phi_R + \bar{\phi}_R - 2\phi_l) B(y) |\mathbf{R}_T| |\bar{\mathbf{R}}_T| \mathcal{F} \left[\frac{H_1^\Delta \bar{H}_1^\Delta}{M_h \bar{M}_h} \right] + \dots \right\}$$

“Artru-Collins” azimuthal asymmetry

$$A_H \propto \frac{\sum_f e_f^2 H_1^\Delta(R)}{\sum_f e_f^2 D_1^f \bar{D}_1^f}$$

same as in SIDIS
universality verified
at leading twist !

N.B. production of collinear pairs \rightarrow reduced background ?

Before HERMES & COMPASS data

(Jaffe, Jin, Tang, P.R.L. **80** (98) 1166)

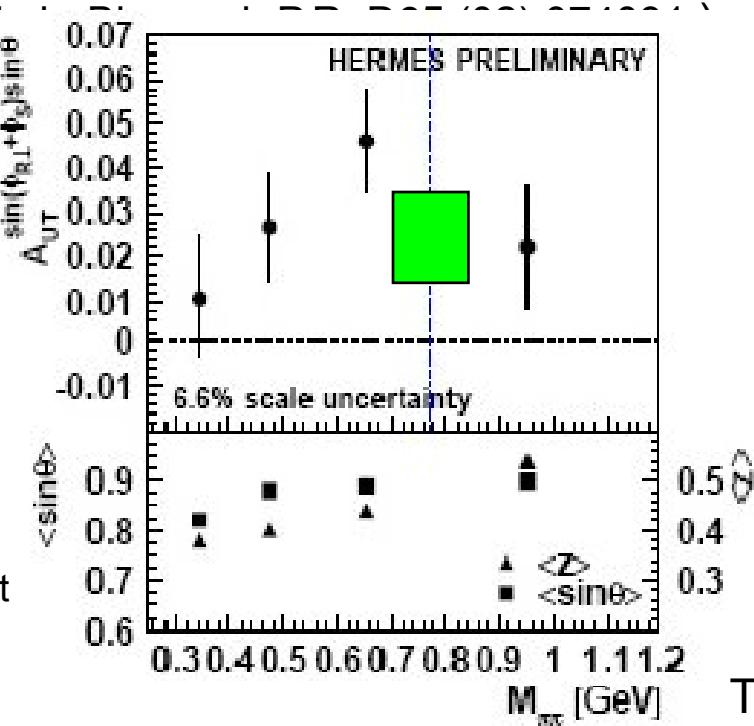
$$H_1^{\Delta sp} \sim \delta \hat{q}_I(z) \sin \delta_0 \sin \delta_1 \sin(\delta_0 - \delta_1)$$

- s-p interference from $\pi\pi$ elastic scattering phase shifts only; sign change from $\text{Re}[\rho]$

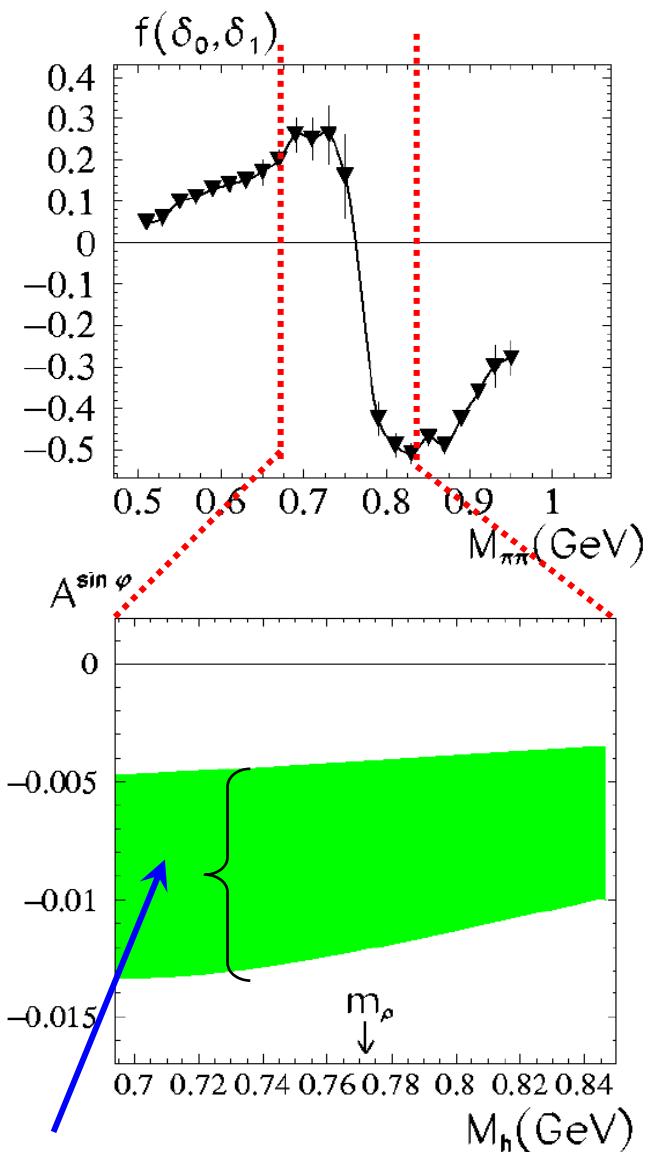
(Radici, Ja

spectator
interference

P. van der Nat
DIS2005



Trento conventions $\rightarrow \times (-8/\pi)$

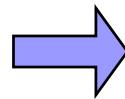


upgraded spectator model

$$|P_1, P_2, X\rangle \sim |(\pi^+ \pi^-)_L, \tilde{q}\rangle$$

[Bacchetta & Radici, P.R.D**74** (06) 114007]

- 1. background $\equiv q \rightarrow \pi^+ \pi^- X_1$ no resonance \rightarrow real s-wave channel
 - 2. $q \rightarrow \rho X_2 \rightarrow \pi^+ \pi^- X_2$
 - 3. $q \rightarrow \omega X_3 \rightarrow \pi^+ \pi^- X_3$
 - 4. $q \rightarrow \omega X'_4 \rightarrow \pi^+ \pi^- (\underbrace{\pi^0 X'_4}_{X_4})$
- $X_1 = X_2 = X_3 = X_4 = X$
 p-wave channel = coherent sum $|2.+3.+4.|$
- Warning: $\omega \rightarrow [(\pi \pi)_{L=1} \pi]_{J=1}$



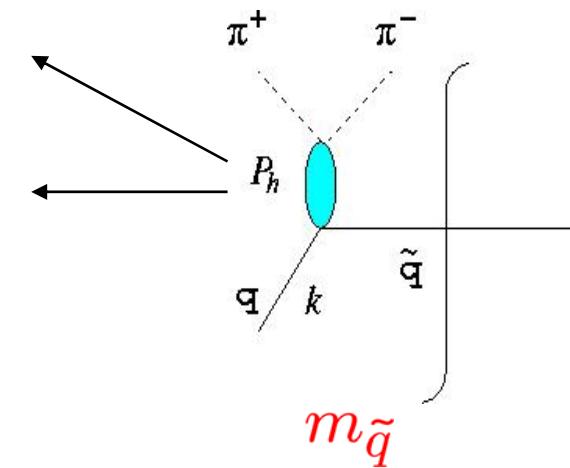
max number of $(\pi^+ \pi^-)$ pairs in s-p interference $\sim \text{Im} [\text{p-wave channel}]$

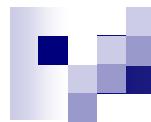
parameters

s-wave $f_s e^{-k^2/\Lambda_s^2}$

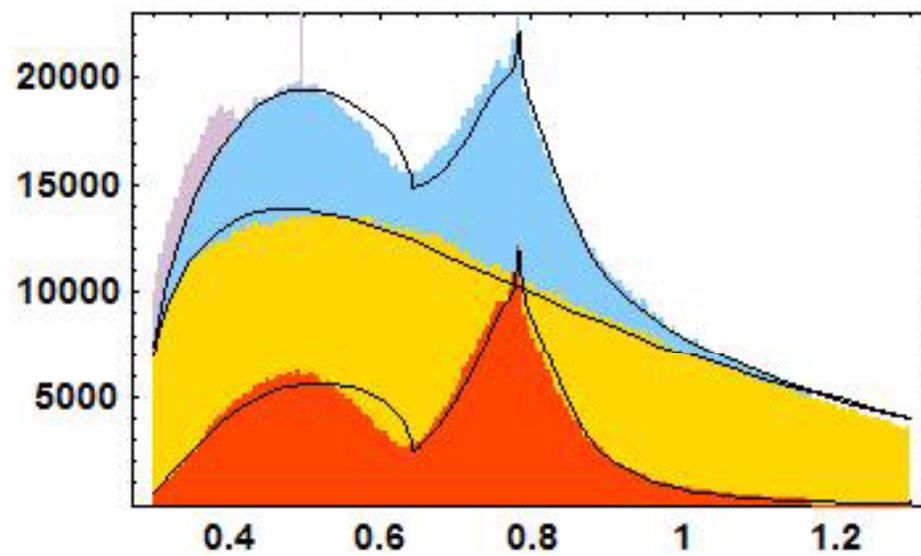
p-wave
$$\begin{aligned} & [f_\rho \text{BW}(M_h^2, m_\rho, \Gamma_\rho) + f_\omega \text{BW}(M_h^2, m_\omega, \Gamma_\omega) \\ & + f_{\omega_3} \int dp_{\pi^0} \text{BW}(M_{3\pi}^2, m_\omega, \Gamma_\omega)] e^{-k^2/\Lambda_p^2} \end{aligned}$$

$$\Lambda_{s/p} = \alpha_{s/p} z^{\beta_{s/p}} (1-z)^{\gamma_{s/p}}$$





fit PYTHIA distributions of pair invariant mass and z



2.+3.+4. p-wave
1. background s-wave
Total
Total + 5.+6.

[Bacchetta & Radici, P.R.D74 (06) 114007]

$$\alpha_s = 2.598 \pm 0.051 \text{ GeV}^2$$

$$\beta_s = -0.751 \pm 0.008$$

$$\gamma_s = -0.193 \pm 0.004$$

$$\alpha_p = 7.069 \pm 0.11 \text{ GeV}^2$$

$$\beta_p = -0.038 \pm 0.003$$

$$\gamma_p = -0.085 \pm 0.004$$

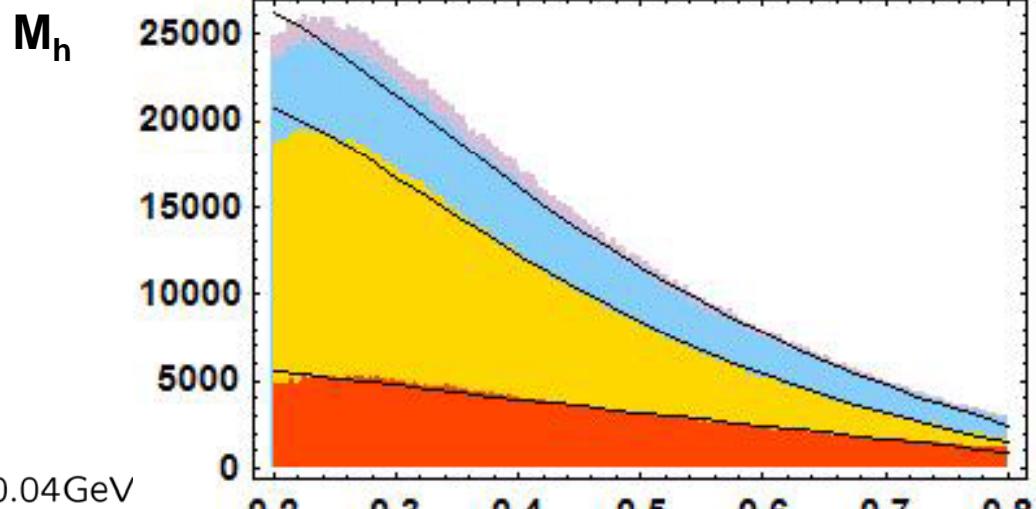
$$f_s = 1197.2 \pm 2.0 \text{ GeV}^{-1}$$

$$f_\rho = 93.49 \pm 1.58$$

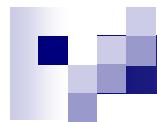
$$f_\omega = 0.635 \pm 0.026$$

$$f_{\omega_3} = 450.83 \pm 7.02$$

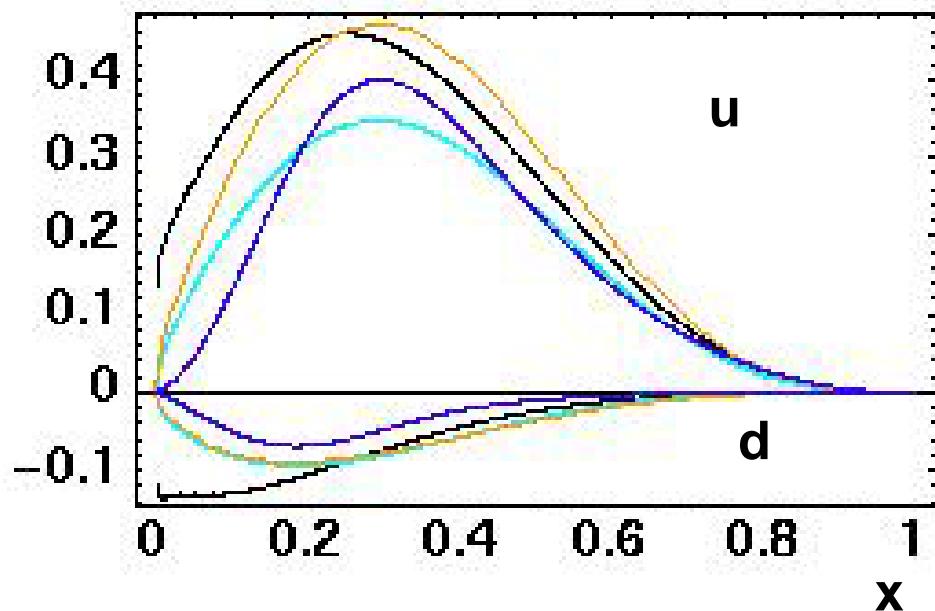
$$\tilde{m}_q = 2.972 \pm 0.04 \text{ GeV}$$



z



models for transversity



- Strat
- Kor
- Schw
- Wak
- Strat
- Kor
- Schw
- Wak

Strat

Soffer, Stratmann, Vogelsang
P.R. **D65** (02) 114024

Kor

Korotkov, Nowak, Oganessian
E.P.J. **C18** (01) 639

Schw

Schweitzer *et al.*
P.R. **D64** (01) 034013

Wak

Wakamatsu
P.L. **B509** (01) 59

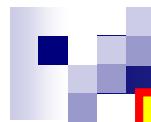
$$D_1^u = D_1^{\bar{d}} = D_1^d = D_1^{\bar{u}}$$

$$H_1^{\not\rightarrow} u = H_1^{\not\rightarrow} \bar{d} = -H_1^{\not\rightarrow} d = -H_1^{\not\rightarrow} \bar{u}$$

$$A_{UT}^{\sin(\phi_R + \phi_S)}(z, M_h^2) = -\frac{\int_{0.1}^{0.85} dy B(y)/y^2}{\int_{0.1}^{0.85} dy A(y)/y^2} \frac{\pi |\vec{R}| H_1^{\not\rightarrow sp}(z, M_h^2)}{4 M_h D_1^{ss+pp}(z, M_h^2)} \frac{\int_{x_{min}}^{x_{max}} dx 4(h_1^u - h_1^d + h_1^{\bar{d}} - h_1^{\bar{u}})/x}{\int_{x_{min}}^{x_{max}} dx 4(f_1^u + f_1^d + f_1^{\bar{u}} + f_1^{\bar{d}})/x}$$

$$x_{min} = \max [0.023, Q_{min}^2/y(s - M^2)] \quad x_{max} = \min [0.4, 1 - (W_{min}^2 - M^2)/y(s - M^2)] \quad s = 56.2 \text{ GeV}^2$$

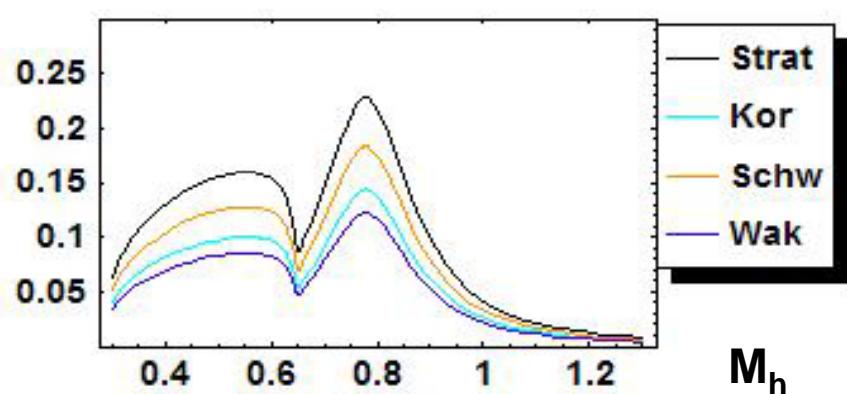
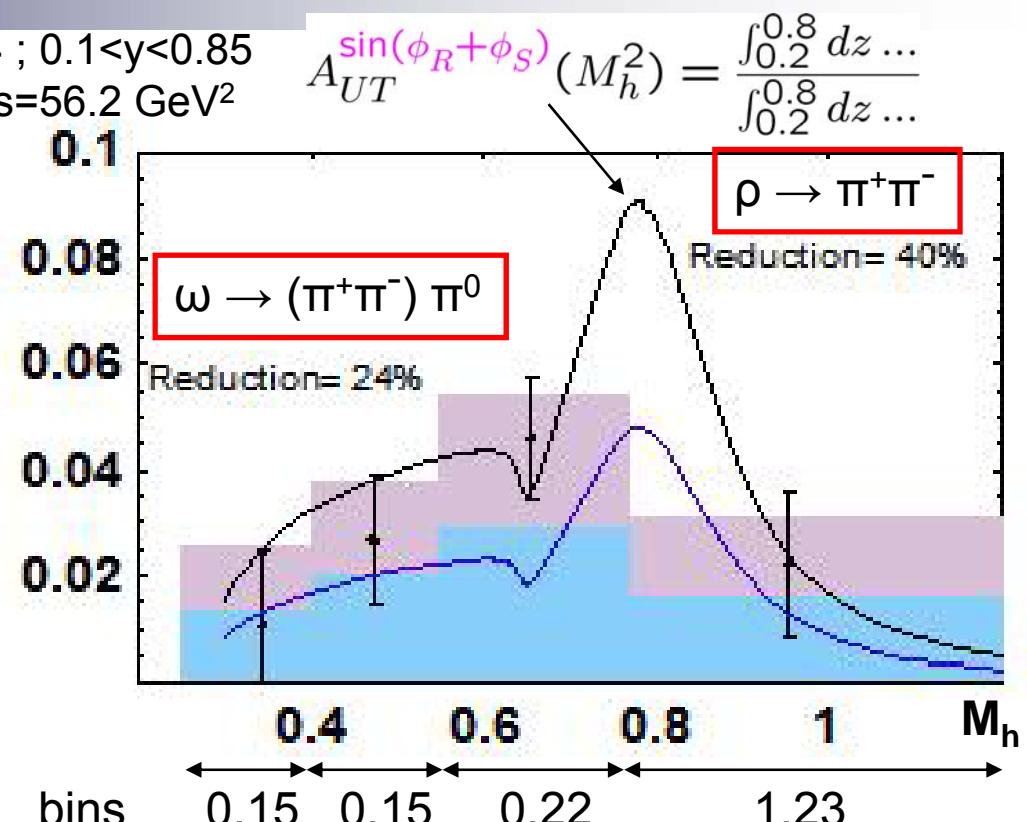
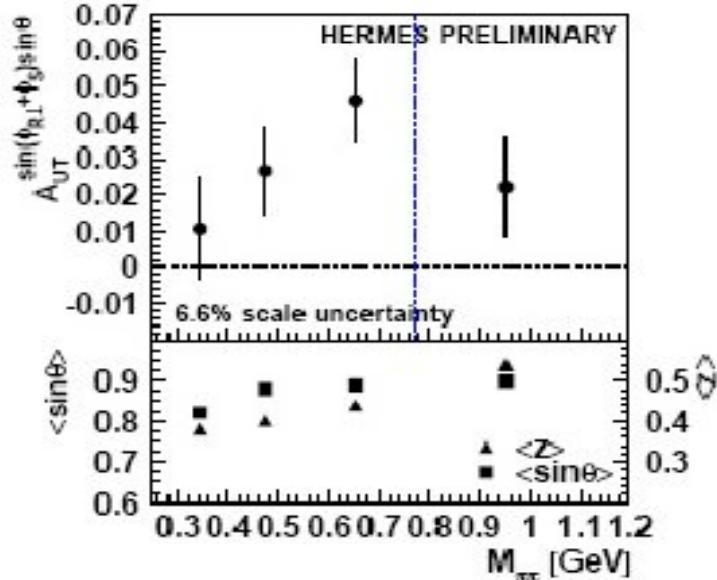
$$f_1^u / d / \bar{u} / \bar{d} \quad \text{from GRV98-LO} \\ @ Q^2 = 2.5 \text{ GeV}^2$$



spin asymmetry

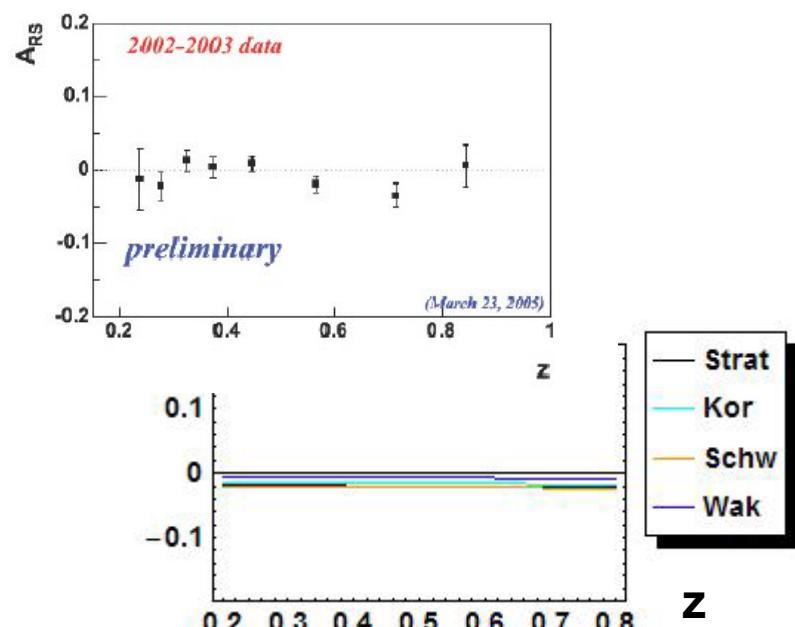
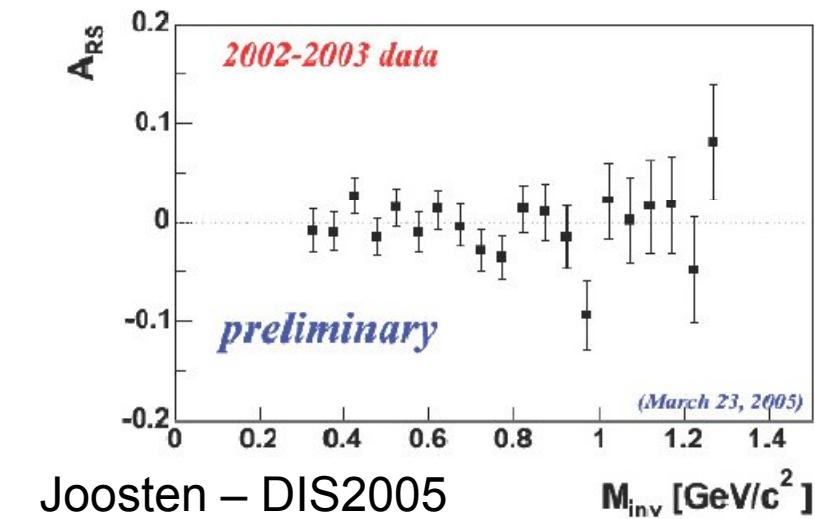
$0.023 < x < 0.4 ; 0.1 < y < 0.85$
 $Q^2 > 1 \text{ GeV}^2 s = 56.2 \text{ GeV}^2$

HERMES 6.6% scale
 PRELIMINARY uncertainty

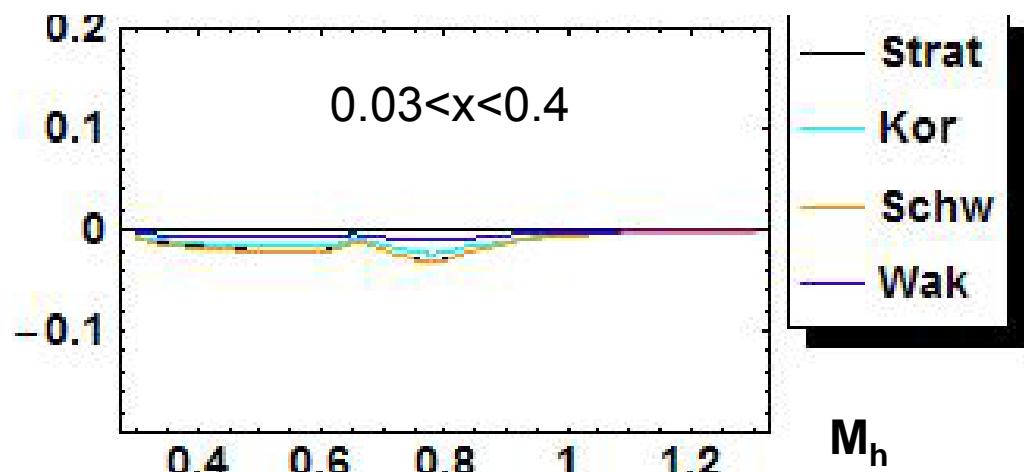
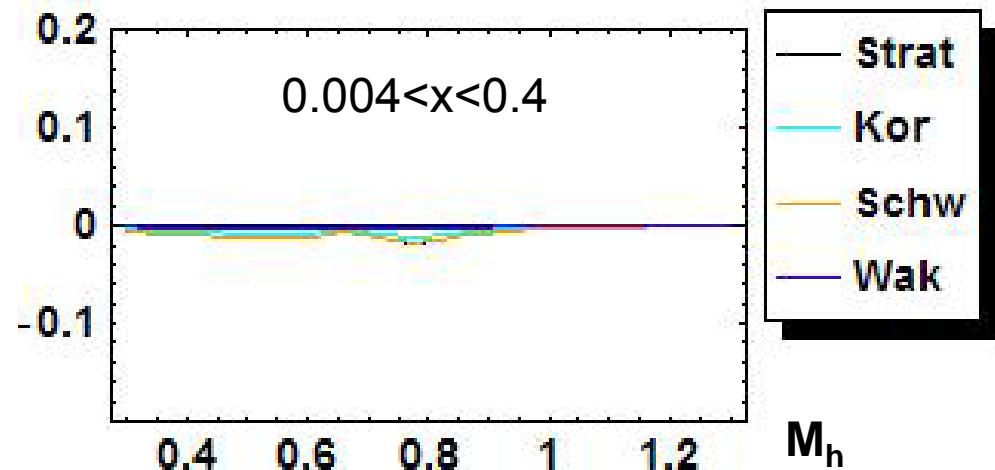


$$A_{UT}^{\sin(\phi_R + \phi_S)}(\text{bin}[M_h]) = \frac{\int_{\text{bin}} dM_h 2M_h \int_{0.2}^{0.8} dz ...}{\int_{\text{bin}} dM_h 2M_h \int_{0.2}^{0.8} dz ...}$$

spin asymmetry @ COMPASS



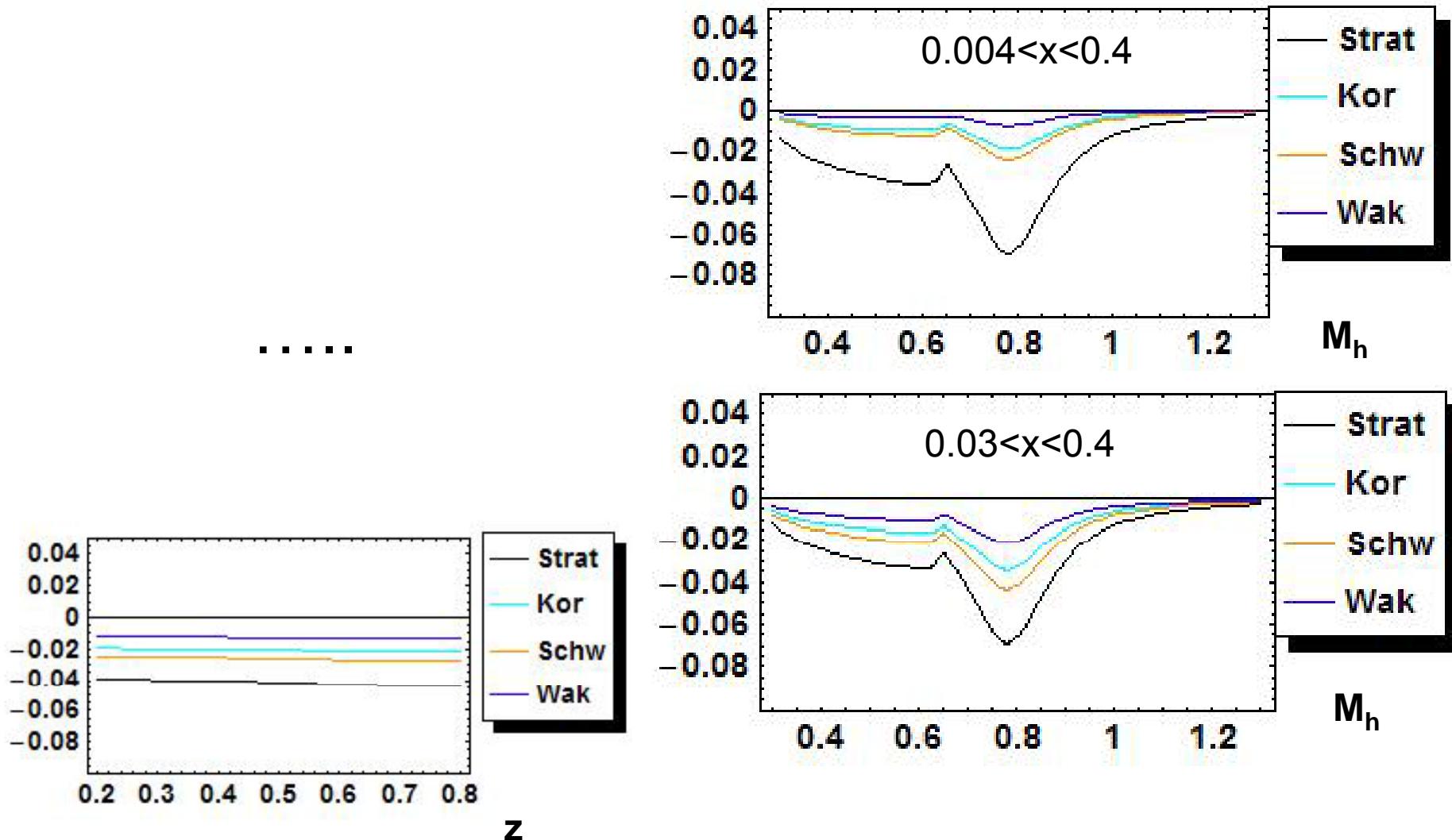
deuteron $0.1 < y < 0.9$ $Q^2 > 1 \text{ GeV}^2$ $s = 604 \text{ GeV}^2$



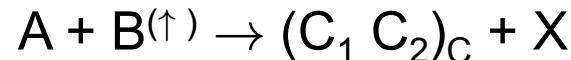
spin asymmetry @ COMPASS

proton

$0.1 < y < 0.9$ $Q^2 > 1 \text{ GeV}^2$ $s = 301 \text{ GeV}^2$

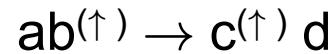
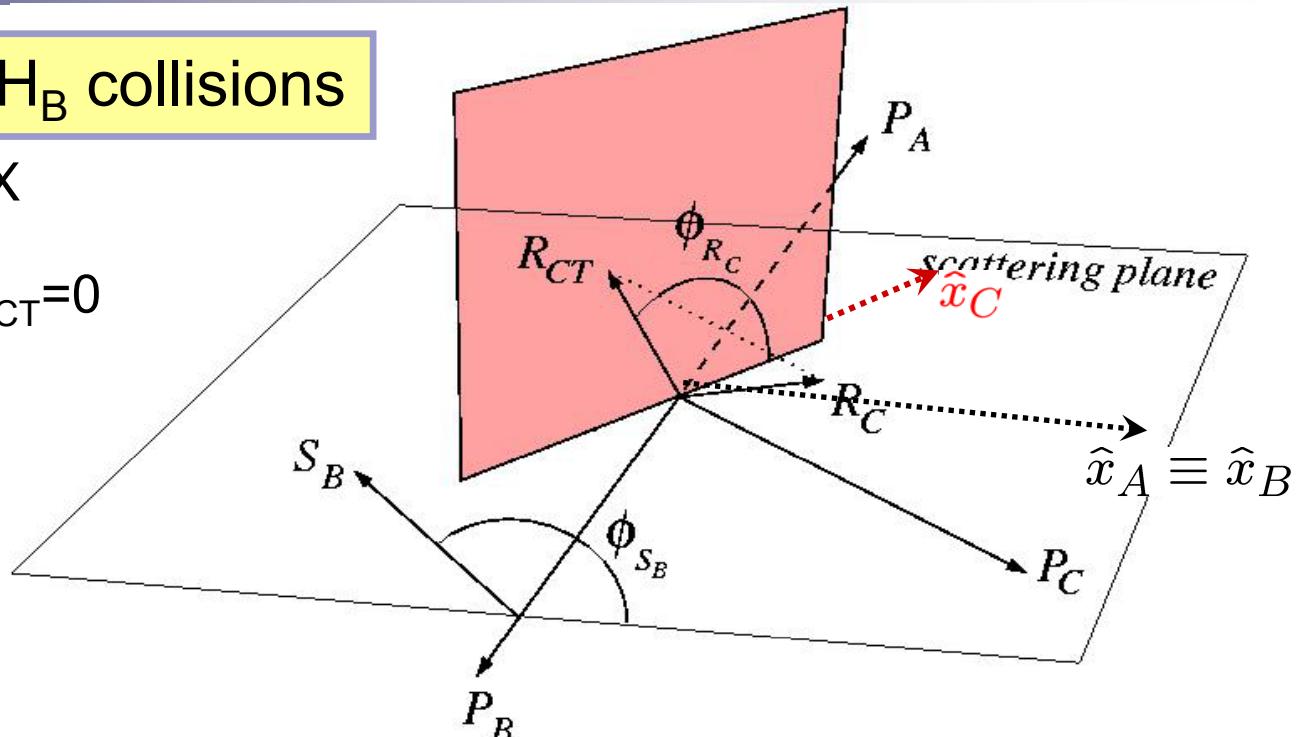


kin. of semi-incl. $H_A H_B$ collisions



$\mathbf{P}_C = \mathbf{P}_{C1} + \mathbf{P}_{C2} \parallel \text{jet axis}$ $\mathbf{P}_{CT} = 0$
but

$\mathbf{P}_C \cdot \mathbf{P}_A \propto \mathbf{P}_{C\perp}$ large
 $\mathbf{P}_{C\perp}$ hard scale
analysis at leading twist
 $\mathcal{O}(1/|\mathbf{P}_{C\perp}|)$



$$\begin{aligned} p_a &= x_a \mathbf{P}_A \\ p_b &= x_b \mathbf{P}_B \\ p_c &= \mathbf{P}_C / z_c \end{aligned}$$

$$s = (P_A + P_B)^2$$

$$t = (P_C - P_A)^2$$

$$u = (P_C - P_B)^2$$

$$\hat{s} = (p_a + p_b)^2 = x_a x_b s$$

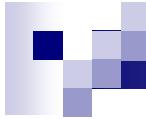
$$\hat{t} = (p_c - p_a)^2 = \frac{x_a}{z_c} t$$

$$\hat{u} = (p_c - p_b)^2 = \frac{x_b}{z_c} u$$

$$\cos \phi_{S_B} = \frac{(\hat{\mathbf{P}}_B \times \mathbf{P}_C) \cdot (\hat{\mathbf{P}}_B \times \mathbf{S}_B)}{|\hat{\mathbf{P}}_B \times \mathbf{P}_C| |\hat{\mathbf{P}}_B \times \mathbf{S}_B|}$$

$$\cos \phi_{R_C} = \frac{(\hat{\mathbf{P}}_C \times \mathbf{P}_A) \cdot (\hat{\mathbf{P}}_C \times \mathbf{R}_C)}{|\hat{\mathbf{P}}_C \times \mathbf{P}_A| |\hat{\mathbf{P}}_C \times \mathbf{R}_C|}$$

N.B. ϕ_{Sb} around P_B defined as ϕ_{SB}
 ϕ_{Sc} around P_C defined as ϕ_{RC}
 $\phi_{Sc} = \phi_{Sb}$



$$\pi(\vec{p}) \, p^{(\uparrow)} \rightarrow (\pi\pi) X$$

$$\frac{d\sigma}{d\eta_C d|\mathbf{P}_{C\perp}| dM_C^2 d\phi_{R_C} d\phi_{S_B}} = 2 |\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \int d\phi_{S_A} \int \frac{dx_a dx_b dz_c dz_d}{4\pi^2 z_c^2} \hat{s} \delta(\hat{s} + \hat{t} + \hat{u})$$

$$\times \Phi_a(x_a, S_A) \Phi_b(x_b, S_B) \frac{d\hat{\sigma}_{ab \rightarrow cd}}{d\hat{t}} \Delta_c(z_c, M_C^2, \phi_{R_C}) \delta(z_d - 1)$$

$$= d\sigma_{UU} + |\mathbf{S}_{BT}| \frac{|\mathbf{R}_C|}{M_C} \sin(\phi_{S_B} - \phi_{R_C}) d\sigma_{UT}$$

$$d\sigma_{UU}$$

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

$$d\sigma_{UT}$$

$$f_1 \otimes$$

$$h_1 \otimes$$

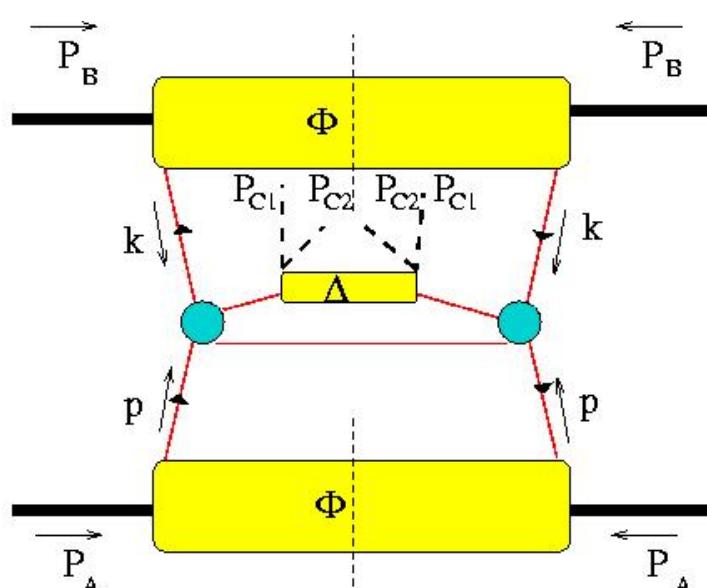
$$\hat{\sigma}_{ab \rightarrow cd} \otimes D_1$$

$$d\Delta\hat{\sigma}_{ab \uparrow \rightarrow c \uparrow d} \otimes H_1^{\cancel{c}}$$

$$\otimes$$

$$f_1$$

$$f_1$$

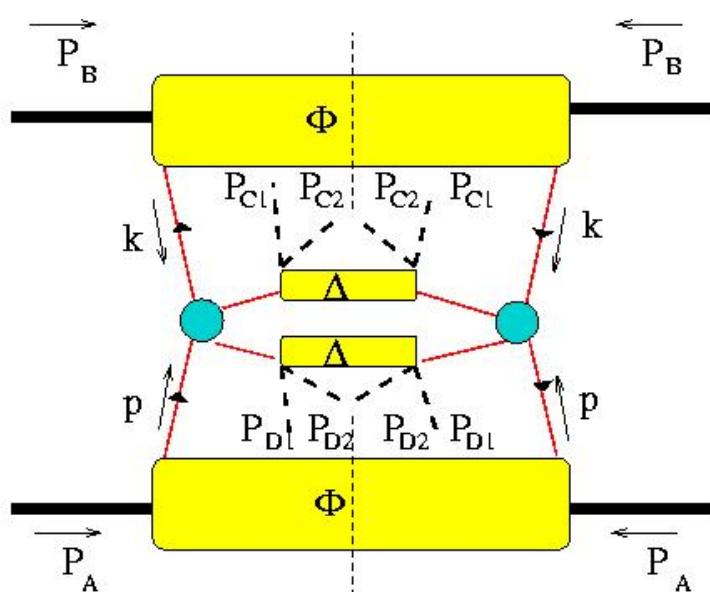


$$\begin{aligned} qq &\rightarrow qq & qq' &\rightarrow q'q \\ q\bar{q} &\rightarrow q\bar{q} & q\bar{q} &\rightarrow q'\bar{q}' \\ q\bar{q} &\rightarrow gg & qg &\rightarrow qg \\ gg &\rightarrow gg & gg &\rightarrow q\bar{q} \end{aligned}$$

$$\boxed{\begin{aligned} q q^\uparrow &\rightarrow q^\uparrow q & q q'^\uparrow &\rightarrow q'^\uparrow q \\ q \bar{q}^\uparrow &\rightarrow q^\uparrow \bar{q} & q \bar{q}^\uparrow &\rightarrow \bar{q}^\uparrow q \\ g q^\uparrow &\rightarrow q^\uparrow g \end{aligned}}$$

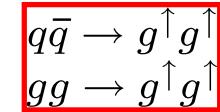
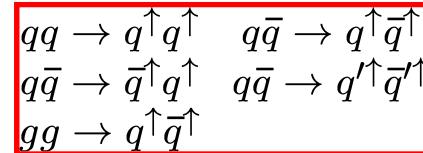
$$\pi(\bar{p}) p \rightarrow (\pi \pi)_C (\pi \pi)_D X$$

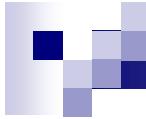
$$\begin{aligned} \frac{d\sigma}{d\eta_C d|\mathbf{P}_{C\perp}| dM_C^2 d\phi_{R_C} d\eta_D d|\mathbf{P}_{D\perp}| dM_D^2 d\phi_{R_D}} &= 2 \sum_{a,b,c,d} \int d\phi_{S_A} d\phi_{S_B} \int \frac{dx_a dx_b dz_c dz_d}{4\pi^2} \\ &\times \hat{s} \delta(\hat{s} + \hat{t} + \hat{u}) \Phi_a(x_a, S_A) \Phi_b(x_b, S_B) \frac{d\hat{\sigma}_{ab \rightarrow cd}}{d\hat{t}} \Delta_c(z_c, M_C^2, \phi_{R_C}) \Delta_d(z_d, M_D^2, \phi_{R_D}) \\ &= \mathcal{A} + \frac{|\mathbf{R}_C| |\mathbf{R}_D|}{M_C M_D} \cos(\phi_{R_C} - \phi_{R_D}) \mathcal{B} + \frac{|\mathbf{R}_C^2| |\mathbf{R}_D^2|}{M_C^2 M_D^2} \cos(2\phi_{R_C} - 2\phi_{R_D}) \mathcal{C} \end{aligned}$$



self-consistent extraction of
 $D_1, H_1^\leftrightarrow \Rightarrow h_1$

\mathcal{A}	\mathcal{B}	\mathcal{C}
f_1	f_1	f_1
\otimes	\otimes	\otimes
$d\hat{\sigma}_{ab \rightarrow cd}$	$d\Delta\hat{\sigma}_{ab \rightarrow cd}$	$d\Delta\hat{\sigma}_{ab \rightarrow g^\uparrow g^\uparrow}$
$\otimes D_1 \otimes D_1$	$\otimes H_1^\leftrightarrow c \otimes H_1^\leftrightarrow d$	$\otimes \delta\hat{G}^\leftrightarrow c \otimes \delta\hat{G}^\leftrightarrow d$
\otimes	\otimes	\otimes
f_1	f_1	f_1





or extracted self consistently also from p-p collisions (Bacchetta, M.R. 2004)

$$p\ p^\uparrow \rightarrow (\pi\pi) X \quad SSA \sim d\sigma^\uparrow - d\sigma^\downarrow \propto (S_T \times R_T)_{\hat{p}} \sum_{abc} f_1^a \otimes h_1^b \otimes \Delta\hat{\sigma} \otimes H_1^{\not{c}}$$

$$\Delta\hat{\sigma} = d\hat{\sigma}(ab^\uparrow \rightarrow c^\uparrow d) - d\hat{\sigma}(ab^\uparrow \rightarrow c^\downarrow d)$$

$$p\ p \rightarrow (\pi\pi)_C (\pi\pi)_D X \quad SSA \sim d\sigma^\uparrow - d\sigma^\downarrow \propto R_{TC} \cdot R_{TD} \sum_{abcd} f_1^a \otimes f_1^b \otimes \Delta\hat{\sigma} \otimes H_1^{\not{c}} \otimes H_1^{\not{d}}$$

$$\Delta\hat{\sigma} = d\hat{\sigma}(ab \rightarrow c^\uparrow d^\uparrow) - d\hat{\sigma}(ab \rightarrow c^\uparrow d^\downarrow) - d\hat{\sigma}(ab \rightarrow c^\downarrow d^\uparrow) + d\hat{\sigma}(ab \rightarrow c^\downarrow d^\downarrow)$$

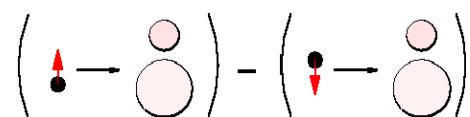
$$SSA \sim d\sigma^\uparrow - d\sigma^\downarrow \propto [(R_{TC} \cdot R_{TD})^2 - (R_{TC} \times R_{TD})^2] \sum_{abcd} f_1^a \otimes f_1^b \otimes \Delta\hat{\sigma} \otimes \delta\hat{G}^{\not{c}} \otimes \delta\hat{G}^{\not{d}}$$

$$d\hat{\sigma} : q\bar{q} \rightarrow g^\uparrow g^\uparrow \quad gg \rightarrow g^\uparrow g^\uparrow$$

$$\Delta\hat{\sigma} = d\hat{\sigma}(ab \rightarrow g^\uparrow g^\uparrow) - d\hat{\sigma}(ab \rightarrow g^\uparrow g^\downarrow) - d\hat{\sigma}(ab \rightarrow g^\downarrow g^\uparrow) + d\hat{\sigma}(ab \rightarrow g^\downarrow g^\downarrow)$$

$\delta\hat{G}^{\not{x}}$ same as $H_1^{\not{x}}$ for gluons

available for spin $1/2$ hadron
otherwise chiral-odd δg for spin ≥ 1



Conclusions: perspectives for (\perp polarized) hadronic collisions at COMPASS

1. Drell-Yan

- large asymmetries expected because of leading-twist TMD f_{1T}^\perp , h_1^\perp , and chiral-odd transversity h_1 (see Haegler talk)
- target dilution factor (NH_3^\uparrow) and exp. constraints (NA10, E615,...) reduce size of asymmetry, but
- outcome of MC simulation: good statistics in short running time (preliminary & optimistic → see Denisov talk) allows to disentangle bulk features of most important effects: violation of Lam-Tung sum rule, sign change of f_{1T}^\perp and h_1^\perp in SIDIS ↔ Drell-Yan, .., alternative source of info on h_1 ?

2. Semi-inclusive production of low p_T pion pairs

- induced asymmetry already measured in SIDIS
- hadronic collisions: possibility of self-consistent extraction of all unknowns (Dihadron fragmentation functions) → alternative source of info on h_1 ,
- requires q^\uparrow in the “target fragmentation region” → check acceptance (see Denisov talk)