Spin physics with antiprotons

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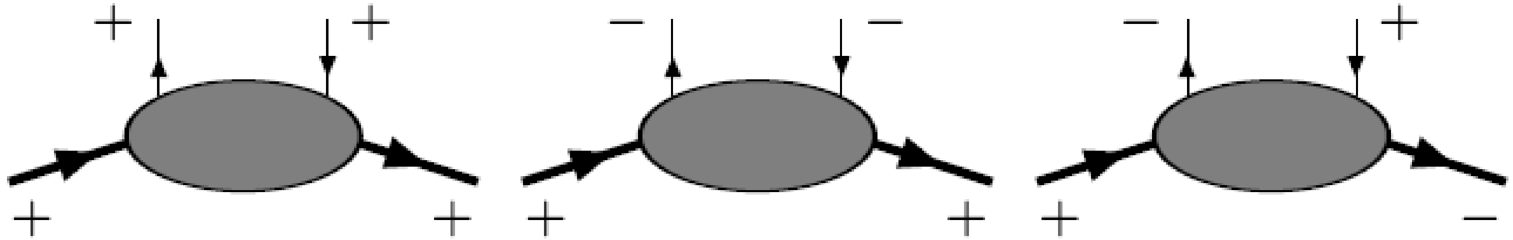
- Transversity distribution h_1
- Why at PAX
- First estimate of h_1
  Anselmino et al. PRD75(2007)054032
- Measuring the transverse sea
- About single spin asymmetries

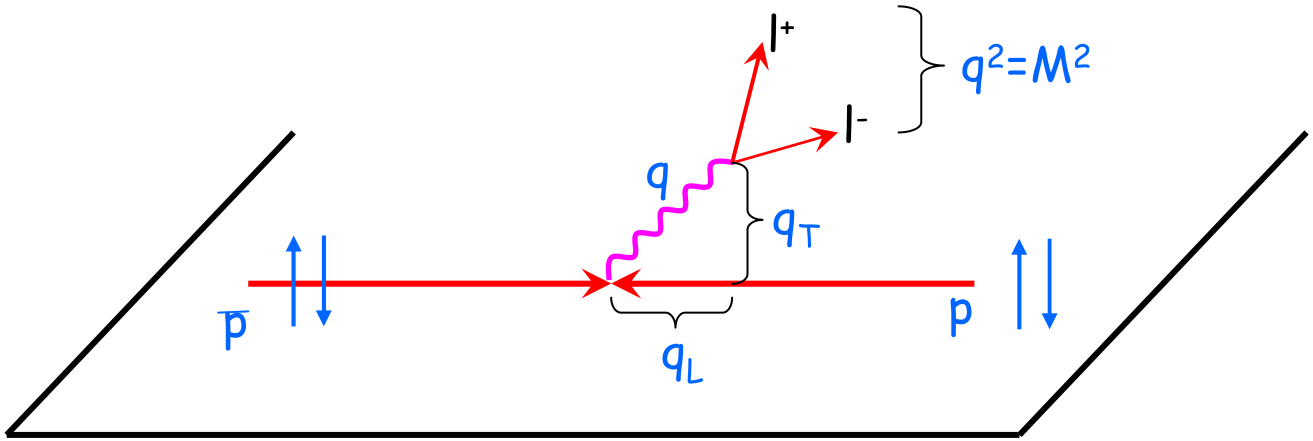
The three leading twist (and transverse momentum integrated) quark distributions



$$f(x) = f_+(x) + f_-(x) \sim \mathrm{Im}(\mathcal{A}_{++,++} + \mathcal{A}_{+-,+-}) \,,$$
$$\Delta f(x) = f_+(x) - f_-(x) \sim \mathrm{Im}(\mathcal{A}_{++,++} - \mathcal{A}_{+-,+-}) \,,$$
$$\Delta_T f(x) = f_\uparrow(x) - f_\downarrow(x) \sim \mathrm{Im}\,\mathcal{A}_{+-,-+} \,.$$

Transversity in Drell-Yan processes

PAX: Polarized antiproton beam → polarized proton target (both transverse)



$$A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)}$$

$q = u, \bar{u}, d, \bar{d}, \ldots$

M invariant Mass of lepton pair

A_{TT} for PAX kinematic conditions

RHIC: $\tau = x_1 x_2 = M^2/s \sim 10^{-3}$

→ Exploration of the sea quark content at very small x

A_{TT} very small (~ 1 %)

PAX: $M^2 \sim 10\text{-}100\ GeV^2$, $s \sim 45\text{-}200\ GeV^2$, $\tau = x_1 x_2 = M^2/s \sim 0.05\text{-}0.6$

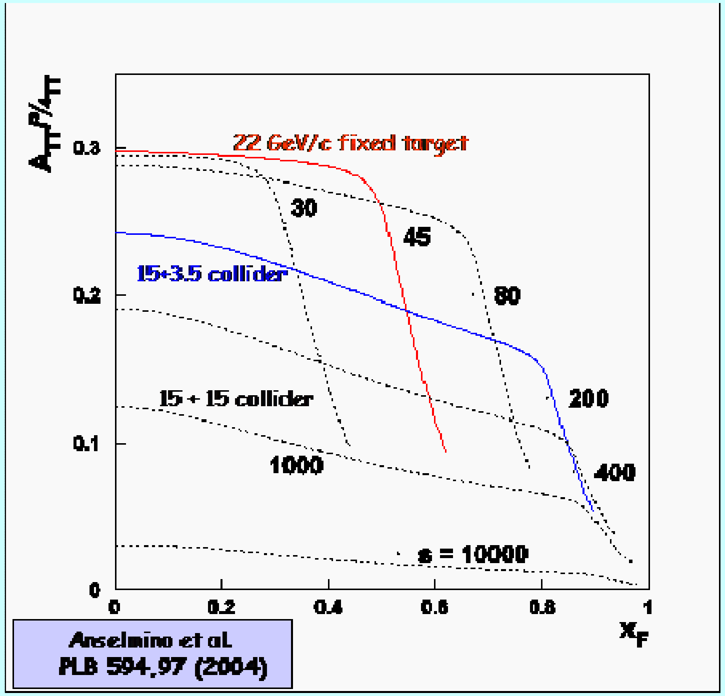
→ Exploration of valence quarks ($h_1^q(x,Q^2)$ large)

$A_{TT}/a_{TT} > 0.2$

Models predict $|h_1^u| \gg |h_1^d|$

$$A_{TT} = \hat{a}_{TT} \frac{h_1^u(x_1,M^2) h_1^u(x_1,M^2)}{u(x_1,M^2) u(x_1,M^2)}$$

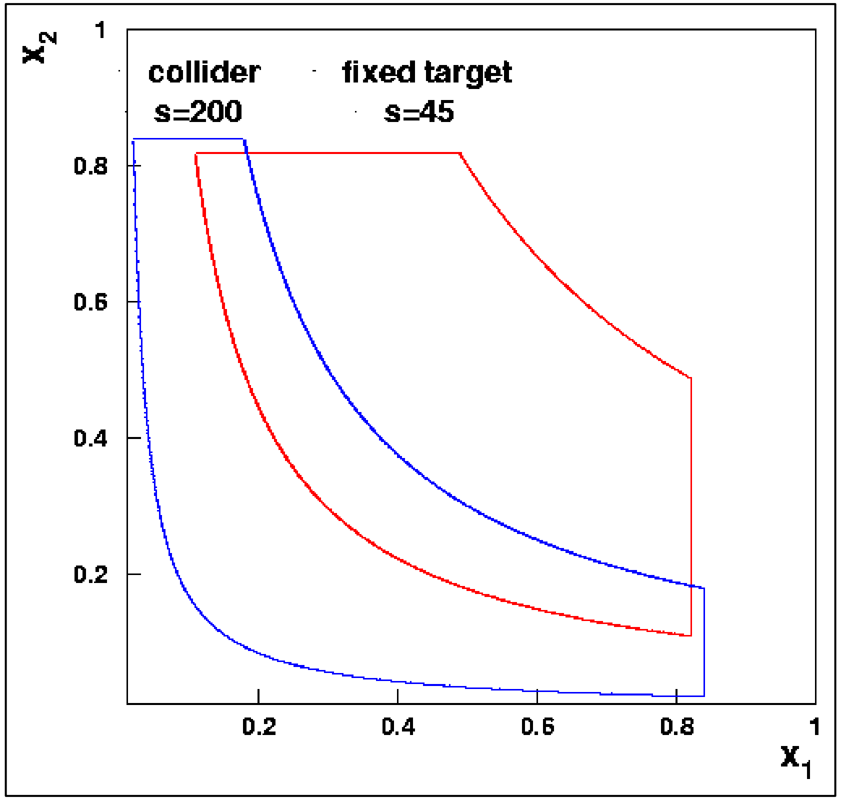
$$(\text{where } \bar{q}^{\bar{p}} = q^p = q)$$

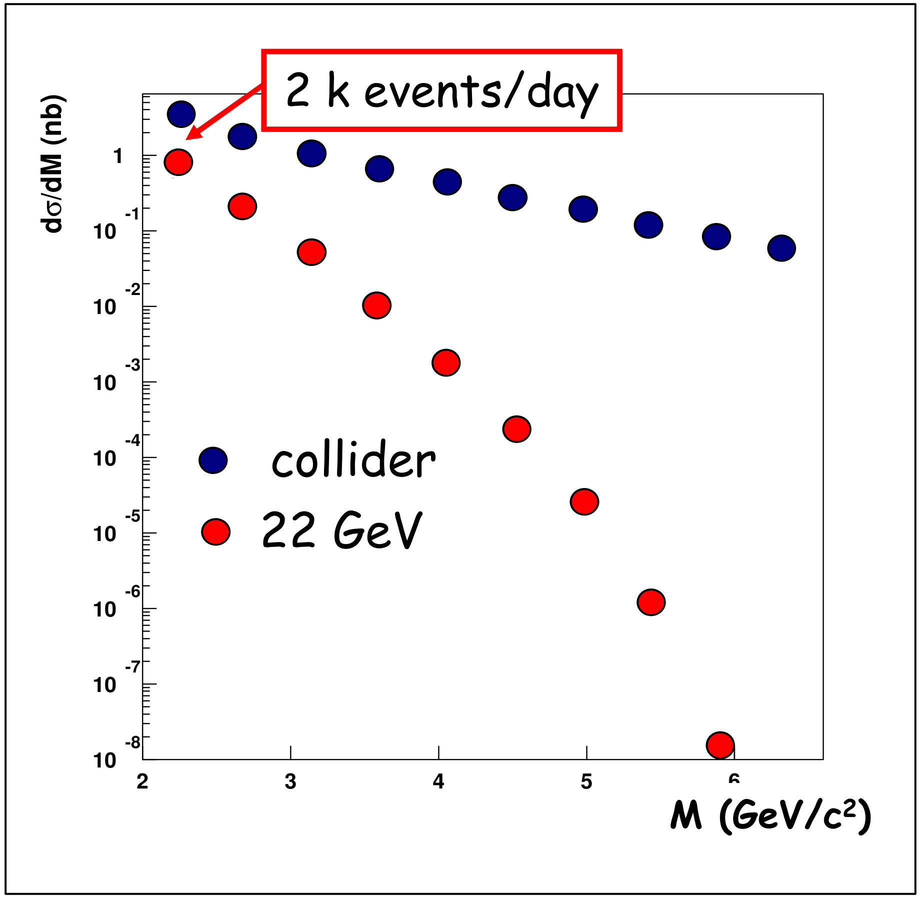


Kinematics and cross section

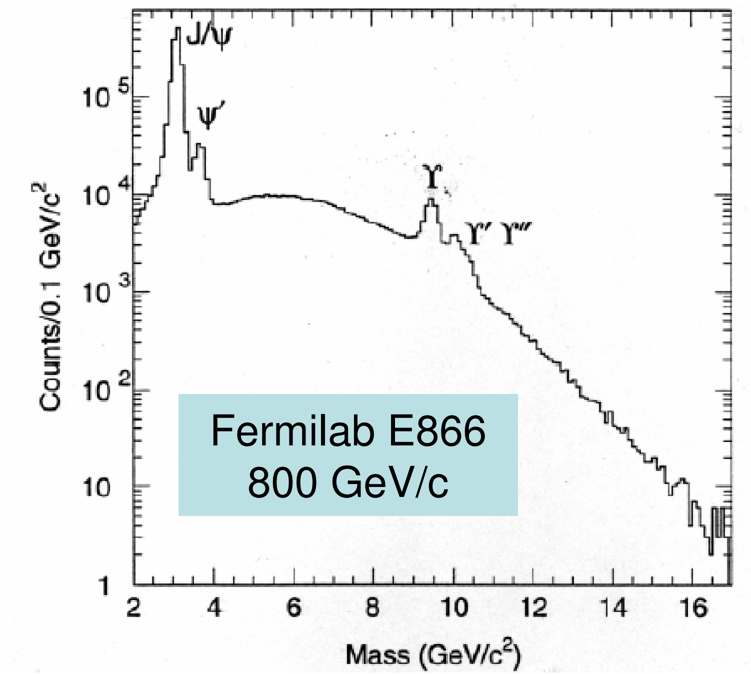
$$\frac{d^2\sigma}{dM^2 dx_F} = \frac{4\alpha^2\pi}{9M^2 s(x_1+x_2)} \cdot \sum_q e_q^2 \left[q(x_1,M^2)\bar{q}(x_2,M^2) + \bar{q}(x_1,M^2)q(x_2,M^2) \right]$$

- $M^2 = s\, x_1 x_2$
- $x_F = 2Q_L/\sqrt{s} = x_1 - x_2$





Energy for Drell-Yan processes



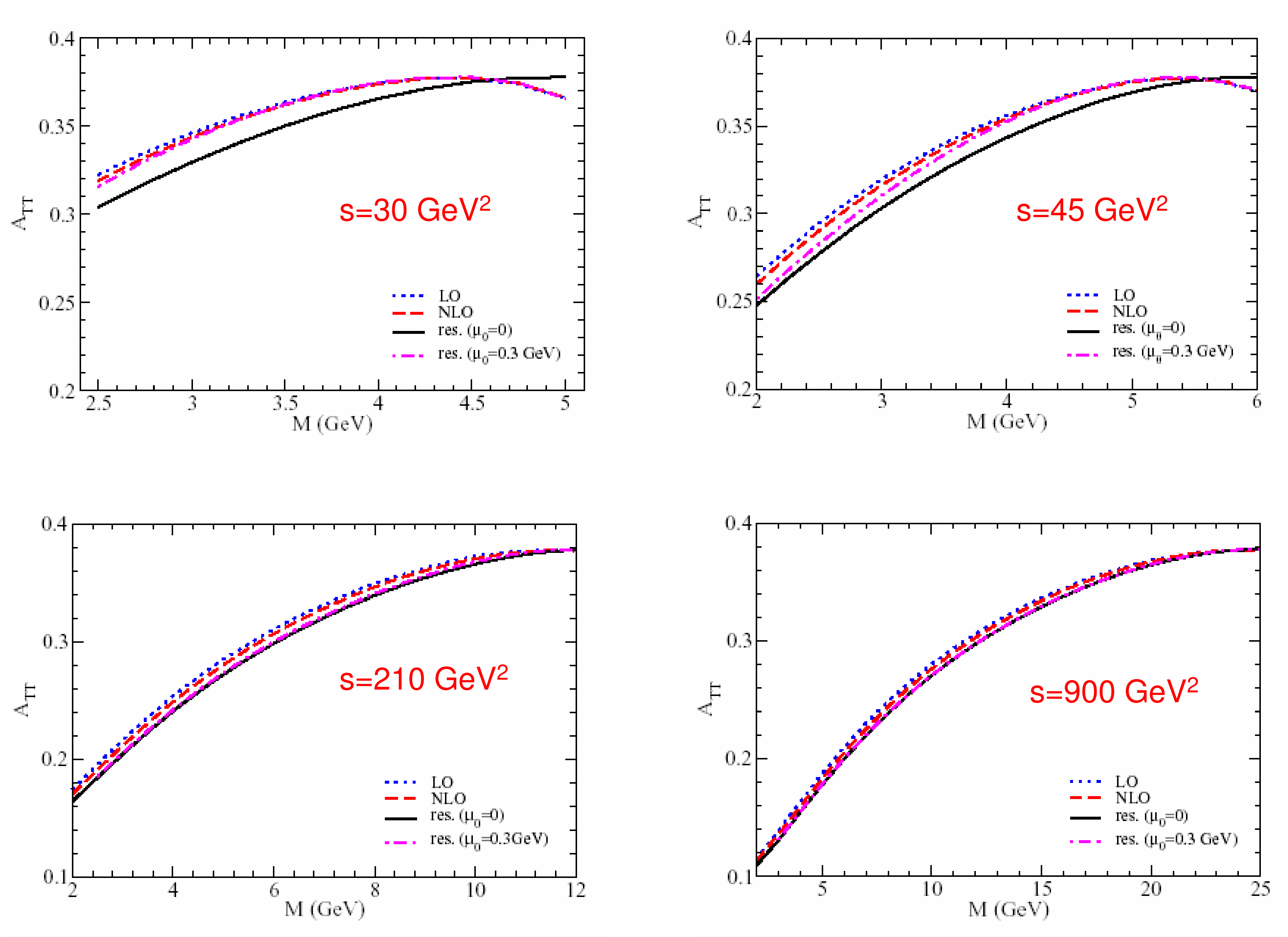
"safe region": $M \geq M_{J/\Psi}$

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

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

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

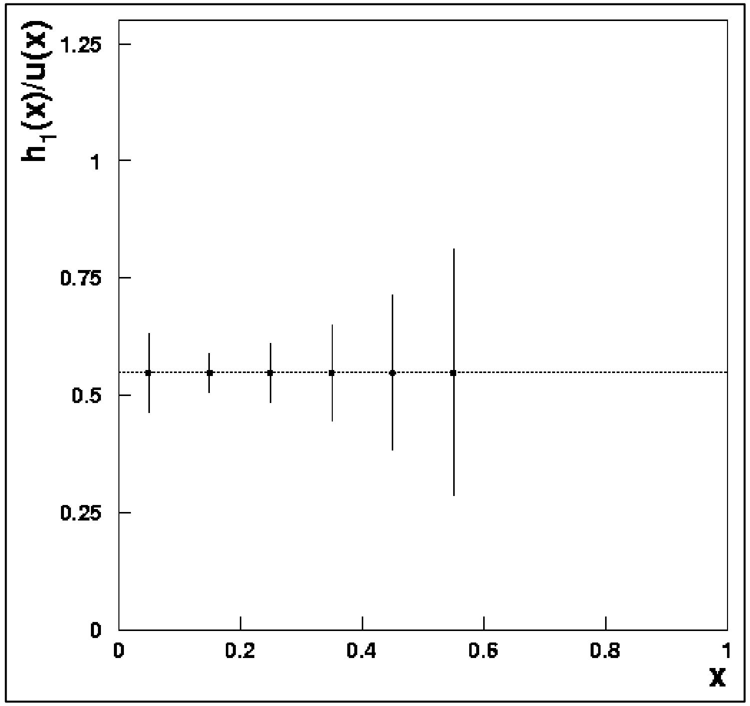
H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya, hep-ph/0503270

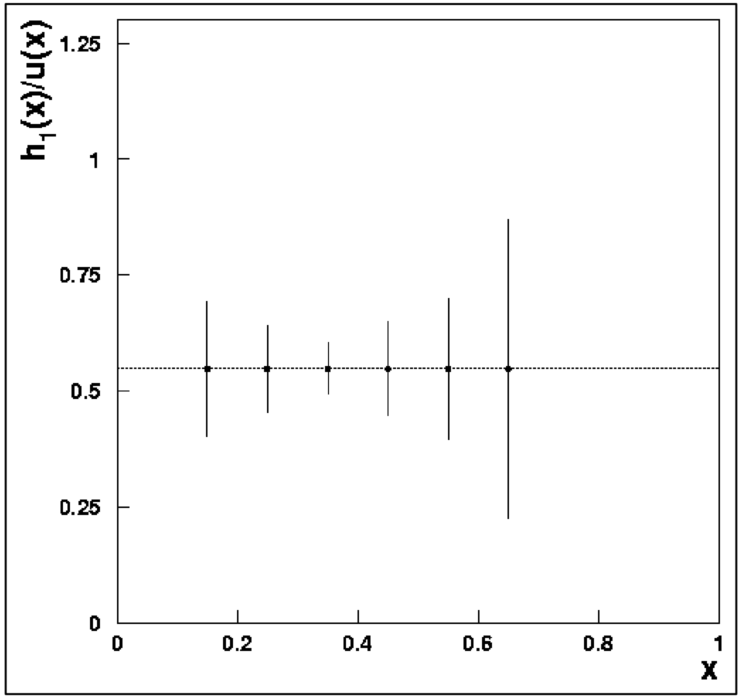


s=30 GeV²
s=45 GeV²
s=210 GeV²
s=900 GeV²
A_{TT}
M (GeV)
LO
NLO
res. (μ_0=0)
res. (μ_0=0.3 GeV)

Estimated signal for h_1 (phase II)

1 year of data taking





Collider:

$L=2\times10^{30}\ cm^{-2}s^{-1}$

Fixed target:

$L=2.7\times10^{31}\ cm^{-2}s^{-1}$

How to estimate transversity from present data?

Transversity and Collins from SIDIS

$$A_{UT}^{\sin(\phi_S+\phi_h)} = \frac{\sum_q e_q^2 \int d\phi_S\, d\phi_h\, d^2\boldsymbol{k}_\perp\, \Delta_T q(x,k_\perp)\, \frac{d(\Delta\hat\sigma)}{dy}\, \Delta^N D_{h/q^\uparrow}(z,p_\perp) \sin(\phi_S+\varphi+\phi_q^h)\sin(\phi_S+\phi_h)}{\sum_q e_q^2 \int d\phi_S\, d\phi_h\, d^2\boldsymbol{k}_\perp\, f_{q/p}(x,k_\perp)\, \frac{d\hat\sigma}{dy}\, D_{h/q}(z,p_\perp)}$$

Collins from $e_+ e_- \longrightarrow h_1\, h_2\, X$

$$\frac{d\sigma^{e^+e^-\to h_1 h_2 X}}{dz_1\, dz_2\, d\cos\theta\, d(\varphi_1+\varphi_2)} = \frac{3\alpha^2}{4s}\sum_q e_q^2 \Big\{(1+\cos^2\theta)\, D_{h_1/q}(z_1)\, D_{h_2/\bar q}(z_2) + \frac{1}{4}\sin^2\theta\, \cos(\varphi_1+\varphi_2)\, \Delta^N D_{h_1/q^\uparrow}(z_1)\, \Delta^N D_{h_2/\bar q^\uparrow}(z_2)\Big\}$$

Parametrizations for transversity distribution and Collins function
Anselmino et al. 2007

$$\Delta_T q(x, k_\perp) = \frac{1}{2} \mathcal{N}_q^T(x) \; [f_{q/p}(x) + \Delta q(x)] \; \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle_T}}{\pi \langle k_\perp^2 \rangle_T}$$

$$\Delta^N D_{h/q^\uparrow}(z, p_\perp) = 2 \mathcal{N}_q^C(z) \; D_{h/q}(z) \; h(p_\perp) \; \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\pi \langle p_\perp^2 \rangle}$$

$$\mathcal{N}_q^T(x) = N_q^T \; x^\alpha (1-x)^\beta \, \frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^\alpha \beta^\beta} \,,$$

$$\mathcal{N}_q^C(z) = N_q^C \; z^\gamma (1-z)^\delta \, \frac{(\gamma+\delta)^{(\gamma+\delta)}}{\gamma^\gamma \delta^\delta} \,,$$

$$h(p_\perp) = \sqrt{2e} \, \frac{p_\perp}{M} \, e^{-p_\perp^2/M^2} \,,$$

Asymmetries in Hermes and Compass from Anselmino et al. 2007

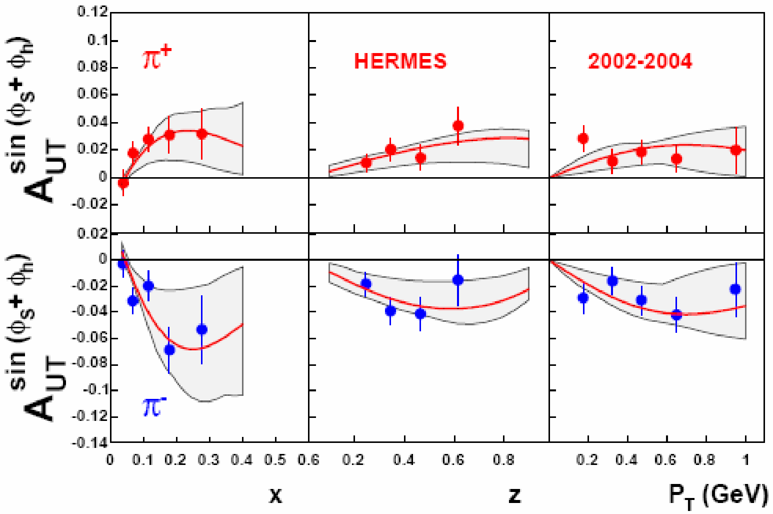


FIG. 4: HERMES experimental data [8, 9] on the azimuthal asymmetry $A_{UT}^{\sin(\phi_S+\phi_h)}$ for $\pi^{\pm}$ production are compared to the curves obtained from Eq. (20) with the parameterizations of Eqs. (13)-(17), and the parameter values, determined through our global best fit, given in Table I. The shaded area corresponds to the theoretical uncertainty on the parameters, as explained in the text.

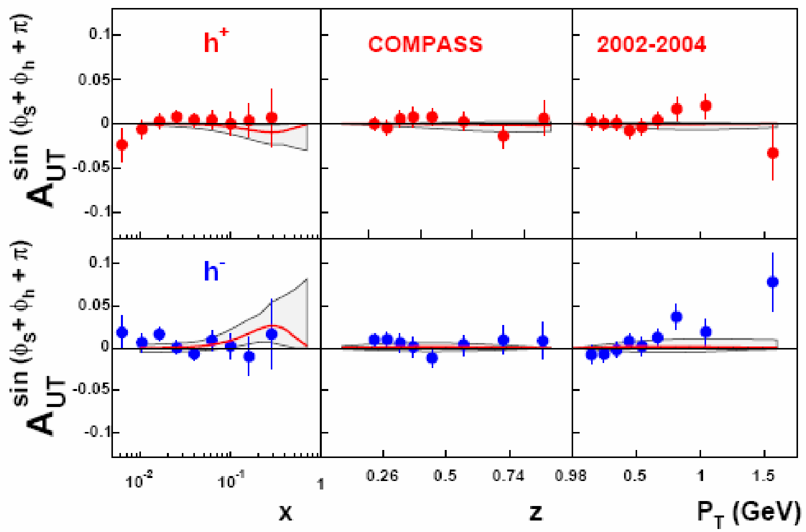
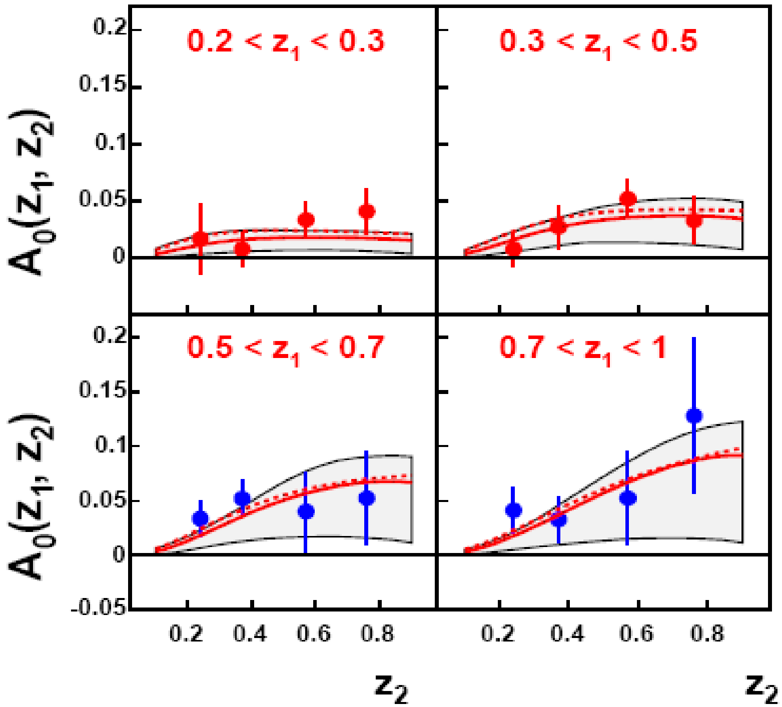
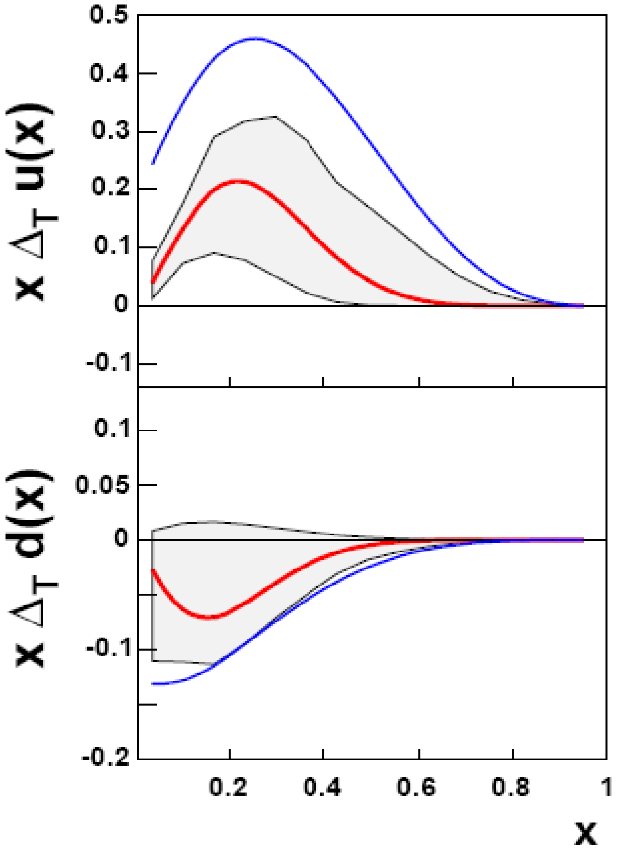


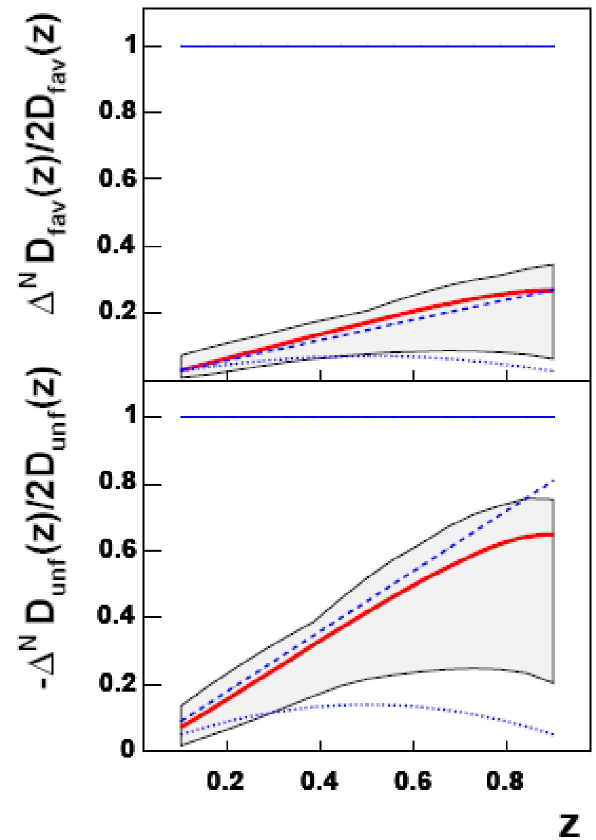
FIG. 5: The measurements of $A_{UT}^{\sin(\phi_S+\phi_h)}$, for the production of positively and negatively charged hadrons, from the COMPASS experiment operating on a deuterium target [10] are compared to the curves obtained from Eq. (20) with the parameterizations of Eqs. (13)-(17), and the parameter values, determined through our global best fit, given in Table I.

Asymmetries from Belle from Anselmino et al. 2007



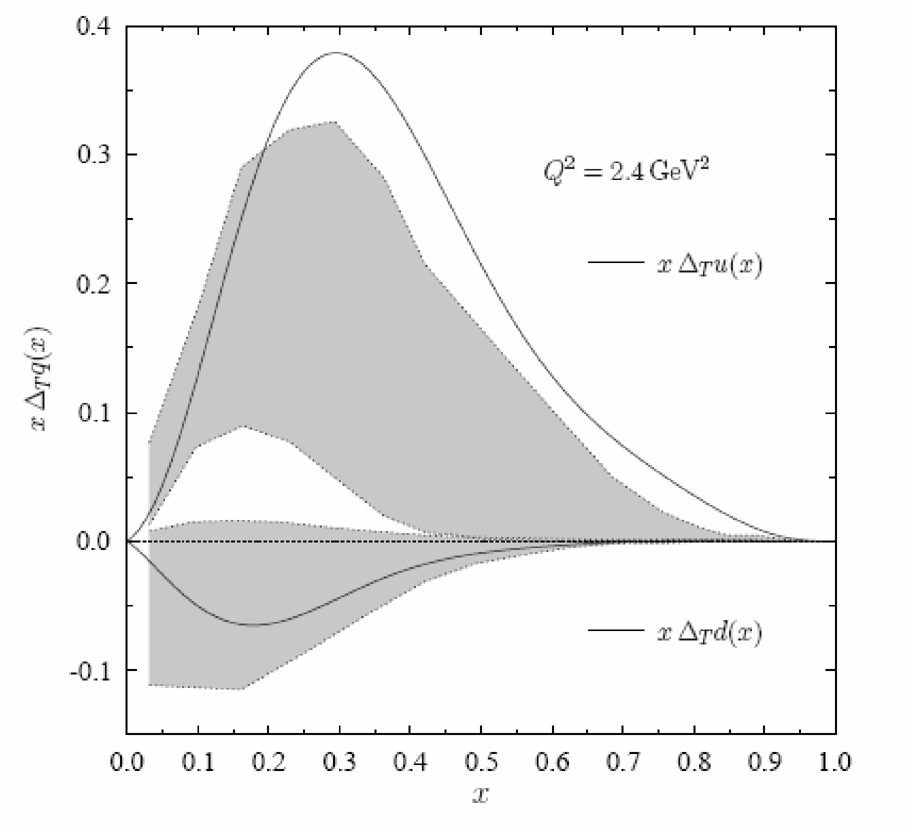
Transversity and Collins function
Anselmino et al. 2007





Soffer inequality $f(x) + \Delta f(x) \geq 2|\Delta_T f(x)|$

Comparing Anselmino et al. to CQSM Wakamatsu 2007



Vector, axial and tensor charges

$$\int_{-1}^{+1} \mathrm{d}x\, f(x) = \int_0^1 \mathrm{d}x \left[f(x) - \bar{f}(x)\right] = g_V \,,$$

$$\int_{-1}^{+1} \mathrm{d}x\, \Delta f(x) = \int_0^1 \mathrm{d}x \left[\Delta f(x) + \Delta\bar{f}(x)\right] = g_A \,,$$

$$\int_{-1}^{+1} \mathrm{d}x\, \Delta_T f(x) = \int_0^1 \mathrm{d}x \left[\Delta_T f(x) - \Delta_T\bar{f}(x)\right] = g_T \,.$$

Tensor charges

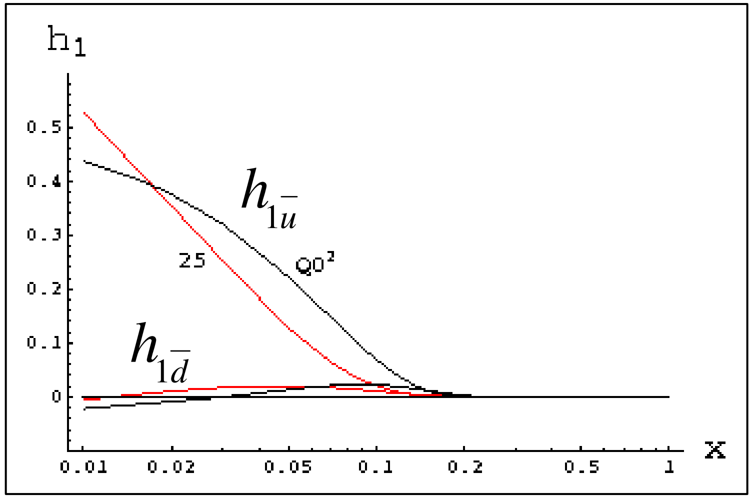
Model [Ref.]	Δu	Δd	$\Delta\Sigma$	δu	δd	**δu+δd**	$\lvert\delta u/\delta d\rvert$	Q_0[GeV]	$\delta u(Q^2)$	$\delta d(Q^2)$
NRQM ⋆	1.33	-0.33	1	1.33	-0.33	**1**	4.03	0.28	0.97	-0.24
MIT [14] ◇	0.87	-0.22	0.65	1.09	-0.27	**0.82**	4.04	0.87	0.99	-0.25
CDM [92] ⊕	1.08	-0.29	0.79	1.22	-0.31	**0.91**	3.94	0.40	0.99	-0.25
CQSM1 [223] ×	0.90	-0.48	0.37	1.12	-0.42	**0.70**	2.67	0.60	0.97	-0.37
CQSM2 [226] +	0.88	-0.53	0.35	0.89	-0.33	**0.56**	2.70	0.60	0.77	-0.29
CQM [231] ⊗	0.65	-0.22	0.43	0.80	-0.15	**0.65**	5.33	0.80	0.72	-0.13
LC [86] ∘	1.00	-0.25	0.75	1.17	-0.29	**0.88**	4.03	0.28	0.85	-0.21
Spect. [252] ∗	1.10	-0.18	0.92	1.22	-0.25	**0.87**	4.88	0.25	0.83	-0.17
Lattice [260] ▷	0.64	-0.35	0.29	0.84	-0.23	**0.61**	3.65	1.40	0.80	-0.22

Anselmino et al. central values $\delta u \simeq 0.49, \quad \delta d \simeq -0.20,$ $\delta u \simeq 0.39, \quad \delta d \simeq -0.16,$

→ Extremely small δu ; δu+δd similar to Δu+Δd ←

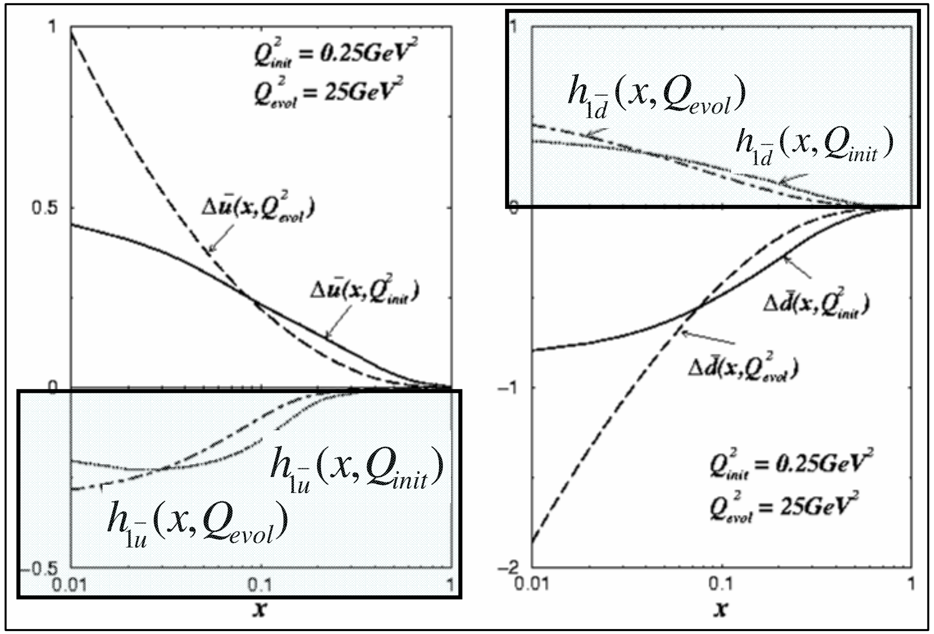
Transverse sea

CDM



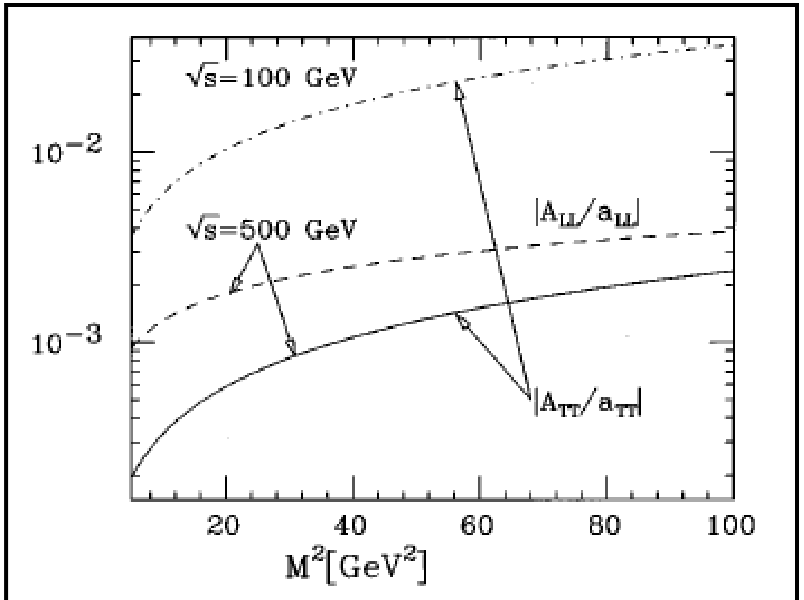
V. Barone, T. Calarco and A. Drago
Phys. Lett. B 390 (1997) 287

CQSM

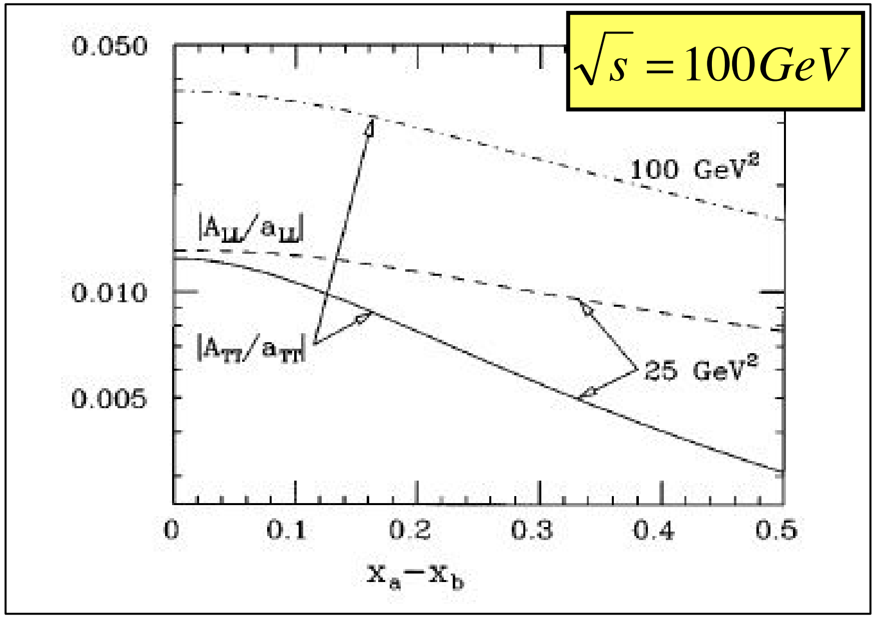


M. Wakamatsu and T. Kubota
Phys. Rev. D 63 (1999) 034020

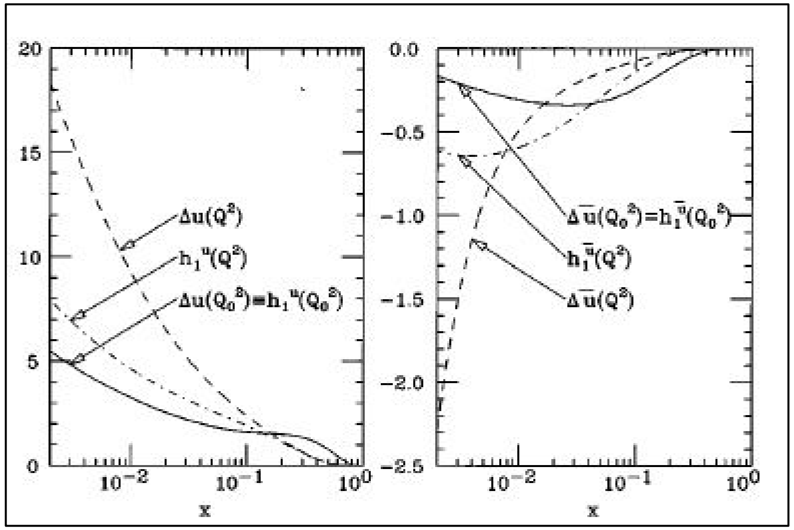
High energy p-p machine



V. Barone, T. Calarco and A. Drago
Phys. Rev. D 56 (1997) 527

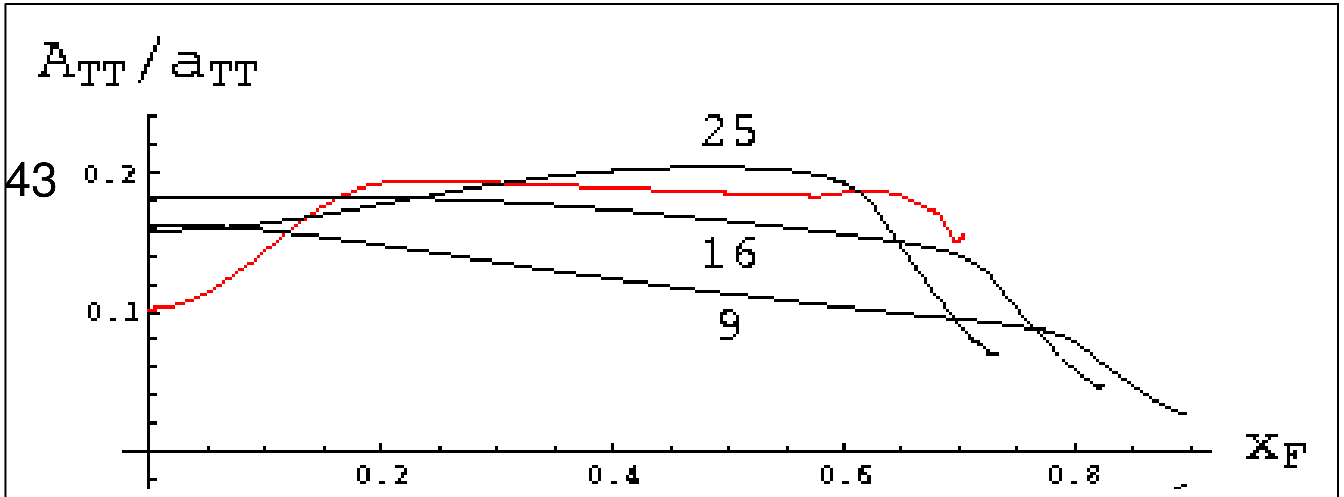


Small asymmetries

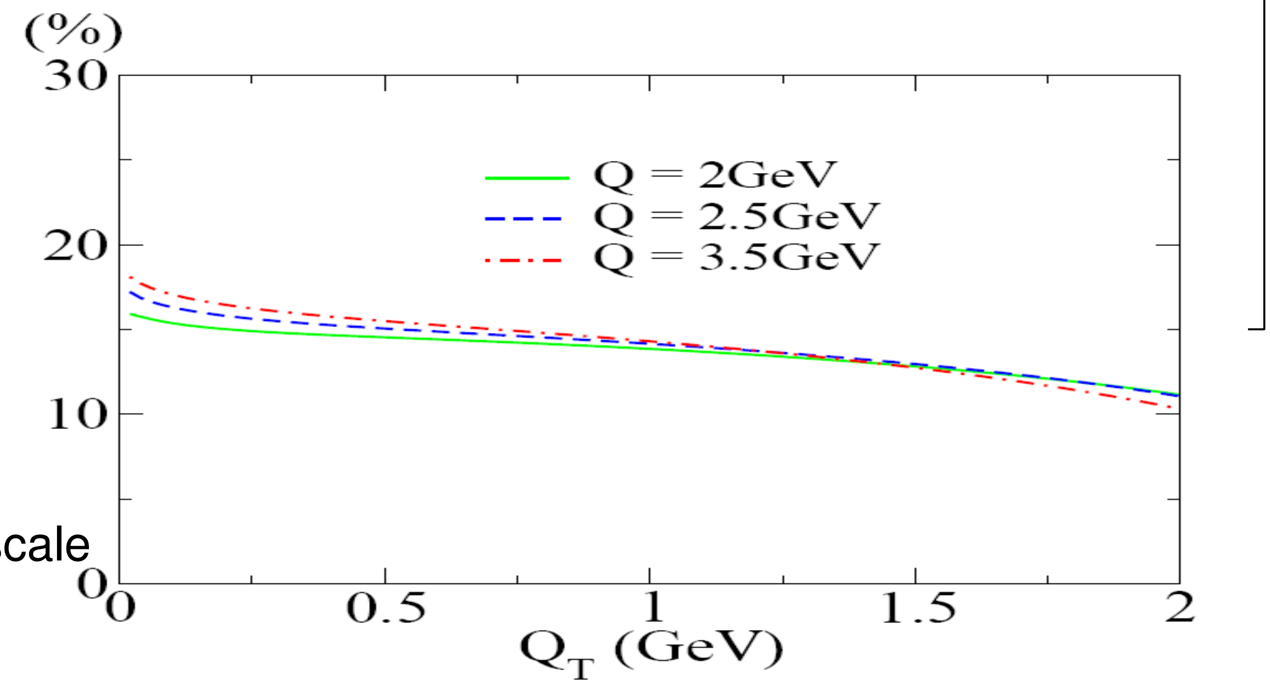


Drell-Yan asymmetries in pp at **moderate energies**

Contalbrigo, A.D., Lenisa
Hep-ph/0607143
Bag models



Kawamura et al.
hep-ph/0703079
Assuming Soffer saturated at low scale



Measuring the Sivers function

$$A_N^{\text{D-Y}} \propto f_{1T}^{\perp}(x_1, k_{1\perp}) \otimes f(x_2)$$

Direct access to Sivers function

Sivers function — usual parton distribution

test QCD basic result: $(f_{1T}^{\perp})_{\text{D-Y}} = -(f_{1T}^{\perp})_{\text{DIS}}$ J. Collins

$$A_N^{p\bar{p}\to DX} \propto (f_{1T}^{\perp})_q \otimes D_q$$

process dominated by $q\bar{q} \to c\bar{c}$
no Collins contribution

usual fragmentation function

same process at RHIC is dominated by $gg \to c\bar{c}$

Sivers function non-vanishing in gauge theories.
Chiral models with vector mesons as gauge bosons can be used A.D. PRD71(2005)057501.

$(\text{Sivers})_u = -(\text{Sivers})_d$ in chiral models at leading order in $1/N_c$.

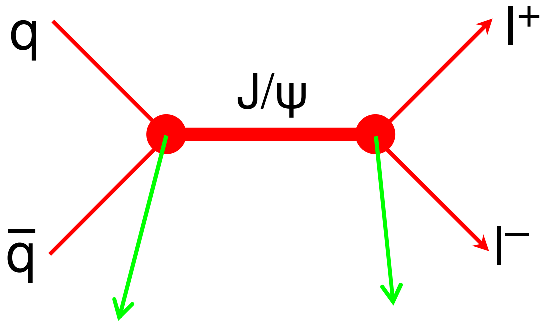
PAX project on transversity

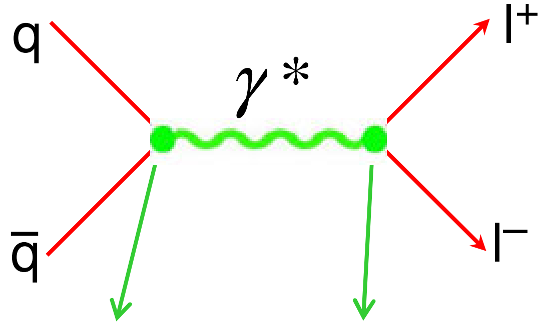
- Extract the transversity distribution of quarks in the valence region from Drell-Yan production in transversely polarized p - (anti p)

Possible extensions:

- Extract the transversity distribution of anti-quarks in the valence region from Drell-Yan production in transversely polarized p – p
- Flavor separation by (anti p)-deuterium scattering

$$p\bar{p} \to J/\Psi\, X \to l^+ l^-$$





$$\frac{(g_q^V \bar{v}\gamma^\mu u)(g_l^V \bar{u}\gamma_\mu v)}{M^2 - M_{J/\Psi}^2 + i\,\Gamma M_{J/\Psi}} \qquad \frac{(e_q \bar{v}\gamma^\mu u)(e\,\bar{u}\gamma_\mu v)}{M^2}$$

all vector couplings, same spinor structure

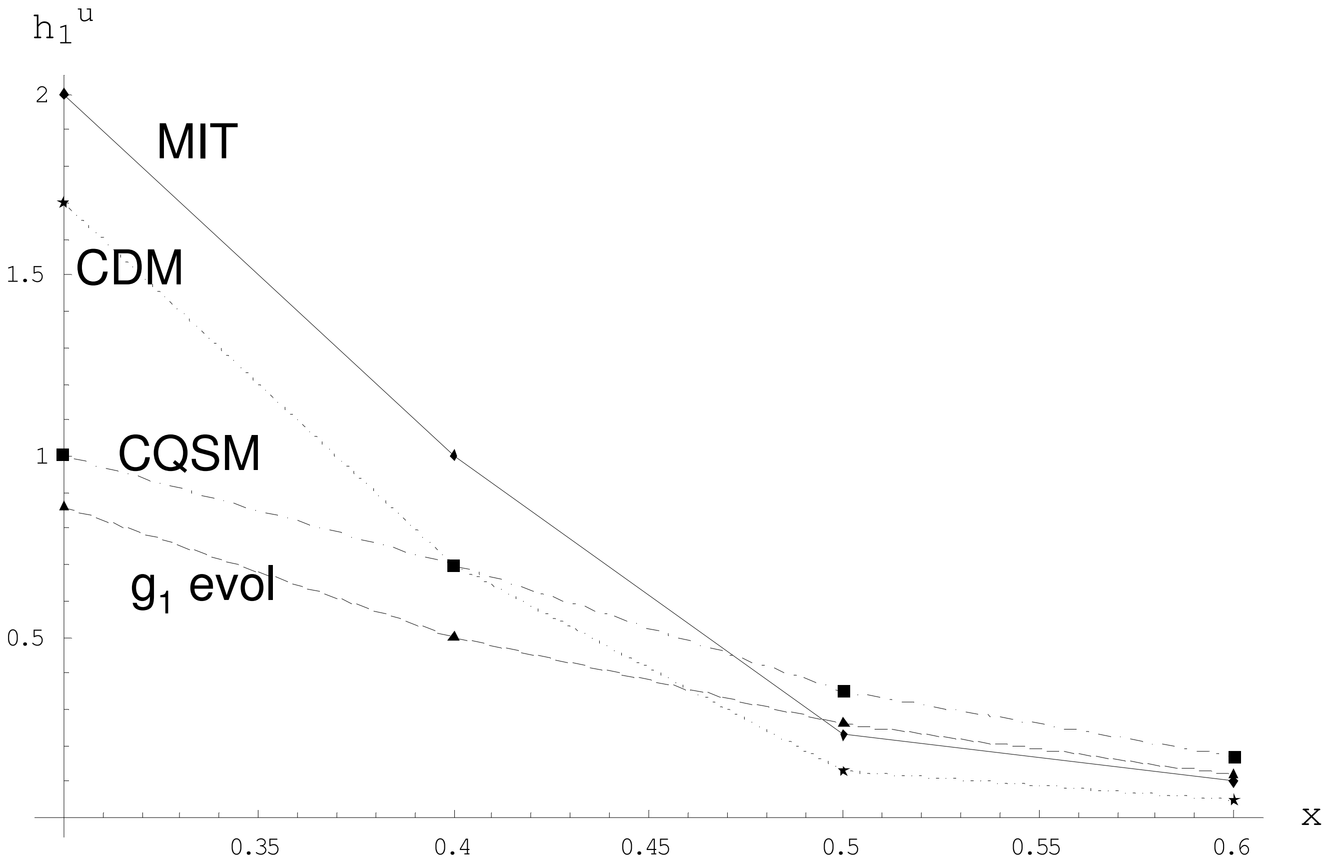
$\Rightarrow$ $\hat{a}_{TT}^{J/\Psi} = \hat{a}_{TT}^{\gamma^*}$ and, at large x_1, x_2

$$A_{TT} \approx \hat{a}_{TT}\,\frac{\sum_q (g_q^V)^2 h_{1q}(x_1) h_{1q}(x_2)}{\sum_q (g_q^V)^2 q(x_1) q(x_2)} \approx \frac{h_{1u}(x_1) h_{1u}(x_2)}{u(x_1) u(x_2)}$$

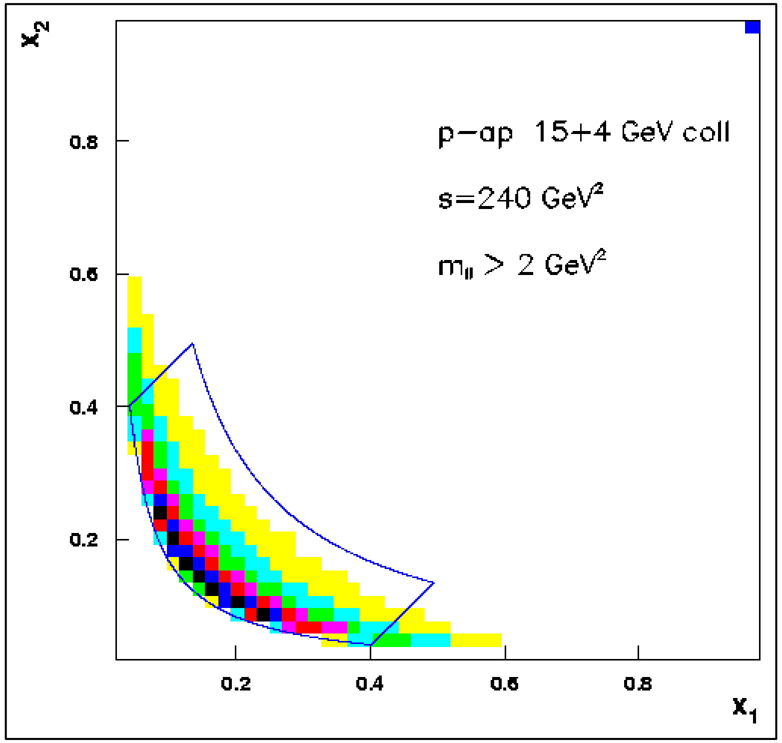
measure A_{TT} also in J/ψ resonance region

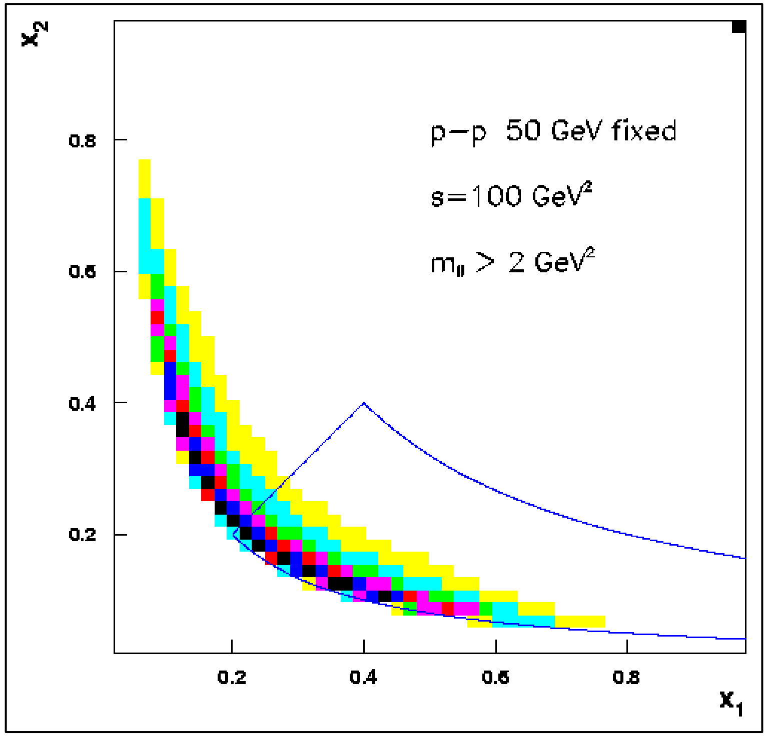
M. Anselmino, V. Barone, A. D. and N. Nikolaev PLB 594 (2004) 97

Transversity in various quark models



DY events distribution





$M^2/s = x_1 x_2 \sim 0.01\text{-}0.3$

$x_1 = x_2 \Longrightarrow A_{TT} \propto h_{1u}^{\,2}$

Measurement of h_{1u} for $0.15 < x < 0.5$

→ Extraction of $h_{1\bar{u}}$ for $0.05 < x < 0.2$

complete mapping of transversity