1958

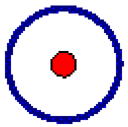
Nucleon Spin Structure Today and Tomorrow

2013

Anatoly Efremov, JINR, Dubna

- Introduction. Parton model of spin structure.
- Quark Models Results. Interesting relations.
- PDFs. Some experimental results. Transversity, Collins, Sivers, pretzelosity and other PDFs.
- TMD Evolution Eq. and handedness (IFF)
- Drell-Yan process.
- Conclusions.

Main (twist-2) parton characteristics of hadron (integrated over k_T)

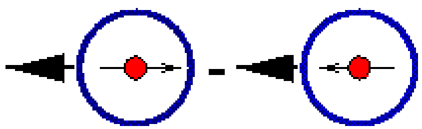


- Non-polarized PDF $f_1^a(x, Q^2)$.

-Measured for decades. Rather well known.

-Q^2-evolution, $\alpha_s(Q^2)$ extraction

-Problem of very small x-behavior (bare Pomeron, BFKL-equation)

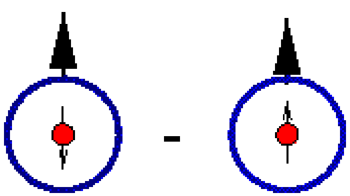


- Longitudinal spin distribution.

$$\Delta f^a \equiv f^{a\rightarrow}_{\rightarrow} - f^{a\leftarrow}_{\rightarrow} \equiv g_1^a(x, Q^2) \ .$$

-Parton content of proton spin. Main problem ΔG. Dedicated experiments (e.g. COMPASS, RHIC).

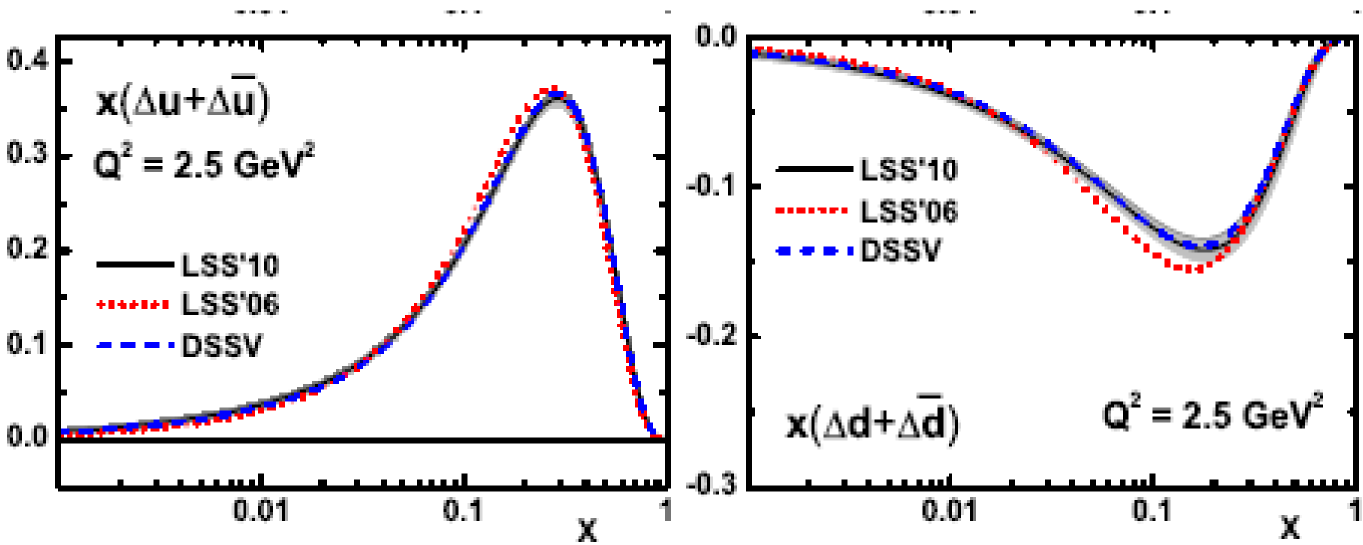
-Sea spin flavour asymmetry (spectacular in DY).



- Transverse spin distribution. (transversity)

$$\delta f^a \equiv f^{a\uparrow}_{\uparrow} - f^{a\downarrow}_{\uparrow} \equiv h_1^a(x, Q^2)$$

Not measured in DIS (χ–odd).

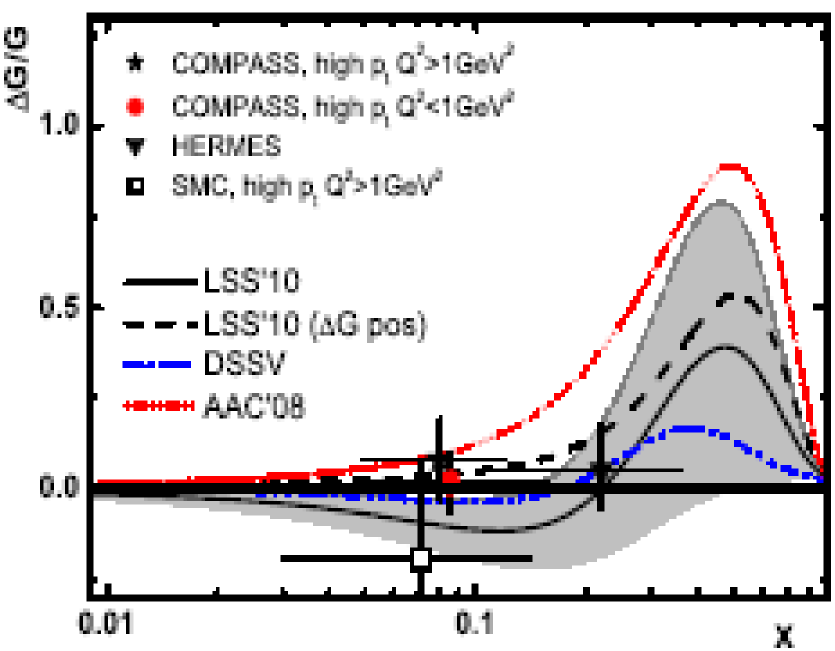


Leader, Sidorov, Stamenov, PRD82(2010) 114018.

$$J_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta G(Q^2) + L_z(Q^2)$$

$$= -0.21 \pm 0.46 + L_z(Q^2) \quad (\text{node } \Delta G),$$

$$= 0.42 \pm 0.19 + L_z(Q^2) \quad (\text{pos } \Delta G).$$



DVCS or spin-orbit correlation?

Why k_T is also necessary?

INCLUSIVE PION PRODUCTION

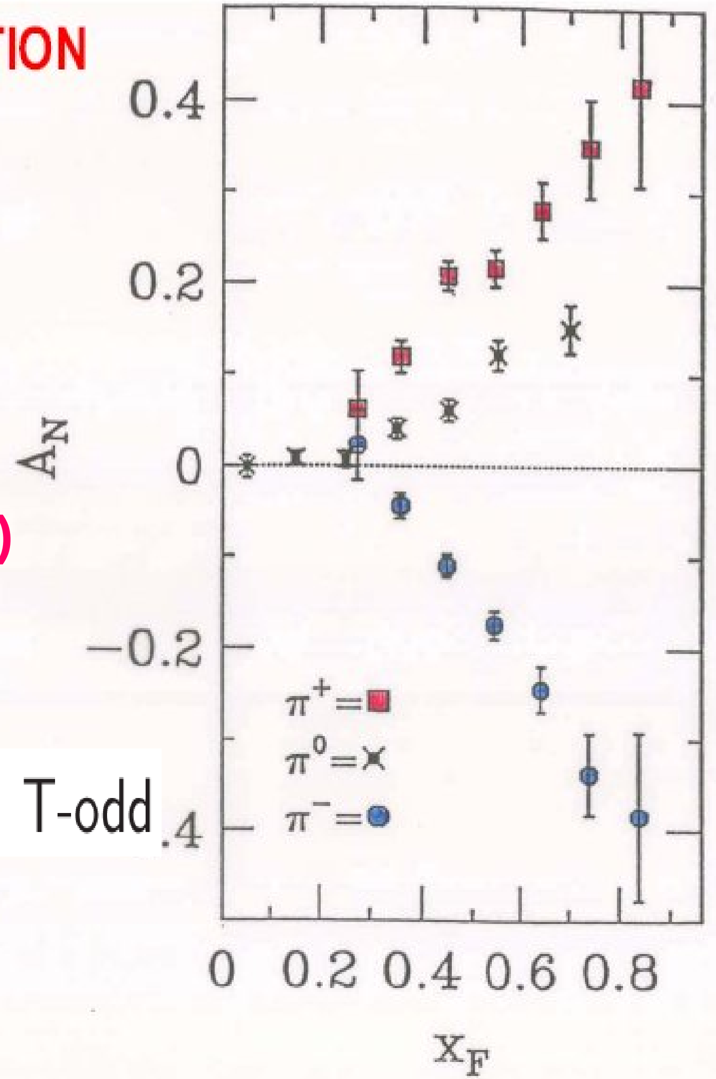
200 GeV Polarized Proton Beam
from Polarized Hyperon Decay
1990s Fermilab E-704
Yokosawa *et al.*
Phys Lett B264, 462 (1991)

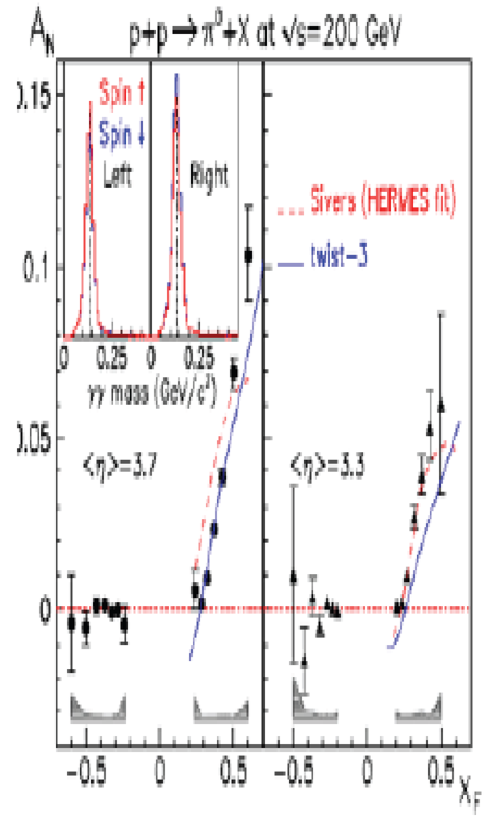
$A_n \sim 40\%$

QCD said $A_n \sim 0$ **(naïve)**

Collins PFF

$H_1^\perp \, \sigma[kP]$ χ-odd, T-odd



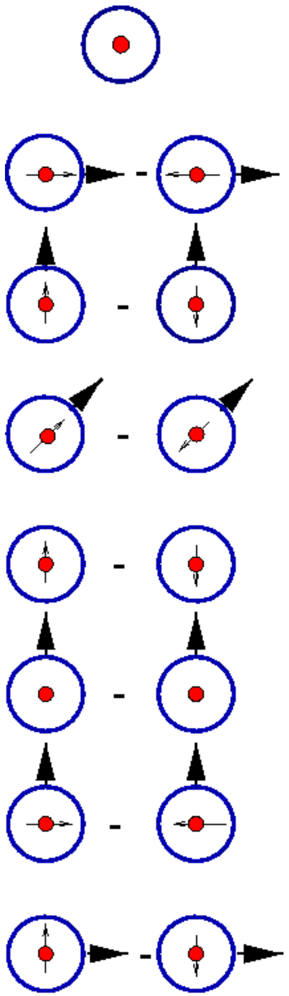


$\sqrt{s}$ = 200 GeV [STAR coll. (2008)]

Sivers PDF

$(f_{1T}^\perp)$ $S[kP]$ χ–even, T-odd **+twist-3 ETQS - functions...**
(Efremov-Teryaev-Qiu-Sterman)

New possibilities with k_T account.



$(f_1)\ D_1$

$(g_{1L})\ G_{1L}\ (\boldsymbol{\sigma P})(\boldsymbol{SP})/P^2$ **Helicity**

$(h_{1T})\ H_{1T}\ [\boldsymbol{\sigma S} - (\boldsymbol{\sigma P})(\boldsymbol{SP})/P^2]$, χ-odd **Transversity**

$(h_{1T}^{\perp})\ H_{1T}^{\perp}\ \boldsymbol{\sigma}[\boldsymbol{kP}]\boldsymbol{S}[\boldsymbol{kP}]/k_T^2 P^2$, χ-odd **Pretzelosity**

$(h_1^{\perp})\ H_1^{\perp}\ \boldsymbol{\sigma}[\boldsymbol{kP}]/k_T P$, χ-odd, T-odd Boer-Mulders Collins

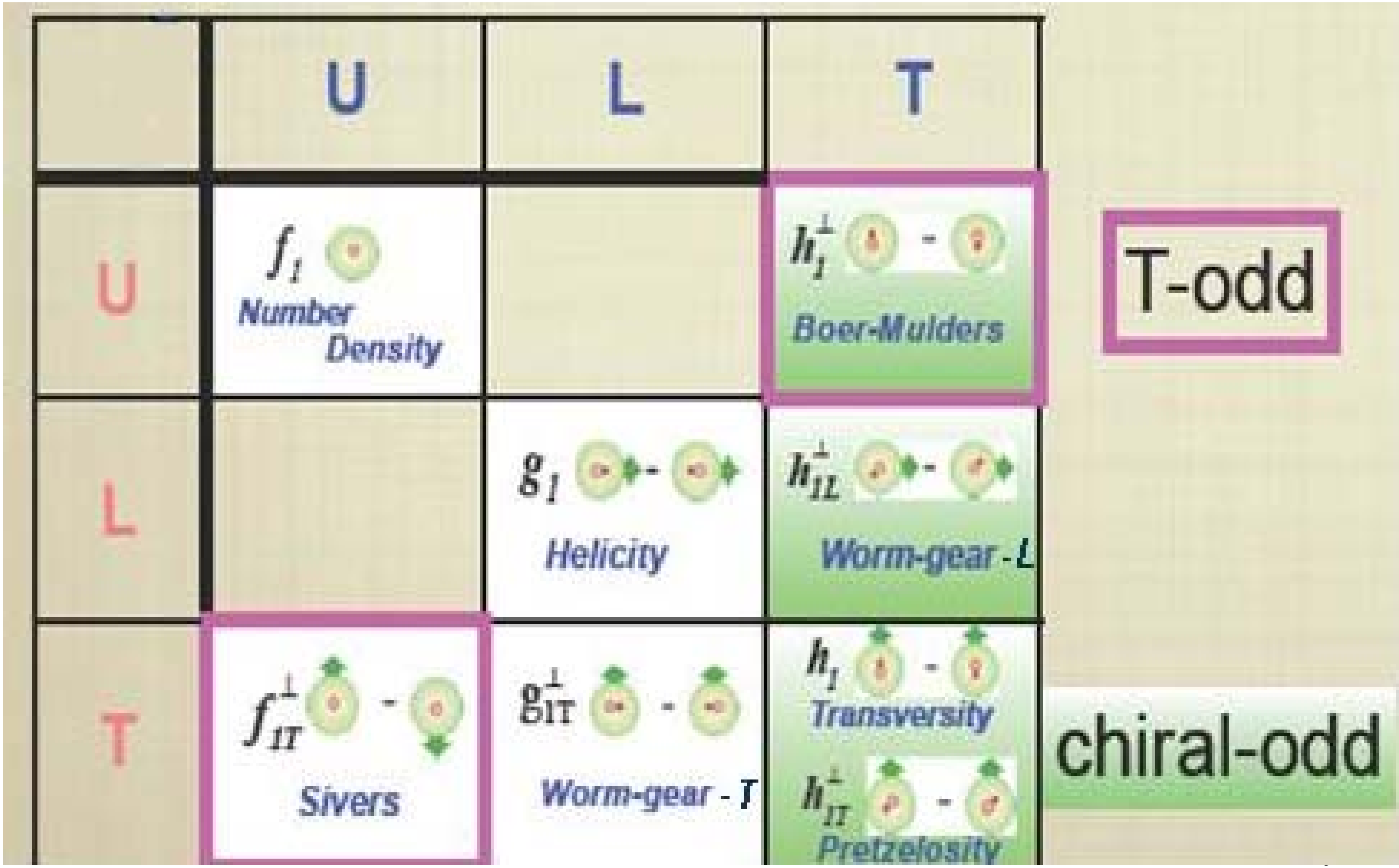
$(f_{1T}^{\perp})\ D_{1T}^{\perp}\ \boldsymbol{S}[\boldsymbol{kP}]/k_T P$, T-odd Sivers

$(g_{1T}^{\perp})\ G_{1T}^{\perp}\ (\boldsymbol{\sigma P})(\boldsymbol{S k}_T)/P k_T$ **Worm-gear-T**

$(h_{1L}^{\perp})\ H_{1L}^{\perp}\ (\boldsymbol{SP})(\boldsymbol{\sigma k}_T)/P k_T$, χ-odd **Worm-gear-L**

(T-odd **Boer-Mulders** and **Sivers** were "forbidden" by naïve T-parity and hermiticity. Reanimated in QCD by Brodsky and Collins.)

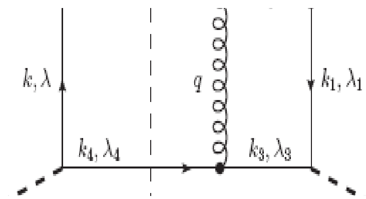
TMD parton distributon functions



Light-front correlators $(z^+ = 0,\ p^+ = xP^+)$:

$$\phi(x,\vec{p}_T)_{ij} = \int \frac{dz^- d^2\vec{z}_T}{(2\pi)^3}\, e^{ipz}\, \langle N(P,S)|\bar{\psi}_j(0)\,\{\text{gauge link}\}\,\psi_i(z)|N(P,S)\rangle$$

$$\{\text{gauge link}\} = \mathrm{P}\exp\left[-ig\int_0^z d\xi_j \hat{A}_j(\xi)\right]_{\text{path}}$$



Sivers

helicity

Worm-gear

transversity

pretzelosity

Boer-Mulders

$$\frac{1}{2}\mathrm{tr}[\gamma^+\,\phi(x,\vec{p}_T)] = f_1 - \frac{\varepsilon^{jk} p_T^j S_T^k}{M_N} f_{1T}^\perp$$

$$\frac{1}{2}\mathrm{tr}[\gamma^+\gamma_5\,\phi(x,\vec{p}_T)] = S_L\, g_1 + \frac{\vec{p}_T\cdot\vec{S}_T}{M_N} g_{1T}^\perp$$

$$\frac{1}{2}\mathrm{tr}[i\sigma^{j+}\gamma_5\phi(x,\vec{p}_T)] = S_T^j h_1 + \frac{\varepsilon^{jk} p_T^k}{M_N} h_1^\perp + S_L \frac{p_T^j}{M_N} h_{1L}^\perp + \boxed{\frac{(p_T^j p_T^k - \frac{1}{2}\vec{p}_T^{\,2}\delta^{jk}) S_T^k}{M_N^2} h_{1T}^\perp}$$

$f_1/g_1/h_1$ 'collinear' well/known/models, lattice, first data & extractions (Anselmino et all.)

$f_{1T}^\perp/h_1^\perp$ 'T-odd' hot!, models, data, extractions (many authors/Drell-Yan)

$g_{1T}^\perp/h_{1L}^\perp$ certain interest, related to g_1/h_1 in Wandzura-Wilczek-type relations (next slides)

$h_{1T}^\perp$ modest interest, undeserved in my view. What is that?

$\otimes D_1$ $\otimes H_1^\perp$ all accessible in SIDIS and e^+e^- (Boer, Mulders, Tangerman, Kotzinian 1996-1998)

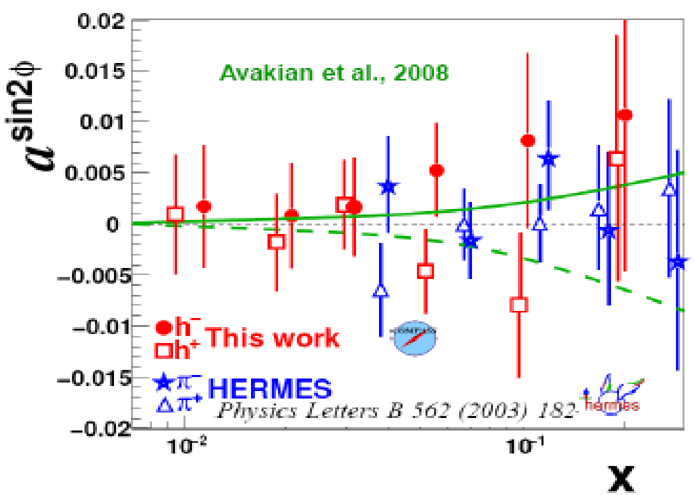
"Deeper into forest, more firewood!"

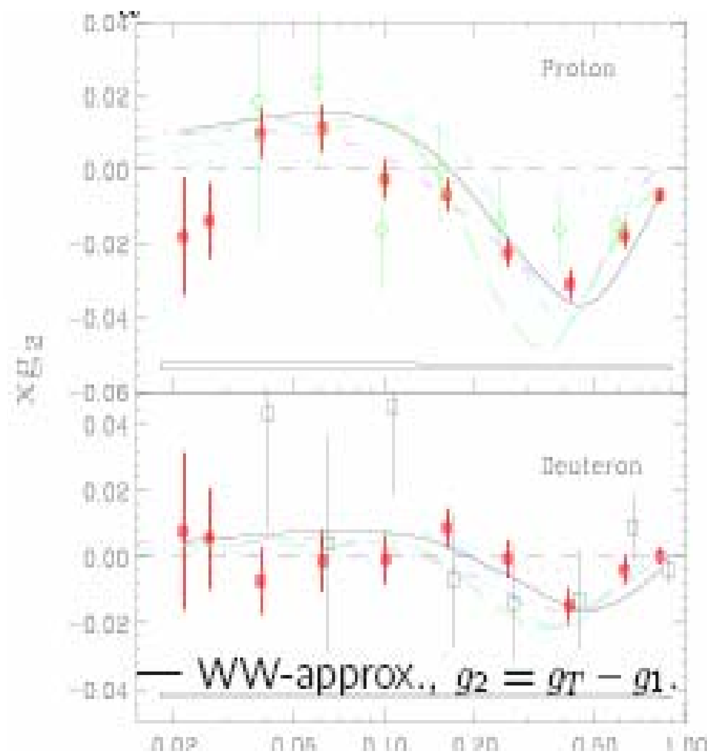
- All 8 leading twist TMDs f_1, g_1, h_1, $f_{1T}^{\perp}$, $h_1^{\perp}$, $g_{1T}^{\perp}$, $h_{1L}^{\perp}$, $h_{1T}^{\perp}$ **but** also 16 subleading twist TMDs g_T, h_L, e, $\ldots$ etc. contain independent information on the nucleon structure.
- There are *no exact relations* among TMDs!
- But having well-motivated "approximations" is valuable! At initial stage important (motivations, proposals for experiments).
- For example, Wandzura-Wilczek-type approximations (neglect pure-twist-3 & mass terms).

$$g_{1T}^{\perp(1)a}(x) \overset{!?}{\approx} x \int_x^1 \frac{\mathrm{d}y}{y}\, g_1^a(y) \approx x g_T^a(x)$$

$$h_{1L}^{\perp(1)a}(x) \overset{!?}{\approx} -x^2 \int_x^1 \frac{\mathrm{d}y}{y^2}\, h_1^a(y) \approx -\tfrac{1}{2}\, x h_L^a(x)$$

+ 7 other relation twist-3 with twist-2





Specifc model relations in twist-2

(1) $f_1^q(x,\vec{p}_T^2) = N_q\, f_1(x,\vec{p}_T^2)$ with $N_u = 2,\ N_d = 1$

(2) $g_1^q(x,\vec{p}_T^2) = P_q\, g_1(x,\vec{p}_T^2)$ $P_u = \frac{4}{3},\ P_d = -\frac{1}{3}$ from SU(6)

(h_1, $h_{1T}^\perp$ analog)

"Bare" distributions satisfy:

(1) $f_1(x,\vec{p}_T^2) + g_1(x,\vec{p}_T^2) = 2h_1(x,\vec{p}_T^2)$

(2) $h_1(x,p_T^2) - h_{1T}^{\perp(1)}(x,p_T^2) = f_1(x,p_T^2)$

(3) $h_{1L}^{\perp(1)}(x,p_T^2) = -g_{1T}(x,p_T^2)$

All T-odd = 0

(4) $$\frac{1}{2}\left[h_{1L}^{\perp q}(x,k_\perp)\right]^2 = -\,h_1^q(x,k_\perp)\,h_{1T}^{\perp q}(x,k_\perp)$$

Hold in LCQM, bag, spectator* and also in "Zavada Model"

(Pasquini et al. PRD72(2005); hep-ph:0806.2298; Avakian et al. arXiv:0805.3355;
AE, Schweitzer, Teryaev, Zavada, PRD80(2009)014021, arXiv:0903.3490)

*In spectator (1) and (2) only if $M^a_{qq}=M^s_{qq}$ (Jakob at al. NPA626(1997))

More general and exciting relation:

In all mentioned models:

$$g_1^q(x) - h_1^q(x) = h_{1T}^{\perp(1)q}(x)$$

'measure' of relativistic effects = pretzelosity!

Valid at low scale in large class of relativistic models,
not valid in models with gluons (Meissner, Metz, Goeke 2007),
not valid in QCD (all TMDs independent, not preserved by evolution).

More important is possible access to quark orbital momentum!

(J.She, J.Zhu,B.Ma, PRD79 (09)054008,
Bag model (Avakian, AE, Schweitzer,Yuan PRD81:074035,2010), Zavada model PoS DIS2010 253

$$L^q(x, \vec{p}_T^{\,2}) = h_1^q(x, \vec{p}_T^{\,2}) - g_1^q(x, \vec{p}_T^{\,2}) = -h_{1T}^{\perp(1)q}(x, \vec{p}_T^{\,2})$$

B.Pasquini et al. (LCQCModel) – true only for P_T-integrated

Rich azimuthal structure

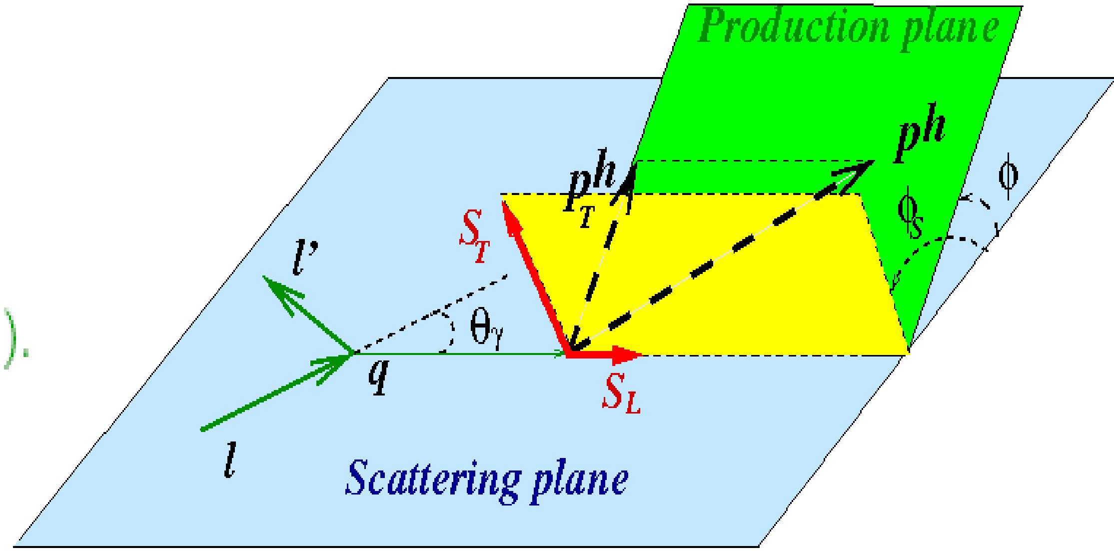
Nucleon spin structure much more complicated than thought!

SIDIS $lN \to l'hX$

8 azimuthal asymmtries

even at twist-2

review: Bacchetta et al., JHEP (2007).



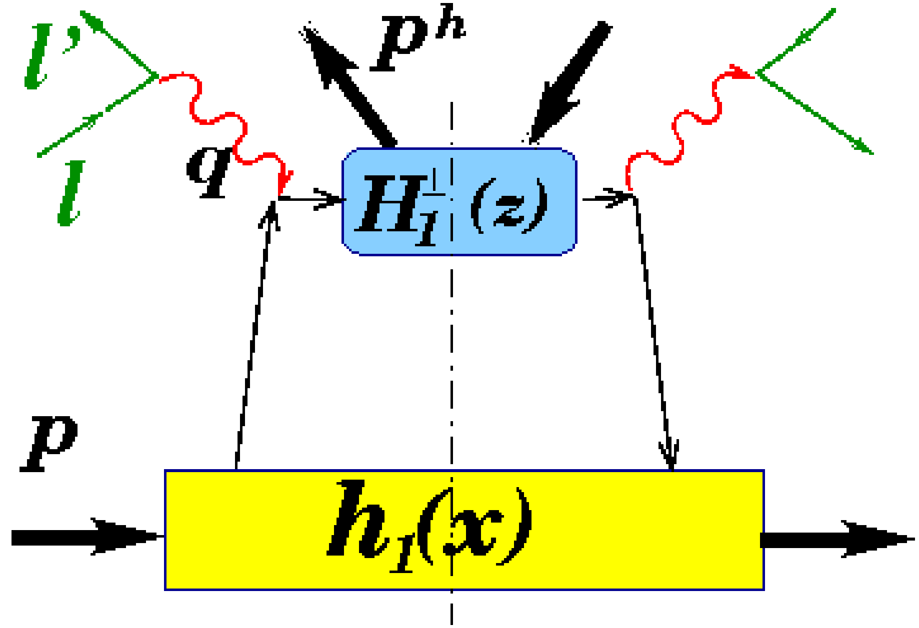
$$\frac{d\sigma}{d\phi_h} = F_{UU} + \lambda_e\, S_L F_{LL}$$

$$+ \quad \cos(2\phi)\, F_{UU}^{\cos(2\phi)} + S_L \sin(2\phi) F_{UL}^{\sin(2\phi)} + \lambda_e S_T \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)}$$

$$+ \quad S_T[\sin(\phi-\phi_S) F_{UT}^{\sin(\phi-\phi_S)} + \sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)}]$$

+ twist-3 terms.

Leading twist approximation



$$F_{UU} \sim \sum_a e_a^2 f_1^a \otimes D_1^a \qquad F_{LT}^{\cos(\phi-\phi_S)} \sim \sum_a e_a^2 g_{1T}^{\perp a} \otimes D_1^a$$

$$F_{LL} \sim \sum_a e_a^2 g_{1L}^a \otimes D_1^a \qquad F_{UT}^{\sin(\phi-\phi_S)} \sim \sum_a e_a^2 f_{1T}^{\perp a} \otimes D_1^a$$

chiral-even TMDs

$$F_{UU}^{\cos(2\phi)} \sim \sum_a e_a^2 h_1^{\perp a} \otimes H_1^{\perp a} \qquad F_{UT}^{\sin(\phi+\phi_S)} \sim \sum_a e_a^2 h_{1T}^a \otimes H_1^{\perp a}$$

$$F_{UL}^{\sin(2\phi)} \sim \sum_a e_a^2 h_{1L}^{\perp a} \otimes H_1^{\perp a} \qquad F_{UT}^{\sin(3\phi-\phi_S)} \sim \sum_a e_a^2 h_{1T}^{\perp a} \otimes H_1^{\perp a}$$

chiral-odd TMDs

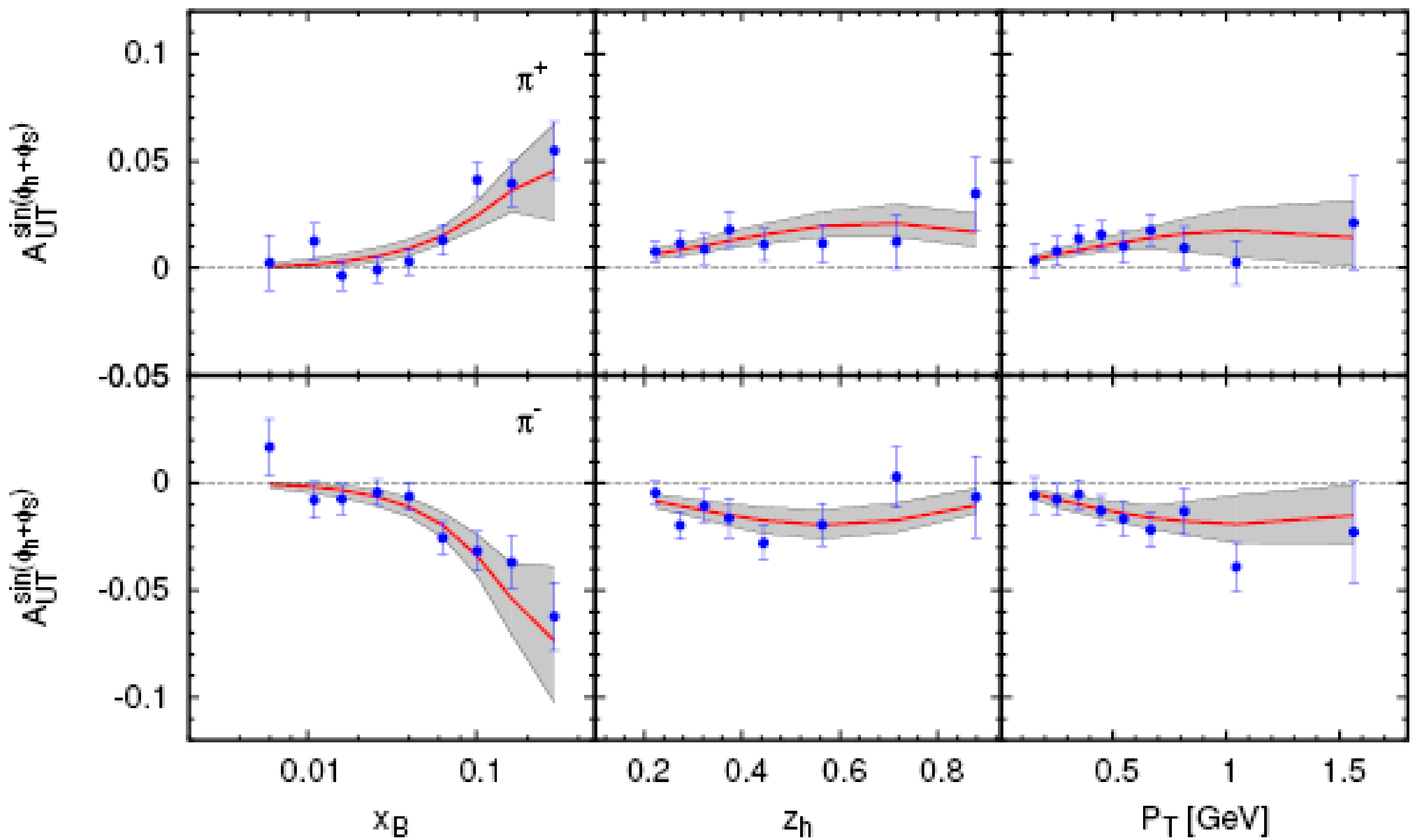
e.g.

$$f \otimes D = x \sum_a e_a^2 \int d^2 p_T \, d^2 k_T \, \delta^{(2)}(p_T - k_T - P_{h\perp}/z)\, w(p_T, k_T)\, f^a(x, p_T^2)\, D^a(z, k_T^2)$$

PDFs. Some experimental results

Transversity for proton from COMPASS and Belle

COMPASS PROTON



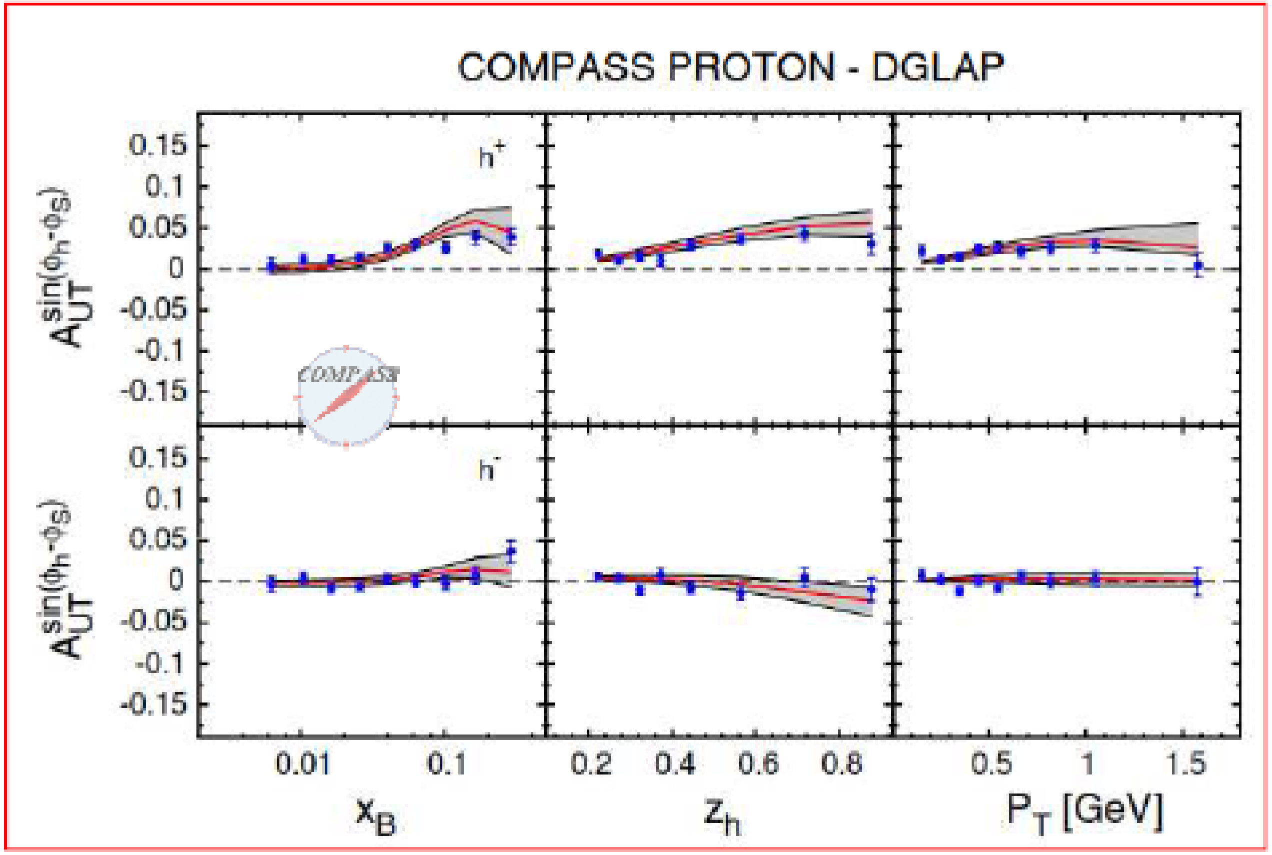
M.Anselmino at al. 1303.3822 But DGLAP evolution Eq?!

Sivers asymmetry on proton

charged hadrons, 2010 data - Q^2 evolution

M. Anselmino, M. Boglione, S. Melis PRD86 (2012) 014028

fit to HERMES p and COMPASS d and p 2010 data



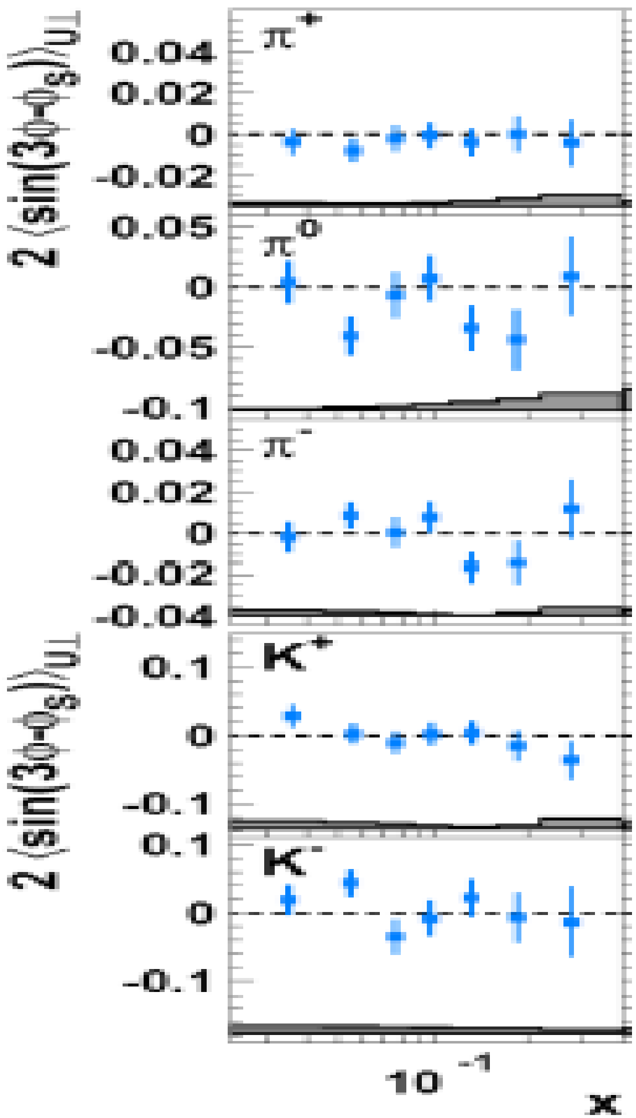
Pretzelosity in SIDIS and theory predictions

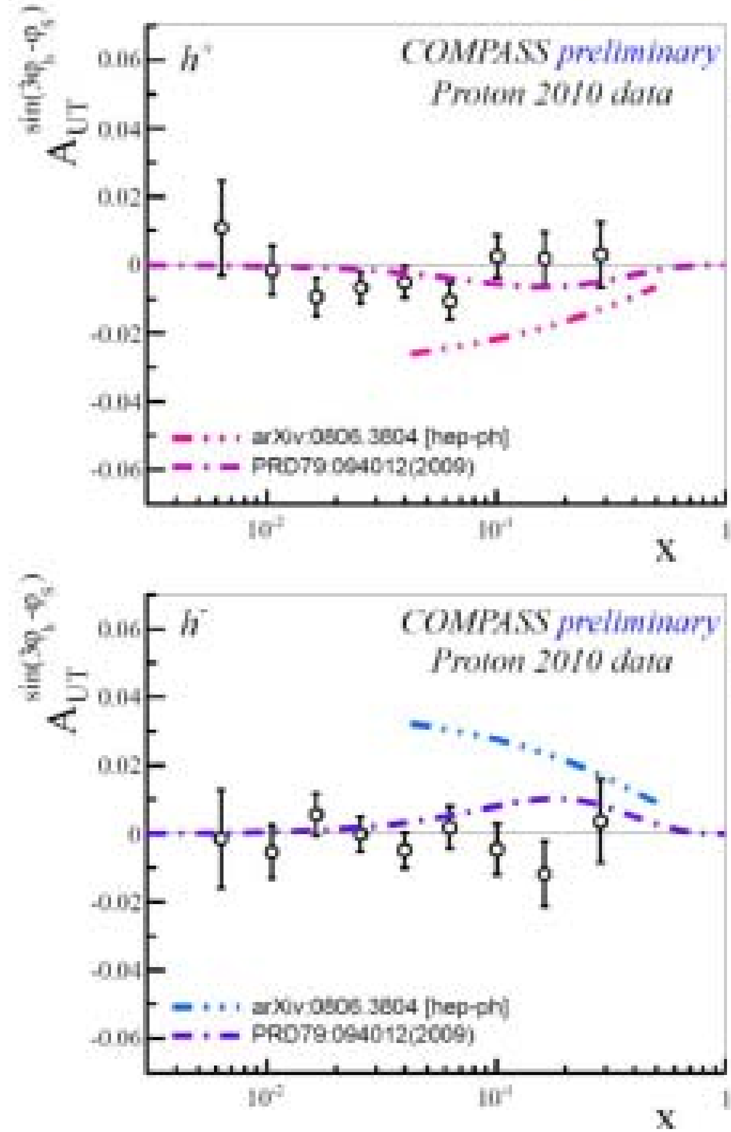
Boffi, A.E, Pasquini,Schweitzer PRD79:094012(2009)

Kotzinian arXiv:0806.3804[hep-ph]

$$A_{UT}^{\sin(3\phi_h - \phi_S)} \propto \sum_q e_q^2 h_{1T}^{\perp q} \otimes H_1^{\perp q}$$

- Proton & deuteron (HERMES & COMPASS) data consistent with zero
- Or just the suppression by third power of p_{hT}?
- Experiment planned at CLAS12





Pretzelosity in SIDIS: prospects

Most preferable conditions:

- intermediate $x \sim (0.2 - 0.4)$
- high luminosity

  $\rightarrow$ JLab

CLAS with 12 GeV (H.Avakian et al, LOI 12-06-108). Error projections for 2000 hours run time at CLAS12

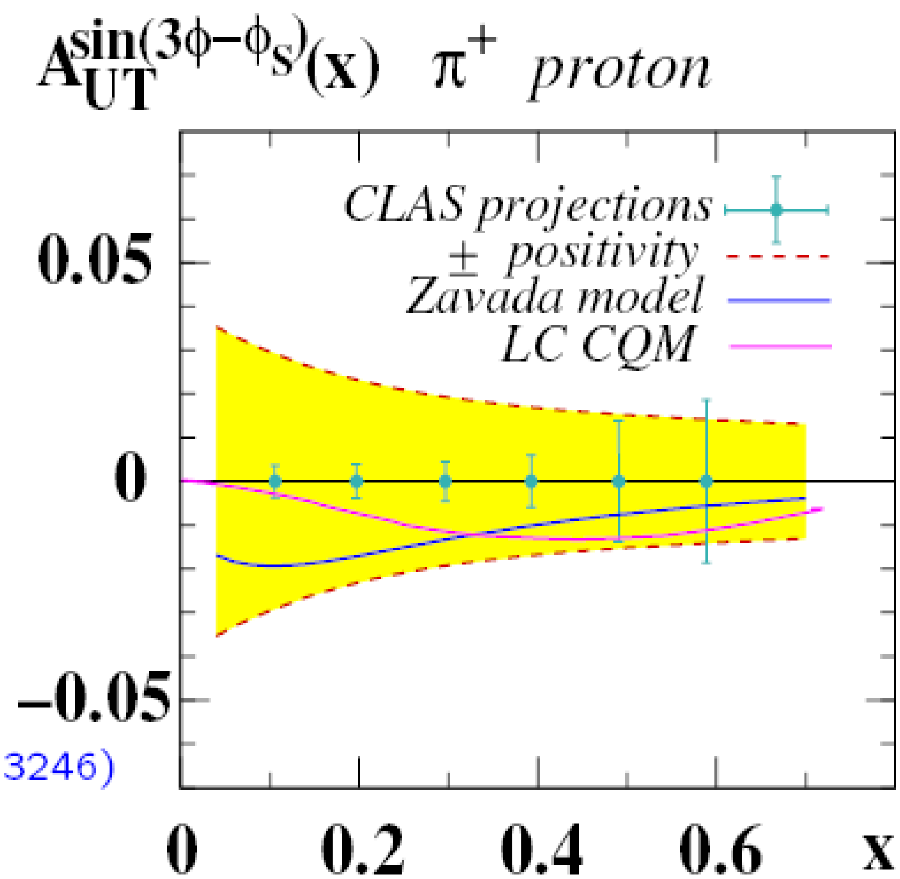
— $|h_{1T}^{(1)\perp q}| < f_1^q - g_1^q$

— Covariant parton model

(AE,Schweitzer, Teryaev, Zavada; arXiv:0812.3246)

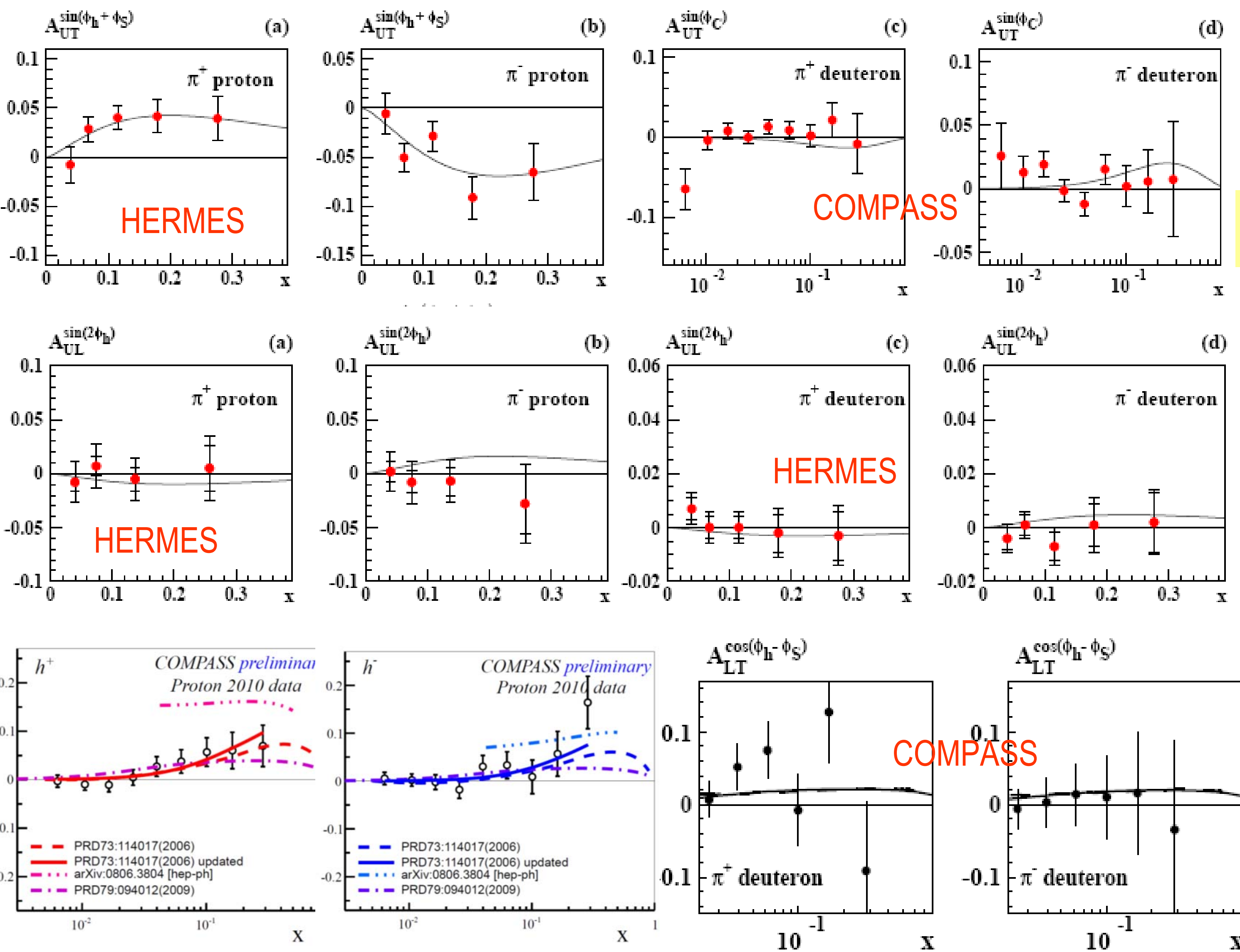
— Light-Cone CQM

(Boffi, AE, Pasquini, Schweitzer – [PRD79(2009)094012]



Can be accessed in Drell-Yan in certain azimuthal spin asymmetries.

T-even asymmetries in SIDIS (LCQCModel)



Transversity

$F_{UT}^{\sin(\phi+\phi_S)} \propto$

$\sum_a e_a^2\, h_1^a \otimes H_1^{\perp a}$

$A_{UT}^{\sin\phi_C} = -A_{UT}^{\sin(\phi_h-\phi_S)}$

Worm-gear-L

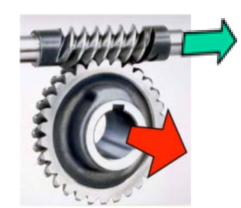
$F_{UL}^{\sin(2\phi)} \propto$

$\sum_a e_a^2\, h_{1L}^{\perp a} \otimes H_1^{\perp a}$

Worm-gear-T

$F_{LT}^{\cos(\phi-\phi_S)} \propto$

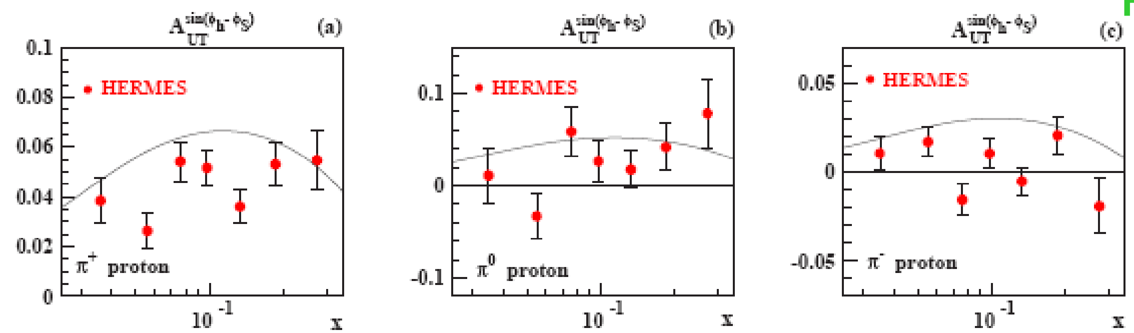
$\sum_a e_a^2\, g_{1T}^{\perp a} \otimes D_1^a$



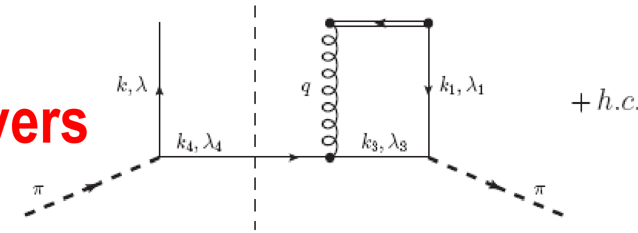
(Boffi, AE, Pasquini, Schweitzer [PRD79(2009)094012]);
Kotzinian, Parsamyan, Prokudin PRD73 (2006)114017;Kotzinian arXiv:0806.3804[hep-ph]

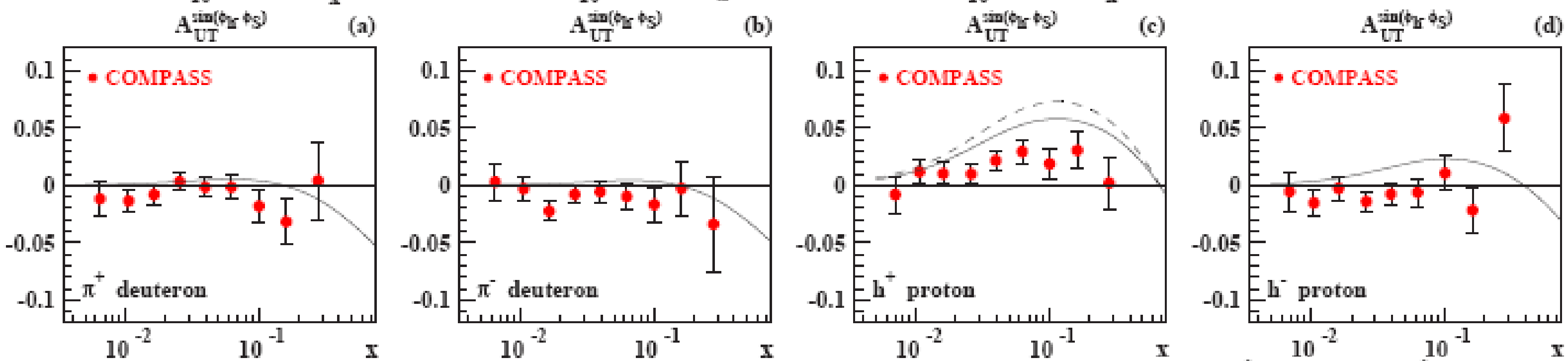
T-odd asymmetries in SIDIS (LCQCModel)

Pasquini, Schweitzer ArXiv:1103.5977



Sivers

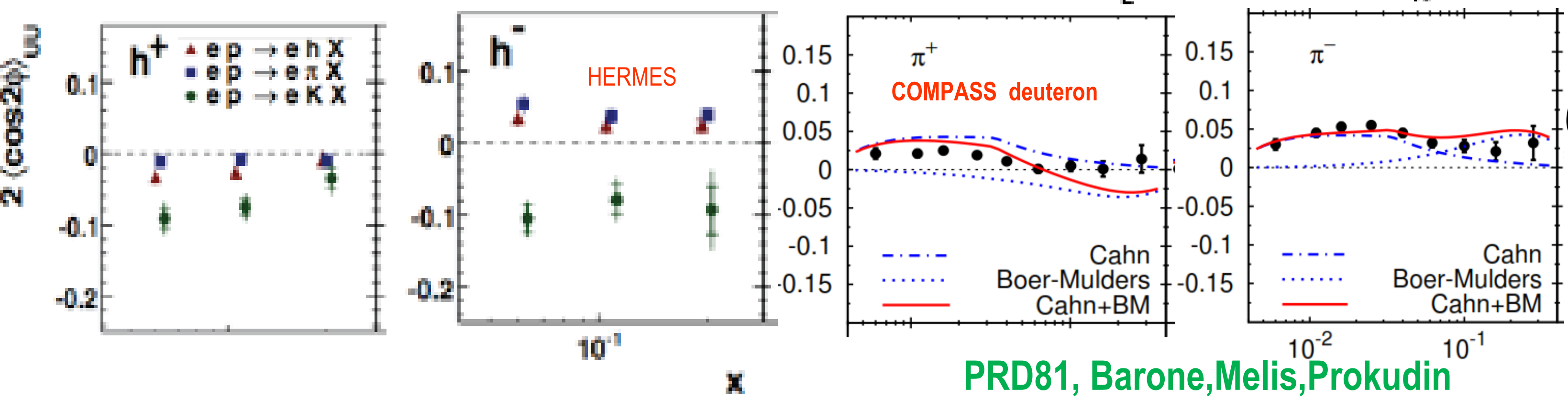




$$F_{UT}^{\sin(\phi_h-\phi_S)} = -\mathcal{C}\left[\frac{\hat{h}\cdot p_T}{M} f_{1T}^{\perp} D_1\right]$$

Boer-Mulders

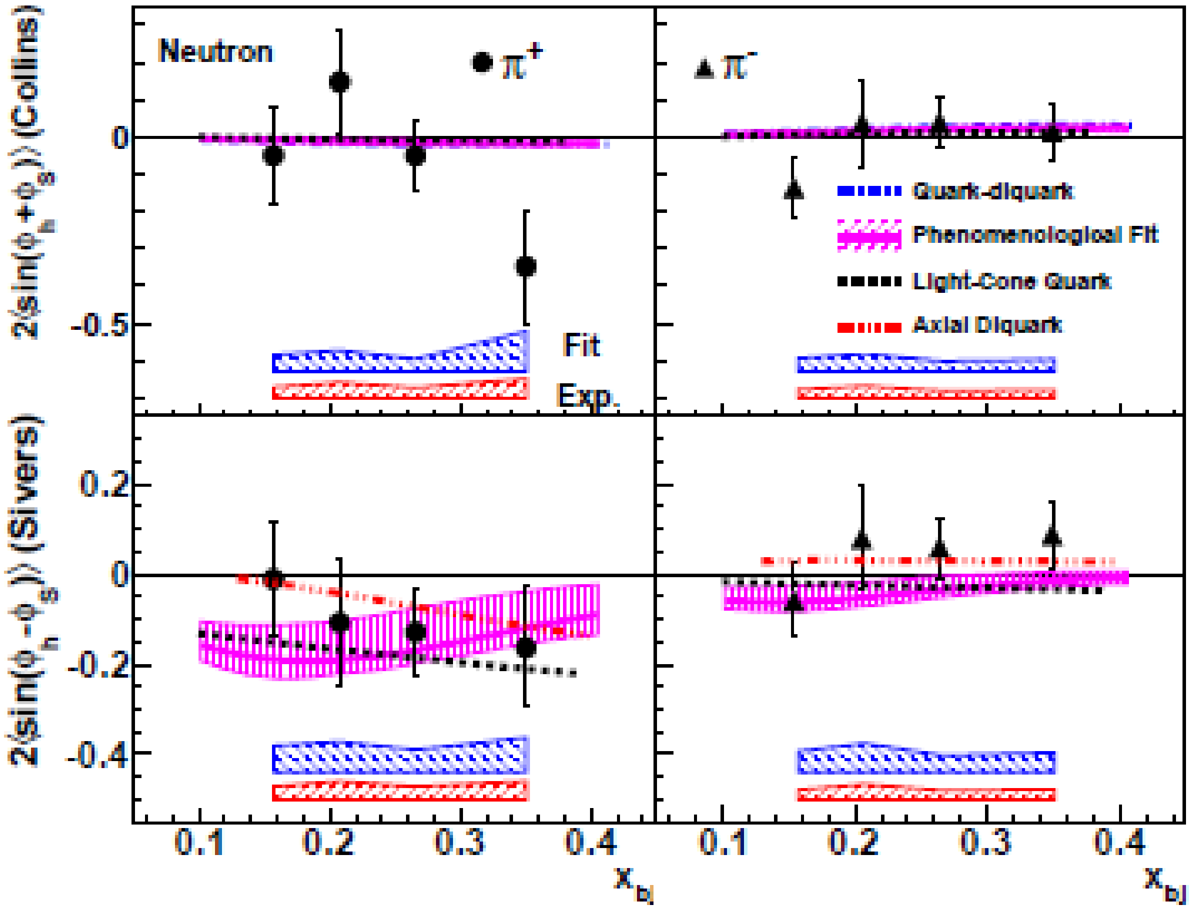
$$F_{UU}^{\cos(2\phi_h)} = \mathcal{C}\left[\frac{2\,(\hat{h}\cdot K_T)\,(\hat{h}\cdot p_T) - K_T\cdot p_T}{z\, m_h M} h_1^{\perp} H_1^{\perp}\right]$$



$$\mathcal{C} \equiv \otimes$$

PRD81, Barone,Melis,Prokudin

Neutron Results with Polarized ^{3}He from JLab



Collins

asymmetries are not large, except at x=0.34

Sivers

$\pi^+ (u\bar{d})$ negative

Blue band: model (fitting) uncertainties

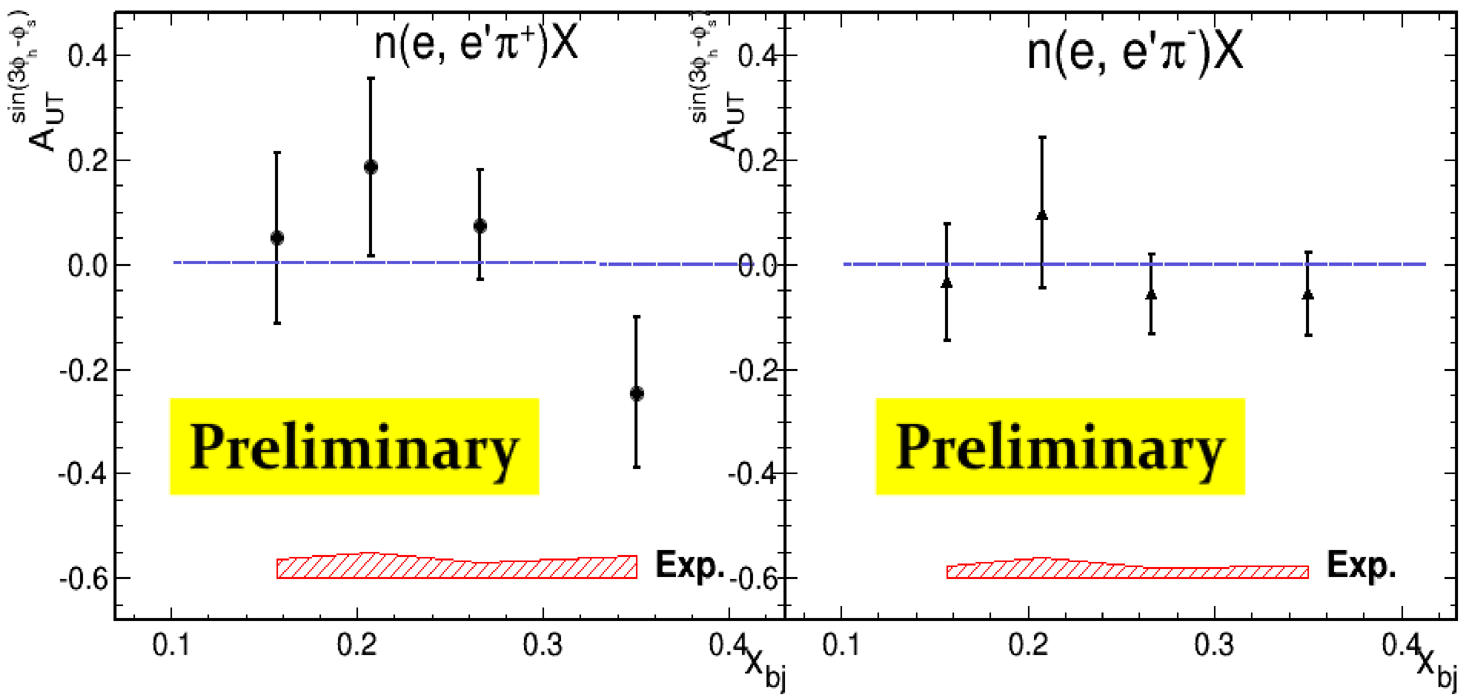
Red band: other systematic uncertainties

Extracted Results on Neutron

Extracted **Pretzelosity** **Asymmetries,**

$A_{UT}\sin(\varphi_h - \varphi_s)$, **on the neutron**

For both π+ and π-, **consistent with zero** within uncertainties.



(Jian-Ping Chen, JLab Hall A E06-010 with a Transversely Polarized ^{3}He (n), QCD Evolution Workshop May 6-10, 2013**)**

TMD Evolution Equations

Historically TMD factorization is formulated as Collins-Soper-Sterman resummation

Collins, Soper, Sterman 1985

Proven for polarized case

Ji, Ma, Yuan 2004; Collins 2011

Alternative formulations

Cherednikov, Stefanis 2008; Echevarria, Idilbi, Scimemi 2011
Trentadue, Ceccoperi, 2008; Hautman, 2008

Equivalence with some approaches was shown Collins, Rogers 2012

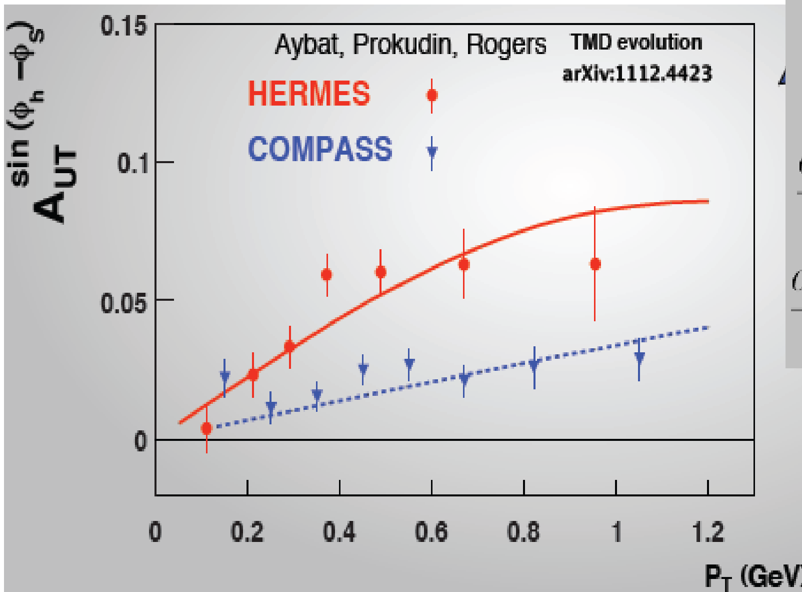
Main differences among the various approached:

- treatment of nonperturbative Sudakov factor

- treatment of leading logarithms

New evolution equation for TMDs

$$\tilde{F}_{1T}^{\prime\perp f}(x,b_T;\mu,\zeta_F) = -(2\pi)\int_0^\infty dk_T k_T^2 J_1(k_T b_T) F_{1T}^{\perp f}(x,k_T;\mu,\zeta_F)$$



$$\frac{\partial \ln \tilde{F}(x,b_\perp,\mu,\zeta)}{\partial \ln\sqrt{\zeta}} = \tilde{K}(b_\perp,\mu)$$

$$\frac{d\tilde{K}(b_\perp,\mu)}{d\ln\mu} = -\gamma_K(g(\mu))$$

$$\frac{d\ln\tilde{F}(x,b_\perp,\mu,\zeta)}{d\ln\mu} = -\gamma_F(g(\mu),\zeta)$$

Collins-Soper kernel in coordinate space. Process independent.

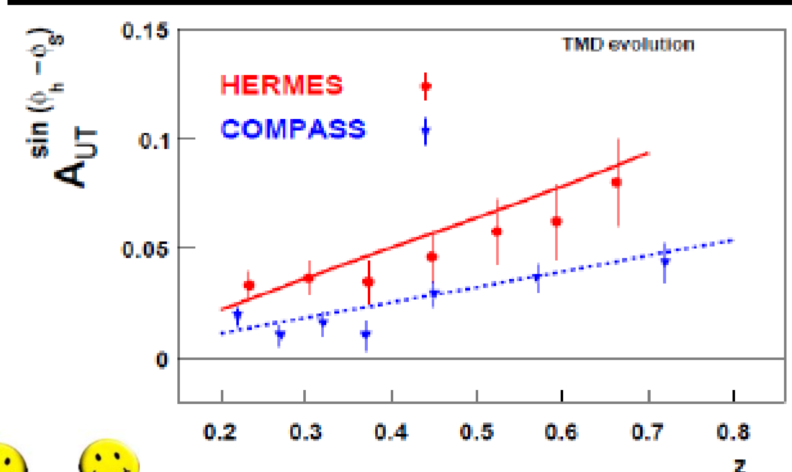
TMD: Collins 2011 Rogers, Aybat 2011 Aybat, Collins, Qiu, Rogers 2012, PRD 85, 034043

$$\tilde{F}_{f/P}(x,b_T;Q,\zeta_F) = \tilde{F}_{f/P}(x,b_T;Q_0,Q_0^2) \times \exp\left[-g_K(b_T)\ln\frac{Q}{Q_0}\right]$$

Non perturbative

$$\times \exp\left[\ln\frac{Q}{Q_0}\tilde{K}(b_*;\mu_b) + \int_{Q_0}^{Q}\frac{d\mu'}{\mu'}\left[\gamma_F(g(\mu');1) - \ln\frac{Q}{\mu'}\gamma_K(g(\mu'))\right] + \int_{Q_0}^{\mu_b}\frac{d\mu'}{\mu'}\ln\frac{Q}{Q_0}\gamma_K(g(\mu'))\right]$$

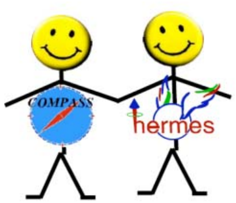
Perturbative



$$\tilde{K}(b_T,\mu) = \tilde{K}(b_*,\mu) - g_K(b_T) \quad b_{max} = 0.5\ (\mathrm{GeV}^{-1})$$

$$g_K(b_T) = \frac{1}{2}g_2 b_T^2 \qquad b_*(b_T) = \frac{b_T}{\sqrt{1+b_T^2/b_{max}^2}}$$

$$g_2 \simeq 0.68\ (GeV^2)$$



COMPASS data is at $\langle Q^2\rangle$=3.6 GeV^2, HERMES data is at $\langle Q^2\rangle$=2.4 GeV^2

New trend: Generalize Bessel Weight

$$\tilde{f}(x, \boldsymbol{b}_T^2) \equiv \int d^2\boldsymbol{p}_T \, e^{i\boldsymbol{b}_T\cdot\boldsymbol{p}_T} \, f(x, \boldsymbol{p}_T^2)$$

$$= 2\pi \int d|\boldsymbol{p}_T||\boldsymbol{p}_T| \; J_0(|\boldsymbol{b}_T||\boldsymbol{p}_T|) \; f^a(x, \boldsymbol{p}_T^2)$$

$$\tilde{f}^{(n)}(x, \boldsymbol{b}_T^2) \equiv n! \left(-\frac{2}{M^2}\partial_{\boldsymbol{b}_T^2}\right)^n \tilde{f}(x, \boldsymbol{b}_T^2)$$

$$= \frac{2\pi \; n!}{(M^2)^n} \int d|\boldsymbol{p}_T||\boldsymbol{p}_T| \left(\frac{|\boldsymbol{p}_T|}{|\boldsymbol{b}_T|}\right)^n J_n(|\boldsymbol{b}_T||\boldsymbol{p}_T|) \; f(x, \boldsymbol{p}_T^2)$$

Boer, Gamberg, Musch, Prokudin JHEP2011
Aghasyan, Avakian, De Sanctis, Gamberg, Mirazita, Musch, Prokudin, Rossi arXiv:1409.0487

News

$$\frac{\mathcal{J}_1^{\mathcal{B}_T}(|\boldsymbol{P}_{hT}|)}{zM} = \frac{2\, J_1(|\boldsymbol{P}_{hT}|\mathcal{B}_T)}{zM\mathcal{B}_T}$$

e.g. for Sivers PDF

$$A_{UT}^{\frac{\mathcal{J}_1^{\mathcal{B}_T}(|\boldsymbol{P}_{hT}|)}{zM}\sin(\phi_h-\phi_S)}(\mathcal{B}_T) = 2\frac{\int d|\boldsymbol{P}_{h\perp}|\,|\boldsymbol{P}_{h\perp}|\,d\phi_h\,d\phi_S\,\frac{\mathcal{J}_1^{\mathcal{B}_T}(|\boldsymbol{P}_{hT}|)}{zM}\sin(\phi_h-\phi_S)\,(d\sigma^\uparrow - d\sigma^\downarrow)}{\int d|\boldsymbol{P}_{h\perp}|\,|\boldsymbol{P}_{h\perp}|\,d\phi_h\,d\phi_S\;\mathcal{J}_0^{\mathcal{B}_T}(|\boldsymbol{P}_{hT}|)\;(d\sigma^\uparrow + d\sigma^\downarrow)}$$

$$A_{UT}^{\frac{\mathcal{J}_1^{\mathcal{B}_T}(|\boldsymbol{P}_{hT}|)}{zM}\sin(\phi_h-\phi_s)}(\mathcal{B}_T) = -2\frac{\tilde{S}(\mathcal{B}_T^2)\,H_{UT,T}^{\sin(\phi_h-\phi_S)}(Q^2)\sum_a e_a^2\,\tilde{f}_{1T}^{\perp(1)a}(x, z^2\mathcal{B}_T^2)\,\tilde{D}_1^a(z, \mathcal{B}_T^2)}{\tilde{S}(\mathcal{B}_T^2)\,H_{UU,T}(Q^2)\sum_a e_a^2\,\tilde{f}_1^a(x, z^2\mathcal{B}_T^2)\,\tilde{D}_1^a(z, \mathcal{B}_T^2)}$$

Cancelation of soft factor!

Advantages of Bessel Weighting

1.“Deconvolution”-SIDIS structure function simple products $\mathcal{P}$[…] instead of $\mathcal{C}$[…]; Renormgroup application.

2. Soft Factor cancels in asymmetries;

3. Circumvents the problem of ill-defined p_T-moments when $\mathcal{B}_T$ is non-zero;

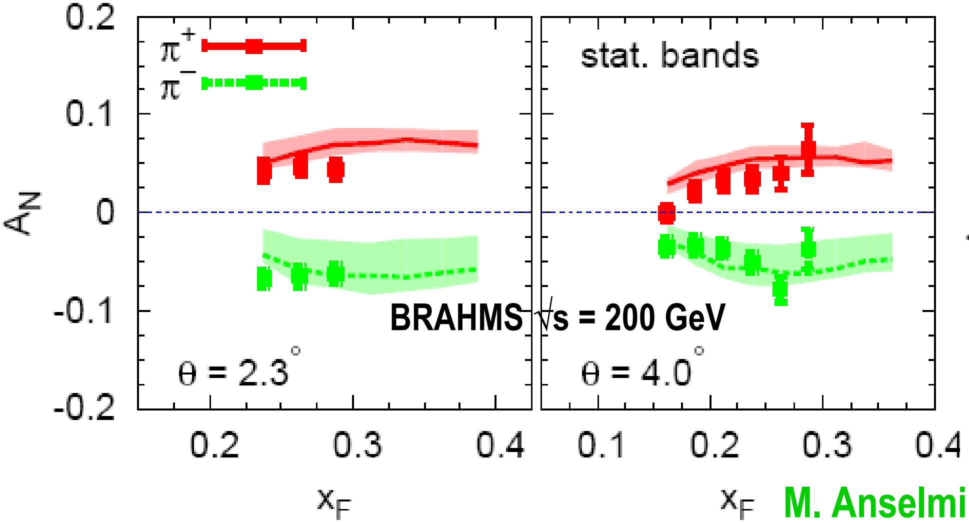
4. Bessel Weight asymmetries sensitive to low P_{hT}-region

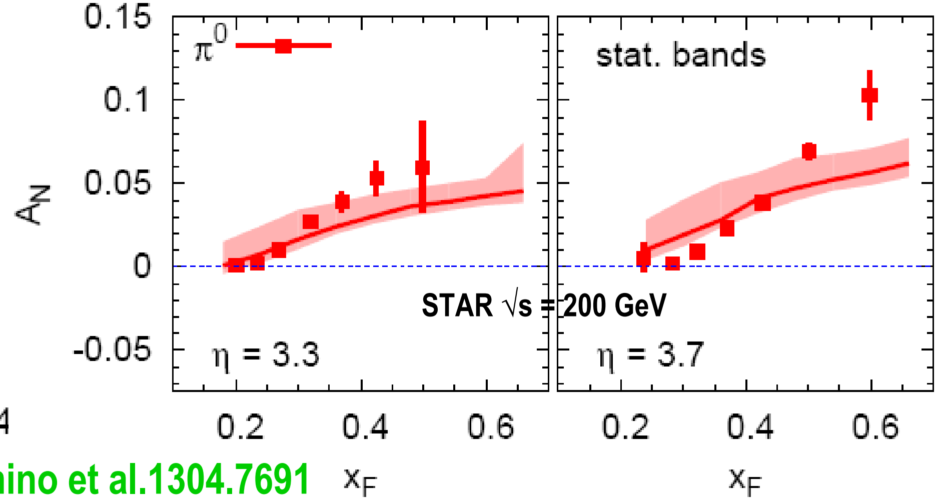
5. Cancellation of perturbative Sudakov broadening mentioned by D. Boer;

6. Possible to compare observables at different $\mathcal{B}_T$ scales.... could be useful for an EIC.

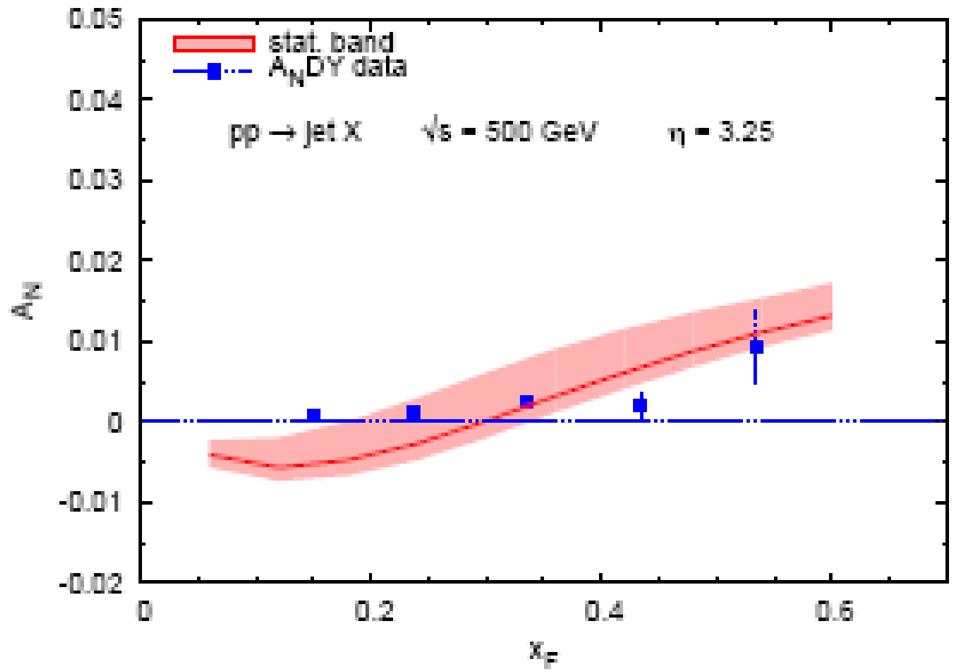
Comment: Traditional k_T-weighted asymmetry recovered but UV divergent.

$$\lim_{\mathcal{B}_T \to 0} w_1 = 2J_1(|\boldsymbol{P}_{h\perp}|\mathcal{B}_T)/zM\mathcal{B}_T \longrightarrow |\boldsymbol{P}_{h\perp}|/zM$$



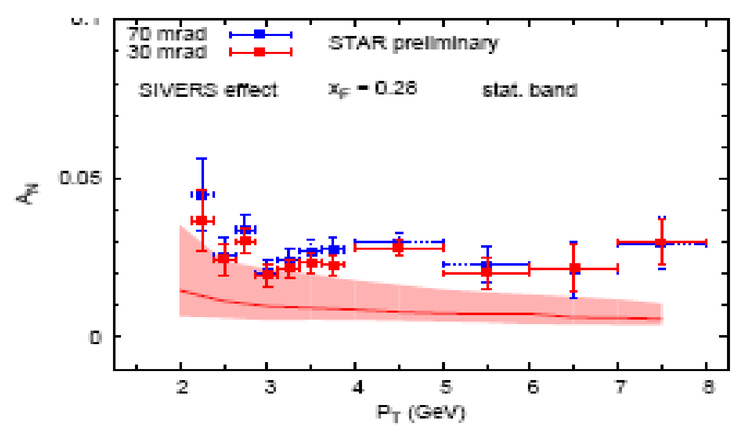


M. Anselmino et al.1304.7691

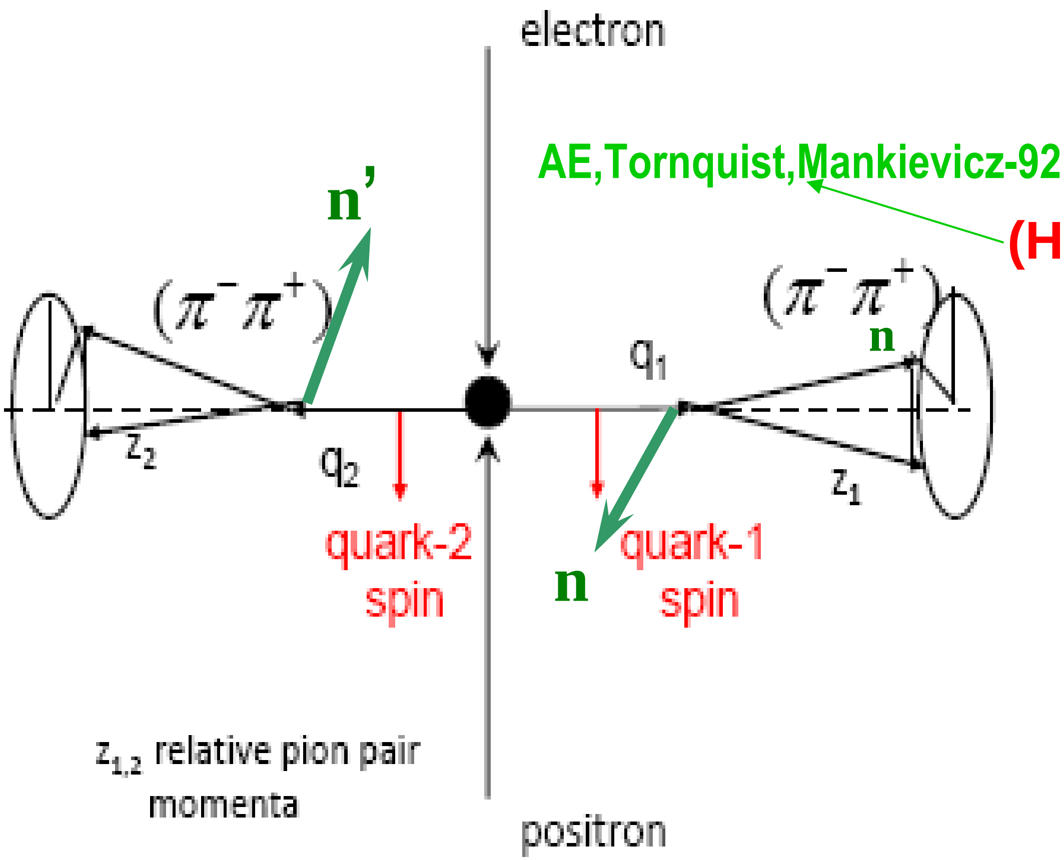


- **GPM model. Generalises the usual collinear factorisation scheme with DGLAP evolution.**
- **No mismatch problem, the same sign as in SIDIS. But predict change sign for pp --> jet X!**

What about *flat* STAR SSA data at large P_T?



Measuring di-Hadron Correlations In e^+e^- Annihilation into Quarks



Interference effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

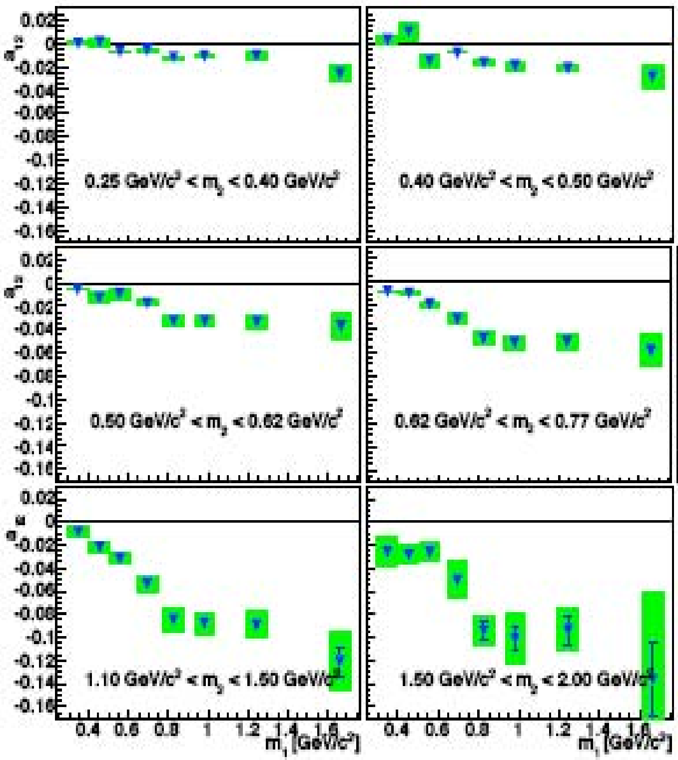
(Handedness correlation!)

Experimental requirements:

- Small asymmetries → very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Observable $\cos(\varphi_{R1} + \varphi_{R2})$

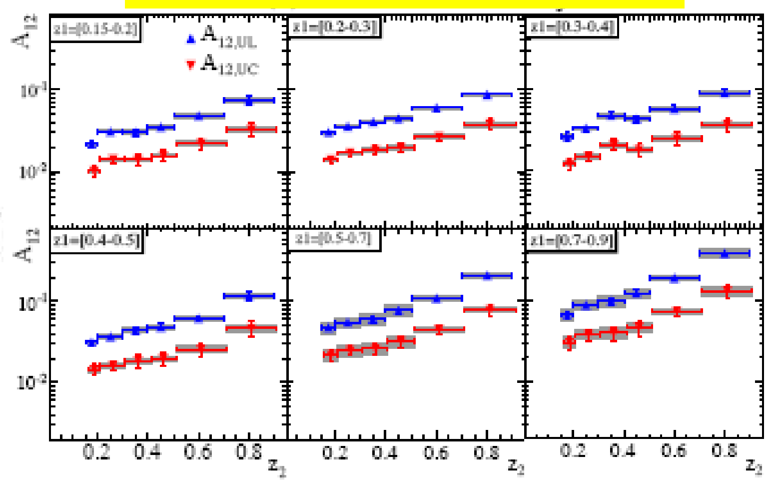
modulation measures $H_1^{\angle} \overline{H}_1^{\angle}$

BELLE data



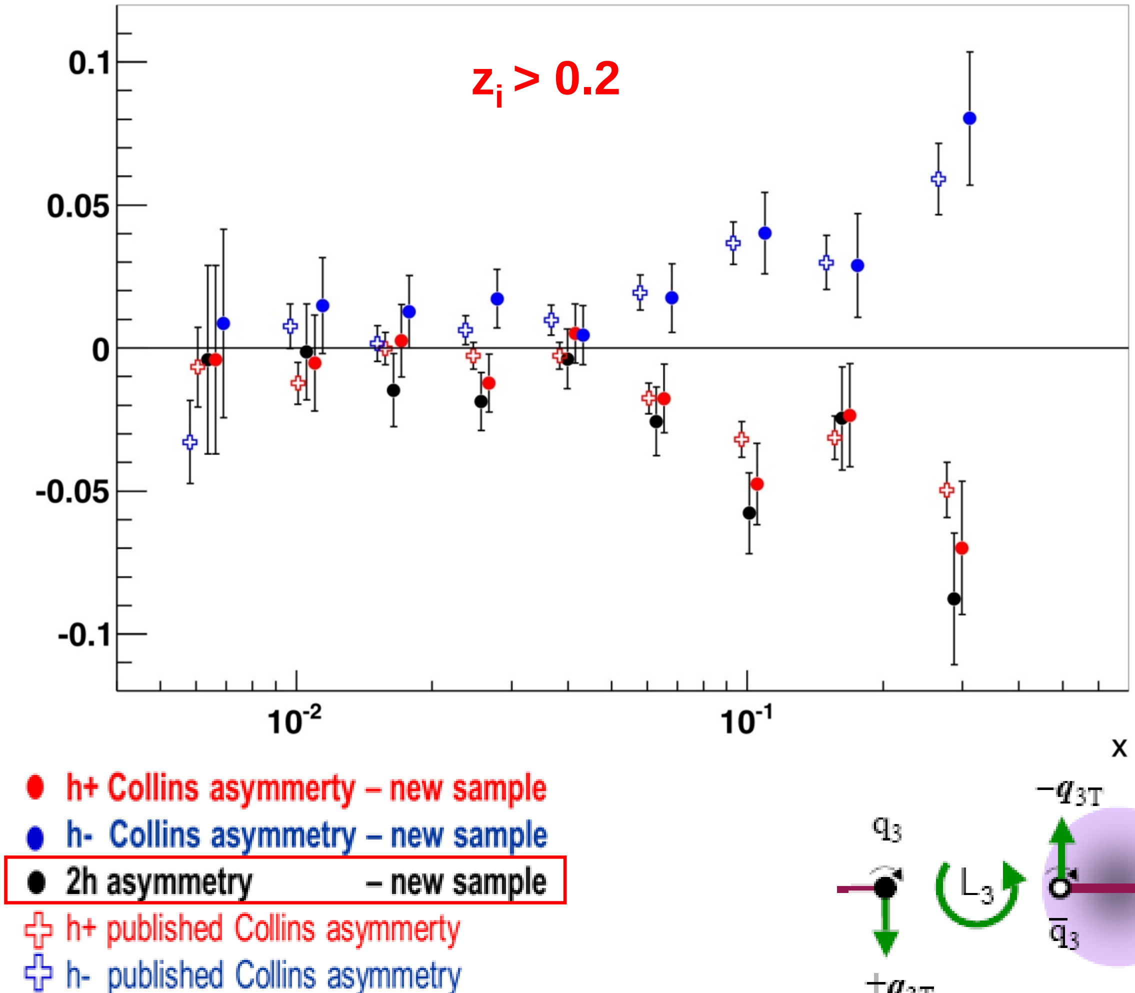
Vossen, Seidl et al. (Belle), PRL 107 (2011)

BaBar Preliminary

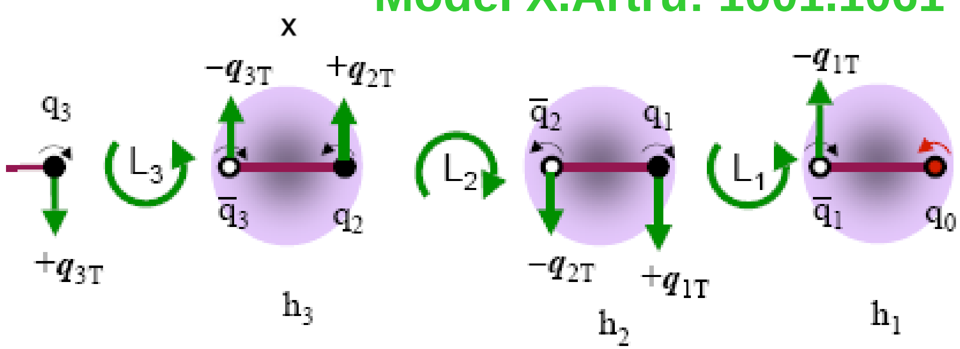


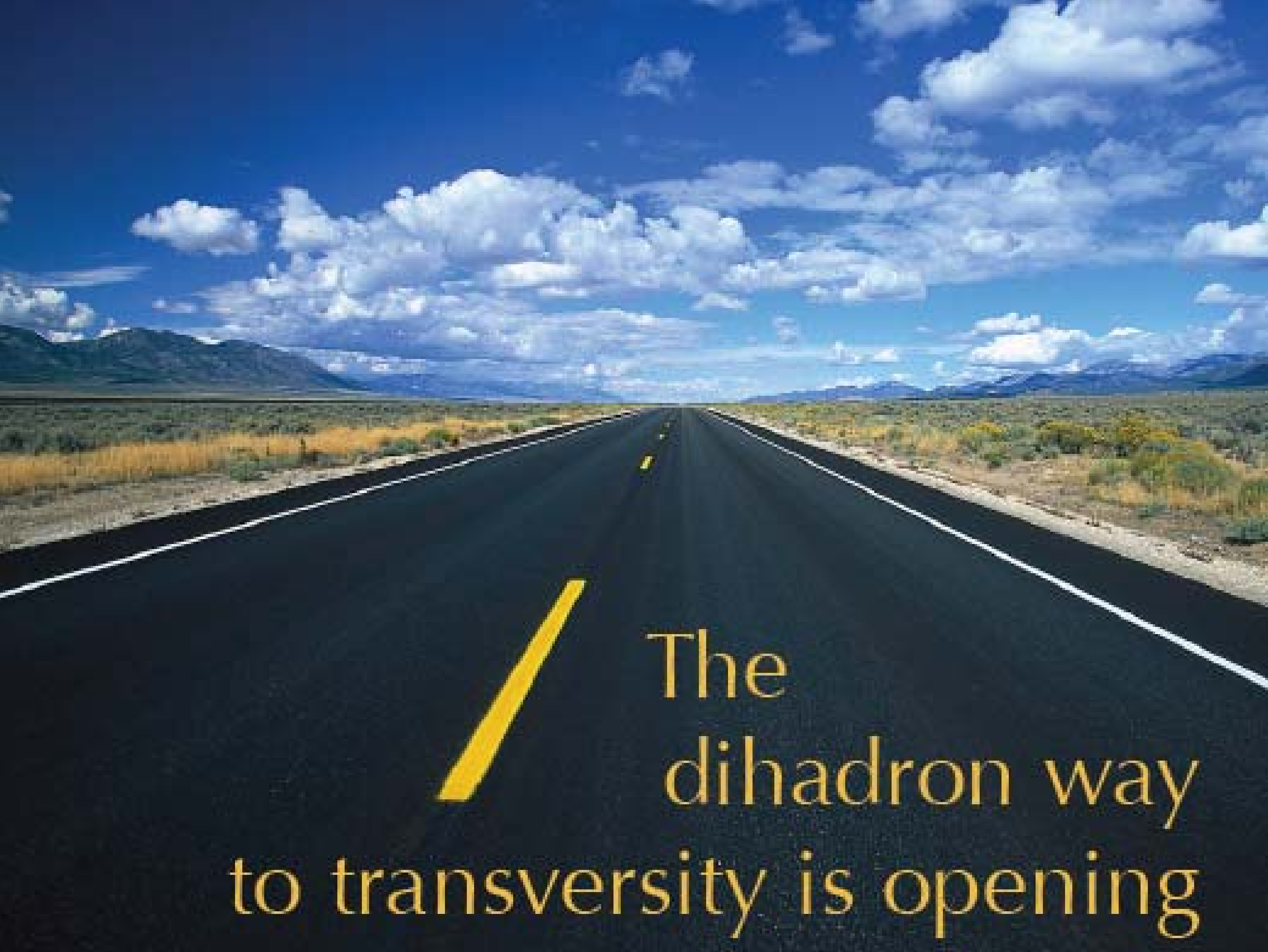
Comparison of 2h and 1h data

in favor of Artru string fragmentation model



Model X.Artru: 1001.1061




The
dihadron way
to transversity is opening

$$A_{DIS}(x,z,M_h^2) = -\langle C_y \rangle \frac{\sum_q e_q^2 h_1^q(x) \frac{|\boldsymbol{R}|}{M_h} H_{1,q}^{\sphericalangle}(z,M_h^2)}{\sum_q e_q^2 f_1^q(x) D_{1,q}(z,M_h^2)}$$

$$A_{e+e-}(z,M_h^2,\bar{z},\bar{M}_h^2) = -\frac{\langle \sin^2\theta_2 \rangle \langle \sin\theta \rangle \langle \sin\bar{\theta} \rangle}{\langle 1+\cos^2\theta_2 \rangle} \frac{\sum_q e_q^2 \frac{|\boldsymbol{R}|}{M_h} H_{1,q}^{\sphericalangle}(z,M_h^2) \frac{|\bar{\boldsymbol{R}}|}{M_h} H_{1,\bar{q}}^{\sphericalangle}(\bar{z},\bar{M}_h^2)}{\sum_q e_q^2 D_{1,q}(z,M_h^2) D_{1,\bar{q}}(\bar{z},\bar{M}_h^2)}$$

Simplified expressions $H_{1q}^{\sphericalangle} = -H_{1\bar{q}}^{\sphericalangle}, H_{1u}^{\sphericalangle} = -H_{1d}^{\sphericalangle}, \; D_1^u = D_1^{\bar{u}} = D_1^d$

Courtoy, Bacchetta, Radici, Bianconi, arXiv:1202.0323, 1202.6150, 1206.1836,1212.3568, 1408.5721

$$\frac{n_u^\uparrow}{n_u} = \frac{\iint \frac{|\boldsymbol{R}|}{M_h} H_{1,u}^{\sphericalangle}(z,M_h^2)}{\iint D_{1,u}(z,M_h^2)}$$

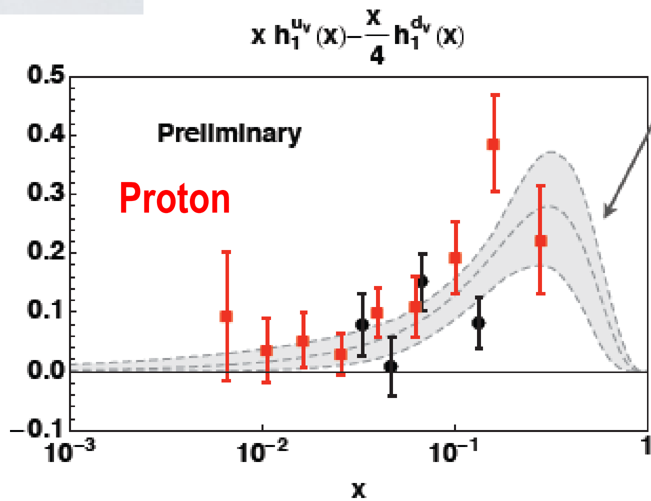
=-21±2%

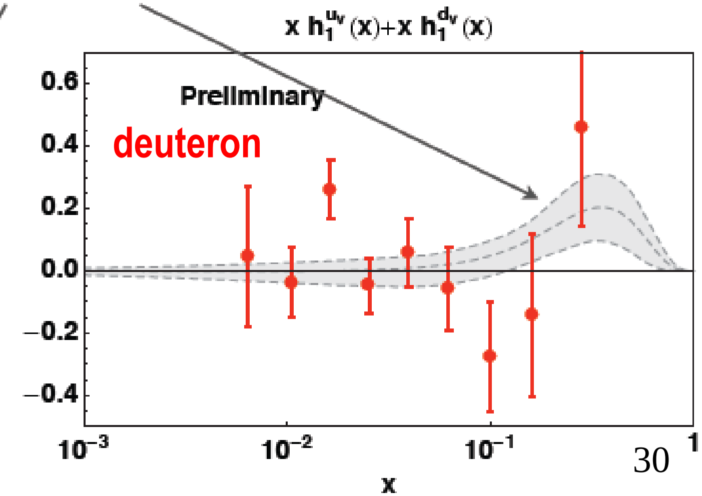
COMPASS

$$A_{DIS}(x) \approx -\langle C_y \rangle \frac{(h_1^{u_v}(x) - h_1^{d_v}(x)/4)}{(f_1^{u+\bar{u}}(x) + f_1^{d+\bar{d}}(x)/4)} \frac{n_u^\uparrow}{n_u}$$

Transversal HANDEDNESS!

Torino's fit

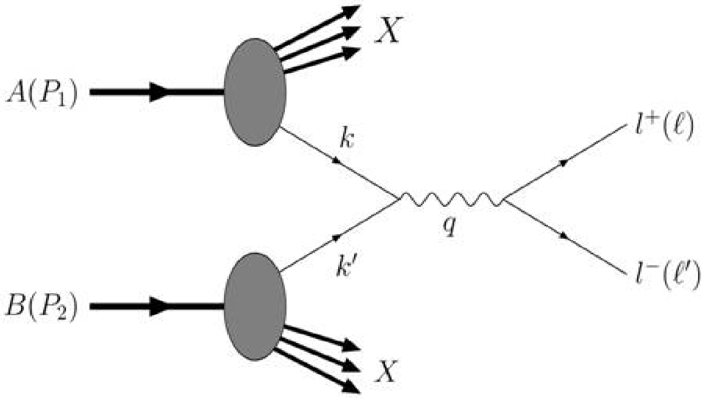


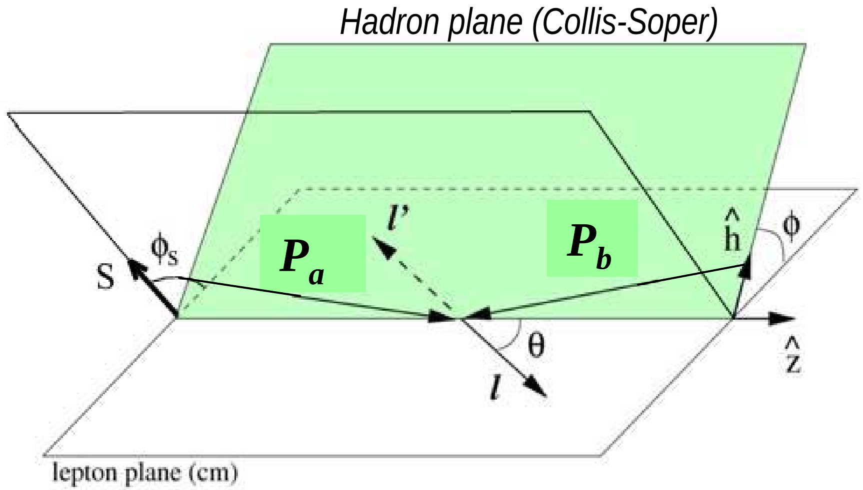


Summary on SIDIS

- transversity is non-zero and quite sizable
  can be measured, e.g., via Collins effect or
  interference in 2-hadron fragmentation
- Sivers and Boer-Mulders effects are also non-zero
  direct probe of "physics of the QCD Wilson line"
  possibly large evolution effects
- so far no sign of a non-zero pretzelosity distribution
- first evidences for non-vanishing worm-gear functions
- let's prepare for
  -precision measurements at ongoing and future SIDIS facilities,
  -fundamental QCD tests in Drell-Yan experiments,

Drell-Yan processes





Arnold, Metz, Schlegel PRD79(2009)034005

$$\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha_{em}^2}{F\, q^2} \times$$

$$x_a = \frac{q^2}{2P_a \cdot q} = \sqrt{\frac{q^2}{s}} e^{y}, \quad x_b = \frac{q^2}{2P_b \cdot q} = \sqrt{\frac{q^2}{s}} e^{-y}$$

$$\Big\{ \Big((1+\cos^2\theta)\, F_{UU}^1 + (1-\cos^2\theta)\, F_{UU}^2 + \sin 2\theta \cos\phi\, F_{UU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{UU}^{\cos 2\phi} \Big)$$

$$+\; S_{aL} \Big(\sin 2\theta \sin\phi\, F_{LU}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{LU}^{\sin 2\phi} \Big)$$

$$+\; |\vec{S}_{aT}| \Big[\sin\phi_a \Big((1+\cos^2\theta)\, F_{TU}^1 + (1-\cos^2\theta)\, F_{TU}^2 + \sin 2\theta \cos\phi\, F_{TU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{TU}^{\cos 2\phi} \Big)$$

$$+ \cos\phi_a \Big(\sin 2\theta \sin\phi\, F_{TU}^{\sin\phi} + \sin^2\theta \sin 2\phi\, F_{TU}^{\sin 2\phi} \Big) \Big]$$ + ….36 (24 tw3) terms

Parton model (leading twist, single-spin)

$$F^1_{UU} = \mathcal{C}\left[f_1 \bar{f}_1\right],$$

$$F^{\cos 2\phi}_{UU} = \mathcal{C}\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_1^\perp \bar{h}_1^\perp\right],$$

$$F^{\sin 2\phi}_{LU} = \mathcal{C}\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_{1L}^\perp \bar{h}_1^\perp\right],$$

$$F_{TU}^{\sin(\phi-\phi_a)} = -C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} f_{1T}^\perp \bar{f}_1\right]$$

$$F_{TU}^{\sin(\phi+\phi_a)} = C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} h_1 \bar{h}_1^\perp\right]$$

$$F_{TU}^{\sin(3\phi-\phi_a)} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{aT}^2(\vec{h}\cdot\vec{k}_{bT})}{2M_a^2 M_b} h_{1T}^\perp \bar{h}_1^\perp\right]$$

$$\mathcal{C}\left[w(\vec{k}_{aT},\vec{k}_{bT}) f_1 \bar{f}_2\right] \equiv \frac{1}{N_c}\sum_q e_q^2 \int d^2\vec{k}_{aT}\, d^2\vec{k}_{bT}\, \delta^{(2)}(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT})\, w(\vec{k}_{aT},\vec{k}_{bT}) \times \left[f_1^q(x_a,\vec{k}_{aT}^2)\, f_2^{\bar{q}}(x_b,\vec{k}_{bT}^2) + f_1^{\bar{q}}(x_a,\vec{k}_{aT}^2)\, f_2^q(x_b,\vec{k}_{bT}^2)\right].$$

For g_{1L} and g_{1T} one needs F^1_{LL} and F^1_{LT}.

Cornestoun QCD prediction

$$f_{1T}^{\perp q}\,|_{SIDIS} = -f_{1T}^{\perp q}\,|_{DY}$$

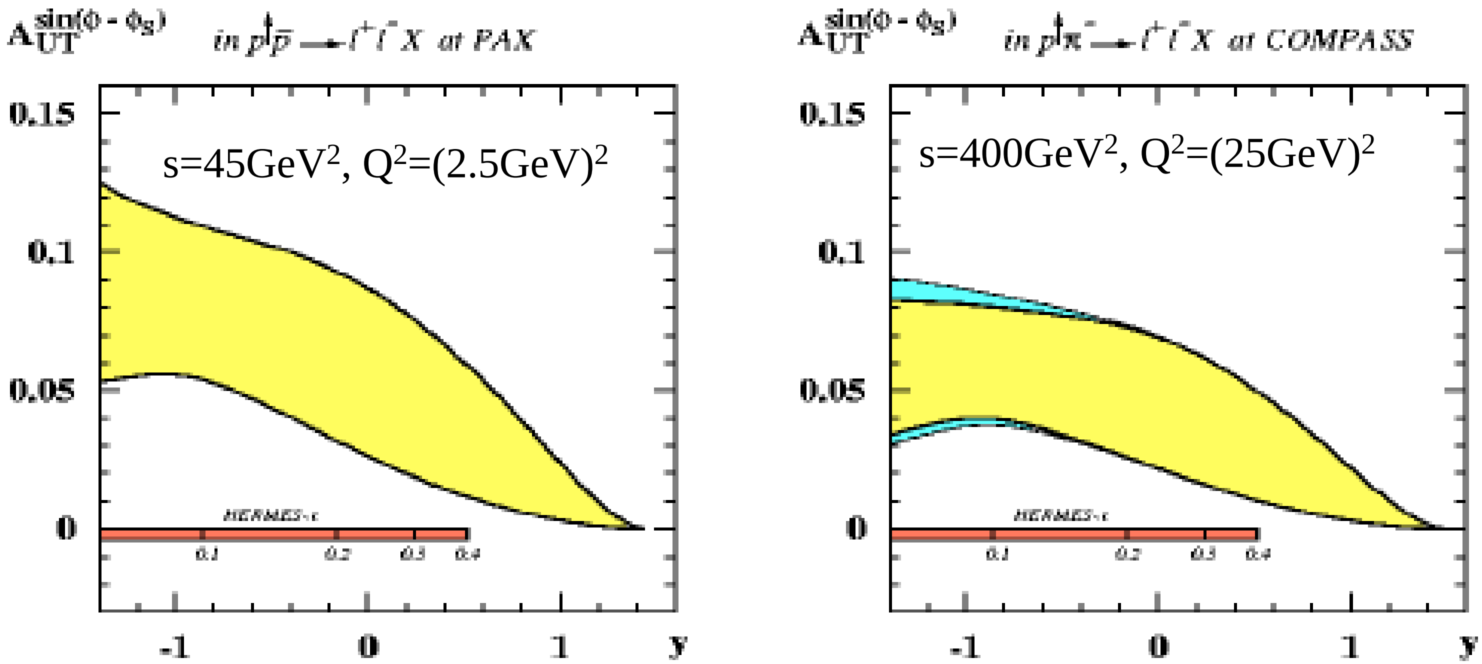
For $p\bar{p}$ Drell-Yan all

$\bar{f}, \bar{h} \rightarrow f, h$

Allows uniquely measure most PDFs!

Predictions for Sivers in PAX and COMPASS

$$A_{UT}^{\sin(\phi-\phi_S)} = + \frac{a_{\text{Gauss}}^{\text{DY}} \sum_a e_a^2 f_{1T_{\text{DY}}}^{\perp(1)a}(x_1) f_1^{\bar{a}}(x_2)}{\sum_a e_a^2 f_1^a(x_1) f_1^{\bar{a}}(x_2)}$$



- **PAX at GSI**

$p^\uparrow \bar{p} \rightarrow l^+ l^- X$ (byproduct)

- **COMPASS**

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

Annihilations of valence dominate.

Prediction for RHIC

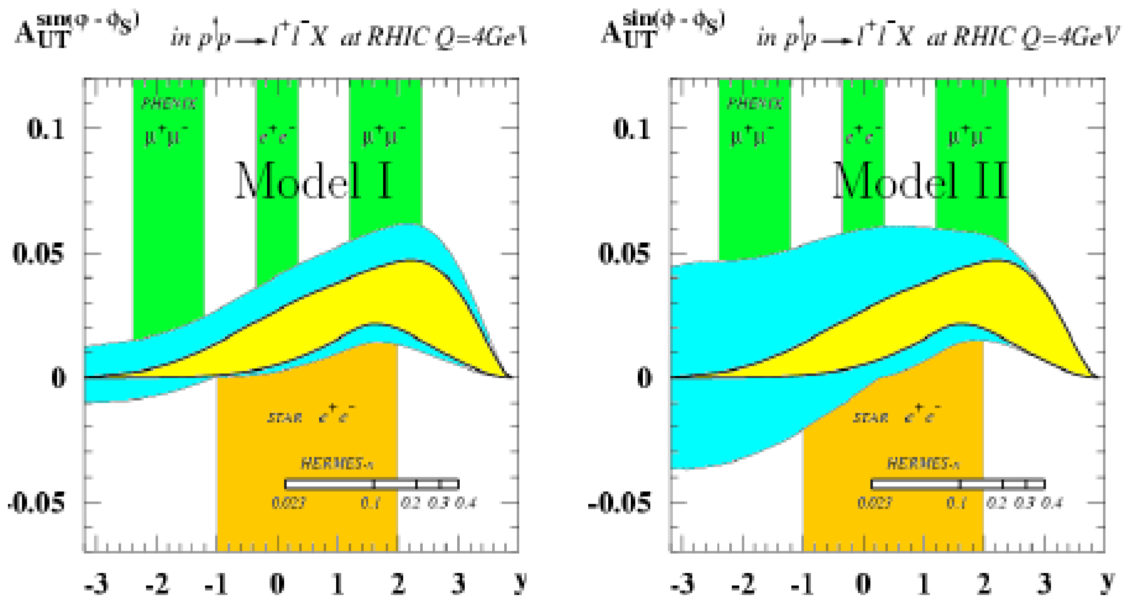
Let us simulate Sivers-$\bar{q}$:

$$f_{1T}^{\perp(1)\bar{q}}(x) = \underbrace{f_{1T}^{\perp(1)q}(x)}_{\text{best fit}} \times \begin{cases} \pm 25\% \\ \pm \dfrac{(f_1^{\bar{u}} + f_1^{\bar{d}})(x)}{(f_1^{u} + f_1^{d})(x)} \end{cases}$$

Collins, AE et al. Phys.Rev. D73 (2006) 094023

RHIC

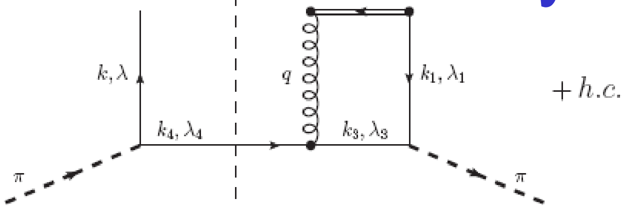
- $p^{\uparrow}p \to l^{+}l^{-}X$
  Valence q and sea $\bar{q}$ on equal footing. Sensitive to Sivers-$\bar{q}$ in certain y-region.
- RHIC can test "change of sign" & provide information on Sivers-$\bar{q}$!



yellow = 1-σ region, blue = effects due to Sivers-$\bar{q}$

Accuracy ($\int L dt = 125\, pb^{-1}$): $\delta A = \begin{cases} 0.7\% \text{ (STAR, PHENIX)} \\ 0.1\% \text{ (RHIC II)} \end{cases}$

The BM-Pretzelosity Asymmetry in π⁻ p Drell Yan



$$\alpha_s(\mu_0^2)/4\pi\,|_{NLO} = 0.100;\ \langle p^2_{pT,\mathrm{unp}}\rangle = 0.08\ \mathrm{GeV}^2$$

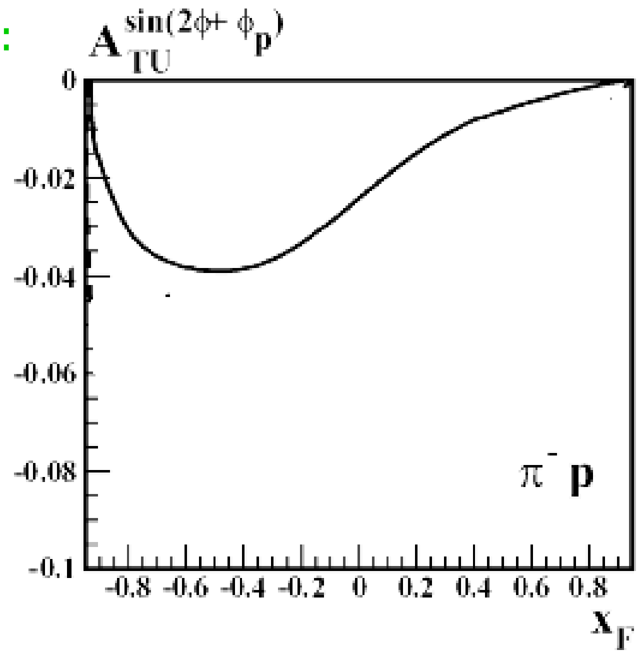
$$\langle p^2_{pT}\rangle = 0.05\ \mathrm{GeV}^2,\ \langle p^2_{\pi T}\rangle = 0.092\ \mathrm{GeV}^2$$

1. Light Cone Model Boer-Mulders function of pion generated from S-P wave interference in one-gluon exchange approximation,
2. COMPASS kinematics: $x_p\, x_\pi = Q^2/s$ with Q^2 =20 GeV^2 and s=400 GeV^2,
3. Evolution equations for $h_{1T}^{\perp}$ and $h_1^{\perp}$ are not yet used → we include "approximate" evolution effects using transversity evolution,

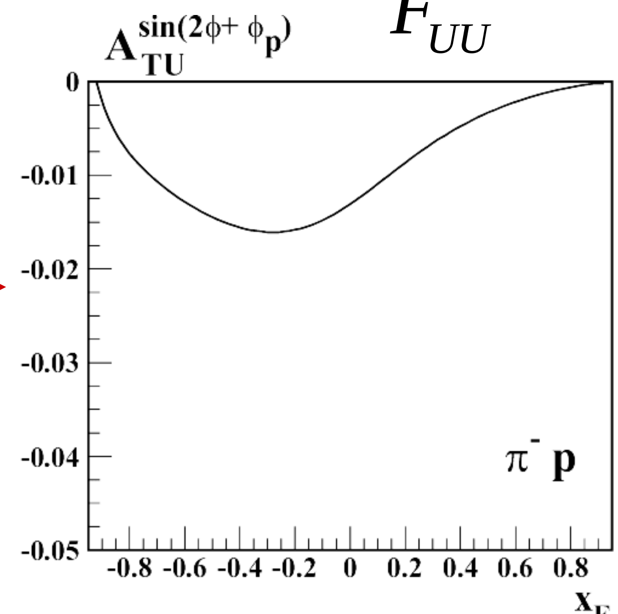
[AE, Pasquini, Schweitzer, Yuan, in preparation]

$$A_{TU}^{\sin(2\phi+\phi_s)} = \frac{F_{TU}^{\sin(2\phi+\phi_s)}}{F_{UU}^{1}}$$

Also Lu, Ma, She: arXiv:1101.2702



"Approximate" evolution



Parton model (leading twist, double spin, LL and TL)

$$F_{LL}^{1} = -C\left[g_{1L}\bar{g}_{1L}\right], \quad F_{LL}^{\cos 2\phi} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_{1L}^{\perp}\bar{h}_{1L}^{\perp}\right],$$

$$F_{LT}^{\cos(\phi-\phi_b)} = -C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} g_{1L}\bar{g}_{1T}\right], \qquad F_{TL}^{\cos(\phi-\phi_a)} = -C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} g_{1T}\bar{g}_{1L}\right],$$

$$F_{TL}^{\cos(\phi+\phi_a)} = C\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} h_1\bar{h}_{1L}^{\perp}\right], \quad F_{LT}^{\cos(\phi+\phi_b)} = C\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} h_{1L}^{\perp}\bar{h}_1\right],$$

$$F_{LT}^{\cos(3\phi-\phi_b)} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{bT}^{2}(\vec{h}\cdot\vec{k}_{aT})}{2M_a M_b^2} h_{1L}^{\perp}\bar{h}_{1T}^{\perp}\right],$$

$$F_{TL}^{\cos(3\phi-\phi_a)} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{aT}^{2}(\vec{h}\cdot\vec{k}_{bT})}{2M_a^2 M_b} h_{1T}^{\perp}\bar{h}_{1L}^{\perp}\right],$$

Parton model (leading twist, double spin, TT)

$$F_{TT}^{\cos(2\phi-\phi_a-\phi_b)} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT})-\vec{k}_{aT}\cdot\vec{k}_{bT}}{2M_aM_b}(f_{1T}^{\perp}\bar{f}_{1T}^{\perp}-g_{1T}\bar{g}_{1T})\right],$$

$$F_{TT}^{\cos(\phi_b-\phi_a)} = -C\left[\frac{\vec{k}_{aT}\cdot\vec{k}_{bT}}{2M_aM_b}(f_{1T}^{\perp}\bar{f}_{1T}^{\perp}+g_{1T}\bar{g}_{1T})\right],$$

$$F_{TT}^{\cos(\phi_b+\phi_a)} = C\left[h_1\bar{h}_1\right],$$

$$F_{TT}^{\cos(2\phi-\phi_a+\phi_b)} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})^2-\vec{k}_{aT}^2}{2M_a^2}h_{1T}^{\perp}\bar{h}_1\right], \quad F_{TT}^{\cos(2\phi+\phi_a-\phi_b)} = C\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})^2-\vec{k}_{bT}^2}{2M_b^2}h_1\bar{h}_{1T}^{\perp}\right],$$

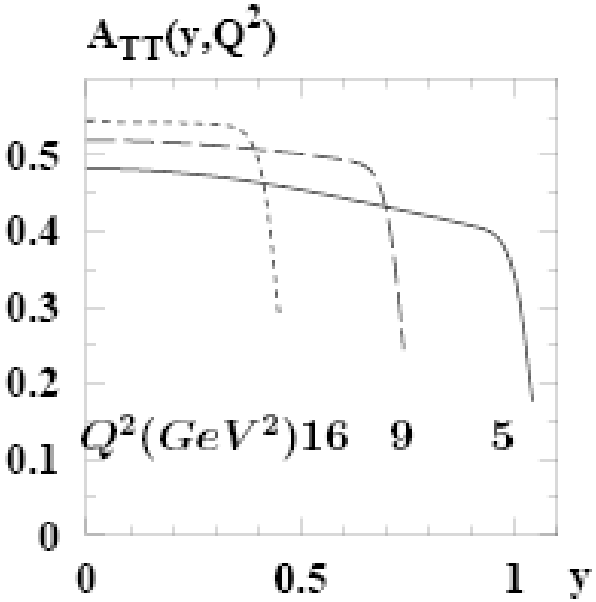
$$F_{TT}^{\cos(4\phi-\phi_a-\phi_b)} = C\left[\left(\frac{4(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT})-\vec{k}_{aT}\cdot\vec{k}_{bT}]}{4M_a^2M_b^2}\right.\right.$$

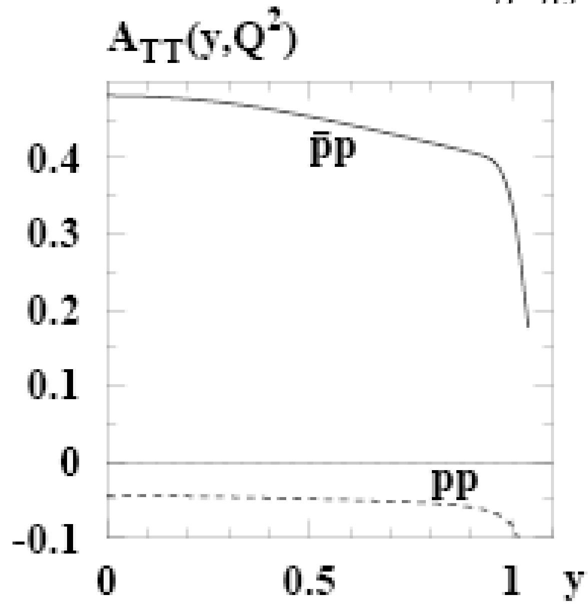
$$\left.\left.+\frac{\vec{k}_{aT}^2\vec{k}_{bT}^2-2\vec{k}_{aT}^2(\vec{h}\cdot\vec{k}_{bT})^2-2\vec{k}_{bT}^2(\vec{h}\cdot\vec{k}_{aT})^2}{4M_a^2M_b^2}\right)h_{1T}^{\perp}\bar{h}_{1T}^{\perp}\right].$$

Transversity in PAX

- Drell-Yan process is cleanest and safest way to access $h_1(x)$.
- Planned at RHIC and NICA but access is more difficult (small $\bar{h}_1(x)$).
- Quantitative estimates for A_{TT} in kinematics of PAX using predictions from the chiral quark soliton model.
- Region 1.5 GeV < Q < 3 GeV the most preferable (counting rate).

$$\frac{N^{\uparrow\uparrow}-N^{\uparrow\downarrow}}{N^{\uparrow\uparrow}+N^{\uparrow\downarrow}} = D_S \, \frac{\sin^2\theta}{1+\cos^2\theta} \, \cos 2\phi \; A_{TT}(y,Q^2) \quad ; \quad A_{TT}(y,Q^2) = \frac{\Sigma_a e_a^2 h_1^a(x_1,Q^2) h_1^a(x_2,Q^2)}{\Sigma_b e_b^2 f_1^b(x_1,Q^2) f_1^b(x_2,Q^2)}$$





A.E.,Goeke, Schweitzer EPJC35:207(04)
Anselmino,at al. PLB594(04)97

23 asymmetries allows in principle to measure all 8 TMDs for quarks and anti-quarks

$$A_{UU} \equiv \frac{\sigma^{00}}{\sigma^{00}_{\text{int}}} = \frac{1}{2\pi}(1 + D\cos 2\phi A^{\cos 2\phi}_{UU})$$

$$A_{LU} \equiv \frac{\sigma^{\to 0} - \sigma^{\leftarrow 0}}{\sigma^{\to 0}_{\text{int}} + \sigma^{\leftarrow 0}_{\text{int}}} = \frac{|S_{aL}|}{2\pi} D\sin 2\phi A^{\sin 2\phi}_{LU}$$

$$A_{UL} \equiv \frac{\sigma^{0\to} - \sigma^{0\leftarrow}}{\sigma^{0\to}_{\text{int}} + \sigma^{0\leftarrow}_{\text{int}}} = \frac{|S_{bL}|}{2\pi} D\sin 2\phi A^{\sin 2\phi}_{UL}$$

$$A_{TU} \equiv \frac{\sigma^{\uparrow 0} - \sigma^{\downarrow 0}}{\sigma^{\uparrow 0}_{\text{int}} + \sigma^{\downarrow 0}_{\text{int}}} = \frac{|\vec{S}_{aT}|}{2\pi}\left[A^{\sin(\phi-\phi_{S_a})}_{TU}\sin(\phi-\phi_{S_a}) + D\left(A^{\sin(3\phi-\phi_{S_a})}_{TU}\sin(3\phi-\phi_{S_a}) + A^{\sin(\phi+\phi_{S_a})}_{TU}\sin(\phi+\phi_{S_a})\right)\right]$$

$$A_{UT} \equiv \frac{\sigma^{0\uparrow} - \sigma^{0\downarrow}}{\sigma^{0\uparrow}_{\text{int}} + \sigma^{0\downarrow}_{\text{int}}} = \frac{|\vec{S}_{bT}|}{2\pi}\left[A^{\sin(\phi-\phi_{S_b})}_{UT}\sin(\phi-\phi_{S_b}) + D\left(A^{\sin(3\phi-\phi_{S_b})}_{UT}\sin(3\phi-\phi_{S_b}) + A^{\sin(\phi+\phi_{S_b})}_{UT}\sin(\phi+\phi_{S_b})\right)\right]$$

$$A_{LL} \equiv \frac{\sigma^{\to\to} + \sigma^{\leftarrow\leftarrow} - \sigma^{\to\leftarrow} - \sigma^{\leftarrow\to}}{\sigma^{\to\to}_{\text{int}} + \sigma^{\leftarrow\leftarrow}_{\text{int}} + \sigma^{\to\leftarrow}_{\text{int}} + \sigma^{\leftarrow\to}_{\text{int}}} = \frac{|S_{aL}S_{bL}|}{2\pi}\left(A^{1}_{LL} + DA^{\cos 2\phi}_{LL}\cos 2\phi\right)$$

$$A_{TL} \equiv \frac{\sigma^{\uparrow\to} + \sigma^{\downarrow\leftarrow} - \sigma^{\downarrow\to} - \sigma^{\uparrow\leftarrow}}{\sigma^{\uparrow\to}_{\text{int}} + \sigma^{\downarrow\leftarrow}_{\text{int}} + \sigma^{\downarrow\to}_{\text{int}} + \sigma^{\uparrow\leftarrow}_{\text{int}}} = \frac{|\vec{S}_{aT}|S_{bL}}{2\pi}\left[A^{\cos(\phi-\phi_{S_a})}_{TL}\cos(\phi-\phi_{S_a}) + D\begin{pmatrix} A^{\cos(3\phi-\phi_{S_a})}_{TL}\cos(3\phi-\phi_{S_a}) \\ +A^{\cos(\phi+\phi_{S_a})}_{TL}\cos(\phi+\phi_{S_a}) \end{pmatrix}\right]$$

$$A_{LT} \equiv \frac{\sigma^{\to\uparrow} + \sigma^{\leftarrow\downarrow} - \sigma^{\to\downarrow} - \sigma^{\leftarrow\uparrow}}{\sigma^{\to\uparrow}_{\text{int}} + \sigma^{\leftarrow\downarrow}_{\text{int}} + \sigma^{\to\downarrow}_{\text{int}} + \sigma^{\leftarrow\uparrow}_{\text{int}}} = \frac{S_{aL}|\vec{S}_{bT}|}{2\pi}\left[A^{\cos(\phi-\phi_{S_b})}_{LT}\cos(\phi-\phi_{S_b}) + D\begin{pmatrix} A^{\cos(3\phi-\phi_{S_b})}_{LT}\cos(3\phi-\phi_{S_b}) \\ +A^{\cos(\phi+\phi_{S_b})}_{LT}\cos(\phi+\phi_{S_b}) \end{pmatrix}\right]$$

$$A_{TT} \equiv \frac{\sigma^{\uparrow\uparrow} + \sigma^{\downarrow\downarrow} - \sigma^{\uparrow\downarrow} - \sigma^{\downarrow\uparrow}}{\sigma^{\uparrow\uparrow}_{\text{int}} + \sigma^{\downarrow\downarrow}_{\text{int}} + \sigma^{\uparrow\downarrow}_{\text{int}} + \sigma^{\downarrow\uparrow}_{\text{int}}} = \frac{|\vec{S}_{aT}||\vec{S}_{bT}|}{2\pi}\Big[A^{\cos(2\phi-\phi_{S_a}-\phi_{S_b})}_{TT}\cos(2\phi-\phi_{S_a}-\phi_{S_b}) + A^{\cos(\phi_{S_b}-\phi_{S_a})}_{TT}\cos(\phi_{S_b}-\phi_{S_a})$$

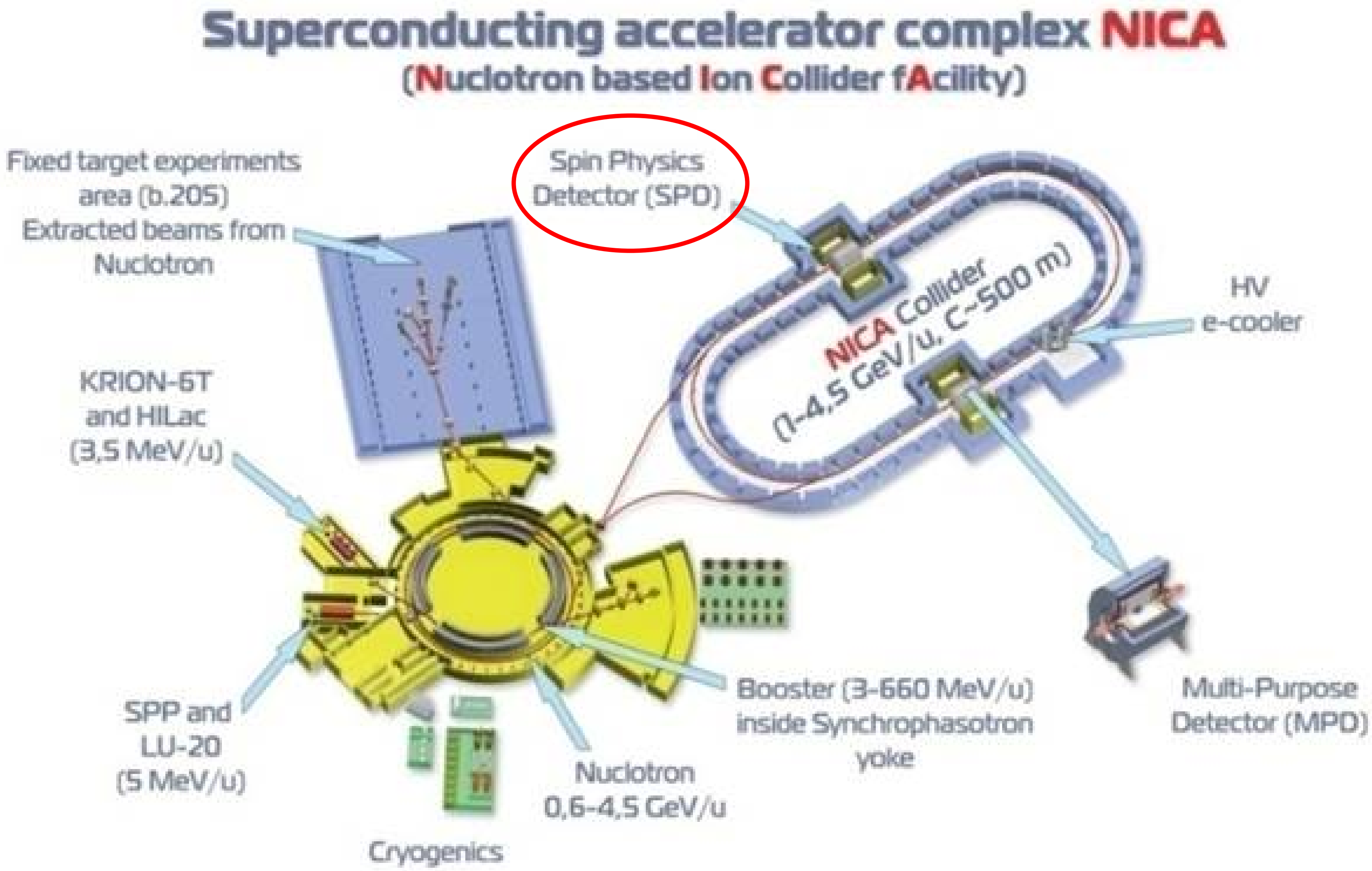
$$+D\Big(A^{\cos(\phi_{S_b}+\phi_{S_a})}_{TT}\cos(\phi_{S_a}+\phi_{S_b}) + A^{\cos(4\phi-\phi_{S_a}-\phi_{S_b})}_{TT}\cos(4\phi-\phi_{S_a}-\phi_{S_b})$$

$$+A^{\cos(2\phi-\phi_{S_a}+\phi_{S_b})}_{TT}\cos(2\phi-\phi_{S_a}+\phi_{S_b}) + A^{\cos(2\phi+\phi_{S_a}-\phi_{S_b})}_{TT}\cos(2\phi+\phi_{S_a}-\phi_{S_b})\Big)\Big]$$

Advanteges of Drell-Yan process

- The large number of independent structure functions (24 or 16 for identical hadrons)— indicates its high potential for studying TMDs.
- Certain advantage over semi-inclusive DIS being just sufficient to map out, in principle, all the eight leading twist TMDs for *q* and $\bar{q}$.
- There are no indefiniteness with fragmentation functions.
- Data on unpolarized $\pi^- N \to \mu^- \mu^+ X$ and unpolarised DIS show a rather large $\cos 2\phi$ – evidence for rather large Boer-Mulders function
- Together with rather large transversity h_1 this can give a clue to all other TMDs.
- Boer-Mulders and Sivers TMDs gives the possibility to check revers of sign -- the core of our present understanding of transverse single spin asymmetries.

Drell-Yan program at SPD



SPD layout.

Preliminary considerations of the event topologies require SPD to be equipped with the sub-detectors covering ~4π angular region around the beam intersection point:

vertex detectors,

tracking detectors,

electromagnetic calorimeters,

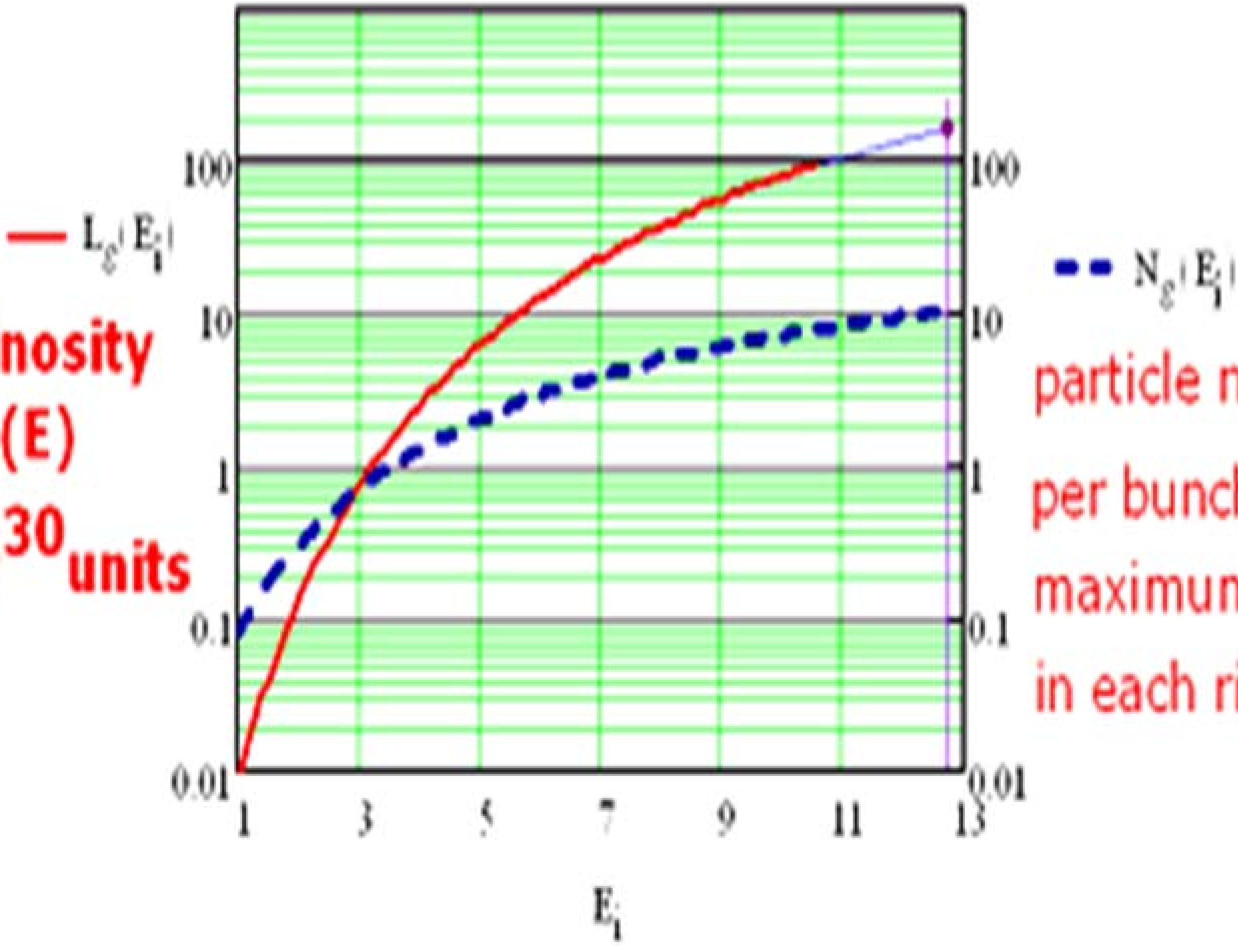
hadron detectors and

muon detectors.

Prototypes of all sub-detectors exist or under development.

Feasible schemes of manipulations with polarized protons and deuterons at Nuclotron and NICA are suggested. The final scheme will be approved at the later stages of the project.

(See LoI arXiv:1408.3959)

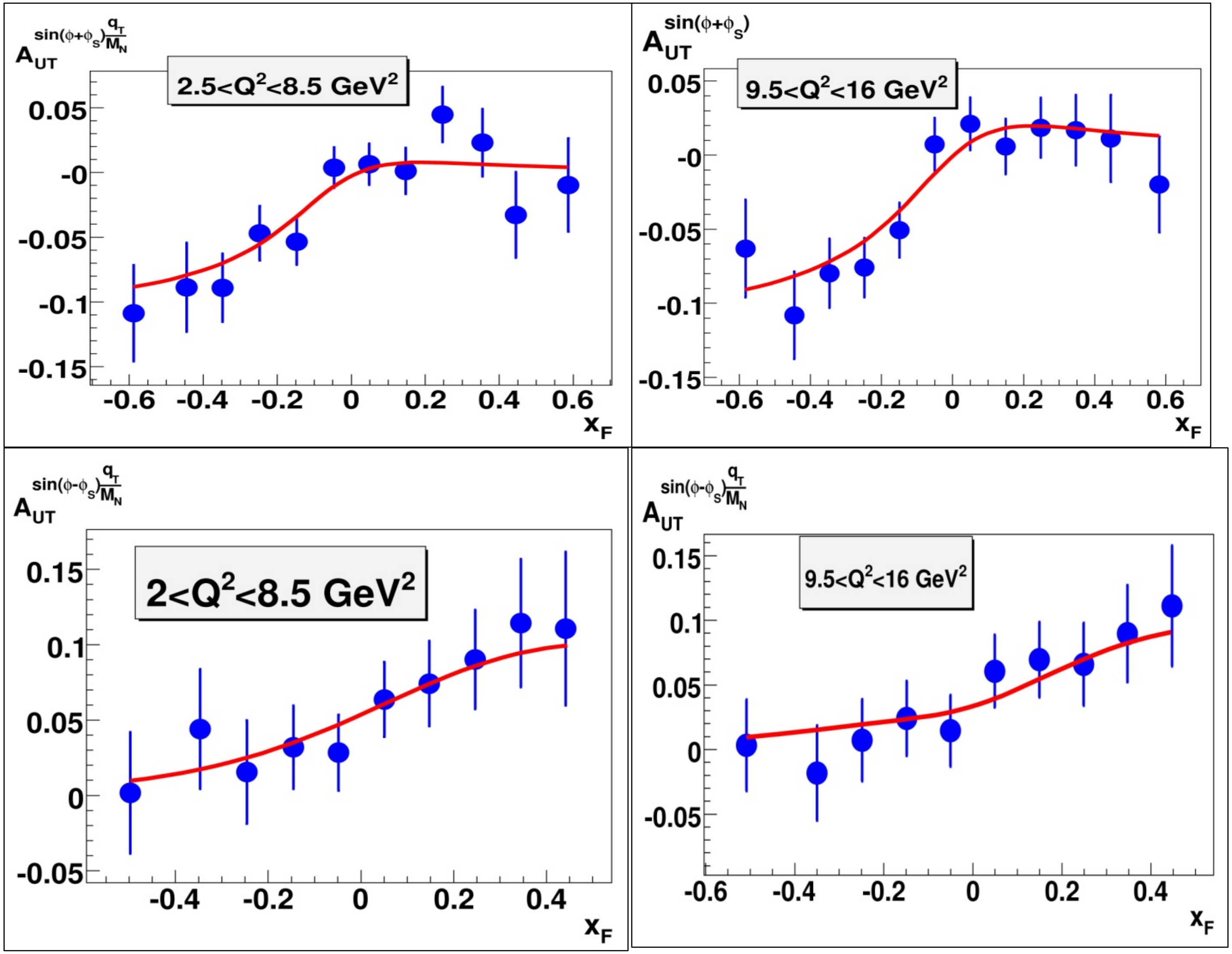


Luminosity L(E) in 10^{30} units

particle number per bunch in 10^{11} units
maximum proton number in each ring – $2.2 \cdot 10^{13}$

MC estimation of precision for D-Y at NICA SPD

100Kevents (s~670 GeV^2 for L=10^{32})



Transversity and B-M

Sivers

Sissakian at al. EPJC46(2006)147

Conclusions

- TMD PDFs are necessary for 3D hadron spin structure description.
- Some experimental information about all twist-2 TMDs are now available.
- Evolution schemes (not single!) & first attempts to phenomenological study of TMDs are in progress.
- More data on TMDs from SIDIS and DY are necessary and planed (COMPASS, JLab, RHIC, FemiLab, JPARK, PAX-Panda, NICA).
- More theoretical prediction for NICA, using various models are necessary!

Thank You!

BACKUP SLIDES

Problem with evolution.

LCQM (and others models) gives TMD functions at low scale μ_0^2.

Evolution equation for $h_{1L,T}^{(1)\perp}(x,Q^2)$ yet unknown.

Two possibilities:

Model I —— no evolution
(chiral odd, no mixture with gluon)

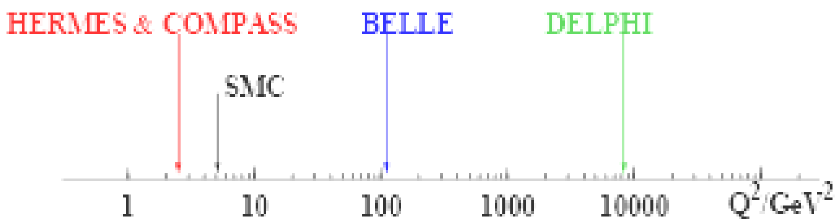
Model II - - - evolution similar to $h_1(x,Q^2)$, i.e.

$$h_{1L}^{(1)\perp}(x,Q^2) = h_{1L}^{(1)\perp}(x,\mu_0^2)\frac{h_1(x,Q^2)}{h_1(x,\mu_0^2)}$$

Data HERMES: PRL84(00); NP.Proc.Suppl.79(99).

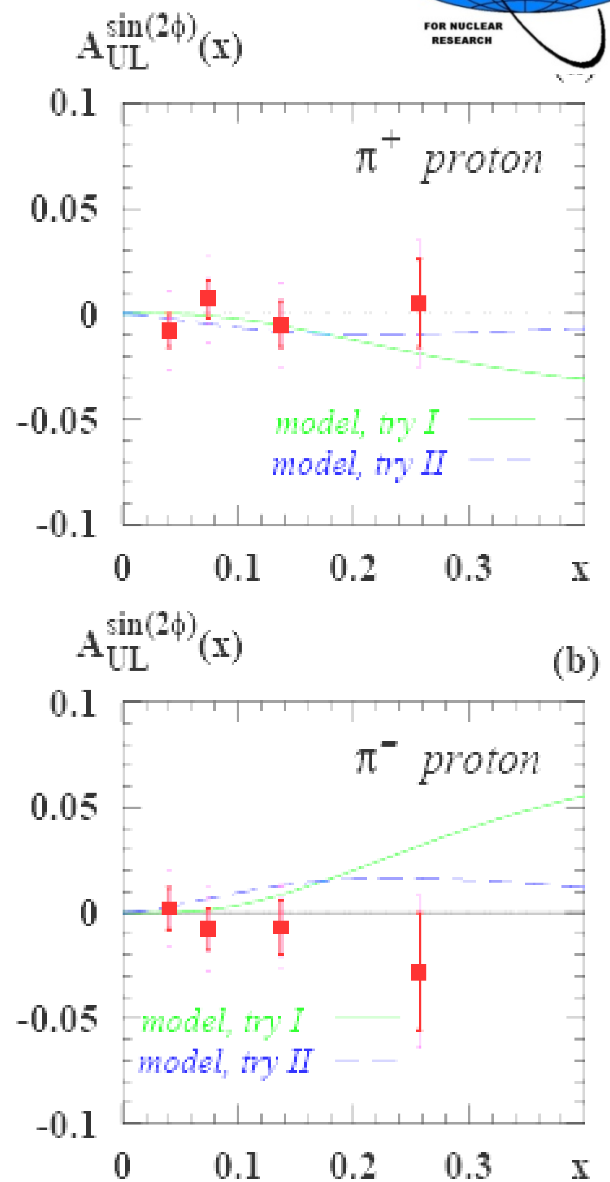
Seems better agrees with experiment.

Similar problem with Collins PFF $H_1^\perp$



Singlet evolution is usually assumed.

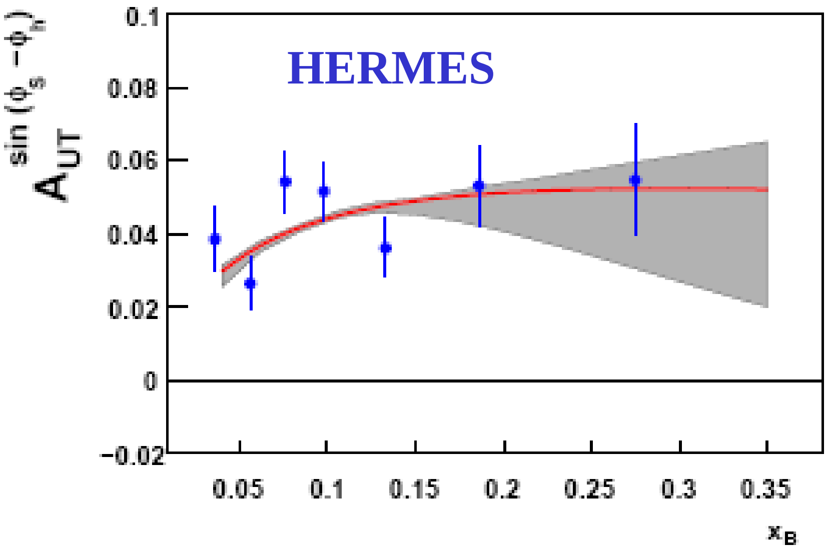
Good important problem for RG-community!

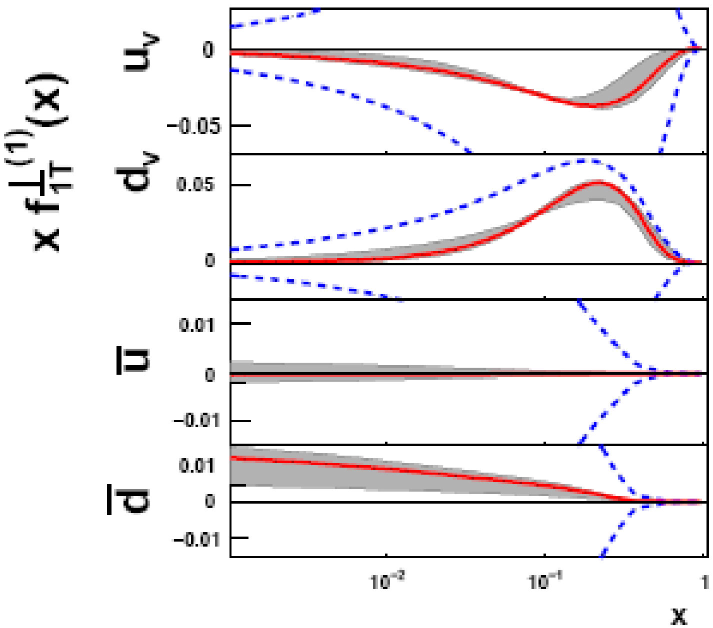


Process-dependence of Sivers effect

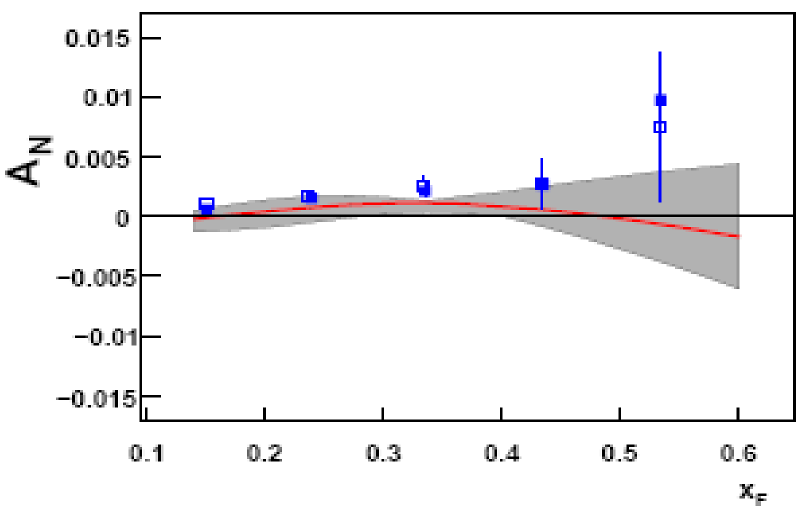
Gamberg, Kang, Prokudin: 1302.3218

Fit HERMES and COMPASS data

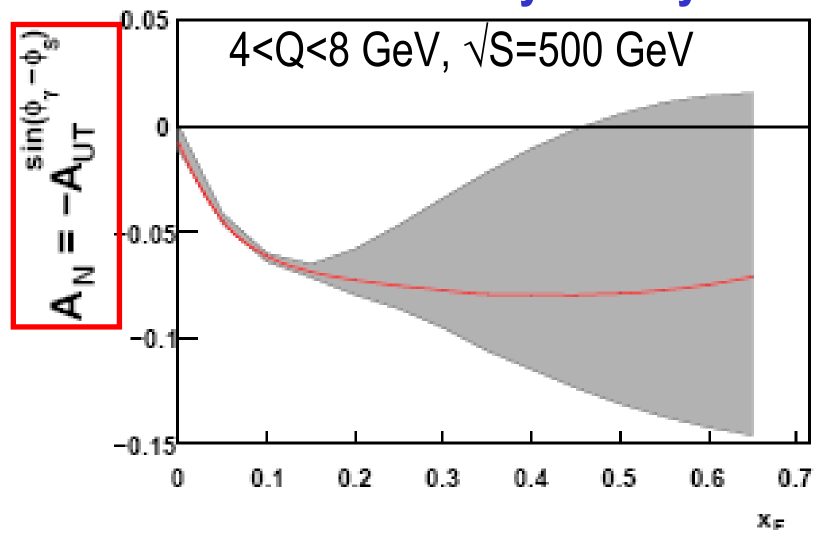




Single jet A_N experiment seems <u>compatible</u> with Sivers SIDIS!



Prediction of Sivers asymmetry for DY



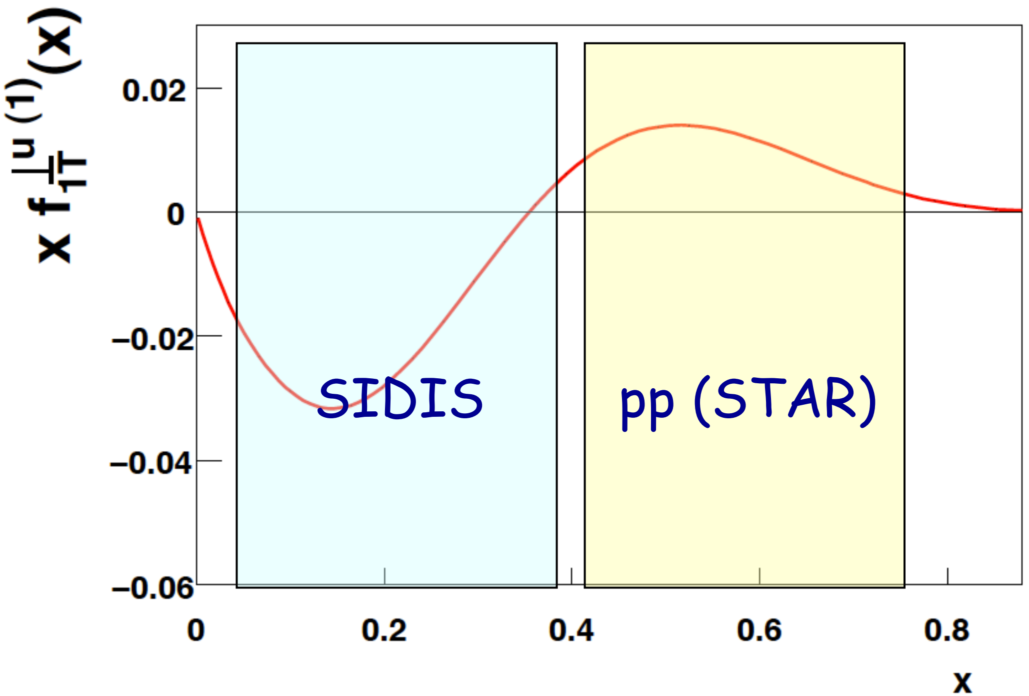
MEGAPROJECT NICA

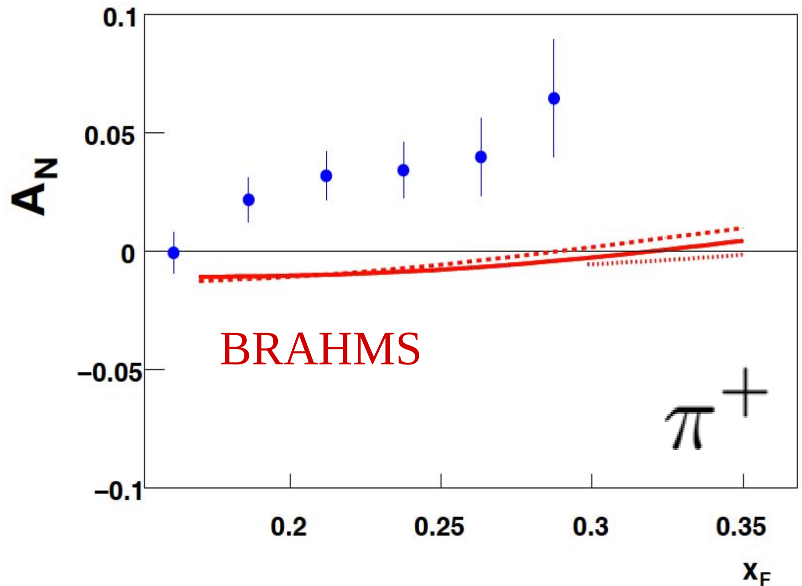
Participation of Russia and International Cooperation

Armenia	
Australia	Italy
Azerbaijan	Japan
Belarus	Kazakhstan
Bulgaria	Moldova
Brazil	Mongolia
CERN	Poland
China	Romania
Cuba	RSA
Czech Rep.	Russia
DPRK	Serbia
France	Slovakia
Georgia	Ukraine
Germany	USA
Greece	Uzbekistan
India	Vietnam

Joint fit to SIDIS and pp data: mismatch problem

other (than Sivers) effects dominant? ep-data: Sivers function only constraint for x<0.4: Nodes? ETQS? Other?





Works (reasonably) well for SIDIS and STAR,

But fails for BRAHMS!

Strengthens case **for study of DY "sign change" !**

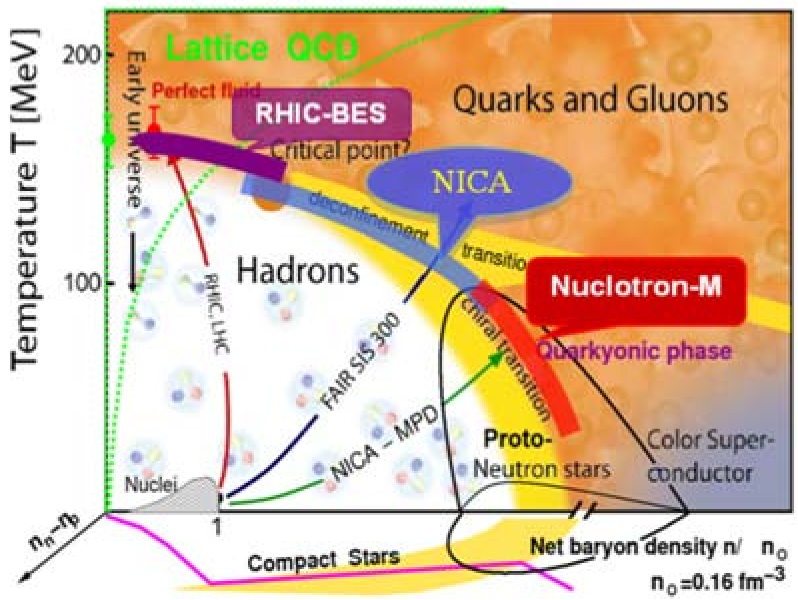
NICA, COMPASS, E906, W bosons at RHIC

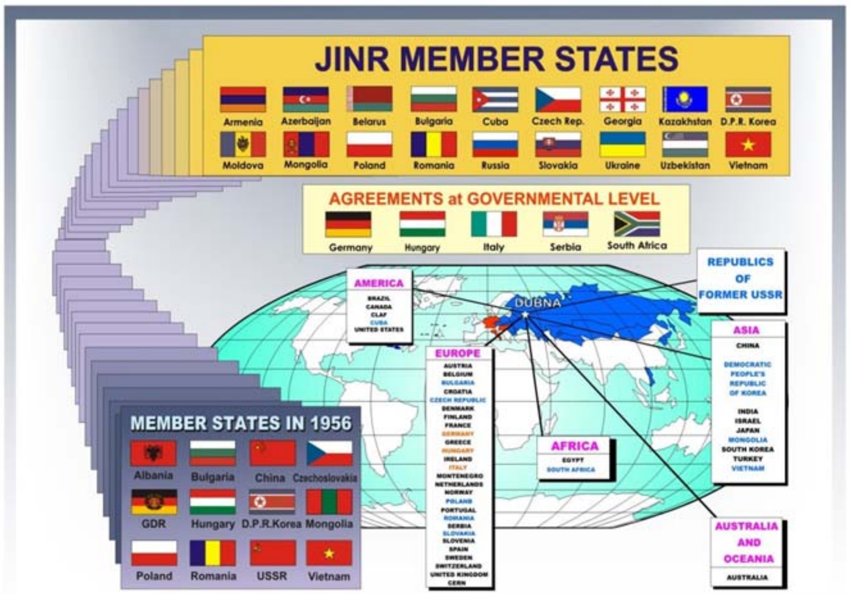
Kang,Prokudin PRD85(2012)07408

MEGAPROJECT NICA

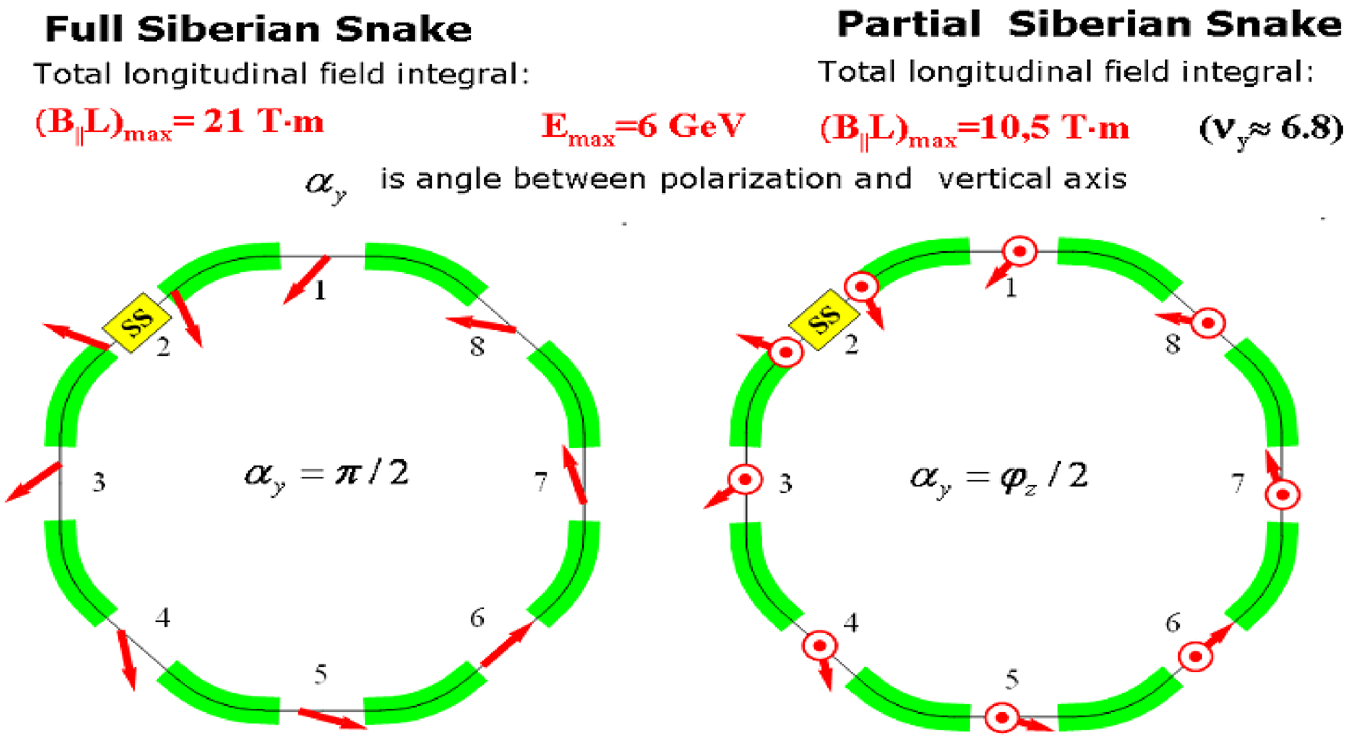
From the blocks of the World to the modern Universe

Construction of the experimental base for studies of baryonic matter fundamental properties and carry out innovational research on the base of the Joint Institute of Nuclear Research (Dubna)





Proton spin dynamics in the Nuclotron ring in the case of a full or partial snake working synchronously with accelerating cycle



Polarized deuterons acceleration in Nuclotron is possible up to the energy of 5.6 GeV/u

53

Possible NICA structure for polarized proton and deuteron beams