A_N in inclusive lepton-proton collisions

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based on work in collaboration with
M. Anselmino, M. Boglione, S. Melis, F. Murgia, and A. Prokudin
PRD 81 (2010) and arXiv:1404.6465

Outline

- Transverse Single Spin Asymmetries (SSA):
  single- vs. two- scale processes
  $pp \to h\,X$ vs. $\ell p \to \ell' h, X$ (SIDIS)

- TMD approach: factorization and universality?

- SSAs in $\ell p \to h\,X$: a bridge or a testing ground of the TMD scheme
  - role of kinematics and dynamics
  - use of TMDs extracted from SIDIS fits

- Recent HERMES results: a comparison

- Predictions for future experiments

- Conclusions

SSAs and theoretical approaches in QCD

single scale process: $pp \to hX$ $A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$

- sizeable over a huge energy range (FermiLab...RHIC)

- subleading SSA

- Twist-3 approach *[Efremov-Teryaev, Qiu-Sterman, Koike- Kanazawa, Kang et al.]*
  - collinear factorization established
  - universal $T_F(x, x)$ quark-gluon correlator, related to the TMD Sivers function
  - T_F from the Sivers function leads to A_N opposite in sign w.r.t. data
  - update: A_N dominated by a twist-3 term in the fragm. *[Kanazawa et al. 2014]*

- TMD scheme (generalization of the parton model with $k_\perp$) *[Anselmino et al.]*
  - factorization (and universality) assumed
  - rich and successful phenomenology

two-scale processes (SIDIS, DY, e^+e^-): large Q^2 and small P_T

- leading SSA
- TMD factorization proved
- equivalence with twist-3 approach in one-scale regime
- modified universality: change of sign of T-odd TMDs from SIDIS to DY (to be tested)
- SIDIS extraction of the Sivers and Collins functions (and transversity distribution)
- recent studies with proper scale evolution

$\ell p \to h + X$...a bridge

no detection of the final lepton!

	$\ell p \to h + X$	$\ell p \to \ell' h + X$	$pp \to h + X$
scales	P_T	Q^2, P_T	P_T
hard scale	P_T	Q^2	P_T
TMD fact.	assumed	proven	assumed
c.m. frame	ℓp	$\gamma^* p$	pp
subprocesses	ℓq	ℓq	$qq,\, qg,\, gg$
channels	t	t	$t,\, u,\, s$

Detailed phenomenology *[Anselmino, Boglione, UD, Murgia, Melis, Prokudin 10 & 14]*

- Analogous/complementary study *[She, Mao, Ma 08]*
- Twist-3 approach *[Kang et al 11]*

Kinematics and hard scattering region

partonic subprocess at LO: $q\ell \to q\ell$

$$d\hat{\sigma}^{q\ell\to q\ell} \simeq \frac{1}{\hat{t}^2} \qquad \hat{t} = (p'_q - p_q)^2 \equiv -Q^2$$

hard scattering $\Leftrightarrow$ large $|\hat{t}|$ (≥ 1 GeV^2)

TMD factorization scheme at large P_T [assumed as in $pp \to h + X$]:

$$d\sigma^{p\ell\to hX} = \sum_q f_{q/p}(x, \boldsymbol{k}_\perp; Q^2) \otimes d\hat{\sigma}^{q\ell\to q\ell} \otimes D_{h/q}(z, \boldsymbol{p}_\perp; Q^2)$$

TMD: $\boldsymbol{p}_q \simeq x\boldsymbol{p} + \boldsymbol{k}_\perp$, $p_h \simeq z\boldsymbol{p}'_q + \boldsymbol{p}_\perp$

Kinematical regions

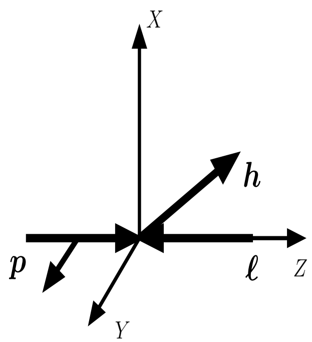
- high statistics at low P_T (around 0.5 GeV)
  $\Rightarrow$ dominated by quasi-real photon exchange $\Rightarrow$ OUT of pQCD regime
- consider larger P_T values and proper forward/backward proton hemisphere

large scattering angles: $|t|_{\rm min} \simeq 1$ GeV^2
[$\sqrt{s} \simeq$ 5-10 GeV]

P_T	collinear		TMD	
	forward	backward	forward	backward
1 GeV	OK	OK	NO	OK
2 GeV	OK	OK	OK	OK

Note: under the assumption of no hard gluon emission

TMD approach to $p\,\ell \to h\,X$:



$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{2d\sigma^{\rm unp}}$$

$$d\sigma^\uparrow - d\sigma^\downarrow = \sum_q \Big\{ \Delta^N f_{q/p^\uparrow} \cos\phi_q \otimes d\hat\sigma \otimes D_{h/q} \qquad \text{Sivers effect}$$

$$+\, h_1^{q/p} \otimes d\Delta\hat\sigma \otimes \Delta^N D_{h/q^\uparrow} \cos\phi_C \qquad \text{Collins effect I}$$

$$+\, h_{1T}^{\perp q/p} \otimes d\Delta\hat\sigma \otimes \Delta^N D_{h/q^\uparrow} \cos(\phi_C - 2\phi_q) \Big\} \qquad \text{Collins effect II}$$

$$d\hat\sigma \simeq e_q^2 \frac{\hat s^2 + \hat u^2}{\hat t^2} \qquad\qquad d\Delta\hat\sigma \simeq -e_q^2 \frac{\hat s \hat u}{\hat t^2}$$

$\phi_C \equiv \phi_h^H + \phi_{q'}$ [ϕ_h^H hadron azimuthal angle in $\boldsymbol{p}'_q$ helicity frame, Collins effect]

Single plane (w.r.t. two planes in SIDIS):
$\sin(\phi_h \pm \phi_S)$ not measurable $\Rightarrow$ No separation of effects:

$\Rightarrow$ hopeless???? Not really:

- single partonic channel: clear
- t-channel: $\hat{t}$ strongly dependent on ϕ_q (Sivers azimuthal dependence)
- backward region (small $\hat{u}$):
  - moderately large Q^2 (ok pQCD)
  - absence of u-channel (with $\hat{u}$ almost independent on ϕ_q)
    - Sivers effect still active
    - Collins effect strongly suppressed
  - $p^\uparrow p \to \pi\, X$: all spin-TMD effects in A_N strongly suppressed

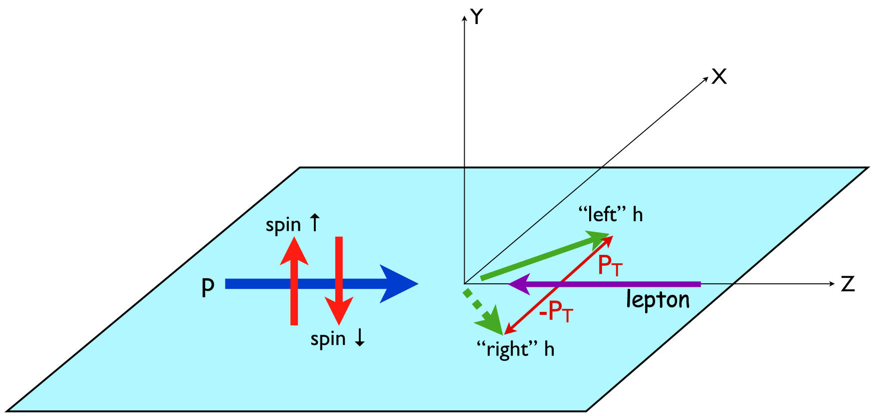
Unified picture

- use of Sivers and Collins functions (and transversity) from fits to SIDIS and e^+e^-:

1. SIDIS 1:
   - FFs from *Kretzer 2000*;
   - Sivers functs. for up and down quarks [*Anselmino et al, 05*]
   - first extraction of transversity [*Anselmino et al. 07*]
2. SIDIS 2:
   - FFs from *de Florian-Sassot-Stratmann 07*;
   - Sivers functs. with sea quarks [*Anselmino et al. 09*]
   - updated h_1 [*Anselmino et al. 09*]

- Some differences in the SIDIS unconstrained large x region for the Sivers and transversity functions (crucial in A_N in pp collisions)
- well representative of the uncertainties in the available extractions
- Envelope of the statistical uncertainty bands

Kinematics vs. HERMES setup



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

$$A(\phi_S, S_T) = \boldsymbol{S}_T \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{P}}_T)\, A_N = S_T \sin\phi_S\, A_N$$

HERMES: $d\sigma = d\sigma_{UU}[1 + S_T \sin\psi\, A_{UT}^{\sin\psi}]$ $\sin\psi = \hat{\boldsymbol{S}}_T \cdot (\hat{\boldsymbol{P}}_T \times \hat{\boldsymbol{k}})$ and $\hat{\boldsymbol{k}} = -\hat{\boldsymbol{p}}$

HERMES configuration: left and right interchanged but defined looking downstream w.r.t. opposite directions (lepton vs. proton) $\to$
only a sign change in x_F: $x_F > 0$ means backward proton hemisphere.

$$A_{UT}^{\sin\psi}(x_F, P_T)|_{\rm HERMES} = A_N^{p^\uparrow \ell \to hX}(-x_F, P_T)$$

Results

- Fully inclusive case
  - one large scale $P_T \simeq 1$ GeV $\rightarrow Q^2 \geq 1$ GeV^2 BACKWARD proton hemisphere
  - only one HERMES bin with $\langle P_T \rangle \simeq 1$ GeV

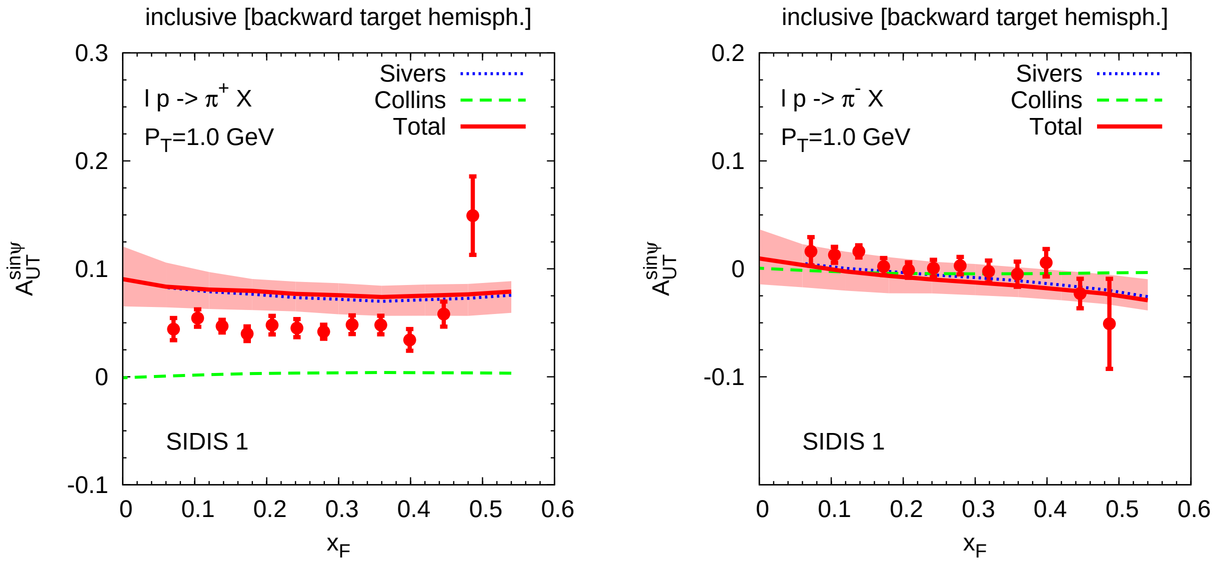
- lepton-tagged or SIDIS category
  - subsample with detection of the final lepton (low rates)
  - $Q^2 > 1$ GeV^2 (plus usual SIDIS cuts on x_B, z_h, y, W^2)
  - extra cut: $P_T > 1$ GeV [ℓp c.m. frame]

    SIDIS azimuthal asym. $P_T < 1$ GeV [$\gamma^* p$ c.m. frame] to access intrinsic $k_\perp$).

    Note: in $\ell p \rightarrow h\, X$ the final P_T comes also from the hard scattering

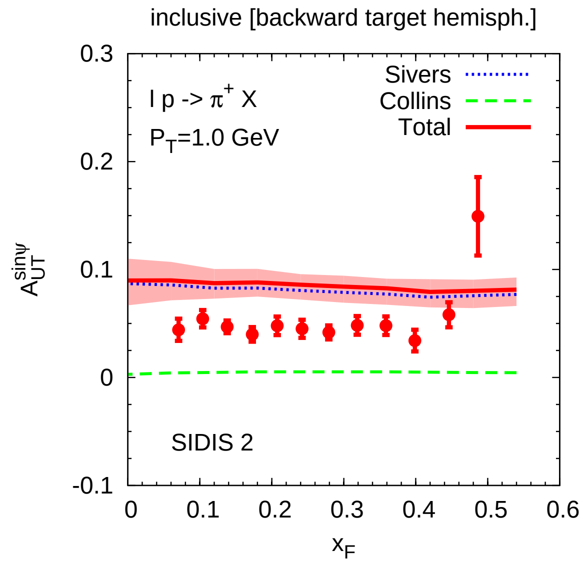
HERMES data: PLB 728 (2014)

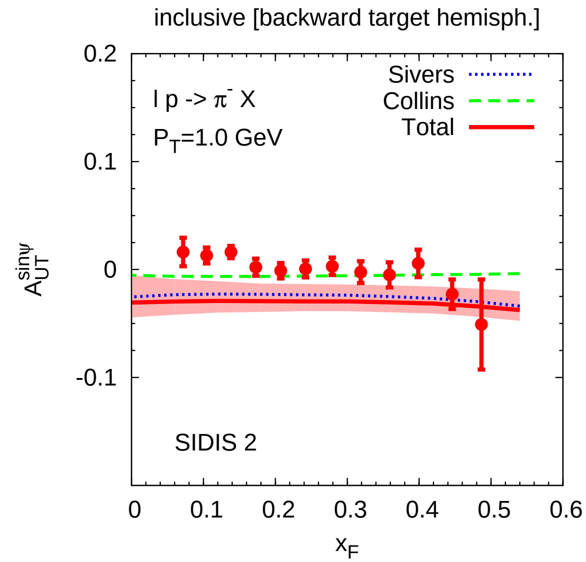
Fully inclusive case: SIDIS 1



- Collins effect suppressed: azimuthal phase integration and dynamics
- Sivers effect sizeable:
  - backward region but only t channel, and moderate $Q^2 = |\hat{t}| \rightarrow$:
    Sivers azimuthal phase active in the hard scattering
  - backward hemisphere but valence region ($\sqrt{s} \simeq 7$ GeV and $P_T = 1$ GeV)
  - π^-: role of up quark Sivers function coupled to non-leading FF

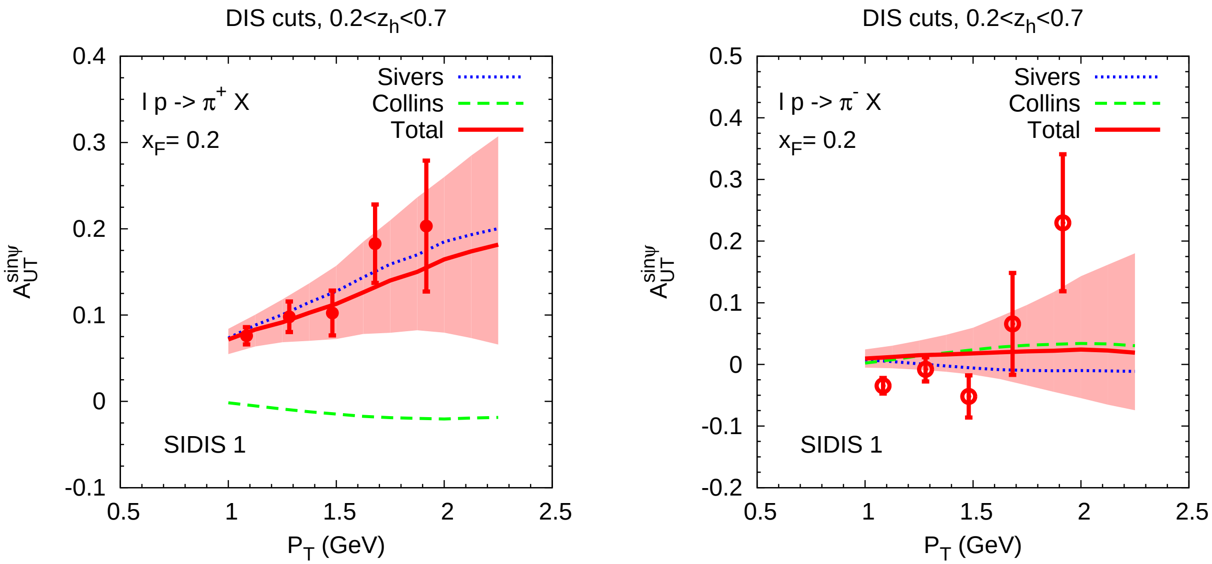
Fully inclusive case: SIDIS 2





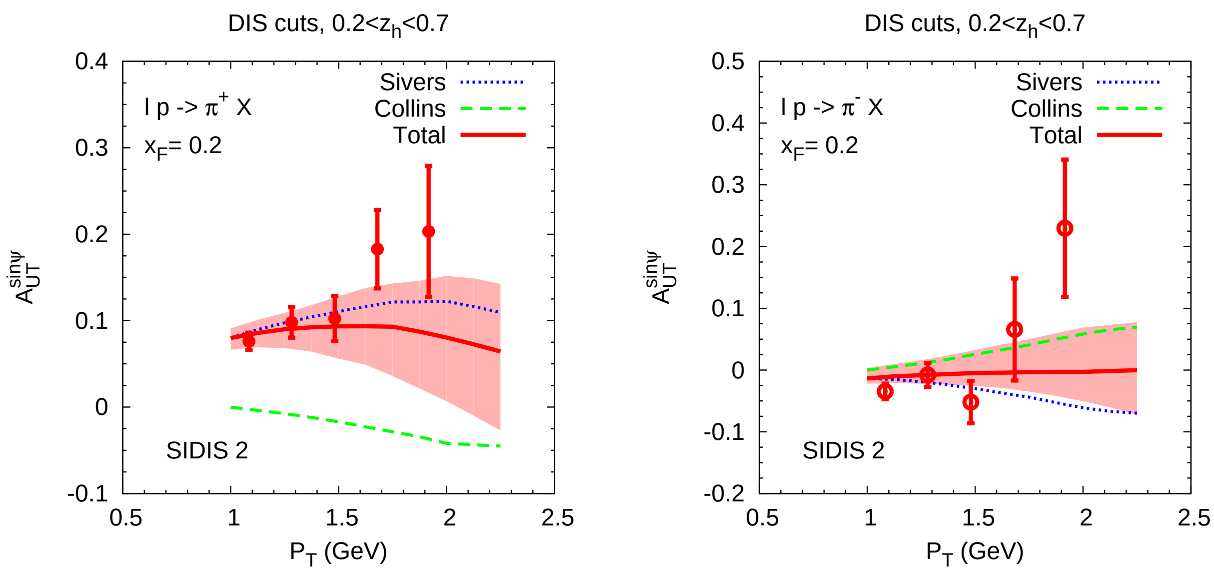
- π^+ similar to SIDIS 1
- π^- dominated by negative down quark Sivers function (w.r.t. SIDIS 1)

lepton-tagged - SIDIS 1



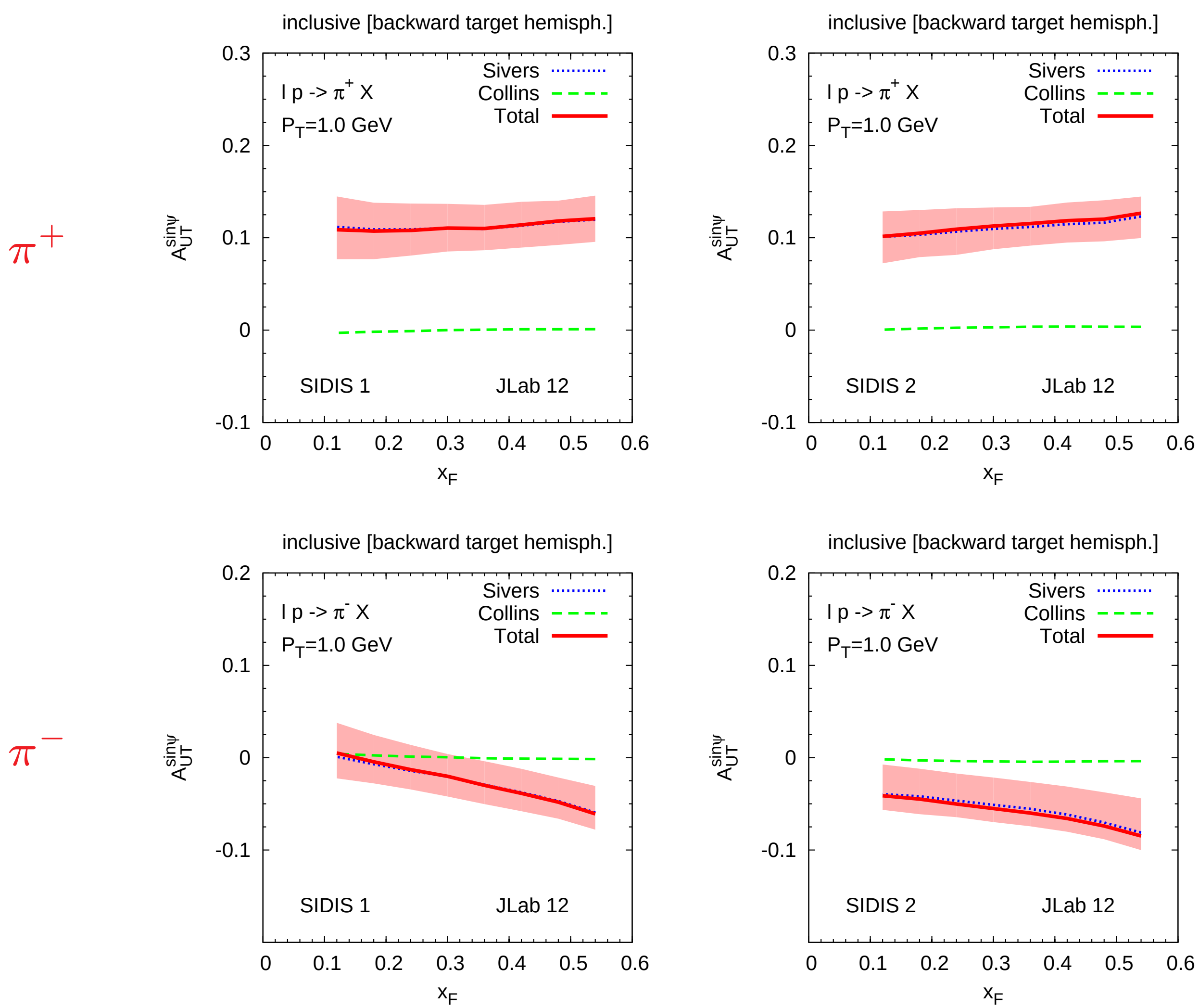
- Collins effect only partially suppressed (Collins phase picks to -1)
- Sivers effect sizeable (cancelation in π^- due to the large role of up quark)

lepton-tagged - SIDIS 2



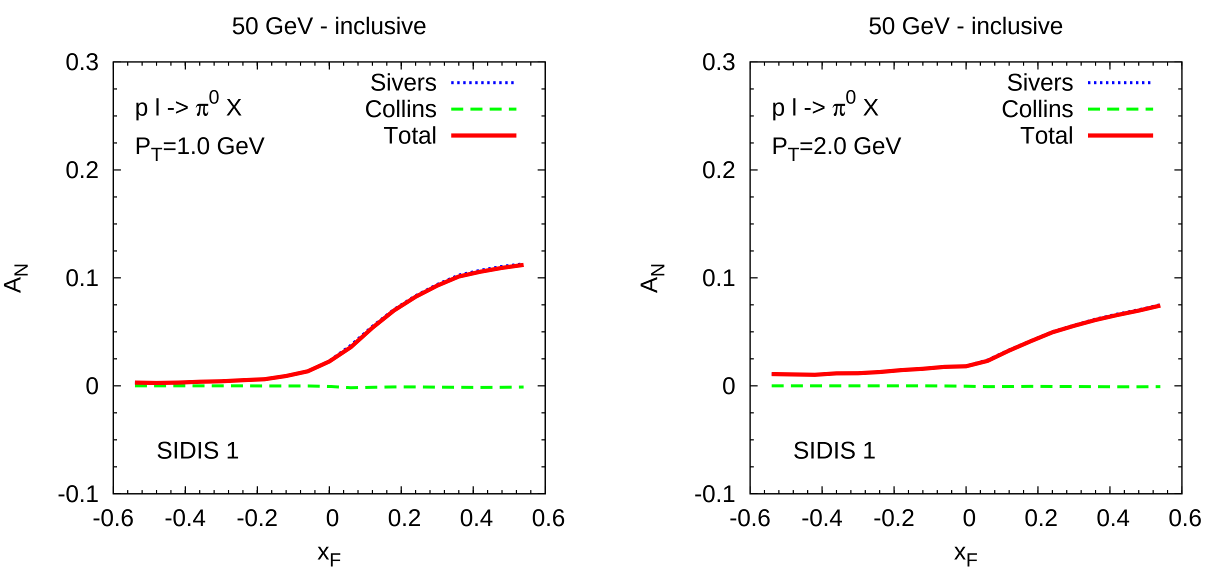
- Collins effect: larger w.r.t. SIDIS 1 (transversity unsuppressed at large x)
- Sivers effect: no cancelation in π^- (same large x behaviour of up and down quarks)

Predictions: JLab 12



Predictions at large energies

- Look for a behaviour similar to A_N in $p^\uparrow p \to \pi X$
- To facilitate the comparison: $p^\uparrow$ along $+Z_{cm}$, i.e. forward region $\equiv x_F > 0$
- Use of SIDIS 1 (better agreement with STAR data *Boglione-UD-Murgia 08*)



$P_T = 1$ GeV $\qquad$ $P_T = 2$ GeV

Notice: here $Q^2 > 1$ GeV^2 also in the forward region

Comments

- Collins effect
  - suppressed in the backward region: azimuthal phase integration
  - small in the forward region even if the Collins phase is active
- Sivers effect
  - suppressed in the backward region: one channel but large Q^2 are not sensitive to the Sivers phase
  - sizeable and increasing in the forward region
  - similar behaviour as for A_N in $pp \to \pi^0 X$
  - very similar results for $p^\uparrow \ell \to \mathrm{jet}\ X$
- Twist-3 (a comparison)
  - $A_N^{p\ell \to \mathrm{jet}\ X}$ with T_F from Sivers function: similar results *[Kang et al 11]*
  - impact of the new large piece in the fragmentation to $p\,\ell \to \pi^0\,X$?

Conclusions

- Test of TMD factorisation in single large-scale inclusive processes
- strong analogy with $p^{\uparrow}p \to h\,X$, where A_N are large and still puzzling
- from $\ell p \to \ell' h\,X$ (SIDIS), to $\ell p \to h\,X$ at large P_T (i.e. large Q^2)
- use of a unified TMD approach (same Sivers and Collins functions)
- new HERMES data and theoretical estimates agree in shape and sign (inclusive and lepton tagged events)
- size a bit overestimated ($\ell p \to \pi^+\,X$): other mechanism at work?
- predictions for a EIC, same behaviour as in $pp \to \pi\,X$:
  crucial to assess the validity of the TMD approach

Thank you

and don't forget:

TRANSVERSITY 2014 Workshop
9-13 June, Cagliari (Italy)

- 3D-structure of the nucleon: TMDs, GPDs, OAM
- Data from COMPASS, HERMES, JLab, RHIC, BaBar, Belle

Back-up slides

Statistical error band

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{y_i - F(x_i; \boldsymbol{a})}{\sigma_i} \right)^2$$

- N measurements y_i at known points x_i, with variance σ_i^2.
- $F(x_i; \boldsymbol{a})$ depends *non-linearly* on M unknown parameters a_i.
- Best fit: $\chi^2_{\rm min} \to \boldsymbol{a}_0$

Error band: all sets of parameters such that $\chi^2(\boldsymbol{a}_j) \leq \chi^2_{\rm min} + \Delta\chi^2$
- $\Delta\chi^2 = 1 \leftrightarrow 1$-$\sigma$: small errors, uncorrelated parameters, linearity, χ^2 parabolic
- $\Delta\chi^2$: fixed according to the coverage probability

$$P = \int_0^{\Delta\chi^2} \frac{1}{2\Gamma(M/2)} \left(\frac{\chi^2}{2} \right)^{(M/2)-1} \exp\left(-\frac{\chi^2}{2} \right) {\rm d}\chi^2$$

P= probability that true set of parameters falls inside the M-hypervolume

$[P = 0.68 \leftrightarrow 1\text{-}\sigma,\ P = 0.95 \leftrightarrow 2\text{-}\sigma]$