Quasi-real photon contribution to A_N in $\ell p \to \pi X$ in a TMD approach

Umberto D'Alesio
Physics Department & INFN
University of Cagliari, Italy

QCD Evolution 2016
Amsterdam, May 30 - June 3, 2016

M. Anselmino, M. Boglione, UD, S. Melis, F. Murgia, and A. Prokudin
PRD 81 (2010) and PRD89 (2014)
UD, C. Flore, and F. Murgia hep-ph xxxx.xxxx (2016)

Outline

- Transverse Single Spin Asymmetries (SSAs):
  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
  - kinematics, scales and dynamics
  - use of TMDs from SIDIS fits

- Role of quasi-real photon exchange

- Comparison with HERMES results and predictions

- Conclusions

SSAs and theoretical approaches in pQCD

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

- 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
  - A_N dominated by a twist-3 term in the fragmentation *[Kanazawa et al. 14]*
- TMD scheme (generalization of the parton model with $k_\perp$) *[Anselmino et al.]*
  - factorization (and universality) assumed
  - rich and successful phenomenology

[UD, Murgia 08; Aschenauer, UD, Murgia 16]

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

- leading SSA
- TMD factorization proven
- 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
LO subprocesses	ℓq	ℓq	qq, qg, gg

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

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

[Kang et al. 11; Gamberg et al. 14] [Kanazawa et al. 16]

Kinematics, scales, and approaches in $\ell p \to h\, X$

- NO detection of the final lepton: anti-tagged events
- hard scale: $P_T \gtrsim 1$ GeV

- Collinear approach
  - LO ($\ell q \to \ell q$) $\Rrightarrow Q^2 > 1$ GeV^2 (photon exchange)
  - NLO $\Rrightarrow Q^2 \approx 0$ (large P_T from $\gamma b \to cd$ with a quasi-real γ)

- TMD approach at LO
  - proton backward region $\Rrightarrow Q^2 \gtrsim 1$ GeV^2
  - proton forward region $\Rrightarrow Q^2 \approx 0$ (P_T from intrinsic $k_\perp$)

- HERMES SSA data (backward region)
  - higher statistics at $P_T \ll 1$ GeV: out of pQCD regime
  - anti-tagged events, $P_T \geq 1$ GeV: mixture of low and large Q^2 components
  - tagged events: $Q^2 > 1$ GeV^2

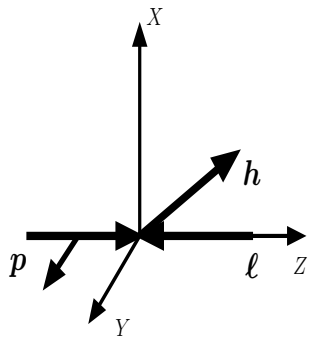
Previous study *[Anselmino et al. 14]*
- anti-tagged events: TMD-LO calculation $\Rrightarrow$ OK but only $Q^2 \gtrsim 1$ GeV^2 component
- tagged events: OK large Q^2

Present study *[UD, Flore, Murgia in preparation]*
anti-tagged events: inclusion of quasi-real photon contribution ($Q^2 \approx 0$ component)

HOW?

use of the Weizsäcker-Williams approximation *[see Hinderer, Schlegel, Vogelsang 15]*

Remarks on the new results
- confirm the general features of previous study
- improve substantially the description of data



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

TMD approach to $p\ell \to h\,X$: Leading Order (i.e. $q\ell \to q\ell$) - $\alpha_{\rm em}^2$

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

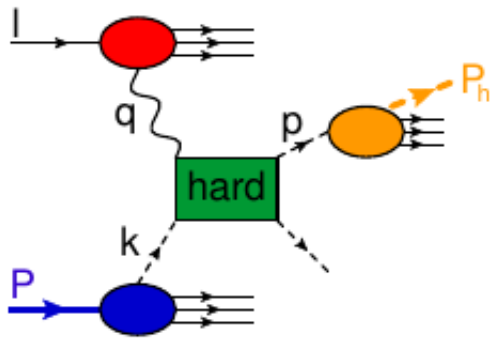
$$+\, h_1^{q/p} \otimes d\Delta\hat\sigma \otimes \Delta^N D_{h/q^\uparrow} \cos\phi_C \qquad \text{Collins effect I}$$

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

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

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

Quasi-real photon exchange



lepton as a source of quasi-real photons

$\ell \to \ell\gamma$ final lepton almost collinear

$$d\sigma(p\ell \to h\,X) = \int_0^1 dz\, f_{\gamma/\ell}(z)\, d\sigma(p\gamma \to h\,X)$$

$$f_{\gamma/\ell}(z) = \frac{\alpha_{\rm em}}{2\pi}\,\frac{1+(1-z)^2}{z}\left[\ln\left(\frac{\mu^2}{z^2 m_\ell}\right) - 1\right] \qquad [\mathrm{WWdistribution}]$$

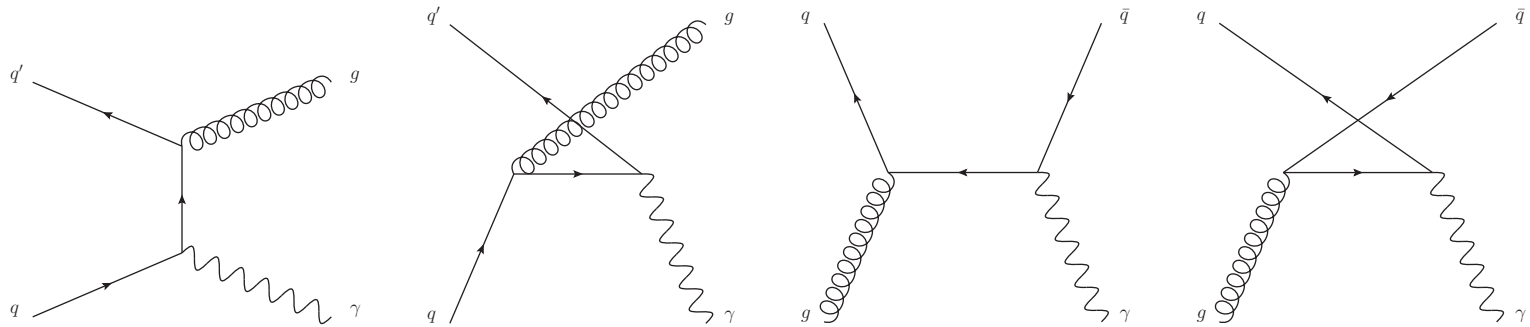
[Hinderer, Schlegel, Vogelsang 15]

related to the classic WW: log-term coming from

$$\int_{m_\ell z^2/(1-z)}^{Q^2_{\rm max}} \frac{dq^2}{q^2}$$

Real γ-parton contributions: $q\gamma \to qg$, and $g\gamma \to q\bar{q}$

$\uparrow$



$q\gamma \to qg$ $g\gamma \to q\bar{q}$

Detailed calculation in the helicity formalism for a non-planar kinematics

$d\sigma(p^\uparrow\gamma \to h\,X)$ in a TMD approach: $\alpha_{\rm em}\alpha_s$

$$d\sigma^\uparrow_{p\gamma} - d\sigma^\downarrow_{p\gamma} = \sum_q \Big\{ \Delta^N f_{q/p^\uparrow} \cos\phi_q \otimes [d\hat\sigma^{q\gamma\to q} \otimes D_{h/q} + d\hat\sigma^{q\gamma\to g} \otimes D_{h/g}] \quad \text{quark Sivers}$$

$$+ \Delta^N f_{g/p^\uparrow} \cos\phi_g \otimes [d\hat\sigma^{g\gamma\to q} \otimes D_{h/q} + d\hat\sigma^{g\gamma\to \bar q} \otimes D_{h/\bar q}] \quad \text{gluon Sivers}$$

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

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

$$d\hat\sigma^{q\gamma\to q} = -\frac{4}{3}\, e_q^2\, \frac{\hat s^2 + \hat u^2}{\hat s \hat u} \qquad d\hat\sigma^{g\gamma\to q\bar q} = e_q^2\, \frac{\hat u^2 + \hat t^2}{\hat t \hat u}$$

$$d\Delta\hat\sigma^{q\gamma\to qg} = \frac{8}{3} e_q^2$$

Notice: $\hat u$ dependence (absent in the LO term)

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

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

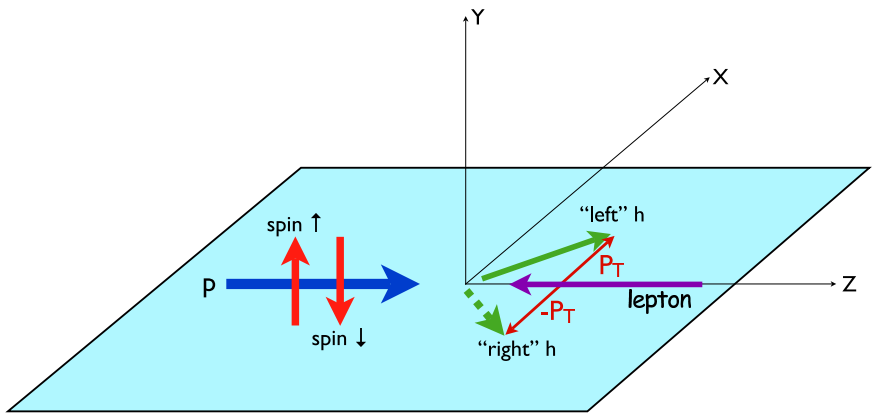
- moderate $\sqrt{s}$ $\Rrightarrow$
  - $\hat{t}$ and $\hat{u}$ dependent on ϕ_q (Sivers azimuthal dependence)
  - valence region for backward scattering
- proton backward region
  - $Q^2 \lesssim 1$ GeV^2 (ok pQCD)
    - Sivers effect still active
    - Collins effect strongly suppressed
  - A_N in $p^\uparrow p \to \pi\, X$ at high energy: vanishing of all spin-TMD effects

Phenomenological analysis

- TMD parameterizations: factorized and Gaussian $k_\perp$ dependences
- 2 WW distributions and 2 choices of the log-scale μ (P_T and $\sqrt{s}/2$)
- 2 SIDIS extractions(*) of the Sivers and Collins functions $\Rrightarrow$ UNIFIED picture
- gluon Sivers funct. from fit to $A_N^{pp\to\pi^0 X}$ midrapidity data *[UD, Murgia, Pisano 15]*
- HERMES A_N data (fully inclusive set) *[PLB 728 (2014)]*;
  - one bin with $\langle P_T \rangle \simeq 1$ GeV vs. x_F
  - one bin in x_F vs. $P_T \geq 1$ GeV

(*) well representative of the uncertainties in the available extractions
(**) Envelope of the statistical uncertainty bands

Kinematics vs. HERMES setup



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

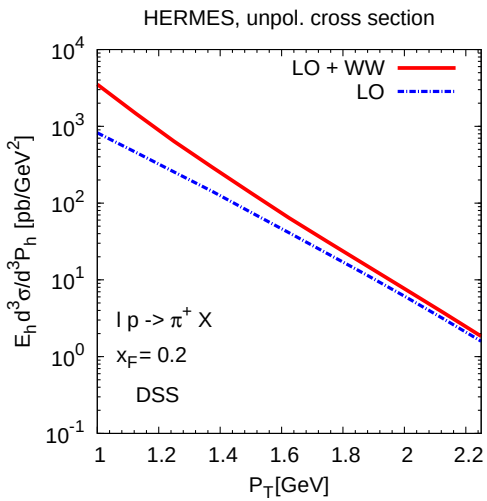
$$A(\phi_S, S_T) = \boldsymbol{S}_T \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{P}}_T)\, A_N = S_T \sin\phi_S\, A_N$$

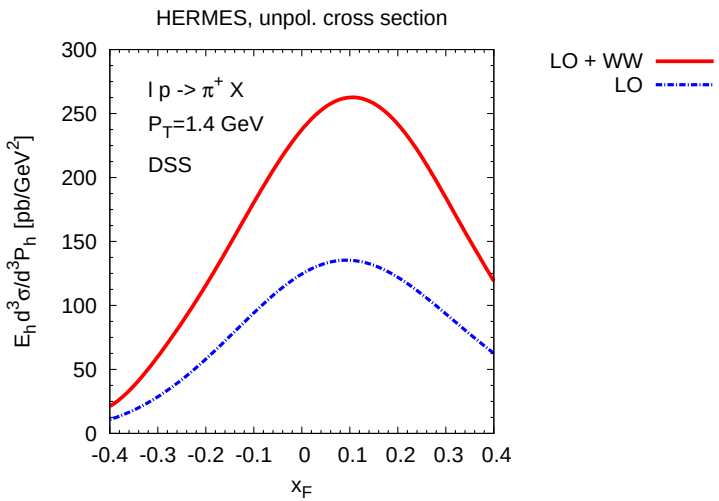
HERMES: $d\sigma = d\sigma_{UU}[1 + S_T \sin\psi\, A_{UT}^{\sin\psi}]$ $\sin\psi = \hat{\boldsymbol{S}}_T \cdot (\hat{\boldsymbol{P}}_T \times \hat{\boldsymbol{k}})$ and $\hat{\boldsymbol{k}} = -\hat{\boldsymbol{p}}$

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

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

Unpolarized cross sections: role of WW contribution (I)





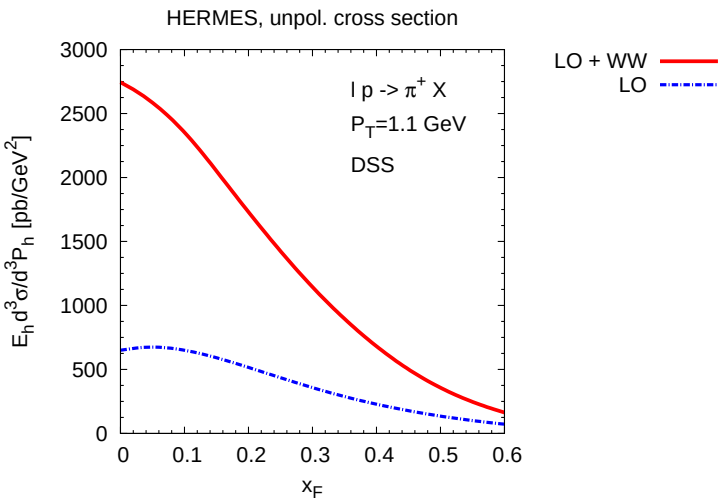
$x_F > 0$: backward region

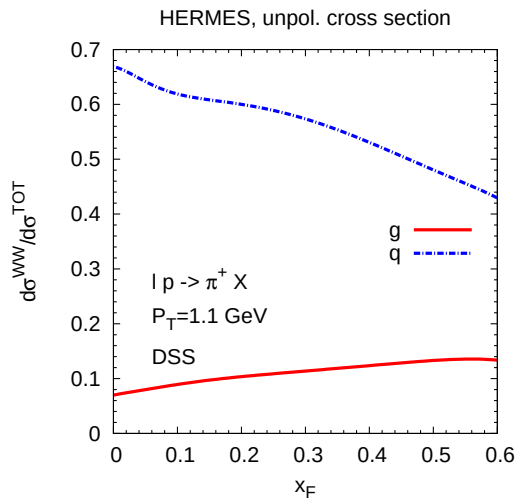
WW contribution: more important at $x_F > 0$...why?

naively: $Q \approx 0$ (i.e. real photon) expected for forward scattering

but $d\hat{\sigma}_{\rm LO} \sim 1/\hat{t}^2$ while $d\hat{\sigma}_{\rm WW} \sim 1/(\hat{s}\hat{u})$ and $|\hat{u}| \ll |\hat{t}|$ in the backward region

Unpolarized cross sections: role of WW contribution (II)



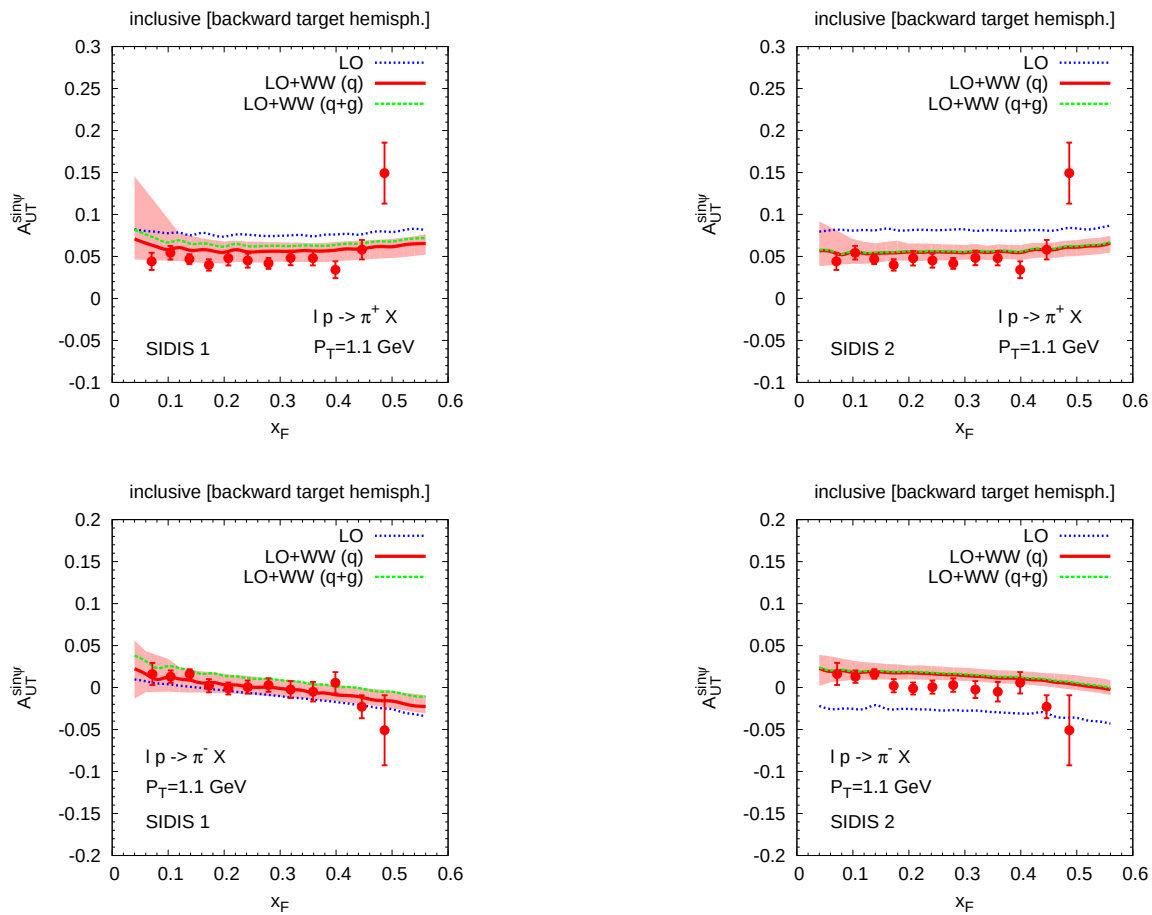


$P_T = 1.1$ GeV relevant for the study of A_N

WW/TOT $\sim$ 70-75% at moderate x_F, and still 60% at large x_F (WW dominant)

gluon channel: only around 10% (γ-quark and ℓ-quark dominated)

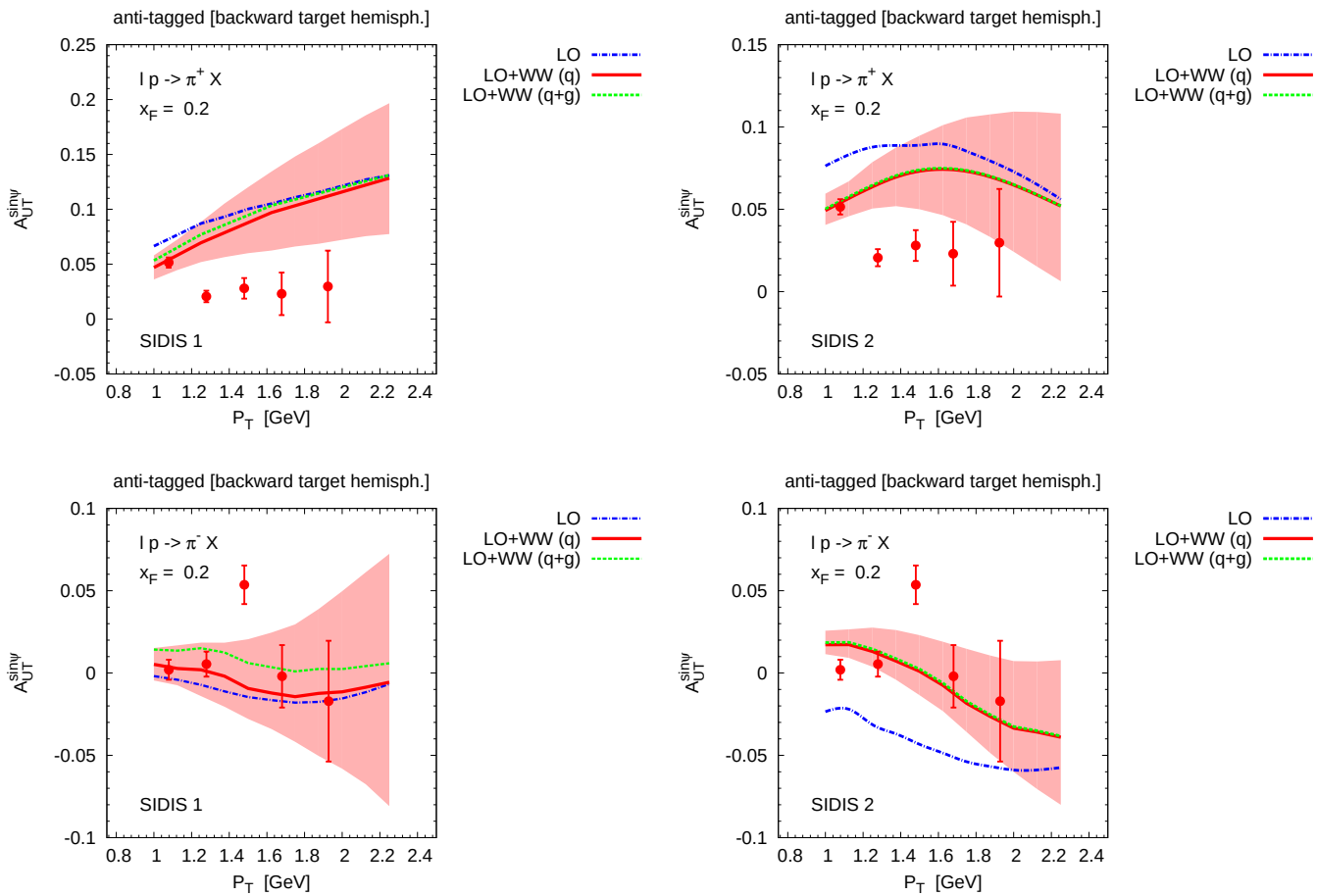
$A_N(\pi)$ vs. x_F: comparison with HERMES data



Collins effect: negligible - Gluon Sivers effect: negligible

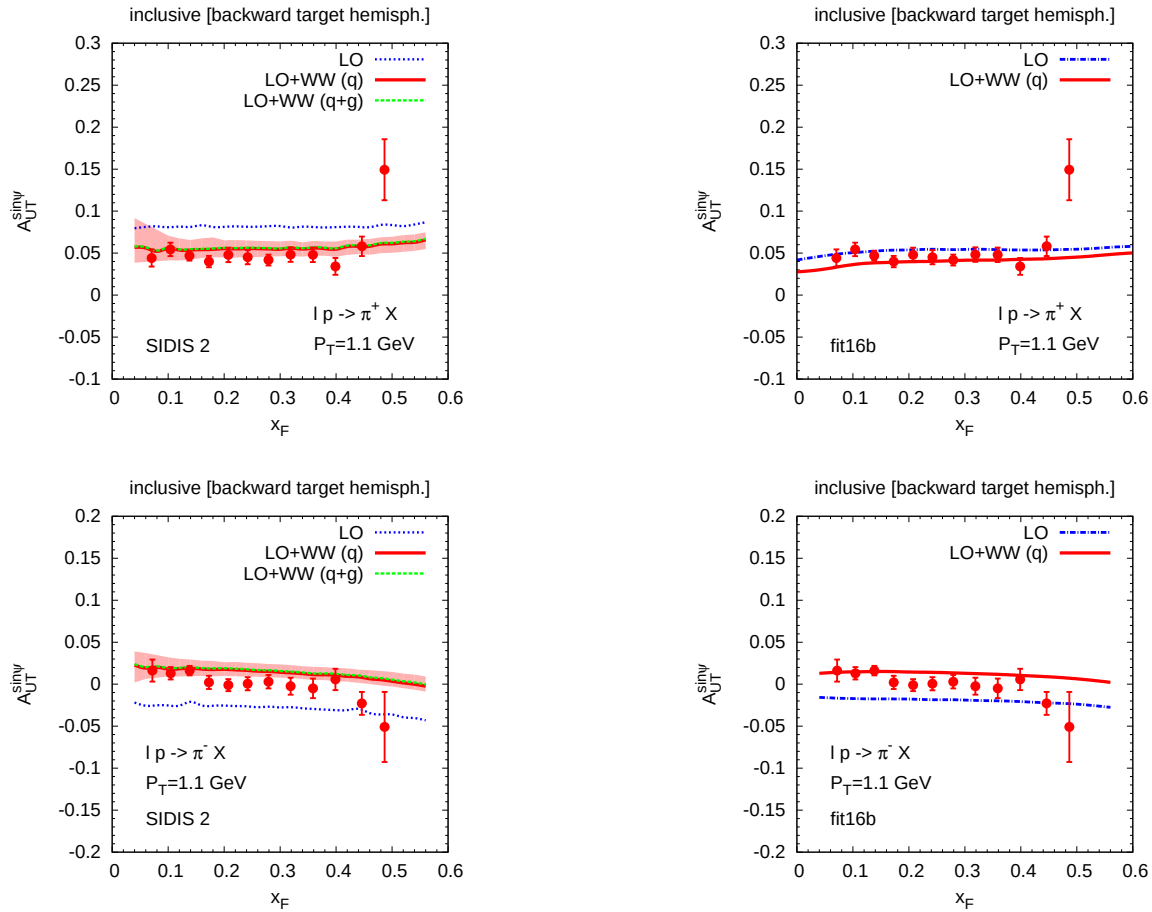
statistical error bands for LO+WW(q) contributions

$A_N(\pi)$ vs. p_T: comparison with HERMES data



- same discrepancies for π^+

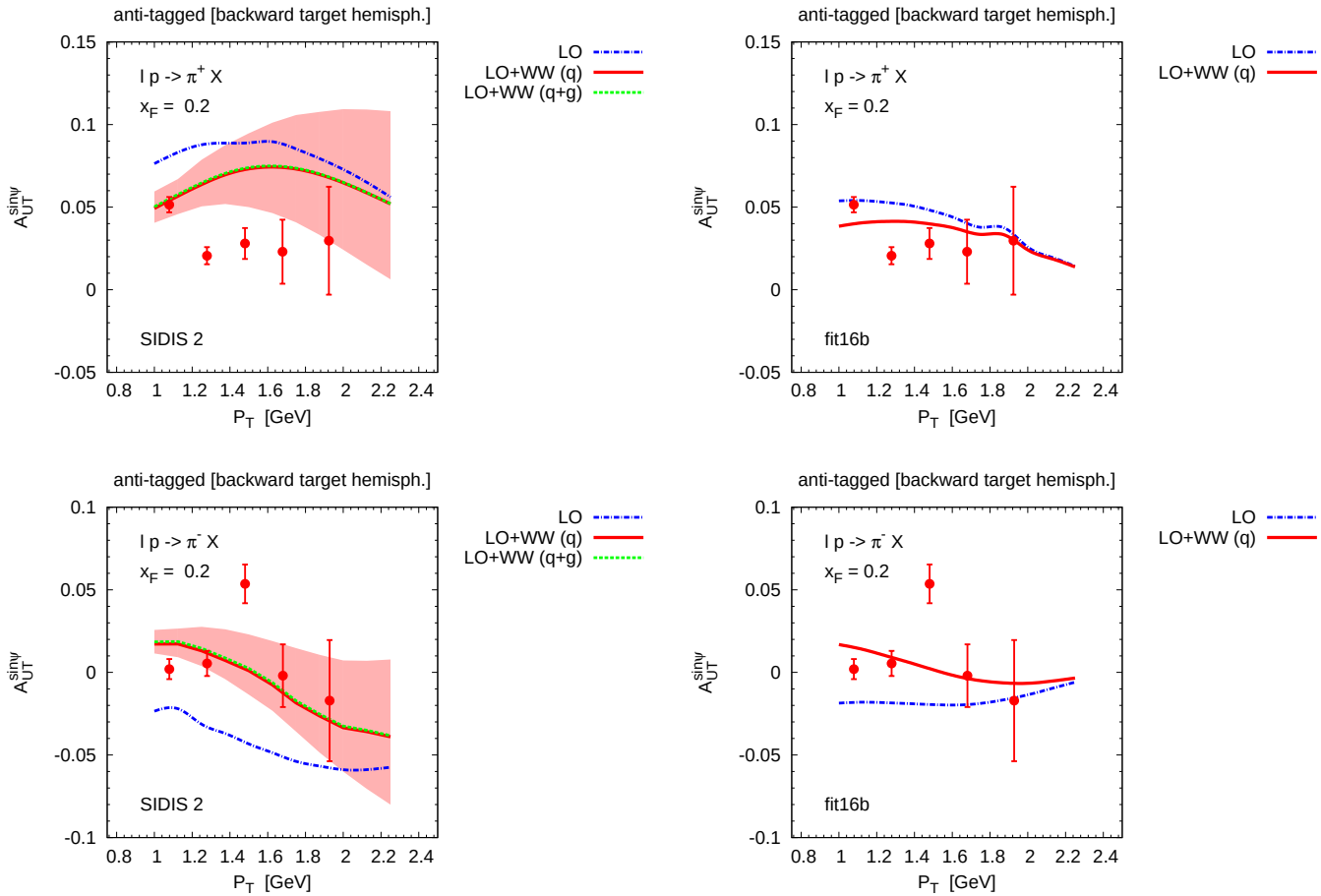
$A_N(\pi)$ vs. x_F: from a new extraction of the Sivers function(*)



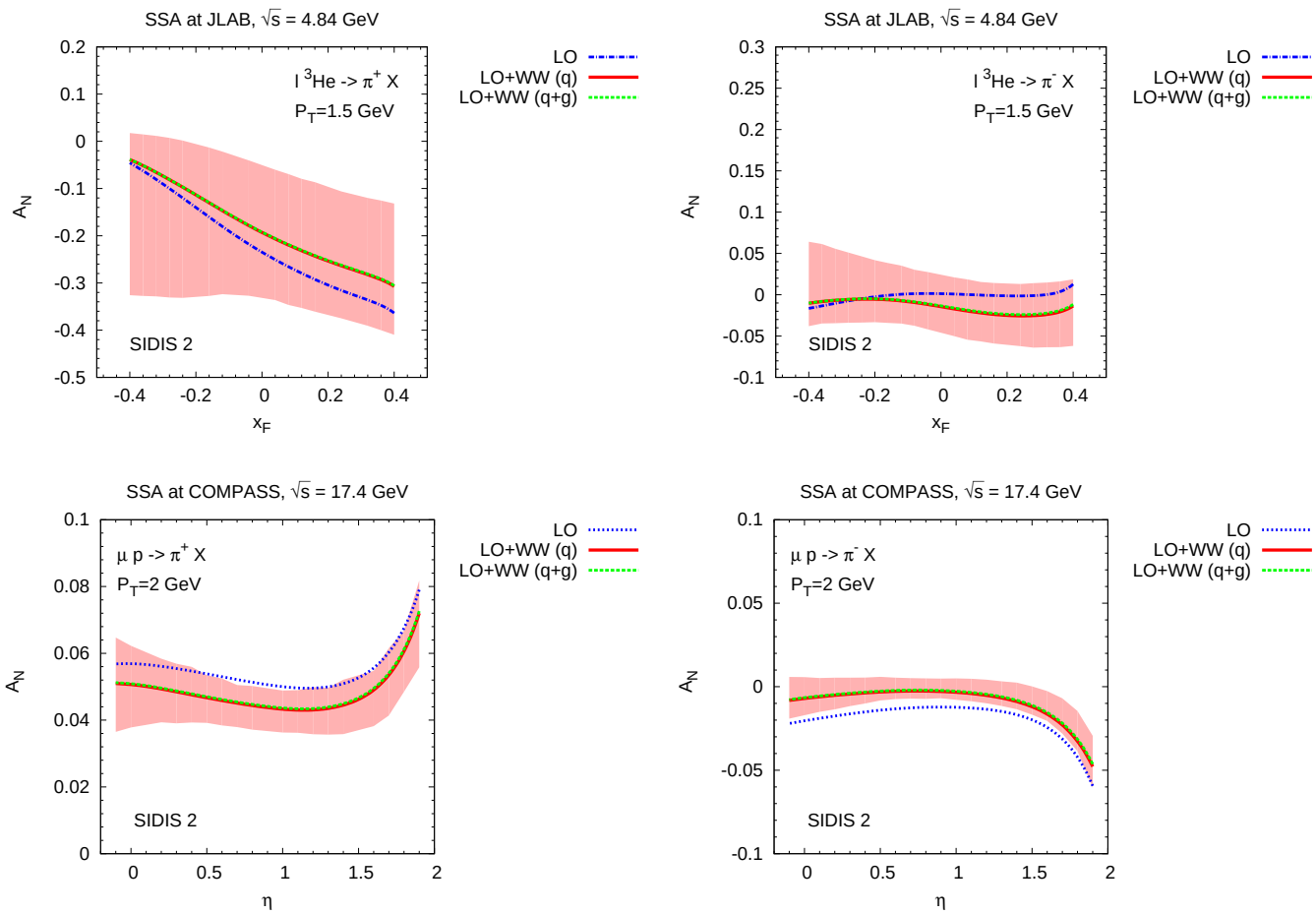
Study of the role of sea-quark contrib.s to $A_N(W)$ and the sign change issue

[Anselmino, Boglione, UD, Murgia, Prokudin, in preparation]

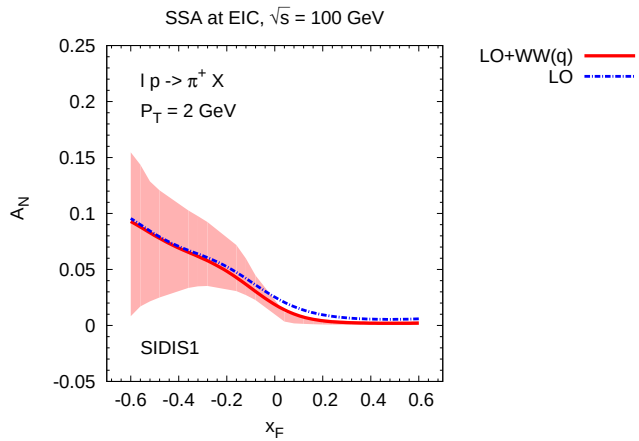
$A_N(\pi)$ vs. p_T: new extraction

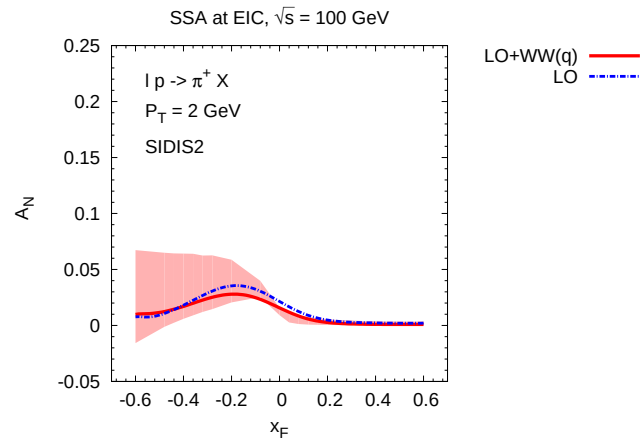


Predictions (I): $A_N(\pi)$ at JLab and COMPASS



Predictions (II): $A_N(\pi^+)$ at EIC





- large energy $\Rightarrow$ suppression of TMD effects in the backward region
- forward region: probing large x $\Rightarrow$ a constraint for TMD parameterizations
- strong similarity with $pp \to \pi X$: check for a unified picture

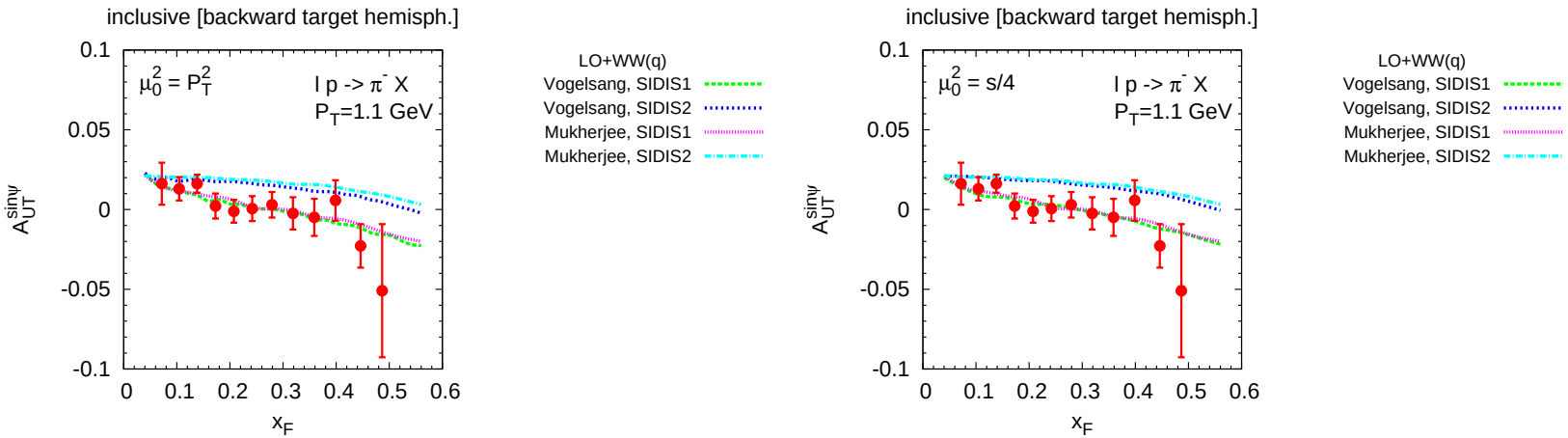
Conclusions

- $\ell p \to h\, X$: test of TMD factorization in single large-scale inclusive processes
- strong analogy with $p^{\uparrow} p \to h\, X$, where A_N are large and still puzzling
- use of a unified TMD picture (same Sivers and Collins functions)
- role of quasi-real photon contribution to unpol. cross sections (huge) and SSAs
- theoretical estimates vs. HERMES data: significant improvement vs. LO calculation
- Predictions for JLab and COMPASS (sizeable for π^+); at EIC, same behaviour as in $pp \to \pi\, X$: crucial to assess the validity of a unified TMD approach

Thank you

Back-up slides

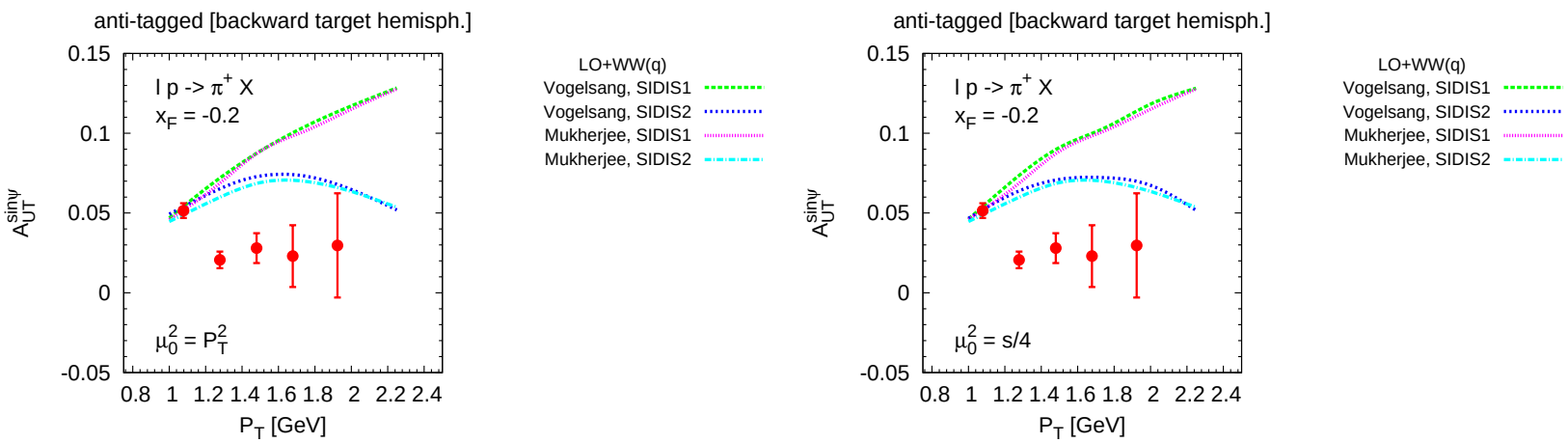
A_N: WW distributions and scale choices (I)



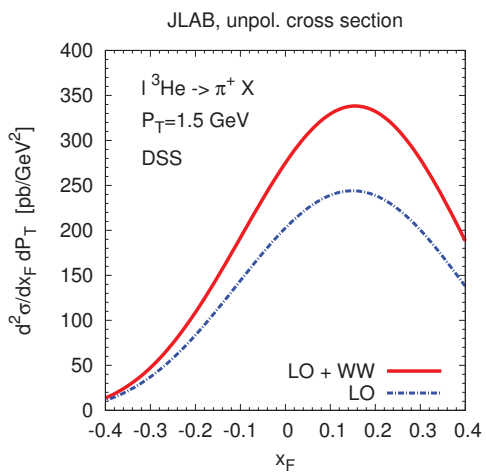
$$f_{\gamma/e}(x_\gamma, E) = \frac{\alpha}{\pi}\left\{\frac{1+(1-x_\gamma)^2}{x_\gamma}\left(\ln\frac{E}{m}-\frac{1}{2}\right)+\frac{x_\gamma}{2}\left[\ln\left(\frac{2}{x_\gamma}-2\right)+1\right]\right.$$
$$\left.+\frac{(2-x_\gamma)^2}{2x_\gamma}\ln\left(\frac{2-2x_\gamma}{2-x_\gamma}\right)\right\}$$

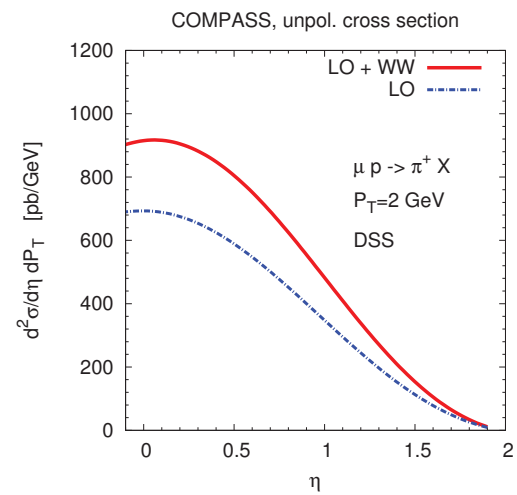
[Brodsky et. al. 71]

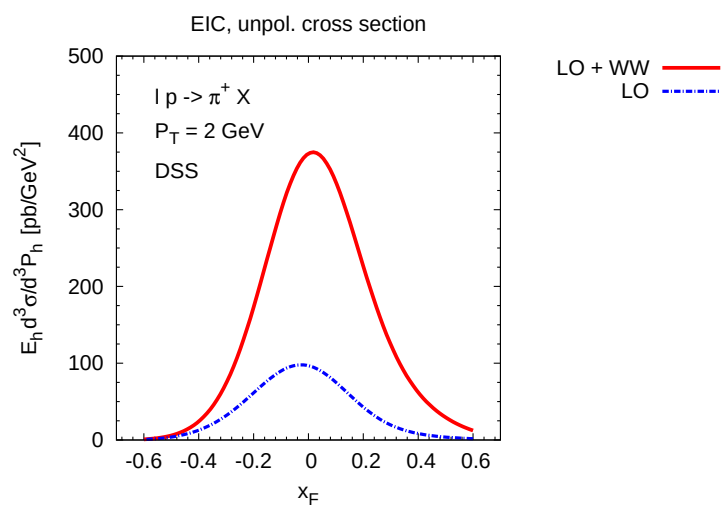
A_N: WW distributions and scale choices (II)



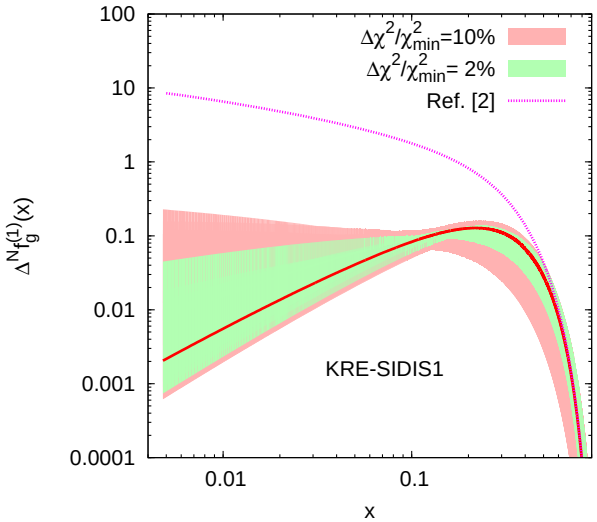
unpol. cross sections: JLab, COMPASS and EIC)

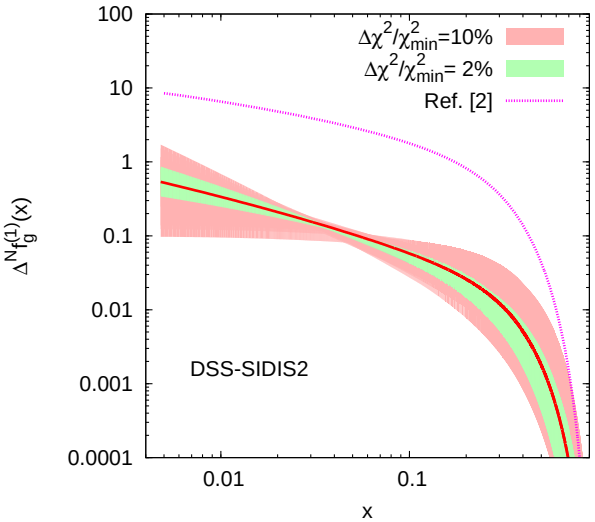






Gluon Sivers function

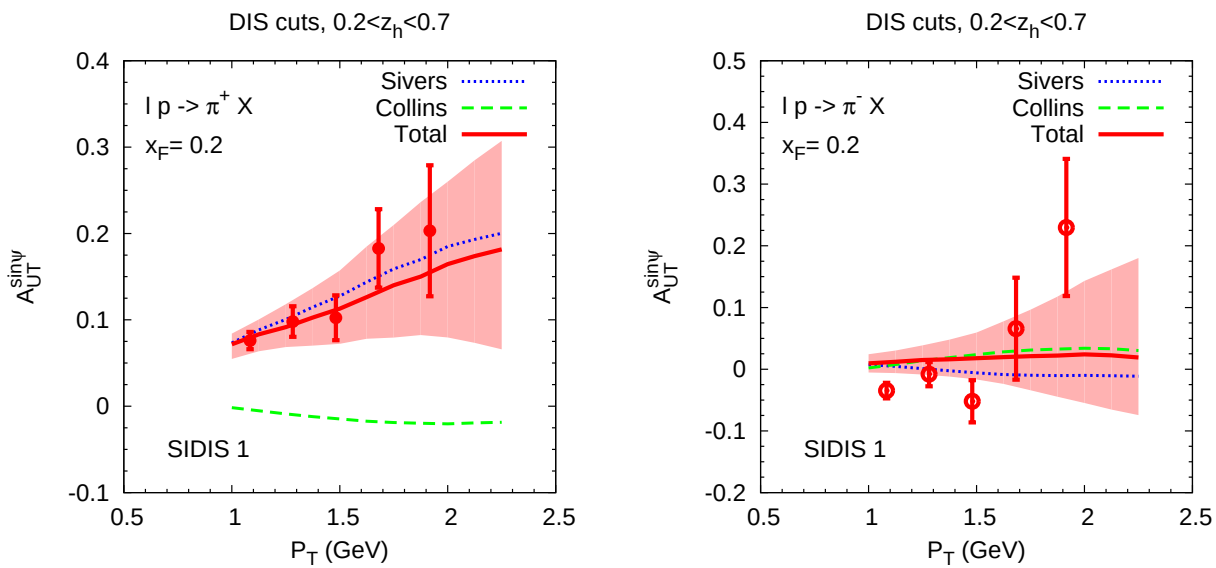




- From analysis of $A_N(pp \to \pi^0 X)$ data (PHENIX Coll.) at midrapidity.

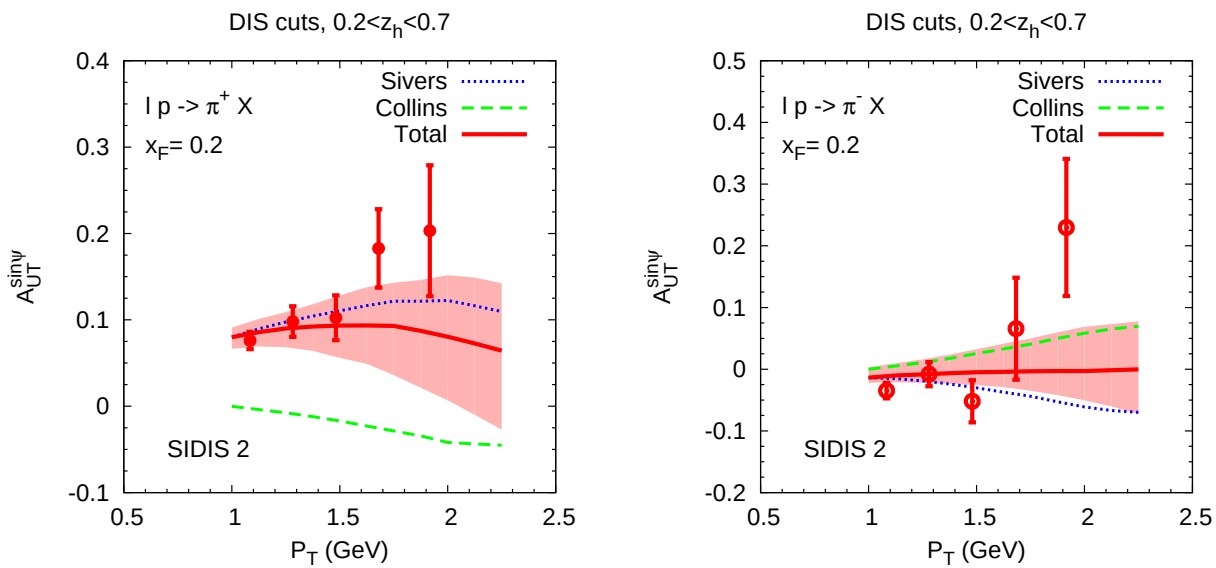
[UD, Murgia, Pisano 15]

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)

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

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

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

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