SSA in $ep^{\uparrow} \rightarrow hX$ and contribution of quasi-real photon

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*based on: U. D'Alesio, CF, F. Murgia, PRD**95** (2017)*

Outline

1. **Introduction**

2. **Quasi-real photon exchange**
   - Weizsäcker-Williams approximation
   - Weizsäcker-Williams contribution to SSA

3. **Phenomenological analysis**
   - Comparison with HERMES data
   - Predictions
     - JLab
     - COMPASS
     - EIC

4. **Conclusions**

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- Inclusive $p^{\uparrow}p$ scattering: $A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\Delta\sigma}{2d\sigma^{\text{unp}}}$

  [see e.g. Aschenauer's, M. Boer's talks]

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- two-scale vs single-scale processes *[see e.g. Prokudin's talk]*

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test for TMD factorisation

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test for TMD factorisation

- two approaches:
  - Generalize Parton Model (GPM) *[Anselmino, Boglione, D'Alesio, Melis, Murgia, Prokudin, PRD**81**(2010) & PRD**89** (2014)]*
  - collinear twist-3 *[Gamberg, Kang, Metz, Pitonyak, Prokudin, PRD**90**(2014)]*

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$\Rightarrow$ extend previous GPM phenomenological studies

Previous studies

- Detailed kinematics and first predictions *[Anselmino et al. (2010)]*
- first comparison with a selection ($Q^2 \gtrsim 1\,\mathrm{GeV}^2$) of HERMES data *[PLB 728 (2014)]*: TMD-LO study, $\ell q \to \ell q$ only partonic channel *[Anselmino et al. (2014)]*;

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

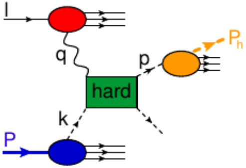
$$+ h_1^{q/p} \otimes d\Delta\hat\sigma \otimes \Delta^N D_{h/q^\uparrow} \cos\phi_C \qquad \text{Collins I}$$

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

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

- anti-tagged ($Q^2 \approx 0$) events <u>not included</u>

Weizsäcker-Williams approximation

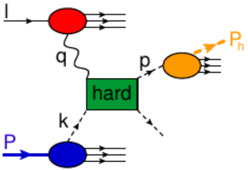


$\ell \to \ell\gamma$ with final lepton almost collinear $\Rightarrow Q^2 \sim 0$ (quasi-real γ)

lepton as a source of real photons

$$d\sigma(p\ell \to hX) = \int_0^1 dy \; f_{\gamma/\ell}(y) \; d\sigma(p\gamma \to hX)$$

Weizsäcker-Williams approximation



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WW distribution *[Hinderer, Schlegel, Vogelsang, PRD**92** (2015); **93** (2016)]*:

$$f_{\gamma/\ell}(y,\mu) = \frac{\alpha}{2\pi} \frac{1+(1-y)^2}{y} \left[\ln\left(\frac{\mu^2}{y^2 m_\ell^2} \right) - 1 \right] + \mathcal{O}(\alpha^2)$$

New partonic channels: $q\gamma \to qg$, $g\gamma \to q\bar{q}$

WW contribution to A_N for $p^{\uparrow}\ell \to hX$

$$A_N = \frac{d\Delta\sigma^{\rm LO} + d\Delta\sigma^{\rm WW}}{2\left[d\sigma^{\rm LO} + d\sigma^{\rm WW}\right]}$$

$$\begin{aligned}
d\Delta\sigma^{\rm WW} &= d\sigma^{\uparrow}_{p\gamma} - d\sigma^{\downarrow}_{p\gamma} = \\
&= \sum_q \Big\{ \Delta^N f_{q/p^\uparrow} \cos\phi_q \otimes \left[d\hat\sigma^{q\gamma\to q} \otimes D_{h/q} + d\hat\sigma^{q\gamma\to g} \otimes D_{h/g} \right] && \text{quark Sivers} \\
&+ \Delta^N f_{g/p^\uparrow} \cos\phi_g \otimes \left[d\hat\sigma^{g\gamma\to q} \otimes D_{h/q} + d\hat\sigma^{g\gamma\to \bar q} \otimes D_{h/\bar q} \right] && \text{gluon Sivers} \\
&+ h_1^{q/p} \otimes d\Delta\hat\sigma^{q\gamma\to q} \otimes \Delta^N D_{h/q^\uparrow} \cos\phi_C && \text{Collins I} \\
&+ h_{1T}^{\perp q/p} \otimes d\Delta\hat\sigma^{q\gamma\to q} \otimes \Delta^N D_{h/q^\uparrow} \cos(\phi_C - 2\phi_q) \Big\} && \text{Collins II}
\end{aligned} \tag{1}$$

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

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

WW contribution to A_N for $p^\uparrow \ell \to hX$

$$A_N = \frac{d\Delta\sigma^{\rm LO} + d\Delta\sigma^{\rm WW}}{2\left[d\sigma^{\rm LO} + d\sigma^{\rm WW}\right]}$$

$$d\Delta\sigma^{\rm WW} = d\sigma^{\uparrow}_{p\gamma} - d\sigma^{\downarrow}_{p\gamma} =$$

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

$\hat u$ dependence absent at LO!

Phenomenological analysis

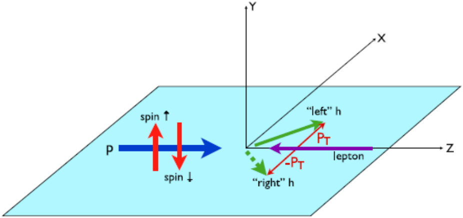
Parametrisation and data selection

- TMD parametrisation: usual factorised form

$$N_q(x) \times [\text{Coll. PDF(FF)}] \times [\text{Gaussian } \boldsymbol{k}_\perp(\boldsymbol{p}_\perp) \text{ factor}]$$

- tested two WW distribution and two different μ scale (P_T and $\frac{\sqrt{s}}{2}$): almost no differences $\Rightarrow$ $\mu = P_T$
- SIDIS1 and SIDIS2 extractions for Sivers and Collins functions *[see Pisano's talk]*
- gluon Sivers function from fit to SSA for $p^\uparrow p \to \pi^0 X$ data at midrapidity *[D'Alesio, Murgia, Pisano, JHEP 09 (2015)]*
- HERMES A_N data *[PLB 728 (2014)]*:
  - one bin with $\langle P_T \rangle \simeq 1$ GeV vs. x_F
  - one bin at fixed x_F vs. $P_T \geq 1$ GeV (anti-tagged data)

Kinematics for HERMES



In $p^{\uparrow}\ell$ *c.m. frame*:

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

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

HERMES: $\ell p^{\uparrow}$ *c.m. frame*

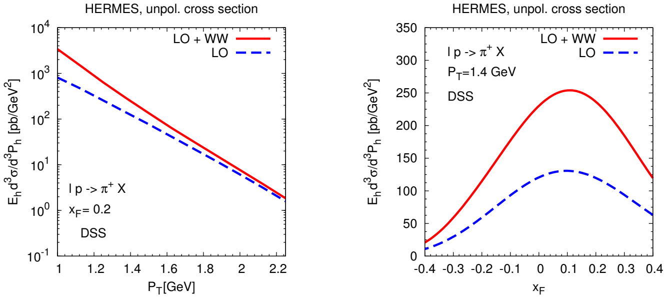
$$d\sigma = d\sigma_{UU}\left[1 + S_T \sin\psi \, A_{UT}^{\sin\psi}\right]$$

$$\sin\psi = \boldsymbol{S}_T \cdot (\hat{\boldsymbol{P}}_T \times \hat{\boldsymbol{k}}) \text{ and } \hat{\boldsymbol{k}} = -\hat{\boldsymbol{p}}$$

- $\uparrow$ ($\downarrow$) pols. are along $+Y_{\rm cm}(-Y_{\rm cm})$ in both $p^{\uparrow}\ell$ or $\ell p^{\uparrow}$ c.m. frames; recall $x_F = 2P_L/\sqrt{s}$, so:

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

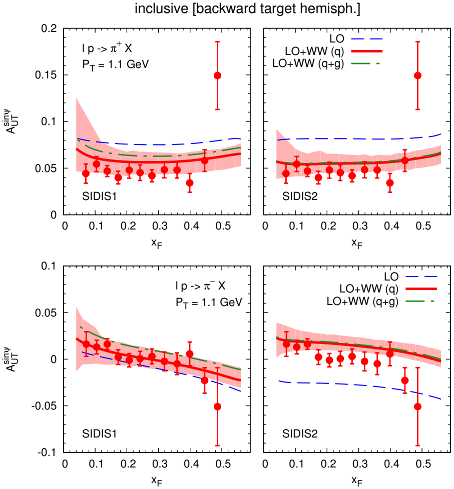
Unpolarized cross sections - HERMES



- $x_F > 0$ proton backward region
- WW contribution more important at $x_F > 0$: naively real photon ($Q^2 \approx 0$) for forward production but, in backward region $|\hat{u}| \ll |\hat{t}|$ and

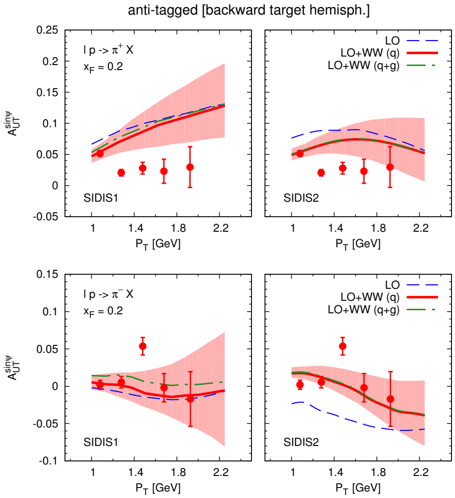
$$d\hat{\sigma}_{\rm LO} \sim \frac{1}{\hat{t}^2}, \quad d\hat{\sigma}_{\rm WW} \sim \frac{1}{\hat{s}\,\hat{u}}$$

A_N vs. x_F and comparison with HERMES data



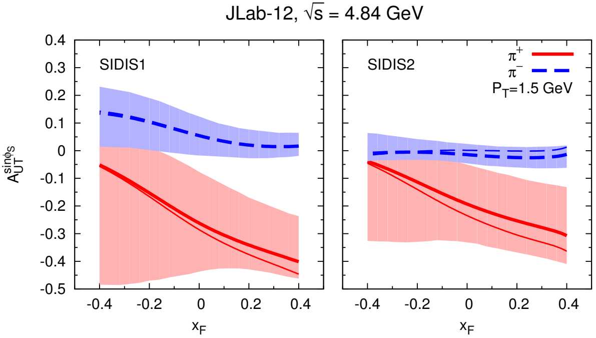
- Collins and gluon Sivers effects negligible
- bands are for LO+WW(q)

A_N vs. P_T and comparison with HERMES data



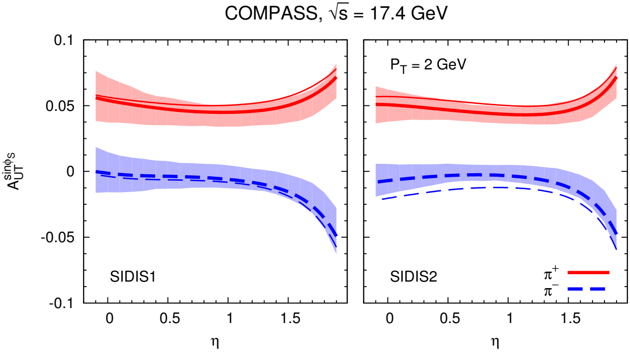
- discrepancies for π^+

A_N predictions - JLab



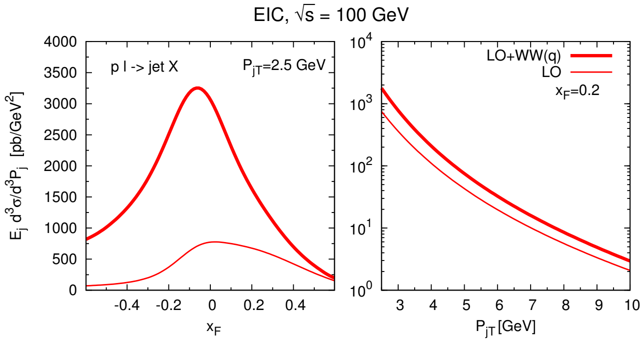
- role of u- and d-quark Sivers function exchanged while adopting SU(2) symmetry for neutron
- large $A_N(\pi^+)$ at large x_F due to the probed values of quark's light-cone momentum fraction (up to 0.1 at $x_F > 0$)
- wider uncertainty bands due to large-x region probed at moderate energies (extractions of Sivers function are uncontstrained at large x)

A_N predictions - COMPASS



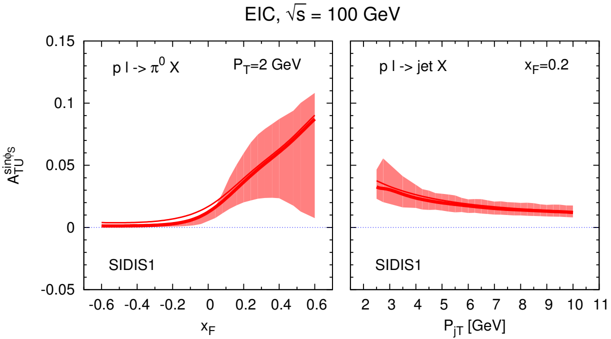
- sizeable SSA for π^+ with quite narrow error bands ⇒ need data to test the approach

$d\sigma_{\text{unp}}$ predictions - jet production at EIC



- here, $x_F > 0$ corresponds to the forward proton hemisphere
- pure Sivers effect - no fragmentation process! ($D_{h/q} \to 1$ and $\Delta^N D_{h/q^\uparrow} \to 0$)

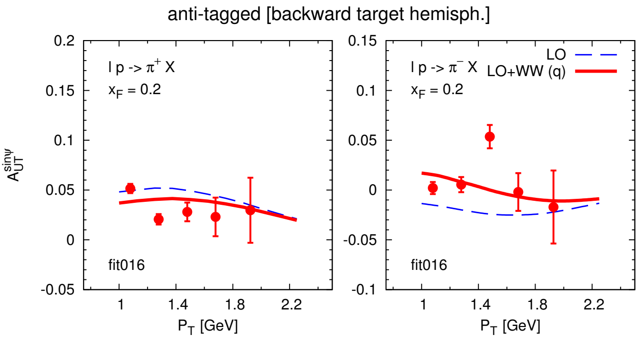
A_N predictions - EIC



- gluon Sivers effect completely negligible
- WW contribution does not change LO behaviour (both enters with the same structure in the SSA)
- interesting flat P_T behaviour - also measurable!

A_N vs. x_F and comparison with HERMES data - new fit

Using the most recent Sivers fit *[Anselmino, Boglione, D'Alesio, Murgia, Prokudin, JHEP04 (2017), see Boglione's talk]*:



- different Gaussian widths and PDFs (CTEQ6L)

Conclusions

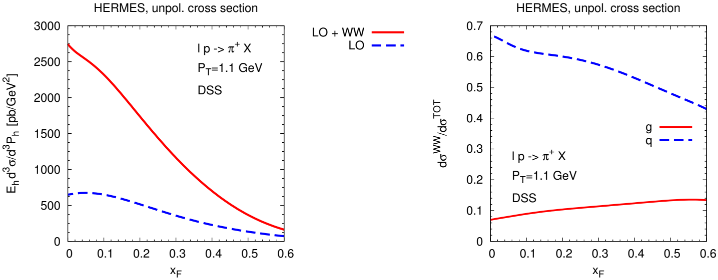
- computed (analytically and numerically), in the spirit of a unified TMD approach, WW contribution to A_N for $\ell p^\uparrow \to hX$
- role of quasi-real photon exchange: huge in unpolarised cross sections, crucial for SSAs description
- comparison with HERMES data improves significantly from previous LO analysis when quasi-real photon contribution is included
- found sizable predictions for JLab and COMPASS for π^+ production and same behaviour as $p^\uparrow p \to hX$ at EIC: fundamental to assess the validity of TMD approach
- further investigation (both experimental and theoretical) are required

Thanks a lot for your attention!

Gratzias meda po' s'attenziòne bostra!

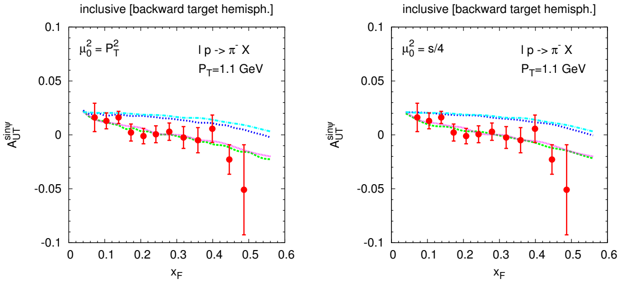
Backup

$d\sigma_{\mathrm{unp}}$: LO and WW relative weights



- WW/TOT $\sim 70 \div 75\%$ at small x_F and still $\sim 60\%$ at large x_F
  $\Rightarrow$ dominance of WW contribution
- gluon channel about 10%: γq and ℓq channels dominate

A_N: WW distrubution and scale choices (I)

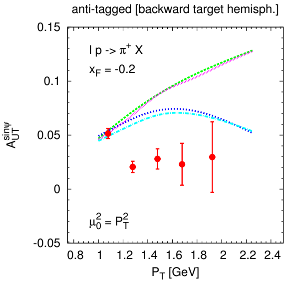


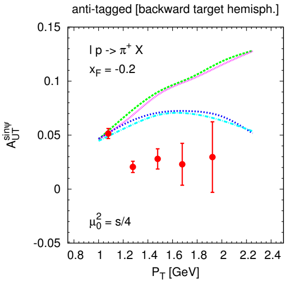
[Vogelsang et al., SIDIS1] [Vogelsang et al., SIDIS2]
[Mukherjee et al., SIDIS1] [Mukherjee et al., SIDIS2]

[Brodsky, Kinoshita, Terazawa (1971), Kniehl (1990)]:

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

A_N: WW distrubution and scale choices (II)





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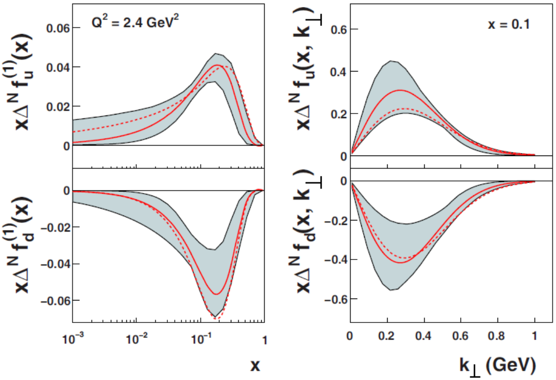
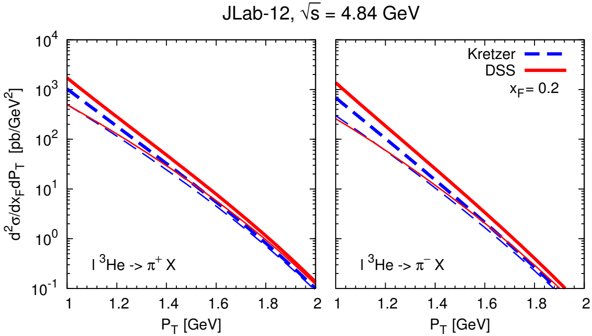
Sivers function from SIDIS extractions



- Dashed line: SIDIS1 extraction (GRV98LO PDFs + Kretzer FFs)
- Solid line + band: SIDIS2 extraction (GRV98LO PDFs + DSS 2007 LO FFs)

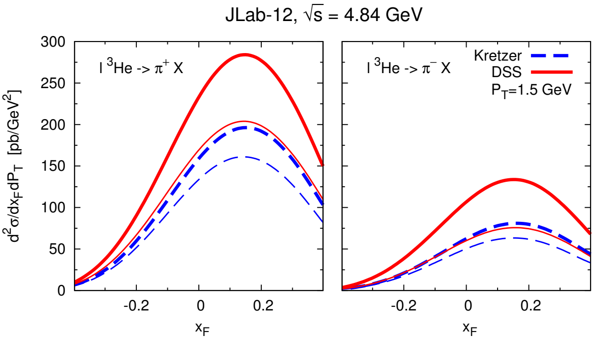
$d\sigma_{\text{unp}}$ predictions - JLAB (I)



$$\frac{d^2\sigma}{dx_F\,dP_T} = \frac{2\pi P_T}{\sqrt{x_F^2 + x_T^2}} E_\pi \frac{d^3\sigma}{d^3\boldsymbol{P}_\pi},$$

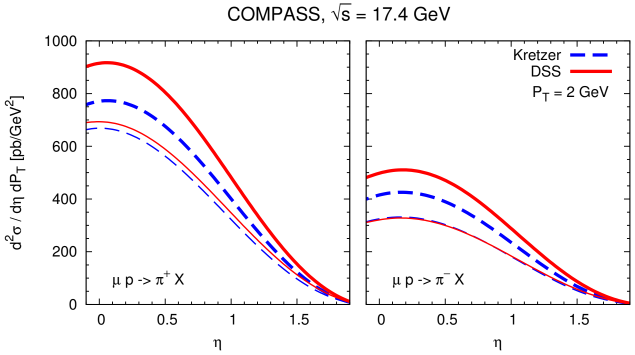
where $x_T = 2P_T/\sqrt{s}$.

$d\sigma_{\text{unp}}$ predictions - JLAB (II)



- LO different results due to large-z region explored more relevant for DSS FFs

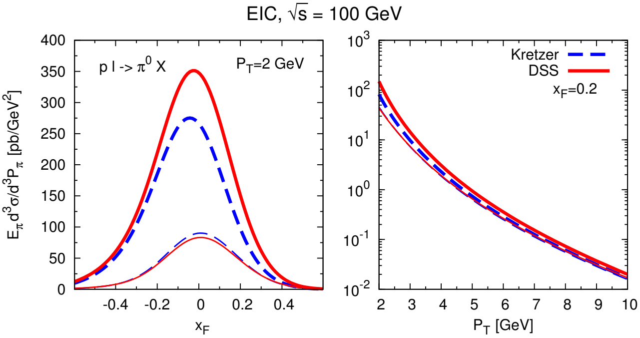
$d\sigma_{\text{unp}}$ predictions - COMPASS



$$\frac{d^2\sigma}{d\eta dP_T} = 2\pi P_T E_\pi \frac{d^3\sigma}{d^3\boldsymbol{P}_\pi}$$

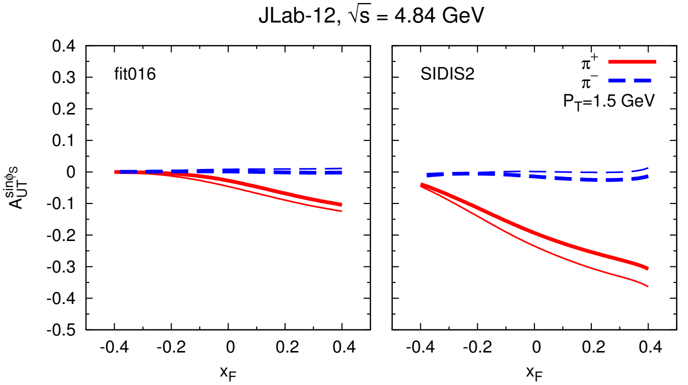
- log term in WW distribution is smaller ($m_\mu \sim 200 m_e$)

$d\sigma_{\text{unp}}$ predictions - π^0 at EIC



- here, $x_F > 0$ corresponds to the forward proton hemisphere
- pure Sivers effect - no fragmentation process!

A_N predictions - sign change fit at JLab



A_N predictions - sign change fit at COMPASS