High Energy Physics Colloquia

Quasi-real photon exchange in transverse single-spin asymmetries for $\ell\, p^{\uparrow} \to h\, X$

Carlo Flore (UniCa & INFN - CA)

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- Phenomenological results

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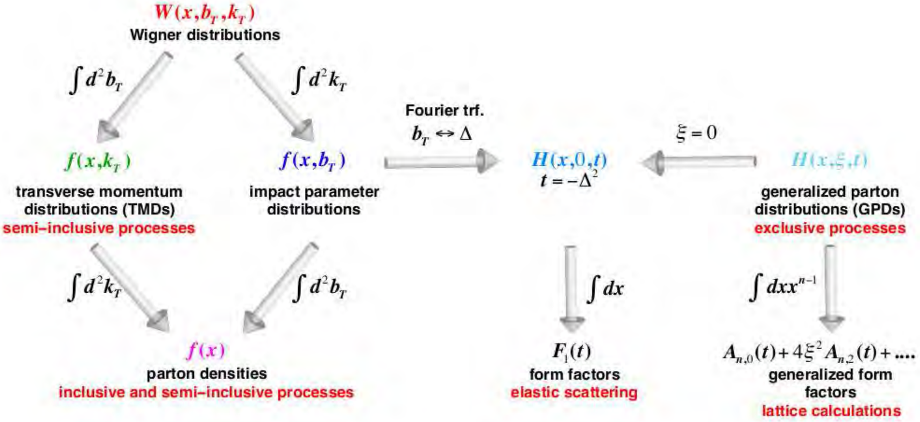
- Phenomenological results
- Conclusions

Introduction: TMDs and SSAs definitions

From Umberto's HEP Colloquium..



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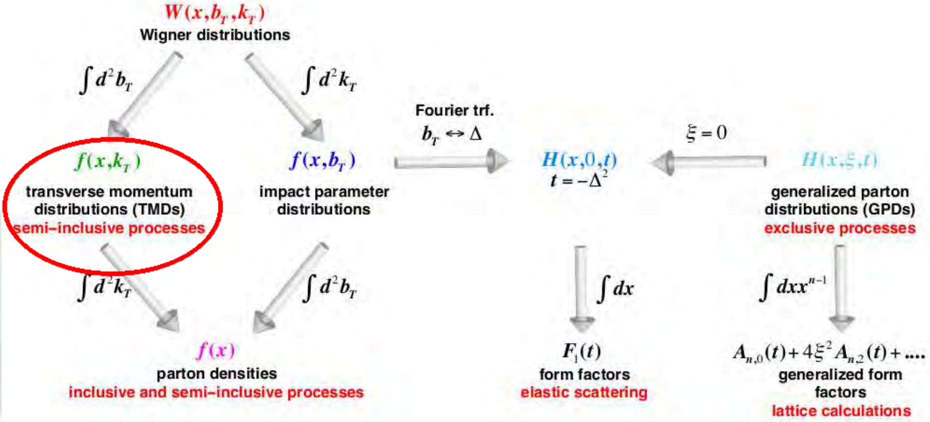

Introduction: TMDs and SSAs definitions

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$$f_1(x), \qquad g_1(x), \qquad h_1(x);$$

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$$f_1(x), \qquad g_1(x), \qquad h_1(x);$$

- inclusion of $\boldsymbol{k}_\perp$ effects $\Rightarrow$ from 3 to 8 independent TMD-PDF:

parton pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

collinear T-odd

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Relevant TMDs:

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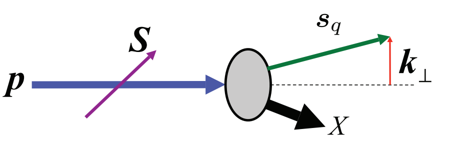
Sivers function



$$f_{q/p^\uparrow}(x, k_\perp) - f_{q/p^\uparrow}(x, -k_\perp)$$

$$= \Delta^N f_{q/p^\uparrow}(x, k_\perp) \frac{(\hat{\boldsymbol{P}} \times \boldsymbol{k}_\perp) \cdot \boldsymbol{S}}{|\boldsymbol{k}_\perp|}$$

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) = -\frac{2|\boldsymbol{k}_\perp|}{M} f_{1T}^{\perp q}(x, k_\perp)$$

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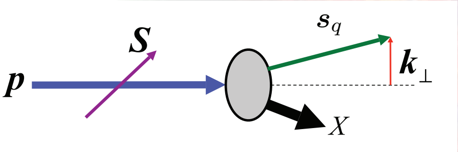
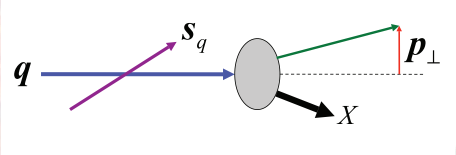


Collins function



$$f_{q/p^\uparrow}(x, k_\perp) - f_{q/p^\uparrow}(x, -k_\perp) = \Delta^N f_{q/p^\uparrow}(x, k_\perp) \frac{(\hat{\boldsymbol{P}} \times \boldsymbol{k}_\perp) \cdot \boldsymbol{S}}{|\boldsymbol{k}_\perp|}$$

$$D_{h/q^\uparrow}(z, p_\perp) - D_{h/q^\uparrow}(z, -p_\perp) = \Delta^N D_{h/q^\uparrow}(z, p_\perp) \frac{(\hat{\boldsymbol{k}} \times \boldsymbol{p}_\perp) \cdot \boldsymbol{S_q}}{|\boldsymbol{p}_\perp|}$$

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$$\Delta^N D_{h/q^\uparrow}(z, p_\perp) = \frac{2|\boldsymbol{p}_\perp|}{zM_h} H_1^{\perp q}(z, p_\perp)$$

Introduction: TMDs and SSAs definitions

Sivers & Collins effects play role in the Single Spin Asymmetry (SSA):

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\Delta\sigma}{2d\sigma^{\rm unp}} \tag{1}$$

where $d\sigma^{\uparrow(\downarrow)}$ is the polarized (differential) cross section:

$$\begin{aligned} d\sigma^{(A,S_A)+(B,S_B)\to C+X} = \sum_{a,b,c,d,\{\lambda\}} \rho^{a/A,S_{\boldsymbol{A}}}_{\lambda_{\boldsymbol{a}},\lambda'_{\boldsymbol{a}}} \hat{f}_{a/A,S_{\boldsymbol{A}}}(x_a, \boldsymbol{k}_{\perp a}) \otimes \\ \rho^{b/B,S_{\boldsymbol{B}}}_{\lambda_{\boldsymbol{b}},\lambda'_{\boldsymbol{b}}} \hat{f}_{b/B,S_{\boldsymbol{B}}}(x_b, \boldsymbol{k}_{\perp b}) \otimes \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \otimes \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z, \boldsymbol{k}_{\perp C}); \end{aligned} \tag{2}$$

with:

(i) $\rho^{a/A,S_{\boldsymbol{A}}}_{\lambda_{\boldsymbol{a}},\lambda'_{\boldsymbol{a}}}$ $(\rho^{b/B,S_{\boldsymbol{B}}}_{\lambda_{\boldsymbol{b}},\lambda'_{\boldsymbol{b}}})$: helicity density matrix for parton a (b);

(ii) $\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}$: helicity amplitude $ab \to cd$:

(iii)

$$\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}} = \frac{1}{16\pi\hat{s}^2}\frac{1}{4}\sum_{\lambda_a,\lambda_b,\lambda_c,\lambda_d} |\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}|^2; \tag{3}$$

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Main motivations:

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  - Anselmino, Boglione, D'Alesio, Melis, Murgia & Prokudin: proposed as a test for TMD factorization (PRD, 2010); predictions for SSA @ LO and comparison w/ HERMES data (PRD, 2014);

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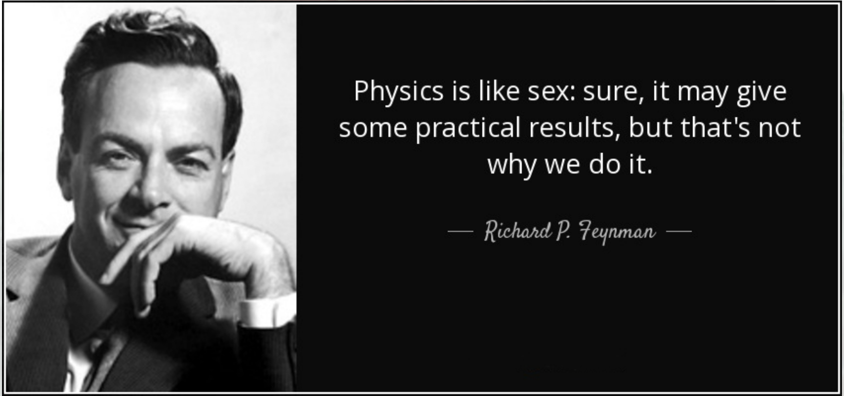
From Physics Letters B 728 (2014) 183–190
(HERMES Collaboration)

[26–28]. The present data sample is dominated by the kinematic regime $Q^2 \approx 0$ GeV^2 of quasireal photoproduction where the cross section is largest and where the hadronic component of the photon plays an important role. Generally speaking, in this kinematic

the hadrons. After correction for trigger efficiency, about 98% of all hadrons belong to the 'anti-tagged' category. The fraction of these

WW approximation or why physics is often like a pork



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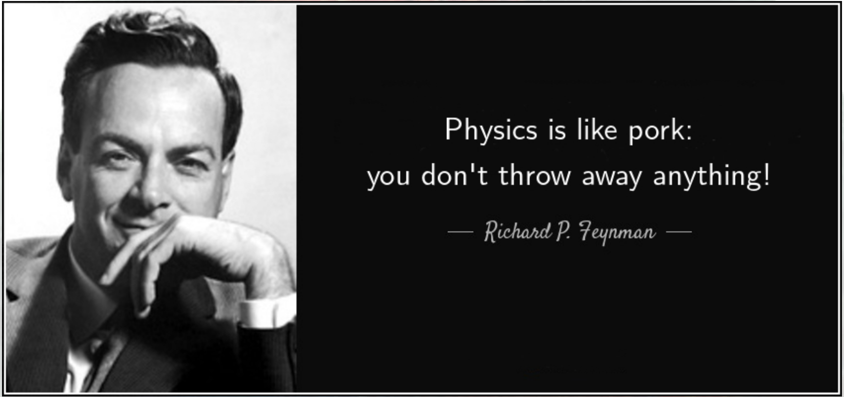

Weizsäcker-Williams or equivalent photon approximation

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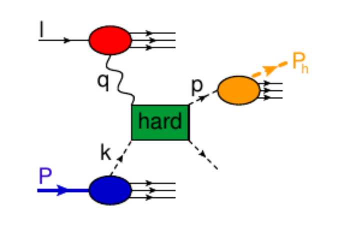

Lepton as a source of real photons

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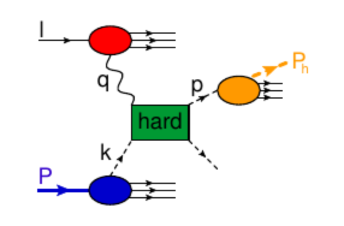

Lepton as a source of real photons

By evaluating the fundamental vertex $\ell \to \ell' \gamma$, with ℓ and ℓ' almost collinear ($Q^2 \sim 0$), one can define:

$$f_{\gamma/\ell}(y) = \frac{\alpha}{2\pi}\left(\frac{1+(1-y)^2}{y}\right)\ln\frac{s}{m_\ell^2}.$$

New partonic channels:

(i) $q\gamma \to qg$;

(ii) $g\gamma \to q\bar{q}$.

WW contribution to SSA for $\ell\, p^\uparrow \to\, h\, X$

We assume the following factorization formula:

$$\sigma^{\mathrm{WW}}(\ell p \to hX) = \int dy\, f_{\gamma/\ell}(y)\sigma(\gamma p \to hX)$$

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using the following WW distribution (Vogelsang et.al./2015):

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

μ: factorization scale.

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We write:

$$A_N = \frac{d\Delta\sigma^{\mathrm{LO}} + d\Delta\sigma^{\mathrm{WW}}}{2[d\sigma^{\mathrm{LO}} + d\sigma^{\mathrm{WW}}]} \tag{4}$$

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Master equation:

$$\begin{aligned} E_h \frac{d\sigma_{WW}^{(p,S)\ell\to hX}}{d^3\boldsymbol{P}_h} = & \sum_{a,c,d,\{\lambda\}} \int \frac{dx\, dy\, dz}{16\pi^2 xyz^2 s} d^2\boldsymbol{k}_\perp d^3\boldsymbol{p}_\perp \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c) J(p_\perp) \\ & \times \delta\left(\hat{s} + \hat{t} + \hat{u}\right) \rho^{a/p,S}_{\lambda_a,\lambda'_a} \hat{f}_{a/p,S}(x, \boldsymbol{k}_\perp) \rho^{\gamma/\ell}_{\lambda_\gamma,\lambda'_\gamma} f_{\gamma/\ell}(y) \\ & \times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_\gamma} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_\gamma} D^{\lambda_h,\lambda_h}_{\lambda_c,\lambda'_c}(z, \boldsymbol{p}_\perp), \end{aligned} \tag{5}$$

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$$\times\, \delta\left(\hat{s} + \hat{t} + \hat{u}\right) \rho^{a/p,S}_{\lambda_a,\lambda'_a} \hat{f}_{a/p,S}(x, \boldsymbol{k}_\perp) \rho^{\gamma/\ell}_{\lambda_\gamma,\lambda'_\gamma} f_{\gamma/\ell}\,(y)$$
$$\times\, \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_\gamma} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_\gamma} D^{\lambda_h,\lambda_h}_{\lambda_c,\lambda'_c}(z, \boldsymbol{p}_\perp), \tag{5}$$

- Note: $f_{\gamma/\ell}\,(y)$ is consistently adopted as a function of only y and not also of $\boldsymbol{k}_{\perp\gamma}$

WW contribution to SSA for $\ell\, p^{\uparrow} \to h\, X$

Schematically:

$$d\sigma^{\mathrm{WW}}(S) = \sum_{a,c,d} \int \frac{dx\, dy\, dz}{16\pi^2 xyz^2 s} d^2\boldsymbol{k}_\perp d^3\boldsymbol{p}_\perp \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c) J(p_\perp) \delta\left(\hat{s} + \hat{t} + \hat{u}\right) \Sigma(S)^{a\gamma \to cd} \tag{6}$$

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Numerator

$$d\Delta\sigma^{\rm WW} = \sum_{a,c,d} \int \frac{dx\, dy\, dz}{16\pi^2 xyz^2 s} d^2\boldsymbol{k}_\perp d^3\boldsymbol{p}_\perp \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c) J(p_\perp) \times \delta\left(\hat{s}+\hat{t}+\hat{u}\right) [\Sigma(\uparrow) - \Sigma(\downarrow)]^{a\gamma\to cd} \quad (7)$$

Denominator

$$2 d\sigma^{\rm WW} = \sum_{a,c,d} \int \frac{dx\, dy\, dz}{16\pi^2 xyz^2 s} d^2\boldsymbol{k}_\perp d^3\boldsymbol{p}_\perp \delta(\boldsymbol{p}_\perp \cdot \hat{\boldsymbol{p}}_c) J(p_\perp) \times \delta\left(\hat{s}+\hat{t}+\hat{u}\right) [\Sigma(\uparrow) + \Sigma(\downarrow)]^{a\gamma\to cd} \quad (8)$$

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with

$$\sum_{a,c,d} [\Sigma(\uparrow) \pm \Sigma(\downarrow)]^{a\gamma \to cd} = [\Sigma(\uparrow) \pm \Sigma(\downarrow)]^{q\gamma \to qg} + [\Sigma(\uparrow) \pm \Sigma(\downarrow)]^{q\gamma \to gq} + [\Sigma(\uparrow) \pm \Sigma(\downarrow)]^{\bar{q}\gamma \to \bar{q}g} + [\Sigma(\uparrow) \pm \Sigma(\downarrow)]^{\bar{q}\gamma \to g\bar{q}} + [\Sigma(\uparrow) \pm \Sigma(\downarrow)]^{g\gamma \to q\bar{q}} + [\Sigma(\uparrow) \pm \Sigma(\downarrow)]^{g\gamma \to \bar{q}q} \qquad (9)$$

WW contribution to SSA for $\ell\, p^{\uparrow} \to h\, X$

$$[\Sigma(\uparrow) - \Sigma(\downarrow)]^{q\gamma\to qg} = f_{\gamma/\ell}(y)\Big\{\frac{1}{2}\Delta^N f_{q/p^\uparrow}(x, k_\perp)\cos\phi\left[|\hat{M}_1^0|^2 + |\hat{M}_2^0|^2\right]^{q\gamma\to qg} D_{h/q}(z, p_\perp)$$

$$+ h_{1q}(x, k_\perp)\left[\hat{M}_1^0\hat{M}_2^0\right]^{q\gamma\to qg}\Delta^N D_{h/q^\uparrow}(z, p_\perp)\cos(\phi' + \phi_q^h)$$

$$- \frac{k_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp)\left[\hat{M}_1^0\hat{M}_2^0\right]^{q\gamma\to qg}\Delta^N D_{h/q^\uparrow}(z, p_\perp)\cos(2\phi - \phi' - \phi_q^h)\Big\}$$

$$[\Sigma(\uparrow) + \Sigma(\downarrow)]^{q\gamma\to qg} = f_{\gamma/\ell}(y) f_{q/p}(x, k_\perp)\left[|\hat{M}_1^0|^2 + |\hat{M}_2^0|^2\right]^{q\gamma\to qg} D_{h/q}(z, p_\perp)$$

$$- \frac{k_\perp}{M} h_1^{\perp q}(x, k_\perp)\left[\hat{M}_1^0\hat{M}_2^0\right]^{q\gamma\to qg}\Delta^N D_{h/q^\uparrow}(z, p_\perp)\cos(\phi - \phi' - \phi_q^h)$$

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Sivers⊗unp., transv.(pretz.)⊗Collins, BM⊗Collins

WW contribution to SSA for $\ell\, p^{\uparrow} \to\; h\, X$

For jet production:

$$E_{\rm j}\,\frac{d\sigma_{WW}^{(p,S)\ell\to{\rm jet}\,X}}{d^3\boldsymbol{P}_{\rm j}} = \sum_{a,c,d,\{\lambda\}} \int \frac{dx\, dy}{16\pi^2 xys}\, d^2\boldsymbol{k}_\perp\, \delta\left(\hat{s}+\hat{t}+\hat{u}\right) \times \rho^{a/p,S}_{\lambda_{\boldsymbol{a}},\lambda'_{\boldsymbol{a}}}\, \hat{f}_{a/p,S}(x,\boldsymbol{k}_\perp)\, \rho^{\gamma/\ell}_{\lambda_\gamma,\lambda'_\gamma}\, f_{\gamma/\ell}(y)\, \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_\gamma}\, \hat{M}^{*}_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_\gamma} \qquad (10)$$

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and

$$d\Delta\sigma^{\rm WW}_{\rm jet} = \sum_{a,c,d} \int \frac{dx\, dy}{16\pi^2 xys} d^2\boldsymbol{k}_\perp \delta\left(\hat{s} + \hat{t} + \hat{u}\right) [\Sigma(\uparrow) - \Sigma(\downarrow)]^{a\gamma \to cd}_{\rm jet} \tag{11}$$

$$2 d\sigma^{\rm WW} = \sum_{a,c,d} \int \frac{dx\, dy}{16\pi^2 xys} d^2\boldsymbol{k}_\perp \delta\left(\hat{s} + \hat{t} + \hat{u}\right) [\Sigma(\uparrow) + \Sigma(\downarrow)]^{a\gamma \to cd}_{\rm jet} \tag{12}$$

WW contribution to SSA for $\ell\, p^\uparrow \to h\, X$

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$$d\Delta\sigma^{\rm WW}_{\rm jet} = \sum_{a,c,d} \int \frac{dx\, dy}{16\pi^2 xys} d^2\boldsymbol{k}_\perp \delta\left(\hat{s}+\hat{t}+\hat{u}\right) [\Sigma(\uparrow)-\Sigma(\downarrow)]^{a\gamma\to cd}_{\rm jet} \tag{11}$$

$$2d\sigma^{\rm WW} = \sum_{a,c,d} \int \frac{dx\, dy}{16\pi^2 xys} d^2\boldsymbol{k}_\perp \delta\left(\hat{s}+\hat{t}+\hat{u}\right) [\Sigma(\uparrow)+\Sigma(\downarrow)]^{a\gamma\to cd}_{\rm jet} \tag{12}$$

- Note: replace $D_{h/q,g}(z,p_\perp) \to 1$ and $\Delta^N D_{h/q^\uparrow}(z,p_\perp) \to 0$ (no fragmentation process! – pure Sivers effect)

Phenomenological results

We computed predictions for

hermes COMPASS Jefferson Lab EIC

unpolarized cross sections + SSAs

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hermes COMPASS Jefferson Lab EIC

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Comparison w/ HERMES data:

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

with

$$\sin\psi = \boldsymbol{S}_T \cdot \left(\hat{\boldsymbol{P}}_T \times \hat{\boldsymbol{k}}\right),$$

so

$$\boxed{A_{UT}^{\sin\psi}(x_F, P_T) = A_N^{p^\uparrow \ell \to hX}(-x_F, P_T)} \qquad (13)$$

Phenomenological results

- Parametrizations for unpolarized TMDs:

$$f_{a/p}(x, k_\perp) = f_{a/p}(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\exp\left\{-\frac{k_\perp^2}{\langle k_\perp^2\rangle}\right\},$$
$$D_{h/c}(z, p_\perp) = D_{h/c}(z)\,\frac{1}{\pi\langle p_\perp^2\rangle}\exp\left\{-\frac{p_\perp^2}{\langle p_\perp^2\rangle}\right\},$$

with $\langle k_\perp^2\rangle = 0.25\,\mathrm{GeV}^2$ and $\langle p_\perp^2\rangle = 0.2\,\mathrm{GeV}^2$;

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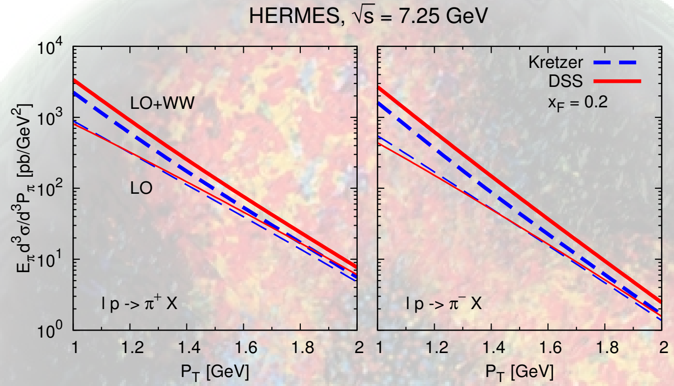
  with $\langle k_\perp^2\rangle = 0.25\,\text{GeV}^2$ and $\langle p_\perp^2\rangle = 0.2\,\text{GeV}^2$;
- Collinear PDFs set: GRV98;
- Collinear FFs sets: Kretzer, De Florian+Sassot+Stratmann (DSS) (different role of gluon FF);
- Tested new extraction of Sivers function: $\langle k_\perp^2\rangle = 0.57\,\text{GeV}^2$ and $\langle p_\perp^2\rangle = 0.12\,\text{GeV}^2$ (CTEQ6L PDFs were used).

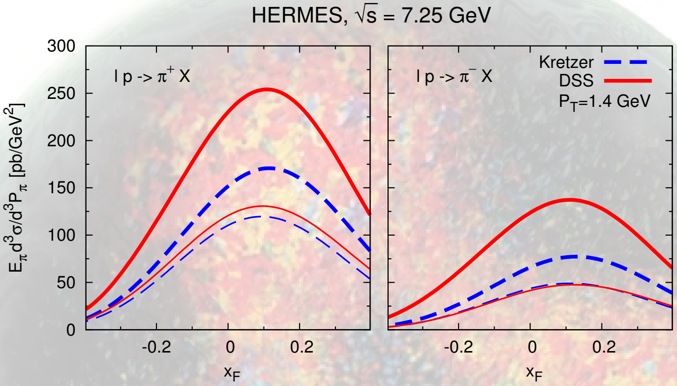
Phenomenological results - unpolarized cross sections



Note:

- $x_F = P_L/P_L^{\max} \equiv 2P_L/\sqrt{s}$;
- WW contribution more important at small P_T.

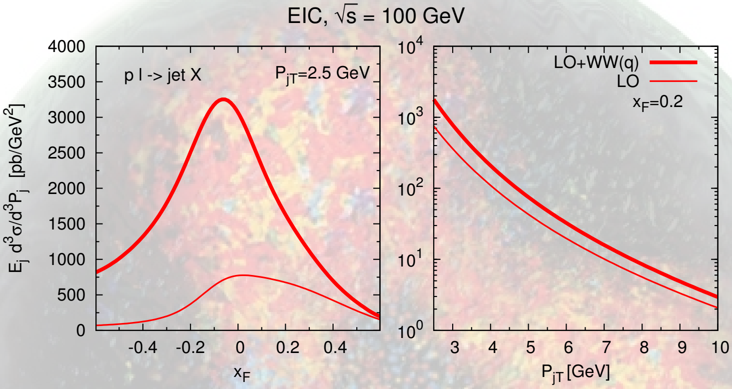
Phenomenological results - unpolarized cross sections



Note:

- for large positive x_F (final hadron produced in backward proton hemisphere) $|\hat{u}| \ll |\hat{t}|$;
- favoured region for WW contribution! LO: $1/Q^2 \equiv 1/\hat{t}^2$, WW: $1/Q^2 \equiv 1/\hat{s}\hat{u}$.

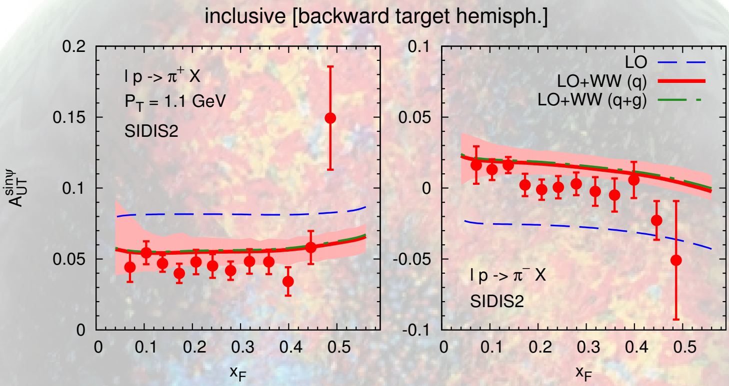
Phenomenological results - unpolarized cross sections



Note:

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

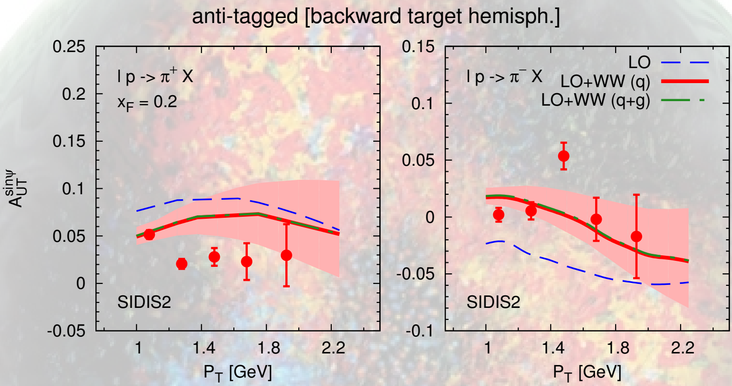
Phenomenological results - comparison with HERMES data



Note:

- improved description of data;
- gluon Sivers function contribution pratically negligible.

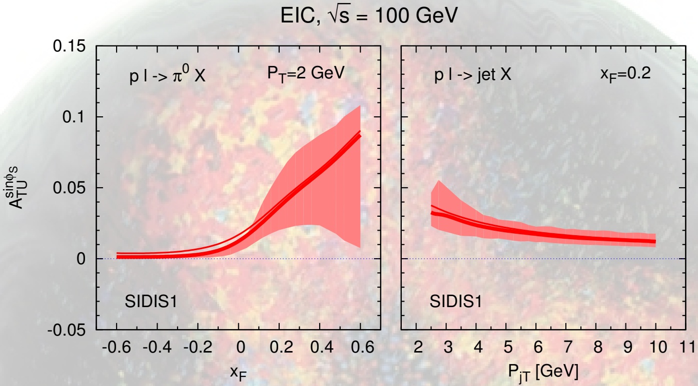
Phenomenological results - comparison with HERMES data



Note:

- same considerations as inclusive data;
- some discrepancies for π^+.

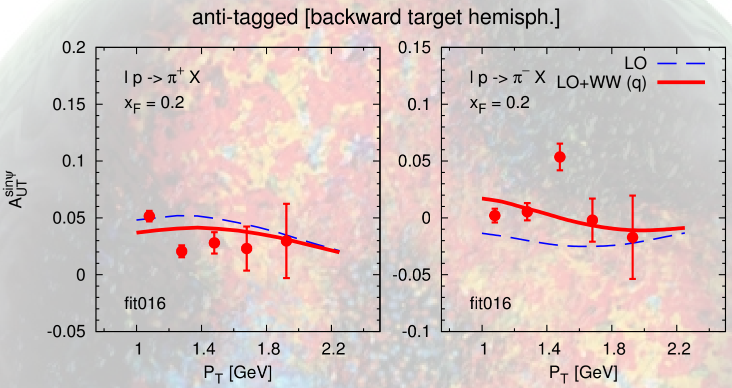
Phenomenological results - predictions for EIC



Note:

- 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!

Phenomenological results - comparison with HERMES data (2)



Note:

- only Sivers effect is showed;
- different widths: $\langle k_\perp^2 \rangle = 0.57\,\mathrm{GeV}^2$ and $\langle p_\perp^2 \rangle = 0.12\,\mathrm{GeV}^2$;
- CTEQ6L PDFs were used for the new fit of Sivers function

Conclusions

- computed, in the spirit of a TMD approach, WW contribution;
- found new theoretical expression within helicity formalism;
- predictions for unpolarized cross sections and SSAs for ongoing and future experiments were gived;
- found that WW contribution plays a huge role in $\ell p^\uparrow \to hX$;
- very good description of HERMES data, both for inclusive and untagged data (new extraction of Sivers enhanced the agreement with the data);
- future measurments, especially at EIC, would test TMD approach;
- a further step towards a deeper understanding of the origin of SSAs for inclusive processes and towards a unified TMD picture.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BACKUP

WW contribution - Helicity amplitudes

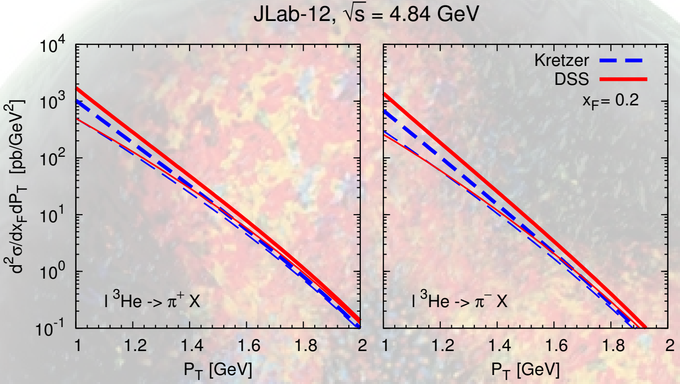
Besides an overall factor $16\pi^2\alpha\alpha_s$:

$$\left[|\hat{M}_1^0|^2 + |\hat{M}_2^0|^2\right]^{q\gamma\to qg} = \frac{16}{3}e_q^2\frac{\hat{s}^2+\hat{u}^2}{-\hat{s}\hat{u}}, \qquad \left[\hat{M}_1^0\hat{M}_2^0\right]^{q\gamma\to qg} = \frac{16}{3}e_q^2,$$

$$\left[|\hat{M}_1^0|^2 + |\hat{M}_3^0|^2\right]^{q\gamma\to gq} = \frac{16}{3}e_q^2\frac{\hat{s}^2+\hat{t}^2}{-\hat{s}\hat{t}},$$

$$\left[|\hat{M}_2^0|^2 + |\hat{M}_3^0|^2\right]^{g\gamma\to q\bar{q}} = 2e_q^2\frac{\hat{u}^2+\hat{t}^2}{-\hat{u}\hat{t}}.$$

Phenomenological results - unpolarized cross sections

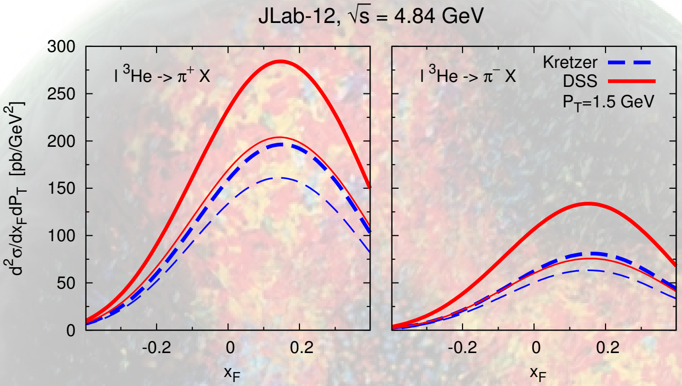


Note:

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

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

Phenomenological results - unpolarized cross sections



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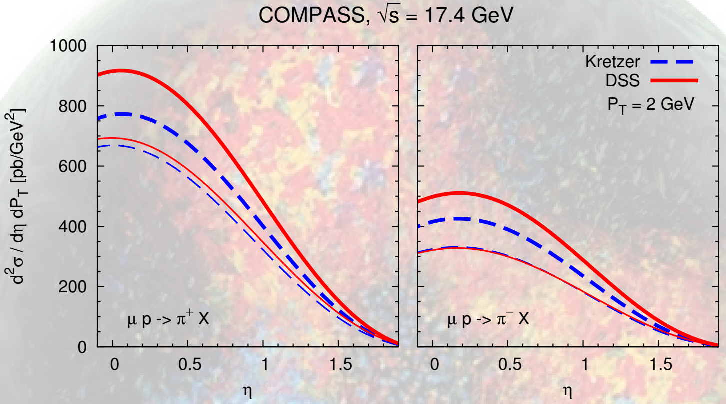
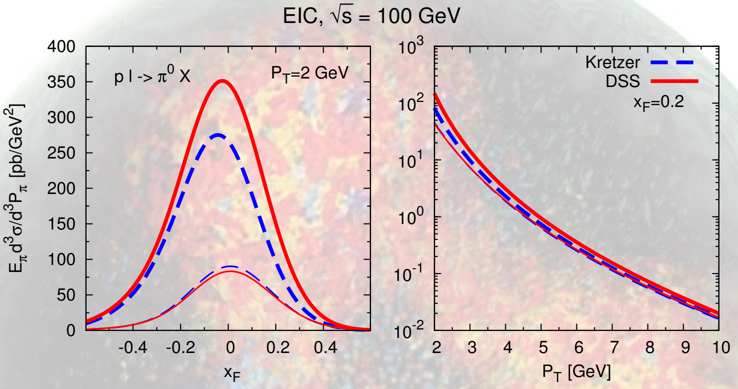


Note:

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

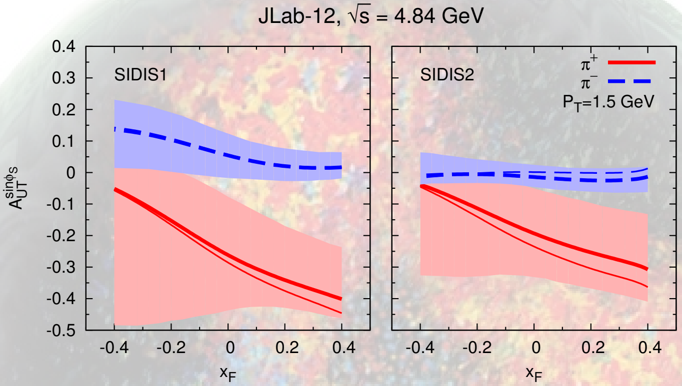
Phenomenological results - unpolarized cross sections



Note:

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

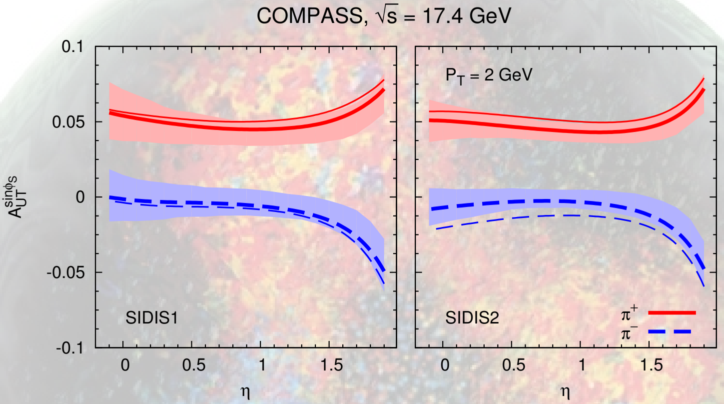
Phenomenological results - predictions for JLAB



Note:

- wider uncertainty bands due to large-x region probed at moderate energies;
- extractions of Sivers function are uncontstrained at large x.

Phenomenological results - predictions for COMPASS



Note:

- sizeable SSA for π^+;
- data would be useful as a clear test of TMD approach.

References

- Article: arxiv:1701.01148v1 [hep-ph];
- QCD Evolution 2016 proceedings: PoS(QCDEV2016)002.