Polarized pion induced Drell-Yan and TMD factorization

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The Drell-Yan process with pions and polarized nucleons

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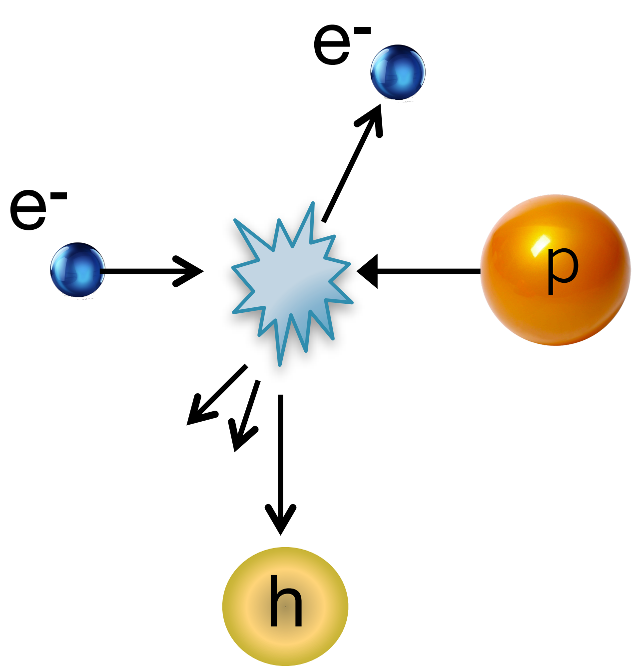
TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

Small scale → $q_T \ll Q$ ← Large scale

The confined motion (k_T dependence) is encoded in TMDs

Semi-Inclusive DIS

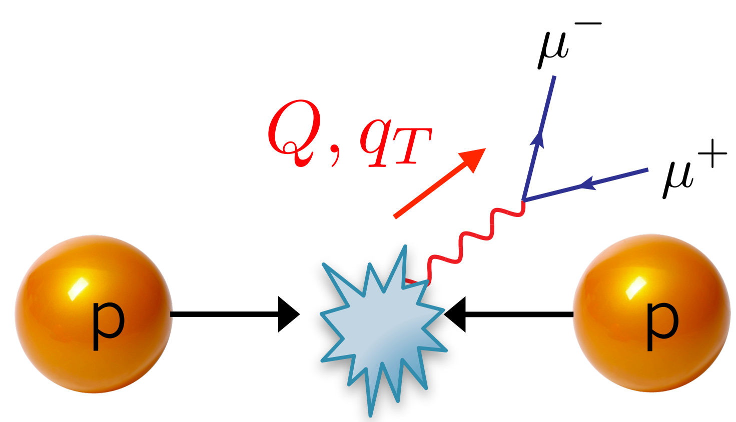
$$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(z, k_T)$$



Meng, Olness, Soper (1992)
Ji, Ma, Yuan (2005)
Idilbi, Ji, Ma, Yuan (2004)
Collins (2011)

Drell-Yan

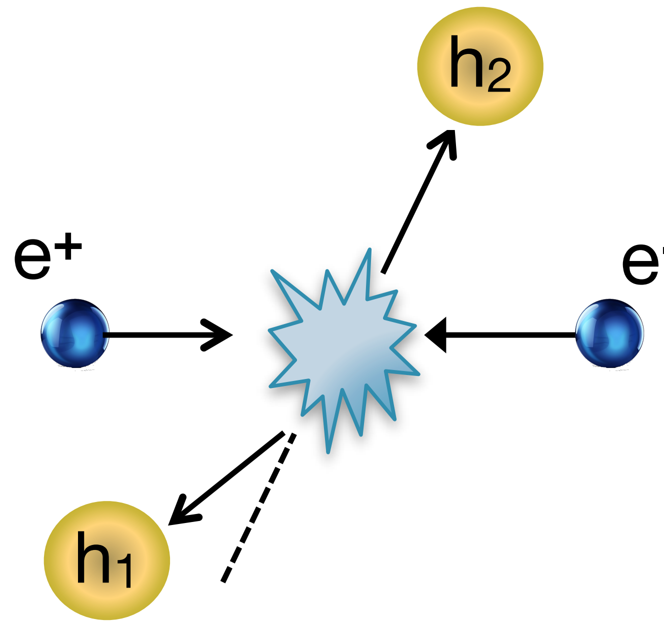
$$\sigma \sim f_{q/P}(x_1, k_T) f_{\bar{q}/P}(x_2, k_T)$$



Collins, Soper, Sterman (1985)
Ji, Ma, Yuan (2004)
Collins (2011)

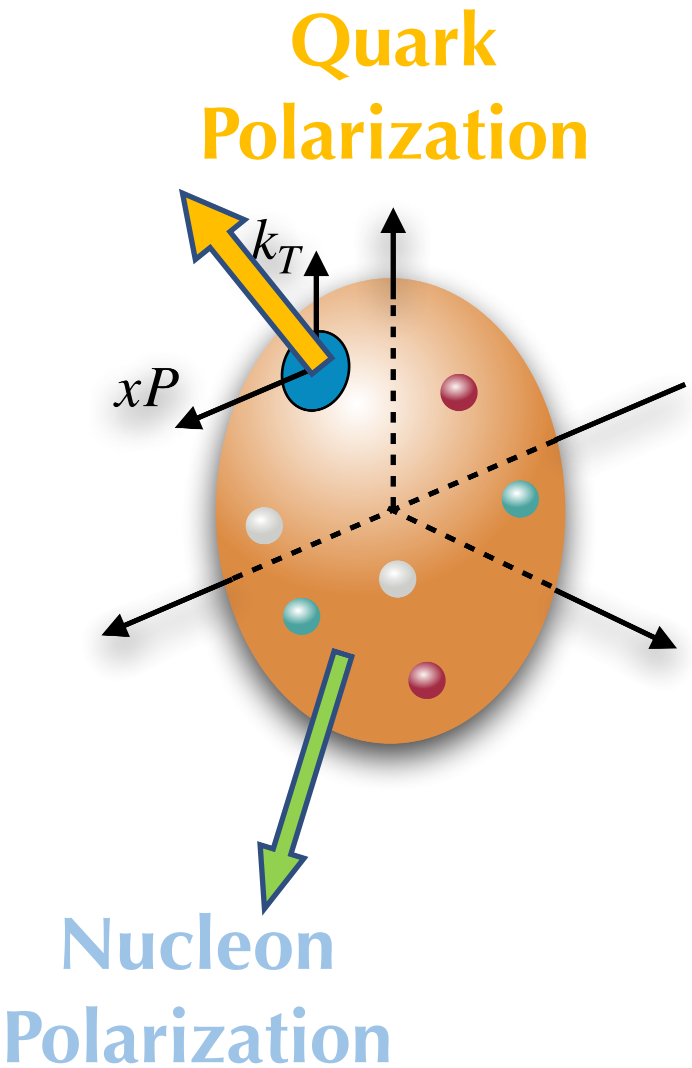
Dihadron in e^+e^-

$$\sigma \sim D_{h_1/q}(z_1, k_T) D_{h_2/\bar{q}}(z_2, k_T)$$



Collins, Soper (1983)
Collins (2011)

TMD FUNCTIONS



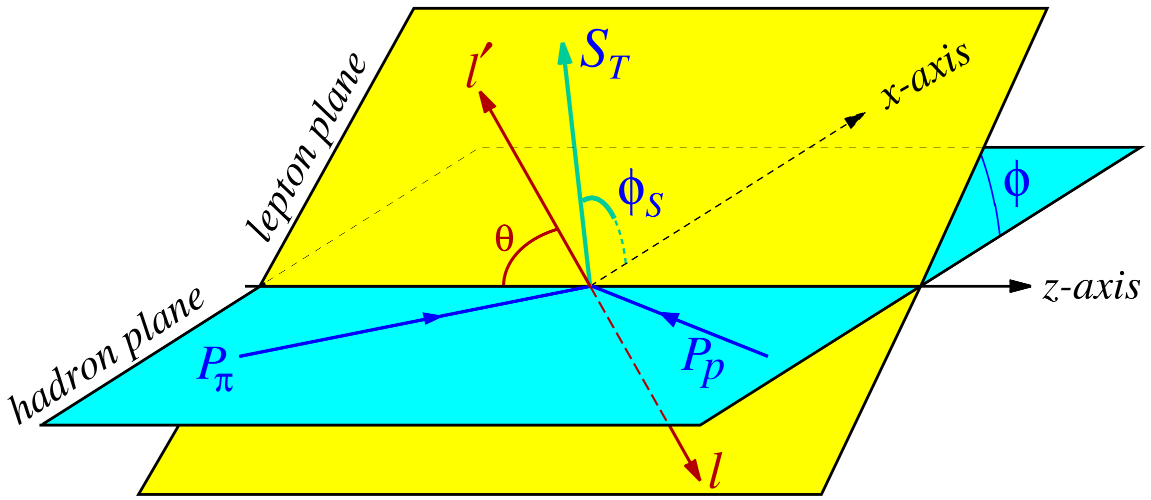
		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ **Boer-Mulders**
	L		$g_1(x,k_T^2)$ **Helicity**	$h_{1L}^\perp(x,k_T^2)$ **Kotzinian-Mulders**
	T	$f_{1T}^\perp(x,k_T^2)$ **Sivers**	$g_{1T}(x,k_T^2)$ **Kotzinian-Mulders**	$h_1(x,k_T^2)$ **Transversity** $h_{1T}^\perp(x,k_T^2)$ **Pretzelosity**

Analogous tables for:

- Gluons $f_1 \to f_1^g$ etc
- Fragmentation functions
- Pion, nuclear targets $S \neq \frac{1}{2}$

PION INDUCED DRELL-YAN

$$\pi^-(P_\pi) + N(P_p, S) \to \ell^+\ell^- + X$$



Collins-Soper frame

➤ Measured by COMPASS

Advantageous, since

$$\bar{u} + u \to \gamma^*$$

subprocess is enhanced

Cross-Section is expressed in terms of structure functions

$$\frac{d\sigma}{d^4q\, d\Omega} = \frac{\alpha_{em}^2}{F\, q^2} \times$$
$$\left\{ \left((1+\cos^2\theta)\, F_{UU}^1 + (1-\cos^2\theta)\, F_{UU}^2 + \sin 2\theta \cos\phi\, F_{UU}^{\cos\phi} + \sin^2\theta \cos 2\phi\, F_{UU}^{\cos 2\phi} \right) \quad \ldots \right.$$

Structure functions are convolutions of TMDs

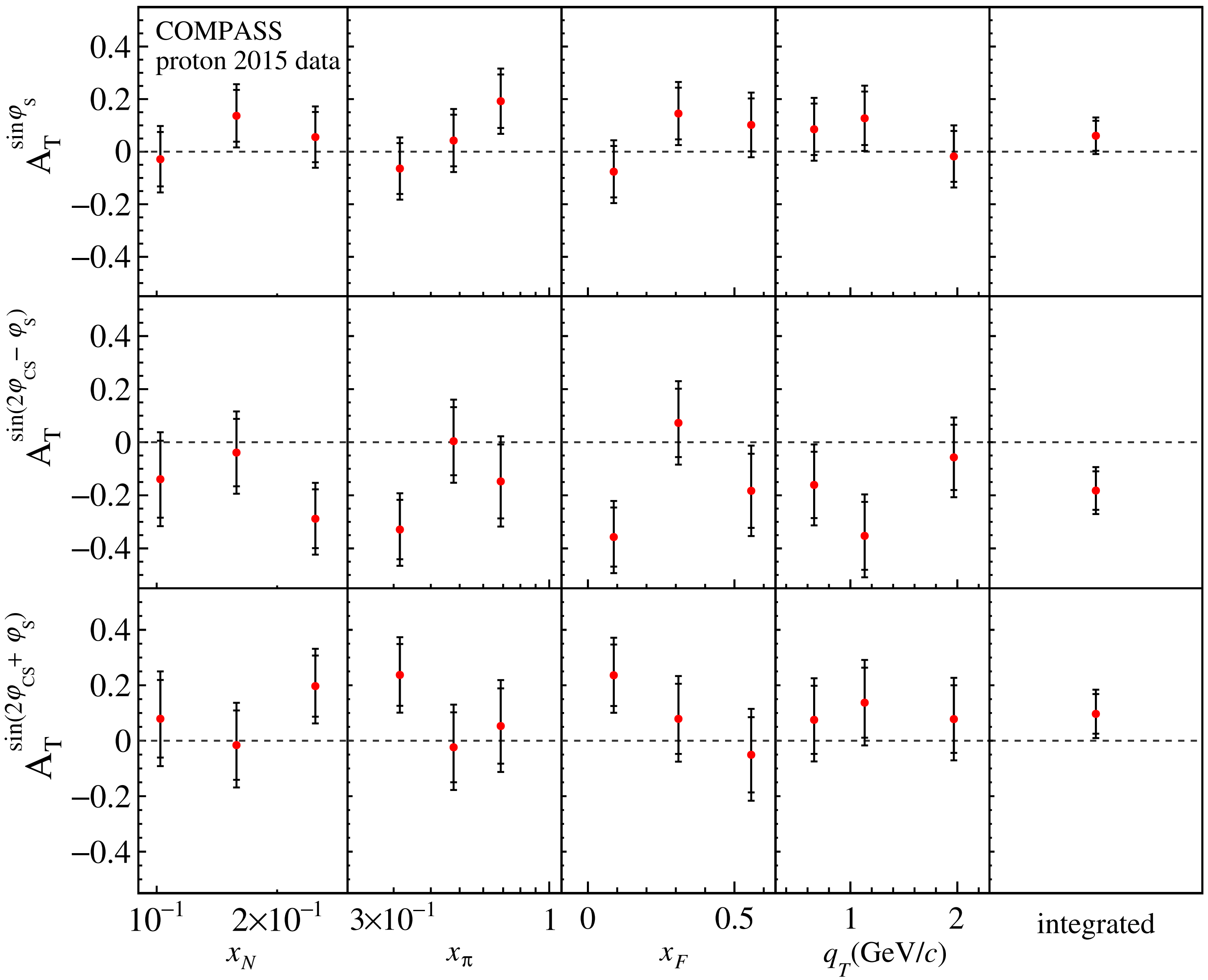
$$\mathcal{C}[\omega\, f_\pi^{\bar{a}}\, f_p^a] = \frac{1}{N_c} \sum_a e_a^2 \int d^2\boldsymbol{k}_{T\pi}\, d^2\boldsymbol{k}_{Tp}\, \delta^{(2)}(\boldsymbol{q}_T - \boldsymbol{k}_{T\pi} - \boldsymbol{k}_{Tp})\, \omega\, f_\pi^{\bar{a}}(x_\pi, \boldsymbol{k}_{T\pi}^2) f_p^a(x_p, \boldsymbol{k}_{Tp}^2)$$

Arnold, Metz, Schlegel *Phys.Rev.D* 79 (2009) 034005

PION INDUCED DRELL-YAN

$$\pi^-(P_\pi) + N(P_p, S) \to \ell^+\ell^- + X$$

- Measured by COMPASS



$\propto \mathcal{C}[f_{1\pi} f_{1T}^{\perp}]$

Unpolarized x Sivers

$\propto \mathcal{C}[h_{1\pi}^{\perp} h_1]$

Boer-Mulders x Transversity

$\propto \mathcal{C}[h_{1\pi}^{\perp} h_{1T}^{\perp}]$

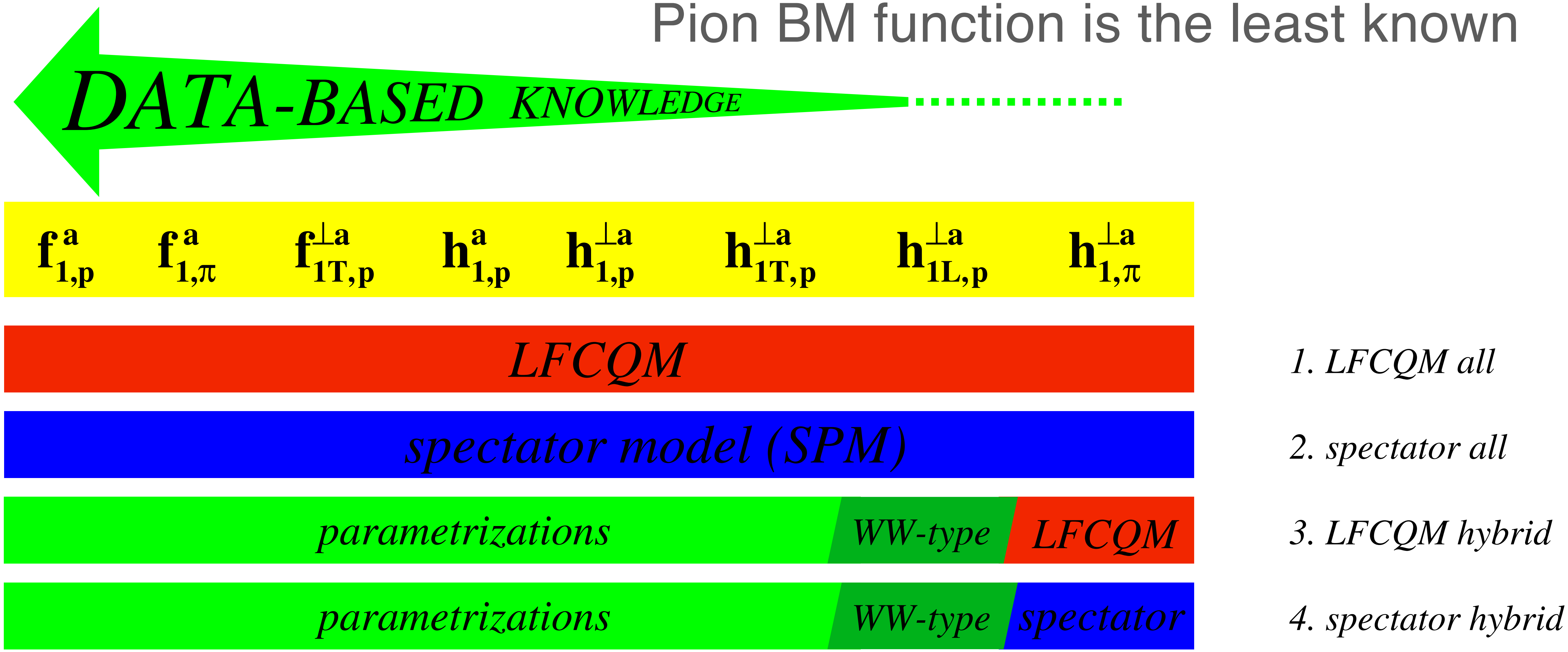
Boer-Mulders x Pretzelosity

Aghasyan et al PRL 119, 112002 (2017)

Arnold, Metz, Schlegel *Phys.Rev.D* 79 (2009) 034005

PION INDUCED DRELL-YAN

Pion BM function is the least known



Models are rich source of information in QCD

We will use models in our estimates and include Light Front Constituent Quark Models, spectator models, and a hybrid approach with phenomenological extractions

PION INDUCED DRELL-YAN

Structure functions at leading twist:

Measured

Not yet measured

$$F_{UU}^{1} = \mathcal{C}\left[f_{1,\pi}^{\bar{a}}\, f_{1,p}^{a}\right],$$

$$F_{UU}^{\cos 2\phi} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{T\pi})(\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{Tp}) - \vec{\boldsymbol{k}}_{T\pi}\cdot\vec{\boldsymbol{k}}_{Tp}}{M_\pi\, M_p}\, h_{1,\pi}^{\perp\bar{a}}\, h_{1,p}^{\perp a}\right],$$

Boer-Mulders x Boer-Mulders

$$F_{UL}^{\sin 2\phi} = -\mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{T\pi})(\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{Tp}) - \vec{\boldsymbol{k}}_{T\pi}\cdot\vec{\boldsymbol{k}}_{Tp}}{M_\pi\, M_p}\, h_{1,\pi}^{\perp\bar{a}}\, h_{1L,p}^{\perp a}\right],$$

Boer-Mulders x Kotzinian-Mulders

$$F_{UT}^{\sin \phi_S} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{Tp}}{M_p}\, f_{1,\pi}^{\bar{a}}\, f_{1T,p}^{\perp a}\right],$$

$$F_{UT}^{\sin(2\phi-\phi_S)} = -\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{T\pi}}{M_\pi}\, h_{1,\pi}^{\perp\bar{a}}\, h_{1,p}^{a}\right],$$

$$F_{UT}^{\sin(2\phi+\phi_S)} = -\mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{Tp})[2(\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{T\pi})(\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{Tp}) - \vec{\boldsymbol{k}}_{T\pi}\cdot\vec{\boldsymbol{k}}_{Tp}] - \vec{\boldsymbol{k}}_{Tp}^{2}(\hat{\boldsymbol{h}}\cdot\vec{\boldsymbol{k}}_{T\pi})}{2\, M_\pi\, M_p^2}\, h_{1,\pi}^{\perp\bar{a}}\, h_{1T,p}^{\perp a}\right]$$

EVOLUTION

- TMD evolution is governed by two differential equations in ultraviolet and rapidity renormalization scales
- TMDs are defined in Fourier space b_T (conjugate to q_T)
- Structure functions become FT of products of TMDs in b_T-space

$$\mathcal{B}_n[\tilde{f}_\pi\ \tilde{f}_p] \equiv \frac{1}{N_c}\sum_a e_a^2 \int_0^\infty \frac{db_T\, b_T}{2\pi}\, b_T^n\, J_n(q_T b_T)$$
$$\times\ \tilde{f}_\pi^{\bar{a}}(x_\pi, b_T, Q_0, Q_0^2)\ \tilde{f}_p^{a}(x_p, b_T, Q_0, Q_0^2)\ e^{-S(b_T,Q_0,Q)}$$

where S is the evolution factor Collins, Rogers Phys. Rev. D **91**, 074020

$$S(b_T, Q_0, Q) = -\tilde{K}(b_T, Q_0)\ln\frac{Q^2}{Q_0^2} + \int_{Q_0}^{Q}\frac{d\bar{\mu}}{\bar{\mu}}\left[\gamma_K(\alpha_s(\bar{\mu}))\ln\frac{Q^2}{\bar{\mu}^2} - 2\gamma_i(\alpha_s(\bar{\mu});1)\right]$$

Collins-Soper kernel Anomalous dimension, K Anomalous dimension, f

EVOLUTION

We implement evolution at Next-to-Leading-Logarithmic precision

Collins-Soper kernel is needed for all b Collins, Rogers Phys. Rev. D **91**, 074020

$$S(b_T, b_*, Q_0, Q) = \left(g_K(b_T; b_{\max}) - \tilde{K}(b_*; \mu_{b_*}) + \int_{\mu_{b_*}}^{Q_0} \frac{d\bar{\mu}}{\bar{\mu}} \gamma_K(\alpha_s(\bar{\mu})) \right) \ln \frac{Q^2}{Q_0^2} + \int_{Q_0}^{Q} \frac{d\bar{\mu}}{\bar{\mu}} \left[\gamma_K(\alpha_s(\bar{\mu})) \ln \frac{Q^2}{\bar{\mu}^2} - 2\gamma_i(\alpha_s(\bar{\mu}); 1) \right] .$$

$$\tilde{K}(b_*; \mu_{b_*}) = \frac{C_F}{2} \left(\frac{\alpha_s(\mu_{b_*})}{\pi} \right)^2 \left[\left(\frac{7}{2}\zeta_3 - \frac{101}{27} \right) C_A + \frac{28}{27} T_F n_f \right]$$

Collins-Soper perturbative, valid at small-b

g_K is a non perturbative function for large-b

$$\gamma_i = \sum_{n=1}^{\infty} \gamma_i^{(n)} (\alpha_s/\pi)^n, \text{ and } \gamma_K = \sum_{n=1}^{\infty} \gamma_K^{(n)} (\alpha_s/\pi)^n$$

Anomalous dimensions

$$\gamma_K^{(1)} = 2C_F, \quad \gamma_K^{(2)} = C_F \left[C_A \left(\frac{67}{18} - \frac{\pi^2}{6} \right) - \frac{10}{9} T_F n_f \right], \quad \gamma_i^{(1)} = \frac{3}{2} C_F$$

EVOLUTION FROM MODEL TO EXPERIMENTAL SCALE

Models, < 1 GeV

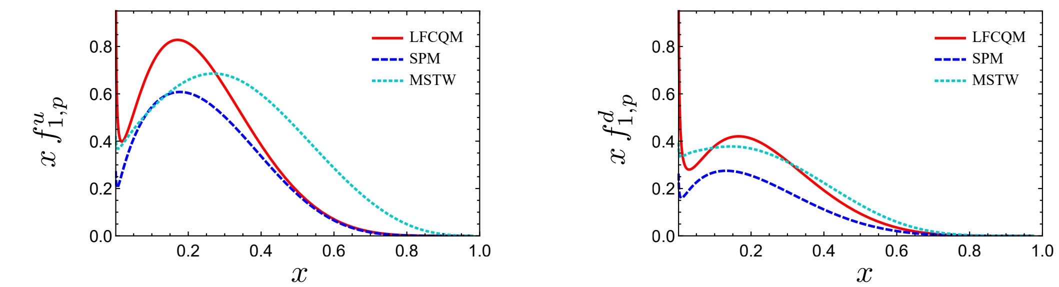
DGLAP-type of TMD moments

Initial scale, Q_0 = 1.5 GeV typical for TMD phenomenology

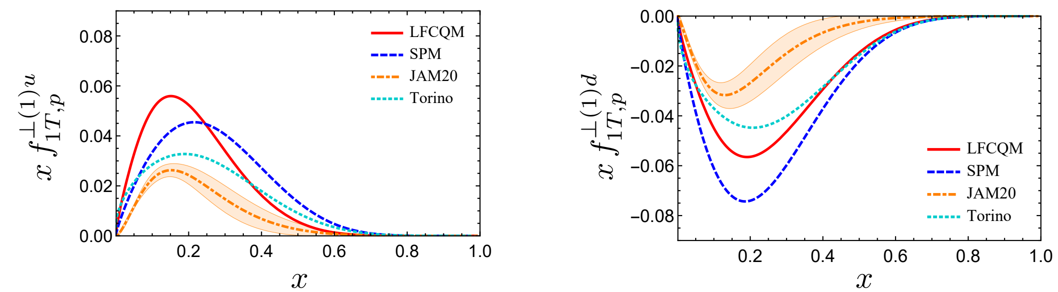
NLL, TMD evolution

Experimental scale Q > 5 GeV

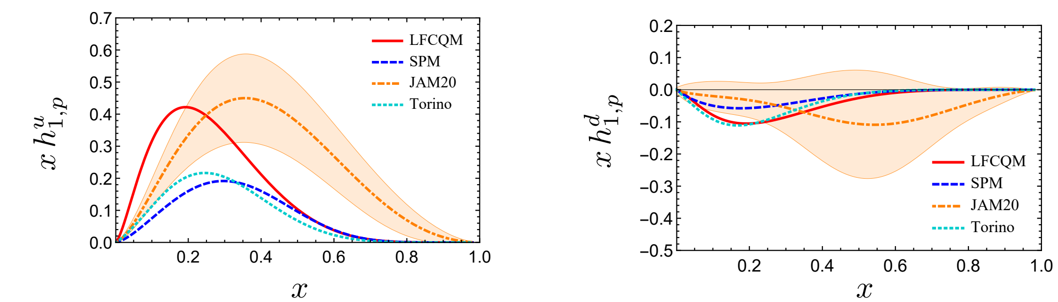
PROTON TMDS



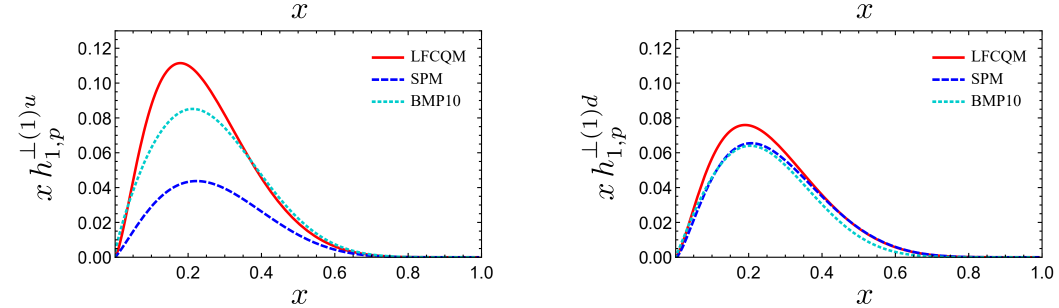
Unpolarized



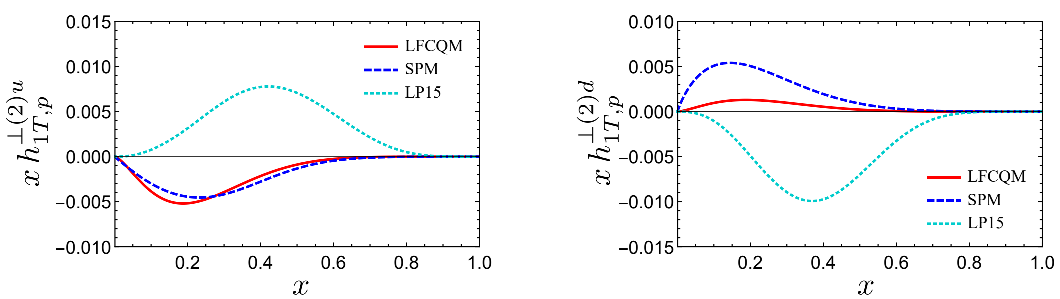
Sivers function



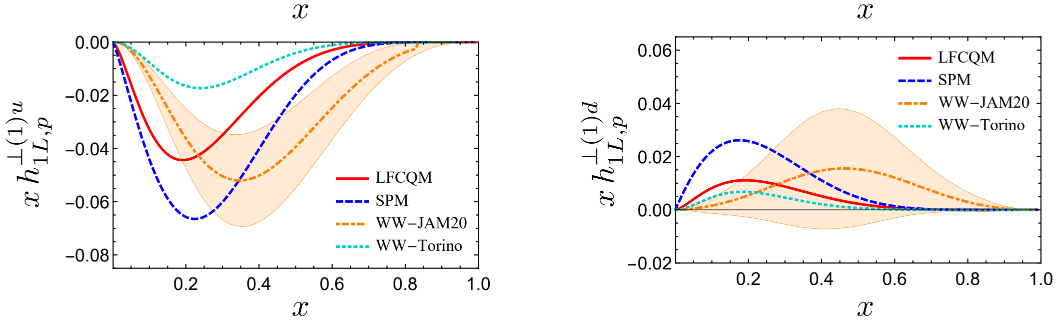
Transversity



Boer-Mulders



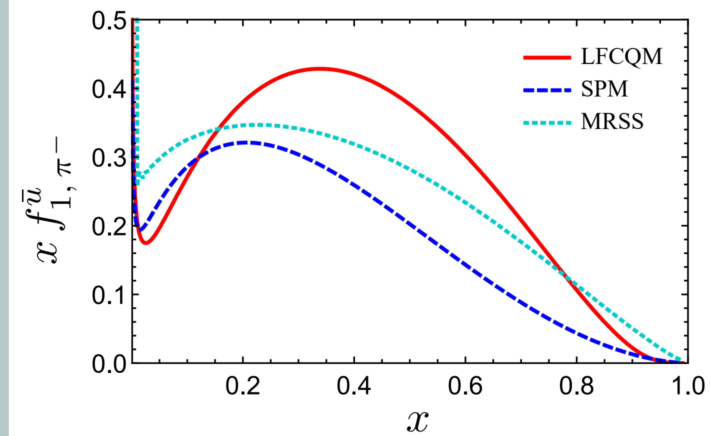
Pretzelosity



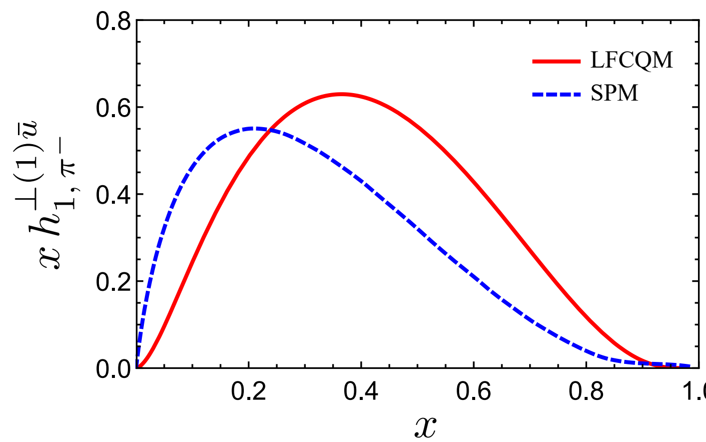
Kotzinian-Mulders

PION TMDS

Unpolarized



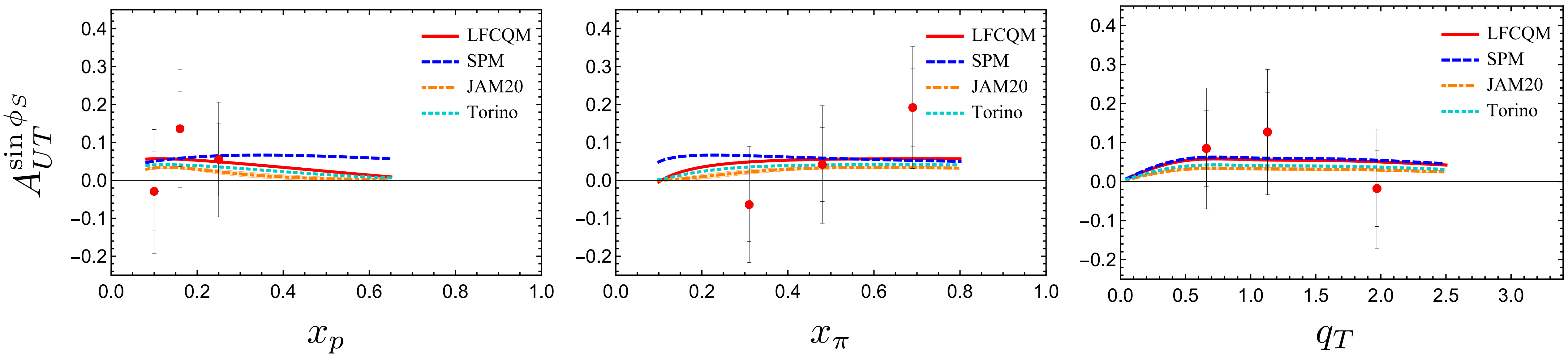
Boer-Mulders



COMPARISON TO EXPERIMENT

COMPASS data: Aghasyan et al PRL 119, 112002 (2017)

Unpolarized x Sivers

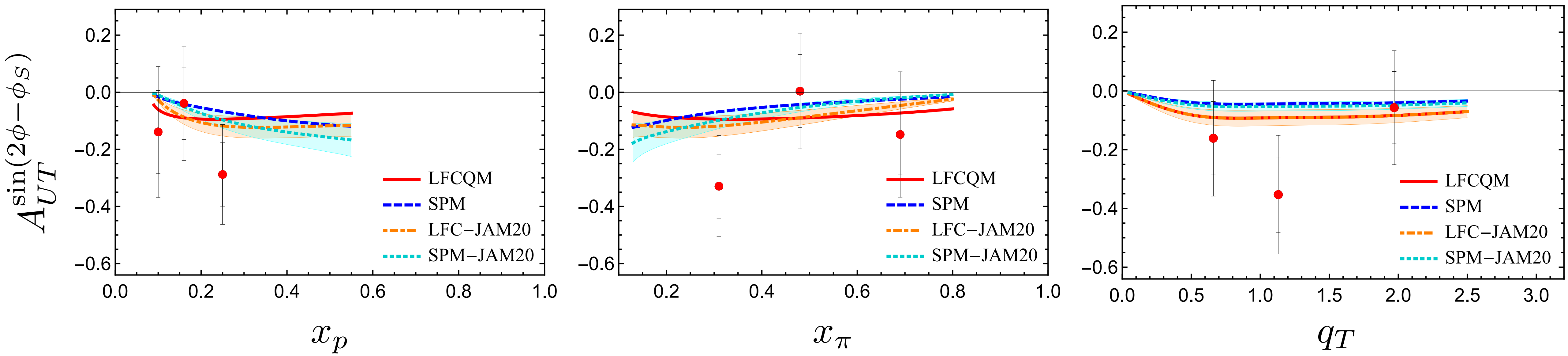


Bastami et al (2020)

COMPARISON TO EXPERIMENT

COMPASS data: Aghasyan et al PRL 119, 112002 (2017)

Pion Boer-Mulders x Transversity



Bastami et al (2020)

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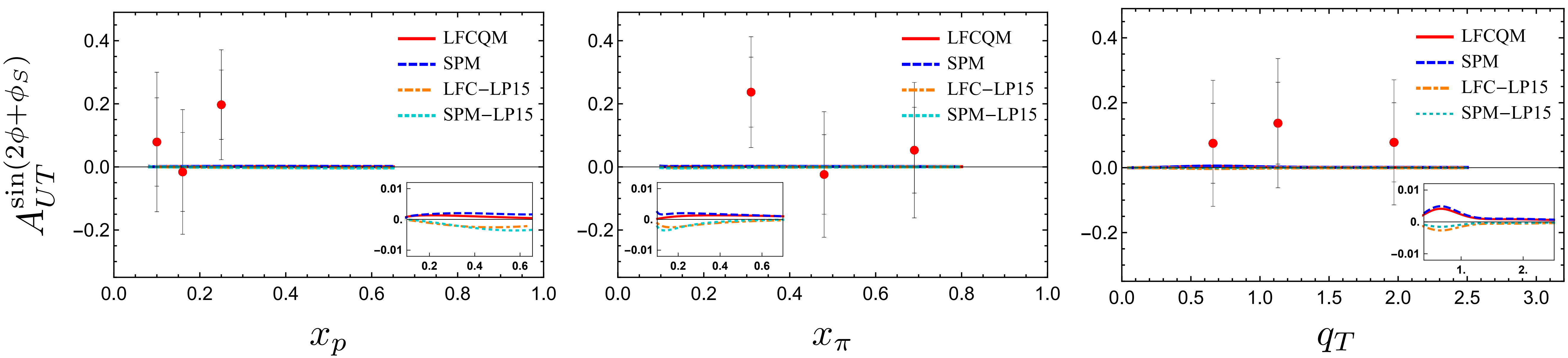
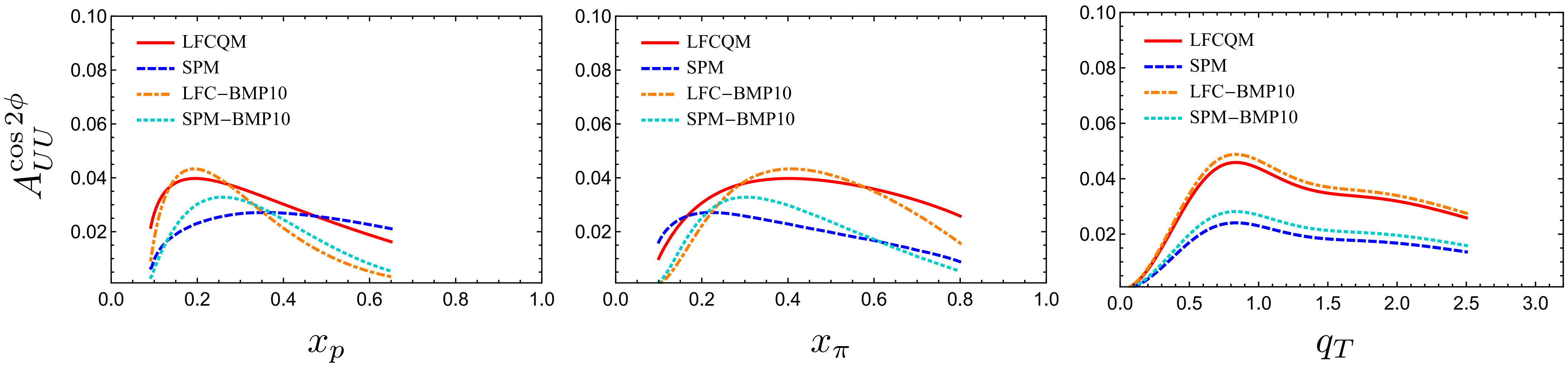


Bastami et al (2020)

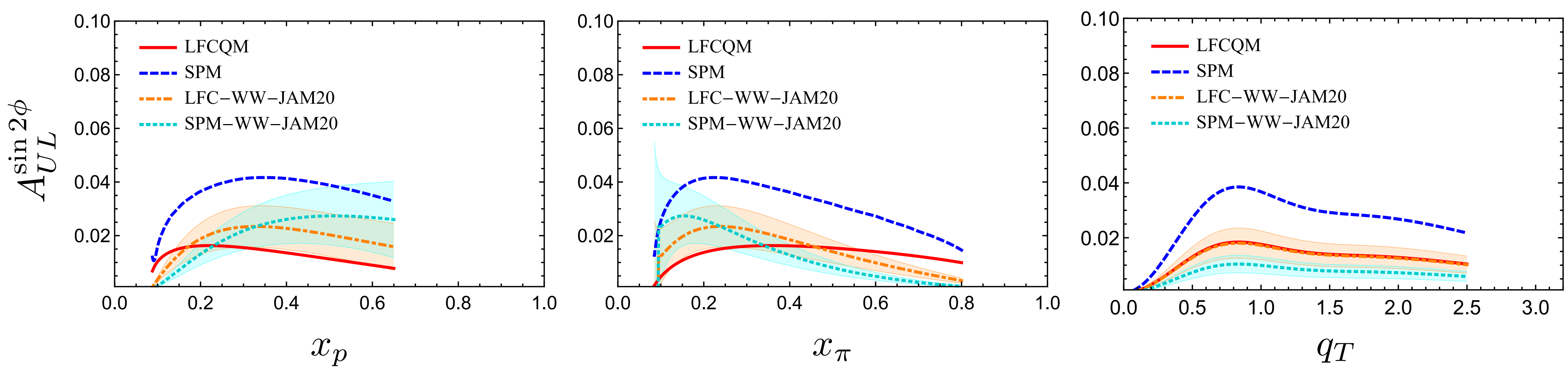
PREDICTIONS

Bastami et al (2020)

Pion Boer-Mulders x Boer-Mulders



Pion Boer-Mulders x Kotzinian-Mulders



CONCLUSIONS

- We have studied pion induced polarized Drell-Yan process within TMD factorization at NLL precision
- Results, including model and phenomenological input, are compared to the existing data from COMPASS experiment and show a good agreement with the data
- Predictions are given for the future measurements