Precision Phenomenology of SIDIS for Intermediate qT

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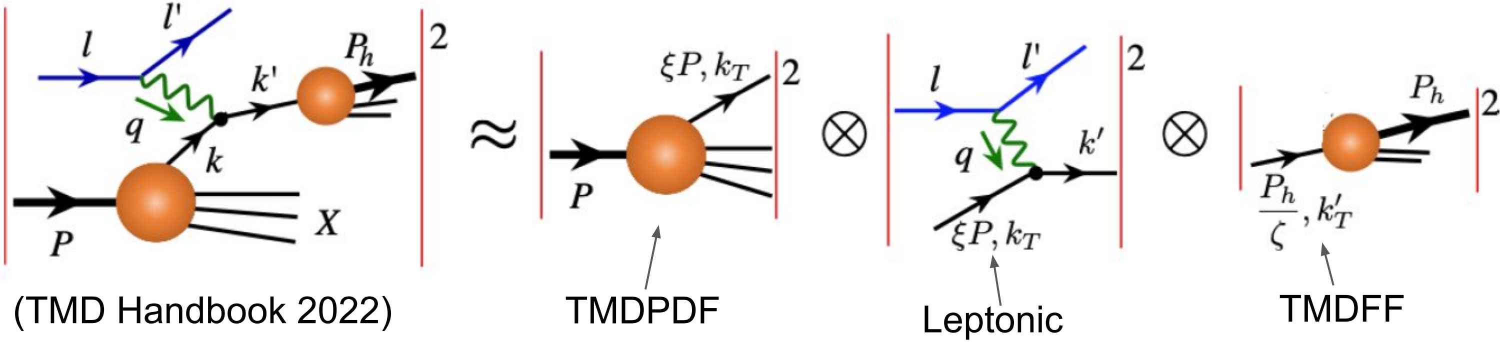
Outline

- Overview of Semi-Inclusive Deep Inelastic Scattering
- Hybrid Momentum Impact Parameter Resummation
- TMD Nonperturbative Model
- Error Analysis
- Comparison with HERMES data

Semi-Inclusive Deep Inelastic Scattering (SIDIS)



(TMD Handbook 2022)

- Used to probe internal structure of protons and other nucleons
- In SCET, TMD’s can be factorized into Collinear and Soft pieces
- Complications in predicting cross sections over large transverse momentum range
- Complications in performing resummation

SIDIS

$$\frac{d\sigma_W}{dxdydzd^2k_\perp} = \sigma_0(Q^2)H(Q^2,\mu) \qquad (2.15)$$
$$\times \sum_{f_1,f_2} e_{f_1}e_{f_2}\int d^2\boldsymbol{r}_\perp \int d^2\boldsymbol{p}_\perp f_{\perp n}^{(f_1/p)}(x,\boldsymbol{p}_\perp;\mu,\nu) D_{\perp\bar{n}}^{(h/f_2)}(z,\boldsymbol{r}_\perp;\mu,\nu)\mathcal{S}_\perp\big(\boldsymbol{r}_\perp+\boldsymbol{p}_\perp+\boldsymbol{k}_\perp;\mu,\nu\big),$$

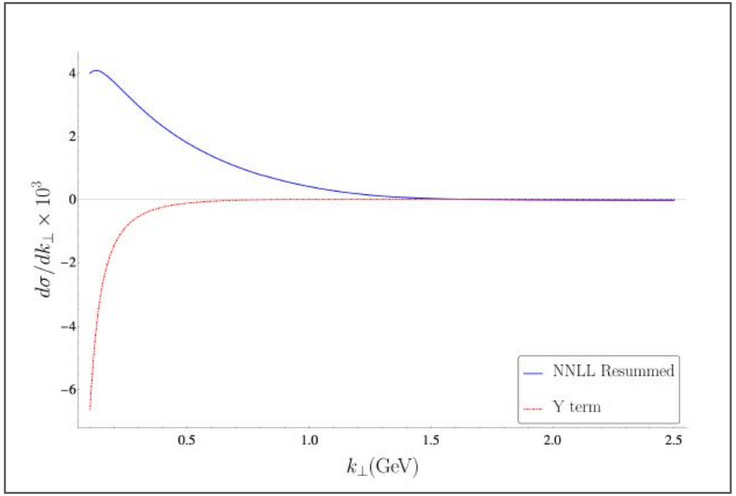
$$f_{\perp n}^{(f_1/p)}(x,\boldsymbol{p}_\perp;\mu_0,\nu) \to \int_x^1 \frac{d\xi}{\xi} f^{(f_1/p)}(\xi;\mu)H_f(\frac{x}{\xi},\boldsymbol{p}_\perp;\mu_0,\mu,\nu) + \mathcal{O}\left(\frac{\Lambda}{p_\perp}\right),$$

Collinear Expansion

$$\frac{d\sigma}{dxdydzd^2k_\perp} = \frac{d\sigma_W}{dxdydzd^2k_\perp} + \frac{d\sigma_Y}{dxdydzd^2k_\perp}.$$

Resummed Piece

Correction to match FO



$Q^2 = 9.2\,\mathrm{GeV}^2$

$$\mu_0(p_\perp) \to \mu_0(p_\perp)^{1-\zeta(p_\perp)}\mu_H^{\zeta(p_\perp)}$$
$$\nu_0^*(p_\perp) \to \nu^*(p_\perp)^{1-\zeta(p_\perp)}\nu_H^{\zeta(p_\perp)}$$

$$\zeta(p_\perp) = \frac{1}{2}\left\{1+\tanh\left[\rho\left(\frac{p_\perp}{q_0}-1\right)\right]\right\}$$

SIDIS - Resummation

$$\gamma_\nu^{f(D)}(p_\perp) = -\Gamma_{\text{cusp}} \frac{1}{\pi\mu^2}\left[\frac{1}{p_\perp^2/\mu^2}\right]_+^{\mathcal{D}_\mu}$$

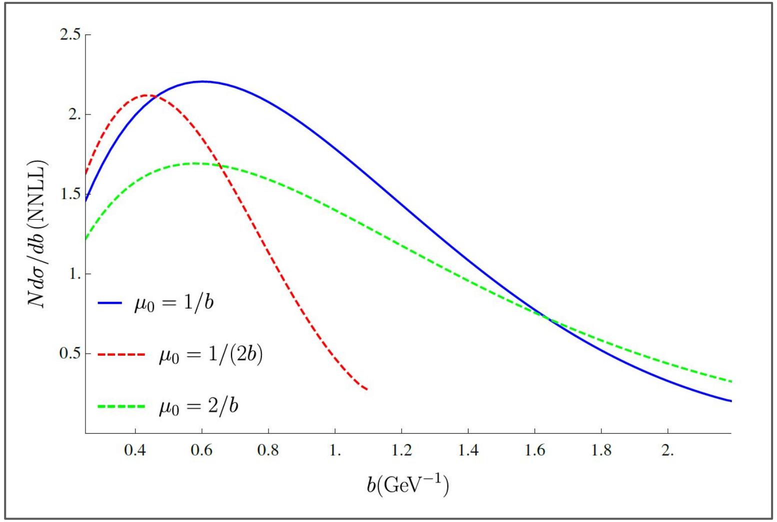
$$\gamma_\nu^{\mathcal{S}}(\ell_\perp) = 2\Gamma_{\text{cusp}} \frac{1}{\pi\mu^2}\left[\frac{1}{\ell_\perp^2/\mu^2}\right]_+^{\mathcal{D}_\mu}$$

$$\tilde{\gamma}_\nu^{f(D)}(\boldsymbol{b};\mu) = \Gamma_{\text{cusp}} \ln\left(b_0^2\mu^2\right)$$

$$\tilde{\gamma}_\nu^{\mathcal{S}}(\boldsymbol{b};\mu) = -2\Gamma_{\text{cusp}} \ln\left(b_0^2\mu^2\right)$$

Minimized at μ = 1/b

$\alpha_s(1/b)$



$Q^2 = 9.2\,\text{GeV}^2$

$$b_* = \frac{b}{\sqrt{1+\frac{b^2}{b_{\text{max}}^2}}}\,.$$

(J. C. Collins, D. E. Soper and G. Sterman) Nucl. Phys. B250 (1985) 199

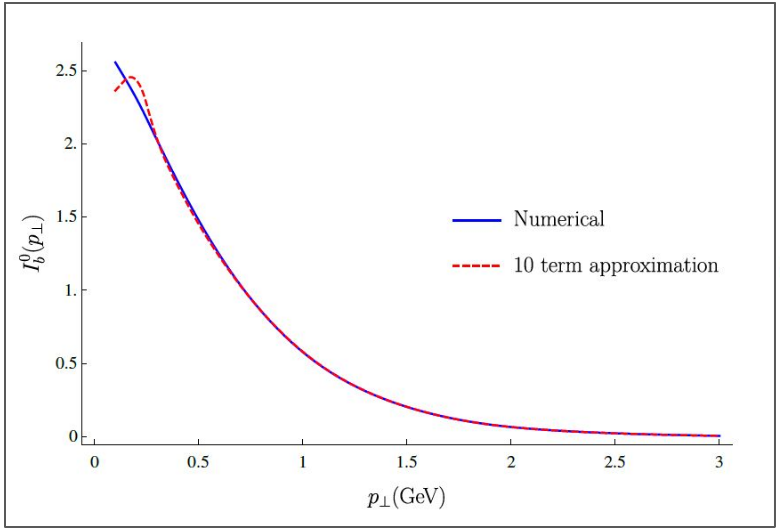
Hybrid Momentum Impact parameter Resummation

arxiv:1710.00078 (D. Kang, C. Lee, V. Vaidya)

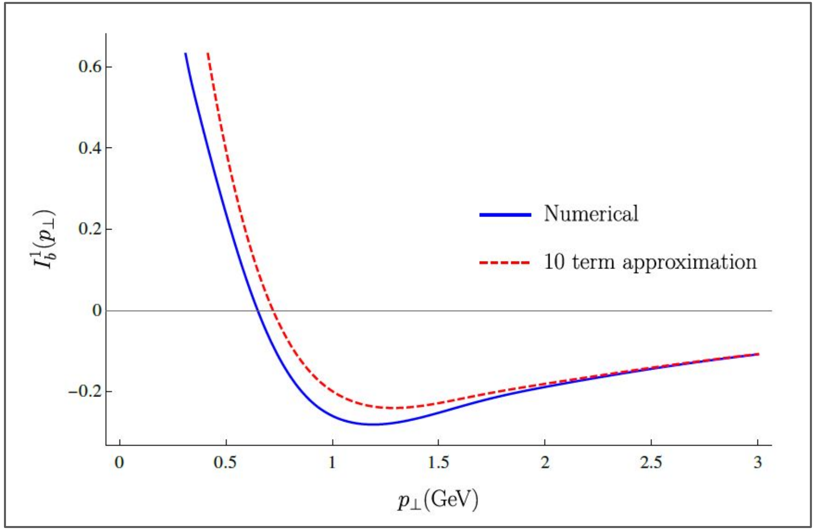
$$I_b^k(p_\perp) \equiv \int_0^\infty dbbJ_0(bp_\perp)\ln^k(\mu_0 b_0)e^{-A\ln^2(\Omega b)}$$

$$\nu_0 \to \nu_0^* = \nu_0(\mu_0 b_0)^{-1+p}, \quad p = \frac{1}{2}\left[1 - \frac{\alpha_s(\mu_0)\beta_0}{2\pi}\ln\left(\frac{\nu_c}{\nu_0}\right)\right]$$

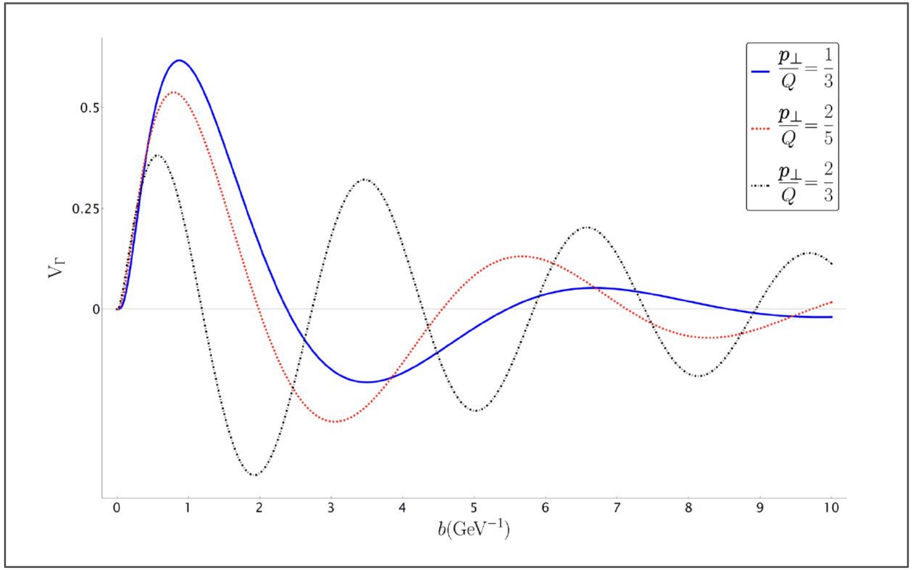
$$V_S^{\rm NLL}(\nu_H, \nu_L^*; \mu_L) = \exp\left\{-\frac{\alpha_s(\mu_L)}{4\pi}4\Gamma_0\ln(\mu_L b_0)\ln\frac{\nu_H}{\nu_L^*}\right\}.$$



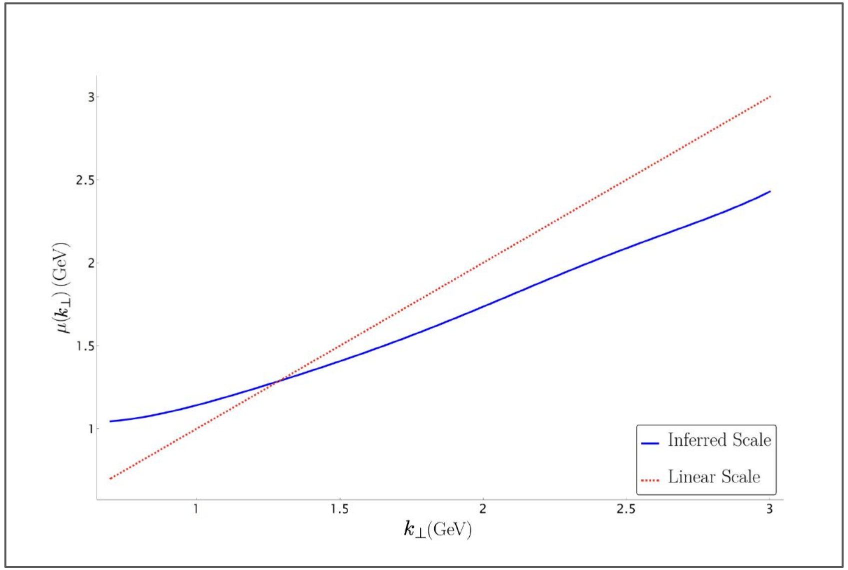
$Q^2 = 9.2\,\mathrm{GeV}^2$



Resummation Cont.



$Q^2 = 9.2\,\mathrm{GeV}^2$



$Q^2 = 9.2\,\mathrm{GeV}^2$

$$\mu_0(p_\perp) \to \mu_0(p_\perp)^{1-\zeta(p_\perp)}\mu_H^{\zeta(p_\perp)}$$
$$\nu_0^*(p_\perp) \to \nu^*(p_\perp)^{1-\zeta(p_\perp)}\nu_H^{\zeta(p_\perp)}$$

$$\zeta(p_\perp) = \frac{1}{2}\left\{1 + \tanh\left[\rho\left(\frac{p_\perp}{q_0} - 1\right)\right]\right\}$$

TMD Nonperturbative Model

$$\tilde{S}(\boldsymbol{b};\mu,\nu) = \tilde{H}_S(\boldsymbol{b};\mu,\nu)\tilde{M}_S(b)$$

$$\tilde{f}_{\perp n}^{(f_1/p)}(x,\boldsymbol{b};\mu_0,\nu) = \int_x^1 \frac{d\xi}{\xi} f^{(f_1/p)}(\xi;\mu)\tilde{H}_f(\frac{x}{\xi},\boldsymbol{b};\mu_0,\mu,\nu)\tilde{M}_f(b)$$

$$\tilde{D}_{\perp n}^{(h/f_2)}(z,\boldsymbol{b};\mu_0,\nu) = \int_z^1 \frac{d\eta}{\eta} D^{(h/f_2)}(\eta;\mu)\tilde{H}_D(\frac{z}{\eta},\boldsymbol{b};\mu_0,\mu,\nu)\tilde{M}_D(b),$$

$$\frac{d\sigma}{dxdydzd^2k_\perp} = \int d^2k'_\perp \frac{d\sigma_W}{dxdydzd^2k'_\perp} M(|\mathbf{k}_\perp - \mathbf{k}'_\perp|) + \frac{d\sigma_Y}{dxdydzd^2k_\perp},$$

$$\tilde{M}(b) = \tilde{N}(x,z)e^{-\lambda(x,z)\frac{b^2}{2}}$$

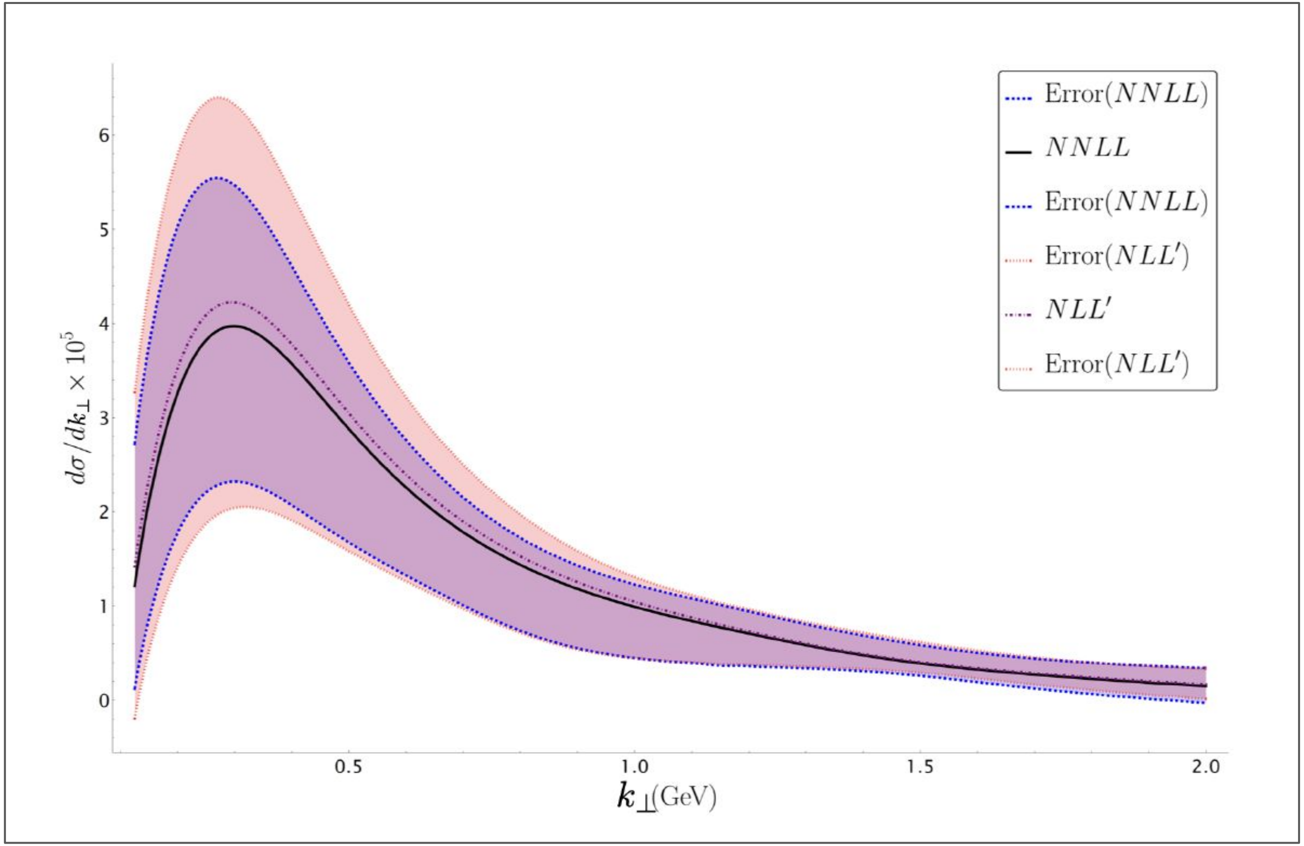
$$\lambda(x,z) = \sigma\left(x + \frac{1}{z} + 1\right)$$

$$\sigma \sim \Lambda_{QCD}$$

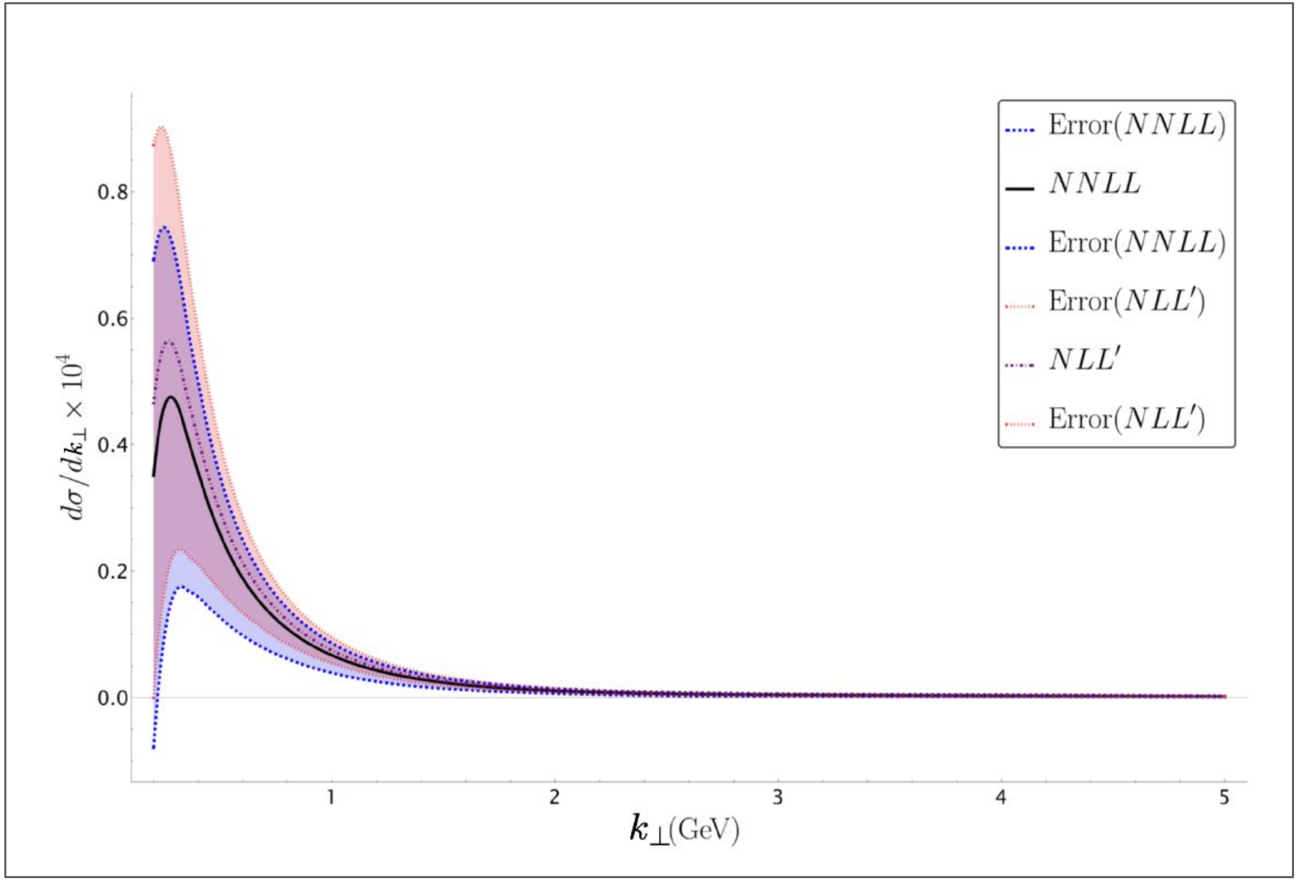
Error Analysis

Parameter	Lower	Central	Upper
q_0	0.65 GeV	1.3 GeV	2.6 GeV
ρ	2.5	5	10
μ_L	1 GeV	$\mu_L(q_\perp)$	$2 \times \mu_L(q_\perp)$
μ_H	$Q/2$	Q	$2Q$
ν_L	$\mu_L(q_\perp)/2$	$\mu_L(q_\perp)$	$2 \times \mu_L(q_\perp)$
ν_c	$Q/2$	Q	$2Q$
N	1.01	1.29	1.57

Prediction Q^2=9.2 GeV^2

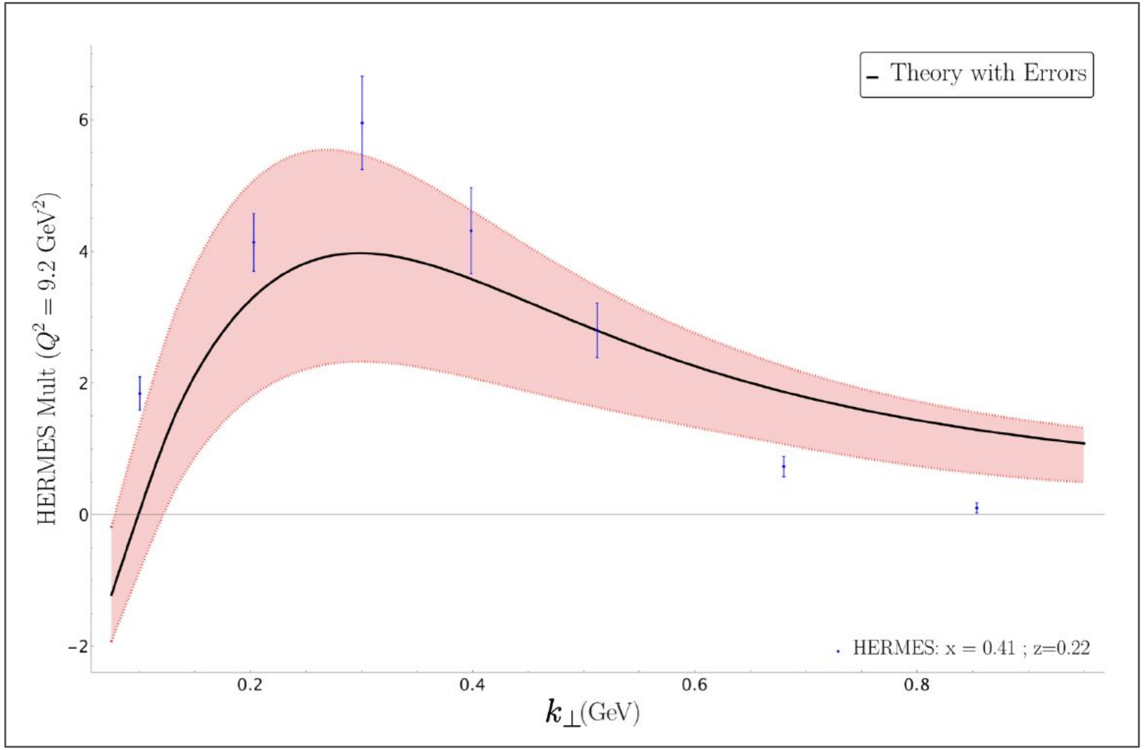


Prediction Q^2=125 GeV^2



HERMES Comparison

- Measures the differential hadron multiplicity for charged pion production
  - SIDIS cross section normalized to the DIS cross section for charged pion production



arXiv:1212.5407 (HERMES Collaboration)

Conclusion

- Hybrid Momentum Impact Parameter resummation provides a way to resum SIDIS without inputting additional nonperturbative physics

- A very simple model can then be used to give moderate results at intermediate qT

- Errors are still large and abundant at intermediate qT

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Supplements

$$f_{\perp n}^{q/p}(\xi, \boldsymbol{p}_\perp) = \frac{1}{2}\sum_{\text{spin}} \langle P_n| \bar{\chi}_n(0)\frac{\bar{\not{n}}}{2}\delta\big(2\bar{n}\cdot P_n\,\xi - \hat{P}_n^+\big)\delta^{(2)}\big(\boldsymbol{p}_\perp - \hat{\boldsymbol{P}}_{n\perp}\big)\chi_n(0)\,|P_n\rangle\ .$$

$$\begin{aligned} &D_{\perp\bar{n}}^{h/q}(z, \boldsymbol{p}_\perp) \qquad\qquad (2.12)\\ &= \frac{1}{2N_c z}\sum_{X_{\bar{n}}}\int d^{-2\epsilon}k_{\perp\epsilon}\,\mathrm{Tr}\,\langle 0|\,\frac{\not{n}}{2}\chi_{\bar{n}}(0)\delta^{(2-2\epsilon)}\big(\hat{\boldsymbol{P}}_{\bar{n}\perp}\big)\delta(\omega - \hat{P}_{\bar{n}}^+)\,|p_{\bar{n},h}X_{\bar{n}}\rangle \\ &\qquad \times \langle p_{\bar{n},h}X_{\bar{n}}|\,\bar{\chi}_{\bar{n}}(0)\,|0\rangle\Big|_{p_{\bar{n},h}=\left(\frac{(p_\perp + k_{\perp\epsilon})^2}{z\omega},\, z\omega,\, p_\perp + k_{\perp\epsilon}\right)} \\ &= \frac{(2\pi)^{3-2\epsilon}}{N_c}\mathrm{Tr}\,\langle 0|\,\frac{\not{n}}{2}\chi_{\bar{n}}(0)\delta^{(2)}\big(\boldsymbol{p}_\perp - \hat{\boldsymbol{P}}_{h,\bar{n}\perp}\big)\delta\left(z - \frac{\hat{P}_{h,\bar{n}}^+}{\omega}\right)\delta(\omega - \hat{P}_{\bar{n}}^+)\delta^{(2-2\epsilon)}\big(\hat{\boldsymbol{P}}_{\bar{n}\perp}\big)\bar{\chi}_{\bar{n}}(0)\,|0\rangle\ , \end{aligned}$$

$$\mathcal{S}_\perp(\boldsymbol{\ell}_\perp) = \frac{1}{N_c}\mathrm{Tr}\,\langle 0|\,\bar{\mathrm{T}}\Big[Y_n^\dagger(0)\tilde{Y}_{\bar{n}}(0)\Big]\delta^{(2)}\big(\boldsymbol{\ell}_\perp - \hat{\boldsymbol{P}}_\perp\big)\mathrm{T}\Big[\tilde{Y}_{\bar{n}}^\dagger(0)Y_n(0)\Big]\,|0\rangle$$