The nonperturbative Contribution to TMD Cross sections in SIDIS

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Outline

Background and motivation

- Polarized and unpolarized cross sections in TMD factorization
- Large and small transverse momentum

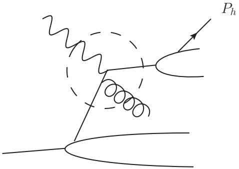
Recent progress and next steps

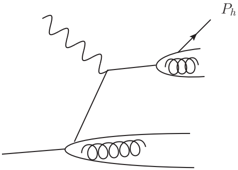
- Phenomenology
- Issues

TMD physics at different q_T

$$q_T \gtrsim Q$$

$$q_T \sim \Lambda_{\mathrm{QCD}}$$

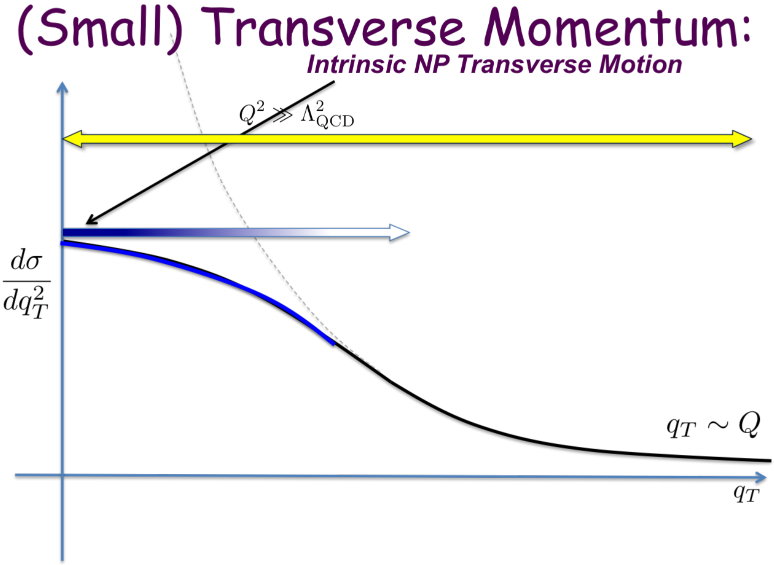




Pert. approx.
Coll. Factorization

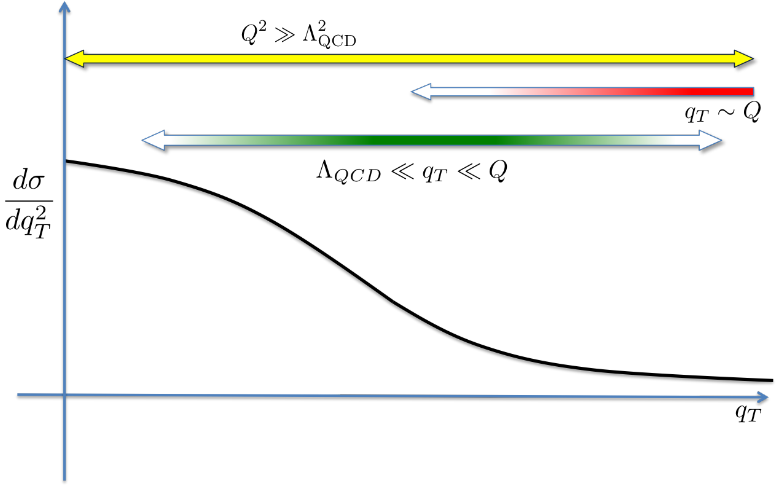
Small q_T approx.
TMD Factorization

Physics at different q_T

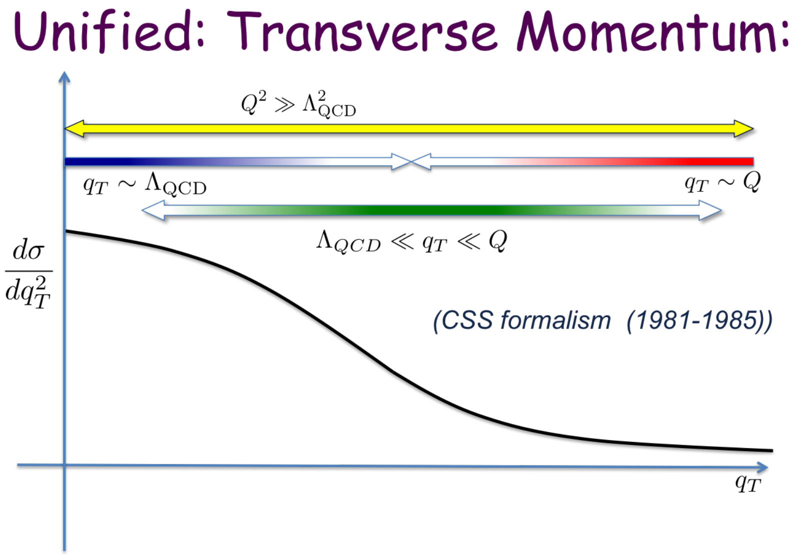


Physics at different q_T

(Large) Transverse Momentum:



Physics at different q_T



Structure of TMD cross sections

$$\begin{aligned}\Gamma &= \mathbf{T}_{\rm TMD}\Gamma + \left[\Gamma - \mathbf{T}_{\rm TMD}\Gamma\right] \\ &\approx \underbrace{\mathbf{T}_{\rm TMD}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\rm coll}\left[\Gamma - \mathbf{T}_{\rm TMD}\Gamma\right]}_{\mathbf{Y}}\end{aligned}$$

$\Gamma =$ Cross section

$\mathbf{T}_{TMD} =$ Small q_T approximant

$\mathbf{T}_{\rm coll} =$ Large q_T approximant corrections

Structure of TMD cross sections

Cross section

$$\begin{aligned}\Gamma &= \mathbf{T}_{\rm TMD}\Gamma + [\Gamma - \mathbf{T}_{\rm TMD}\Gamma] \\ &\approx \underbrace{\mathbf{T}_{\rm TMD}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\rm coll}\,[\Gamma - \mathbf{T}_{\rm TMD}\Gamma]}_{\mathbf{Y}}\end{aligned}$$

$\mathbf{W}$: $q_T \ll Q$
$\mathbf{Y}$: $q_T \sim Q$
$\mathbf{W}+\mathbf{Y}$:
$\Lambda_{QCD} < q_T \lesssim Q$

Why study the $\mathbf{W}$ $\rightarrow$ Nucleon structure

- TMD PDFs (flavor dependence)
- Spin dependent effects
- Non-perturbative evolution
- Contains perturbative contribution

Role of $\mathbf{Y}$ term

- Calculable in pQCD
- Needed to identify non-perturbative effects

Interplay between $\mathbf{W}$ and $\mathbf{Y}$

Cross section

$$\Gamma = \mathbf{T}_{\mathrm{TMD}}\Gamma + [\Gamma - \mathbf{T}_{\mathrm{TMD}}\Gamma]$$
$$\approx \underbrace{\mathbf{T}_{\mathrm{TMD}}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\mathrm{coll}}\left[\Gamma - \mathbf{T}_{\mathrm{TMD}}\Gamma\right]}_{\mathbf{Y}}$$

Region of $\mathbf{q_T} \ll \mathbf{Q}$

- TMD approx. dominates $\rightarrow$ $\Gamma \approx \mathbf{T}_{\mathrm{TMD}}\Gamma$
- Y term small

Region of $\mathbf{q_T} \sim \mathbf{Q}$

- Collinear approx. dominates $\rightarrow$ $\Gamma \approx \mathbf{T}_{\mathrm{coll}}\Gamma$
- Consistency demands $\rightarrow \mathbf{T}_{\mathrm{TMD}}\Gamma - \mathbf{T}_{\mathrm{coll}}\mathbf{T}_{\mathrm{TMD}}\Gamma \sim$ Small

Perturbative and nonperturbative QCD

Complementary

- One has universal properties: hadron structure and fragmentation
- Other is directly computable, can give high precision

Pert. calculations need non-perturbative input (e.g., W boson mass extraction)

Non-perturbative extractions need isolation of pert./non-pert parts.

Polarized and unpolarized TMD physics

TMD evolution

- Nonperturbative component
- Strongly universal, same for unpolarized and polarized TMDs

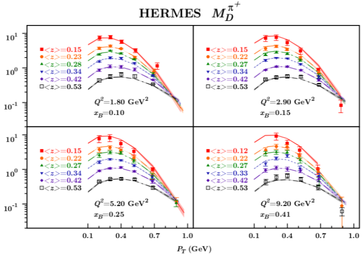
Phenomenology in SIDIS

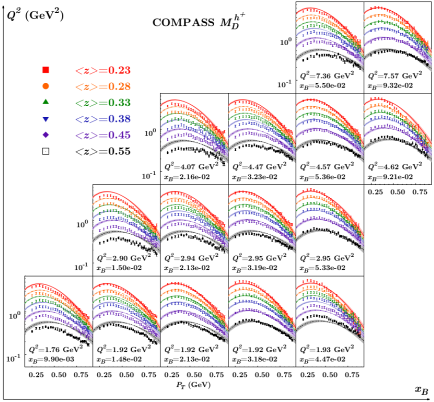
Qualitative success with Gaussians: $\rightarrow$Anselmino *et al.*

HERMES $\rightarrow$

Points: ~ 497

$\chi^2_{dof} = 1.69$





$\leftarrow$**COMPASS**

Points: ~ 5385

$\chi^2_{dof} = 8.54$

$$M \propto \sum_q f_{q/p}(x_B) D_{h/q}(z_h) \frac{e^{-P_T^2/\langle P_T^2 \rangle}}{\pi \langle P_T^2 \rangle}$$

Questions to address

How important is TMD evolution at low Q?

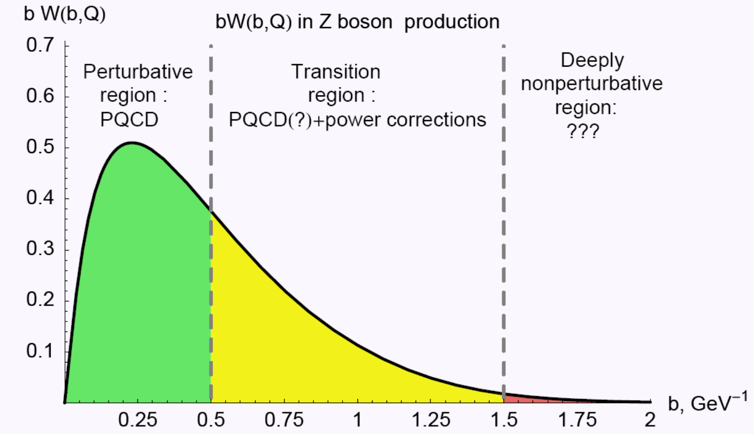
Can we consistently use a Y term in fits that include low Q?

- Nadolsky et al,1999. Energy flow/HERA

Do nonperturbative parts prefer Gaussian or exponential large b_T dependence? Schweitzer et al. 2012 $\rightarrow \sim e^{-mb_T}$

Treatment of $\mathbf{W}$

$$W(q_T, Q) = \int \frac{d^2\mathbf{b}_T}{(2\pi)^2} e^{i\mathbf{q}_T\cdot\mathbf{b}_T} \tilde{W}(\mathbf{b}_T, Q)$$



Parameterization of $\mathbf{W}$

In TMD factorization $\tilde{W}$ takes the form

$$\begin{aligned}\tilde{W}(b_T, Q) = &\sum_j H_{jj}(\mu_Q, Q)\tilde{F}_j(x, b_T, Q_0^2, \mu_{Q_0})\tilde{D}_j(z, b_T, Q_0^2, \mu_{Q_0} l) \\ &\times E^P(b_*(b_T), Q)E^{NP}(b_T, Q)\end{aligned}$$

At some input scale Q_0, the nonperturbative part of TMD PDF and FF are parameterized with a power law function in q_T space

$$F^{NP}(q_T, x, Q_0^2, \mu_{Q_0}) \to \mathcal{K}(q_T) = \frac{C}{(q_T^2 + m^2)^\nu}$$

The nonperturbative evolution factor is parameterized as

$$\begin{aligned}E^{NP}(b_T, Q) =& e^{-2g_K(b_T, b_{max})\ln(Q/Q_0)} \\ g_K(b_T; b_{max}) =& g_0(b_{max})\left(1 - \exp\left[-\frac{C_F \alpha_s(\mu_{b_*}) b_*^2(b_T)}{\pi g_0(b_{max})\, b_{max}^2}\right]\right)\end{aligned}$$

(Collins and Rogers, 2014)

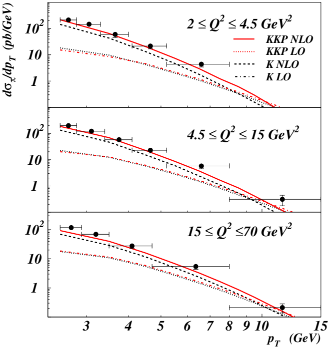
Accuracy of $\mathbf{Y}$

Region of $\mathbf{q_T \ll Q}$

- not important, the region is dominated by $\mathbf{W}$

Region of $\mathbf{q_T \gtrsim Q}$

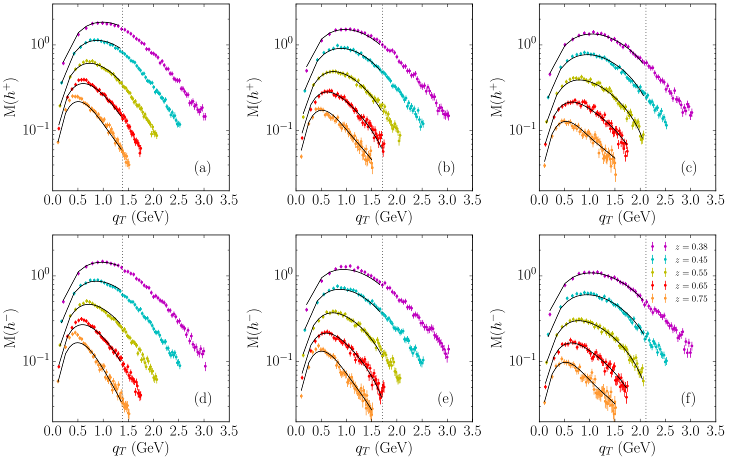
- important high order corrections needed to describe data. Due to lack of NLO perturbative terms we cut large q_T region in our study.



Perturbative cross section in SIDIS.
A. Daleo et al., *etal* (2004)

Baseline fit of COMPASS with power law (Preliminary)

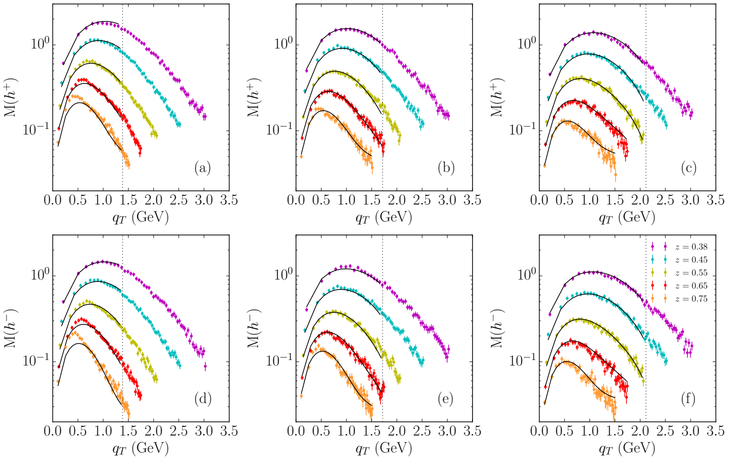
$$M(x,Q^2,z,P_T) \equiv \frac{1}{\frac{d^2\sigma^{DIS}(x,Q^2)}{dxdQ^2}} \frac{d^4\sigma(x,Q^2,z,P_T)}{dxdQ^2dzdP_T}, P_T = zq_T$$



$$x = 0.03, Q^2 = 1.92, 2.95, 4.47\text{GeV}^2$$

Baseline fit of COMPASS with Gaussian (Preliminary)

$$M(x,Q^2,z,P_T) \equiv \frac{1}{\frac{d^2\sigma^{DIS}(x,Q^2)}{dxdQ^2}} \frac{d^4\sigma(x,Q^2,z,P_T)}{dxdQ^2dzdP_T}, P_T = zq_T$$



$$x = 0.03, Q^2 = 1.92, 2.95, 4.47\text{GeV}^2$$

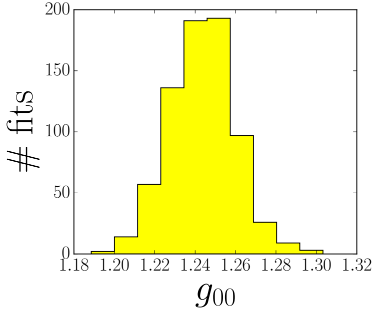
Baseline fit of COMPASS (Preliminary)

Power law fit

g_0	χ^2_{dof}	# pts
1.24	0.995	1042

Gaussian fit

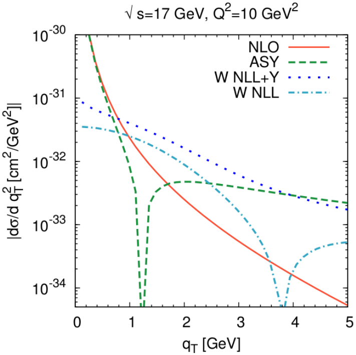
g_0	χ^2_{dof}	# pts
1.19	1.364	1042



- g_0 parameter for NP evolution
- Stability is good evidence for strong universality

Matching at large q_T

$$\Gamma = \mathbf{T}_{\mathrm{TMD}}\Gamma + [\Gamma - \mathbf{T}_{\mathrm{TMD}}\Gamma]$$
$$\approx \underbrace{\mathbf{T}_{\mathrm{TMD}}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\mathrm{coll}}\,[\Gamma - \mathbf{T}_{\mathrm{TMD}}\Gamma]}_{\mathbf{Y}}$$



M. Boglione, J. Gonzalez. H. *etal* (2014)

At large Q

- $W = \mathbf{T}_{\mathrm{TMD}}\Gamma$ is mostly perturbative
- broader region where W overlaps with its perturbative approximation
- matching is almost automatic

The difficulty at small Q

- W dominated by NP contributions
- Smooth transition occurs between the NP, and a perturbative part.
- Parameterize W itself : difficult, under study,
  e.g. $\int dq_T \frac{d\sigma}{dQ^2 dq_T dx dz} = \frac{d\sigma}{dQ^2 dx dz}$

Summary

- ✓ Can we do fits including Y term?
- ✓ Strong universal NP evolution
- ✓ Large b_T behavior $\sim e^{-mb_T}$

Next

- $q_T > Q$?
- $O(\alpha_S^2)$ Y term

Backup slides

Parameterize the nonperturbative contribution

Use variable b_* to freeze perturbative contribution at large b_T

$$b_*(b_T) = \begin{cases} b_T & b_T \ll b_{max} \\ b_{max} & b_* \gg b_{max} \end{cases}$$

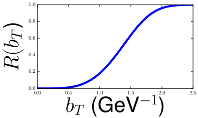
Normally, $\tilde{W}$ is parameterized as

$$\tilde{W}(b_T, Q) = \tilde{W}(b_*(b_T), Q)\tilde{W}_{NP}(b_T, Q)$$

Our parameterization is

$$\tilde{G}(b_T, Q) = \tilde{G}^{NP}(b_T, Q)R(b_T) + \tilde{G}(b_*(b_T), Q)(1 - R(b_T))$$

where G stands for TMD PDF or FF
and R is a switching function $\rightarrow$



Baseline fit of COMPASS (Preliminary)

$$\Gamma =\approx \underbrace{\mathbf{T}_{\rm TMD}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\rm coll}\left[\Gamma - \mathbf{T}_{\rm TMD}\Gamma\right]}_{\mathbf{Y}}$$