Describing Unpolarized SIDIS data at order α_s

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Outlook

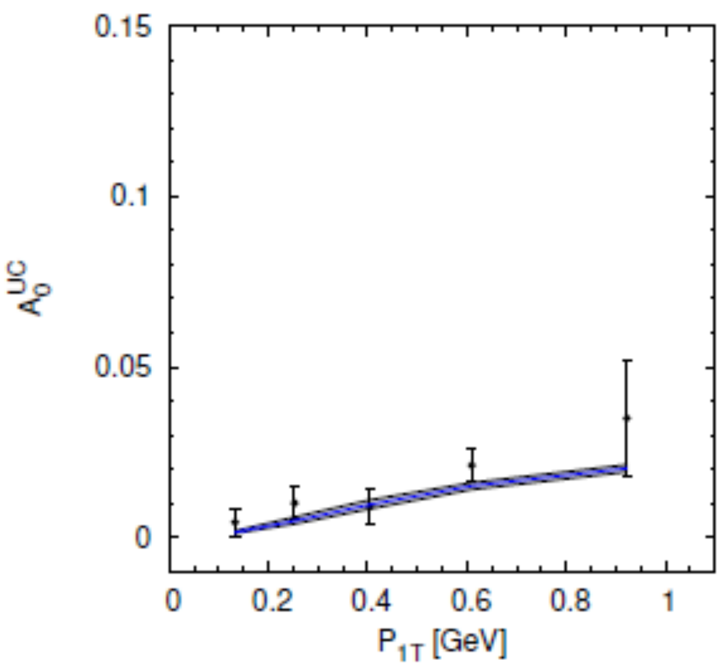
- Importance of unpolarized functions
- Some challenges extracting unpolarized functions from SIDIS
- Signals of non-perturbative dominance
- Testing the kinematics where factorization theorems hold.

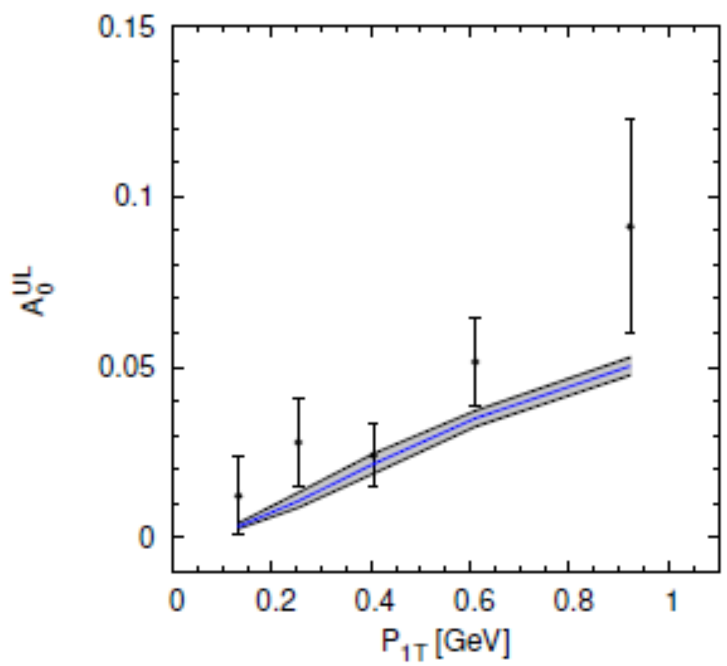
TMD physics, rich phenomenology.

Gateway to 3D structure of hadrons

e^+e^- double ratios (Collins function)

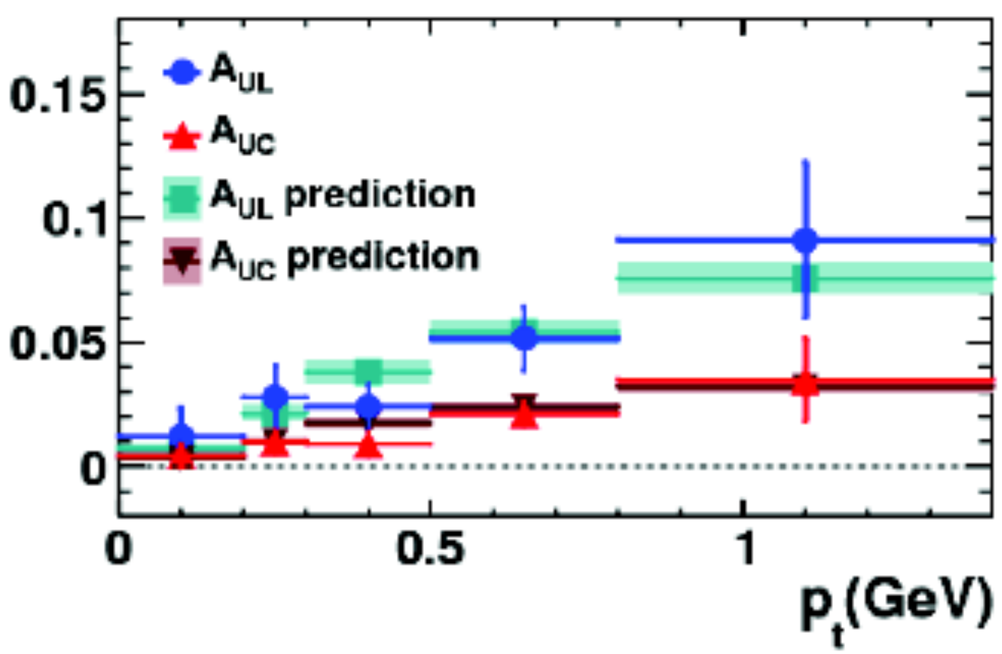
Q^2 = 13 GeV^2





Predictions for BES III

Simple gaussian picture



Picture within QCD-factorization

Kang, Prokudin, Sun, Yuan

Phys.Rev. D93 (2016) no.1, 014009
arXiv:1505.05589 [hep-ph] JLAB-THY-15-2044

Input needed : Unpolarized functions

$e^+e^- \to \pi\,\pi\,X$

Unpolarized TMDFF **Collins TMDFF**

$$\frac{d\sigma^{e^+e^-\to h_1 h_2 X}}{dz_1\,dz_2\,d^2\boldsymbol{P}_{1T}\,d\cos\theta_2} = \frac{3\pi\alpha^2}{2s}\left\{D_{h_1\,h_2} + N_{h_1\,h_2}\cos 2\phi_1\right\}$$

$$P_0^{U,L,C} = \frac{N^{U,L,C}}{D^{U,L,C}}$$

Ratio

$$D^U = D_{\pi^+\,\pi^-} + D_{\pi^-\,\pi^+} \qquad N^U = N_{\pi^+\,\pi^-} + N_{\pi^-\,\pi^+}$$

$$D^L = D_{\pi^+\,\pi^+} + D_{\pi^-\,\pi^-} \qquad N^L = N_{\pi^+\,\pi^+} + N_{\pi^-\,\pi^-}$$

$$D^C = D^U + D^L \qquad N^C = N^U + N^L\,,$$

$$\frac{A_0^U}{A_0^{L(C)}} \equiv 1 + \cos(2\phi_1)\,A_0^{UL(C)}$$

Double Ratio

SIDIS

$$\frac{d\sigma^{\ell(S_\ell)+p(S)\to\ell' hX}}{dx_B dQ^2 dz_h d^2\boldsymbol{P}_T d\phi_S} =$$

$$\frac{2\alpha^2}{Q^4}\left\{\frac{1+(1-y)^2}{2}F_{UU} + \quad \ldots\right.$$

$$\left. + S_T(1-y)(\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}\right\}.$$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim \frac{F_{UT}^{\sin(\phi_h+\phi_S)}}{F_{UU}}$$

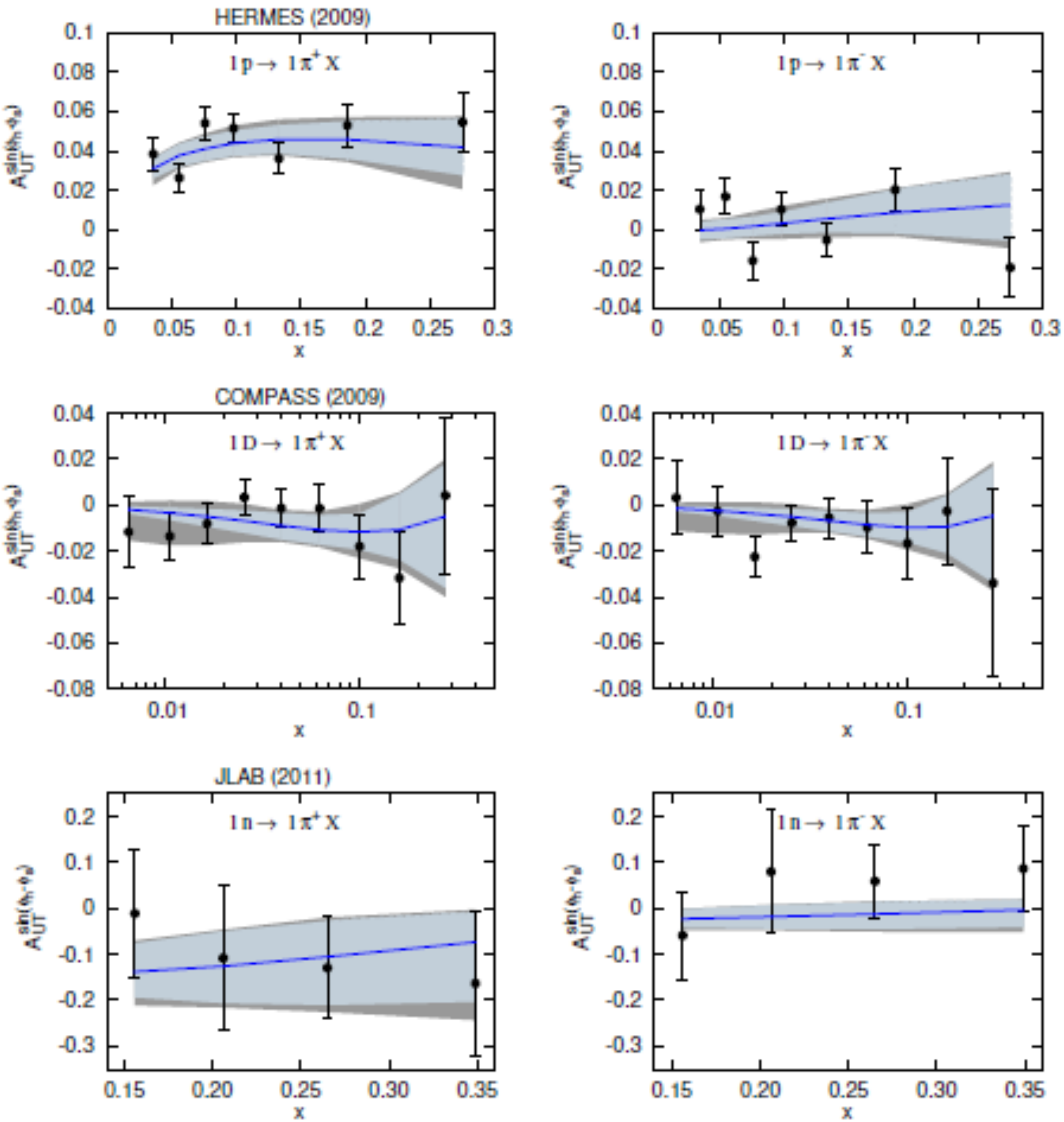
Ratio

Unpolarized TMDFF &TMDPDF

TMD Transversity & Collins function

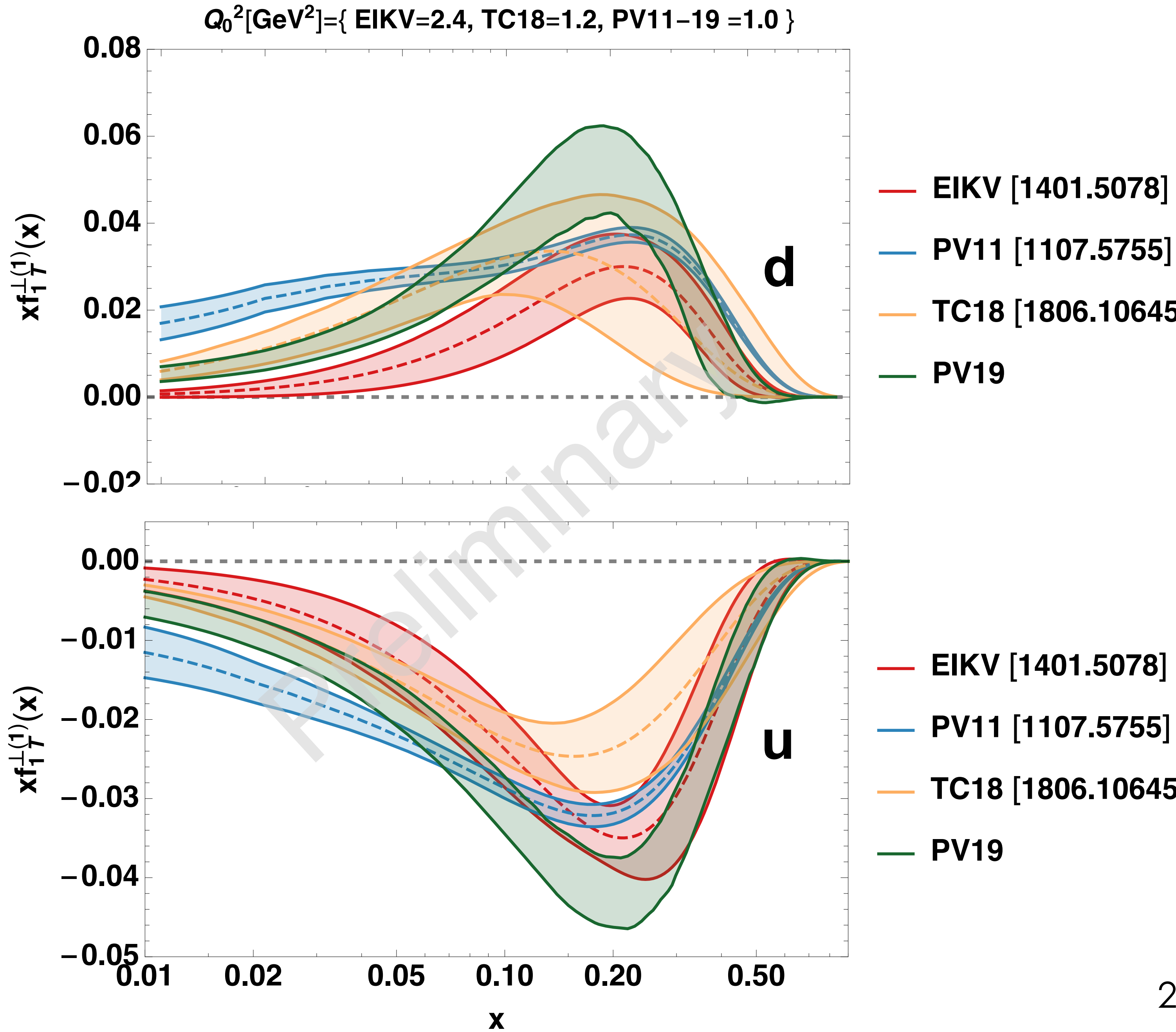
SIDIS Sivers Asymmetry

Unpolarized Functions needed as input



Results comparison

Differences partly due to different assumptions on unpolarized functions, not necessarily from type of picture, i.e.
Gaussian Ansatz
CSS
SCET…



Slide by Filippo Delcarro (JLAB)
-QCD evolution 2019-

How well can we extract unpolarized TMDs from SIDIS data? (challenges)

Theoretical Framework: Factorization theorems

W **(TMD region)**

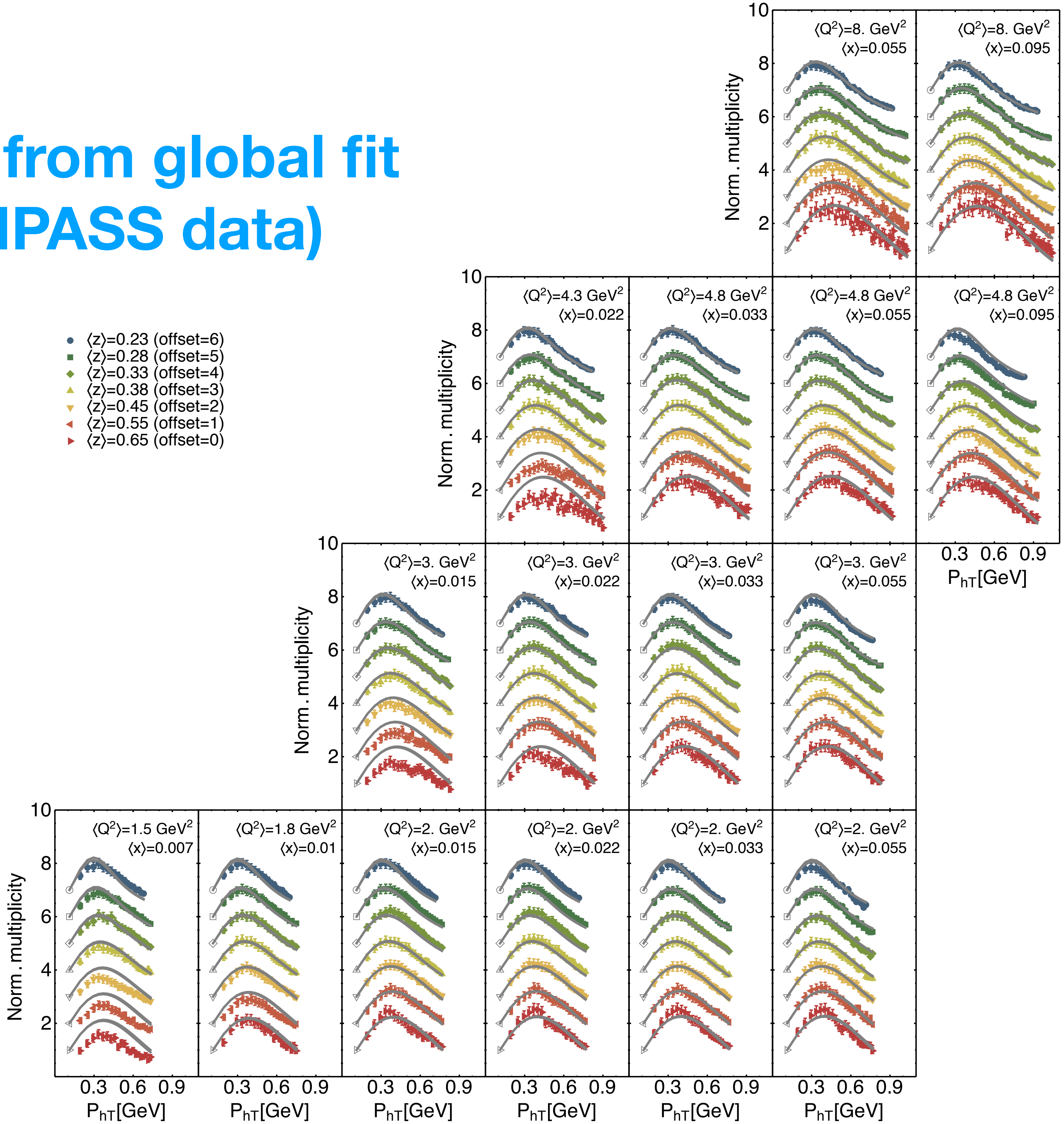
$$\sum_q \mathcal{H}_q \text{ F.T.} \left\{ \tilde{D}_{h/q}(z, z\,\boldsymbol{b}_\perp; Q)\ \tilde{f}_{q/P}(x, \boldsymbol{b}_\perp; Q) \right\}$$

Fourier Transform of:

$$\tilde{F}_j(x, b_T, Q, \zeta_F) = \left(\frac{\sqrt{\zeta_F}}{\mu_b} \right)^{\tilde{K}(b_*, \mu_b)} \sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{ji}^{in}(x/\hat{x}, b_*, \mu_b, \mu_b^2) f_i(\hat{x}, \mu_b)$$
$$\times \exp\left\{ \int_{\mu_b}^{Q} \frac{d\mu}{\mu} \left(\gamma_F(\mu; 1) - \ln\left(\frac{\sqrt{\zeta_F}}{\mu} \right) \gamma_K(\mu) \right) \right\}$$
$$\times \exp\left\{ -g_P(x, b_T) - g_K(b_T) \ln\left(\frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F0}}} \right) \right\},$$

- (blue line) pQCD
- (green line) Input (extraction from collinear cross section)
- (red line) Non-perturbative functions to extract from data.

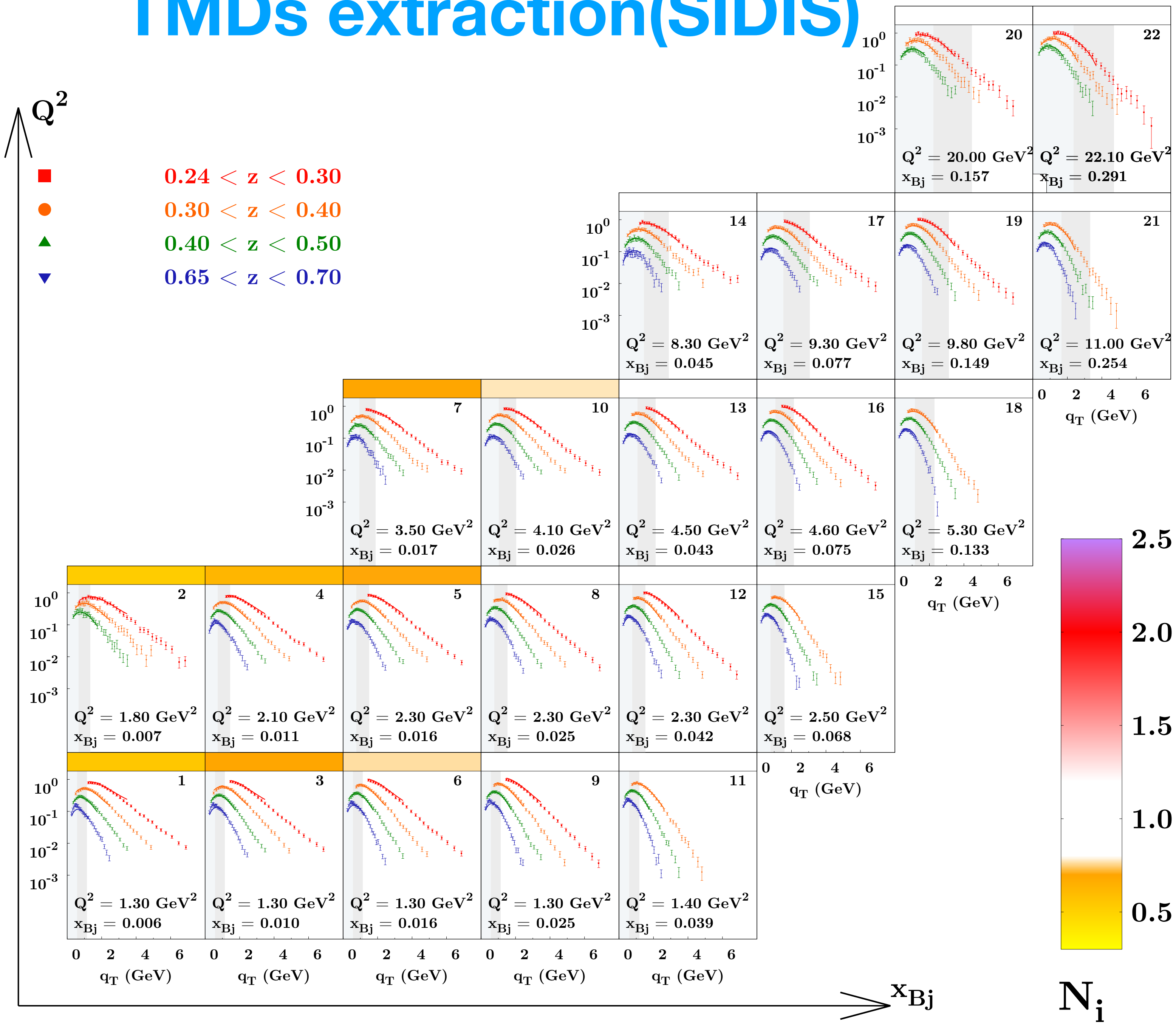
Example: extraction from global fit (2013 COMPASS data)

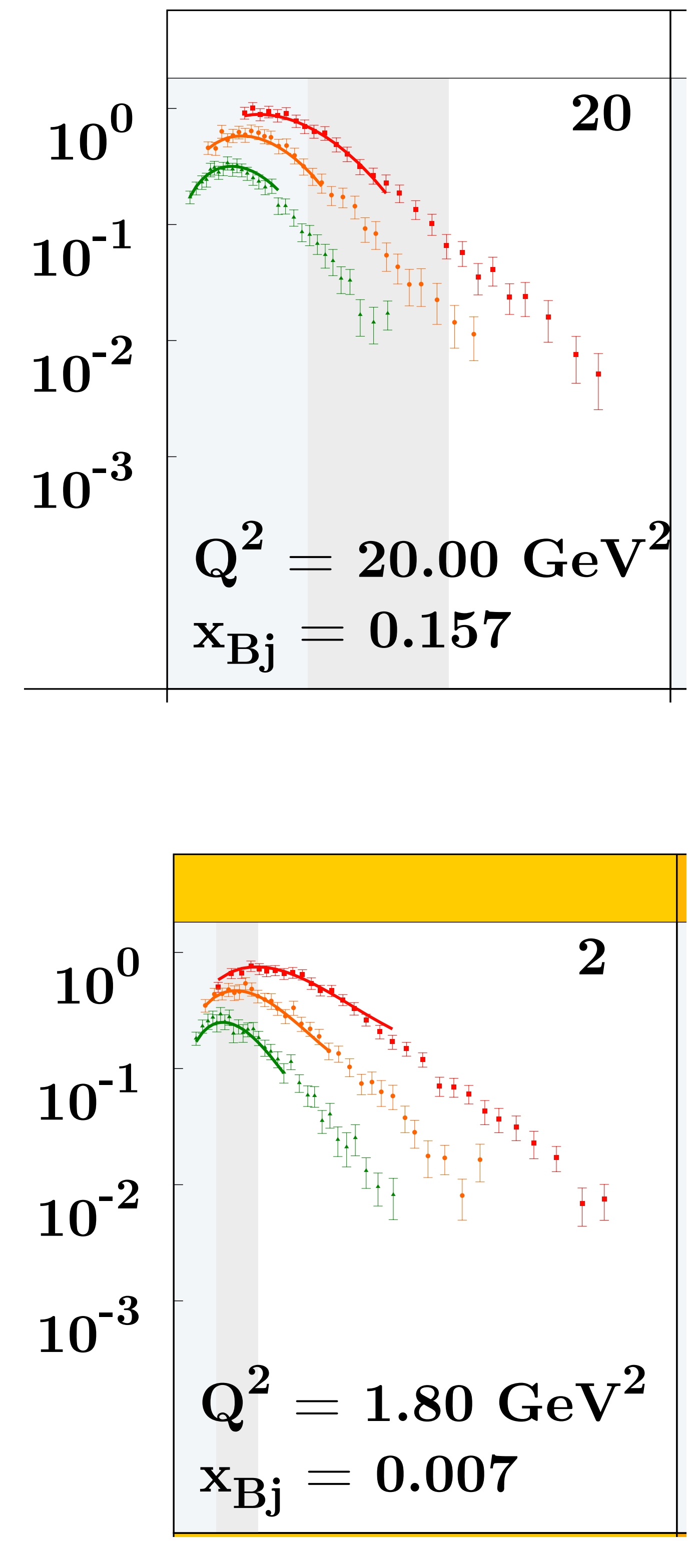


Bacchetta, Delcarro, Pisano, Radici, Signori
JHEP 1706 (2017) 081

Some issues with unpolarized TMDs extraction(SIDIS)

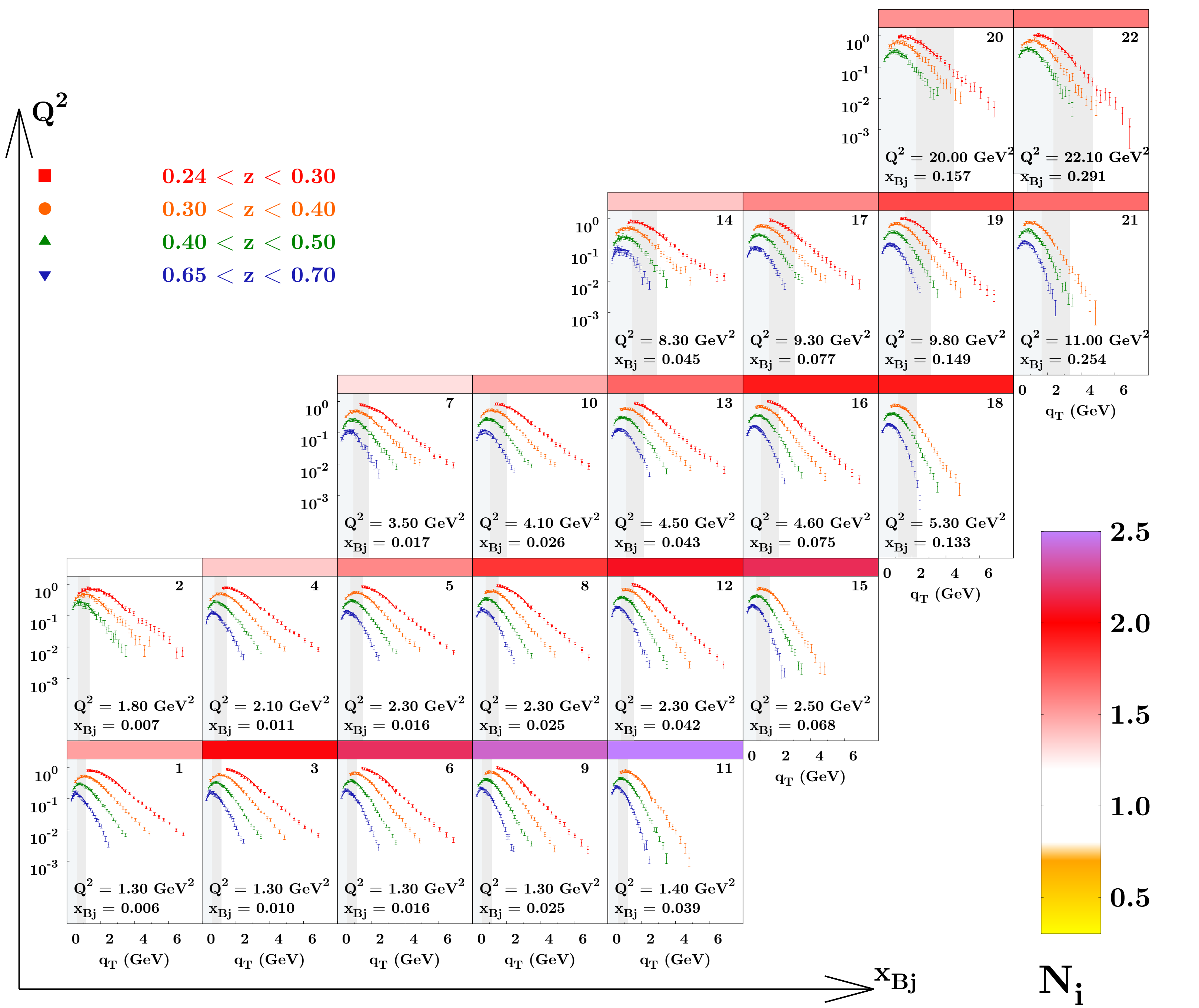
$$\mathcal{O}(\alpha_s^0)$$

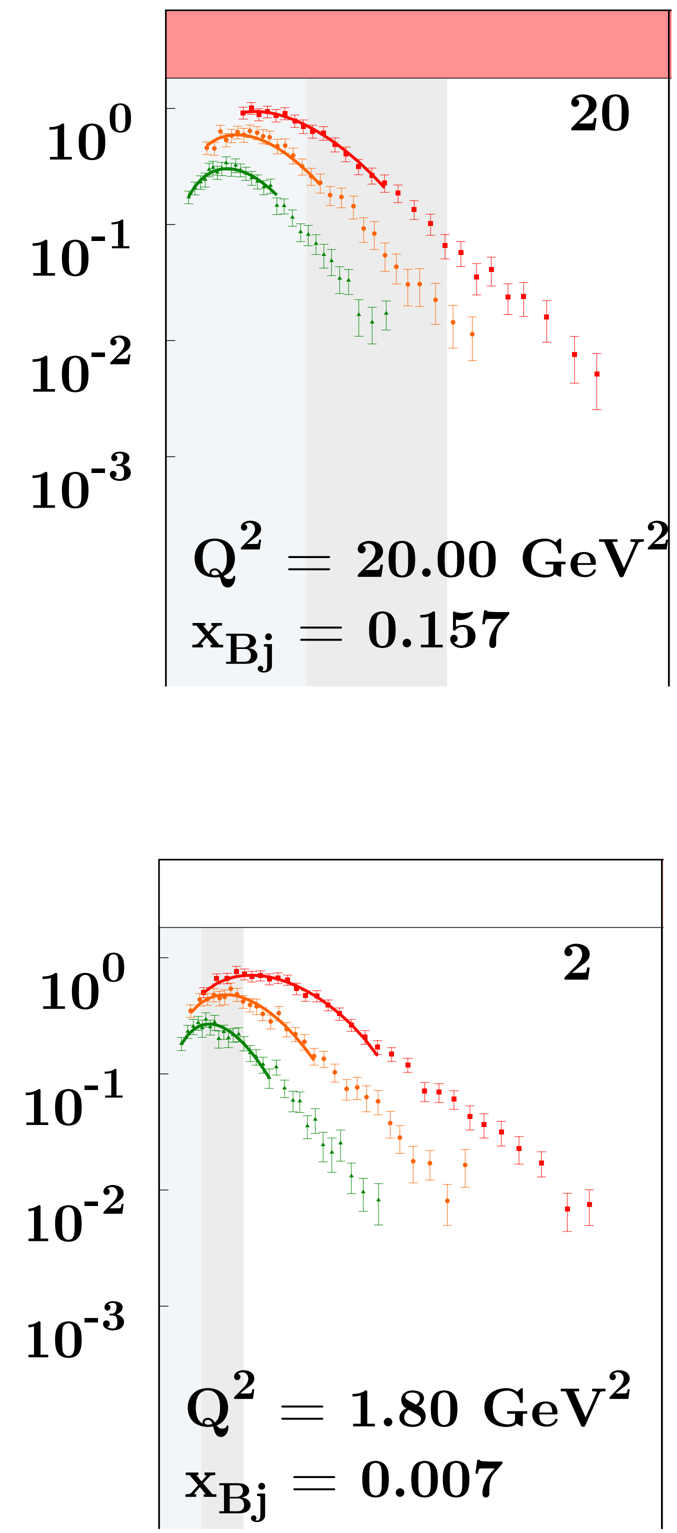




$$\tilde{F}_j = f(x, \mu_b) \exp\left\{ g_P(x, b_T) - g_K(b_T) \ln\left(\frac{Q}{Q_0}\right) \right\}$$

$\mathcal{O}(\alpha_s)$

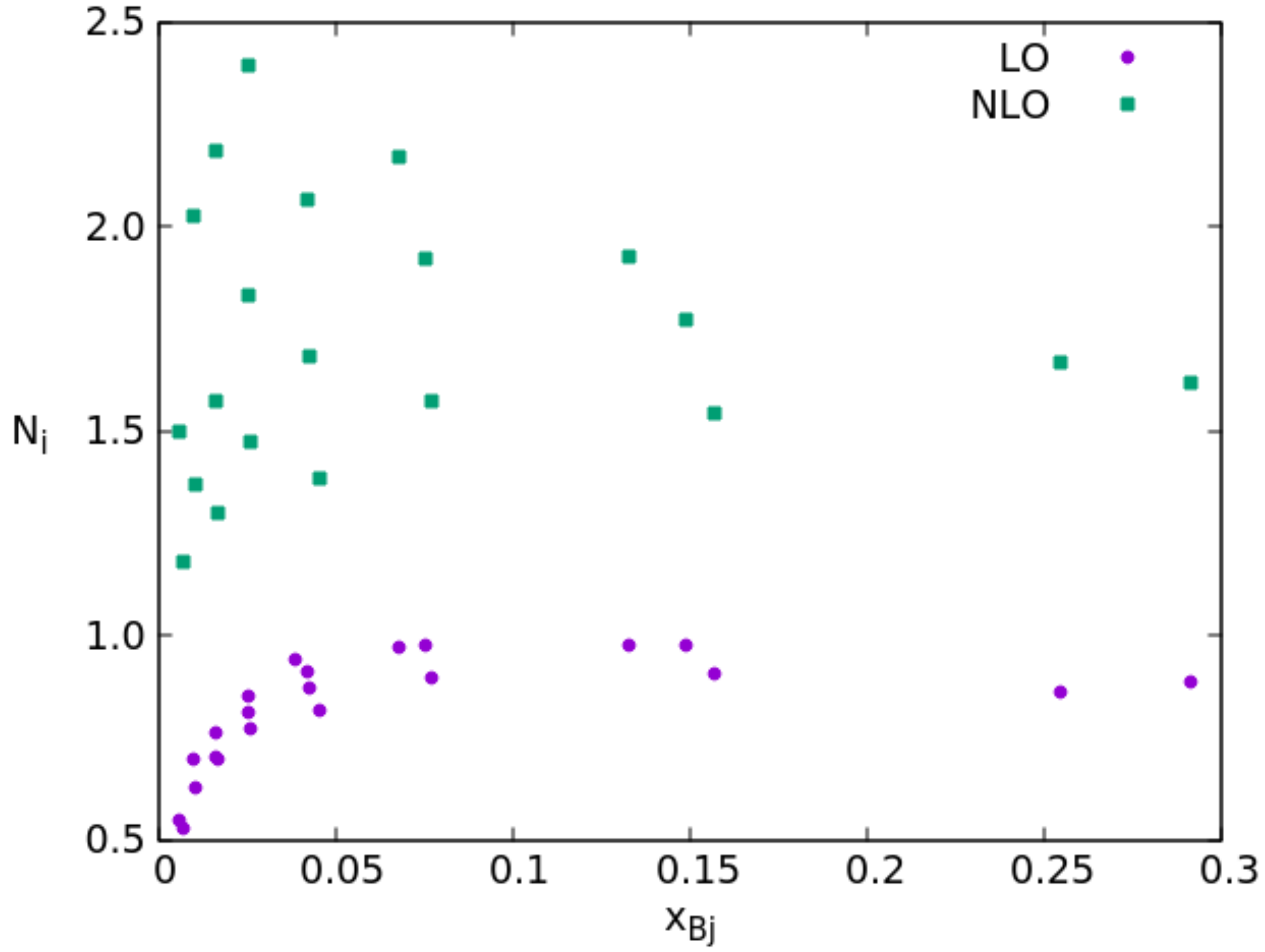




$$
\begin{aligned}
\tilde{F}_j(x, b_T, Q, \zeta_F) = {} & \left(\frac{\sqrt{\zeta_F}}{\mu_b}\right)^{\tilde{K}(b_*,\mu_b)} \sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}^{in}_{ji}(x/\hat{x}, b_*, \mu_b, \mu_b^2) f_i(\hat{x}, \mu_b) \\
& \times \exp\left\{ \int_{\mu_b}^{Q} \frac{d\mu}{\mu} \left(\gamma_F(\mu; 1) - \ln\left(\frac{\sqrt{\zeta_F}}{\mu}\right) \gamma_K(\mu) \right) \right\} \\
& \times \exp\left\{ -g_P(x, b_T) - g_K(b_T) \ln\left(\frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F0}}}\right) \right\} ,
\end{aligned}
$$

Some challenges:

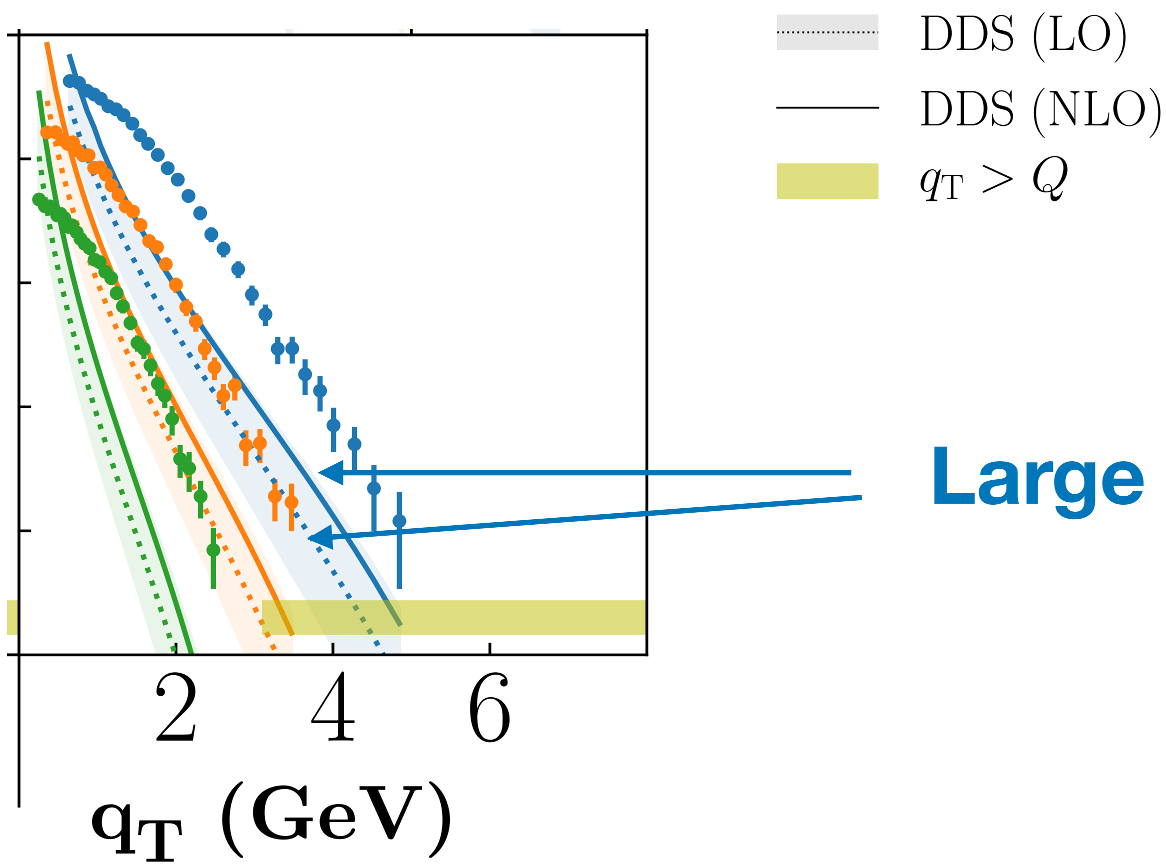
Large (spurious) normalizations have to be introduced to described data



A bit counter-intuitive

Some challenges:

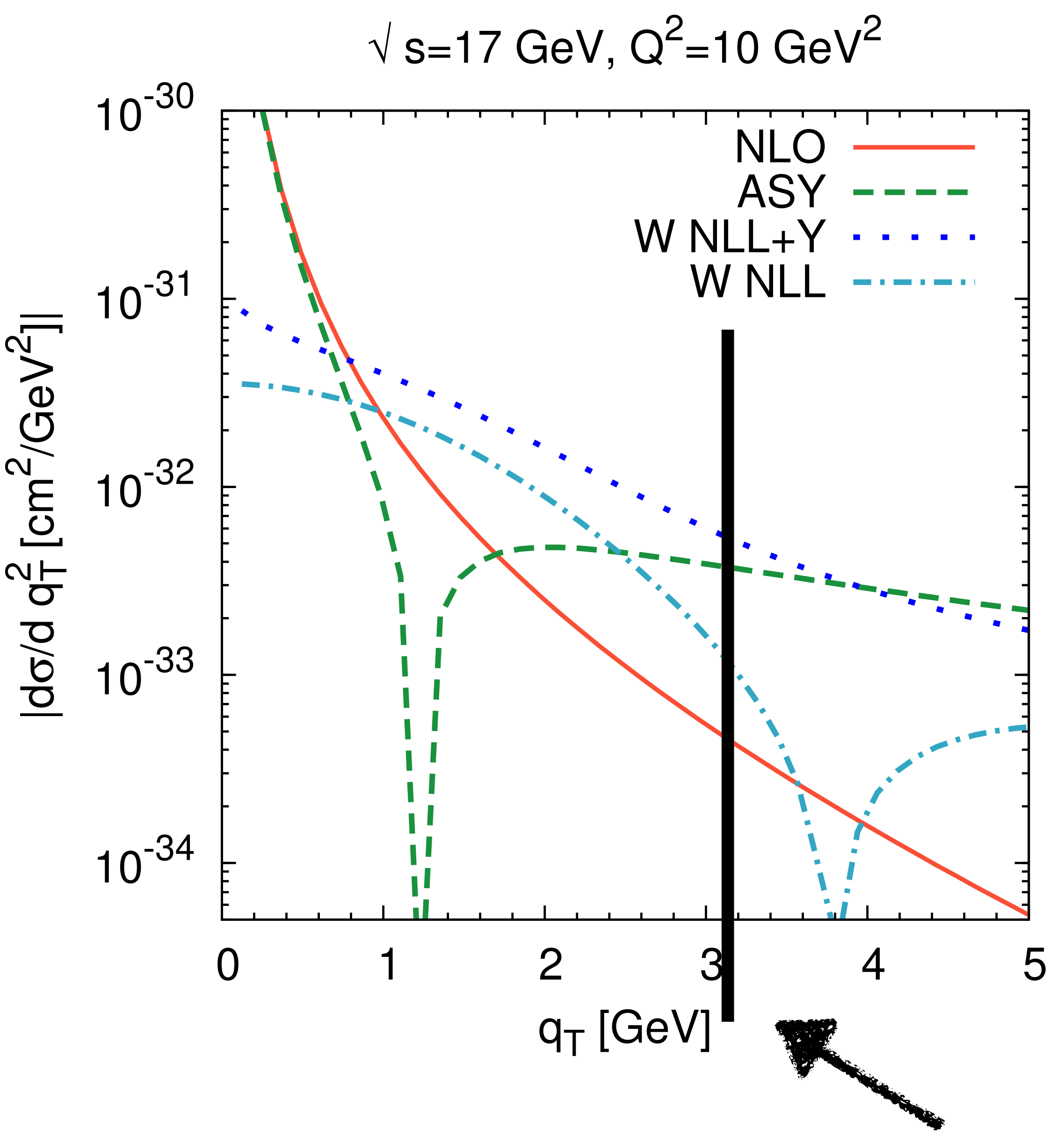
Large qT region cannot be described with modern Collinear PDF sets



Large K factors

Some challenges:

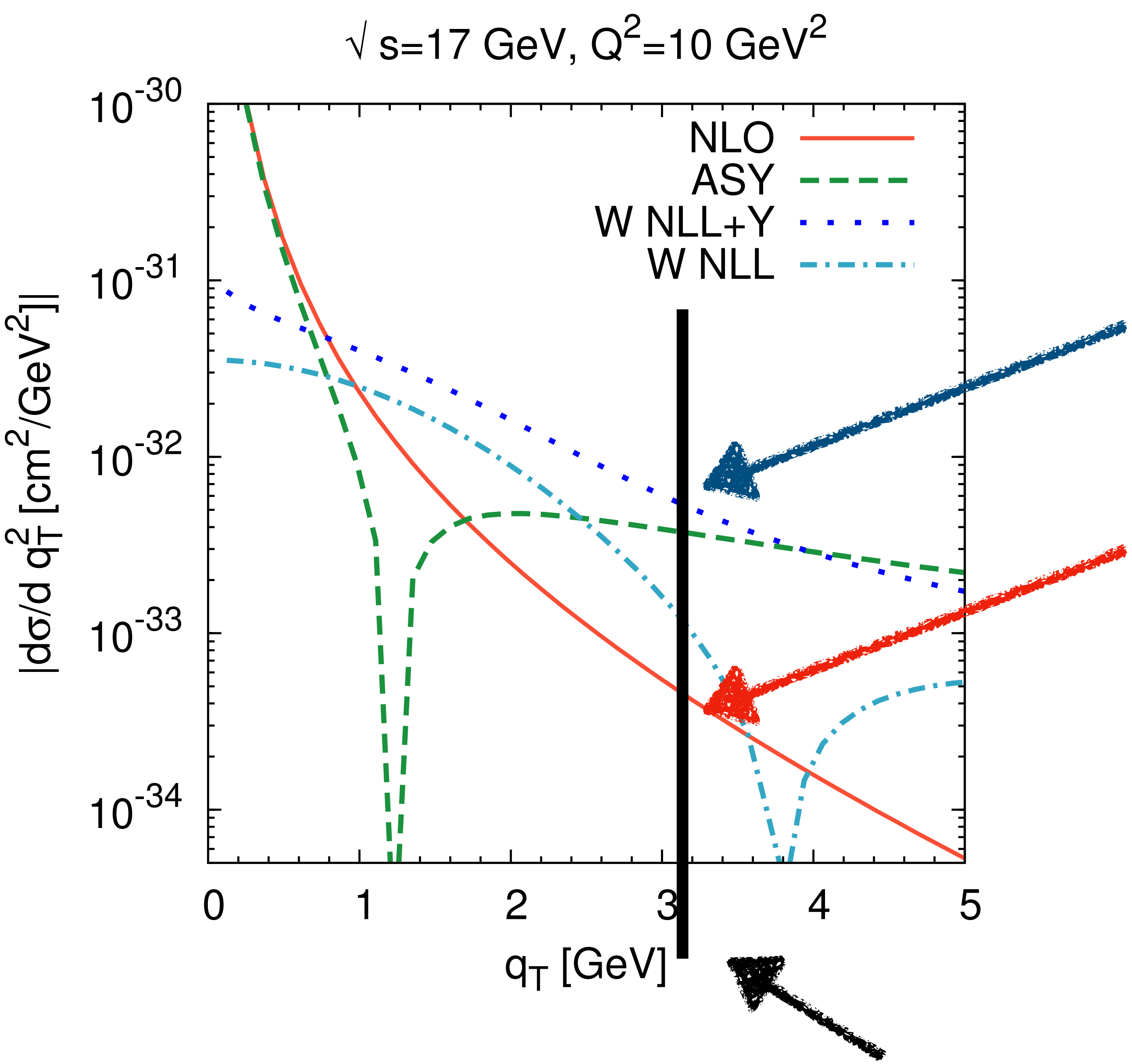
Matching between small and large qT regions



Matching region qT ~ Q

Some challenges:

Matching between small and large qT regions



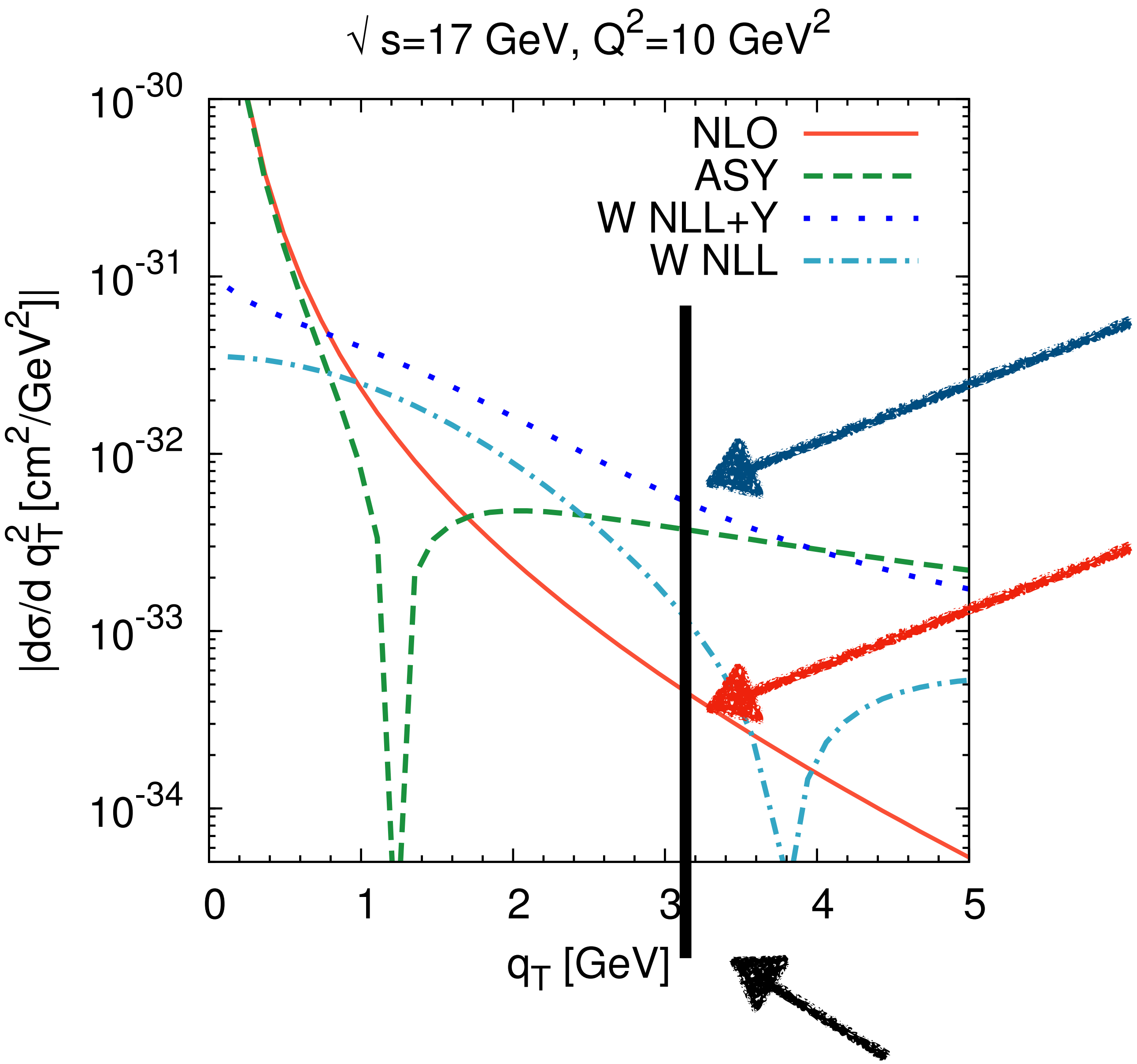
Small qT + intermediate qT (W+Y)

Fixed order large qT calculation

Matching region qT ~ Q

Some challenges:

Matching between small and large qT regions

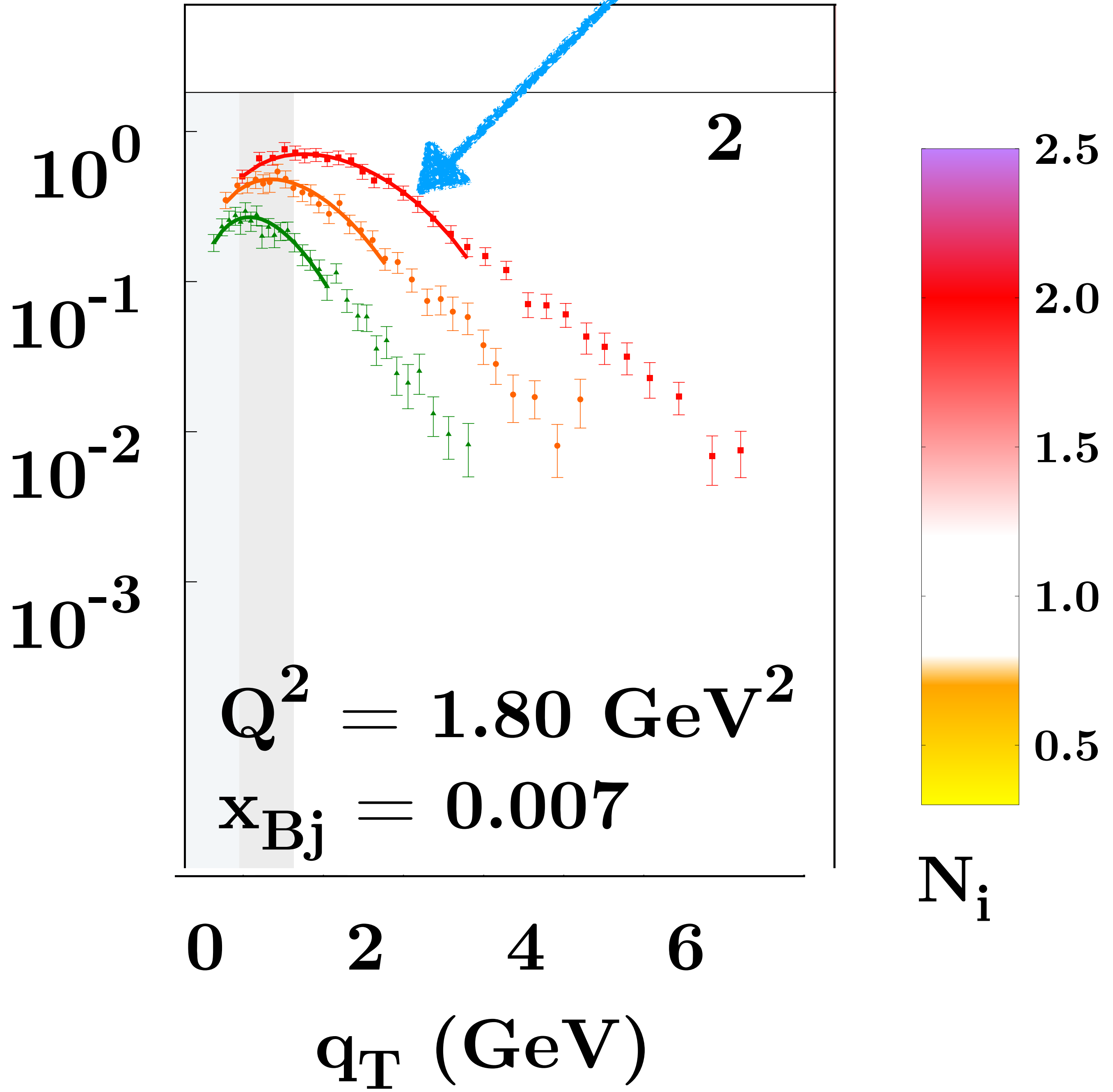


Large differences between Small and large qT theory lines

Matching region qT ~ Q

Signals of non-perturbative dominance

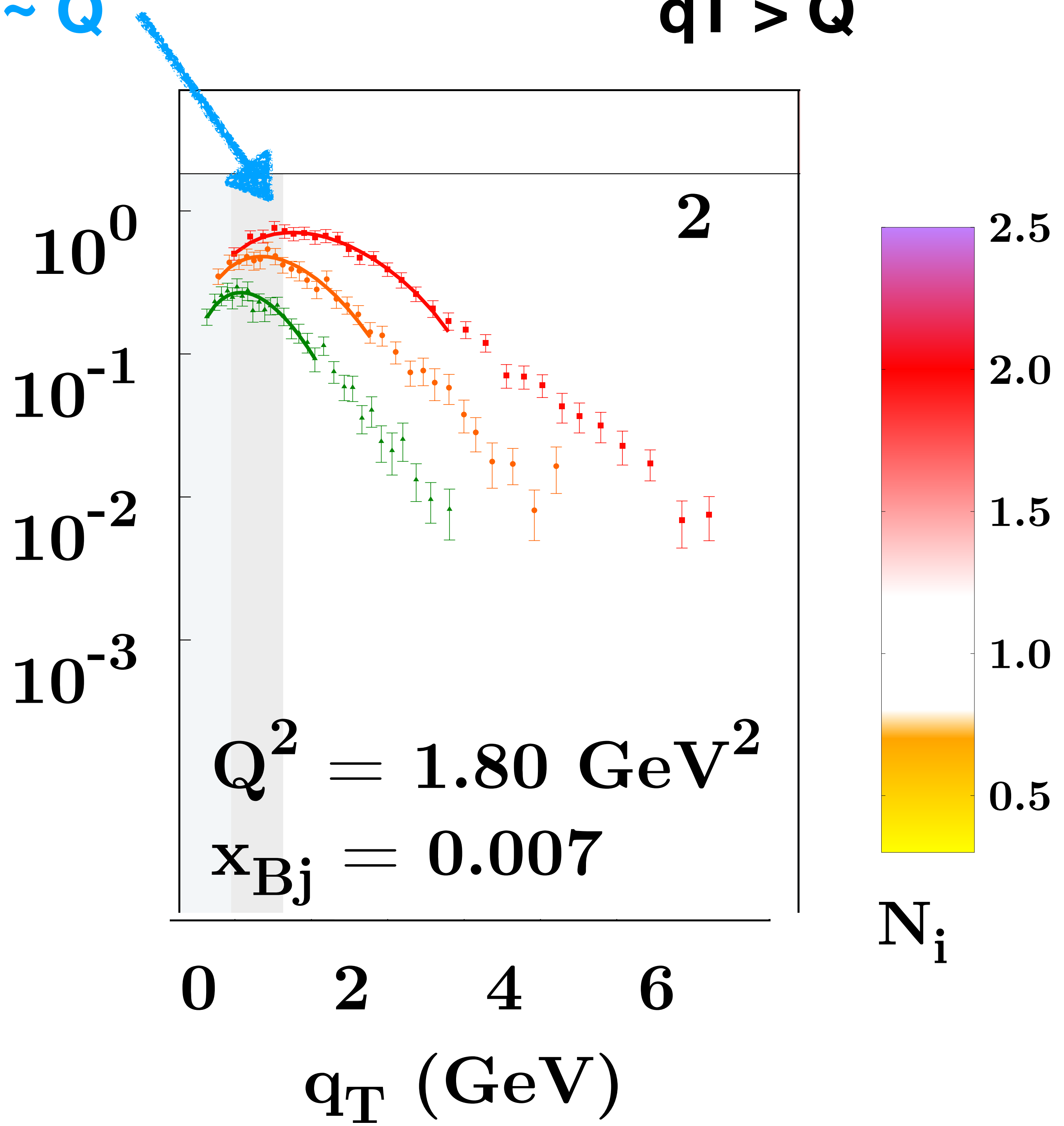
Here TMD term describes data at values qT > Q



No large normalization Needed for this panel

Formalism only justified up to qT ~ Q

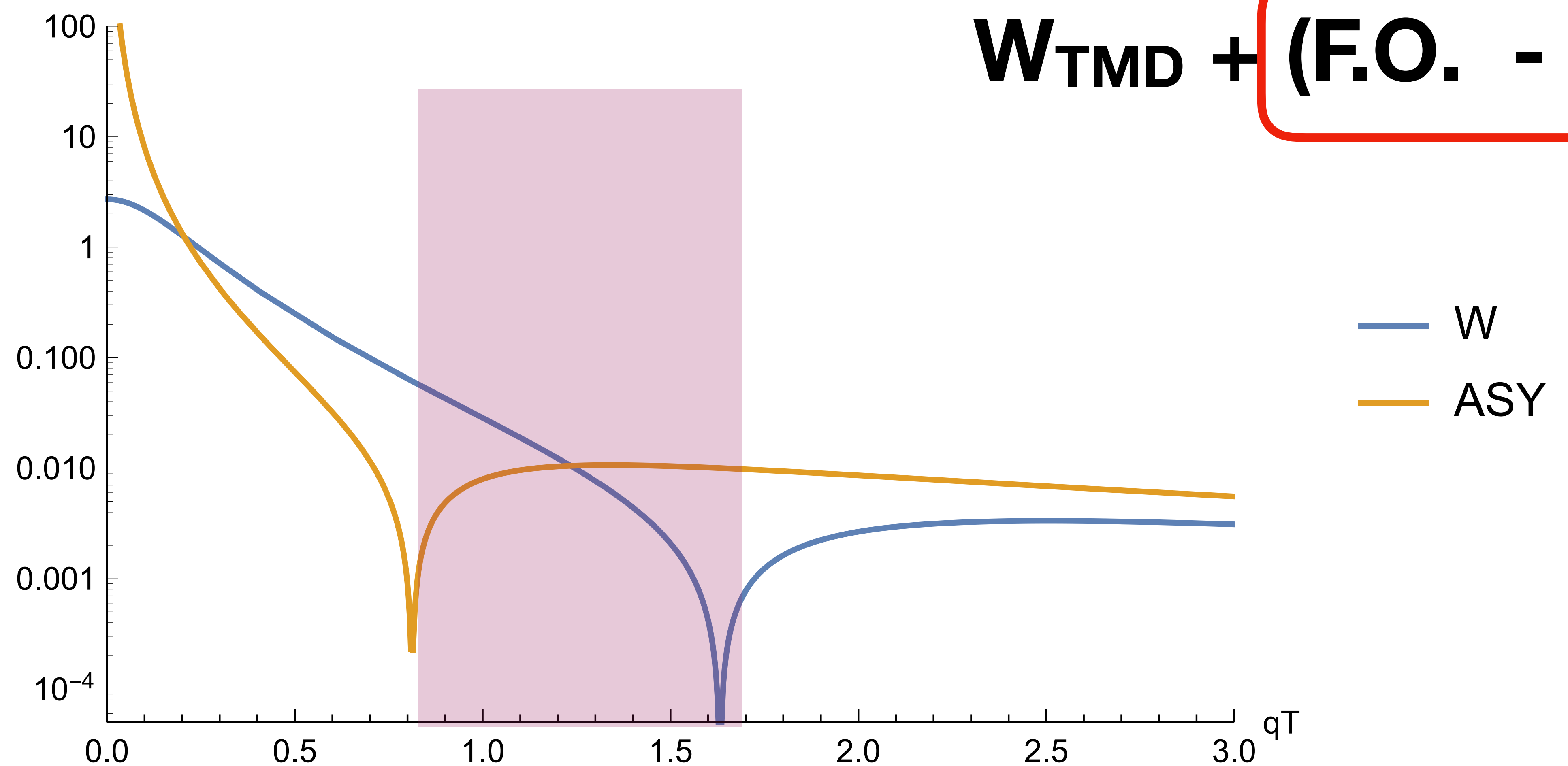
Here TMD term describes data at values qT > Q



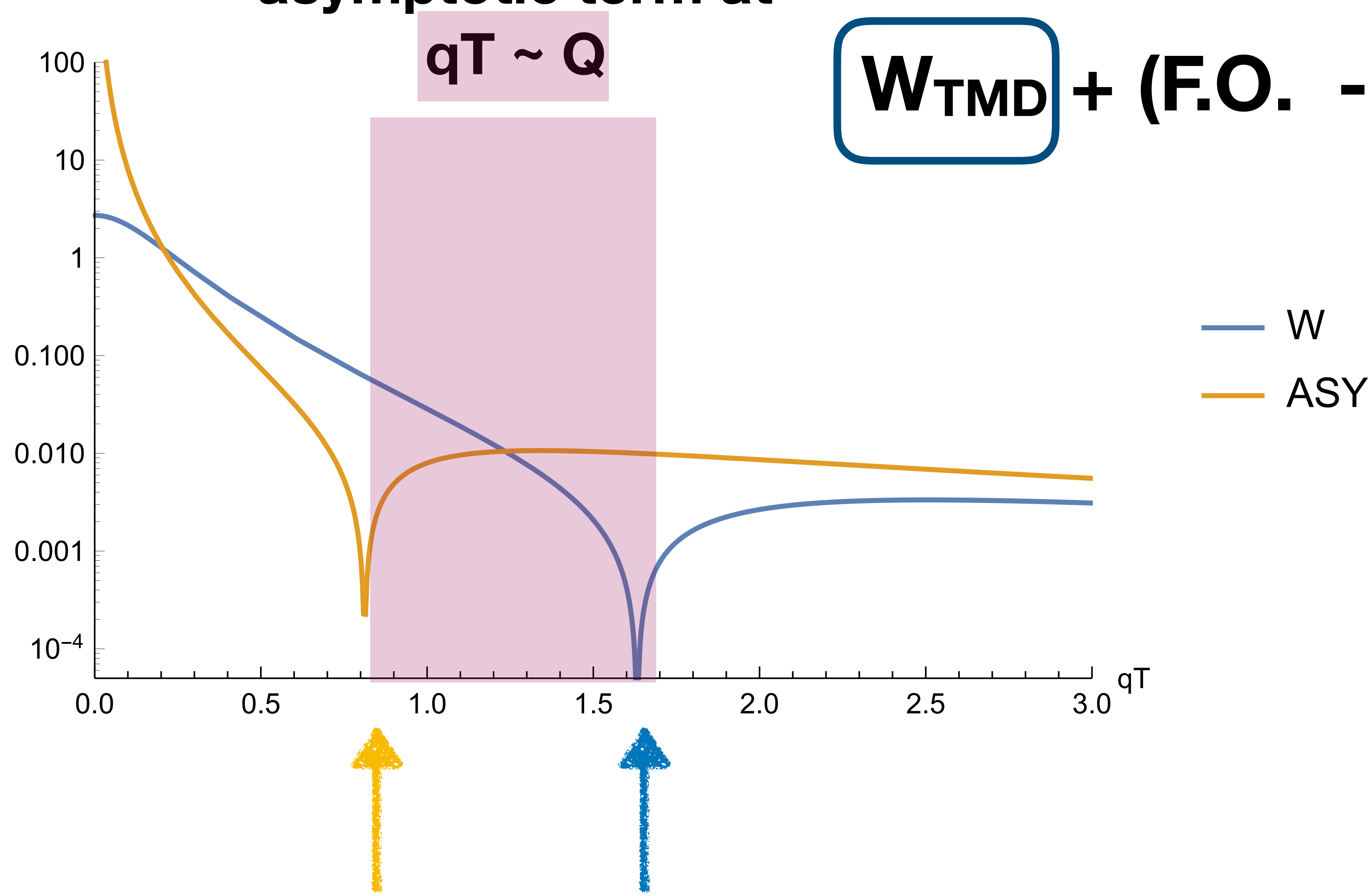
No large normalization Needed for this panel

Corrections extend TMD term up to qT~Q

W_{TMD} + (F.O. - ASY)

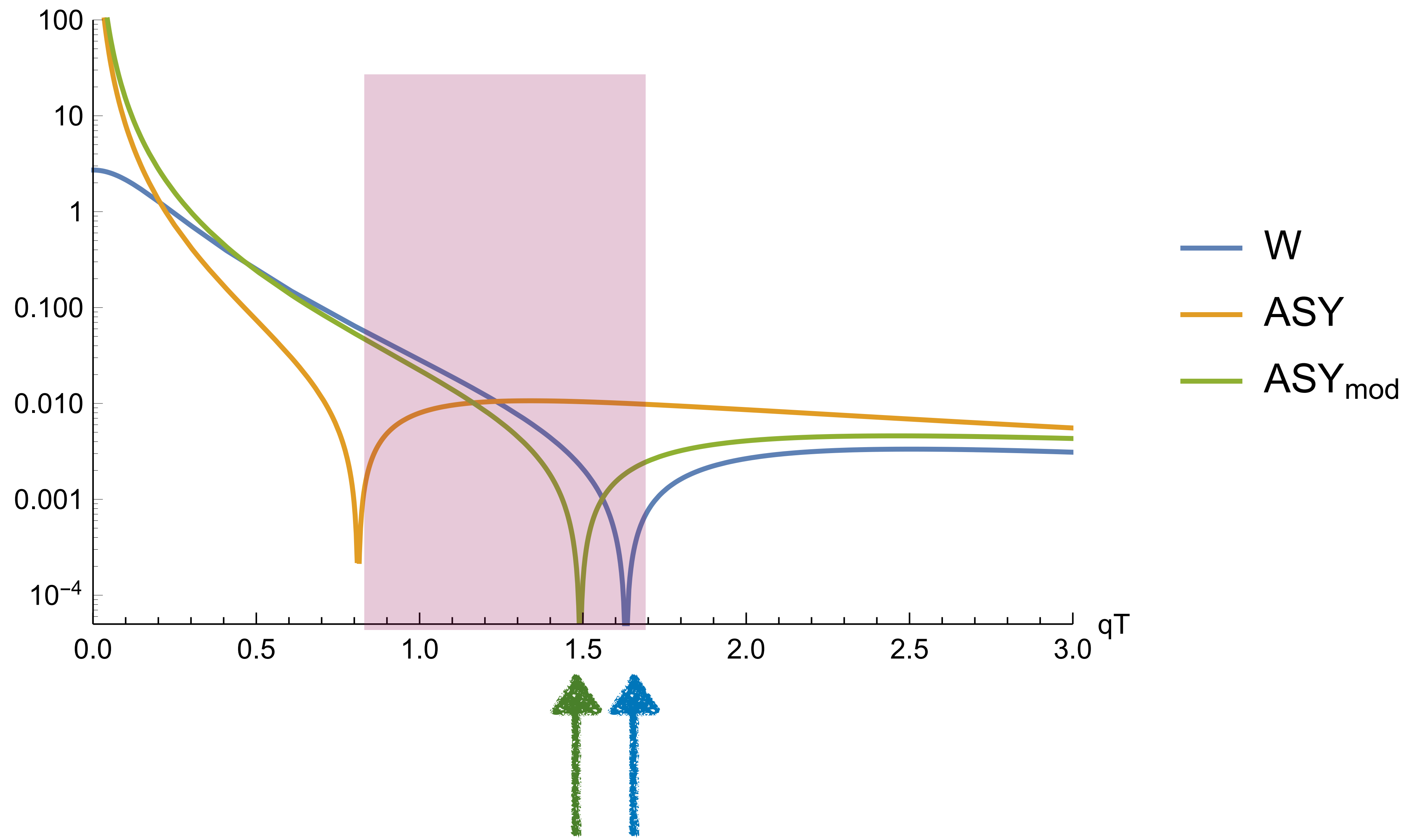


One of the issues with the matching can be traced to large differences Between TMD (W) and asymptotic term at



$$W_{TMD} + (F.O. - ASY)$$

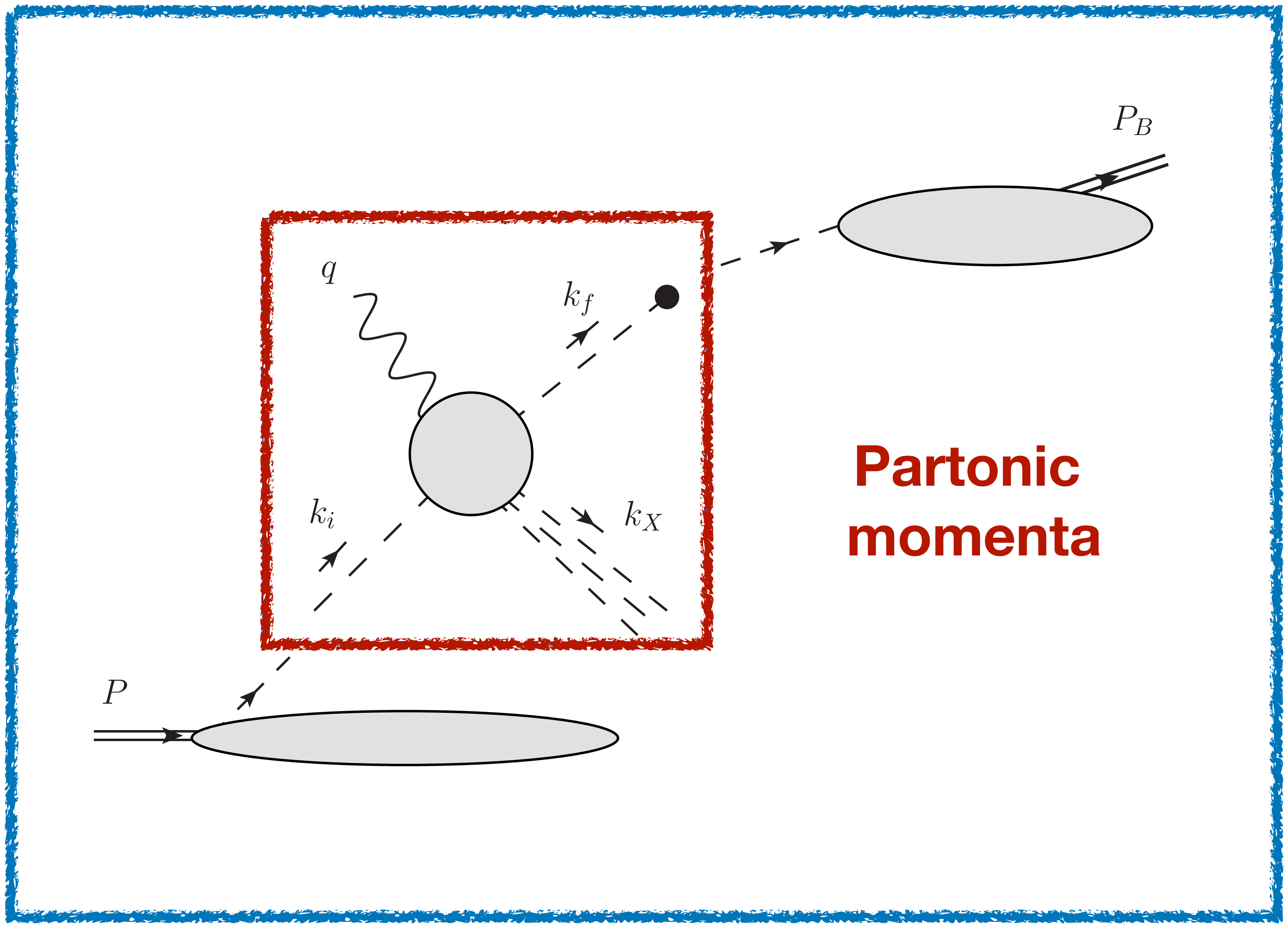
Large differences due to non-perturbative effects. Here, model with mass parameter M/Q ~ 0.2



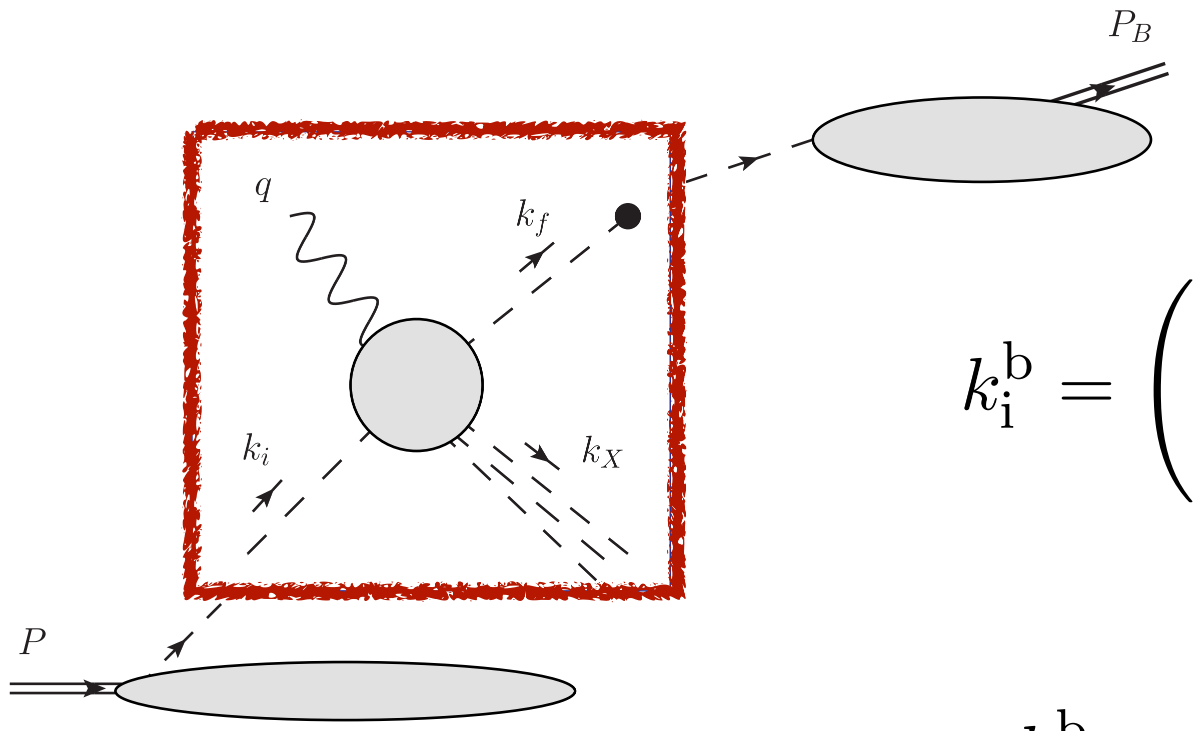
Testing the kinematics where factorization theorems hold

Different types of approximations

External momenta kinematics



Partonic kinematics



$$k_{\rm i}^{\rm b} = \left(\frac{Q}{\hat{x}_{\rm N}\sqrt{2}}, \frac{\hat{x}_{\rm N}(k_{\rm i}^2 + \mathbf{k}_{\rm i,b,T}^2)}{\sqrt{2}Q}, \mathbf{k}_{\rm i,b,T} \right)$$

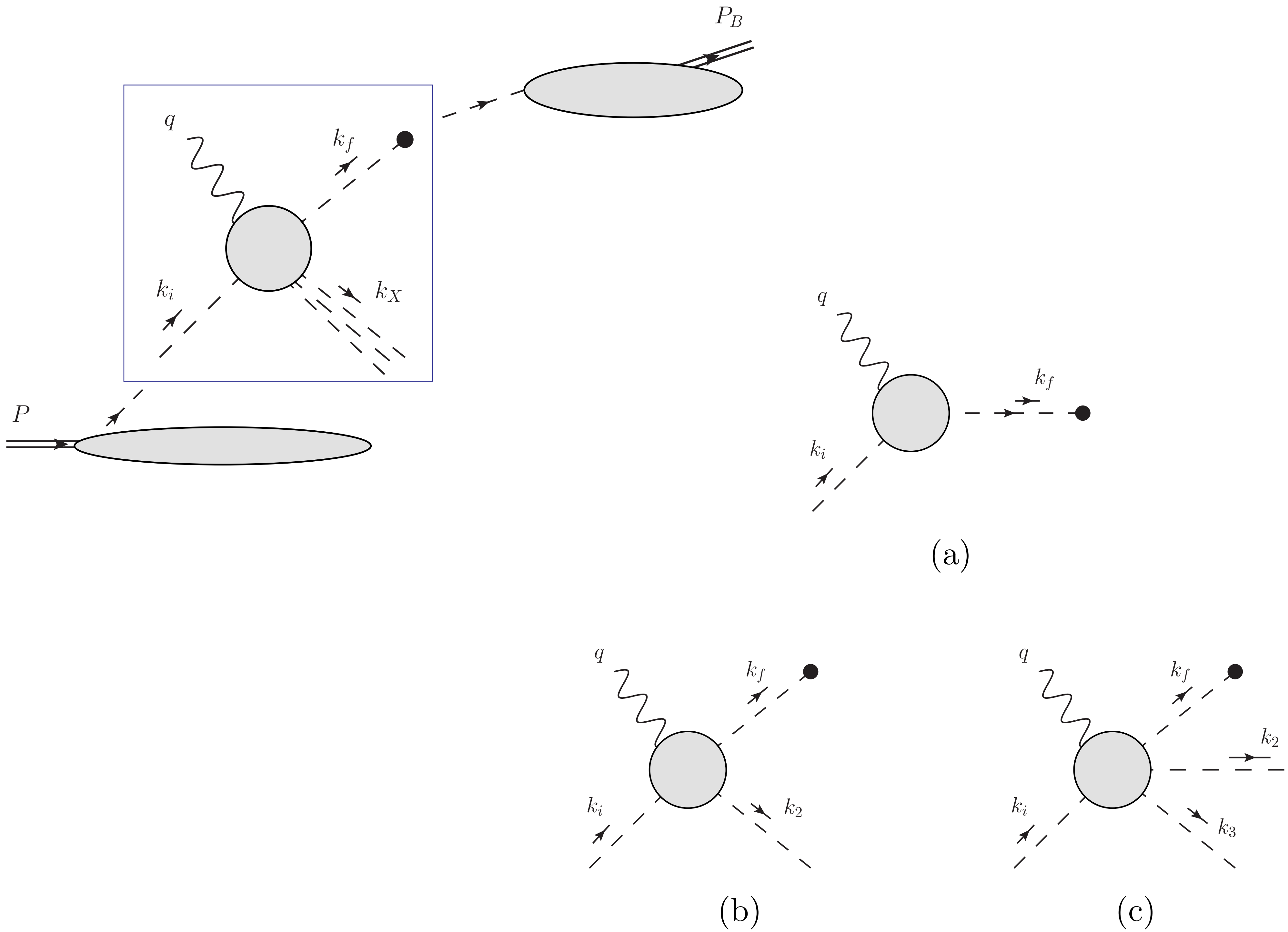
$$k_{\rm f}^{\rm b} = \left(\frac{\mathbf{k}_{\rm f,b,T}^2 + k_{\rm f}^2}{\sqrt{2}\hat{z}_{\rm N}Q}, \frac{\hat{z}_{\rm N}Q}{\sqrt{2}}, \mathbf{k}_{\rm f,b,T} \right)$$

$$k_{\rm i}^+ \equiv \xi P_{\rm b}^+$$

$$\hat{x}_{\rm N} \equiv -\frac{q_{\rm b}^+}{k_{\rm i,b}^+} = \frac{x_{\rm N}}{\xi}$$

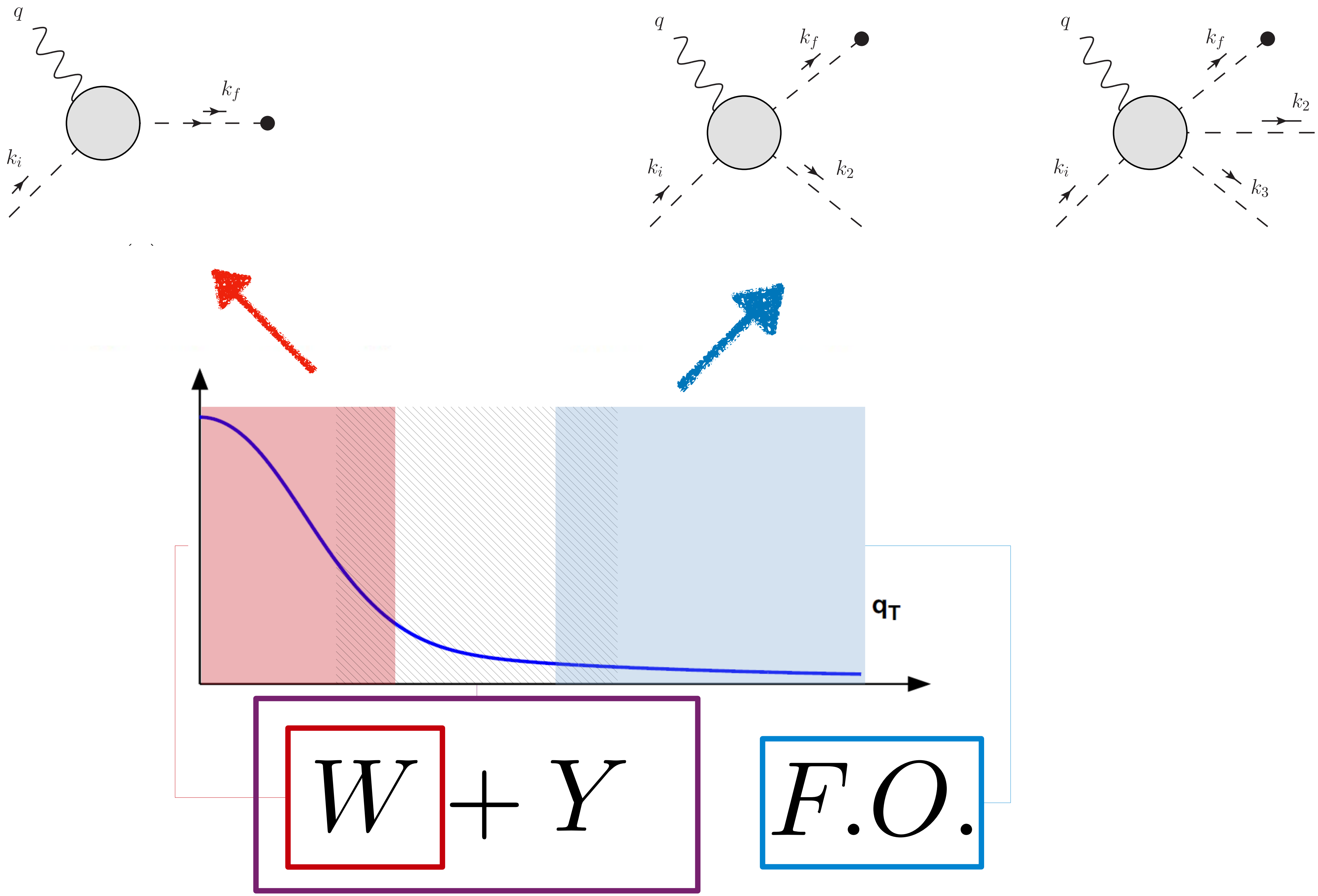
$$P_{\rm B,b}^- \equiv \zeta k_{\rm f}^-$$

$$\hat{z}_{\rm N} \equiv \frac{k_{\rm f,b}^-}{q_{\rm b}^-} = \frac{z_{\rm N}}{\zeta}$$

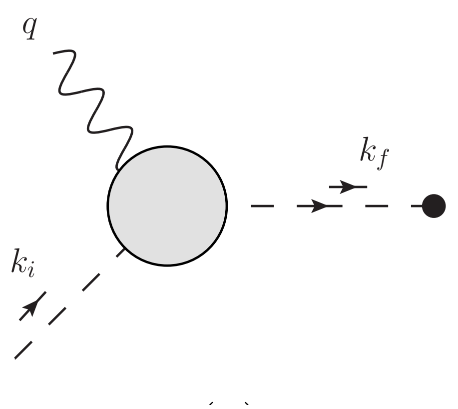


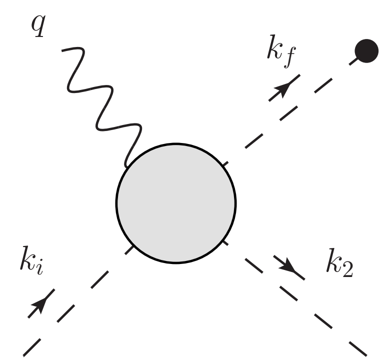
P_B
q
k_f
k_i
k_X
P
q
k_f
k_i
(a)
q
k_f
k_i
k_2
(b)
q
k_f
k_2
k_i
k_3
(c)

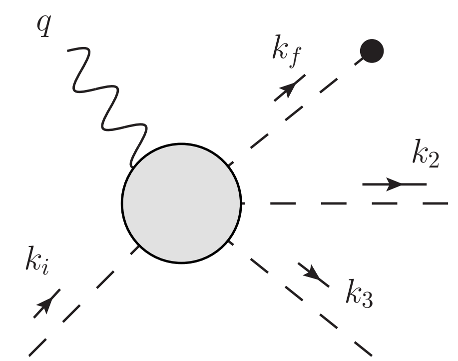
$$k \equiv k_{\mathrm{f}} - q$$



$$k^2 = (k_f - q)^2$$





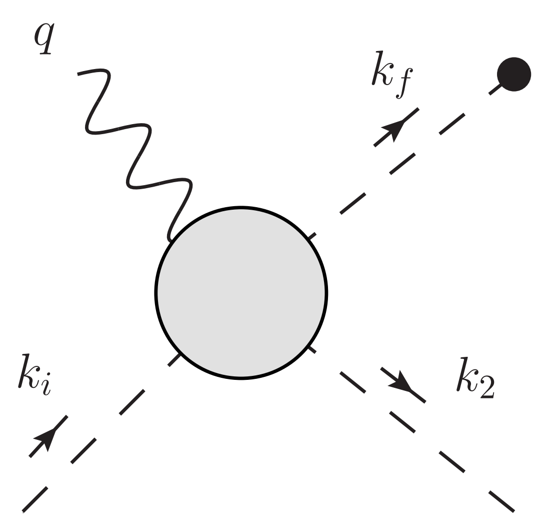


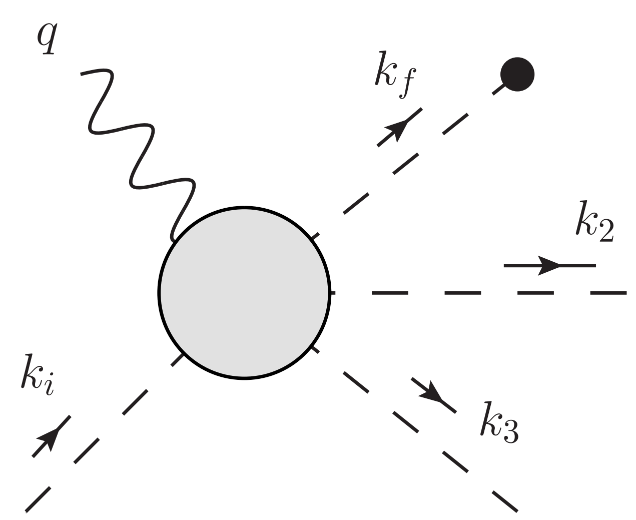
$$k^2 = 0$$

$$k^2 \neq 0$$

Allows to distinguish handbag from real emission kinematics

$$k_{\mathrm{X}}^2 = (k_{\mathrm{i}} + q - k_{\mathrm{f}})^2$$

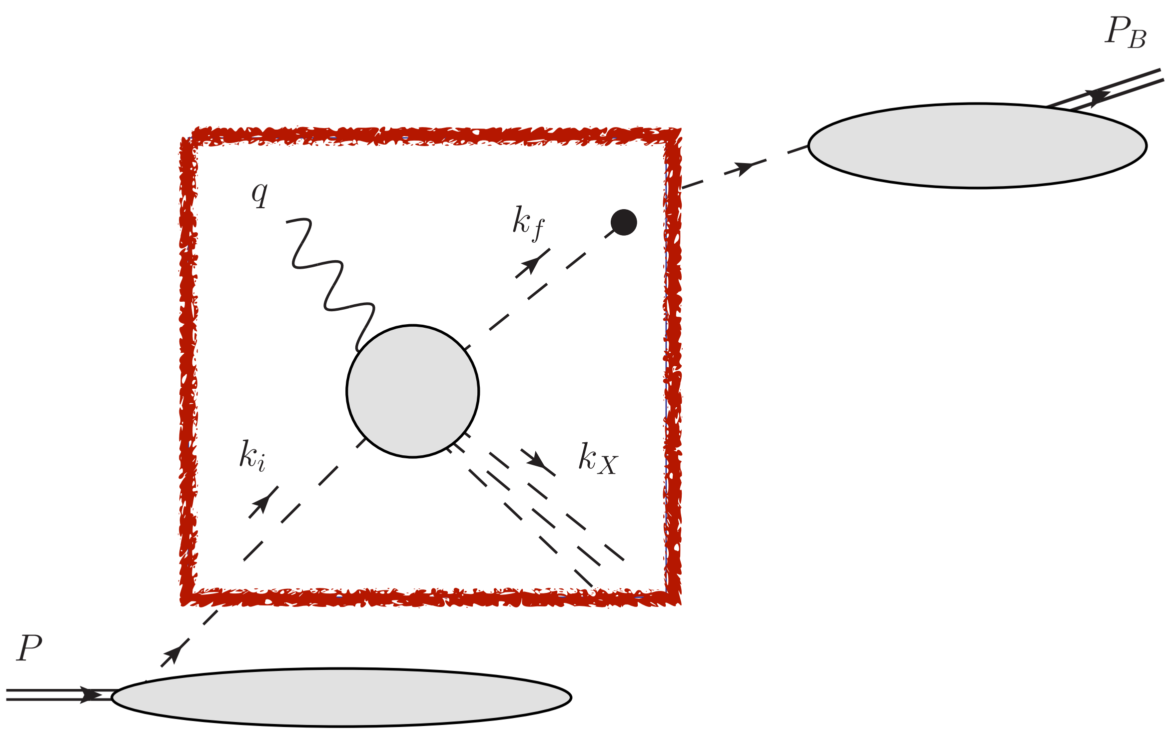




$$k_X^2 = 0$$

$$k_X^2 \neq 0$$

Higher order pQCD corrections in large qT cross section associated to larger values of virtuality spectator



$$k_X^2 = (k_i + q - k_f)^2$$

$$k \equiv k_f - q$$

$$\text{Collinearity} = R_1 \equiv \frac{P_B \cdot k_f}{P_B \cdot k_i}$$

$$\text{Transverse Hardness Ratio} = R_2 \equiv \frac{|k^2|}{Q^2}$$

$$\text{Spectator Virtuality Ratio} = R_3 \equiv \frac{|k_X^2|}{Q^2}$$

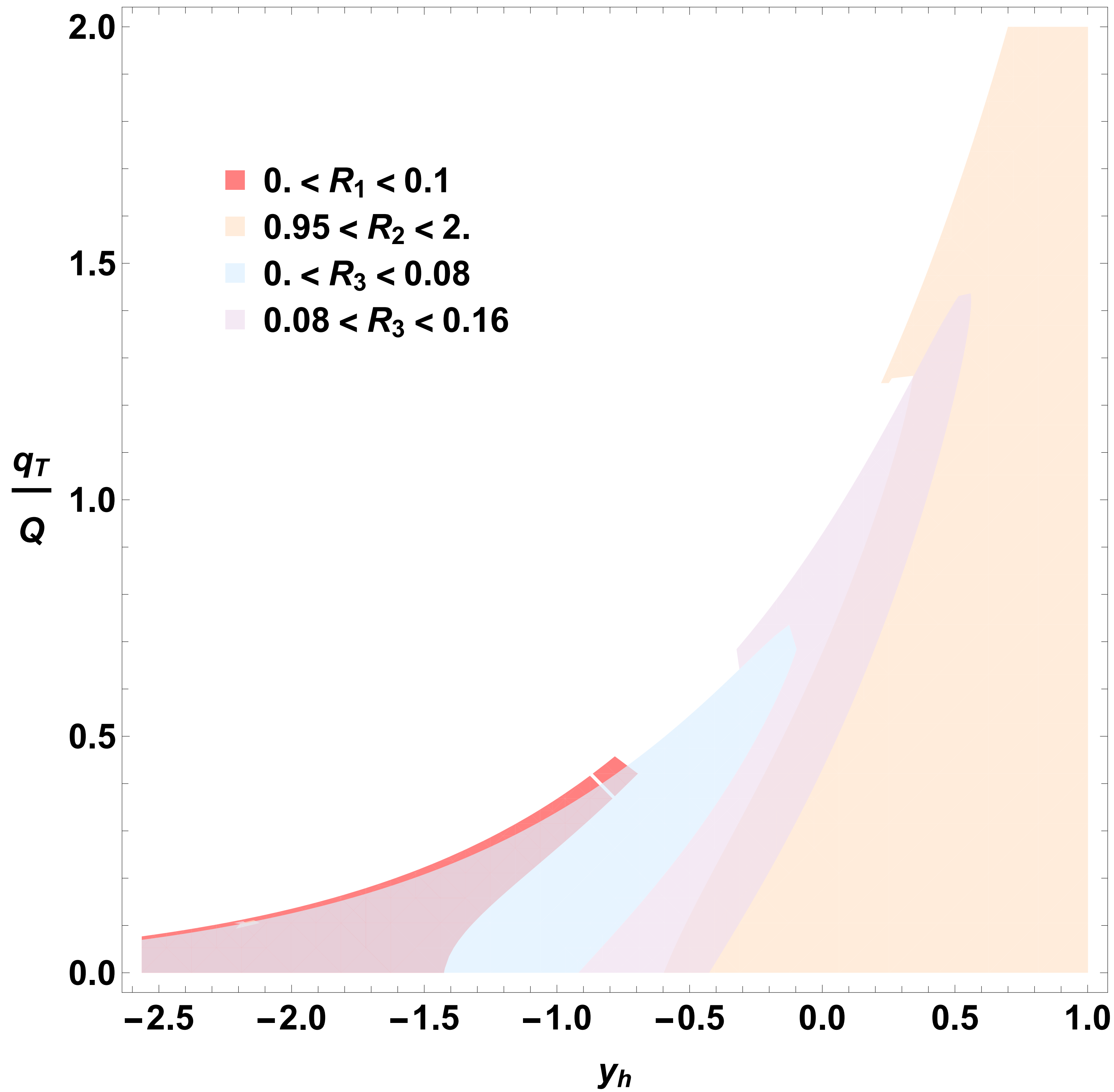
The size of these ratios determine partonic configurations (factorization theorem) and map to kinematical regions of the observables

$$\text{Collinearity} = R_1 \equiv \frac{P_{\rm B} \cdot k_{\rm f}}{P_{\rm B} \cdot k_{\rm i}}$$

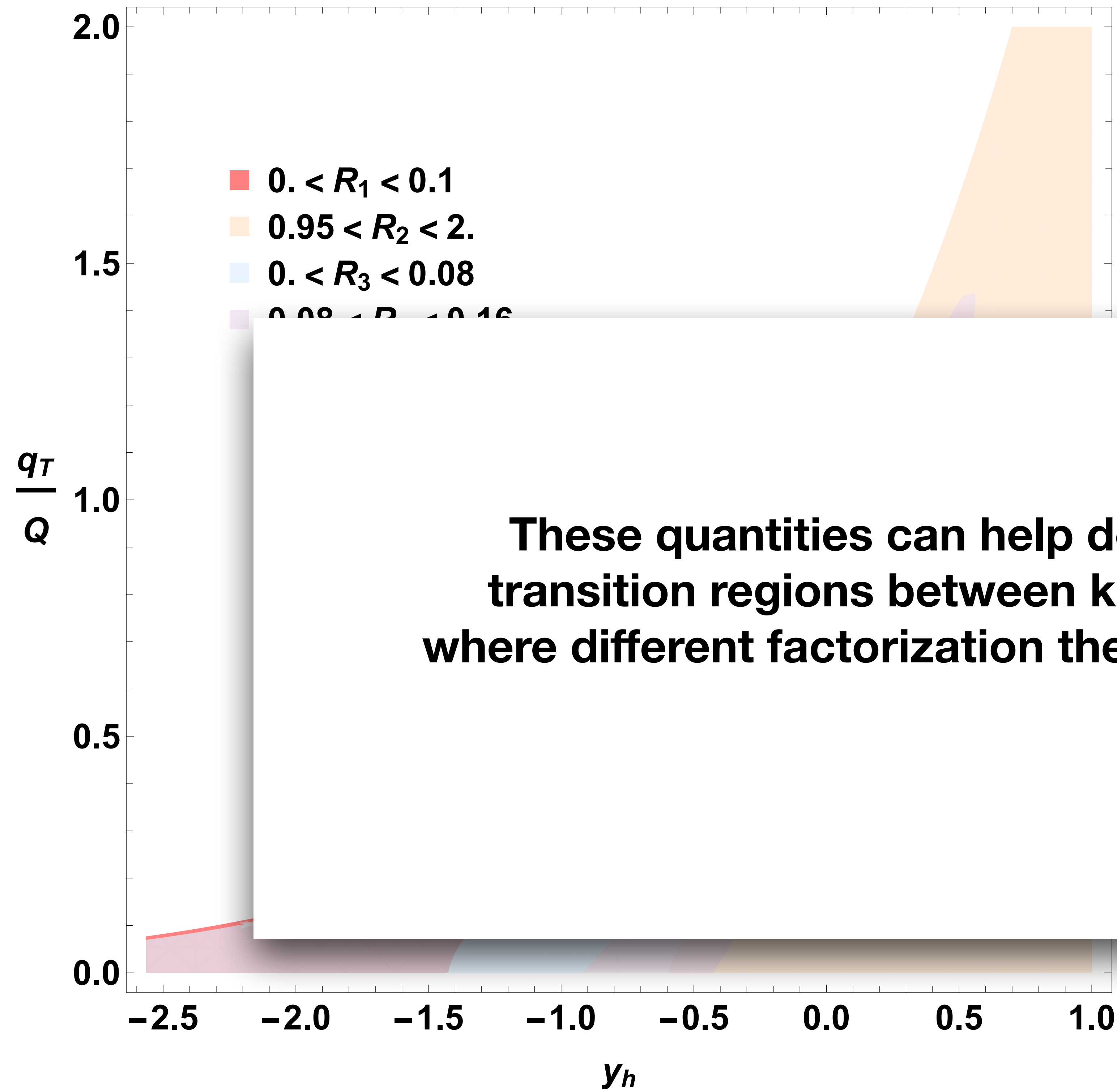
$$\text{Transverse Hardness Ratio} = R_2 \equiv \frac{|k^2|}{Q^2}$$

$$\text{Spectator Virtuality Ratio} = R_3 \equiv \frac{|k_{\rm X}^2|}{Q^2}$$

(caveat: Parton momenta have to be estimated, so this is just an example)



(caveat: Parton momenta have to be estimated, so this is just an example)



These quantities can help determine transition regions between kinematics where different factorization theorems apply

Final Remarks

- Some progress on TMD extraction from SIDIS (evolution)
- Currently, some results are counter-intuitive.
- Matching is quite important, it is a non-trivial component of the TMD formalism (otherwise must cut data)
- Must think of solutions to describe the data: Fixed order large qT region a good starting point.
- Does non-perturbative dominance compromises the validity of the formalism?
- Mapping (optimal) regions of applicability of factorization is crucial (like using R1,R2,R3 shown in this talk.)


Thanks