TMD physics and phenomenology in a hadron structure oriented approach

Tommaso Rainaldi – Old Dominion University

CFNS Summer School, Stony Brooks, NY

June 3-14, 2024

Jefferson Lab

Center for Frontiers in Nuclear Science

OLD DOMINION UNIVERSITY

Based on

- Phenomenology of TMD parton distributions in Drell-Yan and Z^0 boson production in a hadron structure oriented approach

(ArXiv:2401.14266)

- (F. Aslan, M. Boglione, J. O. Gonzalez-Hernandez, T. Rainaldi, T. C. Rogers, A. Simonelli)

- The resolution to the problem of consistent large transverse momentum in TMDs (PhysRevD.107.094029)

- (J. O. Gonzalez-Hernandez, T. Rainaldi, T. C. Rogers)

- Combining nonperturbative transverse momentum dependence with TMD evolution (PhysRevD.106.034002)

- (J. O. Gonzalez-Hernandez, T. C. Rogers, N. Sato)

Conventional approach

Standard CSS parametrization of a TMD

$$\tilde{f}_{j/p}\left(x;\boldsymbol{b}_\mathrm{T};\mu_Q,Q\right) = \tilde{f}^{\mathrm{OPE}}_{j/p}\left(x;\boldsymbol{b}_*;\mu_{b_*},\mu_{b_*}\right)\times$$

$$\times\exp\left\{\int_{\mu_{b_*}}^{\mu_Q}\frac{\mathrm{d}\mu'}{\mu'}\left[\gamma\left(\alpha_S(\mu');1\right) - \ln\left(\frac{Q}{\mu'}\right)\gamma_K\left(\alpha_S(\mu')\right)\right] + \ln\left(\frac{Q}{\mu_{b_*}}\right)\tilde{K}\left(\boldsymbol{b}_*;\mu_{b_*}\right)\right\}$$

$$\times\exp\left\{-g_{j/p}\left(x,\boldsymbol{b}_\mathrm{T}\right) - g_K\left(\boldsymbol{b}_\mathrm{T}\right)\ln\left(\frac{Q}{Q_0}\right)\right\}$$

Nonperturbative

Perturbatively calculable

Drop this

$$\tilde{f}^{\mathrm{OPE}}_{j/p}\left(x,\boldsymbol{b}_*;\mu_{b_*},\mu_{b_*}\right) = \widetilde{C}_{j/j'}\left(x/\xi,\boldsymbol{b}_*;\mu_{b_*},\mu_{b_*}\right)\otimes\tilde{f}_{j'/p}\left(\xi;\mu_{b_*}\right) + \mathcal{O}\left(m^2 b^2_{\mathrm{max}}\right)$$

Same for FF

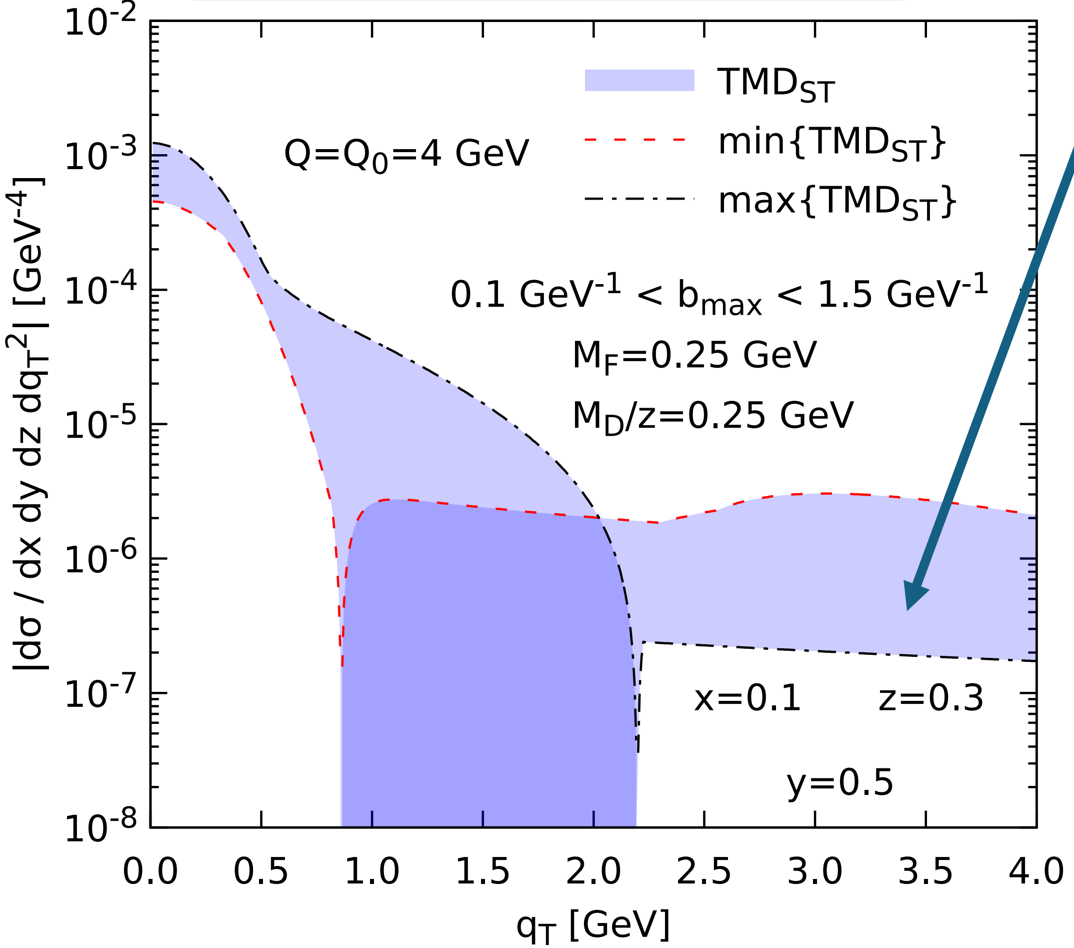
Fixed order collinear factorization

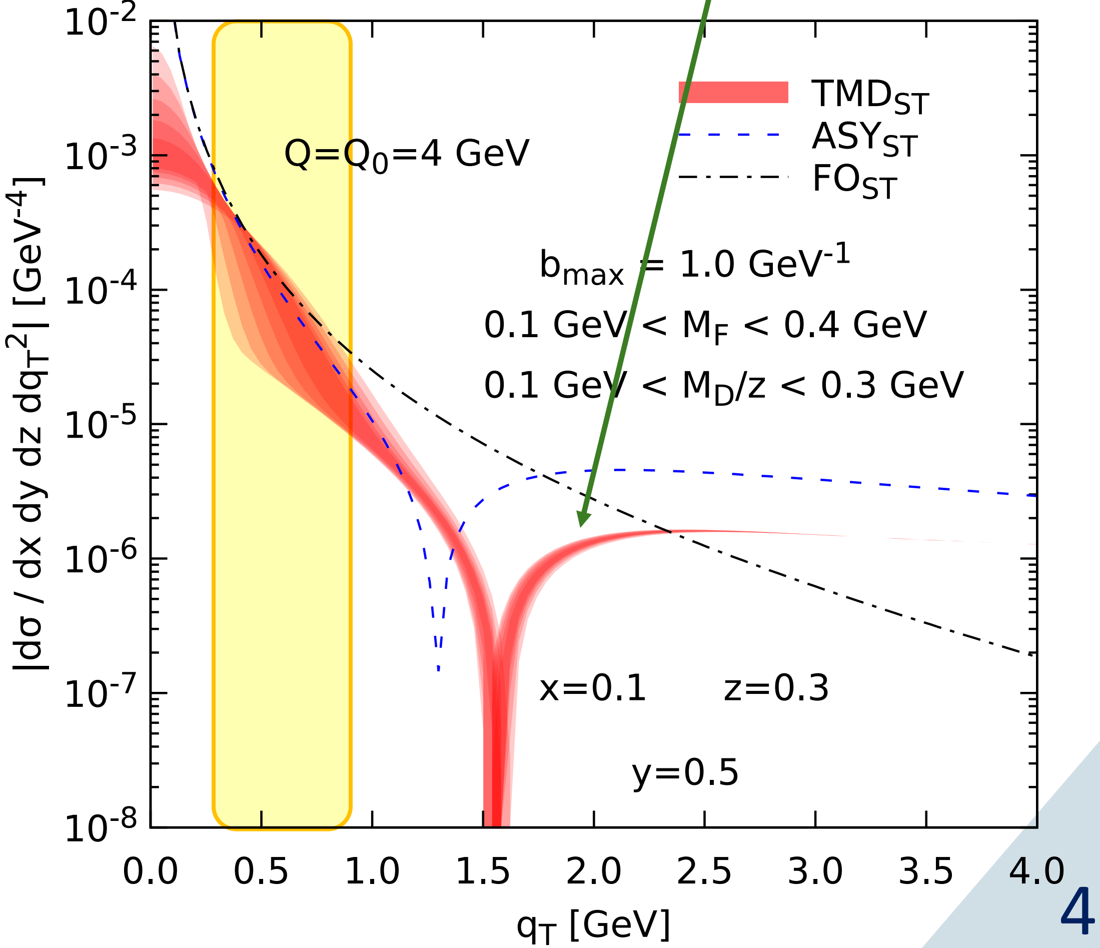
(Some) Issues with conventional approach

Large b_{max} dependence

What is going on?

Large q_T inconsistency





Big problems !?

- What are the effects of the assumptions, ansatz and auxiliary parameters?
- Can we actually tell whether or not we are being consistent with theory?
- Can we maximize the predictive power while minimizing the theoretical uncertainties?

In the standard approach this is either hard or not possible

Why are b_* and b_{max} used ?

$$f_{i/H}(x, b_T; \mu, \zeta) = \widetilde{C}_{ij}(x, b_T; \mu, \zeta) \otimes f_{j/H}(x; \mu) + \mathcal{O}(m b_T)$$

Powers of $\ln\left(\frac{\mu b_T}{2e^{-\gamma_E}}\right)$ = $\overset{b_T \to +\infty}{\longrightarrow} +\infty$, $\overset{b_T \to 0}{\longrightarrow} -\infty$

LARGE b_T: solved by arbitrary cutoff b_{max}

SMALL b_T: solved by choosing a different scale $\mu_{b_*}(b_T, b_{max})$

Why b_* and b_{max}?

$$f_{i/H}(x, b_T; \mu, \zeta) = \widetilde{C}_{ij}(x, b_T; \mu, \zeta) \otimes f_{j/H}(x; \mu) + \mathcal{O}(m b_T)$$

Powers of $\ln\left(\frac{\mu b_T}{2e^{-\gamma_E}}\right) = \begin{cases} \xrightarrow{b_T \to +\infty} +\infty \\ \xrightarrow{b_T \to 0} -\infty \end{cases}$

These problems are treated simultaneously in the stardard approach

BUT they are completely independent
and there is more to the story

Hadron Structure Oriented approach (still CSS)

Let's build an input scale parametrization that already satisfies the constraints the theory gives us

OPE expansion at small b_T (equivalently at large k_T)

Integral relation (quasi probabilistic interpretation)

Derivable from pQCD

We can do it without the b_{max} or b_{min} issues

Bypassed by imposing integral relation

Solved by using renormalization group improvement

Hadron Structure Oriented approach

TMD PDF HSO parametrization at input scale

Fixed order collinear factorization

$\mathcal{O}(\alpha_S)$

Large k_T OPE coefficients

$$f_{\text{inpt,i/p}}(x, \boldsymbol{k}_T; \mu_{Q_0}; Q_0^2) = \frac{1}{2\pi}\frac{1}{k_T^2+m^2}\left[A^f_{i/p}(x;\mu_{Q_0}) + B^f_{i/p}(x;\mu_{Q_0})\ln\frac{Q_0^2}{k_T^2+m^2}\right] + \frac{1}{2\pi}\frac{1}{k_T^2+m^2}A^{f,g}_{i/p}(x;\mu_{Q_0})$$
$$+ C^f_{i/p} f_{\text{core,i/p}}(x, \boldsymbol{k_T}; Q_0^2)$$

Small k_T model

NP parameters

Such that

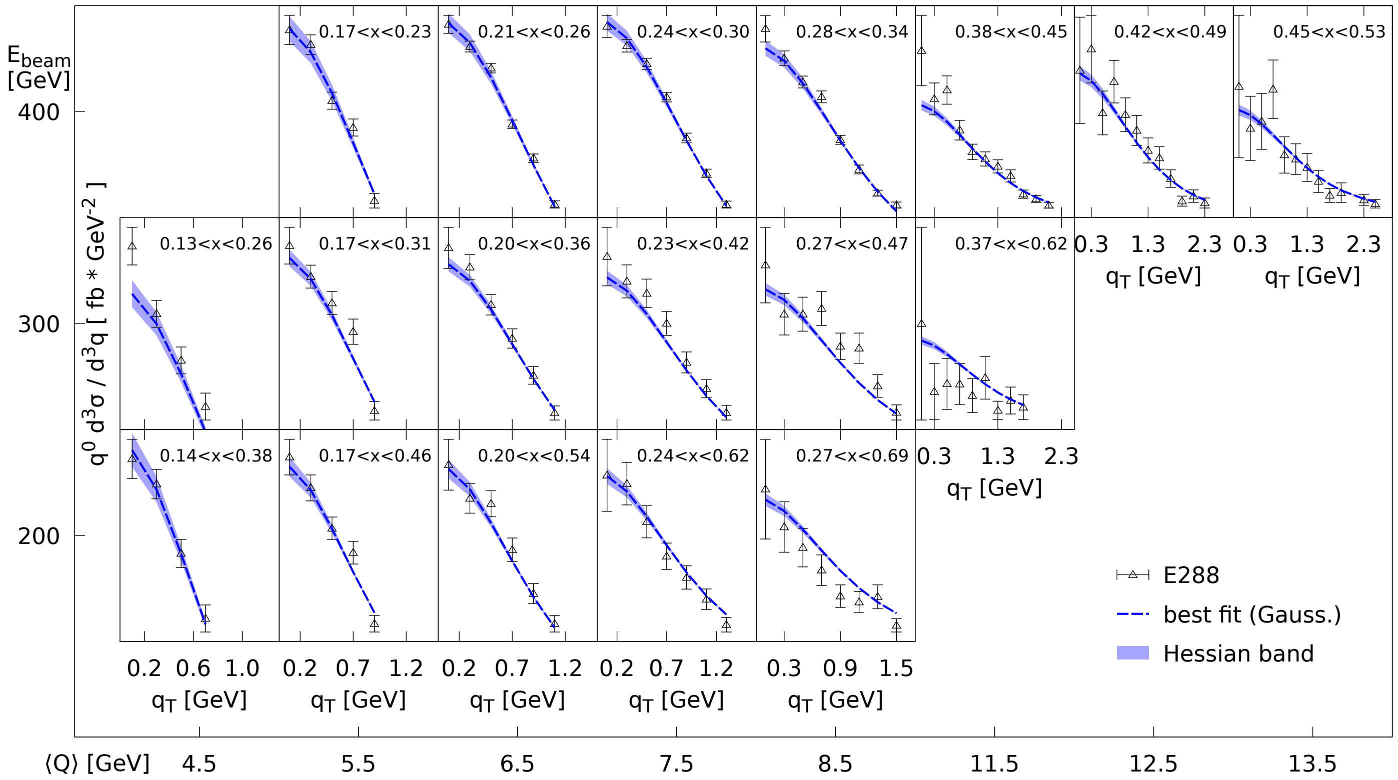
$$f^c_{j/p}(x;\mu_Q) \equiv 2\pi\int_0^{k_c} \mathrm{d}k_\mathrm{T}\, k_\mathrm{T} f_{j/p}\left(x, \boldsymbol{k}_\mathrm{T}; \mu_Q, \sqrt{\zeta}\right)$$
$$= f_{j/p}(x;\mu_Q) + \Delta_{j/p}(x;\mu_Q, k_c) + \text{p.s.}$$

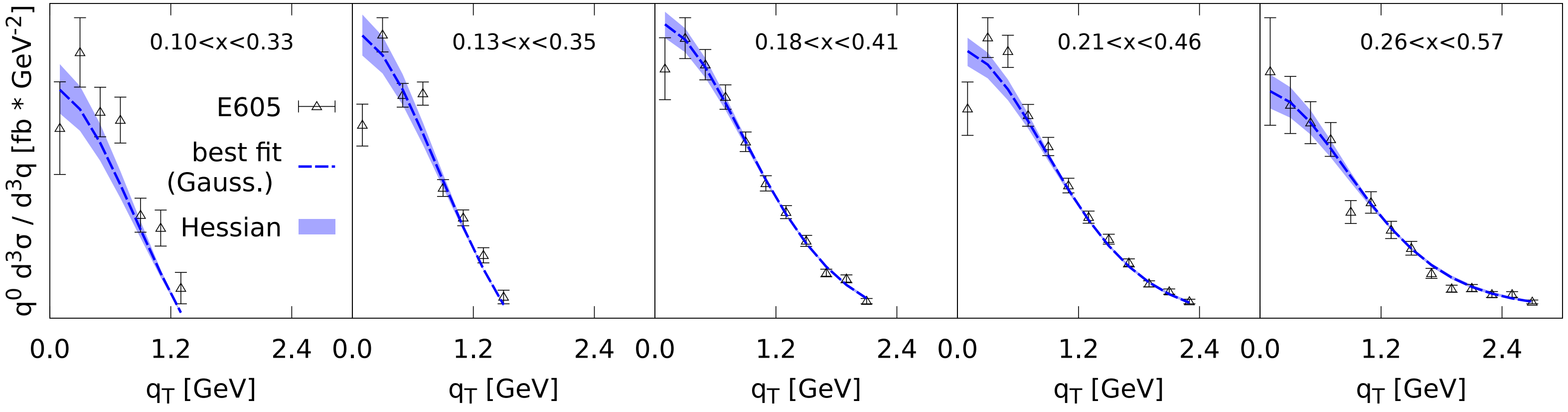
Low Q fit results

Gaussian fits

	E288 (130 pts.)	E605 (52 pts.)
χ^2_{dof}	1.04	1.68

Just 4 parameters for now





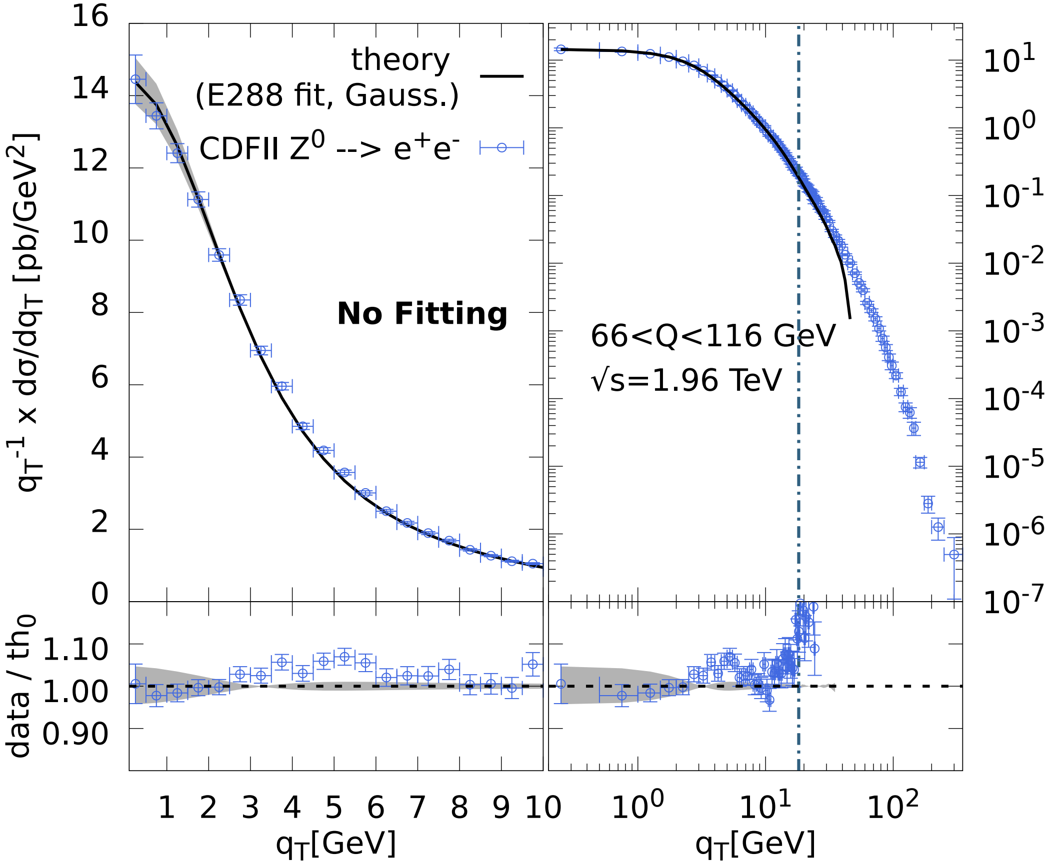
Spectator model too:

Spectator model fit

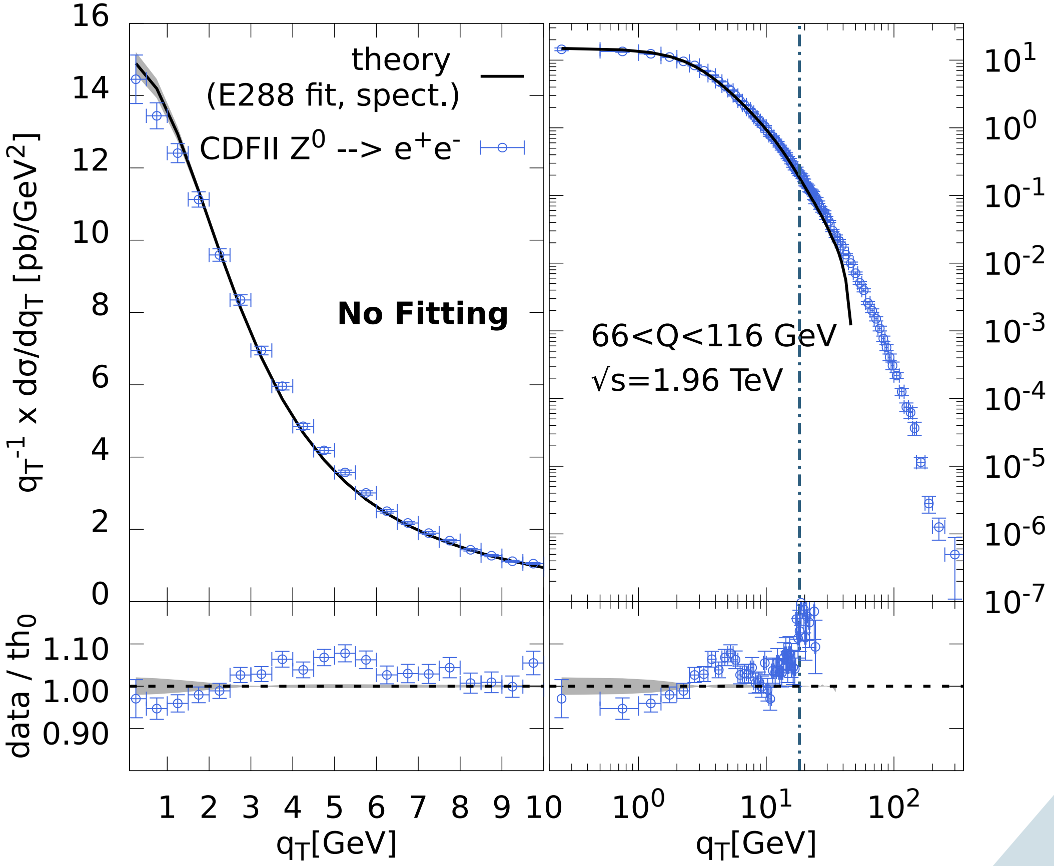
	E288 (130 pts.)
χ^2_{dof}	1.04

Higher Q postdictions: test different models on the same experiment

A postdiction of CDFII with E288 GAUSSIAN fit



A postdiction of CDFII with E288 SPECTATOR fit



Summary

We have a framework that

1. Is consistent with the large k_T tail from theory (where it should)
2. Satisfies an integral relation: pseudo probabilistic interpretation
3. No b_{max} or b_{min} dependance: all errors are under control
4. NP (core) models are very easily swappable and testable

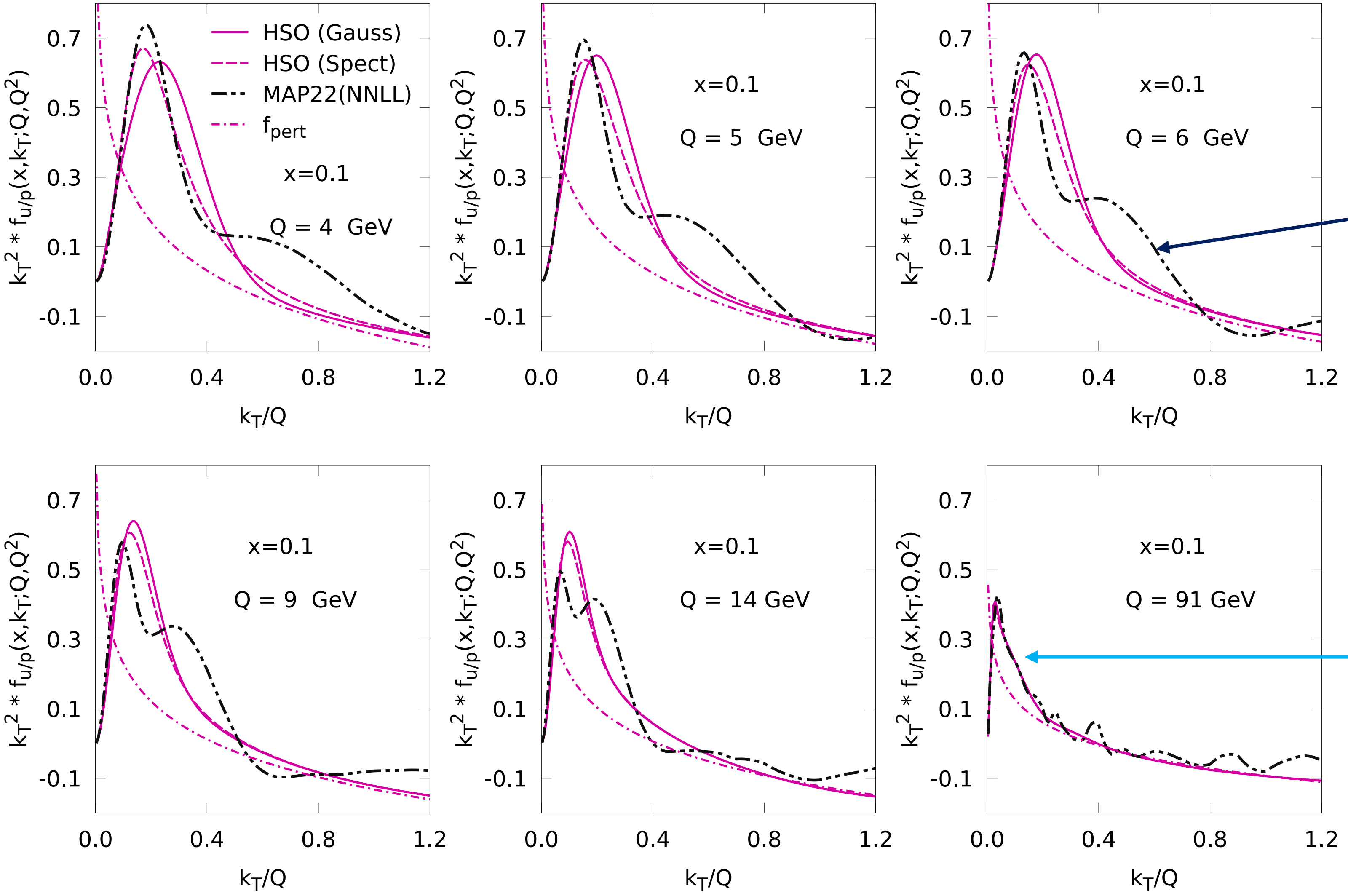
Pheno methodology: Fit low Q, test against higher Q (not mandatory)

NEXT/SOON:

SIDIS large q_T issue, more refined models, input from Lattice?, higher orders…

Thank you

Comparison with MAP22



Observations:

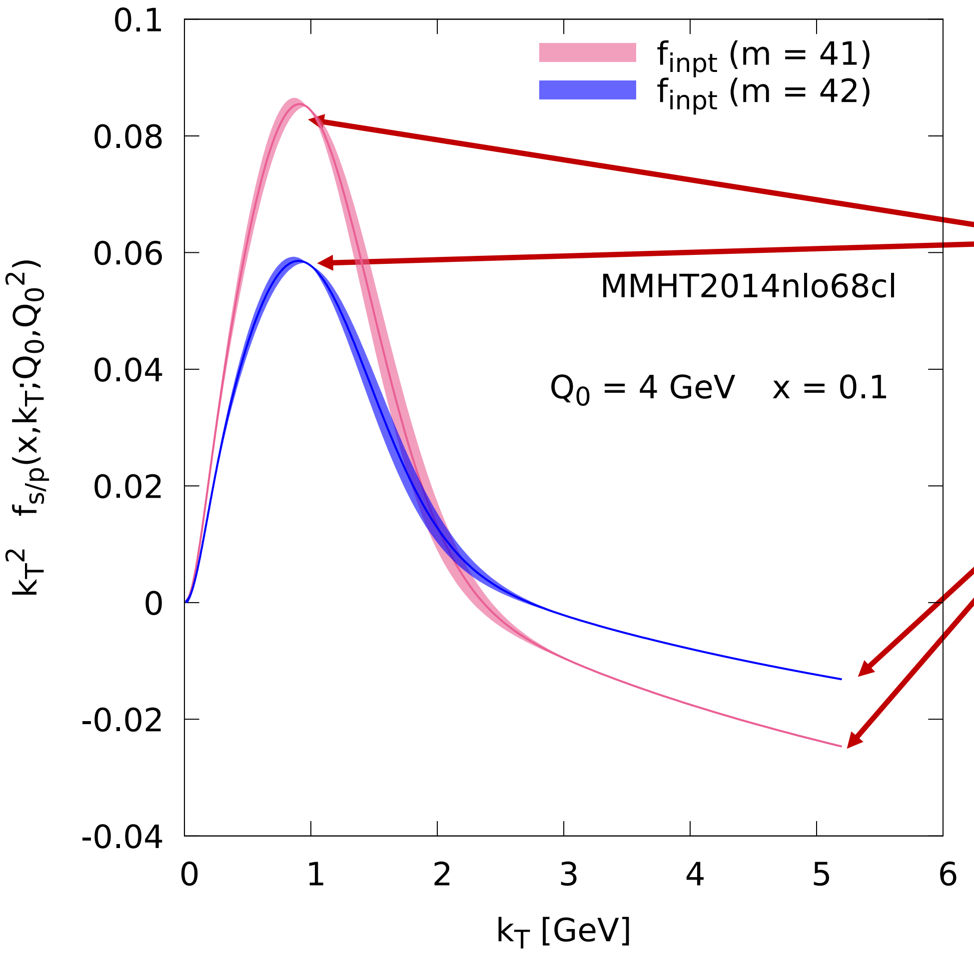
No tail matching for MAP

Different models can describe the small k_T region at low Q

Model dependence washes out at large Q

How do we choose?

TMDs are affected by collinear distributions



Example: take two pdfs associated with the same flavor (s here) and compute the input TMD

Maybe unexpected **different small k_T behavior** because of integral relation

Expected **different tails** because of the OPE expansion

Changing the integral **necessarily** changes the integrand

Why is this important?

- We can **quantitatively** and **conclusively** answer the question:

  How much collinear dependence do my TMD extractions carry?