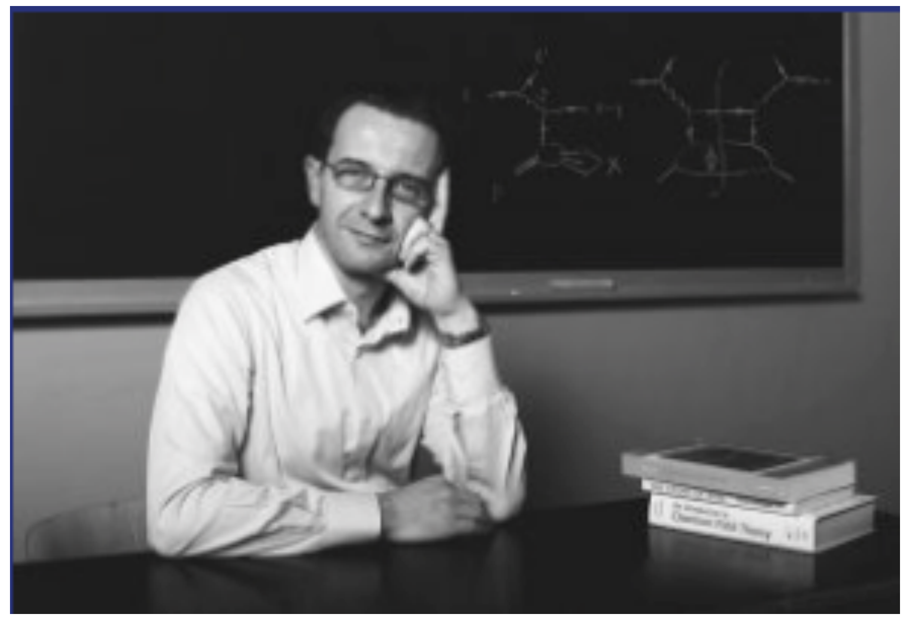
PROGRESS IN THE EXTRACTION OF UNPOLARIZED TMDS FROM GLOBAL DATA SETS

Matteo Cerutti

MAP Collaboration

RESULTS OBTAINED WITH CONTRIBUTIONS FROM

Alessandro Bacchetta



Marco Radici

Andrea Signori

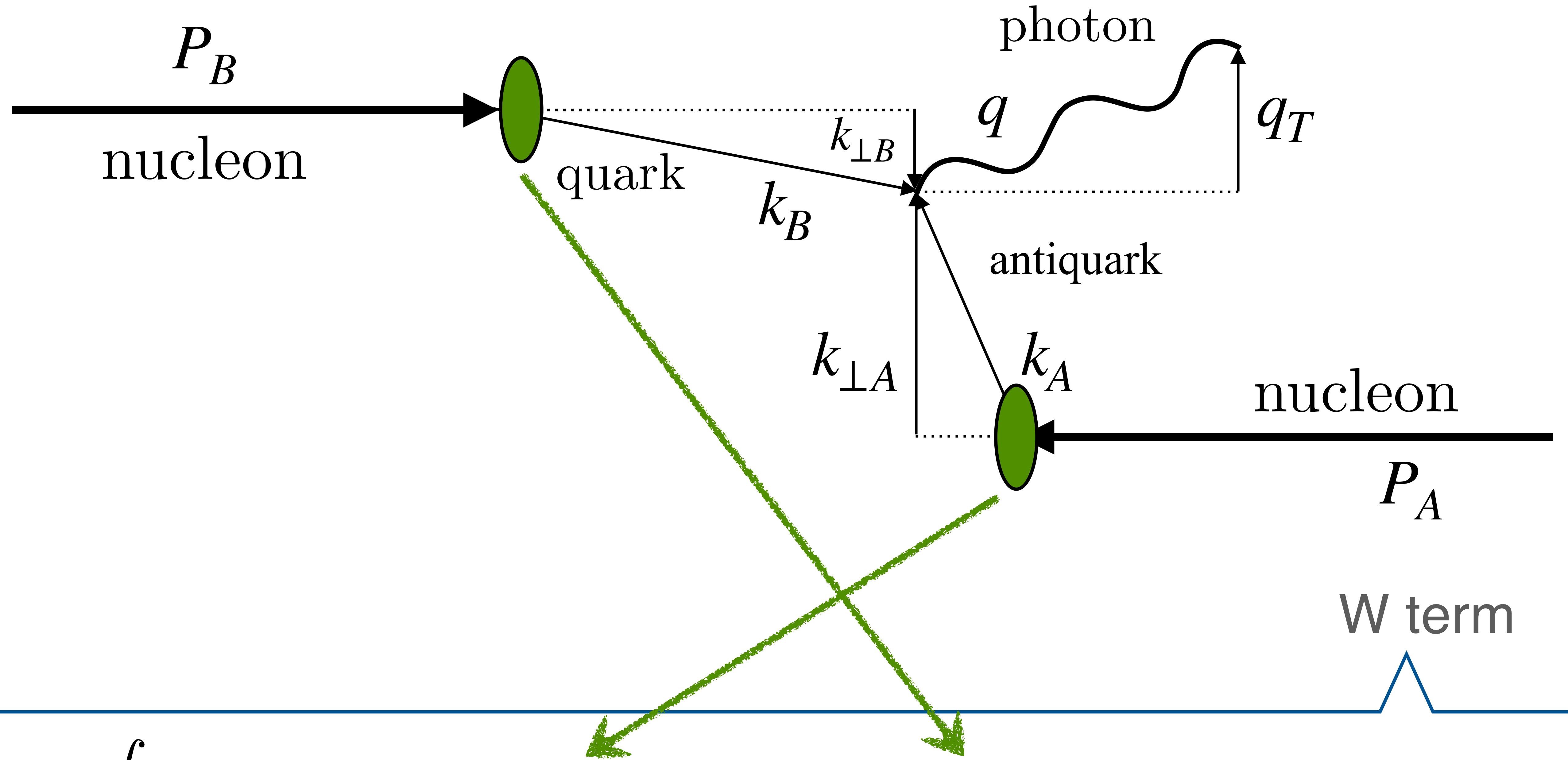
Valerio Bertone

Chiara Bissolotti

Giuseppe Bozzi

Fulvio Piacenza

TMDS IN DRELL-YAN PROCESSES



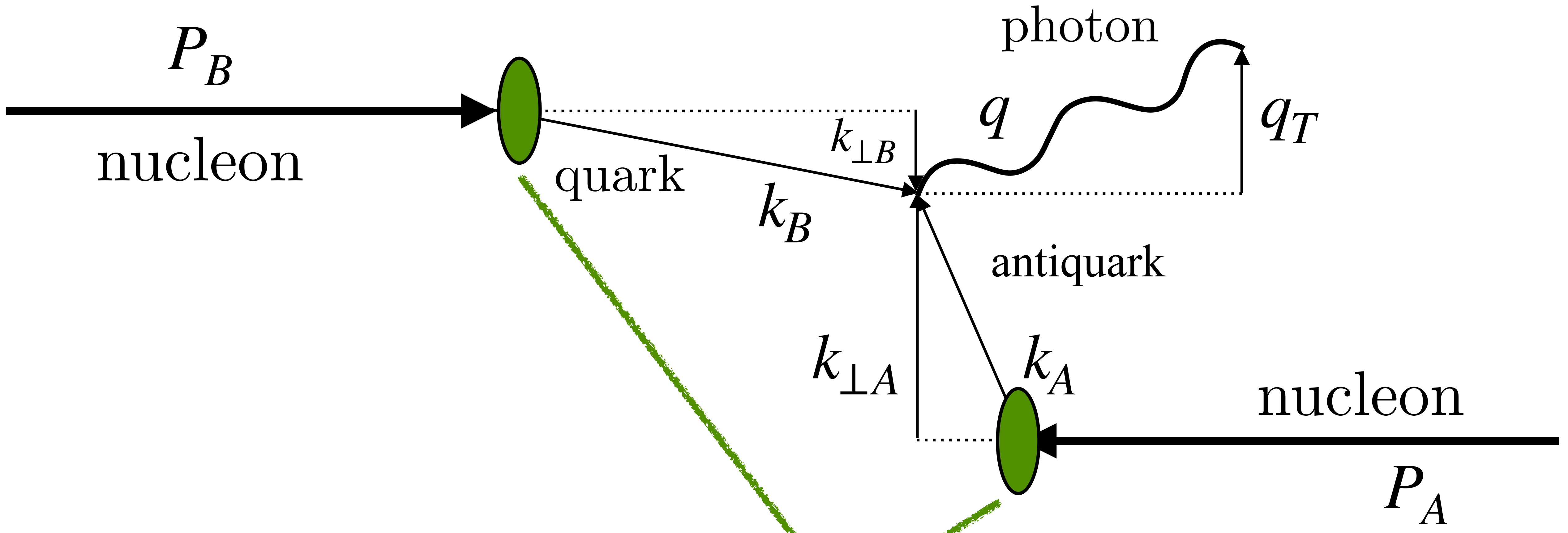
W term

$$F_{UU}^1(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$= \sum_a \mathcal{H}_{UU}^{1a}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a\big(x_A, \boldsymbol{k}_{\perp A}^2; \mu^2\big)\, f_1^{\bar{a}}\big(x_B, \boldsymbol{k}_{\perp B}^2; \mu^2\big)\, \delta^{(2)}\big(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}\big)$$

$$+ Y_{UU}^1\big(Q^2, \boldsymbol{q}_T^2\big) + \mathcal{O}\big(M^2/Q^2\big)$$

TMDS IN DRELL-YAN PROCESSES



$$F^1_{UU}(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

W term

$$= \sum_a \mathcal{H}^{1a}_{UU}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a\left(x_A, \boldsymbol{k}_{\perp A}^2; \mu^2\right) f_1^{\bar{a}}\left(x_B, \boldsymbol{k}_{\perp B}^2; \mu^2\right) \delta^{(2)}\left(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}\right)$$

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- The W term dominates in the region where $q_T \ll Q$

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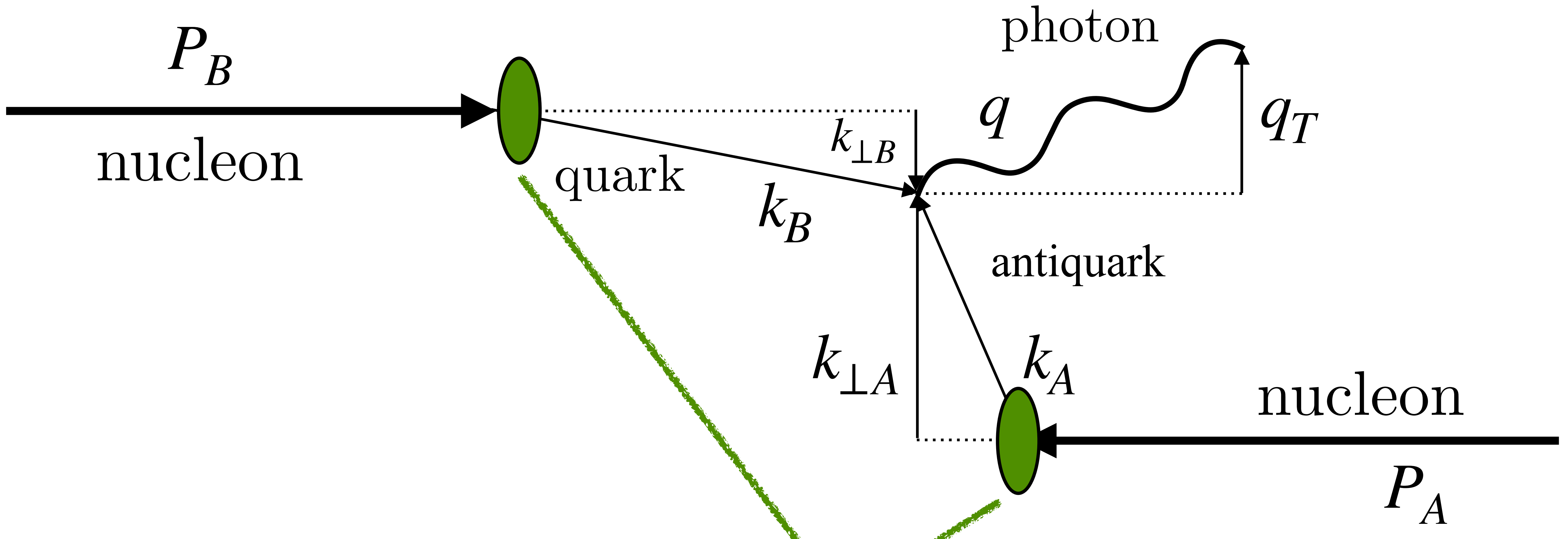
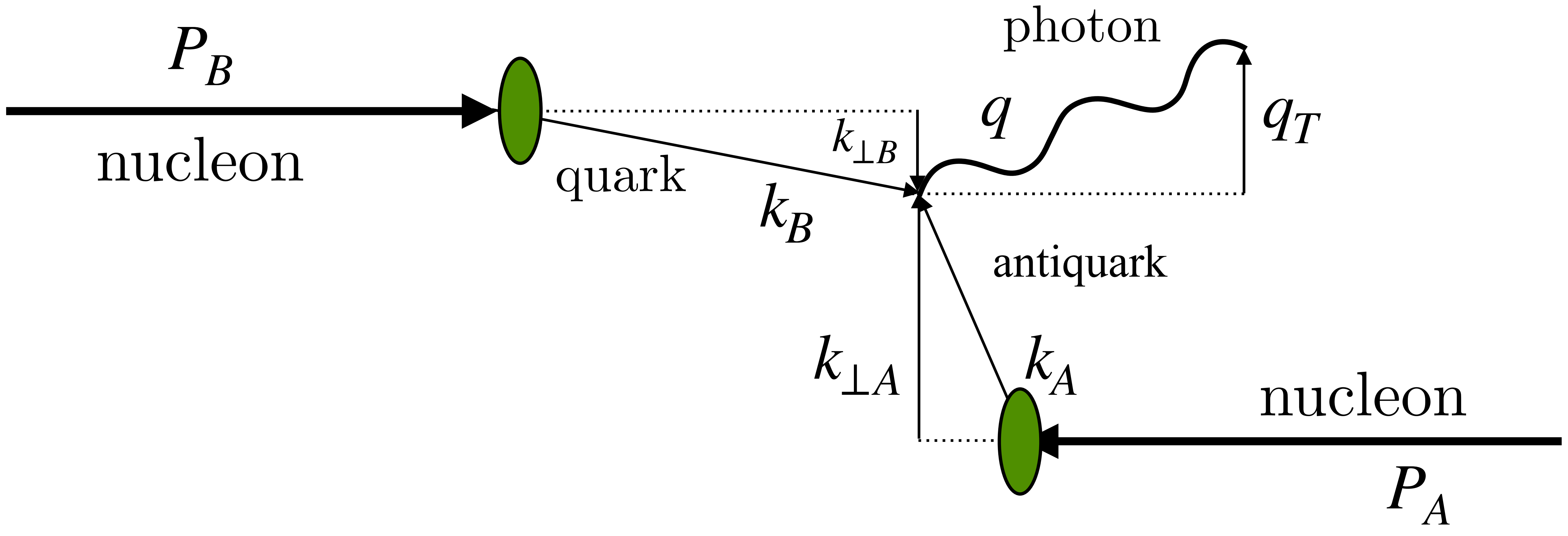


W term

$$
\begin{aligned}
F_{UU}^{1}(x_A, x_B, \boldsymbol{q}_T^2, Q^2) \\
= \sum_a \mathcal{H}_{UU}^{1a}(Q^2,\mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a\left(x_A, \boldsymbol{k}_{\perp A}^2;\mu^2\right) f_1^{\bar a}\left(x_B, \boldsymbol{k}_{\perp B}^2;\mu^2\right) \delta^{(2)}\left(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}\right) \\
+ Y_{UU}^{1}\left(Q^2, \boldsymbol{q}_T^2\right) + \mathcal{O}\left(M^2/Q^2\right)
\end{aligned}
$$

- The W term dominates in the region where $q_T \ll Q$
- Y term has been excluded in the Pavia analyses

TMDS IN DRELL–YAN PROCESSES

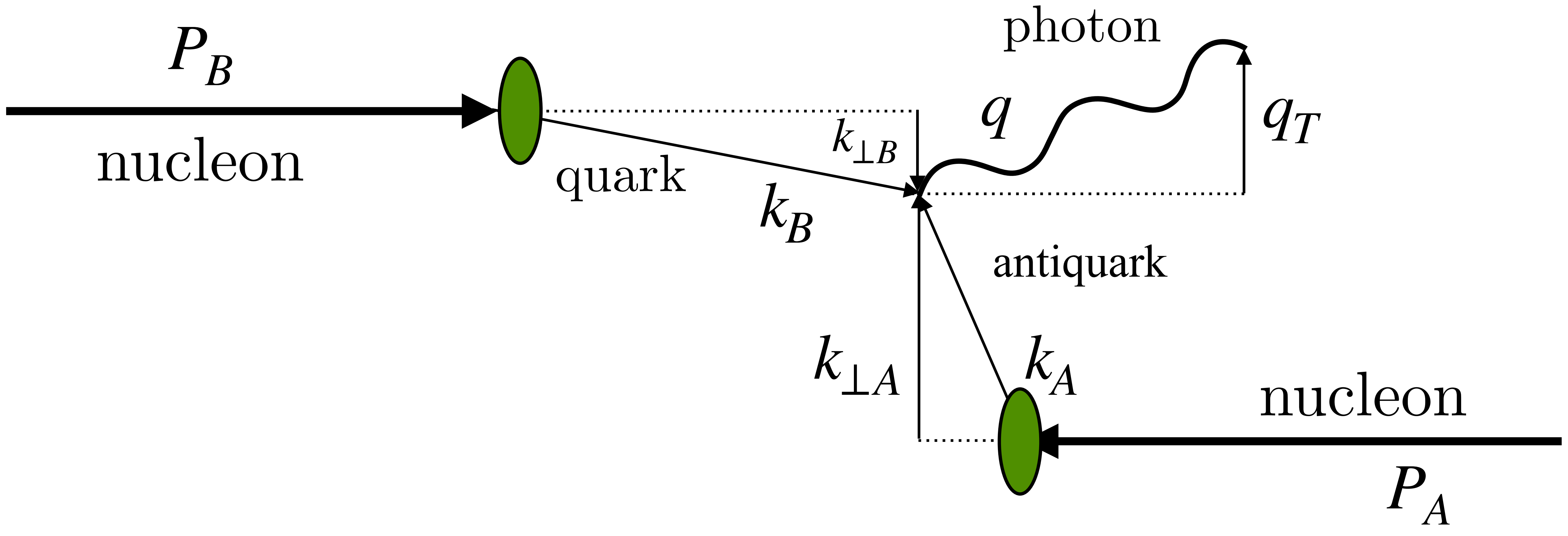


$$F_{UU}^{1}(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$\approx \sum_q \mathcal{H}_{UU}^{1q}(Q^2,\mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^q(x_A, \boldsymbol{k}_{\perp A}^2;\mu^2)\, f_1^{\bar{q}}(x_B, \boldsymbol{k}_{\perp B}^2;\mu^2)\, \delta^{(2)}(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B})$$

$$= \sum_q \mathcal{H}_{UU}^{1q}(Q^2,\mu^2) \int db_T b_T J_0(b_T|\boldsymbol{q}_T|) \hat{f}_1^q(x_A, b_T^2;\mu^2)\, \hat{f}_1^{\bar{q}}(x_B, b_T^2;\mu^2)$$

TMDS IN DRELL-YAN PROCESSES



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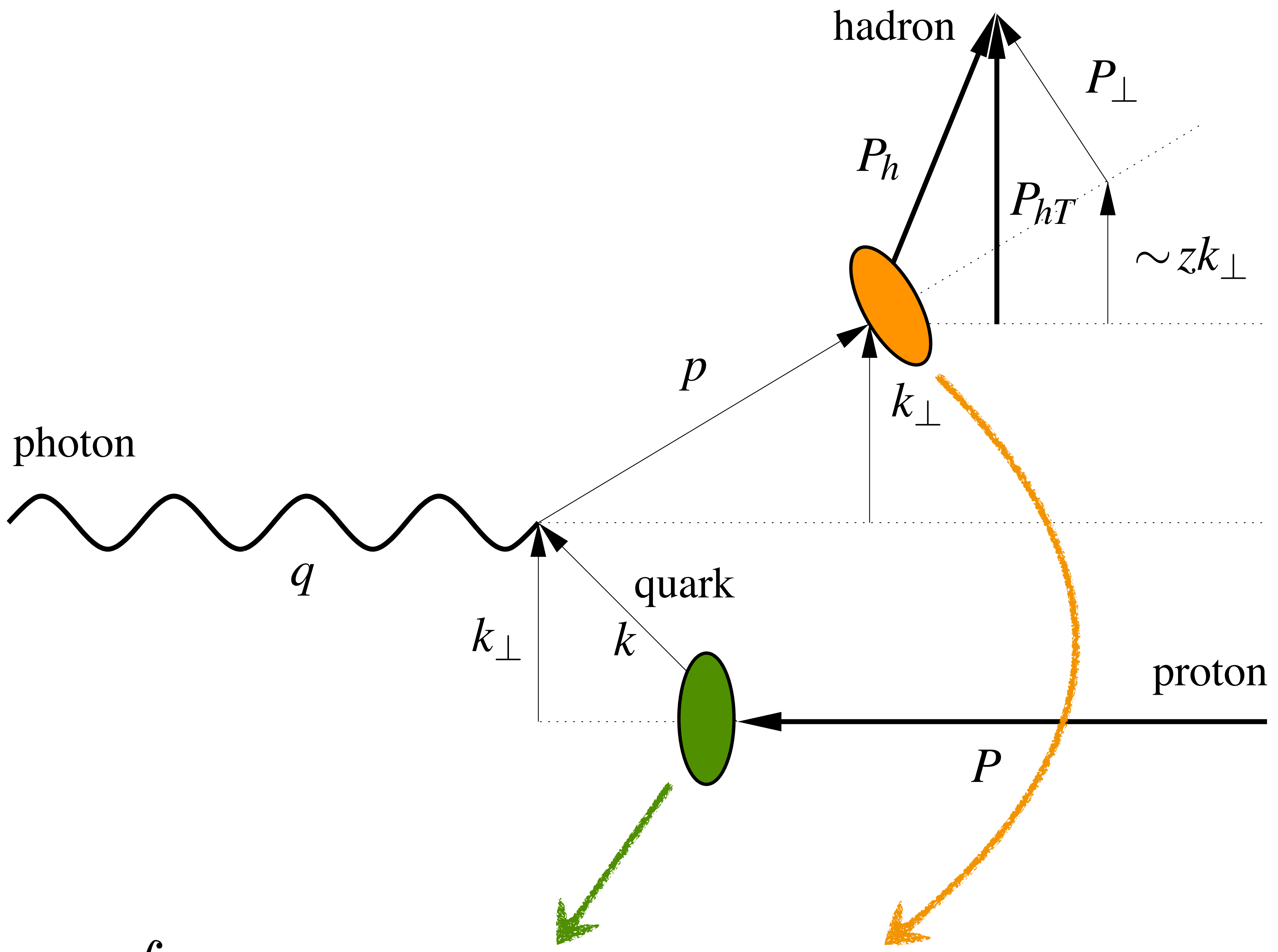
- At small q_T the dominant part is given by TMDs
- Fourier-transformed space to avoid convolutions
- TMDs formally depend on two scales, but we set them equal.

TMDS IN SEMI-INCLUSIVE DIS PROCESS



$$F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$$

$$= x \sum_q \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int d^2\boldsymbol{k}_\perp \, d^2\boldsymbol{P}_\perp \, f_1^a\big(x, \boldsymbol{k}_\perp^2; \mu^2\big) \, D_1^{a\to h}\big(z, \boldsymbol{P}_\perp^2; \mu^2\big) \, \delta\big(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp\big)$$

$$= x \sum_a \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|) \hat{f}_1^q\big(x, z^2 b_\perp^2; \mu^2\big) \, \hat{D}_1^{a\to h}\big(z, b_\perp^2; \mu^2\big)$$

TMD STRUCTURE

$$\hat{f}_1^q(x, b_T; \mu^2) = \int d^2\boldsymbol{k}_\perp e^{i\boldsymbol{b}_T \cdot \boldsymbol{k}_\perp} f_1^q(x, \boldsymbol{k}_\perp^2; \mu^2)$$

see, e.g.,
Collins, "Foundations of Perturbative QCD" (11)

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matching coefficients
(perturbative)

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nonperturbative part of TMD

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PERTURBATIVE ORDER OF EACH INGREDIENT

Orders in powers of α_S

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Hard factor and matching coefficient → H and C

Ingredients in perturbative Sudakov form factor → K and γ_F, γ_K

Accuracy	H and C	K and γ_F	γ_K	PDF and α_S evol.
LL	0	-	1	-
NLL	0	1	2	LO
NLL'	1	1	2	NLO
NNLL	1	2	3	NLO

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N^3LL	2	3	4	NNLO
N^3LL'	3	3	4	N^3LO

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Collinear fragmentation functions not available beyond NLO!!

RECENT GLOBAL FITS OF UNPOLARIZED TMD DATA

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	N^3LL^-	✔	✔	✔	✔	1039	1.06
Pavia 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353	1.02

OUR WORK IN THE LAST TWO YEARS

New Global Fit

Simultaneously extraction of unpolarized TMD PDFs and FFs

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- SIDIS + Drell Yan

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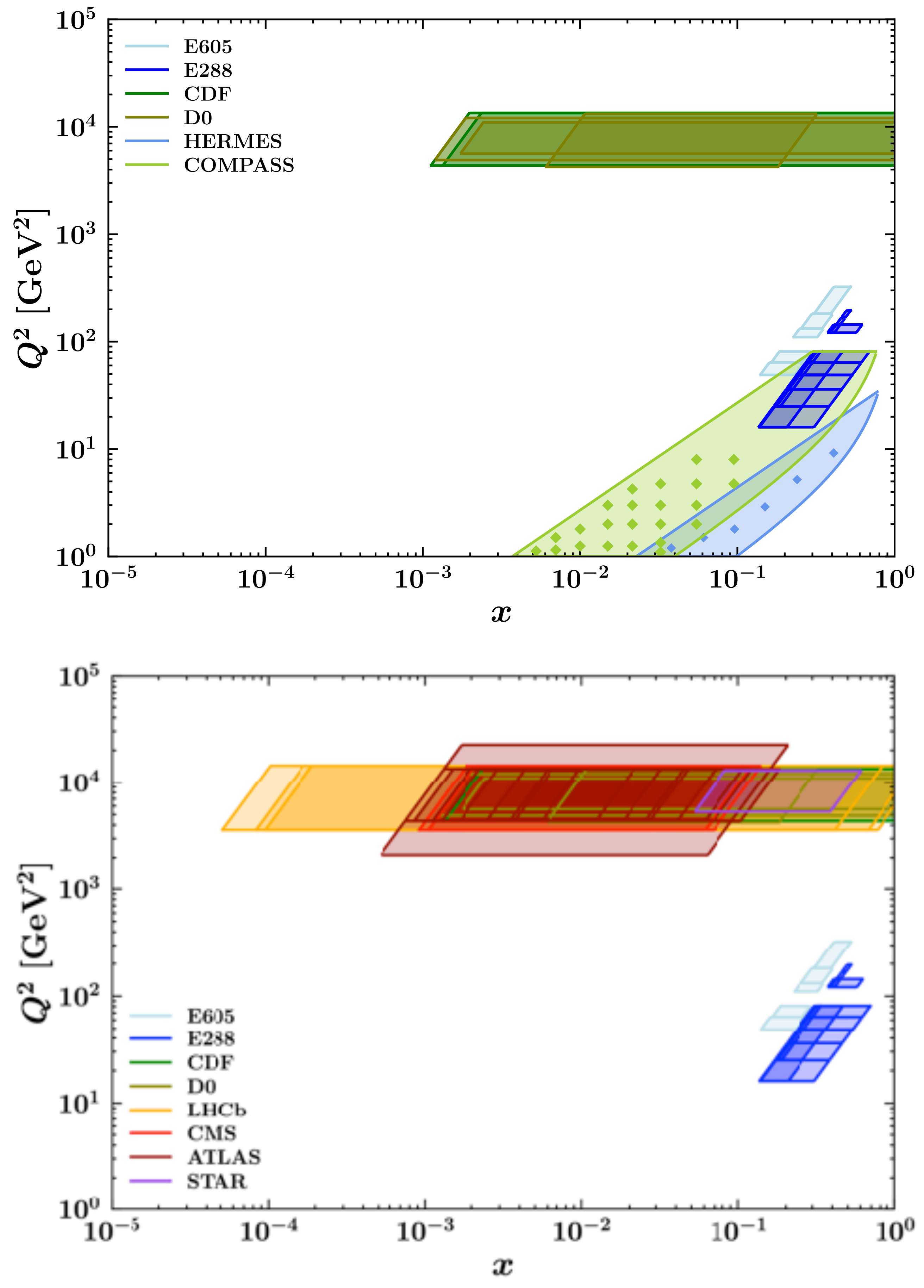

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- ✓ SIDIS + Drell Yan
- ○ Integrated variables

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Nanga Parbat: a TMD fitting framework

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

You can obtain NangaParbat directly from the github repository:

https://github.com/vbertone/NangaParbat/releases

For the last development branch you can clone the master code:

```
git clone git@github.com:vbertone/NangaParbat.git
```

If you instead want to download a specific tag:

https://github.com/MapCollaboration

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Simultaneously extraction of unpolarized TMD PDFs and FFs

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- ✓ Integrated variables
- ○ Up to N^2LL/N^3LL

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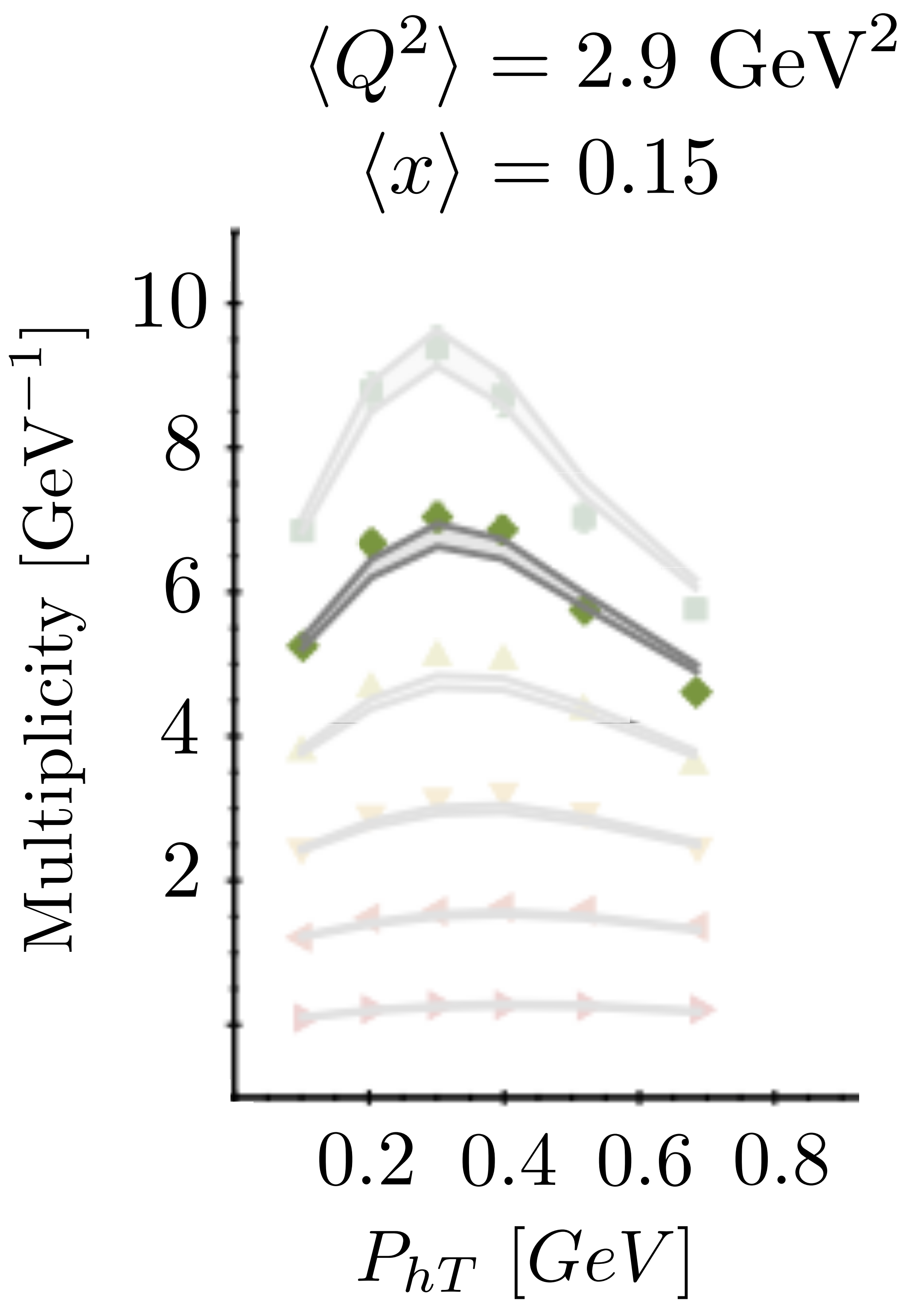
RESULTS AT NLL: SIDIS (MULTIPLICITIES)

What we expected

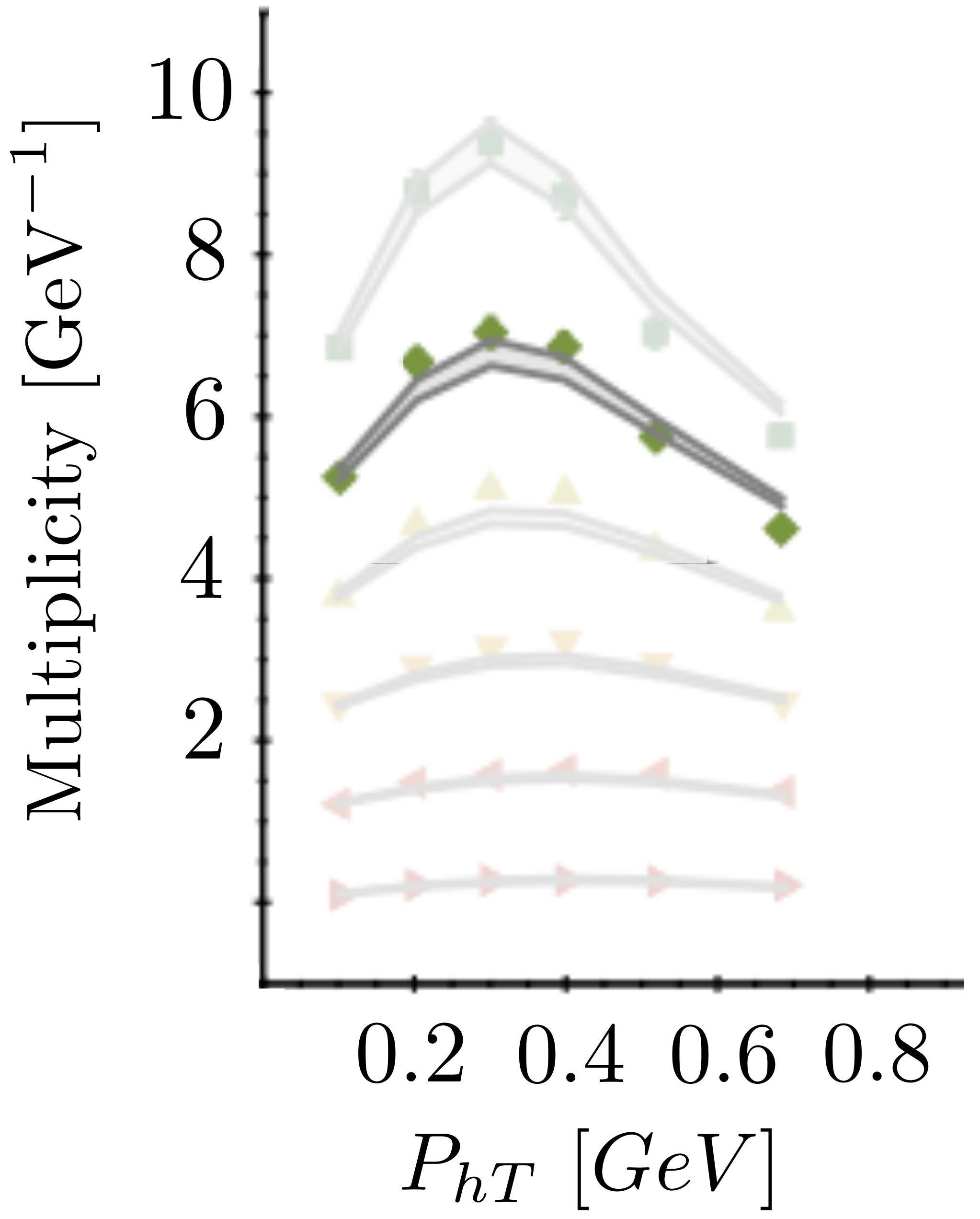


Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

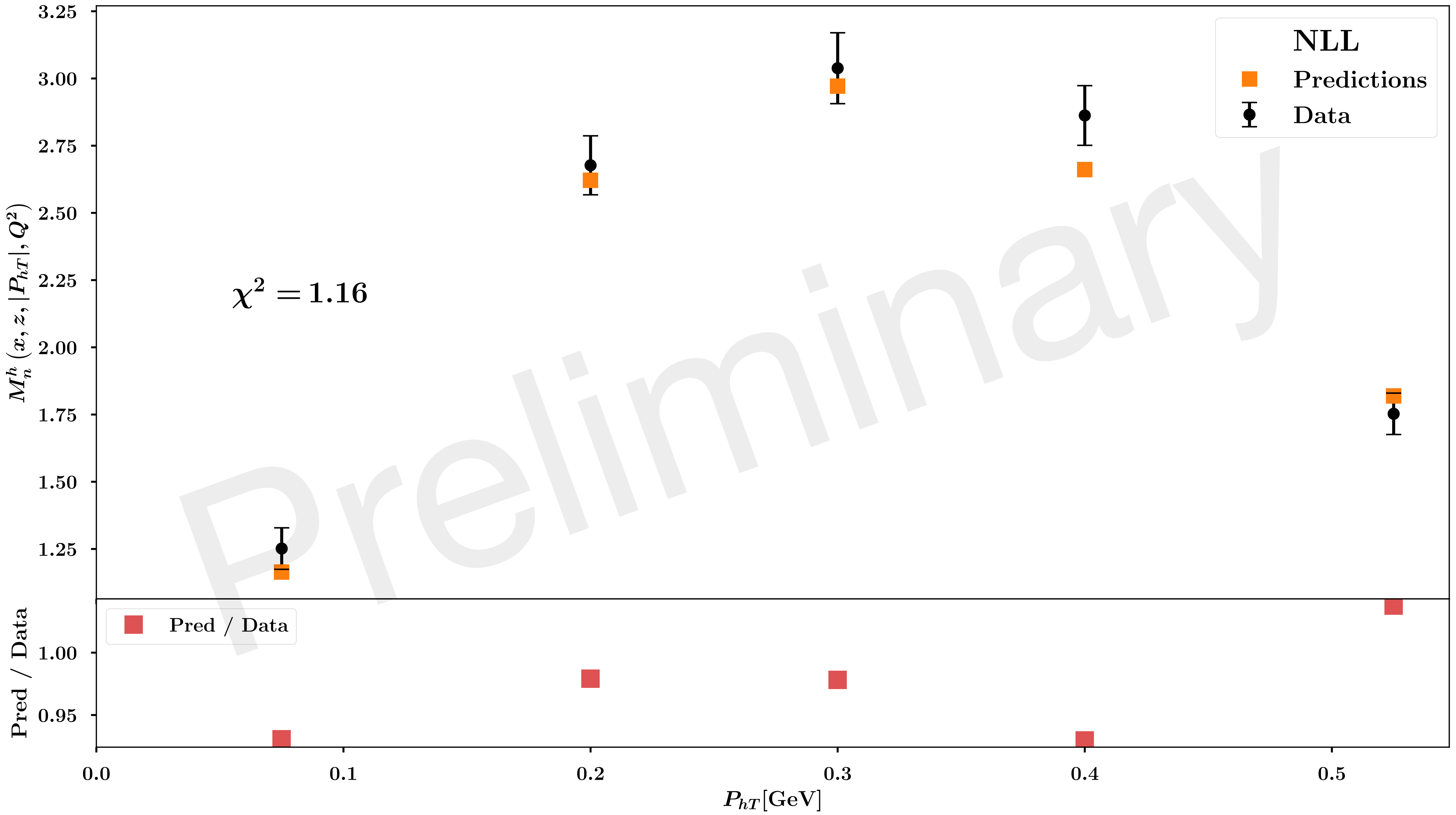
RESULTS AT NLL: SIDIS (MULTIPLICITIES)

What we expected

$$\langle Q^2 \rangle = 2.9\ \mathrm{GeV}^2$$
$$\langle x \rangle = 0.15$$



What we found



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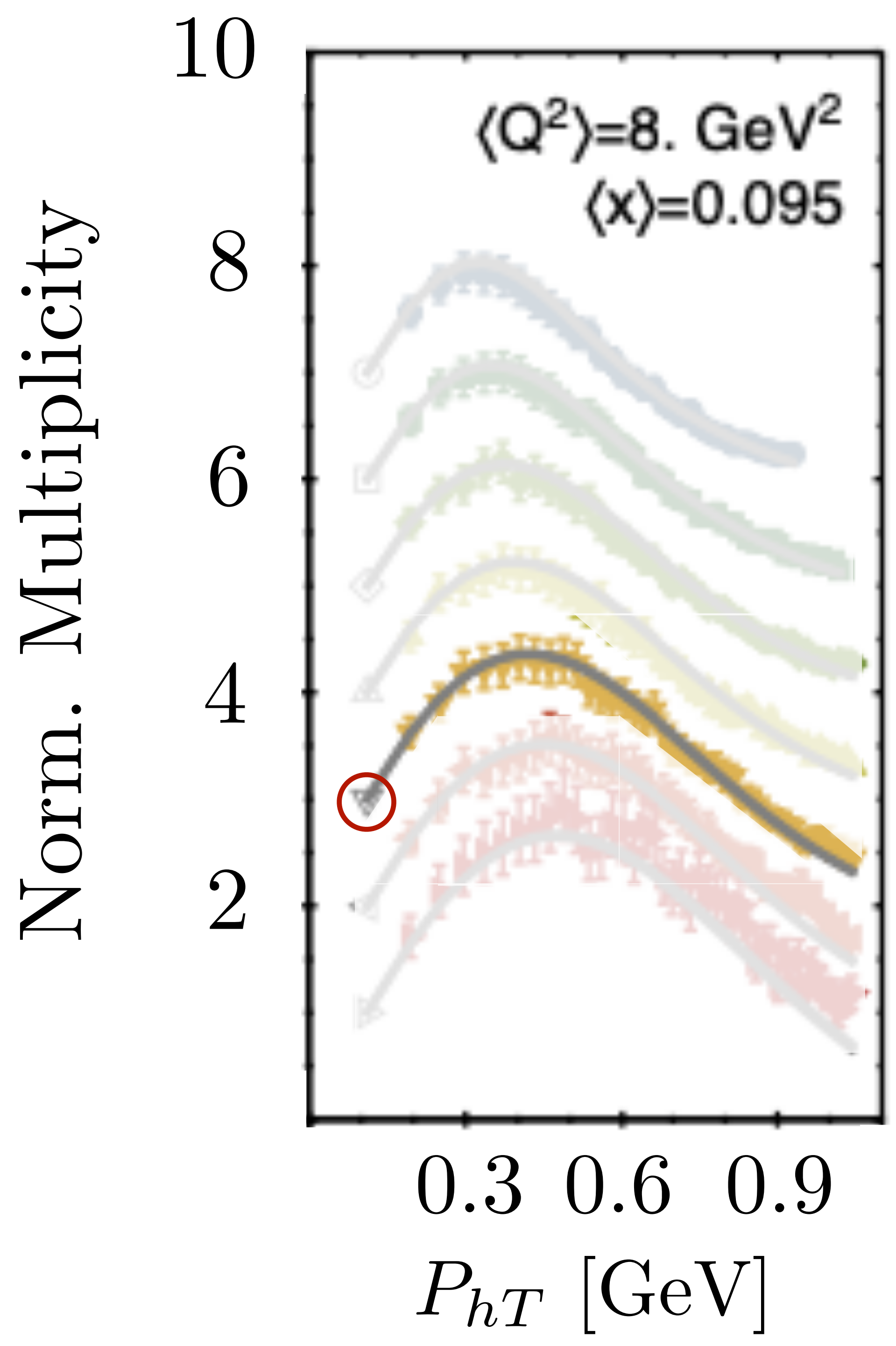

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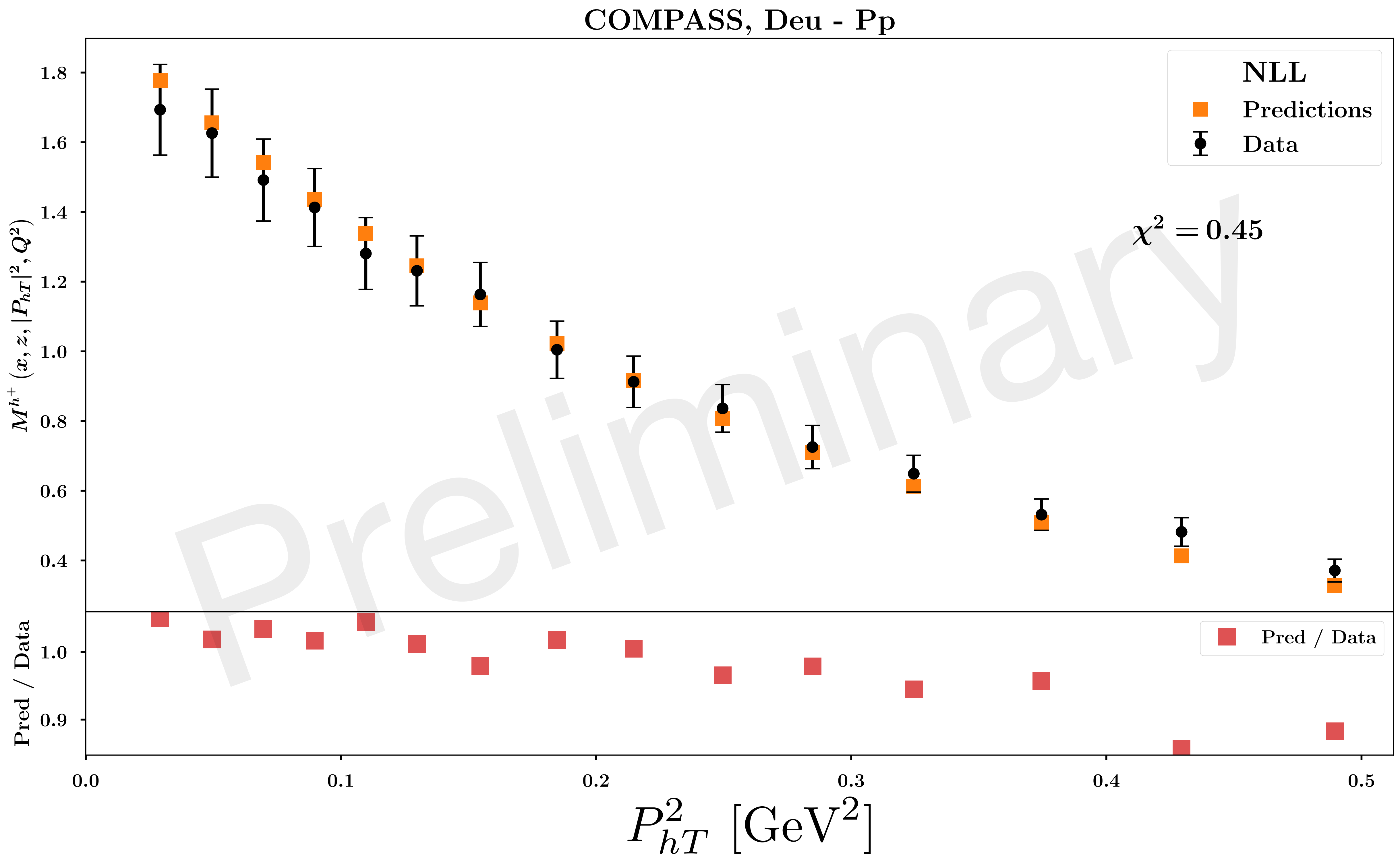

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RESULTS AT NLL: DRELL YAN

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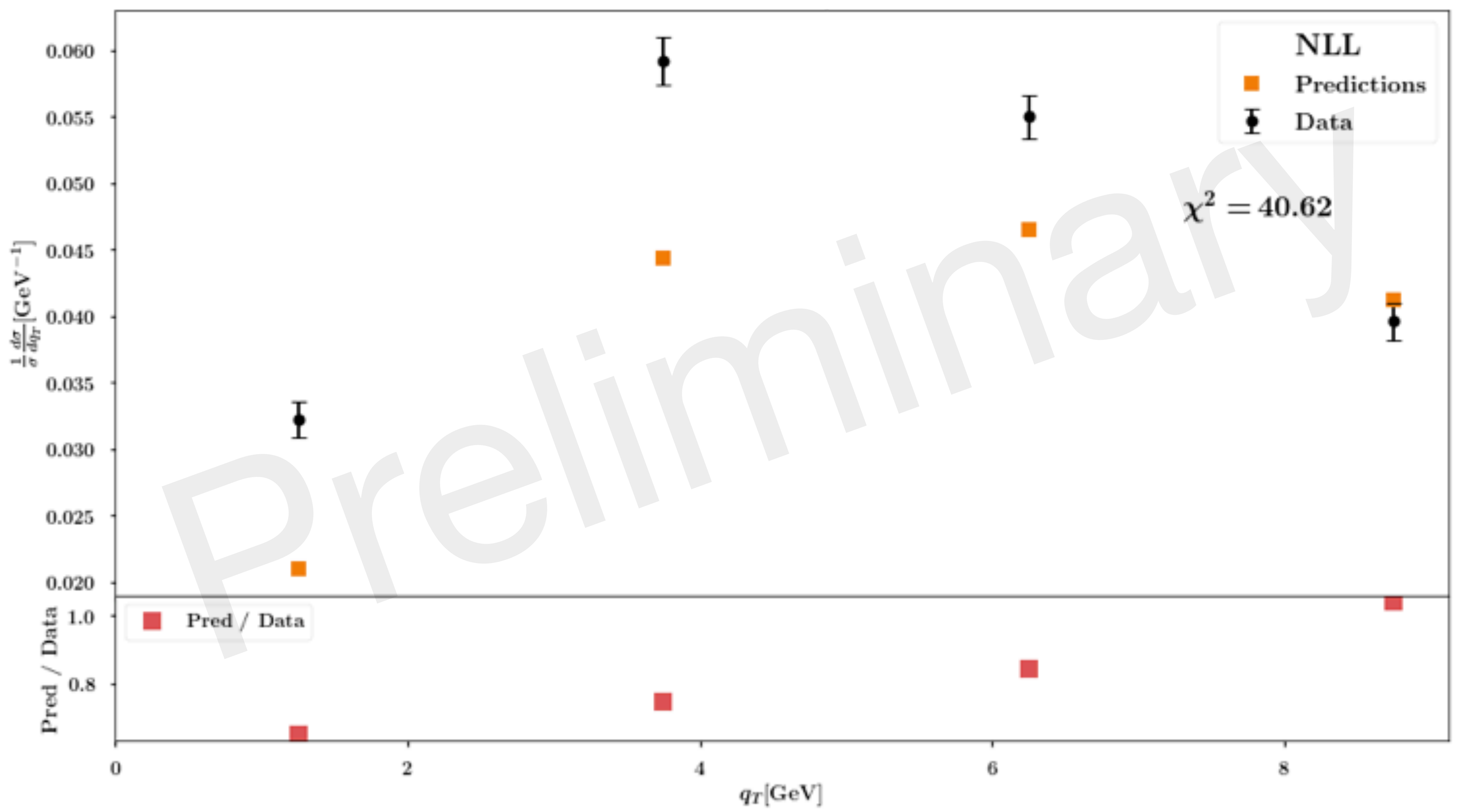
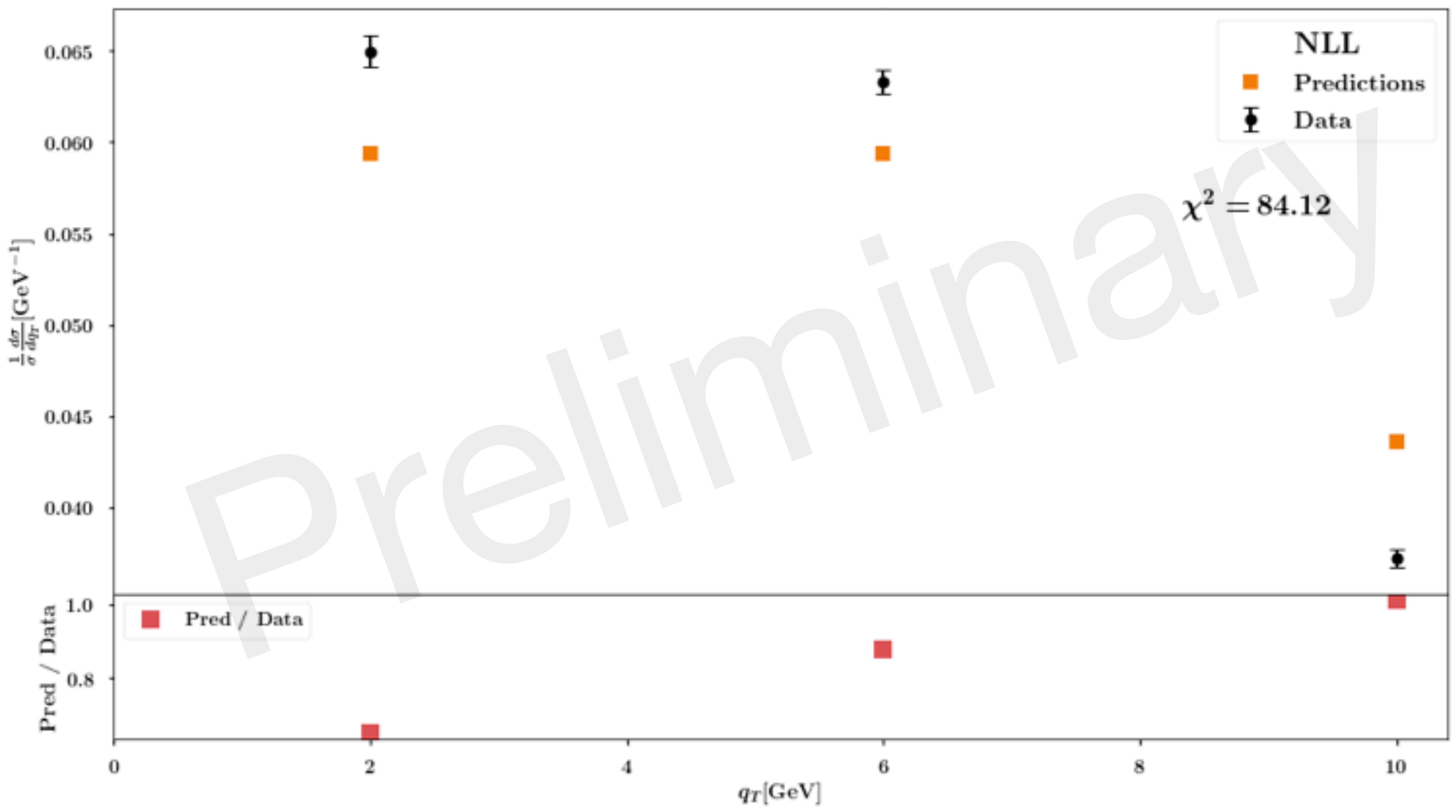
CMS 7 TeV



D0 Run II muons



RESULTS AT NLL: DRELL YAN

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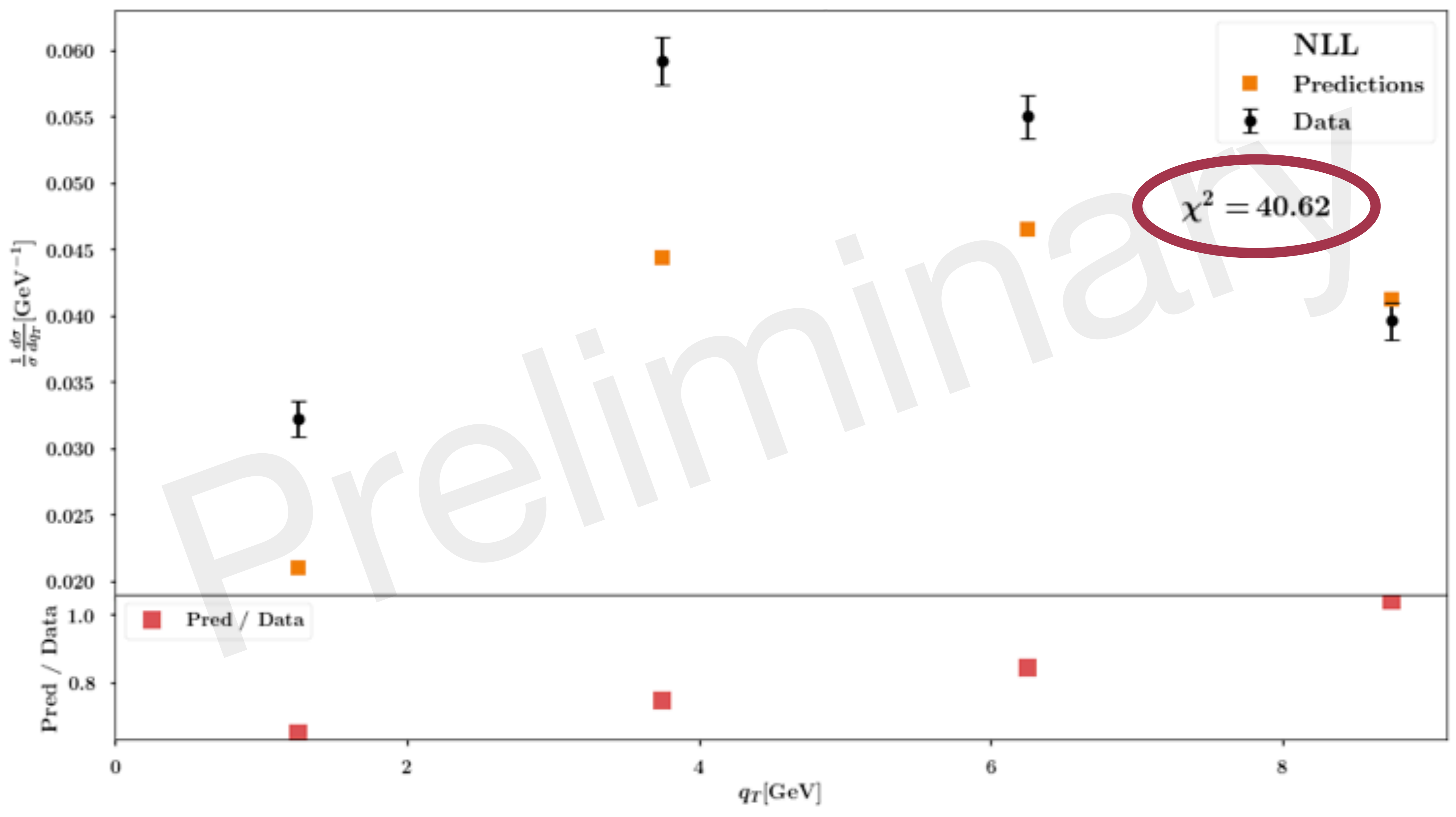

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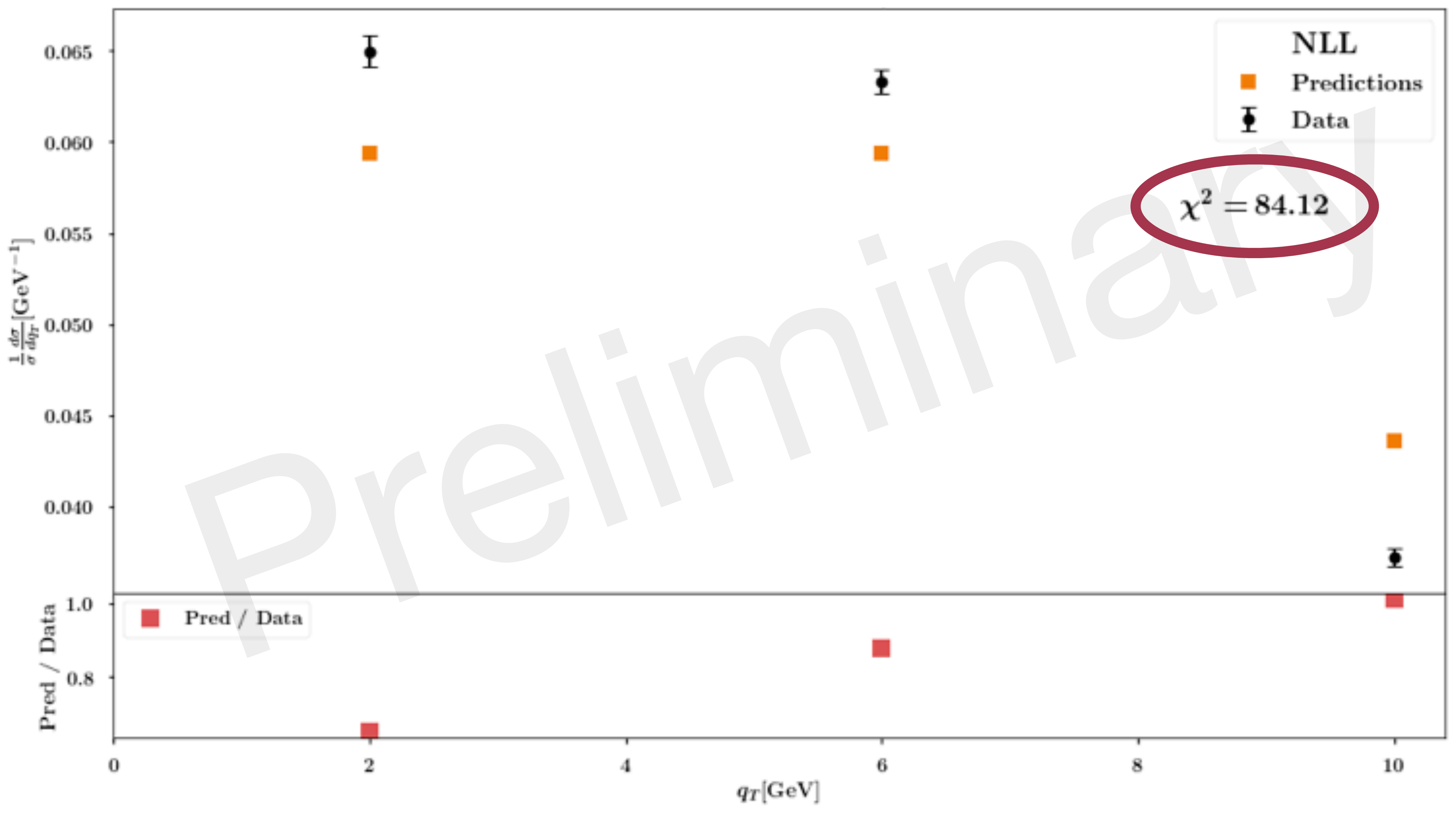

We need to increase the accuracy!!

COMPARISON OF DIFFERENT ORDERS

Accuracy at N^2LL and N^3LL

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What we expected

COMPARISON OF DIFFERENT ORDERS

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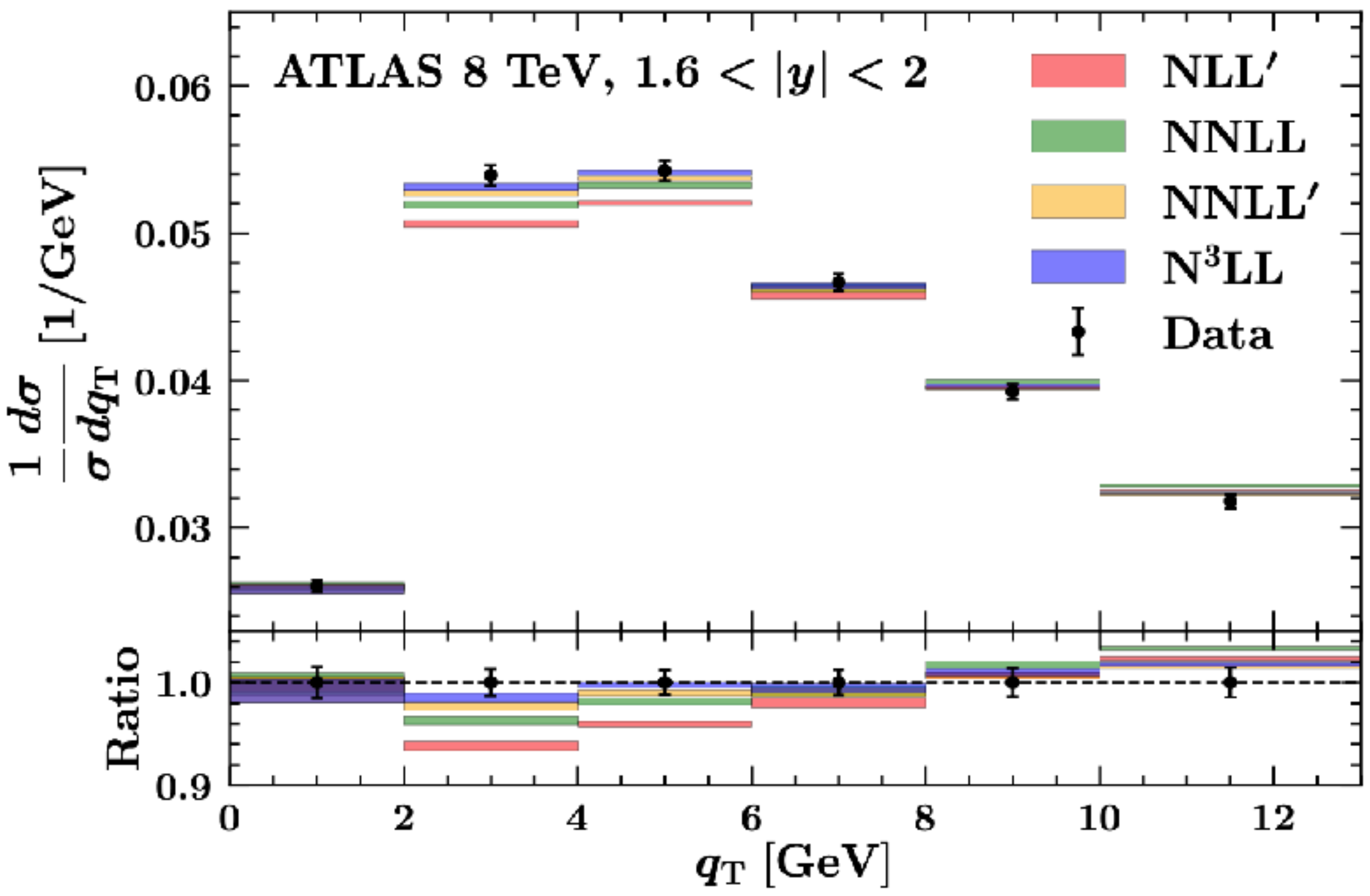
$Q \sim 100$ GeV



Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550

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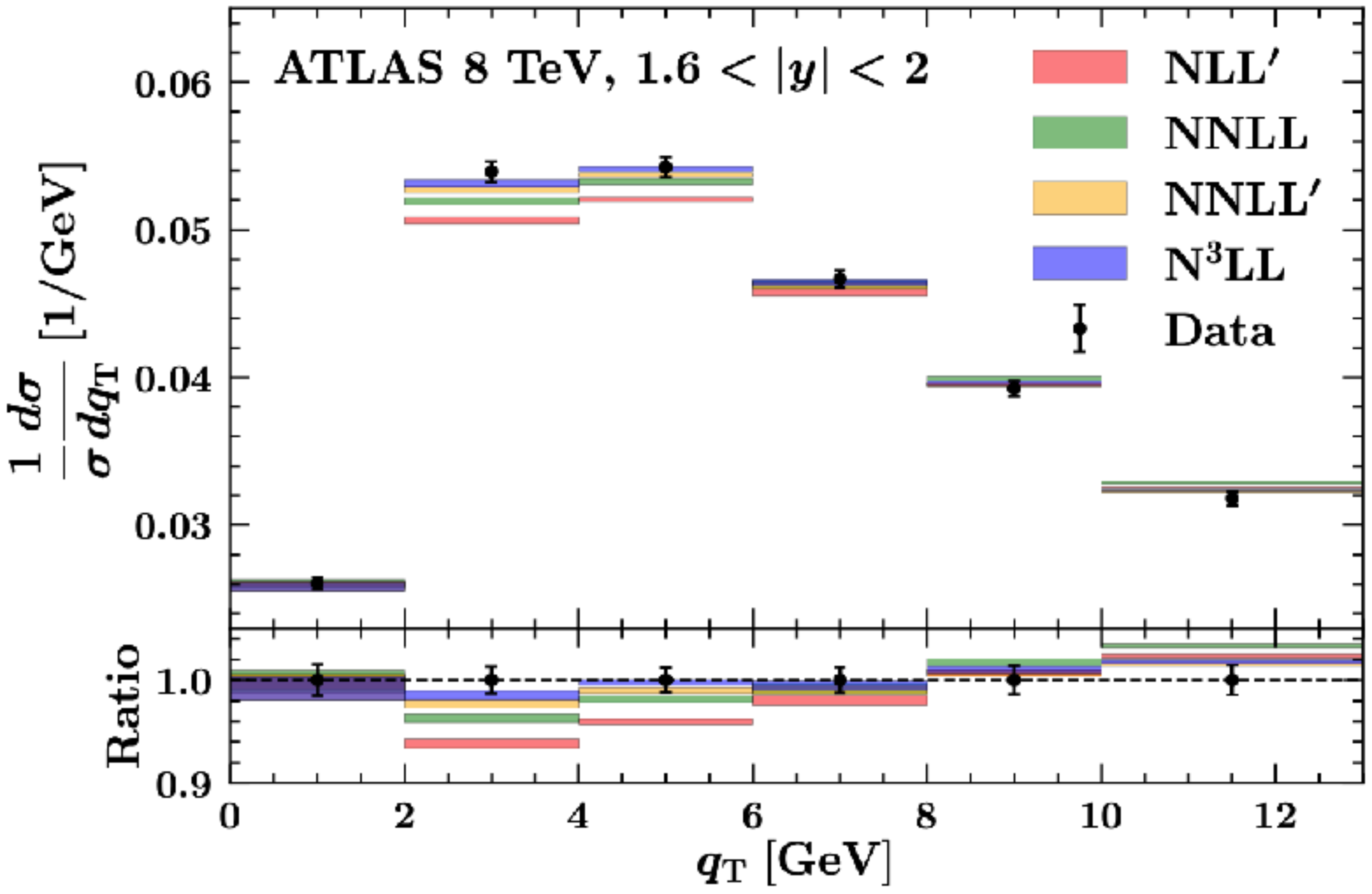
What we expected

$Q \sim 100$ GeV

What we get



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COMPARISON OF DIFFERENT ORDERS

Accuracy at N²LL and N³LL

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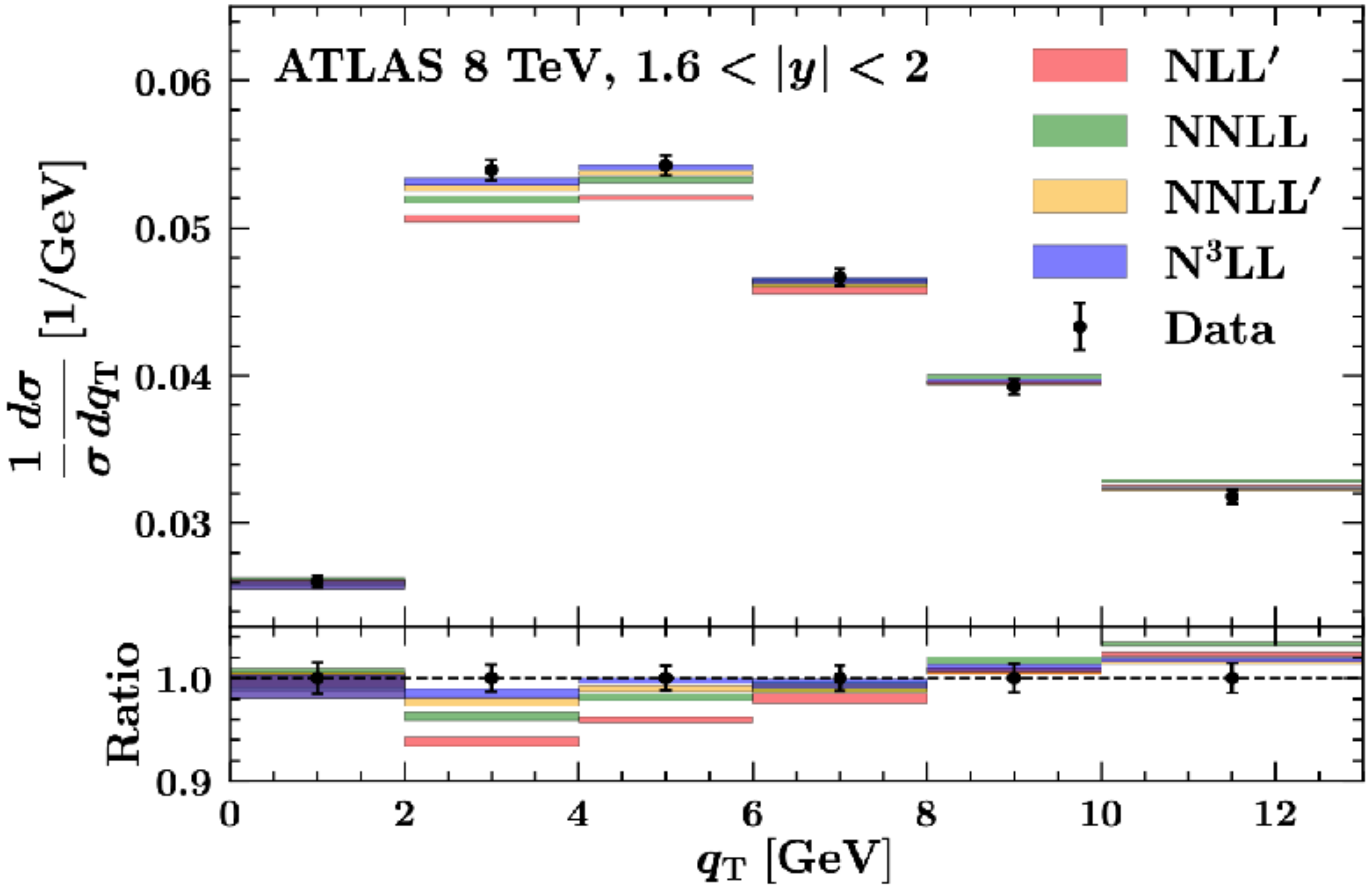
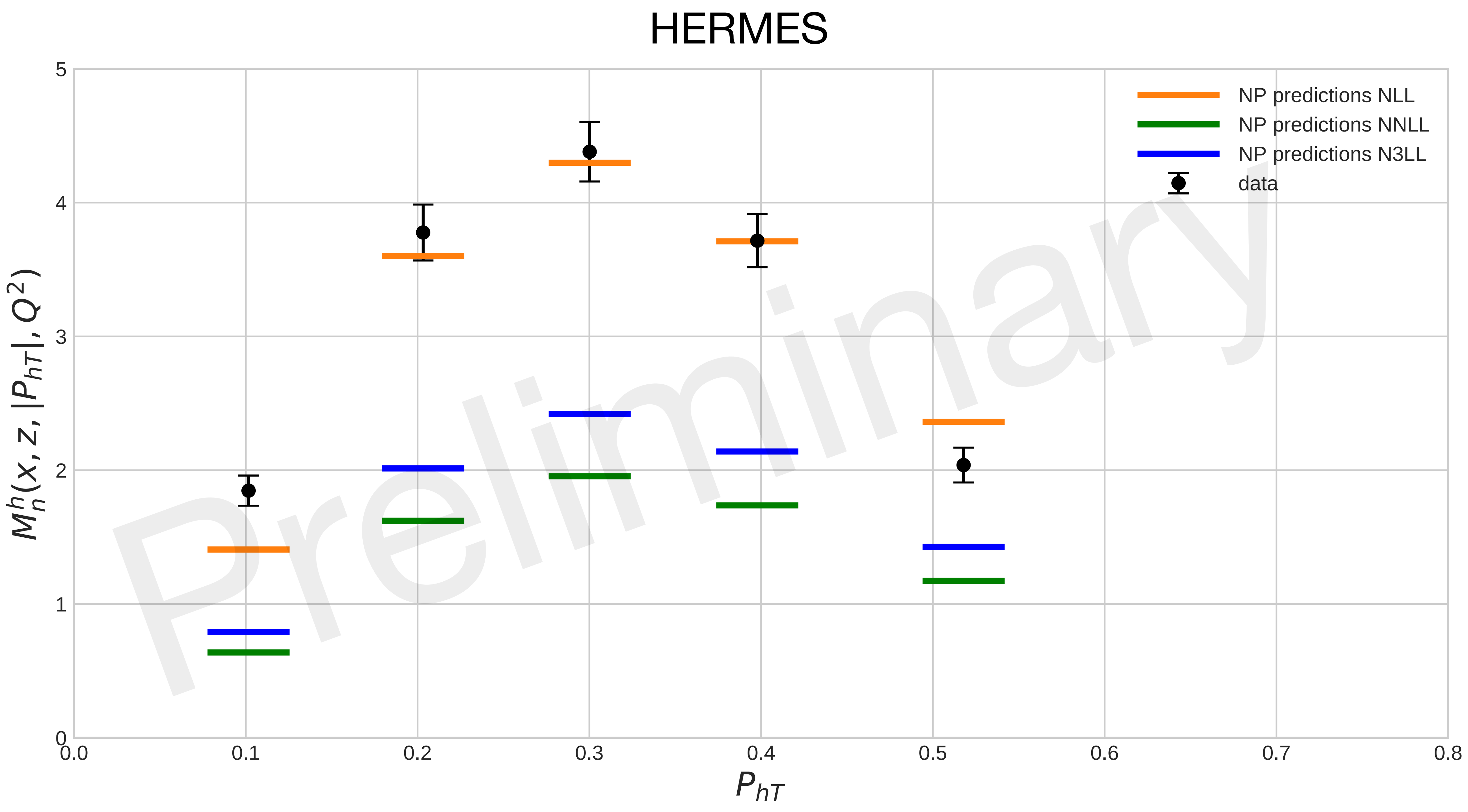


What we get $Q \sim 2$ GeV



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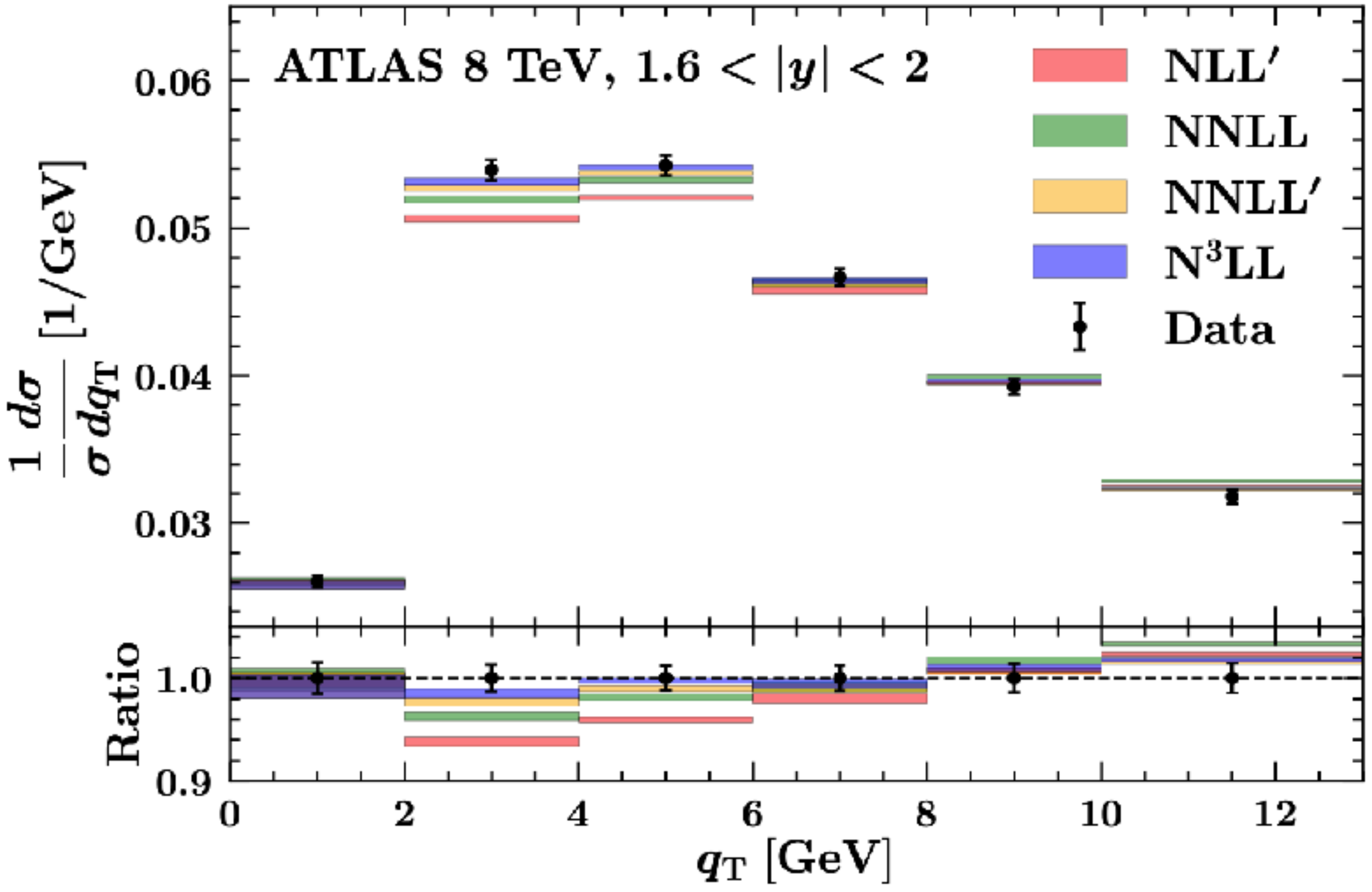

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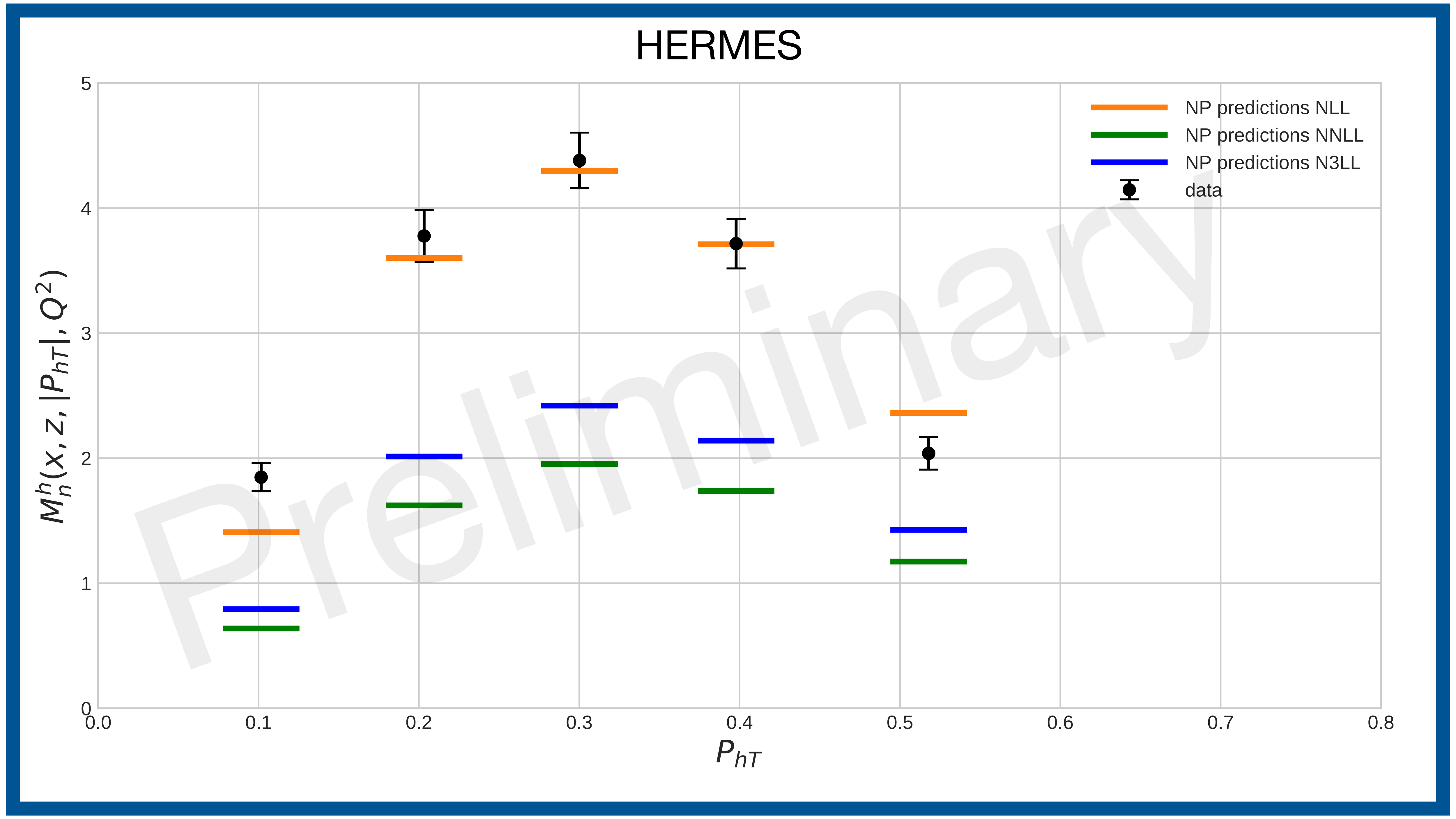
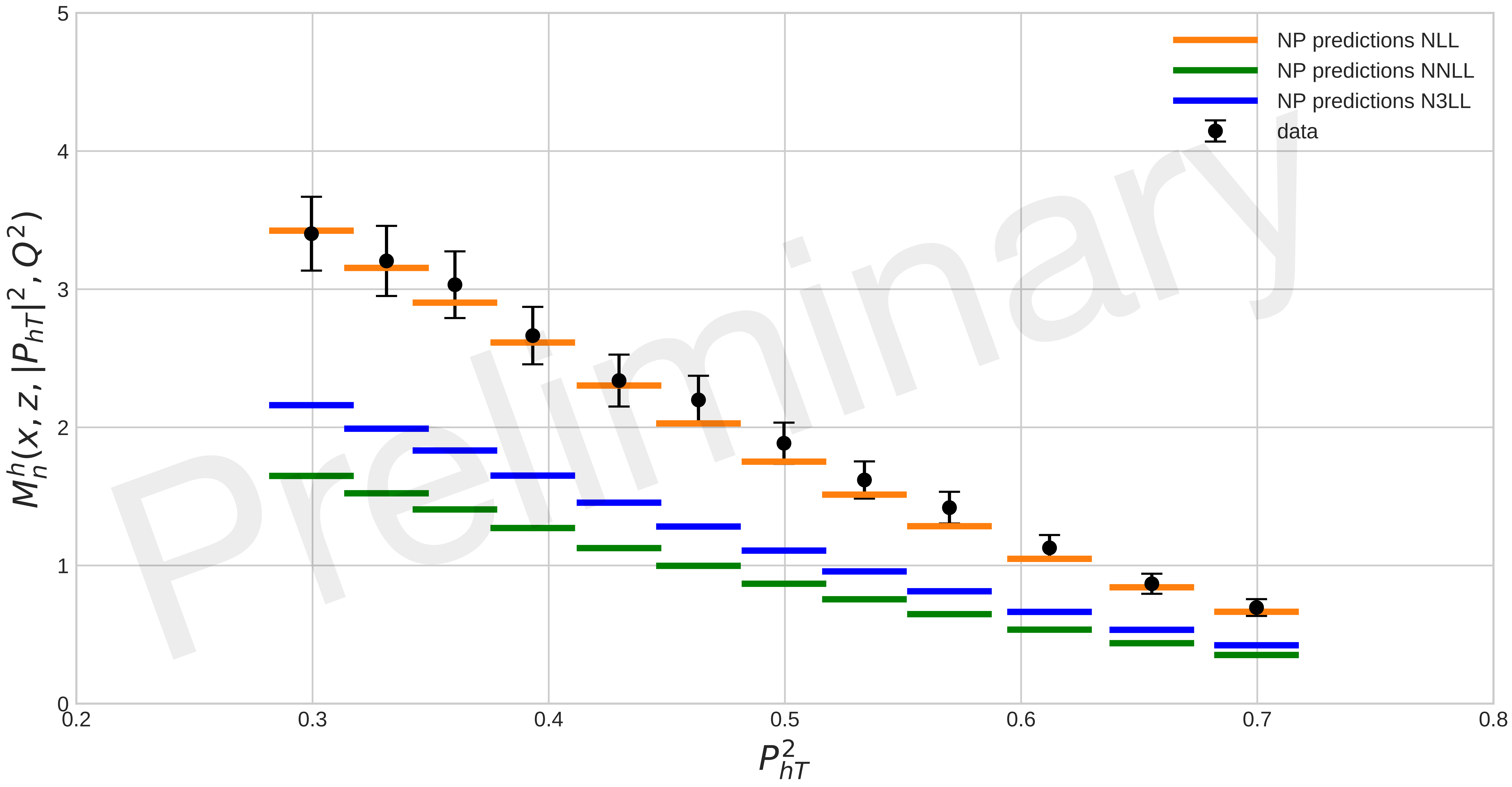


The description considerably worsens at higher orders!!

COMPARISON OF DIFFERENT ORDERS – SIDIS

COMPASS multiplicities (one of many bins)



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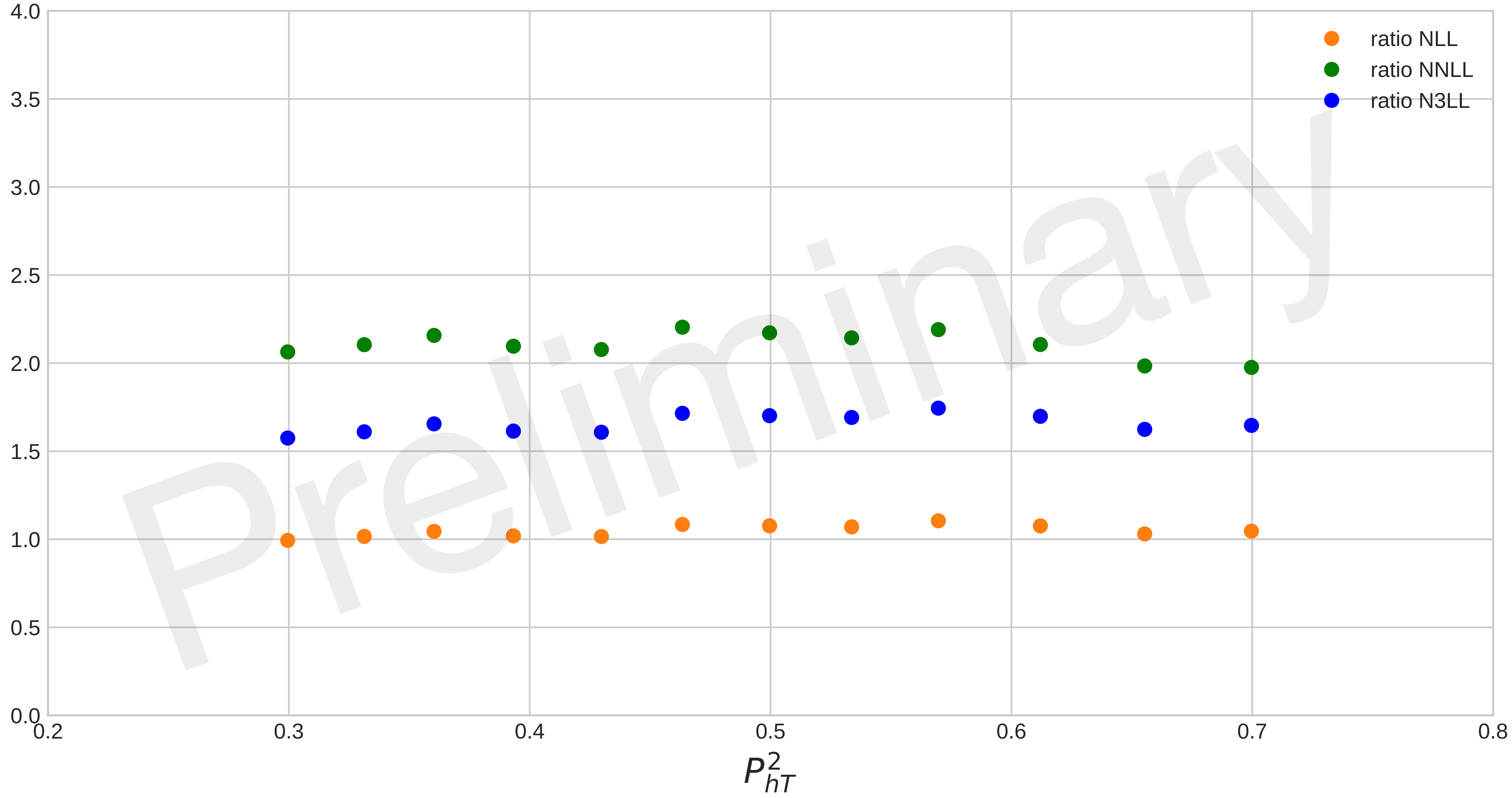
RATIO DATA/PREDICTIONS: SIDIS

COMPASS multiplicities (one of many bins)



The discrepancy amounts to an almost <u>constant factor</u>!!

OUR TENTATIVE SOLUTION

Introduction of a normalization prefactor

$$\text{PREFACTOR}(x, z, Q) = \frac{\left.\frac{d\sigma^h}{dx dQ^2 dz}\right|_{\text{nonmix.}}}{\int W d^2 q_T}$$

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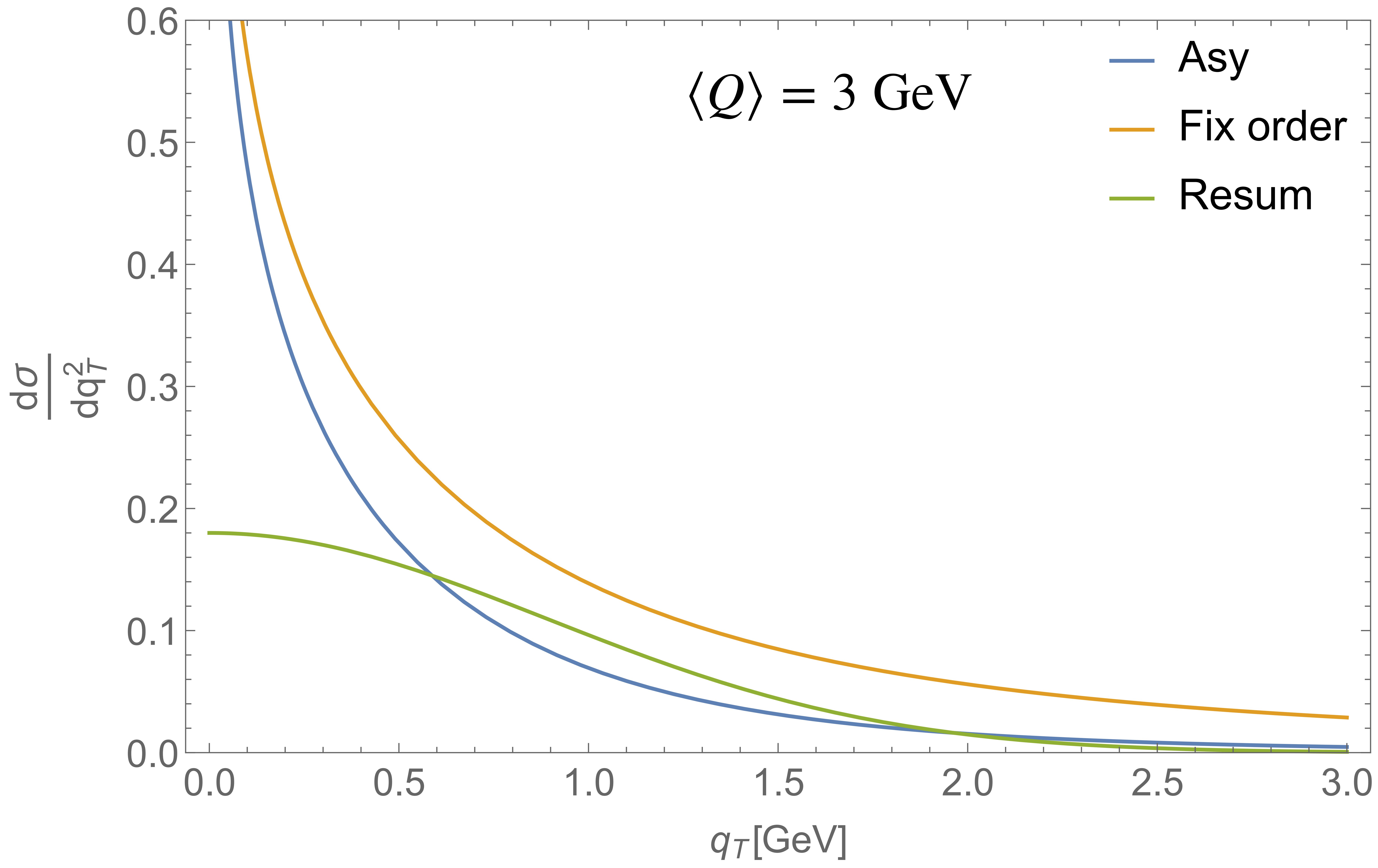
Independent of the fitting parameters!!

SOME JUSTIFICATION: INITIAL SITUATION



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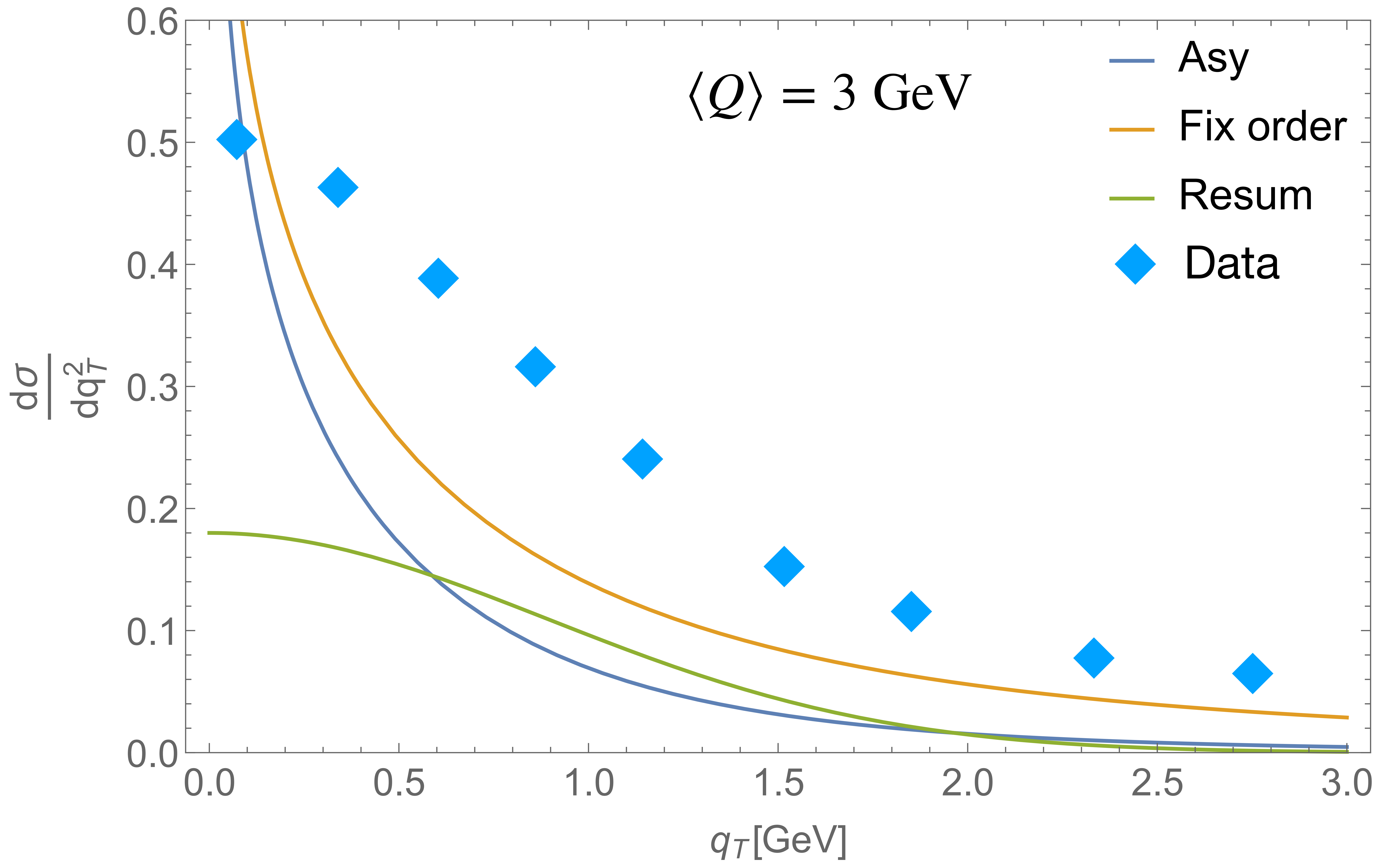
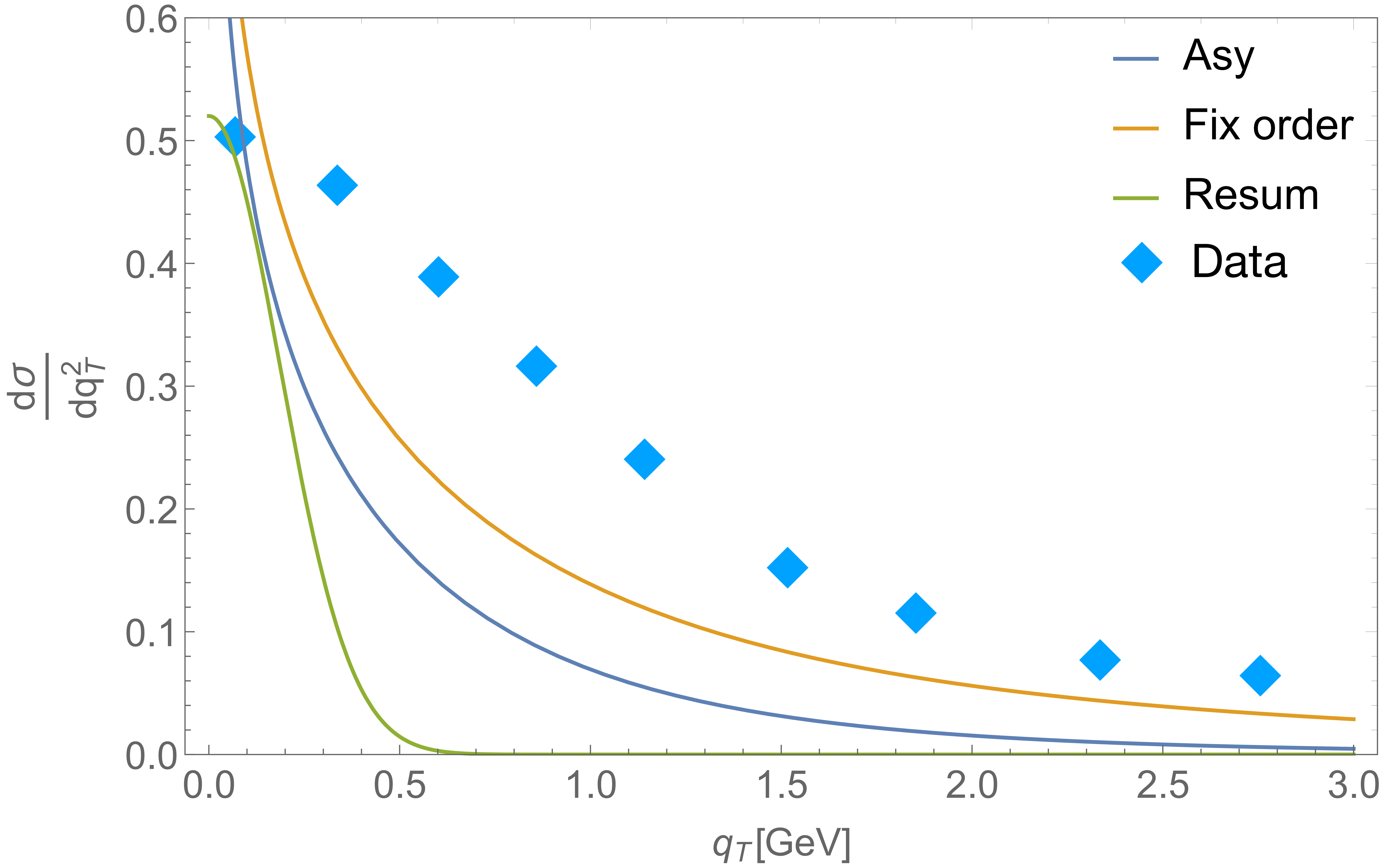
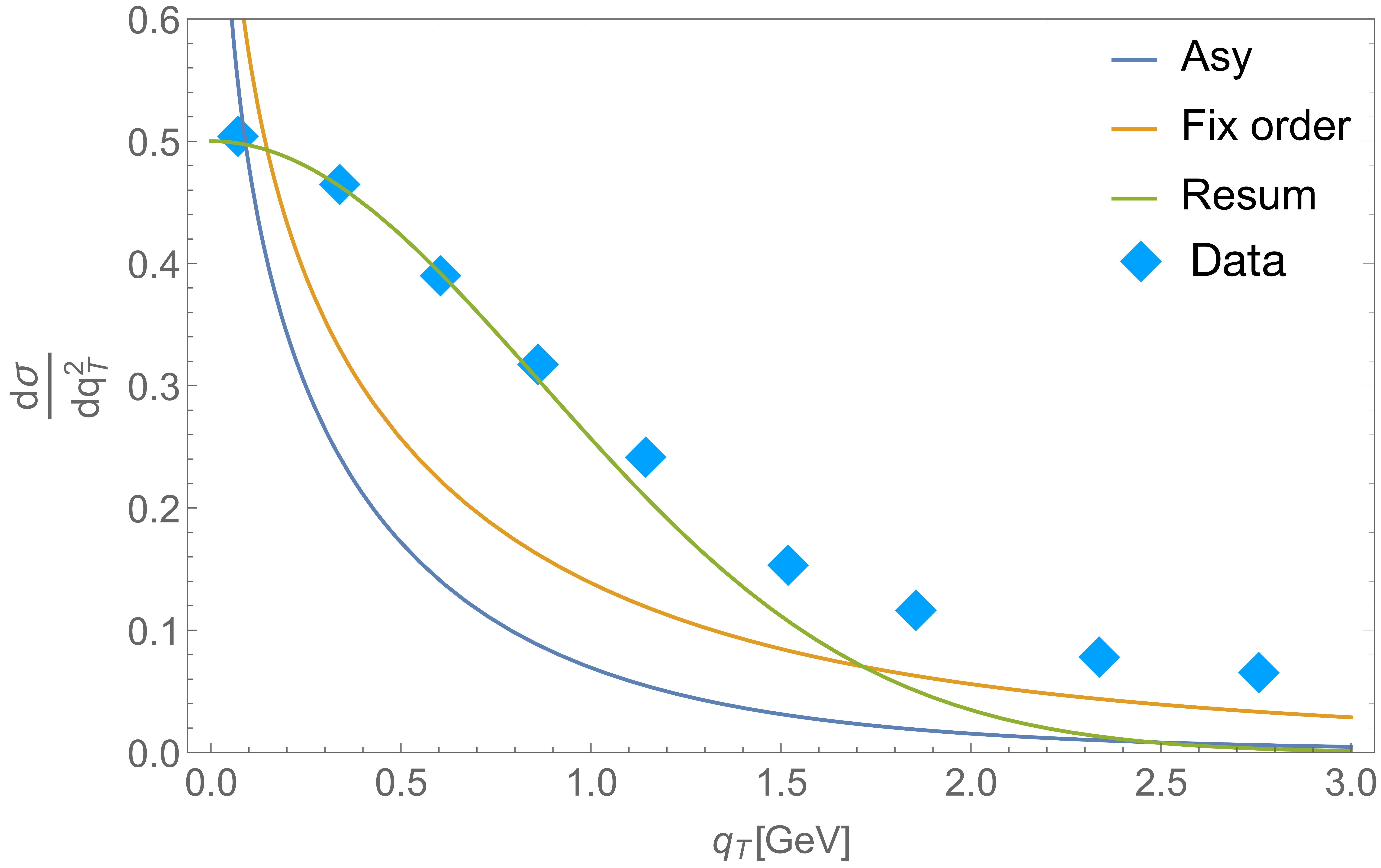


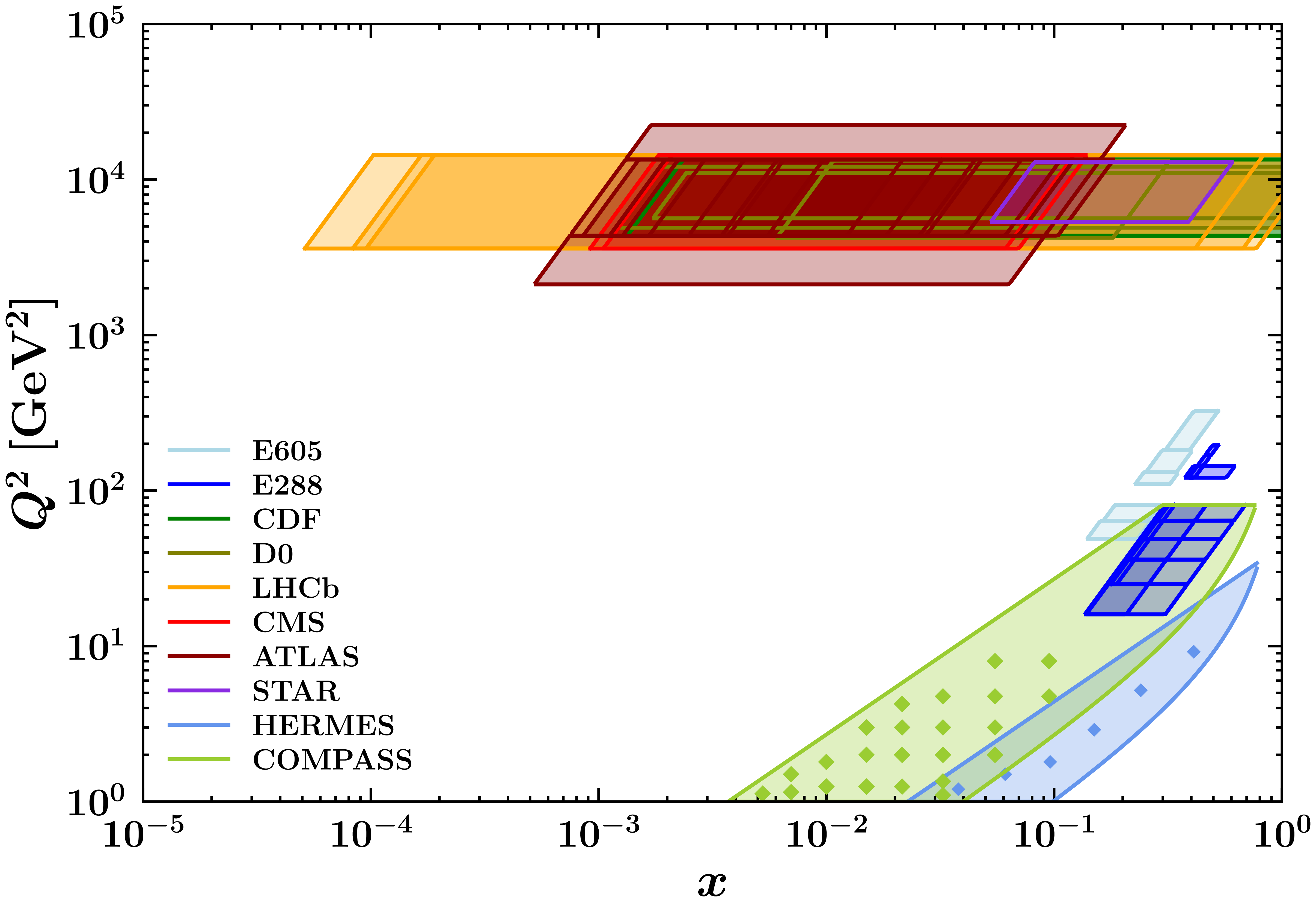
SOLUTION1: RESTRICT TMD REGION



SOLUTION2: ENHANCE TMD CONTRIBUTIONS



MAP21 TMD FIT CHOICES (PRELIMINARY)



$\langle Q \rangle > 1.3$ GeV

$0.2 < z < 0.6$

$q_T < 0.2\ Q \quad$ (DY)

$P_{hT} < \min[\min[0.2Q, 0.5zQ] + 0.3\ \text{GeV}, zQ] \quad$ (SIDIS)

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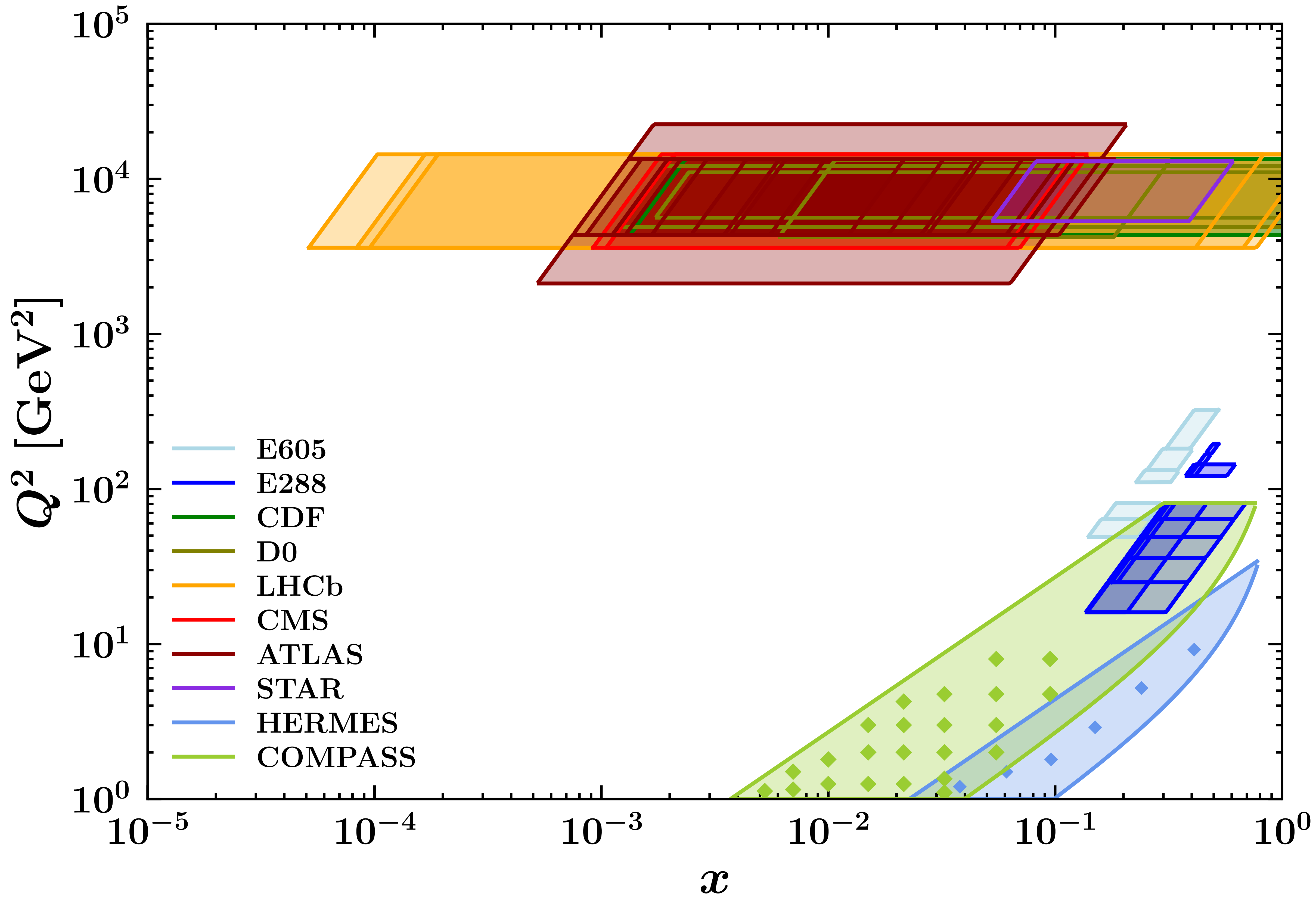

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Number of points > 1500

FUNCTIONAL FORM (PRELIMINARY)

$$f_{1\mathrm{NP}}(x, b_T^2) \propto \mathrm{F.T.\ of} \left(e^{-\frac{k_\perp^2}{g1A}} + \lambda_B k_\perp^2 e^{-\frac{k_\perp^2}{g1B}} + \lambda_C e^{-\frac{k_\perp^2}{g1C}} \right)$$

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Still working on the flexibility of the final form

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$$g_K(b_T^2) = -\frac{g_{2A}}{2} b_T^2 - \frac{g_{2B}}{2} b_T^4$$

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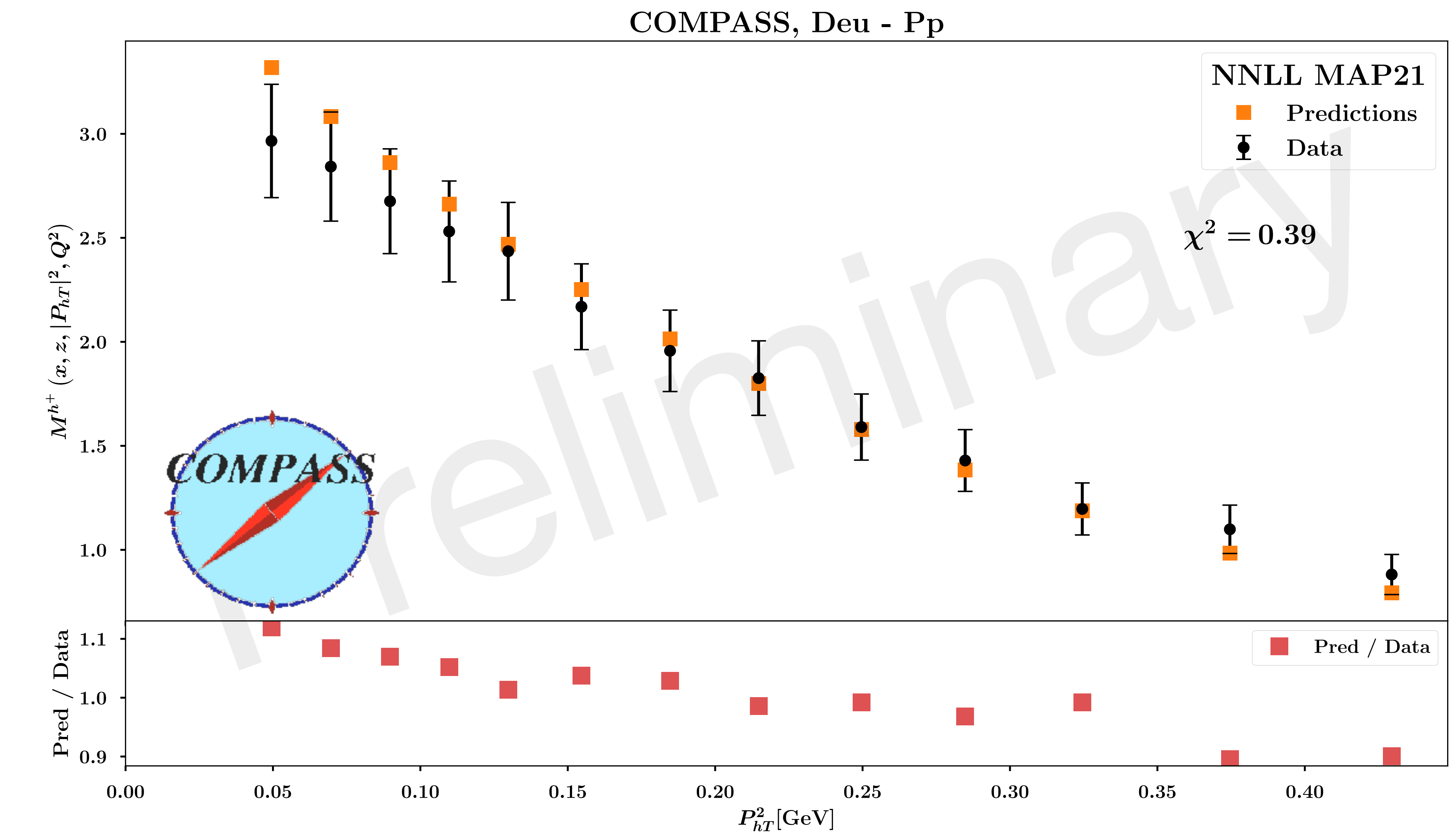
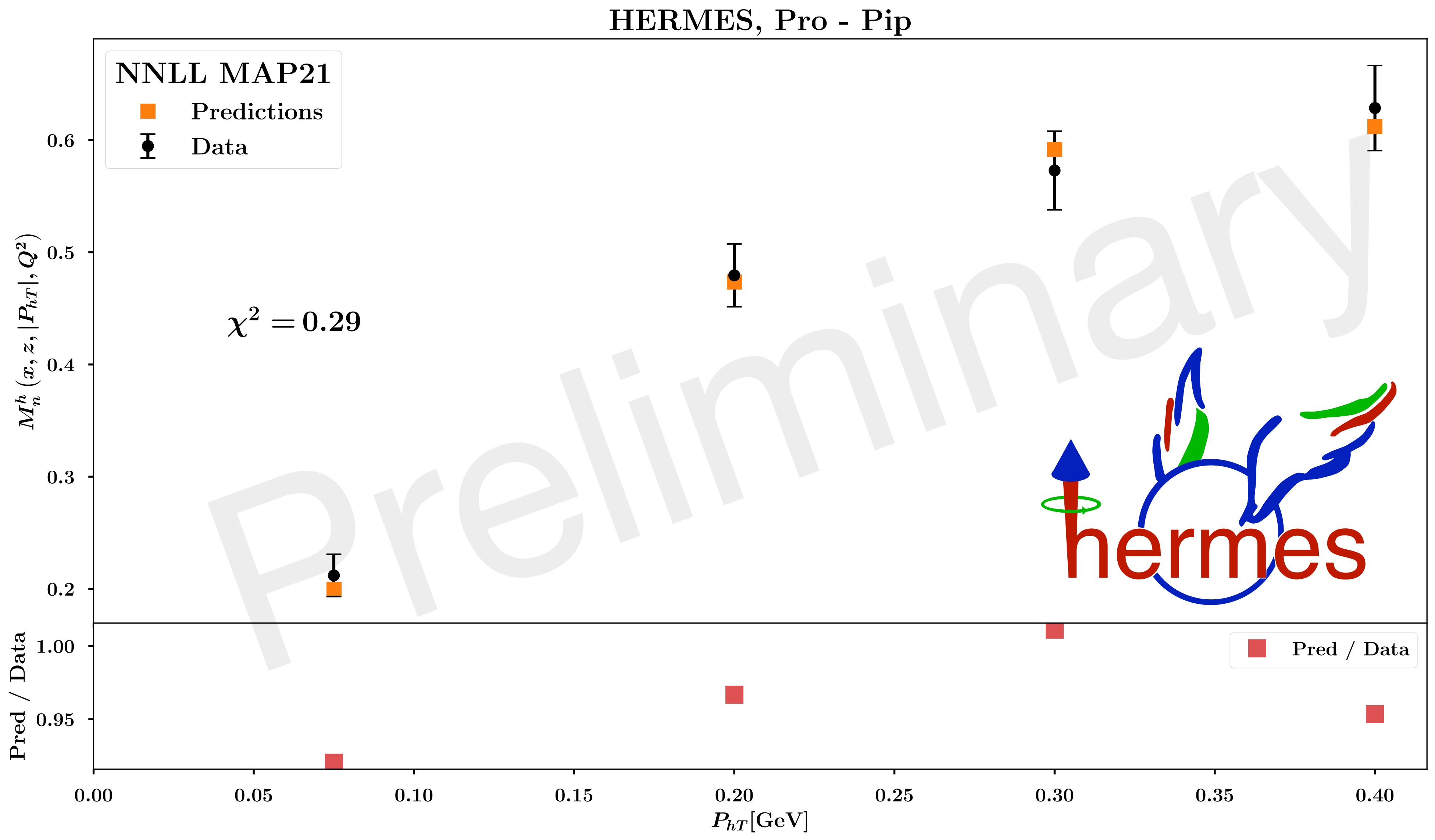
11 parameters for TMD PDF
+ 2 for NP evolution +14 for FF
= 27 free parameters

N^2LL: EXAMPLE OF GOOD BINS

Global $\chi^2 < 1.1$





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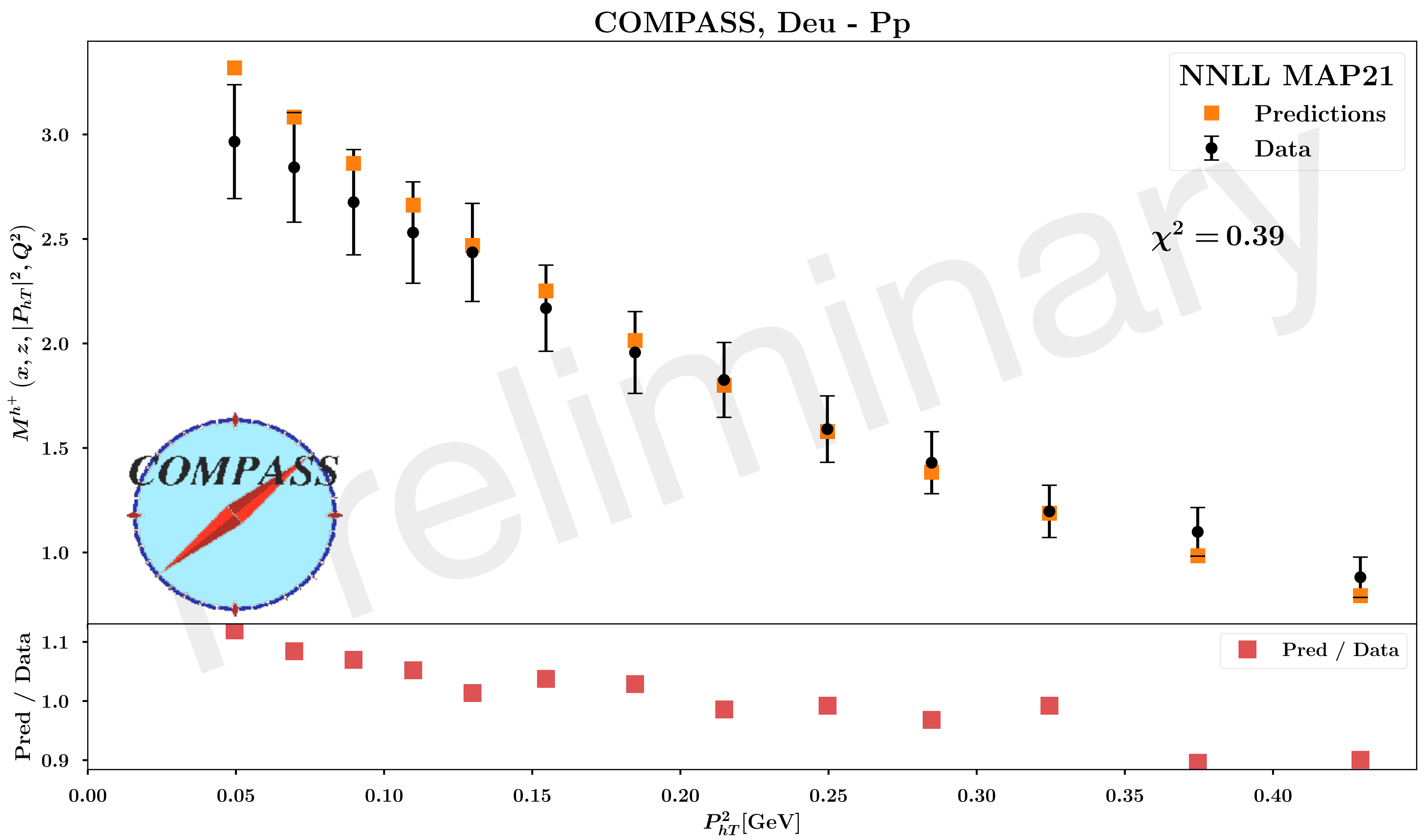
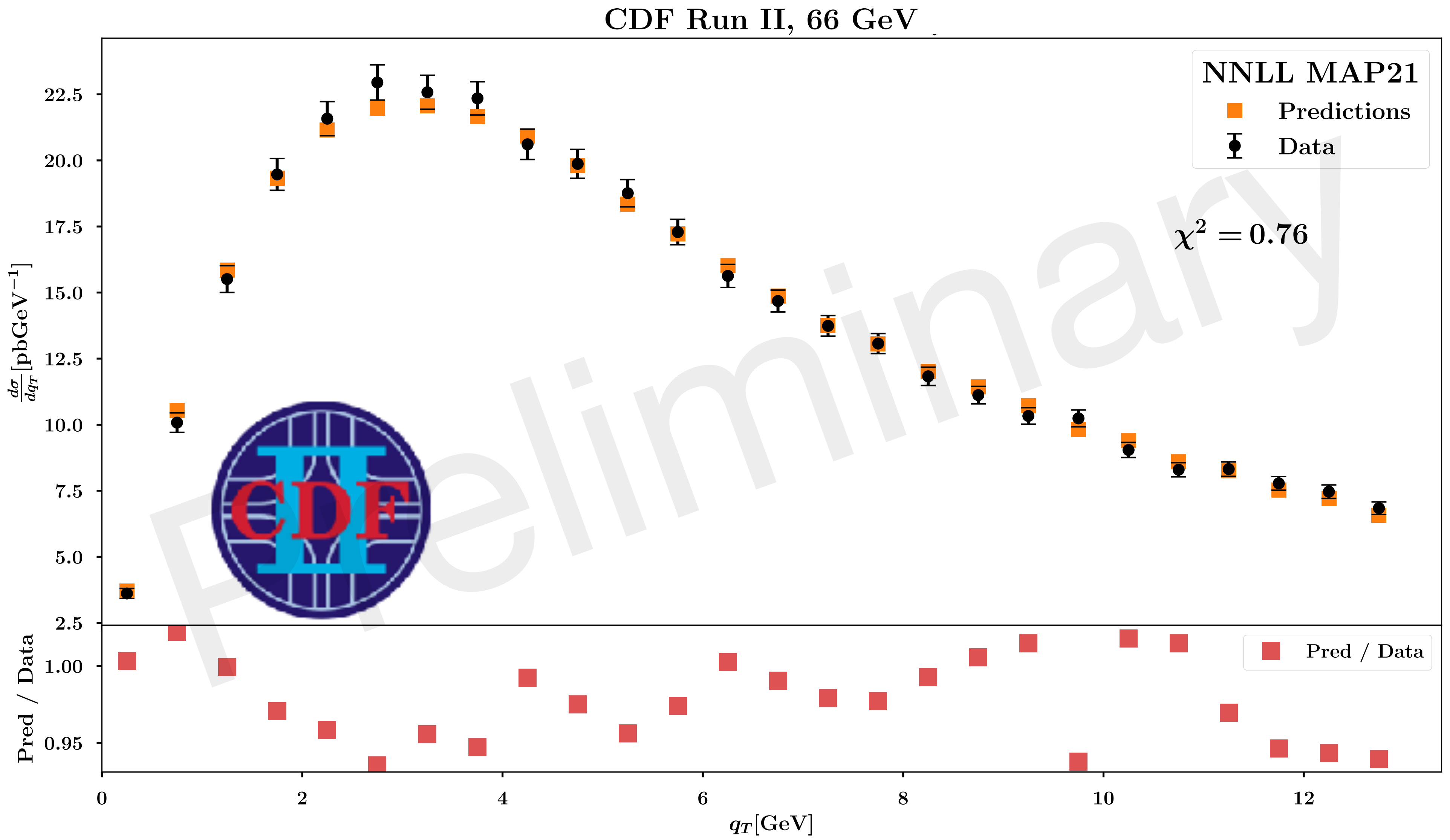
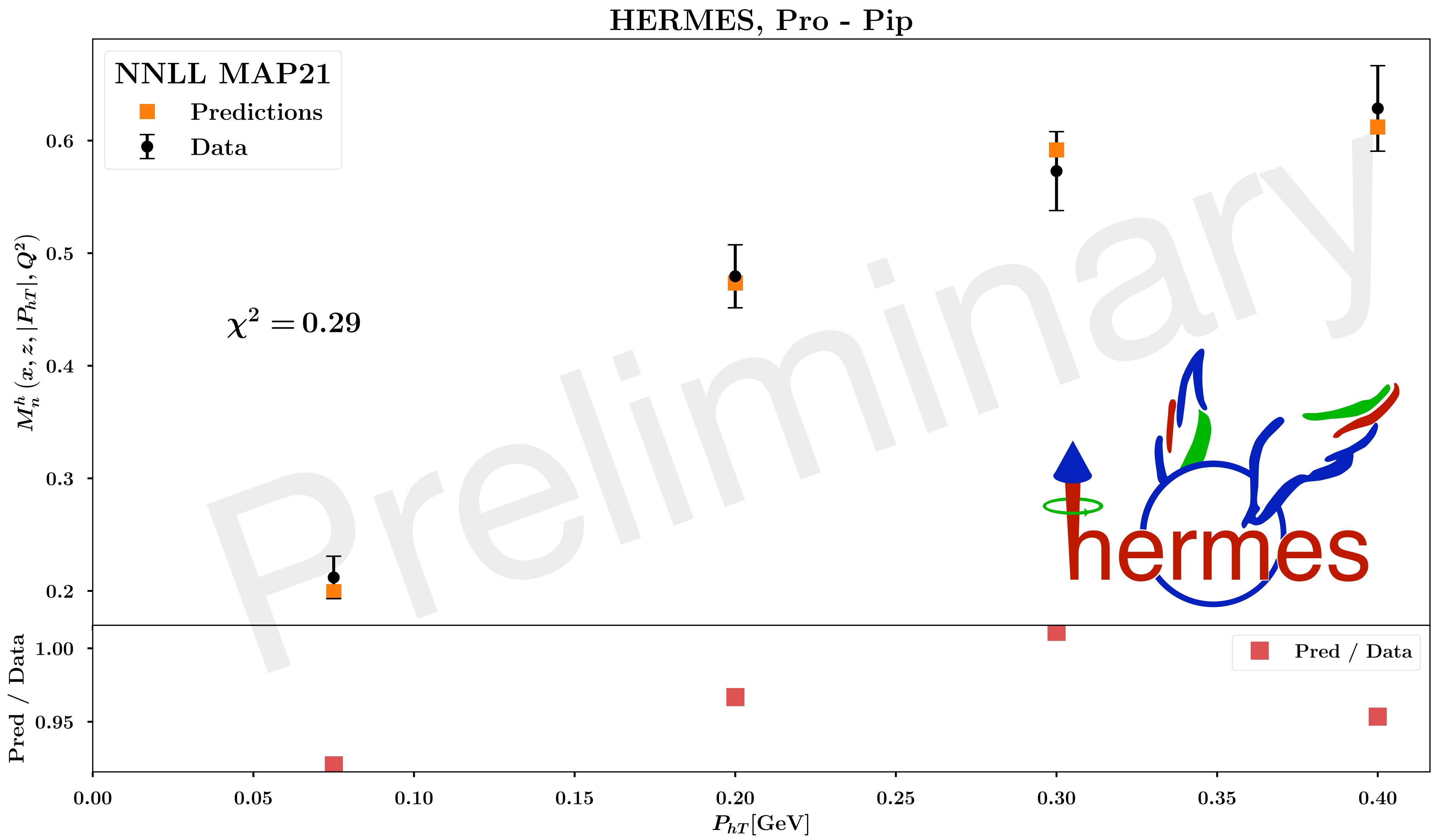
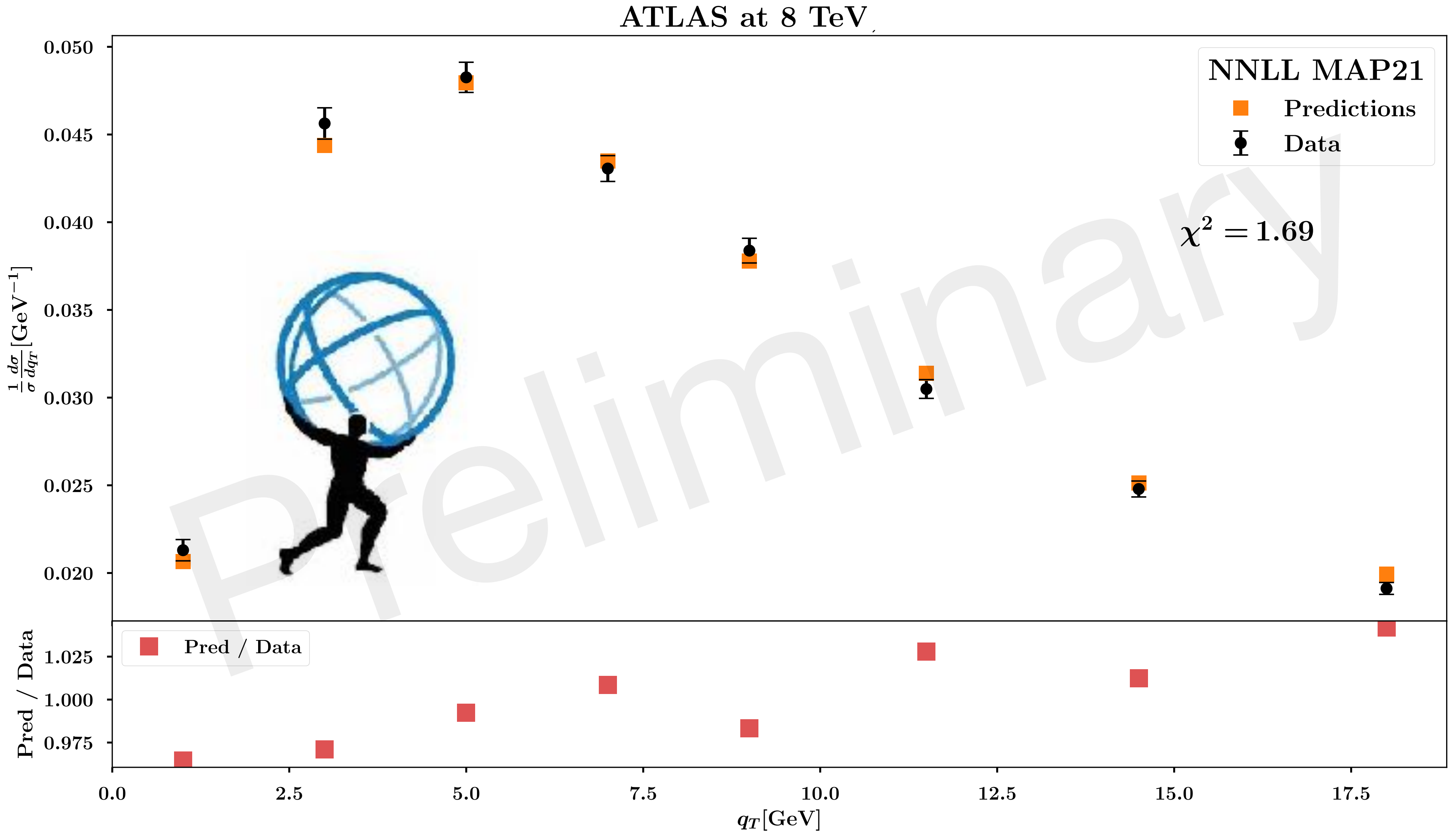


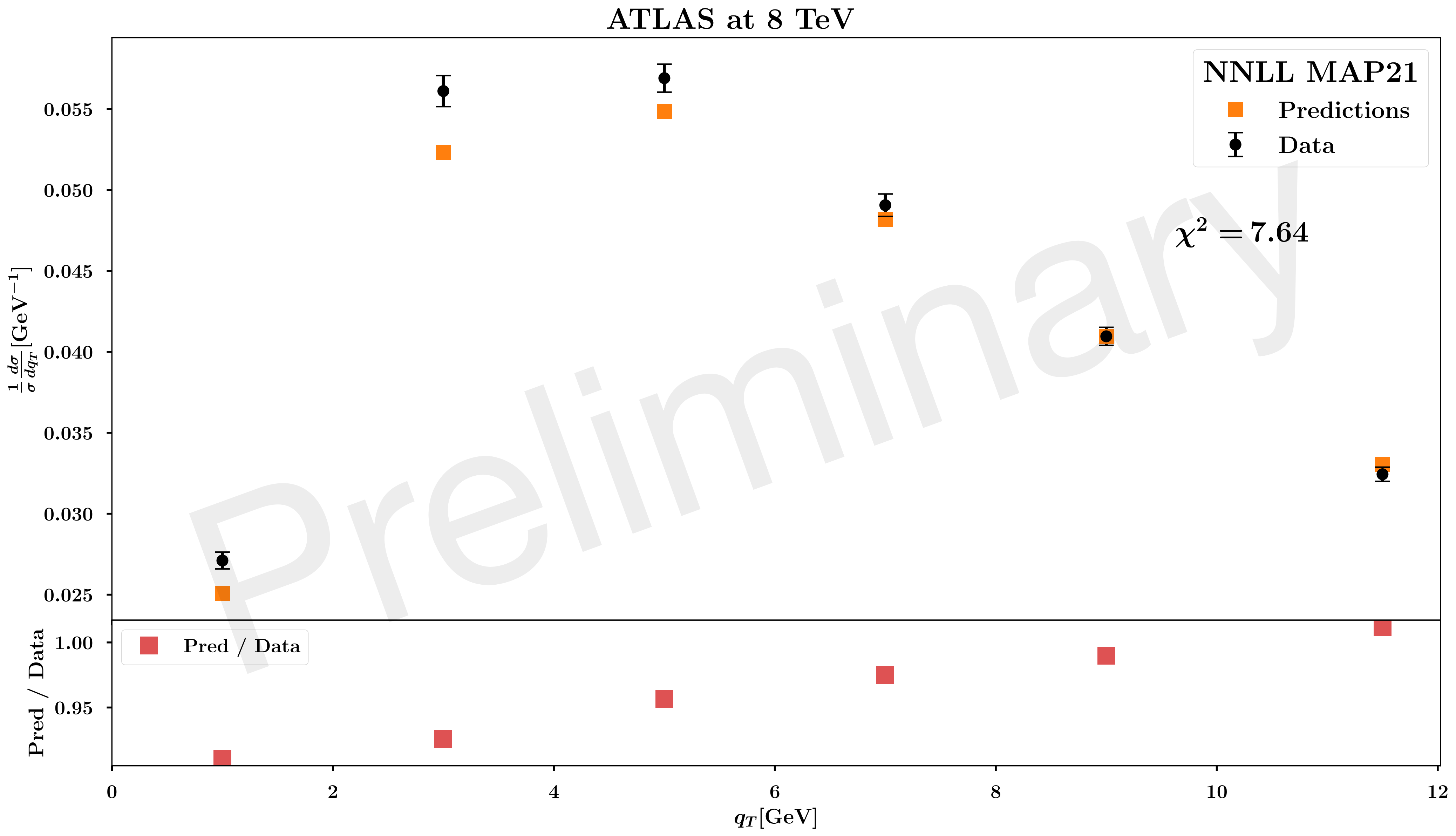


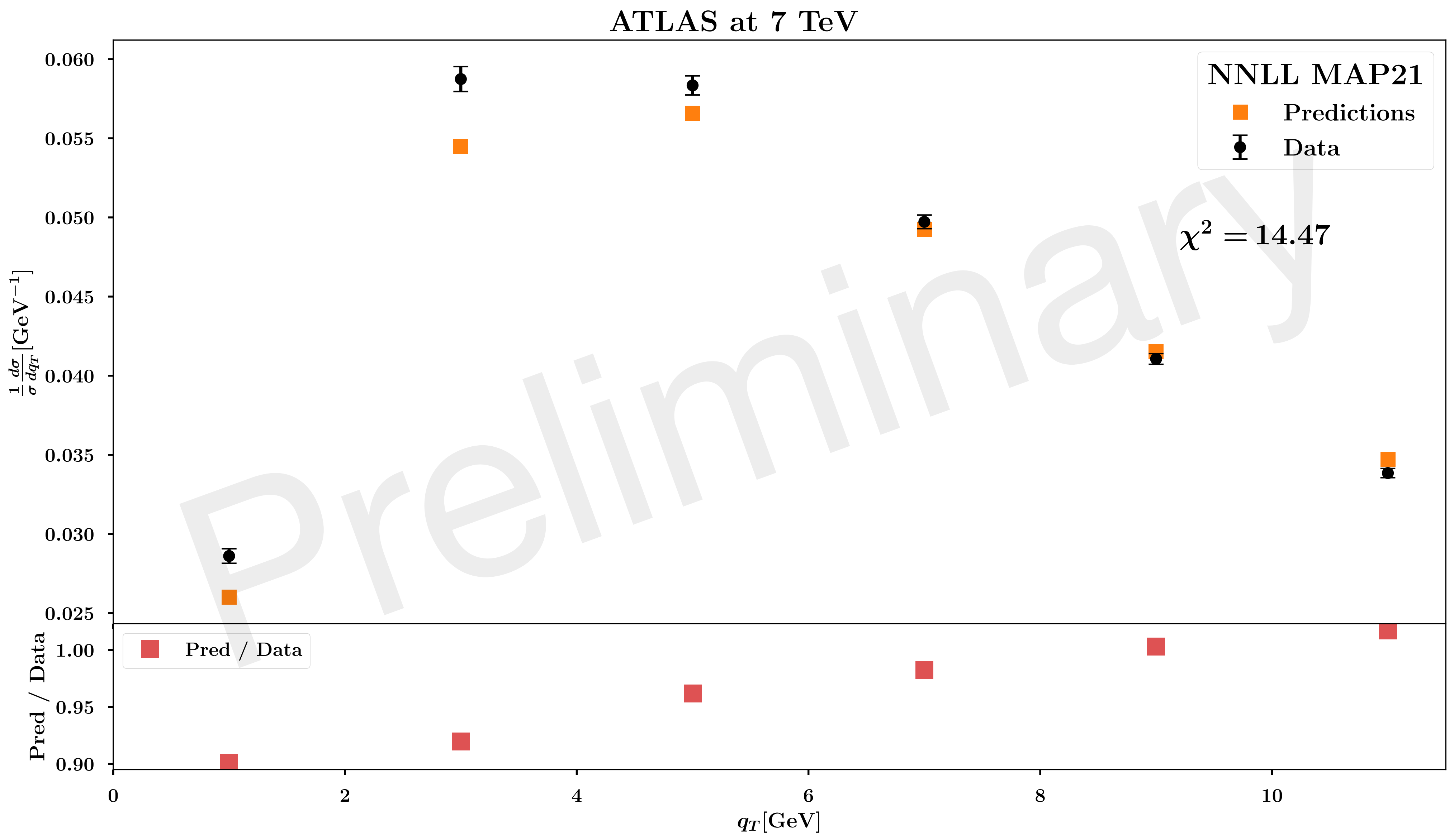


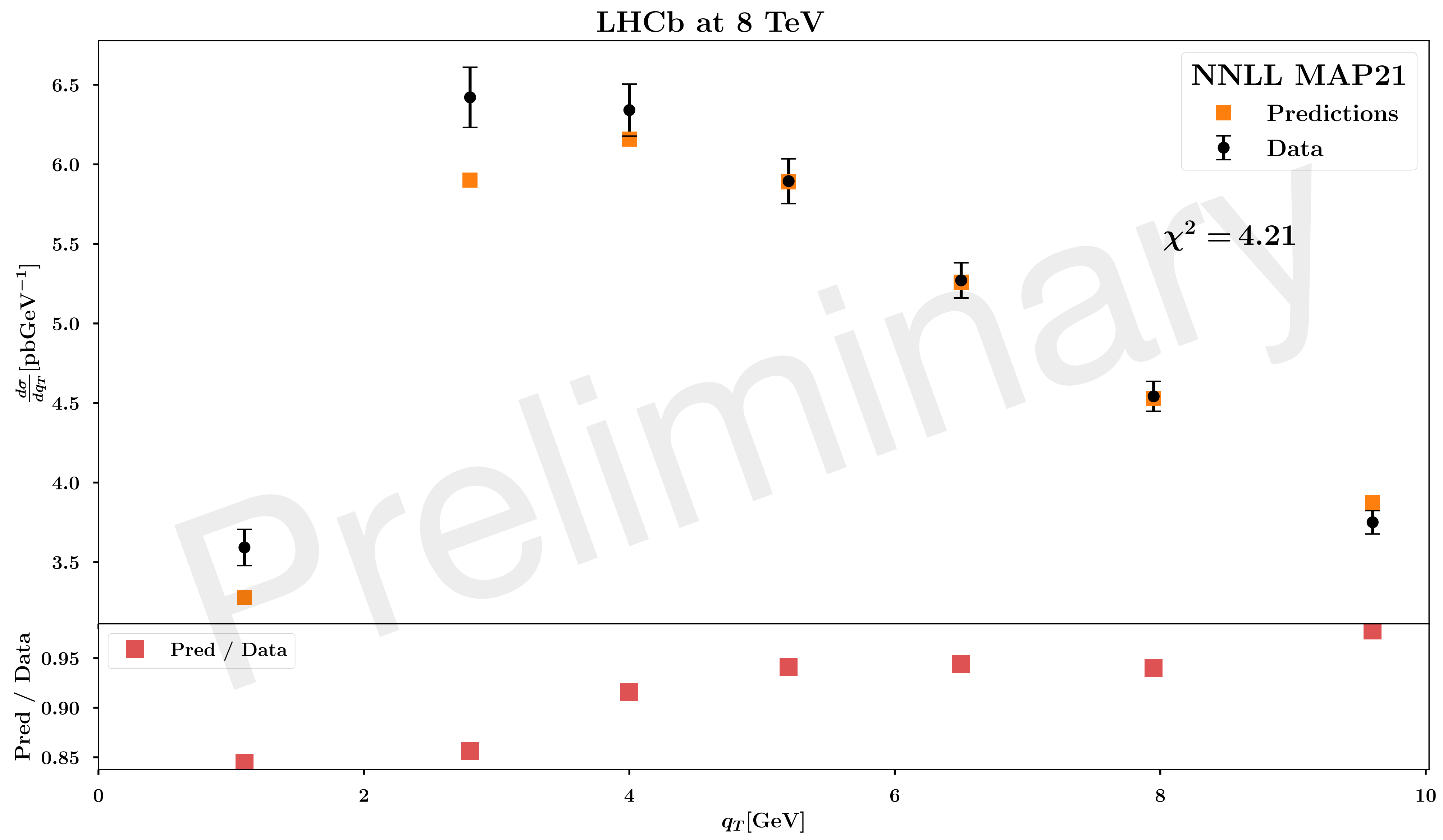


N²LL: EXAMPLE OF BAD BINS

Global $\chi^2 < 1.1$







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- DY data can NOT be described at NLL, but only at higher orders
- SIDIS data can be described very well at NLL, but require normalization prefactors at NLL' or higher
- The identification of the region of applicability of the TMD formalism is still an open issue
- Good global χ^2 can be reached at N^2LL, but some LHC data remain hard to describe

BACKUP SLIDES

LOGARITHMIC ACCURACY

	Sudakov form factor	Matching coefficient
LL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$	$\tilde{C}^0$
NLL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$\tilde{C}^0$
NLL$'$	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$\left(\tilde{C}^0 + \alpha_S \tilde{C}^1\right)$

the difference between the two is NNLL: $\alpha_S^n \ln^{2n-2}\left(\frac{Q^2}{\mu_b^2}\right)$

NON-MIXED TERMS IN COLLINEAR SIDIS CROSS SECTION - BACKUP

$$\left.\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z}\right|_{\mathcal{O}(\alpha_s^1)} = \sigma_0 \sum_{ff'} \frac{e_f^2}{z^2} \left(\delta_{f'f} + \delta_{f'g}\right) \frac{\alpha_s}{\pi} \Bigg\{ \left[D_1^{h/f'} \otimes C_1^{f'f} \otimes f_1^{f/N}\right](x, z, Q) + \frac{1-y}{1+(1-y)^2} \left[D_1^{h/f'} \otimes C_L^{f'f} \otimes f_1^{f/N}\right](x, z, Q) \Bigg\},$$

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$$C_1^{qq} = \frac{C_F}{2} \Bigg\{ -8\delta(1-x)\delta(1-z) + \delta(1-x) \left[P_{qq}(z) \ln \frac{Q^2}{\mu_F^2} + L_1(z) + L_2(z) + (1-z) \right] + \delta(1-z) \left[P_{qq}(x) \ln \frac{Q^2}{\mu^2} + L_1(x) - L_2(x) + (1-x) \right] + 2\frac{1}{(1-x)_+}\frac{1}{(1-z)_+} - \frac{1+z}{(1-x)_+} - \frac{1+x}{(1-z)_+} + 2(1+xz) \Bigg\},$$

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$$\left. + \frac{1-y}{1+(1-y)^2} \left[D_1^{h/f'} \otimes C_L^{f'f} \otimes f_1^{f/N}\right](x, z, Q) \right\},$$

$$C_1^{qq} = \frac{C_F}{2} \left\{ -8\delta(1-x)\delta(1-z) \right.$$

$$+ \delta(1-x)\left[P_{qq}(z)\ln\frac{Q^2}{\mu_F^2} + L_1(z) + L_2(z) + (1-z)\right]$$

$$+ \delta(1-z)\left[P_{qq}(x)\ln\frac{Q^2}{\mu^2} + L_1(x) - L_2(x) + (1-x)\right]$$

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