Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

PROGRESS IN THE EXTRACTION OF UNPOLARIZED TMDS FROM GLOBAL DATA SETS

Matteo Cerutti

University of Pavia - INFN PV

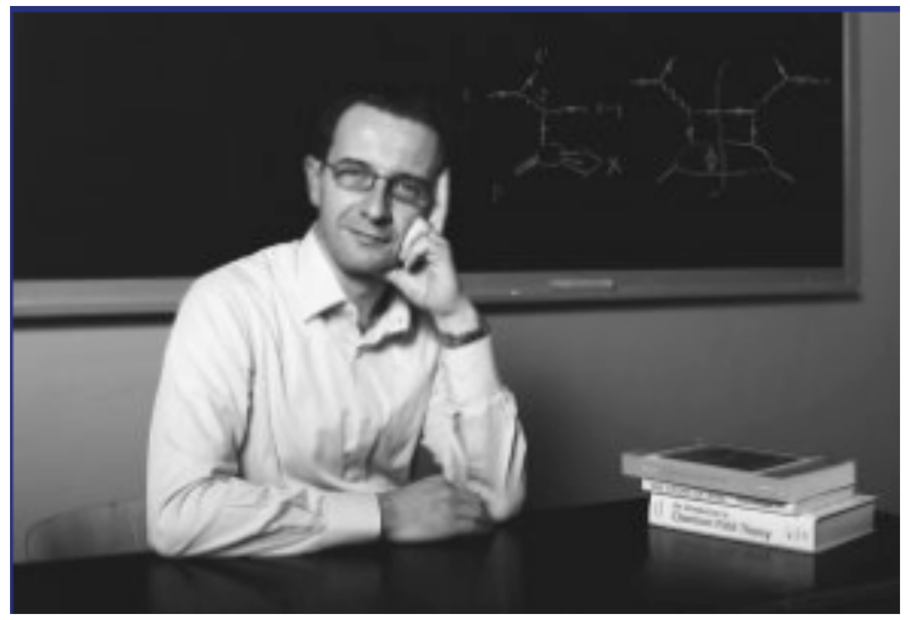
TNPI 2021

Conference on Theoretical Nuclear Physics in Italy

November 24th

RESULTS OBTAINED WITH CONTRIBUTIONS FROM

Alessandro Bacchetta



Marco Radici

Andrea Signori

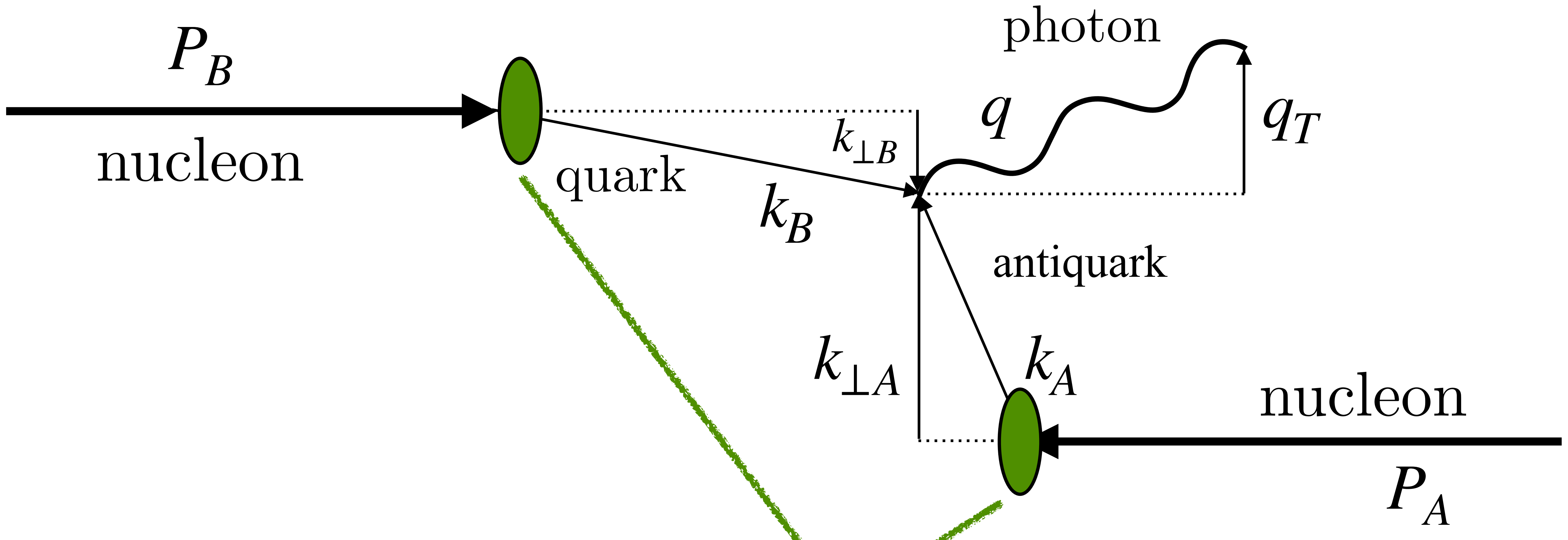
Valerio Bertone

Chiara Bissolotti

Giuseppe Bozzi

Fulvio Piacenza

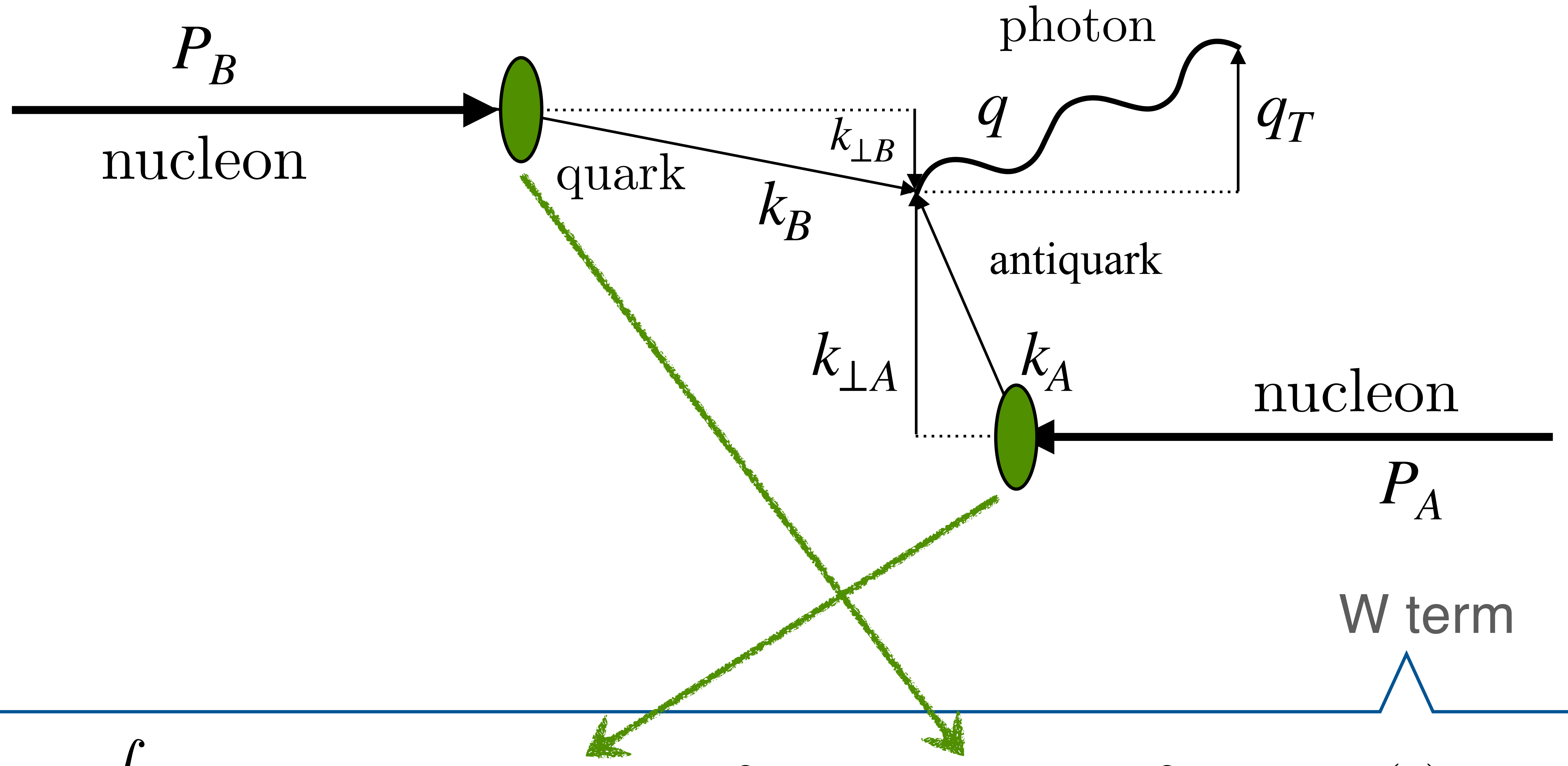
TMDS IN DRELL-YAN PROCESSES



W term

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

TMDS IN DRELL-YAN PROCESSES



W term

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

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

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

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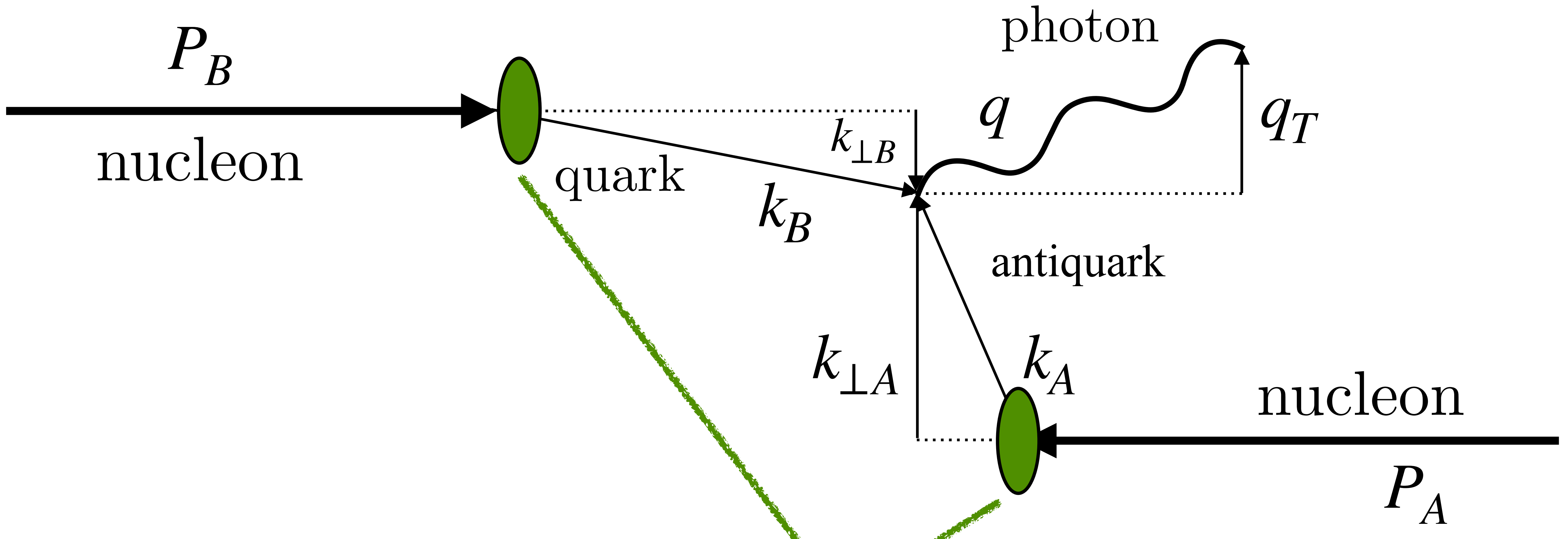

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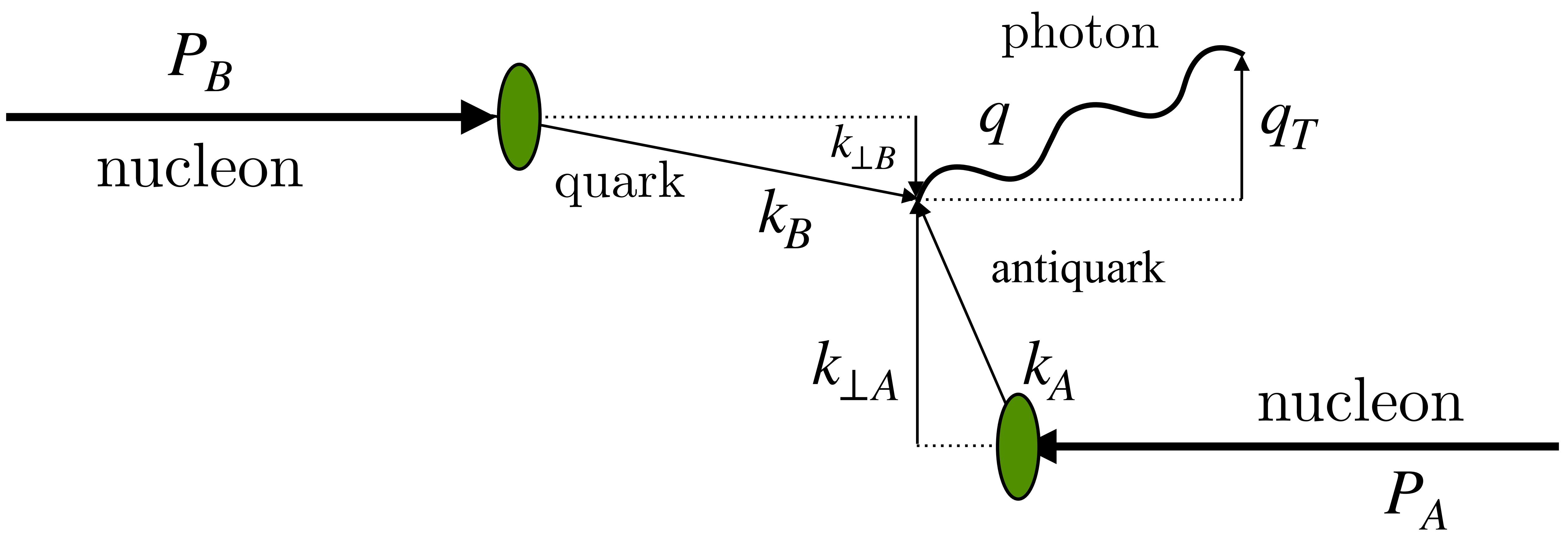
- The W term dominates in the region where $q_T \ll Q$
- Y term has been excluded in the Pavia analyses

TMDS IN DRELL-YAN PROCESSES

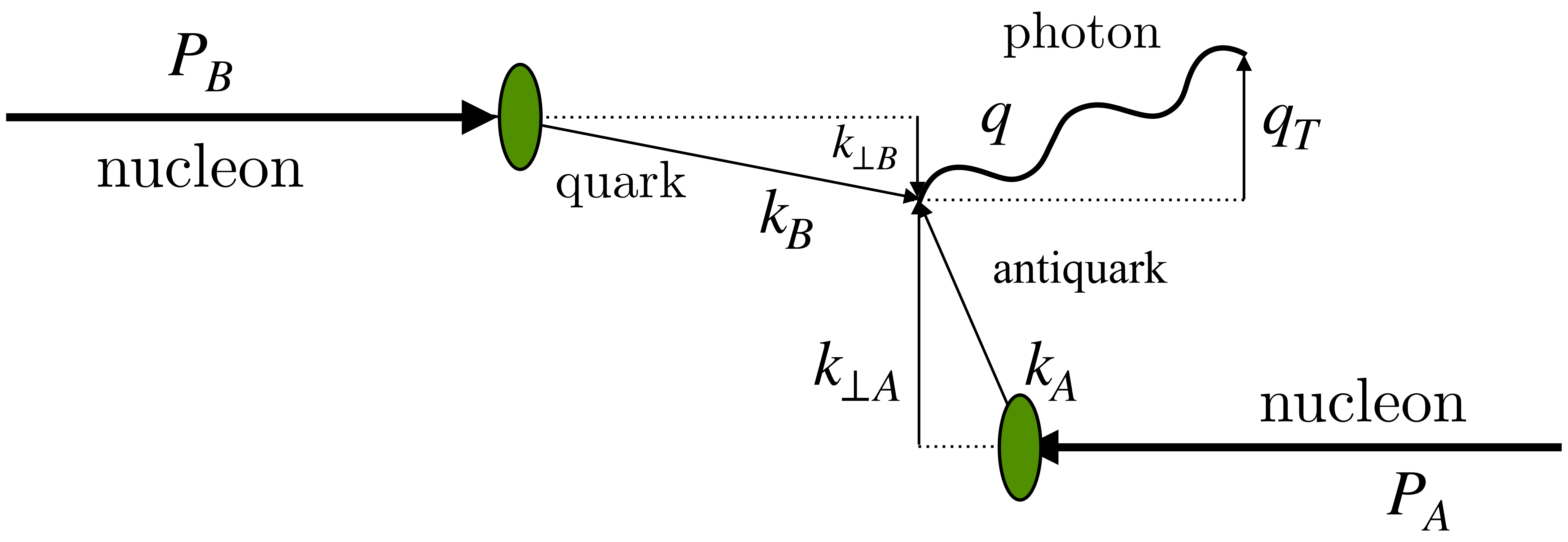


$$F_{UU}^1(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

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

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

TMDS IN DRELL–YAN PROCESSES



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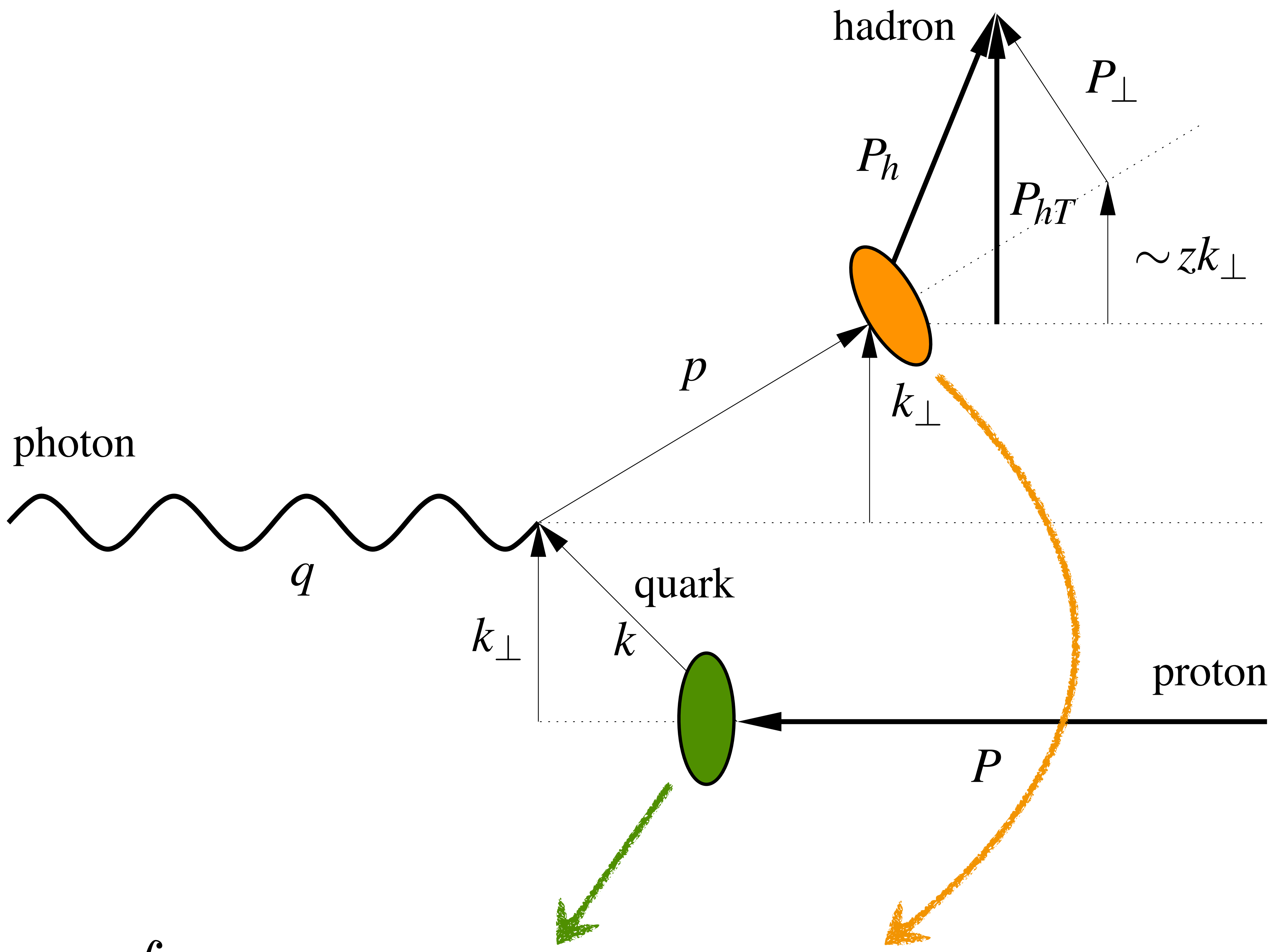
- At small q_T the dominant part is given by TMDs
- Fourier-transformed space to avoid convolutions
- TMDs formally depend on two scales, but we set them equal.

TMDS IN SEMI-INCLUSIVE DIS PROCESS



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

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

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

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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perturbative Sudakov form factor

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collinear PDF

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collinear PDF

nonperturbative part of evolution

nonperturbative part of TMD

matching coefficients (perturbative)

see, e.g.,
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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
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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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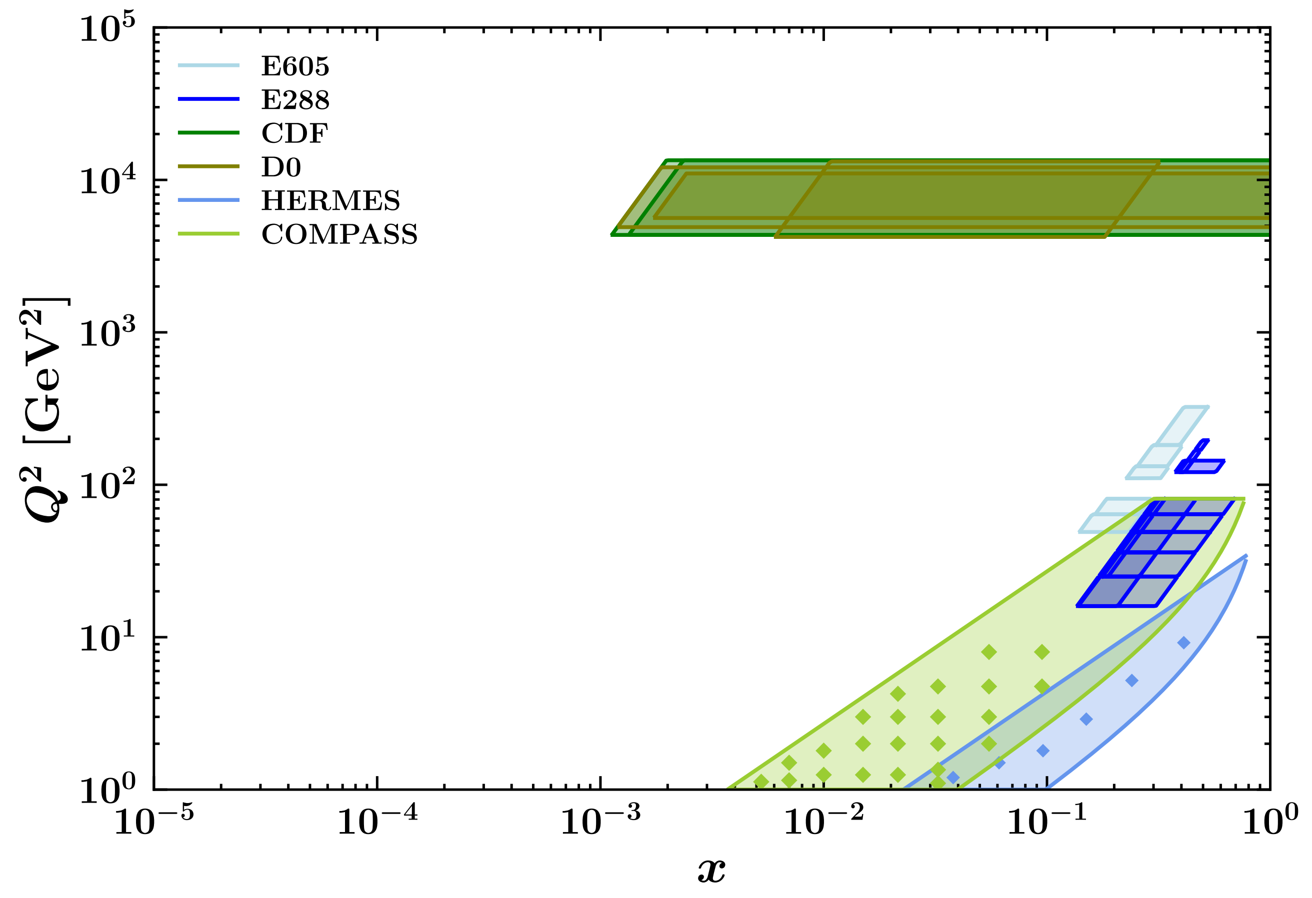

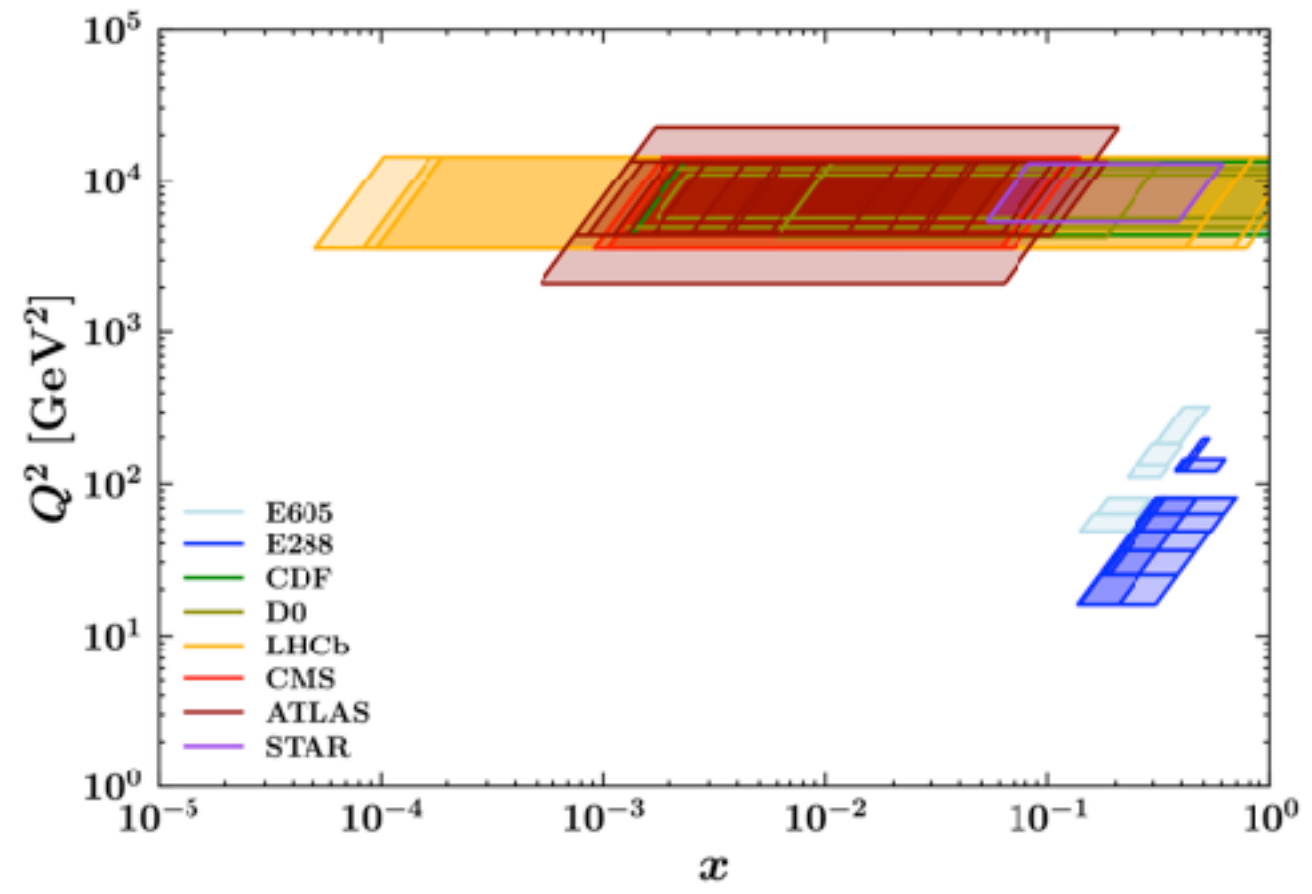

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- ✓ SIDIS + Drell Yan
- ○ Integrated variables

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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

OUR WORK IN THE LAST TWO YEARS

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- ○ Up to N^2LL/N^3LL

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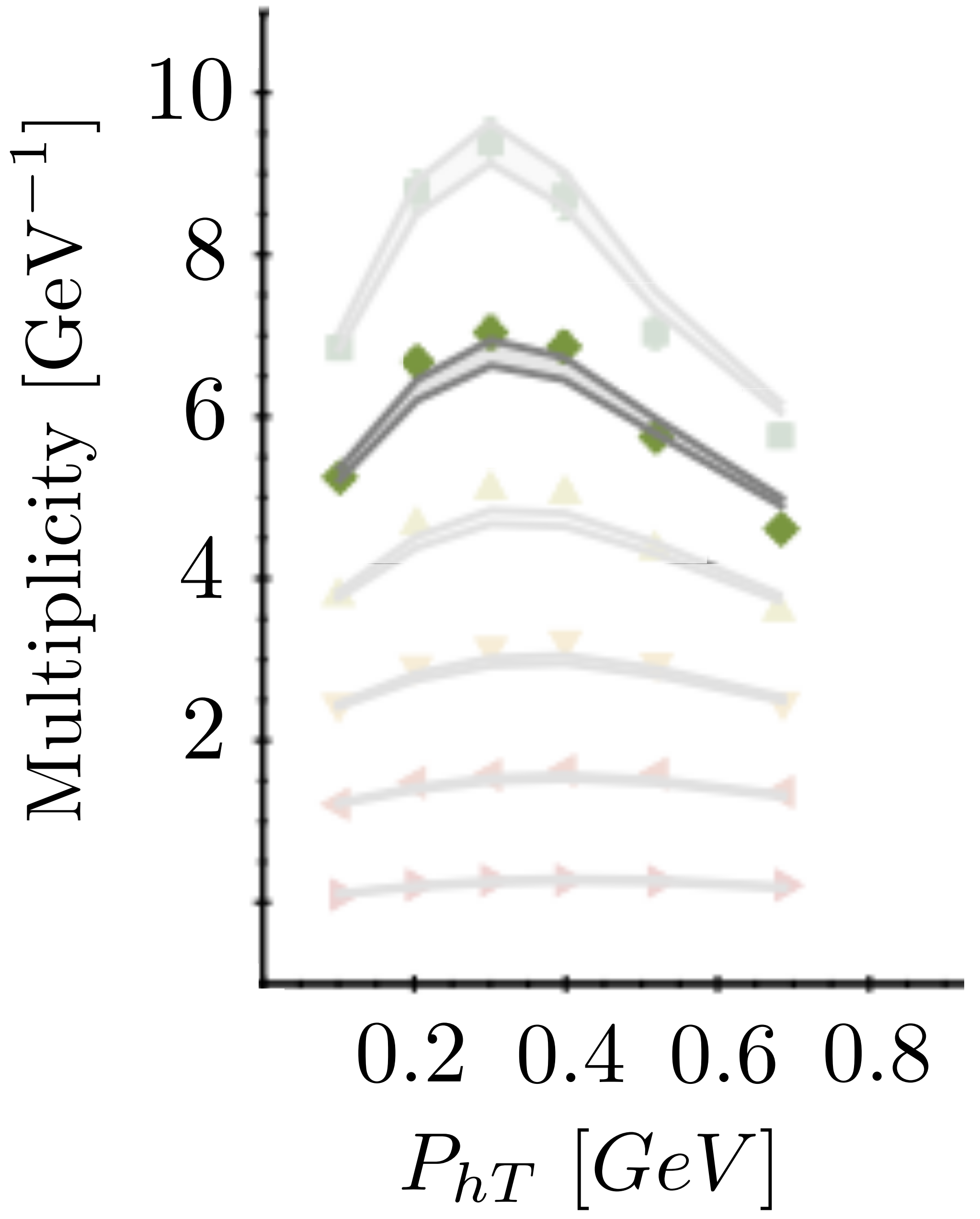
RESULTS AT NLL: SIDIS (MULTIPLICITIES)

What we expected

$\langle Q^2 \rangle = 2.9\ \text{GeV}^2$

$\langle x \rangle = 0.15$



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

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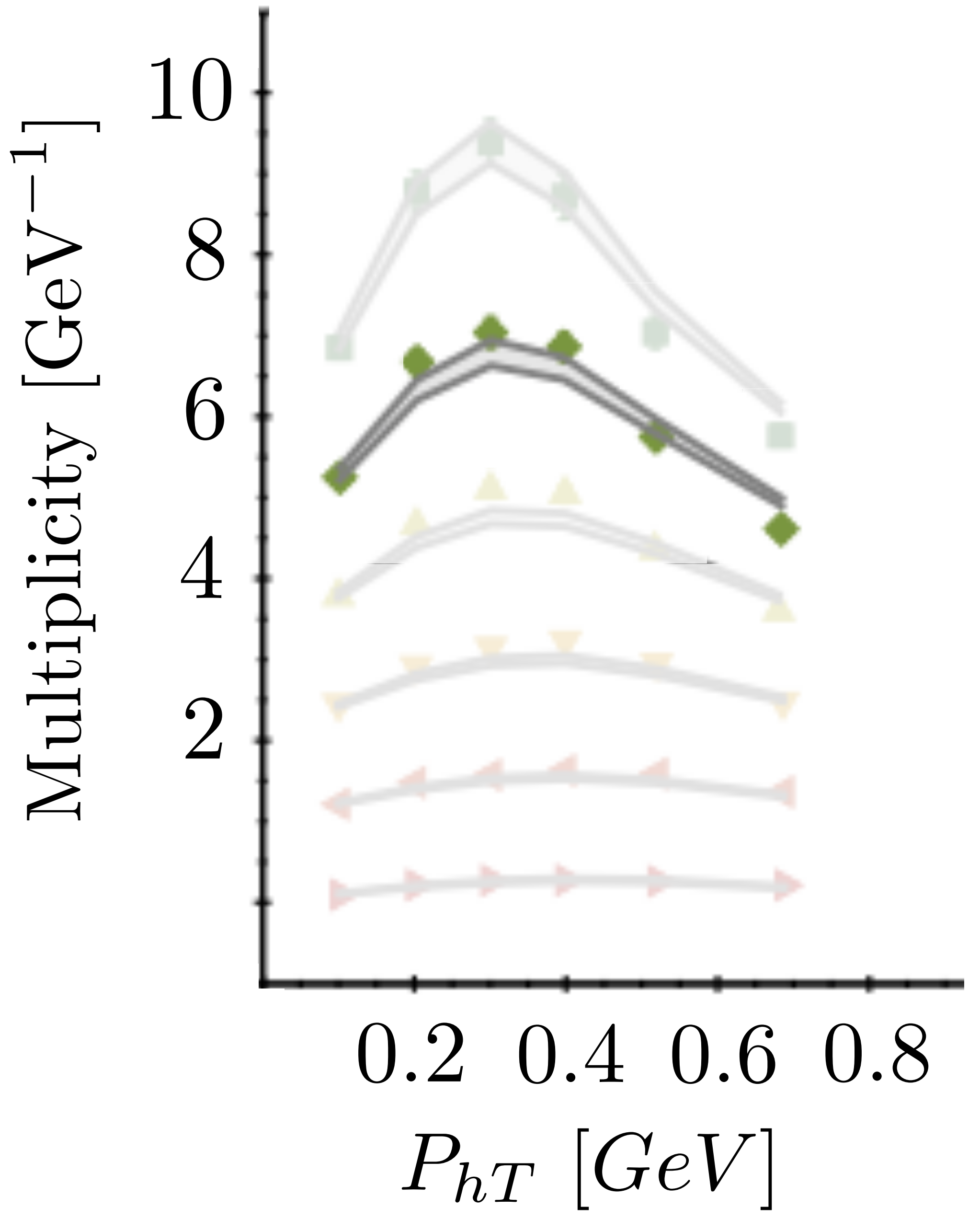
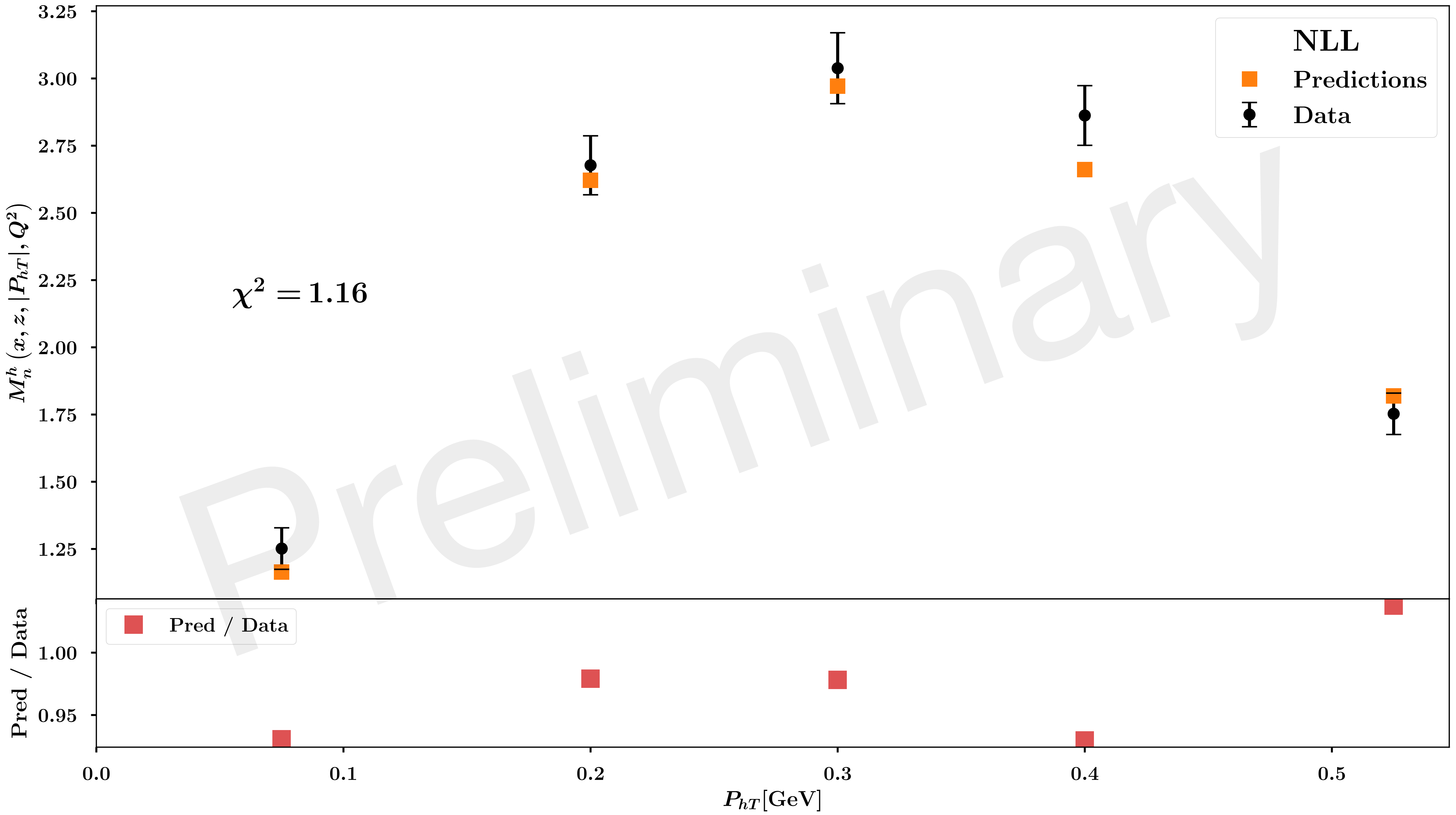


What we found



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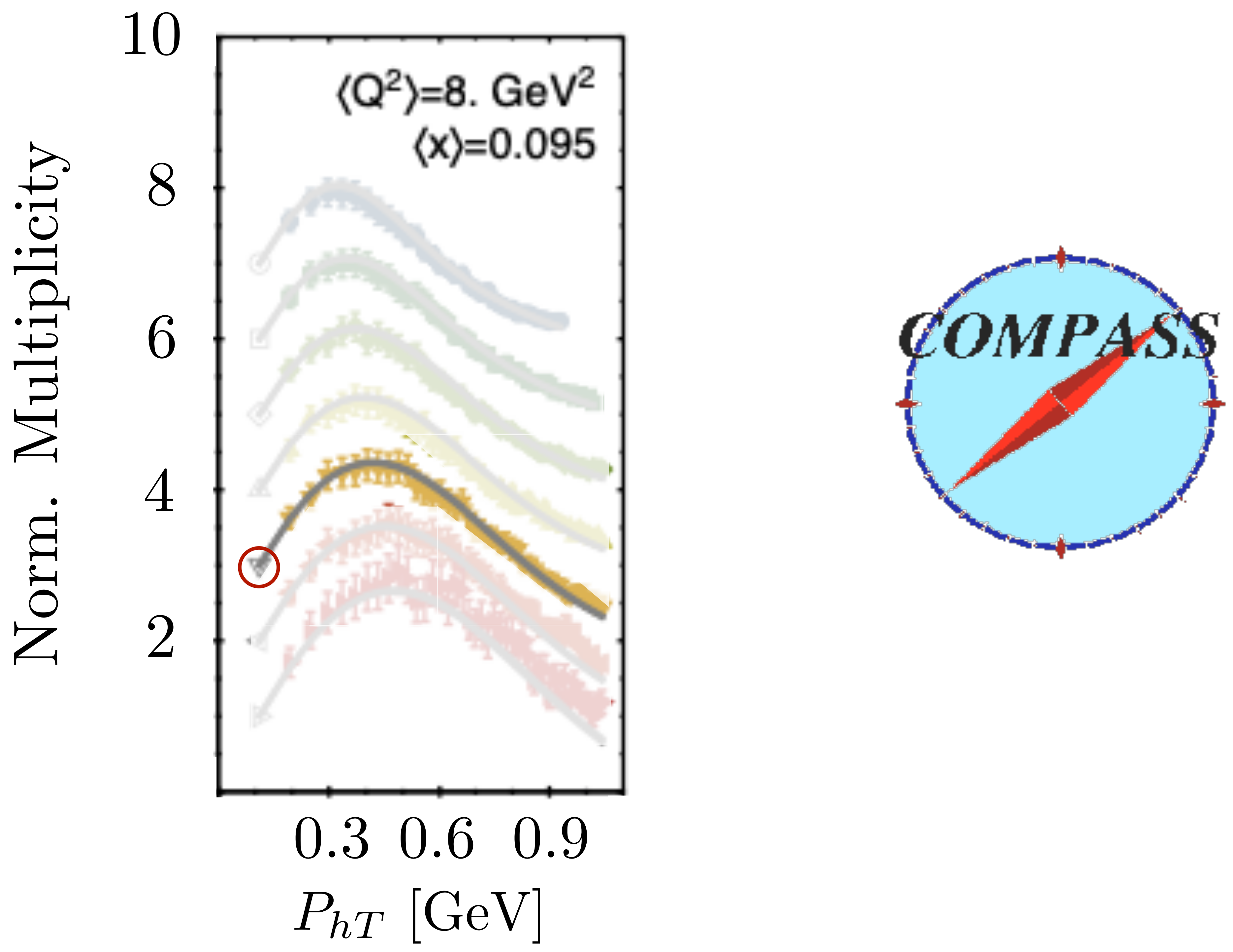

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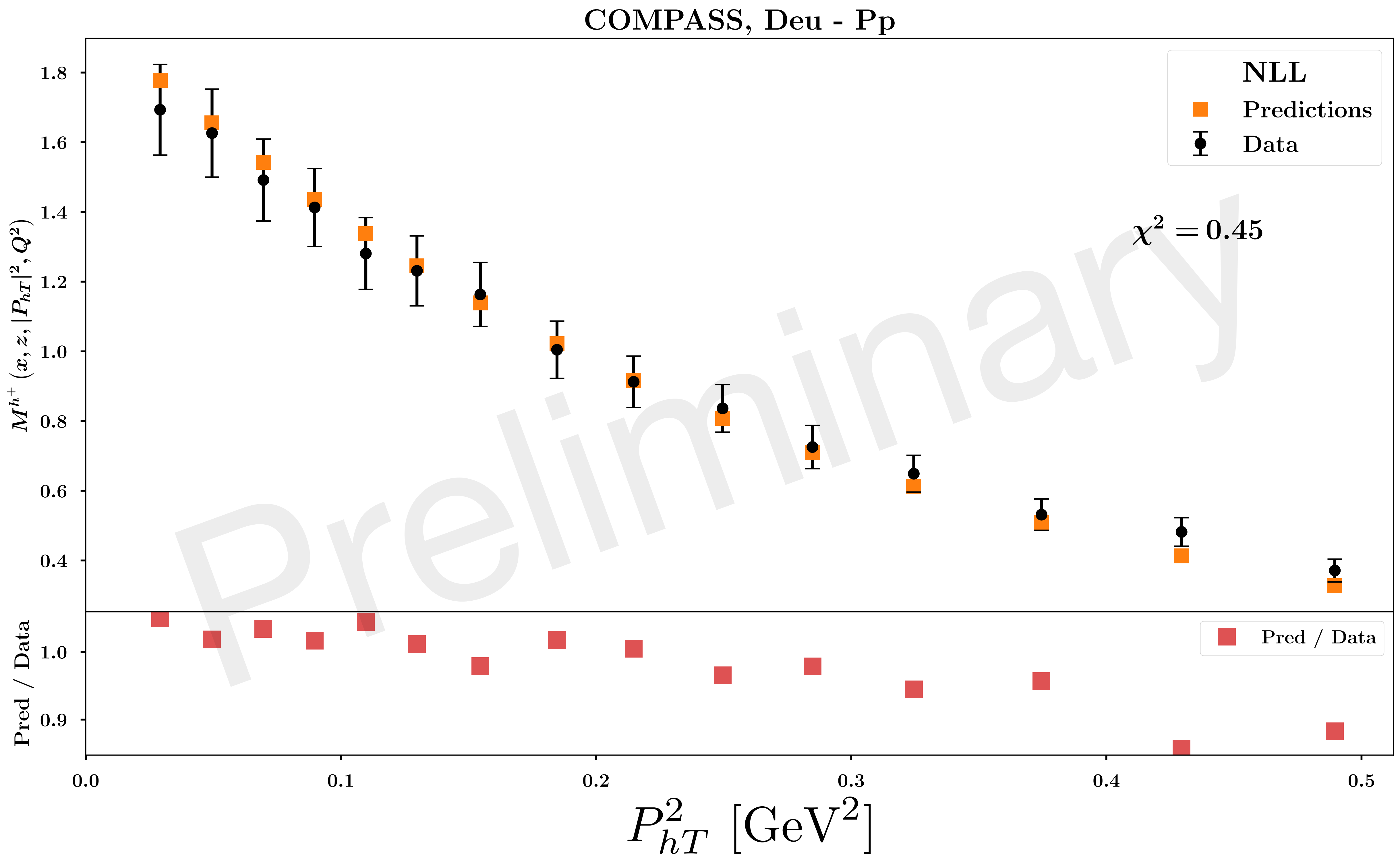

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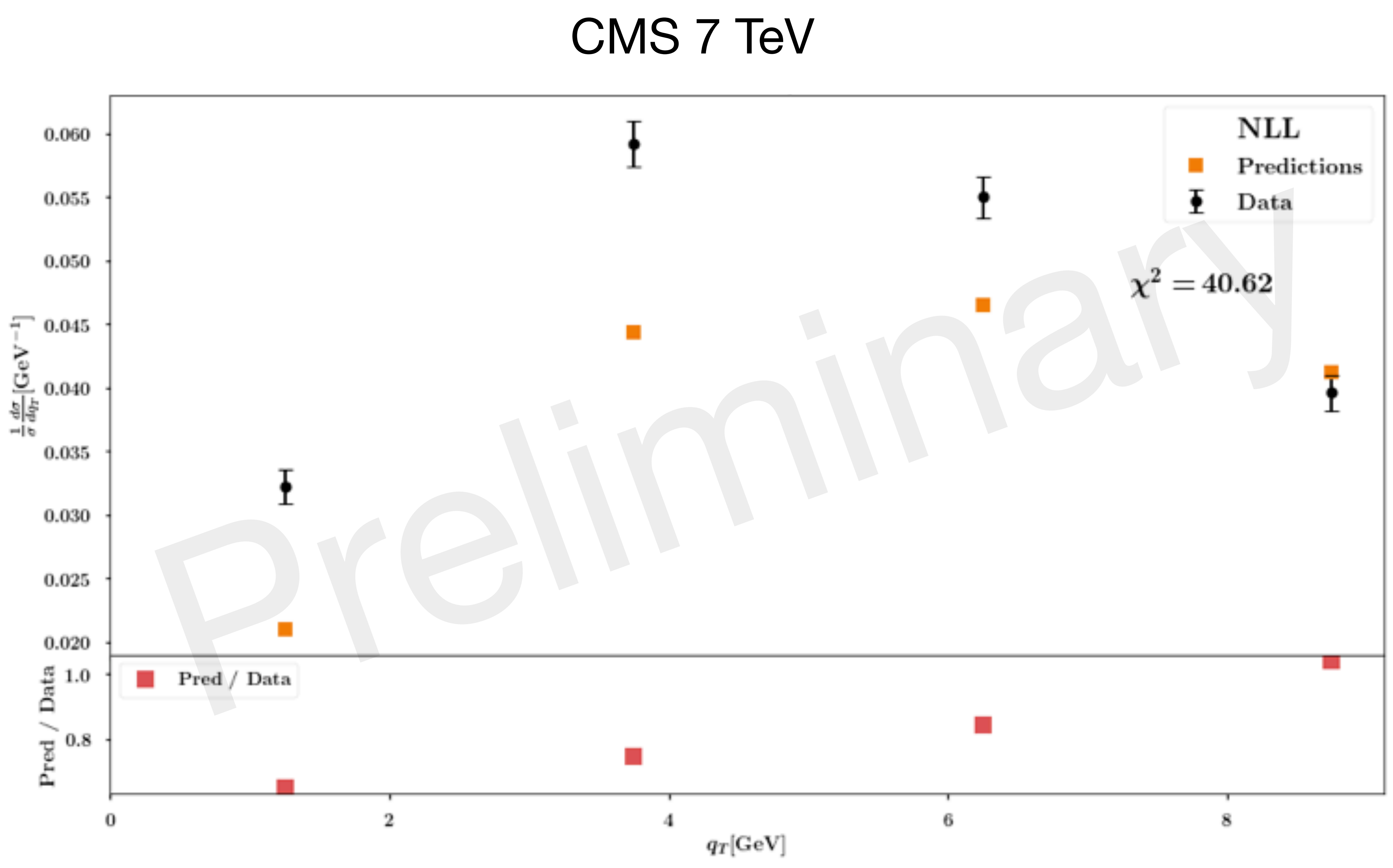
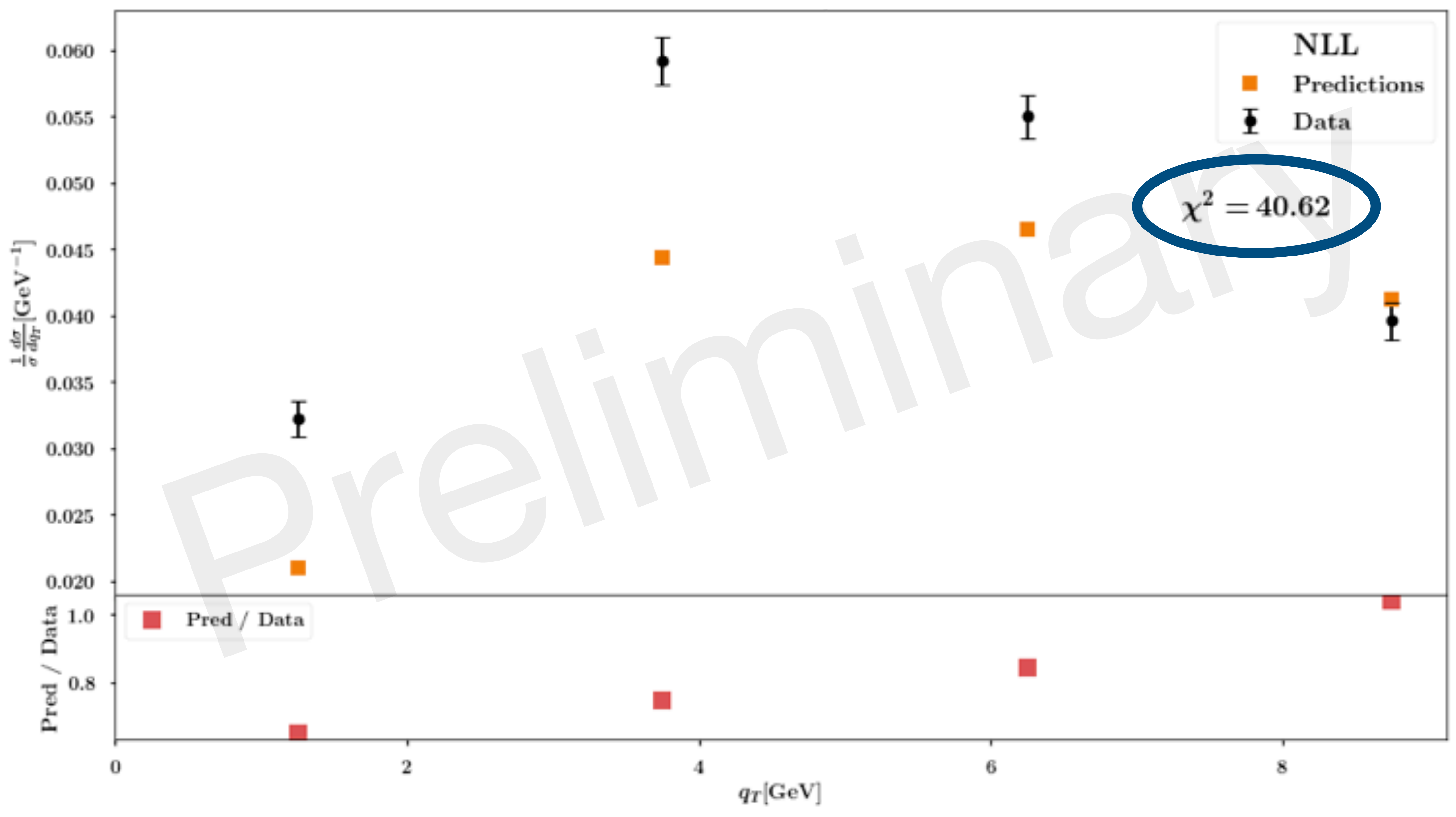
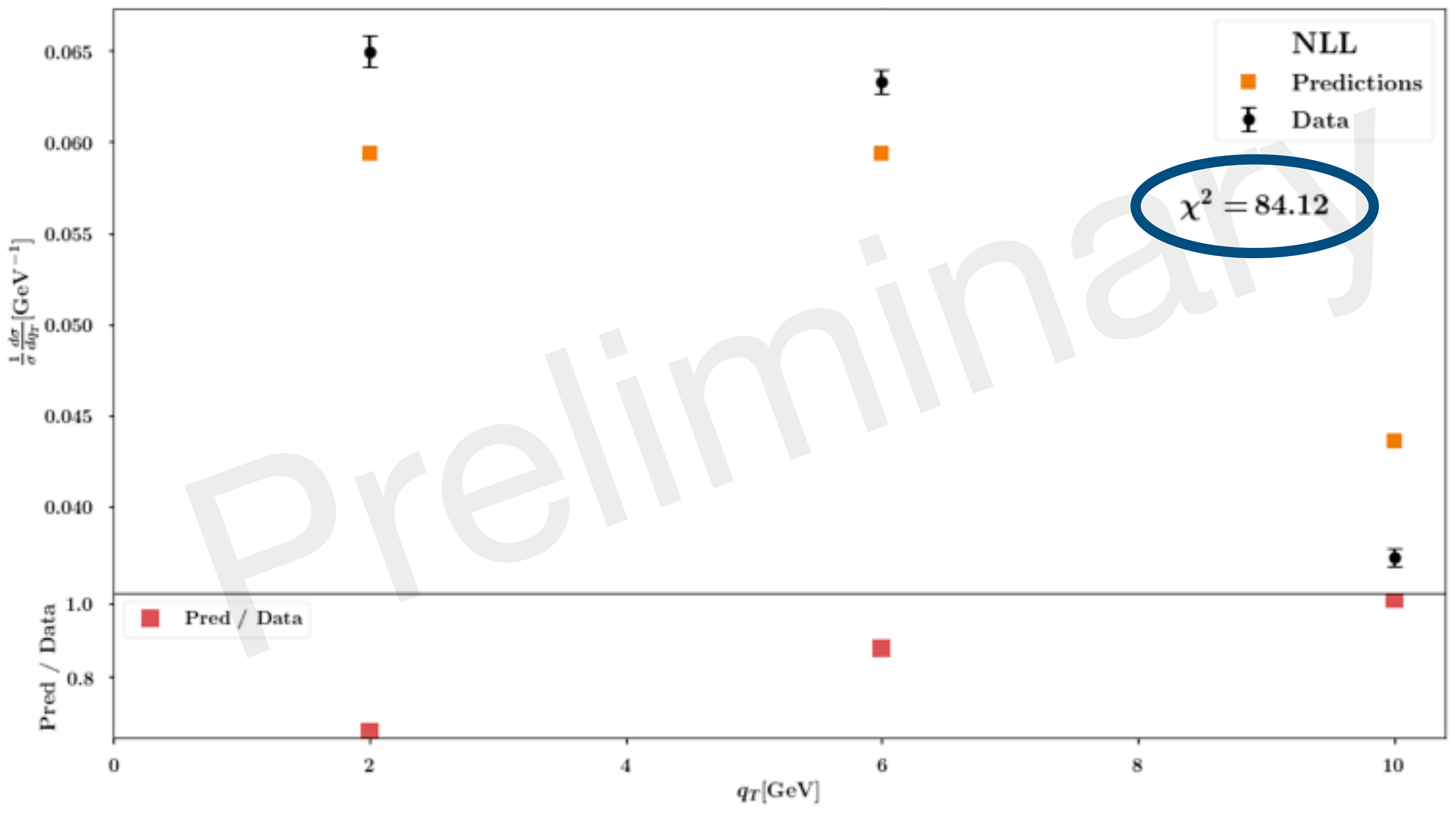


RESULTS AT NLL: DRELL YAN

CMS 7 TeV



D0 Run II muons



We need to increase the accuracy!!

COMPARISON OF DIFFERENT ORDERS

Accuracy at N^2LL and N^3LL

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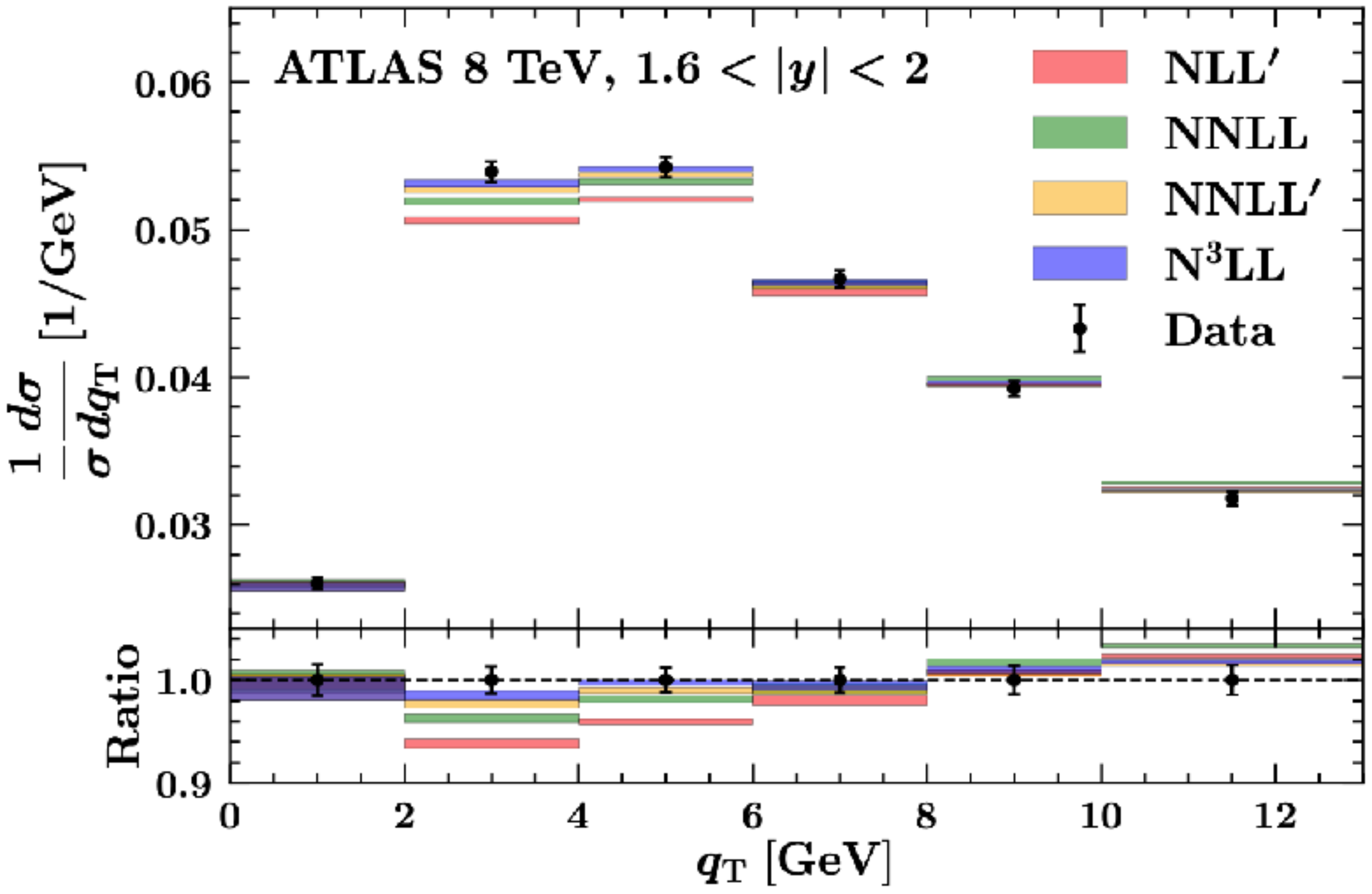
$Q \sim 100$ GeV



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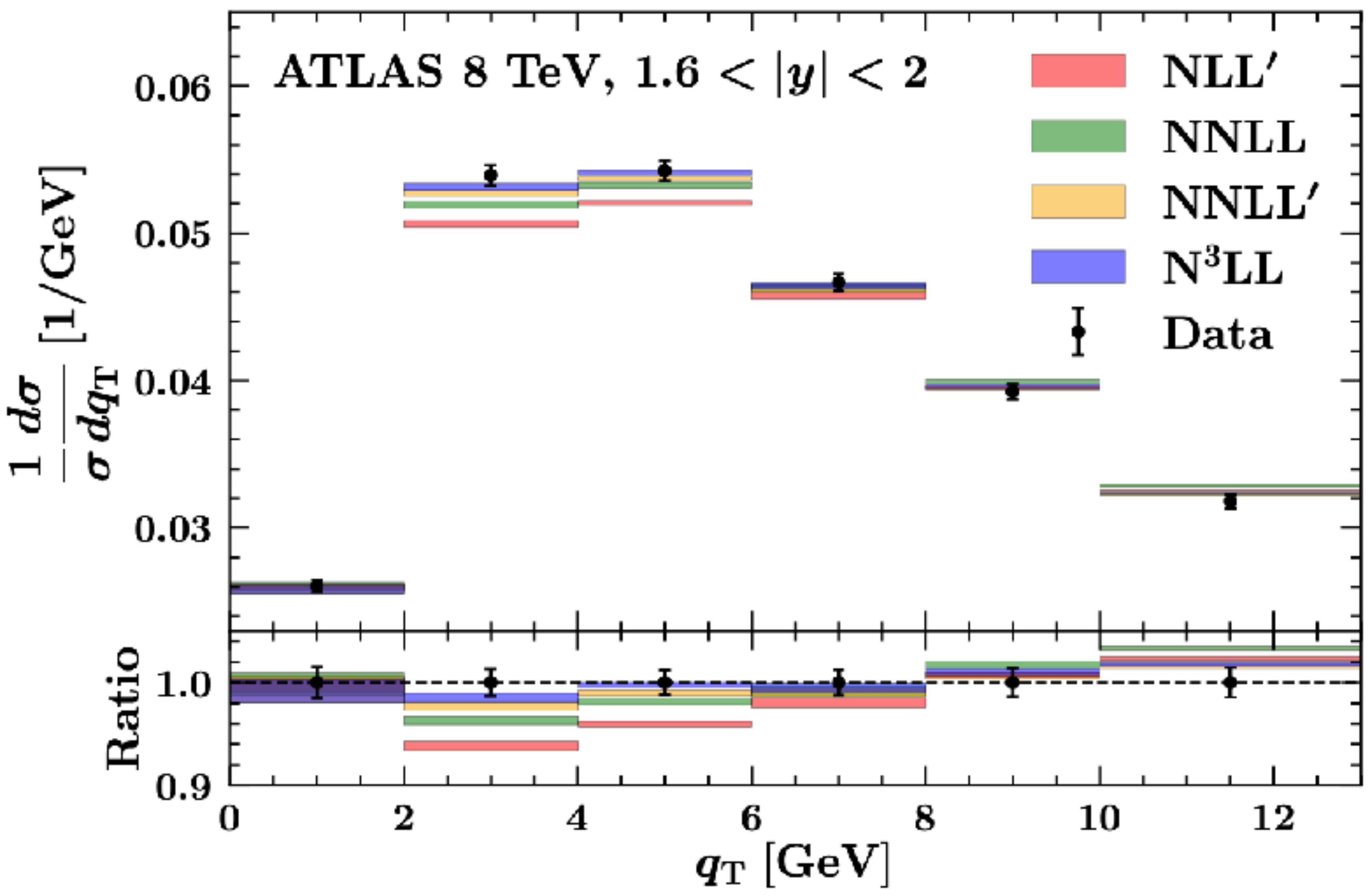
COMPARISON OF DIFFERENT ORDERS

Accuracy at N²LL and N³LL

What we expected $Q \sim 100$ GeV What we get



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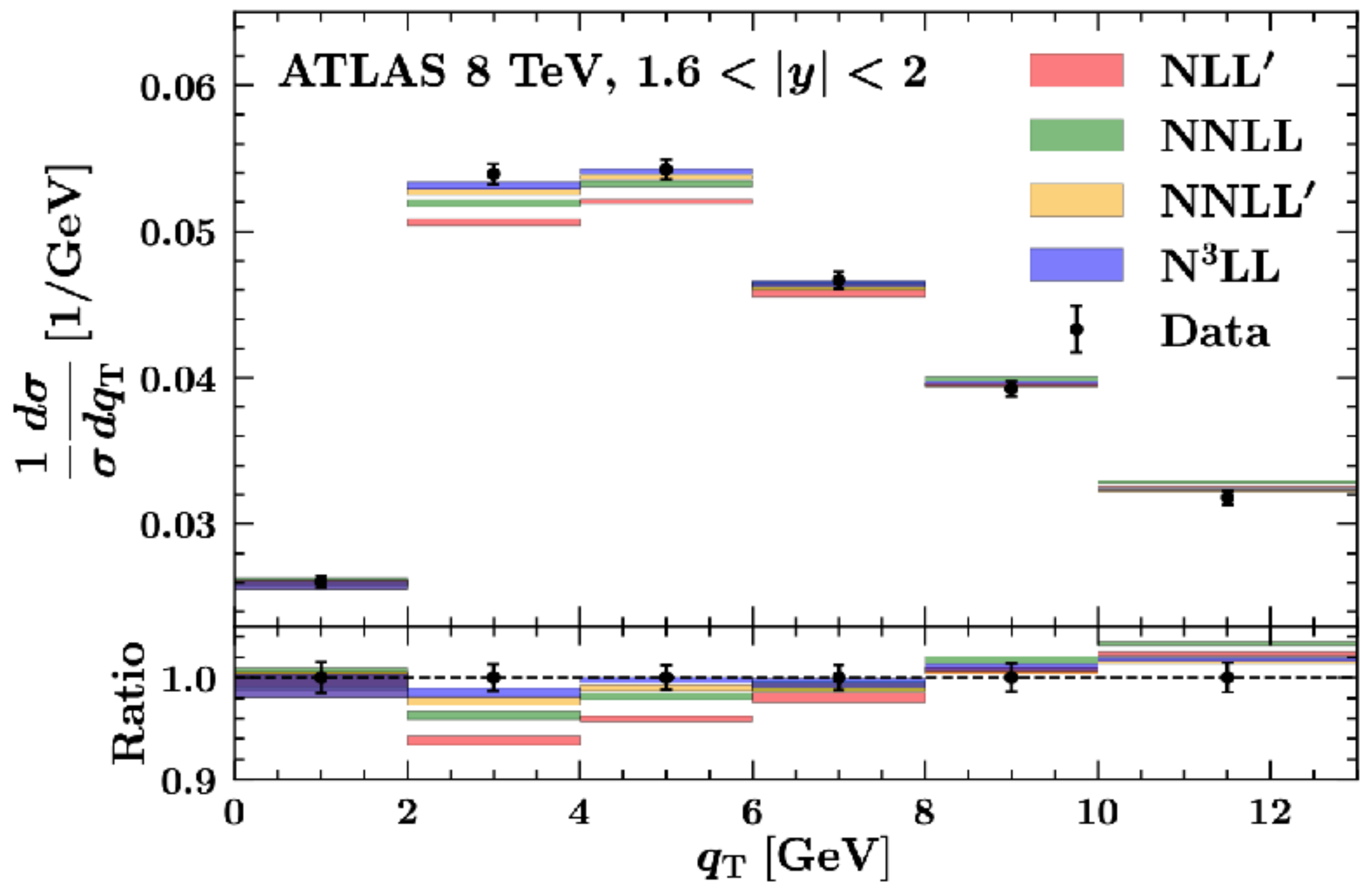

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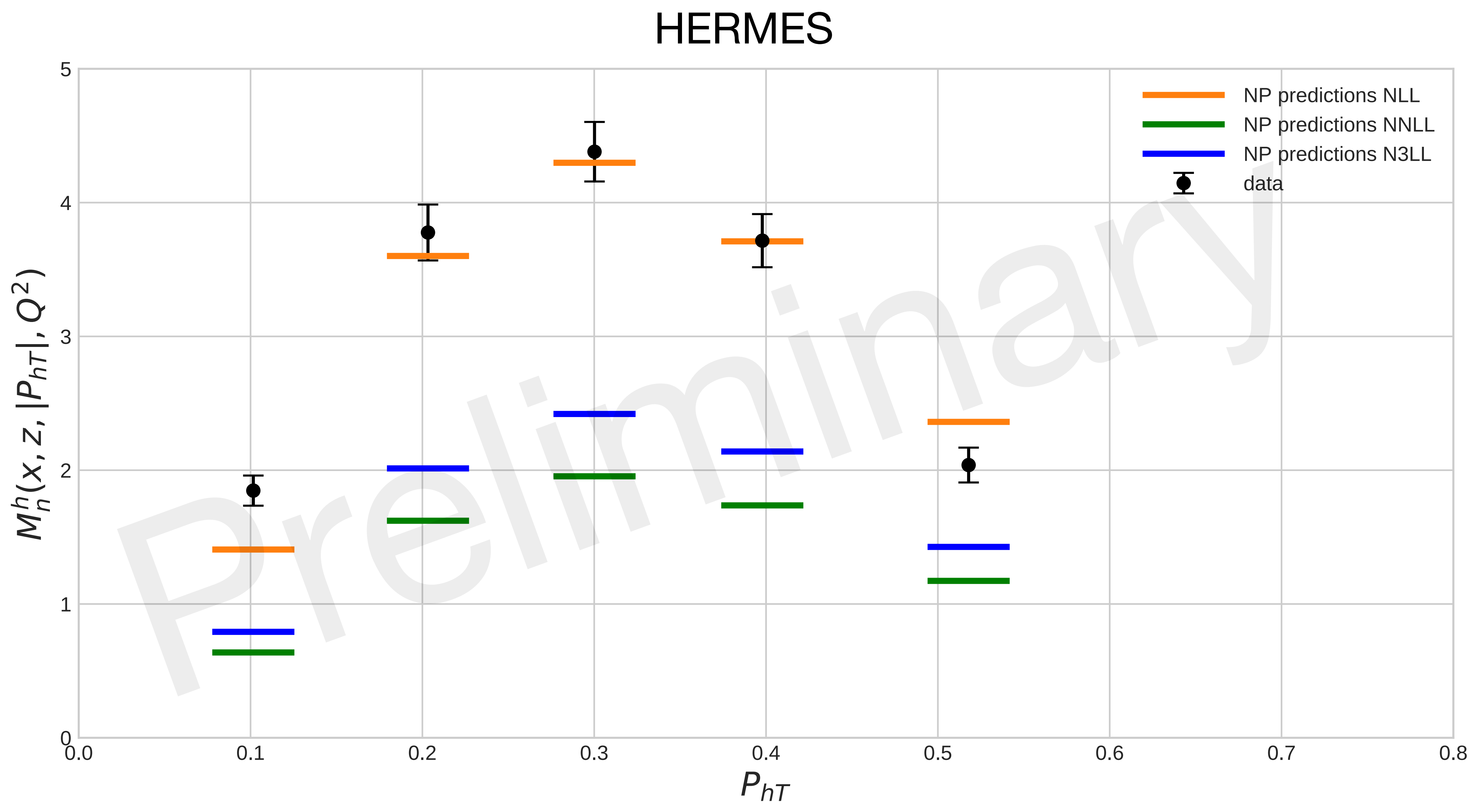
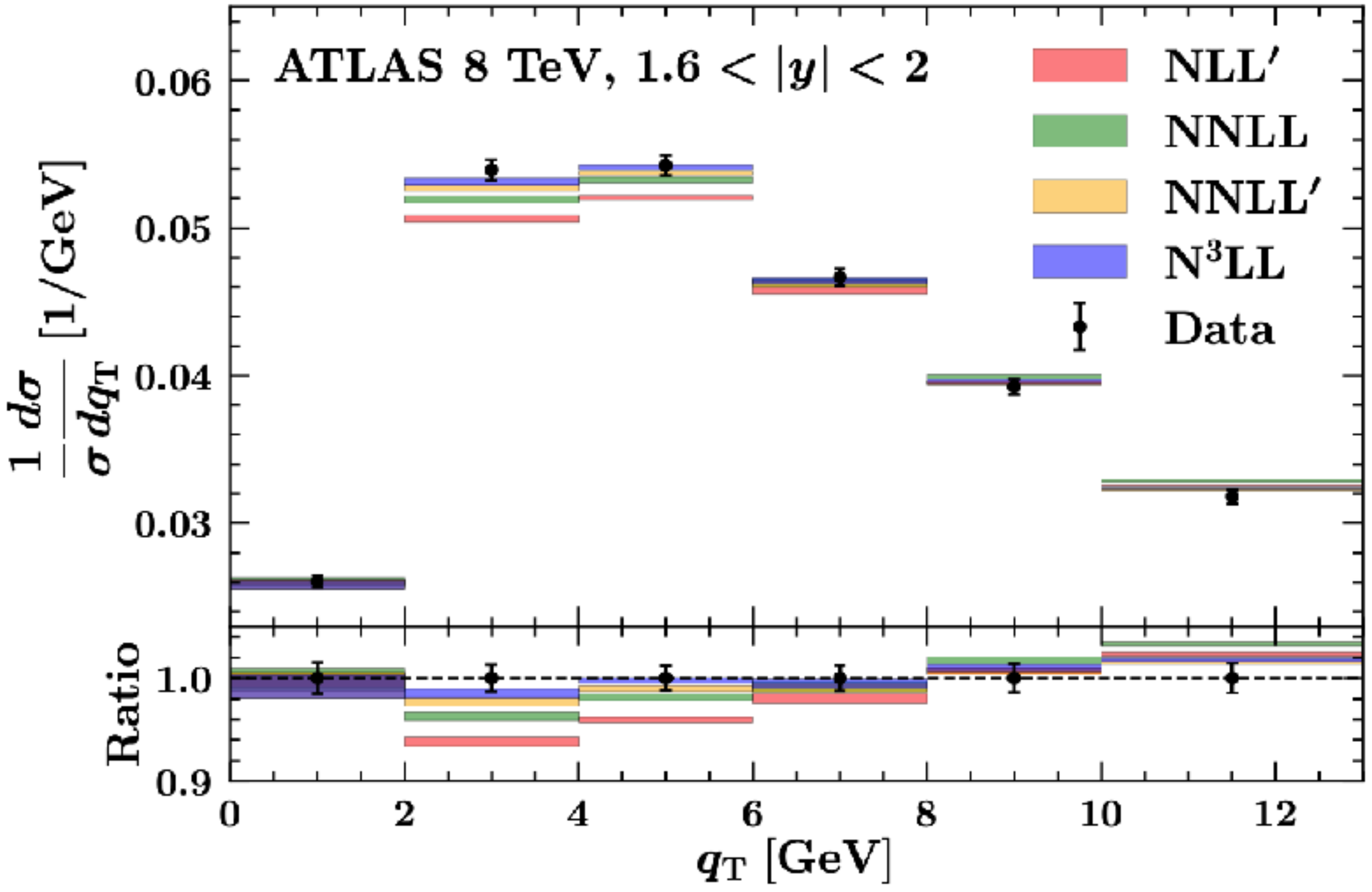
What we get $Q \sim 2$ GeV



COMPARISON OF DIFFERENT ORDERS

Accuracy at N²LL and N³LL

What we expected $Q \sim 100$ GeV



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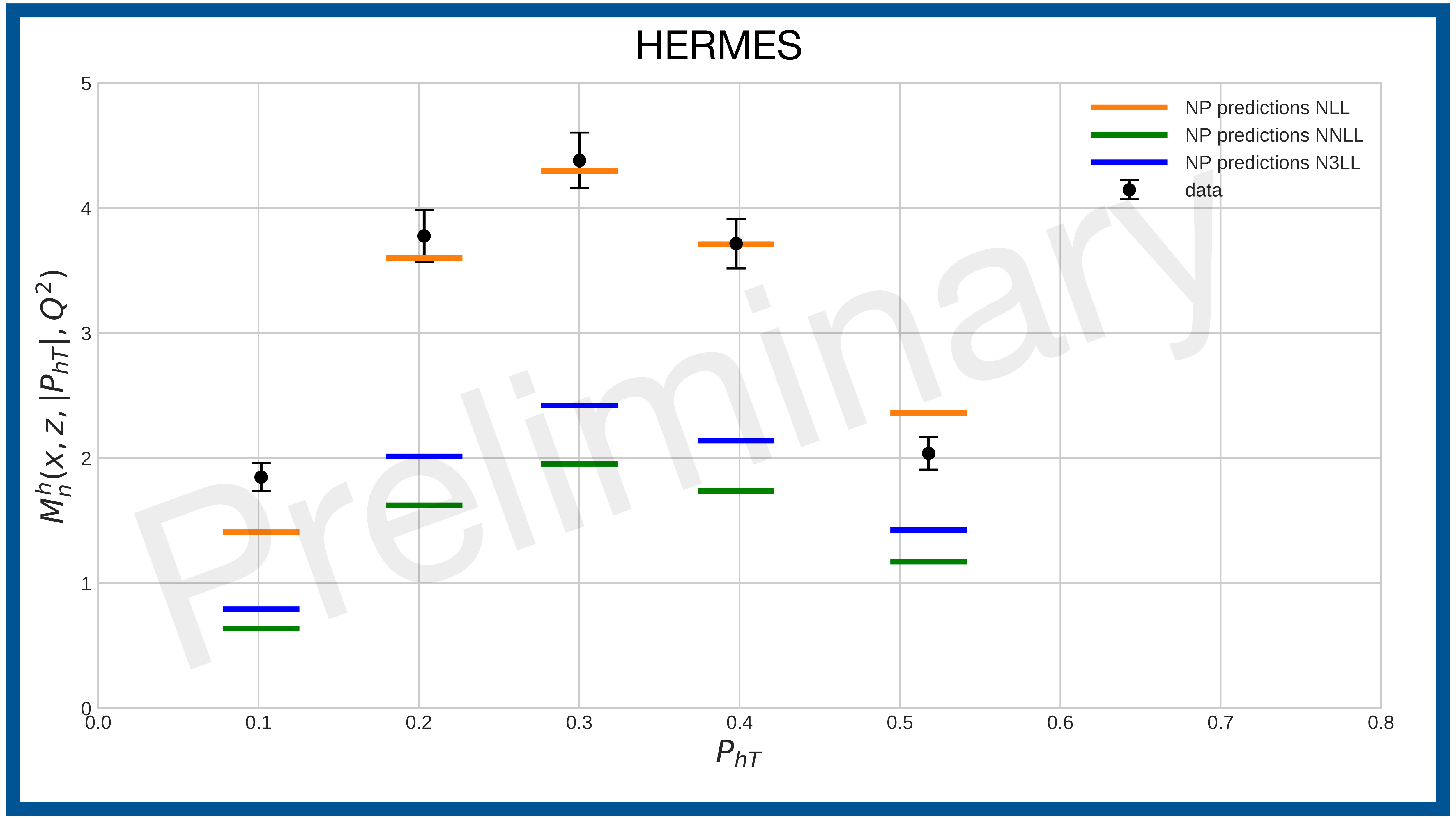
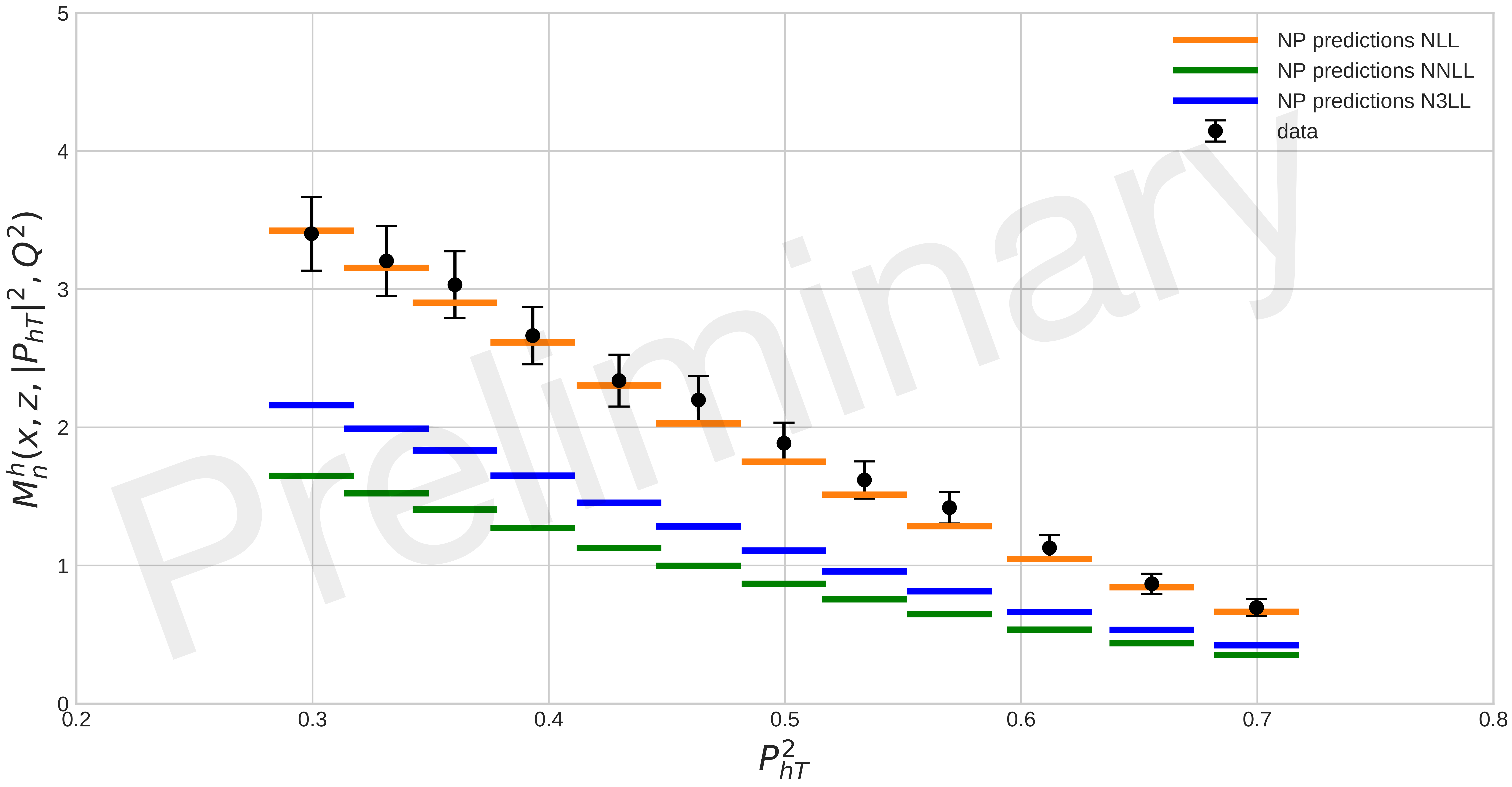


The description considerably worsens at higher orders!!

COMPARISON OF DIFFERENT ORDERS – SIDIS

COMPASS multiplicities (one of many bins)



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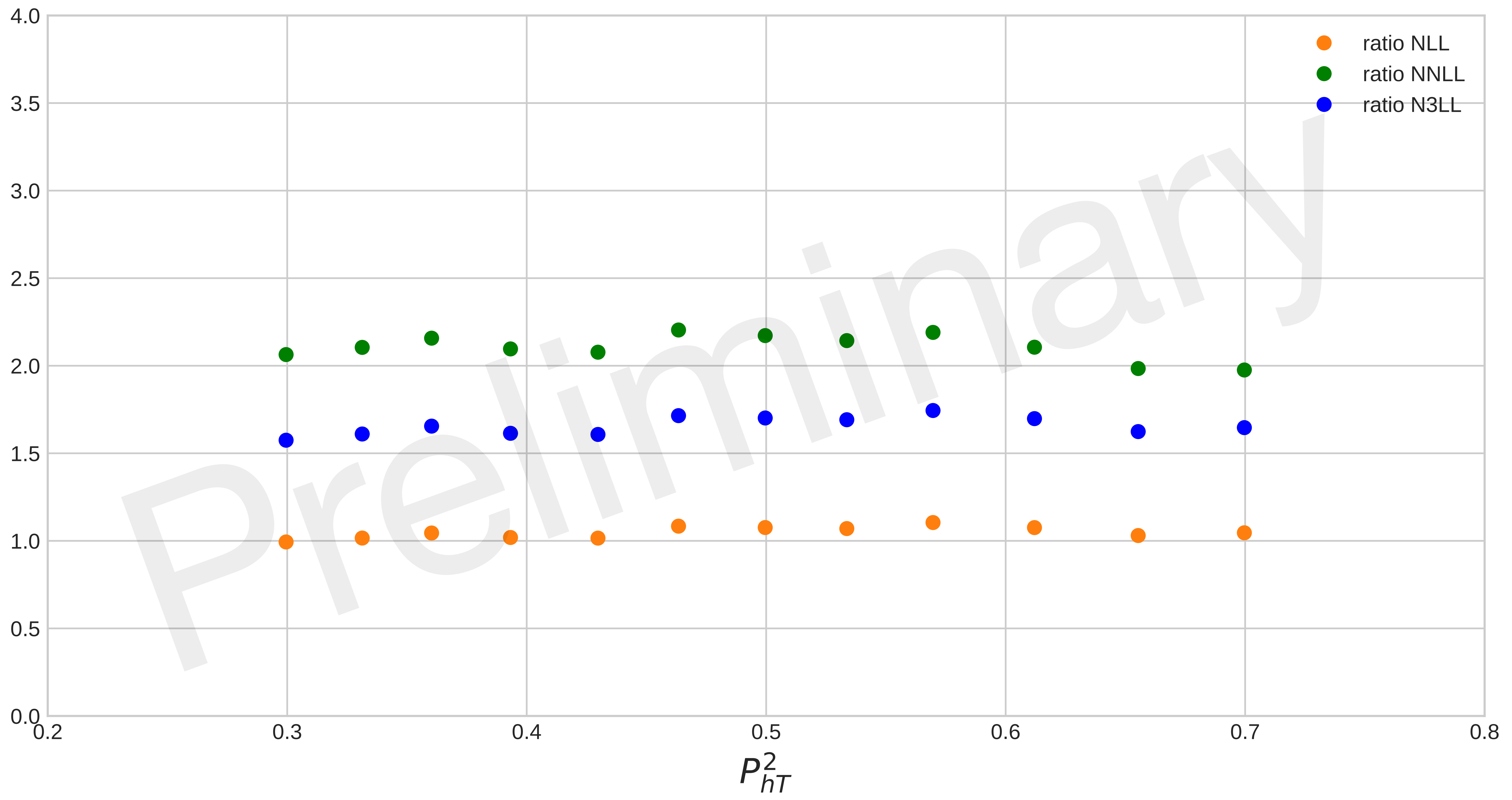
RATIO DATA/PREDICTIONS: SIDIS

COMPASS multiplicities (one of many bins)



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

OUR TENTATIVE SOLUTION

Introduction of a normalization prefactor

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

OUR TENTATIVE SOLUTION

Introduction of a normalization prefactor

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

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$$\int W \bigg|_{O(\alpha_S)} = \sigma_0 \sum_{f,f'} \frac{e_f^2}{z^2} (\delta_{f'f} + \delta_{f'g}) \frac{\alpha_S}{\pi} \left[D_1^{h/f'} \otimes C_{\mathrm{TMD}}^{f'f} \otimes f_1^{f/N} \right](x,z,Q)$$

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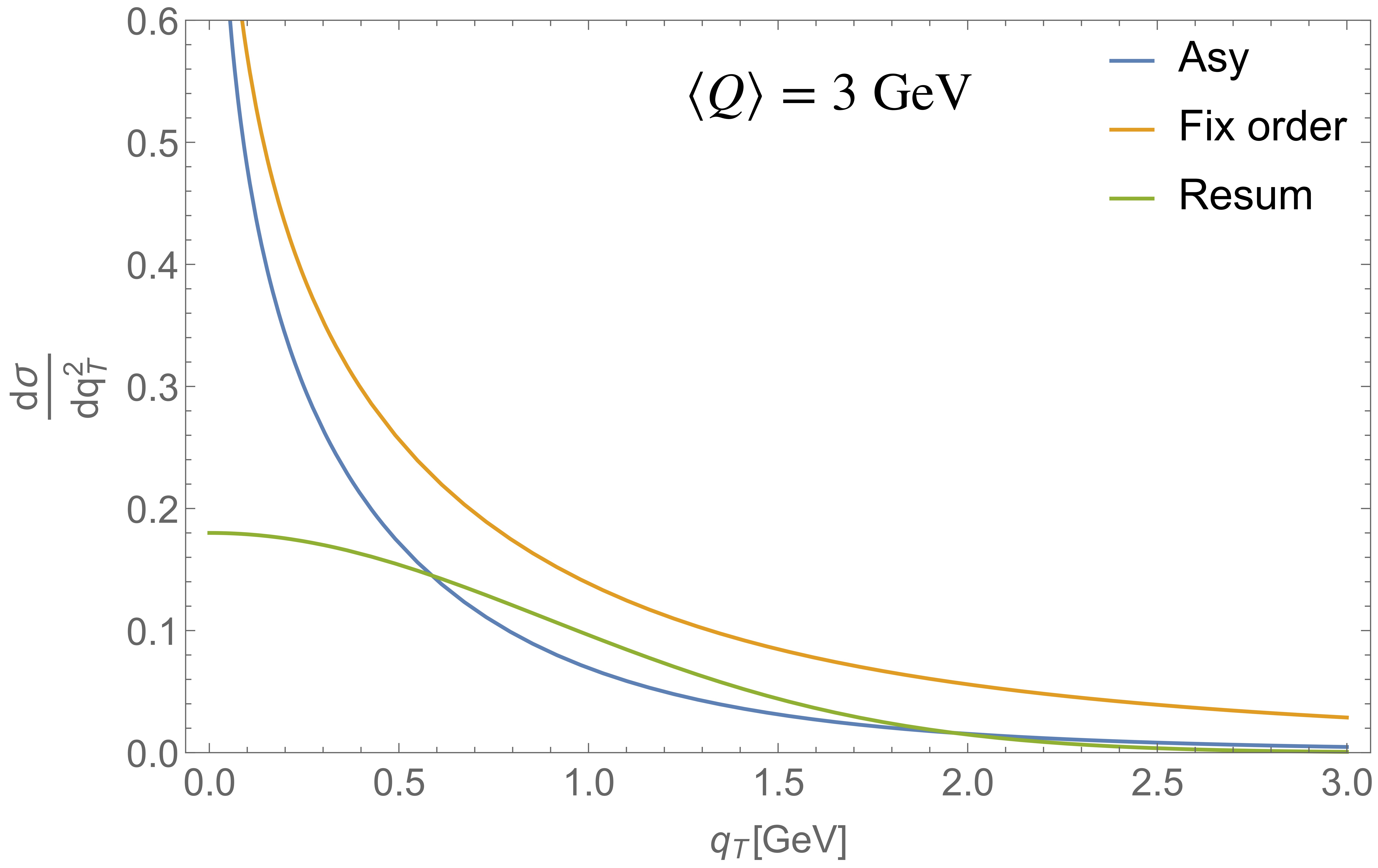
Independent of the fitting parameters!!

SOME JUSTIFICATION: INITIAL SITUATION



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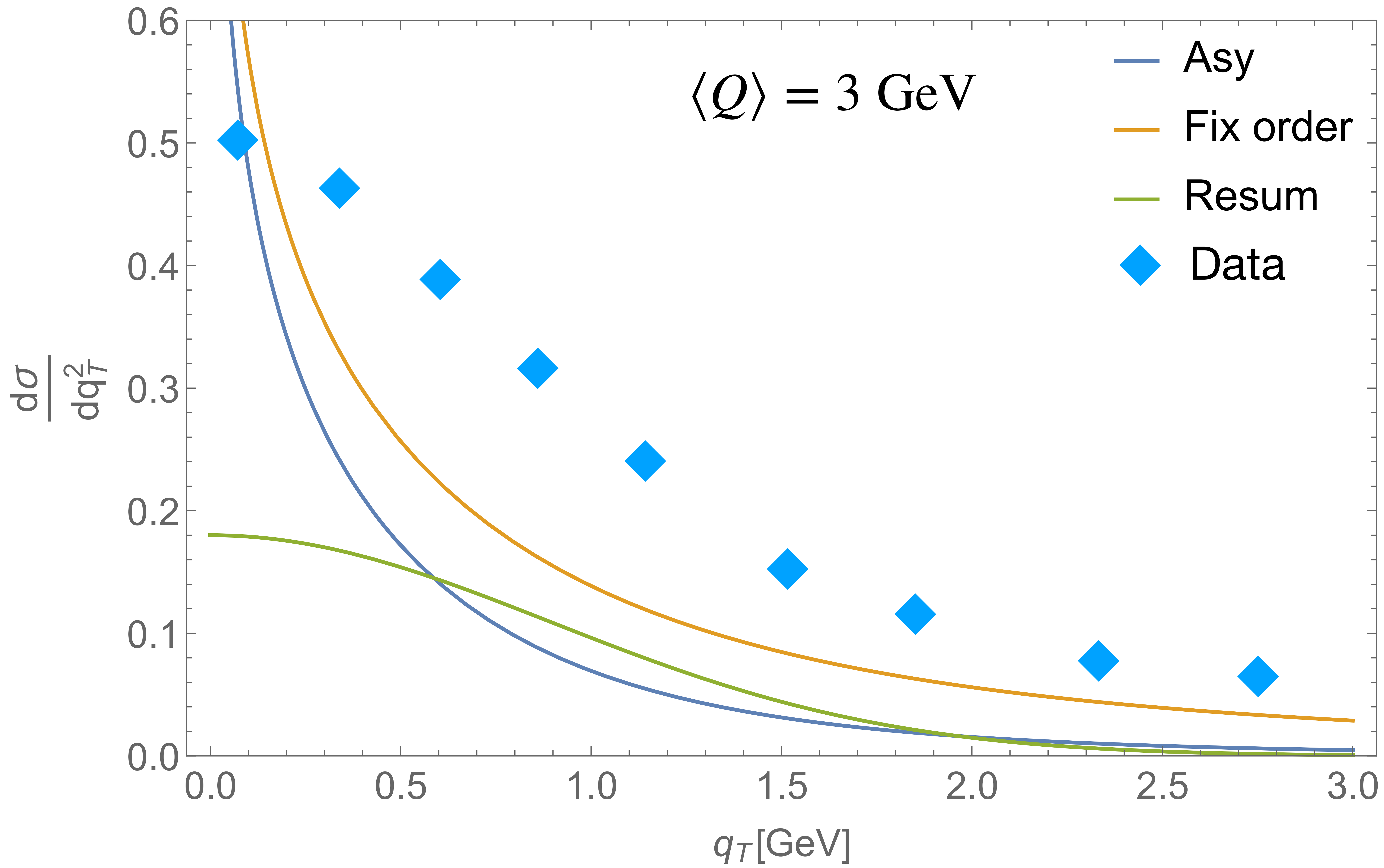
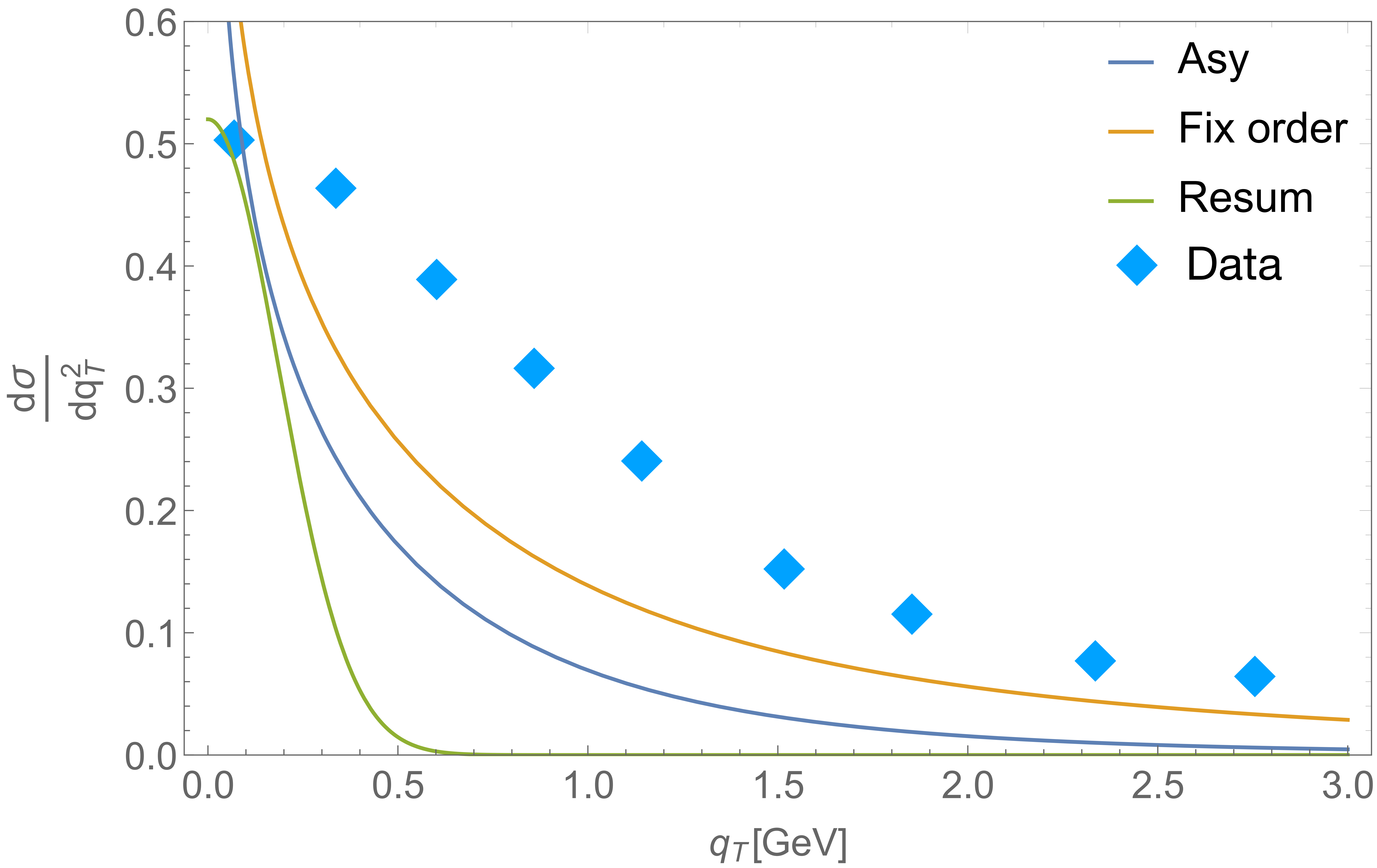
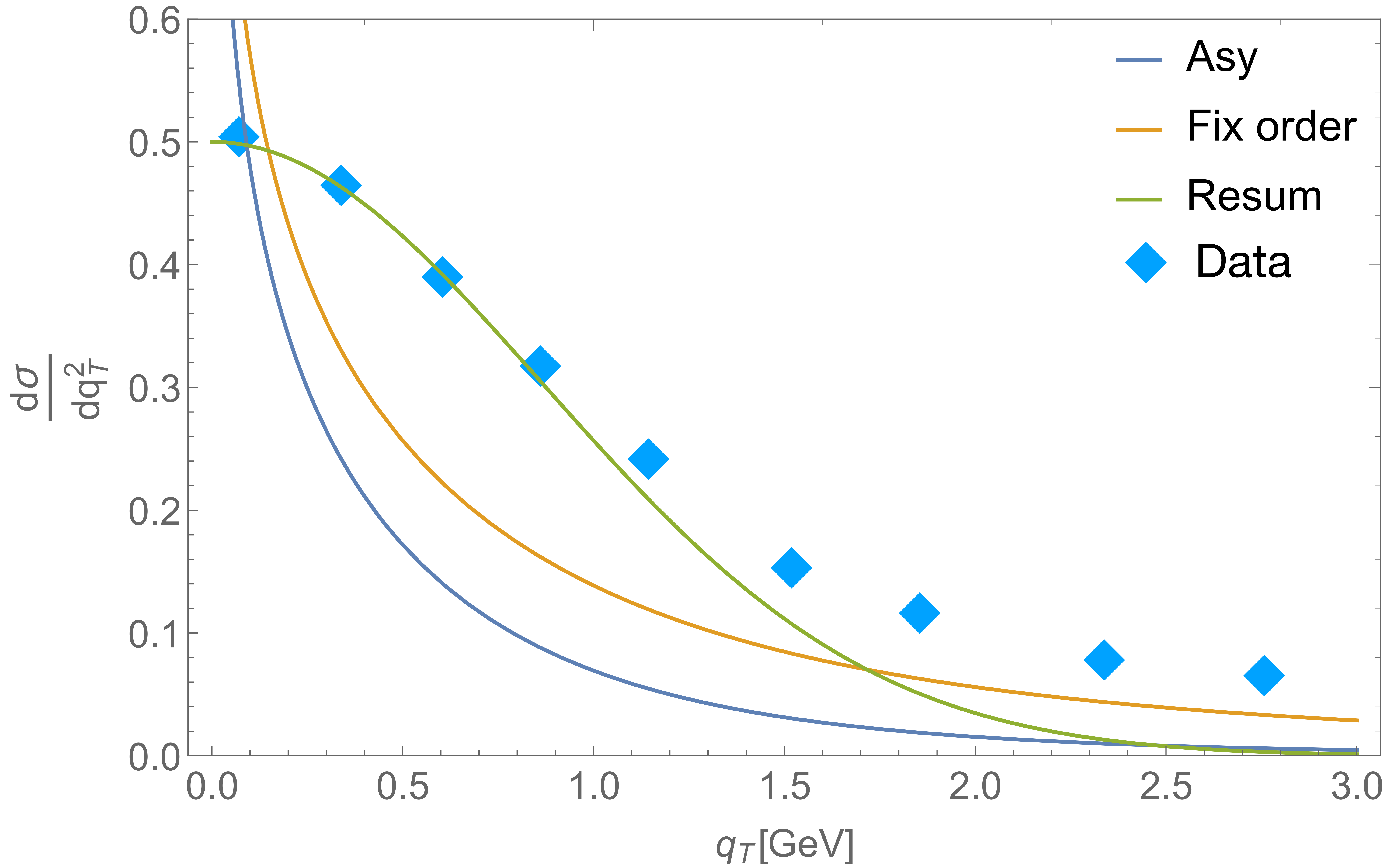


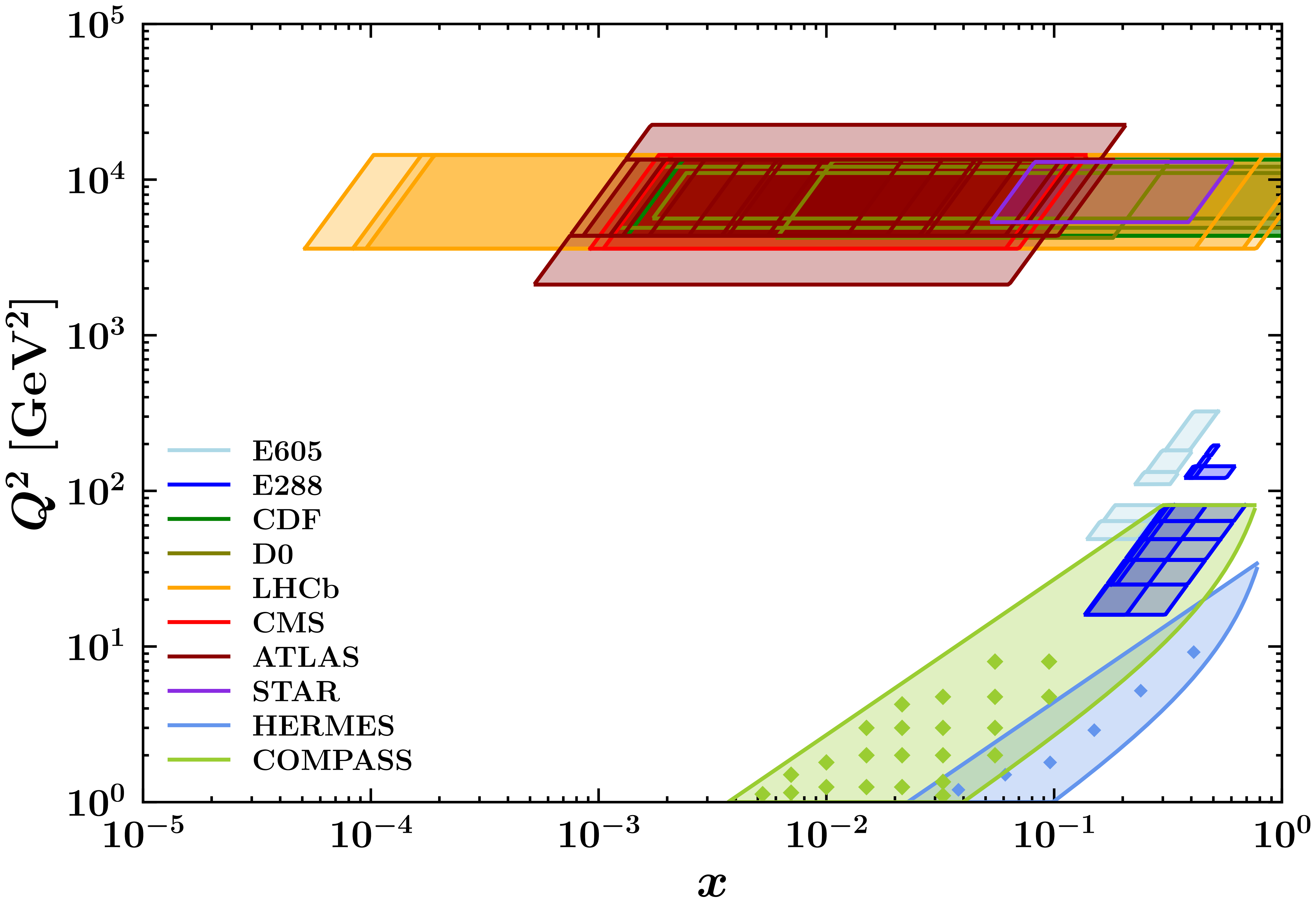
SOLUTION1: RESTRICT TMD REGION



SOLUTION2: ENHANCE TMD CONTRIBUTIONS



MAP21 TMD FIT CHOICES (PRELIMINARY)



$$\langle Q \rangle > 1.3 \text{ GeV}$$

$$0.2 < z < 0.6$$

$$q_T < 0.2\ Q \quad \text{(DY)}$$

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

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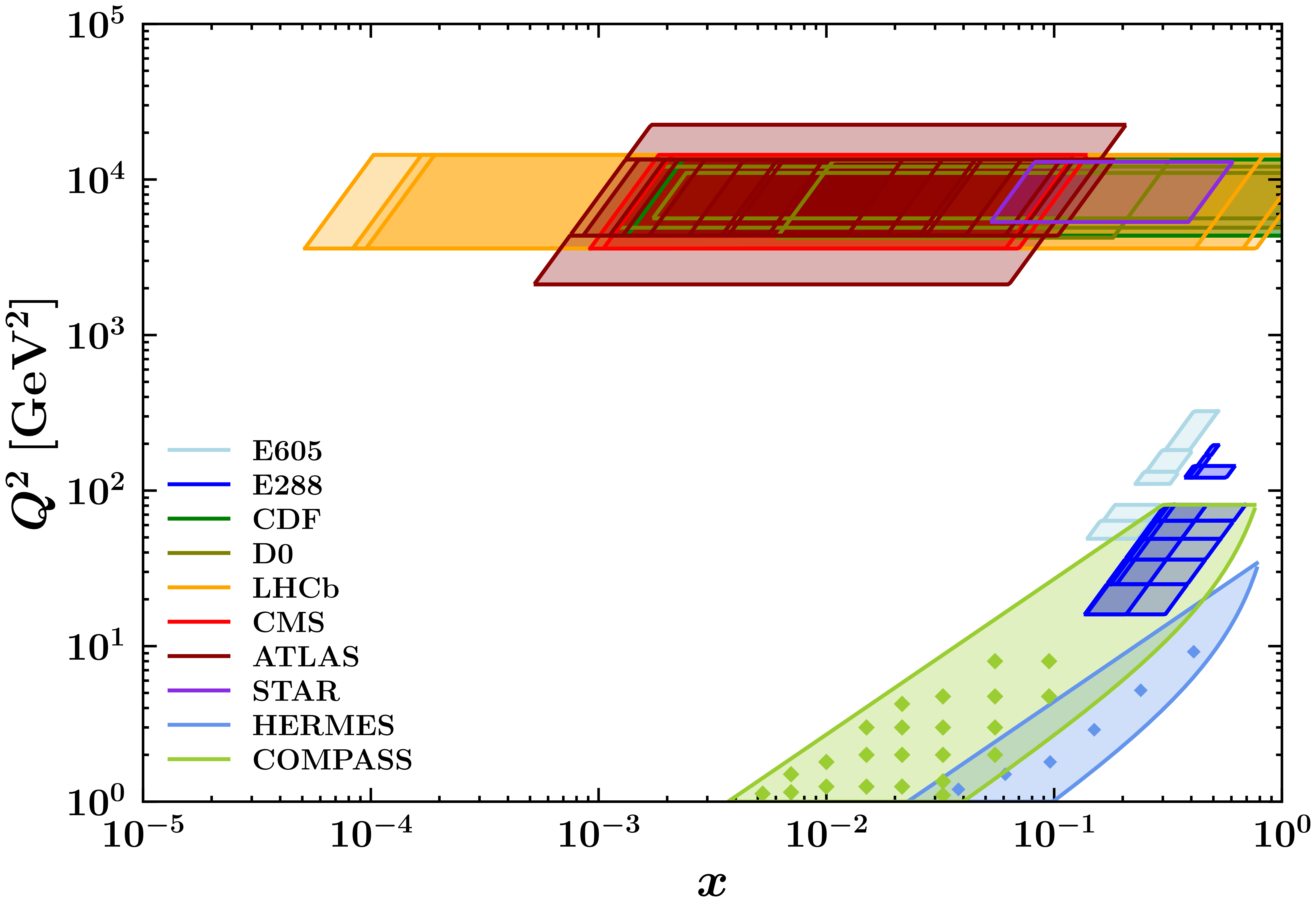

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Number of points > 1500

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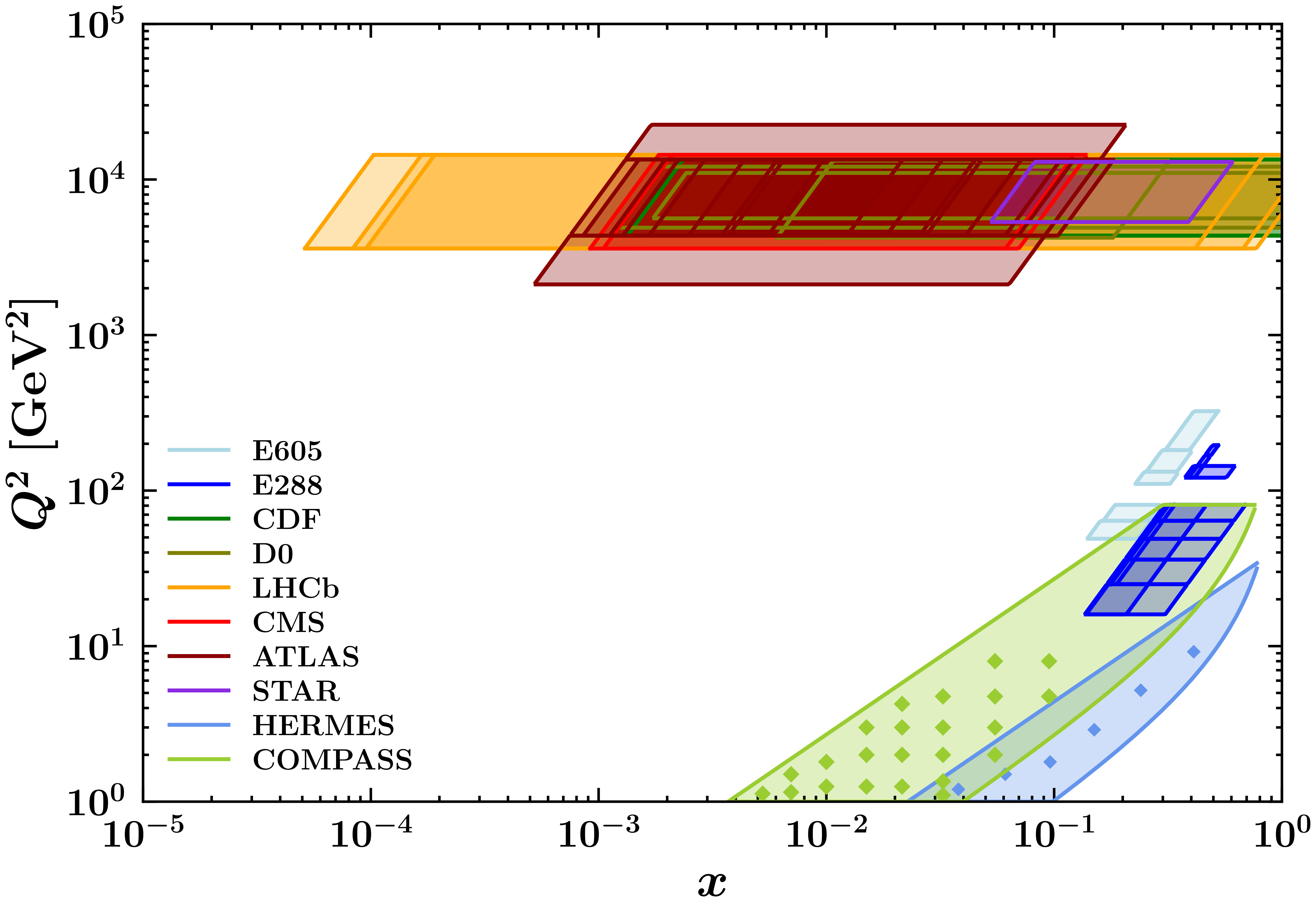

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$0.2 < z < 0.6 \rightarrow 0.7$

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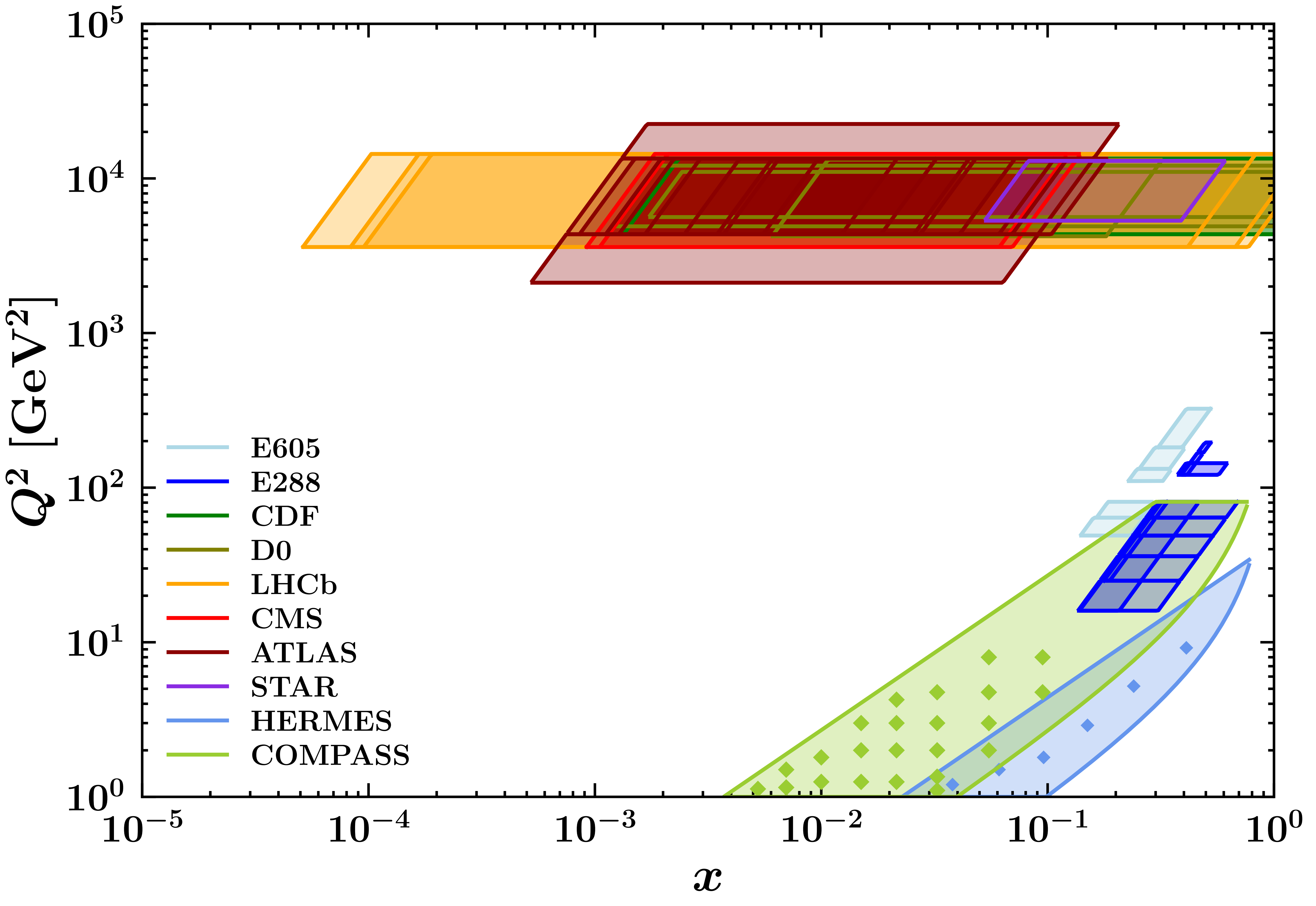

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Number of points > 1500 $\rightarrow$ **2000 ?**

FUNCTIONAL FORM (PRELIMINARY)

$$f_{1\mathrm{NP}}(x, b_T^2) \propto \text{F.T. of } \left(e^{-\frac{k_\perp^2}{g_{1A}}} + \lambda_B k_\perp^2 e^{-\frac{k_\perp^2}{g_{1B}}} + \lambda_C e^{-\frac{k_\perp^2}{g_{1C}}} \right)$$

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Still working on the flexibility of the final form

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$$g_1(x) = N_1 \, \frac{(1-x)^\alpha \; x^\sigma}{(1-\hat{x})^\alpha \; \hat{x}^\sigma}$$

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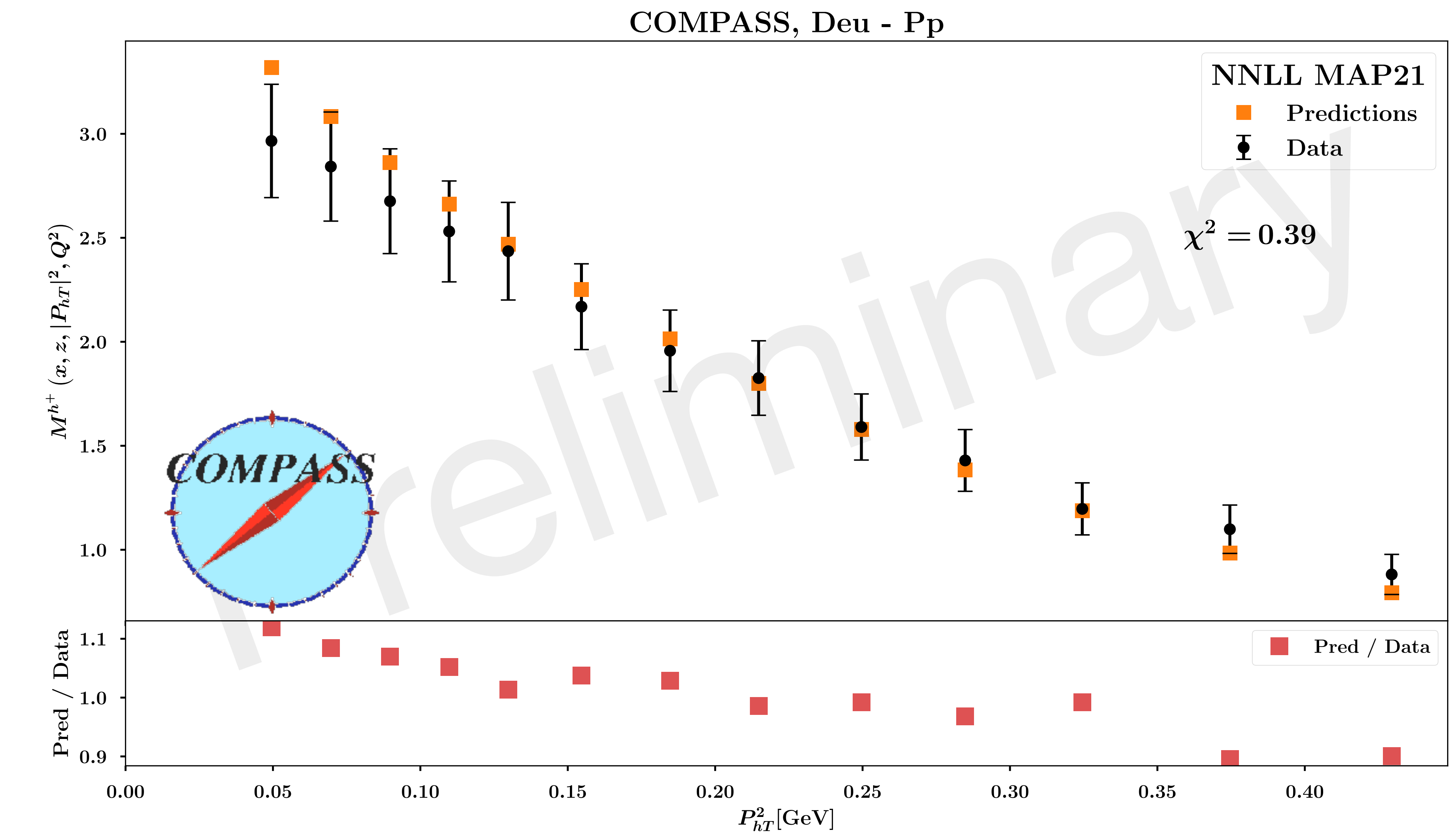
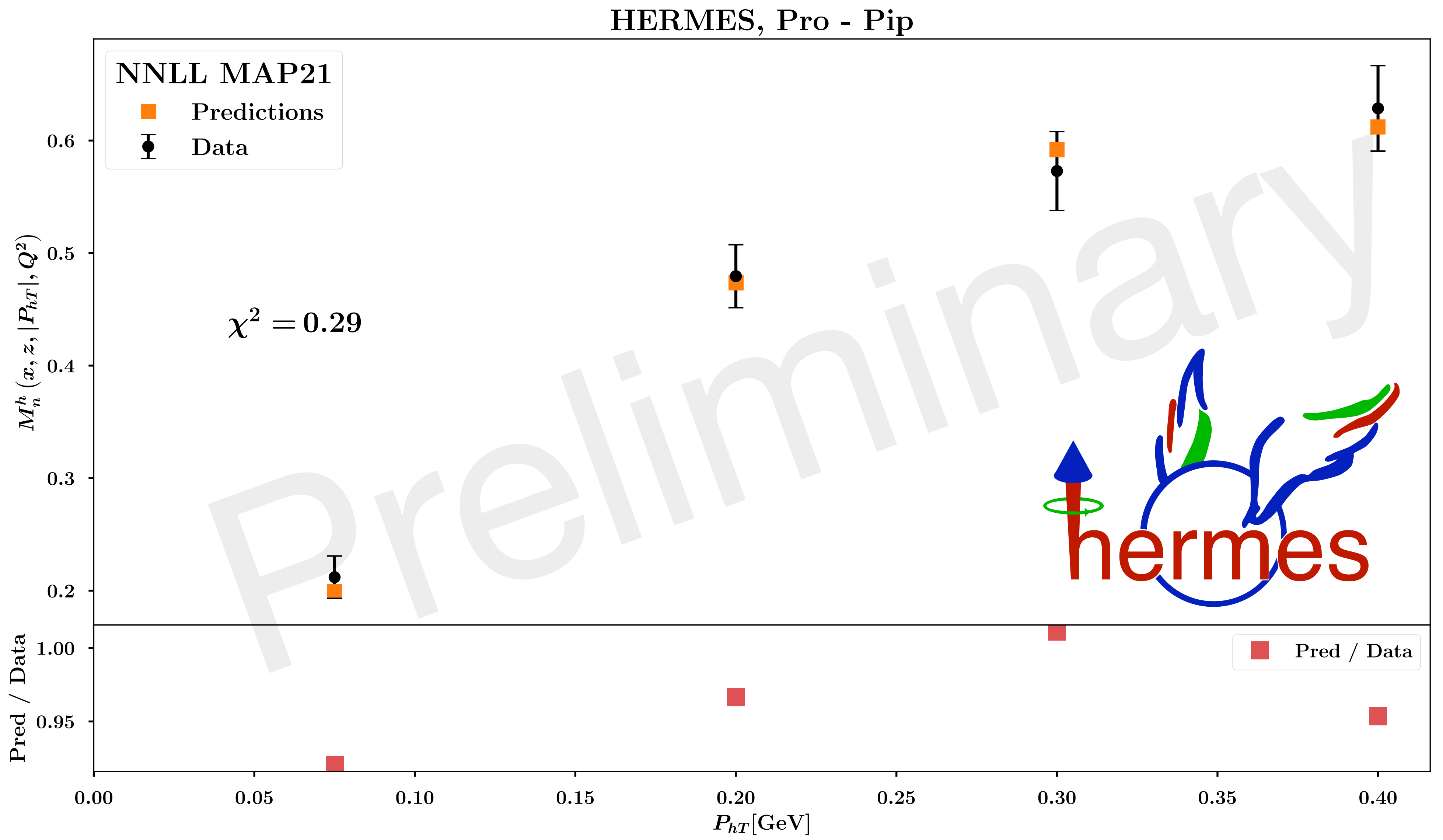
Still working on the flexibility of the final form

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

N²LL: EXAMPLE OF GOOD BINS

Global $\chi^2 < 1.1$





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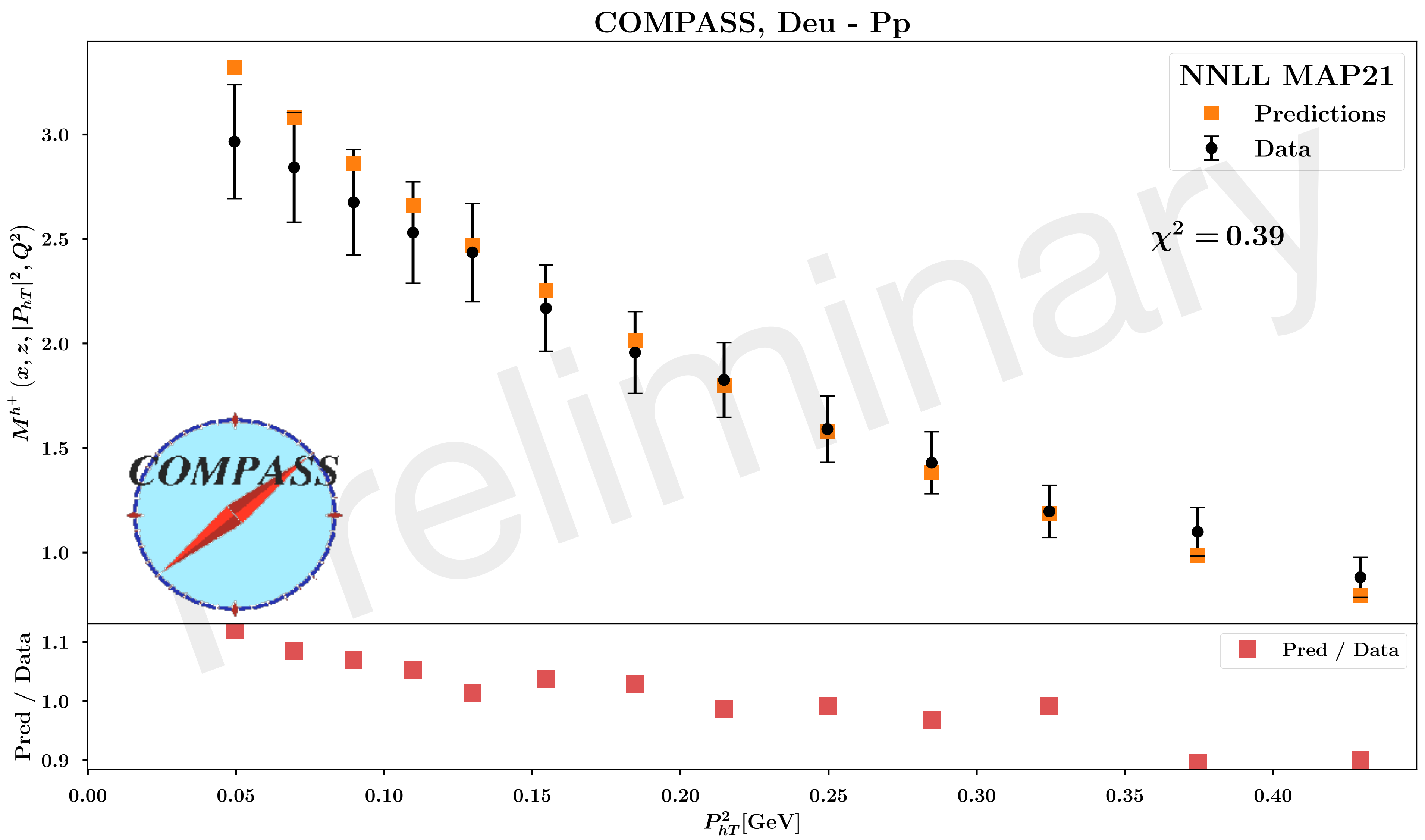
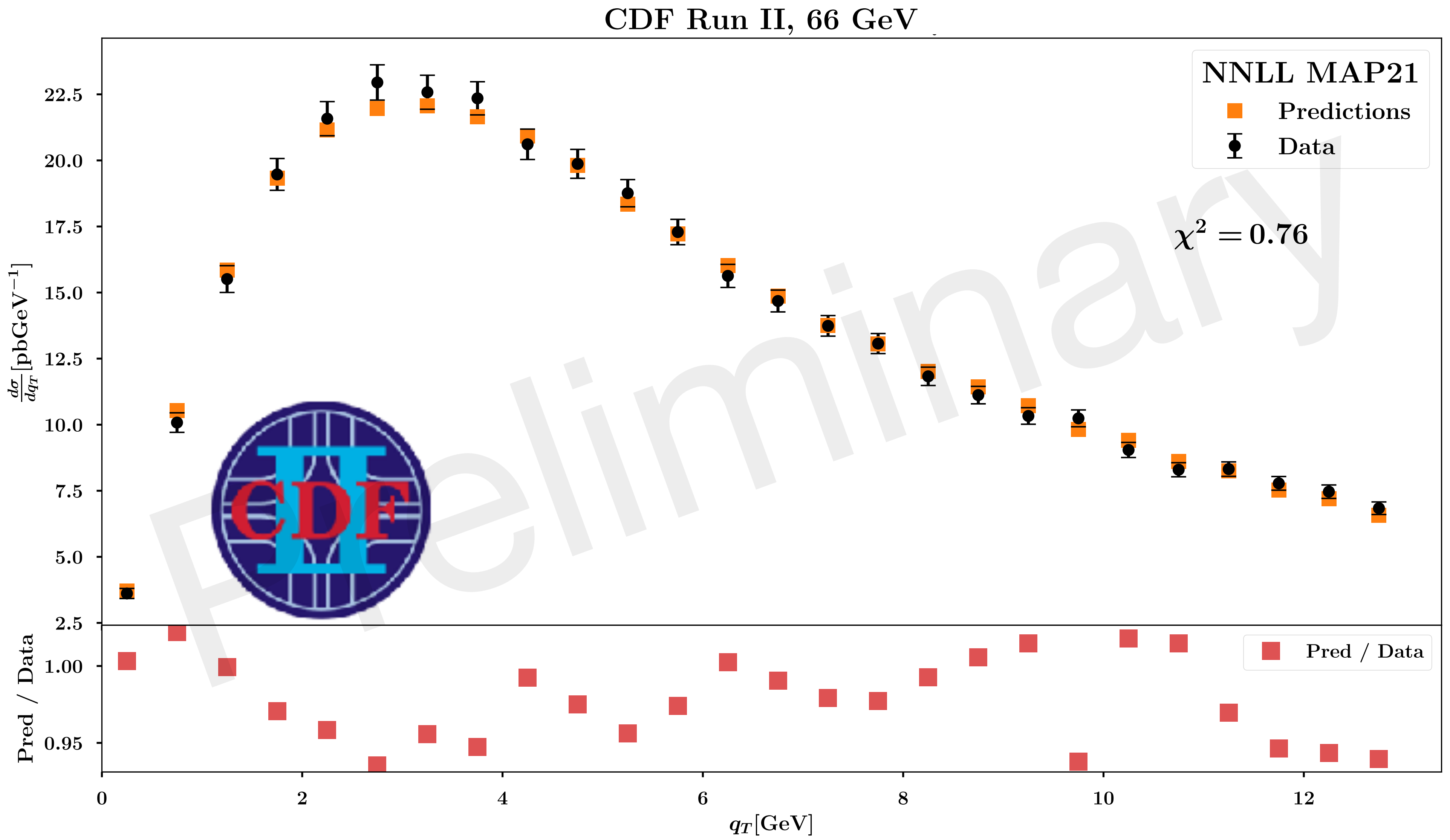
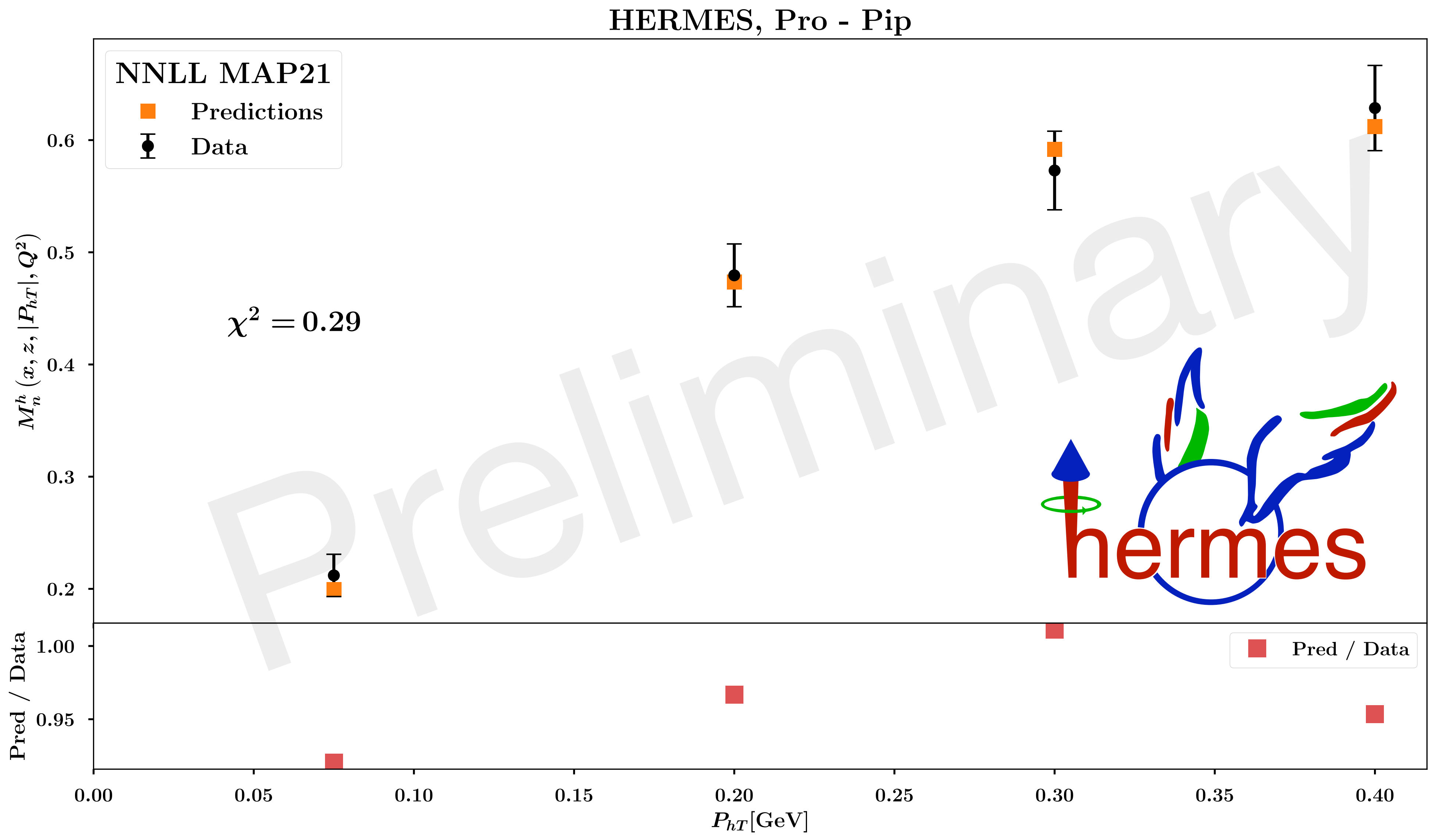
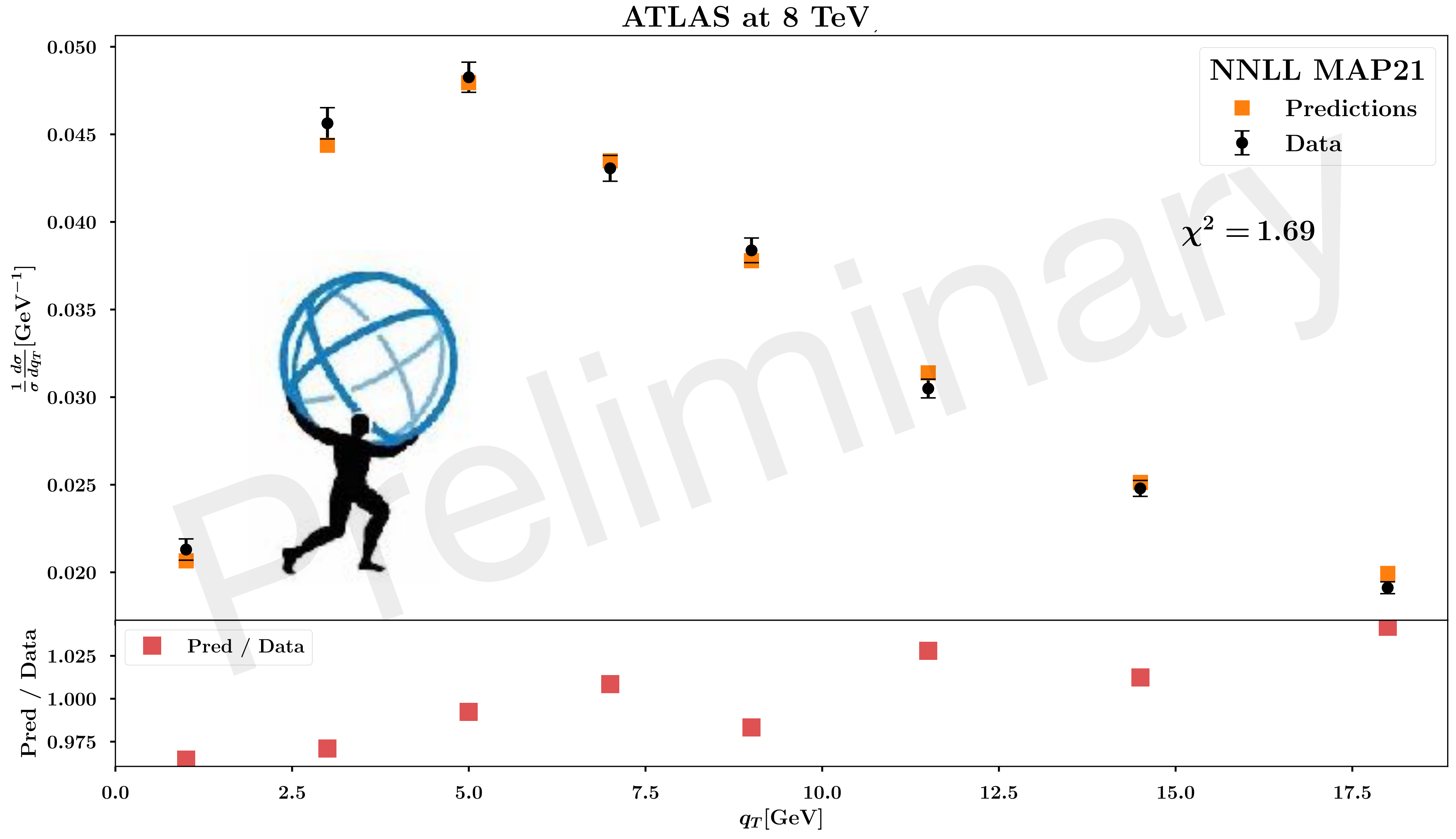


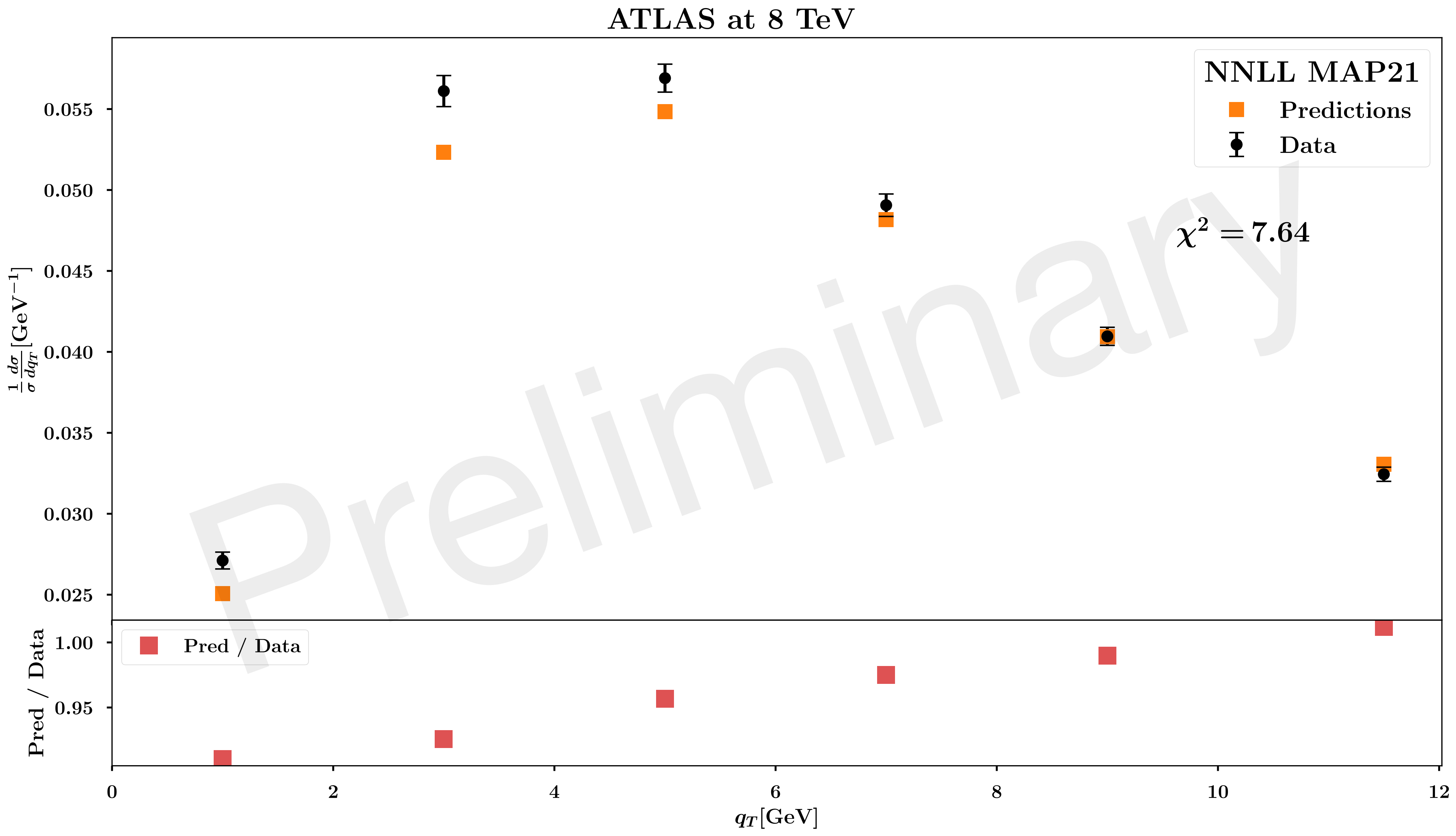


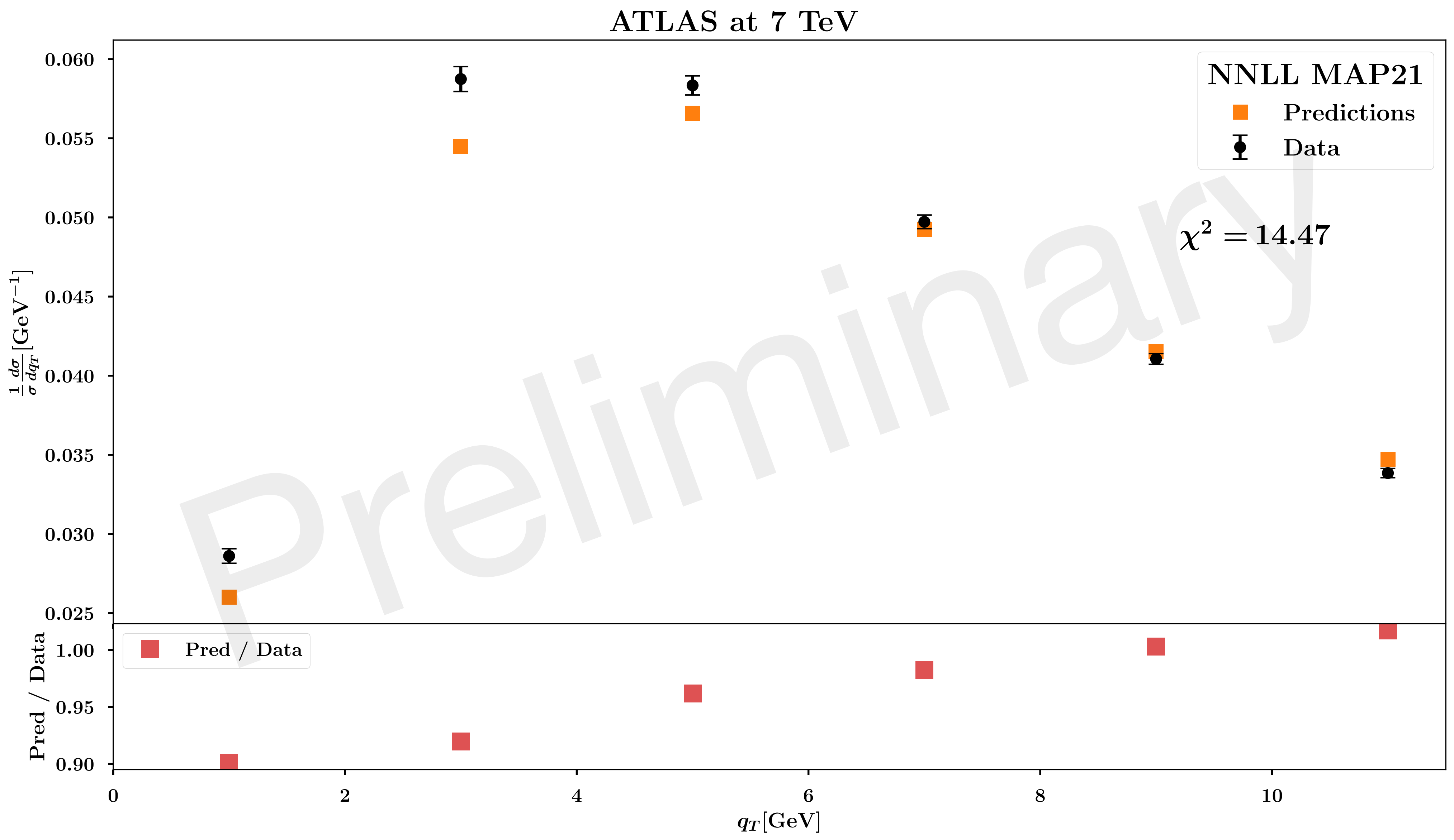


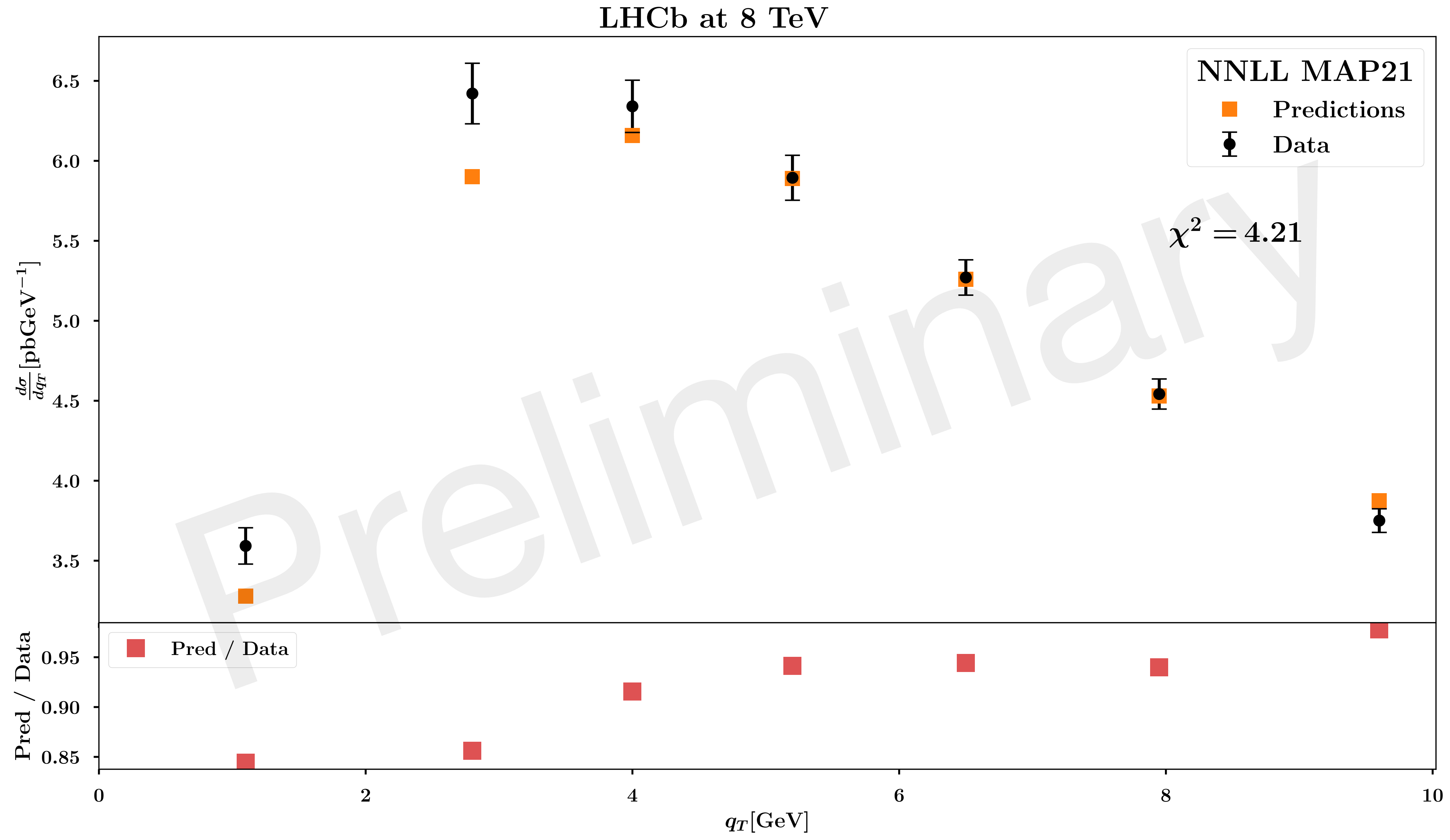


N²LL: EXAMPLE OF BAD BINS

Global $\chi^2 < 1.1$







CONCLUSIONS

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- 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

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

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

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

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

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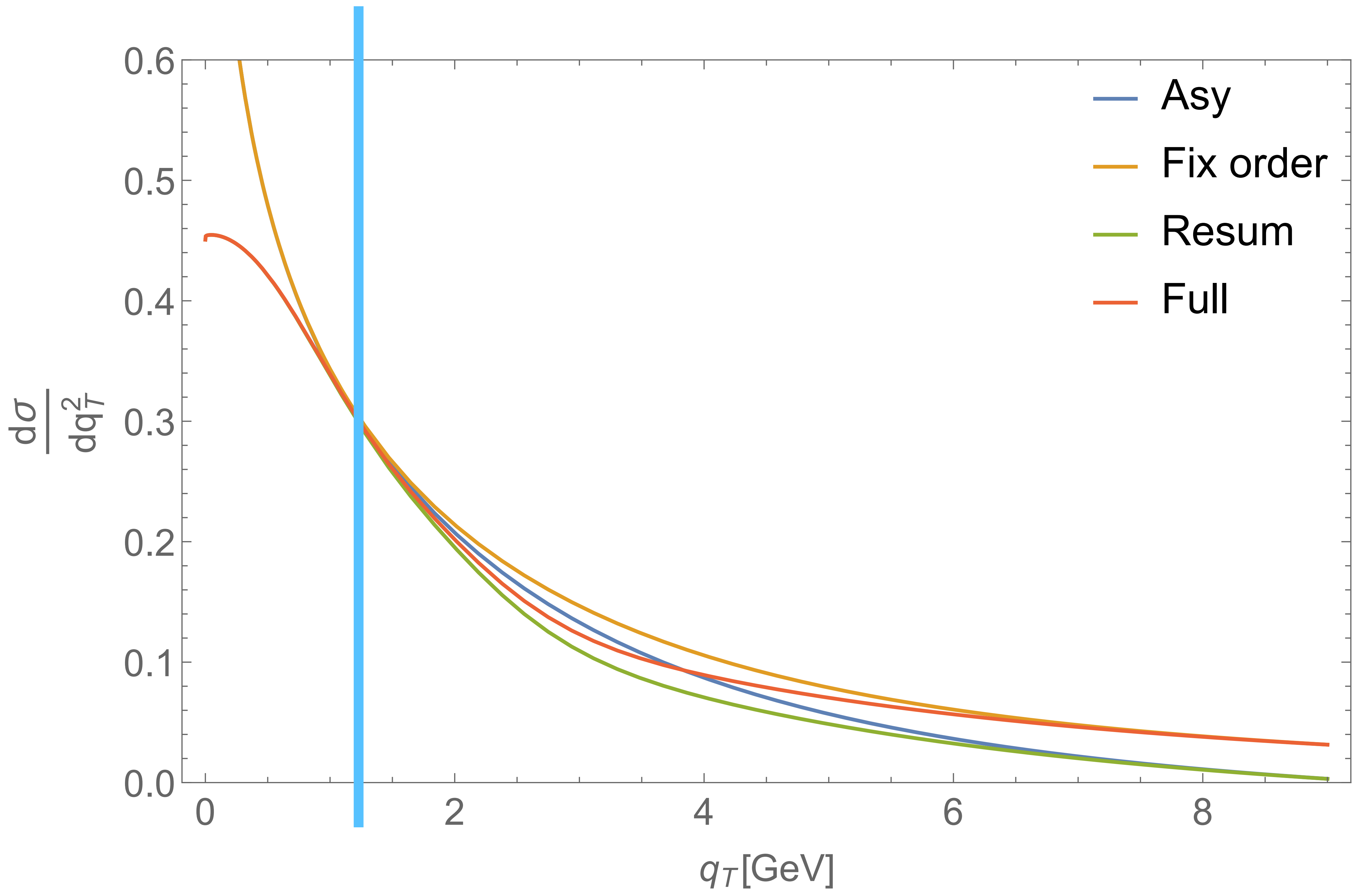
SOURCE OF W TERM SUPPRESSION - IDEAL SITUATION - LARGE Q

Ideal situation at high Q



Standard approach

- Resummed contribution is dominant where the Asymptotic term is close to the Fixed Order

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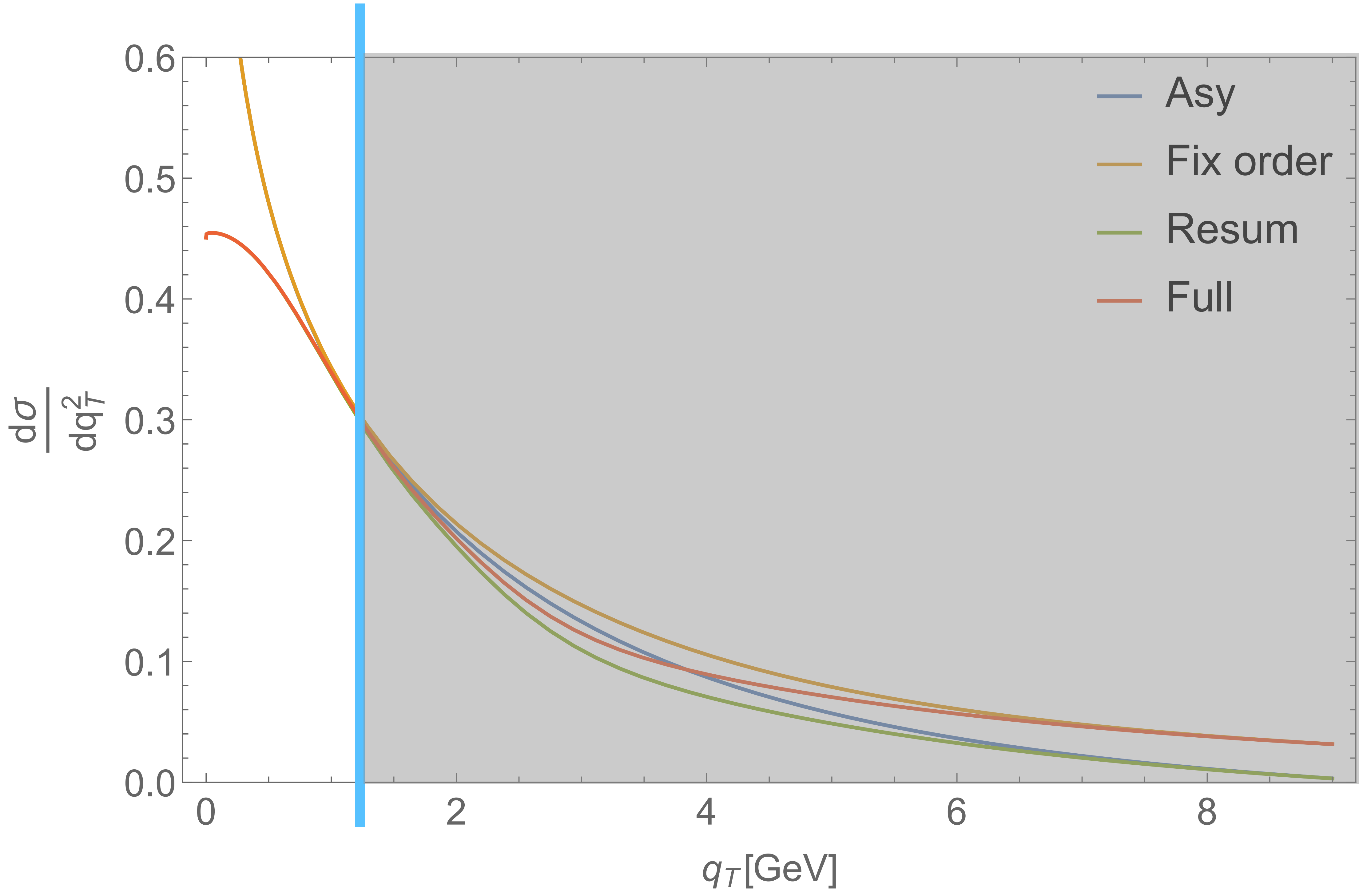

Standard approach

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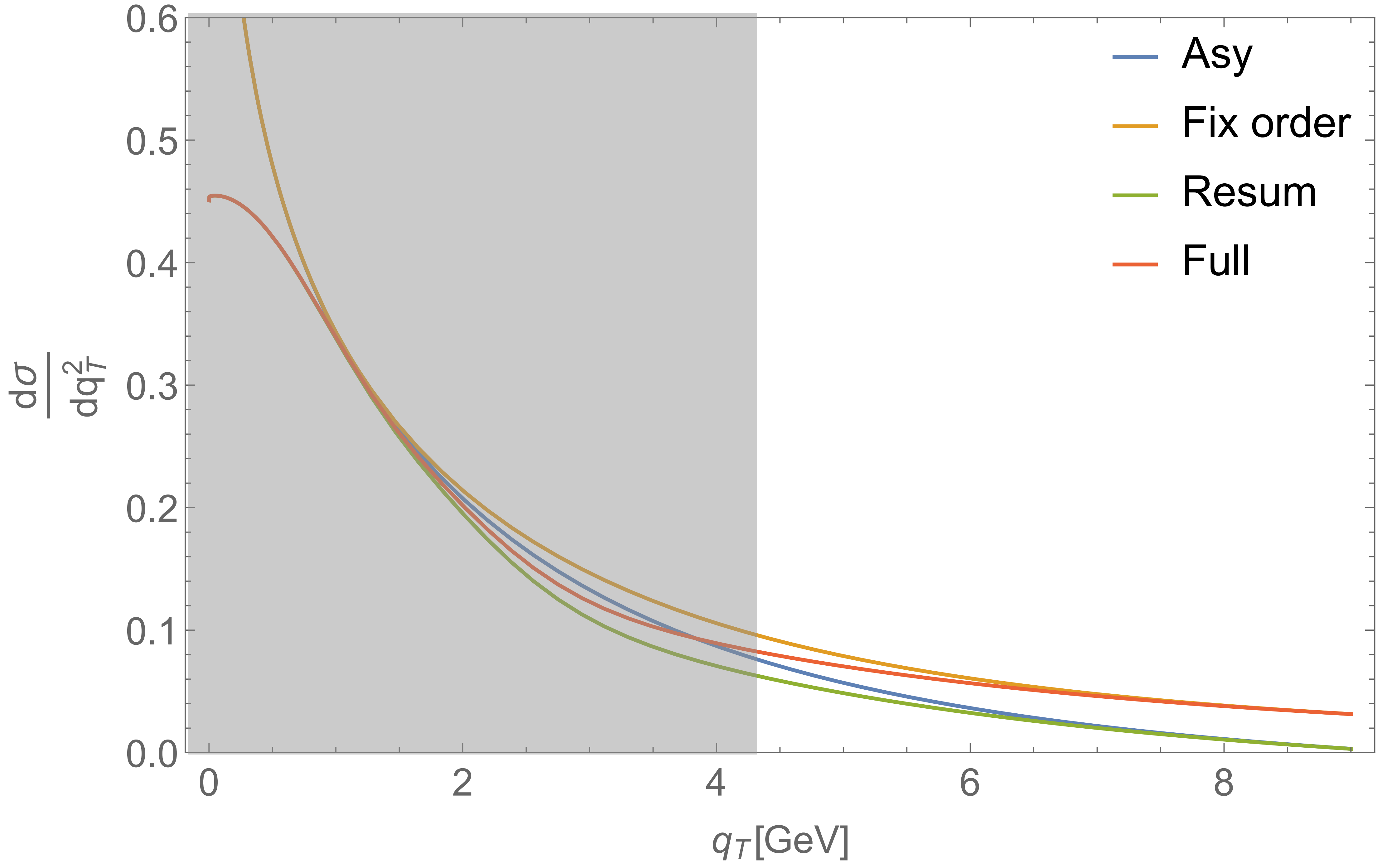
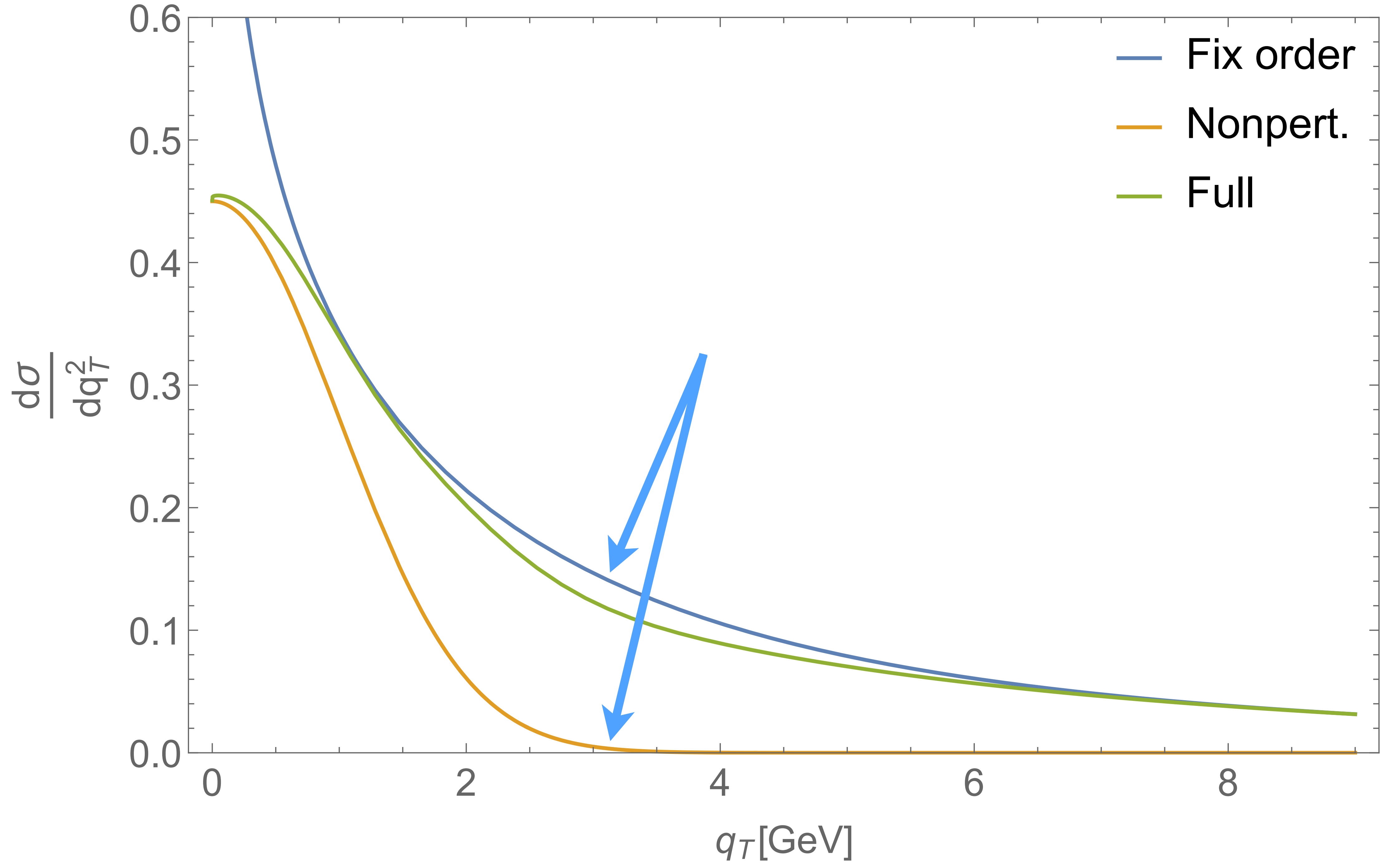


Standard approach

- Resummed contribution is dominant where the Asymptotic term is close to the Fixed Order
- From a certain value of qT the total cross section follows the Fixed Order term

SOURCE OF W TERM SUPPRESSION - IDEAL SITUATION - LARGE Q

Ideal situation at high Q

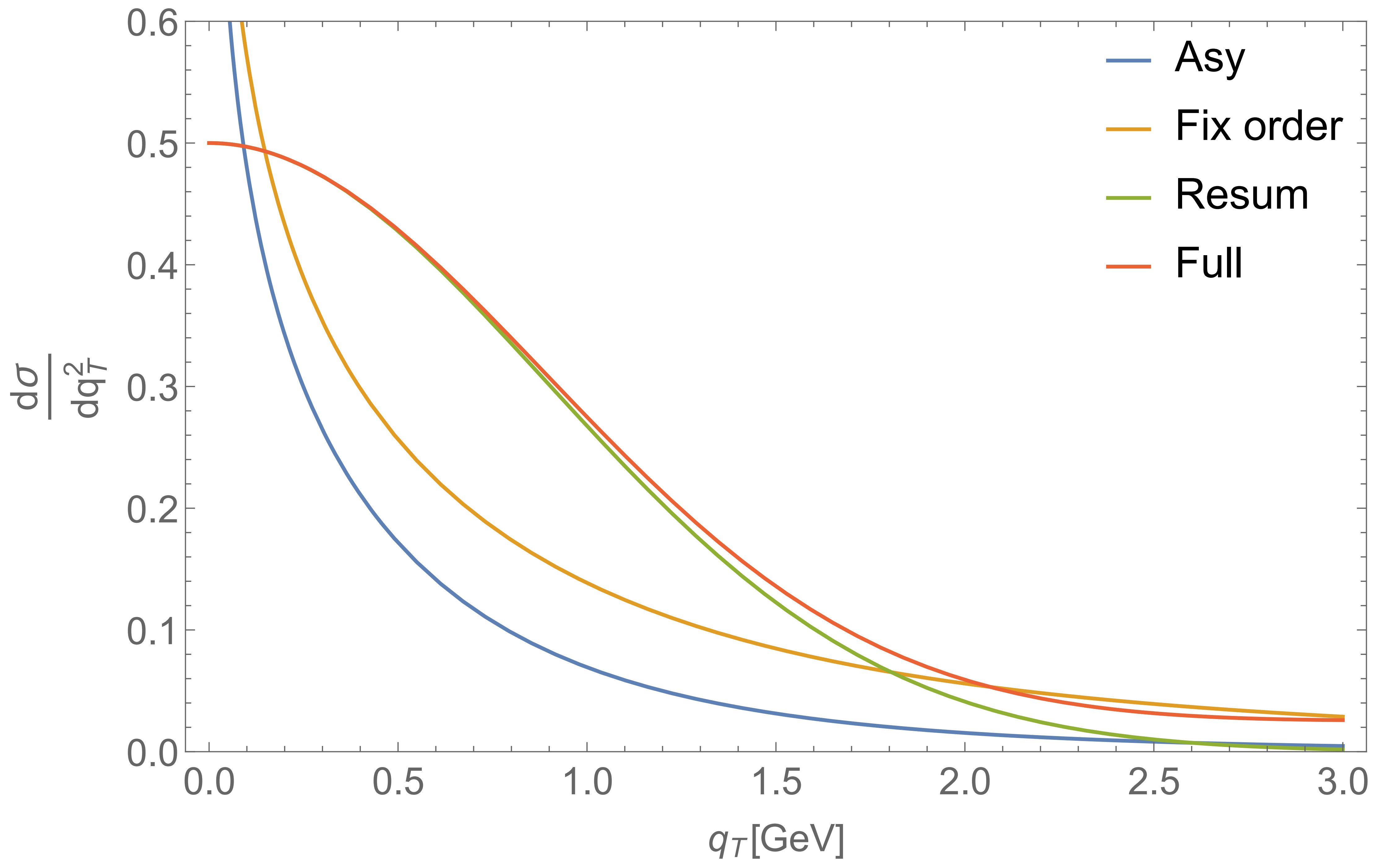


Standard approach

- Collinear result is mostly given by the integral of the Fixed Order
- The Non-Perturbative term is only a small correction

SOURCE OF W TERM SUPPRESSION - IDEAL SITUATION - LOW Q

Ideal situation at low Q



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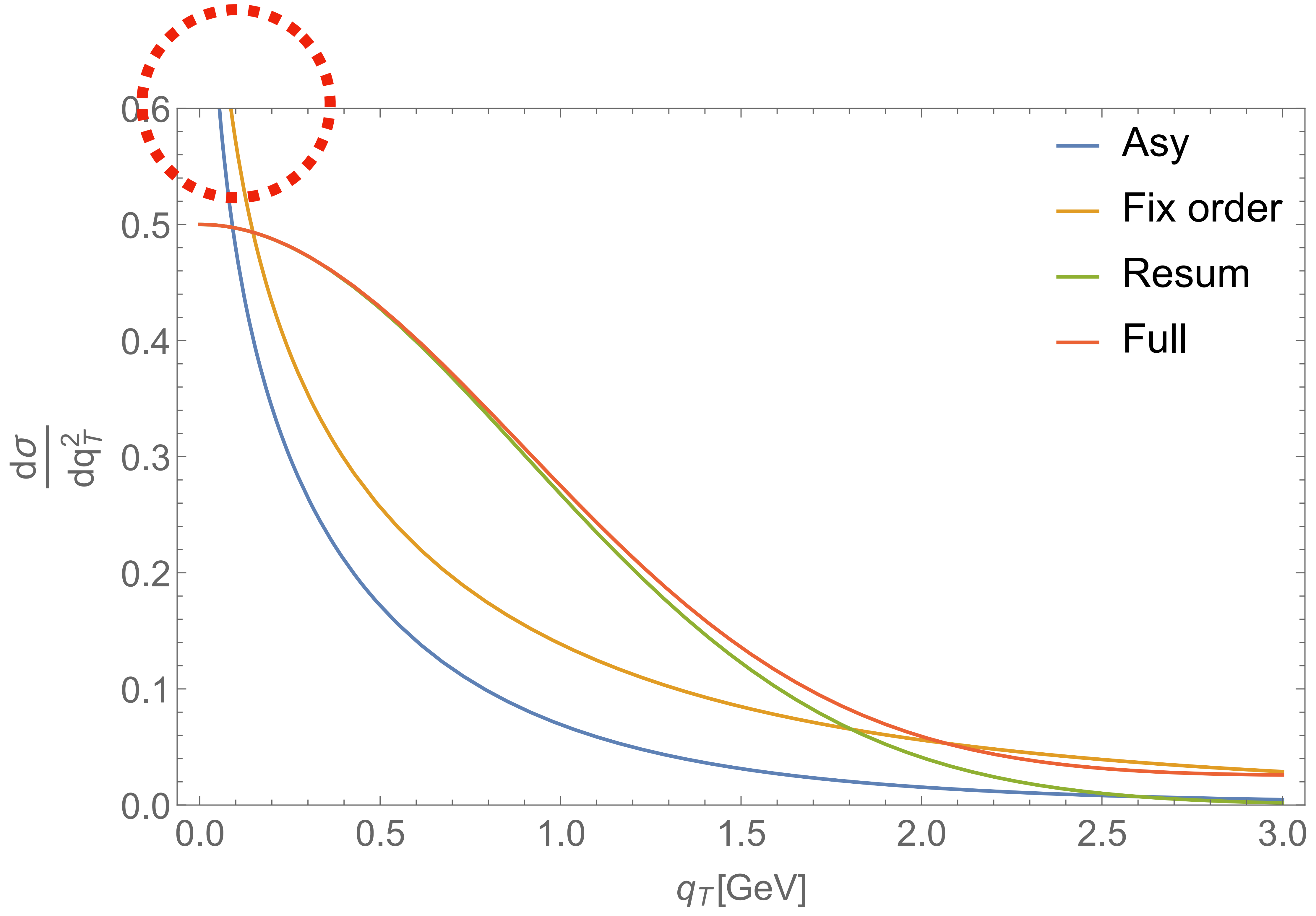

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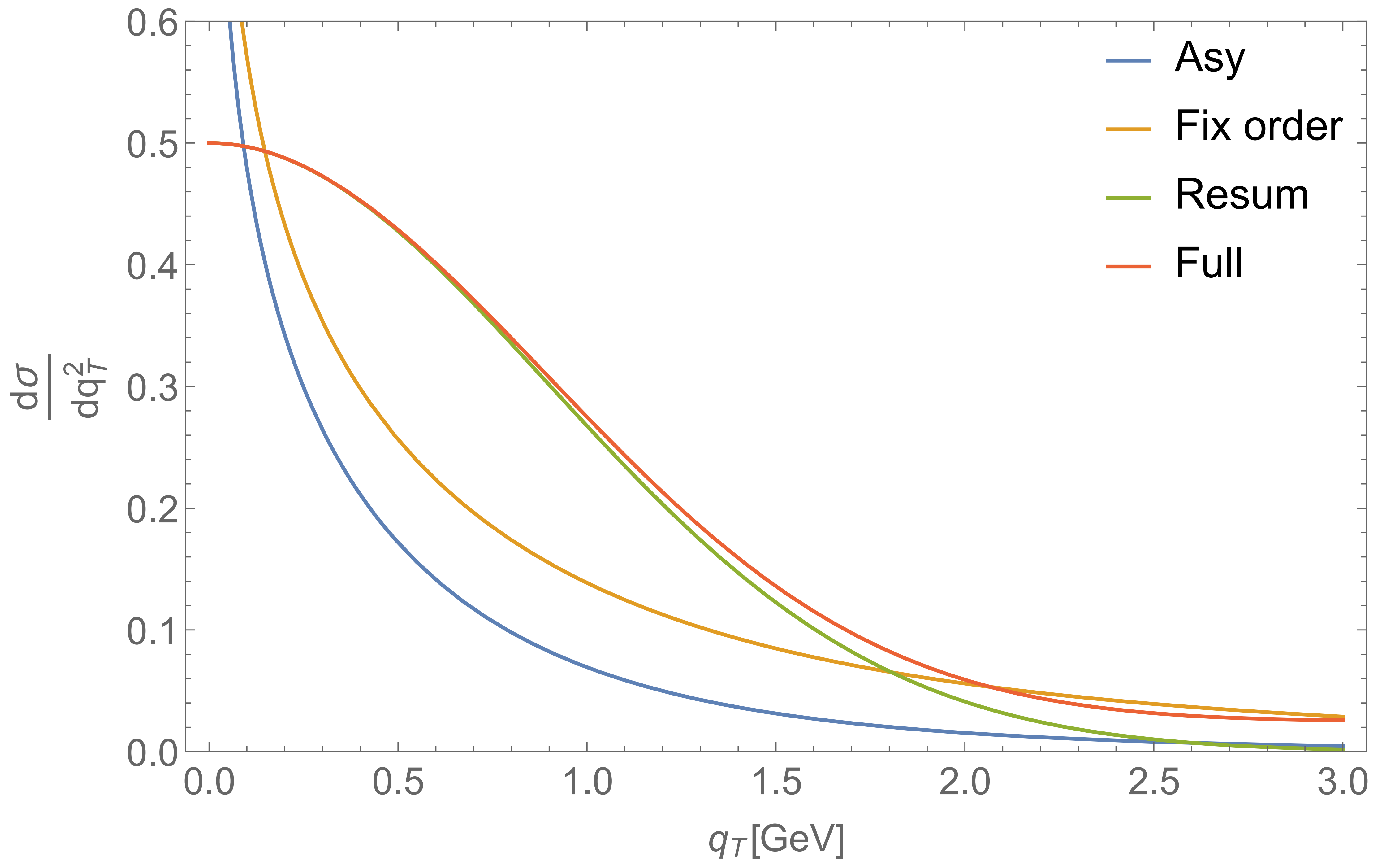

Non-Perturbative approach

- Resummed contribution is dominant where the Asymptotic term is close to the Fixed Order OR the Non-Perturbative contributions dominates

SOURCE OF W TERM SUPPRESSION - IDEAL SITUATION - LOW Q

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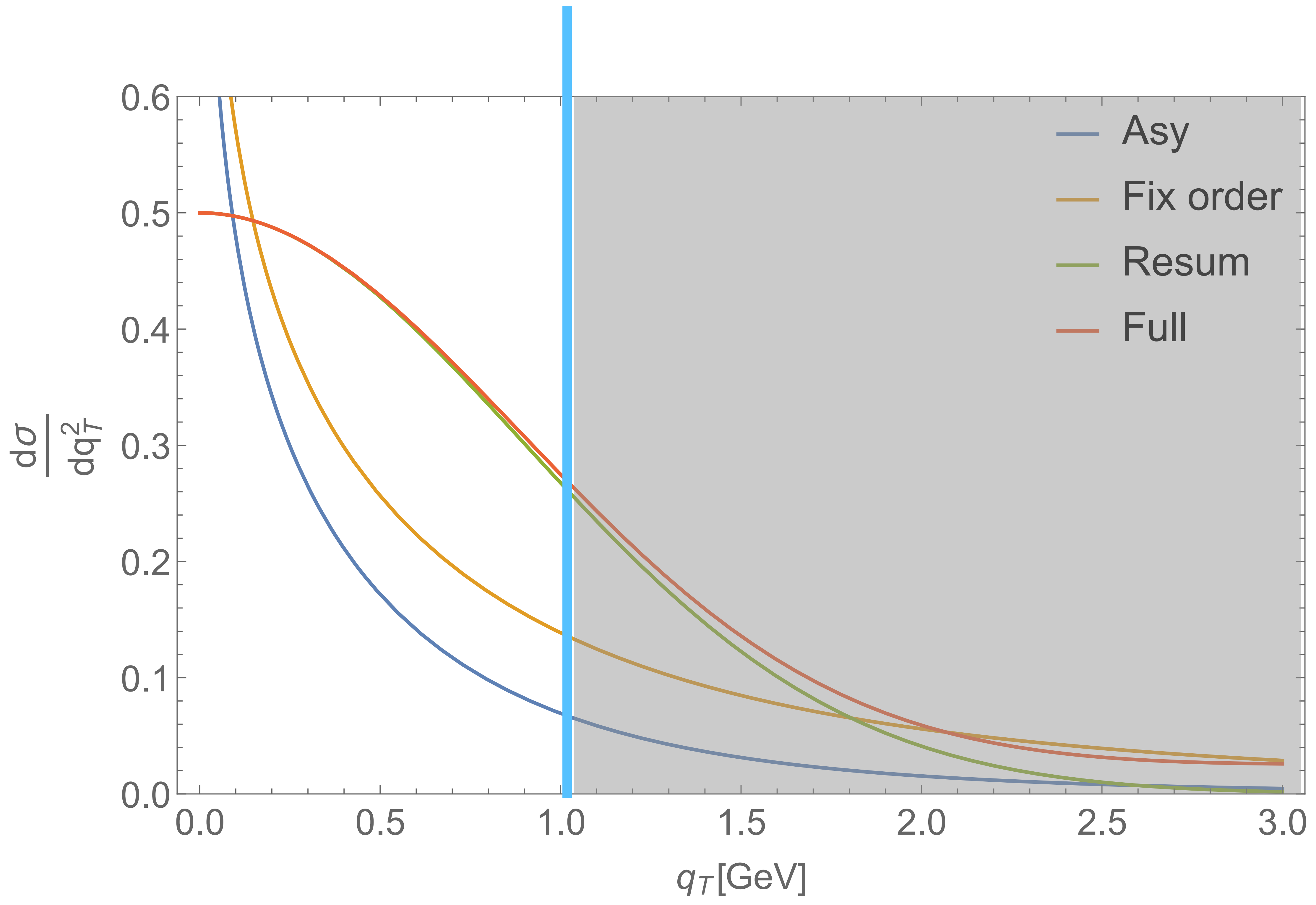

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→ **TMD Region**

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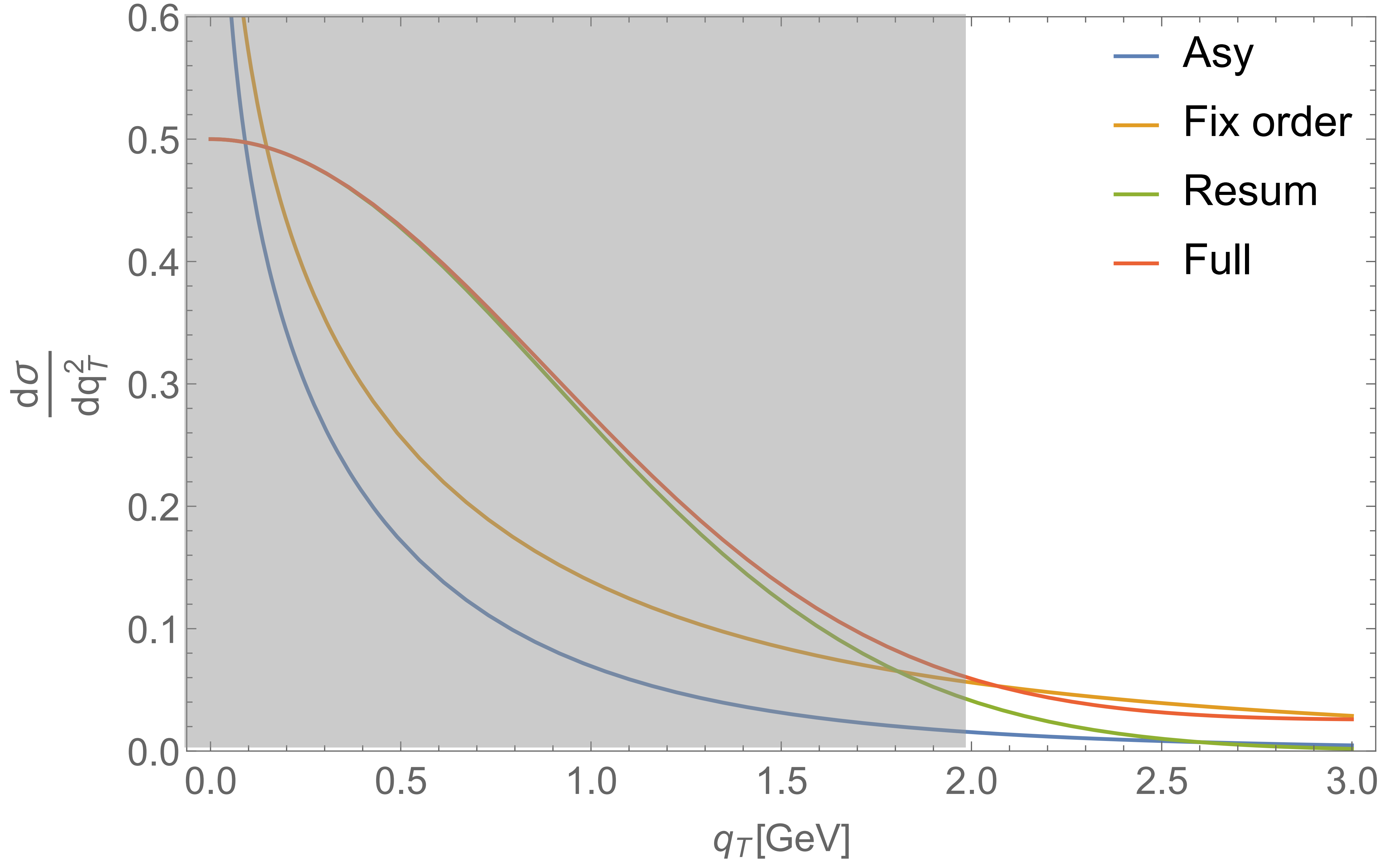
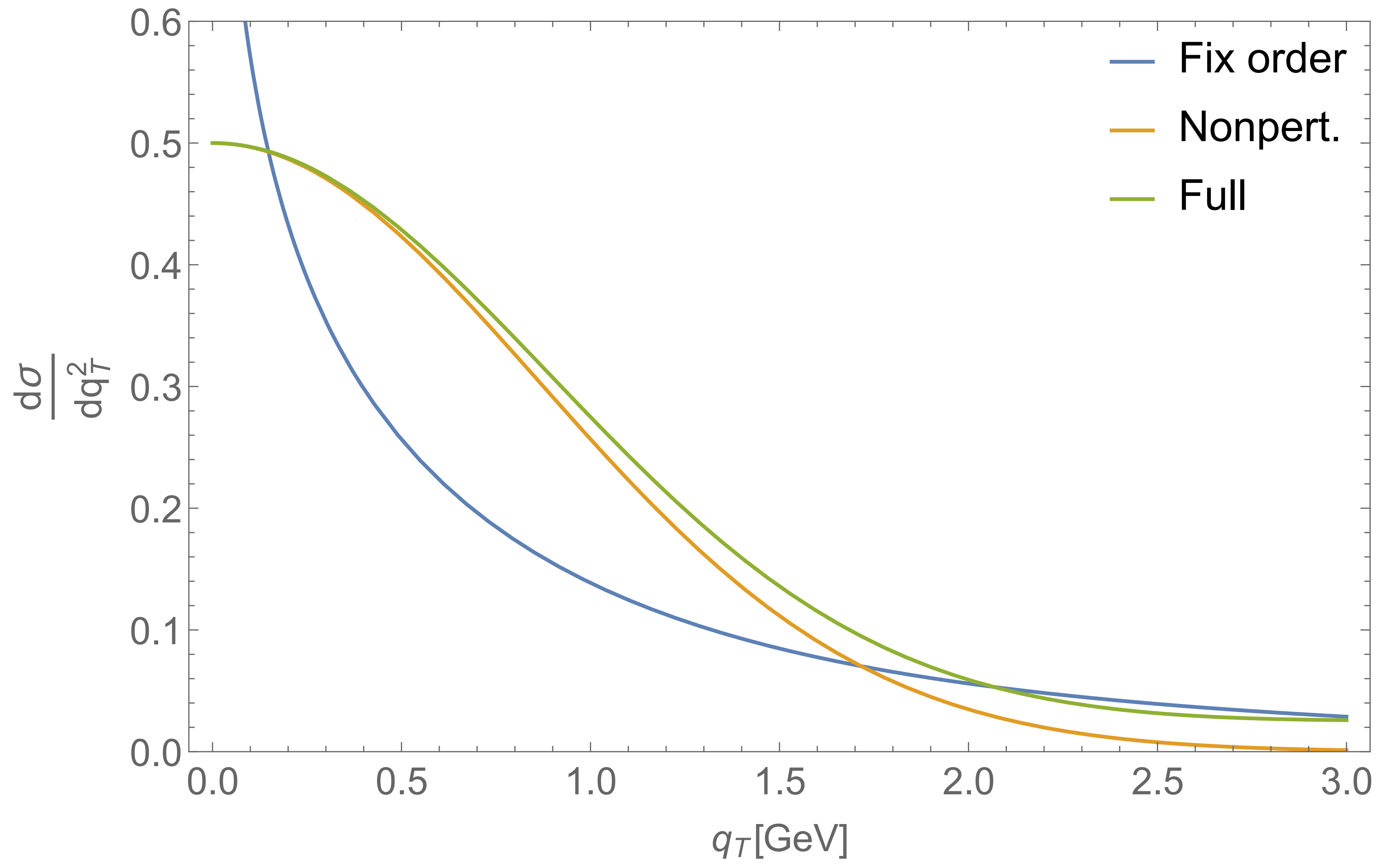


Non-Perturbative approach

- Resummed contribution is dominant where the Asymptotic term is close to the Fixed Order OR the Non-Perturbative contributions dominates
- From a certain value of qT the cross section follows the Fixed Order term

SOURCE OF W TERM SUPPRESSION - IDEAL SITUATION - LOW Q

Ideal situation at low Q



Non-Perturbative approach

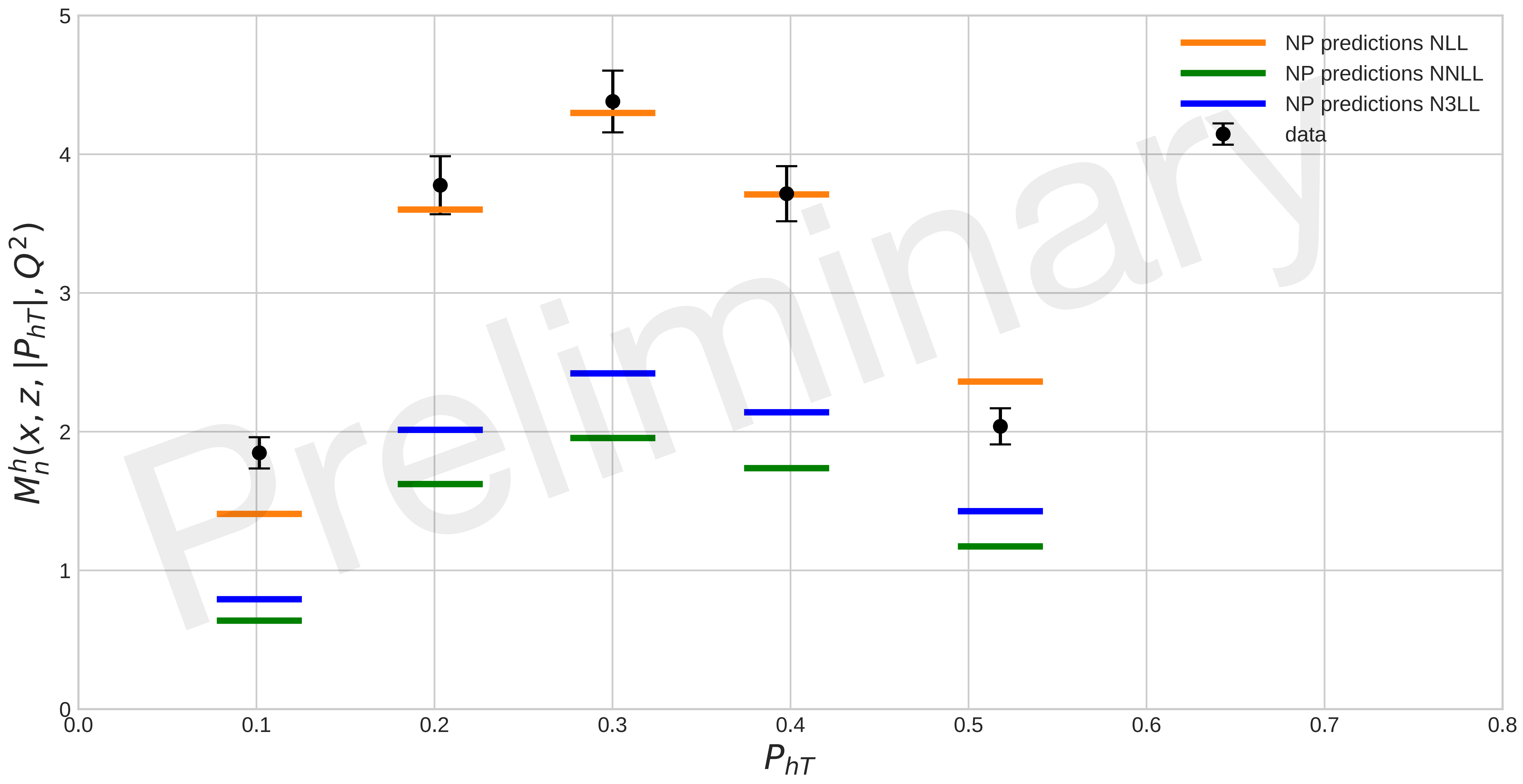
- Collinear result is no more mostly given by the integral of the Fixed Order
- The Non-Perturbative term is not only a small correction, but is even larger than the Fixed Order contribution

SOURCE OF W TERM SUPPRESSION

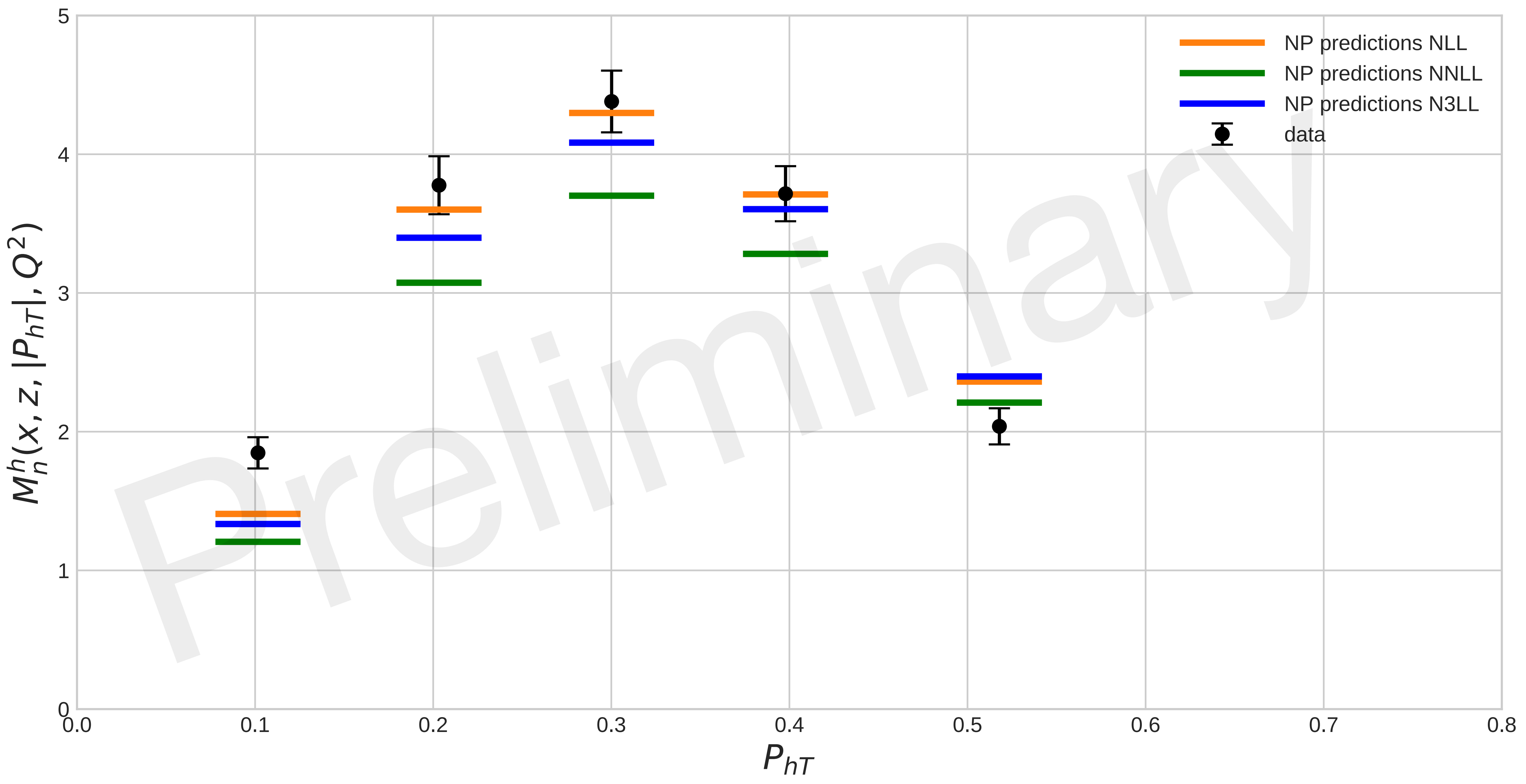
Present situation at low Q

HERMES multiplicity

Full Hard Factor



Hard Factor = 1



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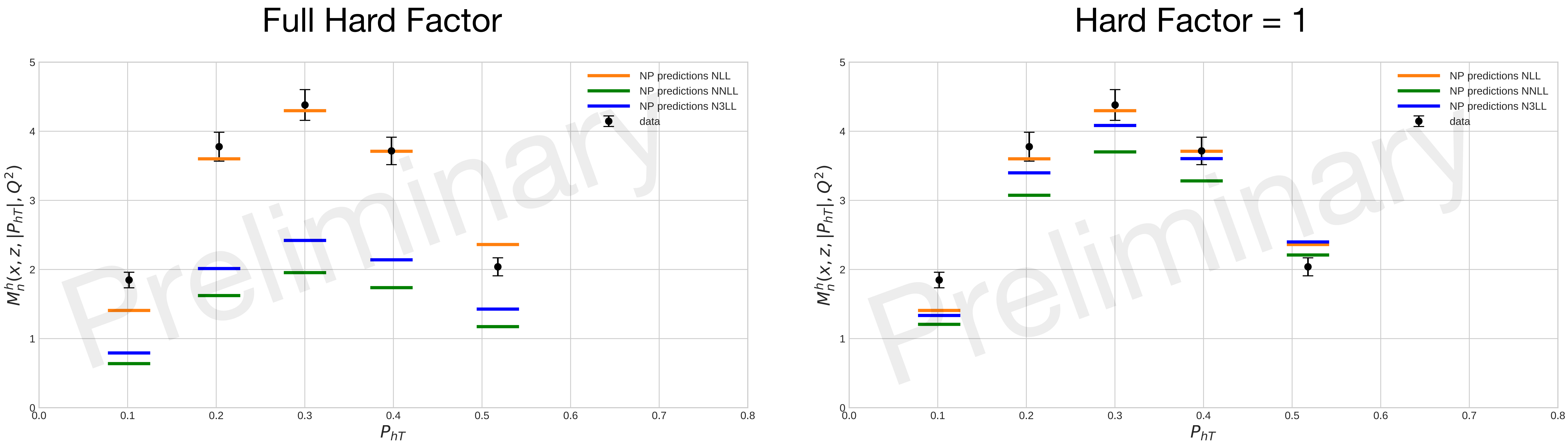

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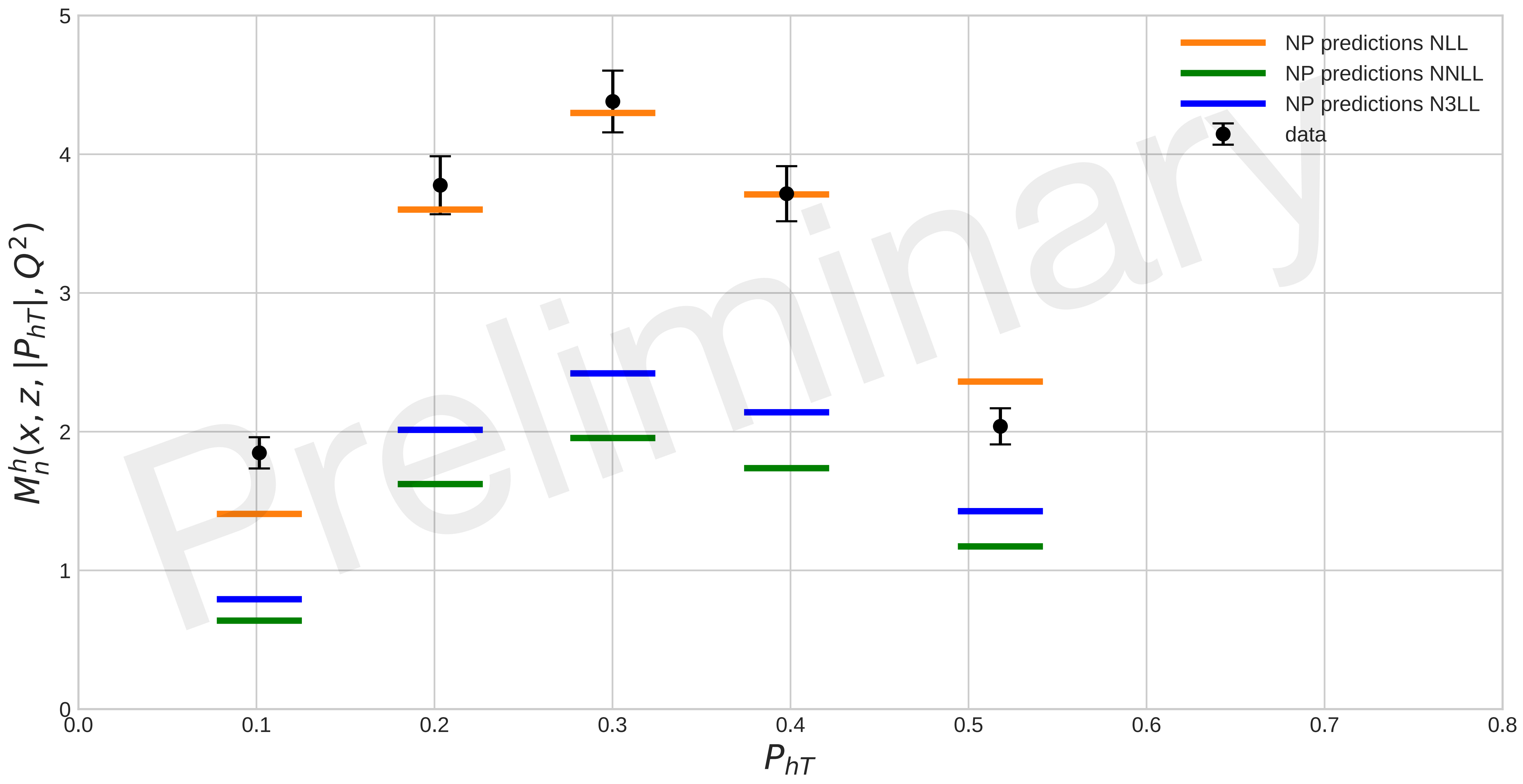

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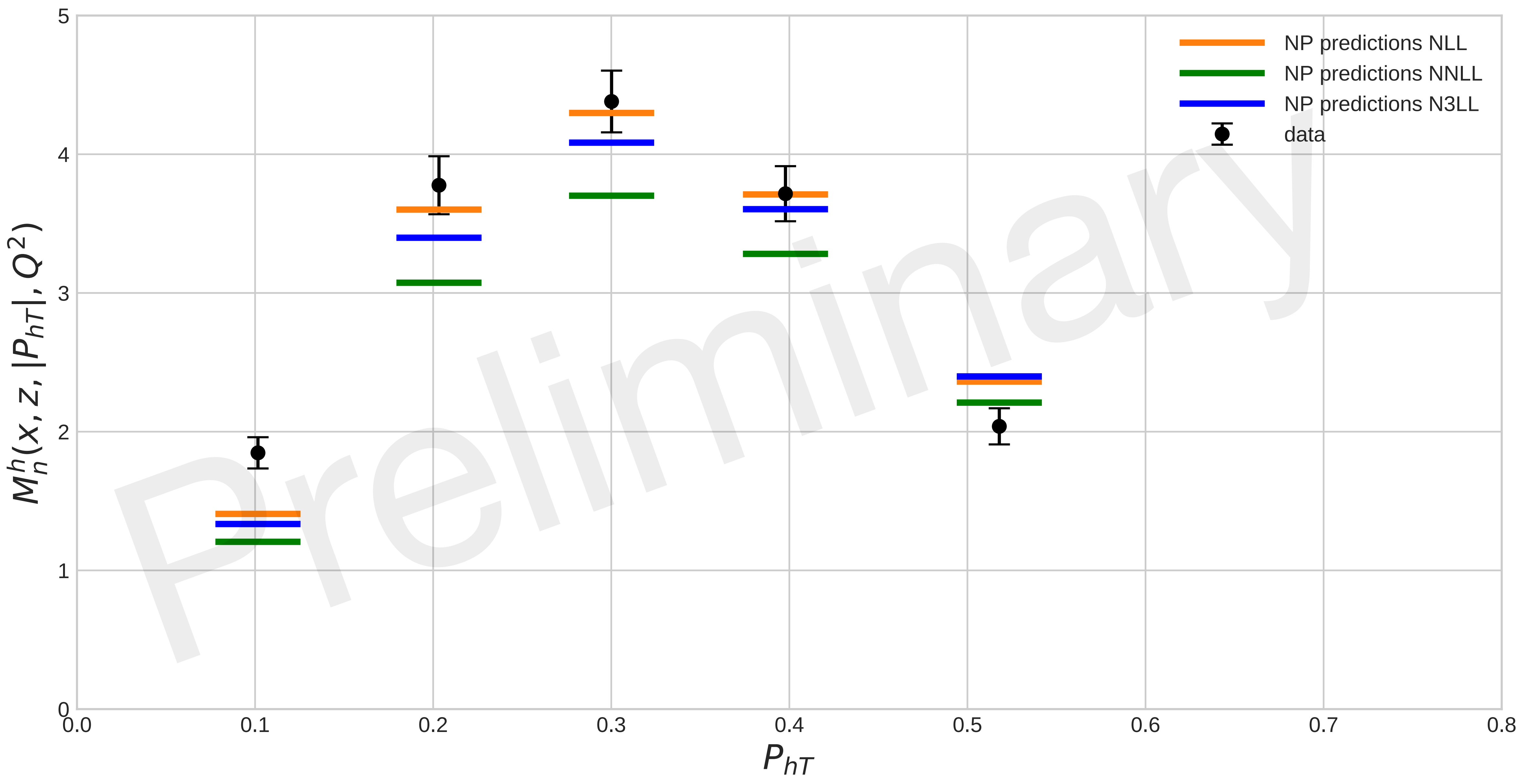
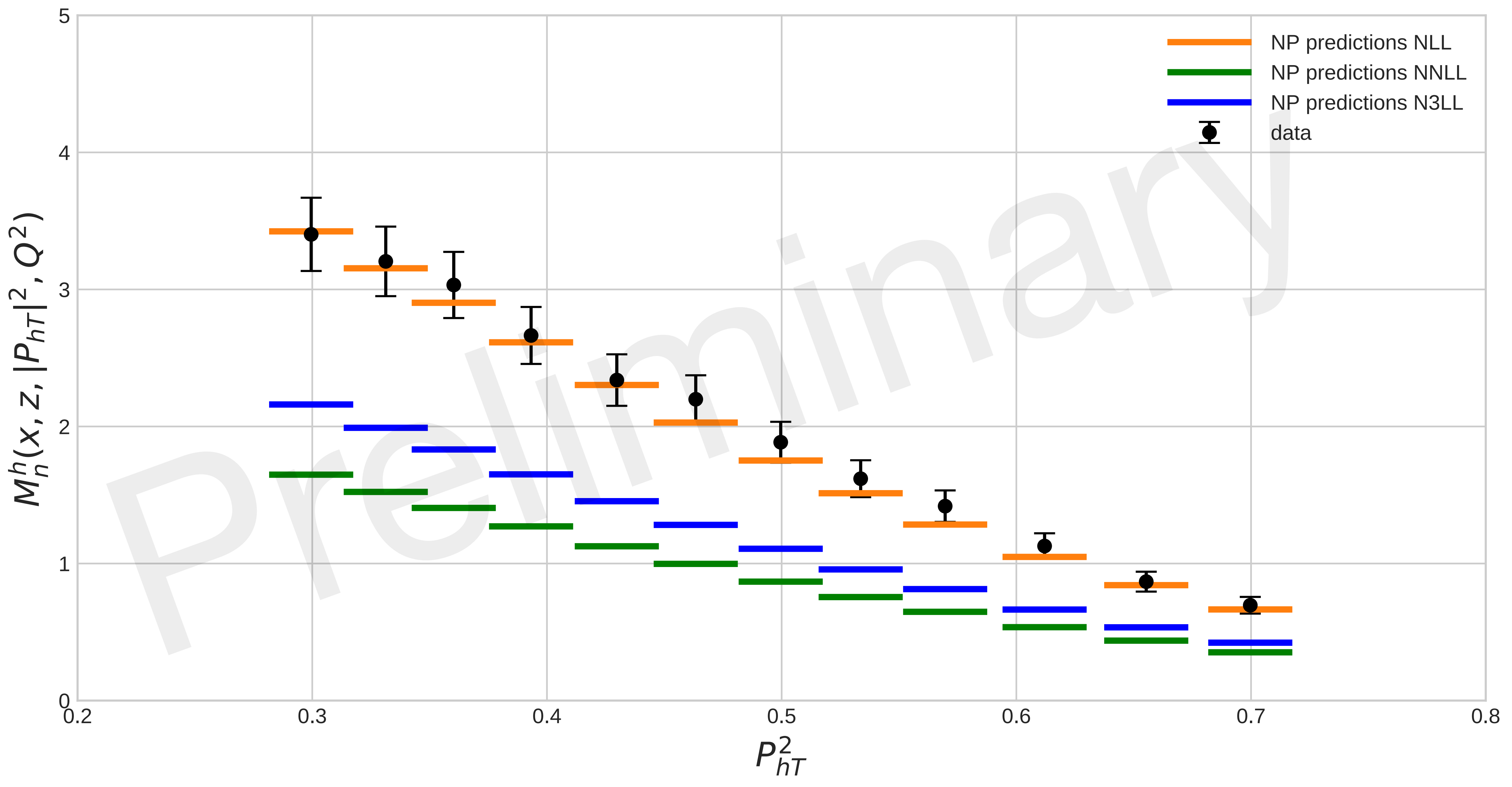


SOURCE OF W TERM SUPPRESSION

Present situation at low Q

COMPASS multiplicity

Full Hard Factor



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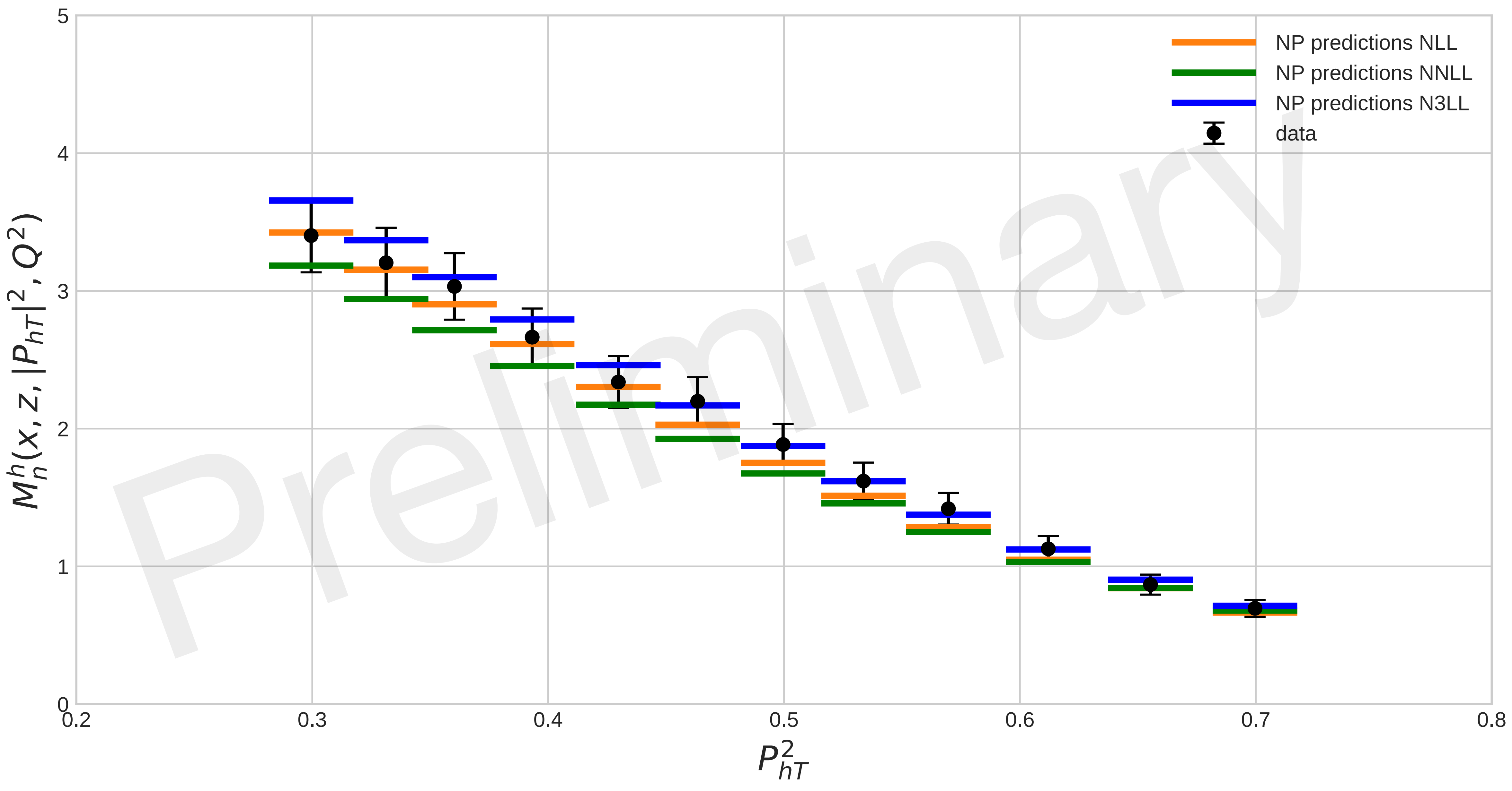

SOURCE OF W TERM SUPPRESSION

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COMPASS multiplicity

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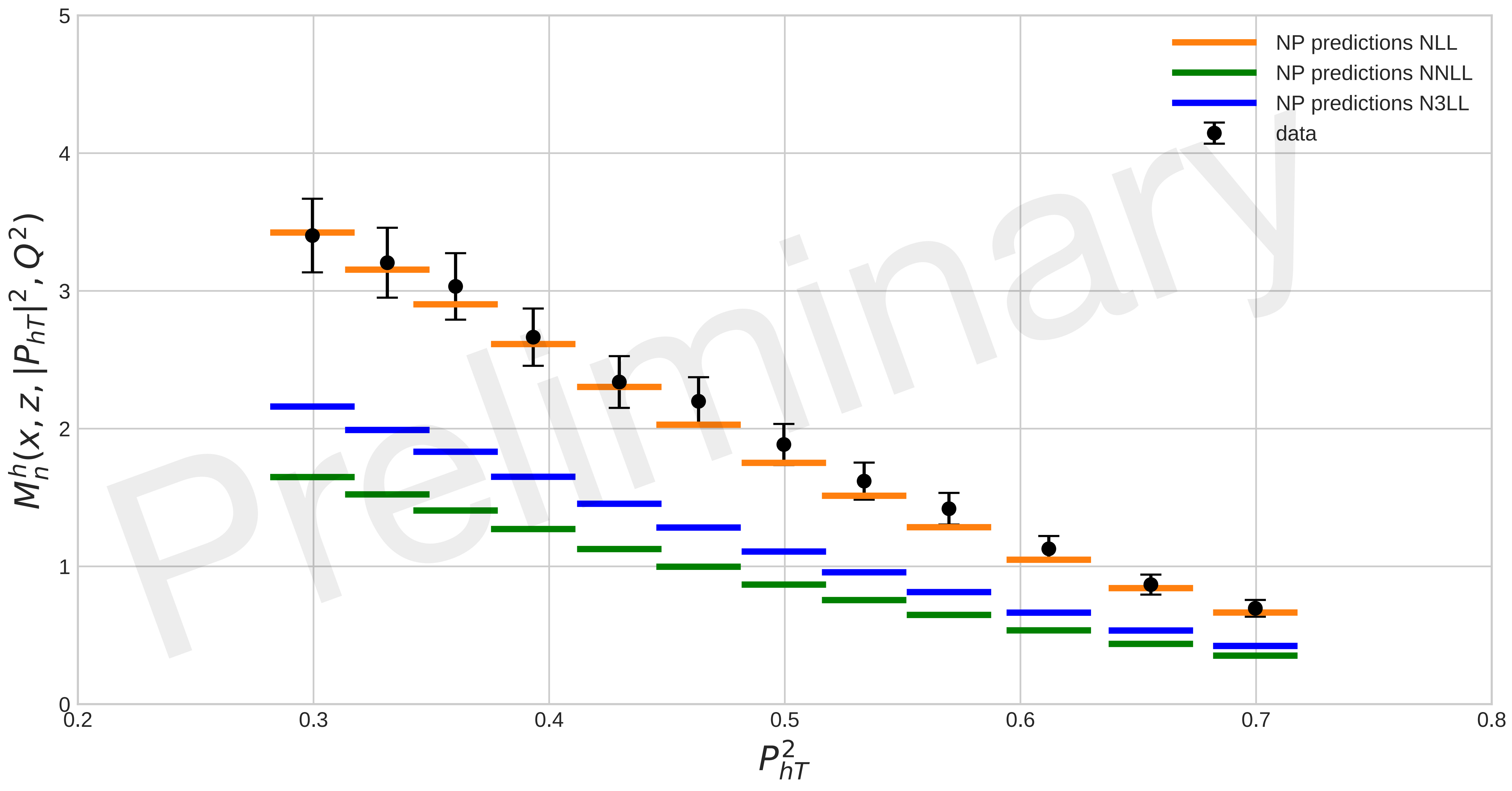

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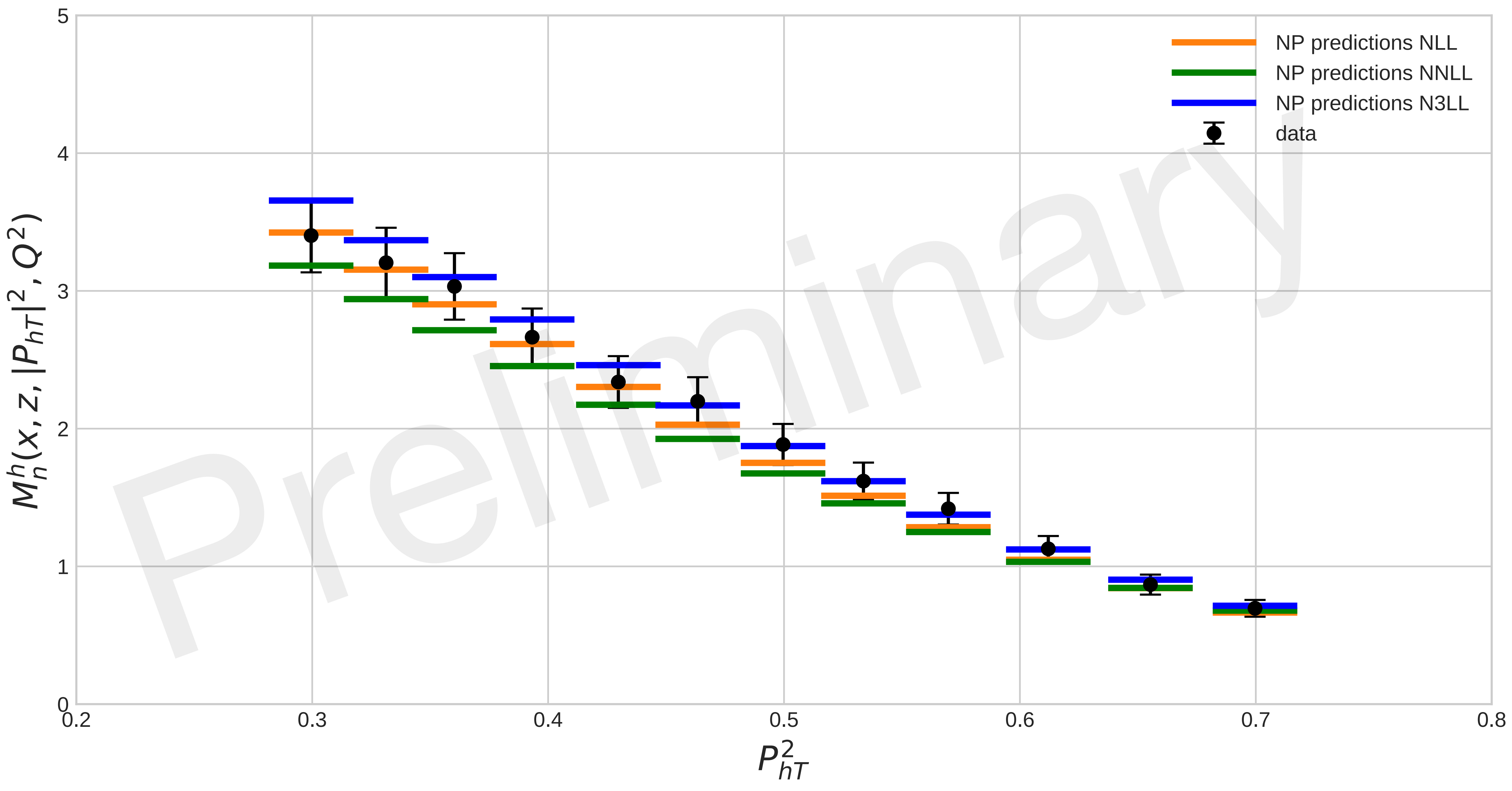

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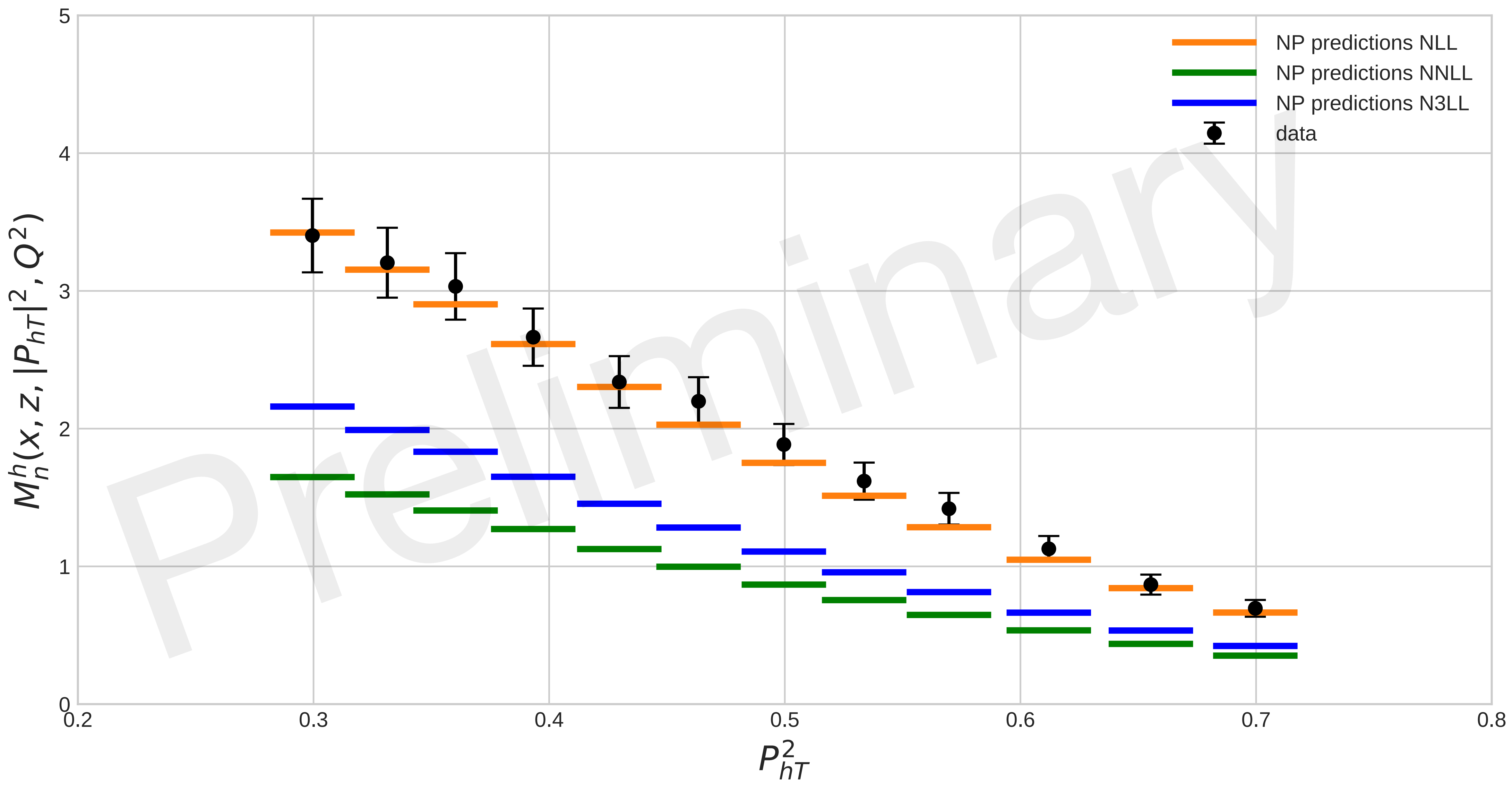
COMPASS multiplicity

Full Hard Factor



Hard Factor = 1