MAP 22: a new global (SIDIS-DY) fit of unpolarised TMDs at $N^3LL^{(-)}$

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(MAP collaboration)

arXiv: 2206.07598 [hep-ph]

INFN

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Quick facts

Perturbative accuracy: $N^3LL^{(-)}$

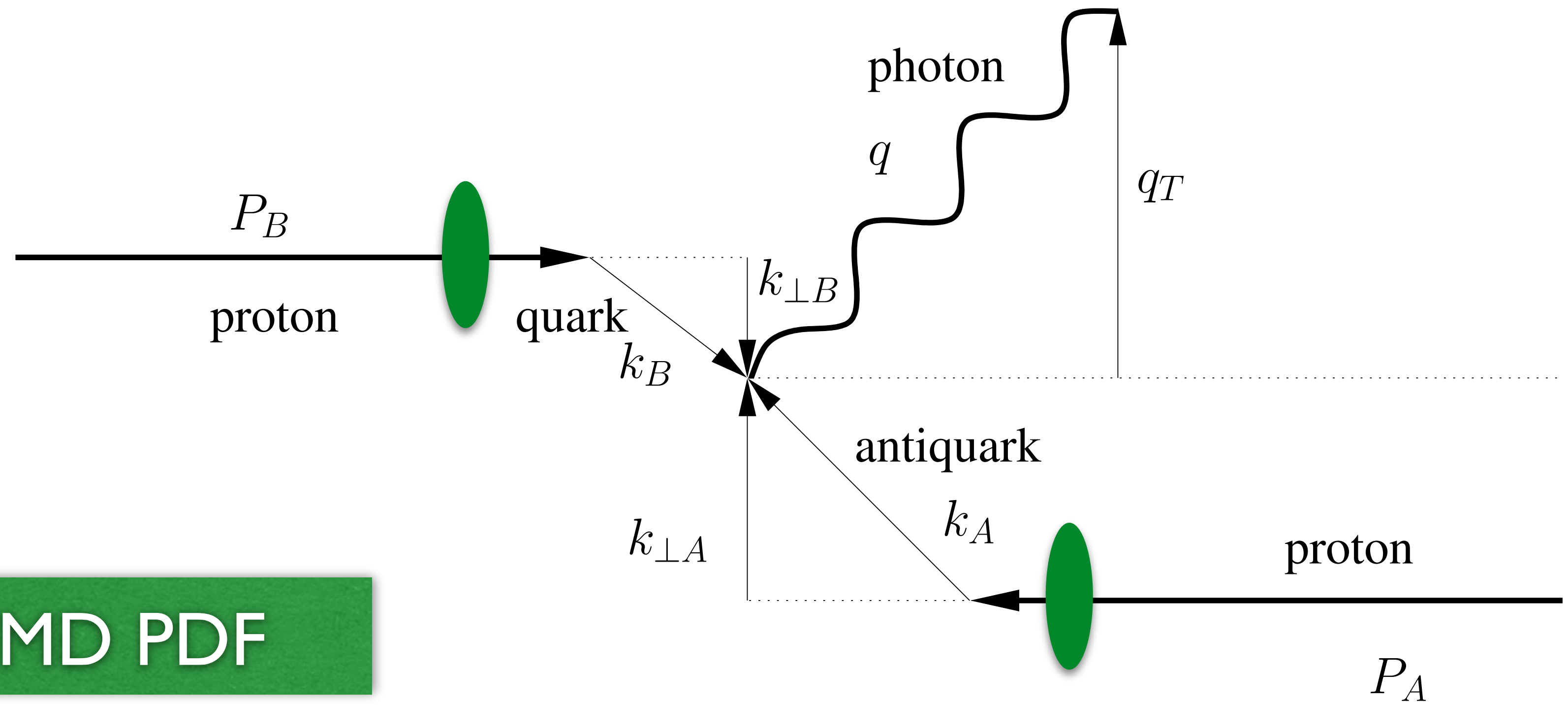
2031 SIDIS + (high/low)-energy DY data

(SIDIS) normalisation factors

21 free parameters

$\chi^2/N_{data} = 1.06$

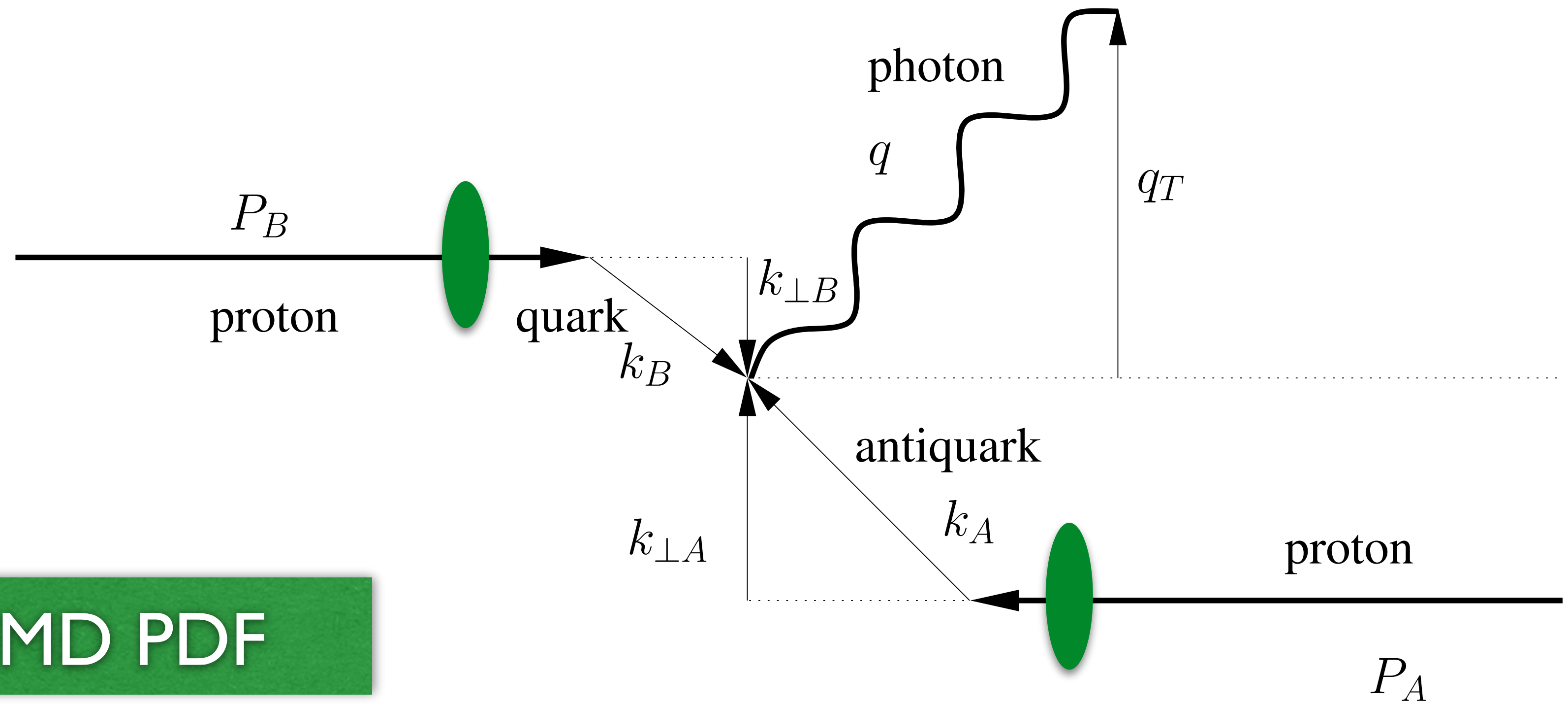
TMD factorisation for DY



quark TMD PDF

$$\frac{d\sigma}{dq_T\,dy\,dQ} \propto x_A x_B H^{DY}(Q,\mu) \sum_q c_q(Q^2) \int d^2\mathbf{k}_{\perp A}\, d^2\mathbf{k}_{\perp B}\, \boxed{F^{\bar{q}}(x_A, \mathbf{k}^2_{\perp A}; \mu, \zeta_A)}\, \boxed{F^{q}(x_B, \mathbf{k}^2_{\perp B}; \mu, \zeta_B)}\, \delta^{(2)}(\mathbf{k}_{\perp A} + \mathbf{k}_{\perp B} - \mathbf{q}_T)$$

TMD factorisation for DY



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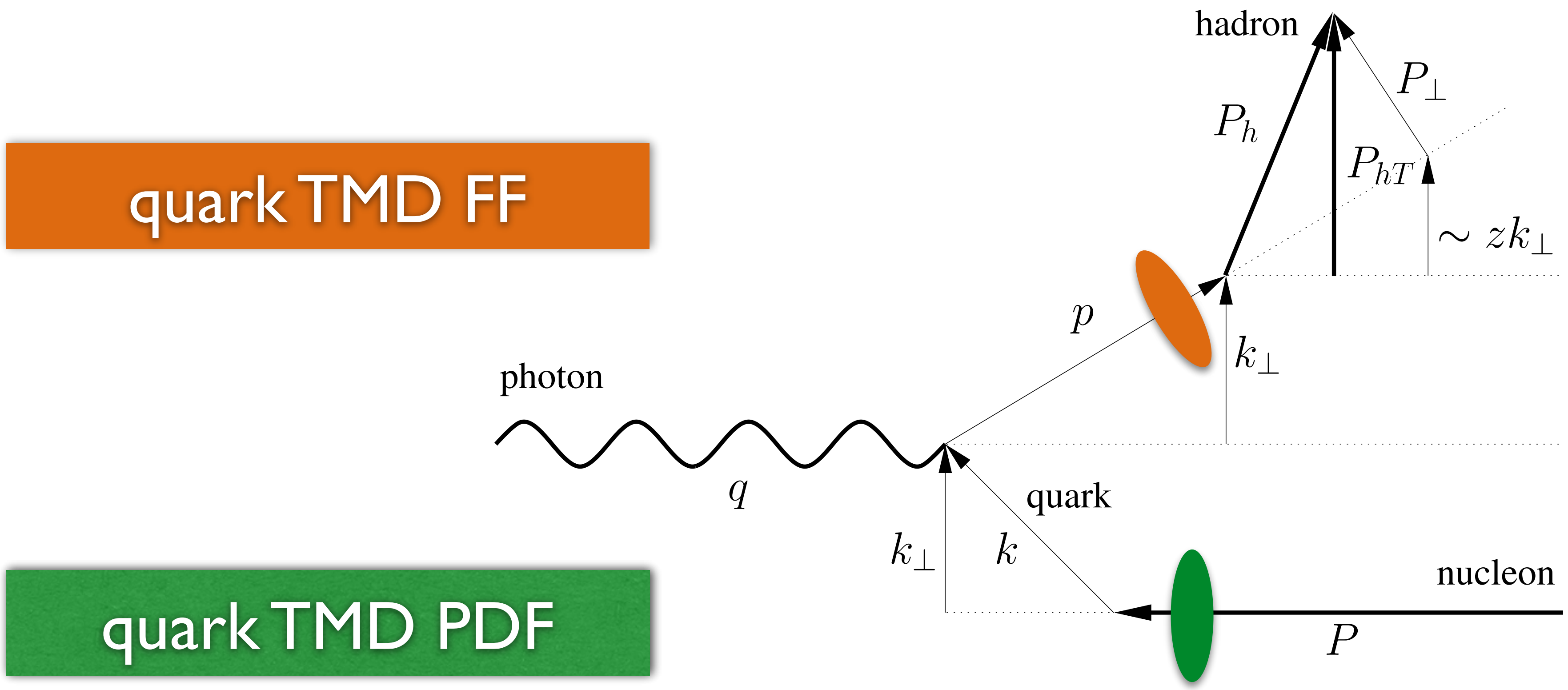
$$= x_A x_B H^{DY}(Q,\mu) \sum_q c_q(Q^2) \int \frac{db_T}{2\pi}\, b_T\, J_0(b_T q_T)\, \hat{F}^{\bar{q}}(x_A, b_T^2; \mu, \zeta_A)\, \hat{F}^{q}(x_B, b_T^2; \mu, \zeta_B)$$

TMD factorisation for SIDIS

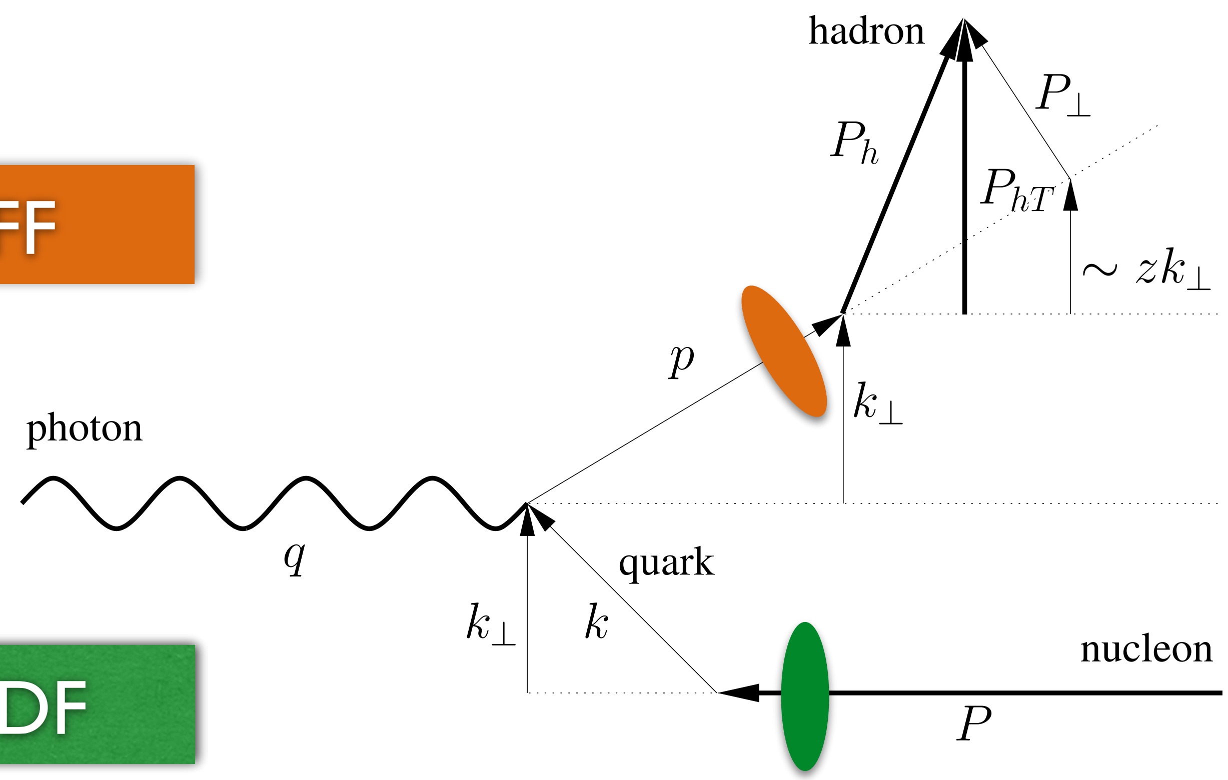


$$\frac{d\sigma}{dx\,dz\,dq_T\,dQ} \propto xH^{SIDIS}(Q,\mu) \sum_q e_q(Q^2) \int d^2\mathbf{k}_\perp \int \frac{d^2\mathbf{P}_\perp}{z^2} \boxed{F^q(x,\mathbf{k}_\perp^2;\mu,\zeta_A)} \boxed{D^{q\to h}(z,\mathbf{P}_\perp^2;\mu,\zeta_B)} \; \delta^{(2)}(\mathbf{k}_\perp + \mathbf{P}_\perp/z + \mathbf{q}_T)$$

TMD factorisation for SIDIS

quark TMD FF

quark TMD PDF



$$\frac{d\sigma}{dx\,dz\,dq_T\,dQ} \propto xH^{SIDIS}(Q,\mu)\sum_q e_q(Q^2)\int d^2\mathbf{k}_\perp \int \frac{d^2\mathbf{P}_\perp}{z^2}\, \boxed{F^q(x,\mathbf{k}_\perp^2;\mu,\zeta_A)}\ \boxed{D^{q\to h}(z,\mathbf{P}_\perp^2;\mu,\zeta_B)}\ \delta^{(2)}(\mathbf{k}_\perp+\mathbf{P}_\perp/z+\mathbf{q}_T)$$

$$= xH^{SIDIS}(Q,\mu)\sum_q e_q(Q^2)\int \frac{db_T}{2\pi}\, b_T\, J_0(b_T q_T)\, \boxed{\hat{F}^{\bar{q}}(x,b_T^2;\mu,\zeta_A)}\,\boxed{\hat{D}^q(z,b_T^2;\mu,\zeta_B)}$$

TMD structure

$$
\begin{aligned}
F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) &= \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) && : A \\
&\times \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\} && : B \\
&\times \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} && : C
\end{aligned}
$$

TMD structure

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) \quad : A$$

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- matching to collinear PDF at $b_T \ll 1/\Lambda_{QCD}$
- **perturbative**

TMD structure

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- CS and RGE evolution to large b_T
- **perturbative**

TMD structure

$$F_{f/P}(x,\mathbf{b}_T;\mu,\zeta) = \sum_j C_{f/j}(x,b_*;\mu_b,\zeta_F) \otimes f_{j/P}(x,\mu_b) \qquad : A$$

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$$\times \exp\left\{g_{j/P}(x,b_T) + g_K(b_T)\ln\frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}}\right\} \qquad : C$$

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Accuracy	H and C	K and γ_F	γ_K	PDF and α_s evolution
LL	0	-	1	-
NLL	0	1	2	LO
NLL’	1	1	2	NLO
NNLL	1	2	3	NLO
NNLL’	2	2	3	NNLO
N^3LL	2	3	4	NNLO

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TMD structure

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) \qquad : A$$

$$\times \exp\left\{ K(b_*; \mu_b) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\} \qquad : B$$

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N^3LL	2	3	4	NNLO

- CS and RGE evolution to large b_T
- **perturbative**

$N^3LL^- = N^3LL$ with NLO FF

TMD structure

$$F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) = \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) \quad : A$$

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$$\times \exp\left\{g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}}\right\} \quad : C$$

- matching to collinear PDF at $b_T \ll 1/\Lambda_{QCD}$
- **perturbative**

$$\left(\mu_b = 2e^{-\gamma_E}/b_*\right)$$

- CS and RGE evolution to large b_T
- **perturbative**

- b_* prescription to avoid Landau pole

$N^3LL^- = N^3LL$ with NLO FF

TMD structure

$$F_{f/P}(x,\mathbf{b}_T;\mu,\zeta) = \sum_j C_{f/j}(x,b_*;\mu_b,\zeta_F)\otimes f_{j/P}(x,\mu_b) \quad : A$$

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$$\times \exp\left\{g_{j/P}(x,b_T) + g_K(b_T)\ln\frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}}\right\} \quad : C$$

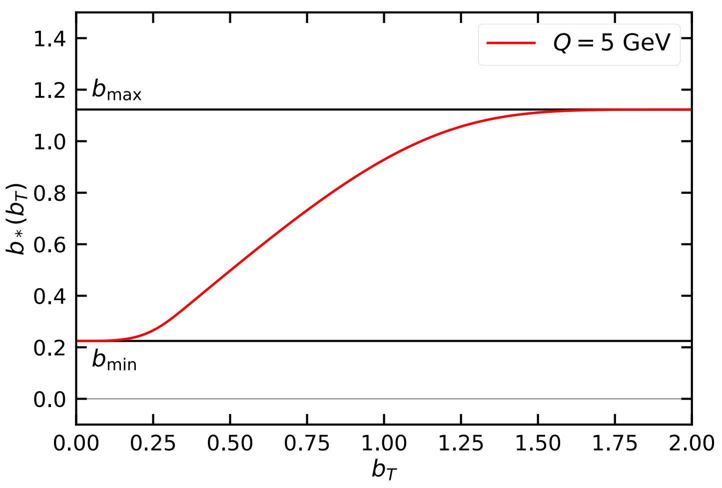
- matching to collinear PDF at $b_T \ll 1/\Lambda_{QCD}$
- **perturbative**

$$(\mu_b = 2e^{-\gamma_E}/b_*)$$

$$b_*(b) = b_{\max}\left(\frac{1-\exp\left(-\frac{b^4}{b_{\max}^4}\right)}{1-\exp\left(-\frac{b^4}{b_{\min}^4}\right)}\right)^{\frac{1}{4}}$$

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = 2e^{-\gamma_E}/Q$$



- CS and RGE evolution to large b_T
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$N^3LL^- = N^3LL$ with NLO FF

TMD structure

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$$\times \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} \quad f_{NP} \quad : C$$

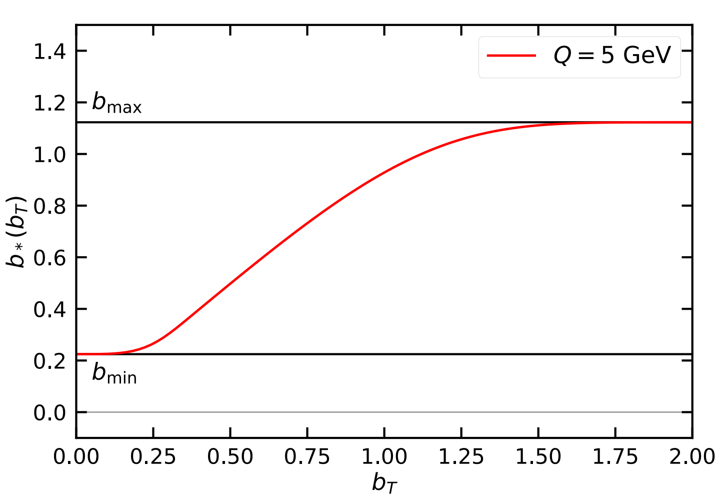
- matching to collinear PDF at $b_T \ll 1/\Lambda_{QCD}$
- **perturbative**

$$\left(\mu_b = 2e^{-\gamma_E}/b_*\right)$$

$$b_*(b) = b_{\max} \left(\frac{1 - \exp\left(-\frac{b^4}{b_{\max}^4}\right)}{1 - \exp\left(-\frac{b^4}{b_{\min}^4}\right)} \right)^{\frac{1}{4}}$$

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = 2e^{-\gamma_E}/Q$$



$N^3LL^- = N^3LL$ with NLO FF

- CS and RGE evolution to large b_T
- **perturbative**

- b_* prescription to avoid Landau pole
- f_{NP} “parametrises” the **non-perturbative** transverse modes
- **fit** f_{NP} to data

Non-perturbative: f_{NP}

$$F(x,b;\mu,\zeta) = \left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right] F(x,b_*(b);\mu,\zeta)$$

Non-perturbative: f_{NP}

f_{NP}

$$F(x, b; \mu, \zeta) = \left[\frac{F(x, b; \mu, \zeta)}{F(x, b_*(b); \mu, \zeta)} \right] F(x, b_*(b); \mu, \zeta)$$

- depends on choice of b* and collinear PDFs
- requires definition of a functional form

Non-perturbative: f_{NP}

$$F(x,b;\mu,\zeta) = \underbrace{\left[\frac{F(x,b;\mu,\zeta)}{F(x,b_*(b);\mu,\zeta)}\right]}_{f_{NP}} F(x,b_*(b);\mu,\zeta)$$

- depends on choice of b* and collinear PDFs
- requires definition of a functional form

Our functional form

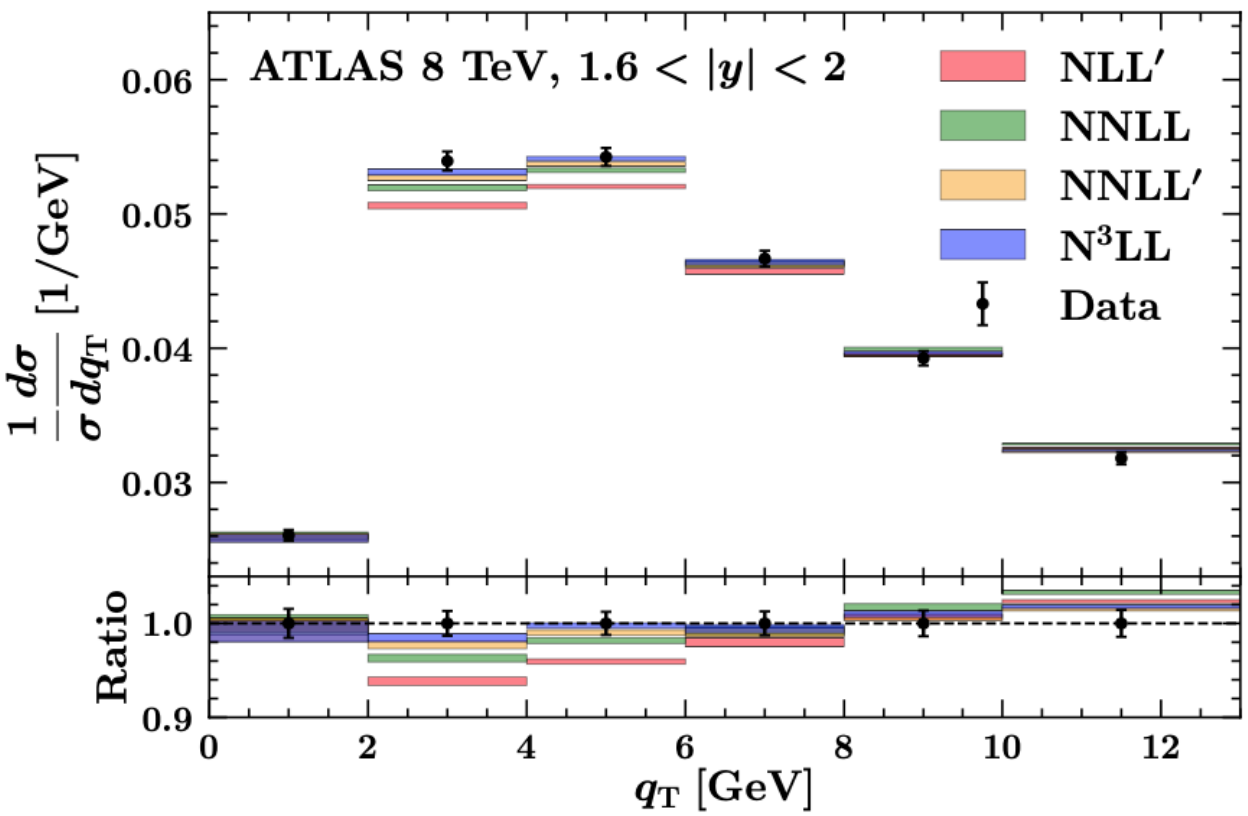
$$f_{1NP}(x,b_T^2) \propto \text{F.T. of} \left(e^{-\frac{k_T^2}{g1}} + \lambda^2 k_T^2 e^{-\frac{k_T^2}{g1B}} + \lambda_2^2 e^{-\frac{k_T^2}{g1C}}\right)$$

$$g_{\{1,1B,1C\}}(x) = N_{\{1,1B,1C\}} \frac{x^{\sigma_{\{1,2,3\}}}(1-x)^{\alpha^2_{\{1,2,3\}}}}{\hat{x}^{\sigma_{\{1,2,3\}}}(1-\hat{x})^{\alpha^2_{\{1,2,3\}}}}$$

- similar form for TMD FF
- 21 free parameters

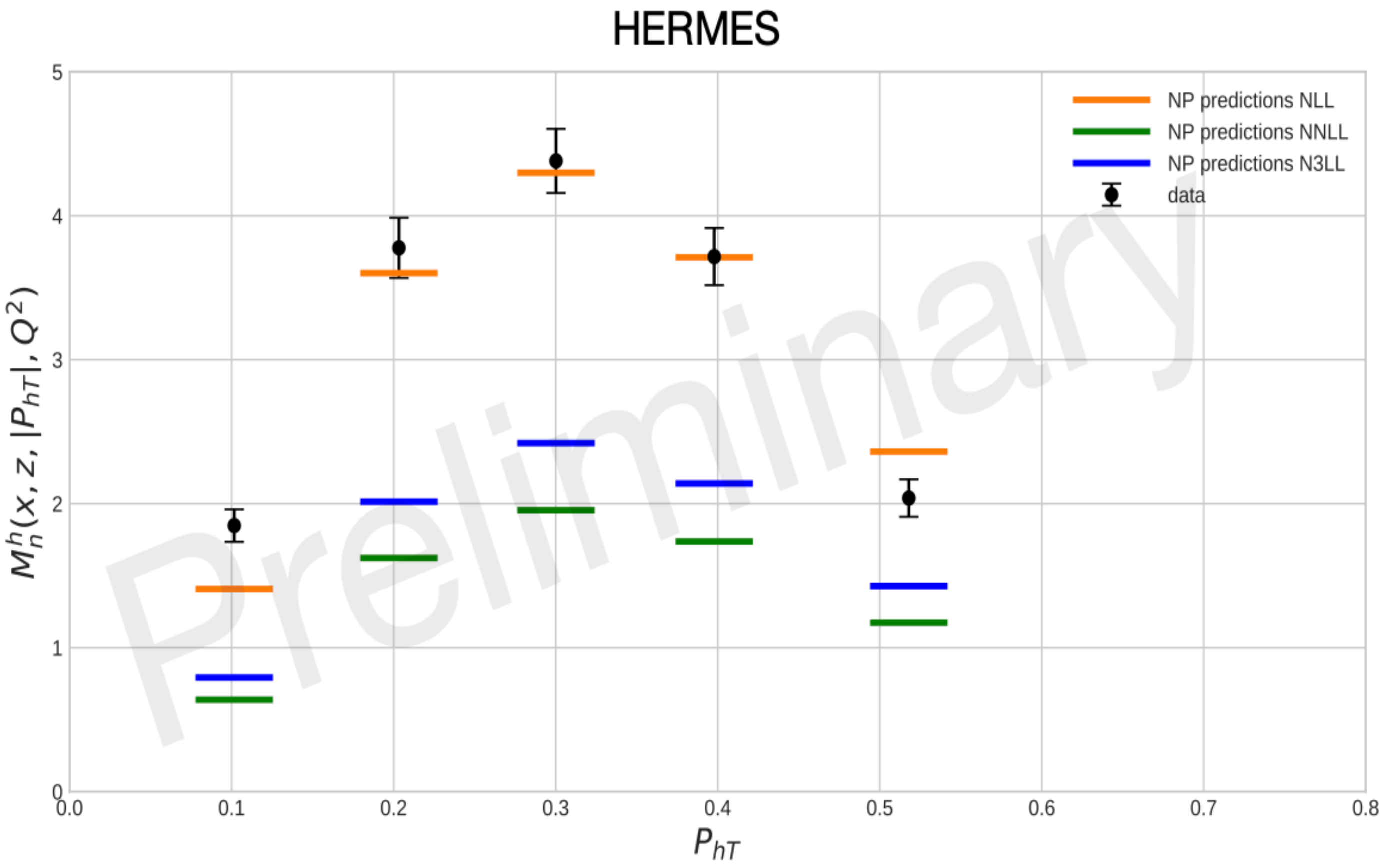
SIDIS normalisation

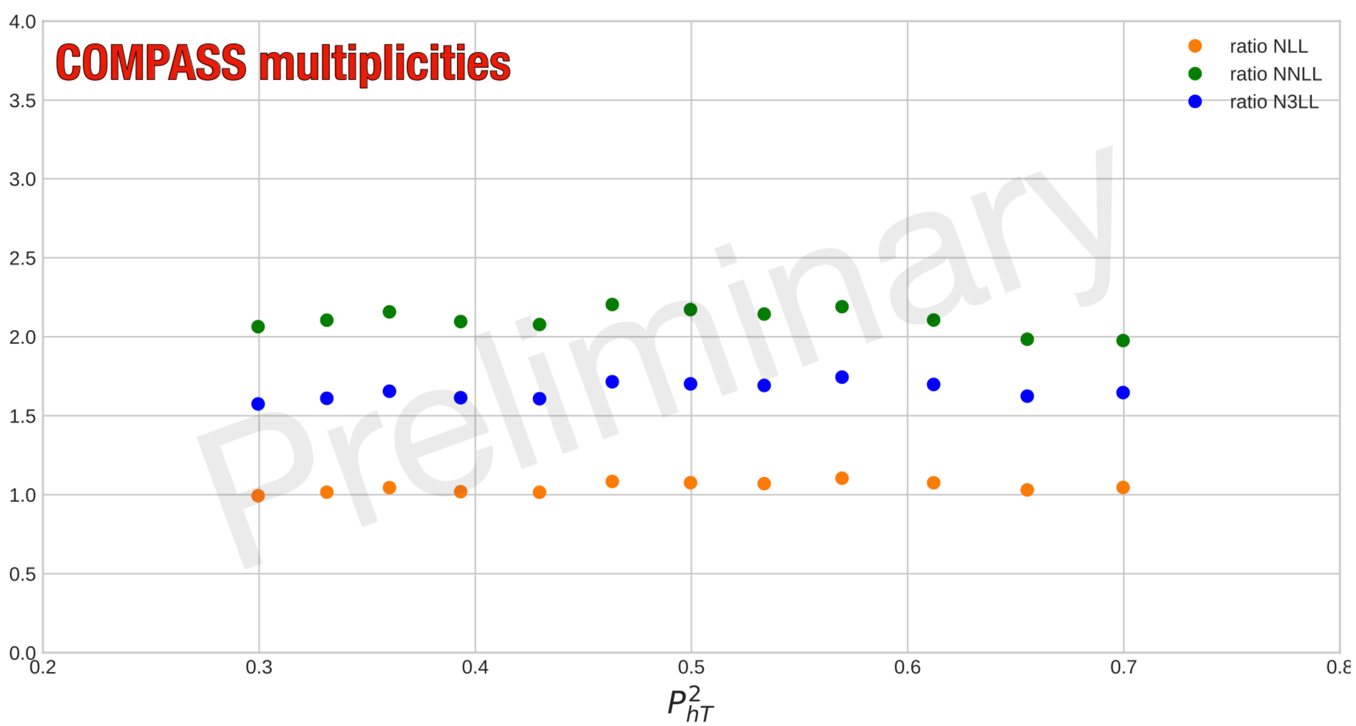
DY beyond NLL



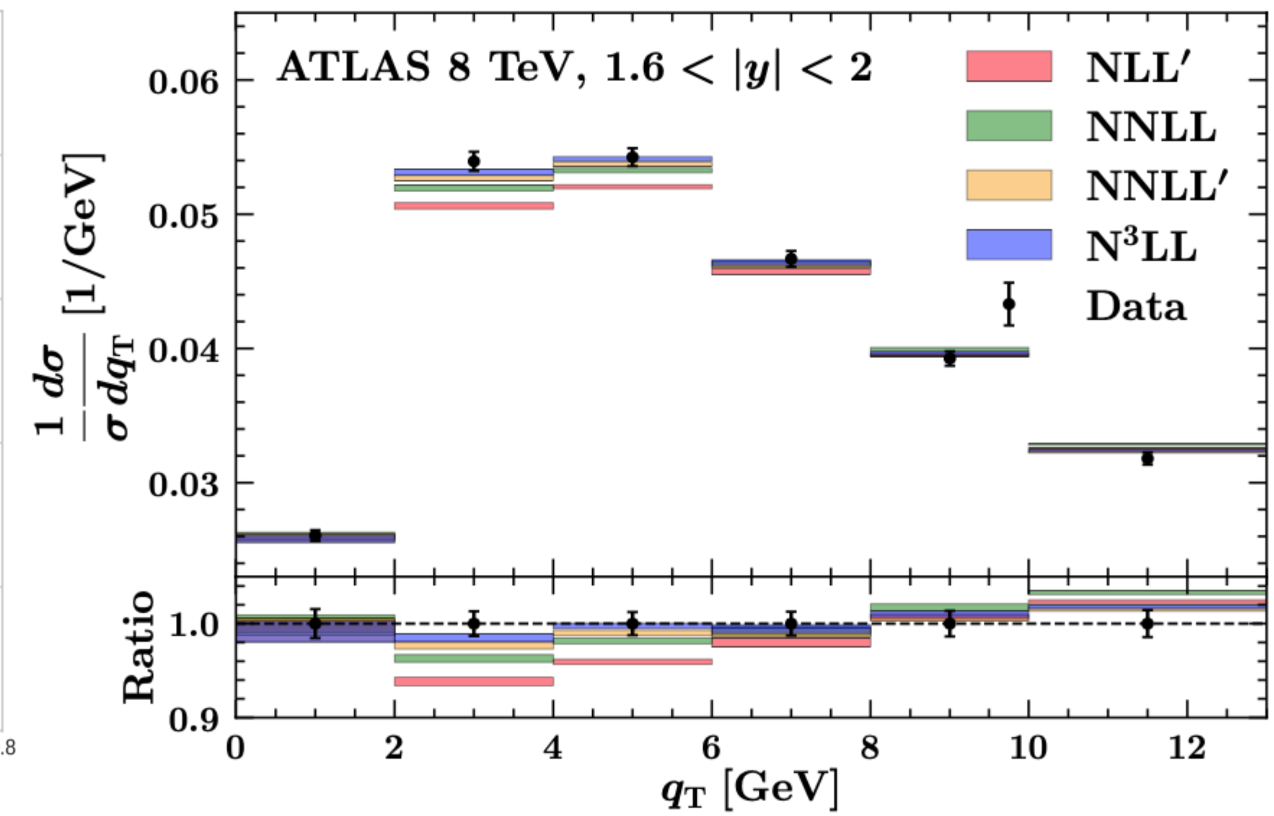
SIDIS normalisation

SIDIS beyond NLL



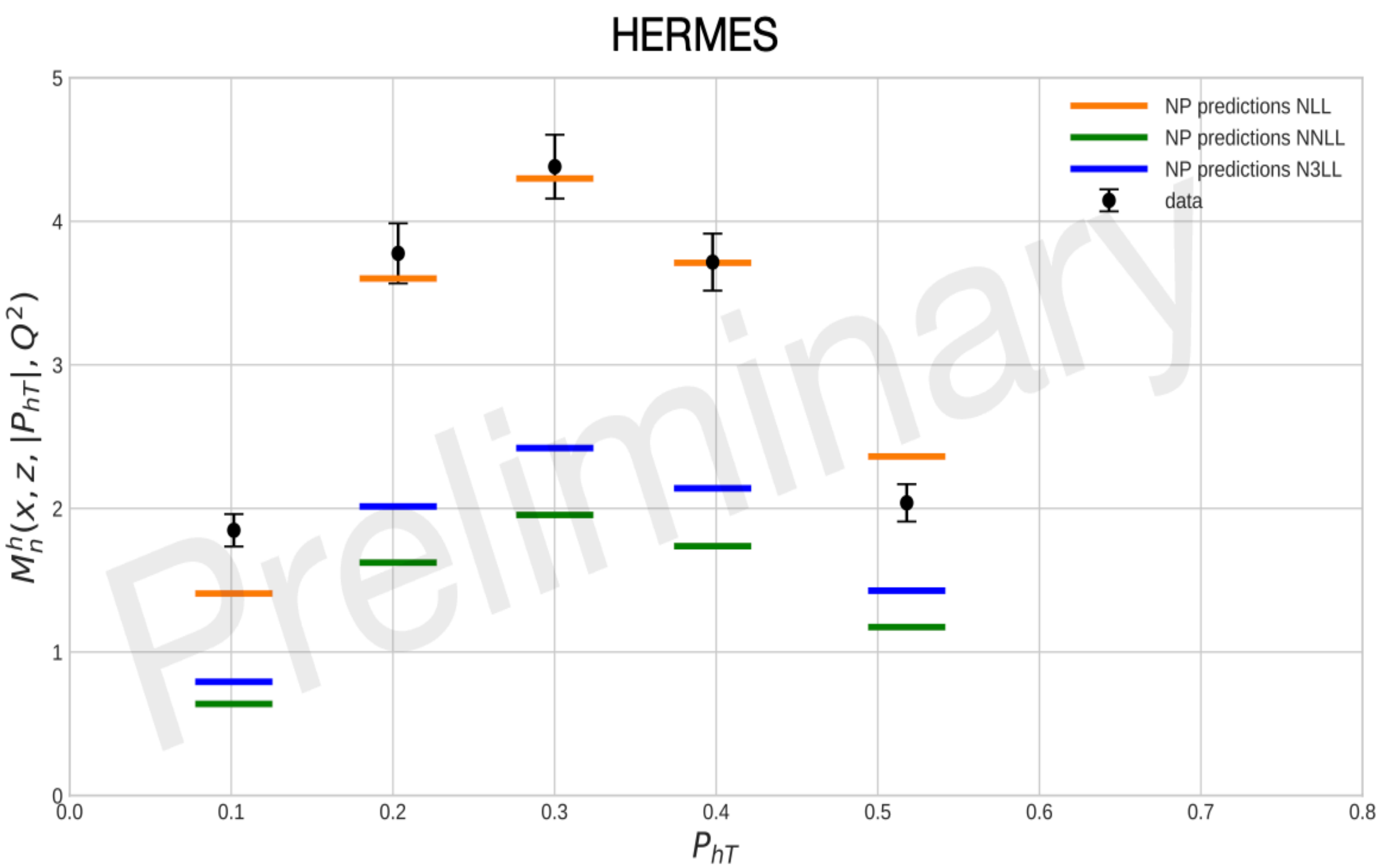


DY beyond NLL

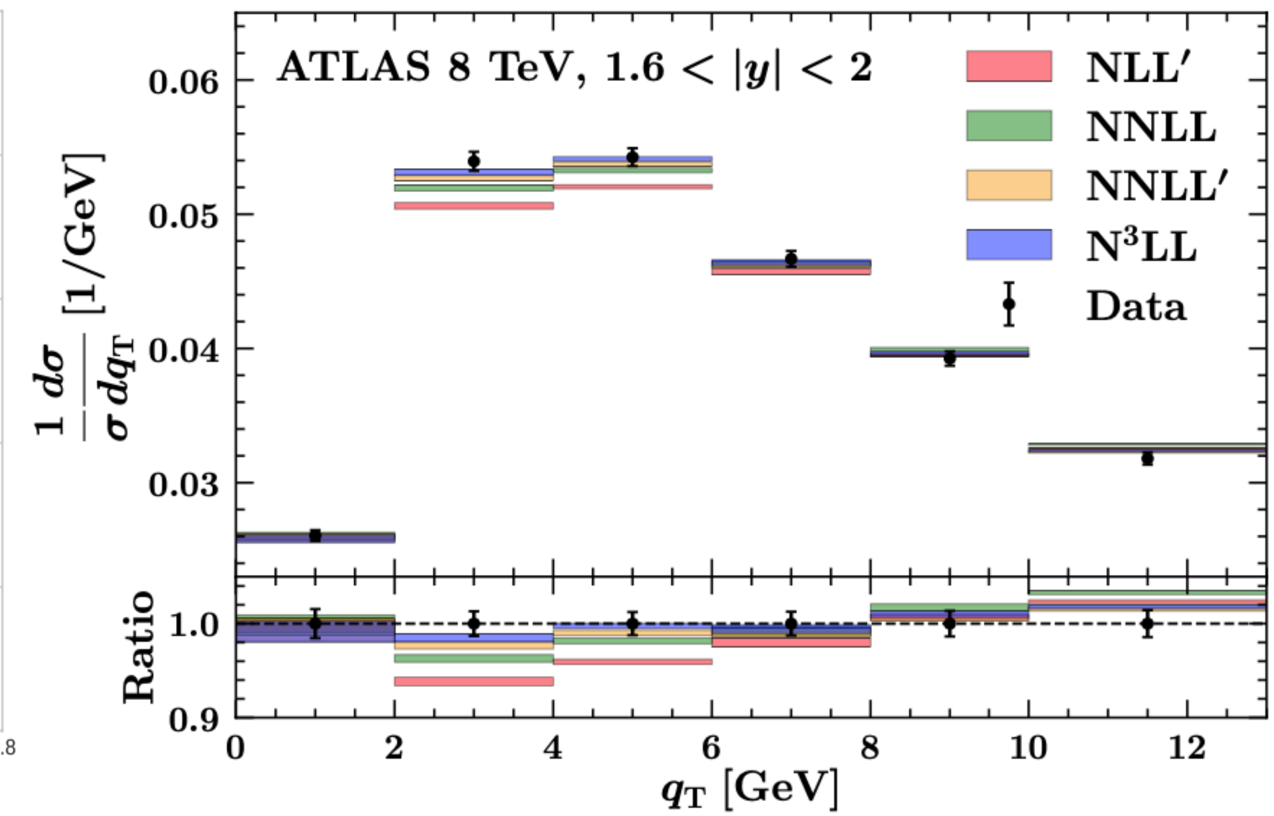


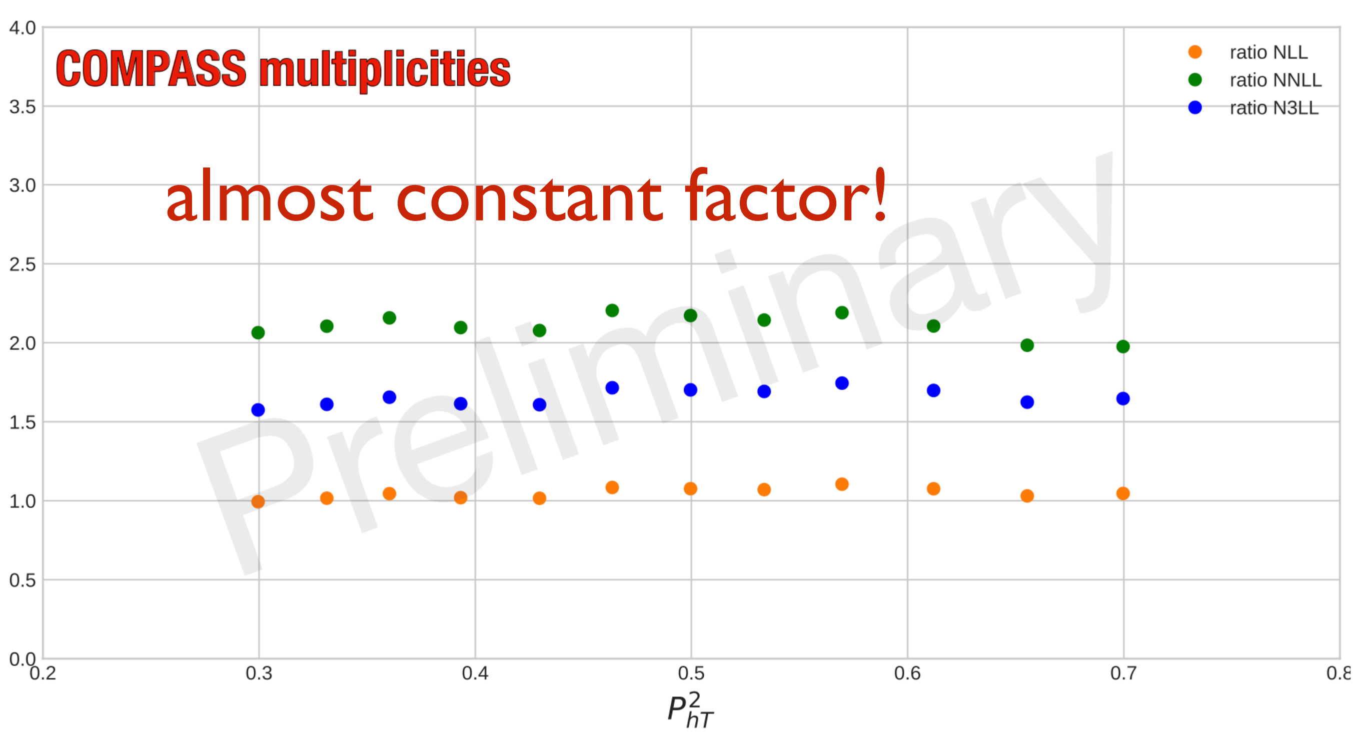
SIDIS normalisation

SIDIS beyond NLL



DY beyond NLL





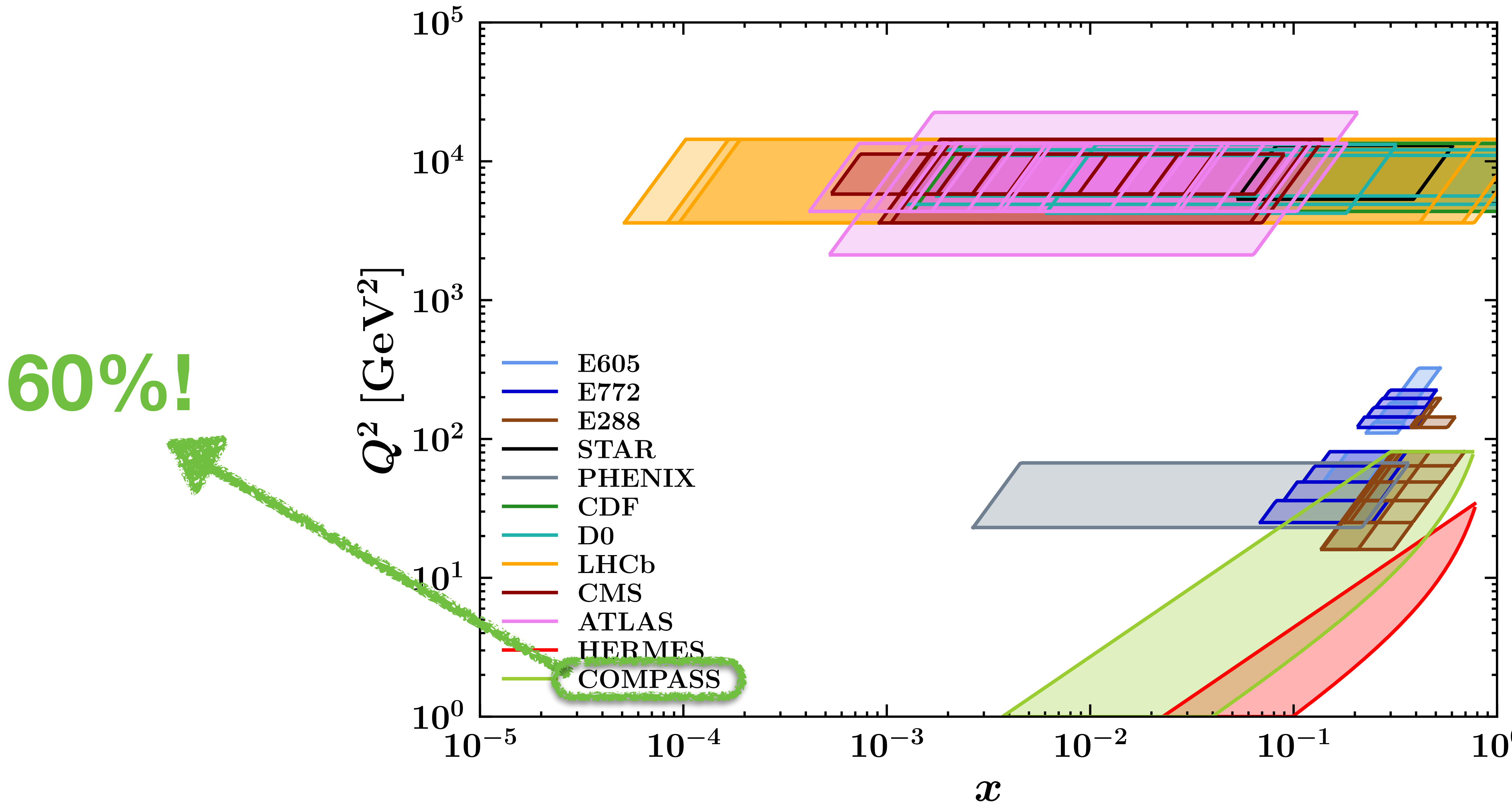
<u>normalisation factor for SIDIS</u>

- computed a priori, before the fit
- independent on the fitting parameters
- dependent on collinear PDFs

TMD global fits

	Accuracy	HERMES	COMPASS	DY fixed target	DY collider	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2019 arXiv:1912.06532	N^3LL^-	✔	✔	✔	✔	1039	1.06
MAP22 arXiv:2206.07598	N^3LL^-	✔	✔	✔	✔	2031	1.06

Datasets

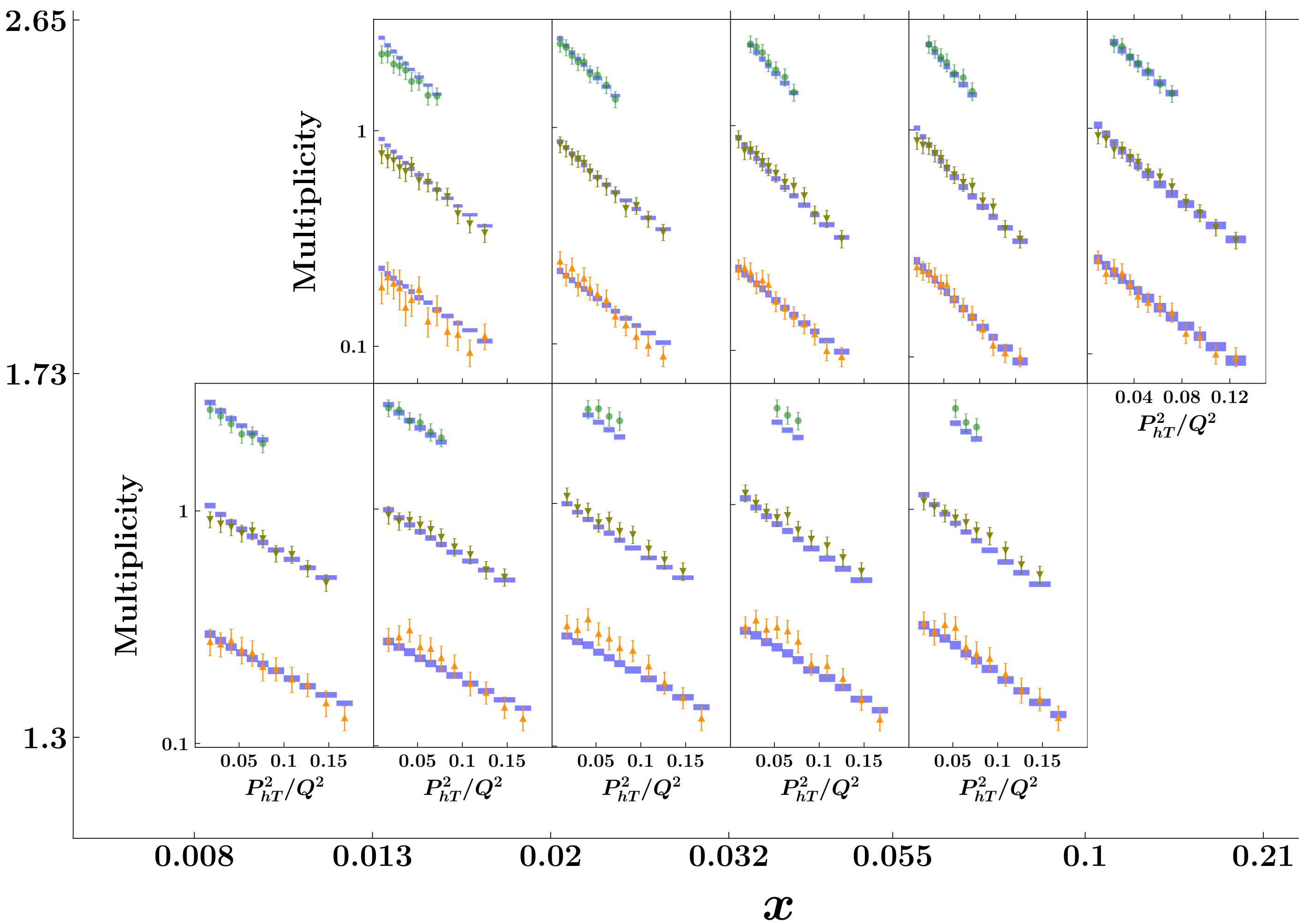


Cuts on kinematics

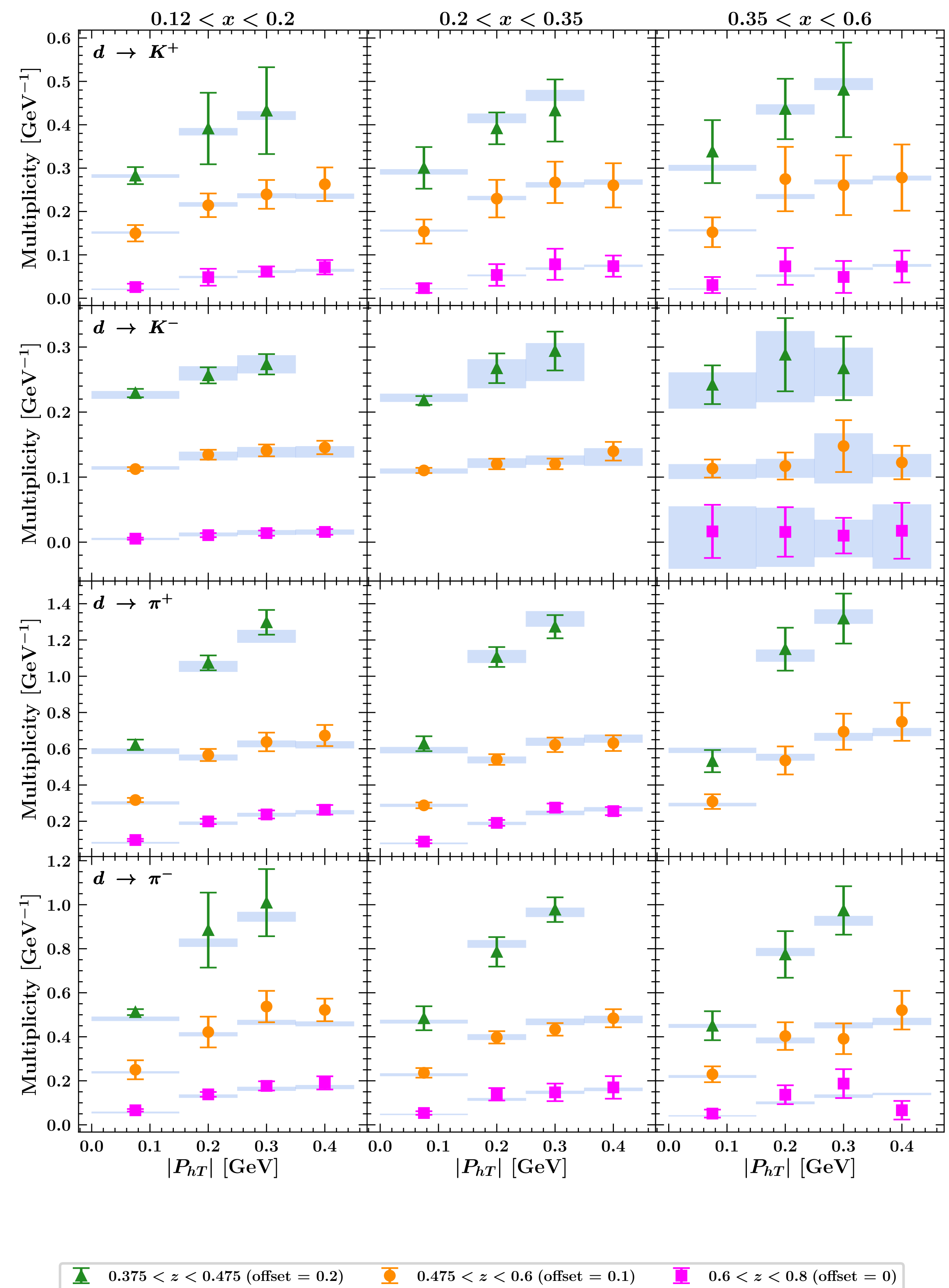
- $\langle Q \rangle > 1.3$ GeV
- $0.2 < \langle z \rangle < 0.7$
- $q_T/Q \leq 0.2$ (Drell-Yan)
- $P_{hT}|_{max} = min[min[\,0.2Q,\, 0.5zQ\,] + 0.3\text{ GeV},\, zQ\,]$ (SIDIS)

Fit quality: SIDIS

COMPASS



HERMES

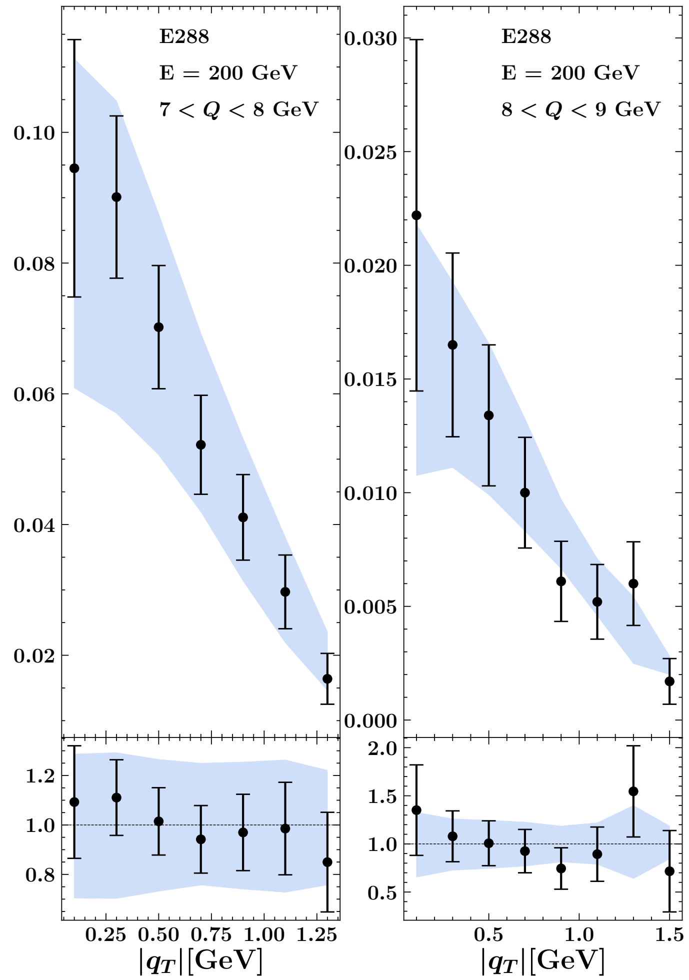


Good agreement for almost all bins

$\chi^2/N_{data} = 0.87$ (SIDIS total)

Fit quality: Drell-Yan

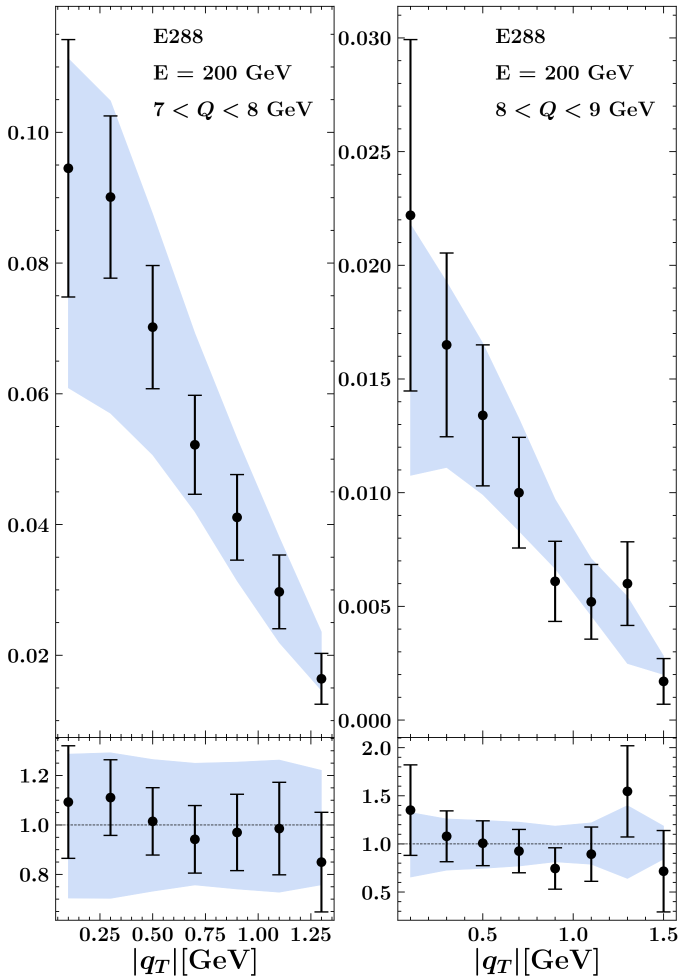
E288



$\chi^2/N_{data} = 1.24$
(DY fixed-target)

Fit quality: Drell-Yan

E288



$\chi^2/N_{data} = 1.24$
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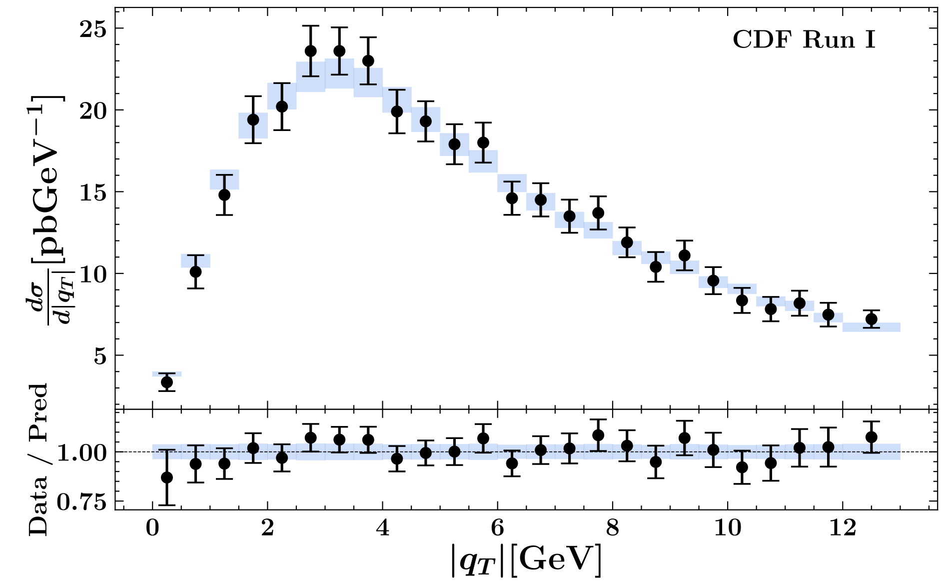
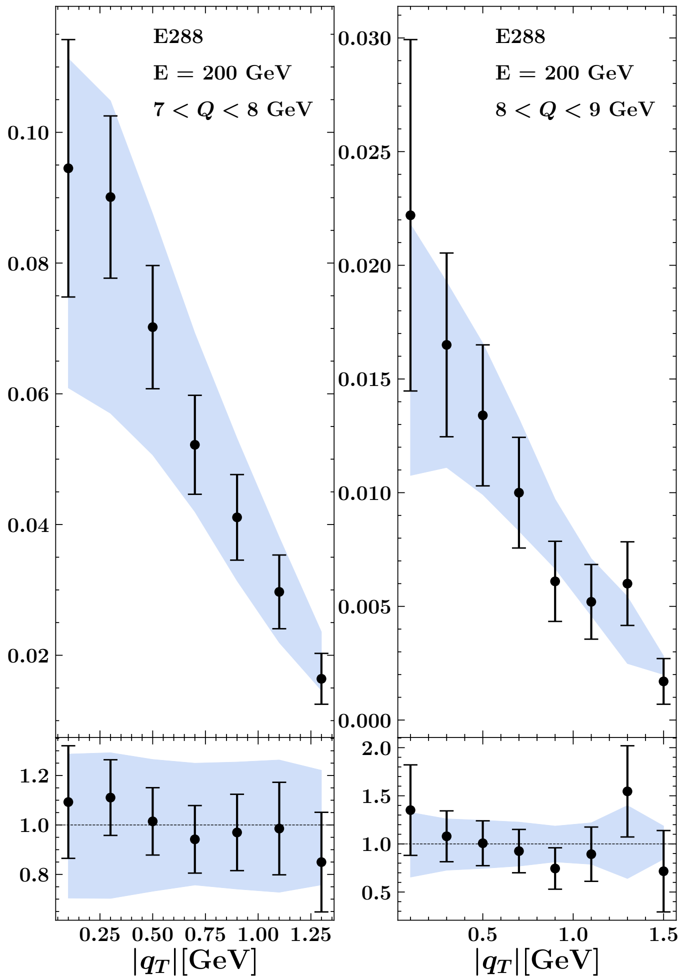
CDF



$\chi^2/N_{data} = 0.93$
(DY Tevatron)

Fit quality: Drell-Yan

E288



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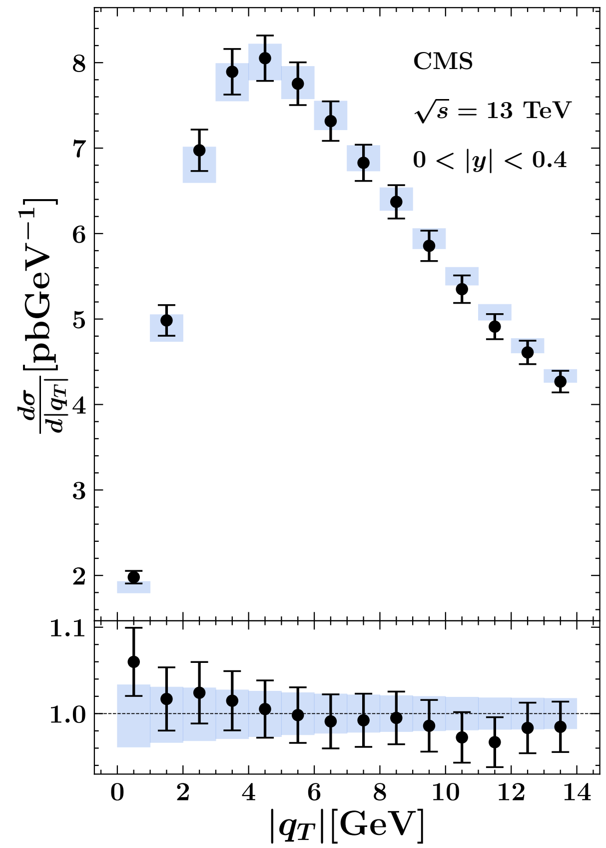
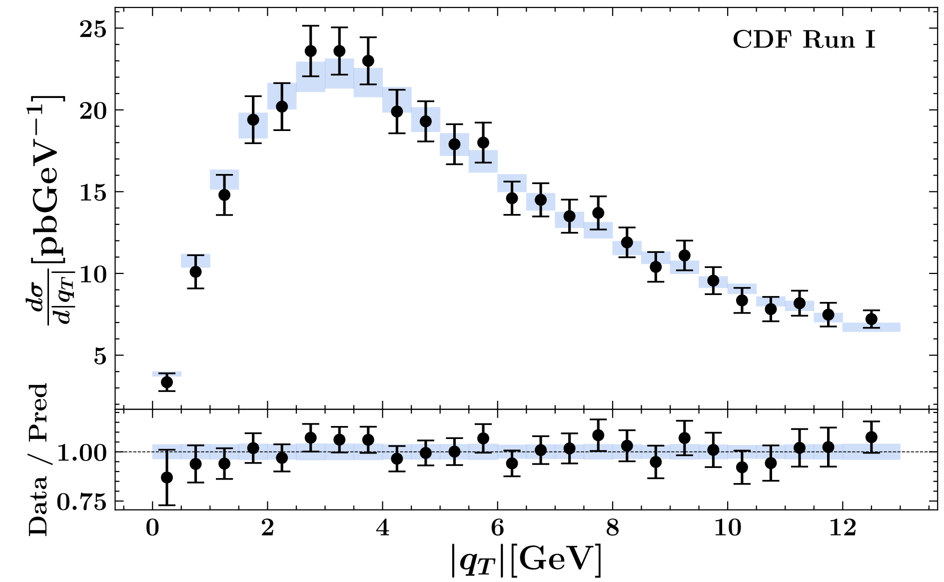
CMS



$\chi^2/N_{data} = 0.55$
(DY CMS)

CDF



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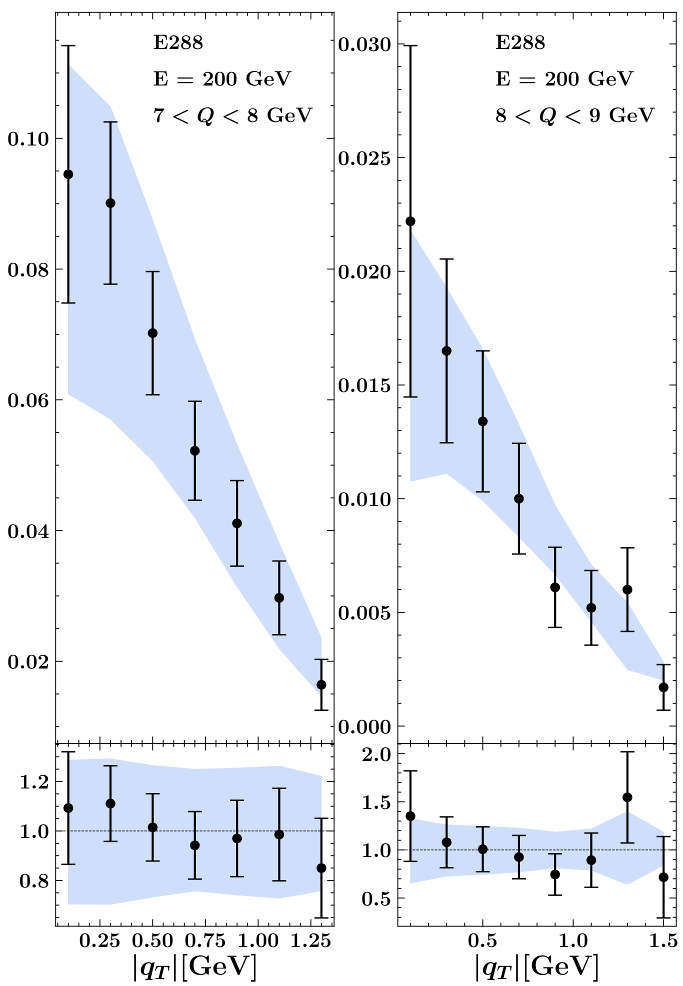

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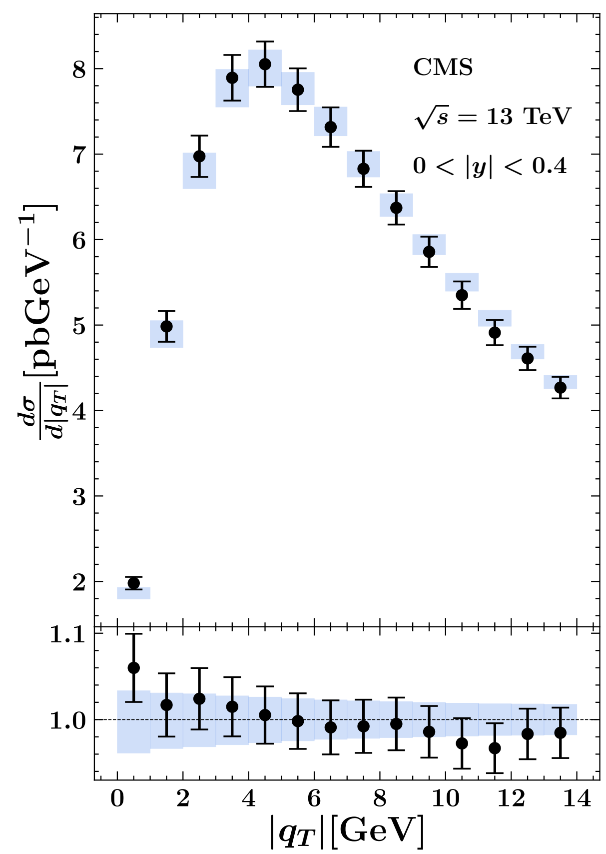
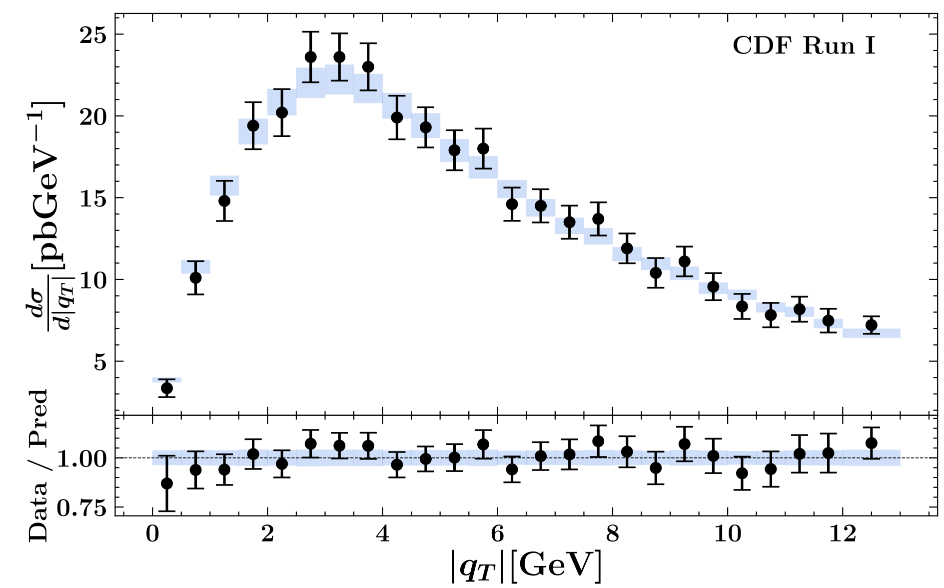


$\chi^2/N_{data} = 0.55$
(DY CMS)

$\chi^2/N_{data} = 5.05$
(DY ATLAS)

CDF



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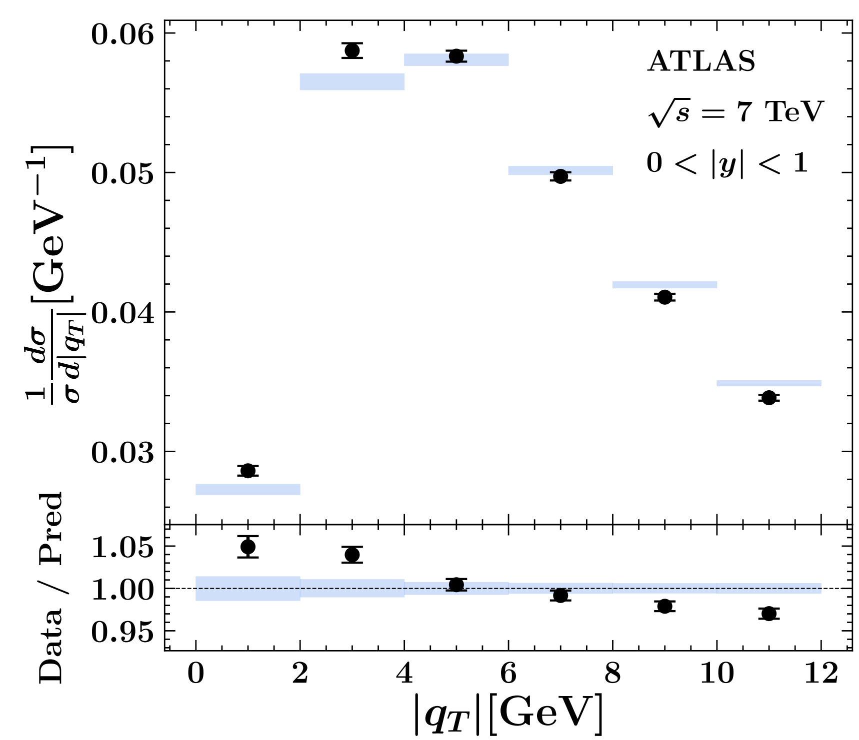
ATLAS



Fitting parameters

Parameter	Average over replicas
g_2 [GeV]	0.248 ± 0.008
N_1 [GeV^2]	0.316 ± 0.025
α_1	1.29 ± 0.19
σ_1	0.68 ± 0.13
λ [GeV^{-1}]	1.82 ± 0.29
N_3 [GeV^2]	0.0055 ± 0.0006
β_1	10.23 ± 0.29
δ_1	0.0094 ± 0.0012
γ_1	1.406 ± 0.084
λ_F [GeV^{-2}]	0.078 ± 0.011
N_{3B} [GeV^2]	0.2167 ± 0.0055
N_{1B} [GeV^2]	0.134 ± 0.017
N_{1C} [GeV^2]	0.0130 ± 0.0069
λ_2 [GeV^{-1}]	0.0215 ± 0.0058
α_2	4.27 ± 0.31
α_3	4.27 ± 0.13
σ_2	0.455 ± 0.050
σ_3	12.71 ± 0.21
β_2	4.17 ± 0.13
δ_2	0.167 ± 0.006
γ_2	0.0007 ± 0.0110

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δ_1	0.0094 ± 0.0012
γ_1	1.406 ± 0.084
λ_F [GeV^{-2}]	0.078 ± 0.011
N_{3B} [GeV^2]	0.2167 ± 0.0055
N_{1B} [GeV^2]	0.134 ± 0.017
N_{1C} [GeV^2]	0.0130 ± 0.0069
λ_2 [GeV^{-1}]	0.0215 ± 0.0058
α_2	4.27 ± 0.31
α_3	4.27 ± 0.13
σ_2	0.455 ± 0.050
σ_3	12.71 ± 0.21
β_2	4.17 ± 0.13
δ_2	0.167 ± 0.006
γ_2	0.0007 ± 0.0110

- $\lambda \sim 2$: weighted Gaussian important

Fitting parameters

Parameter	Average over replicas
g_2 [GeV]	0.248 ± 0.008
N_1 [GeV^2]	0.316 ± 0.025
α_1	1.29 ± 0.19
σ_1	0.68 ± 0.13
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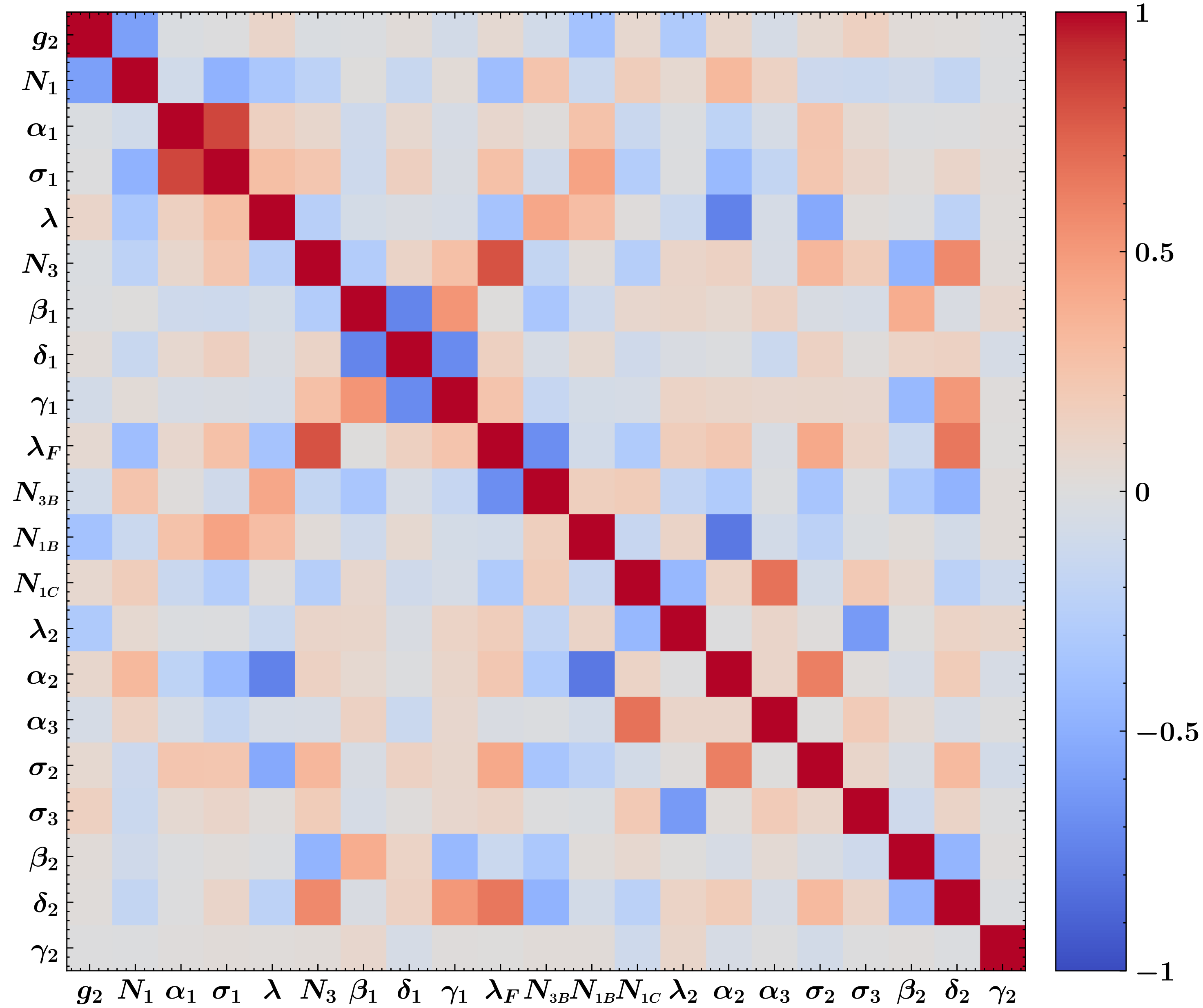
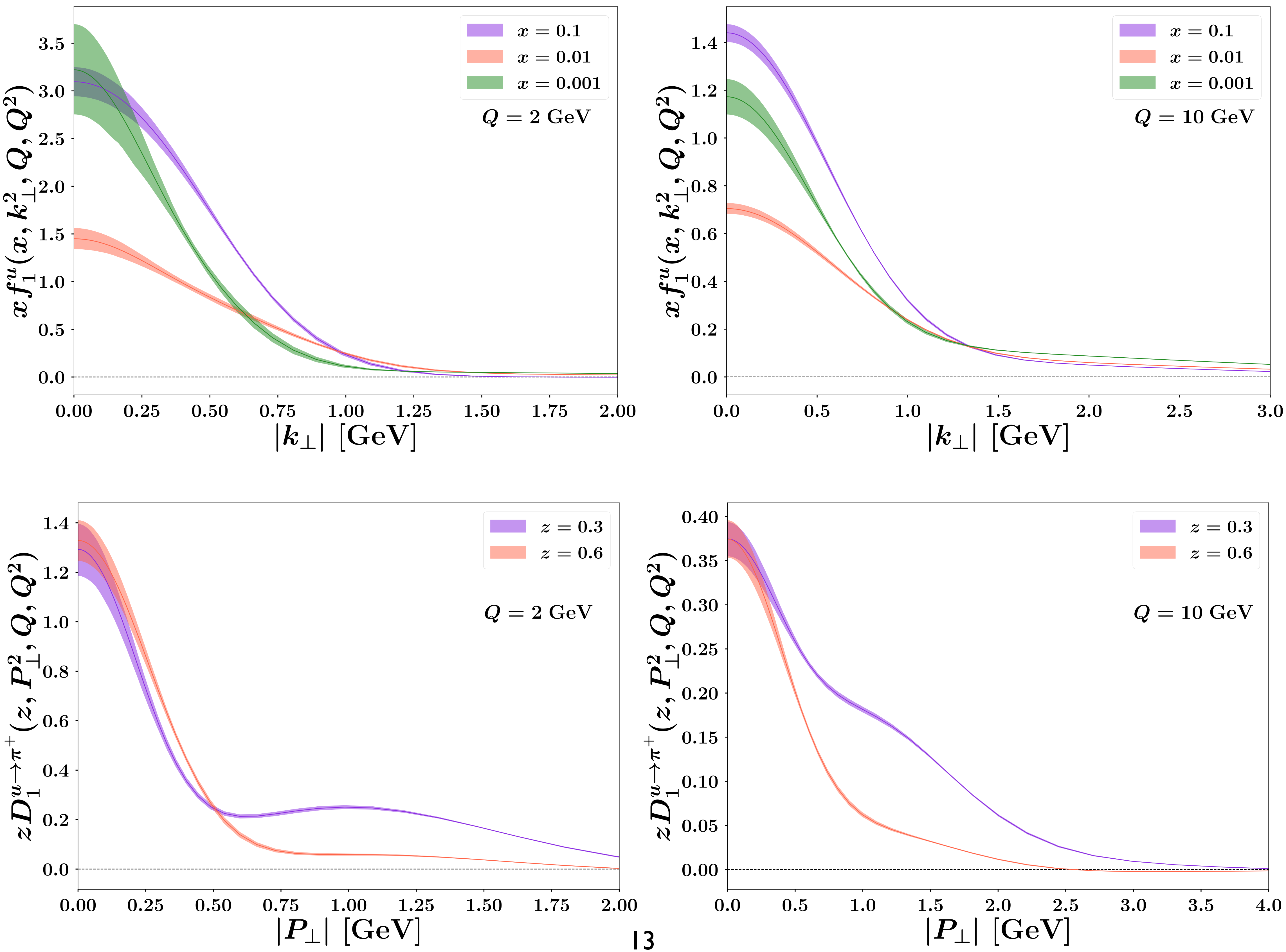
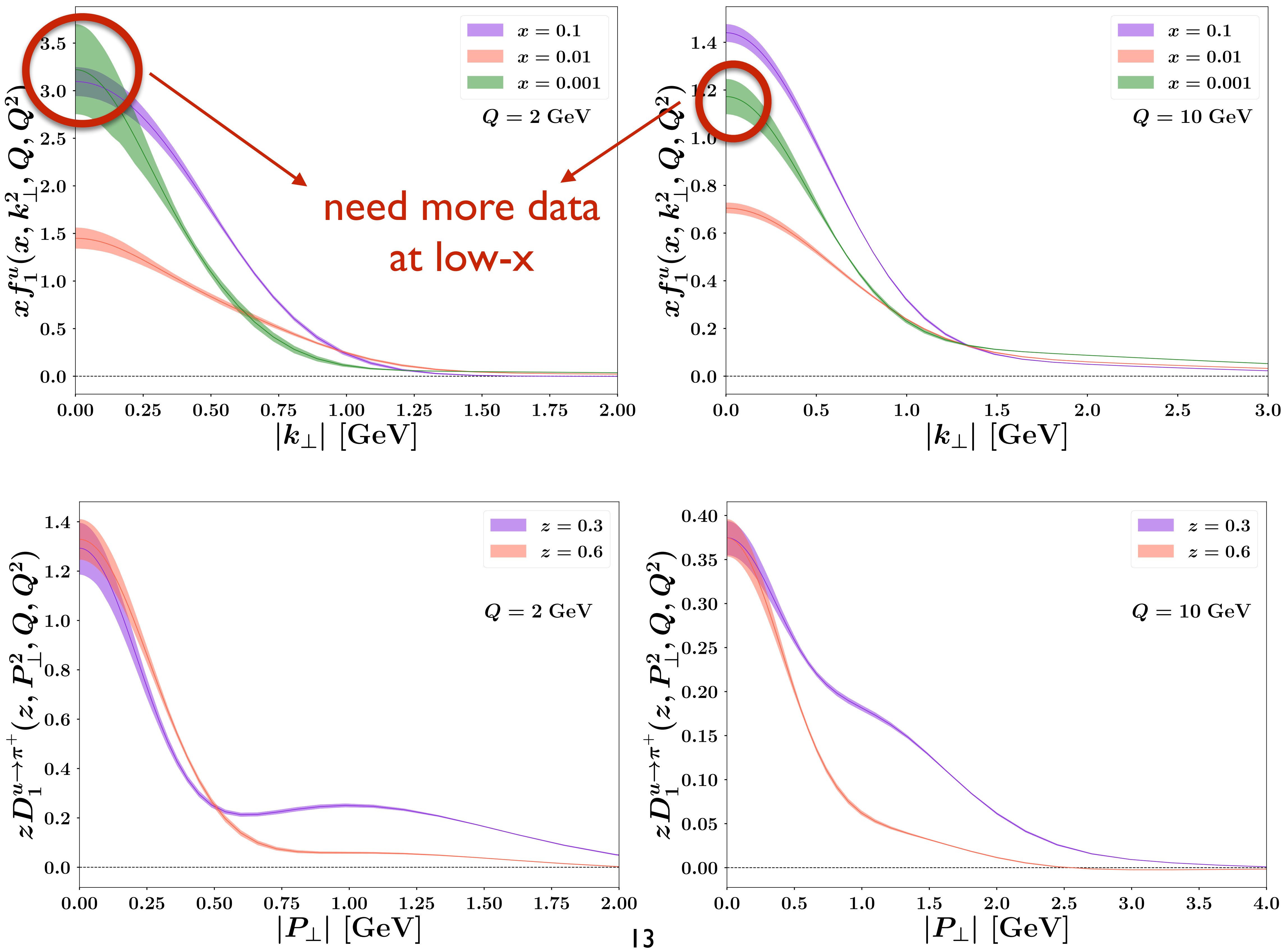


- $\lambda \sim 2$: weighted Gaussian important
- $\lambda_2 \neq 0$: third Gaussian non-negligible
- g_2 very small standard deviation
- correlation matrix nearly diagonal

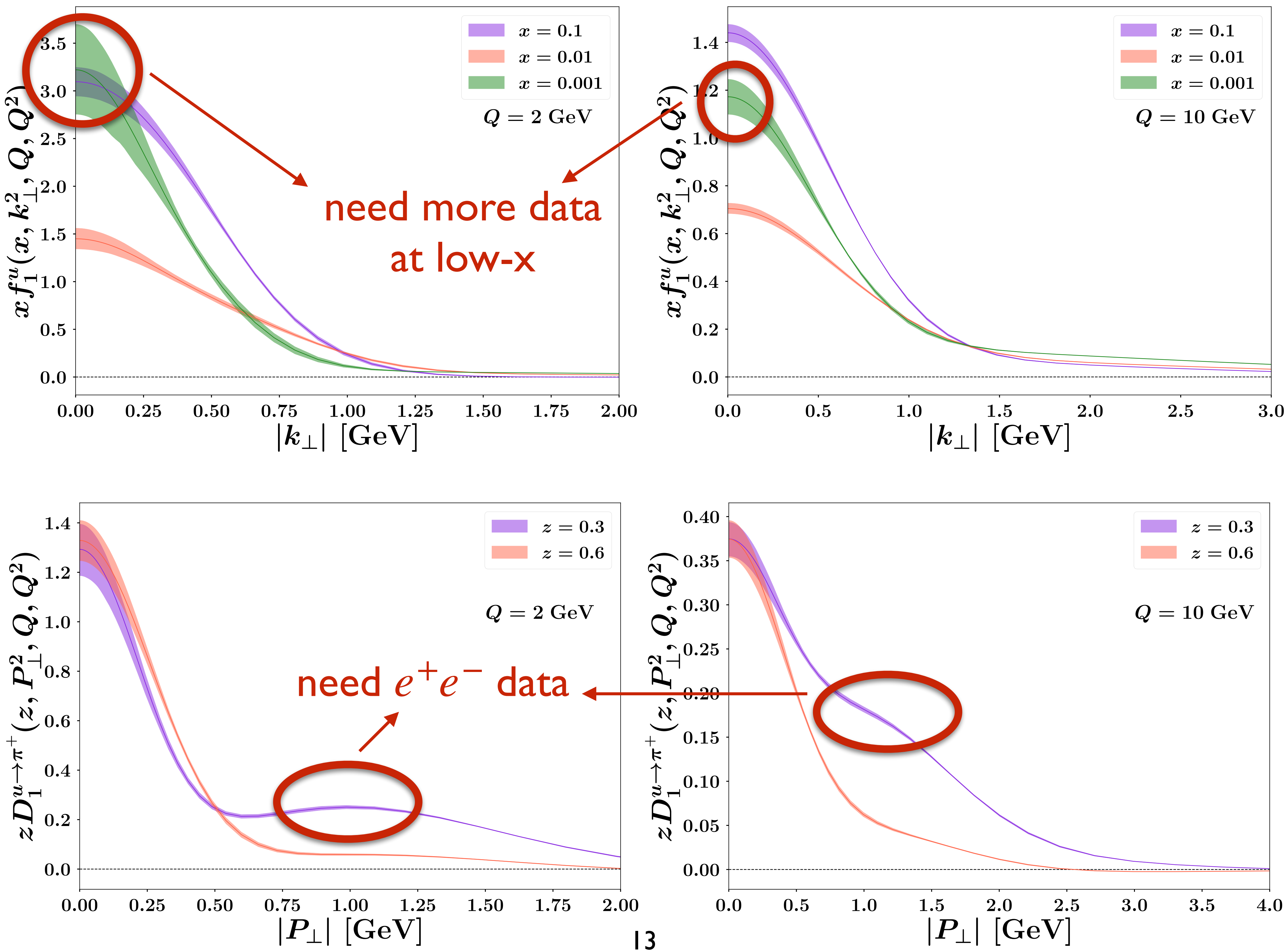
TMD PDFs and FFs



TMD PDFs and FFs



TMD PDFs and FFs



The Nanga Parbat framework

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/MapCollaboration/NangaParbat

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

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

Conclusions

- Extraction of **TMD PDFs and FFs** from DY and SIDIS data at **N^{3}LL$^{(-)}$**
- 484 DY (Fermilab, LHC, RHIC) + 1547 SIDIS (COMPASS, Hermes): **2031 data points**
- **Normalisation factors** used for SIDIS data
- Very good description of entire dataset ($\chi^2 = 1.06$) **except for ATLAS data**
- **Code and TMD grids** available at the NangaParbat website
- **Plans for the future**:
  - improve perturbative accuracy
  - matching with fixed order
  - include theoretical uncertainties
  - flavour dependence

Backup

Normalisation of SIDIS multiplicities

Introduction of a normalisation prefactor

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

$$\left.\frac{d\sigma^h}{dx dQ^2 dz}\right|_{O(\alpha_S)} = \sigma_0 \sum_{f,f'} \frac{e_f^2}{z^2} (\delta_{f'f} + \delta_{f'g}) \frac{\alpha_S}{\pi} \left.\left\{ \left[D_1^{h/f'} \otimes C_1^{f'f} \otimes f_1^{f/N} \right](x, z, Q) \right\}\right|_{\text{nonmix.}}$$

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

Independent of the fitting parameters!!

Slide by M. Cerutti

Non-mixed terms in collinear SIDIS cross section

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

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

Slide by M. Cerutti

Experimental uncertainties

$$m_i \pm \sigma_{i,\mathrm{stat}} \pm \sigma_{i,\mathrm{unc}} \pm \sigma^{(1)}_{i,\mathrm{corr}} \pm \cdots \pm \sigma^{(k)}_{i,\mathrm{corr}}$$

uncorrelated

correlated

additive **multiplicative**

$$\chi^2 = \sum_{i,j=1}^{n} (m_i - t_i) V^{-1}_{ij} (m_j - t_j)$$

$$\sigma^{(l)}_{i,\mathrm{corr}} \equiv \delta^{(l)}_{i,\mathrm{corr}} m_i$$

covariance matrix

$$V_{ij} = s_i^2 \delta_{ij} + \left(\sum_{l=1}^{k_a} \delta^{(l)}_{i,\mathrm{add}} \delta^{(l)}_{j,\mathrm{add}} + \sum_{l=1}^{k_m} \delta^{(l)}_{i,\mathrm{mult}} \delta^{(l)}_{j,\mathrm{mult}} \right) m_i m_j$$

Slide by C. Bissolotti

χ^2 chisquare

systematic shift

shift

$$d_i = \sum_{\alpha=1}^{k} \lambda_\alpha \sigma_{i,\mathrm{corr}}^{(\alpha)}$$

$$\frac{\partial \chi^2}{\partial \lambda_\alpha} = 0$$

nuisance parameters

$$\bar{t}_i = t_i + d_i$$

shifted prediction

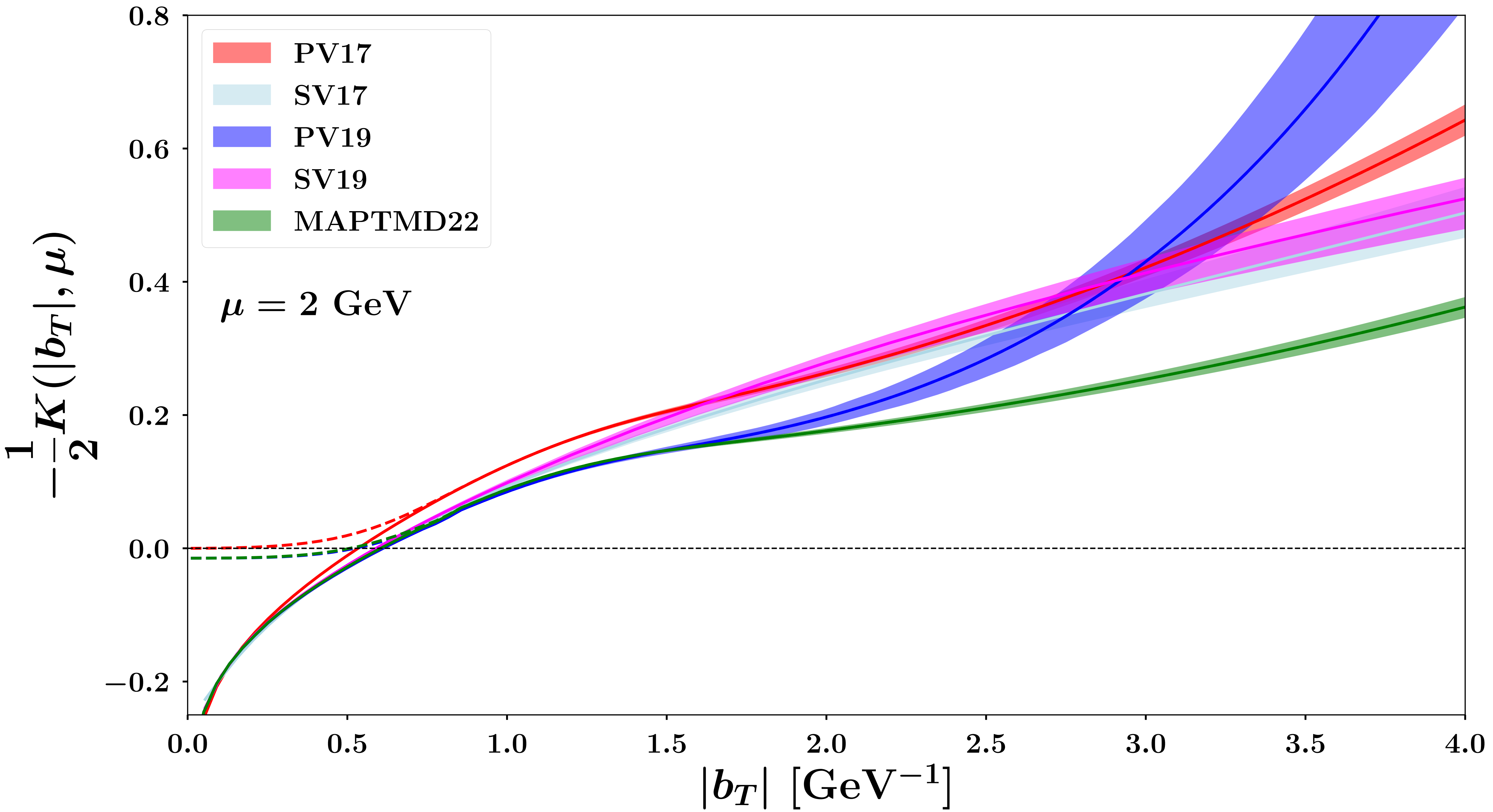
$$\chi^2 = \sum_{i=1}^{n} \left(\frac{m_i - \bar{t}_i}{s_i} \right)^2 + \sum_{\alpha=1}^{k} \lambda_\alpha^2$$

recover the form of
the uncorrelated definition

penalty term

Slide by C. Bissolotti

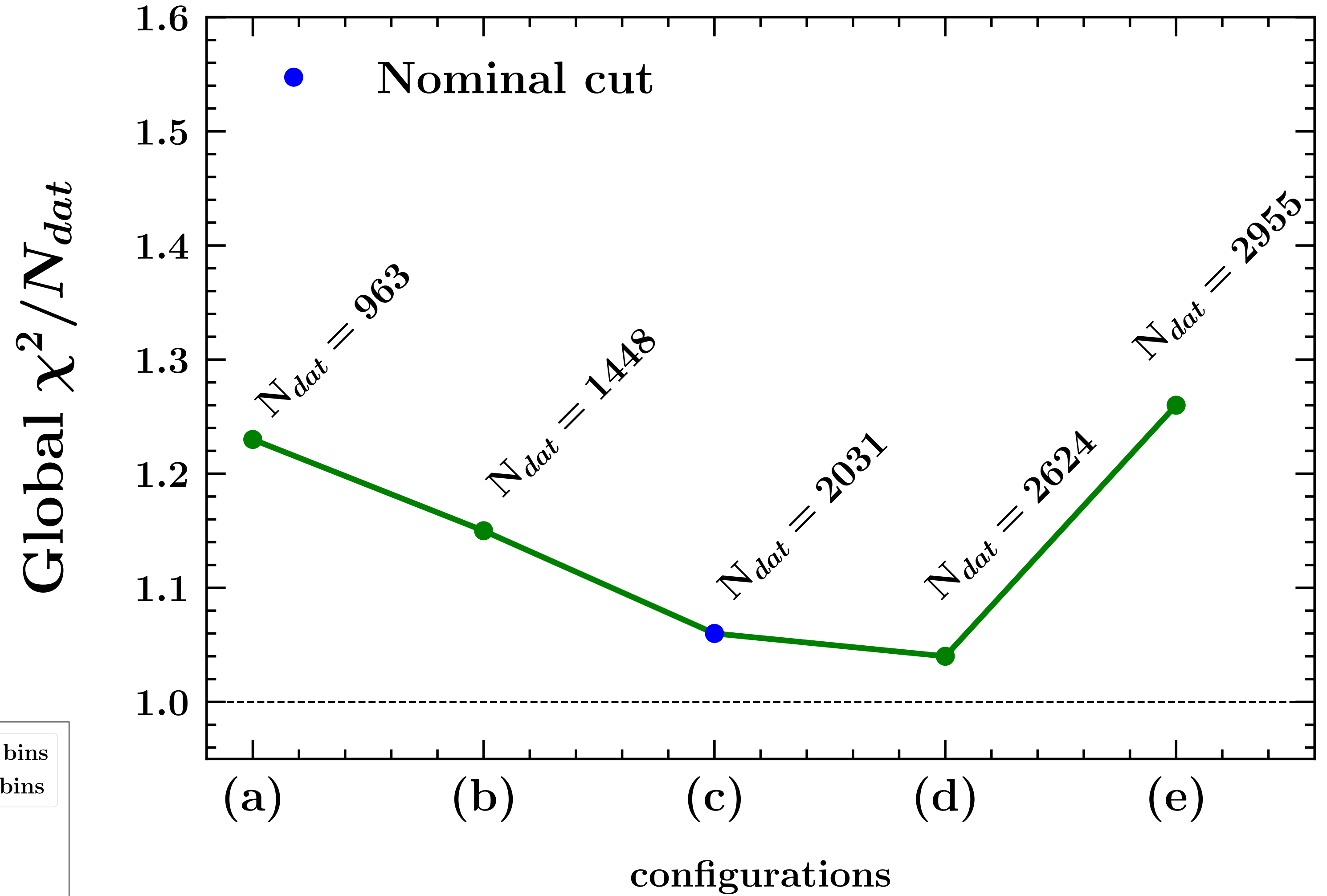
Collins-Soper kernel

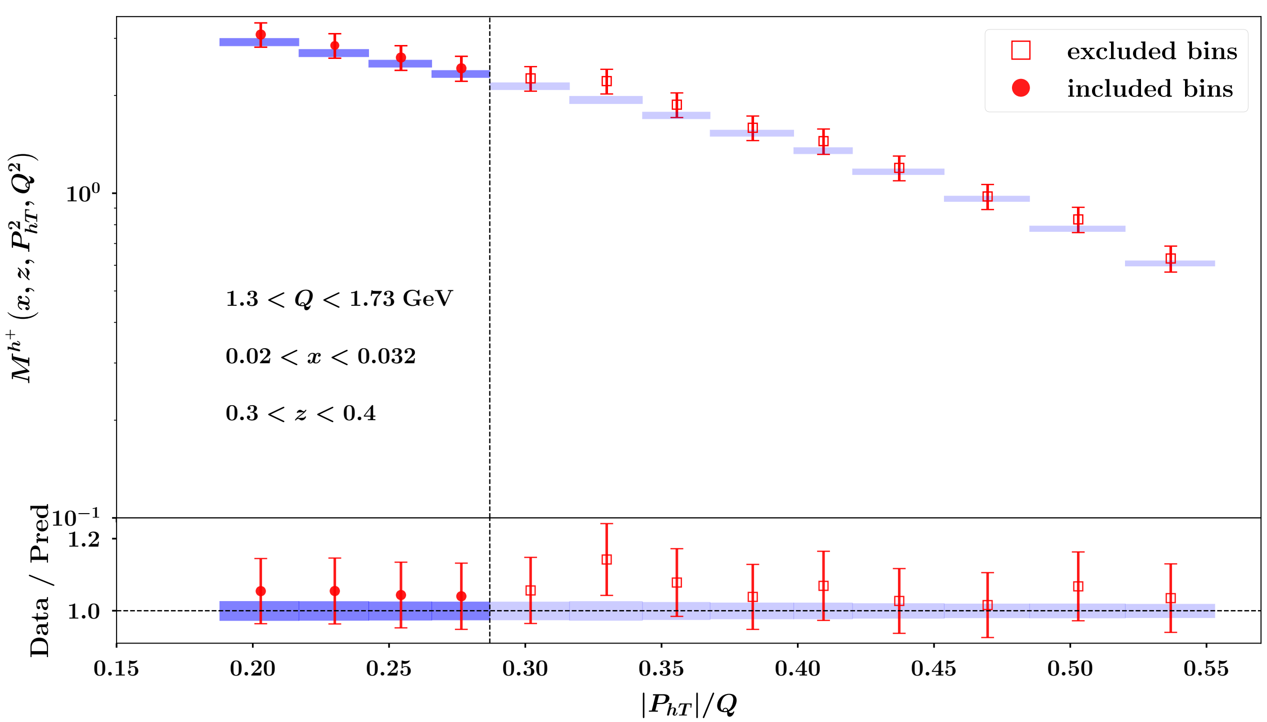


Different SIDIS cuts

$$P_{hT}|_{max} = min[min[\,0.2Q,\, 0.5zQ\,] + 0.3\ \text{GeV},\, zQ\,]$$

- (a) $c_1 = 0.4, c_2 = 0.4, c_3 = 0$
- (b) $c_1 = 0.15, c_2 = 0.4, c_3 = 0.2$
- (c) $c_1 = 0.2, c_2 = 0.5, c_3 = 0.3$ (baseline)
- (d) $c_1 = 0.2, c_2 = 0.6, c_3 = 0.4$
- (e) $c_1 = 0.2, c_2 = 0.7, c_3 = 0.5$





Different logarithmic orders

	N^3LL^-		NNLL		NLL	
Data set	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$
ATLAS	72	5.01 ± 0.26	/	/	/	/
PHENIX 200	2	3.26 ± 0.31	2	0.81 ± 0.11	/	/
STAR 510	7	1.16 ± 0.04	7	0.99 ± 0.03	/	/
Other sets	170	0.83 ± 0.01	170	2.37 ± 0.11	/	/
DY collider	251	2.06 ± 0.07	179	2.3 ± 0.1	/	/
E772	53	2.48 ± 0.12	53	2.05 ± 0.22	/	/
Other sets	180	0.87 ± 0.04	180	0.71 ± 0.04	180	0.81 ± 0.04
DY fixed-target	233	1.24 ± 0.04	233	1.01 ± 0.05	180	0.81 ± 0.04
HERMES	344	0.71 ± 0.04	344	1.1 ± 0.06	344	0.51 ± 0.02
COMPASS	1203	0.95 ± 0.02	1203	0.6 ± 0.06	1203	0.41 ± 0.01
SIDIS	1547	0.89 ± 0.02	1547	0.71 ± 0.05	1547	0.43 ± 0.01
Total	2031	1.08 ± 0.01	1959	0.89 ± 0.01	1727	0.47 ± 0.01