Nanga Parbat 2019 (Drell-Yan) fit

Transverse-momentum-dependent parton distributions up to N^3LL from Drell-Yan data

Alessandro Bacchetta, Valerio Bertone, Chiara Bissolotti (INFN, Pavia & Pavia U.), Giuseppe Bozzi (Florence U. & INFN, Florence), Filippo Delcarro (Pavia U.), Fulvio Piacenza (INFN, Pavia & Pavia U.), Marco Radici (INFN, Pavia)

Dec 16, 2019 - 43 pages

JLAB-THY-19-3121
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We present an extraction of unpolarised Transverse-Momentum-Dependent Parton Distribution Functions based on Drell-Yan production data from different experiments, including those at the LHC, and spanning a wide kinematic range. We deal with experimental uncertainties by properly taking into account correlations. We include resummation of logarithms of the transverse momentum of the vector boson up to N^3LL order, and we include non-perturbative contributions. These ingredients allow us to obtain a remarkable agreement with the data.

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Phase-space factor (lepton cuts)

Hard factor

$$\frac{d\sigma}{dQ\,dy\,dq_T} = \frac{8\pi\alpha^2 q_T \mathcal{P}}{9Q^3} H(Q,\mu) \times \sum_q c_q(Q) \int_0^\infty db_T\, b_T\, J_0(b_T q_T)\, x_1 \hat{f}_1^q(x_1, b_T; \mu, \zeta_1)\, x_2 \hat{f}_1^{\bar{q}}(x_2, b_T; \mu, \zeta_2)$$

electroweak charges

TMD PDFs

Regularisation

b* prescription

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

b_{max} $\alpha_s\left(\frac{2e^{-\gamma_E}}{b_{\max}}\right) \ll 1$

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

(not strictly necessary)

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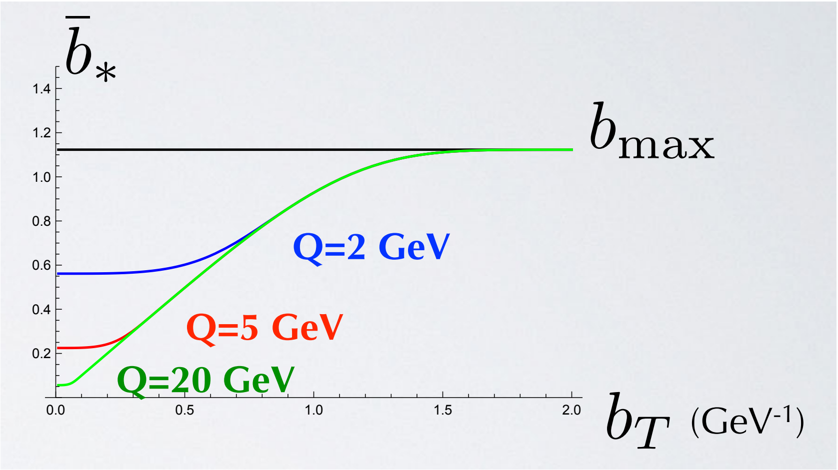
limiting values

$$b_*(b_T) \to b_{\min} \quad \text{for} \quad b_T \to 0\,,$$
$$b_*(b_T) \to b_{\max} \quad \text{for} \quad b_T \to \infty\,.$$



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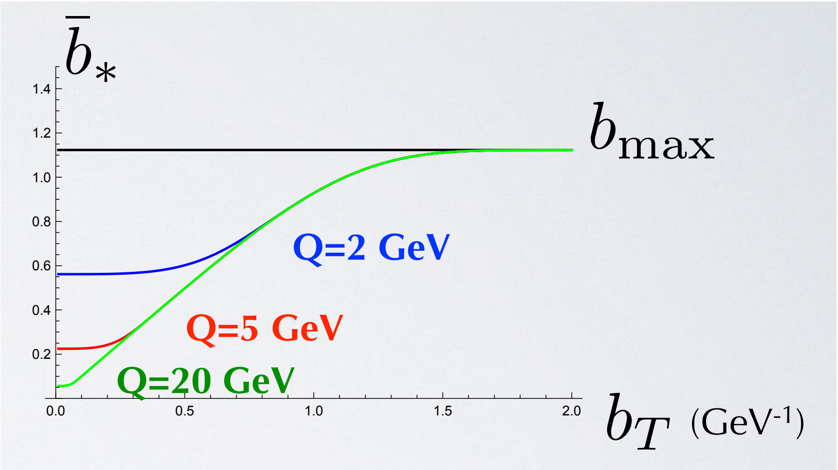

Definition of f_{NP}

$$\hat{f}_1(x, b_T; \mu, \zeta) = \left[\frac{\hat{f}_1(x, b_T; \mu, \zeta)}{\hat{f}_1(x, b_*(b_T); \mu, \zeta)}\right]\hat{f}_1(x, b_*(b_T); \mu, \zeta)$$

$$\equiv f_{\mathrm{NP}}(x, b_T, \zeta)\hat{f}_1(x, b_*(b_T); \mu, \zeta)\,.$$

Parameterisation

$$f_{\mathrm{NP}}(x, b_T, \zeta) = \left[\frac{1-\lambda}{1 + g_1(x)\frac{b_T^2}{4}} + \lambda \exp\left(-g_{1B}(x)\frac{b_T^2}{4}\right)\right]$$

$$\times \exp\left[-\left(g_2 + g_{2B} b_T^2\right) \ln\left(\frac{\zeta}{Q_0^2}\right) \frac{b_T^2}{4}\right] ,$$

$$g_1(x) = \frac{N_1}{x\sigma} \exp\left[-\frac{1}{2\sigma^2} \ln^2\left(\frac{x}{\alpha}\right)\right] ,$$

$$g_{1B}(x) = \frac{N_{1B}}{x\sigma_B} \exp\left[-\frac{1}{2\sigma_B^2} \ln^2\left(\frac{x}{\alpha_B}\right)\right] .$$

Parameterisation

"intrinsic" NP contribution (x- and b_T-dependent)

$$f_{\mathrm{NP}}(x, b_T, \zeta) = \left[\frac{1-\lambda}{1+g_1(x)\frac{b_T^2}{4}} + \lambda \exp\left(-g_{1B}(x)\frac{b_T^2}{4}\right)\right]$$

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- **"intrinsic" contribution: q-Gaussian (Tsallis) + simple Gaussian**
    - **q-Gaussian has larger tail —> bigger contribution at small q_T**

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"intrinsic" NP contribution (x- and b_T-dependent)

NP correction to pert. evolution (b_T-dependent)

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  - **quartic term allows to reproduce energy evolution**

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“intrinsic” NP contribution (x- and b_T-dependent)

NP correction to pert. evolution (b_T-dependent)

x-dep. width of TMDs

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NP correction to pert. evolution (b_T-dependent)

$$g_1(x) = \frac{N_1}{x\sigma}\exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{x}{\alpha}\right)\right],$$

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9 parameters $(\lambda, g_2, g_{2B}, N_1, \sigma, \alpha, N_{1B}, \sigma_B, \alpha_B)$

Experimental data

Experiment	N_{dat}	Observable	$\sqrt{s}$ [GeV]	Q [GeV]	y or x_F	Lepton cuts
E605	50	$Ed^3\sigma/d^3q$	38.8	7 - 18	$x_F = 0.1$	-
E288 200 GeV	30	$Ed^3\sigma/d^3q$	19.4	4 - 9	$y = 0.40$	-
E288 300 GeV	39	$Ed^3\sigma/d^3q$	23.8	4 - 12	$y = 0.21$	-
E288 400 GeV	61	$Ed^3\sigma/d^3q$	27.4	5 - 14	$y = 0.03$	-
STAR 510	7	$d\sigma/dq_T$	510	73 - 114	$\|y\| < 1$	$p_{T\ell} > 25$ GeV $\|\eta_\ell\| < 1$
CDF Run I	25	$d\sigma/dq_T$	1800	66 - 116	Inclusive	-
CDF Run II	26	$d\sigma/dq_T$	1960	66 - 116	Inclusive	-
D0 Run I	12	$d\sigma/dq_T$	1800	75 - 105	Inclusive	-
D0 Run II	5	$(1/\sigma)d\sigma/dq_T$	1960	70 - 110	Inclusive	-
D0 Run II (μ)	3	$(1/\sigma)d\sigma/dq_T$	1960	65 - 115	$\|y\| < 1.7$	$p_{T\ell} > 15$ GeV $\|\eta_\ell\| < 1.7$
LHCb 7 TeV	7	$d\sigma/dq_T$	7000	60 - 120	$2 < y < 4.5$	$p_{T\ell} > 20$ GeV $2 < \eta_\ell < 4.5$
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ATLAS 7 TeV	6 6 6	$(1/\sigma)d\sigma/dq_T$	7000	66 - 116	$\|y\| < 1$ $1 < \|y\| < 2$ $2 < \|y\| < 2.4$	$p_{T\ell} > 20$ GeV $\|\eta_\ell\| < 2.4$
ATLAS 8 TeV on-peak	6 6 6 6 6 6	$(1/\sigma)d\sigma/dq_T$	8000	66 - 116	$\|y\| < 0.4$ $0.4 < \|y\| < 0.8$ $0.8 < \|y\| < 1.2$ $1.2 < \|y\| < 1.6$ $1.6 < \|y\| < 2$ $2 < \|y\| < 2.4$	$p_{T\ell} > 20$ GeV $\|\eta_\ell\| < 2.4$
ATLAS 8 TeV off-peak	4 8	$(1/\sigma)d\sigma/dq_T$	8000	46 - 66 116 - 150	$\|y\| < 2.4$	$p_{T\ell} > 20$ GeV $\|\eta_\ell\| < 2.4$
Total	353	-	-	-	-	-

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Only data with
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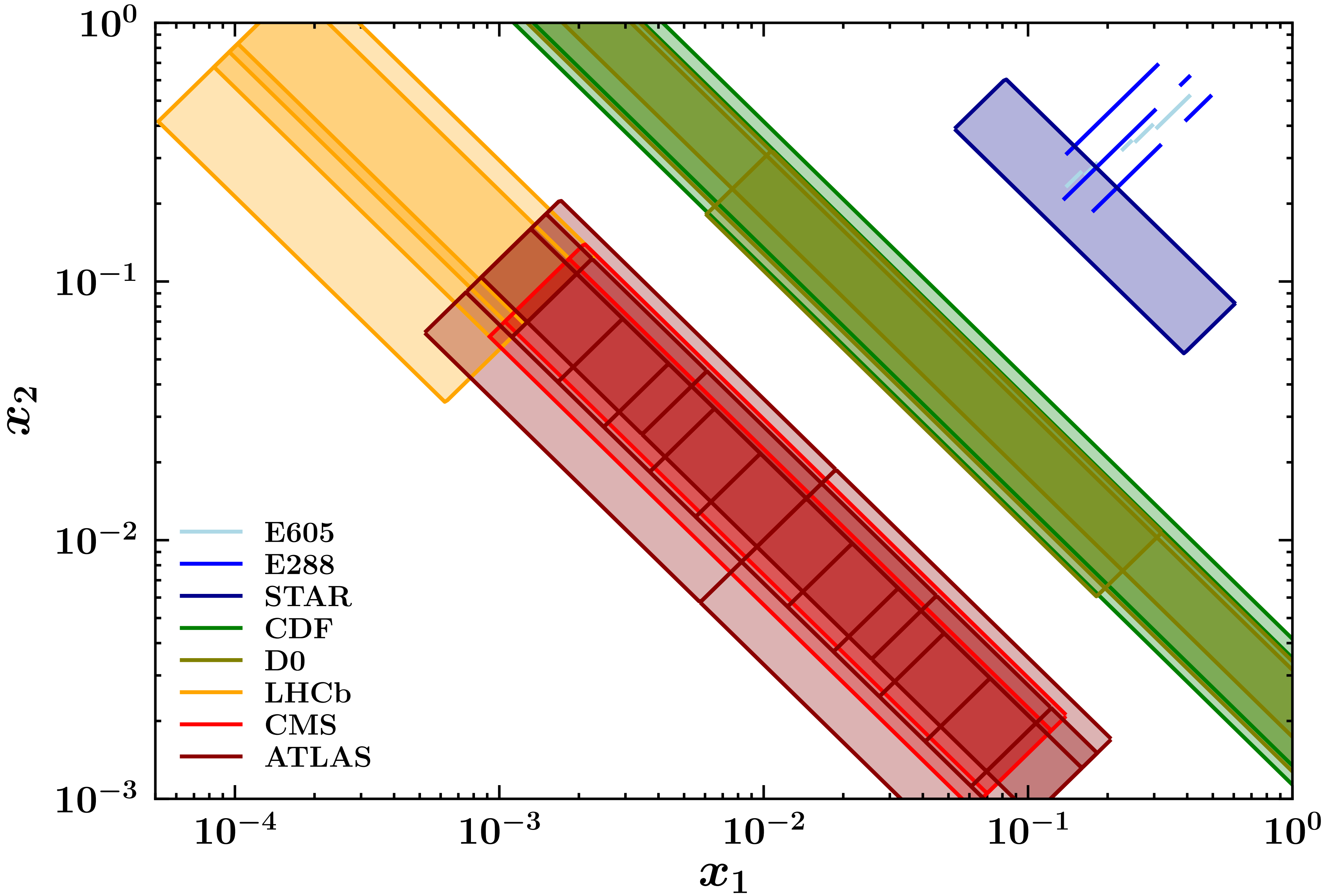
Total	353	-	-	-	-	-

Only data with $q_T/Q \leq 0.2$

DYNNLO for total σ

Experimental data



Uncertainties

Correlation matrix

$$V_{ij} = \left(\sigma^2_{i,\mathrm{stat}} + \sigma^2_{i,\mathrm{unc}}\right)\delta_{ij} + \sum_{l=1}^{k} \sigma^{(l)}_{i,\mathrm{corr}}\sigma^{(l)}_{j,\mathrm{corr}}$$

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Chi-square

$$\begin{aligned} \chi^2 &= \sum_{i,j=1}^{n} (m_i - t_i)\, V^{-1}_{ij}\, (m_j - t_j) \\ &= \sum_{i=1}^{n} \frac{1}{s_i^2} \left(m_i - t_i - \sum_{\alpha=1}^{k} \lambda_\alpha \sigma^{(\alpha)}_{i,\mathrm{corr}} \right)^2 + \sum_{\alpha=1}^{k} \lambda_\alpha^2 \end{aligned}$$

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$$s_i^2 = \sigma^2_{i,\text{stat}} + \sigma^2_{i,\text{unc}}$$

Uncertainties

Correlation matrix

$$V_{ij} = \left(\sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{unc}}^2\right)\delta_{ij} + \sum_{l=1}^{k} \sigma_{i,\mathrm{corr}}^{(l)} \sigma_{j,\mathrm{corr}}^{(l)}$$

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

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nuisance parameters

$$s_i^2 = \sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{unc}}^2$$

Uncertainties

Correlation matrix

$$V_{ij} = \left(\sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{unc}}^2\right)\delta_{ij} + \sum_{l=1}^{k} \sigma_{i,\mathrm{corr}}^{(l)} \sigma_{j,\mathrm{corr}}^{(l)}$$

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- **Minimising χ^2 with respect to λ_α —> optimal values for λ_α**

Uncertainties

Correlation matrix

$$V_{ij} = \left(\sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{unc}}^2\right)\delta_{ij} + \sum_{l=1}^{k} \sigma_{i,\mathrm{corr}}^{(l)} \sigma_{j,\mathrm{corr}}^{(l)}$$

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nuisance parameters

$$s_i^2 = \sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{unc}}^2$$

- **Minimising** χ^2 **with respect to** λ_α **—> optimal values for** λ_α
- $\sum_{\alpha=1}^{k} \lambda_\alpha \sigma_{i,corr}^{\alpha}$ **= shift induced by systematic correlated uncertainties**

Uncertainties

Correlation matrix

$$V_{ij} = \left(\sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{unc}}^2\right)\delta_{ij} + \sum_{l=1}^{k} \sigma_{i,\mathrm{corr}}^{(l)} \sigma_{j,\mathrm{corr}}^{(l)}$$

Chi-square

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$$= \sum_{i=1}^{n} \frac{1}{s_i^2} \left(m_i - t_i - \sum_{\alpha=1}^{k} \lambda_\alpha \sigma_{i,\mathrm{corr}}^{(\alpha)} \right)^2 + \sum_{\alpha=1}^{k} \lambda_\alpha^2$$

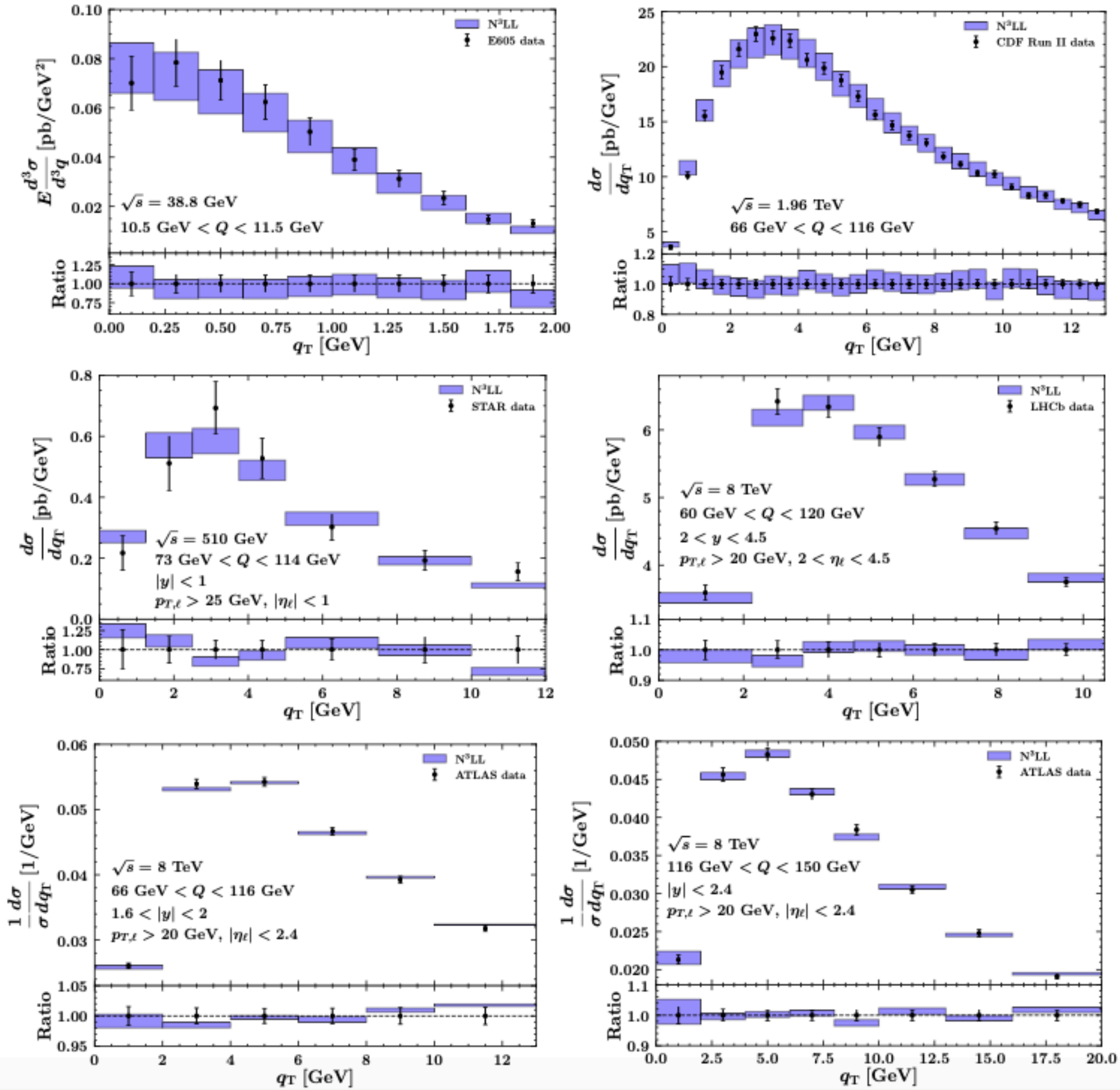
nuisance parameters

$$s_i^2 = \sigma_{i,\mathrm{stat}}^2 + \sigma_{i,\mathrm{unc}}^2$$

- **Minimising χ^2 with respect to λ_α —> optimal values for λ_α**
- $\sum_{\alpha=1}^{k} \lambda_\alpha \sigma_{i,corr}^{\alpha}$ **= shift induced by systematic correlated uncertainties**
- **By shifting theoretical predictions, $\chi^2 = \chi_D^2 + \chi_\lambda^2$ (diagonal + penalty term)**

Fit quality

Experiment		$\chi^2_D/N_{\rm dat}$	$\chi^2_\lambda/N_{\rm dat}$	$\chi^2/N_{\rm dat}$
E605	7 GeV $< Q <$ 8 GeV	0.419	0.068	0.487
	8 GeV $< Q <$ 9 GeV	0.995	0.034	1.029
	10.5 GeV $< Q <$ 11.5 GeV	0.191	0.137	0.328
	11.5 GeV $< Q <$ 13.5 GeV	0.491	0.284	0.775
	13.5 GeV $< Q <$ 18 GeV	0.491	0.385	0.877
E288 200 GeV	4 GeV $< Q <$ 5 GeV	0.213	0.649	0.862
	5 GeV $< Q <$ 6 GeV	0.673	0.292	0.965
	6 GeV $< Q <$ 7 GeV	0.133	0.141	0.275
	7 GeV $< Q <$ 8 GeV	0.254	0.014	0.268
	8 GeV $< Q <$ 9 GeV	0.652	0.024	0.676
E288 300 GeV	4 GeV $< Q <$ 5 GeV	0.231	0.555	0.785
	5 GeV $< Q <$ 6 GeV	0.502	0.204	0.706
	6 GeV $< Q <$ 7 GeV	0.315	0.063	0.378
	7 GeV $< Q <$ 8 GeV	0.056	0.030	0.086
	8 GeV $< Q <$ 9 GeV	0.530	0.017	0.547
	11 GeV $< Q <$ 12 GeV	1.047	0.167	1.215
E288 400 GeV	5 GeV $< Q <$ 6 GeV	0.312	0.065	0.377
	6 GeV $< Q <$ 7 GeV	0.100	0.005	0.105
	7 GeV $< Q <$ 8 GeV	0.018	0.011	0.029
	8 GeV $< Q <$ 9 GeV	0.437	0.039	0.477
	11 GeV $< Q <$ 12 GeV	0.637	0.036	0.673
	12 GeV $< Q <$ 13 GeV	0.788	0.028	0.816
	13 GeV $< Q <$ 14 GeV	1.064	0.044	1.107
STAR		0.782	0.054	0.836
CDF Run I		0.480	0.058	0.538
CDF Run II		0.959	0.001	0.959
D0 Run I		0.711	0.043	0.753
D0 Run II		1.325	0.612	1.937
D0 Run II (μ)		3.196	0.023	3.218
LHCb 7 TeV		1.069	0.194	1.263
LHCb 8 TeV		0.460	0.075	0.535
LHCb 13 TeV		0.735	0.020	0.755
CMS 7 TeV		2.131	0.000	2.131
CMS 8 TeV		1.405	0.007	1.412
ATLAS 7 TeV	$0 < \|y\| < 1$	2.581	0.028	2.609
	$1 < \|y\| < 2$	4.333	1.032	5.365
	$2 < \|y\| < 2.4$	3.561	0.378	3.939
ATLAS 8 TeV on-peak	$0 < \|y\| < 0.4$	1.924	0.337	2.262
	$0.4 < \|y\| < 0.8$	2.342	0.247	2.590
	$0.8 < \|y\| < 1.2$	0.917	0.061	0.978
	$1.2 < \|y\| < 1.6$	0.912	0.095	1.006
	$1.6 < \|y\| < 2$	0.721	0.092	0.814
	$2 < \|y\| < 2.4$	0.932	0.348	1.280
ATLAS 8 TeV off-peak	46 GeV $< Q <$ 66 GeV	2.138	0.745	2.883
	116 GeV $< Q <$ 150 GeV	0.501	0.003	0.504
Global		**0.88**	**0.14**	**1.02**


N³LL
E605 data
$E\frac{d^3\sigma}{d^3q}$ [pb/GeV²]
$\sqrt{s}$ = 38.8 GeV
10.5 GeV < Q < 11.5 GeV
Ratio
q_T [GeV]
N³LL
CDF Run II data
$\frac{d\sigma}{dq_T}$ [pb/GeV]
$\sqrt{s}$ = 1.96 TeV
66 GeV < Q < 116 GeV
Ratio
q_T [GeV]
N³LL
STAR data
$\frac{d\sigma}{dq_T}$ [pb/GeV]
$\sqrt{s}$ = 510 GeV
73 GeV < Q < 114 GeV
|y| < 1
$p_{T,\ell}$ > 25 GeV, $|\eta_\ell|$ < 1
Ratio
q_T [GeV]
N³LL
LHCb data
$\frac{d\sigma}{dq_T}$ [pb/GeV]
$\sqrt{s}$ = 8 TeV
60 GeV < Q < 120 GeV
2 < y < 4.5
$p_{T,\ell}$ > 20 GeV, 2 < η_ℓ < 4.5
Ratio
q_T [GeV]
N³LL
ATLAS data
$\frac{1}{\sigma}\frac{d\sigma}{dq_T}$ [1/GeV]
$\sqrt{s}$ = 8 TeV
66 GeV < Q < 116 GeV
1.6 < |y| < 2
$p_{T,\ell}$ > 20 GeV, $|\eta_\ell|$ < 2.4
Ratio
q_T [GeV]
N³LL
ATLAS data
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$\sqrt{s}$ = 8 TeV
116 GeV < Q < 150 GeV
|y| < 2.4
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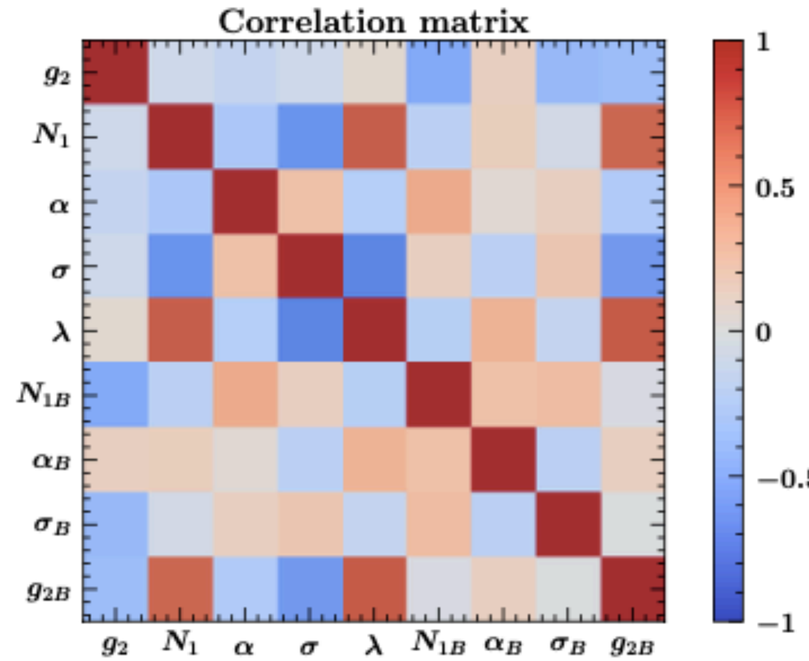
Ratio
q_T [GeV]

TMD distributions

Parameter	Value
g_2	0.036 ± 0.009
N_1	0.625 ± 0.282
α	0.205 ± 0.010
σ	0.370 ± 0.063
λ	0.580 ± 0.092
N_{1B}	0.044 ± 0.012
α_B	0.069 ± 0.009
σ_B	0.356 ± 0.075
g_{2B}	0.012 ± 0.003



- $\lambda \sim 0.5$: **gaussian and q-gaussian equally important**
- g_{2B} **(NP quartic term) small but significantly different from zero**
- **off-diagonal elements (correlations) not very large except for** λ **and** σ

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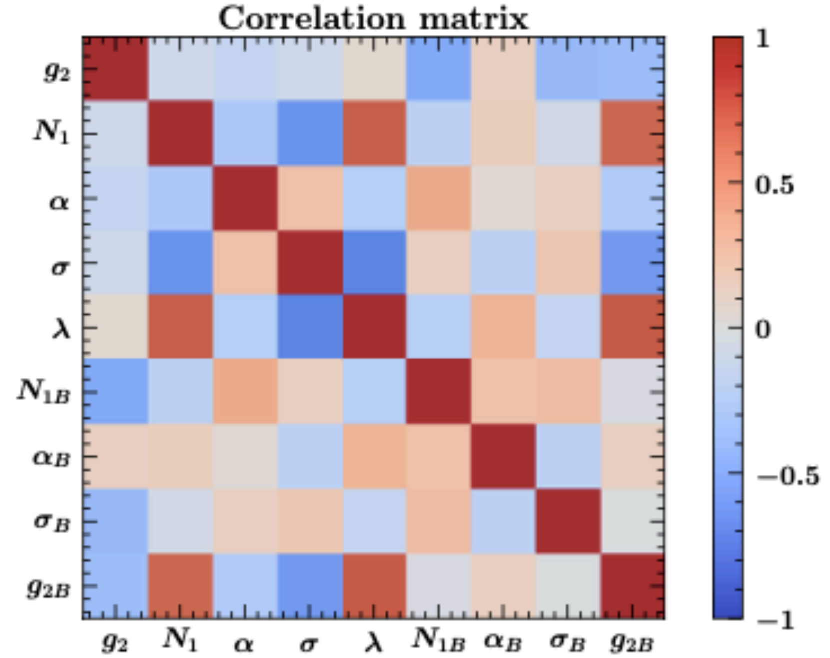

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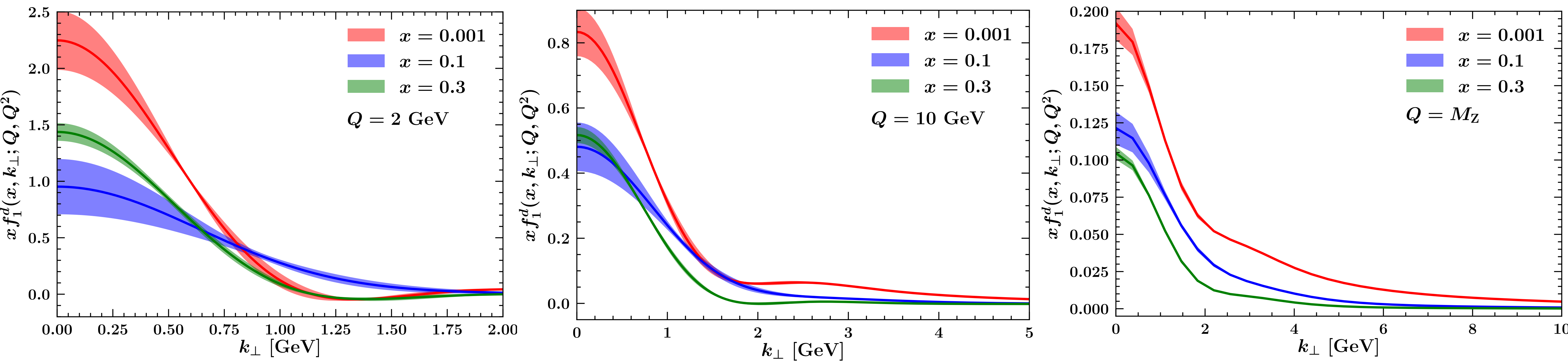
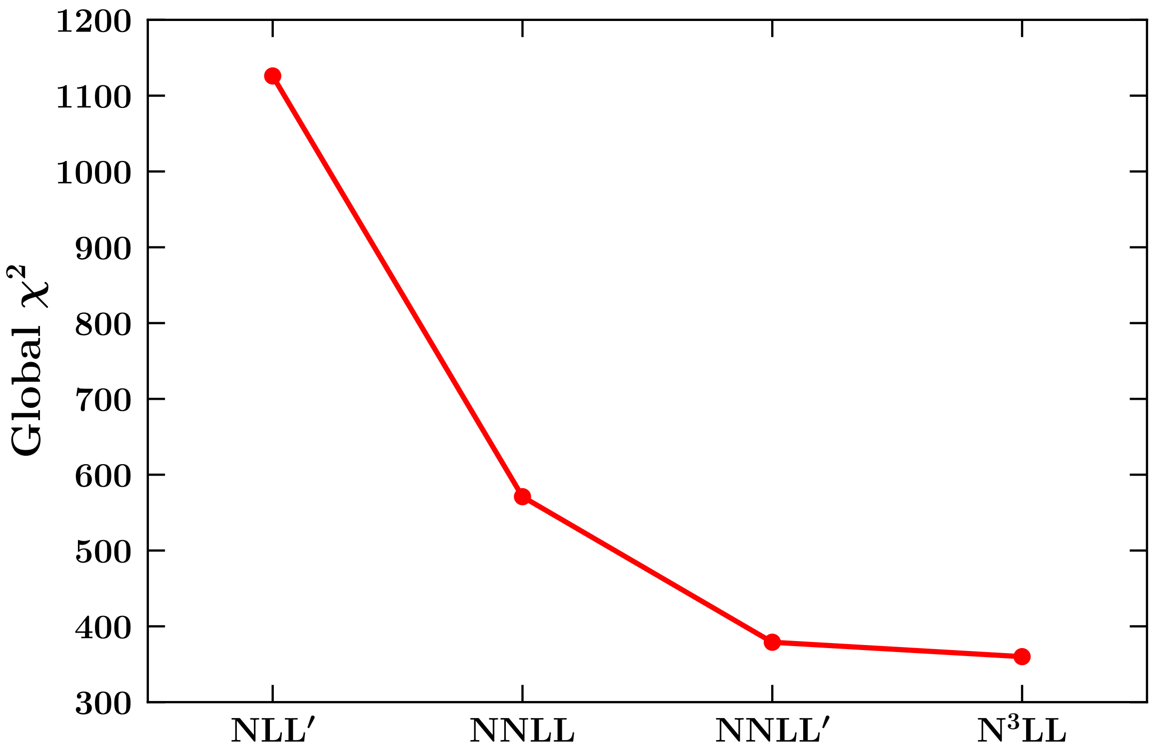
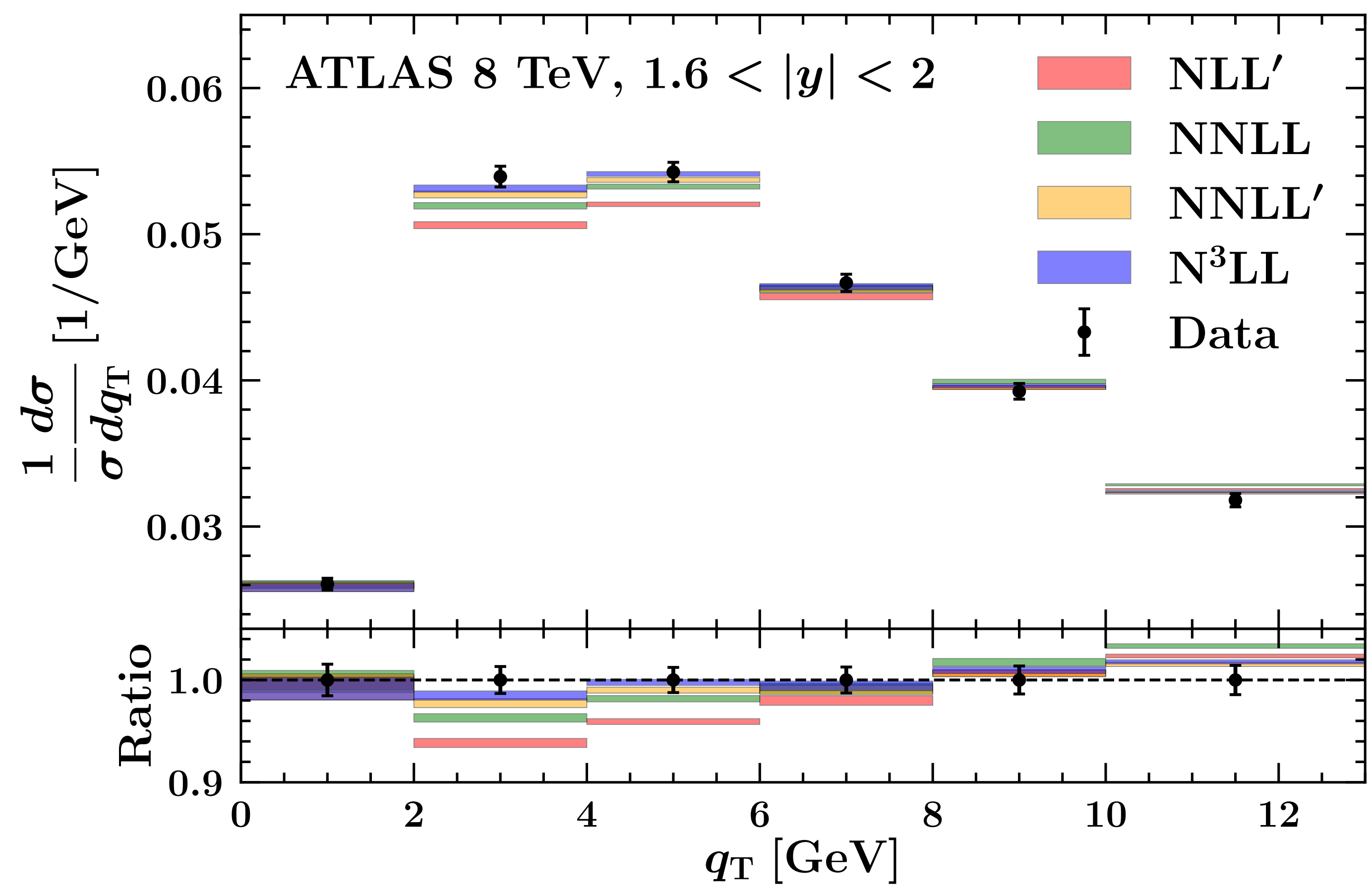


Impact of different logarithmic accuracies





Test of x-dependence

Tried a fit at N3LL with Davies, Webber, Stirling (1985) NP parameterisation:

$$f_{\rm NP}^{\rm DWS}(b_T,\zeta) = \exp\left[-\frac{1}{2}\left(g_1 + g_2\ln\left(\frac{\zeta}{2Q_0^2}\right)\right)b_T^2\right]$$

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with and without ATLAS data

	Full dataset	No y-differential data
Global $\chi^2/N_{\rm dat}$	1.339	0.895
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—> x-dependence of TMDs at N3LL driven by ATLAS data