TMD phenomenology with the **NangaParbat** code

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Factorisations

- The q_T distribution of a generic **high-mass** (Q) system produced, for example, in hadronic collisions has two main regimes:

  - for $q_\mathrm{T} \gtrsim Q$ **collinear factorisation** at *fixed perturbative order* is appropriate:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{coll.}} = \int_0^1 dx_1 \int_0^1 dx_2 f_1(x_1, Q) f_2(x_2, Q) \frac{d\hat{\sigma}}{dq_T} + \mathcal{O}\left[\left(\frac{\Lambda_{\text{QCD}}}{Q}\right)^n\right]$$

  - for $q_\mathrm{T} \ll Q$ **transverse-momentum-dependent (TMD) factorisation** at *fixed logarithmic accuracy* is appropriate:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{TMD}} = \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1, \mathbf{b}_T, Q, Q^2) F_2(x_2, \mathbf{b}_T, Q, Q^2) + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

  - Collinear and TMD factorisations may eventually be **matched** to produce accurate results over the the full q_T spectrum.

TMD factorisation

- TMD factorisation introduces two independent *artificial* scales:
  - the **renormalisation scale $\boldsymbol{\mu}$**, originating from UV renormalisation,
  - the **rapidity scale ζ**, originating from the cancellation of rapidity divergencies.
- The respective **evolution equations** are:

$$\frac{\partial \ln F}{\partial \ln \sqrt{\zeta}} = K(\mu)$$

$$\frac{\partial \ln F}{\partial \ln \mu} = \gamma_F(\alpha_s(\mu)) - \gamma_K(\alpha_s(\mu)) \ln \frac{\sqrt{\zeta}}{\mu}$$

with: $$\frac{\partial K}{\partial \ln \mu} = -\gamma_K(\alpha_s(\mu))$$

- In addition, for small b_{T}, TMDs can be matched onto coll. distributions:

$$F(\mu, \zeta) = C(\mu, \zeta) \otimes f(\mu)$$

- The solution is:

$$F(\mu,\zeta) = \exp\left\{K(\mu_0)\ln\frac{\sqrt{\zeta}}{\sqrt{\zeta_0}} + \int_{\mu_0}^{\mu}\frac{d\mu'}{\mu'}\left[\gamma_F(\alpha_s(\mu')) - \gamma_K(\alpha_s(\mu'))\ln\frac{\sqrt{\zeta}}{\mu'}\right]\right\} C(\mu_0,\zeta_0) \otimes f(\mu_0)$$

- Anomalous dims. and matching funcs. **perturbatively** computable.

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Matching onto collinear

$$F(\mu,\zeta) = C(\mu,\zeta) \otimes f(\mu)$$

- The solution is:

Evolution (Sudakov) factor

$\mu_b = b_0 / b_T$

$$F(\mu,\zeta) = \exp\left\{ K(\mu_0) \ln \frac{\sqrt{\zeta}}{\sqrt{\zeta_0}} + \int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F(\alpha_s(\mu')) - \gamma_K(\alpha_s(\mu')) \ln \frac{\sqrt{\zeta}}{\mu'} \right] \right\} C(\mu_0,\zeta_0) \otimes f(\mu_0)$$

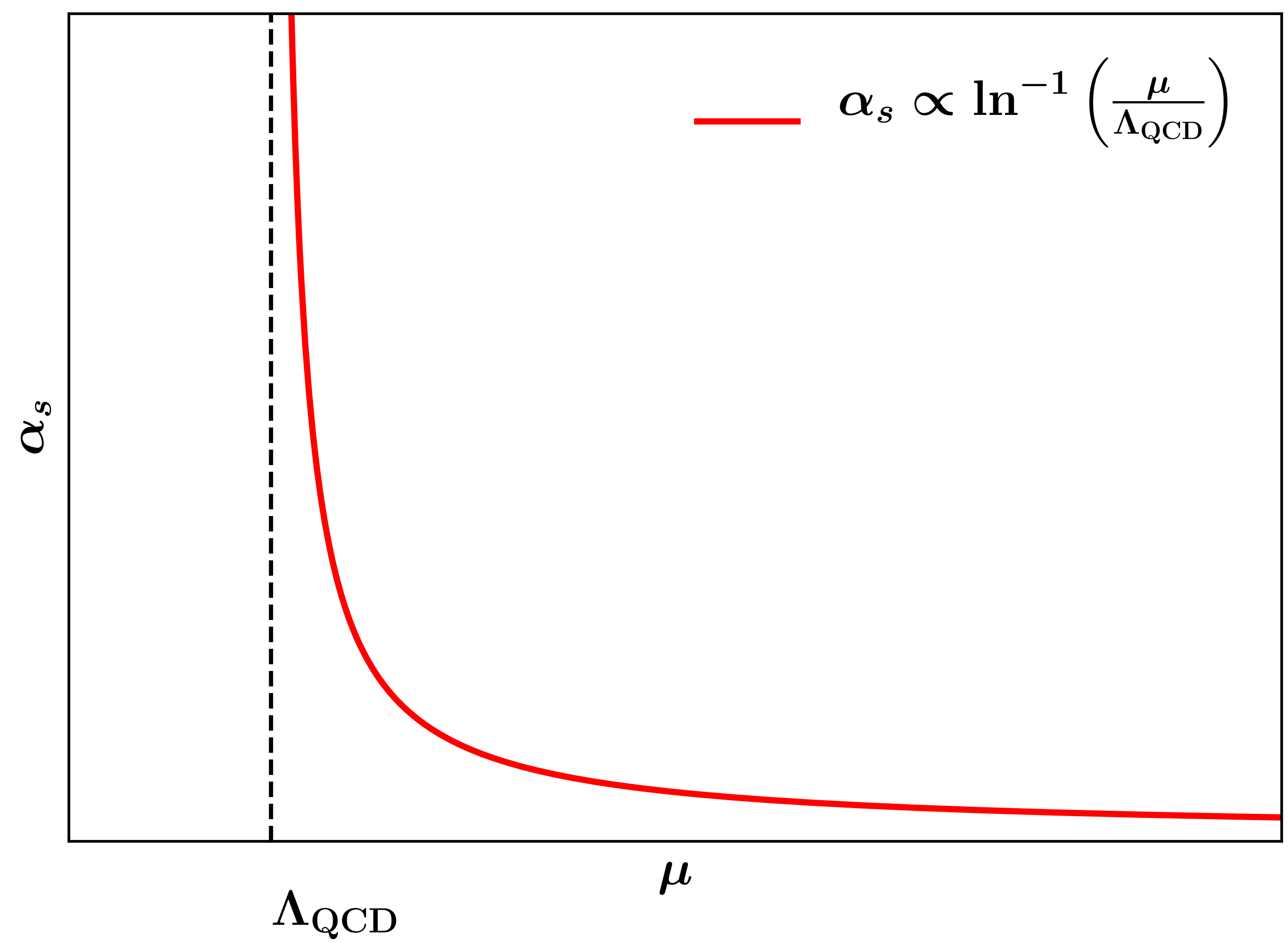
- Anomalous dims. and matching funcs. **perturbatively** computable.

TMD factorisation

- When integrating over b_T, **large values of** b_T give rise to low scales in the **non-perturbative** region:

$$\frac{d\sigma}{dq_T} \propto \int_0^\infty db_T\, \alpha_s^p\left(\frac{1}{b_T}\right)\cdots \sim \int_0^Q dk_T\, \alpha_s^p\,(k_T)\ldots$$

TMD



- Blindly integrating over the full phase space would give a **divergent** result.

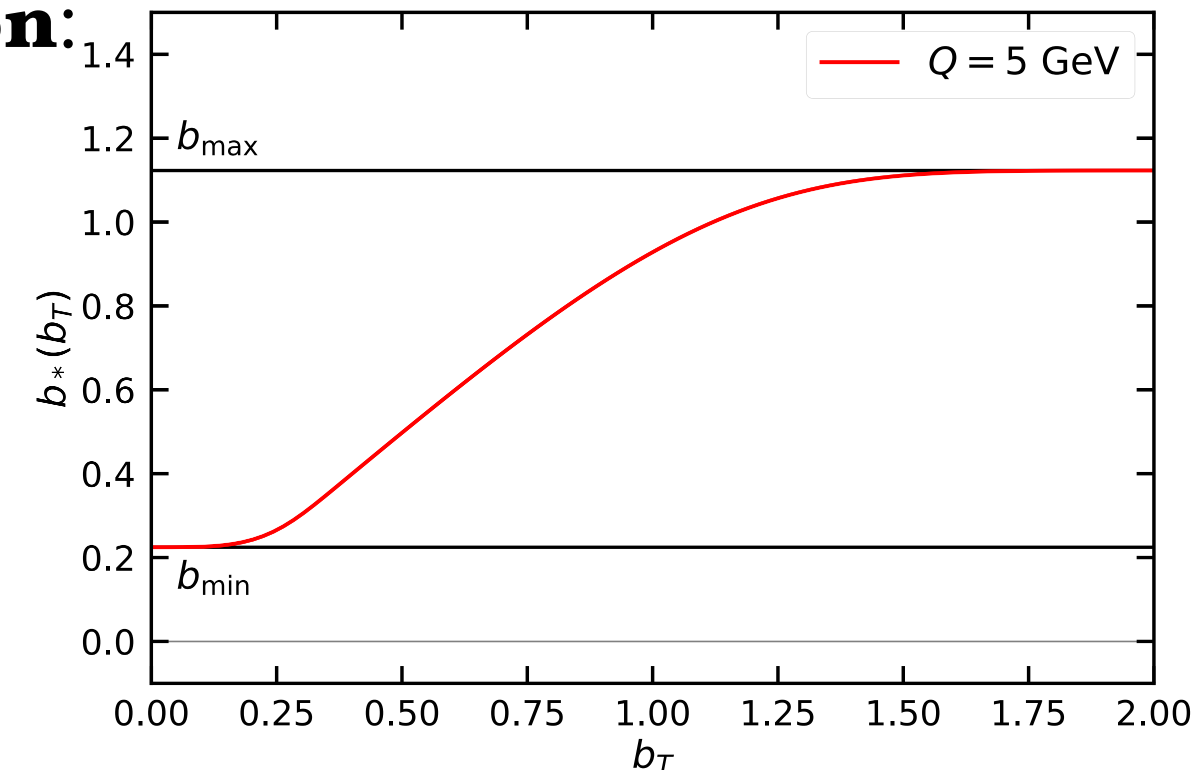
TMD factorisation

- Introduce the so-called **b*-prescription**:

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

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

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



- and rewrite (CSS approach):

$$F(x,b_T,\mu,\zeta) = \left[\frac{F(x,b_T,\mu,\zeta)}{F(x,b_*(b_T),\mu,\zeta)}\right]F(x,b_*(b_T),\mu,\zeta) \equiv f_{\rm NP}(x,b_T,\zeta)F(x,b_*(b_T),\mu,\zeta)$$

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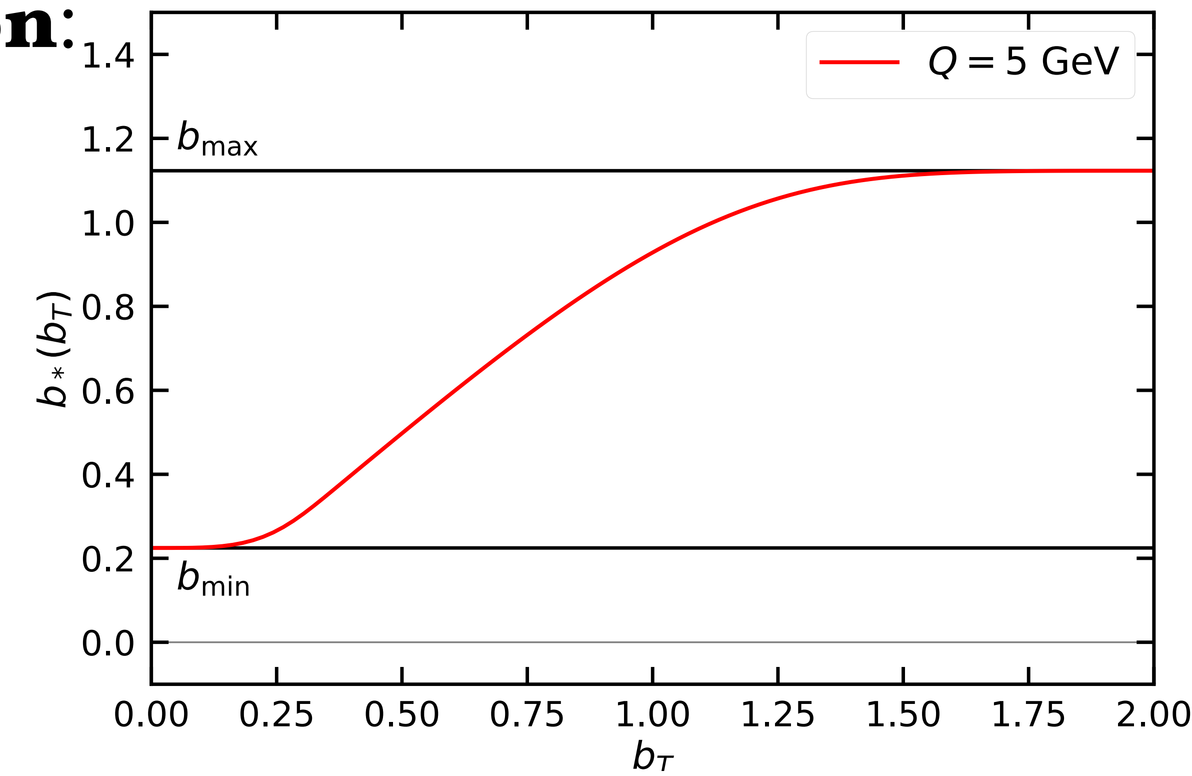

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Non-perturbative

Purely perturbative

- Properties of $f_{\rm NP}$:
  - has to go to **one** as $b_{\rm T}$ goes to zero: reproduce the fully perturbative regime,
  - has to go to **zero** as $b_{\rm T}$ becomes large: mimic the Sudakov suppression.
- Bottom line: avoidance of the non-perturbative region upon integration in $b_{\rm T}$ implies the presence of **both** b_*-prescription and $f_{\rm NP}$.

TMD factorisation

- Final expression:

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

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

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

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- matching onto the collinear region at $b_{\rm T} \ll 1/\Lambda_{\rm QCD}$,
- factorises as *hard* (perturbative) and *longitudinal* (*i.e.* collinear, non-perturbative).

TMD factorisation

- Final expression:

$$
\begin{aligned}
F_{f/P}(x, \mathbf{b}_T; \mu, \zeta) \quad = \quad & \sum_j C_{f/j}(x, b_*; \mu_b, \zeta_F) \otimes f_{j/P}(x, \mu_b) && : A \\
\times \quad & \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 \quad & \exp\left\{ g_{j/P}(x, b_T) + g_K(b_T) \ln \frac{\sqrt{\zeta_F}}{\sqrt{\zeta_{F,0}}} \right\} && : C
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- CS and RGE evolution,
- evolution to large scales,
- perturbative.

TMD factorisation

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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\} & : C
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$$

- matching onto the collinear region at $b_T \ll 1/\Lambda_{QCD}$,
- factorises as *hard* (perturbative) and *longitudinal* (*i.e.* collinear, non-perturbative).

- avoid the Landau pole through b_*,
- f_{NP} accounts for the introduction of b_*,
- f_{NP} is non-perturbative thus **fitted** to data.

- CS and RGE evolution,
- evolution to large scales,
- perturbative.

Logarithmic counting

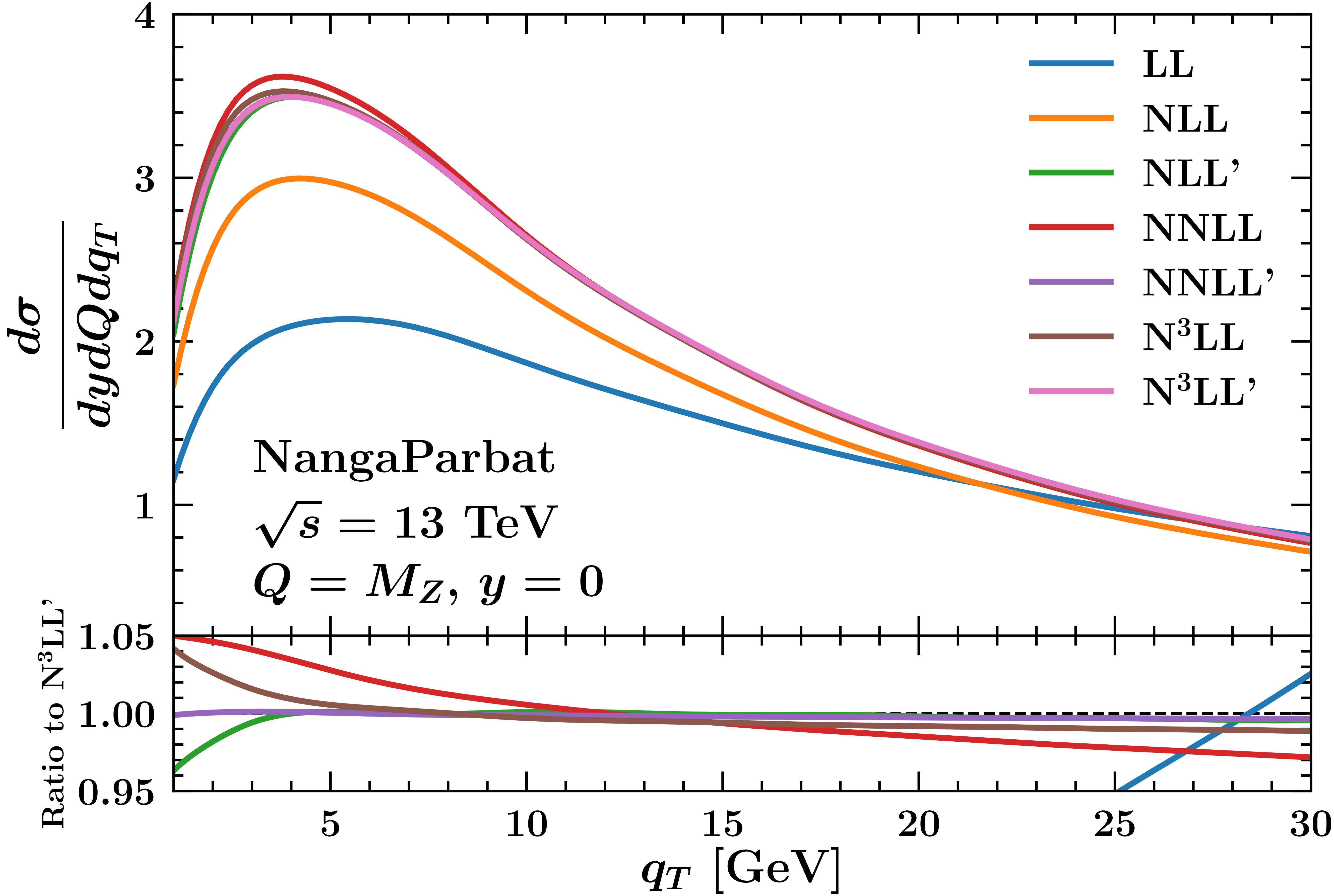
- TMD factorisation allows us to **resum large logarithms**:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{TMD}} = \sigma_0 H(Q) \int d^2\mathrm{b}_T e^{i\mathrm{b}_T\cdot\mathrm{q}_T} F_1(x_1, \mathrm{b}_T, Q, Q^2) F_2(x_2, \mathrm{b}_T, Q, Q^2)$$

$$F_f(x, \mathrm{b}_T, \mu, \zeta) = \sum_j C_{f/j}(c, b_T; \mu_b, \zeta) \otimes f_j(x, \mu_b) \times \exp\left\{K(b_T, \mu_b)\ln\frac{\sqrt{\zeta}}{\mu_b} + \int_{\mu_b}^{\mu}\frac{d\mu'}{\mu'}\left[\gamma_F - \gamma_K \ln\frac{\sqrt{\zeta}}{\mu'}\right]\right\}$$

Accuracy	γ_K	γ_F	K	$C_{f/j}$	H
LL	α_s	-	-	1	1
NLL	α_s^2	α_s	α_s	1	1
NLL’	α_s^2	α_s	α_s	α_s	α_s
N²LL	α_s^3	α_s^2	α_s^2	α_s	α_s
N²LL’	α_s^3	α_s^2	α_s^2	α_s^2	α_s^2
N³LL	α_s^4	α_s^3	α_s^3	α_s^2	α_s^2
N³LL’	α_s^4	α_s^3	α_s^3	α_s^3	α_s^3

Logarithmic counting



Matching TMD and collinear

- Accurate predictions for all q_T's by **additive matching**, order by order in perturbation theory, of collinear and TMD calculations:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{matched}} = \left(\frac{d\sigma}{dq_T}\right)_{\text{TMD}} + \left(\frac{d\sigma}{dq_T}\right)_{\text{coll.}} - \left(\frac{d\sigma}{dq_T}\right)_{\text{d.c.}}$$

- In order for the match to actually take place:

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{TMD}} \xrightarrow[\text{f.o.}]{} \left(\frac{d\sigma}{dq_T}\right)_{\text{d.c.}} \xleftarrow[q_T \ll Q]{} \left(\frac{d\sigma}{dq_T}\right)_{\text{coll.}}$$

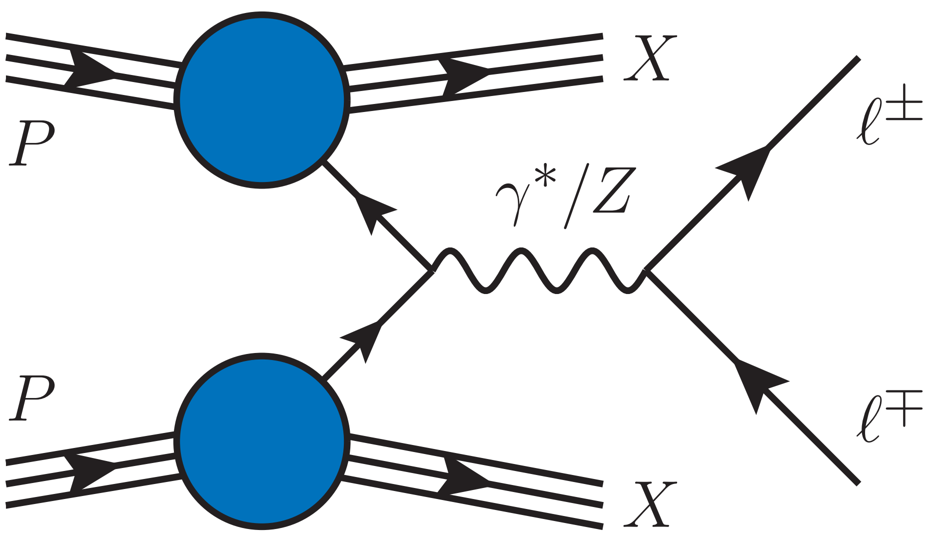
- Therefore, the "fixed-order" parts have to match in the relevant limits:

Logarithmic accuracy	Minimal f.o. accuracy
NLL'	α_s (LO)
N^2LL	α_s (LO)
N^2LL'	α_s^2 (NLO)
N^3LL	α_s^2 (NLO)
N^3LL'	α_s^3 (NNLO)

Factorising processes

- Processes for which leading-power factorisation has been **proven**:

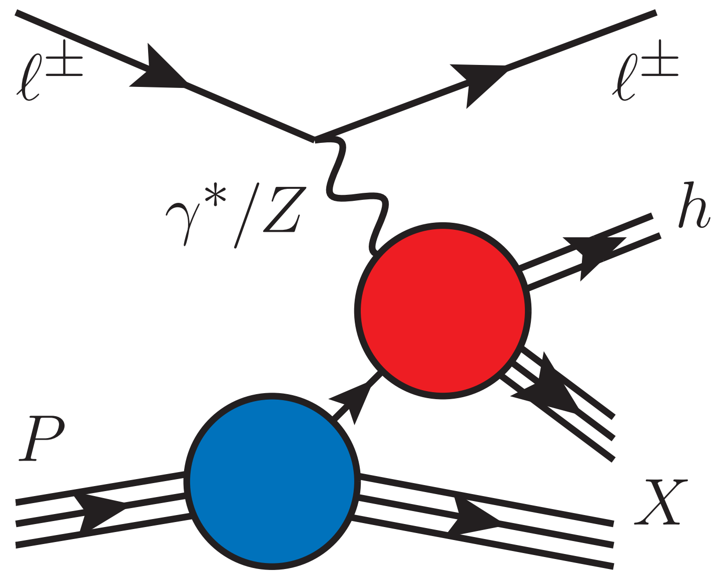
Drell-Yan



$PP \longrightarrow \ell^\pm \ell^\mp X$

- **Two PDFs**:
- Lots of data:
  - low-energy: FNAL,
  - mid-energy: RHIC,
  - high-energy: Tevatron, LHC.

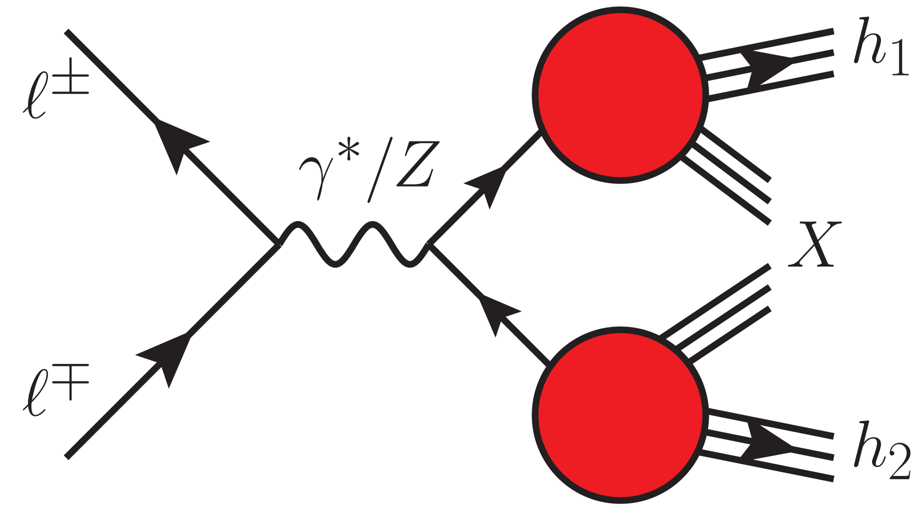
Semi-inclusive DIS



$P\ell^\pm \longrightarrow \ell^\pm h\ X$

- One **PDF** and one **FF**:
- many precise data points:
  - HERMES at DESY,
  - COMPASS at CERN.

e^+e^- annihilation



$\ell^\pm \ell^\mp \to h_1 h_2\ X$

- **Two FFs**:
- di-hadron prod. from:
  - BELLE at KEK,
  - BABAR at SLAC.

A framework for TMD analyses

NangaParbat

- Public implementation of TMD factorisation and CSS formalism:
  - **Drell-Yan** with fiducial cuts operative,
  - validating **semi-inclusive DIS**.
- Main focus on fast and accurate computations aimed at TMD fits:
  - exploitation of **interpolation** techniques.

https://github.com/MapCollaboration/NangaParbat

Nanga Parbat: a TMD fitting framework

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

A framework for TMD analyses

NangaParbat

- The numerical computation of a cross section can be reduced to:

$$\left(\frac{d\sigma}{dq_T}\right)_{\rm TMD} \simeq \sum_{n,\alpha,\tau} W_{n\alpha\tau} f_{\rm NP}^{(1)}(x_1^{(\alpha,\tau)}, b_T^{(n)}, \zeta^{(\tau)}) f_{\rm NP}^{(2)}(x_2^{(\alpha,\tau)}, b_T^{(n)}, \zeta^{(\tau)})$$

- The weights W can be **precomputed** and **stored**:
  - perturbative ingredients,
  - non-perturbative ingredients: collinear distributions and Landau pole regularisation,
  - integration over the final-state phase space including fiducial cuts.
- The cross section is thus obtained by "convoluting" the weights with the non-perturbative function(s) $f_{\rm NP}$:
  - **fast computation** that can thus be used during a fit.

Pavia 2019 (PV19): the settings

[Bacchetta *et al.*, *JHEP* 07 (2020) 117, arXiv:1912.07550]

- Functional form of the non-perturbative function:

$$f_{\rm NP}(x, b_T, \zeta) = \left[\frac{1-\lambda}{1+g_1(x)\frac{b_T^2}{4}} + \lambda \exp\left(-g_{1B}(x)\frac{b_T^2}{4}\right)\right] \exp\left[-\left(g_2 + g_{2B} b_T^2\right) \ln\left(\frac{\zeta}{Q_0^2}\right) \frac{b_T^2}{4}\right]$$

$$g_1(x) = \frac{N_1}{x\sigma} \exp\left[-\frac{1}{2\sigma^2} \ln^2\left(\frac{x}{\alpha}\right)\right] \quad \text{and} \quad g_{1B}(x) = \frac{N_{1B}}{x\sigma_B} \exp\left[-\frac{1}{2\sigma_B^2} \ln^2\left(\frac{x}{\alpha_B}\right)\right]$$

  - a total of 9 free parameters.
- Complete treatment of the experimental uncertainties:
  - **correlated** systematics (additive and multiplicative) properly treated,
  - uncertainties deriving from **collinear PDFs** also included.
- Fits using all the available perturbative orders: **from NLL to N^{3}LL**.
- **Full integration** over q_T, Q and y when required:
  - no narrow-width nor "middle-point" approximations.
- No *ad hoc* **normalisation**:
  - fit both shape and normalisation.
- **Monte Carlo** method for the experimental error propagation.

PV19 fit: Drell-Yan data

Fixed target

RHIC

Tevatron

LHC

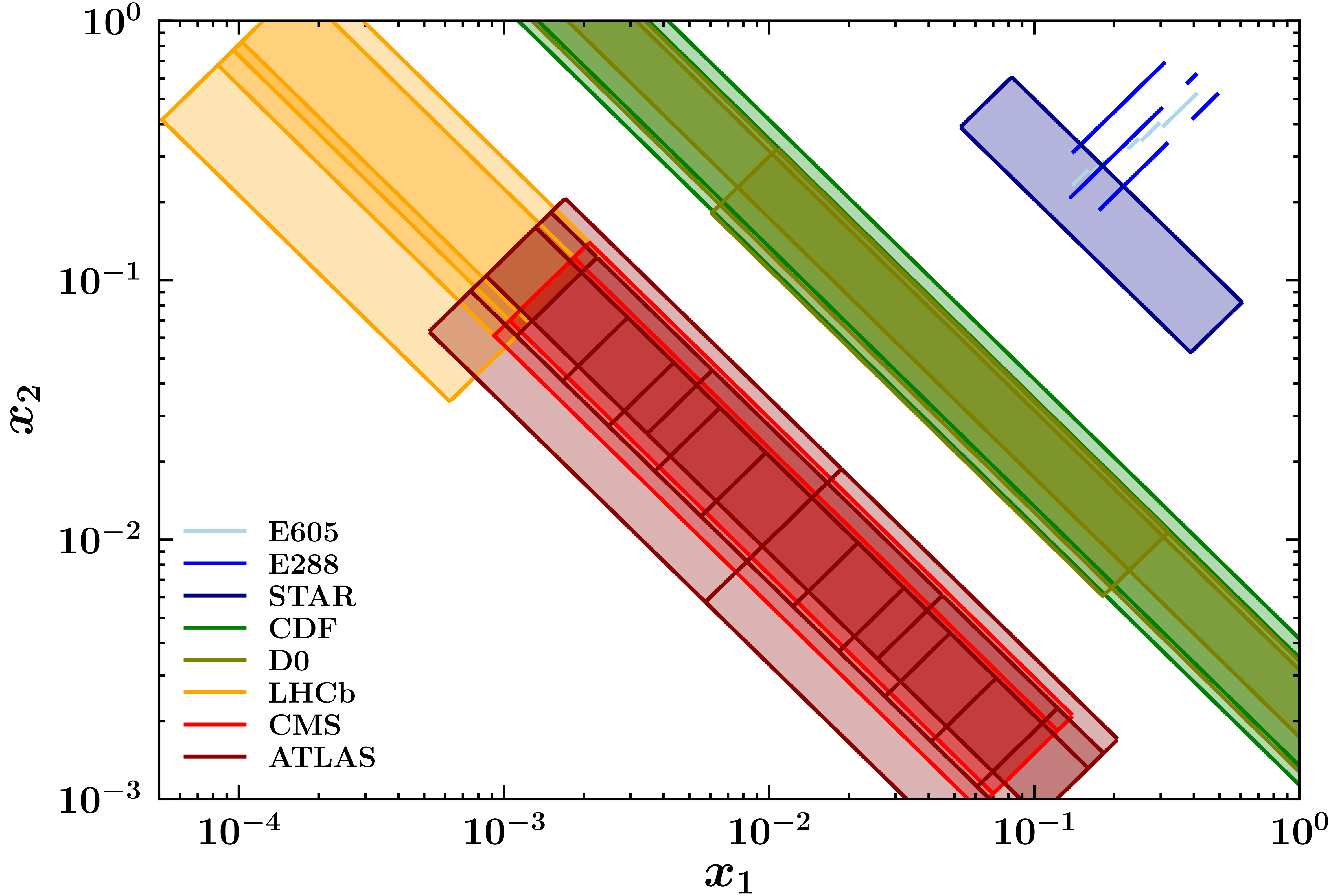
Experiment	$N_{\rm dat}$	Observable	$\sqrt{s}$ [GeV]	Q [GeV]	y or x_F	Lepton cuts	Ref.
E605	50	$Ed^3\sigma/d^3q$	38.8	7 - 18	$x_F = 0.1$	-	[79]
E288 200 GeV	30	$Ed^3\sigma/d^3q$	19.4	4 - 9	$y = 0.40$	-	[80]
E288 300 GeV	39	$Ed^3\sigma/d^3q$	23.8	4 - 12	$y = 0.21$	-	[80]
E288 400 GeV	61	$Ed^3\sigma/d^3q$	27.4	5 - 14	$y = 0.03$	-	[80]
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	-	[81]
CDF Run II	26	$d\sigma/dq_T$	1960	66 - 116	Inclusive	-	[82]
D0 Run I	12	$d\sigma/dq_T$	1800	75 - 105	Inclusive	-	[83]
D0 Run II	5	$(1/\sigma)d\sigma/dq_T$	1960	70 - 110	Inclusive	-	[84]
D0 Run II (μ)	3	$(1/\sigma)d\sigma/dq_T$	1960	65 - 115	$\|y\| < 1.7$	$p_{T\ell} > 15$ GeV $\|\eta_\ell\| < 1.7$	[85]
LHCb 7 TeV	7	$d\sigma/dq_T$	7000	60 - 120	$2 < y < 4.5$	$p_{T\ell} > 20$ GeV $2 < \eta_\ell < 4.5$	[86]
LHCb 8 TeV	7	$d\sigma/dq_T$	8000	60 - 120	$2 < y < 4.5$	$p_{T\ell} > 20$ GeV $2 < \eta_\ell < 4.5$	[87]
LHCb 13 TeV	7	$d\sigma/dq_T$	13000	60 - 120	$2 < y < 4.5$	$p_{T\ell} > 20$ GeV $2 < \eta_\ell < 4.5$	[92]
CMS 7 TeV	4	$(1/\sigma)d\sigma/dq_T$	7000	60 - 120	$\|y\| < 2.1$	$p_{T\ell} > 20$ GeV $\|\eta_\ell\| < 2.1$	[88]
CMS 8 TeV	4	$(1/\sigma)d\sigma/dq_T$	8000	60 - 120	$\|y\| < 2.1$	$p_{T\ell} > 15$ GeV $\|\eta_\ell\| < 2.1$	[89]
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 $\|\eta_\ell\| < 2.4$	[93]
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 $\|\eta_\ell\| < 2.4$	[90]
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 $\|\eta_\ell\| < 2.4$	[90]
Total	353	-	-	-	-	-	-

[Bacchetta *et al.*, *JHEP* 07 (2020) 117, arXiv:1912.07550]

- Only data with $q_T / Q < 0.2$ (TMD factorisation region).

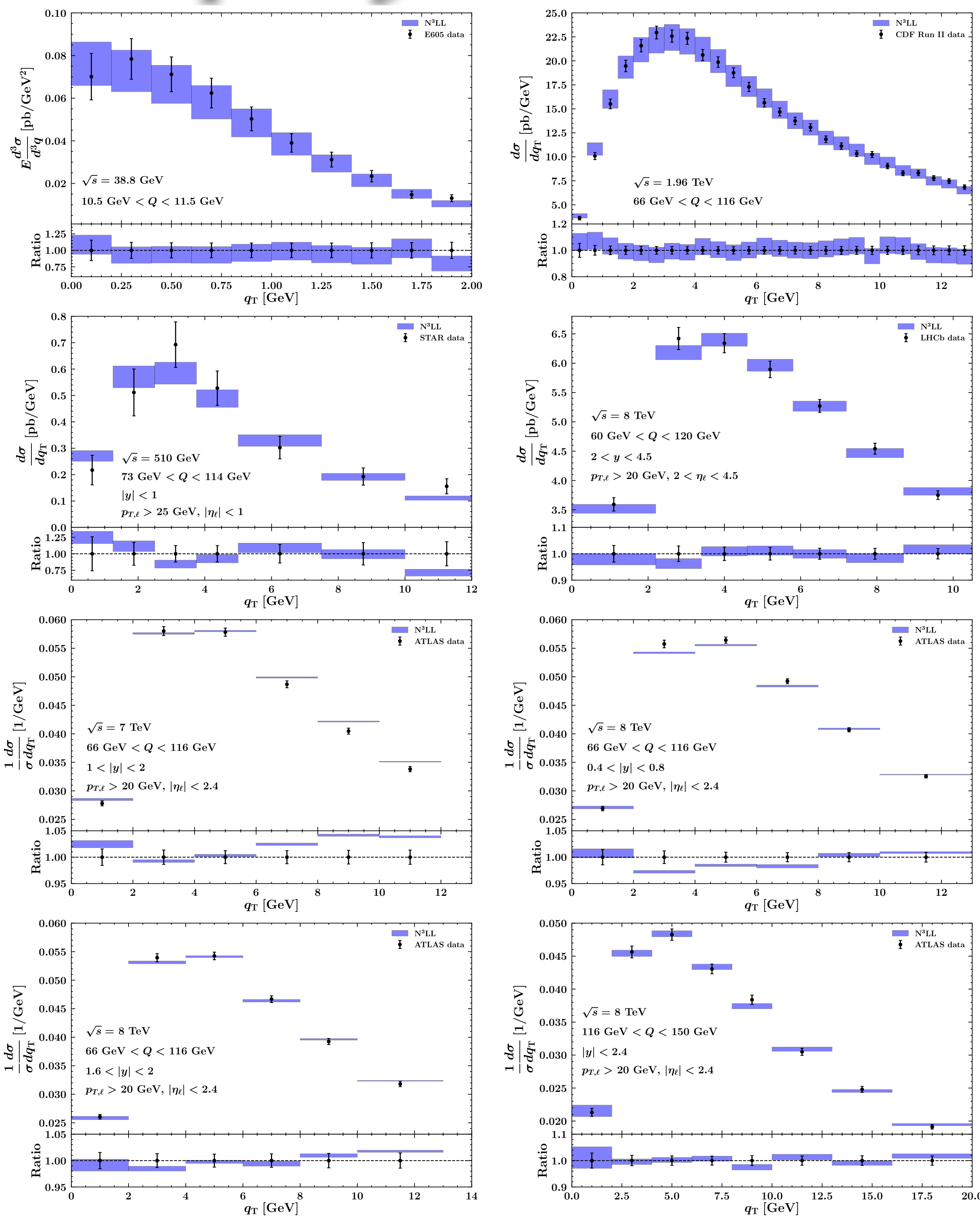
PV19 fit: Drell-Yan data

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{TMD}} = \sigma_0 H(Q) \int d^2\mathbf{b}_T e^{i\mathbf{b}_T\cdot\mathbf{q}_T} F_1(x_1, \mathbf{b}_T, Q, Q^2) F_2(x_2, \mathbf{b}_T, Q, Q^2)$$



PV19 fit

Fit quality at N^3LL



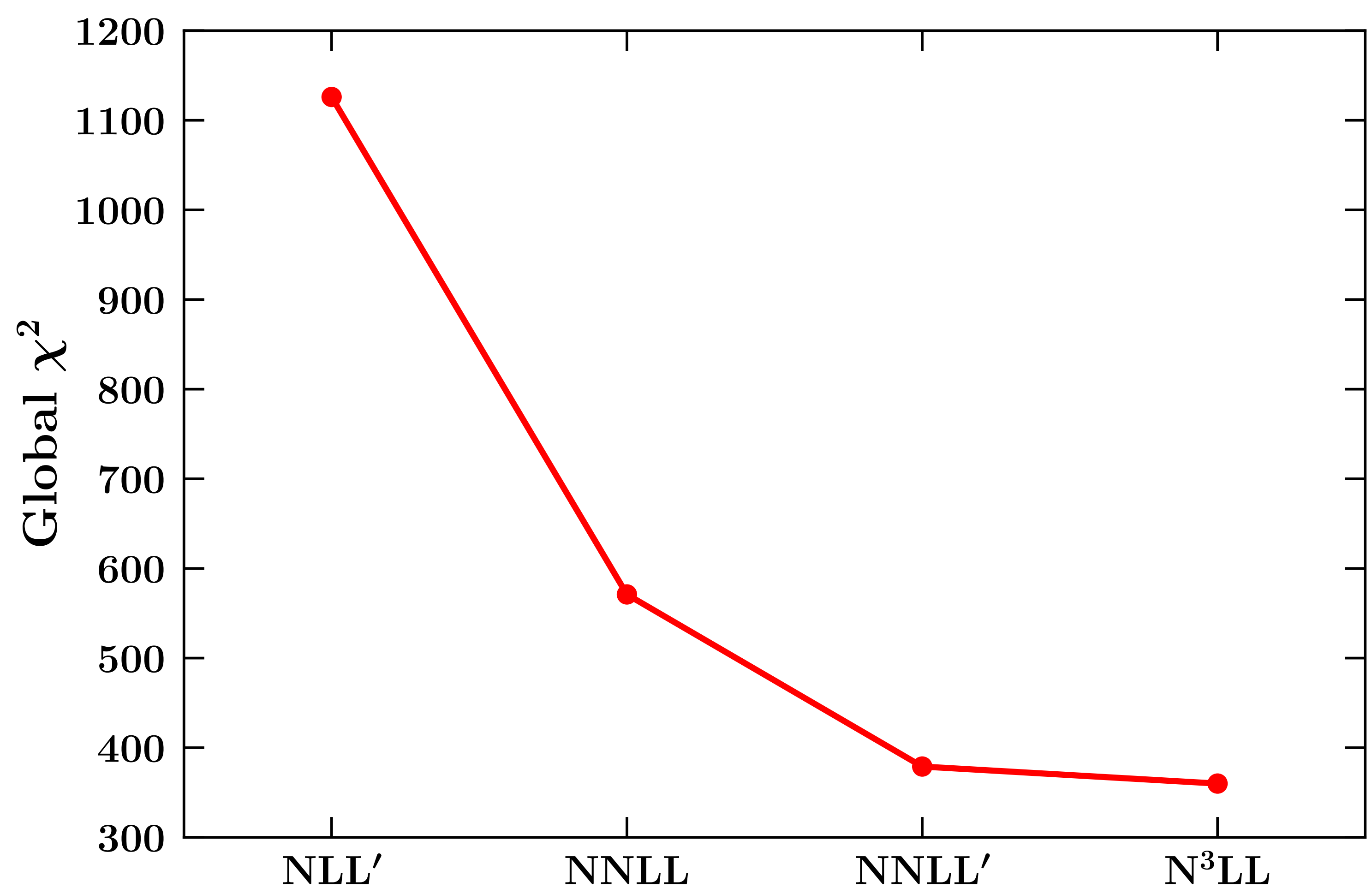
Experiment		$\chi^2_D/N_{\rm dat}$	$\chi^2_\lambda/N_{\rm dat}$	$\chi^2/N_{\rm dat}$
E605	7 GeV $< Q <$ 8 GeV	0.419	0.068	0.487
	8 GeV $< Q <$ 9 GeV	0.995	0.034	1.029
	10.5 GeV $< Q <$ 11.5 GeV	0.191	0.137	0.328
	11.5 GeV $< Q <$ 13.5 GeV	0.491	0.284	0.775
	13.5 GeV $< Q <$ 18 GeV	0.491	0.385	0.877
E288 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**

PV19 fit
Perturbative convergence

- Global χ^2 as a function of the perturbative accuracy:

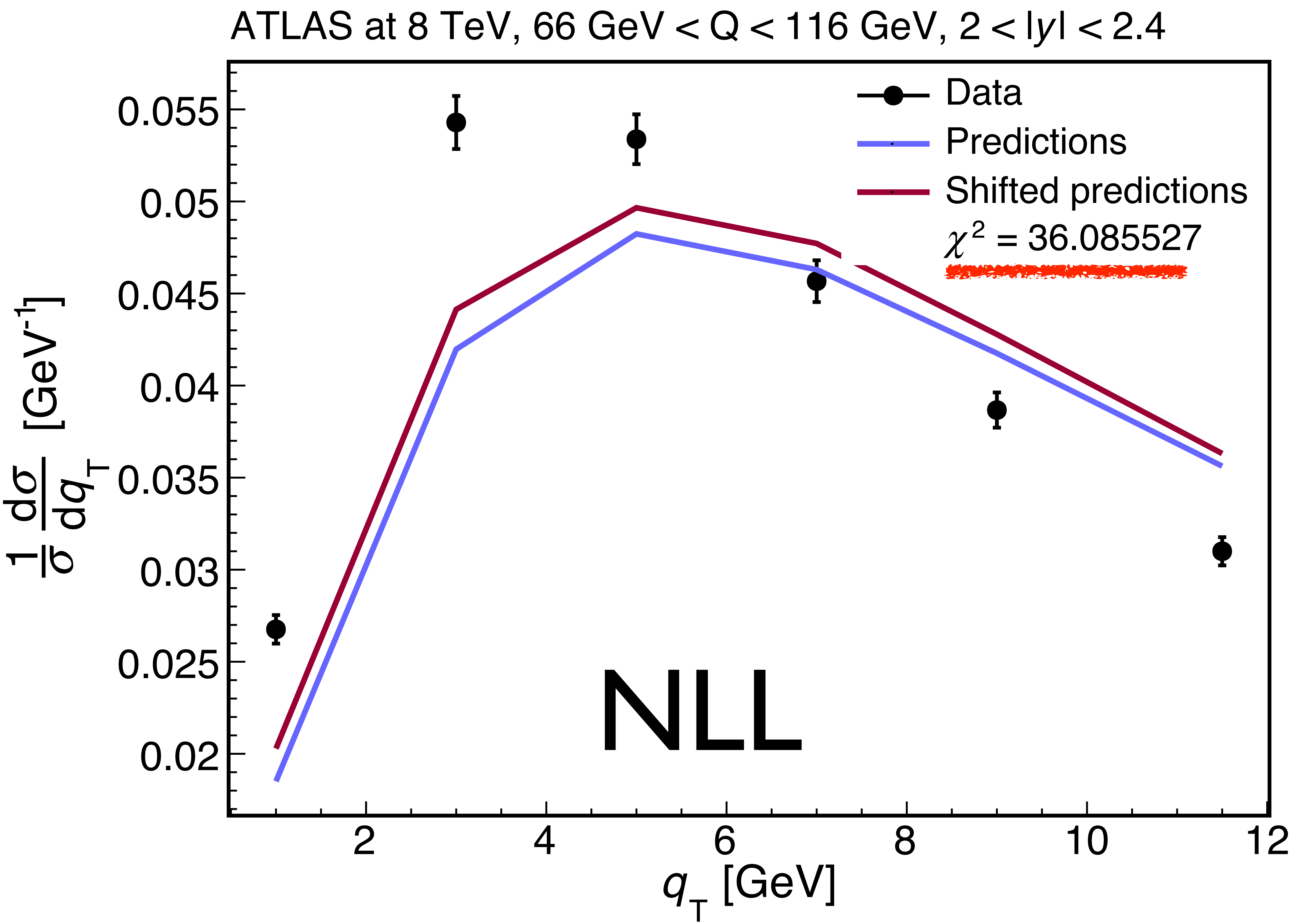
Order	**NLL**	**NLL'**	**NNLL**	**NNLL'**	**N^{3}LL**
χ^2 **/ n.d.p.**	**~20**	**3.19**	**1.62**	**1.07**	**1.02**

- Clear perturbative **convergence**.



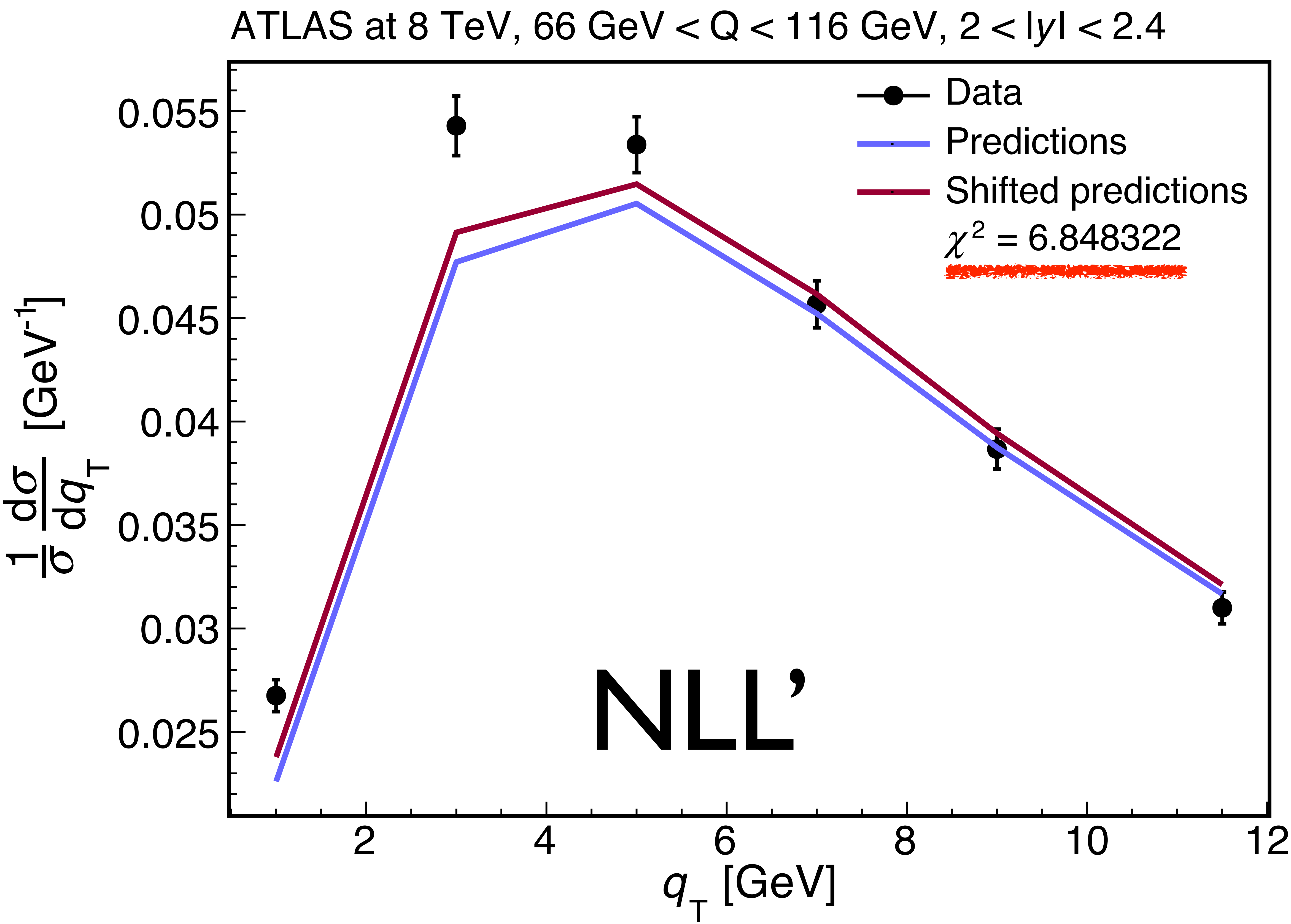
PV19 fit

Perturbative convergence



PV19 fit

Perturbative convergence



PV19 fit

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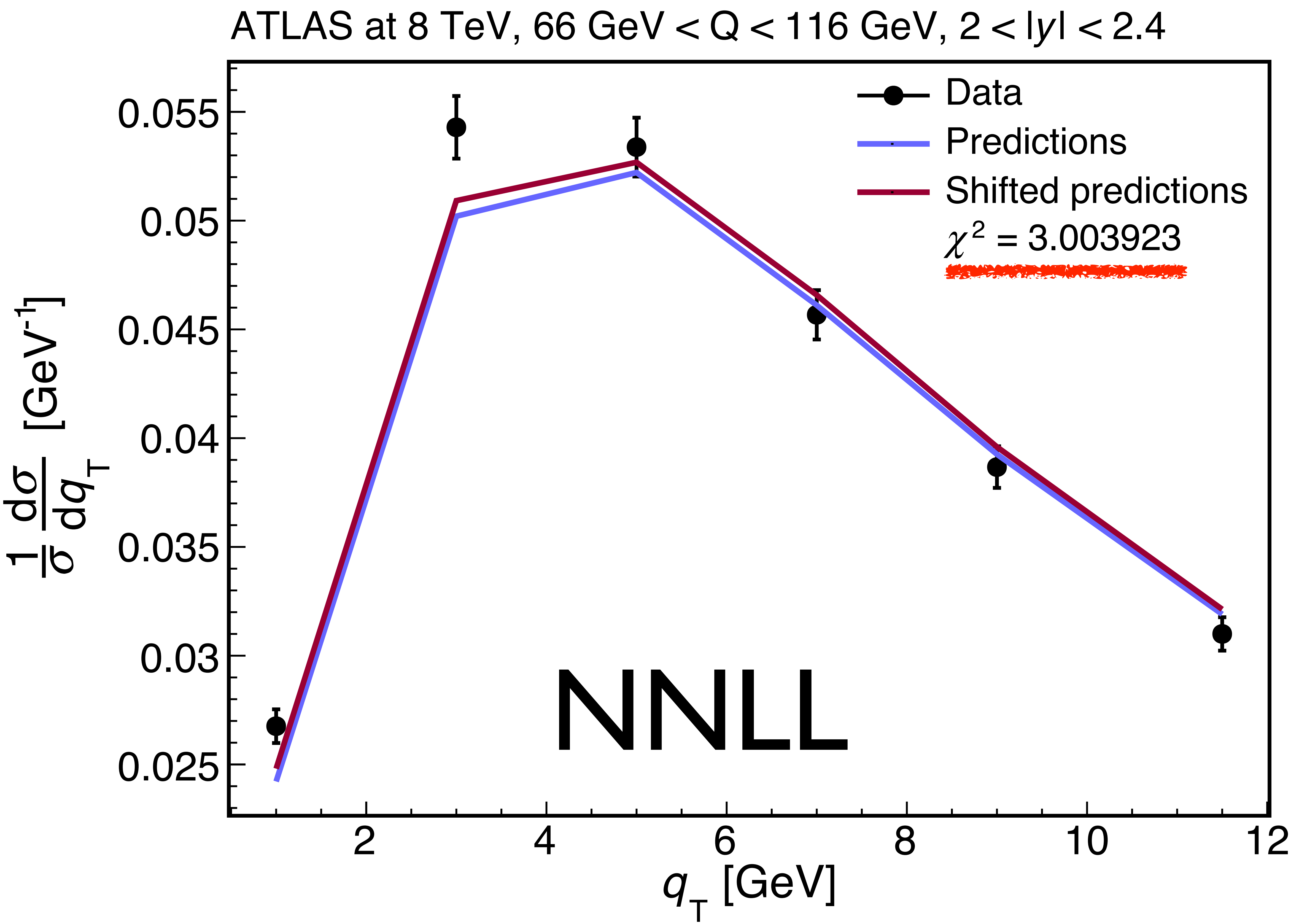

PV19 fit

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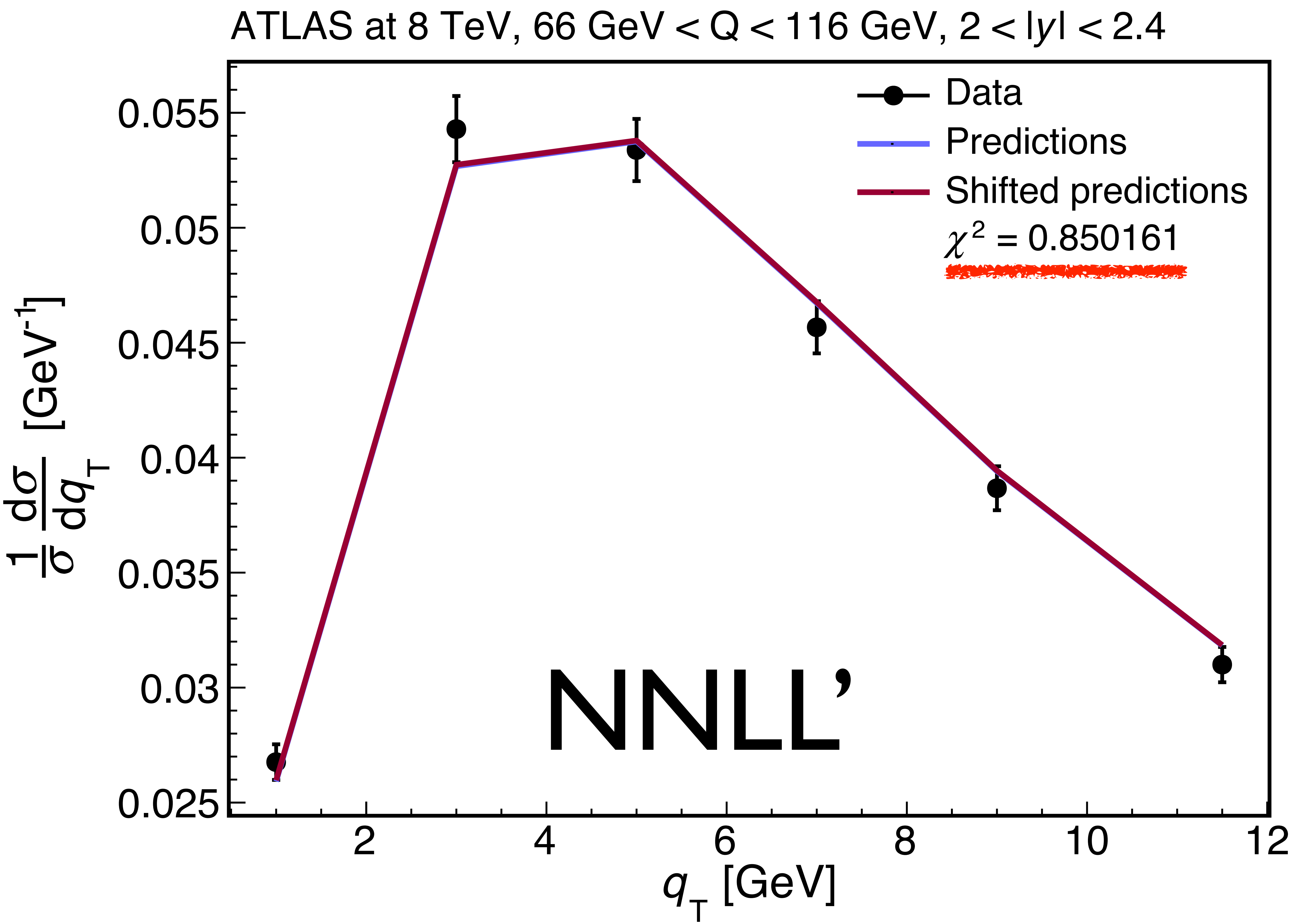
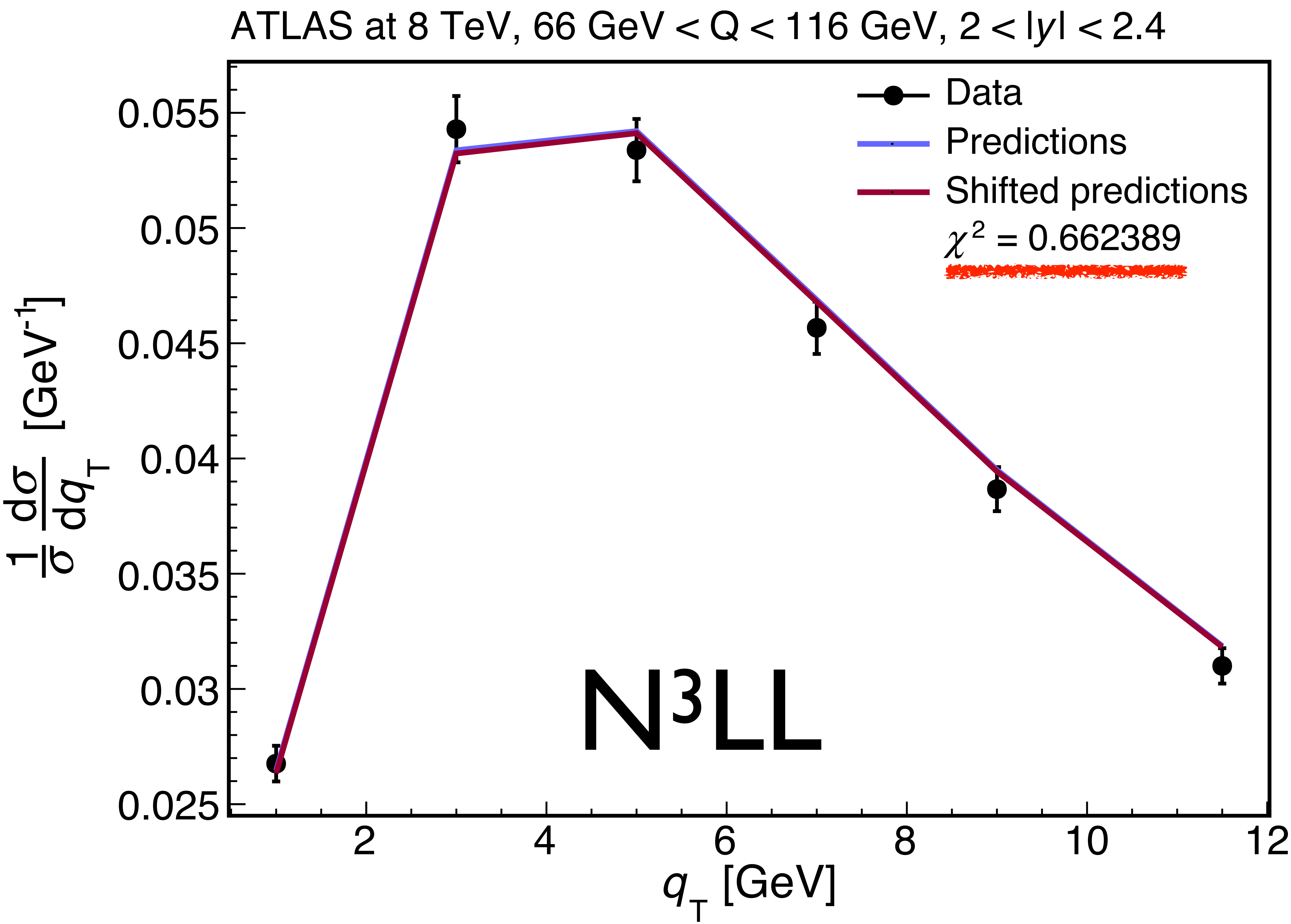


PV19 fit

Perturbative convergence



Recent results

The LHC electroweak precision working group

- ***W* mass** measurement now possible to increasing precision at the LHC, **utilises *Z* q_{T} spectrum**.
- Necessitates increased accuracy in theory predictions - many development in this area.
- Sudakov **double** logarithms ($L = \ln(Q^2/q_{\mathrm{T}}^2)$) are left over from the cancellation of IR divergences.
- At low q_{T}, $\alpha_S L^2 \sim 1$, perturbative expansion breaks down $\Rightarrow$ **resummation**.

$$\frac{d\sigma}{dq_{\mathrm{T}}} \underset{q_{\mathrm{T}}\to 0}{\simeq} 1 + \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \ldots$$

- Resum these large logs up to given order - Possible up to **N^{3}LL**.
- **Many different approaches** - the goal is to compare them to understand their **differences**, **uncertainties** and **accuracy**.

Recent results

The LHC electroweak precision working group

Groups and Codes involved

- q_T resummation
  - DYRes/DYTURBO — Camarda et al., '19
  - reSolve — Coradeschi, T.C., '17
- TMD
  - NangaParbat — Bacchetta et al., '19
  - arTeMiDe — Scimemi, Vladimirov, '17
- SCET
  - SCETLib — Ebert et al. '17
  - (CuTe) — Becher et al. '11,'20
- Parton Shower-like/Branching
  - RadISH — Monni et al. '16,'17
  - (PB–TMD) — Martinez et al. '20

Many groups, well spread across the several different approaches.

[T. Cridge, https://indico.cern.ch/event/961431/]

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q_T resummation	
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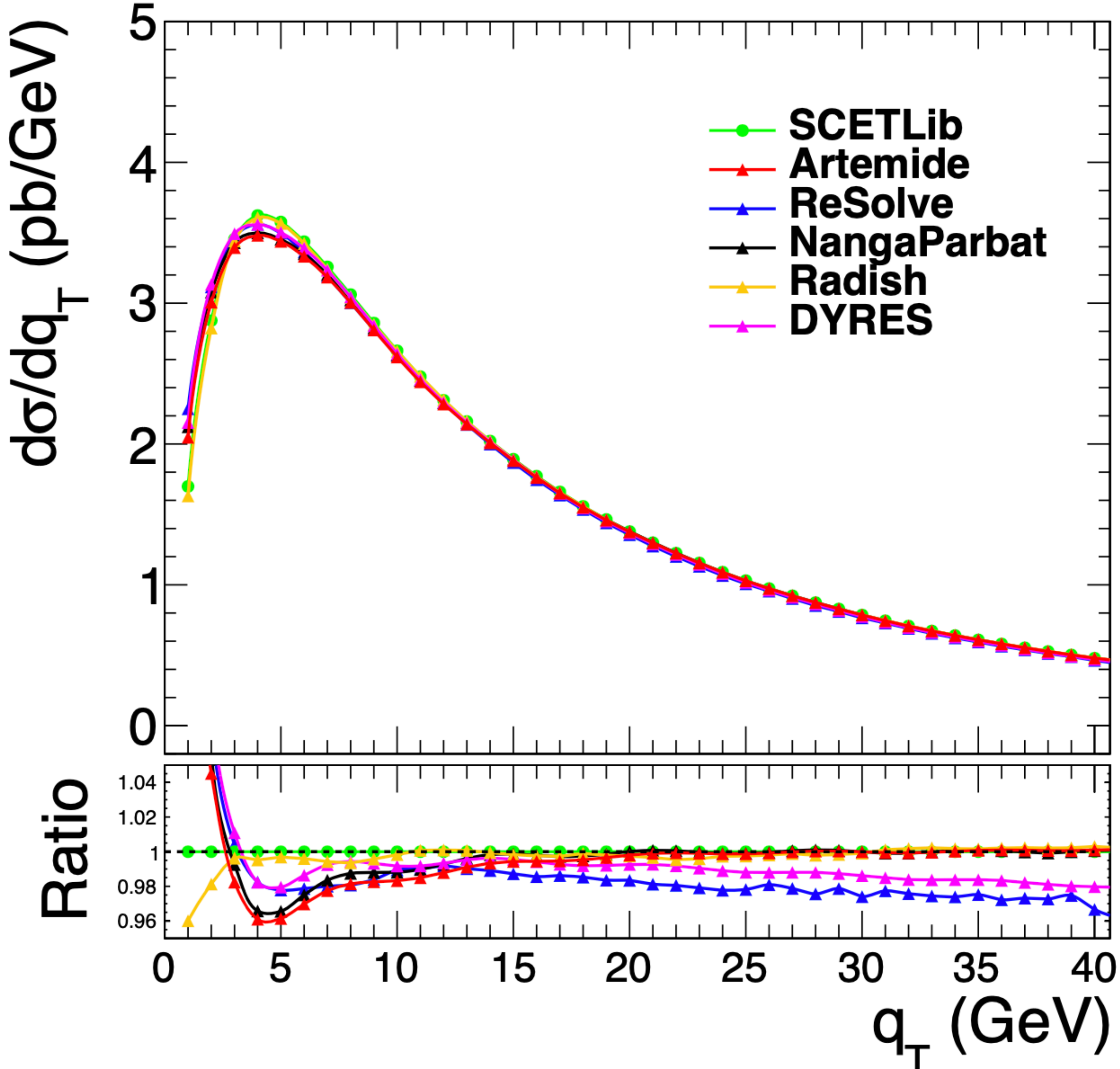
Recent results

The LHC electroweak precision working group

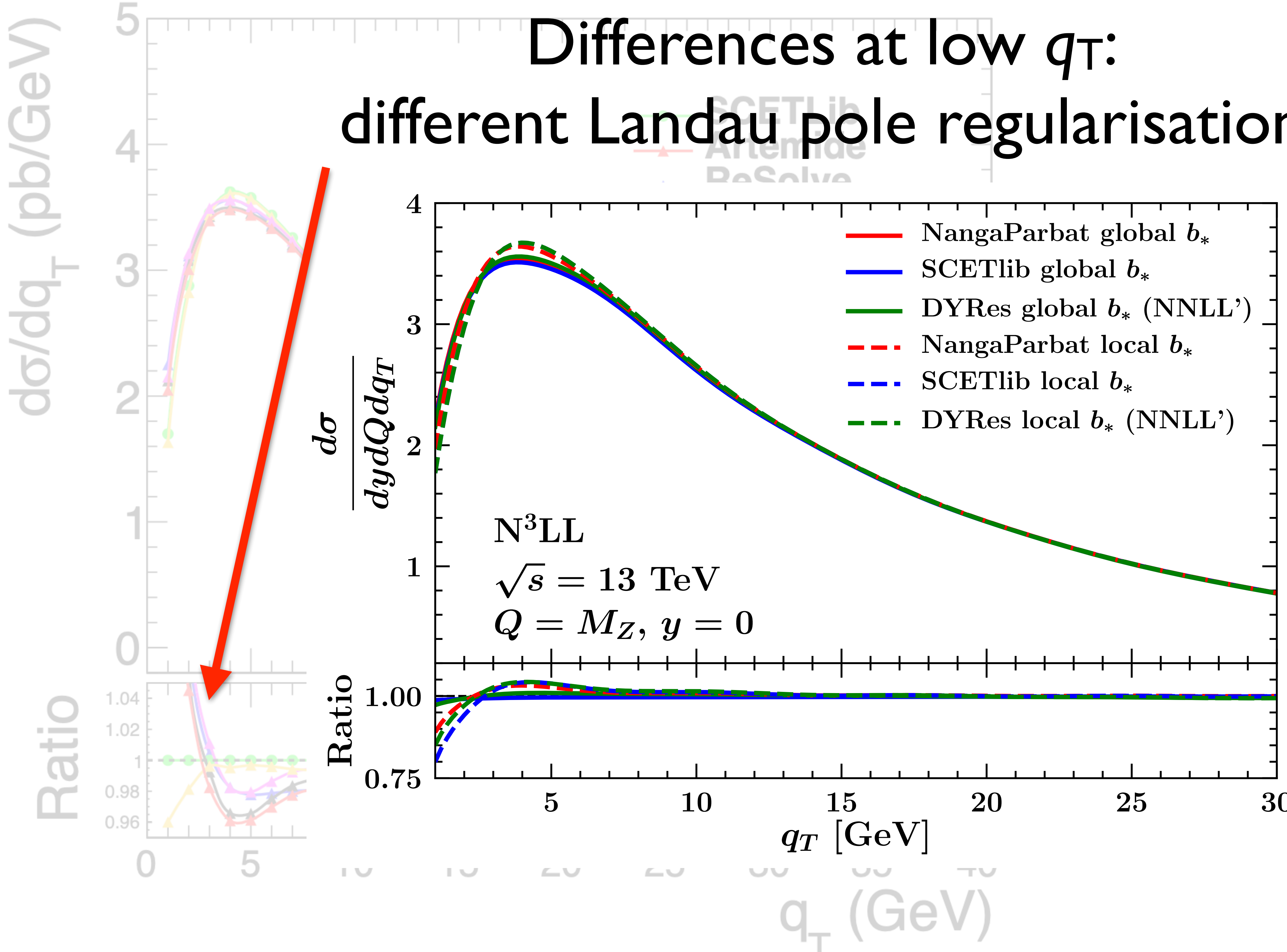


- Small differences and well understood.

Recent results

The LHC electroweak precision working group

Differences at low q_T: different Landau pole regularisation

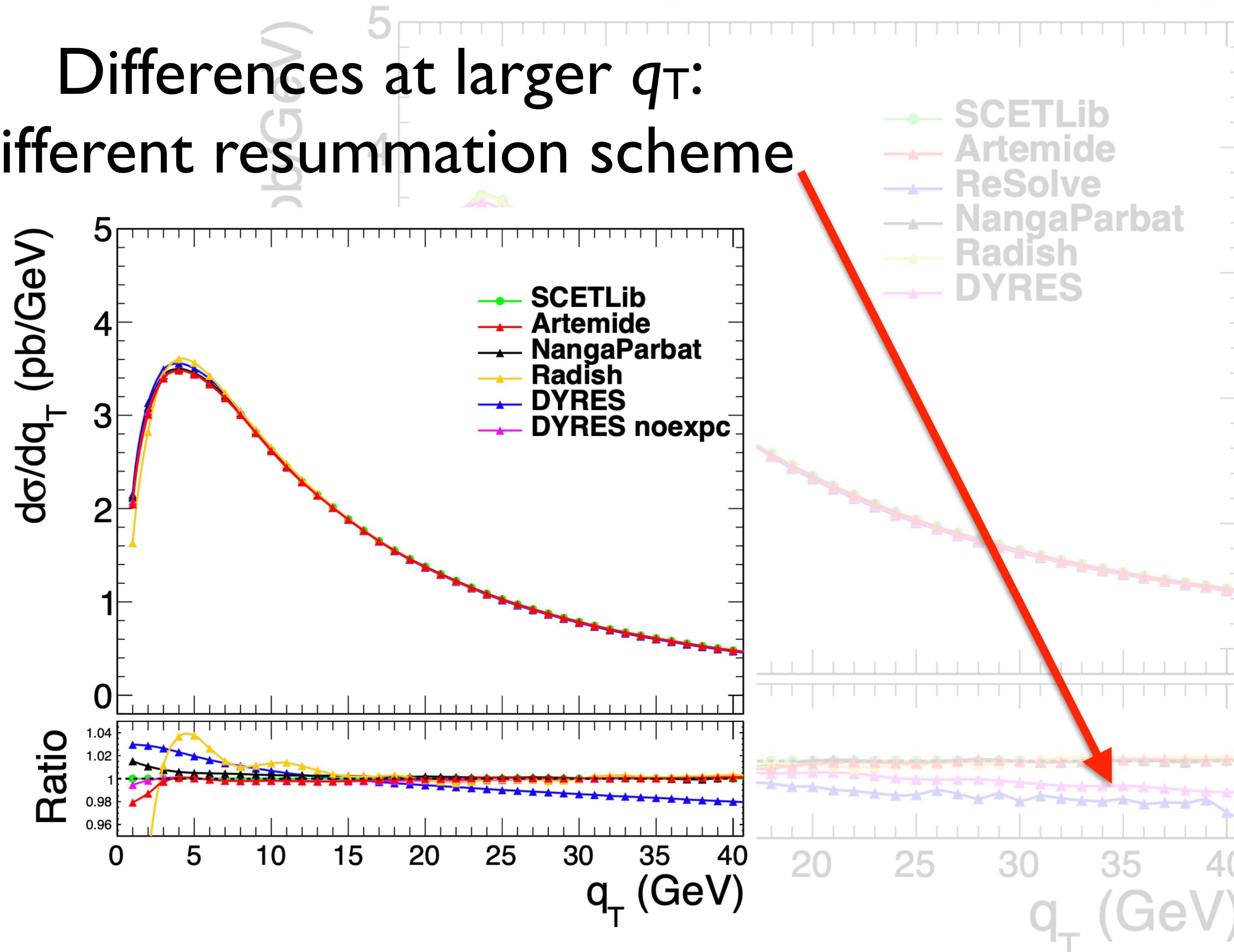


- Small differences and well understood.

Recent results

The LHC electroweak precision working group

Differences at larger q_T:
different resummation scheme



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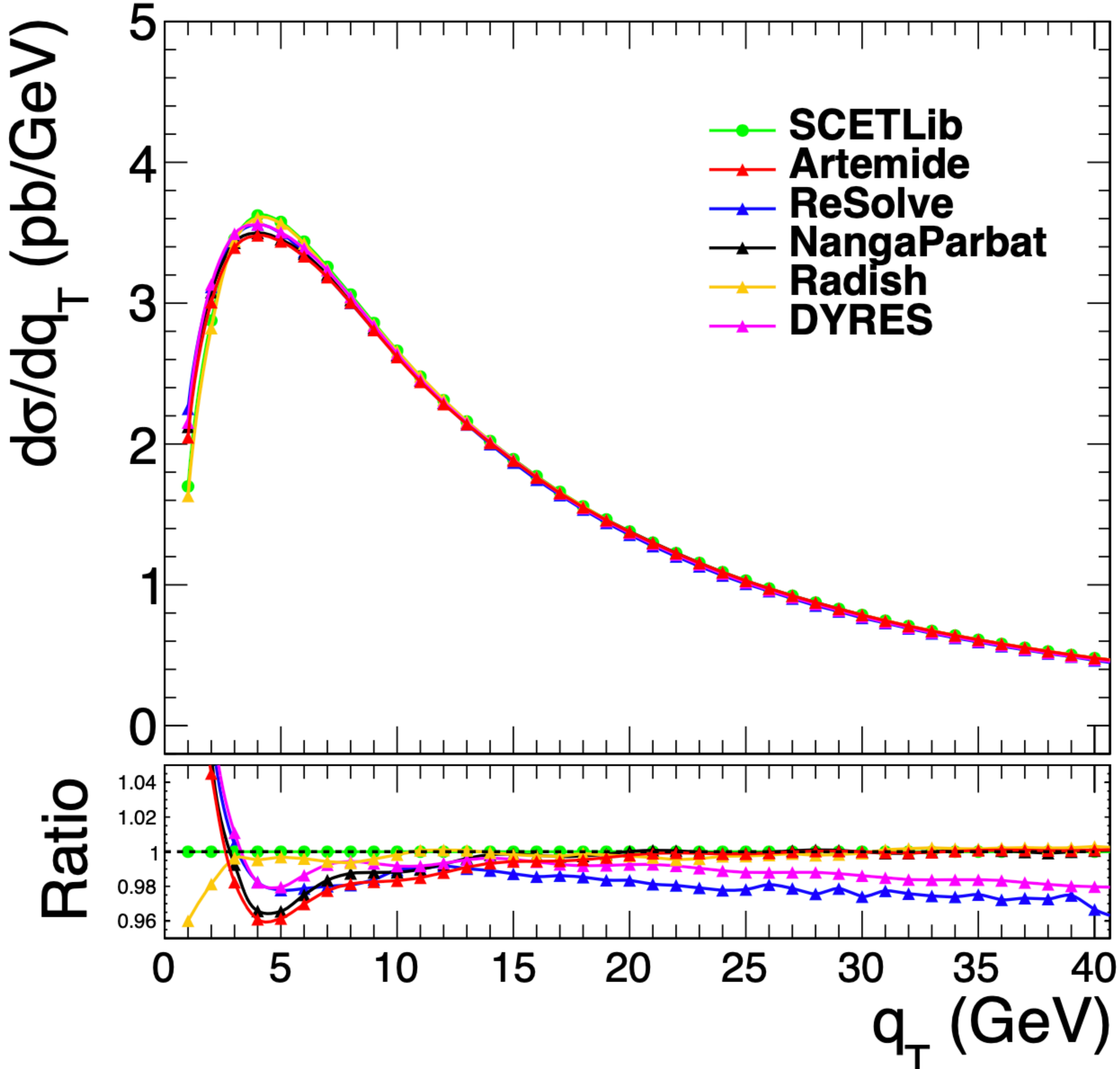
Recent results

The LHC electroweak precision working group



- Benchmark extremely **successful**!

Conclusions

- **TMD factorisation** *à la* CSS well-established and phenomenologically successful.
- Implementation within **NangaParbat**:
  - fast $\Rightarrow$ suitable for **TMD fits**,
  - already used for the **PV19** TMD PDF extraction,
  - currently being extended to analyse **SIDIS** data and determine TMD FFs,
  - accurate $\Rightarrow$ state-of-the-art perturbative accuracy (**N^{3}LL**) necessary for precision physics (involved in the LHC electroweak precision working group).
  - Extensive comparisons against other formalisms and codes make it extremely solid.
  - Used for impact studies for the **Electron-Ion Collider**.
- NangaParbat can be employed for a fundamental study of TMDs as non-perturbative objects defined in terms of light-cone operators:
  - interface to **PARTONS** being planned.