Limits and uncertainties of TMD factorization

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in collaboration with I.Scimemi
based on [1706.01473]

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Motivation

- The theory of TMD made huge progress in recent years
  - Evolution at N^3LO [Li & Zhu,1604.01404; AV,1610.05791]
  - Coefficient function at NNLO [many]
  - Matching coefficients at NNLO [many]
  - Structure of power suppressed terms on small-b OPE [Scimemi & AV,1609.06047]
- Not widely used in phenomenology!

Talk synopsis

We have made the global fit of Drell-Yan data, that include high and low energy measurements, and the extraction of unpolarized TMDPDF with the use of latest theory achievements.

additionally we made

- Study of (perturbative) theory converge.
- Study of limits of TMD factorization (Y-term).
- Evaluate theoretical uncertainties.
- Consider multiple NP inputs, and favour/disfavour particular structures.

High- & low-energy data are used

- High-energy ⇒ precise fixation of asymptotic
- Low-energy ⇒ better access to NP structure
- To start with we considered only "well-established" data
- In the final fit $309 = \underbrace{163}_{\text{high}} + \underbrace{146}_{\text{low}}$ points used.

Included data

	reaction	$\sqrt{s}$	Q	comment	points
E288	$p + Cu \to \gamma^* \to \mu\mu$	19.4 GeV	4-9 GeV	norm=0.8	35
E288	$p + Cu \to \gamma^* \to \mu\mu$	23.8 GeV	4-9 GeV	norm=0.8	45
E288	$p + Cu \to \gamma^* \to \mu\mu$	27.4 GeV	4-9 & 11-14 GeV	norm=0.8	66
CDF+D0	$p + \bar{p} \to Z \to ee$	1.8 TeV	66-116 GeV		44
CDF+D0	$p + \bar{p} \to Z \to ee$	1.96 TeV	66-116 GeV		43
ATLAS	$p + p \to Z \to \mu\mu$	7 & 8 TeV	66-116 GeV	tiny errors!	18
CMS	$p + p \to Z \to \mu\mu$	7 & 8 TeV	60-120 GeV		14
LHCb	$p + p \to Z \to \mu\mu$	7 & 8 & 13 TeV	60-120 GeV		30
ATLAS	$p + p \to Z/\gamma^* \to \mu\mu$	8 TeV	46-66 GeV		5
ATLAS	$p + p \to Z/\gamma^* \to \mu\mu$	8 TeV	116-150 GeV		9

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unpolarized Drell-Yan⇒ unpolarized TMDPDF

Theory input

$$\frac{d\sigma}{dQdy\,d^2q_T} = H(Q,\mu)\int \frac{d^2b}{(2\pi)^2}\,e^{-ibq_T}\,F(x_A,b;\mu,\zeta)F(x_B,b;\mu,\zeta) + Y$$

$$F(x,\mathbf{b};\mu,\zeta) = R[\mathbf{b};(\mu,\zeta)\to(\mu_{\text{low}},\zeta_\mu)]F^{\text{low}}(x;\mathbf{b})$$

$$F_k^{\text{low}}(x,\mathbf{b}) = \int_x^1 \frac{dy}{y}C_{k\leftarrow l}(y,\mathbf{b};\mu)f_l\left(\frac{x}{y},\mu\right)f_{NP}(y;\mathbf{b})$$

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hard c.
LO
NLO
NNLO

$$F(x,\mathbf{b};\mu,\zeta) = R[\mathbf{b};(\mu,\zeta)\to(\mu_{\text{low}},\zeta_\mu)]F^{\text{low}}(x;\mathbf{b})$$

evolution kernel

cusp	ADs
NLO	LO
NNLO	NLO
N^3LO	**NNLO**

$$F_k^{\text{low}}(x,\mathbf{b}) = \int_x^1 \frac{dy}{y}\,C_{k\leftarrow l}(y,\mathbf{b};\mu)f_l\left(\frac{x}{y},\mu\right)f_{NP}(y;\mathbf{b})$$

small-b mach.
LO
NLO
NNLO

MHHT2014

We can define four successive orders

Name	$\lvert C_V\rvert^2$	$C_{f\leftarrow f'}$	Γ	γ_V	$\mathcal{D}$	PDF set	a_s(run)	ζ_μ
NLL	a_s^0	a_s^0	a_s^2	a_s^1	a_s^1	nlo	nlo	NLL
NLO	a_s^1	a_s^1	a_s^2	a_s^1	a_s^1	nlo	nlo	NLO
NNLL	a_s^1	a_s^1	a_s^3	a_s^2	a_s^2	nnlo	nnlo	NNLL
NNLO	a_s^2	a_s^2	a_s^3	a_s^2	a_s^2	nnlo	nnlo	NNLO

unpolarized Drell-Yan ⇒ unpolarized TMDPDF

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hard c.: LO, NLO, **NNLO**

pure TMD factorization ⇒ small q_T

$$F(x,\mathbf{b};\mu,\zeta) = R[\mathbf{b};(\mu,\zeta)\to(\mu_{\text{low}},\zeta_\mu)]F^{\text{low}}(x;\mathbf{b})$$

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small-b mach.: LO, NLO, **NNLO**

f_l: **MHHT2014**

$f_{NP}(y;\mathbf{b})$: object of the fit minory restricted

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NNLL	a_s^1	a_s^1	a_s^3	a_s^2	a_s^2	nnlo	nnlo	NNLL
NNLO	a_s^2	a_s^2	a_s^3	a_s^2	a_s^2	nnlo	nnlo	NNLO

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ζ-prescription to handle large logs

$$F_k^{\text{low}}(x,\mathbf{b}) = \int_x^1 \frac{dy}{y}C_{k\leftarrow l}(y,\mathbf{b};\mu)f_l\left(\frac{x}{y},\mu\right)f_{NP}(y;\mathbf{b})$$

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NLO	a_s^1	a_s^1	a_s^2	a_s^1	a_s^1	nlo	nlo	NLO
NNLL	a_s^1	a_s^1	a_s^3	a_s^2	a_s^2	nnlo	nnlo	NNLL
NNLO	a_s^2	a_s^2	a_s^3	a_s^2	a_s^2	nnlo	nnlo	NNLO

ζ-prescription

$$\ln(\mu^2 \mathbf{b}^2),$$

- There are (potentially large) logs of **b**. Some prescription is needed to handle it.
- Typically, b^*-prescription used $\Rightarrow$ induces power corrections (difficult to control)
- ζ-prescription does not introduce any artificial dependence

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ζ-prescription

$$\ln(\mu^2 \mathbf{b}^2), \qquad \ln(\zeta\, \mathbf{b}^2)$$

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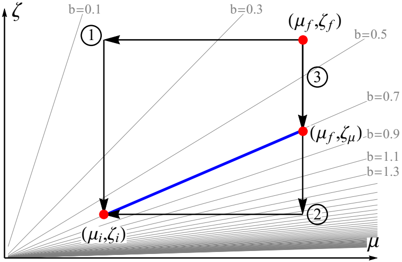
ζ-prescription in a nutshell



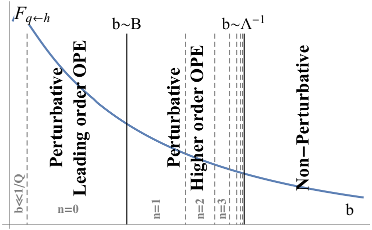
TMD evolves by a pair of equations.
Let logs cancel each other exactly.

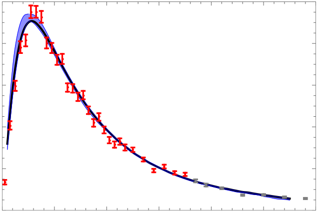
$$\mu^2 \frac{d}{d\mu^2} F(x, \mathbf{b}; \mu, \zeta_\mu) = 0.$$

ζ_μ defined perturbatively

$$\text{NLO:} \quad \zeta_\mu = \frac{2\mu}{|\mathbf{b}|} e^{-\gamma_E} e^{3/2+\ldots}$$

Non-perturbative input





$b \ll Q^{-1}$	Perturbative	Not observable, deeply in Y-term dominated region
$b \ll B$	Perturbative	Leading twist contribution $F(x,b) \sim C(x,b) \otimes f(x)$
$b \sim B$	Perturbative but not calculable	Higher twist $F(x,b) \sim \sum_n \left(\frac{xb^2}{B^2}\right)^n C_n(x,b) \otimes f_n(x)$ the main scale parameter is xb^2 [I.Scimemi,AV, 1609.06047] $n = 1$ term can be estimated.
$b > \Lambda^{-1}$	Non-perturbative	Nothing is know. Exponential? Gaussian?

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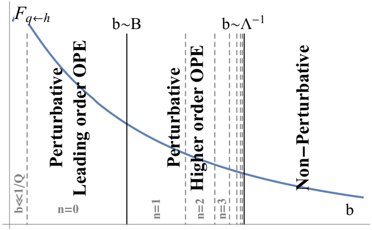

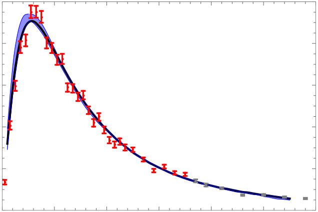

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Additionally, there can be non-perturbative contribution to the rapidity evolution

only even powers can appear

$$\mathcal{D}(b) = \mathcal{D}^{\text{perp}}(b) + g_K b^2 + \ldots$$

Theory prediction: very small or zero $g_K = 0.01 \pm 0.03\text{GeV}^2$ [I.Scimemi,AV, 1609.06047]

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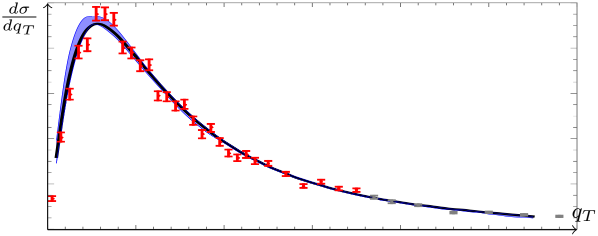
Limits of application of TMD factorizaiton ↔ size of Y-term

$$\frac{d\sigma}{dQdy\,d^2q_T} = H(Q,\mu)\int \frac{d^2b}{(2\pi)^2}\,e^{-ibq_T}\,F(x_A,b;\mu,\zeta)F(x_B,b;\mu,\zeta)+Y$$

TMD factorization derived at small q_T
the leading correction $\sim q_T^2/Q^2$



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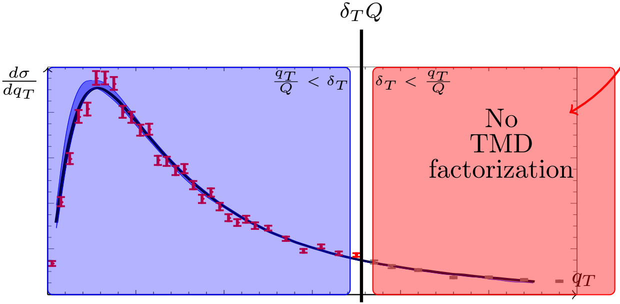
We include all points with $q_T < \delta_T Q$

To find the value of δ_T, we check **the stability of the fit**

- Make fits with increasing δ_T (0.1→0.3)(165→399 points)
- The value of $\chi^2/d.o.f.$ should be indepent on δ_T in allowed region



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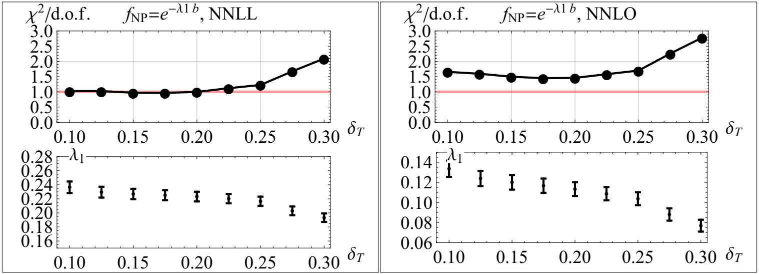
Example: $f_{NP} = e^{-\lambda b}$, no E288



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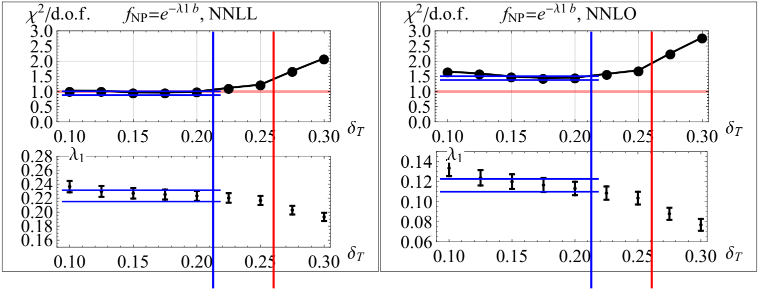


- $\delta_T < 0.2$ save region,
- $\delta_T < 0.25$ un-save region,
- $\delta_T > 0.25$ TMD factorization does not work.

To be on the save side we used $\delta_T = 0.2$
There are 309 data points

Asymptotic of f_{NP}

Large-b $\Leftrightarrow$ small-q_T

The δ_T scans are very instructive!

The smaller-δ_T the better (not worse!) the fit should be. Unless f_{NP} is wrong.

Asymptotic of f_{NP}

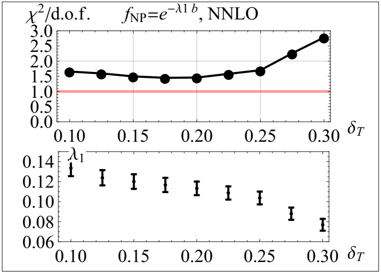
Domination of f_{NP} → Large-b ⇔ small-q_T ← Very precise at HE

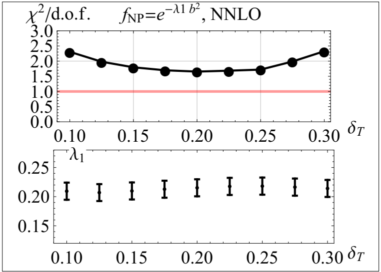
f_{NP} at large-b is nicely fixed from high-energy measurements.

The δ_T scans are very instructive!

The smaller-δ_T the better (not worse!) the fit should be. Unless f_{NP} is wrong.

Exp: 1.4 → 1.6 vs. Gauss: 1.7 → 2.3

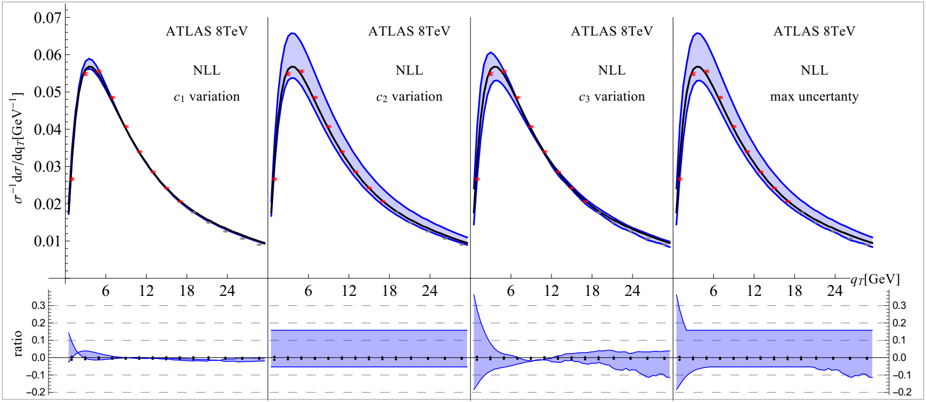




Perturbative uncertainties

$c_1 \to$ uncertainty of RAD definition	$c_2 \to$ uncertainty of hard matching	$c_3 \to$ uncertainty of small-b matching	Total uncertainty is the maximum of three
$\int_{c_1\mu_0}^{\mu}\Gamma + \mathcal{D}^{\text{pert}}(c_1\mu_0)$	$H(c_2\mu)F(c_2\mu)F(c_2\mu)$	$C(c_3\mu_{\text{low}}) \otimes f(c_3\mu_{\text{low}})$	$c_i \in (0.5, 2)$

High-energy example: ATLAS 8 TeV (best precision)



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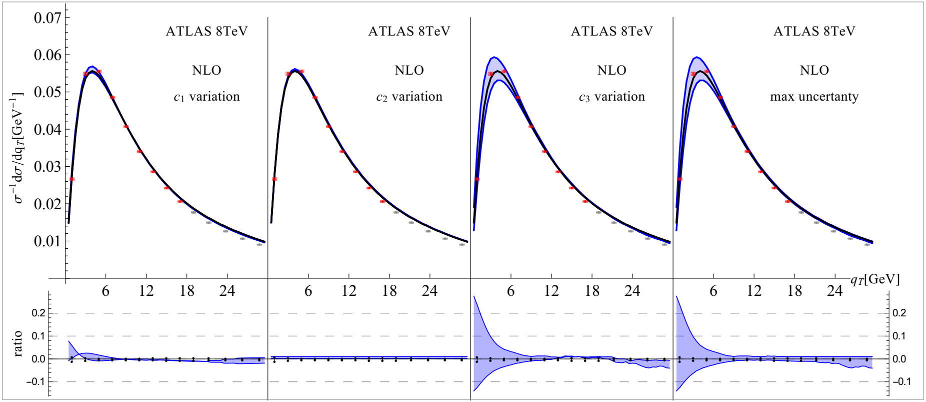

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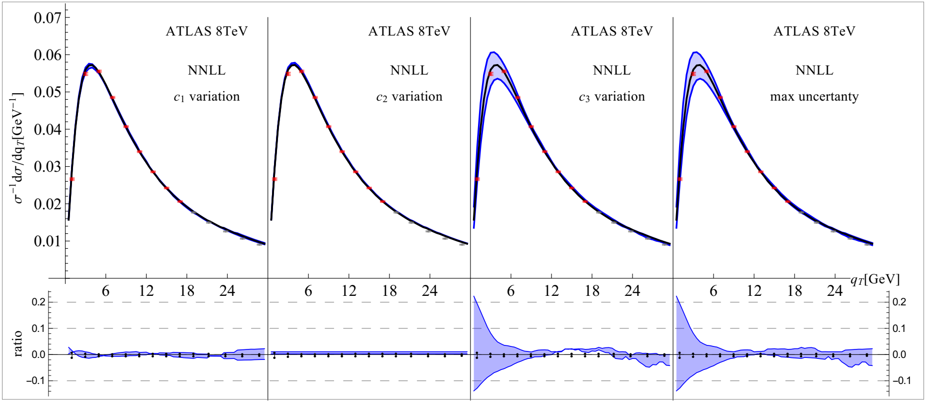

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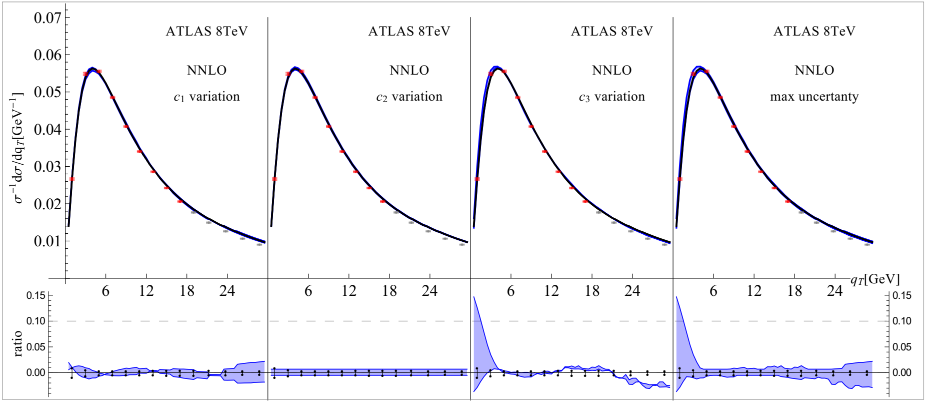

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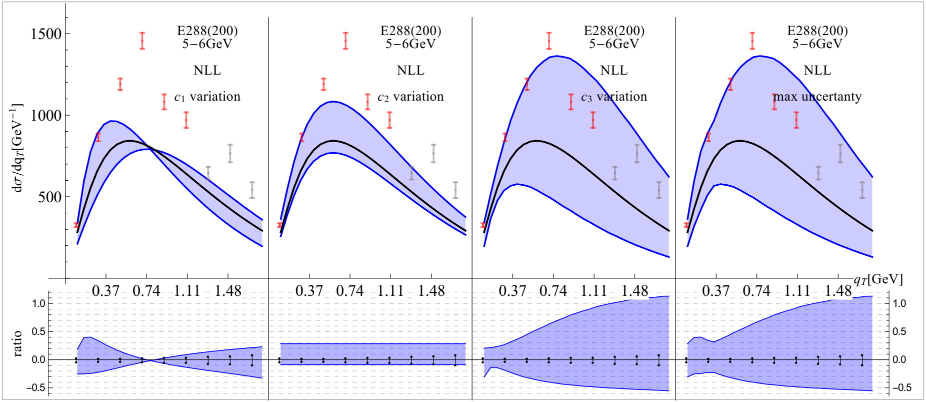

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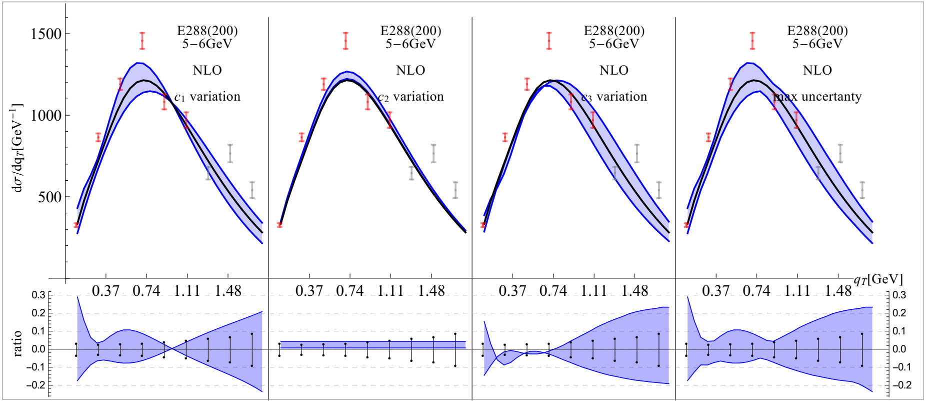

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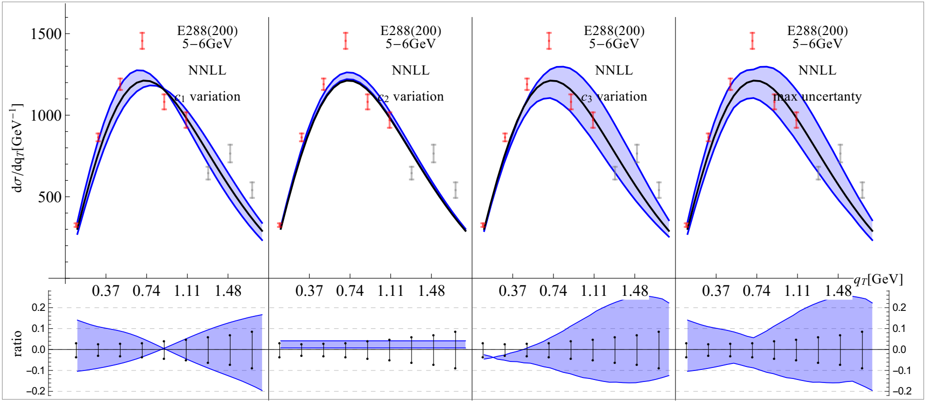

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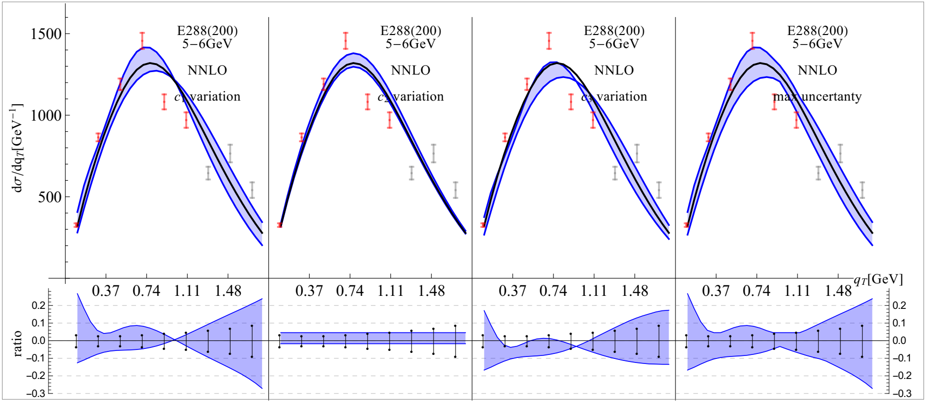

Convergence of theory

We have selected 3 main models (all with 2 parameters)

Model 1

$$f_{NP} = e^{-\lambda_1 b}(1+\lambda_2 b^2)$$

[D'Alesio, et al,1407.3311]

Model 2

$$f_{NP} = \exp\left(\frac{-\lambda_q z b}{\sqrt{1+\frac{\lambda_q z^2 b^2}{\lambda_1^2}}}\right)$$

$+$ renomalon correction $\times\lambda_2$
[Scimemi,AV,1609.06047]

Model 3

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$$\mathcal{D}^{\text{NP}} = -g_K \mathbf{b}^2$$

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$$\mathcal{D}^{\text{NP}} = -g_K \mathbf{b}^2$$

All models show similar behaviour

$$\lim_{b\to\infty} f_{NP}(x,b) \sim e^{-\lambda_1 b} \qquad f_{NP}(x,b) \sim 1+\lambda_2 b^2 f'(x,0)+...$$

$\lambda_1 = 0.156(6)\text{GeV}$	$\lambda_1 = 0.162(5)\text{GeV}$	$\lambda_1 = 0.174(6)\text{GeV}$
$\lambda_2 = 3.7(2)\times 10^{-2}\text{GeV}^2$	$\lambda_2 = 1.3(8)\times 10^{-2}\text{GeV}^2$	$g_K = 1.5(2)\times 10^{-2}\text{GeV}^2$

We cannot distinguish NP evolution from a power correction.

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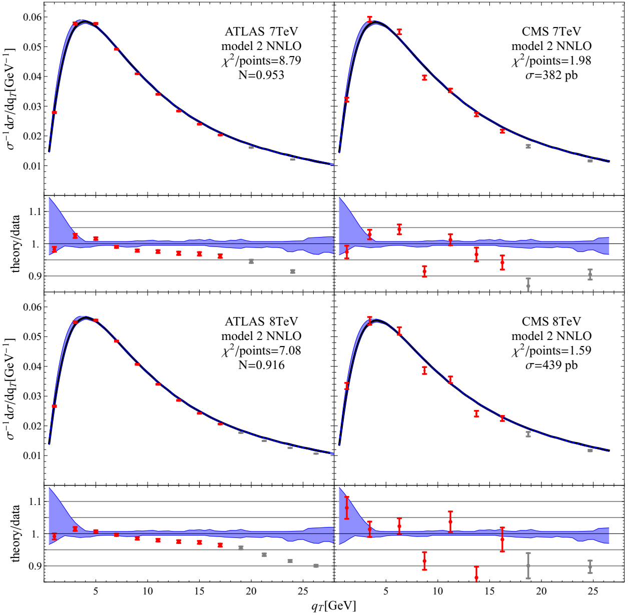
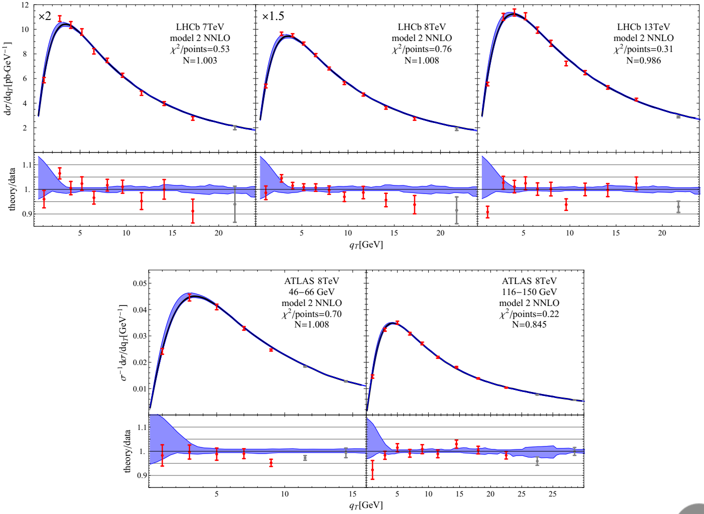
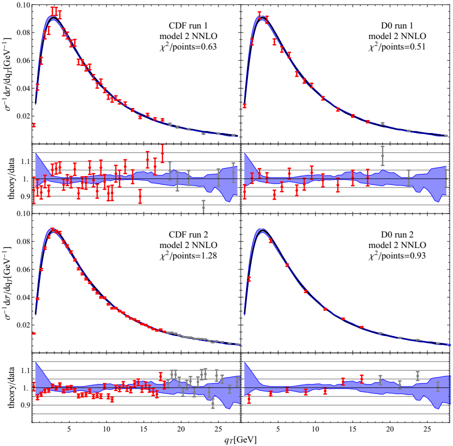
$$\mathcal{D}^{\text{NP}}=-g_K \mathbf{b}^2$$

$\chi^2/d.o.f$			
	Model 1	Model 2	Model 3
NLL	9.21	9.07	8.90
NLO	2.62	2.64	1.90
NNLL	1.43	1.46	1.16
NNLO	1.84 (1.40)	1.79 (1.39)	1.94 (1.42)

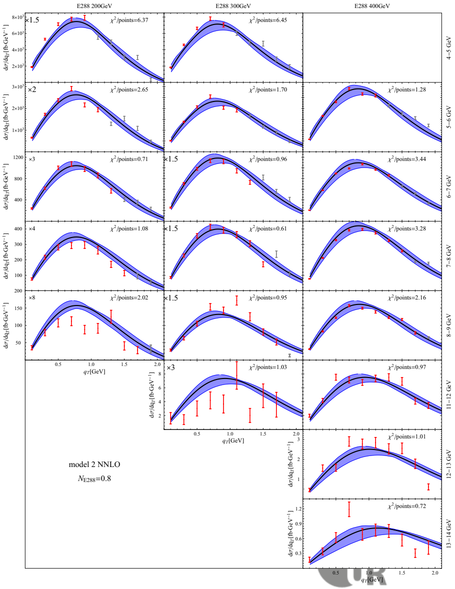
Main source of "problems" is ATLAS Z-boson


ATLAS 7TeV
model 2 NNLO
χ^2/points=8.79
N=0.953
CMS 7TeV
model 2 NNLO
χ^2/points=1.98
σ=382 pb
ATLAS 8TeV
model 2 NNLO
χ^2/points=7.08
N=0.916
CMS 8TeV
model 2 NNLO
χ^2/points=1.59
σ=439 pb
$\sigma^{-1} d\sigma/dq_T$[GeV^{-1}]
theory/data
q_T[GeV]


×2
LHCb 7TeV
model 2 NNLO
χ²/points=0.53
N=1.003
×1.5
LHCb 8TeV
model 2 NNLO
χ²/points=0.76
N=1.008
LHCb 13TeV
model 2 NNLO
χ²/points=0.31
N=0.986
dσ/dq_T[pb·GeV⁻¹]
theory/data
q_T[GeV]
ATLAS 8TeV
46−66 GeV
model 2 NNLO
χ²/points=0.70
N=1.008
ATLAS 8TeV
116−150 GeV
model 2 NNLO
χ²/points=0.22
N=0.845
σ⁻¹dσ/dq_T[GeV⁻¹]
theory/data
q_T[GeV]



CDF run 1
model 2 NNLO
χ^2/points=0.63
D0 run 1
model 2 NNLO
χ^2/points=0.51
CDF run 2
model 2 NNLO
χ^2/points=1.28
D0 run 2
model 2 NNLO
χ^2/points=0.93
$\sigma^{-1} d\sigma/dq_T$[GeV^{-1}]
theory/data
q_T[GeV]



E288 200GeV
E288 300GeV
E288 400GeV
4–5 GeV
5–6 GeV
6–7 GeV
7–8 GeV
8–9 GeV
11–12 GeV
12–13 GeV
13–14 GeV
χ^2/points=6.37
χ^2/points=6.45
χ^2/points=2.65
χ^2/points=1.70
χ^2/points=1.28
χ^2/points=0.71
χ^2/points=0.96
χ^2/points=3.44
χ^2/points=1.08
χ^2/points=0.61
χ^2/points=3.28
χ^2/points=2.02
χ^2/points=0.95
χ^2/points=2.16
χ^2/points=1.03
χ^2/points=0.97
χ^2/points=1.01
χ^2/points=0.72
model 2 NNLO
N_{E288}=0.8
$d\sigma/dq_T$[fb·GeV^{-1}]
q_T[GeV]

Conclusion

arTeMiDe

- Code available : **https://teorica.fis.ucm.es/artemide/**
- Optimized (but not limited to) ζ-prescription.
- Evolution (up to N^{3}LO), unpolarized TMDPDF (with up to NNLO matching), DY cross-sections.
- Flexible structure: input PDFs, f_{NP}.
- More to come...

Results of global fit

- Exponential TMD is preferable (ζ-prescription) $f_{NP} \sim \exp(-\lambda_1 b)$
- Natural large-distance scale $\lambda_1 \simeq 0.14 - 0.17$ GeV ($\sim m_\pi$).
- The TMD factorization works at $q_T \lesssim 0.2Q$
- Theory uncertainty is significant at small-Q (10-20% for $Q \sim 4 - 9$GeV)
- We cannot distinguish NP evolution from NP corrections.
- NNLO ingredients significantly reduce the theory uncertainties and prediction power.

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LHC normalization

order	ATLAS Z-boson 7TeV	ATLAS Z-boson 8TeV	ATLAS 46-66 8TeV	ATLAS 116-150 8TeV	CMS 7TeV	CMS 8TeV	LHCb 7TeV	LHCb 8TeV	LH 13
NLL	*0.80(1)*	0.79(1)	**0.86(1)**	**0.74(0)**	*0.83(1)*	*0.84(1)*	0.86(1)	0.87(1)	0.8
NLO	*0.89(1)*	0.87(1)	**0.96(3)**	**0.81(1)**	*0.91(2)*	*0.93(2)*	0.95(2)	0.95(1)	**0.9**
NNLL	*0.95(2)*	0.93(2)	**1.04(4)**	**0.86(1)**	*0.98(2)*	*1.00(2)*	**1.01(2)**	**1.01(2)**	**1.0**
NNLO	*0.94(1)*	0.92(1)	**1.01(2)**	**0.85(1)**	*0.97(1)*	*0.99(1)*	**1.00(1)**	**1.01(1)**	**0.9**