Ignazio Scimemi (UCM)

Recent analysis of DY (and Z-boson) data

Most recent results in collaboration with **Alexey Vladimirov**

arXiv:1706.01473

Outline & Issues

- DY data: basic test of TMD factorization
- Theory status of unpolarized TMD's
- Scale prescriptions, convergence, models, theoretical errors,..
- The impact of LHC
- arTeMiDe

....TMD factorization ....

.. for DY and heavy boson production we have (Collins 2011, Echevarria, Idilbi, Scimemi (EIS) 2012)

$$\frac{d\sigma}{dQ^2 dq_T dy} = \sum_q \sigma_q^\gamma H(Q^2, \mu^2) \int \frac{d^2\mathbf{b}}{4\pi} e^{-i\mathbf{q_T}\cdot\mathbf{b}} \Phi_{q/A}(x_A, \mathbf{b}, \zeta_A, \mu) \Phi_{q/B}(x_B, \mathbf{b}, \zeta_B, \mu)$$

$$\sqrt{\zeta_A \zeta_B} = Q^2$$

…and similar formulas are valid for SIDIS (EIC) and hadron production in ee colliders

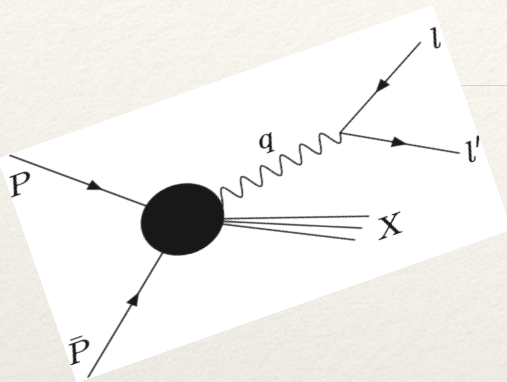
The pathological behavior is associated to a particular kind of divergences: rapidity divergences

The renormalization of the rapidity divergences is responsible for the a new resummation scale

We have new non-perturbative effects which cannot be included in PDFs.

THE CASE OF UNPOLARIZED TMDS: THE PERTURBATIVE CALCULABLE PART OF UNPOLARIZED TMDS IS KNOWN AT NNLO! HOW CAN WE USE THIS INFORMATION?
WHICH SCALE PRESCRIPTION ALLOWS AN OPTIMAL EXTRACTION OF TMD'S?
WHAT IS THE RANGE OF VALIDITY OF THE TMD FACTORIZATION THEOREM?
DO LHC DATA HAVE AN IMPACT ON TMD EXTRACTION?

TMD's factorization and Operator Product Expansion: general outlook



Factorized hadronic tensor

$q^2 = Q^2 \gg q_T^2$

Q=M=di-lepton invariant mass

Factorization $q_T^2 \sim \Lambda_{QCD}^2$ → $\tilde{M} = H(Q^2/\mu^2)\, \tilde{F}_n(x_n, b; Q^2, \mu^2)\, \tilde{F}_{\bar{n}}(x_{\bar{n}}, b; Q^2, \mu^2)$

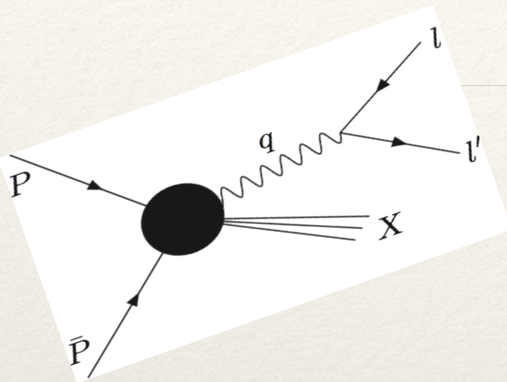
OPE $q_T^2 \gg \Lambda_{QCD}^2$ → $\tilde{F}_n = \tilde{C}_{n\leftarrow j}(x_n, b, Q^2, \mu^2) \otimes f_{j\leftarrow h}(x_n, \mu^2) + \mathcal{O}(x_n b^2/B^2)$

Very important

The factorization theorem predicts that each coefficient can be extracted on its own.
The evolution of TMD is universal (process independent)
Renomalons: power corrections are x-dependent

ALL THESE MATCHINGS ON COLLINEAR FUNCTIONS ARE JUST THE ASYMPTOTIC EXPANSION OF A MORE COMPLEX STRUCTURE: HOW CAN WE EXPLORE IT?

TMD's factorization and Operator Product Expansion: general outlook



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Very important

TMDs are built joining a perturbative calculable part (in QCD) and a non-perturbative part (Models, Lattice):
This separation is crucial for TMD extractions

EACH EXPERIMENT HAS ITS OWN SENSITIVENESS TO EACH PART

Status of unpolarized TMDs in perturbation theory

Perturbative Calculations

- Evolution to N3LO Y. Li, H.X. Zhu, arXiv:1604.01404 A. Vladimirov, arXiv:1610.05791
- Soft function at NNLO M.G. Echevarría, I.S., A. Vladimirov, arXiv:1511.05590.
- NNLO coefficients for TMDPDFs M.G. Echevarría, I.S., A. Vladimirov, arXiv1604.07869, T. Lübbert, J. Oredsson, M. Stahlhofen, arXiv:1602.01829, T. Gehrmann, T. Lübbert, Li Lin Yang arXiv:1403.6451
- NNLO coefficients for TMD Fragmentation Functions M.G. Echevarría, I.S., A. Vladimirov, arXiv:1509.06392, arXiv:1604.07869

Phenomenology

- Global Fits (SIDIS+DY) A. Bacchetta et al. arxiv:1703.10157, Talk of F. Delcarro
- DY and Z-boson fits (ResBos, D'Alesio et al. arXiv:1410.4522 up to NNLL)
- Implementation of standard CSS (DYres/DyqT)

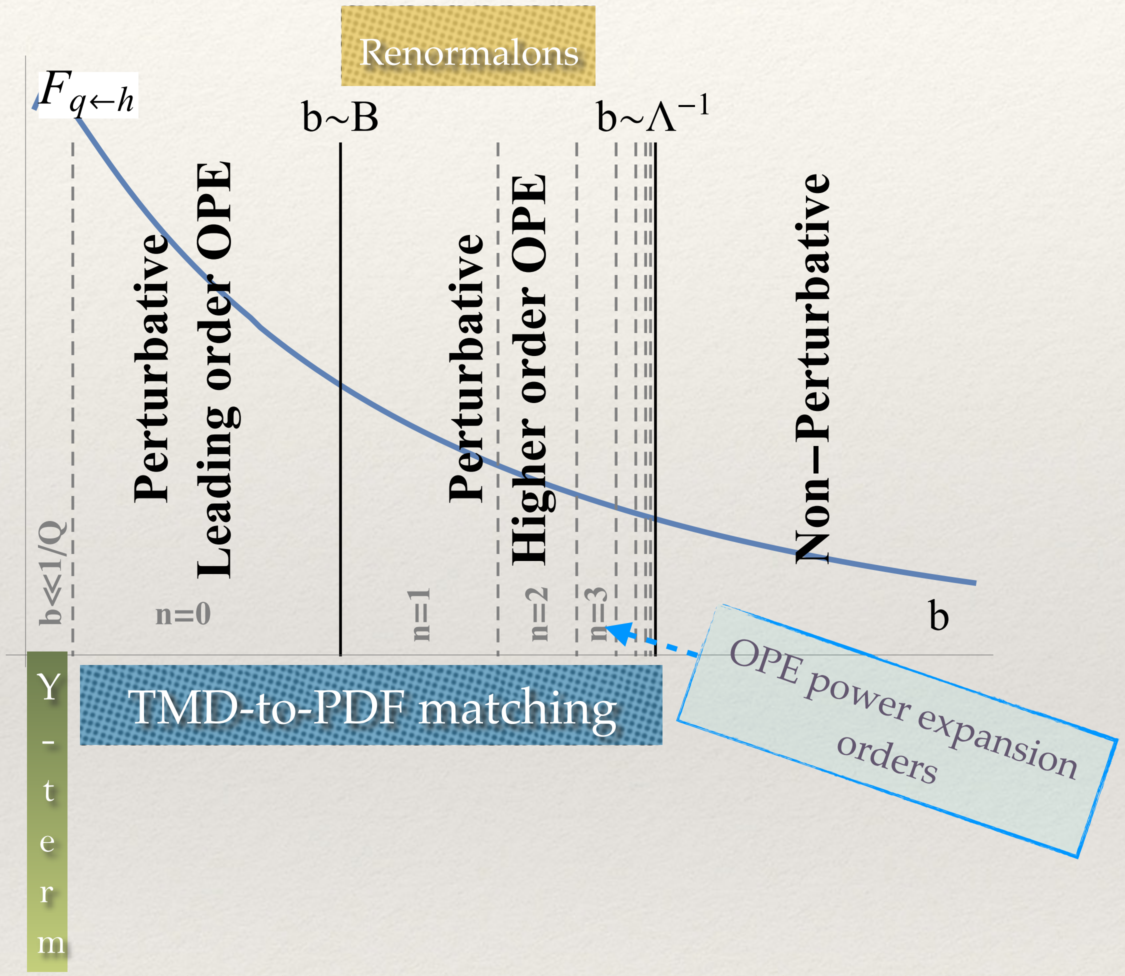
IT IS POSSIBLE TO MAKE A COMPLETE ANALYSIS OF UNPOLARIZED TMD IN DRELL-YAN AND SIDIS USING NNLO RESULTS

The study of polarized TMDs at the same precision is just started:

D. Gutierrez-Reyes, I.S., A. Vladimirov, arXiv:1702.06558

Regions in *b*-space

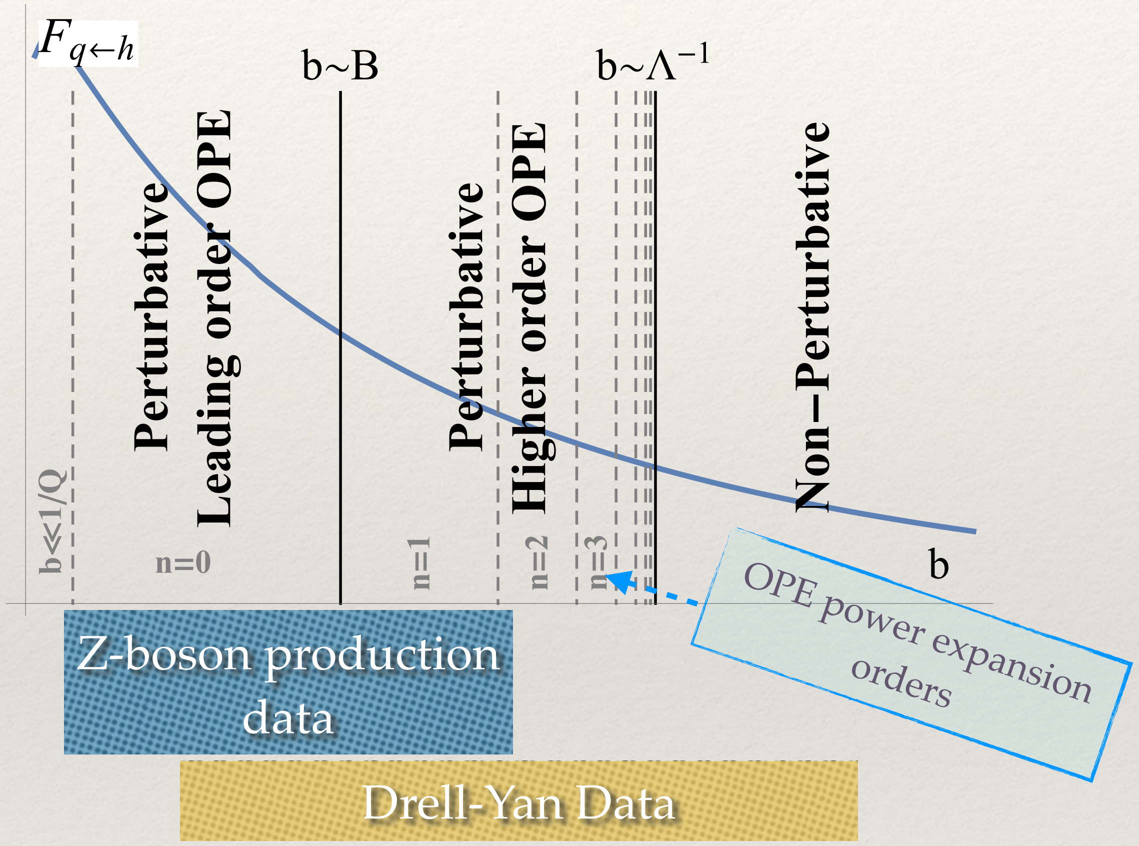
The factorization theorem works in b-space.
The perturbative expansion does not work on the whole space...



EACH REGION NEEDS A PARTICULAR TREATMENT

Regions in *b*-space

The factorization theorem works in b-space.
The perturbative expansion does not work on the whole space...



NOT ALL REGIONS ARE EQUALLY IMPORTANT FOR EACH EXPERIMENT

Cross section and TMD structure

$$\frac{d\sigma}{dQ^2 dy d(q_T^2)} = \frac{4\pi}{3N_c}\frac{\mathcal{P}}{sQ^2}\sum_{GG'} z_{ll'}^{GG'}(q)\sum_{ff'} z_{ff'}^{GG'}|C_V(q,\mu)|^2\int\frac{d^2\vec{b}}{4\pi}e^{i(\vec{b}\vec{q})}$$
$$\times F_{f\leftarrow h_1}(x_1,\vec{b};\mu,\zeta)F_{f'\leftarrow h_2}(x_2,\vec{b};\mu,\zeta) + Y,$$

Lepton tensor cuts

E.w. charges

Hard Coefficient

Y-term 1/Q^2 corrections

$$F_{f\leftarrow h}(x,\mathbf{b};\mu_f,\zeta_f) = R^f[\mathbf{b};(\mu_f,\zeta_f)\leftarrow(\mu_i,\zeta_i)]F_{f\leftarrow h}(x,\mathbf{b};\mu_i,\zeta_i)$$
$$R^f[\mathbf{b};(\mu_f,\zeta_f)\leftarrow(\mu_i,\zeta_i)] = \exp\left[\int_P\left(\gamma_F^f(\mu,\zeta)\frac{d\mu}{\mu} - \mathcal{D}^f(\mu,\mathbf{b})\frac{d\zeta}{\zeta}\right)\right]$$

Evolution factor

Low energy TMD

$$F_{f\leftarrow h}(x,\vec{b};\mu,\zeta) = \sum_q\int_x^1\frac{dz}{z}C_{f\leftarrow q}(z,\mathbf{L}_\mu;\mu,\zeta)f_{q\leftarrow h}\left(\frac{x}{z},\mu\right)f_{NP}(z,\mathbf{b})$$

Matching (Wilson) coefficient

PDF

Non-perturbative input

Cross section and TMD structure

Lepton tensor cuts

E.w. factors

Hard Coefficient

$$\frac{d\sigma}{dQ^2 dy d(q_T^2)} = \frac{4\pi}{3N_c}\frac{\mathcal{P}}{sQ^2}\sum_{GG'} z_{ll'}^{GG'}(q) \sum_{ff'} z_{ff'}^{GG'} |C_V(q,\mu)|^2 \int \frac{d^2\vec{b}}{4\pi} e^{i(\vec{b}\vec{q})}$$

$$\times F_{f\leftarrow h_1}(x_1,\vec{b};\mu,\zeta) F_{f'\leftarrow h_2}(x_2,\vec{b};\mu,\zeta) + Y$$

Only small qT data

See Talk of L. Gamberg

Evolution factor

Low energy TMD

$$F_{f\leftarrow h}(x,\mathbf{b};\mu_f,\zeta_f) = R^f[\mathbf{b};(\mu_f,\zeta_f)\leftarrow(\mu_i,\zeta_i)] F_{f\leftarrow h}(x,\mathbf{b};\mu_i,\zeta_i)$$

$$R^f[\mathbf{b};(\mu_f,\zeta_f)\leftarrow(\mu_i,\zeta_i)] = \exp\left[\int_P \left(\gamma_F^f(\mu,\zeta)\frac{d\mu}{\mu} - \mathcal{D}^f(\mu,\mathbf{b})\frac{d\zeta}{\zeta}\right)\right]$$

$$F_{f\leftarrow h}(x,\vec{b};\mu,\zeta) = \sum_q \int_x^1 \frac{dz}{z} C_{f\leftarrow q}(z,\mathbf{L}_\mu;\mu,\zeta) f_{q\leftarrow h}\left(\frac{x}{z},\mu\right) f_{NP}(z,\mathbf{b})$$

Matching (Wilson) coefficient

PDF

Gaussian? Exponential?

Perturbative orders…

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

NEW!!

…Theoretical uncertainties…

In the implementation we must choose matching prescriptions such that the perturbative series is as convergent as possible, undesired power corrections are not introduced

Matching Scales

Hard Scale

Low Scale

$$\frac{d\sigma}{dQ^2 dy d(q_T^2)} = \frac{4\pi}{3N_c}\frac{\mathcal{P}}{sQ^2}\sum_{GG'} z_{ll'}^{GG'}(q)\sum_{ff'} z_{ff'}^{GG'}\int\frac{d^2\vec{b}}{4\pi}e^{i(\vec{b}\vec{q})}|C_V(Q,c_2Q)|^2\Big\{R^f[\vec{b};(c_2Q,Q^2)\to(c_3\mu_i,\zeta_{c_3\mu_i});c_1\mu_i]\Big\}$$
$$\times F_{f\leftarrow h_1}(x,\vec{b};c_4\mu_{\text{OPE}},\zeta_{c_4\mu_{\text{OPE}}})F_{f'\leftarrow h_2}(x,\vec{b};c_4\mu_{\text{OPE}},\zeta_{c_4\mu_{\text{OPE}}})$$

Rapidity Evolution

Small b Scale

Parameters and quality of the fits depend strongly on the choices made for the implementation

Details of scale variations

$c_1 \sim \text{perturbative matching of rapidity anomalous dimension}$

This uncertainty arises from the dependence (at the fixed perturbative order) on the initial evolution point and should be compensated between the Sudakov factor and the boundary term in the TMD evolution factor.

$c_2 \sim \text{hard factorization scale}$

This uncertainty arises from the dependence (at the fixed perturbative order) on the hard factorization scale which is to be compensated between the hard coefficient function and the TMD evolution factor.

$c_3 \sim \text{TMD evolution factor}$

This uncertainty arises from the dependence (at the fixed perturbative order) on initial scale of TMD evolution, which is to be compensated between the evolution integral and the mu-dependence of zeta_i.

$c_4 \sim \text{small-}b \text{ matching}$

This uncertainty arises from the dependence (at the fixed perturbative order) on the scale of the small-b matching mu_OPE which is to be compensated between the small-b Wilson coefficient function C_{f /f'} and the evolution of PDF.

Details of scale variations

$c_1 \sim$ perturbative matching of rapidity anomalous dimension

$c_2 \sim$ hard factorization scale

$c_3 \sim$ TMD evolution factor

Usually these two scales changed together: C3

$c_4 \sim$ small-b matching

TMD evolution and scale prescriptions

The perturbative expression for the evolution kernel work only `up to a certain scale`...

$$R^f[\mathbf{b};(\mu_f,\zeta_f)\leftarrow(\mu_i,\zeta_i);\mu_0]=\exp\left[\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma_F^f(\mu,\zeta_f)-\int_{\mu_0}^{\mu_i}\frac{d\mu}{\mu}\Gamma^f(\mu)\ln\left(\frac{\zeta_f}{\zeta_i}\right)\right]\left(\frac{\zeta_f}{\zeta_i}\right)^{-\mathcal{D}^f_{\text{perp}}(\mu_0,\mathbf{b})-g_K\mathbf{b}^2}.$$

...and in principle we include some (RENORMALON CONSISTENT) corrections

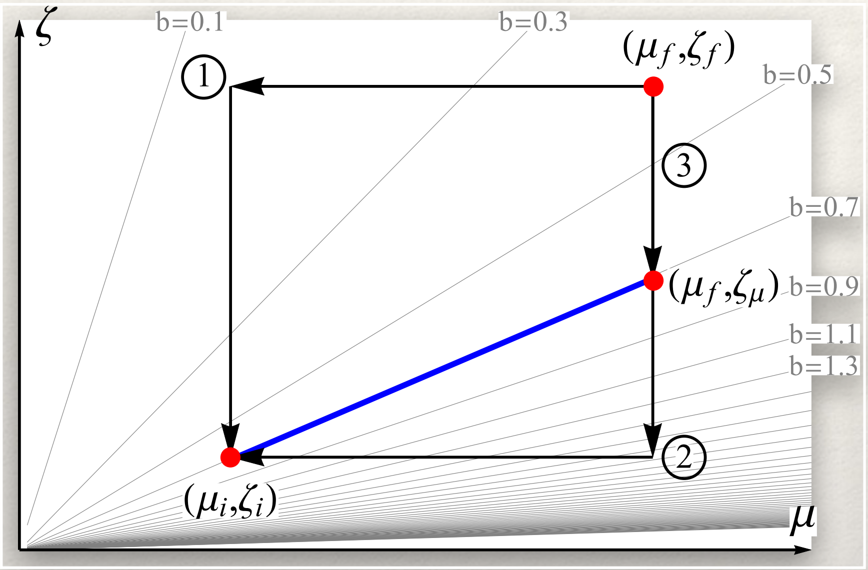
What is the best prescription to choose scales?

b prescription is not satisfactory (not fully inconsistent, but very confusing):*

- It is not fully consistent with renormalon calculations (I.S., A. Vladimirov 2016)
- It introduces undesired power corrections (which alter model building):

Often parameters are due just to cancel induced power corrections

ζ-prescription



We choose $\zeta = \zeta(\mu) \equiv \zeta_\mu$

such that double logs are eliminated in PDF matching

$$C_{q\leftarrow q}(x,\mathbf{L}_\mu;\mu,\zeta) = \delta(\bar{x}) + a_s(\mu)C_F\Big[-2\mathbf{L}_\mu\Big(\frac{2}{(1-x)_+}-1-x\Big)+2\bar{x}+\delta(\bar{x})\Big(-\mathbf{L}_\mu^2+2\mathbf{L}_\mu\mathbf{l}_\zeta-\frac{\pi^2}{6}\Big)\Big]\ldots$$

In practice we implement..

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

...and obtain iso-evolution curves..

$$\zeta_\mu = \frac{2\mu}{b}\exp\Big(-\gamma_E + a_s\Big[\frac{11C_A-4T_FN_f}{36}\mathbf{L}_\mu^2 + C_F\Big(-\frac{3}{4}+\pi^2-12\zeta_3\Big)+C_A\Big(\frac{649}{108}-\frac{17\pi^2}{12}+\frac{19}{2}\zeta_3\Big)$$
$$+T_FN_f\Big(-\frac{53}{27}+\frac{\pi^2}{3}\Big)\Big]+\mathcal{O}(a_s^2)\Big).$$

See also other prescription as in D. Kang, C. Lee, V. Vaidya, arXiv:1710.00078

ζ-prescription

In this prescription the structure of coefficient is much simpler

$$C_{q\leftarrow q}(x,\mathbf{L}_\mu;\mu,\zeta_\mu)=\delta(\bar{x})+a_s(\mu)C_F\Big[-2\mathbf{L}_\mu\Big(\frac{2}{(1-x)_+}-1-x\Big)+2\bar{x}+\delta(\bar{x})\Big(-3\mathbf{L}_\mu-\frac{\pi^2}{6}\Big)\Big]+\cdots$$

We do not introduce undesired power corrections

We have several proof of scale stability: TMD area, ...

$$\int_0^1 dx C_{q\leftarrow q}(x,\mathbf{L}_\mu;\mu,\zeta_\mu)=1+a_s(\mu)C_F\Big(1-\frac{\pi^2}{6}\Big)+\cdots$$

Cancellation of logs

$$\mu^2\frac{d}{d\mu^2}C_{f\leftarrow f'}(x,\mathbf{b};\mu,\zeta_\mu)\otimes f_{f'\leftarrow h}(x,\mu)=0$$

We are left with the freedom to choose

$$\mu=\mu_b=\frac{C_0}{b}+2\text{ GeV}$$

DATA: Z-boson production....

	CDF run I	D0 run I
$\sqrt{s}$	1.8 TeV	1.8 TeV
process	$p+\bar{p} \to Z \to e^+e^-$	$p+\bar{p} \to Z \to e^+e^-$
M_{ll} range	66-116 GeV	75-105 GeV
y	y-integrated	y-integrated
Observable	$\frac{d\sigma}{dq_T}$	$\frac{d\sigma}{dq_T}$
Exp. σ_{tot} [pb]	248 ± 17	$\sigma = 221 \pm 11$

	CDF run II	D0 run II
$\sqrt{s}$	1.96 TeV	1.96 GeV
process	$p+\bar{p} \to Z \to e^+e^-$	$p+\bar{p} \to Z \to e^+e^-$
M_{ll} range	66-116 GeV	70-110 GeV
y	y-integrated	y-integrated
Observable	$\frac{d\sigma}{dq_T}$	$\frac{1}{\sigma}\frac{d\sigma}{dq_T}$
Exp. σ_{tot} [pb]	256 ± 2.91	$\sigma = 255$

	ATLAS	ATLAS
$\sqrt{s}$	7 TeV	8 TeV
process	$pp \to Z \to ee+\mu\mu$	$pp \to Z \to \mu\mu$
M_{ll} range	66 - 116 GeV	66 - 116 GeV
lepton cuts	$p_T > 20$ GeV $\lvert\eta\rvert < 2.4$	$p_T > 20$ GeV $\lvert\eta\rvert < 2.4$
y	$-2.4 < y < 2.4$	$-2.4 < y < 2.4$
Observable	$\frac{1}{\sigma}\frac{d\sigma}{dq_T}$	$\frac{1}{\sigma}\frac{d\sigma}{dq_T}$

	CMS	CMS
$\sqrt{s}$	7 TeV	8 TeV
process	$pp \to Z \to ee+\mu\mu$	$pp \to Z \to \mu\mu$
M_{ll} range	60-120 GeV	60-120 GeV
lepton cuts	$p_T > 20$ GeV $\lvert\eta\rvert < 2.1$	$p_T > 15$ GeV $\lvert\eta\rvert < 2.1$
y	$\lvert y\rvert < 2.1$	$\lvert y\rvert < 2.1$
Observable	$\frac{1}{\sigma}\frac{d\sigma}{dq_T}$	$\frac{1}{\sigma}\frac{d\sigma}{dq_T}$

	LHCb	LHCb	LHCb
$\sqrt{s}$	7 TeV	8 TeV	13 TeV
process	$pp \to Z \to \mu\mu$	$pp \to Z \to \mu\mu$	$pp \to Z \to \mu\mu$
M_{ll} range	60-120 GeV	60-120 GeV	60-120 GeV
lepton cuts	$p_T > 20$ GeV $2 < \eta < 4.5$	$p_T > 20$ GeV $2 < \eta < 4.5$	$p_T > 20$ GeV $2 < \eta < 4.5$
y	$2 < y < 4.5$	$2 < y < 4.5$	$2 < y < 4.5$
Observable	$d\sigma(q_T)$	$d\sigma(q_T)$	$\frac{d\sigma}{dq_T}$
Norm. exp.	$\sigma = 76.0 \pm 3.1$ pb	$\sigma = 95.0 \pm 3.2$ pb	$\sigma = 198.0 \pm 13.3$ pb

NEW!

DATA: and Drell-Yan….

	E288 200	E288 300	E288 400
$\sqrt{s}$	19.4 GeV	23.8 GeV	27.4 GeV
process	p+Cu→ $\gamma \to \mu^+\mu^-$	p+Cu→ $\gamma \to \mu^+\mu^-$	p+Cu→ $\gamma \to \mu^+\mu^-$
Q range	4-9 GeV	4-9 GeV	5-14 GeV
ΔQ-bin	1 GeV	1 GeV	1 GeV
y	y=0.4	y=0.21	y=0.03
Observable	$E\frac{d^3\sigma}{d^3q}$	$E\frac{d^3\sigma}{d^3q}$	$E\frac{d^3\sigma}{d^3q}$

	ATLAS	ATLAS
$\sqrt{s}$	8 TeV	8 TeV
process	$pp \to Z/\gamma^* \to \mu\mu$	$pp \to Z/\gamma^* \to \mu\mu$
M_{ll} range	46 - 66 GeV	116 - 150 GeV
lepton cuts	$p_T > 20$ GeV $\lvert\eta\rvert < 2.4$	$p_T > 20$ GeV $\lvert\eta\rvert < 2.4$
y	$-2.4 < y < 2.4$	$-2.4 < y < 2.4$
Observable	$\frac{1}{\sigma}\frac{d\sigma}{dq_T}$	$\frac{1}{\sigma}\frac{d\sigma}{dq_T}$

NEW!

Lepton cuts…

Lepton cuts have implemented numerically for LHC.
However all experiments suffer from lepton cuts: they should always be reported!!

Normalization of the cross sections

Not all experiments provide a value for total cross sections:

- N_{E288}=0.8 fixed
- For CDF, D0 we use DYNNLO
- for LHC we normalize areas of partially integrated cross sections. N=th/exp
  General agreement within errors with published results

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	LHCb 13TeV
NLL/NLO	438 pb	0.92	**1.01**	**0.93**	369 pb	407 pb	0.92	0.93	0.93
NNLL/NLO	438 pb	0.92	**1.01**	**0.93**	368 pb	407 pb	0.92	0.93	0.93
NNLL/NNLO	461 pb	**0.97**	**1.08**	**0.98**	387 pb	429 pb	**0.97**	**0.99**	**0.98**

Models, data, stability

Data are sensitive to models for non-perturbative part of TMDs.
We explore models with

- Minimal set of parameters
- renormalon consistency
- Independent on number of data points (Stability)
- We do not include Y-terms: we should select q_T/Q proper interval

To be checked on data!!

Models fun

$$R^f[\mathbf{b};(\mu_f,\zeta_f)\leftarrow(\mu_i,\zeta_i);\mu_0]=\exp\left[\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma_F^f(\mu,\zeta_f)-\int_{\mu_0}^{\mu_i}\frac{d\mu}{\mu}\Gamma^f(\mu)\ln\left(\frac{\zeta_f}{\zeta_i}\right)\right]\left(\frac{\zeta_f}{\zeta_i}\right)^{-\mathcal{D}^f_{\rm perp}(\mu_0,\mathbf{b})-g_K\mathbf{b}^2}.$$

Renormalon for kernel

Theory prediction: very small or zero $g_K=0.01\pm0.03\text{GeV}^2$

I.S., A. Vladimirov: arXiv:1609.06147

$$F_{q\leftarrow h}(x,\mathbf{b};\mu,\zeta)=\int_x^1\frac{dz}{z}\sum_f C_{q\leftarrow f}(z,\mathbf{b};\mu,\zeta)\,f_{f\leftarrow h}\left(\frac{x}{z},\mu\right)f_{NP}(z,\mathbf{b})$$

Non-perturbative corrections to TMD-PDF matching

$f_{NP}=1$	$f_{NP}=e^{-\lambda_1 b^2}$	$f_{NP}=e^{-\lambda_1 b}$	$f_{NP}=1,\ g_K\neq 0$

?

NNLO

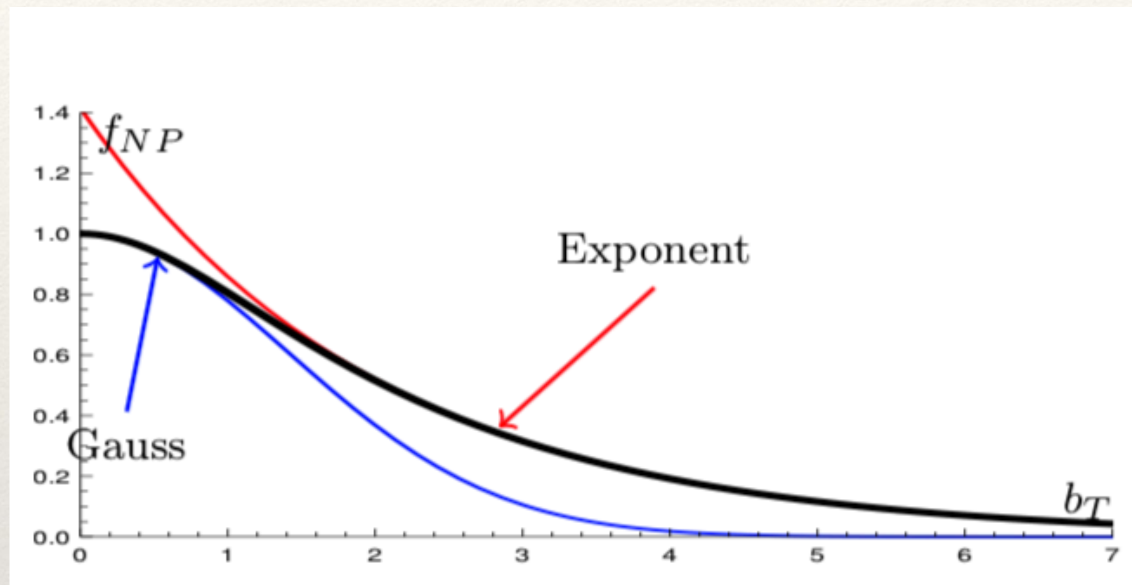
data/f_{NP}	$e^{-\lambda b}$	$e^{-\lambda b^2}$	$\cosh^{-1}(\lambda b)$
ATLAS	4.78	1.43	1.42
E288	2.70	5.68	3.64
E288+ATLAS	8.18	5.77	3.72

- High energy data favors Gaussian (also theoretically)
- Low energy data favors Exponential (also theoretically)

The difference between model is not much at NLO, but it is important at NNLO

- We need at least 2 parameters (+gK)

Models fun



$$\frac{\chi^2}{d.o.f.}(\text{Total}) \simeq 1.2$$

$$\frac{\chi^2}{d.o.f.}(\text{High E. data}) \simeq 1.0$$

$$\frac{\chi^2}{d.o.f.}(\text{Low E. data}) \simeq 1.4$$

MODEL 1

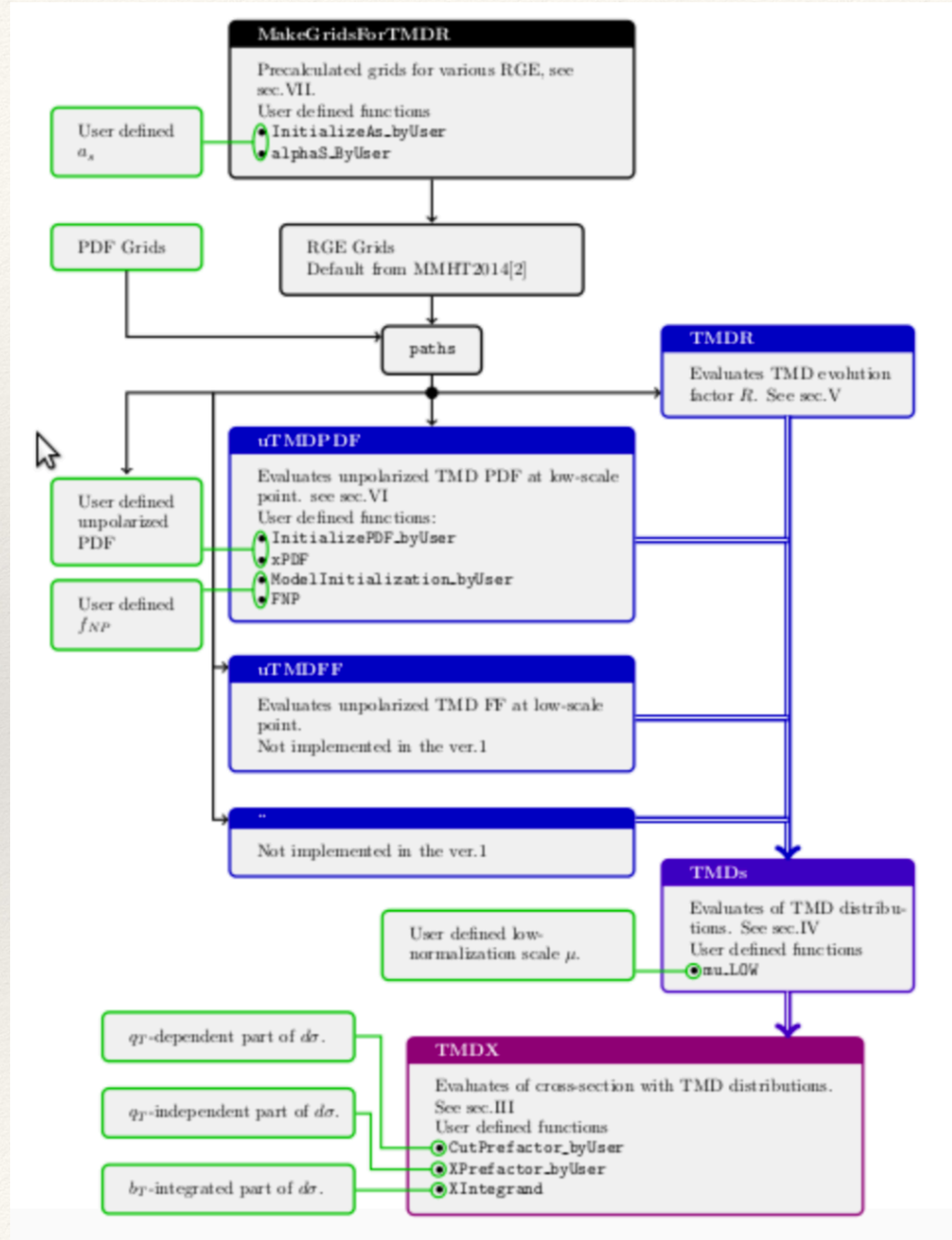
$$f_{NP}(b) = \frac{\cosh\left(\left(\frac{\lambda_2}{\lambda_1} - \frac{\lambda_1}{2}\right) b\right)}{\cosh\left(\left(\frac{\lambda_2}{\lambda_1} + \frac{\lambda_1}{2}\right) b\right)}$$

MODEL 2

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

NEW (renormalon consistent) ansatz!

arTeMiDe



- FORTRAN 90 code
- Module structure
- Convolutions, evolution (LO,NLO,NNLO)
- Fourier to q_T-space, integrations over phase space
- Scale-variation (ζ-prescription)
- User defined PDFs, scales, f_{NP}
- Efficient code ($\sim 10^9$ TMDs $\sim$ 6. min at NNLO)

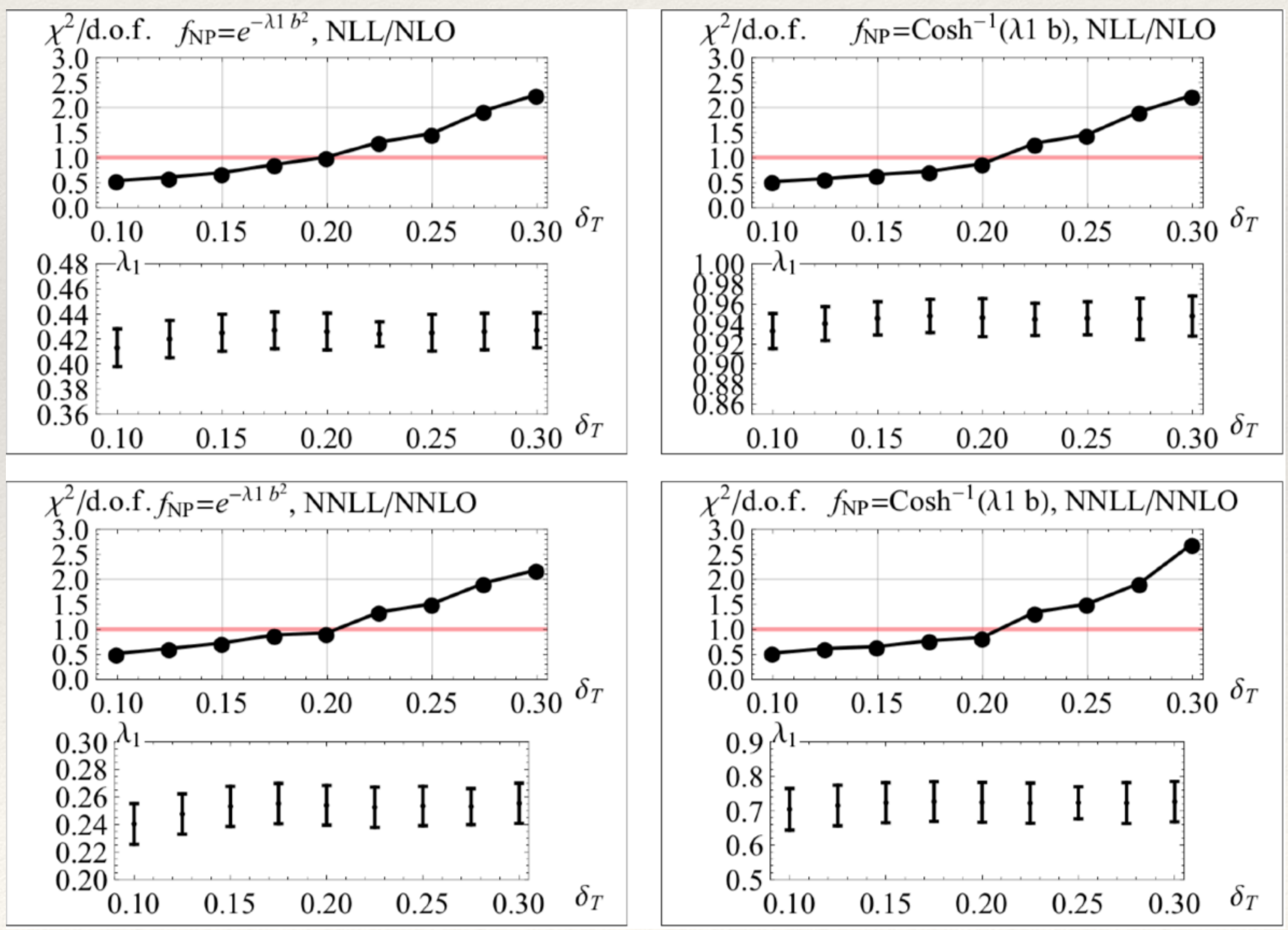
Currently ver 1.1

Available at: https://teorica.fis.ucm.es/artemide

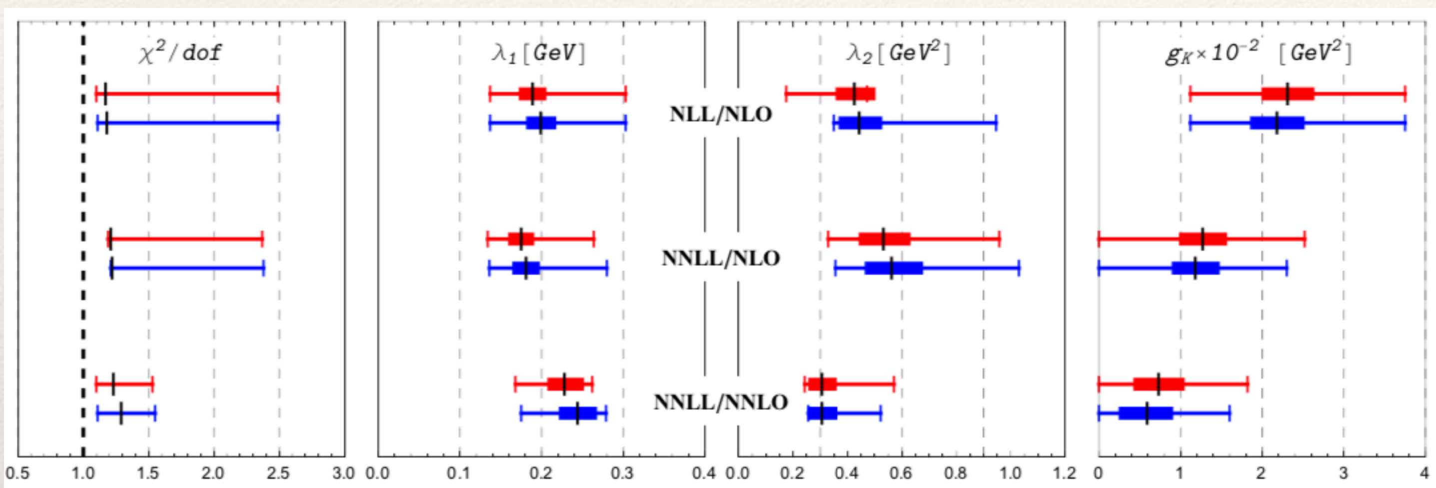
Future plans: add modules for fragmentations, and polarized TMDs

Stability

- Different models show different stability of chi^2: *Check on high energy data*
- For $\delta_T = q_T/Q \lesssim 0.2$power corrections (Y-terms) are not needed



Fitted constants



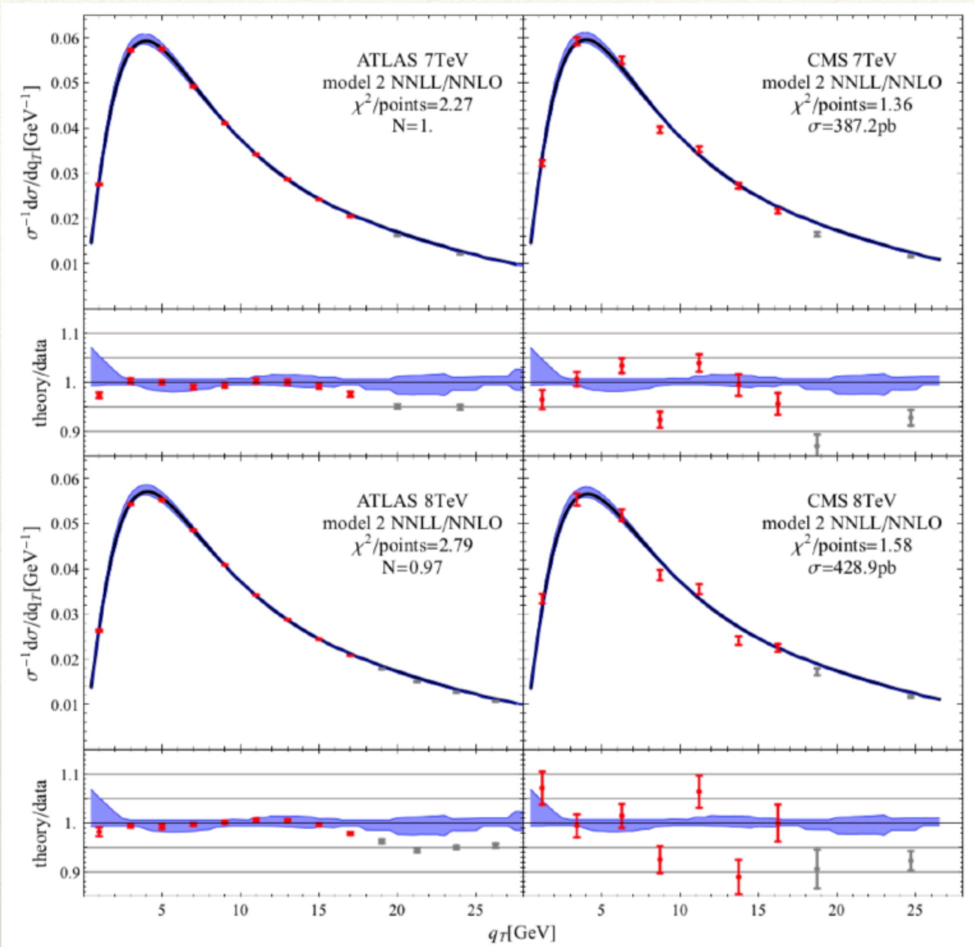
Variation	$\frac{\chi^2}{d.o.f.}$	λ_1	λ_2	$g_K \times 10^{-2}$
Model 1 NNLL/NLO				
$c_{1,2,3,4} = 1$	1.17	0.189	0.425	2.31
$c_1 = 2$	1.31 (**+0.14**)	0.201 (**+0.012**)	0.316 (**−0.109**)	3.00 (**+0.69**)
$c_1 = 0.5$	1.10 (**−0.07**)	0.184 (**−0.005**)	0.308 (**−0.117**)	1.60 (**−0.71**)
$c_2 = 2$	1.19 (**+0.02**)	0.204 (**+0.015**)	0.223 (**−0.202**)	2.12 (**−0.19**)
$c_2 = 0.5$	1.20 (**+0.03**)	0.219 (**+0.030**)	0.226 (**−0.199**)	1.93 (**−0.38**)
$c_3 = 2$	1.23 (**+0.06**)	0.251 (**+0.062**)	0.315 (**−0.110**)	3.75 (**+1.44**)
$c_3 = 0.5$	1.13 (**−0.04**)	0.160 (**−0.029**)	0.220 (**−0.205**)	1.12 (**−1.19**)
$c_4 = 2$	1.76 (**+0.59**)	0.137 (**−0.052**)	0.473 (**+0.046**)	2.71 (**+0.40**)
$c_4 = 0.5$	2.49 (**+1.32**)	0.303 (**+0.114**)	0.175 (**−0.250**)	1.15 (**−1.16**)
Result	$1.17^{+1.32}_{-0.07}$	$0.189^{+0.114}_{-0.052}$	$0.425^{+0.047}_{-0.250}$	$2.31^{+1.44}_{-1.19}$
Model 1 N^{3}LL/NNLO				
$c_{1,2,3,4} = 1$	1.23	0.228	0.306	0.73
$c_1 = 2$	1.40 (**+0.17**)	0.242 (**+0.014**)	0.296 (**−0.010**)	1.21 (**+0.48**)
$c_1 = 0.5$	1.14 (**−0.09**)	0.221 (**−0.007**)	0.346 (**+0.020**)	0.12 (**−0.61**)
$c_2 = 2$	1.22 (**−0.01**)	0.217 (**−0.011**)	0.295 (**−0.011**)	0.86 (**+0.13**)
$c_2 = 0.5$	1.26 (**+0.03**)	0.252 (**+0.024**)	0.326 (**+0.020**)	0.48 (**−0.25**)
$c_3 = 2$	1.27 (**+0.04**)	0.260 (**+0.032**)	0.344 (**+0.038**)	1.82 (**+1.09**)
$c_3 = 0.5$	1.31 (**+0.08**)	0.198 (**−0.030**)	0.358 (**+0.052**)	0.00 (**−0.73**)
$c_4 = 2$	1.10 (**−0.13**)	0.168 (**−0.060**)	0.571 (**+0.265**)	1.27 (**+0.54**)
$c_4 = 0.5$	1.53 (**+0.30**)	0.262 (**+0.034**)	0.243 (**−0.063**)	0.68 (**−0.05**)
Result	$1.23^{+0.30}_{-0.13}$	$0.228^{+0.034}_{-0.060}$	$0.306^{+0.265}_{-0.063}$	$0.73^{+1.09}_{-0.73}$

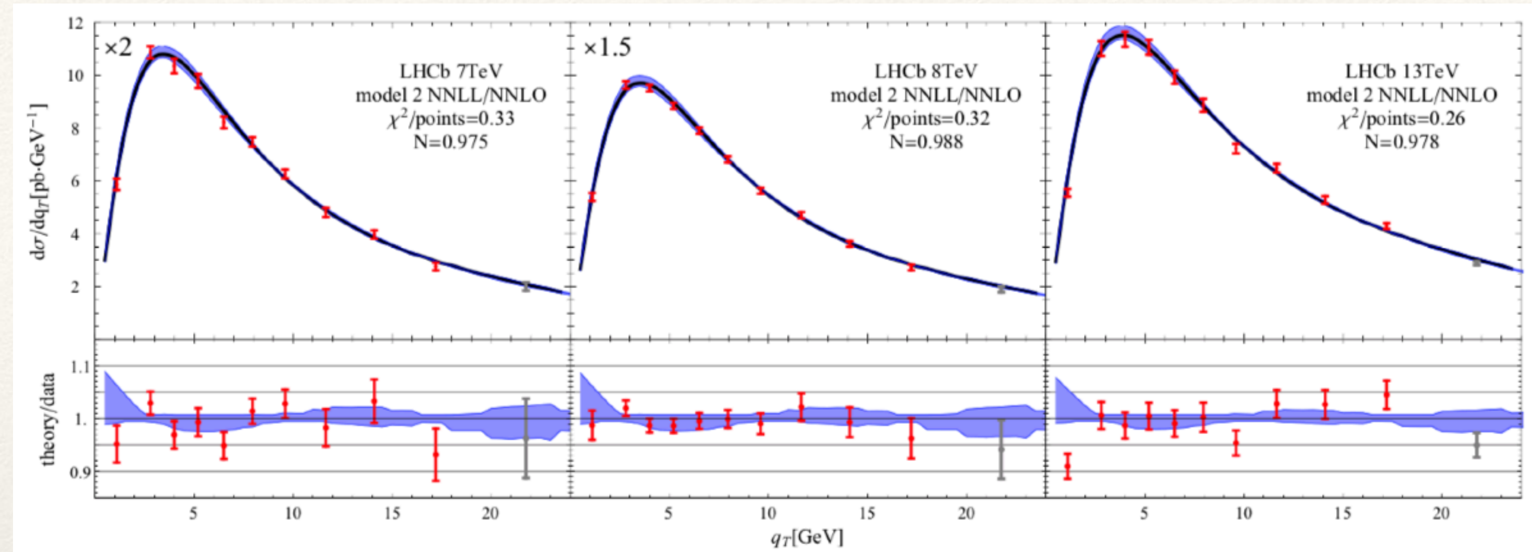
Order	$\frac{\chi^2}{d.o.f.}$	λ_1	λ_2	$g_K \times 10^{-2}$
Model 1				
NLL/NLO	$1.17^{+1.32}_{-0.07}$	$0.189^{+0.009}_{-0.009}{}^{+0.114}_{-0.052}$	$0.425^{+0.054}_{-0.045}{}^{+0.047}_{-0.250}$	$2.31^{+0.25}_{-0.24}{}^{+1.44}_{-1.19}$
NNLL/NLO	$1.21^{+1.16}_{-0.02}$	$0.175^{+0.008}_{-0.008}{}^{+0.089}_{-0.041}$	$0.532^{+0.076}_{-0.067}{}^{+0.426}_{-0.203}$	$1.27^{+0.22}_{-0.21}{}^{+1.19}_{-1.27}$
NNLL/NNLO	$1.23^{+0.30}_{-0.13}$	$0.228^{+0.016}_{-0.013}{}^{+0.034}_{-0.060}$	$0.306^{+0.031}_{-0.026}{}^{+0.265}_{-0.063}$	$0.73^{+0.24}_{-0.23}{}^{+1.09}_{-0.73}$
Model 2				
NLL/NLO	$1.18^{+1.31}_{-0.07}$	$0.199^{+0.011}_{-0.010}{}^{+0.104}_{-0.062}$	$0.443^{+0.061}_{-0.052}{}^{+0.503}_{-0.093}$	$2.18^{+0.26}_{-0.25}{}^{+1.57}_{-1.06}$
NNLL/NLO	$1.22^{+1.16}_{-0.01}$	$0.181^{+0.009}_{-0.009}{}^{+0.099}_{-0.045}$	$0.562^{+0.076}_{-0.075}{}^{+0.468}_{-0.206}$	$1.18^{+0.22}_{-0.21}{}^{+1.12}_{-1.18}$
NNLL/NNLO	$1.29^{+0.26}_{-0.18}$	$0.244^{+0.016}_{-0.015}{}^{+0.035}_{-0.069}$	$0.306^{+0.034}_{-0.029}{}^{+0.216}_{-0.050}$	$0.59^{+0.24}_{-0.27}{}^{+1.01}_{-0.59}$

- Not much difference between models
- gK consistent with renormalons
- Renormalons effects small
- Error on fitted constants converges

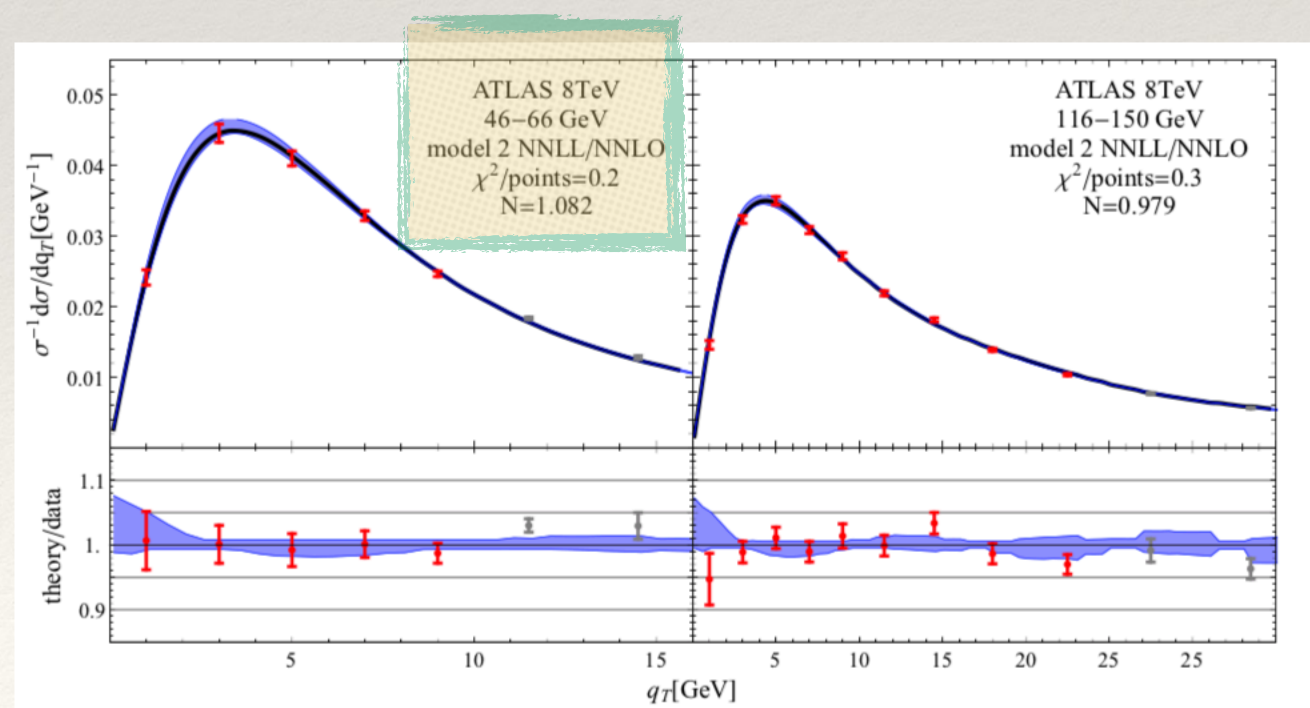
arTeMiDe :

Results for LHC in Z-production ….

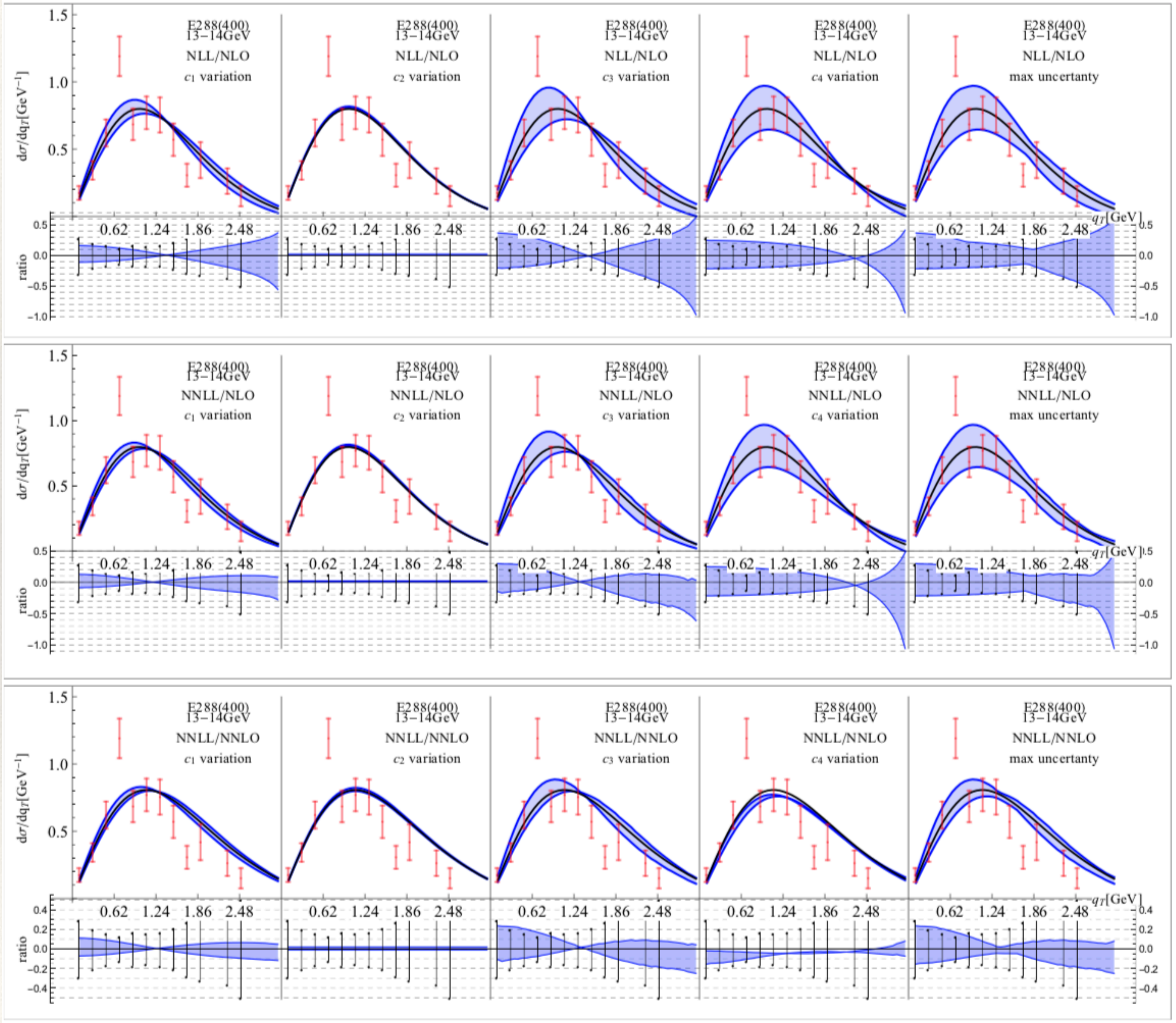




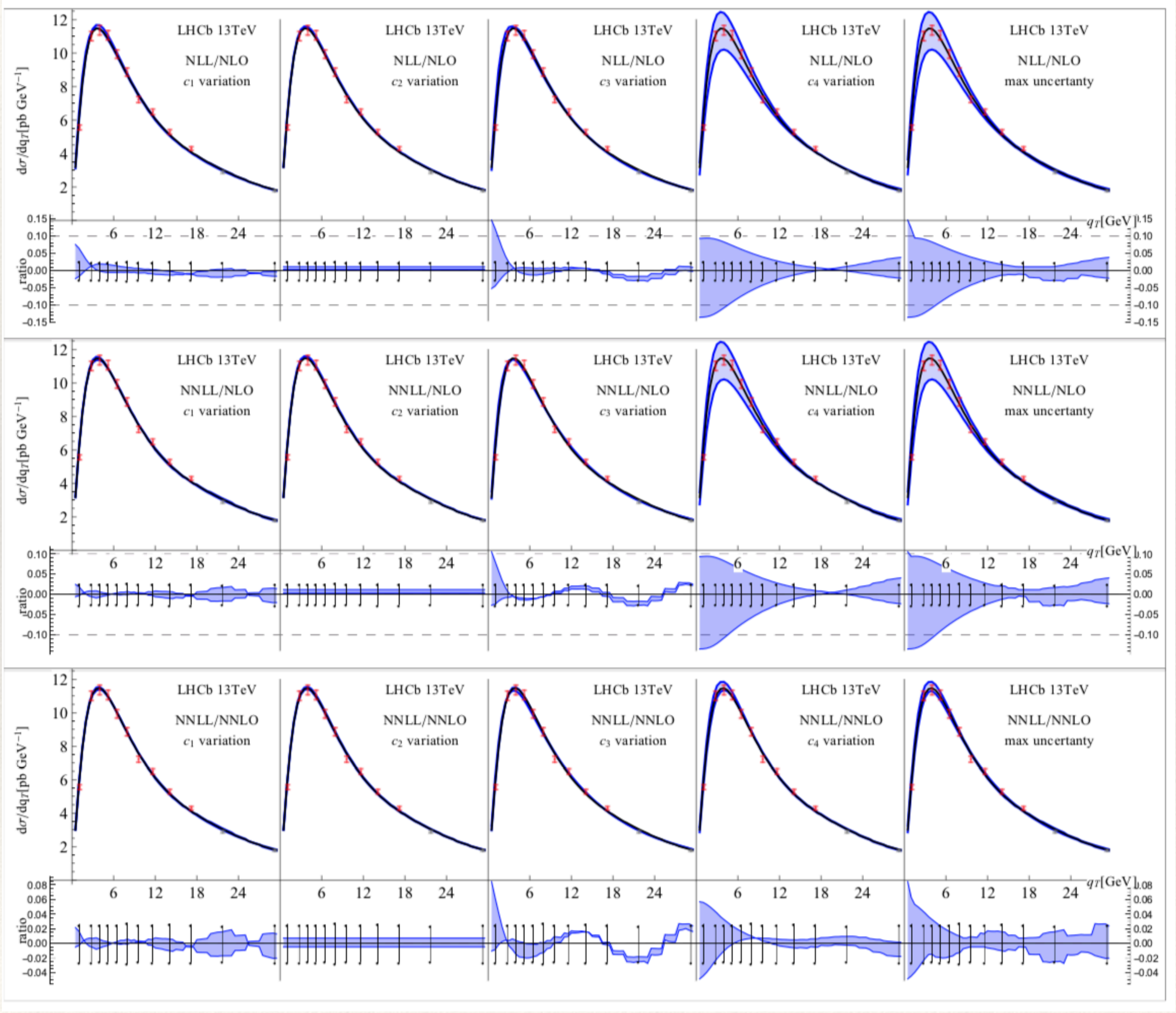
…and Drell-Yan at NNLO



Errors and orders: E288

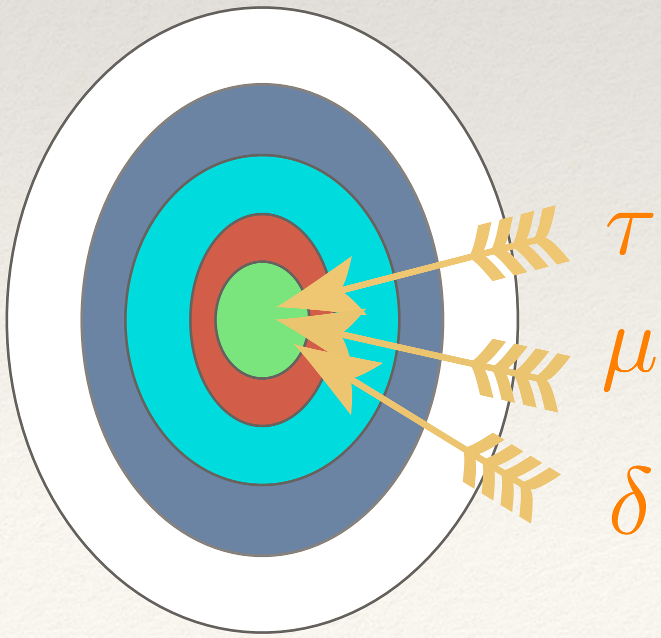


Errors and orders: LHCb



Conclusions

- A NNLO analysis is necessary for fitting data and extracting TMD (many issues solved just increasing the perturbative order).
- LHC provides very precise data that should be included in fits (especially data off the Z-boson peak). ATLAS and CMS could do better at 13 TeV!!
- We have discussed a number of issues which are relevant in TMD analysis (data choice, normalizations, prescriptions, scale choices, stability, theoretical errors,..etc.)
- All this is included in arTeMiDe (version 1.1)



Back up

Results of the fit

Data set	point	Model 1			Model 2		
		NLL/ NLO	NNLL/ NLO	NNLL/ NNLO	NLL/ NLO	NNLL/ NLO	NNLL/ NNLO
CDF run1	30	0.67	0.68	0.64	0.67	0.67	0.64
D0 run1	14	0.50	0.52	0.60	0.49	0.51	0.62
CDF run2	36	1.22	1.36	1.30	1.17	1.29	1.33
D0 run2	7	2.52	2.69	2.75	2.45	2.64	2.79
ATLAS (7TeV) Z-boson	9	1.54	1.55	2.01	1.60	1.59	2.27
ATLAS (8TeV) Z-boson	9	2.32	2.48	2.69	2.46	2.70	2.79
ATLAS (8TeV) 46-66 GeV	5	0.04	0.05	0.16	0.05	0.04	0.20
ATLAS (8TeV) 116-150 GeV	9	0.30	0.35	0.31	0.30	0.36	0.30
CMS (7 TeV)	7	1.38	1.39	1.36	1.38	1.38	1.36
CMS (8 TeV)	7	1.38	1.38	1.54	1.38	1.37	1.58
LHCb (7 TeV)	10	0.26	0.26	0.31	0.25	0.26	0.33
LHCb (8 TeV)	10	0.11	0.12	0.27	0.11	0.12	0.32
LHCb (13 TeV)	10	0.50	0.50	0.28	0.50	0.50	0.27
High energy data	163	0.95	1.00	0.94	0.94	1.00	1.04
E288(200) 4-5 GeV	5	3.86	4.28	3.86	4.25	4.59	4.30
E288(200) 5-6 GeV	6	3.00	3.03	1.92	3.05	3.07	1.92
E288(200) 6-7 GeV	7	1.68	1.68	0.84	1.66	1.67	0.79
E288(200) 7-8 GeV	8	1.10	1.10	0.93	1.13	1.11	1.00
E288(200) 8-9 GeV	9	1.83	1.84	0.78	1.89	1.87	1.87
E288(300) 4-5 GeV	5	1.93	2.20	4.09	2.24	2.44	4.90
E288(300) 5-6 GeV	6	1.15	1.18	1.15	1.19	1.21	1.21
E288(300) 6-7 GeV	7	0.84	0.83	0.66	0.85	0.83	0.69
E288(300) 7-8 GeV	8	1.18	1.17	0.90	1.16	1.17	0.86
E288(300) 8-9 GeV	9	1.13	1.14	1.13	1.11	1.36	1.10
E288(300) 11-12 GeV	12	1.08	1.08	1.00	1.11	1.10	1.04
E288(400) 5-6 GeV	6	2.11	2.04	1.12	1.94	1.92	1.01
E288(400) 6-7 GeV	7	2.59	2.68	2.55	2.59	2.64	2.55
E288(400) 7-8 GeV	8	0.83	0.97	2.02	0.99	1.07	2.44
E288(400) 8-9 GeV	9	1.36	1.31	1.37	1.37	1.32	1.54
E288(400) 11-12 GeV	12	1.08	1.06	1.25	1.05	1.05	1.17
E288(400) 12-13 GeV	12	0.88	0.88	1.10	0.87	0.88	1.14
E288(400) 13-14 GeV	12	0.39	0.38	0.72	0.39	0.39	0.71
Low energy data	146	1.38	1.41	1.35	1.50	1.48	1.49
Total	309	1.17	1.21	1.23	1.18	1.22	1.29

Tevatron Z-boson plots