# PDFs @ LO, NLO, NNLO with correlated uncertainties between orders.



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- Predictions for various processes @ LHC are available at LO, NLO, NNLO in pQCD. Each should be paired with PDFs extracted at appropriate order.
- Theoretical uncertainties arise from PDFs (PDF uncertainties) and missing higher orders (typically, µ<sub>R</sub> and µ<sub>F</sub> variations).
- > LO: used with parton showers. More details in the paper.
- > NLO: scale variations often exceed PDF uncertainties.



#### Motivation.

- Ratios of cross sections are used to reduce uncertainties (both theoretical and experimental).
- Precision of LHC data is comparable to accuracy of predictions. beneficial to use state-of-the-art predictions:





PDF uncertainties at

different orders!

- QCD fit to the combined HERAI data using the HERAFitter framework (talk by H. Pirumov).
- > 13-parameter HERAPDF-style parametrisation.
- > Include all 114 correlated point-to-point systematics.
- Vary model parameters and parametrisation following HERAPDF-like prescription to provide model and parametrisation uncertainties.

Settings	LO	NLO	NNLO
HF scheme	RT Opt	RT Opt	RT Opt
r <sub>s</sub>	1.0	1.0	1.0
m <sub>c</sub> [GeV]	1.38	1.38	1.32
m <sub>t</sub> [GeV]	14317.82	14317.82	14317.82
α <sub>s</sub>	0.13	0.1184	0.1184
$Q_0^2$ [GeV <sup>2</sup> ]	1.7	1.7	1.7
Q <sup>2</sup> <sub>min</sub> [GeV <sup>2</sup> ]	7.5	7.5	7.5



Slide 4

- Use MC replica method to preserve correlations between PDFs at different orders:
- > prepare O(1000) MC replicas of the data fluctuating the inputs within uncertainties using Gaussian probability densities;
- > do a consistent fit of PDFs at different orders to each replica;
- > covariance matrix/ratios can be built using individual PDF replicas;
- > central PDFs: average over replicas; 68% CL uncertainties: RMS.

#### Eigenvector representation is often more convenient:

- Extract full covariance matrix for PDFs at the starting scale on the QCDNUM x-grid;
- > diagonalise the covariance matrix and keep leading eigenvalues to capture all features of correlations;
- > do DGLAP evolution of the tabulated central and eigenvetrors using QCDNUM.



## **QCD fit quality.**

#### arXiv:1404.4234



 Mean of the χ<sup>2</sup> distributions agrees with the expectation 2·N<sub>dof</sub>. Clear correlation of the quality of the fits at NLO and NNLO.



#### **Eigenvector representation.**

#### arXiv:1404.4234



The eigenvectors reproduce the original uncertainties extracted from MC PDF replicas very good.



### **Correlation of PDFs at different orders.**

#### MC replicas Eigenvectors 100 100 180 Number 160 140 180<mark>- U,</mark> 160 NNLO 50 -50 140 120 120 100 100√ 0 80 80 60 60 NLO -50 > -50 40 40 20 20 -100-100 20 40 60 80 100120140160180 20 40 60 80 100120140160180 NLO **NNLO Bin Number** MC replicas Eigenvectors 100 180 Number 160 140 100 180<mark>- g</mark> 160 NNLO 50 50 140 120 120 100 100√ 0 80 80 60 60 NLO -50 -50 40 40

20

20

NLO

40 60 80 100120140160180

**NNLO** 

-100

#### arXiv:1404.4234

- The eigenvectors reproduce the correlation patterns very good.
- High degree of
   correlation between
   neighboring x points:
   smooth
   parametrisation and
- parametrisation and constraints from similar data.
- A strong correlation between NLO and NNLO PDFs (mild for

high-x gluon).



Anchor points: 10<sup>-5</sup>, 0.01, 0.1, 0.4, 0.7

**Bin Number** 

20 40 60 80 100120140160180

20

M. Lisovyi | DIS 2014 | 29/04/2014 | Slide 8

-100

- WW measurements @ LHC are 1-2·σ away from the NLO QCD predictions. Higher orders? EW corrections? New physics?
- Build ratio to the Z cross sections: cancel part of experimental and theoretical (same initial state at LO) uncertainties. But no rigorous path to benefit from existing NNLO QCD Z predictions.
- > Use correlated PDFs to make the optimal predictions for WW/Z ratio.
- Compare predictions to the recent WW/Z measurement by CMS (arXiv:1306.1126).
- > Use MCFM 6.6 for WW and FEWZ for Z.



#### W<sup>+</sup>W<sup>-</sup>/Z: correlations.

#### arXiv:1404.4234

Cross section	Value	Exp. PDF	Mod. PDF	Scale	Correlation coefficient		
	$\rm pb$	$\mathrm{pb}$	$\mathrm{pb}$	$\mathrm{pb}$	$\sigma_Z^{ m NLO}$	$\sigma_Z^{ m NNLO}$	$\sigma^{ m NLO}_{WW}$
$\sigma_Z^{ m NLO}$	29890	$\pm 450$	$+490 \\ -490$	$+680 \\ -940$	1	0.697	0.736
$\sigma_Z^{ m NNLO}$	30390	$\pm 420$	$+520 \\ -540$	$^{+190}_{-260}$	0.697	1	0.451
$\sigma_{WW}^{ m NLO}$	46.1	$\pm 0.6$	+0.7 -0.6	$^{+1.5}_{-1.4}$	0.736	0.451	1



- Experimental (Exp.) PDF uncertainties are strongly correlated between Z@NNLO and WW@NLO.
- Model and parametrisation (Mod.) PDF uncertainties are somewhat anticorrelated.



# W<sup>+</sup>W<sup>-</sup>/Z: model and parametrisation uncertainties.

arXiv:1404,4234

Variation	$\sigma_{WW}^{ m NLO}$	$\sigma_Z^{ m NLO}$	$\sigma_Z^{ m NNLO}$	-	Variation	$\sigma_{WW}^{ m NLO}$ / $\sigma_{Z}^{ m NLO}$	$\sigma_{WW}^{ m NLO}$ / $\sigma_{Z}^{ m NNLO}$
	%	%	%			$\times 10^{-3}$	$\times 10^{-3}$
$r_s(-0.3)$	1.00	-0.29	-0.33		$r_{s}(-0.3)$	0.020	0.020
$r_s(+0.3)$	-0.81	0.39	0.42		$r_s(+0.3)$	-0.018	-0.019
$M_c(-0.06 \text{ GeV})$	-0.81	-0.89	-0.76		$M_c(-0.06 \text{ GeV})$	0.001	-0.001
$M_c(+0.06~{\rm GeV})$	0.55	0.66	0.61		$M_c(+0.06 \text{ GeV})$	-0.002	-0.001
$M_b(-0.45 \text{ GeV})$	0.13	0.11	-0.02		$M_b(-0.45 \text{ GeV})$	0.000	0.002
$M_b(+0.25 \text{ GeV})$	-0.07	-0.07	0.00		$M_b(+0.25 \text{ GeV})$	0.000	-0.001
$\alpha_S(M_Z)(-0.002)$	-0.54	-1.27	-1.17		$\alpha_S(M_Z)(-0.002)$	0.011	0.010
$\alpha_S(M_Z)(+0.002)$	0.52	1.23	1.17		$\alpha_S(M_Z)(+0.002)$	-0.011	-0.010
$Q_{\rm min}^2(-2.5~{\rm GeV^2})$	-0.25	-0.35	0.23		$Q^2_{\rm min}(-2.5~{\rm GeV^2})$	0.002	-0.007
$Q_{\min}^2(+2.5 \text{ GeV}^2)$	0.75	0.73	-1.06		$Q_{\min}^2(+2.5 \ { m GeV^2})$	0.000	0.028
$Q_0^2(-0.2 \ { m GeV^2})$	-0.21	-0.19	-0.14		$Q_0^2(-0.2 \ { m GeV^2})$	0.000	-0.001
$+D_{u_v}$	-0.03	-0.32	0.97		$+D_{u_v}$	0.005	-0.015
$+D_{\bar{U}}$	-0.04	-0.02	-0.01		$+D_{\bar{U}}$	0.000	-0.001
$+E_{\bar{U}}$	0.01	0.00	0.00	_	$+E_{\bar{U}}$	0.000	0.000

- > r is anti-correlated between Z and WW.
- >  $M_{c}$ ,  $M_{b}$ ,  $\alpha_{s}$  are correlated and mostly cancel in the ratio.
- The low-Q<sup>2</sup> DIS data have anti-correlated effect on Z at NLO and at NNLO



# W<sup>+</sup>W<sup>-</sup>/Z: predictions vs. data.

Exp. PDF Mod. PDF Scale Ratio Value 🗱 Exp. 🕀 Mod. 🕀 Scale √s = 7 TeV  $\times 10^{-3}$  $\times 10^{-3}$  $\times 10^{-3}$  $\times 10^{-3}$ Exp. ⊕ Mod.  $\frac{\sigma_{WW}^{\rm NLO}}{\sigma_Z^{\rm NLO}}$ Exp. +0.069+0.0231.543 $\pm 0.008$ -0.021-0.058 $\frac{\sigma_{WW}^{\rm NLO}}{\sigma_Z^{\rm NNLO}}$ +0.036+0.0501.517 $\pm 0.010$ -0.046-0.027 $\sigma_{WW}^{NLO}$  /  $\sigma_{Z}^{NNLO}$  $\sigma_{WW}^{
m NLO}/\sigma_Z^{
m NNLO}$  $= [1.517^{+0.051}_{-0.047}] \times 10^{-3}$  $\sigma_{WW}^{NLO}$  /  $\sigma_{Z}^{NLO}$  $\sigma_{WW}^{\rm NLO} / \sigma_Z^{\rm NLO} = [1.543^{+0.073}_{-0.062}] \times 10^{-3}$ HERAFitter 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2  $10^3$  imes  $\sigma_{ww}$  /  $\sigma_z$ 

- > Predictions agree with the data within  $1-2\sigma$ .
- > The total theoretical uncertainty is reduced by 30-40%.
- The usage of the mixed-order calculations with new PDFs with correlations between orders allow to benefit from cancellation of experimental PDF uncertainties and reduction of the scale uncertainties.



arXiv:1404 4234

- Sets of LO, NLO and NNLO PDFs correlated at different orders were extracted using HERAFitter.
- The MC method was used to determine the experimental PDF uncertainties. The uncertainties were decomposed into the eigenvector representation.
- > A high degree of correlation was observed for PDFs at different orders and similar x.
- The correlated NLO and NNLO PDFs were used to calculate WW/Z ratio. Significant correlation of the PDF uncertainties was observed.
- The total theoretical uncertainty is reduced for the mixed-order calculation by 30-40% due to reduced scale uncertainties.
- > PDFs will be released in LHAPDF v6 soon: HF14cor\*







#### **NLO-NNLO correlations (cont.)**



#### WW/Z : correlation of experimental uncertainties

