Towards a NNLO global analysis of helicity PDFs

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Precision QCD predictions for ep physics at the EIC (II) Center for Frontiers in Nuclear Science, Stony Brook September 2023

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In collaboration with **Ignacio Borsa**
Daniel de Florian
Marco Stratmann
Werner Vogelsang

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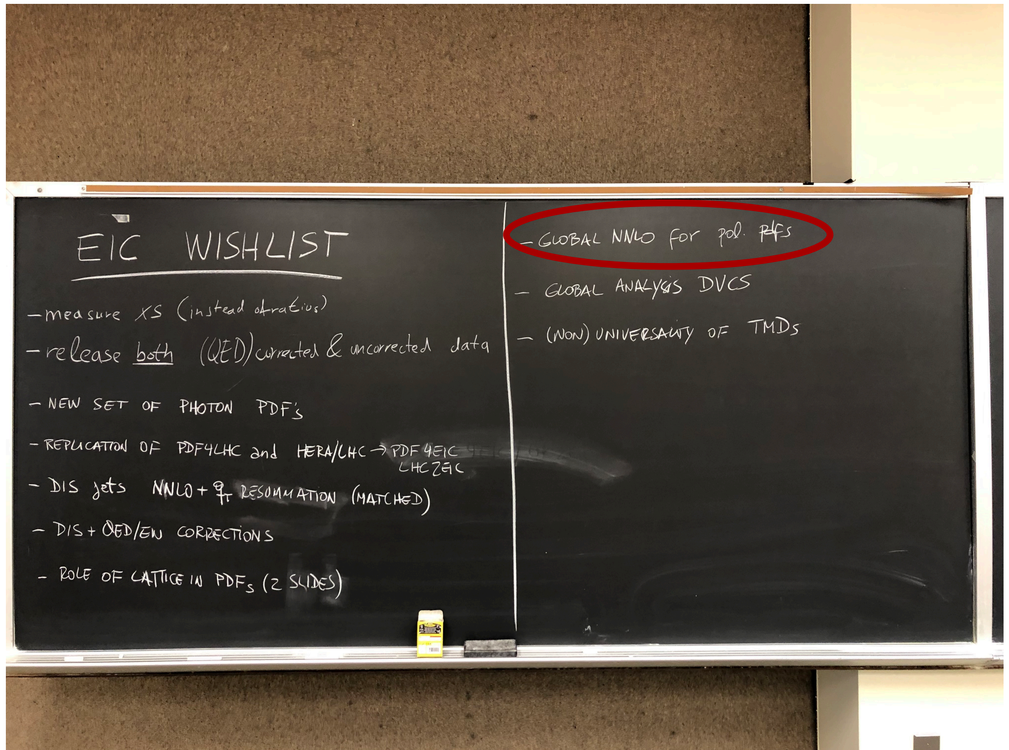

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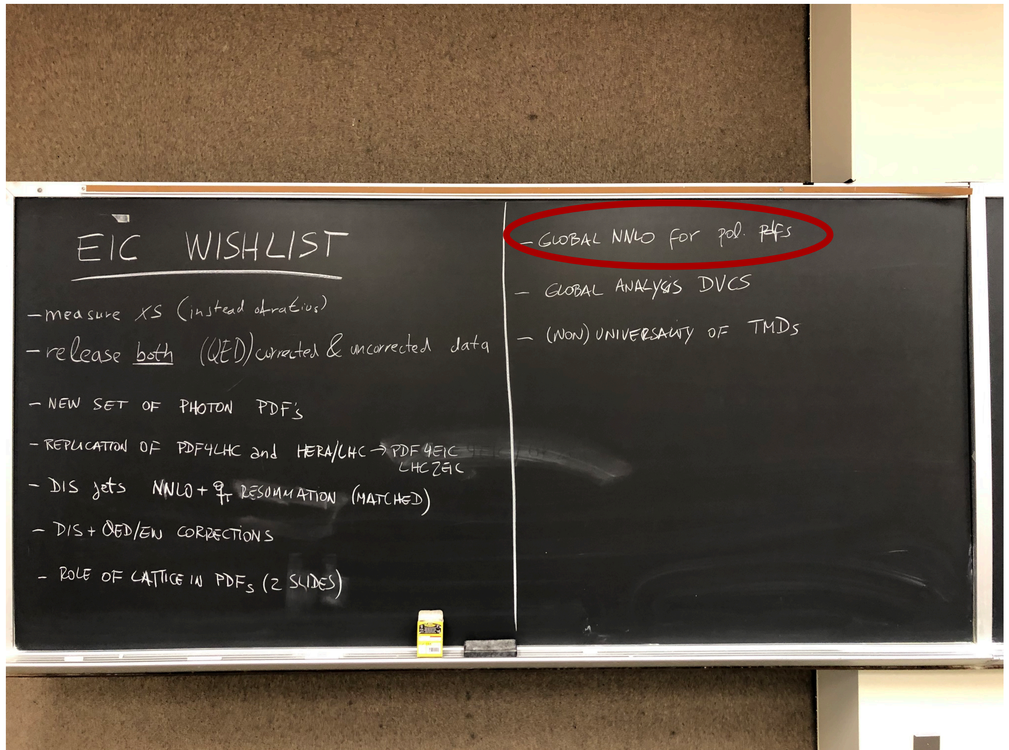

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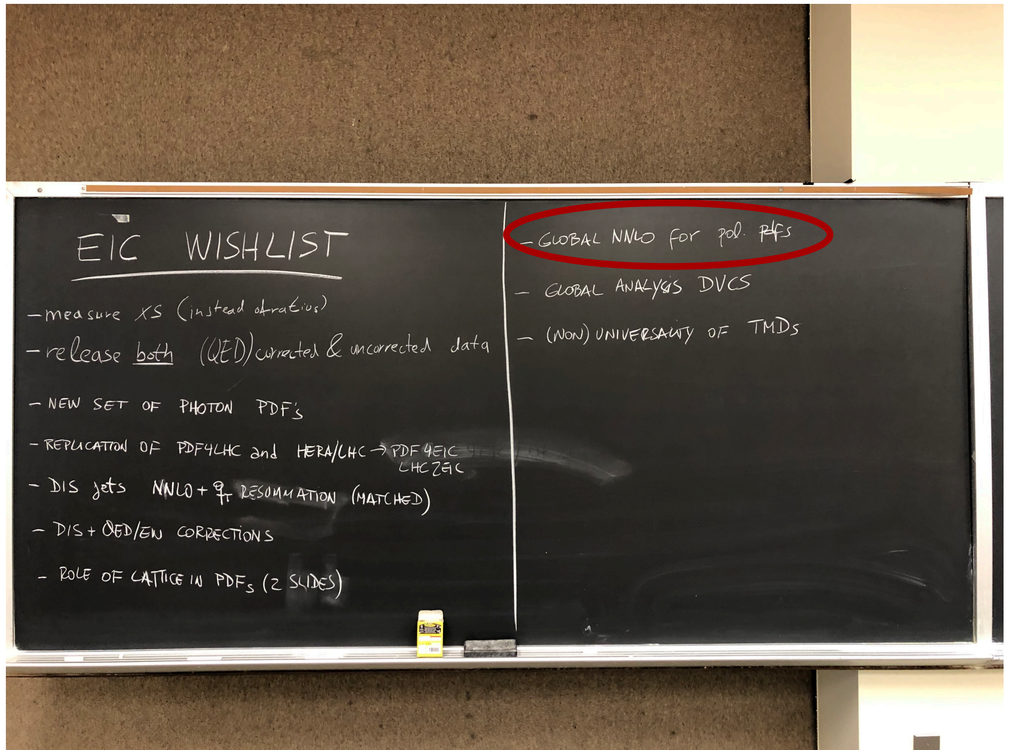

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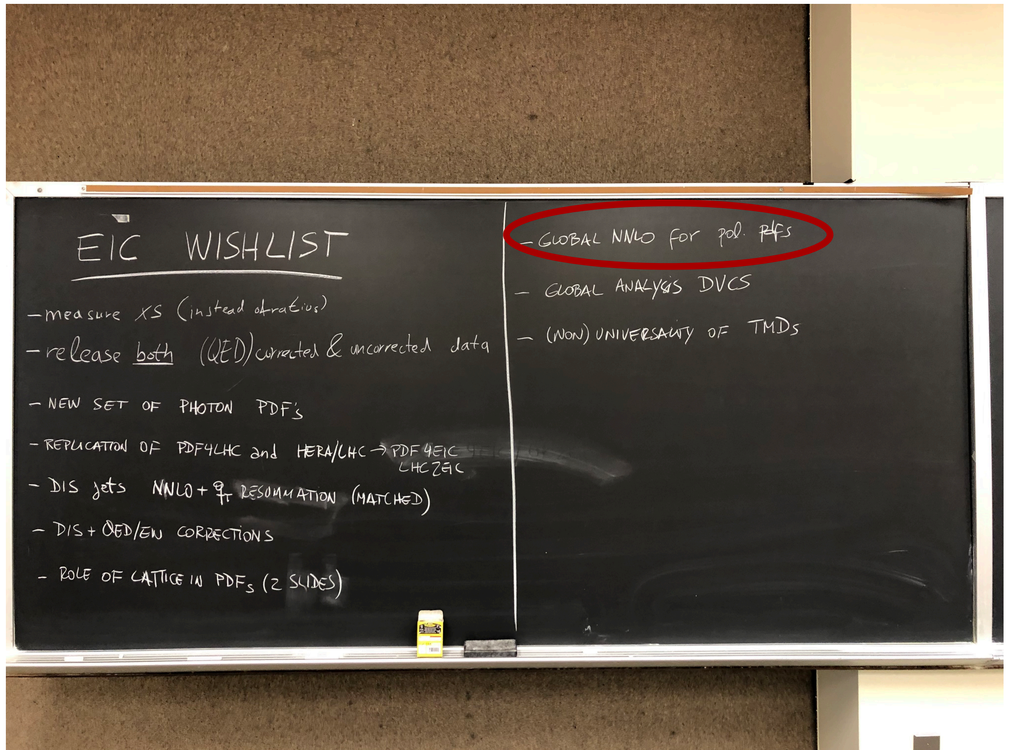
How ready are we to implement them and analyze EIC data?



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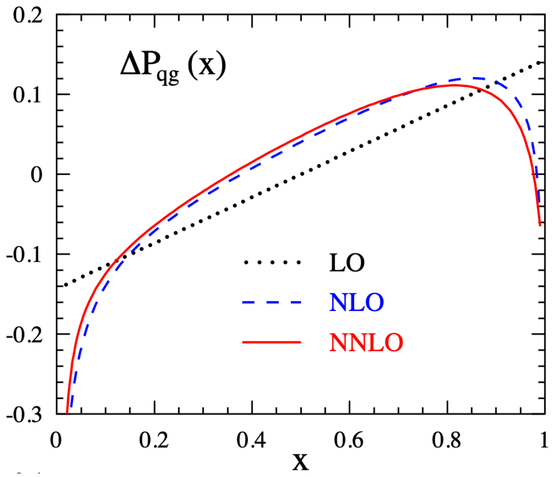

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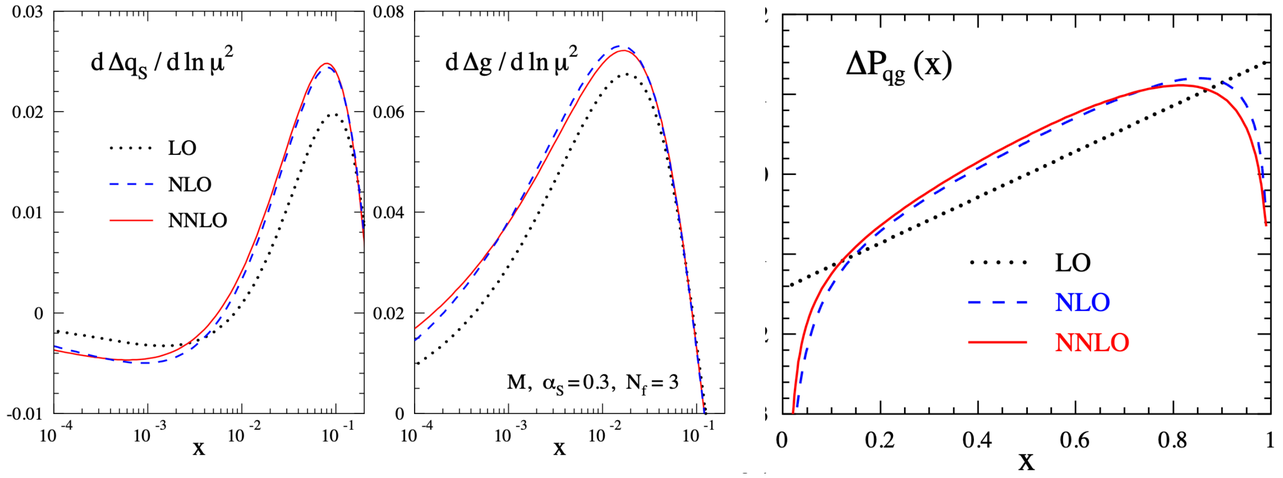

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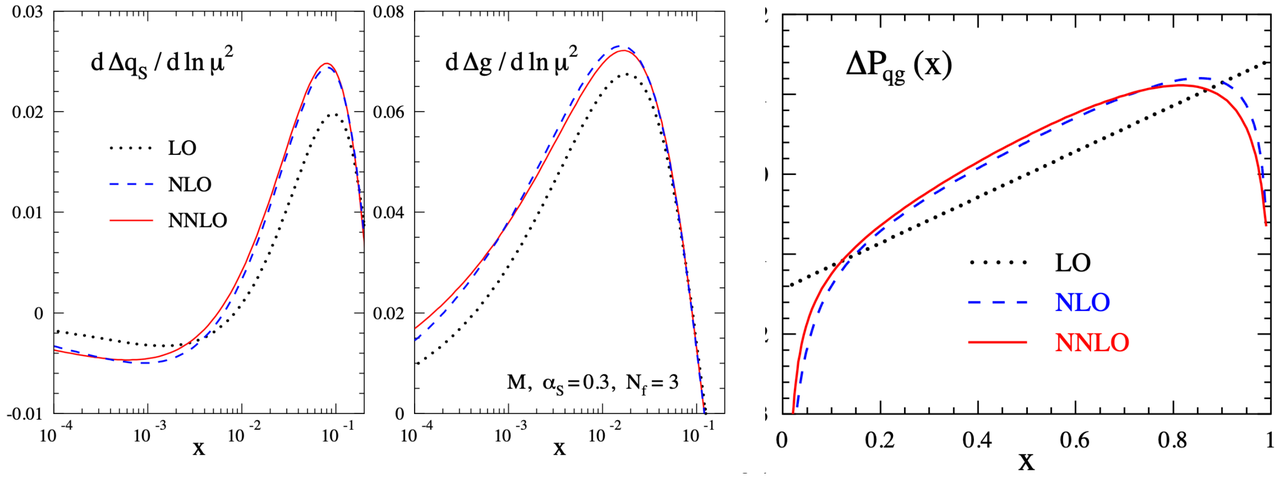

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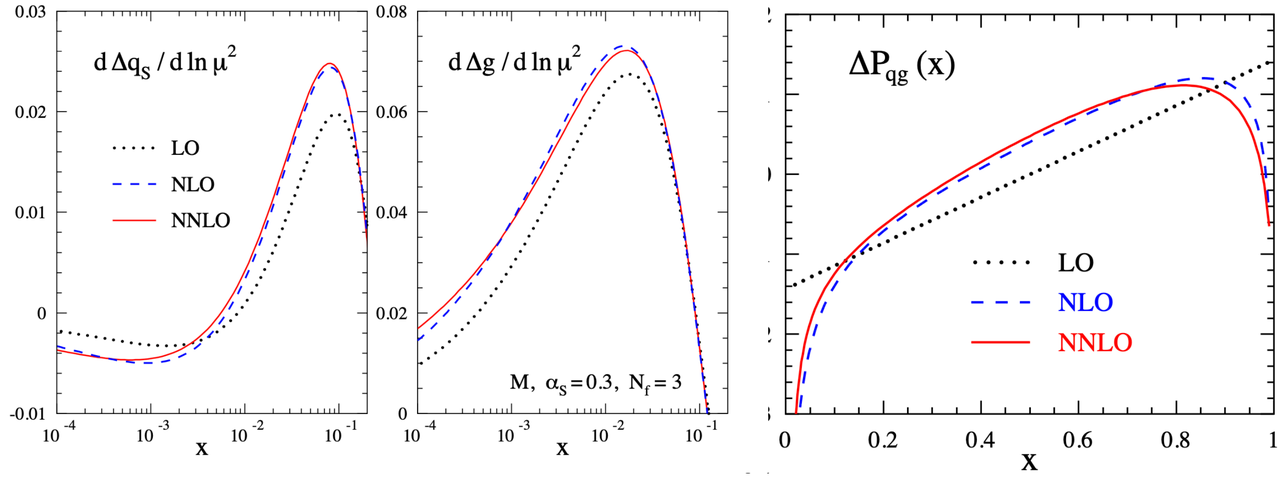

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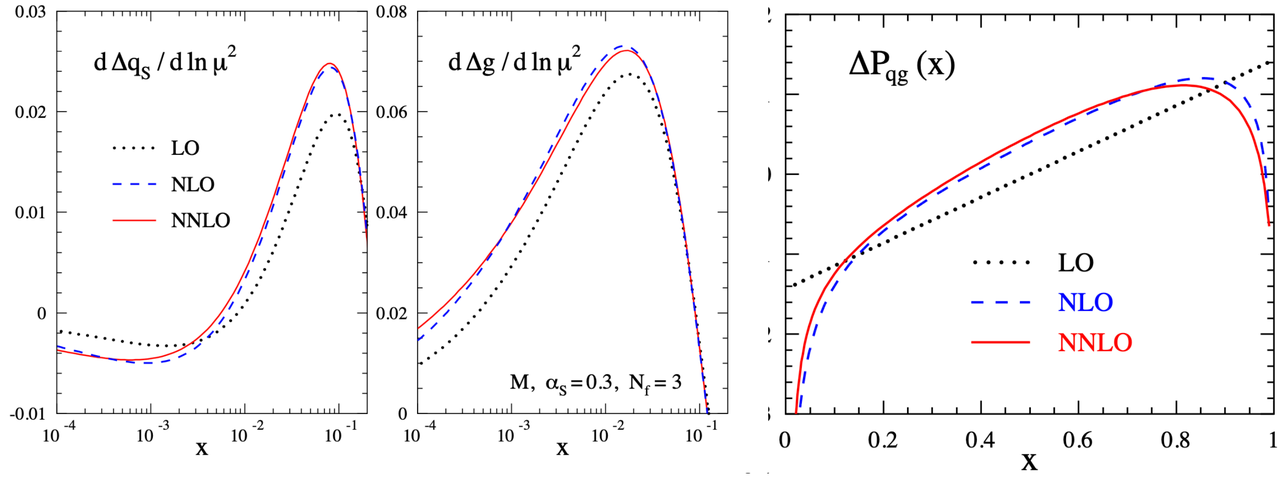

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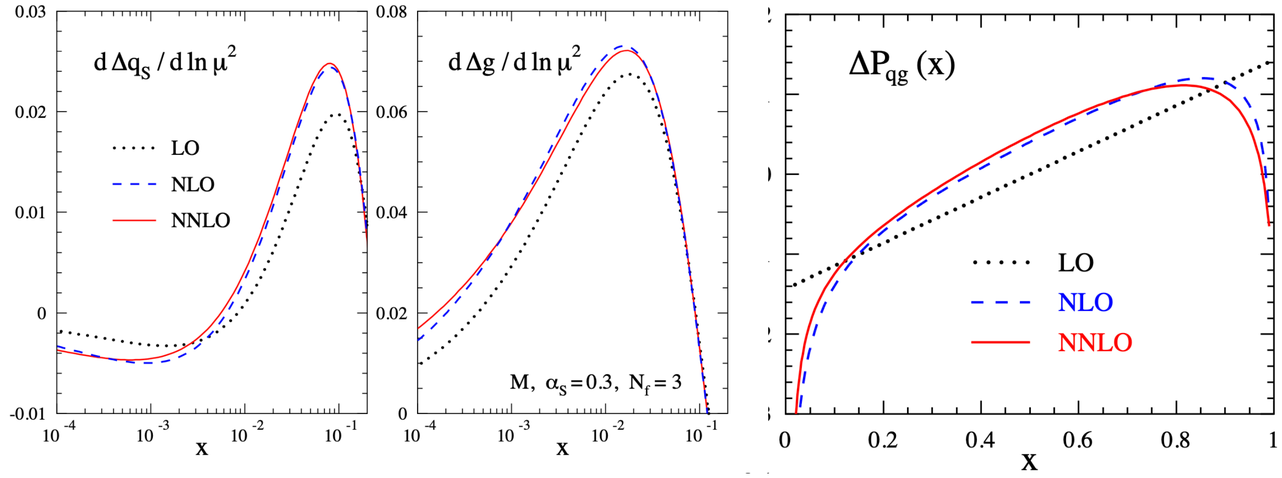

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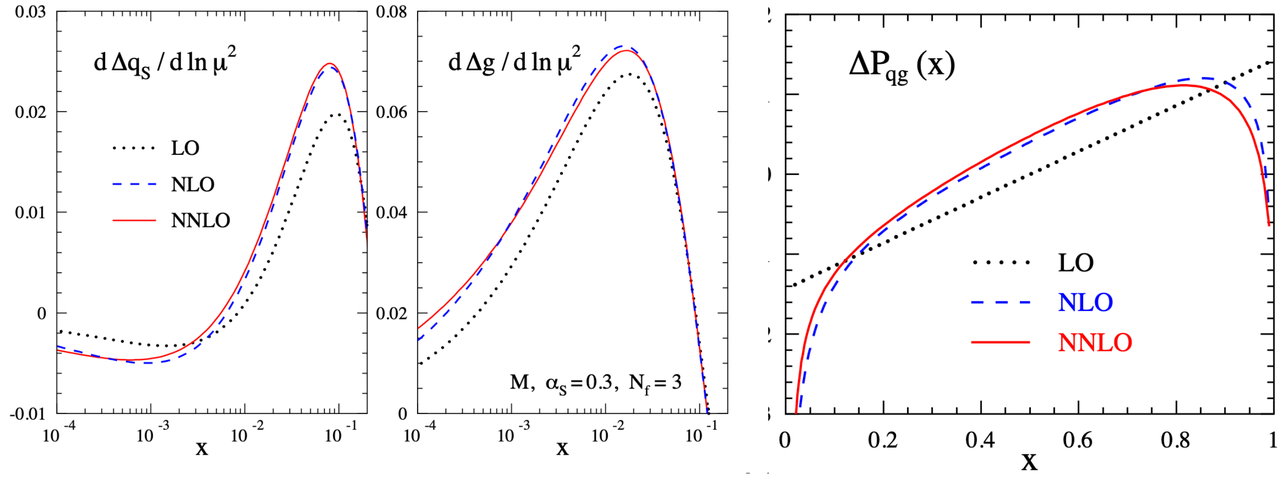

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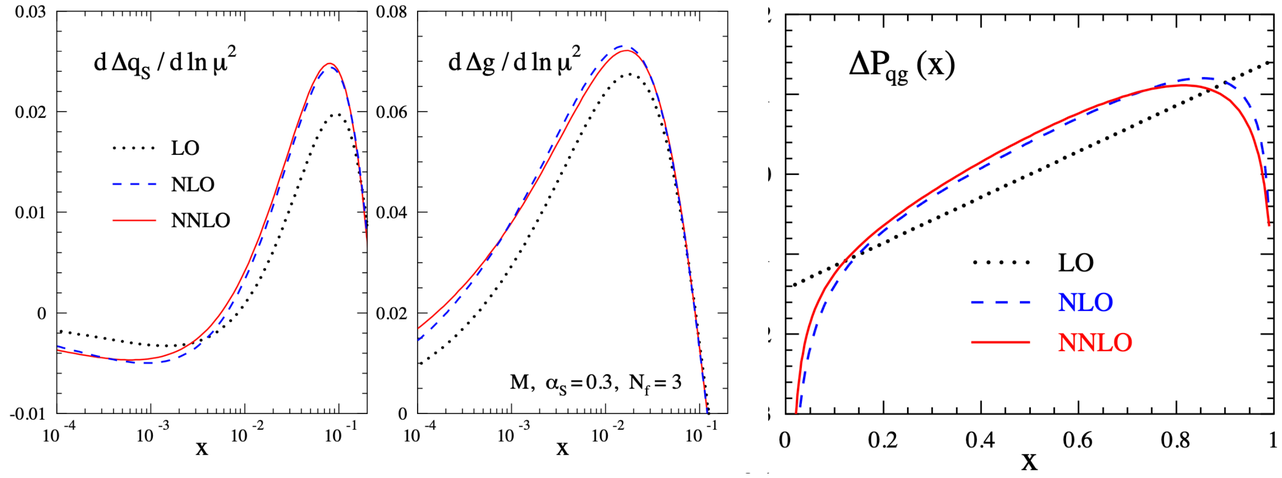

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$$\Delta v^{\pm}_l = \sum_{i=1}^{k} (\Delta q_i \pm \Delta \bar{q}_i) - k(\Delta q_k \pm \Delta \bar{q}_k) \qquad l = k^2 - 1 \quad k = 1,\ldots,n_f$$

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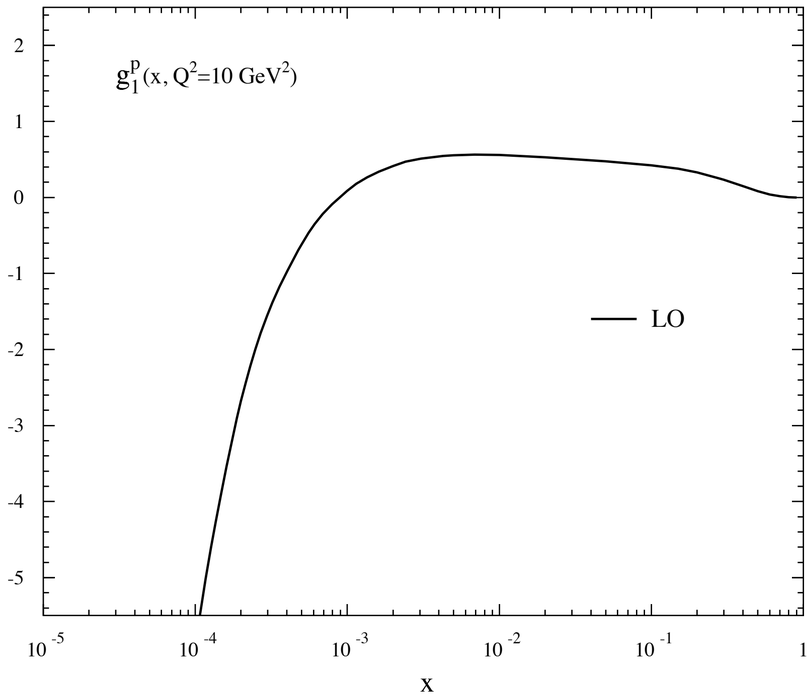

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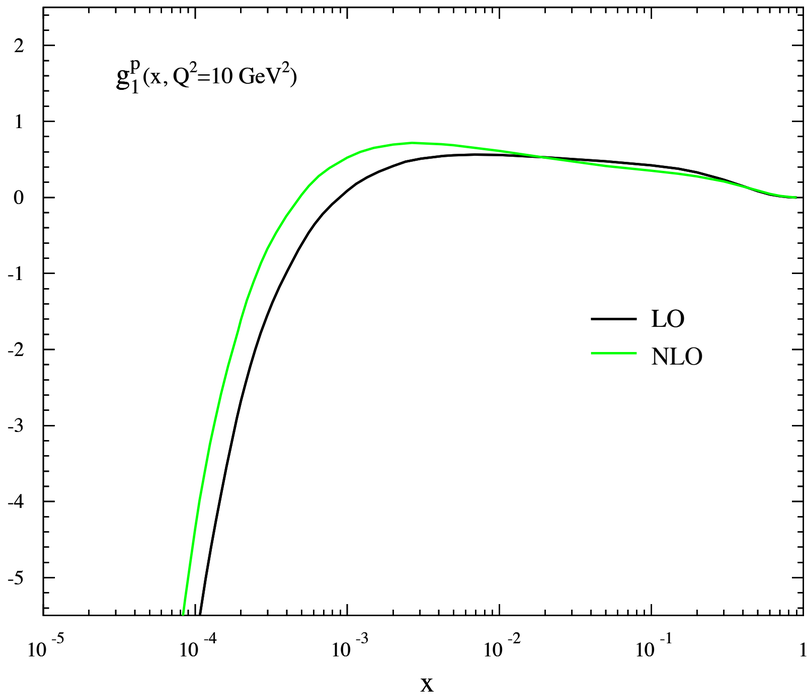

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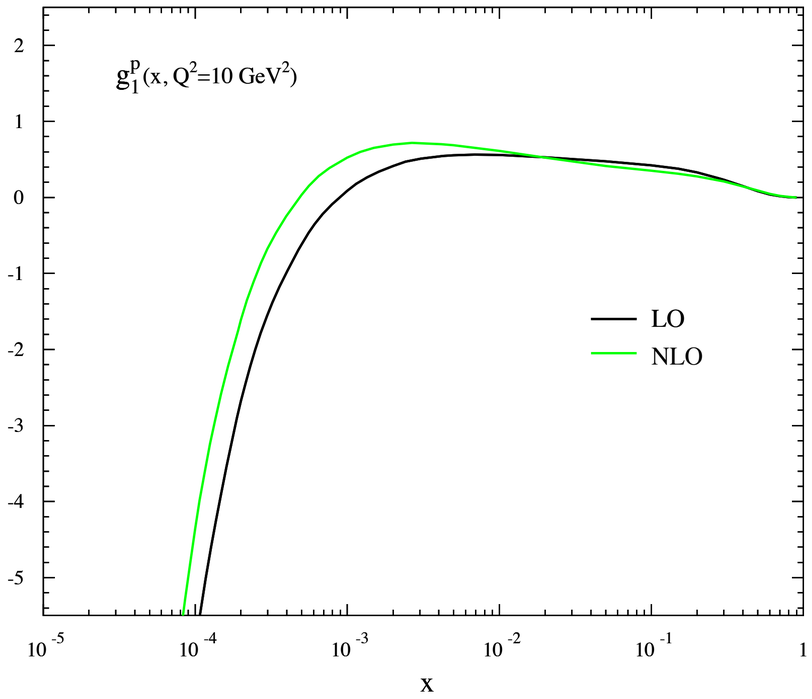

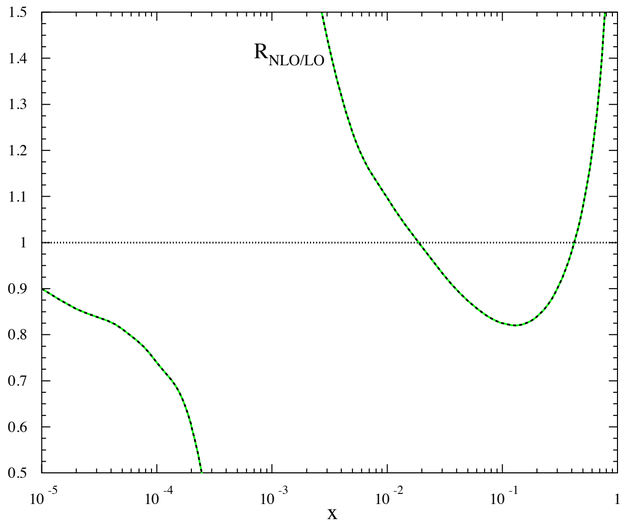

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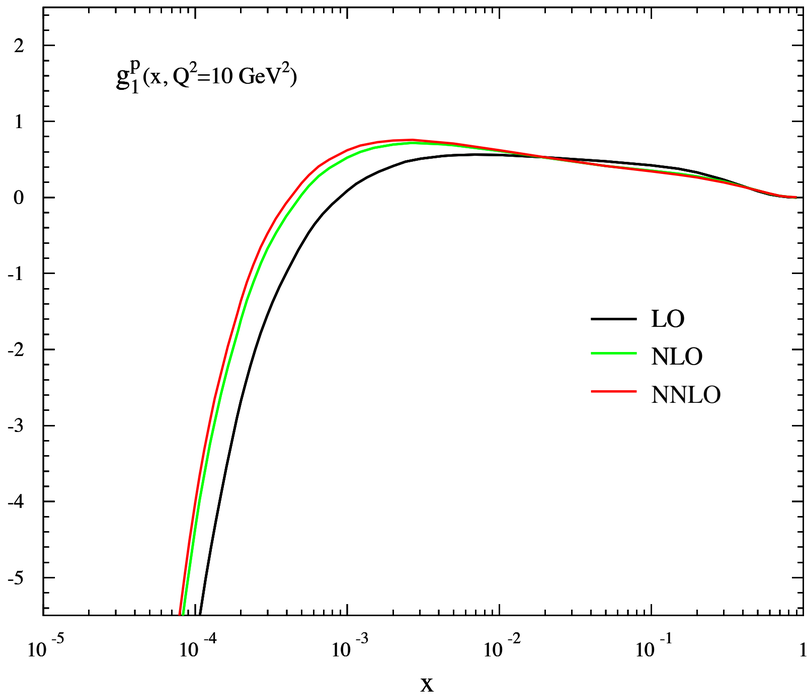

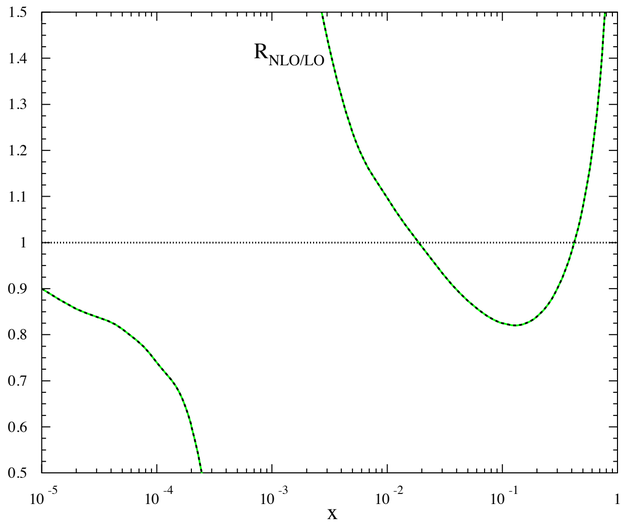

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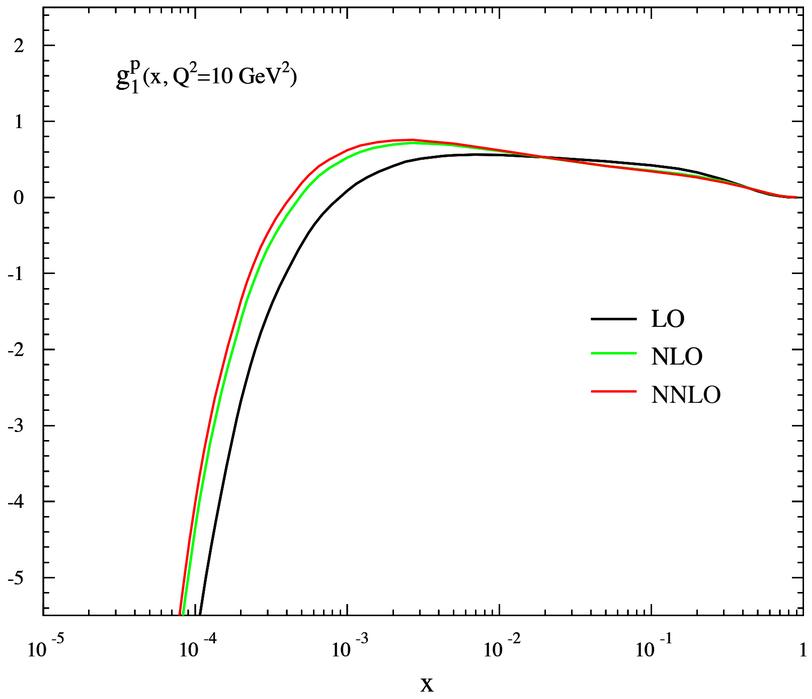

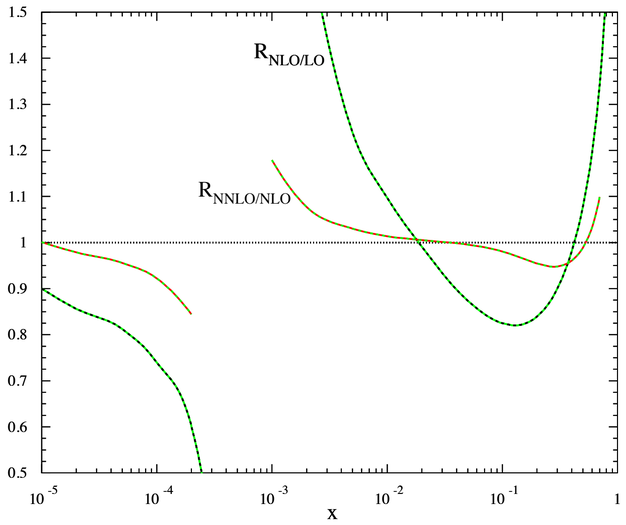

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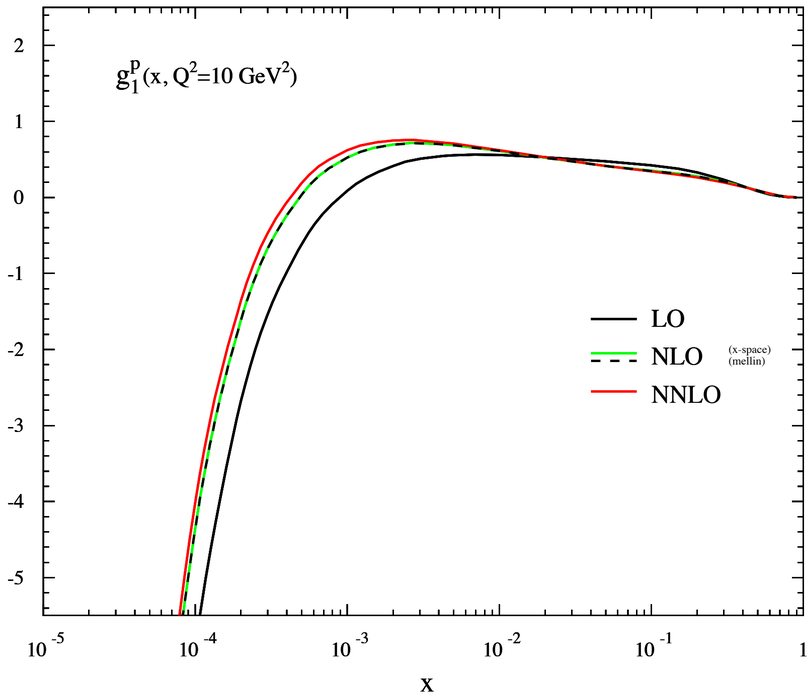

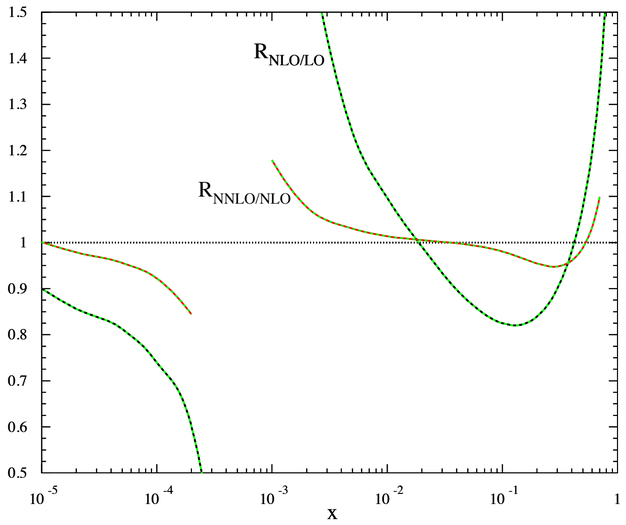

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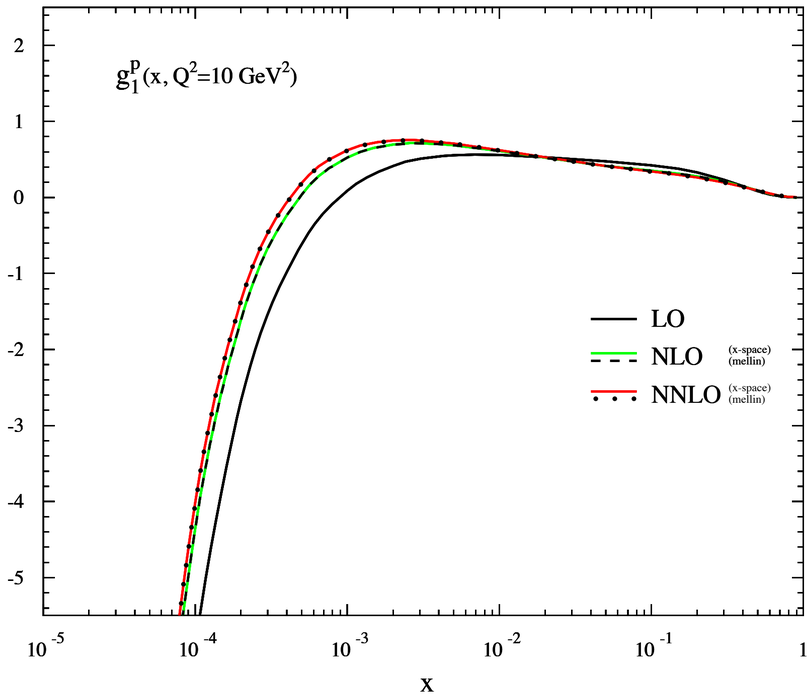

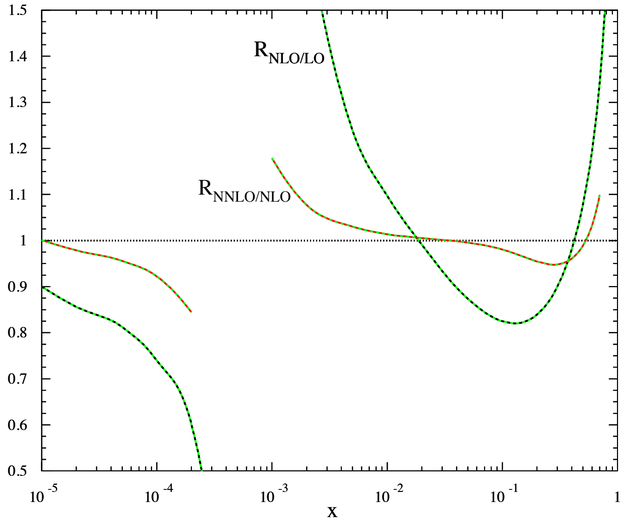

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g_1 **coefficients at** $\mathcal{O}(\alpha_s^2)$ **(massless, x-space)** E. B. Zijlstra and W. L. van Neerven, Nucl. Phys. B 417, 61 (1994) and erratum

Mellin moments computed with MT Mathematica package M. Hoeschele, Jens Hoff, A. Pak, M. Steinhauser, T. Ueda arXiv:1307.6925

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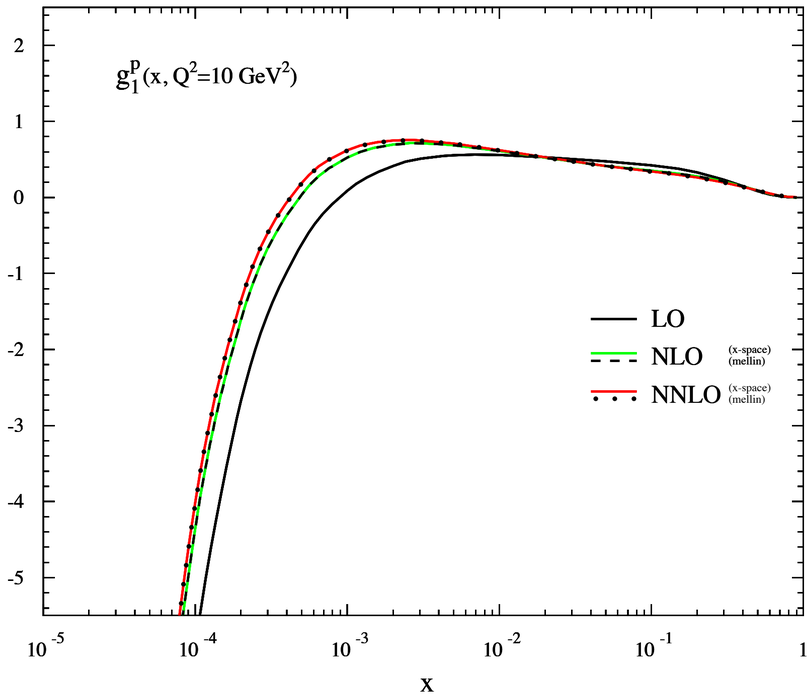

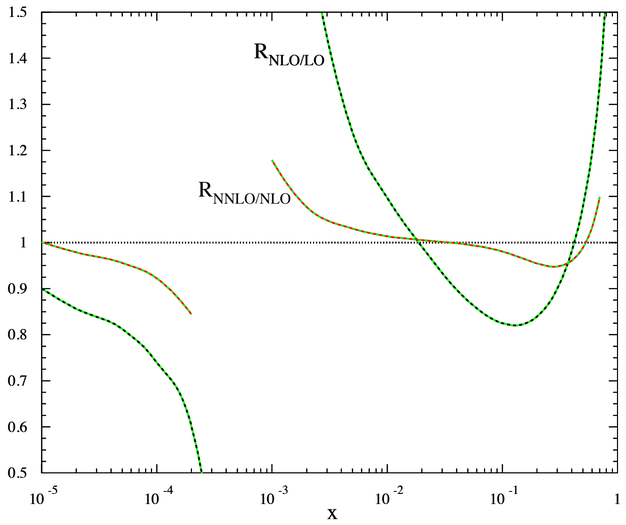

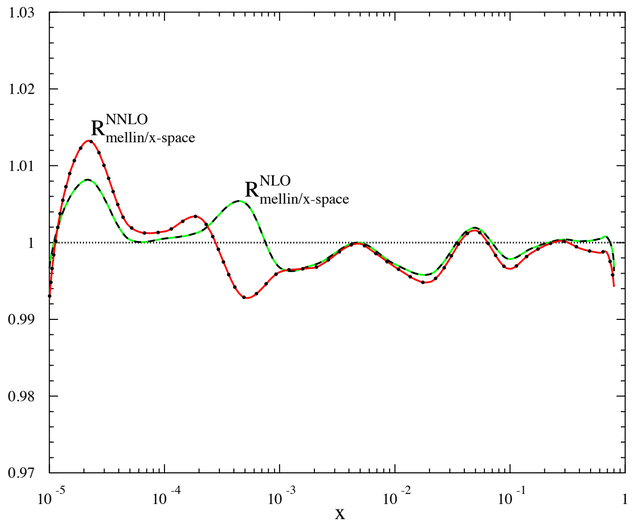

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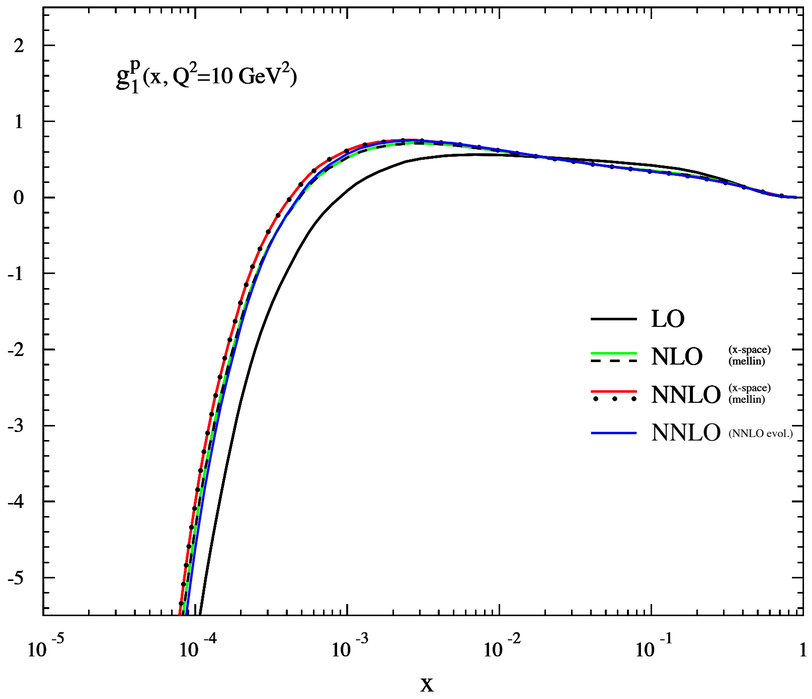

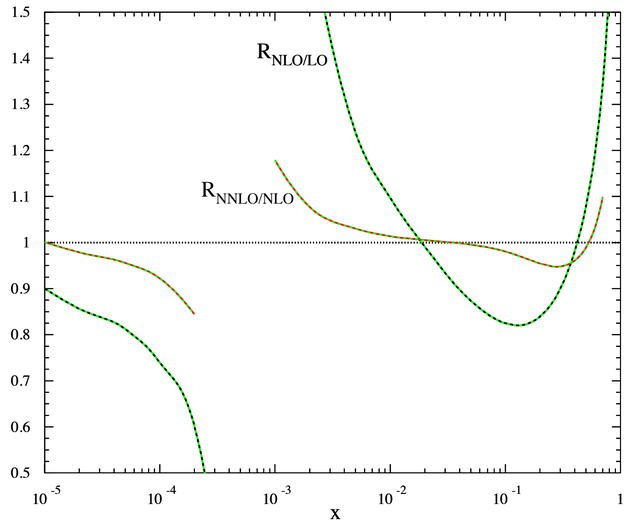

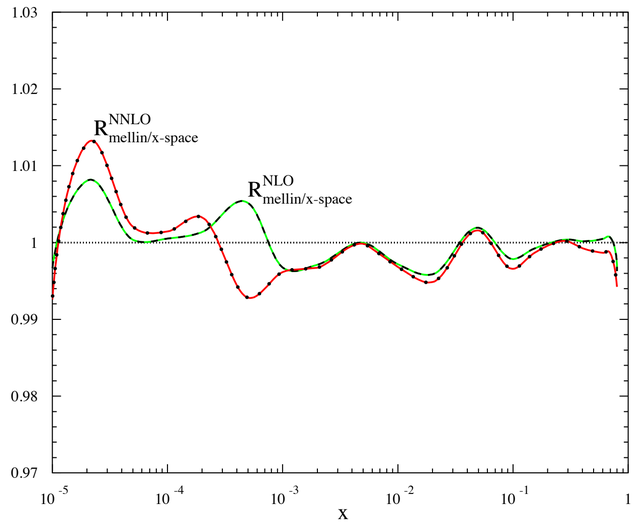

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Δv_3^+, Δv_8^+, $\Delta\Sigma$, Δg

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DIS: EMC,SMC,E142,E143,E154,E155, HERMES, COMPASS, HALL-A,CLAS (p,n,d,He) **378**

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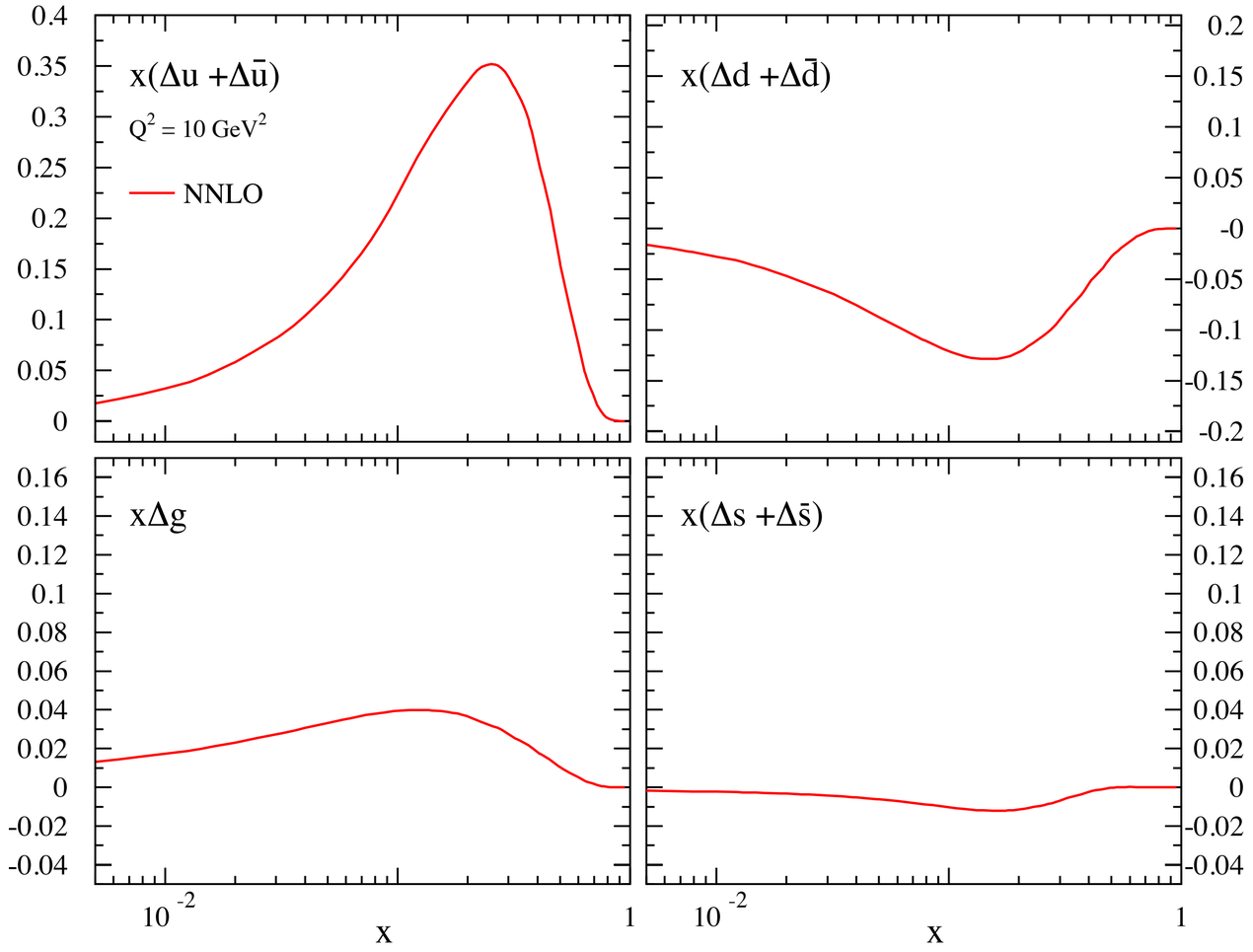
$\chi^2_{NNLO} = 385\ \ (378)$



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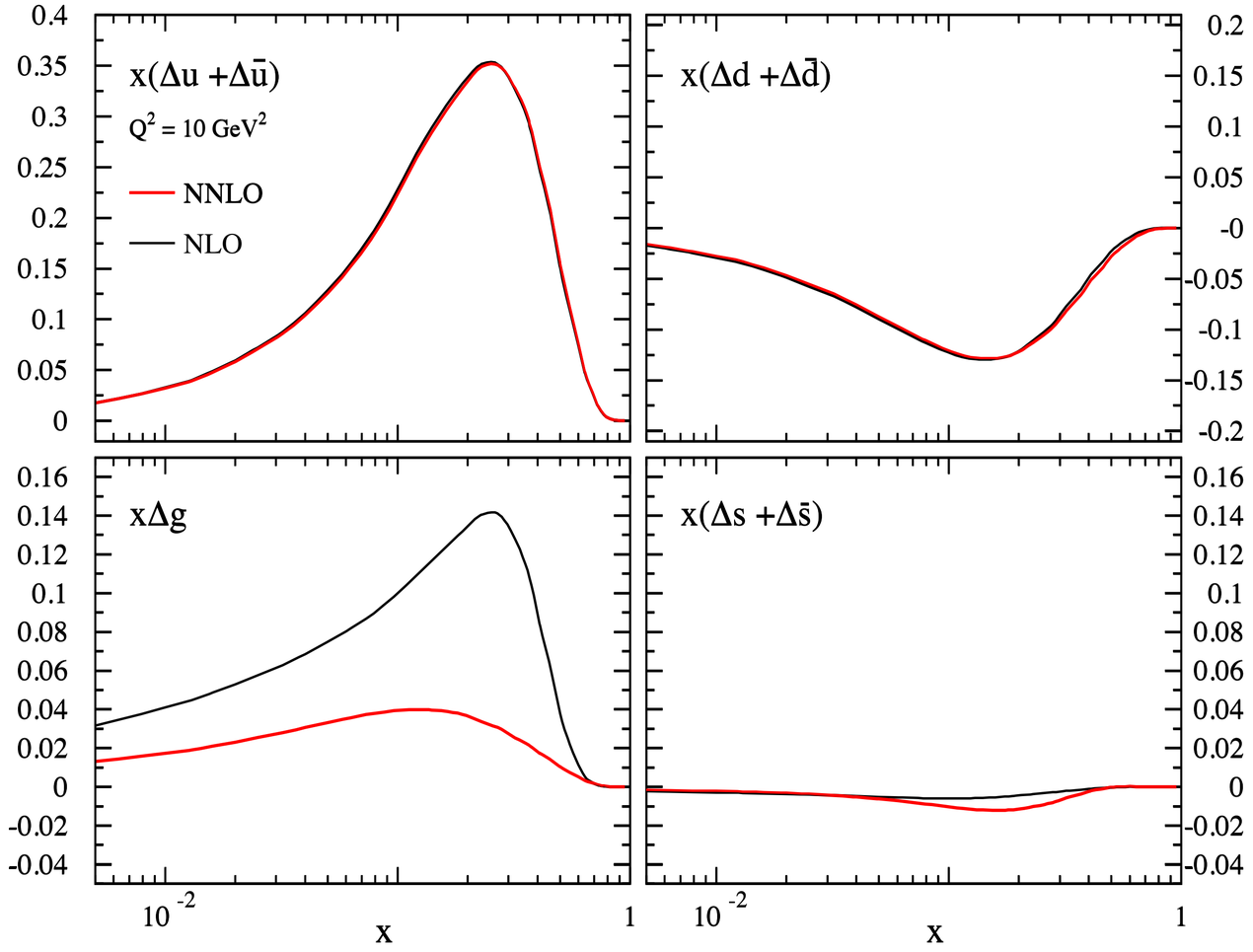

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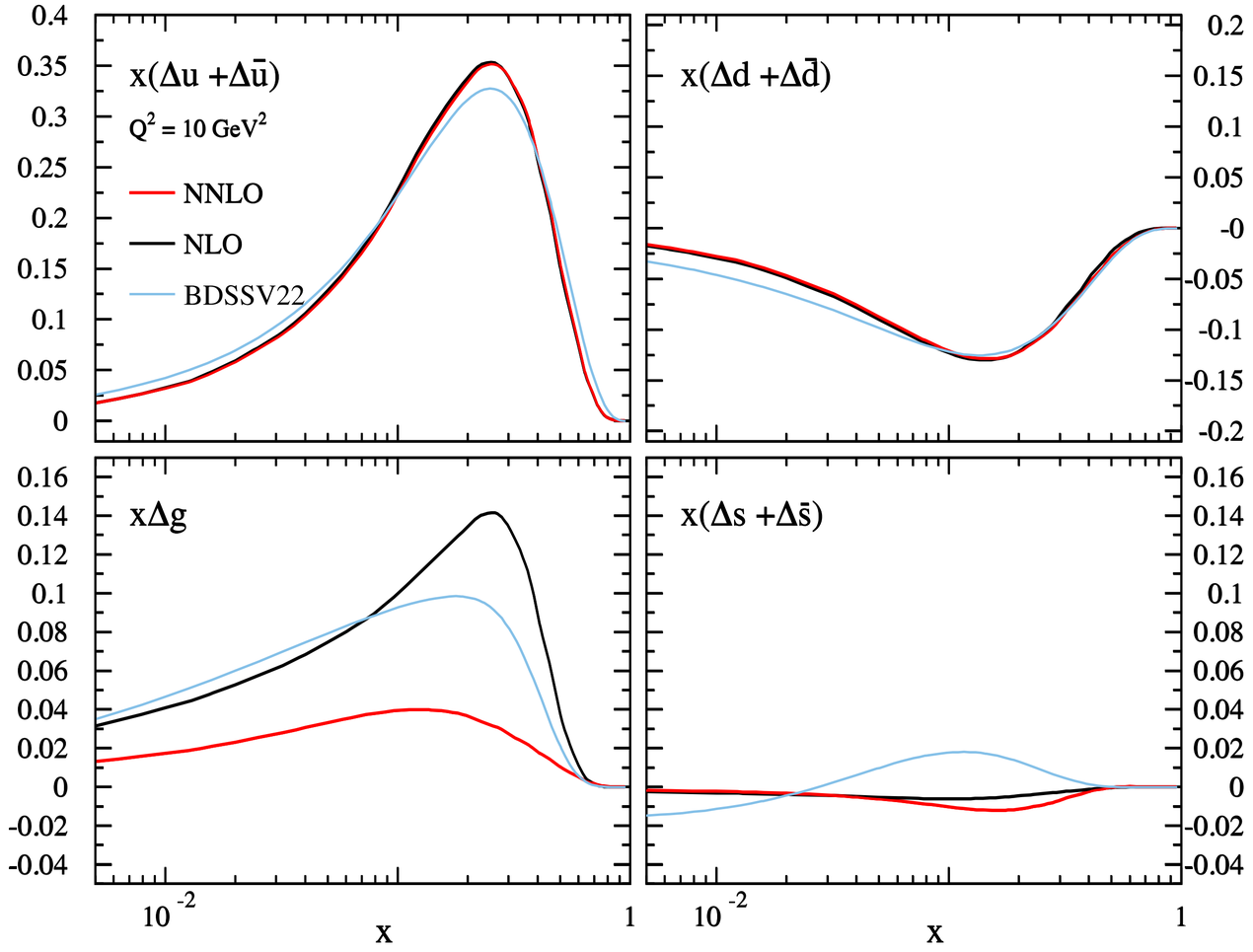

$g_1^h(x, z, Q^2)$:

M. Abele, D. de Florian, W. Vogelsang arXiv:210900847

$g_1^h(x, z, Q^2)$: “threshold resummation”

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M. Cacciari, S. Catani hep-ph/0107138

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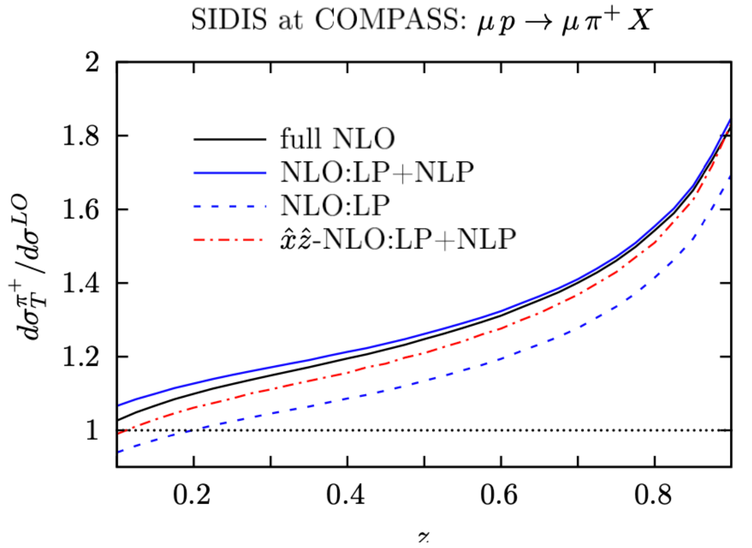

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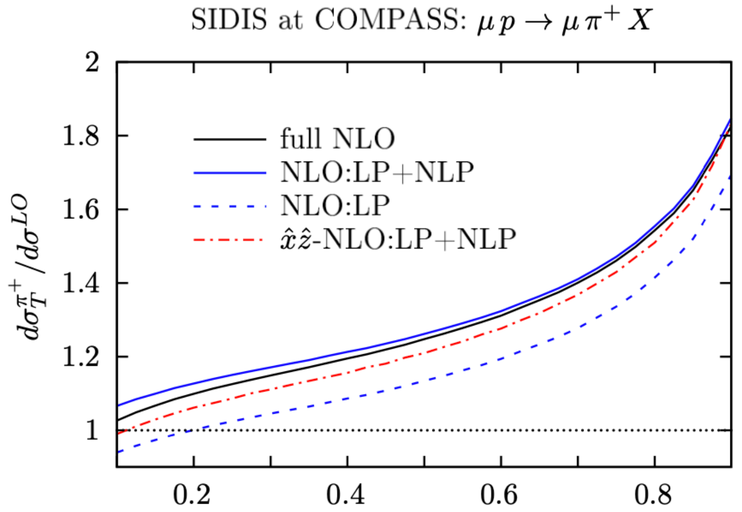

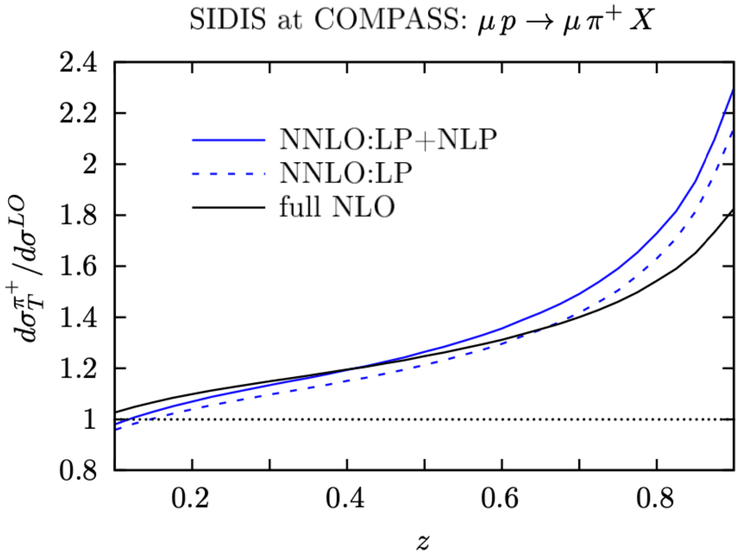

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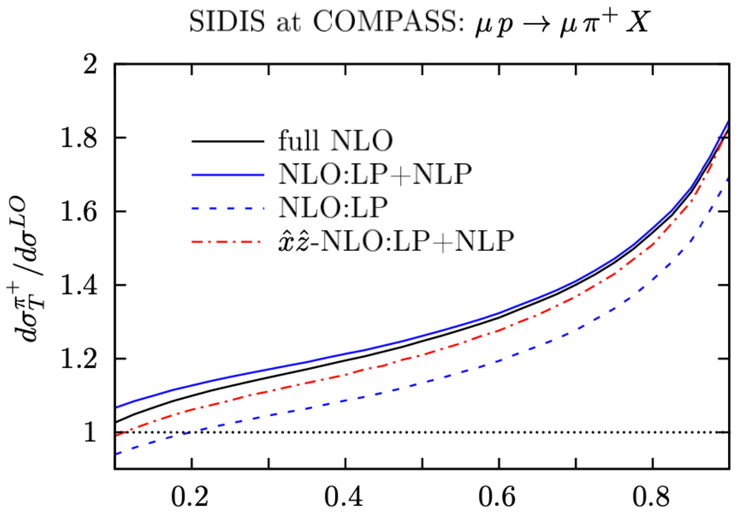

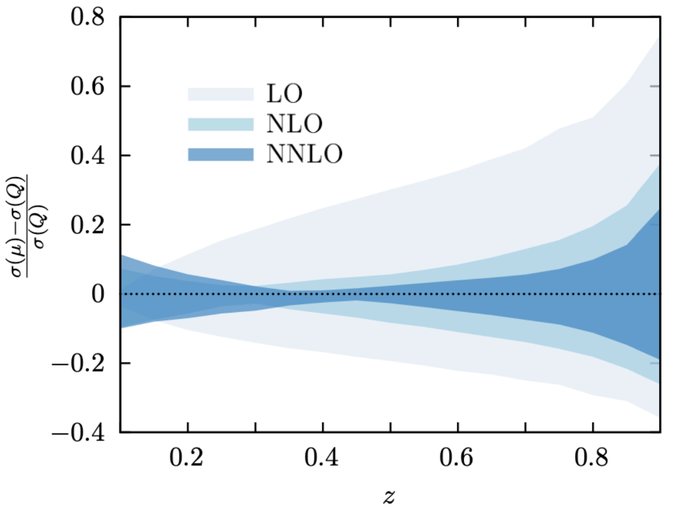

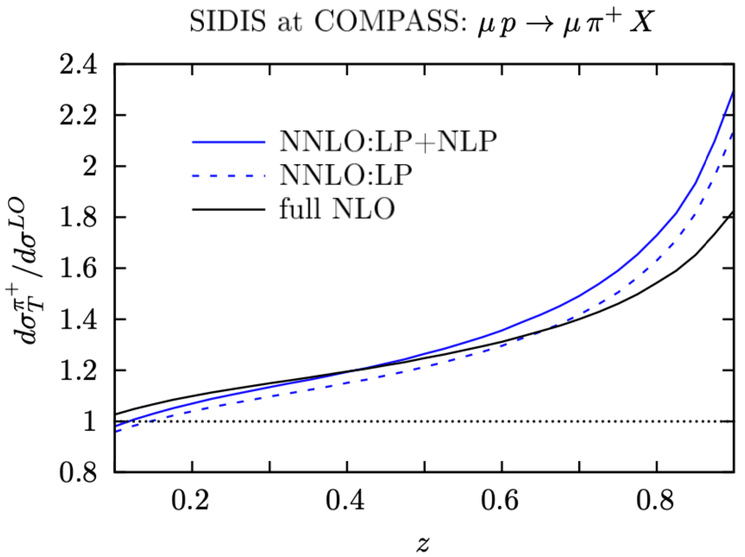

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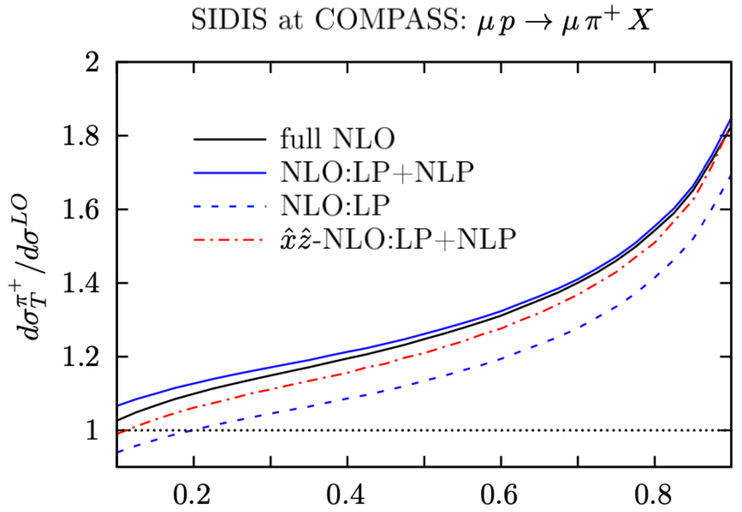
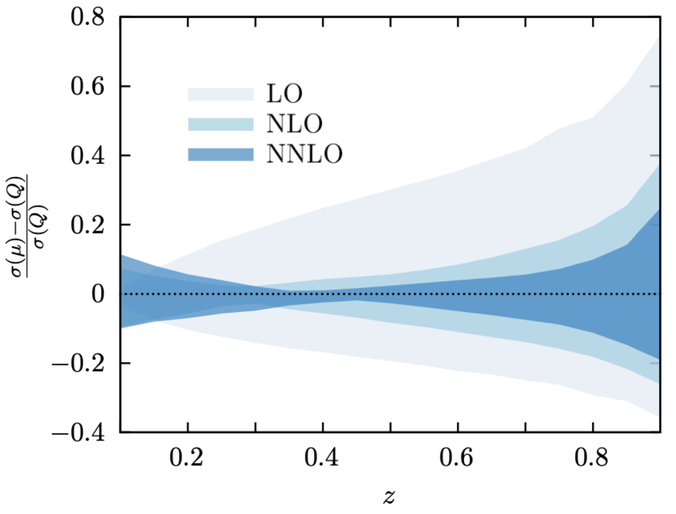
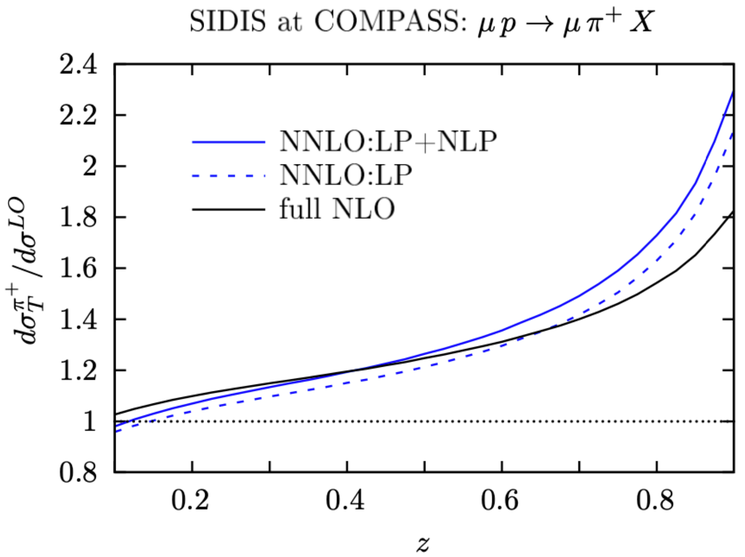
Already in Mellin space ✔







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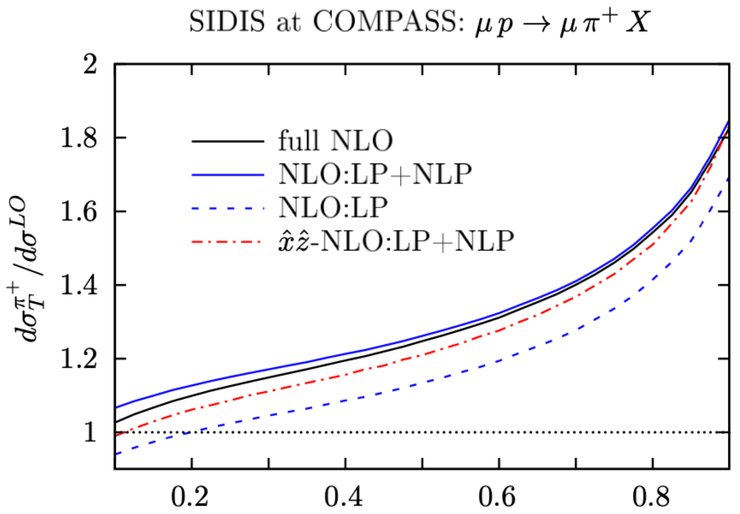
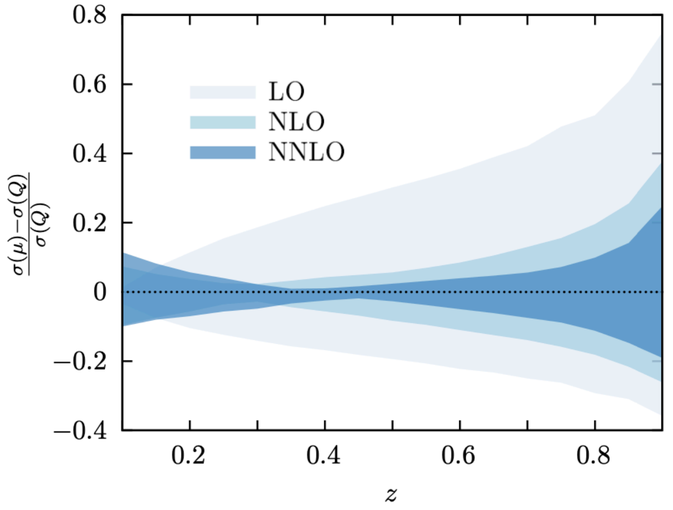
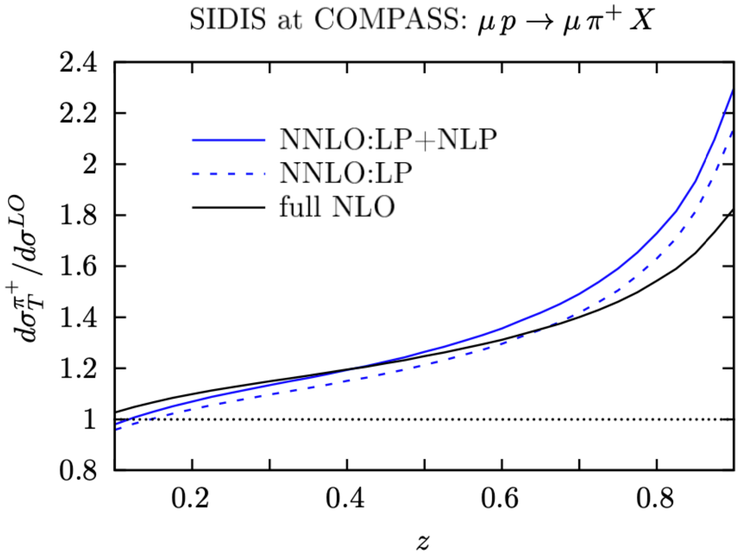


Already in Mellin space ✔

Already used for “NNLO” FFs

I. Borsa, D. de Florian, R. S., M. Stratmann W. Vogelsang arXiv:210900847





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$\sigma(pp \longrightarrow hadron + X)$ **“threshold resummation 2.0”**

D. de Florian, W. Vogelsang in preparation

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D. de Florian, W. Vogelsang in preparation

$\sigma(pp \longrightarrow jet + X)$

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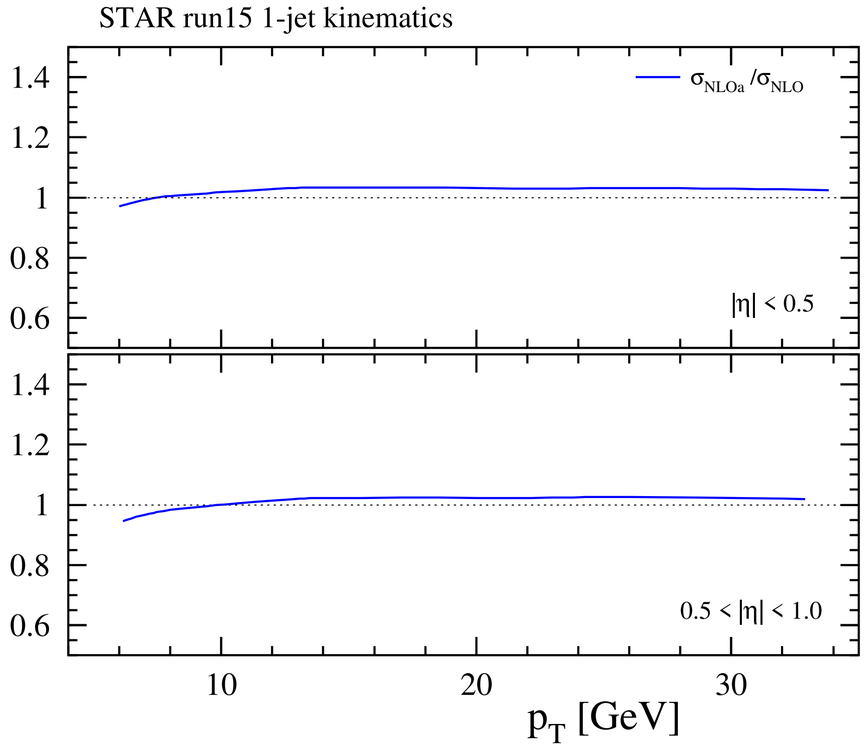

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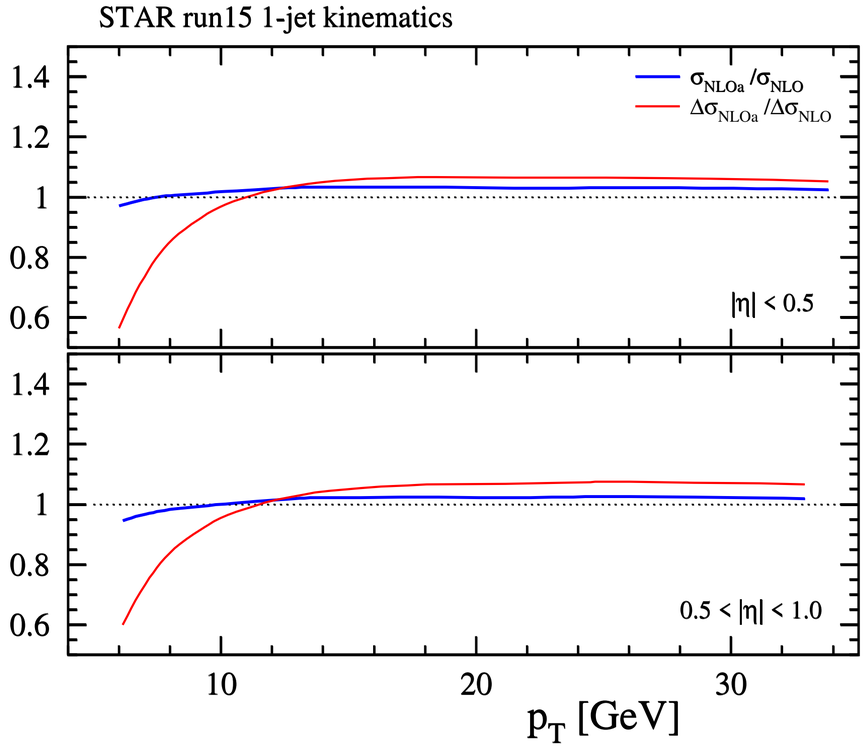

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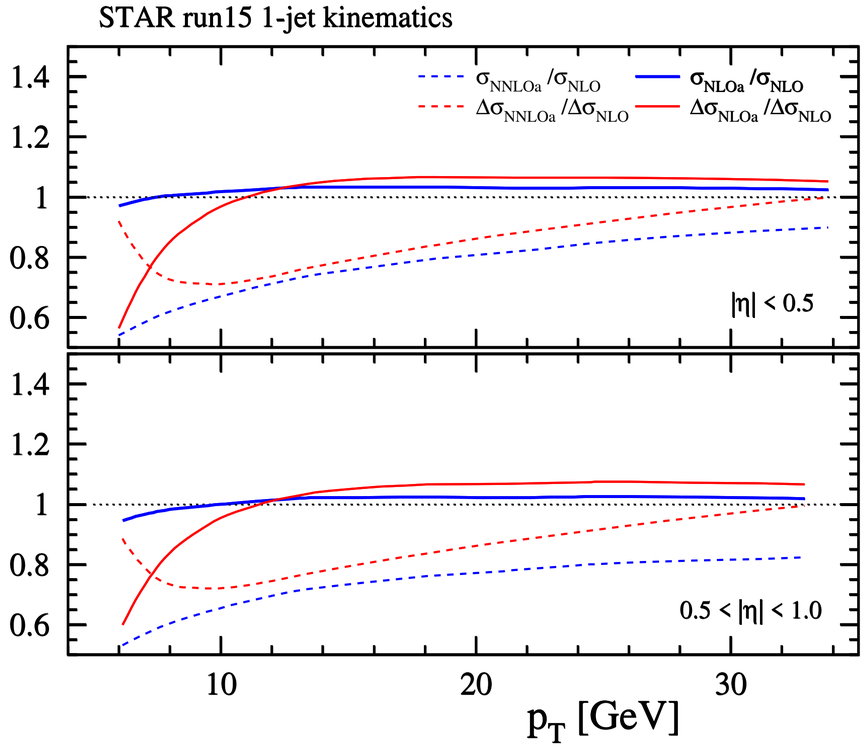

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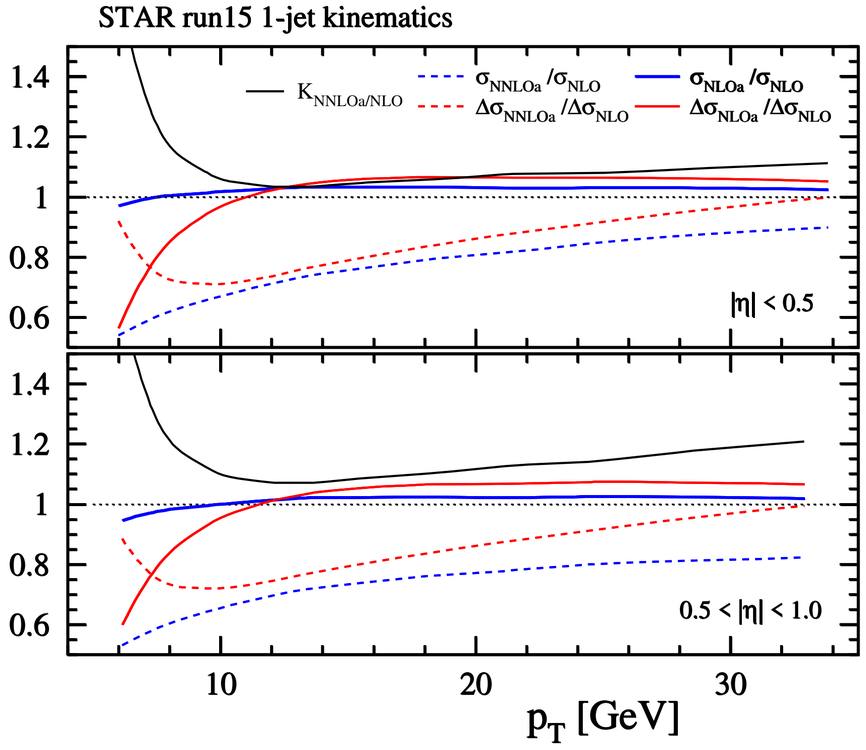

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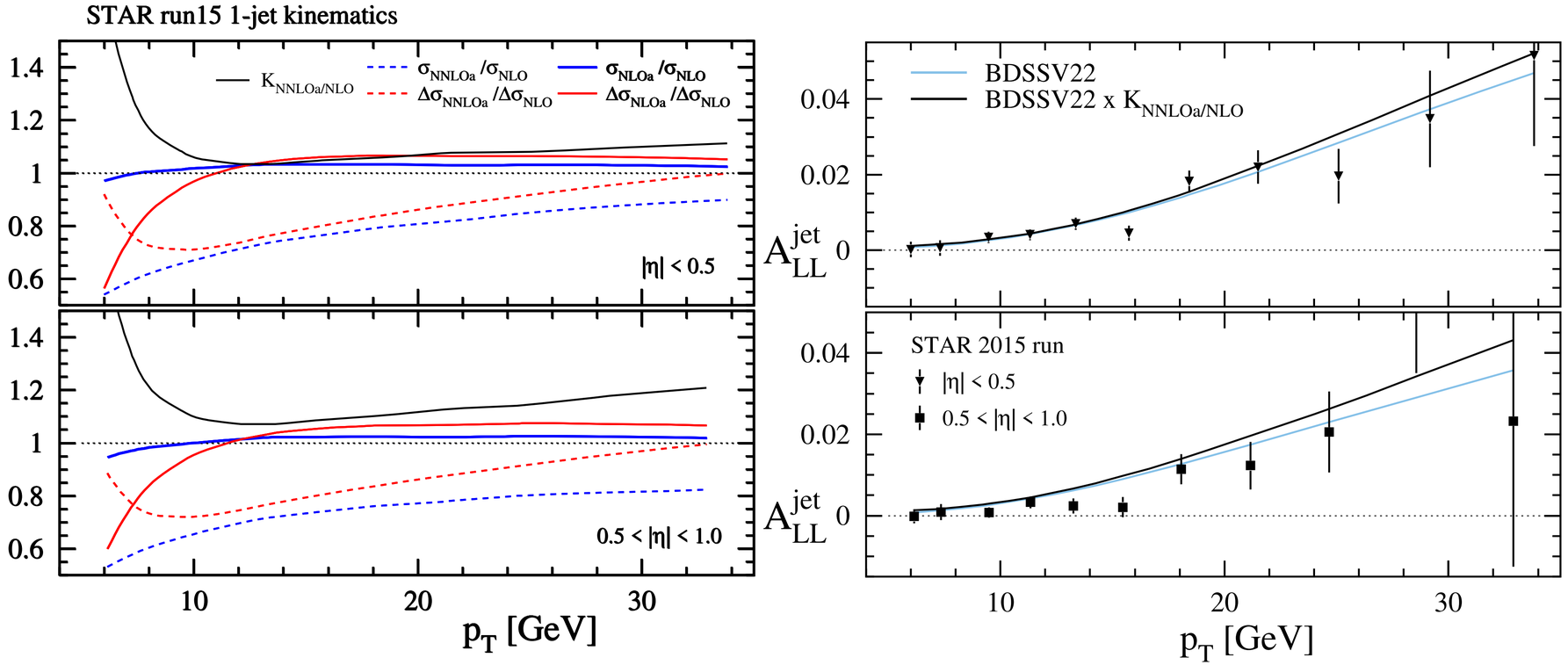

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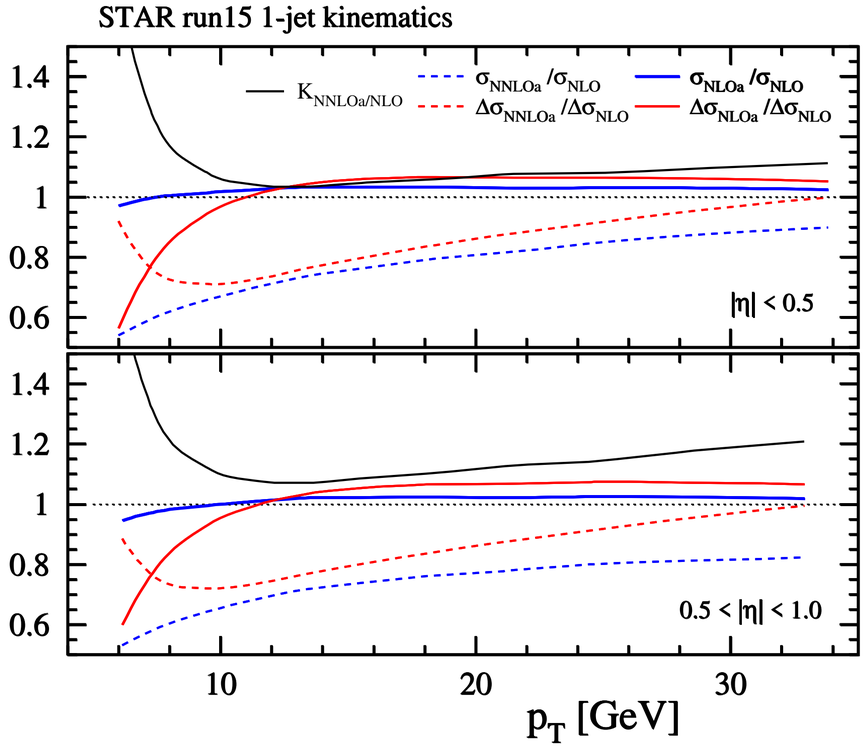
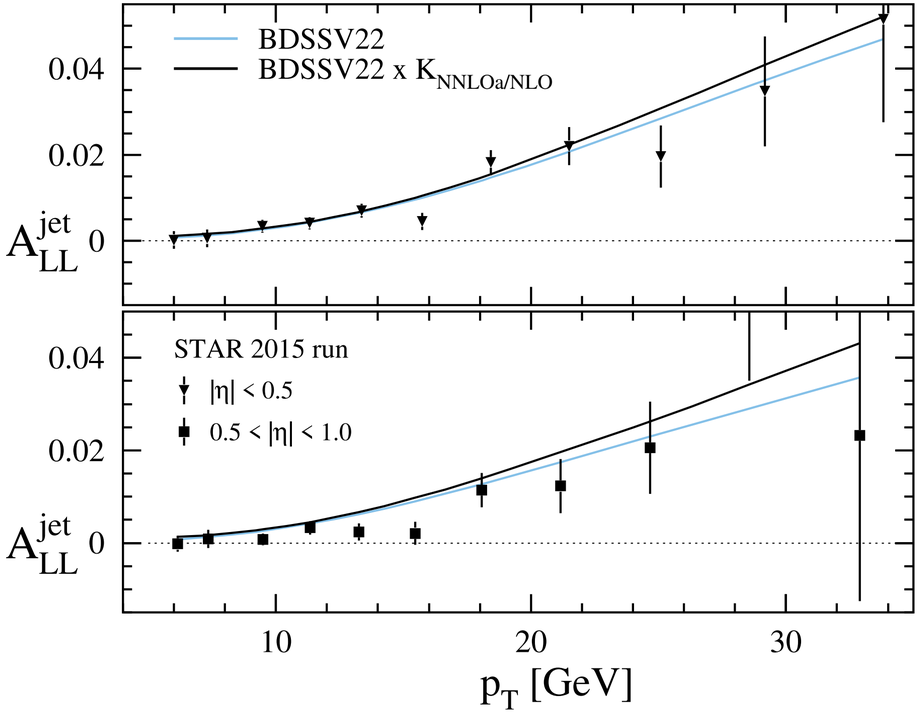
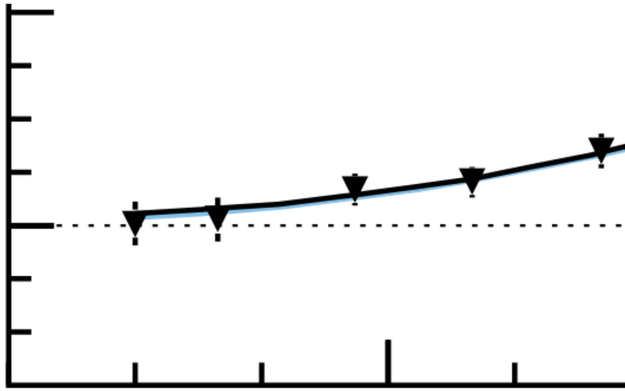
D. de Florian, W. Vogelsang in preparation







$\sigma(pp \longrightarrow hadron + X)$ **“threshold resummation 2.0”**

$\sigma(pp \longrightarrow jet + X)$

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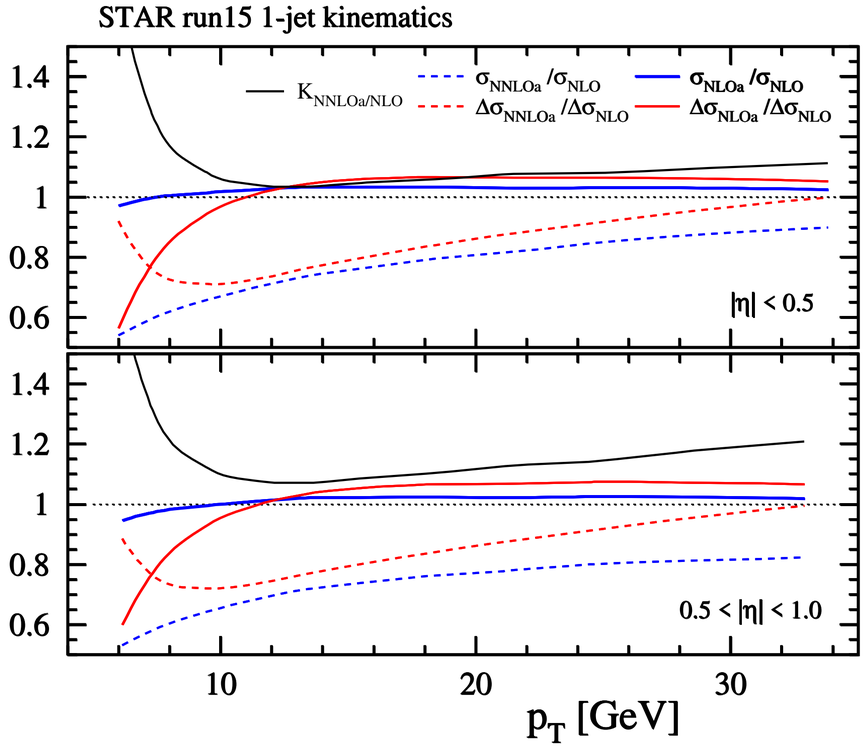

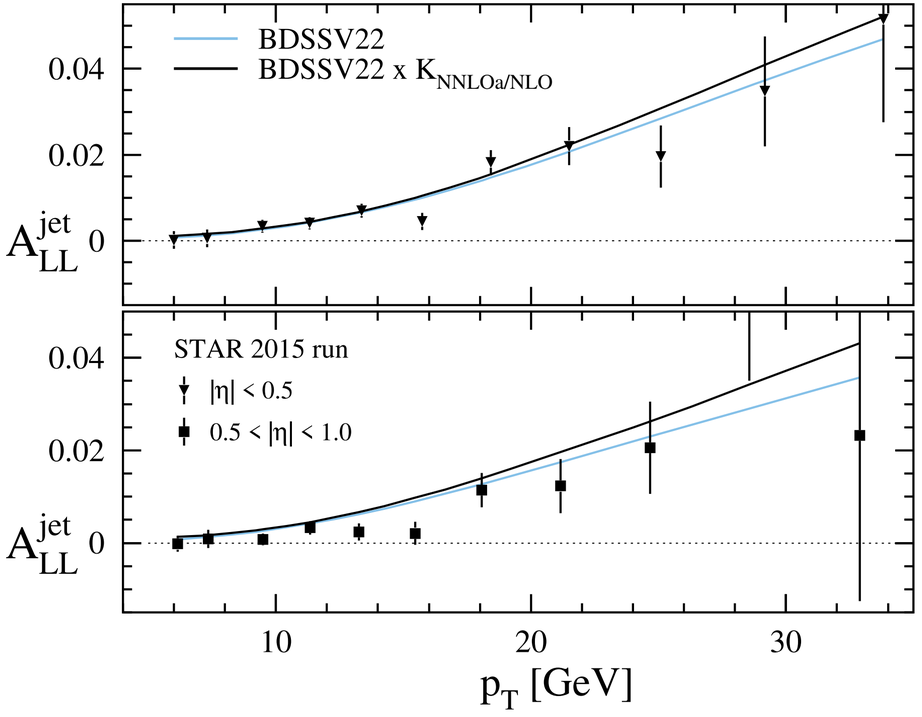

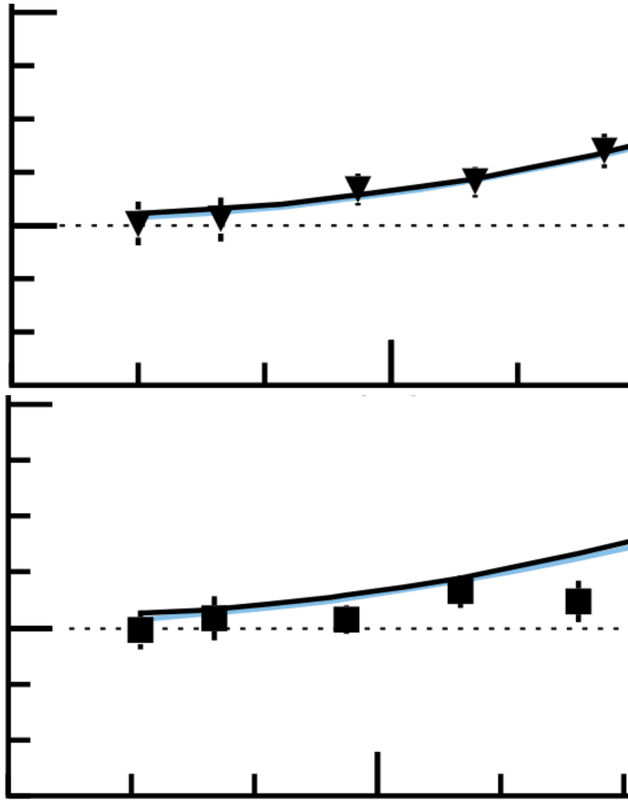

$$\sigma(pp \longrightarrow W^{\pm} \longrightarrow e^{\pm} + \nu^{(-)})$$

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Radja Boughezal, Hai Tao Li, Frank Petriello arXiv2101.02214

R. Boughezal, J. M. Campbell, R. K. Ellis, C. Focke, W. Giele, X. Liu, F. Petriello, and C. Williams,1605.08011.

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$$A_L^{W^-} \propto \frac{\Delta\bar{u}(x_1)d(x_2) - \Delta d(x_1)\bar{u}(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)},$$

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$0.05 < x < 0.25$

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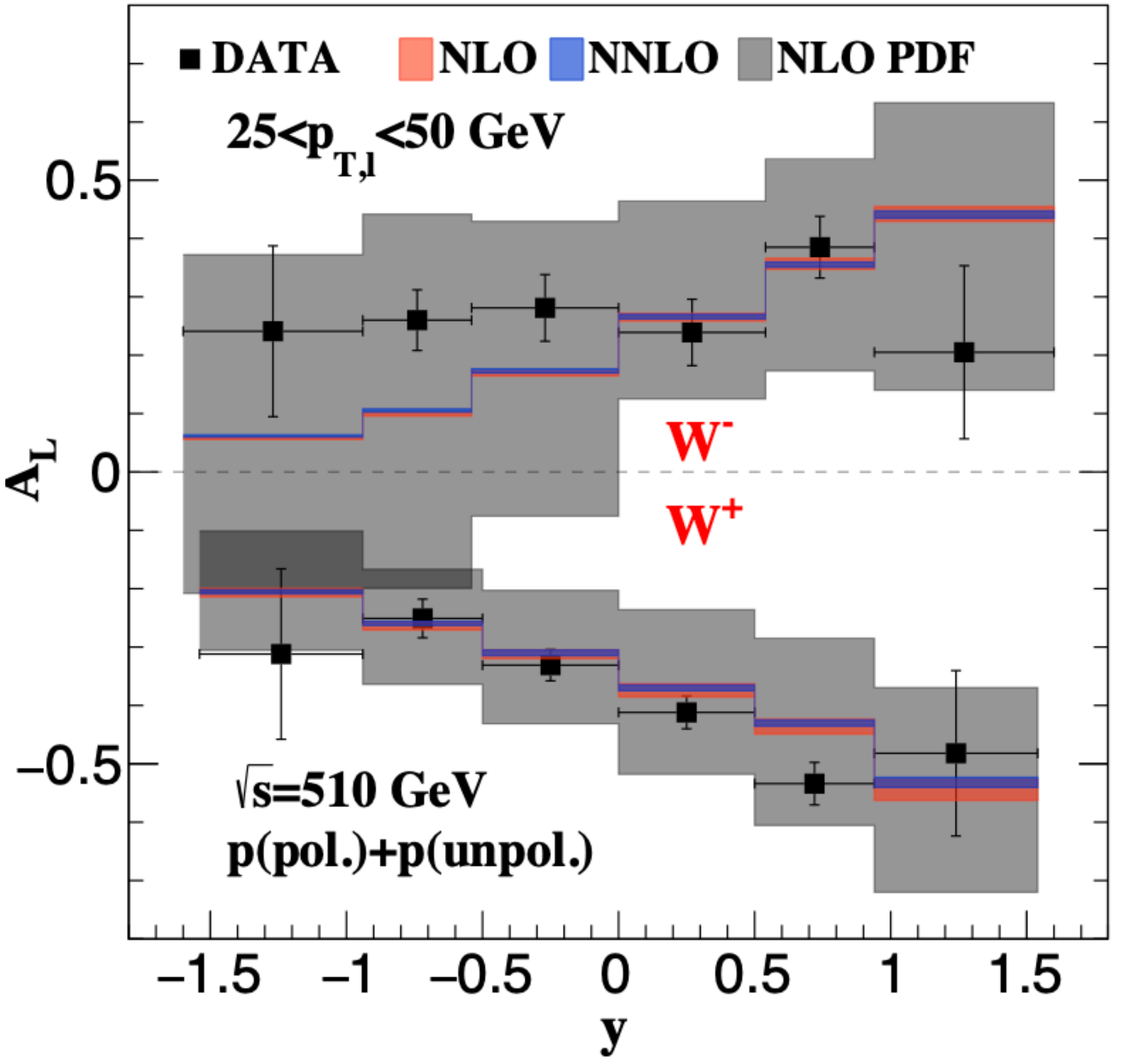

ready for the “NNLO” fit:

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Parameterizations:

$$(\Delta q + \Delta\bar{q})(x, Q_0^2) = N_q\, x^{\alpha_q}(1-x)^{\beta_q}\Big(1 + \gamma_q x^{\delta_q} + \eta_q x\Big)$$

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Positivity relative to MSHT20 (NLO/NNLO)

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Positivity relative to MSHT20 (NLO/NNLO)

Data:

DIS:	EMC,SMC,E142,E143,E154,E155, HERMES, COMPASS, HALL-A,CLAS (p,n,d,He)	**378**

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SIDIS:	HERMES, COMPASS (p-$\pi^{\pm}$,d-$\pi^{\pm}$)	**80**

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PP-$\pi^0/\pi^{\pm}$:	PHENIX, STAR	**82**

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PP-$\pi^0/\pi^{\pm}$:	PHENIX, STAR	**82**
PP $W^{\pm}$:	PHENIX, STAR	**22**
Total:		**653**

Results:

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$\chi^2_{NNLO} = 592.32\ (653)$

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DIS (378)

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	NNLO
DIS (378)	302

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	NNLO	*NLO*
DIS (378)	302	298

Results:

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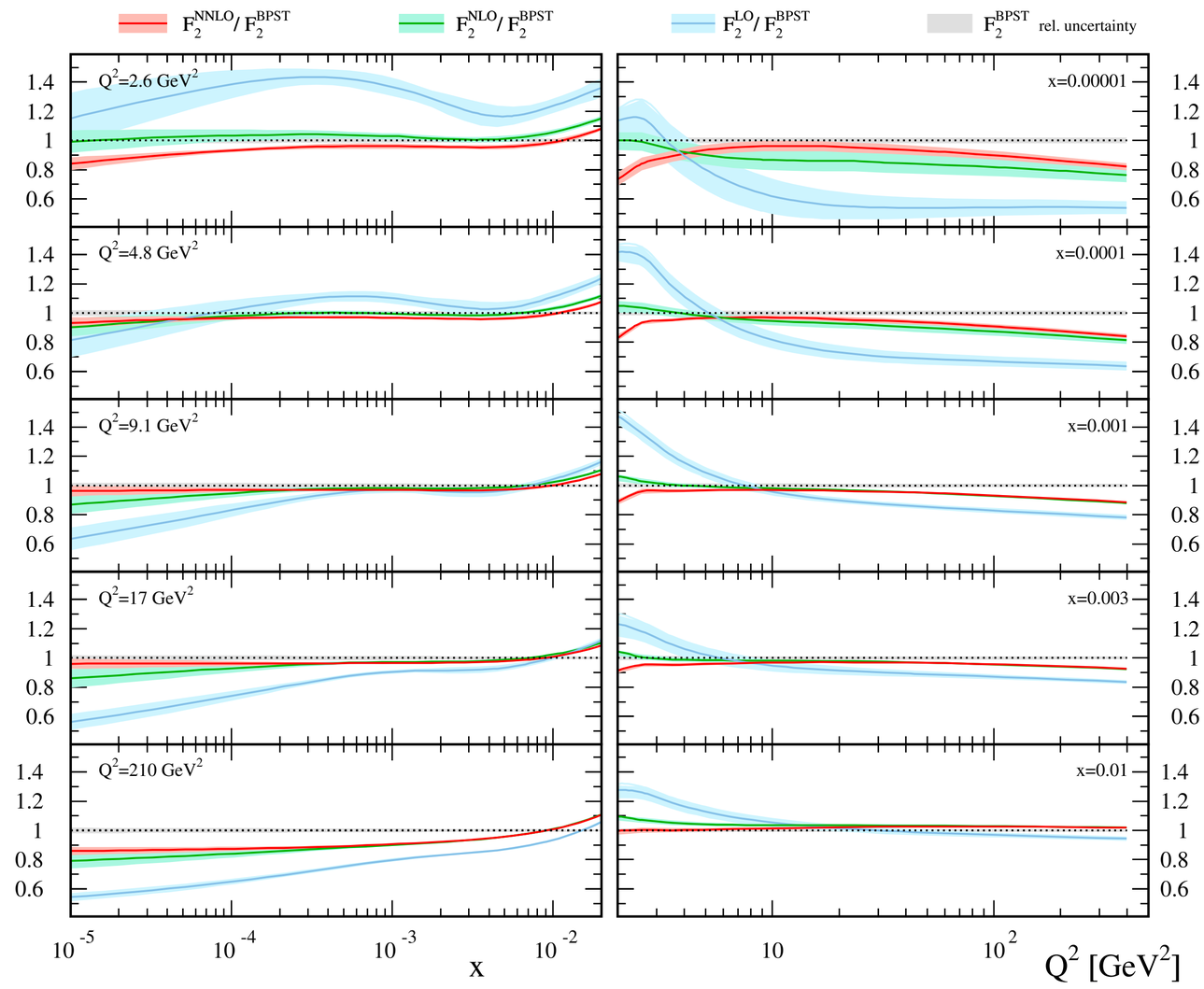
	NNLO	*NLO*	*DIS − only*
DIS (378)	302	298	385/386

Results:

I. Borsa et al. arXiv:2308.01975

$\chi^2_{NNLO} = 592.32\ (653)$ $\chi^2_{NLO} = 590.92\ (653)$

	NNLO	*NLO*	*DIS − only*
DIS (378)	302	298	385/386



*NNPDF*4.0 + *APFEL*

V. Bertone, S. Carrazza, J. Rojo arXiv:1310.1394

Results:

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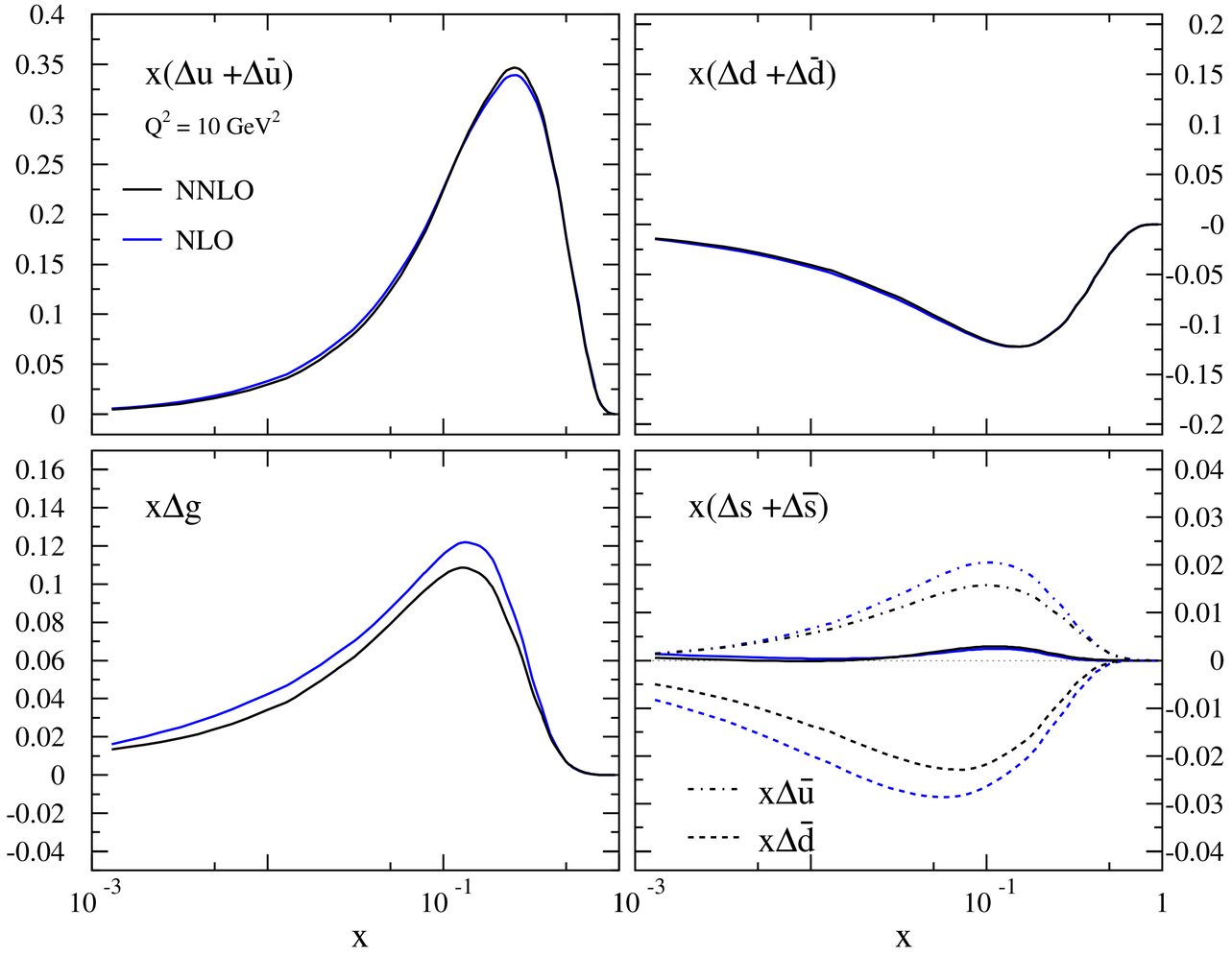
	NNLO	*NLO*	*DIS − only*
DIS (378)	302	298	385/386



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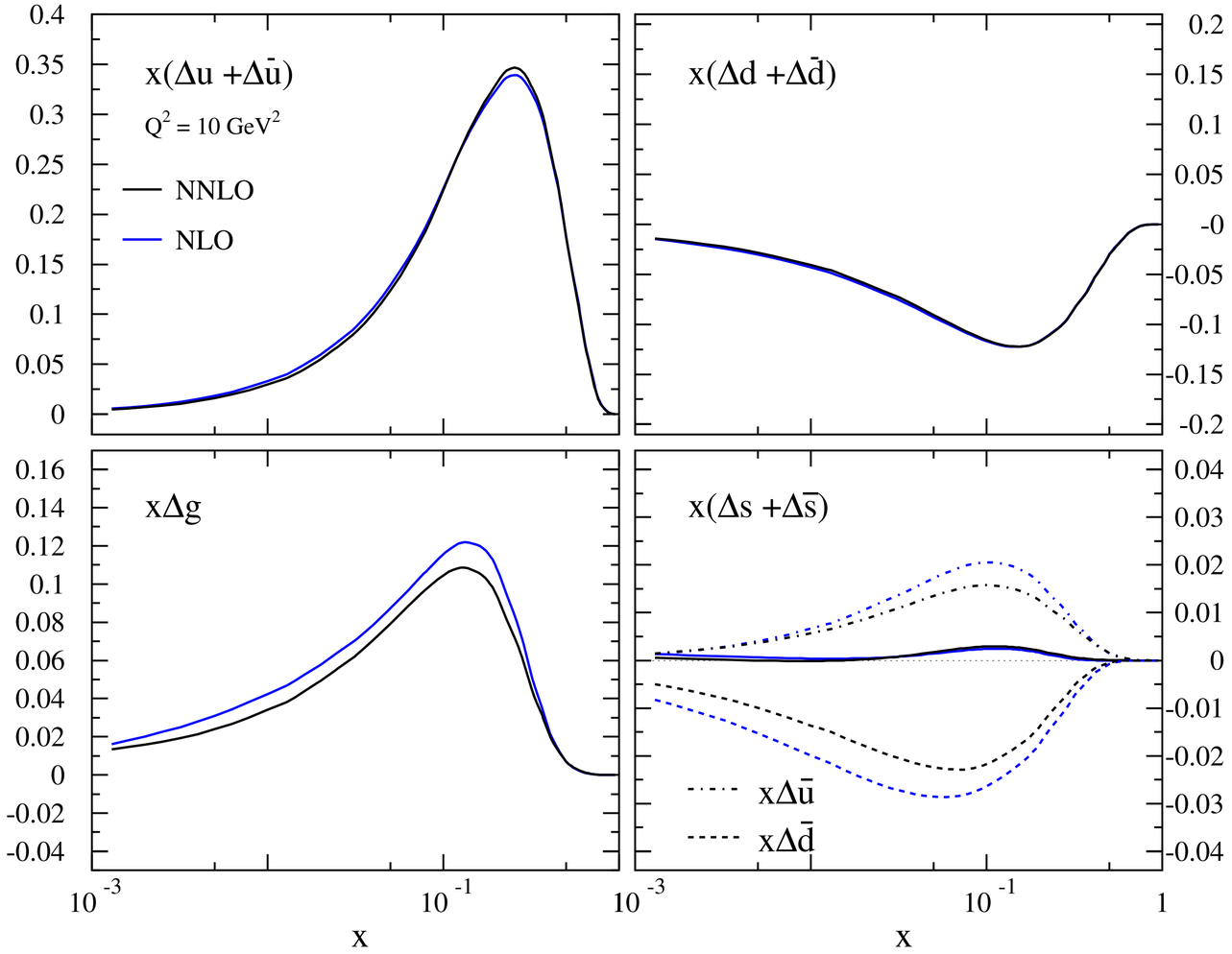
	NNLO	*NLO*	*DIS − only*
DIS (378)	302	298	385/386
SIDIS (80)	99	93	



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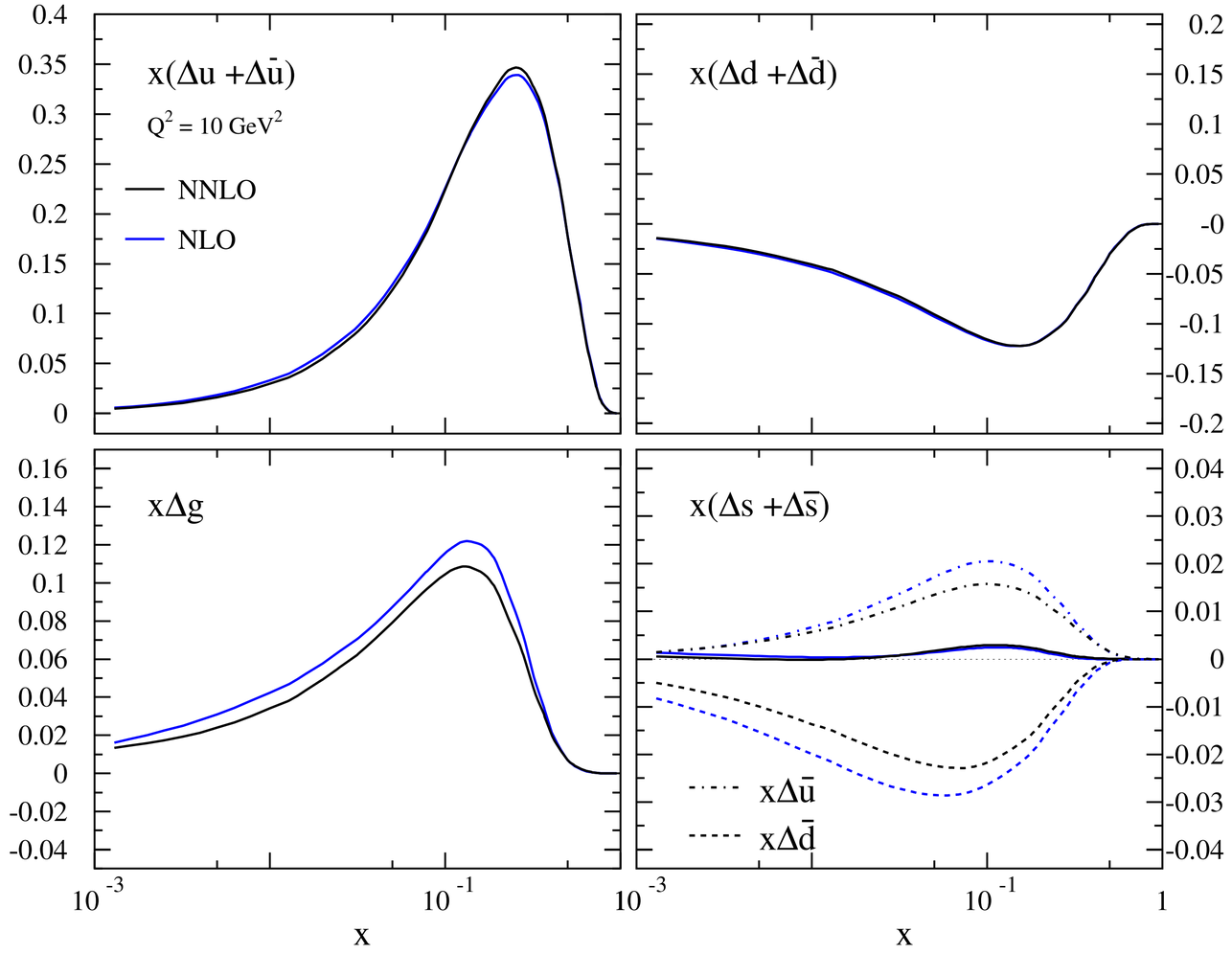
	NNLO	*NLO*	*DIS − only*
DIS (378)	302	298	385/386
SIDIS (80)	99	93	
JETS (91)	103	111	



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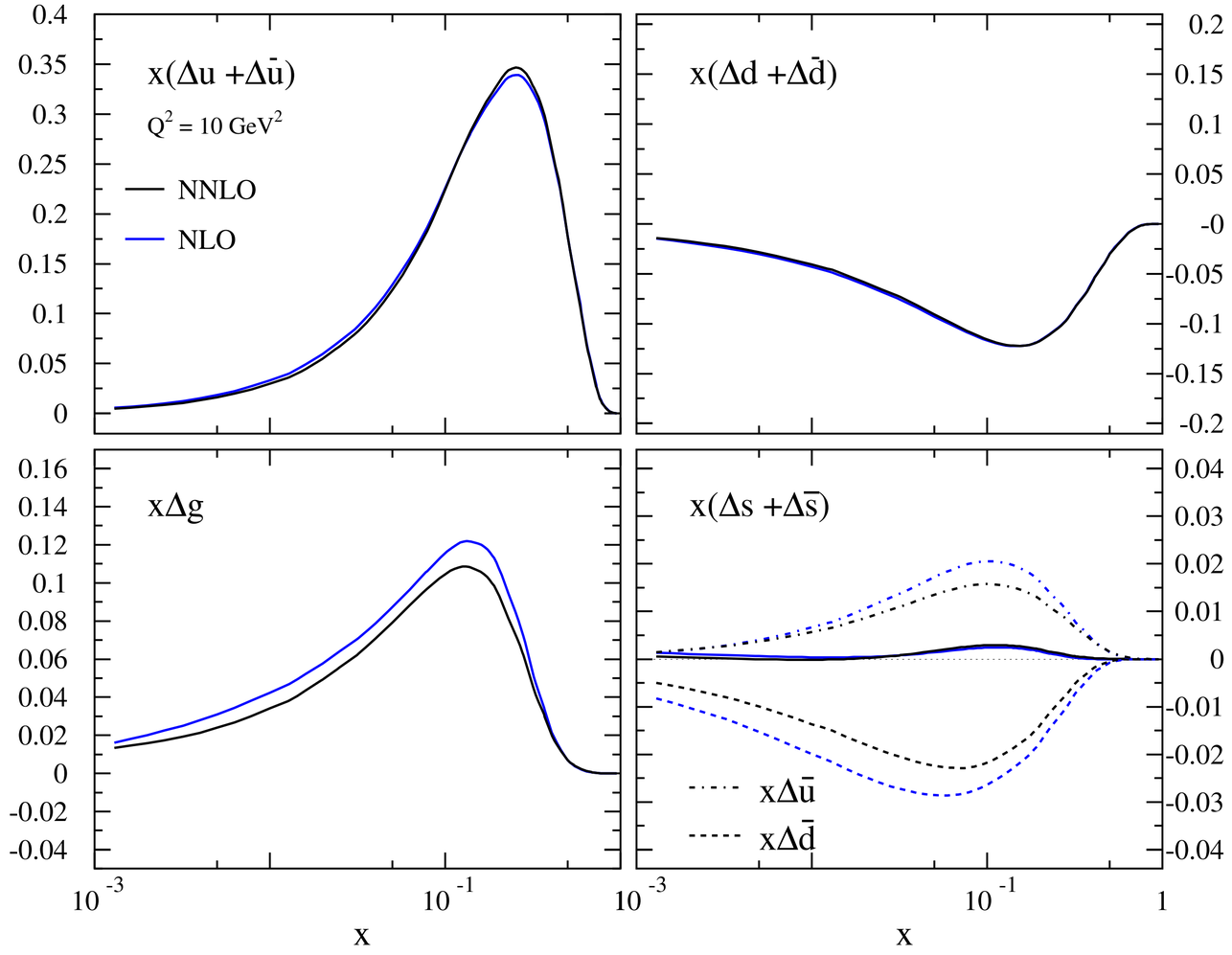
SIDIS (80)	99		93	
JETS (91)	103	112	111	



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	NNLO	*NNLO**	*NLO*	*DIS – only*
DIS (378)	302		298	385/386
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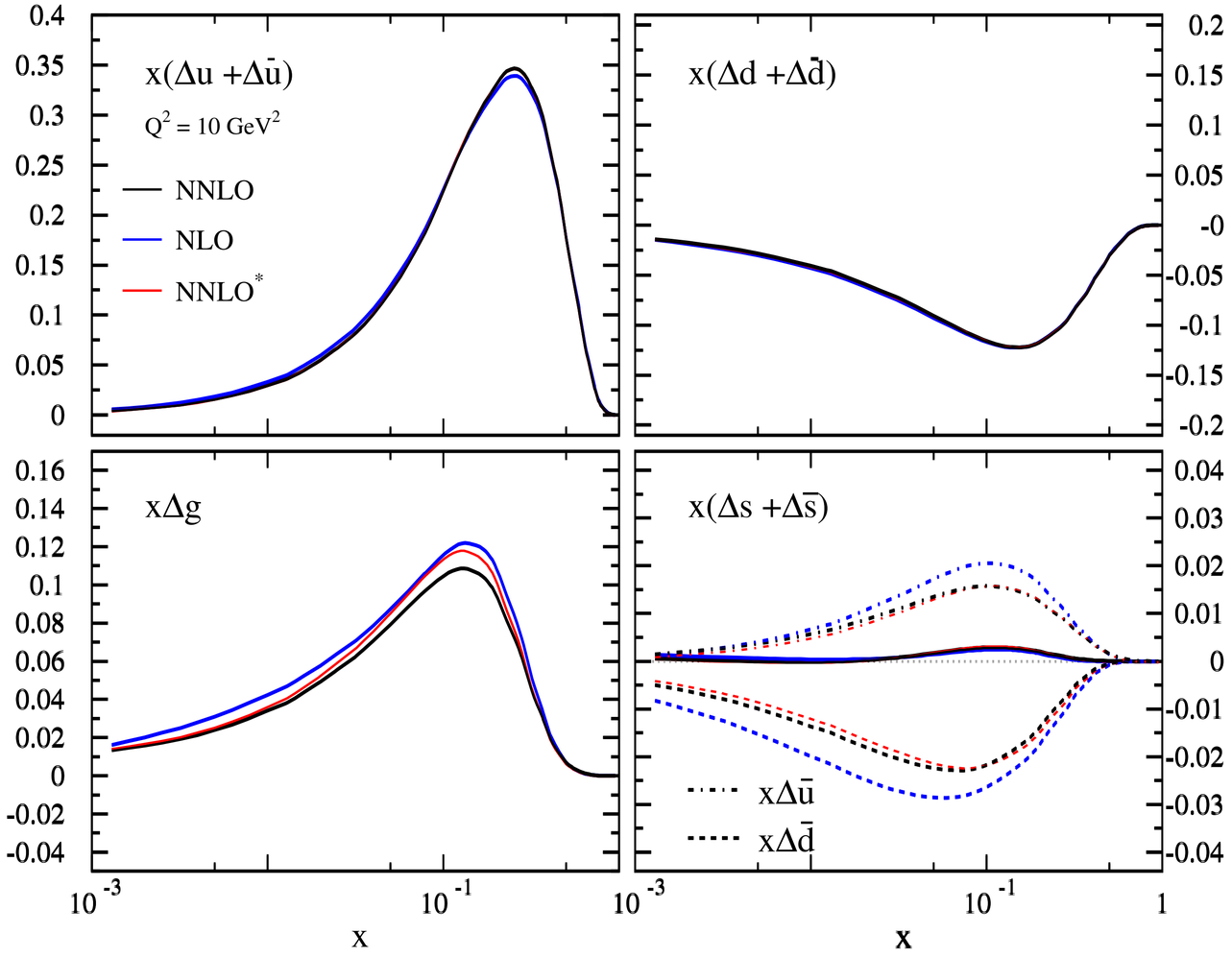
JETS (91)	103	112	111	



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DIS (378)	302	302	298	385/386
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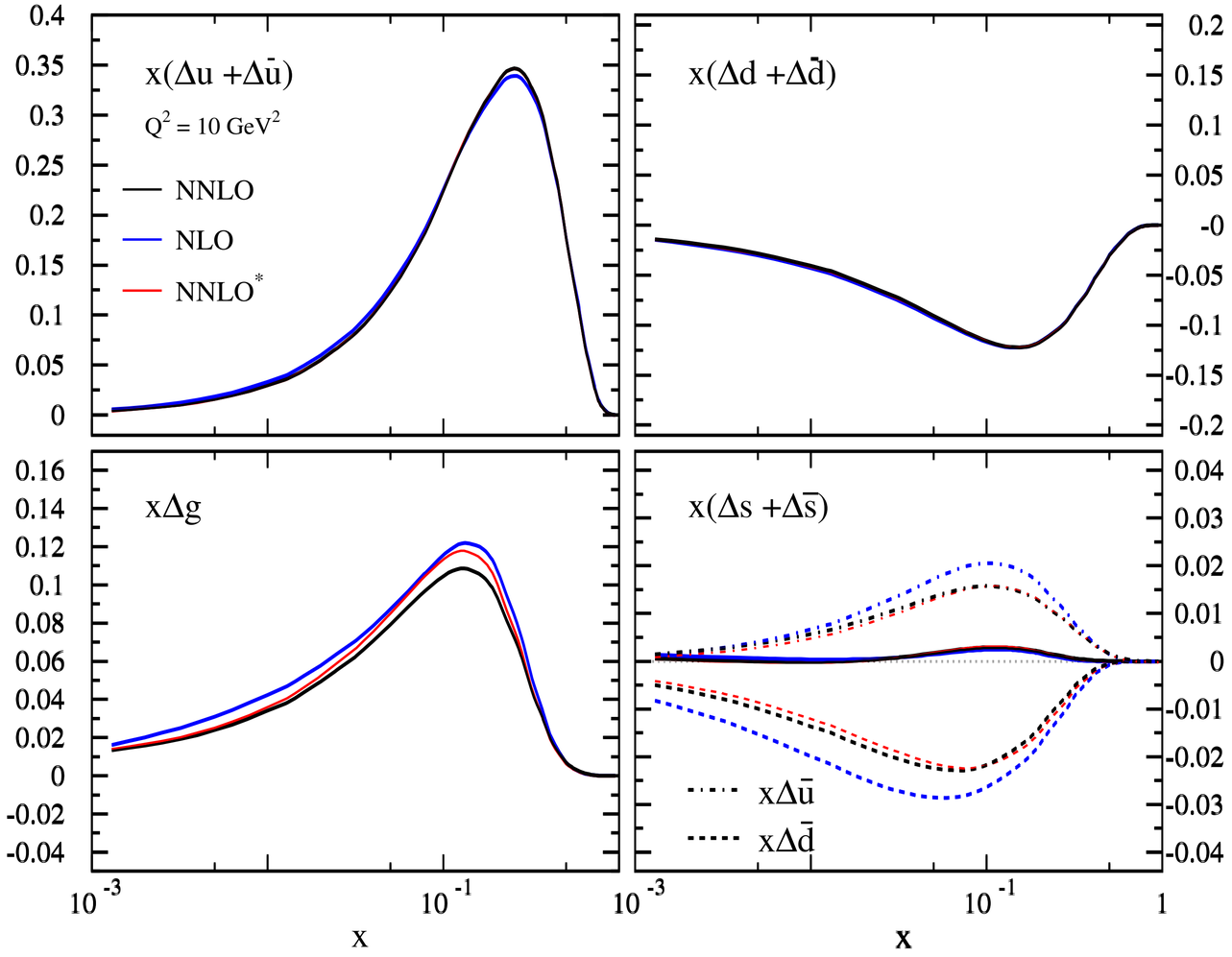

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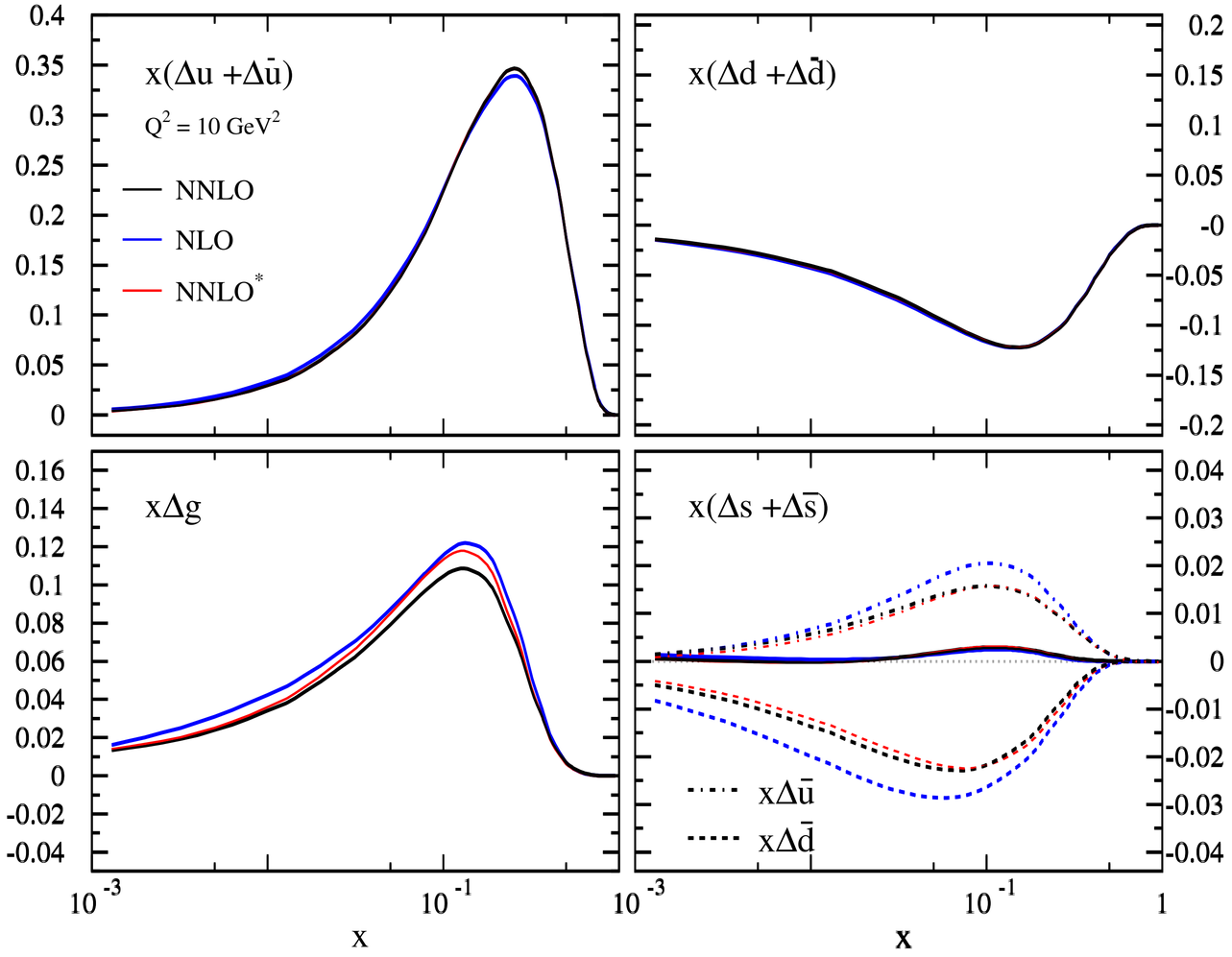
	NNLO	*NNLO**	*NLO*	*DIS – only*
DIS (378)	302	302	298	385/386
SIDIS (80)	99	99	93	
JETS (91)	103	112	111	
$\pi^{0,\pm}$ (82)	65	65	65	



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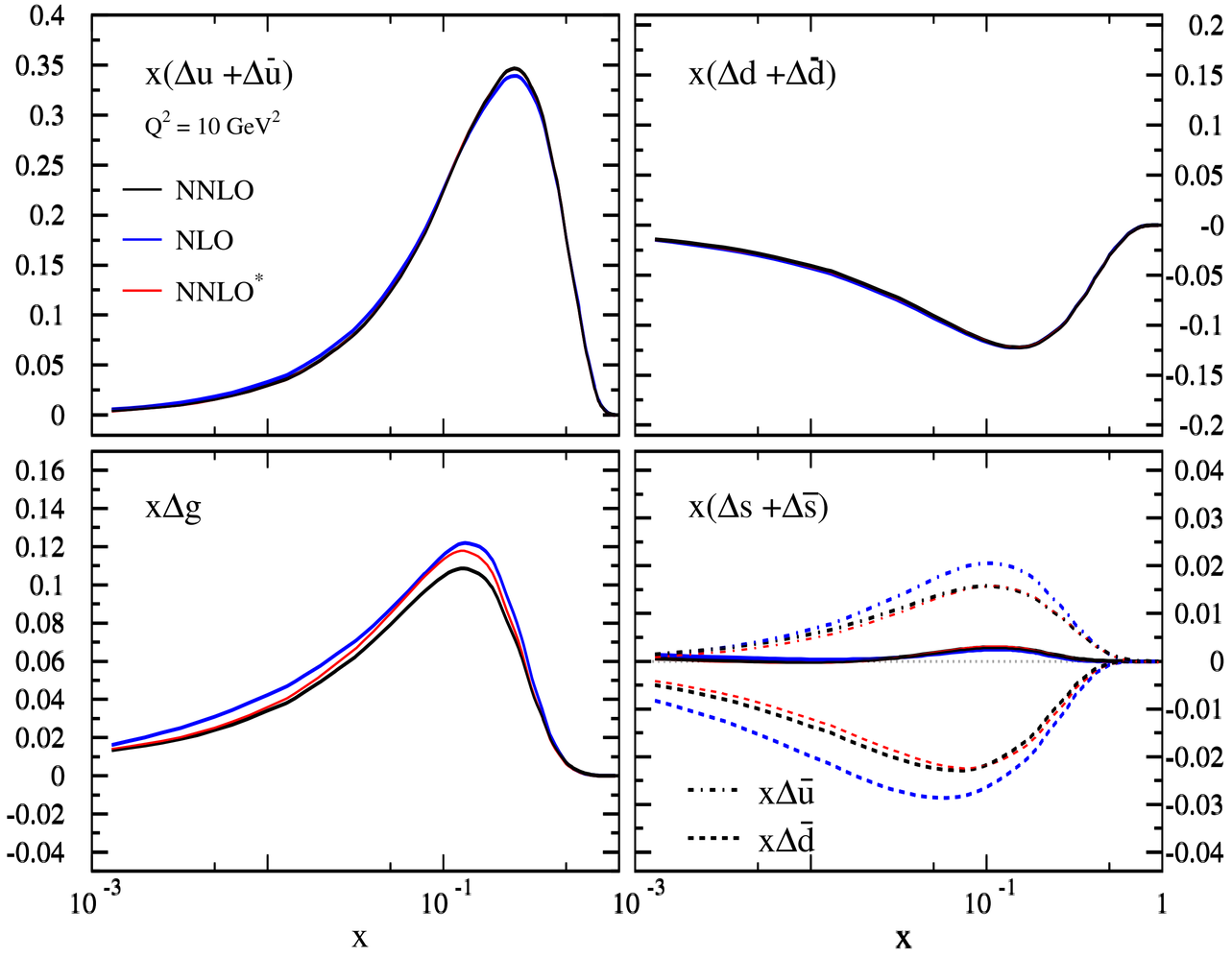
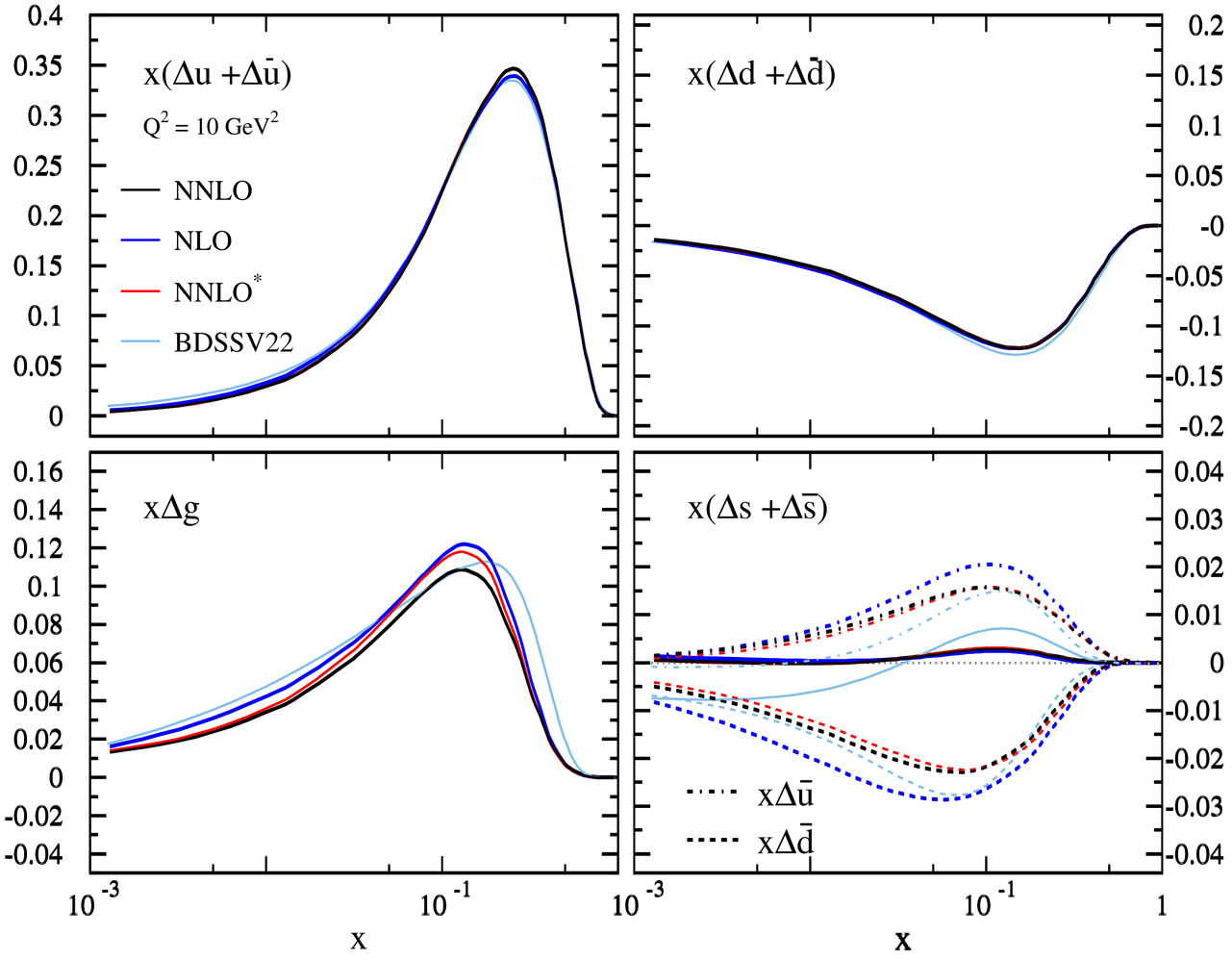
	NNLO	*NNLO**	*NLO*	*DIS – only*
DIS (378)	302	302	298	385/386
SIDIS (80)	99	99	93	
JETS (91)	103	112	111	
$\pi^{0,\pm}$ (82)	65	65	65	
$W^{\pm}$ (22)	22	22	21	



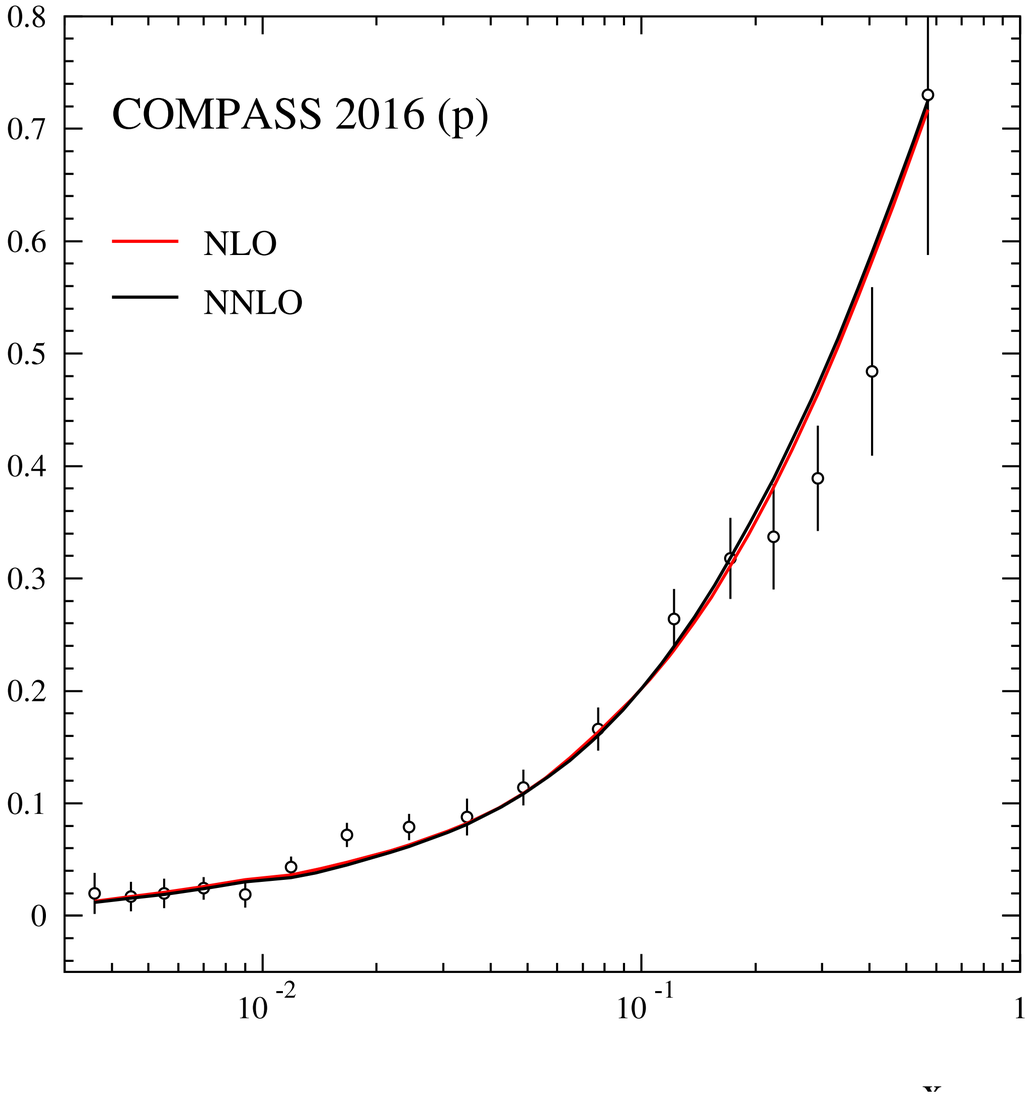
Results:

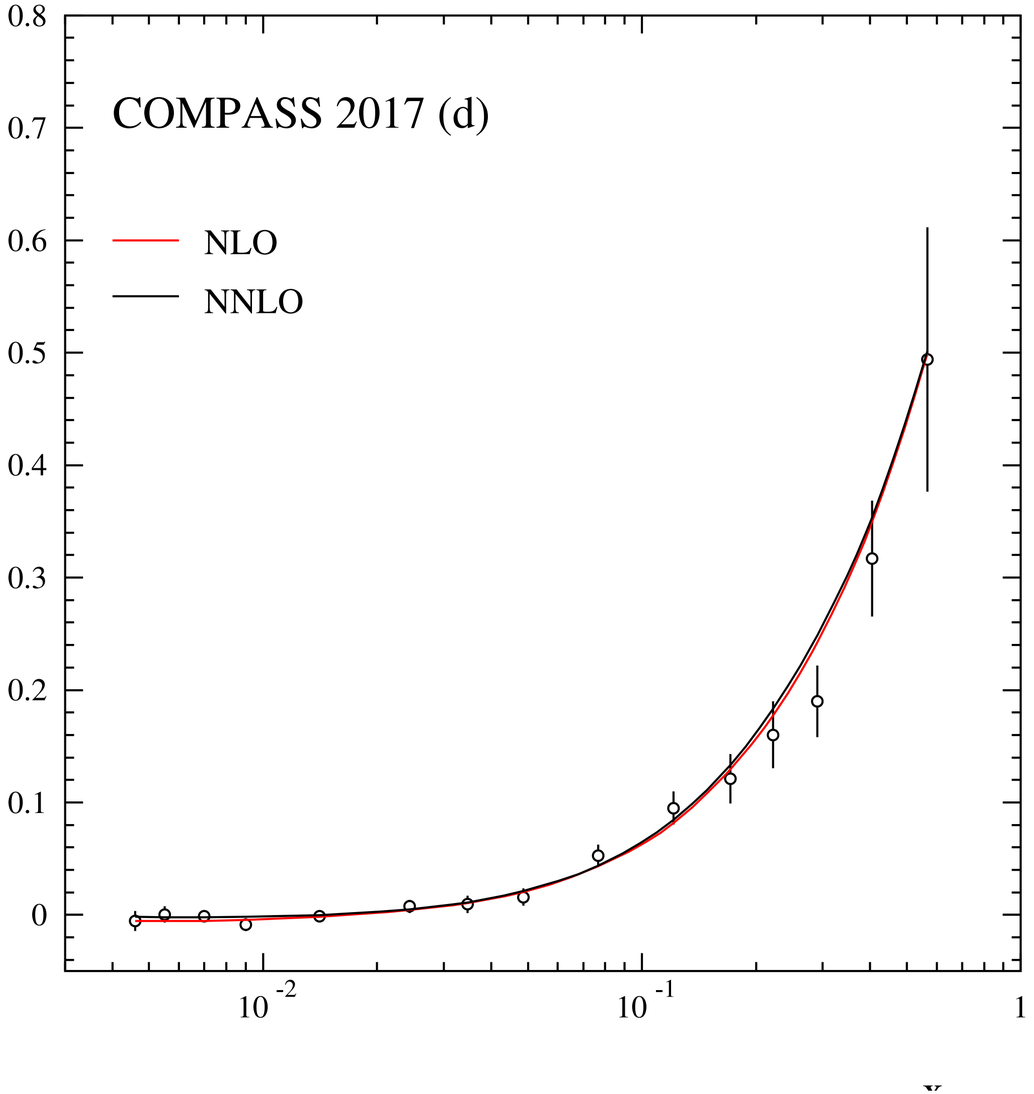
$\chi^2_{NNLO} = 592.32\ (653)$ $\chi^2_{NLO} = 590.92\ (653)$

	NNLO	*NNLO**	*NLO*	*DIS – only*
DIS (378)	302	302	298	385/386
SIDIS (80)	99	99	93	
JETS (91)	103	112	111	
$\pi^{0,\pm}$ (82)	65	65	65	
$W^{\pm}$ (22)	22	22	21	

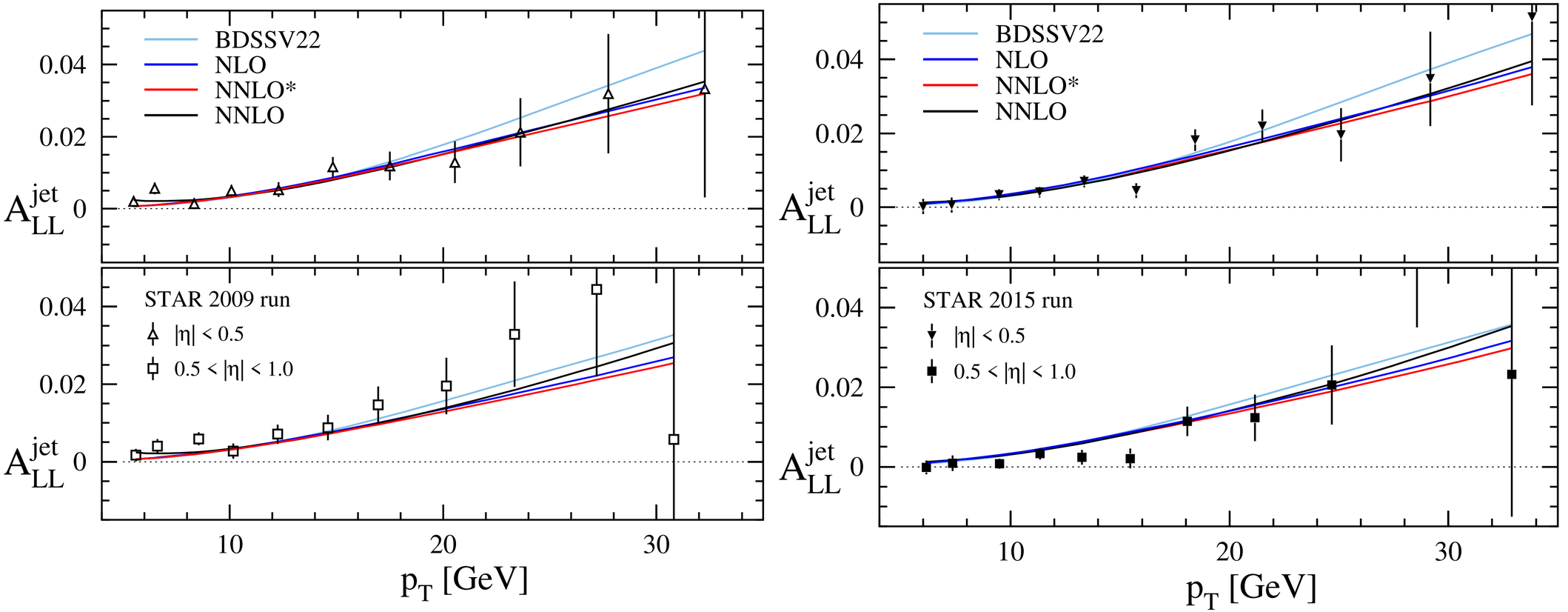


Picture Gallery:





Picture Gallery:



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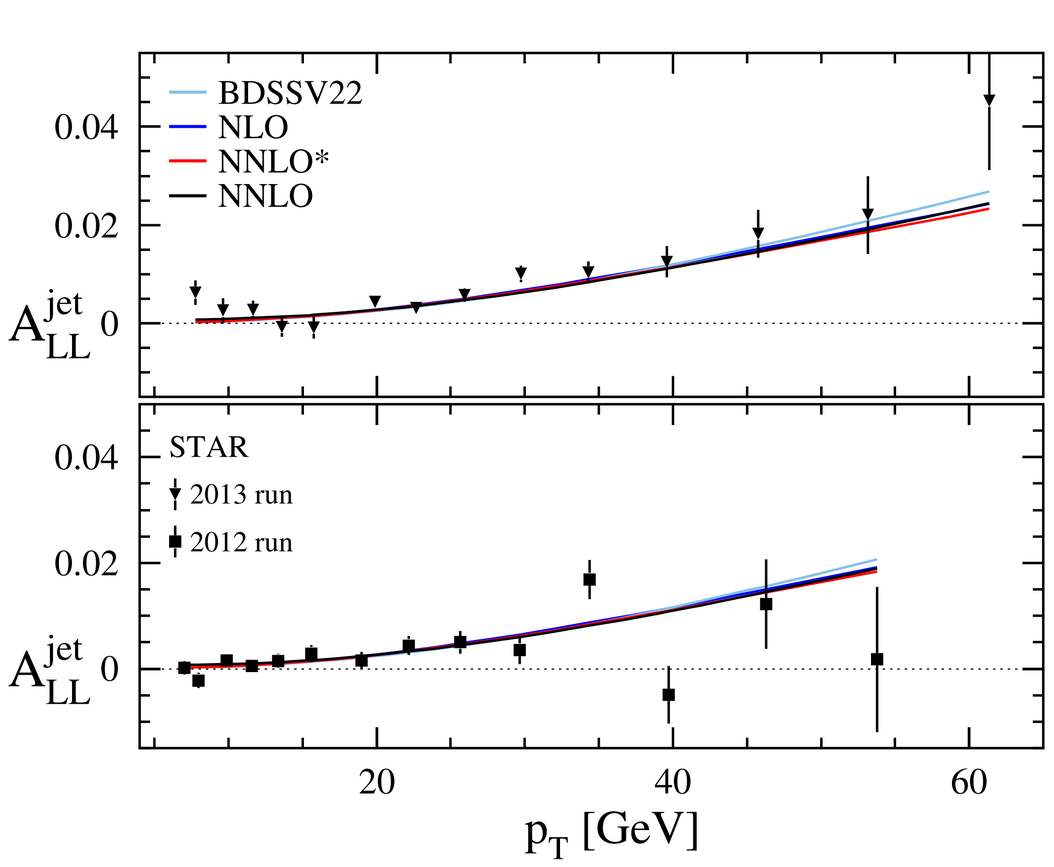

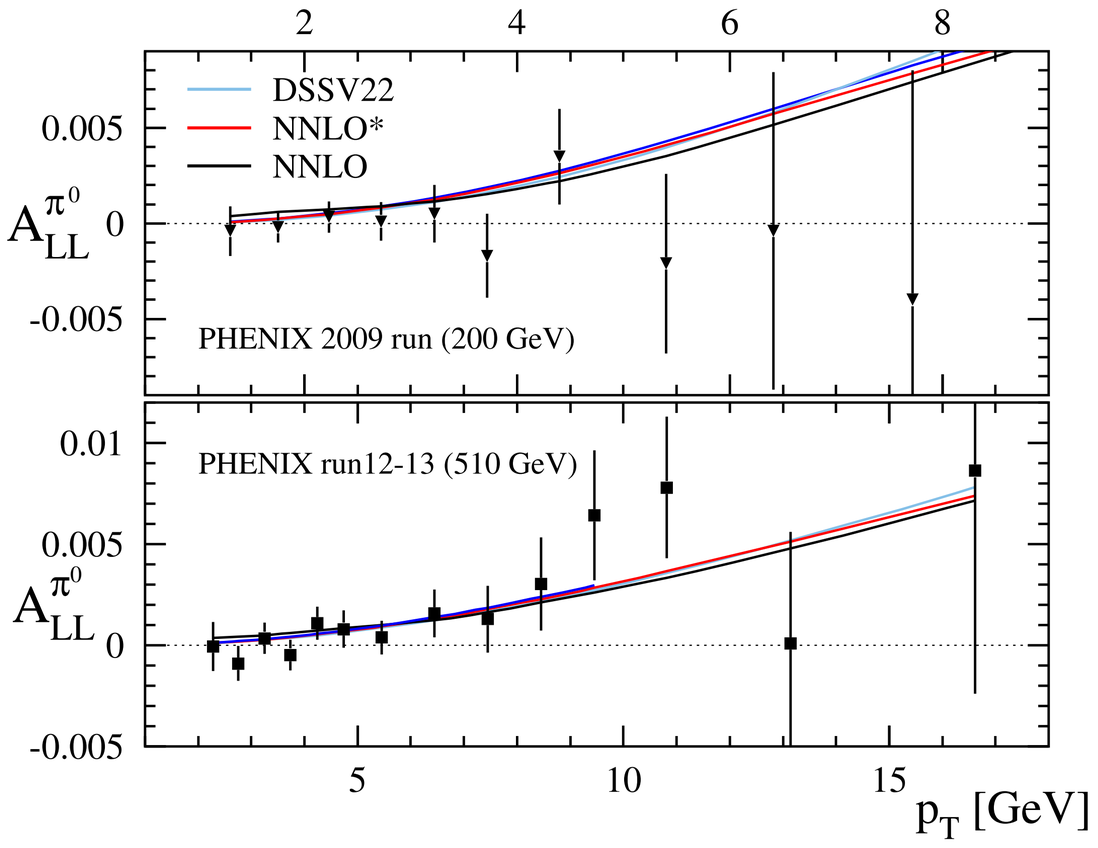

To do list:

To do list:

Still work in progress…

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Still work in progress…

factorization scale uncertainty

To do list:

Still work in progress…

factorization scale uncertainty

pdfs uncertainties

To do list:

Still work in progress…

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pdfs uncertainties

kaon and charged hadron sidis

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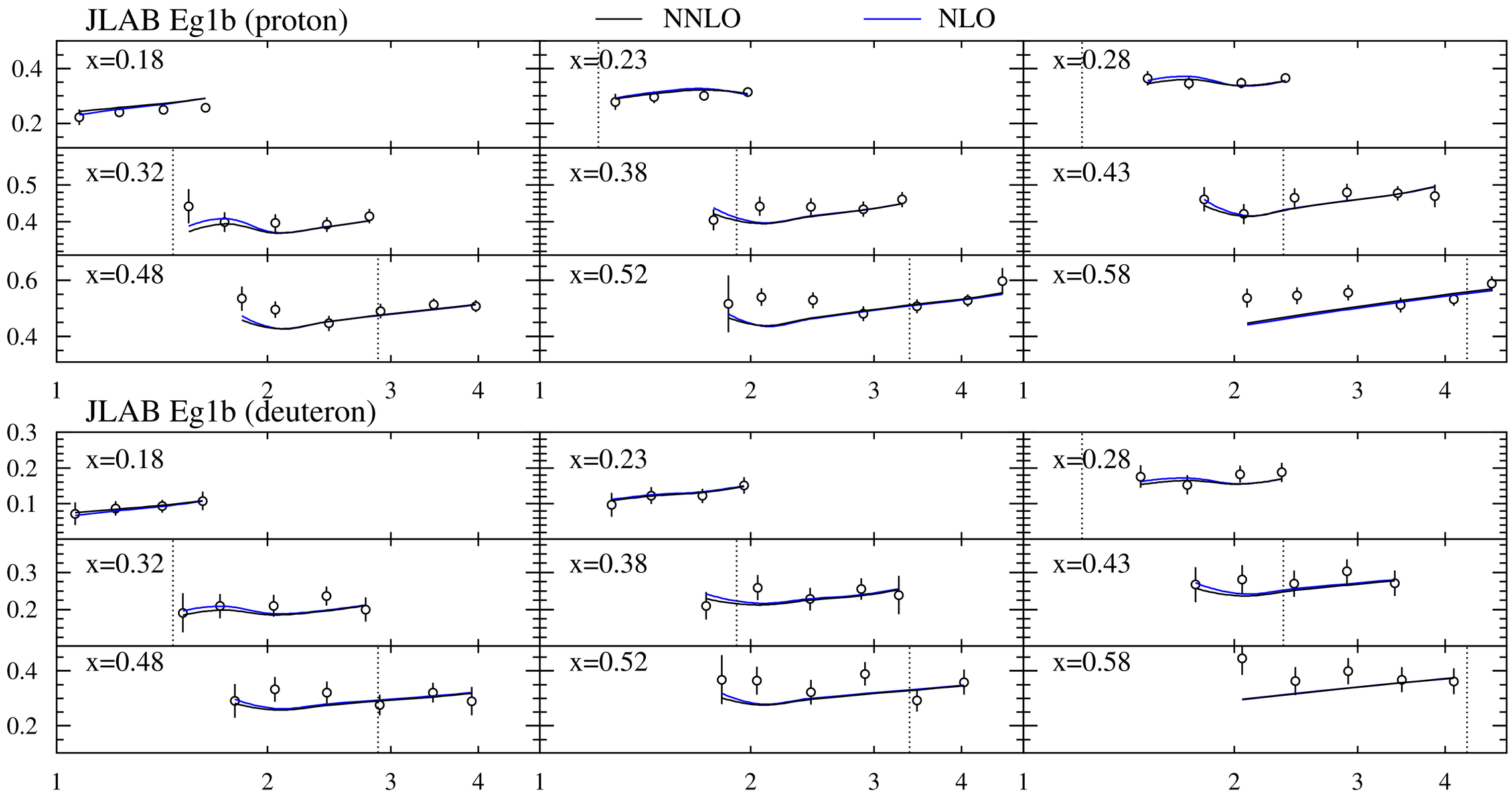
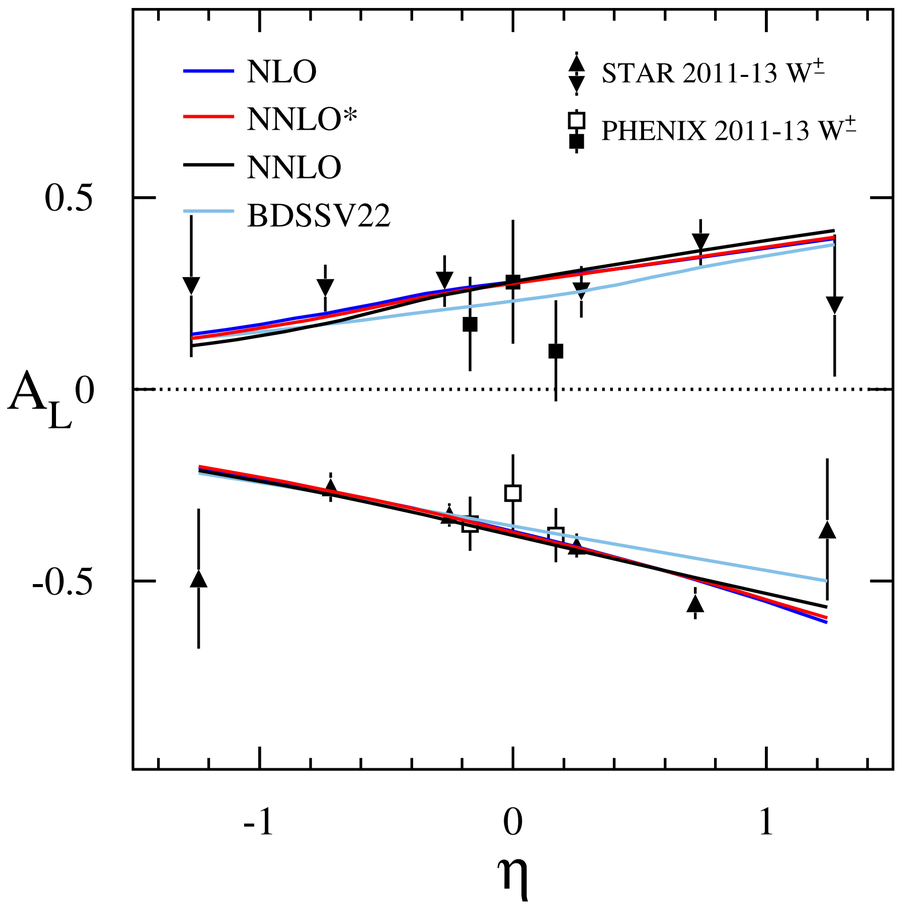
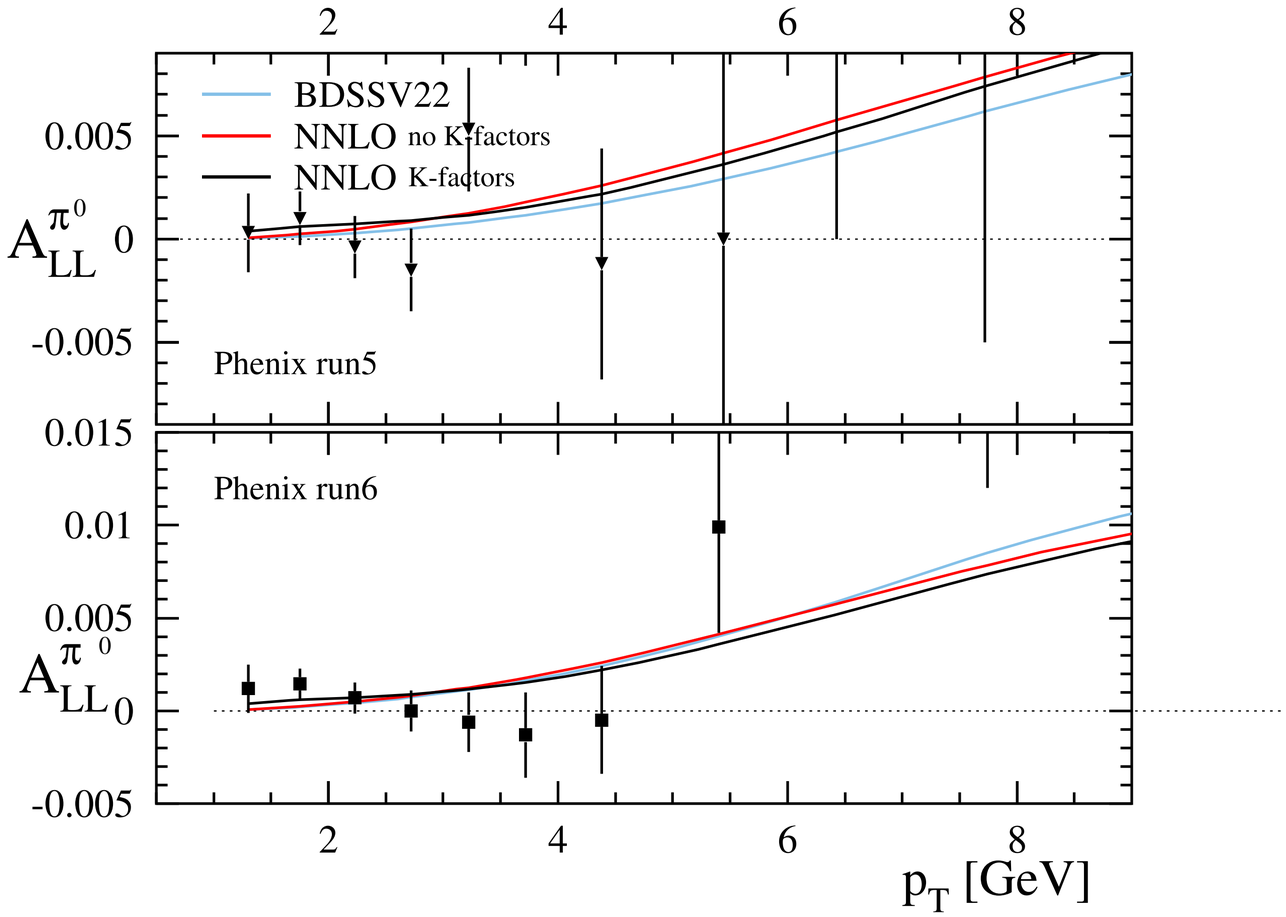
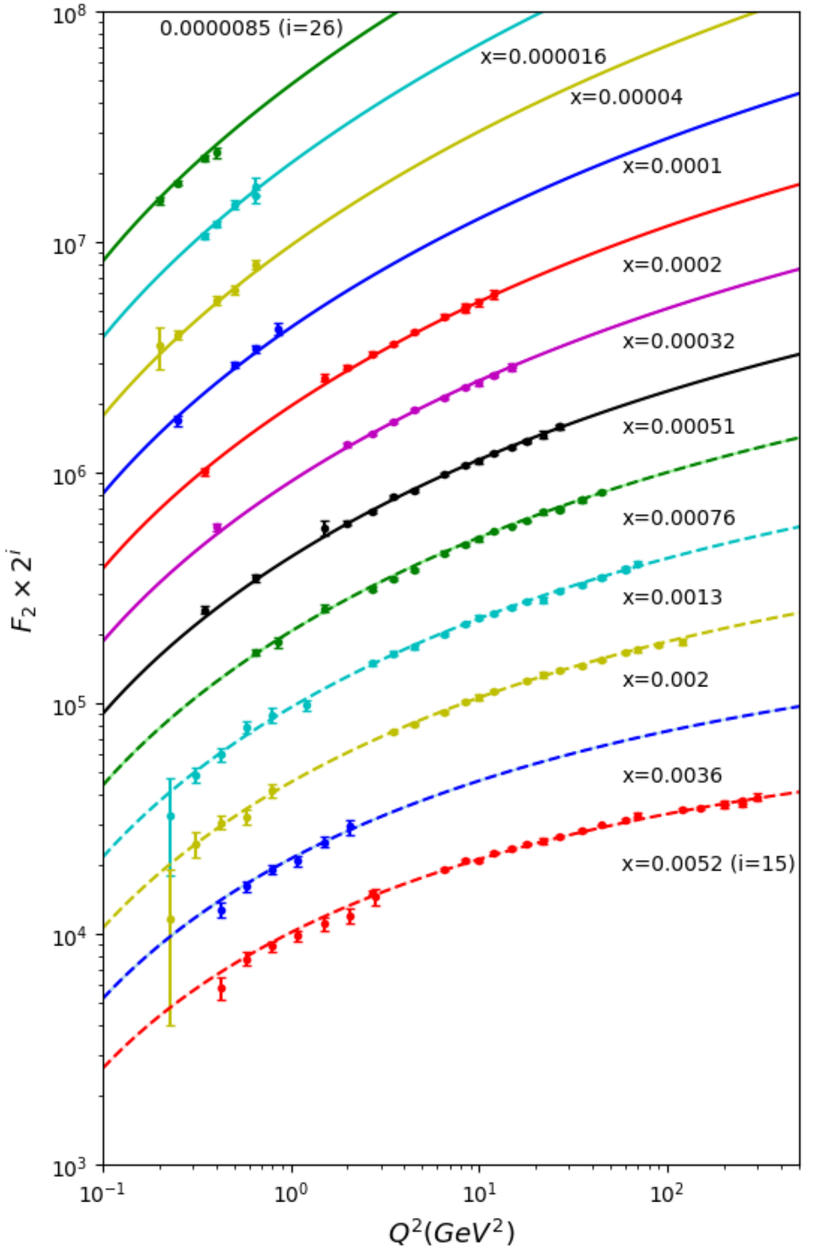
Convergence of the perturbative expansion in very good health

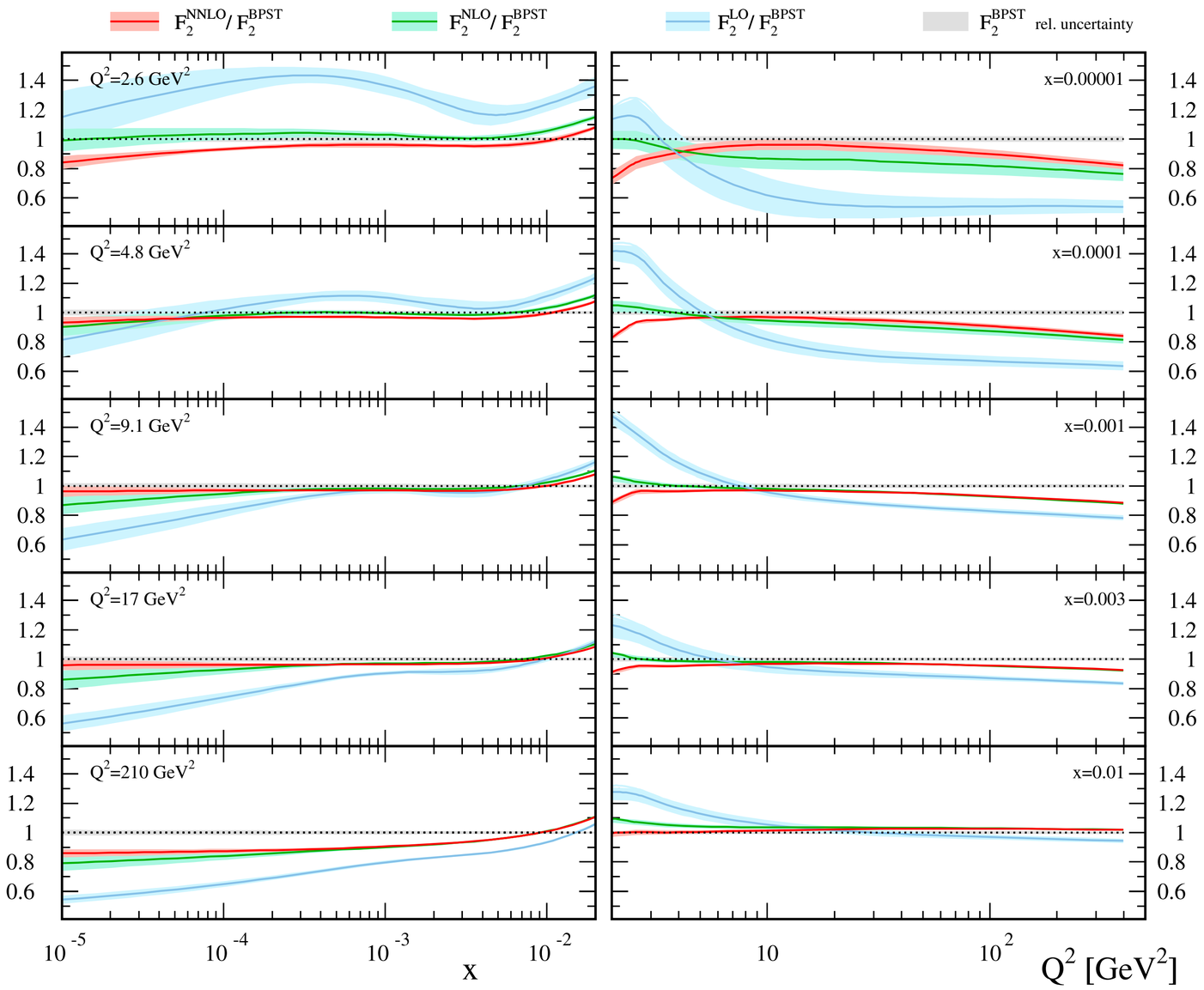
Thanks!

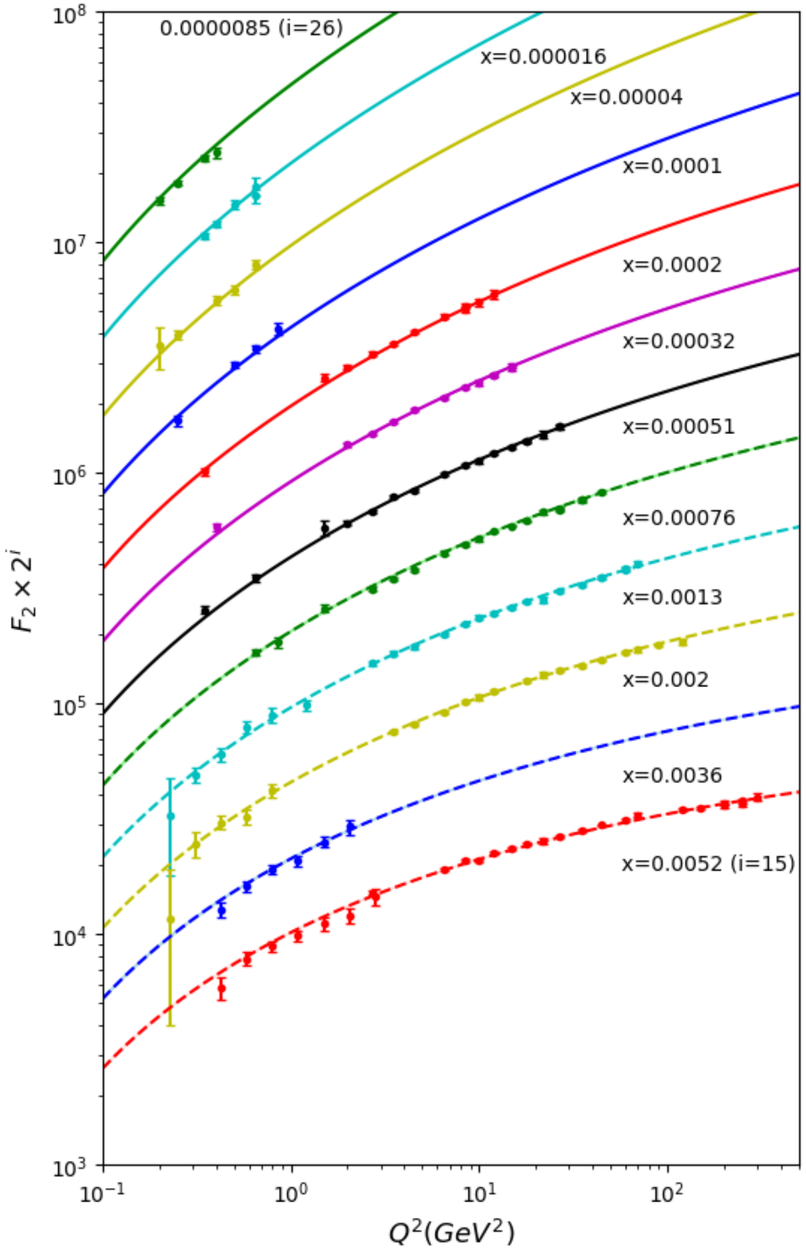

JLAB Eg1b (proton)
NNLO
NLO
x=0.18
x=0.23
x=0.28
x=0.32
x=0.38
x=0.43
x=0.48
x=0.52
x=0.58
JLAB Eg1b (deuteron)
x=0.18
x=0.23
x=0.28
x=0.32
x=0.38
x=0.43
x=0.48
x=0.52
x=0.58


NLO
NNLO*
NNLO
BDSSV22
STAR 2011-13 W±
PHENIX 2011-13 W±
0.5
-0.5
A_L
0
-1
0
1
η


BDSSV22
NNLO no K-factors
NNLO K-factors
Phenix run5
Phenix run6
A_LL^π0
0.005
0
-0.005
0.015
0.01
2
4
6
8
p_T [GeV]


0.0000085 (i=26)
x=0.000016
x=0.00004
x=0.0001
x=0.0002
x=0.00032
x=0.00051
x=0.00076
x=0.0013
x=0.002
x=0.0036
x=0.0052 (i=15)
$F_2 \times 2^i$
$Q^2(GeV^2)$
10^8
10^7
10^6
10^5
10^4
10^3
10^{-1}
10^0
10^1
10^2


F_2^{NNLO}/F_2^{BPST}
F_2^{NLO}/F_2^{BPST}
F_2^{LO}/F_2^{BPST}
F_2^{BPST} rel. uncertainty
Q^2=2.6 GeV^2
Q^2=4.8 GeV^2
Q^2=9.1 GeV^2
Q^2=17 GeV^2
Q^2=210 GeV^2
x=0.00001
x=0.0001
x=0.001
x=0.003
x=0.01
x
Q^2 [GeV^2]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$F_2 \times 2^i$
$Q^2(GeV^2)$

I. Borsa et al. arXiv:2308.01975