TUJU21: Nuclear PDFs with electroweak-boson data at NNLO

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Outline

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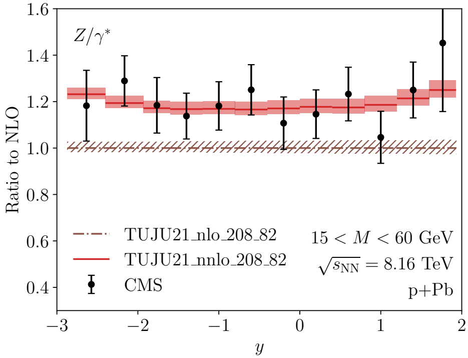
Based on arXiv:2112.11904

Accepted in PRD



Modern nuclear PDF sets

EPPS21 [arXiv:2112.12462]

- Long tradition (since 90's)
- NLO, CT18A as a baseline
- LHC data: dijets, D^0 and $Z, W^\pm$

nCTEQ15WZSIH [PRD 104, 094005]

- Builds upon CTEQ proton PDF analysis
- NLO, CTEQ6-like baseline
- LHC data: π^0, $\pi^\pm$, $K^\pm$ and $Z, W^\pm$

nNNPDF3.0 [arXiv:2201.12363]

- Based on neural networks
- NLO, NNPDF4.0-like baseline
- LHC data: dijet, D^0, γ and $W^\pm$, Z

TUJU21 [arXiv:2112.11904]

- Using open-source framework (xFitter 2.0.1N: Nuclear Daiquiri)
- NLO and NNLO, Proton baseline fitted in the framework
- LHC data: $W^\pm$, Z

TUJU Fitting framework

Proton baseline PDF

- Use similar parametrization as in HERAPDF2.0

$$xf_i^p(x, Q_0^2) = c_0 x^{c_1}(1-x)^{c_2}(1+c_3x+c_4x^2)$$

- Parametrization scale $Q_0^2 = 1.69\ \mathrm{GeV}^2$
- Kinematical cuts for data
  - $Q^2 > 3.5\ \mathrm{GeV}^2$
  - $x < 0.7$
  - $W^2 > 12\ \mathrm{GeV}^2$
- Assume $\bar{\mathrm{u}} = \bar{\mathrm{d}} = \bar{\mathrm{s}} = \mathrm{s}$

Nuclear PDFs

- A-dependent parameters

$$c_k(A) = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$

  where $c_{k,0}$ from proton baseline
- Same kinematical cuts for data
- For an average nucleon

$$f_i^{N/A}(x, Q^2) = \frac{Zf_i^{p/A}(x,Q^2)+(A-Z)f_i^{n/A}(x,Q^2)}{A}$$

  where $f_i^{n/A}$ using Isospin symmetry ($f_u^{n/A} = f_d^{p/A}$)
- Assume $\bar{\mathrm{u}} = \bar{\mathrm{d}} = \bar{\mathrm{s}} = \mathrm{s}$

TUJU21: Proton baseline fit

DIS data (TUJU19)

- BCDM (327 data points)
- Combined HERA (1145)
- NMC-97 (100)

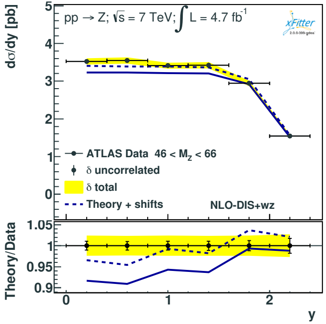
EW boson data

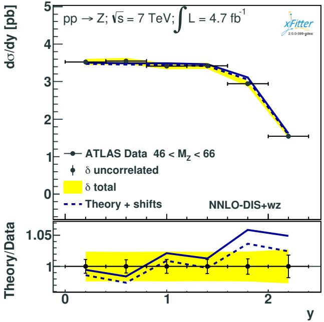
- ATLAS DY, $W^{\pm}, Z$ (112)
- CMS $W^{\pm}$ (22)

$\Rightarrow$ Total: 1706 data points

Resulting χ^2/N_{df}

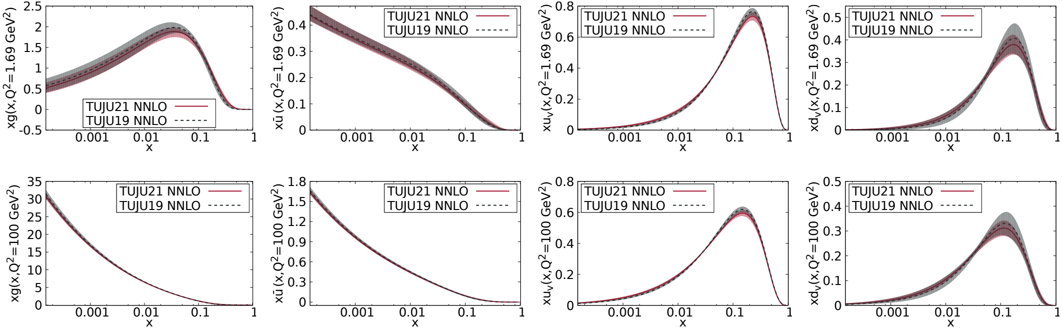
- NLO: 1.30
- NNLO: 1.24





- DIS data equally described with NLO and NNLO
- EW-boson data better described with NNLO fit

Resulting proton baseline PDFs



- Small differences for gluons and valence quarks
- Very similar sea-quark distributions
- Slightly reduced uncertainties
- TUJU19 were very similar to HERA2.0 PDFs

TUJU21: Nuclear PDF analysis

Applied data

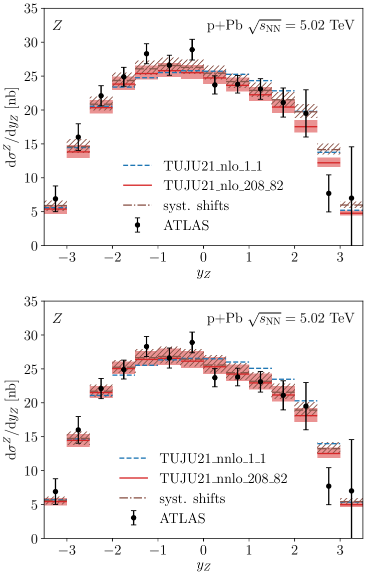
- Nuclear-target DIS, ratios between different A (600 data points)
- Neutrino DIS, absolute dσ with Fe (CDHSW) and Pb (CHORUS) targets, both, neutrino and antineutrino beams (1736)
- LHC EW-boson data in p+Pb (74)

$\Rightarrow$ 2410 data points

Resulting χ^2/N_{df}

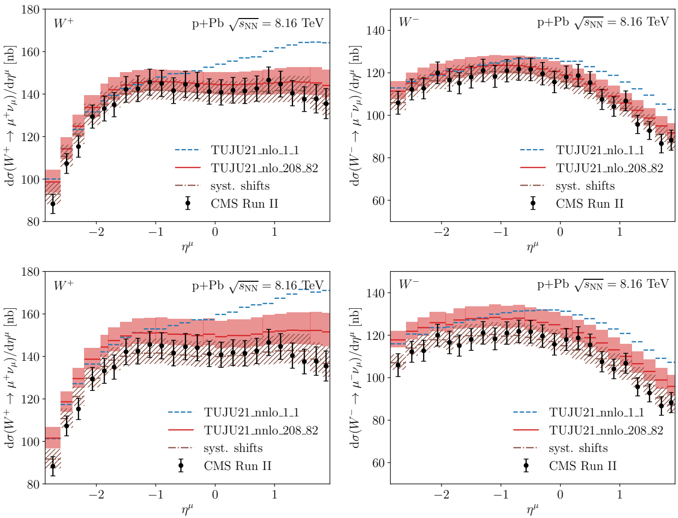
- NLO: 0.94
- NNLO: 0.84

$\Rightarrow$ Reduced χ^2 mainly in νDIS and ATLAS Z

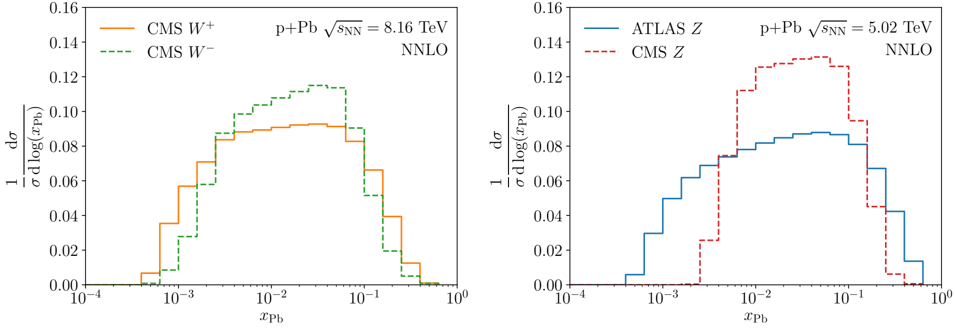


CMS $W^{\pm}$ data in p+Pb collisions

- Improved precision thanks to increased Run II luminosity
- Show clear deviation from proton PDF result at large η^l
- Shape equally well described by NLO and NNLO fits
- Slightly larger shifts in normalization preferred in NNLO

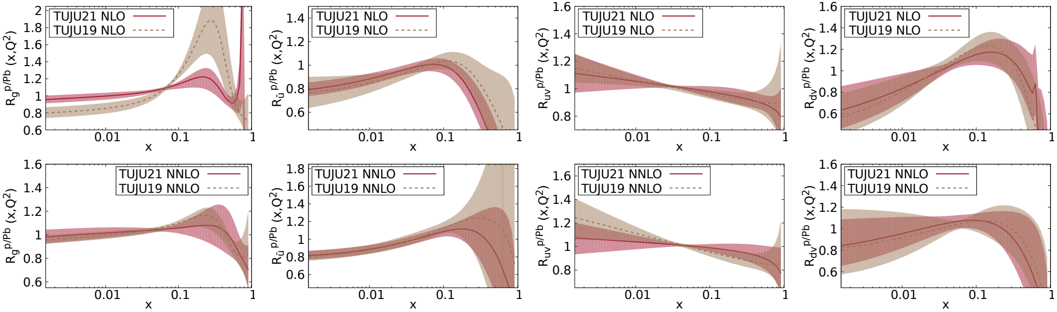


Kinematic region probed by EW-boson data



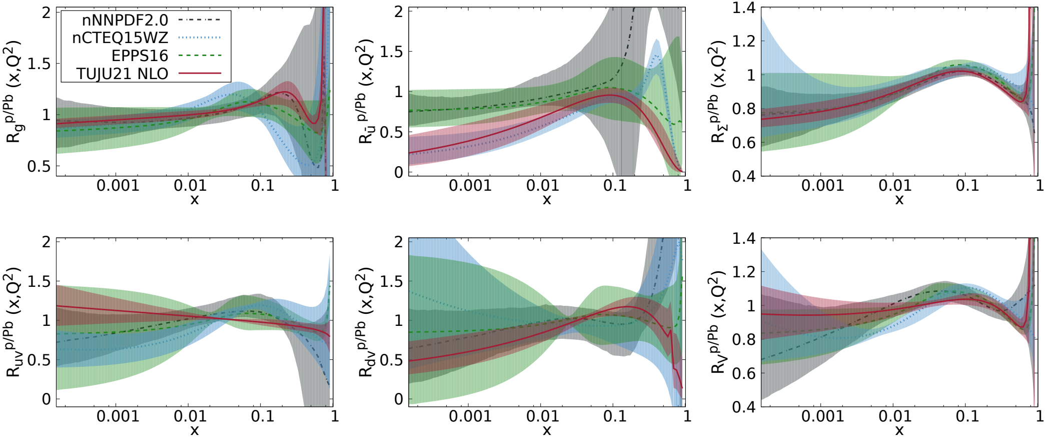
- Both Z and $W^{\pm}$ data sensitive down to $x \sim 10^{-3}$
- W^+ and W^- couple differently to quarks $\Rightarrow$ slightly different x-sensitivity
- ATLAS Z looser cuts on lepton kinematics $\Rightarrow$ probes smaller values of x

TUJU21: Nuclear modification ratios



- Gluons: Milder antishadowing at NLO than in TUJU19, NNLO consistent
- Antiquarks: Similar trends but reduced uncertainties in TUJU21
- Valence quarks: Still mutually opposite effects for u_V and d_V
- NLO and NNLO nuclear effects in better agreement in TUJU21

Comparison to other analyses at NLO

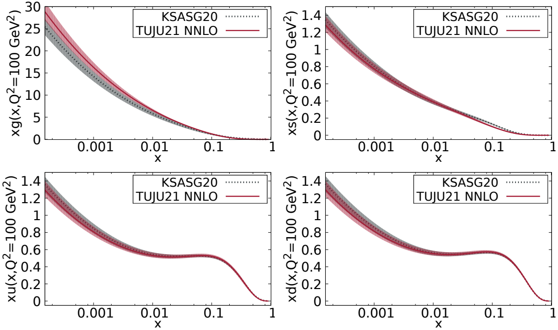


- Large differences in flavour separation
- Good agreement for Σ and total valence modification

Comparison to other analyses at NNLO

- Another recent NNLO analysis KSASG20 uses (ν)DIS and fixed-target DY [PRD 104, 034010]
- Some difference in gluons and in sea quarks around $x \sim 0.1$
- Very similar u and d

full nuclear PDFs for Pb:

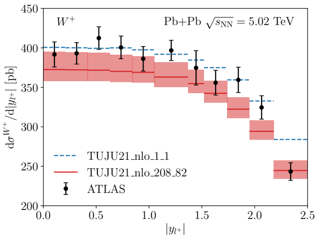


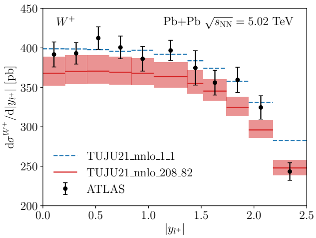
Applications to W^+-boson production in Pb+Pb

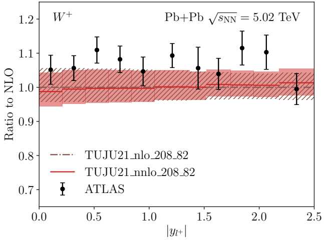
- EW-bosons do not couple with QCD medium

$\Rightarrow$ Can use study initial-state effects also in Pb+Pb

- Shape well described with nPDF-based calculation
- ATLAS data above the (N)NLO result, see also [Phys. Rev. Lett. 125, 212301 (2020)]
- NNLO corrections small for W^+, similar results for W^-





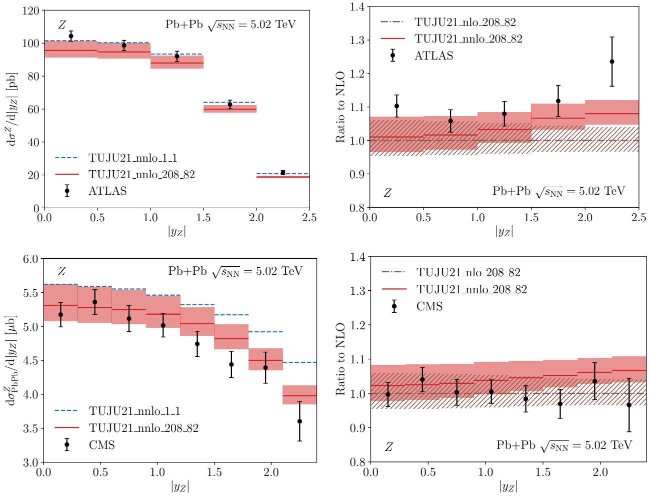


[ATLAS: EPJC 79, 935 (2019)]

Applications to Z-boson production in Pb+Pb

- NNLO corrections larger than for $W^{\pm}$
- ATLAS data above the NNLO result
- CMS data below NNLO

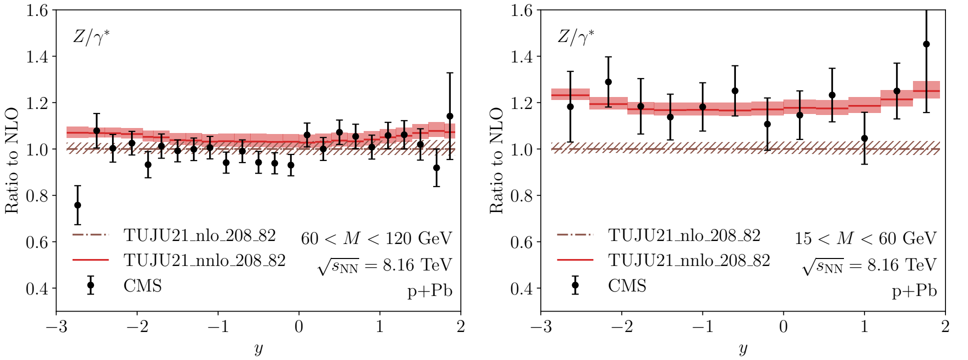
$\Rightarrow$ Hints of tension between the datasets?
(agreement with both when accounting all the uncertainties)



[ATLAS: PLB 802, 135262 (2020)] [CMS: PRL 127, 102002 (2021),]

New CMS data for DY in p+Pb

[CMS: JHEP 05, 182 (2021)]



- NNLO corrections moderate for $60 < M_{l\bar{l}} < 120$ GeV
- Large NNLO corrections for $15 < M_{l\bar{l}} < 60$ GeV

	χ^2/N_{dp}(NLO)	χ^2/N_{dp}(NNLO)
$15 < M < 60$ GeV	3.002	0.735
$60 < M < 120$ GeV	1.894	2.009
combined	2.261	1.554
Scaling factor	0.989	1.037

Summary & Outlook

TUJU21:

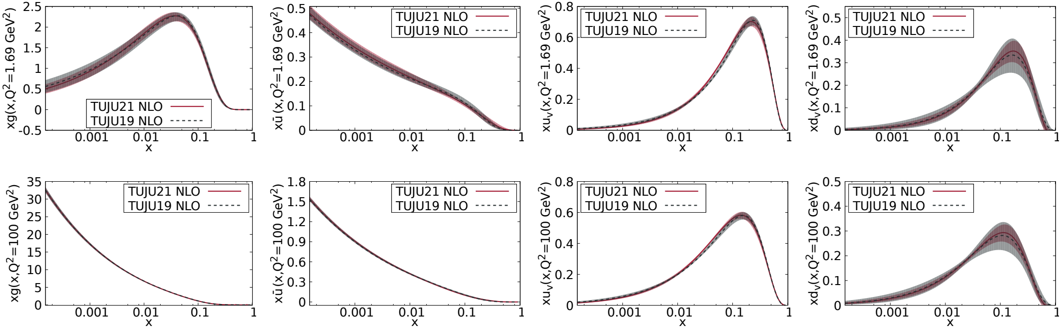
- Update of TUJU19 by including also EW-boson production in LHC
- First NNLO nPDF analysis to include LHC data
- Fitting the proton baseline in the same setup to ensure consistency
- Significant improvement in χ^2/N_{dp} when going from NLO to NNLO: $0.94 \rightarrow 0.84$
- NNLO corrections improve description of the LHC EW-boson data

Future directions

- Include more data and increase flexibility
- Fit proton and nuclear PDF simultaneously

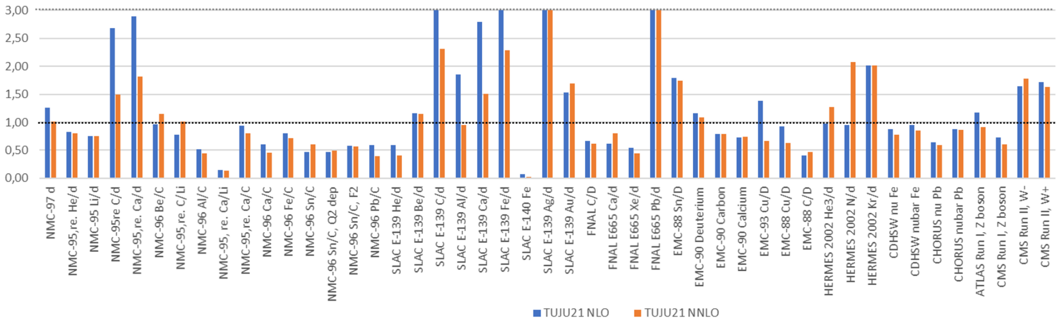
Backup slides

Comparison to TUJU19 with DIS data only



- Small differences for gluons and valence quarks
- Slightly reduced uncertainties, similar with the NLO fit
- TUJU19 were very similar to HERA2.0 PDFs

TUJU21: χ^2/N_{df} for different data sets



TUJU21 proton baseline data

Exp.	Data set	Year	Ref.	N_{dp}	χ^2 NLO	χ^2 NNLO
BCDMS	F2p 100GeV	1996	[65]	83	96.30	93.69
	F2p 120GeV			90	70.54	68.70
	F2p 200GeV			79	91.81	86.32
	F2p 280GeV			75	67.52	69.71
HERA 1+2	NCep 920	2015	[66]	377	459.71	482.23
	NCep 820			70	72.91	73.47
	NCep 575			254	222.64	231.35
	NCep 460			204	218.84	225.68
	NCem			159	227.80	232.79
	CCep			39	46.59	43.17
	CCem			42	60.49	63.60
NMC-97	NCep	1997	[67]	100	117.72	111.31
			In total:	1559		

Exp.	Data set	Year	Ref.	N_{dp}	χ^2 NLO	χ^2 NNLO
ATLAS DY	high mass DY	2013	[61]	13	10.91	11.54
	low mass DY	2014	[62]	8	22.86	8.68
ATLAS $W^\pm$, Z	W^+ lepton η	2012	[63]	11	15.77	14.00
	W^- lepton η			11	7.98	8.54
	Z y			8	4.10	2.71
	W^+ lepton y	2016	[64]	11	19.57	10.71
	W^- lepton y			11	11.11	11.82
	high mass CC Z y			6	7.61	6.05
	high mass CF Z y			6	3.92	3.95
	low mass Z y			6	41.32	23.84
	peak CC Z y			12	45.76	14.40
	peak CF Z y			9	21.85	7.55
CMS $W^\pm$	W^+ σ 8 TeV	2016	[68]	11	10.64	4.81
	W^- σ 8 TeV			11	8.14	9.27
			In total:	134		

TUJU21 nuclear data

Nucleus	Exp.	Year	Ref.	N_{dp}	χ^2 NLO	χ^2 NNLO
D	NMC 97	1996	[67]	120	151.61	121.52
	EMC 90	1989	[76]	21	24.31	22.89
He/D	HERMES	2002	[77]	7	6.79	8.92
	NMC 95, re.	1995	[78]	13	10.67	10.42
	SLAC E139	1994	[79]	11	6.47	4.42
Li/D	NMC 95	1995	[80]	12	9.10	9.00
Be/D	SLAC E139	1994	[79]	10	11.58	11.51
Be/C	NMC 96	1996	[81]	14	13.56	16.06
C	EMC 90	1989	[76]	17	13.41	13.44
C/D	FNAL E665	1995	[82]	3	2.00	1.83
	SLAC E139	1994	[79]	6	20.69	13.86
	EMC 88	1988	[83]	9	3.70	4.22
	NMC 95, re.	1995	[78]	13	34.96	19.49
C/Li	NMC 95, re.	1995	[78]	10	7.77	10.18
N/D	HERMES	2002	[77]	1	0.95	2.08
Al/D	SLAC E139	1994	[79]	10	18.49	9.49
Al/C	NMC 96	1996	[81]	14	7.29	6.23
Ca	EMC 90	1989	[76]	19	13.41	13.44
Ca/D	NMC 95, re.	1995	[78]	12	34.75	21.82
	FNAL E665	1995	[82]	3	1.84	2.41
	SLAC E139	1994	[79]	6	16.74	9.01
Ca/Li	NMC 95, re.	1995	[78]	10	1.45	1.33
Ca/C	NMC 95, re.	1995	[78]	10	9.35	8.00
	NMC 96	1996	[81]	14	8.45	6.42

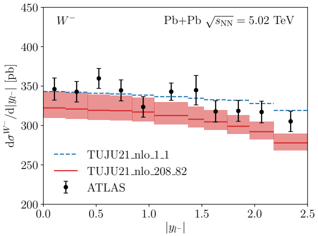
Fe	SLAC E140	1993	[84]	2	0.14	0.04
Fe/D	SLAC E139	1994	[79]	14	44.53	32.07
Fe/C	NMC 96	1996	[81]	14	11.17	9.93
ν Fe	CDHSW	1991	[85]	464	404.26	358.19
$\bar{\nu}$ Fe	CDHSW	1991	[85]	462	439.53	395.99
Cu/D	EMC 88	1988	[83]	9	8.38	5.71
	EMC 93	1993	[86]	19	26.38	12.58
Kr/D	HERMES	2002	[77]	1	2.02	2.02
Ag/D	SLAC E139	1994	[79]	6	21.37	18.80
Sn/D	EMC 88	1988	[83]	8	14.37	13.98
Sn/C	NMC 96	1996	[81]	14	6.48	8.52
	NMC 96, Q^2 dep.	1996	[87]	134	76.13	75.03
Xe/D	FNAL E665	1992	[88]	3	1.64	1.34
Au/D	SLAC E139	1994	[79]	11	16.89	18.66
Pb/D	FNAL E665	1995	[82]	2	8.28	7.72
Pb/C	NMC 96	1996	[81]	14	8.32	5.42
ν Pb	CHORUS	2005	[89]	405	259.48	237.85
$\bar{\nu}$ Pb	CHORUS	2005	[89]	405	356.01	352.09
			In total:	2336		

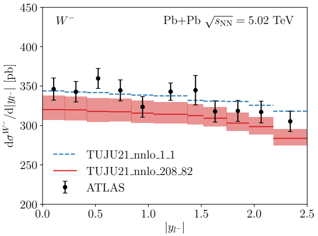
Nucleus	Proc.	Exp.	Year	Ref.	N_{dp}	χ^2 NLO	χ^2 NNLO
pPb	Z	LHC Run I ATLAS	2015	[5]	14	16.40	12.82
	Z	LHC Run I CMS	2015	[7]	12	8.76	7.30
	W^-	LHC Run II CMS	2019	[69]	24	39.58	42.83
	W^+	LHC Run II CMS			24	41.08	39.07
				In total:	74		

Applications to W^--boson production in Pb+Pb

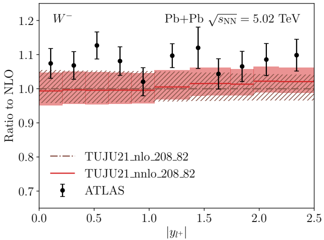
- EW-bosons do not couple with QCD medium

$\Rightarrow$ Can use study initial-state effects also in Pb+Pb





- Shape well described with nPDF-based calculation
- ATLAS data above the (N)NLO result, see also [Phys. Rev. Lett. 125, 212301 (2020)]
- NNLO corrections small for W^-



[ATLAS: EPJC 79, 935 (2019)]