Recent developments on precision W & Z

Tobias Neumann, Brookhaven Nat'l Lab

artemide

NangaParbat

ResBos2

DYTurbo

reSolve

CuTe-MCFM

SCETlib

RadISH

(see General Meeting last February)

N^3LO fixed order frontier

N^4LL q_T resummation frontier

N^3LO (α_s^3) is becoming the norm for W & Z

Two-loop QCDxEW corrections by two groups

(see General Meeting last February)

Bonciani and Vicini:
Bonciani, Buccioni, Mondini, Vicini '16;
Bonciani, Buccioni, Rana, Triscari, Vicini '19;
+ combinations (+ Armadillo, Devoto, Buonocore, Grazzini, Kallweit) '20 '21; '22

and Buccioni, Caola, Chawdhry, Devoto, Heller, von Manteuffel, Melnikov, Röntsch, Signorile '22

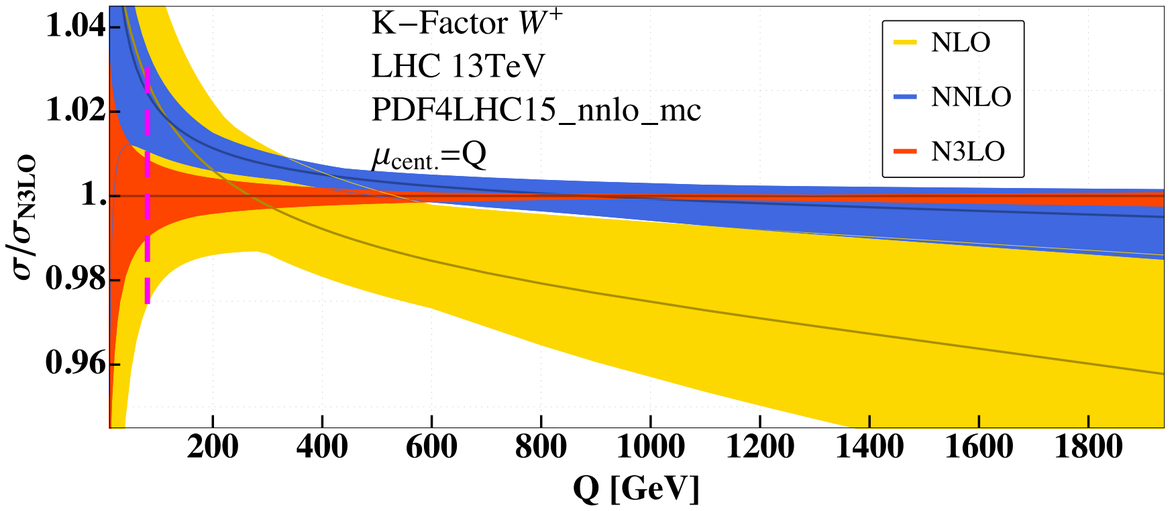
+ ...

Non-perturbative effects and TMDs

see LHE-EWWG mini-workshop: low pT DY

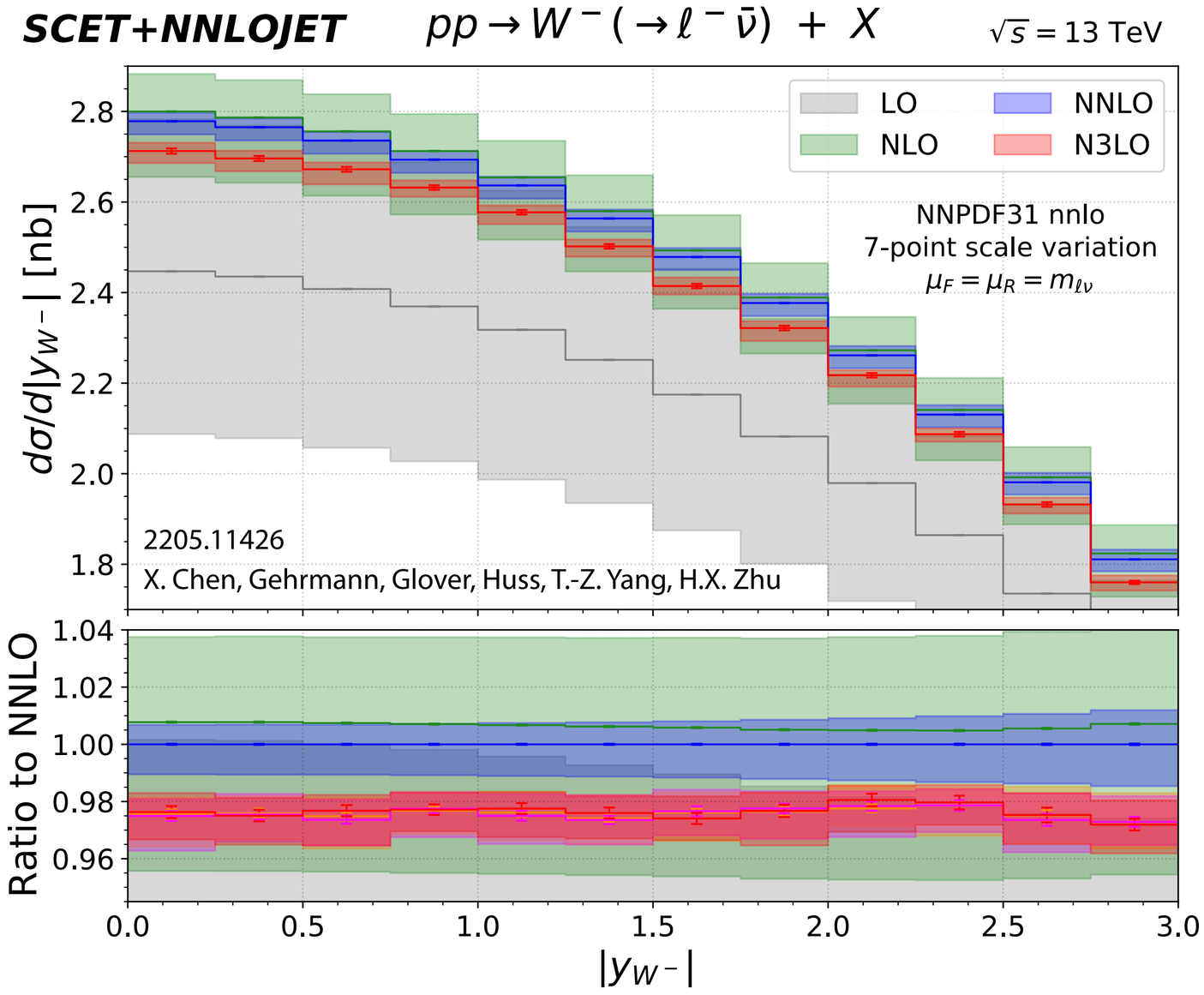
W production

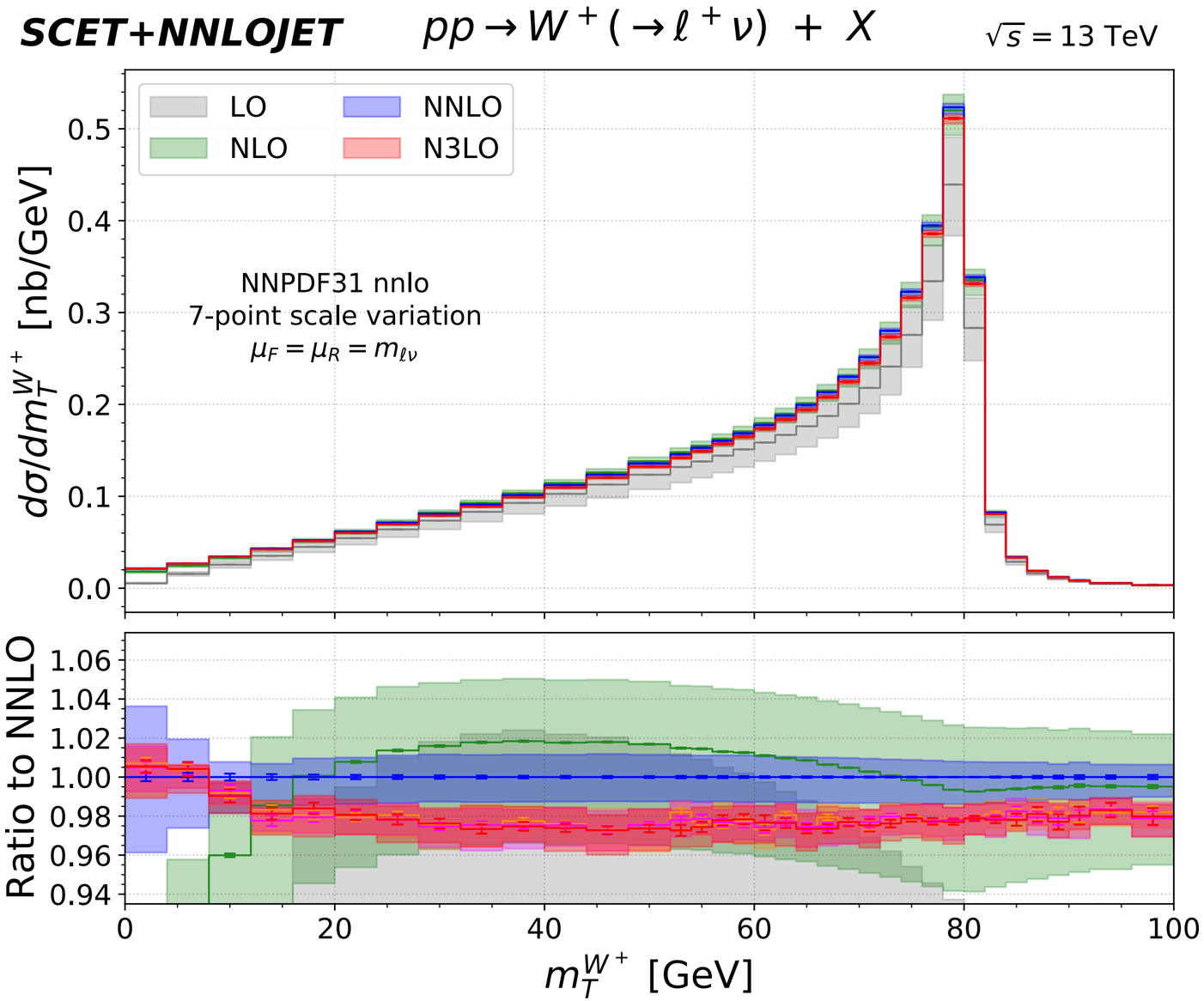
Total inclusive DY

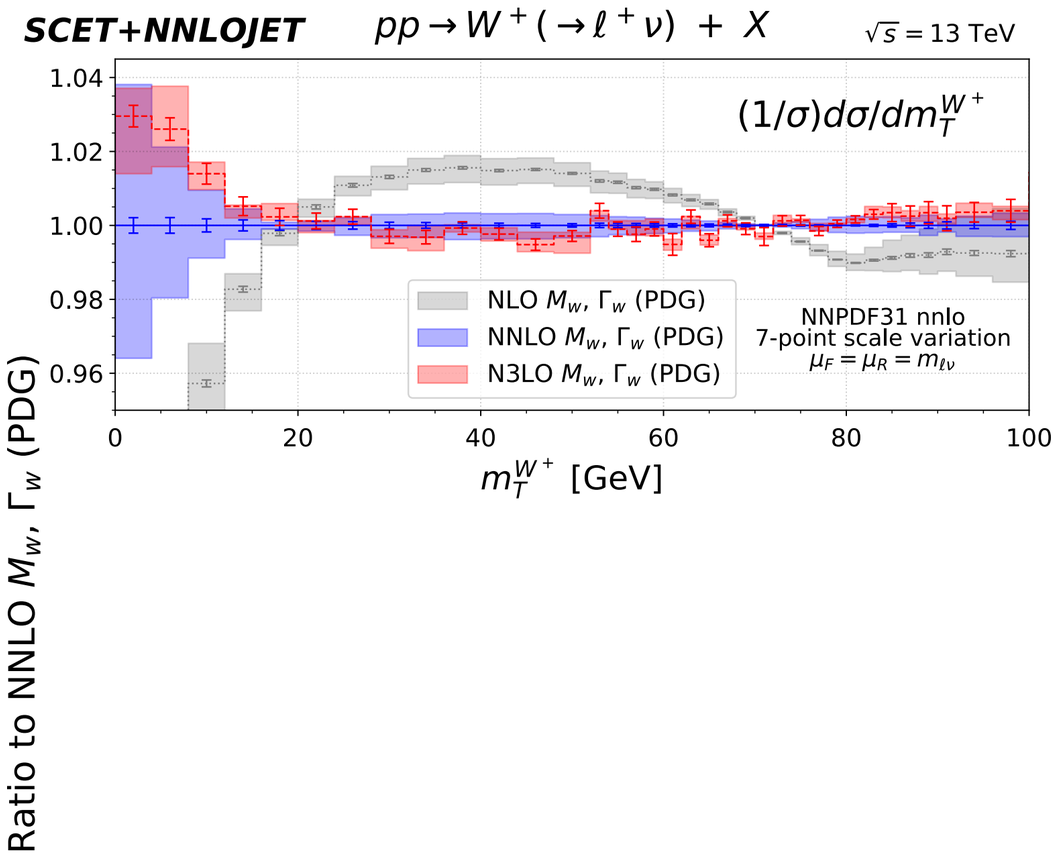


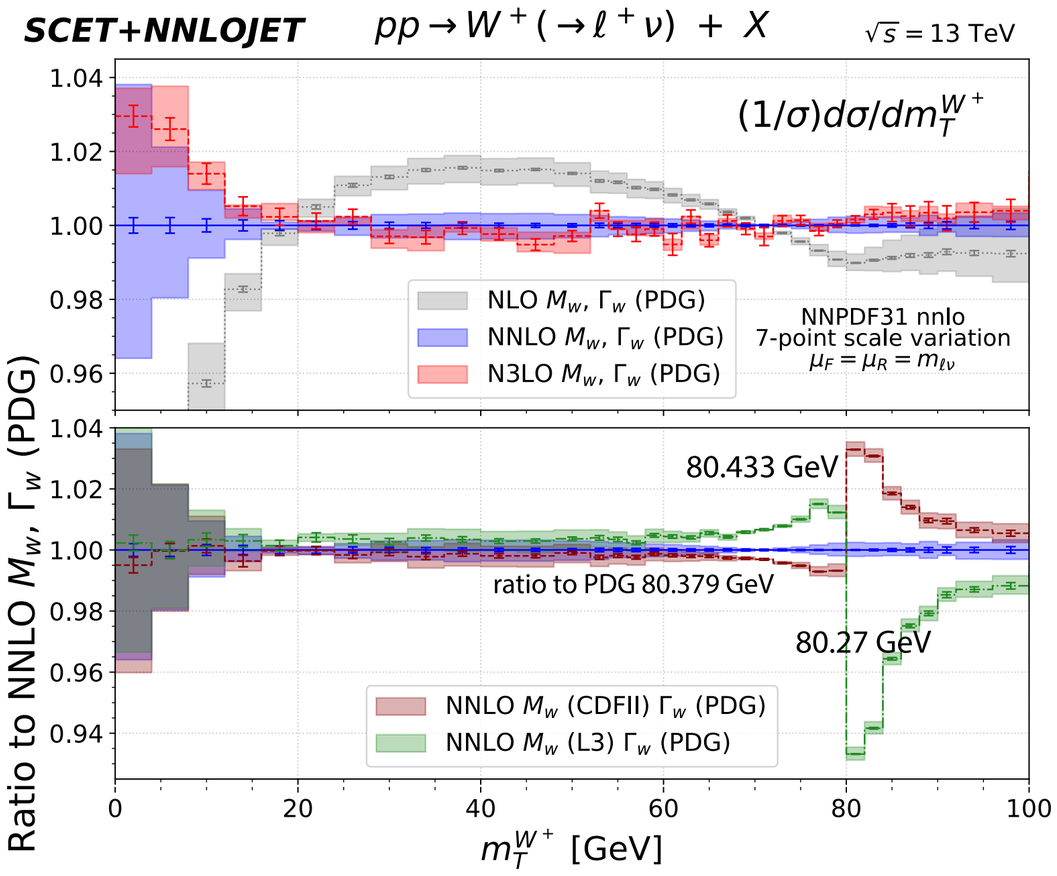
2007.13313 Duhr, Dulat, Mistlberger '20

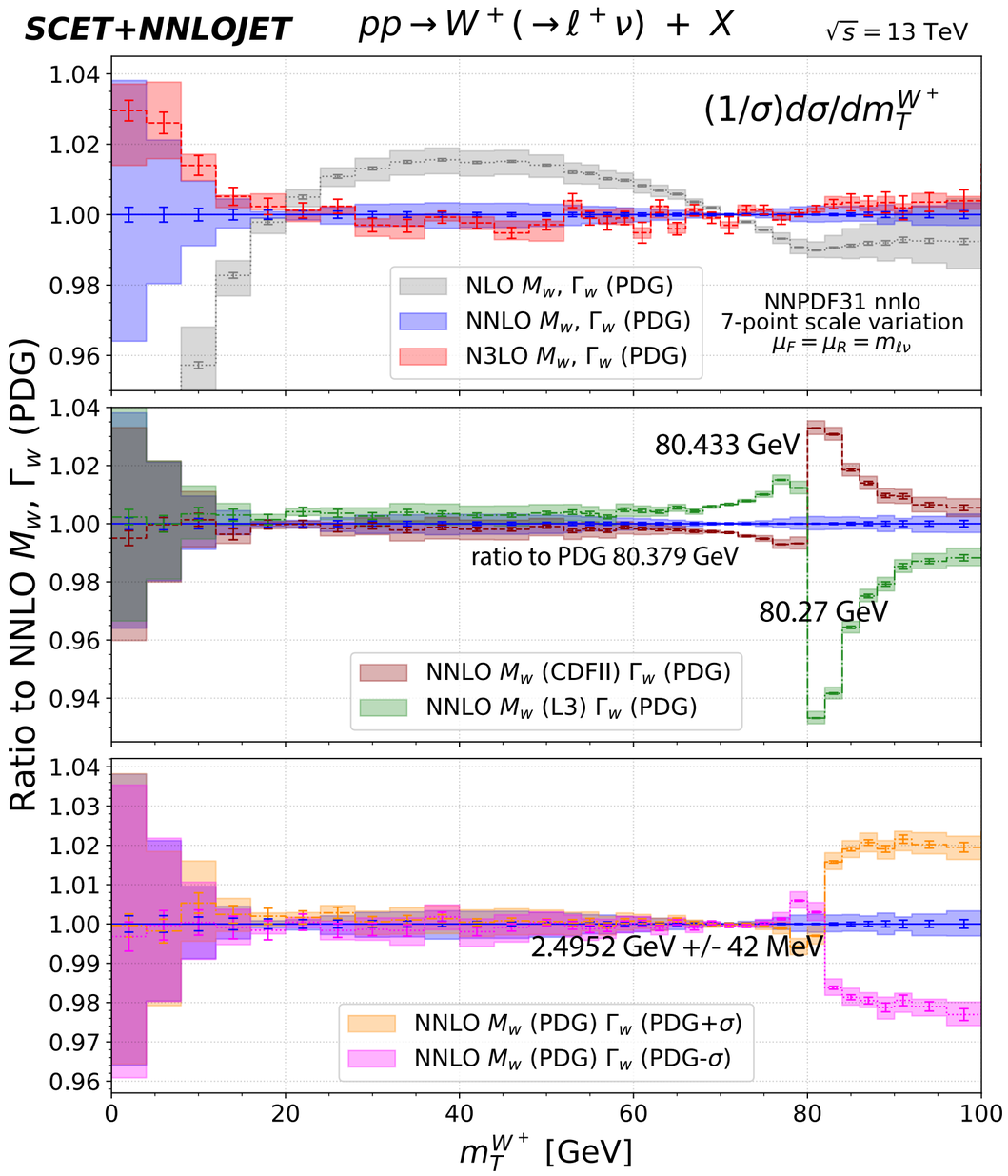
See also Baglio, Duhr, Mistlberger, Szafron '22


SCET+NNLOJET
$pp \to W^-(\to \ell^- \bar{\nu}) + X$
$\sqrt{s} = 13$ TeV
LO
NLO
NNLO
N3LO
NNPDF31 nnlo
7-point scale variation
$\mu_F = \mu_R = m_{\ell\nu}$
2205.11426
X. Chen, Gehrmann, Glover, Huss, T.-Z. Yang, H.X. Zhu
$d\sigma/d|y_{W^-}|$ [nb]
Ratio to NNLO
$|y_{W^-}|$


SCET+NNLOJET
$pp \to W^+(\to \ell^+ \nu) + X$
$\sqrt{s} = 13$ TeV
LO
NLO
NNLO
N3LO
NNPDF31 nnlo
7-point scale variation
$\mu_F = \mu_R = m_{\ell\nu}$
$d\sigma/dm_T^{W^+}$ [nb/GeV]
Ratio to NNLO
$m_T^{W^+}$ [GeV]


SCET+NNLOJET
$pp \to W^+(\to \ell^+\nu) + X$
$\sqrt{s} = 13$ TeV
$(1/\sigma)d\sigma/dm_T^{W^+}$
NLO M_W, Γ_W (PDG)
NNLO M_W, Γ_W (PDG)
N3LO M_W, Γ_W (PDG)
NNPDF31 nnlo
7-point scale variation
$\mu_F = \mu_R = m_{\ell\nu}$
Ratio to NNLO M_W, Γ_W (PDG)
$m_T^{W^+}$ [GeV]
1.04
1.02
1.00
0.98
0.96
0
20
40
60
80
100


SCET+NNLOJET
$pp \to W^+(\to \ell^+\nu) + X$
$\sqrt{s} = 13$ TeV
$(1/\sigma)d\sigma/dm_T^{W^+}$
NLO M_W, Γ_W (PDG)
NNLO M_W, Γ_W (PDG)
N3LO M_W, Γ_W (PDG)
NNPDF31 nnlo
7-point scale variation
$\mu_F = \mu_R = m_{\ell\nu}$
80.433 GeV
ratio to PDG 80.379 GeV
80.27 GeV
NNLO M_W (CDFII) Γ_W (PDG)
NNLO M_W (L3) Γ_W (PDG)
Ratio to NNLO M_W, Γ_W (PDG)
$m_T^{W^+}$ [GeV]


SCET+NNLOJET
$pp \to W^+(\to \ell^+\nu) + X$
$\sqrt{s} = 13$ TeV
$(1/\sigma)d\sigma/dm_T^{W^+}$
NLO M_W, Γ_W (PDG)
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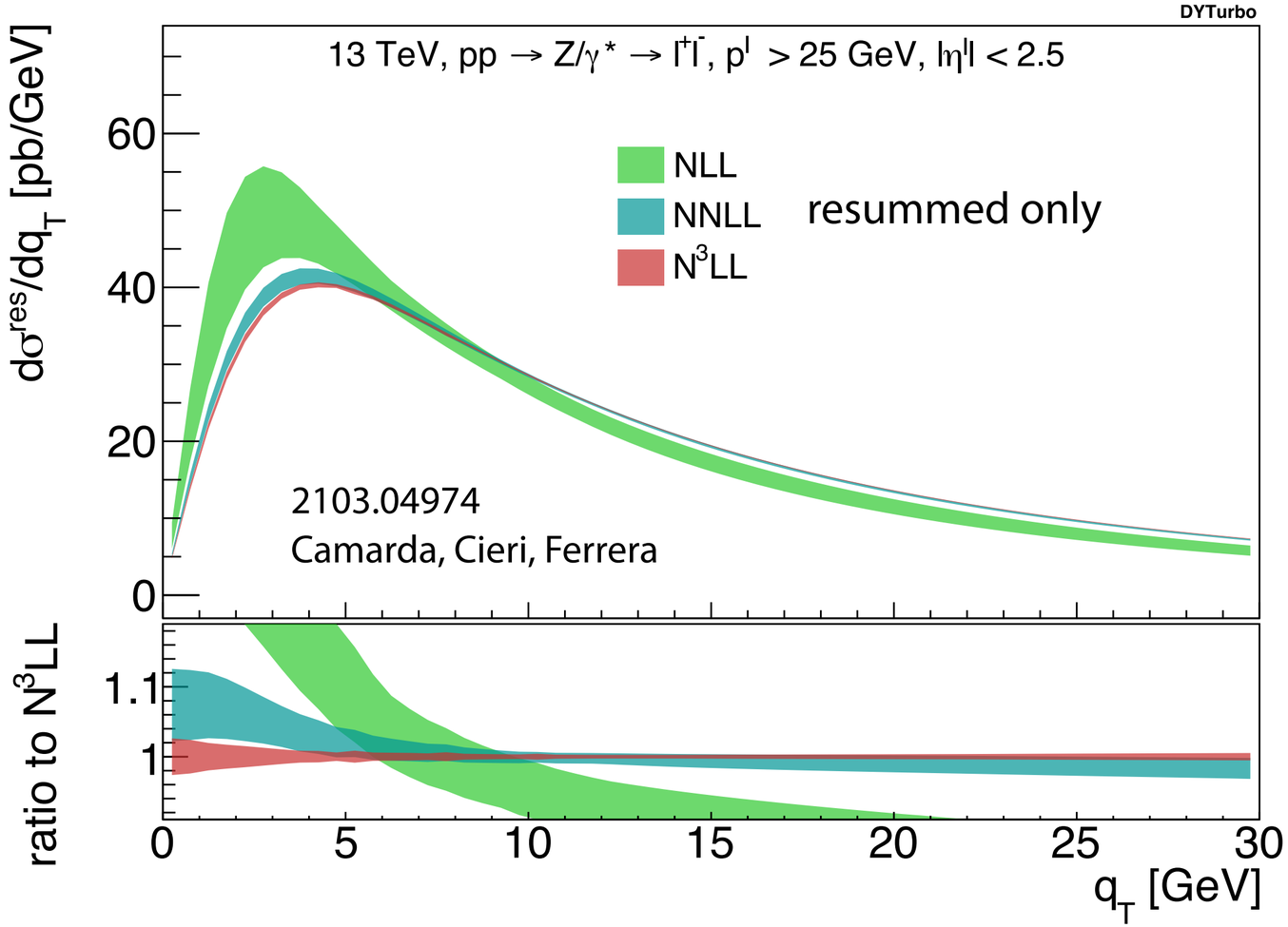
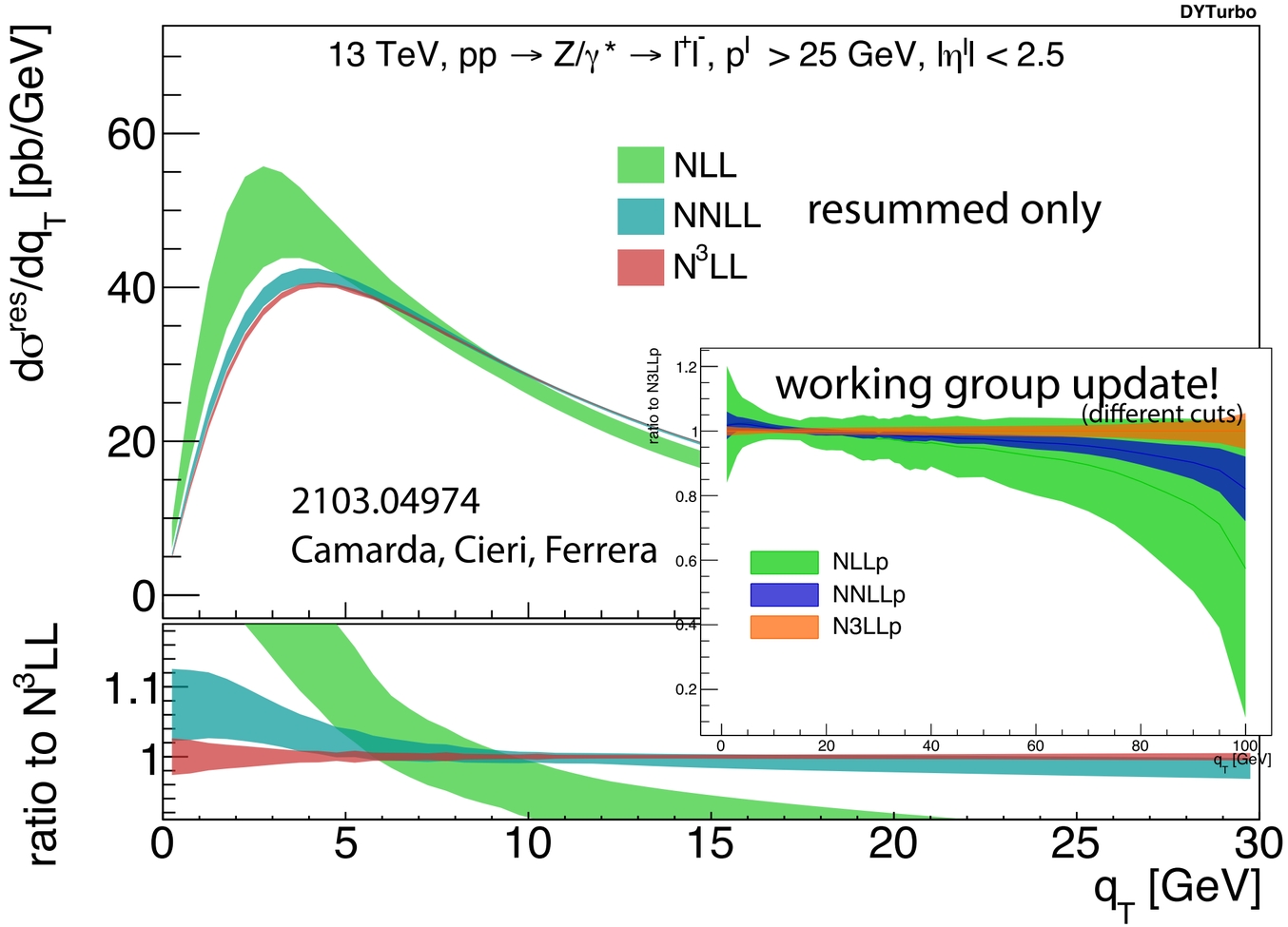
NNPDF31 nnlo
7-point scale variation
$\mu_F = \mu_R = m_{\ell\nu}$
80.433 GeV
ratio to PDG 80.379 GeV
80.27 GeV
NNLO M_W (CDFII) Γ_W (PDG)
NNLO M_W (L3) Γ_W (PDG)
2.4952 GeV +/- 42 MeV
NNLO M_W (PDG) Γ_W (PDG+σ)
NNLO M_W (PDG) Γ_W (PDG-σ)
Ratio to NNLO M_W, Γ_W (PDG)
$m_T^{W^+}$ [GeV]

Z production


DYTurbo
13 TeV, pp → Z/γ* → l+l-, pl > 25 GeV, |ηl| < 2.5
NLL
NNLL
N3LL
resummed only
2103.04974
Camarda, Cieri, Ferrera
dσres/dqT [pb/GeV]
ratio to N3LL
qT [GeV]
0
20
40
60
1
1.1
0
5
10
15
20
25
30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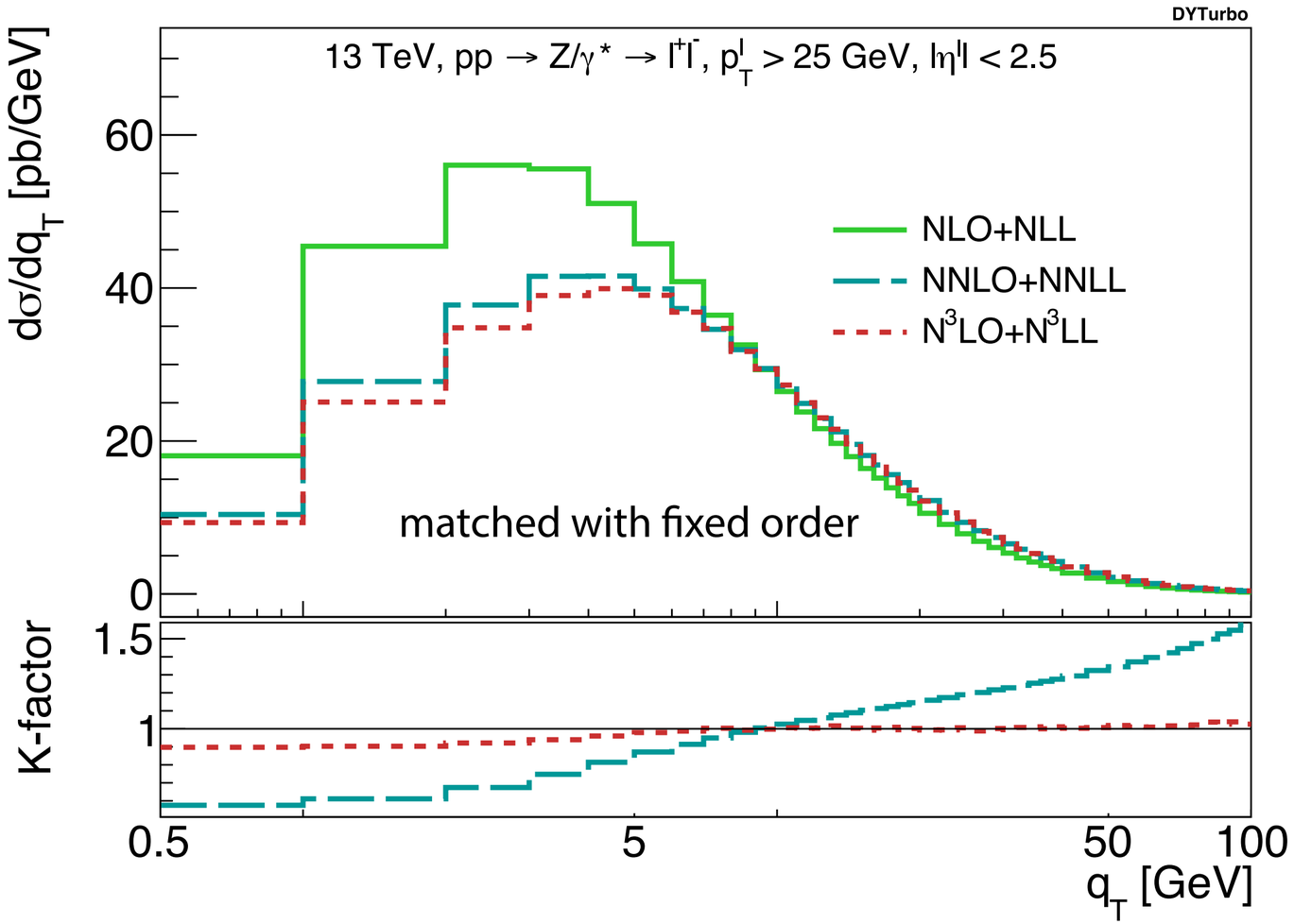
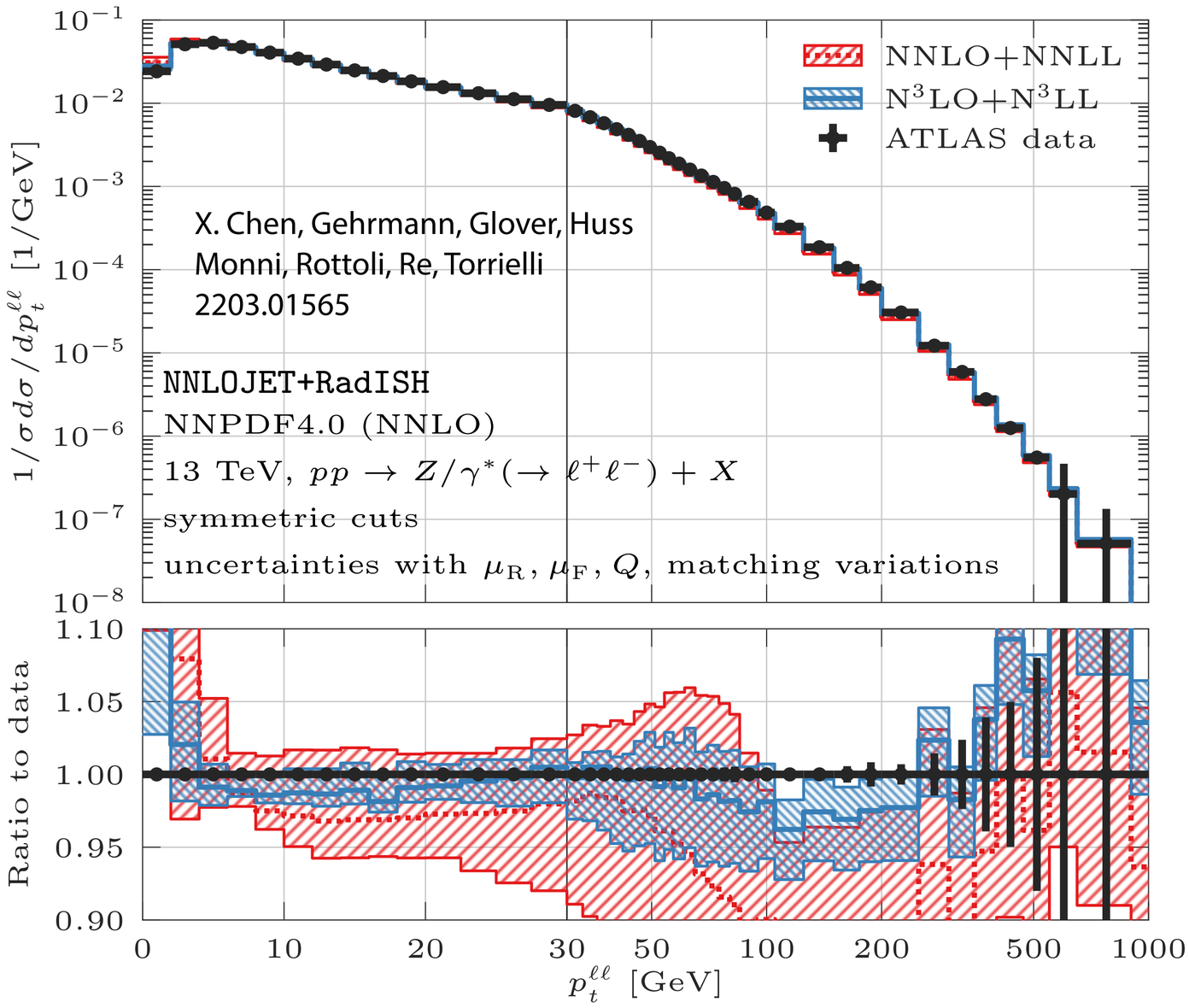
13 TeV, pp → Z/γ* → l+l-, pl > 25 GeV, |ηl| < 2.5
NLL
NNLL
N3LL
resummed only
2103.04974
Camarda, Cieri, Ferrera
working group update!
(different cuts)
NLLp
NNLLp
N3LLp
ratio to N3LLp
dσres/dqT [pb/GeV]
ratio to N3LL
qT [GeV]



matched with tabulated NNLOjet Z+jet fixed order results


NNLO+NNLL
N³LO+N³LL
ATLAS data
X. Chen, Gehrmann, Glover, Huss
Monni, Rottoli, Re, Torrielli
2203.01565
NNLOJET+RadISH
NNPDF4.0 (NNLO)
13 TeV, $pp \to Z/\gamma^*(\to \ell^+\ell^-) + X$
symmetric cuts
uncertainties with μ_R, μ_F, Q, matching variations
$1/\sigma\, d\sigma/dp_t^{\ell\ell}$ [1/GeV]
Ratio to data
$p_t^{\ell\ell}$ [GeV]

N^3LO results

RadISH+NNLOjet

X. Chen, Gehrmann, Glover, Huss, Monni, Rottoli, Re, Torrielli '22

Order	σ [pb] Symmetric cuts	
k	N^kLO	N^kLO+N^kLL
0	$721.16^{+12.2\%}_{-13.2\%}$	—
1	$742.80(1)^{+2.7\%}_{-3.9\%}$	$748.58(3)^{+3.1\%}_{-10.2\%}$
2	$741.59(8)^{+0.42\%}_{-0.71\%}$	$740.75(5)^{+1.15\%}_{-2.66\%}$
3	$722.9(1.1)^{+0.68\%}_{-1.09\%} \pm 0.9$	$726.2(1.1)^{+1.07\%}_{-0.77\%}$

N^3LO results

RadISH+NNLOjet

X. Chen, Gehrmann, Glover, Huss, Monni, Rottoli, Re, Torrielli '22

Order	σ [pb] Symmetric cuts	
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Resummed predictions in CuTe-MCFM at α_s^3

Neumann, Campbell '22

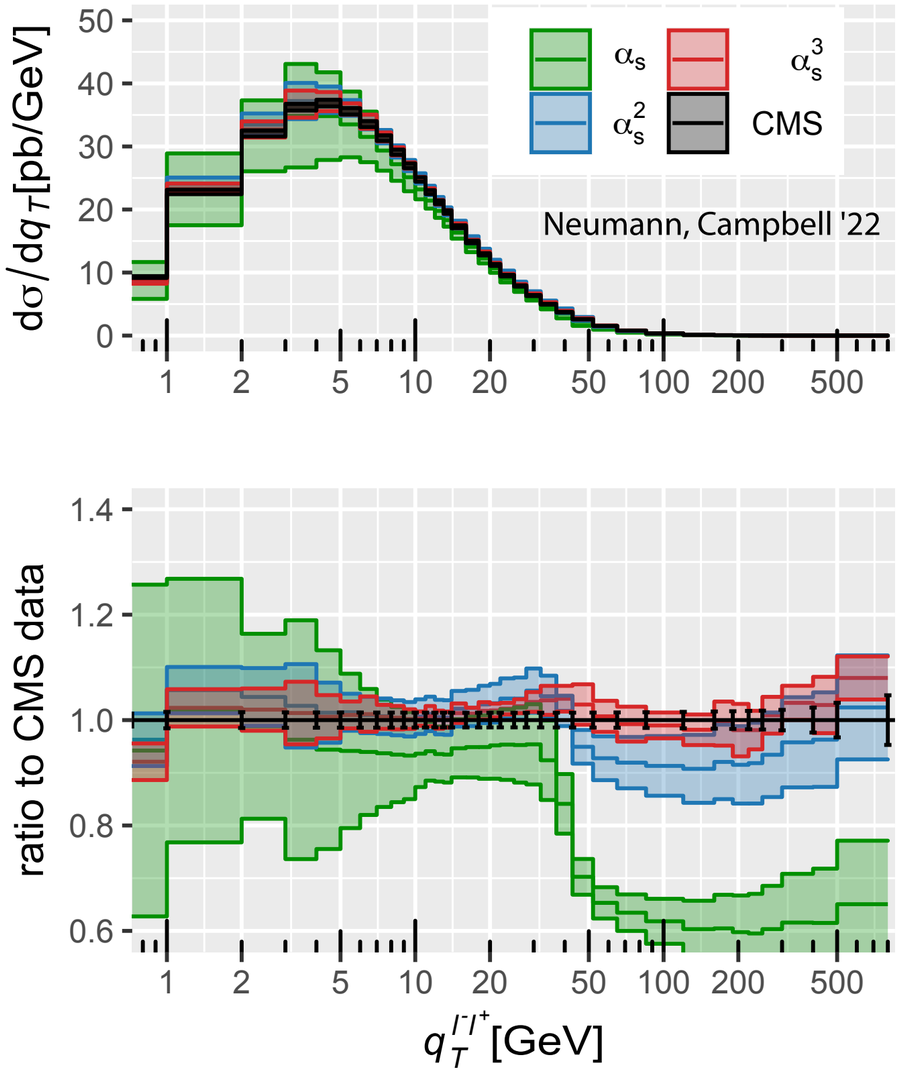
- Use independent Z+jet NNLO calculation (via 1-jettiness slicing)
  Boughezal, Focke, Liu, Petriello; Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello '15

- towards N^{4}LL: Four loop rapidity anomalous dimension
  Duhr, Mistlberger, Vita '22; Moult, H.X. Zhu, Y. J. Zhu '22

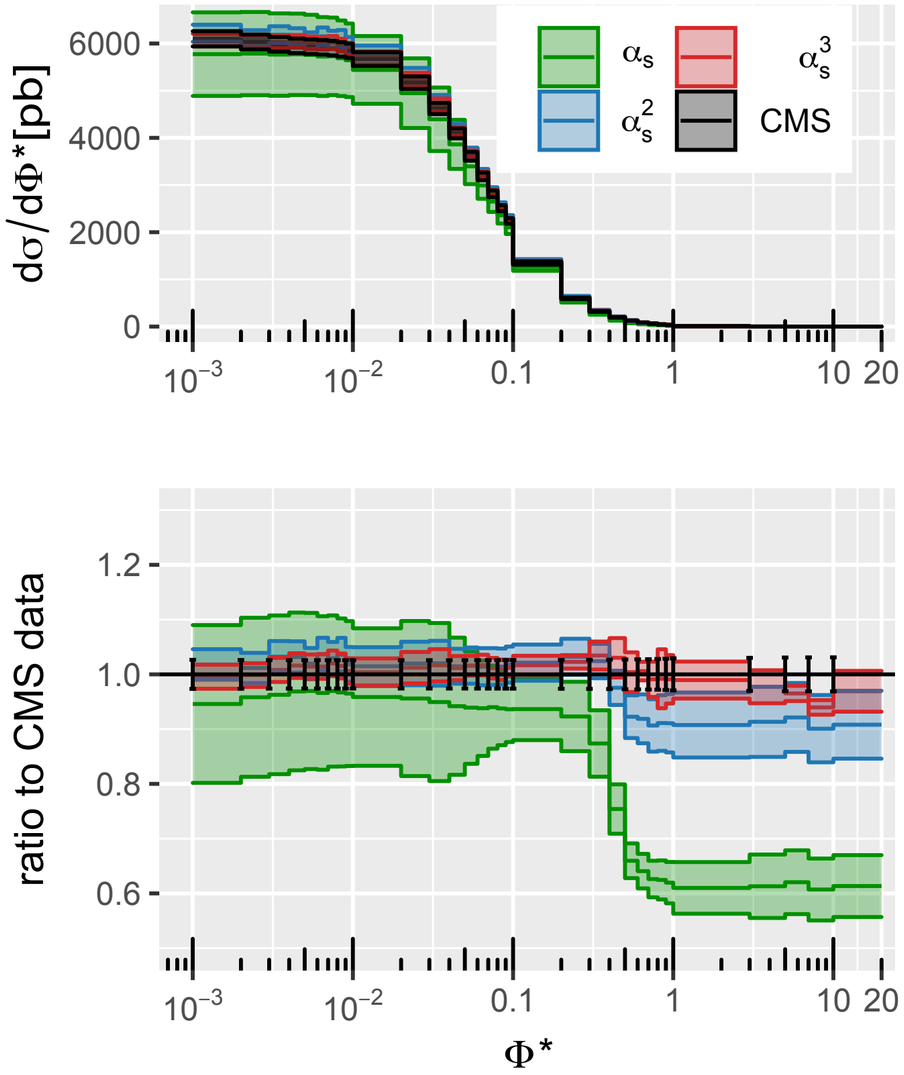
- (Massive three-loop axial singlet contributions)
  Chen, Czakon, Niggetiedt '22

Fixed-order α_s^3 and logarithmic α_s^3 accuracy
while counting $\log(q_T^2/Q^2) \sim 1/\alpha_s$: **up to N^{3}LO PDF's!**

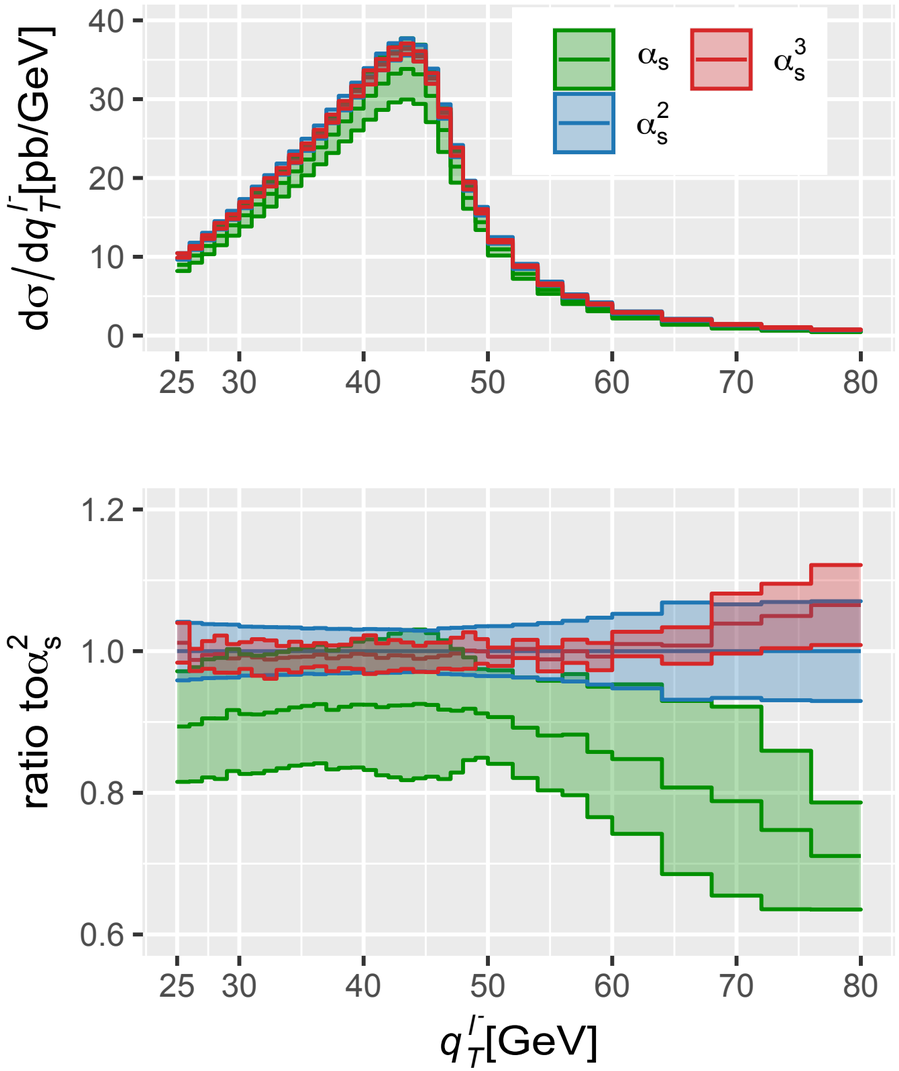
Fiducial results in comparison with CMS 13 TeV data



Fiducial results in comparison with CMS 13 TeV data



Cure for Jacobian peak in lepton q_T



Total fiducial cross-sections

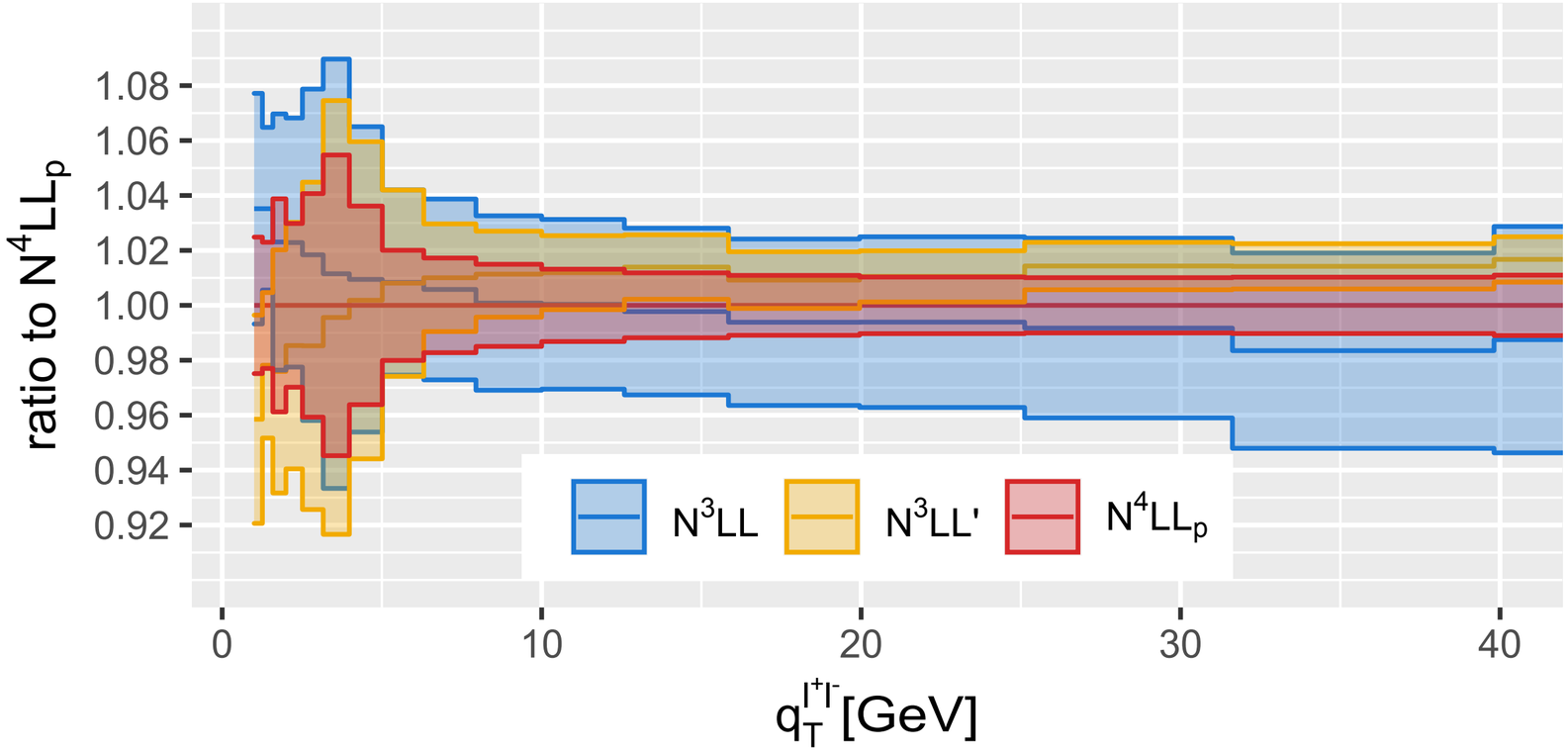
Order k	fixed-order α_s^k	res. improved α_s^k
0	694^{+85}_{-92}	—
1	732^{+19}_{-30}	$637 \pm 8_{\text{mat.}} \pm 70_{\text{sc.}}$
2	720^{+4}_{-3}	$707 \pm 3_{\text{mat.}} \pm 29_{\text{sc.}}$
3	$700^{+4}_{-6} \pm 1_{\text{slicing}}$	$702 \pm 1_{\text{mat.}} \pm 17_{\text{sc.}}$

$699 \pm 5\,(\text{syst.}) \pm 17\,(\text{lumi.})$ (e, μ combined) [3]

This brings up the question of realistic uncertainites.

We find 2.5%, only other estimate is given with RadISH resummation: 1% (2203.01565).

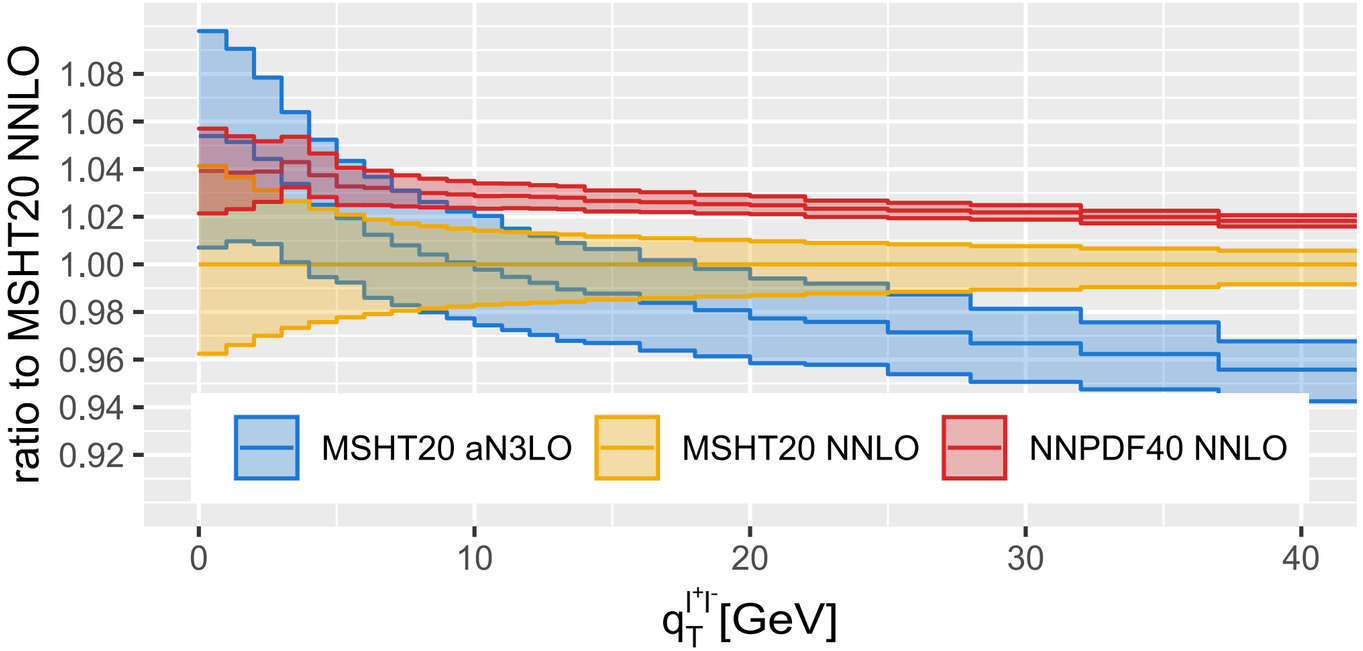
Inclusion of four-loop rapidity anom. dim. $N^3LL' \rightarrow N^4LL_p$



uncertainty decrease at N^3LL', but N^4LL_p shifts noticeably

Question of PDFs!

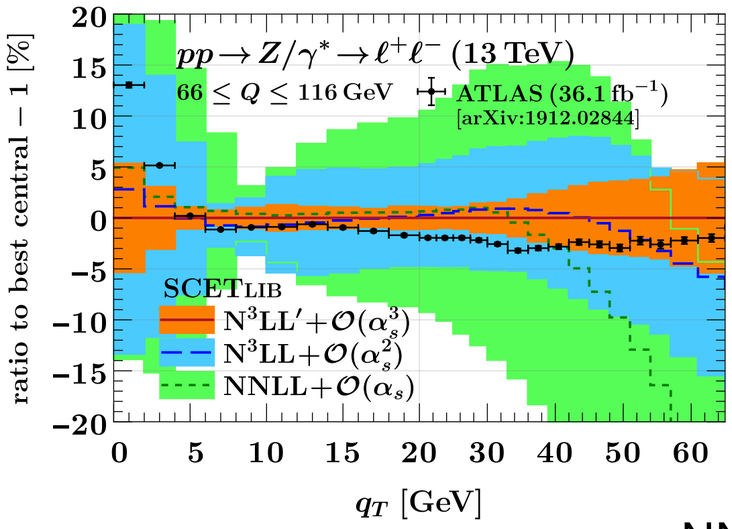
$$x^{a_1}(1-x)^{a_2}P(\sqrt{x}, a_j)$$



MSHT approximate N^{3}LO PDFs. Approximations for four-loop splitting functions, known information on small and large x, available Mellin moments.

These MHO effects are included in Hessian procedure as nuisance parameters.

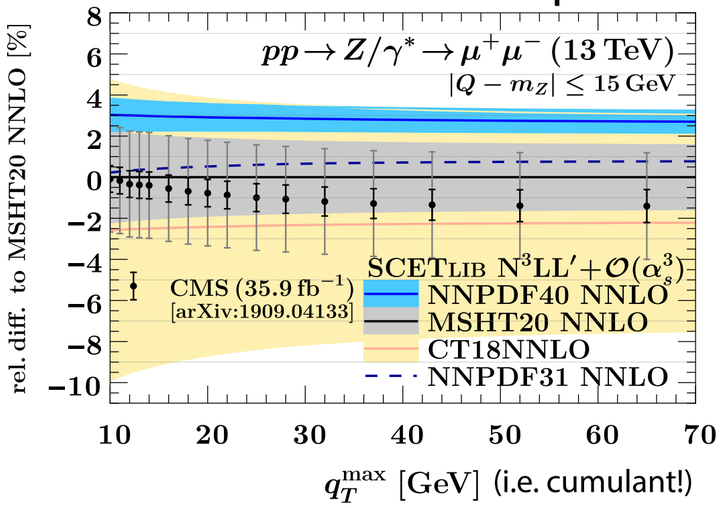
comparison with ATLAS data

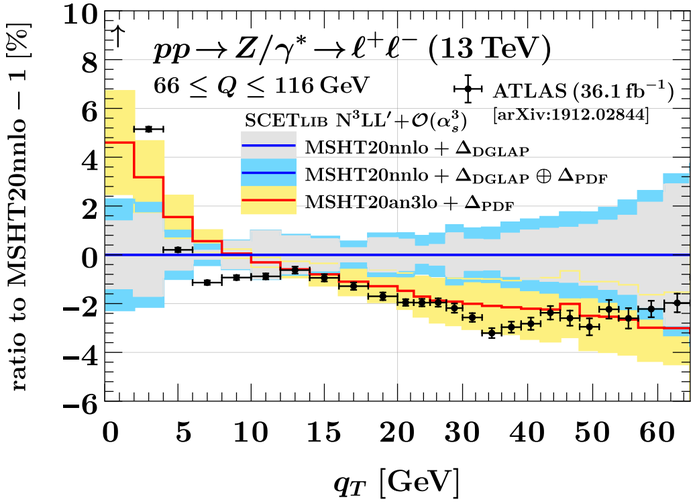


non-pert. modeling

see low pT workshop
Sept. 7 with further contributions
from NangaParbat and Artemide

compare NNLO and N3LO PDFs





preliminary results by Billis, Ebert, Michel, Stewart, Sun, Tackmann
see EW W/Z meeting Oct. 4

Summary and Outlook

- DY inclusive and fully differential at α_s^3 and $\alpha\alpha_s$
- Moved from total inclusive ('20) to fiducial and fully differential ('22 + ongoing)
- Future discussions: Uncertainty estimates (now maybe relevant for the first time!)
- Working group efforts push uncertainty discussion and non-perturbative and TMD effects
- PDFs are crucial bottleneck now! (Need full α_s^3 running and fits)