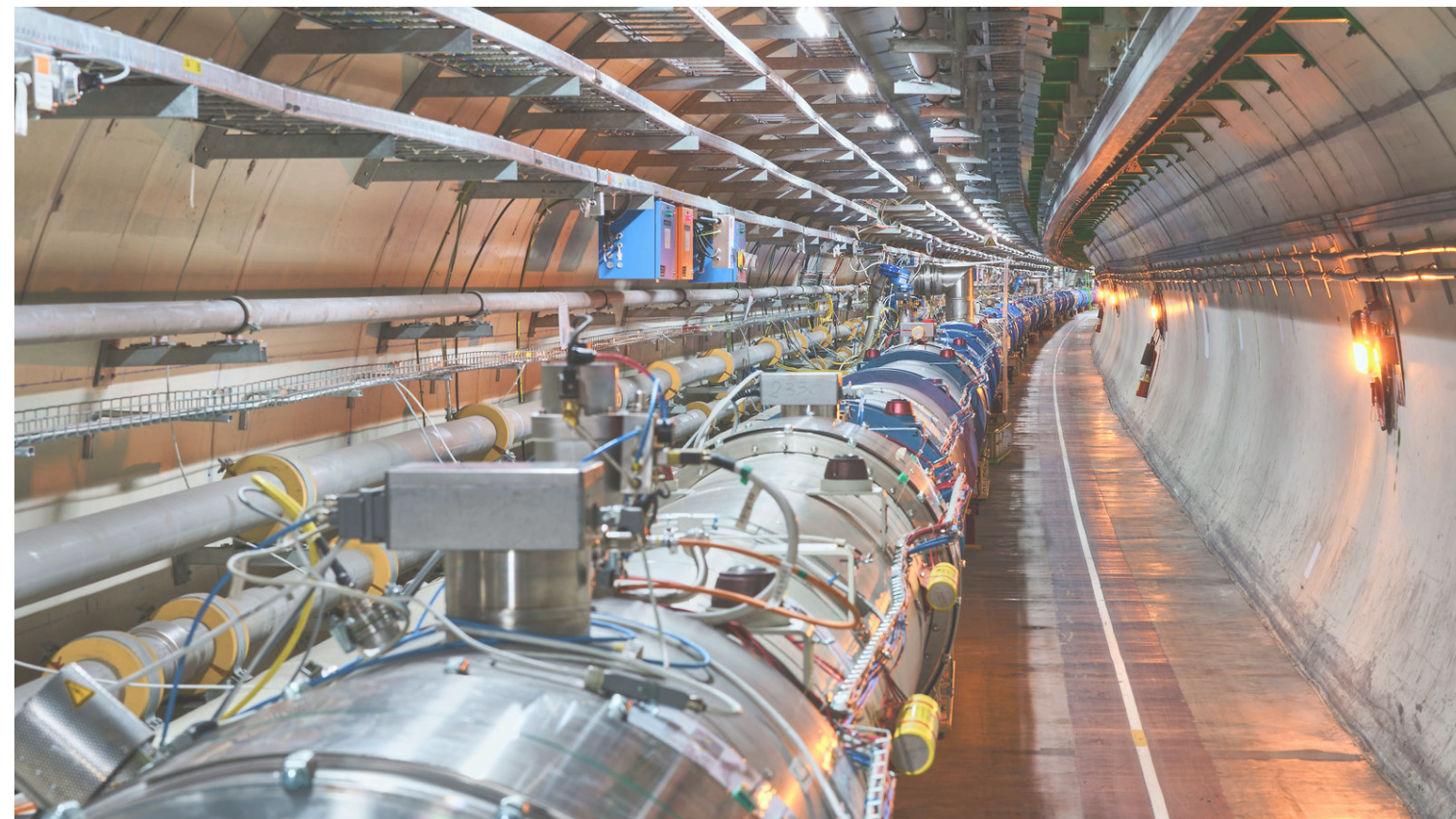


Third order QCD predictions for W- and Z-bosons

based on arXiv:2207.07056 and 2308.15382
with John Campbell



Tobias Neumann
William & Mary

W/Z measurements at the luminosity limit!

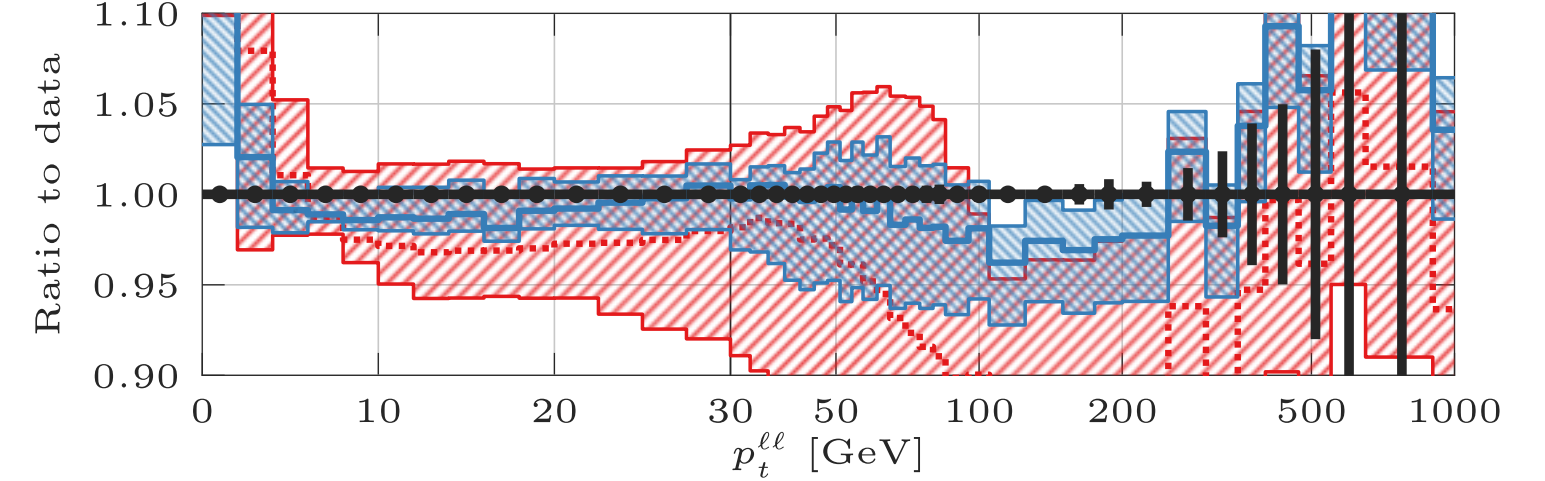
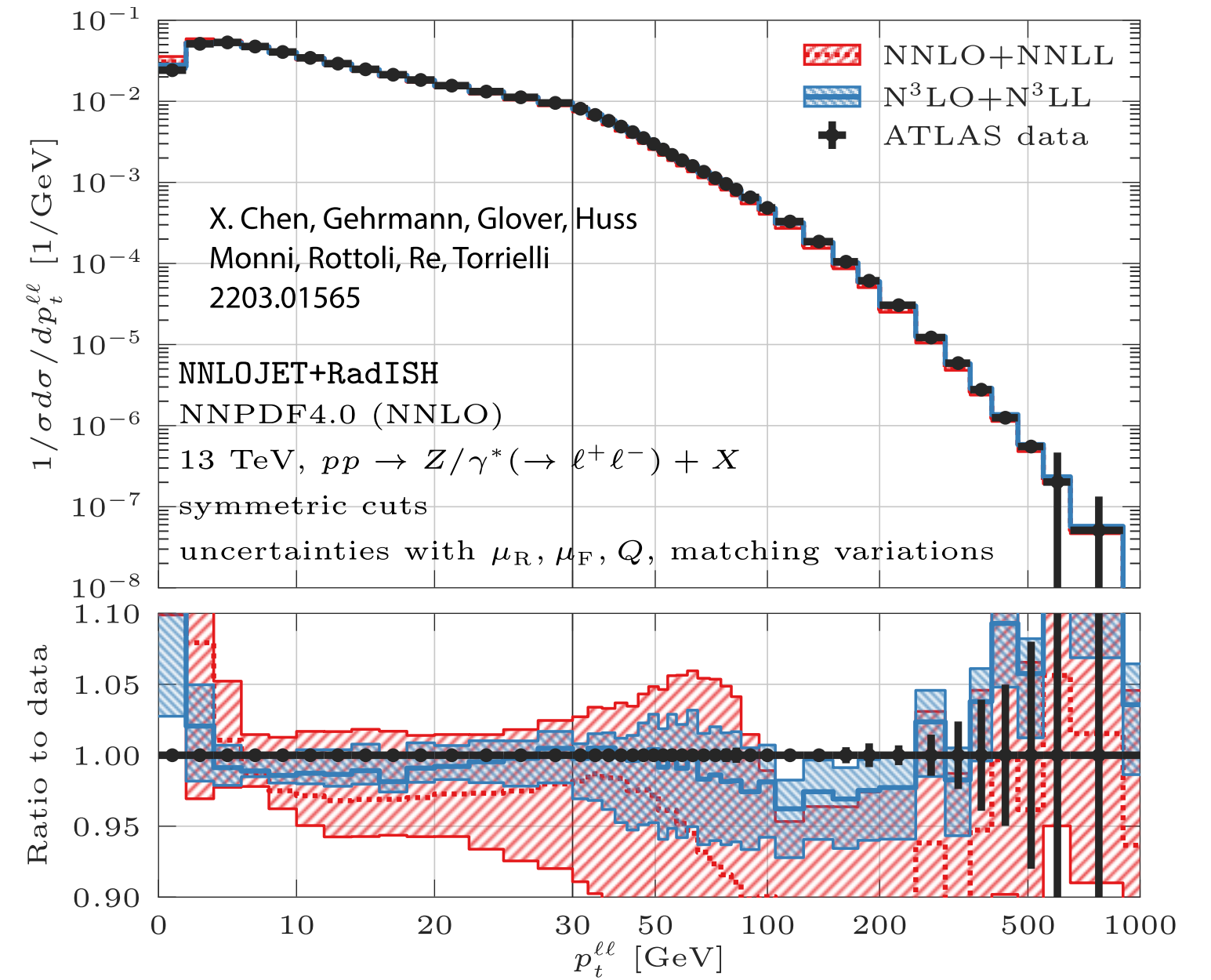
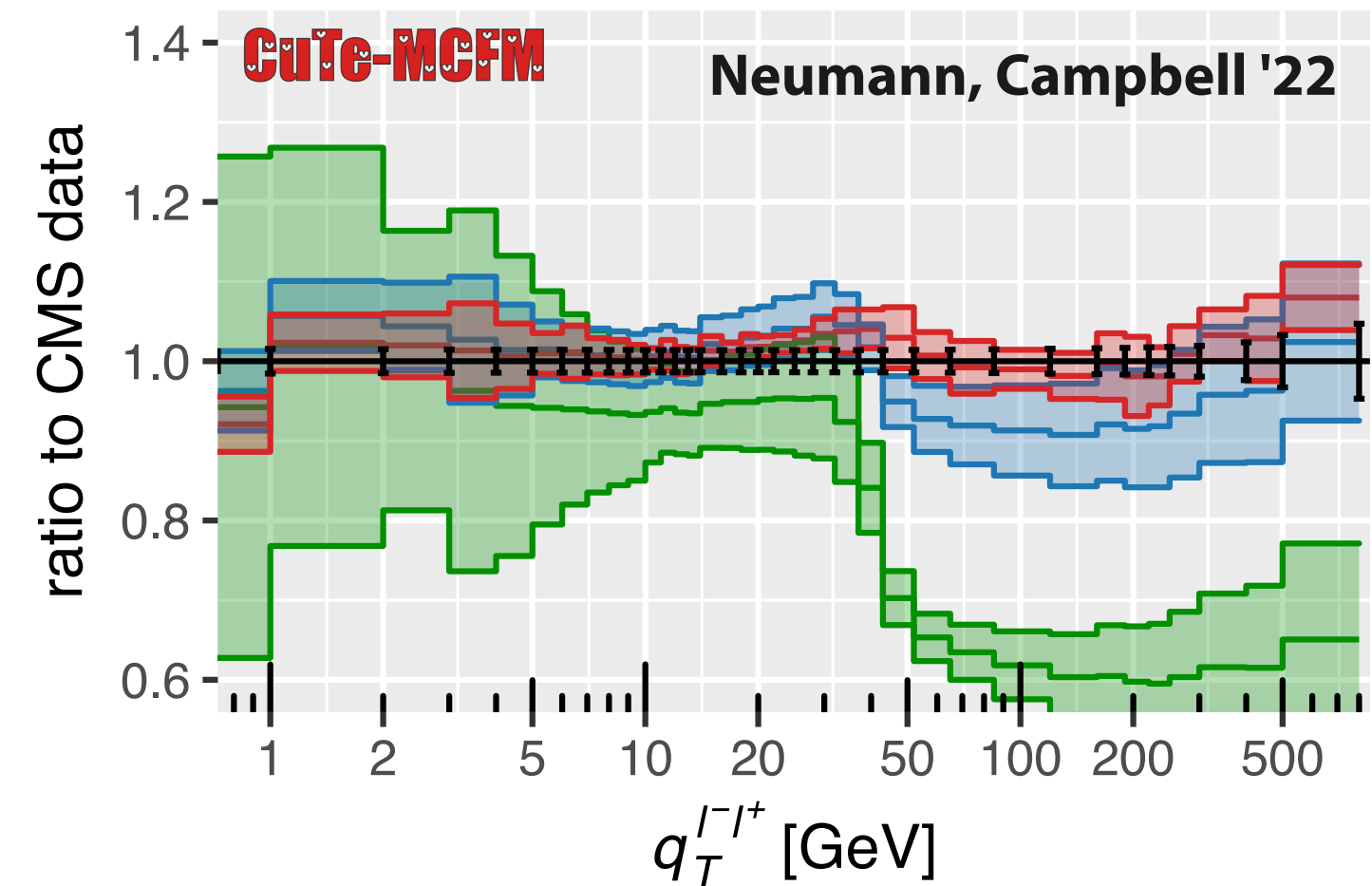
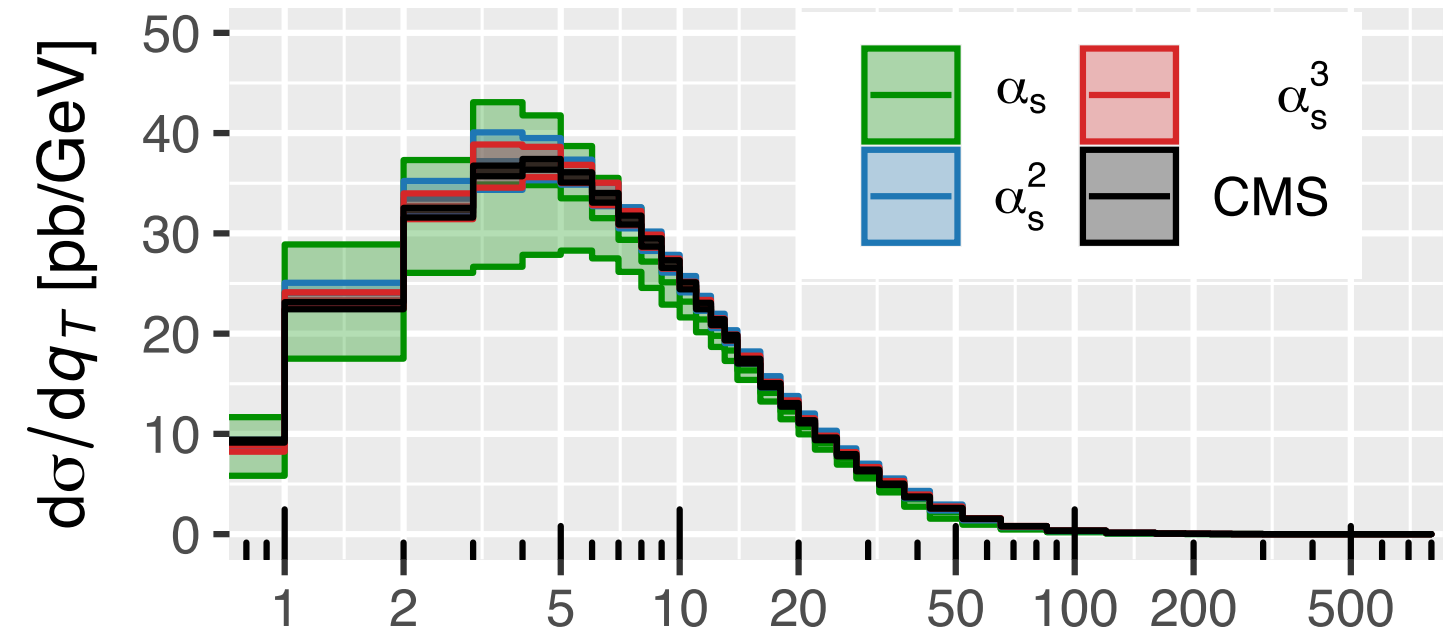
Luminosity measurements with 1% uncertainty

ATLAS arXiv:2104.01927; CMS arXiv:2212.09379

ATLAS W/Z arXiv:2404.06204

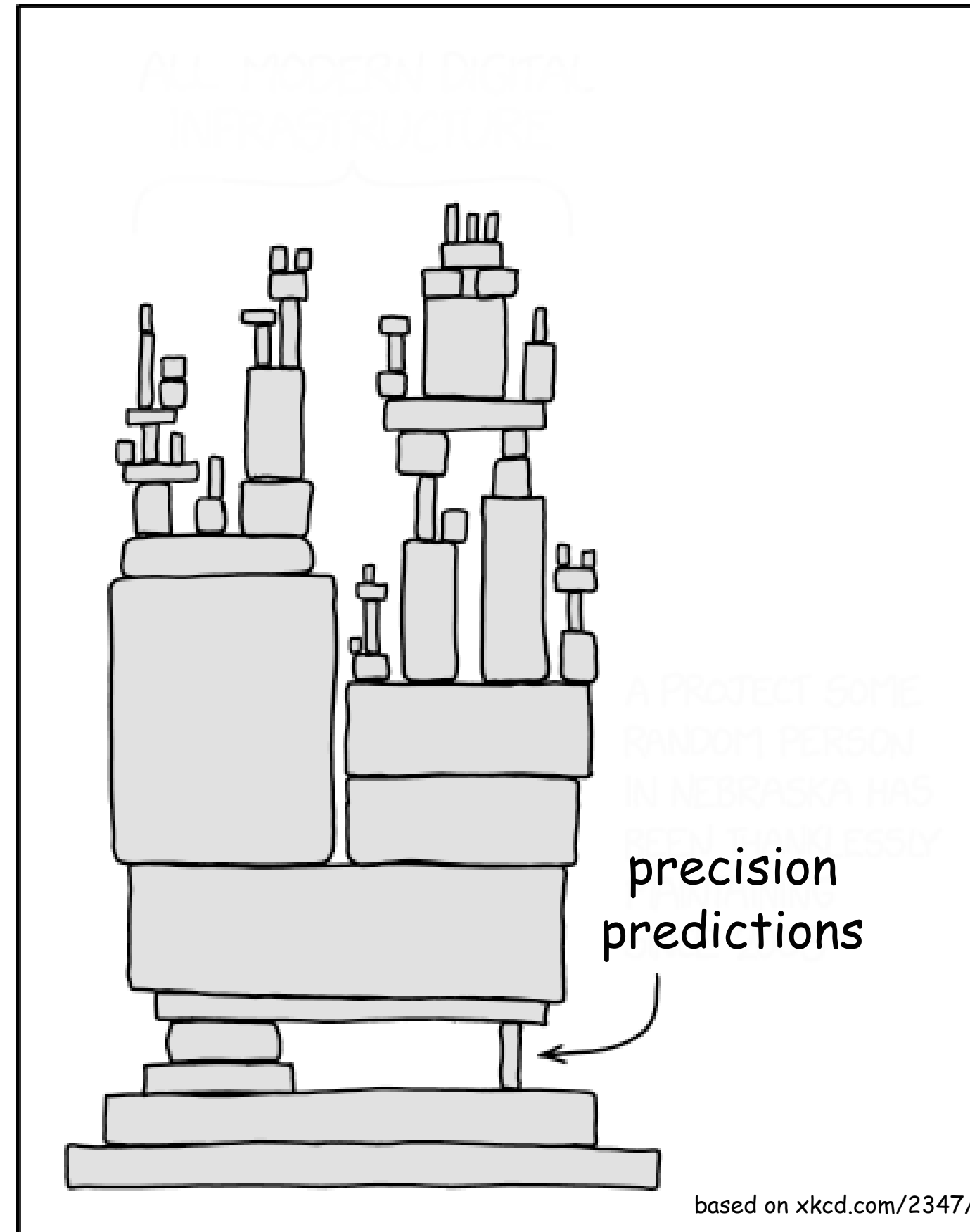
Process	$\sigma_{\text{fid}}(\sqrt{s} = 5.02 \text{ TeV})$ [pb]
$W^- \rightarrow \ell^- \nu$	$1384 \pm 2 \text{ (stat.)} \pm 5 \text{ (syst.)} \pm 15 \text{ (lumi.)}$
$W^+ \rightarrow \ell^+ \nu$	$2228 \pm 3 \text{ (stat.)} \pm 8 \text{ (syst.)} \pm 23 \text{ (lumi.)}$
$Z \rightarrow \ell\ell$	$333.0 \pm 1.2 \text{ (stat.)} \pm 2.2 \text{ (syst.)} \pm 3.3 \text{ (lumi.)}$

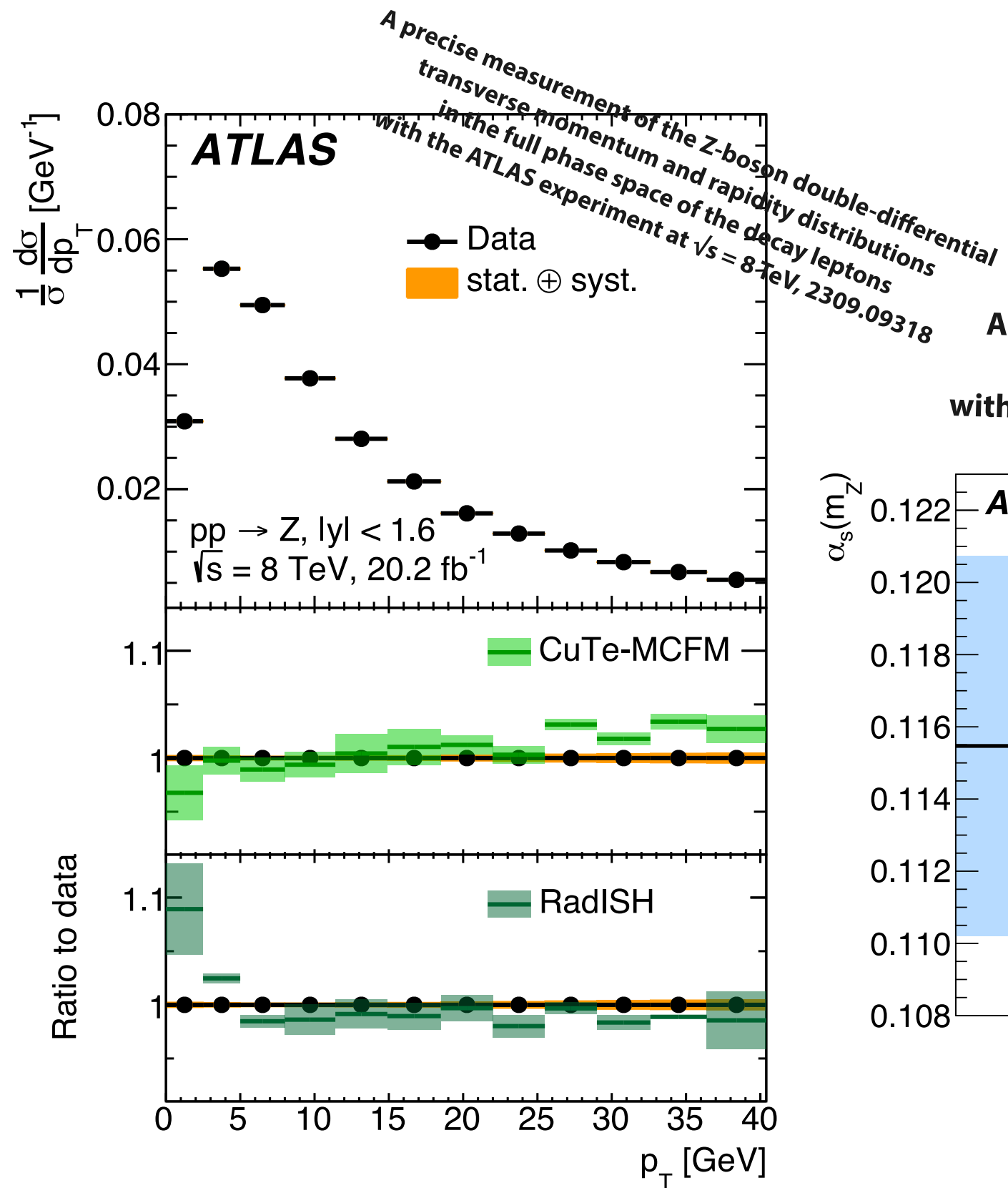
State of the art in QCD: $N^3\text{LO} + N^4\text{LL}$



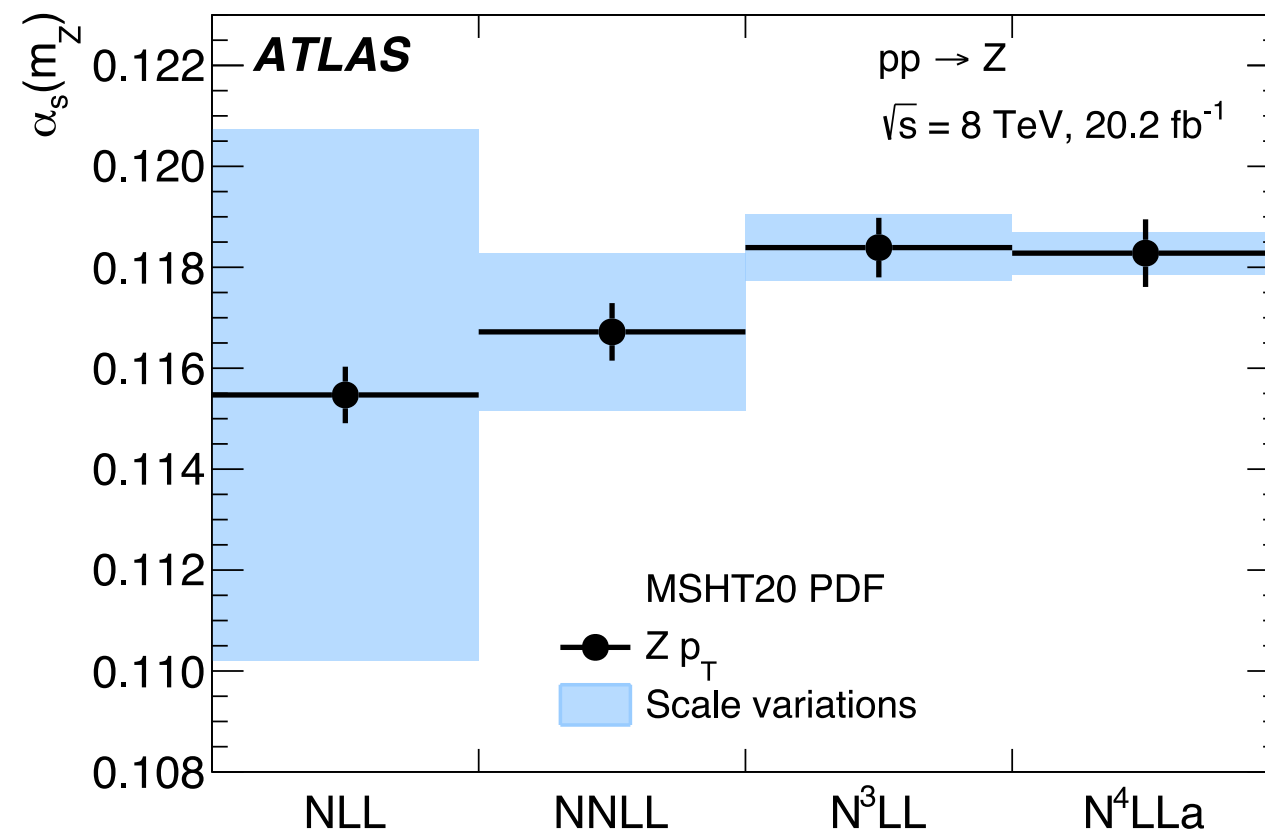
see Xuan Chen's talk Tuesday morning

The LHC and future colliders *literally* depend on us!





A precise determination of the strong-coupling constant from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s} = 8$ TeV, 2309.12986



- + Tevatron DY strong-coupling fit
- + ongoing low-mass DY by ATLAS
- + ongoing and upcoming W-mass measurements by ATLAS/CMS
- + ...

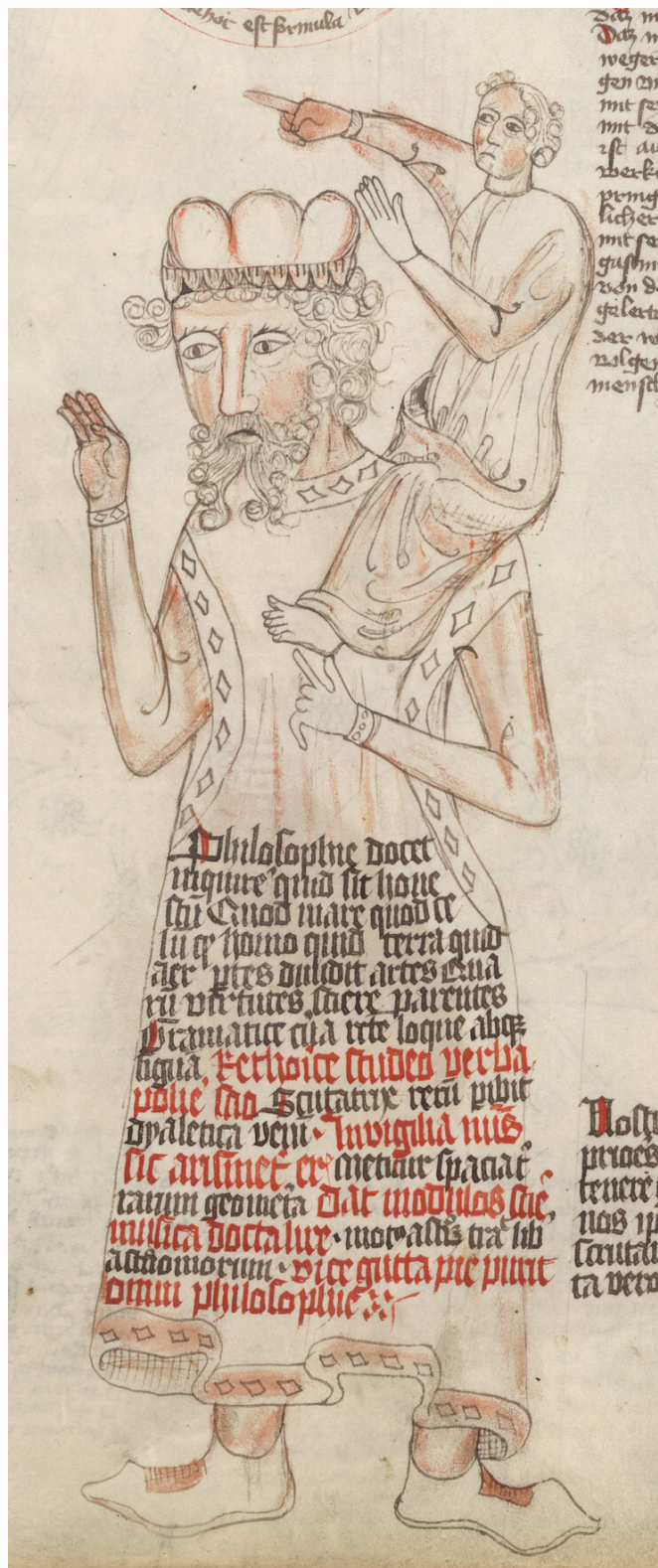


Precision W/Z in recent literature

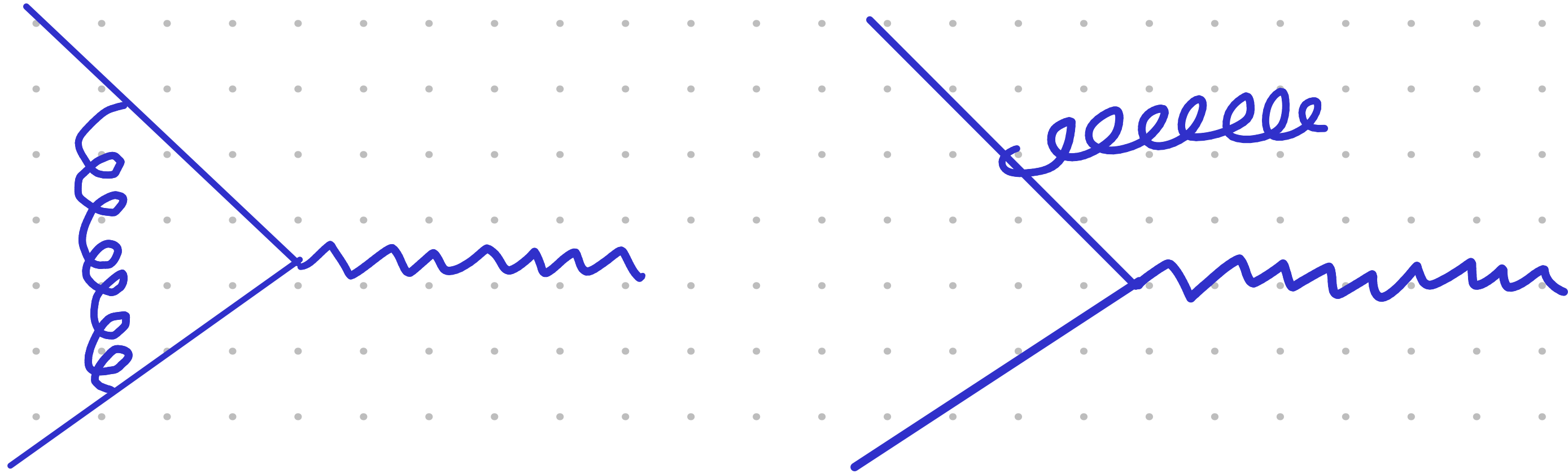


- Total inclusive at N^3 LO
Duhr, Dulat, Mistlberger '20, '21; n3loxs code: Baglio, Duhr, Mistlberger, Szafron '22
- W/Z+jet at NNLO
*Gehrmann De-Ridder, Gehrmann, Glover, Huss, Morgan '15; Gehrmann-De Ridder, Gehrmann, Glover, Huss, Walker '17
Boughezal, Focke, Liu, Petriello; Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello '15*
- N^3 LL' q_T resummation matched to NNLO W/Z+jet
*Monni, Re, Torrielli '16; Bizon, Monni, Re, Rottoli, Torrielli '17; Bizon, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni,
Re, Rottoli, Walker '19; Re, Rottoli, Torrielli '21; see also Camarda, Cieri, Ferrera '21; '23*
- Third order fiducial QCD
*X. Chen, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli '22; X. Chen, Gehrmann, Glover, Huss, T.-Z. Yang, H. X. Zhu;
Camarda, Cieri, Ferrera '21*
- Linear power corrections and fiducial cut sensitivity
*Ebert, Michel, Stewart, Tackmann '20; Salam, Slade '21; Billis, Dehnadi, Ebert, Michel, Tackmann '21; Catani, de Florian,
Ferrera, Grazzini '15; see also Buonocore, Kallweit, Rottoli, Wiesemann '21*
- Mixed QCDxEW corrections
*Heller, von Manteuffel, Schabinger, Spiesberger '20; Buonocore, Grazzini, Kallweit, Savoini, Tramontano '21; Behring,
Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch '20; Buccioni, Caola, Chawdhry, Devoto, Heller, von Manteuffel,
Melnikov, Röntsch, Signorile-Signorile '22; Dittmaier, Schmidt, Schwarz '20; Dittmaier, Huss, Schwinn '14; '15*
- QED+QCD resummation
Autieri, Cieri, Ferrera, Sborlini '23
- ...

N^3 LO + N^4 LL W/Z: On the shoulders of giants



- Resummation and subtraction via small- q_T factorization
based on formalism of Becher, Neubert '10; Becher, Neubert, Wilhelm '11; implemented to N^3 LL Becher, Neumann '20
 q_T subtractions Catani, Grazzini '07
- Three-loop beam functions
M.-x. Luo, T.-Z. Yang, H. X. Zhu, Y. J. Zhu '19, '20; Ebert, Mistlberger, Vita '20
- N^4 LL: Four loop rapidity anomalous dimension
Duhr, Mistlberger, Vita '22; Moul, H.X. Zhu, Y. J. Zhu '22
- Four-loop collinear anomalous dimension
Agarwal, von Manteuffel, Panzer, Schabinger '21
- Three-loop quark form factor
Gehrmann, Glover, Huber, Ikizlerli, Studerus '10; Baikov, Chetyrkin, A.V. Smirnov, V.A. Smirnov, Steinhauser '09; Lee, A.V. Smirnov, V.A. Smirnov '10
- Massive three-loop axial singlet contributions
Chen, Czakon, Niggetiedt '22; see also Gehrmann, Primo '21
- Fixed-order Z+jet NNLO calculation via 1-jettiness slicing
re-implementation of Boughezal, Focke, Liu, Petriello; Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello '15
- One-jettiness soft function
Campbell, Ellis, Mondini, Williams '17; Boughezal, Liu, Petriello '15
- Four-loop splitting functions (for N^3 LO PDFs; full N^4 LL)
Moch, Ruijl, Ueda, Vermaseren, Vogt '23; Falcioni, Herzog, Moch, Vermaseren, Vogt '23;
Gehrmann, von Manteuffel, Sotnikov, T.-Z. Yang '23; ...
(see Tong-Zhi Yang and Sven-Olaf Moch, Wednesday morning)



q_T subtractions (for N³LO)

Legs: $\int_{q_T^{\text{cut}}} dq_T |\mathcal{M}|^2 = \text{finite!}$

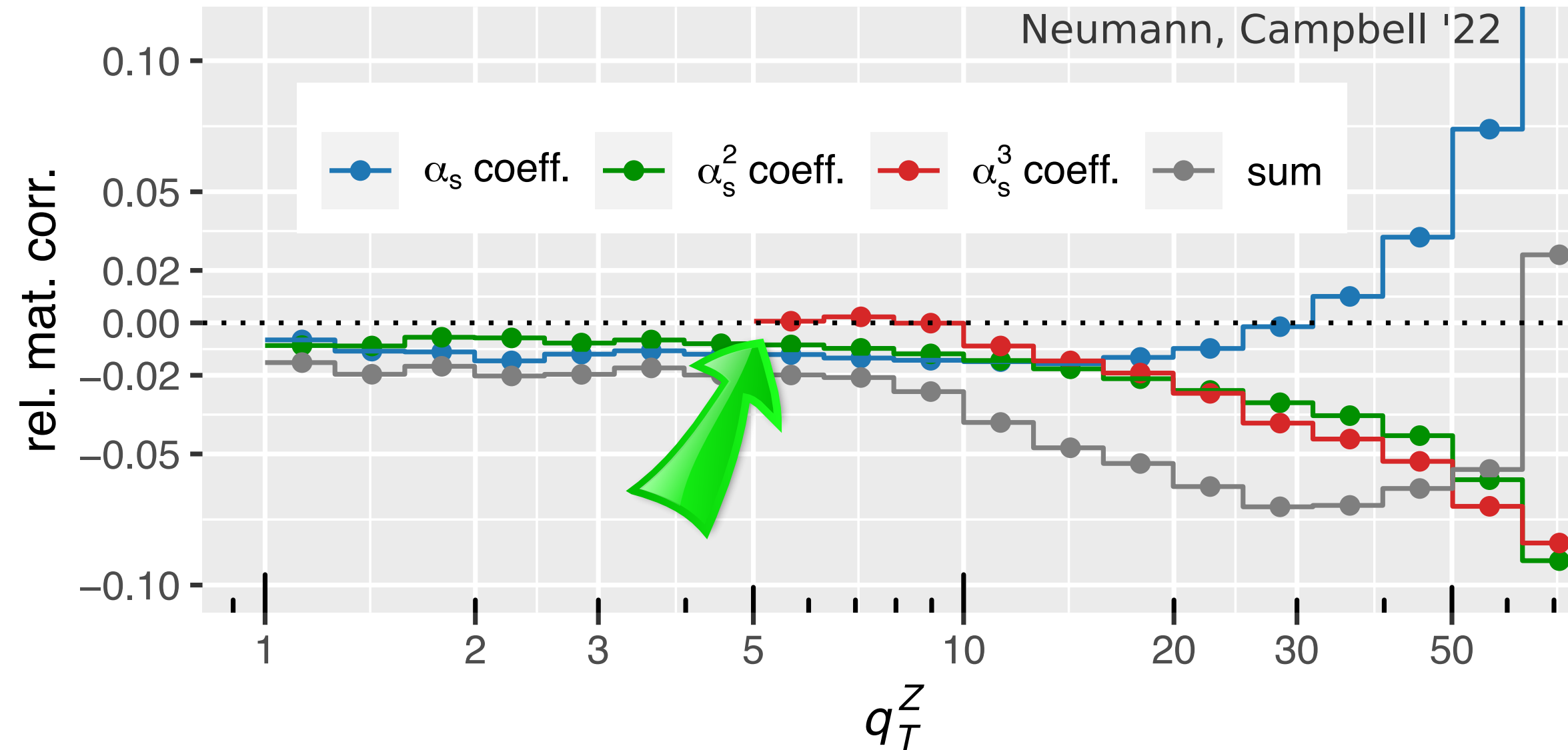
Loops: Factorization at small q_T

$$\sigma \sim \hat{\sigma} \otimes B \otimes B + \mathcal{O}(q_T^{\text{cut}}/m_Z) = \text{finite} + \mathcal{O}(q_T^{\text{cut}}/m_Z)$$

Nested slicing! NNLO W/Z+jet with 1-jettiness

Z transverse momentum distribution

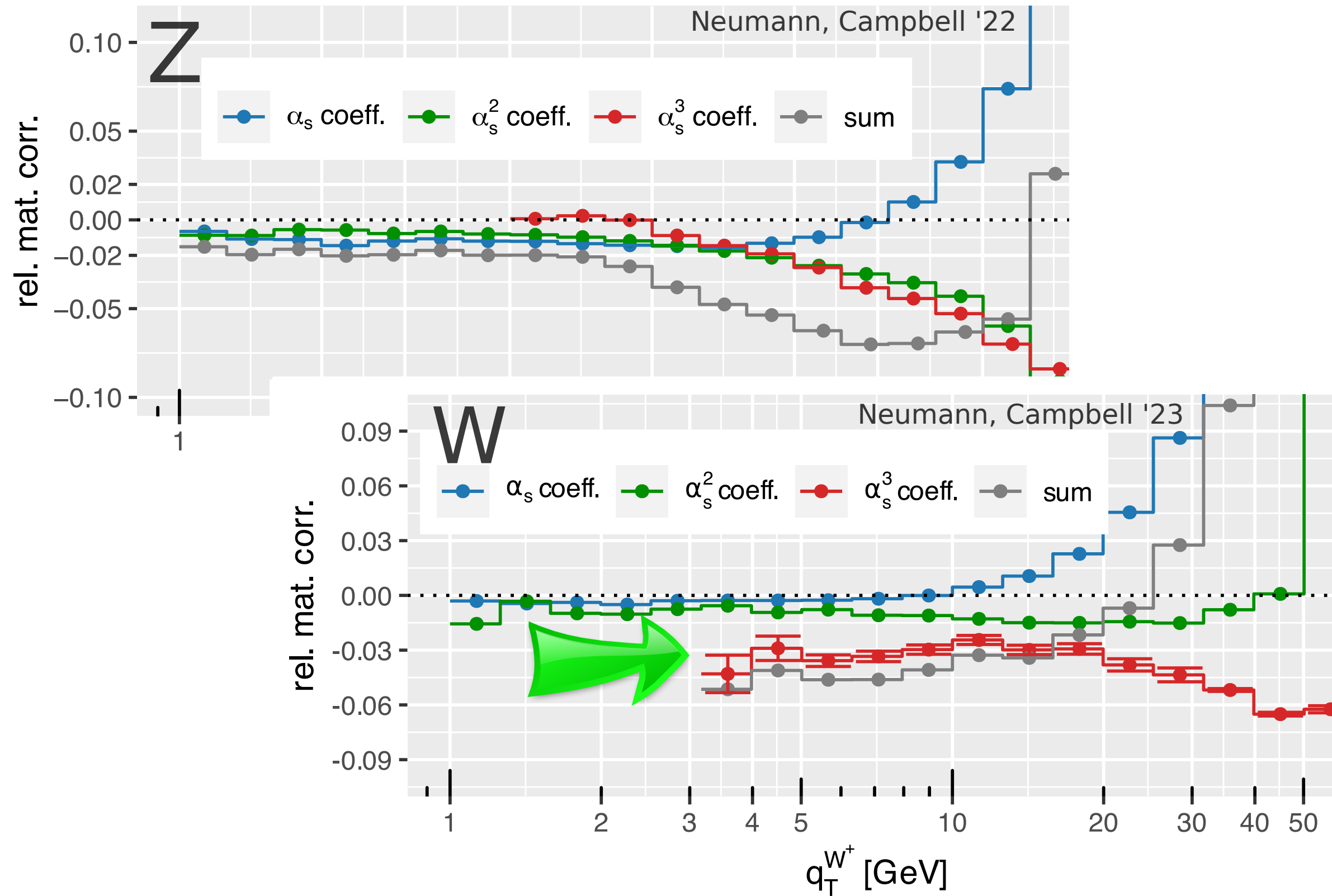
Matching corrections



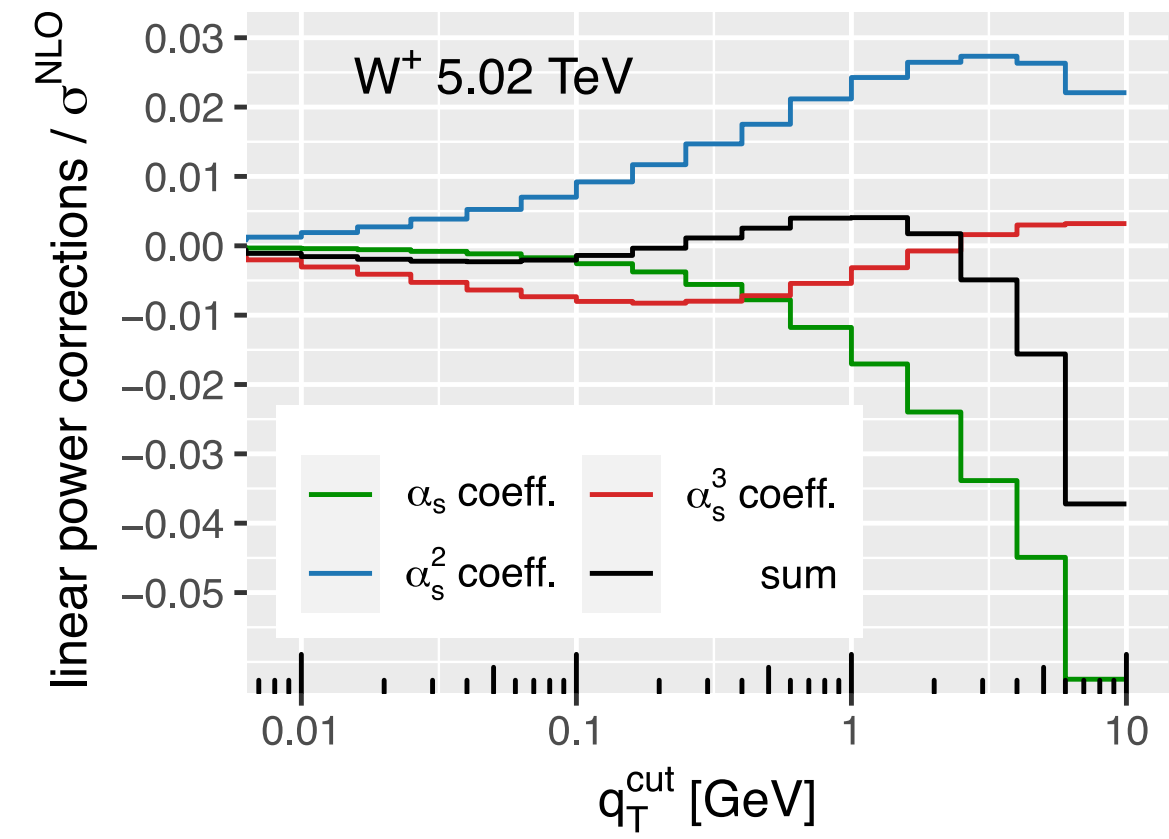
(0.007 GeV 1-jettiness cutoff for Z+jet at NNLO)

W transverse momentum distribution

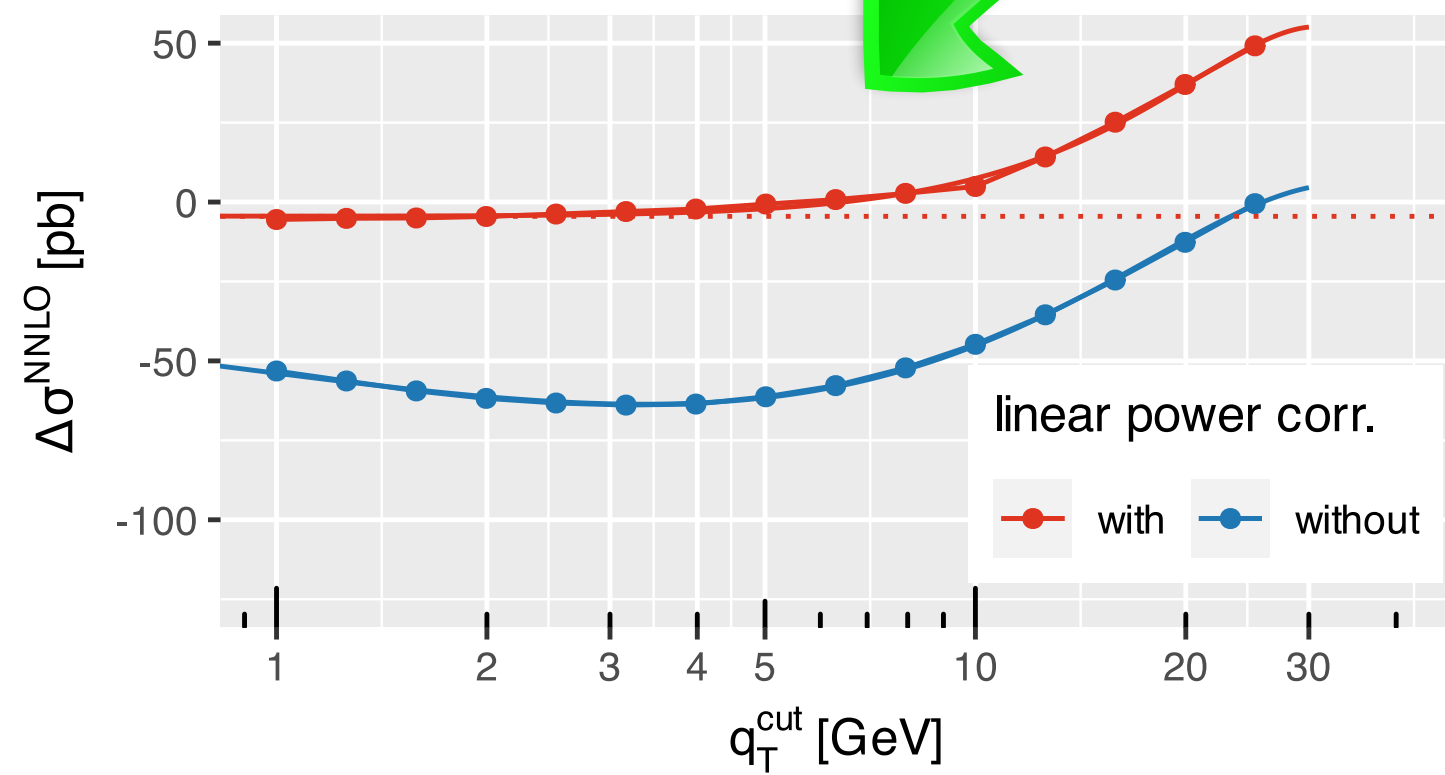
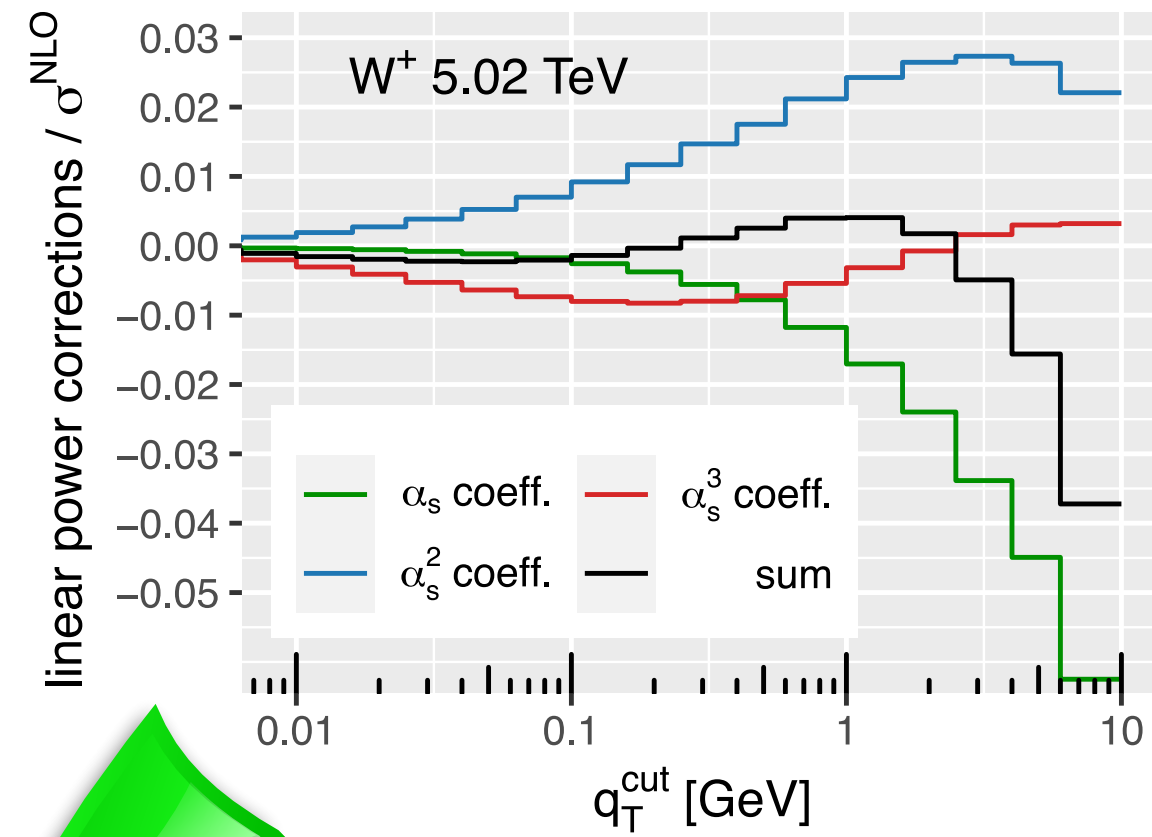
Matching corrections



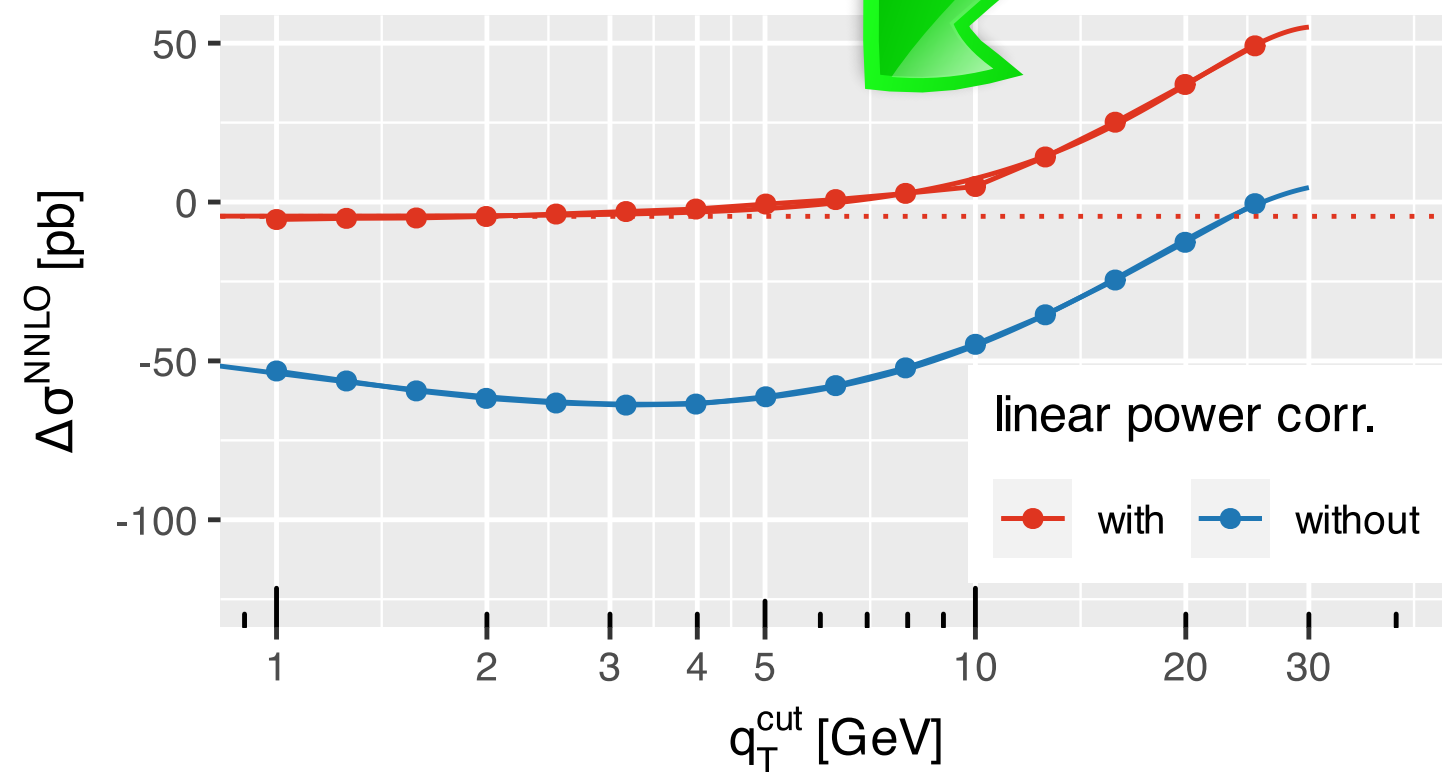
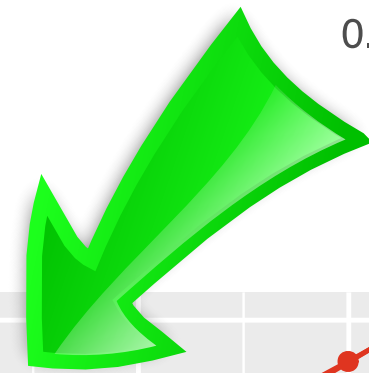
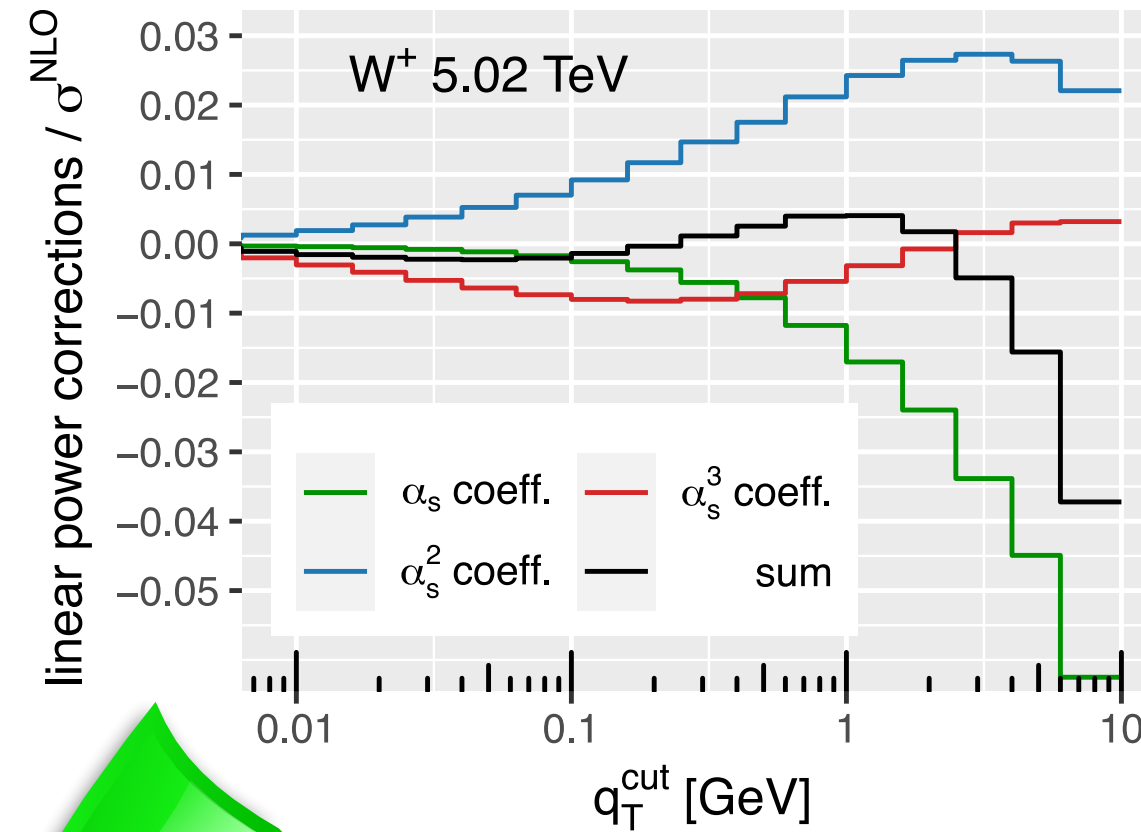
Fixed-order cross-sections



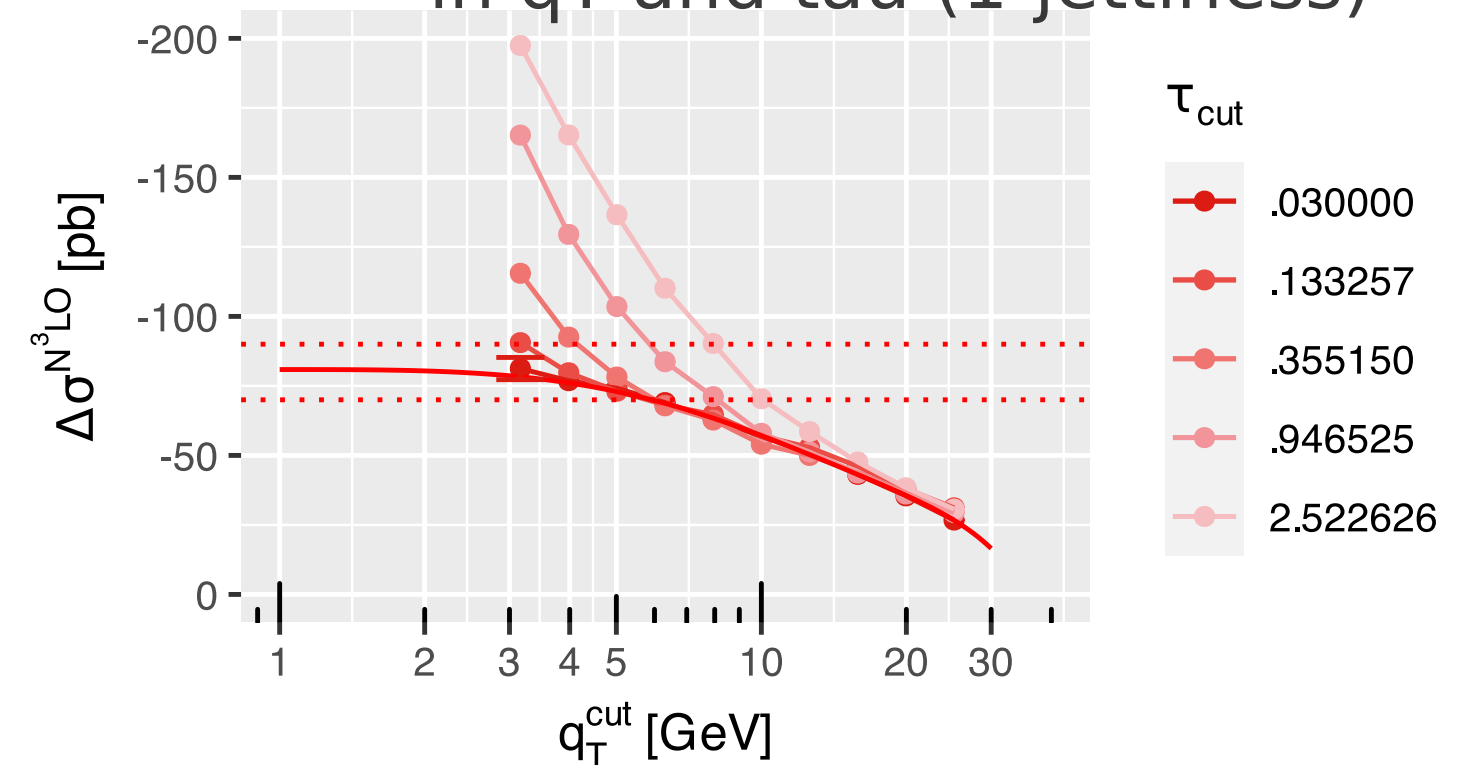
Fixed-order cross-sections



Fixed-order cross-sections

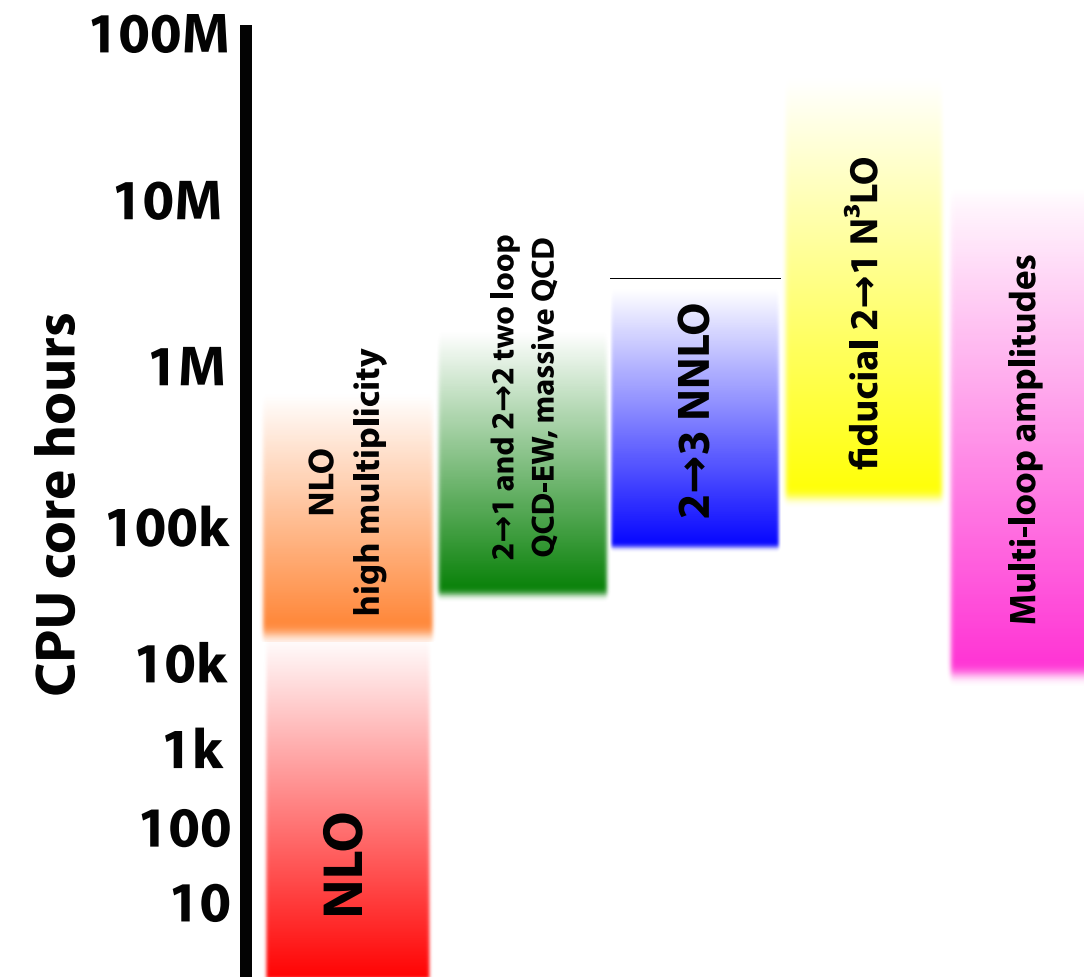


Nested slicing extrapolation
in q_T and τ (1-jettiness)



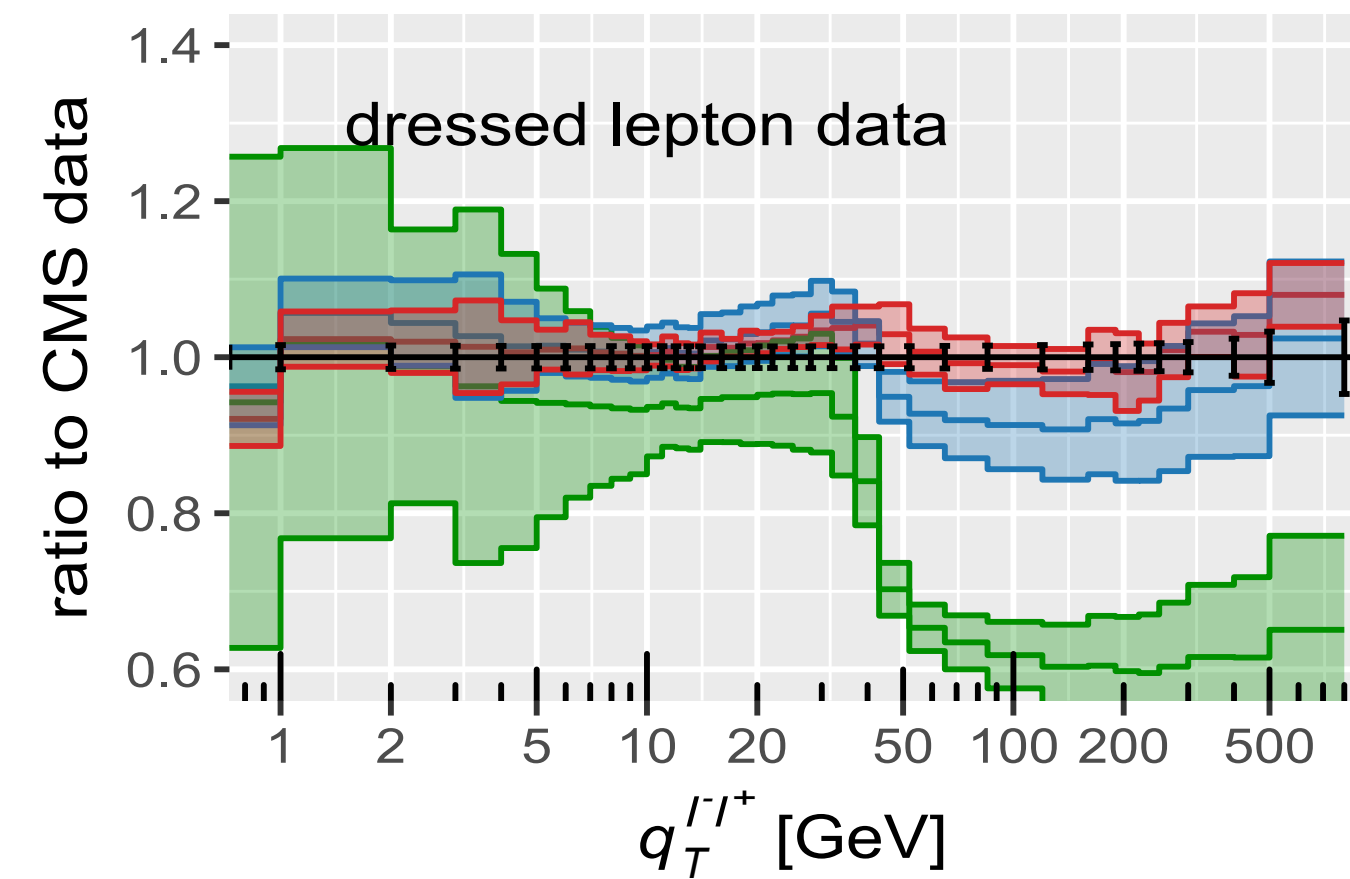
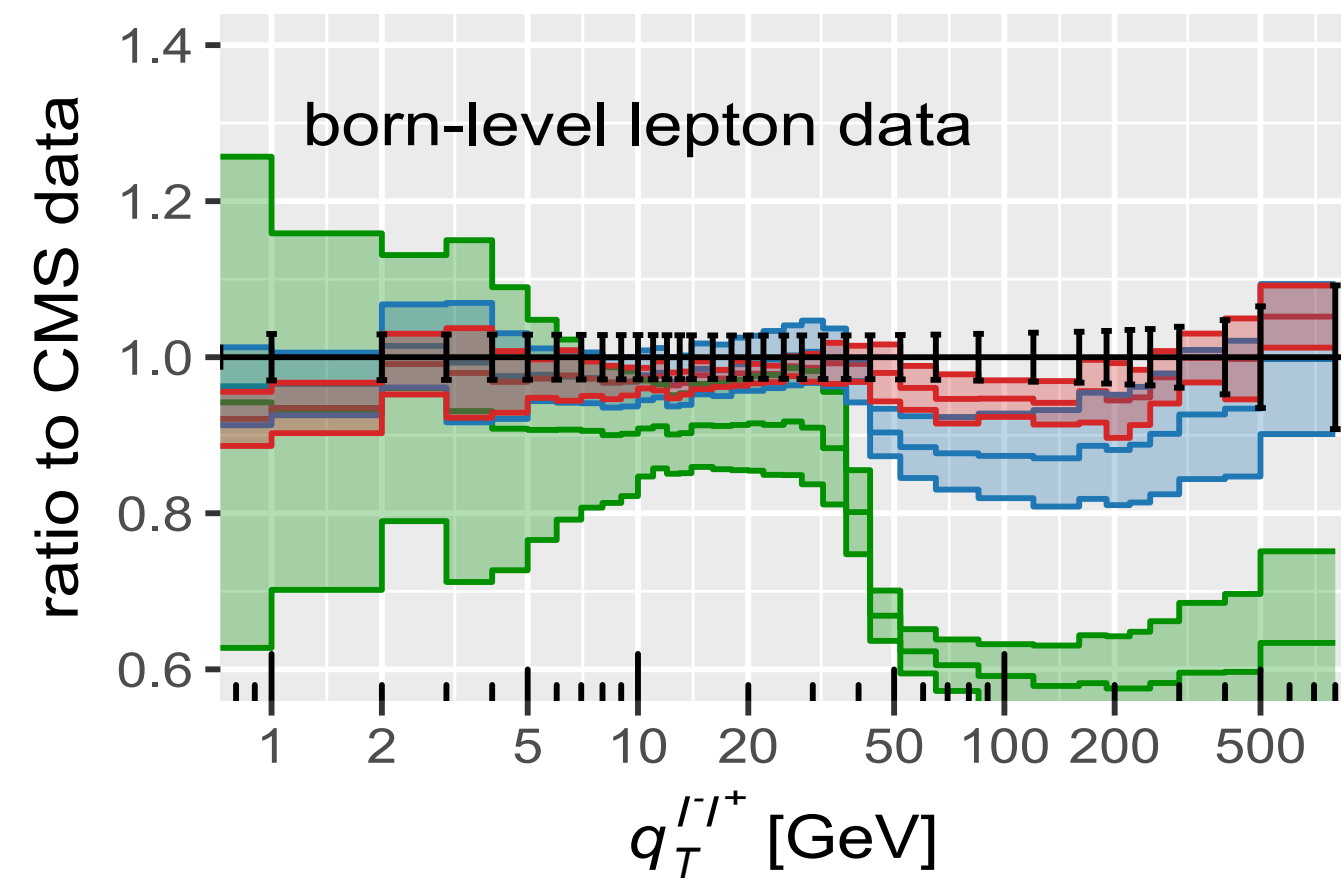
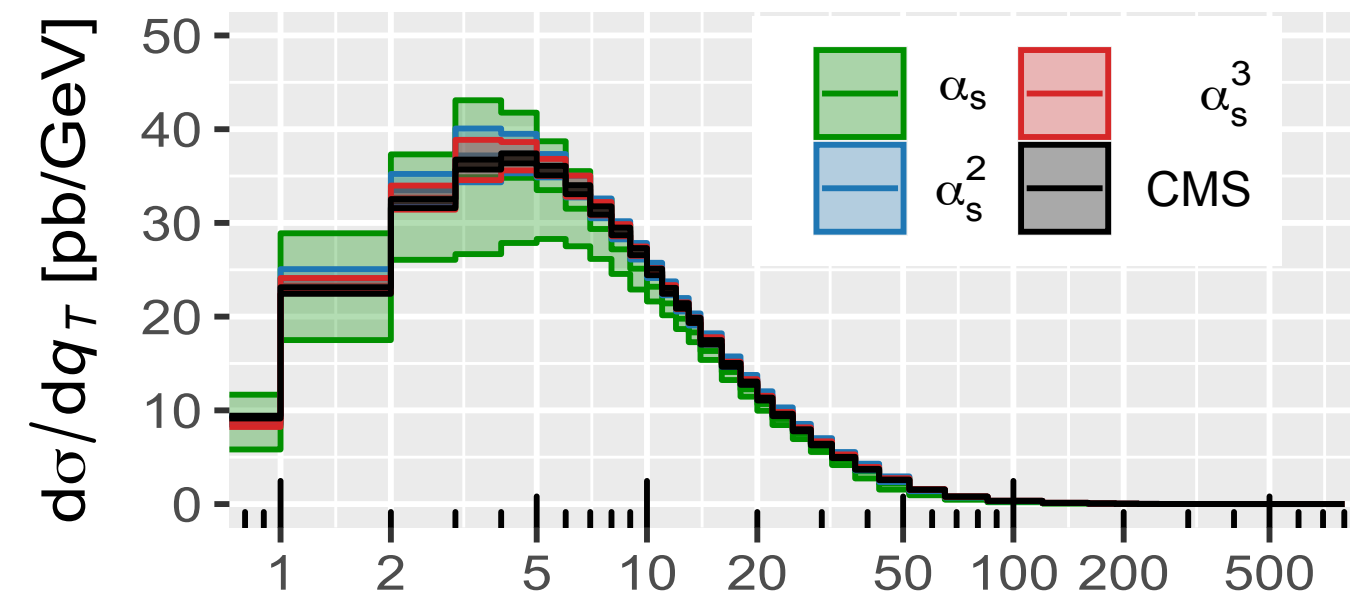
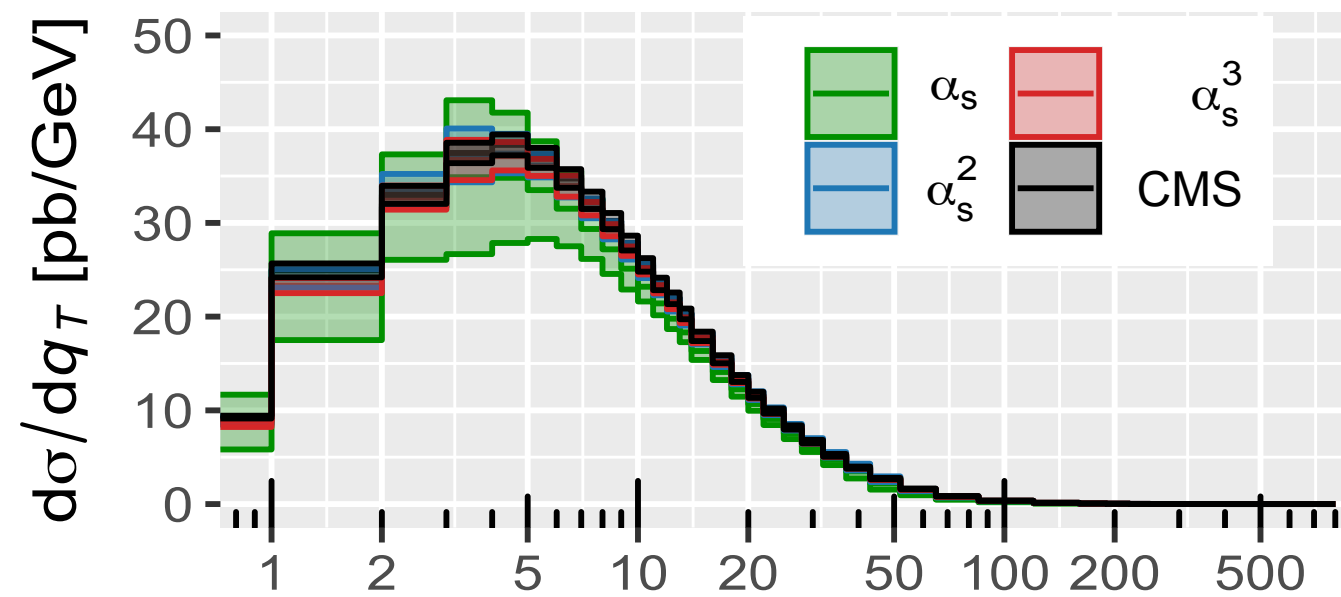
0.5% N^3 LO precision: What does it cost?

About 50-150k node hours on Perlmutter at NERSC
(64-128 nodes for about 12 hours)



Febres Cordero, von Manteuffel, Neumann '22

Comparison with CMS 13 TeV, 1909.04133



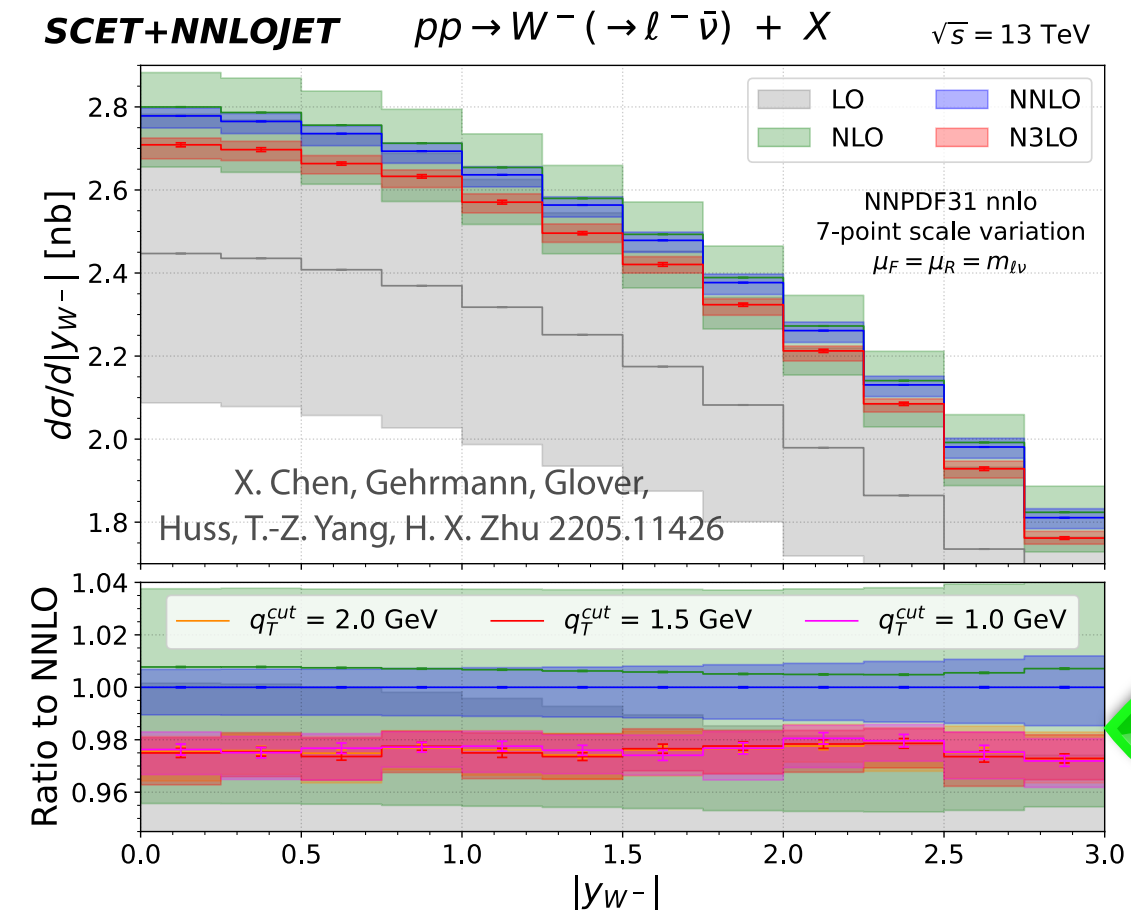
using NNPDF 4.0; Neumann, Campbell '22

Large N³ LO corrections (with fixed PDFs): Are we in trouble?

Fiducial Z cross-sections:

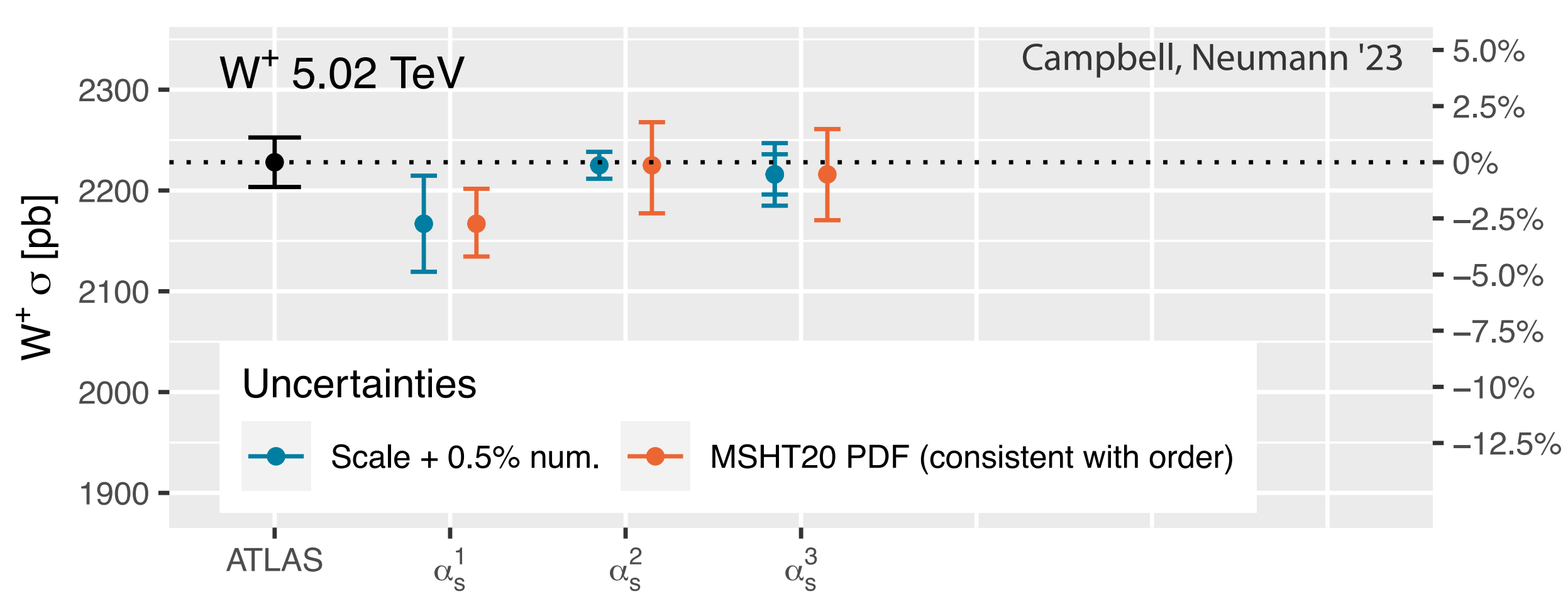
Order k	fixed-order α_s^k	Neumann, Campbell '22
0	694^{+85}_{-92}	
1	732^{+19}_{-30}	
2	720^{+4}_{-3}	
3	$700^{+4}_{-6} \pm 1_{\text{slicing}}$	

(CMS meas.) 699 ± 5 (syst.) ± 17 (lumi.) (e, μ combined)



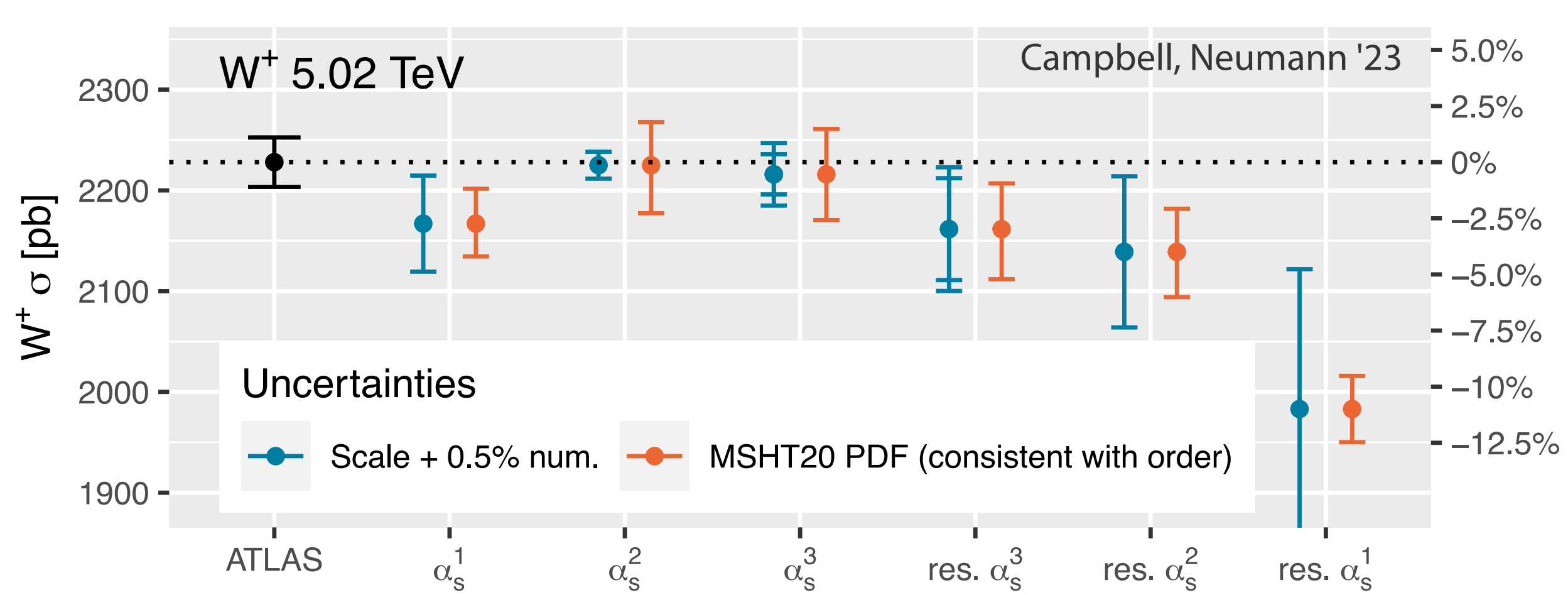
See also Duhr, Dulat, Mistlberger '20; Duhr, Mistlberger '21; X. Chen, Gehrmann, Glover, Huss, T.-Z. Yang, H. X. Zhu '22

PDF and truncation uncertainties



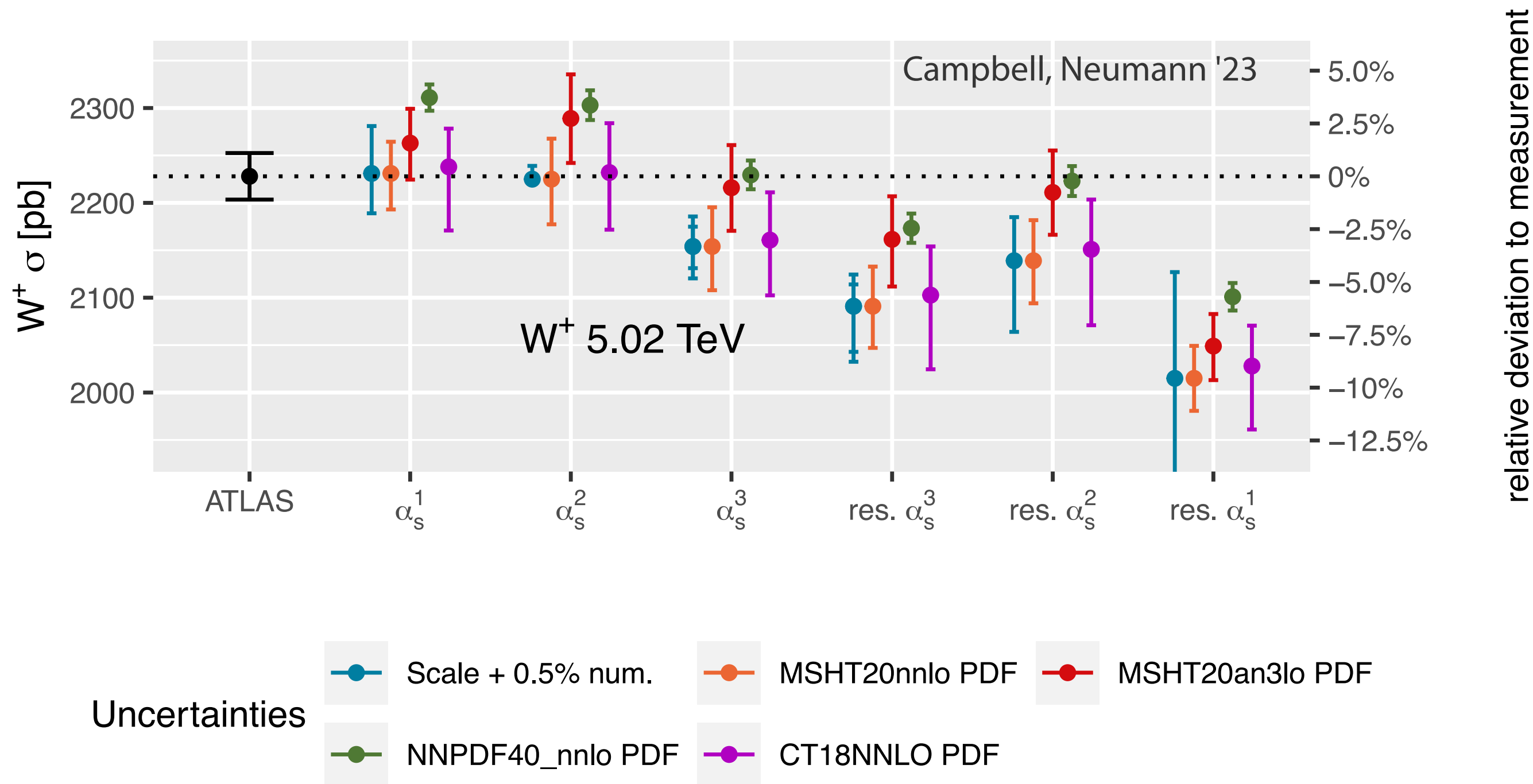
relative deviation to measurement

PDF and truncation uncertainties

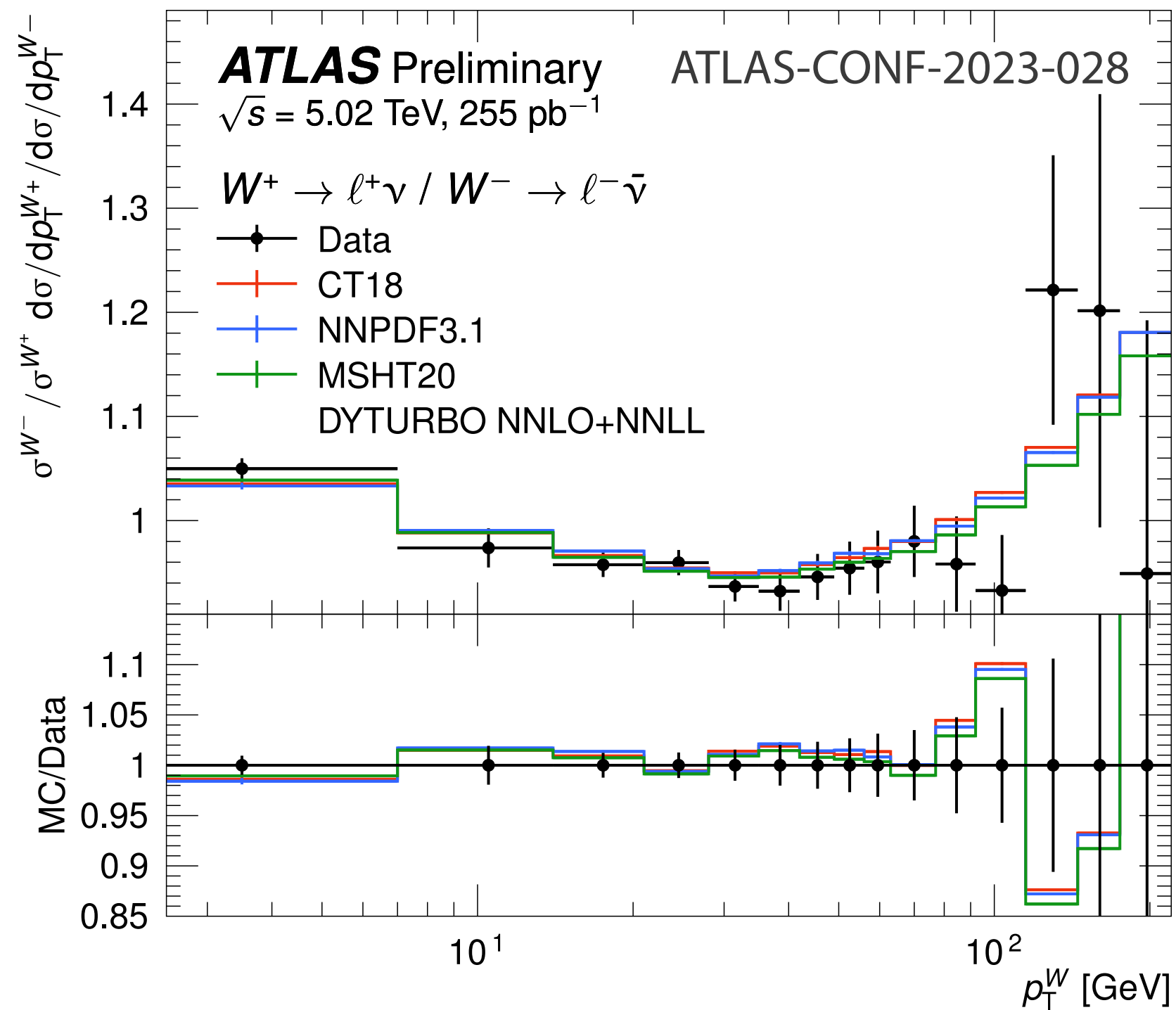
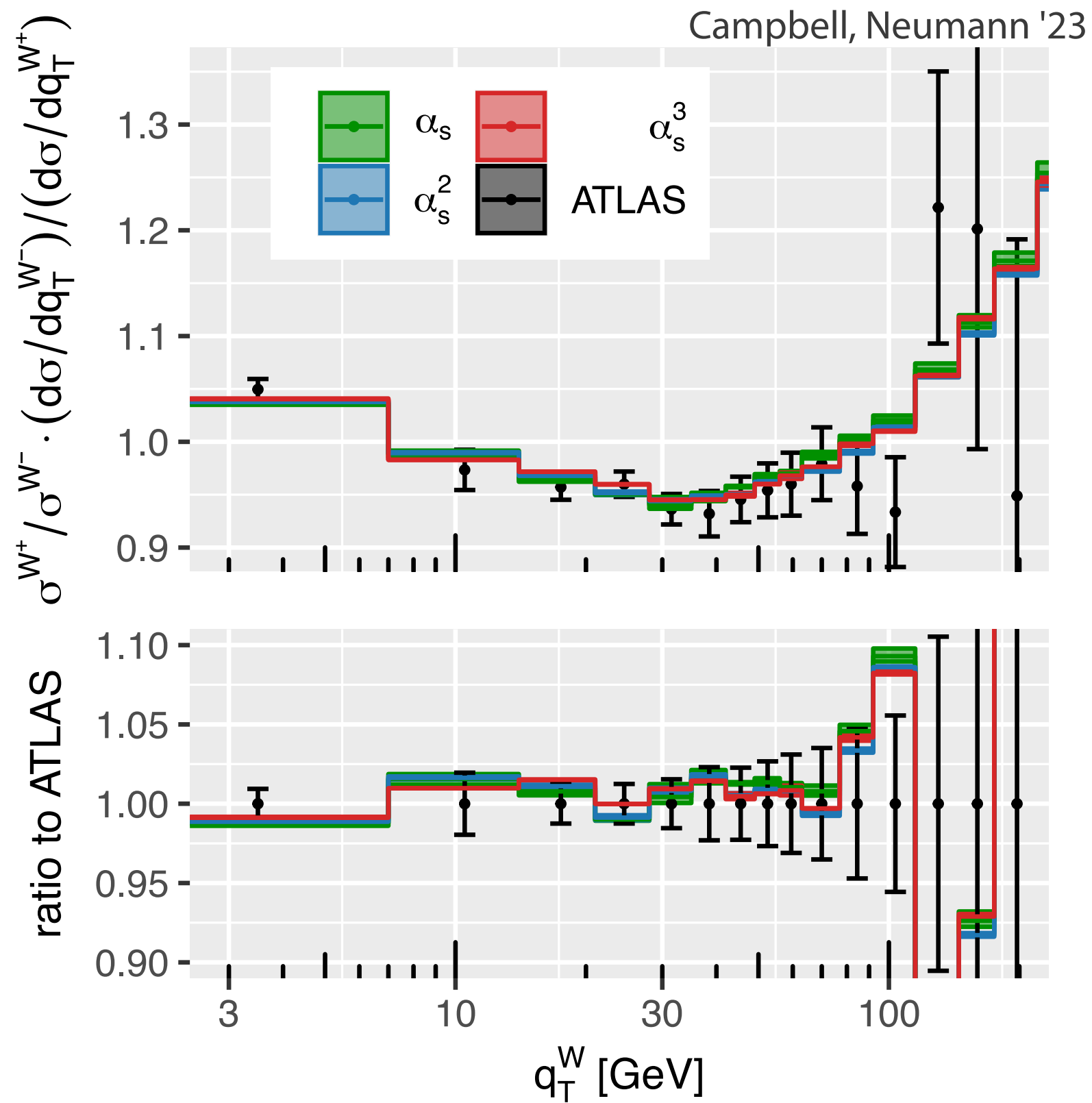


relative deviation to measurement

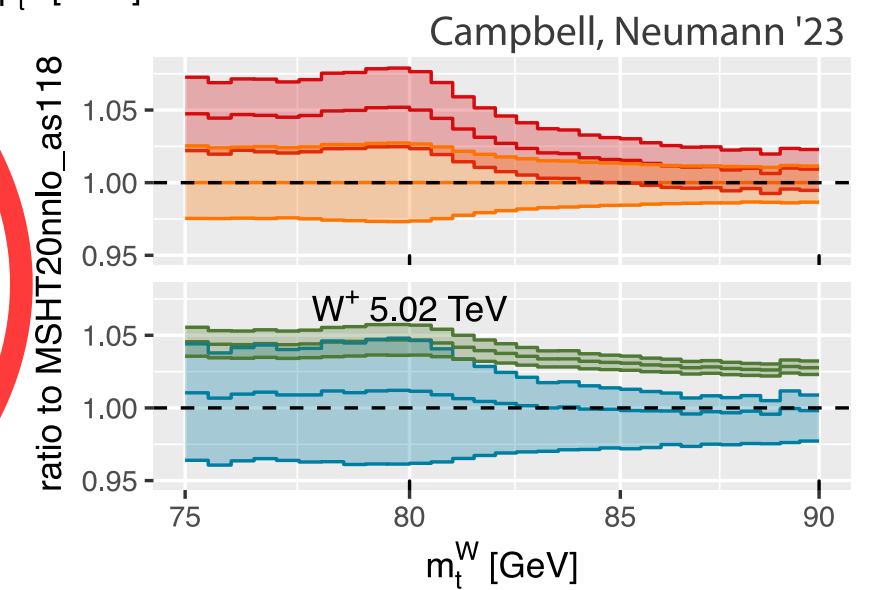
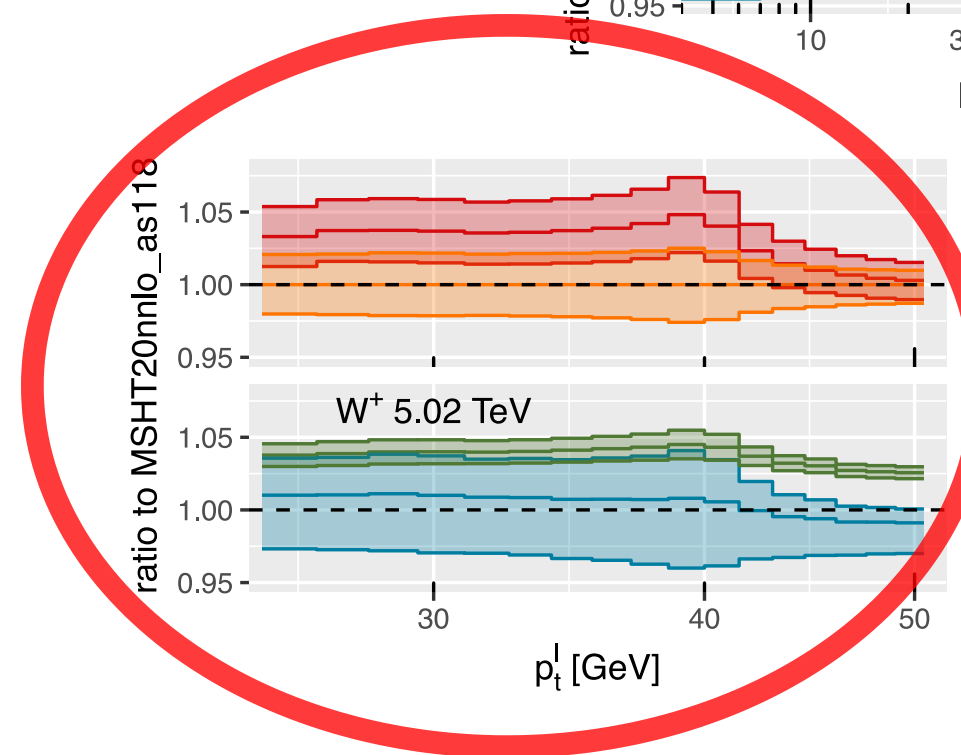
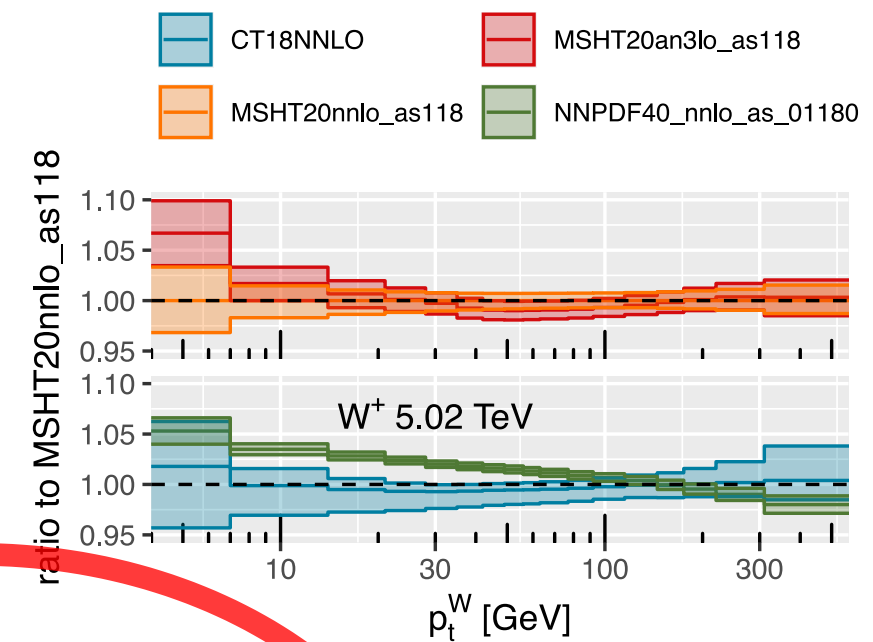
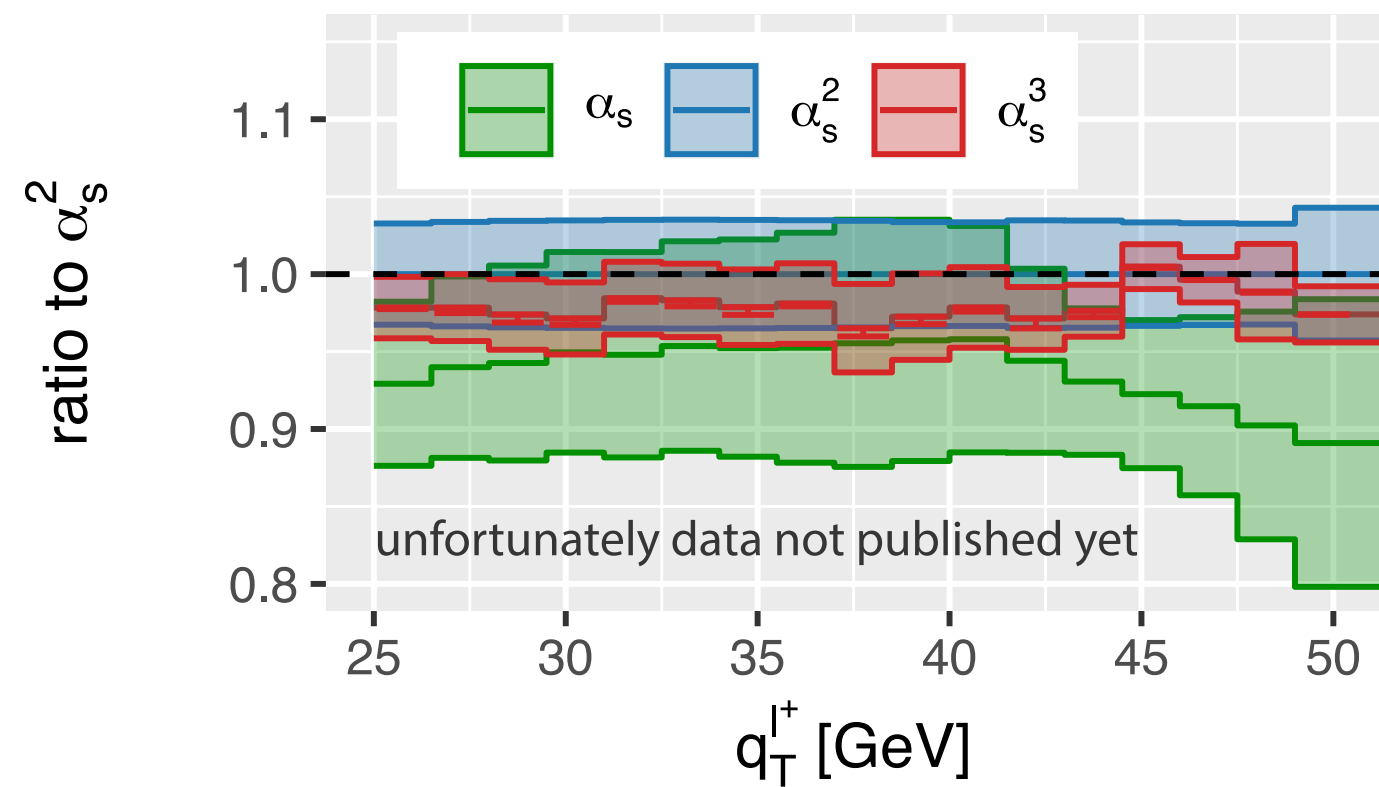
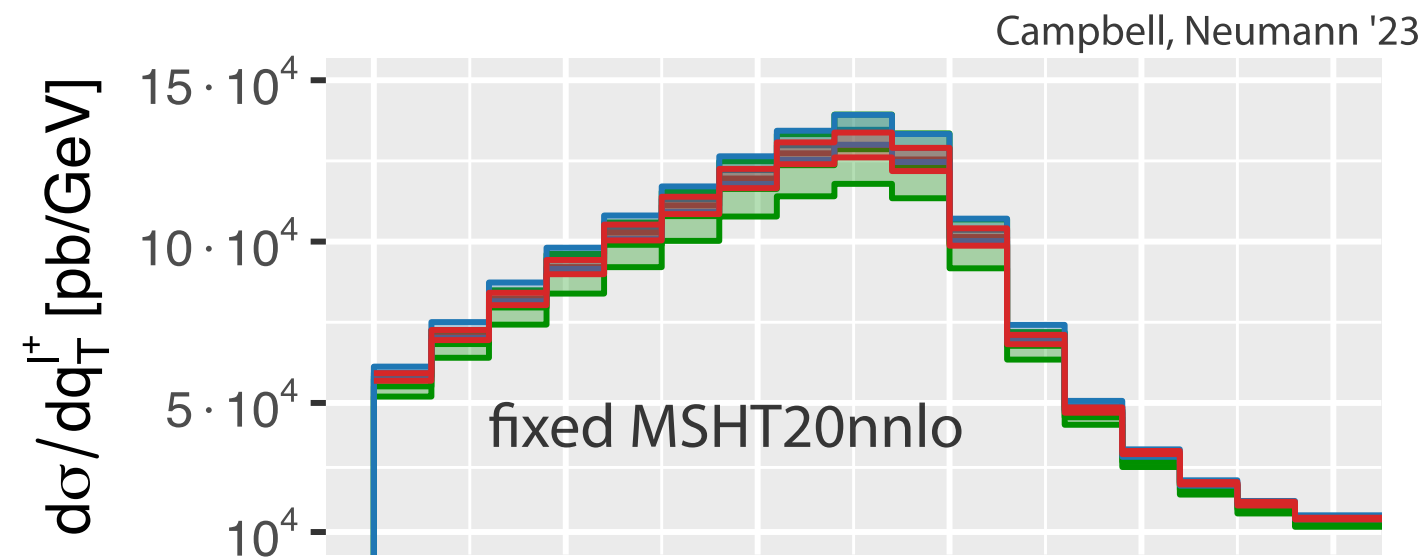
Full spectrum of PDF uncertainties



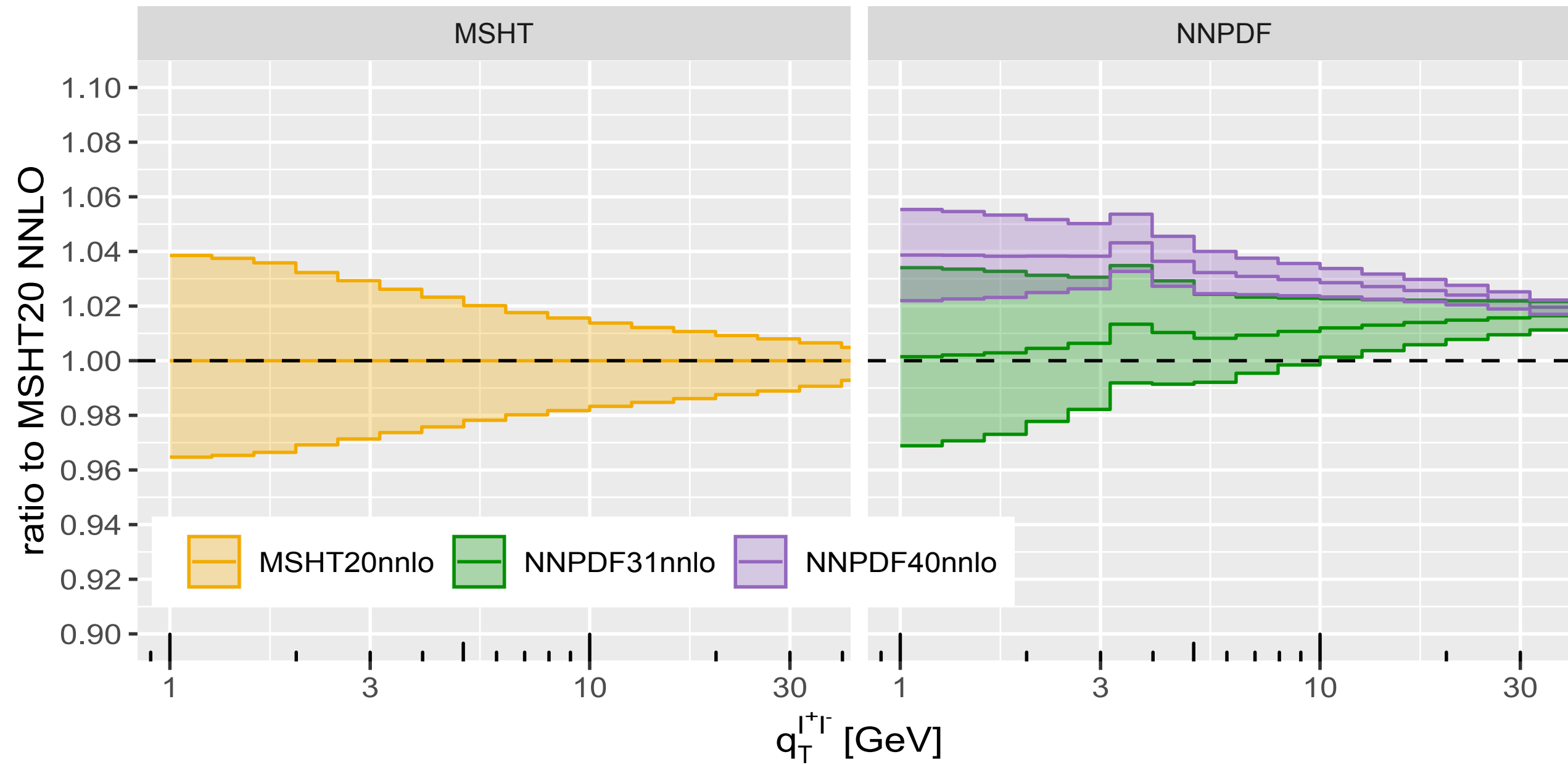
W^+ / W^- ratio



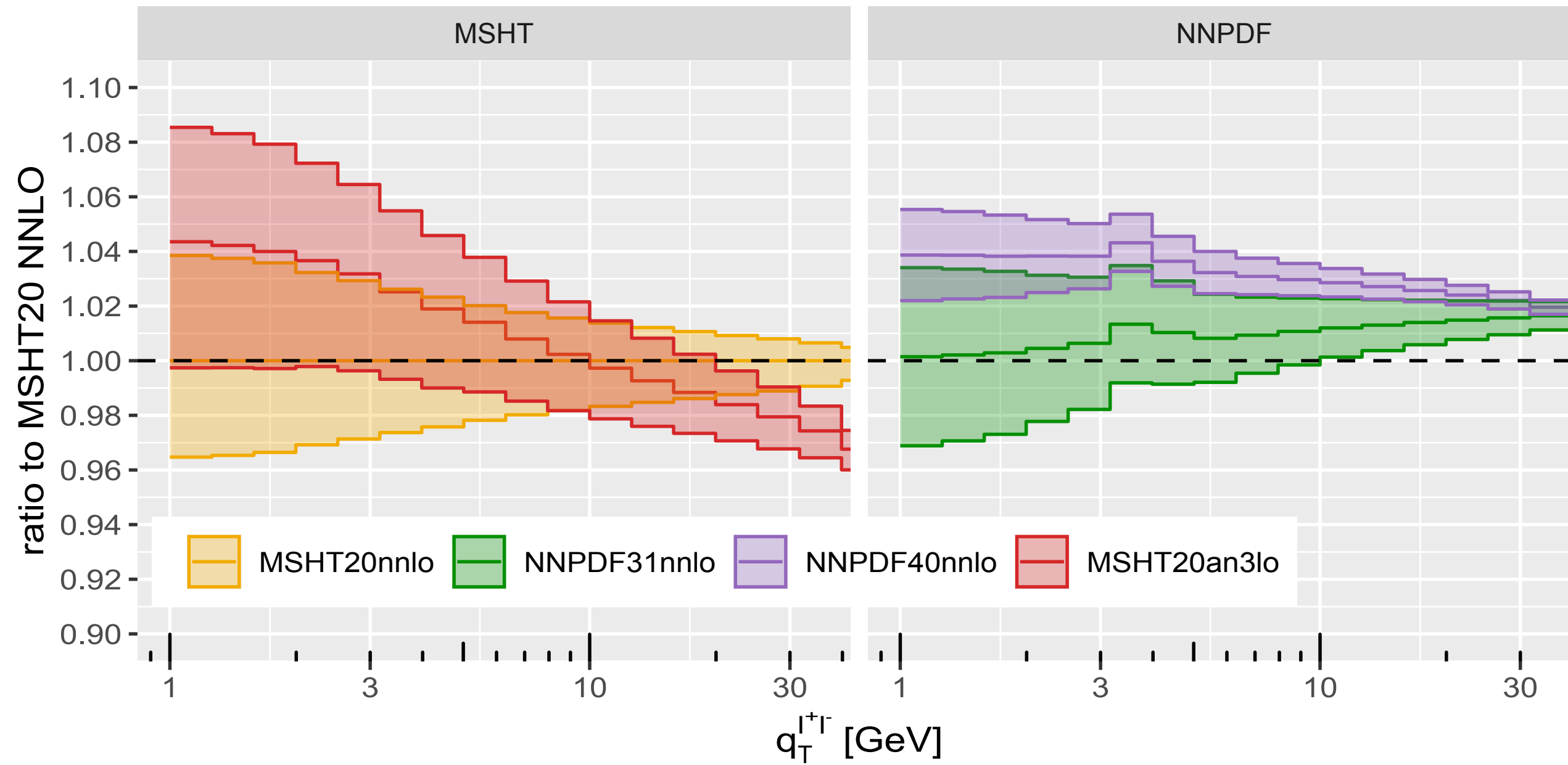
Ultimately distributions will guide us..



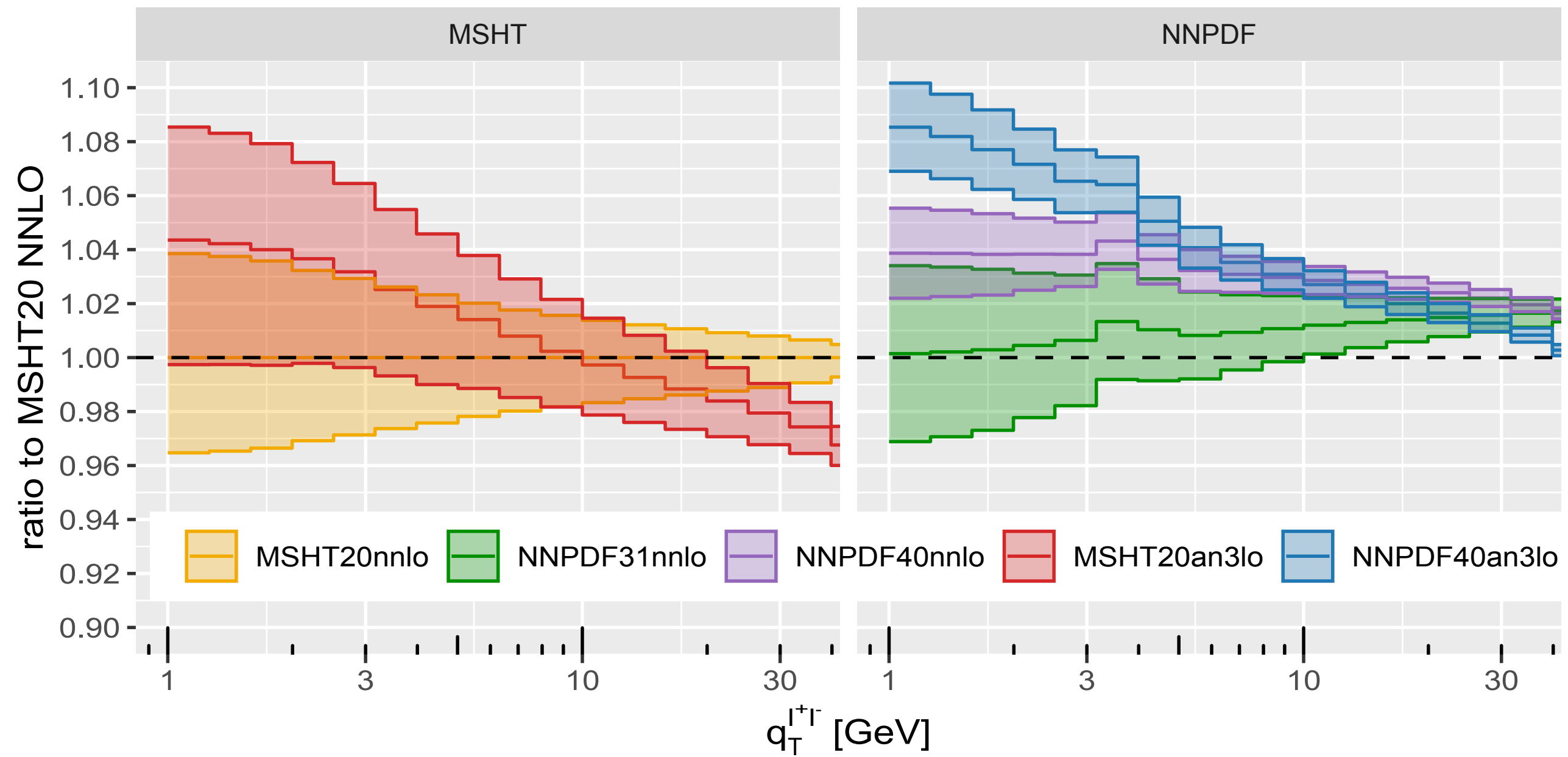
Impact of PDFs (e.g. in the Z transverse momentum)



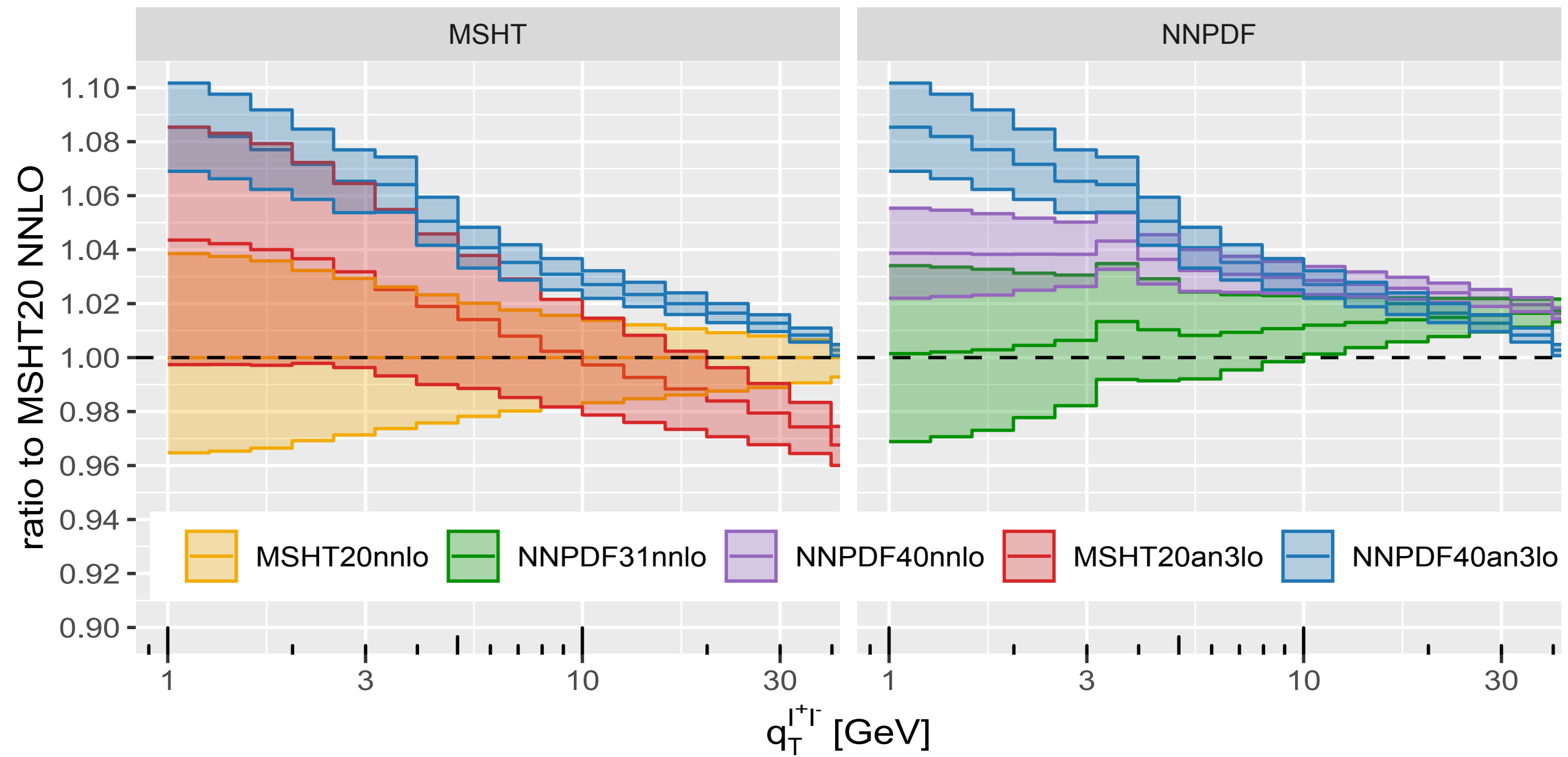
Impact of PDFs (e.g. in the Z transverse momentum)



Impact of PDFs (e.g. in the Z transverse momentum)



Impact of PDFs (e.g. in the Z transverse momentum)



Outlook: Towards generic and better subtractions

Which ones are most promising in moving forward?

Performance, higher orders? How to compare?

- Antenna subtractions

Gehrmann De Ridder, Gehrmann, Glover, Heinrich et al.

- CoLoRFul subtractions

Del Duca, Duhr, Kardos, Somogyi, Troscanyi et al.

- SecToR-ImProved Phase space for Real radiation (STRIPPER)

Czakon et al.

- Nested soft-collinear subtractions

Caola, Melnikov, Röntsch et al.

- Local analytic subtractions

Magnea, Maina, Pelliccioli, Signorile-Signorile, Torrielli, Uccirati

- Projection to Born

Cacciari, Salam, Zanderighi et al.

- 4D unsubtractions

Sborlini, Hernandez-Pinto, Rodrigo et al.

- Geometric subtractions

Herzog

- q_T slicing

Catani, Grazzini et al.

- N -jettiness slicing

Gaunt, Stahlhofen, Tackmann, Walsh; Boughezal, Petriello et al.

see talks by Andrey Pikelner and Ivan Pedron, Thursday

- k_T -ness slicing (NLO)

Buonocore, Grazzini, Haag, Rottoli, Savoini

see talk by Flavio Guadagni, Thursday

- + many calculations of power corrections for 0/1-jettiness

Third order QCD predictions for W and Z bosons

- Completed set of W and Z at N³ LO/N⁴ LL as public code **CuTe-MCFM**
Neumann, Campbell '22, '23; [arXiv:2207.07056](https://arxiv.org/abs/2207.07056), [arXiv:2308.15382](https://arxiv.org/abs/2308.15382)
- Residual QCD truncation uncertainties of about 1-2%
- PDF uncertainties dominant, spread of up to 14% in distributions!
- Contributes to wealth of SM precision phenomenology: α_s , PDFs, TMDs, m_W , ...
- Nested slicing in q_T and 1-jettiness: $\sim 3-5$ GeV in q_T , 0.005 GeV in 1-jettiness
0.5% numerical+slicing precision requires about 100k hours on modern CPUs
- Future needs:
 - Precision proton structure
 - Fourth order QCD
 - More efficient subtractions in MCFM (public codes), *reach out to me!*
(local subtractions, slicing power corrections)
 - Parton shower event generation
 - Combination with EW effects in unified framework

