Z-boson transverse momentum at $(\mathrm{N}^4\mathrm{LL}+\mathrm{N}^3\mathrm{LO})_\mathrm{p}$

based on arXiv:2207.07056

Tobias Neumann, Brookhaven Nat'l Lab

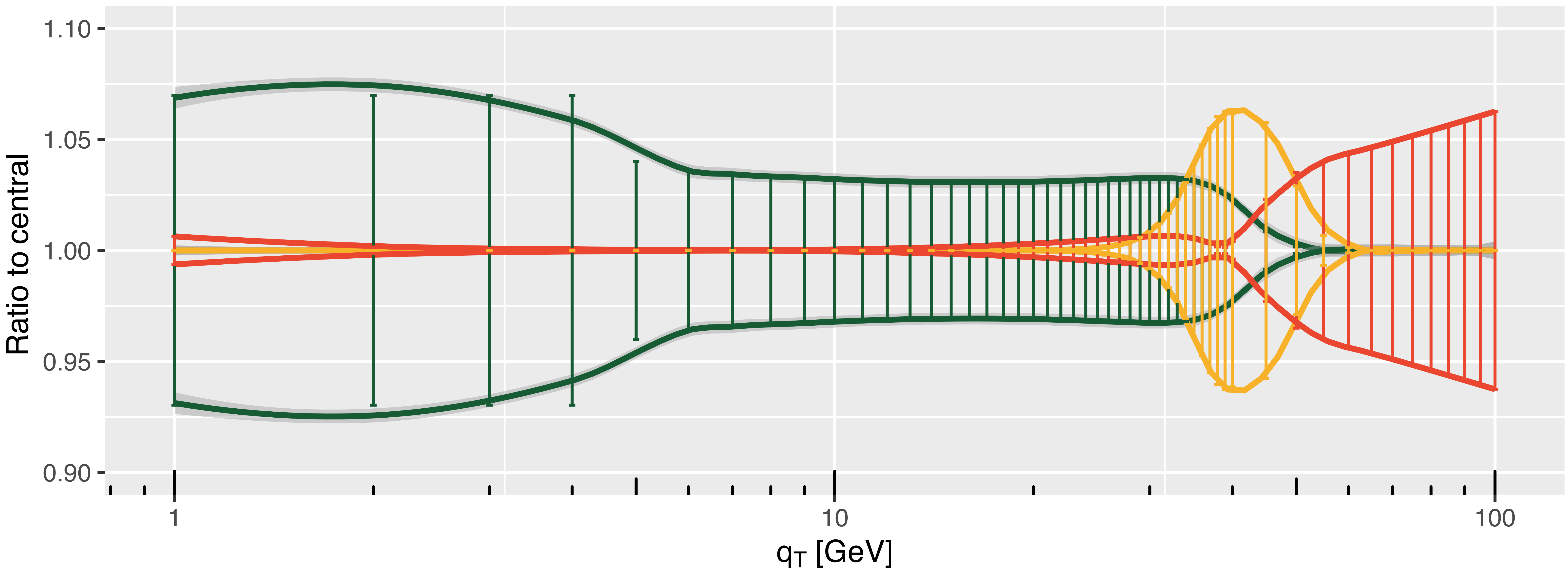
with John Campbell, Fermilab

Z p_T: The Standard Model standard candle

direct comparison with Z measurements
(see e.g. Jelena and Meena on Tuesday)

W-mass measurement (calibration)

PDF's, α_s, ...



Three regimes: resummation, transition, fixed-order

Fixed-order Z+jet NNLO calculation

- 1. via 1-jettiness slicing
  Boughezal, Focke, Liu, Petriello; Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello '15
- 2. via antenna subtractions
  Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan '15

Resummation for N^3LL'

- three-loop beam functions
  M.-x. Luo, T.-Z. Yang, H. X. Zhu, Y. J. Zhu '19, '20; Ebert, Mistlberger, Vita '20

State of the field: antenna NNLO Z+jet interfaced to resummation:

- with DYturbo
  Camarda, Cieri, Ferrera '21
- with RadISH
  Bizon, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Walker '19; Chen, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli '22

Resummed predictions in CuTe-MCFM at α_s^3

- Fixed-order Z+jet NNLO calculation (via 1-jettiness)
- Resummation (via small-q_T factorization)

$$\mathrm{d}\sigma_{ij} \sim \int \mathrm{d}\xi_1 \mathrm{d}\xi_2\, \mathrm{d}\sigma_{ij}^0 \cdot H(\xi_1 p_1, \xi_2 p_2, \mu) \cdot$$

$$\cdot \int \mathrm{d}^2 x_\perp e^{-iq_\perp x_\perp} (x_T^2 Q^2)^{-F(x_\perp,\mu)} \cdot B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu)$$

based on formalism of Becher, Neubert '10; Becher, Neubert, Wilhelm '11

needs hard function, beam functions, anomalous dimensions..

Moving beyond

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

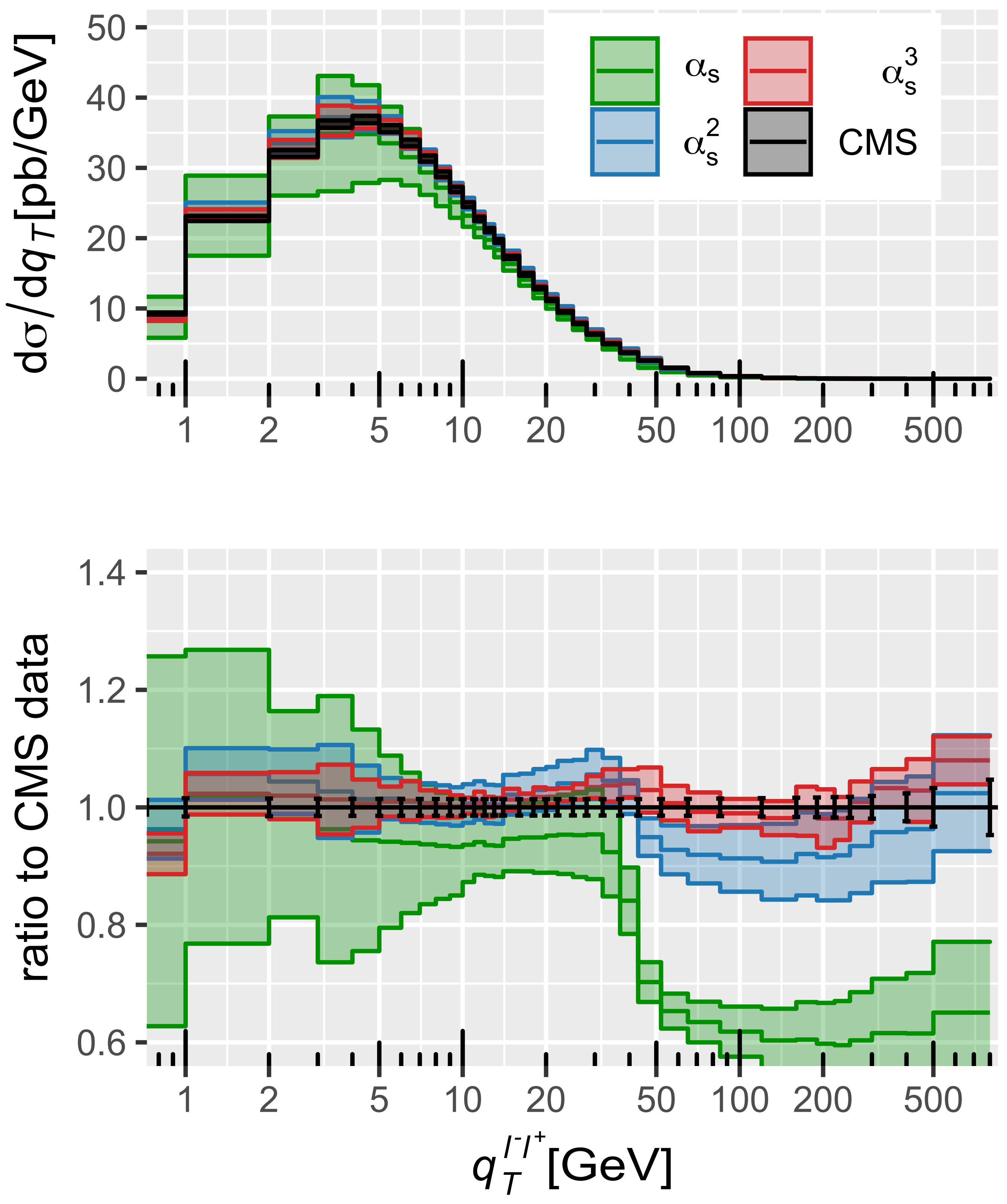
- N^{4}LL: Four loop rapidity anomalous dimension (see Gherardo's talk later)
  Duhr, Mistlberger, Vita '22; Moult, H.X. Zhu, Y. J. Zhu '22

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

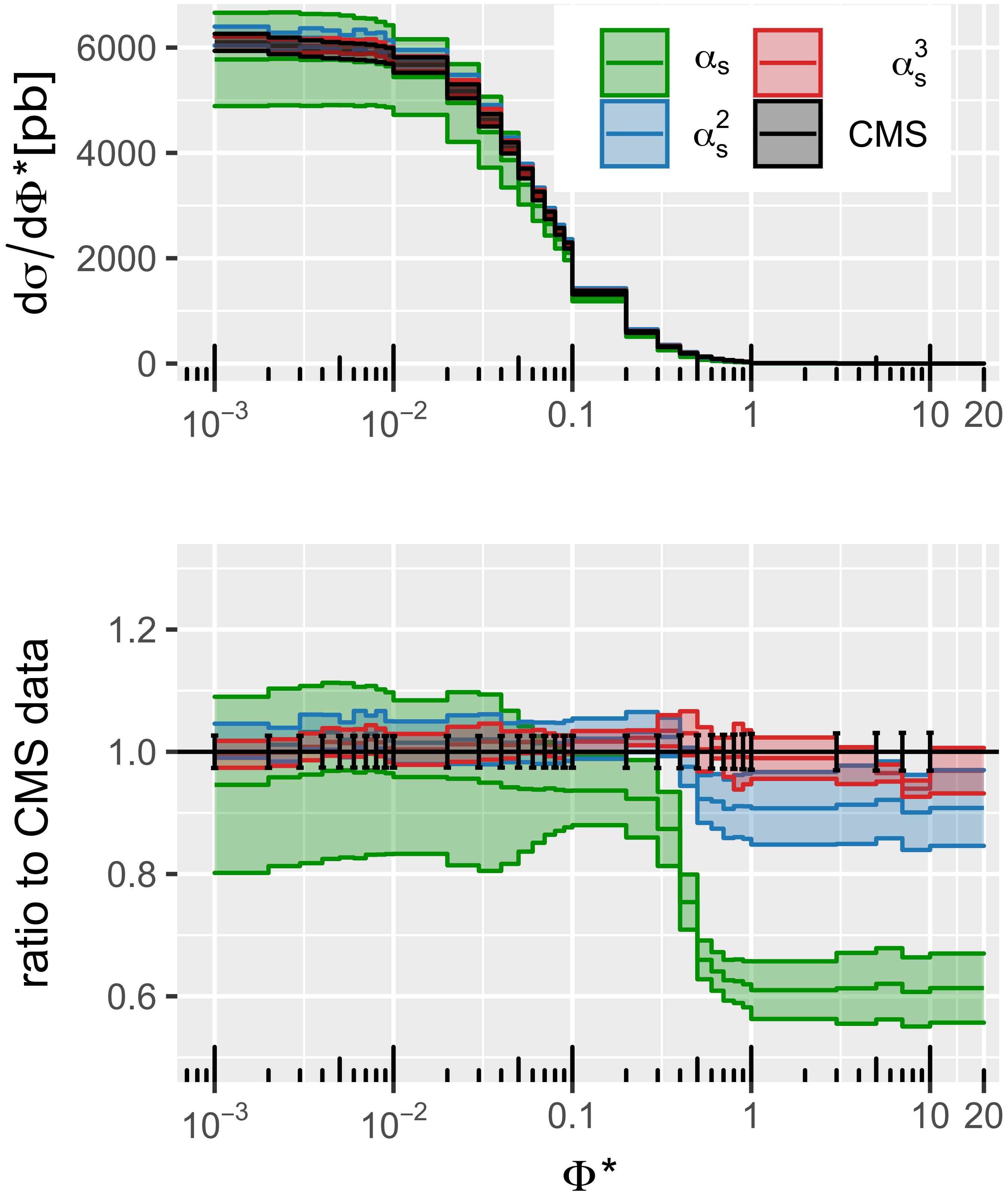
Fixed-order α_s^3 and Logarithmic α_s^3 accuracy while counting $\log(q_T^2/Q^2) \sim 1/\alpha_s$:

(N^{4}LL+N^{3}LO)$_\mathrm{p}$ **up to N^{3}LO PDF's!**

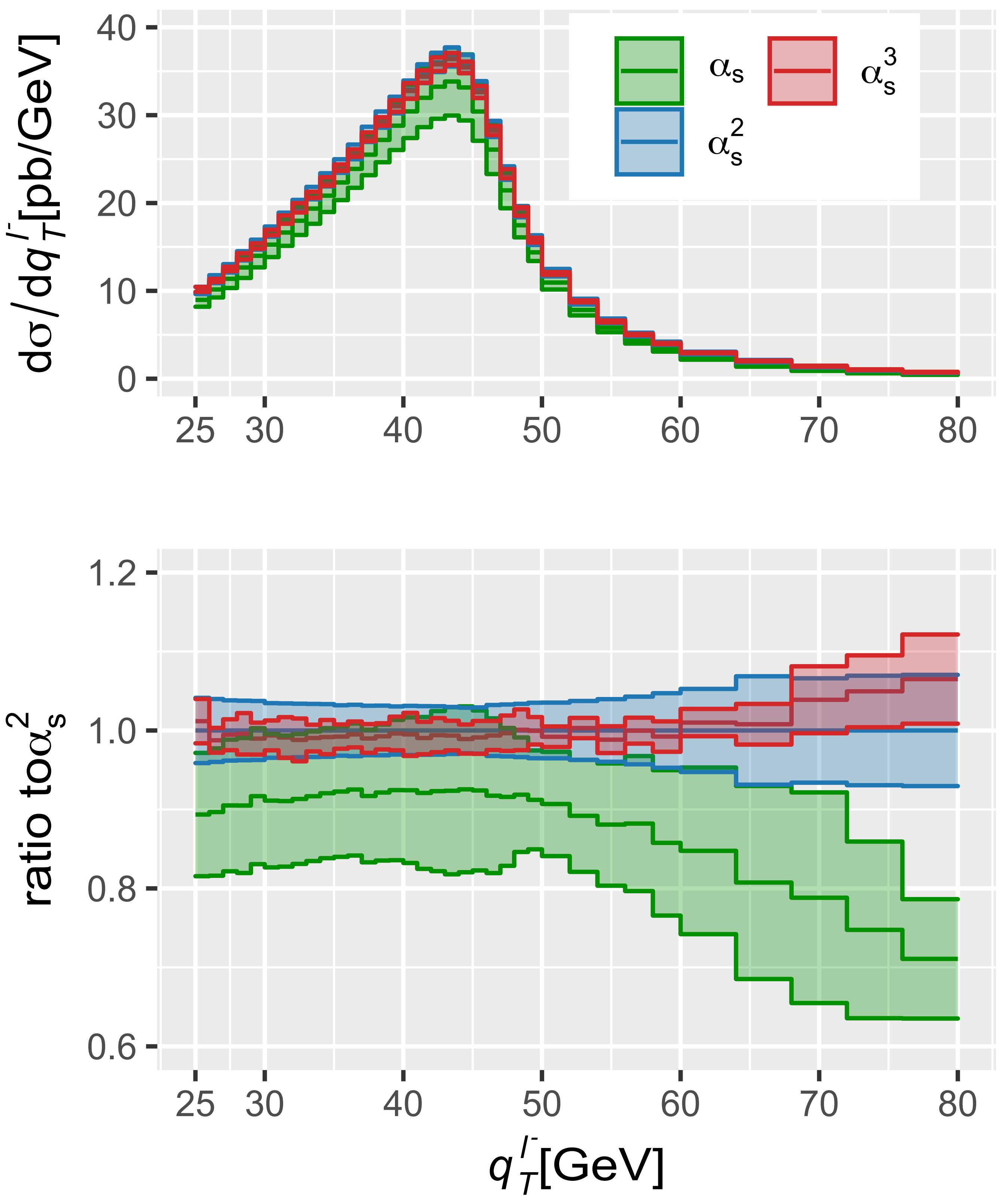
Fiducial results in comparison with CMS 13 TeV data



Fiducial results in comparison with CMS 13 TeV data



Cure for Jacobian peak in lepton q_T



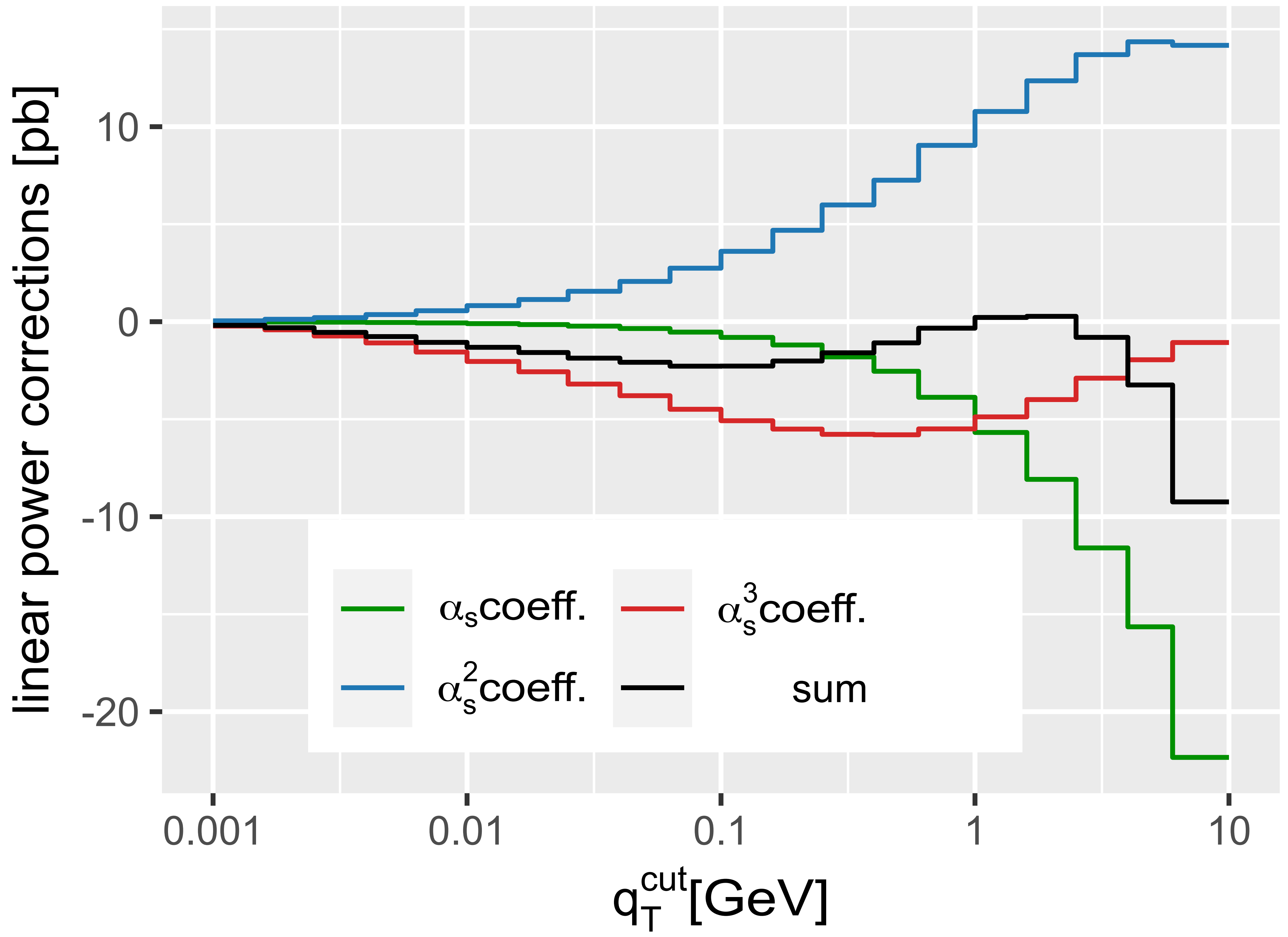
Total fiducial cross-sections

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	$700^{+4}_{-6} \pm 1_{\text{slicing}}$	$702 \pm 1_{\text{mat.}} \pm 17_{\text{sc.}}$

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

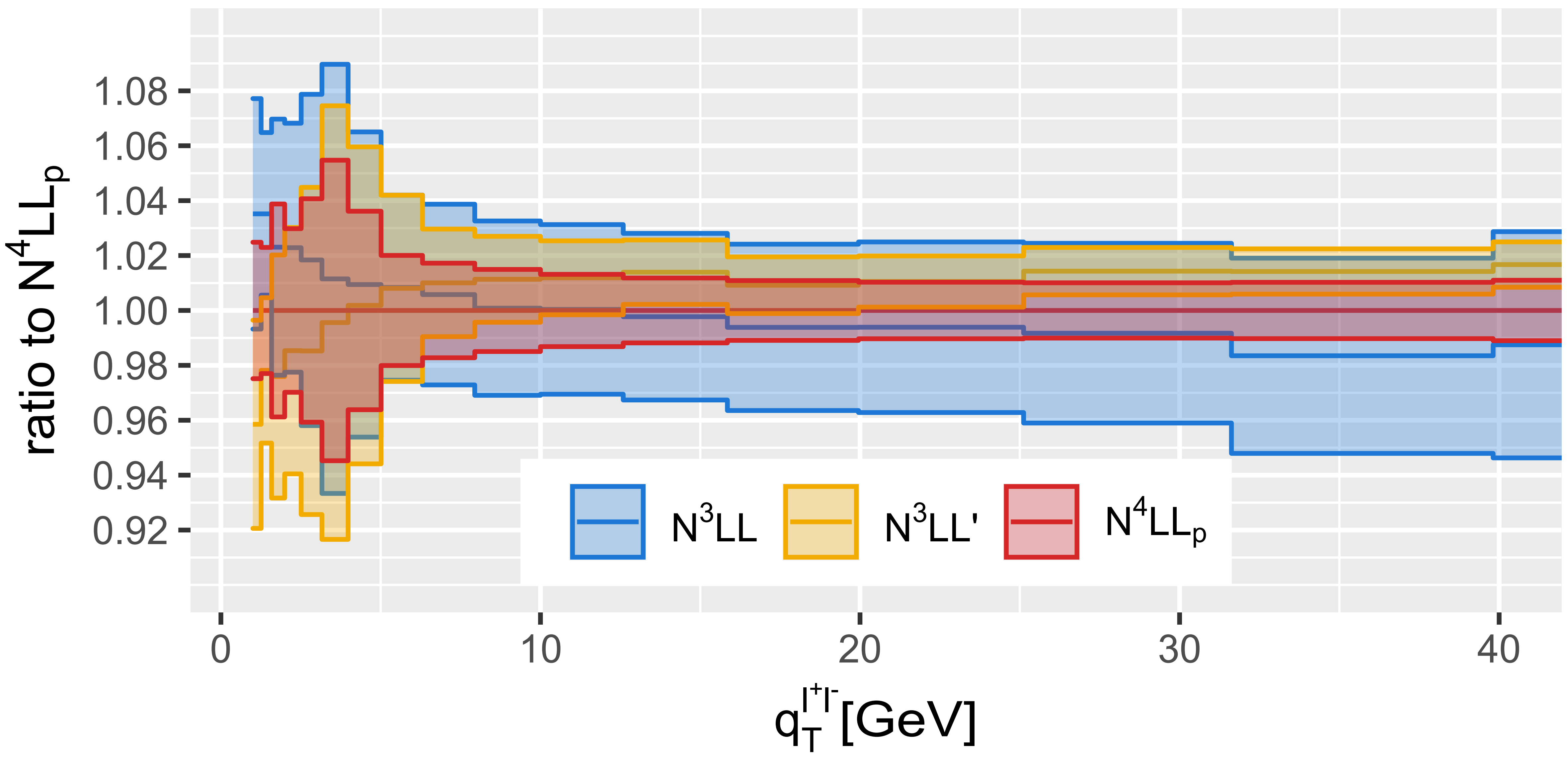
This brings up the question of realistic uncertainites.
We find 2.5%, only other estimate with RadISH resummation: 1% (2203.01565).

N^3LO with a 5 GeV cutoff thanks to linear power corrections



(symmetric lepton q_T cuts)

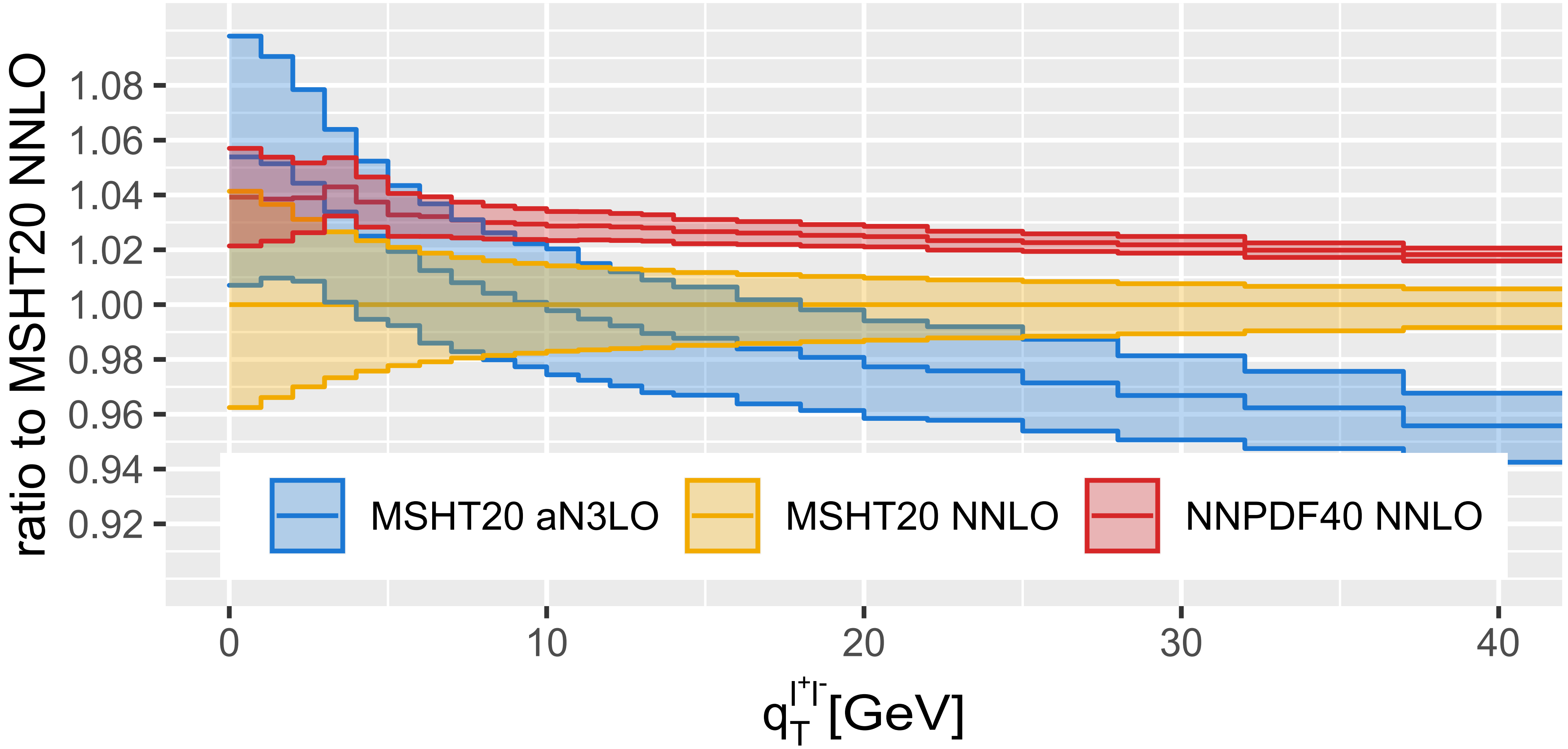
Comparison of N^3LL' with N^4LL_p



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

Question of PDFs!

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



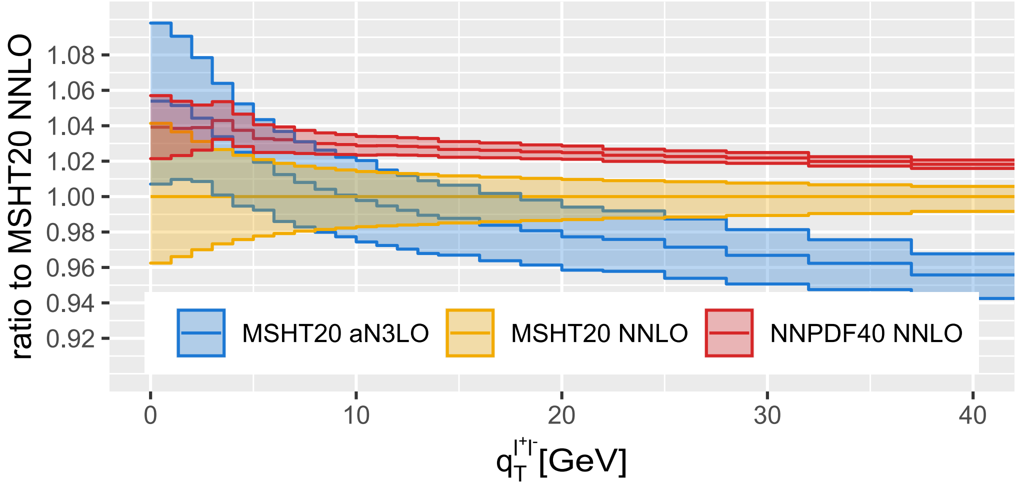
MSHT approximate N^{3}LO PDFs. Approximations for four-loop splitting functions, known information on small and large x, available Mellin moments.

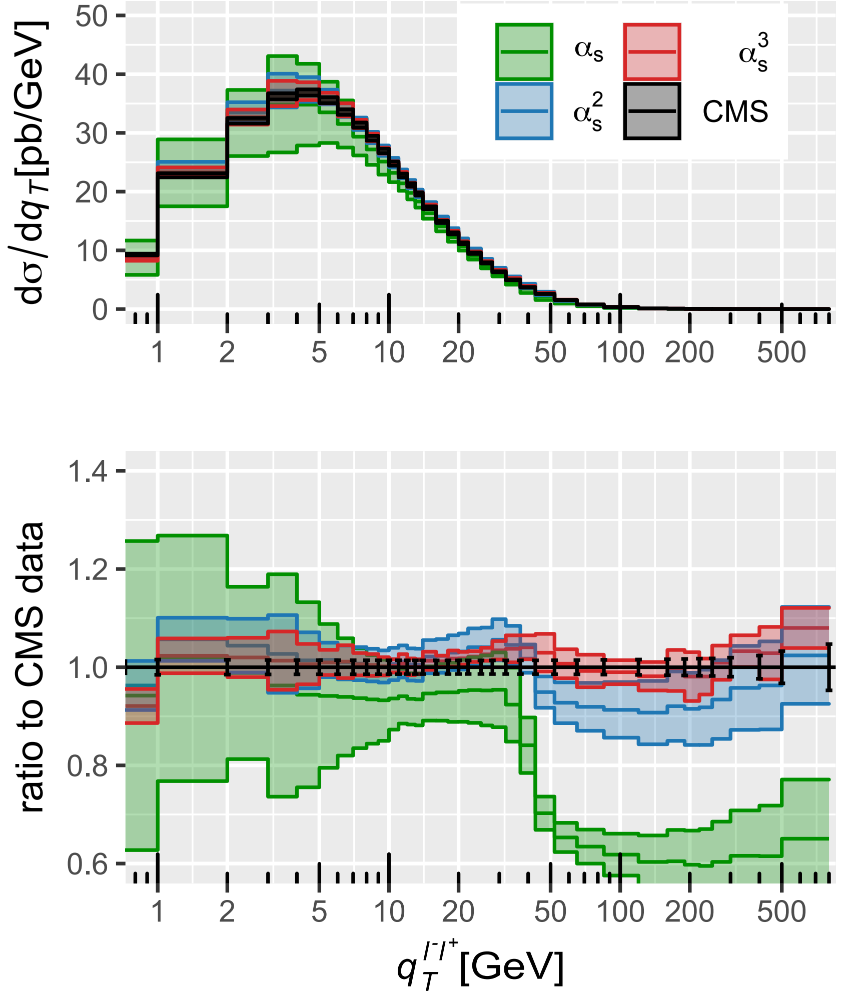
These MHO effects are included in Hessian procedure as nuisance parameters.

(See Monday: Thomas Cridge, Giulio Falcioni, Sebastian Sapeta)

Summary and Outlook

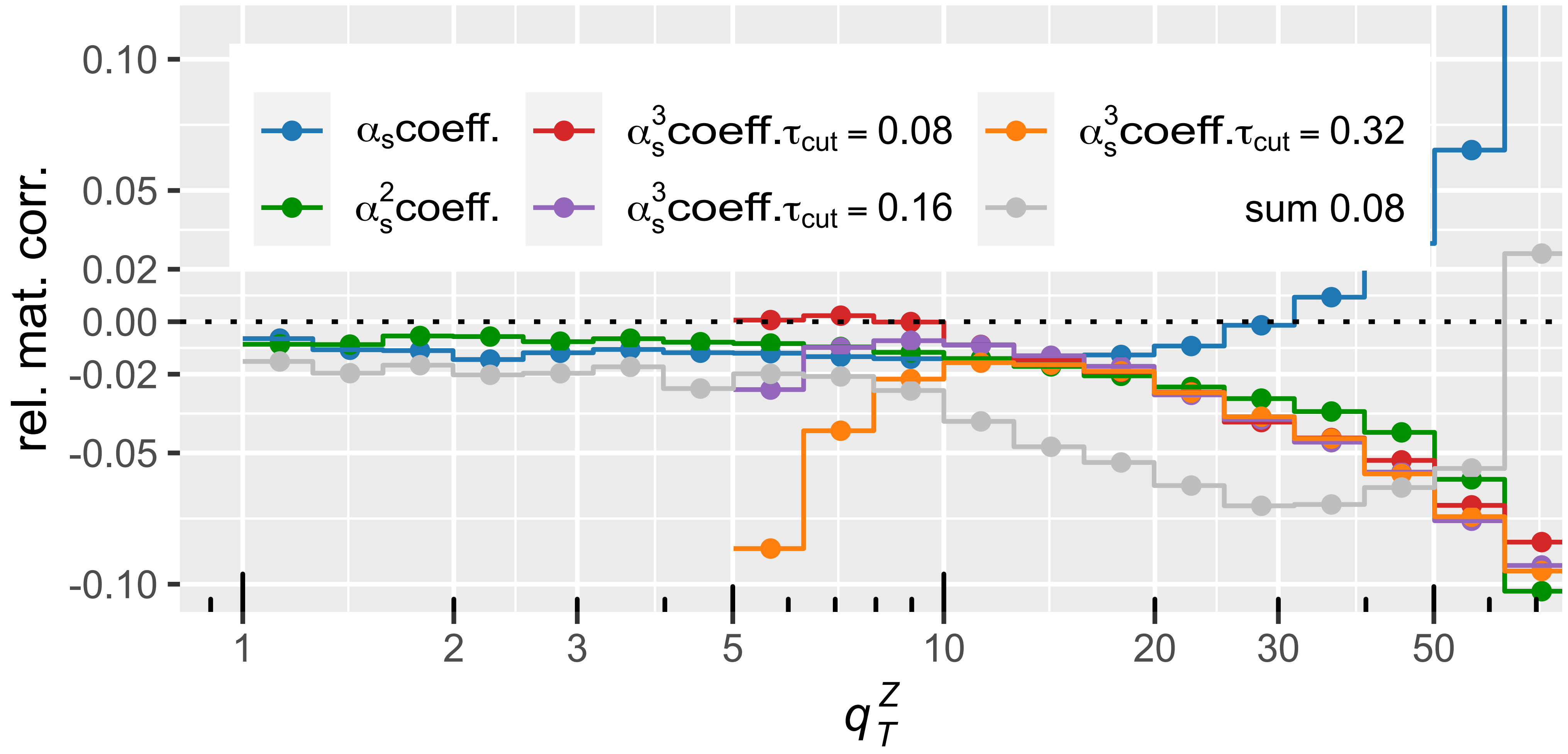
- First independent calculation of DY at α_s^3: independent Z+jet NNLO calculation, upgraded resummation to N^{4}LL *up to N^{3}LO PDFs*
- Our resummation uncertainties are more conservative than RadISH+NNLOjet
- PDFs are crucial bottleneck in the future, not just for Drell-Yan!
- Full calculation will be publicly available in MCFM soon: mcfm.fnal.gov





Backup

τ_{cut} dependence and matching corrections



- Matching corrections below 1 GeV neglected at α_s and α_s^2, and for the α_s^3 coeff. below 5 GeV
- 6000 NERSC Perlmutter node hours for all results

Uncertainty estimation

$$\mathrm{d}\sigma_{ij} \sim \int \mathrm{d}\xi_1 \mathrm{d}\xi_2 \, \mathrm{d}\sigma^0_{ij} \cdot H(\xi_1 p_1, \xi_2 p_2, \mu) \cdot$$

$$\cdot \int \mathrm{d}^2 x_\perp e^{-iq_\perp x_\perp} (x_T^2 Q^2)^{-F(x_\perp, \mu)} \cdot B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu)$$

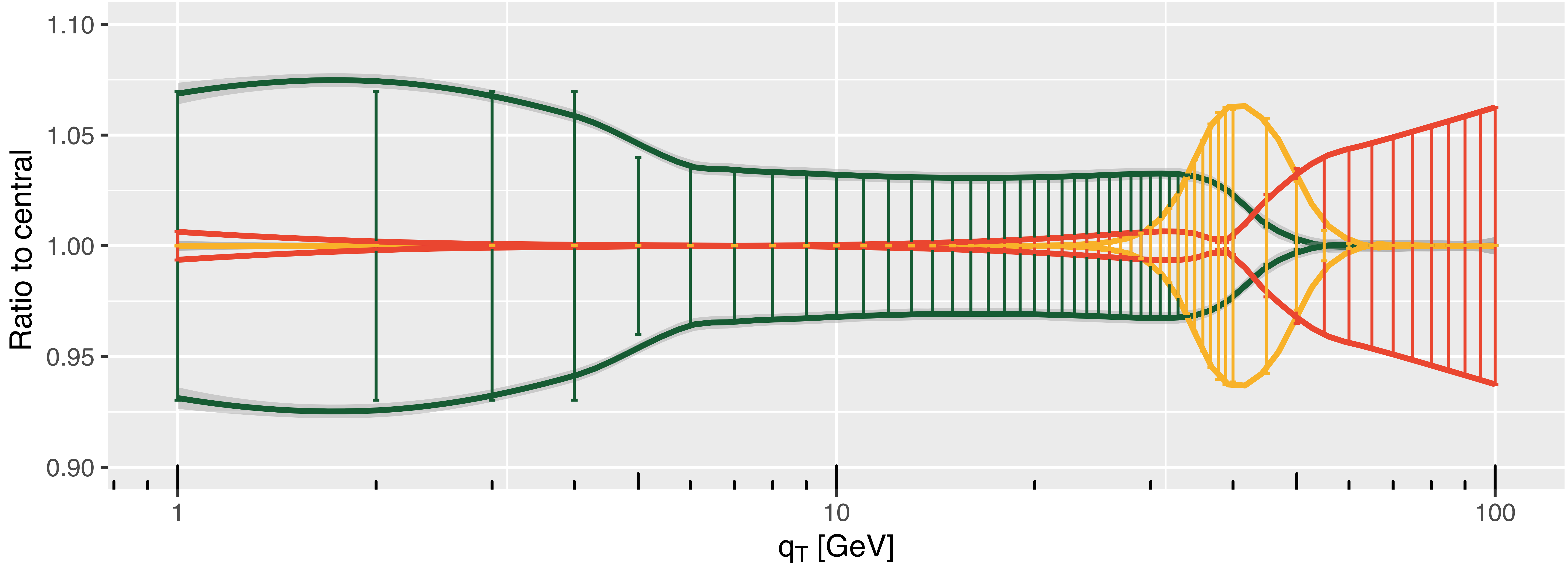
- Resummation scale
- Hard scale (evolved down to resummation scale)
- Rapidity scale uncertainty: vary r by factor of 6, $1/6$

$$(x_T^2 Q^2)^{-F} B_i B_j \to (x_T^2 Q^2 r)^{-F} (B_i B_j r^F)|_{\text{exp. to } \alpha_s^k}$$

F: rapidity anomalous dimension / collinear anomaly exponent
captures ambiguity in exponentiation of rapidity logs

Uncertainties at N^3LL+NNLO

- Resummation: resummation scale, hard scale, rapidity scale
- Matching: variation of transition function
- Fixed order: factorization and renormalization scale



Comparison of uncertainties