QCD precision predictions for W-mass measurements

Tobias Neumann, Brookhaven National Lab

LHC EW precision sub-group DY resummation benchmark

artemide

NangaParbat

ResBos2

DYTurbo

reSolve

CuTe-MCFM

SCETlib

RadISH

(see also General Meeting last February)

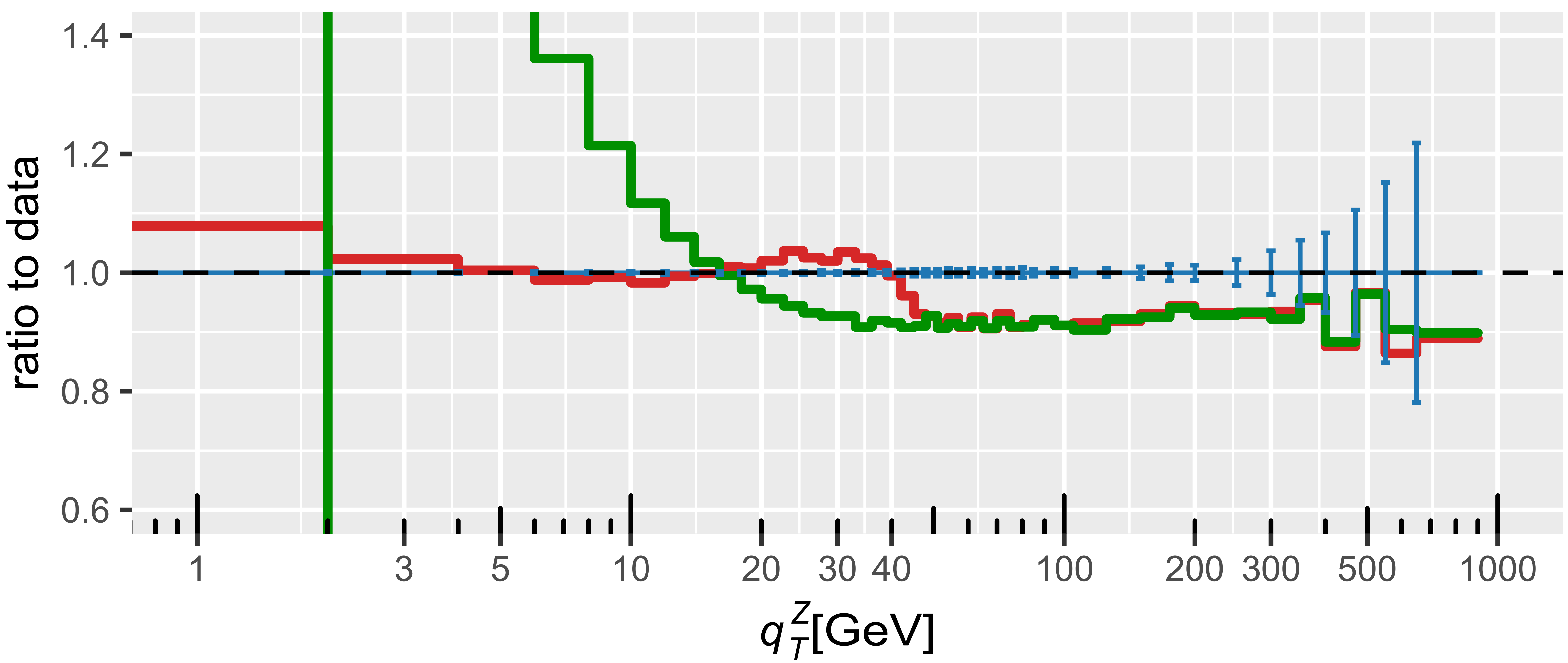
$$\log(m_Z/q_T)$$

Improved power counting

$$\log(m_Z/q_T) \sim 1/\alpha_s$$

$$\alpha_s\left(\alpha_s \log\left(\frac{m_Z}{q_T}\right)\right)^n$$

e.g. is the new α_s (NNLL)



ratio to data
1.4
1.2
1.0
0.8
0.6
1
3
5
10
20
30
40
100
200
300
500
1000
q_T^Z[GeV]

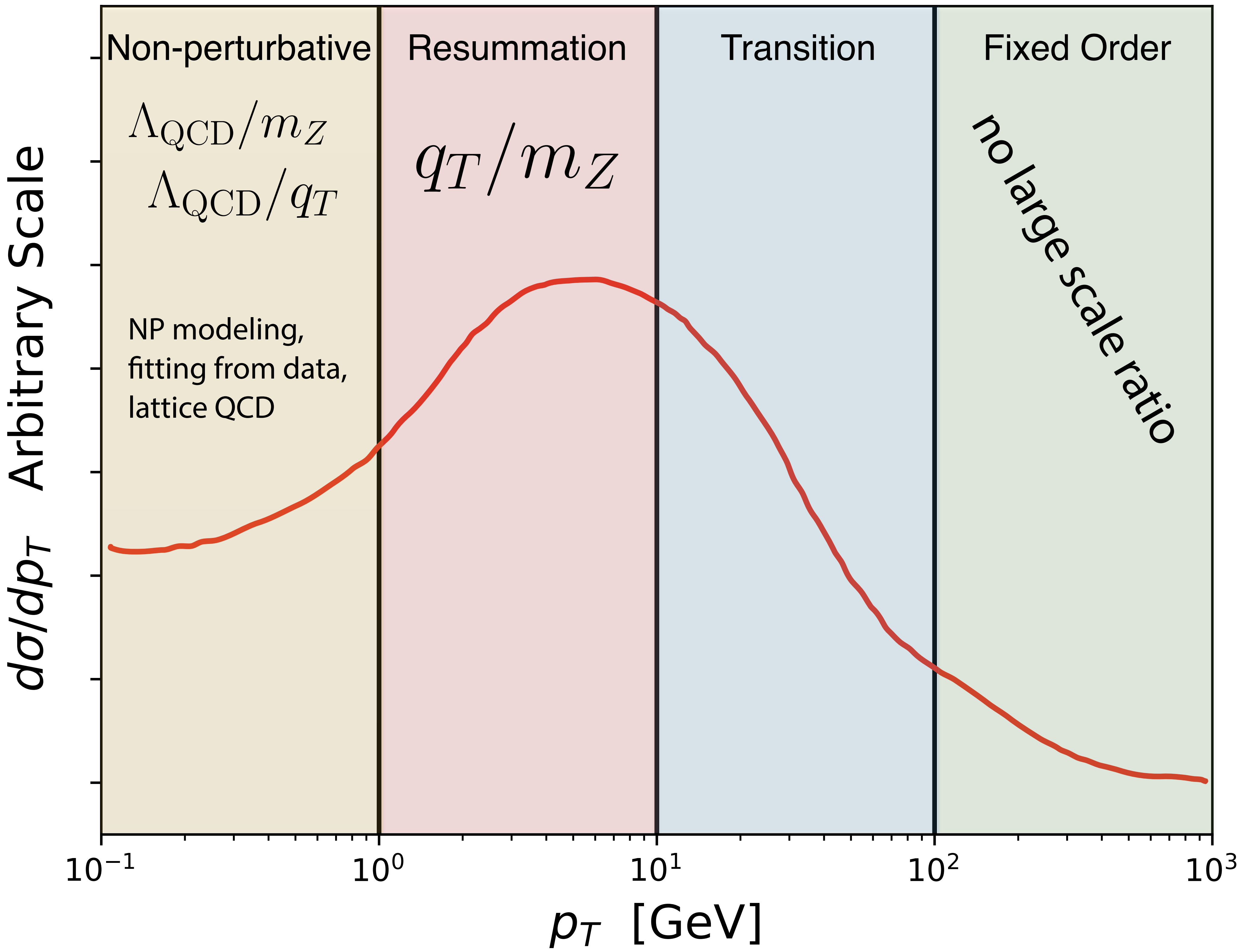
Resummation through RG-evolution

- via small-q_T factorization

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

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

needs hard function, beam functions, anomalous dimensions..


Non-perturbative
Resummation
Transition
Fixed Order
$\Lambda_{\mathrm{QCD}}/m_Z$
$\Lambda_{\mathrm{QCD}}/q_T$
q_T/m_Z
no large scale ratio
NP modeling,
fitting from data,
lattice QCD
$d\sigma/dp_T$ Arbitrary Scale
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
p_T [GeV]

Currently participating groups and codes

Slide from Johannes Michel

TMD global fit tools (Collins/Soper/Sterman formalism):

`artemide` — Scimemi, Vladimirov ’17, ’19

`NangaParbat` — Bacchetta et al. ’19 — Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro '19

`ResBos2` — Isaacson ’17

Direct QCD (Catani/de Florian/Grazzini formalism):

`DYRes/DYTurbo` — Camarda et al. ’15, ’19, ’21 — Catani, de Florian, Ferrera, Grazzini '15; Camarda, Boonekamp, Bozzi, Catani, Cieri, Cuth, Ferrera, de Florian, Glazov, Grazzini, Vincter, Schott '19; Camarda, Cieri, Ferrera '21

`reSolve` — Coradeschi, Cridge ’17

SCET-based tools:

`CuTe-MCFM` — Becher, Neumann ’11, ’20 — Becher, Neubert, Wilhelm '11, '12

`SCETlib` — Billis, Ebert, JM, Tackmann ’17, ’20

Coherent branching/momentum-space resummation:

`RadISH` — Monni, Re, Rottoli, Torrielli ’16, ’17, ’19, ’21

Different benchmark levels

Z at 13 TeV, $Q = m_Z, y = 0$

Level 1 & 2

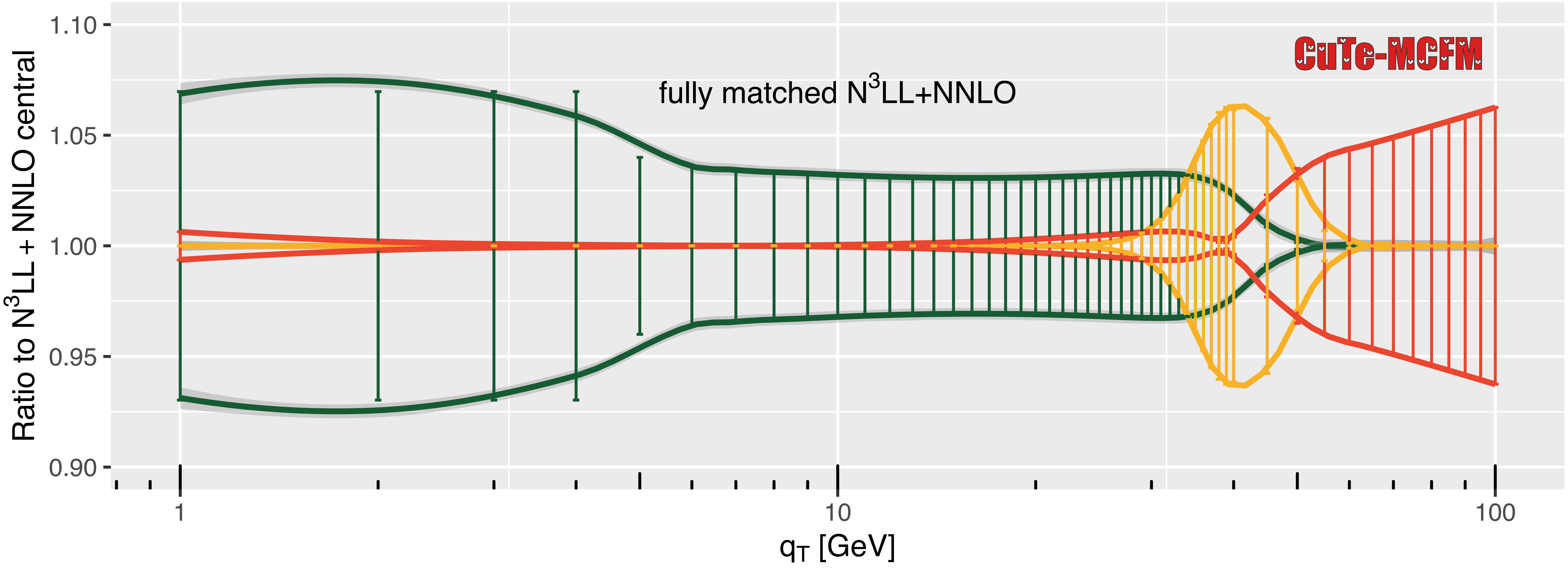
- only resummation, at different N^{k}LL, no non-perturbative model (Landau pole regulated similarly)

Level 3

- include matching, default settings for Landau pole; physical spectrum

Uncertainties at level 3

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

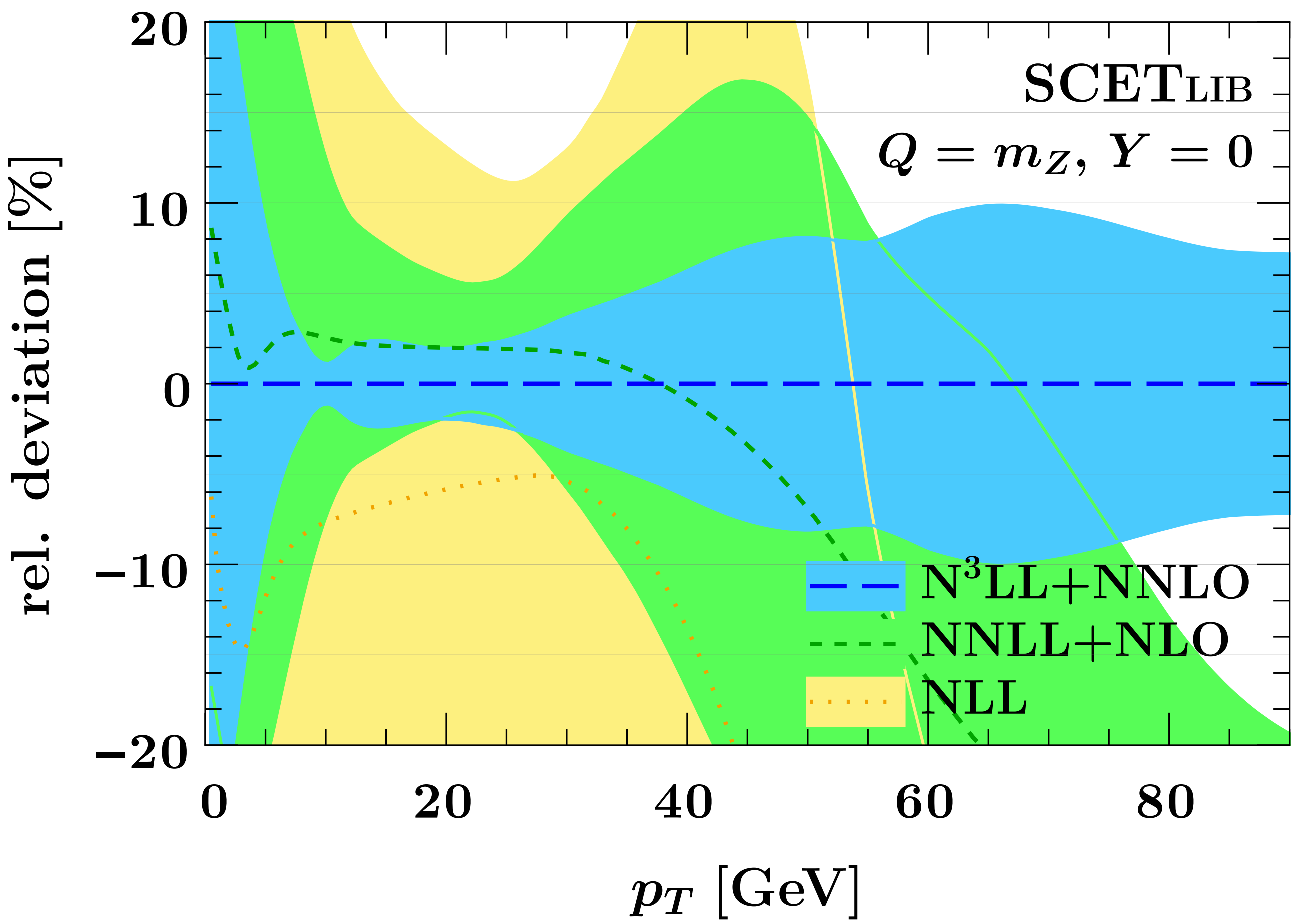


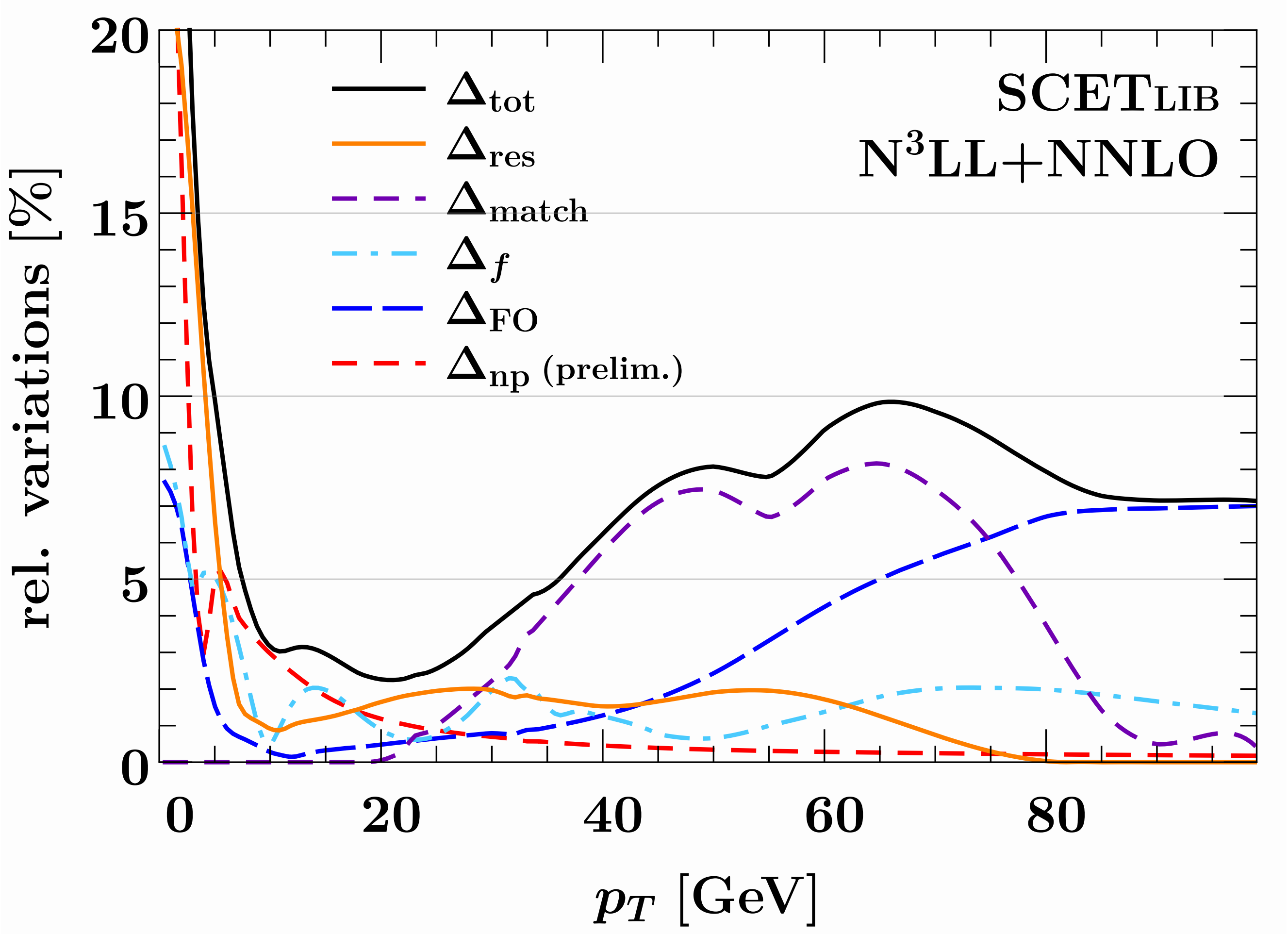
Many (different) scales in resummation – which ones to vary & how to interpret?

	Sudakov/ Resummation	Non-Sudakov	Matching
arTeMiDe	$\mu_f\ (\mu, \zeta_\mu)$	μ_{OPE}	No level 3
Cute-MCFM	$\mu,\ \mu_h,\ r$	$\mu_R,\ \mu_F$	Parameters of damping func.
DYTURBO	Q	$\mu_R,\ \mu_F$	Parameters of Damping func.
NangaParbat	$Q,\ \mu_b$	$\mu_R,\ \mu_F$	Still none (damping func.)
RadISH	Q	$\mu_R,\ \mu_F$	Parameters of Damping func.
ResBos	$C_1,\ C_2,\ C_3$	$\mu_R,\ \mu_F$	Parameters of damping func.
Resolve	μ_S	$\mu_R,\ \mu_F$	No level 3
SCETlib	Δ_{resum}	Δ_{FO}	Profile scales Δ_{match}

Valerio Bertone, Nov '21

SCETlib, Tackmann, Michel '22





See https://indico.cern.ch/event/1108518/ for a full overview

'21, '22, moving beyond: Fixed-order α_s^3 and logarithmic α_s^3 accuracy while counting $\log(q_T^2/Q^2) \sim 1/\alpha_s$: N^4LL+N^3LO **up to N^3LO PDF's!**

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

  Fixed-order Z+jet NNLO calculation

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

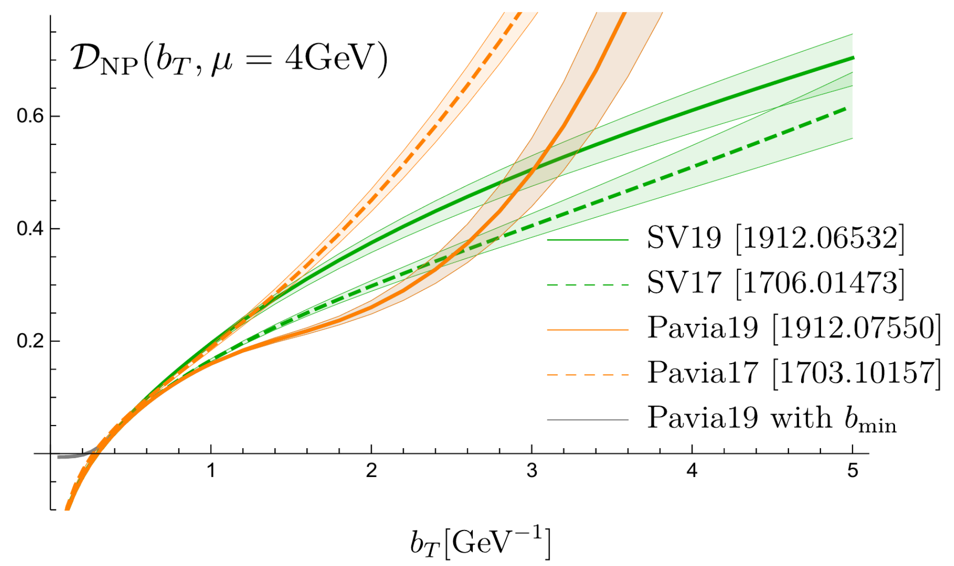
- N^4LL: Four loop rapidity anomalous dimension
  Duhr, Mistlberger, Vita '22; Moult, H.X. Zhu, Y. J. Zhu '22
- e.g. Four-loop collinear anomalous dimension
  Agarwal, von Manteuffel, Panzer, Schabinger '21

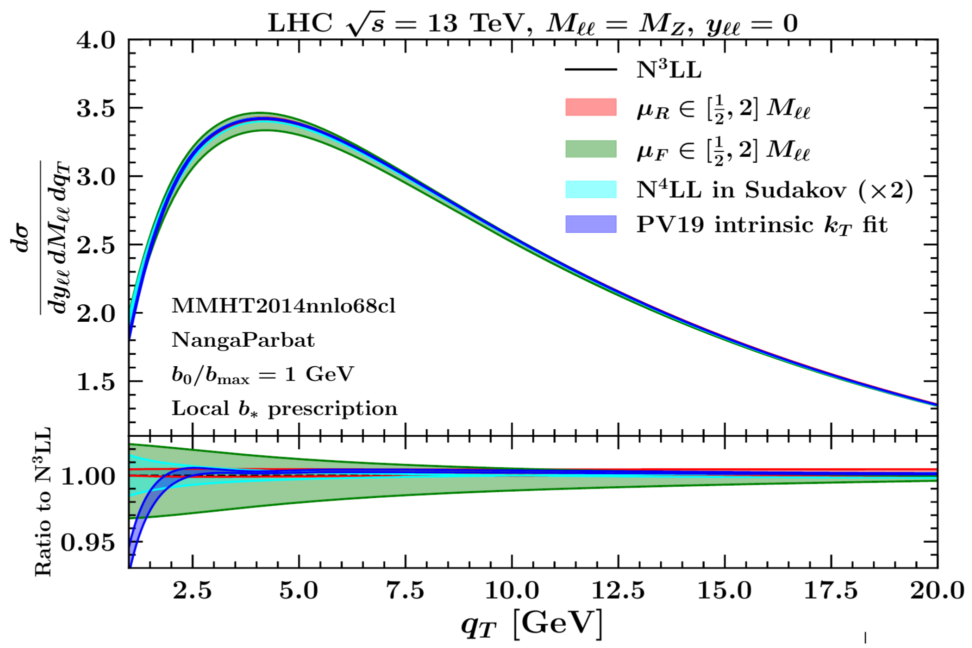
- Massive three-loop axial singlet contributions
  Chen, Czakon, Niggetiedt '22
- Two-loop axial singlet V+jet
  Gehrmann, Peraro, Tancredi '22

Slide from Johannes Michel

Future directions:

- Some groups (`artemide`, `NangaParbat`) have performed dedicated global fits of the nonperturbative TMD structure at $b_T \sim 1/\Lambda_{\rm QCD}$
  [Scimemi, Vladimirov '19; Bacchetta et al. '19]



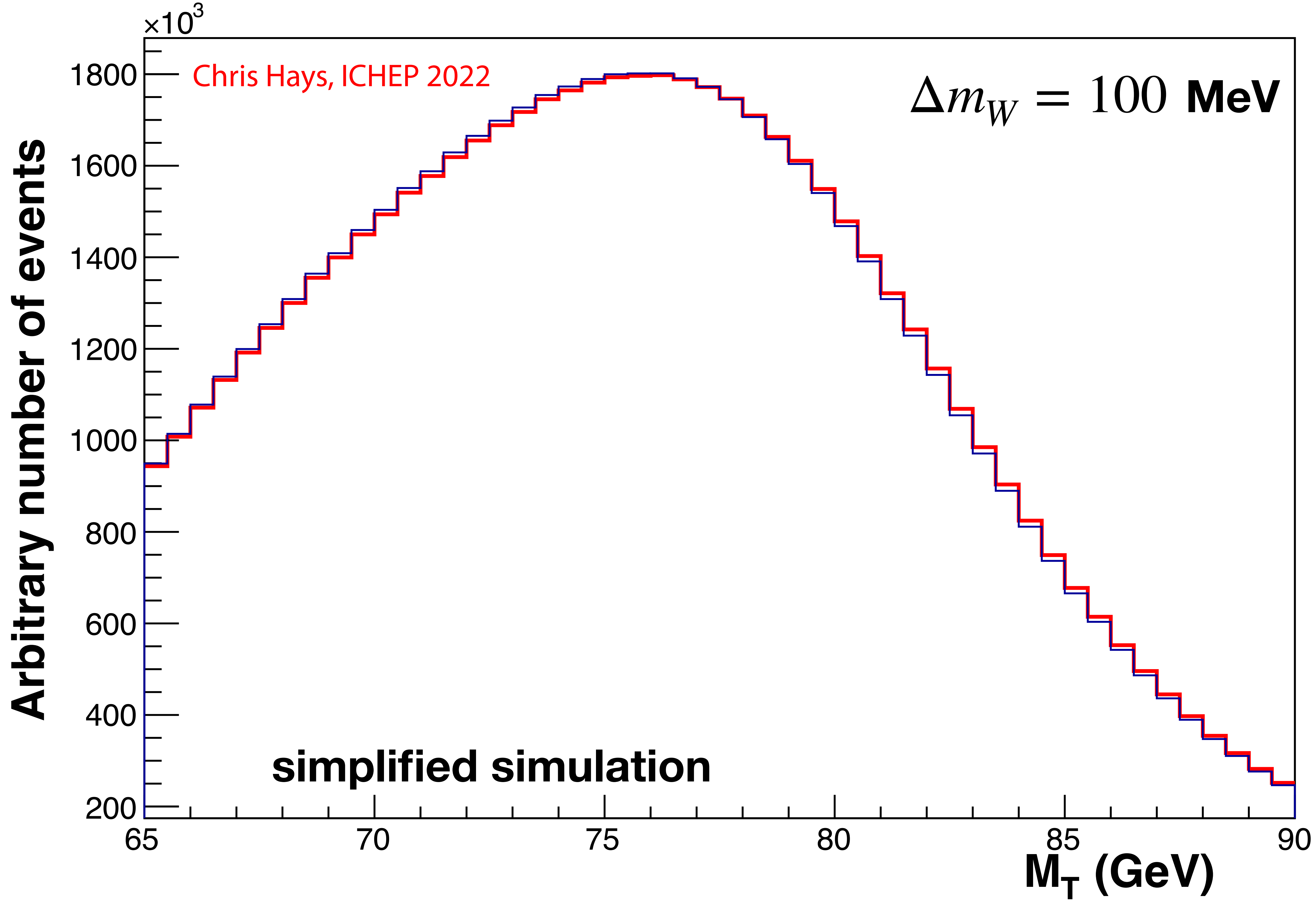


- Fit includes low-energy Drell-Yan and (for `artemide`) SIDIS data

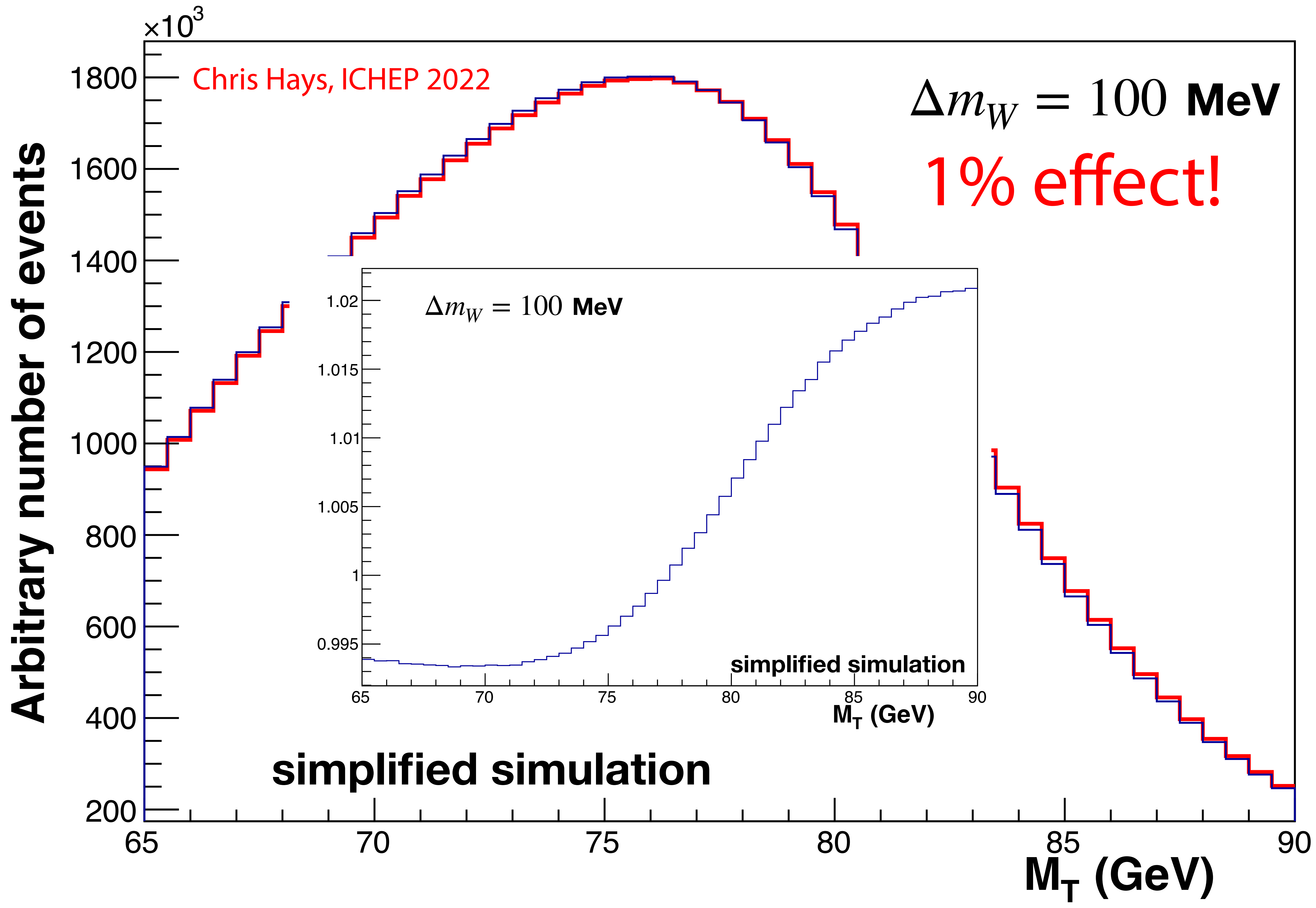
  ....

▸ Level 3.5 benchmark with nonperturbative effects included?

See workshop on low pT DY, NP effects, intrinsic kT tuning, CS kernel, ...
https://indico.cern.ch/event/1194333/

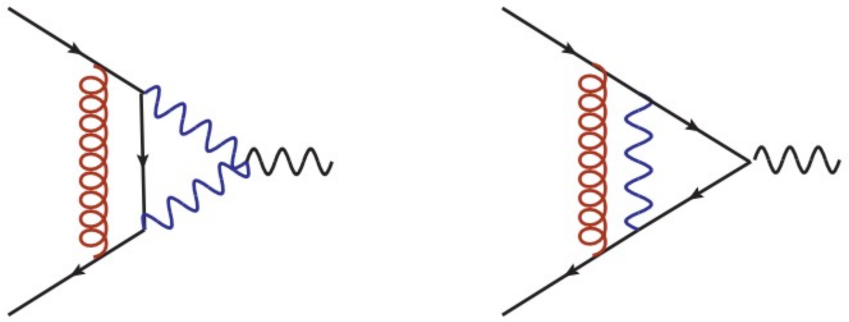


×10^3
Chris Hays, ICHEP 2022
$\Delta m_W = 100$ MeV
Arbitrary number of events
1800
1600
1400
1200
1000
800
600
400
200
simplified simulation
65
70
75
80
85
90
M_T (GeV)



Chris Hays, ICHEP 2022
$\Delta m_W = 100$ MeV
1% effect!
$\times 10^3$
Arbitrary number of events
M_T (GeV)
simplified simulation
$\Delta m_W = 100$ MeV
simplified simulation
M_T (GeV)

Two-loop QCDxEW corrections to W production



Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch, 2009.10386, 2103.02671, ...

Shifts in W-mass, inclusive:

- NLO EW: $\Delta m_W = 1 \text{ MeV}$
- QCD-EW: $\Delta m_W = -7 \text{ MeV}$

Shifts in W-mass: fiducial setup

- Inclusive setup: $\Delta m_W = -7 \text{ MeV}$
- "ATLAS" cuts: $\Delta m_W = -17 \text{ MeV}$
- "Tuned" cuts: $\Delta m_W = -1 \text{ MeV}$

➔ Cuts can have dramatic impact

- ➢ "ATLAS" cuts have stronger cuts on leptons from (lighter) *W* than from *Z* → decorrelation.

➔ QCD-EW shifts potentially relevant for target precision of 8 MeV.

see presentation by Raoul Röntsch

Theory uncertainties

- Fixed-order expansions in QCD and EW
- Higher-order resummation
- Parton showers
- Non-perturbative effects, PDFs, TMDs
- Higher power/twist terms in factorization
- Understanding universality of tuning
- Numerical precision
- ...

Fully theory-driven SM measurement far away from 10 MeV,
even with state-of-the-art results

CuTe-MCFM

Resummation at α_s^3

- via small-q_T factorization

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

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

based on formalism of Becher, Neubert '10; Becher, Neubert, Wilhelm '11; Becher, Hager '19
implemented in CuTe-MCFM (Becher, Neumann '19)

- three-loop beam functions
  M.-x. Luo, T.-Z. Yang, H. X. Zhu, Y. J. Zhu '19, '20; Ebert, Mistlberger, Vita '20
- Z+jet NNLO calculation (via 1-jettiness slicing)
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- N^4LL: Four loop rapidity anomalous dimension
  Duhr, Mistlberger, Vita '22; Moult, H.X. Zhu, Y. J. Zhu '22
- e.g. Four-loop collinear anomalous dimension
  Agarwal, von Manteuffel, Panzer, Schabinger '21
- Massive three-loop axial singlet contributions
  Chen, Czakon, Niggetiedt '22

are *some* ingredients

Public and well supported (you tell me)!

CuTe-MCFM

mcfm.fnal.gov

> *"If a theoretical calculation is done, but it can not be used by any experimentalist, does it make a sound?"*
>
> *— Joey Huston*

See also "Computational Challenges for Multi-loop Collider Phenomenology: A Snowmass 2021 White Paper"

Febres Cordero, von Manteuffel, Neumann '22

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mcfm.fnal.gov

> *"If a theoretical calculation is done, but it can not be used by any experimentalist, does it make a sound?"*
>
> *— Joey Huston*

> *"It's just a push to GitHub!"*
>
> *— Josh Bendavid*

See also "Computational Challenges for Multi-loop Collider Phenomenology: A Snowmass 2021 White Paper"

Febres Cordero, von Manteuffel, Neumann '22

RadISH+MATRIX

N^{3}LL+NNLO (α_s^2)

Kallweit, Re, Rottoli, Wiesemann '20

DYTurbo

N^{3}LL+NNLO (α_s^2)

Camarda, Cieri, Ferrera '21

but can use external α_s^3 fixed-order for N^{4}LL$_p$

CuTe-MCFM

N^{4}LL$_p$ + N^{3}LO (α_s^3)

Neumann, Campbell '22; Becher, Neumann '20

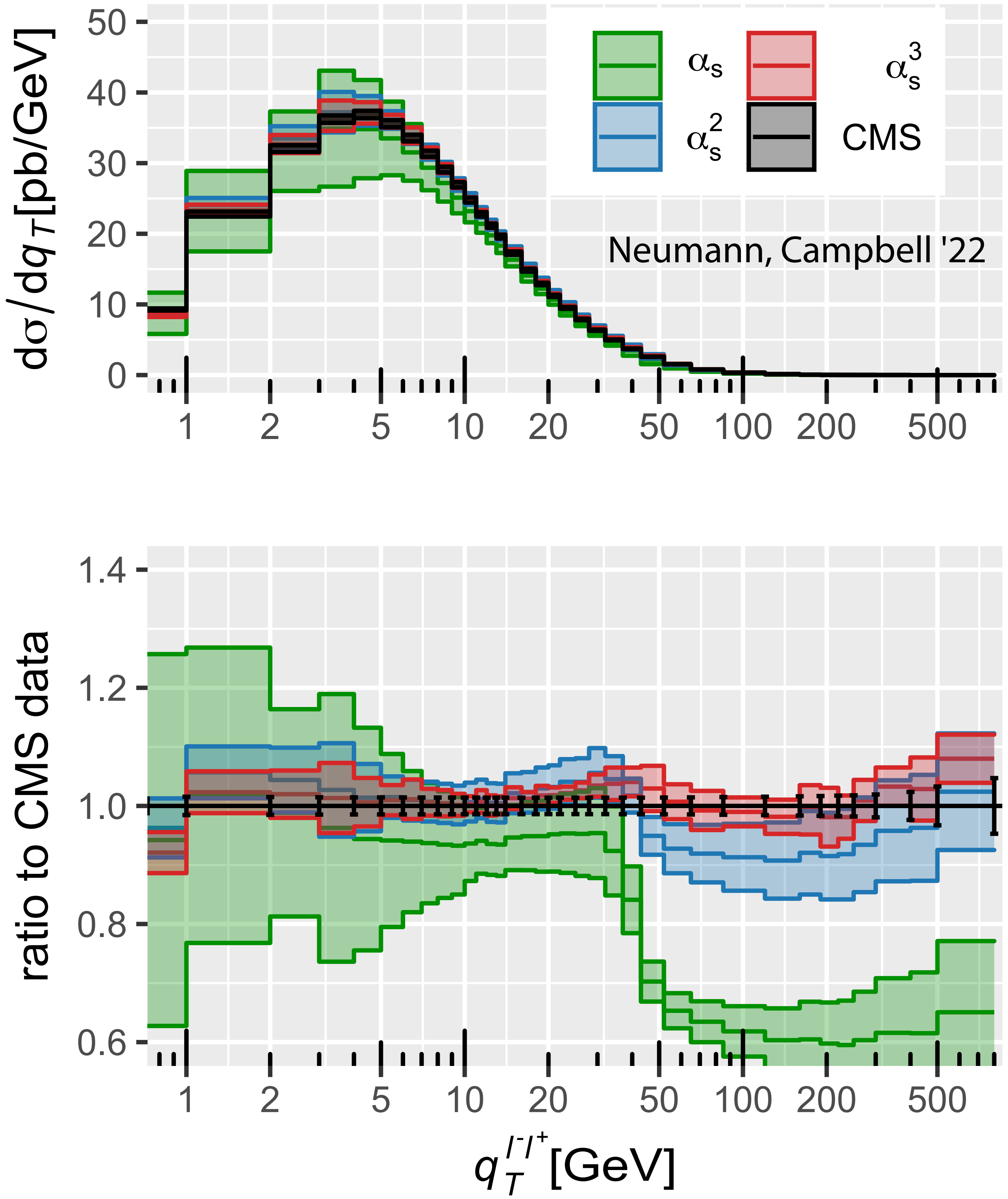
allows for NNLO Z+jet calculation to be used by other codes (DYTurbo)

MiNNLO-PS+POWHEG

Parton shower + NNLO

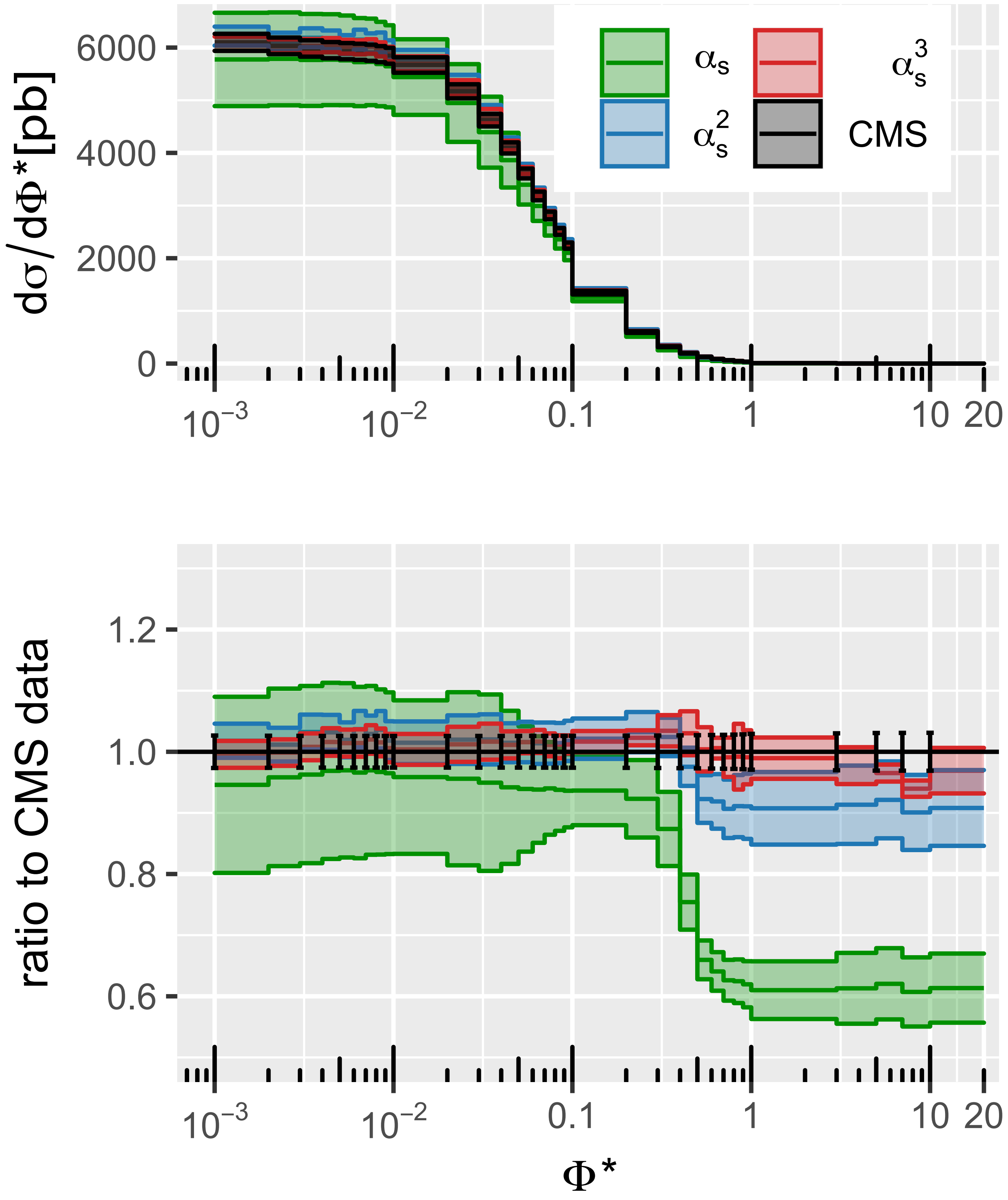
Monni, Nason, Re, Wiesemann, Zanderighi '20

Fiducial results in comparison with CMS 13 TeV data

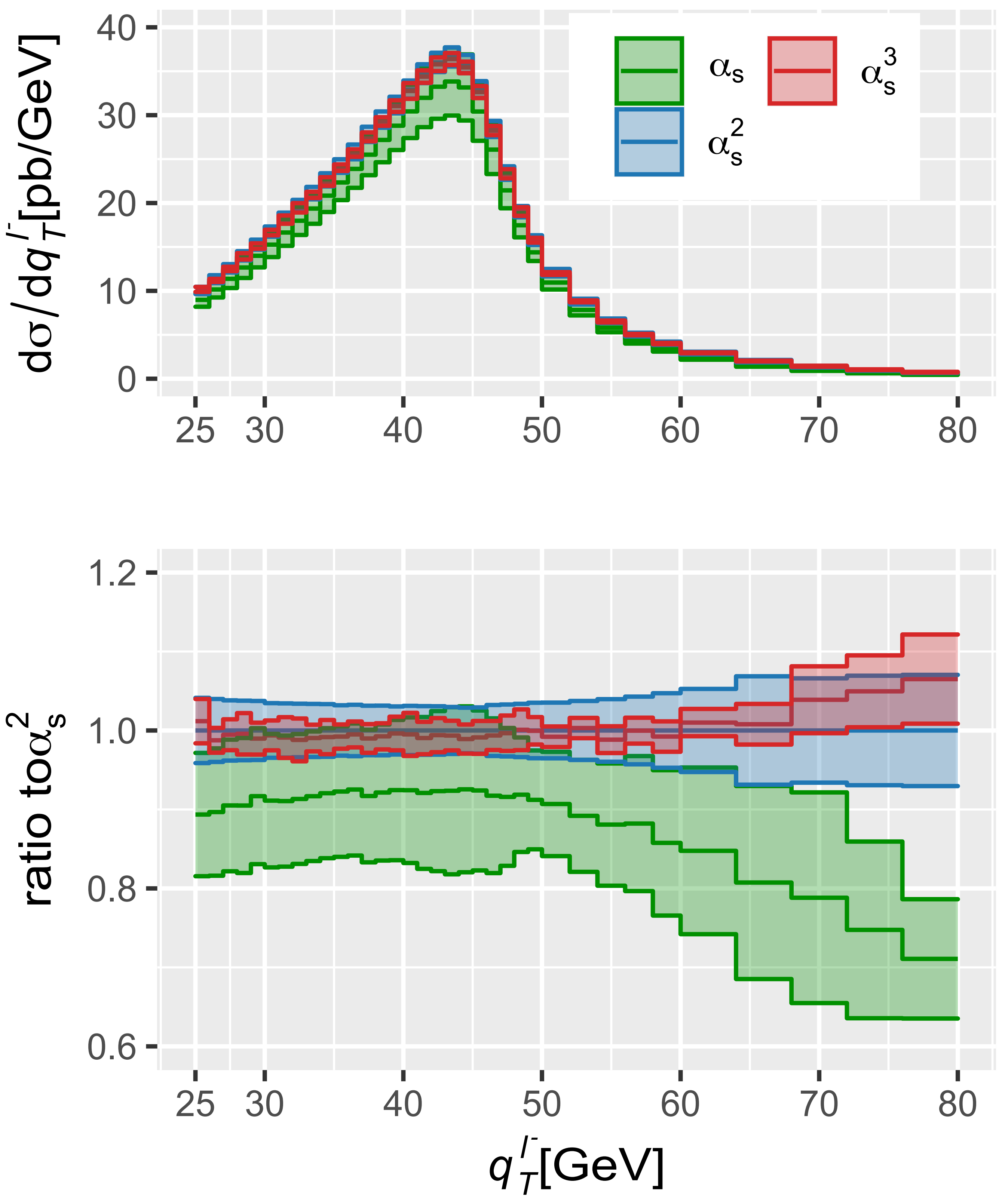


CMS measurement: 1909.04133

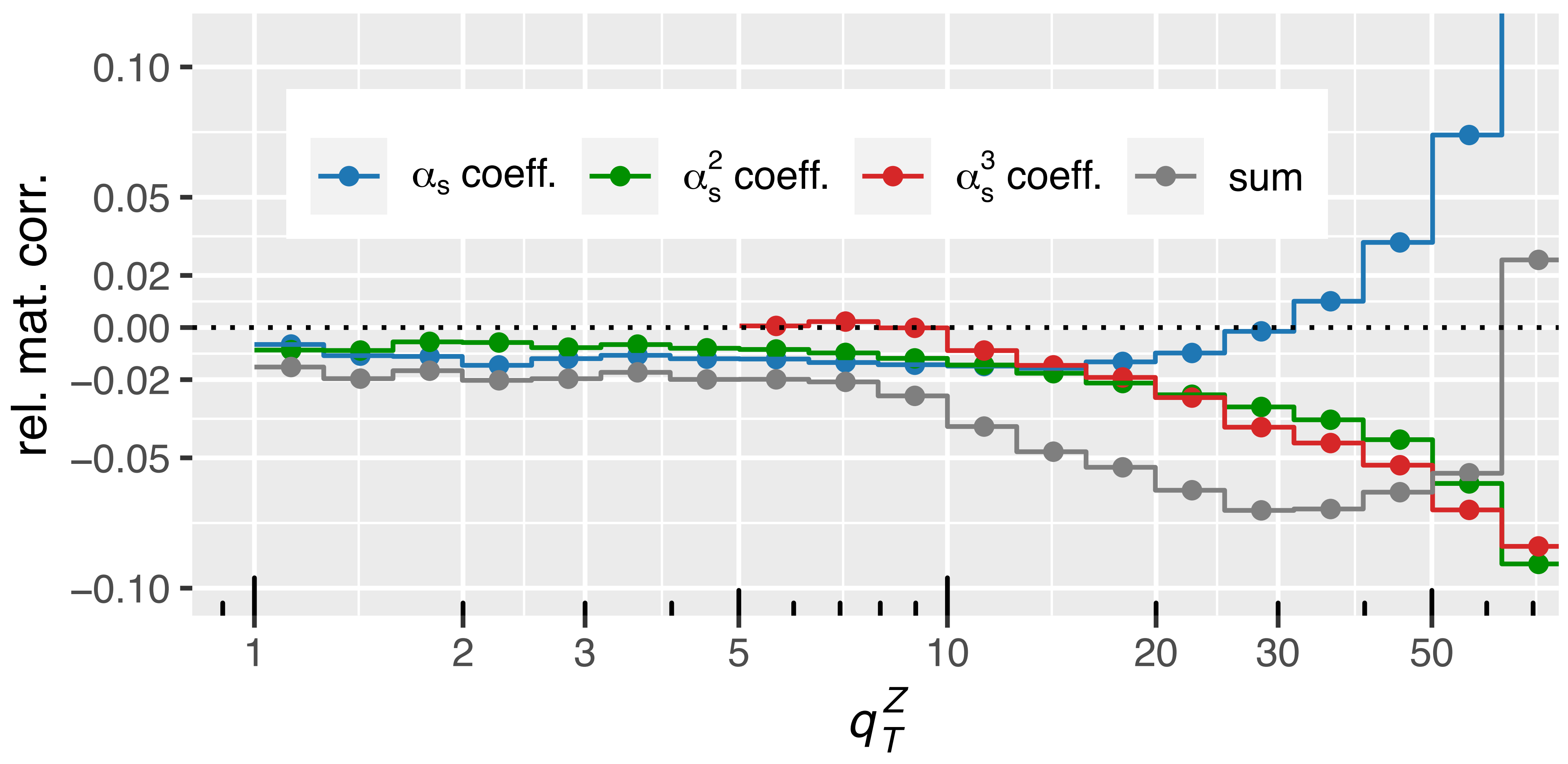
Fiducial results in comparison with CMS 13 TeV data



Cure for Jacobian peak in lepton q_T



Why can we use a 5 GeV cutoff for the N^4LL_p matching corrections?

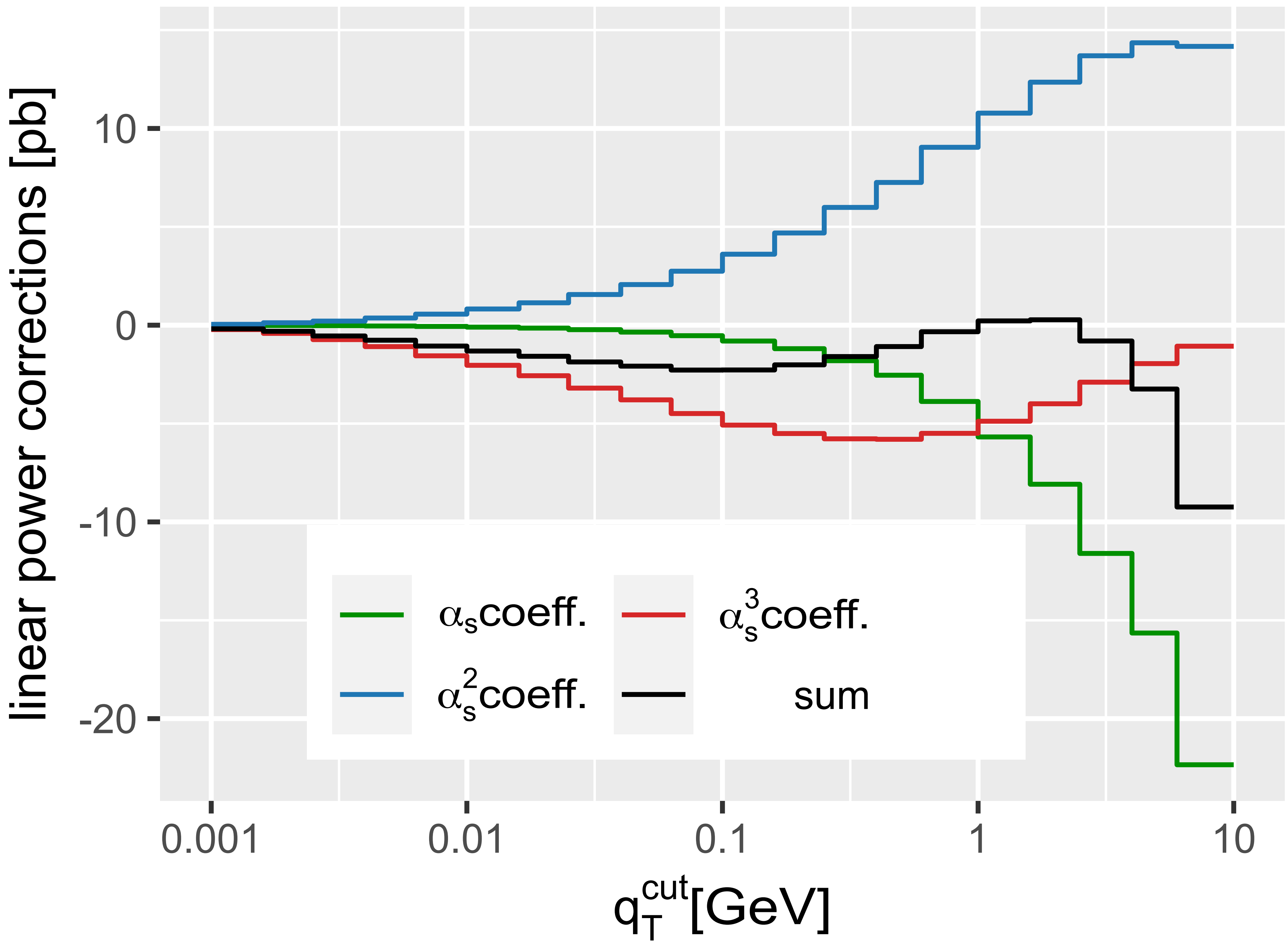


Total fiducial cross-sections

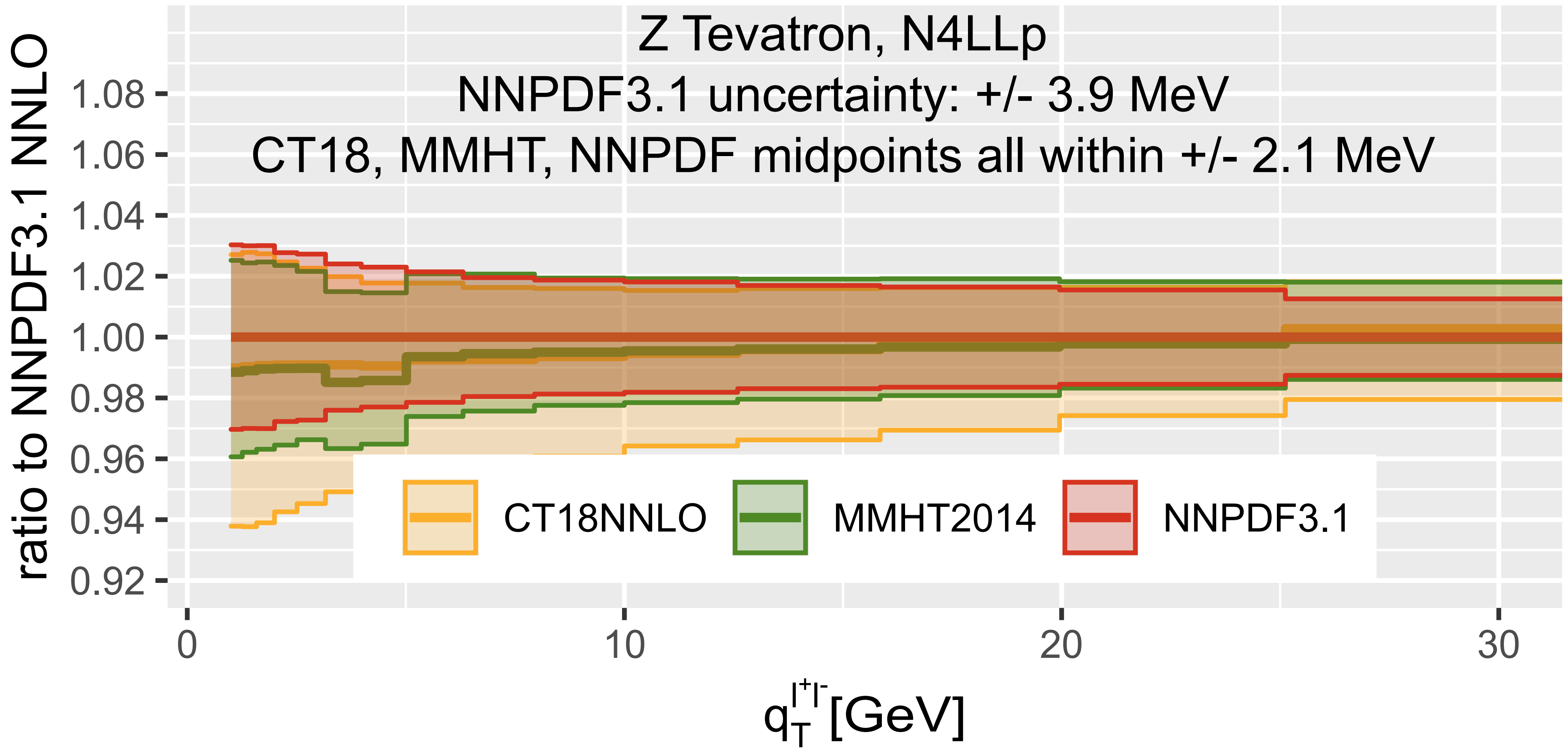
Order k	fixed-order α_s^k	res. improved α_s^k
0	694^{+85}_{-92}	—
1	732^{+19}_{-30}	$637 \pm 8_{\text{mat.}} \pm 70_{\text{sc.}}$
2	720^{+4}_{-3}	$707 \pm 3_{\text{mat.}} \pm 29_{\text{sc.}}$
3	$700^{+4}_{-6} \pm 1_{\text{slicing}}$	$702 \pm 1_{\text{mat.}} \pm 17_{\text{sc.}}$

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

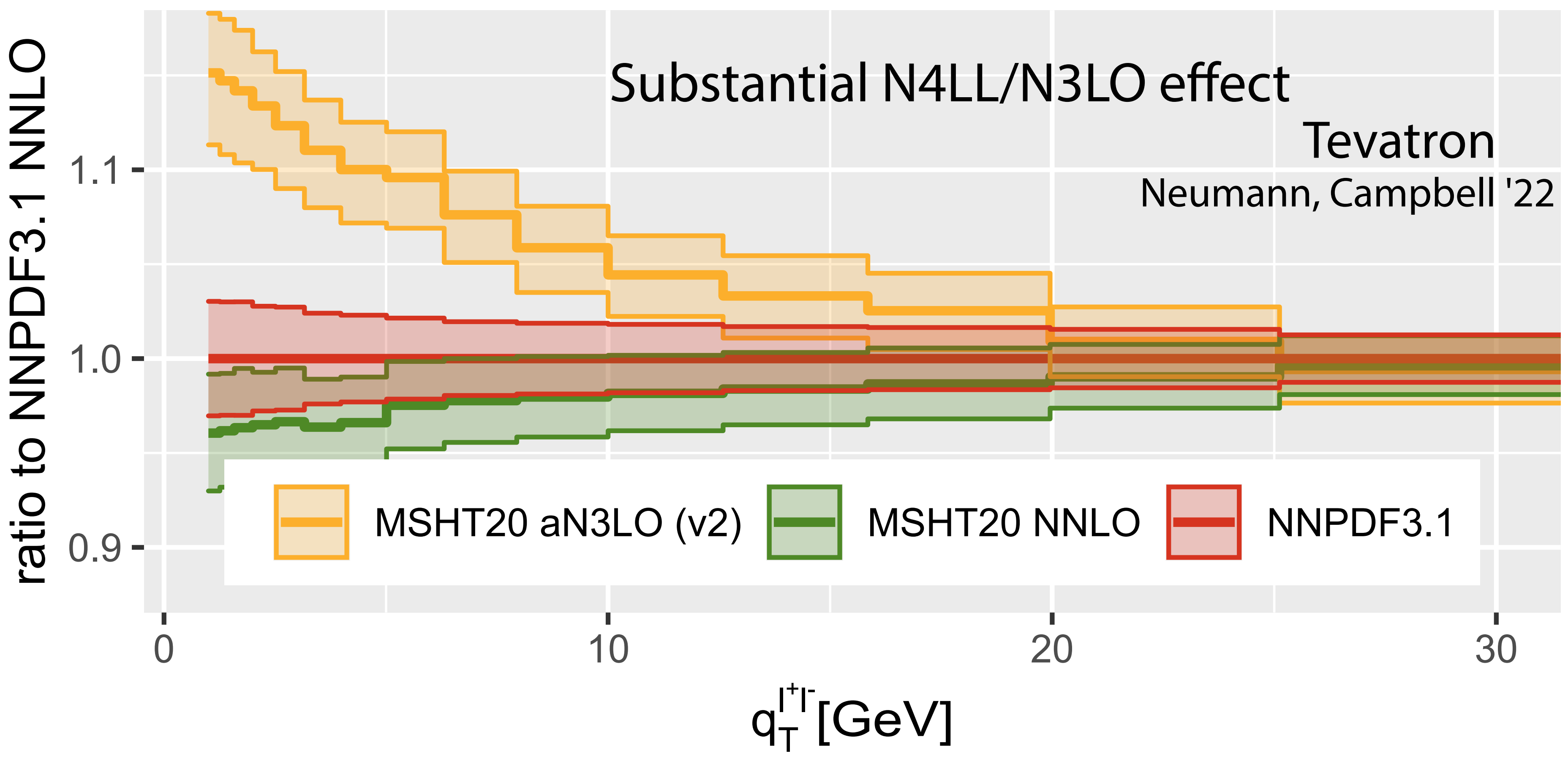
Why can we use a 5 GeV cutoff for N^{3}LO q_T subtractions?

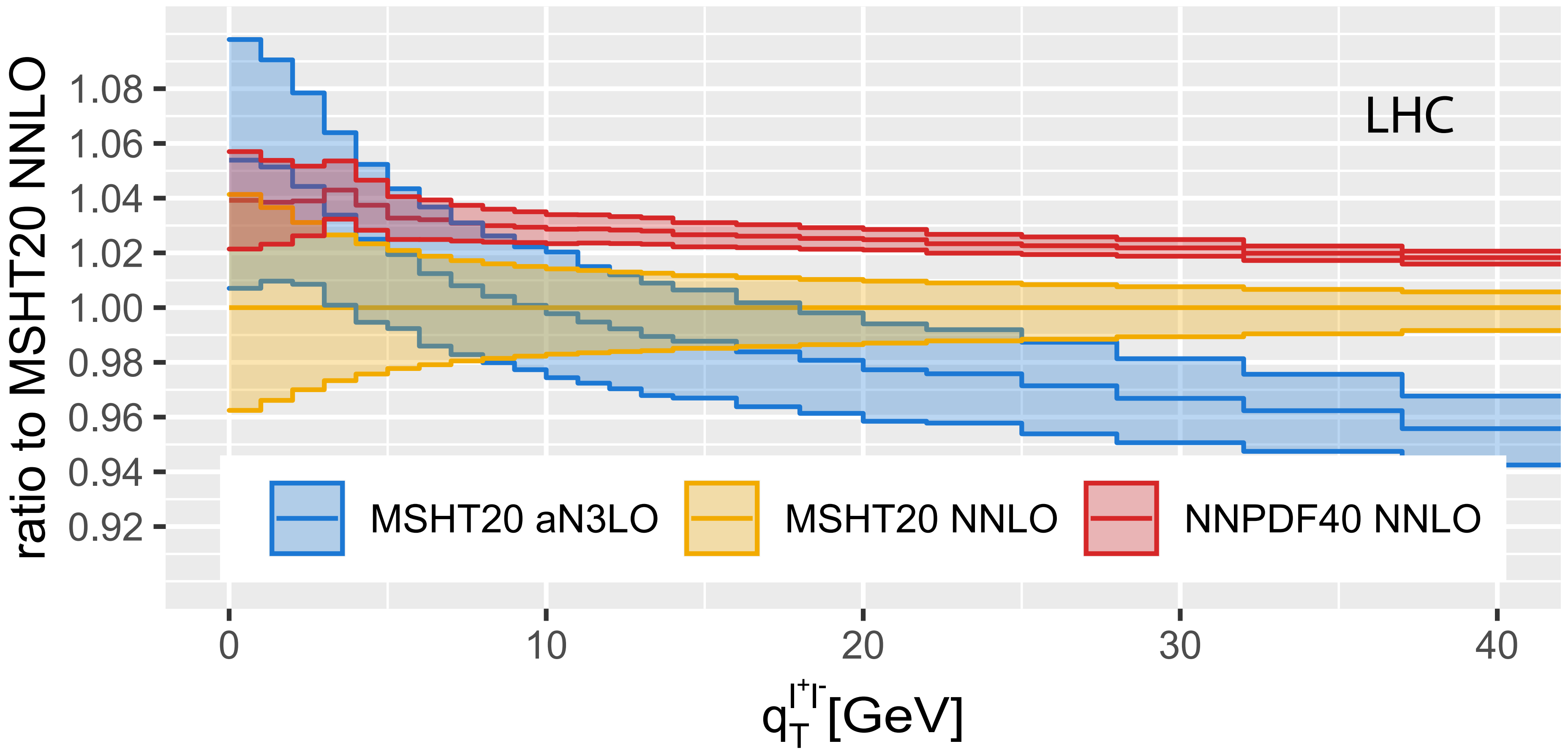


How about for the Tevatron (W-mass)...



This doesn't look too bad...


Substantial N4LL/N3LO effect
Tevatron
Neumann, Campbell '22
ratio to NNPDF3.1 NNLO
1.1
1.0
0.9
0
10
20
30
MSHT20 aN3LO (v2)
MSHT20 NNLO
NNPDF3.1
$q_T^{l^+l^-}$ [GeV]


LHC
ratio to MSHT20 NNLO
1.08
1.06
1.04
1.02
1.00
0.98
0.96
0.94
0.92
0
10
20
30
40
MSHT20 aN3LO
MSHT20 NNLO
NNPDF40 NNLO
$q_T^{l^+l^-}$ [GeV]

Non-perturbative effects

In the Becher, Neubert formalism (as implemented in CuTe-MCFM):

Enhanced non-perturbative effects through the collinear anomaly

Becher, Bell '13

$$(b_T^2 Q^2)^{-F_{ij}(b_T)}, F_{ij} \to F_{ij} + \Lambda^2_{\mathrm{NP,ij}} b_T^2$$

OPE analysis of NP power corrections; $\Lambda_{\mathrm{NP,ij}}$ has matrix-element definition

Typical b^* prescription is ad-hoc and intertwines perturbative and non-perturbative physics

$$f(x, b_T) \to f^{\mathrm{pert.}}(x, b^*(b_T)) F^{\mathrm{NP}}_{b^*}(b_T)$$

Typical choice

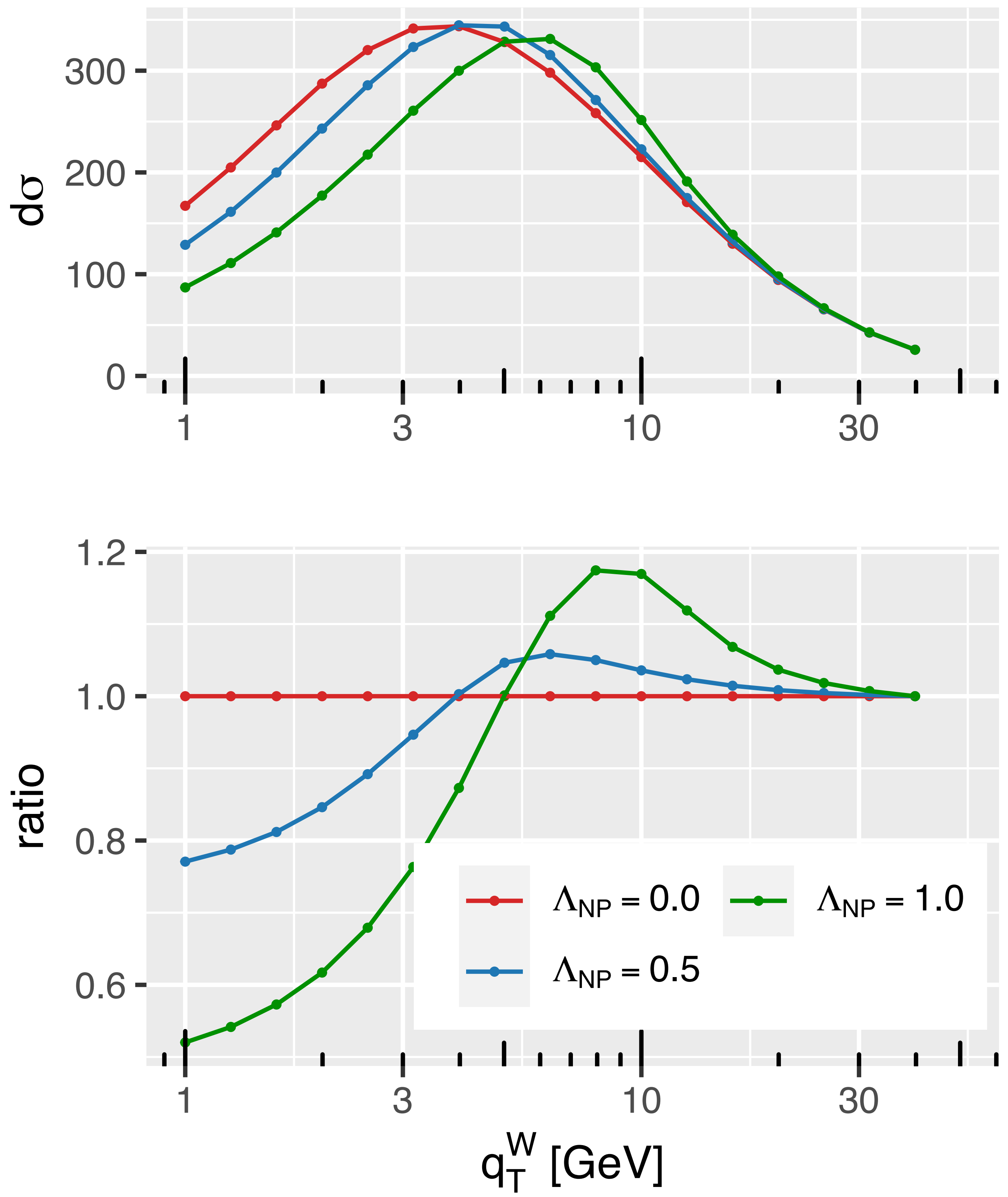
$$F^{\mathrm{NP}}_{b^*} \sim e^{-\Lambda^2 b_T^2}$$

Formalism to include non-perturbative OPE effects model-independently for b^* prescription:

Ebert, Michel, Stewart, Sun '22

Preliminary CuTe-MCFM results

to appear as Neumann, Campbell '23



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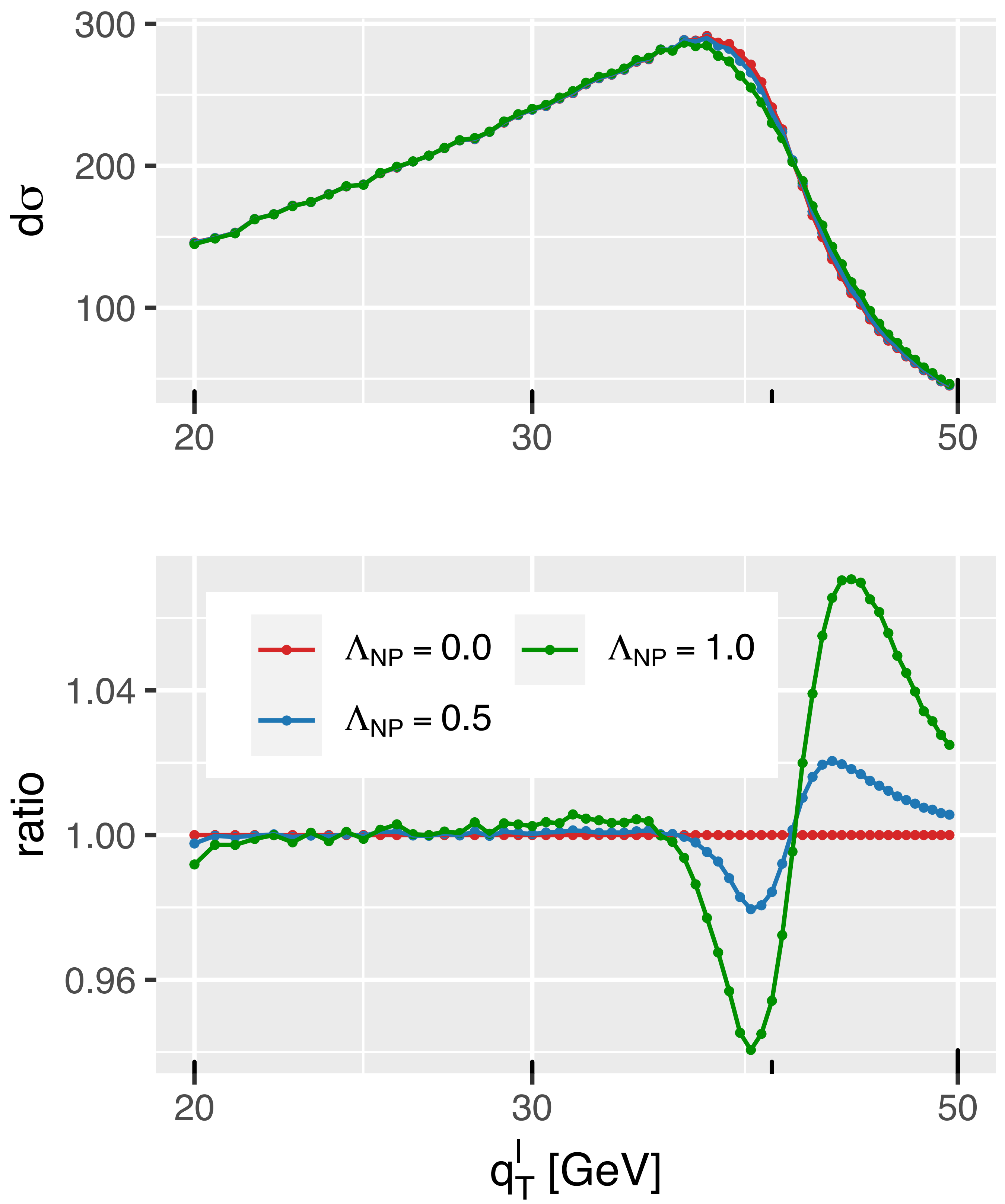

An α_s^3 + non-pert. + NLO EW event generator

- Differential grid in Z kinematics $\frac{\mathrm{d}\sigma}{\mathrm{d}y\mathrm{d}q_T\mathrm{d}Q}$ for Z polarisations

- At the level of α_s^3 in QCD (N^{3}LO+N^{4}LL$_p$) (+ possibly NLO EW)

- Decay Z using Photos (resummed QED FSR)
  Golonka, Was '06

- $\rightarrow$ Generate events based on generated probability grid

Is there a place for this?

Outlook

- Hadronic SM W-mass measurement is complex!
- Decades of work ahead (to squeeze out 10 MeV in less data driven way)
- We need to aim for public and reliable pipelines:
  - on both the theory side
  - and the experimental analysis side
- Theory: Combine higher-order QCD,EW effects, higher-order resummation, non-perturbative effects into a parton-shower MC
- Allow for higher-order tuning, less guesstimating and to increase universality of tuning

I am working on making CuTe-MCFM more useful for this