LHC powered by factorization: some resummation and some fixed-order QCD

Tobias Neumann, BNL

April 22nd, 2021

Factorization

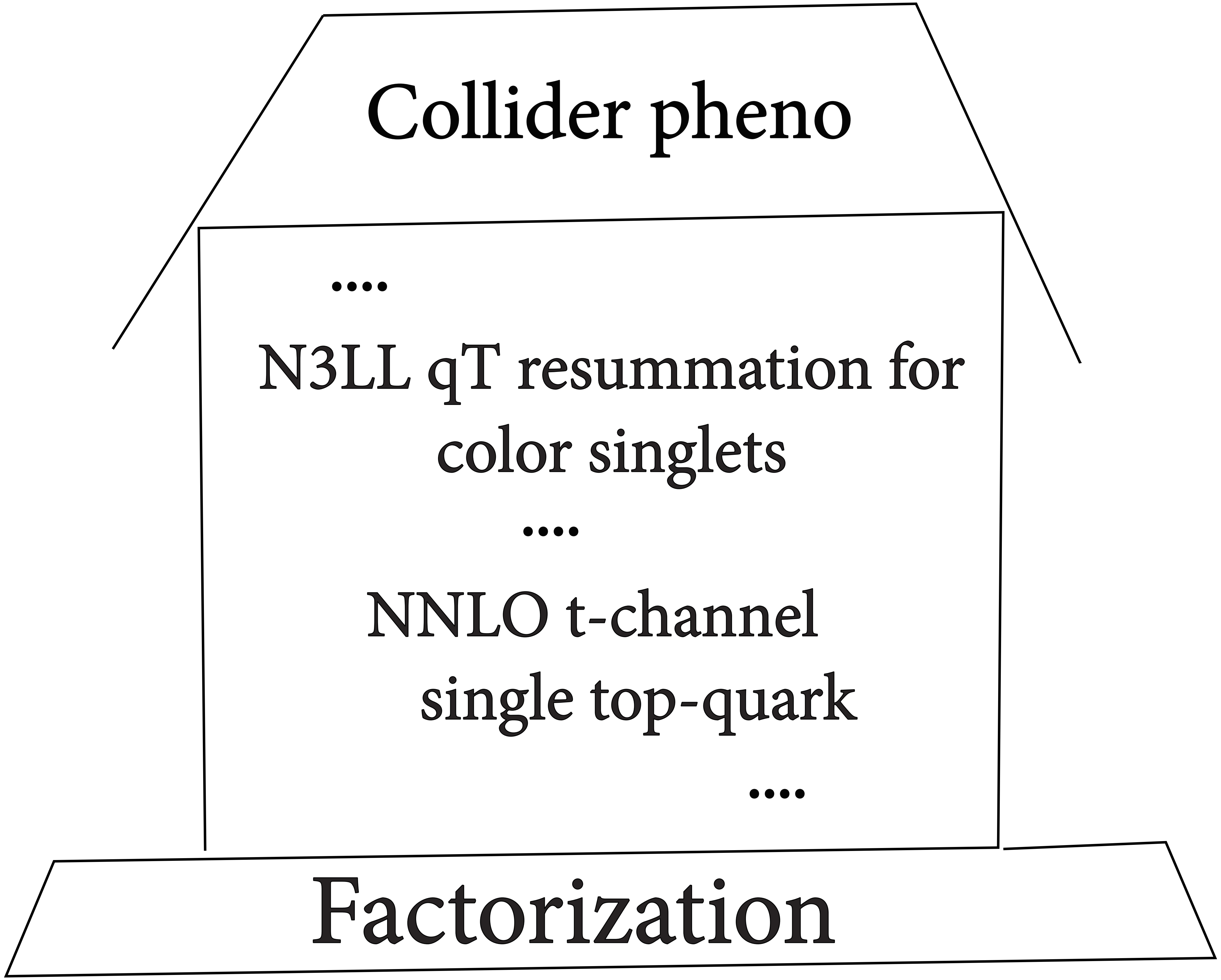
Loops & Legs

RGE

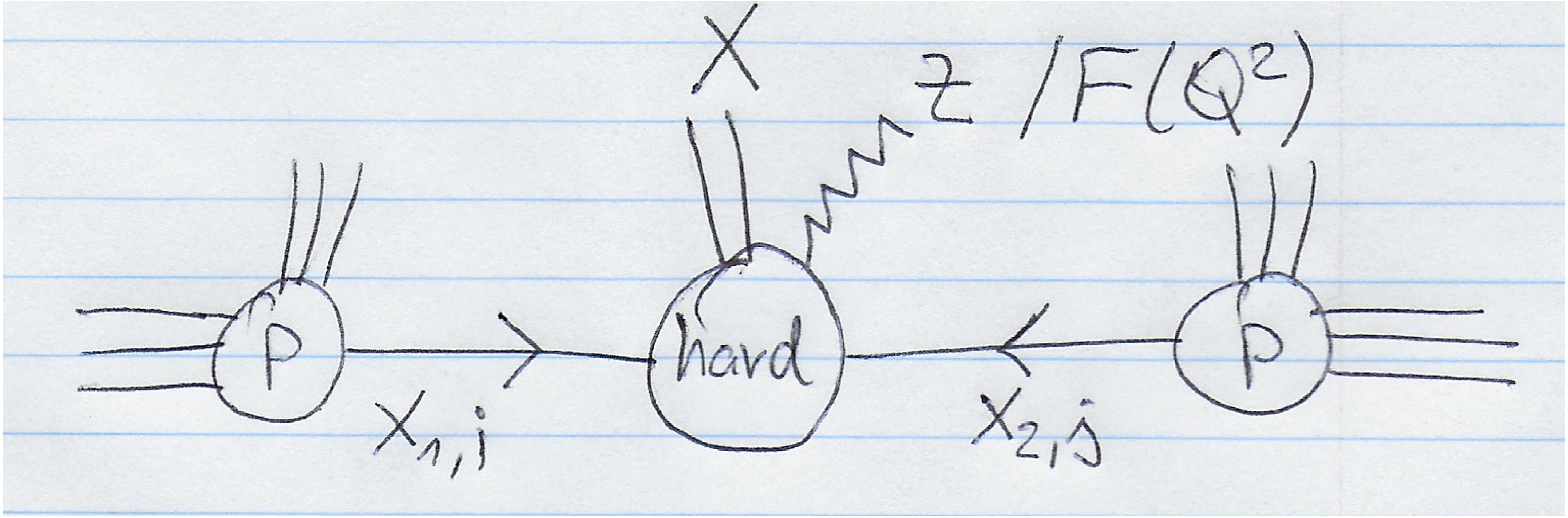
PDF's,

α_s

EFT


Collider pheno
....
N3LL qT resummation for color singlets
....
NNLO t-channel single top-quark
....
Factorization

$$\sigma_{i,j} = f_i(x_i, \mu_F) \otimes f_j(x_j, \mu_F) \otimes \sigma^H_{i,j}(\mu_R, \mu_F, \vec{p}) + \mathcal{O}(\Lambda_{\mathrm{QCD}}$$



$$\sigma_{i,j} = \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_a(x_i, \mu_F) f_b(x_j, \mu_F) \cdot \sigma_{i,j}^{H}(\mu_R, \mu_F, \vec{p})$$

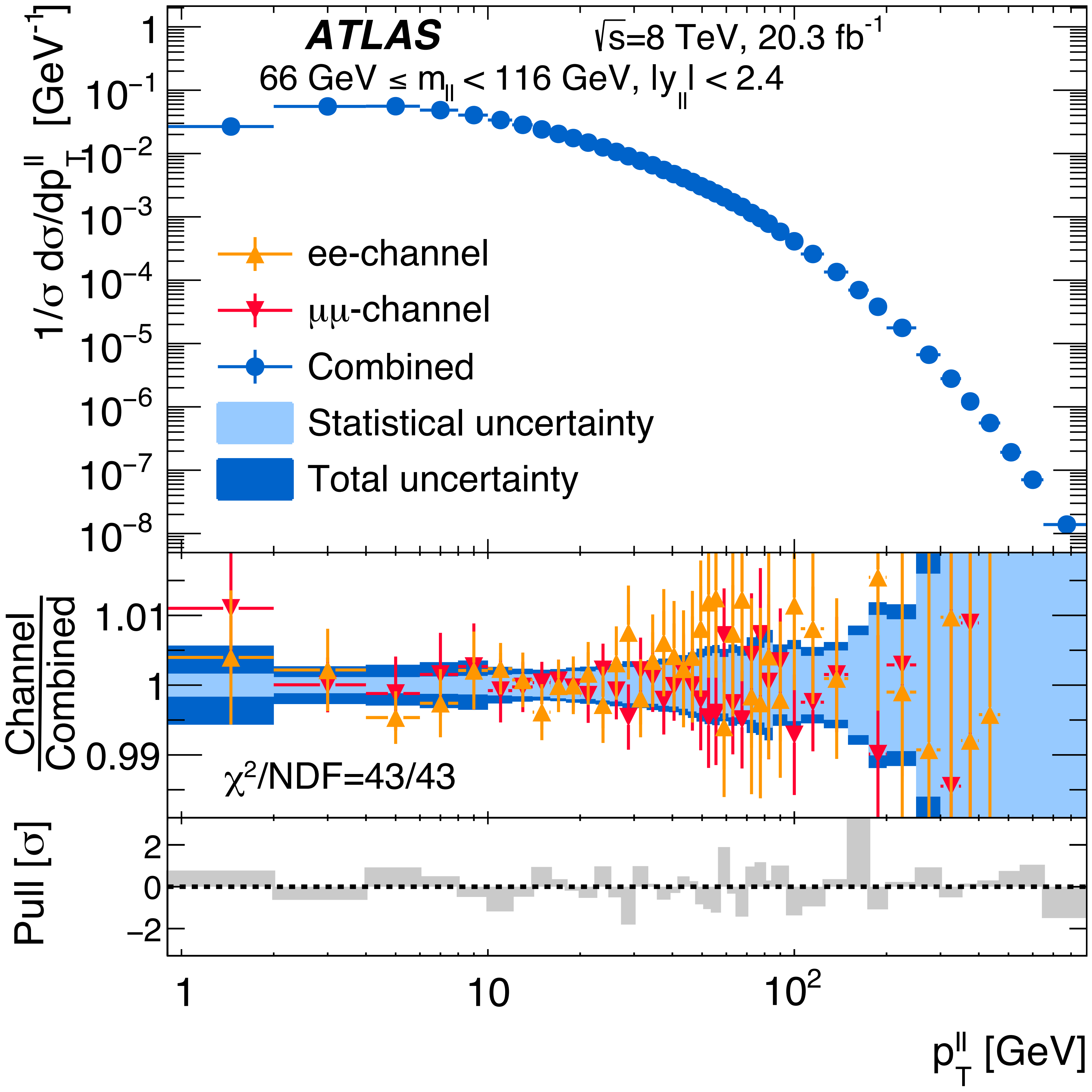
transverse dependence

$$\sigma_{i,j} = \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_i(x_i, \mu_F) f_j(x_j, \mu_F) \cdot \sigma^H_{i,j}(\mu_R, \mu_F, \vec{p})$$

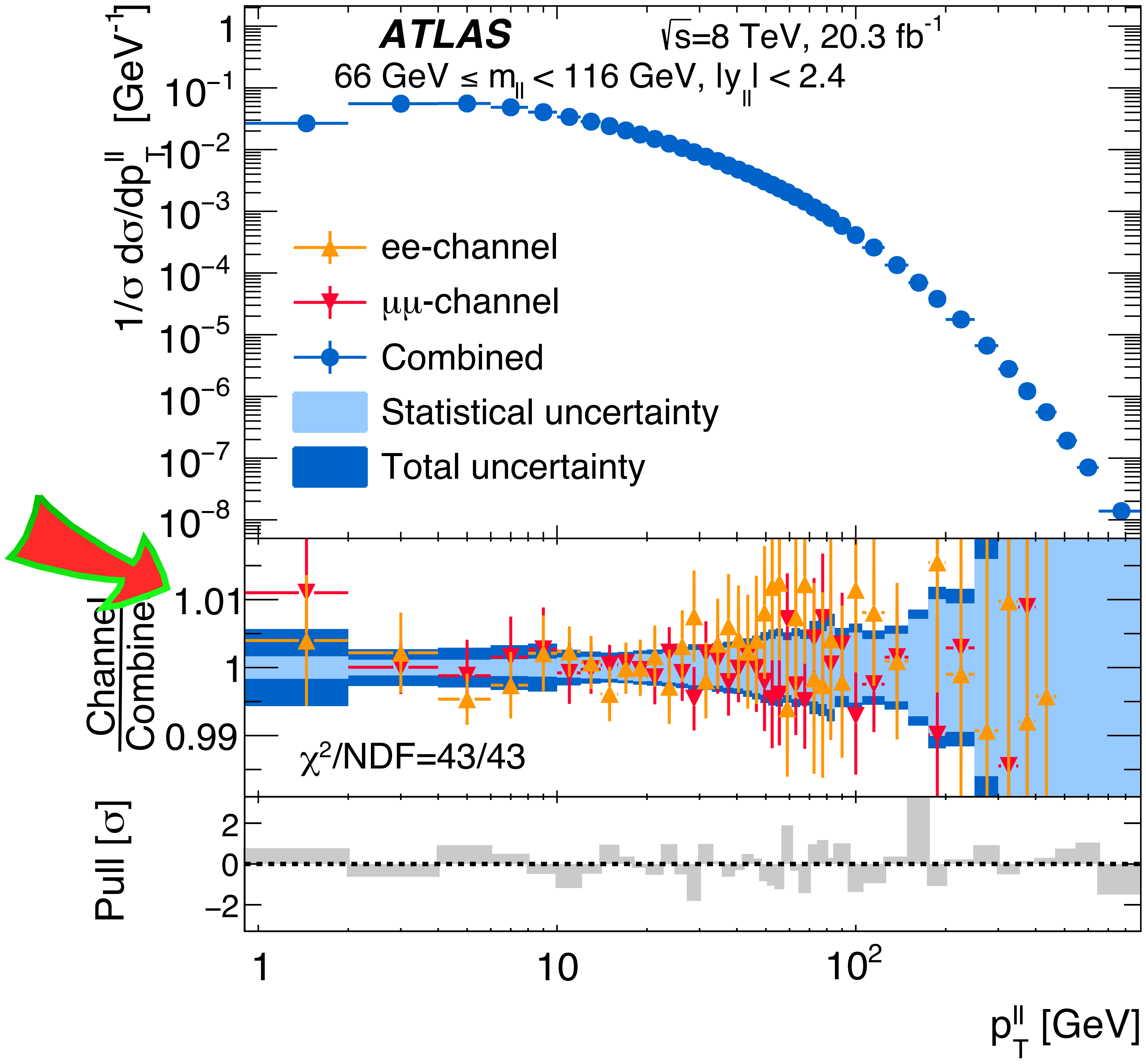
transverse dependence

spin dependence

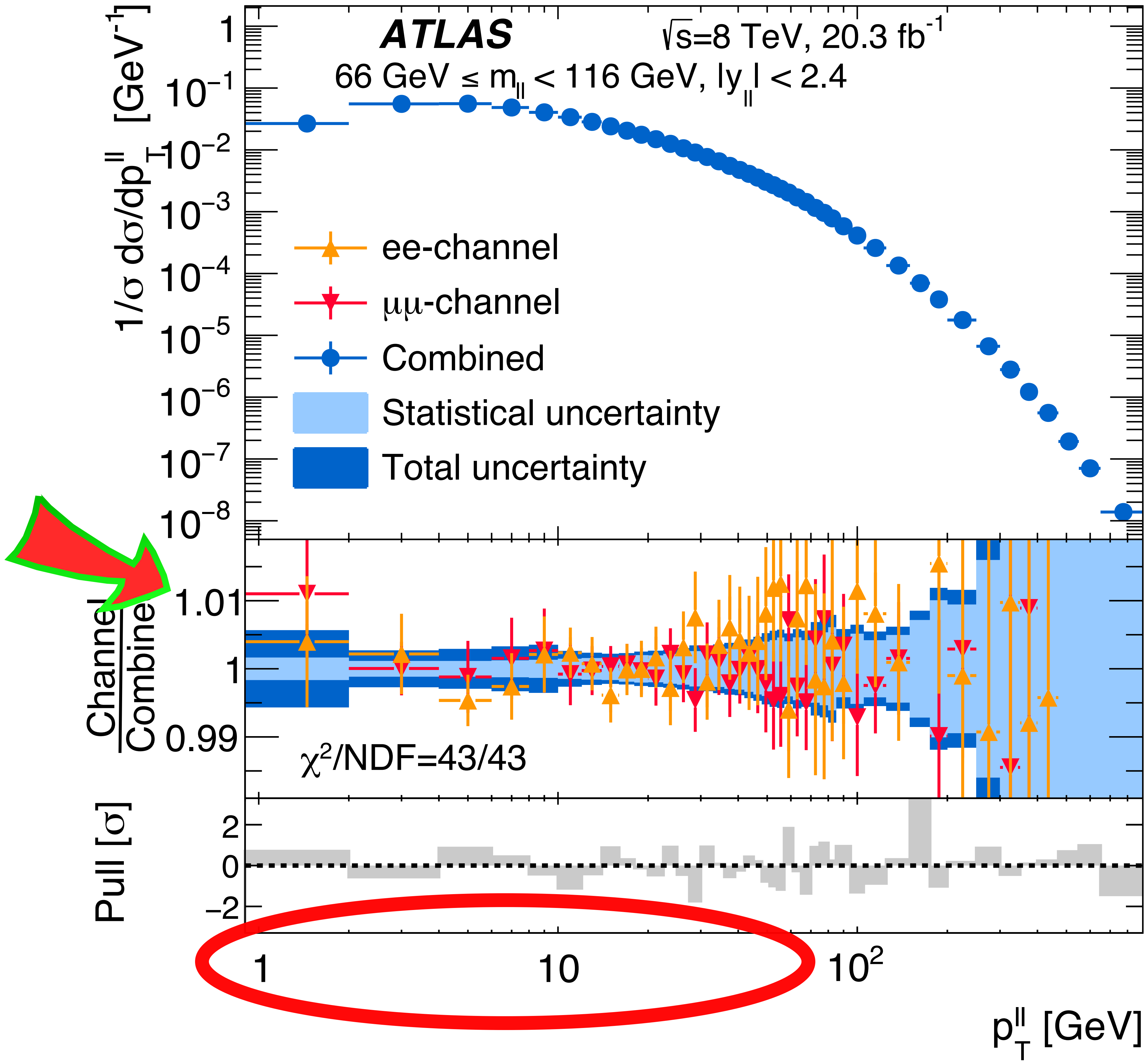
Why q_T resummation?

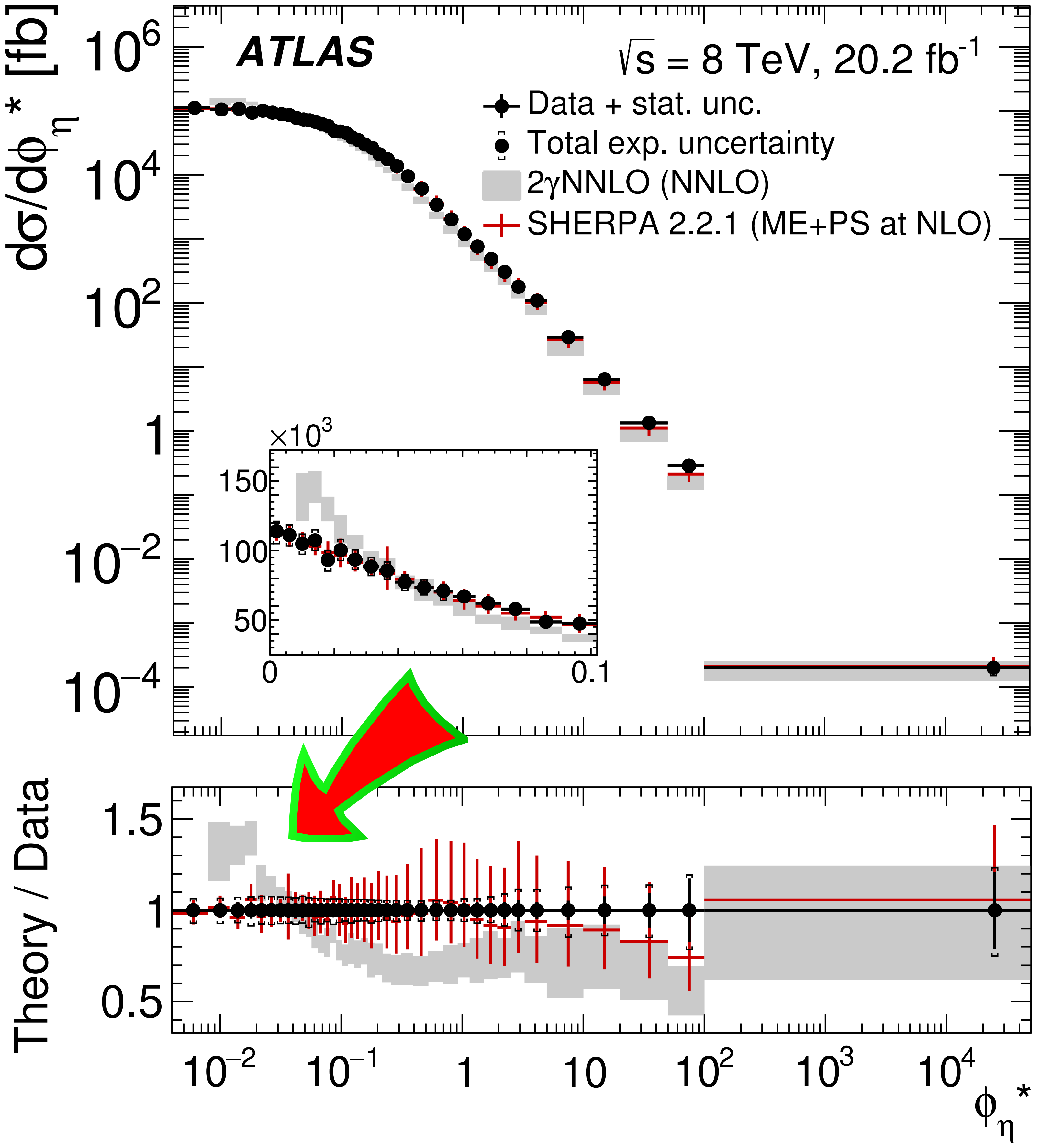


ATLAS
√s=8 TeV, 20.3 fb⁻¹
66 GeV ≤ m_ll < 116 GeV, |y_ll| < 2.4
ee-channel
μμ-channel
Combined
Statistical uncertainty
Total uncertainty
1/σ dσ/dp_T^ll [GeV⁻¹]
Channel / Combined
χ²/NDF=43/43
Pull [σ]
p_T^ll [GeV]

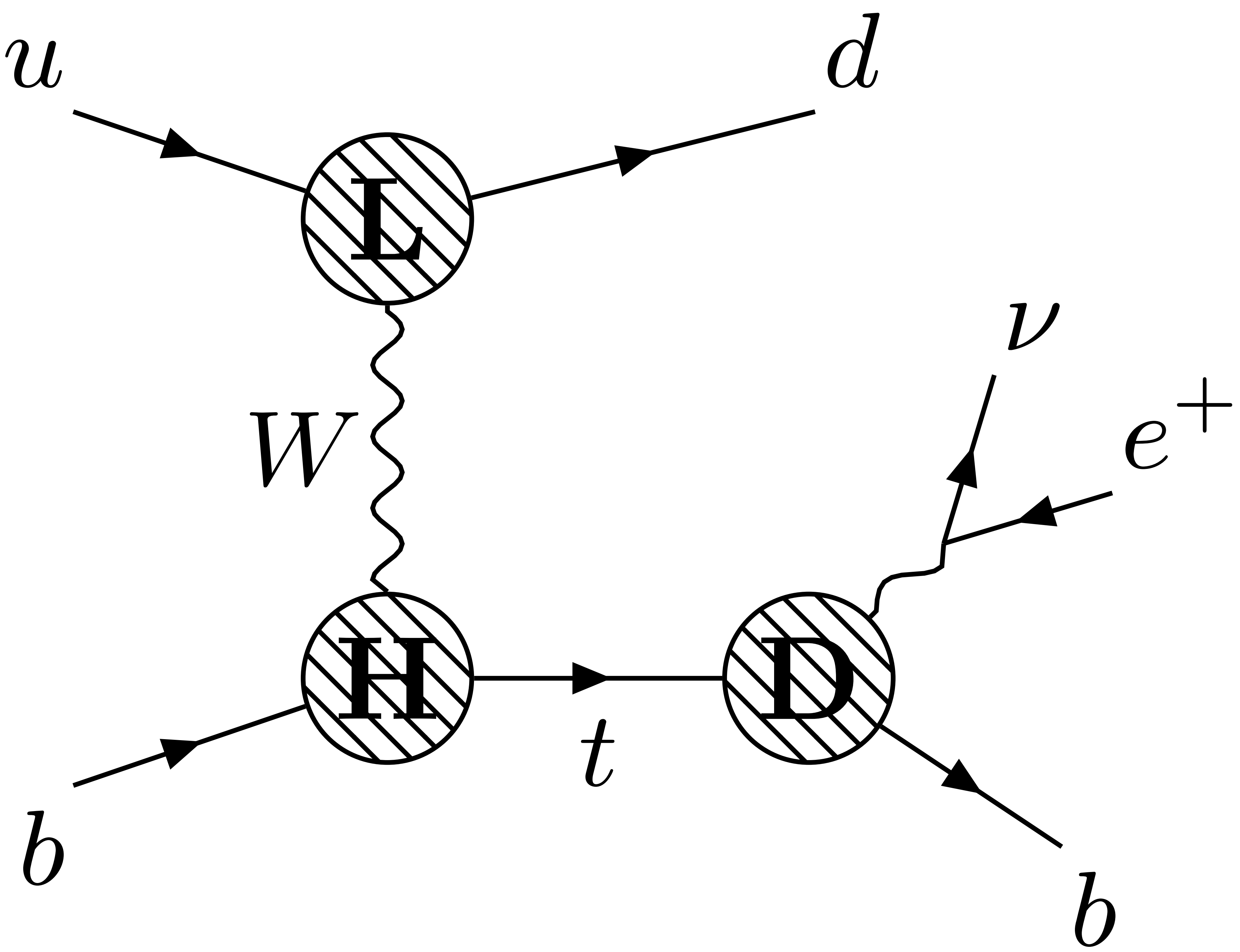


ATLAS
√s=8 TeV, 20.3 fb-1
66 GeV ≤ mll < 116 GeV, |yll| < 2.4
ee-channel
μμ-channel
Combined
Statistical uncertainty
Total uncertainty
1/σ dσ/dpTll [GeV-1]
Channel/Combined
χ2/NDF=43/43
Pull [σ]
pTll [GeV]


ATLAS
√s=8 TeV, 20.3 fb-1
66 GeV ≤ mll < 116 GeV, |yll| < 2.4
ee-channel
μμ-channel
Combined
Statistical uncertainty
Total uncertainty
1/σ dσ/dpTll [GeV-1]
Channel / Combined
χ2/NDF=43/43
Pull [σ]
pTll [GeV]


ATLAS
√s = 8 TeV, 20.2 fb-1
Data + stat. unc.
Total exp. uncertainty
2γNNLO (NNLO)
SHERPA 2.2.1 (ME+PS at NLO)
dσ/dφη* [fb]
Theory / Data
φη*

Why t-channel single-top-quark?



> *"We found a difference of ~1% on the NNLO cross sections. [...] It has not been possible to further pin down the differences"*
>
> *— Berger, Gao, Zhu '07*

$$\sigma_{i,j} = \int \mathrm{d}x_1 \mathrm{d}x_2 \mathrm{f_i}(\mathrm{x_i}, \mu_\mathrm{F}) \mathrm{f_j}(\mathrm{x_j}, \mu_\mathrm{F}) \cdot \sigma_{i,j}^{H}(\mu_R, \mu_F, \vec{p})$$

$$\mathbf{f_i(x_i, \boldsymbol{\mu}_F) f_j(x_j, \boldsymbol{\mu}_F)}$$

Part 1

q_T resummation of color singlets at N^{3}LL+NNLO

q_T factorization from SCET

$$\mathrm{d}\sigma_{ij}(p_1, p_2, \{\underline{q}\}) = \int_0^1 \mathrm{d}\xi_1 \int_0^1 \mathrm{d}\xi_2\, \mathrm{d}\sigma^0_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\})\, \mathcal{H}_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}, \mu) \cdot$$
$$\frac{1}{4\pi} \int \mathrm{d}^2 x_\perp\, e^{-i q_\perp x_\perp} \left(\frac{x_T^2 Q^2}{b_0^2}\right)^{-F_{ij}(x_\perp, \mu)} B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu)$$

(Becher, Neubert '10; Becher, Neubert, Wilhelm '11 '12), (Mantry, Petriello '09)

$$
\mathrm{d}\sigma_{ij}(p_1, p_2, \{\underline{q}\}) = \int_0^1 \mathrm{d}\xi_1 \int_0^1 \mathrm{d}\xi_2 \, \mathrm{d}\sigma^0_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}) \, \mathcal{H}_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}, \mu) \cdot
$$

$$
\frac{1}{4\pi} \int \mathrm{d}^2 x_\perp \, e^{-i q_\perp x_\perp} \left(\frac{x_T^2 Q^2}{b_0^2} \right)^{-F_{ij}(x_\perp, \mu)} B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu)
$$

$$
\mathrm{d}\sigma_{ij}(p_1, p_2, \{\underline{q}\}) = \int_0^1 \mathrm{d}\xi_1 \int_0^1 \mathrm{d}\xi_2 \, \mathrm{d}\sigma^0_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}) \, \mathcal{H}_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}, \mu) \cdot
$$

$$
\frac{1}{4\pi} \int \mathrm{d}^2 x_\perp \, e^{-i q_\perp x_\perp} \left(\frac{x_T^2 Q^2}{b_0^2} \right)^{-F_{ij}(x_\perp, \mu)} B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu)
$$

$$
\mathrm{d}\sigma_{ij}(p_1, p_2, \{\underline{q}\}) = \int_0^1 \mathrm{d}\xi_1 \int_0^1 \mathrm{d}\xi_2 \, \mathrm{d}\sigma^0_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}) \, \mathcal{H}_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}, \mu) \cdot
\frac{1}{4\pi} \int \mathrm{d}^2 x_\perp \, e^{-i q_\perp x_\perp} \left(\frac{x_T^2 Q^2}{b_0^2} \right)^{-F_{ij}(x_\perp, \mu)} B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu)
$$

Collinear anomaly

Becher, Neubert '10, 11

$$\mathrm{d}\sigma_{ij}(p_1, p_2, \{\underline{q}\}) = \int_0^1 \mathrm{d}\xi_1 \int_0^1 \mathrm{d}\xi_2 \, \mathrm{d}\sigma^0_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}) \, \mathcal{H}_{ij}(\xi_1 p_1, \xi_2 p_2, \{\underline{q}\}, \mu) \cdot$$

$$\frac{1}{4\pi} \int \mathrm{d}^2 x_\perp \, e^{-i q_\perp x_\perp} \left(\frac{x_T^2 Q^2}{b_0^2} \right)^{-F_{ij}(x_\perp, \mu)} B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu)$$

Rapidity anomalous dimension

$$\boldsymbol{\sigma \sim H \otimes B \otimes B + \mathcal{O}(q_T/Q)}$$

$$\frac{d}{d\ln\mu} C_V(-q^2,\mu) = \left[\Gamma^F_{\rm cusp}(a_s)\,\ln\frac{-q^2}{\mu^2} + 2\gamma^q(a_s)\right] C_V(-q^2,\mu)\,, \tag{5}$$

$$\frac{d}{d\ln\mu} F_{q\bar{q}}(L_\perp, a_s) = 2\Gamma^F_{\rm cusp}(a_s) \tag{6}$$

$$\frac{d}{d\ln\mu} I_{q\leftarrow i}(z, L_\perp, a_s) = \left[\Gamma^F_{\rm cusp}(a_s)\, L_\perp - 2\gamma^q(a_s)\right] I_{q\leftarrow i}(z, L_\perp, a_s) - \sum_j \int_z^1 \frac{du}{u}\, I_{q\leftarrow j}(u, L_\perp, a_s)\, \mathcal{P}_{j\leftarrow i}(z/u, a_s)\,, \tag{7}$$

(Becher, Neubert '06 '10 '11)

Three and four loop ingredients have been published in the past 2-3 years.

Thank you MPI (Henn, Korchemsky, Mistlberger '19; Manteuffel, Panzer, Schabinger '20)
(also for NNLO beamfunctions)

CuTe-MCFM

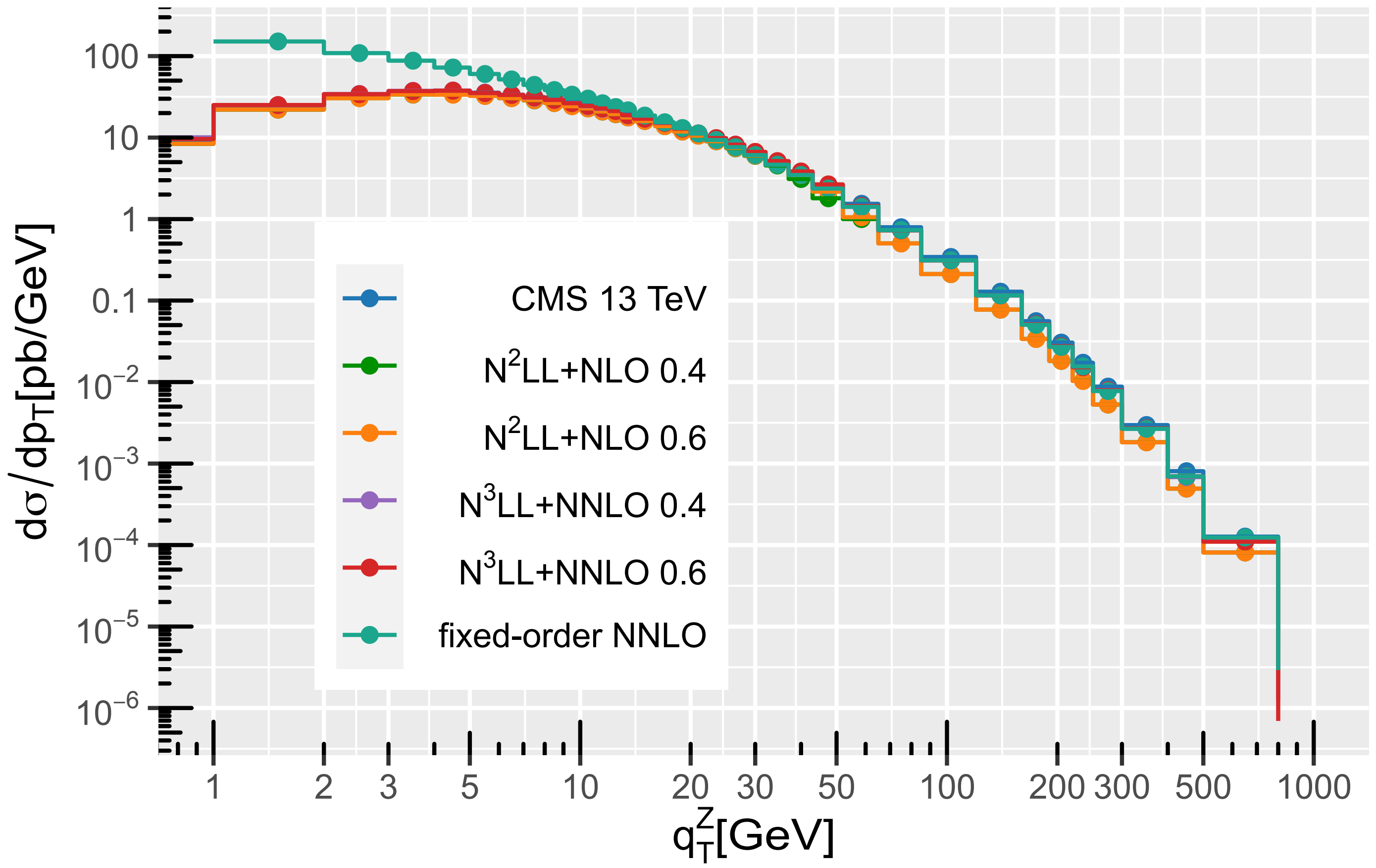
$=$

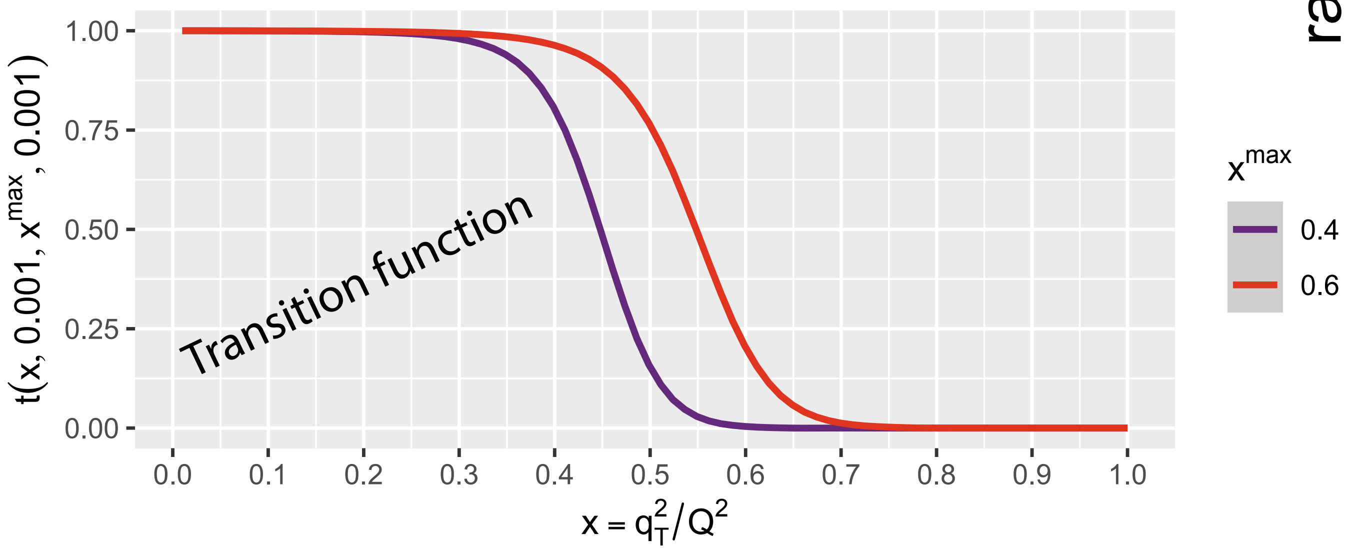
fixed-order MCFM + SCET-based N^{3}LL resummation framework

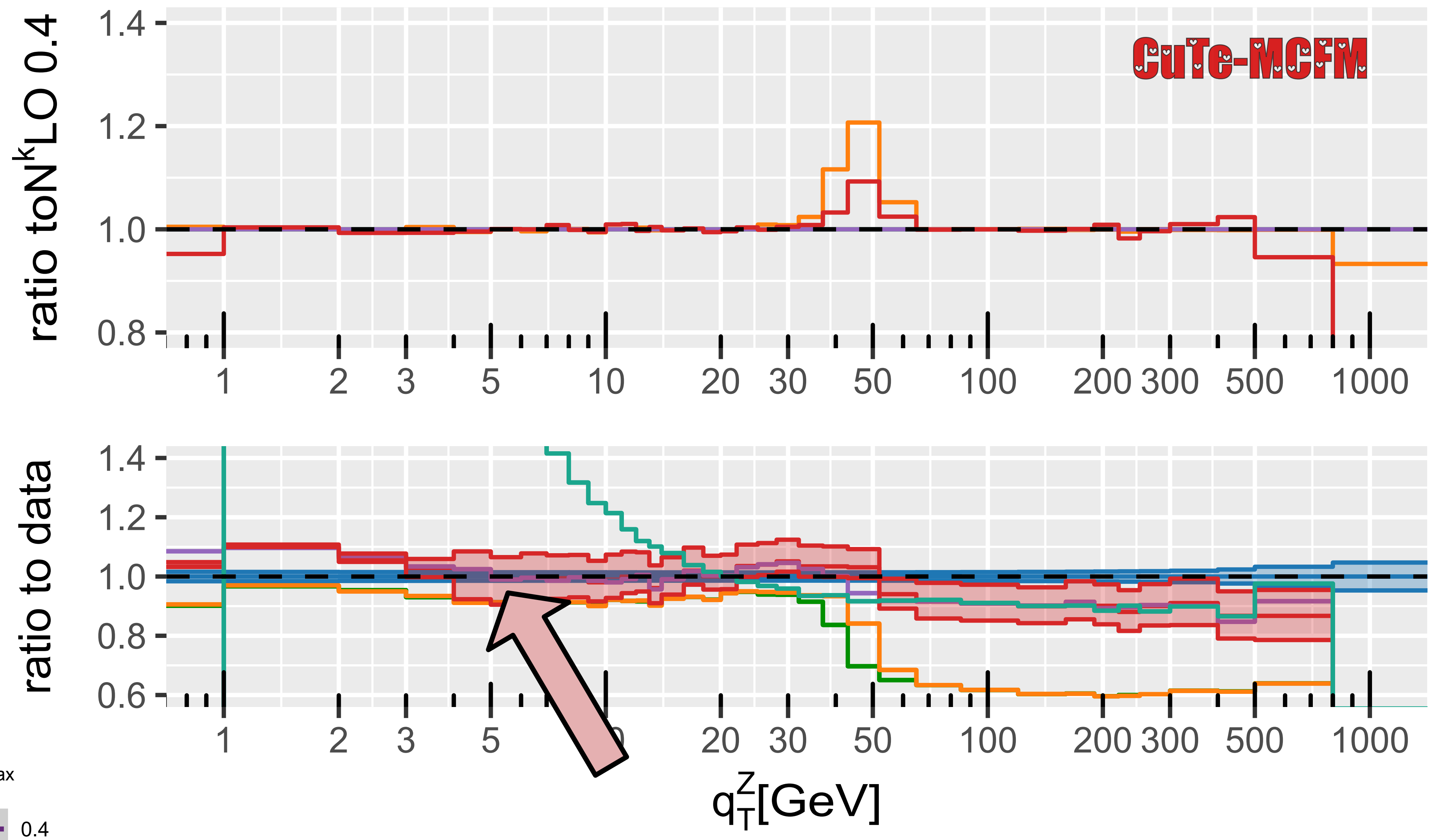
$$W^\pm, Z, H,\ \gamma\gamma, Z\gamma, ZH, W^\pm H$$

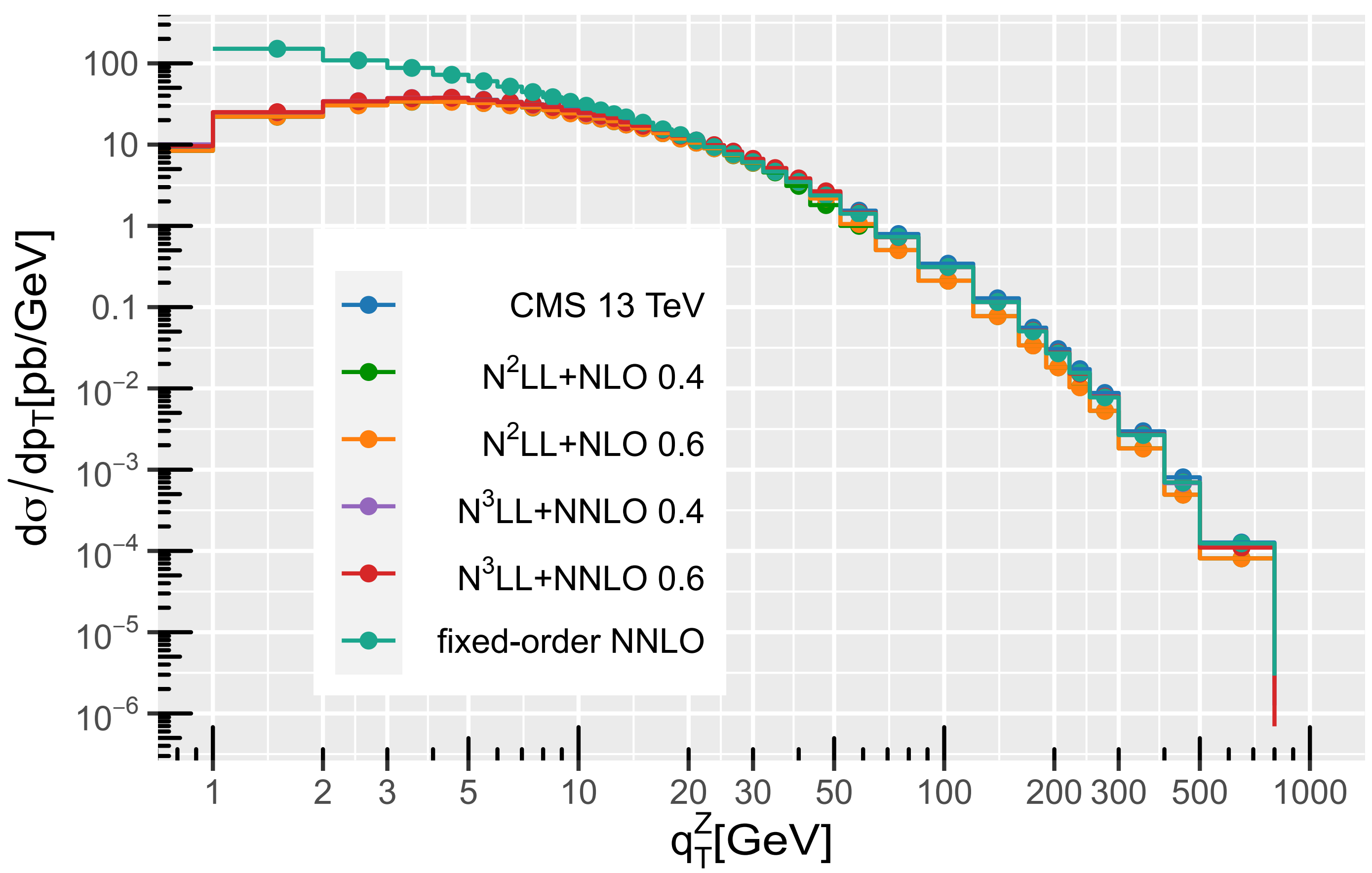
@ N^{3}LL+NNLO

with Thomas Becher

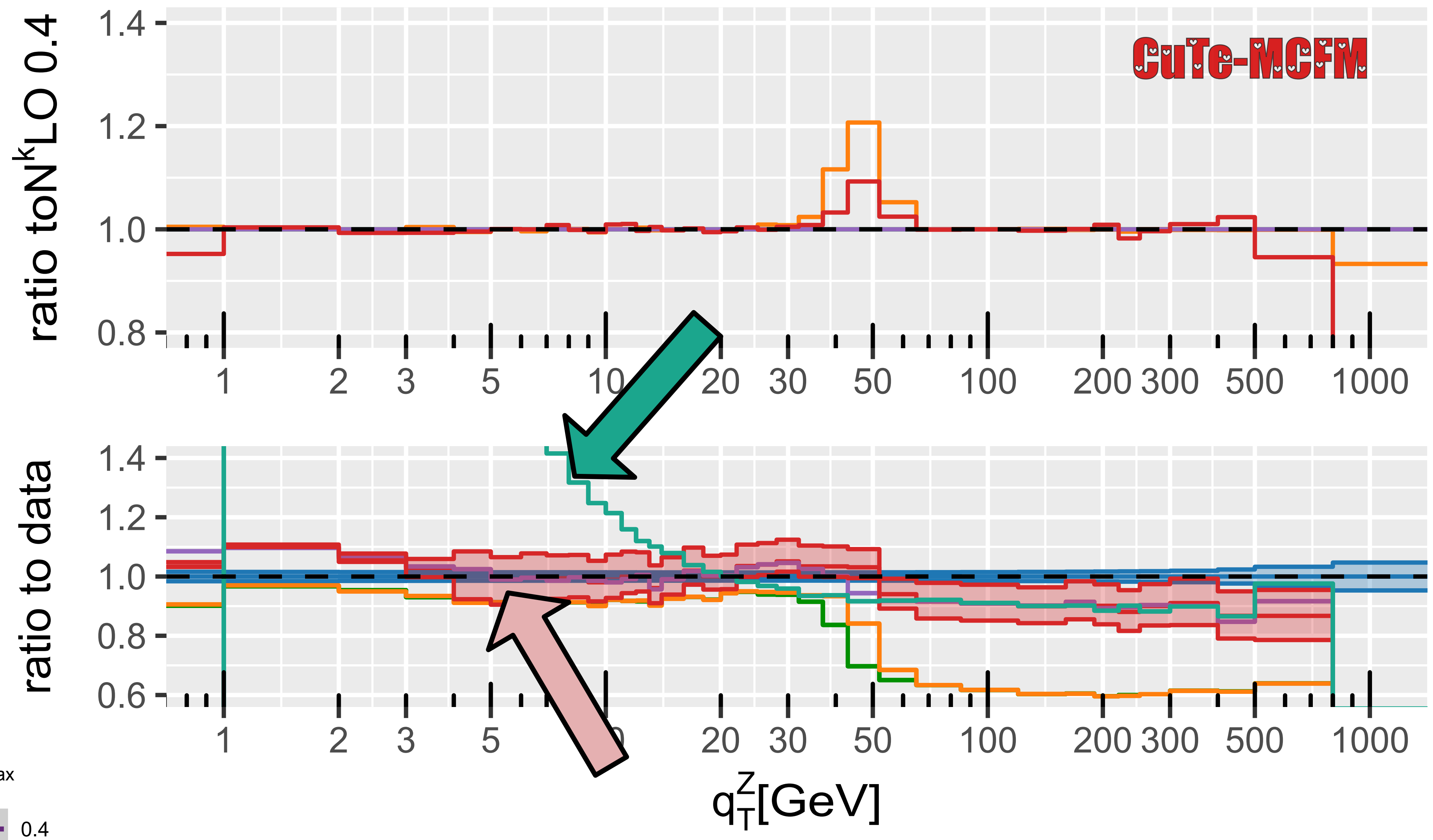

CMS 13 TeV
N2LL+NLO 0.4
N2LL+NLO 0.6
N3LL+NNLO 0.4
N3LL+NNLO 0.6
fixed-order NNLO
dσ/dpT[pb/GeV]
qTZ[GeV]


Transition function
t(x, 0.001, xmax, 0.001)
x = qT2/Q2
xmax
0.4
0.6

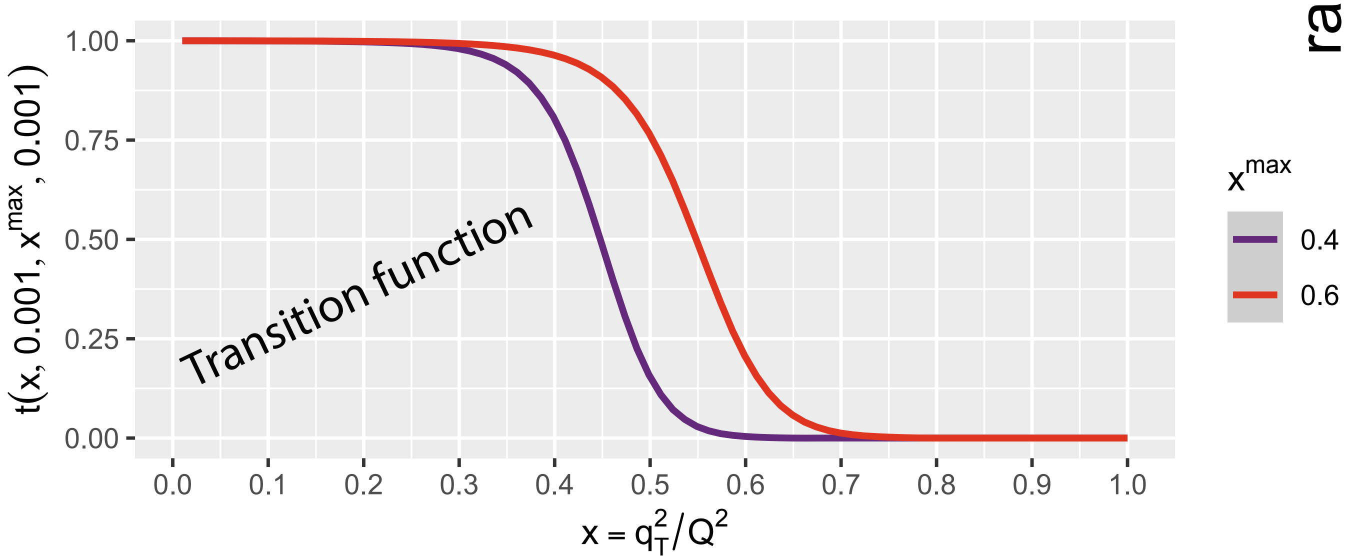

CuTe-MCFM
ratio toNkLO 0.4
ratio to data
qTZ[GeV]



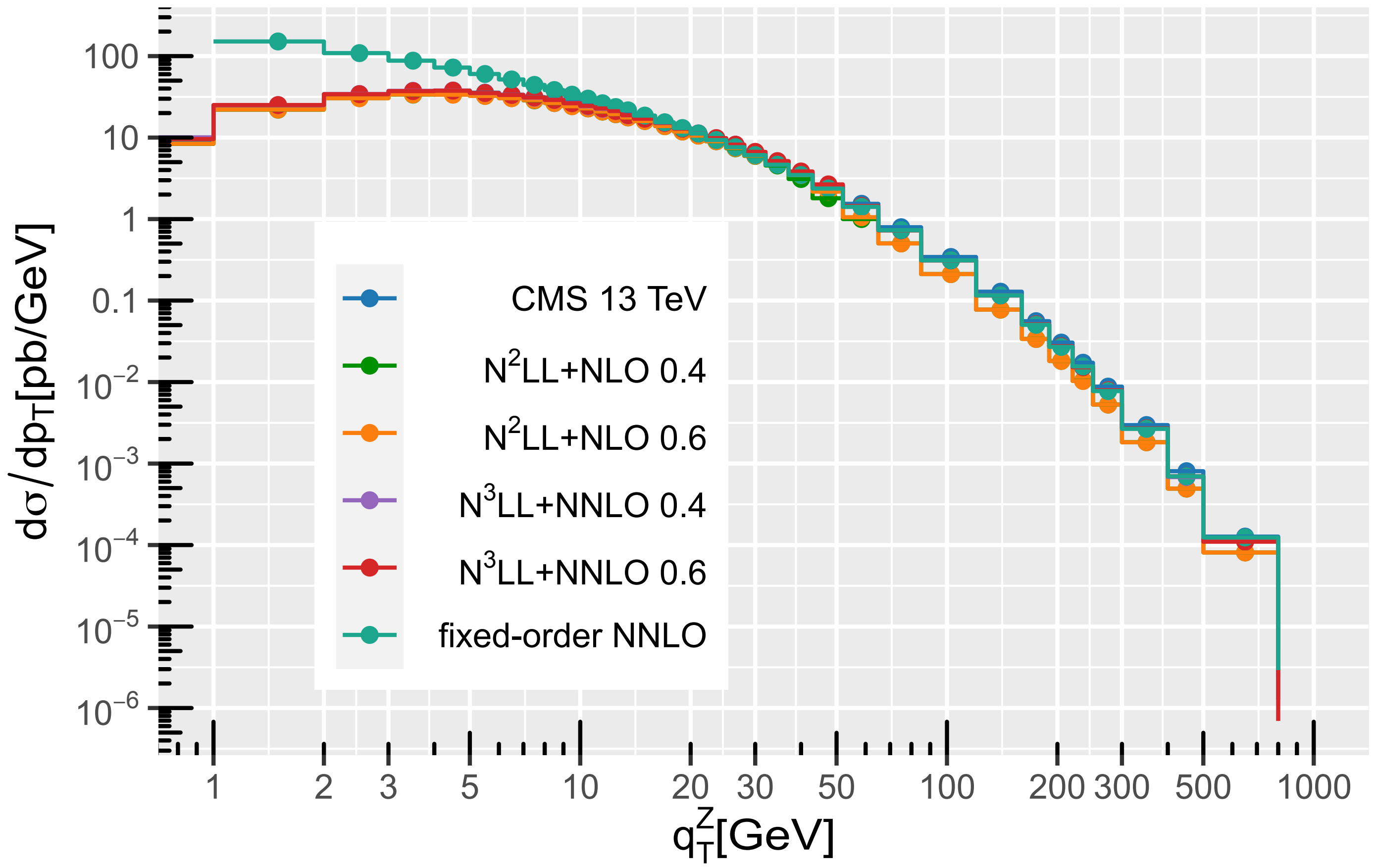
CMS 13 TeV
N²LL+NLO 0.4
N²LL+NLO 0.6
N³LL+NNLO 0.4
N³LL+NNLO 0.6
fixed-order NNLO
dσ/dp_T[pb/GeV]
q_T^Z[GeV]



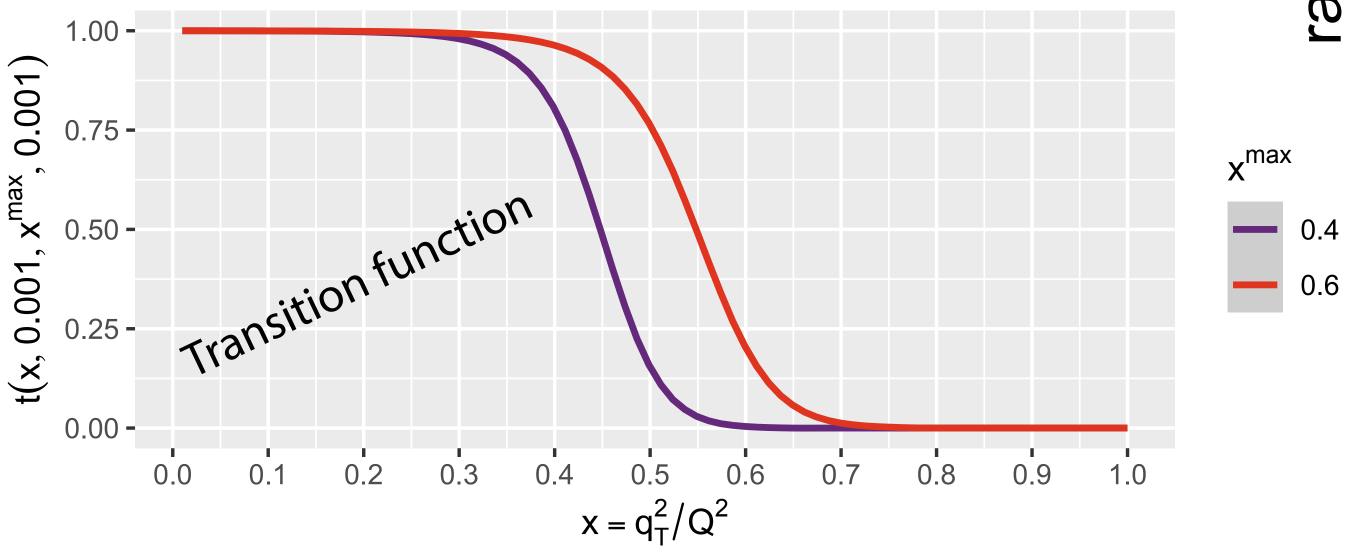
CuTe-MCFM
ratio to N^kLO 0.4
ratio to data
q_T^Z[GeV]



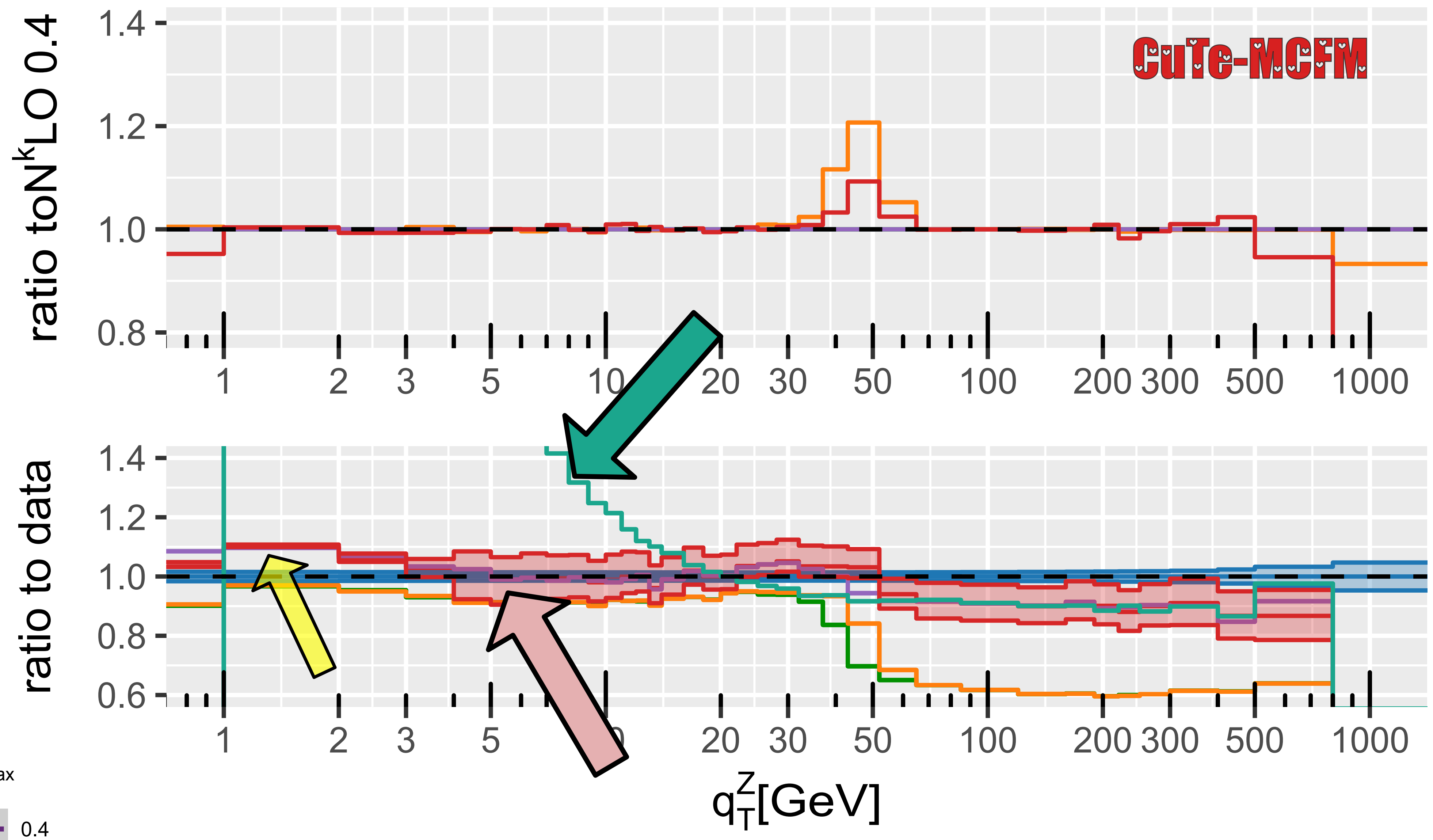
Transition function
t(x, 0.001, x^max, 0.001)
x = q_T^2/Q^2
x^max
0.4
0.6



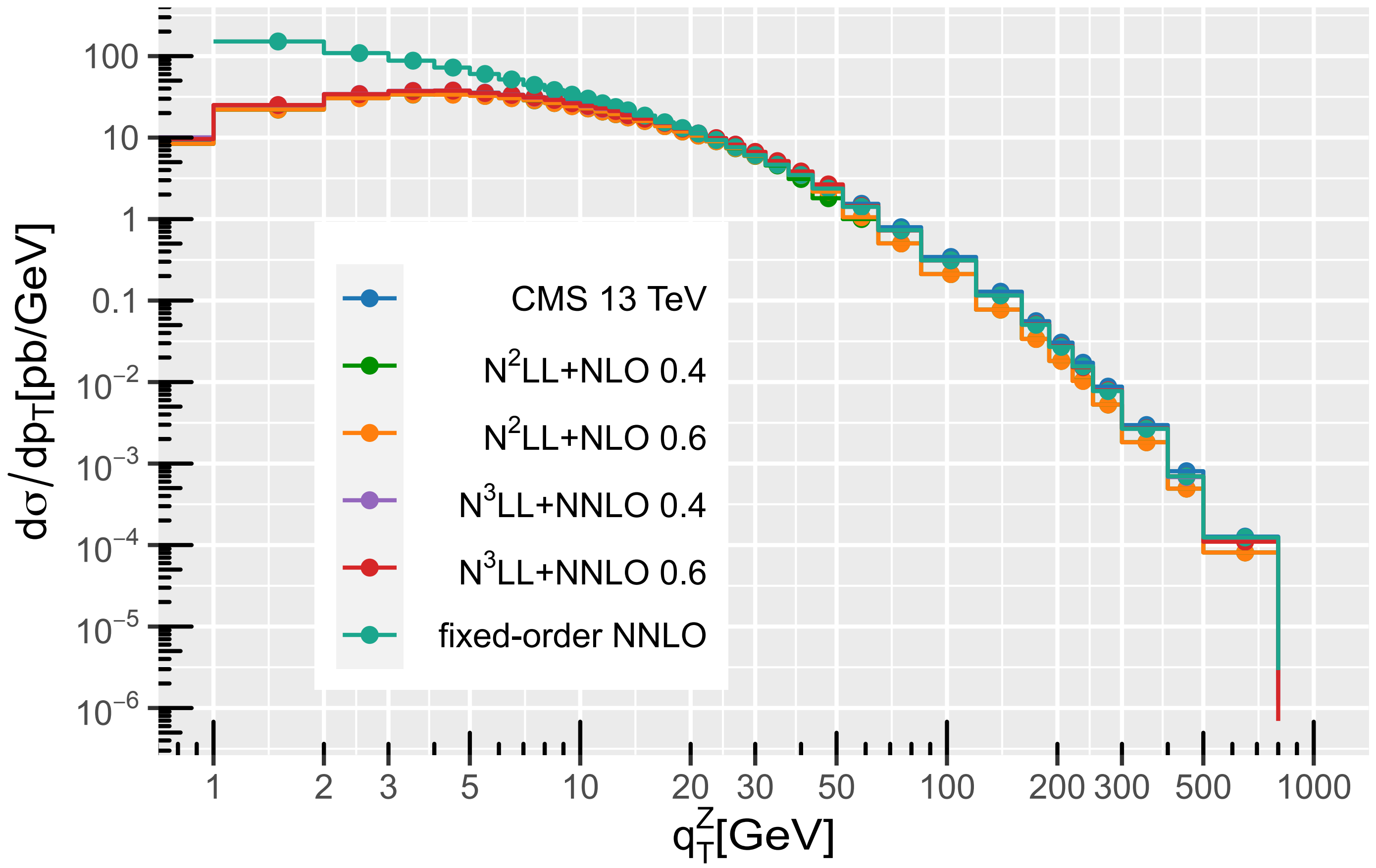
CMS 13 TeV
N²LL+NLO 0.4
N²LL+NLO 0.6
N³LL+NNLO 0.4
N³LL+NNLO 0.6
fixed-order NNLO
dσ/dp_T[pb/GeV]
q_T^Z[GeV]



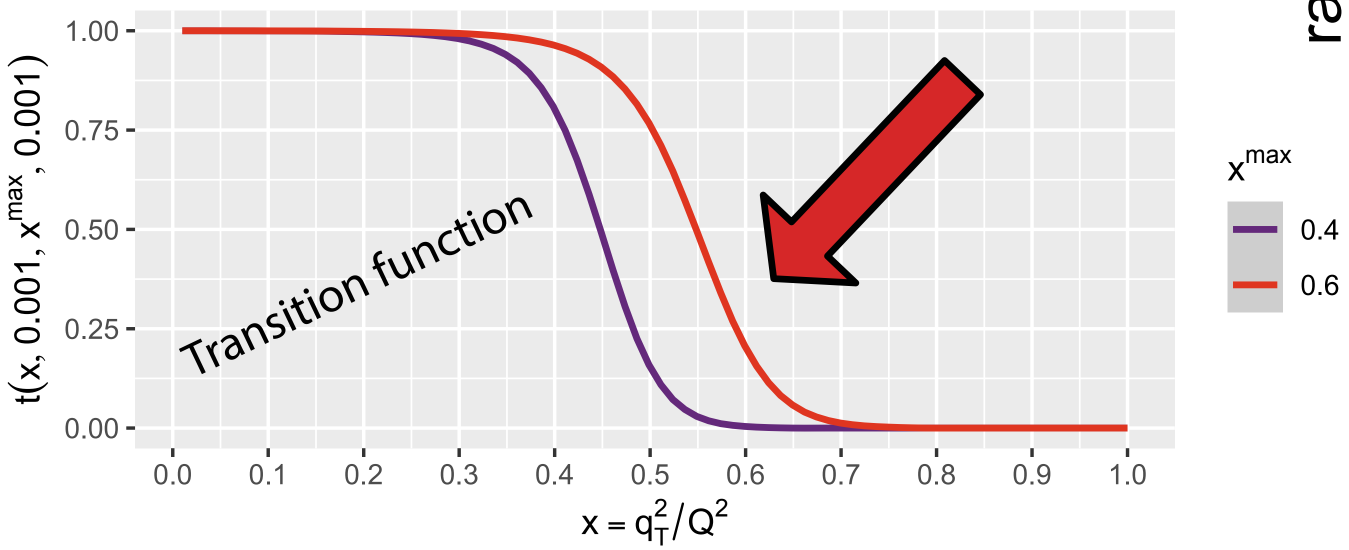
Transition function
t(x, 0.001, x^max, 0.001)
x = q_T^2/Q^2
x^max
0.4
0.6



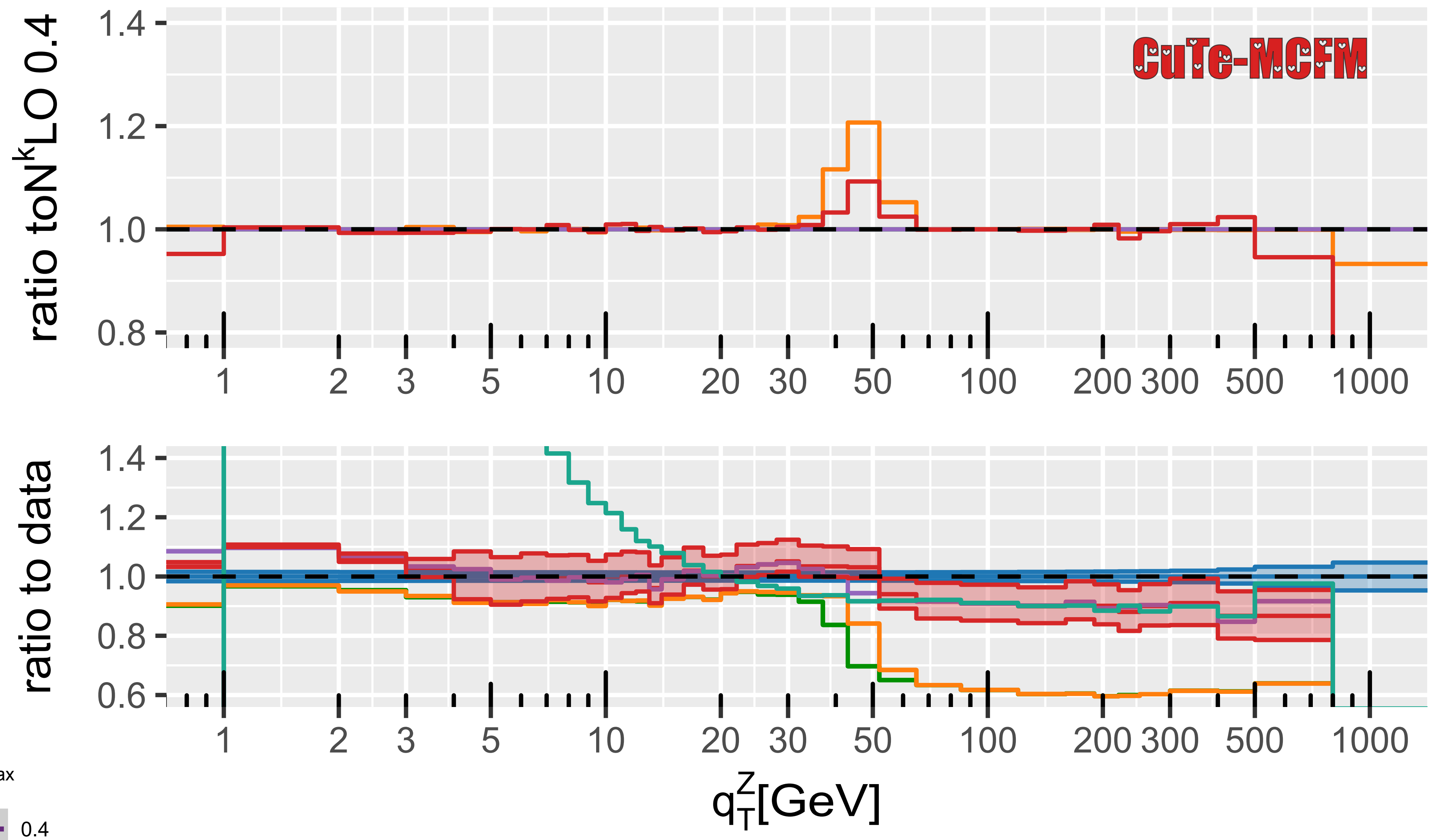
CuTe-MCFM
ratio to N^kLO 0.4
ratio to data
q_T^Z[GeV]



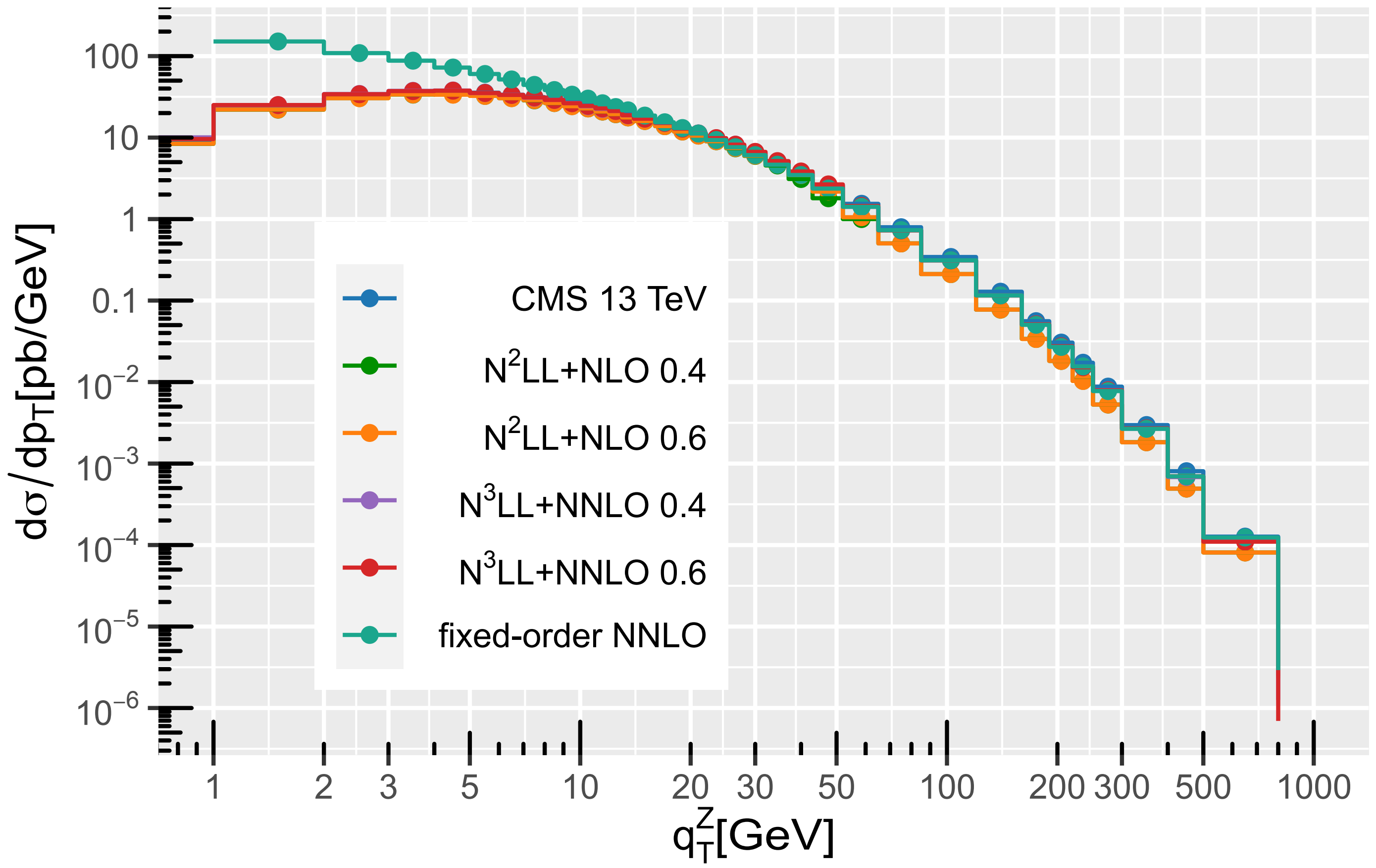
$d\sigma/dp_T$[pb/GeV]
CMS 13 TeV
N^2LL+NLO 0.4
N^2LL+NLO 0.6
N^3LL+NNLO 0.4
N^3LL+NNLO 0.6
fixed-order NNLO
q_T^Z[GeV]

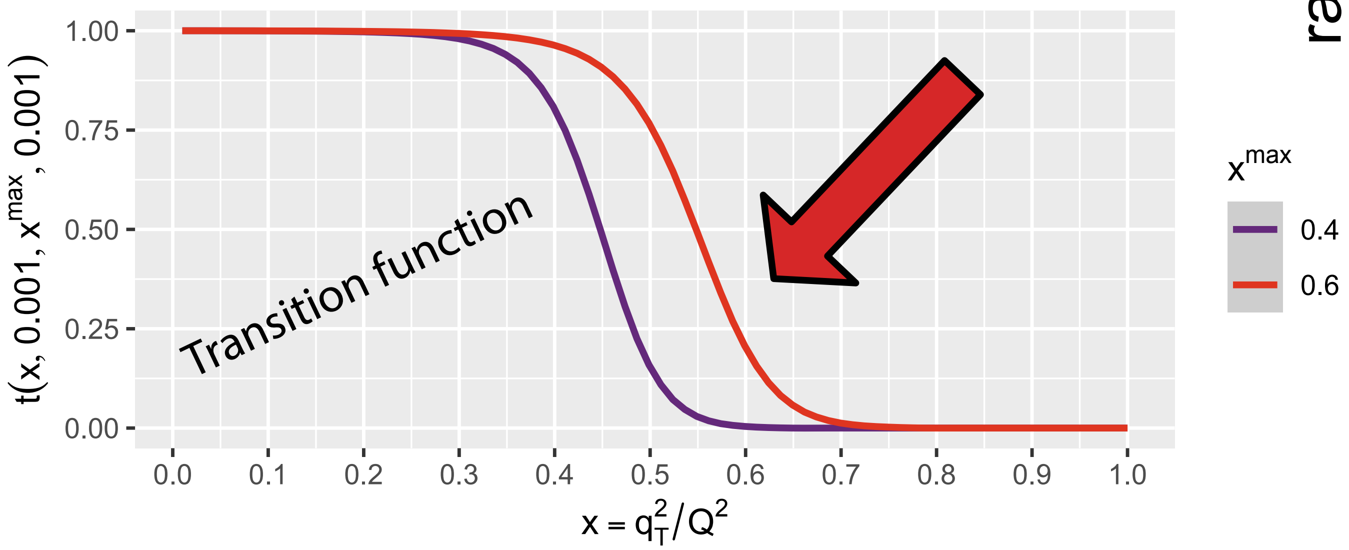


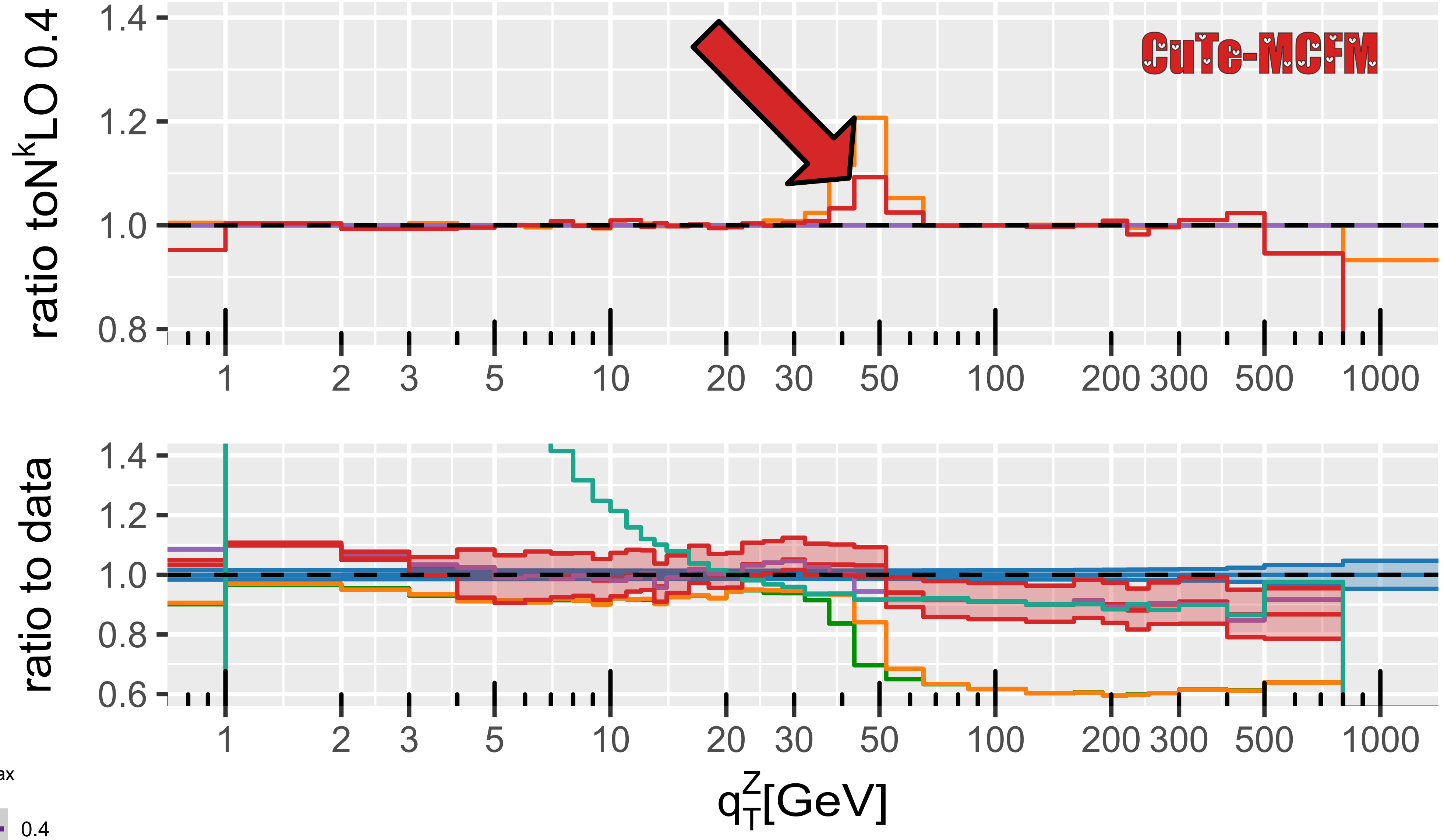
$t(x, 0.001, x^{max}, 0.001)$
Transition function
$x = q_T^2/Q^2$
x^{max}
0.4
0.6

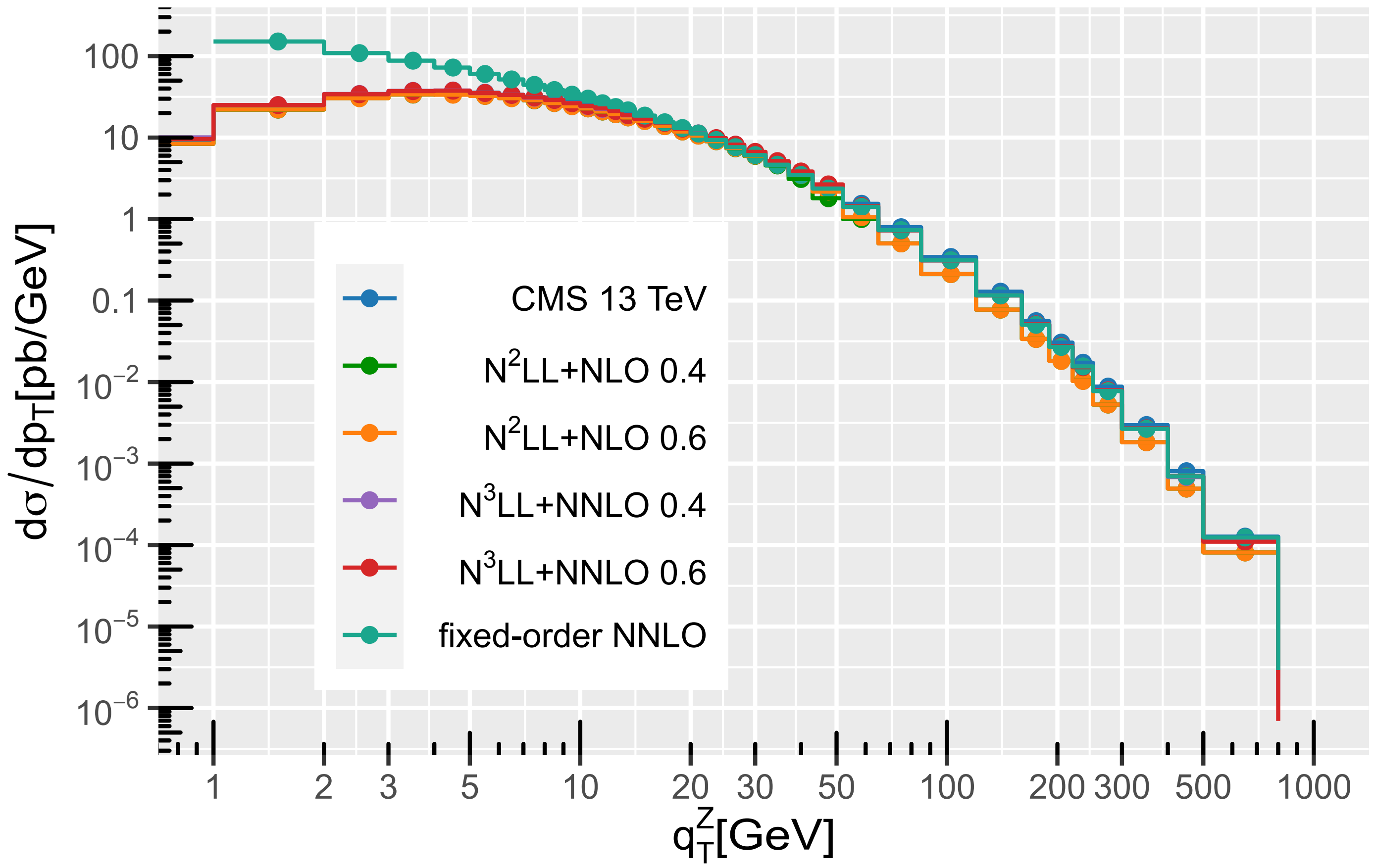


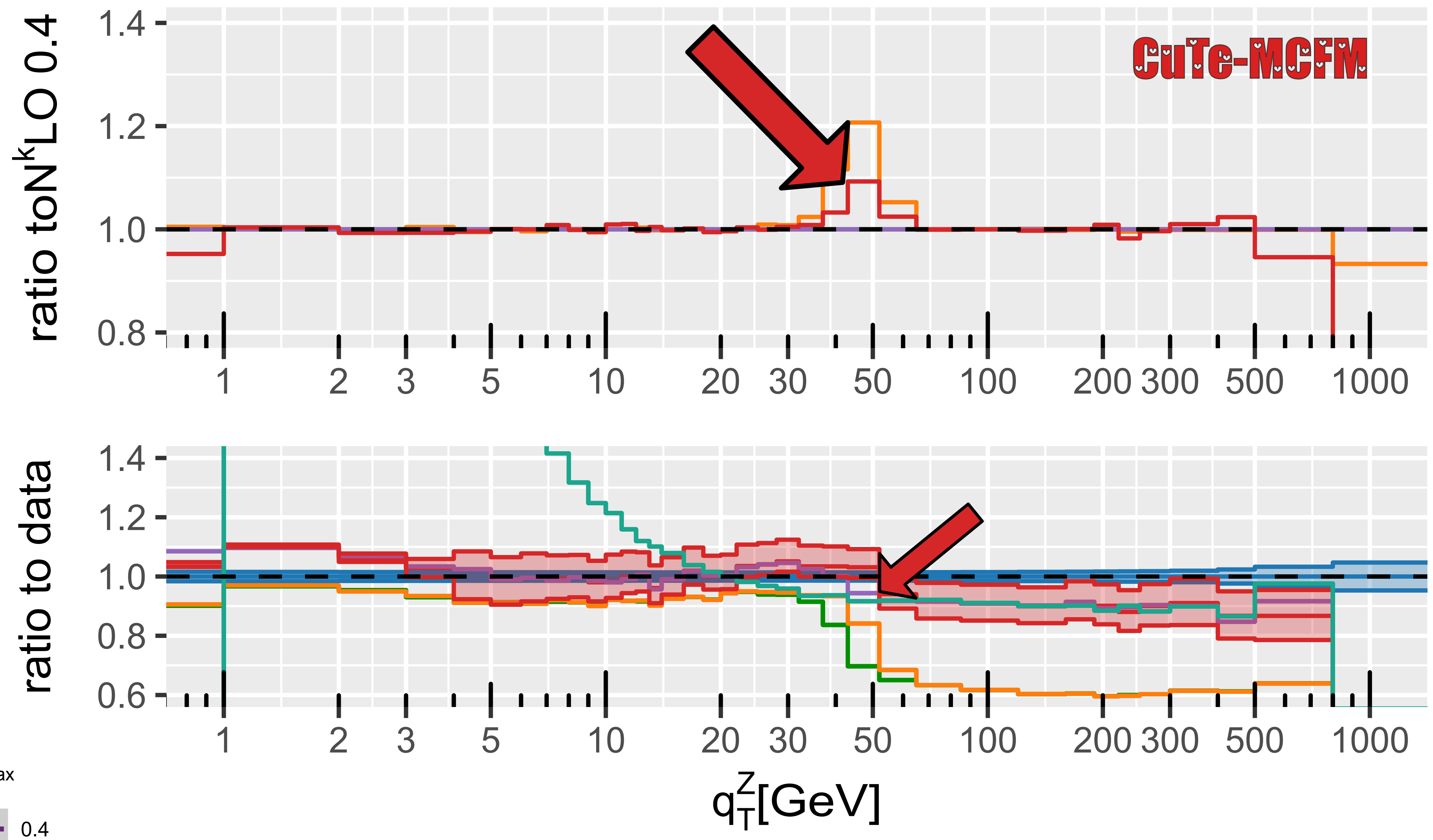
ratio toN^kLO 0.4
CuTe-MCFM
ratio to data
q_T^Z[GeV]

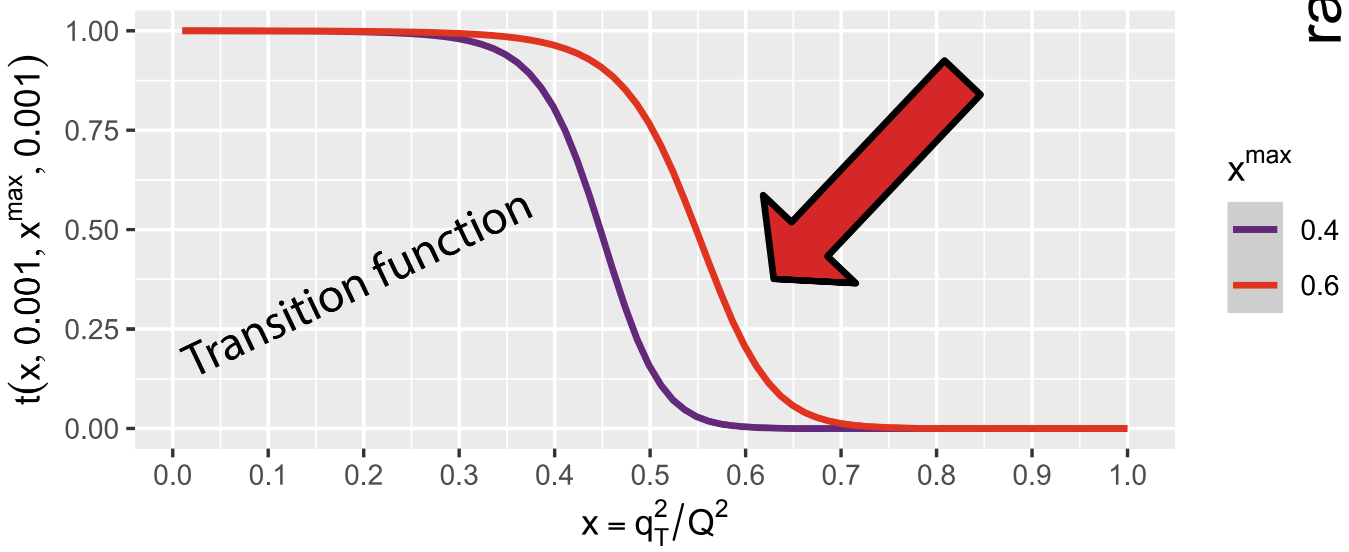

CMS 13 TeV
N2LL+NLO 0.4
N2LL+NLO 0.6
N3LL+NNLO 0.4
N3LL+NNLO 0.6
fixed-order NNLO
dσ/dpT[pb/GeV]
qTZ[GeV]

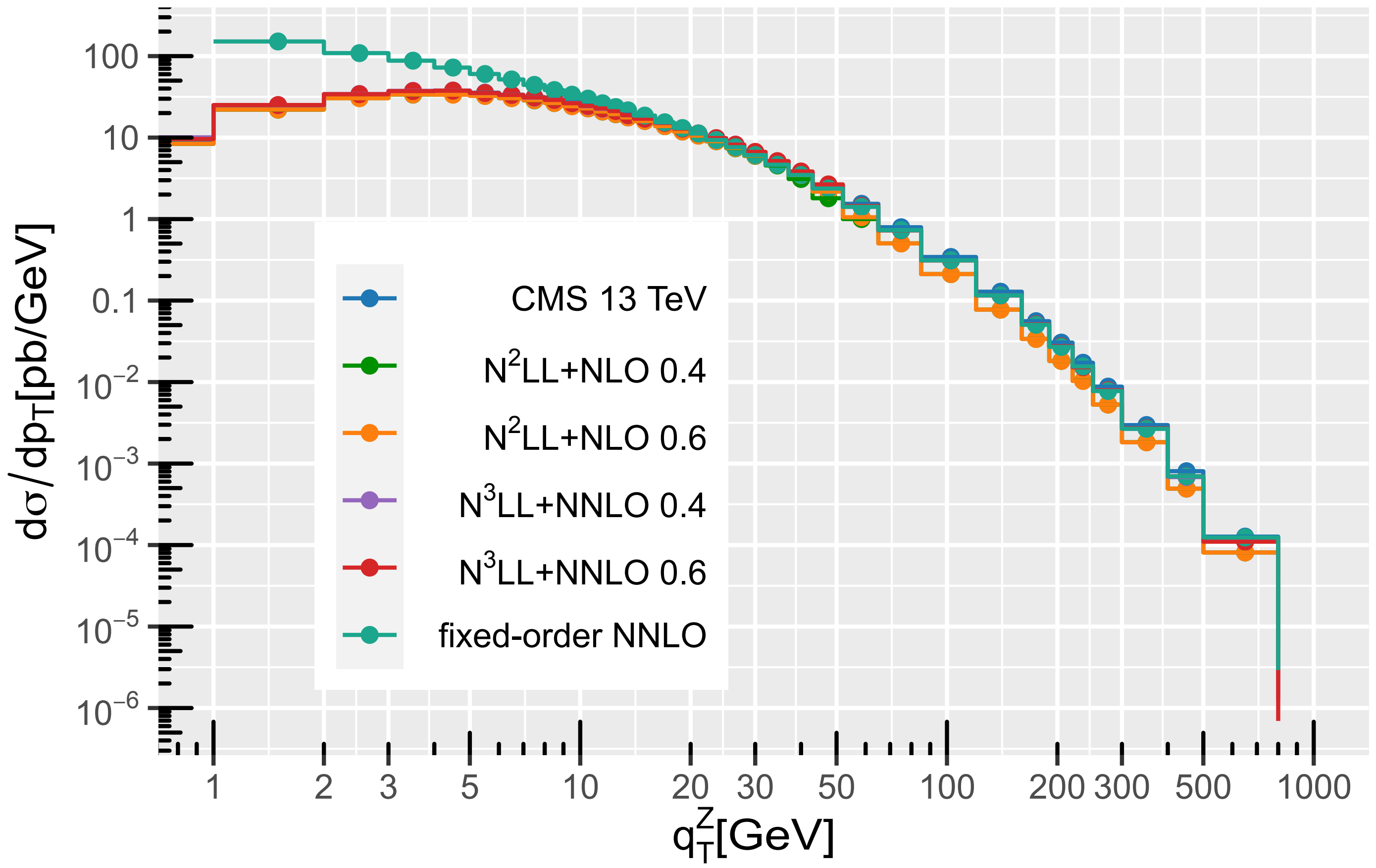

Transition function
t(x, 0.001, xmax, 0.001)
x = qT2/Q2
xmax
0.4
0.6

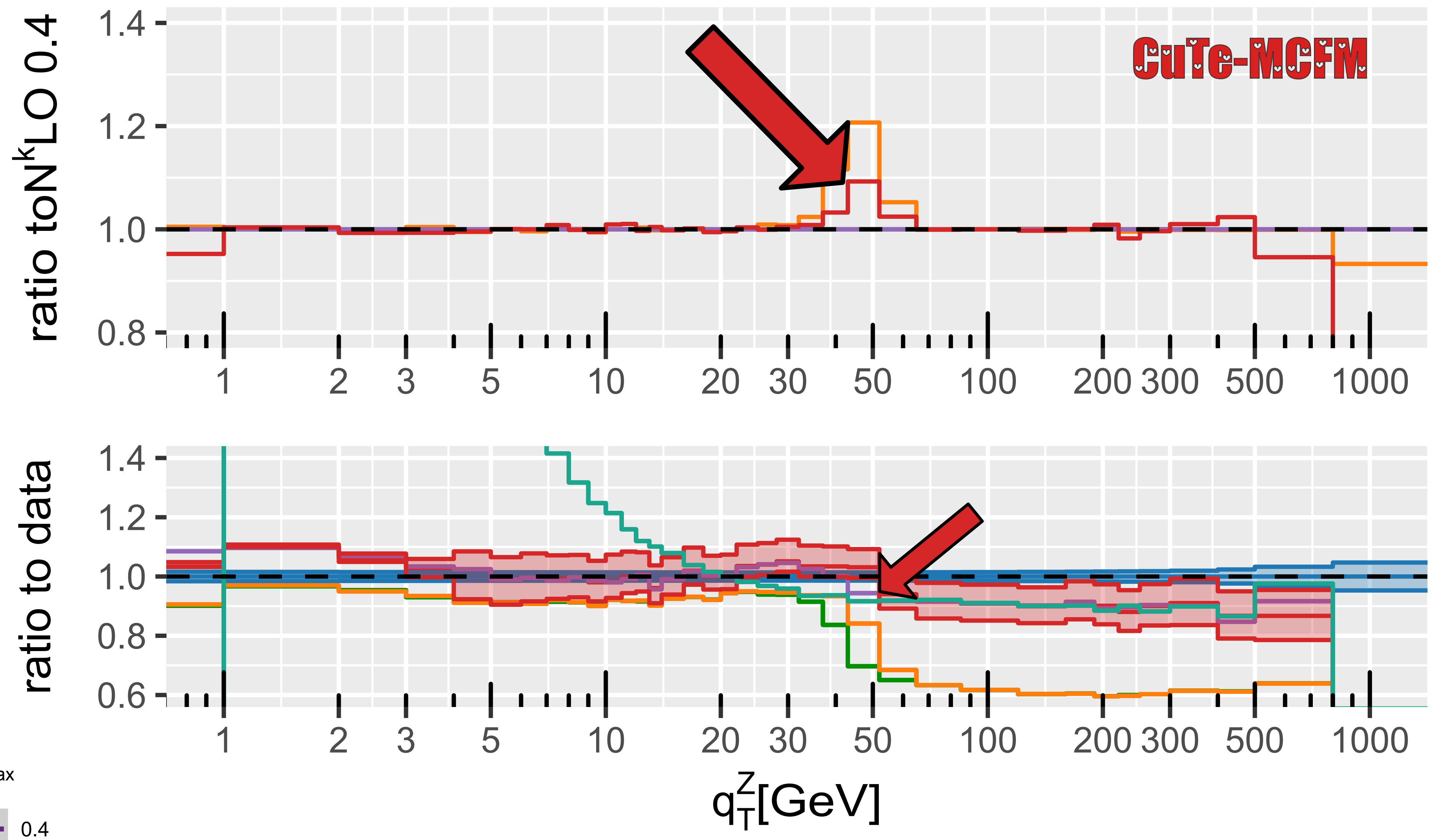

CuTe-MCFM
ratio to NkLO 0.4
ratio to data
qTZ[GeV]

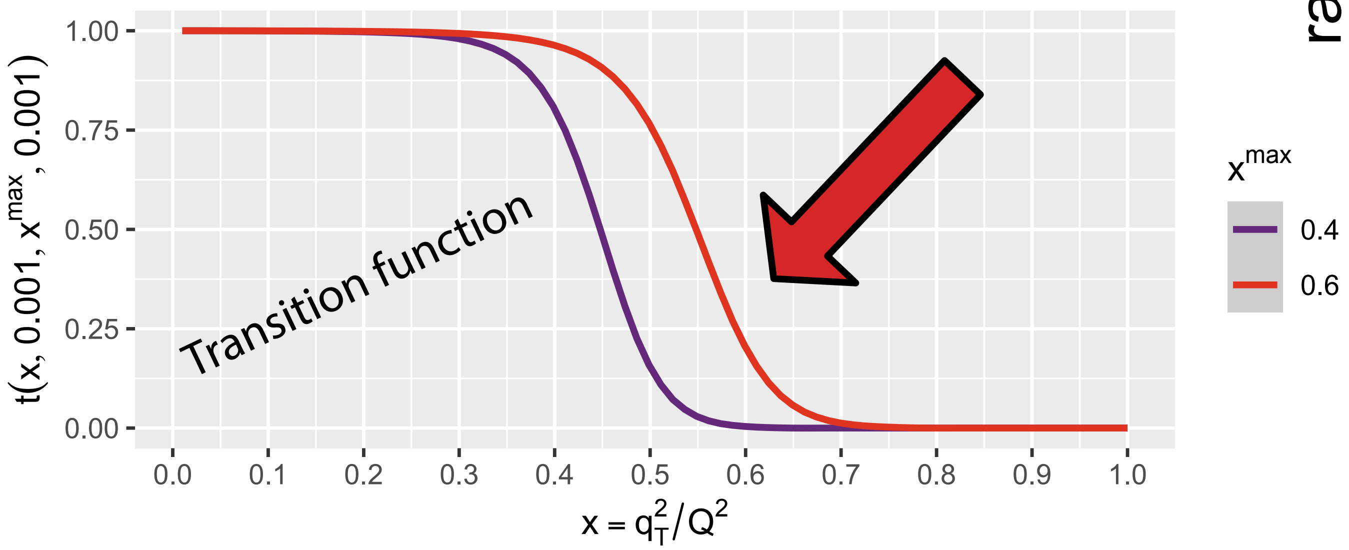

dσ/dp_T[pb/GeV]
CMS 13 TeV
N2LL+NLO 0.4
N2LL+NLO 0.6
N3LL+NNLO 0.4
N3LL+NNLO 0.6
fixed-order NNLO
q_T^Z[GeV]


ratio to NkLO 0.4
CuTe-MCFM
ratio to data
q_T^Z[GeV]


t(x, 0.001, x^max, 0.001)
Transition function
x^max
0.4
0.6
x = q_T^2/Q^2

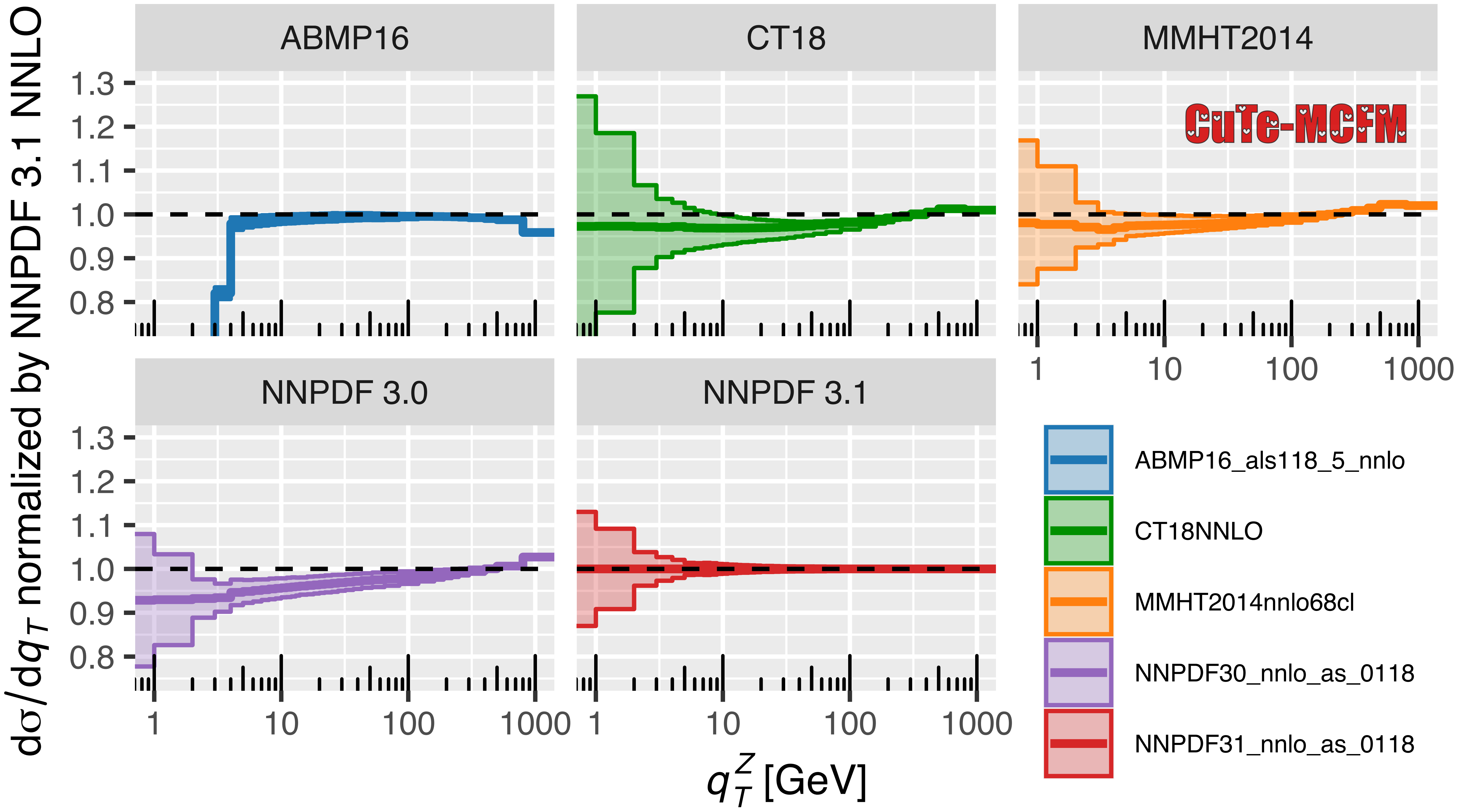






Recoil prescription takes into account $\mathcal{O}(q_T/Q)$ power corrections

(Ebert, Michel, Stewart, Tackmann '20)

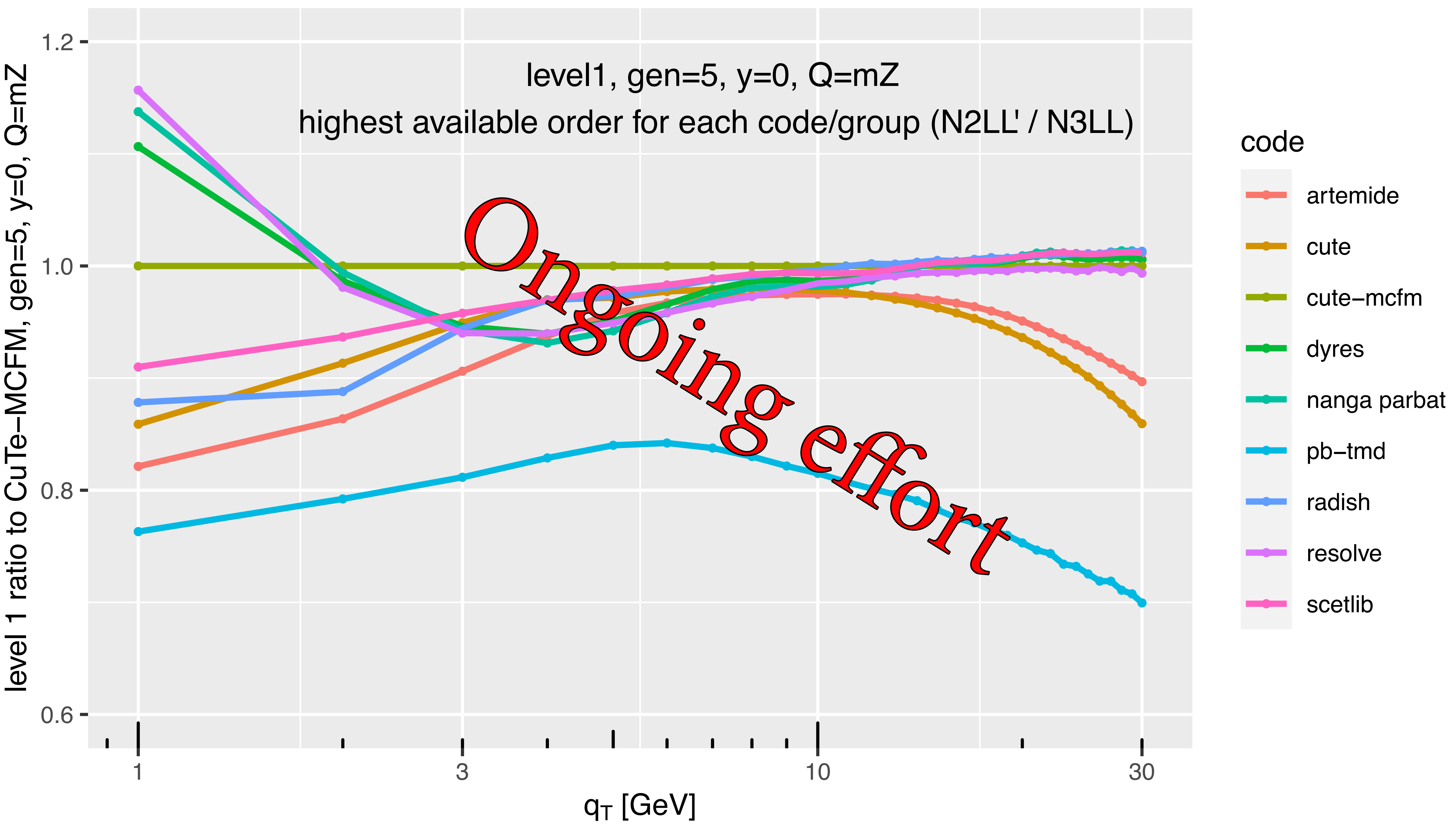

ABMP16
CT18
MMHT2014
NNPDF 3.0
NNPDF 3.1
CuTe-MCFM
1.3
1.2
1.1
1.0
0.9
0.8
1
10
100
1000
dσ/dq_T normalized by NNPDF 3.1 NNLO
q_T^Z [GeV]
ABMP16_als118_5_nnlo
CT18NNLO
MMHT2014nnlo68cl
NNPDF30_nnlo_as_0118
NNPDF31_nnlo_as_0118

CuTe-MCFM is not alone

Lots of public and private codes and implementations…

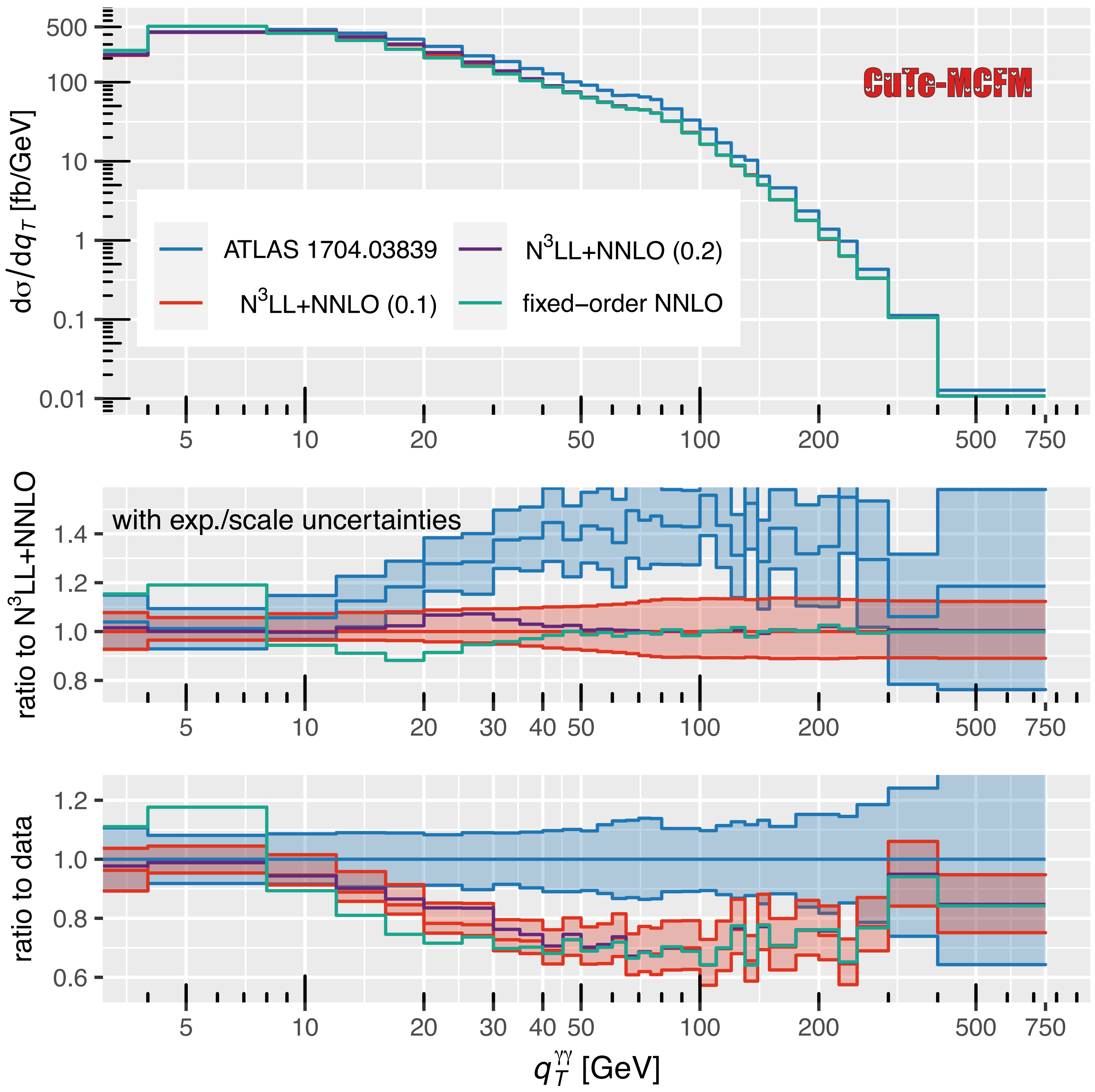
different orders, formalisms, matching prescriptions, processes, limitations …

CuTe, DYRes, HRes, Resbos, ReSolve, **RadISH+MATRIX**, RadISH+NNLOjet, SCETlib, TMD focus: NangaParbat, Artemide,…

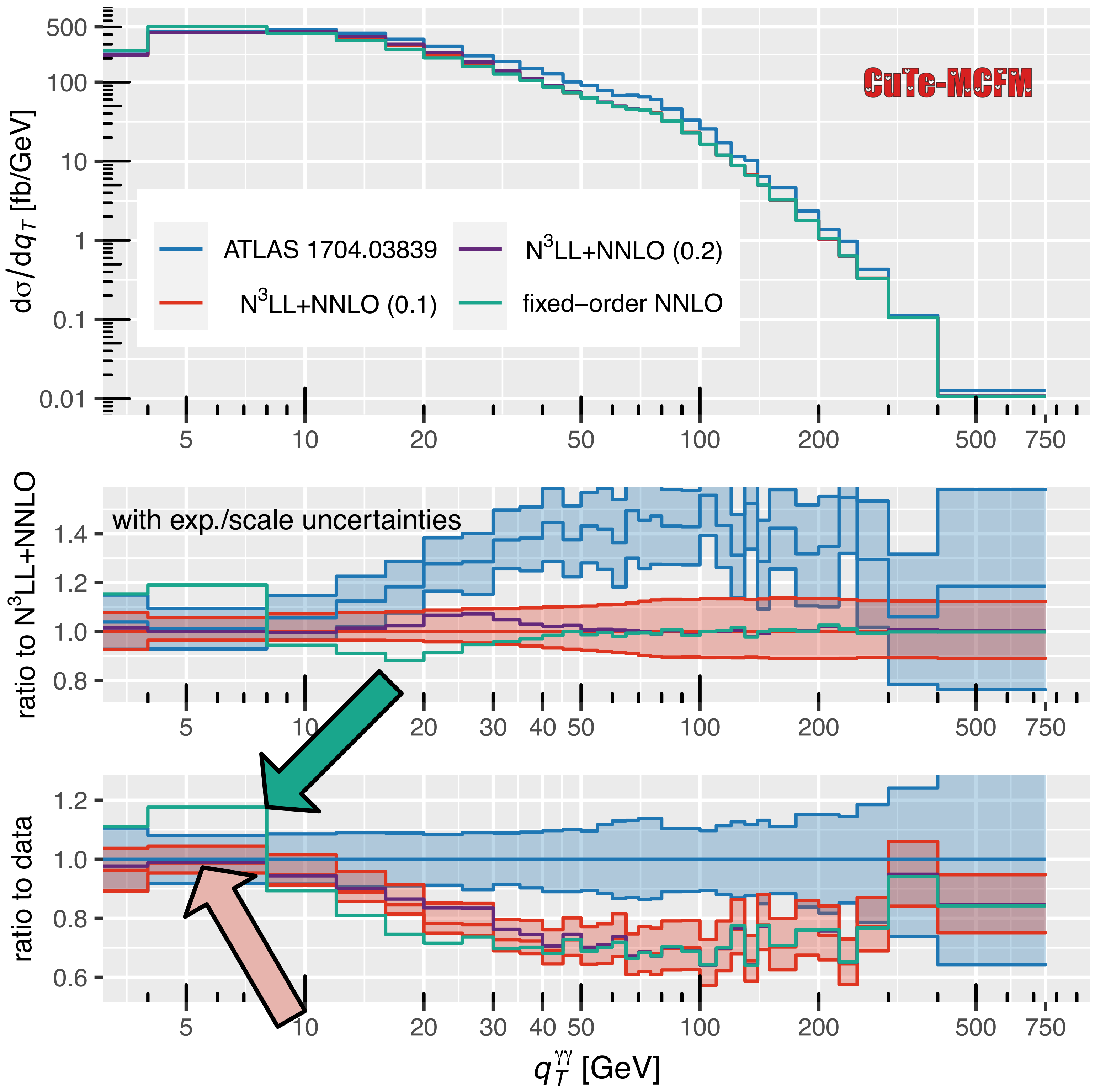


level1, gen=5, y=0, Q=mZ
highest available order for each code/group (N2LL' / N3LL)
Ongoing effort
level 1 ratio to CuTe−MCFM, gen=5, y=0, Q=mZ
1.2
1.0
0.8
0.6
1
3
10
30
qT [GeV]
code
artemide
cute
cute−mcfm
dyres
nanga parbat
pb−tmd
radish
resolve
scetlib

$\gamma\gamma, q_T^{\gamma,1} > 40, q_T^{\gamma,2} > 30$

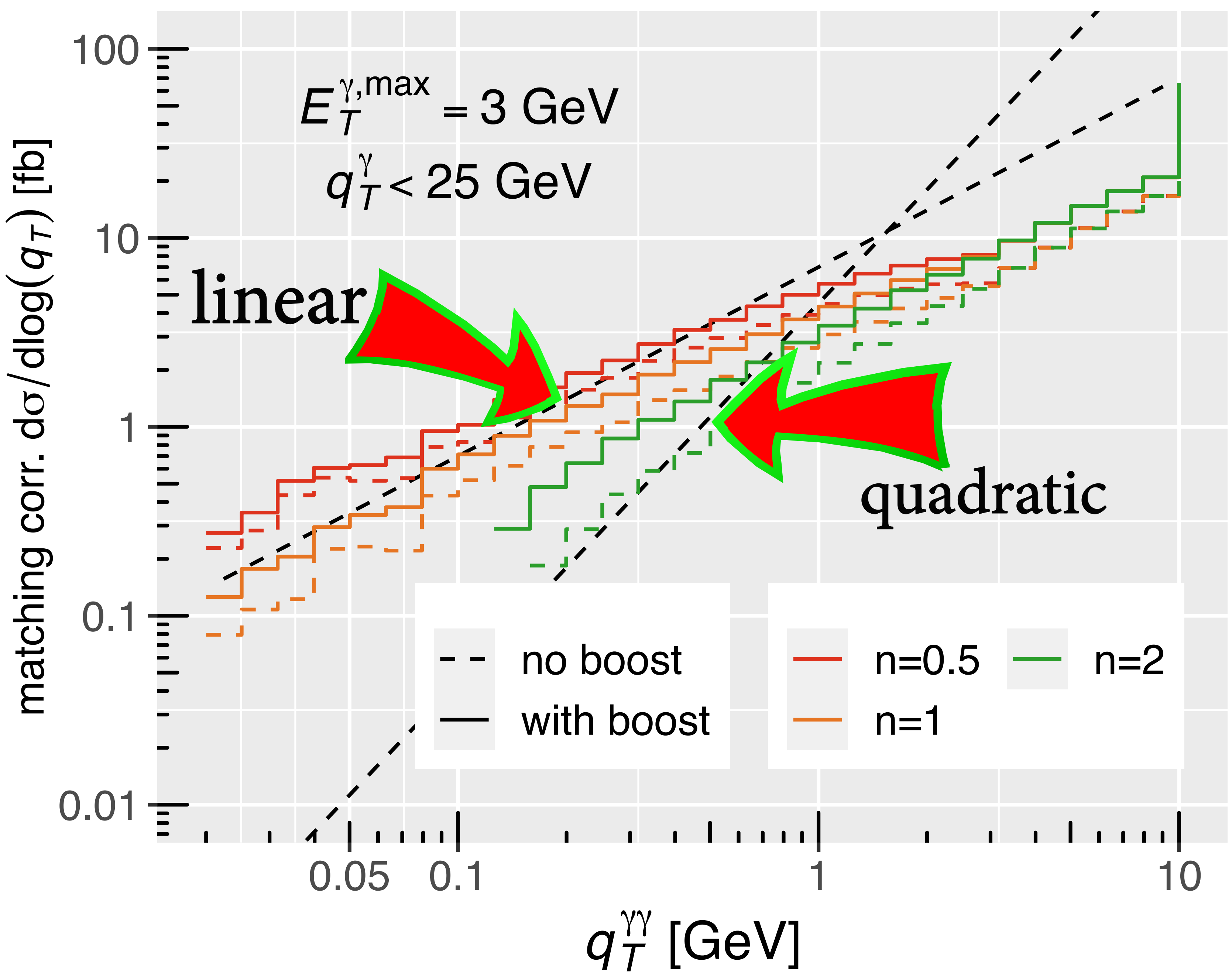


$\gamma\gamma, q_T^{\gamma,1} > 40, q_T^{\gamma,2} > 30$

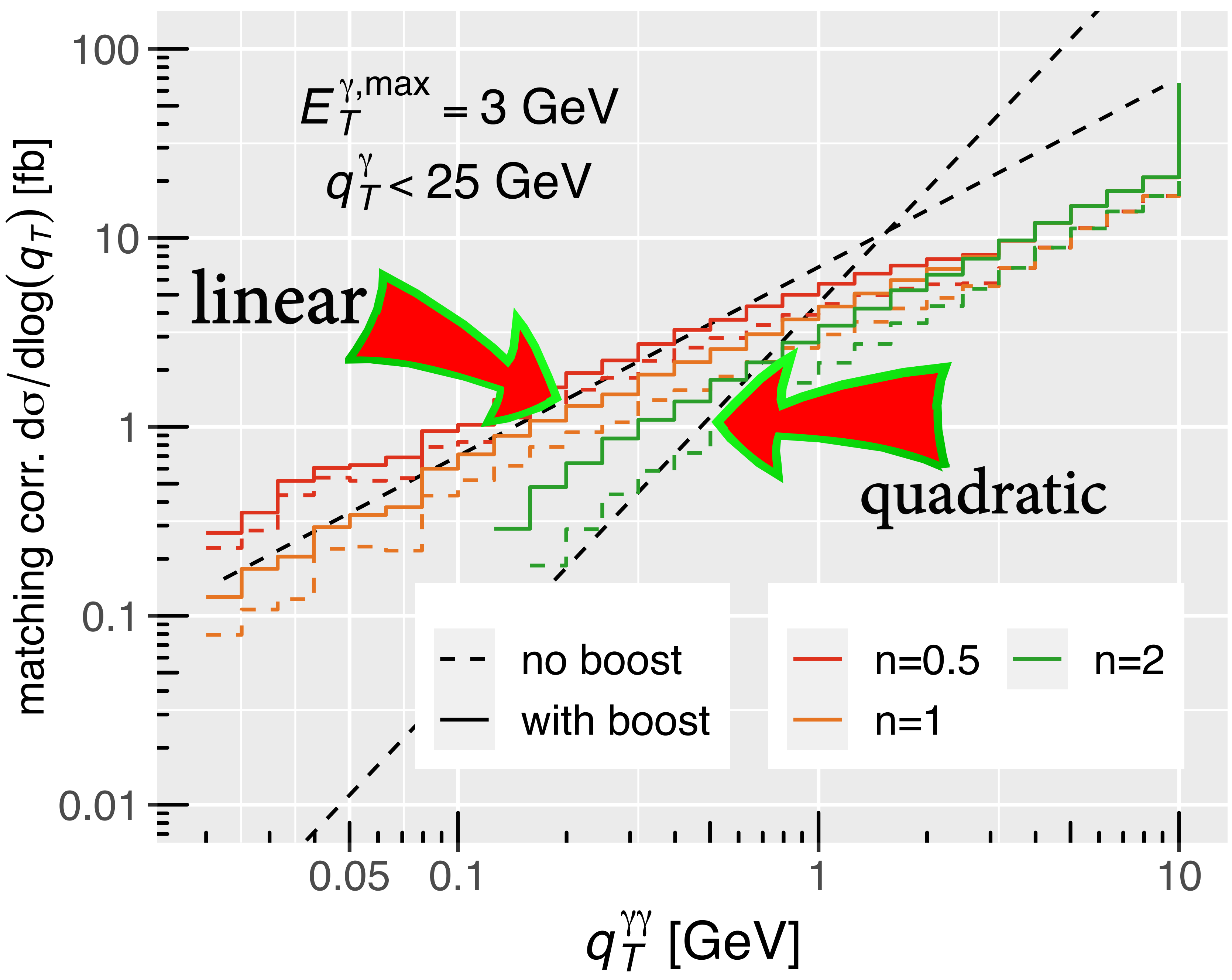


Power corrections in the factorization theorem

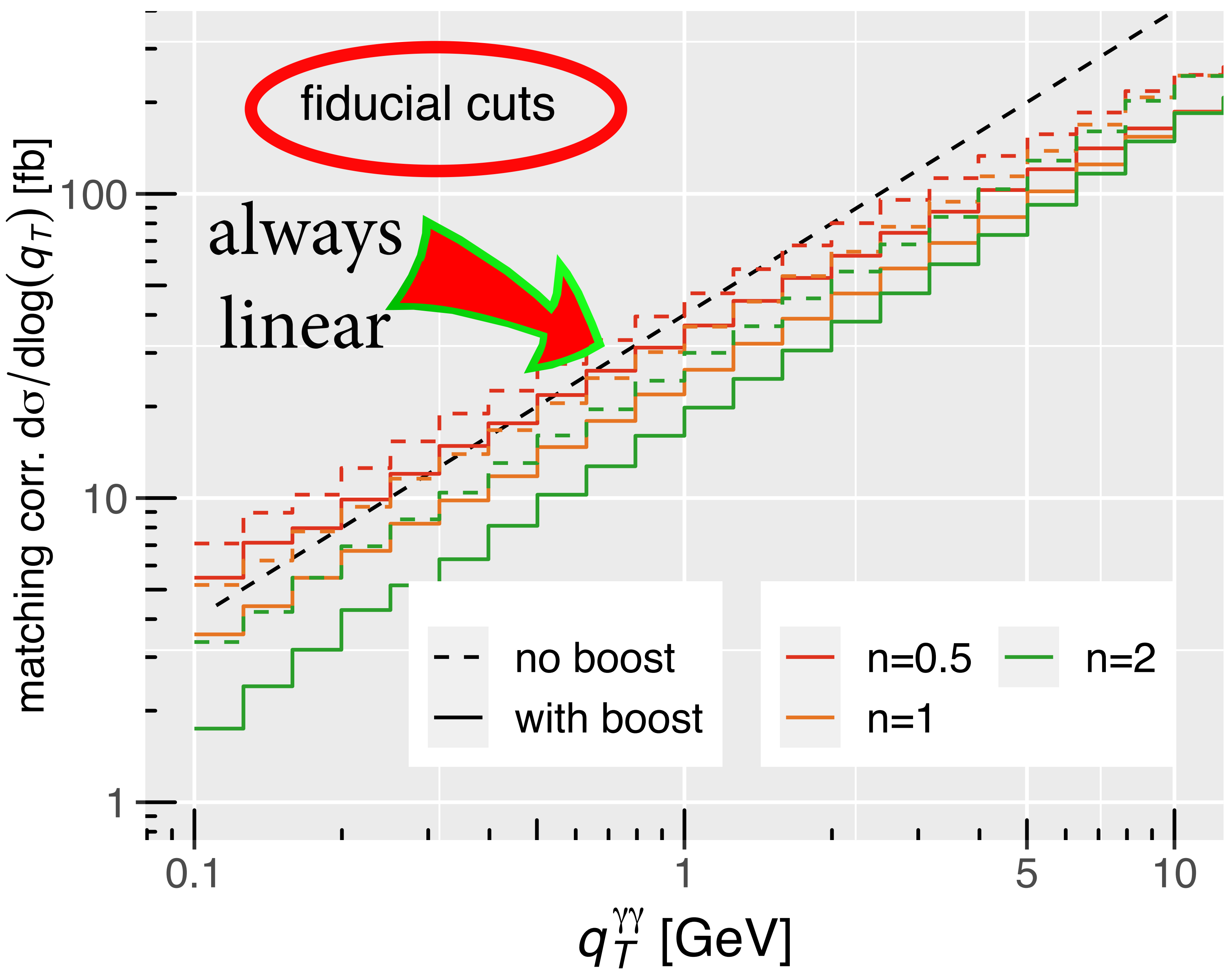
$$\mathrm{d}\sigma = \ldots + \mathcal{O}(q_T/Q) + \mathcal{O}(q_T^2/Q^2) + \ldots$$



(see also Ebert; Tackmann '19)



$E_T^{\gamma,\max} = 3$ GeV
$q_T^{\gamma} < 25$ GeV
linear
quadratic
matching corr. dσ/dlog(q_T) [fb]
$q_T^{\gamma\gamma}$ [GeV]
no boost
with boost
n=0.5
n=1
n=2



fiducial cuts
always linear
matching corr. dσ/dlog(q_T) [fb]
$q_T^{\gamma\gamma}$ [GeV]
no boost
with boost
n=0.5
n=1
n=2

CuTe-MCFM

https://mcfm.fnal.gov/cute-mcfm.html

CuTe-MCFM

MCFM CuTe-MCFM

N^3LL q_T resummation for color-singlet processes in MCFM

Authors: Thomas Becher, Tobias Neumann

CuTe-MCFM is a program and framework for q_T resummation at N^3LL accuracy for color-singlet processes based on a factorization theorem in SCET. It is fully differential in the Born kinematics and matches to large-q_T fixed-order predictions in MCFM at relative order α_s^2. It provides an efficient way to estimate uncertainties from fixed-order truncation, resummation, and parton distribution functions. In addition to $W^\pm$, Z and H production, also the diboson processes $\gamma\gamma$, $Z\gamma$, ZH and $W^\pm H$ are available, including decays.

The program is based on the publication

- *Fiducial q_T resummation of color-singlet processes at N^3LL+NNLO*
  Thomas Becher, Tobias Neumann, JHEP 03 (2021) 199, arXiv:2009.11437

We release CuTe-MCFM and MCFM as a combined code: Please refer to it as CuTe-MCFM if you use the resummation and simply as MCFM otherwise.

Download

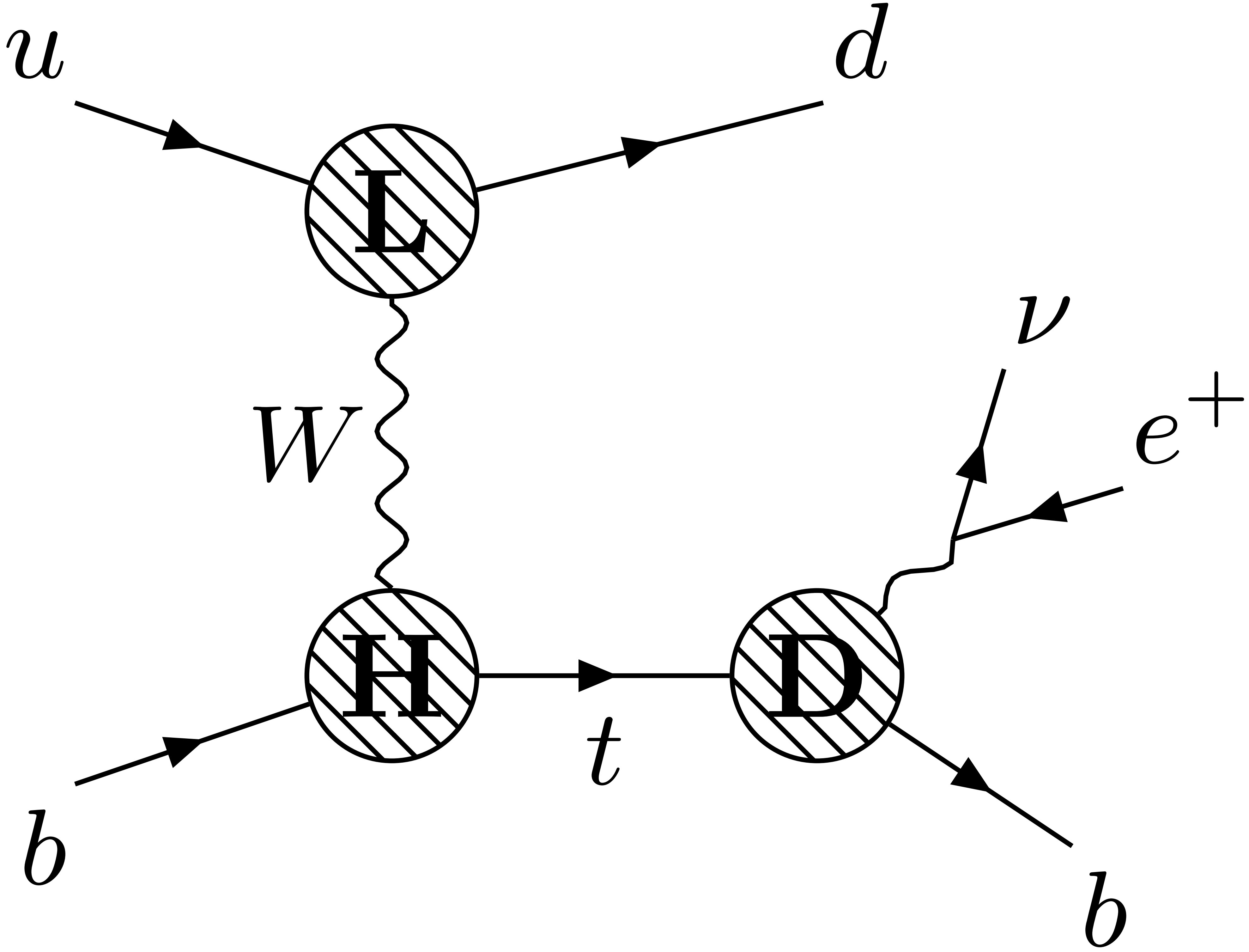
A quickstart manual for CuTe-MCFM is included in the distribution in Doc/cute-mcfm.pdf. The manual for MCFM itself is included in Doc/manual.pdf. Example input files for all color-singlet processes are included in the Bin/ directory and can be used to reproduce the results in our publication.

- Initial release MCFM 10.0 / CuTe-MCFM 1.0 (March 2021)

Please feel free to contact the authors for any questions.

CuTe-MCFM now released: https://mcfm.fnal.gov/cute-mcfm.html

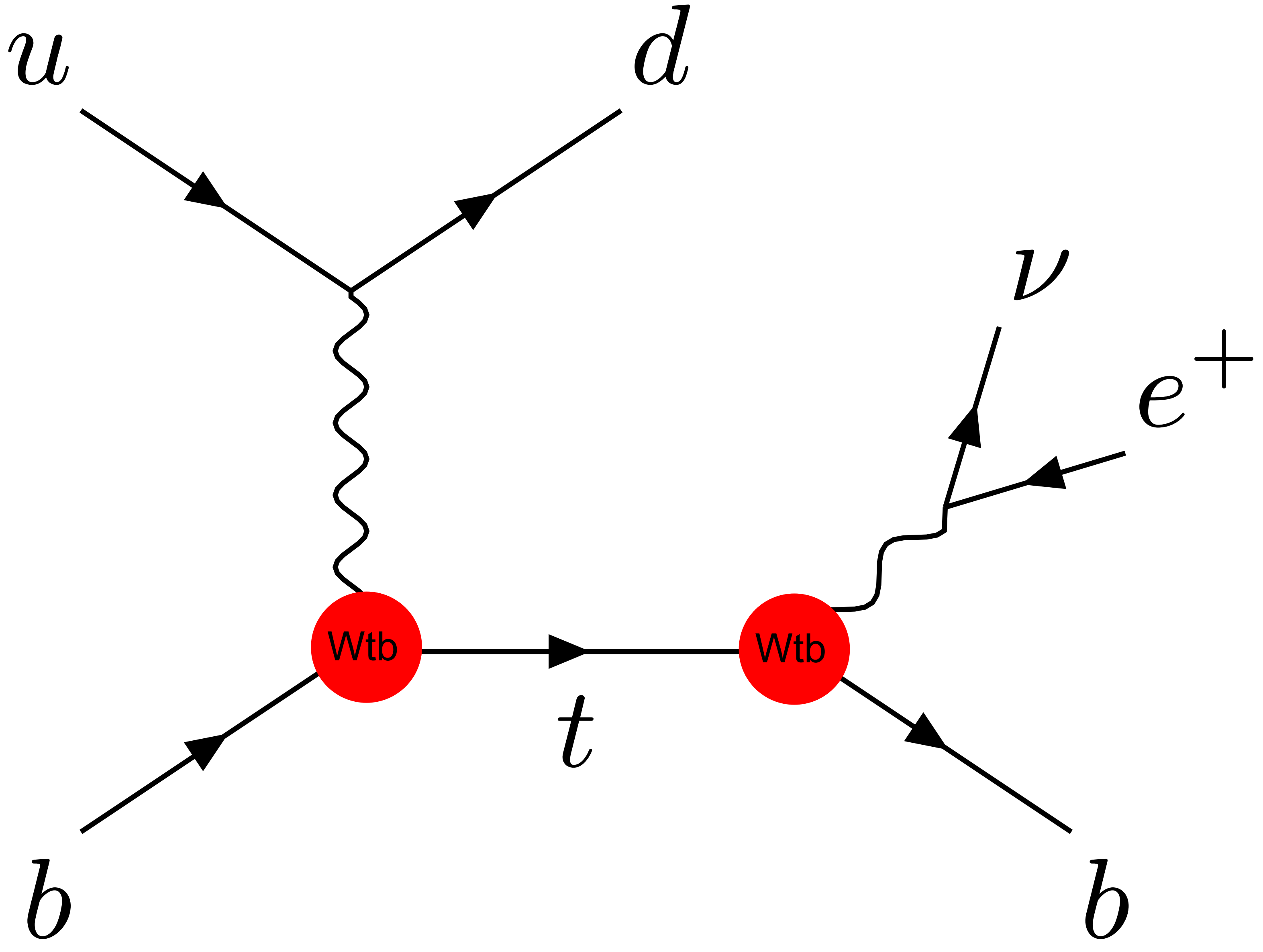

resummation
fixed-order



@ NNLO; with John Campbell and Zack Sullivan

Why is this process relevant?

... is it because ... ?



Access to V_{tb}: $\propto |V_{tb}|^2$

Top-quark mass: m_{bl} lineshape

As background with signature W, b + light jets

Prime process to test V-A structure $\gamma^\mu P_L$

1. non-decaying top, needs decay

(Brucherseifer, Caola, Melnikov '14)

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2. full calculation, "found discrepancy of ~1%"

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(NNLO corrections are ~1-2%)

$\sigma = \int dx \, f_q^{LO}(x)$  = **physics**

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$= \boxed{\text{physics}}$

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$\parallel$

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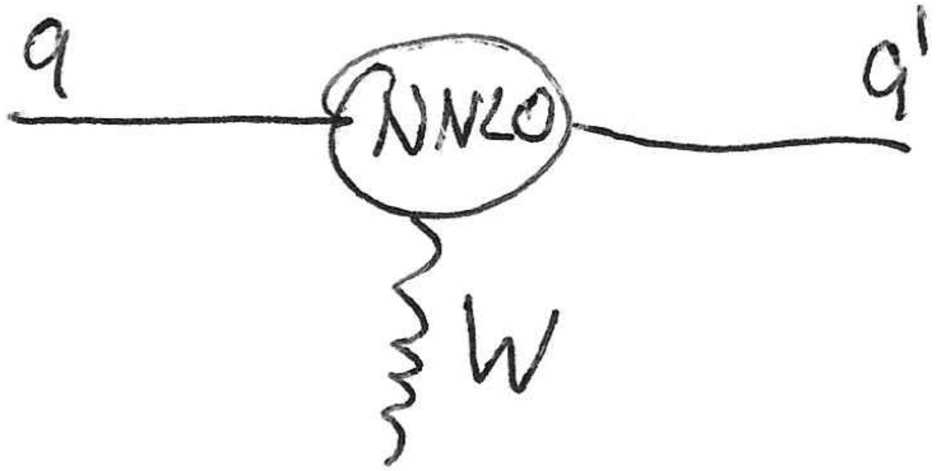
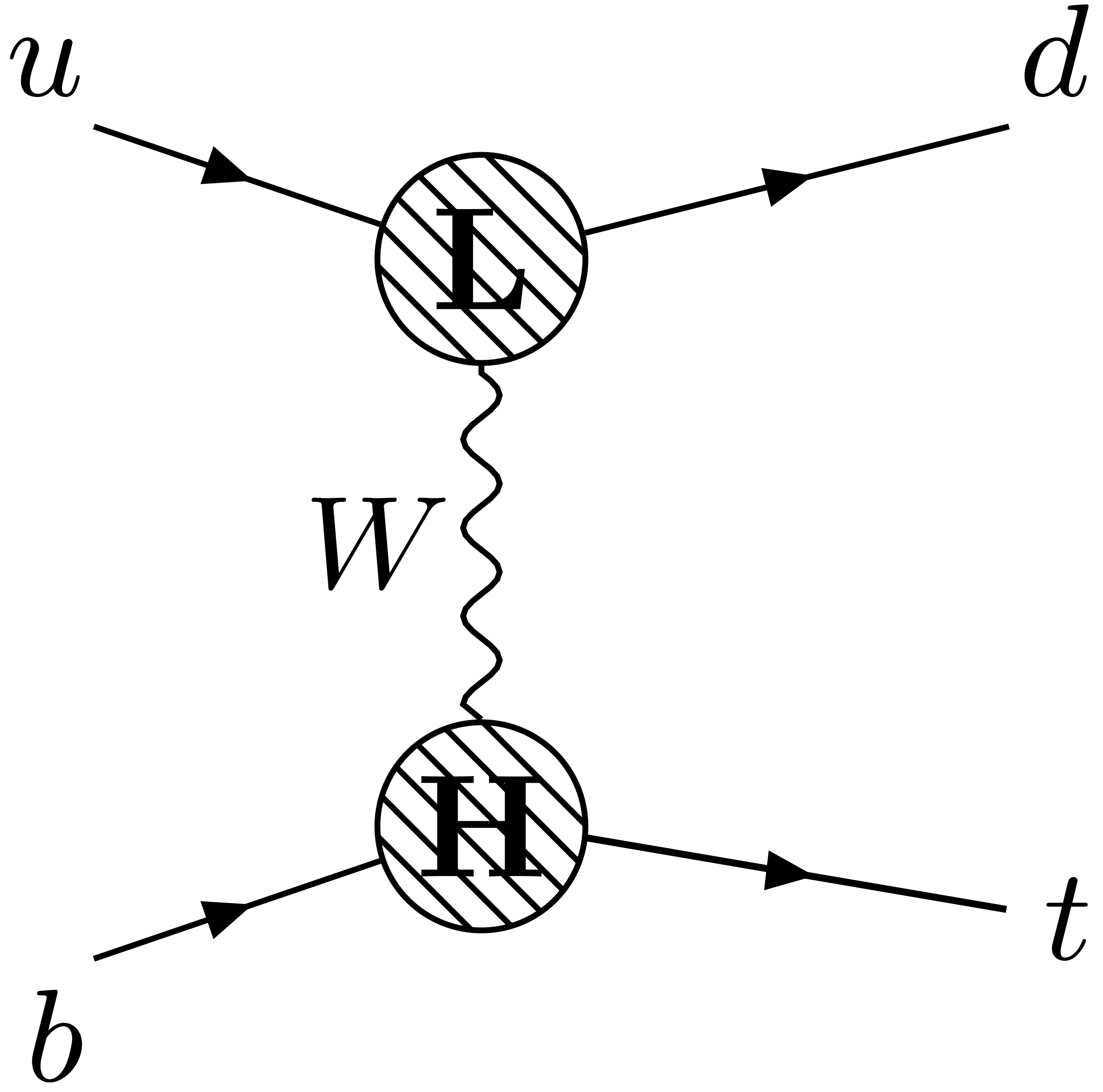


$= \boxed{\text{physics}}$

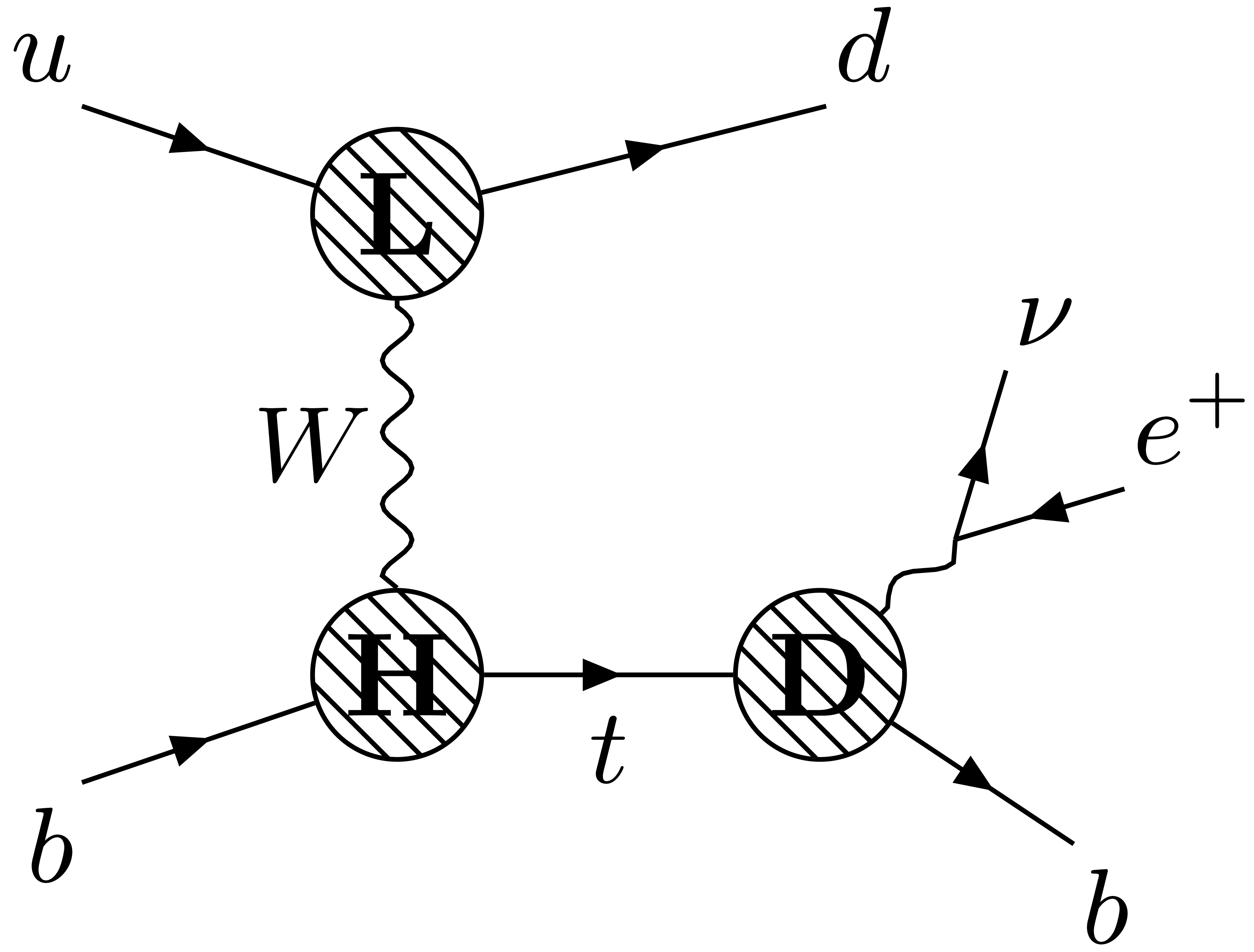
Double DIS = DDIS



DDIS contraint at NLO: "Are PDFs still consistent with Tevatron data?"

(Sullivan '17)

Double DIS = DDIS



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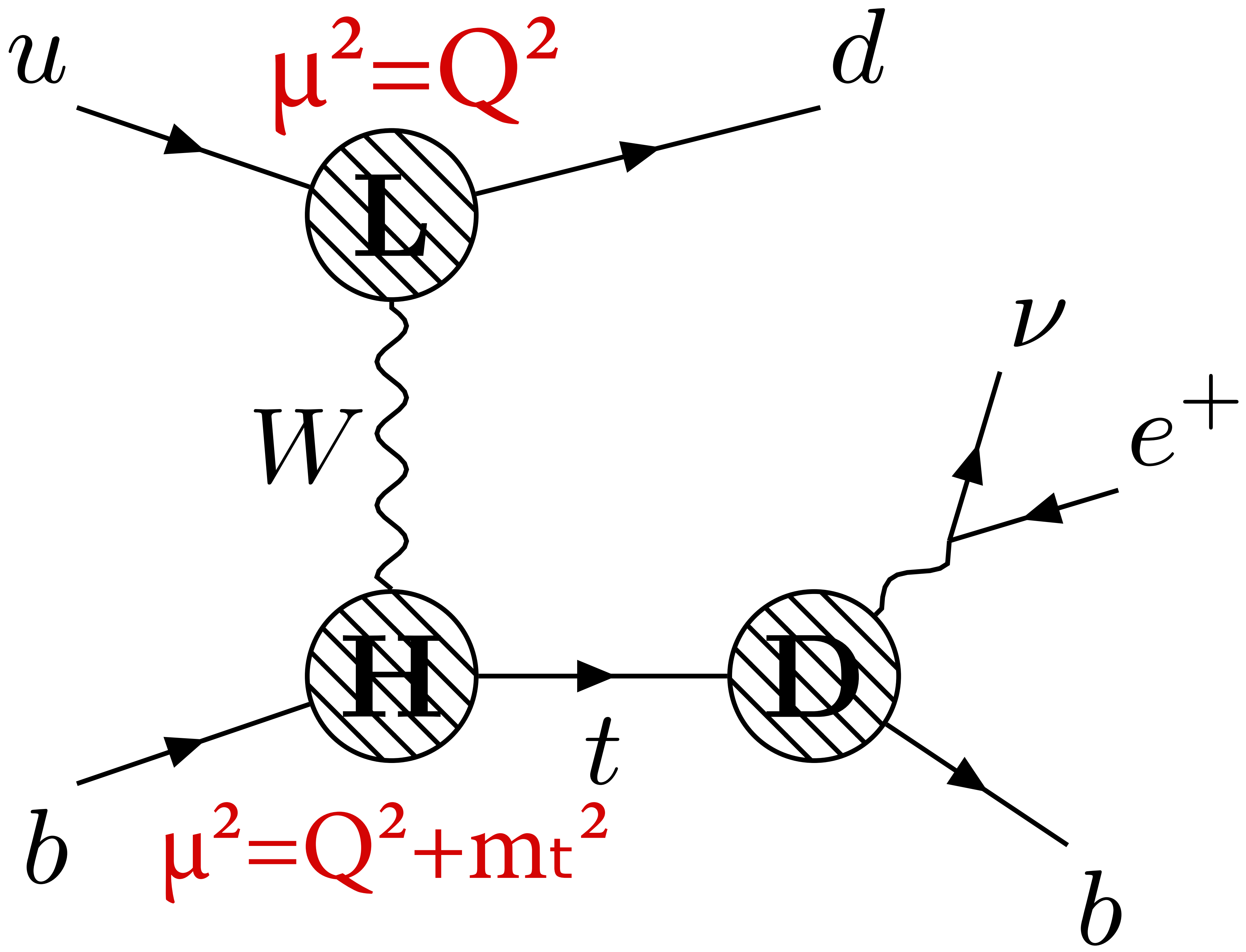
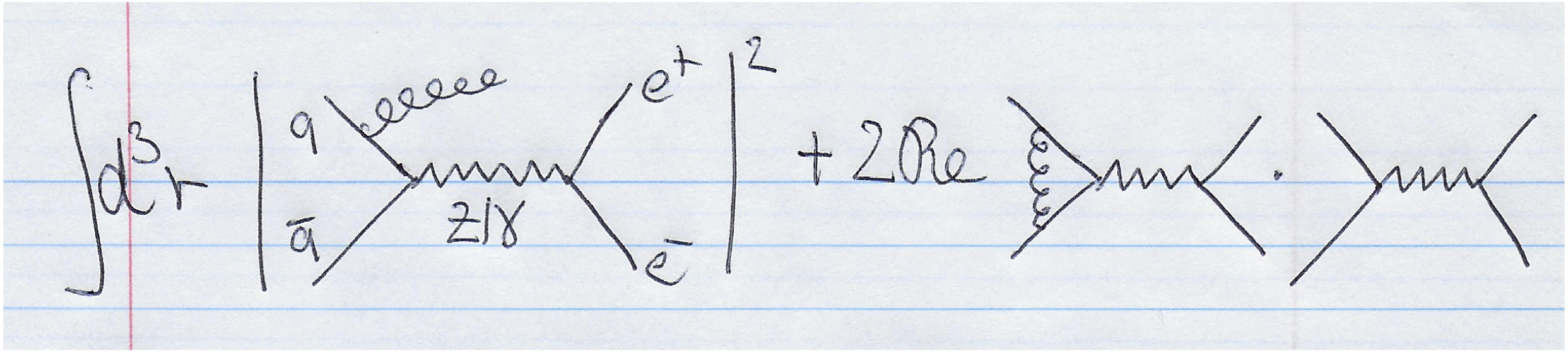
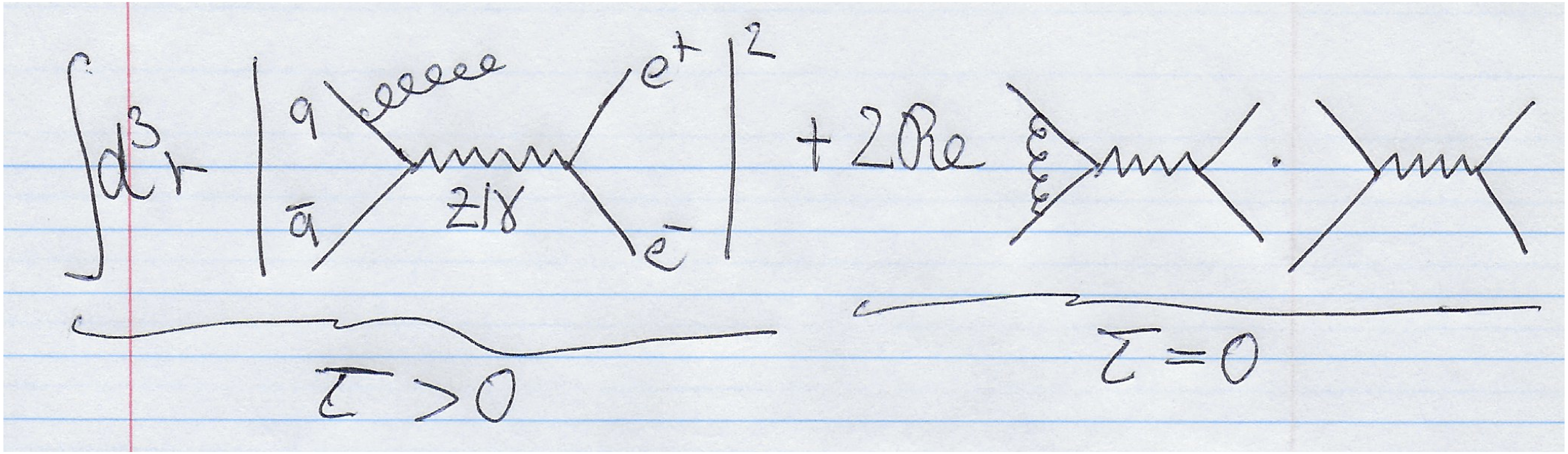
Why is the same scale everywhere a problem?

Double DIS



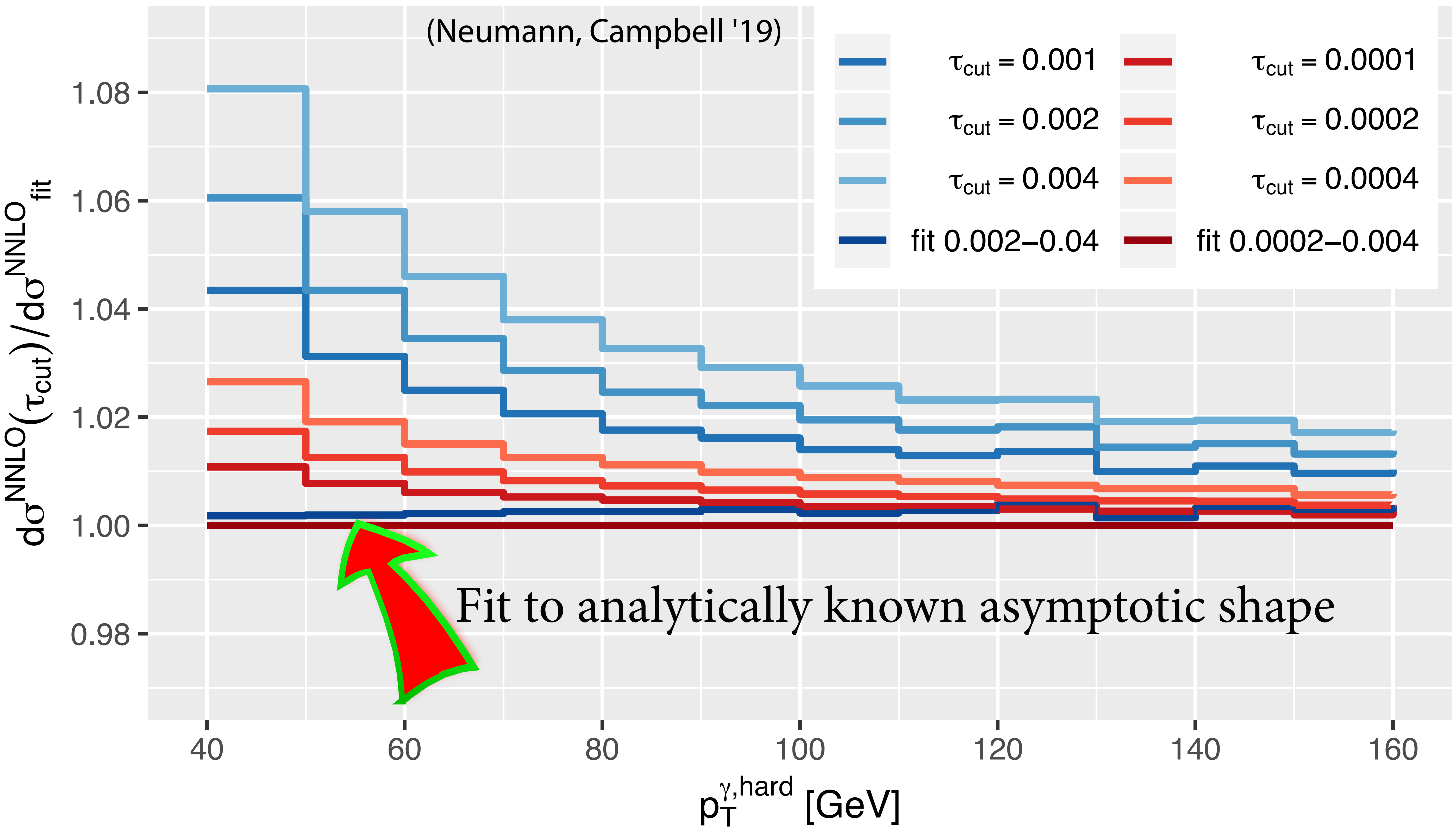
Mini interlude: higher-order pQCD





$$\sigma^{\rm NNLO} = \lim_{\tau_c \to 0} \Big((H^{\rm NNLO\ loop} \otimes S \otimes B \otimes B \otimes J)(\tau_c) + \sigma^{\rm NLO}_{\rm X+jet}(\tau_c) + \mathcal{O}(\tau_c) \Big) + \mathcal{O}(\Lambda_{\rm QCD}/Q)$$

- H ~ two loop amplitude
- B collinear singularities for radiation close to beam
- J collinear singularities associated with final-state jets
- S all remaining soft singularities
- $\sigma^{\rm NLO}_{\rm X+jet}(\tau_c)$ radiation pieces, finite for $\tau > 0$



Systematically improvable: subleading power corrections

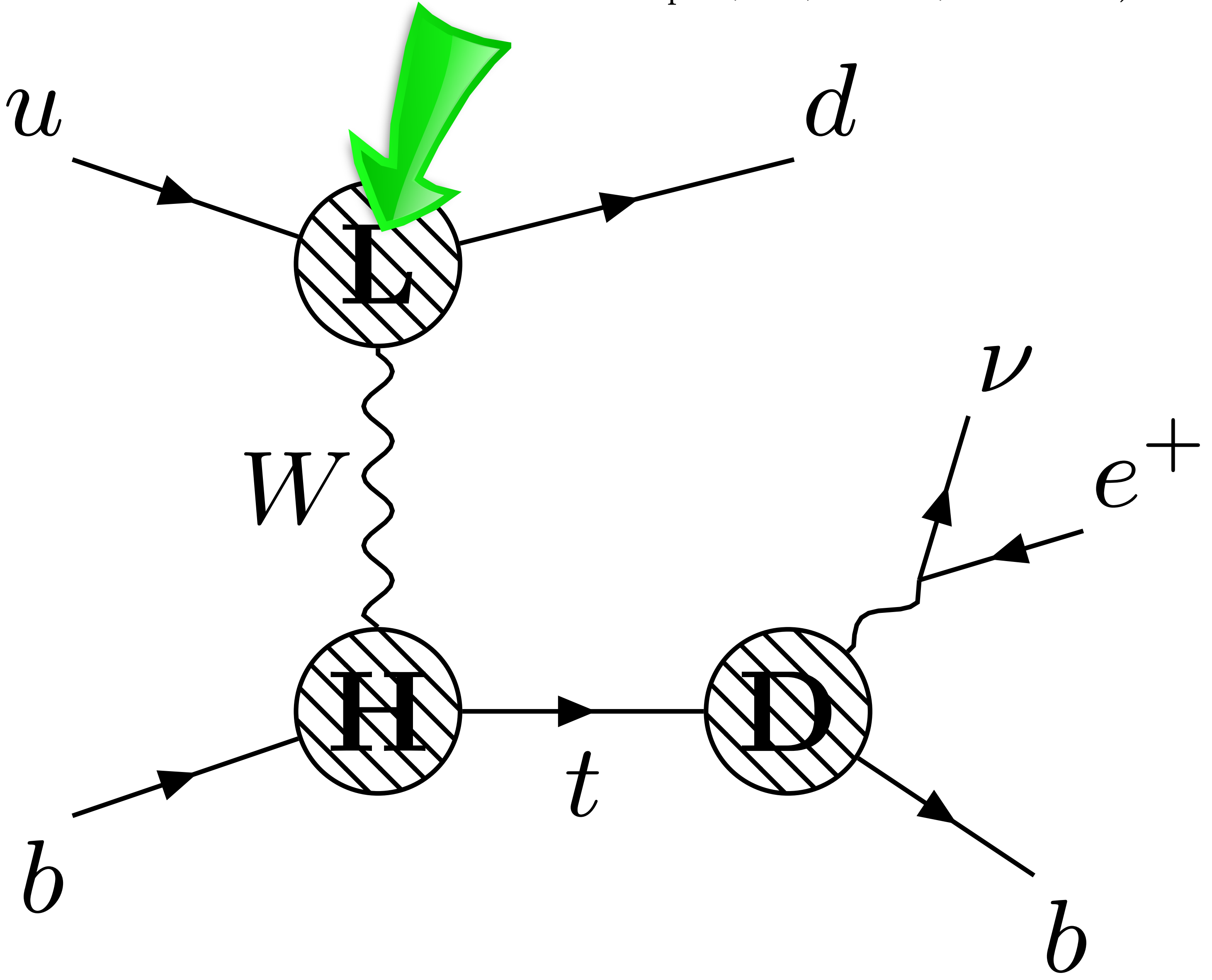
(Moult, Rothen, Stewart, Tackmann '16; Ebert, Moult, Stewart, Tackmann, Vita, Zhu '18)

Back to t-channel single-top-quark

Three NNLO calculations

massless 1-jettiness

(Boughezal, Focke, Liu, Petriello '15; Gaunt, Stahlhofen, Tackmann, Walsh '15;
NNLO soft functions: Campbell, Ellis, Mondini, Williams '17)



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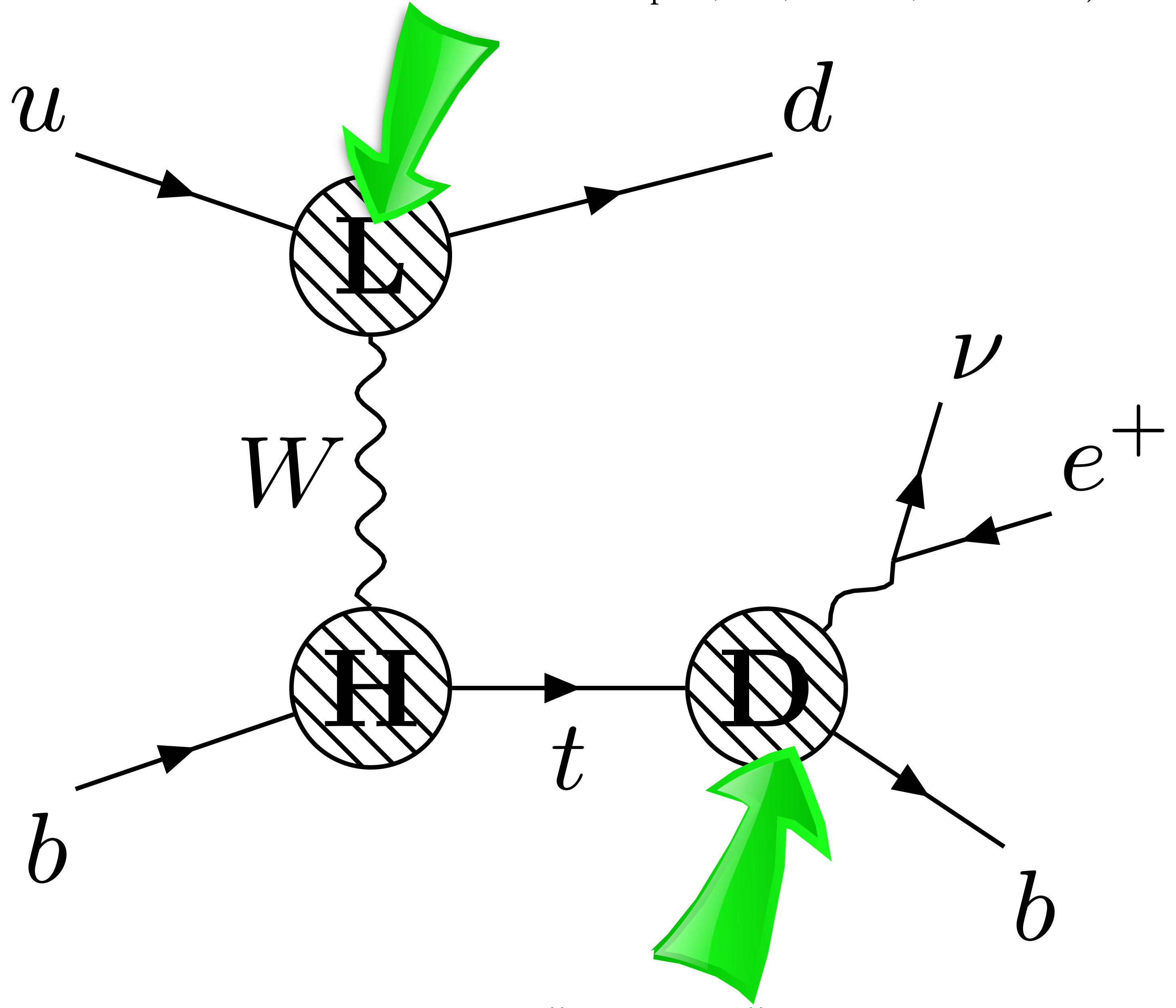

"massive" jettiness

(Liu '10; Bosch, Lange; Neubert, Paz '04; Bauer, Manohar '04)
(soft: Becher, Neubert '05; jet: Becher, Neubert '06)
(hard: Bonciani, Ferroglia '08; Asatrian, Greub, Pecjak '08; Beneke, Huber, Li '08; Bell '08)

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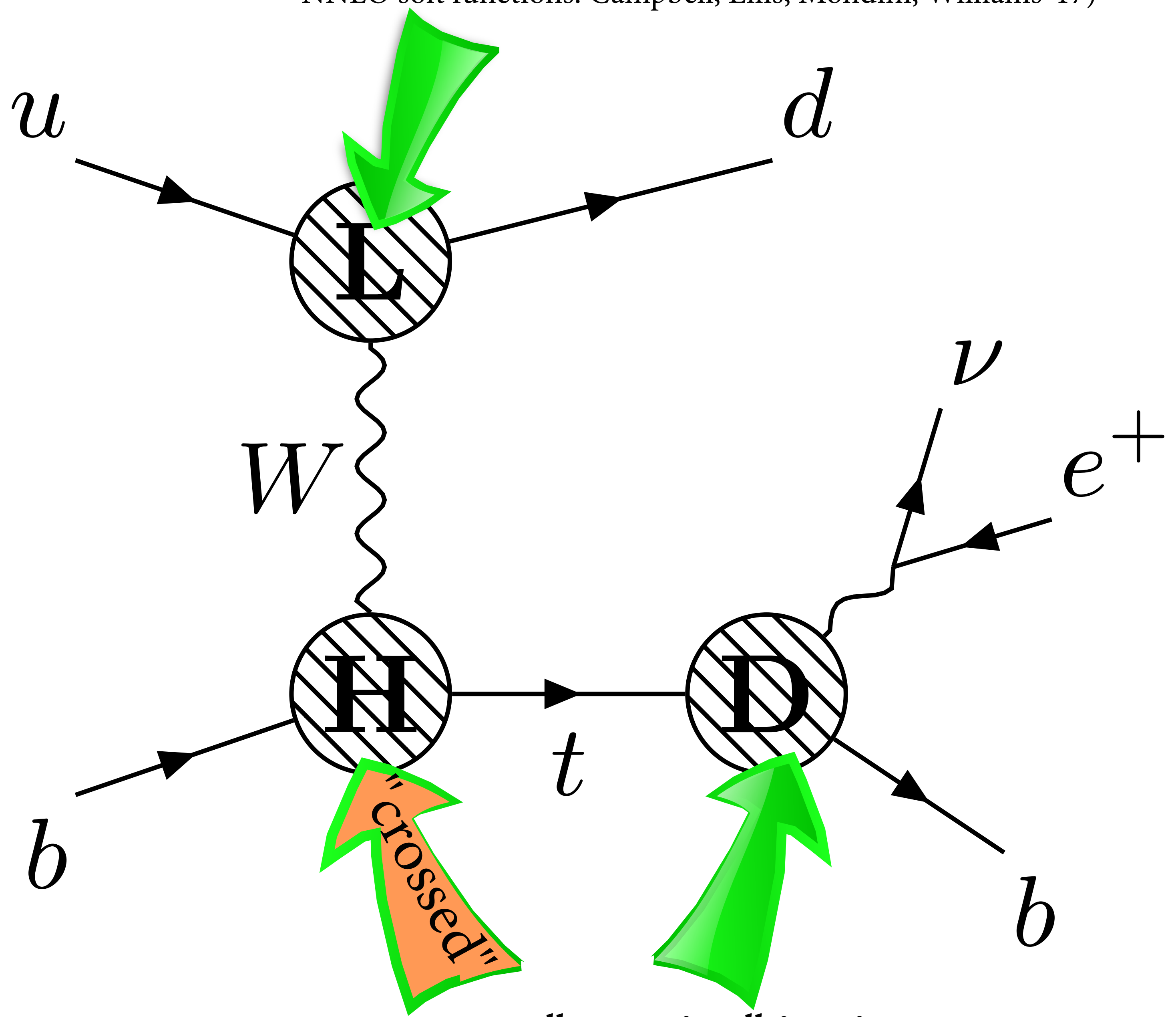

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Three NNLO calculations + three NLOxNLO calculations

massless 1-jettiness

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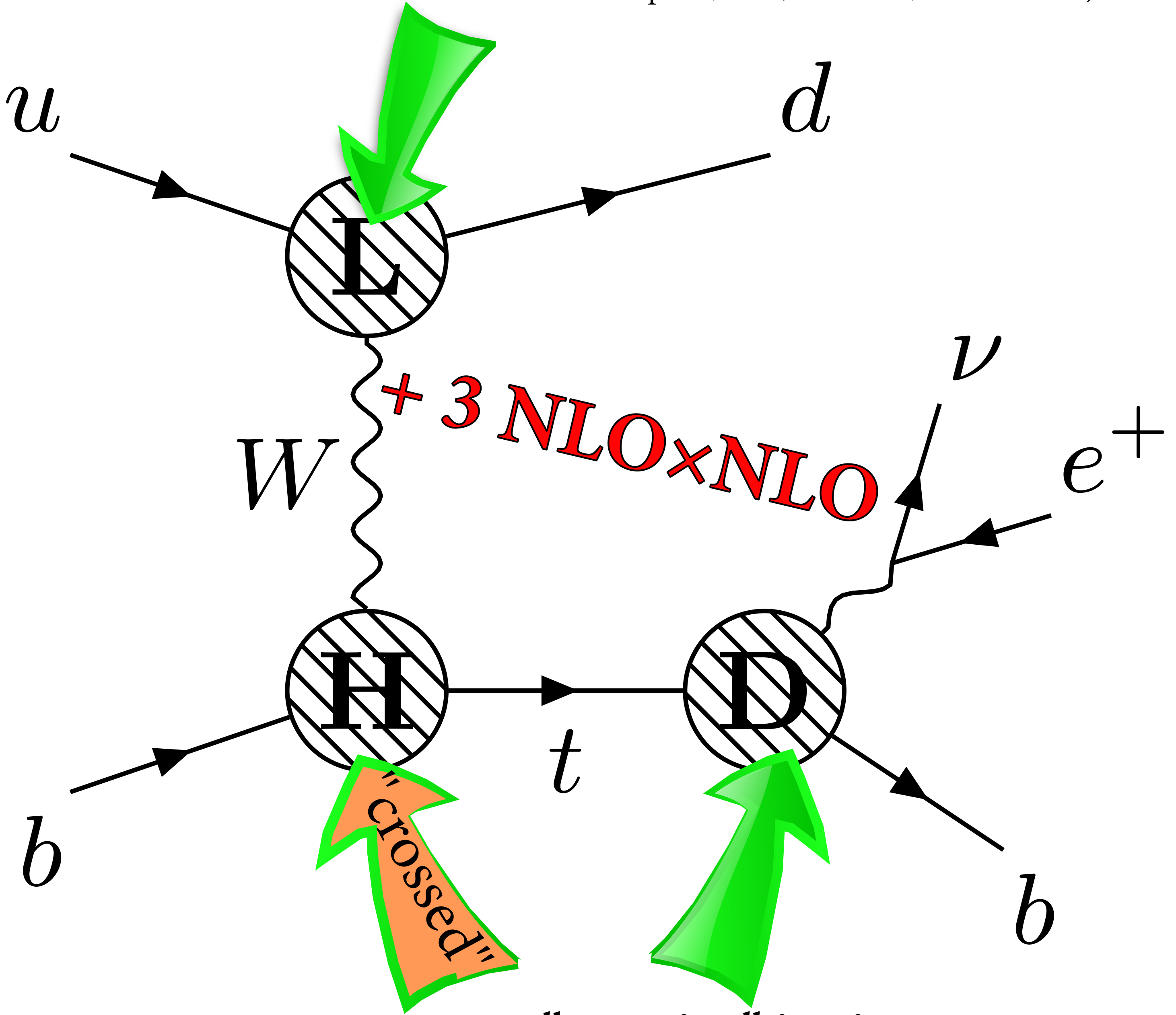

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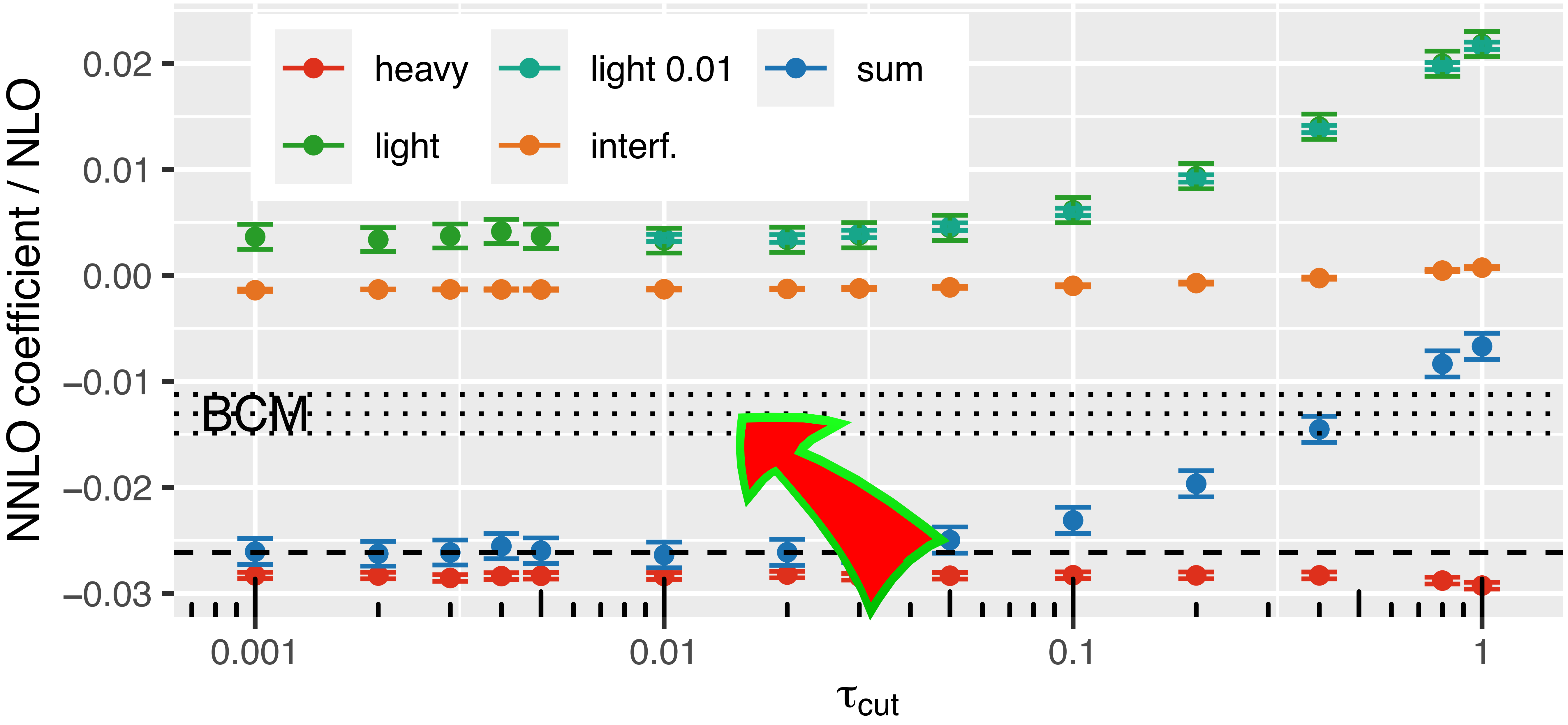
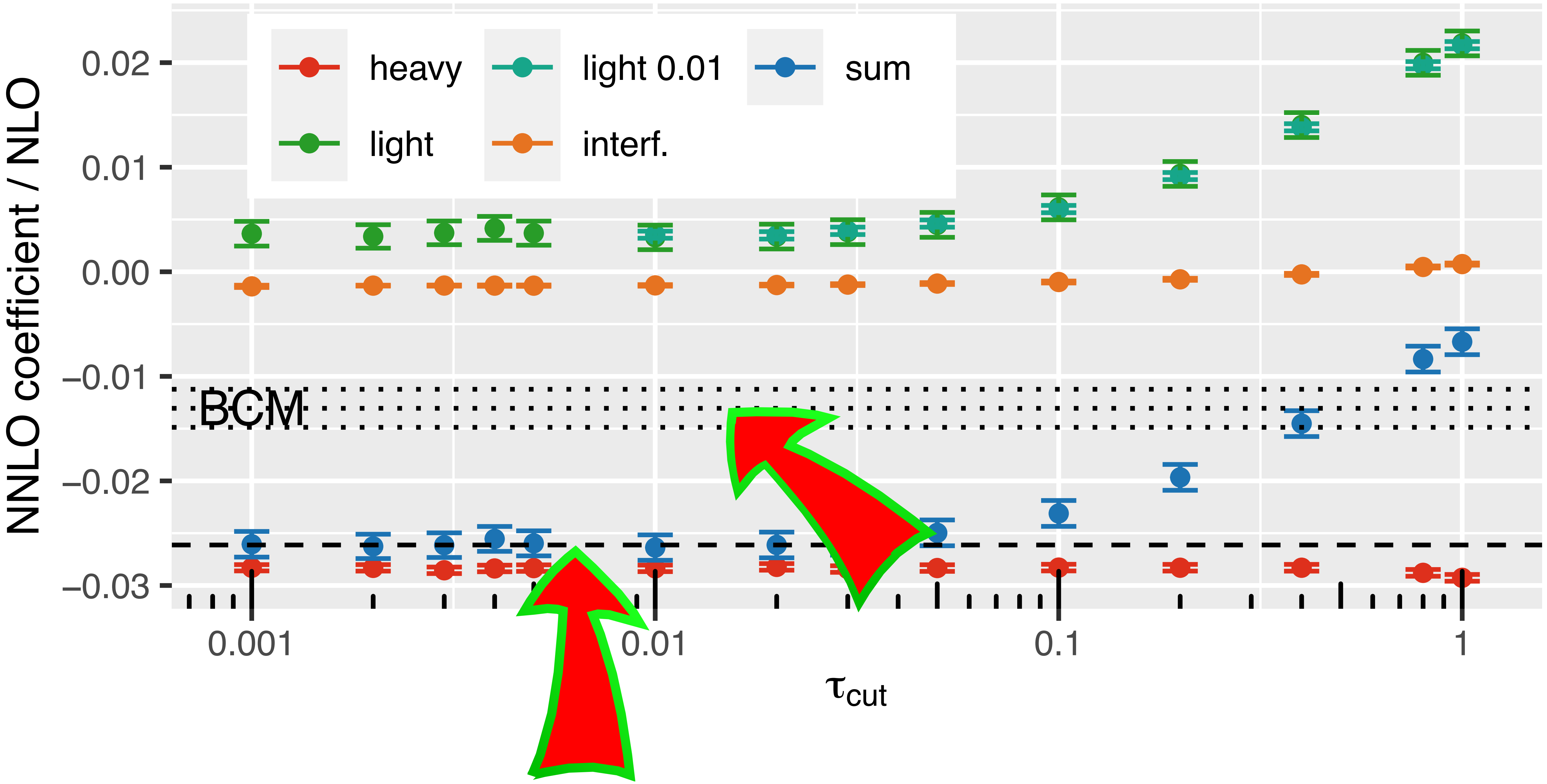
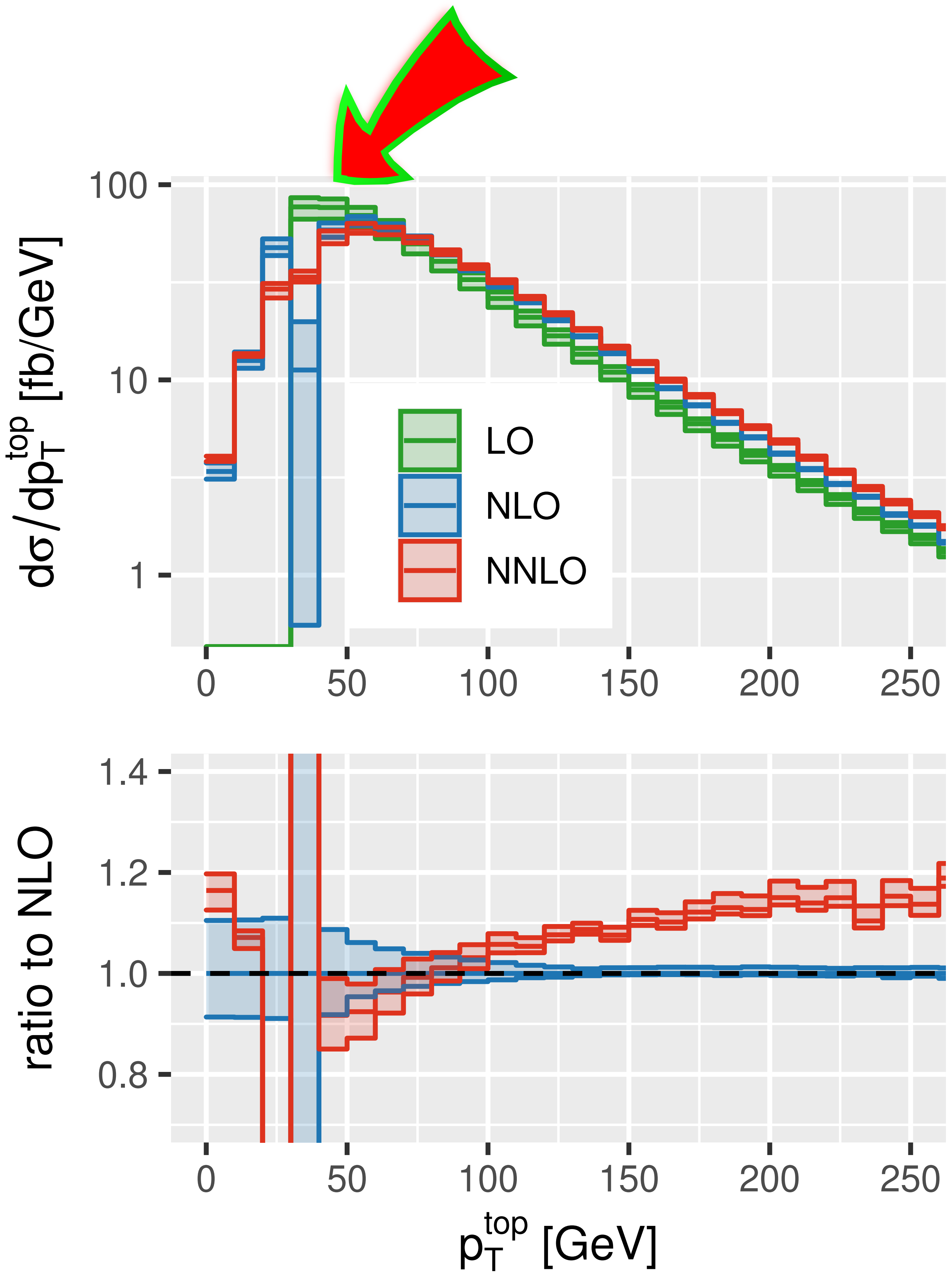


heavy
light 0.01
sum
light
interf.
BCM
NNLO coefficient / NLO
0.02
0.01
0.00
−0.01
−0.02
−0.03
0.001
0.01
0.1
1
τ_{cut}

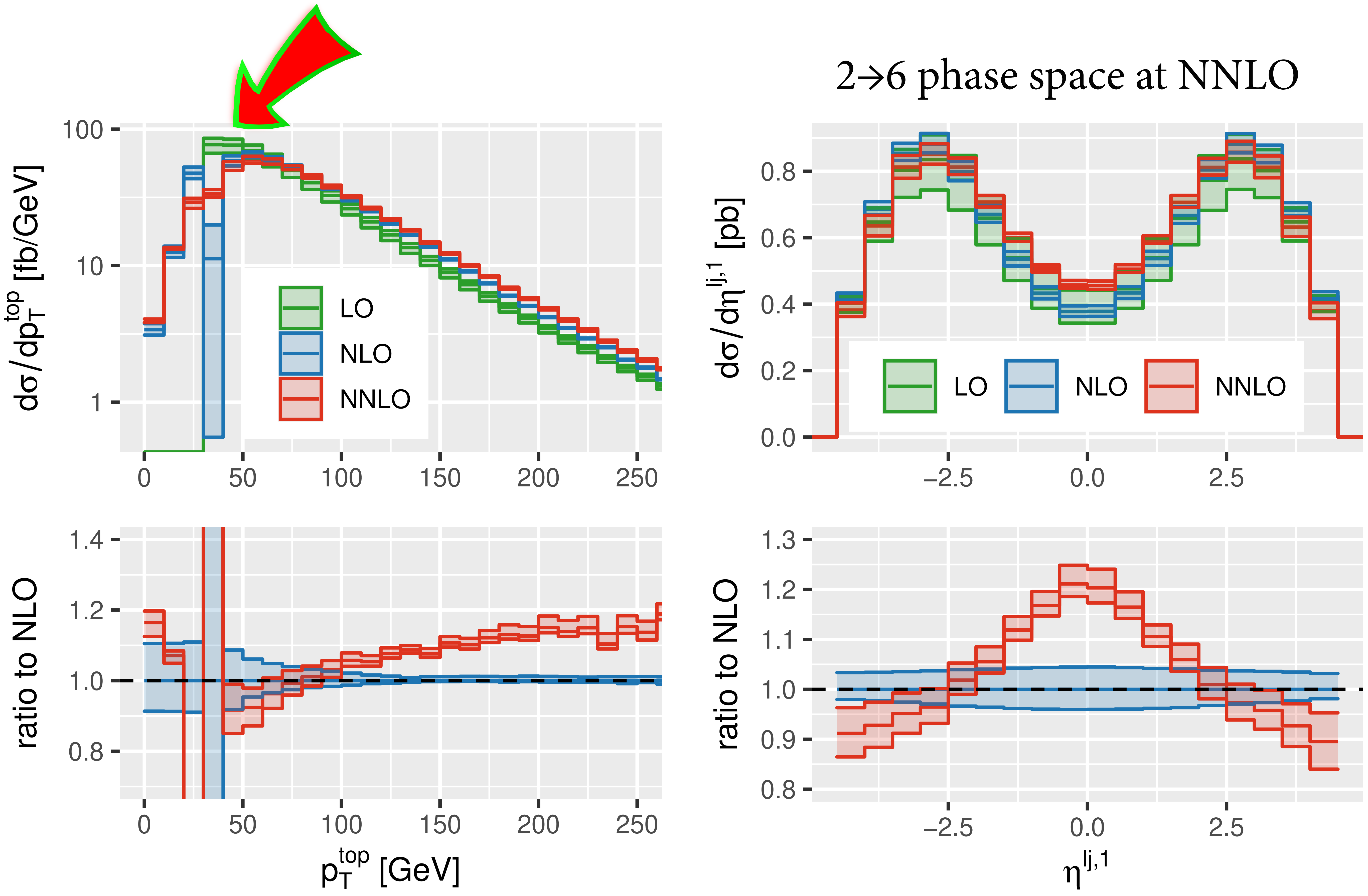


On the other hand: We find full agreement with Berger, Gao, Zhu in extensive comparisons.



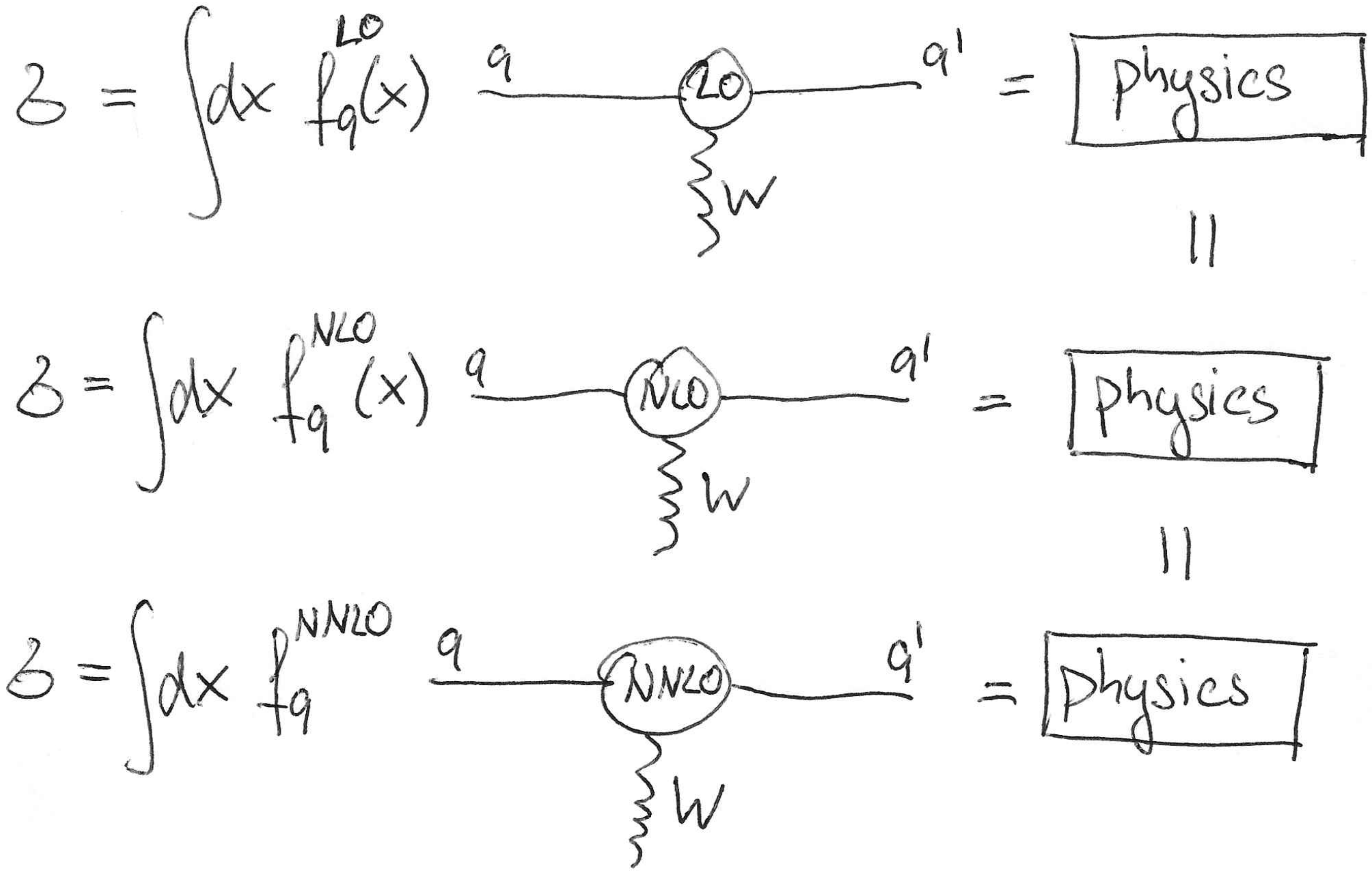
(LHC, typical fiducial cuts, DDIS scales)

2→6 phase space at NNLO



(LHC, typical fiducial cuts, DDIS scales)

Study of PDFs discrepancies with DDIS in upcoming study!



Contributions

CuTe-MCFM: N^3LL+NNLO SCET-based resummation framework

Prime tool to contribute to W/Z precision physics (unique SCET formulation)

Improvements for diboson processes at small q_T ($\gamma\gamma, Z\gamma, ZH, WH$)

Demonstrated power corrections using recoil-scheme
in presence of fiducial cuts and photon isolation

General framework for future processes and other codes

Calculation of t-channel single-top-quark production at NNLO

Resolved discrepancies between previous two calculations

Large fiducial corrections make NNLO important

Double-DIS scales allow for novel PDF constraint

Backup/Details

CuTe-MCFM

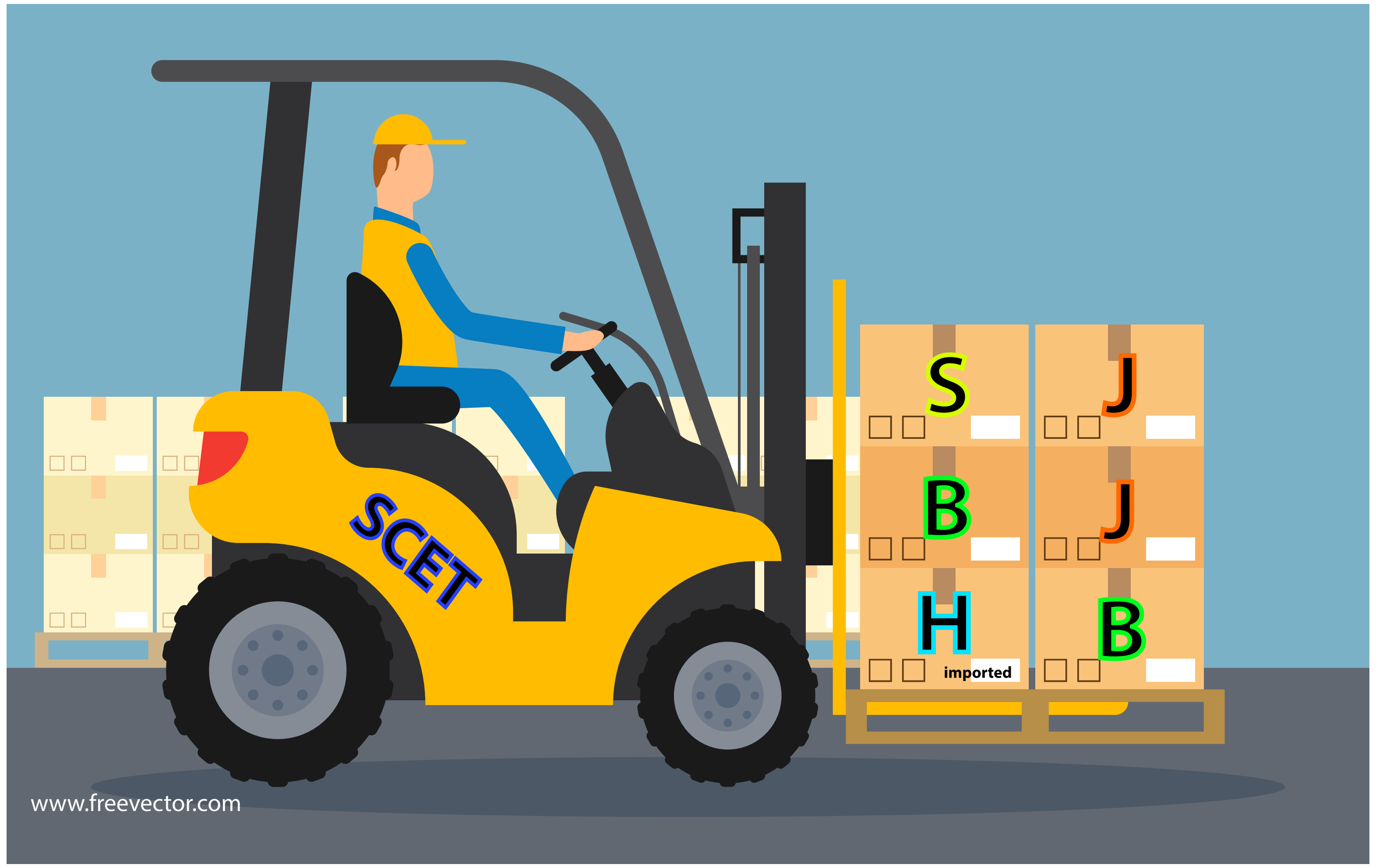
q_T-resummation framework

- All-order formula for resummation of q_T-logs first by Collins, Soper, Sterman '85
- Semi-analytical / PS-like approach: Radish
  Monni, Re, Torrielli '16; Bizon, Monni, Re, Rottoli, Torrielli '17; Banfi, Salam, Zanderighi '04; …
- Modern development in SCET: (re-)derivation of factorization theorem
  ***Becher, Neubert '10**; Chiu, Jain, Neill, Rothstein '12; see also Gao, Li, Liu '05, Idilbi, Ji, Yuan '05, Mantry, Petriello '09; rapidity RGE in q_T space: Ebert, Tackmann '16*

$$\mathrm{d}\sigma = \sum_{i,j} \iint \mathrm{d}\xi_1 \mathrm{d}\xi_2 \, \mathrm{d}\sigma^0_{ij}(p) \, H_{ij}(p,\mu) \times$$

$$\frac{1}{4\pi} \int_{-\infty}^{\infty} \mathrm{d}^2 x_\perp e^{-i q_\perp x_\perp} \left(\frac{x_T^2 Q^2}{2 e^{-\gamma_E}} \right)^{-F_{ij}(x_\perp,\mu)} B_i(\xi_1, x_\perp, \mu) B_j(\xi_2, x_\perp, \mu)$$

N^3LL color-singlet q_T resummation



A pot-pourri of cutting-edge ingredients:

- NNLO / Hard function: process dependent

  qq/gg-formfactors at 2-loop; diboson Gehrmann, Manteuffel, Tancredi '15

- Hard function RGE evolution

  4-loop cusp: Henn, Korchemsky, Mistlberger '19; Manteuffel, Panzer, Schabinger '20
  other ingredients: see Becher, Neubert '09 for overview

- Collinear anomaly/rapidity anom. dim.

  α_s^3*: Li, Zhu '16; Vladimirov '16*

- NNLO beam functions

  Gehrmann, Lübbert, Lin Yang '14; Echevarria, Scimemi, Vladimirov '16; Luebbert, Oredsson, Stahlhofen '16, ...

N^3LL+NNLO: overall α_s^2 accuracy for

$$\log(q_T^2/Q^2) \sim 1/\alpha_s$$

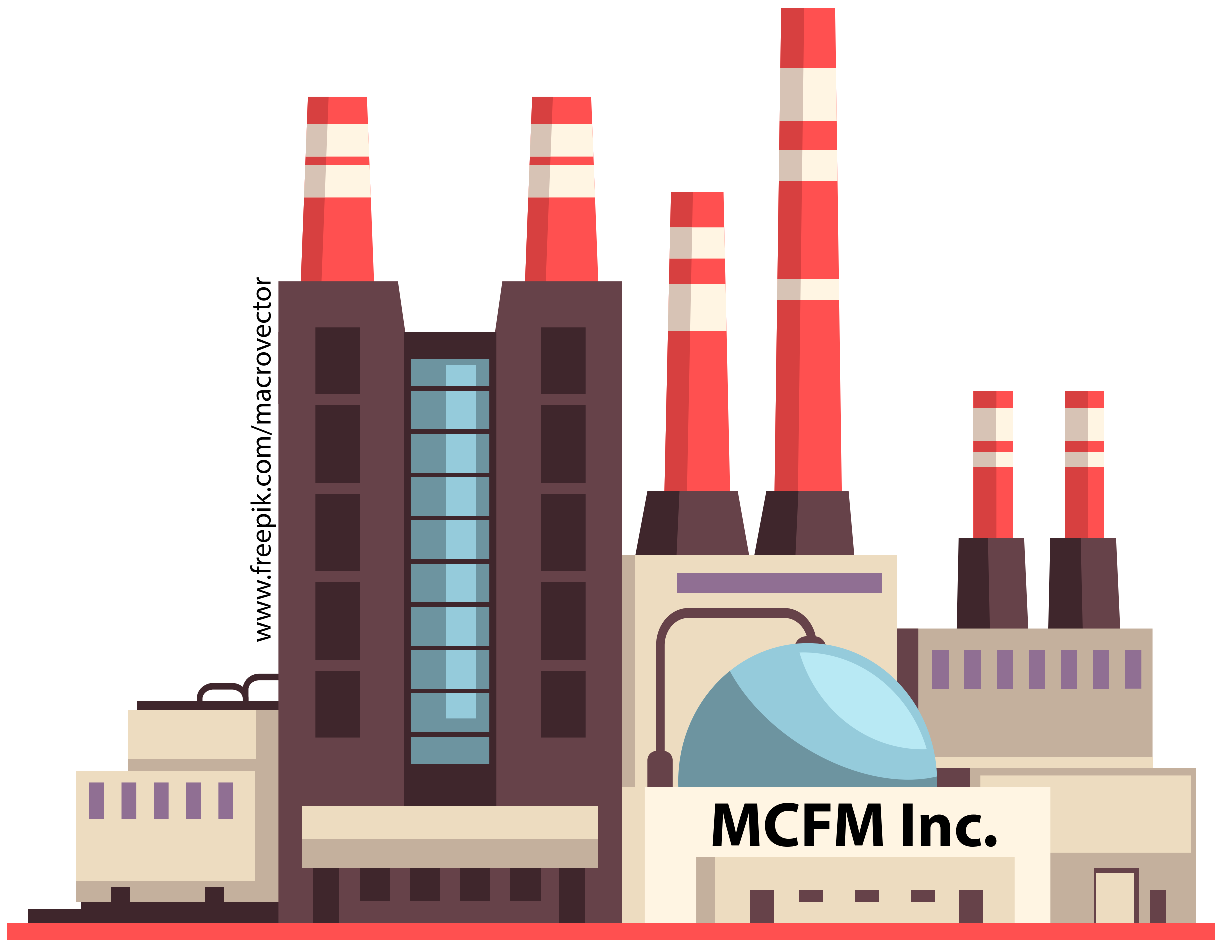
Meanwhile also N^3LO beam functions

Ebert, Mistlberger, Vita '20; Luo, Yang, H.X. Zhu, Y.J. Zhu '20

Our implementation: CuTe-MCFM

Uses broad availability of fixed/higher-order processes in MCFM

- MCFM v9 as basis
  Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams '16
  Neumann, Campbell '19;
- Set of standard NNLO processes: $W^{\pm}$, Z, H, $\gamma\gamma$, $Z\gamma$, $W^{\pm}$H, ZH + many NLO processes
- q_T resummation: Same formalism as CuTe (and cross checks against it), but completely independent implementation and different subleading choices
- Beam-function grid generation
- Scale variation, PDF uncertainties
- Precise control over all numerical uncertainties, OMP+MPI



MCFM-RE N^2LL jet-veto based on JetVHeto
Arpino, Banfi, Jäger, Kauer '19; Banfi, Monni, Salam, Zanderighi '12

(Subleading) Choices

$$\mathrm{d}\sigma = \sum_{i,j} \iint \mathrm{d}\xi_1 \mathrm{d}\xi_2 \, \mathrm{d}\sigma^0_{ij}(p) \, H_{ij}(p,\mu) \times$$

$$\frac{1}{4\pi} \int_{-\infty}^{\infty} \mathrm{d}^2 x_\perp e^{-iq_\perp x_\perp} \left(\frac{x_T^2 Q^2}{2e^{-\gamma_E}} \right)^{-F_{ij}(x_\perp,\mu)} B_i(\xi_1, x_\perp, \mu) B_j(\xi_2, x_\perp, \mu)$$

- Each ingredient separately expanded in RG improved perturbation theory (compare CuTe)
- Collinear anomaly formalism (equivalent to rapidity RGE with fixed ν)
- Reorganized resummation for $q_t \to 0$ ("ϵ"-expansion)
  Becher, Neubert, Wilhelm '11, follows Parisi, Petronzio '79
- No non-perturbative (Landau-pole) treatment necessary, resummation scale always within perturbative regime
- Tree-level kinematics boosted to have $q_\perp^\mu = (0, q_T \cos\Phi, q_T \sin\Phi, 0)$

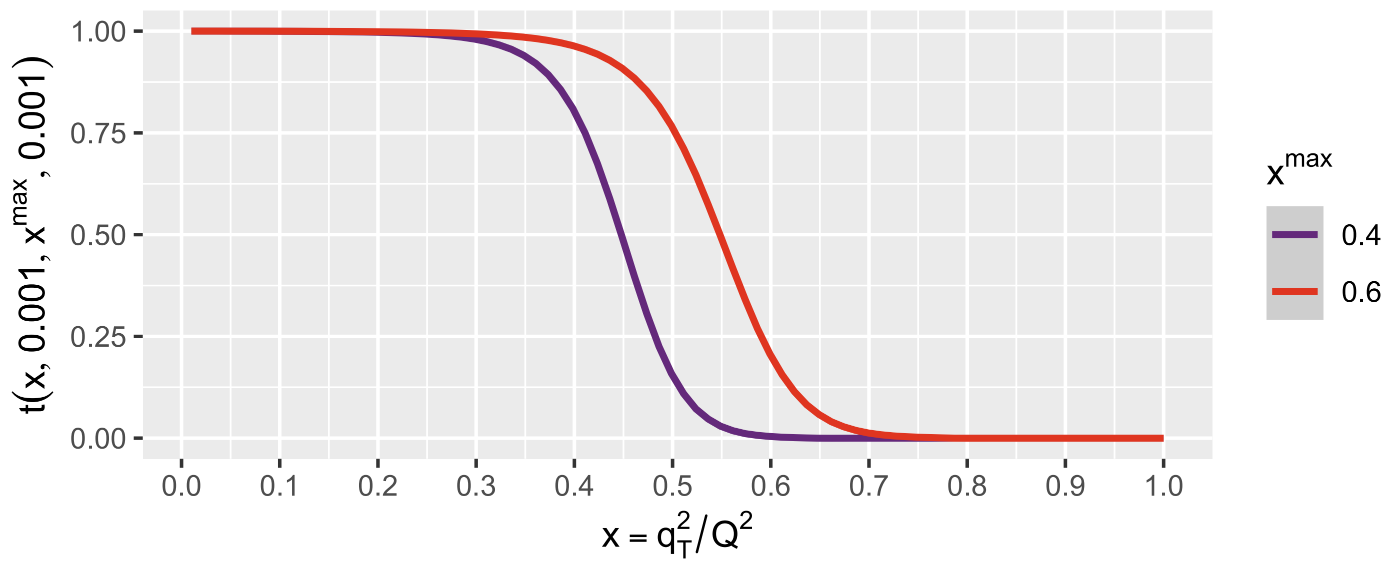
Matching to fixed-order (NNLO)

Naive matching

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T}^{\mathrm{N^3LL,\,naive}} = \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}^{\mathrm{N^3LL}} + \left(\frac{\mathrm{d}\sigma}{\mathrm{d}q_T}^{\mathrm{f.o.}} - \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}^{\mathrm{N^3LL,\,exp.}} \right)$$

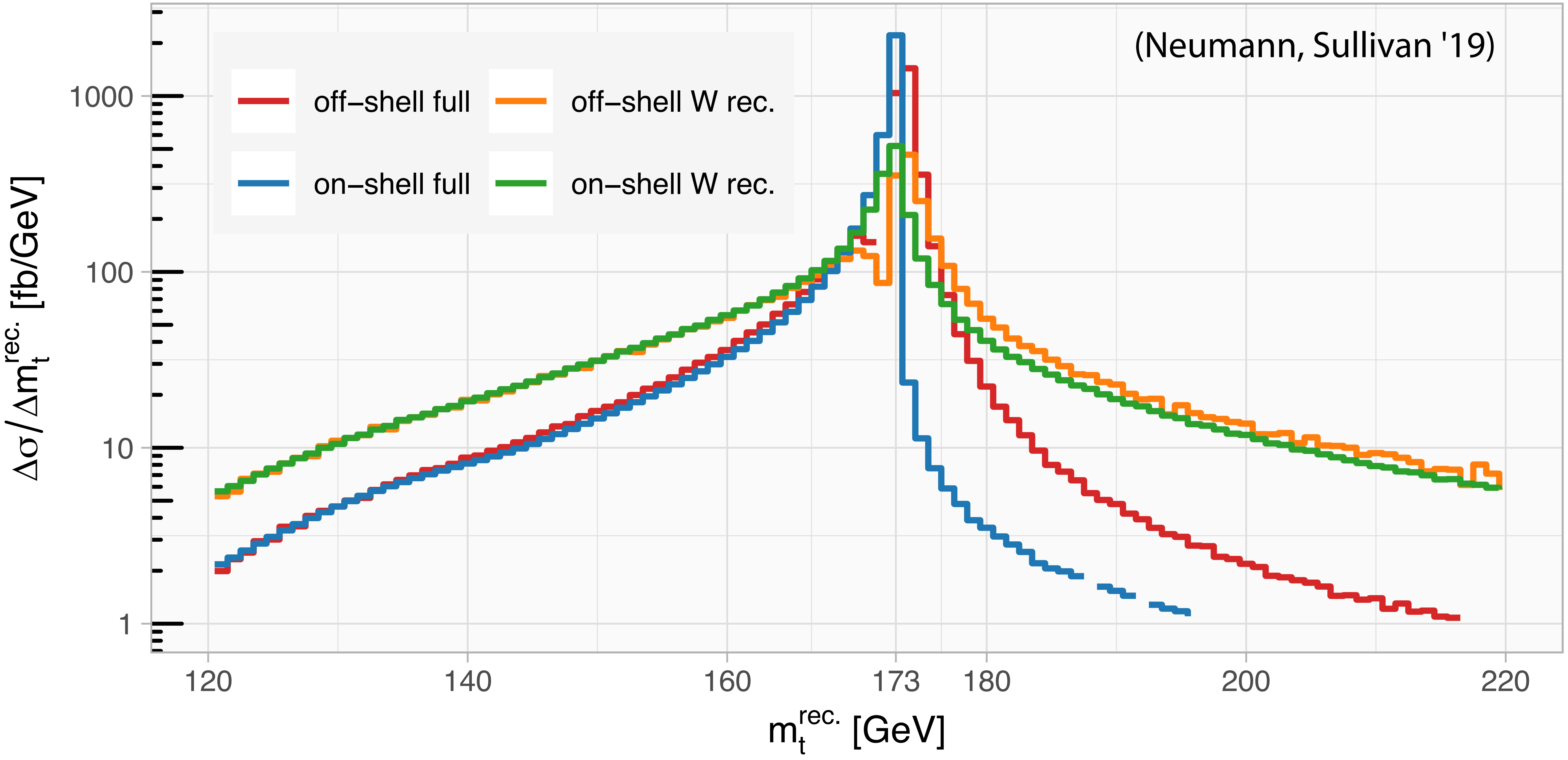
Resummed result only valid for $q_t^2/Q^2 \ll 1$: Transition-function

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T}^{\mathrm{N^3LL,\,full}} = t\left(\frac{q_T^2}{Q^2}\right)\frac{\mathrm{d}\sigma}{\mathrm{d}q_T}^{\mathrm{N^3LL,\,naive}} + \left(1 - t\left(\frac{q_T^2}{Q^2}\right)\right)\frac{\mathrm{d}\sigma}{\mathrm{d}q_T}^{\mathrm{f.o.}}$$



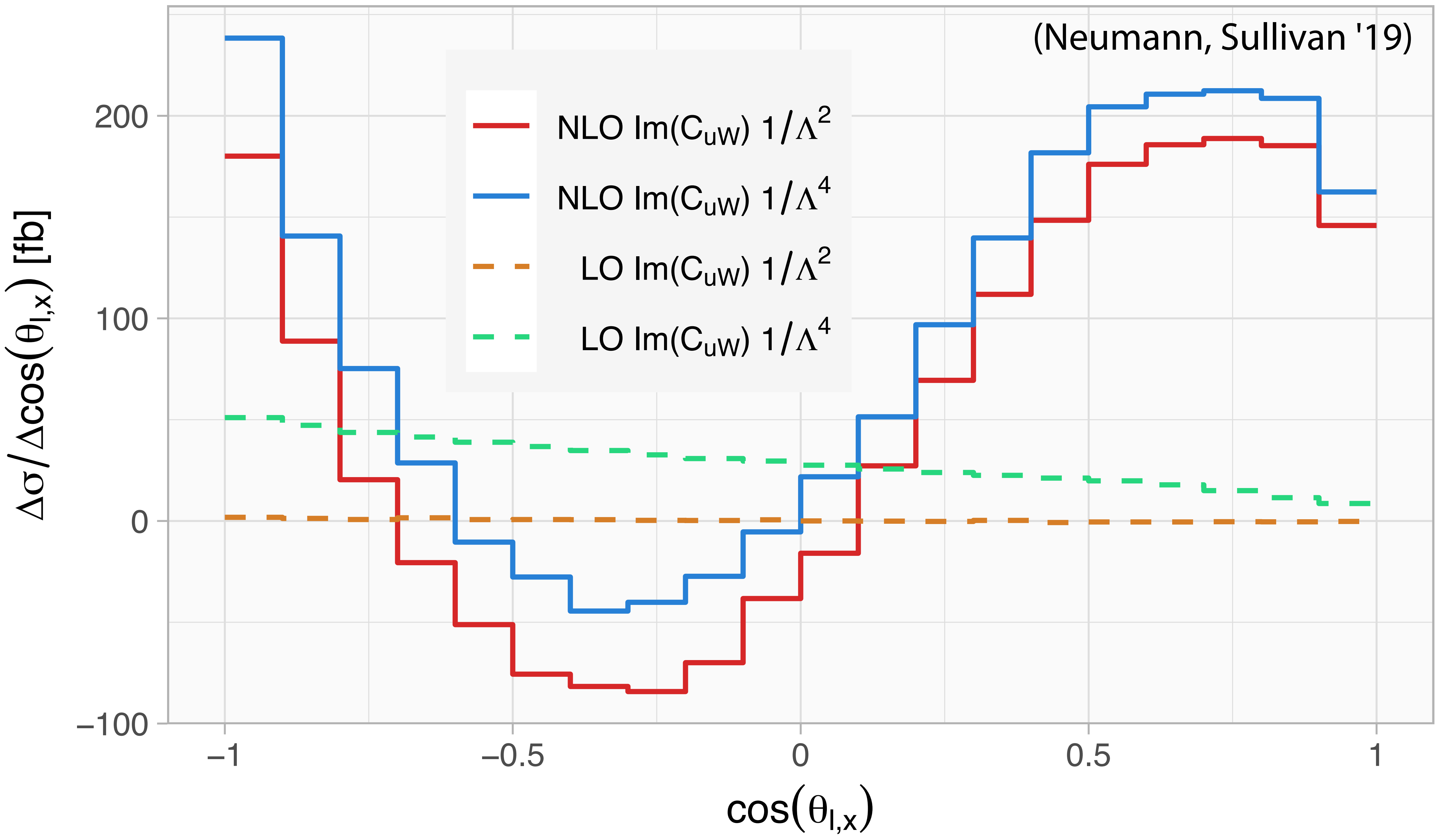
t-channel single-top-quark off-shell + SMEFT

Inclusively: Off-shell effects $\mathcal{O}(\Gamma_t/m_t)$



(for a decay study see also (Boughezal, Chen, Petriello, Wiegand '19))

Importance of NLO effects in the SMEFT



MCFM 9

Improvements in MCFM 9 (Neumann, Campbell '19)
automatic taucut fitting, power corrections, improved jettiness definition

Color singlets at NNLO, public in MCFM	
H	1605.08011: Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, Williams
Z (w. NLO EW)	
$W^{\pm}$	
ZH	
$W^{\pm}H$	1601.00658: Campbell, Ellis, Williams
γ	1612.04333: Campbell, Ellis, Williams
$\gamma\gamma$	1603.02663: Campbell, Ellis, Li, Williams
$Z\gamma$	1708.02925: Campbell, Neumann, Williams

NNLO benchmark results in MCFM-9.0

Process	`nproc`	$\tau_{\rm cut}$ [GeV]	$\sigma^{\rm NLO}$	$\sigma^{\rm NNLO}$	fitted corr.	CPU time [h]
W^+	1	$6 \cdot 10^{-3}\, m_W$	$4.221\,\rm nb$	$4.209 \pm 0.005\,\rm nb$	$-27 \pm 15\,\rm pb$	7.6
W^-	6	$6 \cdot 10^{-3}\, m_W$	$3.315\,\rm nb$	$3.275 \pm 0.004\,\rm nb$	$-25 \pm 10\,\rm pb$	7.8
Z	31	$6 \cdot 10^{-3}\, m_Z$	$885.3\,\rm pb$	$875.8 \pm 0.9\,\rm nb$	$-3.5 \pm 2.0\,\rm fb$	13.0
H	112	$4 \cdot 10^{-3}\, m_H$	$1.396\,\rm pb$	$1.872 \pm 0.002\,\rm pb$	$7 \pm 6\,\rm fb$	9.7
$\gamma\gamma$	285	$1 \cdot 10^{-4}\, m_{\gamma\gamma}$	$27.91\,\rm pb$	$43.54 \pm 0.08\,\rm pb$	$0.36 \pm 0.10\,\rm pb$	83.2
W^+H	91	$3 \cdot 10^{-3}\, m_{W^+H}$	$2.204\,\rm fb$	$2.262 \pm 0.004\,\rm fb$	$0.002 \pm 0.008\,\rm fb$	16.0
W^-H	96	$3 \cdot 10^{-3}\, m_{W^-H}$	$1.491\,\rm fb$	$1.526 \pm 0.003\,\rm fb$	$-0.005 \pm 0.007\,\rm fb$	13.0
ZH	110	$3 \cdot 10^{-3}\, m_{ZH}$	$0.753\,\rm fb$	$0.842 \pm 0.001\,\rm fb$	$-0.005 \pm 0.003\,\rm fb$	12.5
$Z\gamma$	300	$3 \cdot 10^{-4}\, m_{Z\gamma}$	$434\,\rm fb$	$525.5 \pm 1.0\,\rm fb$	$4.5 \pm 1.7\,\rm fb$	202.5

Large performance improvements through implementation of subleading terms in τ-factorization

(Moult, Rothen, Stewart, Tackmann, Zhu '17; Ebert, Moult, Stewart, Tackmann, Vita, Zhu '18;) and (Boughezal, Liu, Petriello '16; Boughezal, Isgro, Petriello '18)