N3LO CORRECTIONS TO NEUTRAL AND CHARGED CURRENT AT THE LHC

W质量研讨会： UNCERTAINTIES AND OPPORTUNITIES

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Online, 7 May, 2022

Karlsruher Institut für Technologie

"THREE CLOUDS" IN PARTICLE PHYSICS SINCE 2021

Test of lepton universality in beauty-quark decays #1
LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Mar 22, 2021)
Published in: *Nature Phys.* 18 (2022) 3, 277-282 • e-Print: 2103.11769 [hep-ex]
pdf links DOI cite datasets 313 citations

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Muon g-2 Collaboration • B. Abi (Oxford U.) et al. (Apr 7, 2021)
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CDF Collaboration • T. Aaltonen (Helsinki U. and Helsinki Inst. of Phys.) et al. (Apr 8, 2022)
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Statistics from iNSPIRE-HEP by 19-04-2022

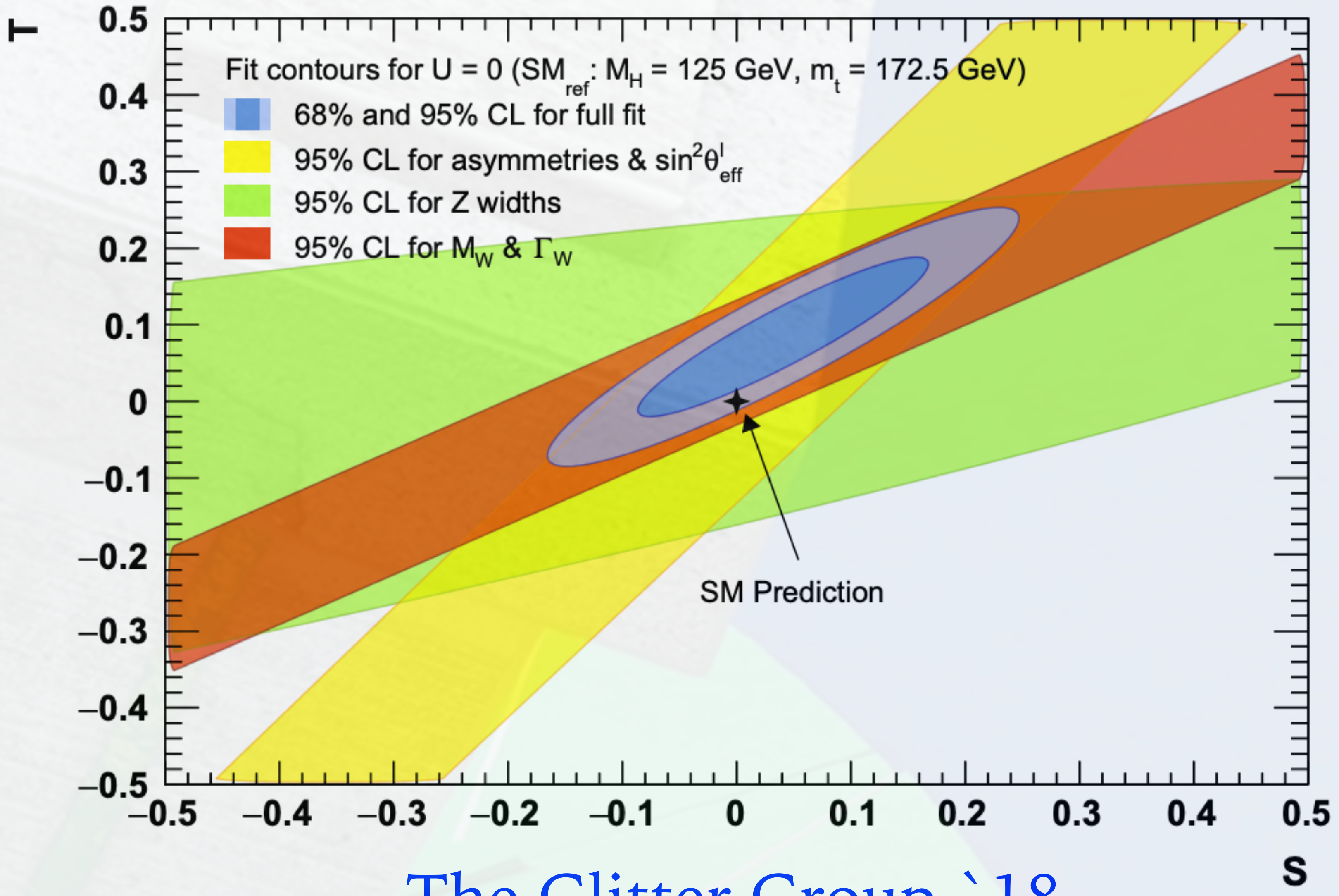
- Fitting the elephant with BSM free parameters
  - The "oblique corrections" S-T-U in vacuum polarisation:

$$\alpha S = 4e^2[\Pi'_{33}(0) - \Pi'_{3Q}(0)]$$

$$\alpha T = \frac{e^2[\Pi_{11}(0) - \Pi_{33}(0)]}{\sin^2(\theta_W)\cos^2(\theta_W)m_Z^2}$$

$$\alpha U = 4e^2[\Pi'_{11}(0) - \Pi'_{33}(0)]$$

Peskin and Takeuchi `92



The Glitter Group `18

- Further experimental confirmation
  - Fermilab Run 2 ~ Run 5 analysis
  - LHCb Upgrade I (2025) and II (2030)
  - ATLAS, LHCb, CMS all have on-going analysis of W mass.

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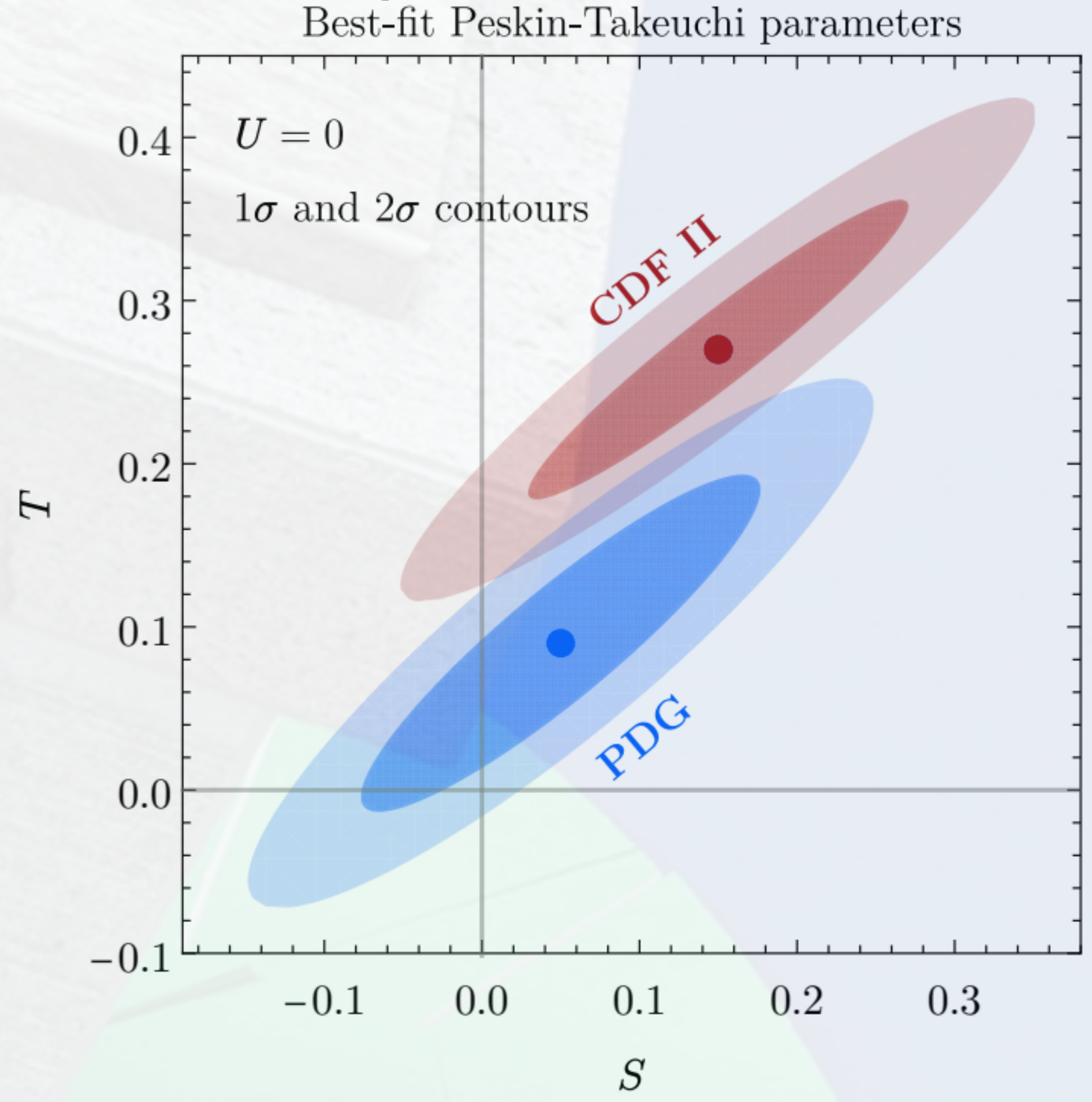
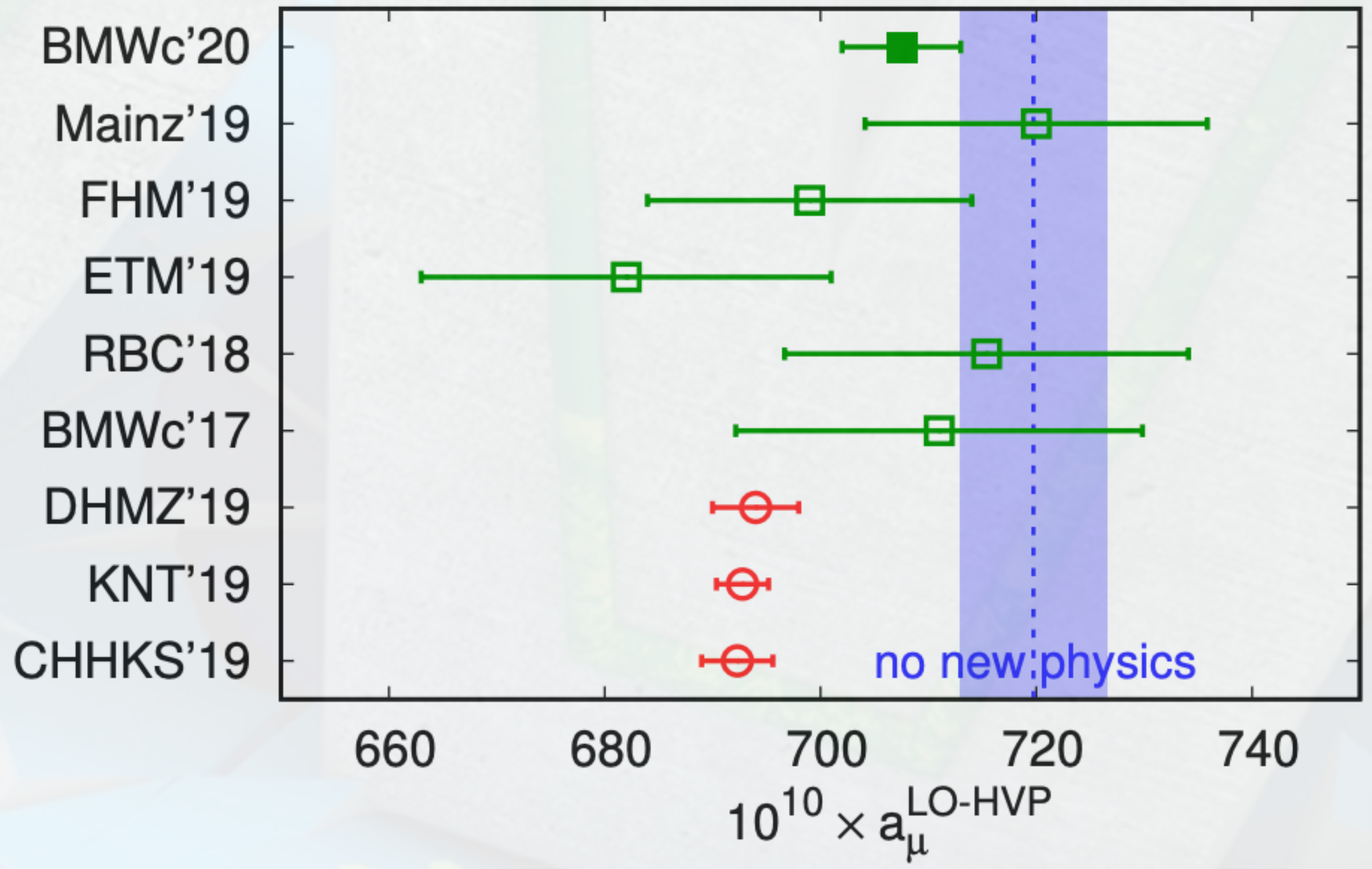
Carpenter, Murphy, Smylie `22





- Challenge experiment with better/alternative predictions
  - Lattice prediction of HVP in g-2
    Borsanyi, Fodor et. al. `21
  - Improve template fit in CDFII (ResBos@NLO+NNLL)

W MASS IN CDFII MEASUREMENT

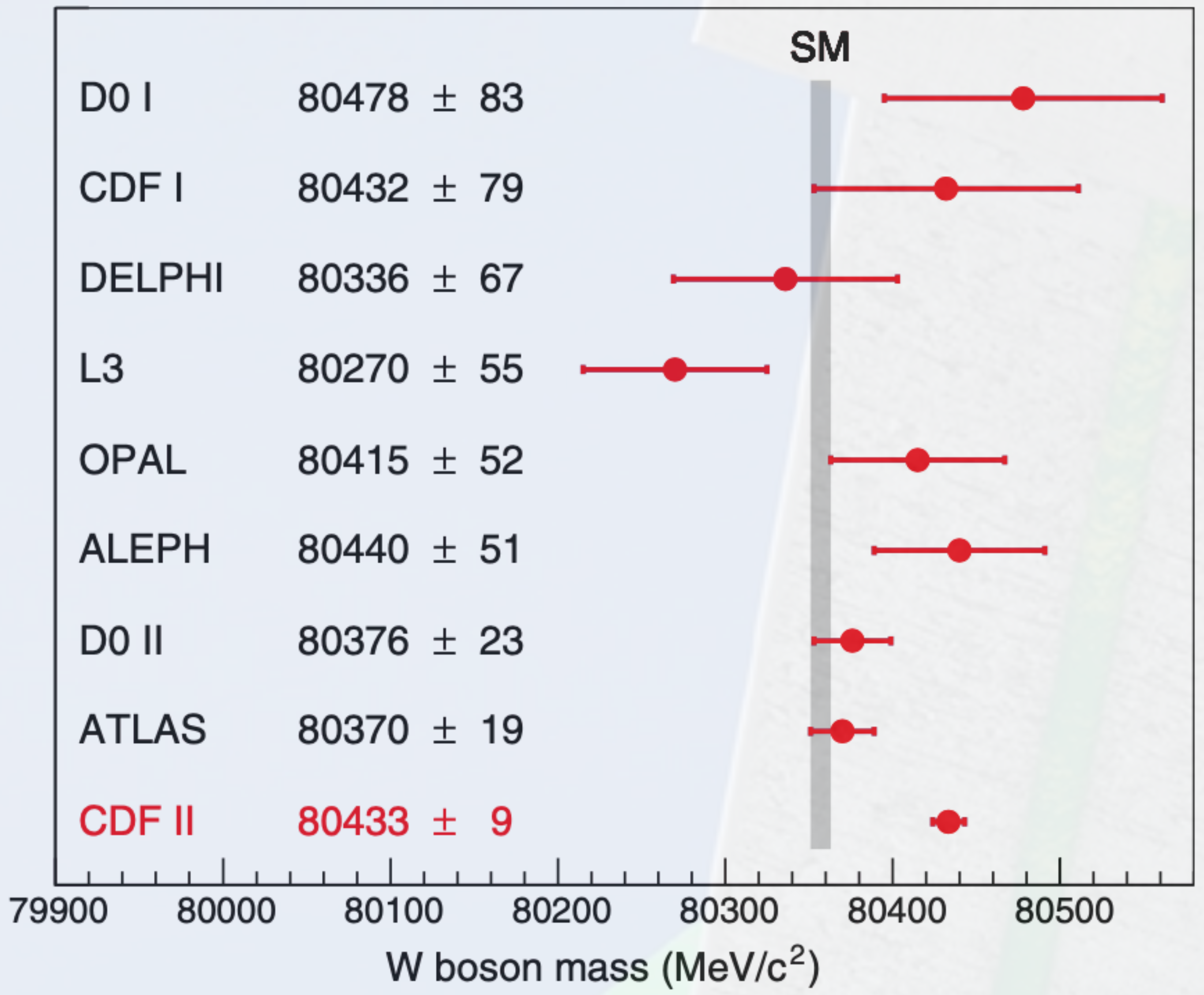


Table 1. Individual fit results and uncertainties for the M_W measurements. The fit ranges are 65 to 90 GeV for the m_T fit and 32 to 48 GeV for the p_T^ℓ and p_T^ν fits. The χ^2 of the fit is computed from the expected statistical uncertainties on the data points. The bottom row shows the combination of the six fit results by means of the best linear unbiased estimator (66).

Distribution	W boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^\ell(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^\nu(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu,\nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^\ell(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^\nu(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

- PDG world average: $m_W = 80379 \pm 12\ MeV$ (Particle Data Group `20)
- CDFII latest result: $m_W = 80433 \pm 9\ MeV$ (CDF `22)
  - Indirect measurement of m_T^W, p_T^l, p_T^ν distributions

$$p_T^{l(\nu)} = \sqrt{(p_x^{l(\nu)})^2 + (p_y^{l(\nu)})^2}$$

$$E_T^{l(\nu)} = \sqrt{m^2 + (p_x^{l(\nu)})^2 + (p_y^{l(\nu)})^2} \approx p_T^{l(\nu)}$$

$$m_T^W = \sqrt{2E_T^l E_T^\nu (1 - \cos\Delta\phi)}$$

  - Template fit to best best parameter values
  - Full error = Experiment + Theory model
  - Experiment statistics: $\pm 6.4\ MeV$
  - Experiment systematic: $\pm 5.3\ MeV$
  - Theory model: $\pm 5.2\ MeV$ $\pm ??\ MeV$

    ResBos, DYqT, PHOTOS, HORACE

Table 2. Uncertainties on the combined M_W result.

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

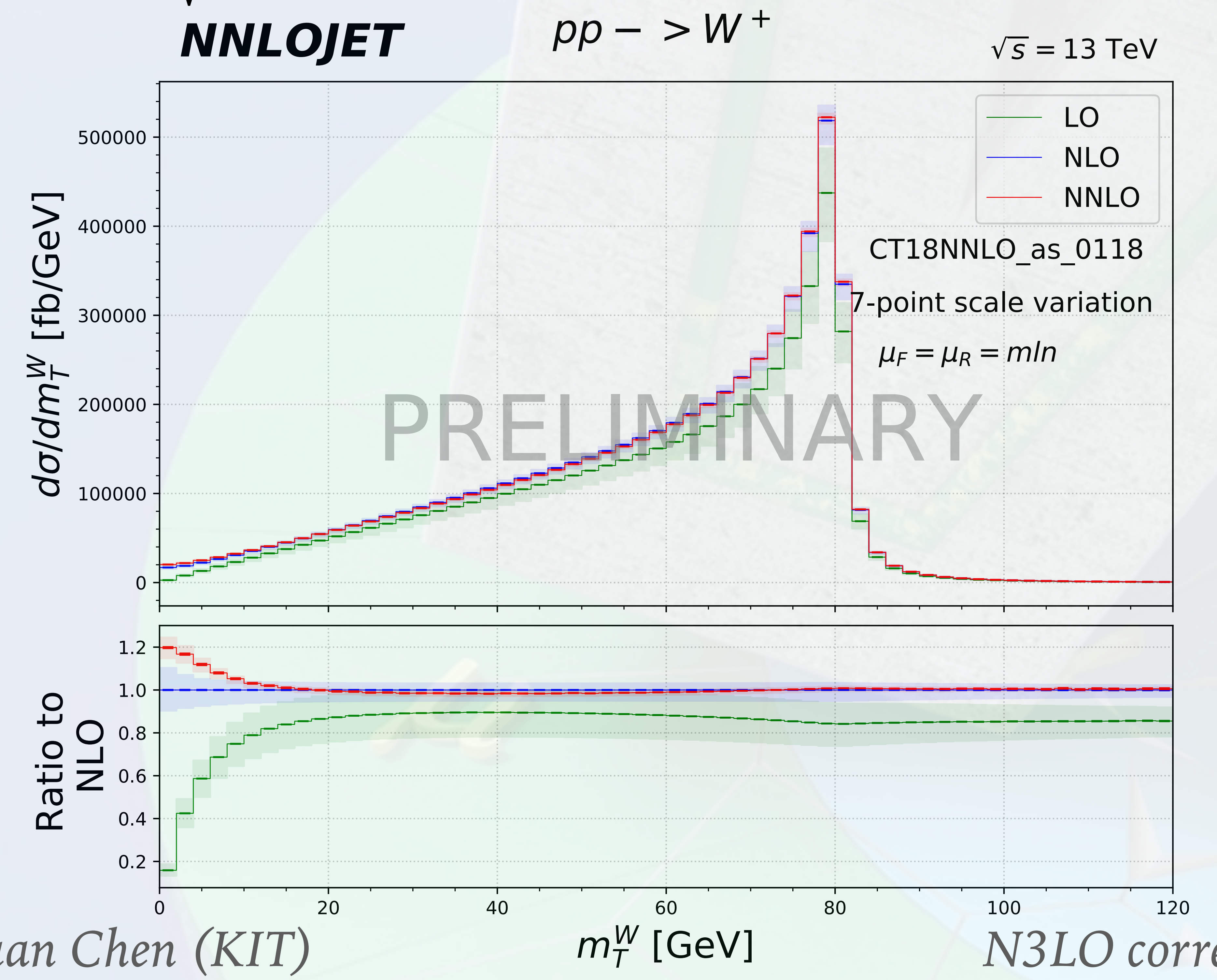
W MASS IN CDFII MEASUREMENT

➤ $d\sigma/dp_T^{l(\nu)}$, $d\sigma/dm_T^W$ at hadron colliders ($p_a, p_b \to p_1, p_2$ at centre of mass frame):

$$p_a = (\sqrt{p^2 + m_a^2}, 0, 0, p)$$
$$p_b = (\sqrt{p^2 + m_b^2}, 0, 0, -p)$$
$$p_1 = (\sqrt{q^2 + m_1^2}, q\sin\theta\cos\phi, q\sin\theta\sin\phi, q\cos\theta)$$
$$p_2 = (\sqrt{q^2 + m_2^2}, -q\sin\theta\cos\phi, -q\sin\theta\sin\phi, -q\cos\theta)$$

$$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ac$$
$$p = \frac{\lambda^{\frac{1}{2}}(s, m_a^2, m_b^2)}{2\sqrt{s}},$$
$$q = \frac{\lambda^{\frac{1}{2}}(s, m_1^2, m_2^2)}{2\sqrt{s}},$$

$$p_T^{l(\nu)} = \sqrt{(p_x^{l(\nu)})^2 + (p_y^{l(\nu)})^2} = \frac{\sqrt{s}}{2}\sin\theta \to m_W/2$$
$$E_T^{l(\nu)} = \sqrt{m^2 + (p_x^{l(\nu)})^2 + (p_y^{l(\nu)})^2} \approx p_T^{l(\nu)} \to m_W/2$$
$$m_T^W = \sqrt{2E_T^l E_T^\nu(1 - \cos\Delta\phi)} \to m_W$$

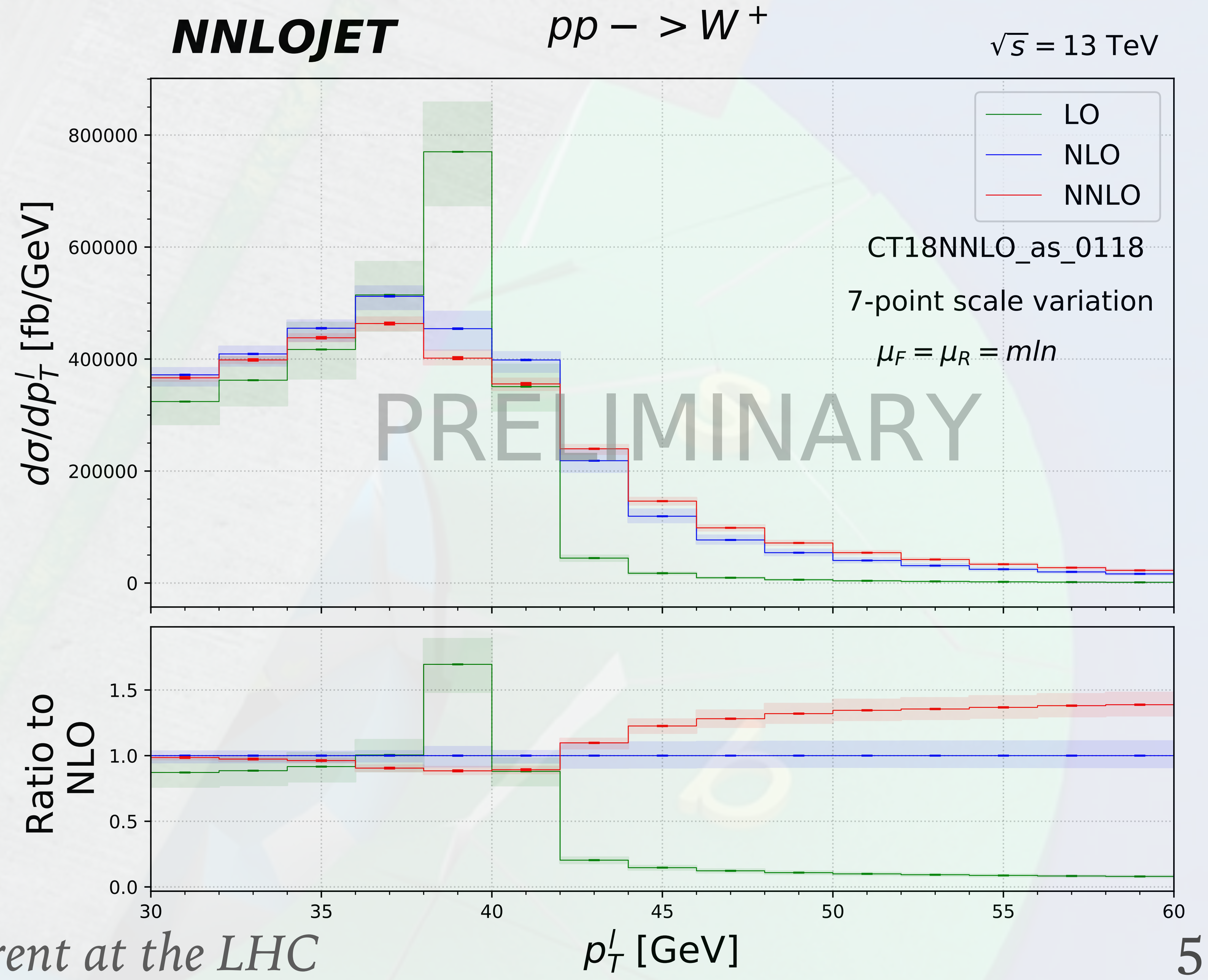


➤ Γ_W sensitive region

➤ m_W sensitive region

➤ PDF sensitive

➤ Resumation region



W MASS IN CDFII MEASUREMENT

➤ $d\sigma/dm_T^W$ Template fit to best best parameter values:

CDFII: 0.2 MeV granularity of m_W with fixed Γ_W

W MASS IN CDFII MEASUREMENT

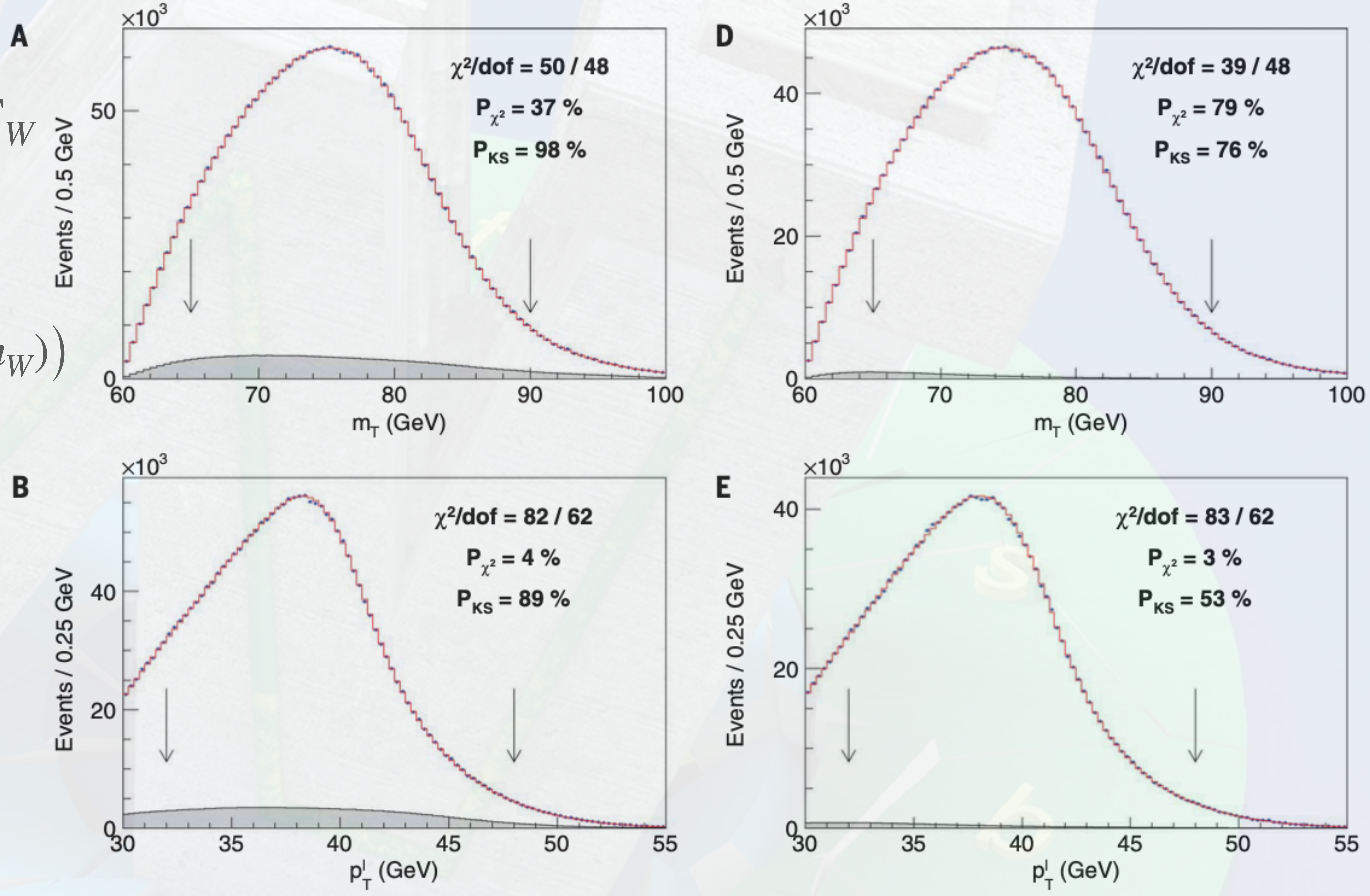
- $d\sigma/dm_T^W$ Template fit to best best parameter values:
  - Relativistic Breit-Wigner form: $(s^2 - m_W^2 + is^2\Gamma_W/m_W)^{-1}$ with fixed Γ_W
  - Binned maximum-likelihood fit: (Poisson distribution cross bins)

$$-\ln\mathscr{L}_b(m_W) = -\sum_b \left(n_b \ln\left(\Delta\sigma_b(m_W)\right) - \Delta\sigma_b(m_W)\right)$$

  - χ^2 analysis for the best fit of each obs.
  - The best linear unbiased estimator to combine each obs.:
    - $\chi^2/\text{dof} = 7.4/5 \rightarrow$ p-value = 20%
    - Weight distribution:

$m_T^W \sim 64.2\,\%$, $p_T^l \sim 25.4\,\%$, $p_T^\nu \sim 10.4\,\%$

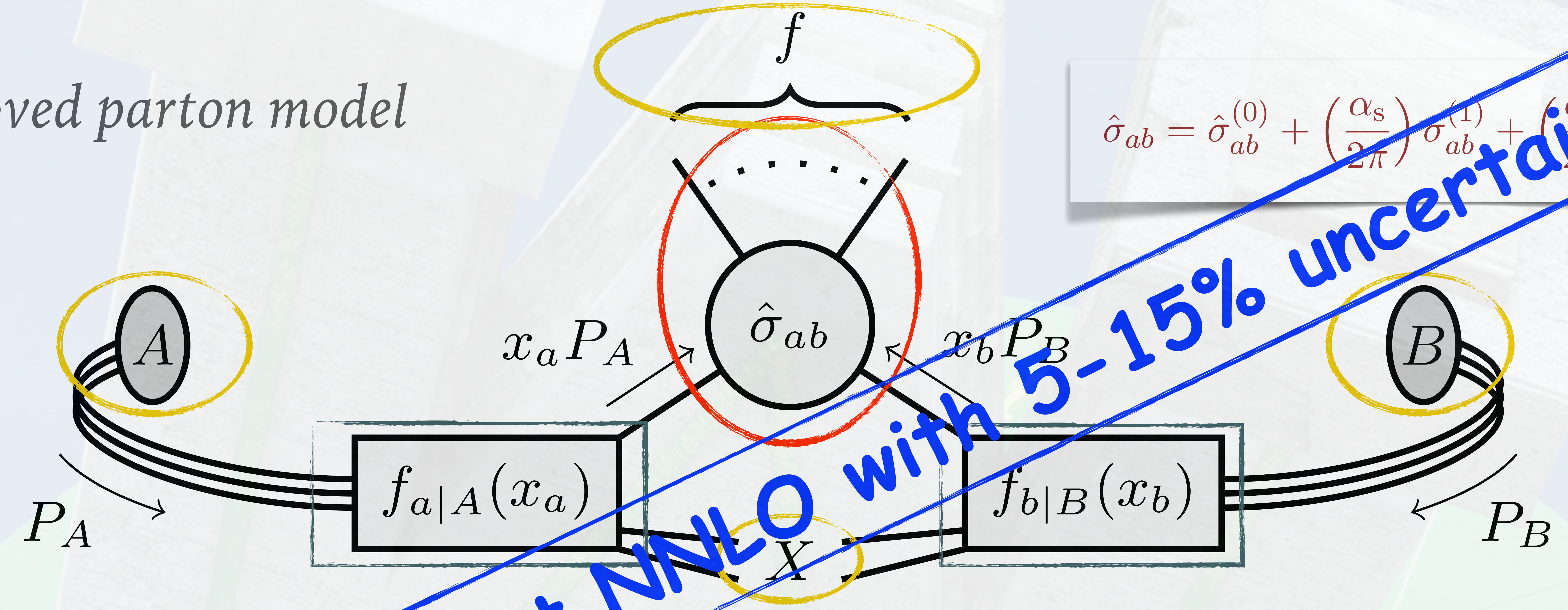
CDFII: Best fitted results for m_T^W, p_T^l



PRECISION PREDICTIONS AT THE LHC

QCD improved parton model

$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0)} + \left(\frac{\alpha_s}{2\pi}\right)\hat{\sigma}_{ab}^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2\hat{\sigma}_{ab}^{(2)} + \dots$$



Typical precision at NNLO with 5-15% uncertainties

$$\sigma_{AB} = \sum_{ab}\int_0^1 dx_a \int_0^1 dx_b\, f_{a|A}(x_a)\, f_{b|B}(x_b)\, \hat{\sigma}_{ab}(x_a, x_b)\, (1+\mathcal{O}(\Lambda_{QCD}/Q))$$

Parton distribution functions
(Energy evolution from all exp.)
± 3-5 % at LHC energy

Hard scattering
(Perturbative quantum field theory)
± 10 % level!

non-perturbative effects
(Fragmentation, hadronisation)
± 1.2 GeV/13 TeV

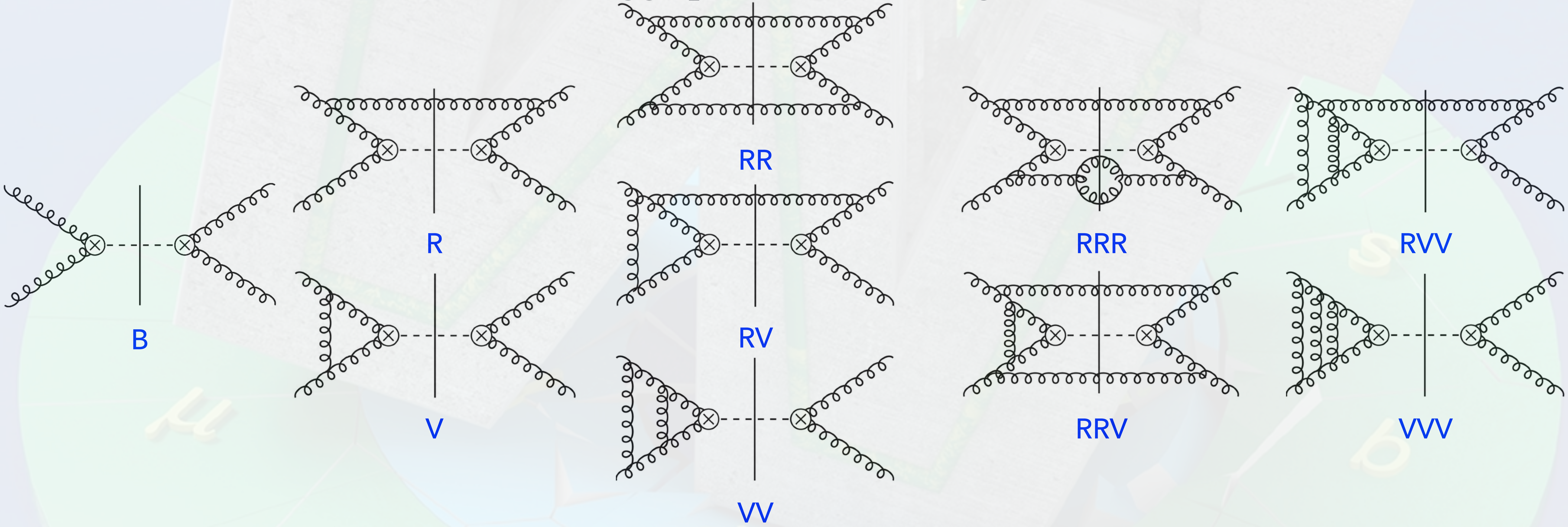
ANATOMY OF HARD SCATTERING $\hat{\sigma}_{ab}$

➤Building blocks from perturbative QFT

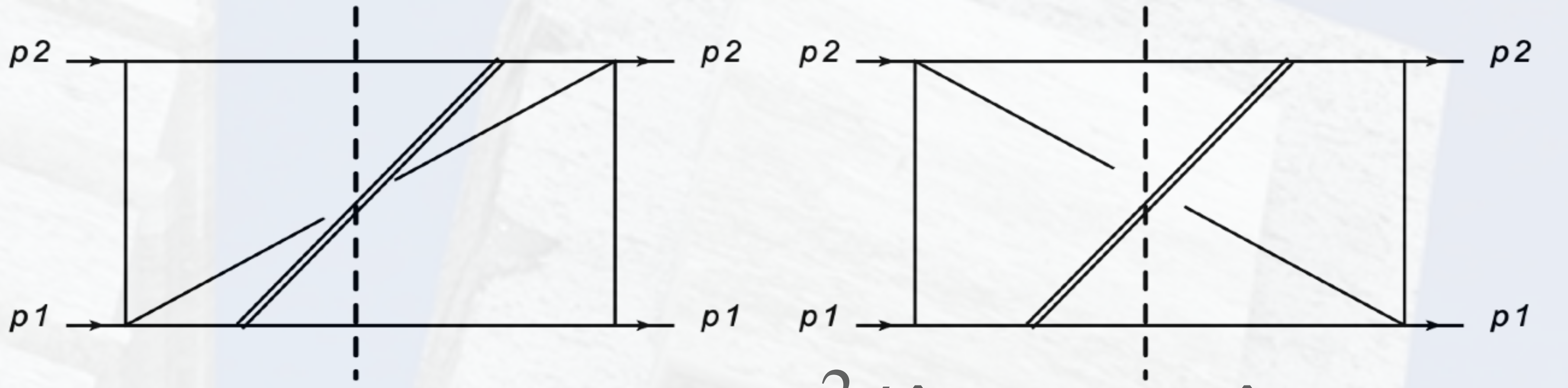
$$\hat{\sigma} = \alpha_s(\hat{\sigma}^B) + \alpha_s^2(\hat{\sigma}^R + \hat{\sigma}^V) + \alpha_s^3(\hat{\sigma}^{RR} + \hat{\sigma}^{RV} + \hat{\sigma}^{VV}) + \alpha_s^4(\hat{\sigma}^{RRR} + \hat{\sigma}^{RRV} + \hat{\sigma}^{RVV} + \hat{\sigma}^{VVV}) + \mathcal{O}(\alpha_s^5)$$

$\hat{\sigma}_{LO}$ $\hat{\sigma}_{NLO}$ $\hat{\sigma}_{NNLO}$ $\hat{\sigma}_{N^3LO}$ ...

Matrix elements for Higgs production from gluon fusion (in HTL)



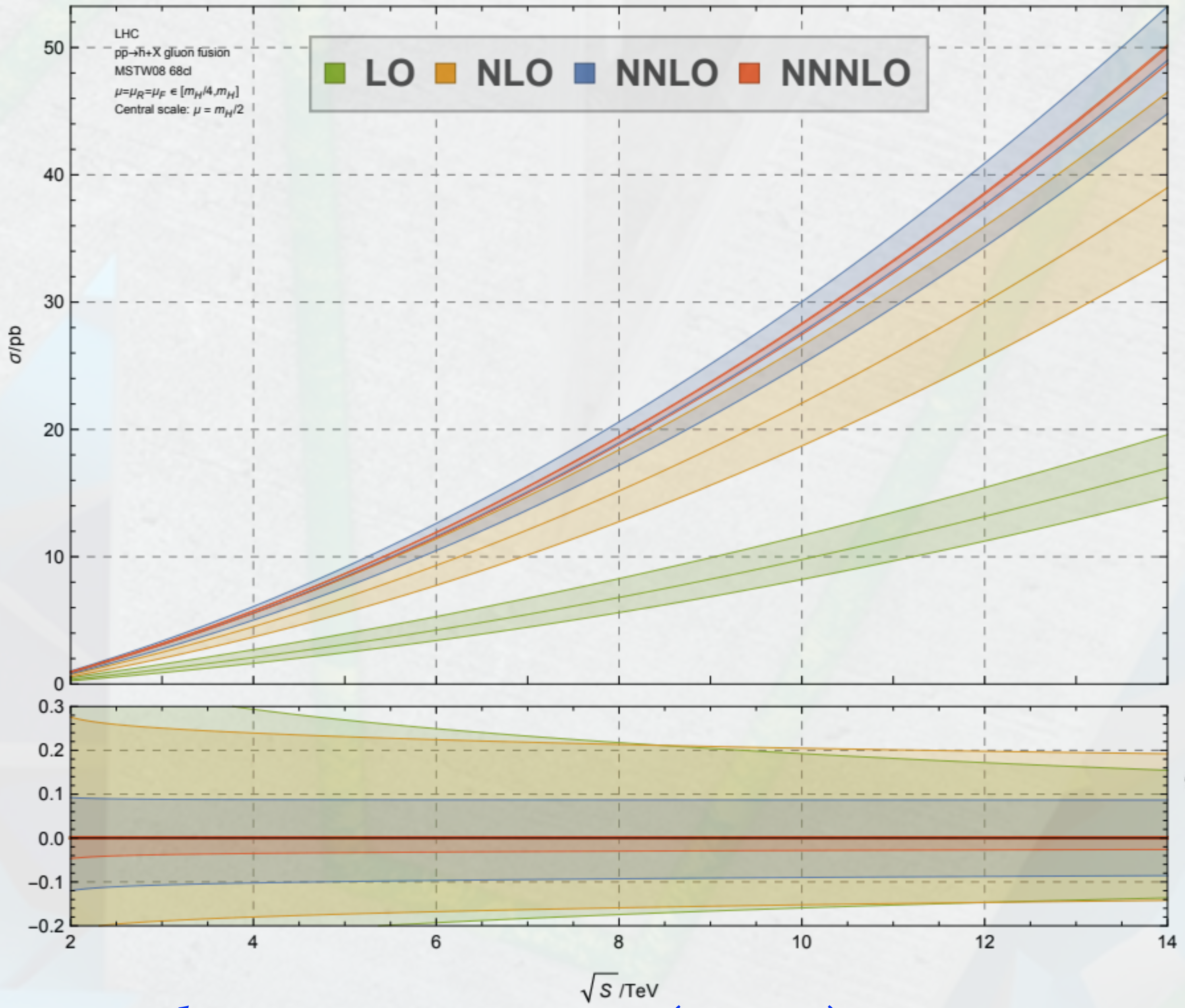
STATE-OF-THE-ART PREDICTIONS FOR σ_{N^3LO}



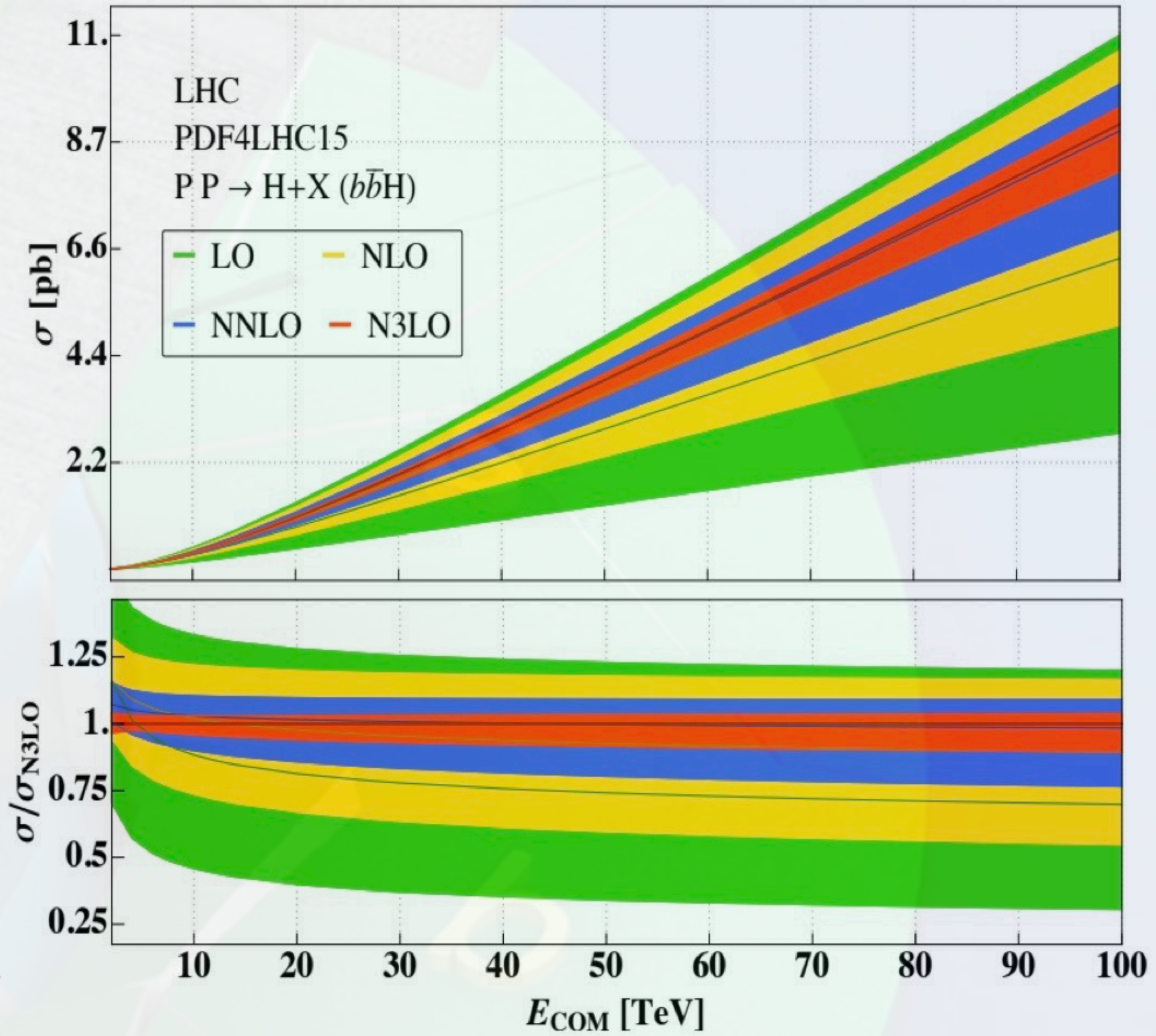
- Assemble each $\hat{\sigma}_{ab}(x_a, x_b)$ at N3LO
  - Integration of QCD radiation with unitarity cuts
  - Standard treatment of multi-loop calculations except elliptic integrals with $\tau = m^2/\hat{s}$ where $\hat{s} = x_a x_b s$
  - Use threshold expansion at different region of τ and truncate at sufficiently high orders. (Mistlberger `18)
  - Use generalised power series ansatz to test the approximation and match coeff. of overlapping regions.

Not exact analytical solution of elliptic integrals but numerically precise enough for phenomenology

- Application of ggF Higgs production
  - Remarkable precision of the first N3LO XS (Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger `15 to `18)
  - Available in public code iHixs 2 (Dulat, Lazopoulos, Mistlberger `18)
  - Further application to bbF Higgs (Dulat, Lazopoulos, Mistlberger `19)
- VBF to Higgs and HH using DIS structure function (Dreyer, Karlberg `17 `19)



Phys.Rev.Lett. 114 (2015) 212001

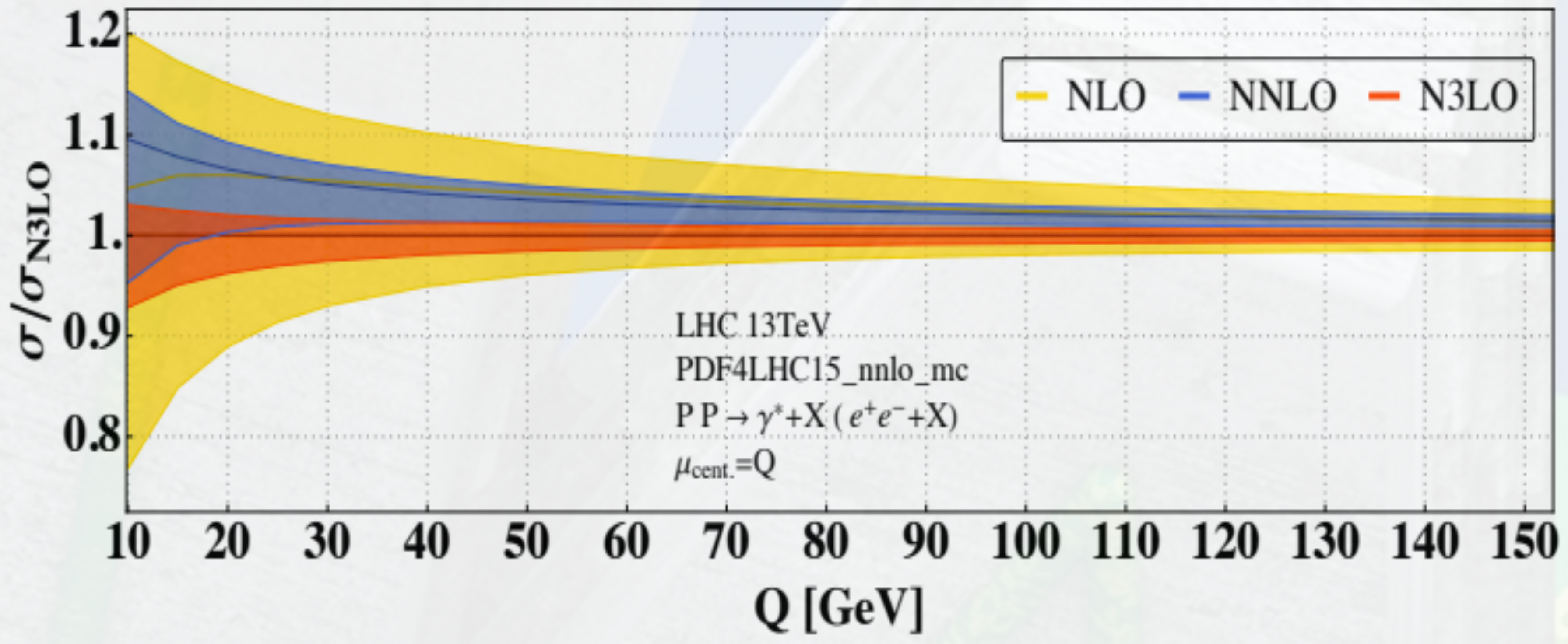


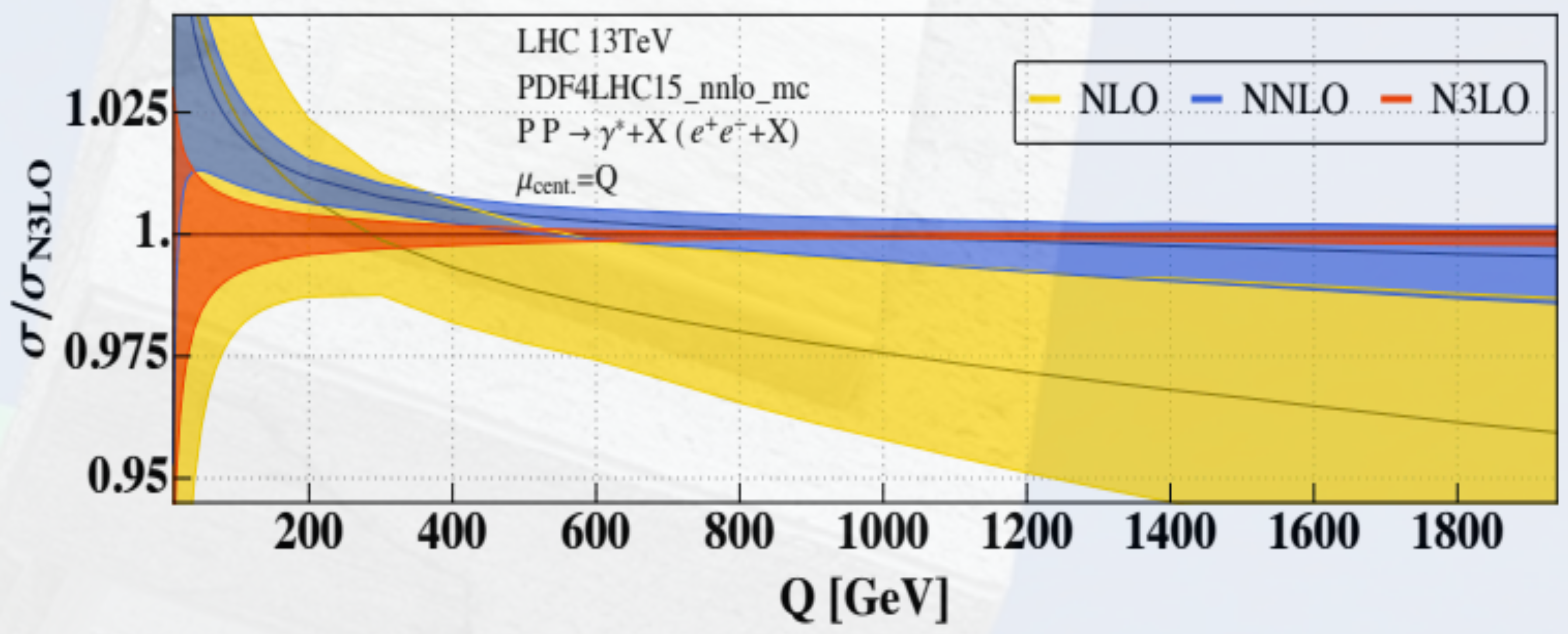
Phys.Rev.Lett. 125 (2020) 5, 051804

STATE-OF-THE-ART PREDICTIONS FOR σ_{N^3LO}

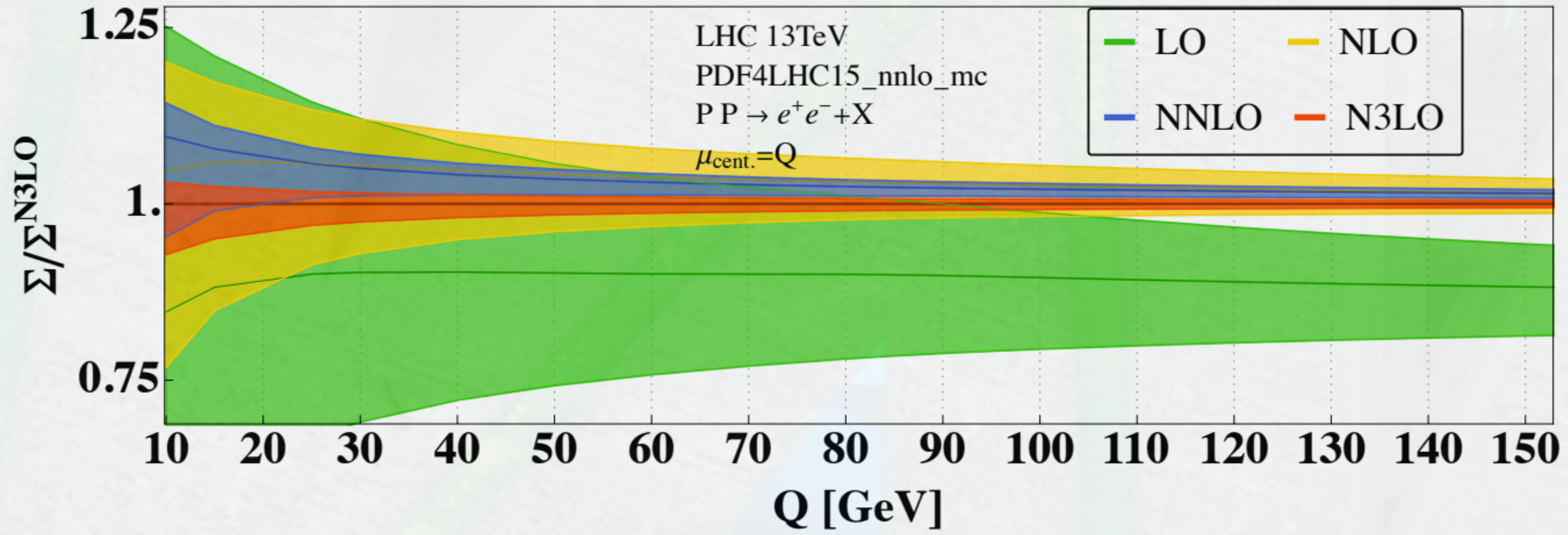
➤Application to $2 \to 1$ colour singlet production at the LHC (Duhr, Dulat, Mistlberger `20 `21)

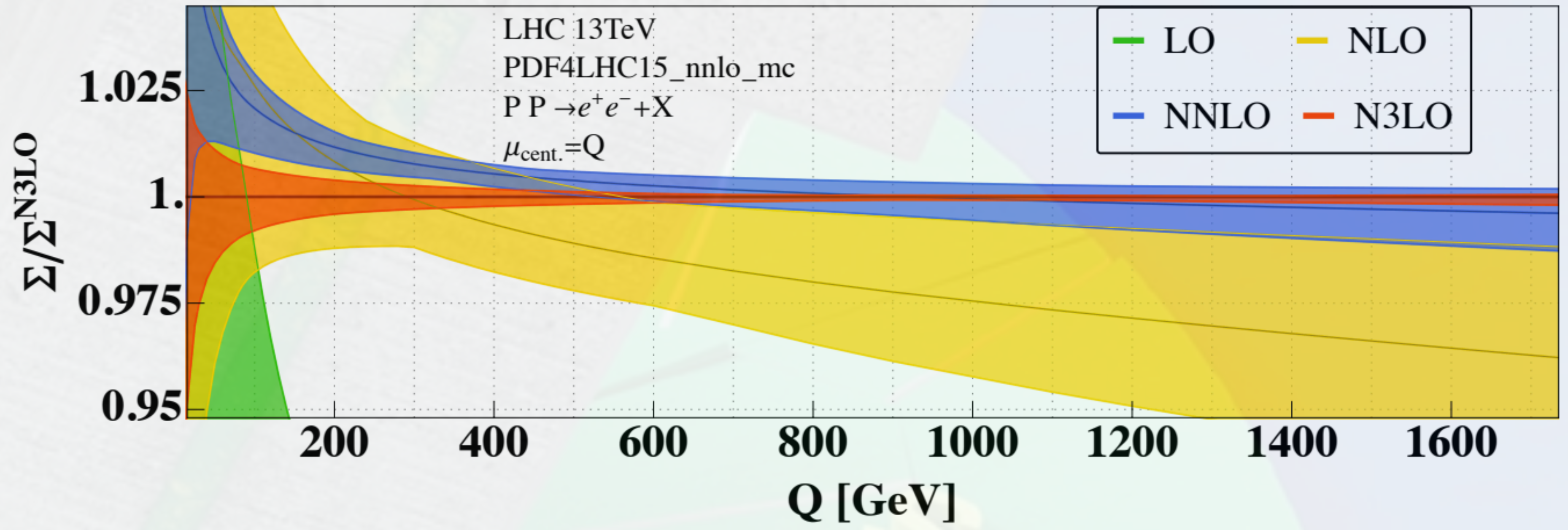
$pp \to \gamma^*$



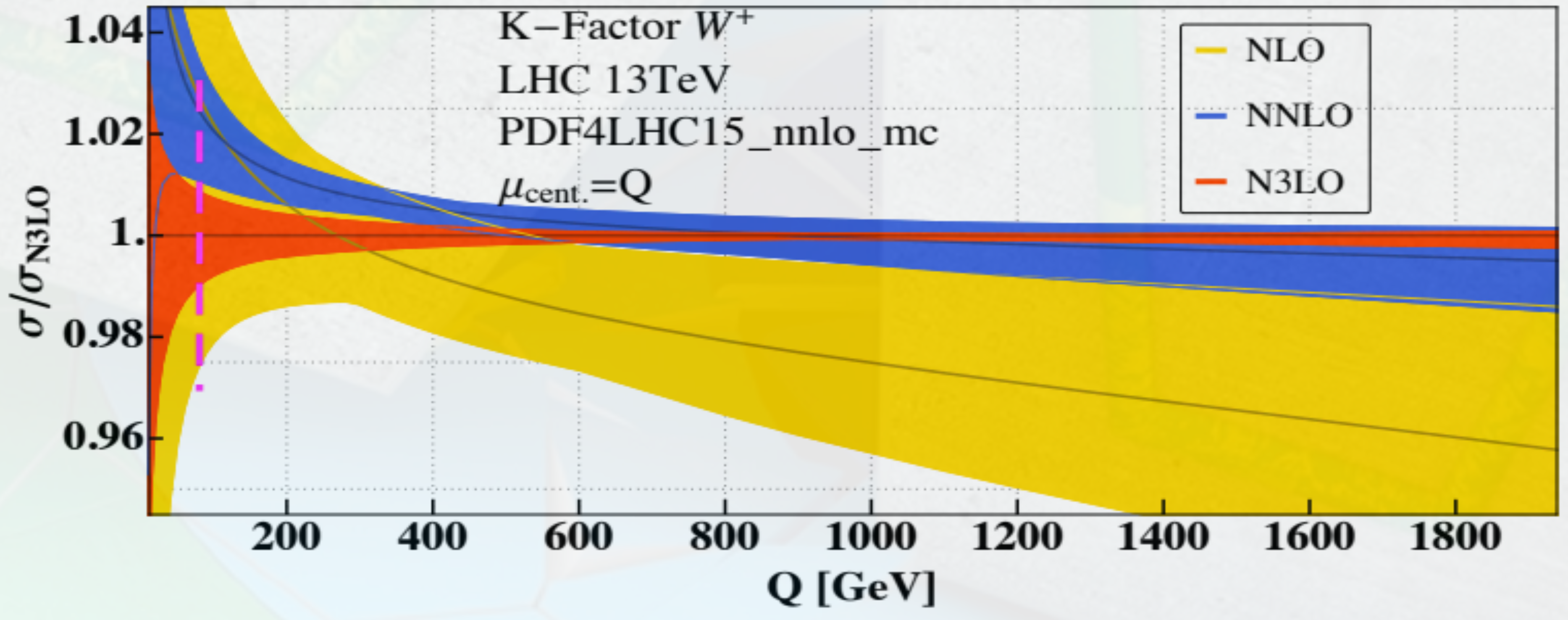


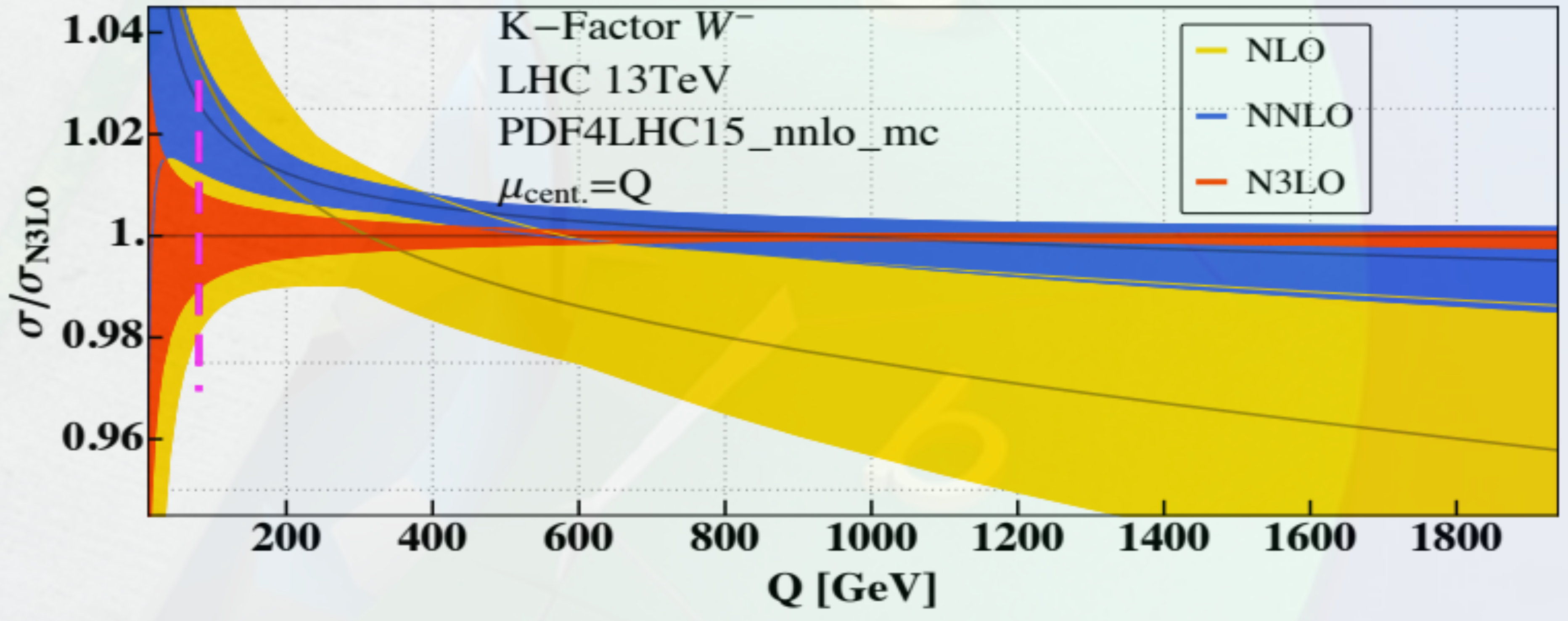
$pp \to Z/\gamma^* \to e^+e^-$





$pp \to W^{\pm}$





STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

- Differential N3LO accuracy

$$\frac{d\sigma^F_{N^kLO}}{d\mathcal{O}} = \left(\frac{d\sigma^{F+jet}_{N^{k-1}LO}}{d\mathcal{O}} - \frac{d\sigma^{F+jet}_{N^{k-1}LO}}{d\tilde{\mathcal{O}}}\right) + \frac{d\sigma^F_{N^kLO}}{d\tilde{\mathcal{O}}}$$

  - Projection to Born
    - Jet production in DIS (NNLOJET) Currie, Gehrmann, Glover, Huss, Niehues `18
    - Higgs decay to $b\bar{b}$ (MCFM) Mondini, Schiavi, Williams `19
    - Higgs production via ggF (RapidiX+NNLOJET) XC, Gehrmann, Glover, Huss, Mistlberger, Pelloni `21
  - qT slicing

$$d\sigma^F_{N^kLO} = \mathcal{H}^F_{N^kLO} \otimes d\sigma^F_{LO}\Big|_{\delta(\tau)} + \left[d\sigma^{F+jet}_{N^{k-1}LO} - d\sigma^{F\ CT}_{N^kLO}\right]_{\tau>\tau_{cut}} + \mathcal{O}(\tau^2_{cut}/Q^2)$$

    - Higgs production via ggF (HN3LO+NNLOJET) Cieri, XC, Gehrmann, Glover, Huss `18
    - Higgs pair production via ggF (with modified iHixs2) Chen, Li, Shuo, Wang `19
    - Drell-Yan production (NNLOJET) XC, Gehrmann, Glover, Huss, Yang, Zhu `21
- Combined with resummation (N3LL at small qT)
  - Drell-Yan production (DYTurbo) Camarda, Cieri, Ferrera `21 (RadISH+NNLOJET) XC, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Torrielli `22
  - Higgs production via ggF (SCETlib) Billis, Dehnadi, Ebert, Michel, Tackmann `21

STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

- Differential N3LO predictions for neutral current production
  - Fully differential N3LO Drell-Yan production (XC, Gehrmann, Glover, Huss, Yang, Zhu `21)
  - Apply qt-slicing at N3LO with SCET factorisation and expand to N3LO:

$$\frac{d^3\sigma}{dQ^2 d^2\vec{q}_T dy} = \int \frac{d^2 b_\perp}{(2\pi)^2} e^{-iq_\perp \cdot b_\perp} \sum_q \sigma_{\rm LO}^{\gamma^*} H_{q\bar{q}} \Big[\sum_k \int_{x_1}^1 \frac{dz_1}{z_1} \mathcal{I}_{qk}(z_1, b_T^2, \mu) f_{k/h_1}(x_1/z_1, \mu)$$
$$\times \sum_j \int_{x_2}^1 \frac{dz_2}{x_2} \mathcal{I}_{\bar{q}j}(z_2, b_T^2, \mu) f_{j/h_2}(x_2/z_2, \mu) \mathcal{S}(b_\perp, \mu) + (q \leftrightarrow \bar{q}) \Big] + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

  - All factorised functions are recently known up to N3LO:
    1) 3-loop hard function $H_{q\bar{q}}^{(3)}$ (Gehrmann, Glover, Huber, Ikizlerli, Studerus `10)
    2) Transverse-momentum-dependent (TMD) soft function $S(b_\perp, \mu)$ at α_s^3 (Li, Zhu `16)
    3) Matching kernel of TMD beam function I_{qk} at α_s^3 (Luo, Yang, Zhu, Zhu `19, Ebert, Mistlberger, Vita `20)
  - Apply qt cut to factorise N3LO contribution into two parts:

$$\mathrm{d}\sigma_{N^3LO}^{\gamma^*} = [\mathscr{H}^{\gamma^*} \otimes \mathrm{d}\sigma^{\gamma^*}]_{N^3LO}\Big|_{\delta(p_{T,\gamma^*})} + \left[\mathrm{d}\sigma_{NNLO}^{\gamma^*+jet} - \mathrm{d}\sigma_{N^3LO}^{\gamma^*\ CT}\right]_{p_{T,\gamma^*} > q_T^{cut}} + \mathcal{O}((q_T^{cut}/Q)^2)$$

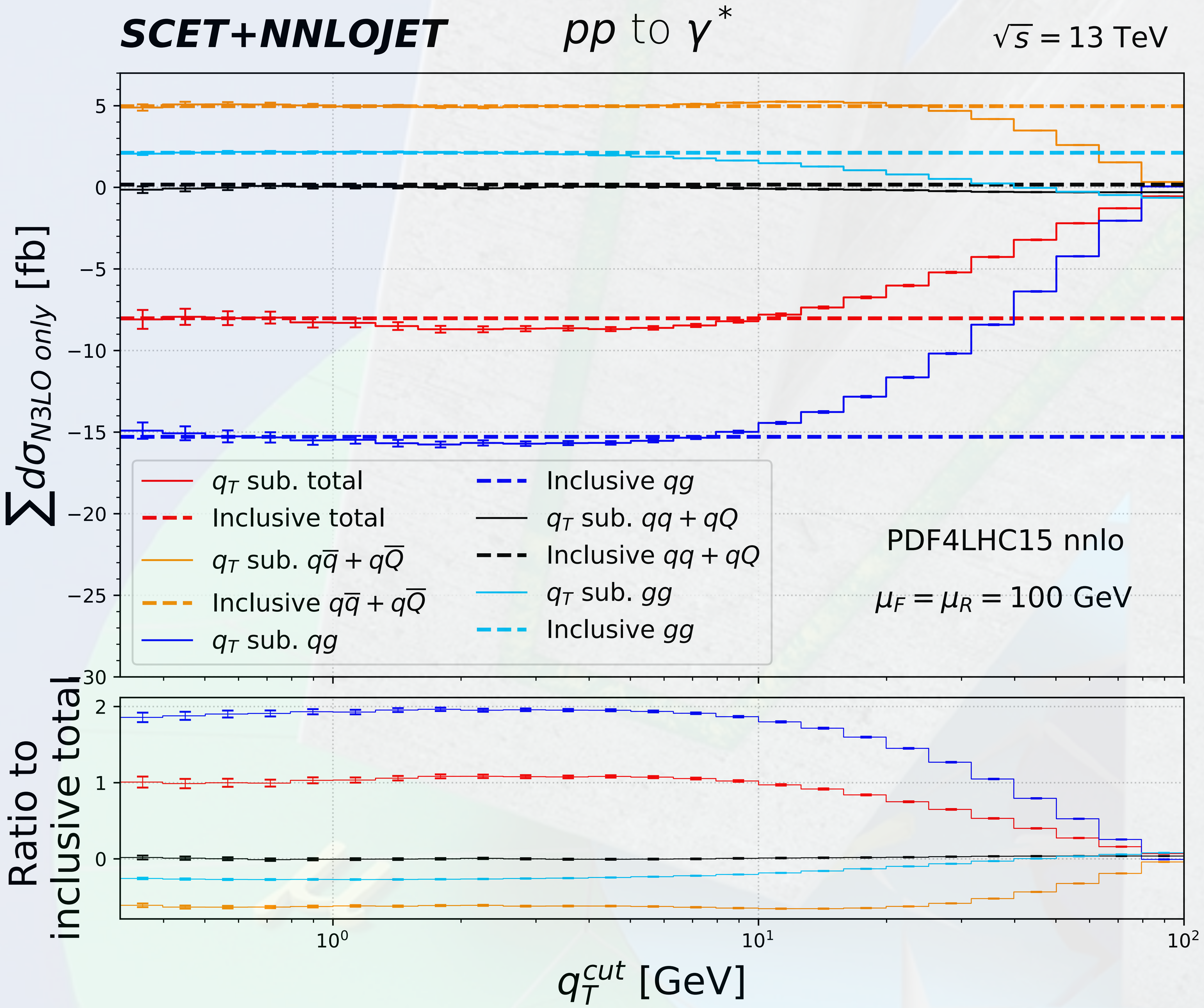
STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

- Differential N3LO predictions for neutral and charged current production $\mathcal{O}(\alpha\alpha_s^3)$
  - Computational setup for $pp \to \gamma^* \to l^+l^-$
    (identical setup in the inclusive calculation by Durh, Dulat and Mistlberger in *Phys.Rev.Lett.* 125 (2020) 17, 172001)
    - Fix Q value for γ^* at 100 GeV (NNLO and N3LO scale variations deviate)
    - Use central value of PDF4LHC15_nnlo_mc as benchmark input
    - $\mu_R = \mu_F = 100$ GeV for central QCD scale and use 7-point variations for uncertainty estimation
    - Apply $p_{T,\gamma^*} > 0.25$ GeV constrain for NNLO $\gamma^* + Jet$ without jet definition
  - Computational setup for $pp \to W^\pm \to l^\pm\nu$
    - Dynamic QCD scale $\mu_R = \mu_F = m_{l\nu}$ with 7 variations and $m_{l\nu} \in [0, +\infty]$
    - Use NNPDF31_nnlo PDFs and $p_{T,l\nu} > 0.5$ GeV
  - Common setup
    - Consider LO decay with $m_e = m_\mu = 0$
    - $\alpha_s(m_Z) = 0.118$, G_μ EW-scheme with fixed α value

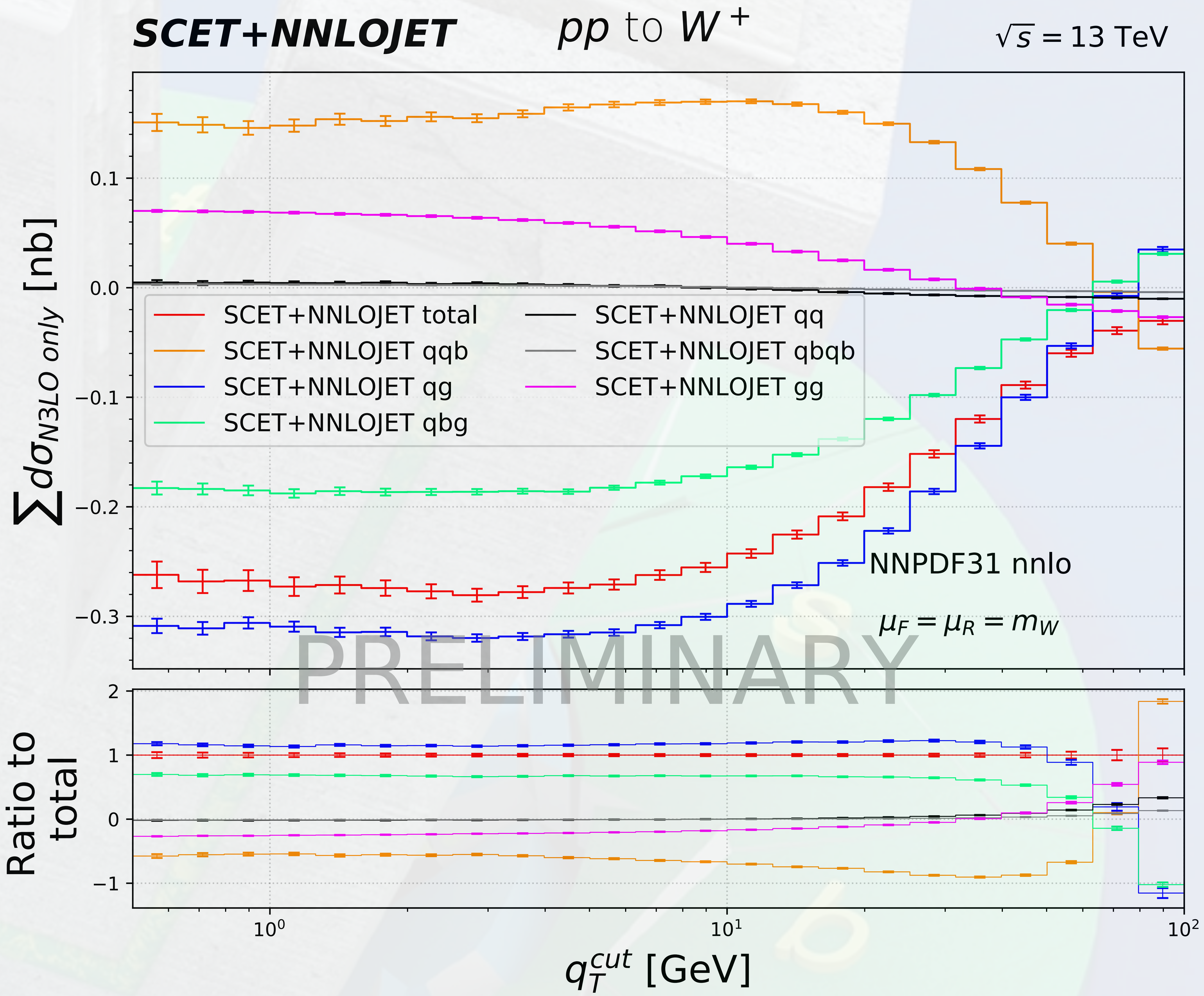
STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

➤Differential N3LO predictions for neutral and charged current production

$$\sum_{\mathrm{d}p_{T,V}} \mathrm{d}\sigma^{V}_{N3LO} \equiv \sum_{\mathrm{d}p_{T,V}} \mathrm{d}\sigma^{V+jet}_{NNLO}/\mathrm{d}p_{T,V}\big|_{p_{T,V}>q_T^{cut}} + \sum_{\mathrm{d}p_{T,V}} \mathrm{d}\sigma^{V\,SCET}_{N^3LO}/\mathrm{d}p_{T,V}\big|_{p_{T,V}\in[0,q_T^{cut}]}$$



XC, Gehrmann, Glover, Huss, Yang, Zhu *Phys.Rev.Lett.* 128 (2022) 5



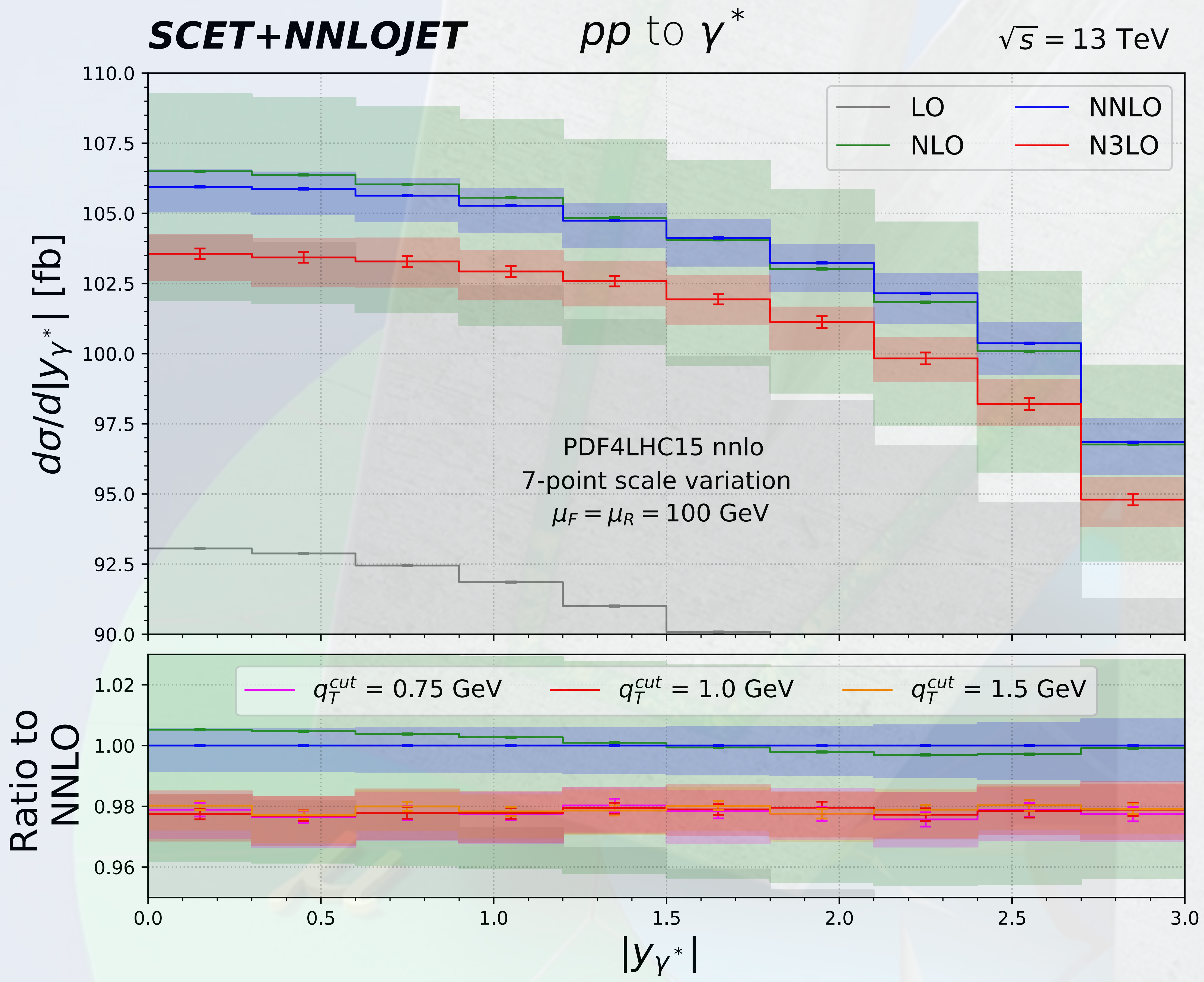
XC, Gehrmann, Glover, Huss, Yang, Zhu in preparation

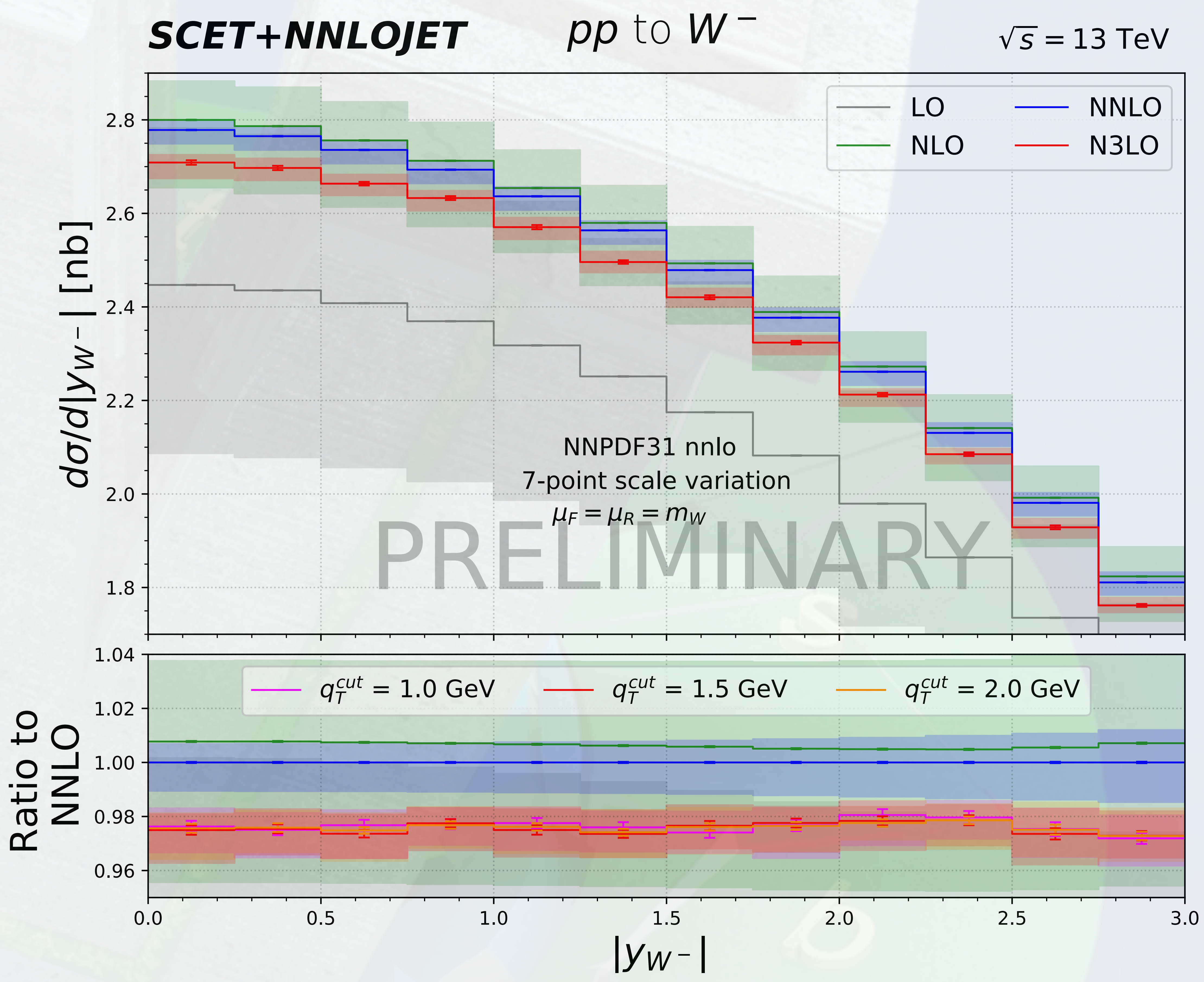
STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

➤Differential N3LO predictions for neutral current production

$d\sigma^{\gamma*}_{FO}/d|y_{\gamma*}|$

$d\sigma^{W^-}_{FO}/d|y_{W^-}|$





XC, Gehrmann, Glover, Huss, Yang, Zhu *Phys.Rev.Lett*. 128 (2022) 5

XC, Gehrmann, Glover, Huss, Yang, Zhu in preparation

STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

➤Differential N3LO predictions for charged current production

$$m_T = (E_T^l + E_T^\nu)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2 = \sqrt{2E_T^l E_T^\nu(1 - cos\phi)}$$

Breit-Wigner form (running decay width):

$$\frac{1}{s^2 - m_W^2 + is^2\Gamma_W/m_W}$$

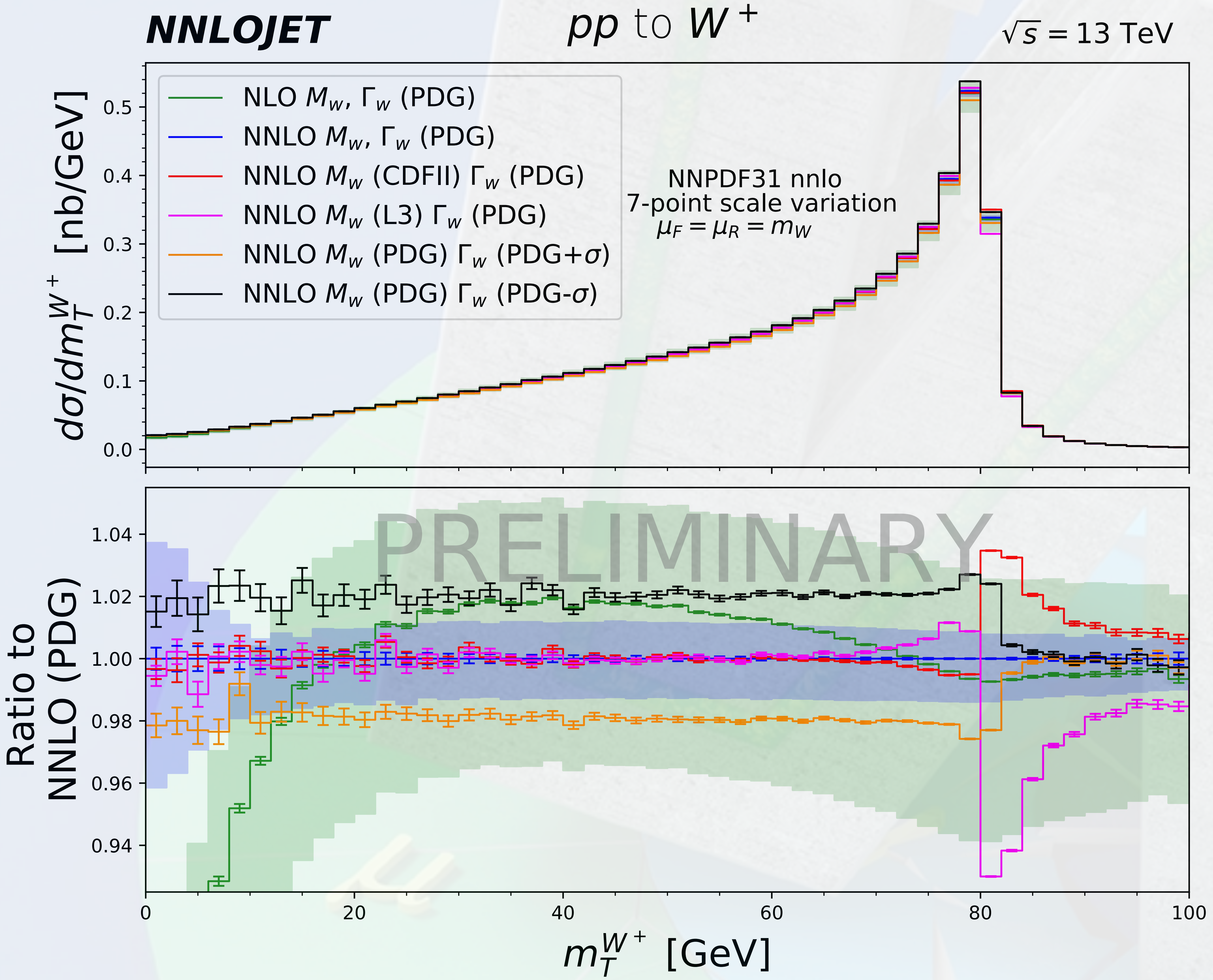
(MeV)	W mass	W width
PDG (2020)	80379 ± 12	2085 ± 42
CDFII	80433 ± 9	2089.5 ± 0.6
L3	80270 ± 55	2180 ± 14

XC, Gehrmann, Glover, Huss, Yang, Zhu in preparation

STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

➤Differential N3LO predictions for charged current production

$$m_T = (E_T^l + E_T^\nu)^2 - (\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu})^2 = \sqrt{2E_T^l E_T^\nu(1 - cos\phi)}$$



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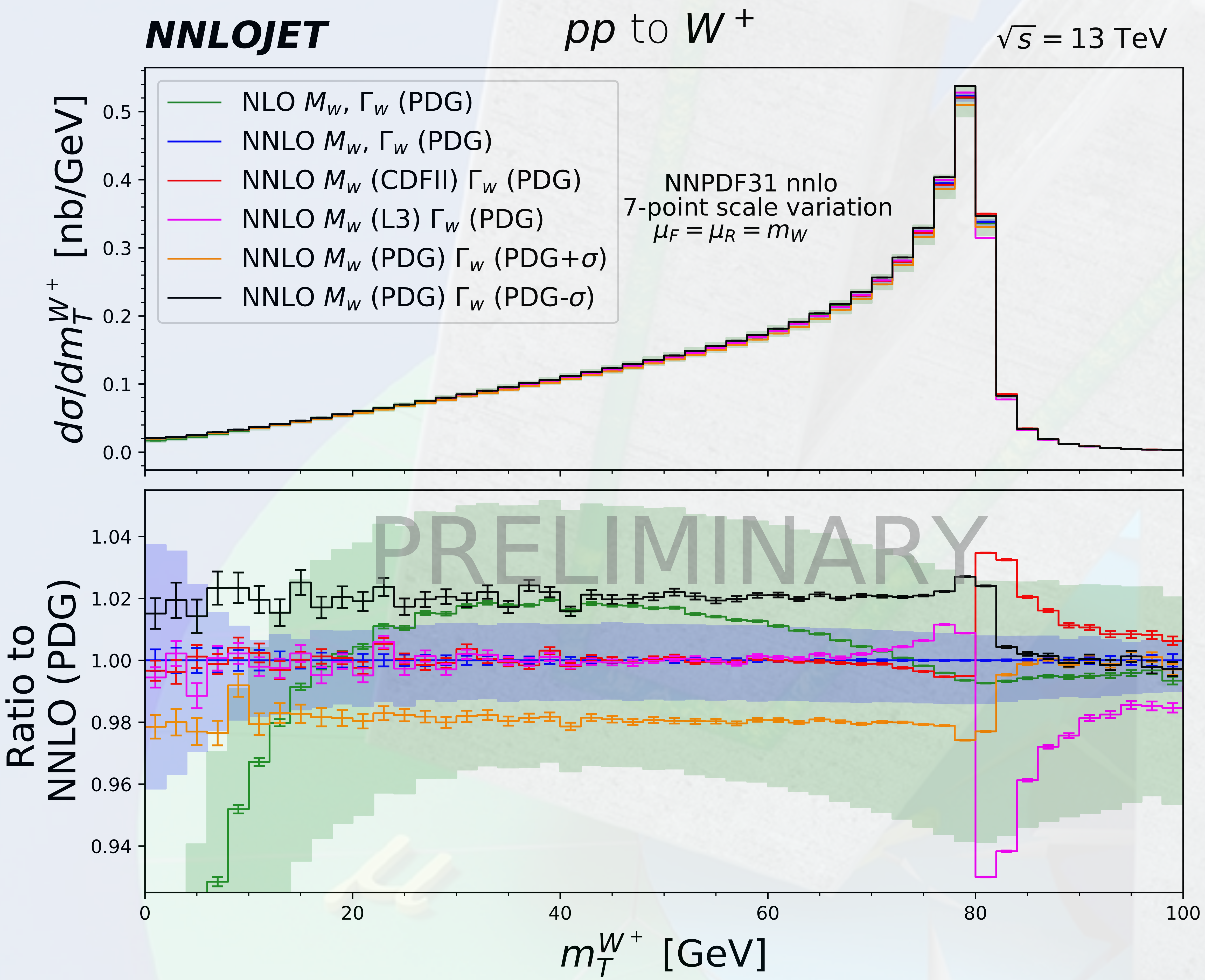

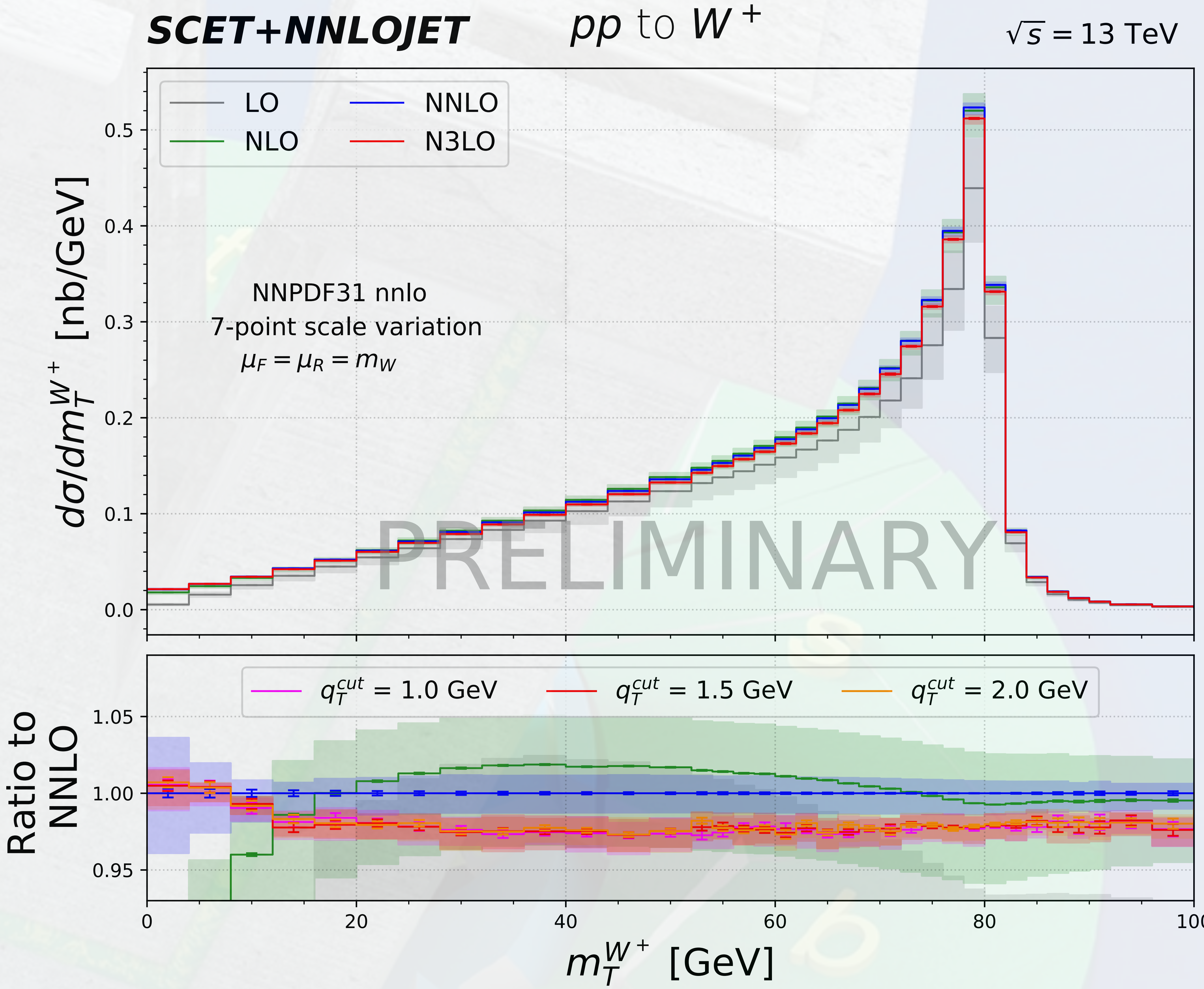

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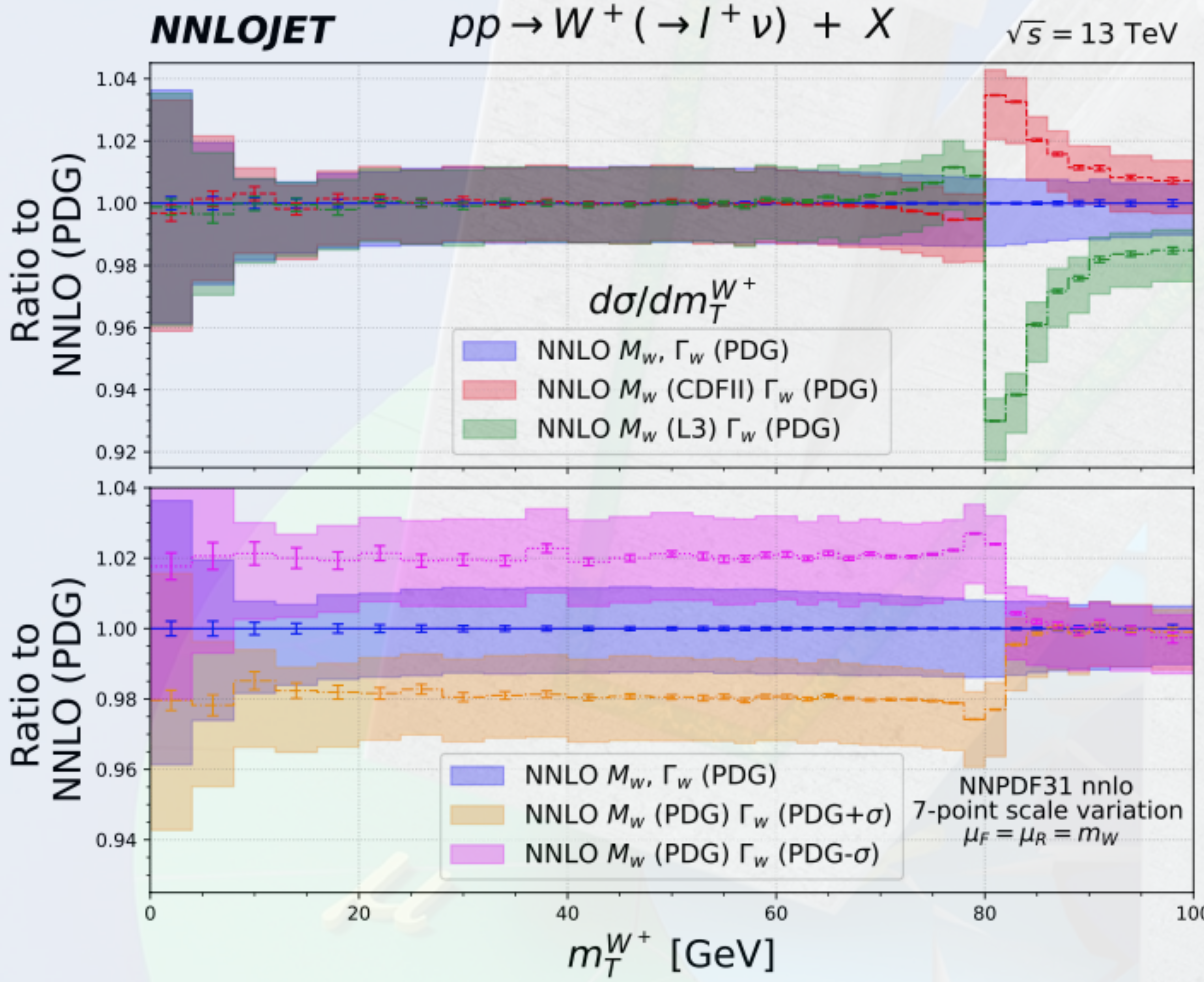

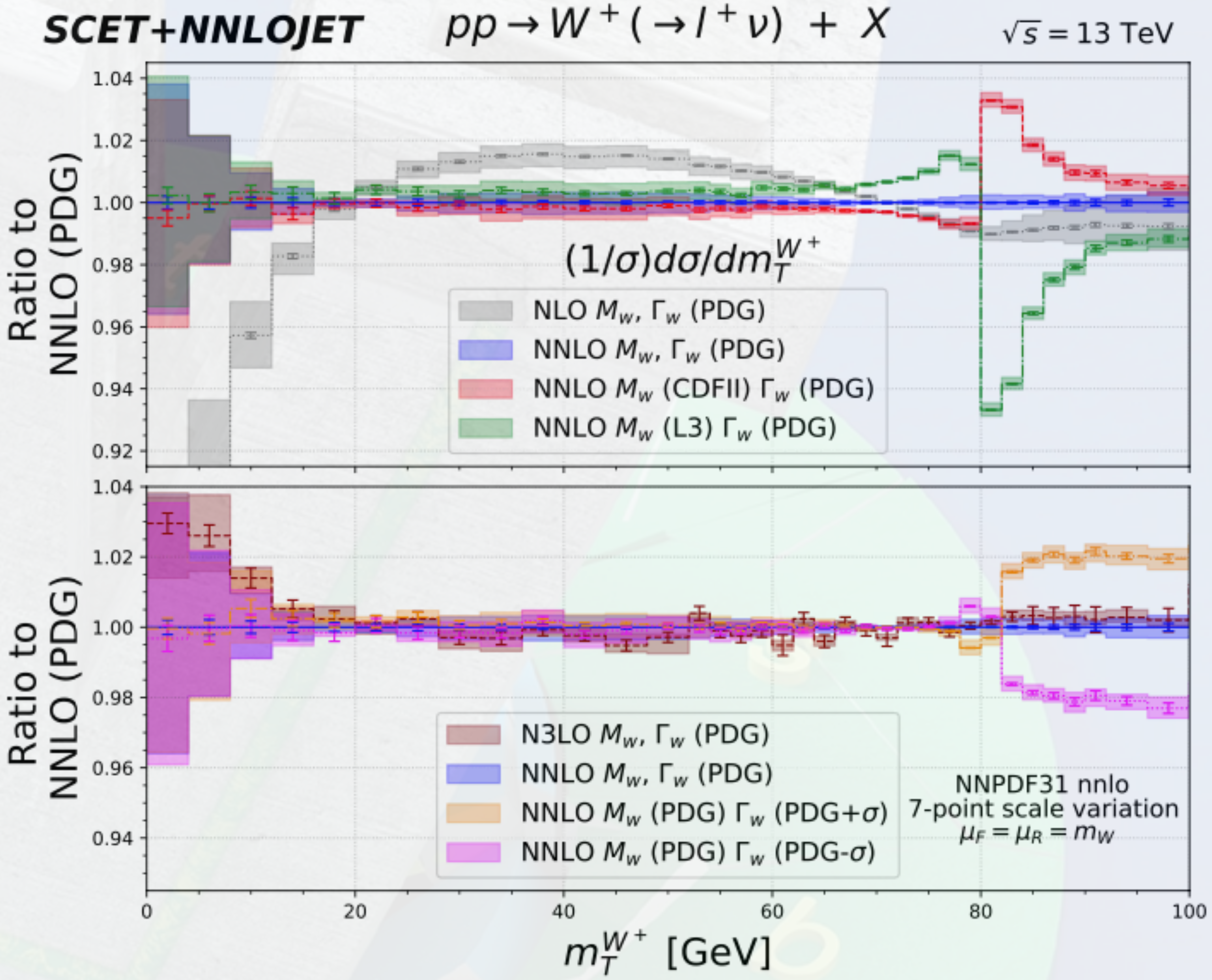

XC, Gehrmann, Glover, Huss, Yang, Zhu in preparation

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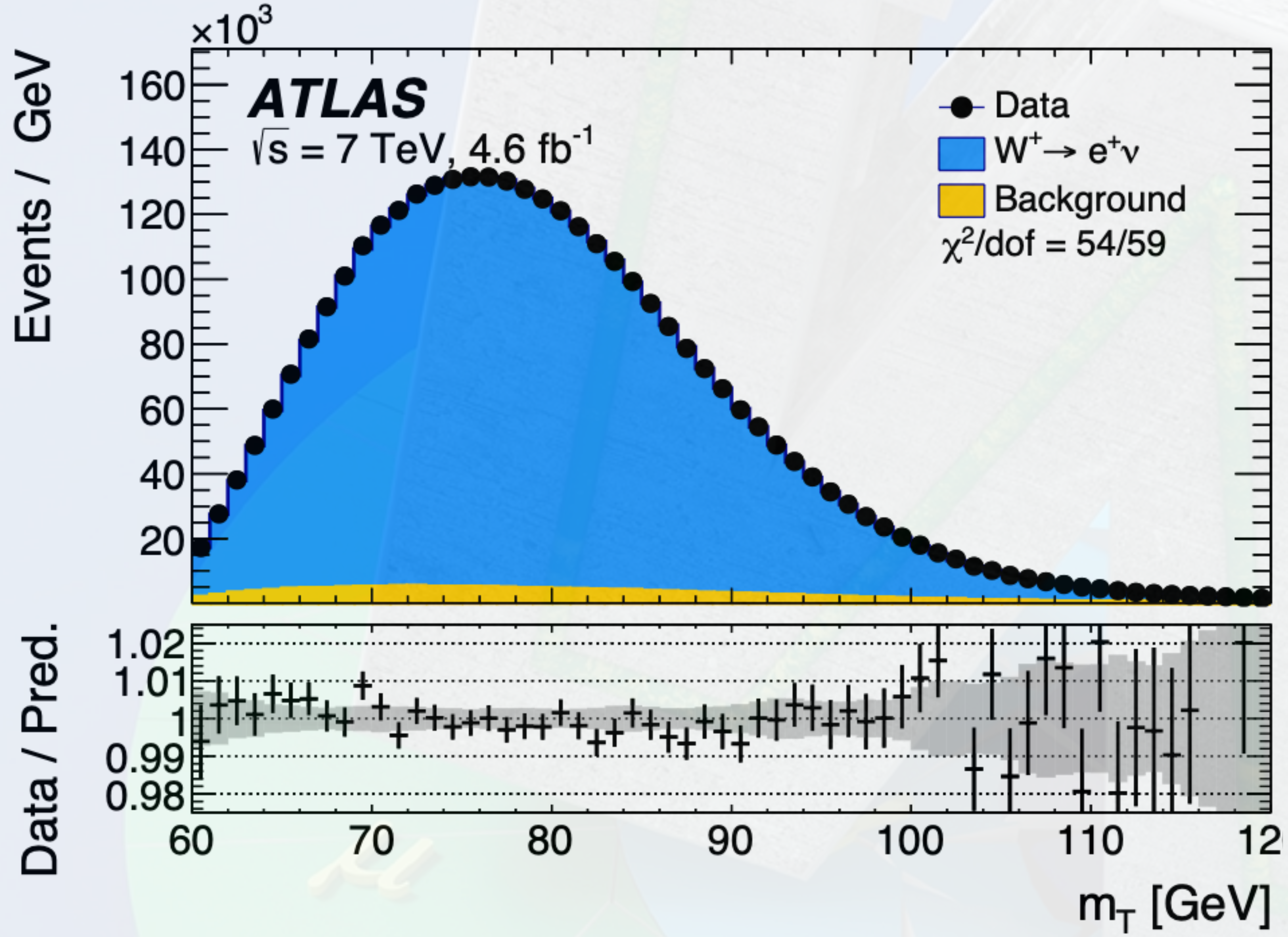
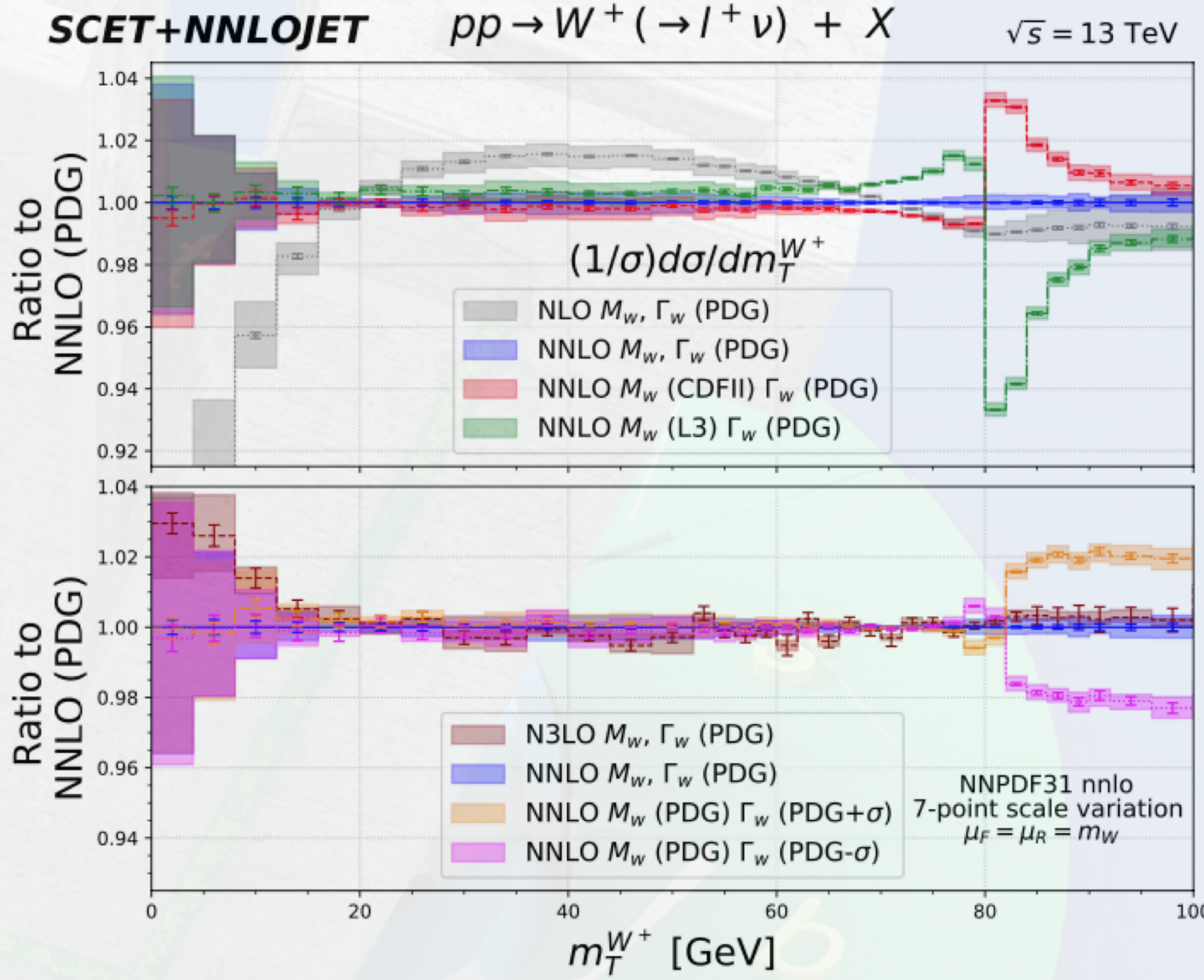


ATLAS `17



XC, Gehrmann, Glover, Huss, Yang, Zhu in preparation

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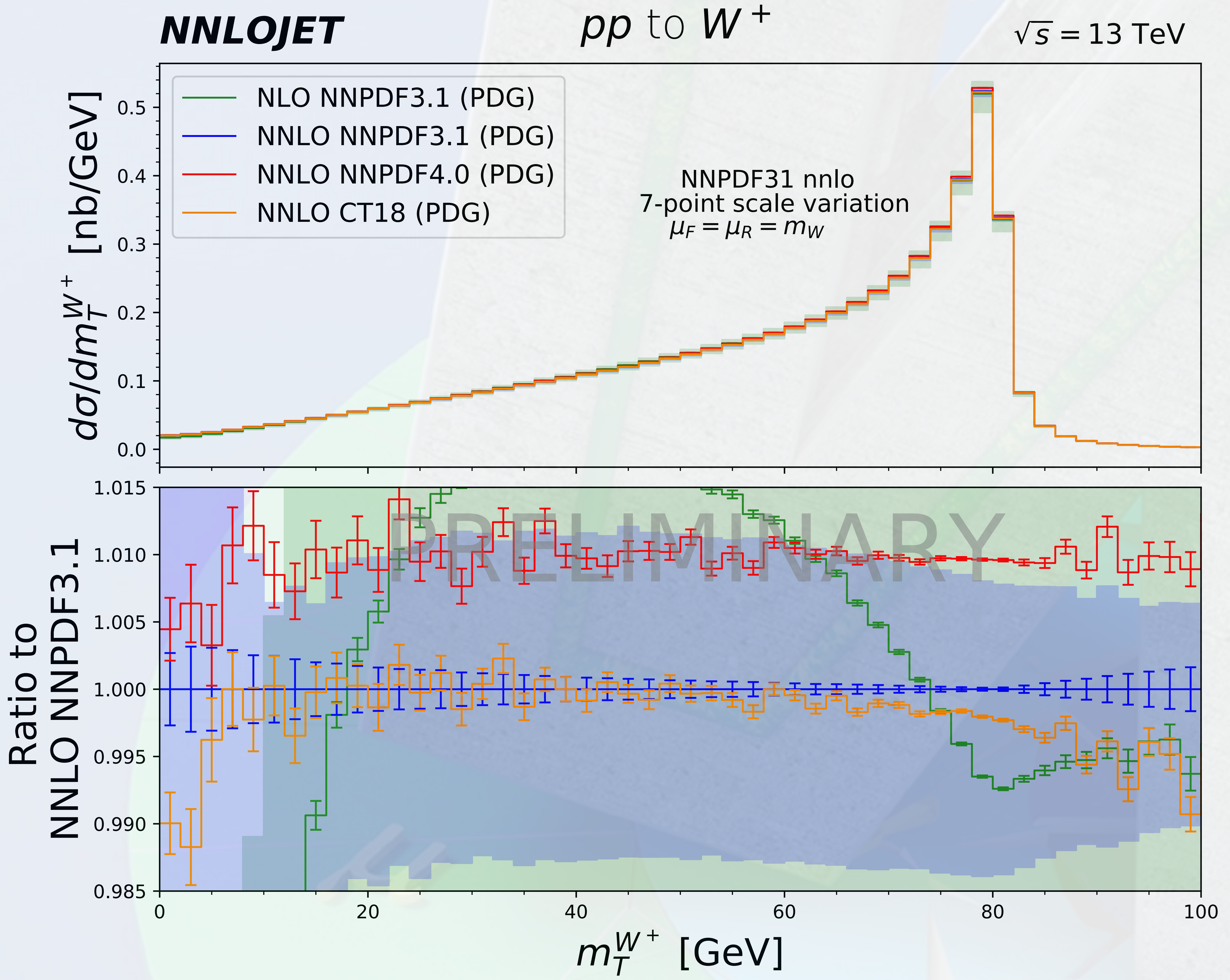

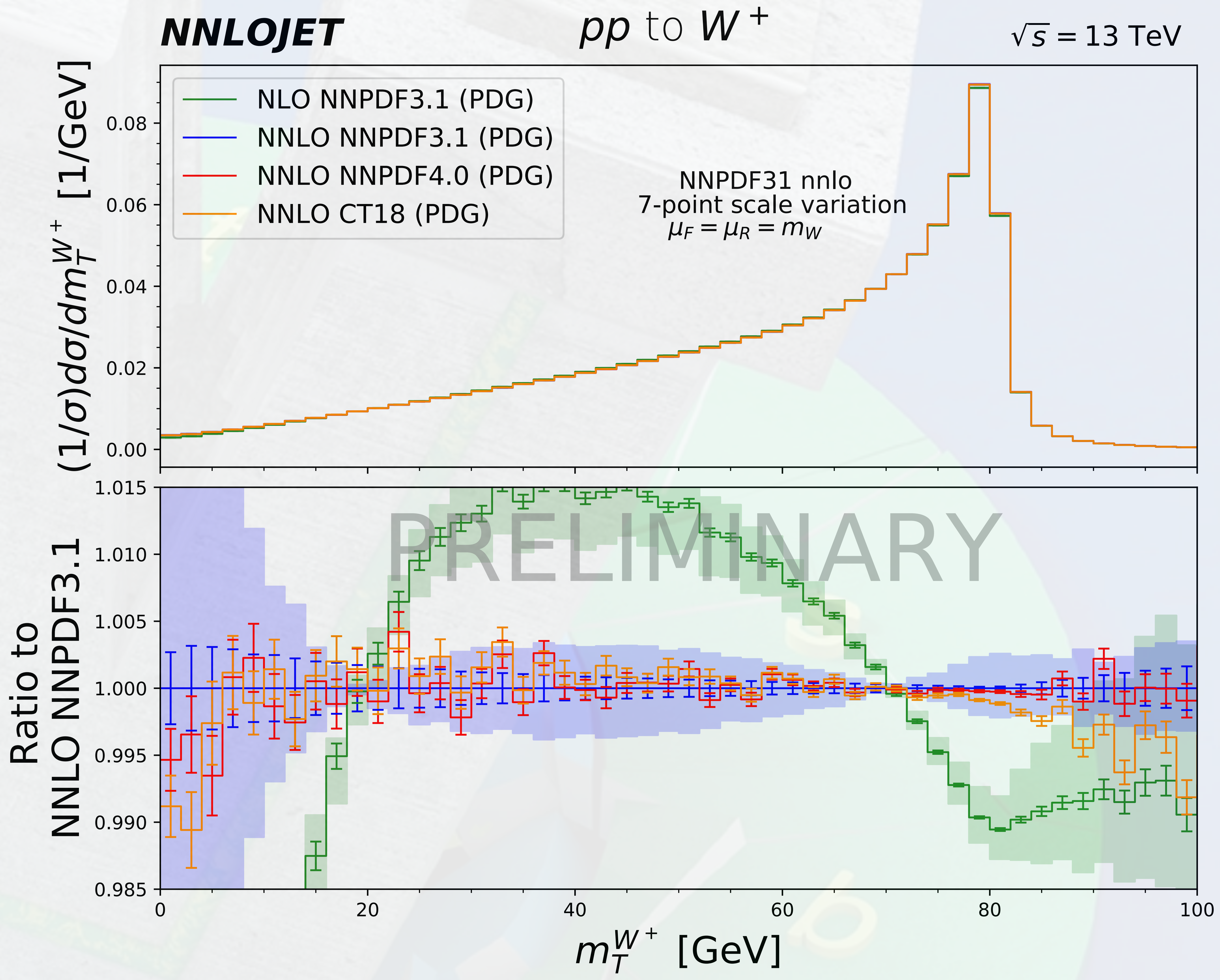

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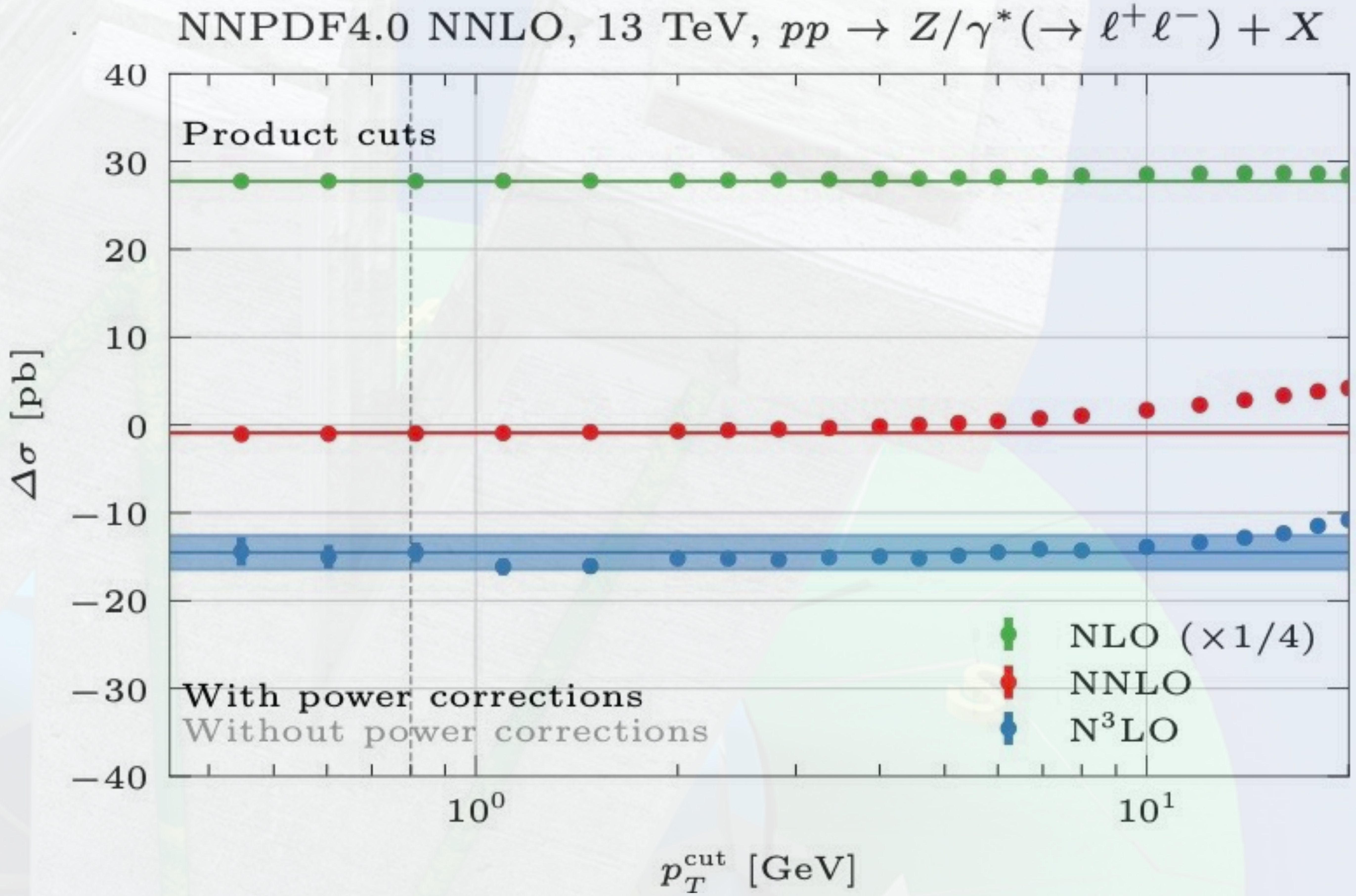
STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

- Differential N3LO predictions for neutral current production with fiducial cuts
  - Apply ATLAS fiducial cuts at 13 TeV
    - Dynamical scale $\mu_F = \mu_R = \sqrt{m_{ll}^2 + p_T^{ll2}}$
    - $m_{ll} \in [66,116]$ GeV, $|\eta^{l^\pm}| < 2.5$
    - Symmetric cuts: $|p_T^{l^\pm}| > 27$ GeV
      Introduce power correction at $\mathcal{O}(q_T^{cut}/m_{ll})$
    - Solution:
      - Apply Lorentz Boost below q_T^{cut}
        Buonocore, Rottoli, Kallweit, Wiesemann \`21
        Camarda, Cieri, Ferrera \`21
      - Product cuts: $\sqrt{p_T^{l^+} p_T^{l^-}} > 27$ GeV
        Salam, Slade \`21
        $\min\{p_T^{l^+}, p_T^{l^-}\} > 20$ GeV
  - Typical fiducial cuts for m_T^V, p_T^V in DY production
    - Large log terms appear in $p_T^l \sim m_V/2$, $m_T^V \sim 2 \times \min[p_T^l]$, $p_T^V \sim 0$



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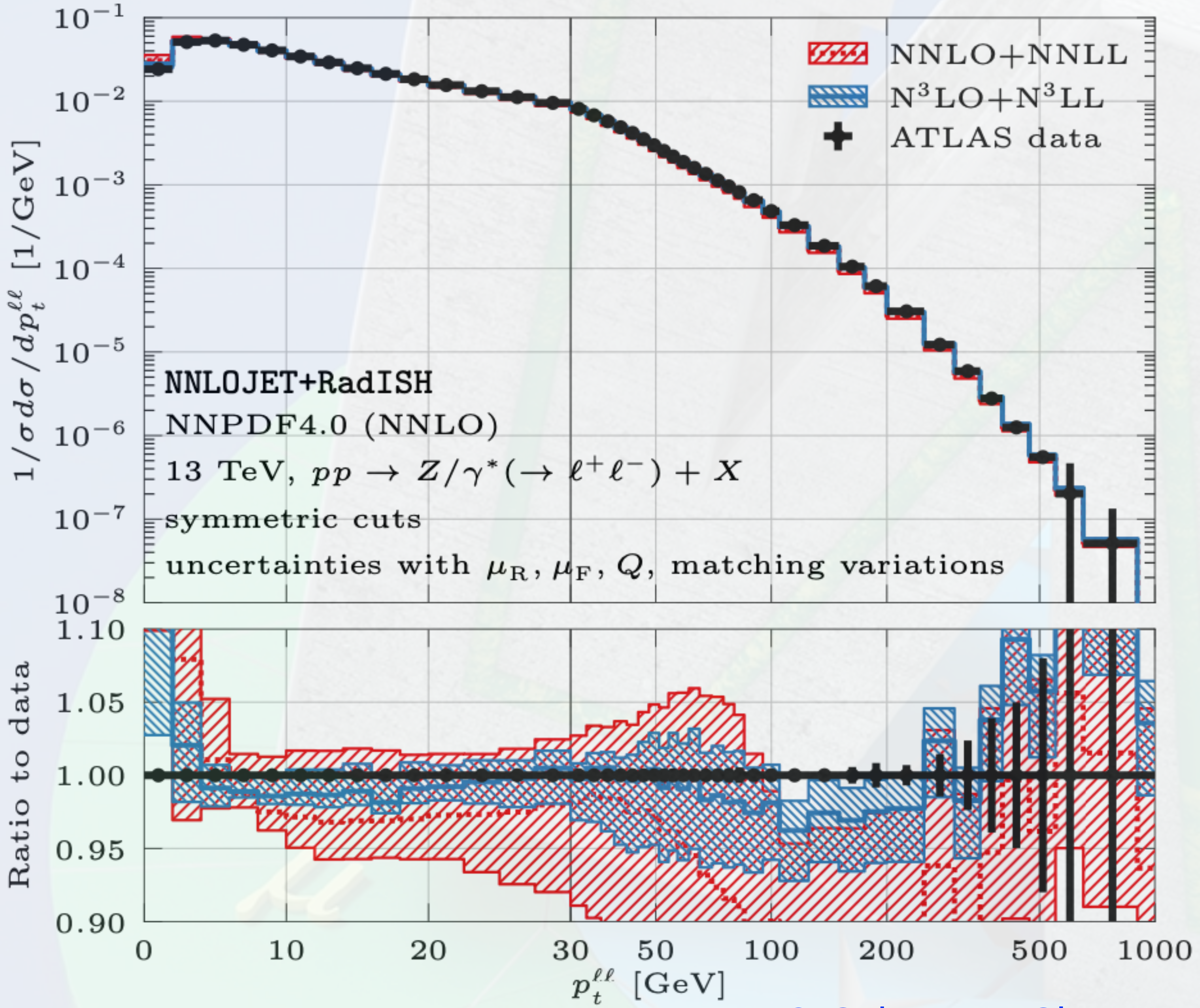
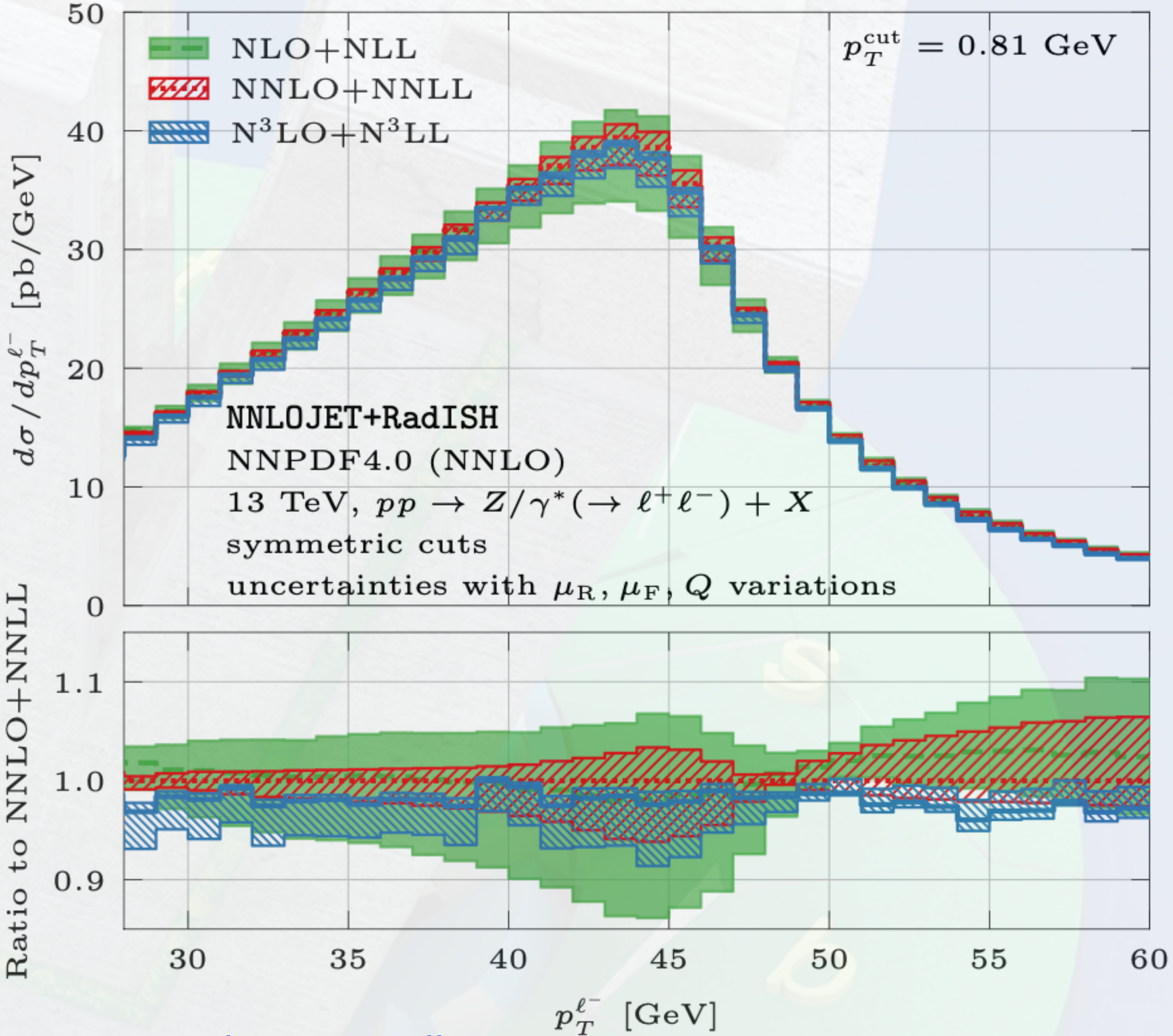
STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO+N^3LL}$

- Differential N3LO predictions for neutral current production with fiducial cuts
  - Resum all order contributions at N3LL using RadISH and matched to N3LO





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CONCLUSION AND OUTLOOK

- Precision phenomenology could be the key to reveal new physics principles.
- For theory predictions of LHC observables, there has been rapid progress in perturbative QCD calculations at NNLO and N3LO accuracy.
- Differential N3LO precision is now available for neutral and charged current production at the LHC.
- Our standard methodology to estimate theoretical uncertainties via scale variation is challenged at N3LO.
- Resumed N3LO+N3LL predictions are essential to compare with data and help to stabilise the convergence of scale variations.
- EW, QCD-EW corrections are not included in this talk but equivalent important at the level of accuracy. How to combine different source of corrections/uncertainties is the key to make accurate interpretation of experiment data.

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Thank You for Your Attention

BACKUP SLIDES

- ➤Differential N3LO predictions for neutral current production with fiducial cuts
  - ➤ Resum all order contributions at N3LL using RadISH and matched to N3LO

Order	σ [pb] Symmetric cuts		σ [pb] Product cuts	
k	$\mathrm{N}^k\mathrm{LO}$	$\mathrm{N}^k\mathrm{LO}+\mathrm{N}^k\mathrm{LL}$	$\mathrm{N}^k\mathrm{LO}$	$\mathrm{N}^k\mathrm{LO}+\mathrm{N}^k\mathrm{LL}$
0	$721.16^{+12.2\%}_{-13.2\%}$	—	$721.16^{+12.2\%}_{-13.2\%}$	—
1	$742.80(1)^{+2.7\%}_{-3.9\%}$	$748.58(3)^{+3.1\%}_{-10.2\%}$	$832.22(1)^{+2.7\%}_{-4.5\%}$	$831.91(2)^{+2.7\%}_{-10.4\%}$
2	$741.59(8)^{+0.42\%}_{-0.71\%}$	$740.75(5)^{+1.15\%}_{-2.66\%}$	$831.32(3)^{+0.59\%}_{-0.96\%}$	$830.98(4)^{+0.74\%}_{-2.73\%}$
3	$722.9(1.1)^{+0.68\%}_{-1.09\%} \pm 0.9$	$726.2(1.1)^{+1.07\%}_{-0.77\%}$	$816.8(1.1)^{+0.45\%}_{-0.73\%} \pm 0.8$	$816.6(1.1)^{+0.87\%}_{-0.69\%}$

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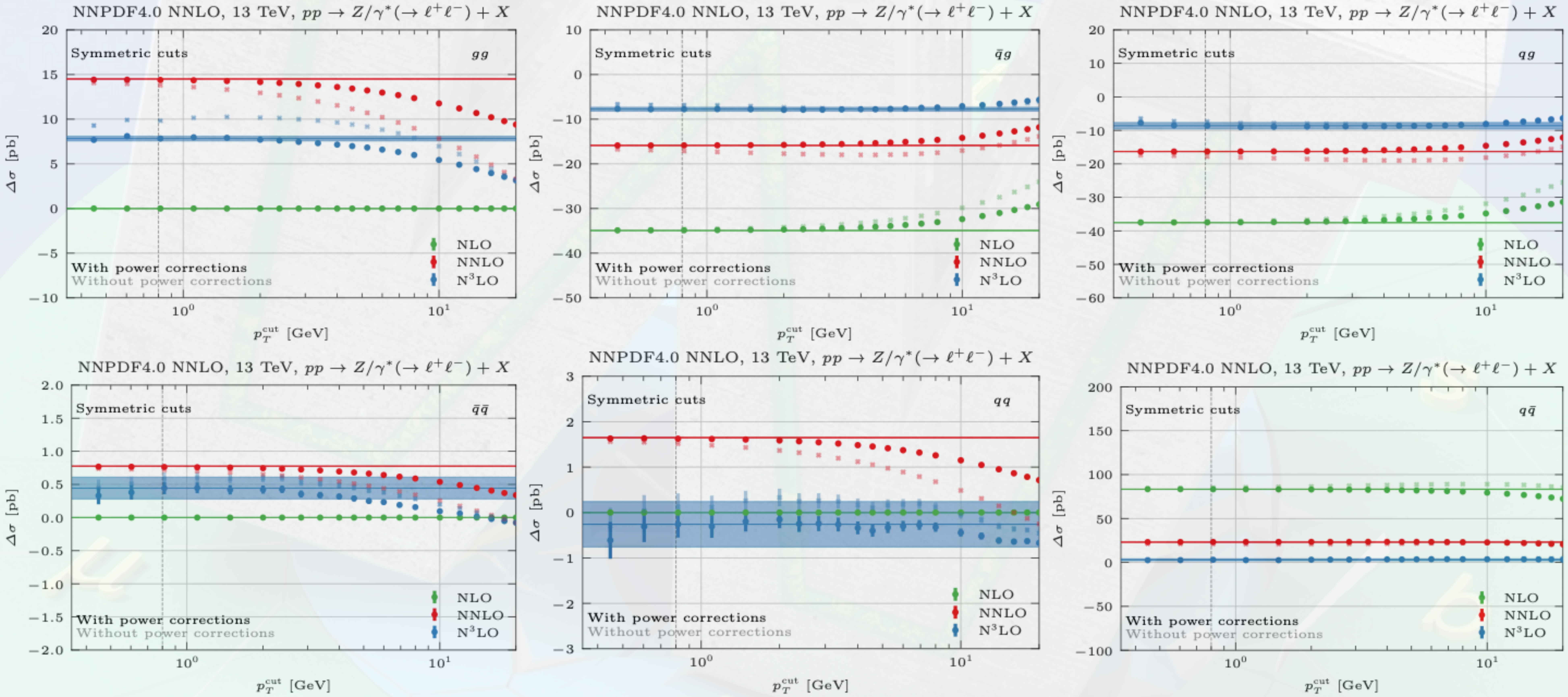

BACKUP SLIDES

➤Differential N3LL +NNLO predictions for charged current production with fiducial cuts

- Precise W measurement with calibration against Z.
- Improved QCD uncertainties through out pT.
- Different EW and QCD-EW correction between Z and W are not yet considered.

Bizon, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, Rottoli, Walker `19