N3LO CORRECTIONS TO NEUTRAL AND CHARGED CURRENT AT THE LHC

LOOPS AND LEGS IN QUANTUM FIELD THEORY 2022

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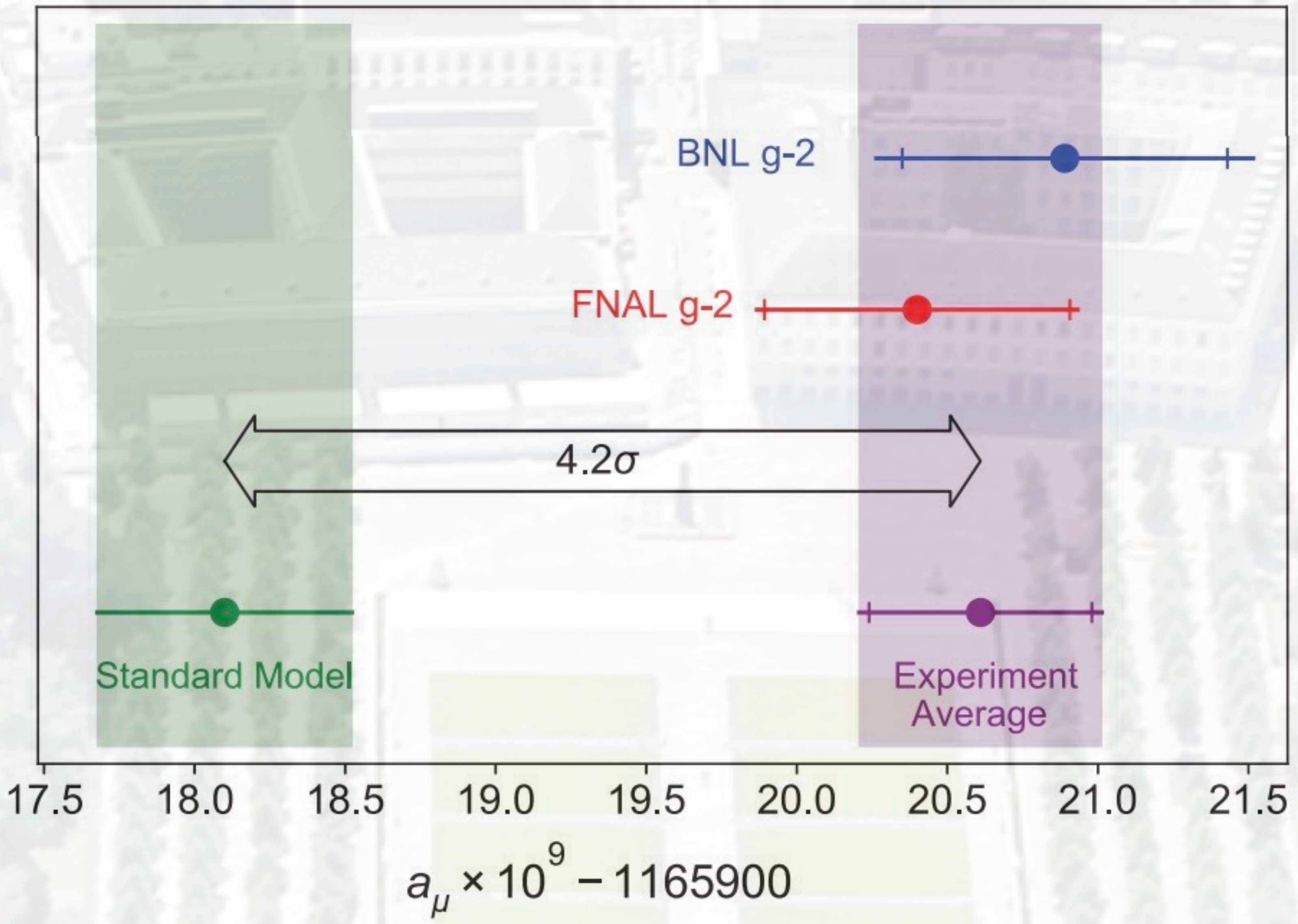
"THREE CLOUDS" IN PARTICLE PHYSICS SINCE 2021

- Fermilab's Muon g-2 experiment
- Measure the precession difference of Muon in magnetic field
- Observe 4.2 σ deviation from SM
- Precision at 0.46 ppm

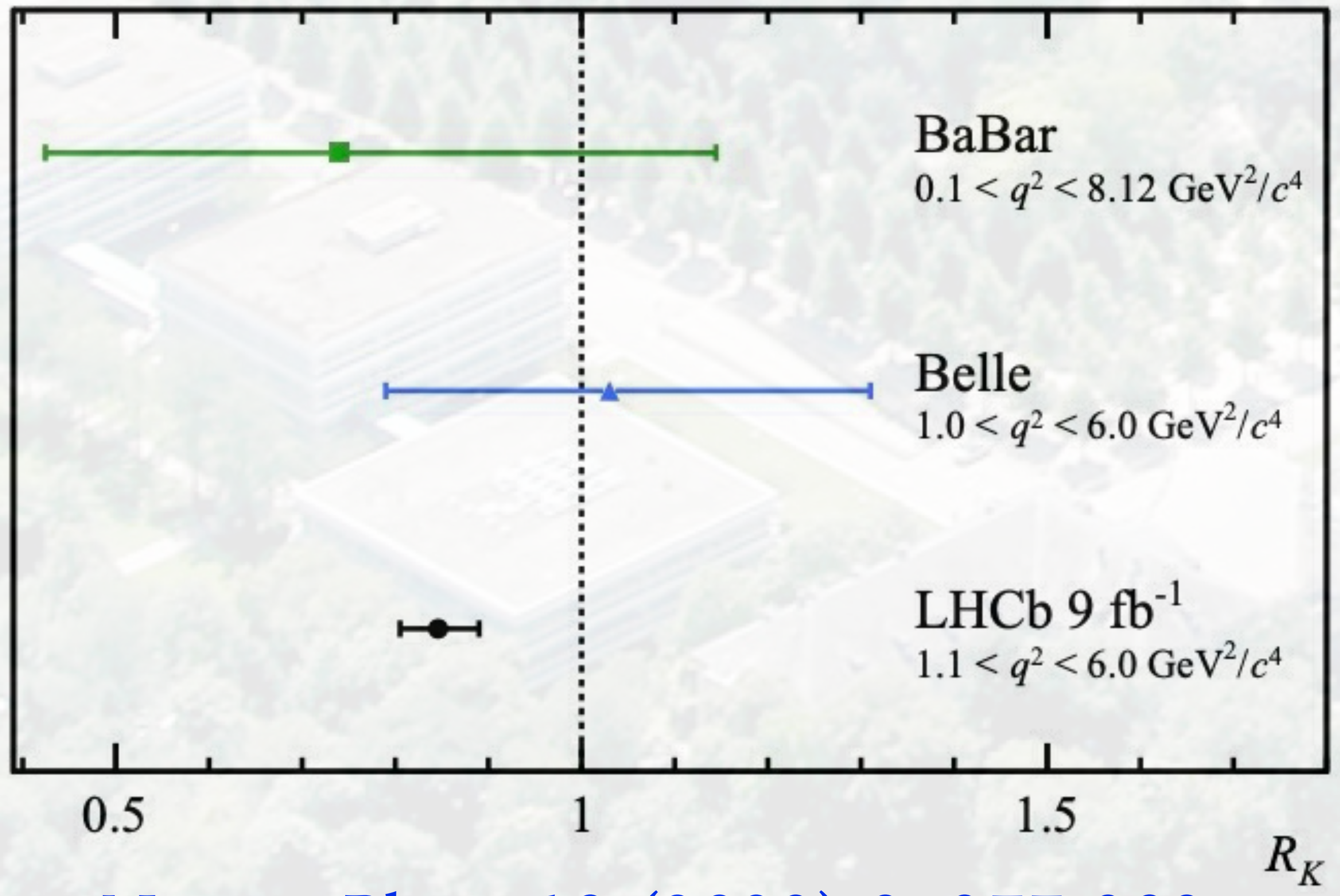
$$a_\mu = \frac{g-2}{2}$$

$a_\mu^{EXP} = 116592061(41) \times 10^{-11}$ *Phys.Rev.Lett*. 126, 141801

$a_\mu^{SM} = 116591810(43) \times 10^{-11}$ *Phy. Reports* 887 (2020) 1-116



Phys.Rev.Lett. 126, 141801 (2021)



Nature Phys. 18 (2022) 3, 277-282

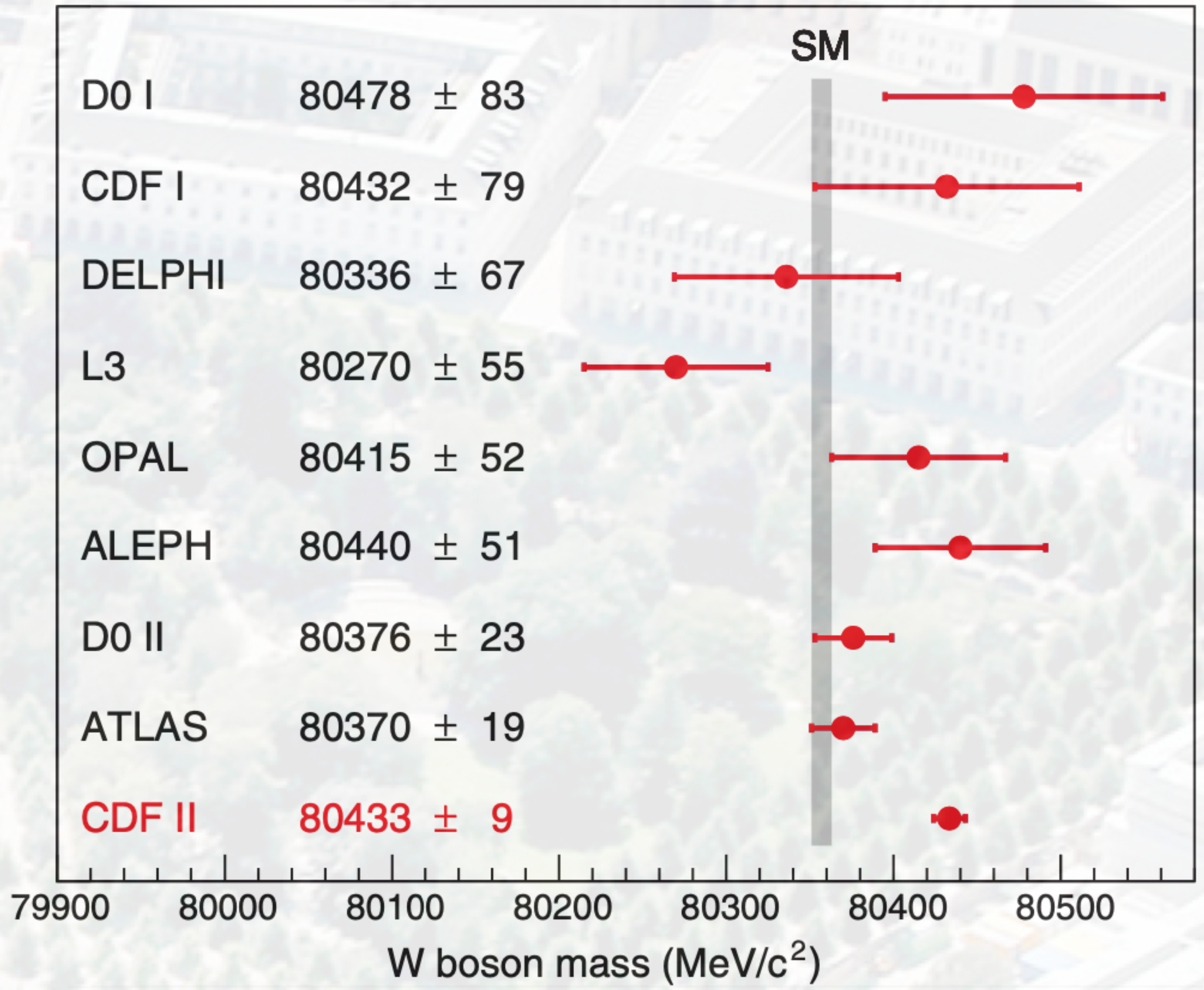
- LHCb measure B meson decays

$$R_H \equiv \frac{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to H\mu^+\mu^-)}{dq^2} dq^2}{\displaystyle\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\mathcal{B}(B\to He^+e^-)}{dq^2} dq^2}$$

- Three generations of experiments
- Beauty-quark decays with 3.1 σ

$$R_K = 0.846\,^{+0.044}_{-0.041}$$

- W boson mass measurements
- CDFII full statistic result reports 7 σ



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

Science 376 (2022) 170-176

“THREE CLOUDS” IN PARTICLE PHYSICS SINCE 2021

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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]
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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:

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

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

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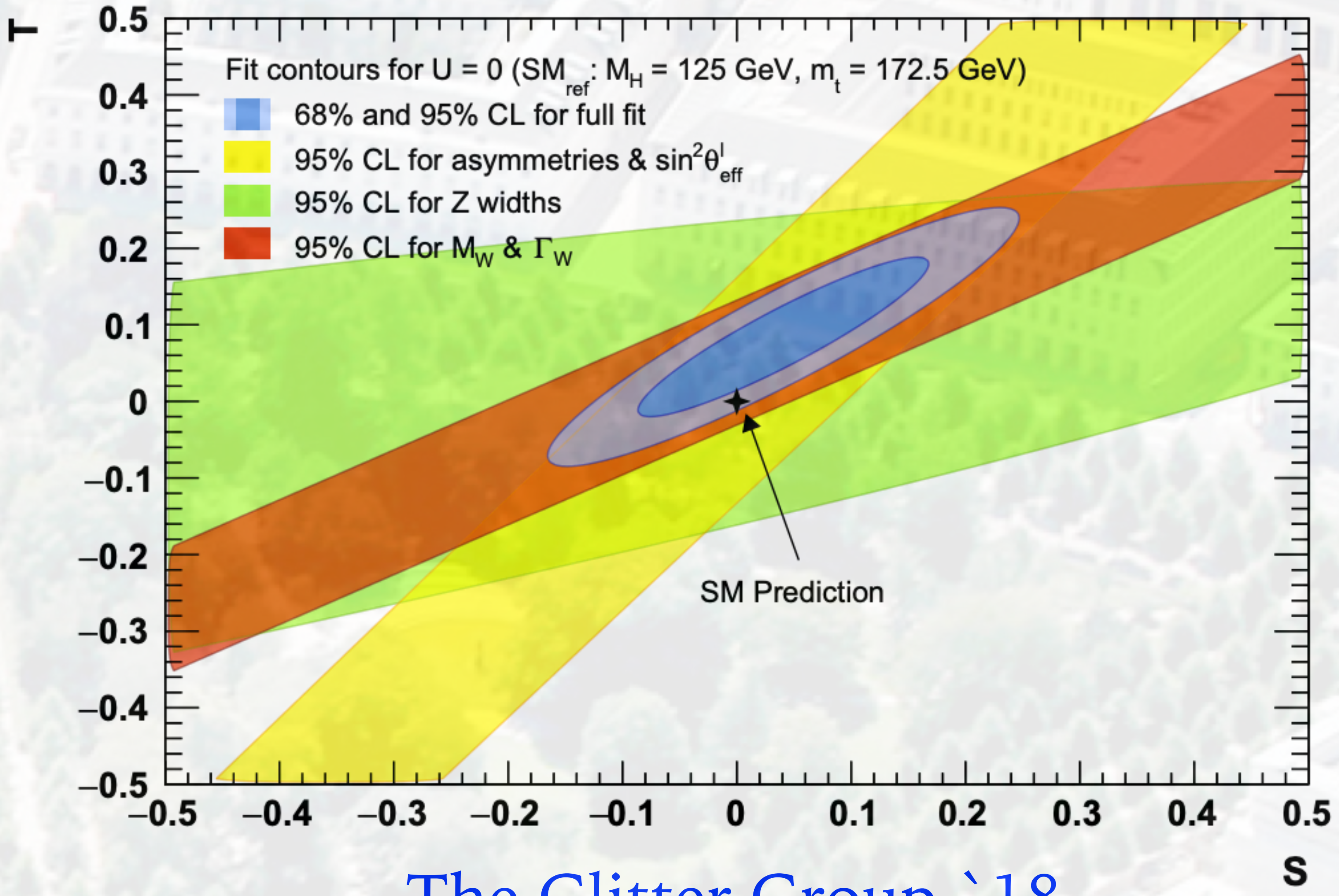
Peskin and Takeuchi `92



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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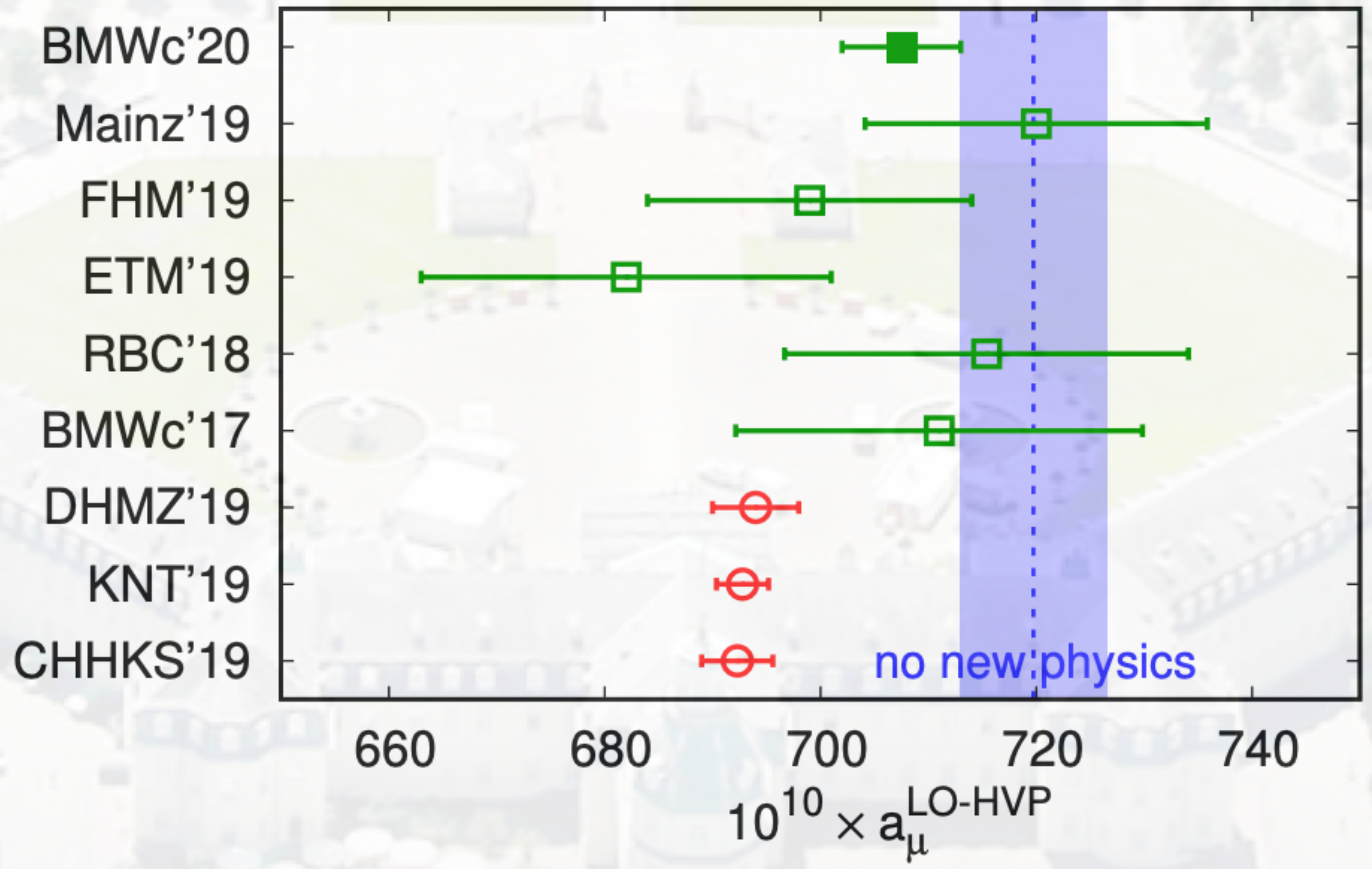
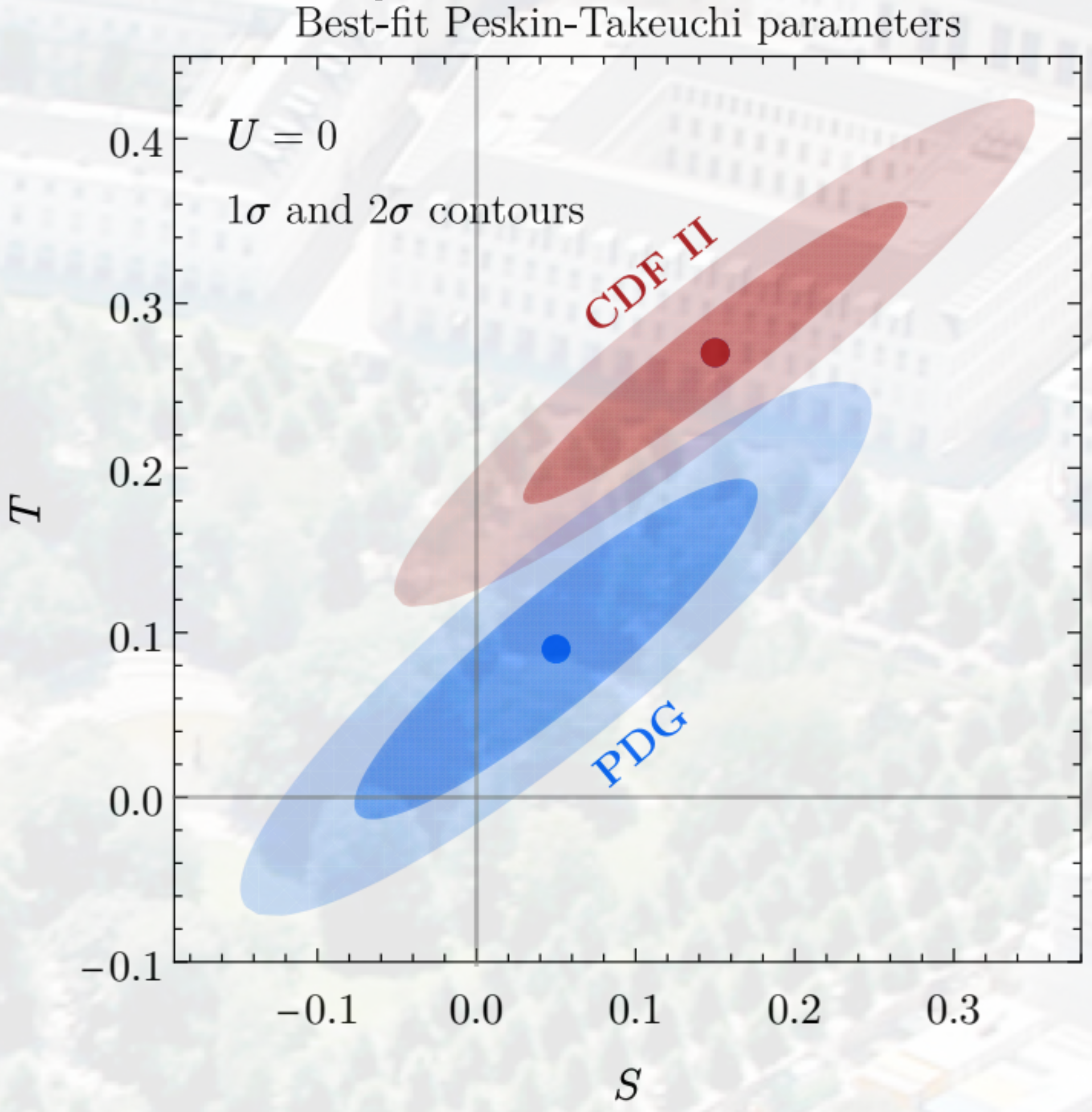


Carpenter, Murphy, Smylie `22

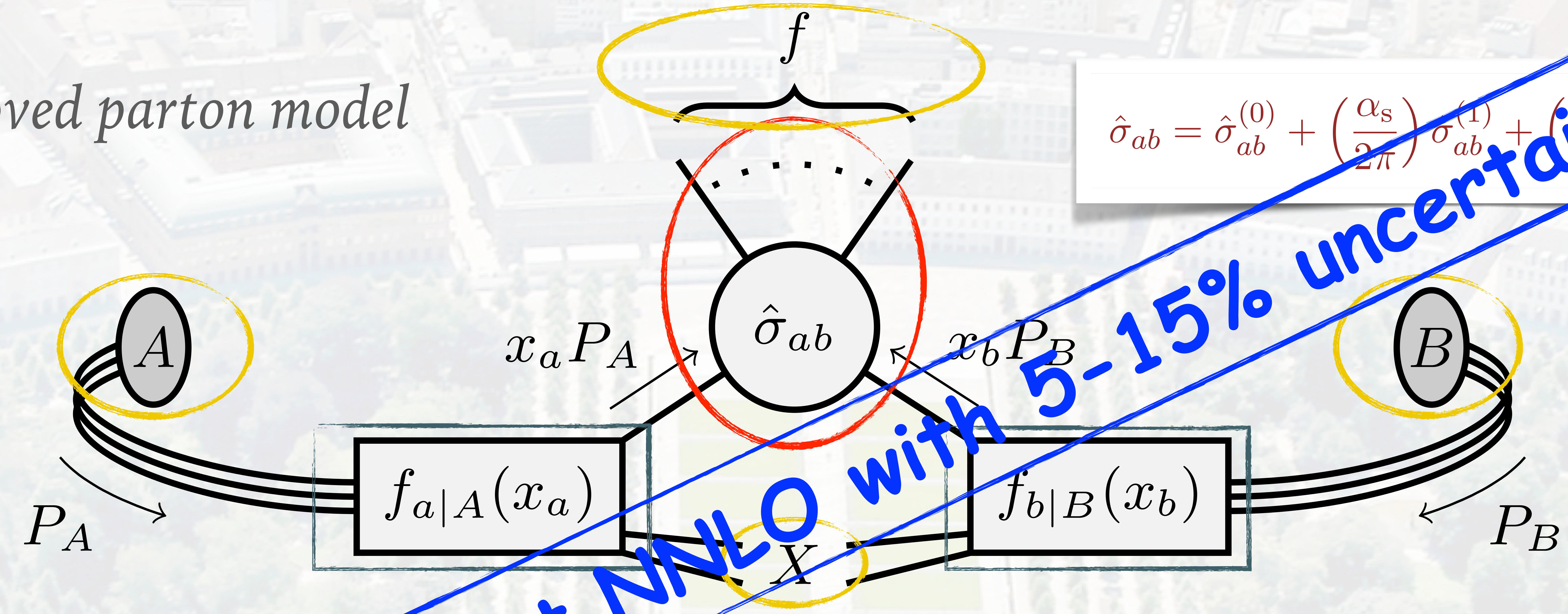


- Challenge experiment with better/alternative predictions
  - Lattice prediction of HVP in g-2
  - Improve template fit in CDFII (ResBos@NLO+NNLL)

PRECISION PREDICTIONS AT THE LHC

QCD improved parton model

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



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

Typical precision at NNLO with 5-15% uncertainties

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

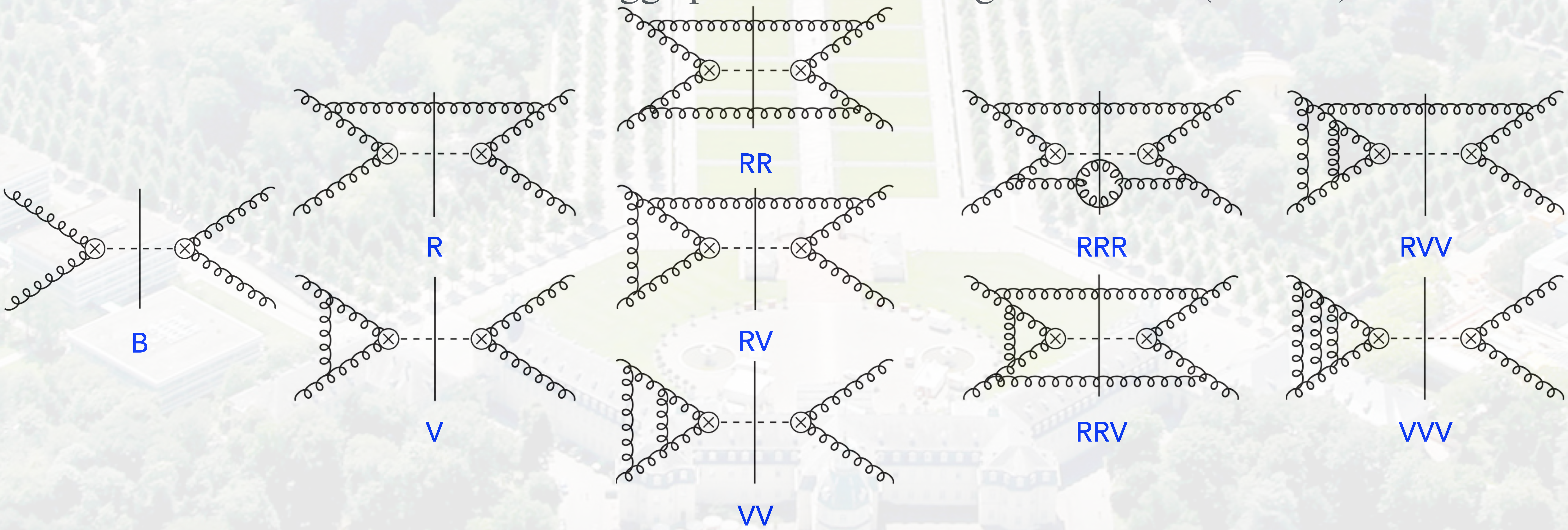
ANATOMY OF HARD SCATTERING $\hat{\sigma}_{ab}$

➤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)



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

➤ All matrix elements have Infrared (IR) divergency

Single soft gluon with momentum $p_j \to 0$:

$$|\mathcal{M}^0_{m+1}(\cdots, i, j, k, \cdots)|^2 \to s_{ijk}|\mathcal{M}^0_m(\cdots, i, k, \cdots)|^2 \quad \text{with Eikonal factor} \quad s_{ijk} = \frac{2s_{ik}}{s_{ij}s_{jk}}$$

Double soft gluon with momentum $p_b + p_c \to 0$:

$$s_{abcd} = \frac{2s_{ad}^2}{s_{ab}s_{bcd}s_{abc}s_{cd}} + \frac{2s_{ad}}{s_{bc}}\left(\frac{1}{s_{ab}s_{cd}} + \frac{1}{s_{ab}s_{dcd}} + \frac{1}{s_{cd}s_{abc}} - \frac{4}{s_{abc}s_{bcd}}\right) + \frac{2(1-\epsilon)}{s_{bc}^2}\left(\frac{s_{ab}}{s_{abc}} + \frac{s_{cd}}{s_{bcd}} - 1\right)^2$$

Various double unresolved limits:
Double soft, triple collinear, soft and collinear (Gehrmann-De Ridder, Gehrmann, Glover `05) (Braun-White, Glover `22)

Various N3LO unresolved limits:
Triple soft (Catani, Colferai, Torrini `19) Quad collinear (Del Duca, Duhr et. al. `19), One-loop unresolved (Badger, Buciuni, Peraro `15, Catani, Cieri `21) Two-loop unresolved (Duhr, Gehrmann, Jaquier `15) etc.

Explicit IR divergence for 1-loop matrix elements (Catani `98)

$$|\mathcal{M}^1_m\rangle = |\mathcal{M}^1_m(\mu^2;\{p\})\rangle = \mathbf{I}^{(1)}(\epsilon,\mu^2;\{p\})|\mathcal{M}_m(\{p\})\rangle + |\mathcal{M}^{1,fin}_m(\mu^2;\{p\})\rangle$$

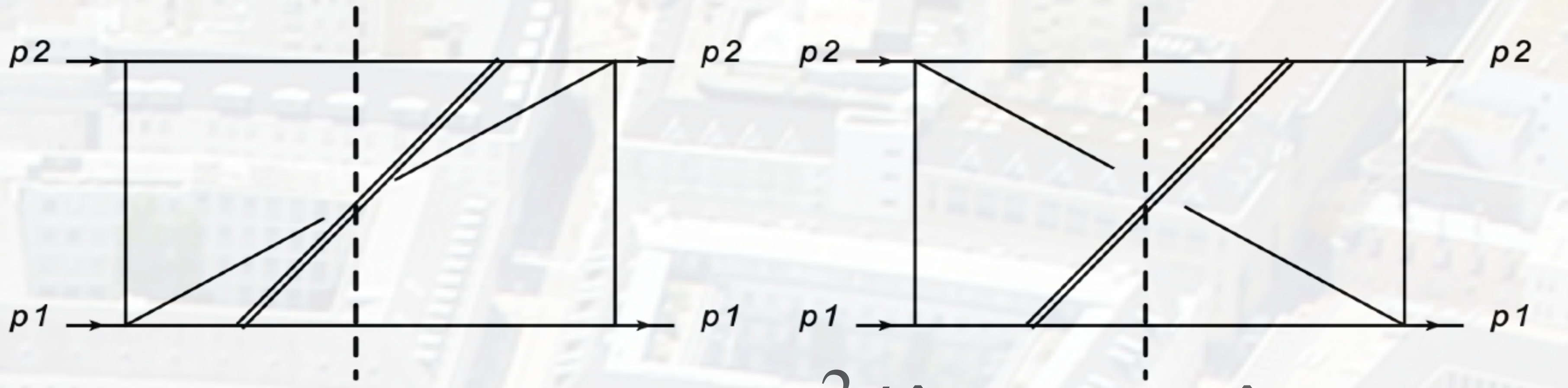
Explicit IR divergence for 2-loop matrix elements

$$|\mathcal{M}^2_m\rangle = |\mathcal{M}^2_m(\mu^2;\{p\})\rangle = \mathbf{I}^{(1)}(\epsilon,\mu^2;\{p\})|\mathcal{M}^1_m(\mu^2;\{p\})\rangle + \mathbf{I}^{(2)}(\epsilon,\mu^2;\{p\})|\mathcal{M}^0_m(\mu^2;\{p\})\rangle + |\mathcal{M}^{2,fin}_m(\mu^2;\{p\})\rangle$$

$$\mathbf{I}^{(2)}(\epsilon,\mu^2;\{p\}) = -\frac{1}{2}\mathbf{I}^{(1)}(\epsilon,\mu^2;\{p\})\left(\mathbf{I}^{(1)}(\epsilon,\mu^2;\{p\}) + \frac{4\pi\beta_0}{\epsilon}\right) + \frac{e^{+\epsilon\psi(1)}\Gamma(1-2\epsilon)}{\Gamma(1-\epsilon)}\left(\frac{2\pi\beta_0}{\epsilon} + K\right)\mathbf{I}^{(1)}(2\epsilon,\mu^2;\{p\}) + \mathbf{H}^{(2)}(\epsilon,\mu^2;\{p\})$$

➤ Kinoshita-Lee-Nauenberg theorem (`64): all IR divergences cancel at each perturbation order of QFT

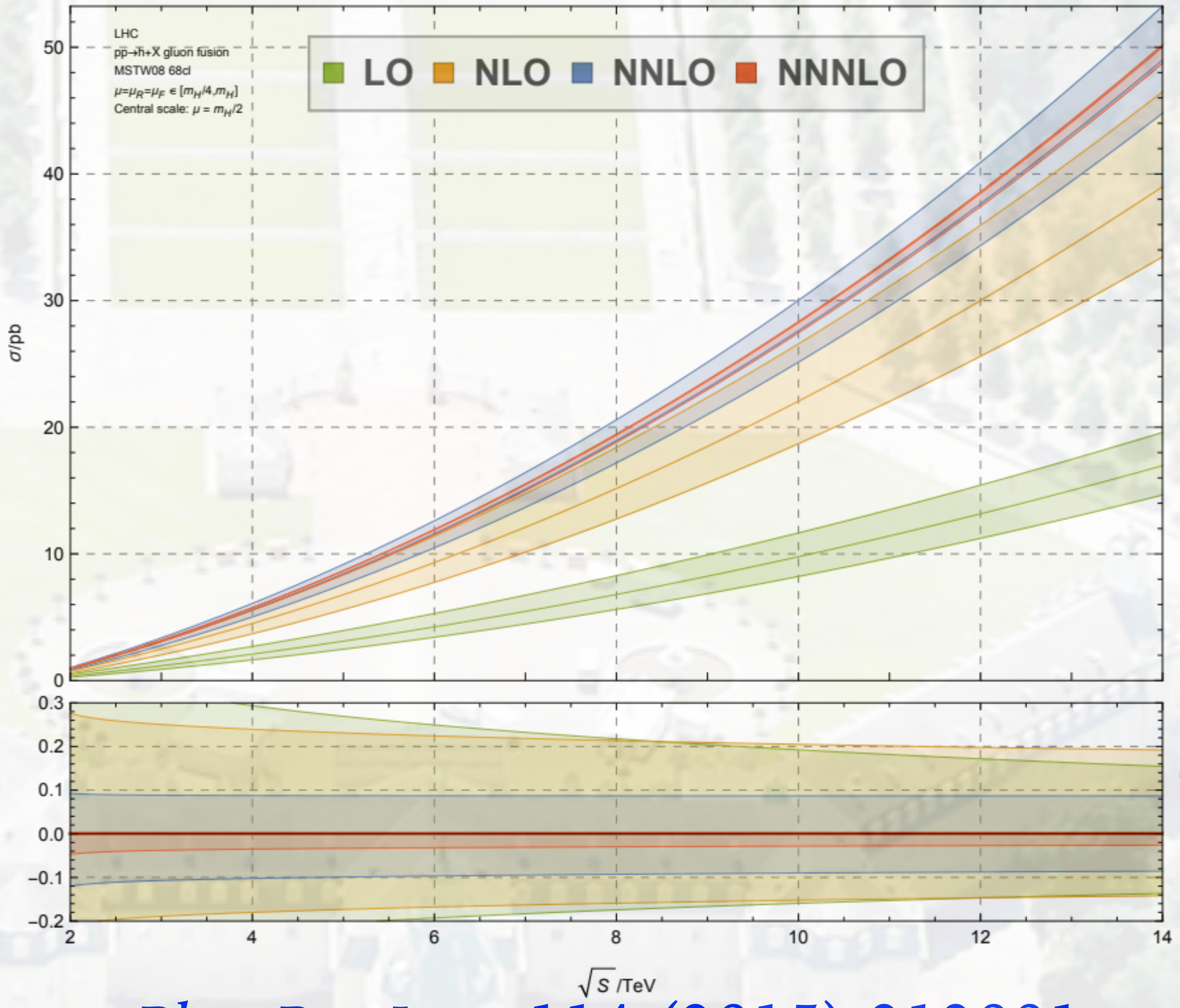
STATE-OF-THE-ART PREDICTIONS FOR σ_{N^3LO}



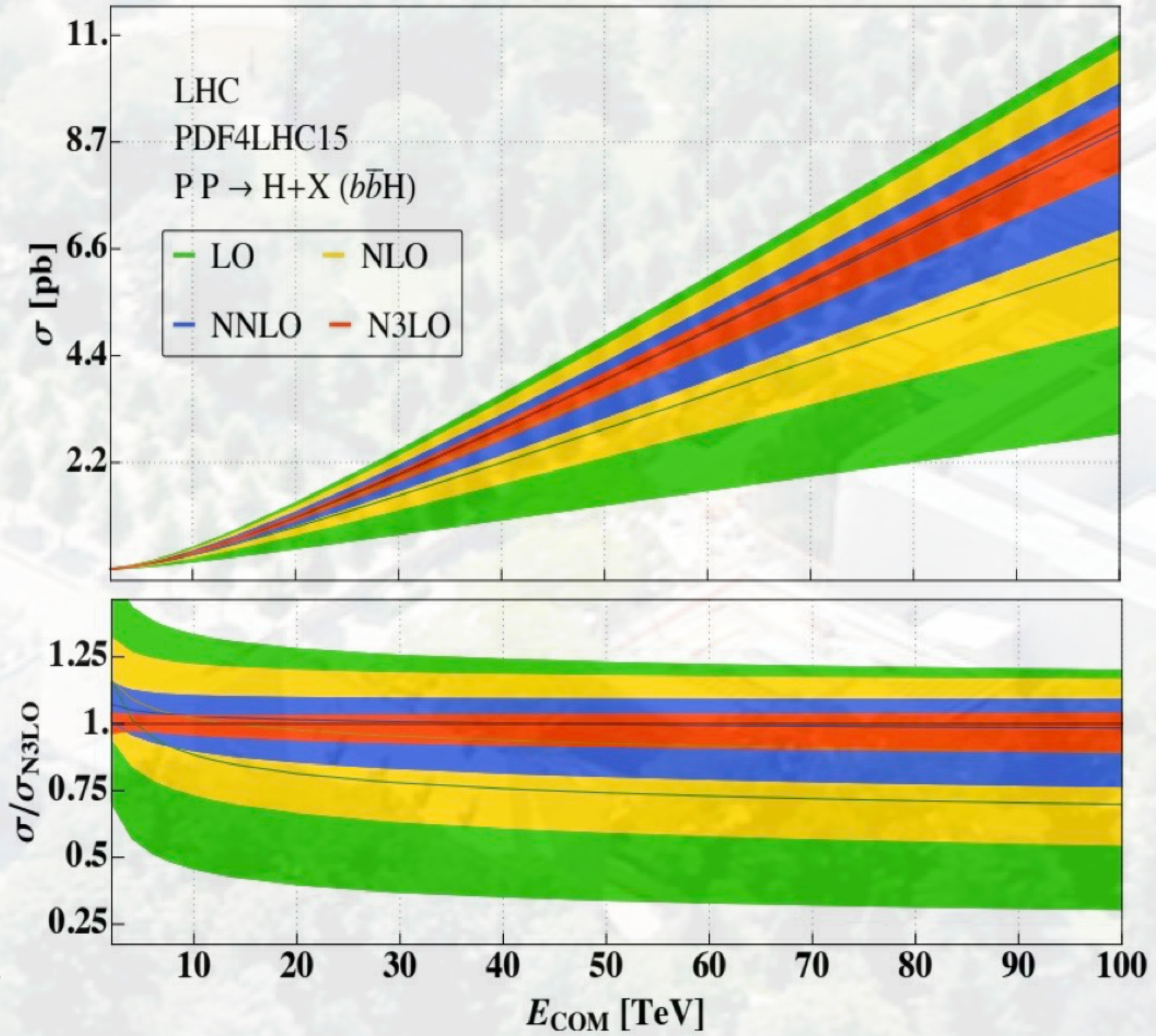
- Assemble each $\hat{\sigma}_{ab}(x_a, x_b)$ at N3LO
  - Integration of QCD radiation with unitarity cuts
  - Standard treatment of multi-loop calculations except elliptic integrals with $\tau = m^2/\hat{s}$ where $\hat{s} = x_a x_b s$
  - Use threshold expansion at different region of τ and truncate 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

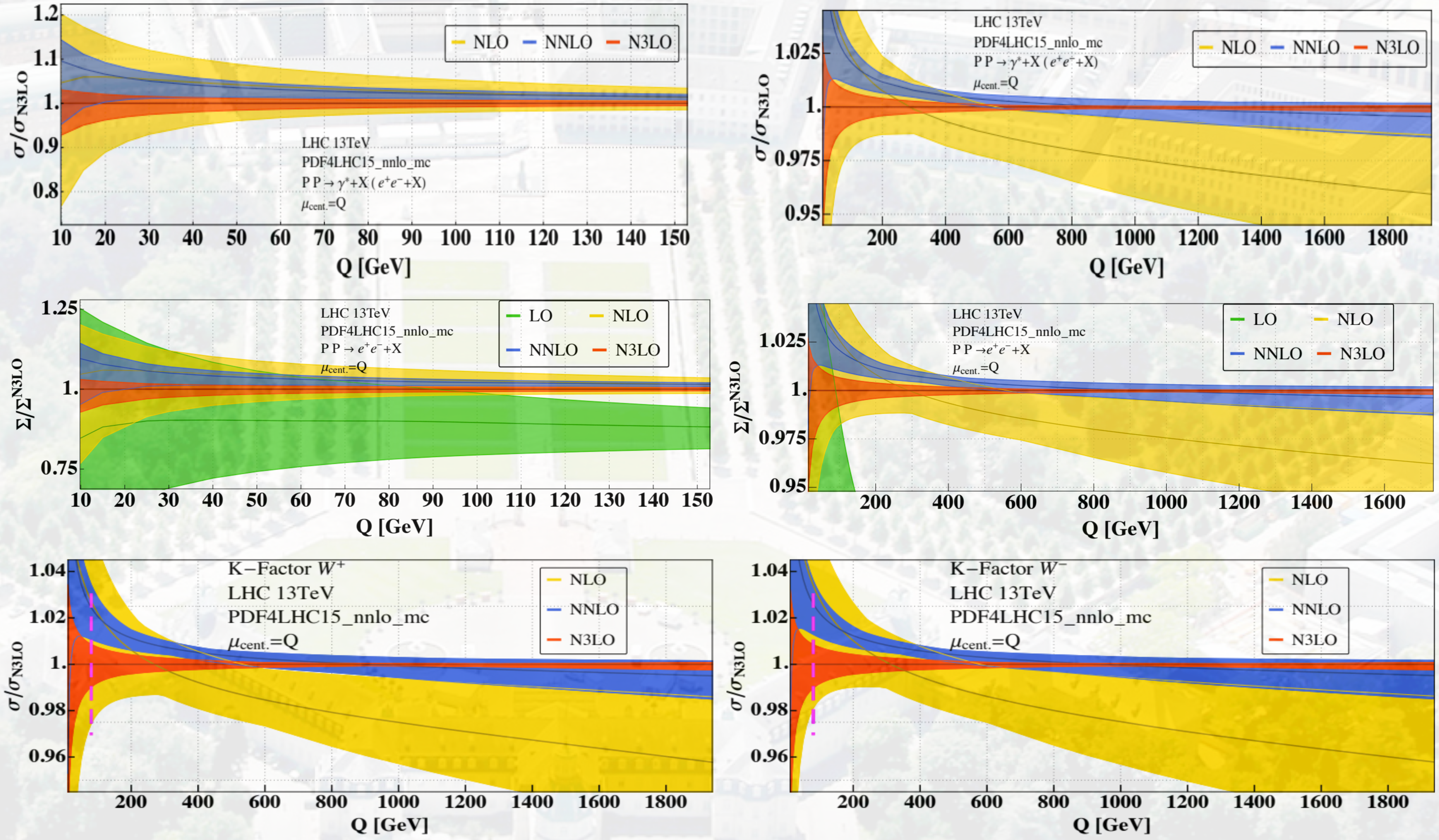
STATE-OF-THE-ART PREDICTIONS FOR σ_{N^3LO}

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

$pp \rightarrow \gamma^*$

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

$pp \rightarrow W^\pm$



ANATOMY OF DIFFERENTIAL CROSS SECTIONS $d\hat{\sigma}_{ab}$

- Method to control IR divergence?
  - Subtraction of IR divergence

    NLO: ***di-pole*** (Catani, Seymour `96), ***FKS*** (Frixione et al.`95), ***Nagy-Soper*** (Nagy, Soper `07, Chung et al. '11, Bevilacqua et al.`13)

    NNLO: ***Antenna subtraction*** (Gehrmann-De Ridder, Gehrmann et al. `05),

    STRIPPER (Czakon `10), ***ColourfullNNLO*** (Del Duca, Kardos et al. `16),

    Nested-soft-collinear subtraction (Caola, Melnikov, Rontsch `17),

    Analytic Sector Subtraction (Magnea, Maina, Pelliccioli, Signorile-Signorile, Torrielli, Uccirati `18),

    Geometric IR subtraction (Herzog `18)
  - Slice IR sensitive phase space region (applicable to all orders)

    qT slicing (Bozzi, Catani, De Florian, Grazzini et al. `06 `07), ***N-jettiness slicing*** (Boughezal, Liu, Petriello et al. `15)
  - ***Projection to Born*** (applicable to all orders)

    (Cacciari, Dreyer, Karlberg, Salam, Zanderighi `15)
  - Amplitude level removal

    Loop-Tree Duality (Bierenbaum, Catani, Draggiotis et al. `08 to `10, Runkel, Szor et al. `19, Capatti, Hirschi et al. `19 `20, Aguilera-Verdugo et al. `20) ***Universal factorisation*** (Anastasiou, Haindl, Sterman, Yang, Zeng `18 to `20)

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$$d\hat{\sigma}_{NNLO} = \int_{d\Phi_{N+2}} \left(d\hat{\sigma}^{RR}_{NNLO} - d\hat{\sigma}^S_{NNLO}\right) + \int_{d\Phi_{N+1}} \left(d\hat{\sigma}^{RV}_{NNLO} - d\hat{\sigma}^T_{NNLO}\right) + \int_{d\Phi_N} \left(d\hat{\sigma}^{VV}_{NNLO} - d\hat{\sigma}^U_{NNLO}\right)$$

  - Slice IR sensitive phase space region (applicable to all orders)

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

    qT slicing (Bozzi, Catani, De Florian, Grazzini et al. `06 `07), ***N-jettiness slicing*** (Boughezal, Liu, Petriello et al. `15)

  - ***Projection to Born*** (applicable to all orders)

    (Cacciari, Dreyer, Karlberg, Salam, Zanderighi `15)

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

  - Amplitude level removal

    Loop-Tree Duality (Bierenbaum, Catani, Draggiotis et al. `08 to `10, Runkel, Szor et al. `19, Capatti, Hirschi et al. `19 `20, Aguilera-Verdugo et al. `20) ***Universal factorisation*** (Anastasiou, Haindl, Sterman, Yang, Zeng `18 to `20)

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

- Differential N3LO accuracy
  - 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
    - 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 (via γ^*) (XC, Gehrmann, Glover, Huss, Yang, Zhu `21)
  - Apply qt-slicing at N3LO with SCET factorisation and expand to N3LO:

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

  - 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:

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

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

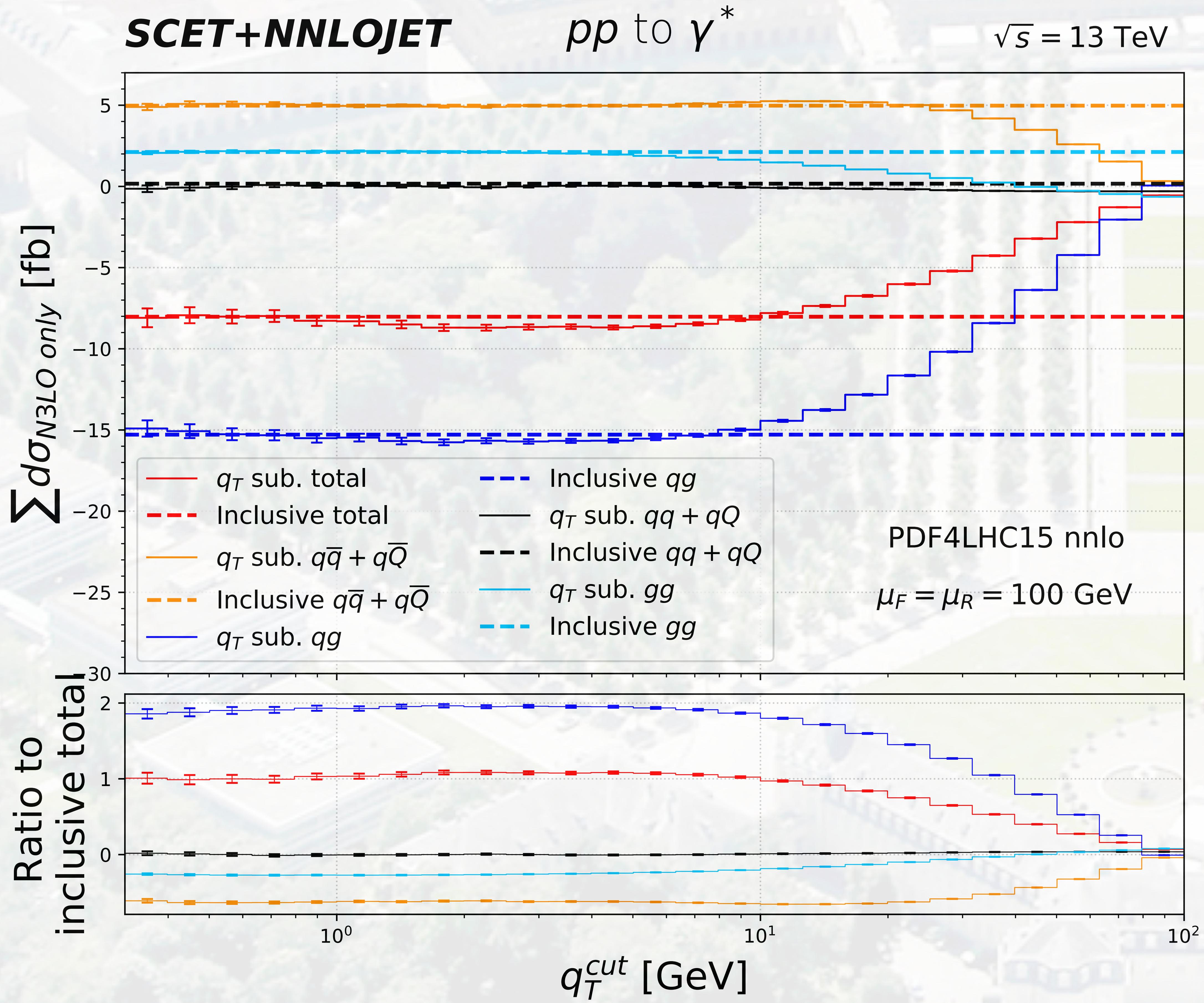
- Differential N3LO predictions for neutral current production $\mathcal{O}(\alpha\alpha_s^3)$
  - Computational setup for $pp \to \gamma^*$
    (identical setup in the inclusive calculation by Durh, Dulat and Mistlberger in *Phys.Rev.Lett.* 125 (2020) 17, 172001)
    - Fix Q value for γ^* at 100 GeV (NNLO and N3LO scale variations deviate)
    - Use central value of PDF4LHC15_nnlo_mc as benchmark input
    - $\alpha_s(m_Z) = 0.118$ with scale variation values calculated from LHAPDF
    - G_μ EW-scheme with fixed α value
    - $\mu_R = \mu_F = 100$ GeV for central QCD scale and use 7-point variations for uncertainty estimation
    - Consider LO decay with $m_e = m_\mu = 0$
  - Apply $p_{T,\gamma^*} > 0.25$ GeV constrain for NNLO $\gamma^* + Jet$ without jet definition
  - Use SCET factorisation to integrate contributions below qt cut.
  - Dedicated MC adaption to four sub-channels:

gg, qqb = (qqb+qbq), qg = (qg+gq+qbg+gqb), qq = (qq+qbqb)

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

➤Differential N3LO predictions for neutral current production

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



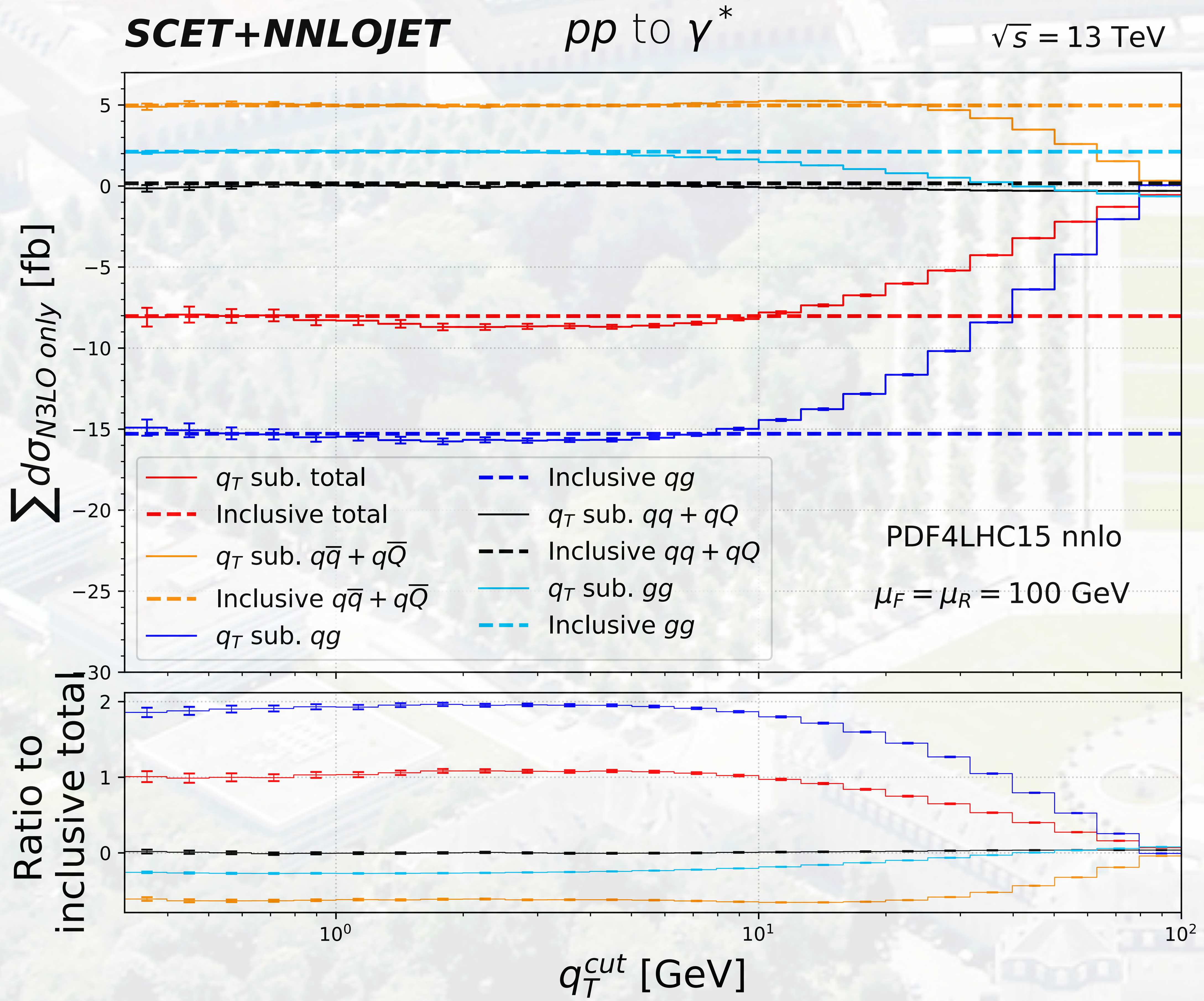
XC, Gehrmann, Glover, Huss, Yang, Zhu *Phys.Rev.Lett.* 128 (2022) 5

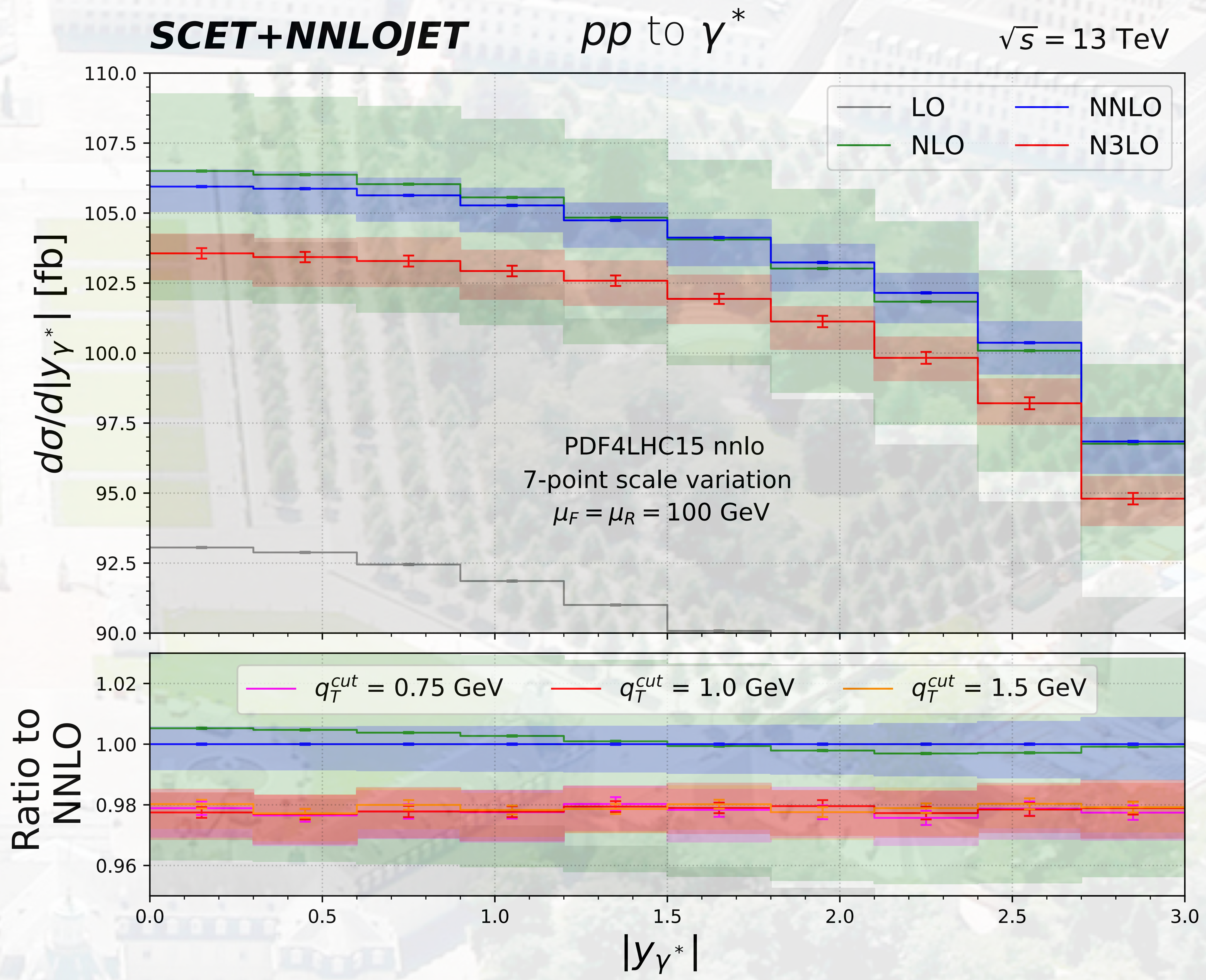
STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

➤Differential N3LO predictions for neutral current production

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

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

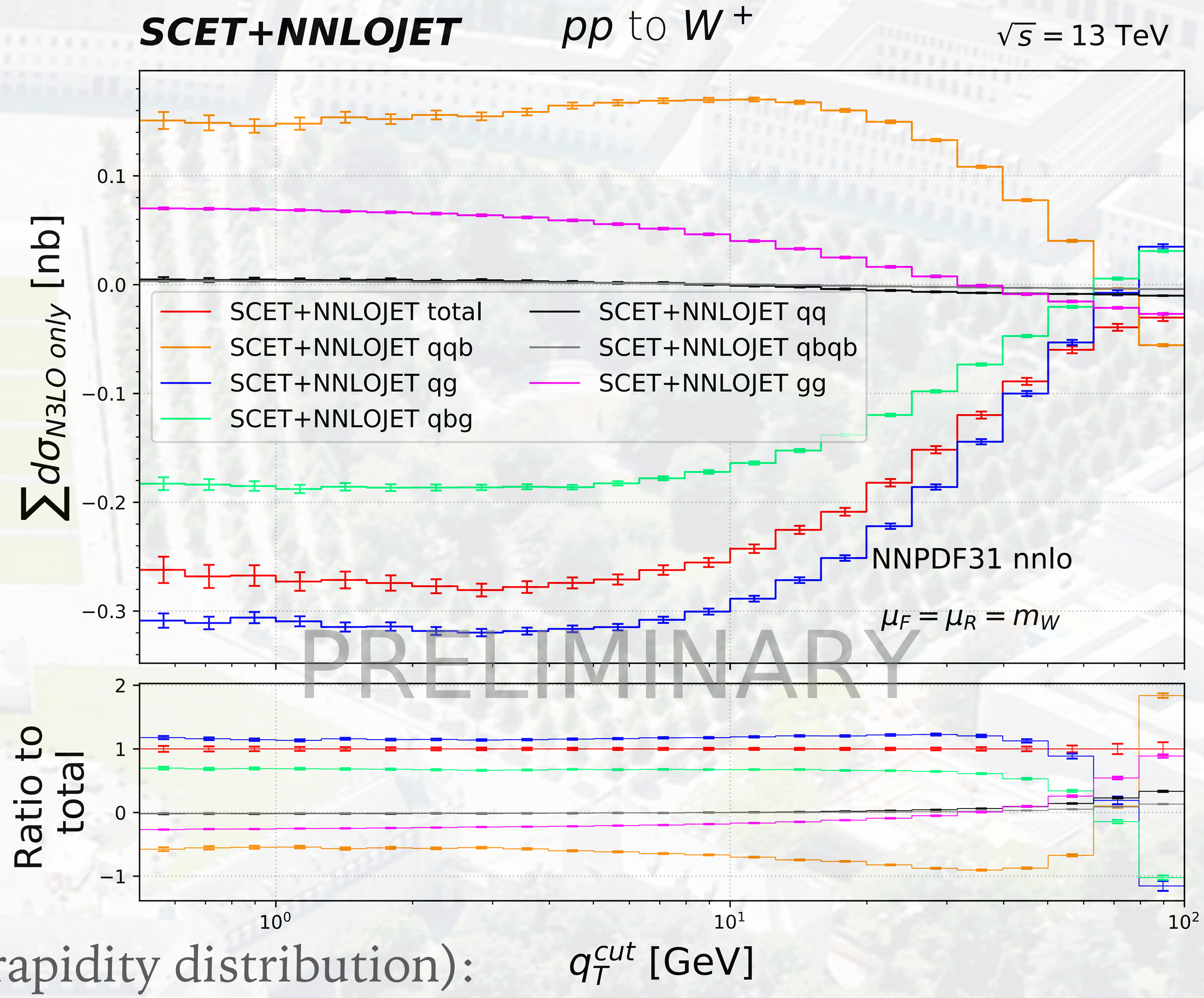




XC, Gehrmann, Glover, Huss, Yang, Zhu *Phys.Rev.Lett.* 128 (2022) 5

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

- Differential N3LO predictions for charged current production
  - Fully differential N3LO $W^{\pm}$ production (XC, Gehrmann, Glover, Huss, Yang, Zhu in preparation)
  - Computational setup for LHC observables:
    - No constrain on W boson mass, $m_{l\nu} \in [0, +\infty]$
    - Use NNPDF31_nnlo PDFs with α_s values from LHAPDF.
    - G_μ EW-scheme with fixed α value.
    - Dynamic QCD scale $\mu_R = \mu_F = m_{l\nu}$ with 7 variations.
    - Consider LO decay with $m_e = m_\mu = 0$
  - Apply $p_{T,l\nu} > 0.5$ GeV constrain for NNLO W+jet
  - Use SCET factorisation for $p_{T,l\nu} < 0.5$ GeV and to check asymptotic agreement of pT distribution.
  - Dedicated MC adaption to six sub-channels (symmetric in rapidity distribution): gg, qqb = (qqb+qbq), qg = (qg+gq), qbg = (qbg+gqb), qq, qbqb

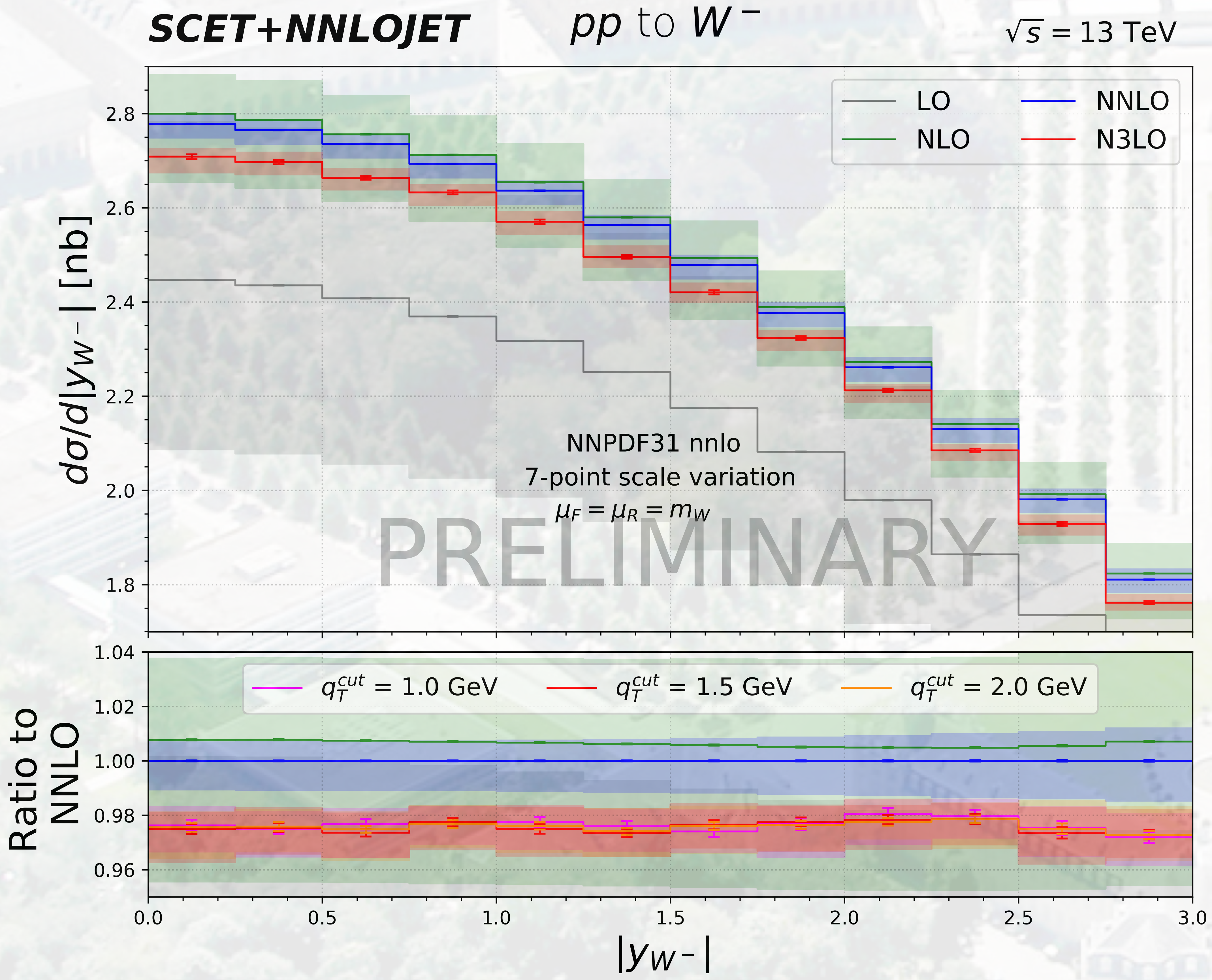


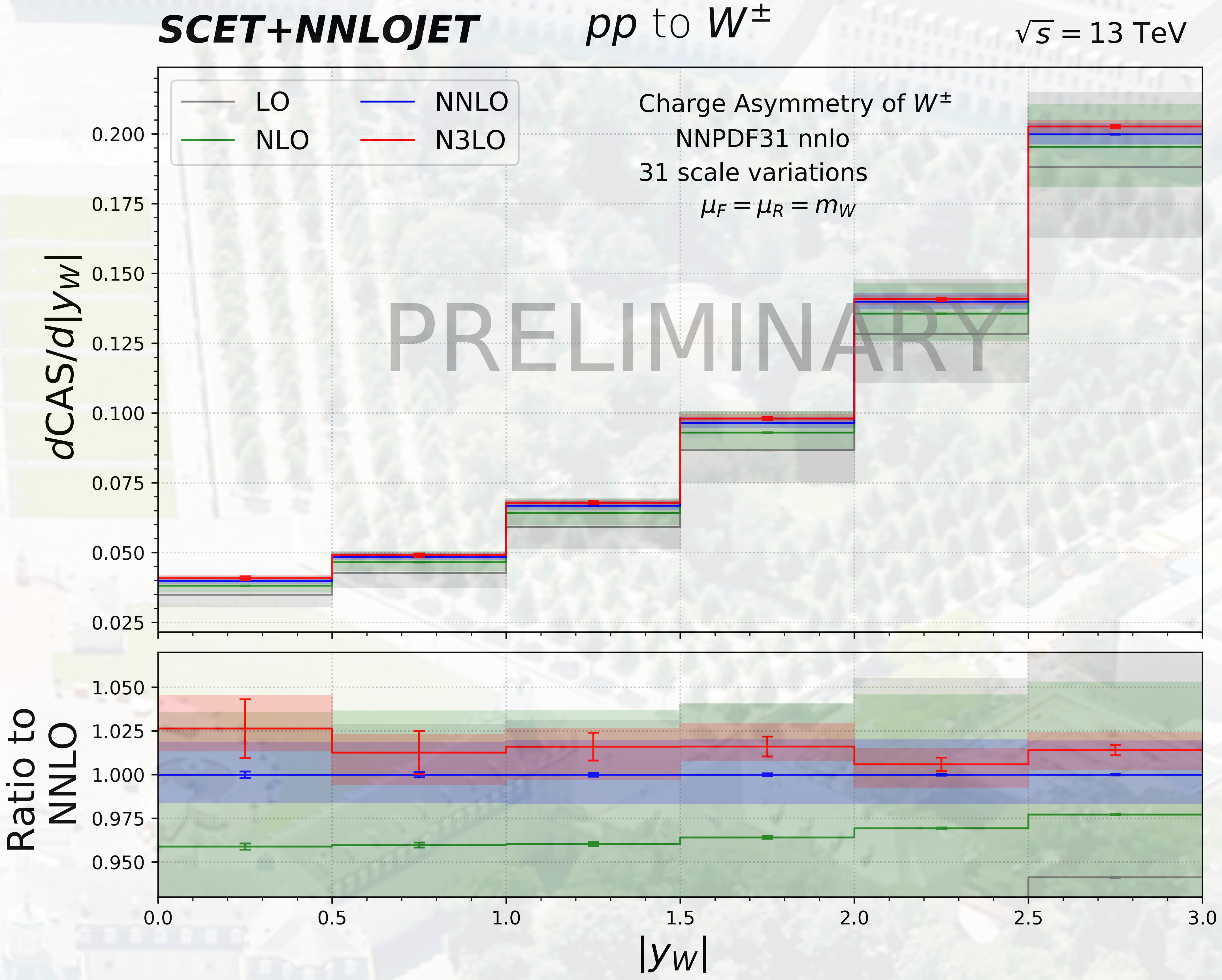
STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

➤Differential N3LO predictions for charged current production

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

$$A(|y_W|) = \frac{d\sigma^{W^+}/d|y_{W^+}| - d\sigma^{W^-}/d|y_{W^-}|}{d\sigma^{W^+}/d|y_{W^+}| + d\sigma^{W^-}/d|y_{W^-}|}$$





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):

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

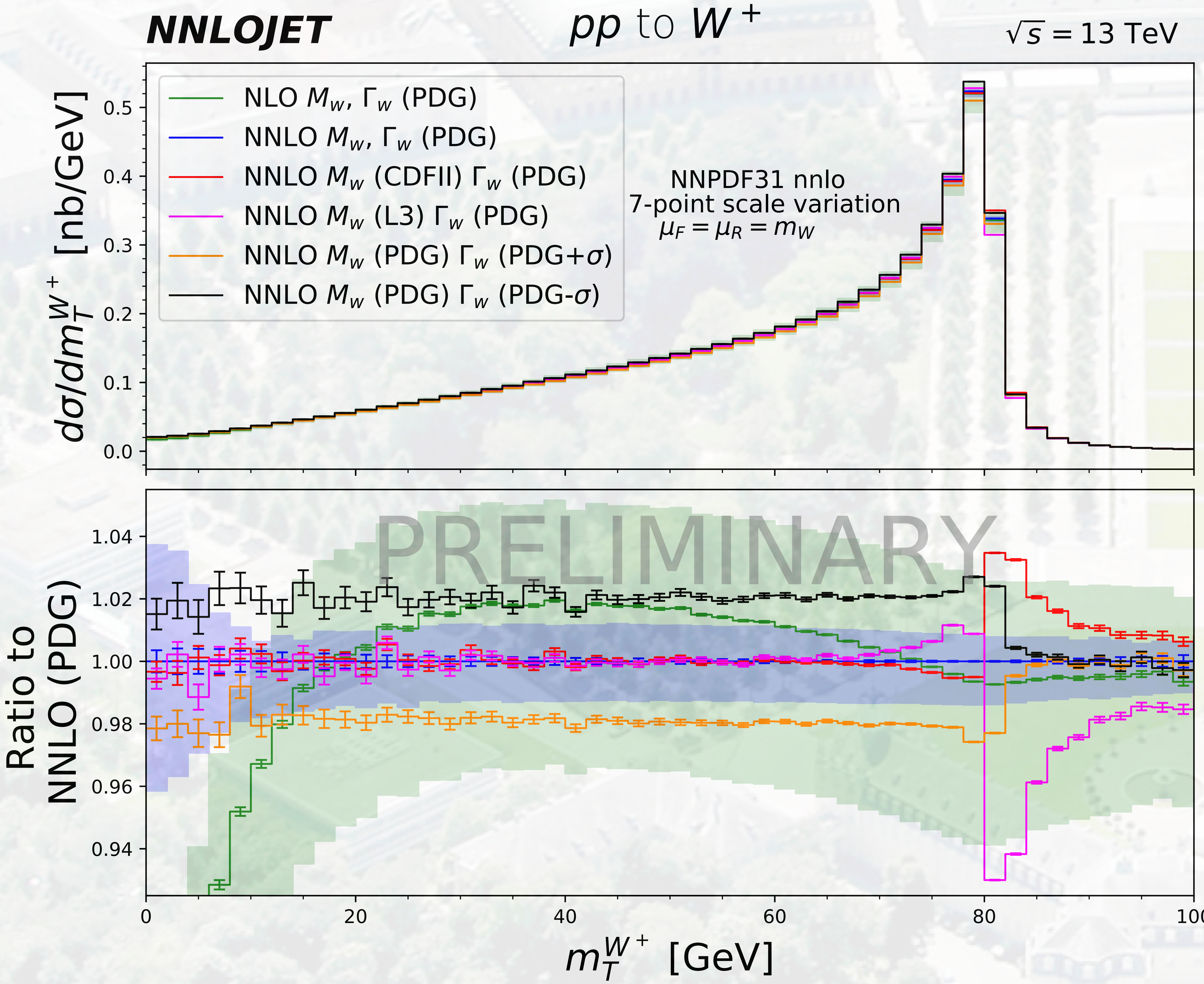
(MeV)	W mass	W width
PDG (2020)	80379 ± 12	2085 ± 42
CDFII	80433 ± 9	2089.5 ± 0.6
L3	80270 ± 55	2180 ± 14

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

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



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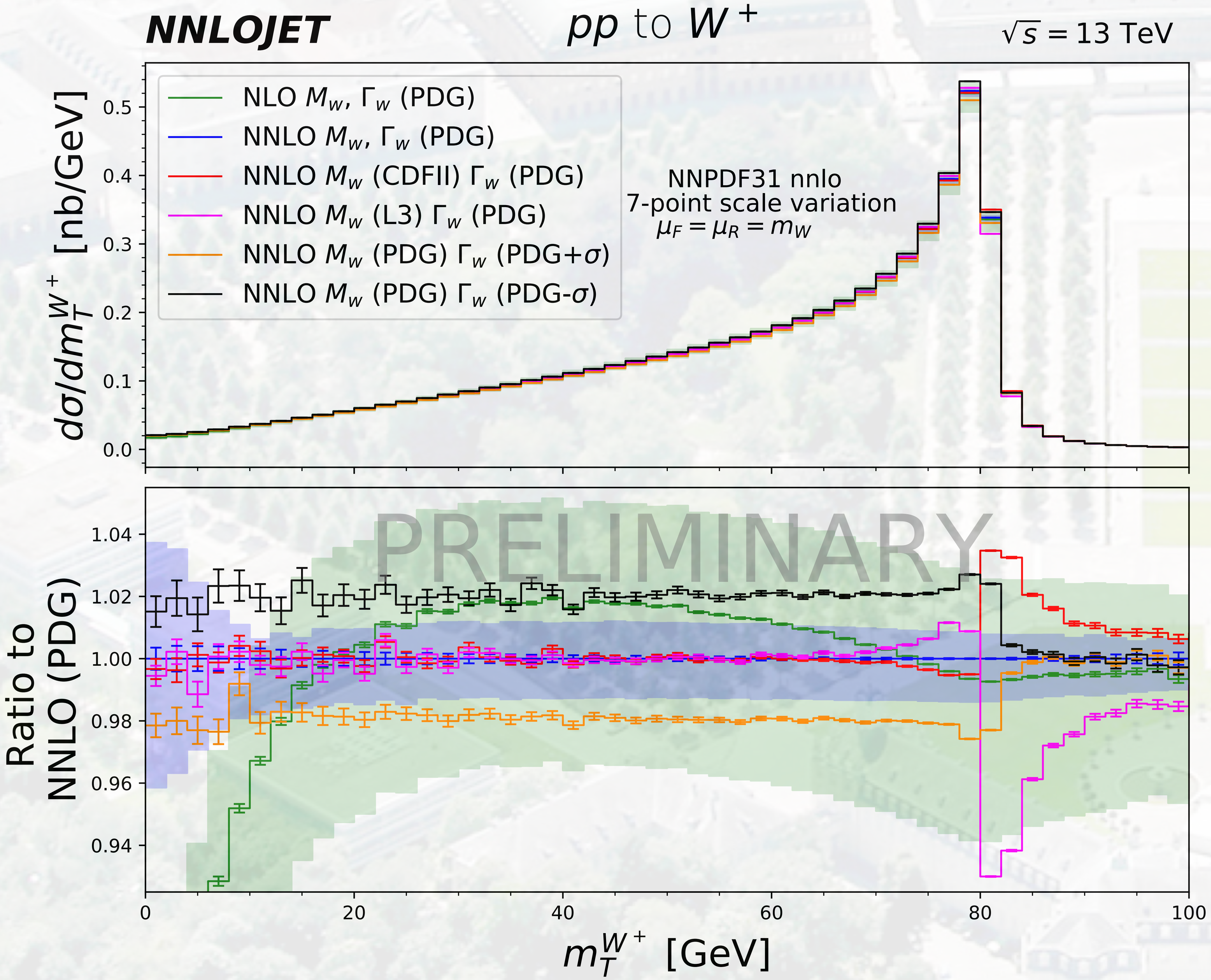
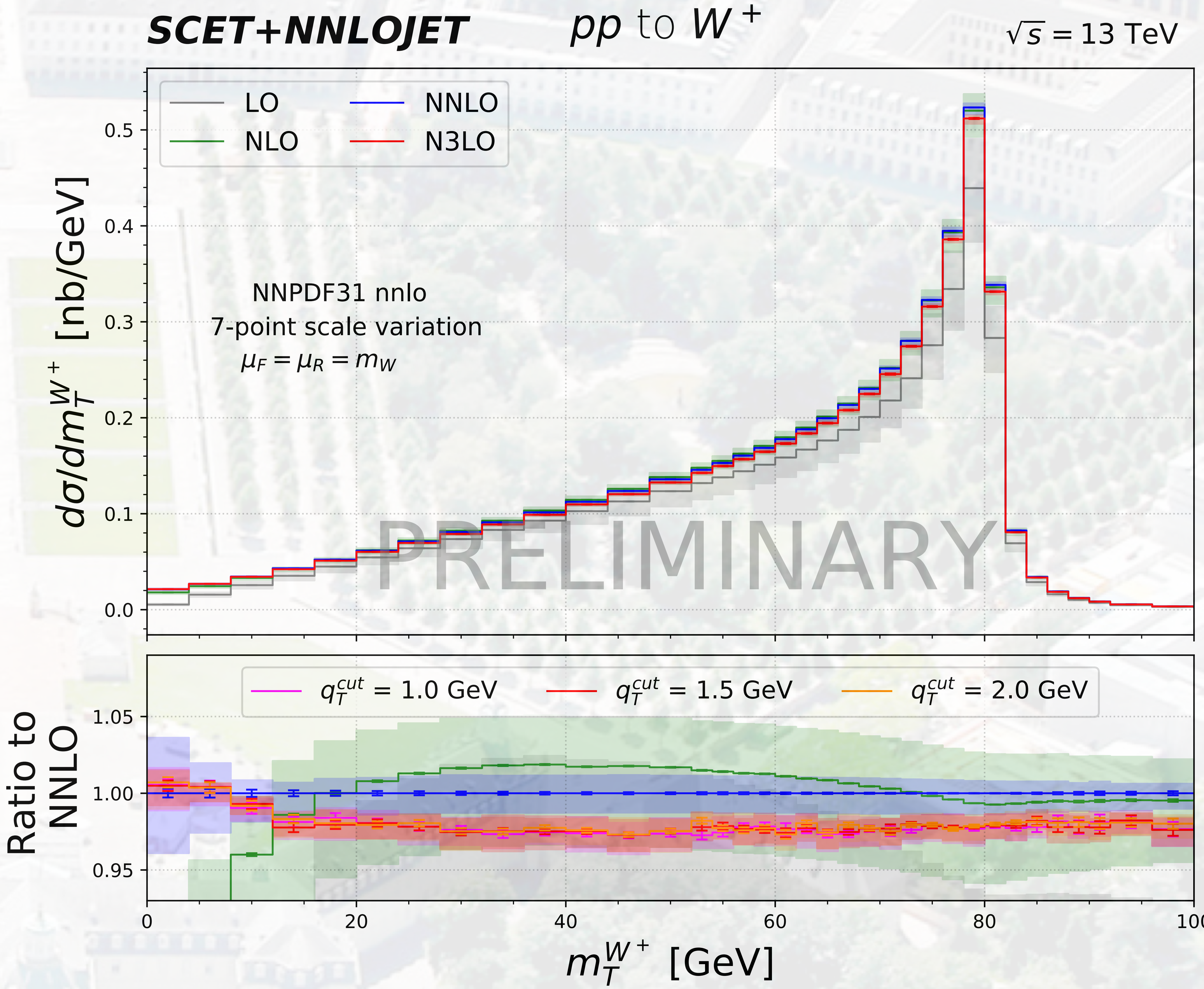
STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

➤Differential N3LO predictions for charged current production

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





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 with fiducial cuts
  - Apply ATLAS fiducial cuts at 13 TeV
    - Dynamical scale $\mu_F = \mu_R = \sqrt{m_{ll}^2 + p_T^{ll^2}}$
    - $m_{ll} \in [66,116]$ 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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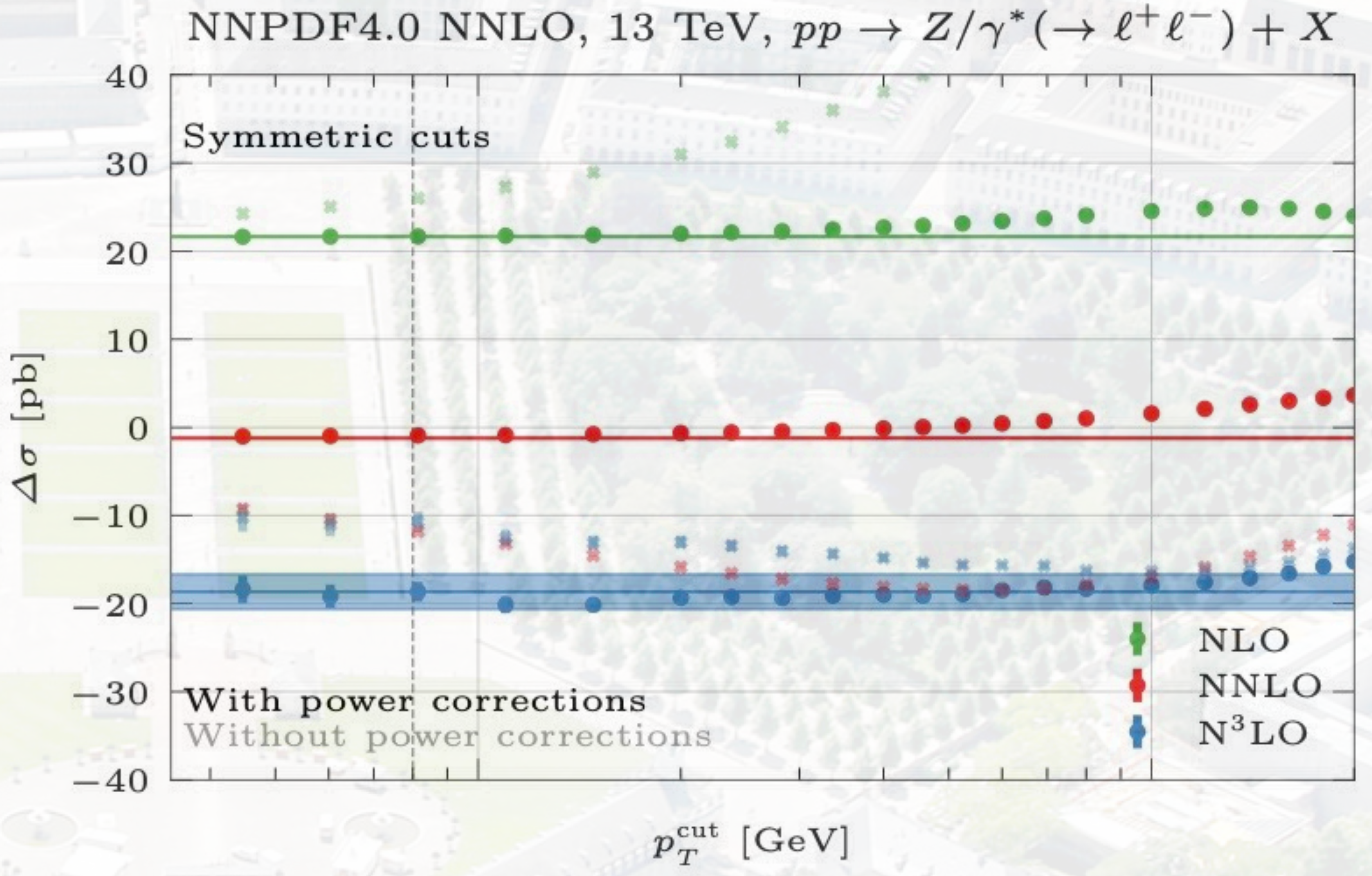

XC, Gehrmann, Glover, Huss, Monni, Rottoli, Re, Torrielli `22

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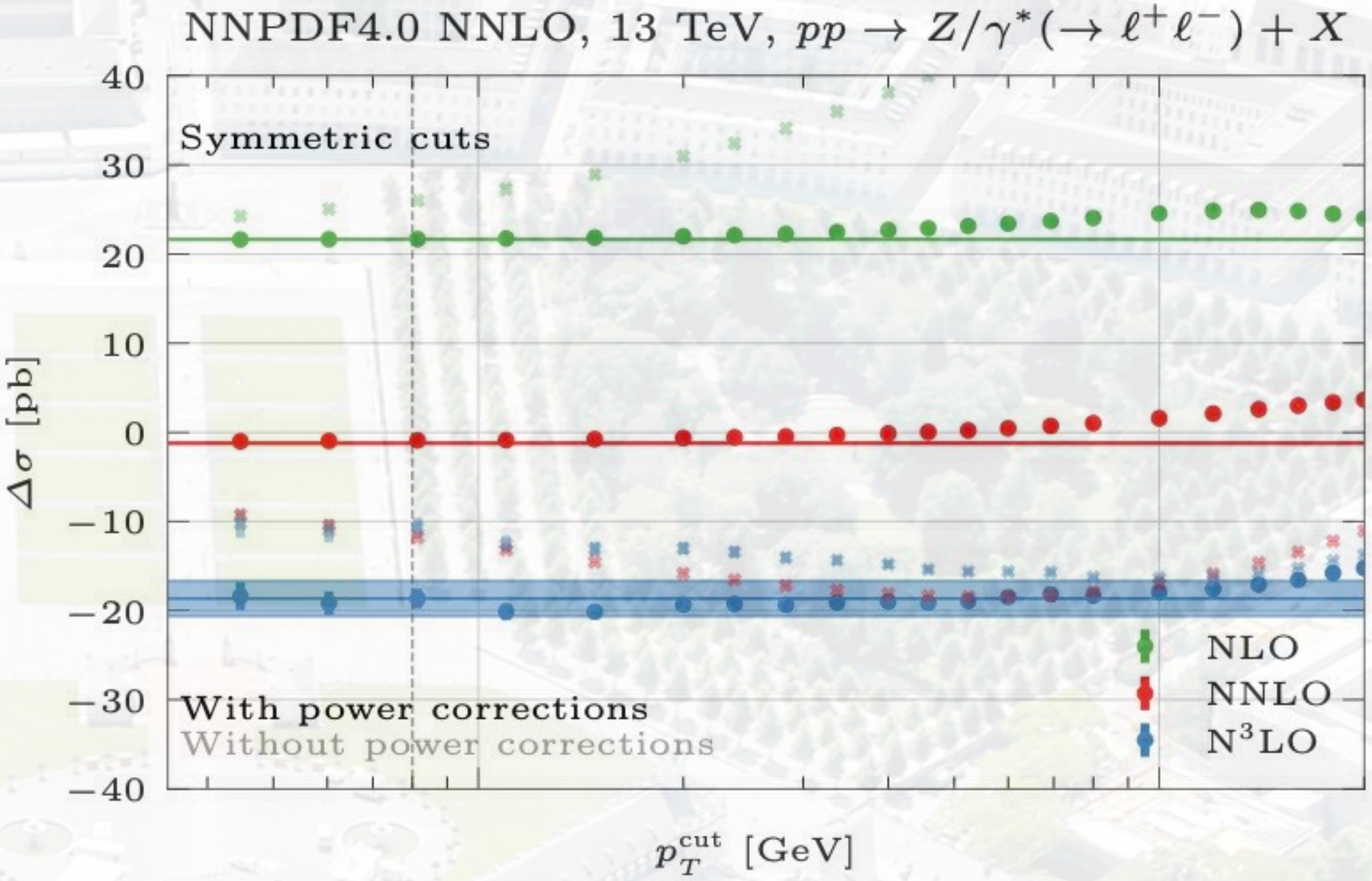

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STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

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  - Apply ATLAS fiducial cuts at 13 TeV
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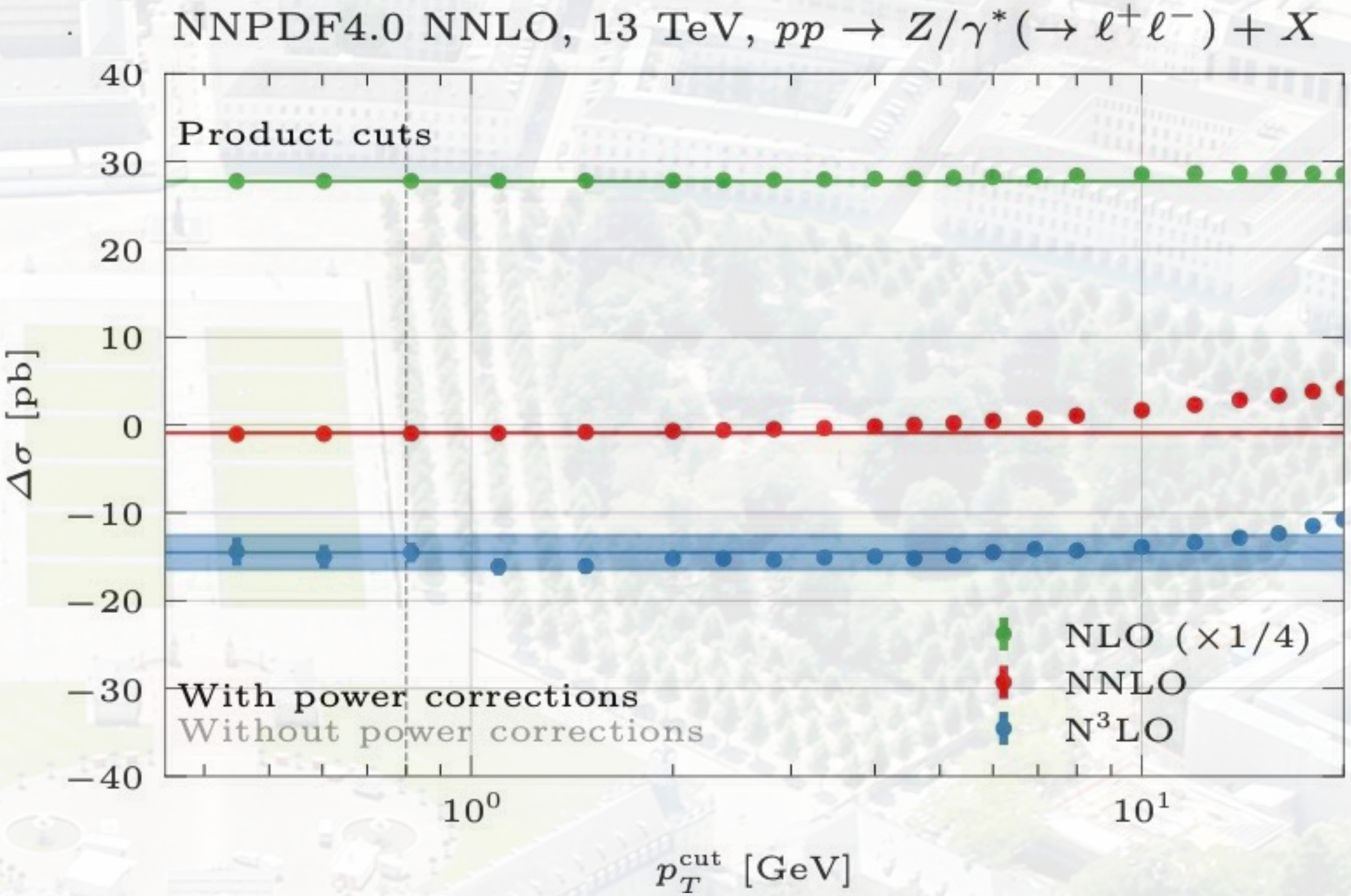

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STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

➤ Differential N3LO predictions for neutral current production with fiducial cuts

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  - Dynamical scale $\mu_F = \mu_R = \sqrt{m_{ll}^2 + p_T^{ll2}}$
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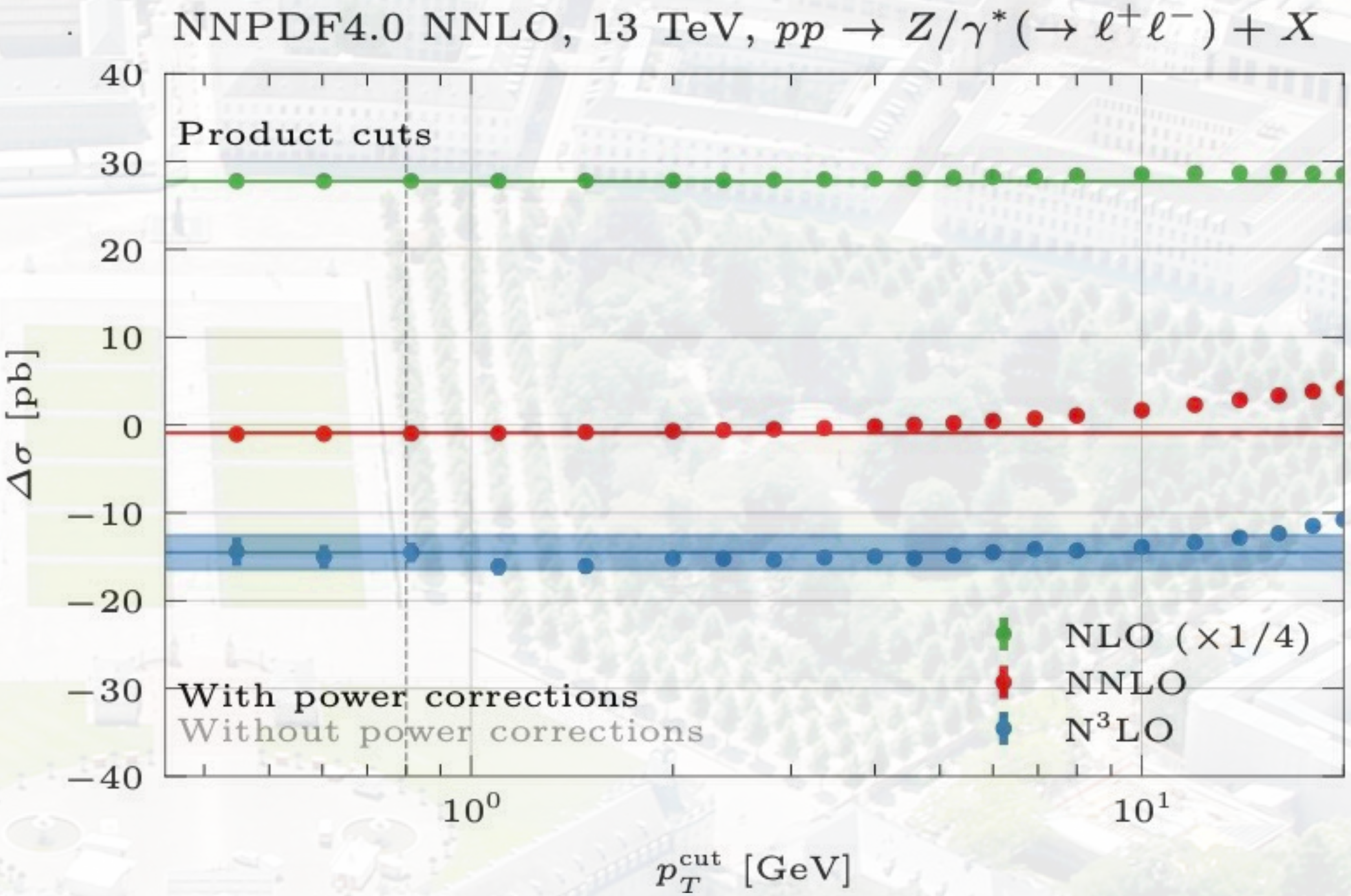

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STATE-OF-THE-ART PREDICTIONS FOR $d\sigma_{N^3LO}$

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  - Apply ATLAS fiducial cuts at 13 TeV
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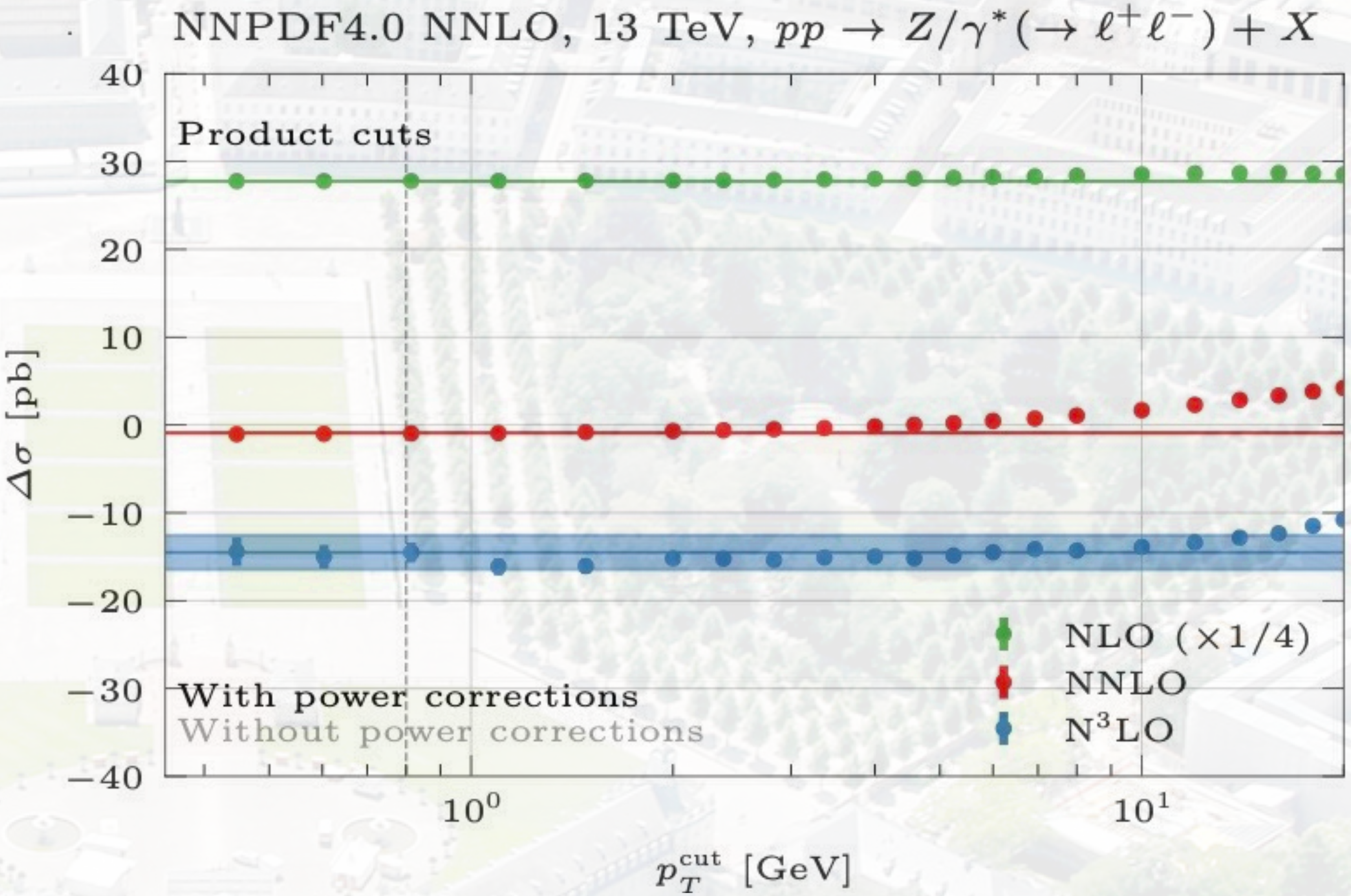

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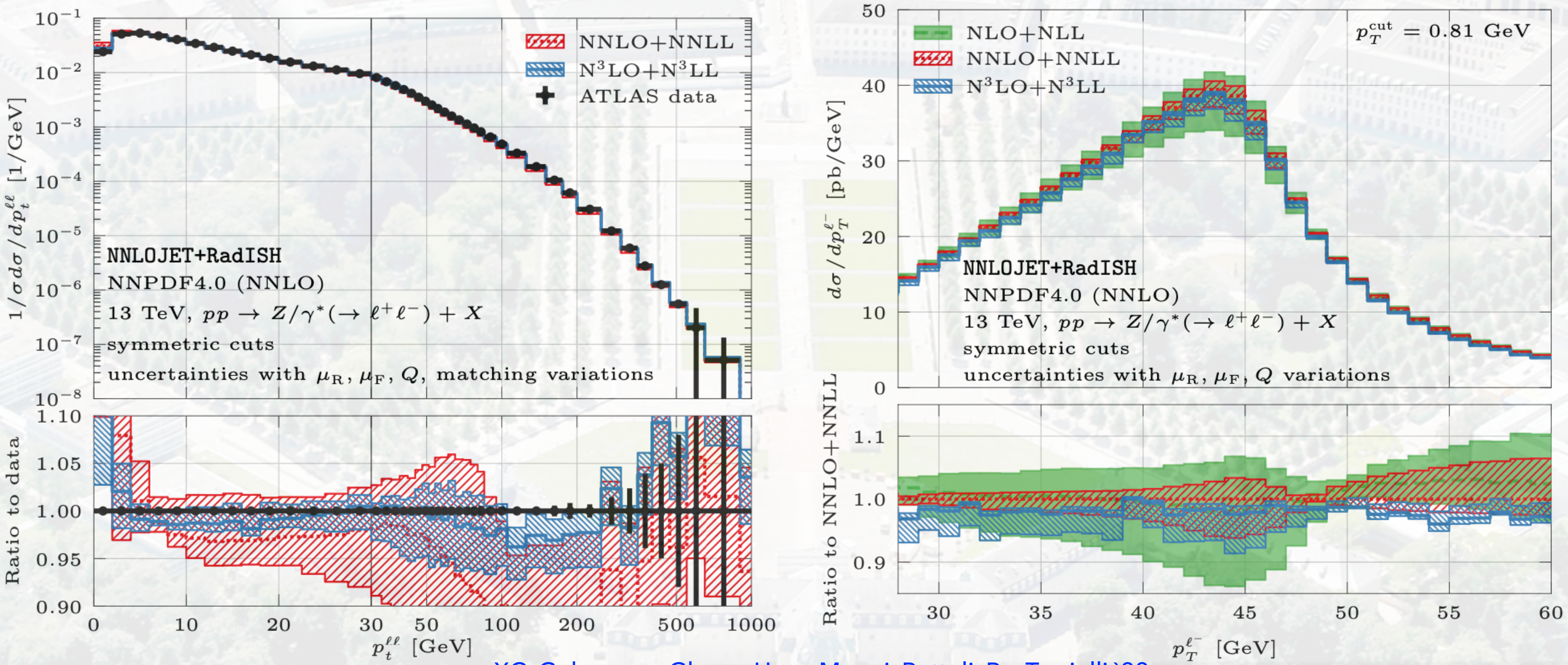
  - Typical fiducial cuts for m_T^V, p_T^V in DY production
    - Large log terms appear in $p_T^l \sim m_V/2$, $m_T^V \sim 2 \times \min[p_T^l]$, $p_T^V \sim 0$

Require resummation at small p_T^V

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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- 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.

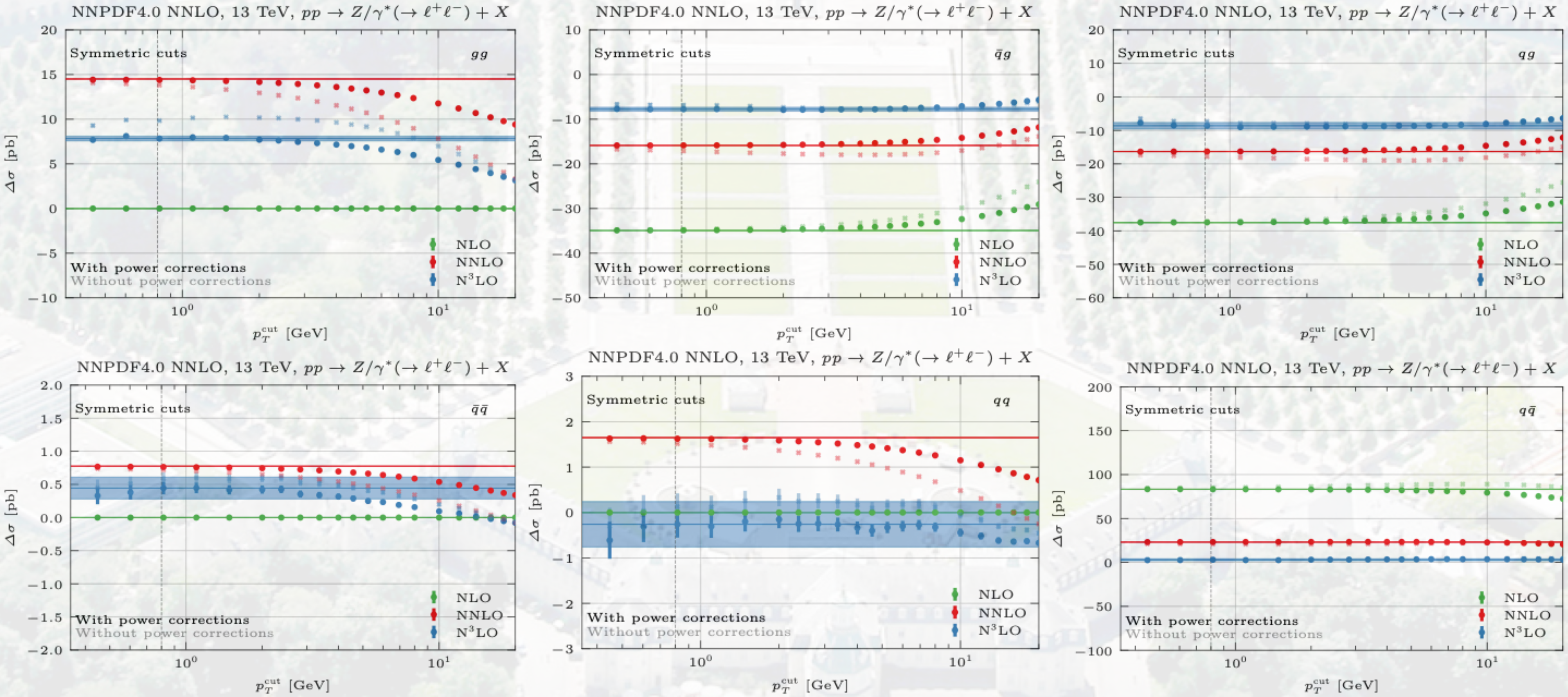
Thank You for Your Attention

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	N^{k}LO	N^{k}LO+N^{k}LL	N^{k}LO	N^{k}LO+N^{k}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	$722.9(1.1)^{+0.68\%}_{-1.09\%} \pm 0.9$	$726.2(1.1)^{+1.07\%}_{-0.77\%}$	$816.8(1.1)^{+0.45\%}_{-0.73\%} \pm 0.8$	$816.6(1.1)^{+0.87\%}_{-0.69\%}$

XC, Gehrmann, Glover, Huss, Monni, Rottoli, Re, Torrielli `22



BACKUP SLIDES

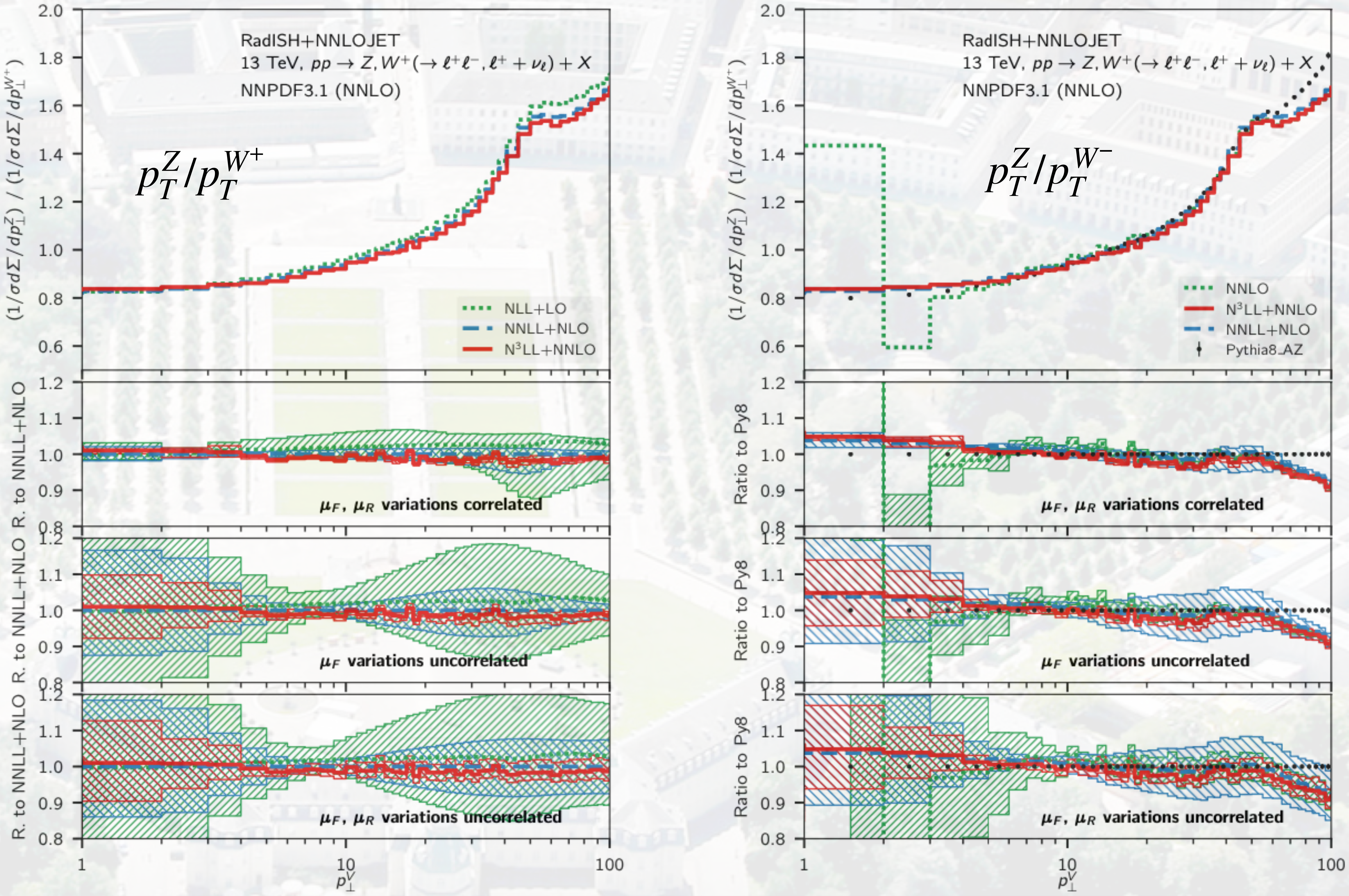
➤ Differential N3LL +NNLO predictions for charged current production with fiducial cuts

➤ Precise W measurement with calibration against Z.

➤ Improved QCD uncertainties through out pT.

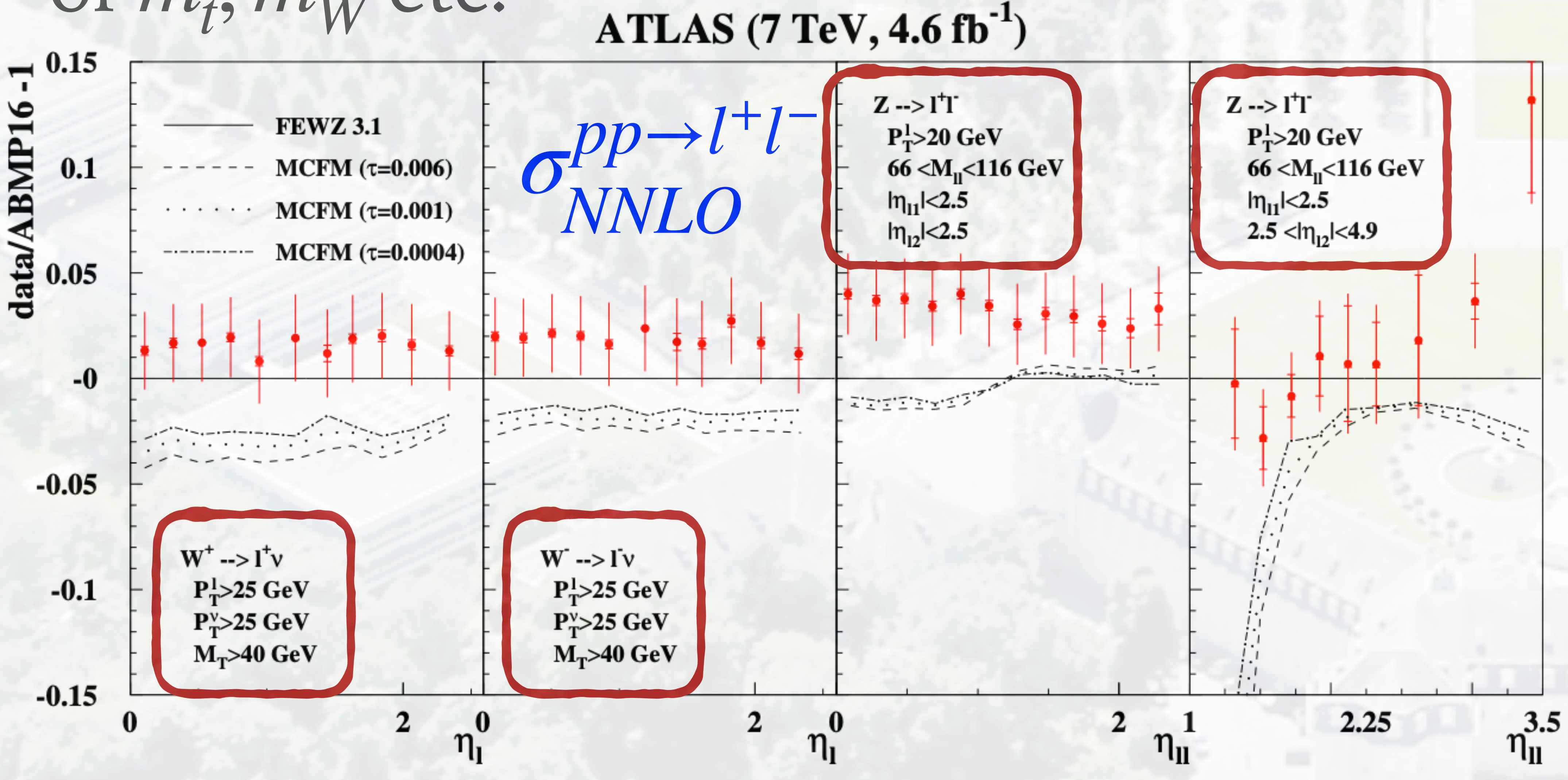
➤ Different EW and QCD-EW correction between Z and W are not yet considered.

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

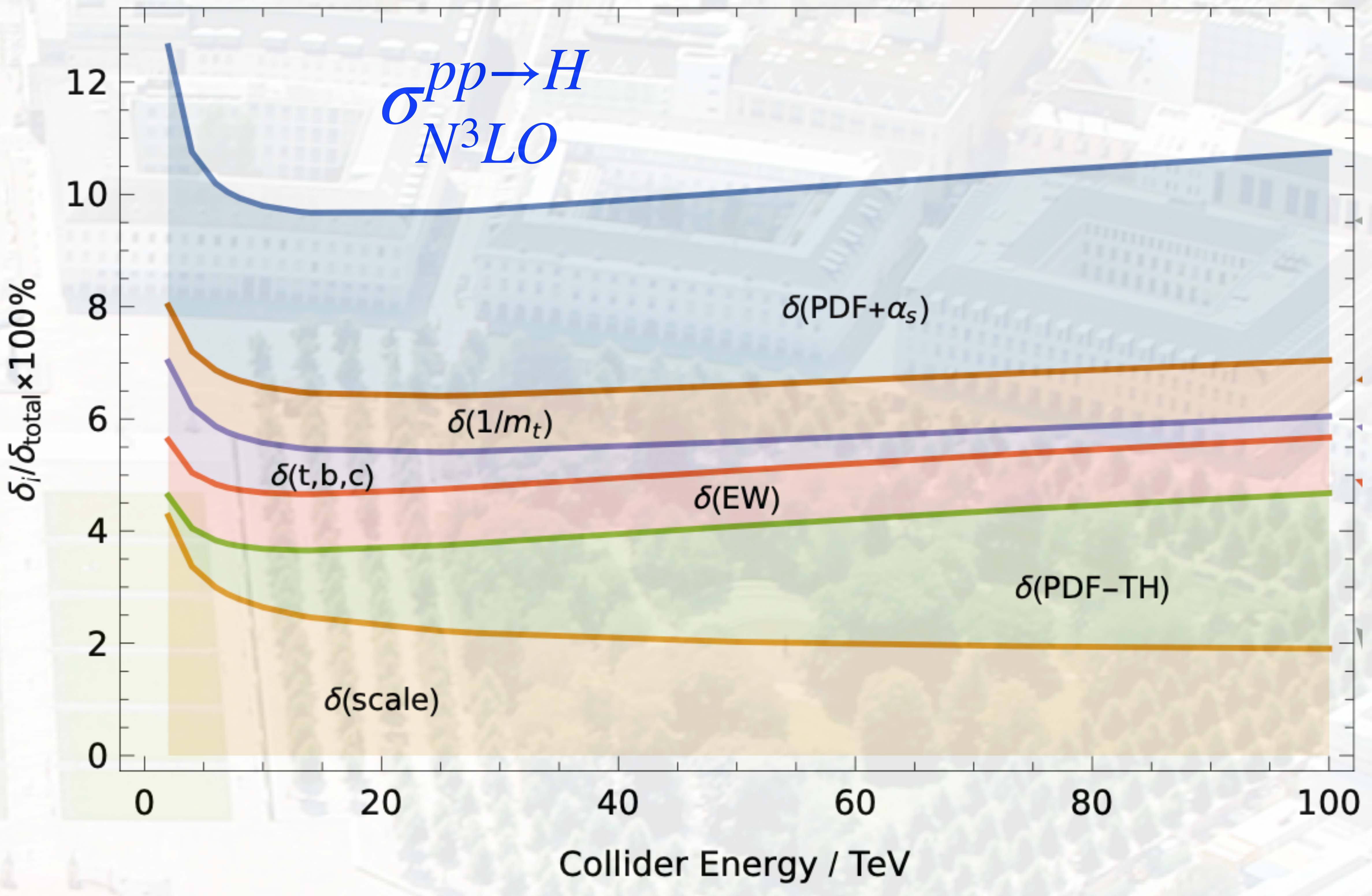


BACKUP SLIDES

- ➤Budget of theoretical uncertainties
  - ➤Dominant theory error of $\sigma^{pp\to H}_{N^3LO}$ from PDFs.
  - ➤EW corrections especially $\alpha_s\alpha$ corrections become relevant and even dominant.
  - ➤Time to reflect all approximations being involved: 5-flavour, Heavy Top limit, running of m_t, m_W etc.



S. Alekhin, A. Kardos, S. Moch, Z. Trocsanyi 2021



F. Dulat, A. Lazopoulos, B. Mistlberger 2018

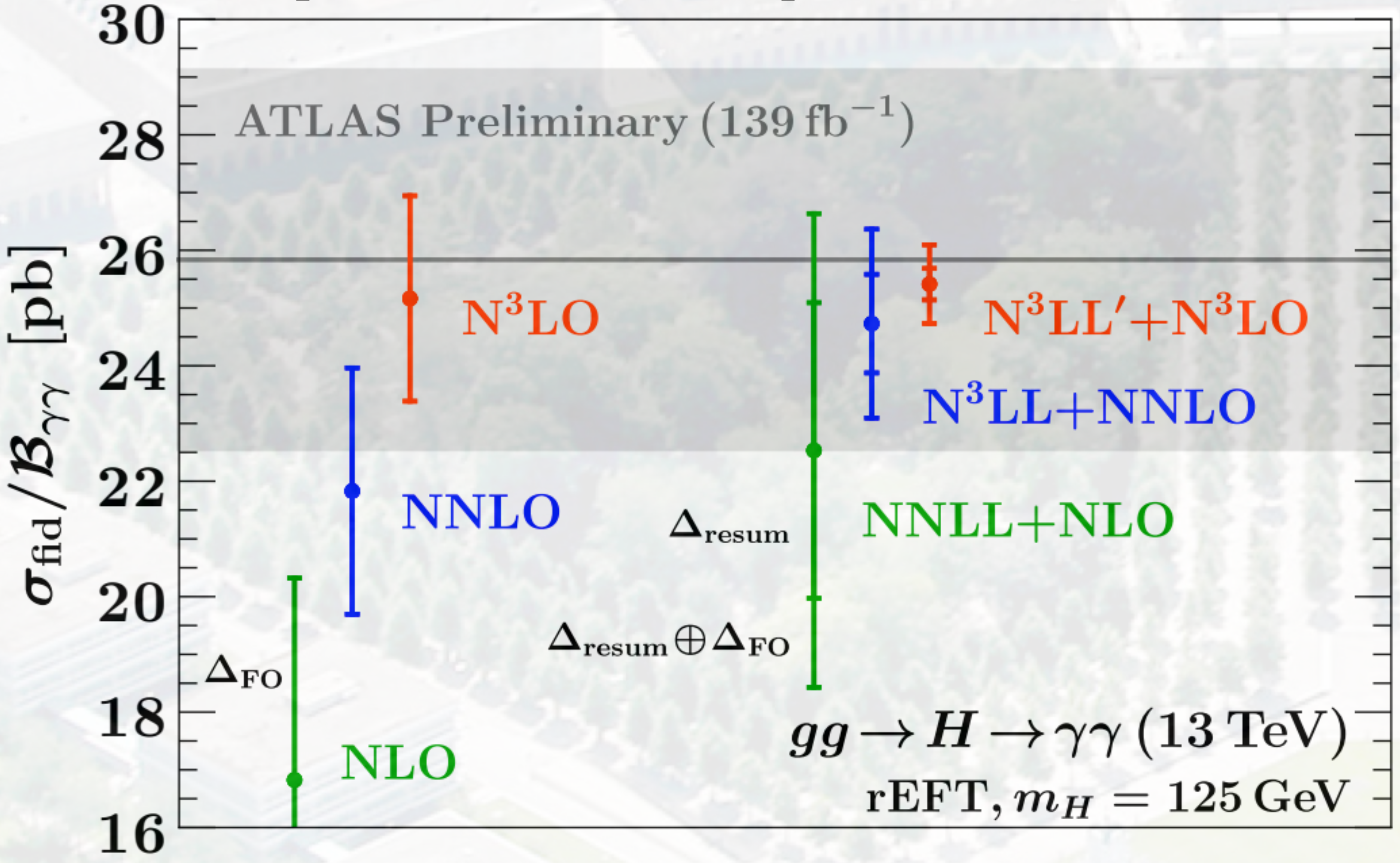
- ➤Fiducial cuts introduce linear power correction due to illy defined region for QCD factorisation
- ➤The effect can be dominant at N3LO precision
- ➤New ideas emerge recently to rescue

BACKUP SLIDES

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

➤ Resummation with current/legacy fiducial cuts

$$p_T^{\gamma_1} > 0.35 \times m_H, \quad p_T^{\gamma_2} > 0.25 \times m_H$$



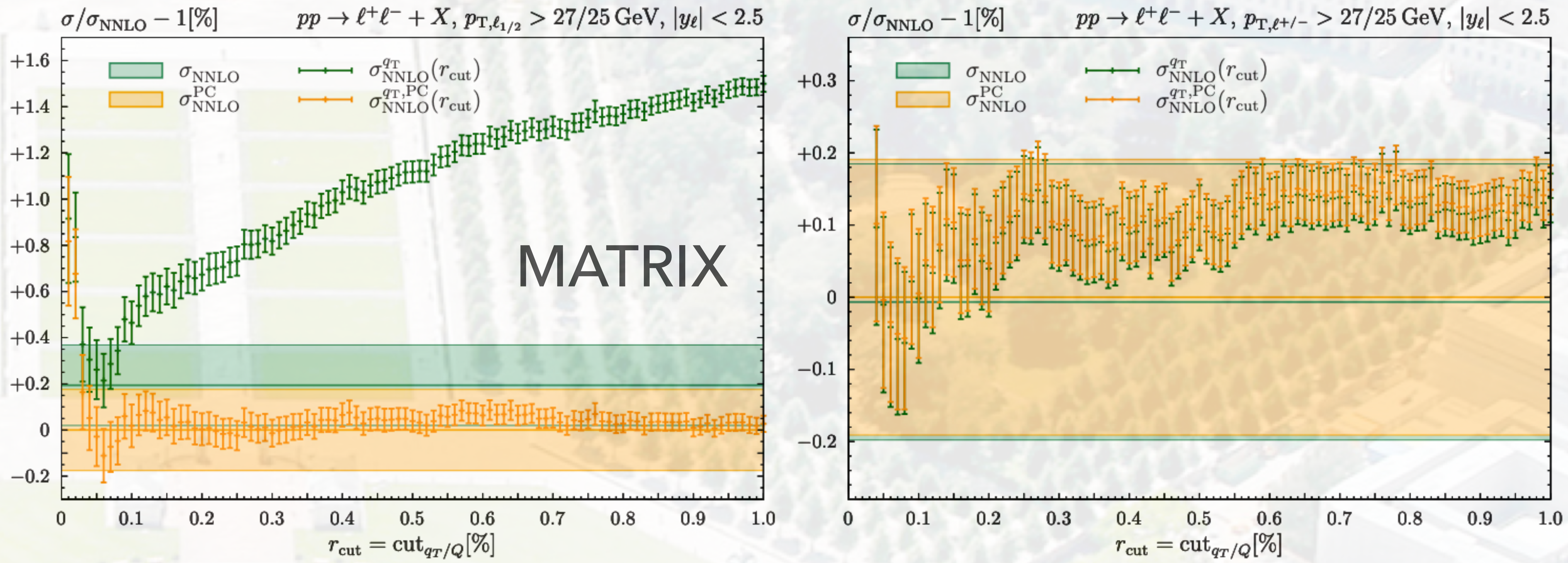
Billis, Dehnadi, Ebert, Michel, Tackmann 2021

- Introduce new source of uncertainty due to matching.
- Not an issue with through test.
- Ideal for legacy experimental analysis.

➤ Change fiducial cuts

$$p_T^{\gamma_1} \times p_T^{\gamma_2} > (0.35 \times m_H)^2, \quad p_T^{\gamma_2} > 0.25 \times m_H$$

A through study of linear power correction in G. Salam, E. Slade 2021



L. Buonocore, L. Rottoli, S. Kallweit, M. Wiesemann 2021
(see also S. Camarda, L. Cieri, G. Ferrera 2021)

- Straightforward for theory tools to implement
- Require further experiment study to lower trigger of leading photon

➤ Defiducialization (A. Glazov 2020)