The Drell–Yan Process as a Precision Laboratory

Luca Rottoli

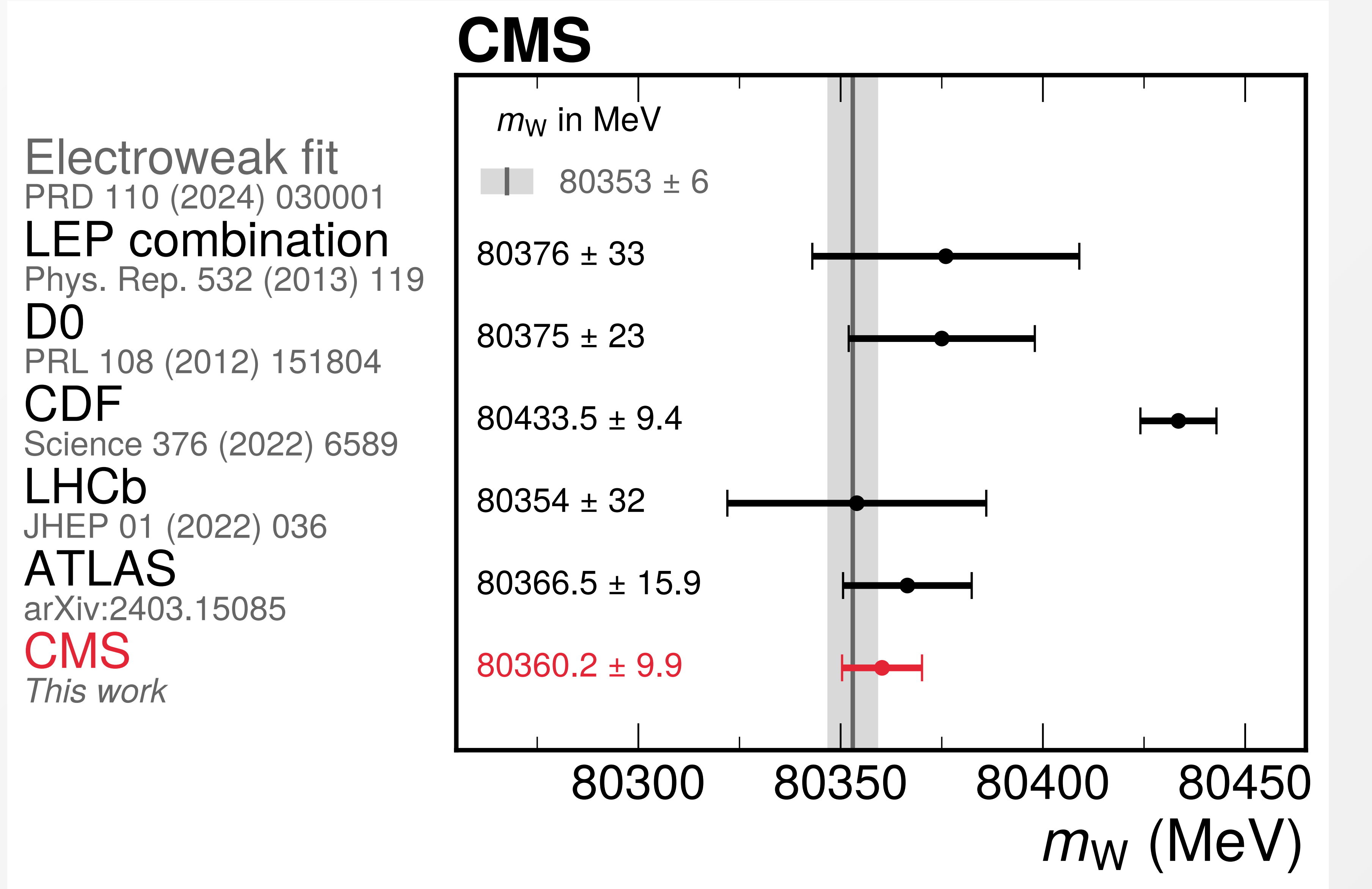
Open Symposium on *W* mass, Pisa, 2 March 2026

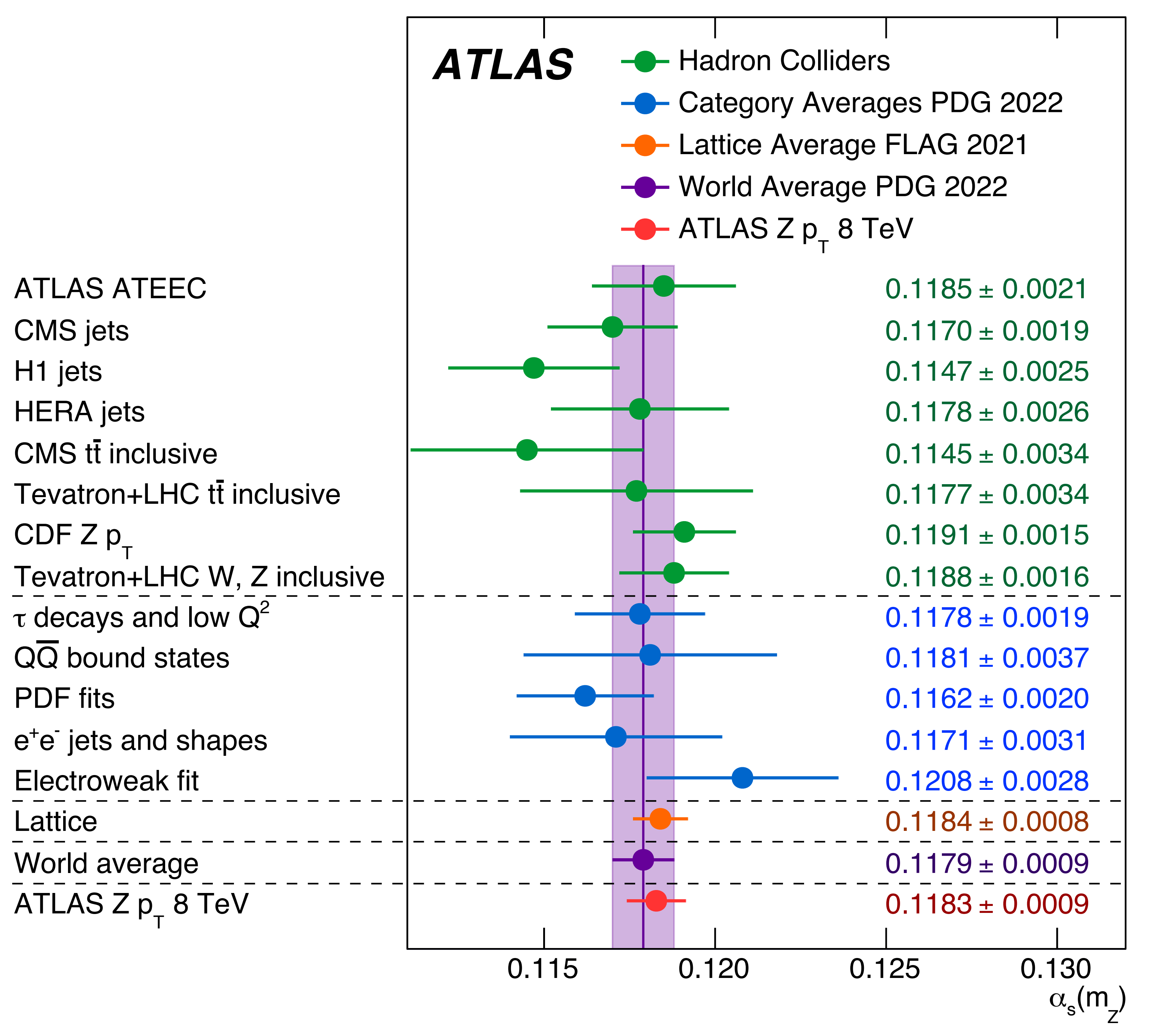
[Book of the Dead of Hunefer, British Museum]

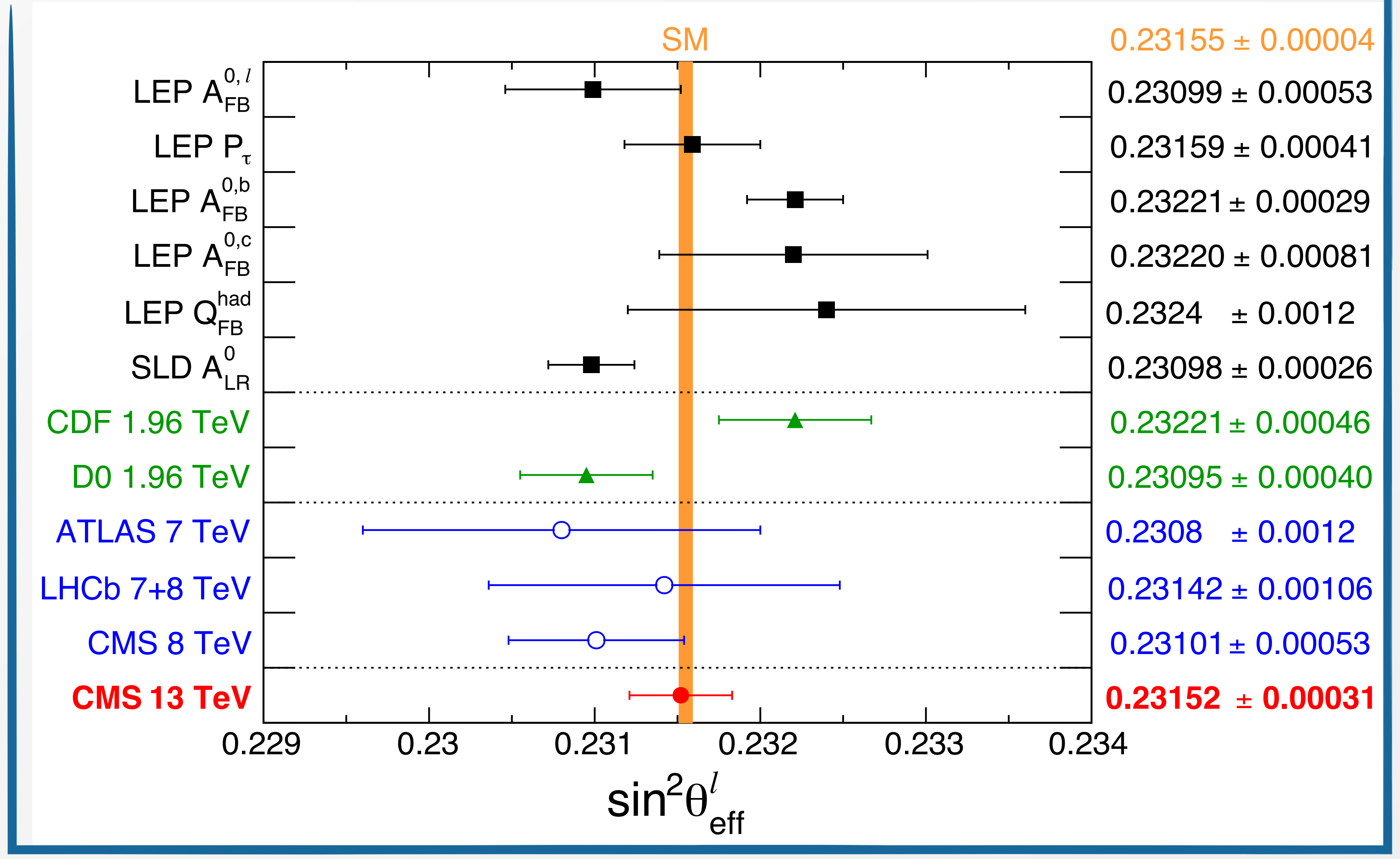
J’étais affecté du mal aigu de la précision

[Monsieur Teste, P. Valery]

Three of the **most precise measurements** of fundamental SM parameters have been performed at the LHC in the last couple of years







Dilepton production plays a central role in the LHC precision programme

Drell-Yan production and precision

NC DY lepton-pair **invariant mass** → Z properties (Z resonance) and $\sin^2\theta_{\rm eff}^{\ell\ell}$ ($A_{FB}(m_{\ell\ell})$)

CC DY lepton-pair **transverse mass** → m_W (W resonance)

NC/CC DY charged lepton p_T^{ℓ} → m_Z (Z resonance), m_W (W resonance)

NC DY lepton pair $p_T^{\ell\ell}$ → α_s (low $p_T^{\ell\ell}$)

+ important PDF constraints using multi-differential distributions (rapidity, transverse momentum…)
+ Constraints on BSM models

Drell-Yan production and precision

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Reliable predictions through fixed-order perturbation theory

NC/CC DY charged lepton p_T^{ℓ} → m_Z (Z resonance), m_W (W resonance)

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All-order resummation needed for meaningful predictions due to sensitivity to QCD/EW radiation

+ important PDF constraints using multi-differential distributions (rapidity, transverse momentum…)

+ Constraints on BSM models

Drell-Yan production and precision

NC DY lepton-pair **invariant mass** → Z properties (Z resonance) and $\sin^2\theta_{\text{eff}}^{\ell\ell}$ ($A_{FB}(m_{\ell\ell})$)

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NC/CC DY

Theoretical understanding of fixed-order and all-order structure of QCD/EW radiation in Drell-Yan process is crucial

NC DY lepton pair $p_T^{\ell\ell}$ → α_s (low $p_T^{\ell\ell}$)

+ important PDF constraints using multi-differential distributions (rapidity, transverse momentum…)

+ Constraints on BSM models

Precision physics at the LHC

collinear factorisation

$$\sigma(s, Q^2) = \sum_{a,b} \int dx_1 dx_2\, f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) \hat{\sigma}_{ab\to X}(Q^2, x_1 x_2 s) + \mathcal{O}(\Lambda^p_{\mathrm{QCD}}/Q^p)$$

Input parameters:

strong coupling α_s

PDFs f

Thomas' talk

few percent uncertainty; improvable

Non-perturbative effects

percent effect; not yet fully under control

Alessandro's talk

Precision physics at the LHC

collinear factorisation

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$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0,0)} + \hat{\sigma}_{ab}^{(1,0)} + \hat{\sigma}_{ab}^{(2,0)} + \hat{\sigma}_{ab}^{(3,0)} + \ldots \qquad \alpha_s \sim 0.1$$

$$+ \hat{\sigma}_{ab}^{(0,1)} + \ldots \qquad \alpha \sim 0.01$$

$$+ \hat{\sigma}_{ab}^{(1,1)} + \ldots \qquad \alpha\alpha_s \sim 0.001$$

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$$+ \hat{\sigma}^{(1,1)}_{ab} + \dots \qquad \alpha\alpha_s \sim 0.001$$

$\mathcal{O}(1)$ accuracy (order of magnitude)

Precision physics at the LHC

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$\mathcal{O}(10 - 20\%)$
accuracy

Precision physics at the LHC

collinear factorisation

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$$+ \hat{\sigma}^{(0,1)}_{ab} + \dots \qquad \alpha \sim 0.01$$

$$+ \hat{\sigma}^{(1,1)}_{ab} + \dots \qquad \alpha\alpha_s \sim 0.001$$

$\mathcal{O}(5-10\%)$
accuracy

Precision physics at the LHC

collinear factorisation

$$\sigma(s, Q^2) = \sum_{a,b} \int dx_1 dx_2\, f_{a/h_1}(x_1, Q^2) f_{b/h_2}(x_2, Q^2) \hat{\sigma}_{ab \to X}(Q^2, x_1 x_2 s) + \mathcal{O}(\Lambda^p_{\rm QCD}/Q^p)$$

$$\hat{\sigma}_{ab} = \hat{\sigma}^{(0,0)}_{ab} + \hat{\sigma}^{(1,0)}_{ab} + \hat{\sigma}^{(2,0)}_{ab} + \hat{\sigma}^{(3,0)}_{ab} + \ldots$$

$$+ \hat{\sigma}^{(0,1)}_{ab} + \ldots$$

$$+ \hat{\sigma}^{(1,1)}_{ab} + \ldots$$

$\alpha_s \sim 0.1$

$\alpha \sim 0.01$

$\alpha \alpha_s \sim 0.001$

$\mathcal{O}(1-5\%)$
accuracy

NLO EW and mixed QCD×EW corrections

$$\hat{\sigma}_{ab} = \hat{\sigma}^{(0,0)}_{ab} + \hat{\sigma}^{(1,0)}_{ab} + \hat{\sigma}^{(2,0)}_{ab} + \hat{\sigma}^{(3,0)}_{ab} + \ldots$$
$$+ \hat{\sigma}^{(0,1)}_{ab} + \ldots$$
$$+ \hat{\sigma}^{(1,1)}_{ab} + \ldots$$

Luca's talk

- **NLO EW** corrections

known since long time ago
[S. Dittmaier and M. Kramer (2002)], [Baur,Wackeroth (2004)], [Baur, Brein, Hollik, Schappacher, Wackeroth (2002)], [Zykunov (2006,2007)]

automatised and readily available in different generators
[Les Houches 2017, 1803.07977]

Neutral current DY NNLO QCDxEW

[Bonciani, Buonocore, Grazzini, Kallweit,Rana, Tramontano, Vicini '21] [Armadillo, Bonciani, Devoto, Rana, Vicini '22] [Buccioni, Caola, Chawdhry, Devoto, Heller, von Manteuffel, Melnikov, Röntsch, Signorile-Signorile '22][Armadillo, Bonciani, Buonocore, Devoto, Grazzini, Kallweit, Rana, Vicini '24]

Charged-current DY (2-loop amplitude QCDxEW)
[Armadillo, Bonciani, Devoto, Rana, Vicini '24]

+ Results in pole approx
[Dittmaier, Huss, and Schwinn (2014,2015)] [Dittmaier, Huss, and Schwarz (2024)]

The purest and most thoughtful minds are those which love colour the most

$$\hat{\sigma}_{ab} = \hat{\sigma}_{ab}^{(0,0)} + \hat{\sigma}_{ab}^{(1,0)} + \hat{\sigma}_{ab}^{(2,0)} + \hat{\sigma}_{ab}^{(3,0)} + \ldots$$
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- **QCD** corrections by and large **dominant**

NNLO differential cross sections

[Anastasiou, Dixon, Melnikov, Petriello (2003)], [Melnikov, Petriello (2006)] [Catani, Cieri, Ferrera, de Florian, Grazzini (2009)] [Catani, Ferrera, Grazzini (2010)]

N^3LO inclusive cross sections and di-lepton rapidity distribution

[Duhr, Dulat, Mistlberger (2020)] [Chen, Gehrmann, Glover, Huss, Yang, and Zhu (2021)] [Duhr, Mistlberger (2021)]

N^3LO fiducial cross sections and distributions

[Camarda, Cieri, Ferrera (2021)], [Chen, Gehrmann, Glover, Huss, Monni, Re, LR, Torrielli (2022)] [Chen, Gehrmann, Glover, Huss, Yang, and Zhu (2022)], [Neumann, Campbell (2022) and (2023)] [Billis, Michel, Tackmann (2024)]

Drell-Yan: NNLO QCD

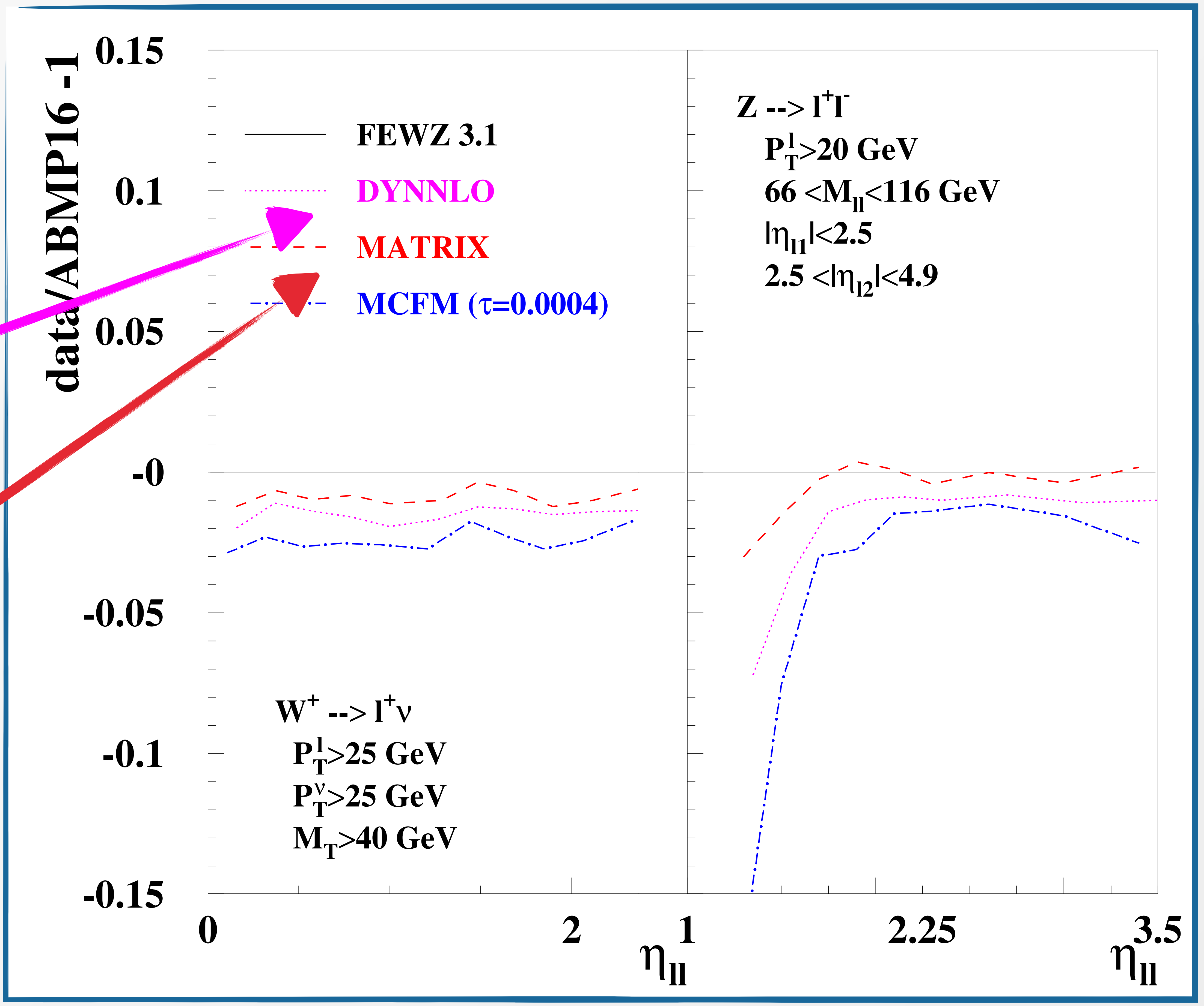
Reliability of state-of-art predictions is crucial. Several public codes available reaching fully differential NNLO QCD accuracy.

- Local subtraction: FEWZ, NNLOJET
- Slicing: DYTURBO, MATRIX (q_T slicing), MCFM (0-jettines, q_T slicing,)

Slicing methods suffer in the presence of symmetric / **asymmetric cuts on the leptons**: **percent-level** differences when compared to results obtained with **local subtractions** may be present due to **linear power corrections** in the slicing variable

$r_{\mathrm{cut}} \sim 0.01$

$r_{\mathrm{cut}} \sim 0.0005 - 0.001$



[Alekhin, Kardos, Moch, Trócsányi '21]

Solutions:

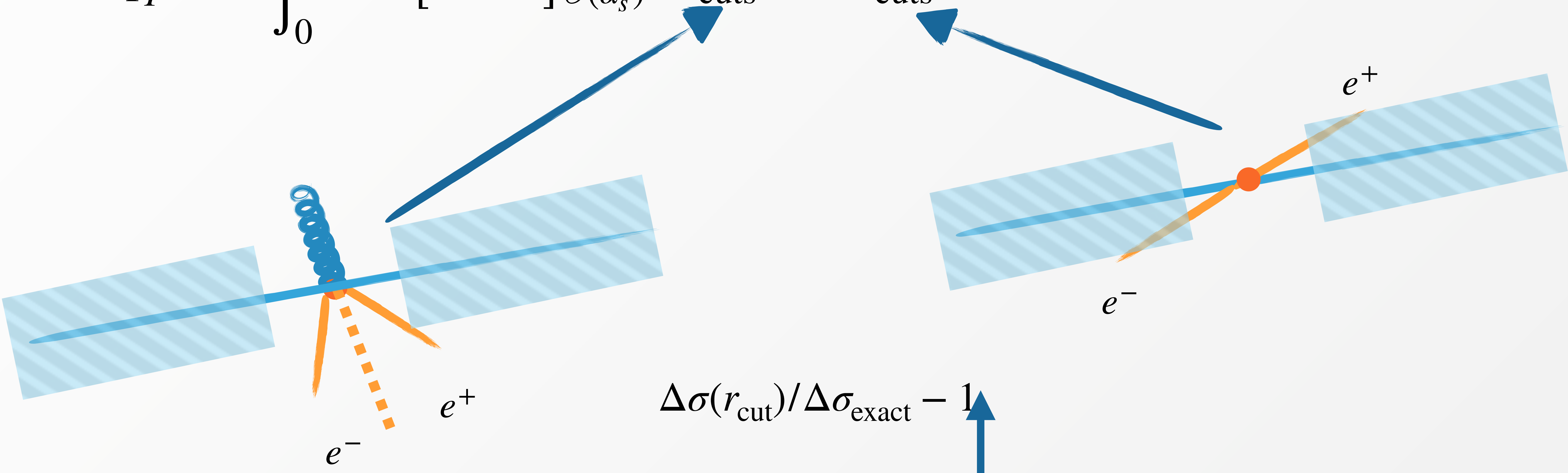
- Transverse momentum recoil for q_T slicing
  [Buonocore, Kallweit, LR, Wiesemann'21] [Camarda, Cieri, Ferrera '21]
- Projection to Born for jettiness-slicing
  [Vita 2401.03017][Campbell et al 2408.05265]

Linear power corrections

Linear power corrections in q_T have a **purely kinematical origin** and can **be predicted by factorisation**

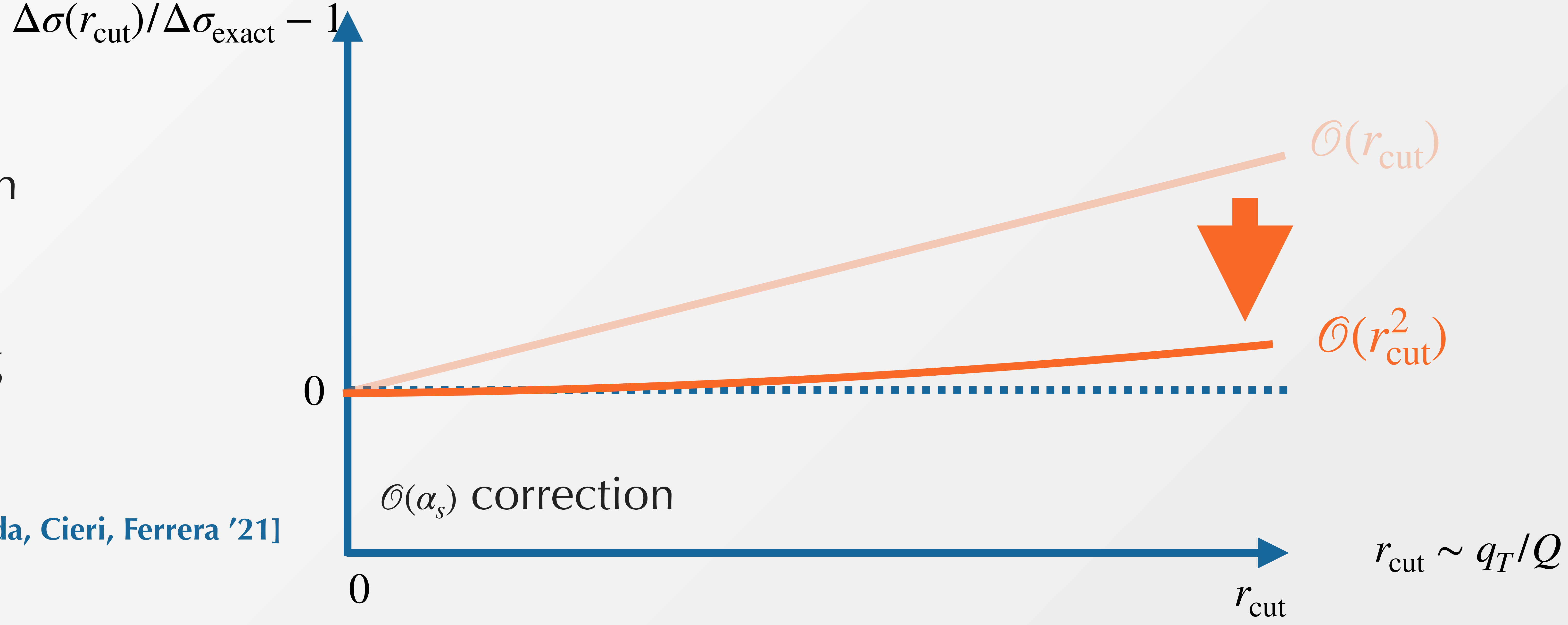
[Ebert, Michel, Stewart, Tackmann '20]

$$\Delta\sigma^{\mathrm{linPCs}}(q_T^{\mathrm{cut}}) = \int_0^{r_{\mathrm{cut}}} dr' \left[d\sigma^{\mathrm{sing}}\right]_{\mathcal{O}(\alpha_s^k)} \left(\Theta_{\mathrm{cuts}}^{\mathrm{recoil}} - \Theta_{\mathrm{cuts}}^{\mathrm{Born}}\right)$$



Resorting to the recoil prescription allows for the inclusion of all missing fiducial linear power corrections below q_T^{cut}, improving dramatically the efficiency of the non-local subtraction

[Buonocore, Kallweit, LR, Wiesemann'21] [Camarda, Cieri, Ferrera '21]



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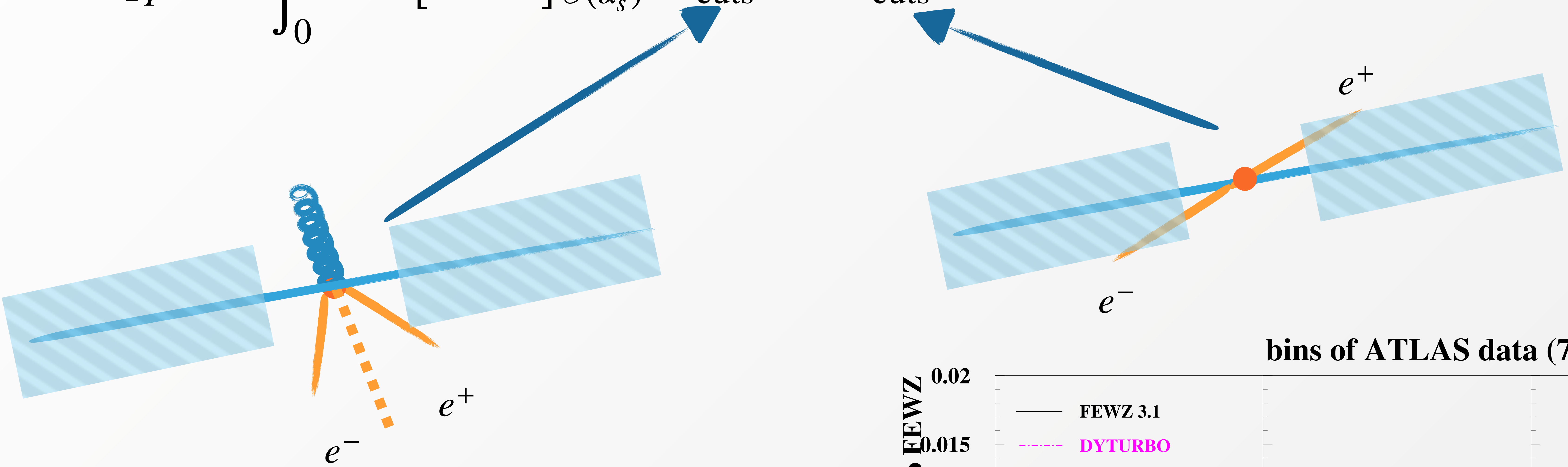
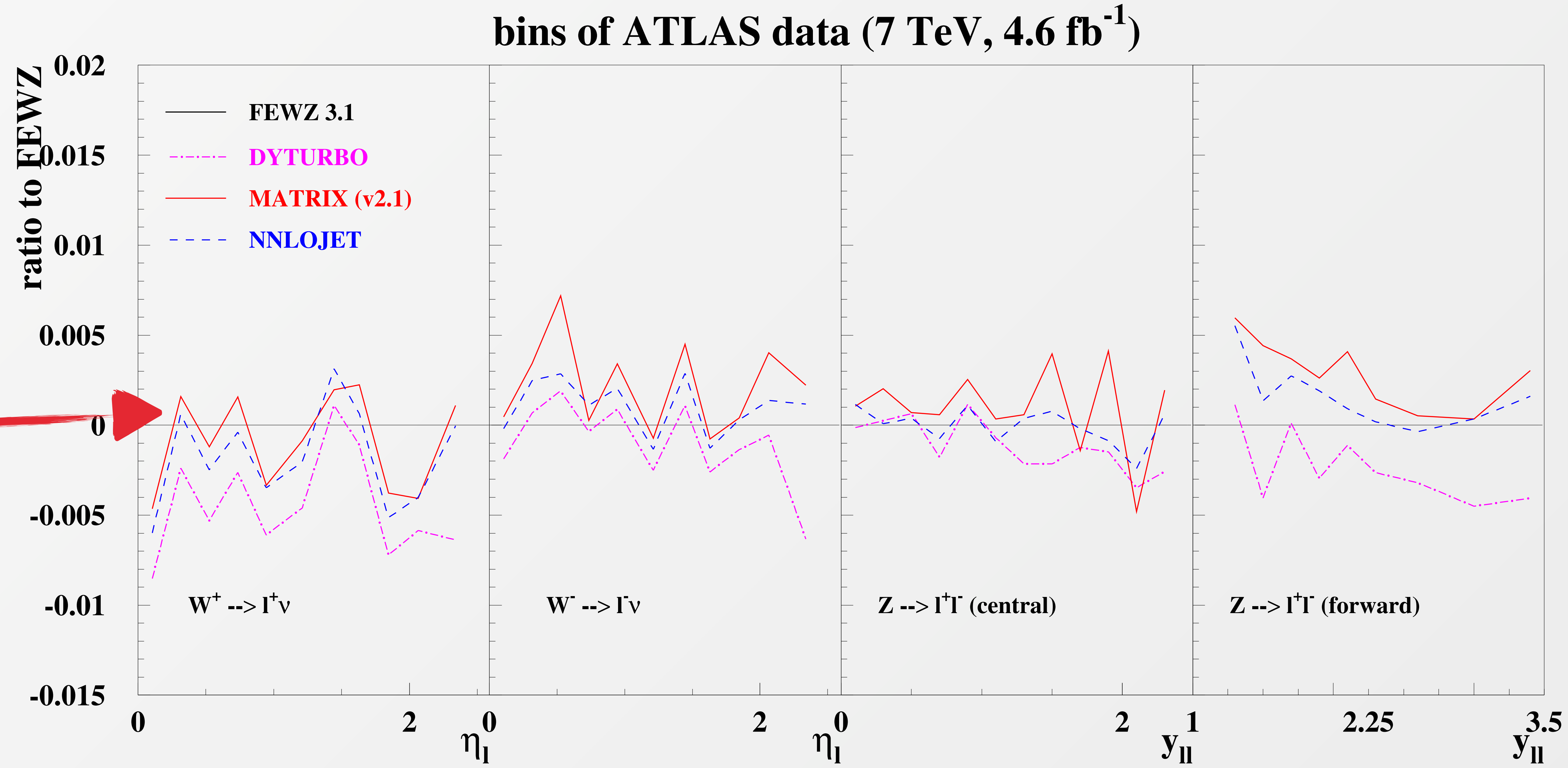


Excellent agreement between available public codes once improved slicing is used



Linear power corrections and perturbative instability

Problems related to symmetric / asymmetric cuts have been known since a long time

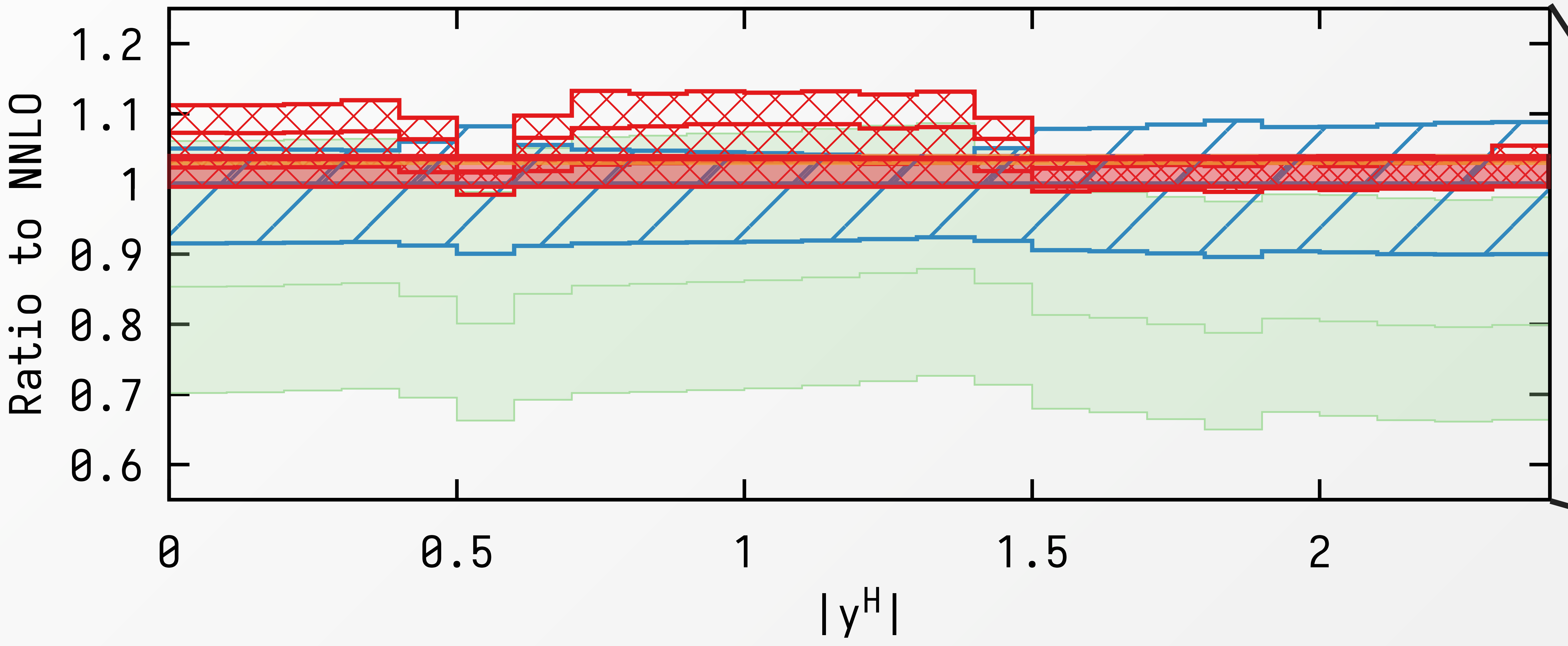
Perturbative instability induced by sensitivity to soft radiation in configurations close to the back-to-back limit

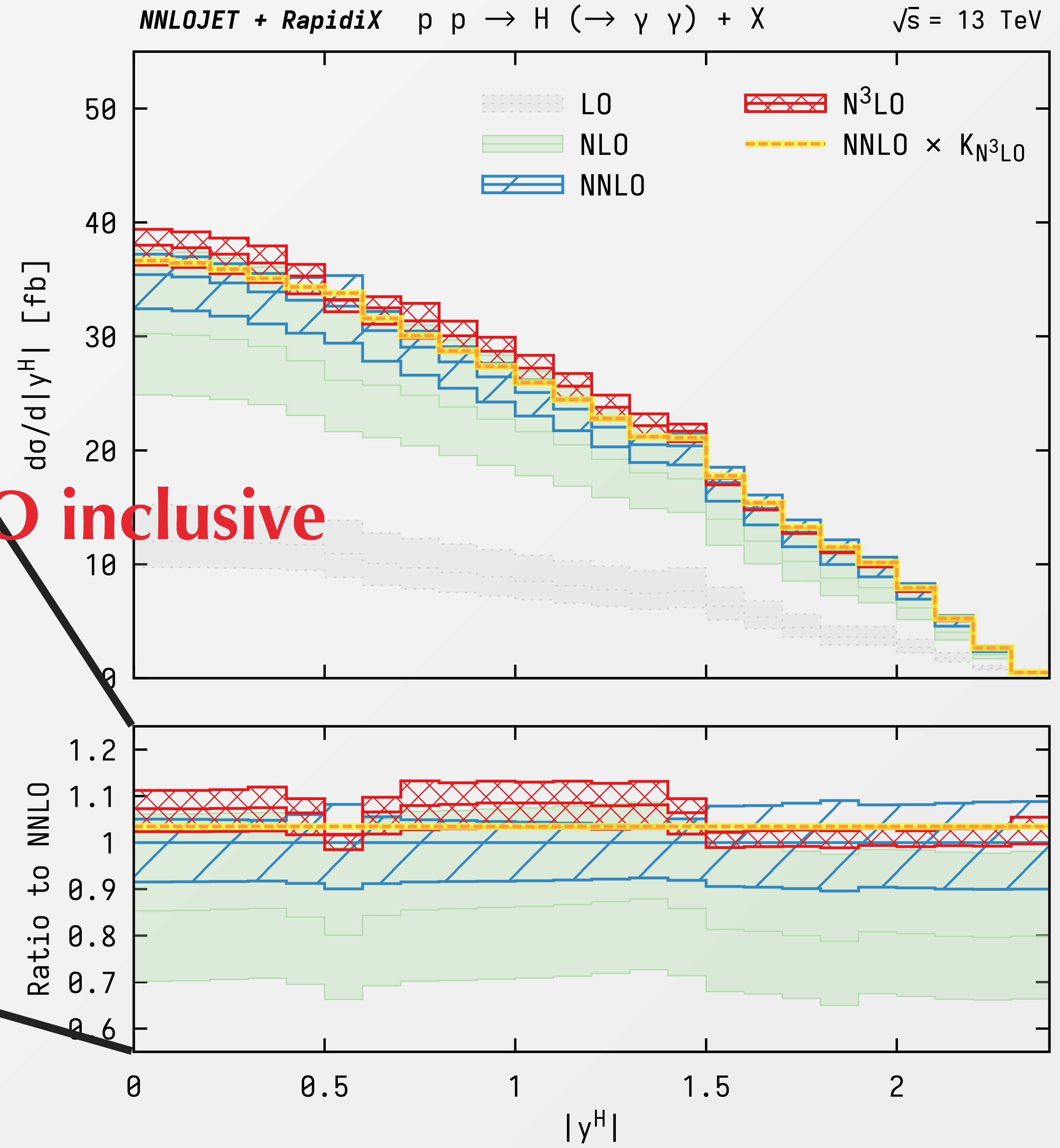
[Klasen, Kramen '96][Harris, Owen '97][Frixione, Ridolfi '97]

Linear sensitivity of the acceptance at small q_T leads to a (alternating sign) **factorial growth**

[Salam, Slade '21]

Visible artefacts in $H \to \gamma\gamma$ when comparing to the inclusive case





[Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni, '21]

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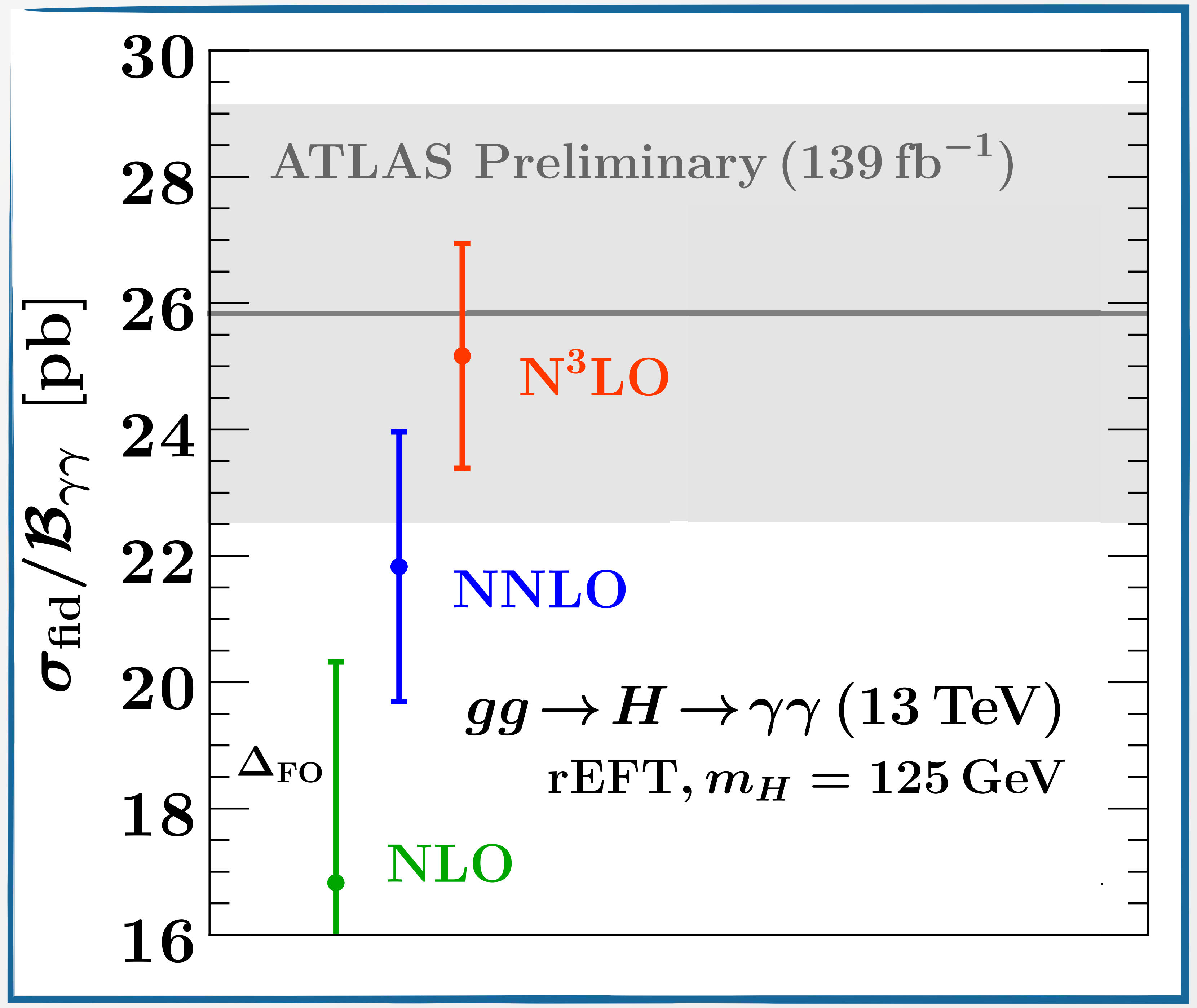
Solution 1: Linear fiducial power corrections can be resummed at all orders in perturbation theory

$$\sigma^{\rm FO}_{\rm incl} = 13.80\,[1 + 1.291 + 0.783 + 0.299]\,{\rm pb}$$

$$\begin{aligned}\sigma^{\rm FO}_{\rm fid}/\mathcal{B}_{\gamma\gamma} = 6.928\,[1 &+ (1.300 + 0.129_{\rm fpc})\\ &+ (0.784 - 0.061_{\rm fpc})\\ &+ (0.331 + 0.150_{\rm fpc})]\,{\rm pb}\,.\end{aligned}$$



[Billis, Dehnadi, Ebert, Michel, Stewart, Tackmann '21]

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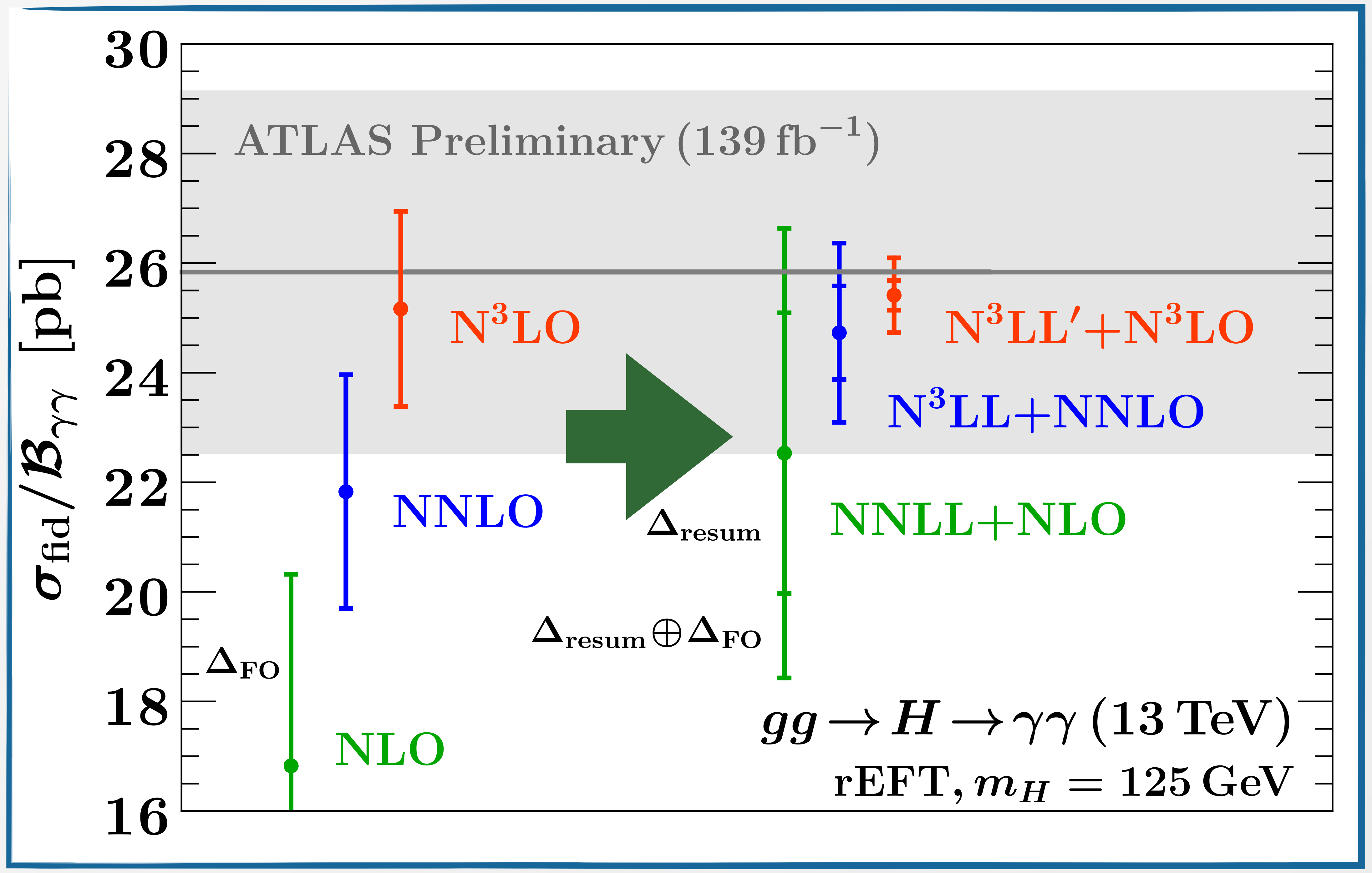

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[Klasen, Kramen '96][Harris, Owen '97][Frixione, Ridolfi '97]

Linear sensitivity of the acceptance at small q_T leads to a (alternating sign) **factorial growth**

Solution 1: Linear **fiducial power corrections** can be resummed at all orders in perturbation theory

Solution 2: Resorting to alternative definition of cuts can resolve the issue of linear fiducial power corrections altogether

[Salam, Slade '21]

Symmetric $p_T^{\ell_1}, p_T^{\ell_2} > p_T^{\rm cut}$

Asymmetric $\begin{cases} p_T^{\ell_1} > p_T^{\rm cut} + \Delta \\ p_T^{\ell_2} > p_T^{\rm cut} \end{cases}$

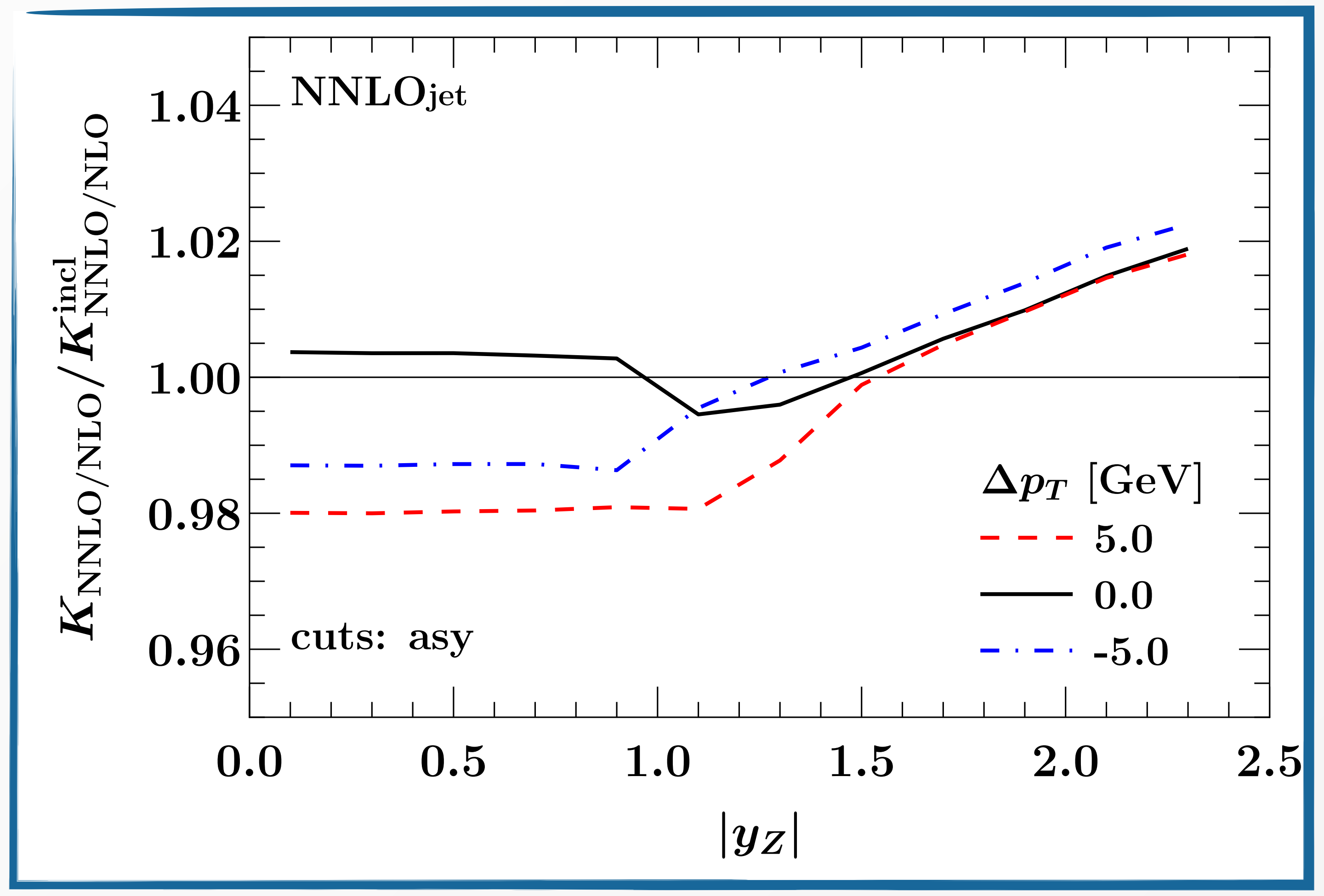
Product $\begin{cases} \sqrt{p_T^{\ell_1} p_T^{\ell_2}} > p_T^{\rm cut} + \Delta \\ p_T^{\ell_2} > p_T^{\rm cut} \end{cases}$

Linear power corrections and NC Drell-Yan@NNLO

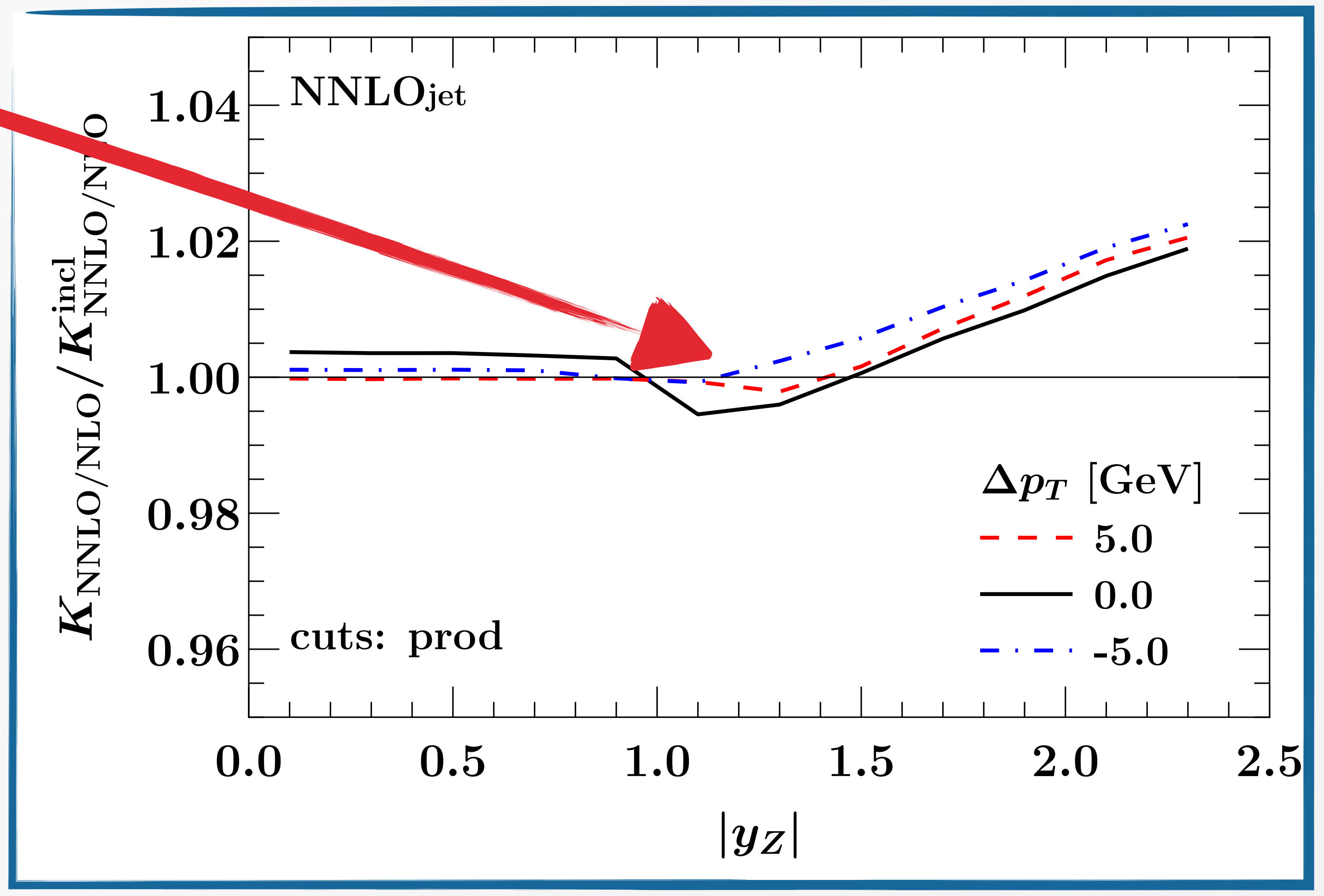
[Alekhin, …, LR et al 2405.19714]

(A)Symmetric cuts: impact on DY rapidity distribution

Double ratio of NNLO/NLO K-factors fiducial/inclusive cuts



Better and smoother behaviour of product cuts, although overall smaller effects with respect to the $H \to \gamma\gamma$ case



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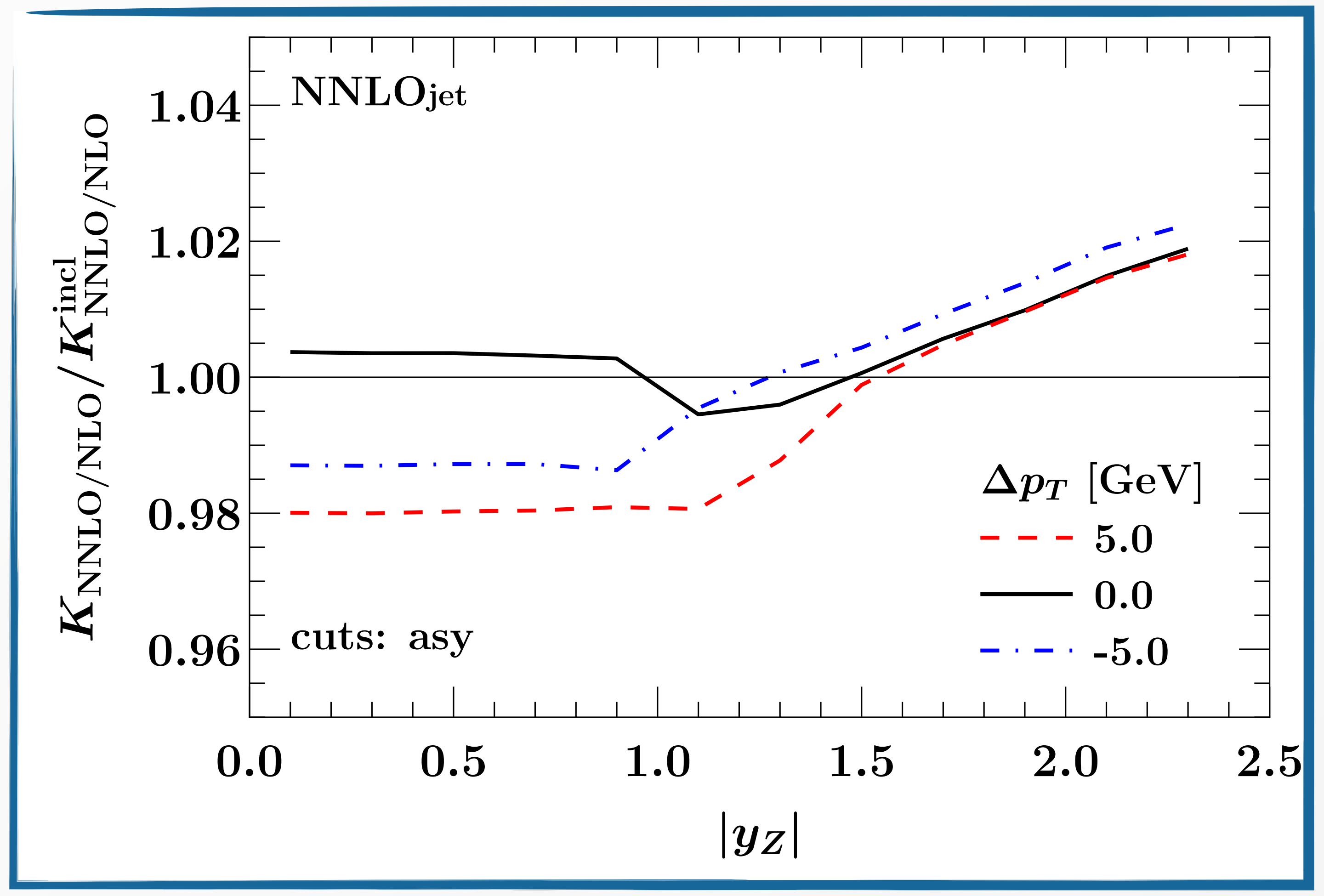
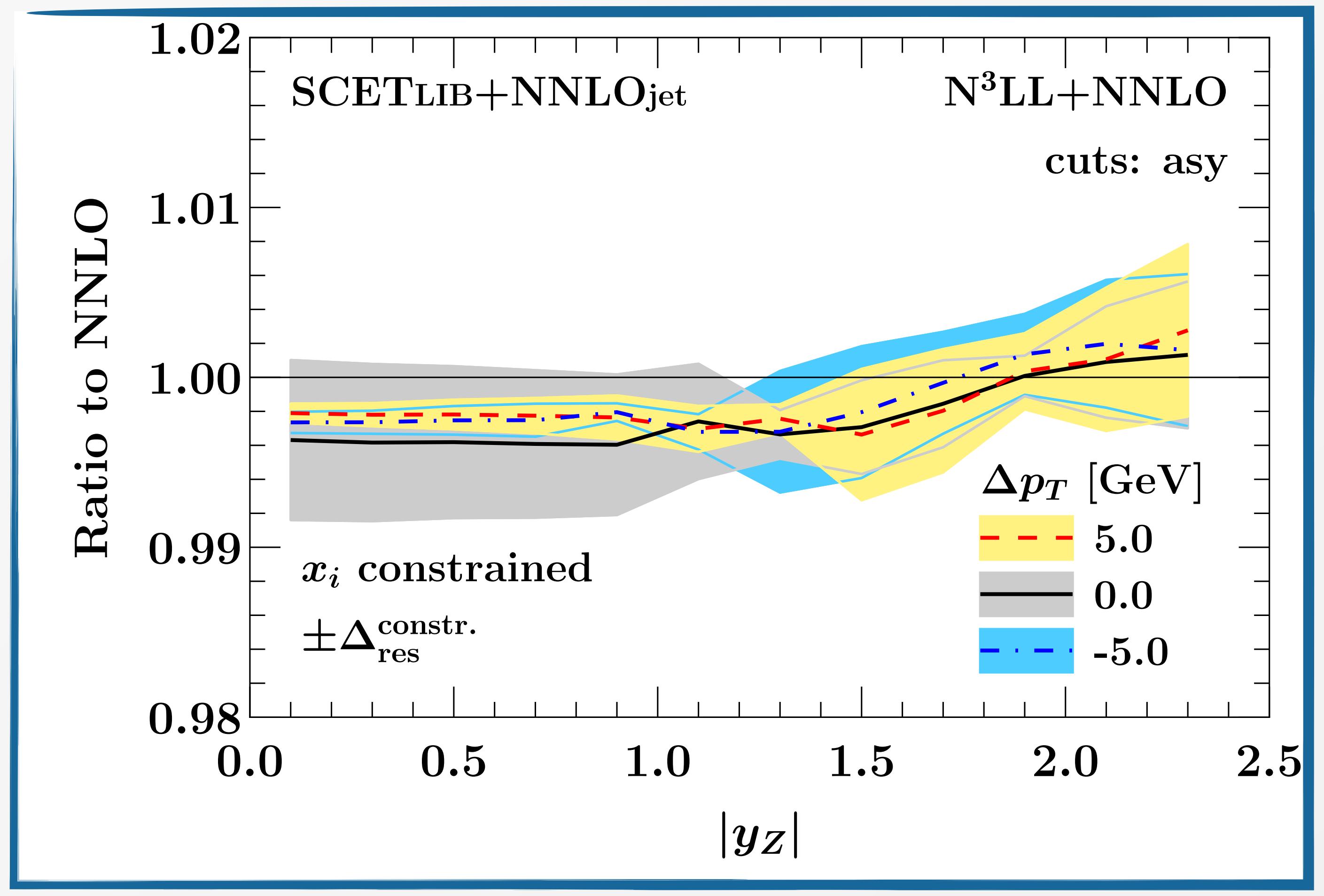
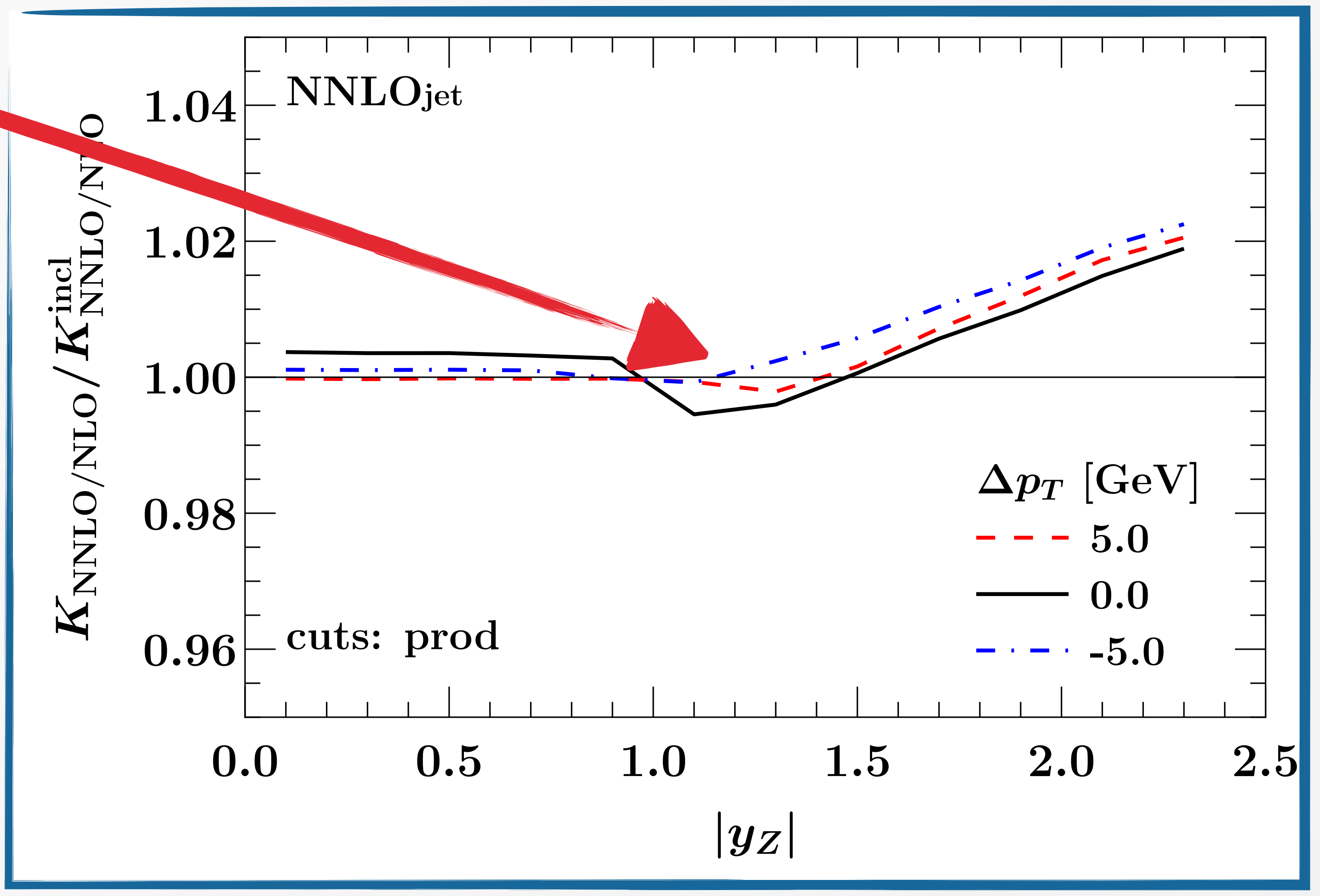


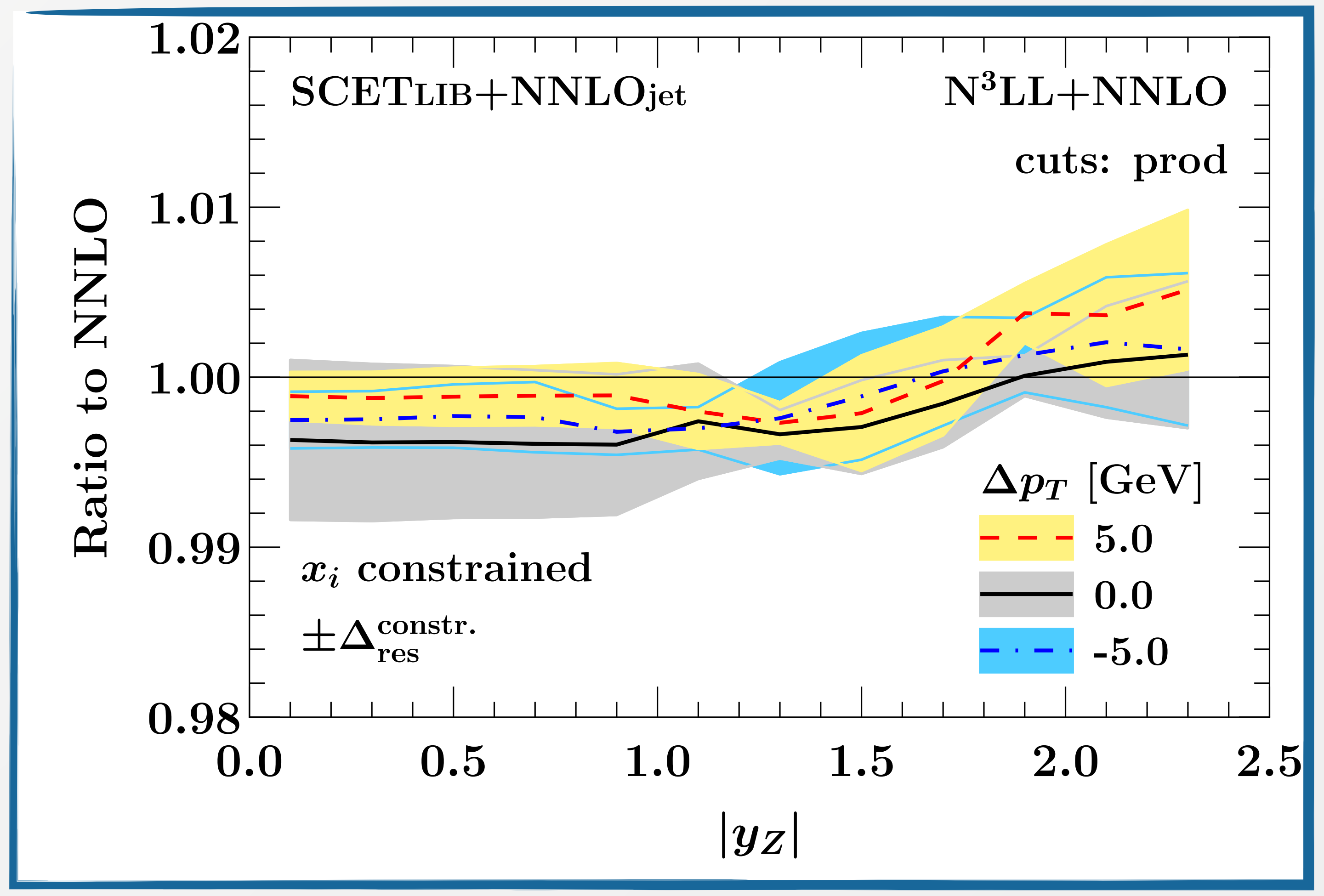


Impact of all-order resummation of linear power corrections studied at N^{3}LL′ with SCETLIB and RadISH

Effects below 0.5% with respect to the NNLO prediction

Better and smoother behaviour of product cuts, although overall smaller effects with respect to the $H \to \gamma\gamma$ case





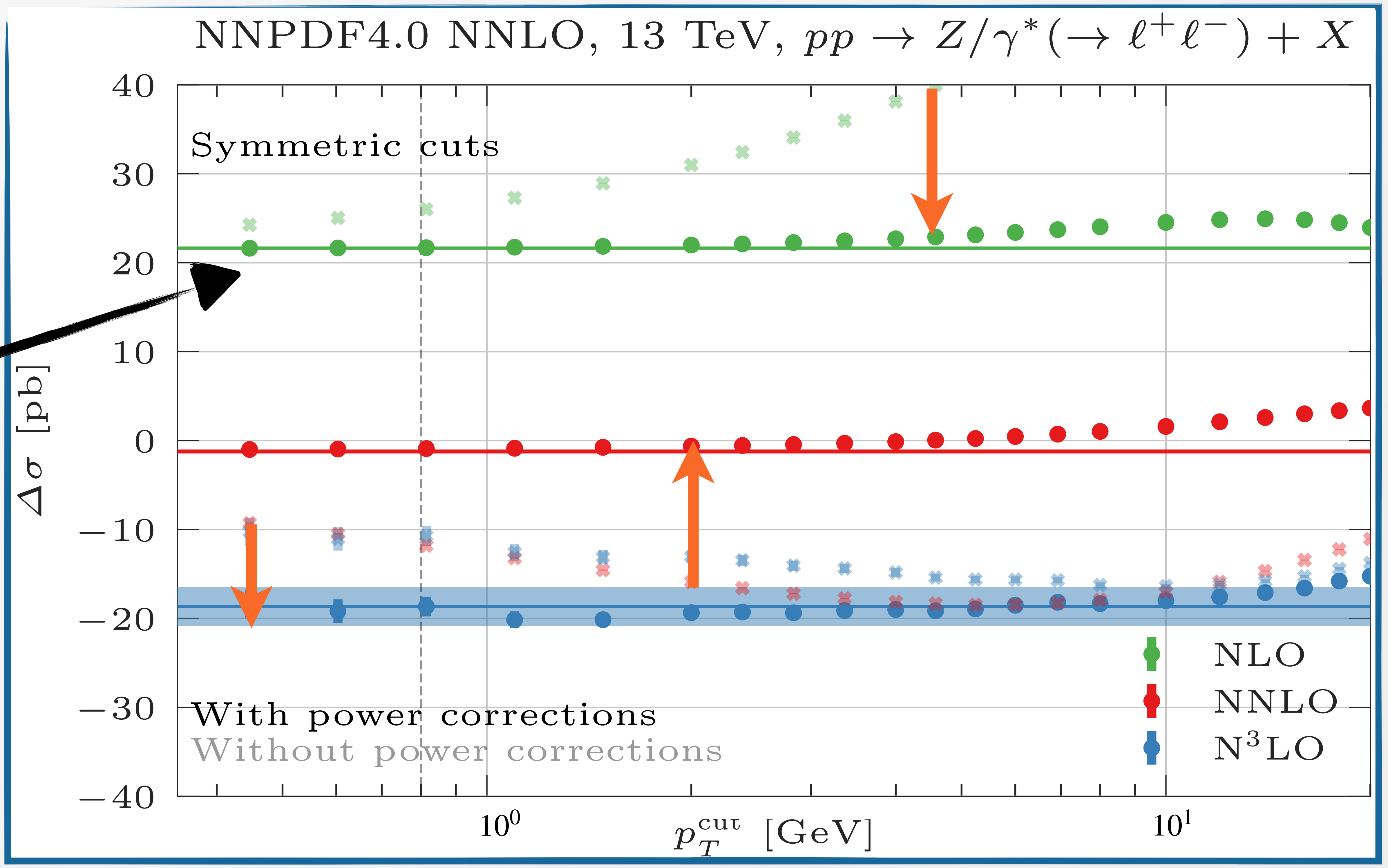
Impact of the choice of cuts **relatively minor**, although in perspective the **underlying ambiguity may be a insurmountable issue with legacy data**

Linear power corrections and NC Drell-Yan@N³LO

$$d\sigma_V^{\mathrm{N^3LO}} \equiv \mathcal{H}_V^{\mathrm{N^3LO}} \otimes d\sigma_V^{\mathrm{LO}} + \left(d\sigma_{V+\mathrm{jet}}^{\mathrm{NNLO}} - \left[d\sigma_V^{\mathrm{N^3LL}} \right]_{\mathcal{O}(\alpha_s^k)} \right) \Theta(p_T > p_T^{\mathrm{cut}}) + \mathcal{O}((p_T^{\mathrm{cut}}/M)^n)$$

ATLAS fiducial region $\quad p_T^{\ell^\pm} > 27\,\mathrm{GeV} \qquad |\eta^{\ell^\pm}| < 2.5$

- When using symmetric cuts, mandatory to include missing linear **power corrections** to reach a **precise control of the N^kLO correction** down to small values of p_T^{cut}
- Plateau at small p_T^{cut} indicates the desired independence of the slicing parameter



[Chen, Gehrmann, Glover, Huss, Monni, Re, LR, Torrielli '22]

Linear power corrections and NC Drell-Yan@N³LO

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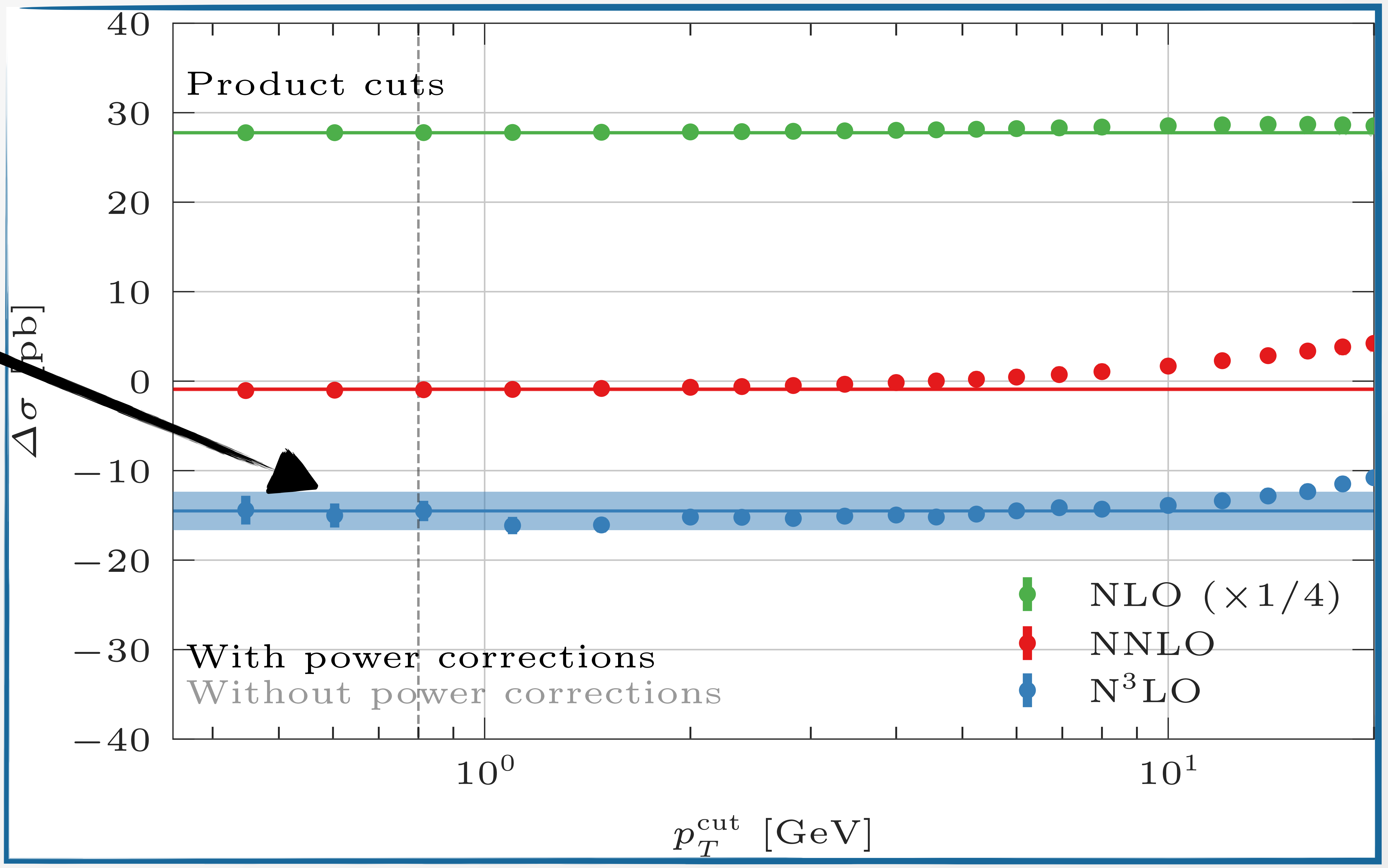
Product cuts $\sqrt{|\vec{p}_T^{\,\ell^+}|\,|\vec{p}_T^{\,\ell^-}|} > 27\,\mathrm{GeV}$ $\min\{|\vec{p}_T^{\,\ell^\pm}|\} > 20\,\mathrm{GeV}$ $|\eta^{\ell^\pm}| < 2.5$

[Salam, Slade '21]

- **Alternative set of cuts** which does not suffer from linear power corrections
- Improved convergence, result independent of the recoil procedure
- Exquisite control on the **fixed order component** (from NNLOJET) allows to push to low values of the slicing parameter p_T^{cut}
- Computation extremely demanding computationally in the NNLO V+j component: $\mathcal{O}$(several M) CPU hours

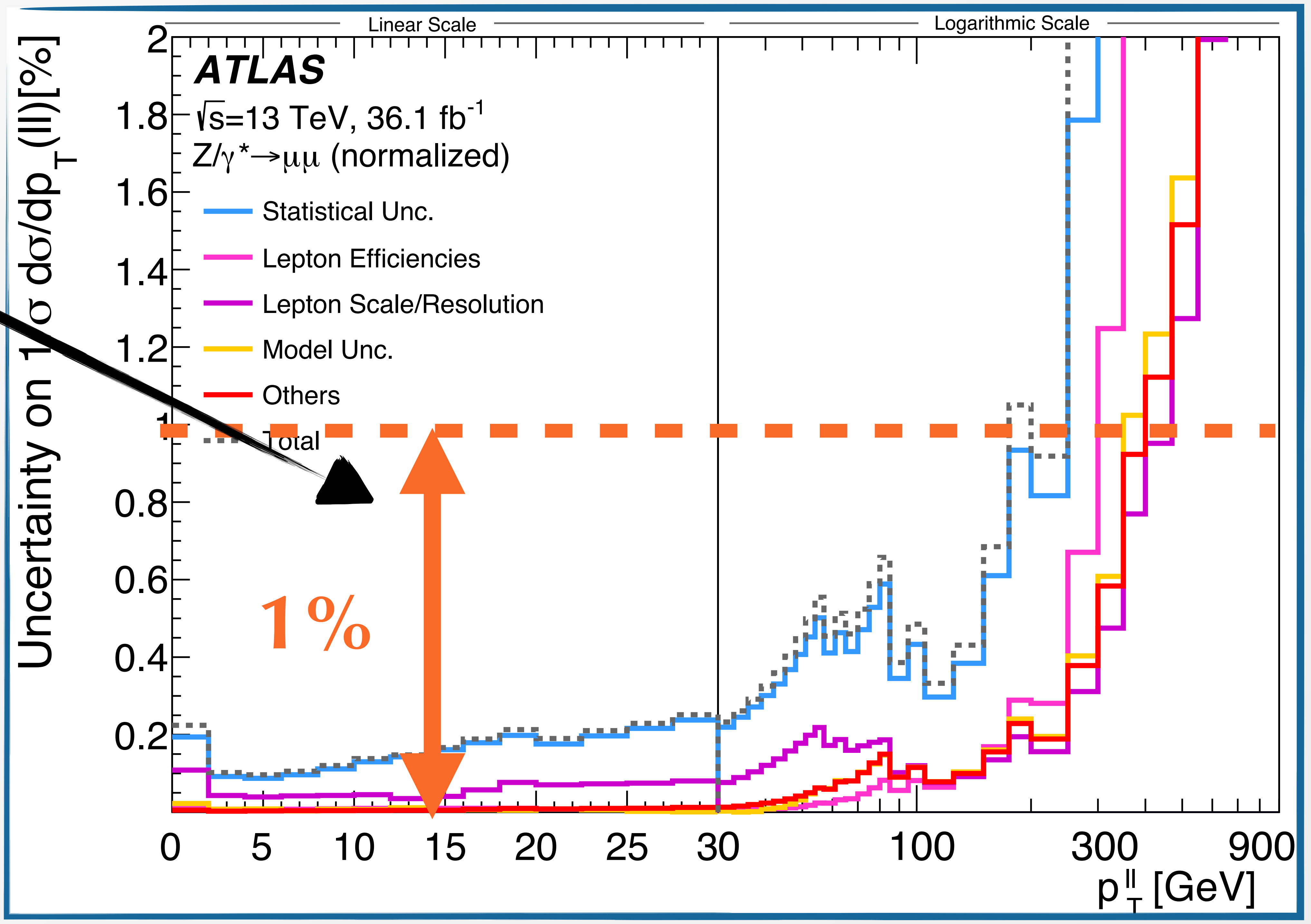


[Chen, Gehrmann, Glover, Huss, Monni, Re, LR, Torrielli '22]

NC Drell-Yan: transverse observables

Kinematic distributions which involve the production of a lepton pair in association with QCD radiation play a special role, as they are sensitive to accompanying hadronic activity **only through kinematic recoil**

Measurement of transverse and angular observables often lead to very small experimental uncertainties



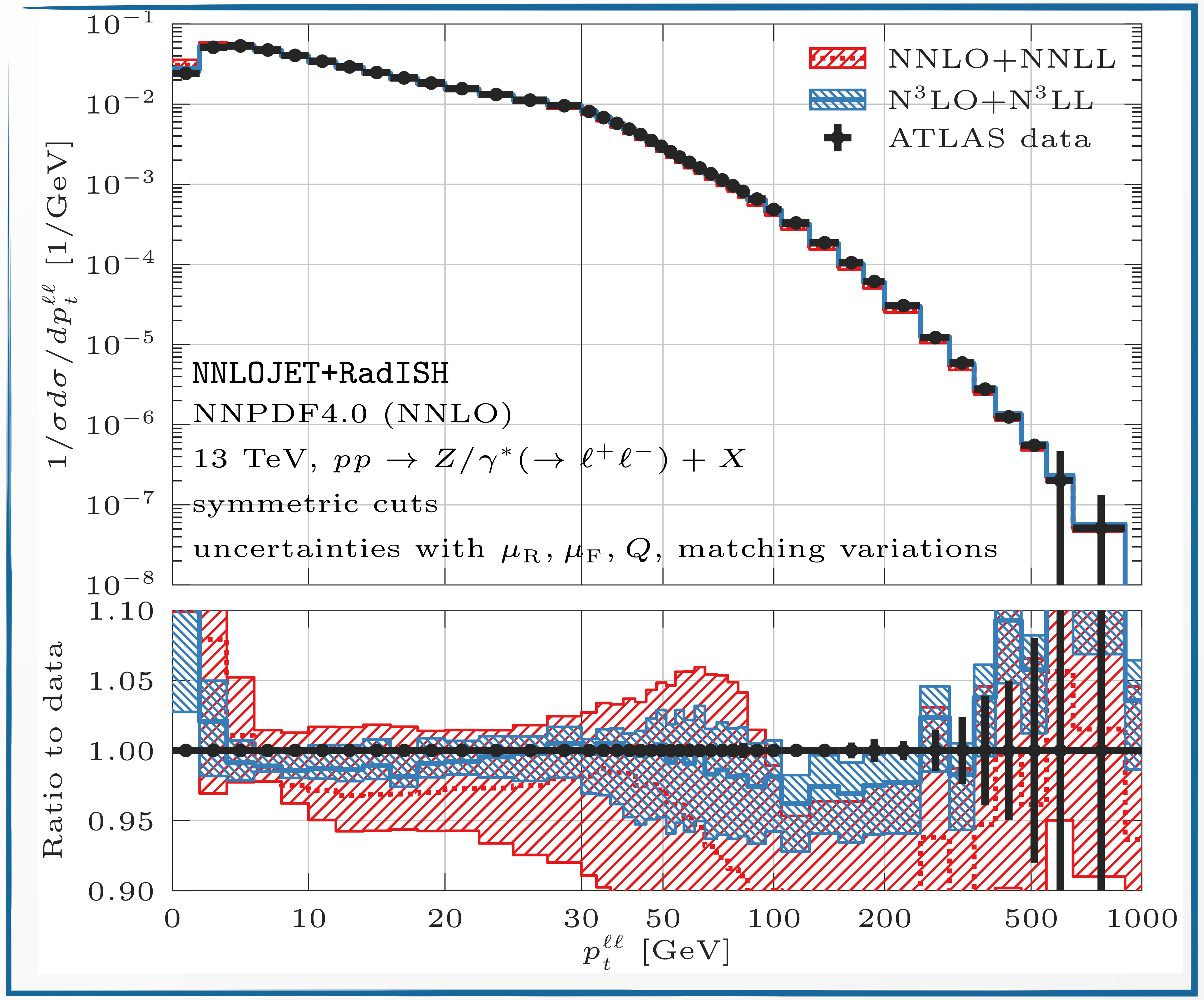
[ATLAS 2019]

Fixed-order perturbative description breaks in the $p_T \to 0$ limit, due to the appearance of large logarithms of $p_T/m_{\ell\ell}$, which must be resummed lest they spoil the perturbative convergence

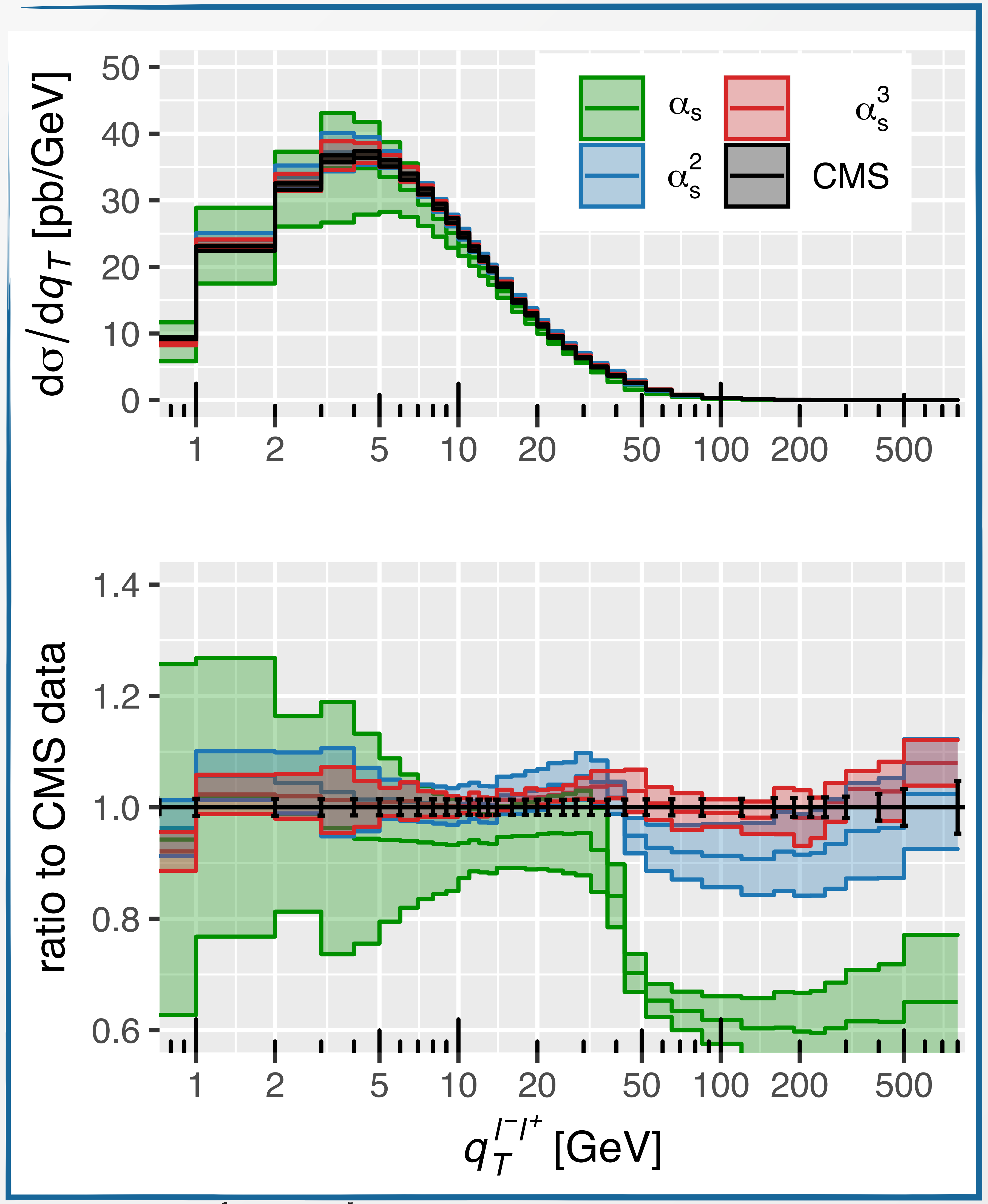
Resummation for DY production performed within a variety of formalisms (**direct QCD in *b* or momentum space**, **SCET**, **TMD**) with high-logarithmic accuracy N³LL′ ($\alpha_S^n \ln^{n-2} q_T/M$ and $\alpha_S^n \ln^{2n-6} q_T/M$). N⁴LL ingredients partially available

NC Drell-Yan: precise description of the transverse momentum spectra

State-of-the-art predictions achieve N^{3}LL′/aN^{4}LL+N^{3}LO accuracy



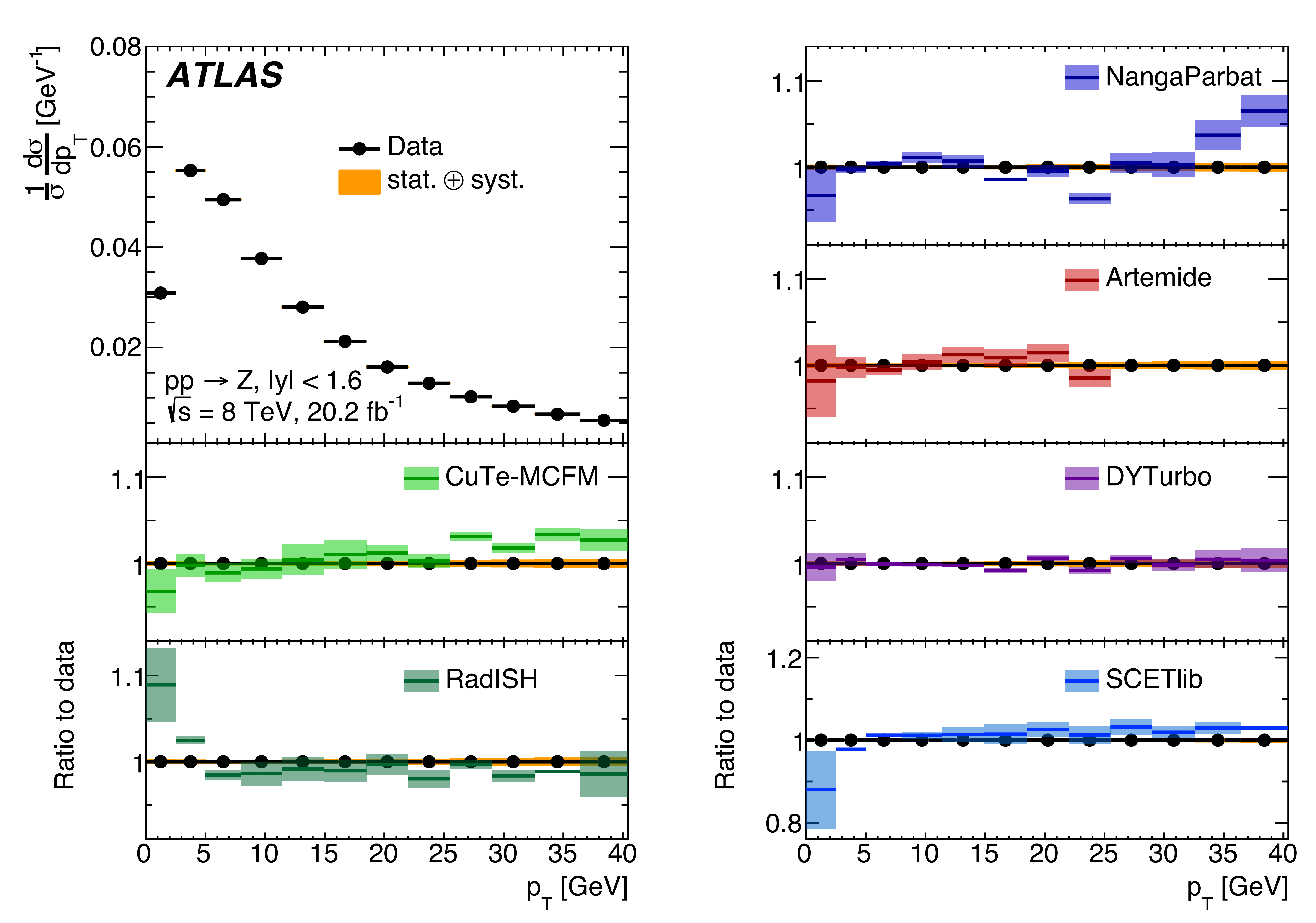
direct-space approach (RadISH)
[Chen, Gehrman, Glover, Huss, Monni, Re, LR, Torrielli 2022]



SCET formalism (Cute-MCFM)
[Neumann, Campbell 2022]

Excellent description of experimental data, with **residual scale uncertainties at the few % level**

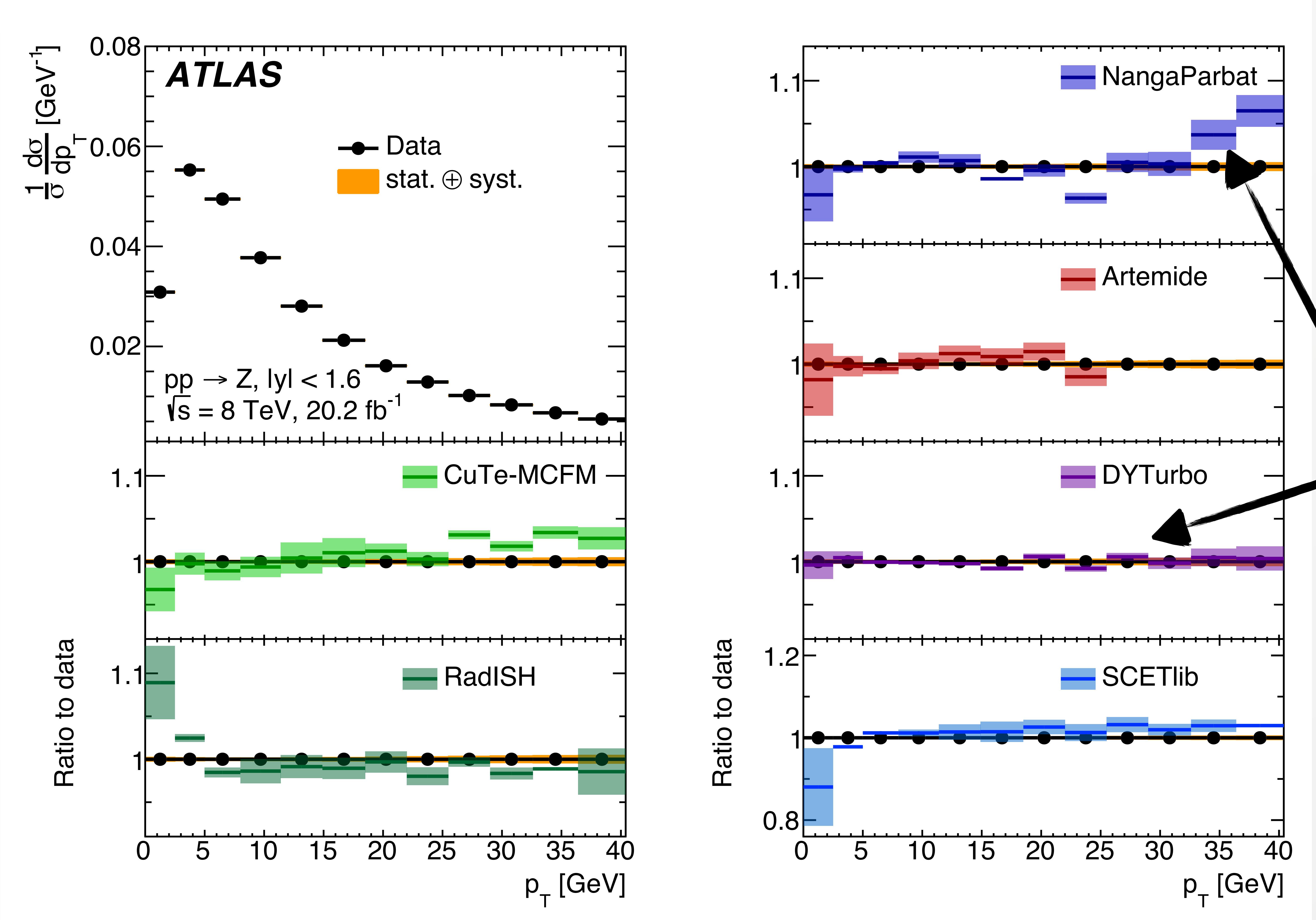
Resummation formalisms benchmarking



[ATLAS '23]

Comparison with ATLAS data at 8 TeV with different codes shows **overall good description of the data** at low transverse momentum, but highlights **some differences between alternative approaches**

Comparison with ATLAS data



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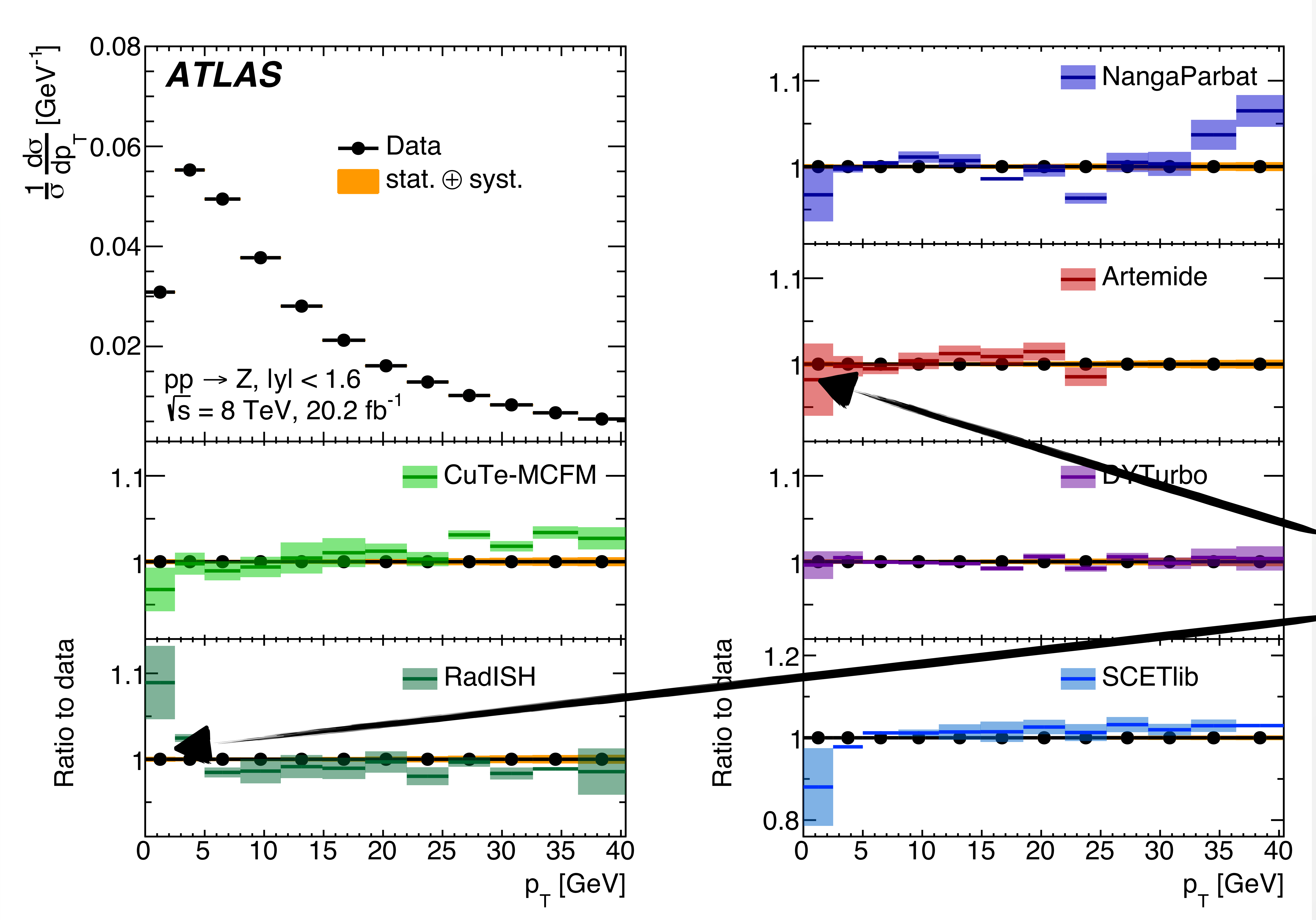
Comparison with ATLAS data at 8 TeV with different codes shows **overall good description of the data** at low transverse momentum, but highlights **some differences between alternative approaches**

Matching ambiguities affect description of data in the transition region

Comparison with ATLAS data

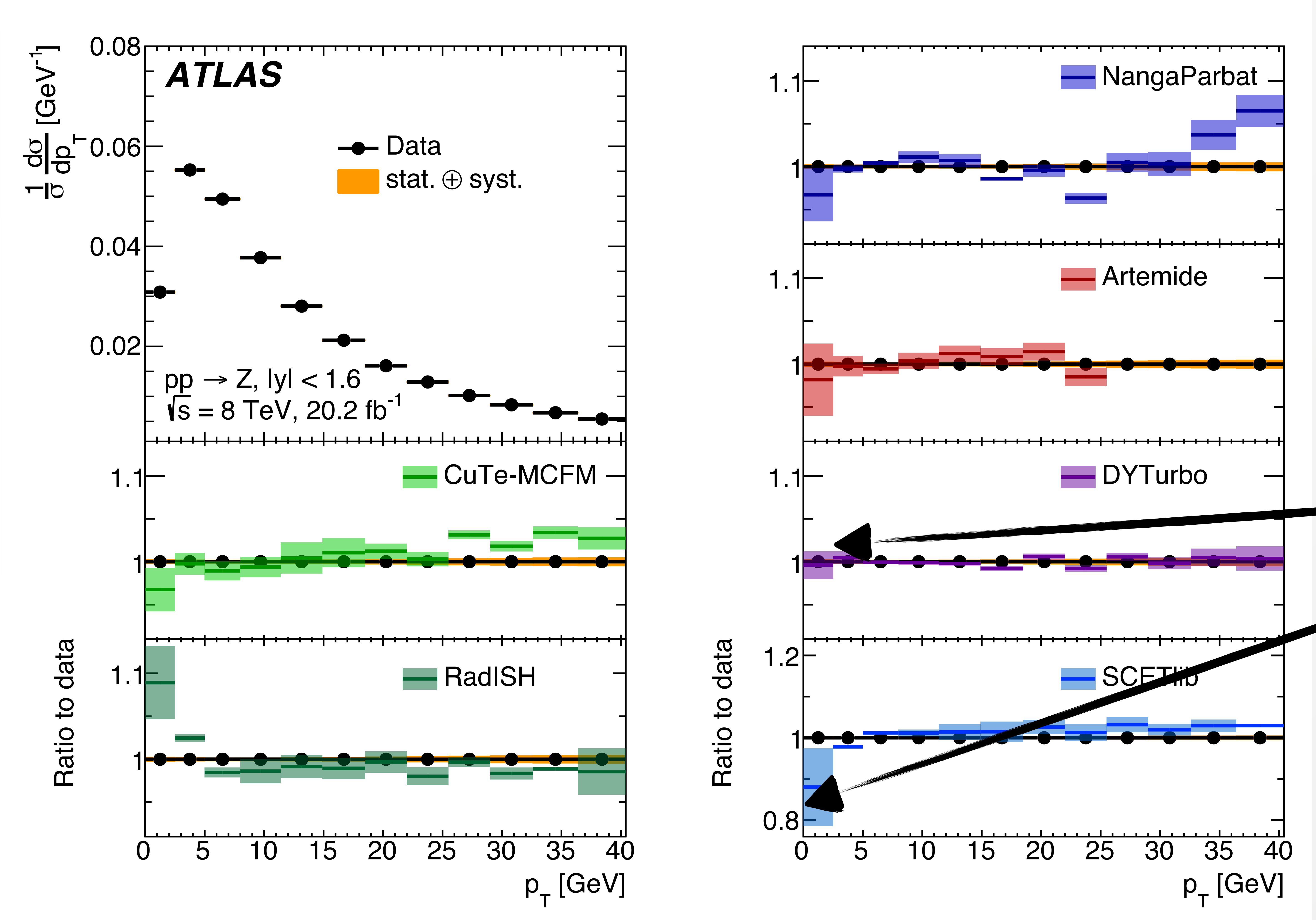


Comparison with ATLAS data at 8 TeV with different codes shows **overall good description of the data** at low transverse momentum, but highlights **some differences between alternative approaches**

Description at low transverse momentum affected by the inclusion of (tuned) NP corrections, absent in some formalisms

[ATLAS '23]

Comparison with ATLAS data

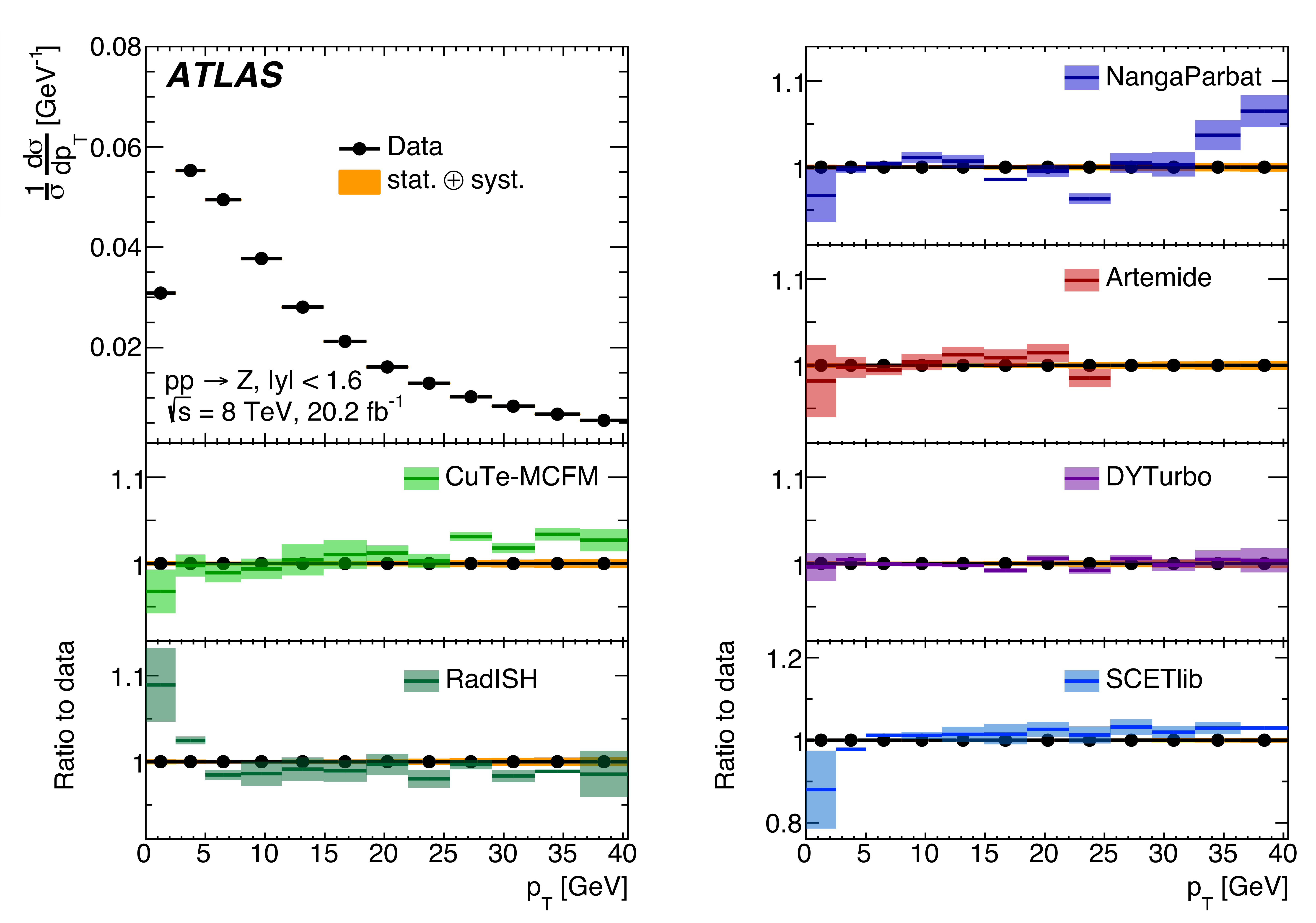


[ATLAS '23]

Comparison with ATLAS data at 8 TeV with different codes shows **overall good description of the data** at low transverse momentum, but highlights **some differences between alternative approaches**

Estimate of missing higher-order corrections can vary significantly among different approaches

Comparison with ATLAS data



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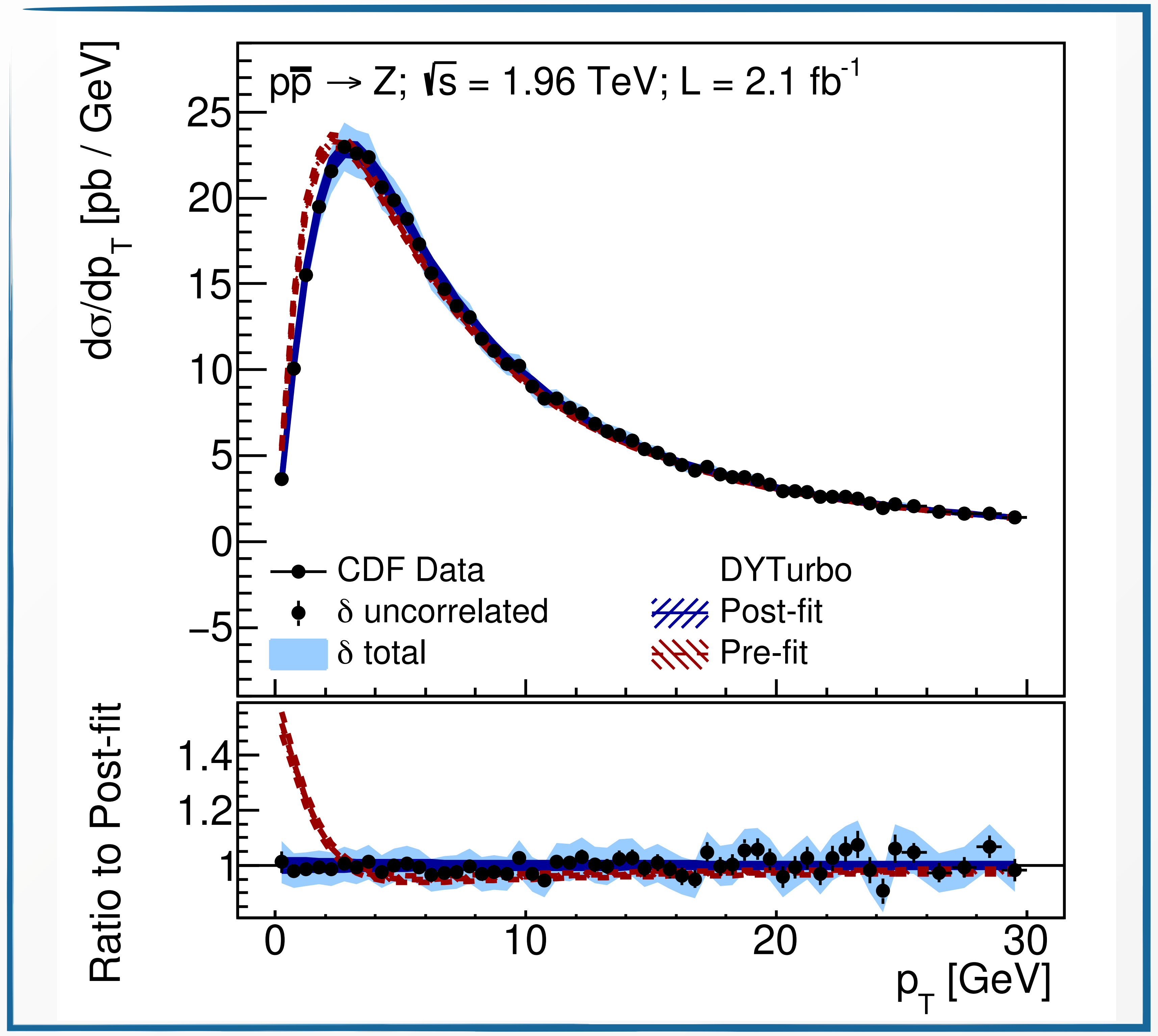
Ongoing benchmark (adiabatically convergent…) in EW WG1

NC Drell-Yan and α_s

Precise assessment of the theoretical uncertainties crucial to estimate error on EW precision measurement such as α_s from $Z\ q_T$ measurements



[Camarda, Ferrera, Schott '23]

Sensitivity to α_s intertwined with

- Non-perturbative physics / flavour modelling at low q_T, for which we lack a full-fledged theoretical description
- PDF parameterisation: **strong correlation** between PDFs and α_s, which should be determined simultaneously lest to introduce a bias [Forte, Kassabov '20]
- Estimate of missing higher order uncertainties and its correlation across $Z\ q_T$ bins

NC Drell-Yan and α_s

Precise assessment of the theoretical uncertainties crucial to estimate error on EW precision measurement such as α_s from $Z\ q_T$ measurements

Experimental uncertainty	±0.44	
PDF uncertainty	±0.51	
Scale variation uncertainties	±0.42	
Matching to fixed order	0	−0.08
Non-perturbative model	+0.12	−0.20
Flavour model	+0.40	−0.29
QED ISR	±0.14	
N^4LL approximation	±0.04	
Total	+0.91	−0.88

Summary of the uncertainties in the determination of $\alpha_s(m_Z)$, in units of 10^{-3}.

[ATLAS '23 (currently unpublished)]

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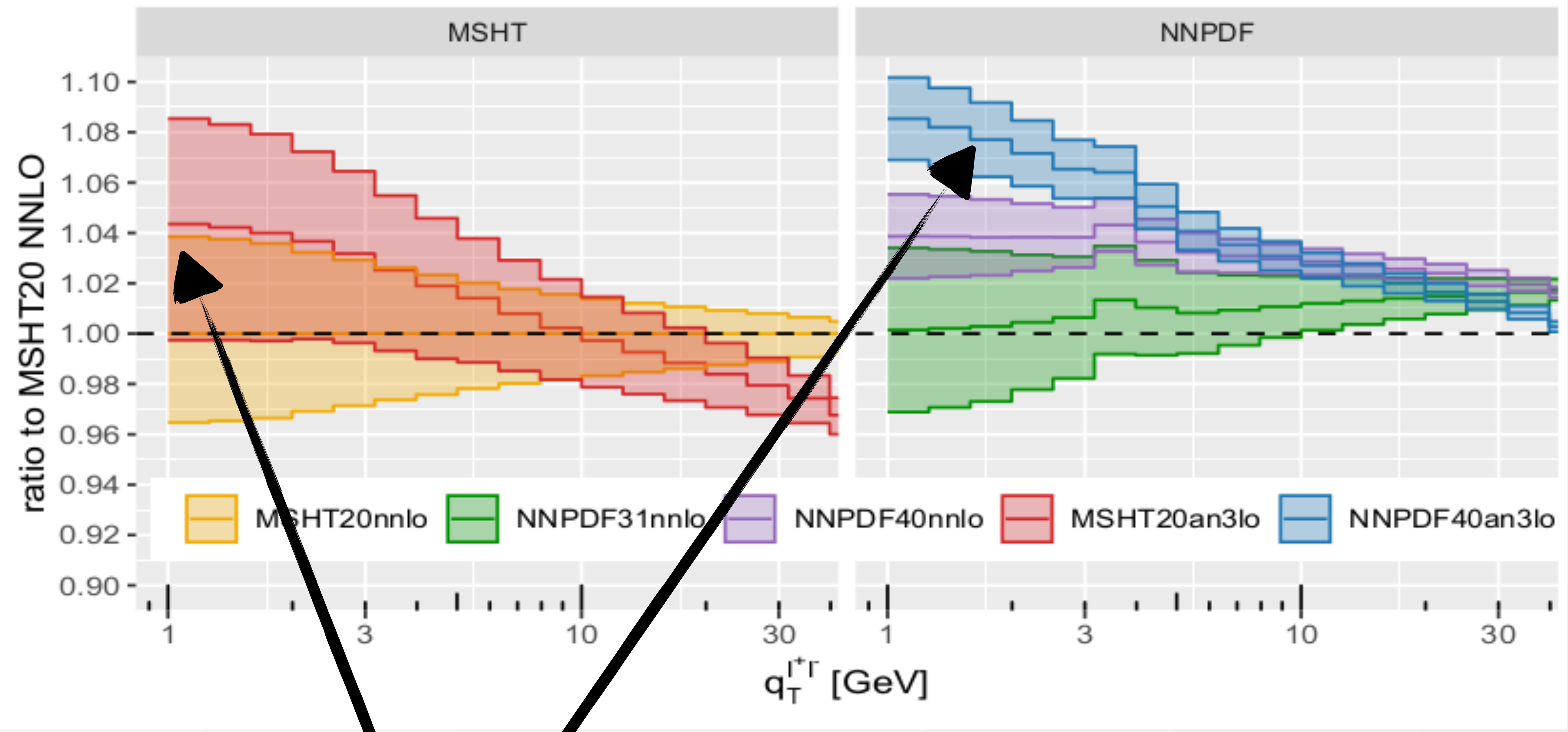
Bulk of the theoretical uncertainty: how much are we confident of these estimates?

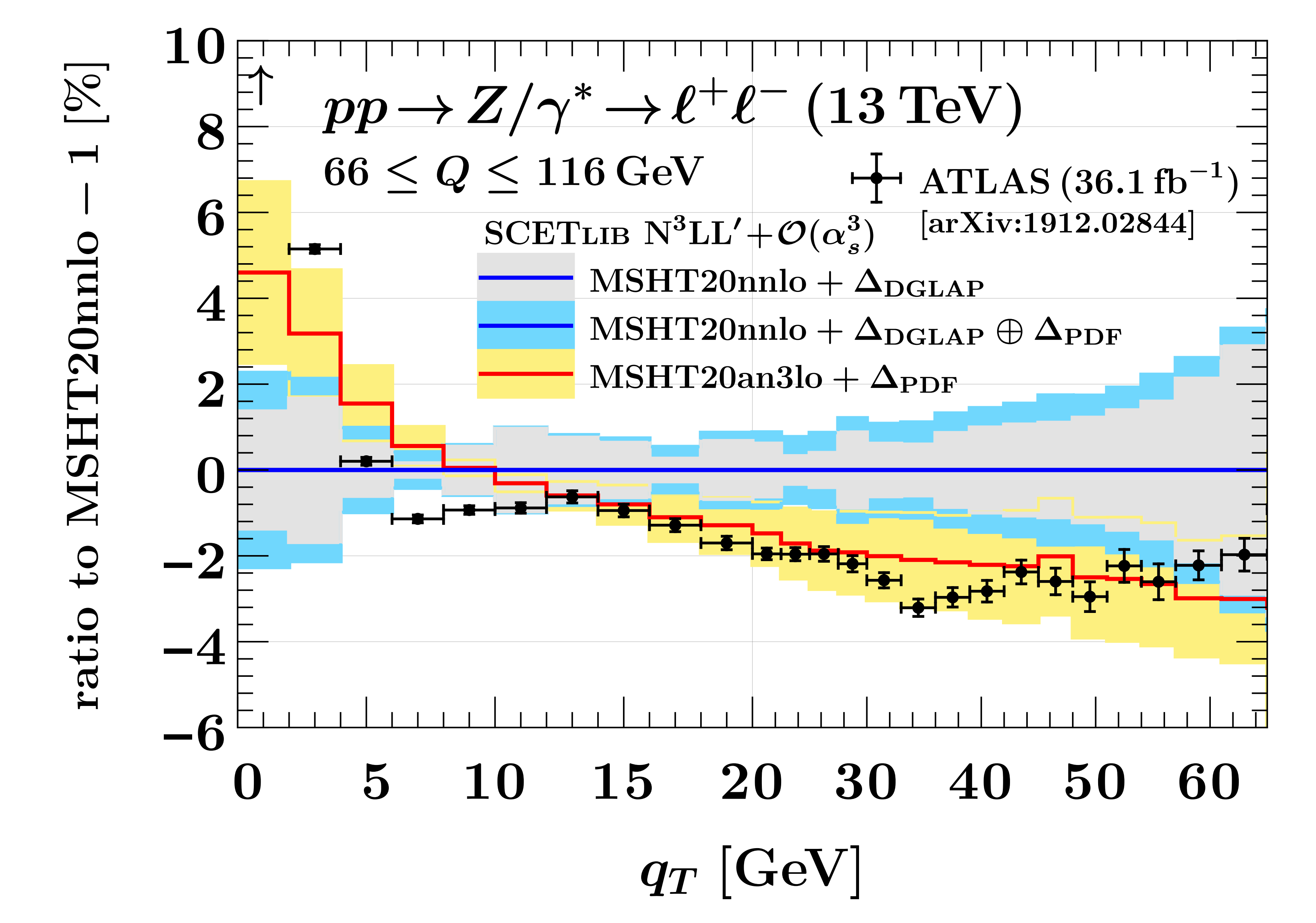
The role of PDFs

Non negligible differences in absolute value between different groups (NNPDF, MHST)

Discrepancy explained by fitted (NNPDF) vs. perturbative (MSHT) charm and different value of the charm mass, still state-of-the-art PDFs set **can differ at the few % level**



[Neumann @ Loops and Legs 2024]



aN³LO PDFs from MSHT or NNPDF have a similar impact in shape on the $Z\ p_T$ spectrum. Substantial differences can impact the agreement with the experimental data

Precision programme requires a deeper understanding of PDF/ N³LO DGLAP role for such a crucial observable

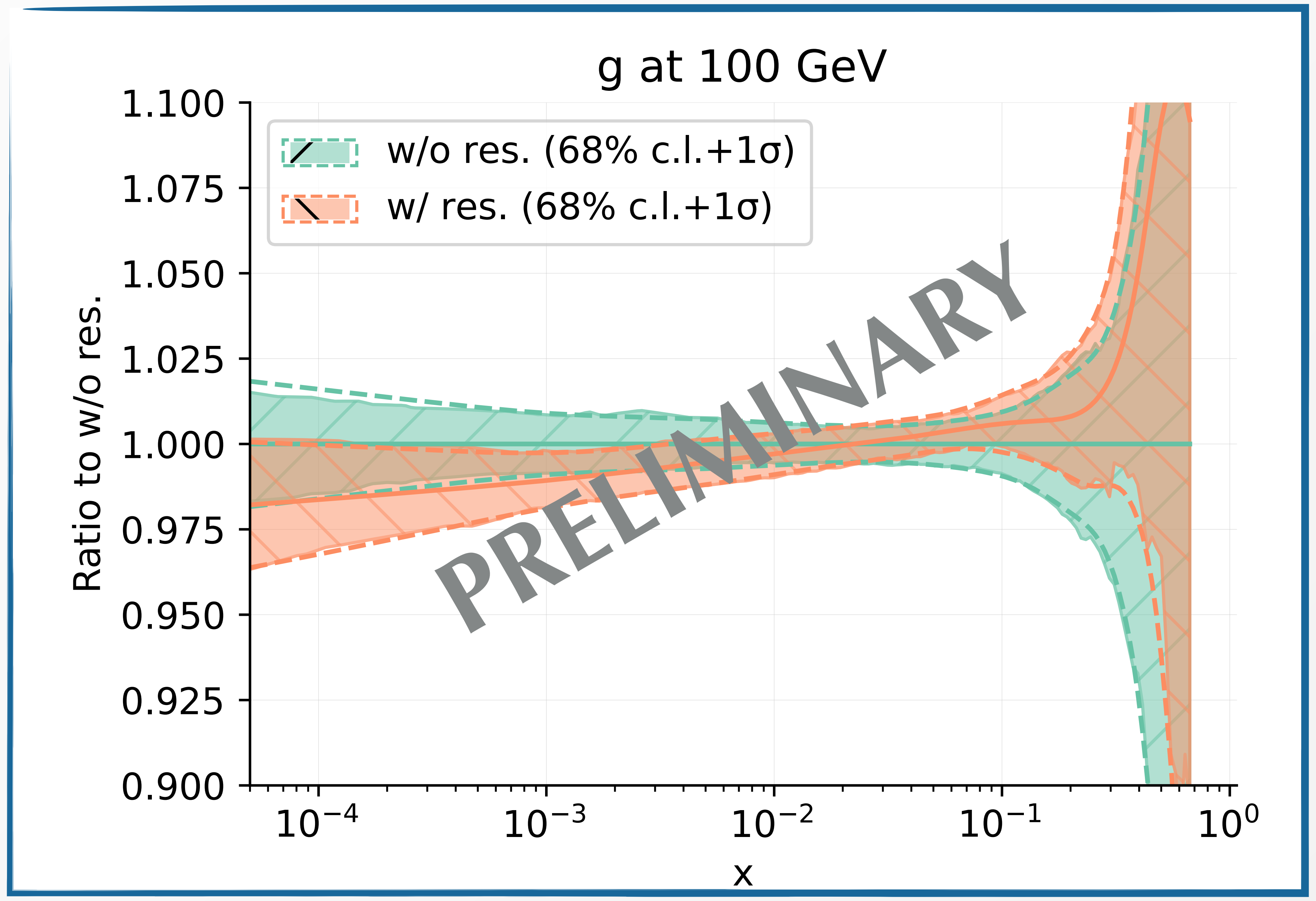
[J. Michel @ EW WG 2022]

Fitting transverse momentum data at low q_T [Cruz-Martinez, Nocera, LR, Torrielli, WIP]

Conservative cuts on the Z transverse momentum typically enforced in PDF determinations (e.g. NNPDF) to remove resummation effects

Assessing the impact of resummation has a twofold effect:

- Understanding whether the current cut ($q_T^{\ell\ell} > 30\,\mathrm{GeV}$ for NNPDF) is sufficiently conservative



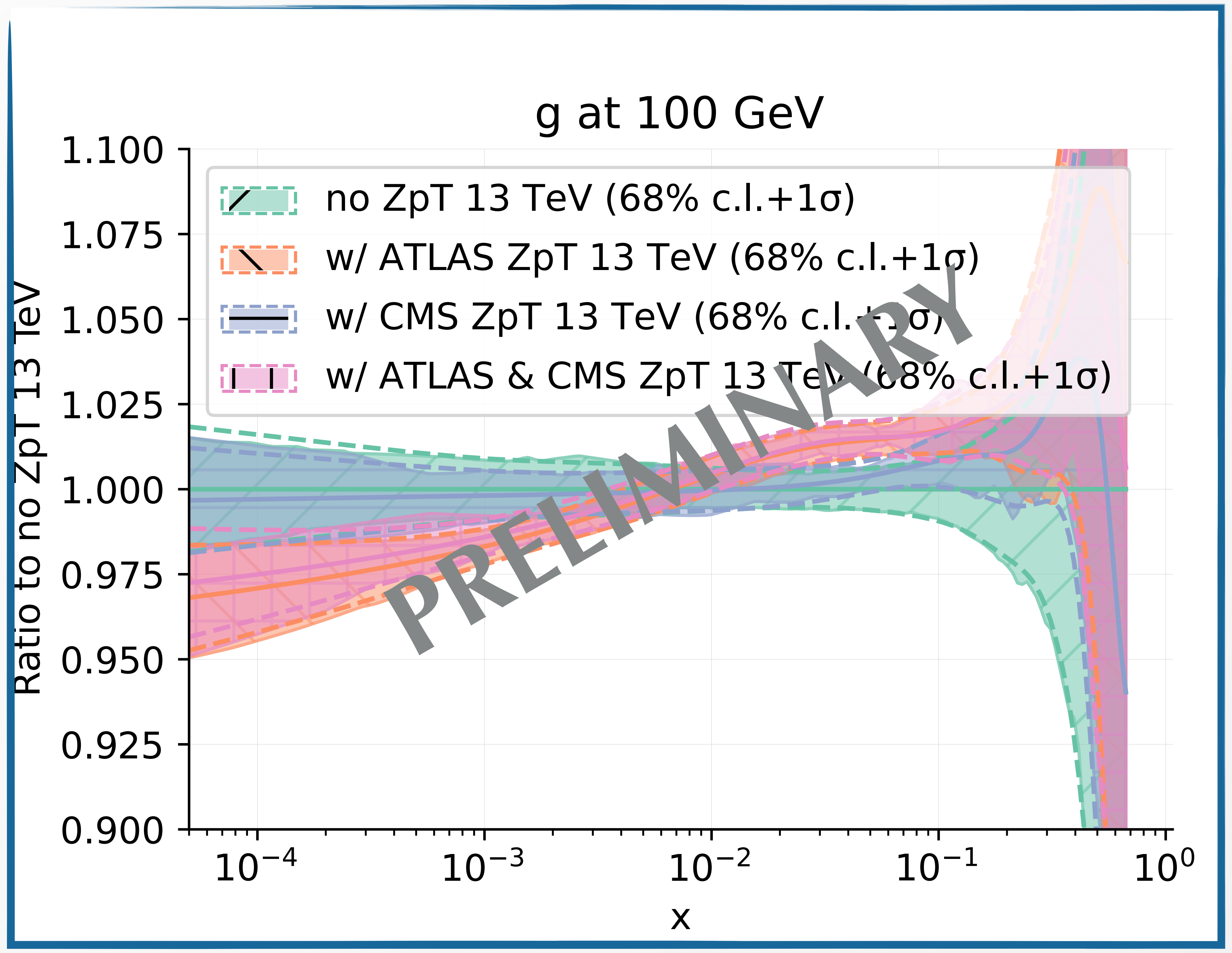
(**Preliminary**) answer: maybe not enough?

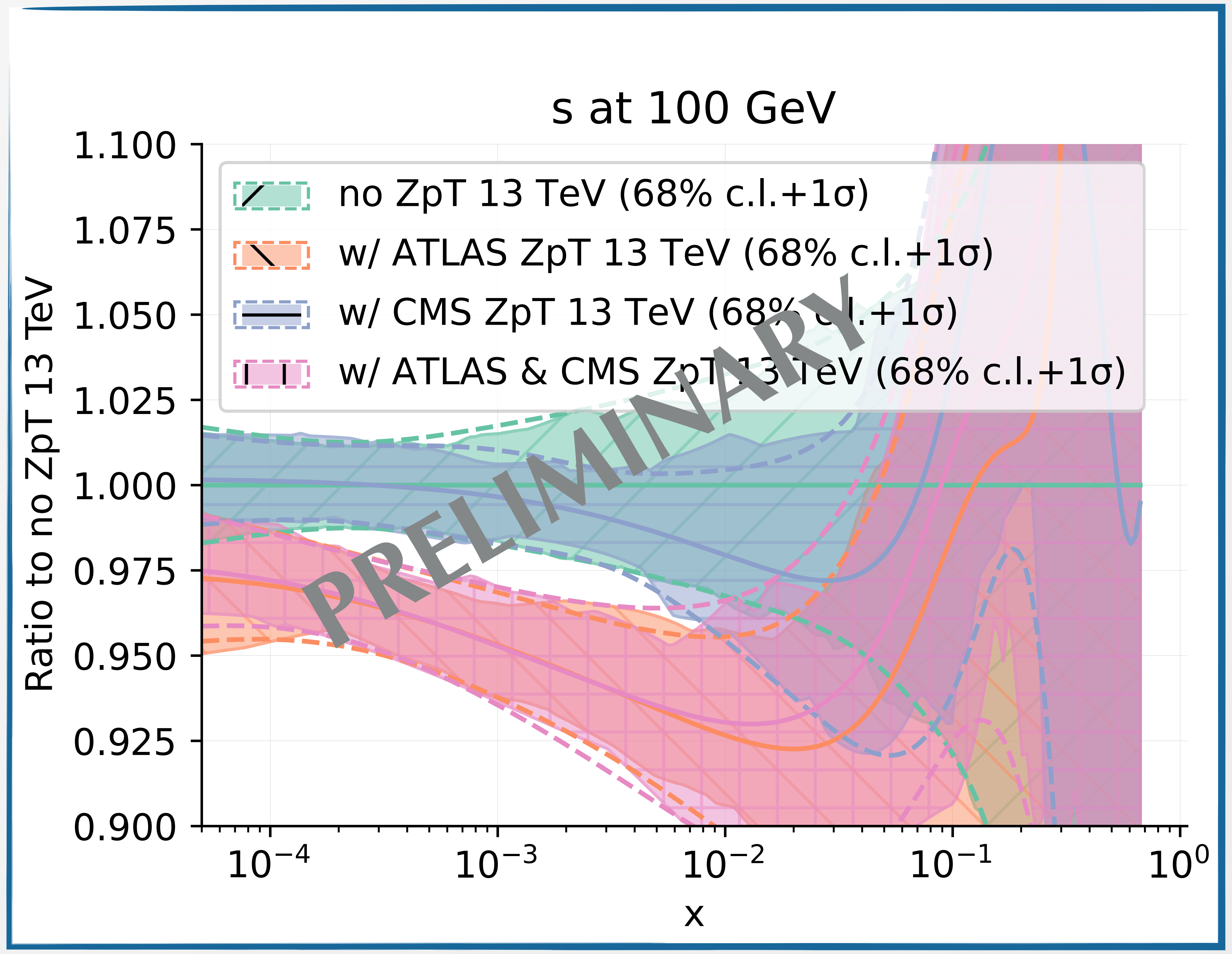
Fitting transverse momentum data at low q_T [Cruz-Martinez, Nocera, LR, Torrielli, WIP]

Conservative cuts on the Z transverse momentum typically enforced in PDF determinations (e.g. NNPDF) to remove resummation effects

Assessing the impact of resummation has a twofold effect:

- Understanding whether the current cut ($q_T^{\ell\ell} > 30\,\mathrm{GeV}$ for NNPDF) is sufficiently conservative
- Relax cut on $q_T^{\ell\ell}$ and assess the impact on PDFs





Theory uncertainties and their correlations

Scale variations not particularly suited to model correlations across bins. In the resummation region, theory predictions depend on a few semi-universal parameters: treat them as **theory nuisance parameters** [Tackmann, 2411.18606]

NB: Extension to fixed order regime presents further challenges (functions vs. constants) ***René' talk***

Perturbative uncertainty	Absolute uncertainty on $\alpha_s(m_Z)$ in units of 10^{-3} Ref. [33]	Our estimate of expected size
Scale variations	± 0.42	± 2.43
N^4LL^* approximation	± 0.04	
N^4LL' approximation		± 0.75
Flavor/quark masses	$+0.40\ -0.29$	± 1.32
Total	$+0.58\ -0.51$	± 2.87

[Cridge, Martinelli, Tackmann '25]

Cridge et al. result uses TNP and SCETLIB (n.b.: scale variation scan with SCETLIB yields ± 1.73, still larger than ATLAS result)

ATLAS estimate based on scale variations scan and DYTURBO

Tension between independent estimate of missing higher order uncertainty motivates detailed study to assess the size of theory errors

W and Z production: the role of correlations

Precise data on q_T^Z spectrum can be employed in measurement of m_W only indirectly, by modelling the differences between Z and W production processes

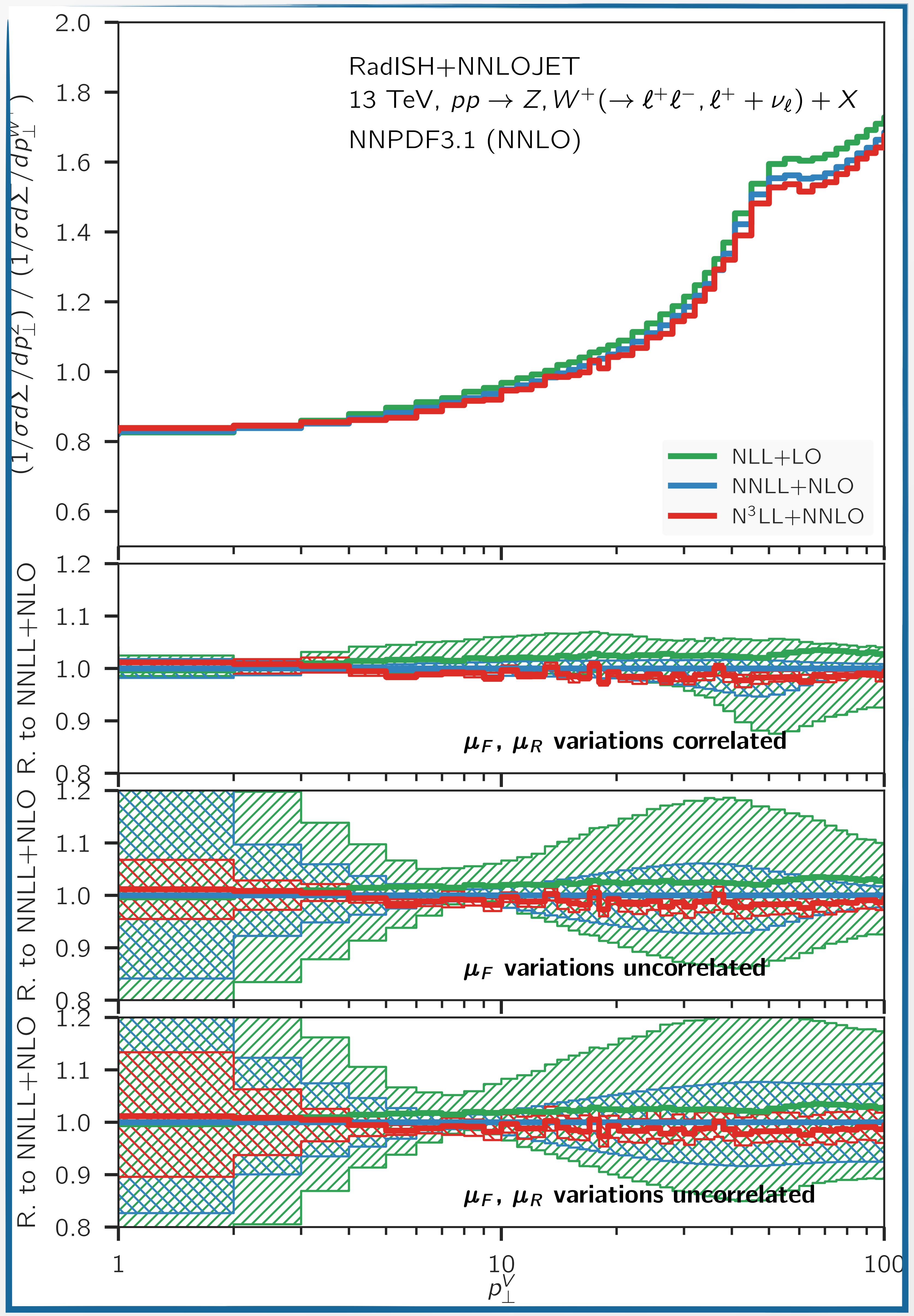
$$\frac{1}{\sigma^W}\frac{d\sigma^W}{q_T^W} \sim \frac{1}{\sigma^Z_{\rm data}}\frac{d\sigma^Z_{\rm data}}{q_T^Z}\,\frac{\frac{1}{\sigma^W_{\rm theory}}\frac{d\sigma^W_{\rm theory}}{q_T^W}}{\frac{1}{\sigma^Z_{\rm theory}}\frac{d\sigma^Z_{\rm theory}}{q_\perp^Z}}$$

e.g. m_W determination by ATLAS

Z and W production share a similar pattern of QCD radiative corrections, but a **precise understanding of the correlation** between the two processes is crucial to propagate consistently the information

Ratio **very stable perturbatively**, suggesting high correlation. Size of uncertainty strongly depends on the assumption of the correlations

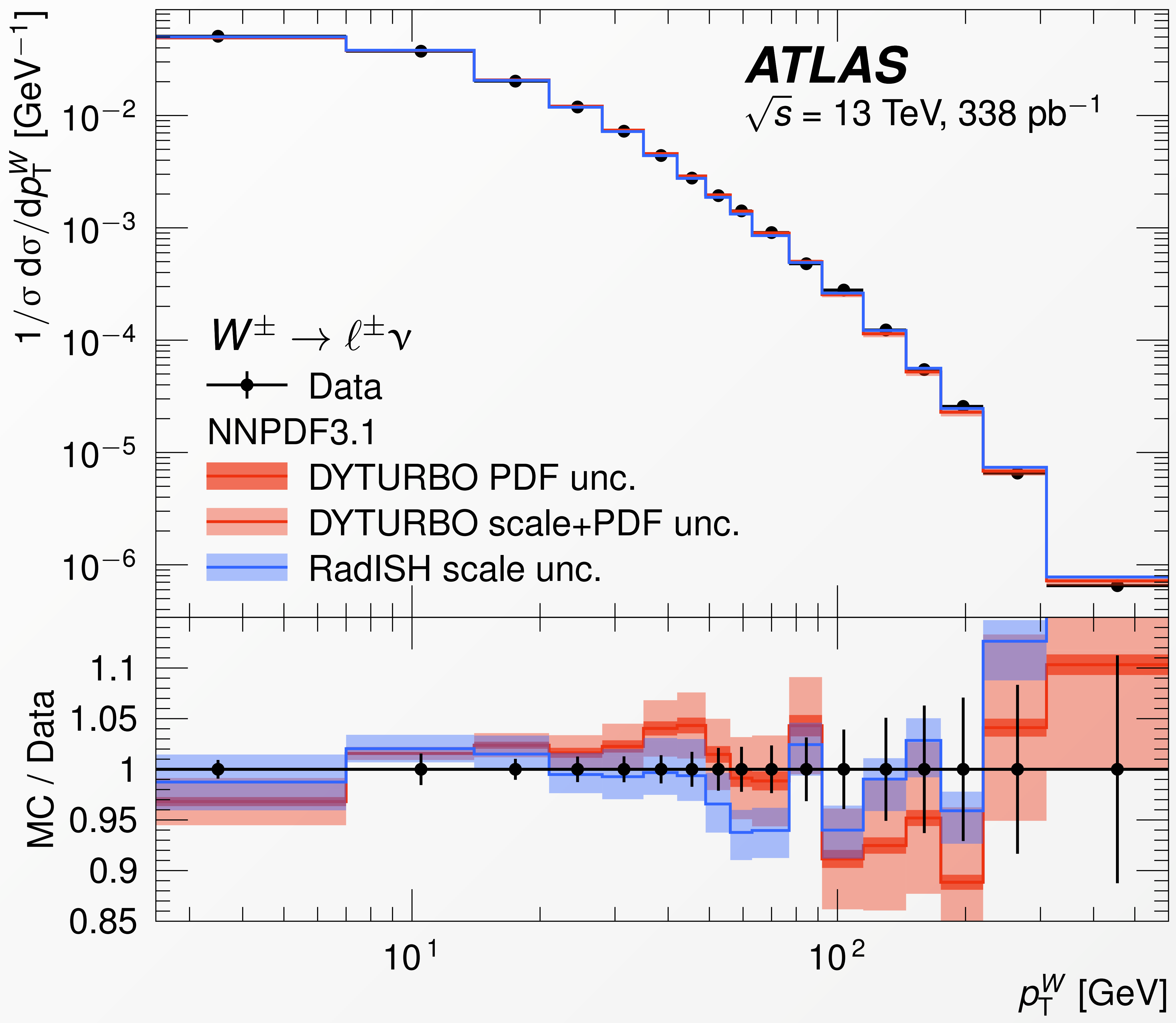
Alternative way of estimating the correlation (e.g. TNP) may prove useful



[Bizon, Gehrmann-De Ridder, Gehrmann, Glover, Huss, Monni, Re, LR, Walker '19]

Transverse momentum in W production

Direct measurement of W transverse momentum would provide a direct way to test W/Z modelling and reduce the related uncertainties in a measurement of m_W



Low-pileup runs in recent ATLAS measurement show good agreement with N^{3}LL+N^{3}LO (RadISH+NNLOJET) and NNLL+NNLO (DYTURBO) predictions

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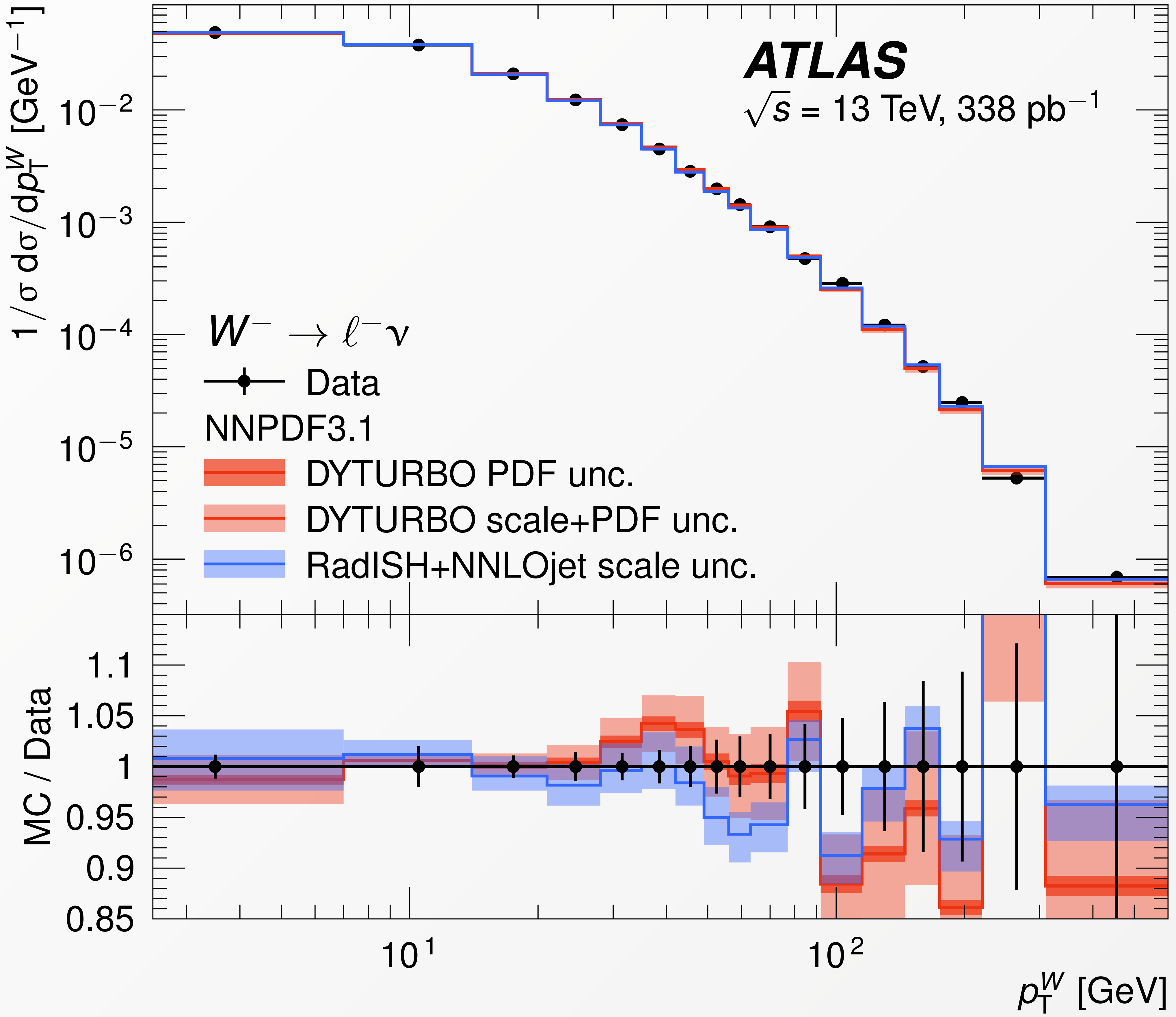

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Especially for W^-…

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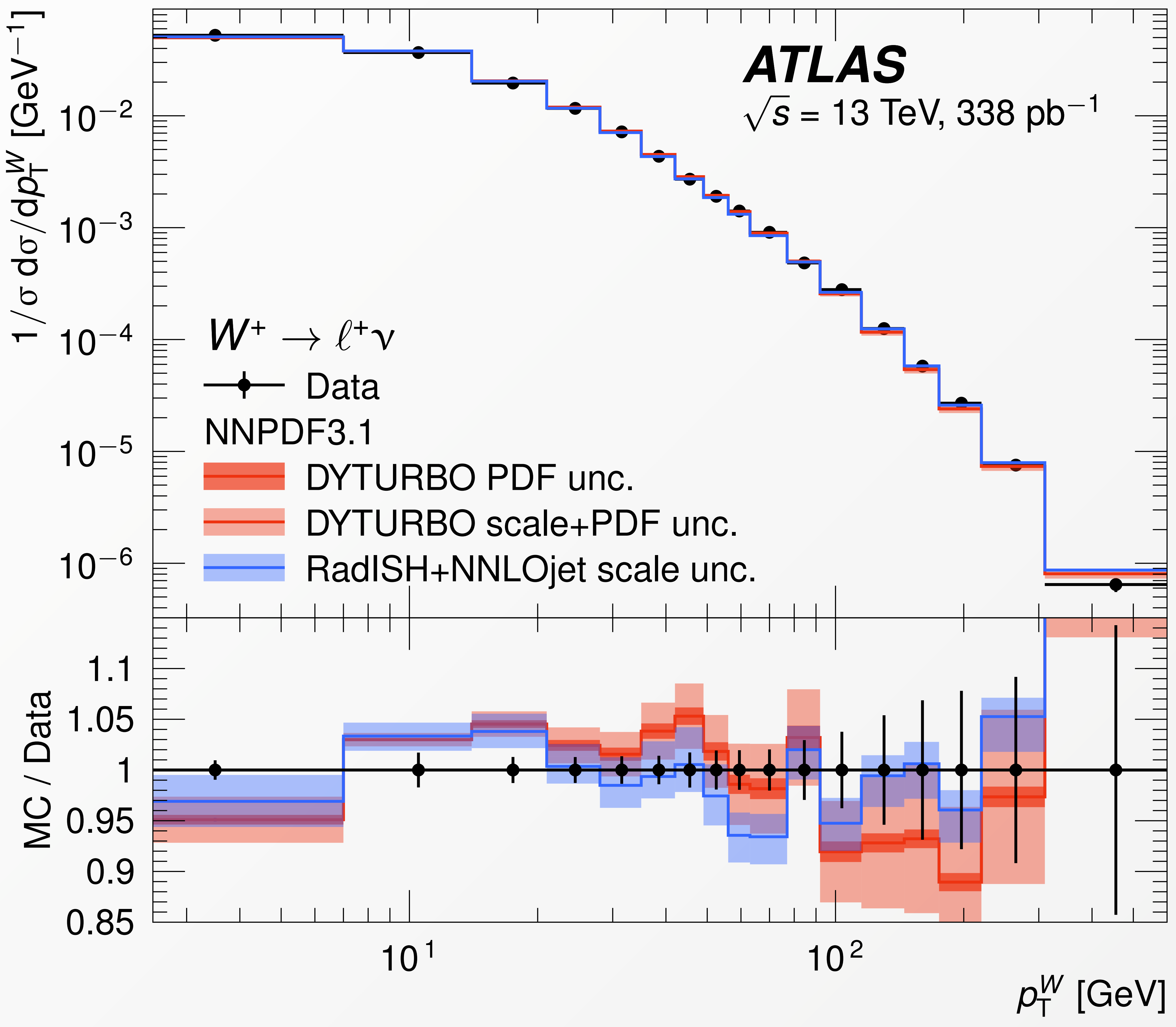

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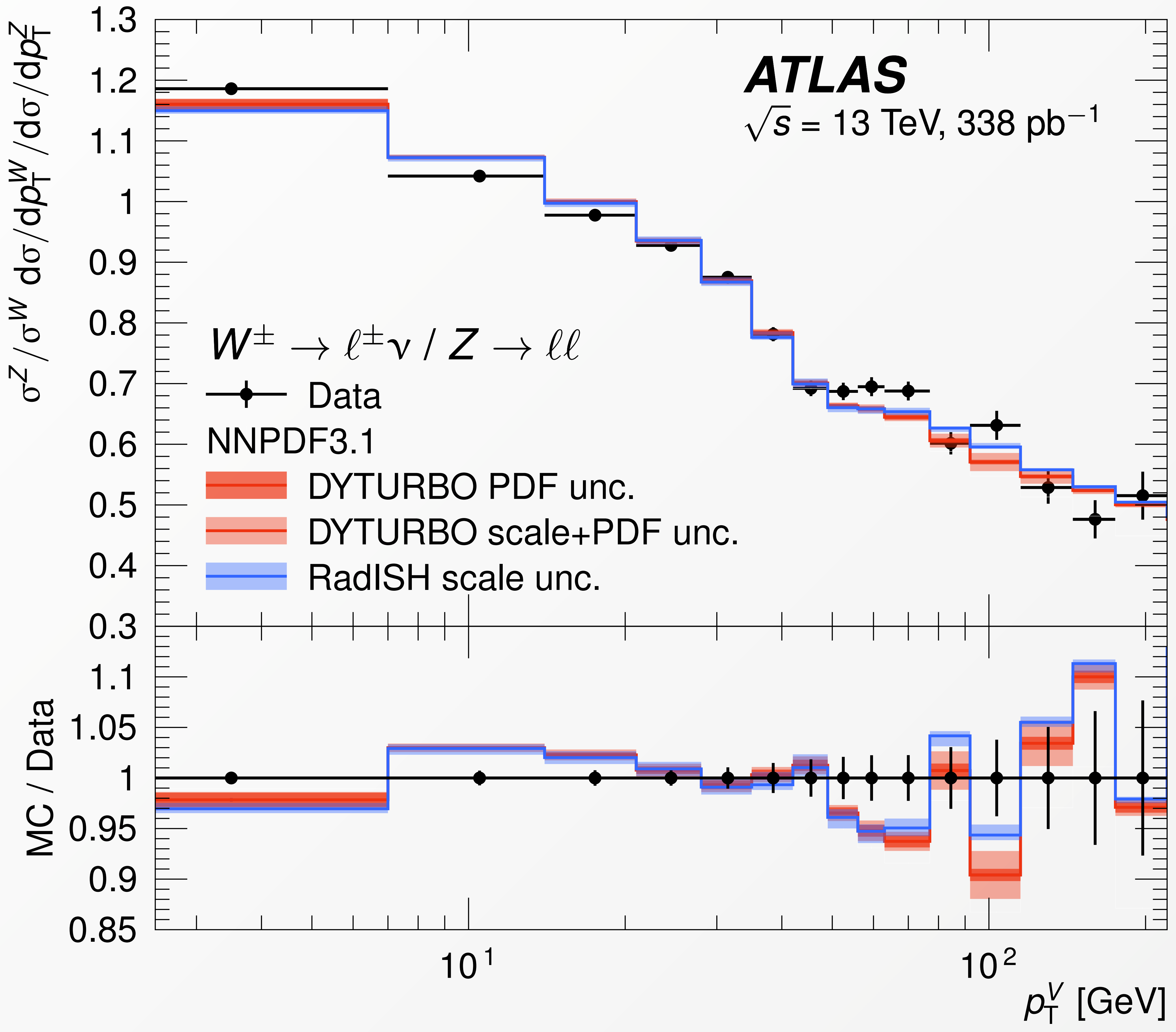

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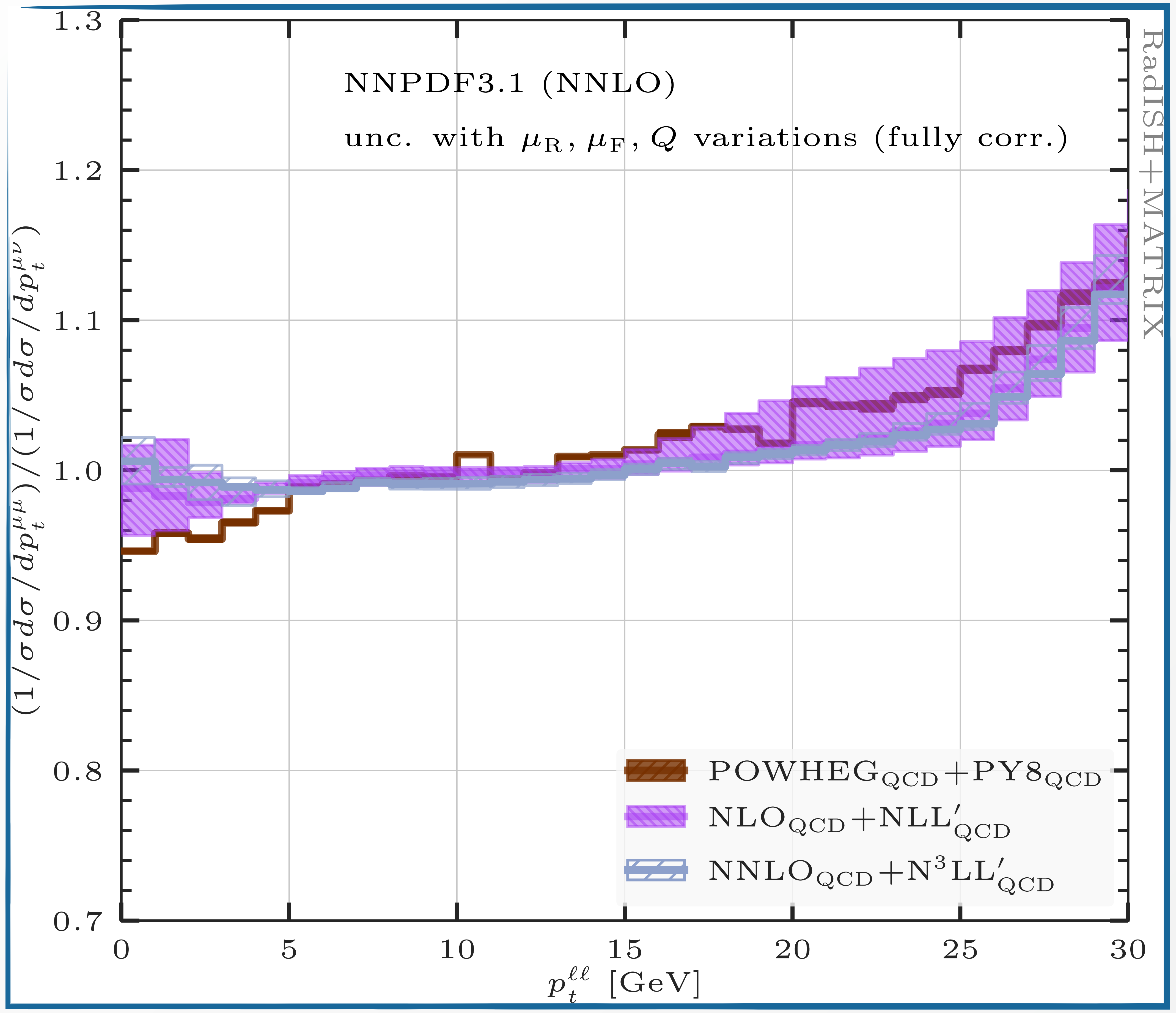

[Buonocore, LR, Torrielli '24]

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Tuned MC predictions (POWHEG+PY8) display the same level of discrepancy and are relatively insensitive to choice of tune, intrinsic k_T, MPI and hadronisation effects

Understanding the different pattern of EW corrections to the two processes may help to shed light on the discrepancy

Luca's talk

Is the *W* enough?

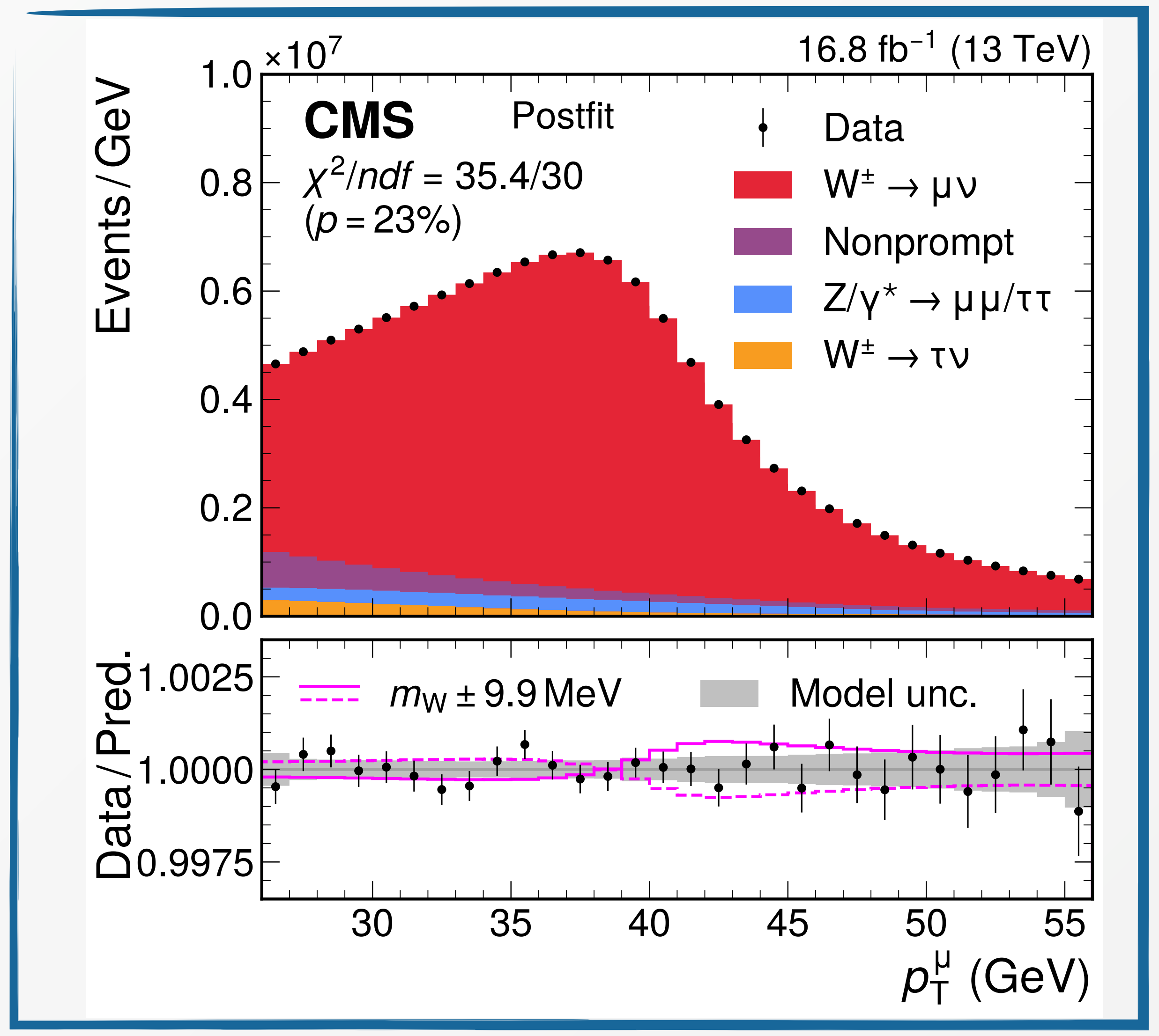
Recent CMS and LHCb m_W measurements relies solely on W data

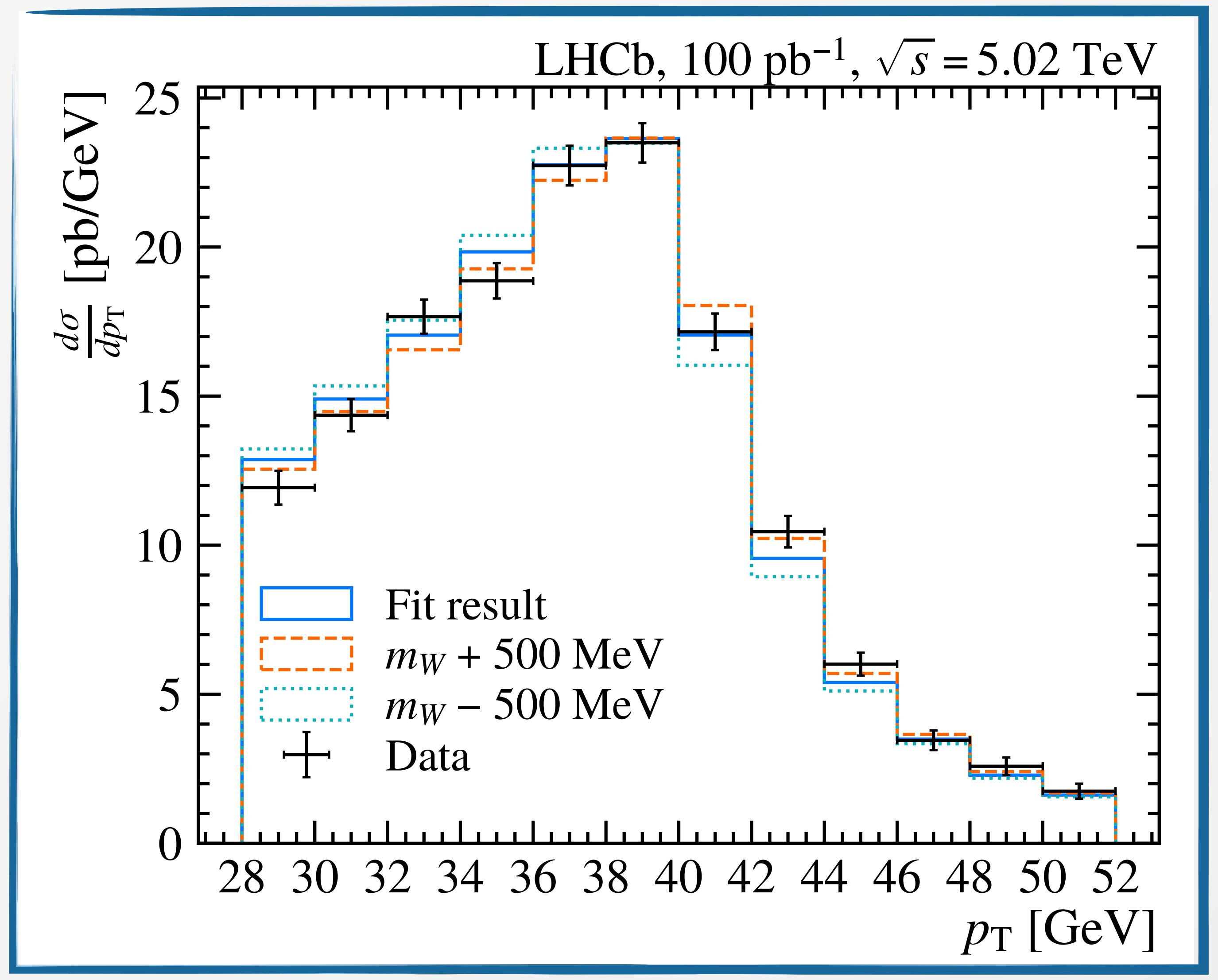
$$m_{\mathrm{W}} = 80\,360.2 \pm 2.4\,(\mathrm{stat}) \pm 9.6\,(\mathrm{syst}) = 80\,360.2 \pm 9.9\,\mathrm{MeV}$$

[CMS '24]

$$m_W = 80369 \pm 130 \pm 33\,\mathrm{MeV}$$

[LHCb '25]





Theoretical (and PDF) uncertainty is constrained by a **profiling procedure**, contributing to a fraction of the overall uncertainty

NB: uncertainty can be ~10x larger without profiling

Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8

[CMS '24]

13 MeV

14 MeV

22 MeV

[LHCb '25]

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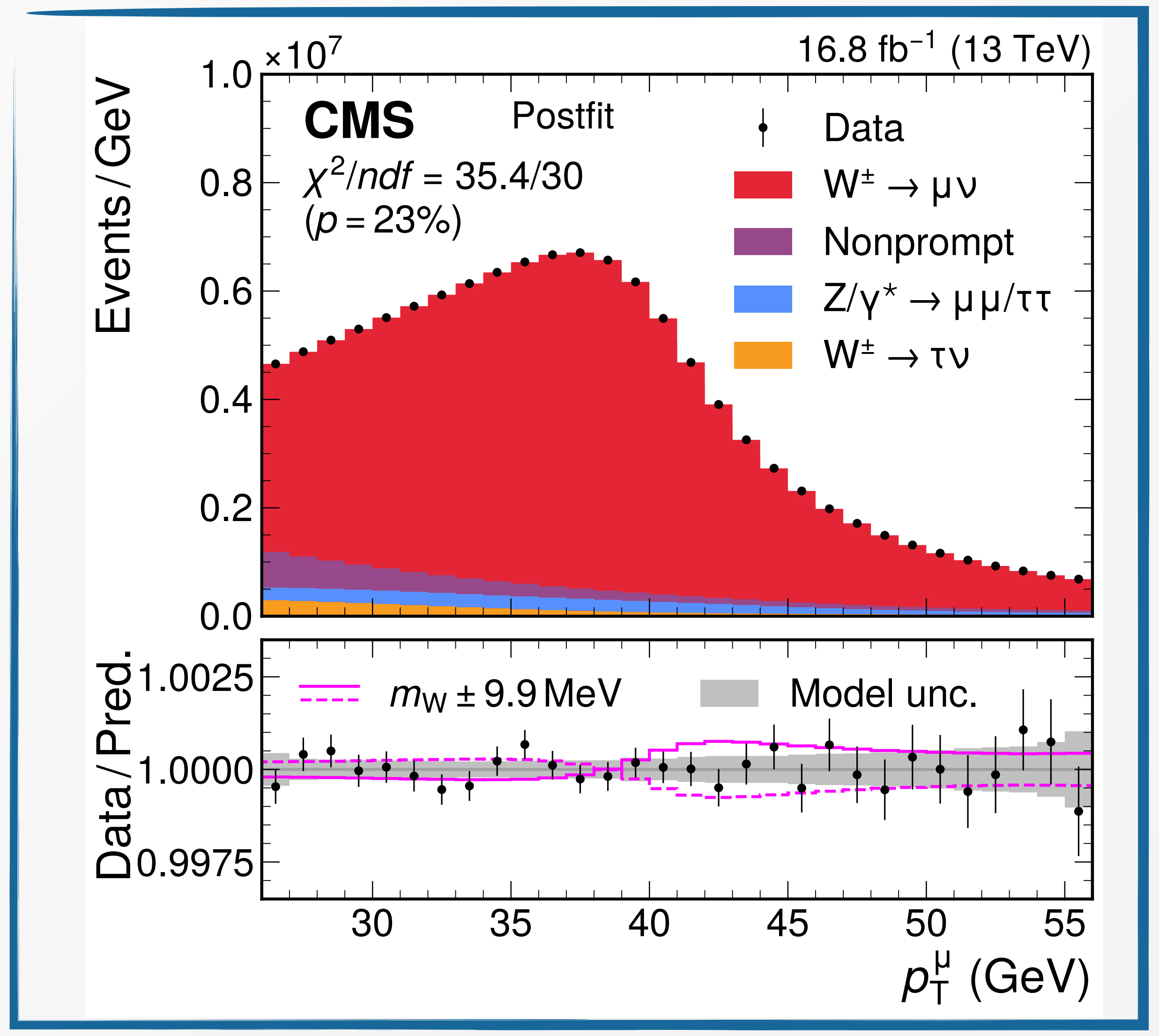

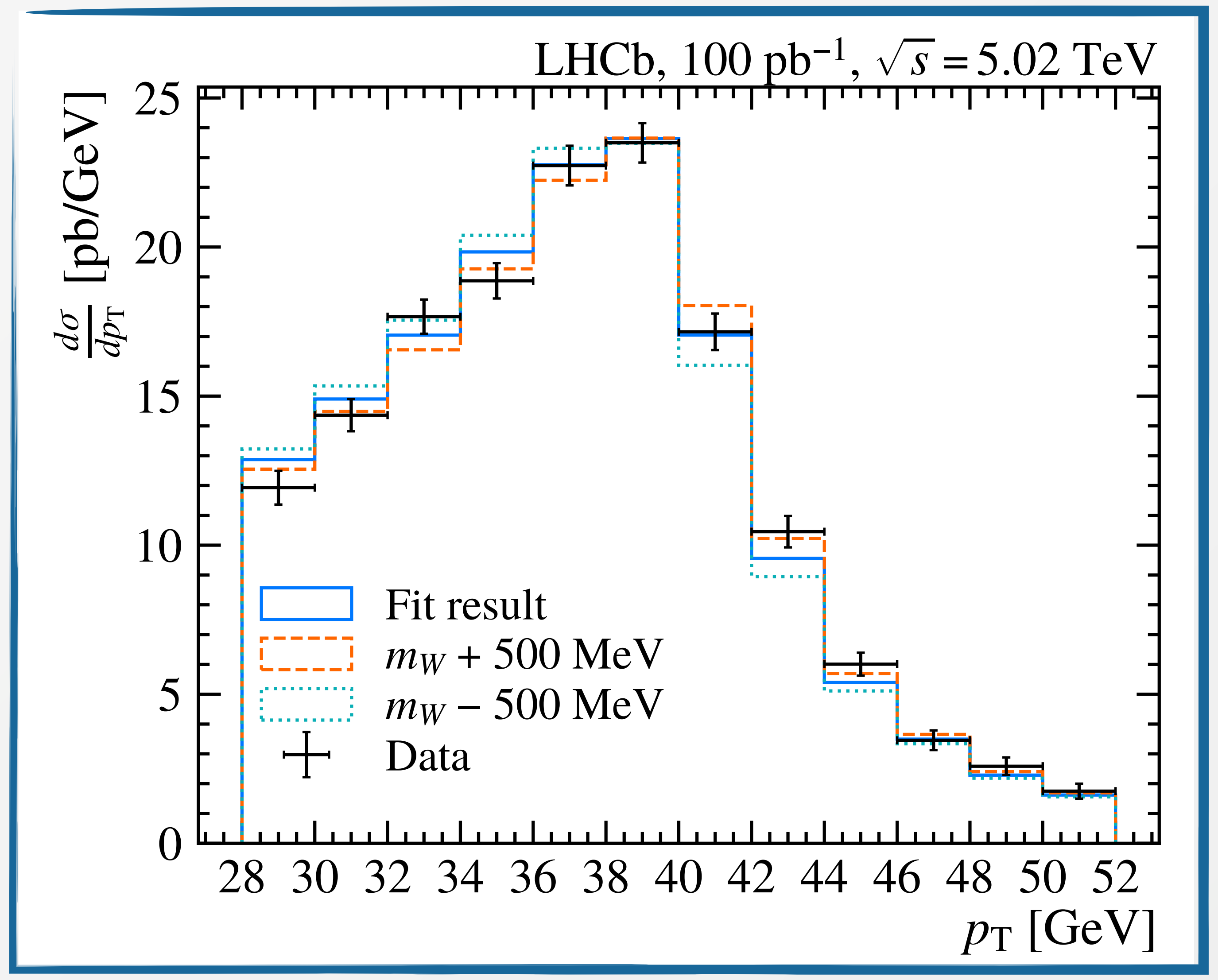

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[CMS '24]

Can we really forget the correlation between Z and W?

Is the *W* enough?

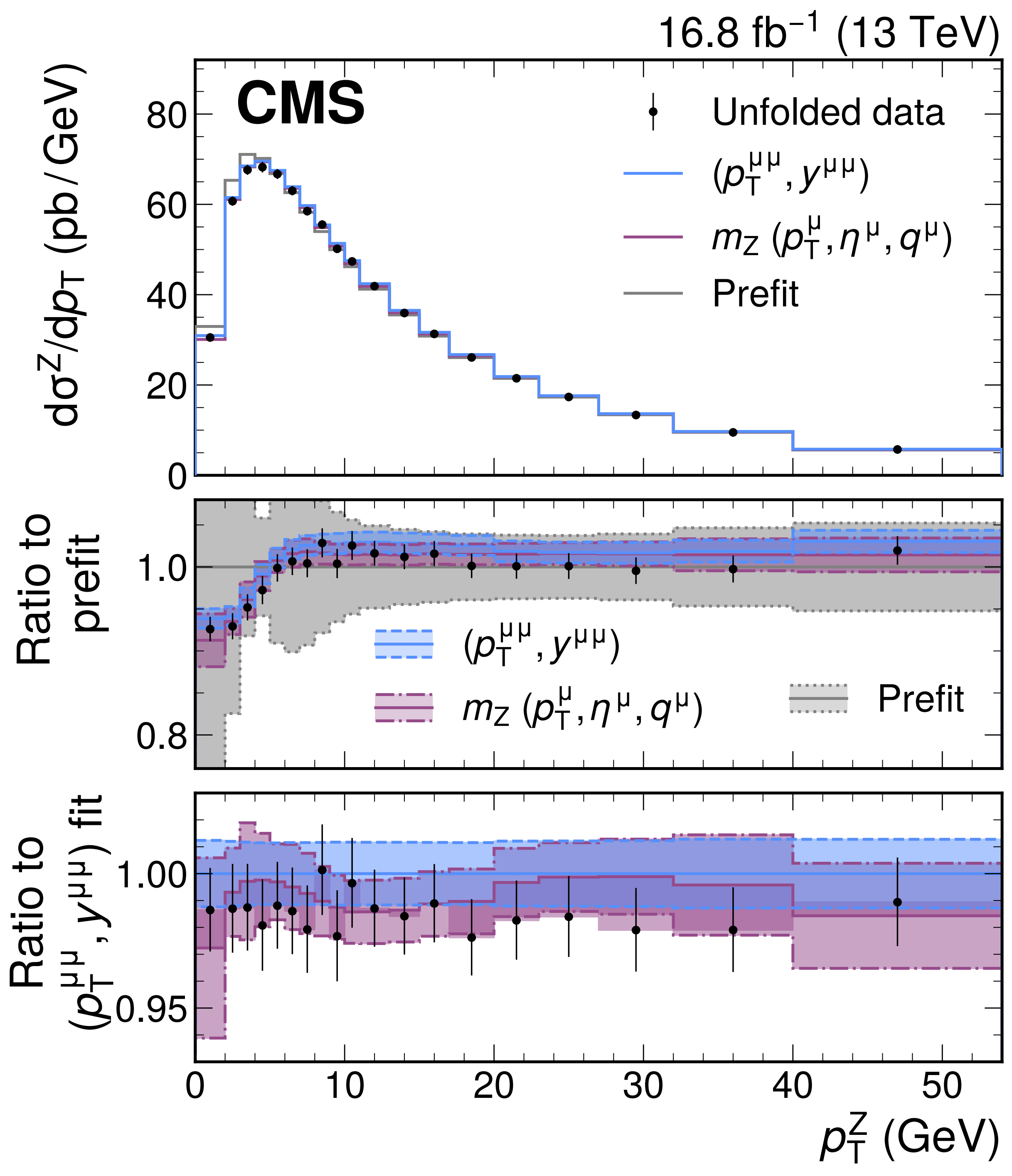
CMS model validated by performing W-like extraction of the Z mass, finding agreement with the SM value (n.b. muon calibration uses m_Z constraint from PDG)

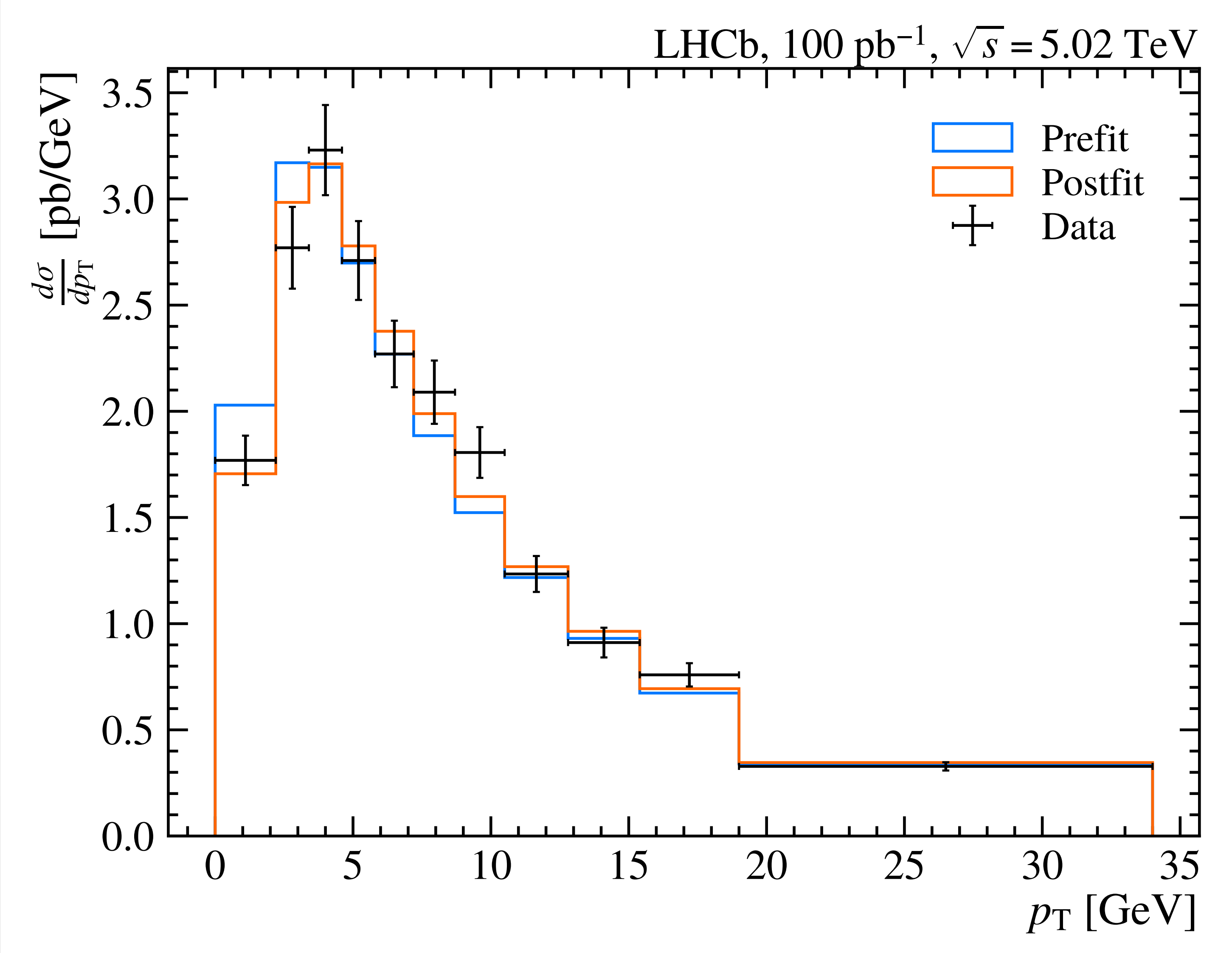
$$m_Z^{\text{W-like}} - m_Z^{\text{PDG}} = -6 \pm 7\,(\text{stat}) \pm 12\,(\text{syst}) = -6 \pm 14\,\text{MeV}$$

Validation fits for *Z* model predictions used in LHCb analysis too

Similarity between *Z* and *W* production mechanisms are at the basis of the validation of the the *W*-like m_Z analysis, where the predicted p_T^Z distribution can be directly compared with the measured $p_T^{\mu\mu}$ spectrum.

QCD model robustness relies on a likeness of charged and neutral-current processes, but **assessment of the exact correlation between the two is still lacking**





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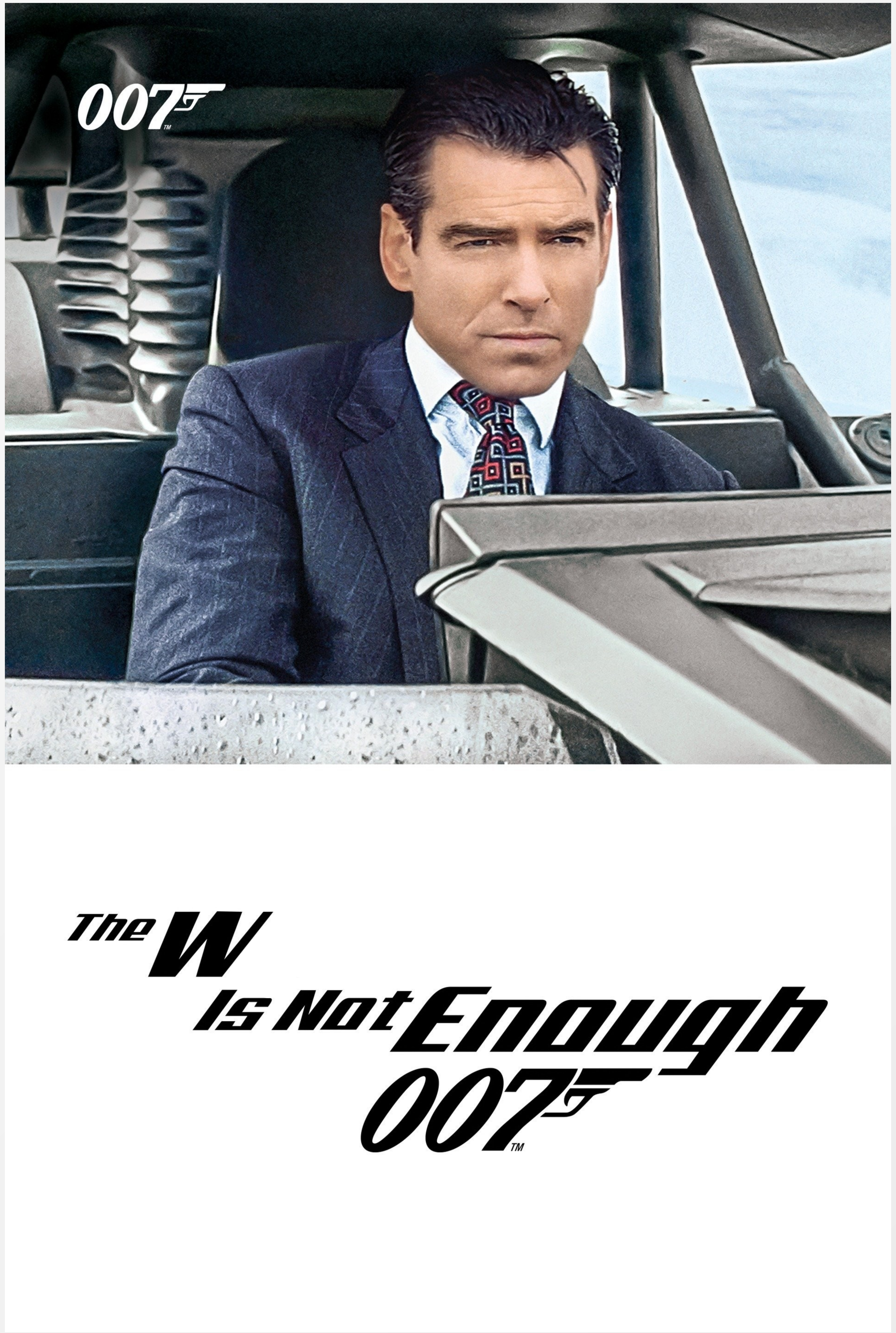
QCD model robustness relies on a likeness of charged and neutral-current processes, but **assessment of the exact correlation between the two is still lacking**

If we aim to measure m_W with per myriad precision, relation between *Z* and *W* production should be thoroughly investigated

(Especially if we don't understand data/theory discrepancy in p_T^W/p_T^Z!)

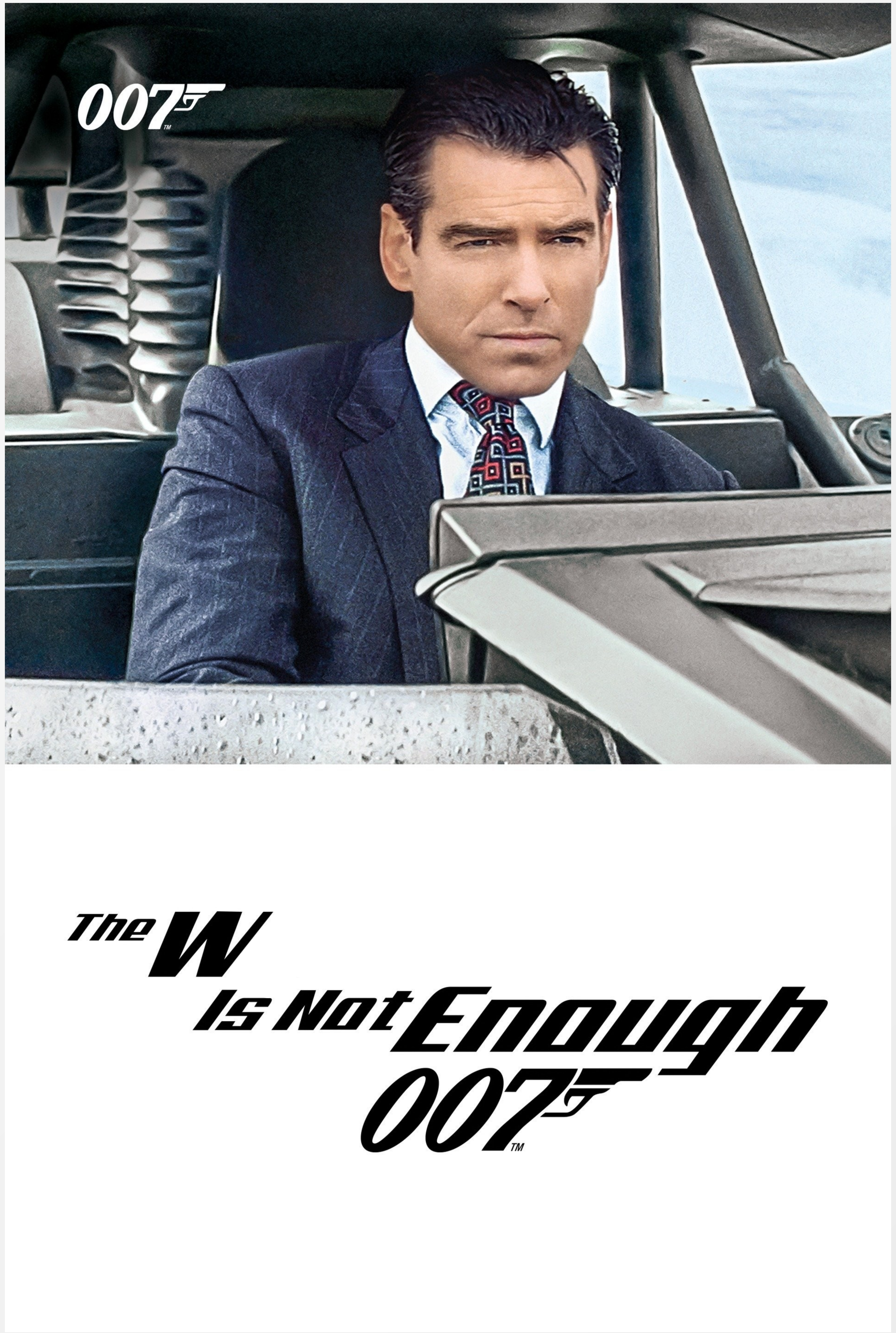


Is the *W* enough?

How?

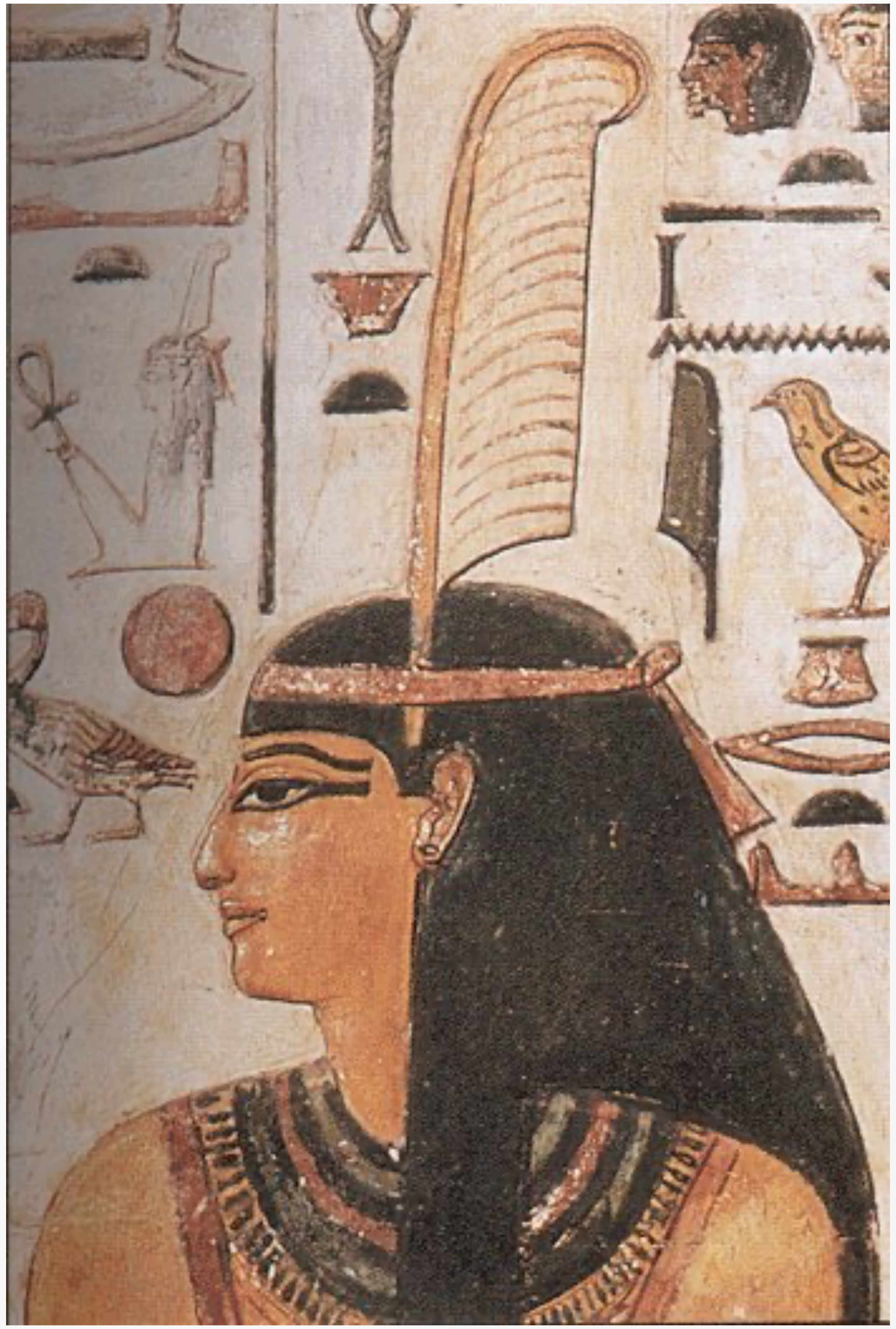
- Asses quantitatively similarities and differences between NC and DY production (EW correction pattern, heavy quarks, flavour-dependence, PDFs…)
- Inspect whether data/theory discrepancy in p_T^W/p_T^Z and $p_T^{W^+}/p_T^{W^-}$ is due to poor understanding of correlations (e.g. scale uncertainties vs TNP) or hints at more fundamental issues (flavour)
- Using profiling to constraint PDF and theory uncertainty is legitimate, but should be performed cautiously if p_T^W/p_T^Z is poorly described when assuming the validity of the **same underlying QCD model**
- Toy models and/or theoretically clean observables (e.g. Jacobian asymmetry) valuable

[LR, Torrielli, Vicini '23]



Summary

- Modelling of **theoretical uncertainties** crucial for EW precision programme at the LHC
- High-accuracy fixed order predictions, supplemented with resummation for observable sensitive to soft/collinear radiation, needed to treat the acute disease of precision which afflicts us
- Perturbative QCD predictions have reached a **remarkable level of accuracy**
- **Interplay with QED/mixed QCD/EW predictions mandatory** for a successful precision programme, alongside comprehension of NP physics, PDF uncertainty, including MHOU
- Correlation pattern in Z/W production should be understood when profiling is used to constrain uncertainties (especially if analyses uses similarity between NC and CC Drell-Yan as underlying assumption on the validity of the QCD modelling)
- Monte Carlo tunes for sub-percent precision must be handled with care. Availability of accurate perturbative calculation may provide insight on tuning parameters to avoid unphysical correlations



The aim of science is not to open a door to infinite wisdom, but to set a limit to infinite error

G. Galilei, The Life of Galileo, by B. Brecht