Progress on theoretical predictions for Drell-Yan production & prospectives for future precision measurements

Luca Buonocore

SM@LHC

Durham - April 7-10th 2025

Progress on theoretical predictions for Drell-Yan production & prospectives for future precision measurements

DISCLAIMER:
Loaded with personal bias and sprinkled with (hopefully) constructive criticism

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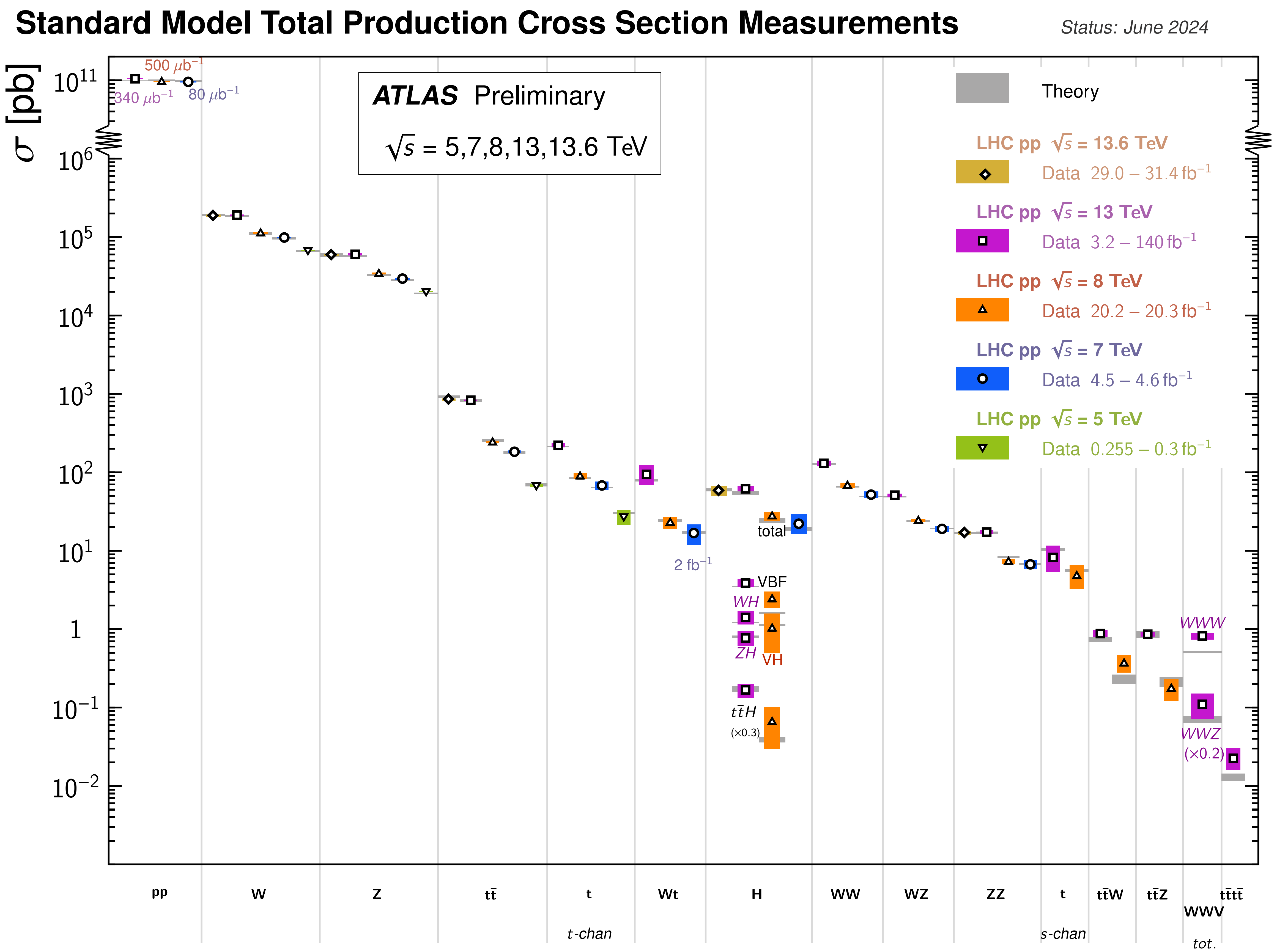
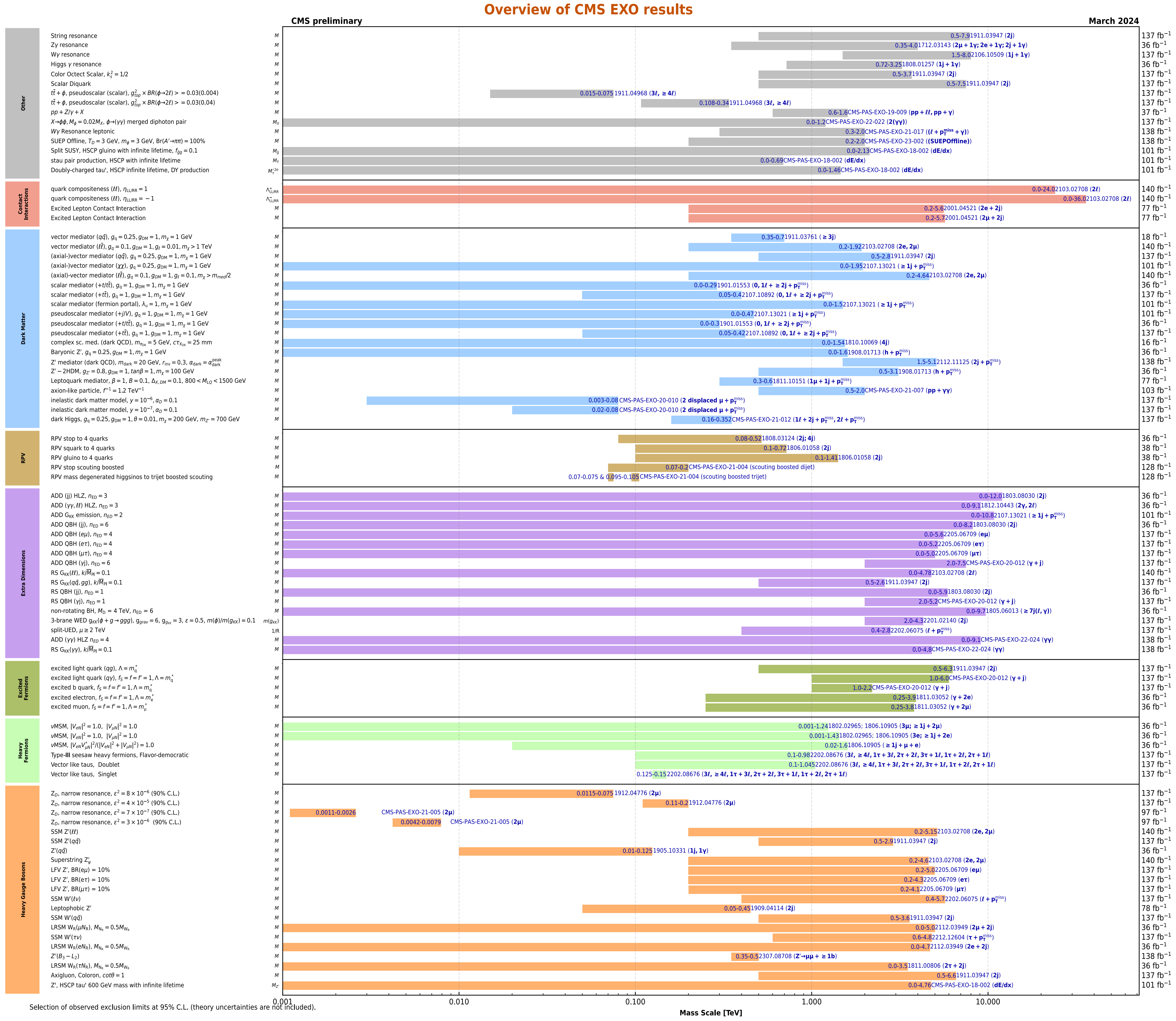
Where Do We Come From? What Are We? Where Are We Going?

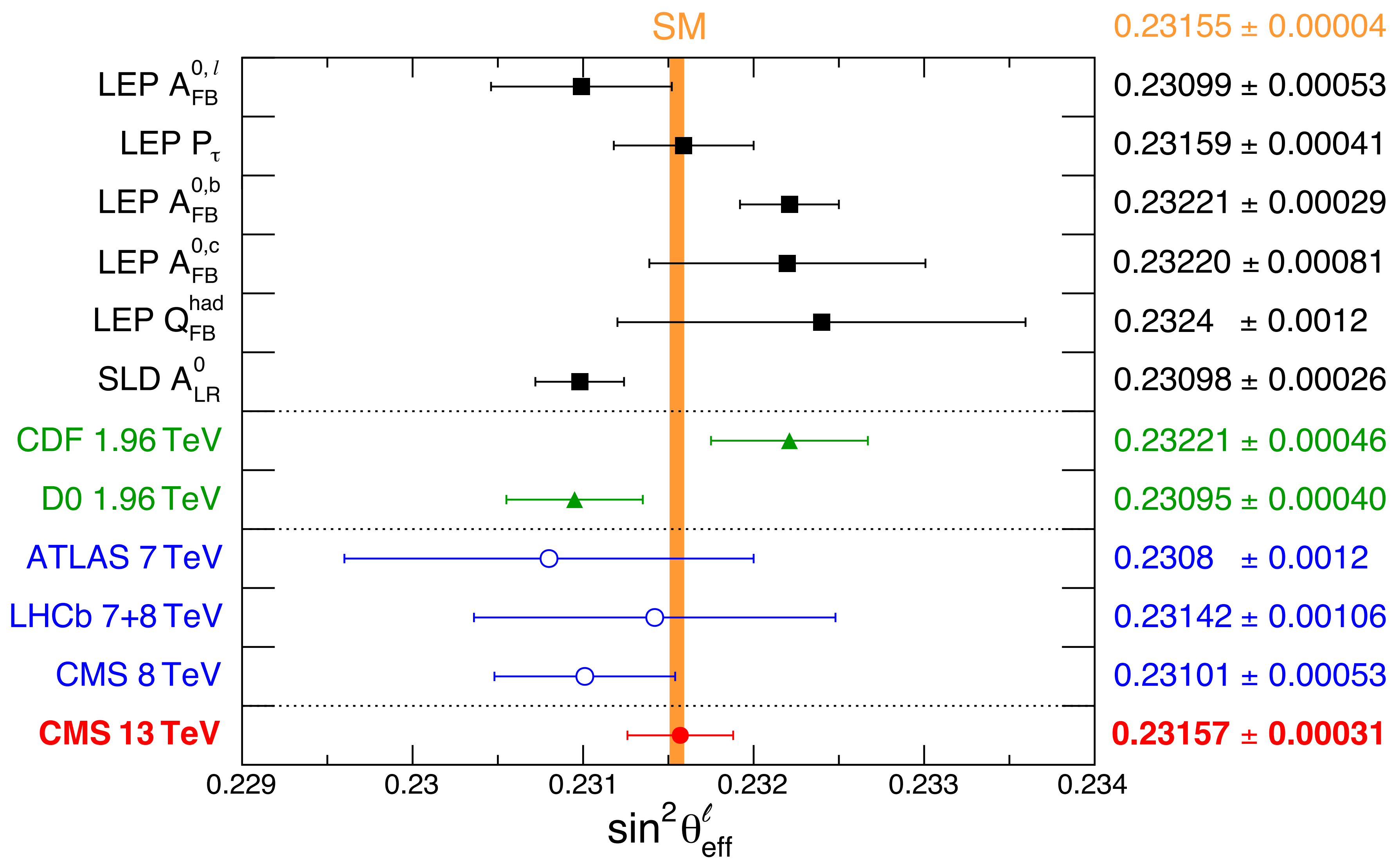
- Astonishing measurements of SM processes, agreement with (high-order) theory predictions
- Wealth program of searches at few TeVs





Where Do We Come From? What Are We? Where Are We Going?

The LHC is not only a discovery machine, it is a **precision machine**!



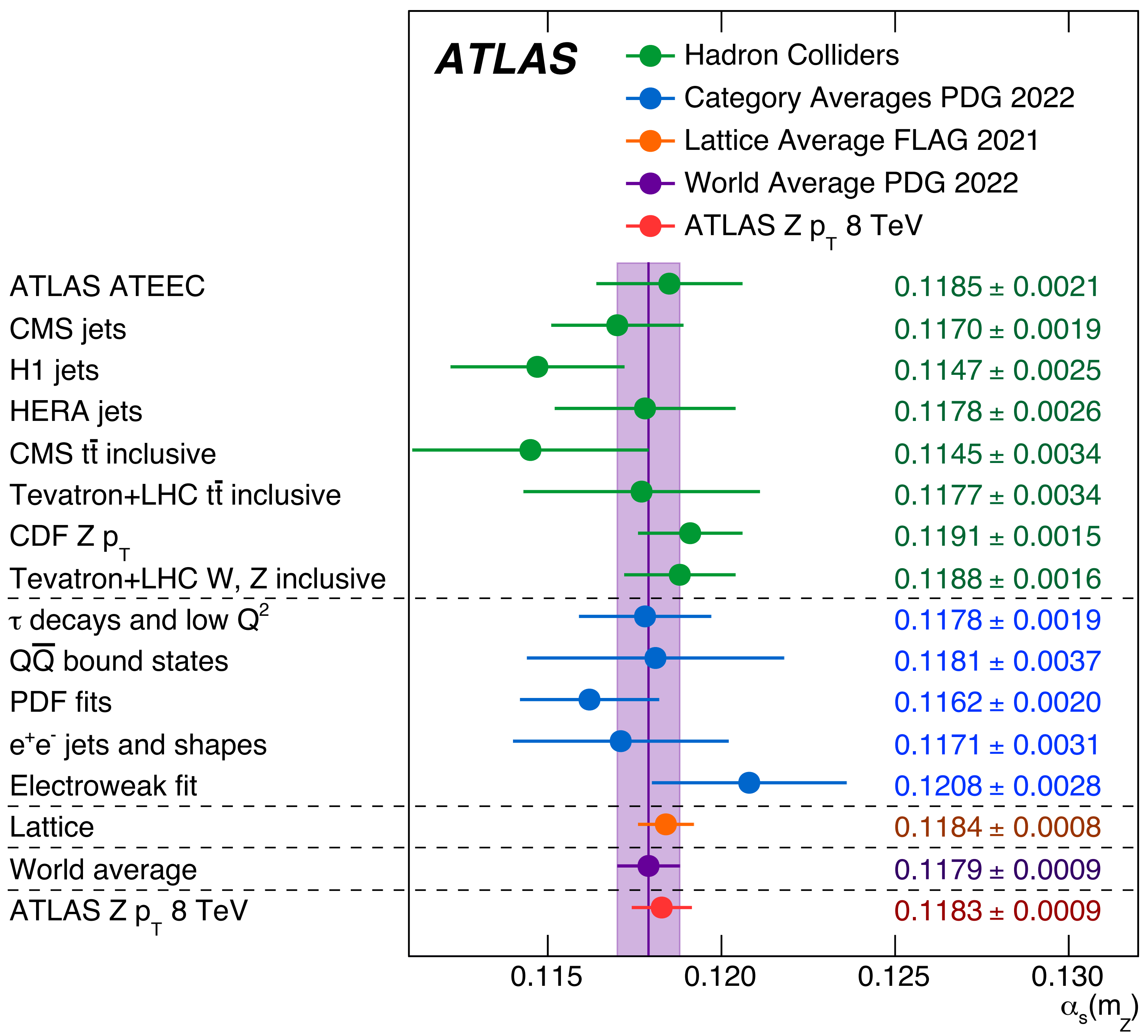
[CMS, 2408.07622]

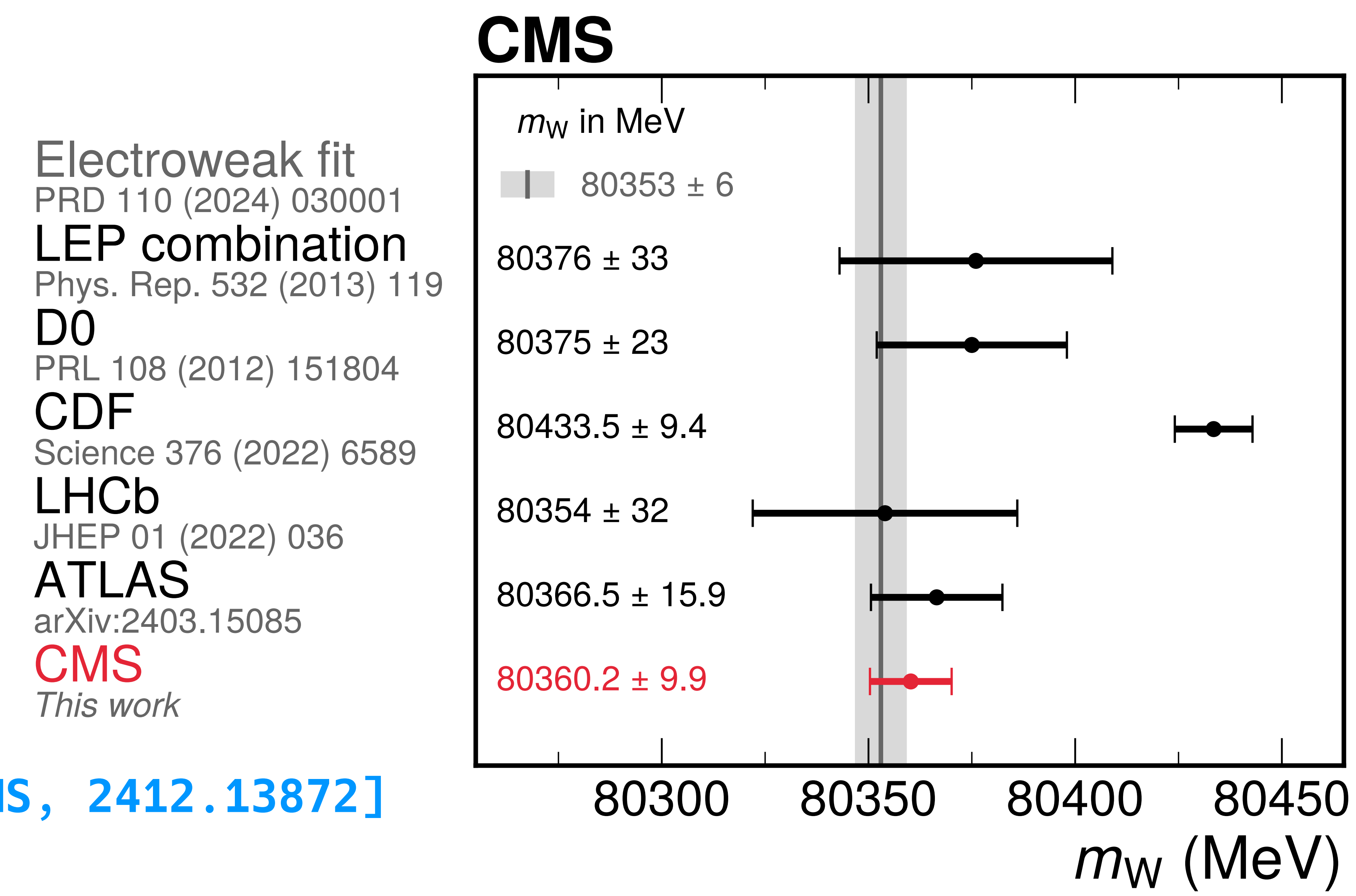
See talk by Abdelmotteleb

Among the most precise single measurements of fundamental Standard Model parameters

Results of more than a decade of experimental improvements and advancements

[ATLAS, 2309.12986]





See talk by Aime

[CMS, 2412.13872]

Special role of DY dilepton production for the LHC precision program

Where Do We Come From? What Are We? Where Are We Going?

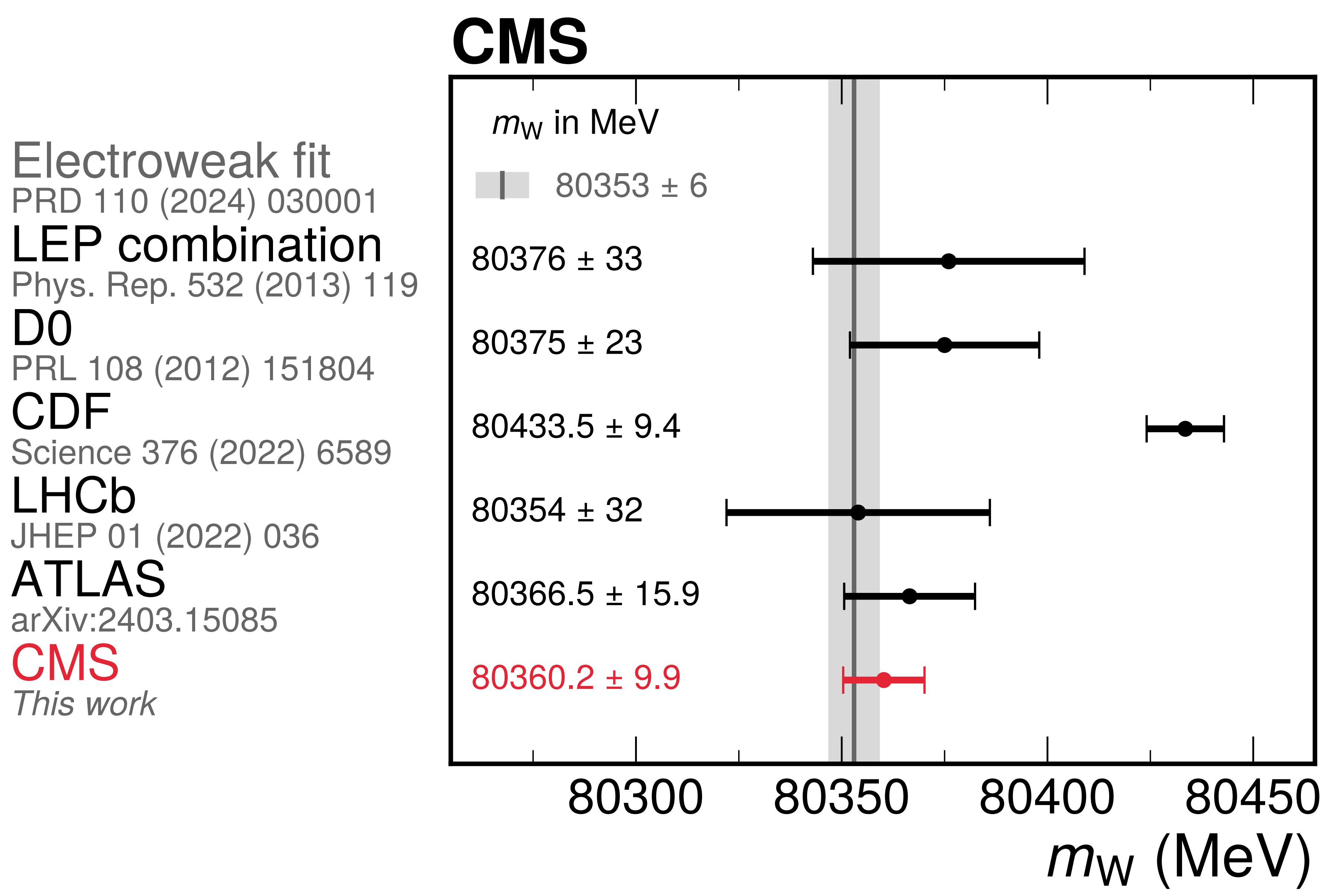
General remarks (very basic)

The determination of these fundamental SM parameters is **model-dependent**

→ **Input from SM theoretical predictions** is required, usually for template fits
(Already introduce some bias)

Concerning the measurement outcome, both the **central value and its uncertainty are very important** (IMHO, the uncertainty is even more important!)

→ **Not a race for the smallest uncertainty!**

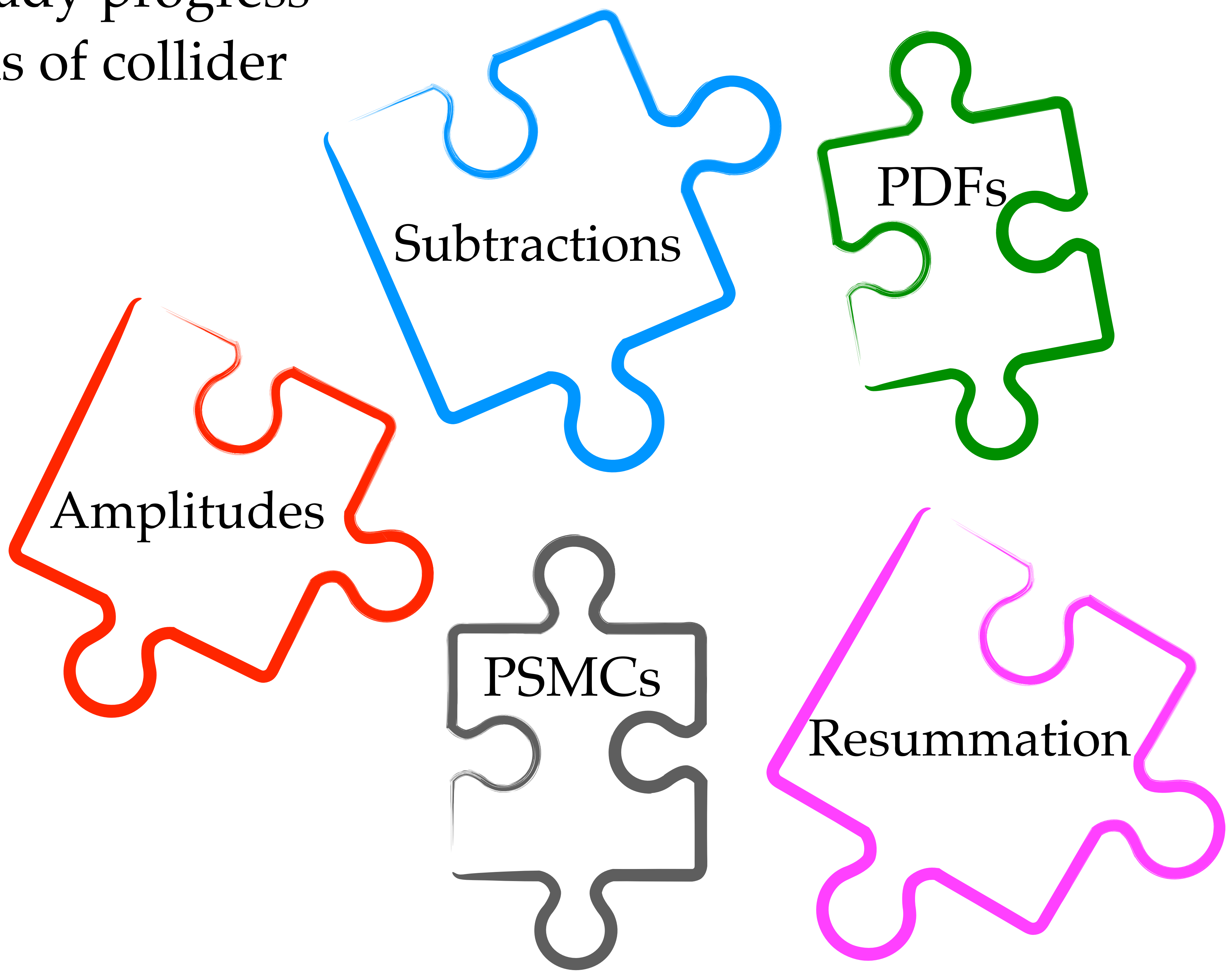


- A measurement remains "valid" unless challenged by strong scientific consensus
- Credibility of community
- **Stringent test of the Standard Model, Guide for serious model building, Constraints for parametric uncertainties**

→ **The outcome is what it is**: alignment with the Standard Model does not justify being less critical of uncertainties

Where Do We Come From? What Are We? Where Are We Going?

Tremendous and steady progress in theory calculations of collider observables



Uncertainties: embarrassing situation!

$$\Delta_{TH} \gg \Delta_{EXP}$$

Requires a robust understanding of the correlations!

TH uncertainty: the Conventional Approach

- **Missing higher orders (MHO)**: scale variation prescriptions, rough order of magnitude, no probability interpretation, no correlations
- **Matching/Merging/Shower/Hadronization/UE:** variation of algorithms, parameters, PSMC programs

MHO, OdiEtAmo:
Simple&neat, but many limitations

- Ad-hoc prescription. Is there a best central scale?
- Uncertainties can be underestimated
- **No probabilistic interpretation of the uncertainties**
- **No correlations**

New Approaches as "Theory Nuisance parameters" (also progress within the Bayesian Approach, A.Huss)

Use data to constrain theory uncertainty

Talks by Marinelli & Lim

Outline

DY status of theoretical: review of (some) recent progress/results

Some thoughts and considerations on current&future precision measurements

Conclusive discussion

Outline

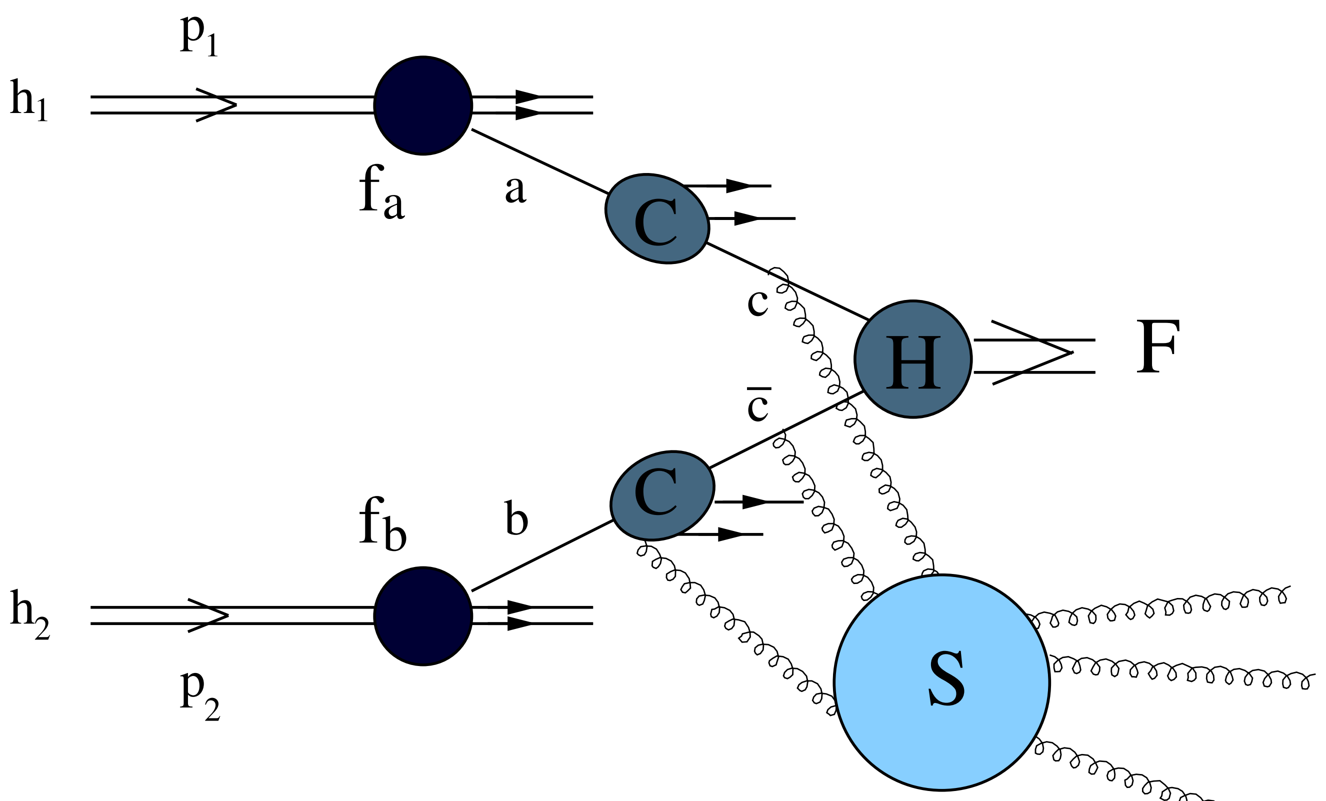
DY status of theoretical: review of (some) recent progress/results

Some thoughts and considerations on current&future precision measurements

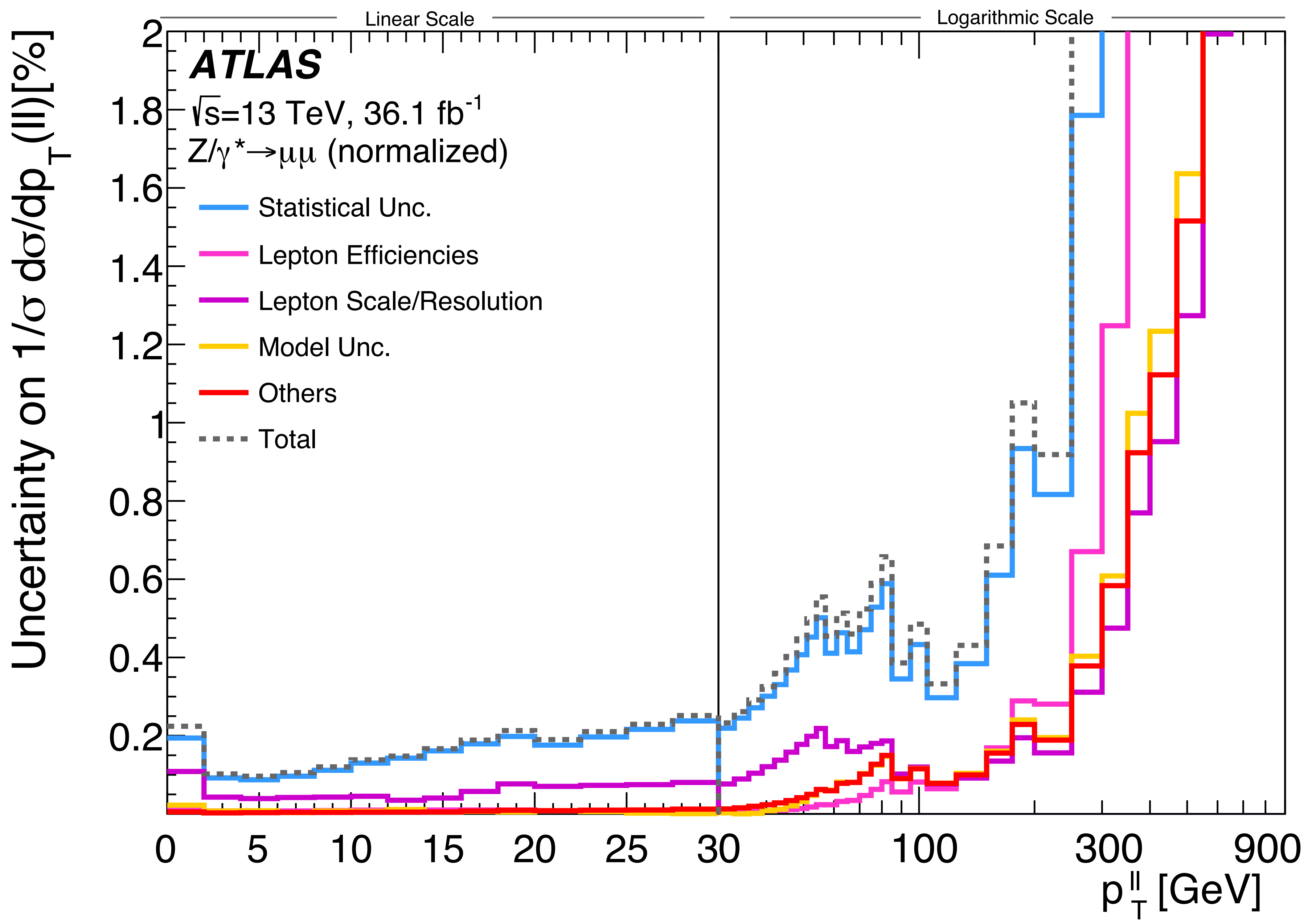
Conclusive discussion

DY th-status: Transverse momentum resummation

The transverse momentum of the lepton pair **is an instrumental distribution** for precise measurements



[Cute+MCFM: Becher, Campbell, Neumann, et al.; RadISH:Monni, Re, Rottoli, Torrielli; NangaParbat: Bacchetta, Bertone, Bozzi, et al.; Artemide: Scimemi, Vladimirov; DYTurbo: Catani,Grazzini, Ferrera, Cieri, Camarda, et al.; SCETlib: Billis, Ebert,Michel, Tackmann, et al.; reSolve: Coradeschi, Cridge;Resbos: Isaacson, Yuan, et al.; …]



At small transverse momentum $q_T \ll M$, breakdown of fixed-order perturbation theory

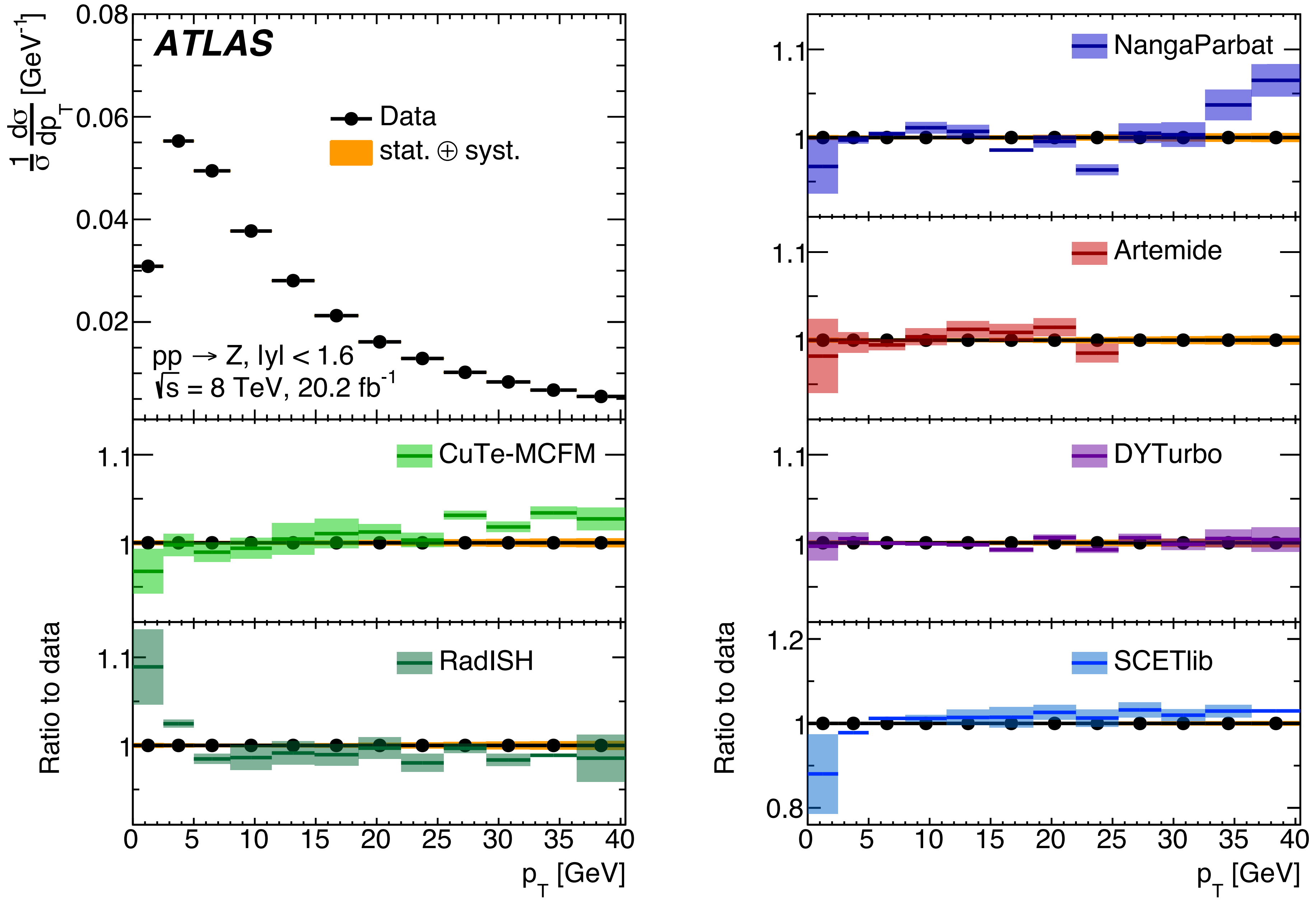
- Large soft/collinear logarithms $\ln q_T/M$ must be **resummed to all orders**
- **Very advanced status**: variety of frameworks (b-space/momentum-space, QCD/SCET, TMD) and high-logarithmic accuracy N^{3}LL′ ($\alpha_S^n \ln^{n-2} q_T/M$ and $\alpha_S^n \ln^{2n-6} q_T/M$). N^{4}LL partially available

Experimental uncertainties: few per mille on the normalised distributions!

DY th-status: Transverse momentum resummation

The transverse momentum of the lepton pair **is an instrumental distribution** for precise measurements

[ATLAS, 2309.12986]

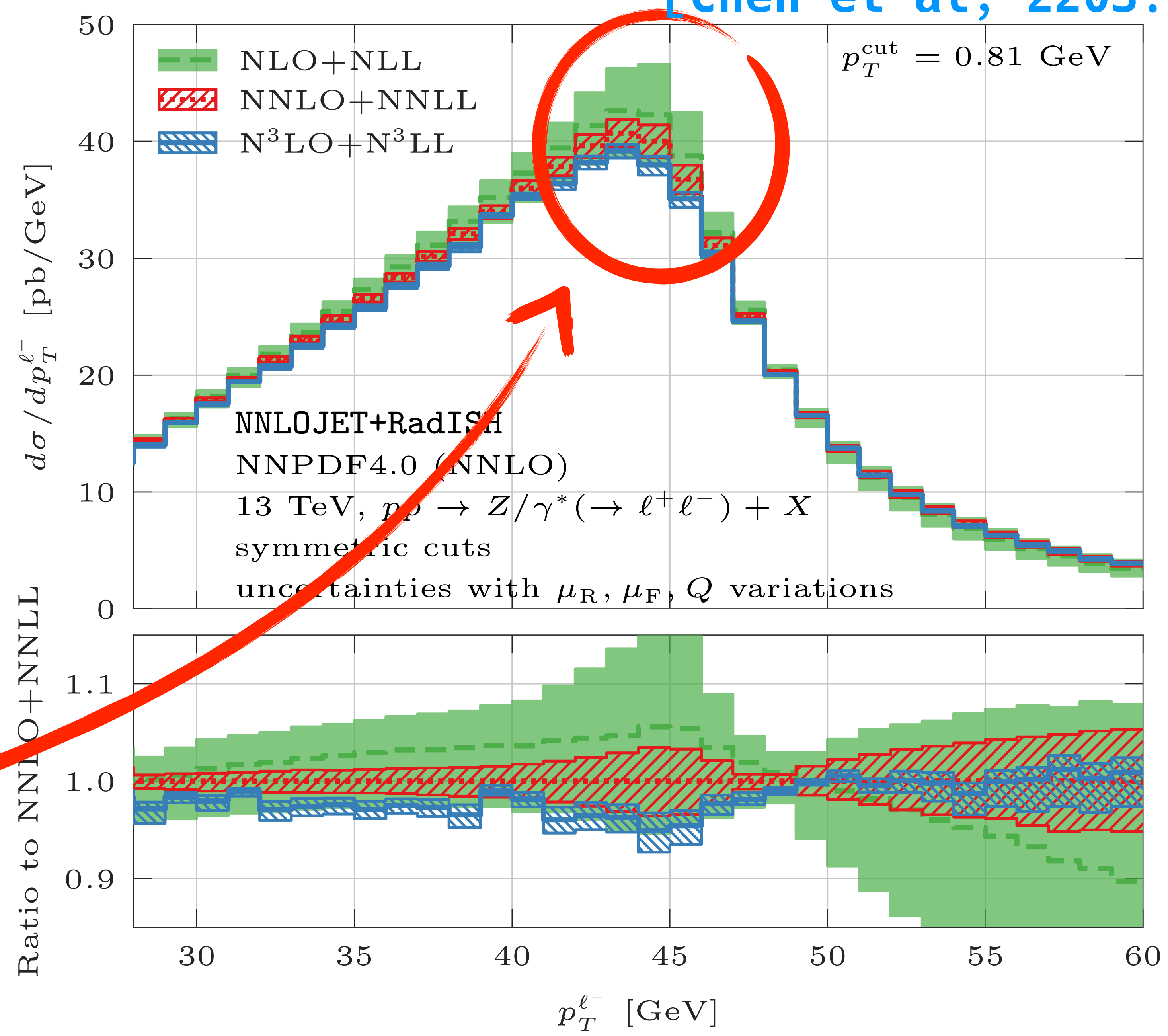


N³LL′/aN⁴LL (plus fixed order matching at $\mathcal{O}(\alpha_S^3)$)

- remarkable agreement with data and **few-% QCD residual uncertainty** in the resummation region (scale variations)
- **Non-Perturbative physics** required for describing $q_T < 5\,\text{GeV}$

Community success!

[Chen et al, 2203.01565]



Lepton transverse momentum: q_T-resummation restores the validity of perturbation theory at the Jacobian peak $p_T^\ell \sim m_V/2$

- **No sensible fixed-order** descrition [Catani,Webber,9710333]
- Requires resummation of **(kinematics) linear power correction** [Catani et al 1507.06937][Ebert et al 2006.11382]

DY th-status: Fixed-Order Predictions

$$\sigma = \int dx_1 dx_2 f_{a/h_1}(x_1, \mu_F) f_{b/h_2}(x_2, \mu_F) \hat{\sigma}_{ab}(\hat{s}, \mu_R, \mu_F) + \mathcal{O}(\Lambda/Q)$$

$$\begin{aligned}\hat{\sigma}_{ab} = \hat{\sigma}^{(0,0)}_{ab} + \hat{\sigma}^{(1,0)}_{ab} + \hat{\sigma}^{(2,0)}_{ab} + \hat{\sigma}^{(3,0)}_{ab} + \dots \\ + \hat{\sigma}^{(0,1)}_{ab} + \dots \\ + \hat{\sigma}^{(1,1)}_{ab} + \dots\end{aligned}$$

☑ QCD corrections <u>dominant effects</u>

- **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, Rottoli, Torrielli (2022)] [Chen, Gehrmann, Glover, Huss, Yang, and Zhu (2022)], [Neumann, Campbell (2022) and (2023)] [Billis, Michel, Tackmann (2024)]

☑ **NLO EW** corrections

- known since long
  [S. Dittmaier and M. Kramer (2002)], [Baur,Wackeroth (2004)], [Baur, Brein, Hollik, Schappacher, Wackeroth (2002)],
- nowadays **automatised** in different available generators
  [Les Houches 2017, 1803.07977]

DY th-status: Fixed-Order Predictions - NNLO QCD

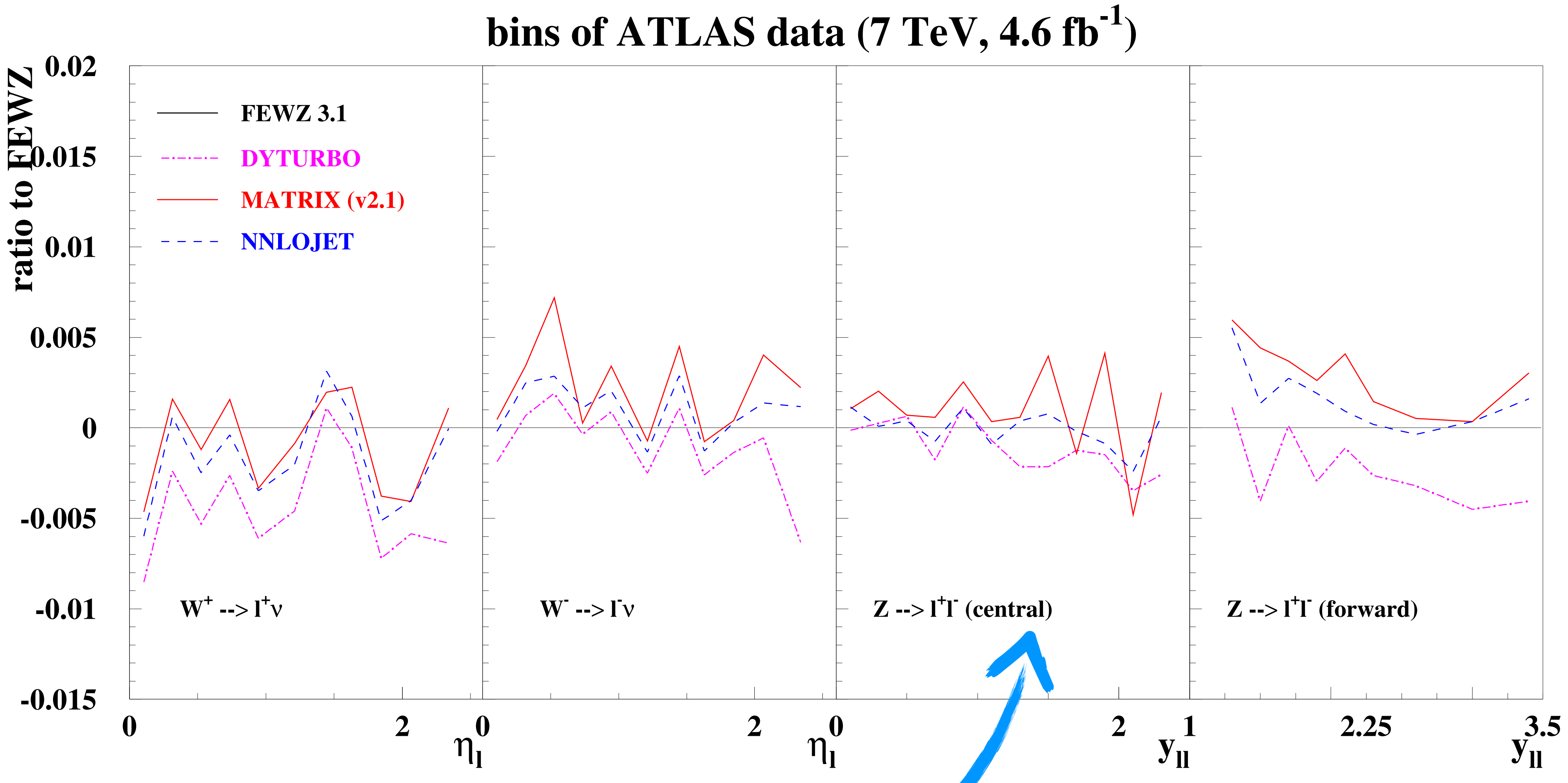
Availability and reliability of state-of-art predictions is a crucial aspect

Public and reliable codes & Benchmarking

- Codes based on local subtraction
  FEWZ, NNLOJET (**since last week**)
- Codes based on slicing:
  DY-TURBO, MATRIX, MCFM

(+ NNLO+PS implementations, e.g. MiNNLOPS, GENEVA, but not "pure" fixed-order accuracy)

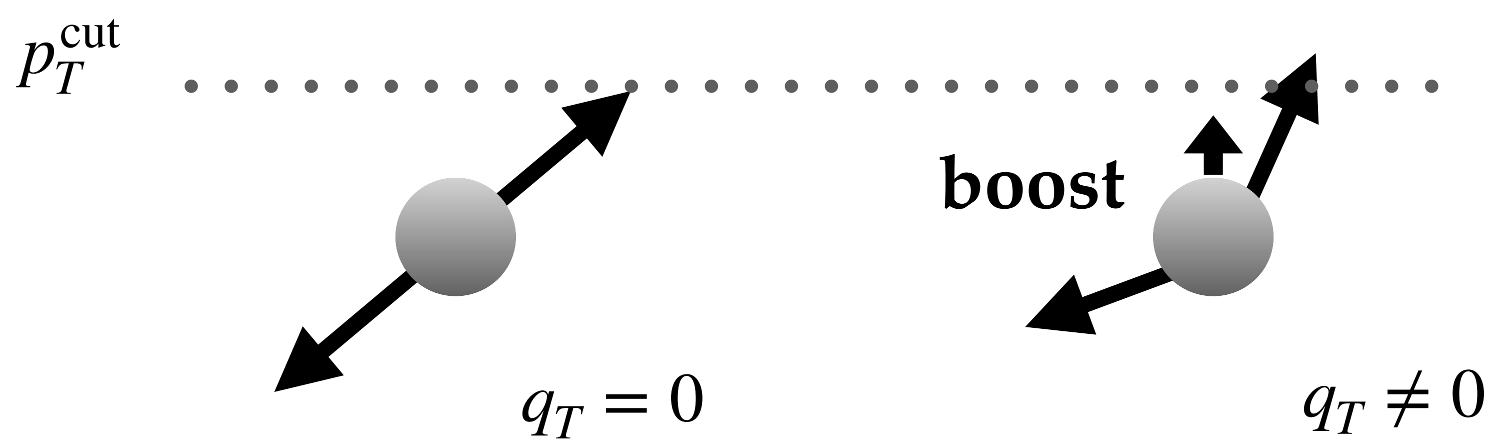
[Alekhin,Amoroso,LB et al 2405.19714]



(A)Symmetric cuts on (hardest/softest) leptons challenges slicing approaches. Solutions

- **Transverse momentum recoil** for q_T-slicing
  [LB et al 2111.13661][Camarda et al 2111.14509]
- Project to Born for jettiness-slicing
  [Vita 2401.03017][Campbell et al 2408.05265]

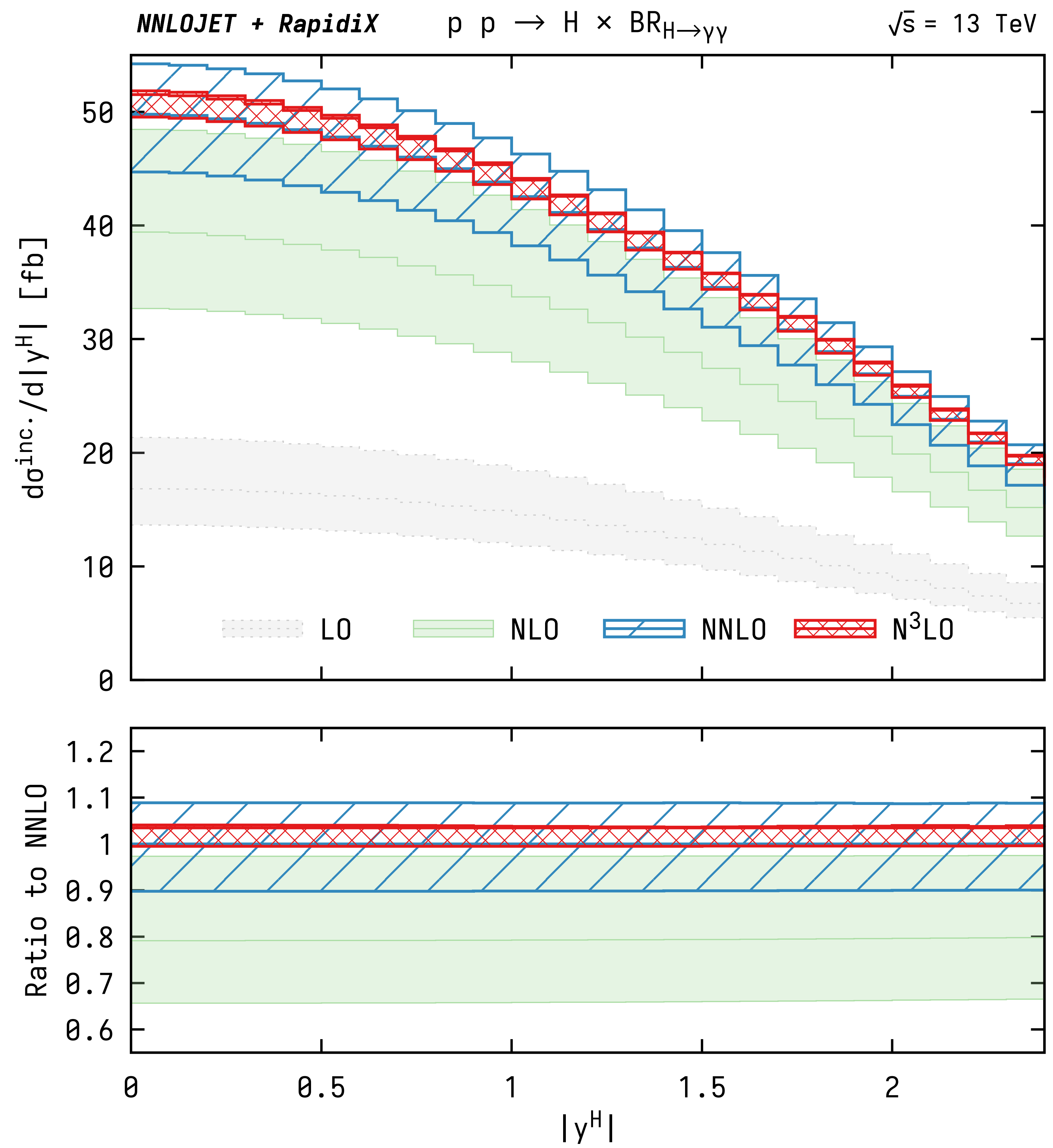
Excellent agreement among available public codes when improved-slicing is used

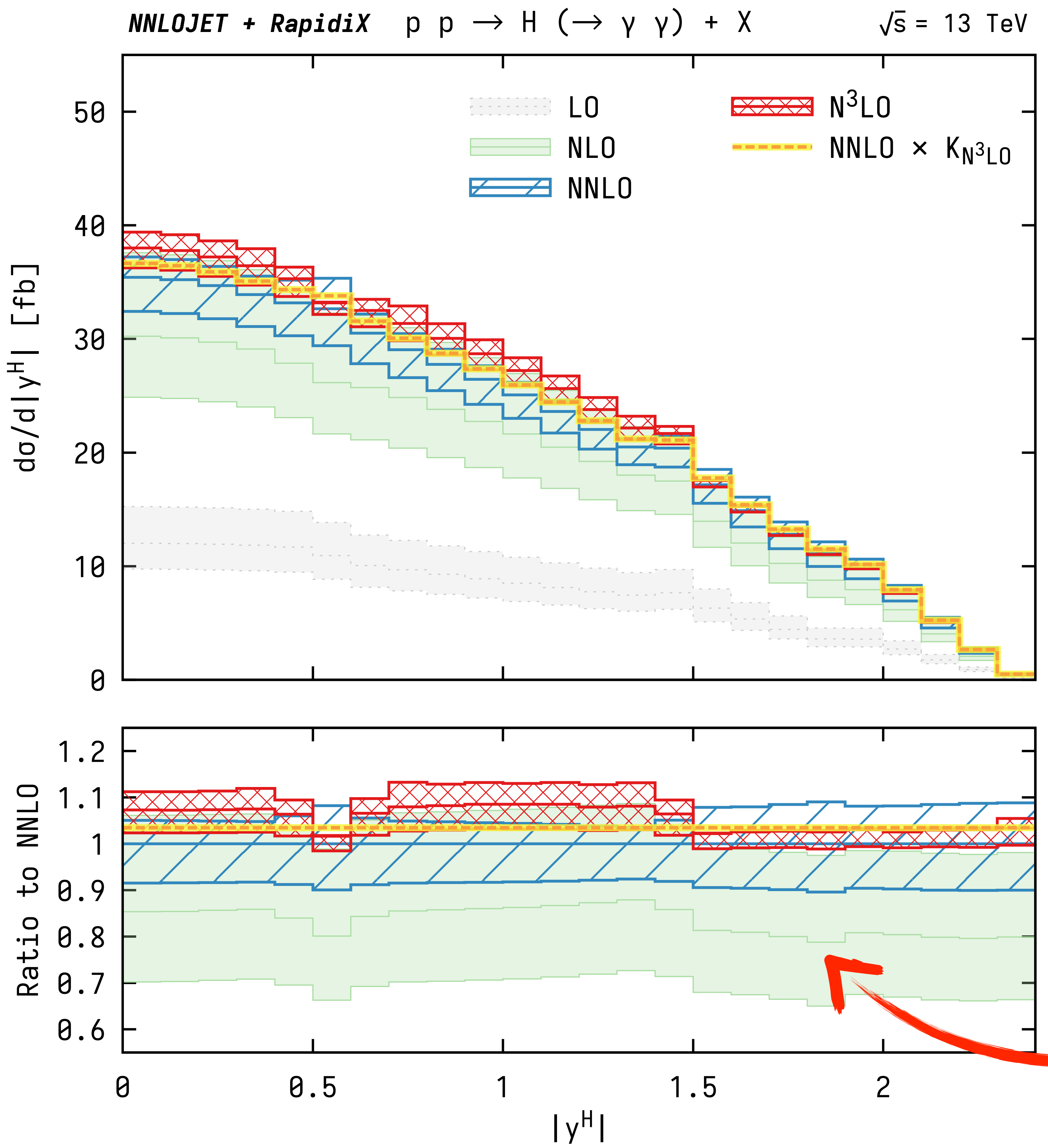


DY th-status: Fixed-Order Predictions - NNLO QCD

(A)Symmetric cuts: old [Frixione,Ridolfi,9707345] and more profound problem [Salam,Slade,2106.08329]!

- **Linear sensitivity** of the acceptance at small q_T $\Longrightarrow$ **factorial growth of perturbative expansion**
- Perturbation theory rescued by **resummation of kinematic linear power corrections**
- Alternatively, design of "better" fiducial cuts with quadratic (or better) scaling of the acceptance [Salam,Slade,2106.08329]





Delay the insurgence of the problem extending the domain of fixed-order perturbation theory (used, for example, in PDF fits)

In $H \to \gamma\gamma$, visible artifacts in the rapidity distribution compared to inclusive case

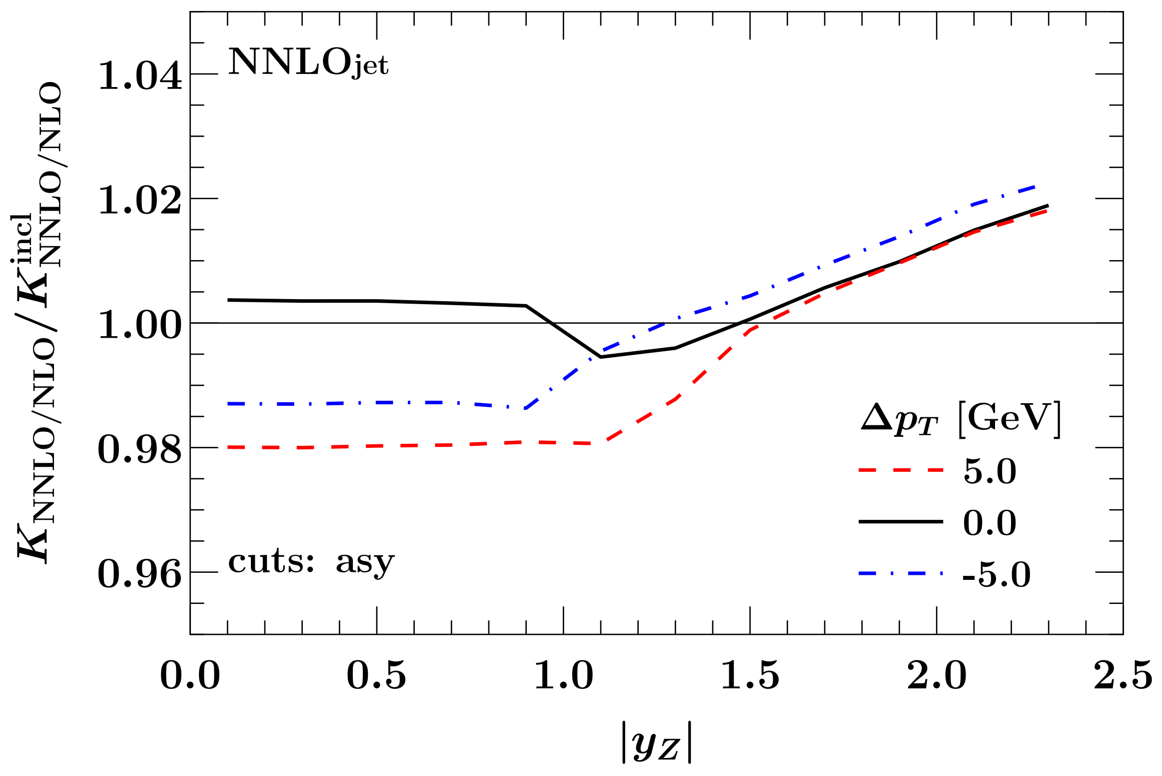
DY th-status: Fixed-Order Predictions - NNLO QCD

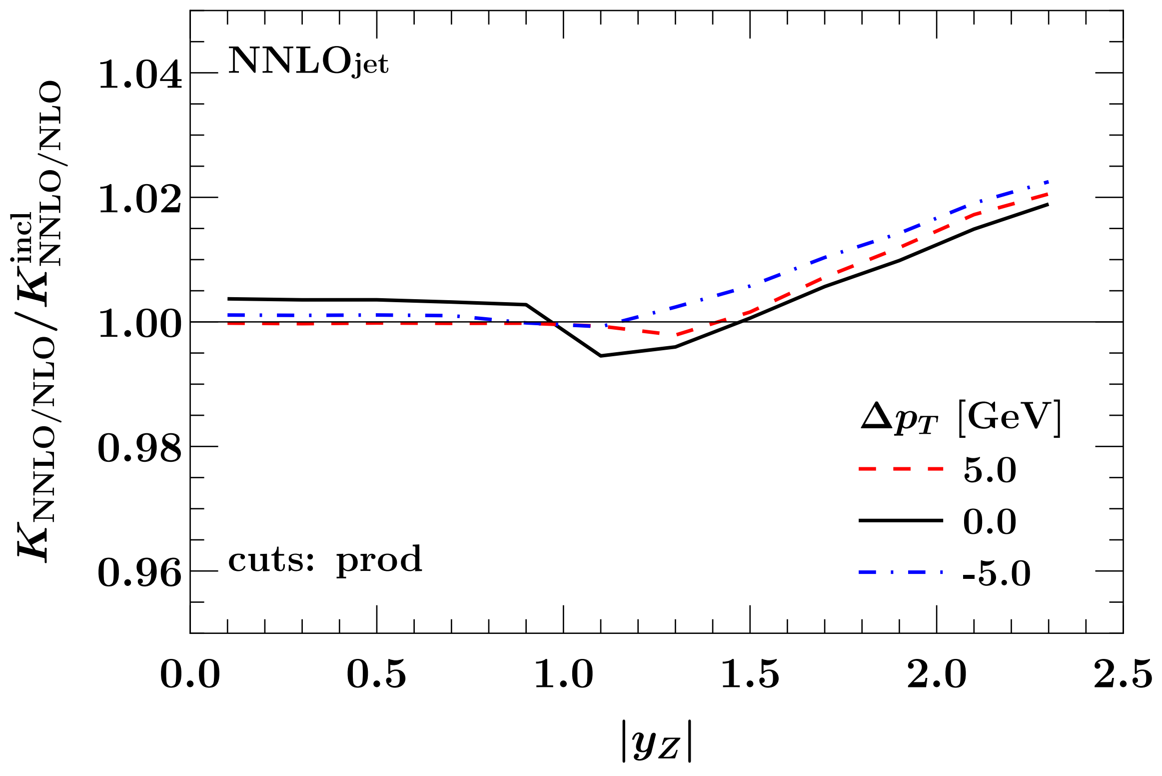
(A)Symmetric cuts: impact on DY rapidity distribution [Alekhin,Amoroso,LB et al 2405.19714]

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

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

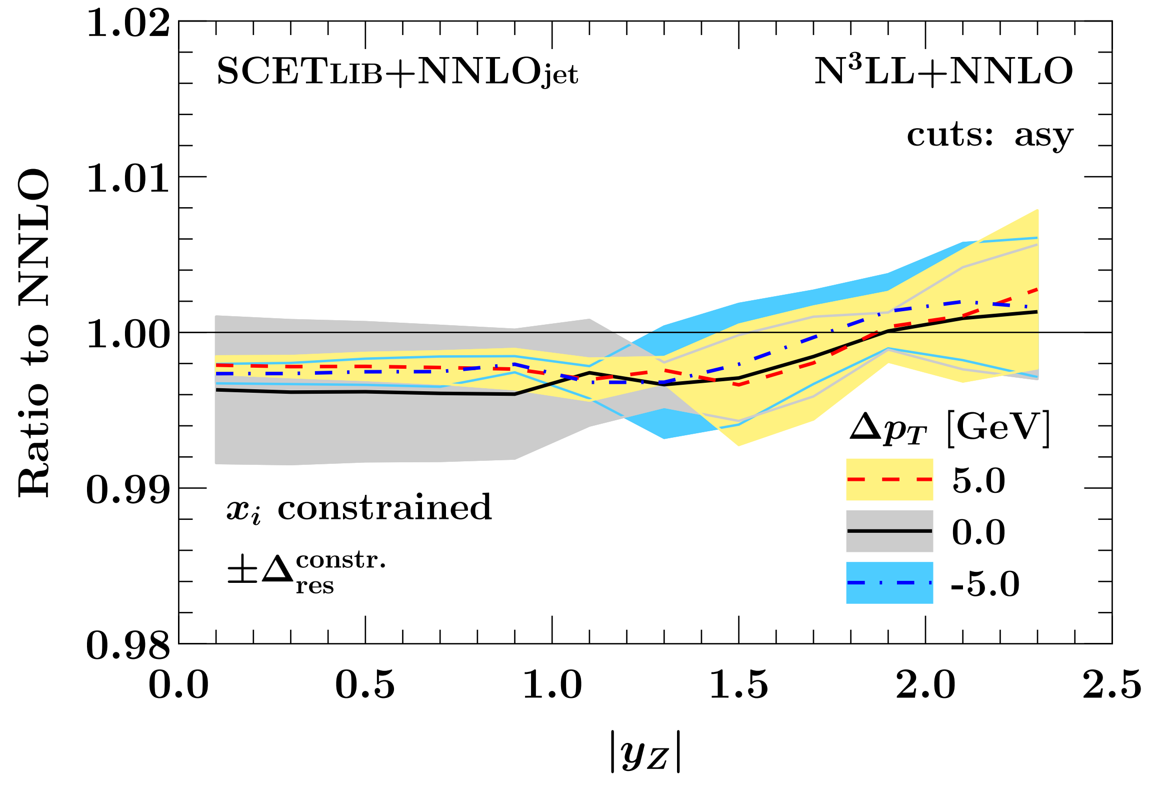
Prod: $\begin{cases} \sqrt{p_T^{\ell_1} p_T^{\ell_2}} > p_T^{\rm cut} + \Delta \\ p_T^{\ell_2} > p_T^{\rm cut} \end{cases}$

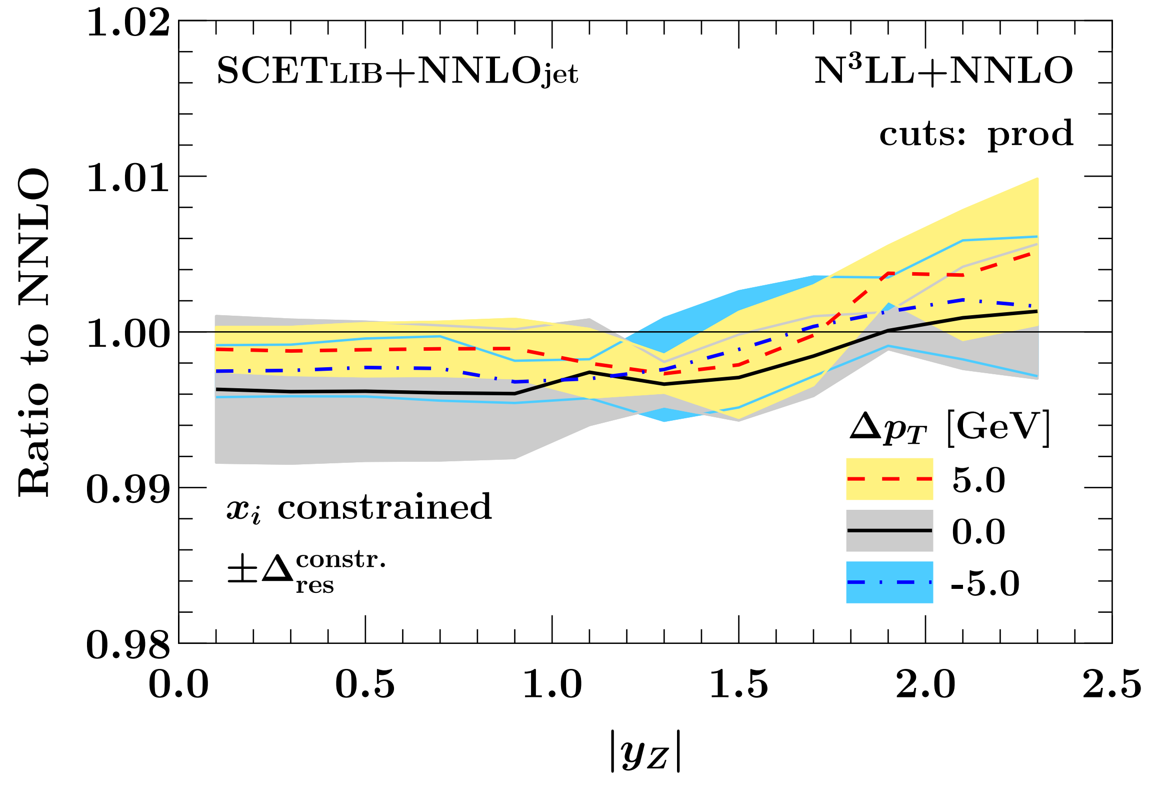




Fixed-order analysis

- Double ratio of NNLO/ NLO K-factors fiducial/ inclusive cuts
- As expected, better and smoother behavior of product cuts
- Smaller effects with respect to the Higgs case (as expected from Casimir scaling)





[see also Amoroso et al 2209.13535]

Resummation analysis

- Resummation of linear power corrections at N3LL′ with SCETLib (checked with RADiSH)
- Ratio to NNLO predictions
- Effects below 0.5%

- @NNLO: minor impact of (a)symmetric cuts when compared to current theory/exp uncertainties
- But putting it on a future perspective, it may lead to issues with LEGACY data!

DY th-status: Fixed-Order Predictions - N³LO QCD

So far, a **slicing approach is the only viable option** to perform differential N³LO calculations for DY production.
All available predictions are based only q_T-slicing

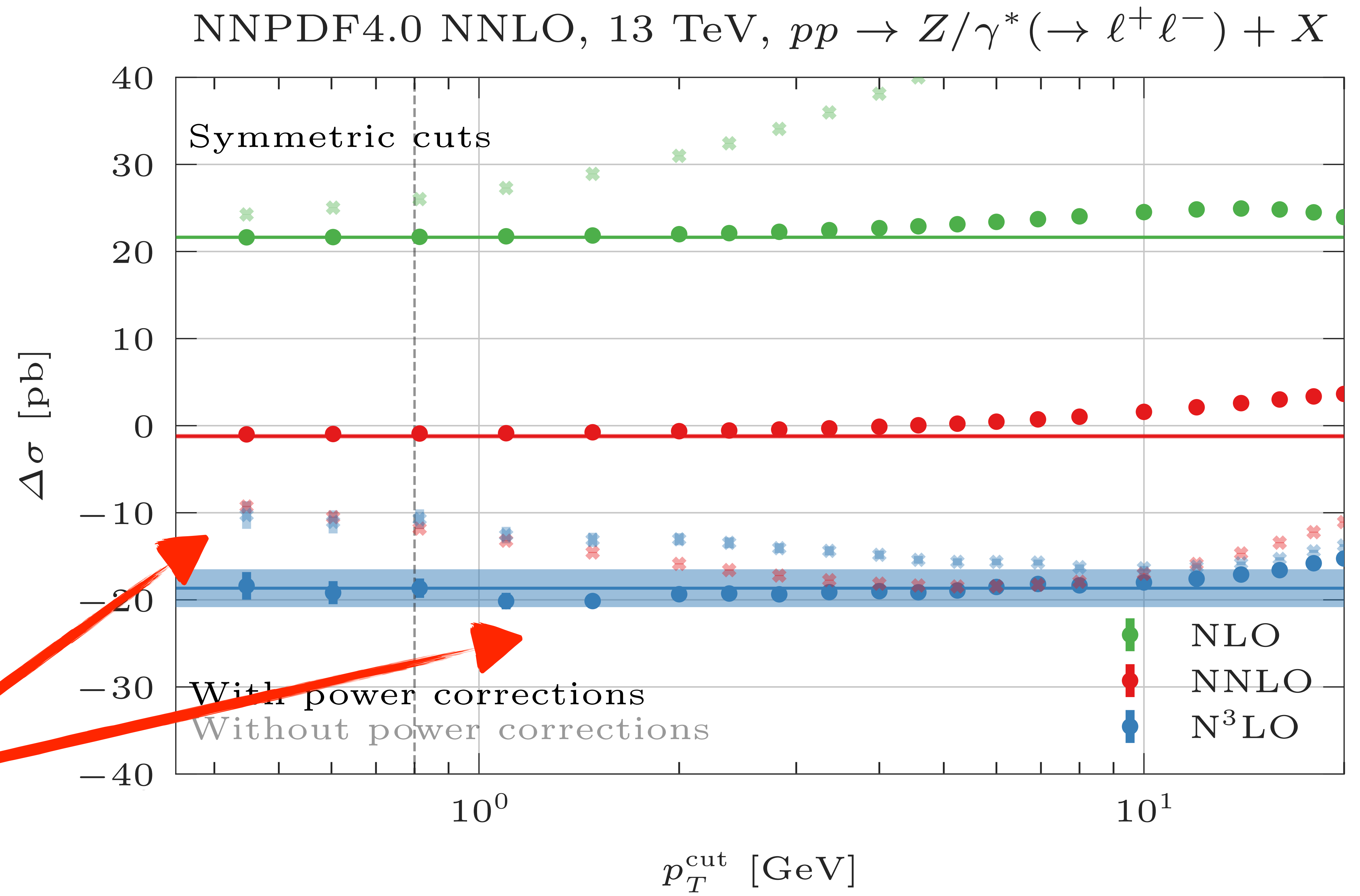
Requires a very stable and reliable implementation of $V+1j$@ NNLO in the deep infrared region

Necessary q_T-slicing ingredients efficiently computable
time load: $\mathcal{O}(\lesssim 1\%)$

Calculation of $Z+1j$ @ NNLO
(ANTENNA subtraction as implemented in the NNLOJET)
time load: $\mathcal{O}(99\%)$

Knowledge of linear power corrections **crucial for this application**

[Chen,Gehrmann,Glover,Huss,Monni,Re,Rottoli,Torrielli,2023]



Running time: $\mathcal{O}(5M)$ CPU hours for single differential distributions

- As of now, two public implementations of V+1jet@NNLO: MCFM (1-jettiness subtraction) [Neumann,Campbell,2207.07056] and NNLOJet (Antenna Subtraction) [Huss et al,2503.22804]
- However, the situation is still far from maturity: the calculation remain delicate and time-consuming (Is there a better way?)

DY th-status: Fixed-Order Predictions - Mixed QCD-EW

$$\sigma = \int dx_1 dx_2 f_{a/h_1}(x_1, \mu_F) f_{b/h_2}(x_2, \mu_F) \hat{\sigma}_{ab}(\hat{s}, \mu_R, \mu_F) + \mathcal{O}(\Lambda/Q)$$

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

Theoretical developments

- renormalization
  [Dittmaier, Schmidt, Schwarz (2020)]
- 2-loop amplitudes for $2 \to 2$ neutral current DY for massless leptons
  [Heller, von Manteuffel, Schabinger, Spiesberger (2020)]
- 2-loop amplitudes for $2 \to 2$ neutral current DY (retaining logarithms of the lepton mass)
  [Armadillo, Bonciani, Devoto, Rana, Vicini (2022)]
- 2-loop amplitudes for $2 \to 2$ charged current DY (retaining logarithms of the lepton mass)
  [Armadillo, Bonciani, Devoto, Rana, Vicini (2024)]

On-shell Z/W production ($2 \to 1$ process)

- mixed QCD–QED corrections to inclusive on- shell Z production
  [De Florian, Der, Fabre (2018)]
- mixed QCD–EW corrections to inclusive on- shell Z production
  [Bonciani, Buccioni, Rana, Vicini (2020)]
- fully differential NNLO QCD-EW to on-shell Z and W production [Delto, Jaquier, Melnikov, Röntsch (2019)] [F. Buccioni, F. Caola, M.Delto, M.Jaquier, K.Melnikov, R.Roentsch (2020)], [Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch (2020)]

Beyond on-shell computations

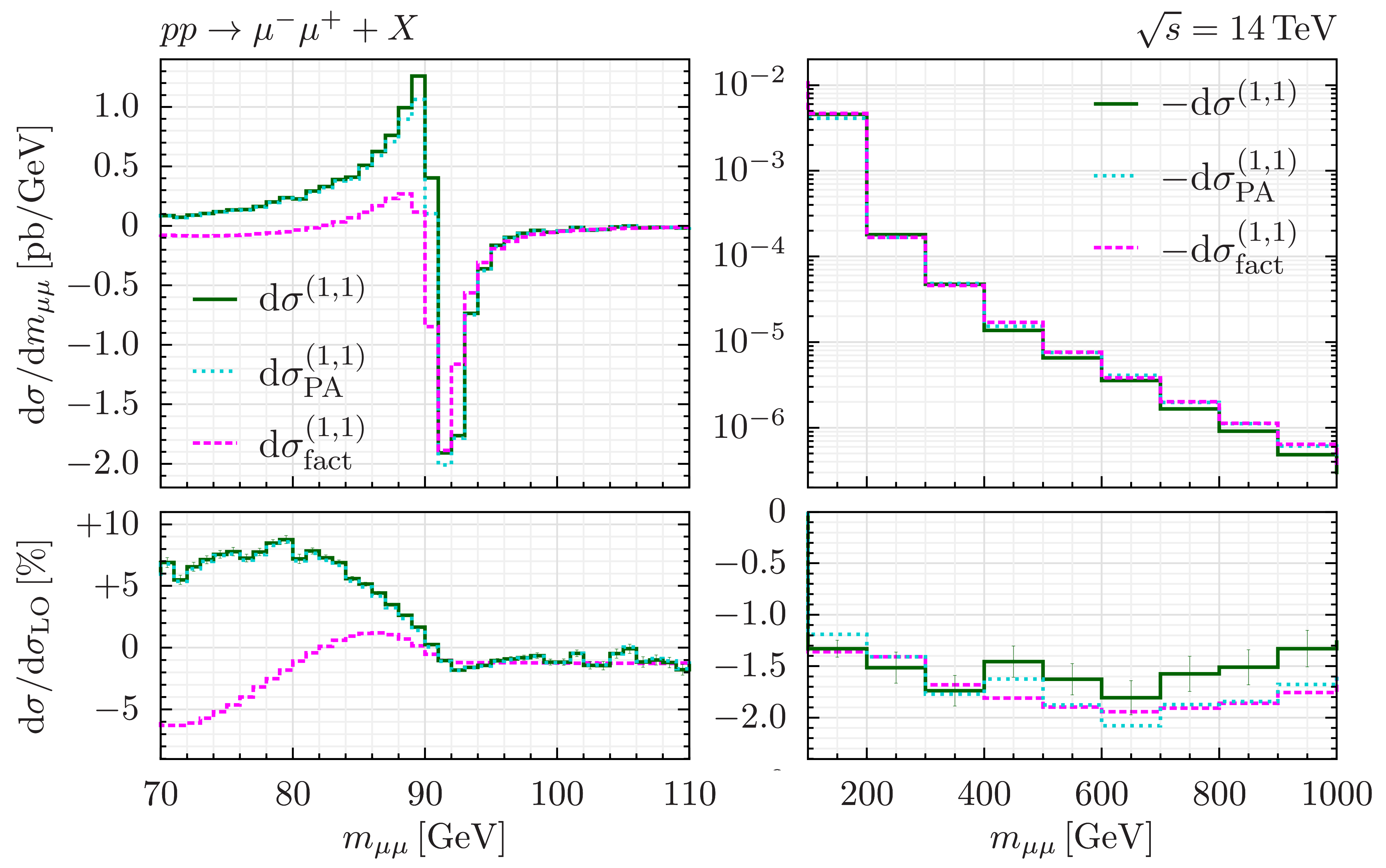
- approximate corrections in parton showers based on a factorised approach
  [Balossini et al (2010)], [Bernaciak,Wackeroth (2012)], [Barze' et al (2012,2013)], [Calame et al (2017)]
- NNLO QCD-QED corrections to neutrino-pair production
  [Cieri, Der, De Florian, Mazzitelli (2020)]
- Mixed QCD-EW corrections in Pole Approximation
  [Dittmaier, Huss, and Schwinn (2014,2015)] [Dittmaier, Huss, and Schwarz (2024)]

DY th-status: Fixed-Order Predictions - Mixed QCD-EW

NC current Drell-Yan

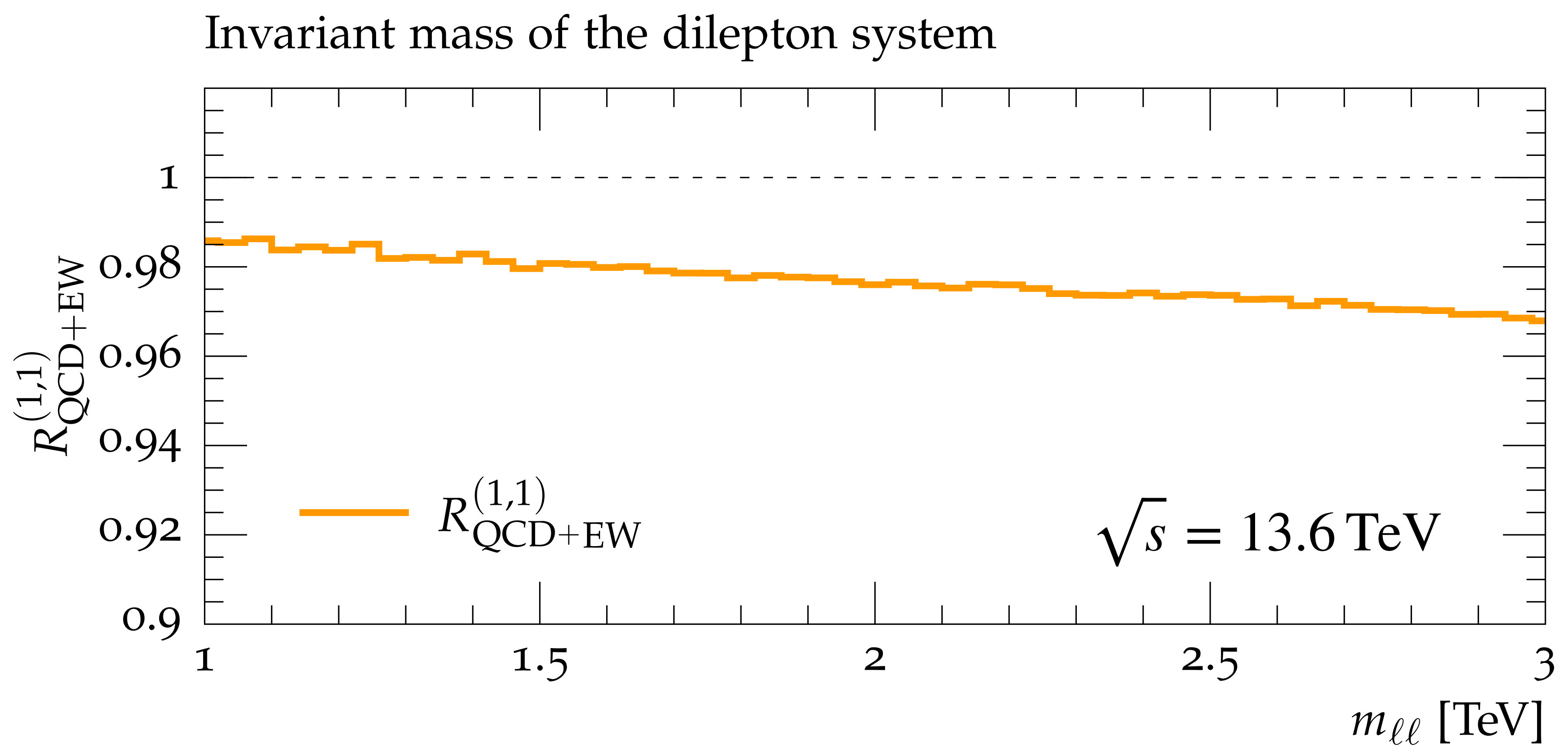
Bare muons (massive calculation)
[Bonciani, LB, Grazzini, Kallweitt, Rana, Tramontano, Vicini '21]

Impact at large invariant masses (massless leptons)
[Buccioni, Caola, Chawdhry, Devoto, Heller, von Manteuffel, Melinokov, Röntsch, Signorile-Signorile et al '22]



Two independent calculations
Different subtraction schemes
(q_T-slicing / Nested-Soft-Collinear Subtraction)
Independent calculations of the 2-loop amplitudes

$m_{\ell\ell} > 200$ GeV, $p_{T,\ell} > 30$ GeV, $|y_\ell| < 2.5$, $\sqrt{p_{T,\ell}\, p_{T,\bar{\ell}}} > 35$ GeV



- **Negligible?**
  mixed QCD-EW parametrically of similar importance as N³LO in QCD
- **Factorized ansatz?**
  is a multiplicative combination of QCD and EW justified?

Non-negligible impact at high invariant masses

Well described by the **product** of QCD and EW (large Sudakov log) corrections

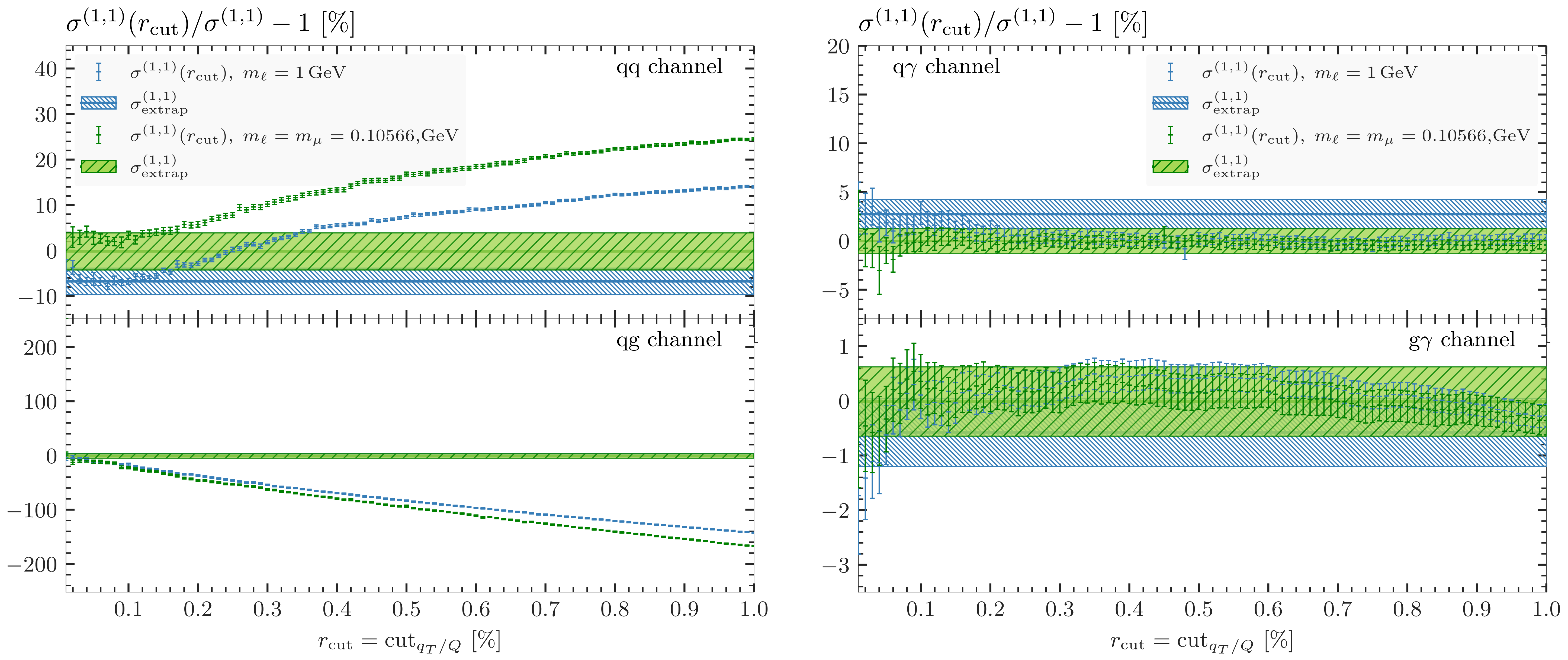
DY th-status: Fixed-Order Predictions - Mixed QCD-EW

Benchmarking of the two calculations [Armadillo,Bonciani,LB,Devoto,Grazzini,Kallweitt,Rana,Vicini '24]

In general, emission of photons collinear to a final state lepton requires the definition of collinear-safe observables:

- The **mass** of the lepton acts as a physical regulator of collinear divergences, therefore "bare" leptons.
  Fiducial cuts (e.g. on p_T^ℓ or $m_{\ell\ell}$) lead to an unbalance between real and virtual corrections $\Longrightarrow$ **(potentially large)** $\ln m_\ell/Q_h$
  Relevant for **muons**

- For **massless** leptons, collinear-safe objects must be defined similarly to jets in QCD.
  Definition of "dressed" lepton via photon-to closeby lepton recombination procedure $\Longrightarrow$ $\ln \delta$ (δ recombination cone)
  Relevant for electrons (calorimetric measurement)



Observation: cross sections for dressed leptons can be computed startign from a parton-level calculation with massive lepton up to power correction of the lepton mass

Repeating the calculation at different lepton masses finding, we verifie that the residual mass dependence is power suppressed

Residual power corrections in the lepton mass are phenomenologically negligible for $m_\ell = m_\mu$

DY th-status: Fixed-Order Predictions - Mixed QCD-EW

Benchmarking of the two calculations [Armadillo,Bonciani,LB,Devoto,Grazzini,Kallweitt,Rana,Vicini '24]

In general, emission of photons collinear to a final state lepton requires the definition of collinear-safe observables:

- The **mass** of the lepton acts as a physical regulator of collinear divergences, therefore "bare" leptons.
  Fiducial cuts (e.g. on p_T^ℓ or $m_{\ell\ell}$) lead to an unbalance between real and virtual corrections $\Longrightarrow$ **(potentially large)** $\ln m_\ell/Q_h$
  Relevant for **muons**

- For **massless** leptons, collinear-safe objects must be defined similarly to jets in QCD.
  Definition of "dressed" lepton via photon-to closeby lepton recombination procedure $\Longrightarrow$ $\ln \delta$ (δ recombination cone)
  Relevant for electrons (calorimetric measurement)

$$m_{\ell\ell} > 200\ \text{GeV}, \quad \mathrm{p}_{\mathrm{T},\ell} > 30\,\text{GeV}, \quad |\mathrm{y}_\ell| < 2.5, \quad \sqrt{\mathrm{p}_{\mathrm{T},\ell}\mathrm{p}_{\mathrm{T},\bar{\ell}}} > 35\,\text{GeV}$$

σ [pb]	σ_{LO}	$\sigma^{(1,0)}$	$\sigma^{(0,1)}$	$\sigma^{(2,0)}$	$\sigma^{(1,1)}$
$q\bar{q}$	1561.52(5)	340.3(3)	−49.77(5)	44.6(4)	−17.2(7)
qg	—	0.0601(3)	—	−32.7(2)	2.09(9)
$q\gamma$	—	—	−0.30(2)	—	−0.230(3)
$g\gamma$	—	—	—	–	0.2648(17)
gg	—	—	—	2.02(6)	—
$\gamma\gamma$	59.645(6)	—	3.174(9)	—	—

Observation: cross sections for dressed leptons can be computed startign from a parton-level calculation with massive lepton up to power correction of the lepton mass

Good agreement between the two calculations (after the correction of a bug in massless calculation)
Important to build confidence in their correctness!

Additional checks are ongoing (in particular, direct comparison of the 2-loop amplitudes)

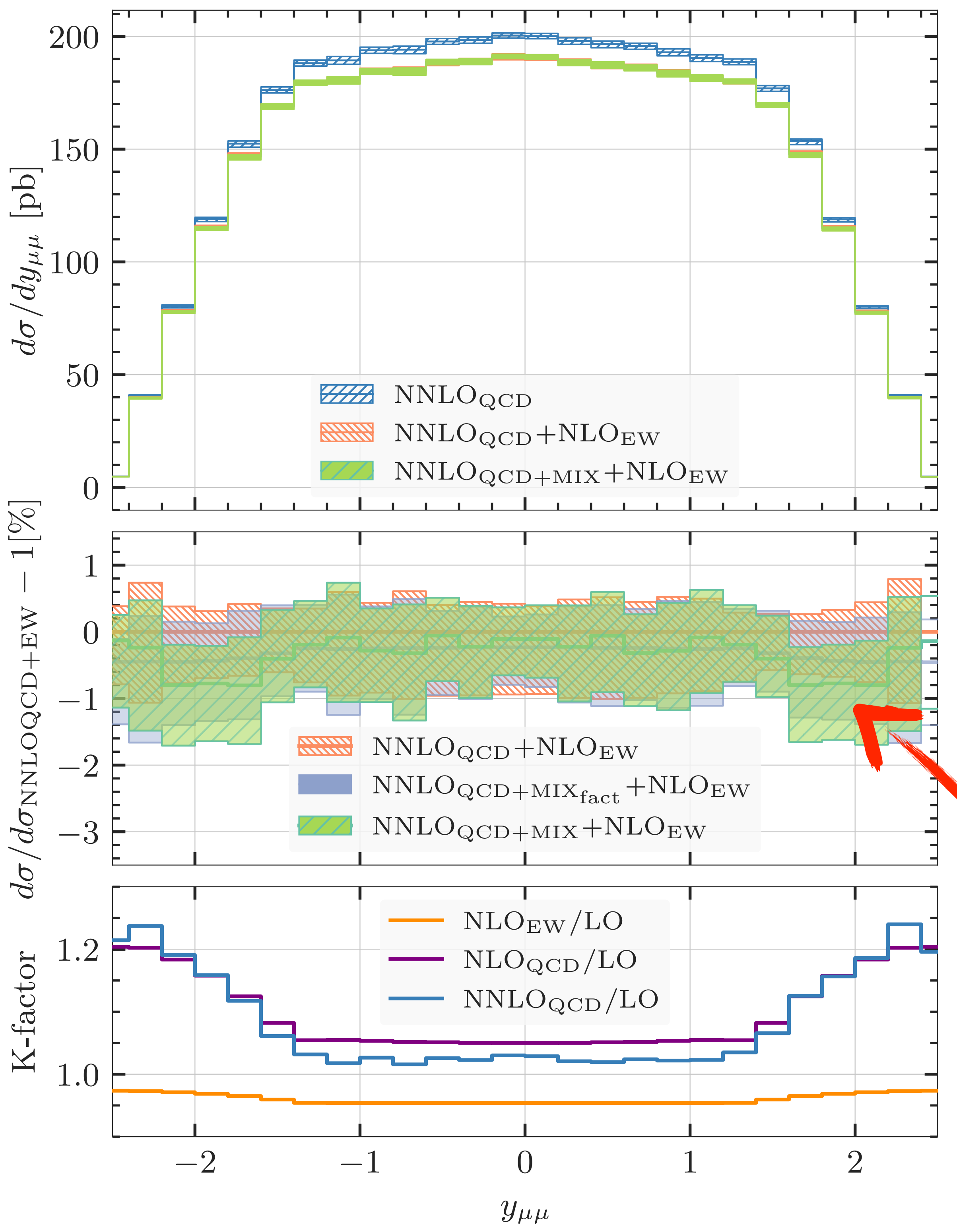
DY th-status: Fixed-Order Predictions - Mixed QCD-EW

[Armadillo,Bonciani,LB,Devoto,Grazzini,Kallweitt,Rana,Vicini '24]

New pheno results for bare muons in NC-DY

@resonance

$$p_T^{\mu^+} > 27\text{ GeV}, \quad p_T^{\mu^-} > 25\text{ GeV}, \quad |y_\mu| < 2.5$$
$$66\text{ GeV}, < m_{\mu\mu} < 116\text{ GeV}$$

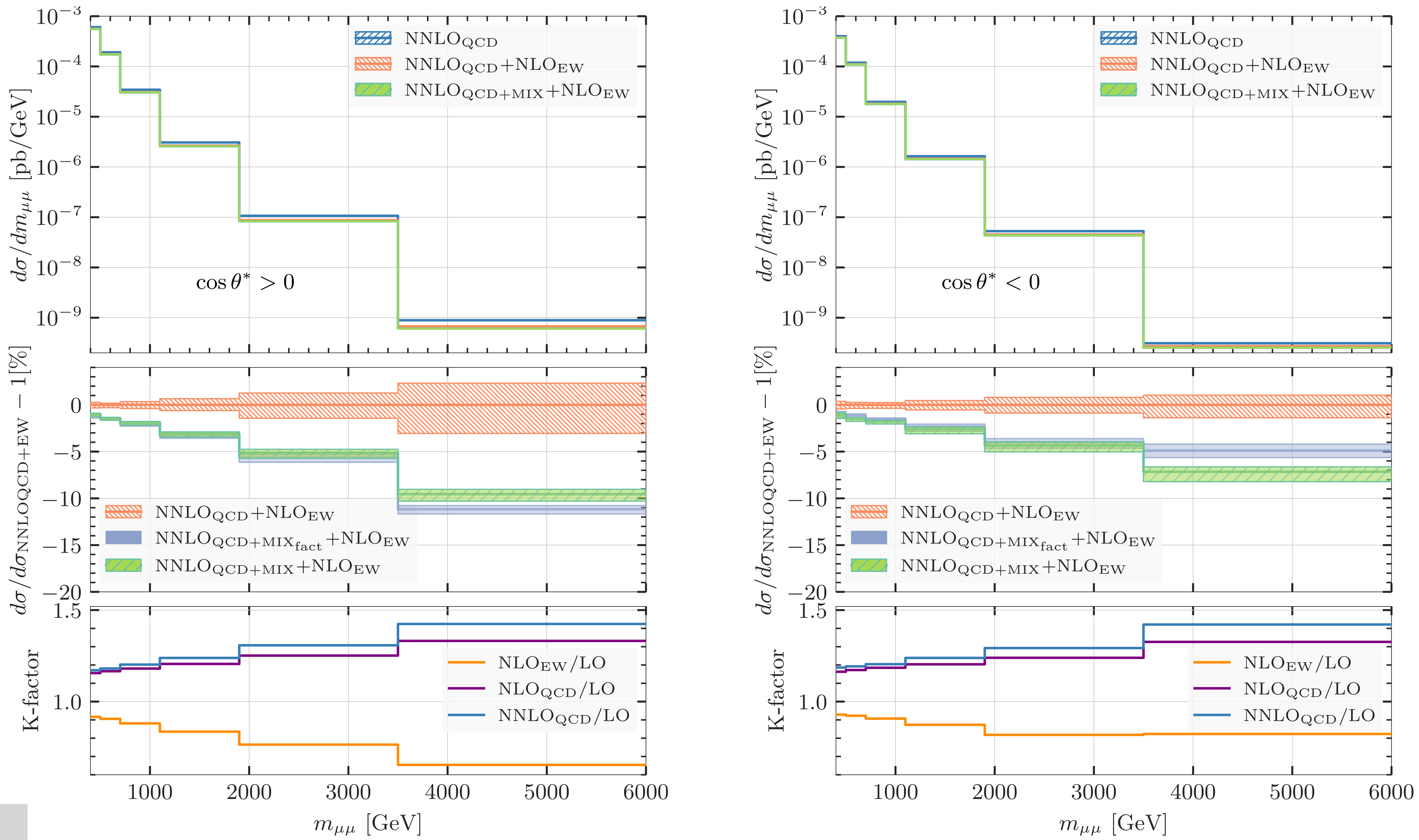


Staggered cuts on transverse momentum of positive/negative muon. Restoration of quadratic sensitivity of the acceptance [Grazzini et al, 1711.06631] [Alekhin et al, 2104.02400]

Overall small mixed QCD-EW corrections, but non-trivial shape distortion up to 0.8% at $|y_{\mu\mu}| \gtrsim 1.5$

@large invariant masses

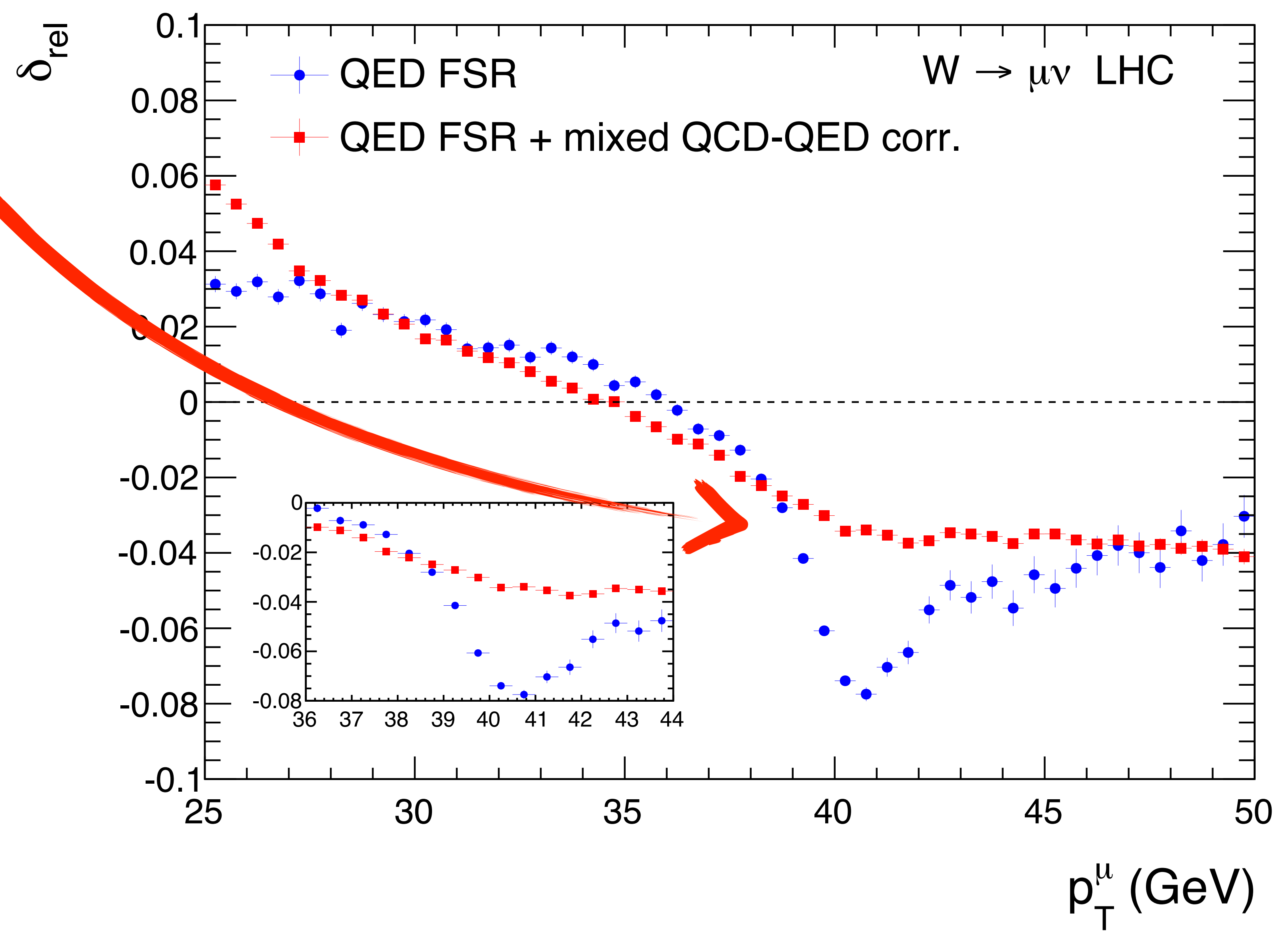
$$p_T^{\mu^\pm} > 53\text{ GeV}, \quad |y_\mu| < 2.4, \quad m_{\mu\mu} > 150\text{ GeV}$$



$\mathcal{O}(5\%)$ mixed QCD-EW corrections at TeV scales, relatively well described by naive factorisation of QCD and EW (large EW Sudakov logs)

DY th-status: Combined QCD-QED q_T-resummation

Data/Theory comparisons usually made at the level of **pure QCD models** considering **"Born" lepton**
Large FSR QED removed relying on Monte Carlo modeling (PHOTOS) [Barberio, van Eijk ,Was '91][Golonka, Was, '06]



- The definition of "Born" leptons is theoretically not rigorous
- It provides a good description of the main QED effects but makes less transparent the impact of full EW effects and the interplay with QCD corrections (underlying assumption of complete factorization)
- Modeling and uncertainties through different dedicated MC codes (PHOTOS, HORACE, PYTHIA). Better way?
- Unfolded data for bare/dressed leptons for **LEGACY data**?

GOAL: combining higher-order QCD resummation with the resummation of leading EW and mixed QCD-EW effects in a flexible "analytic" resummation tool, including matching to available fixed-order results

First results obtained in the on-shell approximation; no realistic treatment of leptonic final-state

[Cieri, Ferrera, Sborlini, 2018][Autieri, Cieri, Ferrera, Sborlini, 2023]

DY th-status: Combined QCD-QED q_T-resummation

First implementation in the RADiSH framework **[LB, Rottoli, Torrielli, 2404.15112]**

$$\frac{d\Sigma(v)}{d\Phi_B} = \int \frac{dk_{T,1}}{k_{T,1}} \mathscr{L}(k_{T,1})\, e^{-R(k_{T,1})}\, \mathscr{F}(v, \Phi_B, k_{T,1})$$

Luminosity: includes $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s\alpha)$ constants and photon-initiated channels

Radiator: accounts for the tower of $\alpha_s^m \alpha^n ln^{m+n} q_T/M$ terms, including **soft wide-angle photon radiation**

DY th-status: Combined QCD-QED q_T-resummation

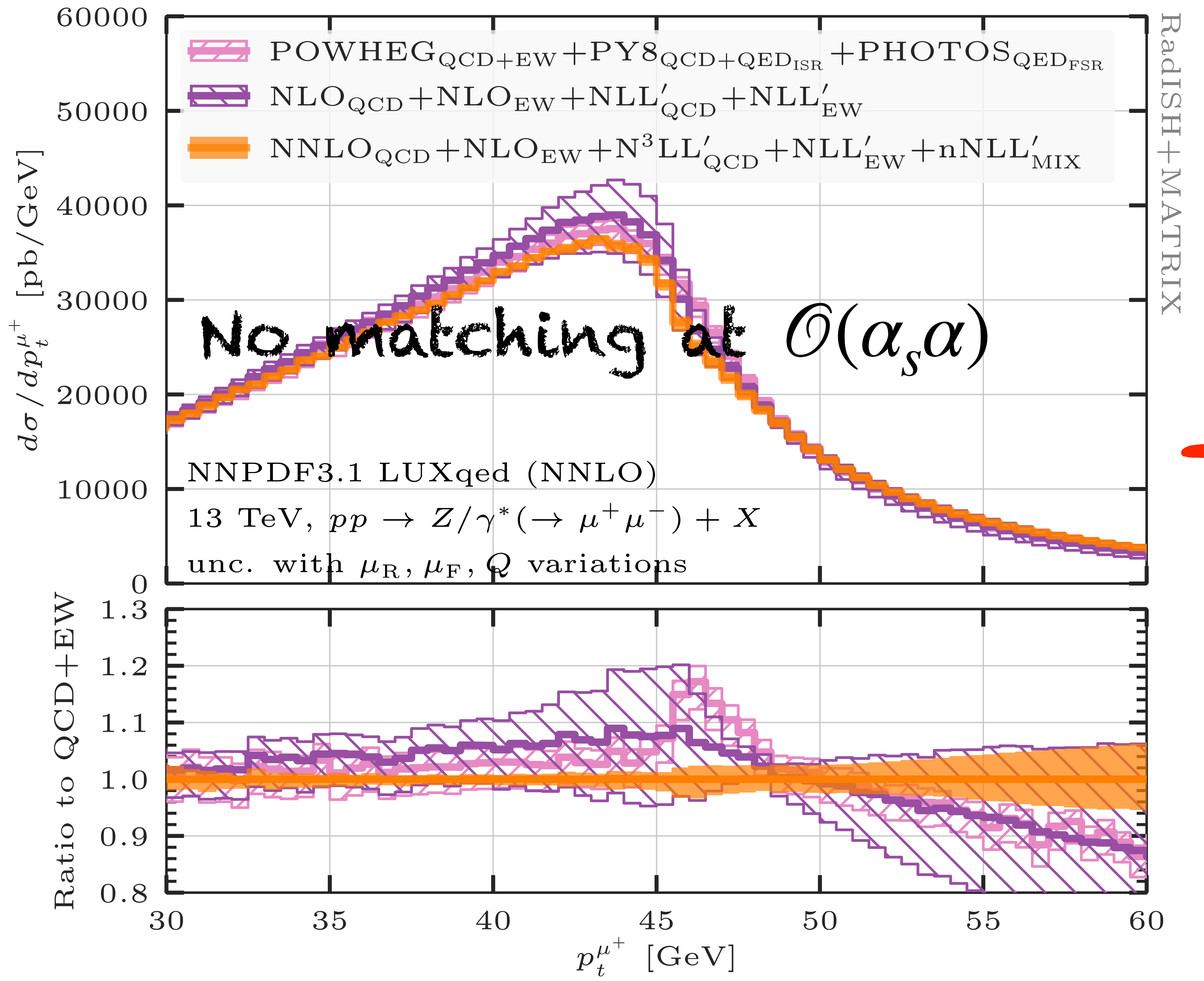
First implementation in the RADiSH framework [LB, Rottoli, Torrielli, 2404.15112]

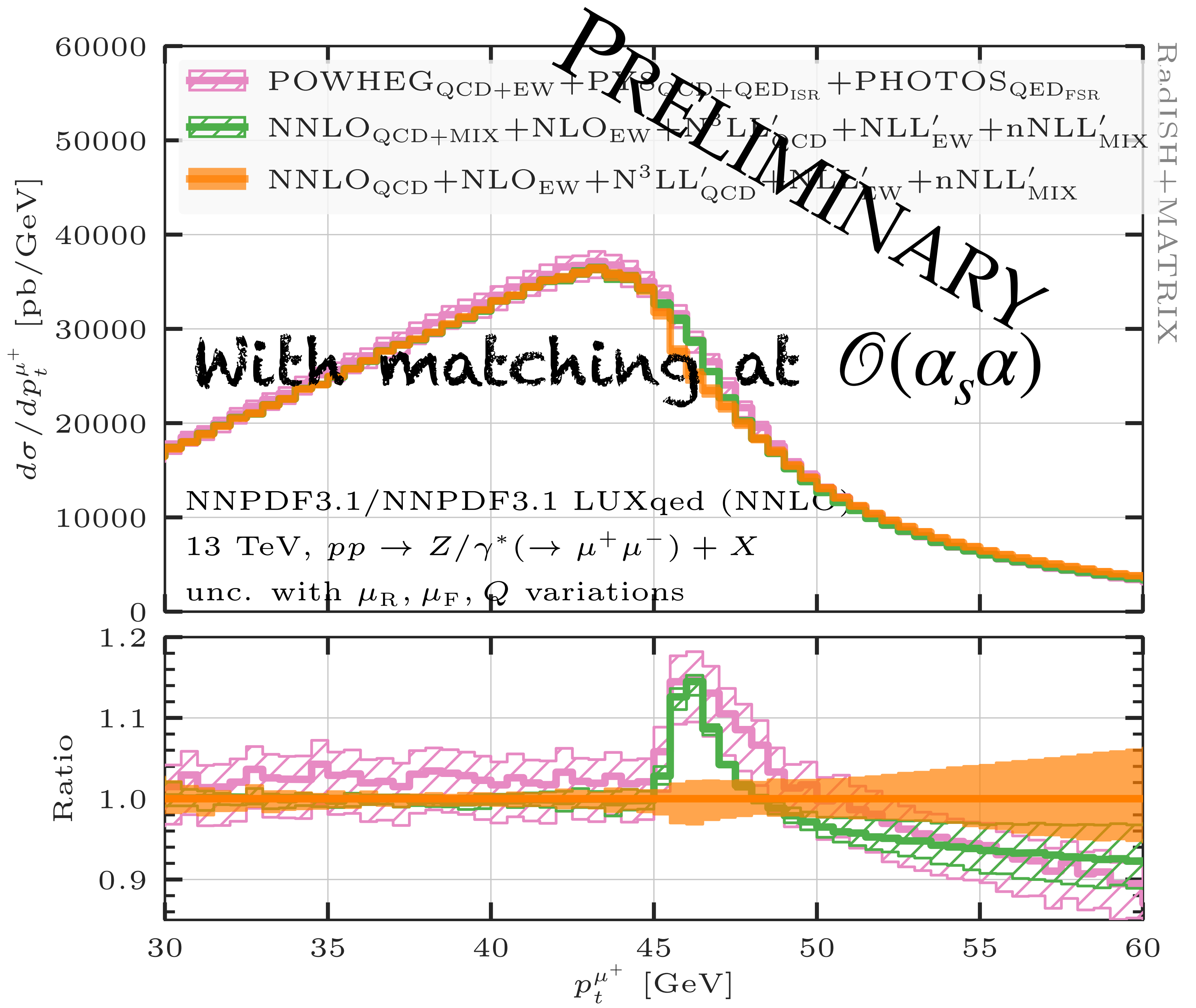
Formal power counting
$q_T \ll m_l, Q_h$

$$\frac{d\Sigma(v)}{d\Phi_B} = \int \frac{dk_{T,1}}{k_{T,1}} \mathcal{L}(k_{T,1})\, e^{-R(k_{T,1})}\, \mathcal{F}(v, \Phi_B, k_{T,1})$$

Resummation of large logarithms of the lepton mass associated with fiducial cuts is missing
Fixed-order terms retrieved upon **matching**.

$p_T^{\mu^\pm} > 27$ GeV, $|y_\mu| < 2.5$, $66 \text{ GeV} < m_{\mu\mu} < 116$ GeV





$\mathcal{O}(\alpha_s\alpha)$ matching mandatory, it induces large corrections

The situation can be mitigated by an **improved treatment of the quasi-collinear** photon emission region (**WIP**)

Outline

DY status of theoretical: review of (some) recent progress/results

Some thoughts and considerations on current&future precision measurements

Conclusive discussion

QCD uncertainties

See talk by Marinelli

[Tackmann, 2411.18606]

If you have a good understanding of all-order structure of the observable

[CMS, 2412.13872]

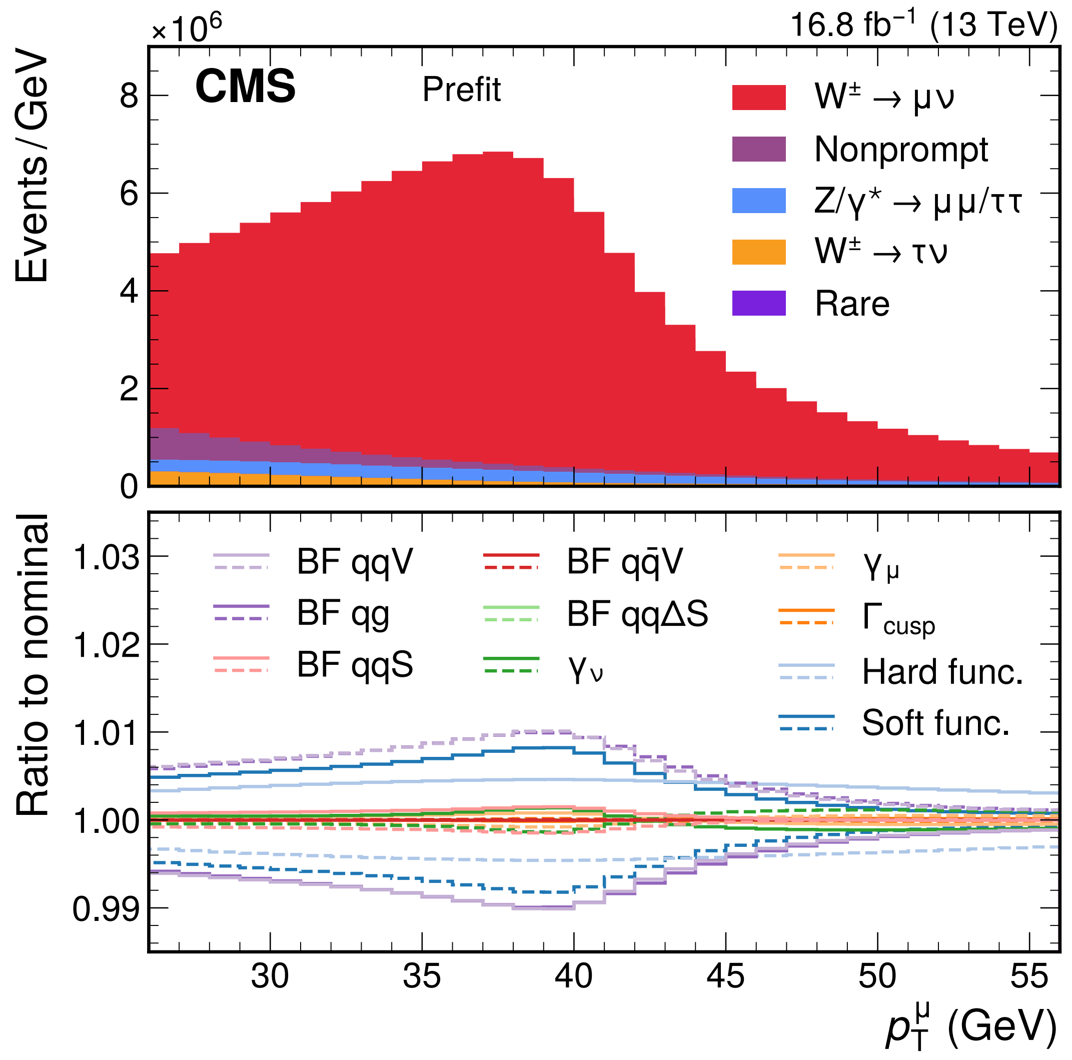
$$\frac{d\sigma}{dq_T^2} = H \otimes B_a \otimes B_b \otimes S(\alpha_s, L) + \mathcal{O}(q_T/Q)$$

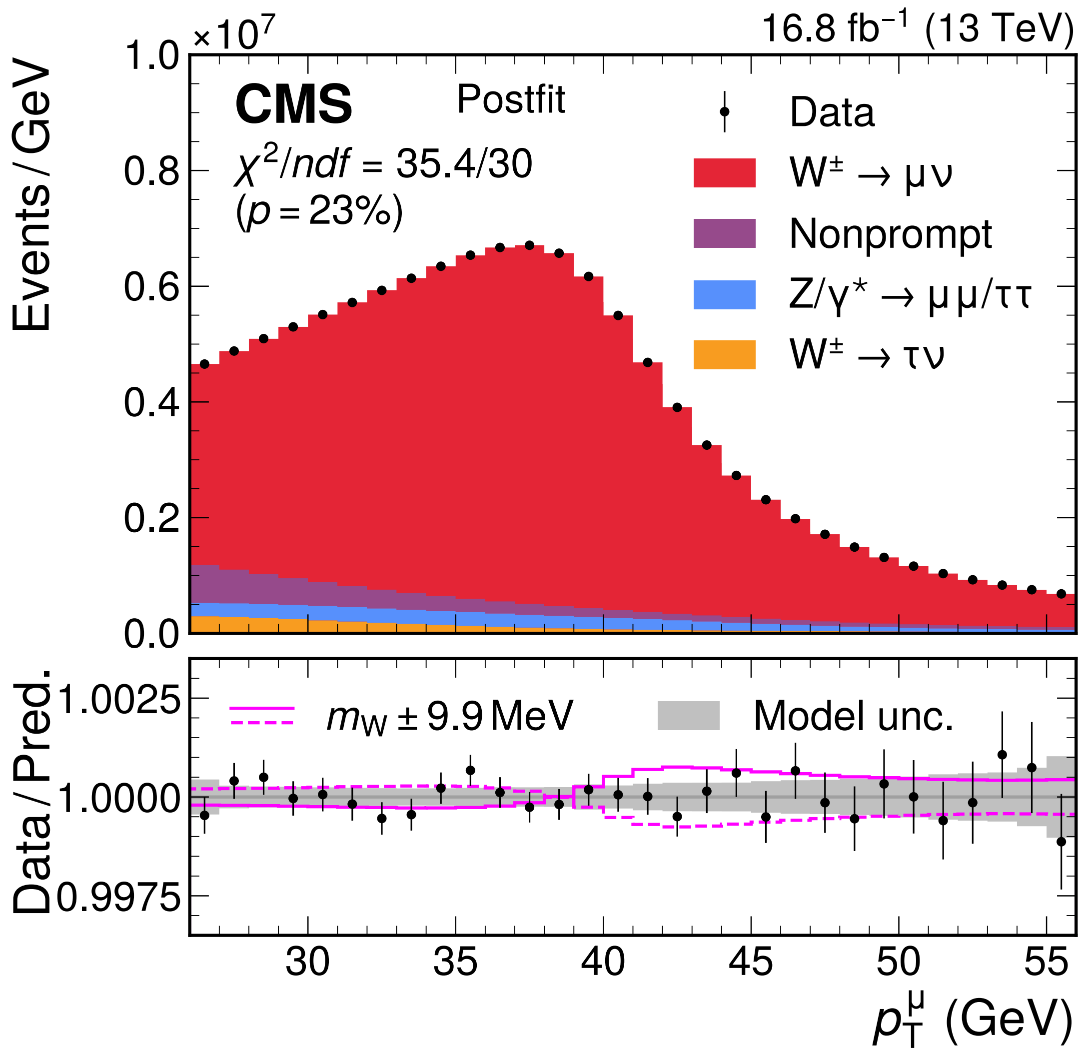
Parametrise missing higher orders as TNPs $\vec{\theta}$
(anomalous dimension, boundary conditions)

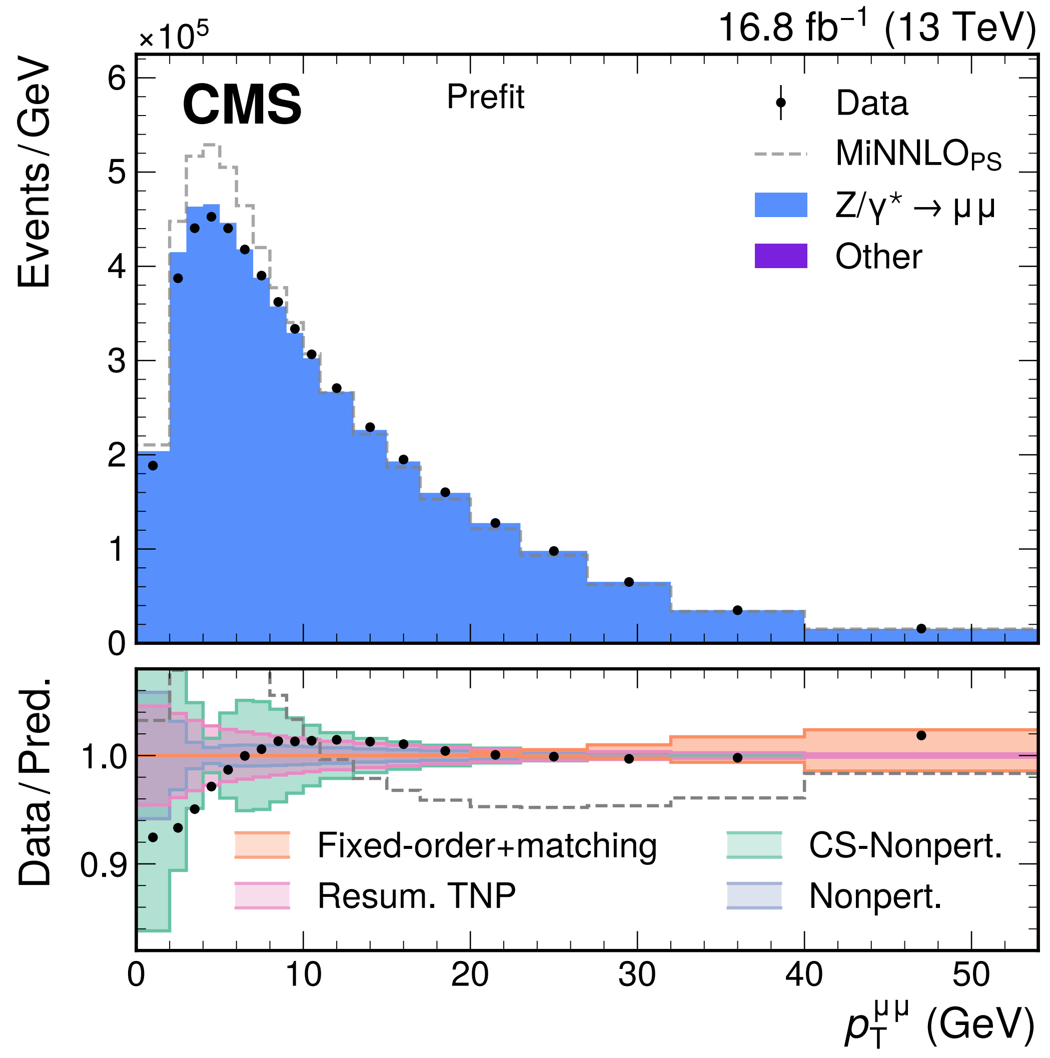
Assign probability distribution to $\vec{\theta}$ Selection Bias?

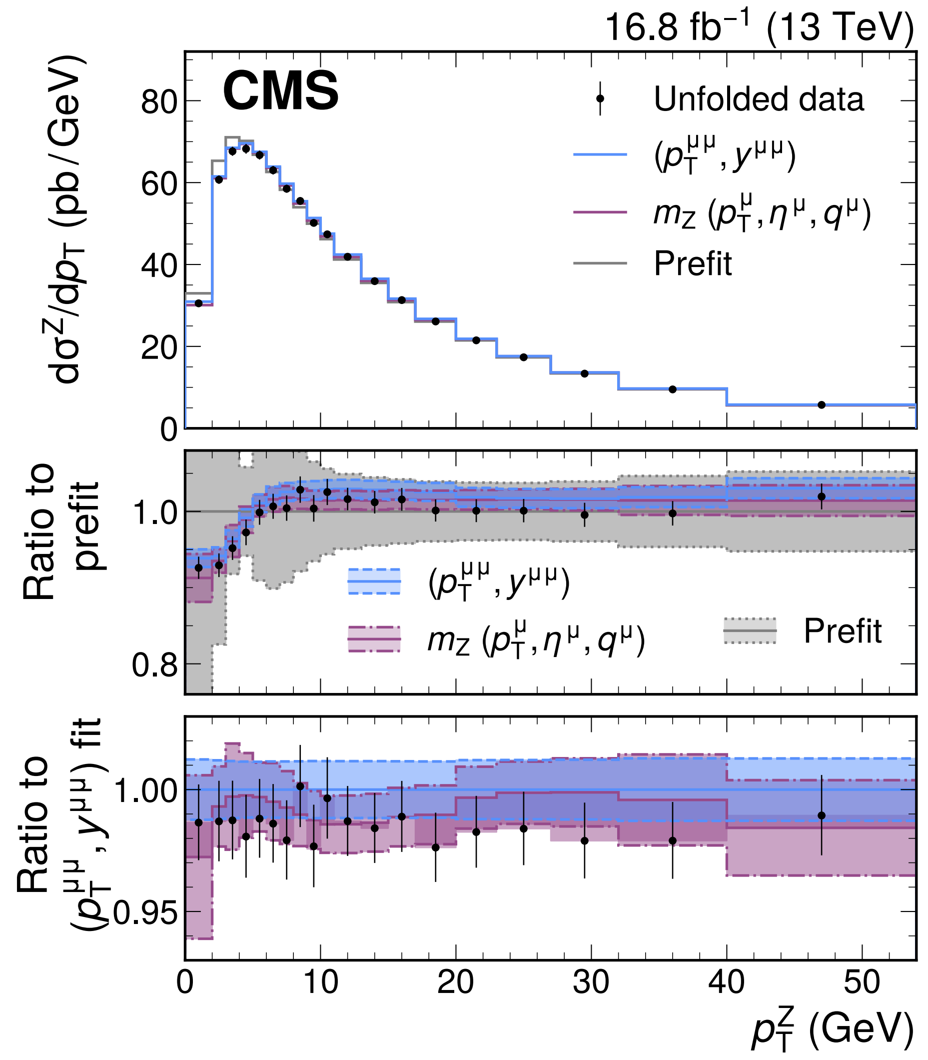
Assume 100% correlation among the $\vec{\theta}$

Constrain $\vec{\theta}$ from data









QCD uncertainties

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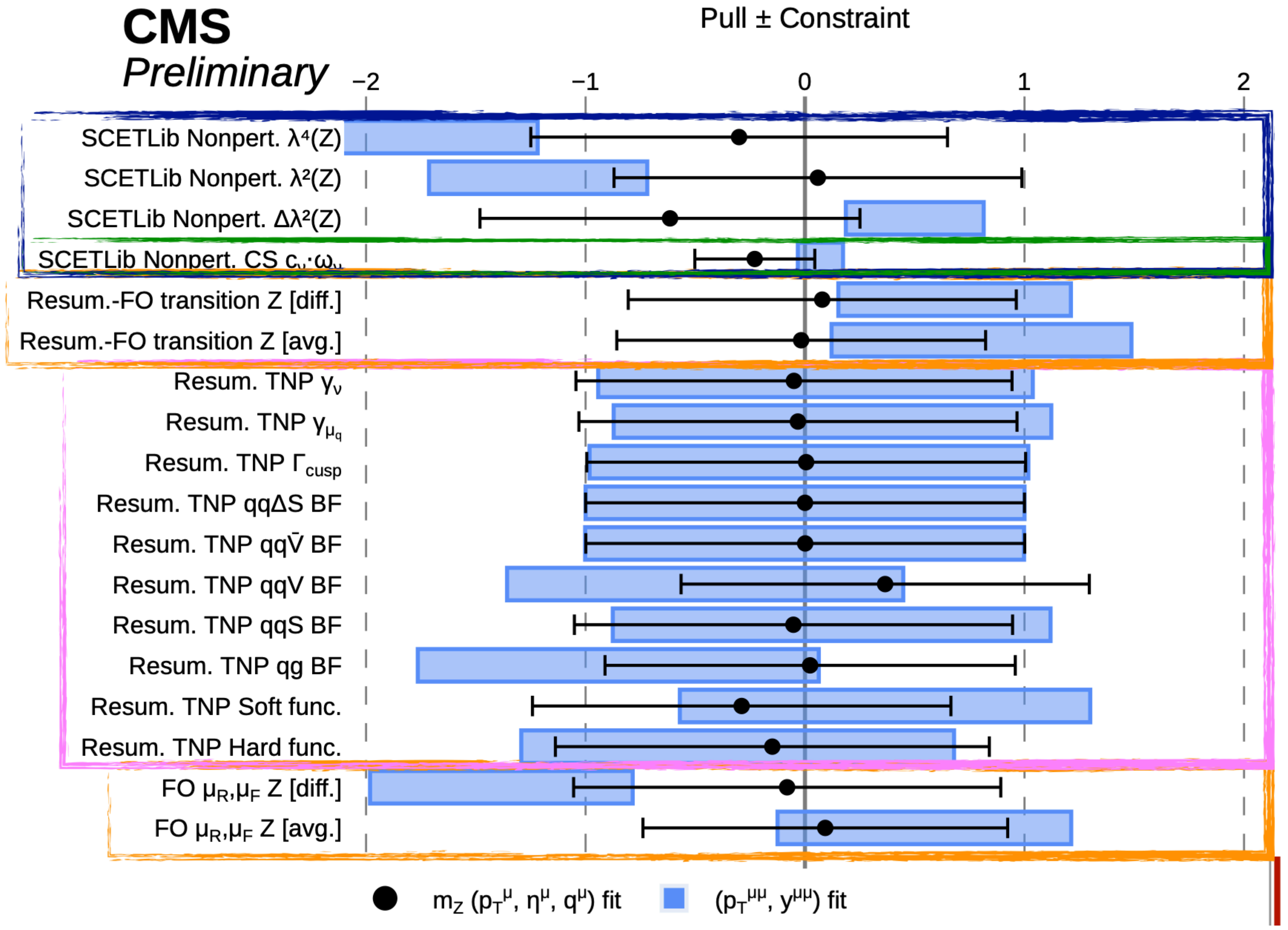
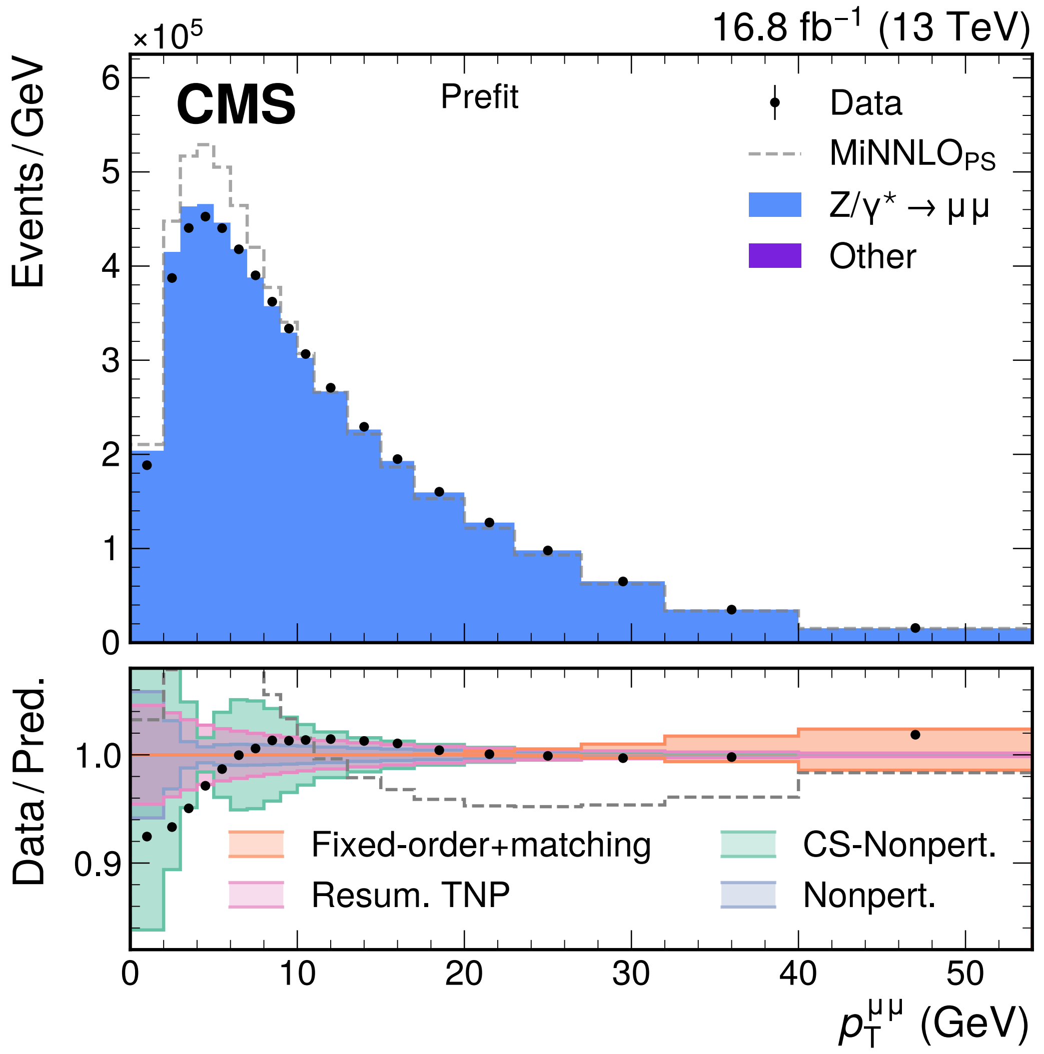
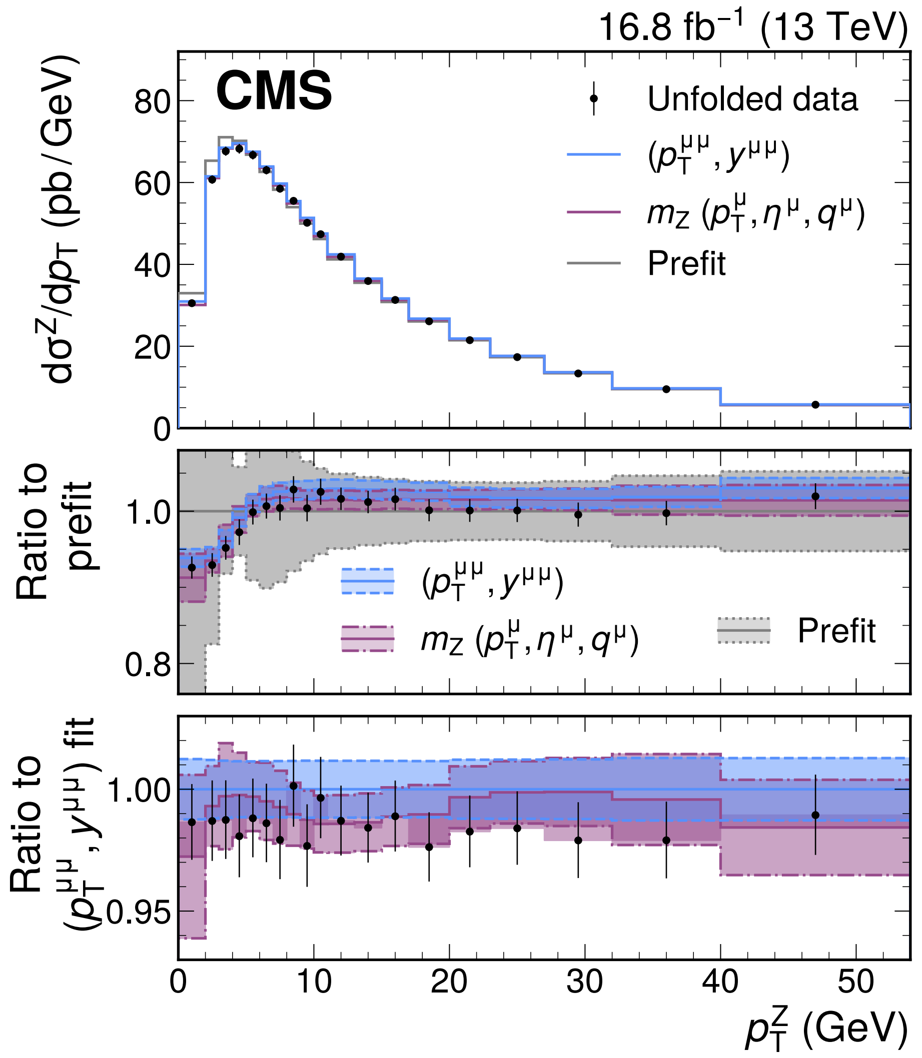


[from K. Long talk, https://indico.fnal.gov/event/66577/]





Talk by Bertone

Incorporates a model of leading **Non-Perturbative corrections** based on TMD factorization (in terms of the Collin-Soper evolution kernel and a x-indepentent non-Perturbative model)

TNPs in the low-q_T region. In fixed-order large-q_T region, **standard scale variations** μ_R, μ_F. Which correlation model?

Small pulls/constraints on TNPs. Non-Perturbative most important

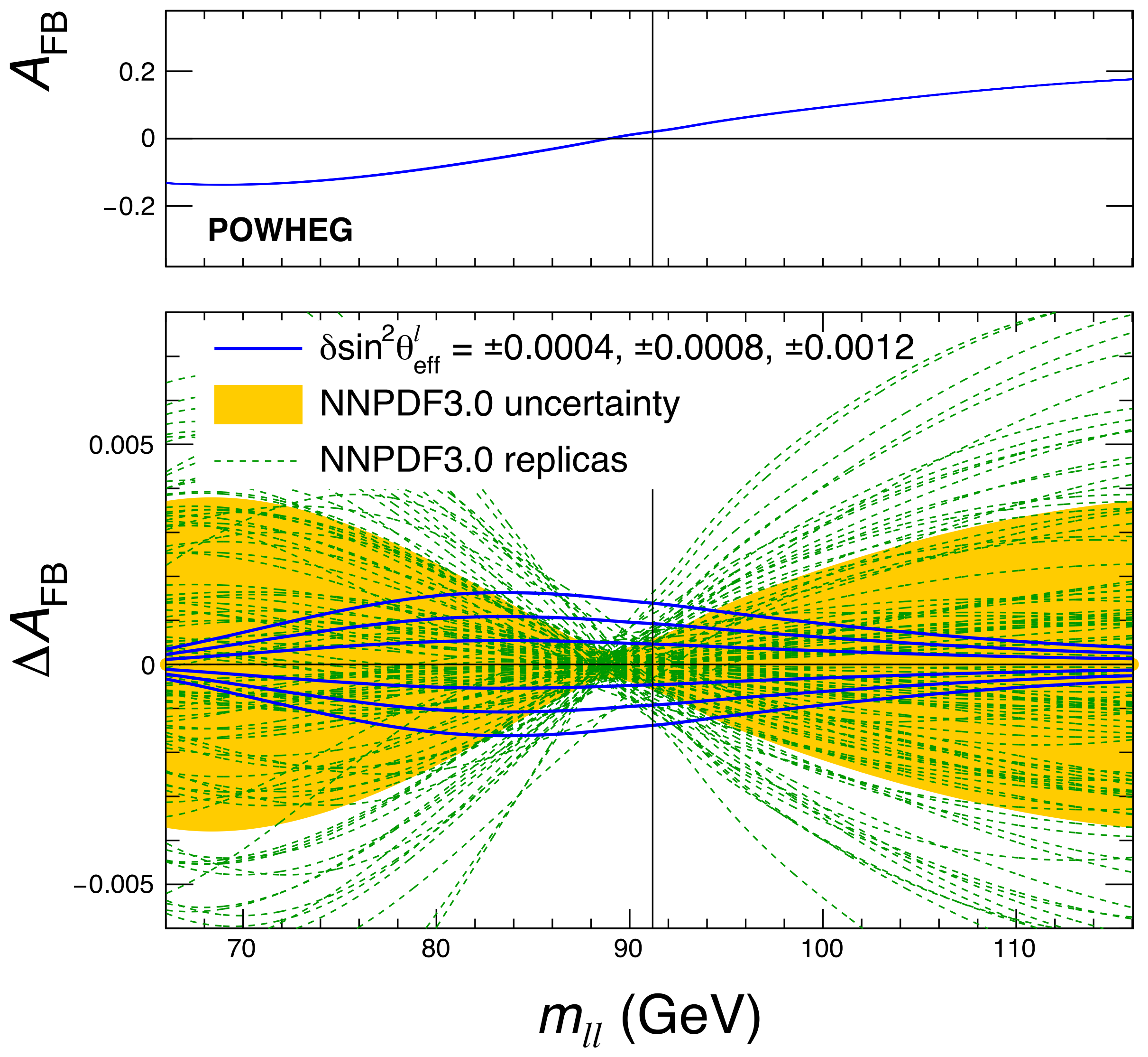
PDF uncertainties

PDF uncertainties among the dominant sources

See talk by Stegeman

→ Profile / reweighting: use correlation to **tame their impact**!

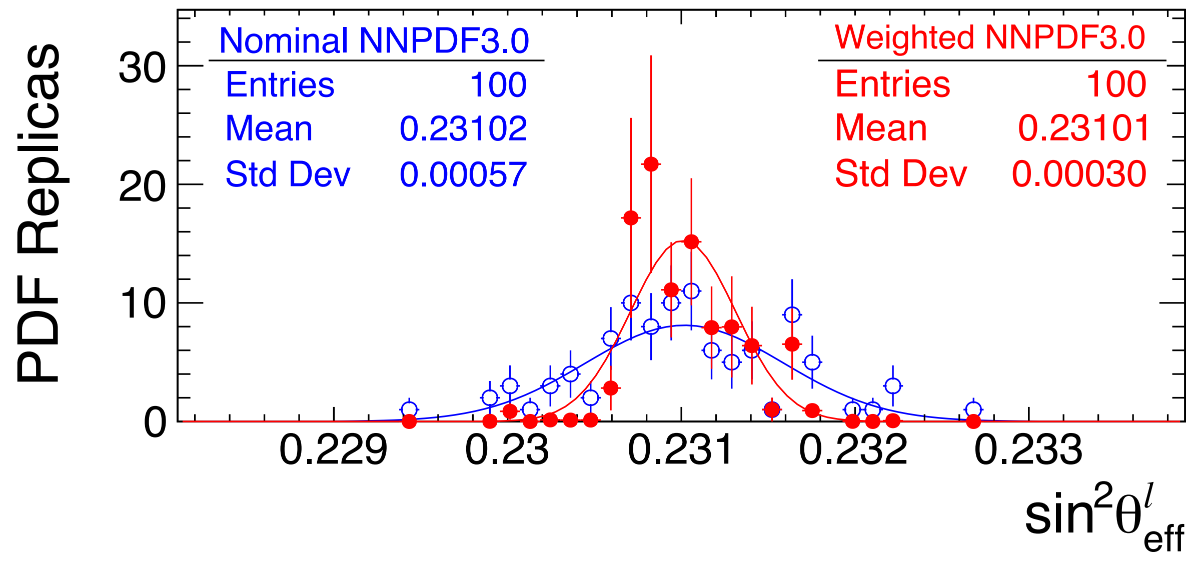
[CMS, 1806.00863]



[Bodek et al 1507.02470]

Apply Bayesian reweighting

Reduction of PDF uncertainty by **almost a factor of 2**



Warning: this data carries effectively a very high weight

$\sin^2\theta^\ell_{\rm eff} = 0.23101 \pm 0.00036\,({\rm stat}) \pm 0.00018\,({\rm syst}) \pm 0.00016\,({\rm theo}) \pm 0.00031\,({\rm PDF})$

[CMS, 2408.07622]

Similar size!

$\sin^2\theta^\ell_{\rm eff} = 0.23157 \pm 0.00010\,({\rm stat}) \pm 0.00015\,({\rm exp}) \pm 0.00009\,({\rm theo}) \pm 0.00027\,({\rm PDF})$

New test: simultaneous extraction of PDF and $\sin^2\theta^\ell_{\rm eff}$ provides similar results for both central value and uncertainty!

[ATLAS, 2309.12986]

The situation is even more delicate for extraction of the strong coupling as PDF and α_s are strongly correlated!

Can profiling induce a bias?

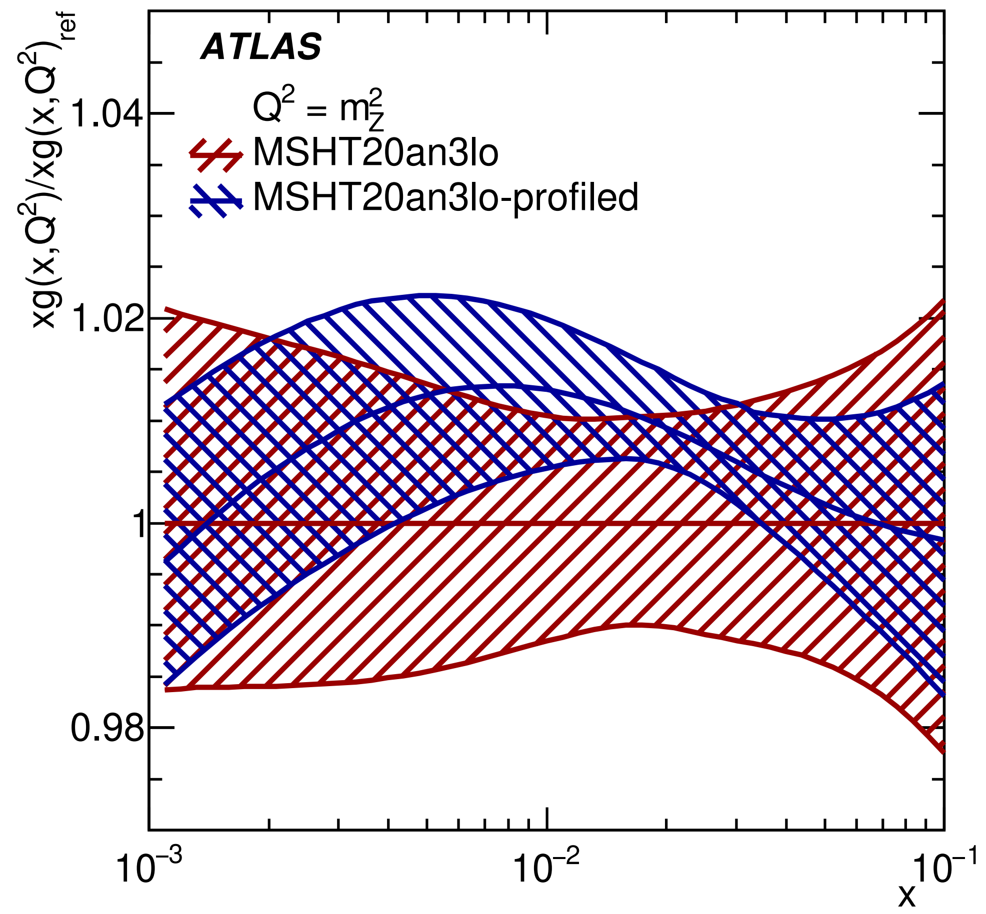
Mature?

Nominal prediction is obtained by profiling **MSHT20an3lo** consistently with the aN⁴LL+N³LO baseline. PDF uncertainty: $\Delta_{\rm PDF} = 0.00051$

PDF set	$\alpha_s(m_Z)$	PDF uncertainty
MSHT20 [37]	0.11839	0.00040
NNPDF4.0 [84]	0.11779	0.00024
CT18A [29]	0.11982	0.00050
HERAPDF2.0 [65]	0.11890	0.00027

N³LL′+N³LO → $\Delta_{\rm PDF,NNLO} = 0.001$

ATLAS also has performed simultaneous fits of PDF, $\alpha_s(m_Z)$ and non-perturbative parameters including DIS data



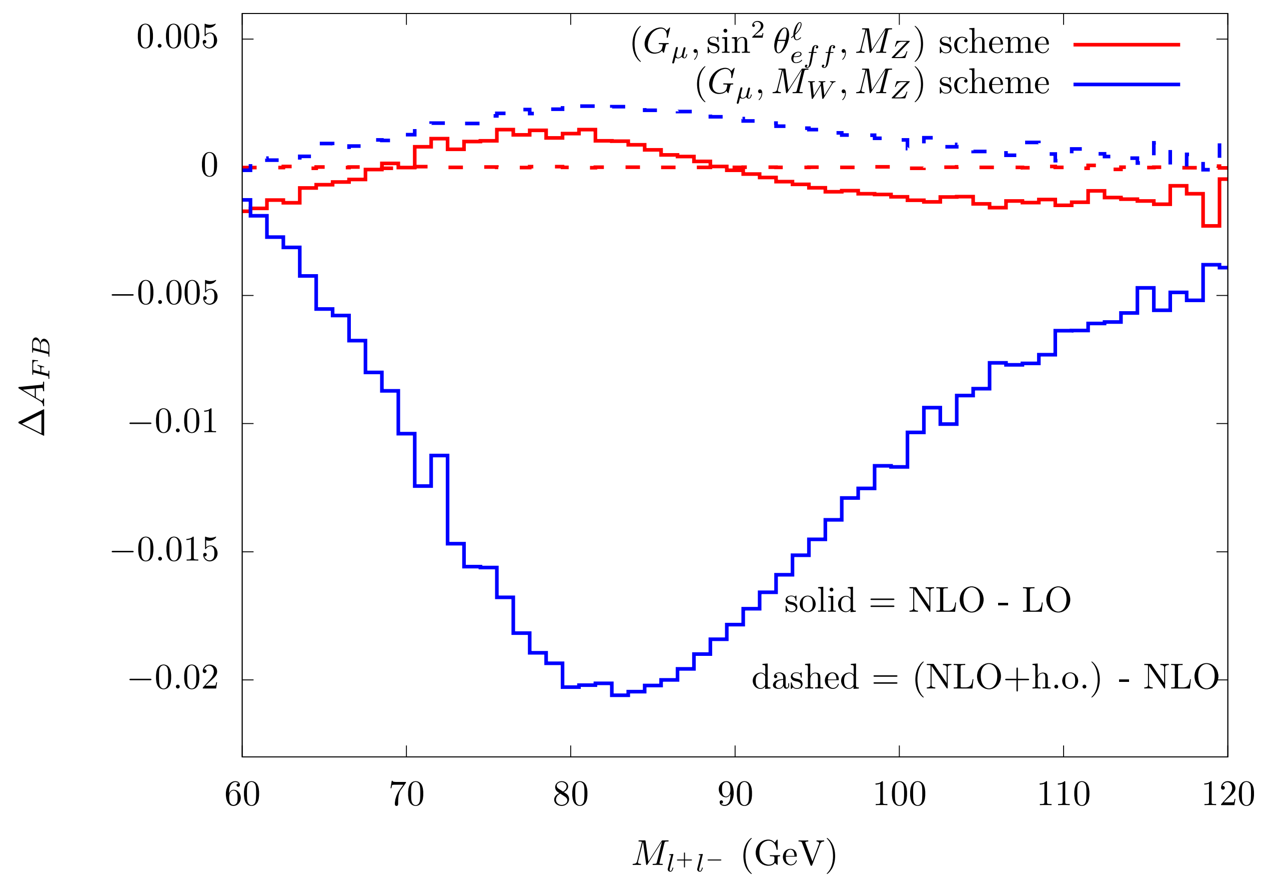
Does it affect other datapoints in the PDF global fit?

Alternative/complementary strategies

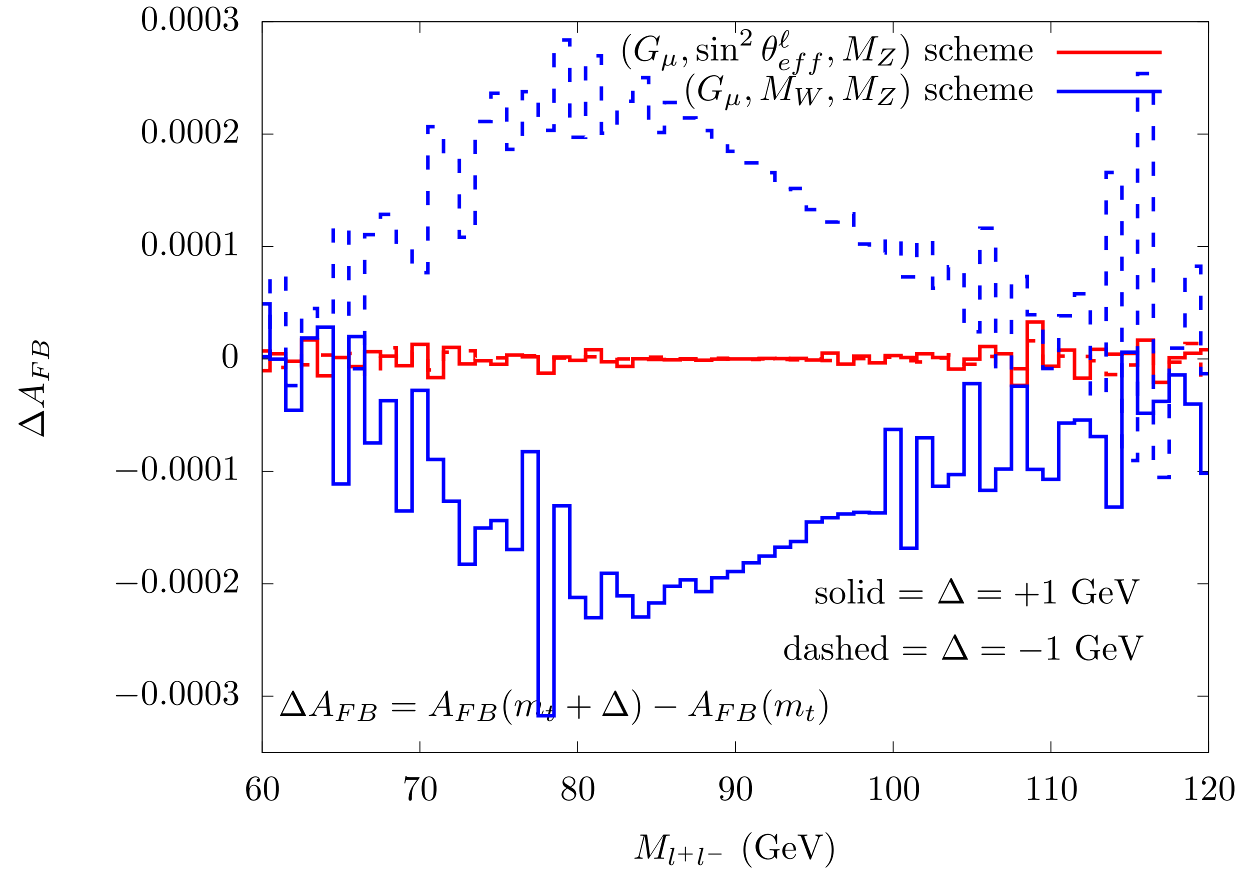
1. Different schemes are formally equivalent, but some schemes are better than others

Example: renormalization scheme with the leptonic effective mixing weak angle an an input parameter

[Chiesa,Piccini,Vicini,1906.11569]



Better perturbative convergence (reduction of missing higher-order uncertainty)



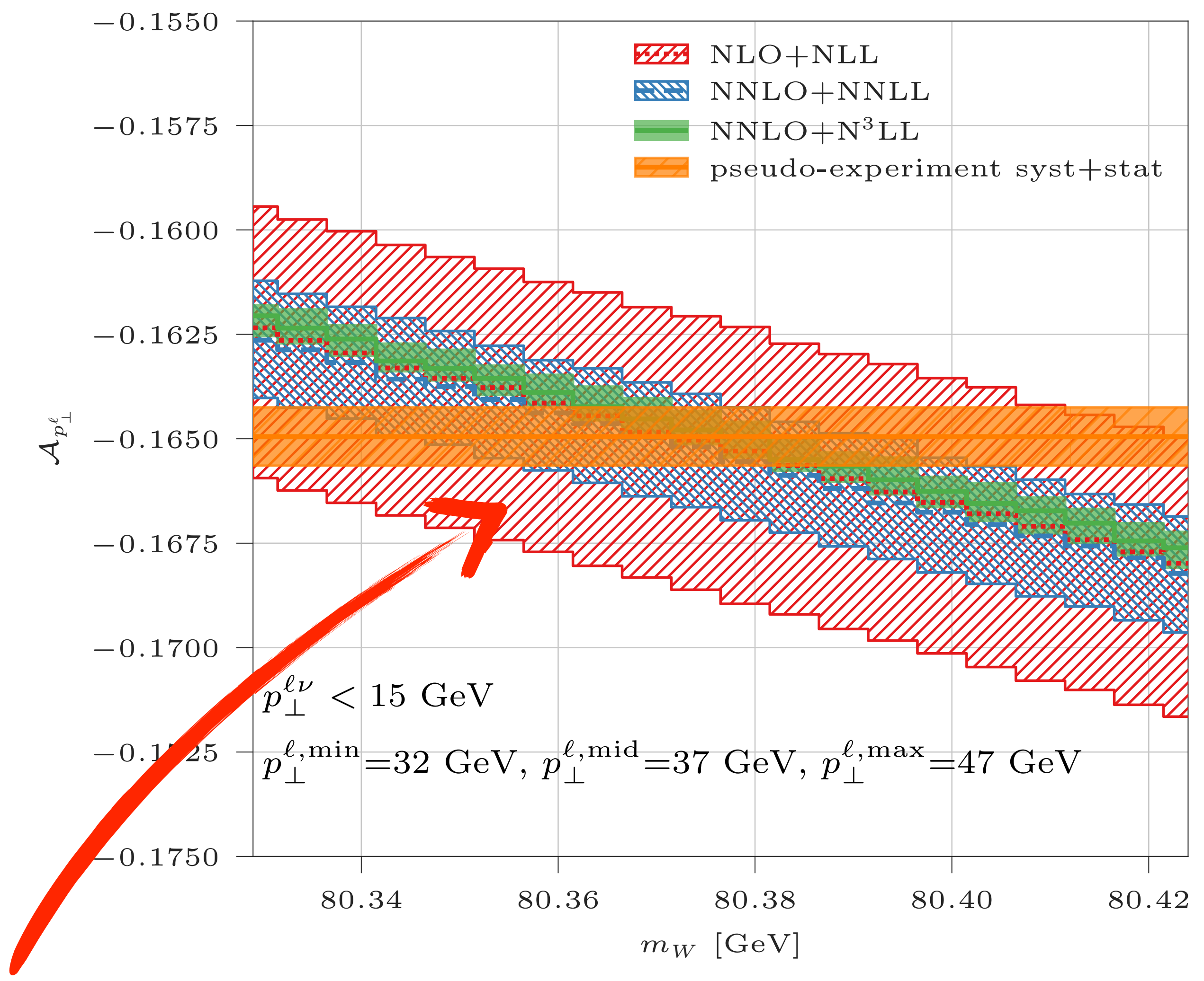
Smaller parametric uncertainty (for example, dependence on the top mass)

2. Develop alternative observables with better theoretical control

Example: Jacobian asymmetry for W mass determination

[Rottoli,Torrielli,Vicini,2301.04059]

$$A_{p_T^\ell} = \frac{L - U}{L + U} \qquad L = \int_{p^\ell_{T,\mathrm{min}}}^{p^\ell_{T,\mathrm{mid}}} dp_T^\ell \frac{d\sigma}{dp_T^\ell} \qquad U = \int_{p^\ell_{T,\mathrm{mid}}}^{p^\ell_{T,\mathrm{max}}} dp_T^\ell \frac{d\sigma}{dp_T^\ell}$$



Same slope at different perturbative QCD orders: QCD ISR factorised from m_W-sensitivity in propagation/decay

- Corresponds to the eigenvalue with largest sensitivity to m_W (rigid shift in p_T^ℓ distribution)
- Excellent perturbative convergence ($\Delta m_W \sim 5$ MeV in perturbative QCD)
- Impact of PDF, QED, Non-Perturbative QCD to be assessed but likely clean disentangling of effect
- Experimentally viable?

Alternative/complementary strategies

3. Data-driven measurements

[CMS, 2412.13872]

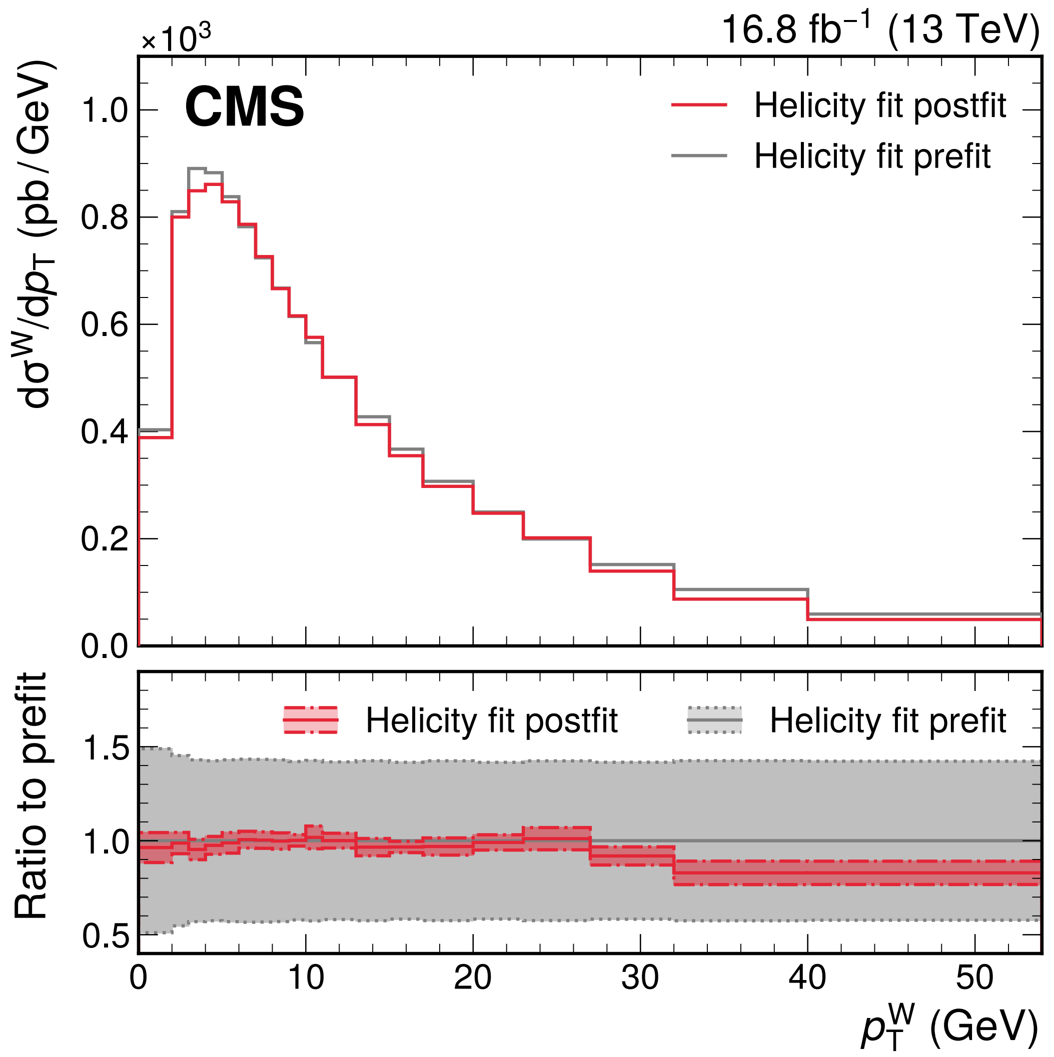
Example: CMS determination of W mass with alternative "helicity fit" strategy

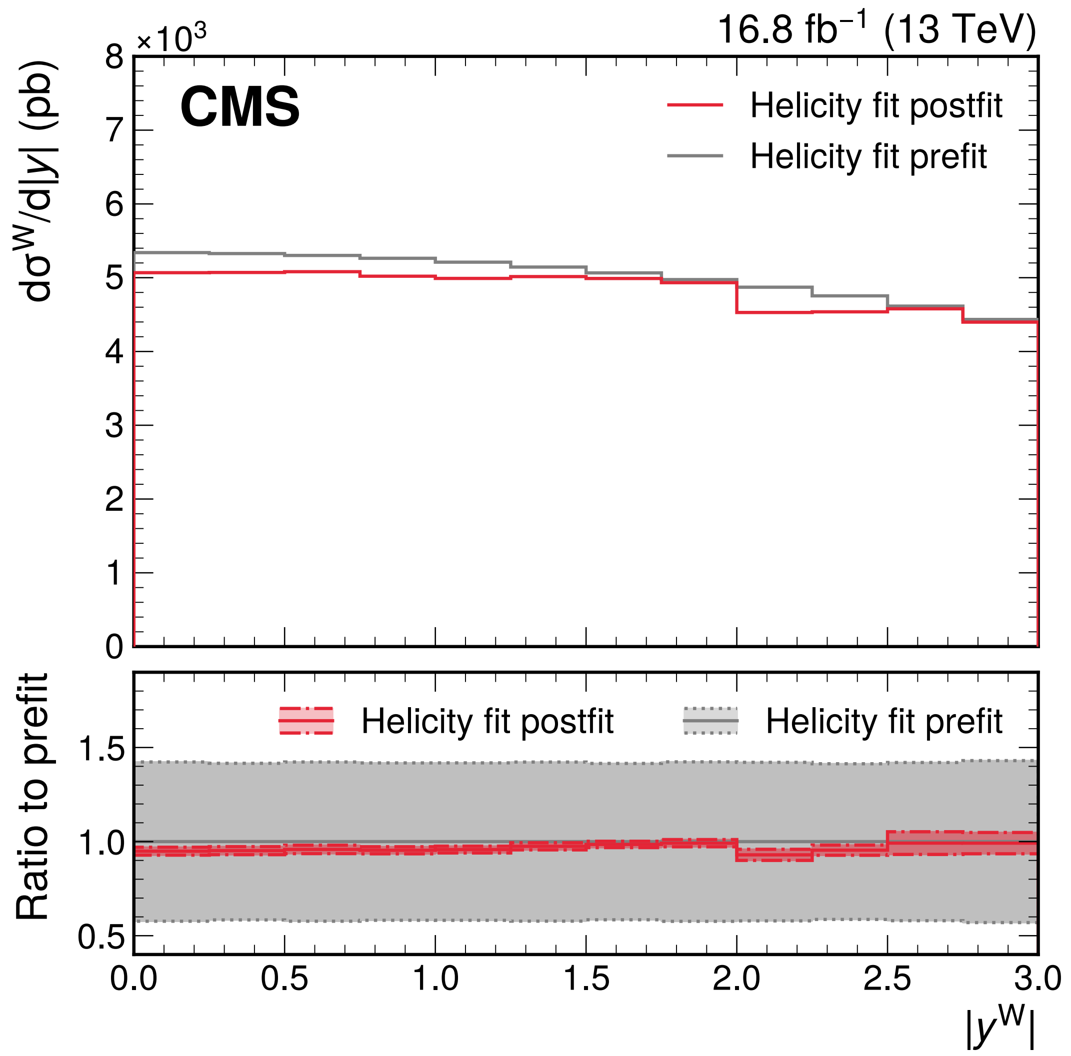
Main Assumption: pure QCD model, spin 1 particle decay

$$\frac{d\sigma}{dq_T^2\, dm\, dy\, d\cos\theta^*\, d\phi^*} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dq_T^2\, dm\, dy}\left[(1+\cos^2\theta^*) + \sum_{i=0}^{7} A_i(q_T, m, y) P_i(\cos\theta^*, \phi^*)\right]$$

Main observation: W polarizations induce changes in (p_T^ℓ, η^ℓ) different from the one induced by variations of m_W. [CMS, 2008.04174]

→ **Constrain simultaneously m_W and angular coefficients/helicity** from a likelihood fit to $(p_T^\ell, \eta^\ell, m_W)$
Reduce theory modeling





Nominal

$$m_W = 80360.2 \pm 2.4\,(\text{stat}) \pm 9.6\,(\text{syst}) = 80360.2 \pm 9.9 \text{ MeV}$$

$$m_W = 80360.8 \pm 15.2 \text{ MeV}$$ from Helicity fit

- Currently, used as a cross-check (for systematic errors)
- **Statistically dominated**, some theory input still injected to not loose sensitivity
  to what extent?
- Room for improvement in methodology and statistics

Conclusive discussion

Focus on precise measurements of SM parameters

Experimental side - All in all, robust analyses, still some room for improvements

[CMS, 2412.13872]

$m_W = 80360.2 \pm 2.4\,(\text{stat}) \pm 9.6\,(\text{syst}) = 80360.2 \pm 9.9$ MeV

Dominant sources: Calibration & PDF

Data-driven approach statistically dominated

[ATLAS, 2309.12986]

$\alpha_s(m_Z) = 0.1183 \pm 0.0009$

Different treatment of TH uncertainty?

See talk by Marinelli

Dominant source?

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

[CMS, 2408.07622]

$\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(exp) \pm 0.00009\,(\text{theo}) \pm 0.00027\,(\text{PDF})$

PDF dominated, complementarity between different LHC experiments can be very beneficial

See talk by Abdelmotteleb

[LHCb, 2410.02502]

$\sin^2\theta^\ell_{\text{eff}} = 0.23152 \pm 00044\,(\text{stat}) \pm 0.00005\,(exp) \pm 0.00009\,(\text{theo}) \pm 0.00022\,(\text{PDF})$

Statistically dominated!
No PDF profiling!

Conclusive discussion

Focus on precise measurements of SM parameters

Theory side

Uncertainties: embarrassing situation!

$$\Delta_{\rm TH} \gg \Delta_{\rm EXP}$$

→ OPPORTUNITY

Tremendous community effort and progress in computing **more loops, more legs, more logs.** The show must go on, but there are now other clear pressing problems

(After 40+ years) go beyond scale uncertainties	Serious rethinking, some ideas on the table. More work and time to build consensus on a new prescription (hopefully from an improved understanding)
PDFs	Bottleneck for precision measurements of SM parameters at hadron colliders. Uncertainty already reduced by profiling by factors 2-3…
Non-perturbative effects	Except for rare exceptions, as DY production at small q_T, NP physics is described relying solely on Monte Carlos.

$$\sigma = \sum_{ab} \int dx_1 \int dx_2 \; f_{a/h_1}(x_1, \mu_F)\, f_{b/h_2}(x_2, \mu_F)\, \hat{\sigma}(\hat{s}, \mu_R) \; + \mathcal{O}\left(\frac{\Lambda^p}{Q^p}\right)$$

For example, what is p in V+1 jet in QCD?
[Ferrario Ravasio et at, 2011.14114]

Conclusive discussion

Focus on precise measurements of SM parameters

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New ideas/observables (EECs (Waalewijn, Pathak) ? Lattice?). Importance of legacy data

Conclusive discussion

Focus on precise measurements of SM parameters

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Stay tuned for more QCD-EW results (CC, resummation)

Conclusive discussion

Focus on precise measurements of SM parameters

Thank you!

Theory side

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BACKUP

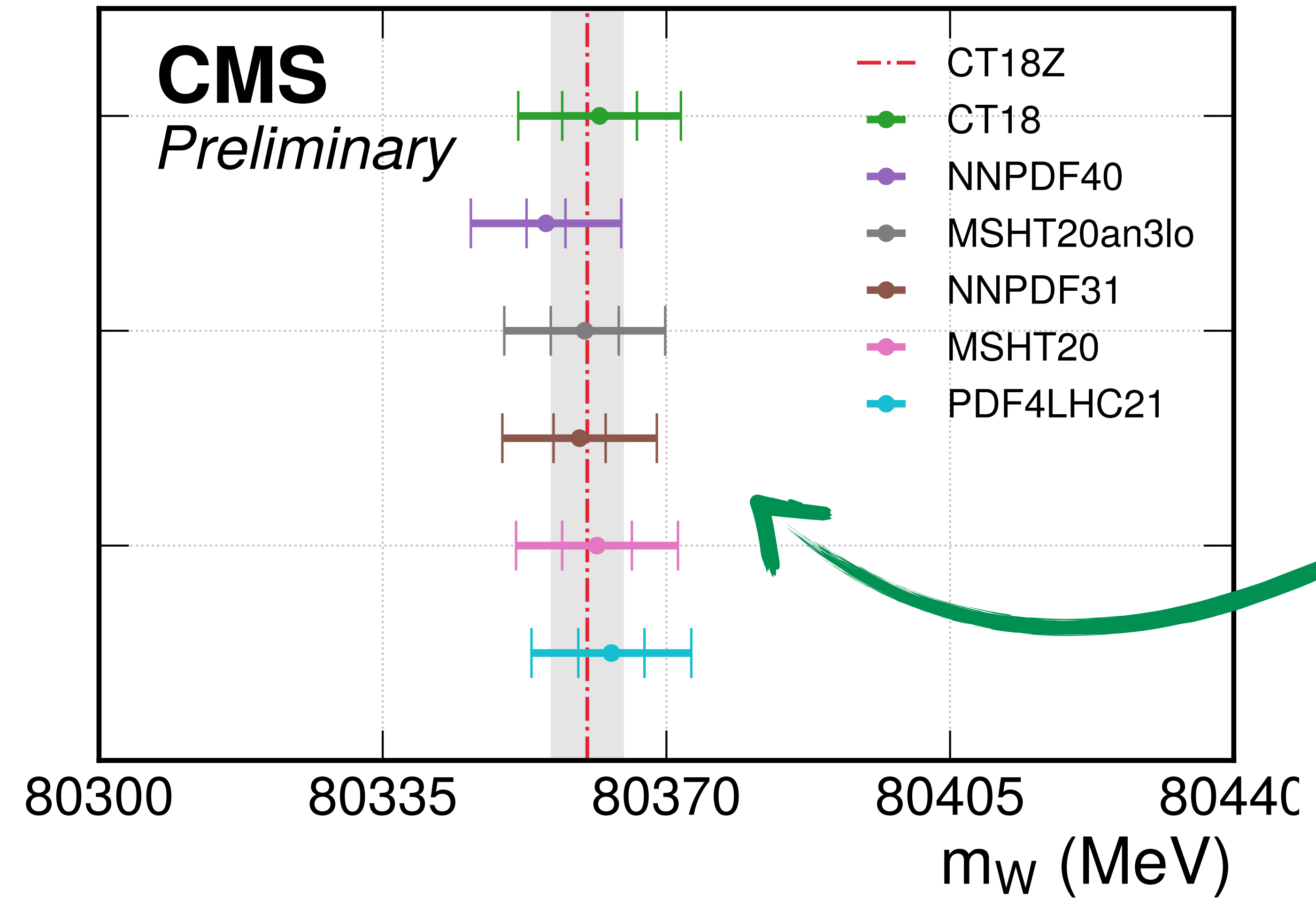
(A few) percent precision phenomenology: theory challenges

Compute more loops&legs, but not only …

$$\sigma = \sum_{ab} \int dx_1 \int dx_2 \, f_{a/h_1}(x_1, \mu_F) \, f_{b/h_2}(x_2, \mu_F) \, \hat{\sigma}(\hat{s}, \mu_R) \; + \mathcal{O}\left(\frac{\Lambda^p}{Q^p}\right)$$

Parton distribution Functions

- Enter **any** predictions/simulations for hadron-collider processes
- Theory input (splitting functions and coefficient functions) + **non-perturbative** component (initial conditions) from **global fit** to DIS and collider data
- **Approaching %-level** (?)
  How to estimate uncertainties?

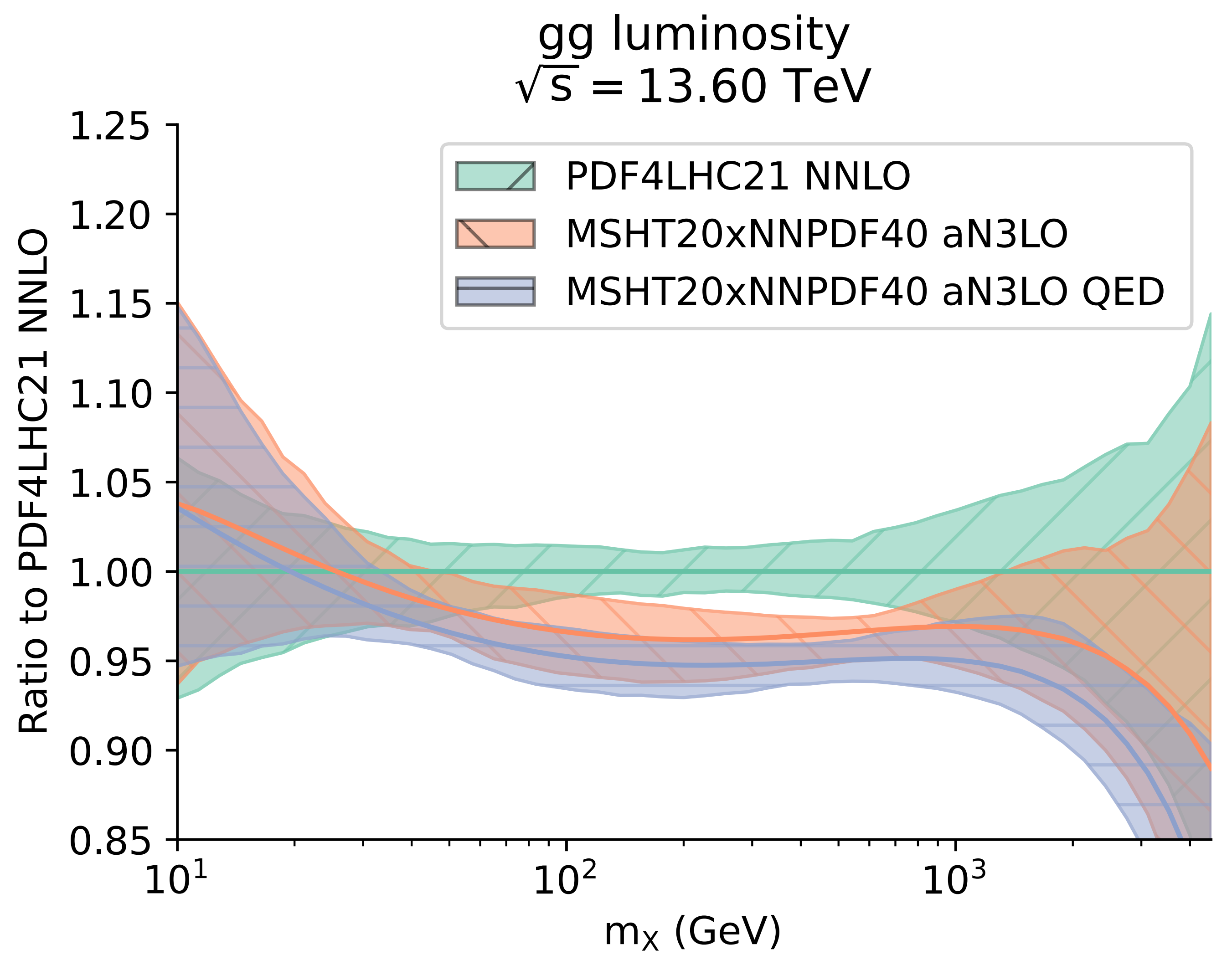


Among largest uncertainties

Warning from approximate N³LO PDFs

- 4-5% difference wrt NNLO (not covered by uncertainty bands)
- Careful assessment required

[MSHT&NNPDF, 2411.05373]



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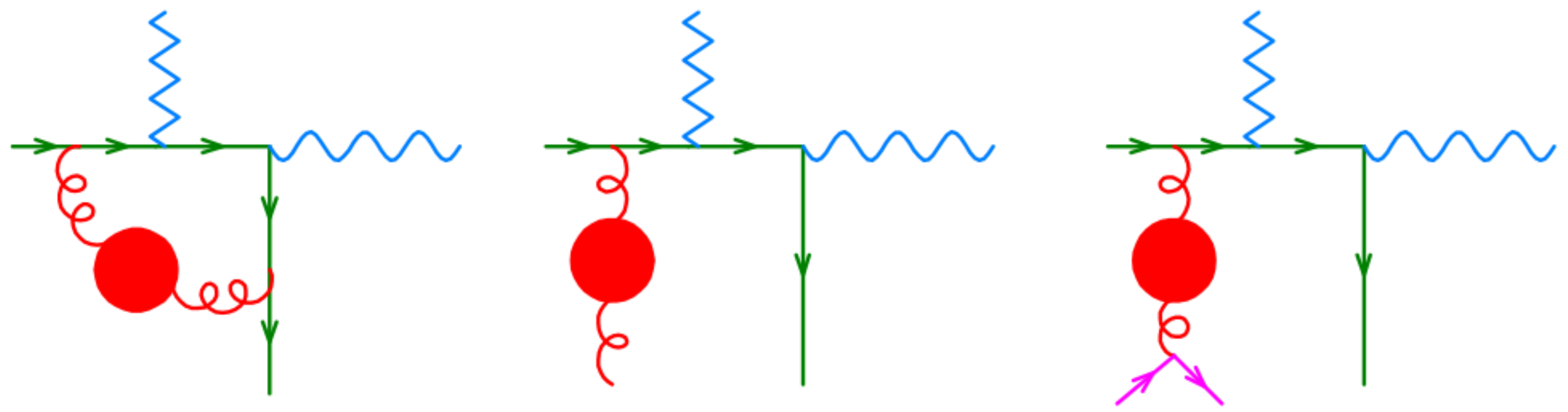
No linear renormalon in DY pt spectrum
from a simplified renormalon calculation

[Ferrario Ravasio et at, 2011.14114]



Linear infrared renormalons plague the definition of top pole mass

Renormalon ambiguity 100-200 MeV

Non perturbative corrections

- Observable dependent
- With $\Lambda \lesssim 1$ GeV and $Q \approx 100$ GeV

$$\left(\frac{\Lambda}{Q}\right)^p \approx 1\,\% \quad \text{for } p = 1$$

$$\left(\frac{\Lambda}{Q}\right)^p \approx 0.01\,\% \quad \text{for } p = 2$$

DY theory: Fixed-Order Predictions - Mixed QCD-EW

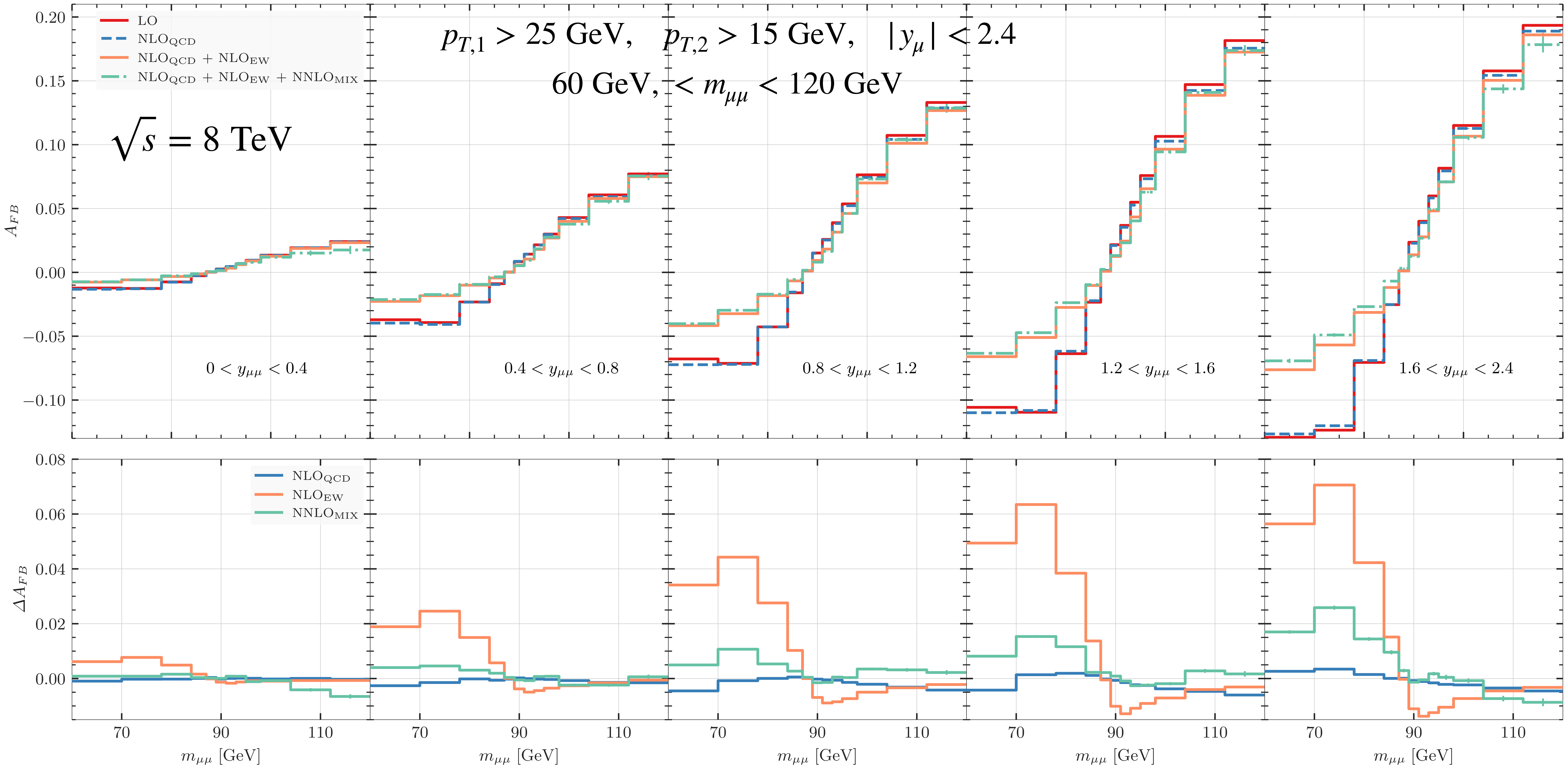
Sosme pheno results for bare muons [Armadillo,Bonciani,LB,Devoto,Grazzini,Kallweitt,Rana,Vicini '24]

$$A_{FB} = \frac{F-B}{F+B} \qquad \Delta A_{FB}^X = A_{FB}^X - A_{FB}^{LO}$$

$$\cos\theta^* = \frac{y_{\mu\mu}}{|y_{\mu\mu}|} \frac{2(p_{\mu^-}^+ p_{\mu^+}^- - p_{\mu^-}^- p_{\mu^+}^+)}{m_{\mu\mu}\sqrt{m_{\mu\mu}^2 + p_{T,\mu\mu}^2}}$$

Forward-Backward asymmetry

- Relevant for extraction of the leptonic effective weak mixing angle
- Considering forward dilepton rapidities helps to reduce the dilution of asymmetry due to symmetric pp collisions
- Double-differential distribution computation demanding
- Relatively large mixed QCD-EW effects, driven by QED FSR
- Demaning calculation: $\mathcal{O}()$ CPU hours



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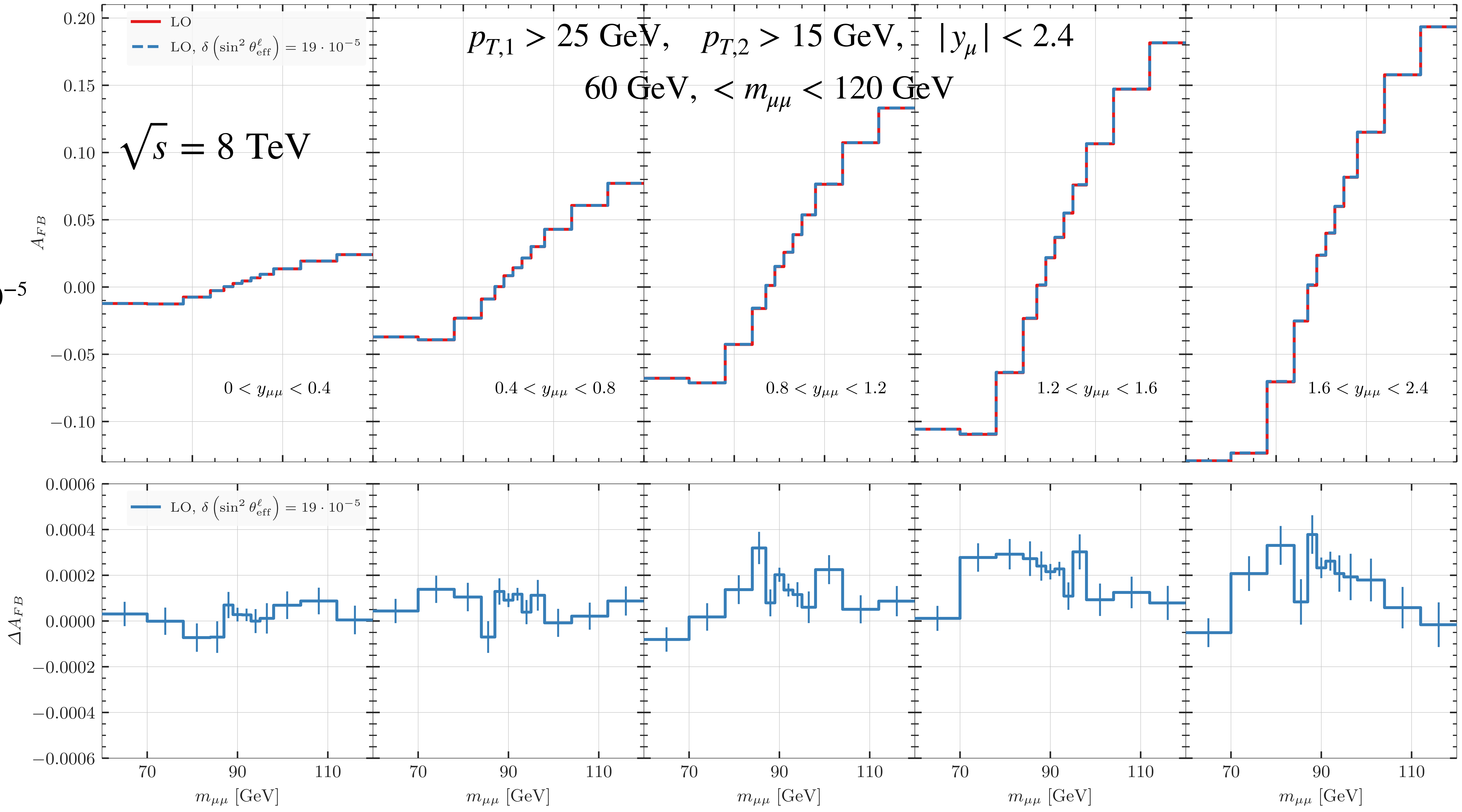
$$A_{FB} = \frac{F-B}{F+B} \qquad \Delta A^X_{FB} = A^X_{FB} - A^{LO}_{FB}$$

$$\cos\theta^* = \frac{y_{\mu\mu}}{|y_{\mu\mu}|} \frac{2(p^+_{\mu^-}p^-_{\mu^+} - p^-_{\mu^-}p^+_{\mu^+})}{m_{\mu\mu}\sqrt{m^2_{\mu\mu} + p^2_{T,\mu\mu}}}$$

- Target sensitivity on ΔA_{FB}
  $\delta m_W = 10$ MeV $\leftrightarrow \delta(sin^2\theta^\ell_{\text{eff}}) = 19 \times 10^{-5}$



First "pheno" studies

RadISH+Matrix predictions

- $\text{N}^3\text{LL}'_{\text{QCD}} + \text{N}^2\text{LO}_{\text{QCD}}$ **(pure QCD model,** `NNPDF31_nnlo_as_0118`)
- $\text{NLL}'_{\text{QCD}} + \text{NLO}_{\text{QCD}} + \text{NLL}'_{\text{EW}} + \text{NLO}_{\text{EW}}$
- $\text{N}^3\text{LL}'_{\text{QCD}} + \text{N}^2\text{LO}_{\text{QCD}} + \text{NLL}'_{\text{EW}} + \text{NLO}_{\text{EW}} + \text{nNLL}'_{\text{MIX}}$
- Caveat: not matched at $\mathcal{O}(\alpha_s \alpha)$

SETUP - NC DY (LHC @ $\sqrt{s} = 13$ TeV)

- `NNPDF31_nnlo_as_0118_luxqed`
- $p_{T,\mu} > 27$ GeV, $|y_\mu| < 2.5$, 66 GeV $< m_{\mu\mu} <$ 116 GeV
- **massive muons** (no photon lepton recombination)
- G_μ scheme, complex mass scheme
- fixed scale $\mu_F = \mu_R = m_{\mu\mu}$

Compared with
(no hadronization, no MPI, AZNLO tune)

- PWGEW+PY8+PHOTOS: include NLO QCD + NLO EW with massive leptons (and factorized mixed contributions)
- PWGQCD+PY8+PHOTOS: Simple NLO QCD + PS generator interfaced with PHOTOS to include FSR QED

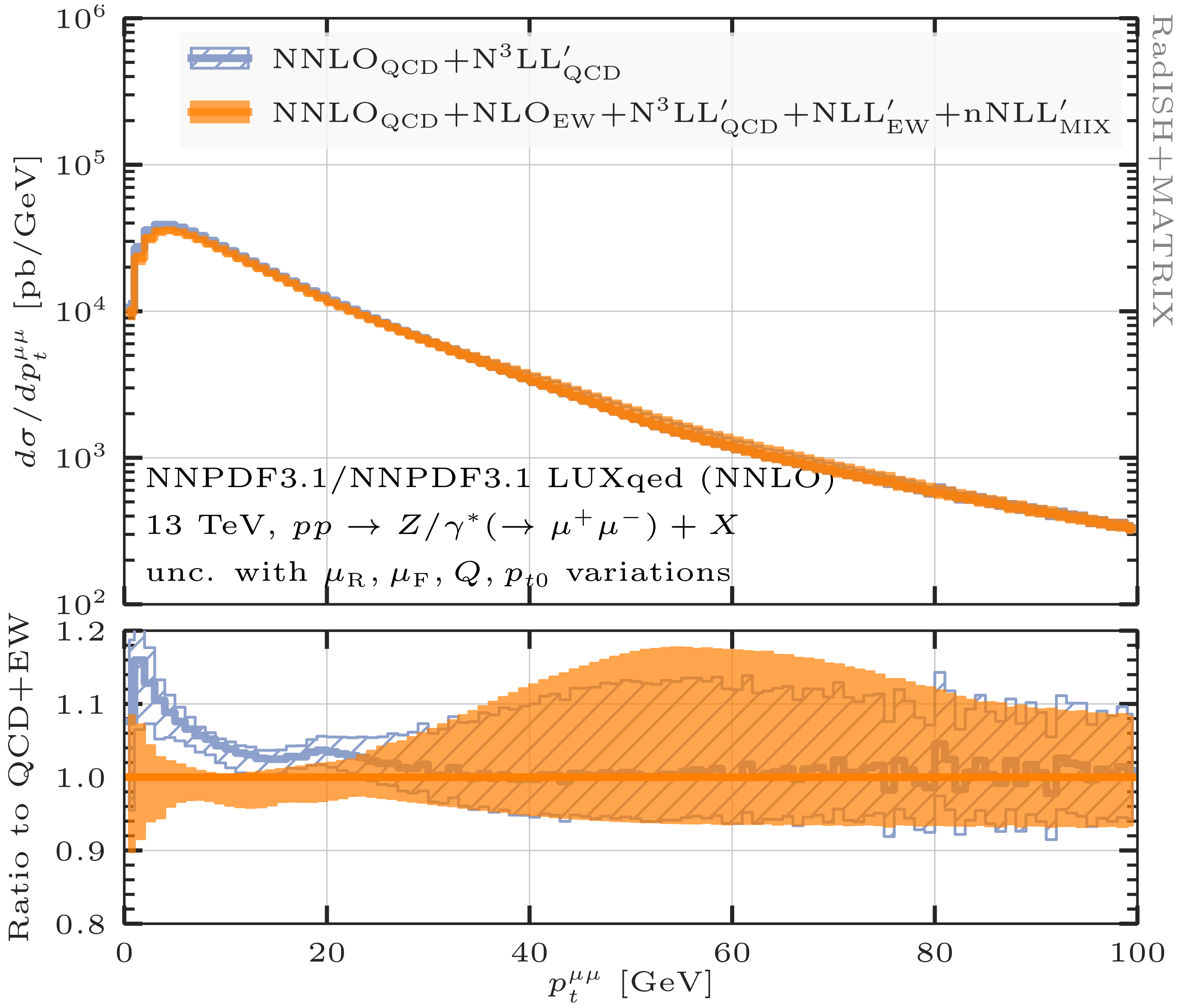
SETUP - CC DY (LHC @ $\sqrt{s} = 13$ TeV)

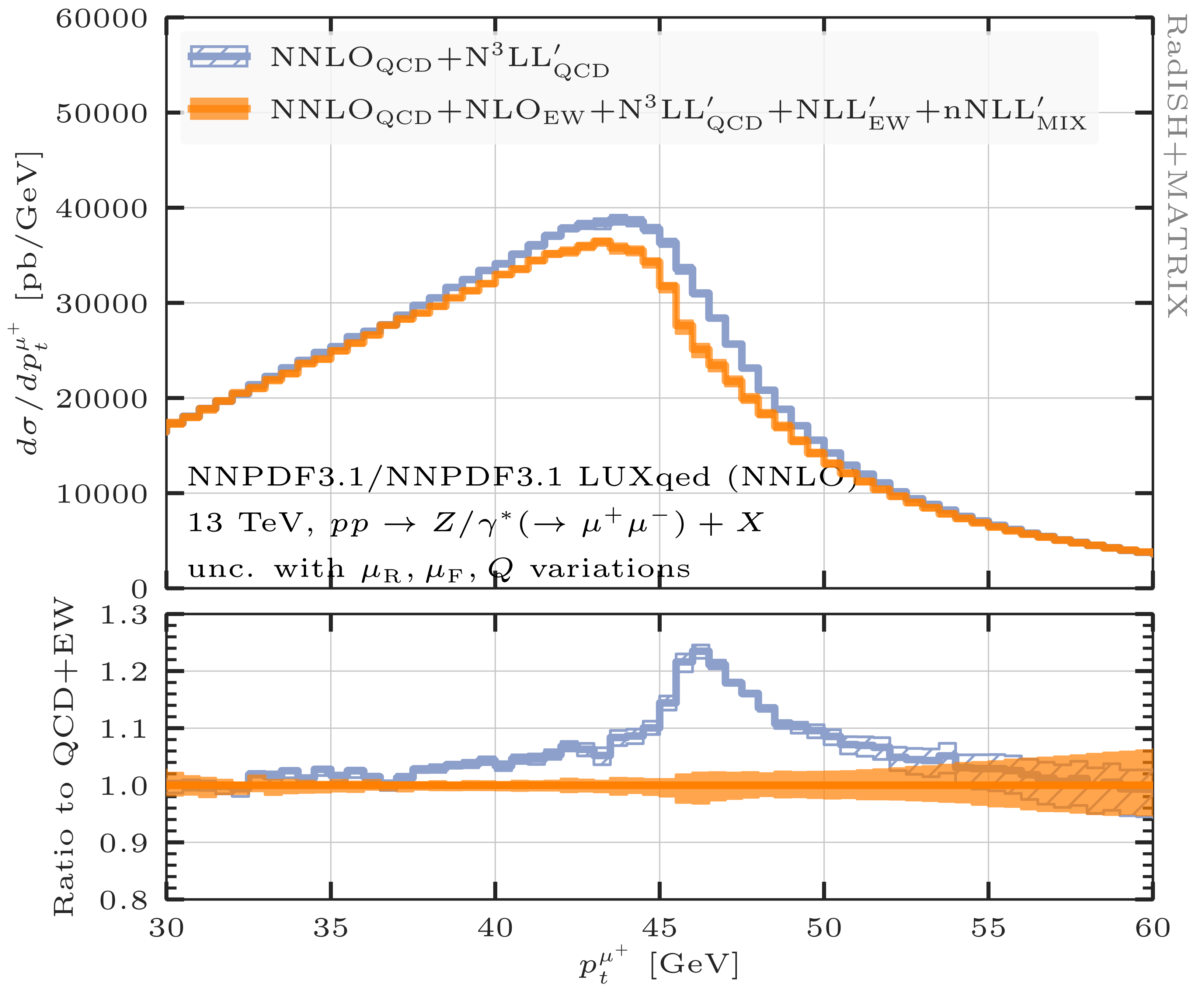
- `NNPDF31_nnlo_as_0118_luxqed`
- 26 GeV $< p_{T,\mu} <$ 55 GeV, $|y_\mu| < 2.4$, $m_T^{\mu\nu} = \sqrt{2 p_T^\mu p_T^\nu (1 - \cos \Delta\Phi^{\mu\nu})} > 40$ GeV
- massive muons (no photon lepton recombination)
- G_μ scheme, complex mass scheme
- fixed scale $\mu_F = \mu_R = \sqrt{m_{\mu\nu}^2 + (p_T^{\mu\nu})^2}$

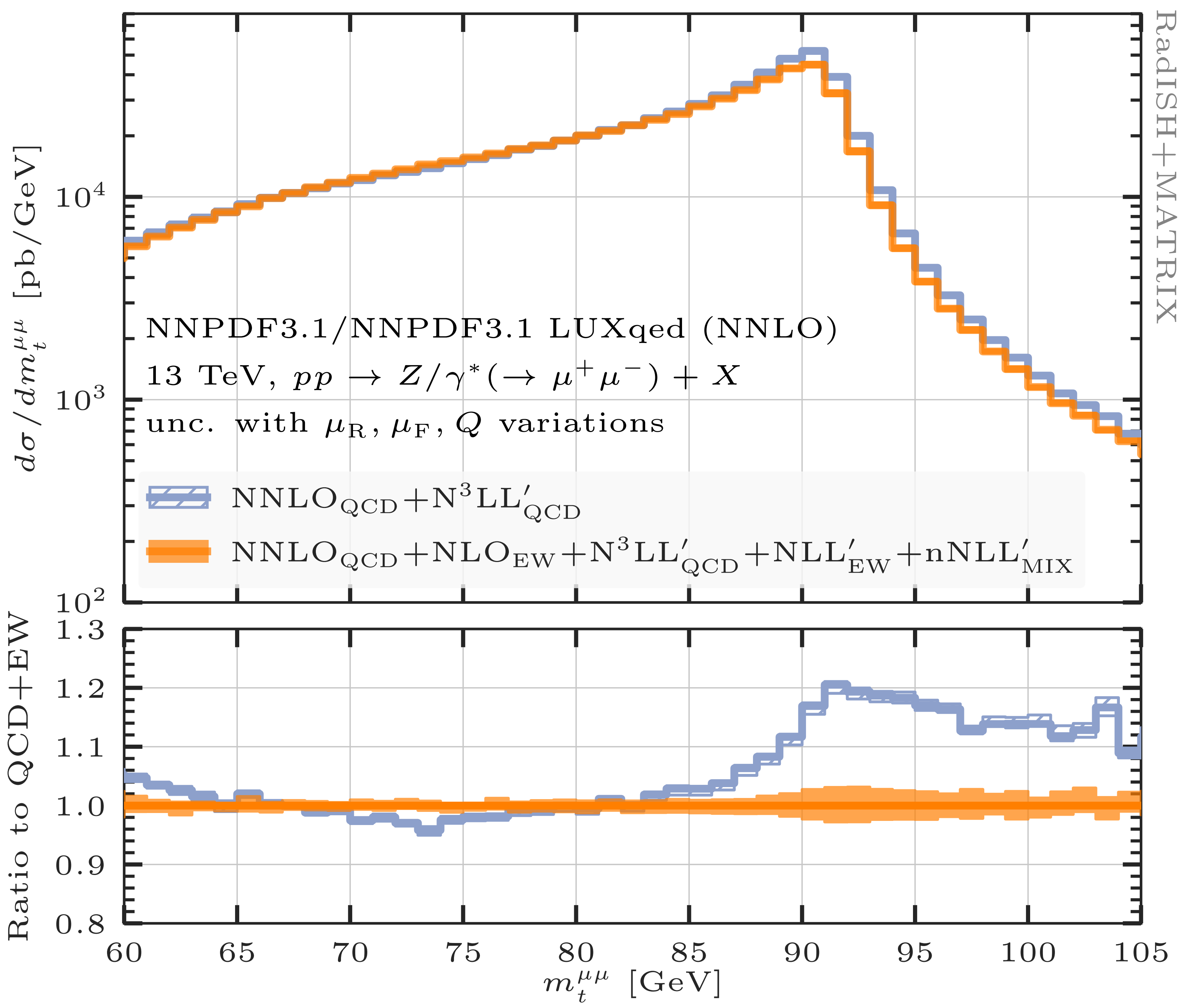
Phenomenology impact on NC DY

Impact of EW

- Large effects in observables where either all-order resummation or radiative kinematic effects are relevant
- FSR QED drives the impact of the corrections
- EW effects exceed the uncertainty bands of the pure QCD model: not unexpected as they are genuine “new” contributions



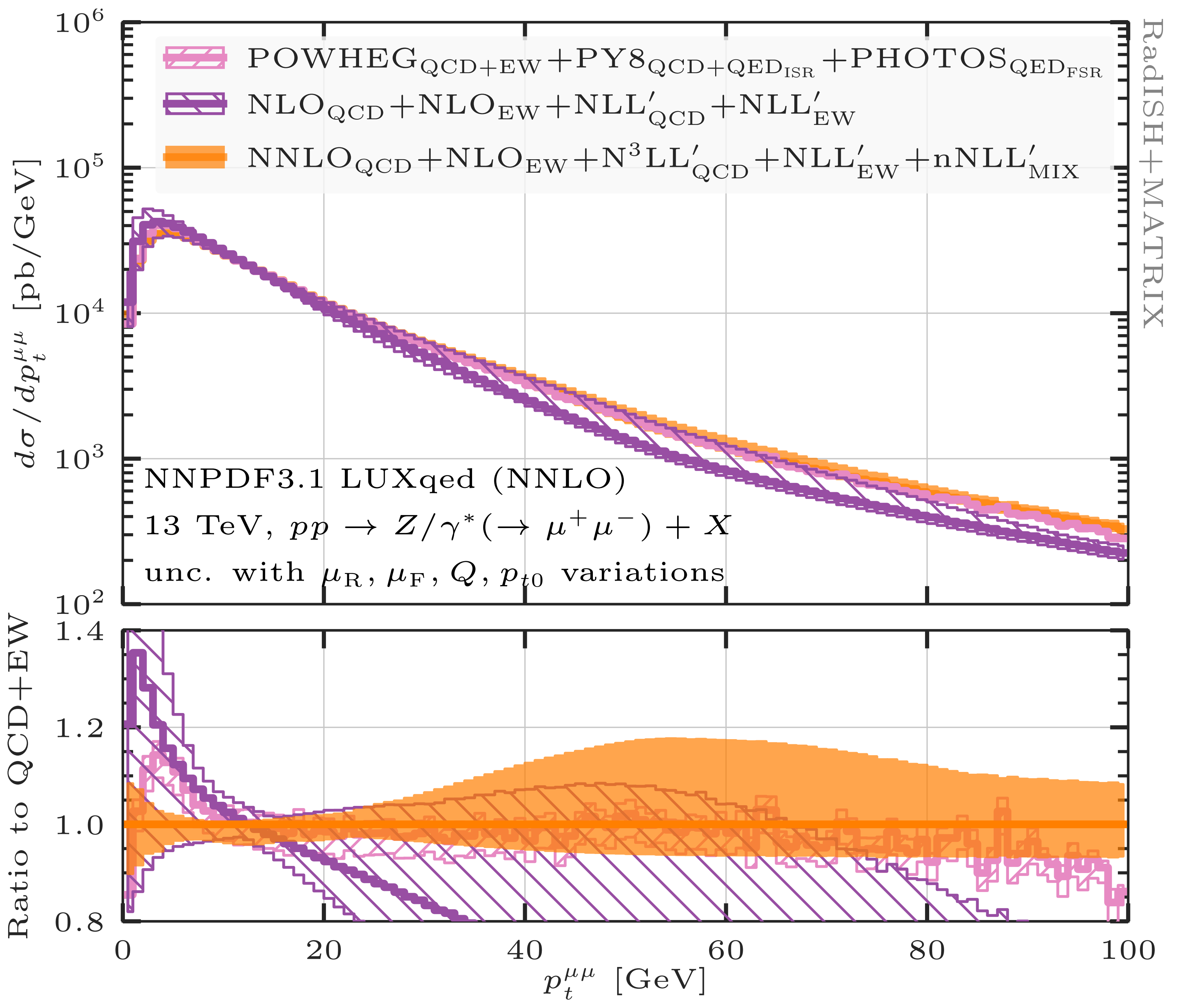


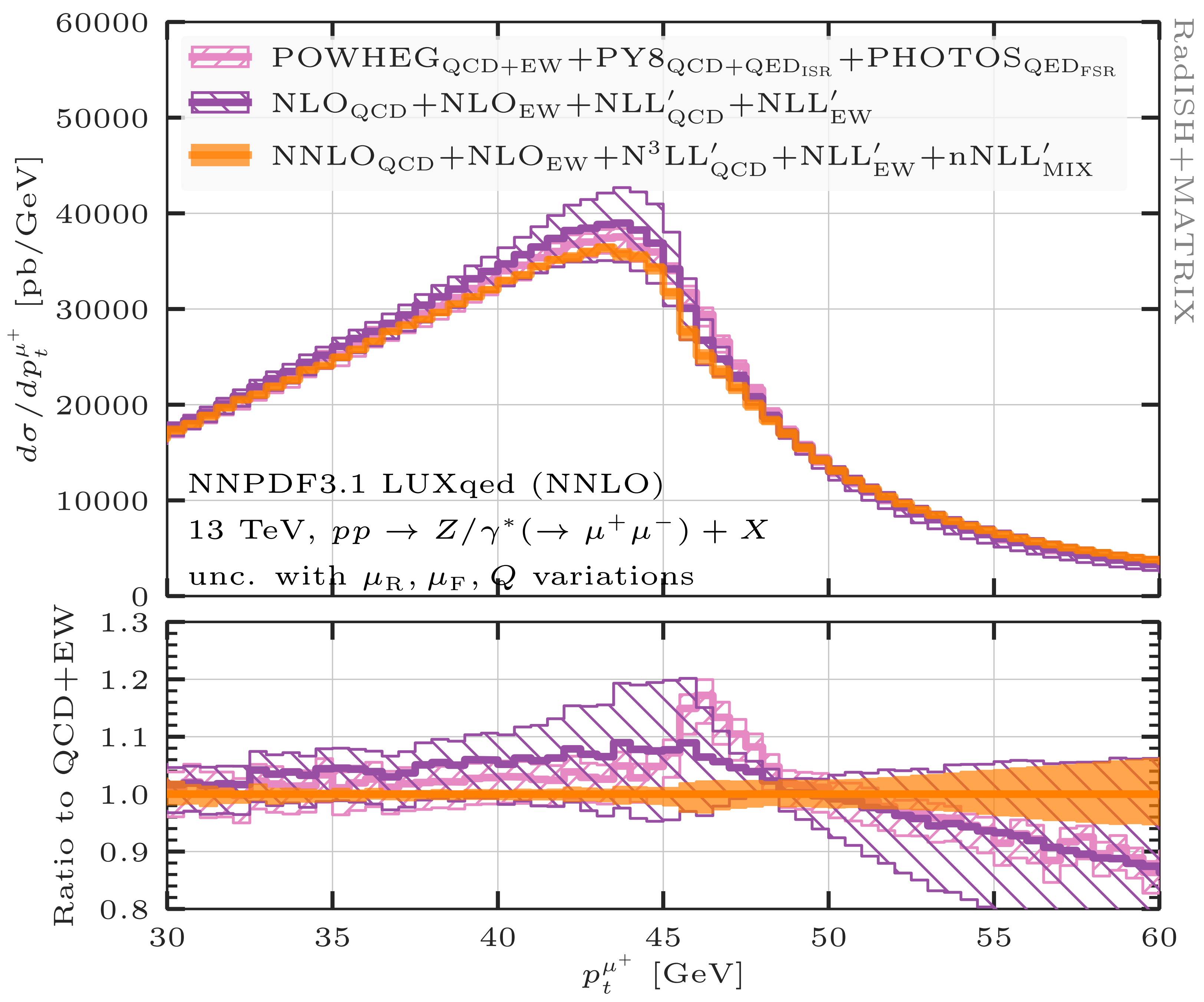


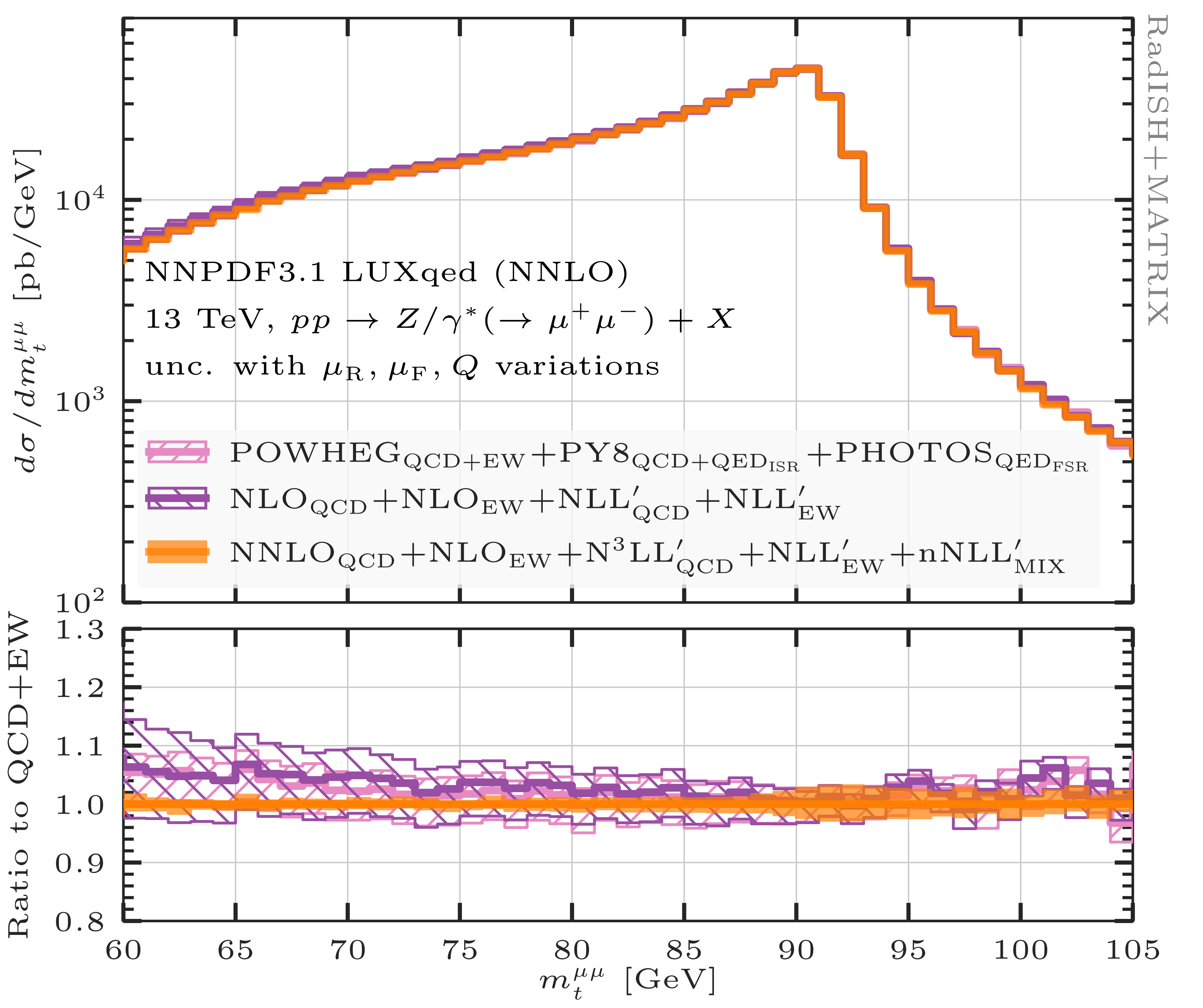
Phenomenology impact on NC DY

Comparison with PWG$_{EW}$+PY8+PHOTOS / $\mathrm{NLL}'_{\mathrm{QCD}} + \mathrm{NLO}_{\mathrm{QCD}} + \mathrm{NLL}'_{\mathrm{EW}} + \mathrm{NLO}_{\mathrm{EW}}$

- PWG$_{EW}$+PY8+PHOTOS : uncertainty bands only scale variations (no estimate of resummation uncertainties)
- Good agreement for Born observables with some shape distortion at the Jacobian peak of $p_T^{\mu^+}$
- Relative good agreement at small transverse momentum, large differences in the transition region; delayed matching to fixed order result for PWG$_{EW}$+PY8+PHOTOS (accidentally closer to the higher-order result)





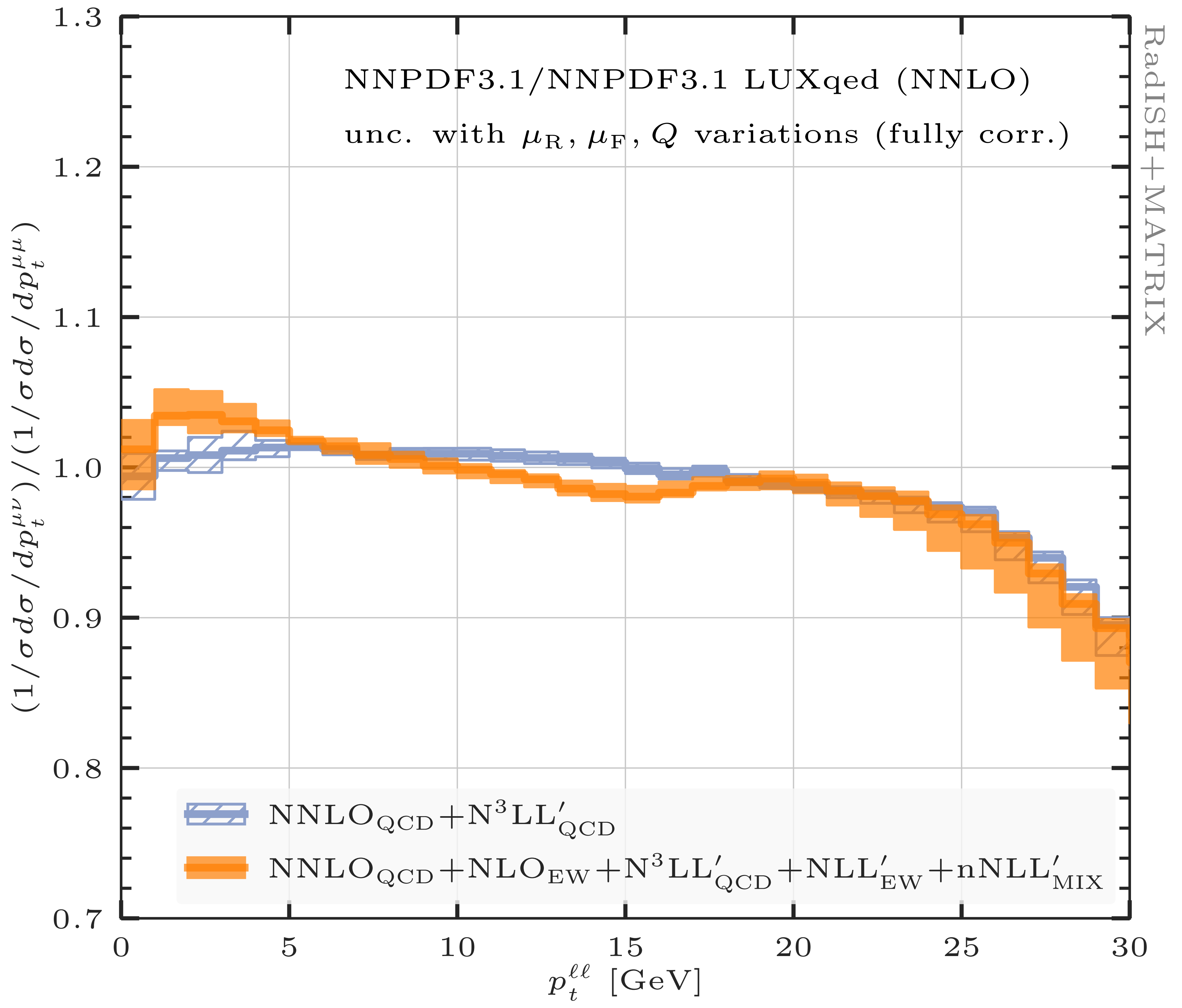


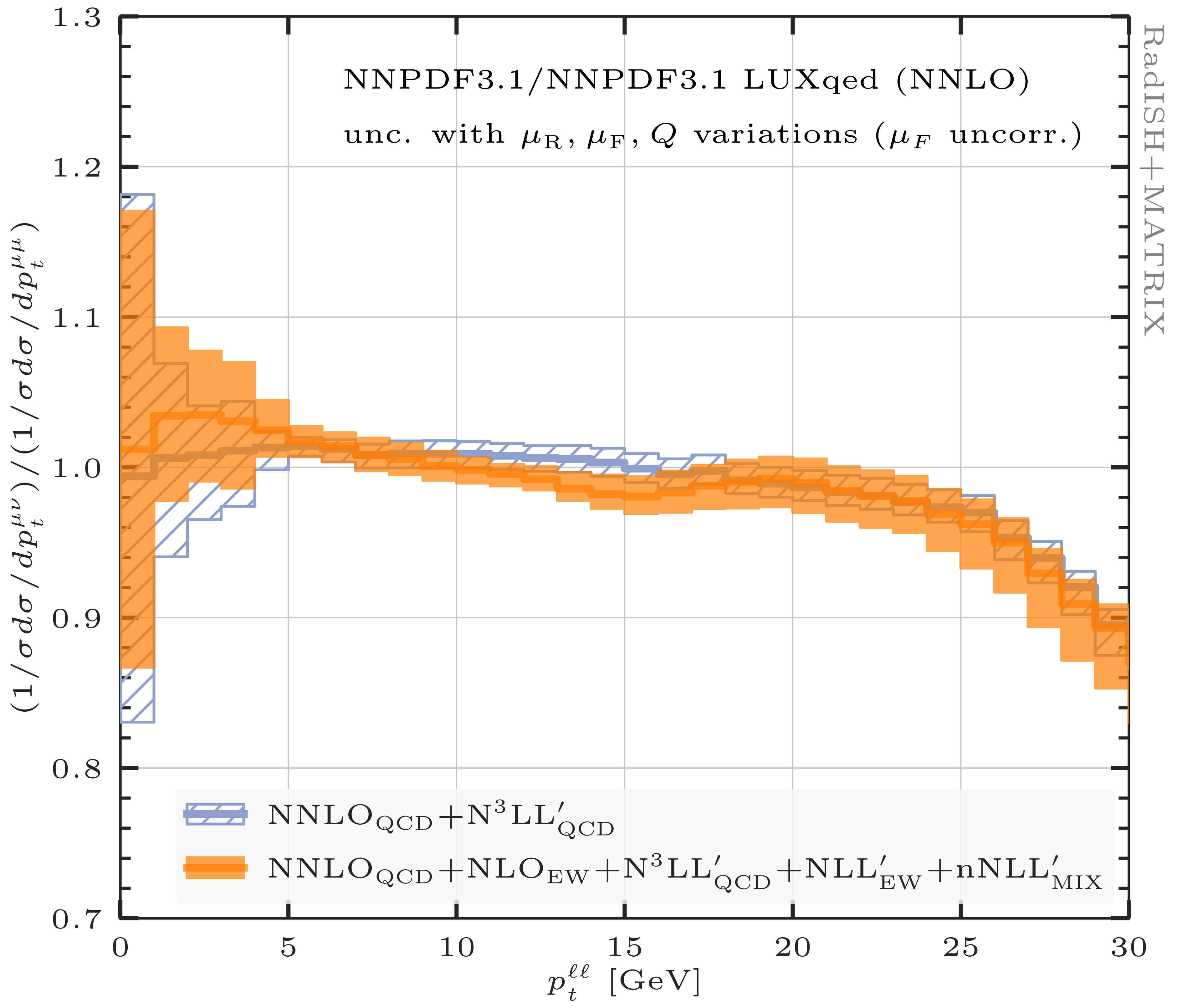
(Normalised) Ratio p_T^W / p_T^Z

Key ingredient in experimental strategies for measuring the W mass

- The impact of EW effects on the normalized ratio is mild but not negligible
- Under the assumption of correlated μ_R and uncorrelated μ_F variations, barely overlap within uncertainty bands

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





Ratio p_T^W / p_T^Z

Comparison with PWG$_{\text{EW}}$+PY8+PHOTOS, PWG$_{\text{QCD}}$+PY8+PHOTOS and $\text{NLL}'_{\text{QCD}} + \text{NLO}_{\text{QCD}} + \text{NLL}'_{\text{EW}} + \text{NLO}_{\text{EW}}$

- Nice perturbative stability and robustness against shower tuning
- Better agreement of "simpler" PWG$_{\text{QCD}}$+PY8+PHOTOS to RadISH, residual difference similar to pure QCD case
- PWG$_{\text{EW}}$+PY8+PHOTOS result deviates significantly from our best prediction