Università degli Studi
di Milano

Istituto Nazionale
di Fisica Nucleare

Precision Standard Model physics at LHC

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LHCb implications workshop CERN, October 25th 2024

Outline

Precision physics at the LHC and future colliders

Developments in the prediction of standard candles: towards fermion-pair production at NNLO (QCD + QCDxEW + EW)

Interplay of PDF studies and SM parameters determination

Motivations

Motivation: statistical precision from small to large fermion-pair invariant masses

Statistical errors

FCC-ee $\sigma(e^+e^- \to \mu^+\mu^- + X)$
arXiv:2206.08326

sqrt(S) (GeV)	luminosity (ab^{-1})	σ (fb)	% error
91	150	$2.17595\ 10^6$	0.0002
240	5	1870.84 ± 0.612	0.03
365	1,5	787.74 ± 0.725	0.09

LHC and HL-LHC $\sigma(pp \to \mu^+\mu^- + X)$
arXiv:2106.11953

bin range (GeV)	% error 140 fb^{-1}	% error 3 ab^{-1}
91-92	0.03	$6\ 10^{-3}$
120-400	0.1	0.02
400-600	0.6	0.13
600-900	1.4	0.30
900-1300	3.2	0.69

Theoretical systematics

EW input parameters
large QED corrections
increasingly large EW corrections

proton PDFs
increasingly large QCD, QCD-EW and EW corrections

Are we able to reach (at least) 0.1% precision throughout the whole invariant mass range?

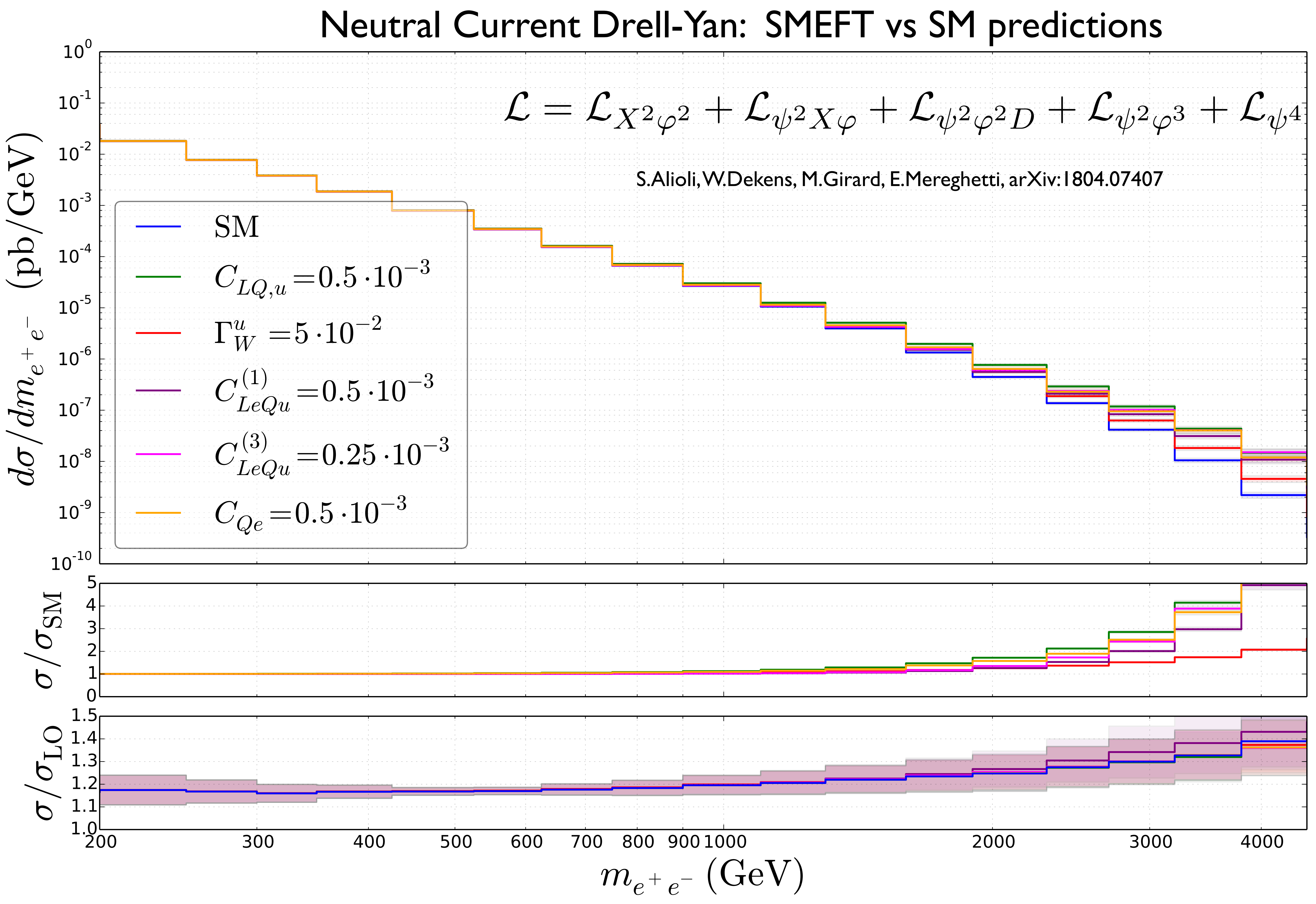
LHCb luminosity at HL-LHC (50 fb^{-1}) implies a rescaling of the errors by a factor $\sqrt{60} \sim 7.7$ the challenge remains

Motivation: impact of higher dimension operators, as a function of the invariant mass

The parameterisation of BSM physics
in the SMEFT language
can be probed by studying the impact
of higher dimension operators
as a function of energy.

Deviations from the SM prediction
require to answer the question
“What is the SM?”

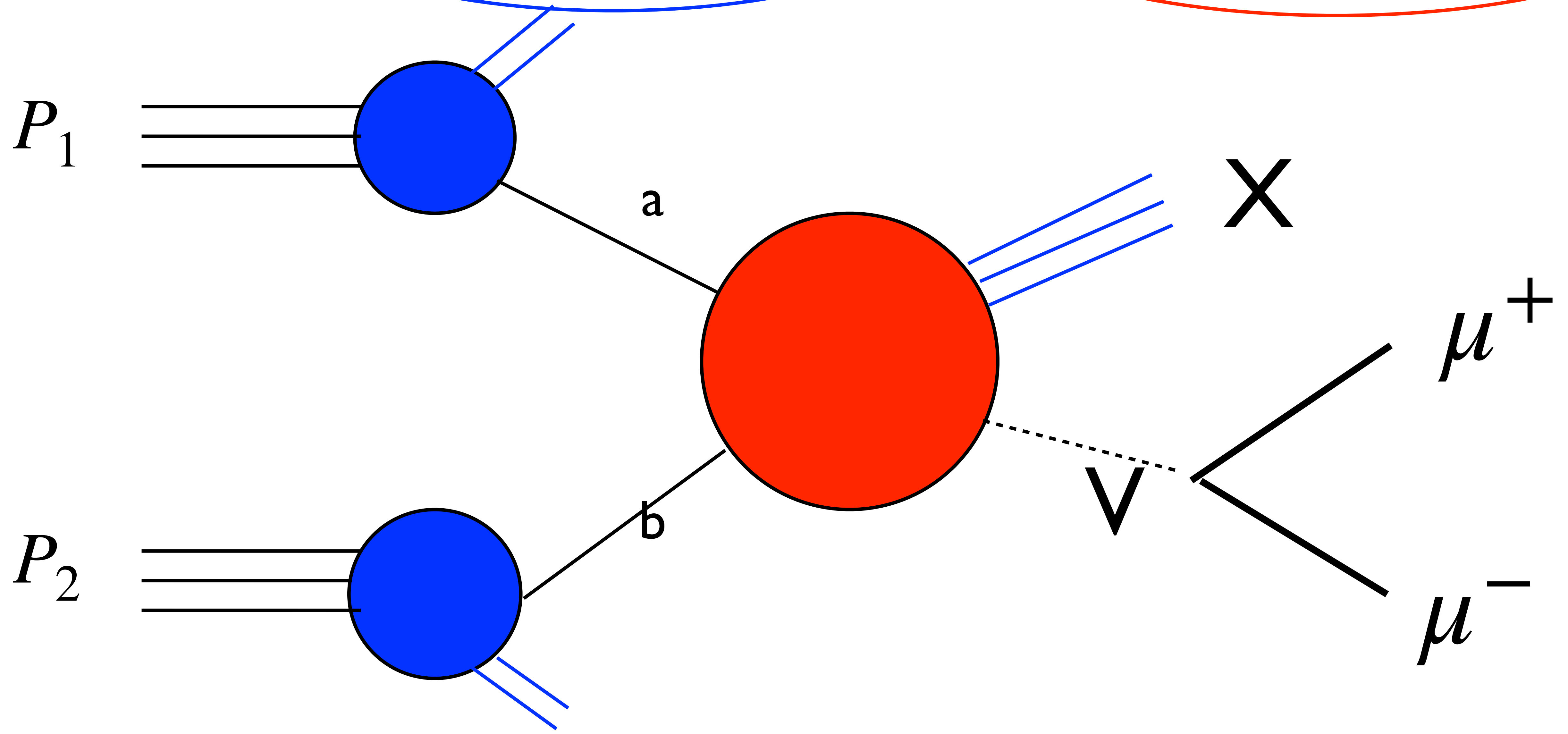
→ SM predictions have to be
at the same precision level of the data
i.e. (sub) per mille level



Computational framework

Factorisation theorems and the cross section in the partonic formalism

$$\sigma(P_1, P_2; m_V) = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1, M_F) f_{h_2,b}(x_2, M_F)\, \hat{\sigma}_{ab}(x_1 P_1, x_2 P_2, \alpha_s(\mu), M_F)$$



Particles $P_{1,2}$ can be protons (→ Drell-Yan @ LHC) or leptons (→ FCC-ee, muon collider)

The partonic content of the scattering particles can be expressed in terms of PDFs

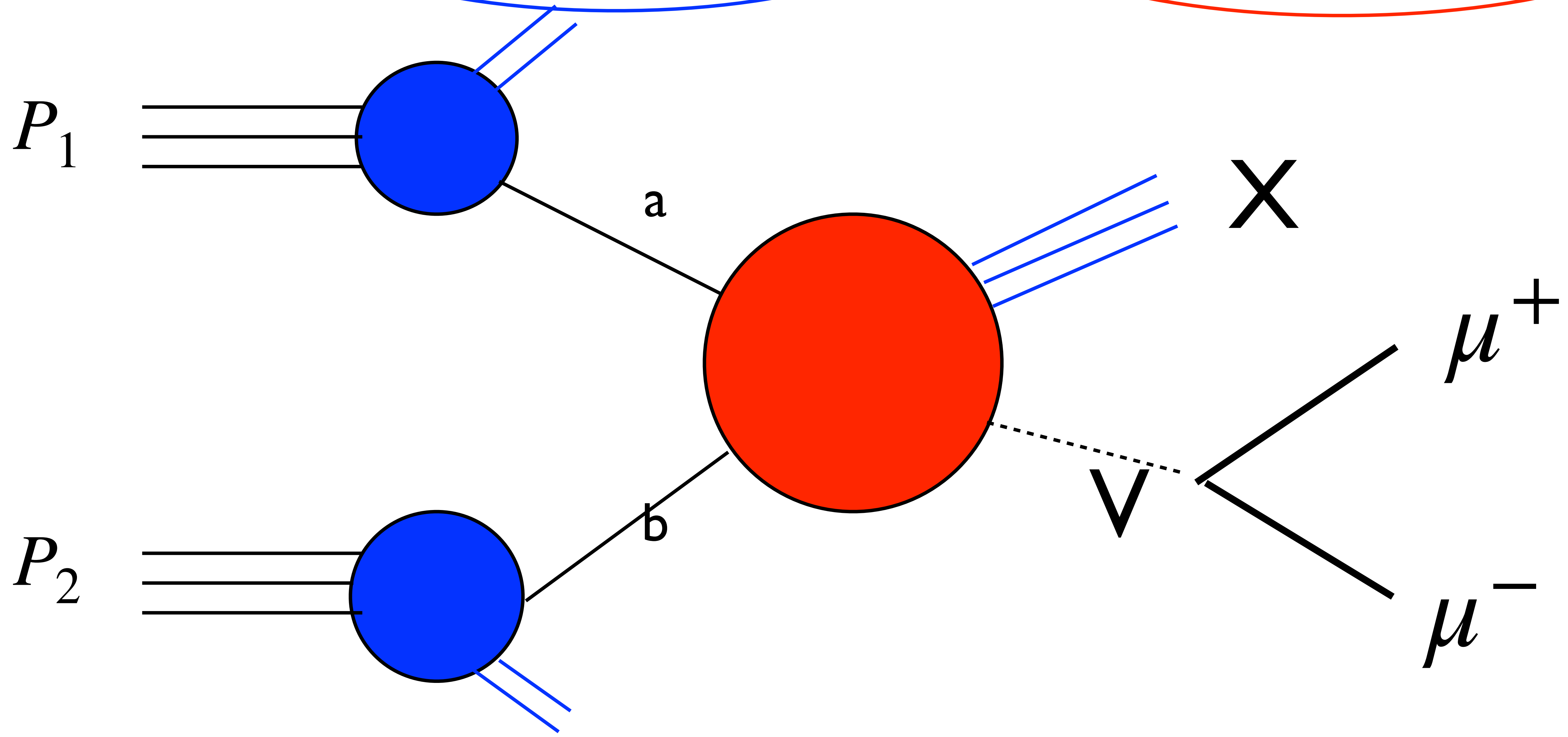
proton PDFs: ABM, CT18, MSHT, NNPDF,… lepton PDFs: Frixione et al. arXiv:1911.12040

The partonic scattering can be computed in perturbation theory, in the full QCD+EW theory, exploiting the theoretical progress in QCD, in the understanding of its IR structure

Factorisation theorems guarantee the validity of the above picture up to power correction effects

Factorisation theorems and the cross section in the partonic formalism

$$\sigma(P_1,P_2;m_V) = \sum_{a,b}\int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1,M_F)\, f_{h_2,b}(x_2,M_F)\, \hat{\sigma}_{ab}(x_1P_1, x_2P_2, \alpha_s(\mu), M_F)$$



The partonic scattering requires a combination of:

- fixed-order results → accuracy of the xsec normalisation
- resummation to all order of logarithmically enhanced terms → curing the breakdown of perturbation theory in specific phase-space regions

The matching (removing double countings) is subject to an ambiguity

The Drell-Yan cross section in a fixed-order expansion

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Assuming that the all-orders corrections are under control at sub-percent level
we can discuss the evaluation of the hard partonic cross section

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we can discuss the evaluation of the hard partonic cross section

Drell-Yan (1970)

Baur, Brein, Hollik, Schappacher, Wackeroth (2001)

$$\sigma(h_1 h_2 \to \ell \bar{\ell} + X) = \sigma^{(0,0)} +$$

Altarelli, Ellis, Martinelli (1978)

$$\alpha_s\, \sigma^{(1,0)} + \alpha\, \sigma^{(0,1)} +$$

Hamberg, Matsuura, van Nerveen, (1991)
Anastasiou, Dixon, Melnikov, Petriello, (2003)
Catani, Cieri, Ferrera, de Florian, Grazzini (2009)

$$\alpha_s^2\, \sigma^{(2,0)} + \alpha\, \alpha_s\, \sigma^{(1,1)} + \alpha^2\, \sigma^{(0,2)} +$$

$$\alpha_s^3\, \sigma^{(3,0)} + \ldots$$

C.Duhr, B.Mistlberger, arXiv:2111.10379

still missing
Sudakov high-energy approximations

Neutral Current

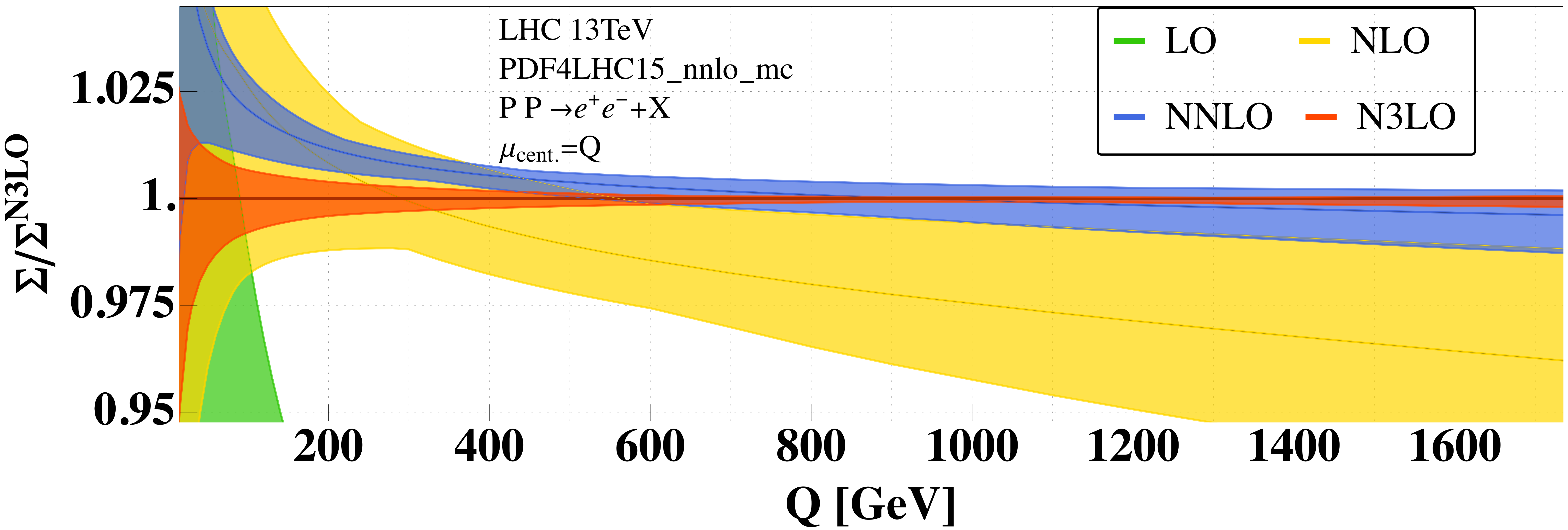
R.Bonciani, L.Buonocore, M.Grazzini, S.Kallweit, N.Rana, F.Tramontano, AV, (2021)
T.Armadillo, R.Bonciani, S.Devoto, N.Rana, AV, (2022)
F.Buccioni, F.Caola, H.Chawdhry, F.Devoto, M.Heller, A.von Manteuffel, K.Melnikov, R.Röntsch, C.Signorile-Signorile, (2022)

New!!! Charged-current 2-loop amplitude

T.Armadillo, R.Bonciani, S.Devoto, N.Rana, AV, (2024)

QCD results: lepton-pair invariant mass

C.Duhr, B.Mistlberger, arXiv:2111.10379



Thanks to the N3LO-QCD results for the Drell-Yan cross section, scale variation band at the few per mille level at any Q

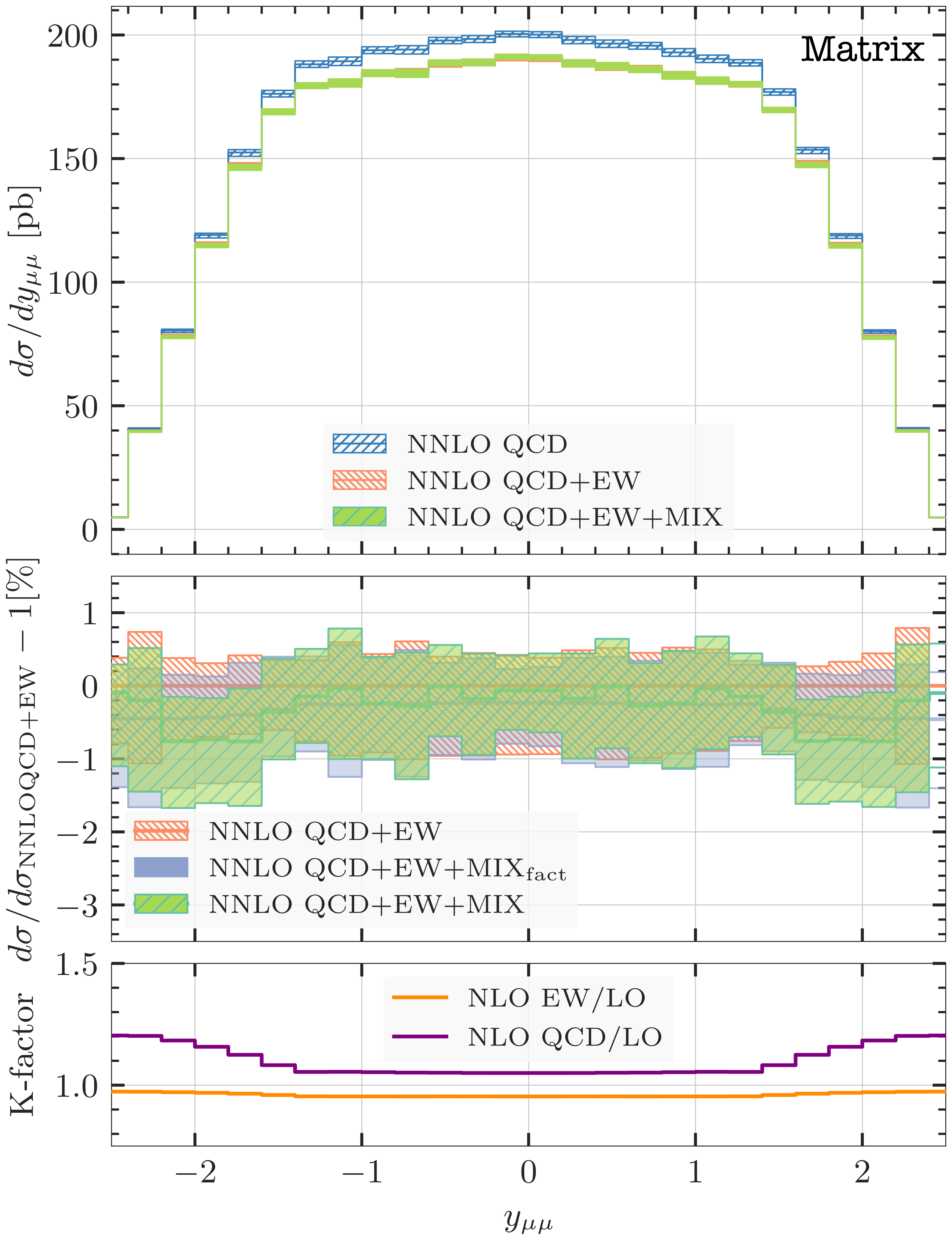
The PDFs are not yet at N3LO

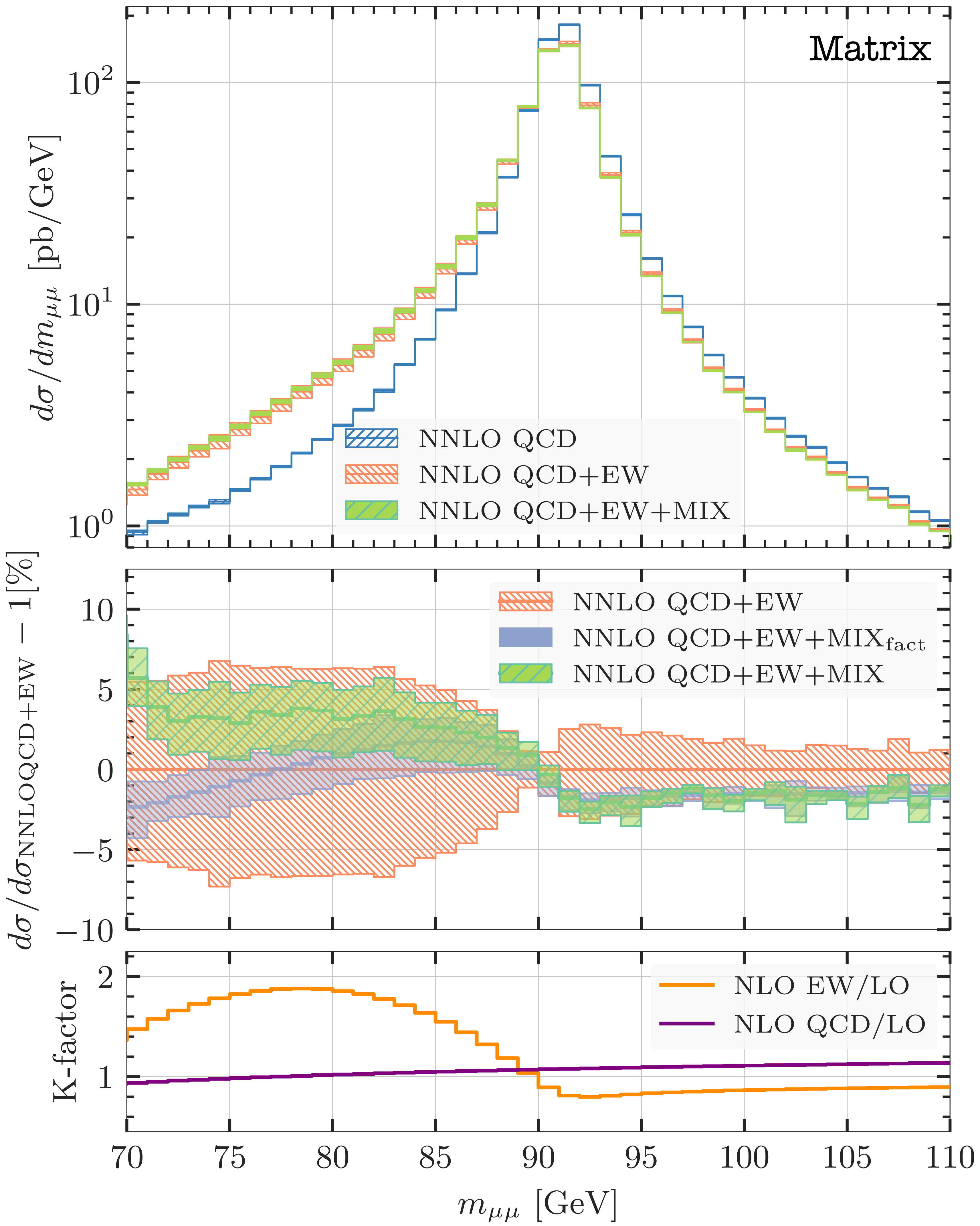
This is promising, in view of the program of searches for deviation from the SM in the TeV range

What about NNLO QCD-EW and NNLO-EW corrections ?

Phenomenology of Neutral Current Drell-Yan including exact NNLO QCD-EW corrections

T.Armadillo, R.Bonciani, L.Buonocore, S.Devoto, M.Grazzini, S.Kallweit, N.Rana, F.Tramontano, AV, arXiv:2106.11953 , Phys.Rev.Lett. 128 (2022) 1, 012002 and work in preparation





Non-trivial distortion of the rapidity distribution (absent in the naive factorised approximation)

Large effects below the Z resonance

O(-1.5%) effects above the resonance

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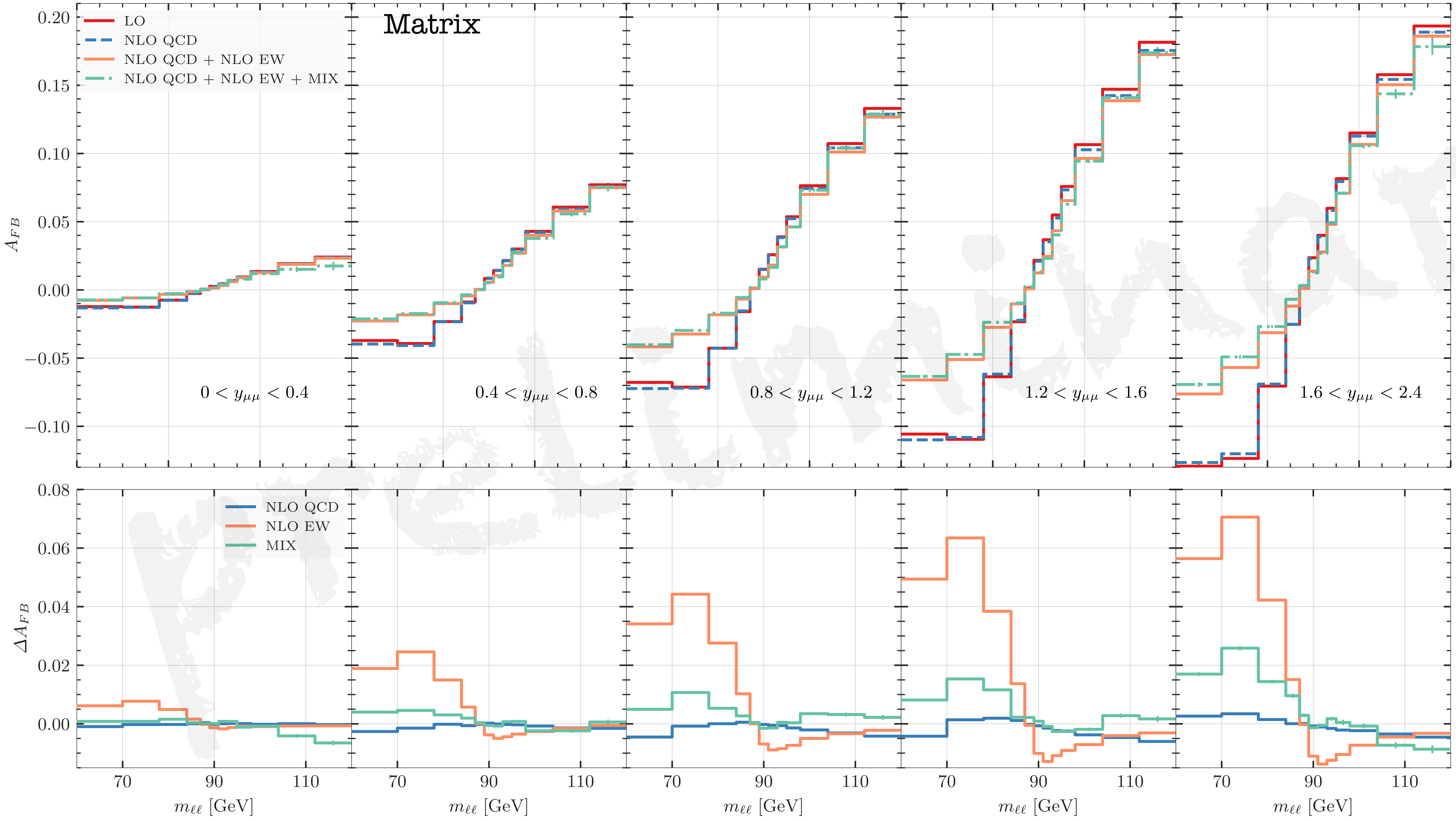
The forward-backward asymmetry $A_{FB}(m_{\ell\ell})$ as a function of the lepton-pair rapidity



Sizeable mixed QCD-EW effects on A_{FB} below the Z resonance → impact on the $\sin^2\theta_{eff}$ determination

A good fraction is already taken into account in MC tools when combining QCD with QED-FSR

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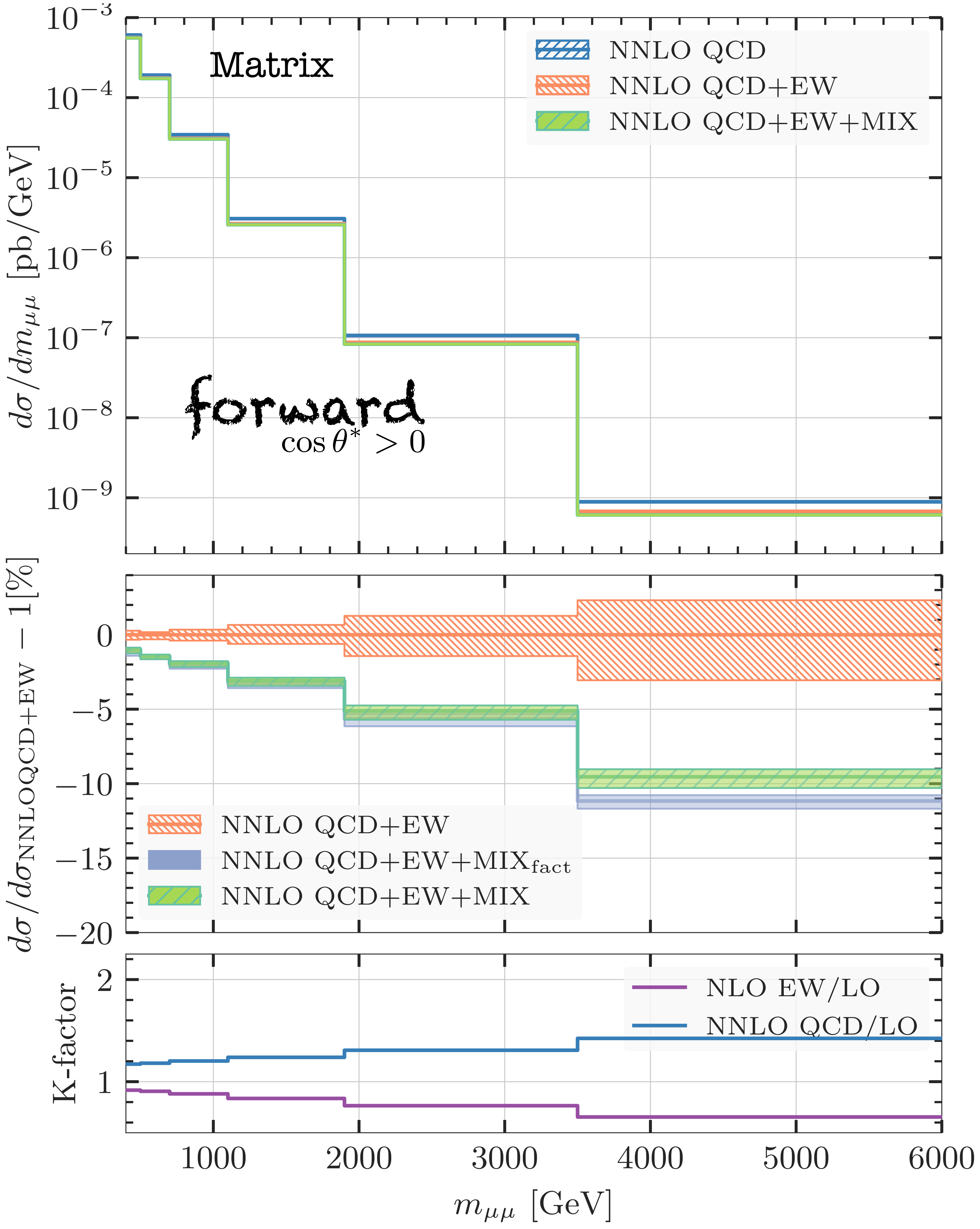
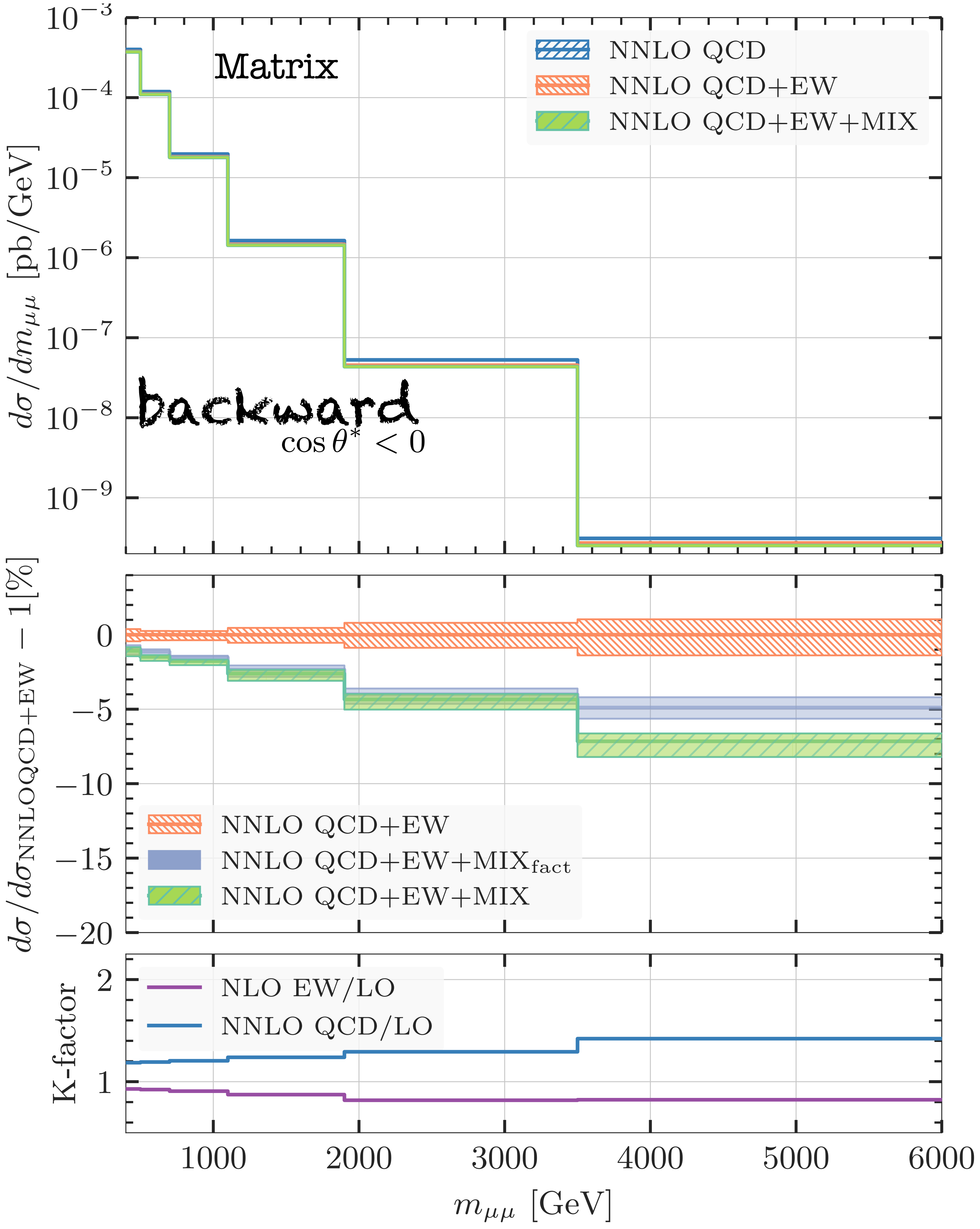


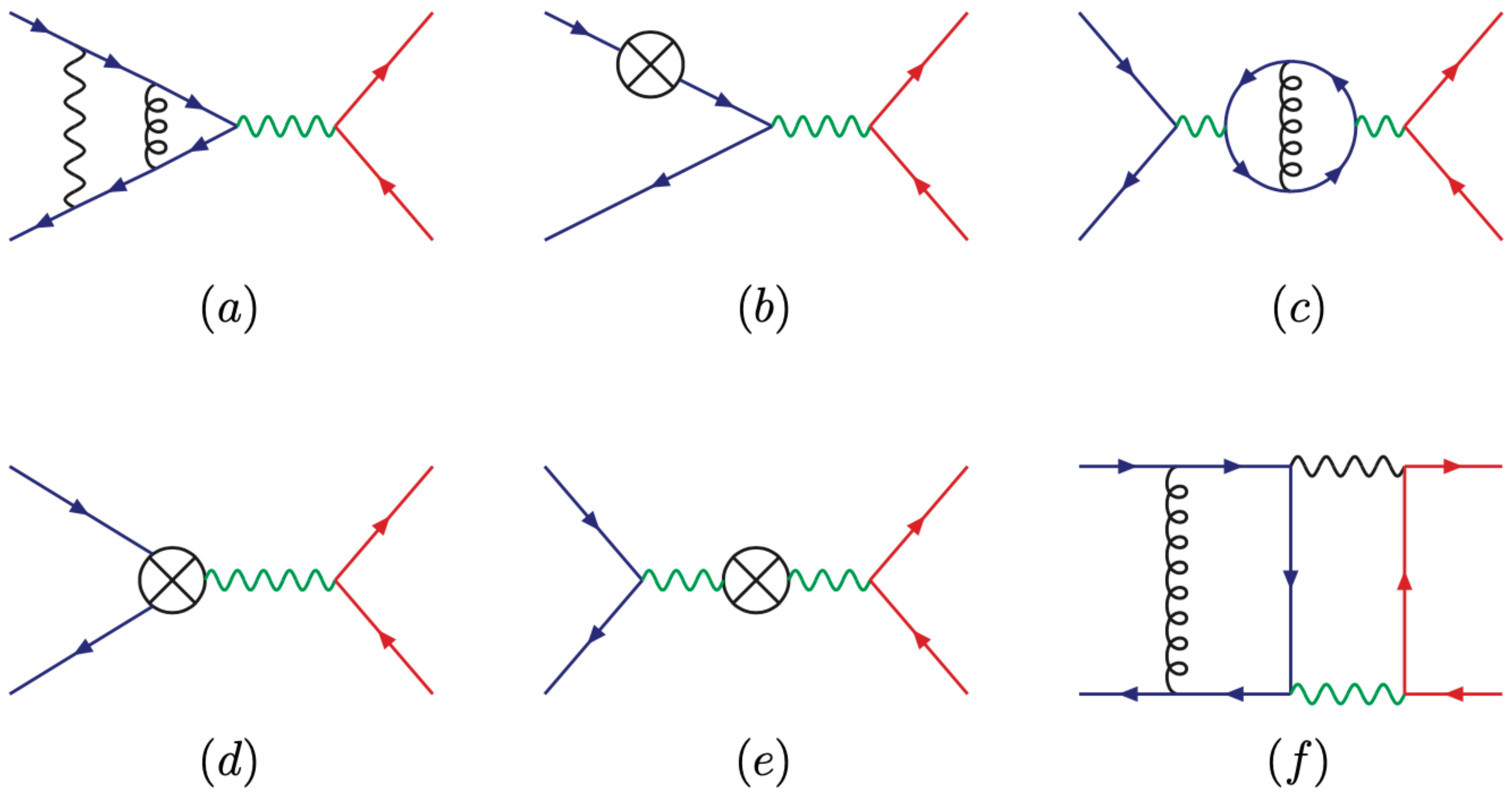


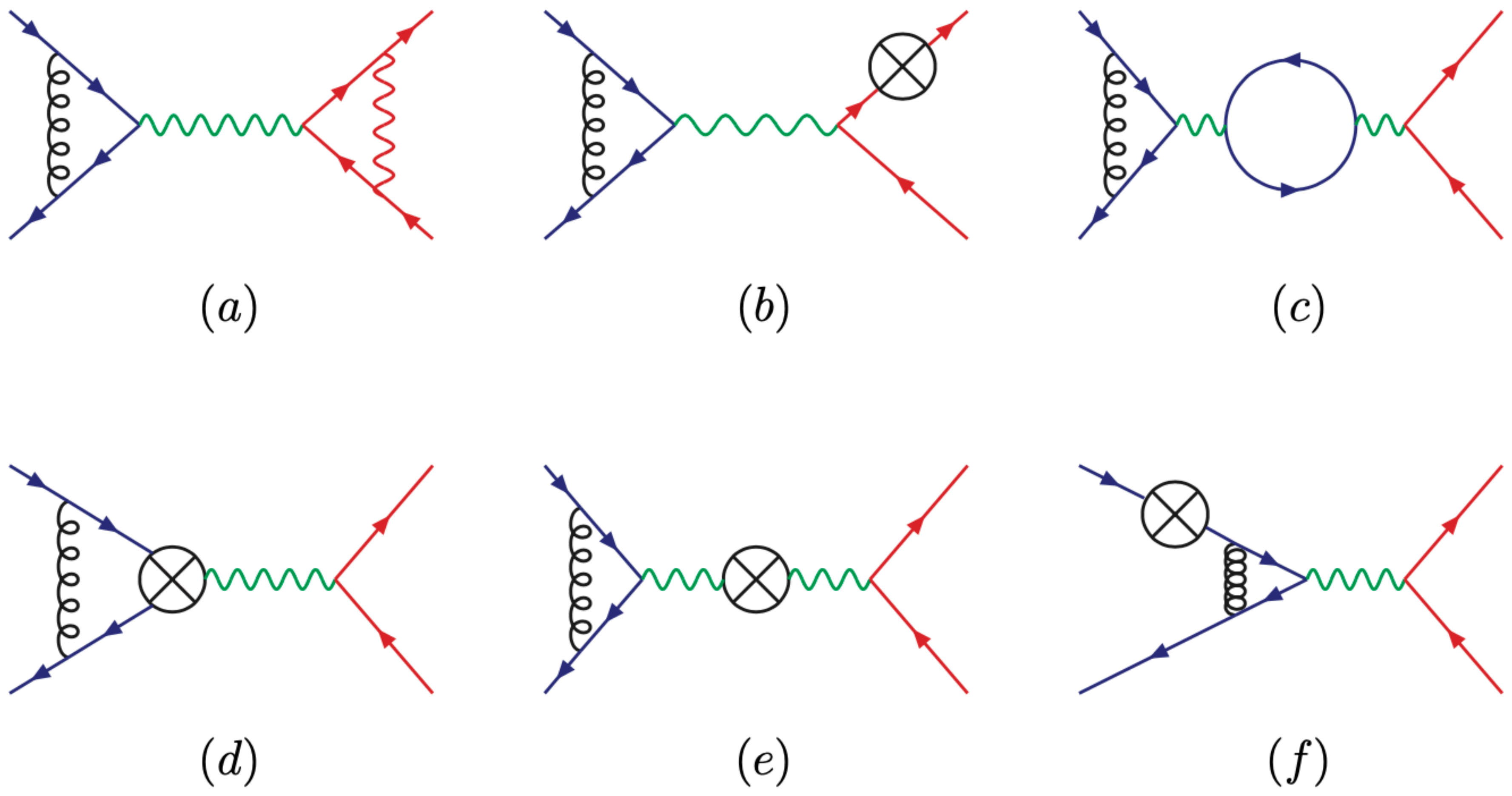
Negative mixed NNLO QCD-EW effects (-3% or more) at large invariant masses,

absent in any additive combination → impact on the searches for new physics → impact on PDF determination

2-loop virtual QCD-EW corrections to the Charged-Current Drell-Yan in the SM

T.Armadillo, R.Bonciani, S.Devoto, N.Rana, AV, arXiv:2405.00612





The Charged-Current process is mediated by a *W* exchange

No general gauge invariant separation of ISR- and FSR-QED,
beyond the LL level
at variance with the NC DY case

Weak bosons with different masses (*W* and *Z*)
→ new challenge for the solution of the Feynman integrals

Semi-analytic representation with power expansions

Large number of terms O(100 MB) → increased automation level

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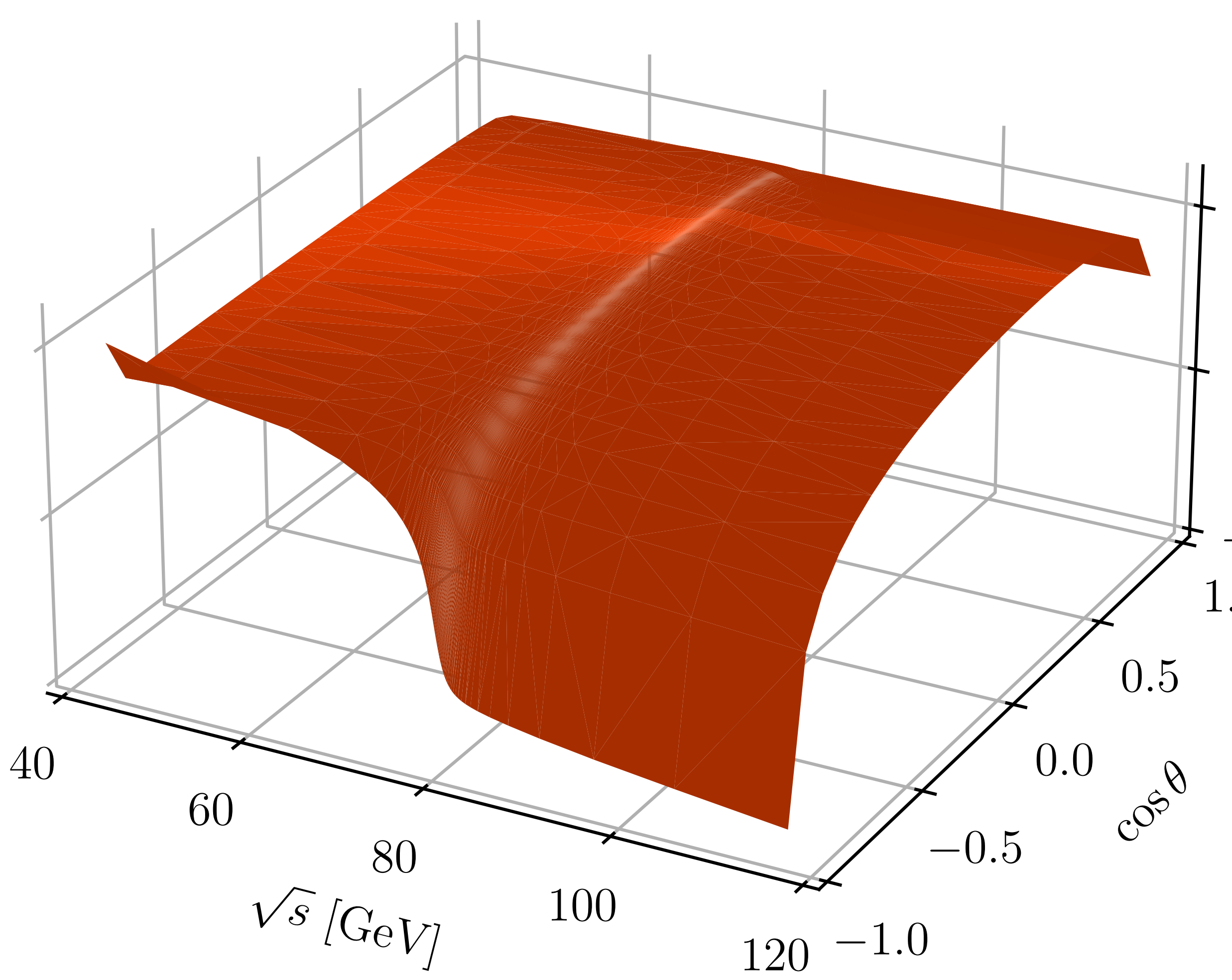
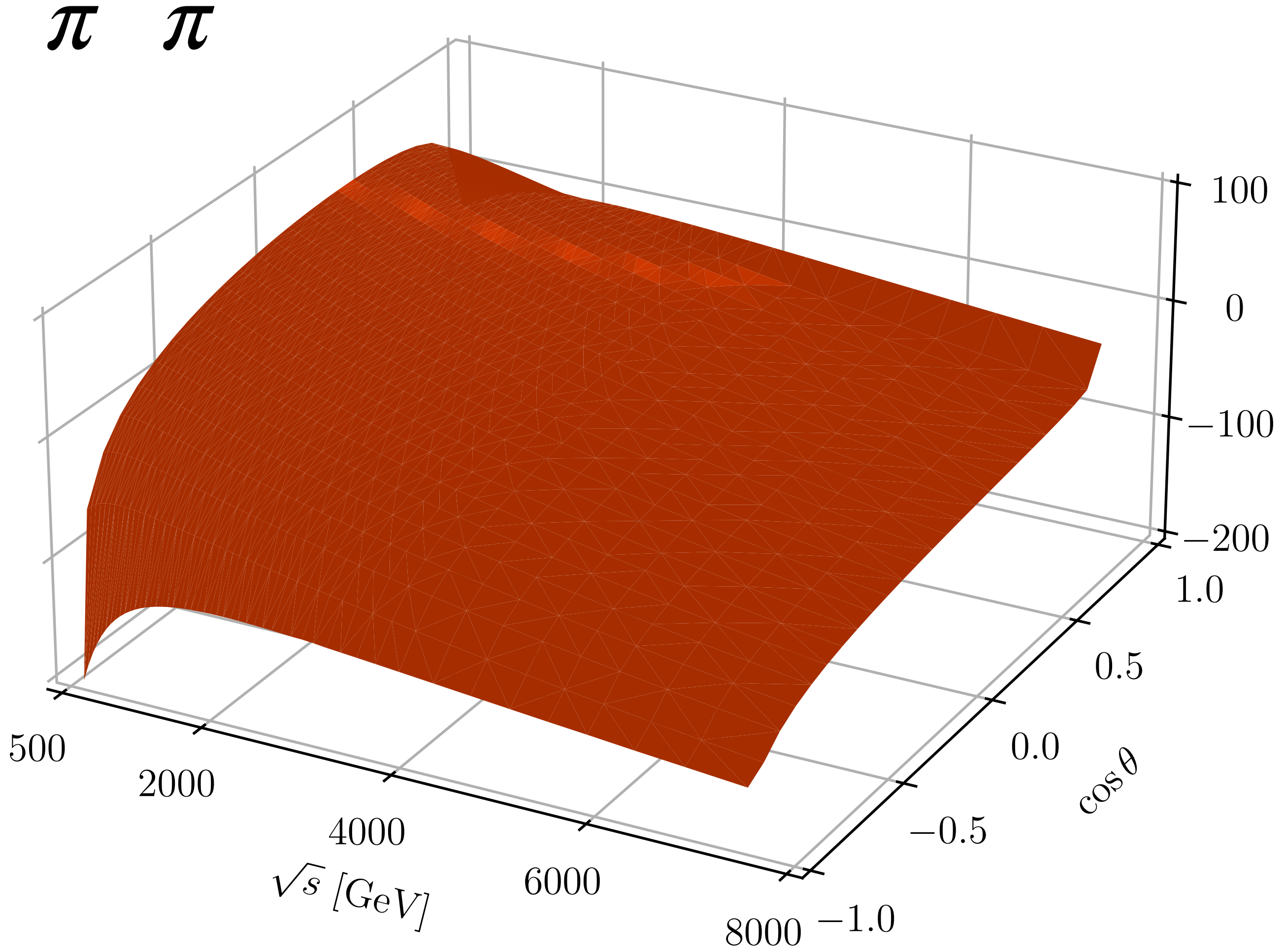


in units $\frac{\alpha}{\pi}\frac{\alpha_s}{\pi}\sigma_0$



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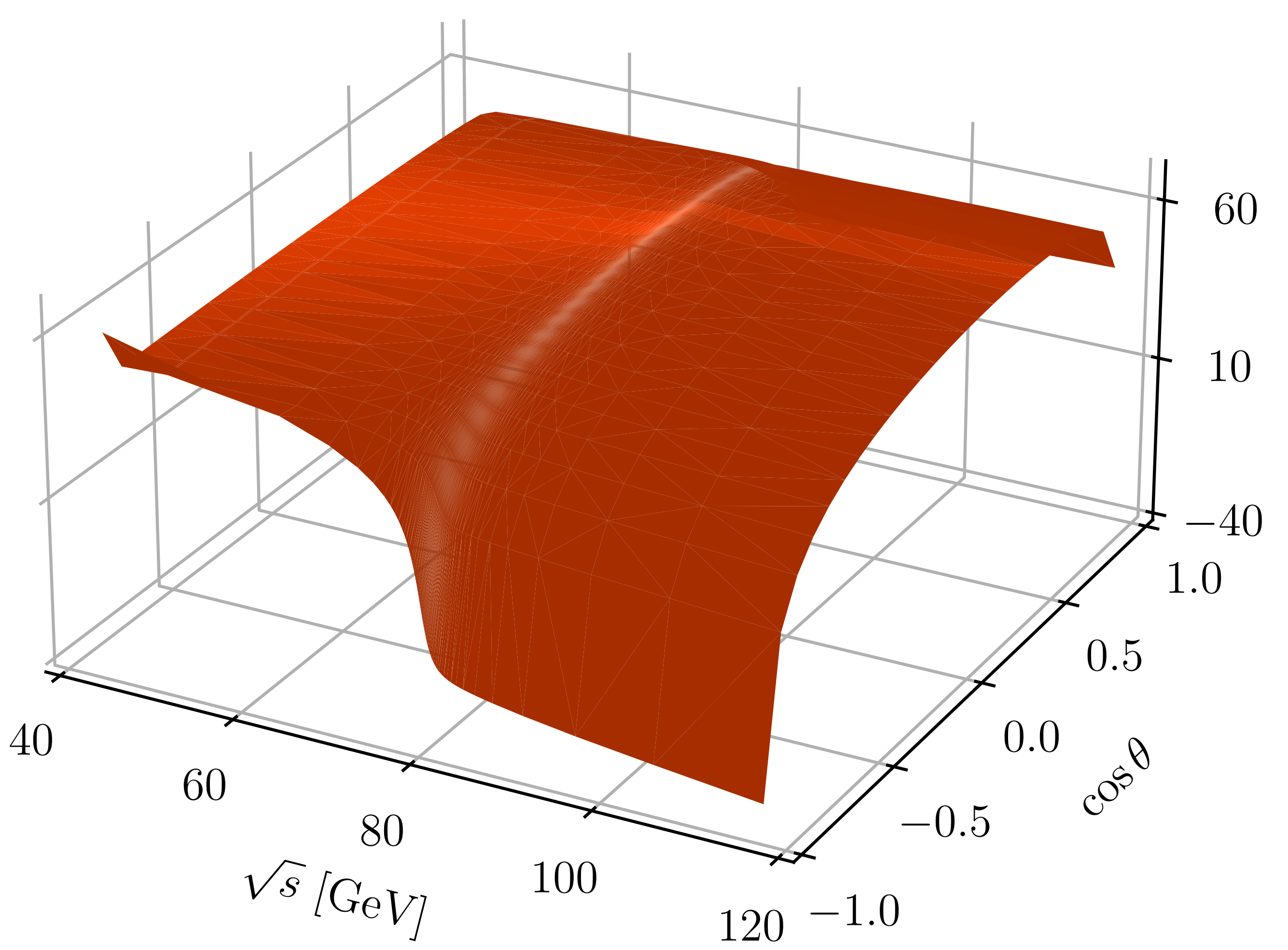

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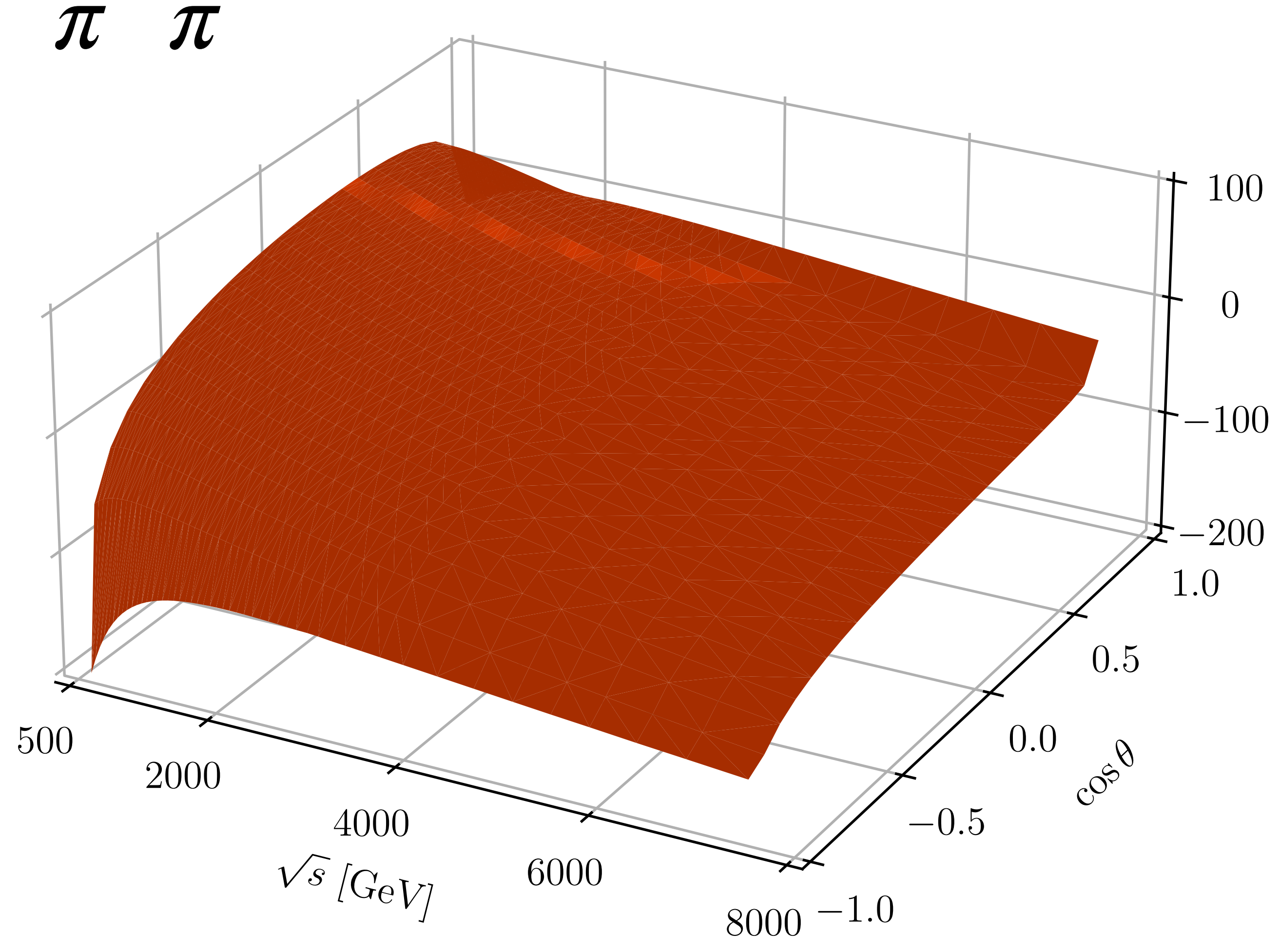

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Where are these corrections relevant ?

Towards a tool matching QCD+QED resummation with NNLO QCD-EW fixed order

- The exact NNLO QCD-EW corrections yield large effects at large transverse/invariant masses → BSM searches
- m_W determination

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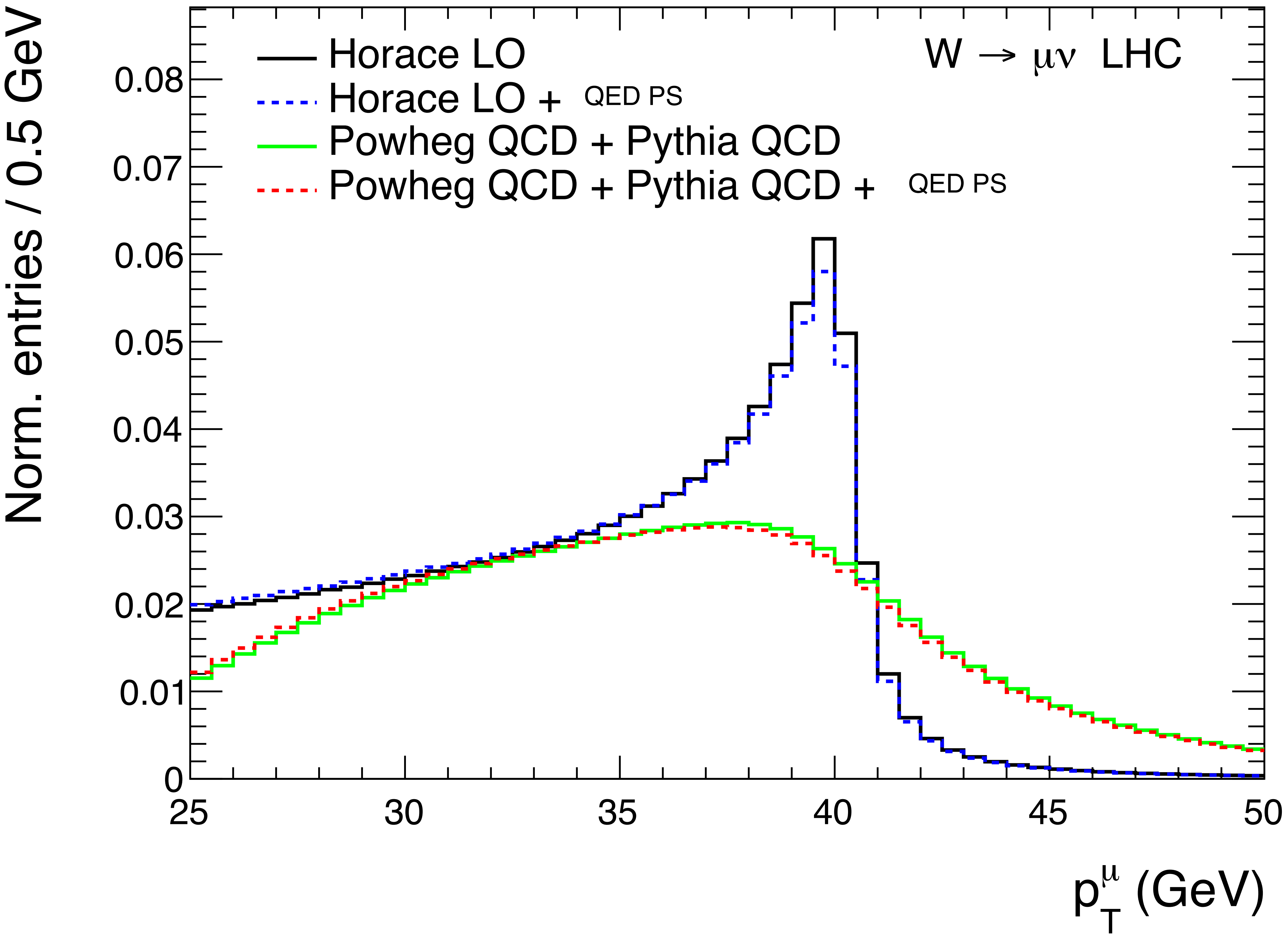
C.Carloni Calame, M.Chiesa, H.Martinez, G.Montagna, O.Nicrosini, F.Piccinini, AV, arXiv:1612.02841



POWHEG simulation NLO QCD+EW +QCDPS + QEDPS

$pp \to W^+$, $\sqrt{s} = 14$ TeV			M_W shifts (MeV)			
Templates accuracy: NLO-QCD+QCD$_{PS}$			$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(dres)	
Pseudodata accuracy		QED FSR	M_T	p_T^ℓ	M_T	p_T^ℓ
1	NLO-QCD+(QCD+QED)$_{PS}$	Pythia	-95.2±0.6	-400±3	-38.0±0.6	-149±2
2	NLO-QCD+(QCD+QED)$_{PS}$	Photos	-88.0±0.6	-368±2	-38.4±0.6	-150±3
3	NLO-(QCD+EW)+(QCD+QED)$_{PS}$two-rad	Pythia	-89.0±0.6	-371±3	-38.8±0.6	-157±3
4	NLO-(QCD+EW)+(QCD+QED)$_{PS}$two-rad	Photos	-88.6±0.6	-370±3	-39.2±0.6	-159±2

Huge impact of QED and mixed QCD-QED corrections in the m_W determination

What is the theoretical uncertainty on this estimated shift ? e.g. what would be the difference using POWHEG vs MC@NLO ?

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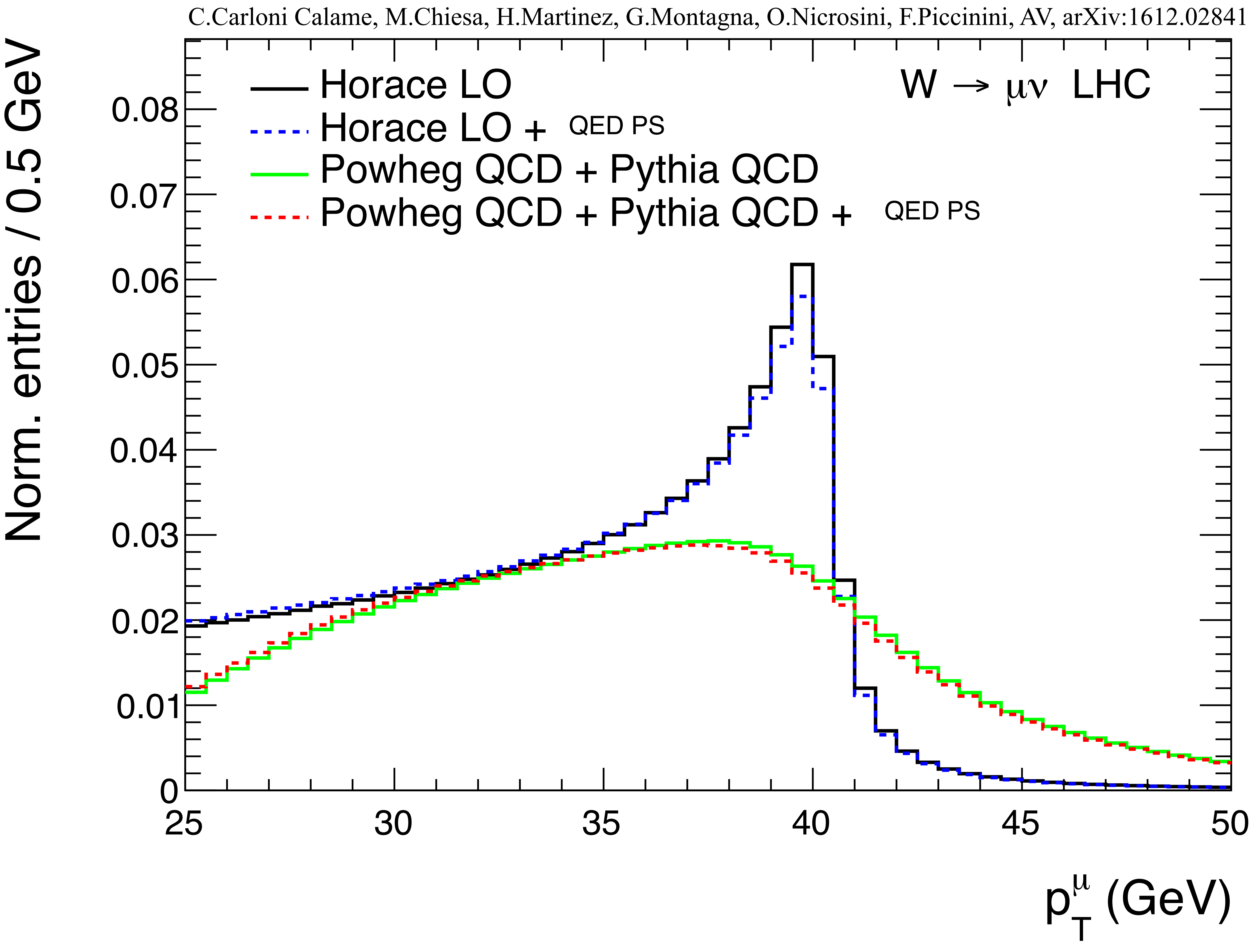

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Huge impact of QED and mixed QCD-QED corrections in the m_W determination
What is the theoretical uncertainty on this estimated shift ? e.g. what would be the difference using POWHEG vs MC@NLO ?

with NNLO QCD-EW results we can fix the dominant source of ambiguity

Towards a tool matching QCD+QED resummation with NNLO QCD-EW fixed order

- The exact NNLO QCD-EW corrections yield large effects at large transverse/invariant masses → BSM searches
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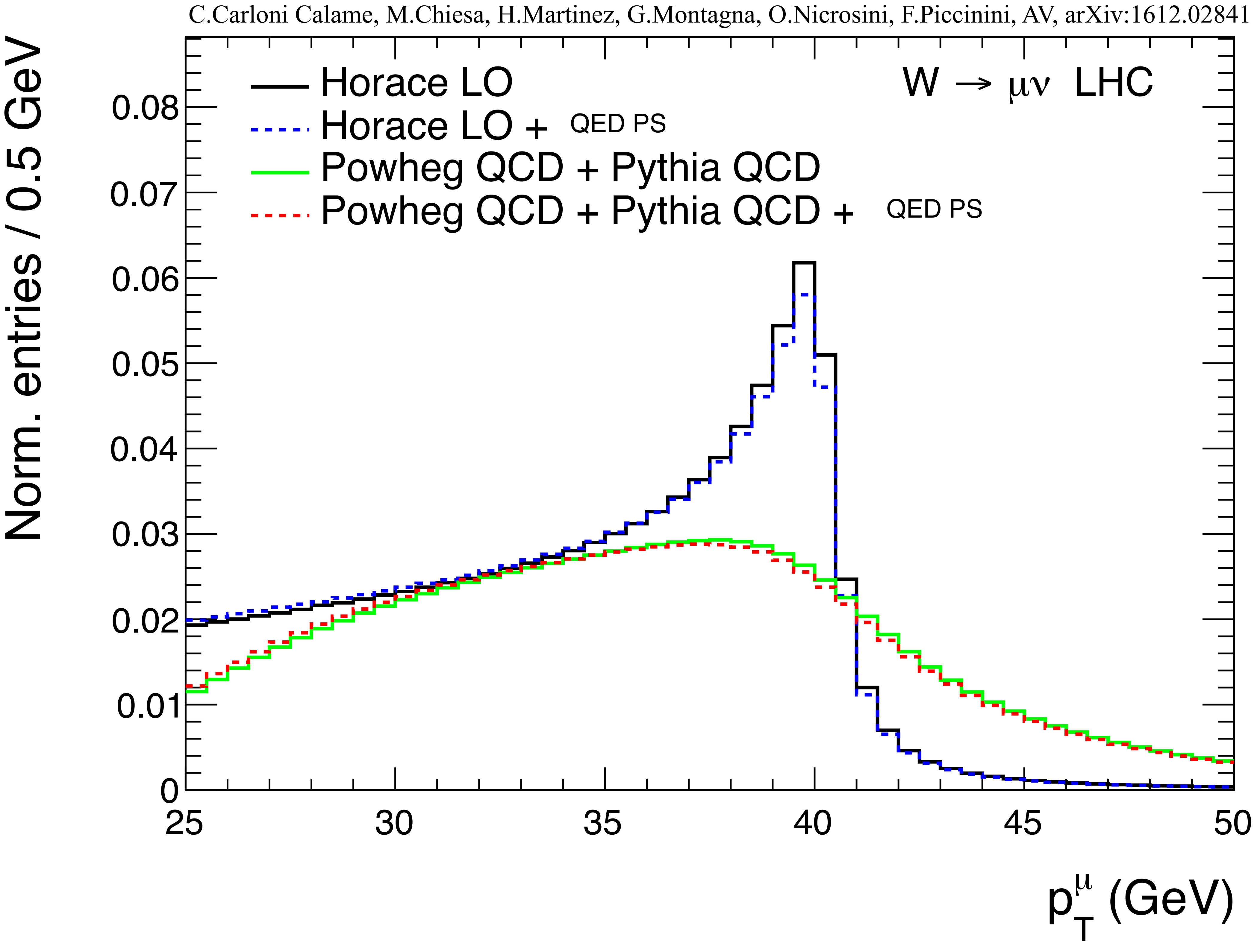

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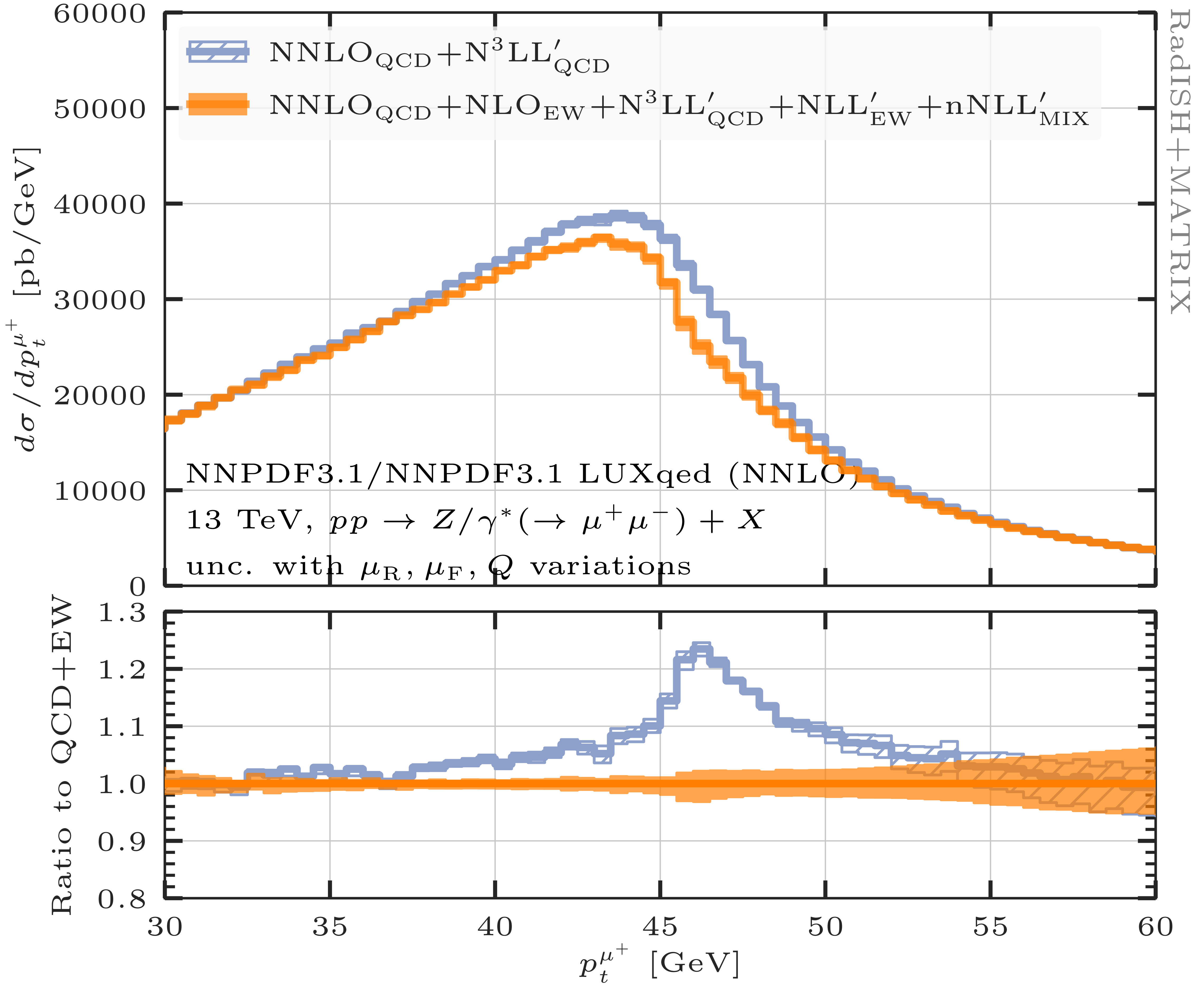
Crucial role of matching with fixed order to keep under control large ambiguities in the shower formulations (e.g. in QED)

Towards a tool matching QCD+QED resummation with NNLO QCD-EW fixed order

L.Buonocore, L.Rottoli, P.Torrielli, arXiv:2404.15112



Joined QCD-QED resummation in the RadIsh formulation at N3LL'-QCD + NLL'-EW + nNLL'-mixed accuracy

including QED effects from all charged legs

Non-trivial interplay of QCD and EW corrections

Missing final step : Matching with the exact $\mathcal{O}(\alpha\alpha_s)$ corrections needed to reach full NNLL-mixed

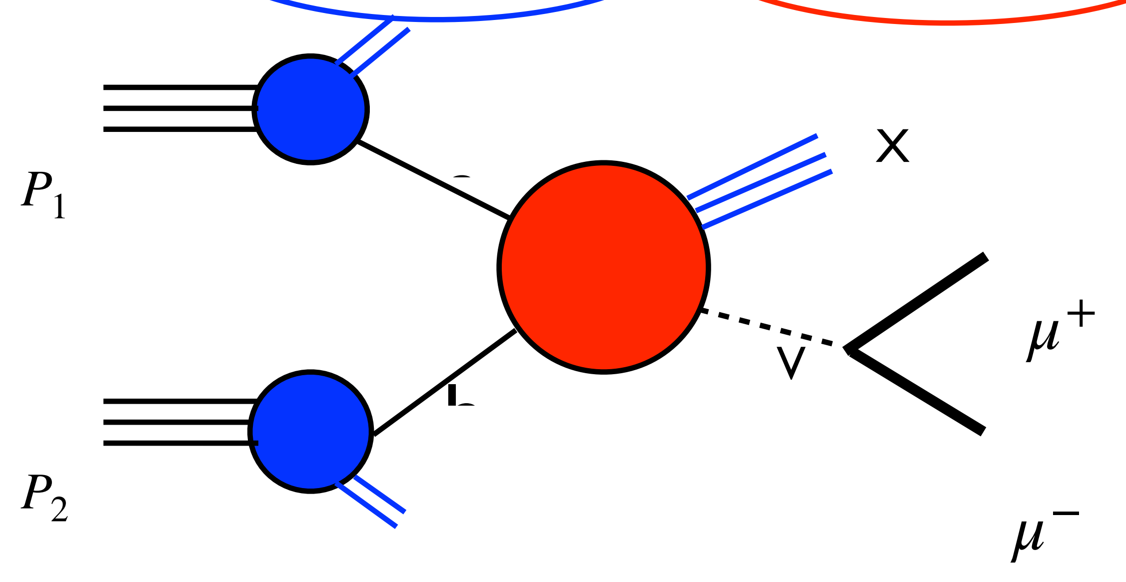
→ Improved estimate of the residual theoretical uncertainties

→ a careful validation of the modelling of QED-FSR is needed

Increasing the significance of a SM test

Tests of the SM and searches for BSM physics: inputs and outputs

$$\sigma(P_1,P_2;m_V)=\sum_{a,b}\int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1,M_F) f_{h_2,b}(x_2,M_F)\, \hat{\sigma}_{ab}(x_1P_1,x_2P_2,\alpha_s(\mu),M_F)$$



The availability of an increasingly large set of high-precision data at HL-LHC will stress the theoretical predictions, with possible tensions

How shall we interpret an inconsistent dataset?
- missing partonic SM higher orders ?
- experimental systematics ?
- data inconsistency ?
- a BSM signal ?

The theoretical predictions depend on the proton PDFs, which are extracted with a fit to collider data.

The systematic usage of higher-order partonic results has improved the quality of PDF fits reducing the associated theoretical uncertainties. cfr. NNPDF, arXiv: 2401.10319

PDFs determination is intrinsically problematic, because BSM signals could be reabsorbed in the PDF fit
This contamination can in turn lead to possible biases in other predictions

cfr. E.Hammou, Z.Kassabov, M.Madigan, M.L.Mangano, L.Mantani, J.Moore, M.Morales Alvarado and M.Ubiali, arXiv:2307.10370

To disentangle the presence of this contamination, complementary studies on PDFs (e.g. antiquarks at large *x*) are important

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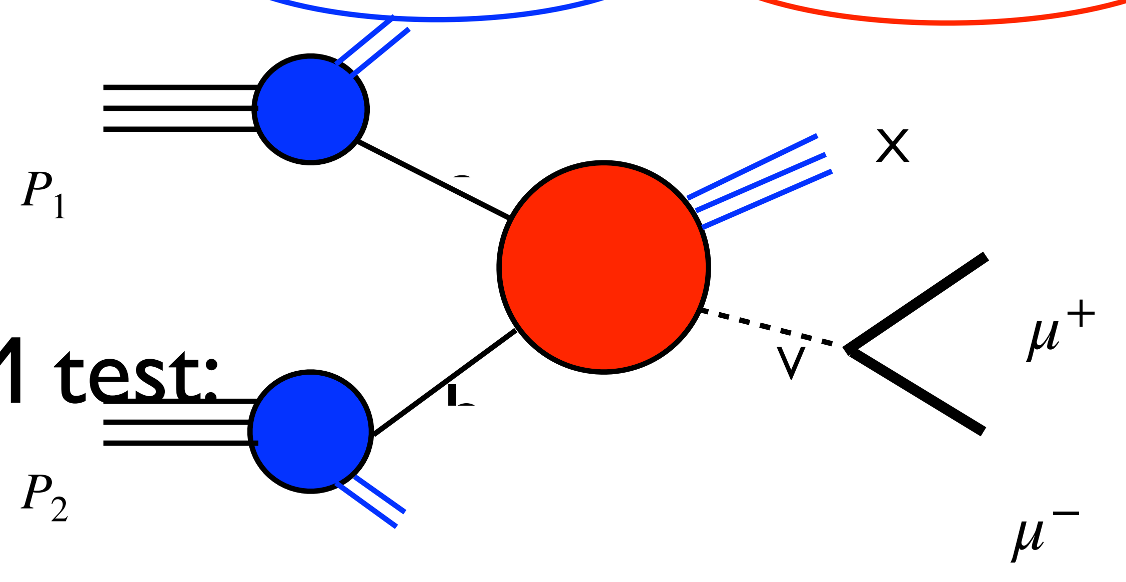

Key element to separate SM and BSM contributions: their different energy dependences
e.g. cfr. an *s*-channel process and a 4-fermion operator at large *s*

The complete inclusion of SM EW corrections emerges again as a crucial component of the SM test:
- photon-induced processes
- NLO and NNLO EW Sudakov logarithms

feature different energy behaviours at large invariant masses compare to quark/gluon processes

cfr. Chiesa, Del Pio, Piccinini, arXiv:2402.14659, Dittmaier, Huss, Schwartz, arXiv:2401.15682

→ their missing inclusion could fake a BSM signal

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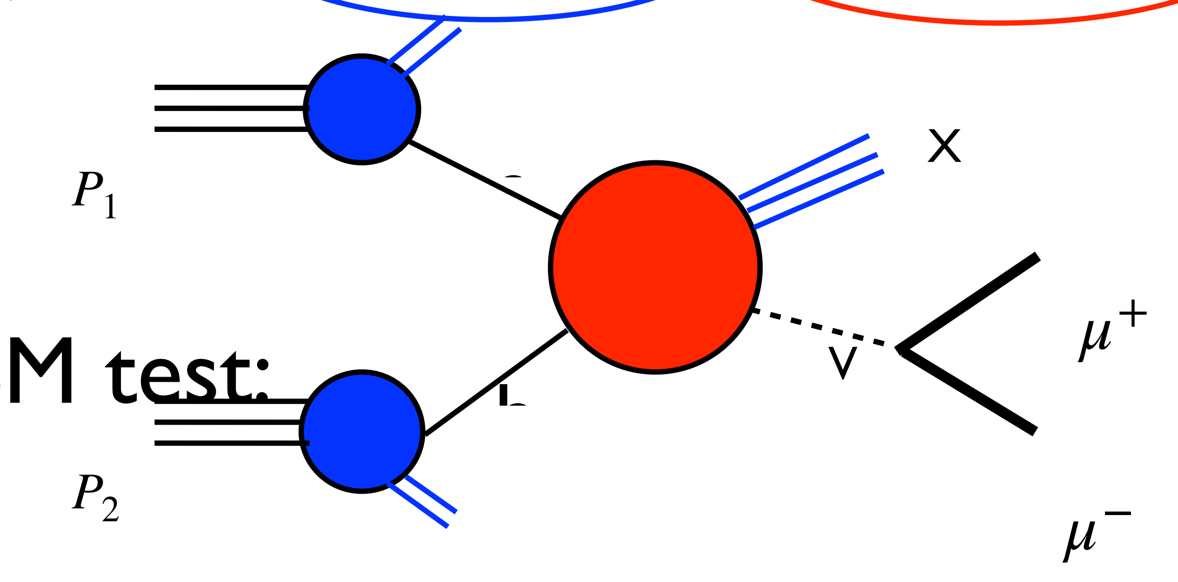

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1) The LHCb sensitivity to different partonic *x* regions, w.r.t. to ATLAS/CMS, offers additional constraints in the PDF determination

e.g. both $\dfrac{d\sigma}{dm_{\ell\ell}}$ and $A_{FB}(m_{\ell\ell})$ at large invariant masses provide crucial information to extract PDFs at large *x*

cfr. NNPDF, arXiv:2209.08115

2) e.g. the W mass determination at LHCb suffers of PDFs uncertainties anticorrelated with those relevant for ATLAS/CMS

→ reduction of the total PDF uncertainty in a global m_W combination

cfr. Bozzi, Citelli, AV, Vesterinen, arXiv:1508.06954, TeV-LHC m_W combination WG, arXiv:2308.09417

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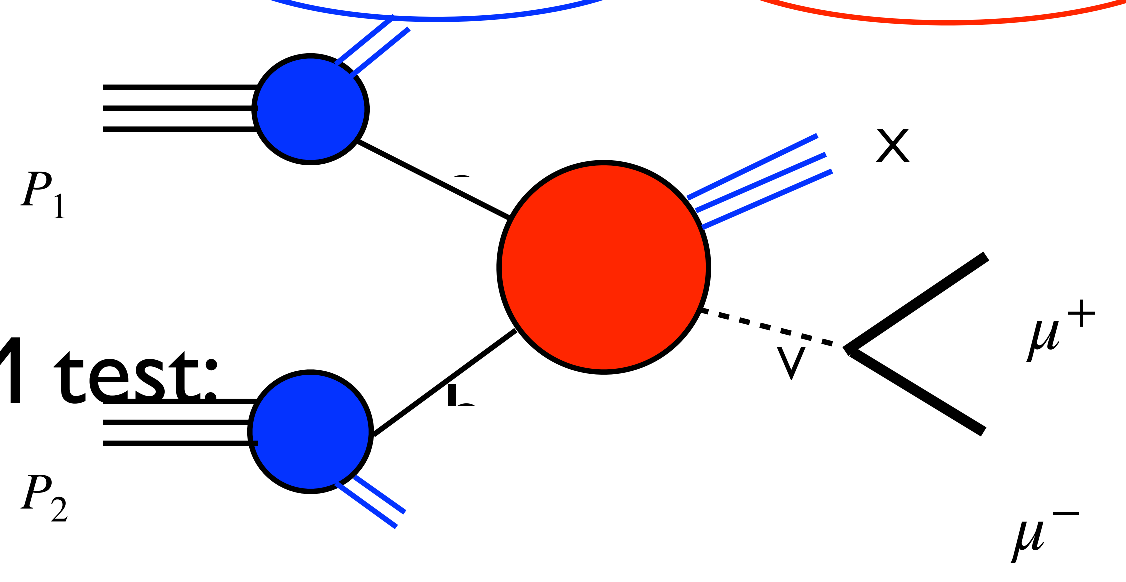

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1) The LHCb sensitivity to different partonic *x* regions, w.r.t. to ATLAS/CMS, offers additional constraints in the PDF determination

e.g. both $\frac{d\sigma}{dm_{\ell\ell}}$ and $A_{FB}(m_{\ell\ell})$ at large invariant masses provide crucial information to extract PDFs at large *x*

cfr. NNPDF, arXiv:2209.08115

2) e.g. the W mass determination at LHCb suffers of PDFs uncertainties anticorrelated with those relevant for ATLAS/CMS

→ reduction of the total PDF uncertainty in a global m_W combination

cfr. Bozzi, Citelli, AV, Vesterinen, arXiv:1508.06954, TeV-LHC m_W combination WG, arXiv:2308.09417

3) Reversing the logic: assuming a PDF set and the validity of the SM, it is possible to determine the SM parameters.

Prospects: interplay of precision measurements at Z resonance, low-, and high-energy

The very high precision determination of EW parameters at the Z resonance is a cornerstone of the whole precision program but there is more…

Prospects: interplay of precision measurements at Z resonance, low-, and high-energy

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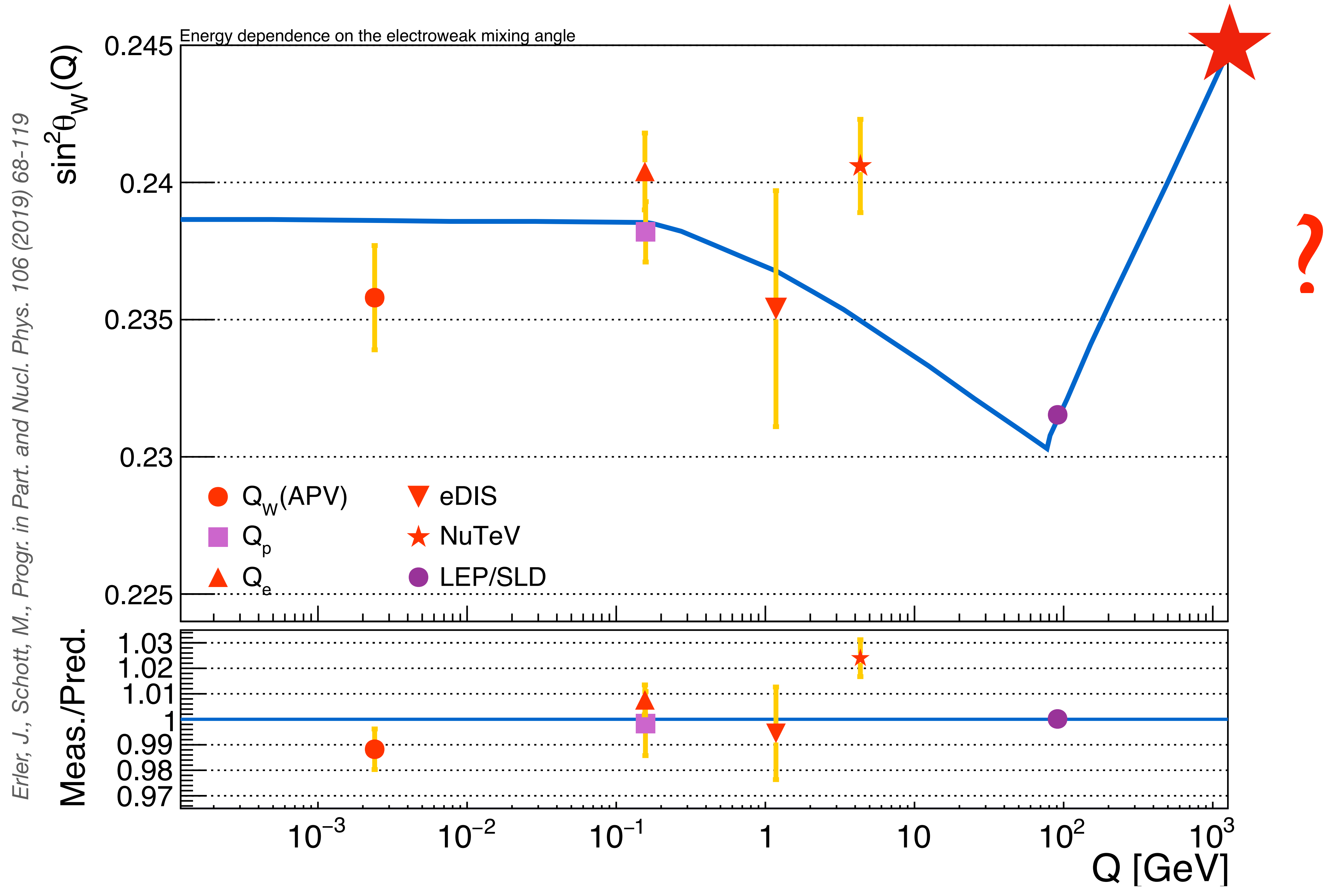
The SM predicts the running of its parameters, like e.g. $\sin^2\hat{\theta}(\mu_R^2)$, with non-trivial features and in turn complementary sensitivity to BSM physics

low-energy (sub-GeV) determinations (P2 in Mainz, Møller at JLab)
high-energy (TeV) determinations (CMS, ATLAS, LHCb ?)
offer a stringent test of the SM
complementary to the results at the Z resonance

The running of an MSbar parameter is completely assigned once boundary and matching conditions are specified

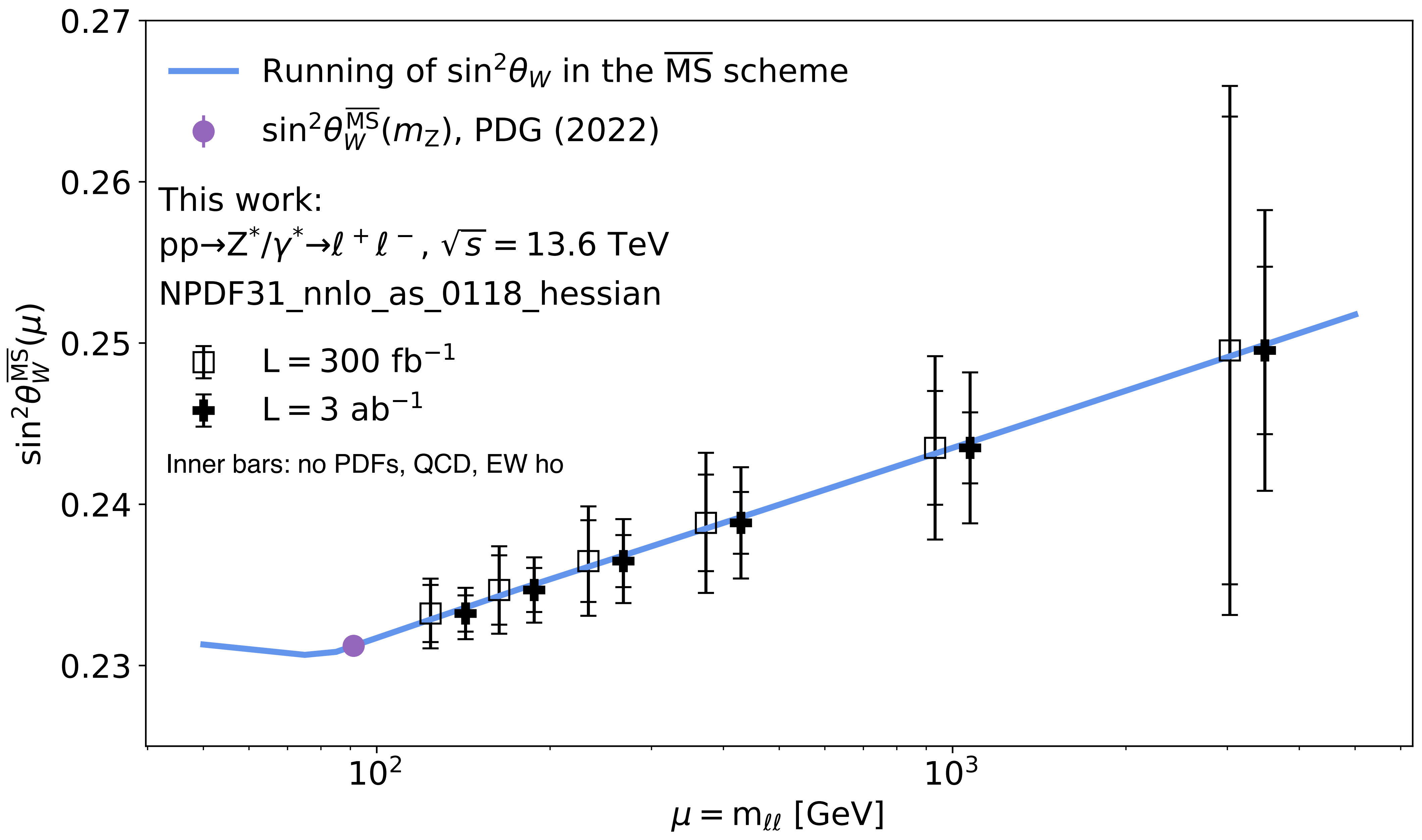


Prospects: exploiting simultaneously Z-resonance and high-mass precision

The sensitivity to the running of $\sin^2\hat\theta(\mu_R^2)$ at the LHC (CMS) demonstrated in Amoroso, Chiesa, Del Pio, Lipka, Piccinini, Vazzoler, AV; arXiv: 2302.10782

A dedicated POWHEG NCDY version has been implemented for this study,
with $\sin^2\hat\theta(\mu_R^2)$ among the input parameters, with NLO-EW renormalisation.
(when fitting the distributions to the data, we can only vary the input parameters of the calculation)

Strongest sensitivity from the xsec rather than from A_{FB}



Can we explore different invariant mass windows, above and below the Z resonance ?

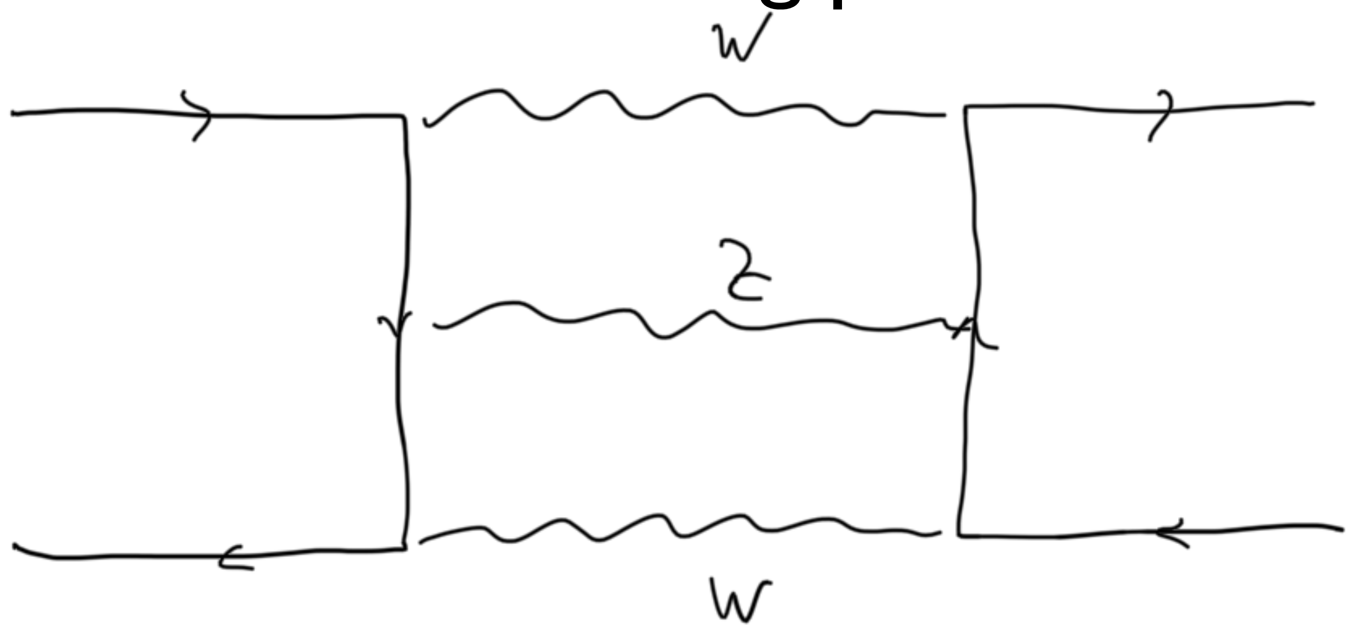
Conclusions

- Steady progress towards the completion of exact NNLO (QCD + QCDxEW + EW) to standard candle processes
- The matching with high logarithmic order QCD and QED resummation is needed for precision EW physics
- PDF determination has a central role in BSM searches
  → precision data extending the (x, Q^2) region crucial to perform consistency test of the proton parameterisation and avoid unexpected unwanted contaminations from weak BSM signals
- The determination of precision EW parameters in different kinematics helps reducing the dependence on PDFs

Thank you

Need for a full NNLO-EW calculation to reduce the uncertainties to sub-percent level

The NNLO-EW corrections to scattering processes are still today one of the frontiers in QFT



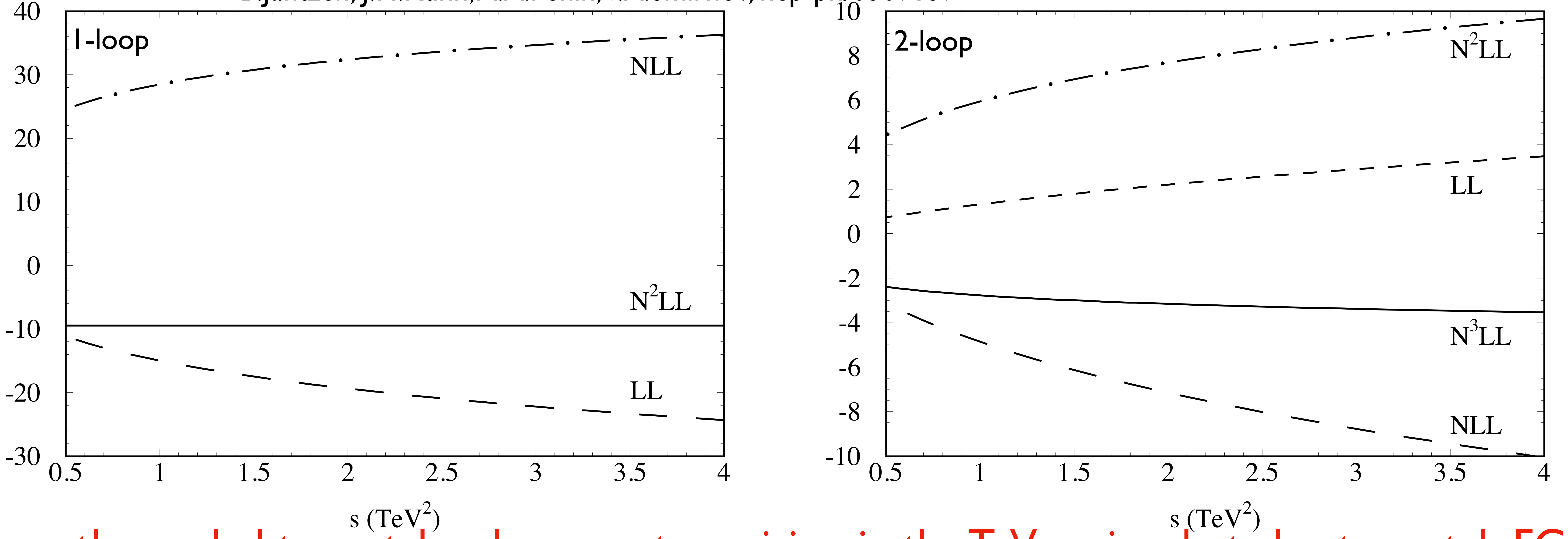
The NNLO-EW corrections could modify in a non-trivial way the large-mass/momentum tails of the distributions

Large logarithmic corrections (EW Sudakov logs) appear in the virtual corrections

At two-loop level, we have up to the fourth power of $\log(s/m_V^2)$

The size of the constant term is not trivial

B.Jantzen, J.H.Kühn, A.A.Penin, V.A.Smirnov, hep-ph/0509157

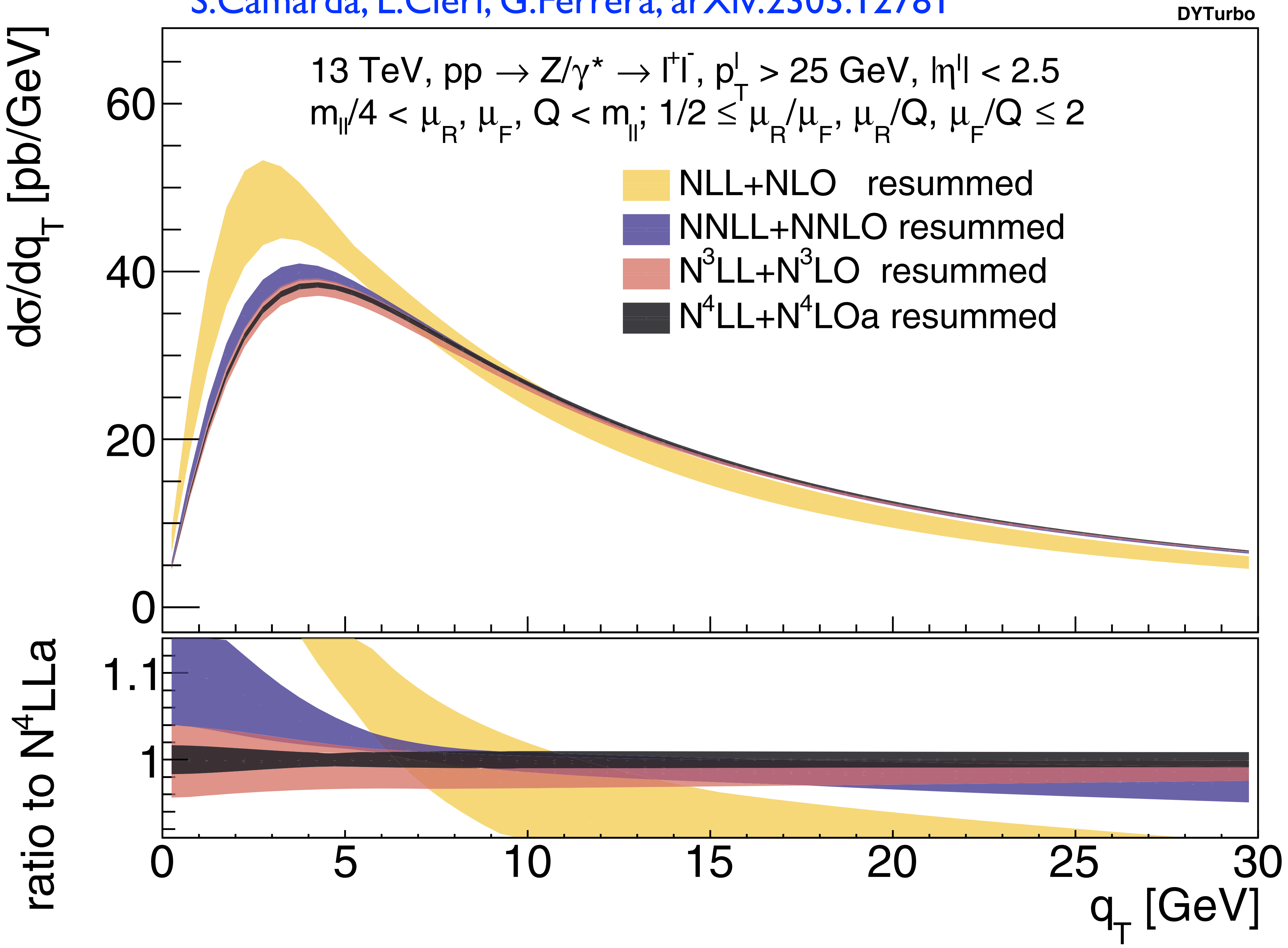


corrections to $e^+e^- \to q\bar{q}$ due to EW Sudakov logs

urgently needed to match sub-percent precision in the TeV region, but also to match FCC-ee precision

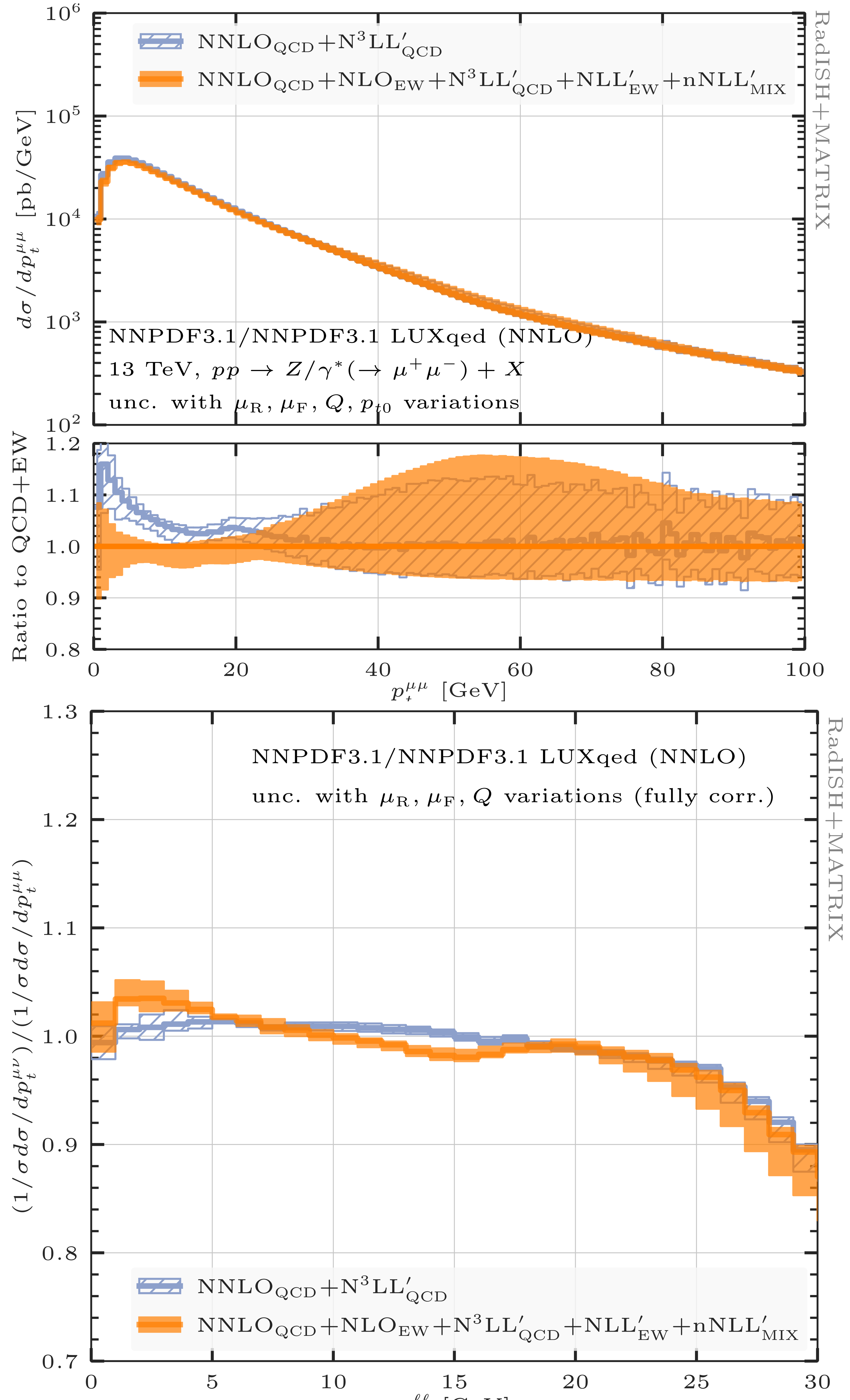
Beyond fixed order: Drell-Yan cross sections resumming large logarithmic corrections

S.Camarda, L.Cieri, G.Ferrera, arXiv:2303.12781



Matching in pure QCD
at approximated N4LL+N4LO accuracy

L.Buonocore, L.Rottoli, P.Torrielli, arXiv:2404.15112



Matching in full QCD-EW SM at N3LL'-QCD + NLL'-EW + nNLL'-mixed accuracy

Combination of the different m_W determinations

Results combined using BLUE

Validation by reproducing internal experimental combinations

The CDF measurement contains an *a posteriori* shift $\delta m_W \sim 3\ \mathrm{MeV}$
accounting for (CTEQ6M→NNPDF3.1, mass modelling, polarisation effects) removed before the combination

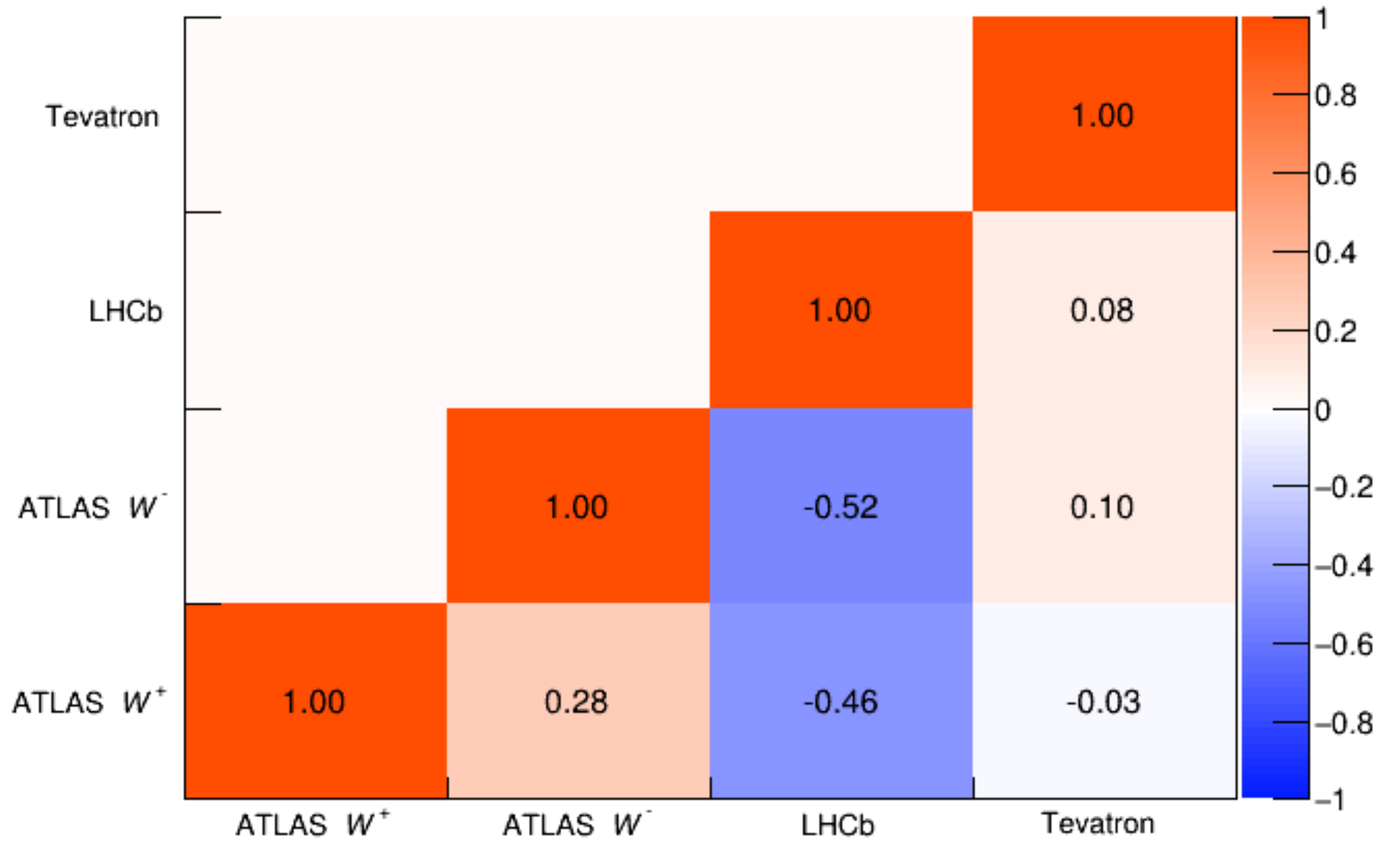
PDF correlations in the combination

Correlations needed in the combination

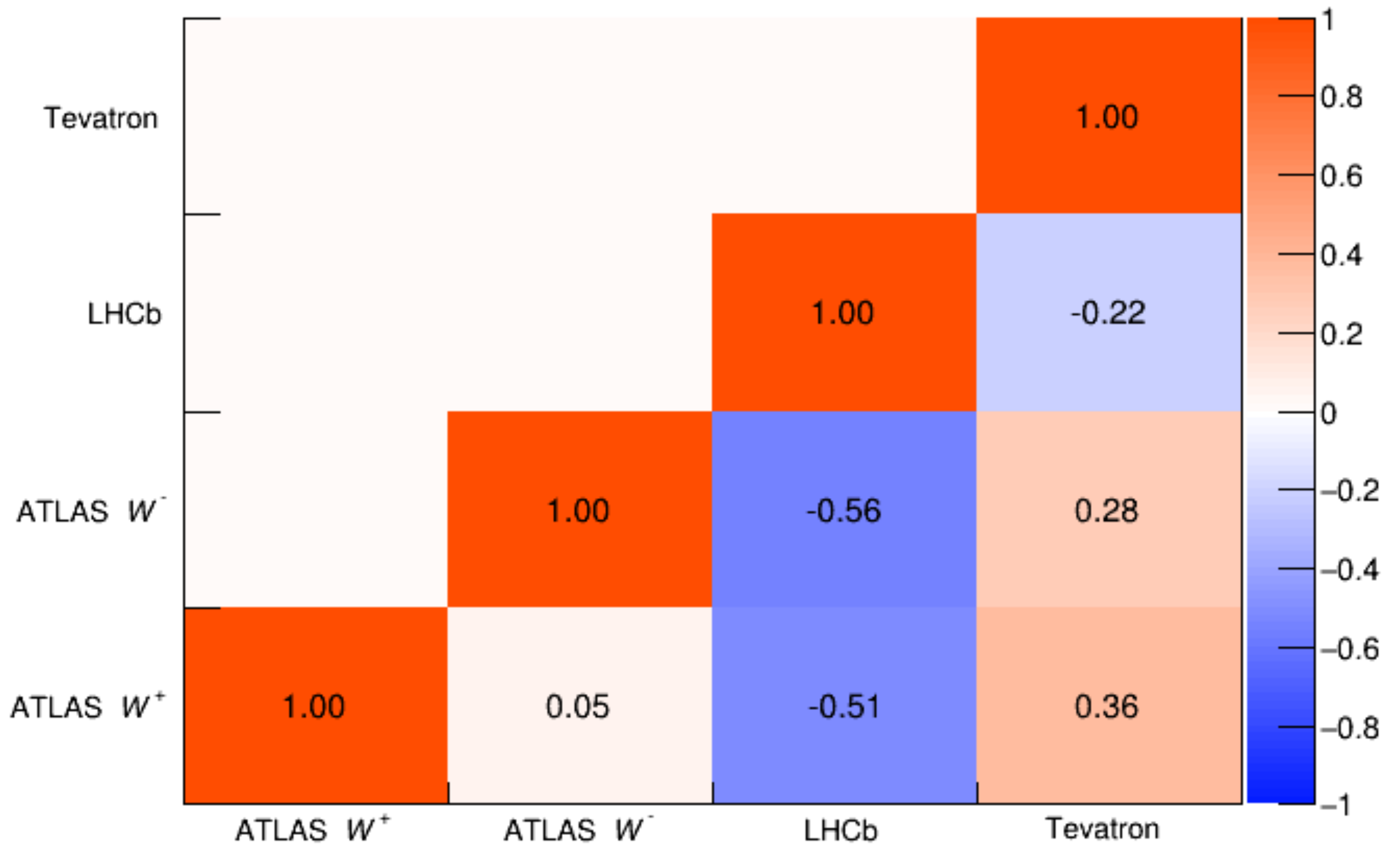
Significantly different correlations between the various PDF sets

PDF anti-correlations between experiments leads to more stable results and reduced PDF dependence
cfr. G.Bozzi, L.Citelli, AV, M.Vesterinen, arXiv:1501.05587, arXiv:1508.06954

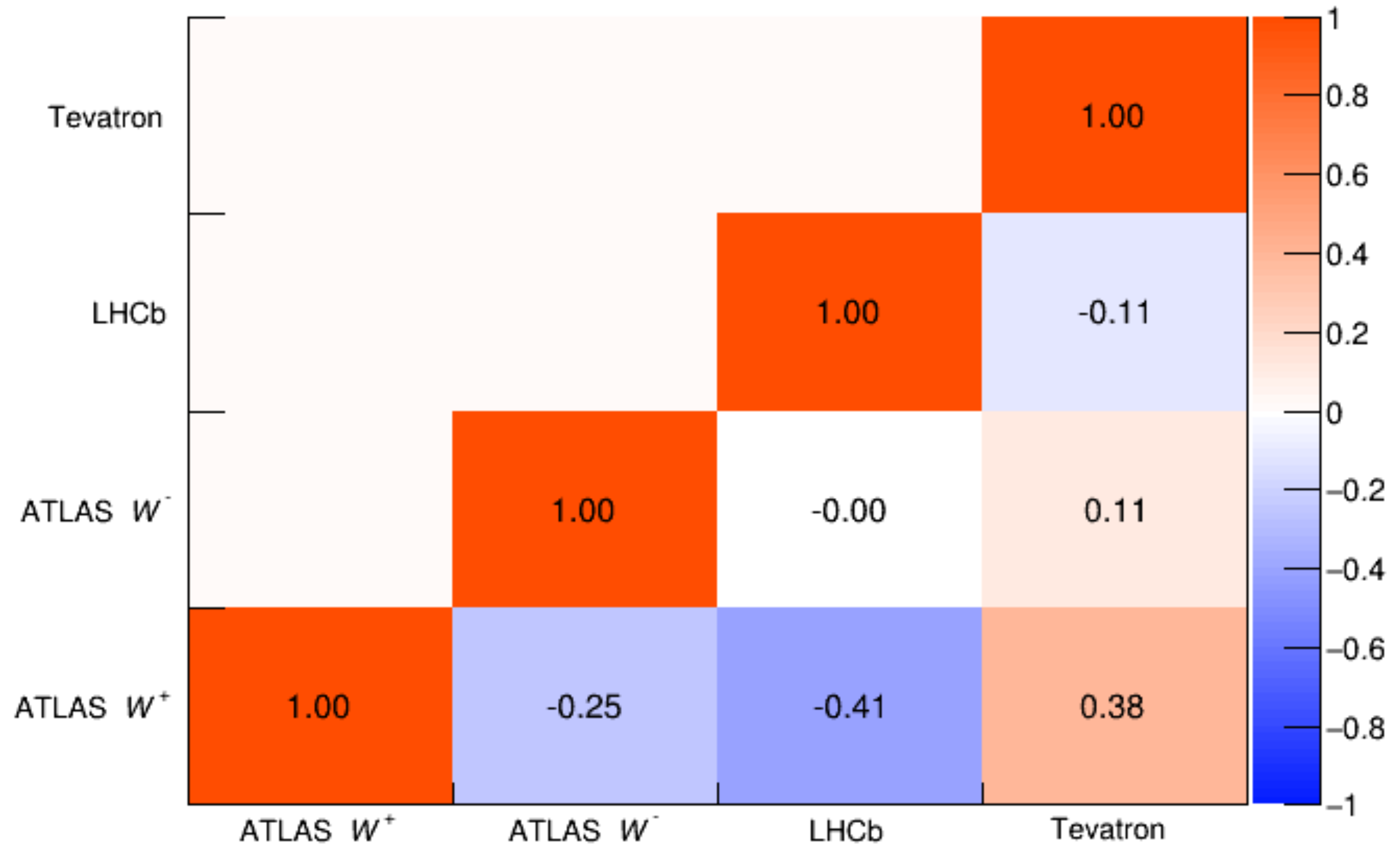
CT18



MSHT20



NNPDF4.0



The Neutral Current Drell-Yan cross section in the SM: perturbative expansion

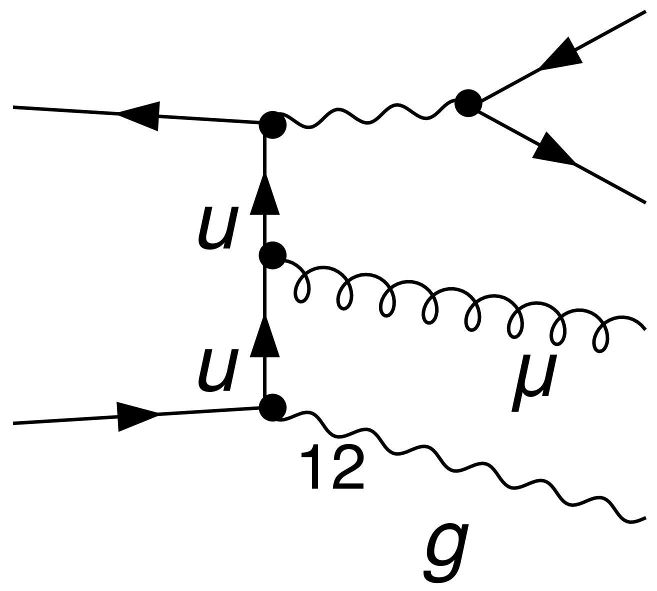
$$\sigma(h_1 h_2 \to \ell\bar{\ell} + X) = \sigma^{(0,0)} + \alpha_s\,\sigma^{(1,0)} + \alpha\,\sigma^{(0,1)} + \alpha_s^2\,\sigma^{(2,0)} + \alpha\,\alpha_s\,\sigma^{(1,1)} + \alpha^2\,\sigma^{(0,2)} + \alpha_s^3\,\sigma^{(3,0)} + \ldots$$

$$\sigma(h_1 h_2 \to l\bar{l} + X) = \sum_{i,j=q\bar{q},g,\gamma} \int dx_1\, dx_2\, f_i^{h_1}(x_1,\mu_F) f_j^{h_2}(x_2,\mu_F)\, \hat{\sigma}(ij \to l\bar{l} + X)$$

$\sigma^{(1,1)}$ requires the evaluation of the xsecs of the following processes, including photon-induced

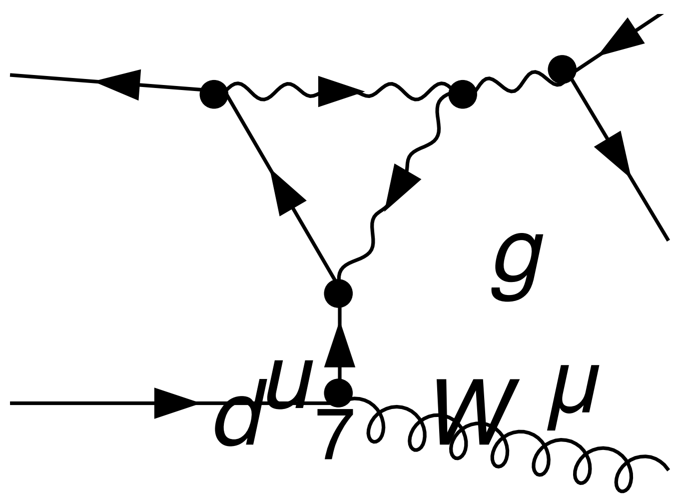
0 additional partons	$q\bar{q} \to l\bar{l},\ \gamma\gamma \to l\bar{l}$	including virtual corrections of $\mathcal{O}(\alpha_s), \mathcal{O}(\alpha), \mathcal{O}(\alpha\alpha_s)$
1 additional parton	$q\bar{q} \to l\bar{l}g,\ qg \to l\bar{l}q$	including virtual corrections of $\mathcal{O}(\alpha)$
	$q\bar{q} \to l\bar{l}\gamma,\ q\gamma \to l\bar{l}q$	including virtual corrections of $\mathcal{O}(\alpha_s)$
2 additional partons	$q\bar{q} \to l\bar{l}g\gamma, qg \to l\bar{l}q\gamma, q\gamma \to l\bar{l}qg, g\gamma \to l\bar{l}q\bar{q}$	
	$q\bar{q} \to l\bar{l}q\bar{q},\ q\bar{q} \to l\bar{l}q'\bar{q}',\ qq' \to l\bar{l}qq',\ q\bar{q}' \to l\bar{l}q\bar{q}',\ qq \to l\bar{l}qq$	at tree level

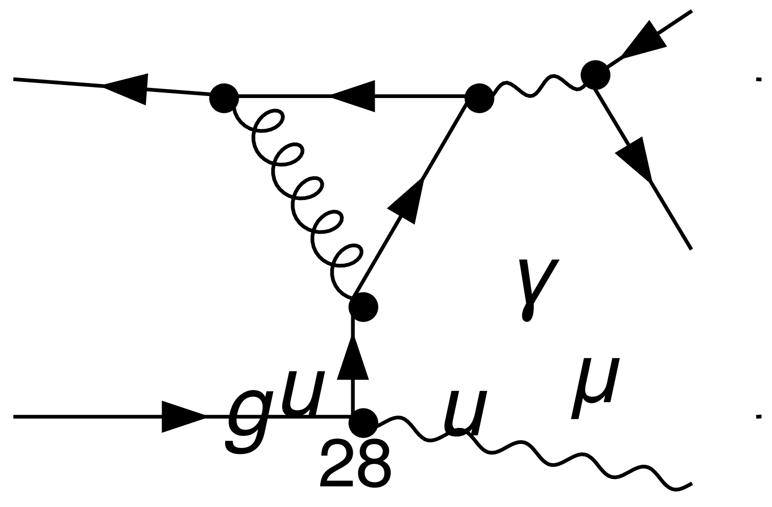
Different kinds of contributions at $\mathcal{O}(\alpha\alpha_s)$ and corresponding problems



double-real contributions

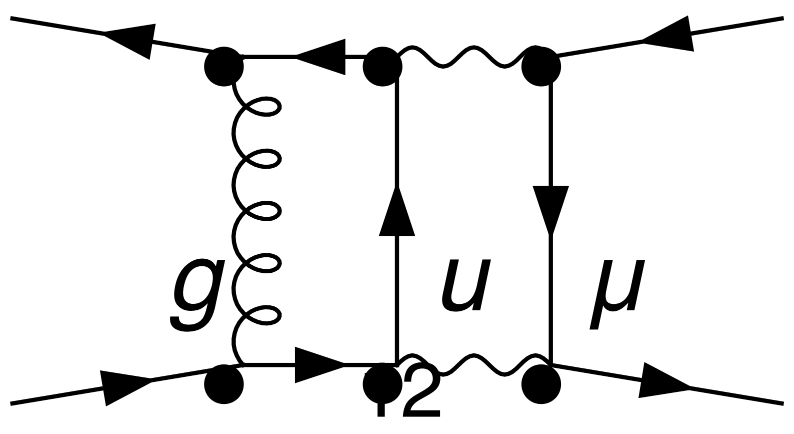
amplitudes are easily generated with OpenLoops
IR subtraction
care about the numerical convergence when aiming at 0.1% precision

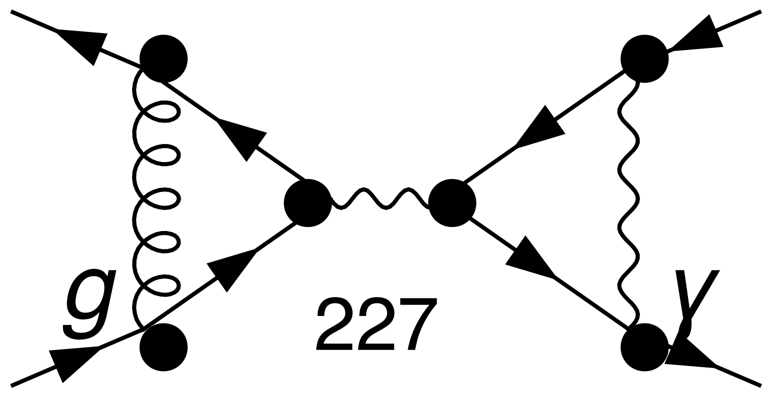




real-virtual contributions

amplitudes are easily generated with OpenLoops or Recola
1-loop UV renormalisation and IR subtraction
care about the numerical convergence when aiming at 0.1% precision





double-virtual contributions

generation of the amplitudes
γ_5 treatment
2-loop UV renormalization
solution and evaluation of the Master Integrals
subtraction of the IR divergences
numerical evaluation of the squared matrix element

Fast numerical evaluation of NNLO QCD-EW corrections with arbitrary W-mass values

Compute once, for a given value $\overline{m}_W$ of the W boson mass, the numerical grid $\mathcal{M}^{(1,1)} = \mathcal{M}^{(1,1)}(\overline{m}_W)$

To determine $\mathcal{M}^{(1,1)} = \mathcal{M}^{(1,1)}(m_W)$

solving the differential equations w.r.t. m_W ,

the first grid $\mathcal{M}^{(1,1)} = \mathcal{M}^{(1,1)}(\overline{m}_W)$ is the boundary condition

The solution is cast as a "symbolic grid" with 3250 power series in $\delta m_W = m_W - \overline{m}_W$,

For a generic m_W choice,

the actual numerical grid is evaluated in negligible time and available for simulation