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A few questions about QCD-EW corrections and their implementations for precision physics at the LHC

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Motivations

- the High-Luminosity phase of the LHC will reduce the statistical uncertainties of several distributions down to the O(1%) level in phase-space regions where both QCD and NLO-EW corrections are separately large, often with opposite sign
  → the presence of large cancellations makes the estimate of the theoretical uncertainties problematic

- the simultaneous precise measurements of observables at two very different energy scales (the Z resonance and the large dilepton invariant mass tail in the TeV region) allows an interesting consistency test of the SM and could give evidence to possible deviations, parameterised via SMEFT

☞ mixed NNLO QCD-EW corrections can help to stabilise the description,
reduce the TH uncertainties,
offer a common framework to interpret O(100 GeV) and O(1000 TeV) observables
(e.g. overcoming the pole approximation limitations)

how can we achieve a reliable estimate of theoretical uncertainties ?

Open theoretical questions (I)

0) there are still many difficult technical challenges (see Mathieu's and Alex's talks),
but considerable progress was achieved for NNLO QCD-EW corrections in the last 24 months;
results are (becoming) available in codes that integrate matrix elements at fully differential level

1) are we ready to embed these new matrix elements into simulation tools ?
e.g. the generation of QED radiation vs QCD radiation can be handled in MC histories via the identification of "resonances"
are the algorithms that generate the radiation ready to match the constraints imposed by the new NNLO matrix elements ?
is there a way to check the consistency between the prediction of NNLO integrator codes vs those of NNLO Shower MC ?

2) the matching of fixed- and all-orders results requires recipes, to avoid double counting;
→ matching uncertainties (some QCD studies in DY and Higgs physics)
the inclusion of higher-order corrections should constrain the formulation and reduce the corresponding uncertainties
(e.g. from NLOPS to NNLOPS)
to what extent do EW precision observables suffer from these issues?
to what extent does the parameter fitting procedure (e.g. MW) suffer from these uncertainties?

Open theoretical questions (II)

3) what is the "best prediction" for a cross section?

in the past, EW corrections were neglected because of their size on inclusive quantities and because of still large QCD uncertainties;

best prediction was typically at NNLO-QCD

today, we have examples where PDF with DGLAP QCD+QED , QCD, EW and QCD-EW corrections are needed

are we ready to consider as best predictions only QCD-EW results,

or shall we live with a dual set of predictions, i.e. pure QCD and full QCD-EW SM ?

4) NNLO QCD-EW can stabilise the theoretical predictions with respect to EW input-scheme dependence

How can we compare SM and SMEFT calculations in this respect?

Shall we build SMEFT simulations only on top of NNLO QCD-EW SM results,

in order to exploit the improved TH stability of the SM prediction ?

Open phenomenological questions

1) to what extent can we consider the "factorised" picture of "an EW scattering process in a QCD environment" accurate ?
i.e. is QCDx QED-FSR sufficient ? can we safely neglect weak effects or non-factorisable mixed QCD-EW corrections, when we aim at interpreting the kinematical distributions ?
→ the precision target of the different measurements and the choice of the observable can lead to different answers
Which is the ultimate precision achievable with the help of new QCD-EW results?

2) the QCD environment includes a modelling component, embedded in the components which are tuned to the data (Parton Shower, UE), which enters in the simulation of multiple QCD radiation; QCD matching recipes eventually tend to correlate low-pt and high-pt regions
to what extent EW physics is sensitive to these choices?

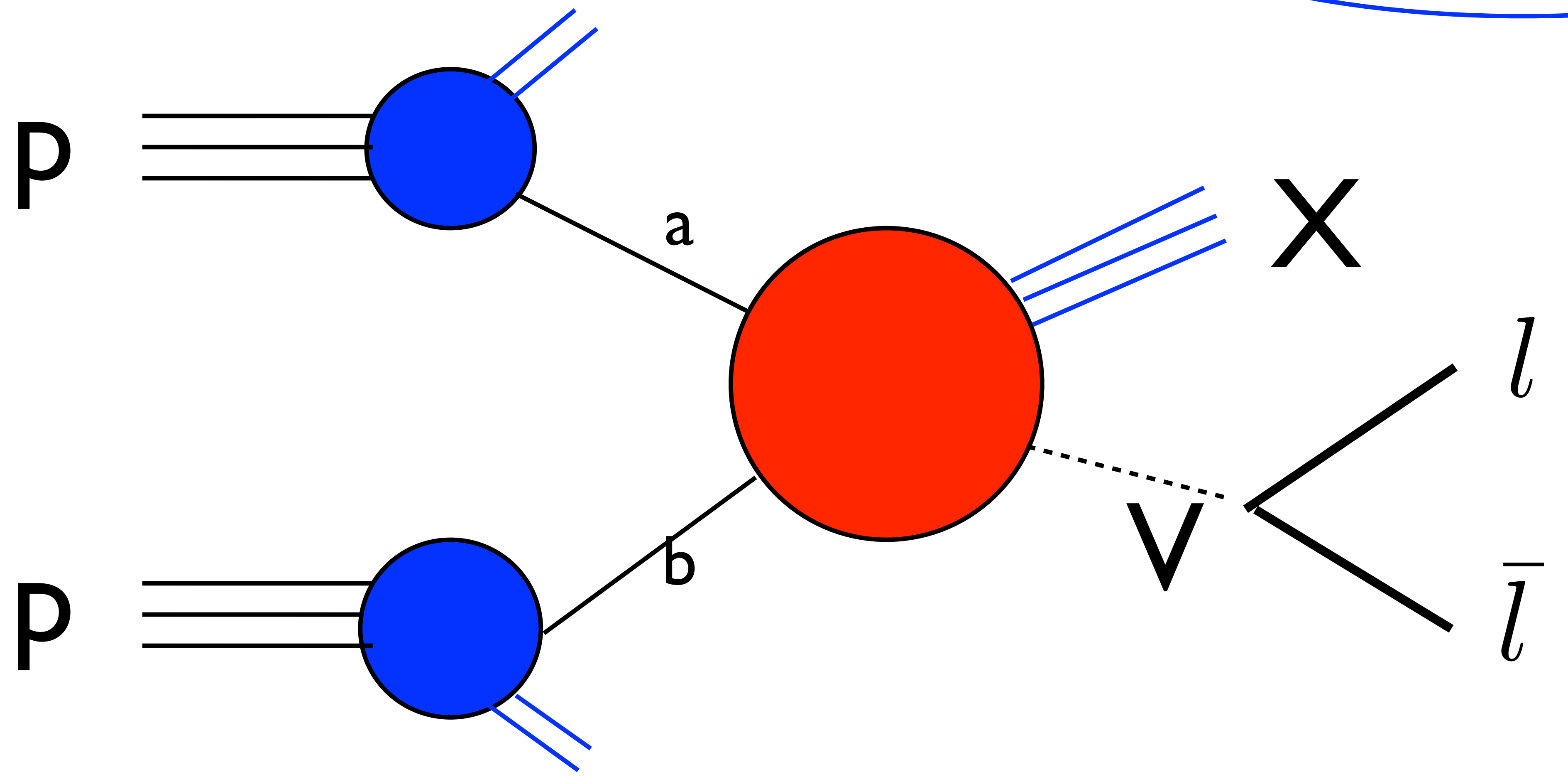
In DY studies for MW we aim at appreciating the "differences" between NC and CC DY.
The evaluation of NLO-EW and NNLO QCD-EW corrections makes these differences explicit (different electric and weak charges).
Are they preserved after the tuning of Parton Showers and UE models to the data? do we have a tuning in a full QCD-EW framework?

Can we imagine a consistency check of the way we describe the data, at different perturbative orders, including uncertainties of the tuning?
Does the modelling component get "reduced", when we add higher-order corrections?

Backup slides

Lepton-pair production at hadron colliders

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



We need

- best description of the partonic cross section including fixed- and all-orders radiative corrections QCD, EW, mixed QCDxEW

- accurate and consistent description of the QCD environment including PDFs, intrinsic partonic kt, QED DGLAP PDF evolution

▻ QCD modelling both perturbative and non-perturbative QCD contributions

transverse d.o.f. → gauge bosons PT spectra; dependent on non-perturbative contributions at low PTZ

longitudinal d.o.f. → rapidity distributions ; affected by PDF uncertainties

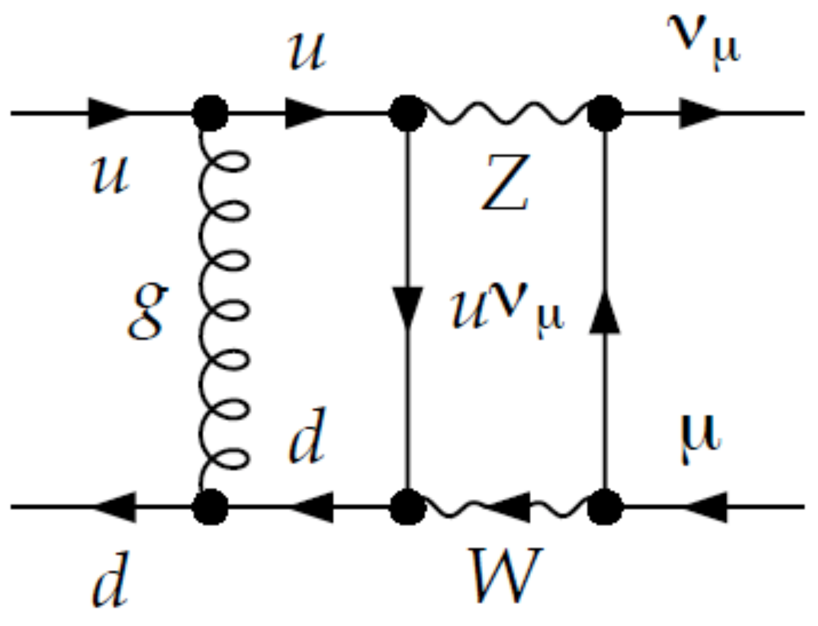
▻ EW and mixed QCDxEW effects

important QED/EW corrections (mostly FSR) modulated by the underlying QCD dynamics

are our current tools adequate for the precision determination of EW parameters ?

The NNLO QCD-EW frontier

Several technical challenges must be solved



- Evaluation of 2-loop virtual corrections with internal massive particles
  Problems to obtain the analytical solution, but also with a numerical approach for direct evaluation

- Subtraction of IR singularities, relevant for fully differential predictions
  different techniques, inherited from QCD calculations, have been applied in recent calculations
  - qt-subtraction
  - nested soft-collinear subtraction

- In higher orders, the scattering might be mediated by both strong and EW interaction,
  so that the same tree-level amplitude contributes to different perturbative orders in the two coupling constants

$$\mathcal{M}(qq \to l^+l^-qq) = \alpha^2 \mathcal{M}_{EW} + \alpha\alpha_s \mathcal{M}_{QCD} \quad \to \quad |\mathcal{M}(qq \to l^+l^-qq)|^2 = \alpha^2 \left[\alpha^2 |M_{EW}|^2 + \alpha\alpha_s 2\mathrm{Re}\mathcal{M}_{EW}\mathcal{M}^\dagger_{QCD} + \alpha_s^2 |\mathcal{M}_{QCD}|^2\right]$$

the identification of all the contributions at a given order and their bookkeeping
is necessary to achieve the complete subtraction of initial state collinear singularities

The NNLO QCD-EW (fixed-order) corrections will constrain the (all-orders) formulation of the hadron level cross section,
reducing the perturbative uncertainties (due to matching and to non-perturbative effects)

Progress towards Drell-Yan simulations at NNLO QCD-EW

Strong boost of the activities in the theory community in the last 2 years!

→ mathematical and theoretical developments and computation of universal building blocks

- 2-loop virtual and phase-space Master Integrals with internal masses
  U. Aglietti, R. Bonciani, arXiv:0304028, arXiv:0401193, R. Bonciani, S. Di Vita, P. Mastrolia, U. Schubert, arXiv:1604.08581, M.Heller, A.von Manteuffel, R.Schabinger arXiv:1907.00491, S.Hasan, U.Schubert, arXiv:2004.14908
- Altarelli-Parisi splitting functions including QCD-QED effects
  D. de Florian, G. Sborlini, G. Rodrigo, arXiv:1512.00612
- renormalization
  G.Degrassi, AV, hep-ph/0307122, S.Dittmaier,T.Schmidt,J.Schwarz, arXiv:2009.02229 S.Dittmaier, arXiv:2101.05154

→ on-shell Z and W production as a first step towards full Drell-Yan

- pole approximation of the NNLO QCD-EW corrections
  S.Dittmaier, A.Huss, C.Schwinn, arXiv:1403.3216, 1511.08016
- analytical total cross section including NNLO QCD-QED and NNLO QED corrections
  D. de Florian, M.Der, I.Fabre, arXiv:1805.12214
- ptZ distribution including QCD-QED analytical transverse momentum resummation
  L. Cieri, G. Ferrera, G. Sborlini, arXiv:1805.11948
- fully differential on-shell Z production including exact NNLO QCD-QED corrections
  M.Delto, M.Jaquier, K.Melnikov, R.Roentsch, arXiv:1909.08428
- total Z production cross section in fully analytical form including exact NNLO QCD-EW corrections
  R. Bonciani, F. Buccioni, R.Mondini, AV, arXiv:1611.00645, R. Bonciani, F. Buccioni, N.Rana, I.Triscari, AV, arXiv:1911.06200, R. Bonciani, F. Buccioni, N.Rana, AV, arXiv:2007.06518
- fully differential on-shell Z and W production including exact NNLO QCD-EW corrections
  F. Buccioni, F. Caola, M.Delto, M.Jaquier, K.Melnikov, R.Roentsch, arXiv:2005.10221, A. Behring, F. Buccioni, F. Caola, M.Delto, M.Jaquier, K.Melnikov, R.Roentsch, arXiv:2009.10386, 2103.02671,

→ complete Drell-Yan

- neutrino-pair production including NNLO QCD-QED corrections
  L. Cieri, D. de Florian, M.Der, J.Mazzitelli, arXiv:2005.01315
- 2-loop amplitudes
  M.Heller, M.von Manteuffel, R.Schabinger, arXiv:2012.05918
- NNLO QCD-EW corrections to charged-current DY including leptonic decay (2-loop contributions in pole approximation).
  L.Buonocore, M.Grazzini, S.Kallweit, C.Savoini, F.Tramontano, arXiv:2102.12539

Uncertainty reduction for the total hadron-level cross section pp→Z+X

R.Bonciani, F.Buccioni, N.Rana, AV, Phys.Rev.Lett.125 (2020) 23, 232004

Different possible approximations

PDF with DGLAP-QCD evolution

$$A_1 = \sigma_{LO} + \sigma_{10} + \sigma_{20}$$ NNLO-QCD

PDF with DGLAP-(QCD+QED) evolution

$$B_1 = \sigma_{LO} + \sigma_{10} + \sigma_{20} \,,$$ NNLO-QCD

$$B_2 = \sigma_{LO} + \sigma_{10} + \sigma_{01} + \sigma_{20} \,,$$ NNLO-QCD + NLO-EW

$$B_3 = \sigma_{LO} + \sigma_{10} + \sigma_{01} + \sigma_{11} + \sigma_{20}$$ NNLO-QCD + NLO-EW + NNLO QCD-EW

$$B_3^\gamma = \sigma_{LO} + \sigma_{10} + \sigma_{01} + \sigma_{11}^\gamma + \sigma_{20}$$ NNLO-QCD + NLO-EW + NNLO QCD-QED

The comparison of Gμ and α(0) schemes gives a conservative estimate of missing higher orders relevant for the overall normalisation

order	G_μ	$\alpha(0)$	$\delta_{G_\mu-\alpha(0)}$ (%)
A_1	55787	53884	3.53
B_1	55651	53753	3.53
B_2	55501	55015	0.88
B_3^γ	55516	55029	0.88
B_3	55469	55340	0.23

the NNLO-QCD results are only LO-EW

remark: the $\sigma_{LO} + \sigma_{01}$ results would yield a change by 0.5% only, but
NLO-QCD and NNLO-QCD are still only LO-EW → 0.88%

the inclusion of NNLO QCD-EW stabilises the NLO-QCD terms
→ EW uncertainty at the 0.2% level

Numerical results for the total hadron-level cross section pp→Z+X

R.Bonciani, F.Buccioni, N.Rana, AV, Phys.Rev.Lett.125 (2020) 23, 232004

Definitions of best prediction

PDF with DGLAP-QCD evolution	$A_1 = \sigma_{LO} + \sigma_{10} + \sigma_{20}$	NNLO-QCD
PDF with DGLAP-(QCD+QED) evolution	$B_3 = \sigma_{LO} + \sigma_{10} + \sigma_{01} + \sigma_{11} + \sigma_{20}$	NNLO-QCD + NLO-EW + NNLO QCD-EW

In a pure QCD model, matrix elements contain only QCD corrections, PDFs evolve with DGLAP-QCD $\sigma(A_1) = 55787$ pb

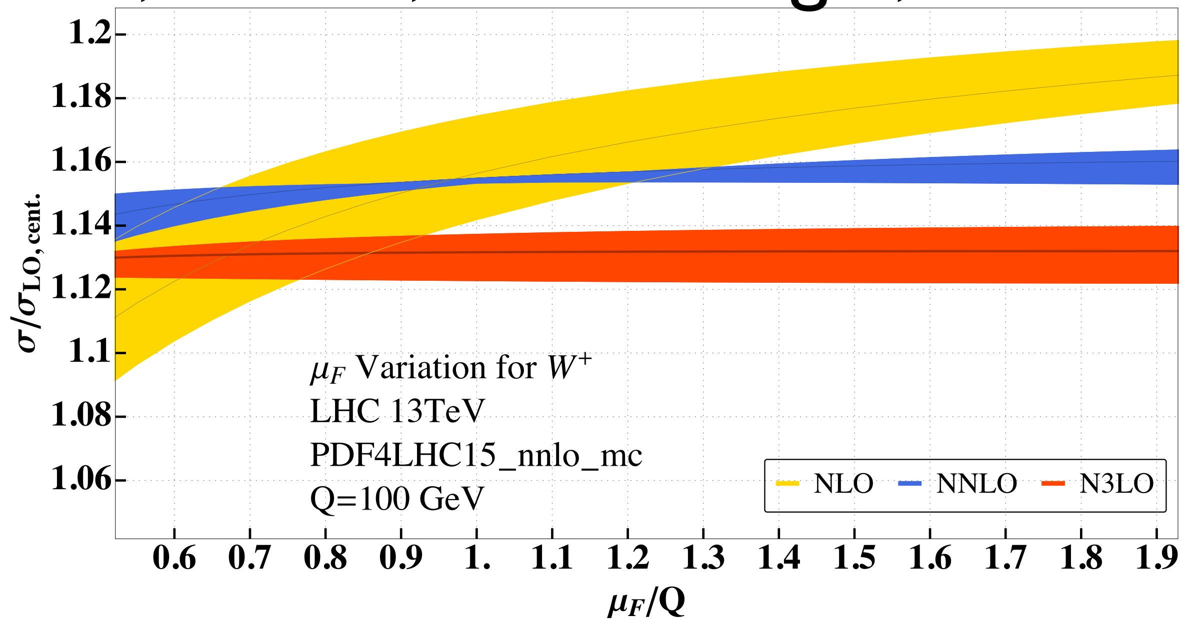
The mandatory inclusion of EW corrections implies the usage of PDFs with DGLAP-(QCD+QED) evolution $\sigma(B_3) = 55469$ pb

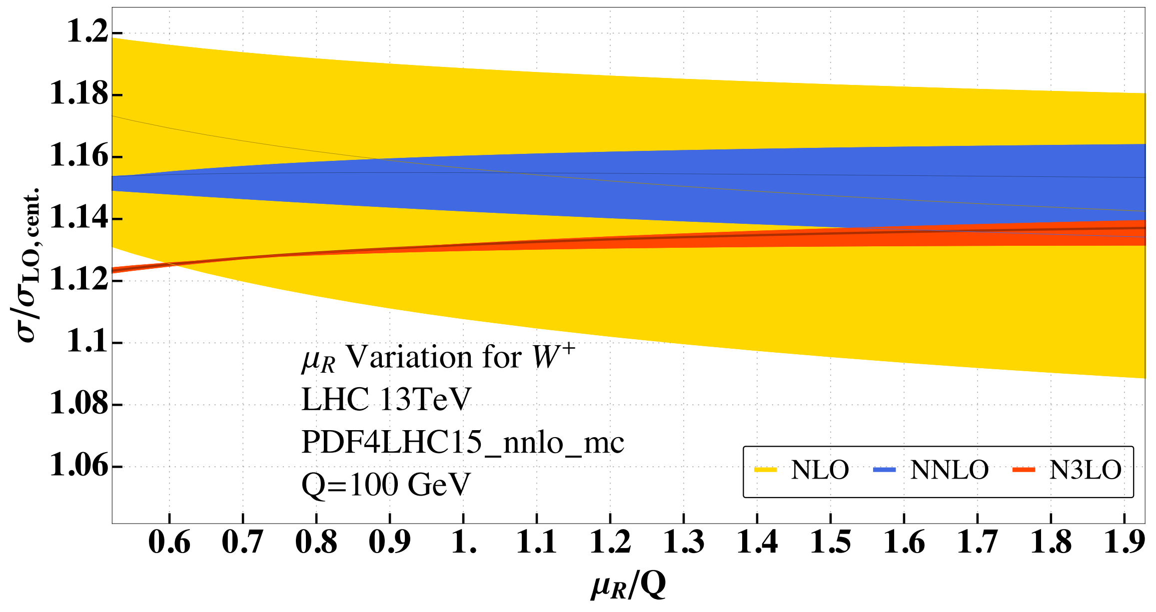
The PDF sets must be based exactly on the same dataset `NNPDF3.1_nnlo_as_0118_nf_4`
`NNPDF3.1_nnlo_as_0118_luxqed_nf_4`

Both models are legitimate and differ by -0.57% .
The full QCD-EW model is the only possible choice for high-precision studies

The recent N3LO-QCD results push the precision of the QCD prediction at the sub-percent level

C.Duhr, F.Dulat, B.Mistlberger, arXiv:2007.13313





- We are getting closer to predict the Z inclusive xsec at the sub percent level, but we need to control several sources of effects at the several per mille level

→ We need N3LO-QCD + NLO-QED proton PDFs to achieve a consistent inclusion of all the effects available at partonic level

Diboson production: NNLO-QCD + NLO-EW corrections

M.Grazzini, S.Kallweit, J.Lindert, S.Pozzorini, M.Wiesemann, arXiv:1912.00068

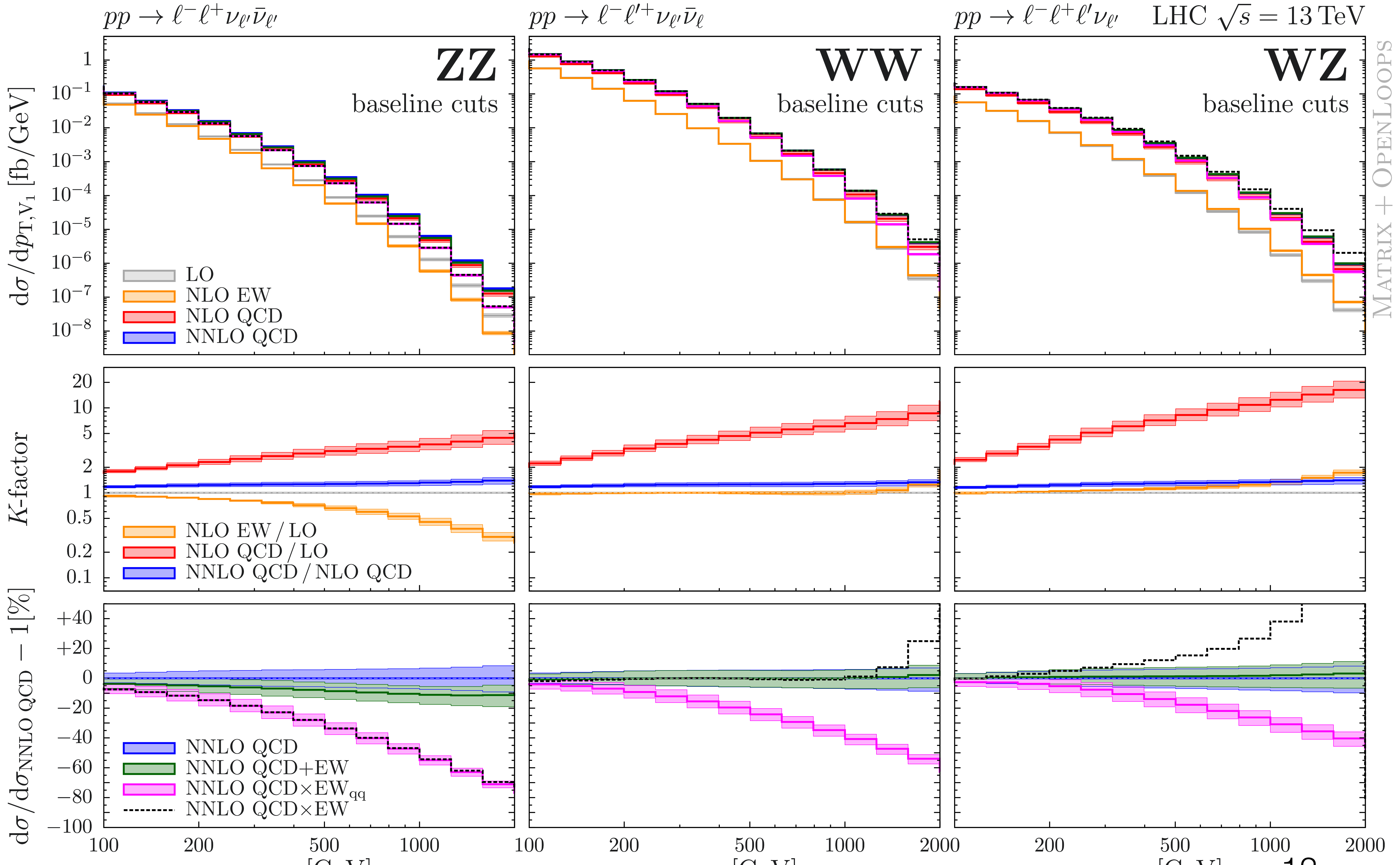
- large QCD and EW corrections need a consistent combination to achieve O(1%) precision → Matrix+OpenLoops
- comparison of additive vs multiplicative combinations of QCD and EW effects, to estimate mixed QCD-EW missing corrections
- differences between 1) hard-hard boson regions and 2) (hard boson, hard jet, soft boson) regions

  in 1) good convergence of the QCD expansion and factorisation of the EW Sudakov logs

  in 2) "giant" K-factors, large EW Sudakov logs, large photon-induced contributions compete to the final result

  → non-trivial estimate of the remaining uncertainties

  jet-vetoes milden the "giant" K-factor and enhance the sensitivity to tri- and quadri-linear couplings



pt_V1 is a "worst-case" observable stressing all potential issues

$$d\sigma_{\mathrm{NNLO\,QCD+EW}} = d\sigma_{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}+\delta_{\mathrm{EW}}\right) + d\sigma^{gg}_{\mathrm{LO}}$$

$$d\sigma_{\mathrm{NNLO\,QCD\times EW}} = d\sigma_{\mathrm{NNLO\,QCD+EW}} + d\sigma_{\mathrm{LO}}\delta_{\mathrm{QCD}}\,\delta_{\mathrm{EW}}$$

$$d\sigma_{\mathrm{NNLO\,QCD\times EW_{qq}}} = d\sigma^{q\bar q}_{\mathrm{LO}}\left(1+\delta^{q\bar q}_{\mathrm{QCD}}\right)\left(1+\delta^{q\bar q}_{\mathrm{EW}}\right) + d\sigma^{\gamma\gamma}_{\mathrm{LO}}\left(1+\delta^{\gamma\gamma/q\gamma}_{\mathrm{EW}}\right) + d\sigma^{gg}_{\mathrm{LO}}$$