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Electroweak theory
multi-lepton production in hadron-hadron collisions

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Topics to be discussed

- precision tests of the gauge sector and of the EW-symmetry-breaking sector of the Standard Model

  basic logic: comparison of the SM predictions against the measured value of the same quantity

  important theoretical progress in the last 12 months, in two different directions

  1) high-precision SM prediction of various quantities, including all the available higher-order radiative corrections

  2) improved predictions in the simulation tools used to prepare the templates to fit the kinematical distributions; reduction of the theoretical systematic error component for the experimental value of the quantity of interest

  → the outcome of 1) and 2) is eventually compared, looking for any possible discrepancy

- towards a test of the SMEFT

- prediction of hadron collider processes
  moving beyond the "EW-processes-in-a-hadronic-environment" factorization
  - single boson production
  - multiple boson production

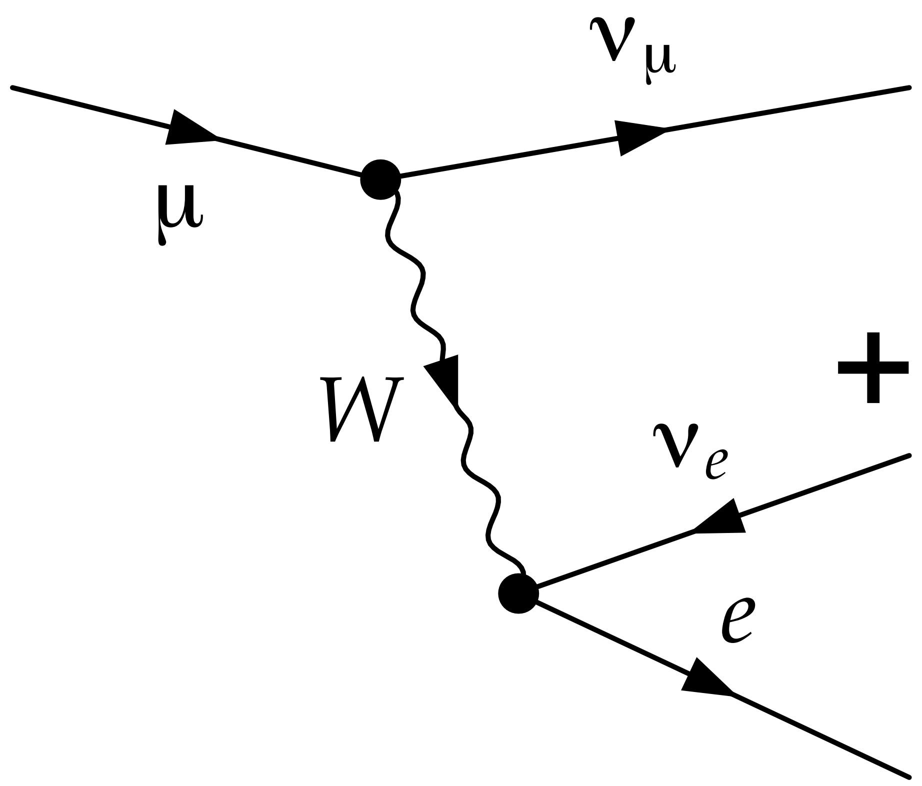
- perspectives towards a new e+e- collider

Predictivity of the SM

SM renormalizable theory → fixed finite number of input parameters (at any perturbative order) → prediction of new quantities

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}(\alpha, G_\mu, m_Z; m_H; m_f; CKM) \qquad \rightarrow \text{we can compute } m_W$$

$$\frac{G_\mu}{\sqrt{2}} = \frac{g^2}{8m_W^2}(1+\Delta r)$$



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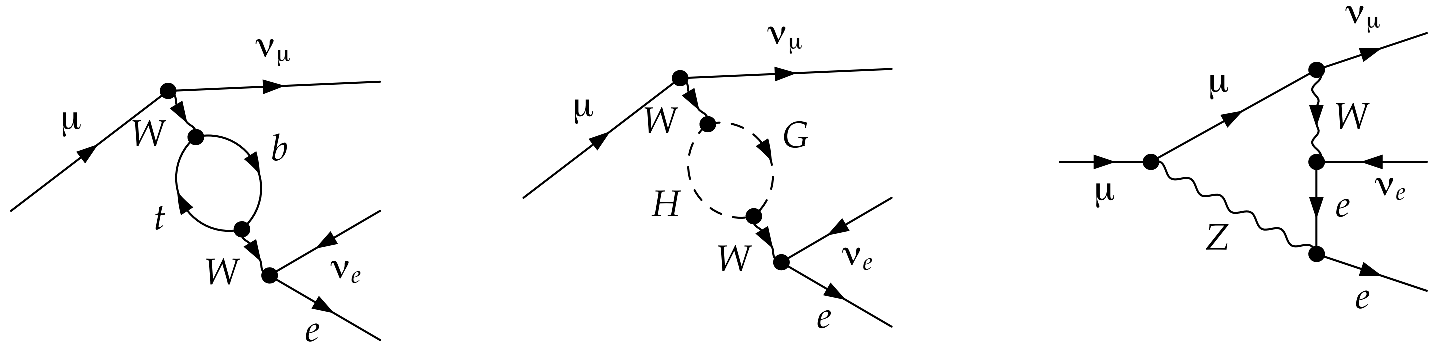


+ ....

$$\Delta r = \Delta r(\alpha, G_\mu, m_Z, m_H; m_f; CKM)$$

$$\Rightarrow \quad m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\alpha}{G_\mu\sqrt{2}m_Z^2}(1+\Delta r)}\right)$$

The W boson mass: theoretical prediction

Sirlin, 1980, 1984; Marciano, Sirlin, 1980, 1981;
van der Bij, Veltman, 1984; Barbieri, Ciafaloni, Strumia 1993; Barbieri, Beccaria, Ciafaloni, Curci, Viceré, 1992, 1993; Fleischer, Tarasov, Jegerlehner, 1993;
Djouadi, Verzegnassi 1987; Chetyrkin, Kühn, Steinhauser, 1995;
Consoli, Hollik, Jegerlehner, 1989; Degrassi, Gambino, AV, 1996; Degrassi, Gambino, Sirlin, 1997;
Freitas, Hollik, Walter, Weiglein, 2000, 2003; Awramik, Czakon, 2002; Awramik, Czakon, Onishchenko, Veretin, 2003; Onishchenko, Veretin, 2003

The best available prediction includes the full 2-loop EW result, higher-order QCD corrections, resummation of reducible terms

$$m_W = w_0 + w_1 dH + w_2 dH^2 + w_3 dh + w_4 dt + w_5 dH dt + w_6 da_s + w_7 da^{(5)}$$

$$dt = [(M_t/173.34\,\mathrm{GeV})^2 - 1]$$

$$da^{(5)} = [\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)/0.02750 - 1]$$

$$dH = \ln\left(\frac{m_H}{125.15\,\mathrm{GeV}}\right)$$

$$dh = [(m_H/125.15\ \mathrm{GeV})^2 - 1].$$

$$da_s = \left(\frac{\alpha_s(m_Z)}{0.1184} - 1\right)$$

	$124.42 \le m_H \le 125.87$ GeV	$50 \le m_H \le 450$ GeV
w_0	80.35712	80.35714
w_1	-0.06017	-0.06094
w_2	0.0	-0.00971
w_3	0.0	0.00028
w_4	0.52749	0.52655
w_5	-0.00613	-0.00646
w_6	-0.08178	-0.08199
w_7	-0.50530	-0.50259

G.Degrassi, P.Gambino, P.Giardino, arXiv:1411.7040

The effective leptonic weak mixing angle: theoretical prediction

- All the form factors and observables needed to describe the Z resonance are available at full 2-loop EW level
  Awramik, Czakon, Freitas, hep-ph/0608099   I.Dubovyk, A.Freitas, J.Gluza, T.Riemann, J.Usovitsch, arXiv:1906.08815

- the best predictions include some sets of 3- and 4-loop corrections
- a convenient parameterisation expresses the residual parametric dependences

$$\sin^2\theta^f_{\rm eff} = s_0 + d_1 L_H + d_2 L_H^2 + d_3 L_H^4 + d_4\Delta_\alpha + d_5\Delta_{\rm t} + d_6\Delta_{\rm t}^2 + d_7\Delta_{\rm t} L_H + d_8\Delta_{\alpha_{\rm s}} + d_9\Delta_{\alpha_{\rm s}}\Delta_{\rm t} + d_{10}\Delta_{\rm Z}$$

Observable	s_0	d_1	d_2	d_3	d_4	d_5
$\sin^2\theta^\ell_{\rm eff}\times 10^4$	2314.64	4.616	0.539	-0.0737	206	-25.71
$\sin^2\theta^b_{\rm eff}\times 10^4$	2327.04	4.638	0.558	-0.0700	207	-9.554

Observable	d_6	d_7	d_8	d_9	d_{10}	max. dev.
$\sin^2\theta^\ell_{\rm eff}\times 10^4$	4.00	0.288	3.88	-6.49	-6560	< 0.056
$\sin^2\theta^b_{\rm eff}\times 10^4$	3.83	0.179	2.41	-8.24	-6630	< 0.025

$$L_{\rm H} = \log\frac{M_{\rm H}}{125.7\,\rm GeV}, \qquad \Delta_{\rm t} = \left(\frac{m_{\rm t}}{173.2\,\rm GeV}\right)^2 - 1,$$

$$\Delta_{\alpha_{\rm s}} = \frac{\alpha_{\rm s}(M_{\rm Z})}{0.1184} - 1, \qquad \Delta_\alpha = \frac{\Delta\alpha}{0.059} - 1, \qquad \Delta_{\rm Z} = \frac{M_{\rm Z}}{91.1876\,\rm GeV} - 1$$

Theoretical uncertainties vs experimental precision for MW and $\sin^2\theta_{eff}$

Limiting factors in the theoretical predictions

Missing higher-order corrections

A.Freitas et al., arXiv:1906.05379

Quantity	FCC-ee	Current intrinsic error		Projected intrinsic error
M_W [MeV]	0.5–$1^{\ddagger}$	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^{\ell}_{\rm eff}$ $[10^{-5}]$	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.4	$(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.15
R_b $[10^{-5}]$	6	11	$(\alpha^3, \alpha^2\alpha_s)$	5
R_l $[10^{-3}]$	1	6	$(\alpha^3, \alpha^2\alpha_s)$	1.5

Parametric uncertainties (mtop, $\Delta\alpha_{had}$)

Quantity	FCC-ee	future parametric unc.	Main source
M_W [MeV]	$0.5 - 1$	1 (0.6)	$\delta(\Delta\alpha)$
$\sin^2\theta^{\ell}_{\rm eff}$ $[10^{-5}]$	0.6	2 (1)	$\delta(\Delta\alpha)$
Γ_Z [MeV]	0.1	0.1 (0.06)	$\delta\alpha_s$
R_b $[10^{-5}]$	6	< 1	$\delta\alpha_s$
R_ℓ $[10^{-3}]$	1	1.3 (0.7)	$\delta\alpha_s$

Theoretical systematic errors entering in the experimental analysis of the data

Missing higher-order corrections in the simulation tools used to describe the kinematical distributions
(2-loop QCD-EW and 2-loop EW, matching with multiple parton radiation)

PDF uncertainties and QCD modelling

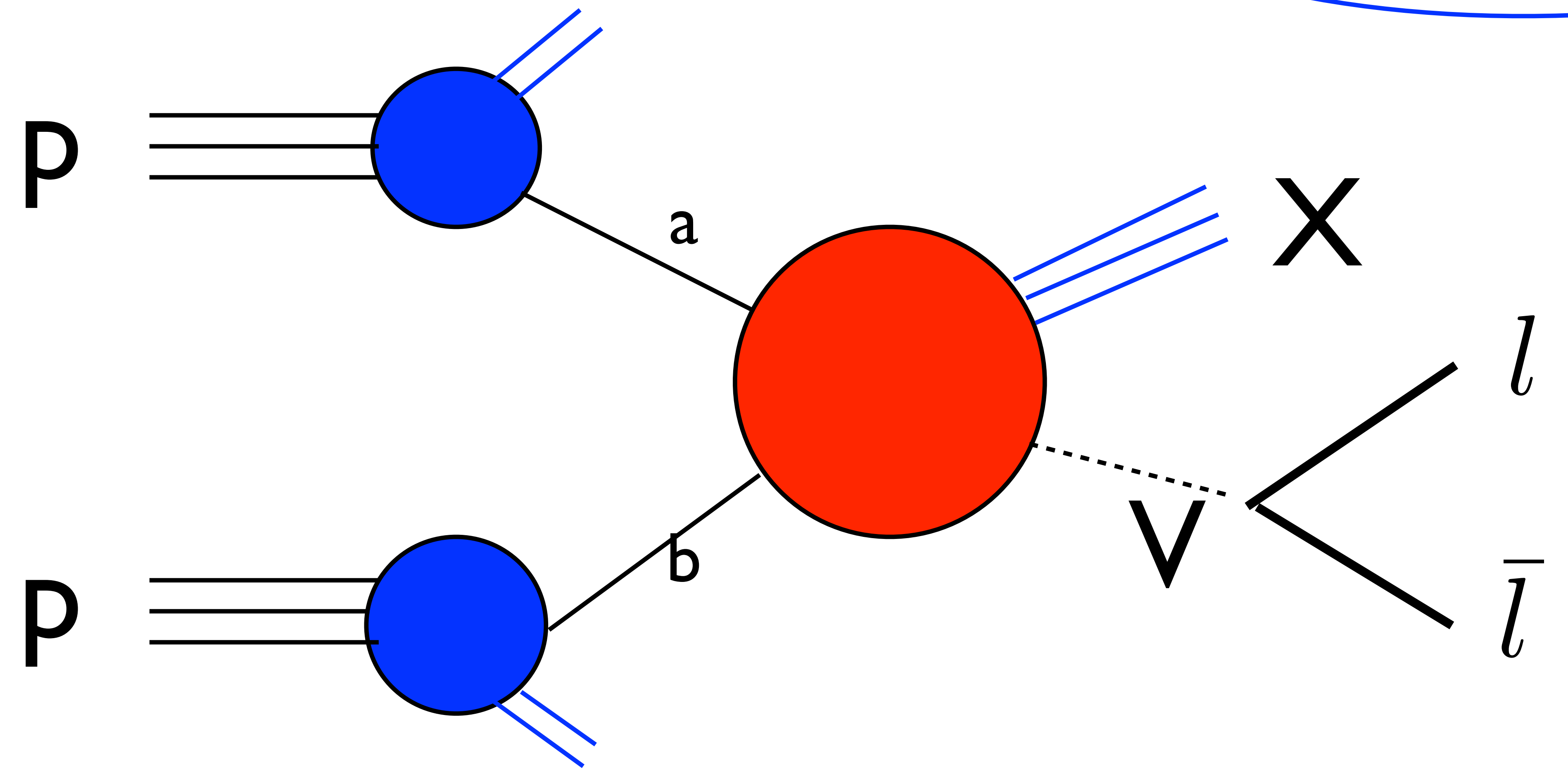
Experimental statistical and systematic errors

P.Azzi et al., arXiv:1902.04070

	ATLAS $\sqrt{s}=8$ TeV	ATLAS $\sqrt{s}=14$ TeV	ATLAS $\sqrt{s}=14$ TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14	CT14	PDF4LHC15$_{HL-LHC}$
$\sin^2\theta^{\rm lept}_{\rm eff}$ $[\times 10^{-5}]$	23140	23153	23153
Stat.	$\pm$ 21	$\pm$ 4	$\pm$ 4
PDFs	$\pm$ 24	$\pm$ 16	$\pm$ 13
Experimental Syst.	$\pm$ 9	$\pm$ 8	$\pm$ 6
Other Syst.	$\pm$ 13	-	-
Total	$\pm$ 36	$\pm$ 18	$\pm$ 15

Vector boson production in hadronic collisions

$$\sigma(P_1,P_2;m_V)=\sum_{a,b}\int_0^1 dx_1dx_2\, f_{h_1,a}(x_1,M_F)f_{h_2,b}(x_2,M_F)\,\hat\sigma_{ab}(x_1P_1,x_2P_2,\alpha_s(\mu),M_F)$$



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 → non-pert contributions at low PTZ

longitudinal d.o.f. → rapidity distributions → PDF uncertainties

▻ EW and mixed QCDxEW effects

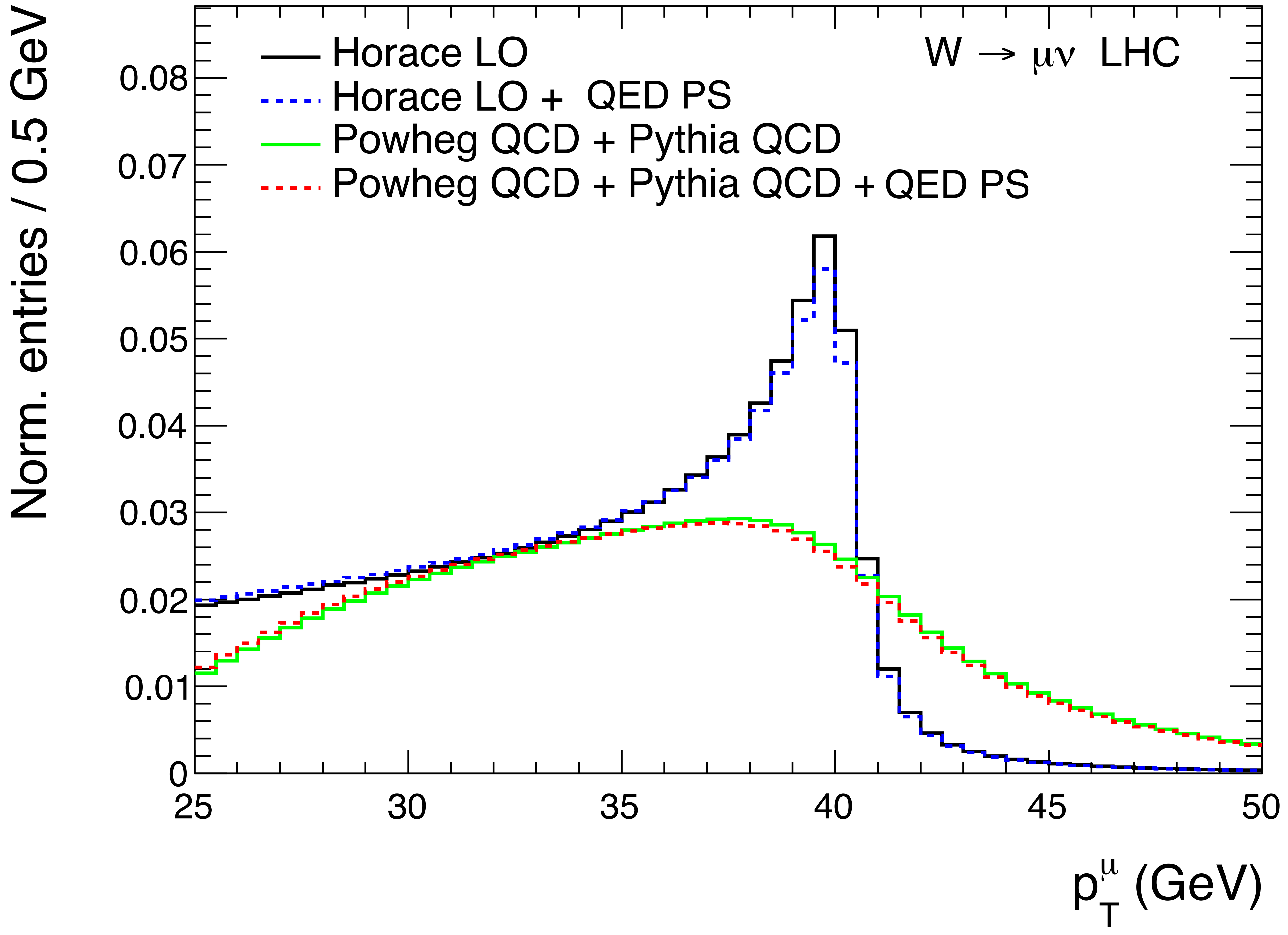
important QED/EW corrections modulated by the underlying QCD dynamics

Existing tools predicting Drell-Yan observables

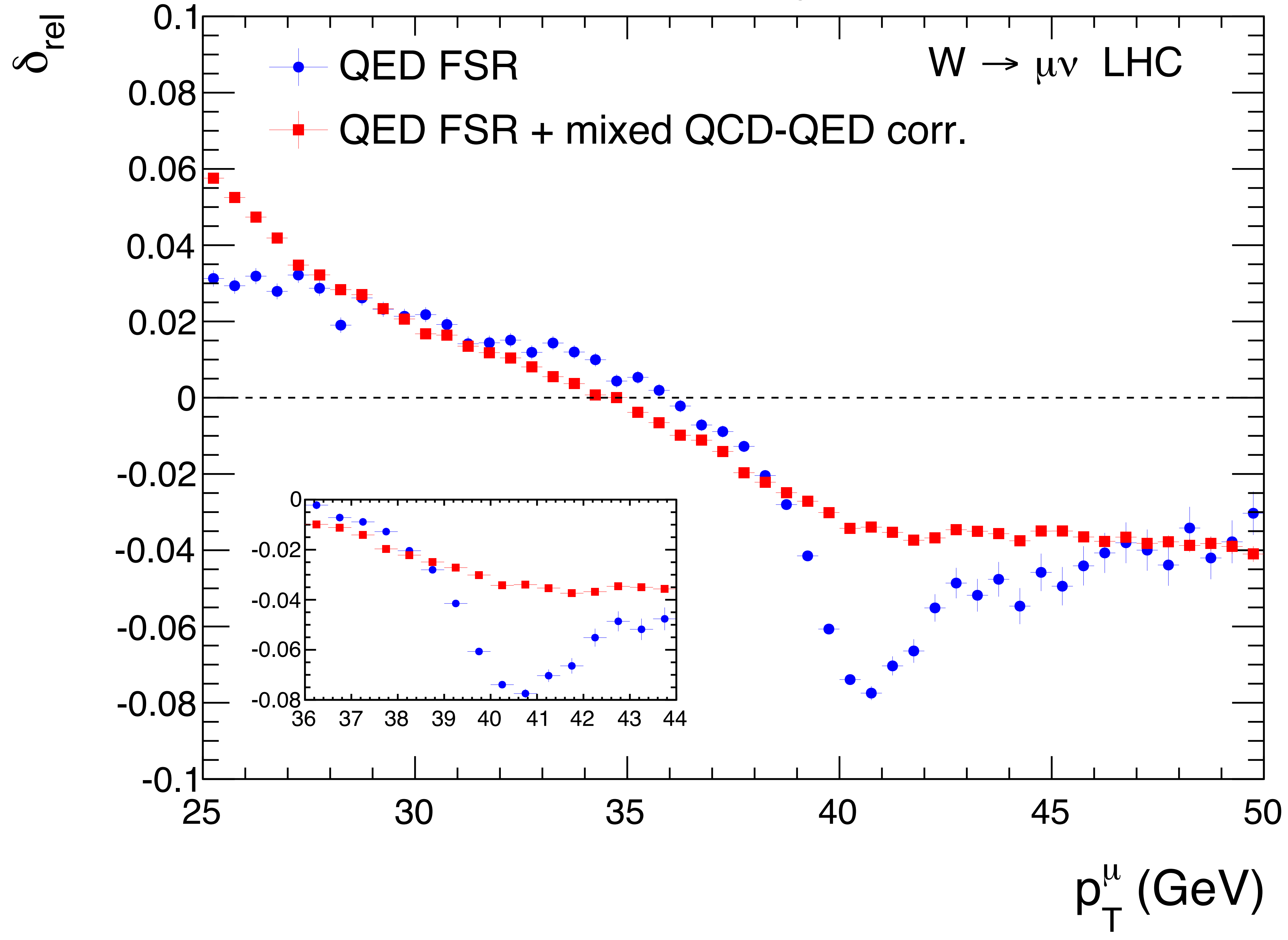
Different observables / physics goals require the inclusion of specific sets of higher-order corrections:
e.g. ptZ → QCD resummation, rapidity distribution → higher-order QCD K-factor, lepton distributions → QED-FSR

Group different codes according to the inclusion of corrections:
1) only-QCD, 2) only EW, 3) also mixed QCD-EW

Leading corrections in DY production are given by QCD K-factor, QCD-ISR and QED-FSR:
standard combination of tools is given by a NLO-QCD Parton Shower MC convoluted with a final-state QED shower



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



Mixed QCD-QED leading effects are included in the analyses as a standard ingredient for more than 15 years.

These effects might be large! Is this sufficient for high-precision analyses? In general no…

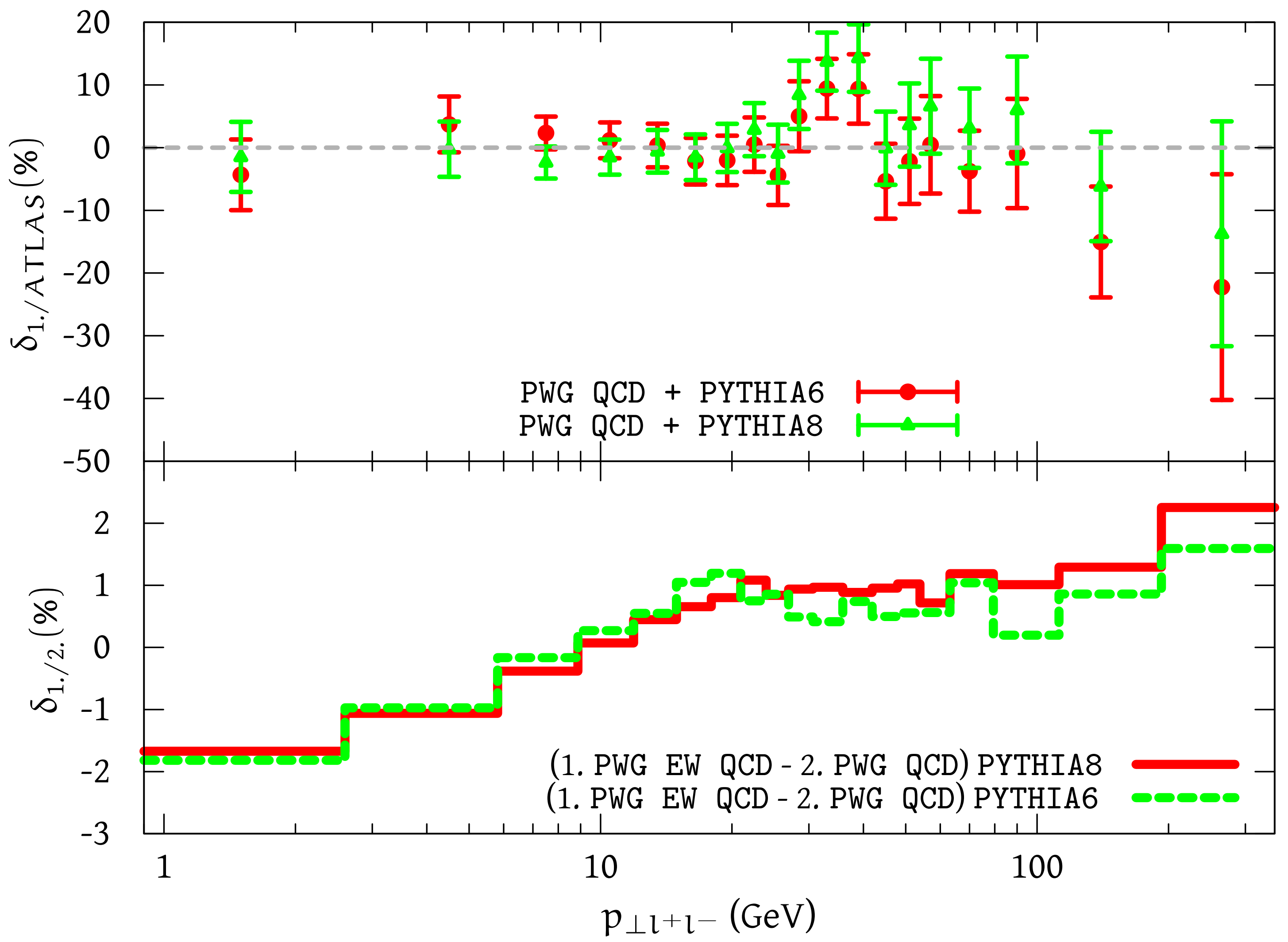
Existing tools predicting Drell-Yan observables

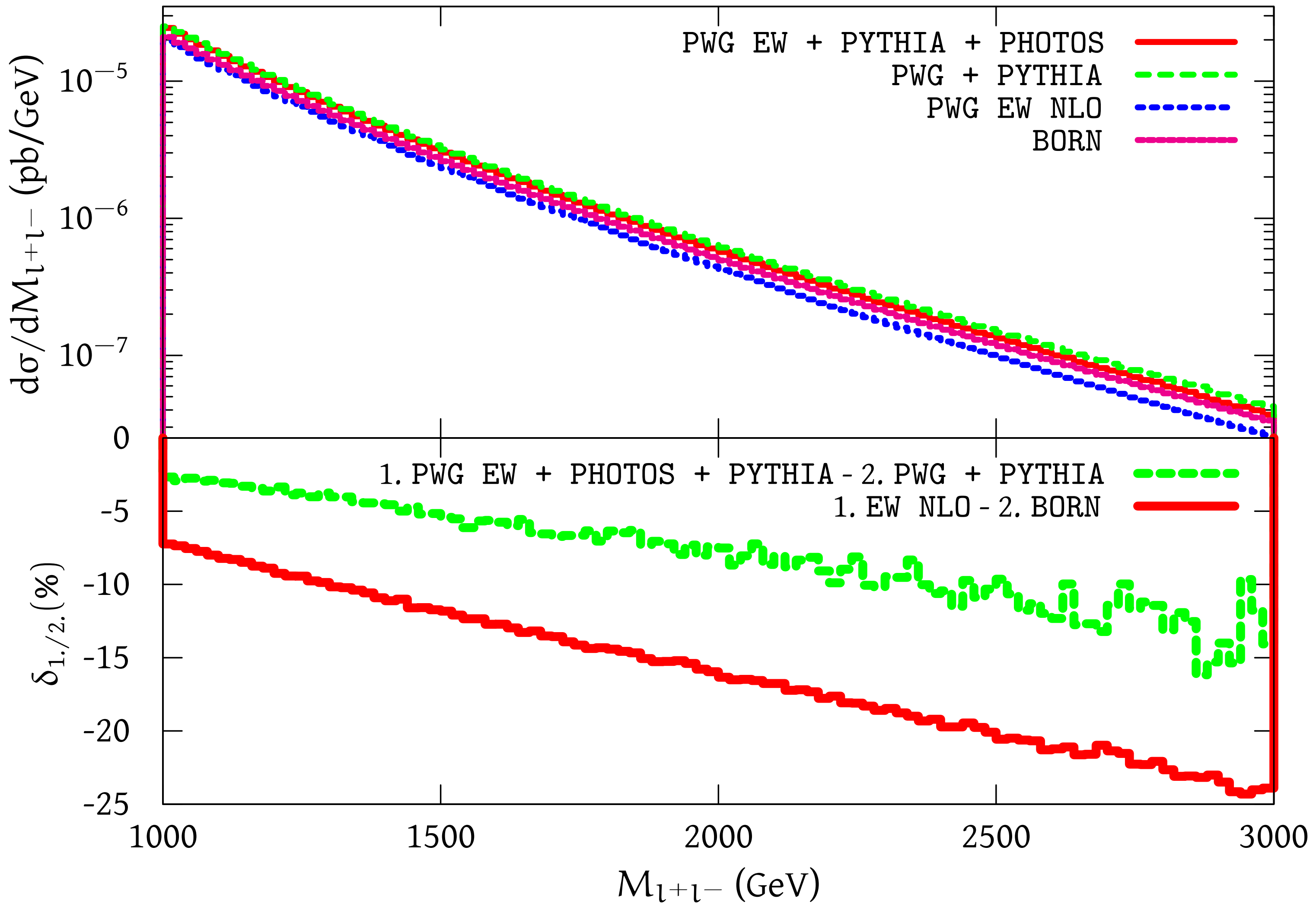
The matching of NLO results with a Parton Shower has become standard also in the EW sector

e.g. POWHEG_W_BMNNP and POWHEG_Z_BMNNPV have NLO-(QCD+EW) + (QCD+QED)-PS accuracy,

pro’s
- → total xsec is NLO-QCD + NLO-EW accurate (including all 1-loop virtual corrections)
- → enhancement factors (log(QCD) log(QED/weak), log(_) K-factor(_)) are included
- → improved description of: 1) resonances, 2) high-energy tails
- → important improvement in the quality of the QED radiation spectra, including QED-ISR

L.Barzè, G.Montagna, P.Nason, O.Nicrosini, F.Piccinini, AV, arXiv:1302.4606





con’s
- → matching ambiguities are present (the POWHEG QCD-EW combination is one possible recipe…)
- → the size of the uncertainty is NLO for both interactions
  potentially affecting the ultimate precision of the code
- → large competing effects could combine in a non-trivial way in an exact combination

an exact NNLO QCD-EW calculation can solve or improve on these issues

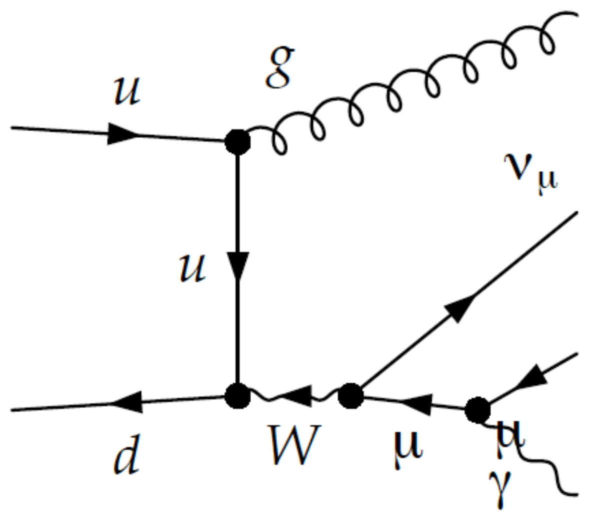
Progress towards Drell-Yan simulations at NNLO QCD-EW

The progress in the development of the simulation codes depends:

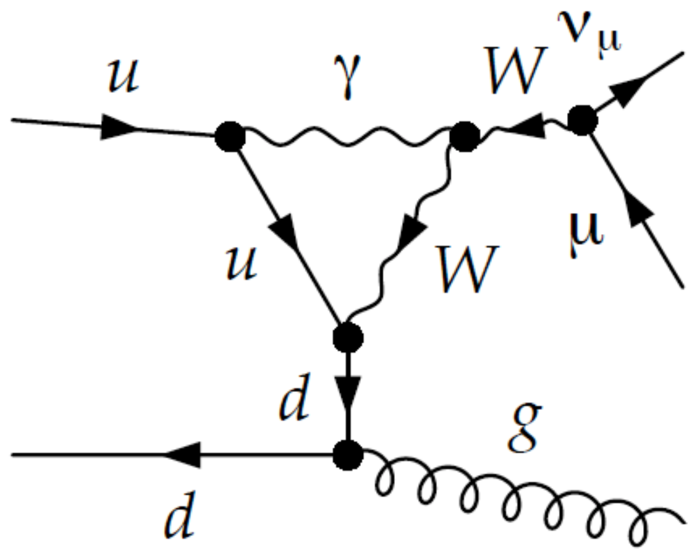
i) on the availability of the matrix elements describing the higher-order radiative corrections

ii) on the existence of PDFs at the same perturbative level of the partonic cross sections

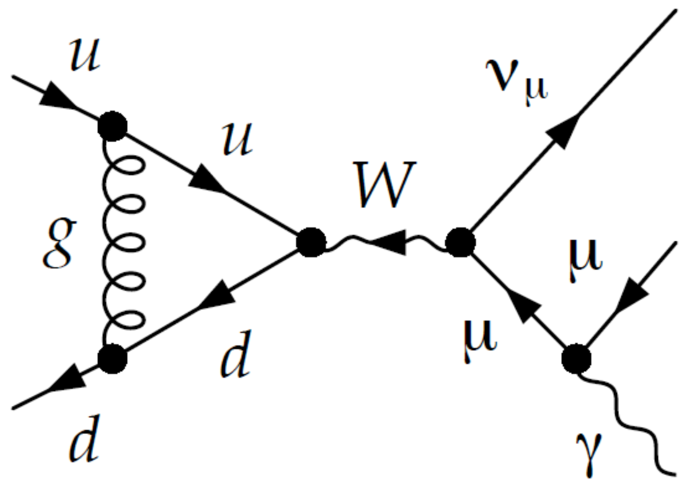
iii) on the possibility of a consistent matching of fixed- and all-order results



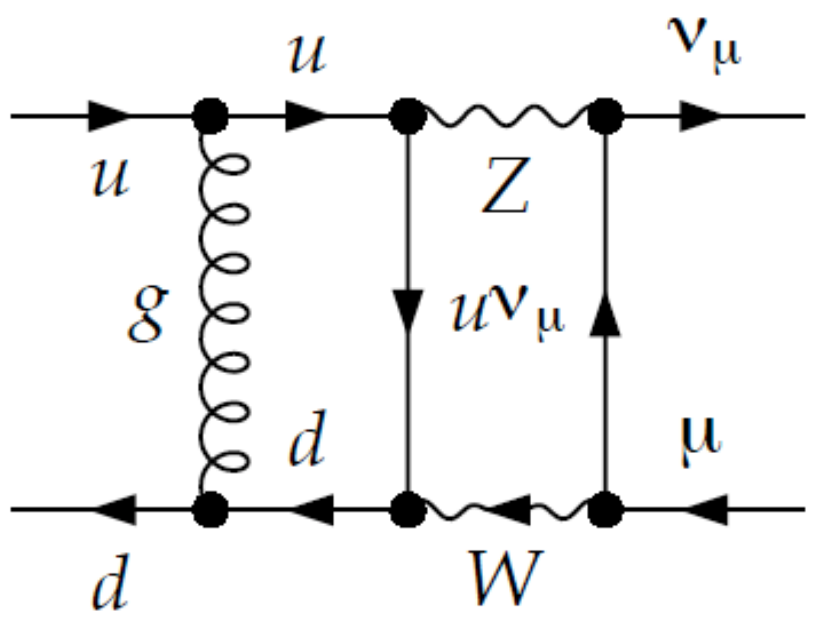
double-real



realQCD-virtualEW



realQED-virtualQCD



double-virtual

the 2-loop Master Integrals with massive lines and the subtraction of collinear singularities are among the main obstacles

Progress towards Drell-Yan simulations at NNLO QCD-EW

Strong boost of the activities in the theory community in the last 12 months !

→ mathematical 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

→ on-shell Z production as a first step towards full Drell-Yan → see F.Buccioni's talk tomorrow

- 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 cross section in fully analytical form (qqbar channel) including 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

- fully differential on-shell Z production including exact NNLO QCD-EW corrections
F. Buccioni, F. Caola, M.Delto, M.Jaquier, K.Melnikov, R.Roentsch, arXiv:2005.10221

- total cross-section for virtual photon production at N3LO-QCD (ultimate QCD precision benchmark)
C.Duhr, F.Dulat, B.Mistlberger, arXiv:2001.07717

→ complete Drell-Yan

- neutrino-pair production including NNLO QCD-QED corrections
L. Cieri, D. de Florian, M.Der, J.Mazzitelli, arXiv:2005.01315

Analytic progress: Master Integrals for DY processes at O(αα$_s$)

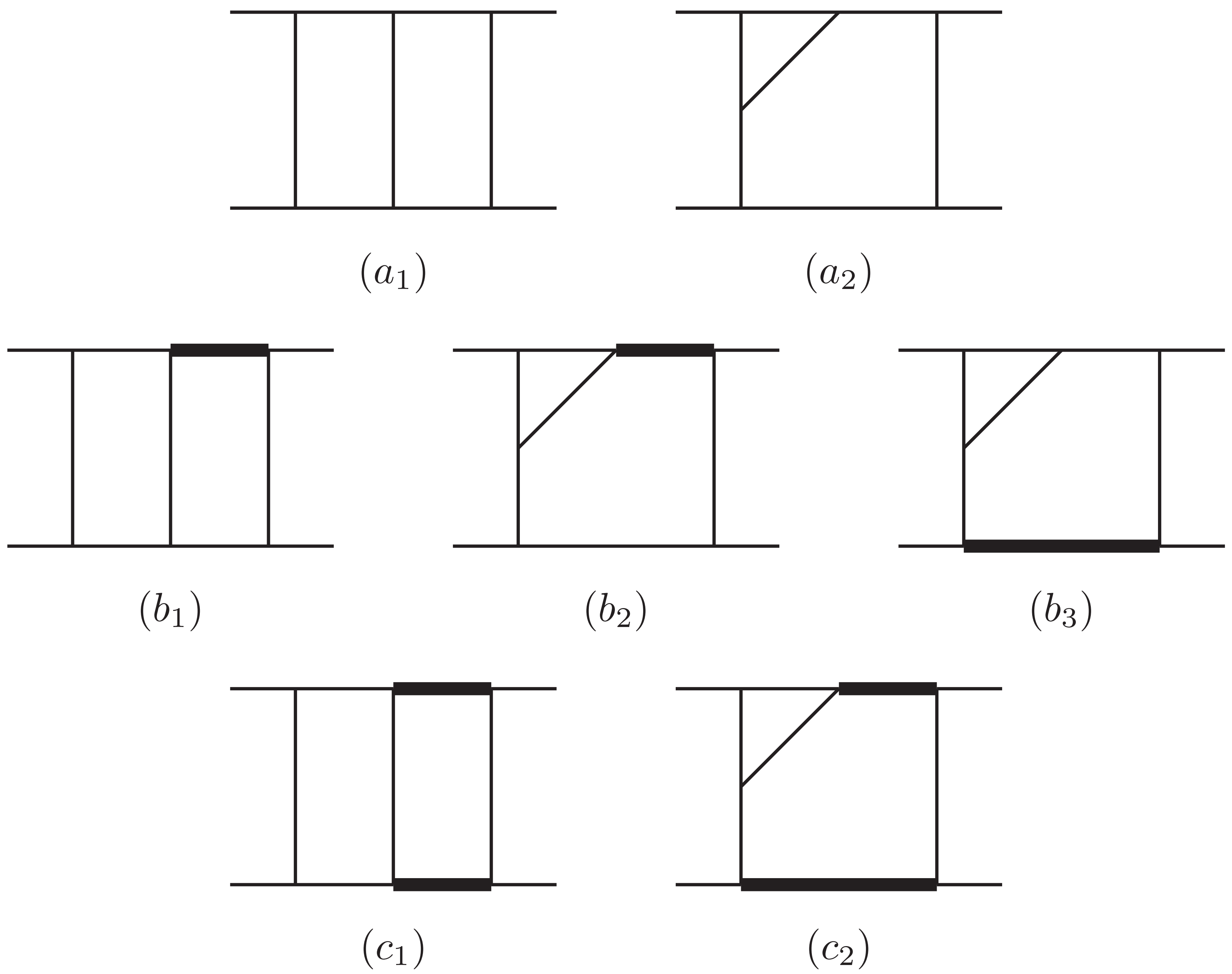
R. Bonciani, S. Di Vita, P. Mastrolia, U. Schubert, arXiv:1604.08581

thin lines massless
thick lines massive
topologies **b** and **c** were not known

2 masses topologies evaluated with the same mass

SM results, where both W and Z appear,
can (sometimes) be evaluated with an expansion in ΔM=MZ-MW

49 MI identified (8 massless, 24 1-mass, 17 2-masses)
solution of differential equations expressed in terms of
iterated integrals (mixed Chen-Goncharov representation)



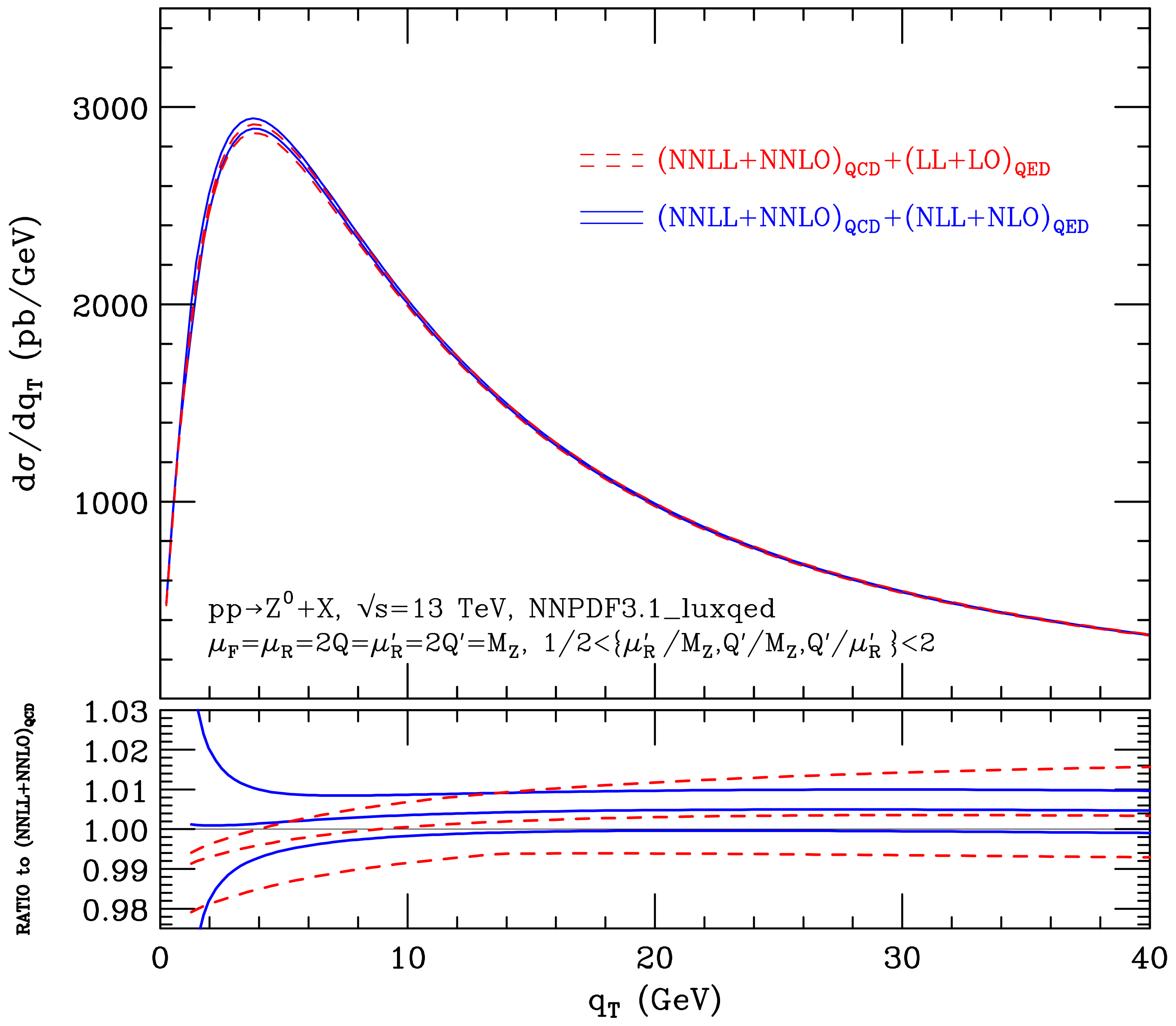
M.Heller, A.von Manteuffel, R.Schabinger arXiv:1907.00491, S.Hasan, U.Schubert, arXiv:2004.14908
same class of diagrams expressed in terms of multiple polylogarithms (two independent solutions)

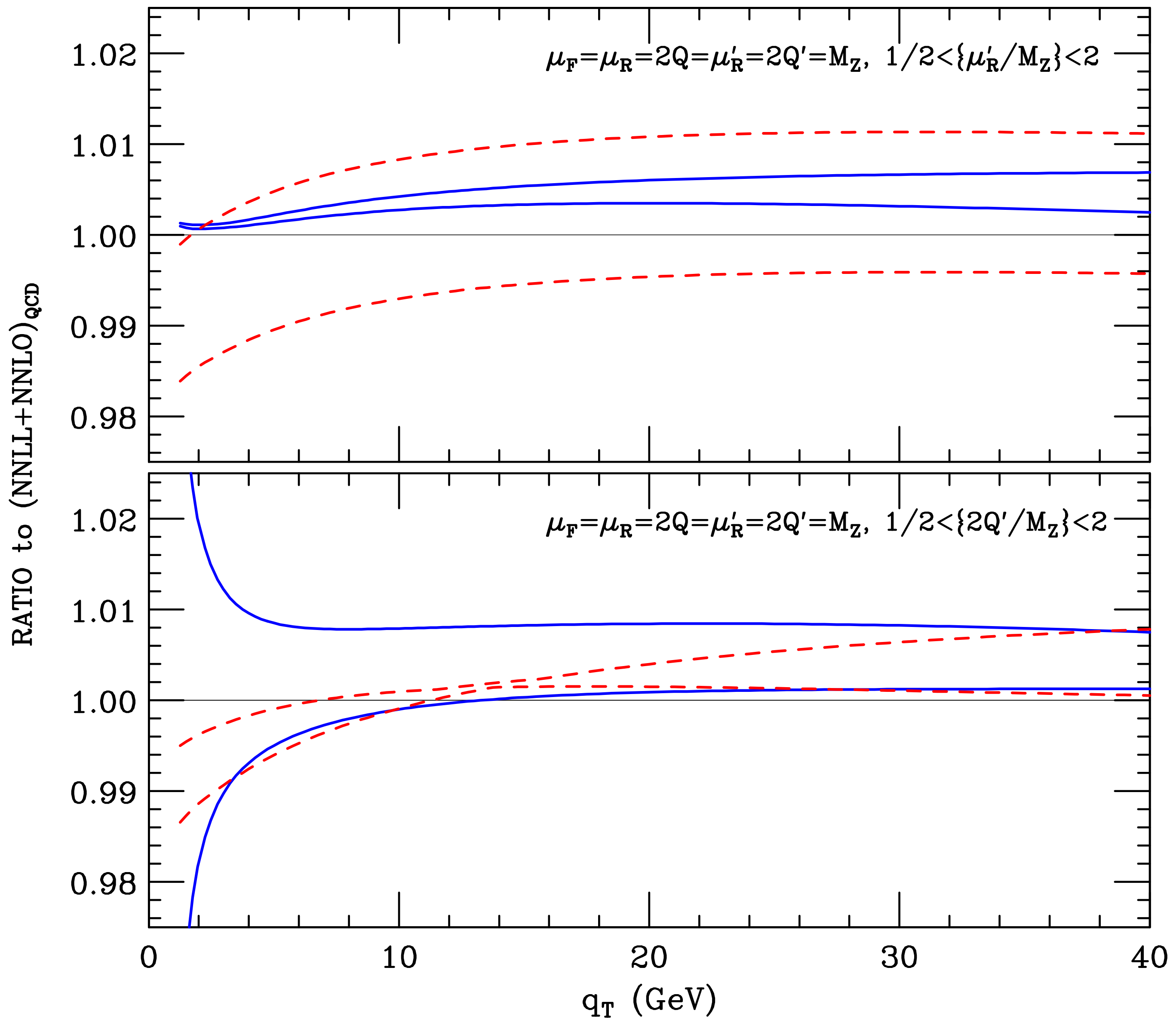
trade-off between
a simpler analytical representation of the results (Chen-Goncharov) (but problematic analytical continuation to the physical region)
and
polylogarithmic representation of the results with more cumbersome arguments

The Master Integrals are solved with the Differential Equation technique
Main issues related to number of energy scales (s, t, MW, MZ, Mmu)
at mathematical level → appearance of elliptic kernels and evaluation of boundary conditions

Differential distributions including NNLO QCD-EW corrections

L. Cieri, G. Ferrera, G. Sborlini, arXiv:1805.11948

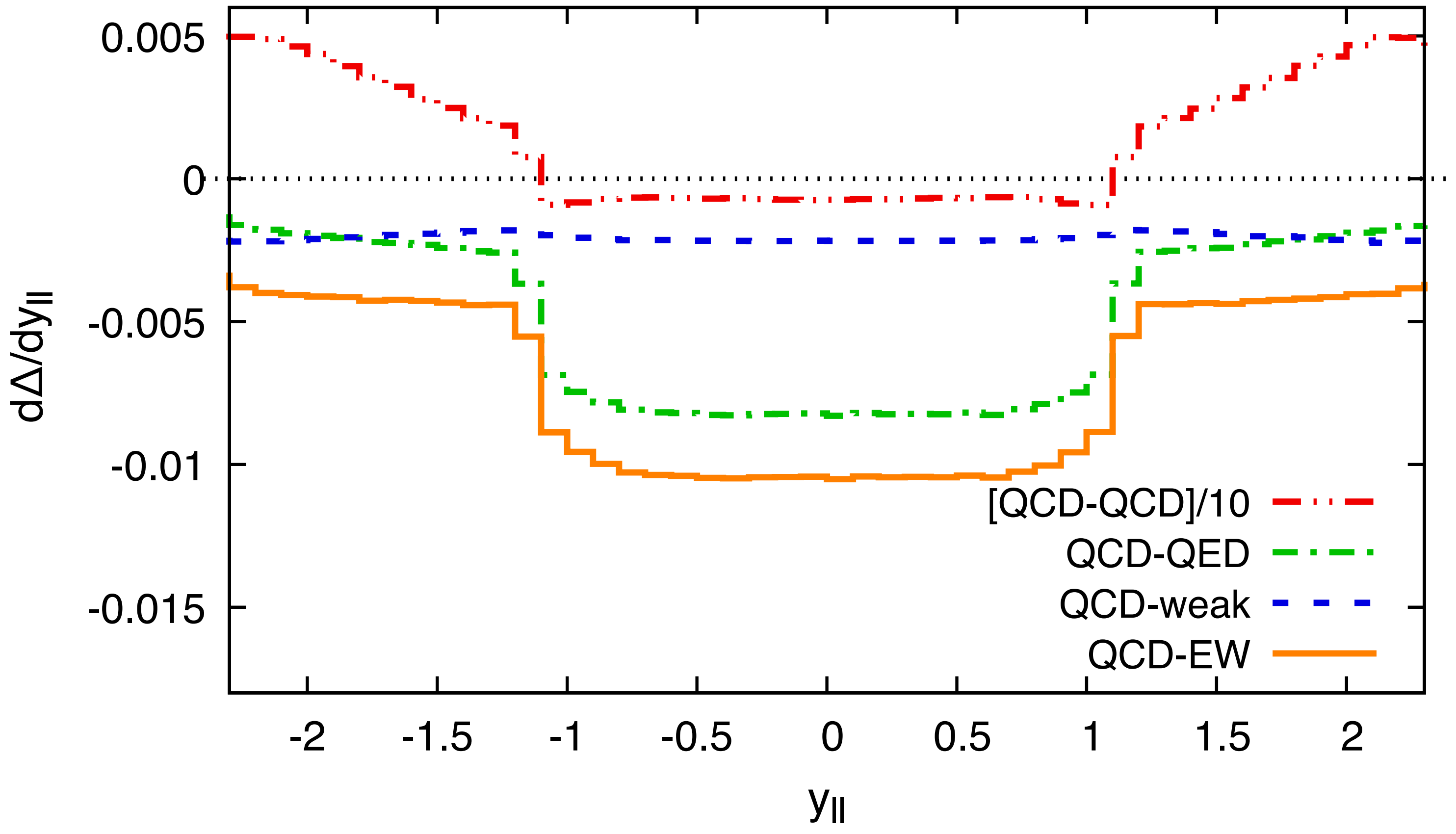


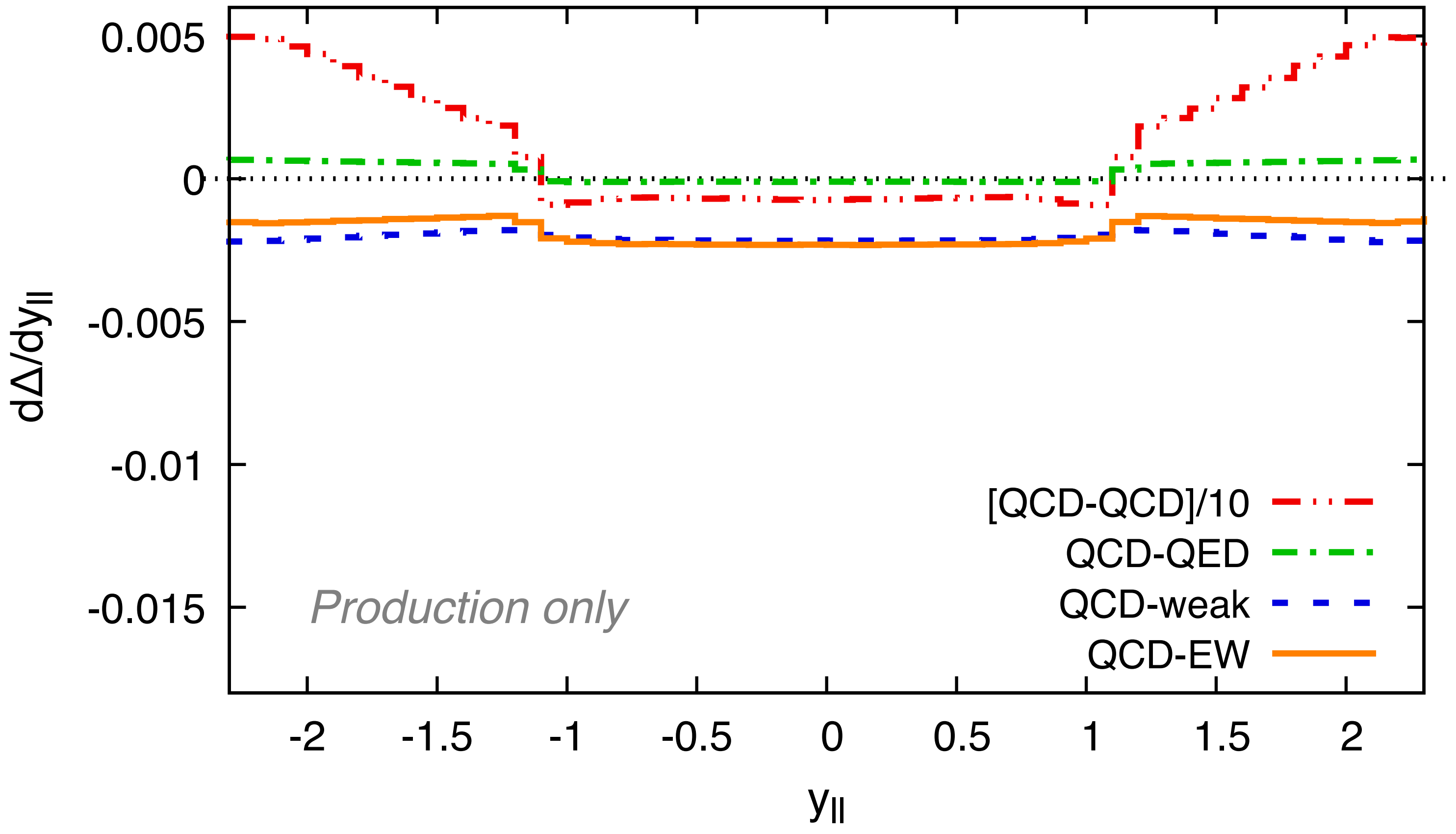


Good qualitative agreement with POWHEG

additional ISR effects from the NLL_QED resummation

F. Buccioni, F. Caola, M.Delto, M.Jaquier, K.Melnikov, R.Roentsch, arXiv:2005.10221





QCD-weak effects are a not negligible fraction of the initial state QCD-EW corrections, possibly larger than QCD-QED

final state QED corrections are in general large their interplay with the initial state is not negligible

DGLAP-QED evolution of proton PDFs

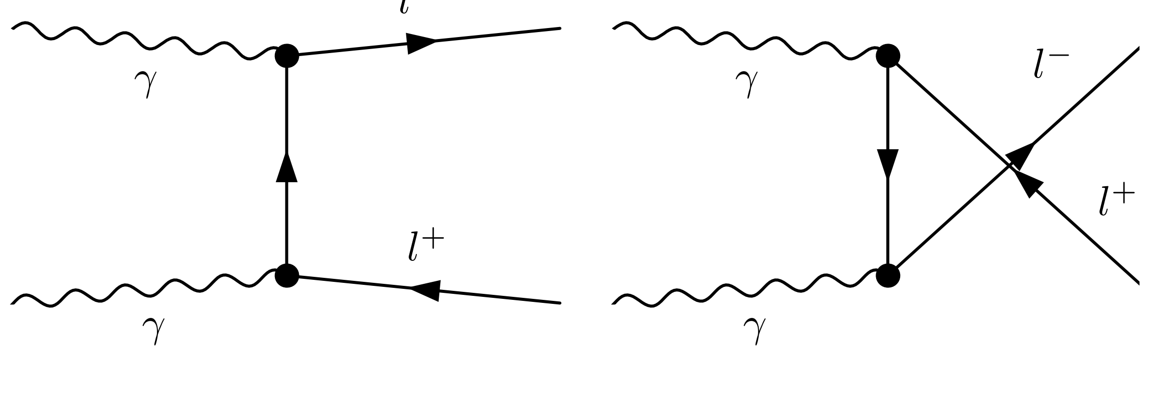
The necessary inclusion of NLO-EW and NNLO QCD-EW corrections NECESSARILY implies the usage of proton PDFs with also a QED kernel in the DGLAP evolution of the parton densities

The presence of a photon density in the proton yields
1) a (small) redistribution of the momentum fraction carried by quarks and gluons
2) the presence of new partonic scattering processes

Only the sum over all partonic channels provides a physically meaningful prediction of the hadron-level cross section
with a non-trivial level of interplay (cfr. C.Duhr et al. arXiv:2001.07717 about N3LO-QCD predictions)

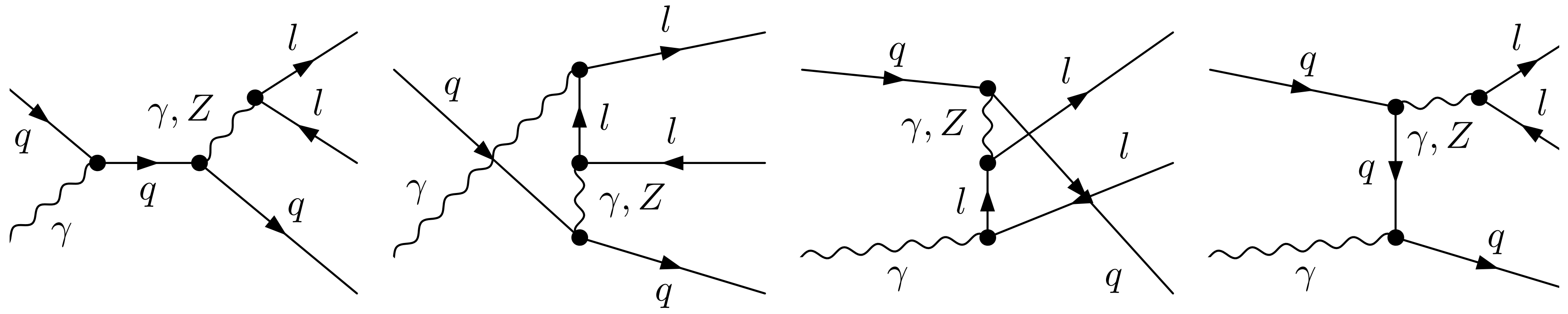
$$\sigma(P_1,P_2;m_V) = \sum_{a,b}\int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1,M_F) f_{h_2,b}(x_2,M_F)\, \hat{\sigma}_{ab}(x_1P_1,x_2P_2,\alpha_s(\mu),M_F)$$

At LO we need to consider also



(b) (c)

At NLO-EW we have



(a) (b) (c) (d)

At NNLO QCD-EW
we have also
γg initiated processes

Best Drell-Yan predictions require proton PDFs with all the relevant QCD factors (now up to N3LO) and NLO-QED evolution

The non-trivial role of photon-induced contributions is evident
in other processes like W+W- production, at high invariant masses
possibly in high-precision analyses like the determination of the effective weak mixing angle (cfr. LHC-EWWG activities)

Fit of observables, parameter determination and EW input schemes

Parameter determination:

The templates are theoretical predictions of the kinematical distributions, functions only of the lagrangian input parameter

e.g. in the SM $\mathcal{T} = \mathcal{T}(g, g', v; \lambda; m_f; CKM)$

We choose a set of experimental quantities (EW inputs) to express the lagrangian couplings.
All the other pseudoobservables and parameters are predictions, which can be tested but not used as fit parameters.

examples: at LEP1 the choice (α, G_μ, MZ, MH) as inputs allowed to determine MZ,

at LEP2 for the MW determination introduction of the (G_μ, MW, MZ, MH) scheme

(no-one would have used (α, G_μ, MZ, MH) as input scheme to fit MW)

in these two schemes $\sin^2\theta_{eff}$ is a prediction and can not be used as a fit parameter!

$\sin^2\theta_{eff}$ determination

Two new schemes with (α, $\sin^2\theta_{eff}$, MZ) and with (G_μ, $\sin^2\theta_{eff}$, MZ) as input parameters M.Chiesa, F.Piccinini, AV, arXiv:1906.11569

→ consistent fit of the data based on templates which are functions of

$$\mathcal{T} = \mathcal{T}(\alpha, \sin^2\theta_{eff}, M_Z) \quad \text{or} \quad \mathcal{T} = \mathcal{T}(G_\mu, \sin^2\theta_{eff}, M_Z)$$

pro's
- direct dependence on the fit parameter, direct control over th. and exp. systematics
- exactly the same definition as at LEP (straightforward possibility to combine results)
- $\sin^2\theta_{eff}$ is defined at the MZ scale → a large fraction of radiative corrections at $q^2=MZ^2$ is reabsorbed in its definition
  - → fast perturbative convergence, → weak sensitivity to mtop (small parametric uncertainty)
  - → robust consistency check of the SM: small systematic uncertainty from the templates

Searches for New Physics exploiting at best the Z resonance information

A scheme with (G_μ, $\sin^2\theta_{eff}$, MZ) has already been mentioned at LEP time

D.C.Kennedy, B.W.Lynn,Nucl.Phys.B322, 1; F.M.Renard, C.Verzegnassi, Phys.Rev.D52,1369;A.Ferroglia, G.Ossola,A.Sirlin,Phys.Lett.B507,147;

as the most convenient parameterisation for New Physics searches,
because it maximises the amount of information which can be reabsorbed and encoded in the LO couplings,
from very precise data (Z resonance)
→ any discrepancy that should further emerge will not be reabsorbed in the parameterisation → New Physics signal

Whether the same choice could be adopted in SMEFT fits, together with the Wilson coefficients of the new operators,
deserves additional investigations (interplay between the EW and EFT communities)

Diboson production

Diboson production is relevant for
- test of the mechanisms of EW symmetry breaking
- test of the non-abelian structure of the EW interaction, probing tri- and quadrilinear couplings
- probe of the existence of new interactions as they can be described in the language of EFT via higher-dim operators

Complexity of the calculations due to
- large number of Feynman diagrams with their interferences
- interplay of QCD and EW interactions already at LO, meaningless distinction at NLO of QCD vs EW corrections
- presence of different mechanisms of enhancement, often in competition
- need for the inclusion of multiple parton (QCD and QED) emissions

Impressive boost of the theoretical activities offering, for several processes, the combination of

(N)NLO QCD results and NLO EW results

matched with QCD and/or QED Parton shower

or

merged including different jet multiplicities that contribute to the same final state signal

Progress possible thanks to different kinds of automation:
- loop-integrals evaluation (e.g. Collier)
- matrix-element generation and reduction (e.g. Recola, OpenLoops, aMC@NLO_Madgraph)
- automated multiple-processes handling

Diboson production: NNLO-QCD + NLO-EW corrections

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

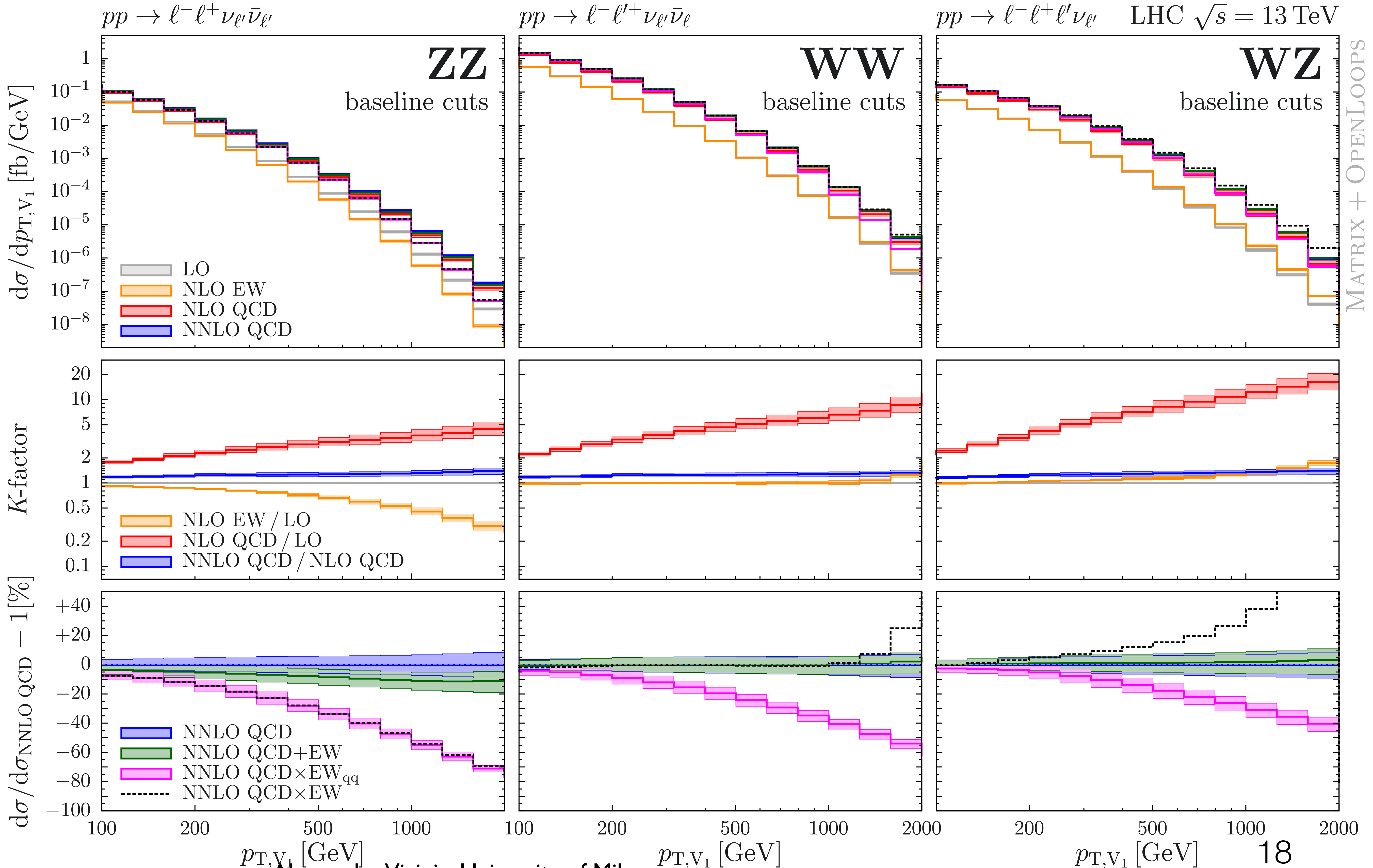
- large QCD and EW corrections need a consistent combination to achieve O(1%) precision → `Matrix+OpenLoops`
- comparison of additive vs multiplicative combinations of QCD and EW effects, to estimate mixed QCD-EW missing corrections
- differences between 1) hard-hard boson regions and 2) (hard boson,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

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

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

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

Diboson production: matching NLO-(QCD+EW) with (QCD+QED)-PS

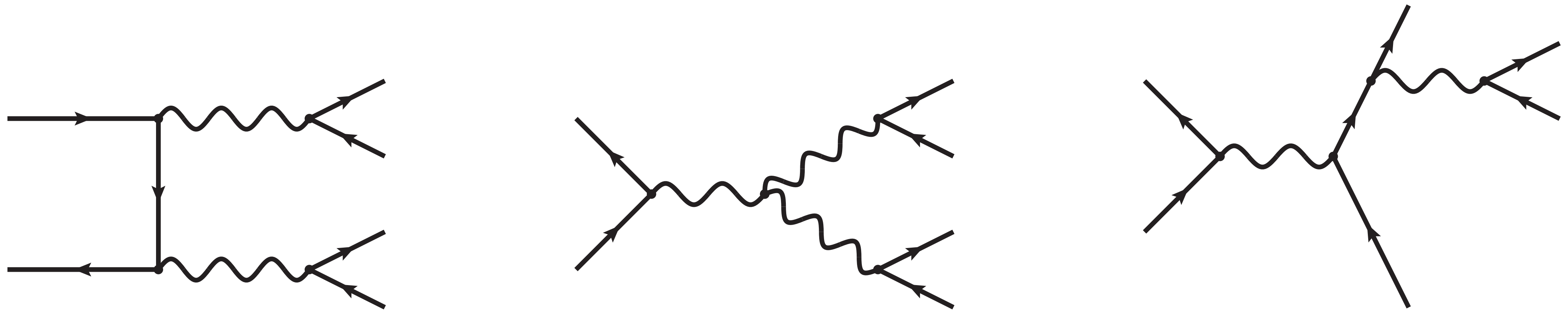
M.Chiesa, C.Oleari, E.Re, arXiv:2005.12146

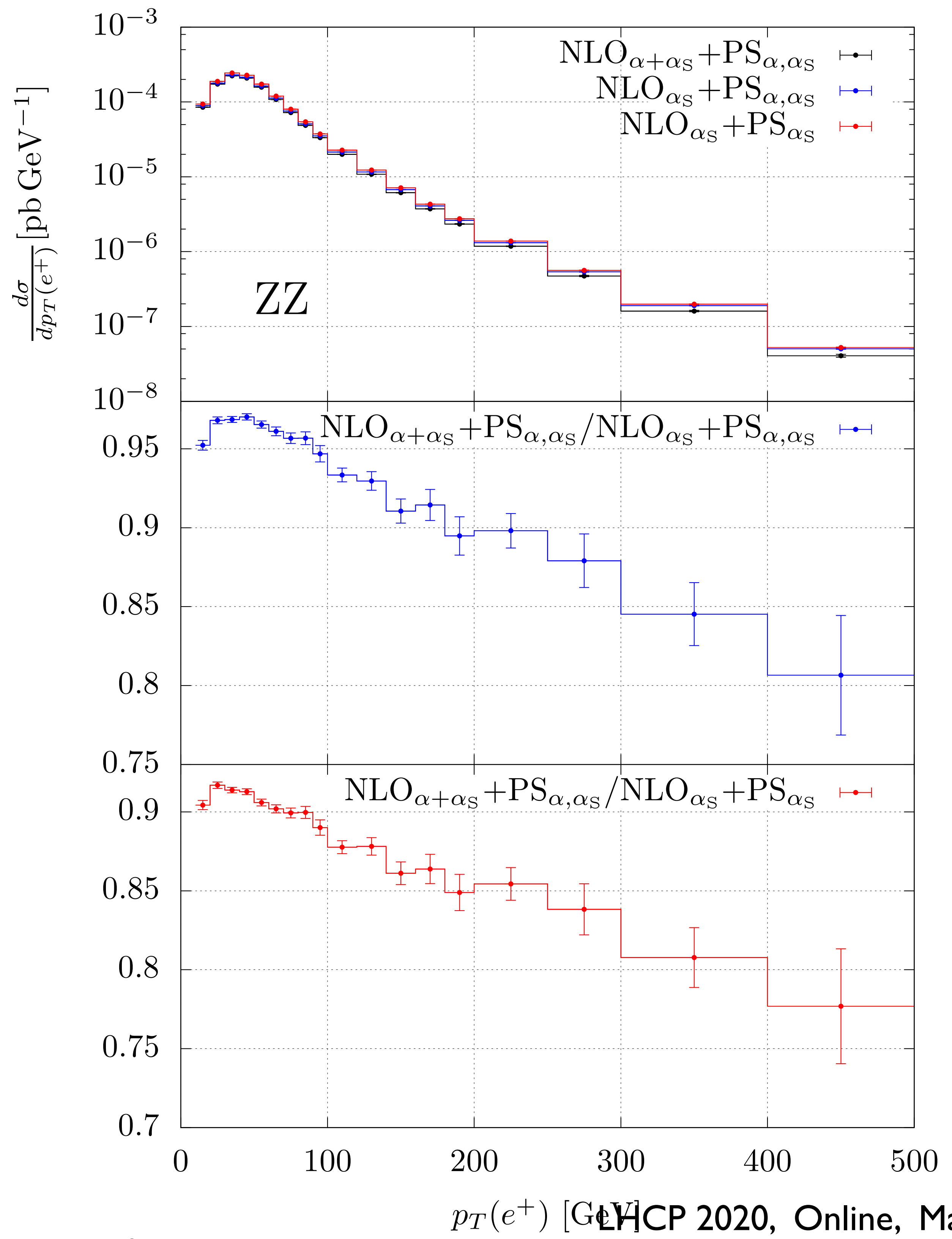
- complete NLO-QCD and NLO-EW corrections to 4-fermion production available for more than 10 years → normalization
- the inclusion of multiple QCD/QED partons is needed to predict kinematical distributions, → shapes
- matching NLO matrix elements with multiple parton radiation via Parton Shower well established for more than 15 years
- problem of competition between QCD and QED in the NLO-(QCD+EW) matching to "emit the hardest parton"

- processes with identifiable subsystems, like resonant particles, are described assuming the existence of different stages: the prevalence of QCD emissions from the initial state and of QED emission from the resonances and final leptons allows a combined matching, which enables the matrix-element description for both kind of partons

- this "resonance"-treatment, including QCD and QED radiation, (developed for DY and ttbar) is now available for diboson production

MC possible histories





important NLO-EW correction (blue)

not negligible impact of QED higher orders (red) in view of O(1%) studies

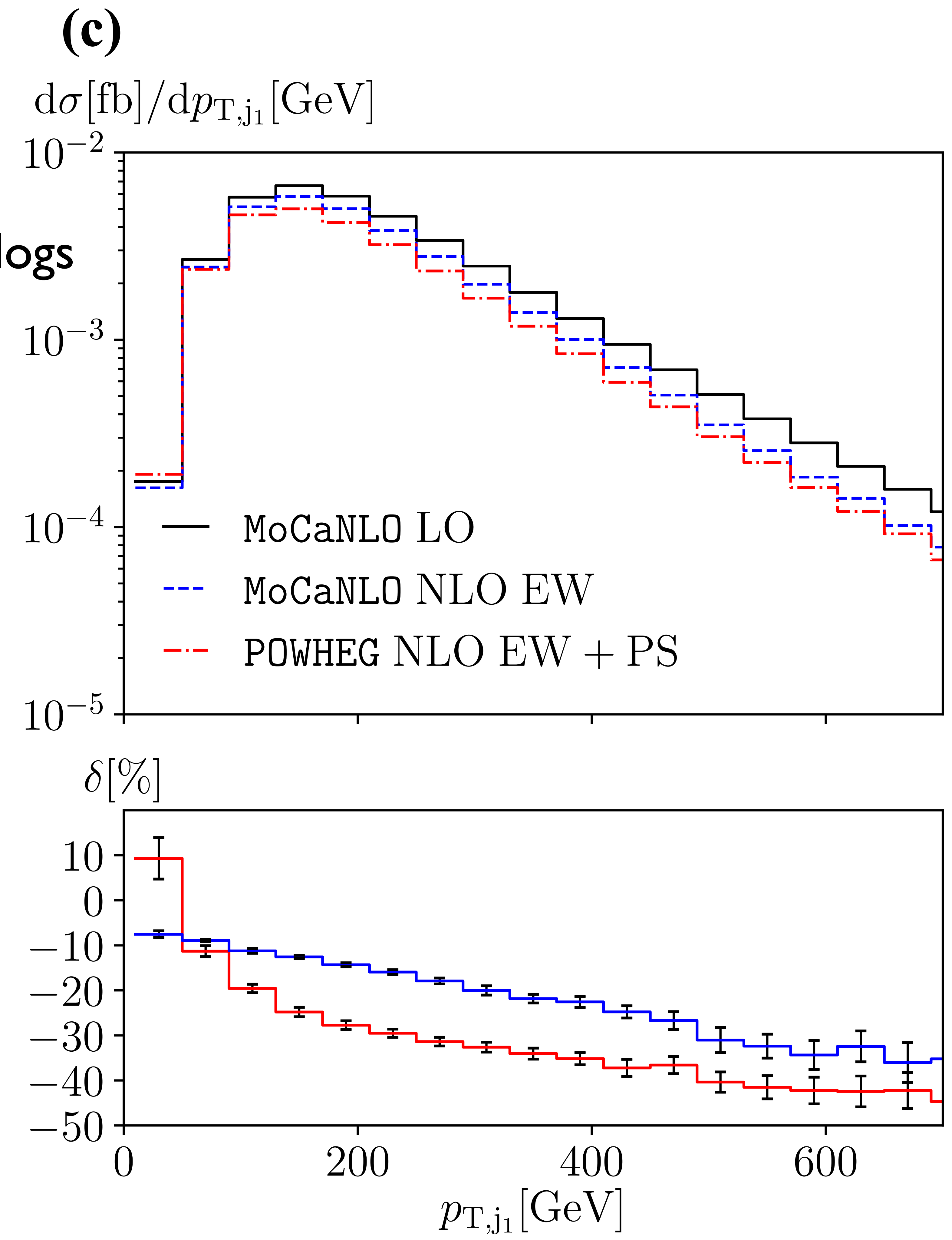
Same-sign W-boson scattering at NLO-EW + QED-PS

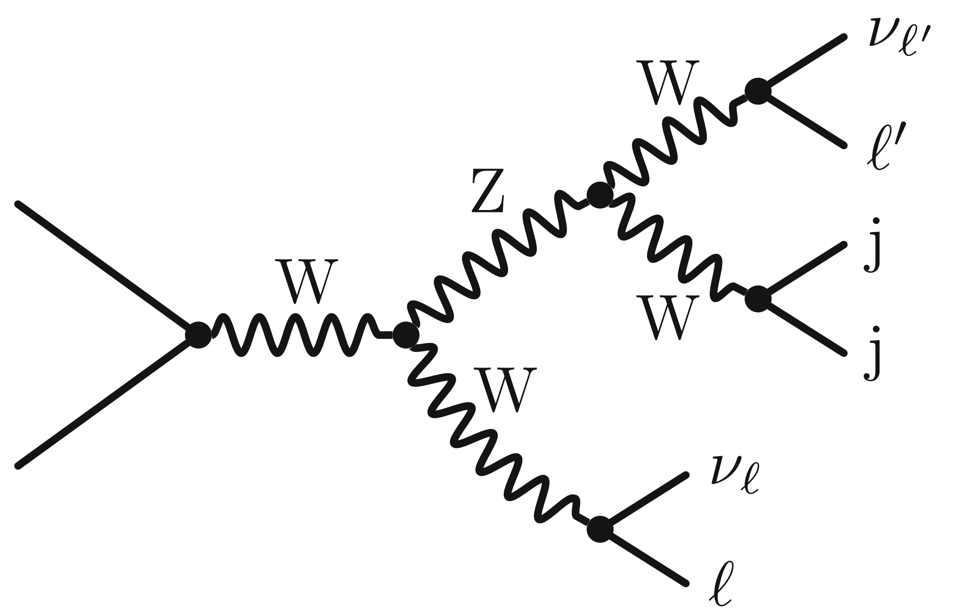
M.Chiesa, A.Denner, N.Lang, M.Pellen, arXiv:1906.1863

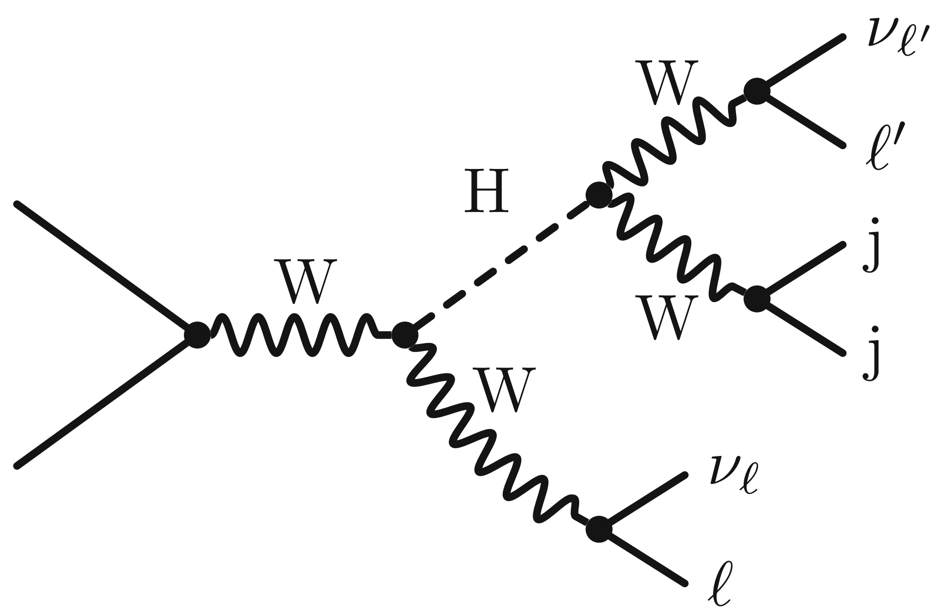
one of the crucial processes to study EW symmetry breaking at hadron colliders
extreme complexity of the EW interaction, with 8 external particles

large EW corrections motivate the inclusion of QED-PS effects

non-trivial interplay of large EW virtual corrections with large collinear enhanced QED logs
significant impact on observables sensitive to radiation details







Conclusions and outlook

The Precision Tests of the SM and the searches for BSM signals
require a control, both experimental and theoretical, at the O(0.1%-1%) level of the theoretical predictions for the kinematical distributions
such a high precision is needed to determine with significant precision the fundamental parameters of the Lagrangian (couplings, masses)
→ non trivial challenge

At this level of precision, the entanglement of QCD and EW corrections is unavoidable, at partonic level and in the PDFs

Impressive theoretical progress, both for single- and di-boson production:

- the combination of (N)NLO-QCD and NLO-EW results is now "routine"
- matching NLO with PS, for complex processes and including QCD and QED effects, is demonstrated
- new analytical results at NNLO QCD-EW are becoming available

In the diboson case, we have observables whose corrections do not obey a specific hierarchy, with large cancellations
→ also in this case mixed QCD-EW corrections might help to fully stabilise the predictions

The ultimate precision of the predictions might depend

- on the observable under study
- on a parallel development of PDFs and partonic results (N3LO-QCD + NLO-EW for DY)
- on the development of procedures to reduce the dependence on the PDFs and the QCD modelling (not discussed here)

Thank you for your attention