UNIVERSITÀ DEGLI STUDI DI MILANO

Istituto Nazionale di Fisica Nucleare

Interplay of QCD and EW corrections and precision physics at hadron colliders

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EPS-HEP 2017

Venezia, July 6th 2017

Plan of the talk

- LHC measurements have reached the percent and even the sub-percent level in several cases
  → a systematic control over all sources of radiative effects at this level is needed

- The classification of radiative corrections depends
  on the observable under study
  on the presence of logarithmic enhancing factors

  → EW corrections can be as important as the QCD ones
  → a systematic analysis of QCD, EW and QCDxEW effects is mandatory

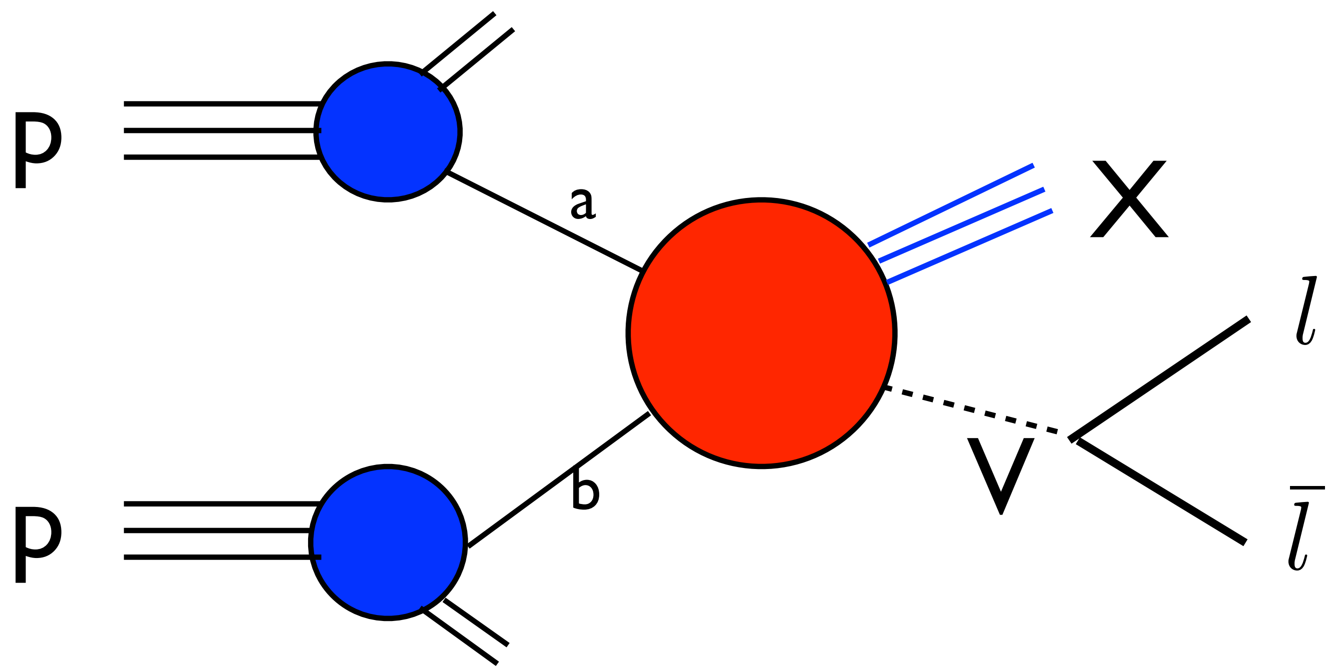
- general overview on the perturbative expansions in in α_s and α
  on the assessment of the uncertainties of the $O(\alpha\alpha_s)$ terms

- MW measurement from charged current Drell-Yan: impact of mixed QCDxEW corrections

- QCD uncertainties and EW parameters determination

Hard scattering in hadronic collisions

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



The prediction of the hadron level cross section requires

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

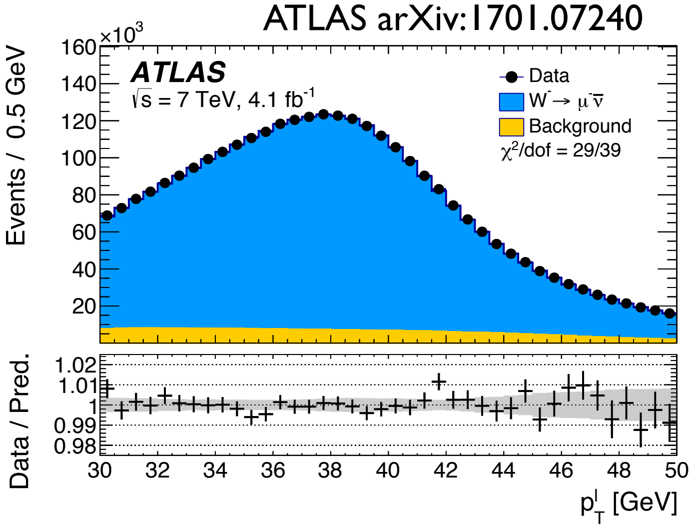
- accurate and consistent description of the QCD environment
  including PDFs, intrinsic partonic kt,
  QED DGLAP PDF evolution

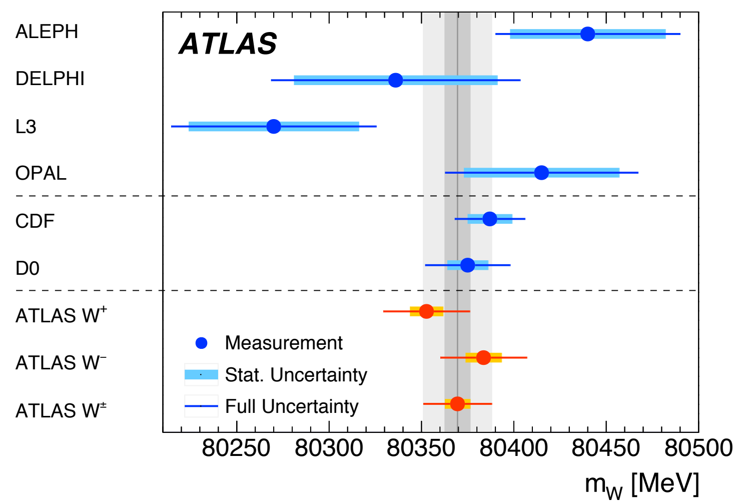
- all the ingredients of the calculations are affected by the QCDxEW interplay
- relative importance of different subsets of corrections depends on the final state/ observable
- non-trivial role in the uncertainty estimate

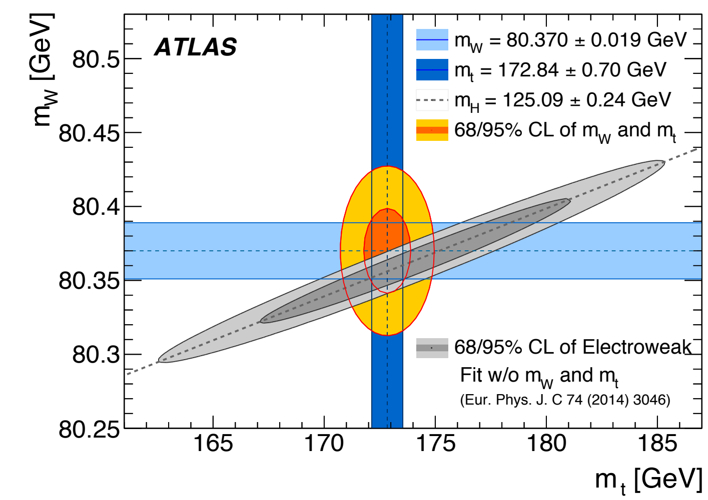
Signatures of interest

- Gauge boson masses and decay widths → shape of distributions at resonance/ jacobian peak
  precision goal: per mil level
  $m_W = 80370 \pm 19$ MeV error at the 2 10^{-4} level

ATLAS arXiv:1701.07240



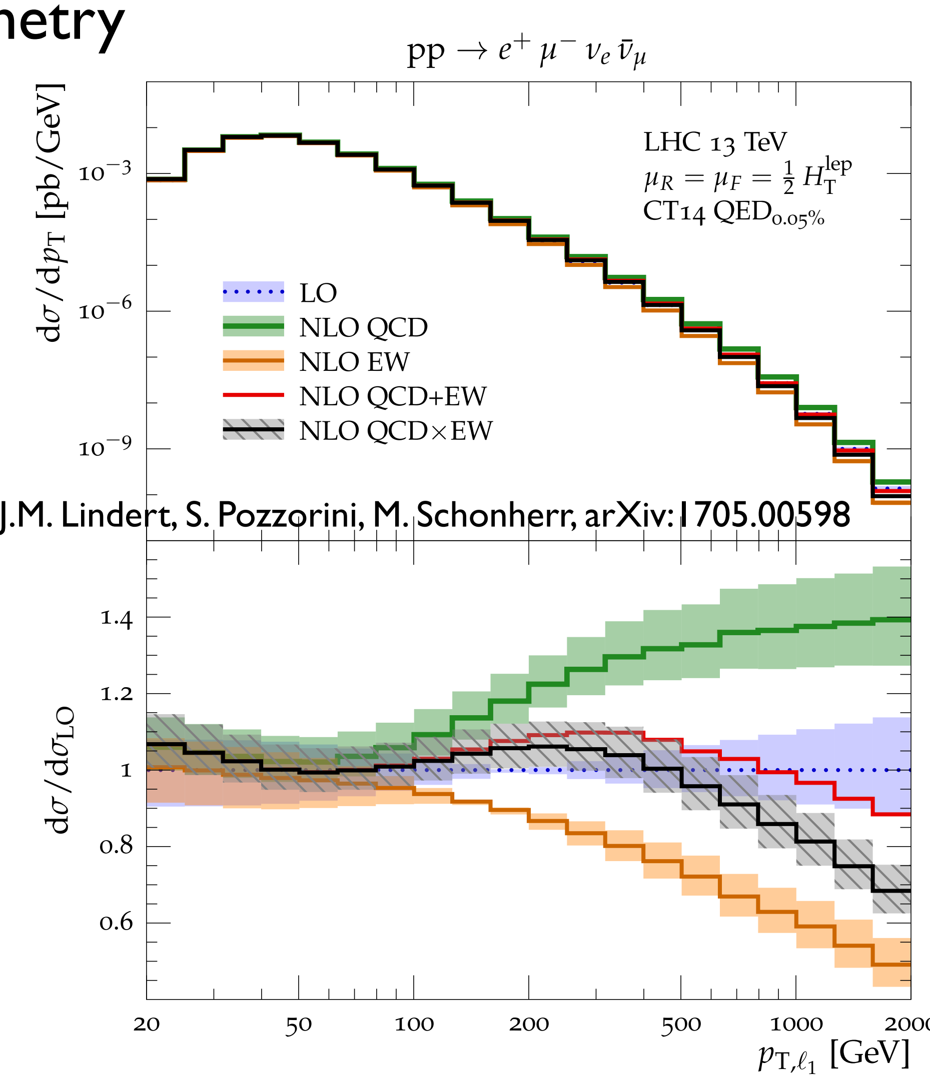




- Weak mixing angle → invariant mass forward/backward asymmetry
  deep understanding of proton PDF uncertainties

- Search for new gauge bosons/dark matter/… →
  tail of kinematical distributions at large momenta
  large cancellations of sizeable radiative corrections

  precision goal: per cent level



S. Kallweit, J.M. Lindert, S. Pozzorini, M. Schonherr, arXiv:1705.00598

Coupling expansion and logarithmic enhancements (1)

$$\alpha_s(m_Z) \simeq 0.118, \qquad \alpha_{em}(m_Z) \simeq 0.0078 \qquad \frac{\alpha_s(m_Z)}{\alpha_{em}(m_Z)} \simeq 15.1 \qquad \frac{\alpha_s^2(m_Z)}{\alpha_{em}(m_Z)} \simeq 1.8$$

Coupling strength → first classification (NNLO-QCD ~ NLO-EW) is appropriate
for those observables that do not receive any logarithmically enhanced correction

$$\begin{aligned}
\sigma_{tot} &= \sigma_0 + \alpha_s \sigma_{\alpha_s} + \alpha_s^2 \sigma_{\alpha_s^2} + \ldots && \text{QCD} \\
&\quad + \alpha \sigma_\alpha + \alpha^2 \sigma_{\alpha^2} + \ldots && \text{EW} \\
&\quad + \alpha\alpha_s\, \sigma_{\alpha\alpha_s} + \alpha\alpha_s^2\, \sigma_{\alpha\alpha_s^2} + \ldots && \text{mixed QCDxEW}
\end{aligned}$$

Coupling expansion and logarithmic enhancements (I)

$$\alpha_s(m_Z) \simeq 0.118, \qquad \alpha_{em}(m_Z) \simeq 0.0078 \qquad \frac{\alpha_s(m_Z)}{\alpha_{em}(m_Z)} \simeq 15.1 \qquad \frac{\alpha_s^2(m_Z)}{\alpha_{em}(m_Z)} \simeq 1.8$$

Coupling strength → first classification (NNLO-QCD ~ NLO-EW) is appropriate
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$$\begin{aligned}\sigma_{tot} \; = \; \sigma_0 \; &+ \; \alpha_s \sigma_{\alpha_s} \; + \; \alpha_s^2 \sigma_{\alpha_s^2} \; + \; \ldots && \text{QCD}\\ &+ \; \alpha \sigma_\alpha \; + \; \alpha^2 \sigma_{\alpha^2} \; + \; \ldots && \text{EW}\\ &+ \; \alpha \alpha_s \, \sigma_{\alpha \alpha_s} \; + \; \alpha \alpha_s^2 \, \sigma_{\alpha \alpha_s^2} \; + \; \ldots && \text{mixed QCDxEW}\end{aligned}$$

At differential level, in specific phase-space corners, a plain coupling constant expansion is inadequate
→ fixed-order EW corrections can become as large as (or even bigger than) QCD corrections
because of log-enhanced factors
→ log-enhanced corrections have to be resummed to all orders, if possible,
analytically or via Parton Shower, rearranging the structure of the perturbative expansion

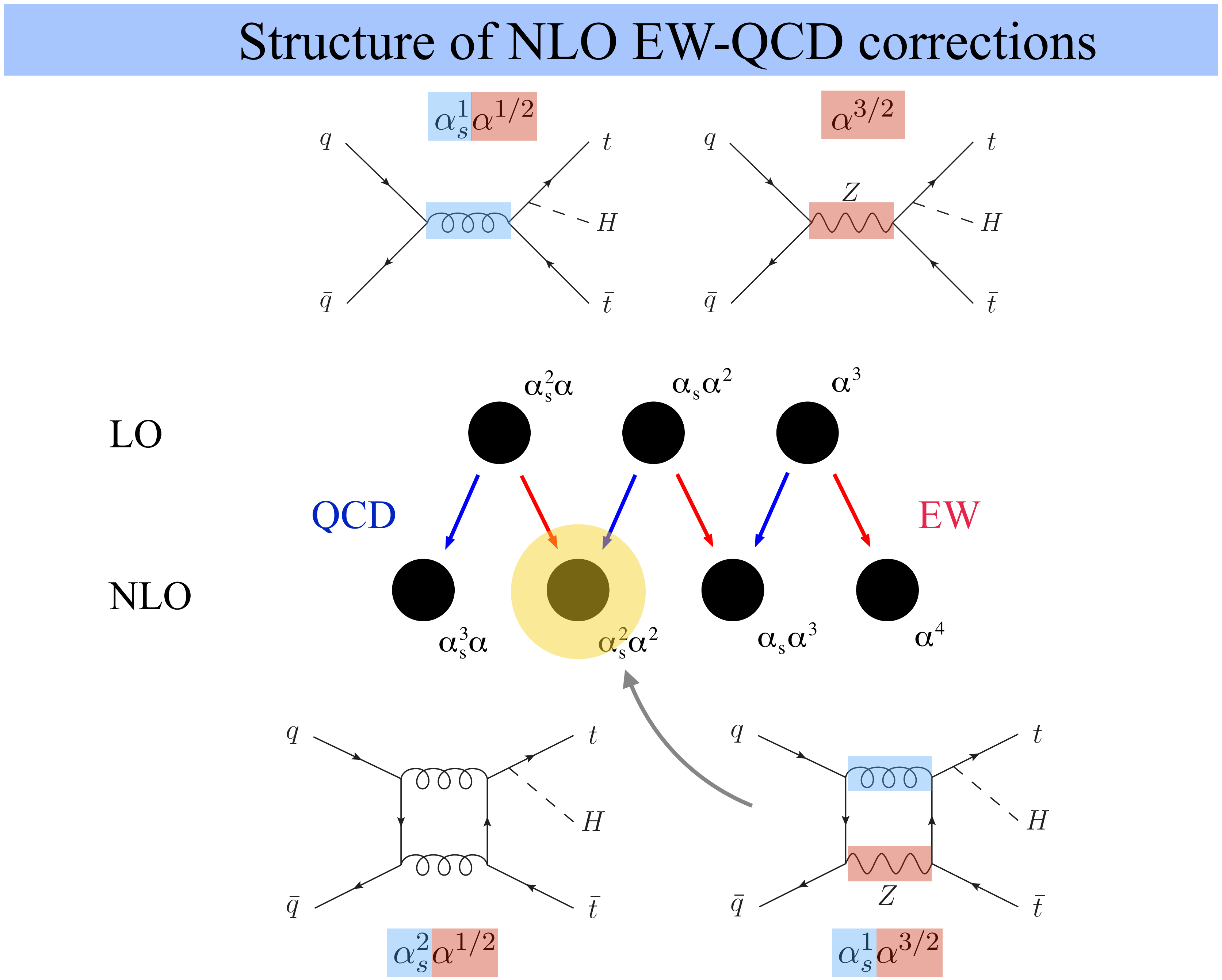
In presence of resummed expressions, the QCDxEW interplay entangles classes of corrections
to all orders in α_s and α

The perturbative convergence depends on the presence of all allowed partonic channel that may
contribute to a given final state.

QCD x EW interplay in the production mechanisms

QCDxEW interplay may occur already at LO
when the production mechanism can be mediated by both QCD or EW bosons
see e.g. ttbarH production

courtesy by Davide Pagani



The loop expansion provides a well defined criterium

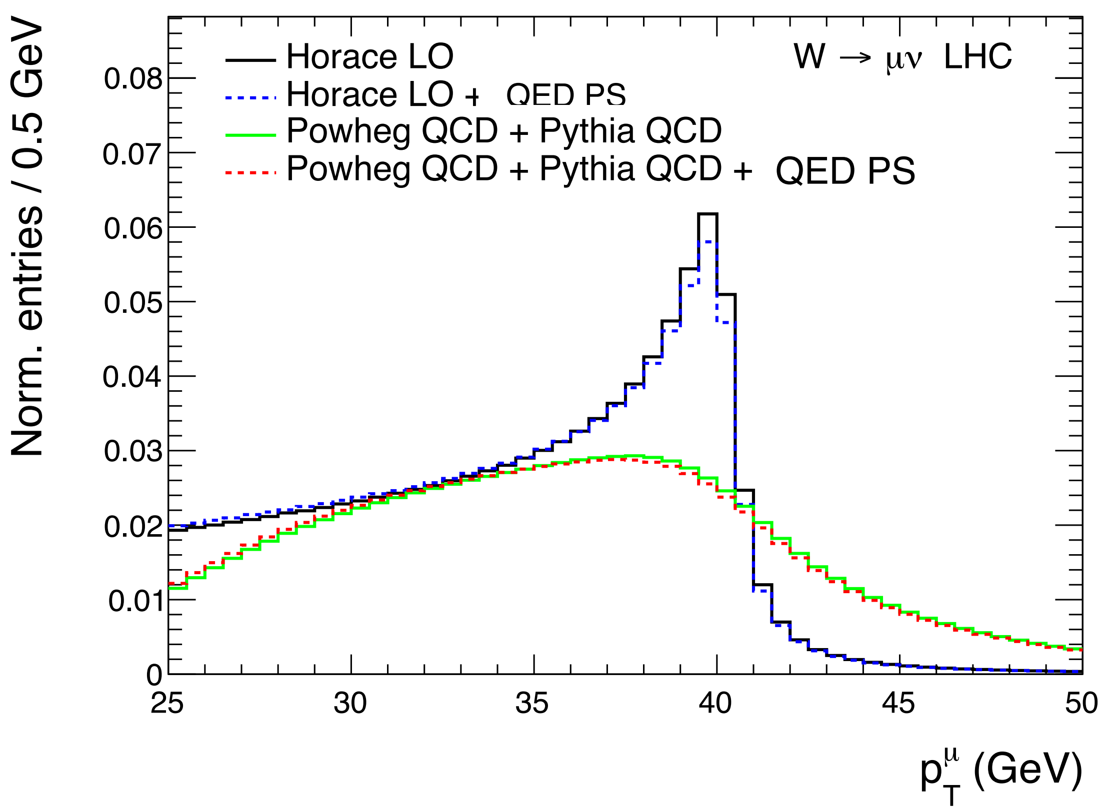
At a given loop order different QCD and EW terms

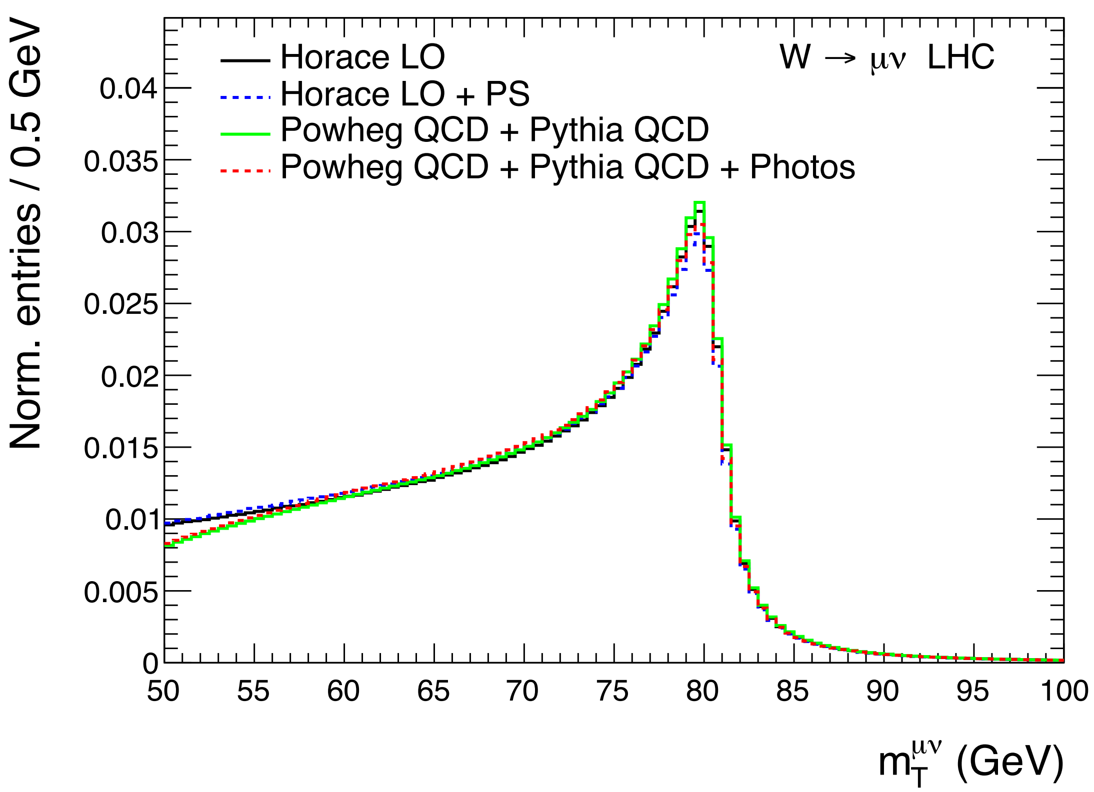
Coupling expansion and logarithmic enhancements (2): QCD

· QCD ISR is responsible for large logarithmic corrections ~ $L_{QCD} \stackrel{\mathrm{def}}{=} \log(p_{tV} / m_V)$ for a final state V which need to be resummed to all orders, e.g. via QCD Parton Shower

two examples in DY: single lepton pt needs resummation, fixed-order QCD prediction meaningless
lepton-pair transverse mass is very mildly affected when integrating over QCD

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841





single lepton pt: sensible lowest order approximation offered by LO+PS

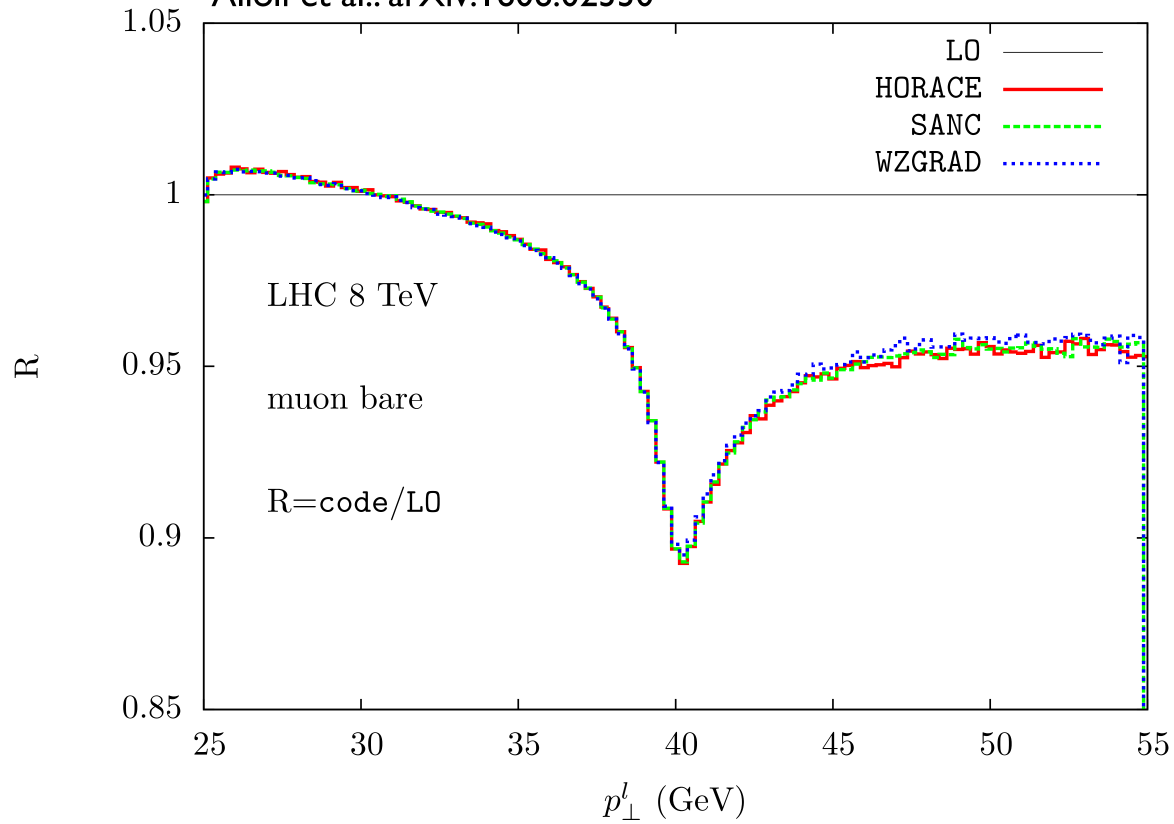
Coupling expansion and logarithmic enhancements (2): EW

- QED FSR is responsible for the energy/momentum loss of final state particles, e.g. leptons,
  yielding large collinear logarithmic corrections ~ $L_{QED} \stackrel{\text{def}}{=} \log(\hat{s}/m_f^2)$
  which strongly affect the value of reconstructed observables

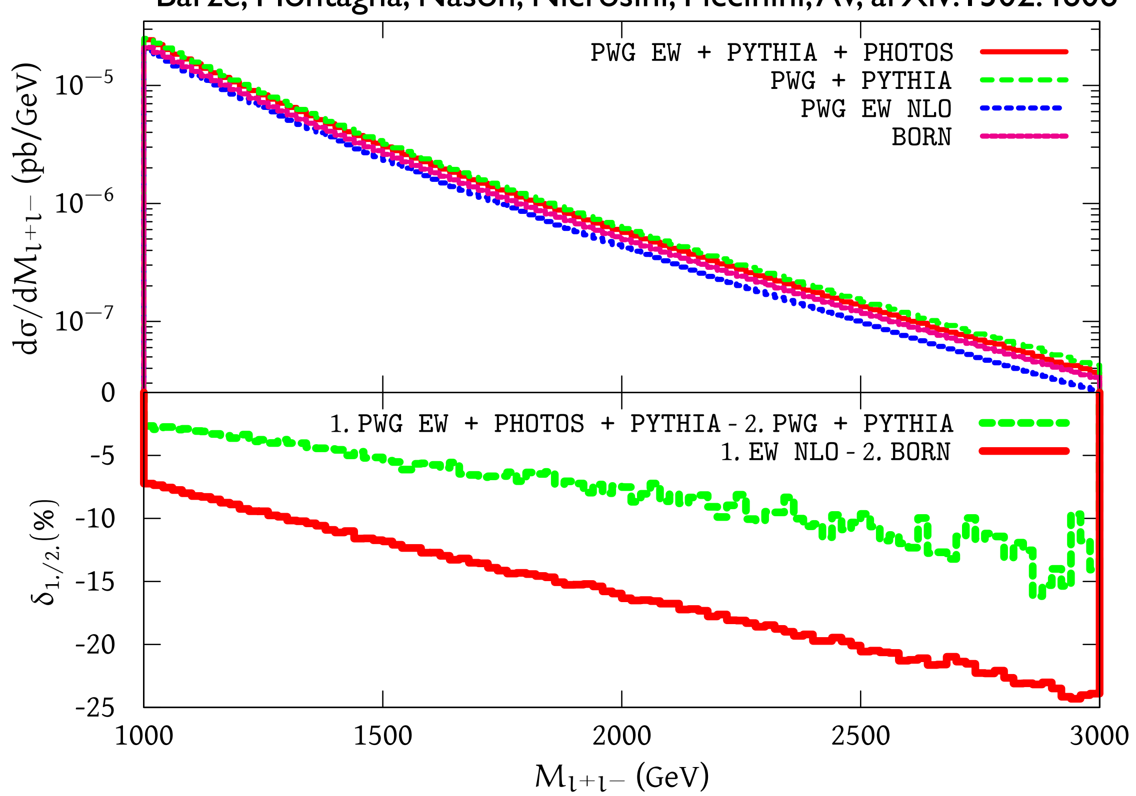
- EW Sudakov logs appear in virtual correction diagrams with the exchange of W or Z bosons
  when one kinematical invariant becomes large
  yielding large negative corrections to the observables

$$-\frac{\alpha}{4\pi \sin^2\theta_W} \log^2 \frac{s}{m_W^2}$$

Alioli et al.: arXiv:1606.02330

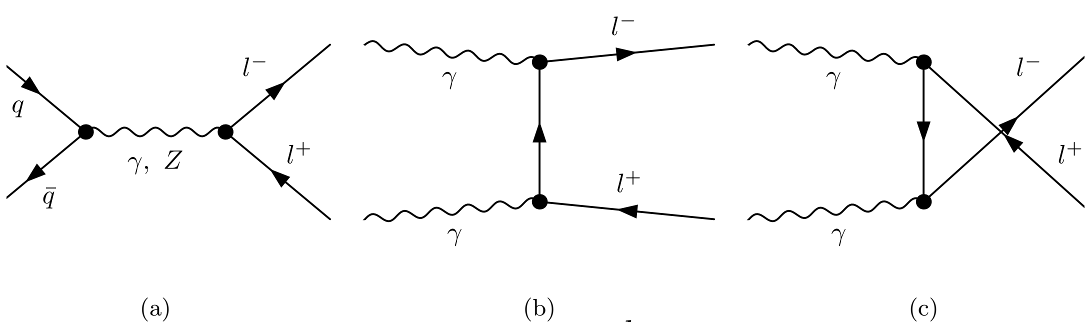


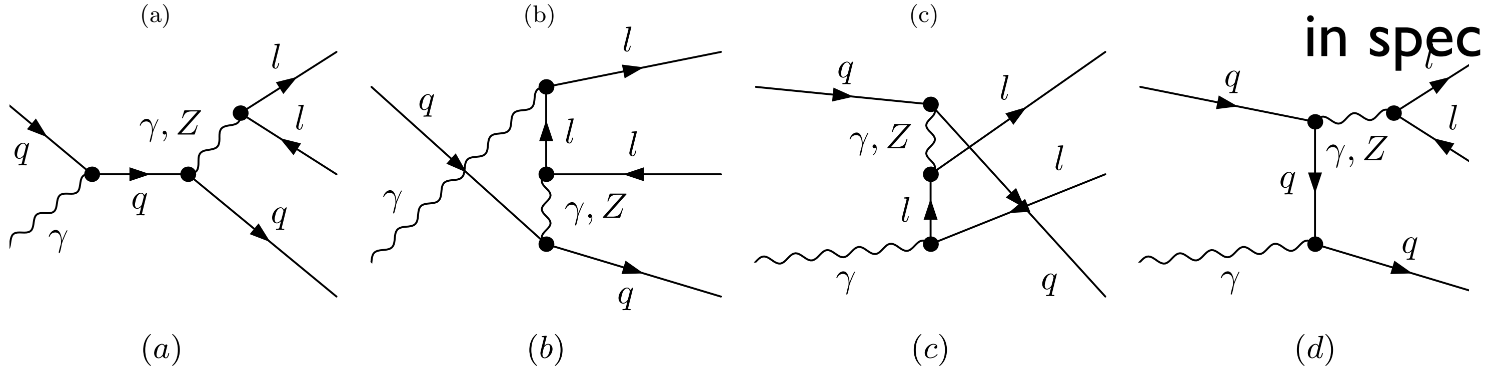
Barzè, Montagna, Nason, Nicrosini, Piccinini, AV, arXiv:1302.4606



Proton PDFs with QCD and QED DGLAP evolution

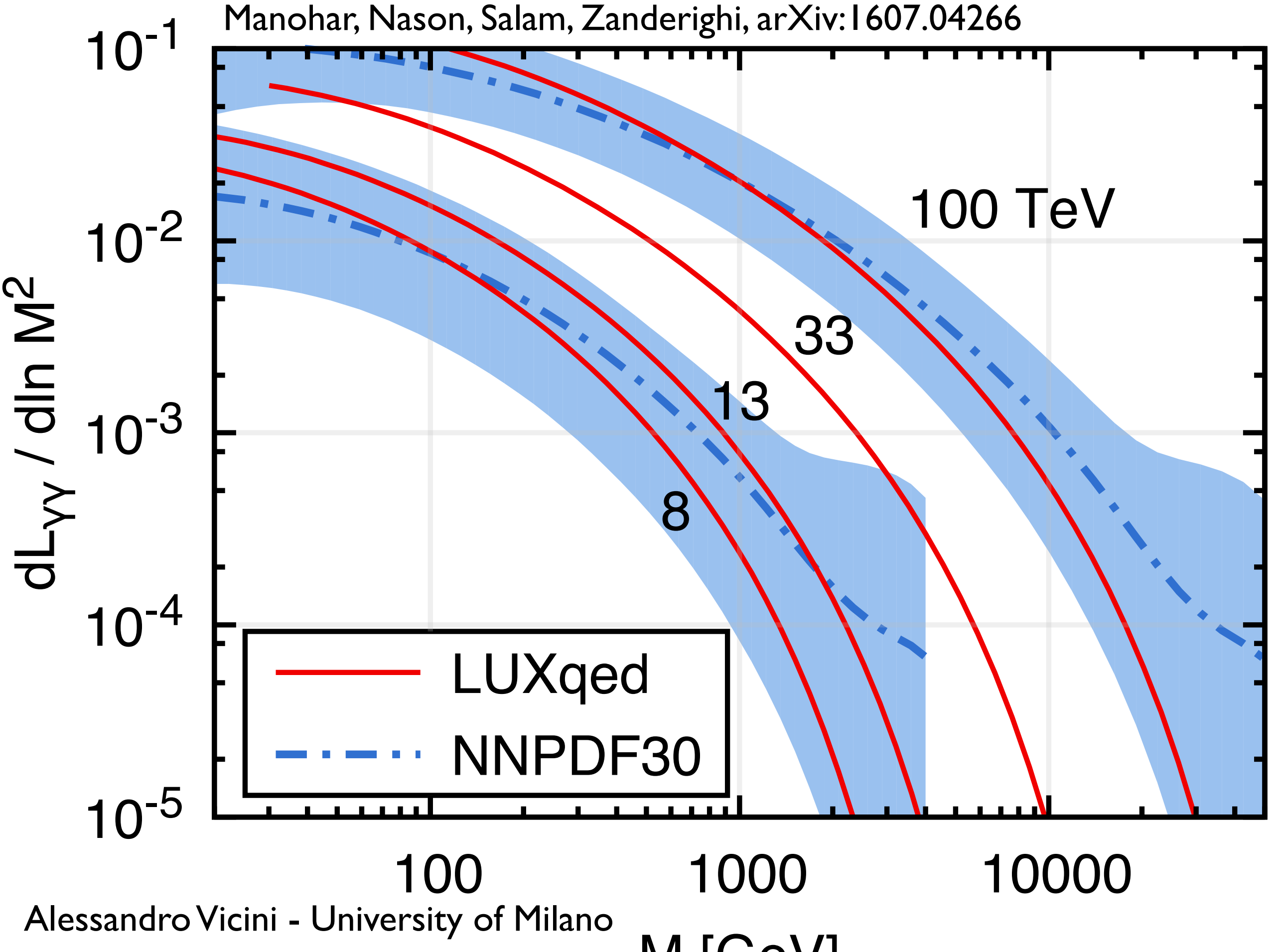
- At NLO-EW, QED-ISR collinear logs appear
  they are universal, factorize and can be reabsorbed in the physical proton PDFs
  a photon density in the proton is predicted and allows new partonic subprocesses



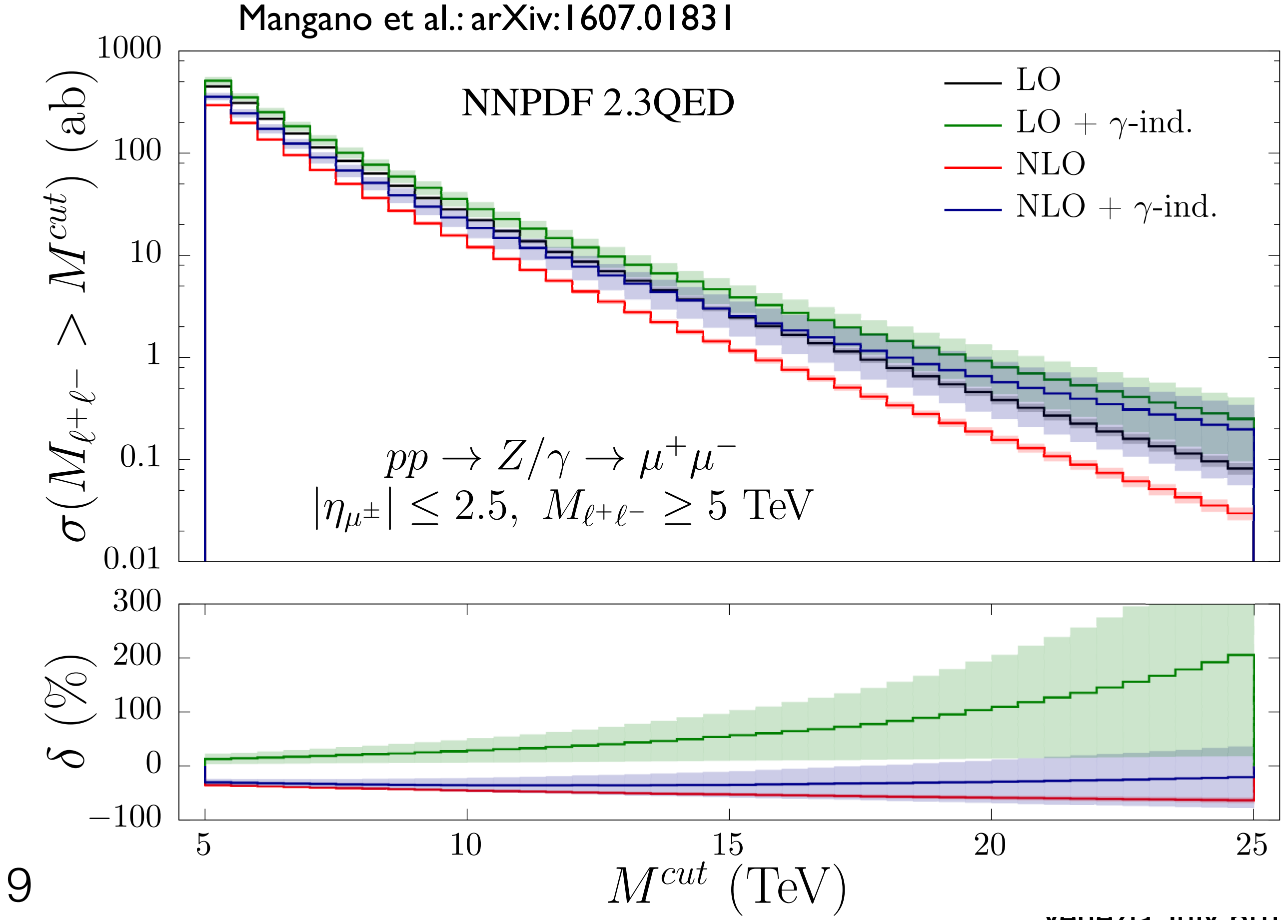


despite the intrinsic smallness of the photon density
the additional production mechanisms
can yield a contribution at the several per cent level
in specific kinematical regimes

Manohar, Nason, Salam, Zanderighi, arXiv:1607.04266



Mangano et al.: arXiv:1607.01831



QCD and EW corrections in simulation tools for Drell-Yan simulations

- Fixed-order results

DYNNLO	NNLO QCD + NLO EW
FEWZ	NNLO QCD
MCFM	NLO QCD
WZGRAD	NLO EW
RADY	NLO EW + QCD
HORACE	NLO EW
SANC	NLO EW + QCD

- All-order results matched with fixed-order matrix elements

DYRes	NNLO+NNLL QCD
ResBos	(N)NLO+NNLL QCD
MC@NLO	NLO+PS QCD
POWHEG	NLO+PS QCD
DYNNLOPS	NNLO+PS QCD
Sherpa	NNLO+PS QCD
HORACE	NLO-EW +QED-PS
POWHEG	NLO-(QCD+EW) + (QCD+QED)-PS

- In general mixed $O(\alpha\alpha_s)$ are not exactly available for LHC processes, only the leading terms
  one relevant exception: NC and CC DY in pole approximation (valid at the boson resonance)

- How can we estimate the size of $O(\alpha\alpha_s)$ missing corrections
  (or judge the accuracy of an approximation based on the available results) ?

Combination of QCD and EW corrections in DY simulation tools (1)

· Fixed-order tools:
additive combination of exact $O(\alpha s)$, $O(\alpha_s^2)$ and $O(\alpha)$ corrections (e.g. FEWZ)

$$\sigma = \sigma_0\,(1 + \delta\alpha_s + \delta\alpha_s^2 + \delta\alpha + \dots)$$

possibility to arrange terms in factorized combinations

$$\sigma = \sigma_0\,(1 + \delta\alpha_s + \dots)\,(1 + \delta\alpha)$$

→ estimate of size $O(\alpha\alpha s)$ terms

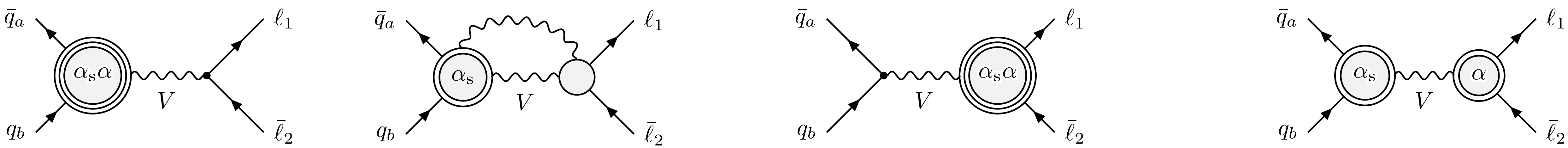
WARNING: kinematics plays a very important role
multiplying integrated corrections factors ≠ convoluting fully differential corrections

O(αα$_s$) corrections in pole approximation

S. Dittmaier, A. Huss, C. Schwinn, Nucl.Phys.B885 (2014) 318, Nucl.Phys.B904 (2016) 216

- The pole approximation provides a good description of the W (Z) region, as it has already been checked for the pure NLO-EW corrections

- At O(αα$_s$) there are 4 groups of contributions



- The last group yields the dominant correction to the process, due to factorizable corrections QCD-initial x QED-final

$$\sigma_{\mathrm{NNLO_{s\otimes ew}}} = \sigma_{\mathrm{NLO_s}} + \alpha\,\sigma_\alpha + \alpha\alpha_s\,\sigma^{\mathrm{prod\times dec}}_{\alpha\alpha_s} \qquad \delta^{\mathrm{prod\times dec}}_{\alpha\alpha_s} = \frac{\alpha\alpha_s\,\sigma^{\mathrm{prod\times dec}}_{\alpha\alpha_s}}{\sigma_{\mathrm{LO}}}$$

full result
pole approximation

$$\sigma^{\mathrm{naive\,fact}}_{\mathrm{NNLO_{s\otimes ew}}} = \sigma_{\mathrm{NLO_s}}(1+\delta_\alpha)$$

naive factorization

$$\frac{\sigma_{\mathrm{NNLO_{s\otimes ew}}} - \sigma^{\mathrm{naive\,fact}}_{\mathrm{NNLO_{s\otimes ew}}}}{\sigma_{\mathrm{LO}}} = \delta^{\mathrm{prod\times dec}}_{\alpha\alpha_s} - \delta_\alpha\delta'_{\alpha_s}$$

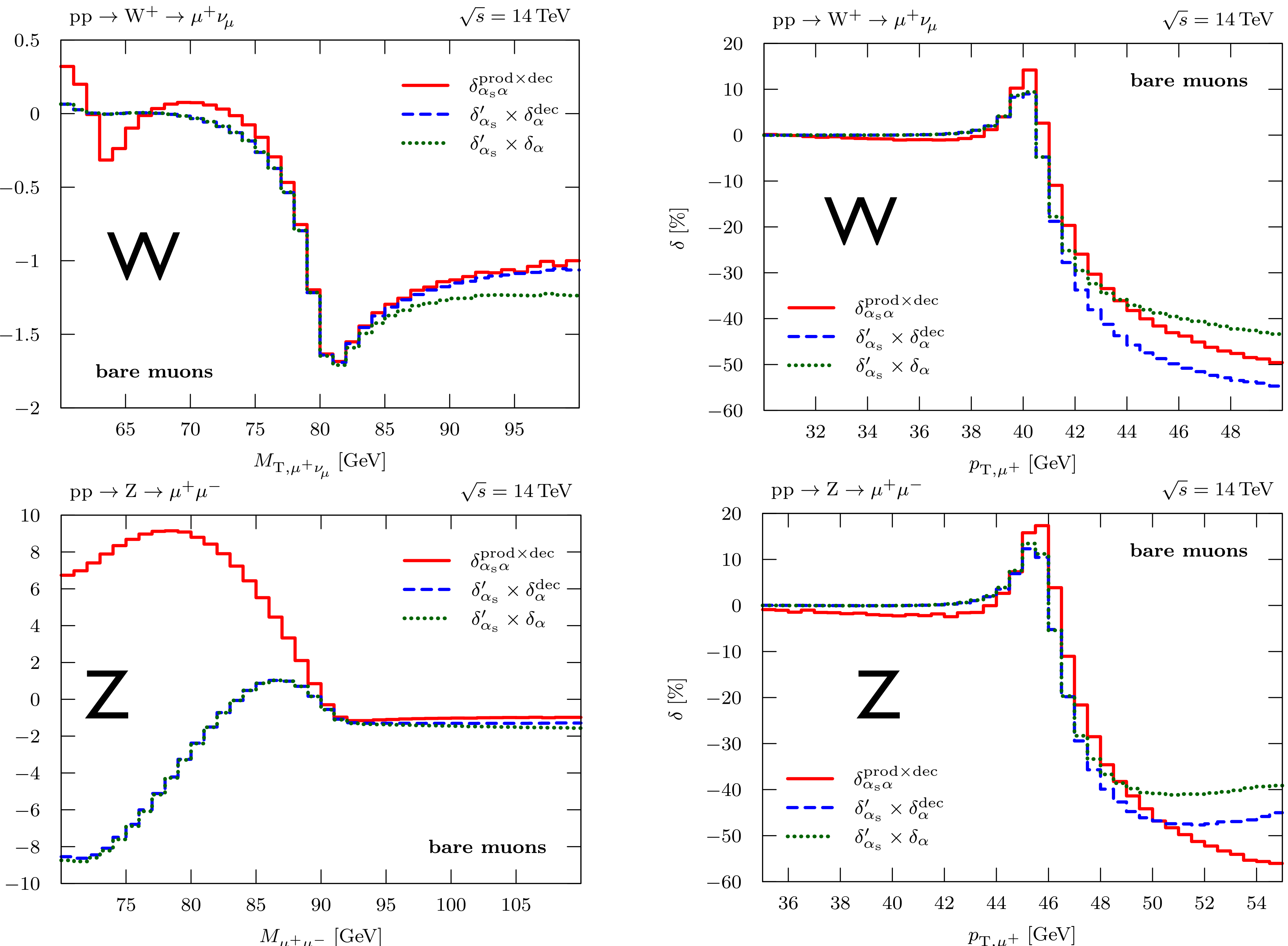
test of the validity of the naive factorization

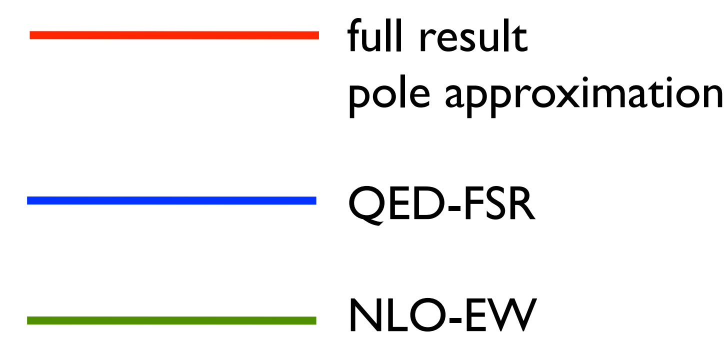
the δ are the inclusive correction factor

- We need to compare these results with the O(αα$_s$) terms available in Monte Carlo (POWHEG)

O(ααs) corrections in pole approximation

S. Dittmaier, A. Huss, C. Schwinn, Nucl.Phys.B885 (2014) 318, Nucl.Phys.B904 (2016) 216





the difference between red and the others tests the naive factorization

the difference between green and blue tests the impact of weak corr. and the pole approximation

the naive factorization works nicely for the W transverse mass, at the resonance

fails in the lepton pt case, where the kinematical interplay of photons and gluons is crucial

fails in the Z invariant mass, where the large FSR correction is modulated by ISR QCD radiation and requires exact kinematics

Combination of QCD and EW corrections in DY simulation tools (2)

· Tools implementing a matching between fixed- and all-orders results

· simulation of multiple parton (gluons/quarks, photons) emissions via Parton Shower MonteCarlo tools including to all orders leading terms proportional to $(\alpha_s L_{QCD})^n$ and $(\alpha L_{QED})^m$

· matching with exact matrix elements to achieve (N)NLO accuracy on the total cross section

· sources of uncertainty (separately for QCD and EW tools):
different shower models → after matching with matrix elements differences go one order higher
different matching recipes (formally subleading, numerically relevant) (e.g. MC@NLO vs POWHEG vs UNLOPS)

· the combination of QCD and EW depends
1) on the formulation of the matching recipe
2) on the behaviour of the individual results
(EW corrections modulated by the shape of the QCD results)
3) on the competition of the two interactions
(relevant e.g. in the generation of the radiation in the choice of the hardest parton)

Matching NLO-(QCD+EW) with (QCD+QED)-PS

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

POWHEG NLO-(QCD+EW)

- it has NLO-(QCD+EW) accuracy on the total cross section
- the virtual QCD and EW corrections (and the integral over radiation of the real corrections) are included in the Bbar function, factored in front of the curly bracket
- it describes with exact matrix elements the hardest parton (gluon, quark, photon) emission
- it includes to all orders QCD and QED effects via Parton Shower

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

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- this structure generates mixed $O(\alpha\alpha_s)$ contribution

  differs with respect to additive fixed-order calculations

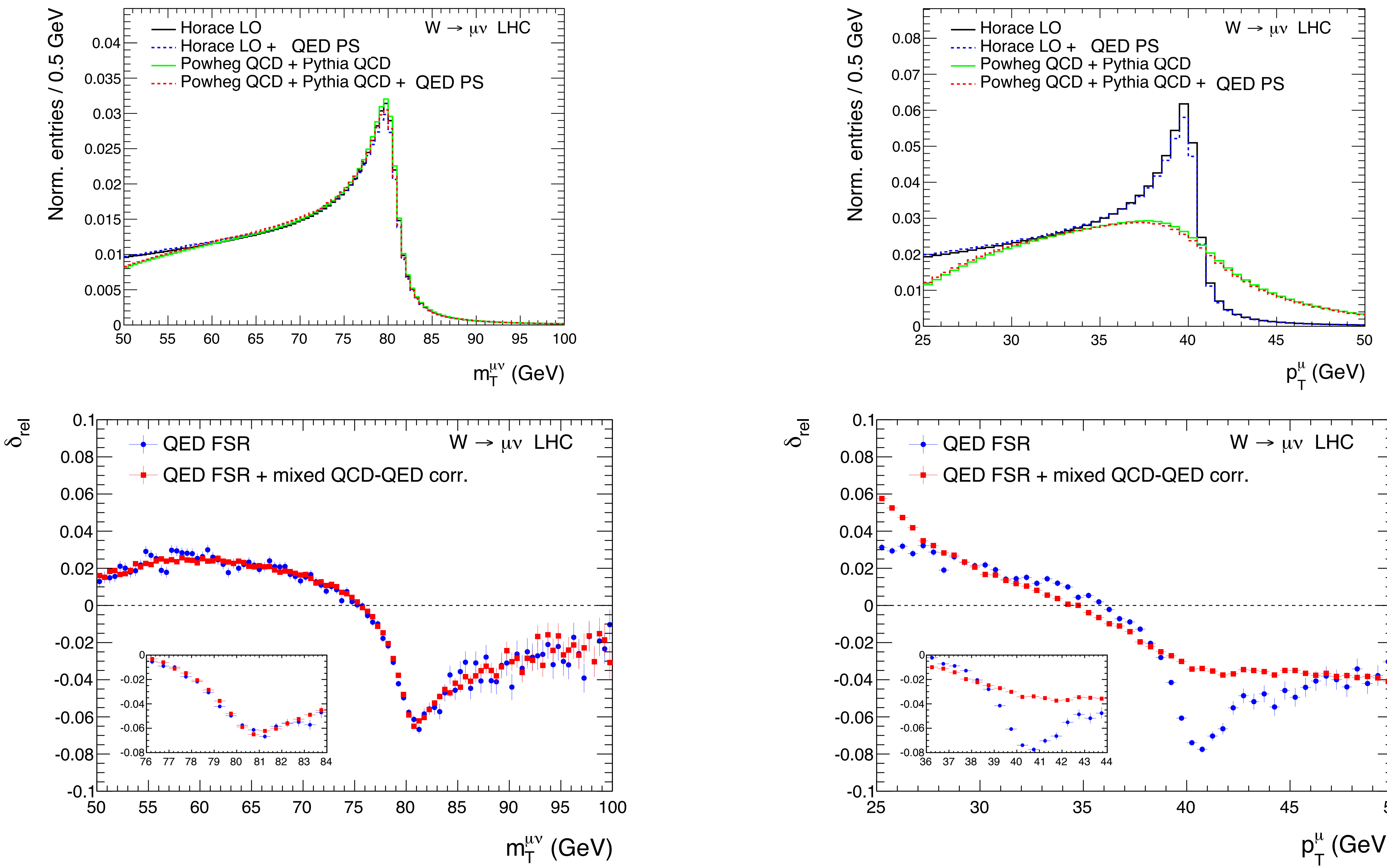
  or to other matching prescriptions (e.g. *à la* MC@NLO)

→need of exact $O(\alpha\alpha_s)$ to constrain these ambiguities

Combination of QCD and QED corrections: POWHEG results

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

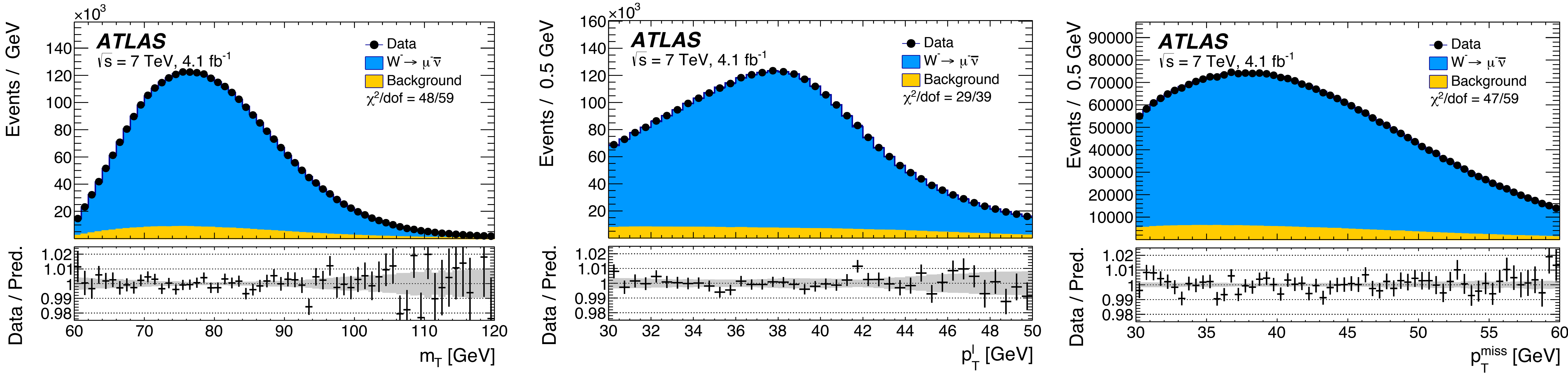
Does the convolution with QCD corrections preserve the QED effects ?



the difference between red and blue is due to mixed QCDxQED terms

MW determination at hadron colliders: observables and techniques

MW extracted from the study of the shape of the MT, pt_lep, ET_miss distributions in CC-DY thanks to the jacobian peak that enhances the sensitivity to MW



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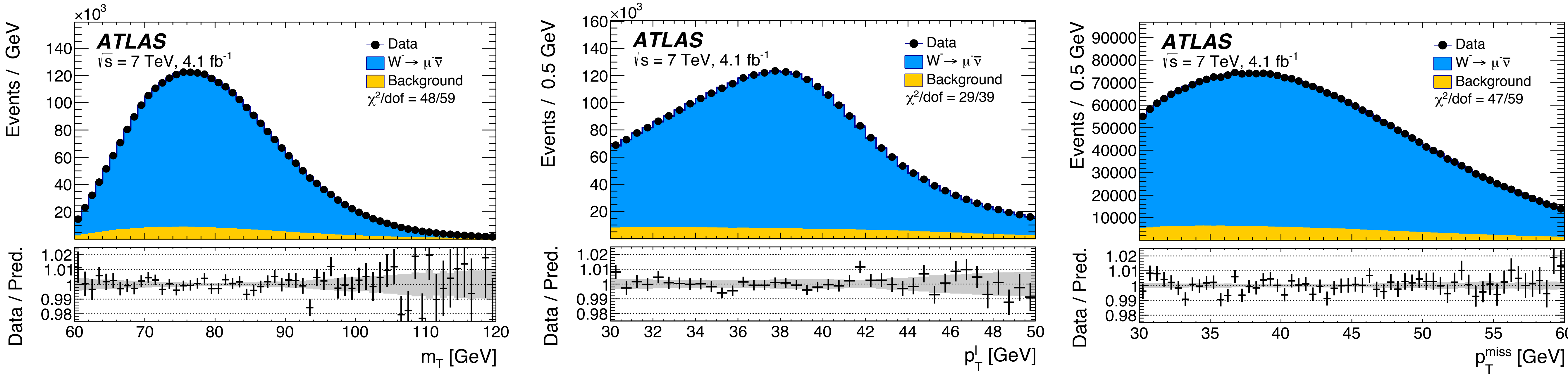


The measurement is based on a template fit technique:

- with the best available simulation tools, using (Gmu, MW, MZ, MH) as input parameters, many distributions are computed with different MW values and compared to the data
  → MW is determined as the value that maximises the agreement

- the template fit technique is model dependent

- theoretical uncertainties that modify the shape of the templates are theoretical systematic errors

- we need to understand all the sources of MW shift of O(5 MeV) or larger

Is the impact of QED corrections preserved in a QCD environment ?

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

Templates accuracy: LO	M_W shifts (MeV)			
	$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$	
Pseudodata accuracy	M_T	p_T^ℓ	M_T	p_T^ℓ
1 HORACE only FSR-LL at $\mathcal{O}(\alpha)$	-94±1	-104±1	-204±1	-230±2
2 HORACE FSR-LL	-89±1	-97±1	-179±1	-195±1
3 HORACE NLO-EW with QED shower	-90±1	-94±1	-177±1	-190±2
4 HORACE FSR-LL + Pairs	-94±1	-102±1	-182±2	-199±1
5 PHOTOS FSR-LL	-92±1	-100±2	-182±1	-199±2

$pp \to W^+$, $\sqrt{s} = 14$ TeV Templates accuracy: NLO-QCD+QCD$_{PS}$		M_W shifts (MeV)			
		$W^+ \to \mu^+\nu$		$W^+ \to e^+\nu$(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

Lepton-pair transverse mass: yes!

Lepton transverse momentum: no, the shifts are sizeably amplified

(these effects are already taken into account in the Tevatron and LHC analyses)

The lepton transverse momentum has a 85% weight in the final ATLAS MW combination

Effect of the NLO-EW matching on subleading QED contributions

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

PHOTOS and PYTHIA-QED Parton Shower share Leading-Logarithmic accuracy

sizeably differ at subleading level in the collinear region

The matching with the exact O(α) matrix elements shifts the differences one order higher

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

$O(\alpha\alpha_s)$ effects: pole approximation *vs* POWHEG-(QCD+EW) for MT

Carloni Calame, Chiesa, Martinez, Montagna, Nicrosini, Piccinini, AV, arXiv:1612.02841

$$d\sigma_{\text{POWHEG}} = d\sigma_0 \left[1 + \delta_{\alpha_s} + \delta_\alpha + \sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n} \right]$$

	Templates	Pseudodata	M_W shifts (MeV)
1	LO	POWHEG(QCD) NLO	56.0 ± 1.0
2	LO	POWHEG(QCD)+PYTHIA(QCD)	74.4 ± 2.0
3	LO	HORACE(EW) NLO	-94.0 ± 1.0
4	LO	HORACE (EW,QEDPS)	-88.0 ± 1.0
5	LO	POWHEG(QCD,EW) NLO	-14.0 ± 1.0
6	LO	POWHEG(QCD,EW) `two-rad`+PYTHIA(QCD)+PHOTOS	-5.6 ± 1.0

correction factor in eq. 6.3	samples in table 7	M_W shift (MeV)
$\sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n}$	[6]-[5]	8.4 ±1.4 MeV
$\sum_{m=2}^{\infty} \delta'_{\alpha_s^m}$	[2]-[1]	18.4 ±2.2 MeV
$\sum_{n=2}^{\infty} \delta'_{\alpha^n}$	[4]-[3]	6.0 ±1.4 MeV

$$\Delta {M_W}^{\alpha_s \alpha} = -16.0 \pm 3.0 \text{ MeV}$$ POWHEG-(QCD+EW)

$$\delta^{M_W}_{NNLO} = -14 \text{ MeV}$$ pole approximation (Dittmaier et al.)

(these sizeable effects are already taken into account in the Tevatron and LHC analyses)

More on the structure of QCDxEW corrections in POWHEG (I)

- EW corrections may become large in the photon soft/collinear limit or in the EW Sudakov regime

POWHEG NLO-(QCD+EW)

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

the difference between QCDxQED and QCDxEW approximations starts at $O(\alpha\alpha_s)$

POWHEG NLO-QCD x (QCD+QED)-PS

$$\alpha_s \alpha \left(c_2 L^2_{\rm QCD} + c_1 L_{\rm QCD} + c_0 \right) \left(c_{11} L_{\rm QED} l_{\rm QED} + c_{10} L_{\rm QED} + c_{01} l_{\rm QED} \right)$$

POWHEG NLO-(QCD+EW) x (QCD+QED)-PS

$$\alpha_s \alpha \left(c_2 L^2_{\rm QCD} + c_1 L_{\rm QCD} + c_0 \right) \left(c_{11} L_{\rm QED} l_{\rm QED} + c_{10} L_{\rm QED} + c_{01} l_{\rm QED} + c_{00} \right)$$

the difference $\alpha_s \alpha\, c_{00} \left(c_2 L^2_{\rm QCD} + c_1 L_{\rm QCD} + c_0 \right)$ important when c_{00} is large

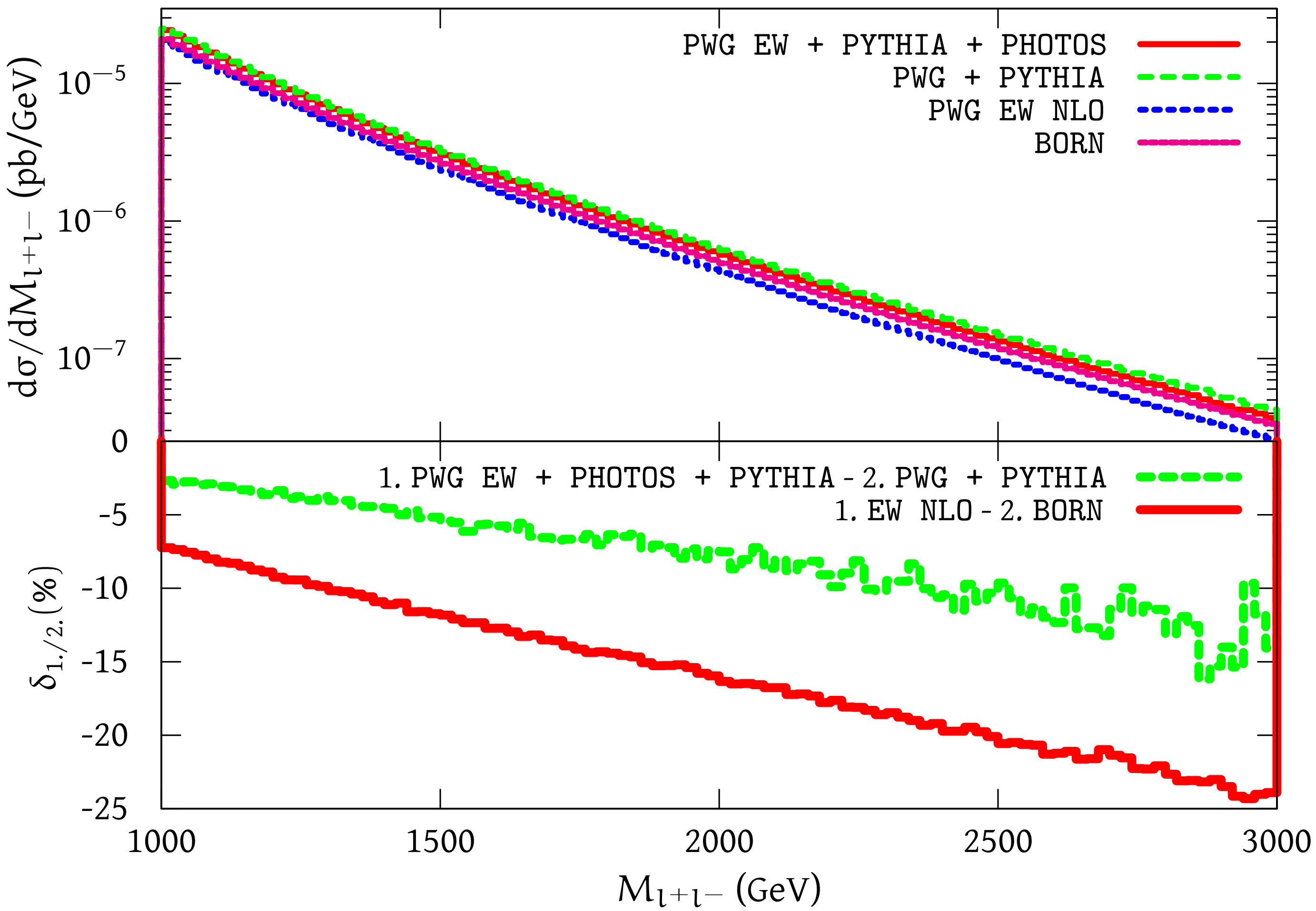
c_{00} does not contain QED logs, but Sudakov EW logs $\quad c_{00} \propto -\frac{\alpha}{4\pi \sin^2\theta_W} \log^2 \frac{s}{m_W^2}$

More on the structure of QCDxEW corrections in POWHEG (I)

- EW corrections may become large in the photon soft/collinear limit or in the EW Sudakov regime

POWHEG NLO-(QCD+EW)

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$



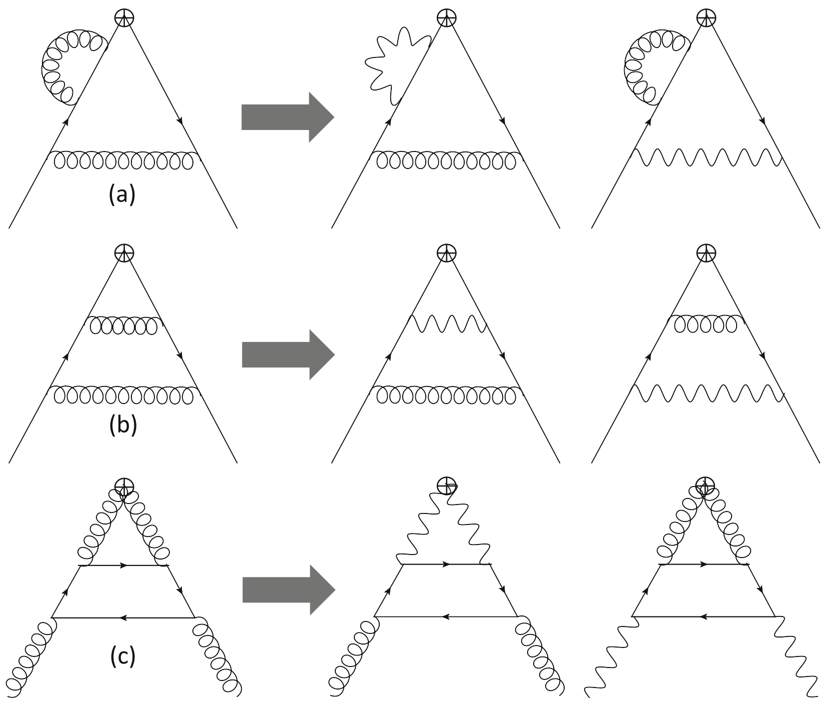
the difference between red and green due to $O(\alpha\alpha_s)$ arising from the product of Bbar x { … }

terms beyond the formal accuracy of the code missing e.g. in FEWZ
→need of exact $O(\alpha\alpha s)$ to provide a more robust prediction

Analytic progress: splitting functions at O(αα$_s$)

D. de Florian, G.F.R. Sborlini, G. Rodrigo, Eur.Phys.J. C76 (2016) no.5, 282 , arXiv:1606.02887

starting from the expressions by Curci-Furmanski-Petronzio



needed for a complete subtraction in partonic calculations of initial state collinear singularities at O(αα$_s$)

not sufficient for a consistent PDF evolution at the same order

$$
\begin{aligned}
P_{q\gamma}^{(1,1)} = {} & \frac{C_F\, C_A\, e_q^2}{2}\Big\{4-9x-(1-4x)\ln(x)-(1-2x) \\
& \times \ln^2(x)+4\ln(1-x)+p_{qg}(x)\Big[2\ln^2\Big(\frac{1-x}{x}\Big) \\
& - 4\ln\Big(\frac{1-x}{x}\Big)-\frac{2\pi^2}{3}+10\Big]\Big\}, \qquad (26)
\end{aligned}
$$

$$
\begin{aligned}
P_{g\gamma}^{(1,1)} = {} & C_F\, C_A\left(\sum_{j=1}^{n_F} e_{q_j}^2\right)\Big\{-16+8x+\frac{20}{3}x^2+\frac{4}{3x} \\
& - (6+10x)\ln(x)-2(1+x)\ln^2(x)\Big\}, \qquad (27)
\end{aligned}
$$

$$
P_{\gamma\gamma}^{(1,1)} = -C_F\, C_A\left(\sum_{j=1}^{n_F} e_{q_j}^2\right)\delta(1-x), \qquad (28)
$$

$$
\begin{aligned}
P_{qg}^{(1,1)} = {} & \frac{T_R\, e_q^2}{2}\Big\{4-9x-(1-4x)\ln(x)-(1-2x) \\
& \times \ln^2(x)+4\ln(1-x)+p_{qg}(x)\Big[2\ln^2\Big(\frac{1-x}{x}\Big) \\
& - 4\ln\Big(\frac{1-x}{x}\Big)-\frac{2\pi^2}{3}+10\Big]\Big\},
\end{aligned}
$$

$$
\begin{aligned}
P_{\gamma g}^{(1,1)} = {} & T_R\left(\sum_{j=1}^{n_F} e_{q_j}^2\right)\Big\{-16+8x+\frac{20}{3}x^2+\frac{4}{3x} \\
& - (6+10x)\ln(x)-2(1+x)\ln^2(x)\Big\},
\end{aligned}
$$

$$
P_{gg}^{(1,1)} = -T_R\left(\sum_{j=1}^{n_F} e_{q_j}^2\right)\delta(1-x),
$$

$$
P_{qq}^{S(1,1)} = P_{q\bar{q}}^{S(1,1)} = 0, \qquad (32)
$$

$$
\begin{aligned}
P_{qq}^{V(1,1)} = {} & -2\, C_F\, e_q^2\Big[\Big(2\ln(1-x)+\frac{3}{2}\Big)\ln(x)\, p_{qq}(x) \\
& + \frac{3+7x}{2}\ln(x)+\frac{1+x}{2}\ln^2(x)+5(1-x) \\
& + \Big(\frac{\pi^2}{2}-\frac{3}{8}-6\zeta_3\Big)\delta(1-x)\Big], \qquad (33)
\end{aligned}
$$

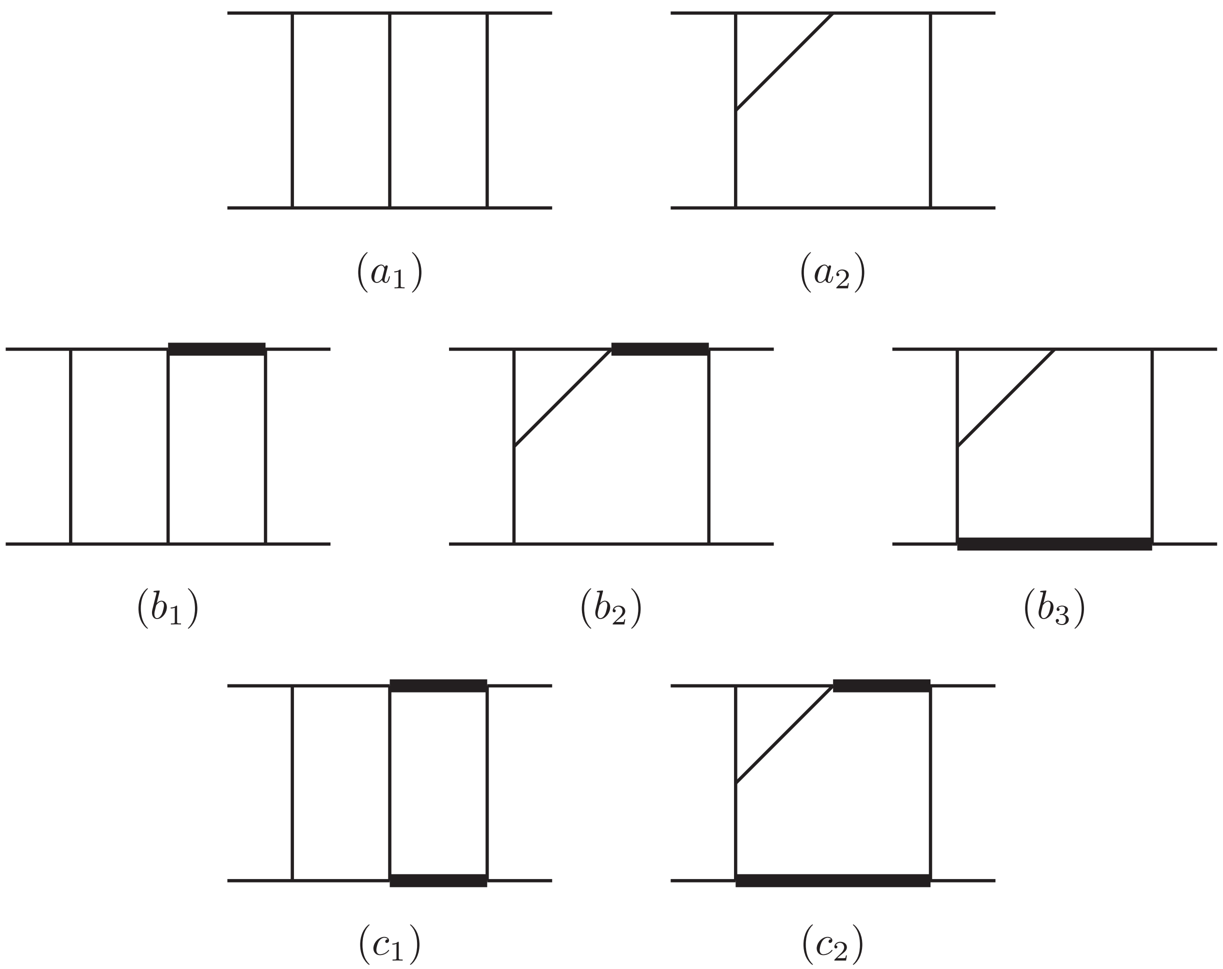
$$
\begin{aligned}
P_{q\bar{q}}^{V(1,1)} = {} & 2\, C_F\, e_q^2\,[4(1-x)+2(1+x)\ln(x) \\
& + 2p_{qq}(-x)S_2(x)], \qquad (34)
\end{aligned}
$$

$$
\begin{aligned}
P_{gq}^{(1,1)} = {} & C_F\, e_q^2\Big[-(3\ln(1-x)+\ln^2(1-x))\,p_{gq}(x) \\
& + \Big(2+\frac{7}{2}x\Big)\ln(x)-\Big(1-\frac{x}{2}\Big)\ln^2(x) \\
& - 2x\ln(1-x)-\frac{7}{2}x-\frac{5}{2}\Big], \qquad (35)
\end{aligned}
$$

$$
P_{\gamma q}^{(1,1)} = P_{gq}^{(1,1)}, \qquad (36)
$$

Analytic progress: Master Integrals for DY processes at O($\alpha\alpha_s$)

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 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)

More on the structure of QCDxEW corrections in POWHEG (2)

- EW corrections may become large in the photon soft/collinear limit or in the EW Sudakov regime

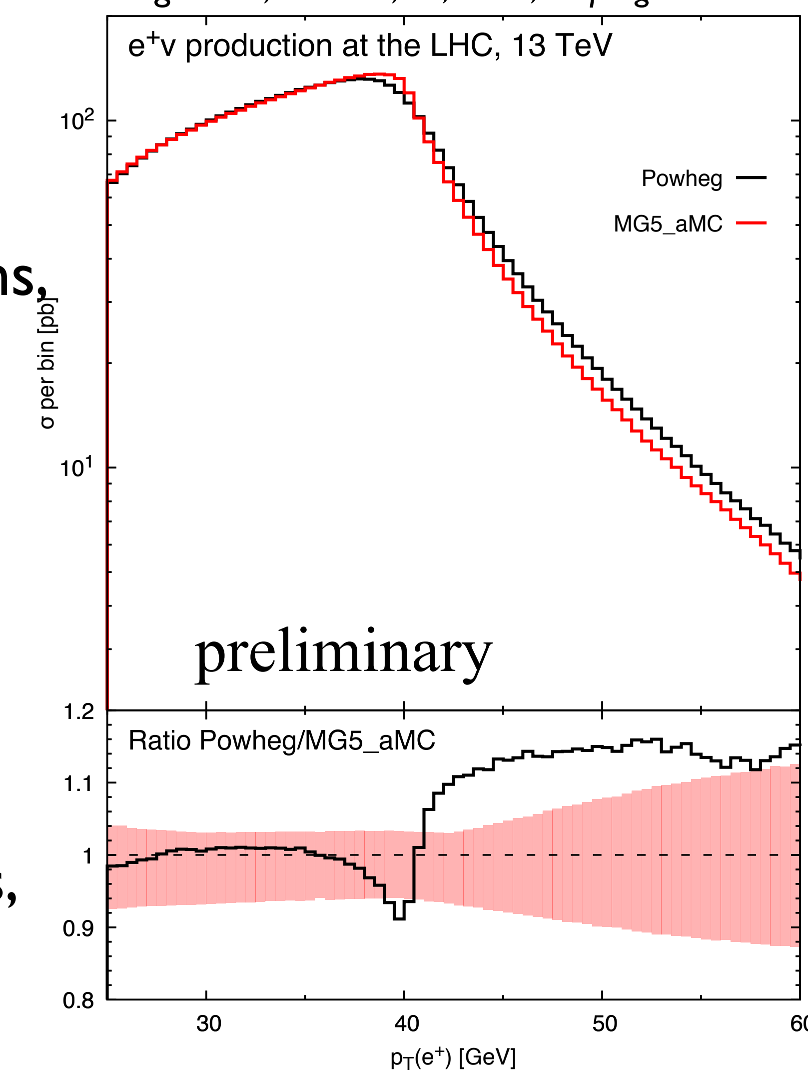
POWHEG NLO-(QCD+EW)

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \Bigg\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \Bigg\}$$

- the use of the Parton Shower guarantees that $(\alpha_s L_{QCD})^n$ $(\alpha L_{QED})^m$ contributions are present good approximation of the full result in the soft/collinear limit

- the matching with exact NLO matrix elements introduces an element of arbitrariness at the level of higher order subleading terms, beyond the formal accuracy, in QCD still numerically sizeable, qualitatively different than renormalization/factorization scale variation effects

Bagnaschi, Maltoni, AV, Zaro, *in progress*



the QCD matching recipe in turn affects also the mixed QCDxEW terms, modulated by the underlying QCD description, and the associated uncertainties

QCD uncertainties and EW parameters (1)

- observables are defined in terms of event counting → cross sections and asymmetries
- the EW parameters (masses, decay widths, mixing angles) are pseudo-observables
- we keep the EW parameters as free inputs of the Lagrangian
  we vary them and compute numerically template distributions, used in the comparison with the data

- in a hadronic environment many important observables suffer of large QCD uncertainties
  → the use of a single quantity to extract the EW parameter is hopeless
  → a global fit of several quantities allows to reduce the impact of the QCD uncertainties
    on the EW parameters to be measured
    by exploiting the similar behaviour of the observables w.r.t. the QCD uncertainties:
    e.g. all NC-DY observables are crucial to calibrate CC-DY simulations and extract MW

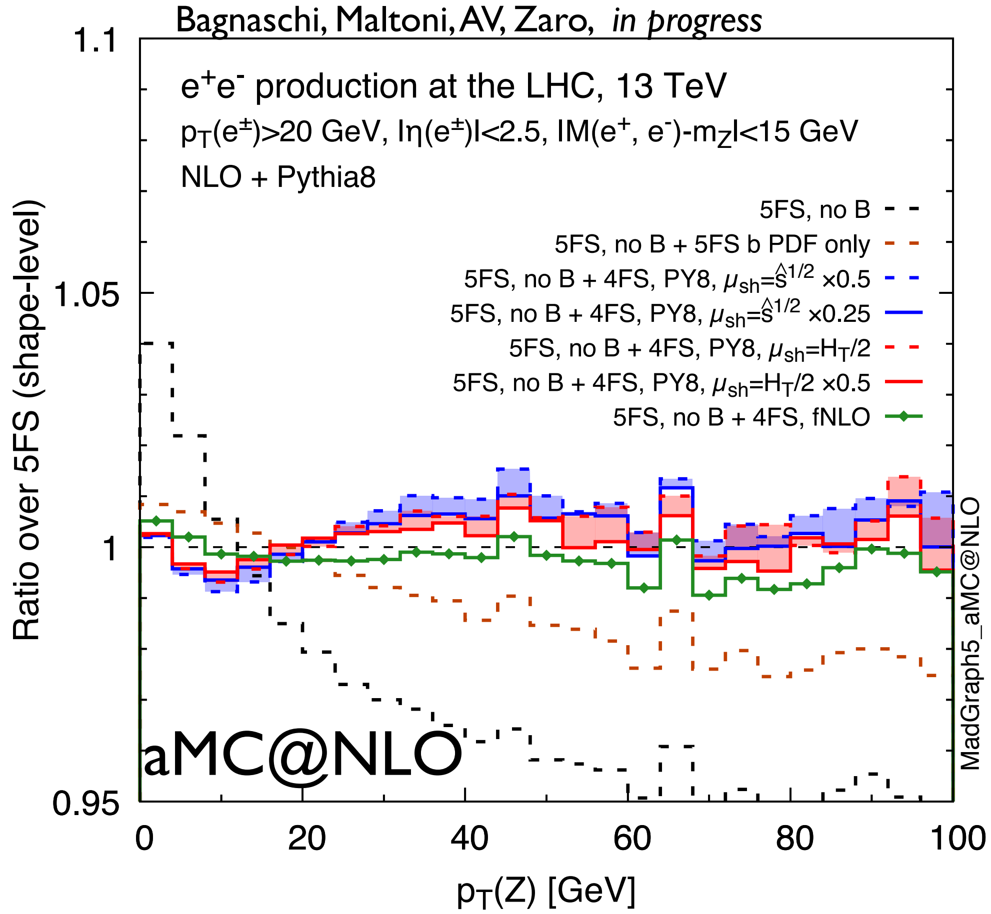
- while QCD is flavour blind, EW observables are flavour sensitive, breaking the possibility
  of perfect correlation w.r.t. QCD of different quantities in the fit

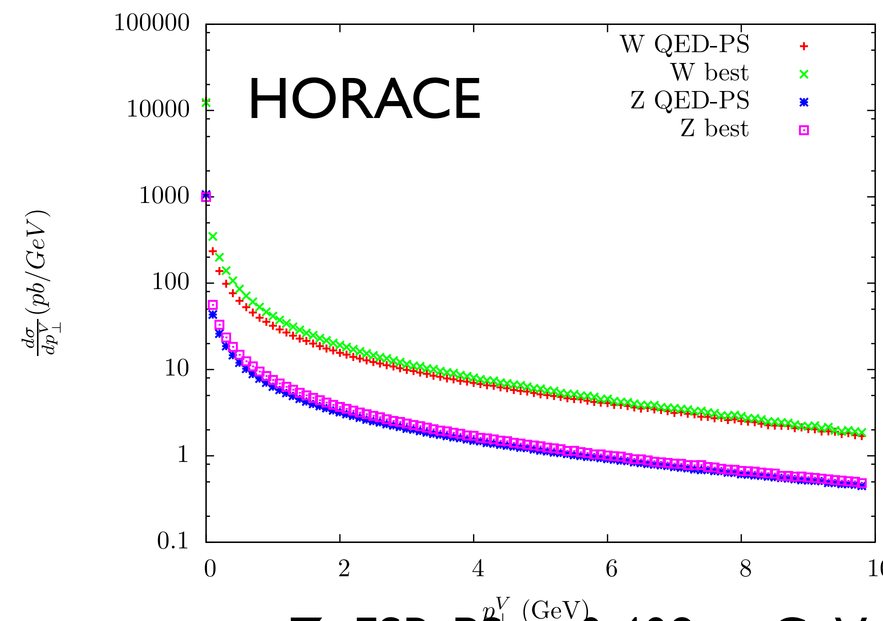
QCD uncertainties and EW parameters (2)

e.g. the ptZ distribution is used to tune the Parton Shower parameters,
this Parton Shower is then used to simulate CC-DY → measure MW

the different flavour of NC-DY w.r.t. CC-DY may induce small but not negligible spurious terms in the CC-DY simulation

- the bottom initiated subprocesses are present in NC-DY but absent (CKM suppressed) in CC-DY
- different initial state electric charge ⇒ different QED contribution to ptZ vs ptW





$$\langle p_\perp^V \rangle =$$

Z	FSR-PS	0.409	GeV	
Z	best	0.463	GeV	Z ISR ~ 0.054 GeV
W	FSR-PS	0.174	GeV	
W	best	0.207	GeV	W ISR ~ 0.033 GeV

→ an explicit improved treatment of all the elements of difference between NC- and CC-DY
increases the universality of the model dependent part
reduces the dependence on QCD uncertainties of the global fit that yields MW

Conclusions

- precision physics at LHC requires the simultaneous treatment of QCD and EW corrections

- in several cases we have a rather good control on purely EW corrections
- mixed $O(\alpha\alpha_s)$ corrections can be sizeable in view of the measurements precision goals

- the numerical size of higher-order subleading QCD effects beyond the formal accuracy of the codes is responsible for a non-negligible QCD matching ambiguity which might propagate to the $O(\alpha\alpha_s)$ terms as well

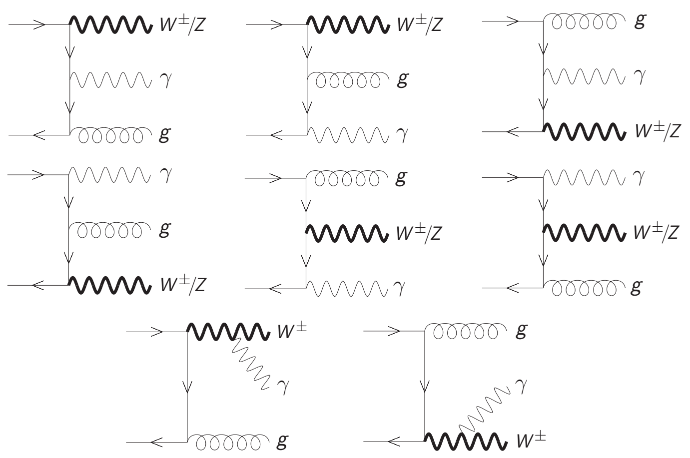
- analytic progress to reduce the impact of $O(\alpha\alpha_s)$ perturbative e.g. in the tails at large momenta

- the precise assessment of the QCD and QCDxEW uncertainties requires a deeper understanding of the global fit procedures currently adopted to determine the EW params backup slides

Analytic progress: total xsec for single gauge boson production at O(αα$_s$)

R.Bonciani, F. Buccioni, R.Mondini, AV, arXiv:1611.00645

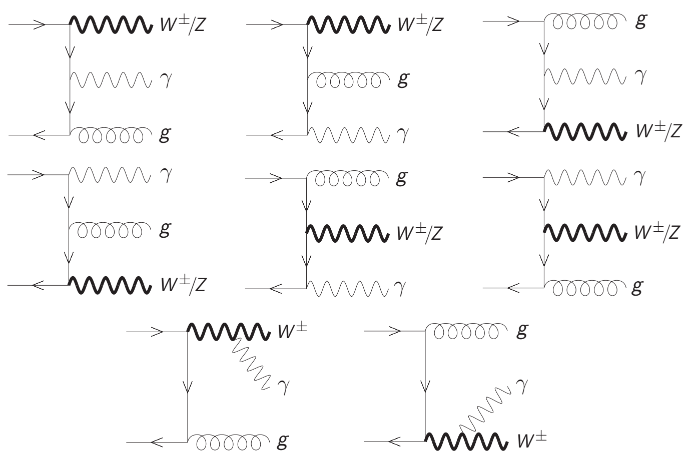
Feynman diagrams



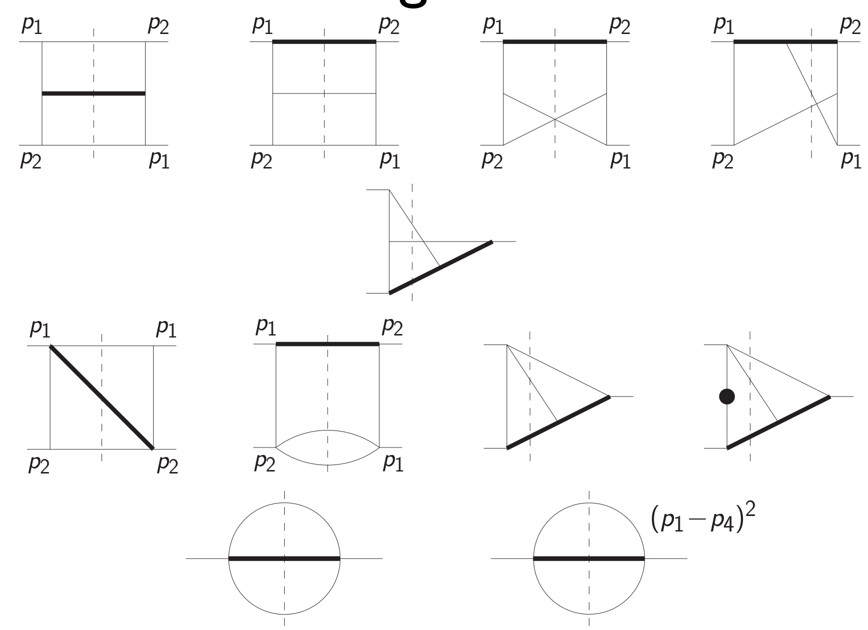
Analytic progress: total xsec for single gauge boson production at $O(\alpha\alpha_s)$

R.Bonciani, F. Buccioni, R.Mondini, AV, arXiv:1611.00645

Feynman diagrams



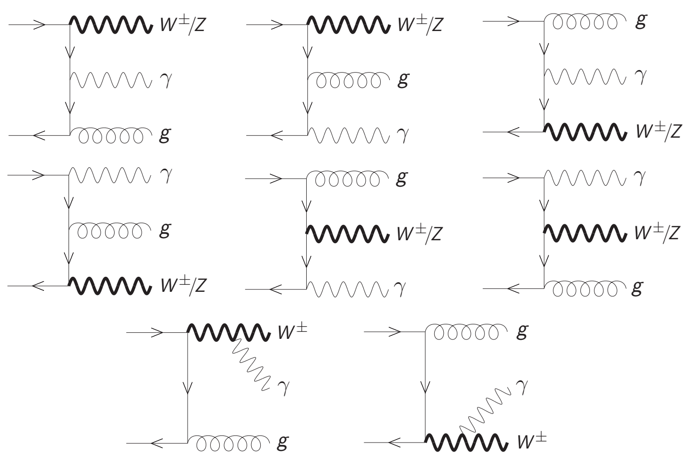
Master Integrals



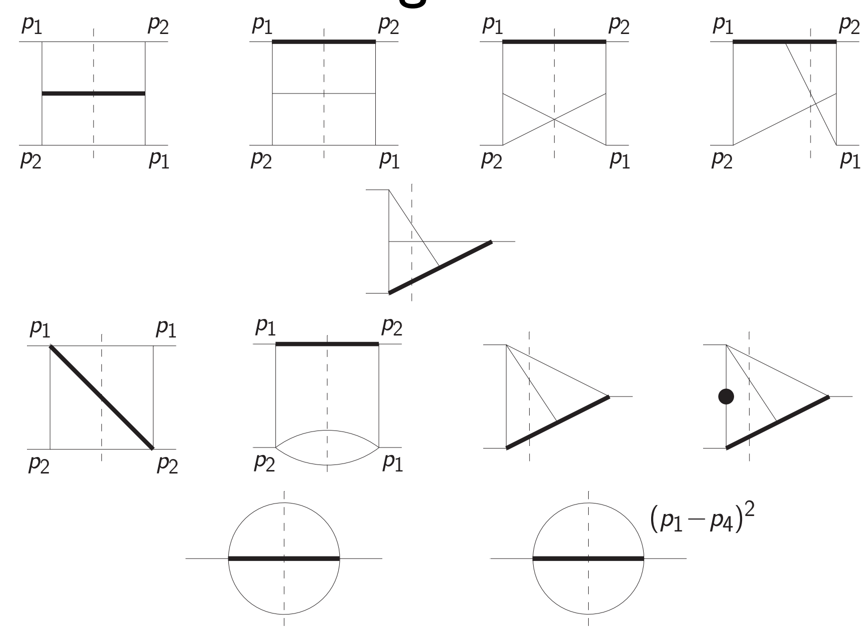
Analytic progress: total xsec for single gauge boson production at O(αα_s)

R.Bonciani, F. Buccioni, R.Mondini, AV, arXiv:1611.00645

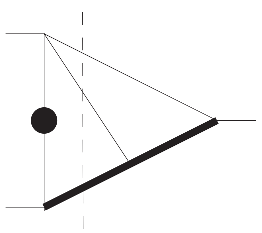
Feynman diagrams



Master Integrals



$$\mathcal{N} = \frac{1}{2}\,\frac{\Gamma^2(1+\epsilon)}{(4\pi)^{3-2\epsilon}}\,\left(\frac{M_V^2}{\mu^2}\right)^{-2\epsilon}$$



$$= \mu^{2(4-D)}\int \frac{\mathrm{d}^D p_4\,\mathrm{d}^D p_5\;\delta((p_1+p_2-p_4-p_5)^2-M_W^2)\,\delta(p_4^2)\,\delta(p_5^2)}{(2\pi)^{2D-3}\,[(p_1+p_2-p_4)^2-M_W^2](p_1-p_4-p_5)^4}$$

$$= \mathcal{N}\,M_W^{-4}\,z\,(1-z)^{-4\epsilon}\Big\{\frac{1}{6\,\epsilon^2}-2\,\zeta_2-8\,\zeta_3\epsilon-4\,\zeta_4\epsilon^2+\mathcal{O}(\epsilon^3)\Big\}$$

$$+\,\mathcal{N}\,M_W^{-4}\,z\,(1-z)^{-4\epsilon}\Big\{\frac{H(0,z)}{2\,\epsilon}+\frac{1}{2}\,H(0,0,z)-H(1,0,z)-\zeta_2$$

$$+\,\epsilon\Big(-\zeta_2\,H(0,z)+4\,\zeta_2\,H(1,z)+\frac{1}{2}\,H(0,0,0,z)+3H(0,1,0,z)$$

$$-\,3H(1,0,0,z)+4H(1,1,0,z)+5\,\zeta_3\Big)+\epsilon^2\Big(-\zeta_2\,H(0,0,z)$$

$$-\,12\,\zeta_2\,H(0,1,z)+2\,\zeta_2\,H(1,0,z)-16\,\zeta_2\,H(1,1,z)$$

$$-\,\zeta_3\,H(0,z)+\frac{1}{2}\,H(0,0,0,0,z)+3H(0,0,1,0,z)+9H(0,1,0,0,z)$$

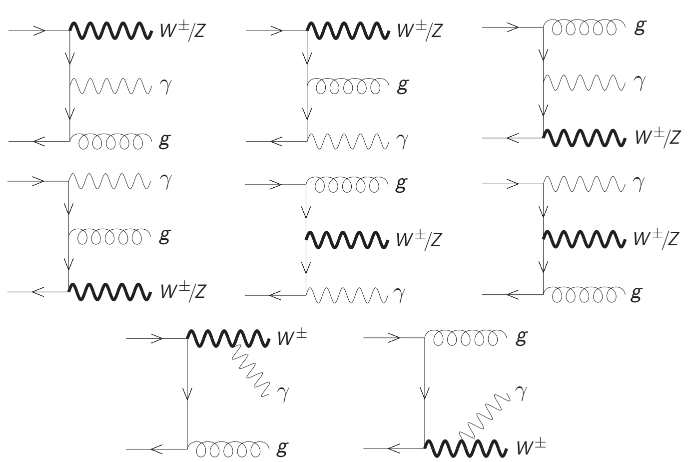
$$-\,12H(0,1,1,0,z)-11H(1,0,0,0,z)-2H(1,0,1,0,z)$$

$$+\,12H(1,1,0,0,z)-16H(1,1,1,0,z)-\frac{37\,\zeta_4}{2}\Big)+\mathcal{O}(\epsilon^3)\Big\}$$

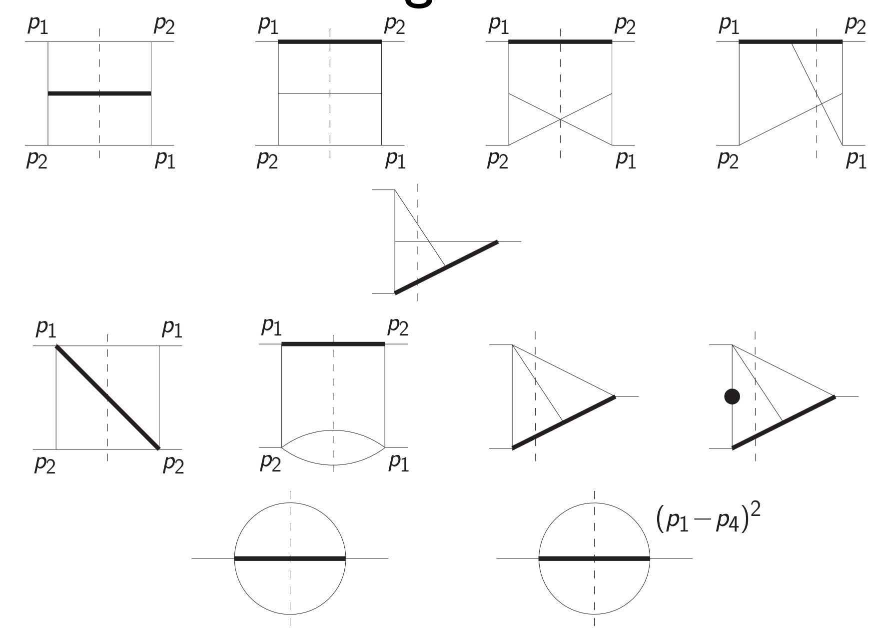
Analytic progress: total xsec for single gauge boson production at O(ααs)

R.Bonciani, F. Buccioni, R.Mondini, AV, arXiv:1611.00645

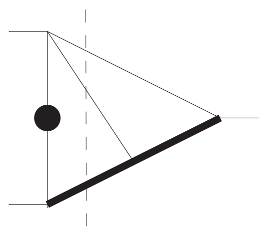
Feynman diagrams



Master Integrals



$$\mathcal{N} = \frac{1}{2}\,\frac{\Gamma^2(1+\epsilon)}{(4\pi)^{3-2\epsilon}}\,\left(\frac{M_V^2}{\mu^2}\right)^{-2\epsilon}$$



$$= \mu^{2(4-D)}\int \frac{\mathrm{d}^D p_4\,\mathrm{d}^D p_5\;\delta((p_1+p_2-p_4-p_5)^2-M_W^2)\,\delta(p_4^2)\,\delta(p_5^2)}{(2\pi)^{2D-3}\,[(p_1+p_2-p_4)^2-M_W^2](p_1-p_4-p_5)^4}$$

$$= \mathcal{N}\,M_W^{-4}\,z\,(1-z)^{-4\epsilon}\left\{\frac{1}{6\,\epsilon^2} - 2\,\zeta_2 - 8\,\zeta_3\epsilon - 4\,\zeta_4\epsilon^2 + \mathcal{O}(\epsilon^3)\right\}$$
$$+ \mathcal{N}\,M_W^{-4}\,z\,(1-z)^{-4\epsilon}\left\{\frac{H(0,z)}{2\,\epsilon} + \frac{1}{2}\,H(0,0,z) - H(1,0,z) - \zeta_2\right.$$
$$+ \epsilon\Big(-\zeta_2\,H(0,z) + 4\,\zeta_2\,H(1,z) + \frac{1}{2}\,H(0,0,0,z) + 3H(0,1,0,z)$$
$$- 3H(1,0,0,z) + 4H(1,1,0,z) + 5\,\zeta_3\Big) + \epsilon^2\Big(-\zeta_2\,H(0,0,z)$$
$$- 12\,\zeta_2\,H(0,1,z) + 2\,\zeta_2\,H(1,0,z) - 16\,\zeta_2\,H(1,1,z)$$
$$- \zeta_3\,H(0,z) + \frac{1}{2}\,H(0,0,0,0,z) + 3H(0,0,1,0,z) + 9H(0,1,0,0,z)$$
$$- 12H(0,1,1,0,z) - 11H(1,0,0,0,z) - 2H(1,0,1,0,z)$$
$$\left. + 12H(1,1,0,0,z) - 16H(1,1,1,0,z) - \frac{37\,\zeta_4}{2}\Big) + \mathcal{O}(\epsilon^3)\right\}$$

total cross section

$$\hat\sigma_{W,RR} = \sum_{i=-4}^{0}\epsilon^i\sigma_{(i)}^{W,RR}(z)$$

$$\hat\sigma_{(-4)}^{W,RR}(z) = \frac{1280\,\pi^3\,|V_{ud}|^2}{81\,\sin^2\theta_w\,M_W^2}\,\delta(1-z)$$

$$\hat\sigma_{(-3)}^{W,RR}(z) = \frac{1280\,\pi^3\,|V_{ud}|^2}{81\,\sin^2\theta_w\,M_W^2}\left\{\frac{4}{5}\,\delta(1-z) - 2\,z\,\frac{1+z^2}{(1-z)_+}\right\}$$

$$\hat\sigma_{(-2)}^{W,RR}(z) = \frac{256\,\pi^3\,|V_{ud}|^2}{81\,\sin^2\theta_w\,M_W^2}\left\{(9-40\,\zeta_2)\,\delta(1-z) - z\,\frac{15-14z+15z^2}{(1-z)_+} + 40z\,(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ - 10z\,\frac{2+3z^2}{1-z}\,\ln z\right\}$$

$$\hat\sigma_{(-1)}^{W,RR}(z) = \frac{256\,\pi^3\,|V_{ud}|^2}{81\,\sin^2\theta_w\,M_W^2}\left\{(18-32\,\zeta_2-100\,\zeta_3)\,\delta(1-z) - \frac{z}{2}\,\frac{149-226z+149z^2}{(1-z)_+} + 20z\,\zeta_2\,\frac{3+5z^2}{(1-z)_+} + 20z\,(1+z)\,\mathrm{Li}_2(z) + 4z\right.$$
$$\left.(15-14z+15z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ - 80z\,(1+z^2)\left(\frac{\ln^2(1-z)}{1-z}\right)_+ + 100z(1+z^2)\ln z\left(\frac{\ln(1-z)}{1-z}\right)_+ - z\,\frac{36-37z+41z^2}{1-z}\ln z - \frac{z}{4}\,\frac{103+153z^2}{1-z}\ln^2 z\right\}$$

$$\hat\sigma_{(0)}^{W,RR}(z) = \frac{1024\,\pi^3\,|V_{ud}|^2}{81\,\sin^2\theta_w\,M_W^2}\left\{(9-18\,\zeta_2-20\,\zeta_3+20\,\zeta_4)\,\delta(1-z) + \frac{z}{8}\,(31+37z-27z^2-9z^3)\,\mathrm{Li}_2(z) - 20z\,(1+z)\,\mathrm{Li}_2(z)\ln(1-z)\right.$$
$$- 19z\,(1+z)\,\mathrm{Li}_3(1-z) - \frac{z}{24}\,\frac{1981-3557z+2035z^2-27z^3}{(1-z)_+} + \frac{z}{4}\,\zeta_2\,\frac{91-106z+170z^2-18z^3-9z^4}{(1-z)_+} + z\,\zeta_3\,\frac{65-9z+45z^2}{(1-z)_+}$$
$$- z\,\frac{15-9z-5z^2}{(1-z)_+}\,\mathrm{Li}_3(z) - 20z\,\zeta_2\,(3+5z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + \frac{z}{2}\,(149-226z+149z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+$$
$$+ \frac{z}{8}\,(319-290z+264z^2+18z^3+9z^4)\ln z\left(\frac{\ln(1-z)}{1-z}\right)_+ - 2z\,(15-14z+15z^2)\left(\frac{\ln^2(1-z)}{1-z}\right)_+ - 20z\,(3+2z^2)\ln z\left(\frac{\ln^2(1-z)}{1-z}\right)_+$$
$$+ \frac{80}{3}\,z\,(1+z^2)\left(\frac{\ln^3(1-z)}{1-z}\right)_+ - \frac{z}{8}\,\frac{412-627z+404z^2-9z^3}{1-z}\ln z + \frac{z}{2}\,\zeta_2\,\frac{85-18z+143z^2}{1-z}\ln z + \frac{z}{2}\,\frac{25-9z-24z^2}{1-z}\,\mathrm{Li}_2(z)\ln z$$
$$\left.+ \frac{z}{4}\,(123+115\,z^2)\,\frac{\ln(1-z)}{1-z}\ln^2 z - \frac{z}{16}\,\frac{197-192z+108z^2+18z^3+9z^4}{1-z}\ln^2 z - \frac{z}{48}\,\frac{267+36z+341z^2}{1-z}\ln^3 z\right\}.$$