QED/EW aspects of precision measurements

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LHC Electroweak WG meeting
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Layout

- Summary from last meetings on M_W and $\sin^2\vartheta^l_{\rm eff}$
  - Cern 25-26 April 2018
  - LAL Orsay 22-25 May 2018

- in presence of QED radiation, which leptons? Born, dressed and bare
- comparison/validation of MC codes including QED FSR/ISR
- validation of the procedure proposed by ATLAS of reweighting existing generated events
- ongoing theoretical work on the extraction of $\sin^2\vartheta^{eff}$
- QCD NNLO, QED NNLO and NNLO QCD$\otimes$QED

Treatment of leptons in experiments

- In ATLAS, it was in 2014 that it became clear that we needed to harmonise the treatment of leptons (at the generator level only!) as much as feasible. This was prompted mostly by complex exclusive measurements in the SM (V+jets) and top groups, where the run-1 analyses had encountered real issues with ambiguities and overlaps when dealing with final-state particles.
- At the same time, confusion at some level was created because some colleagues (experimentalists and theorists!) made loose statements of the type „ATLAS and CMS measure bare muons and dressed electrons"
- The outcome of these discussions was that we should publish always results with all three flavours of leptons, with a tendency to base the main plots on dressed leptons for exclusive measurements and Born leptons for inclusive precision DY measurements
- Today we see that we need to further discuss the precision DY case because we see now MC tools with state-of-the-art. QCD and QED/EW calculations implemented: with such tools, we have to treat the topic with even more care than done until now.
- Here I will give some examples of where we stand in ATLAS in this context

Bare/Dressed/Born leptons

- **Bare:**
  MC generators give „bare leptons" as final-state objects, independently of the level of the calculations. QED radiation (wide-angle part) means that electrons and muons cannot be combined. They correspond to precisely defined off-shell kinematics at a given order, meaning one has a clear picture of what are the virtual/real corrections and their precision.
- **Dressed (all γ with $\Delta R < 0.1$ added to lepton):**
  This concept is ill-defined (compared to the other two) in the language of Feynman diagrams used in calculations to provide e.g. Z lineshape. Some assumptions have to be made on the kinematics of the dressed object (off-shell, on-shell) with consequences also on its direction. The definition will be sensitive to the („unphysical") threshold which does exist in the calculation on the photon radiation. Will any distribution produced in this way be an infrared-safe observable (what about soft and wide-angle photons)? What about the normalisation of such a distribution?
- **Born:**
  Brings the kinematics of the event observables back to the „lowest-order Feynman diagramme" relevant to the process under consideration. Allows to absorb higher-order corrections into the normalisation through „effective couplings". Requires however some care when being defined e.g. for $W\gamma/Z\gamma$ final states etc.

Pros and cons of dressed vs Born

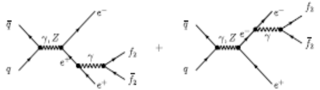
- It is a misconception to argue about bare muons being closer to what we measure or about dressed electrons being closer to what we measure. But there is some truth in these statements. The question is what does it mean?
- Starting with electrons (muons are on next slide): what the above means is that the dressed electrons are the closest one can get to minimising coupling between detector effects and the FSR modelling itself.
  This coupling is usually ignored (even by SM W/Z!) and matters only at the few permil accuracy level
- Advantages of dressed electrons: they can be corrected for improved wide-angle FSR calculations and they can be used for assignment of final-state photons to the electron itself or a nearby jet.
- Disadvantages of dressed electrons: they rely on a somewhat arbitrary cone definition and they are particles with a mass different from the electron mass. Another important disadvantage is that they cannot be combined in an exact way with muons. ATLAS has reached long ago a level of precision (both statistical and systematics) such that we can really quantitatively test the theory even at NNLO QCD and the lepton combination is a major asset in this.

QED corrections and ϕ^* observable:

at high enough level of precision, using dressed or Born leptons cannot be argued to automatically be the best or even an adequate solution

Eur. Phys. J. C (2013) 73:2625
DOI 10.1140/epjc/s10052-013-2625-1

- **Pair creation:**
  syst. error below 0.1-0.2%



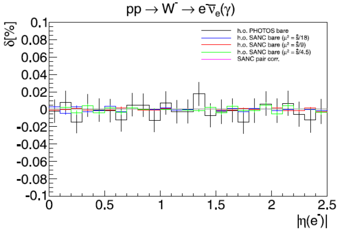


Fig. 19 Higher order photonic and pair corrections (δ in %) for basic distributions from PYTHIA+PHOTOS and SANC in $W^- \to e^- \bar{\nu}$ decay

- **Initial-final state interference:**
  below 0.1% for events after parton shower

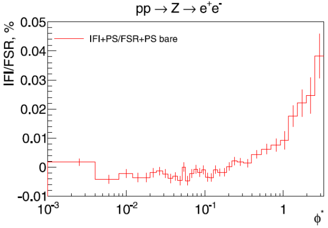


Fig. 21 IFI/FSR ratio in Z decay for ϕ^* distribution combined with parton showers

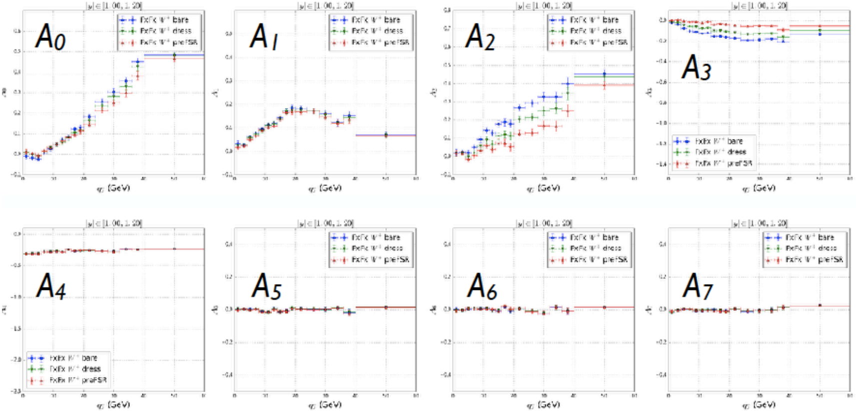
Coefficients in W decay and lepton type (CMS study)

Results (here: W^+ and one bin $|y|\in[1.0,1.2]$)

- Comparing $A_{0,\dots,7}$ for the definition of muons: bare, dress, and Born
  - Large deviations between the three are visible.

E. Manca

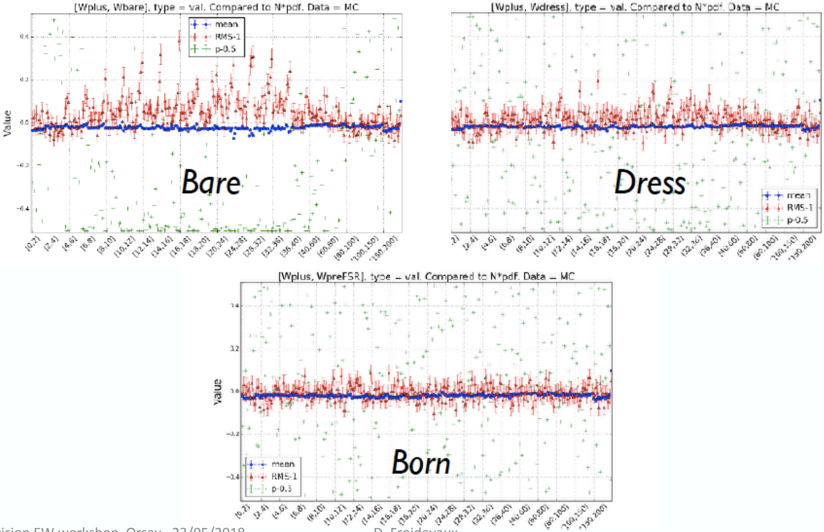
Here: W^+



Coefficients in W decay and lepton type (CMS study)

Closure test: results

E. Manca



comparisons among independent codes at fixed order

- extensive work (from theoretical point of view) in

S. Alioli et al., arXiv:1606.02330

- CC DY (W^+)

code	LO	NLO QCD	NLO EW μ	NLO EW e
HORACE	2897.38(8)	$\times$	2988.2(1)	2915.3(1)
WZGRAD	2897.33(2)	$\times$	2987.94(5)	2915.39(6)
RADY	2897.35(2)	2899.2(4)	2988.01(4)	2915.38(3)
SANC	2897.30(2)	2899.9(3)	2987.77(3)	2915.00(3)
DYNNLO	2897.32(5)	2899(1)	$\times$	$\times$
FEWZ	2897.2(1)	2899.4(3)	$\times$	$\times$
POWHEG-w	2897.34(4)	2899.41(9)	$\times$	$\times$
POWHEG_BMNNP	2897.36(5)	2899.0(1)	2988.4(2)	2915.7(1)
POWHEG_BW	2897.4(1)	2899.2(3)	2987.7(4)	$(\times)$

- NC DY (Z)

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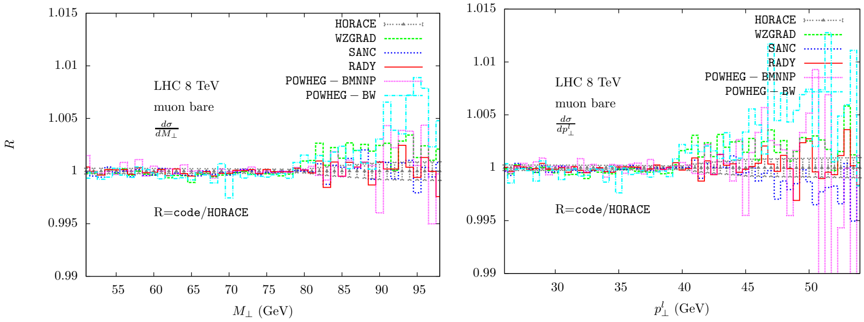
and also for distributions



- no systematic comparisons including h.o. QCD/QED ISR/FSR

proposal (call for interest circulated)

- setup a new benchmarking exercise involving codes able to reach NLO EW + (N)LO + PS QCD/QED accuracy (or similar, e.g. YFS vs. PS)
  - Powheg EW
  - Horace
  - Winhac
  - Sherpa
  - SANC
  - Herwig/Pythia
  - KKMC
  - DIZET form-factor approach
  - PHOTOS as an afterburner
- main settings:
  - same as in arXiv:1606.02330, with $\sqrt{s} = 13$ TeV; pdf set: NNPDF 3.1; fact/renorm scale: $\sqrt{\hat{s}}$
  - EW input: G_μ, M_W, M_Z, with M_W such that $\sin^2\vartheta^l_{\rm eff}$ = PDG value
  - with/without acceptance cuts; $m_{\ell\ell} > 50$ GeV
  - all MC predictions reweighted to the same $p_\perp^V$ distribution
- tests at the LO (shower) level as well as at matched (NLOPS) level

Possible observables and binning

- Lepton and photon definitions
  - Bare μ and "dressed" electrons
  - photons from hard scattering only
- CC DY
  - $M_{\ell\nu}$, 100 bins between 0 – 200 GeV
  - $p_{\perp,\ell}$, 100 bins between 0 – 100 GeV
  - leading γ in lab frame $\log_{10} p_{\perp,\gamma}$, 100 bins -7 – 3 GeV
  - leading γ relative to nearest ch. lepton $\log_{10} p_{\perp,\gamma}$, 100 bins -7 – 3 GeV
  - $\Delta R_{\gamma\ell}$ between hardest γ and nearest lepton
- NC DY
  - $M_{\ell\ell}$, 100 bins between 0 – 200 GeV
  - Collin Soper A_{FB} vs. $m_{\ell\ell}$, 100 bins between 0 – 100 GeV
  - Collin Soper A_{FB} vs. $|y_{\ell\ell}|$, 5 bins between 0 – 5
  - leading γ in lab frame $\log_{10} p_{\perp,\gamma}$, 100 bins -7 – 3 GeV
  - leading γ relative to nearest charged lepton $\log_{10} p_{\perp,\gamma}$, 100 bins -7 – 3 GeV
  - $\Delta R_{\gamma\ell}$ between hardest γ and nearest lepton

$\sin^2 \vartheta^{\ell}_{\rm eff}$ extraction

- In order to use already generated events at LO EW, Elzbieta proposed a method of reweighting with form factors from DIZET to include (electro)weak corrections
  - caveat: DIZET uses the LEP1 EW scheme G_μ, $\alpha(0)$, M_Z scheme
  - started work to cross check the procedure with Powheg EW, switching on only EW corrections and comparing physical observables

$$d\sigma/dm_{\ell\ell}, \qquad A_{\rm FB}(m_{\ell\ell})$$

    - ⋆ relative corrections insensitive, to a large extent, to the detailed generation settings
  - comparisons should be performed, consistently, at LO, NLO and including also $\Delta\alpha$ resummation and two-loops corrections to $\Delta\rho$

Started theoretical discussions

preliminary draft by S. Dittmaier, D. Wackeroth, A. Vicini

- to give recommendations for a solid theoretical recipe for $\sin^2\vartheta^{\ell}_{\rm eff}$ extraction, based on the pole expansion which allowd to define an IBA
- key observation: at the Z^0 pole

$$\mathcal{M}^{\rm vert}_{ij,\rm weak} = \mathcal{M}^0_Z\Big|_{v_q\to\bar{g}_{{\rm V},q},\, a_q\to\bar{g}_{{\rm A},q}} + \mathcal{M}^0_Z\Big|_{v_\ell\to\bar{g}_{{\rm V},\ell},\, a_\ell\to\bar{g}_{{\rm A},\ell}}$$

with the corrected ("effective") vector and axial-vector couplings

$$\begin{aligned} \bar{g}_{{\rm V},f} &= v_f\left(1+\hat{F}^{\rm V}_{{\rm Z}ff,\rm weak}(M^2_{\rm Z})\right), \\ \bar{g}_{{\rm A},f} &= a_f\left(1+\hat{F}^{\rm A}_{{\rm Z}ff,\rm weak}(M^2_{\rm Z})\right). \end{aligned}$$

$$\bar{s}^2_{{\rm eff},f} = \frac{1}{4|Q_f|}\left(1-\frac{{\rm Re}\bar{g}_{{\rm V},f}}{{\rm Re}\bar{g}_{{\rm A},f}}\right).$$

- Outside the Z peak the form factors are not gauge invariant
- the reliabilty of the IBA has to be checked with complete calculations

D. de Florian et al., arXiv:1805.12214

- It is possible to use the NNLO QCD result to obtain the QEDxQCD mixed terms and the QED^2

general expansion in both couplings $$d\sigma = \sum_{i,j} \alpha_s^i \alpha^j d\sigma^{(i,j)}$$

"Full NNLO" means $i + j = 2$

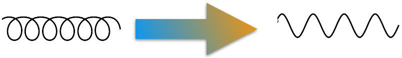
(2,0) QCD^2

(1,1) QEDxQCD

(0,2) QED^2

- Abelianization procedure

QCD → QED



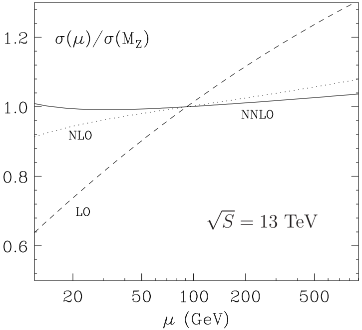
Same kinematical structure for Abelian contributions → change of color factors

Scale dependence

LO $(\sigma^{(0,0)})$

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

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



- Clear improvement in stabilization at higher orders
- Mostly QCD dominated but small QED effect

Conclusions

- Full QED+QCD NNLO corrections to DY (on-shell Z production)
- QED NLO ~ QCD NNLO (opposite sign) around 5 per-mille
- Mixed QEDxQCD below the per-mille level

Cancellation between qq and qg channels

- At 14 TeV QCD NNLO ~ 3.5 mixed QEDxQCD (QCD cancellation)
- Factorization approach for mixed QEDxQCD fails by factor of 2
- Very stable under scale variations at NNLO

Future

- Fully differential cross section
- Add final state QED radiation
- EW corrections

see talk by Frank for resummation issues of QCD and QED effects