QCD-EW corrections to on-shell Z boson production

Maximilian Delto, TTP | 17.06.2020

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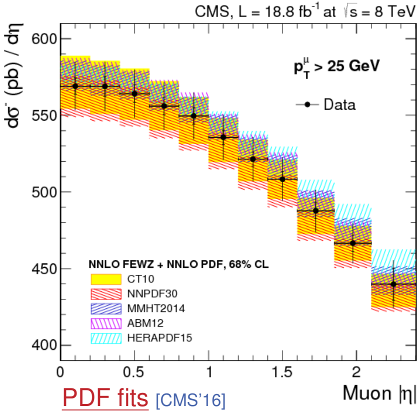
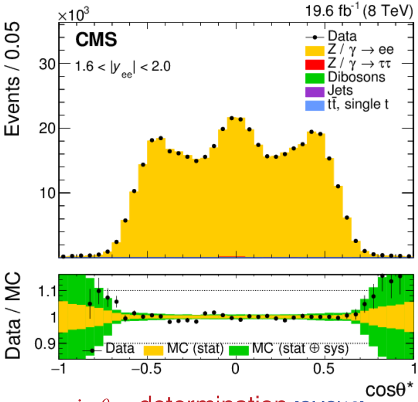
The Drell-Yan process

Lepton-pair production ($\ell\bar{\ell}$ / $\ell\nu$) provides a well-known tool for measuring SM parameters.



PDF fits [CMS'16]



$\sin\theta_{\rm eff}$ determination [CMS'18]

W mass - SM precision test

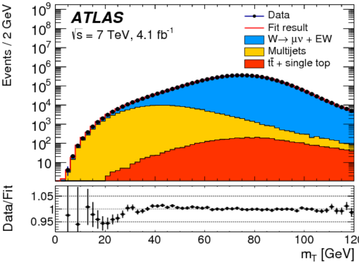
- precision fits of relations between SM parameters [Chetyrkin,Kühn,Steinhauser'95,'96] [Awramik,Czakon,Freitas,Weiglein'03'14],[...]

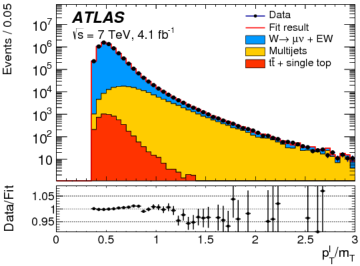
$$M_W^2(1 - M_W^2/M_Z^2) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1 + \Delta r) \Rightarrow M_W = 80354 \pm \mathbf{7}\ \text{MeV}$$ [Gfitter'18]

- recent LHC measurement (uncertainty comparable to Tevatron) [ATLAS '17]

$$M_W = 80370 \pm 7_{\text{stat}} \pm 11_{\text{sys}} \pm \mathbf{14}_{\text{model}}\ \text{MeV} = 80370 \pm \mathbf{19}\ \text{MeV}\ (\underline{\text{goal}}: \pm \mathbf{10}\ \text{MeV})$$

- M_W obtained from template fits to $p_\perp^\ell$ and $m_\perp^W$ spectra in $e\nu$ and $\mu\nu$ channels





- Z samples used for modelling, calibration and measuring M_Z (closure test).

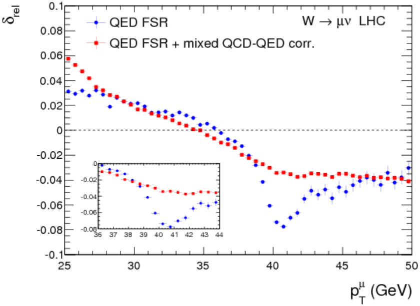
W mass - uncertainties impact

Breakdown of ATLAS modelling uncertainties: $\pm\mathbf{14}$ MeV [ATLAS '17]

- QCD (scale variation, parton shower, angular coefficients): $\pm\mathbf{8}$ MeV
- electroweak corrections: $\pm\mathbf{6}$ MeV
- PDFs: $\pm\mathbf{9}$ MeV

Theory impact on M_W [Calame,Chiesa,Martinez,Montagna,Nicrosini,Piccinini,Vicini'16]

- estimate of $\mathcal{O}(\alpha_{\mathrm{EW}}^2)$ uncertainties by input scheme variation: $\pm\mathbf{1}$ MeV
- shift due to light lepton-pair FSR in $e(\mu)$ channel: $+\mathbf{3}\pm\mathbf{1}$ MeV ($+\mathbf{5}\pm\mathbf{1}$ MeV)
- shift due to QCD-electroweak corrections, estimated by NLO QCD (NLO EW) + QED (QCD) parton shower: $-\mathbf{16}\pm\mathbf{3}$ MeV



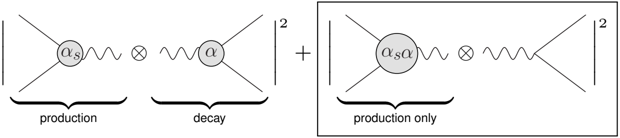
(Differential) Fixed order predictions

$$\frac{d\Sigma}{d\mathbf{O}} = \sum_{i,j} \int dx_1\, dx_2 f_i(x_1) f_j(x_2) \frac{d\sigma_{ij}(x_1,x_2)}{d\mathbf{O}} + \mathcal{O}(\Lambda^n_{\text{QCD}}/Q^n)$$ [Collins,Soper,Sterman '88]

- complexity of (mixed QCD-electroweak) N2LO computations

$$\begin{aligned} d\sigma_{ij}^{\text{N2LO}} = \;& d\sigma^{\text{rr}}_{n+2} && \leftarrow \text{intricate IR singularities in phase space} \\ & + d\sigma^{\text{rv}}_{n+1} && \leftarrow \text{“usually“ known (1-loop)} \\ & + d\sigma^{\text{vv}}_{n} && \leftarrow \text{2-loop, many mass-scales} \end{aligned}$$

- narrow width approximation [Fadin,Khoze,Martin'93], eg. $\Gamma_Z/M_Z \approx 0.03$

$d\sigma =$ 

$+\mathcal{O}(\Gamma/M)$

[Dittmaier,Huss,Schwinn '14 '16]

- important simplification: instead of $\mathbf{2} \to \mathbf{2}$ (full Drell-Yan), mixed QCD-EW corrections become a product of on-shell $\mathbf{2} \to \mathbf{1}$ processes.

Recent developments

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Building blocks

- QCD$\otimes$QED Altarelli-Parisi splitting functions [de Florian,Sborlini,Rodrigo'15]
- photon PDFs [Manohar,Nason,Salam,Zanderighi'17] [NNPDF'17]
- two-loop multi-scale master integrals (virtual & real corrections)

  [Bonciani,Vita,Mastrolia,Schubert'16] [Heller,von Manteuffel,Schabinger'19],[Hasan,Schubert'20]

Inclusive predictions

- QCD$\otimes$QED, $pp \to Z$ [de Florian,Der,Fabre'18] via abelianisation of N2LO QCD results [Hamberg,vNeerven,Matsuura'91][Harlander,Kilgore'02]
- QCD$-$electroweak corrections to $q\bar{q} \to Z$ [Bonciani,Buccioni,Rana,Triscari,Vicini'19]
- N3LO QCD, $pp \to \gamma^*$ [Duhr,Dulat,Mistlberger'20]. $(\alpha_s^3 \sim \alpha_s \alpha)$

Differential predictions

- QCD$-$electroweak (production$\times$decay) $pp \to Z \to \ell\bar{\ell}$

  and $pp \to W \to \ell\nu$ [Dittmaier,Huss,Schwinn '14 '16]
- QCD$\otimes$QED, $pp \to Z \to \ell\bar{\ell}$ [MD,Jaquier,Melnikov,Röntsch'19] via abelianisation of

  [Caola,Melnikov,Röntsch'17'19]
- QCD$\otimes$QED, $pp \to Z^* \to \nu\nu$ using q_T-slicing [Cieri,de Florian,Der,Mazzitelli'20]
- QCD$-$electroweak, $pp \to Z \to \ell\bar{\ell}$ [Buccioni,Caola,MD,Jaquier,Melnikov,Röntsch'20]

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Differential predictions

identical IR structure

- QCD−electroweak (production×decay) $pp \to Z \to \ell\bar{\ell}$ and $pp \to W \to \ell\nu$ [Dittmaier,Huss,Schwinn '14 '16]
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Production corrections for $V = W, Z$

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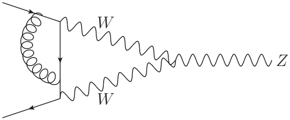
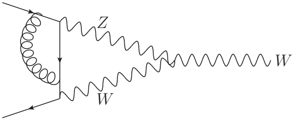
- <u>double-virtual</u> contributions (2-loop 3-point functions with internal masses)

$\mathcal{A}_Z^{\mathrm{vv}} \supset$ 

$\mathcal{A}_W^{\mathrm{vv}} \supset$ 

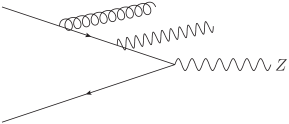
  - (re)-computed both form-factors (neglecting insignificant contributions from top-quark loops) [Aglietti,Bonciani'03,'04] [Kotikov,Kühn,Veretin'07]
  - in case of W production, master integrals with two different internal masses appear.

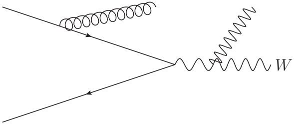
- <u>real-virtual</u> contributions numerically from `OpenLoops`

[Cascioli,Maierhofer,Pozzorini'11]

Production corrections for $V = W, Z$

- double-real contributions

$\mathcal{A}_Z^{\mathrm{rr}} \supset$ 

$\mathcal{A}_W^{\mathrm{rr}} \supset$ 

- handle IR divergences within the nested soft-collinear subtraction scheme

$$\mathrm{d}\sigma^{\mathrm{rr}}_{Vg_4\gamma_5} = \left\langle [1-\hat{S}_4][1-\hat{S}_5] \sum_{(ij)\in\text{dcp}} \left[1-\hat{C}_{i4}\right]\left[1-\hat{C}_{j5}\right] \omega^{i4,j5}[\mathrm{d}k_4][\mathrm{d}k_5]F_{LM} \right\rangle$$

$$+\left\langle [1-\hat{S}_4][1-\hat{S}_5] \sum_{i\in\text{tcp}} \sum_{k=a..d} \left[1-\hat{\mathbb{C}}_i\right]\left[1-\theta^k\hat{C}_k\right] \omega^{i4,i5}[\mathrm{d}k_4][\mathrm{d}k_5]F_{LM} \right\rangle$$

$$+\ \text{counter terms}$$

[Caola,Melnikov,Röntsch'17'19]

- operators $\hat{S}$, $\hat{C}$, $\hat{\mathbb{C}}$ denote soft, single- and triple collinear limits respectively.
- Convenient re-use of *analytic* integrated counter terms obtained for QCD corrections (where possible). Analytic pole cancellation and improved numerical efficiency.

Z production - integrated cross section

corrections relative to NLO QCD: $\mathrm{d}\Delta^{(\alpha_s^n,\alpha^m)} = \mathrm{d}\sigma^{(n,m)}/(\mathrm{d}\sigma^{(0,0)} + \mathrm{d}\sigma^{(1,0)})$

cuts: $p^{\perp}_{\ell_1} > 24\mathrm{GeV},\ p^{\perp}_{\ell_2} > 16\mathrm{GeV},\ |y_{\ell_i}| < 2.4, m_{\ell\bar{\ell}} > 50\mathrm{GeV},\ R_{e\gamma} \leq 0.1$

Type	Inclusive	Cuts	Cuts (*production only*)
$\Delta^{\mathrm{QCD-QCD}}_{\mathrm{NNLO}}$	$+1.3 \times 10^{-2}$	$+5.8 \times 10^{-3}$	$+5.8 \times 10^{-3}$
$\Delta^{\mathrm{QCD-QED}}_{\mathrm{NNLO}}$	$+5.5 \times 10^{-4}$	-5.9×10^{-3}	$+1.4 \times 10^{-4}$
$\Delta^{\mathrm{QCD-weak}}_{\mathrm{NNLO}}$	-1.6×10^{-3}	-2.1×10^{-3}	-2.1×10^{-3}
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cuts: accidental cancellation in QCD-QCD ($q\bar{q}$,qg channels)

$\Rightarrow$ QCD-QCD $\sim$ QCD-EW

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cuts: QED correction is very sensitive to the cuts (sign-flip), bad convergence for final state radiation

Z production - integrated cross section

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fiducial QCD-EW corrections receive a sizable contribution
from corrections to the production

Z production - distributions

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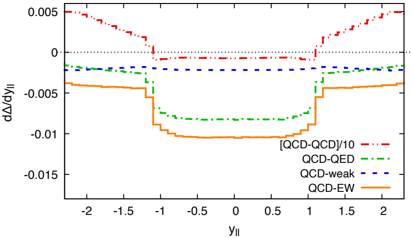

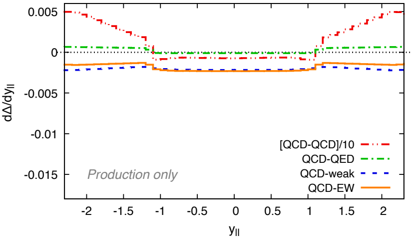

- pure QCD and QCD-EW corrections are comparable for central rapidities
- in production corrections, QCD-weak dominate over QCD-QED, both are flat

Z production - distributions

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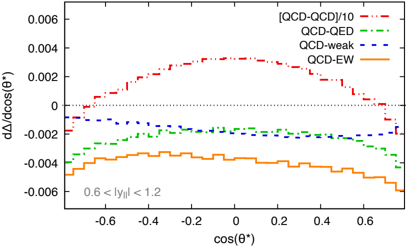

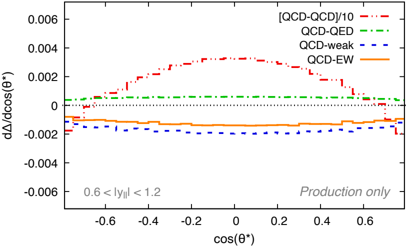

- QCD-QED and QCD-weak corrections have comparable magnitude
- in production corrections, QCD-weak dominate over QCD-QED, both are flat

Conclusions and outlook

- Very precise (HL-)LHC measurement of M_W ($\sim \pm\mathbf{10}$ MeV) requires mixed QCD-electroweak corrections.
- Results for mixed QCD-electroweak corrections to Z boson production
  - are generally small, at the per mill level;
  - show interplay between QED and weak effects;
  - strongly depend on observables and cuts.

[Buccioni,Caola,MD,Jaquier,Melnikov,Röntsch'20]

- Next goal are QCD-electroweak corrections to W boson production.

Backup

Setup

parameters [Buccioni,Caola,MD,Jaquier,Melnikov,Röntsch'20]

- LHC @ $s = 13$TeV
- G_μ scheme: $G_F = 1.16639 \times 10^{-5}$ GeV^{-2} $m_Z = 91.1876$ GeV $m_W = 80.398$ GeV
- PDFs: NNLO NNPDF3.1_LUXqed
- $\alpha_s(m_Z) = 0.118 \;\; 1/\alpha_{\mathrm{EW}} = 132.338$
- $\mu_R = \mu_F = M_Z/2$

kinematic cuts

- $p^{\perp}_{\ell_1} > 24\mathrm{GeV},\; p^{\perp}_{\ell_2} > 16\mathrm{GeV}$
- $|y_{\ell_i}| < 2.4$
- $m_{\ell\bar{\ell}} > 50\mathrm{GeV},$
- Recombination for $R_{e\gamma} \leq 0.1$ ensures collinear robustness despite massless leptons.

Additional formulae

$$
\begin{aligned}
\mathrm{d}\sigma &= \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp^2,\mathrm{d}y\,\mathrm{d}m}\sum_{i=1}^{7} A_i(y,p_\perp,m)P_i(\cos\theta,\phi) \\
m_\perp^W &= \sqrt{2p_\perp^\ell p_\perp^\nu(1-\cos\phi_{\ell\nu})} \\
\cos\theta^* &= \mathrm{sgn}(p_{z,\ell\bar\ell})\frac{(P_\ell^+P_{\bar\ell}^- - P_\ell^-P_{\bar\ell}^+)}{\sqrt{m_{\ell\bar\ell}^2(m_{\ell\bar\ell}^2+p_{\perp,\ell\bar\ell}^2)}} \\
P_i^\pm &= E_i \pm p_{i,z} \\
\frac{\mathrm{d}\sigma_{pp\to Z}\otimes\mathrm{d}\Gamma_{Z\to\ell\bar\ell}}{\Gamma_Z} &= \mathrm{Br}_{Z\to\ell\bar\ell}\,\mathrm{d}\sigma_{pp\to Z}\otimes\frac{\mathrm{d}\Gamma_{Z\to\ell\bar\ell}}{\Gamma_{Z\to\ell\bar\ell}} \\
\frac{1}{(Q^2-M_V^2)^2+M_V^2\Gamma_V^2} &\to \frac{\pi}{M_V\Gamma_V}\delta(Q^2-M_V^2)
\end{aligned}
$$

Nested subtractions - general idea

Energy ordering ($E_4 > E_5$)

$$\mathrm{d}\sigma^{\mathrm{rr}}_{n+2} = \left\langle \mathbb{S} F_{LM} \right\rangle + \left\langle [1-\mathbb{S}] S_5 F_{LM} \right\rangle + \left\langle [1-\mathbb{S}][1-S_5] F_{LM} \right\rangle$$

Partitioning

$$1 = \sum_{i \neq j} \omega^{i4,j5} + \sum_{i} \omega^{i4,i5}$$

$\omega^{i4,j5} \times$

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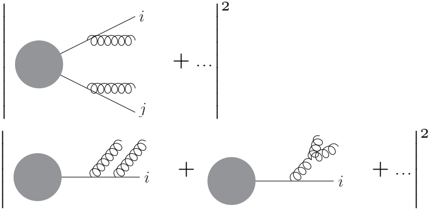
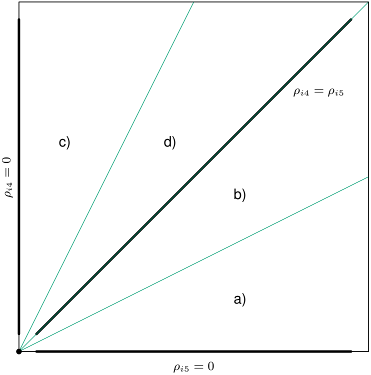


Sector decomposition



Nested subtractions - general idea

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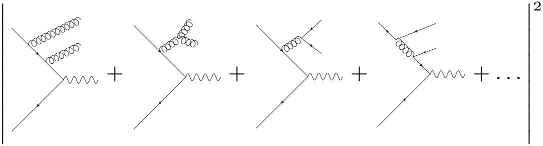
$$+ \underline{\text{counterterms}}$$

[Caola,Melnikov,Röntsch'17'19]

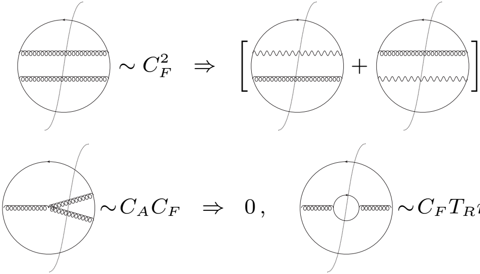
Abelianisation [de Florian,Der,Fabre'18]

double-real matrix element for Z production

$$d\sigma^{rr}_{q\bar{q}\to Z} = \sum \left| \ldots + \ldots \right|^2$$



color structures



$\sim C_F^2 \Rightarrow [\ \ldots + \ldots\ ] \sim 2C_F e_q^2$,

$\sim C_A C_F \Rightarrow 0$, $\quad \sim C_F T_R n_F \Rightarrow 0$

remaining partonic channels: $qg, q\gamma, g\gamma$: $\quad C_F^2 \Rightarrow C_F e_q^2 , \quad C_A \Rightarrow 0$