NLO weak and NLO QED results from RADY

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in collaboration with Alexander Huss

NLO + leading higher order:
S. Dittmaier and M. Krämer, PRD 65 (2002), 073007 [hep-ph/0109062];
S. Brensing et al., PRD 77 (2008), 073006 [arXiv:0710.3309];
S. Dittmaier and M. Huber, JHEP 01 (2010), 060 [arXiv:0911.2329];

Mixed NNLO QCD $\times$ EW:
S. Dittmaier, A. Huss and C. Schwinn, NPB 885 (2014), 318 [arXiv:1403.3216] and NPB 904 (2016), 216 [arXiv:1511.08016];
S. Dittmaier, T. Schmidt and J. Schwarz, arXiv:2009.02229, to appear in JHEP.

Features of RADY:

- Processes: $\mathrm{pp} \to \ell^+\ell^- + X$ and $\mathrm{pp} \to \ell^+\nu_\ell/\ell^-\bar{\nu}_\ell + X$
- Corrections:
  - NLO EW+QCD
  - universal EW corrections beyond NLO
  - higher-order FSR via structure functions
  - dominant $\mathcal{O}(\alpha_\mathrm{s}\alpha)$ corrections in resonance regions
  - off-shell $\mathcal{O}(N_f\alpha_\mathrm{s}\alpha)$ corrections
- Models: SM, MSSM, THDM, SESM

- Special features:
  - NLO corrections to $\gamma\gamma \to \ell^+\ell^-$ channel
  - various EW input schemes:
    $\{G_\mu, M_\mathrm{W}, M_\mathrm{Z}\}$, $\{\alpha(0), M_\mathrm{W}, M_\mathrm{Z}\}$, $\{\alpha(M_\mathrm{Z}), M_\mathrm{W}, M_\mathrm{Z}\}$,
    new: $\{G_\mu, \sin^2\theta^\mathrm{lept}_\mathrm{eff}, M_\mathrm{Z}\}$, $\{\alpha(0), \sin^2\theta^\mathrm{lept}_\mathrm{eff}, M_\mathrm{Z}\}$, $\{\alpha(M_\mathrm{Z}), \sin^2\theta^\mathrm{lept}_\mathrm{eff}, M_\mathrm{Z}\}$
  - different gauge-invariant resonance schemes:
    complex-mass scheme (CMS), pole scheme (PS),
    factorization scheme (FS)
  - optional: leading pole expansion

NLO weak corrections

Comparison of width schemes in RADY/Powheg (RADY results from Nov 2020)

FB asymmetry A_{FB}: (input parameters: G_μ, M_Z, M_W)

Code/scheme:	$89 < M_{\ell\ell}$[GeV]<93	$60 < M_{\ell\ell}$[GeV]<81	$81 < M_{\ell\ell}$[GeV]<101	$101 < M_{\ell\ell}$[GeV]<150
		A_{FB}(LO)		
RADY/CMS	0.046551(4)	−0.202894(5)	0.044817(4)	0.226101(5)
Powheg/CMS	0.04655(2)	−0.20292(4)	0.04481(2)	0.22608(4)
RADY/PS	0.046547(4)	−0.202955(4)	0.044812(3)	0.226090(4)
Powheg/PS	0.04655(2)	−0.202975(24)	0.04481(2)	0.22608(4)
RADY/FS	0.046547(4)	−0.202955(4)	0.044812(3)	0.226090(4)
Powheg/FS	0.04655(2)	−0.202975(24)	0.04481(2)	0.22608(4)
|X−CMS|	<0.00001	0.00006	<0.00001	0.00001
		A_{FB}(NLO weak)		
RADY/CMS	0.028568(4)	−0.215645(5)	0.026846(4)	0.218966(5)
Powheg/CMS	0.02855(2)	−0.21566(2)	0.02682(2)	0.21895(2)
RADY/PS	0.028574(4)	−0.215576(4)	0.026852(4)	0.218938(4)
Powheg/PS	0.02856(2)	−0.21559(2)	0.02683(2)	0.218933(25)
RADY/FS	0.028768(4)	−0.215354(4)	0.027044(4)	0.219037(4)
Powheg/FS	0.02875(2)	−0.21537(2)	0.02702(2)	0.219032(25)
|PS−CMS|	$\lesssim 0.00001$	0.0001	$\lesssim 0.00001$	$\lesssim 0.00002$
|FS−CMS|	0.0002	0.0003	0.0002	0.0001

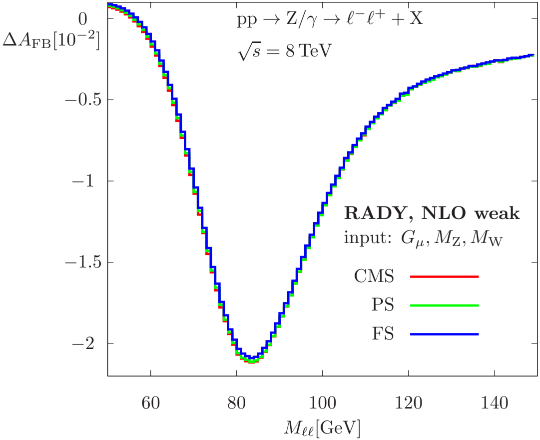
$\hookrightarrow$ |PS-CMS| $\lesssim$ 0.00001 in resonance window

But: FS less solid than CMS and PS

New: agreement with Powheg/CMS within errors

Comparison of width schemes – lepton-invariant-mass distribution

FB asymmetry A_{FB}: (input parameters: $G_\mu, M_\mathrm{Z}, M_\mathrm{W}$)



Comparison of width schemes in RADY/Powheg

FB asymmetry A_{FB}: (input parameters: $G_\mu, M_Z, \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$)

(see Chiesa, Piccinini, Vicini, arXiv:1906.11569)

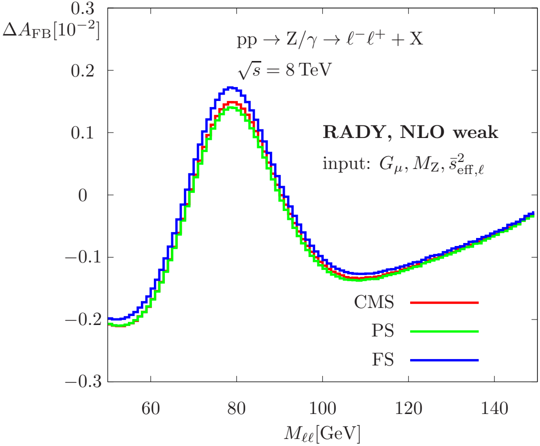
Code/scheme:	$89 < M_{\ell\ell}[\mathrm{GeV}] < 93$	$60 < M_{\ell\ell}[\mathrm{GeV}] < 81$	$81 < M_{\ell\ell}[\mathrm{GeV}] < 101$	$101 < M_{\ell\ell}[\mathrm{GeV}] < 150$
		$A_{\mathrm{FB}}(\mathrm{LO})$		
RADY/CMS	0.030552(3)	−0.214572(4)	0.028815(4)	0.220793(5)
Powheg/CMS	0.03056(2)	−0.21459(2)	0.02881(2)	0.22077(35)
RADY/PS	0.030552(3)	−0.214572(4)	0.028815(4)	0.220793(5)
Powheg/PS	0.03056(2)	−0.21459(2)	0.02881(2)	0.22077(35)
RADY/FS	0.030552(3)	−0.214572(4)	0.028815(4)	0.220793(5)
Powheg/FS	0.03056(2)	−0.21459(2)	0.02881(2)	0.22077(35)
|X−CMS|	0	0	0	0
		$A_{\mathrm{FB}}(\mathrm{NLO\ weak})$		
RADY/CMS	0.030459(3)	−0.214082(4)	0.028738(4)	0.219509(5)
Powheg/CMS	0.03046(2)	−0.21408(2)	0.02873(2)	0.219506(25)
RADY/PS	0.030376(3)	−0.214136(4)	0.028658(4)	0.219475(5)
Powheg/PS	0.03038(2)	−0.21413(2)	0.02865(2)	0.219472(25)
RADY/FS	0.030589(3)	−0.213854(4)	0.028871(4)	0.219573(5)
Powheg/FS	0.03059(2)	−0.21385(2)	0.02886(2)	0.219571(25)
|PS−CMS|	0.00008	0.00005	0.00008	0.00003
|FS−CMS|	0.0001	0.0002	0.0001	0.00006

$\hookrightarrow$ |PS-CMS| $\sim$ 0.00008 in resonance window

Agreement with Powheg/CMS within errors

Comparison of width schemes – lepton-invariant-mass distribution

FB asymmetry $A_{\rm FB}$: (input parameters: $G_\mu, M_{\rm Z}, \sin^2\theta_{\rm eff}^{\rm lept}$)



NLO QED corrections

Comparison of QED corrections to integrated $M_{\ell\ell}$ windows

$\bar{A}_4 = 8/3 \times A_{\rm FB}$:

Code:	$89 < M_{\ell\ell}[\text{GeV}] < 93$	$60 < M_{\ell\ell}[\text{GeV}] < 81$	$81 < M_{\ell\ell}[\text{GeV}] < 101$	$101 < M_{\ell\ell}[\text{GeV}] < 150$
$[A_{\rm FB}(\text{NLO QED ISR}) - A_{\rm FB}(\text{LO})]/10^{-4}$				
MCSANC*	0.2(3)	−5(2)	0.2(3)	5(2)
WZGRAD2	0.2(5)	−5(3)	0.3(5)	6(4)
POWHEG$_{ew}$	0.4(6)	−5(4)	0.2(1)	5(4)
KKMC-hh	−1.0(6)	0.2(1.1)	−0.5(5)	−8(2)
RADY(CMS)	0.16(4)	−4.05(3)	0.12(3)	4.90(3)
A.Huss (ind. code)	0.17(1)	−4.07(1)	0.11(1)	4.94(4)
$[A_{\rm FB}(\text{NLO QED IFI}) - A_{\rm FB}(\text{LO})]/10^{-4}$				
MCSANC*	−2.8(5)	−34(2)	−4.0(4)	−60(3)
WZGRAD2	−1.1(5)	−37(3)	−2.3(5)	−51(4)
POWHEG$_{ew}$	1.6(1.5)	−64(8)	1.2(1.2)	−54(10)
KKMC-hh	2.0(3)	3.4(9)	3.1(2)	−62(1)
RADY(CMS)	−1.5(1)	−33.6(4)	−2.49(7)	−59.5(1)
A.Huss (ind. code)	−1.42(6)	−33.9(6)	−2.57(7)	−58.7(3)

*updated

Comparison of QED corrections to integrated $M_{\ell\ell}$ windows

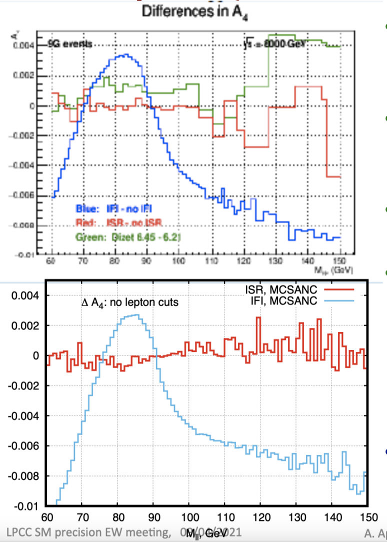
$A_4 = \langle 4 \cos\theta_{\mathrm{CS}} \rangle$:

Code:	$89 < M_{\ell\ell}[\mathrm{GeV}] < 93$	$60 < M_{\ell\ell}[\mathrm{GeV}] < 81$	$81 < M_{\ell\ell}[\mathrm{GeV}] < 101$	$101 < M_{\ell\ell}[\mathrm{GeV}] < 150$
$[A_{\mathrm{FB}}(\mathrm{NLO\ QED\ ISR}) - A_{\mathrm{FB}}(\mathrm{LO})]/10^{-4}$				
RADY(CMS)	0.15(3)	−4.05(3)	0.10(2)	4.89(2)
A.Huss (ind. code)	0.16(1)	−4.07(1)	0.11(1)	4.87(2)
$[A_{\mathrm{FB}}(\mathrm{NLO\ QED\ IFI}) - A_{\mathrm{FB}}(\mathrm{LO})]/10^{-4}$				
RADY(CMS)	−1.7(1)	−42.3(4)	−2.97(6)	−71.6(2)
A.Huss (ind. code)	−1.68(6)	−42.4(6)	−3.05(8)	−71.2(3)

Code:	$60 < M_{\ell\ell}[\mathrm{GeV}] < 150$
$[A_{\mathrm{FB}}(\mathrm{NLO\ QED\ ISR}) - A_{\mathrm{FB}}(\mathrm{LO})]/10^{-4}$	
RADY(CMS)	0.06(2)
MCSANC	0.1(4)
$[A_{\mathrm{FB}}(\mathrm{NLO\ QED\ IFI}) - A_{\mathrm{FB}}(\mathrm{LO})]/10^{-4}$	
RADY(CMS)	−8.15(6)
MCSANC	−9.8(4)

Slide from A.Apyan, D.Froidevaux, LHCEWWG Meeting, 9 April 2021

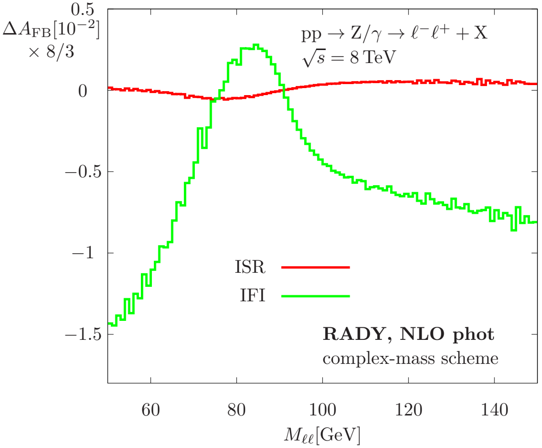
Shape of QED IFI and ISR corrections to A4



- **Shown here from KKMC-hh (top) and MC-SANC (bottom) in full phase space of decay leptons**
- **Bare muons, A4 = 8/3 AFB, AFB computed as $(\sigma_F - \sigma_B)/(\sigma_F + \sigma_B)$**
- **ISR is small, < 1 in units of 10^{-4} and flat versus m_{ll}**
- **IFI is small around Z pole. 1-3 in units of 10^{-4}, but has strong shape vs m_{ll}, with values between -100 and +50 in units of 10^{-4}. It follows roughly shape of asymmetry.**
- **Note that ΔA4 = 1 10^{-4} corresponds to ~ 1 10^{-5} for $\sin^2\theta^{eff}_l$, which means that ΔAFB = 1 10^{-4} → ~ 3 10^{-5}**

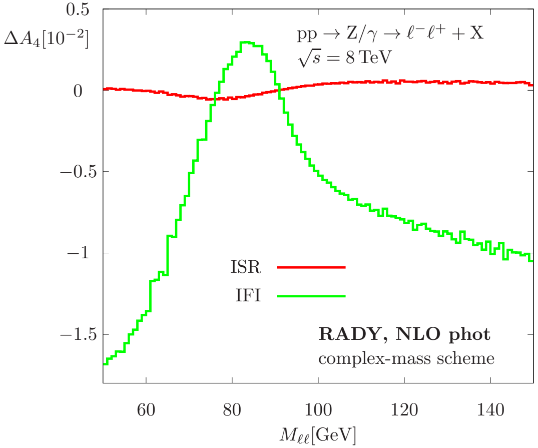
LPCC SM precision EW meeting, 09/04/2021 A. Apyan, D. Froidevaux 16

QED corrections to $\bar{A}_4 = 8/3 \times A_{\mathrm{FB}}$ differential in $M_{\ell\ell}$ from RADY



RADY results in agreement with independent results from A.Huss

QED corrections to $A_4 = \langle 4\cos\theta_{\mathrm{CS}}\rangle$ differential in $M_{\ell\ell}$ from RADY



RADY results in agreement with independent results from A.Huss

Outlook

Further issues in high-precision DY production?

- $\gamma\gamma$ channels: separation of elastic and inelastic parts of photon PDF
  $\hookrightarrow$ influences EW input scheme and PDF factorization
  $\hookrightarrow$ required to control $\gamma\gamma$ contribution at the % level
- Fixed or running Z width in resonance parametrization
  $\hookrightarrow$ extrem care needed concerning gauge invariance (see above!), but consistent studies in leading pole approximation possible with RADY
- BSM effects on DY cross sections
  $\hookrightarrow$ could be studied in RADY for MSSM, THDM, SESM