WG1 goals and paper status

Fulvio Piccinini

LHC EWWG general meeting
10-12 July 2024, CERN

on behalf of the QED/EW precision subgroup WG

Since last EWWG general meeting (november 2022)

- Sub-group meetings
  - May 2024 `http://indico.cern.ch/event/1412120/`
  - November 2023 `https://indico.cern.ch/event/1342373/`
  - April 2023 `https://indico.cern.ch/event/1274770/`
  - March 2023 `https://indico.cern.ch/event/1255813/`

Studies and benchmarking on NC Drell-Yan

having in mind, as a target, the LEP precision of $1.6 \cdot 10^{-4}$ on $\sin^2 \vartheta^{\ell}_{eff}$
$\Longrightarrow \sim 5 \cdot 10^{-4}$ on A_{FB}

Goals of the study on EW/QED

- analysis and benchmarking of NLO-EW corrections to NC DY
- focus on $A_{FB}(m_{\ell\ell})$ and $d\sigma/dM_{\ell\ell}$
- quantitative assessment of the uncertainties of EW origin in the determination of $\sin^2\vartheta^{\ell}_{eff}$
- separate study on $p_T^{W/Z}$ resummation

talk by L. Rottoli

Main focus on

- pure weak corrections
    - Gauge invariance and treatment of the Z-resonance
    - input parameter schemes
    - evaluation of residual theoretical uncertainties
- pure QED corrections on A_4
  breaking of the usual decomposition in angular coefficients
- Programs/groups involved
    - KKMC_hh
    - MCSANC
    - POWHEG_ew
    - RADY
    - WZGRAD2
    - DIZET/TauSpinner

Adopted width schemes

- complex mass scheme (CMS)
  - complex M_W and M_Z

$$\mu_V^2 = M_V^2 - i\Gamma_V M_V \Longrightarrow \cos^2\vartheta = \frac{\mu_W^2}{\mu_Z^2}$$

- factorization scheme (FS): global correction factor in the limit $\Gamma \to 0$

$$d\sigma_{\mathrm{weak}} = \delta_{\mathrm{weak}}^{\Gamma=0} \times d\sigma_{LO}^{\Gamma\neq 0}$$

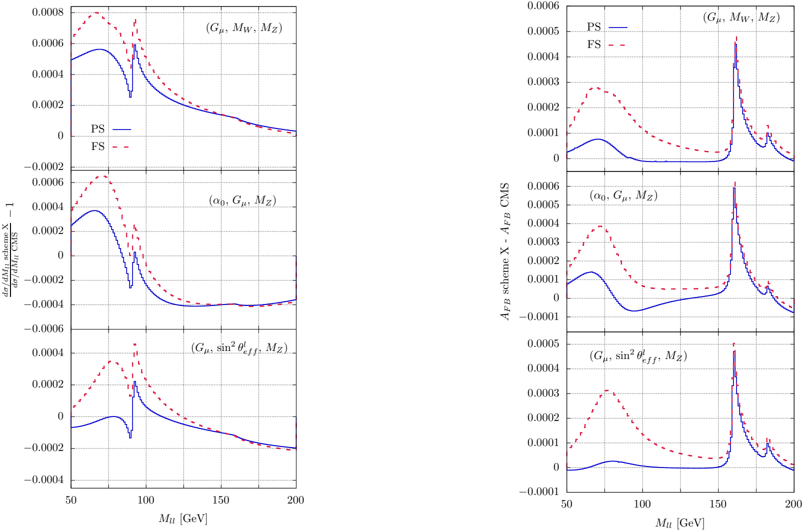
- pole scheme (PS): amplitude organized in resonant g.i. contributions

$$\begin{aligned}\mathcal{M} &= \frac{R(p^2)}{p^2 - M_2} + N(p^2) = \frac{R(M^2)}{p^2 - M_2} + \frac{R(p^2)R(M^2)}{p^2 - M_2} + N(p^2)\\ &\to \frac{\bar{R}(M^2 - i\Gamma M)}{p^2 - M_2 + i\Gamma M} + \frac{R(p^2)R(M^2)}{p^2 - M_2} + \bar{N}(p^2)\end{aligned}$$

Adopted input parameter schemes

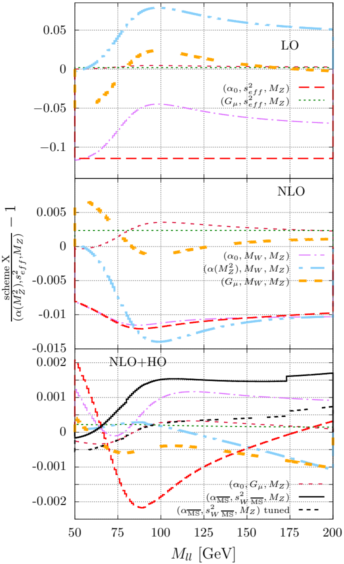
- (G_μ, M_W, M_Z)
  - MCSANC, POWHEG_EW, RADY, WZGRAD2
- $(\alpha(0), M_W, M_Z)$
  - MCSANC, POWHEG_EW, RADY, WZGRAD2
- $(G_\mu, \sin^2\vartheta^\ell_{\rm eff}, M_Z)$, $(\alpha(0), \sin^2\vartheta^\ell_{\rm eff}, M_Z)$
  - POWHEG_EW, RADY
- $(\alpha(0), G_\mu, M_Z)$
  - DIZET

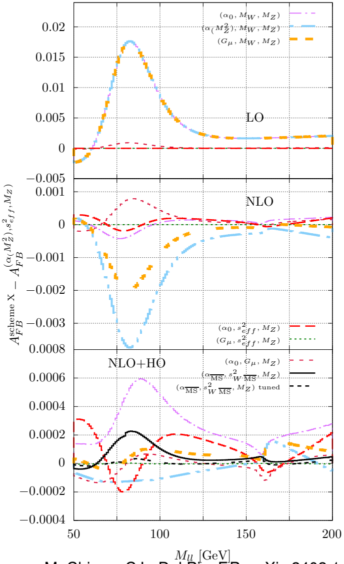
Width schemes with different input par schemes



M. Chiesa, C.L. Del Pio, F.P., arXiv:2402.14659

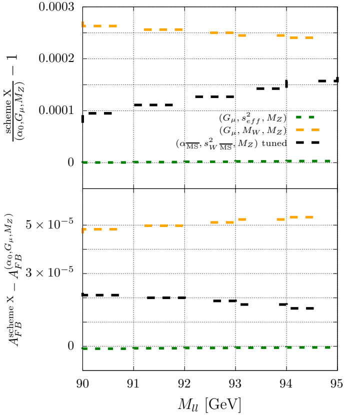
Comparisons between input par schemes





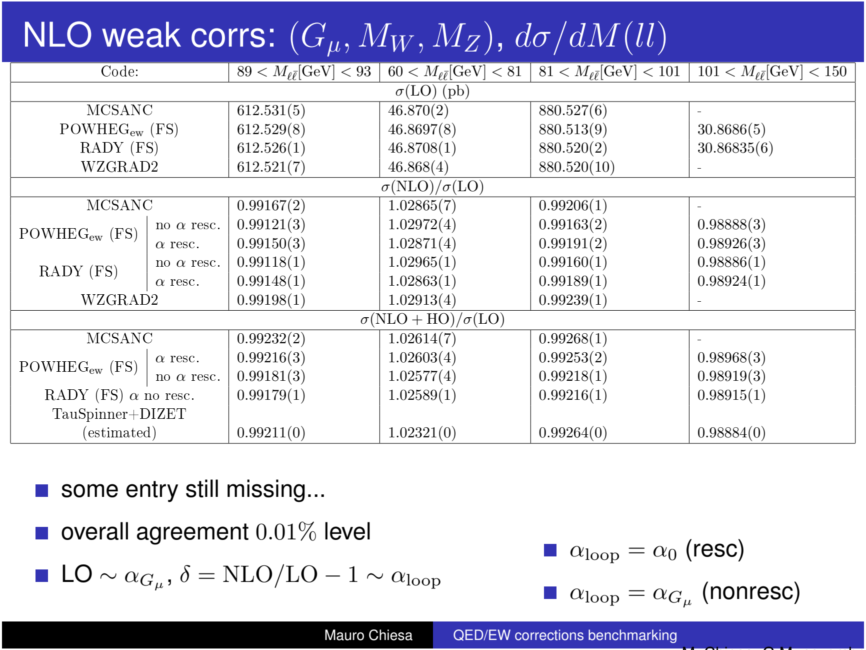
M. Chiesa, C.L. Del Pio, F.P., arXiv:2402.14659

with tuned parameters



M. Chiesa, C.L. Del Pio, F.P., arXiv:2402.14659

Status of benchmarking on weak corrections



NLO weak corrs: (G_μ, M_W, M_Z), $d\sigma/dM(ll)$

Code:		$89 < M_{\ell\bar{\ell}}[\text{GeV}] < 93$	$60 < M_{\ell\bar{\ell}}[\text{GeV}] < 81$	$81 < M_{\ell\bar{\ell}}[\text{GeV}] < 101$	$101 < M_{\ell\bar{\ell}}[\text{GeV}] < 150$
σ(LO) (pb)					
MCSANC		612.531(5)	46.870(2)	880.527(6)	-
POWHEG$_{\text{ew}}$ (FS)		612.529(8)	46.8697(8)	880.513(9)	30.8686(5)
RADY (FS)		612.526(1)	46.8708(1)	880.520(2)	30.86835(6)
WZGRAD2		612.521(7)	46.868(4)	880.520(10)	-
σ(NLO)/σ(LO)					
MCSANC		0.99167(2)	1.02865(7)	0.99206(1)	-
POWHEG$_{\text{ew}}$ (FS)	no α resc.	0.99121(3)	1.02972(4)	0.99163(2)	0.98888(3)
	α resc.	0.99150(3)	1.02871(4)	0.99191(2)	0.98926(3)
RADY (FS)	no α resc.	0.99118(1)	1.02965(1)	0.99160(1)	0.98886(1)
	α resc.	0.99148(1)	1.02863(1)	0.99189(1)	0.98924(1)
WZGRAD2		0.99198(1)	1.02913(4)	0.99239(1)	-
$\sigma(\text{NLO}+\text{HO})/\sigma(\text{LO})$					
MCSANC		0.99232(2)	1.02614(7)	0.99268(1)	-
POWHEG$_{\text{ew}}$ (FS)	α resc.	0.99216(3)	1.02603(4)	0.99253(2)	0.98968(3)
	no α resc.	0.99181(3)	1.02577(4)	0.99218(1)	0.98919(3)
RADY (FS) α no resc.		0.99179(1)	1.02589(1)	0.99216(1)	0.98915(1)
TauSpinner+DIZET (estimated)		0.99211(0)	1.02321(0)	0.99264(0)	0.98884(0)

- some entry still missing...
- overall agreement 0.01% level
- LO $\sim \alpha_{G_\mu}$, $\delta = \text{NLO}/\text{LO} - 1 \sim \alpha_{\text{loop}}$

- $\alpha_{\text{loop}} = \alpha_0$ (resc)
- $\alpha_{\text{loop}} = \alpha_{G_\mu}$ (nonresc)

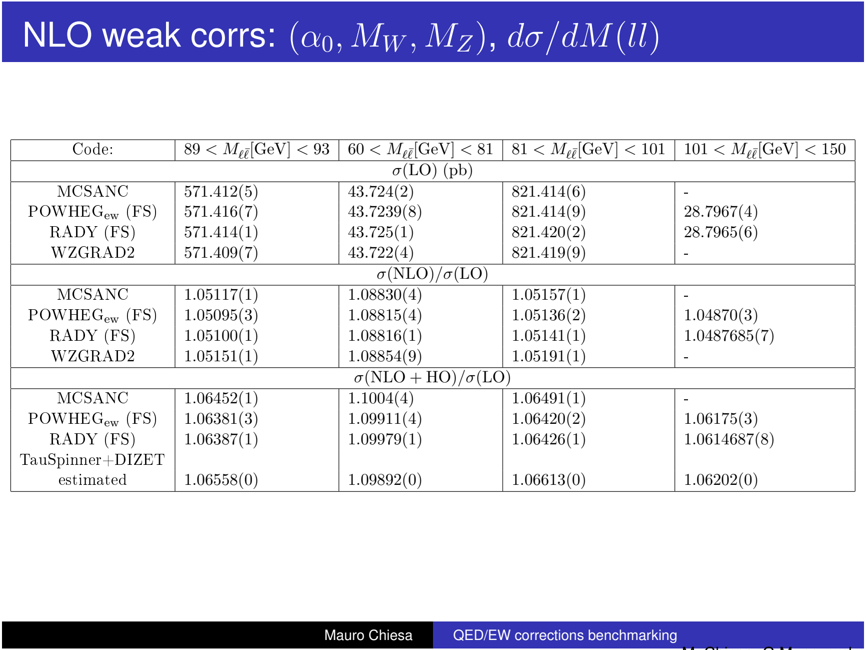
M. Chiesa, G.M. november 2022

NLO weak corrs: (G_μ, M_W, M_Z), A_{FB}

Code:		$89 < M_{\ell\bar{\ell}}[\mathrm{GeV}] < 93$	$60 < M_{\ell\bar{\ell}}[\mathrm{GeV}] < 81$	$81 < M_{\ell\bar{\ell}}[\mathrm{GeV}] < 101$	$101 < M_{\ell\bar{\ell}}[\mathrm{GeV}] < 150$
$\mathrm{A_{FB}(LO)}$					
MCSANC		0.04654(1)	$-0.20299(4)$	0.04481(1)	-
POWHEG$_{\mathrm{ew}}$ (FS)		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)
WZGRAD2		0.04654(1)	$-0.20299(8)$	0.04482(1)	-
$\mathrm{A_{FB}(NLO) - A_{FB}(LO)}$					
MCSANC (FS)		$-0.01717(2)$	$-0.01183(8)$	$-0.01715(2)$	$-0.00688(7)$
POWHEG$_{\mathrm{ew}}$ (FS)	α resc.	$-0.01718(3)$	$-0.01198(3)$	$-0.01718(3)$	$-0.00680(3)$
	no α resc.	$-0.01779(3)$	$-0.01239(3)$	$-0.01778(3)$	$-0.00705(5)$
RADY (FS)	α resc.	$-0.017166(5)$	$-0.011988(6)$	$-0.017156(5)$	$-0.006809(6)$
	no α resc.	$-0.017778(5)$	$-0.012399(6)$	$-0.017767(5)$	$-0.007052(6)$
WZGRAD2		$-0.01716(2)$	$-0.01186(11)$	$-0.01715(2)$	$-0.00686(14)$
$\mathrm{A_{FB}(NLO+HO) - A_{FB}(NLO)}$					
MCSANC		0.00137(2)	0.00111(8)	0.00137(2)	-
POWHEG$_{\mathrm{ew}}$ (FS)	α resc.	0.00136(3)	0.00113(3)	0.00137(3)	0.0004(2)
	no α resc.	0.00183(3)	0.00147(3)	0.00183(2)	0.00057(35)
RADY (FS) no α resc.		0.001829(5)	0.001437(6)	0.001830(5)	0.000582(6)
$\mathrm{A_{FB}(NLO+HO) - A_{FB}(LO)}$					
MCSANC		$-0.01551(2)$	$-0.01059(8)$	$-0.01551(1)$	-
POWHEG$_{\mathrm{ew}}$ (FS)	α resc.	$-0.01582(3)$	$-0.01085(3)$	$-0.01581(3)$	$-0.0064(2)$
	no α resc.	$-0.01597(3)$	$-0.01092(3)$	$-0.01596(3)$	$-0.0065(5)$
RADY (FS) no α resc.		$-0.015948(5)$	$-0.010962(6)$	$-0.015937(5)$	$-0.006470(6)$
TauSpinner+DIZET (estimated)		$-0.01507(0)$	$-0.01104(0)$	$-0.01514(0)$	0.00684(0)

Mauro Chiesa QED/EW corrections benchmarking

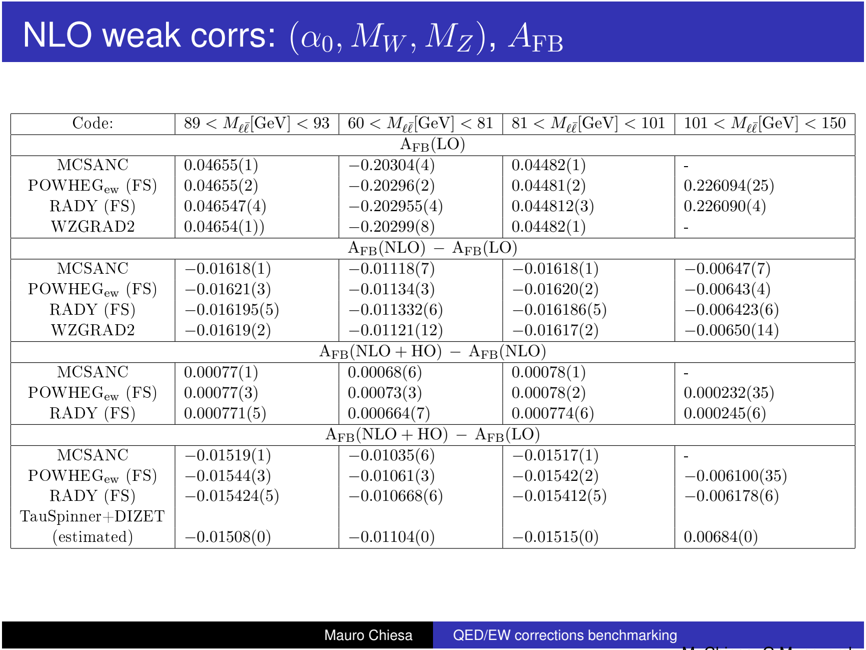
M. Chiesa, G.M. november 2022



NLO weak corrs: (α_0, M_W, M_Z), $d\sigma/dM(ll)$

Code:	$89 < M_{\ell\bar{\ell}}[\text{GeV}] < 93$	$60 < M_{\ell\bar{\ell}}[\text{GeV}] < 81$	$81 < M_{\ell\bar{\ell}}[\text{GeV}] < 101$	$101 < M_{\ell\bar{\ell}}[\text{GeV}] < 150$
σ(LO) (pb)				
MCSANC	571.412(5)	43.724(2)	821.414(6)	-
POWHEG$_{\text{ew}}$ (FS)	571.416(7)	43.7239(8)	821.414(9)	28.7967(4)
RADY (FS)	571.414(1)	43.725(1)	821.420(2)	28.7965(6)
WZGRAD2	571.409(7)	43.722(4)	821.419(9)	-
σ(NLO)/σ(LO)				
MCSANC	1.05117(1)	1.08830(4)	1.05157(1)	-
POWHEG$_{\text{ew}}$ (FS)	1.05095(3)	1.08815(4)	1.05136(2)	1.04870(3)
RADY (FS)	1.05100(1)	1.08816(1)	1.05141(1)	1.0487685(7)
WZGRAD2	1.05151(1)	1.08854(9)	1.05191(1)	-
σ(NLO + HO)/σ(LO)				
MCSANC	1.06452(1)	1.1004(4)	1.06491(1)	-
POWHEG$_{\text{ew}}$ (FS)	1.06381(3)	1.09911(4)	1.06420(2)	1.06175(3)
RADY (FS)	1.06387(1)	1.09979(1)	1.06426(1)	1.0614687(8)
TauSpinner+DIZET estimated	1.06558(0)	1.09892(0)	1.06613(0)	1.06202(0)

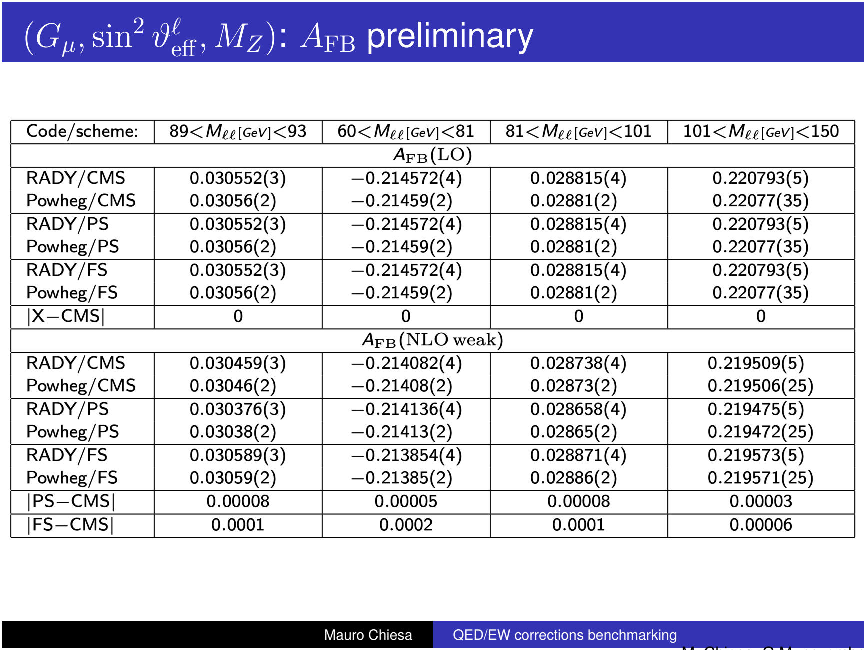
M. Chiesa, G.M. november 2022



NLO weak corrs: (α_0, M_W, M_Z), A_{FB}

Code:	$89 < M_{\ell\bar{\ell}}[\mathrm{GeV}] < 93$	$60 < M_{\ell\bar{\ell}}[\mathrm{GeV}] < 81$	$81 < M_{\ell\bar{\ell}}[\mathrm{GeV}] < 101$	$101 < M_{\ell\bar{\ell}}[\mathrm{GeV}] < 150$
$\mathrm{A_{FB}(LO)}$				
MCSANC	0.04655(1)	−0.20304(4)	0.04482(1)	-
$\mathrm{POWHEG_{ew}}$ (FS)	0.04655(2)	−0.20296(2)	0.04481(2)	0.226094(25)
RADY (FS)	0.046547(4)	−0.202955(4)	0.044812(3)	0.226090(4)
WZGRAD2	0.04654(1))	−0.20299(8)	0.04482(1)	-
$\mathrm{A_{FB}(NLO)} - \mathrm{A_{FB}(LO)}$				
MCSANC	−0.01618(1)	−0.01118(7)	−0.01618(1)	−0.00647(7)
$\mathrm{POWHEG_{ew}}$ (FS)	−0.01621(3)	−0.01134(3)	−0.01620(2)	−0.00643(4)
RADY (FS)	−0.016195(5)	−0.011332(6)	−0.016186(5)	−0.006423(6)
WZGRAD2	−0.01619(2)	−0.01121(12)	−0.01617(2)	−0.00650(14)
$\mathrm{A_{FB}(NLO+HO)} - \mathrm{A_{FB}(NLO)}$				
MCSANC	0.00077(1)	0.00068(6)	0.00078(1)	-
$\mathrm{POWHEG_{ew}}$ (FS)	0.00077(3)	0.00073(3)	0.00078(2)	0.000232(35)
RADY (FS)	0.000771(5)	0.000664(7)	0.000774(6)	0.000245(6)
$\mathrm{A_{FB}(NLO+HO)} - \mathrm{A_{FB}(LO)}$				
MCSANC	−0.01519(1)	−0.01035(6)	−0.01517(1)	-
$\mathrm{POWHEG_{ew}}$ (FS)	−0.01544(3)	−0.01061(3)	−0.01542(2)	−0.006100(35)
RADY (FS)	−0.015424(5)	−0.010668(6)	−0.015412(5)	−0.006178(6)
TauSpinner+DIZET (estimated)	−0.01508(0)	−0.01104(0)	−0.01515(0)	0.00684(0)

M. Chiesa, G.M. november 2022

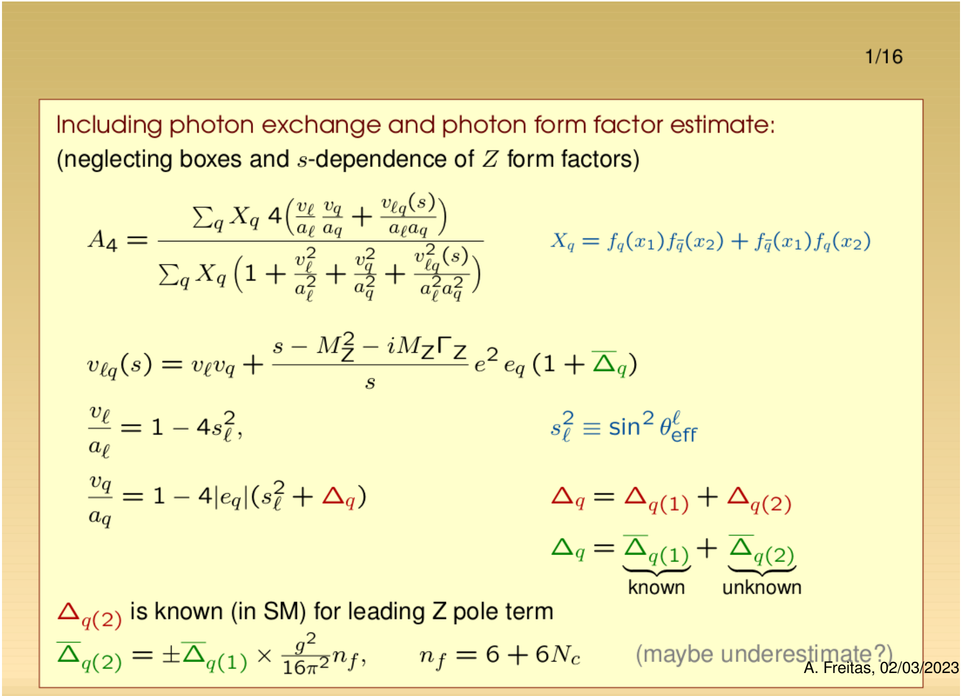


$(G_\mu, \sin^2\vartheta^\ell_{\mathrm{eff}}, M_Z)$: A_{FB} preliminary

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

M. Chiesa, G.M. november 2022

Semianalytical A_4 uncertainties in the pure weak sector



Including photon exchange and photon form factor estimate:

(neglecting boxes and s-dependence of Z form factors)

$$A_4 = \frac{\sum_q X_q \, 4\left(\frac{v_\ell}{a_\ell}\frac{v_q}{a_q} + \frac{v_{\ell q}(s)}{a_\ell a_q}\right)}{\sum_q X_q \left(1 + \frac{v_\ell^2}{a_\ell^2} + \frac{v_q^2}{a_q^2} + \frac{v_{\ell q}^2(s)}{a_\ell^2 a_q^2}\right)} \qquad X_q = f_q(x_1) f_{\bar{q}}(x_2) + f_{\bar{q}}(x_1) f_q(x_2)$$

$$v_{\ell q}(s) = v_\ell v_q + \frac{s - M_Z^2 - iM_Z\Gamma_Z}{s}\, e^2\, e_q\,(1 + \overline{\Delta}_q)$$

$$\frac{v_\ell}{a_\ell} = 1 - 4s_\ell^2, \qquad s_\ell^2 \equiv \sin^2\theta_{\text{eff}}^\ell$$

$$\frac{v_q}{a_q} = 1 - 4|e_q|(s_\ell^2 + \Delta_q) \qquad \Delta_q = \Delta_{q(1)} + \Delta_{q(2)}$$

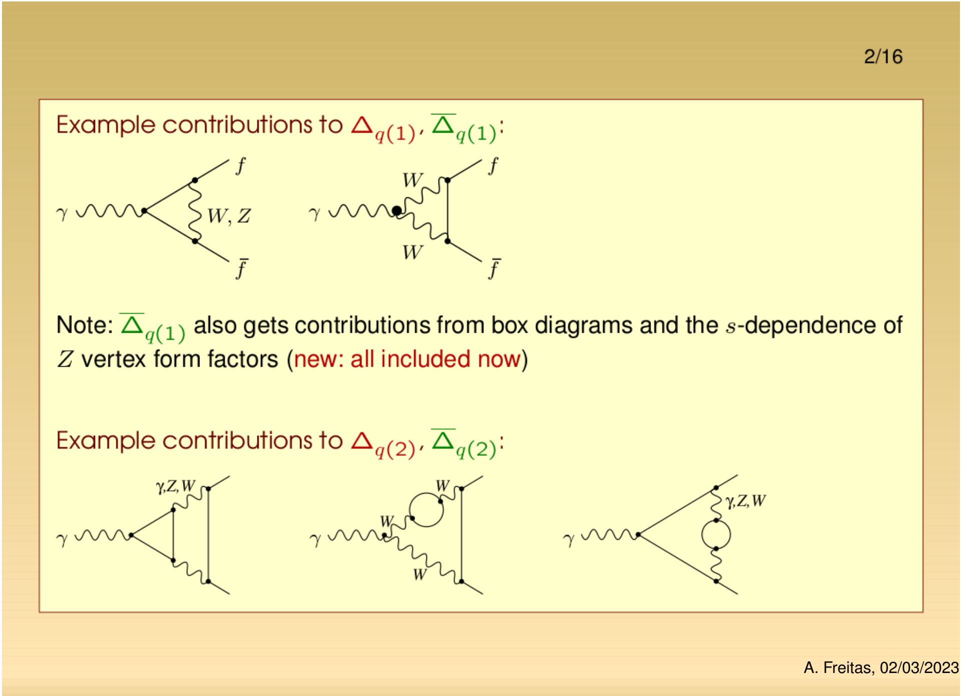
$$\Delta_q = \underbrace{\overline{\Delta}_{q(1)}}_{\text{known}} + \underbrace{\overline{\Delta}_{q(2)}}_{\text{unknown}}$$

$\Delta_{q(2)}$ is known (in SM) for leading Z pole term

$$\overline{\Delta}_{q(2)} = \pm\overline{\Delta}_{q(1)} \times \frac{g^2}{16\pi^2} n_f, \qquad n_f = 6 + 6N_c$$

(maybe underestimate?)

A. Freitas, 02/03/2023



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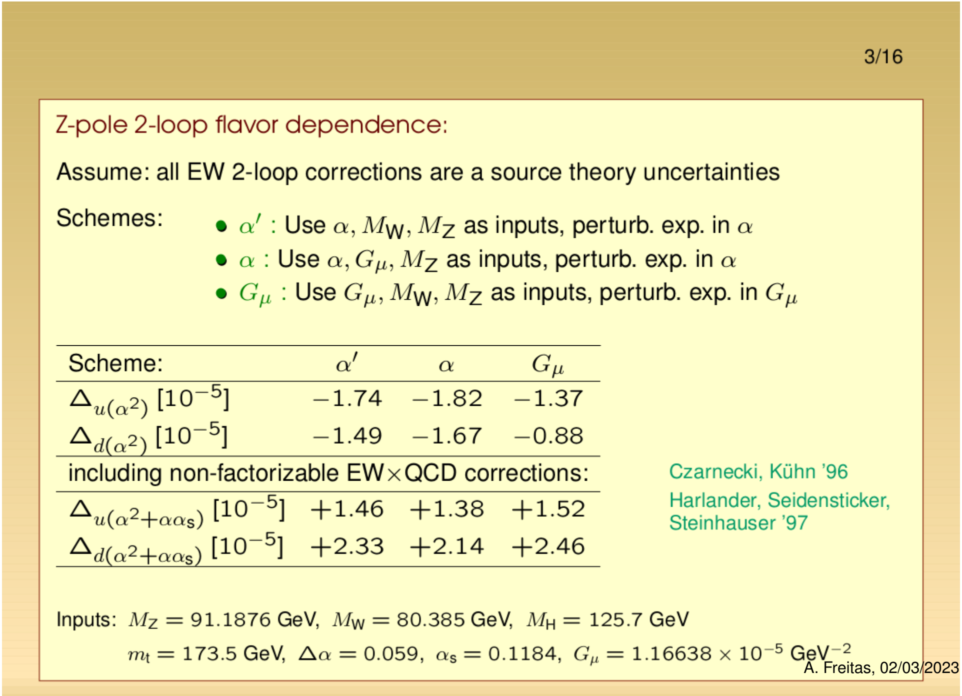
Example contributions to $\Delta_{q(1)}$, $\overline{\Delta}_{q(1)}$:

Note: $\overline{\Delta}_{q(1)}$ also gets contributions from box diagrams and the s-dependence of Z vertex form factors (new: all included now)

Example contributions to $\Delta_{q(2)}$, $\overline{\Delta}_{q(2)}$:

A. Freitas, 02/03/2023



Z-pole 2-loop flavor dependence:

Assume: all EW 2-loop corrections are a source theory uncertainties

Schemes:
- α' : Use $\alpha, M_\mathrm{W}, M_\mathrm{Z}$ as inputs, perturb. exp. in α
- α : Use $\alpha, G_\mu, M_\mathrm{Z}$ as inputs, perturb. exp. in α
- G_μ : Use $G_\mu, M_\mathrm{W}, M_\mathrm{Z}$ as inputs, perturb. exp. in G_μ

Scheme:	α'	α	G_μ
$\Delta_{u(\alpha^2)}$ $[10^{-5}]$	-1.74	-1.82	-1.37
$\Delta_{d(\alpha^2)}$ $[10^{-5}]$	-1.49	-1.67	-0.88
including non-factorizable EW×QCD corrections:			
$\Delta_{u(\alpha^2+\alpha\alpha_\mathrm{s})}$ $[10^{-5}]$	$+1.46$	$+1.38$	$+1.52$
$\Delta_{d(\alpha^2+\alpha\alpha_\mathrm{s})}$ $[10^{-5}]$	$+2.33$	$+2.14$	$+2.46$

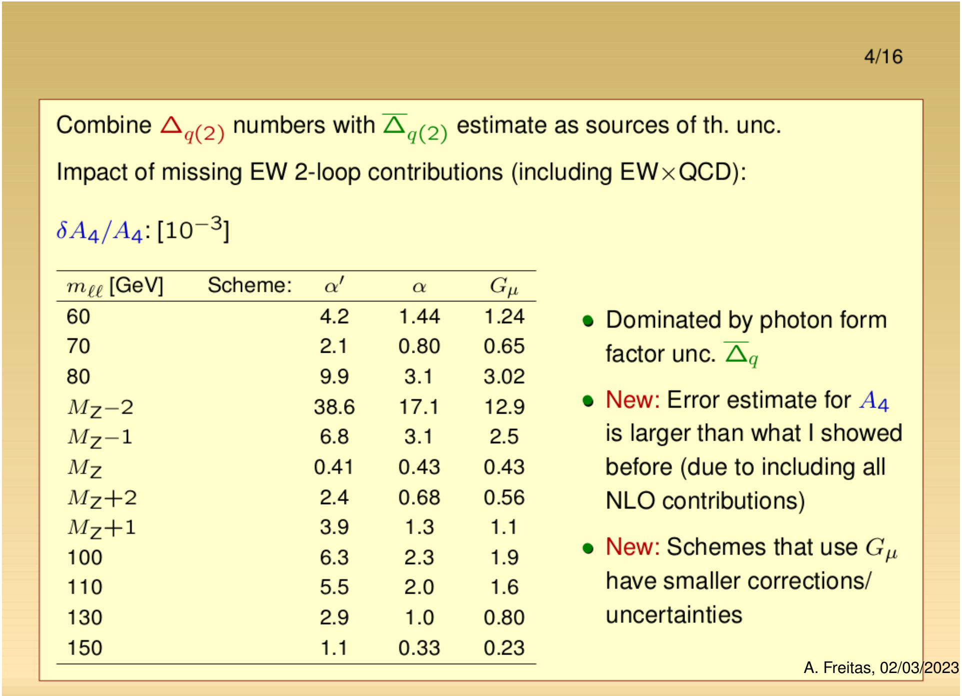
Czarnecki, Kühn '96

Harlander, Seidensticker, Steinhauser '97

Inputs: $M_\mathrm{Z} = 91.1876$ GeV, $M_\mathrm{W} = 80.385$ GeV, $M_\mathrm{H} = 125.7$ GeV

$m_\mathrm{t} = 173.5$ GeV, $\Delta\alpha = 0.059$, $\alpha_\mathrm{s} = 0.1184$, $G_\mu = 1.16638 \times 10^{-5}$ GeV^{-2}

A. Freitas, 02/03/2023



Combine $\Delta_{q(2)}$ numbers with $\overline{\Delta}_{q(2)}$ estimate as sources of th. unc.

Impact of missing EW 2-loop contributions (including EW×QCD):

$\delta A_4/A_4$: $[10^{-3}]$

$m_{\ell\ell}$ [GeV]	Scheme:	α'	α	G_μ
60		4.2	1.44	1.24
70		2.1	0.80	0.65
80		9.9	3.1	3.02
M_Z-2		38.6	17.1	12.9
M_Z-1		6.8	3.1	2.5
M_Z		0.41	0.43	0.43
M_Z+2		2.4	0.68	0.56
M_Z+1		3.9	1.3	1.1
100		6.3	2.3	1.9
110		5.5	2.0	1.6
130		2.9	1.0	0.80
150		1.1	0.33	0.23

- Dominated by photon form factor unc. $\overline{\Delta}_q$
- New: Error estimate for A_4 is larger than what I showed before (due to including all NLO contributions)
- New: Schemes that use G_μ have smaller corrections/ uncertainties

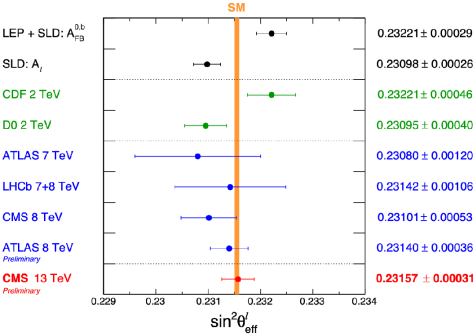
A. Freitas, 02/03/2023

CMS measurement of the weak mixing angle

RESULTS

- The final combined result for $\sin^2\theta^l_{\text{eff}}$, using CT18Z parton densities is:

$$\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(\text{syst}) \pm 0.00009\,(\text{theo}) \pm 0.00027(\text{PDF})$$



- Most precise extraction at hadron collider
- Excellent agreement with the world average and the SM prediction of 0.23155 ± 0.00004
- Precision comparable to LEP/SLD (26-29 10^{-5})

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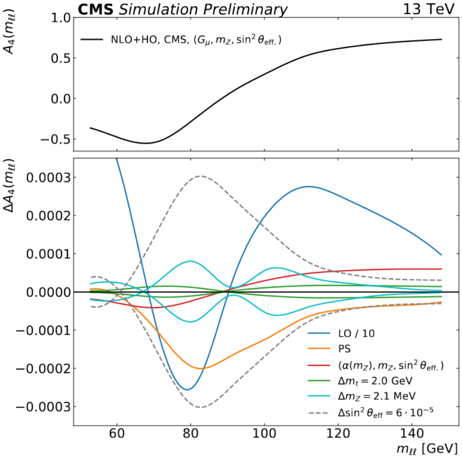
S. Amoroso, 17/05/2024

see talk by Rhys Taus

NLO WEAK UNCERTAINTIES



- Several sources of uncertainties are considered on the NLO weak corrections
- Comparison of the complex-mass and pole scheme for the treatment of the finite width
- Comparison between the $(G_F, m_Z, \sin^2\theta^l_{\mathrm{eff}})$ and $(\alpha(m_Z), m_Z, \sin^2\theta^l_{\mathrm{eff}})$ **input EW schemes**
- Parametric uncertainties on the measured values of m_t and m_Z (others negligible)

S. Amoroso, 17/05/2024

see an update by Rhys Taus

Status of benchmarking on QED ISR and IFI

QED corrections (at QCD LO)

- important to disentangle on A_4
  - ISR
  - FSR
  - IFI

- A_4 defined as $8/3A_{FB}$ or $4\langle\cos\vartheta\rangle$ (equivalent options at LO)

- IFI contributions defined as

$$\begin{aligned}
A_{FB}^{\text{IFI}} &= \frac{(\sigma_F-\sigma_B)^{\text{NLO}}-(\sigma_F-\sigma_B)^{\text{ISR}}-(\sigma_F-\sigma_B)^{\text{FSR}}+2(\sigma_F-\sigma_B)^{\text{LO}}}{(\sigma_F+\sigma_B)^{\text{NLO}}-(\sigma_F+\sigma_B)^{\text{ISR}}-(\sigma_F+\sigma_B)^{\text{FSR}}+2(\sigma_F+\sigma_B)^{\text{LO}}} \\
\langle\cos\vartheta\rangle^{\text{IFI}} &= \frac{\int\cos\vartheta\,d\sigma_{\text{NLO}}-\int\cos\vartheta\,d\sigma_{\text{ISR}}-\int\cos\vartheta\,d\sigma_{\text{FSR}}+-\int\cos\vartheta\,d\sigma_{\text{LO}}}{\int d\sigma_{\text{NLO}}-\int d\sigma_{\text{ISR}}-\int d\sigma_{\text{FSR}}+2\int d\sigma_{\text{LO}}}
\end{aligned}$$

- tuned comparison at fixed order (NLO) level for all codes except for KKMC_hh which produces only exponentiated results for both ISR and FSR

- input parameter scheme: (α, M_W, M_Z)

$A_4 = 8/3 A_{FB}$

Code:	$89 < M_{\ell\bar\ell}[\text{GeV}] < 93$	$60 < M_{\ell\bar\ell}[\text{GeV}] < 81$	$81 < M_{\ell\bar\ell}[\text{GeV}] < 101$	$101 < M_{\ell\bar\ell}[\text{GeV}] < 150$
$8/3 \cdot [\mathrm{A_{FB}}\,(\text{NLO QED ISR}) - \mathrm{A_{FB}}\,(\text{LO})]/10^{-4}$				
MCSANC	0.2(3)	−5(2)	0.2(3)	5(2)
WZGRAD2	0.2(5)	−5(3)	0.3(5)	6(4)
KKMC-hh	−1.0(6)	0(1)	−0.5(5)	−8(2)
KKMC-hh (NISR)	−1(2)	0(4)	0(1)	6(8)
RADY (CMS)	0.16(4)	−4.05(3)	0.12(3)	4.90(3)
A. Huss	0.17(1)	−4.07(1)	0.11(1)	4.94(4)
POWHEG$_{ew}$	0.1(1)	−4.0(4)	0.1(1)	4.5(7)
$8/3 \cdot [\mathrm{A_{FB}}\,(\text{NLO QED IFI}) - \mathrm{A_{FB}}\,(\text{LO})]/10^{-4}$				
MCSANC	−2.8(5)	−34(2)	−4.0(4)	−60(3)
WZGRAD2	−1.1(5)	−37(3)	−2.3(5)	−51(4)
KKMC-hh	−3.8(6)	−25(1)	−2.1(1)	−53(1)
KKMC-hh (NISR)	−3.1(6)	−17(1)	−3.2(5)	−60(3)
RADY (CMS)	−1.5(1)	−33.6(4)	−2.49(7)	−59.5(1)
A. Huss	−1.42(6)	−33.9(6)	−2.57(7)	−58.7(3)
POWHEG$_{ew}$ $\mu_F = M_{\ell\bar\ell\gamma}$	−1.2(3)	−62(1)	−2.5(4)	−59(2)
$\mu_F = M_{\ell\bar\ell}$	−1.3(6)	−34(2)	−2.6(7)	−59(3)

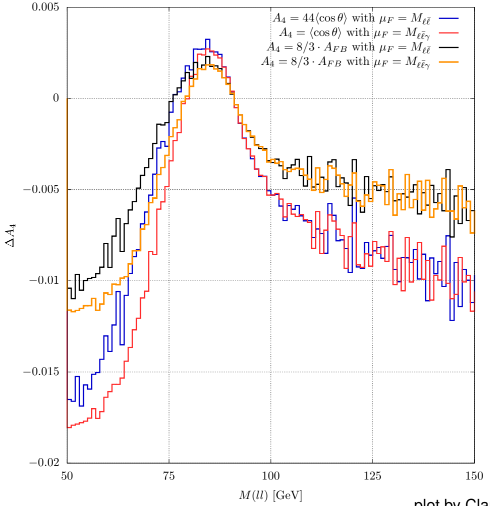
- POWHEG$_{ew}$ $\mu_F(1) \Longrightarrow M_{ll}$ for real rad calculated with underlying Born momenta
- POWHEG$_{ew}$ $\mu_F(2) \Longrightarrow M_{ll}$ for real rad calculated with radiative event momenta
- differences between $\mu_F(1)$ and (2) expected to decrease when including also QCD corrections

$A_4 = 4\langle\cos\vartheta\rangle$

Code:		$89 < M_{\ell\bar\ell}[\text{GeV}] < 93$	$60 < M_{\ell\bar\ell}[\text{GeV}] < 81$	$81 < M_{\ell\bar\ell}[\text{GeV}] < 101$	$101 < M_{\ell\bar\ell}[\text{GeV}] < 150$
$[\mathrm{A}_4\,(\text{NLO QED ISR}) - \mathrm{A}_4\,(\text{LO})]/10^{-4}$					
RADY (CMS)		$0.15(3)$	$-4.05(3)$	$0.10(2)$	$4.89(2)$
A. Huss		$0.16(1)$	$-4.07(1)$	$0.11(1)$	$4.87(2)$
POWHEG$_{ew}$		$0.07(9)$	$-4.0(3)$	$0.10(7)$	$4.8(4)$
$[\mathrm{A}_4\,(\text{NLO QED IFI}) - \mathrm{A}_4\,(\text{LO})]/10^{-4}$					
RADY (CMS)		$-1.7(1)$	$-42.3(4)$	$-2.97(6)$	$-71.6(2)$
A. Huss		$-1.68(6)$	$-42.4(6)$	$-3.05(8)$	$-71.2(3)$
POWHEG$_{ew}$	$\mu_F = M_{\ell\bar\ell\gamma}$	$-1.5(5)$	$-70(1)$	$-3.0(4)$	$-71(3)$
	$\mu_F = M_{\ell\bar\ell}$	$-1.5(5)$	$-43(1)$	$-3.0(4)$	$-71(3)$

- POWHEG$_{ew}$ $\mu_F(1) \Longrightarrow M_{ll}$ for real rad calculated with underlying Born momenta
- POWHEG$_{ew}$ $\mu_F(2) \Longrightarrow M_{ll}$ for real rad calculated with radiative event momenta
- at low and high M_{ll} virtual QED boxes and I-F real radiation interference break factorization assumption for angular coefficients and the LO equality between the two A_4 def's
- differences between $\mu_F(1)$ and (2) expected to decrease when including also QCD corrections

IFI contribution to A_4 according to different definitions



plot by Clara L. Del Pio with POWHEG_EW

- virtual QED boxes and I-F real radiation interference give different contributions according to the definition of A_4

From a recent study

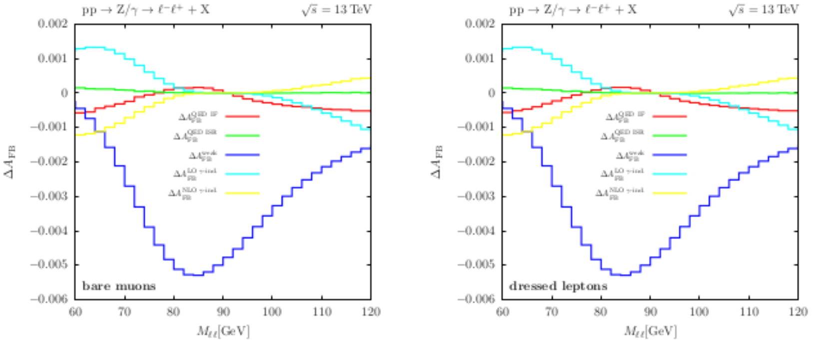
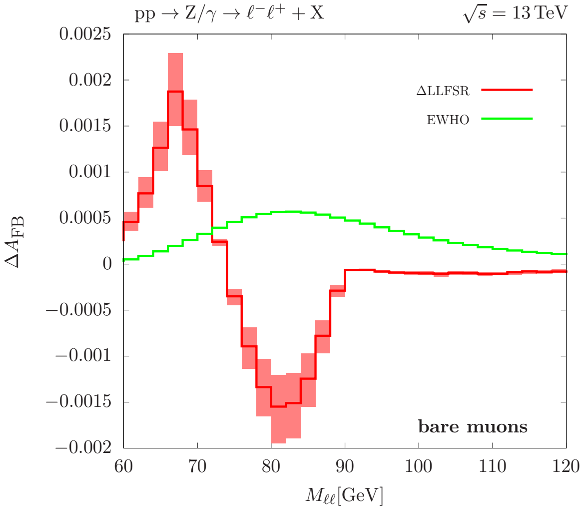


Figure 13: NLO EW corrections to the FB asymmetry A_{FB} for muon pair (left) and dressed-lepton pair (right) production induced by QED IF (red), QED ISR (green), and purely weak (blue) corrections, as well as contributions from LO $\gamma\gamma$ (cyan) and NLO $q\gamma/\bar{q}\gamma$ (yellow) initial states.

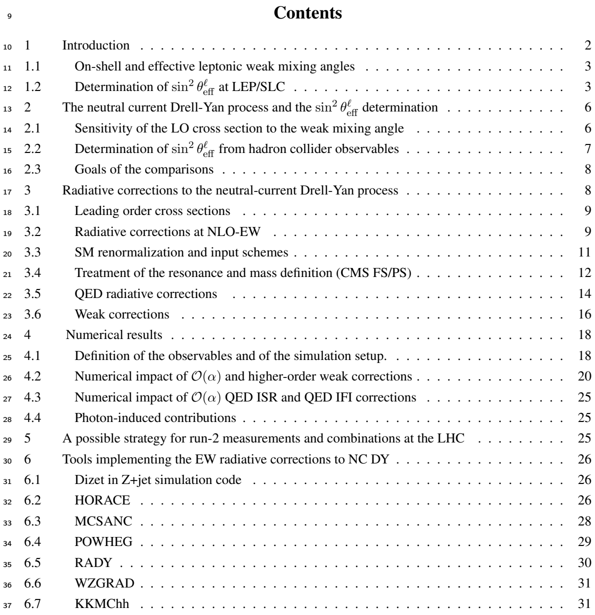
S. Dittmaier, A. Huss, J. Schwarz, arXiv:2401.15682

Uncertainties from scale variations in QED LL FSR



S. Dittmaier, A. Huss, J. Schwarz, arXiv:2401.15682

Draft on overleaf (by A. Vicini from previous version)



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Plans

- in the near future
    - finalize the draft
        - few benchmark numbers missing
        - import last version of tables for benchmark numbers
        - include a more extended description from each code
        - work on section description

Plans

- in the near future
    - finalize the draft
        - few benchmark numbers missing
        - import last version of tables for benchmark numbers
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        - work on section description

- in the future (a proposal)
    - focus on NNLO mixed $\mathcal{O}(\alpha\alpha_s)$ corrections
    - comparison between factorized $O(\alpha\alpha_s)$ corrections contained in evt. generators and the available exact calculation in pole approximation

      S. Dittmaier, A. Huss, J. Schwarz, arXiv:2401.15682
    - comparison between $O(\alpha\alpha_s)$ corrections in PA and the exact calculation

      T. Armadillo et al., arXiv:2201.01754

      R. Bonciani et al., arXiv:2106.11953