The EW (weak) corrections for DY Z->ll comparing/benchmarking:

Powheg_ew; wt^{EW} (IBA approach); MCSANC; DYTURBO

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with contributions from F. Piccinini (Powheg_ew),

S. Bondarenko&L.Kalinovskaya (MCSANC), A. Armbruster (DYTURBO)

- **Strategy for comparison**
- **EW schemes**
- **Results: EW LO, NLO, NLO+HO**

Some slides repeated from „LHCC Precision WG meeting", 25.09.2018

Strategy for comparison: be pragmatic

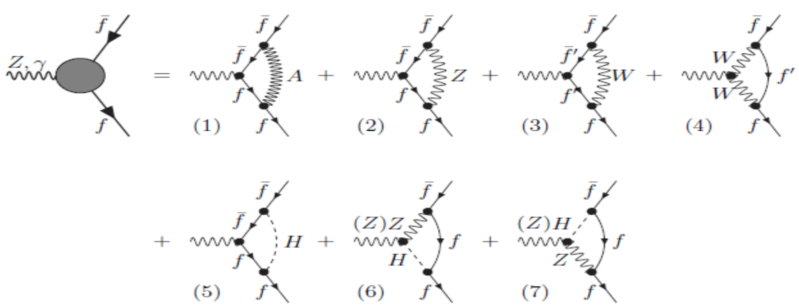
- **Scope:**
  - Genuine EW and lineshape corrections to Drell-Yan production at NLO QCD.
  - Three EW LO schemes chosen to allow for straightforward interpretation of results. We tuned EW LO parameters, otherwise out-of-the-box.
  - The highest available corrections in a given approach used.
  - QED FRS/ISR not included here.
- **Observables:**
  - Lineshape (cross-section) and forward-backward asymmetry A_{FB} in the full phase-space.
  - Compared ratios or absolute differences between different EW LO schemes and/or between NLO, NLO+HO predictions within each EW scheme and same MC generator. Allows to minimize sensitivity to QCD details.
- **Goals:**
  - Check if reweighting with wt^{EW} (TauSpinner) works for NLO QCD MC's. Compared distributions at EW LO (DYTURBO, Powheg_ew).
  - Establish how consistent are predictions between different EW schemes with EW NLO corrections (Powheg_ew, MCSANC).
  - Establish how consistent are EW NLO+HO corrections of Dizet 6.21 form-factors implemented in wt^{EW} and those of Powheg_ew.

Genuine EW and lineshape corrections

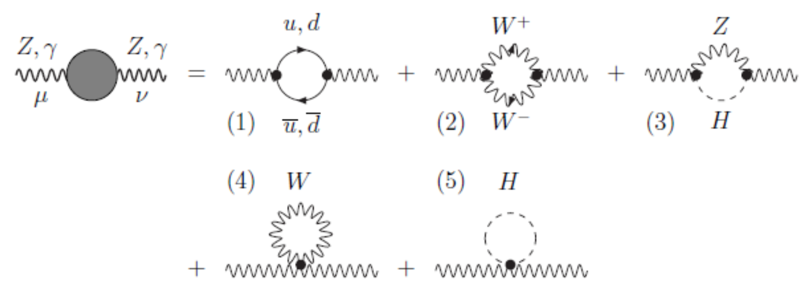
Gauge-invariant set of diagrams.

For Improved Born Approximation (IBA) approach calculated as form-factor corrections to couplings, propagators and masses.

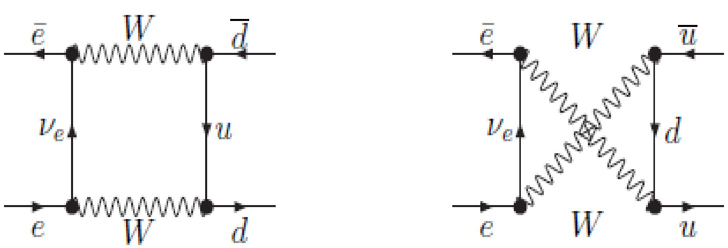
Zff and γ ff vertices



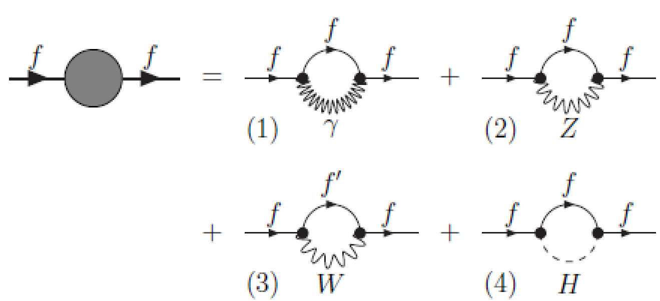
Bosonic self-energies



WW, ZZ boxes **(shown only WW diagrams)**



Fermionic self-energies



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What we have so far .....

PowhegZj: QCD NLO for Z+j
wt^{EW} : TauSpinner + Dizet 6.21

wt^{EW}

EW LO

- $\alpha(0)$ v0: LO, NLO+HO
- $\alpha(0)$ v1: LO
- G_μ: LO

Powheg_ew: QCD LO for Z

- $\alpha(0)$ v0: LO
- $\alpha(0)$ v1: LO, NLO, NLO+HO
- G_μ: LO, NLO, NLO+HO

DYTURBO: QCD LO, NLO for Z

- $\alpha(0)$ 0: LO
- $\alpha(0)$ v1: LO
- G_μ : LO

MCSANC: QCD LO for Z

- $\alpha(0)$ v1: LO, NLO
- G_μ: LO, NLO

EW corrections with event weight wt^{EW}

Reweighting possible because of Drell-Yan factorisation properties, Mirkes et al. arXiv:9406381.

Method follows technique developed for TauSpinner program (for LHC!), arXiv:1201.0117; arXiv1802.05459

Define per event electroweak weight $wt^{EW} = \sigma^{new}_{Born}/\sigma^{old}_{Born}$

$$wt^{EW} = \frac{d\sigma_{Born+EW}(x_1, x_2, \hat{s}, \cos\theta \;, s_W^2)}{d\sigma_{Born}(x_1, x_2, \hat{s}, \cos\theta \;, s_W^2)}$$

$$d\sigma_{Born}(x_1, x_2, \hat{s}, \cos\theta^*, s_W^2) = \sum_{q_f, \bar{q}_f} [f^{q_f}(x_1, ...) f^{\bar{q}_f}(x_2, ...) d\sigma^{q_f \bar{q}_f}_{Born}(\hat{s}, \cos\theta \;, s_W^2) + f^{q_f}(x_2, ...) f^{\bar{q}_f}(x_1, ...) d\sigma^{\bar{q}_f q_f}_{Born}(\hat{s}, -\cos\theta \;, s_w^2]$$

x_1, x_2, $\cos\theta$ (symmetrised) calculated using 4-momenta of outgoing leptons; asymmetry in sign of $\cos\theta$ from weighted average over PDFs

Allows to reweight MC event generated between different EW LO scheme and to Improved Born Approximation in EW scheme used for form-factors calculation. See more in arXiv:1808.08616

Spin amplitude: EW Improved Born (IBA)

$$\mathscr{A}^{Born+EW} = \frac{\alpha}{s}\{ \quad [\bar{u}\gamma^\mu v g_{\mu\nu}\bar{v}\gamma^\nu u]\cdot(q_\ell \cdot q_f)\cdot \boxed{\Gamma_{V_\Pi}} \cdot \chi_\gamma(s)$$
$$+[\bar{u}\gamma^\mu v g_{\mu\nu}\bar{v}\gamma^\nu u\cdot(v_\ell\cdot v_f\cdot vv_{\ell f}) + \bar{u}\gamma^\mu v g_{\mu\nu}\bar{v}\gamma^\nu\gamma^5 u\cdot(v_\ell\cdot a_f)$$
$$+\bar{u}\gamma^\mu\gamma^5 v g_{\mu\nu}\bar{v}\gamma^\nu u\cdot(a_\ell\cdot v_f) + \bar{u}\gamma^\mu\gamma^5 v g_{\mu\nu}\bar{v}\gamma^\nu\gamma^5 u\cdot(a_\ell\cdot a_f)]\cdot \boxed{Z_{V_\Pi}} \cdot \chi_Z(s) \quad \}$$

$$\chi_\gamma(s) = 1$$

$$\chi_Z(s) = \frac{G_\mu \cdot M_z^2 \cdot \Delta^2}{\sqrt{2}\cdot 8\pi\cdot\alpha}\cdot\frac{s}{s - M_Z^2 + i\cdot\Gamma_Z\cdot M_Z}$$

$$v_\ell = (2\cdot T_3^\ell - 4\cdot q_\ell \cdot s_W^2 \cdot \boxed{K_\ell(s,t)})/\Delta$$
$$v_f = (2\cdot T_3^f - 4\cdot q_f \cdot s_W^2 \cdot \boxed{K_f(s,t)})/\Delta$$
$$a_\ell = (2\cdot T_3^\ell)/\Delta$$
$$a_f = (2\cdot T_3^f)/\Delta$$

$$\Delta = \sqrt{16\cdot s_W^2\cdot(1-s_W^2)}$$

$$\boxed{Z_{V_\Pi}} = \rho_{e,f}(s,t)$$

EW form-factors , functions of (s,t)=(m_{ll}, cosθ)
Calculated with Dizet 6.21 library.

$$\boxed{\Gamma_{V_\Pi}} = \frac{1}{2-(1+\boxed{\Pi_{\gamma\gamma}(s)})}$$

Vacuum polarisation corrections, used low-energy experiment input.
Warning: problem for analytic continuation.

$$vv_{\ell f} = \frac{1}{v_\ell\cdot v_f}[(2\cdot T_3^\ell)(2\cdot T_3^f) - 4\cdot q_\ell\cdot s_W^2\cdot\boxed{K_f(s,t)}(2\cdot T_3^\ell) - 4\cdot q_f\cdot s_W^2\cdot\boxed{K_\ell(s,t)}(2\cdot T_3^f)$$
$$+(4\cdot q_\ell\cdot s_W^2)(4\cdot q_f\cdot s_W^2\,\boxed{K_{\ell f}(s,t)}]\frac{1}{\Delta^2}$$

EW LO schemes

SM fundamental relation used to calculate EW parameters in different EW LO schemes, on-mass-shell definition.

EW scheme:	G_μ, α, M_Z	α, M_W, M_Z	G_μ, M_W, M_Z
Parameter	α(0) v0	α(0) v1	Gμ
M_Z	91.1876 GeV	91.1876 GeV	91.1876 GeV
Γ_Z	2.4952 GeV	2.4952 GeV	2.4952 GeV
Γ_W	2.085 GeV	2.085 GeV	2.085 GeV
α	1/137.03599	1/137.03599	1/132.23323
G_μ	$1.1663787 \cdot 10^{-5}$ GeV^{-2}	$1.1254734 \cdot 10^{-5}$ GeV^{-2}	$1.1663787 \cdot 10^{-5}$ GeV^{-2}
M_W	80.93886 GeV	80.385 GeV	80.385 GeV
s_W^2	0.2121517	0.2228972	0.2228972
$\frac{G_\mu \cdot M_Z^2 \cdot \Delta^2}{\sqrt{2} \cdot 8\pi \cdot \alpha}$	1.0	1.0	1.0

PowhegZj
91.1876 GeV
2.4952 GeV
2.085 GeV
1/128.88859
$1.16638 \cdot 10^{-5}$ GeV^{-2}
79.958 GeV
0.2311300
1.0

MC events used for reweighting

$$s_W^2 = 1 - m_W^2/m_Z^2$$

$$G_\mu = \frac{\pi\alpha}{\sqrt{2} M_W^2 s_W^2}$$

EW schemes: α(0) v0, α(0) v1 – same value of α
G_μ, α(0) v1 – same value of s^2w

EW LO schemes: pros and cons

- **EW scheme $\alpha(0)$ v0: input $\alpha(0)$, M_Z, $G\mu$**
  - **Pros:**
    - Precisely measured physics input, LEP legacy EW scheme
  - **Cons:**
    - Moderate NLO and HO corrections (few %) calculated theoretically or taken from low-energy measurements ($\alpha_{had}^{(5)}$)
- **EW scheme $\alpha(0)$ v1: input $\alpha(0)$, M_Z, M_W**
  - **Pros:**
    - Moderate NLO corrections (few %), small HO corrections (<1%)
  - **Cons:**
    - Input M_W with ±15 MeV uncertainties, requires shifting G_μ far from its measuremed value.
- **EW scheme G_μ: input G_μ, M_Z, M_W**
  - **Pros:**
    - Small NLO (1%) and very small HO (0.2%) corrections
  - **Cons:**
    - Input M_W with ±15 MeV uncertainties, requires two definitions for em coupling: $\alpha(0)$ for ISR/FSR/IFI and $\alpha_{G\mu}$ for matrix elements.

Goal is to see level of agreement between predictions calculated in three EW schemes, after including EW NLO+HO corrections?

EW LO schemes: details

EW schemes: come with „on-shell” or „pole” definitions!

Table 44: The EW parameters used at tree-level EW, with on-mass-shell definition (LEP convention).

Parameter	$\alpha(0)$ v0	$\alpha(0)$ v1	G_μ
M_Z	91.1876 GeV	91.1876 GeV	91.1876 GeV
Γ_Z	2.4952 GeV	2.4952 GeV	2.4952 GeV
Γ_W	2.085 GeV	2.085 GeV	2.085 GeV
α	1/137.03599	1/137.03599	1/132.23323
G_μ	$1.1663787 \cdot 10^{-5}$ GeV^{-2}	$1.1254734 \cdot 10^{-5}$ GeV^{-2}	$1.1663787 \cdot 10^{-5}$ GeV^{-2}
M_W	80.93886 GeV	80.385 GeV	80.385 GeV
s_W^2	0.2121517	0.2228972	0.2228972
$\frac{G_\mu \cdot M_z^2 \cdot \Delta^2}{\sqrt{2} \cdot 8\pi \cdot \alpha}$	1.0	1.0	1.0

Table 45: The EW parameters used at tree-level EW, with pole definition of the Z, W masses.

Parameter	$\alpha(0)$ v0	$\alpha(0)$ v1	G_μ
M_Z	91.15348 GeV	91.15348 GeV	91.15348 GeV
Γ_Z	2.494266 GeV	2.494266	2.494266 GeV
Γ_W	2.085 GeV	2.085 GeV	2.085 GeV
α	1/137.03599	1/137.03599	1/132.3572336357709
G_μ	$1.1663787 \cdot 10^{-5}$ GeV^{-2}	$1.126555497 \cdot 10^{-5}$ GeV^{-2}	$1.1663787 \cdot 10^{-5}$ GeV^{-2}
M_W	80.91191 GeV	80.35797 GeV	80.35797 GeV
s_W^2	0.21208680	0.22283820939	0.22283820939
$\frac{G_\mu \cdot M_z^2 \cdot \Delta^2}{\sqrt{2} \cdot 8\pi \cdot \alpha}$	1.0	1.0	1.0

Shift:

- **-30 MeV for M_Z**
- **-0.00005 for s^2w**

Scaling

- **0.99906 for α**

EW LO schemes: details

Running and fixed Z-boson width in the propagator: taking into account photon-loop corrections to Γ_Z

- **Fixed width** $$\chi_Z(s) = \frac{1}{s - M_Z^2 + i \cdot \Gamma_Z \cdot M_Z}.$$

- **Running width (LEP legacy)**

$$\chi_Z'(s) = \frac{1}{s - M_Z^2 + i \cdot \Gamma_Z \cdot s/M_Z}$$

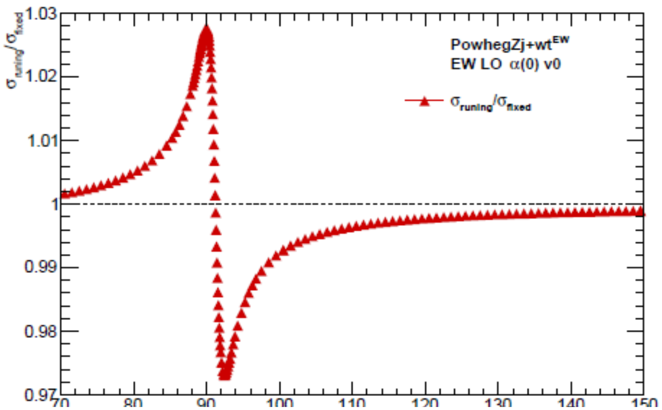
$$\begin{aligned}
\chi_Z'(s) &= \frac{1}{s(1 + i \cdot \Gamma_Z/M_Z) - M_Z^2} \\
&= \frac{(1 - i \cdot \Gamma_Z/M_Z)}{s(1 + \Gamma_Z^2/M_Z^2) - M_Z^2(1 - i \cdot \Gamma_Z/M_Z)} \\
&= \frac{(1 - i \cdot \Gamma_Z/M_Z)}{(1 + \Gamma_Z^2/M_Z^2)} \frac{1}{s - \frac{M_Z^2}{1+\Gamma_Z^2/M_Z^2} + i \cdot \frac{\Gamma_Z M_Z}{1+\Gamma_Z^2/M_Z^2}} \\
&= N_Z \frac{1}{s - M_Z'^{\,2} + i\Gamma_Z' M_Z'} \\
M_Z' &= \frac{M_Z}{\sqrt{1 + \Gamma_Z^2/M_Z^2}} \\
\Gamma_Z' &= \frac{\Gamma_Z}{\sqrt{1 + \Gamma_Z^2/M_Z^2}} \\
N_Z &= \frac{(1 - i \cdot \Gamma_Z/M_Z)}{(1 + \Gamma_Z^2/M_Z^2)} = \frac{(1 - i \cdot \Gamma_Z'/M_Z')}{(1 + \Gamma_Z'^{\,2}/M_Z'^{\,2})}
\end{aligned}$$

Both equivalent if redefined parameters m_Z, Γ_Z, N_Z (normalization). Change in the normalisation can (?) be absorbed into G_μ redefinition. In case of „pole” convention (last slide) it was absorbed into α.

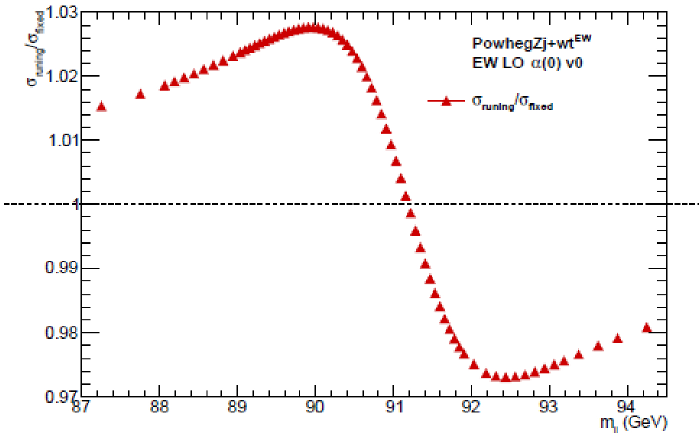
EW LO schemes: details

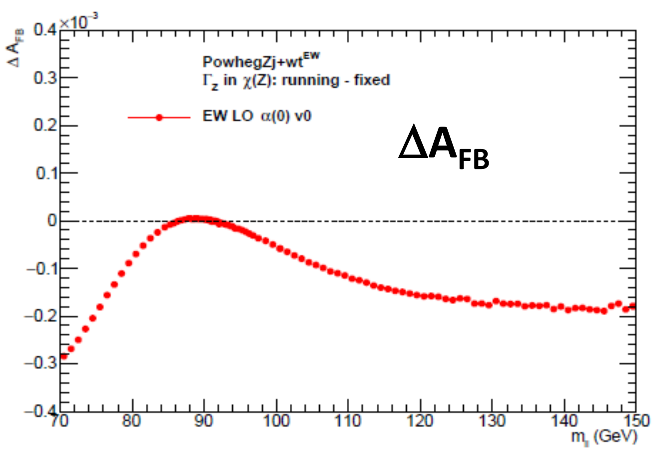
Nowdays MC's are using fixed-width propagators with on-shell $M_Z = 91.1876$.
How does it affect predictions, if running-> fixed without reparametrizing?
ΔA_{FB} (m_{ll}=80-100 GeV) = 0.0005 (thanks to D. Walker for pointing it out)

Lineshape: ratio

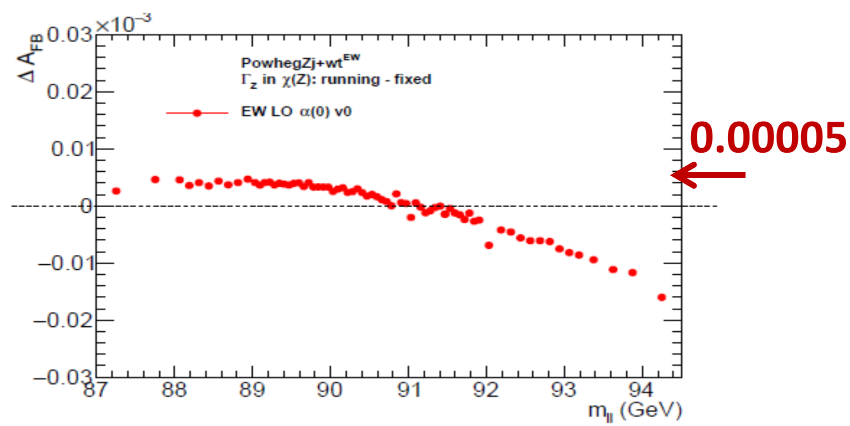


zoom →





zoom →

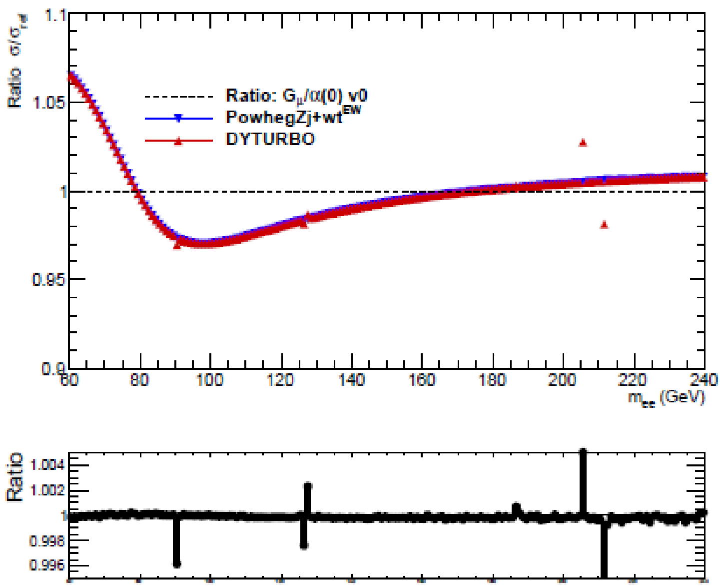


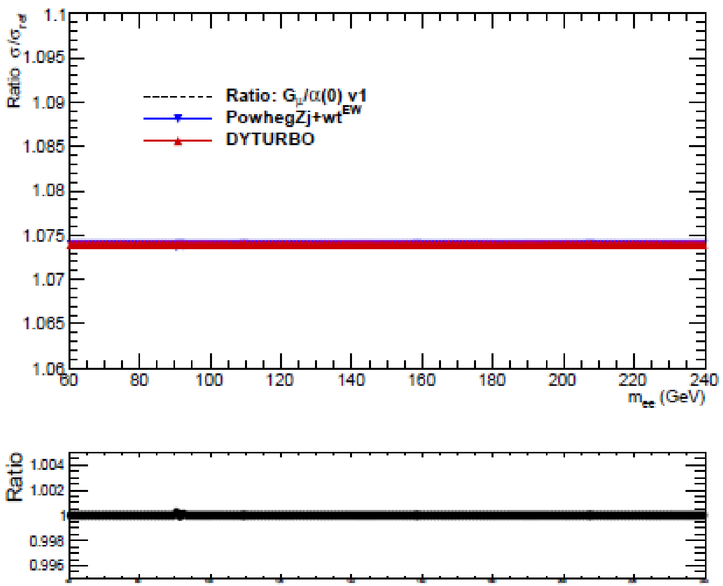
Validating reweighting with wt^{EW}: EW LO

- **Ratio of differential cross-sections (lineshapes) driven by relative balance between Z and γ contributions.**
- **EW $\alpha(0)$ v1 and G_μ schemes chosen as such that ratio of cross-sections is equal to ratio of QED couplings squared.**

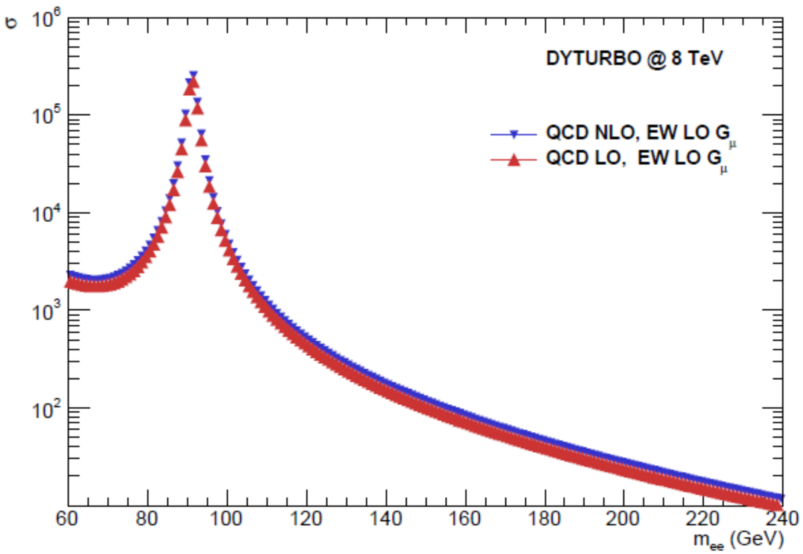
σ/σ_{ref}

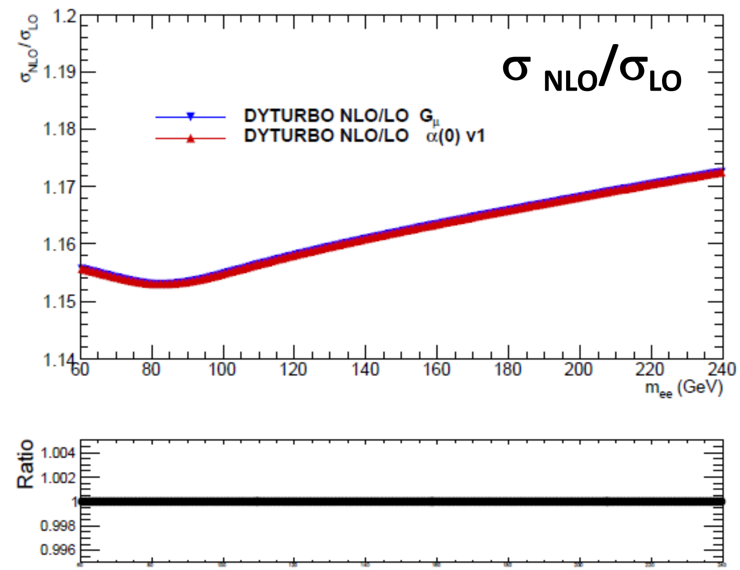
Benchmark for wt^{EW} reweighting

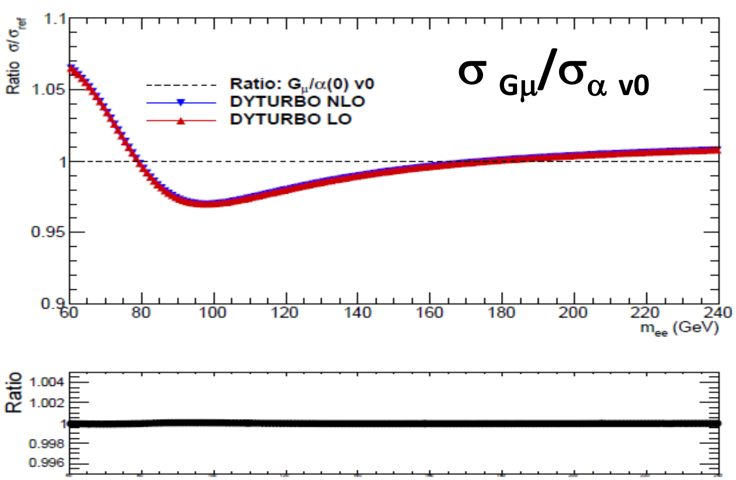


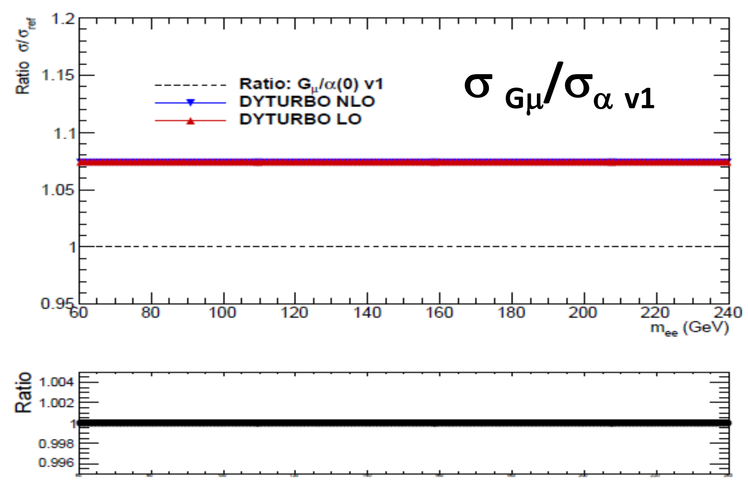


DYTURBO: QCD LO, NLO; EW LO



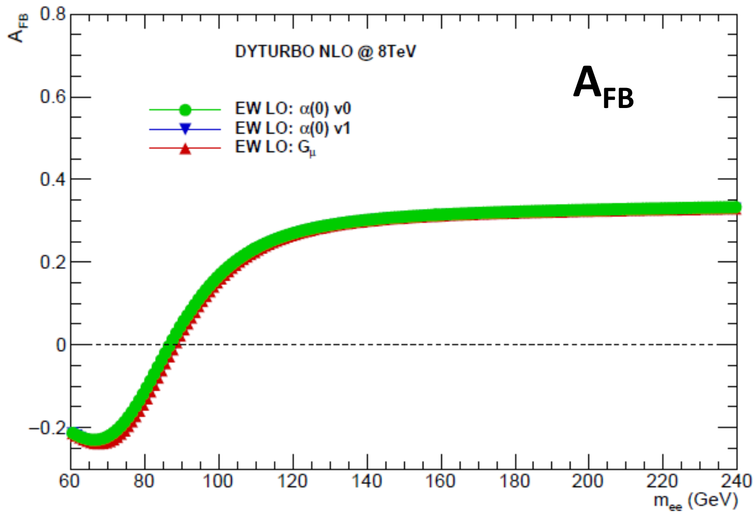




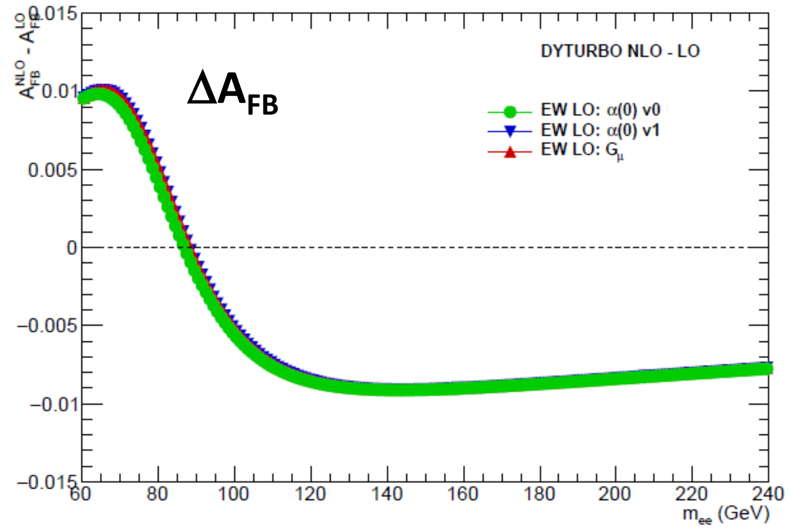


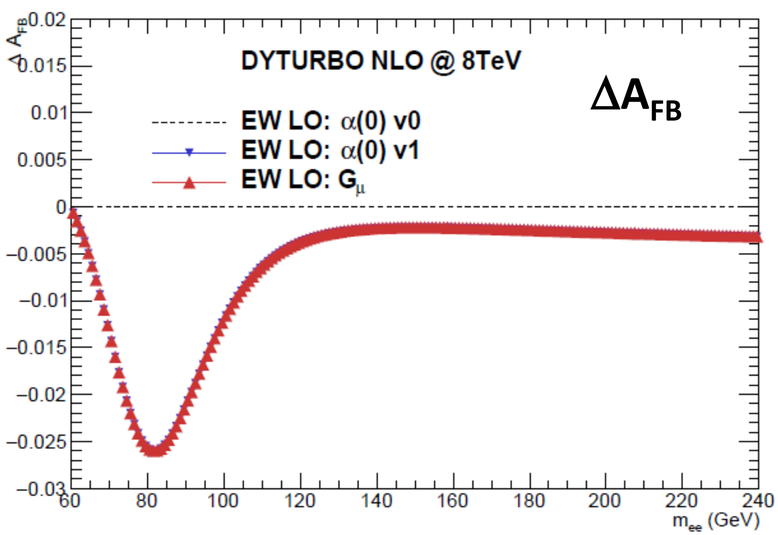
DYTURBO: QCD LO, NLO

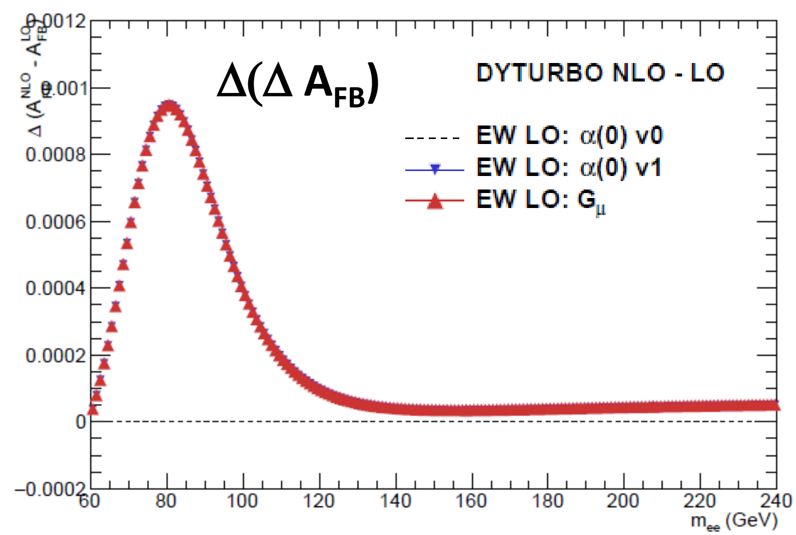
QCD NLO



QCD NLO – LO



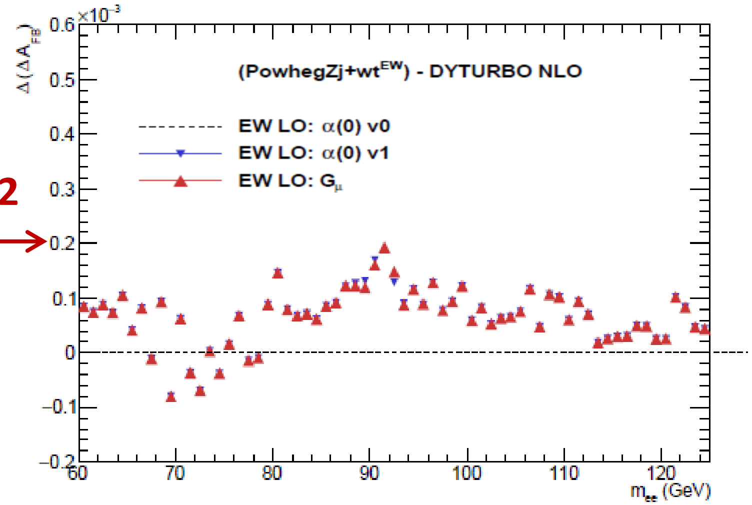




Validating reweighting with wt^{EW}: EW LO

ΔA_{FB}: driven by s^2_W value (same for $\alpha(0)$ v1 and G_μ schemes)

0.0002



Benchmark for wt^{EW} reweighting

Double difference:

ΔA_{FB} (DYTURBO) - ΔA_{FB} (PowhegZj+wt^{EW})

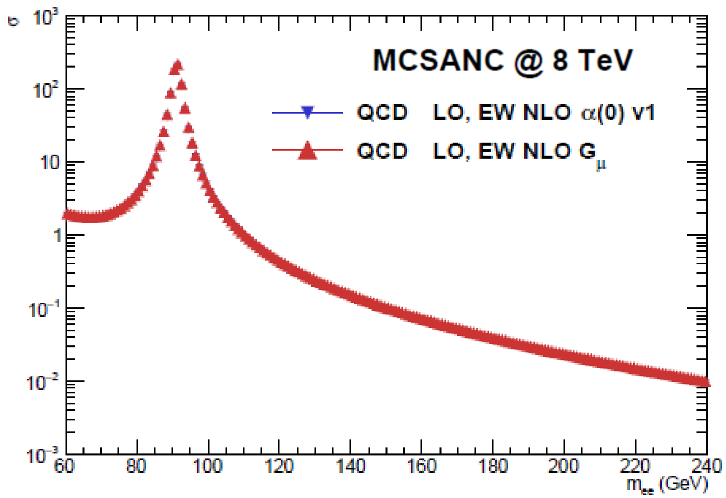
$\alpha(0)$ v1 - $\alpha(0)$ v0

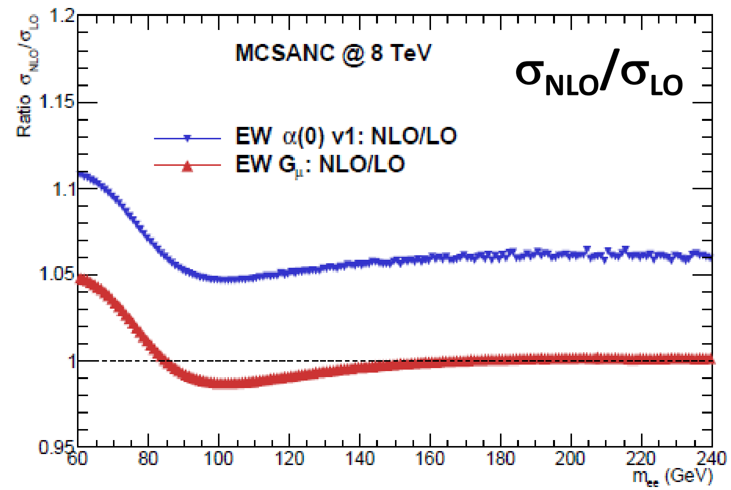
G_μ - $\alpha(0)$ v0

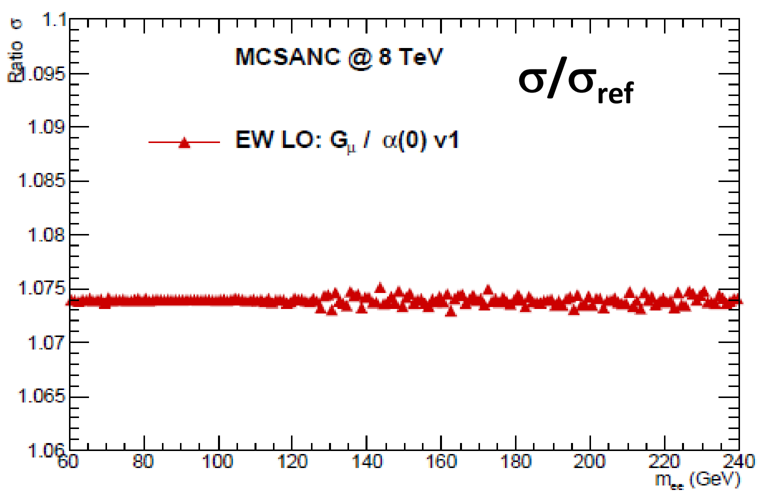
Agreement on $\Delta(\Delta A_{FB})$ within ± 0.0002

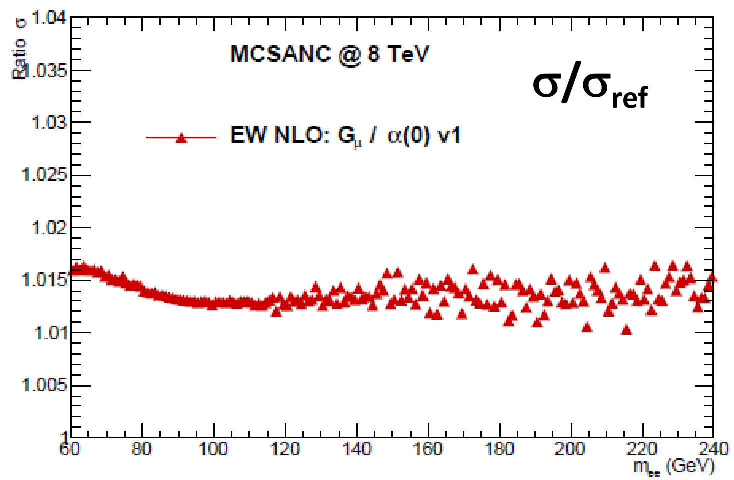
Should redo it with much finer binning around Z-pole to better estimate precision.

MCSANC: QCD LO; EW LO, NLO

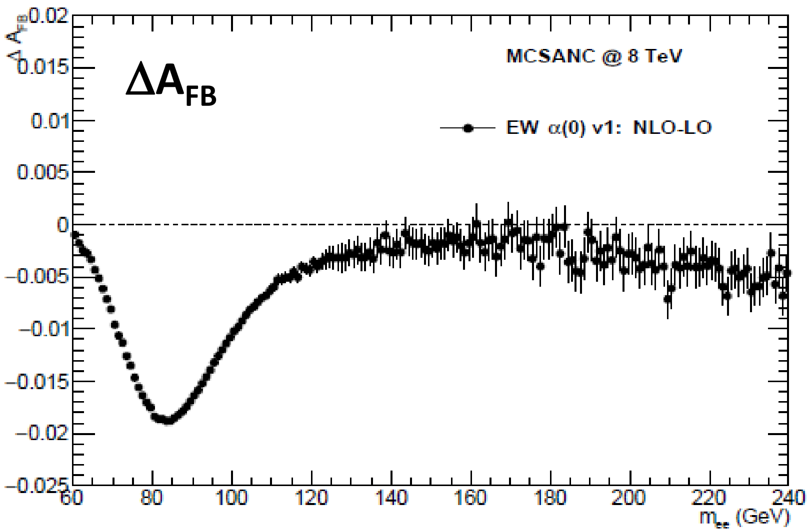


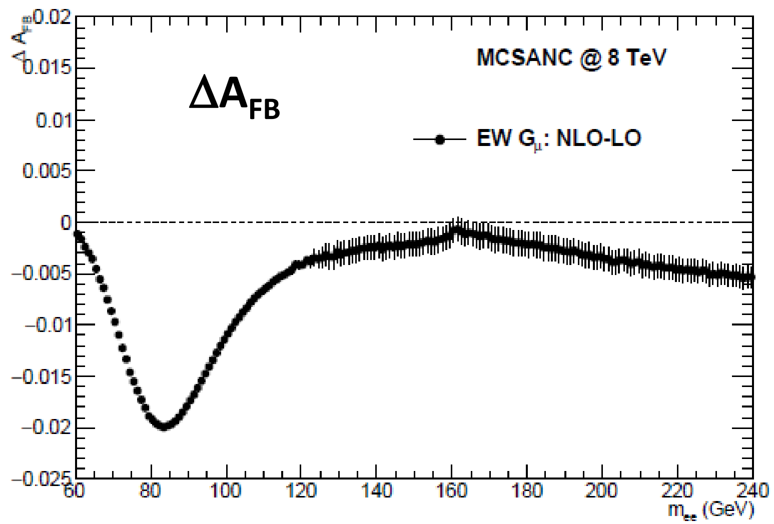


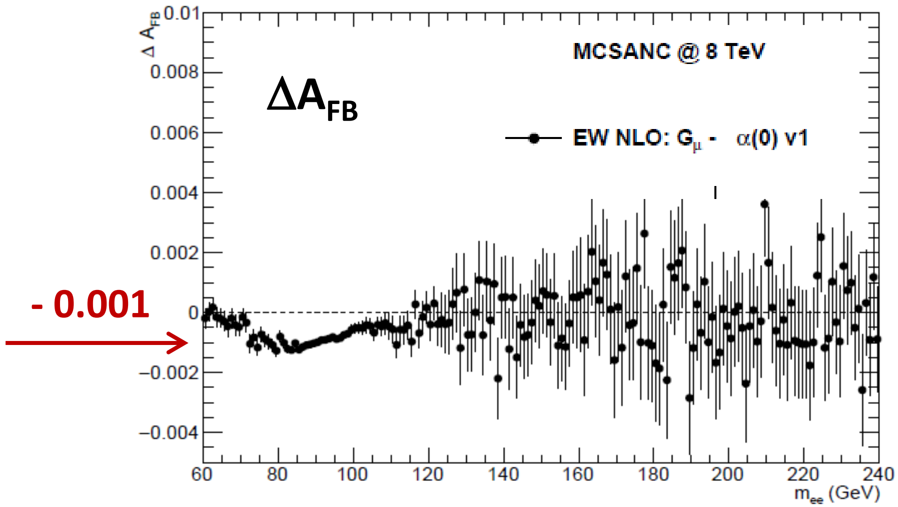




MCSANC: QCD LO, EW LO, NLO



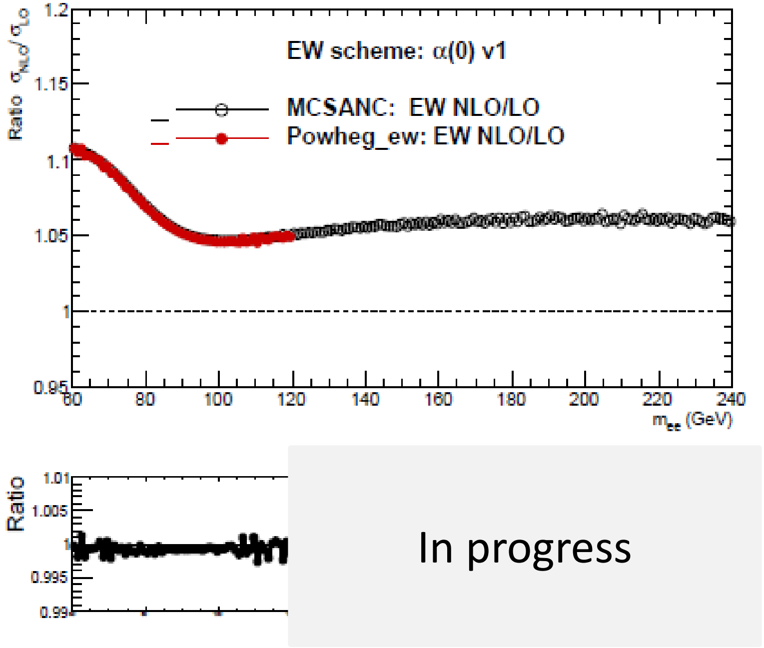


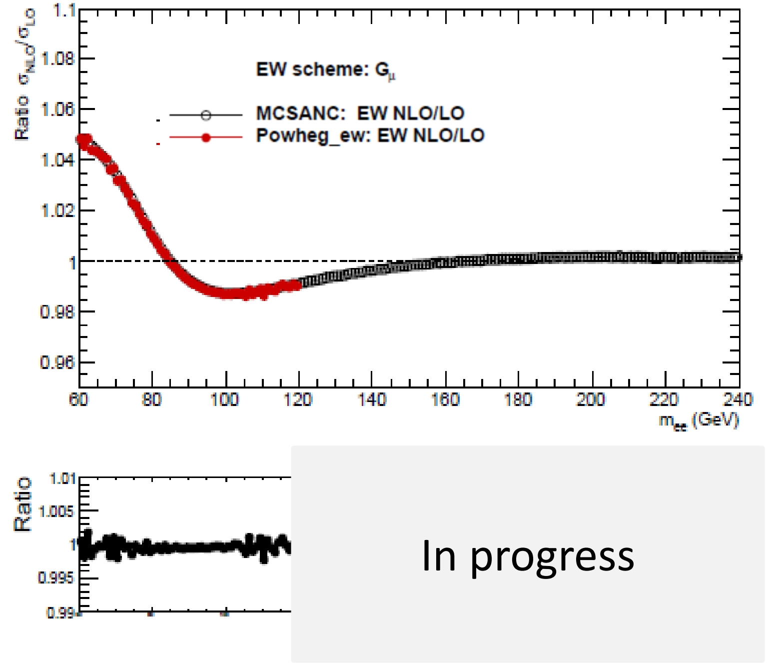


EW NLO not enough for precise s^2w measurement. Needed EW HO corrections.

MCSANC and Powheg_ew: EW LO, NLO

- **Comparing ratio of cross-sections**

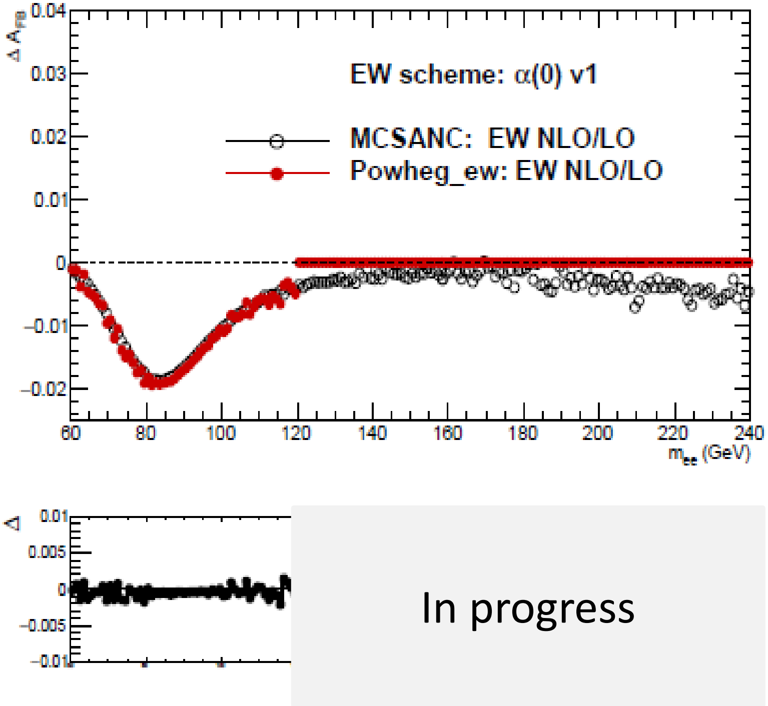


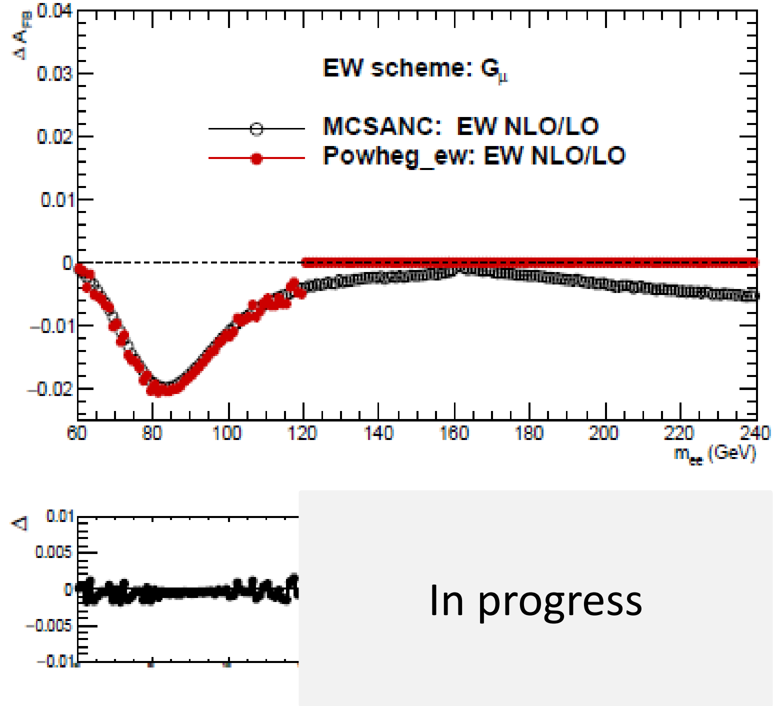


Very good agreement for EW NLO/LO corrections, shown for two EW schemes.

MCSANC and Powheg_ew: EW LO, NLO

- **Comparing ΔA_{FB}**

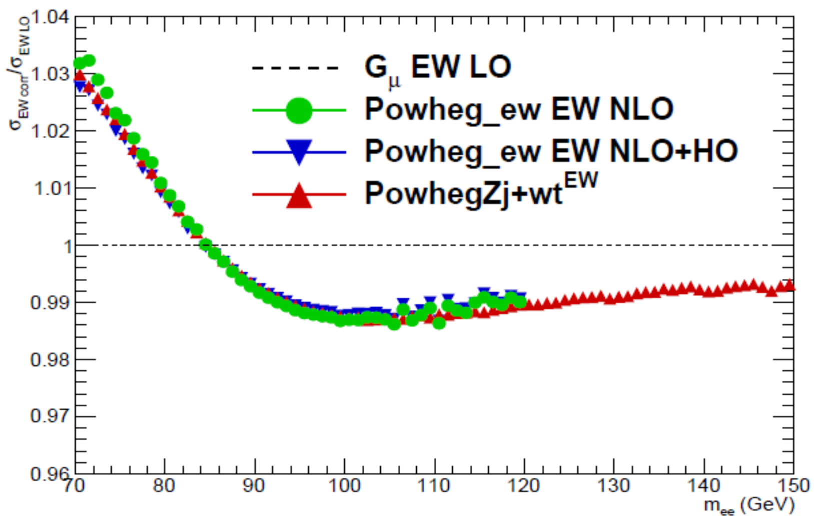


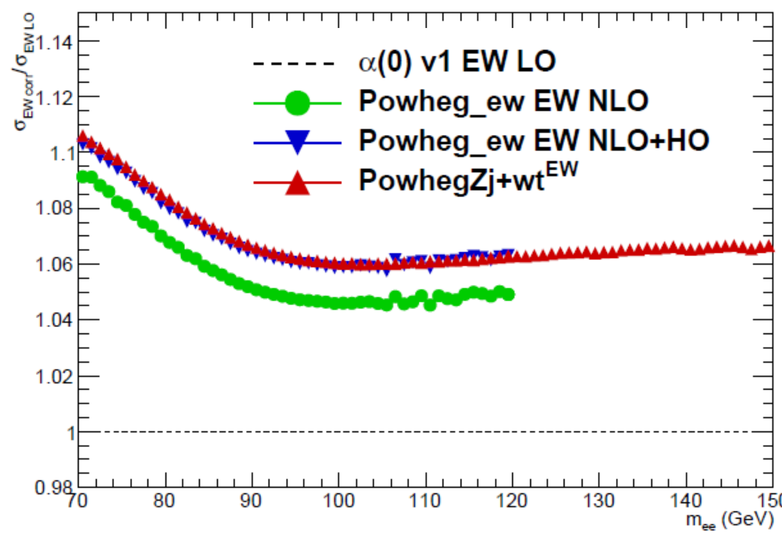


Very good agreement for EW NLO/LO corrections, shown.

Beyond EW LO: xsection NLO+HO

Slide from 25.09.2018





Powheg_ew

	EW order	m_{ee} = 89 - 93 GeV
$\alpha(0)$ v1	NLO/LO	1.050350
G_μ	NLO/LO	0.991230
$\alpha(0)$ v1	NLO+HO/LO	1.063247
G_μ	NLO+HO/LO	0.991038

	EW order	m_{ee} = 89 - 93 GeV
Powheg_ew	NLO+HO/LO	
$\alpha(0)$ v1		1.06325
G_μ		0.99104
PowhegZj+wt^{EW}	NLO+HO/LO	
$\alpha(0)$ v0		0.96452
$\alpha(0)$ v1		1.06506
G_μ		0.99167

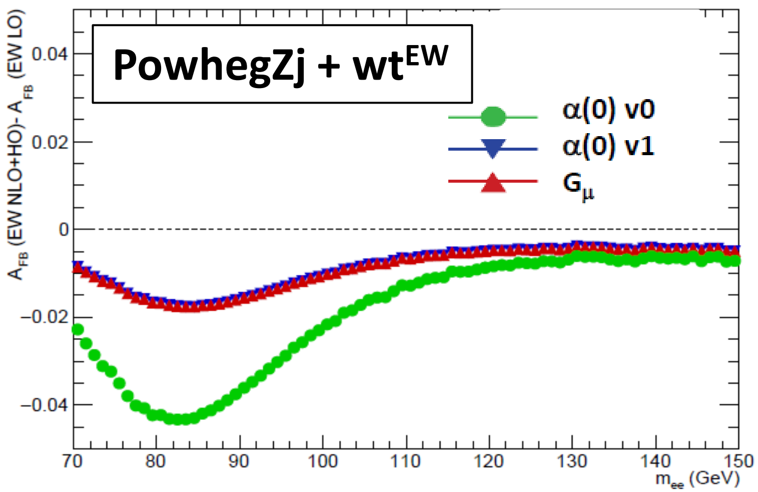
In G_μ scheme, NLO corrections < 1%
HO corrections < 0.02%

Beyond EW LO: A_{FB} NLO+HO

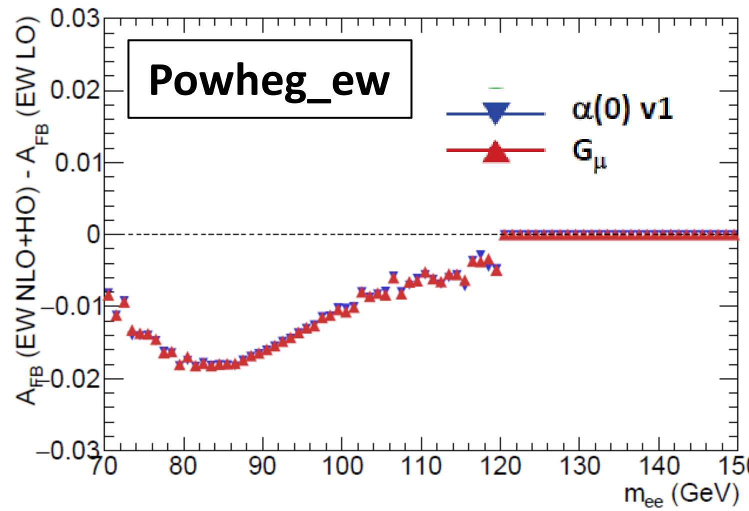
- **Comparing Powheg_ew and PowhegZj+wt^{EW}**

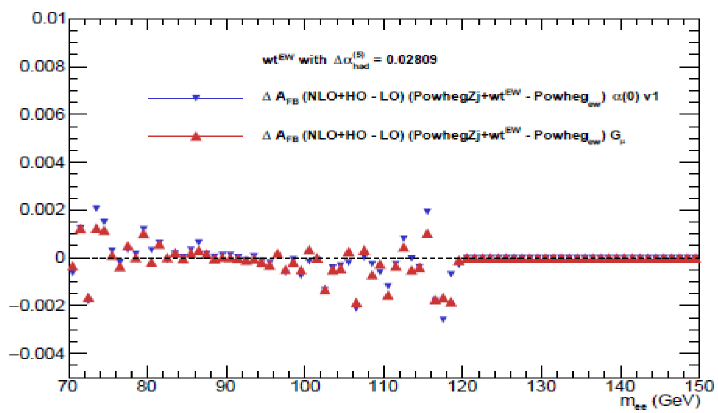
Slide from 25.09.2018

$A_{FB\ NLO+HO} - A_{FB\ LO}$



$A_{FB\ NLO+HO} - A_{FB\ LO}$





Δ A_{FB} (NLO+HO - LO) (Powheg$_{ew}$ - PowhegZj+wt^{EW}) α(0) v1

Δ A_{FB} (NLO+HO - LO) (Powheg$_{ew}$ - PowhegZj+wt^{EW}) G_μ

Excelent agreement on ΔA_{FB}!
Is it accidental?
More discussion (25.09.2018) and in SPARES slides.

Powheg_ew: EW LO, NLO, NLO+HO

Cross-section

From slides 25.09.2018

	EW order	m_{ee} = 89 - 93 GeV	m_{ee} = 80 - 100 GeV	m_{ee} = 70 - 120 GeV
$\alpha(0)$ v0	LO	630.848722	906.156051	959.658977
$\alpha(0)$ v1	LO	571.411296	821.363274	870.729908
G_μ	LO	612.514433	880.446121	933.363827
$\alpha(0)$ v1	NLO	600.185042	863.142557	915.580114
G_μ	NLO	607.142292	873.173294	926.253246
$\alpha(0)$ v1	NLO+HO	607.551746	873.717147	926.761229
G_μ	NLO+HO	607.515354	873.655348	926.681425
$\alpha(0)$ v1	NLO/LO	1.050350	1.05087	1.05151
G_μ	NLO/LO	0.991230	0.99174	0.99238
$\alpha(0)$ v1	NLO+HO/LO	1.063247	1.063740	1.064349
G_μ	NLO+HO/LO	0.991038	0.992287	0.992840
$\alpha(0)$ v1 / $\alpha(0)$ v0	LO	0.90578	0.906426	0.90733
G_μ / $\alpha(0)$ v1	LO	1.07193	1.07193	1.07193
G_μ / $\alpha(0)$ v1	NLO	1.01159	1.01162	1.01166
G_μ / $\alpha(0)$ v1	NLO+HO	0.99994	0.99993	0.99991
G_μ / $\alpha(0)$ v0	LO	0.97094	0.97163	0.97260

σ (pb)

σ_{NLO}/σ_{LO}

$\sigma_{NLO+HO}/\sigma_{LO}$

Ratios between EW schemes LO, NLO, NLO+HO

Better than 0.01% agreement on σ between EW schemes at NLO+HO !

Powheg_ew: EW LO, NLO, NLO+HO

From slides 25.09.2018

	EW order	m_{ee} = 89 - 93 GeV	m_{ee} = 80 - 100 GeV	m_{ee} = 70 - 120 GeV
A_{FB} $\alpha(0)$ v0	LO	0.06691361	0.06392369	0.06253754
A_{FB} $\alpha(0)$ v1	LO	0.04653886	0.04343789	0.04212883
A_{FB} G_μ	LO	0.04653886	0.04343789	0.04212883
A_{FB} $\alpha(0)$ v1	NLO	0.03004289	0.02690785	0.02569858
A_{FB} G_μ	NLO	0.02905841	0.02592168	0.02471918
A_{FB} $\alpha(0)$ v1	NLO+HO	0.03083234	0.02770533	0.02649700
A_{FB} G_μ	NLO+HO	0.03090286	0.02777783	0.02656851
ΔA_{FB} $\alpha(0)$ v1	NLO-LO	-0.0164959	-0.0165300	-0.0164302
ΔA_{FB} G_μ	NLO-LO	-0.0174805	-0.0175162	-0.0174096
ΔA_{FB} $\alpha(0)$ v1	NLO+HO-LO	-0.0157065	-0.0157326	-0.0156318
ΔA_{FB} G_μ	NLO+HO-LO	-0.0156360	-0.0156596	-0.0155603

A_{FB}

ΔA_{FB} (NLO – LO)

ΔA_{FB} (NLO+HO – LO)

ΔA_{FB}	EW order	m_{ee} = 89 - 93 GeV	m_{ee} = 80 - 100 GeV	m_{ee} = 70 - 120 GeV
$\alpha(0)$ v1 - $\alpha(0)$ v0	LO	-0.020375	-0.020486	-0.020487
G_μ - $\alpha(0)$ v0	LO	-0.020375	-0.020486	-0.0204871
G_μ - $\alpha(0)$ v1	LO	0.0	0.0	0.0
G_μ - $\alpha(0)$ v1	NLO	-0.00098	-0.00098	-0.00098
G_μ - $\alpha(0)$ v1	NLO + HO	-0.00007	-0.00007	-0.00007

ΔA_{FB} between EW schemes at LO, NLO, NLO+HO

Better than 0.0001 agreement on A_{FB} between EW schemes at NLO+HO !

Summary

Comparing ratios, double ratios or double-differences turned out to be a very effective strategy. No need (so far) to fine-tune the QCD part of the calculations.

Tests done so far support applicability of IBA approach for Drell-Yan productions around Z-pole at LHC. Implemented in TauSpinner framework using form-factors from Dizet 6.21 library. Documentation: arXiv:1808.08616.

Flexibility to compare different EW schemes in a systematic manner.

Very promising consistency achieved between predictions from:

- **Powheg_ew (EW LO, NLO, NLO+HO)**
- **MCSANC (EW LO, NLO)**
- **DYTURBO (EW LO)**
- **PowhegZj + wt^{EW} from TauSpinner+Dizet (EW LO, NLO+HO)**

Ironning details .....

Adding predictions of NLO+HO type (MCSANC)

Extending m_{ll} range (Powheg_ew)

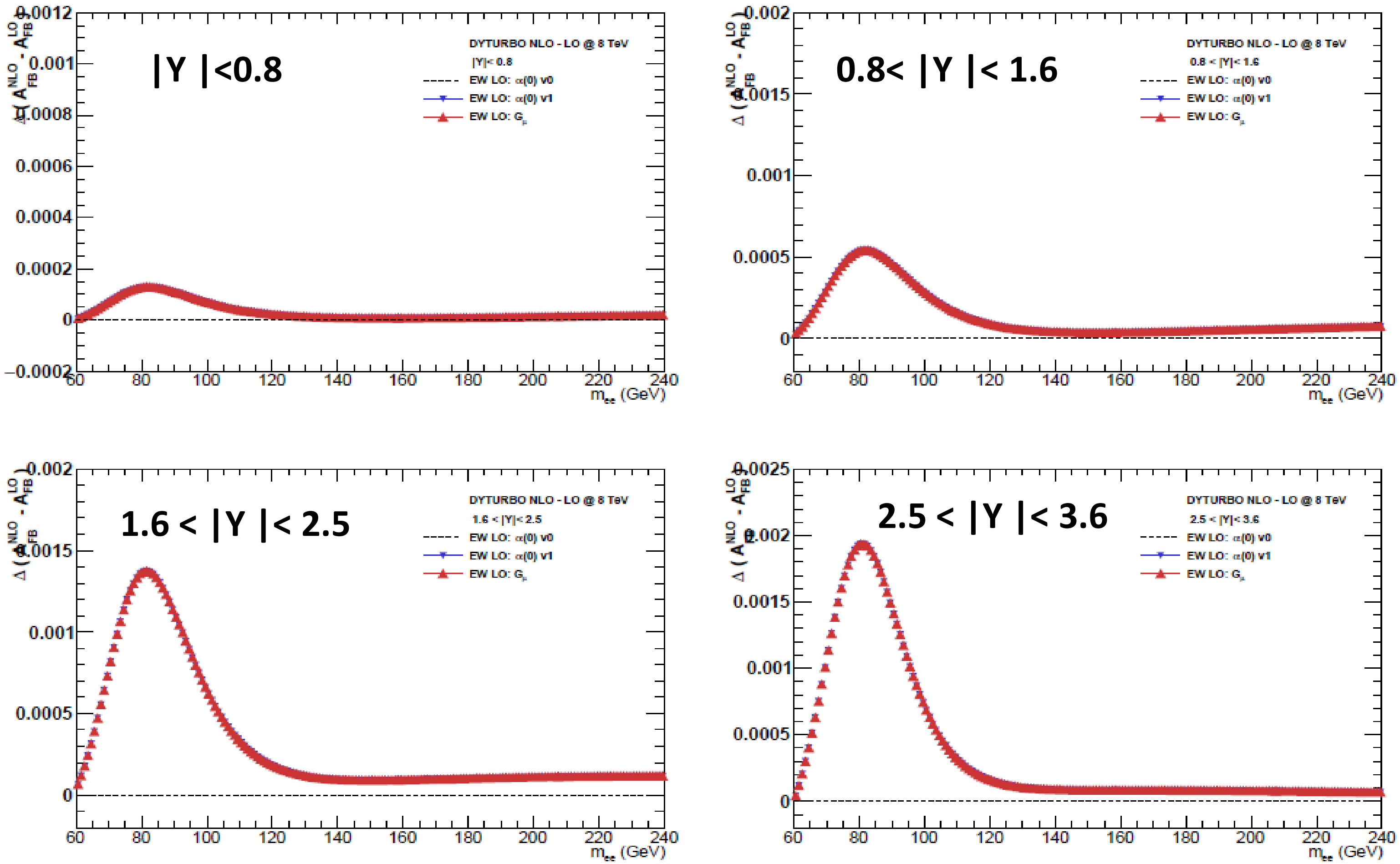
Fine-tunnig wt^{EW} (TauSpinner + Dizet)

Add fiducial selection

SPARES slides

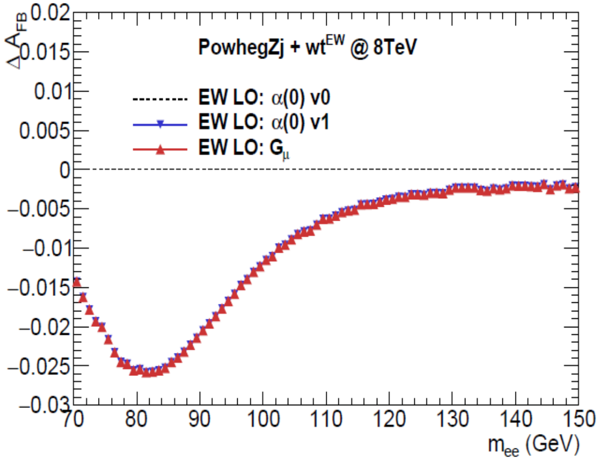
DYTURBO: QCD NLO - LO

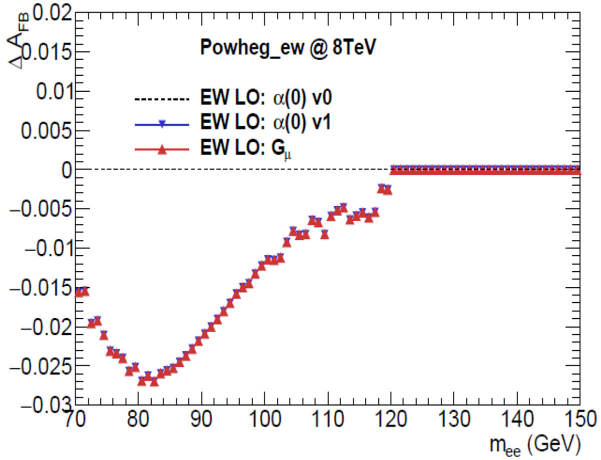
Δ (A_{FB} (NLO) – A_{FB} (LO)) between different EW LO schemes



Validating reweighting wt^{EW} : EW LO

$\Delta\, A_{FB}$: driven by s^2_W value (same for $\alpha(0)$ v1 and G_μ schemes)



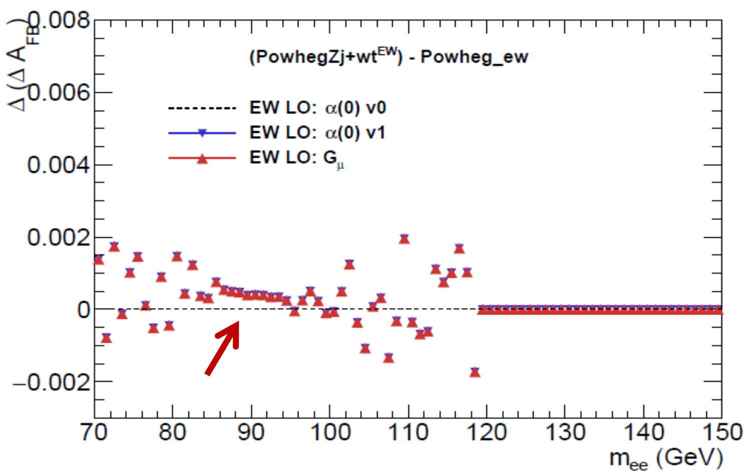


From slides 25.09.2018

$\Delta\, A_{FB} = A_{FB} - A_{FB\ ref}$

$\alpha(0)$ v1 - $\alpha(0)$ v0

G_μ - $\alpha(0)$ v0



Double difference:

ΔA_{FB} (Powheg_ew) - ΔA_{FB} (Powheg+wt^{EW})

$\alpha(0)$ v1 - $\alpha(0)$ v0

G_μ - $\alpha(0)$ v0

Shift of 0.0005 at the Z-pole at EW LO, not precise enough tunning of s2w between „pole" and „on-mass-shell" definitions? Or the limitation of the reweighting with wt^{EW} ?

EW LO schemes in practice

- **SM fundamental relations used to calculate EW parameters in EW LO schemes**

$$G_\mu = \frac{\pi\alpha}{\sqrt{2} M_W^2 s_W^2} \longrightarrow \frac{G_\mu \cdot M_z^2 \cdot \Delta^2}{\sqrt{2} \cdot 8\pi \cdot \alpha} = 1 \qquad \Delta^2 = 16 \cdot s_W^2 \cdot (1 - s_W^2)$$

EW scheme: G_μ, α, M_Z **α(0) v0**	EW scheme: α, M_W, M_Z **α(0) v1**	EW scheme: G_μ, M_W, M_Z **G_μ**
$d2 = \frac{\sqrt{2} \cdot 8\pi \cdot \alpha}{G_\mu \cdot M_z^2}$	$\boxed{s_W^2} = 1 - m_W^2/m_Z^2$	$\boxed{s_W^2} = 1 - m_W^2/m_Z^2$
$\boxed{s_W^2} = (-1 + \sqrt{1 - d2/4})/2$	$c_W^2 = m_W^2/m_Z^2$	$c_W^2 = m_W^2/m_Z^2$
	$g2 = 4 \cdot \pi \cdot \alpha / s_W^2$	$g2 = 8 \cdot G_\mu \cdot m_W^2 / \sqrt{2}$
	$\boxed{G_\mu} = \sqrt{2} \cdot g2/8/m_W^2$	$\boxed{\alpha} = g2 \cdot s_W^2/4/\pi$

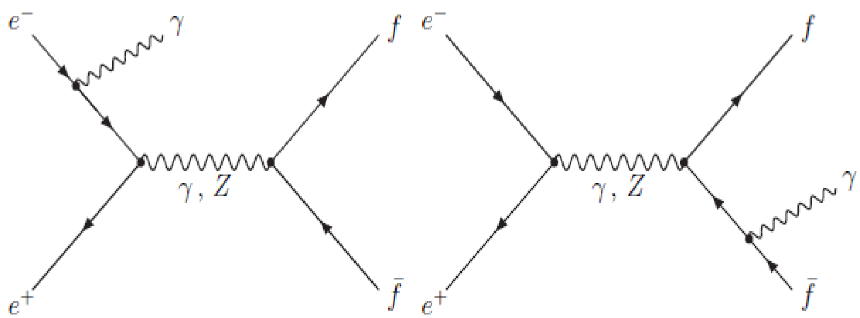
$\boxed{}$ **calculated**

QED (radiative) corrections

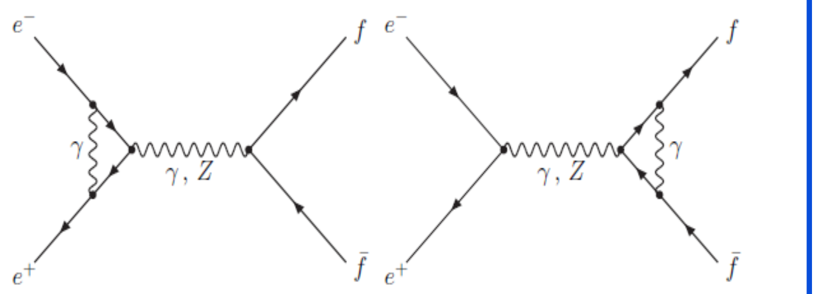
NOT discussed here.

QED FSR can be simulated by PHOTOS implemented as after-burner step on already generated event. QED ISR should be convoluted with QCD ISR. For QED initial/final state interference (see slide 42) and talks by A. Sapronov and S. Yost.

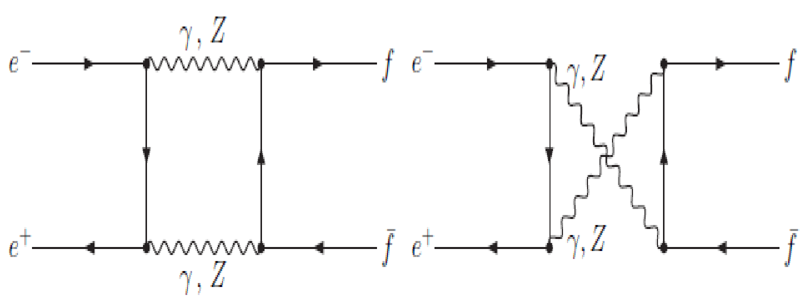
Real emission + pairs creation



Vertex corrections



$\gamma\gamma$ and γZ box diagrams



It is QED gauge-invariant set of diagrams (D. Bardin, hep-ph/9908433) which can be factorised out and/or convoluted with QCD corrections.

Calculated with fixed value of α_{QED}

α_{QED} = 1./137.0359895

Dictionary

EW LO Born (LO = lowest order):
tree-level vertex and propagator of the Z/γ^* bosons, setting of SM EW parameters defines the EW scheme.

EW effective Born:
tree-level vertex and propagator of the Z/γ^* bosons, EW couplings: $\alpha(m_Z)$, $\sin^2\theta_W(m_Z)$, m_Z, set of best measured values.

EW Improved Born Approximation (IBA):
tree-level vertex and propagator of the Z/γ^* bosons, EW couplings and propagators multiplied by form-factors dependent on the scattering angle of the lepton (choice of frame) and virtuality of Z/γ^*.

QED/EW corrections: D. Bardin et al. arXiv:9908433
separate set of „QED corrections” and „genuine EW + lineshape corrections”

Tree level Standard Model relations:

$$G_F = \frac{\pi\alpha}{\sqrt{2} m_W^2 \sin^2\theta_W^{tree}},$$

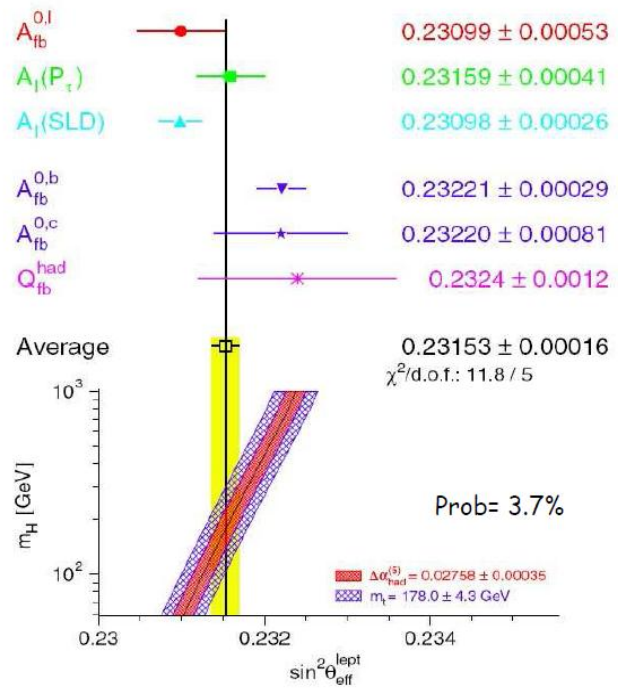
$$\rho_0 = \frac{m_W^2}{m_Z^2 \cos^2\theta_W^{tree}} = 1$$

Uncertainties on TH predictions

We have established such excellent agreement between very different: EW calculations, codes, QCD details (matrix element, PDFs,…).

Lets start now asking more detailed questions about individual corrections.

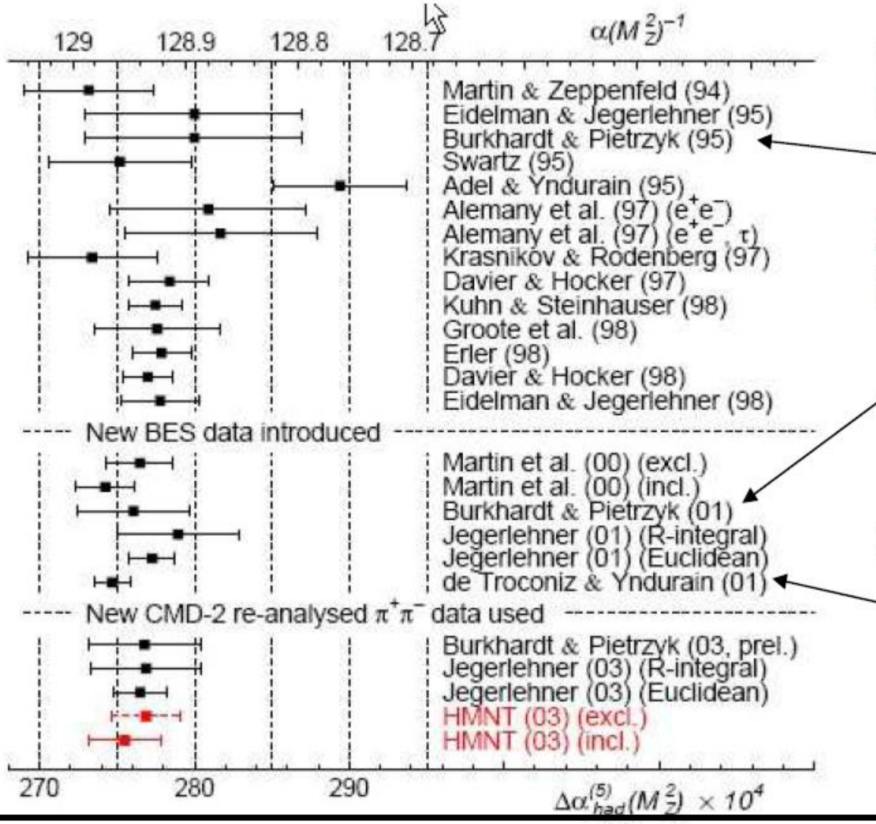
- **Not all terms can/should be directly compared.**
- **The dominant systematics for LEP $\sin^2\theta_{eff}$ measurement, which was $\Delta\alpha^{(5)}_{had}(M_Z^2)$. Are we consistent about this correction term?**
- **The m_t since then known with 10 x better precision. Not an issue anymore.**



New measurement (arXiv:1706.09436)
$\Delta\alpha_{had}^{(5)}(M_Z)$ = 0.02753 +- 0.00009

Status of $\Delta\alpha_{had}^{(5)}(M_Z^2)$

from D. Schlatter, 2007



At end of LEP $\Delta\alpha_{had}$ became limiting uncertainty in SM fits.

$\Delta\alpha_{had}(M_Z)=0.02804\pm0.00065$

Post LEP measurements from BES and CMD-2 improvement.

$\Delta\alpha_{had}(M_Z)=0.02758\pm0.00035$

This value is used by EWWG

Using perturbative QCD

$\Delta\alpha_{had}(M_Z)=0.02749\pm0.00012$

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha_h^{(5)}(s) - \Delta\alpha_\ell(s) - \Delta\alpha^t(s) - \Delta\alpha^{\alpha\alpha_s}(s)}$$

$$\Delta\alpha_h^{(5)}(M_Z^2) = 0.0280398$$

$$\Delta\alpha_\ell(M_Z^2) = 0.0314976$$

$$\Delta\alpha^t(M_Z^2) = -0.585844 \cdot 10^{-4}$$

$$\Delta\alpha^{\alpha\alpha_s}(M_Z^2) = -0.103962 \cdot 10^{-4}$$

Dizet 6.21 default

Recent measurements:

arXiv:1706.09436

$\Delta\alpha_{had}^{(5)}(M_Z) = 0.02753 \pm 0.00009$

arXiv:1802.02995

$\Delta\alpha_{had}^{(5)}(M_Z) = 0.02761 \pm 0.00011$

Impact of $\Delta\alpha_{had}^{(5)}(M_Z^2)$

Predictions from Dizet 6.21 library

Parameter	$\Delta\alpha_h^{(5)}(M_Z^2) = 0.0280398$	$\Delta\alpha_h^{(5)}(M_Z^2) = 0.02753$	Ratio
$\alpha(M_Z^2)$	0.00775884	0.00775463	
$1/\alpha(M_Z^2)$	128.885224	128.95522	0.99932
s_W^2	0.22351946	0.22331458	1.00092
$sin^2\theta_W^{eff}(M_Z^2)$ (electron, muon)	0.23175990	0.23157062	1.00082
$sin^2\theta_W^{eff}(M_Z^2)$ (up-quark)	0.23164930	0.23146414	1.00080
$sin^2\theta_W^{eff}(M_Z^2)$ (down-quark)	0.23152214	0.23133715	1.00080
M_W	80.35281 GeV	80.36341 GeV	1.00013
Δr	0.03694272	0.03631342	1.01733
Δr_{rem}	0.01169749	0.01170244	0.99958
ρ_{eu}	1.005408	1.005426	0.99998
K_e	1.036649	1.036770	0.99988
K_u	1.036172	1.036293	0.99988
K_{eu}	1.074146	1.074397	0.99977
ρ_{ed}	1.005894	1.005906	0.99999
K_e	1.036649	1.036699	0.99995
K_d	1.035603	1.035719	0.99989
K_{ed}	1.073556	1.073859	0.99972

shift of about -0.00020 due to corrections to M_W

shift by +11 MeV

ATLAS measurement
M_W = 80370 ± 19 MeV

$$M_W = \frac{M_Z}{\sqrt{2}}\sqrt{1+\sqrt{1-\frac{4A_0^2}{M_Z^2(1-\Delta r)}}}$$

$$\Delta r = \Delta\alpha(M_Z^2) + \Delta r_{EW}$$

$$A_0 = \sqrt{\frac{\pi\alpha(0)}{\sqrt{2}G_\mu}}$$

Impact of m_t

Parameter	m_t = 171 GeV	m_t = 173 GeV	m_t = 175 GeV
$\alpha(M_Z^2)$	0.00775882	0.00775884	0.00775885
$1/\alpha(M_Z^2)$	128.888558	128.885224	128.885079
s_W^2	0.22375411	0.22351946	0.22328310
$sin^2\theta_W^{eff}(M_Z^2)$ (electron, muon)	0.23181756	0.23175990	0.23169368
$sin^2\theta_W^{eff}(M_Z^2)$ (up-quark)	0.23171096	0.23164930	0.23169368
$sin^2\theta_W^{eff}(M_Z^2)$ (down-quark)	0.23158377	0.23152214	0.23145996
Δr	0.03766186	0.03694272	0.03621664
Δr_{rem}	0.01165959	0.01169749	0.01173500
ρ_{eu}	1.005229	1.005408	1.005589
K_e	1.035837	1.036649	1.037467
K_u	1.035361	1.036172	1.036990
K_{eu}	1.072465	1.074146	1.075843
ρ_{ed}	1.005714	1.005894	1.006075
K_e	1.035837	1.036649	1.037467
K_d	1.034792	1.035603	1.036420
K_{ed}	1.071876	1.073556	1.075252

±2 GeV shift in m_t corresponds to ±0.00005 shift in $\sin^2_{eff}{}^{lep}$

Dizet 6.21 -> 6.42-> 6.44

AMT4 = 4 – available in Dizet 6.21
Pragmatic question: is it indeed more precise estimate to use AMT4=5 or AMT4=6?
Or better stay with well tested AMT4=4 ? What uncertaintity attribute to this correction?

arXiv:1302.1395v3

Table 1: *ZFITTER v.6.44beta, with the input values $\alpha_s = 0.1184$, $M_Z = 91.1876$ GeV, $M_H = 125$ GeV, $m_t = 173$ GeV. The dependence on electroweak NNLO corrections is studied for IMOMS=1 (input values are α_{em}, M_Z, G_μ). AMT4=4: with two-loop sub-leading corrections and re-summation recipe of [23-28] of [13]; AMT4=5: with fermionic two-loop corrections to M_W according to [29,30,32] of [13]; AMT4=6: with complete two-loop corrections to M_W [37] and fermionic two-loop corrections to $\sin^2\theta_W^{\rm lept,eff}$ [52] of [13]. IBAIKOV=0 (no α_s^4 QCD corrections) or IBAIKOV=2012 [190].*

AMT4	4	5	6	Diff.	Exp. Err.
IBAIKOV=0					
$\Gamma_Z(\mu^+\mu^-)$, MeV	83.9782	83.9748	83.9807	0.0059	0.086
Γ_Z, MeV	2494.7863	2494.6019	2494.8688	0.2669	2.3
$\Gamma_W(l\nu)$, MeV	226.3185	226.2877	226.2922	0.0308	1.9
Γ_W, MeV	2090.3308	2090.0465	2090.0882	0.2843	42
M_W, GeV	80.3578	80.3541	80.3546	0.0037	0.015
$\sin^2\theta^{\rm lept}_{\rm eff}$	0.231722	0.231791	0.231670	0.000121	0.00012
IBAIKOV=2012					
$\Gamma_Z(\mu^+\mu^-), MeV$	83.9782	83.9748	83.9807	0.0059	0.086
Γ_Z, MeV	2494.5591	2494.3747	2494.6416	0.2669	2.3
$\Gamma_W(l\nu)$, MeV	226.3185	226.2877	226.2922	0.030	1.9
Γ_W, MeV	2090.1117	2089.8274	2089.8691	0.2843	42
M_W, GeV	80.3578	80.3541	80.3546	0.0037	0.015
$\sin^2\theta^{\rm lept}_{\rm eff}$	0.231722	0.231791	0.231670	0.000121	0.00012

± 0.00005 around nominal value of $\sin^2\theta_{eff}$ with AMT4=4

Dizet 6.21 initialisation (KKMC default)

Internal flag	Default value	Optional valus	Description
ibox	1	0,1	EW boxes on/off
Ihvp	1	1,2,3	Jegerlehner/Eidelman, Jegerlehner(1988), Burkhardt etal.
Iamt4	4	0,1,2,3,4	=4 the best, Degrassi/Gambino
Iqcd	3	1,2,3	approx/fast/lep1, exact/Slow!/Bardin/, exact/fast/Kniehl
Imoms	1	0,1	=1 W mass recalculated
Imass	0	0,1	=1 test only, effective quark masses
Iscre	0	0,1,2	Remainder terms
Ialem	3	1,3 or 0,2,	for 1,3 DALH5 not input
Imask	0	0,1	=0: Quark masses everywhere; =1 Phys. threshold in the ph.sp.
Iscal	0	0,1,2,3	Kniehl=1,2,3, Sirlin=4
Ibarb	2	-1,0,1,2	Barbieri???
Iftjr	1	0,1	FTJR corrections
Ifacr	0	0,1,2,3	Expansion of δ_r; =0 none; =3 fully, unrecommed.
Ifact	0	0,1,2,3,4,5	Expansion of kappa; =0 none
Ihigs	0	0,1	Leading Higgs contribution resummation
Iafmt	1	0,1	=0 for old ZF
Iewlc	1	0,1	???
Iczak	1	0,1	Czarnecki/Kuehn corrections
Ihig2	1	0,1	Two-loop higgs corrections off,on
Iale2	3	1,2,3	Two-loop constant corrections in δ_α
Igfer	2	0,1,2	QED corrections for fermi constant
Iddzz	1	0,1	??? DD-ZZ game, internal flag