Update on Powheg ew

(continuation of previous talk in May)

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LHC EW Precision sub-group meeting
1 July 2019, CERN

with M. Chiesa and the Powheg_ew team

- A proposal for the (SM) direct determination of $\sin^2 \vartheta^{\ell}_{eff}$

M. Chiesa, F.P. and A. Vicini, arXiv:1906.11569

- Fixed vs running width

from last meeting of May 7th

- **independent quantities in the SM:**
  - 3 in the electroweak gauge sector (to be specified)
  - $\alpha_s(Q^2)$, for a given Q^2, e.g. $Q^2 = M_Z^2$
  - lepton masses, m_t, m_H
  - light quark masses (including c and b) crucial for the running of $\alpha \Longrightarrow$ circumvented by using low-energy data and dispersion relations
- possible triplets of input (Lagrangian) parameters
  - (e, M_W, M_Z), (g, M_W, M_Z), $(g, \sin\vartheta, M_Z)$, ...
- **renormalization scheme**: input parameters need to be defined with reference to three data points
- $\Longrightarrow$ everything else is calculated in terms of input parameters
- conceptually, independently of any simplified assumption (e.g. factorization properties at the Z peak), every parameter can be directly determined through a template fit procedure to any observable, provided our theoretical prediction of the observable allows us to freely move the measured parameter without spoiling the accuracy of the calculation
- **the above can be achieved in a formally clear way if we provide a renormalization scheme which adopts the measured parameter as an independent parameter**

requirement for an input/renormal. scheme

- **minimize the parametric uncertainty of the reference observables** defining the scheme
  - e.g. the LEP (G_μ, α, M_Z) scheme
- **minimize the effects of higher order corrections**, in order to have stable predictions in perturb. theory
  - e.g. the (G_μ, M_W, M_Z) scheme used for DY at Tevatron/LHC
- **minimize the parametric uncertainty** due to imperfect knowledge of other Lagrangian parameters (e.g. m_t, $\Delta\alpha_h$)

which scheme for direct determination of $\sin^2\vartheta^\ell_{eff}$ at the LHC?

α/G_μ, M_Z, $\sin^2\vartheta^\ell_{eff}$ as reference data

M. Chiesa, F.P. and A. Vicini, arXiv:1906.11569

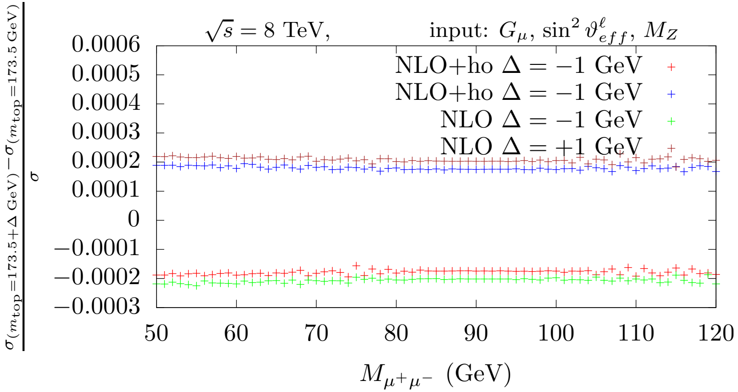
- our Lagrangian parameters: e, $\sin^2\vartheta$, M_Z
- e and M_Z renormalized parameters fixed as usual through α/G_μ and M_Z value measured at LEP
- $\sin^2\vartheta$ renormalized parameter fixed at $\sin^2\vartheta^\ell_{eff}$
    - this can be achieved by requiring that the ratio $\frac{g_V^\ell}{g_A^\ell}$ does not get radiative corrections
    - procedure independent of QED corrections because g_L and g_R receive the same corrections
- the scheme can be used for making predictions
    - "drawback": parametric uncertainty inherited by the LEP measurement of $\sin^2\vartheta^\ell_{eff}$
- most important: the scheme can be used in a fitting procedure to measure $\sin^2\vartheta^\ell_{eff}$ with a template fit

- scheme implemented in POWHEG-V2 framework, Z_ew-BMNNPV, svn v. 3652

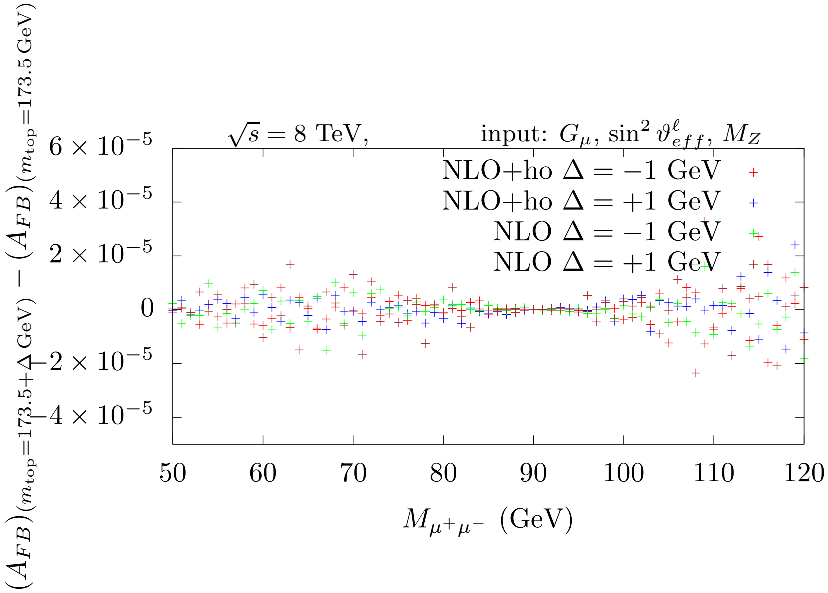
- scheme activated through `use-s2effin input value`
  - scheme 0 $\Longrightarrow$ input: $\alpha(0)$, $\sin^2\vartheta^{\ell}_{eff}$, M_Z
  - scheme 2 $\Longrightarrow$ input: G_μ, $\sin^2\vartheta^{\ell}_{eff}$, M_Z

- code ready for tests and validation

parametric dependence on $m_{\rm top}$



- parametric dependence on $\Delta\alpha_h$ available, when using α as input (according to most recent parameterizations), numerics to be done
- parametric dependece on α_s available, numerics to be done


$\sqrt{s} = 8$ TeV,
input: G_μ, $\sin^2\vartheta^\ell_{eff}$, M_Z
NLO+ho $\Delta = -1$ GeV
NLO+ho $\Delta = +1$ GeV
NLO $\Delta = -1$ GeV
NLO $\Delta = +1$ GeV
$(A_{FB})_{(m_{\rm top}=173.5+\Delta\,{\rm GeV})} - (A_{FB})_{(m_{\rm top}=173.5\,{\rm GeV})}$
6×10^{-5}
4×10^{-5}
2×10^{-5}
0
-2×10^{-5}
-4×10^{-5}
50
60
70
80
90
100
110
120
$M_{\mu^+\mu^-}$ (GeV)

schemes and input parameters

to be merged/expanded with material from Elzbieta

- $\alpha0$ v1: α, M_W, M_Z
  - $M_W = 80.385$ GeV, $\Gamma_W = 2.085$ GeV $\Longrightarrow$ pole mass and width
  - $M_Z = 91.1876$ GeV, $\Gamma_Z = 2.4952$ GeV $\Longrightarrow$ pole mass and width
  - $m_H = 125$ GeV, $m_t = 173.5$ GeV
- G_μ: G_μ, M_W, M_Z
- $\sin^2\vartheta^\ell_{eff}$ v1: $\sin^2\vartheta^\ell_{eff} = 0.23147$, G_μ, M_Z
- $\sin^2\vartheta^\ell_{eff}$ v2: $\sin^2\vartheta^\ell_{eff} = 0.23157$, G_μ, M_Z

- three invariant mass ranges considered
  - $89\,\mathrm{GeV} < m_{\ell\bar\ell} < 93\,\mathrm{GeV}$
  - $80\,\mathrm{GeV} < m_{\ell\bar\ell} < 100\,\mathrm{GeV}$
  - $93\,\mathrm{GeV} < m_{\ell\bar\ell} < 120\,\mathrm{GeV}$

Cross sections

Cross section (pb)	LO	NLO	NLO+HO
$\alpha 0$ v1	571.404(15)	600.185(15)	607.555(15)
	821.358(19)	863.143(16)	873.721(18)
	870.723(20)	915.580(20)	926.769(19)
G_μ	612.514(16)	607.142(15)	607.515(14)
	880.443(20)	873.173(16)	873.655(18)
	933.361(22)	926.253(18)	926.681(19)
$\sin^2\vartheta^\ell_{eff}$ v1	600.910(9)	608.673(8)	607.288(9)
	864.259(10)	875.333(10)	873.341(11)
	916.934(11)	928.481(11)	926.367(11)
$\sin^2\vartheta^\ell_{eff}$ v2	600.777(16)	...	607.152(15)
	864.076(20)	...	873.155(18)
	916.754(21)	...	926.183(19)

$\delta(i,j)$	LO	NLO	NLO+HO
G_μ / $\alpha 0$ v1	1.071946(56)	1.011592(50)	0.999934(48)
	1.071936(49)	1.011621(50)	0.999924(41)
	1.071938(50)	1.011657(50)	0.999905(41)
$\sin^2\vartheta^\ell_{eff}$ v1 / G_μ	0.981055(40)	1.002521(38)	0.999626(38)
	0.981618(34)	1.002474(30)	0.999641(33)
	0.982400(35)	1.002405(31)	0.999661(32)
$\sin^2\vartheta^\ell_{eff}$ v2 / G_μ	0.980837(52)		0.999402(48)
	0.981410(45)		0.999428(41)
	0.982207(46)		0.999801(32)

A_{FB}

A_{FB}	LO	NLO	NLO+HO
$\alpha0$ v1	0.046547(30)	0.030043(30)	0.030830(27)
	0.043445(26)	0.026908(27)	0.027702(22)
	0.042135(25)	0.025699(25)	0.026492(22)
G_μ	0.046548(30)	0.029058(28)	0.030903(27)
	0.043440(26)	0.025922(28)	0.027778(22)
	0.042130(25)	0.024719(26)	0.026569(22)
$\sin^2\vartheta^\ell_{eff}$ v1	0.030598(15)	0.030397(15)	0.030396(15)
	0.027437(13)	0.027267(13)	0.027267(13)
	0.026213(13)	0.026056(13)	0.026057(22)
$\sin^2\vartheta^\ell_{eff}$ v2	0.030417(30)		0.030212(27)
	0.027253(25)		0.027083(22)
	0.026032(25)		0.025876(22)

$\Delta(i,j)$	LO	NLO	NLO+HO
G_μ / $\alpha0$ v1	0.000001(60)	-0.000985(58)	0.000073(54)
	-0.000005(50)	-0.000986(55)	0.000076(44)
	-0.000005(50)	-0.000980(51)	0.000077(44)
$\sin^2\vartheta^\ell_{eff}$ v1 / G_μ	-0.015950(45)	0.001339(43)	-0.000507(42)
	-0.016003(39)	0.001345(41)	-0.000511(35)
	-0.015917(38)	0.001337(39)	-0.000512(44)
$\sin^2\vartheta^\ell_{eff}$ v2 / G_μ	-0.016131(60)		-0.000691(54)
	-0.016187(51)		-0.000695(44)
	-0.016098(50)		-0.000693(44)

Running vs fixed Z width: first considerations

- The definition of Z mass as the zero of the real part of the inverse propagator (the one implied by LEP running width parameterization) is gauge dependent starting from $\mathcal{O}(\alpha^2)$
  - the complex pole position gives a gauge independent mass definition

e.g. A. Sirlin, Phys.Rev.Lett. 67 (1991); R.G. Stuart, Phys.Lett. B262 (1991), S. Willenbrock and G. Valencia, Phys.Lett. B259 (1991)

- neglecting terms of $\mathcal{O}(\alpha^2)$, a gauge invariant definition (closely related to the LEP measured values), is

$$
\begin{aligned}
M_{OS}^2 &= M_{\rm pole}^2 \left(1 + \frac{\Gamma_{\rm pole}^2}{M_{\rm pole}^2}\right) \\
\Gamma_{OS}^2 &= \Gamma_{\rm pole}^2 \left(1 + \frac{\Gamma_{\rm pole}^2}{M_{\rm pole}^2}\right)
\end{aligned}
$$

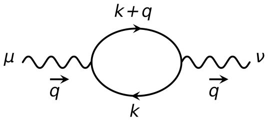
- in general it has been shown that a calculation (for a generic process) which uses running widths in the boson propagators meets gauge violations, which can become severe (extensive numerical studies during the nineties in view of LEP2)

e.g. Argyres et al., Phys.Lett. B358 (1995)

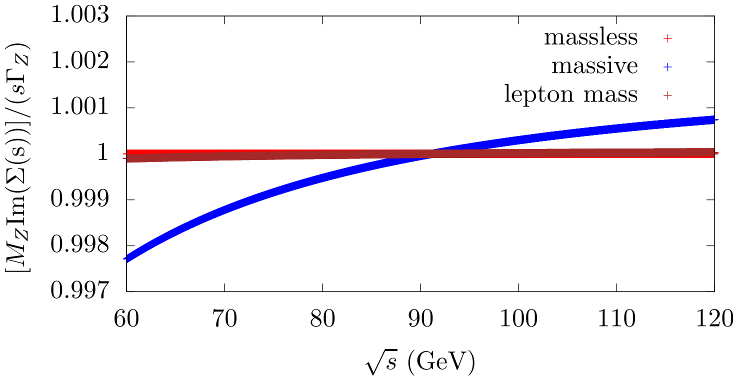
  - e.g.: $f\bar{f} \to 4$ fermions @LEP2 and @LHC
  - it involves the self-gauge coupling at tree level
  - $\Longrightarrow$ the width is related to the imaginary parts of the fermionic corrections; to restore gauge invariance (at least) the imaginary part of the fermionic correction to the self-gauge coupling has to be included (idea of the fermion loop scheme)

- for DY, at one loop, as long as no bosonic corrections are put in the denominator, no problems of gauge invariance arise around the Z pole
- for one loop calculations, the two parameterizations of the Z lineshape can be adopted
  - they can give different predictions of the lineshape
    - ★ which can be expected to decrease when comparing the two scheme at LO level or at NLO level (to be numerically investigated)

idea behind running width



$$\text{for } m = 0\,, \qquad\qquad \mathrm{Im(blob)} = \Gamma_Z \frac{s}{M_Z}$$



back to LEP, where the running width was used

$$\sigma_{\mathrm{f\bar{f}}}^{\mathrm{Z}} = \sigma_{\mathrm{f\bar{f}}}^{\mathrm{peak}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} = \sigma_{\mathrm{f\bar{f}}}^{\mathrm{peak}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + \Gamma(s)^2 M_Z^2}$$

from my slides at our 13 March 2019 meeting

- M_Z and Γ_Z above are "OS" quantities, $\Gamma(s) = \Gamma\frac{s}{M^2}$

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- M_Z and Γ_Z above are "OS" quantities, $\Gamma(s) = \Gamma \frac{s}{M^2}$
- let's express $\sigma_{\mathrm{f\bar{f}}}^{\mathrm{Z}}$ in terms of "pole" quantities, with $\gamma \equiv \frac{\Gamma_{\mathrm{pole}}}{M_{\mathrm{pole}}}$

back to LEP, where the running width was used

$$\sigma^{Z}_{f\bar{f}} = \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} = \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + \Gamma(s)^2 M_Z^2}$$

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$$\begin{aligned}
\sigma^{Z}_{f\bar{f}} &= \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma^2_{\rm pole}(1+\gamma^2)}{(s-M^2_{\rm pole}(1+\gamma^2))^2 + s^2\gamma^2} \\
&= \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma^2_{\rm pole}(1+\gamma^2)}{s^2 + M^4_{\rm pole}(1+\gamma^2)^2 - 2sM^2_{\rm pole}(1+\gamma^2) + s^2\gamma^2} \\
&= \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma^2_{\rm pole}(1+\gamma^2)}{s^2(1+\gamma^2) + M^4_{\rm pole}(1+\gamma^2)^2 - 2sM^2_{\rm pole}(1+\gamma^2)} \\
&= \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma^2_{\rm pole}}{(s-M^2_{\rm pole})^2 + \Gamma^2_{\rm pole}M^2_{\rm pole}}
\end{aligned}$$

including photon exchange

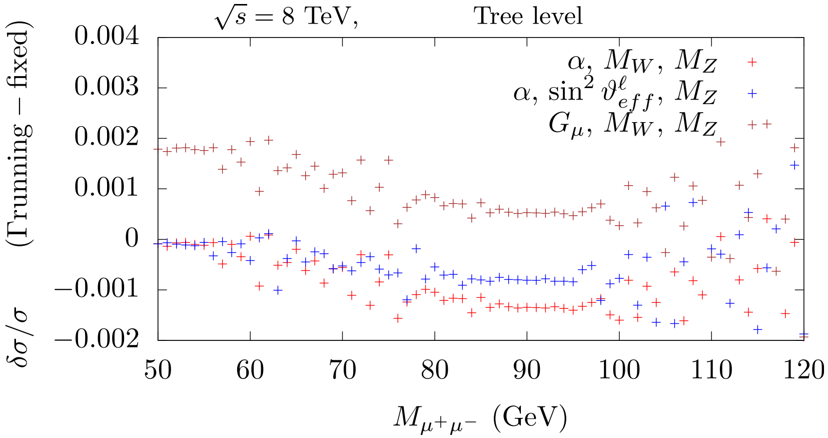
$$
\begin{aligned}
\frac{d\sigma_0^\gamma}{d\Omega} &= \frac{\alpha^2 Q_f^2 N_c}{4s}(1+\cos^2\vartheta) \\
\frac{d\sigma_0^{\gamma Z}}{d\Omega} &= -\frac{\alpha^2 Q_f N_c}{4\sqrt{2} s_\theta^2 c_\theta^2 s}\mathrm{Re}(\chi(s))[g_V^e g_V^f(1+\cos^2\vartheta) + 2 g_A^e g_A^f \cos\vartheta] \\
\frac{d\sigma_0^{Z}}{d\Omega} &= -\frac{\pi\alpha^2 N_c}{32 s_\theta^4 c_\theta^4 s}|\chi(s)|^2[f(g_V^{e,f}, g_A^{e,f})(1+\cos^2\vartheta) + g(g_V^{e,f}, g_A^{e,f})\cos\vartheta] \\
\chi(s) &= \frac{s}{(s-M_Z^2)+i\Gamma_Z M_Z}
\end{aligned}
$$

$$\chi(s)_{\mathrm{running}} = \frac{1}{(1+i\gamma)}\chi(s)_{\mathrm{pole}} \qquad \gamma \simeq 0.0274$$

- the couplings, in schemes where $\sin^2\theta$ is connected to M_Z and M_W, get modified when changing from running- to fixed-width scheme
- the relative weights of channels can get modified

Γ running vs. fixed on $M_{\ell\ell}$

PRELIMINARY



Γ running vs. fixed on A_{FB}

PRELIMINARY