

High precision Monte Carlo tools for EW precision measurements at hadron colliders

Mauro Chiesa⁽¹⁾, Clara Lavinia Del Pio⁽²⁾, Fulvio Piccinini⁽¹⁾

(1) INFN, Sezione di Pavia
 (2) Brookhaven National Laboratory

Weak-mixing angle in the SM

$SU(2)_L \otimes U(1)_Y$ gauge group parameters

$$g_2 = \frac{e}{\sin \theta_W}, \quad g_1 = \frac{e}{\cos \theta_W}$$

neutral gauge boson mixing

$$(Z_\mu) = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}$$

W and Z boson masses and symmetry breaking pattern

$$1 = \frac{M_W}{M_Z \cos \theta_W}$$

gauge-matter interaction, e.g.:

$$ie\gamma_\mu \left(\frac{I_f^3 - \sin^2 \theta_W Q_f}{\sin \theta_W \cos \theta_W} \omega_L - \frac{\sin \theta_W Q_f}{\cos \theta_W} \omega_R \right)$$

The precise determination of $\sin \theta_W$ is a test of the entire EWSM

$\sin \theta_W$ at hadron colliders

The Drell-Yan process is sensitive to the weak mixing angle via the Z-fermion coupling to left and right handed fermions

Observables like the Forward-Backward asymmetry defined in the Collins-Soper frame maximize the dependence on $\sin \theta_{W,eff}^f$

$$A_{FB} = \frac{\sigma(\cos \theta_{CS} > 0) - \sigma(\cos \theta_{CS} < 0)}{\sigma(\cos \theta_{CS} > 0) + \sigma(\cos \theta_{CS} < 0)}$$

$\sin \theta_{W,eff}^f$ measured from A_{FB} via **TEMPLATE FITS**

Template fit method

Measurement: $A_{FB}(m_{ll}, |y_{ll}|)$ data

Theory input: MC samples with different values of $\sin^2 \theta_{eff}^f$

Result: Measured value = MC sample which best fit the data

$\mu\mu$	λ_{min}^2	bins	$p(\%)$	$\sin^2 \theta_{eff}^f$	stat	exp	th	PDF	MC	bg	eff	calib	other
ee	241	264	83	23142 ± 38	17	17	6	30	13	3	2	5	4
eg	257	264	60	23171 ± 41	22	18	5	30	14	4	5	3	7
eh	119	144	93	23253 ± 61	30	40	3	44	23	11	12	20	8
ll	105	144	99	23114 ± 48	18	33	9	37	14	10	16	18	6
ll	731	816	98	23152 ± 31	10	15	8	27	8	4	6	6	3

CMS Collaboration, Phys. Lett. B 866 (2025) 139526

Precise theory predictions AND a robust assessment of theory uncertainties are essential for the high-precision determination of the weak mixing angle

Target precision at (HL-)LHC

The accuracy target for $\sin^2 \theta_{W,eff}^f$ at the end of (HL-)LHC is ~ 0.00015

In order to be sensitive to such small effects, the precision of the Monte Carlo predictions for the asymmetry at the Z peak must be under control at the level of ~ 0.0001

The Monte Carlo templates used for the fitting procedure must include electroweak effects beyond the leading order in perturbation theory

Template fit beyond LO: the $(G_\mu, \sin^2 \theta_{W,eff}^f, M_Z)$ scheme

In the EWSM there are **three independent parameters** besides the Yukawas and the Higgs mass from which all the other parameters can be computed.

The typical choices in Monte Carlo generators for LHC physics use the W and Z masses and some variant of α at the weak scale.

As far as the MC templates are generated at LO, the input parameter choice is immaterial as simple LO relations allow to change input variables.

Beyond LO, relations among parameters are affected by radiative corrections that introduce further theory uncertainties (parametric dependence on SM parameters, truncation of the perturbative expansion).

Moreover, using templates depending on variables other than $\sin \theta_{W,eff}^f$ would only be an indirect determination of the weak mixing angle

A new input parameter/renormalization scheme that uses consistently $\sin \theta_{W,eff}^f$ as an independent variable was developed in [1]

In the $(G_\mu, \sin^2 \theta_{W,eff}^f, M_Z)$ input/renormalization scheme:

Smaller EW corrections

Fit almost independent of radiative corrections and higher-orders

Negligible uncertainties from top mass

Weak radiative corrections and theory uncertainties on A_{FB}

For a given order in perturbation theory, calculations performed in different input parameter / renormalization schemes share the same formal accuracy, yet the results differ numerically because of the truncation of the perturbative expansion.

We interpret the difference between predictions in different schemes as a conservative estimate of the uncertainty from missing higher-order corrections.

At the Z peak, focusing on schemes with variants of α defined at the weak scale, the spread in the predictions for the asymmetry is $\sim 0.0001-0.0002$

It may be excessively conservative to estimate weak theory uncertainties by considering all schemes equivalent.

Certain schemes yield larger parametric uncertainties, whereas others feature significant radiative corrections, pointing to larger uncertainties from missing higher-orders

An alternative strategy is to perform tuned comparisons where input parameters across schemes are treated as dependent. Specifically, one takes a reference scheme (such as α, G_μ, M_Z) to calculate M_W and $\sin^2 \theta_{W,eff}^f$ at the required precision, and subsequently uses these results as inputs for the schemes defined by M_W and $\sin^2 \theta_{W,eff}^f$

After tuning, the spread in the predictions for the asymmetry becomes of order 0.00005

Weak-mixing angle at high energies

Energy dependent weak mixing angle defined in the \overline{MS} scheme. Experimental data points at different scales allow for testing the running predicted by the Standard Model, which depends on the theory's entire particle content

related to the strength of the Z-fermion interaction at the Z peak

Uncertainties

- Statistical**: from predicted N_{events} in each bin
- Lepton syst.**: extrapol. to Run 3 (reduced of 2) and HL-LHC (4); uncorrelated in the fit
- Luminosity**: 1.5% for Run 3 and 1% for HL-LHC
- QCD scale**: n3loxs for cross-sections (2%) and 7-point variations of μ_R and μ_F (negligible) w.r.t. $m_{\ell\ell}$ at N3LO PDF uncertainties (not on plot)
- EW**: scale variations of $\mu = 2m_{\ell\ell}$ or $m_{\ell\ell}/2$ change cross section of % at LO and 0.1% at NLO - same variations of $\sin^2 \theta_{W,eff}^f(\mu)$ at LO and NLO

Invariant mass bin boundaries: 116, 150, 200, 300, 500, 1500, 5000 GeV
 Dilepton rapidity bin boundaries: 0.0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.5

Related Publications and Codes

[1] M. Chiesa, F. Piccinini and A. Vicini, *Direct determination of $\sin^2 \theta_{W,eff}^f$ at hadron colliders*, Phys. Rev. D 100 (2019) no.7, 071302

[2] M. Chiesa, C. L. Del Pio and F. Piccinini, *On electroweak corrections to neutral current Drell-Yan with the POWHEG BOX*, Eur. Phys. J. C 84 (2024) no.5, 539

[3] S. Amoroso, M. Chiesa, C. L. Del Pio, K. Lipka, F. Piccinini, F. Vazzoler and A. Vicini, *Probing the weak mixing angle at high energies at the LHC and HL-LHC*, Phys. Lett. B 844 (2023), 138103

[4] L. Barze, G. Montagna, P. Nason, O. Nicrosini, F. Piccinini and A. Vicini, Eur. Phys. J. C 73 (2013) no.6, 2474

[5] P. Nason, JHEP 11 (2004), 040

[6] S. Frixione, P. Nason and C. Oleari, JHEP 11 (2007), 070

[7] S. Alioli, P. Nason, C. Oleari and E. Re, JHEP 06 (2010), 043

The numerical results have been obtained by using the **Z_ew-BMNNPV** package within the POWHEG-BOX-V2 framework. Z_ew-BMNNPV is a Monte Carlo event generator for neutral current Drell-Yan at NLO QCD+NLO EW (+fermionic higher-orders) consistently matched to QCD and QED parton showers using the POWHEG method:

The code is available at https://gitlab.com/POWHEG-BOX/V2/User-Processes/Z_ew-BMNNPV

The code for charged-current Drell-Yan is available at https://gitlab.com/POWHEG-BOX/V2/User-Processes/W_ew-BMNNPV