EW Input Schemes and NLO Corrections in POWHEG `Z_ew-BMNNPV`

Practical study for measuring $\sin^2\theta_W$ at High Mass

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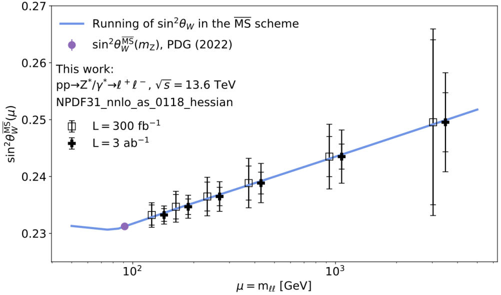
Motivation: $\sin^2\theta_W$ Running at High Mass

- Neutral-current Drell-Yan ($pp \to Z/\gamma^* \to \ell^+\ell^-$): pillar of precision EW physics at the LHC
- $\sin^2\theta_W$: fundamental parameter, sensitive to BSM
- The SM predicts a **running** of $\sin^2\theta_W^{\overline{\mathrm{MS}}}(\mu)$:
  - ~ 0.2315 at M_Z
  - ~ 0.25 at $\sim$3 TeV
- Weak corrections grow from $\sim 0.1\%$ at M_Z to $\mathcal{O}(10\%)$ at TeV scale

The choice of EW input scheme directly impacts the size of these corrections and the precision of predictions



from arXiv:2302.10782

Running of $\sin^2\theta_W^{\mathrm{MS}}(\mu)$ from M_Z to multi-TeV

EW Input Parameter Schemes

Schemes implemented in POWHEG `Z_ew-BMNNPV`

Scheme	Input parameters	Derived	POWHEG flags
G_μ scheme (M_W)	$G_\mu,\ M_W,\ M_Z$	$\sin^2\theta_W, \alpha$	`scheme=2`
G_μ scheme ($\sin^2\theta^\ell_{\rm eff}$)	$G_\mu,\ \sin^2\theta^\ell_{\rm eff},\ M_Z$	M_W, α	`scheme=2 + use-s2effin`
α_0 scheme	$\alpha_0,\ G_\mu,\ M_Z$	$M_W, \sin^2\theta_W$	`scheme=4 + azinscheme4=1`

- $\overline{\rm MS}$ scheme (arXiv:2302.10782): running $\alpha_{\overline{\rm MS}}(\mu)$, $\sin^2\theta_W^{\overline{\rm MS}}(\mu)$ as inputs
- $\sin^2\theta^\ell_{\rm eff}$ as input (arXiv:1906.11569): enables **direct extraction** from $A_{\rm FB}$

Key point

All schemes are **formally equivalent** at a given perturbative order.
Numerical differences arise from **truncation** of the perturbative series.

Ref: Chiesa et al. 2024 (arXiv:2402.14659), Chiesa et al. 2019 (arXiv:1906.11569), Barzè et al. 2013 (arXiv:1302.4606)

Interplay: Scheme Choice $\longleftrightarrow$ Theory Accuracy

1. Perturbative convergence

- G_μ / $\alpha(M_Z^2)$ schemes:
  absorb α running into LO
  $\Rightarrow$ **smaller NLO corrections**
  $\Rightarrow$ better convergence
- α_0 scheme:
  NLO contains $\log(m_f^2/Q^2)$
  $\Rightarrow$ larger corrections
- **Spread between schemes** at a given order = estimate of missing higher orders

2. Experimental uncertainties

- α_0, G_μ, M_Z:
  known with **excellent precision**
  $\Rightarrow$ unc. negligible
- M_W: $\Delta M_W = \pm 10$ MeV
  $\Rightarrow$ **non-negligible**

Trade-off: (α_0, G_μ, M_Z) has negligible parametric unc. but worst perturbative convergence

3. Free parameter for fits

- To extract $\sin^2\theta_{\text{eff}}^\ell$ from A_{FB}:
  need $\sin^2\theta_{\text{eff}}^\ell$ as input
  (Chiesa et al. 2019)
- To measure M_W:
  need M_W as free parameter
- Scheme must be **consistent with the target observable** of the measurement

Ref: arXiv:2402.146596, arXiv:1906.11569

The Tools: POWHEG, Pythia8, PHOTOS

POWHEG-BOX-V2

MC event generator that computes the **hard scattering** at NLO accuracy (QCD and/or EW).

Key idea: NLO precision for the first (hardest) emission, then hands over to the parton shower

Module `Z_ew-BMNNPV`:
adds **NLO EW corrections** to $qq \to Z/\gamma^* \to \ell^+\ell^-$

Barzè et al. 2013, Nason 2004

Pythia8

Parton shower + hadronisation

Takes POWHEG events and adds:

- Additional QCD radiation (softer gluons/quarks)
- Hadronisation: quarks $\to$ hadrons
- Underlying event (multi-parton interactions)

PHOTOS

QED photon radiation

Adds photon emission off final-state leptons ($\ell \to \ell + \gamma$):

- Soft photons resummed to all orders
- Multiple photon emission

POWHEG Configuration: Key Flags

EW content control

Flag	Role
`scheme`	EW renormalization scheme (0, 2, 4)
`no_ew`	Disable all EW corrections (1=off, 0=on)
`weak-only`	1: weak only at matrix-element −1: full EW (QED+weak)
`ew_ho`	Higher-order corrections ($\Delta\alpha$, $\Delta\rho$)
`use s2thetaeff`	Override $\sin^2\theta^{\ell}_{\text{eff}}$ as input

Critical: `weak-only` flag

When using PHOTOS for QED FSR:

- `weak-only = 1`: weak corrections at matrix-element, QED via PHOTOS ✓
- `weak-only =` −1: QED+weak at matrix-element + PHOTOS ⇒ **QED double-counting!**

Validation

POWHEG `Z_ew-BMNNPV` validated against **HORACE** (independent EW generator with completely independent EW form factors)

Barzè et al. 2013 (arXiv:1302.4606)

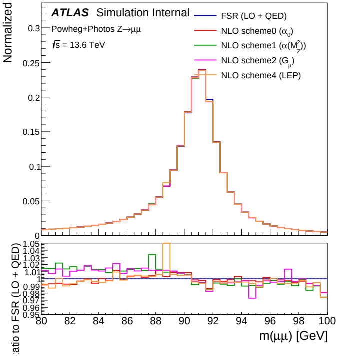
Production Setup:

Scan axes

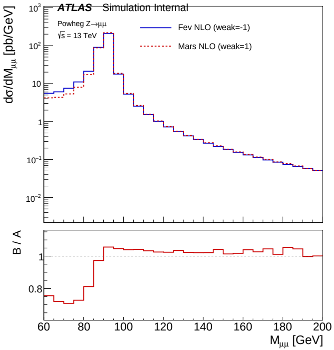
- **3 EW levels:** Born $\to$ NLO $\to$ NLO+HO
- **3 schemes:** (G_μ, M_W, M_Z) / $(G_\mu, \sin^2\theta_{\text{eff}}, M_Z)$ / (α_0, G_μ, M_Z)
- **Variations:** $\Delta \sin^2\theta_{\text{eff}} = \pm 0.01$, PHOTOS on/off
- $\sim$25M events per configuration

Config	scheme	no_ew	weak-only	ew_ho	s2eff
LO (G_μ, M_W, M_Z)	2	1	—	0	-1
NLO (G_μ, M_W, M_Z)	2	0	1	0	-1
NLO $(G_\mu, s^2_{\text{eff}}, M_Z)$	2	0	1	0	0.23154
NLO (α_0, G_μ, M_Z)	4	0	1	0	-1
NLO+HO (same 3 schemes)	*idem with ew_ho=1*				

Impact of EW Corrections on $d\sigma/dM_{\ell\ell}$



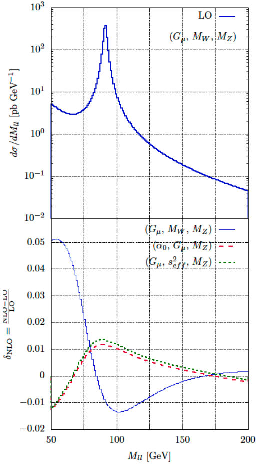
Scheme comparison at Z peak



Full EW vs weak-only

- **Left**: EW corrections modify the Z peak shape — schemes give different corrections
- **Right**: Full EW vs weak-only — quantifies the QED component, the difference between the two being what we want to avoid double-counting when using PHOTOS !

NLO EW Corrections: $d\sigma/dM_{\ell\ell}$ — Scheme Dependence

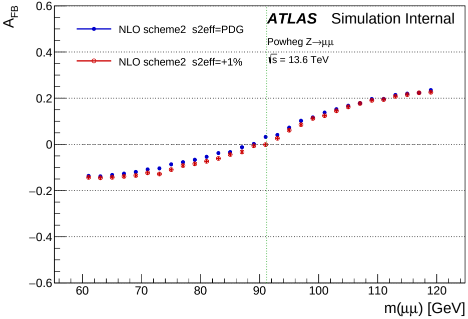


Key observations

- Corrections $\sim$ few % at Z peak
- In G_μ scheme, tree-level $\sin^2\theta_W$ differs from measured s^2_{eff} $\Rightarrow$ compensation by NLO counterterms $\Rightarrow$ visible %-level corrections
- In the two other schemes, LO $\sin^2\theta_W$ is already close to s^2_{eff} $\Rightarrow$ smaller NLO corrections
- Spread between schemes is an estimator of the missing higher orders
  $\Rightarrow$ built-in uncertainty estimate for theoretical predictions

Taken from 2402.14659

NLO EW Corrections: A_{FB}



weak-only=1

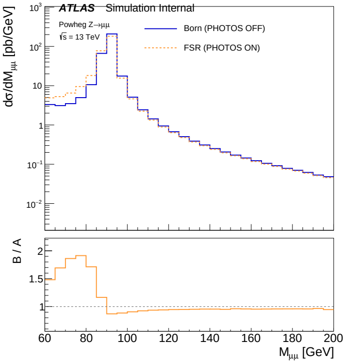
$A_{\text{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$, **with σ_F (σ_B) the forward (backward) cross-sections in $m_{\ell\ell}$.**

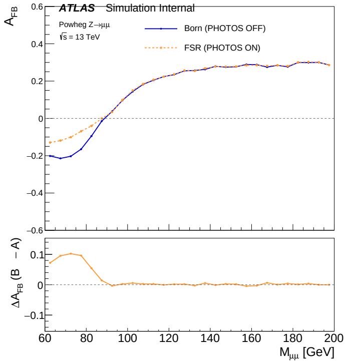
Key observations

- A_{FB} at Z peak: directly sensitive to $\sin^2\theta^{\ell}_{\text{eff}}$
- Observable used to extract $\sin^2\theta^{\ell}_{\text{eff}}$ at the peak

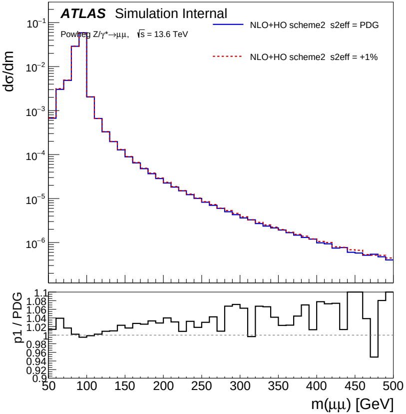
Effect of PHOTOS (QED FSR)

Born without PHOTOS (OFF) vs with PHOTOS (ON). **Only PHOTOS changes.**





From NLO EW Corrections to $\sin^2\theta_W$ Running



We saw that NLO EW corrections **grow with** $M_{\ell\ell}$ and **depend on the scheme**.

This means high-mass observables are sensitive to EW parameters — including $\sin^2\theta^\ell_{\text{eff}}$:

- $\Delta \sin^2\theta_{\text{eff}} = 0.01$: $\sim$5% shape effect at 110–500 GeV, growing at higher masses

Connection to the running

The SM predicts that $\sin^2\theta_W^{\overline{\text{MS}}}$ **evolves with the invariant mass**.

$\Rightarrow$ Measuring $d\sigma/dM_{\ell\ell}$ in mass bins, with NLO EW corrections properly accounted for, directly probes $\sin^2\theta_W(Q^2)$.

Our POWHEG setup provides the tool to do this.

s^2_{eff}: **0.23148 vs 0.24148**

Summary

1. NLO EW corrections to NC DY **grow with** $M_{\ell\ell}$ — from $\sim$0.1% at the Z peak to $\mathcal{O}(10\%)$ at the TeV scale — and **depend on the EW input scheme**
2. The choice of scheme is guided by **3 criteria**: perturbative convergence, parametric precision, and coherence with the fit observable. G_μ schemes offer better convergence than α_0.
3. We provide and test a POWHEG setup:
   `weak-only=1` + PHOTOS, 3 schemes $\times$ 3 EW levels.
   Scheme dependence quantified across the full mass range.
4. High-mass observables are **sensitive to** $\sin^2\theta_W$: this sensitivity, combined with the NLO EW corrections, enables a direct probe of the **scale evolution** of $\sin^2\theta_W$.
5. **Next:** $\overline{\text{MS}}$ running implementation + template fits to measure $\sin^2\theta_W^{\overline{\text{MS}}}(\mu)$ at different scales.

References

- S. Amoroso, M. Chiesa, C.L. Del Pio, K. Lipka, F. Piccinini, F. Vazzoler, A. Vicini,
  "Probing the weak mixing angle at high energies at the LHC and HL-LHC",
  Phys. Lett. B (2023) — arXiv:2302.10782

- M. Chiesa, C.L. Del Pio, F. Piccinini,
  "On electroweak corrections to neutral current Drell-Yan with the POWHEG BOX",
  Eur. Phys. J. C 84 (2024) 539 — arXiv:2402.14659

- M. Chiesa, F. Piccinini, A. Vicini,
  "On the direct determination of $\sin^2\theta^{\ell}_{eff}$ at hadron colliders",
  Phys. Rev. D 100 (2019) 071302 — arXiv:1906.11569

- L. Barzè, G. Montagna, P. Nason, O. Nicrosini, F. Piccinini, A. Vicini,
  "Neutral current Drell-Yan with combined QCD and electroweak corrections in the POWHEG BOX",
  Eur. Phys. J. C 73 (2013) 2474 — arXiv:1302.4606

Backup

Backup: Full Configuration Table

Config	scheme	no_ew	weak-only	ew_ho	s2eff	bornonly	azin4
LO Born (G_μ, M_W, M_Z)	2	1	-1	0	-1	**1**	—
LO Born (G_μ, s^2_{eff}, M_Z)	2	1	-1	0	0.23154	**1**	—
LO (G_μ, M_W, M_Z)	2	1	-1	0	-1	0	—
LO (G_μ, s^2_{eff}, M_Z)	2	1	-1	0	0.23154	0	—
LO (α_0, G_μ, M_Z)	4	1	-1	0	-1	0	**1**
NLO (G_μ, M_W, M_Z)	2	0	1	0	-1	0	—
NLO (G_μ, s^2_{eff}, M_Z)	2	0	1	0	0.23154	0	—
NLO (α_0, G_μ, M_Z)	4	0	1	0	-1	0	**1**
NLO+HO (G_μ, M_W, M_Z)	2	0	1	1	-1	0	—
NLO+HO (G_μ, s^2_{eff}, M_Z)	2	0	1	1	0.23154	0	—
NLO+HO (α_0, G_μ, M_Z)	4	0	1	1	-1	0	**1**

$M_W = 80.385$ GeV, $\sin^2\theta_{\text{eff}} = 0.23154$, `weak-only=1` (weak only)

Definitions of $\sin^2\theta_W$: On-shell vs Effective

$\sin^2\theta_W^{OS}$ (on-shell)

:

$$\boxed{\sin^2\theta_W^{OS} \equiv 1 - \frac{M_W^2}{M_Z^2}}$$

- At tree-level

$\sin^2\theta_{eff}^{lept}$ (effective)

Measured through **asymmetries** at the Z peak :

$$\boxed{\sin^2\theta_{eff}^{lept} \approx 0.23148}$$

- Includes radiative corrections at the $Zf\bar{f}$ vertex
- Measured by A_{FB}

Relation between the two — the factor κ

$$\sin^2\theta_{eff}^{lept} = \kappa_\ell \times \sin^2\theta_W^{OS}, \qquad \kappa_\ell \approx 1.037$$

$\kappa_\ell - 1 \approx 0.037$: dominated by $\Delta\rho \approx 3\,G_\mu\,m_t^2/(8\pi^2\sqrt{2}) \approx 0.009$