Direct determination of $\sin\theta_{\mathrm{eff}}^{\mathrm{lept}}$ at hadron colliders

Mauro Chiesa

LAPTh

Milano, December 20th, 2019

based on Phys.Rev. D100 (2019)

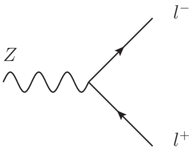
in collaboration with Fulvio Piccinini and Alessandro Vicini

Introduction

θ_W rules the mixing of B and W fields

determination of $\sin\theta_W$

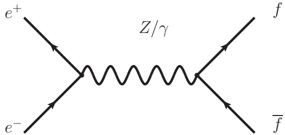
- indirect: $\sin\theta$ can be computed from $\alpha, G_\mu, M_Z, m_H, m_t$
- direct: 4-fermion processes at the Z resonance



$$g_L = \frac{I_3 - s_W^2 Q}{s_W c_W}, \qquad g_R = -\frac{s_W}{c_W} Q$$

measurable from forward/backward asymmetries

$\sin\theta_{\rm eff}^{\rm lept}$ at LEP (1)

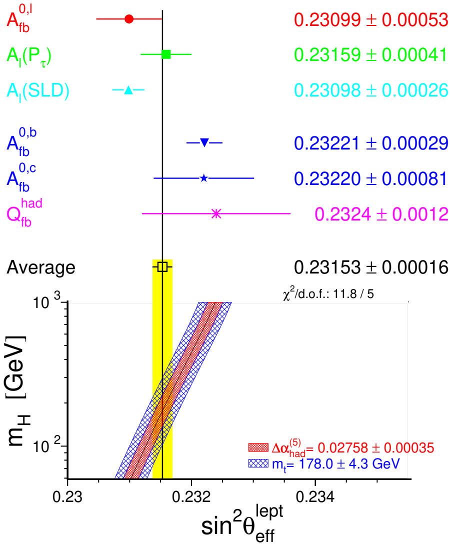


- cross sections and distributions parametrized in terms of pseudo-observables
- pseudo-observables fitted from data
- $\sin\theta_{\rm eff}^{\rm lept}$ derived from tree-level like relations between pseudo-observables

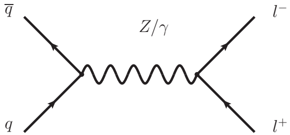
The LEP pseudo-observables approach assumes factorization of on-shell production and on-shell decay for the Z

Some of the constraints come from $e^+e^- \to {\rm hadrons}$ with separation of hadron flavours

$\sin\theta_{\rm eff}^{\rm lept}$ at LEP (2)



$\sin\theta_{\mathrm{eff}}^{\mathrm{lept}}$ at the LHC (1)



Same process as at LEP, with swapped IS and FS

Pseudo-observables approach is NOT used at the LHC:

- M_{ll} window $[50, 120]$ GeV (factorized approach?)
- quark flavour not under control
- additional uncertainties from PDFs

At the LHC $\sin\theta_{\mathrm{eff}}^{\mathrm{lept}}$ is measured using template fits

$\sin\theta_{\rm eff}^{\rm lept}$ at the LHC (2)

measured from invariant-mass forward-backward asymmetry

$$A_{FB}(M_{ll}) = \frac{F(M_{ll}) - B(M_{ll})}{F(M_{ll}) + B(M_{ll})}$$

$$F = \int_0^1 \mathrm{d}\cos\theta^* \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}, \qquad B = \int_{-1}^0 \mathrm{d}\cos\theta^* \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*}$$

θ^* measured in the Collins-Soper frame

using template fits

- measure $A_{FB}(M_{ll})$
- generate Monte Carlo samples with different values of $\sin\theta_W$
- fit the template to the data

measured $\sin\theta_W$ is the one of the sample that describes best the data

$\sin\theta_{\rm eff}^{\rm lept}$ and EW corrections

- calculations are usually done in the on-shell scheme
- in the OS scheme $\sin\theta$ is constant at all orders

$$\sin\theta^2_{OS} = 1 - \frac{M_W^2}{M_Z^2}$$

- in the direct determination of $\sin\theta$ we want to extract $\sin\theta$ from the strength of the Zff coupling that is NOT constant at H.O.

$$\sin\theta^2_{\rm eff} = \frac{1}{4}\Big(1 - {\rm Re}\frac{g_V}{g_A}\Big)$$

- $\sin\theta^2_{\rm eff} = \kappa_l \, \sin\theta_{OS}$, ($\kappa_l = 1$ at LO)

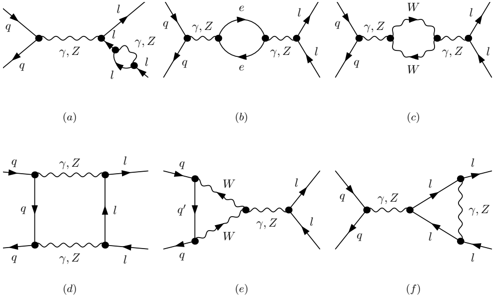
Template fits for $\sin\theta_{\rm eff}^{\rm lept}$ and EW corrections

- Accuracy goal on $\sin^2\theta_W$ is 10^{-4}: EW corrections mandatory
- $\sin\theta_W$ can always be used as input parameter for fits at LO
- The typical input schemes used at the LHC are $(\alpha/G_\mu, M_W, M_Z)$: $\sin\theta_W$ is a derived quantity

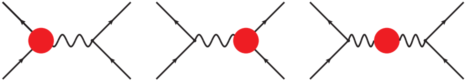
In order to perform a fit at NLO EW and have a clean way to estimate the EW uncertainties, a new input parameter scheme should be used with $\sin\theta_W$ as free parameter

$$(\alpha/G_\mu, \sin\theta, M_Z)$$

NC DY in the $(\alpha/G_\mu, \sin\theta, M_Z)$ scheme

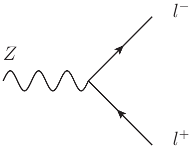


bare diagrams don't change



CT diagrams don't change

w.r.t. the on-shell scheme, different expression for the countertem functions $\frac{\delta s_W^2}{s_W^2}$ and Δr



$$\frac{ie}{2s_W c_W}\gamma^\mu\left[g_V^l - g_A^l\gamma_5\right],$$

$$g_V = \frac{g_L + g_R}{2}, \quad g_A = \frac{g_L - g_R}{2}$$

at LO $\sin\theta^2_{\text{eff}} = \frac{1}{4}(1 - \text{Re}\frac{g_V}{g_A})$

the renormalization condition is

$$\sin\theta^2_{\text{eff}}\Big|_{NLO} = \sin\theta^2_{\text{eff}}\Big|_{LO} \quad \Rightarrow \quad \frac{g_V + \delta g_V}{g_A + \delta g_A} = \frac{g_V}{g_A}$$

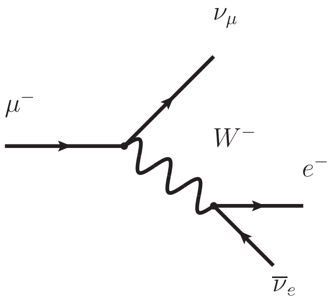
$\delta \sin\theta_{\rm eff}$

$$\frac{\delta \sin\theta^2_{\rm eff}}{\sin\theta^2_{\rm eff}} = {\rm Re}\Big\{ \frac{\cos\theta_{\rm eff}}{\sin\theta_{\rm eff}} \frac{\Sigma_T^{AZ}(M_Z^2)}{M_Z^2} + (1 - \frac{Q_l}{I_3^l} \sin\theta^2_{\rm eff})[\delta V^L - \delta V^R] \Big\}$$

$\delta V^{L/R} =$ bare vertex diagrams+fermion w.f. renorm.

- $\delta^{QED} g_L = \delta^{QED} g_R$: affected only by weak corrections
- no enhancement from logs of fermion masses
- no dependence on $\Delta\rho$ (no m_t^2 enhancement)

Δr, $\Delta\tilde{r}$



computed from the NLO EW corrections to μ-decay after subtracting 1-loop QED corrections in the Fermi model

$$\Delta r = \Delta r(\alpha, M_W, M_Z)$$

$$\Delta\tilde{r} = \Delta r(\alpha, \sin\theta, M_Z)$$

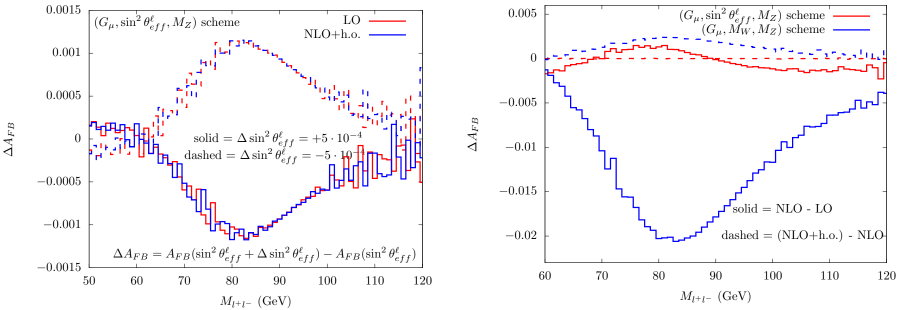
Δr

- LO $\simeq \frac{-1}{M_W^2}$
- CT $\simeq \frac{\delta M_W^2}{M_W^4}$
- $\Delta r = \Delta\alpha(s) - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\rm remn}$

$\Delta\tilde{r}$

- LO $\simeq \frac{-1}{c_W^2 M_Z^2}$
- CT $\simeq \frac{\delta M_Z^2}{c_W^2 M_Z^4} - \frac{2}{M_Z^2}\frac{s_W^2}{c_W^2}\frac{\delta\tilde{s}_W}{\tilde{s}_W}$
- $\Delta\tilde{r} = \Delta\alpha(s) - \Delta\rho + \Delta\tilde{r}_{\rm remn}$

The $(G_\mu, \sin\theta_{\rm eff}, M_Z)$ scheme: numerical results (1)



- sensitivity dominated by LO behaviour
- NLO EW corrections are smaller in the $(G_\mu, \sin\theta_{\rm eff}, M_Z)$ scheme
- H.O. effects smaller in the $(G_\mu, \sin\theta_{\rm eff}, M_Z)$ scheme

Universal fermionic corrections (H.O.) (1)

- Leading fermionic corrections to DY come from $\Delta\alpha$ and $\Delta\rho$

- They can be included at 2-loop rescaling the relevant parameters in the LO amplitudes (subtracting the terms $\mathcal{O}(\alpha)$ already present at NLO)

- In the OS scheme:

  $\alpha_0 \to \frac{\alpha_0}{1-\Delta\alpha(M_Z^2)}$, $s_W^2 \to s_W^2(1+\frac{\delta s_W^2}{s_W^2}) = s_W^2 + \Delta\rho c_W^2$

  g_L and g_R diagrams receive different corrections

- In the $\sin\theta$ scheme:

  $\alpha_0 \to \frac{\alpha_0}{1-\Delta\alpha(M_Z^2)}$, $G_\mu \to G_\mu(1+\Delta\rho)^2$

  overall factor, cancels in A_{FB}

Universal fermionic corrections (H.O.) (2)

$$\Delta\rho = \frac{\Sigma_T^{ZZ}(0)}{M_Z^2} - \frac{\Sigma_T^{WW}(0)}{M_W^2}$$

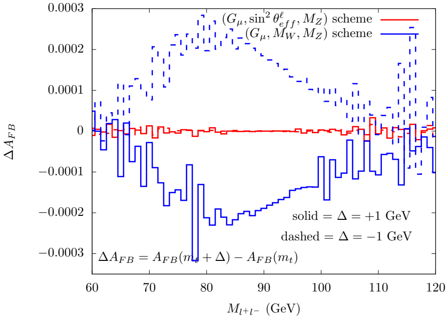
$\Delta\rho$ in H.O. calculation:

$$\Delta\rho = 3x_t[1+\rho^{(2)}x_t]\left[1 - \frac{2\alpha_S}{9\pi}(\pi^2+3)\right]$$

$$3x_t = \frac{3\sqrt{2}G_\mu m_t^2}{16\pi^2} = \Delta\rho^{(1)}$$

including 2-loop EW and QCD effects

The $(G_\mu, \sin\theta_{\rm eff}, M_Z)$ scheme: numerical results (2)



smaller parametric uncertainties from m_t dependence compared to the OS scheme

m_t^2 dependence from $\Delta\rho$

- OS scheme: $\Delta\rho$ enters Δr and δs_W. EW corrections affect γ and Z diagrams in a different way.
- $\sin\theta$ scheme: $\Delta\rho$ enters only Δr. Overall effect, cancels in A_{FB}.

Future steps

- systematic evaluation of the impact of several classes of available radiative corrections

- estimate of the impact of missing higher orders on the observables, and translation into a $\sin\theta_{\text{eff}}$ shift

It is crucial to understand which corrections/ approximations/ contributions must be under control with an accuracy target of 10^{-4} on $\sin^2\theta_{\text{eff}}$, e.g.

- photon induced processes?

- treatment of resonances and decay widths?

Conclusions

- We developed the $(G_\mu, \sin\theta_{\text{eff}}, M_Z)$ renormalization scheme, suitable for the extraction of $\sin\theta_{\text{eff}}$ at NLO EW
- The NLO EW (and H.O.) corrections in the $(G_\mu, \sin\theta_{\text{eff}}, M_Z)$ are smaller than in the OS schemes
- Smaller parametric dependence on m_t in the $(G_\mu, \sin\theta_{\text{eff}}, M_Z)$ scheme
- Future development:
  - assessment of the uncertainties form PS, matching and mixed QCD-EW effects
  - systematic comparison against OS-schemes/other codes (distribution level)
  - study of potential sources of uncertainties $\geq 10^{-4}$ on $\sin^2\theta_{\text{eff}}$

Backup Slides

Collins-Soper frame

θ^* measured in the Collins-Soper frame

$$\cos\theta^* = \frac{2p_z^{ll}}{|p_z^{ll}|} \frac{P_{l^-}^+ P_{l^+}^- - P_{l^-}^- P_{l^+}^+}{m_{ll}\sqrt{m_{ll}^2 + p_{T\,ll}^2}}, \qquad P^{\pm} = \frac{1}{\sqrt{2}}(E \pm p_z)$$