A Transverse-Polarization Null Test for Chirality-Violating Interference at the Z Pole

Observable-Level Reach in ϵ_{CV} with Secondary Sensitivity to Γ_Z

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Heavy Scalar Benchmark

Benchmark idea: a heavy scalar boson S generates a chirality-violating operator. The observed $\sin 2\phi$ coefficient ϵ is nonzero only when $P_T^- P_T^+ \neq 0$.

One clean theory example

$$\mathcal{L} \supset -S\Big(y_e\, \bar{e}_L e_R + y_\mu\, \bar{\mu}_L \mu_R\Big) + \mathrm{h.c.}$$

$$M_S \gg \sqrt{s}: \qquad \mathcal{L}_{\mathrm{eff}}^{\mathrm{CV}} = -\frac{y_e y_\mu}{M_S^2}\Big(\bar{e}_L e_R\Big)\Big(\bar{\mu}_R \mu_L\Big) + \mathrm{h.c.}$$

$$\Rightarrow \qquad \frac{d\sigma}{d\phi} \sim \frac{\sigma_0}{2\pi}\Big[1 + \big(\epsilon_Z^{\mathrm{SM}} + \epsilon_{\mathrm{CV}}\big)\sin 2\phi\Big], \qquad \epsilon_{\mathrm{CV}} \propto \frac{s\, y_e y_\mu}{M_S^2}$$

What the line shape sees

$$\Delta\sigma_{\mathrm{line}} \equiv \sigma_{\mathrm{line}} - \sigma_{\mathrm{line}}^{\mathrm{SM}} = c_2\, \epsilon_{\mathrm{CV}}^2 + \cdots$$

Although the harmonic is $(\epsilon_Z^{\mathrm{SM}} + \epsilon_{\mathrm{CV}})\sin 2\phi$, its linear piece vanishes after the ϕ integral. Hence the **SM-subtracted** rate response starts only at **quadratic order** in ϵ_{CV}.

What the $\sin 2\phi$ observable keeps

$$A_{\sin 2\phi} - A_{\sin 2\phi}^{\mathrm{SM}} = c_1\, \epsilon_{\mathrm{CV}} + \cdots$$

With $P_T^- P_T^+ \neq 0$, the $\sin 2\phi$ weight isolates the same term directly, so the sensitivity is already **linear** in ϵ_{CV}.

Linear Sensitivity in the Transversely Polarized ϕ Shape

Representative size of the extra NP effect

Assume some model generates an extra $\epsilon_{\rm CV} \sim 10^{-4}$, comparable to the study reference size.

If one uses only the line shape

$$\frac{\Delta\sigma_{\rm line}}{\sigma_{\rm SM}} \sim \epsilon_{\rm CV}^2 \approx \left(10^{-4}\right)^2 \approx 10^{-8}$$

This is the SM-subtracted quadratic suppression.

If one uses the transversely polarized ϕ shape

$$\Delta A_{\sin 2\phi} \sim \epsilon_{\rm CV} \approx 10^{-4}$$

$$1/\sqrt{N} \approx 2.7 \times 10^{-6} \qquad (N = 1.35 \times 10^{11})$$

$$\frac{\delta\sigma}{\sigma} \ll \frac{1}{\sqrt{N}}, \qquad \Delta A_{\sin 2\phi} \gg \frac{1}{\sqrt{N}}$$

Take-away: at today's study precision, an extra $\epsilon_{\rm CV} \sim 10^{-4}$ is effectively measurable only through the transversely polarized $\sin 2\phi$ observable; the line-shape effect is too suppressed.

How Γ_Z Enters

Key template statement

$$\mathcal{F}(\theta,\phi) = \mathcal{F}_0(\theta,\phi) + 4A_e P_T^- P_T^+ \frac{\Gamma_Z}{M_Z}(1-\cos^2\theta)\sin 2\phi$$

$$\mathcal{F}_0(\theta,\phi) \equiv (1+\cos^2\theta) + 2A_e A_f \cos\theta - A_f P_T^- P_T^+ (1-\cos^2\theta)\cos 2\phi$$

Only the second term changes when scanning Γ_Z, and it is the same $\sin 2\phi$ harmonic emphasized on the previous slides.

- Start from the $e^+e^- \to \mu^+\mu^-$ template in $(\cos\theta, \phi)$.
- Reweight with the polarized angular formula.
- Extract Γ_Z with a 2D binned likelihood scan.
- In this simplified setup, profiling A_e, A_f changes $\sigma(\Gamma_Z)$ negligibly.

Nominal setup

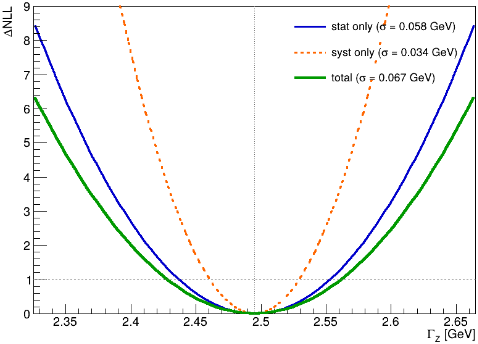
- 50×50 bins
- $P_T^- = 1\%$
- $P_T^+ = 70\%$
- same event-selection baseline throughout this study

Current Error Budget

Nominal fit and current-study error table

Source	Size
Γ_Z best fit	2.495 GeV
statistical error ($\mu\mu$ only)	± 0.138 GeV
visible benchmark stat. (assumption)	± 0.058 GeV
e^+ polarization $(69.3\%, 70.7\%)$	± 0.0245 GeV
e^- polarization $(0.99\%, 1.01\%)$	± 0.0241 GeV
$m_Z = 91.1880 \pm 0.0020$ GeV	± 0.000055 GeV
detector response estimate (from prior A_{FB} study)	< 1 MeV
combined studied syst.	0.0344 GeV
current-study total	0.067 GeV

Assumptions. Visible benchmark ($w_e = w_\mu = 1$, $w_\tau = 0.6$, $w_{qq} = 0.15$) gives $N_{\rm eff}/N_{\mu\mu} = 5.72$ and $\sigma_{\rm stat}^{\rm vis} \approx 0.058$ GeV. The < 1 MeV detector term is guided by prior A_{FB} work. Still excluded: SM backgrounds, lumi spectrum / beam-energy spread, and correlated nuisances.



Observable-Level Result

Observable-level sensitivity

$$\epsilon_Z^{\mathrm{SM}} \simeq 4A_e P_T^- P_T^+ \frac{\Gamma_Z}{M_Z} \approx 1.16 \times 10^{-4}$$

$$\sigma(\epsilon_{\mathrm{CV}}) \simeq \epsilon_Z^{\mathrm{SM}} \frac{\sigma(\Gamma_Z)}{\Gamma_Z}$$

$$\sigma(\Gamma_Z) = 0.058,\ 0.067\ \mathrm{GeV}$$

$$\Rightarrow \sigma(\epsilon_{\mathrm{CV}}) \approx 2.7,\ 3.1 \times 10^{-6}$$

$$95\%\ \mathrm{CL}: \qquad |\epsilon_{\mathrm{CV}}| \lesssim (5.3\text{–}6.1) \times 10^{-6}$$

$$\Lambda_{\mathrm{eff}} \equiv \sqrt{\frac{s}{|\epsilon_{\mathrm{CV}}|}} \Rightarrow \Lambda_{\mathrm{eff}}^{95} \gtrsim 37\text{–}40\ \mathrm{TeV}$$

Range shown for stat-only to current-study-total.

Refs.: Hikasa 1986
Burgess-Robinson 1991
M.-Pick et al. 2008

Experimental Interpretation

- This page simply propagates the fitted Γ_Z precision into the same $\sin 2\phi$ coefficient, using $\epsilon_Z^{\mathrm{SM}} \propto \Gamma_Z$.
- In the inclusive rate, the SM-subtracted BSM response begins at ϵ_{CV}^2, so small signals are strongly suppressed.
- With transverse polarization, the $\sin 2\phi$ observable keeps the **linear** ϵ_{CV} term, so a limit on $|\epsilon_{\mathrm{CV}}|$ is natural and complementary to line-shape measurements.

Take-away

1. The lineshape remains the primary Γ_Z observable; this method is **complementary**, not competitive on raw precision.
2. Its main added value is a $\sin 2\phi$ **null test** for chirality-breaking BSM interference, which can vanish in inclusive rates but survive linearly in the transverse ϕ shape.
3. In this CEPC-inspired benchmark, the $\mu\mu$-only template gives about 138 MeV statistical precision, while conservative visible-channel scaling gives about 58 MeV statistical precision and about 67 MeV current-study uncertainty.
4. The defendable publication path is an observable-level method paper targeting a few$\times 10^{-6}$ reach on $|\epsilon_{\rm CV}|$, with Γ_Z sensitivity presented as a secondary by-product.