

New Physics "right off the Z-pole" at Future Lepton Colliders

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 F_{max} as a function of D . Choudhury et. Al (2001)

couplings necessary to fit the bottom-quark production data at the Z-peak¹. Clearly, no Off the Z-Pole

1 Precision Measurements Future lepton colliders offer opportunity for precise measurements of the Z lineshape. 2 Interference Contribution As the SM $Z - \gamma$ interference contribution, shows linearly right off the Z pole scale.

3 Probing New Physics

Line-shape scan from a "humongous" right-off-the Z pole data can be utilized for searching possible NP contribution of interference type.

Figure 3. The differential cross section and *^AF B* from the *^Z*, and interfering term in *gg* ! *^b*¯*b*``⁺ ZQ, Fady Bishara (2023) Figure 3. The differential cross section and *^AF B* from the *^Z*, and interfering term in *gg* ! *^b*¯*b*``⁺

Off the Z-Pole: Observables Integrating (2.4) over the two body phase space *d*2, one obtains the analytical expression for the leading order total cross sections \mathcal{L}

$-$ *fermion Operators* \blacksquare addition, the final state typically involves two charged leptons or two charged leptons or two charged leptons of two charged leptons of two charged leptons of two charged leptons of two charged leptons or two char The Set of 4-fermion Operators. In addition, flavor fermion states the number of four-fermion states the number of four-fermion states the number of four-fermion, flavor in addition, flavor in addition, flavor in addition, forbid such scalar and tensor operators. The combination of interference and flavor conservation

$$
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i} c_{i} \mathcal{O}_{i} \frac{\partial_{\ell \ell}}{\partial_{\ell \ell}} \frac{\partial_{\ell \ell}}{\partial_{\ell \ell}} \frac{\partial_{\ell q}^{t}}{\partial_{\ell q}} \frac{\partial_{\ell q}^{t}}{\partial_{\ell q}} \frac{\partial_{\ell e}}{\partial_{\ell e}} \frac{\partial_{\ell e}}{\partial_{\ell e}} \frac{\partial_{\ell u}}{\partial_{\ell u}} \frac{\partial_{\ell d}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell e}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell e}} \frac{\partial_{\ell u}}{\partial_{\ell u}} \frac{\partial_{\ell e}}{\partial_{\ell u}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell d}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell d}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell d}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell d}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell d}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell d}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell d}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell d}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell d}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell d}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell d}}{\partial_{\ell d}} \frac{\partial_{\ell e}}{\partial_{\ell d}} \frac{\partial_{\ell u}}{\partial_{\ell d}} \frac{\partial_{\ell d}}{\partial_{\ell d}} \frac{\partial_{
$$

 $\mu^+\mu^-$ *q* \bar{q} $\mathcal{O}_{LL}^s \equiv \frac{1}{2} (\bar{L}\gamma^{\mu}L)(\bar{L}\gamma_{\mu}L)$ *O*^{*s*}_{*L*} $\mathcal{O}_{LO}^s \equiv (\bar{L}\gamma^{\mu}L)(\bar{Q}\gamma_{\mu}Q)$ $\mathcal{O}^t_{LL} = \frac{1}{2} \left(\bar{L} \gamma^\mu \sigma^a L \right) \left(\bar{L} \gamma_\mu \sigma^a L \right)$ $\left(\begin{array}{c} \mathcal{O}^{t}_{LQ} = \left(\bar{L}\gamma^{\mu}\sigma^{a}L\right)\left(\bar{Q}\gamma_{\mu}\sigma^{a}Q\right)\end{array}\right)$ $\mathcal{O}_{L\ell} = \left(\bar{L} \gamma^{\mu} L \right) \left(\bar{\ell} \gamma_{\mu} \ell \right)$ *O*_{*Q*}^{ℓ} = $(\bar{Q}\gamma^{\mu}Q)(\bar{\ell}\gamma_{\mu}\ell)$ $\mathcal{O}_{\ell\ell} = \frac{1}{2} \left(\bar{\ell} \gamma^\mu \ell \right) \left(\bar{\ell} \gamma_\mu \ell \right)$ $\overline{(\ell\gamma_{\mu}\ell)}$ $\overline{(\ell\gamma_{\mu}\ell)}$ $\overline{O_{Lu}} = (\overline{L}\gamma^{\mu}L)(\overline{q}_{u}\gamma_{\mu}q_{u})$ *i* $ee \rightarrow ff$ processes. $\mathcal{O}_{Ld} = (\bar{L}\gamma^{\mu}L) (\bar{q}_d\gamma_{\mu}q_d)$ $\mathcal{O}_{\ell u} = \left(\bar{\ell} \gamma^\mu \ell \right) \left(\bar{q}_u \gamma_\mu q_u \right)$ $\left(\begin{array}{c} {\cal O}_{\ell d} = \left(\bar{\ell} \gamma^\mu \ell \right) \left(\bar{q}_d \gamma_\mu q_d \right) \end{array} \right)$ *DµH*) can also contribute, but are constrained much better at the *Z* pole. $\mu^+\mu^-$ and $q\overline{q}$ $\left[\frac{1}{2}\left(\bar{\ell}_{\alpha} \ell\right)\right]$ $L\ell = (L^{\gamma}V^L) (V^{\gamma} \mu V)$ $L^{\gamma}L^{\gamma}$ $(L^{\gamma}A^{\mu})$ \overline{Q} ¯`*µ*` $\mathcal{O}_{\ell\ell} = \frac{1}{2} (\ell \gamma^{\mu} \ell) (\ell \gamma_{\mu} \ell)$ (¯*quµqu*) (¯*qdµqd*) $\mu^+ \mu^-$ and $\mu^$ max and corresponding NP scales ⇤min *ⁱ* ⌘ ^p4⇡*/ [|]ci[|]* in Han and W. Skiba (2005) $\frac{\mu}{\sqrt{3s}}$ $\frac{1}{\sqrt{7}}$. $\mathcal{O}_{LL} = \frac{1}{2} (L \gamma^r \delta^r L) (L \gamma_\mu \delta^r L)$ $\mathcal{O}_{LQ} = (L \gamma^r \delta^r L) (Q \gamma_\mu \delta^r Q)$ the SM contributions to the $C_{L\ell} = (E \gamma^L)$ (
 $C_{\ell\ell} = \frac{1}{2} (\bar{\ell} \gamma^{\mu} \ell)$ (ι

The dimension-6 four-fermion operators that interfere with $ee \rightarrow ff$ processes.

Future lepton colliders: *Z*-pole options When moving away from the *Z* pole, their sizes first increase with the distance *|s M*²

Taking CEPC as a blueprint: (Proposed Integrated Luminosity and Main Uncertainties) *Ma Ma*^{*t*} (*Me*^{*s*} 17 *M*^{*t*} 25 **a** 1*6 M*^{*t*} 27 *M*

10^{-6} Uncertainties? rates *N±*. So *A* is a↵ected by only the uncorrelated luminosity uncertainty. For the forward-

The experimental precision goals at the CEPC and FCC-ee in comparison with the LEP precision are summarized in Table 4. The luminosity uncertainty reduces from the LEP achieve-

Extending Statistical Uncertainties all cancel out and there is no need to put a correlation pattern for this item in Table 5. For the

Exercise Decrease significantly with these future large samples of Z pole data **AFB is defined at a**^{FB} input $1/\sqrt{N}$. (\sim **10⁻⁶)**

Figure 1 September 10 and 10 september 10 and 10 september 2 and 10 s

- **pse. On the contrary of the contrary of the contrary of the contrary, the contrary reduces from the luminosity** \cdot **Cuminosity uncertainty reduces from the LEP achieve**
	- parametric uncertainty
• (input) parametric uncertainty **between energy calibration**
	- **further expected to reach below 5 µ 105 in the uncorrelated to reach below 5 µ 105 in the uncorrelated luminosity uncer-**

LEP to only 0.1 MeV [10, 57].

For comparison, the collision energy uncertainty

Experimental Uncertainties The experimental precision goals at the CEPC and FCC-ee in comparison with the LEP

- Luminosity/flux
- beam energy calibration
- Polarization
- background processes tainty can leave e↵ect in asymmetry observations, its value shown is for the uncorrelated one. p*s* improves by more than 10 times from

Input Parameter (/Parametric) Uncertainties

Input Parameter (/Parametric) Uncertainties

Contribution to δA_{σ} Contribution to δA_{FB}

Uncertainties for Cross section Asymmetry A_{σ}

 $Uncertainties reaching $\mathcal{O}(10^{-4})$$ nus ruu \overline{A} $\frac{1}{2}$

- Theory Uncertainty: Missing higher Order $O(\alpha^3, \alpha^2 \alpha^s)$ $\frac{1}{2}$, $\frac{1}{2}$ Accfb(NLO)
- Theory Uncertainty: Input Parameter (δM_{z})
- Experimental Uncertainty: Luminosity and Energy
- \triangle Statistical Uncertainty: rises with decrease of σ (negligible)

1. Theory Uncertainty estimated with a relative 10^{-4} uncorrelated uncertainty on the \pm cross sections 2. A. Freitas, "Theory Needs for Future e+e− Colliders," Acta Phys. Polon. B 52 no. 8, (2021) 929–946.

Uncertainties for Cross section Asymmetry A_{FB} , A_{Pol}

- $\sim \mathcal{O}(10^{-4})$
- **External Parametric (δ** α **_{EM})** energy *A*eng, as well as the theoretical *A*th) on the inclusive asymmetry *A* (Left) and FB asymmetry *A*FB
- Missing Higher Order **van addition to the total values** of Higher Order also shown. These results take the CEPC luminosity projection as a conservative illustration.
- **all cancel out and there is no need to put a** correlation of $\mathcal{O}(\text{few } 10^{-5})$ p_{p} at two energy points, p_{p}

$(-)^{-4}$) **Fig. 6: The polarization as** $\mathcal{O}(10^{-4})$ **and its uncertainties** $\mathcal{O}(10^{-4})$

- $\begin{bmatrix} \texttt{`}} \texttt{`} \texttt{$ ⇤ = 1 TeV. For *A*pol, both SM (solid) and SM+NP (dashed) contributions are shown with LO (blue) and NLO
- ssing Higher Order **of the state of the state of the state (x** and collision energy (α^3 , α^2 α^5): $\mathcal{O}(10^{-5})$
	- 3 Experimentals: O (few 10^{-5})

Signal-Uncertainty Ratio

Representative Benchmark O_{tLO} (Λ_{NP} = 20 TeV)

Offset $\Delta = \pm 3$ GeV taken as decent choice, could extend further.

Projected Sensitivity

- A_{FB} reaches overall better bounds
- A_{σ} reaches with overall biggest bounds before experimental error (lumi)
- A_{FB} has controlled Experimental Uncertainty and best reach before theory
- A_{Pol} gives minor improvement

Combined Sensitivity and Last Slide

Thank you for listening!

- **Off-Z-pole asymmetry signals alone reach 10~30 TeV for the 4f-operators.**
- **Sensitivities reduced significantly by theory uncertainties.**
- **❖** Complementary bounds from higher **c.o.m data considering all realistic uncertainties will be interesting for further comparison and discussed.**

More Information on the $ee \rightarrow \mu\mu$ observable

More Information on the $ee \rightarrow \mu\mu$ observable

