

Nearly Degenerate Z - Z' System and its Phenomenologies

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How to detect a Z' ?

- Produce the Z' at a collider, then collect the decay products.
- Observe the Z -line shape, and investigate the off-shell Z' effects through the electroweak precision measurements. (S,T,U, V,W,X,Z,...)

“Direct Detection”

The Z' contribution to the cross sections for $e^+e^- \rightarrow f\bar{f}$ proceeds through an s -channel Z' exchange (when $f = e$, there are also t - and u -channel exchanges). For $M_{Z'} < \sqrt{s}$, the Z' appears as an $f\bar{f}$ resonance in the radiative return process where photon emission tunes the effective center-of-mass energy to $M_{Z'}$. The agreement between the LEP-II measurements and the SM predictions implies that either the Z' couplings are smaller than or of order 10^{-2} , or else $M_{Z'}$ is above 209 GeV, the maximum energy of LEP-II. In the latter case, the Z' exchange may be approximated up to corrections of order $s/M_{Z'}^2$, by the contact interactions

Details???

$\lesssim 300\text{GeV}???$

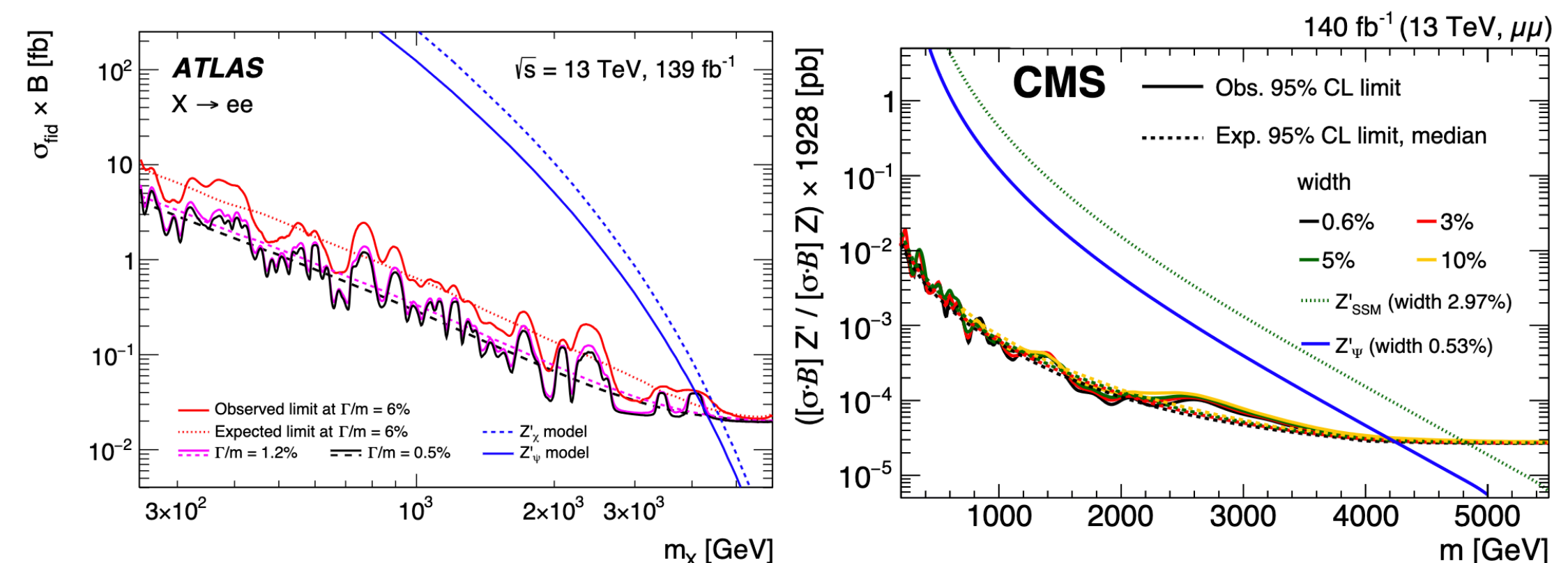
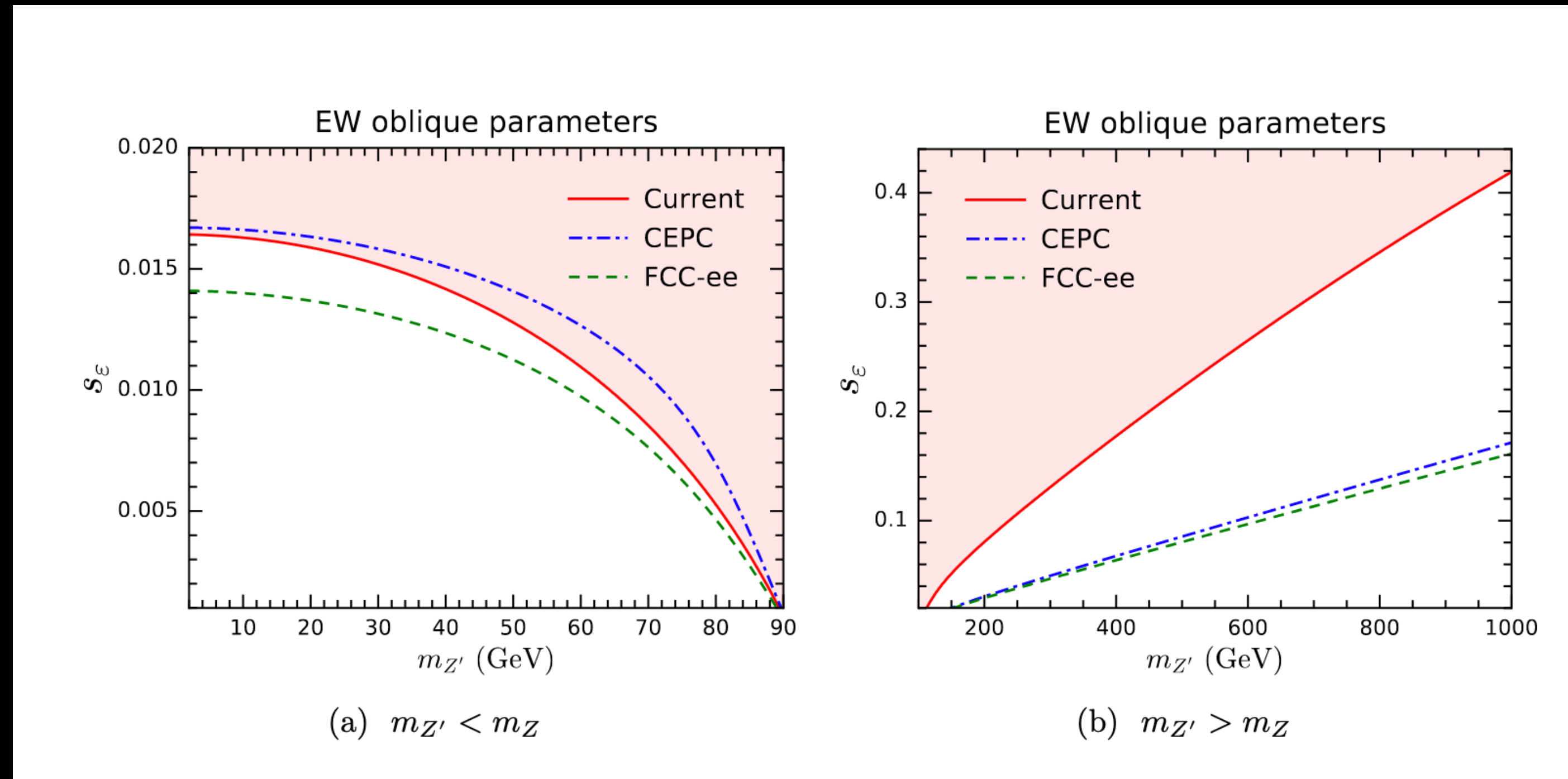


Figure 87.1: Upper limits on the cross section for Z' production times the branching fraction for $Z' \rightarrow e^+e^-$ (left panel, set by ATLAS [22]) or $Z' \rightarrow \mu^+\mu^-$ (right panel, set by CMS [23]) as a function of $M_{Z'}$. The lines labeled by Z'_ψ and Z'_χ are theoretical predictions for the $U(1)_{10+x5}$ models in Table 87.1 with $x = -3$ and $x = +1$, respectively, for g_z fixed by an E_6 unification condition. The Z'_{SSM} line corresponds to Z' couplings equal to those of the Z boson.

“Oblique detection”



arXiv:2003.02516. $m_{Z'} \approx m_Z$?

Model

ϵ_W

ϵ_{BW}

$$\mathcal{L}_{\text{eff}} \supset -\frac{\epsilon_B}{2} \hat{Z}'_{\mu\nu} B^{\mu\nu} - \frac{1}{2\Lambda_W^2} \hat{Z}'_{\mu\nu} W^{a\mu\nu} H^\dagger \sigma^a H - \frac{1}{2\Lambda_{BW}^2} B_{\mu\nu} W^{a\mu\nu} H^\dagger \sigma^a H$$

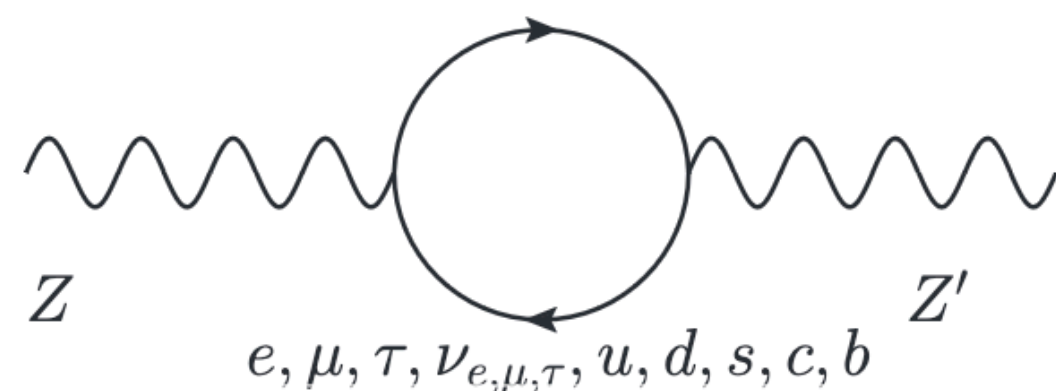
$$- \frac{1}{4\Lambda_{WW}^4} W^{a\mu\nu} H^\dagger \sigma^a H W_{\mu\nu}^b H^\dagger \sigma^b H,$$

ϵ_{WW}

“Perturbativity”?

$$\begin{aligned}
 \alpha S' = & \frac{4gg'}{g^2 + g'^2} \epsilon_{BW} - \frac{g^2 g'^2 v^2 (4m_{Z'}^2 - g^2 v^2)}{4(g^2 + g'^2)(m_{Z'}^2 - m_Z^2)^2} \epsilon_B^2 + \frac{gg'v^2 [4(g^2 + g'^2)m_{Z'}^2 - (g^4 + g'^4)v^2]}{4(g^2 + g'^2)(m_{Z'}^2 - m_Z^2)^2} \epsilon_B \epsilon_W \\
 & - \frac{g^2 g'^2 v^2 (4m_{Z'}^2 - g'^2 v^2)}{4(g^2 + g'^2)(m_{Z'}^2 - m_Z^2)^2} \epsilon_W^2 + \frac{g^2 g' [4m_{Z'}^2 - (g^2 - g'^2)v^2]}{(g^2 + g'^2)(m_{Z'}^2 - m_Z^2)^2} \epsilon_B \delta m^2 \\
 & - \frac{gg'^2 [4m_{Z'}^2 + (g^2 - g'^2)v^2]}{(g^2 + g'^2)(m_{Z'}^2 - m_Z^2)^2} \epsilon_W \delta m^2 + \frac{4g^2 g'^2 (6g^2 g'^2 - g^4 - g'^4)}{(g^4 - g'^4)^2} \epsilon_{BW}^2 \\
 & - \frac{4gg'^3}{(g^2 + g'^2)^2} \epsilon_{WW} \epsilon_{BW} + \frac{8g^3 g'^3}{(g^2 - g'^2)^2 (g^2 + g'^2) v^2} \epsilon_{BW} \delta v^2 + \frac{3g^6 g'^2 - 2g^4 g'^4 + 3g^2 g'^6}{(g^4 - g'^4)^2 v^4} (\delta v^2)^2 \\
 & - \frac{4g^2 g'^2}{(g^2 + g'^2)(m_{Z'}^2 - m_Z^2)^2} (\delta m^2)^2,
 \end{aligned} \tag{30}$$

What had happened for a nearly-degenerate particle pair?



Can this diagram be ignored?

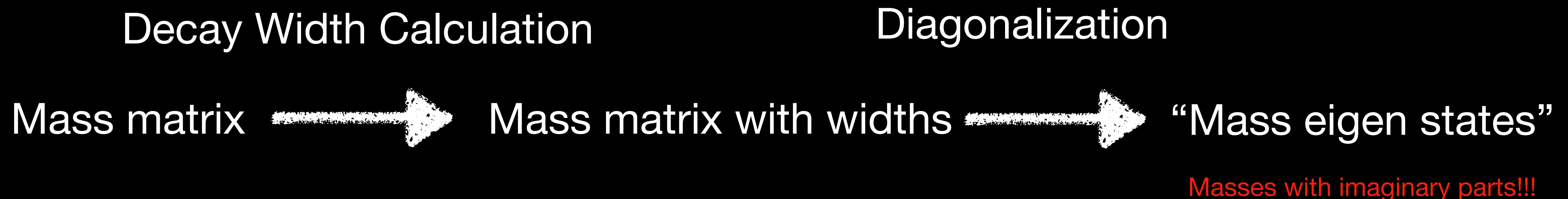
$K^0 \leftrightarrow \bar{K}^0$ System

- $\mathcal{H}_{\text{total}} = \mathcal{H}_0 + \mathcal{H}_{\text{decay}}$
- $\mathcal{H}_0 = \mathcal{H}_0^\dagger, \mathcal{H}_{\text{decay}} \neq \mathcal{H}_{\text{decay}}^\dagger$
- Particle widths affect the “Eigen states”!

Nonstandard Diagonalization Scheme



Traditional Scheme



[90] G. Cacciapaglia, A. Deandrea, and S. De Curtis, “Nearby resonances beyond the Breit-Wigner approximation,” *Phys. Lett. B* **682** (2009) 43–49, [arXiv:0906.3417 \[hep-ph\]](#).

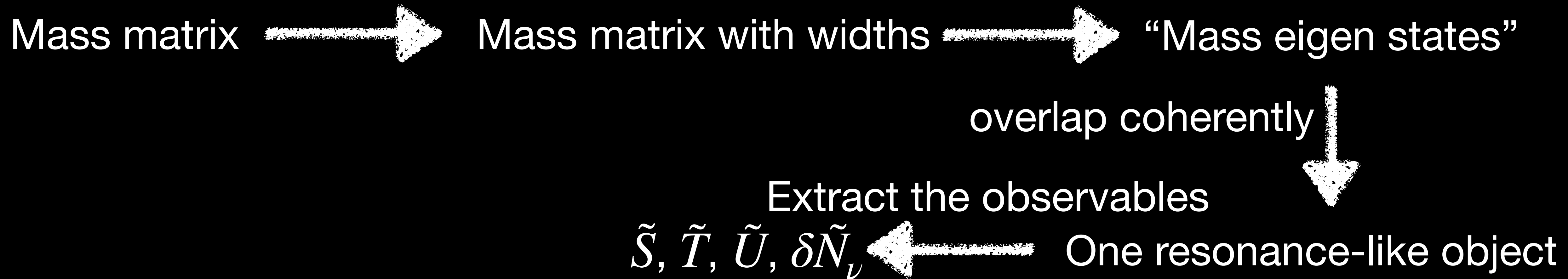
New Diagonalization Scheme

- What is the meaning of mixing the real scalars to form some kind of “complex-like fields”?
- To understand this, resumming the “string diagrams”

$$\sum_{t=0}^{\infty} \frac{i}{p^2 I_{n \times n} - \mathcal{M}_s^2} \left[(-i) \text{Im}(\Sigma(p^2)) \frac{i}{p^2 I_{n \times n} - \mathcal{M}_s^2} \right]^t = \frac{i}{p^2 I_{n \times n} - \mathcal{M}_s^2 - \text{Im}(\Pi(p^2))},$$

Z-Z' mixing

$$\begin{aligned}\mathcal{M}_V^{2'} &= \mathcal{M}_V^2 + i(C_{X \leftrightarrow Y})_{3 \times 3} \\ &= \begin{pmatrix} m_{\hat{Z}'}^2 + ic_{\hat{Z}'\hat{Z}'} & \hat{g}'(\delta m^2 - \frac{ic_{\hat{Z}'\hat{Z}}}{\sqrt{\hat{g}'^2 + \hat{g}^2}}) & -\hat{g}(\delta m^2 - \frac{ic_{\hat{Z}'\hat{Z}}}{\sqrt{\hat{g}'^2 + \hat{g}^2}}) \\ \hat{g}'(\delta m^2 - \frac{ic_{\hat{Z}'\hat{Z}}}{\sqrt{\hat{g}'^2 + \hat{g}^2}}) & \frac{\hat{g}'^2}{4}(\hat{v}^2 + \delta v^2 + \frac{4ic_{\hat{Z}\hat{Z}}}{\hat{g}'^2 + \hat{g}^2}) & -\frac{\hat{g}'\hat{g}}{4}(\hat{v}^2 + \delta v^2 + \frac{4ic_{\hat{Z}\hat{Z}}}{\hat{g}'^2 + \hat{g}^2}) \\ -\hat{g}(\delta m^2 - \frac{ic_{\hat{Z}'\hat{Z}}}{\sqrt{\hat{g}'^2 + \hat{g}^2}}) & -\frac{\hat{g}'\hat{g}}{4}(\hat{v}^2 + \delta v^2 + \frac{4ic_{\hat{Z}\hat{Z}}}{\hat{g}'^2 + \hat{g}^2}) & \frac{\hat{g}^2}{4}(\hat{v}^2 + \delta v^2 + \frac{4ic_{\hat{Z}\hat{Z}}}{\hat{g}'^2 + \hat{g}^2}) \end{pmatrix},\end{aligned}$$



“Pseudo-LEP” experiment

- Some LEP data in the literature, but inapplicable by us theorists.
- Adopt the $\sqrt{s} = [88.2, 89.2, 90.2, 91.2, 92.2, 93.2, 94.2]\text{GeV}$ as samples.
- Simulate the events at an electron-positron collider with these center-of-mass energy samples with/without Z' settings.
- Compare the difference of them to extract the oblique parameters.

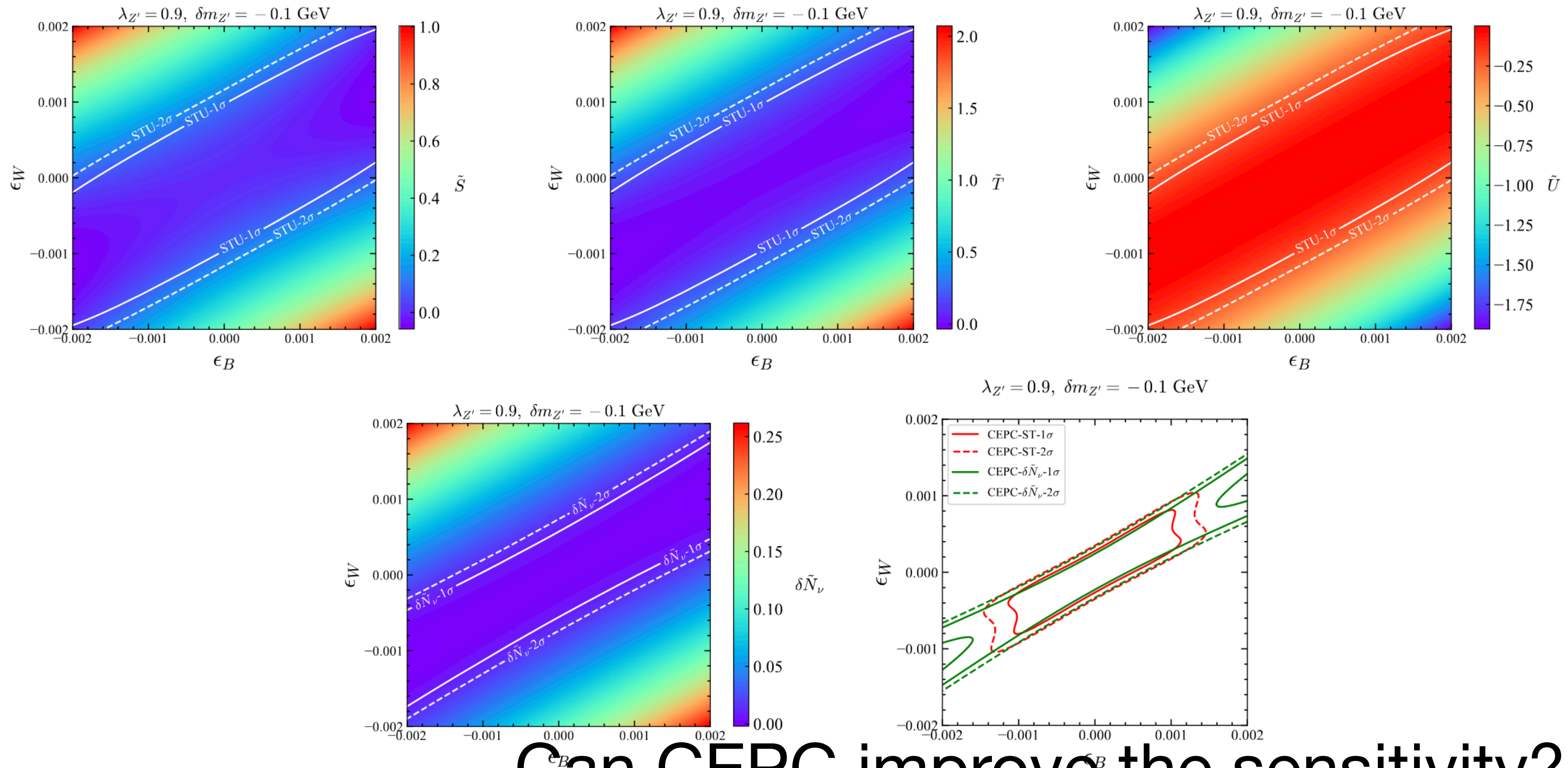
“Pseudo-LEP” experiment

- “Pseudo-SM template”: modify the Feynrules SM-files. change the \tilde{S} , \tilde{T} , \tilde{U} , $\delta\tilde{N}_\nu$. Z-lineshape simulations.
- Z' model comparison with the “Pseudo-SM template” to determine the best fitted \tilde{S} , \tilde{T} , \tilde{U} , $\delta\tilde{N}_\nu$.

Three scenarios

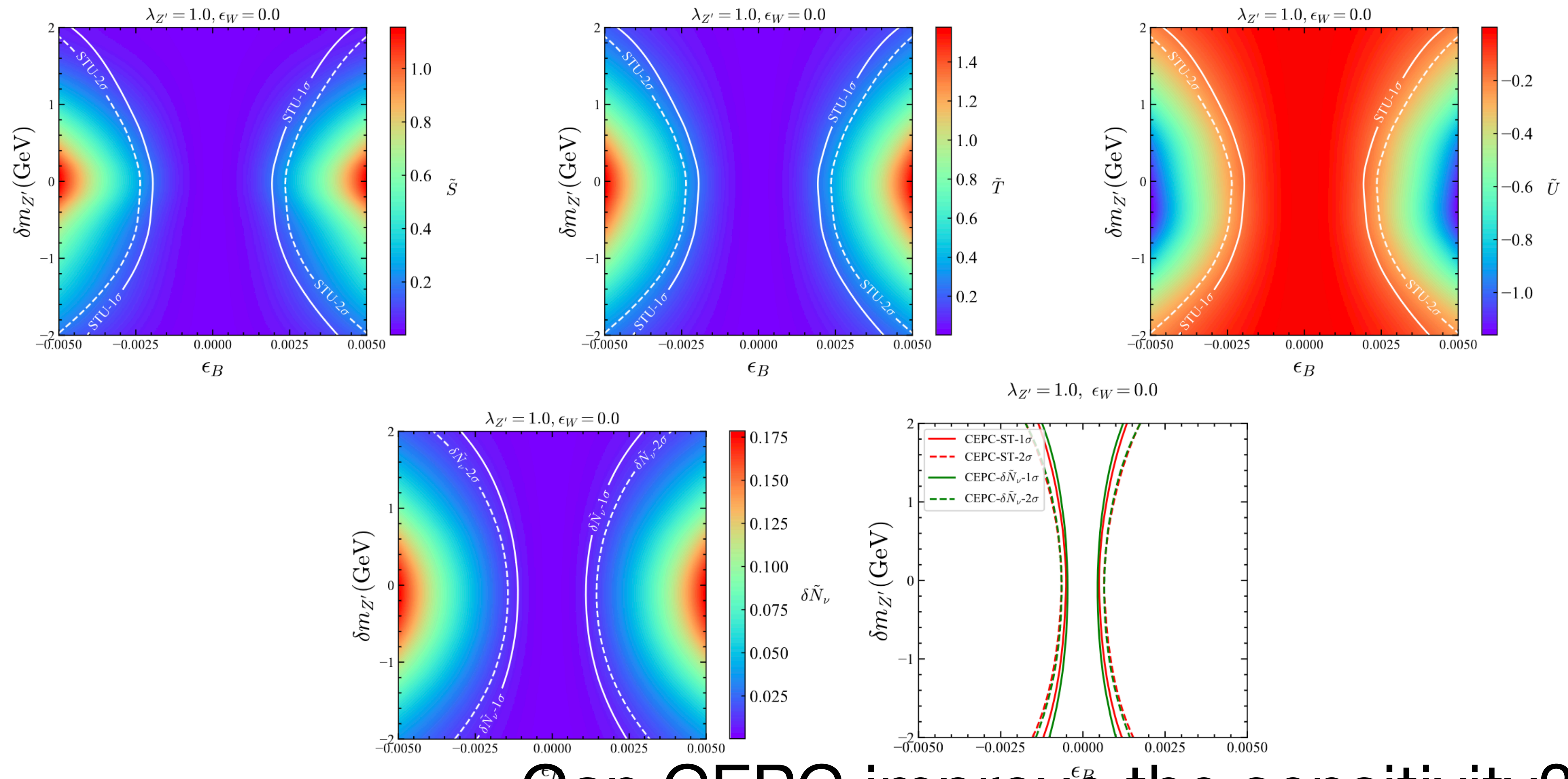
- $Z' \rightarrow$ invisible
- $Z' \rightarrow$ SM, universality.
- $Z' \rightarrow$ SM, $e - \mu$ asymmetry.

Examples of results



Can CEPC improve the sensitivity?

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Can CEPC improve the sensitivity?

Summary

- Non-standard scheme to diagonalize the nearly-degenerate bosonic system.
- Show the sensitivity of a LEP-like pseudo-collider in detecting the Z' “obliquely” when looking through the Z line-shape.
- Preliminarily predict the sensitivity of a CEPC-like collider.