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 $e^+e^- \to f\bar{f}$ 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???

$\lesssim$ 300Gev???

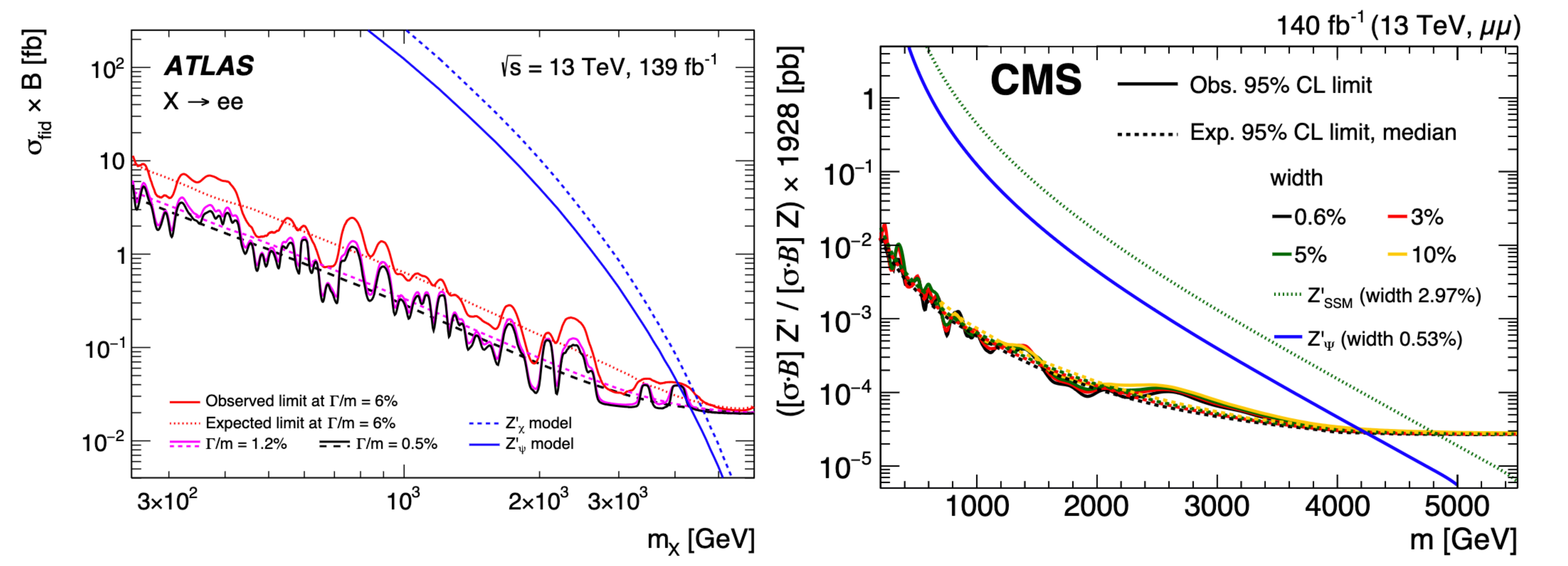
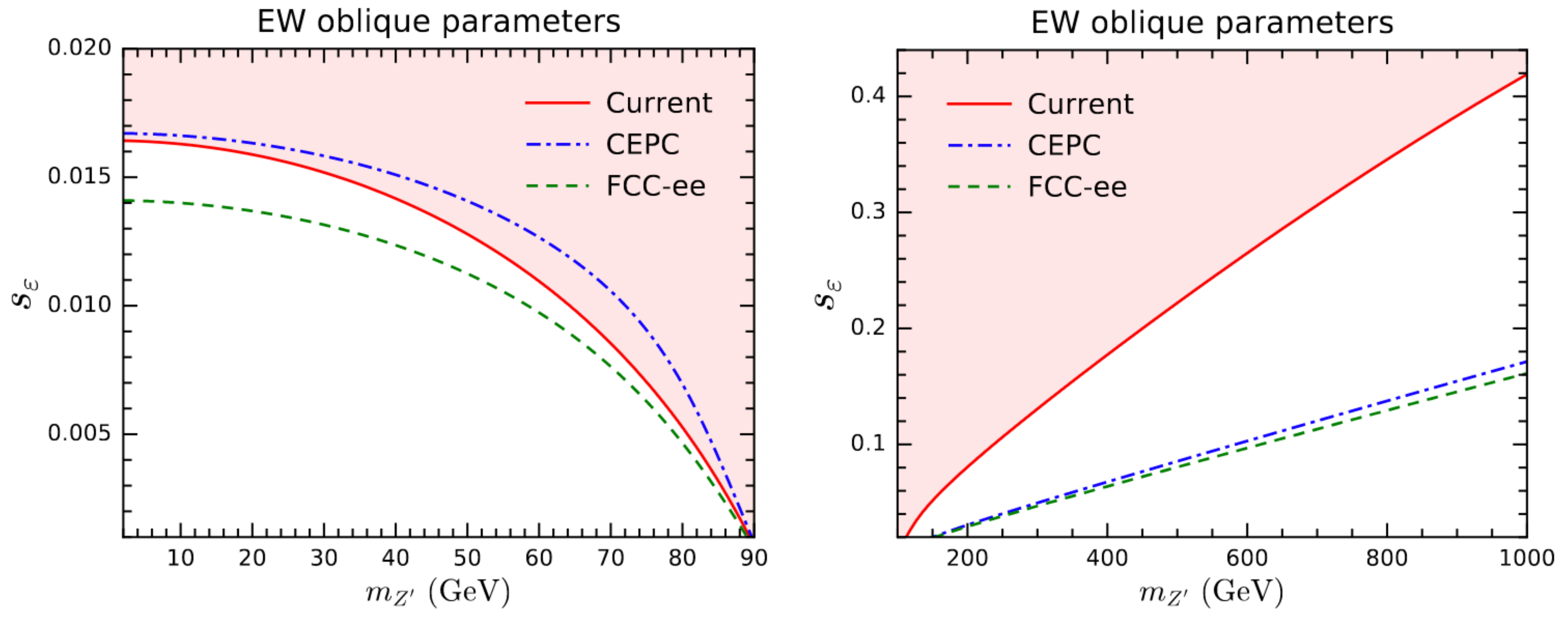


Figure 87.1: Upper limits on the cross section for Z' production times the branching fraction for $Z' \to e^+e^-$ (left panel, set by ATLAS [22]) or $Z' \to \mu^+\mu^-$ (right panel, set by CMS [23]) as a function of $M_{Z'}$. The lines labeled by Z'_ψ and Z'_χ are theoretical predictions for the $U(1)_{10+x\bar{5}}$ models in Table 87.1 with $x = -3$ and $x = +1$, respectively, for g_z fixed by an E_6 unification condition. The $Z'_{\rm SSM}$ line corresponds to Z' couplings equal to those of the Z boson.

“Oblique detection”



(a) $m_{Z'} < m_Z$ (b) $m_{Z'} > m_Z$

Juebin Lao, et. al., arXiv:2003.02516. $m_{Z'} \approx m_Z$?

Model

ϵ_W ϵ_{BW}

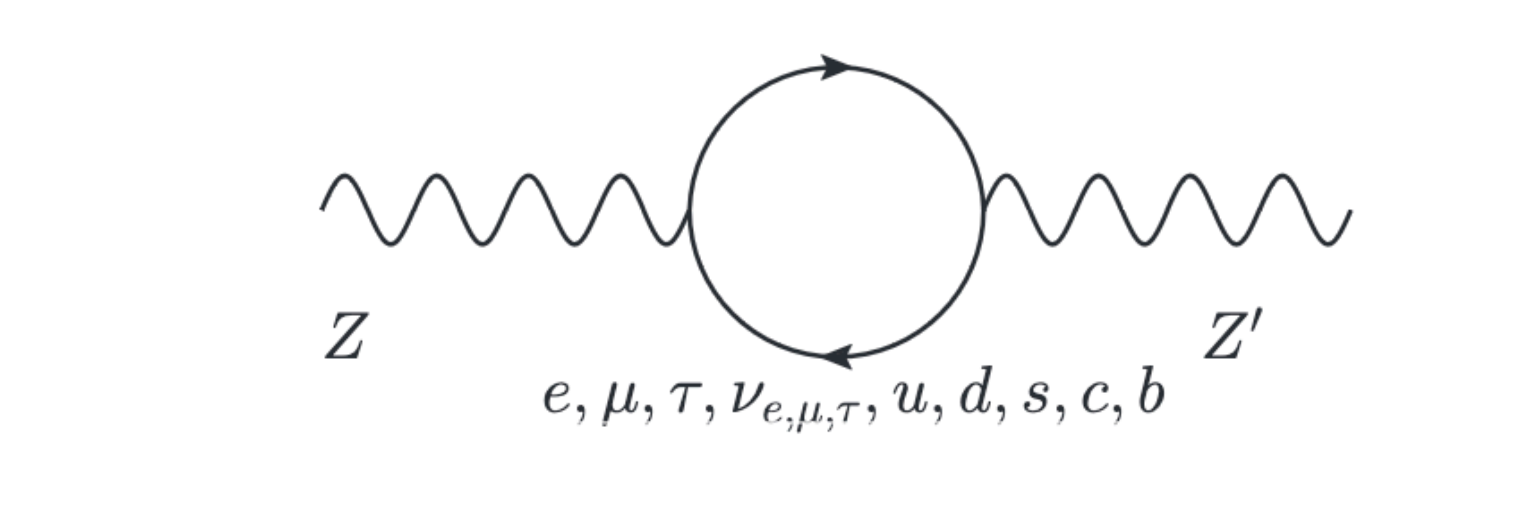
$$\mathcal{L}_{\text{eff}} \supset -\frac{\epsilon_B}{2}\hat{Z}'_{\mu\nu}B^{\mu\nu} - \frac{1}{2\Lambda_W^2}\hat{Z}'_{\mu\nu}W^{a\mu\nu}H^\dagger\sigma^a H - \frac{1}{2\Lambda_{BW}^2}B_{\mu\nu}W^{a\mu\nu}H^\dagger\sigma^a H$$
$$-\frac{1}{4\Lambda_{WW}^4}W^{a\mu\nu}H^\dagger\sigma^a H W^b_{\mu\nu}H^\dagger\sigma^b H,$$

ϵ_{WW}

“Perturbativity”?

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

What had happened for a nearly-degenerate particle pair?



Can this diagram be ignored?

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

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

Nonstandard Diagonalization Scheme

Diagonalization — Decay Width Calculation

Mass matrix → Mass eigenstates → Breit-Wigner Propagator

Traditional Scheme

Decay Width Calculation — Diagonalization

Mass matrix → Mass matrix with widths → "Mass eigen states"

Masses with imaginary parts!!!

[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"

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

Z-Z' mixing

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

Mass matrix → Mass matrix with widths → "Mass eigen states"

↓ overlap coherently

One resonance-like object → Extract the observables → $\tilde{S}, \tilde{T}, \tilde{U}, \delta\tilde{N}_\nu$

“Pseudo-LEP” experiment

- Some LEP data in the literature, but inapplicable by us theorists.
- Adopt the $\sqrt{s} = [88.2, 89.2, 90.2, 91.2, 92.2, 93.2, 94.2]\mathrm{GeV}$ 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.

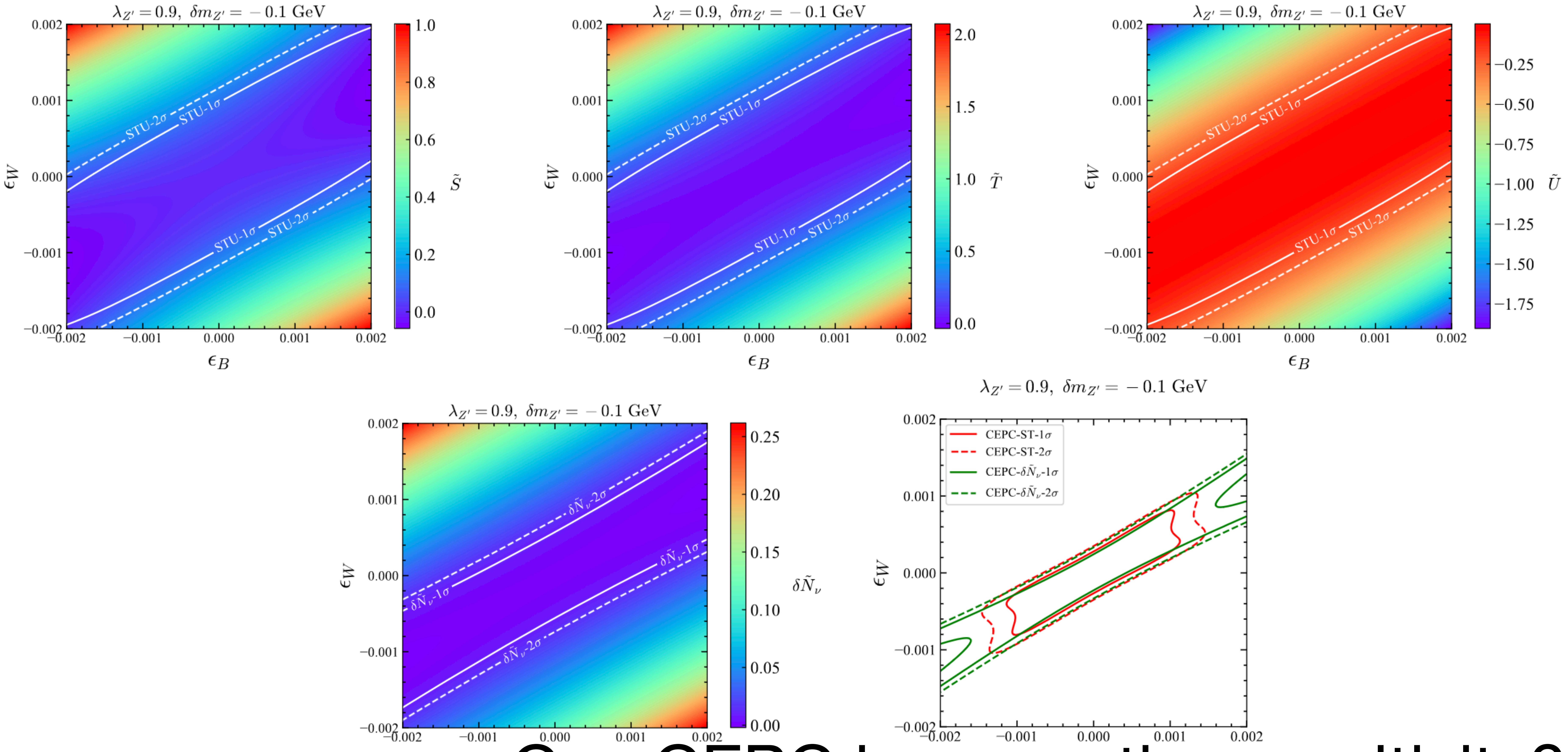
“Pseudo-LEP” experiment

- “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

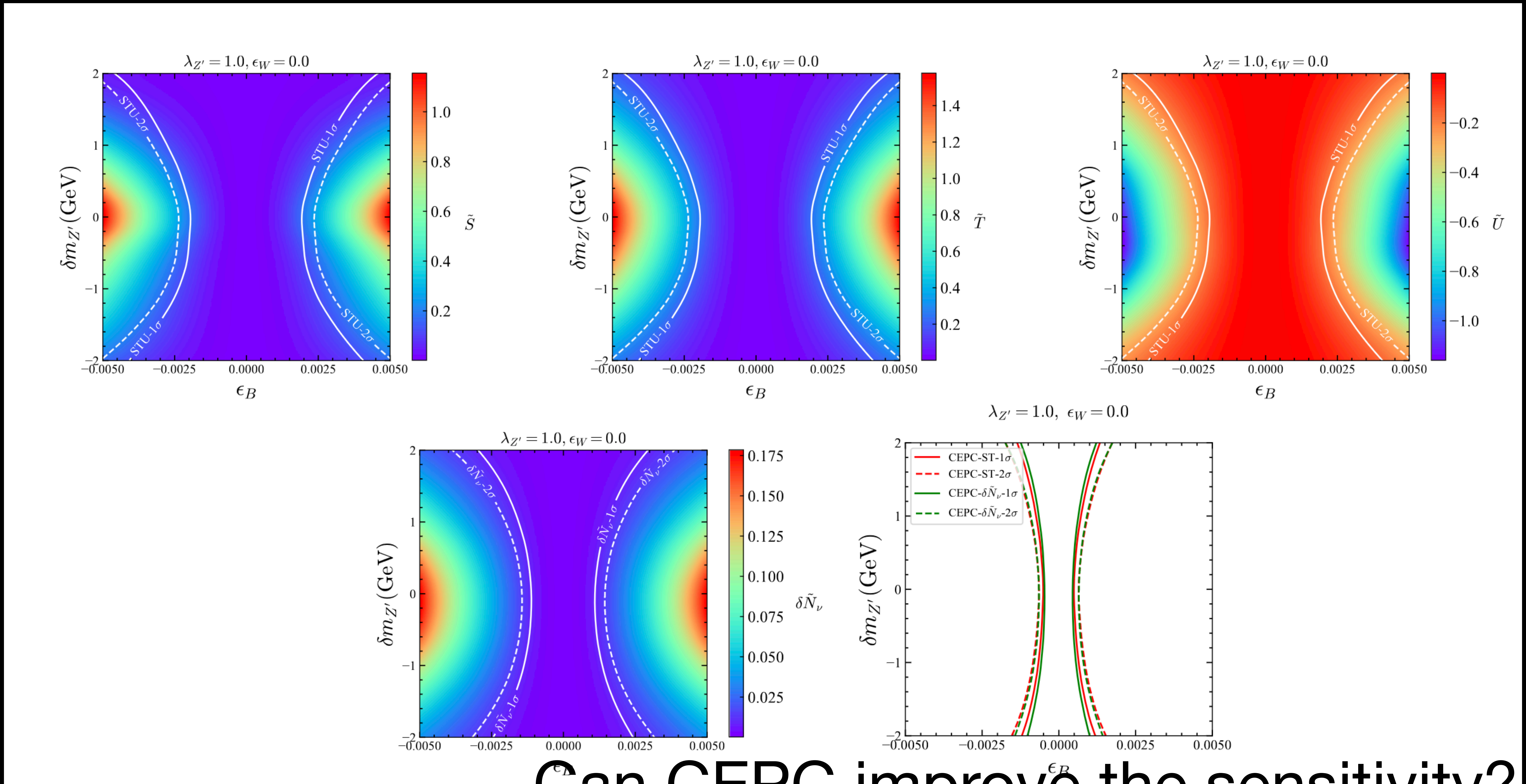
- $Z' \to \mathrm{invisible}$
- $Z' \to \mathrm{SM}$, universality.
- $Z' \to \mathrm{SM}$, $e - \mu$ asymmetry.

Examples of results



Can CEPC improve the sensitivity?

Examples of results



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.