Dark Z boson and the W boson mass anomaly

Kazuki Enomoto
(KAIST)

Based on

- Hooman Davoudiasl[1], KE[2], Hye-Sung Lee[2], Jiheon Lee[2], William J. Marciano[1], Phys. Rev. D108 (2023) 115018 [arXiv:2309.04060[hep-ph]]

1. BNL, 2. KAIST

Extension of gauge symmetries

Problems in the Standard Model (SM)

- Unexplained phenomena ν oscillation, dark matter, baryon asymmetry, …
- Theoretical problems Unification of gauge interactions, gravity, …
- Experimental anomalies Muon g-2, B anomaly, W boson mass anomaly, …

We need new physics!

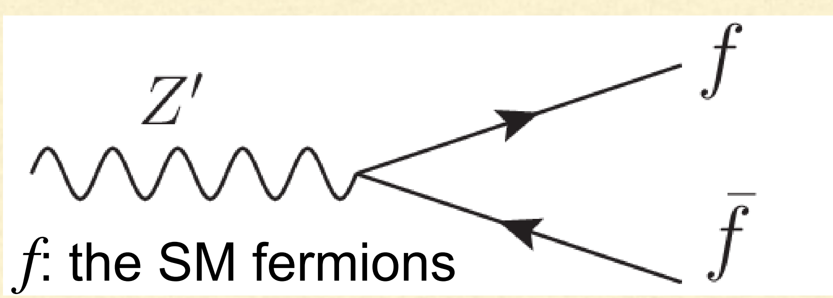
A new $U(1)$ gauge symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)$$

New force!!

New gauge boson Z'

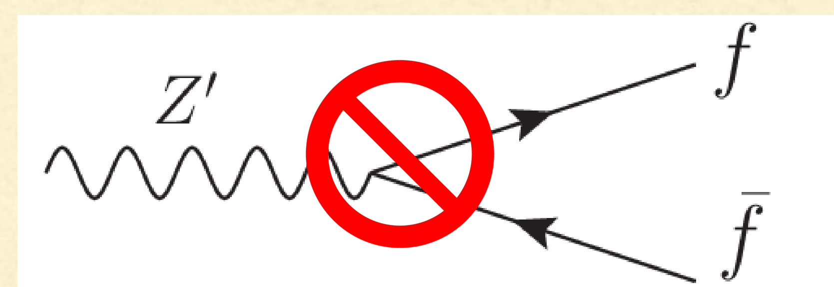
①



f carries $U(1)$ charge

e.g.) $U(1)_{B-L}$ extension

②



f does NOT carry $U(1)$ charge

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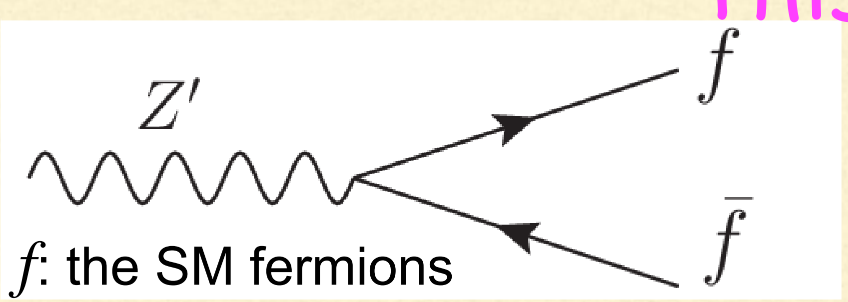
① 

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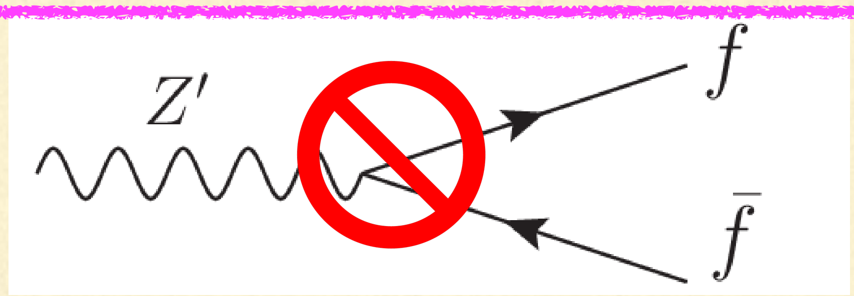
② 

f does NOT carry $U(1)$ charge

e.g.) dark photon model

Dark photon model

Dark gauge symmetry: $U(1)_d$ (The SM fermions don't carry the dark charge Q_d)

$$\mathcal{L} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{\varepsilon}{2c_W}\hat{B}_{\mu\nu}\hat{Z}_d^{\mu\nu} - \frac{1}{4}\hat{Z}_{d\mu\nu}\hat{Z}_d^{\mu\nu}$$

$c_W = \cos\theta_W$

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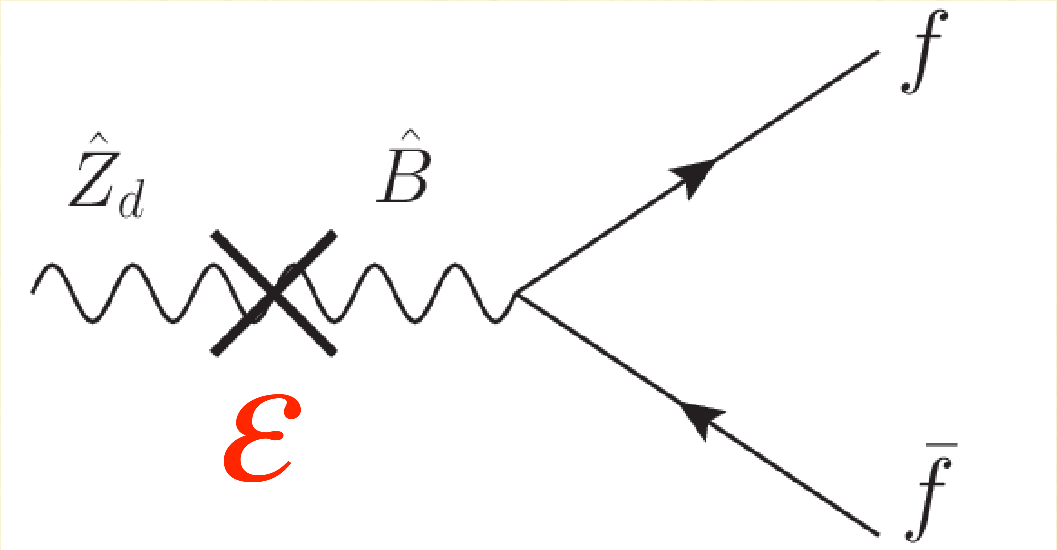

Kinetic mixing

The SM fermions interact with $\hat{Z}_d$

via kinetic mixing Holdom, PLB (1986)

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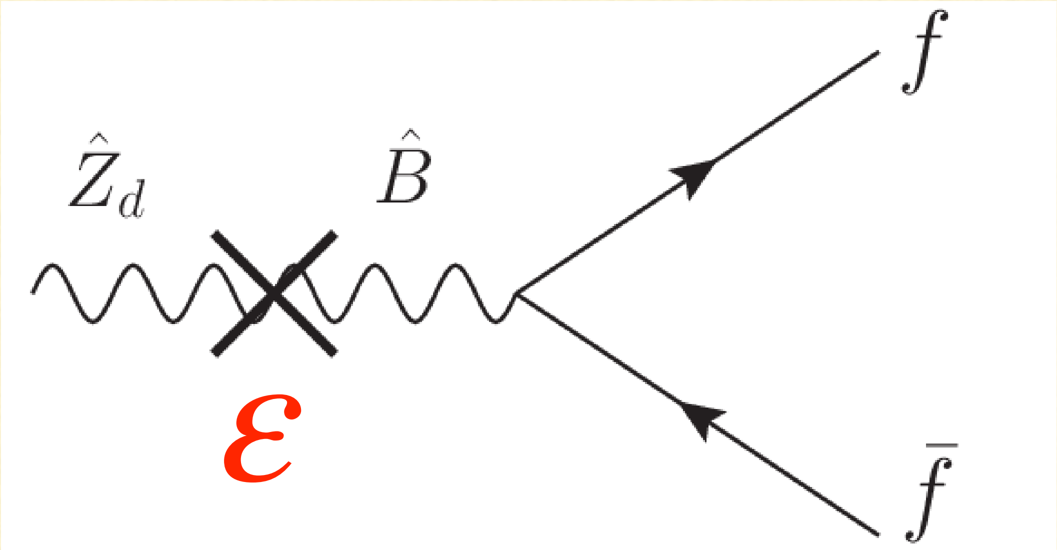

The SM fermions interact with $\hat{Z}_d$ via kinetic mixing Holdom, PLB (1986)

$U(1)_d$ **symmetry breaking:** $\hat{Z}_d$ get the mass term by a singlet VEV

Mass eigenstates: γ, Z, and Z_d New physical gauge boson

$$\mathcal{L}_d \simeq -e\varepsilon J^\mu_{\text{em}} Z_{d\mu} \quad (m^2_{Z_d} \ll m^2_Z)$$

Z_d couples J^μ_{em} (Dark photon)

Dark Z model

Davoudiasl, Lee, Marciano, 1203.2947

Dark gauge symmetry: $U(1)_d$

Nature of gauge symmetry breaking is quite different

Higgs sector: $\Phi_1 : \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}, 0\right)$ $\Phi_2 : \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}, 1\right)$ $\Phi_d : \left(\mathbf{1}, \mathbf{1}, 0, 1\right)$

$U(1)_d$ **symmetry breaking:** $\hat{Z}_d$ get the mass term by the singlet VEV (v_d) and the doublet VEV (v_2)

Mass matrix of neutral gauge bosons

$$\begin{pmatrix} \tilde{m}_Z^2 & -\tilde{m}_Z^2(\varepsilon_Z + \varepsilon t_W) \\ -\tilde{m}_Z^2(\varepsilon_Z + \varepsilon t_W) & \tilde{m}_{Z_d}^2 \end{pmatrix}$$

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New source of mixing!

Mass mixing

independent of ε

$$\varepsilon_Z = \frac{2g_d}{g_Z}\frac{v_2^2}{v^2}$$

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$$\mathcal{L}_d \simeq -\left(e\varepsilon J_{\text{em}}^\mu + \frac{g}{2c_W}\varepsilon_Z J_{\text{NC}}^\mu\right) Z_{d\mu}$$

Z_d couples to J_{NC}^μ

$(m_{Z_d}^2 \ll m_Z^2)$ Dark Z boson

Dark Z model

$$\mathcal{L}_d \simeq -\left(e\varepsilon J^{\mu}_{\rm em} + \frac{g}{2c_W}\varepsilon_Z J^{\mu}_{\rm NC}\right) Z_{d\mu}$$

Z_d predicts various distinctive phenomena

- Parity violation @ low energies — 1203.2947 1507.00352 2309.04060
- Rare meson decays — 1203.2947 2210.15662 1402.3620
- Higgs exotic decays — 1304.4935
- Collider signals — 1401.2164 2205.10304 2209.03240

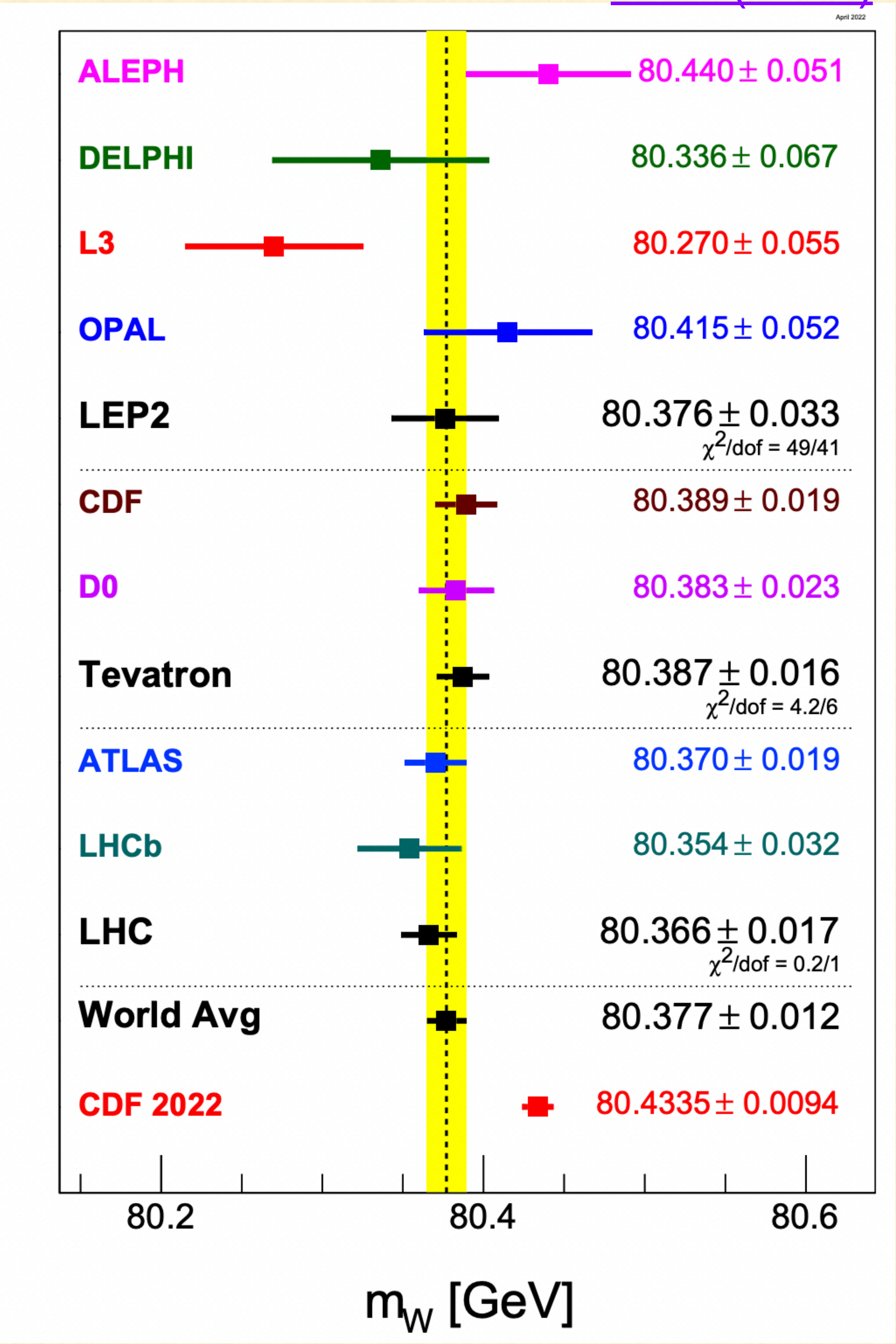
In this talk,

The W boson mass anomaly

in the dark Z boson

W boson mass (m_W) anomaly

PDG (2022)



W boson mass measurements

$$pp(p\bar{p}) \to W \to \ell\nu, \quad e^+e^- \to W^+W^-$$

Before Apr. 2022,

$$m_W^{\rm World-ave.} = 80.377(12)$$

$$m_W^{\rm SM} = 80.356(06)$$ PDG (2022)

Good agreement

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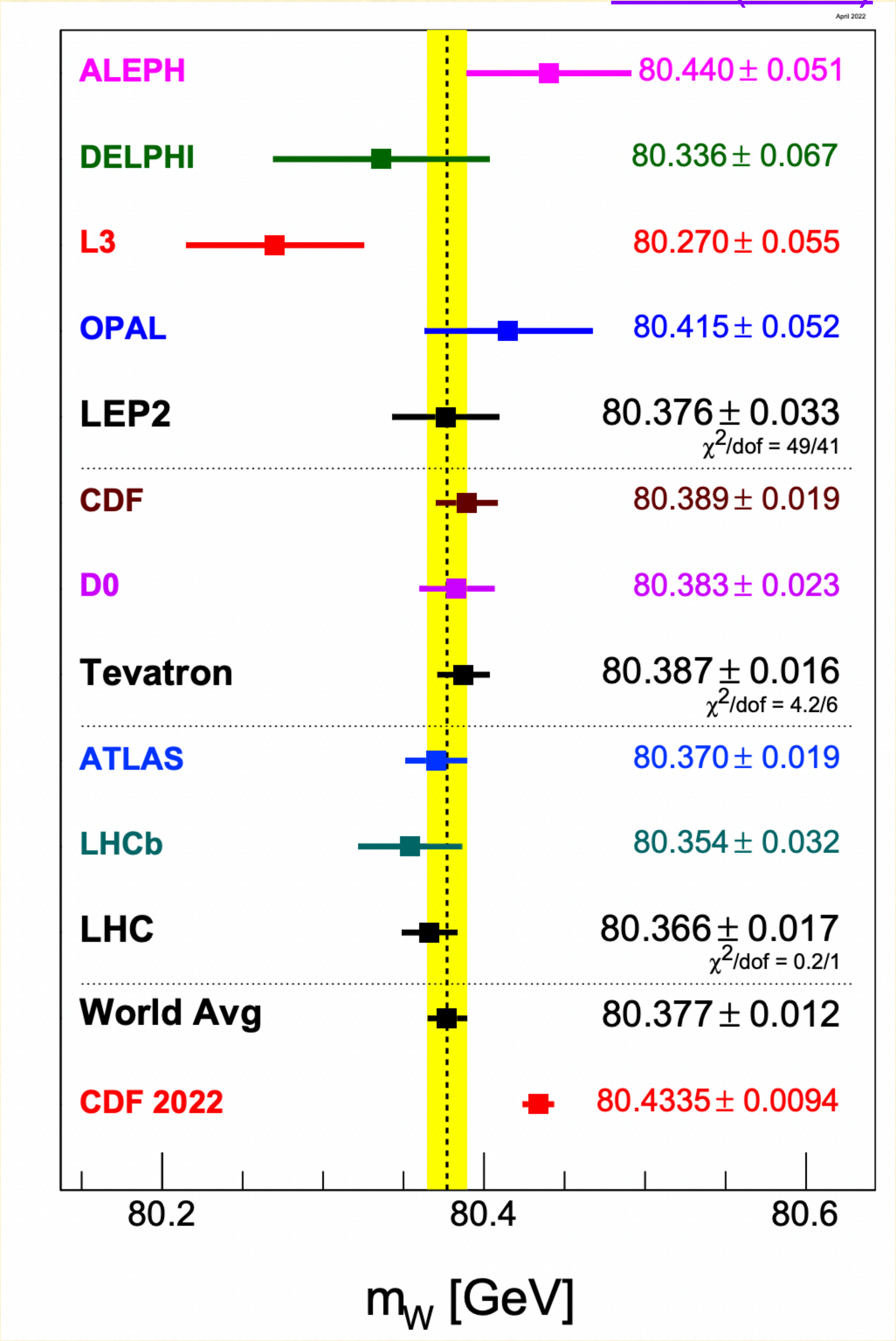

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The CDF-II result CDF, Science (2022)

$$m_W^{\mathrm{CDF-II}} = 80.4335(94)$$

7σ deviation!

New phyiscs?

Need to enhance m_W

m_W anomaly and new physics

New physics effect: S, T, U parameters Peskin, Takeuchi, PRL (1990)

$$\Delta m_W^2 \equiv m_W^2 - (m_W^{\rm SM})^2 = m_Z^2 c_W^2 \left(-\frac{\alpha S}{2(c_W^2 - s_W^2)} + \frac{\alpha T}{1 - t_W^2} + \frac{\alpha U}{4 s_W^2} \right)$$

$$\Delta m_W^2 = (m_W^{\rm CDF-II})^2 - (m_W^{\rm SM})^2 \simeq \boxed{12.5 {\rm GeV}^2}$$

$$\Rightarrow -0.93S + 1.4T + 1.1U \simeq 0.25$$

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$$\rightarrow -0.93 S + 1.4 T + 1.1 U \simeq 0.25$$

EW global fit (w/ the CDF-II result) Lu *et al*, 2204.03796

$$S = 0.06(10) \quad T = 0.11(12) \quad U = 0.14(09)$$

The dark photon model CANNOT explain the anomaly under this constraint. Cheng *et al*, 2204.10156 Thomas, Wang, 2205.01911 Asagi *et al*, 2204.05283

Dark Z bosons and W boson mass anomaly

In the dark Z model, couplings & mass of Z boson deviates from the SM ones because of kinetic & mass mixing

$$\mathcal{L}_{\mathrm{gauge}} = \frac{1}{2}\tilde{m}_Z^2(1+\Delta_1)Z^\mu Z_\mu - \frac{g}{2c_W}(1+\Delta_2)J^\mu_{\mathrm{NC}}Z_\mu - e\Delta_3 J^\mu_{\mathrm{EM}}Z_\mu + \cdots$$

$$\tilde{m}_Z^2 = g^2v^2/(4c_W^2)$$

Other terms are the same in the SM

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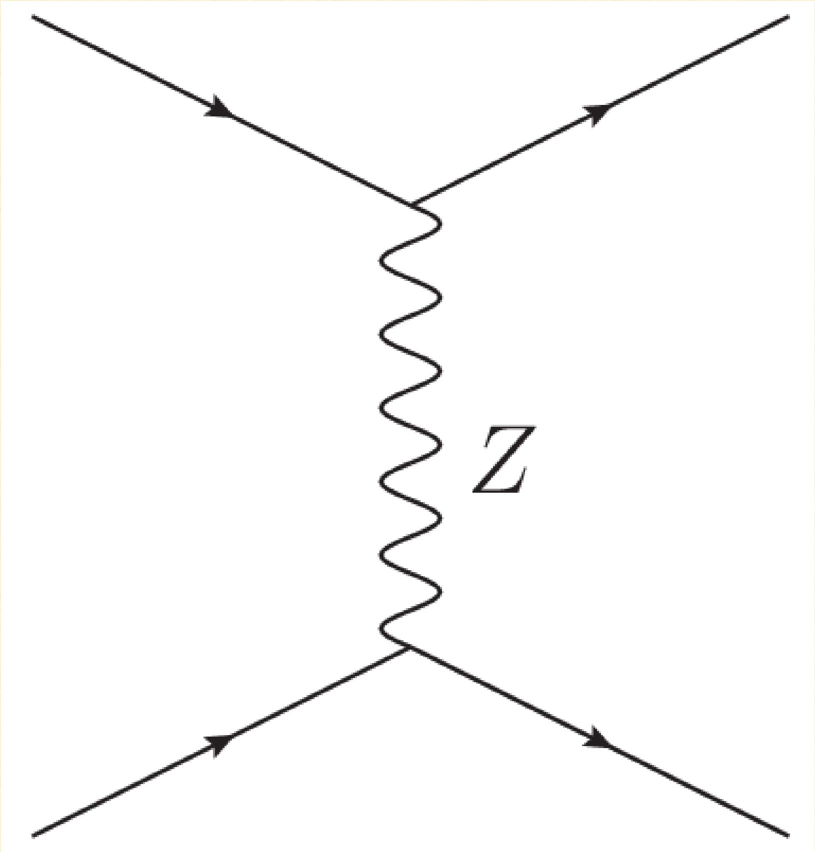

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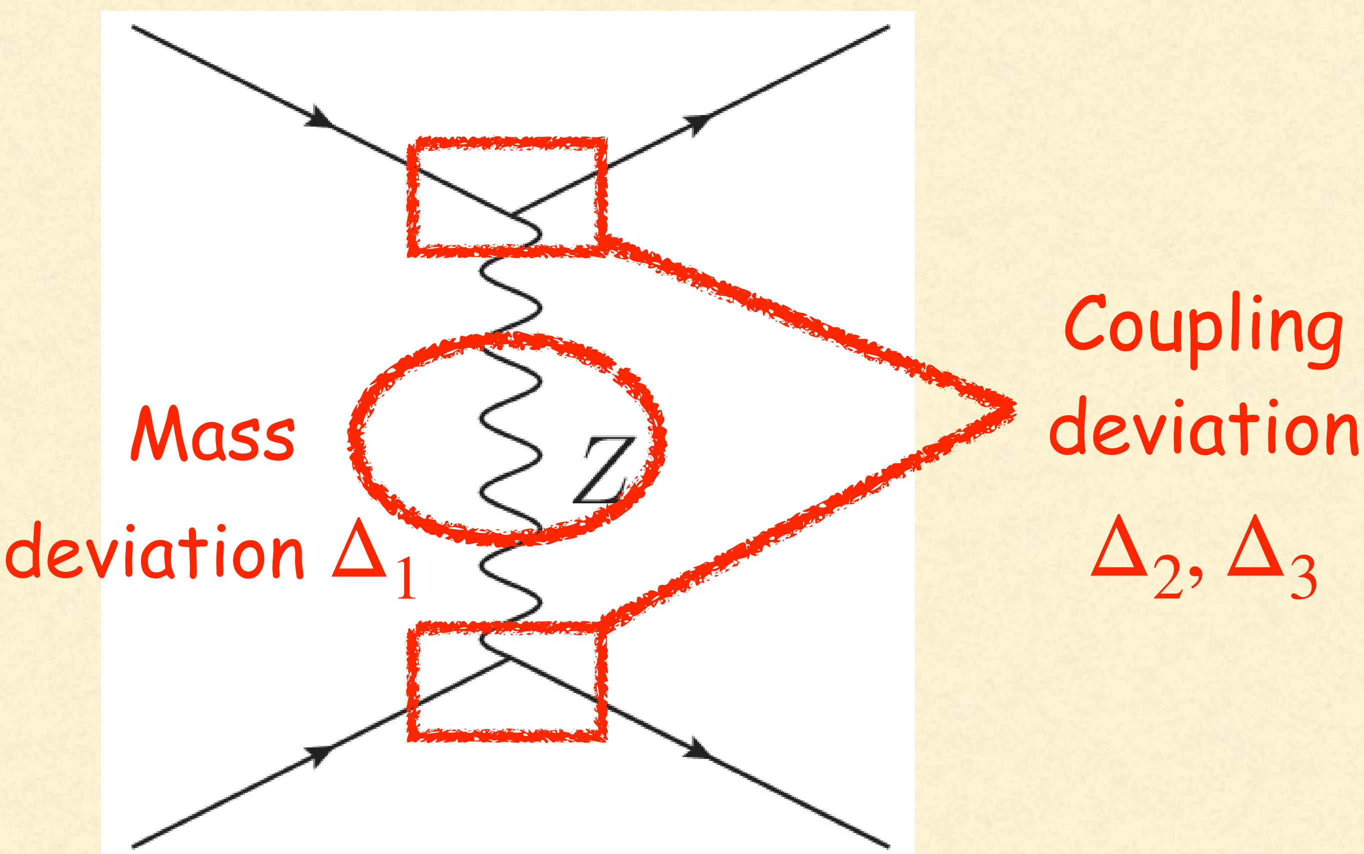

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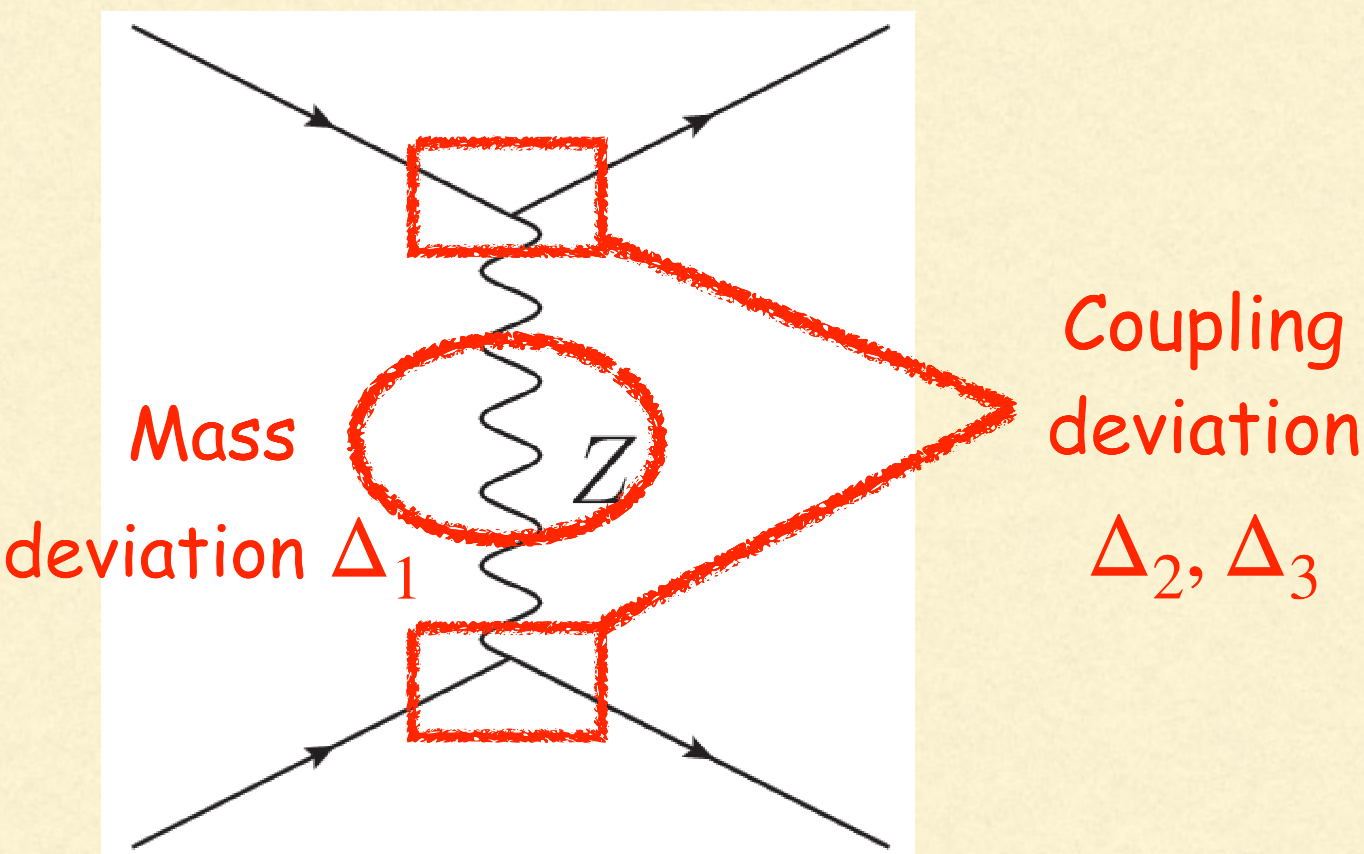

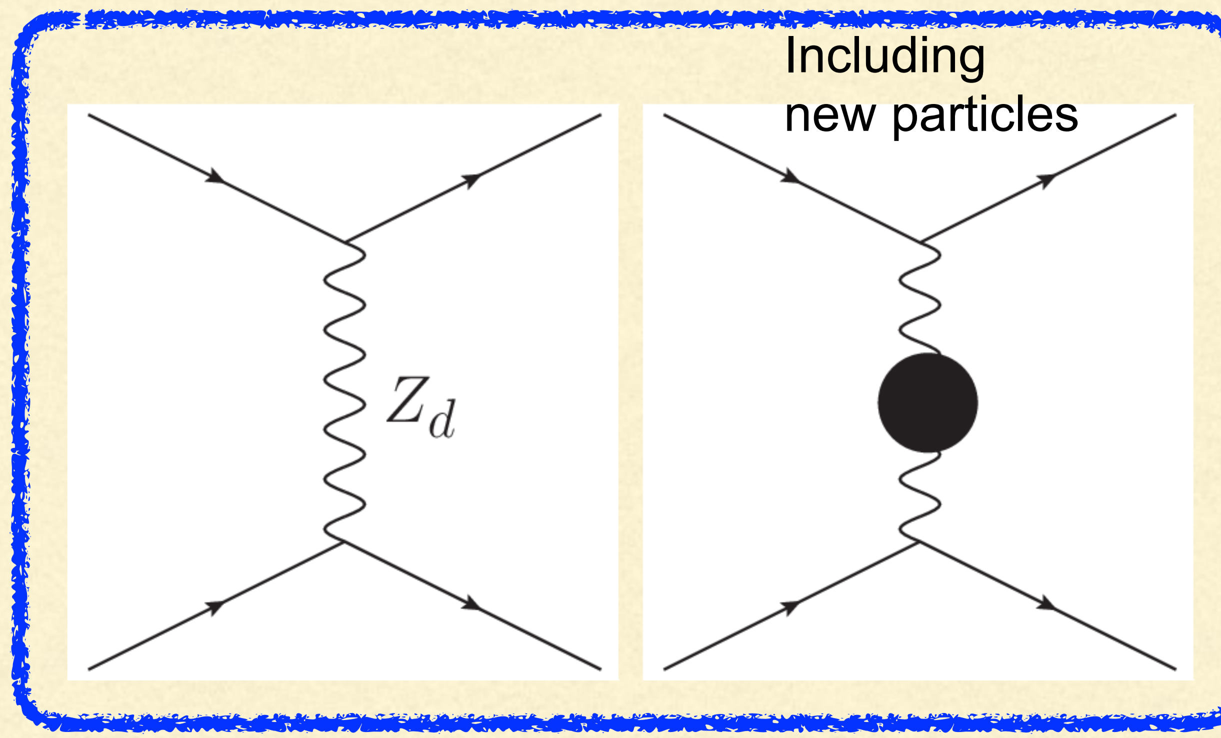

Sub-leading @ Z pole (unless $m_{Z_d} \simeq m_Z$)

Heavy dark Z bosons and W boson mass anomaly

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The effect of the deviations Δ_1, Δ_2, and Δ_3 can be described by

S, T, and U parameters Holdom, PLB (1991)

$$\alpha S = 8s_W^2c_W^2\Delta_2 - 4s_Wc_W(c_W^2-s_W^2)\Delta_3$$

$$\simeq -4s_Wc_W\left(\frac{\varepsilon_Z+\varepsilon t_W}{1-r^2}\right)\left\{s_Wc_W\frac{\varepsilon_Z+\varepsilon t_W}{1-r^2}-\varepsilon\right\}$$

$$\alpha T = -\Delta_1 + 2\Delta_2$$

$$\simeq -\left(\frac{\varepsilon_Z+\varepsilon t_W}{1-r^2}\right)\left(\frac{(2-r^2)\varepsilon_Z+r^2\varepsilon t_W}{1-r^2}\right)$$

$$\alpha U = -8s_W^2c_W(c_W\Delta_2+s_W\Delta_3)$$

$$\simeq 4s_W^2c_W^2\left(\frac{\varepsilon_Z+\varepsilon t_W}{1-r^2}\right)^2$$

$r = m_{Z_d}/m_Z$

$s_W = \sin\theta_W$

$c_W = \cos\theta_W$

EW global fit (w/ CDF-II result)

$S = 0.06(10)$
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Heavy dark Z bosons and W boson mass anomaly

Using S, T, and U parameters,

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Peskin, Takeuchi, PRL (1990); PRD (1992)

$$= -m_Z^2 \left(\frac{c_W^2}{c_W^2 - s_W^2} \right) \left(\frac{1}{1 - r^2} \right) \left(\varepsilon_Z + \varepsilon t_W \right)^2$$

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Favored by the CDF-II result

$m_{Z_d} > m_Z$

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Favored by the CDF-II result

$m_{Z_d} > m_Z$

CDF-II: $\Delta m_W^2 \simeq 12.5 \text{ GeV}^2$

$$\left(\varepsilon_Z - 0.55 \varepsilon \right)^2 \simeq (1.6 \times 10^{-3}) \times \left(\left(\frac{m_{Z_d}}{100 \text{ GeV}} \right)^2 - 0.83 \right)$$

S, T, U parameters in the dark photon limit

In the dark photon (DP) limit ($\varepsilon_Z = 0$),

$$\alpha S_{\rm DP} = 4 s_W^2 (c_W^2 - r^2) \left(\frac{\varepsilon}{1 - r^2} \right)^2$$

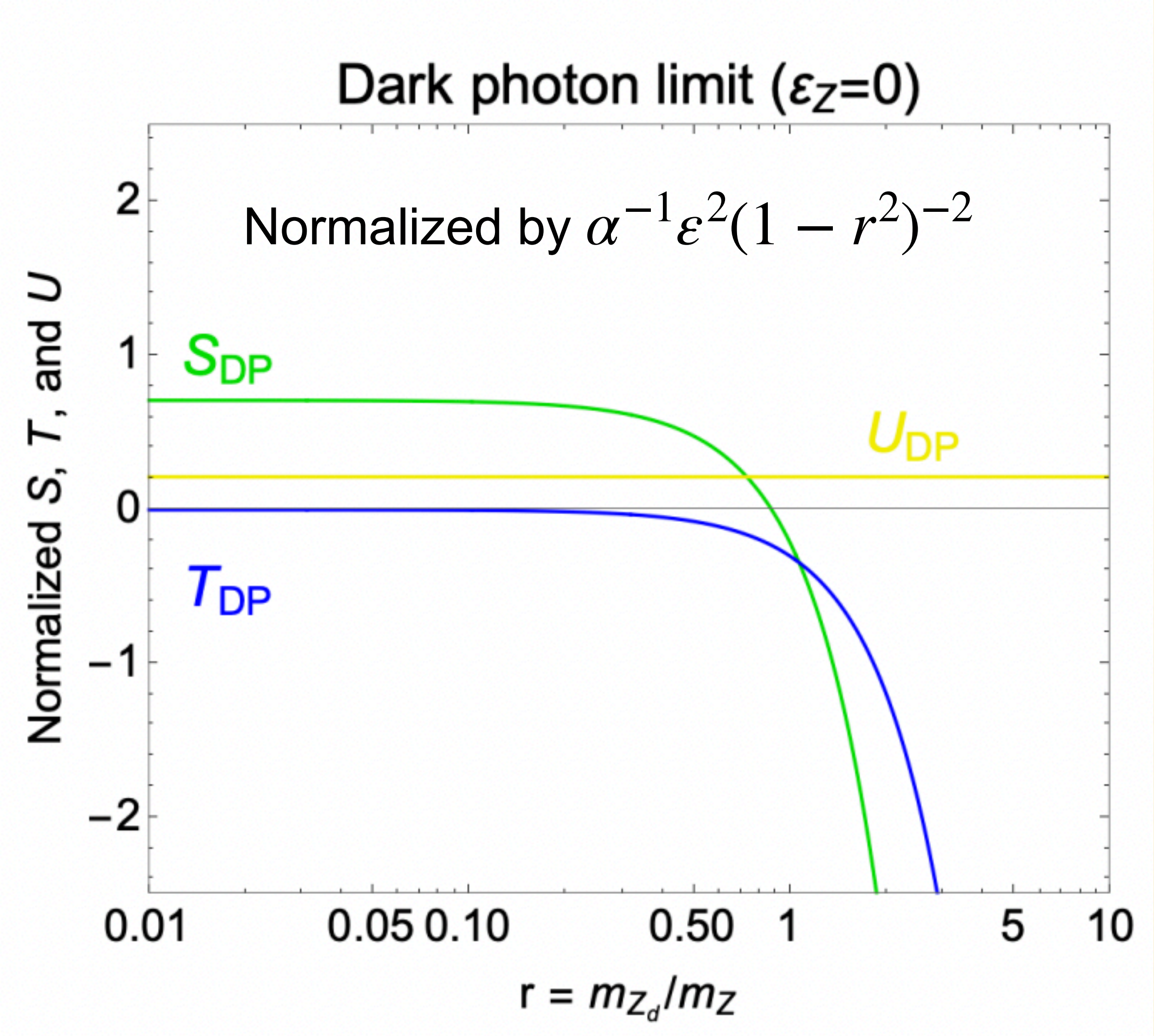
$$\alpha T_{\rm DP} = - t_W^2 r^2 \left(\frac{\varepsilon}{1 - r^2} \right)^2$$

$$\alpha U_{\rm DP} = 4 s_W^2 \left(\frac{\varepsilon}{1 - r^2} \right)^2$$

When $r \gg 1$,

$$|S_{\rm DP}|, |T_{\rm DP}| \gg |U_{\rm DP}|,$$

and $S_{\rm DP} = (4/c_W^2) T_{\rm DP} \simeq 3.0 T_{\rm DP}$



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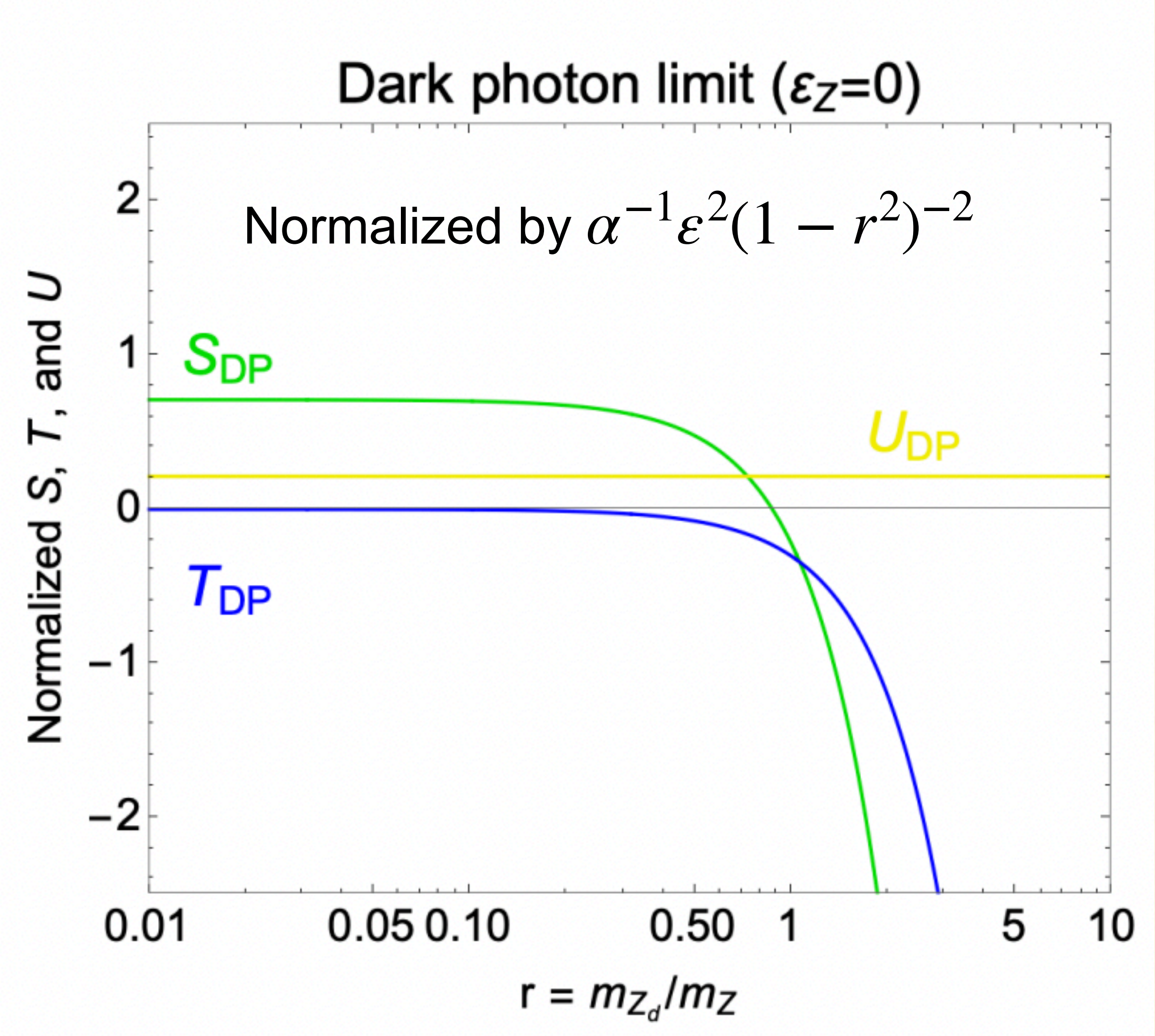
$$\Delta m_W^2 \simeq - S_{\rm DP} \times (35 {\rm GeV}^2)$$



CDF-II result ($\Delta m_W^2 \simeq 12.5 {\rm GeV}^2$) requires

$$S_{\rm DP} \simeq -0.54$$

$$S = 0.06(10)$$

out of 2σ region

$(\sim 6.0\sigma)$

S, T, U parameters in the pure dark Z limit

In the pure dark Z (DZ) limit ($\varepsilon = 0$),

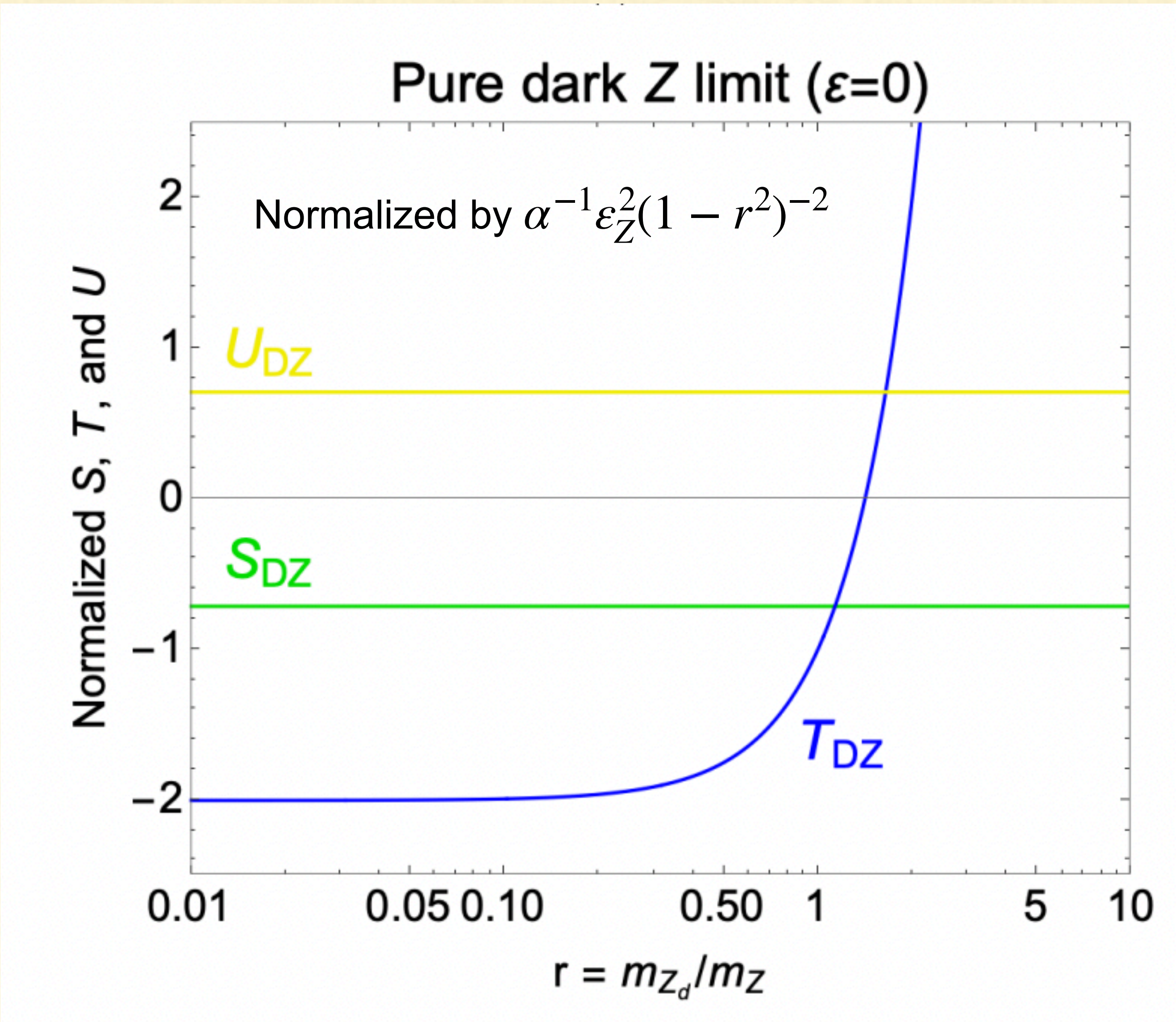
$$\alpha S_{\rm DZ} = -4 s_W^2 c_W^2 \left(\frac{\varepsilon_Z}{1-r^2} \right)^2$$

$$\alpha T_{\rm DZ} = (r^2 - 2) \left(\frac{\varepsilon_Z}{1-r^2} \right)^2$$

$$\alpha U_{\rm DZ} = 4 s_W^2 c_W^2 \left(\frac{\varepsilon_Z}{1-r^2} \right)^2$$

$S_{\rm DZ} = -U_{\rm DZ}$ for all ε_Z and r

When $r \gg 1$, $|T_{\rm DZ}| \gg |S_{\rm DZ}| = |U_{\rm DZ}|$



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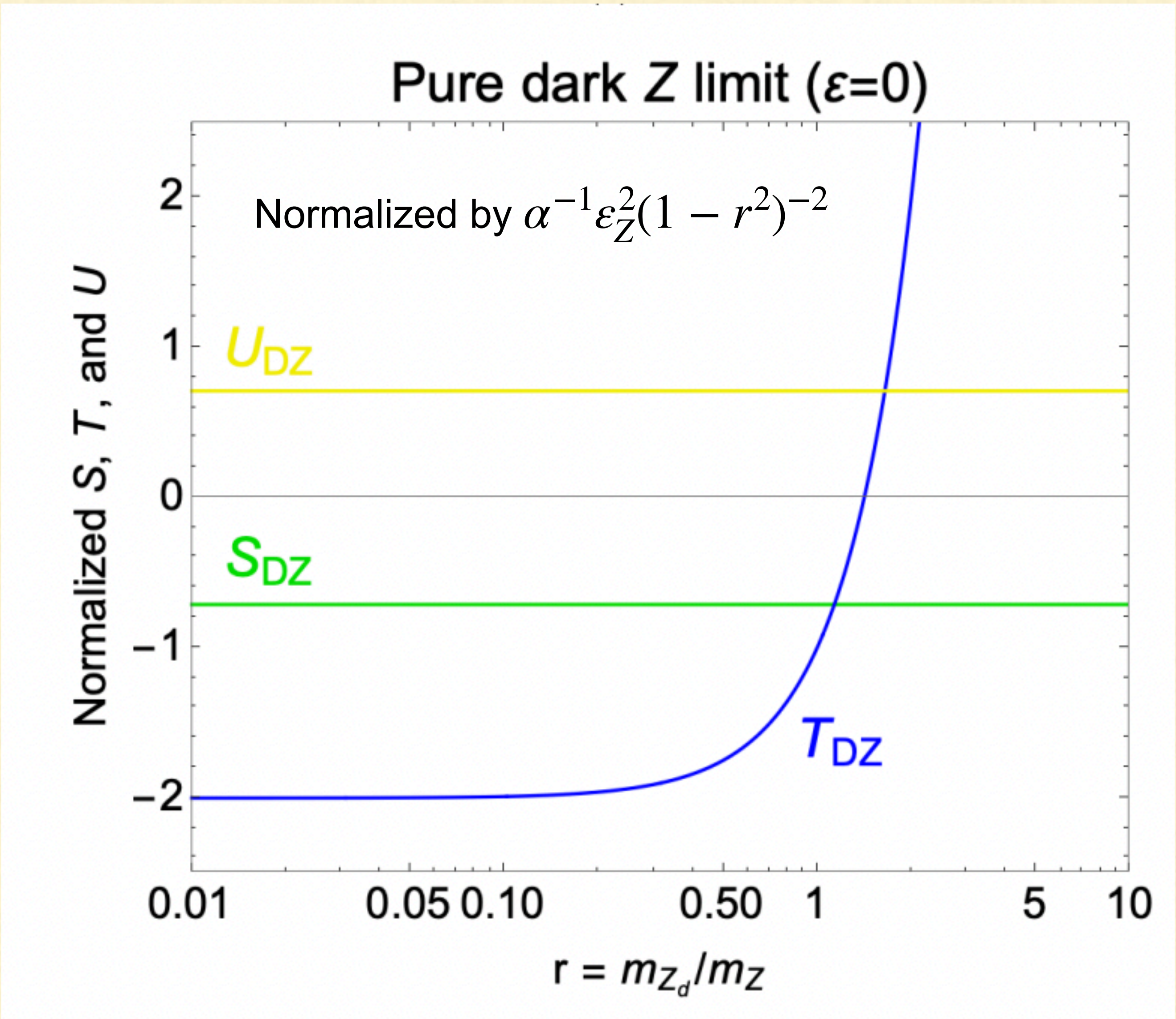
$$\alpha U_{\rm DZ} = 4 s_W^2 c_W^2 \left(\frac{\varepsilon_Z}{1 - r^2} \right)^2$$



$S_{\rm DZ} = -U_{\rm DZ}$ for all ε_Z and r

When $r \gg 1$, $|T_{\rm DZ}| \gg |S_{\rm DZ}| = |U_{\rm DZ}|$

⬇

$$\Delta m_W^2 \simeq T_{\rm DZ} \times (35 {\rm GeV}^2)$$

CDF-II result ($\Delta m_W^2 \simeq 12.5 {\rm GeV}^2$) requires

$$T_{\rm DZ} \simeq 0.18$$

$$T = 0.11(12)$$

Within 2σ region

$(\sim 0.6\sigma)$

The relation $S_{\rm DZ} = -U_{\rm DZ}$

$$\Delta\mathcal{L}_{\rm gauge} = \frac{1}{2}\tilde{m}_Z^2\Delta_1 Z^\mu Z_\mu - \frac{g}{2c_W}\Delta_2 J^\mu_{\rm NC} Z_\mu - e\Delta_3 J^\mu_{\rm EM} Z_\mu$$

In the pure dark Z limit ($\varepsilon = 0$), $\Delta_3 = -\eta\varepsilon\sin\xi = 0$ $\quad \eta = 1/\sqrt{1-\varepsilon^2/c_W^2}$

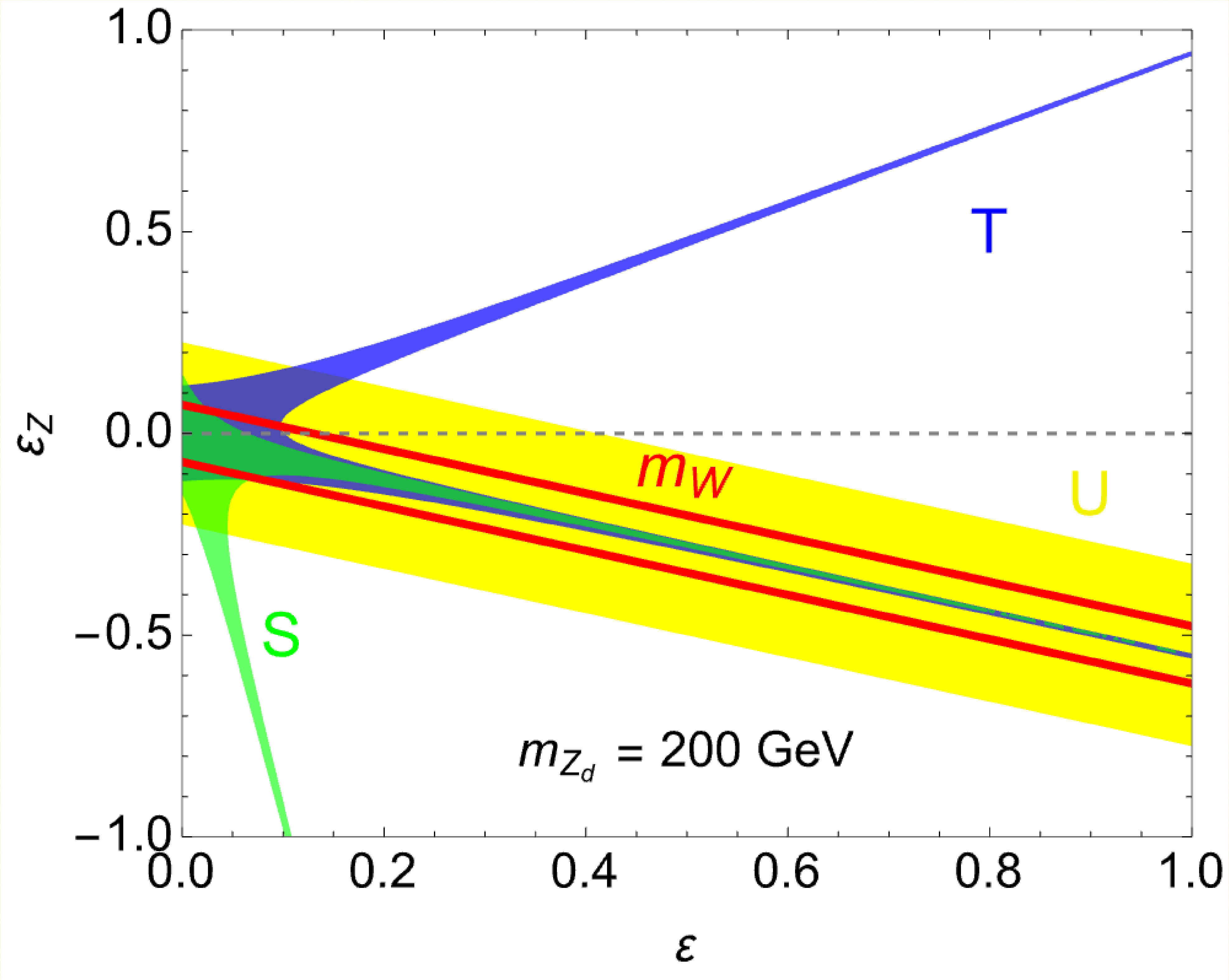
$$\Delta_1,\ \Delta_2\ \neq 0$$

$$\alpha S = 8s_W^2c_W^2\Delta_2 - 4s_Wc_W(c_W^2 - s_W^2)\Delta_3 = 8s_W^2c_W^2\Delta_2$$

$$\alpha U = -8s_W^2c_W(c_W\Delta_2 + s_W\Delta_3) = -8s_W^2c_W^2\Delta_2$$

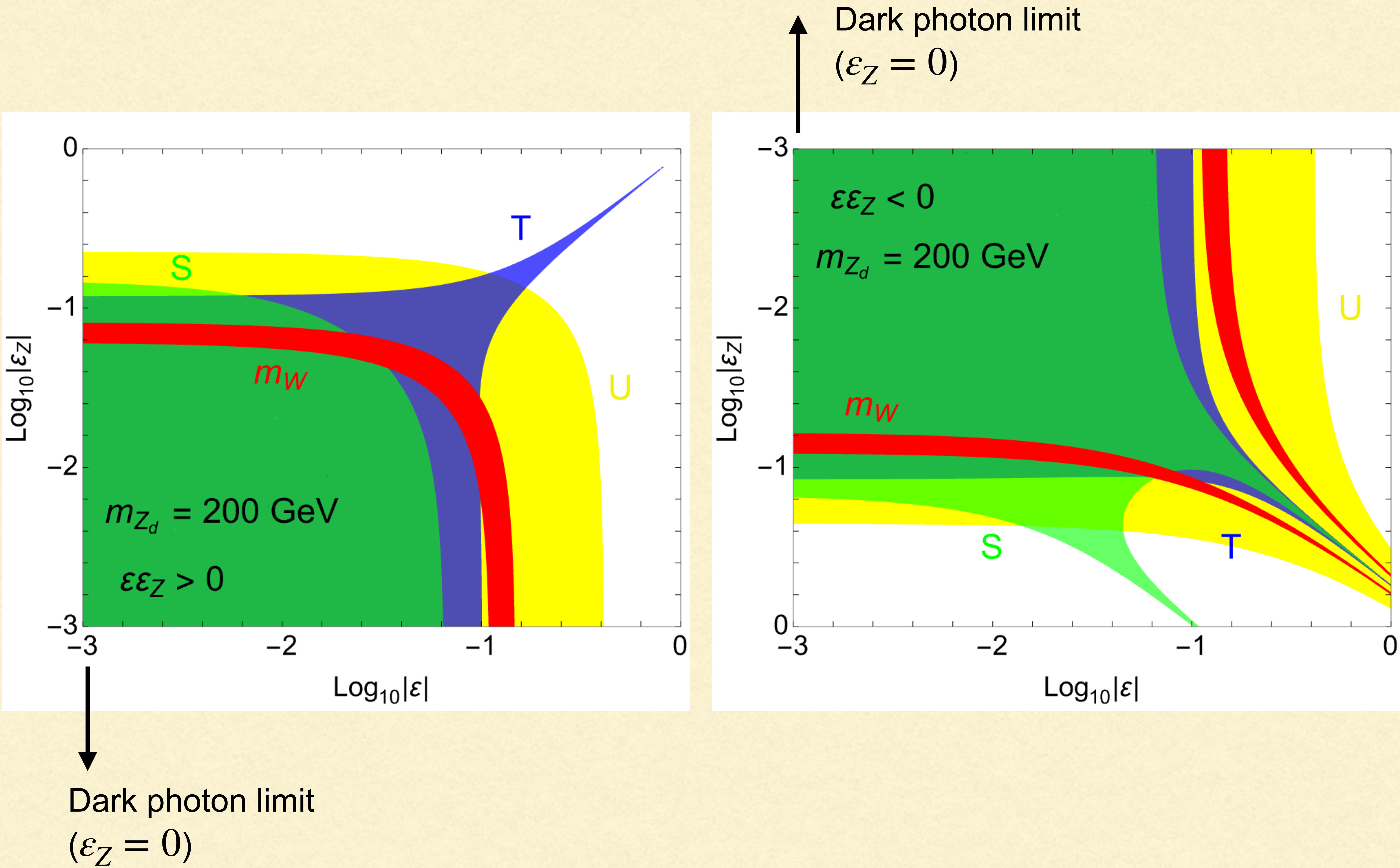
$$\rightarrow\ S = -U$$

W boson mass anomaly & EW global fit



Colored regions = 2σ regions

W boson mass anomaly & EW global fit

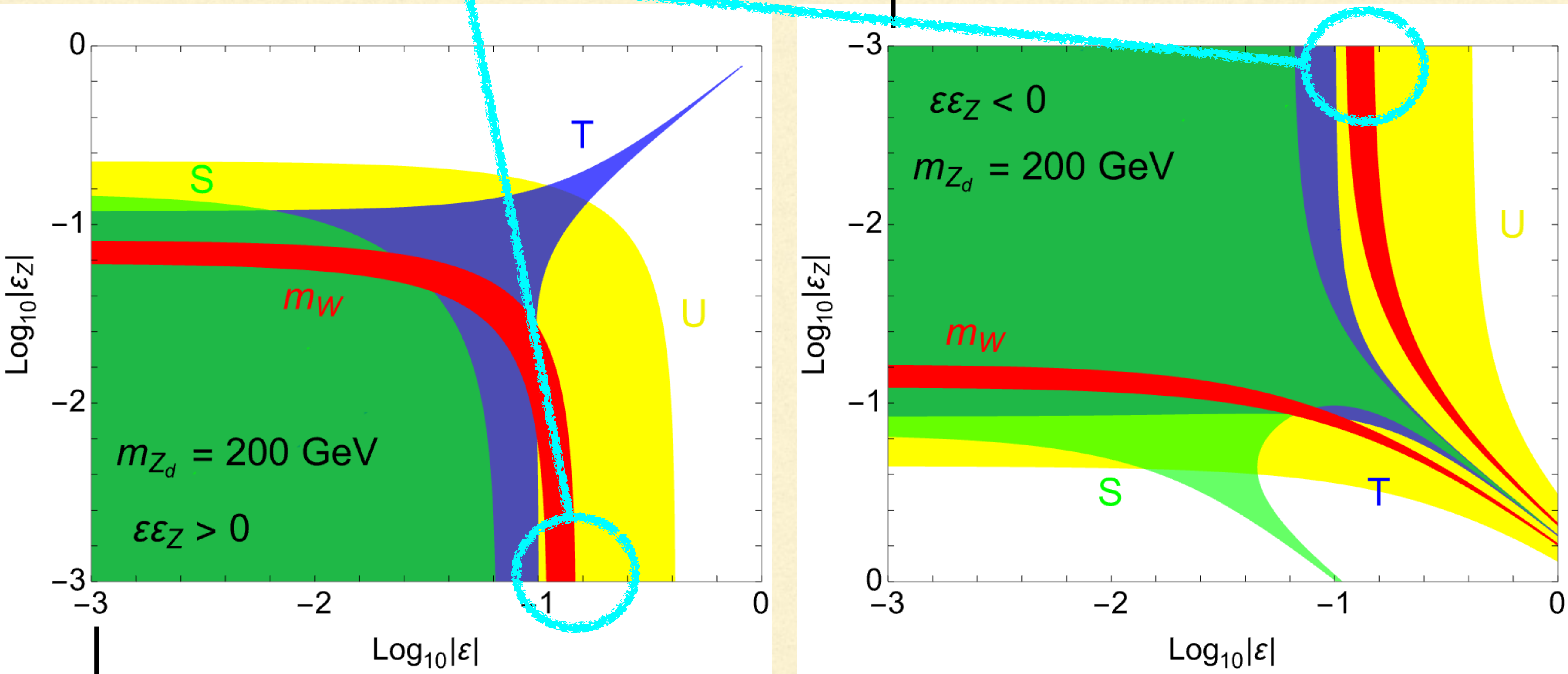


W boson mass anomaly & EW global fit

No overlap region in dark photon limit

Cheng *et al*, 2204.10156
Thomas, Wang, 2205.01911
Asagi *et al*, 2204.05283

Dark photon limit ($\varepsilon_Z = 0$)



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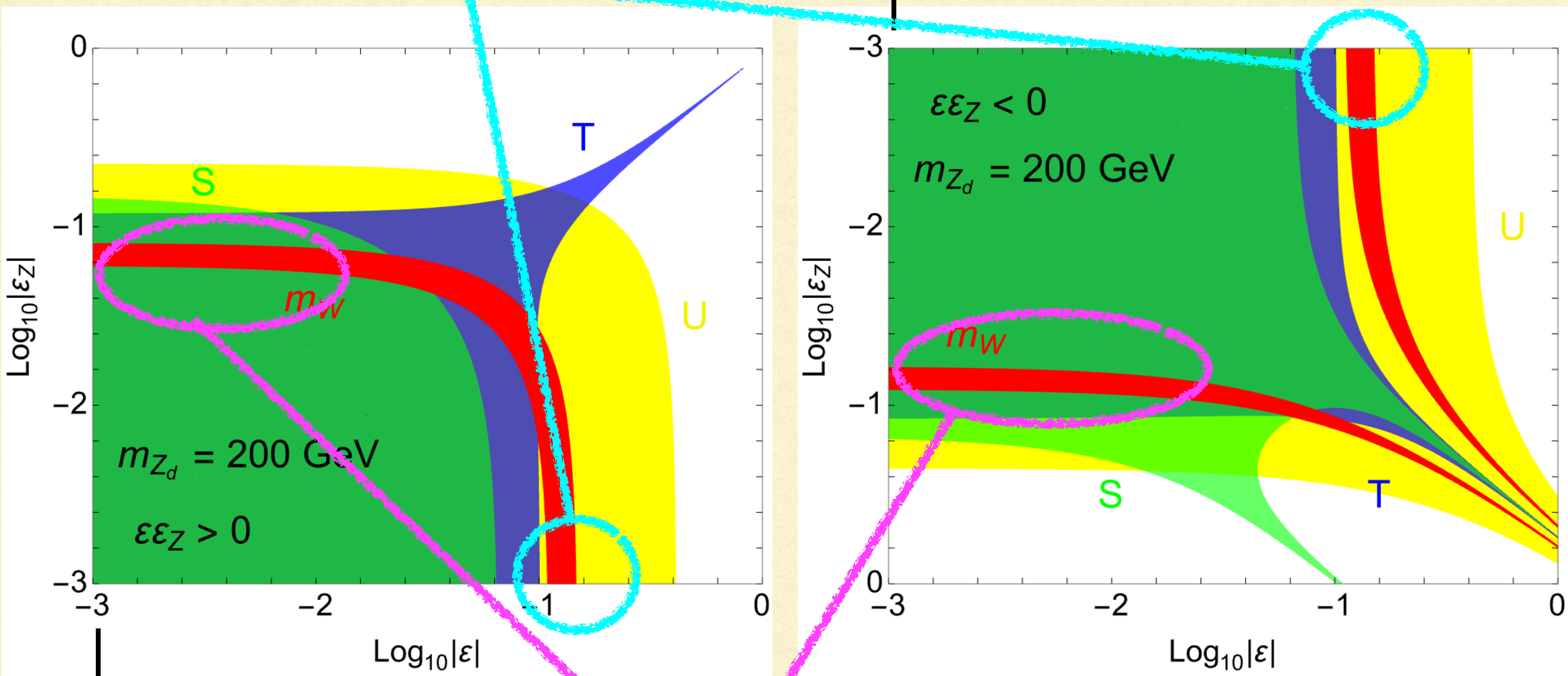
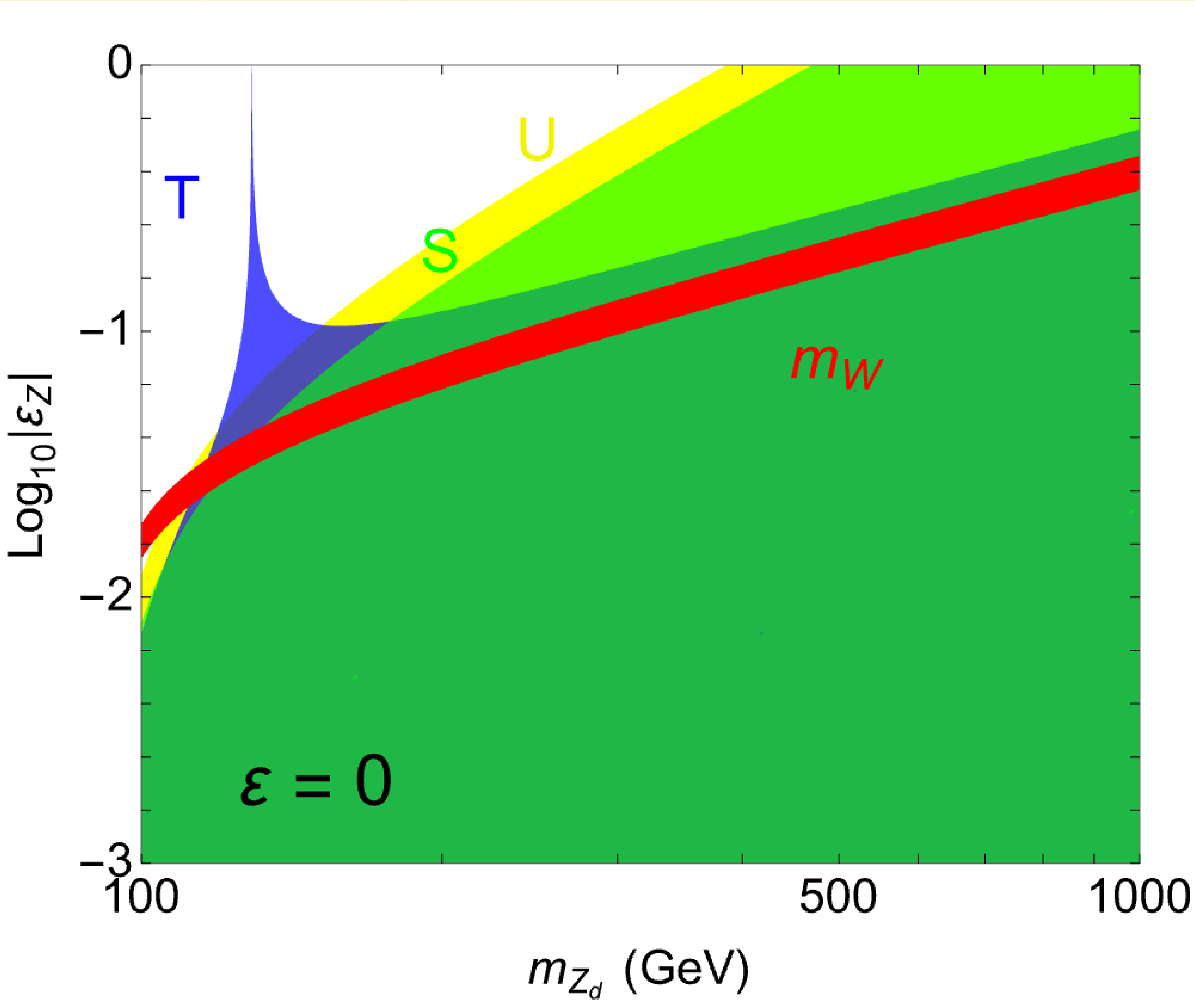


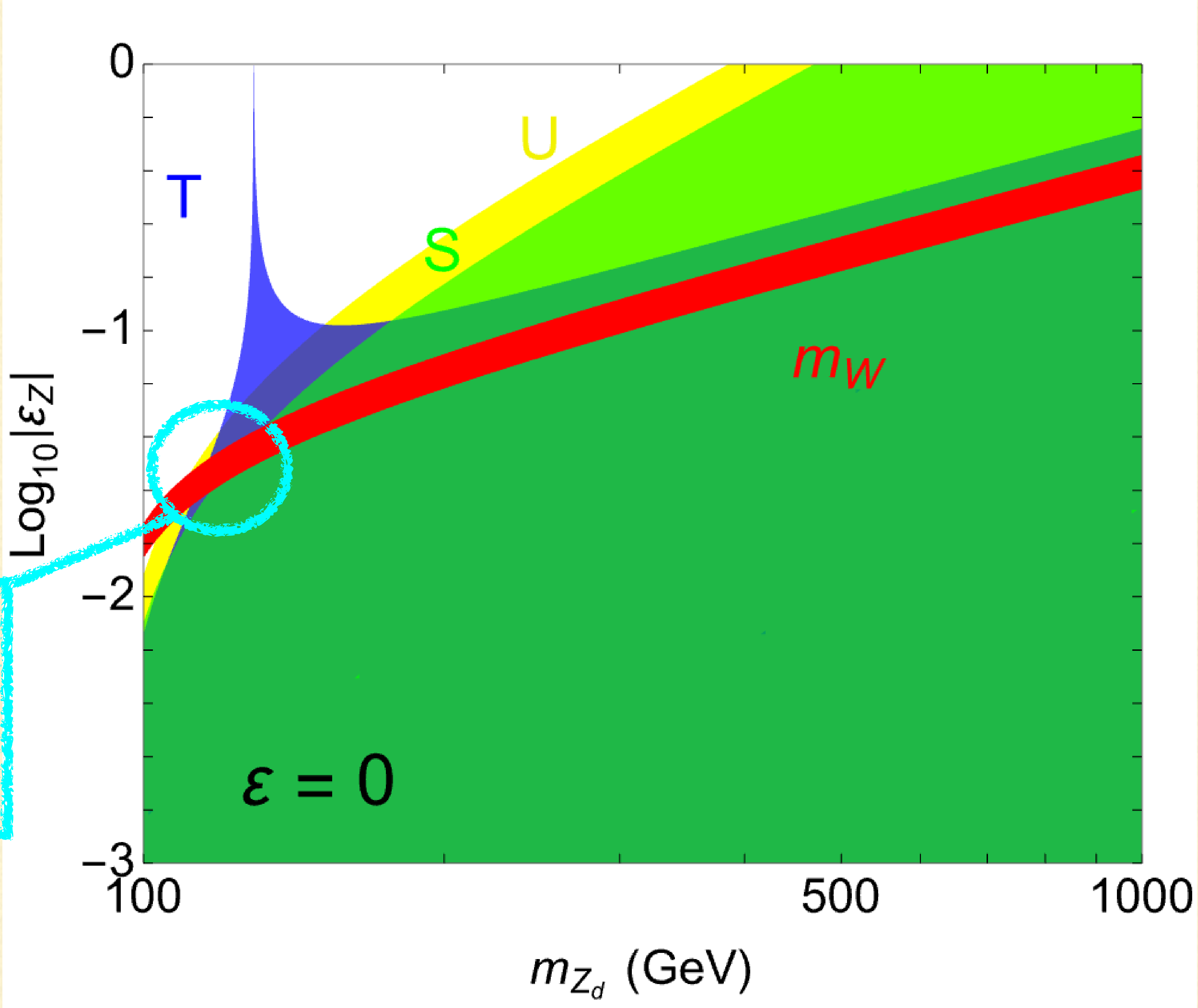
Dark photon limit ($\varepsilon_Z = 0$)

CDF-II result **can be explained** with $|\varepsilon_Z| = O(0.1)$ and small ε

W boson mass anomaly & EW global fit

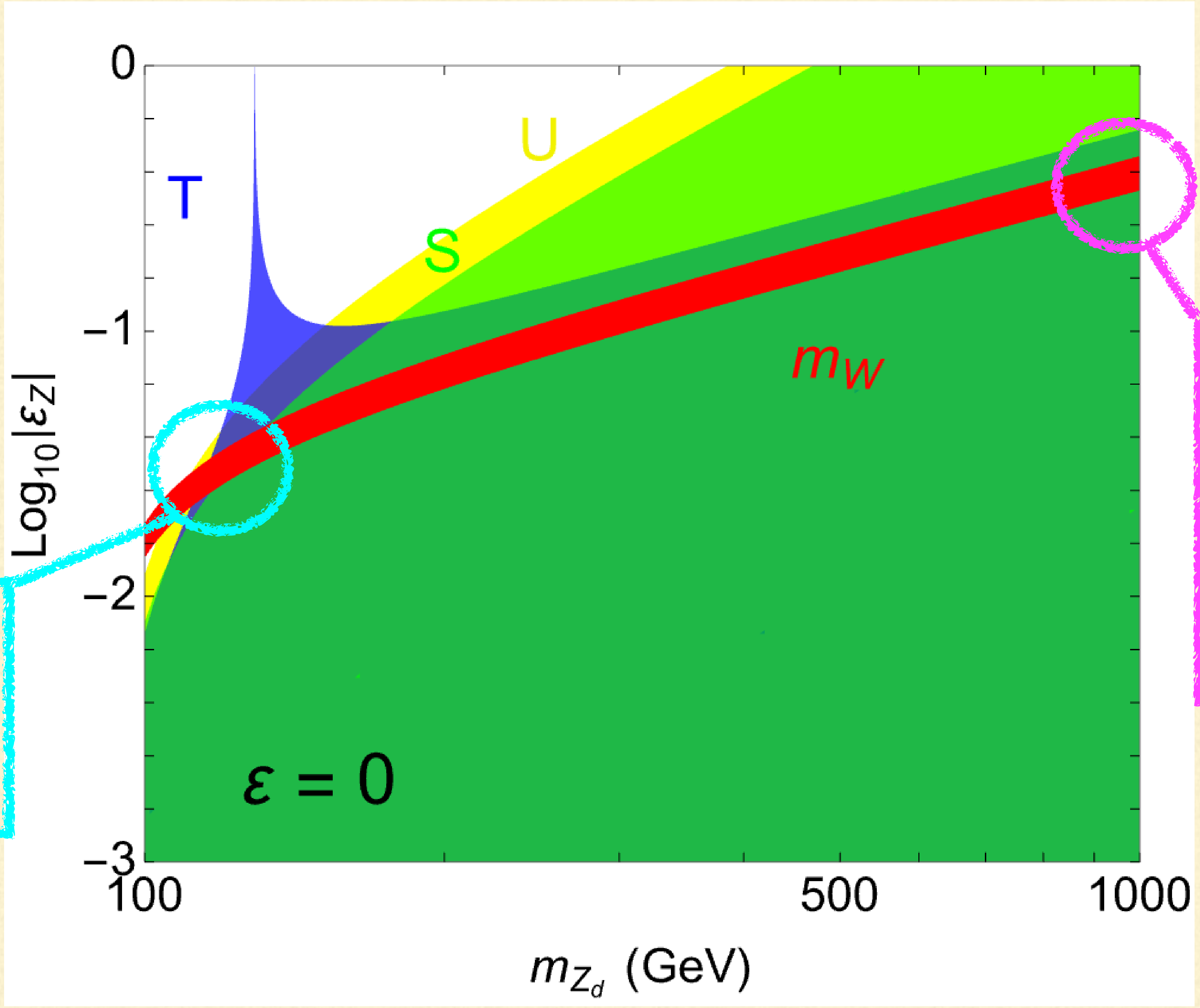


W boson mass anomaly & EW global fit



Minimum m_{Z_d}
$m_{Z_d} \simeq 130$ GeV
($|\varepsilon_Z| \simeq 0.03$)

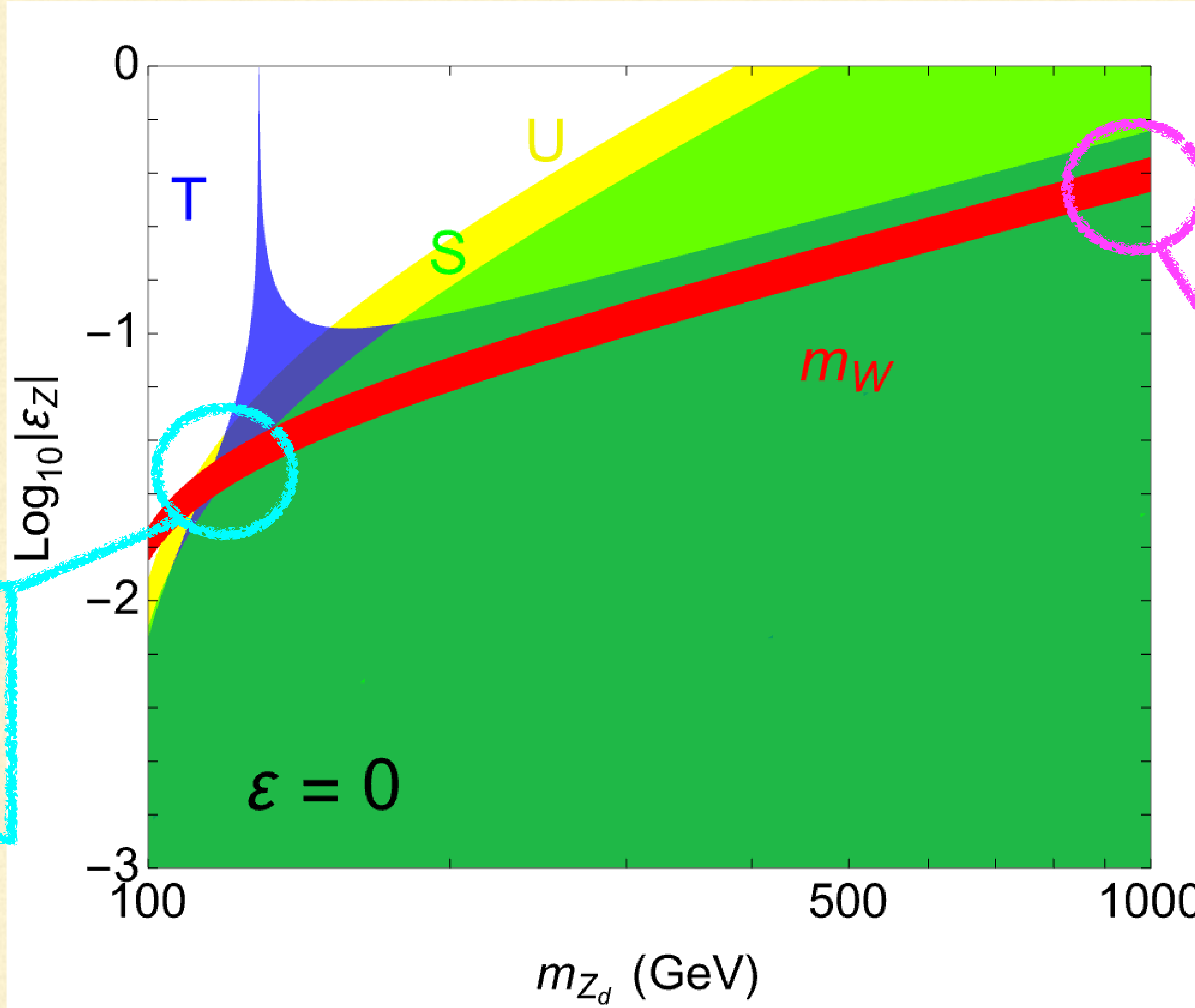
W boson mass anomaly & EW global fit



Minimum m_{Z_d}
$m_{Z_d} \simeq 130$ GeV
$(|\varepsilon_Z| \simeq 0.03)$

Large ε_Z
for heavier Z_d
||
Perturbation
is not good

W boson mass anomaly & EW global fit



Minimum m_{Z_d}

$m_{Z_d} \simeq 130$ GeV

($|\varepsilon_Z| \simeq 0.03$)

Large ε_Z

for heavier Z_d

||

Perturbation

is not good

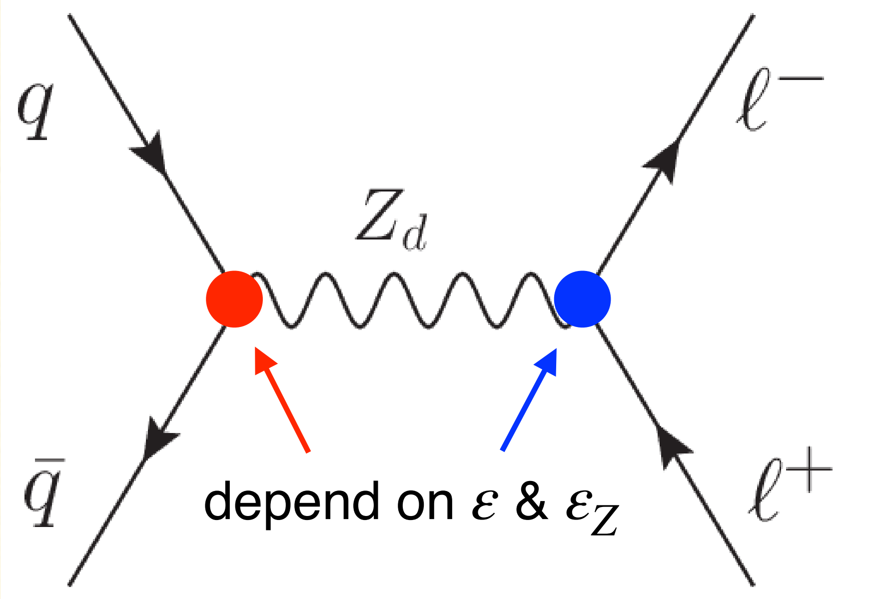
Heavy Z_d ($m_{Z_d} = O(100)\mathrm{GeV}$) and relatively large $|\varepsilon_Z|$ ($\gtrsim 0.03$)

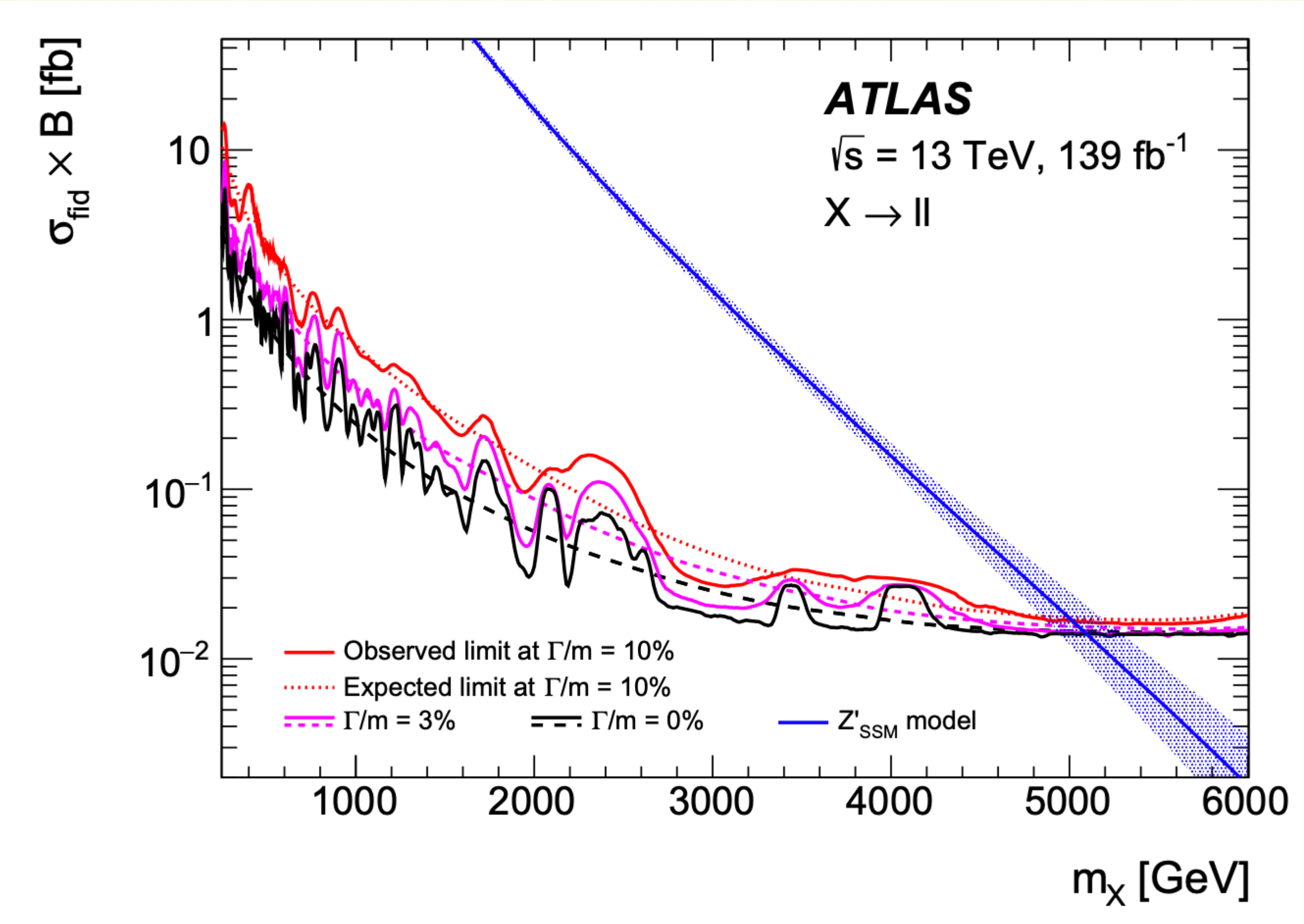
Constraint from direct searches

$$m_{Z_d} = O(100)\ \text{GeV} \qquad |\varepsilon_Z| = 0.03\text{-}O(0.1)$$

Dilepton resonant search @ LHC ATLAS, 1903.06248

$$pp \to Z_d \to \ell^+\ell^- \qquad (225\ \text{GeV} \le m_{Z_d} \le 6000\ \text{GeV})$$





ATLAS, 1903.06248

Dijet resonant search is not effective in the relevant mass range

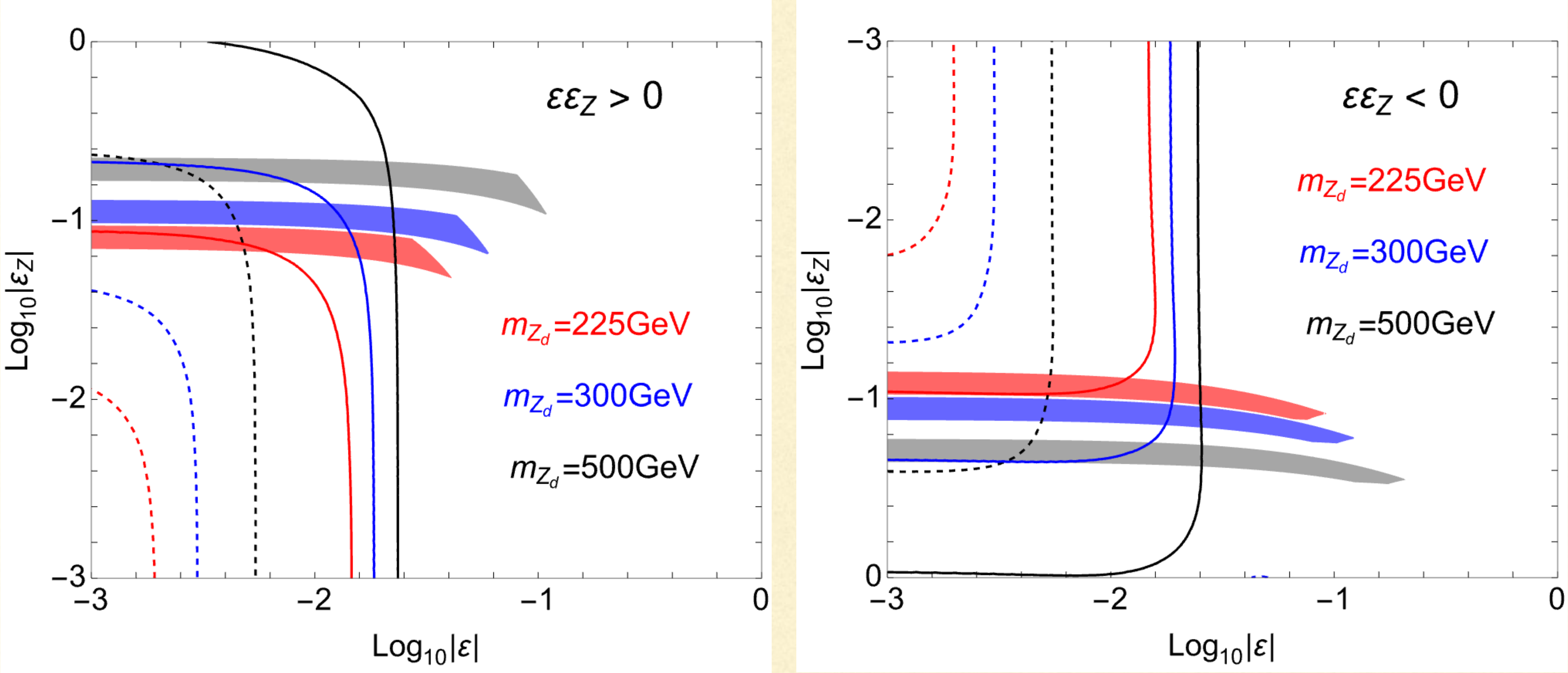
CMS, 1911.03947

Constraint from direct searches

The constraint depends on $\mathrm{Br}[Z_d \to \ell^+\ell^-]$

Case 1: Only the SM fermions (Dashed lines)

Case 2: Including a dark fermion [$m_\psi = 50$ GeV, $g_d = 0.1$] (Solid lines)



Colored regions: CDF-II result & EW global fit within 2σ

Summary

- New $U(1)$ gauge symmetry is an attractive candidate for new physics.

- The dark Z model includes mass mixing ε_Z independent of kinetic mixing ε and provides richer phenomenology.

- Heavy dark Z bosons with relatively large ε_Z can reproduce the CDF-II result of m_W and the result of EW global fit.

$$m_{Z_d} = \mathcal{O}(100)\ \mathrm{GeV} > m_Z, \quad \varepsilon_Z \geq 0.03$$

- Such a dark Z is constrained by the dilepton resonant searches. Considering dark decay channels, this constraint is relaxed.

Thank you for listening!

Backup Slides

Mass eigenstate of neutral gauge bosons

$$\mathcal{L}_{\rm kin} = -\frac{1}{4}\hat{B}^{\mu\nu}\hat{B}_{\mu\nu} + \frac{\varepsilon}{2\cos\theta_W}\hat{B}^{\mu\nu}\hat{Z}_{d\mu\nu} - \frac{1}{4}\hat{Z}_d^{\mu\nu}\hat{Z}_{d\mu\nu},$$

Digonalize the kinetic term

$$\begin{pmatrix}\tilde{B}_\mu \\ \tilde{Z}_{d\mu}\end{pmatrix} = \begin{pmatrix}1 & -\varepsilon/c_W \\ 0 & \sqrt{1-\varepsilon^2/c_W^2}\end{pmatrix}\begin{pmatrix}\hat{B}_\mu \\ \hat{Z}_{d\mu}\end{pmatrix}$$

Mass matrix for $\tilde{B}_\mu$ and $\tilde{Z}_{d\mu}$

$$\mathcal{L}_{\rm mass} = m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}(\tilde{Z}^\mu, \tilde{Z}_d^\mu) M_V^2 \begin{pmatrix}\tilde{Z}_\mu \\ \tilde{Z}_{d\mu}\end{pmatrix},$$

$$\tilde{Z}_\mu = -\sin\theta_W \tilde{B}_\mu + \cos\theta_W \hat{W}^3_\mu, \quad \tan\theta_W = g'/g$$

$$M_V^2 = \begin{pmatrix}\tilde{m}_Z^2 & -\tilde{m}_Z^2\eta(\varepsilon_Z + \varepsilon t_W) \\ -\tilde{m}_Z^2\eta(\varepsilon_Z + \varepsilon t_W) & \tilde{m}_{Z_d}^2\end{pmatrix} \qquad \eta = \frac{1}{\sqrt{1-\varepsilon^2/c_W^2}}$$

Mass eigenstate of neutral gauge bosons

Mass eigenstates Z_μ and $Z_{d\mu}$

$$\begin{pmatrix} Z_\mu \\ Z_{d\mu} \end{pmatrix} = \begin{pmatrix} \cos\xi & -\sin\xi \\ \sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \tilde{Z}_\mu \\ \tilde{Z}_{d\mu} \end{pmatrix}$$

Mixing matrix

$$\sin\xi \simeq \frac{\varepsilon_Z + \varepsilon t_W}{1 - r^2},$$

$$\cos\xi \simeq 1 - \frac{1}{2}\left(\frac{\varepsilon_Z + \varepsilon t_W}{1 - r^2}\right)^2,$$

$$r = m_{Z_d}/m_Z$$

Mass eigenvalues

$$m_Z^2 \simeq \tilde{m}_Z^2 \left(1 + \frac{(\varepsilon_Z + \varepsilon t_W)^2}{1 - \tilde{r}^2}\right),$$

$$m_{Z_d}^2 \simeq \tilde{m}_{Z_d}^2 \left(1 - \frac{\varepsilon_Z^2}{\tilde{r}^2(1 - \tilde{r}^2)} - \frac{\varepsilon^2 t_W^2 + 2\varepsilon_Z \varepsilon t_W}{1 - \tilde{r}^2}\right),$$

$$\tilde{r} = \tilde{m}_{Z_d}/\tilde{m}_Z$$

The covariant derivative in mass eigenstate basis

$$D_\mu = \partial_\mu + igT^a\hat{W}_\mu + ig'Y\hat{B}_\mu + ig_dQ_d\hat{Z}_{d\mu} + (\text{QCD term})$$

After diagonalization of kinetic terms and mass terms,

$$D_\mu = \cdots + \frac{ig}{c_W}(c_\xi + \eta s_\xi \varepsilon t_W)(T^3 - s_W^2 Q)Z_\mu - ie\eta s_\xi \varepsilon Q Z_\mu - ig_d \eta s_\xi Q_d Z_\mu$$

$$+\frac{ig}{c_W}(s_\xi - \eta c_\xi \varepsilon t_W)(T^3 - s_W^2 Q)Z_{d\mu} + ie\eta c_\xi \varepsilon Z_{d\mu} + ig_d \eta c_\xi Q_d Z_{d\mu}$$

$$\simeq \cdots + \frac{ig}{c_W}(T^3 - s_W^2 Q)Z_\mu - ig_d Q_d \left(\frac{\varepsilon_Z + \varepsilon t_W}{1 - r^2}\right) Z_\mu$$

$$+\frac{ig}{c_W(1-r^2)}(r^2 \varepsilon t_W + \varepsilon_Z)Z_{d\mu} + ie\varepsilon Q Z_{d\mu} + ig_d Q_d Z_{d\mu}$$

$\rightarrow 0 \quad (m_{Z_d}/m_Z \rightarrow 0)$

S_{DZ}, T_{DZ}, U_{DZ} parameters in the decoupling limit

In the decoupling limit of Z_d ($r \to \infty$),
the generated dimension-six operator is only

$$O_\varphi^{\prime(6)} = O_2^\mu O_{2\mu} \qquad O_2^\mu = \Phi_2^\dagger D^\mu \Phi_2 - (D^\mu \Phi_2)^\dagger \Phi_2$$

This induces the deviation of $\mathcal{O}(m_{Z_d}^{-2})$

$$\Delta_1 = \varepsilon_Z^2 r^{-2}, \quad \Delta_2 = 0, \quad \Delta_3 = 0.$$

$$\Rightarrow \alpha S = 8 s_W^2 c_W^2 \Delta_2 - 4 s_W c_W (c_W^2 - s_W^2) \Delta_3 = 0$$

S is not generated by the $d = 6$ oeprator.

S_{DZ} and U_{DZ} is generated by $\mathcal{O}_\varphi^{\prime(8)} = \frac{1}{2} O_{2\mu\nu} O_2^{\mu\nu}$

$(O_2^{\mu\nu} = \partial^\mu O_2^\nu - \partial^\nu O_2^\mu)$

$d = 8$ operator