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], **Work in progress**.

1. Brookhaven National Laboratory, 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!

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A new $U(1)$ gauge symmetry

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

New force!!

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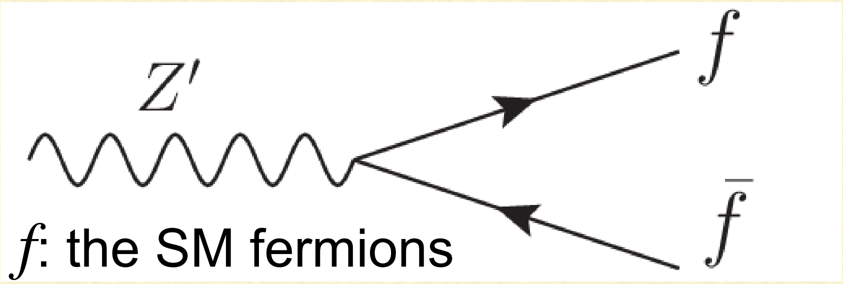
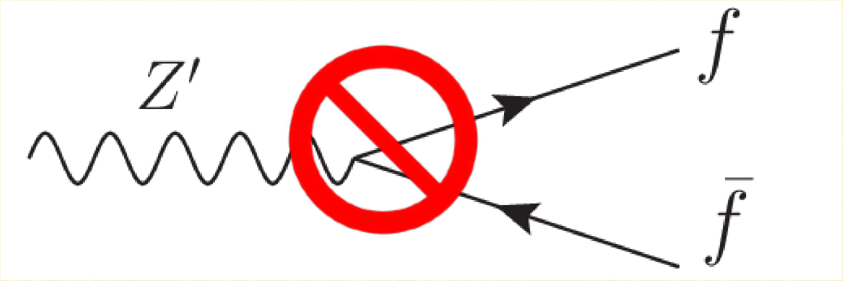


f carries $U(1)$ charge

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

②



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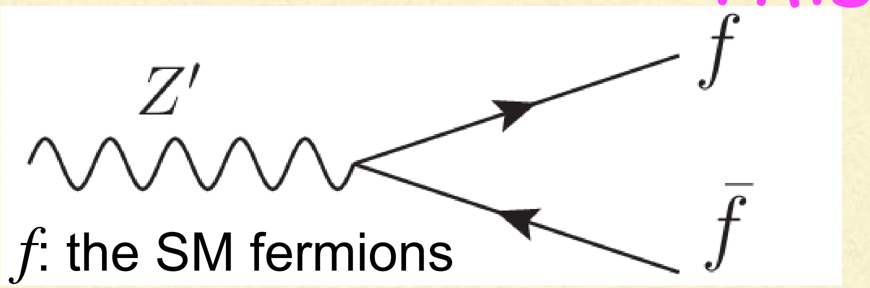
① 

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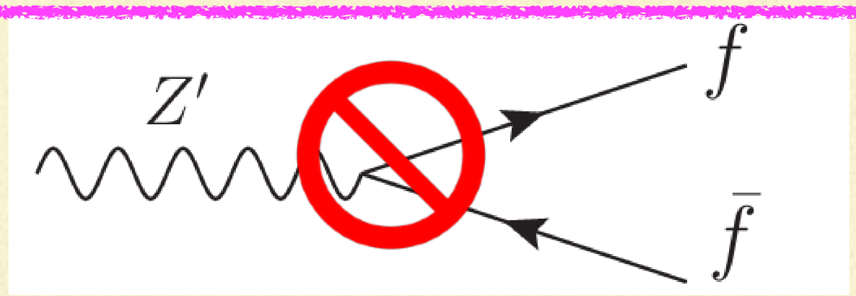
② 

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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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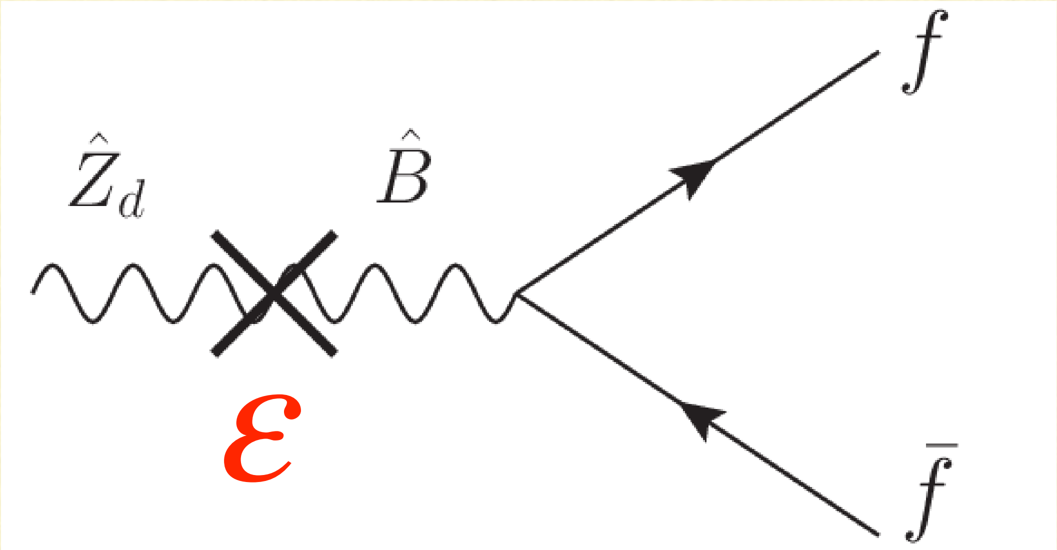

Kinetic mixing

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

via kinetic mixing Holdom, PLB (1986)

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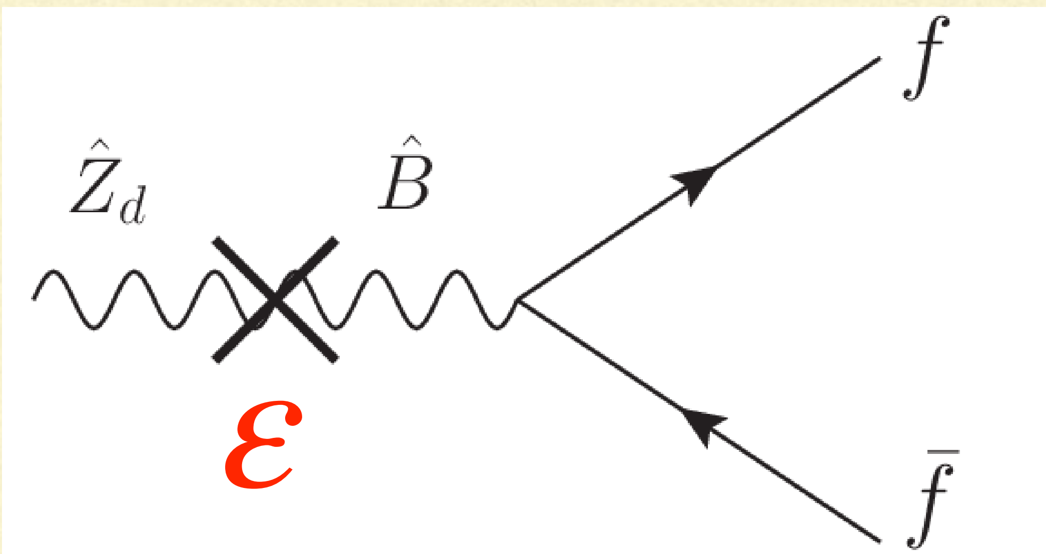

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$U(1)_d$ **symmetry breaking:** $\hat{Z}_d$ get the mass term by a singlet VEV

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

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

Z_d couples $J^\mu_{\rm em}$ (Dark photon)

Dark Z model

Dark gauge symmetry: $U(1)_d$ Davoudiasl, Lee, Marciano, 1203.2947

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)

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Mass matrix

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

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

Z_d couples to $J^\mu_{\rm NC}$

Dark Z boson

Light dark Z boson and the weak mixing angle

The neutral current with light Z_d induces the deviation in the running of $\sin^2\hat{\theta}_W$ @ low energies.

Davoudiasl, Lee, Marciano, 1203.2947
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$$\sin^2\hat{\theta}_W(Q^2) = \kappa_d \sin^2\hat{\theta}_W(Q^2)_{\rm SM} \qquad \kappa_d = 1 - \varepsilon\delta' \frac{m_Z}{m_{Z_d}} \frac{c_W}{s_W} \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$$

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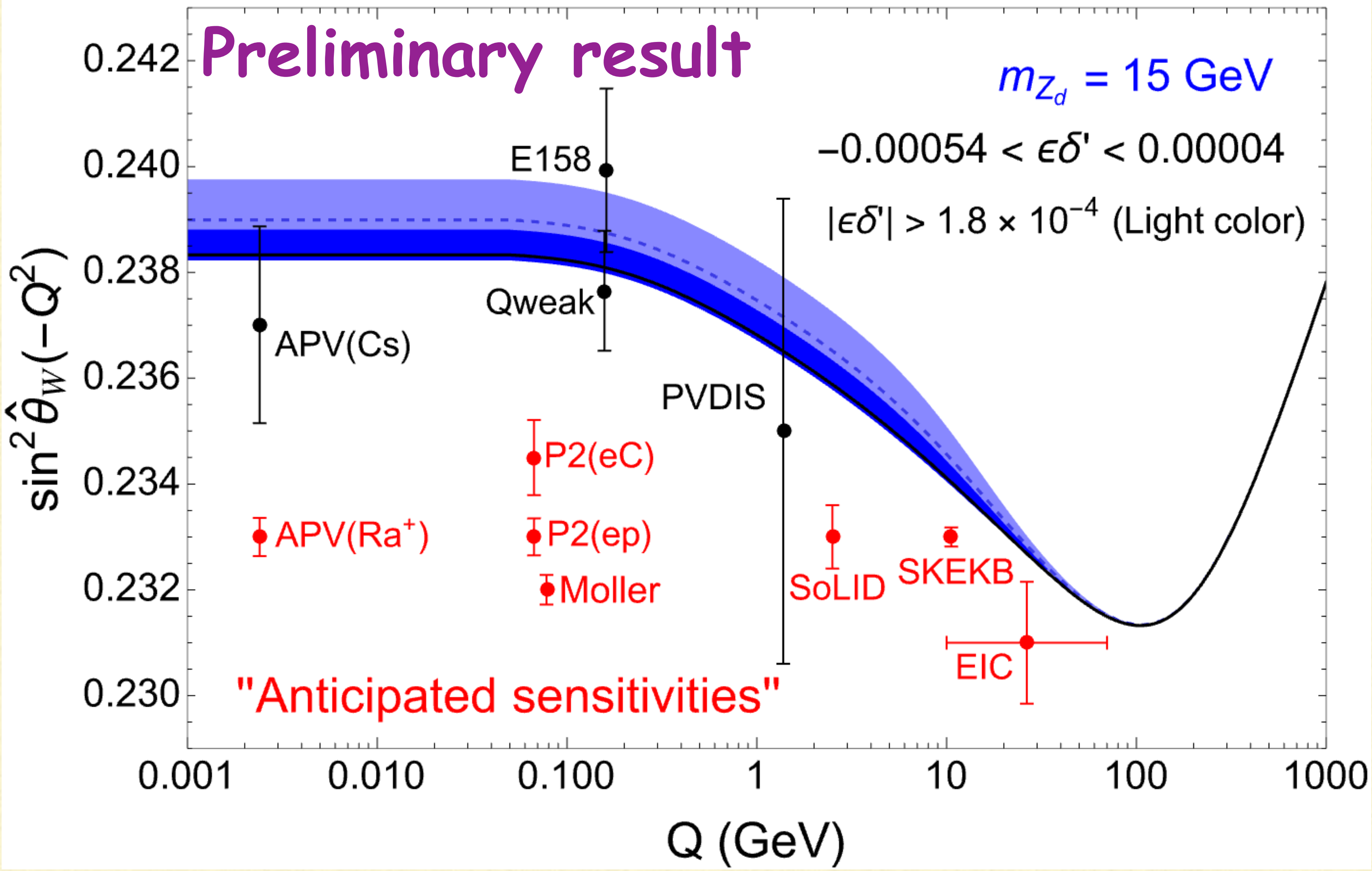

Figure from Davoudiasl, KE, Lee, Lee, Marciano, work in progress (Preliminary result)

(Solid **black** line)

The SM prediction
Czarnecki, Marciano, hep-ph/0003049

(**Blue** regions)

Prediction in the dark Z model

Light Z_d motivated by muon g-2 has also been studied. Davoudiasl, Lee, Marciano, 1205.2709

Heavy dark Z boson and W boson mass anomaly

This talk: **Heavy** dark Z boson ($m_{Z_d} > m_Z$)

Heavy dark *Z* boson and *W* boson mass anomaly

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Why?

A. It can explain **the *W* boson mass anomaly** reported by the CDF

Davoudiasl, KE, Lee, Lee, Marciano, work in progress

$$m_W^{\text{CDF-II}} = 80.4335(94)\ \text{GeV}$$ CDF, Science (2022)

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

$$\Delta m_W^2 \simeq 12.5\ \text{GeV}^2$$

7σ deviation!

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

EW global fit

w/ CDF-II result

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

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We found it CAN be explained in the dark Z model under constraints from EW global fit & direct searches.

Heavy 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

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

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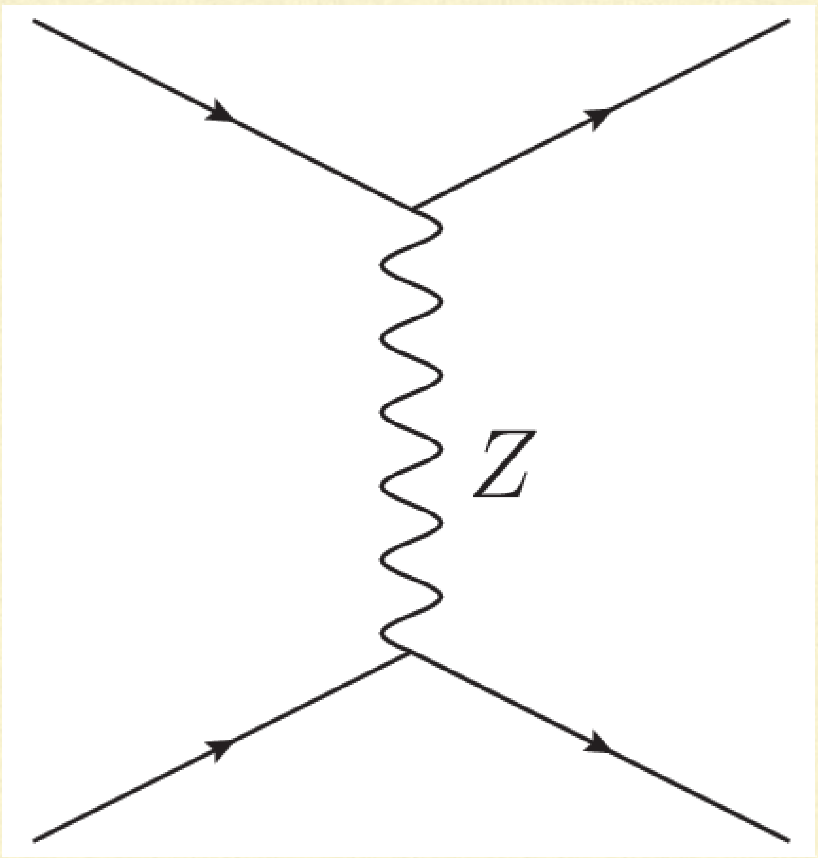
New physics effect in 4 fermion processes



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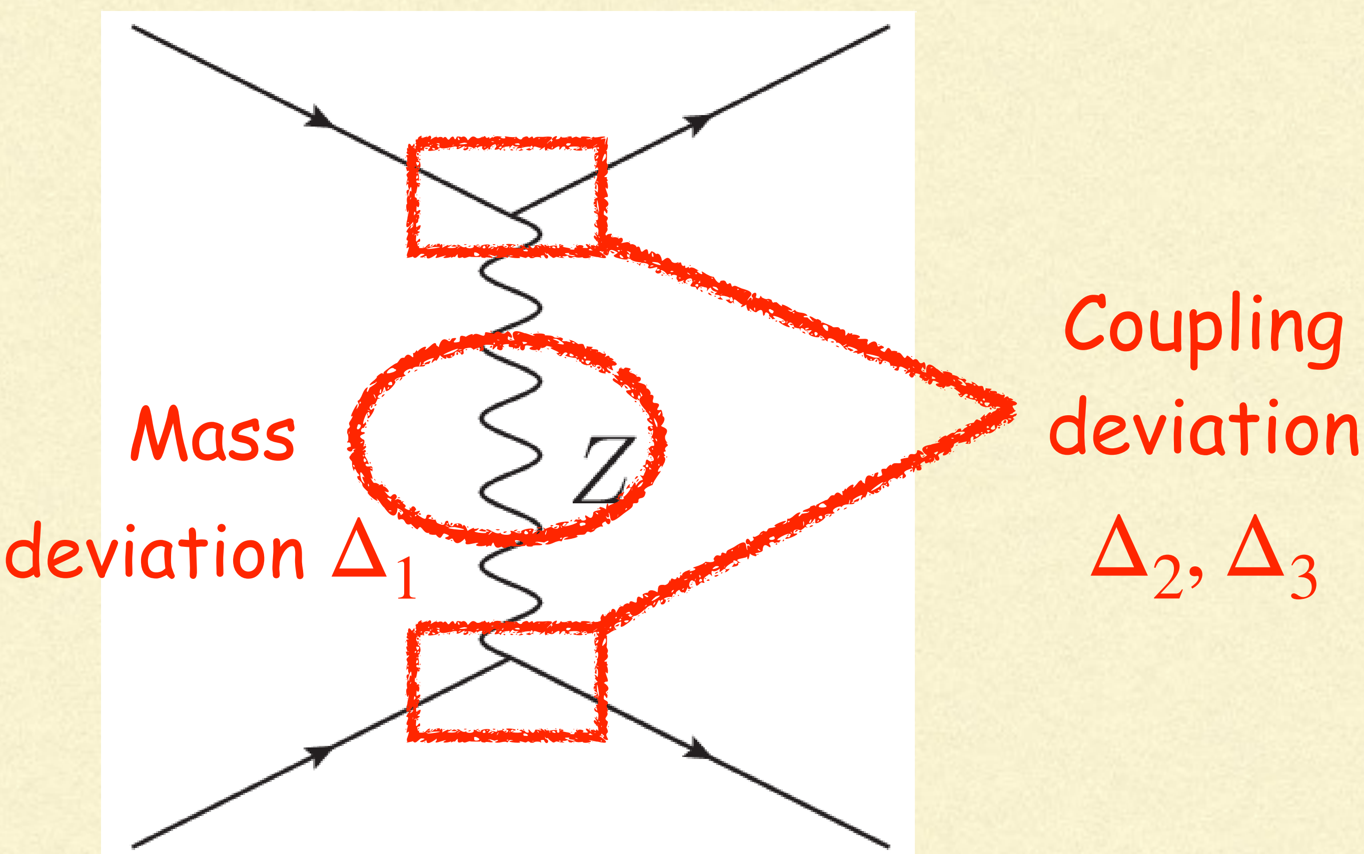

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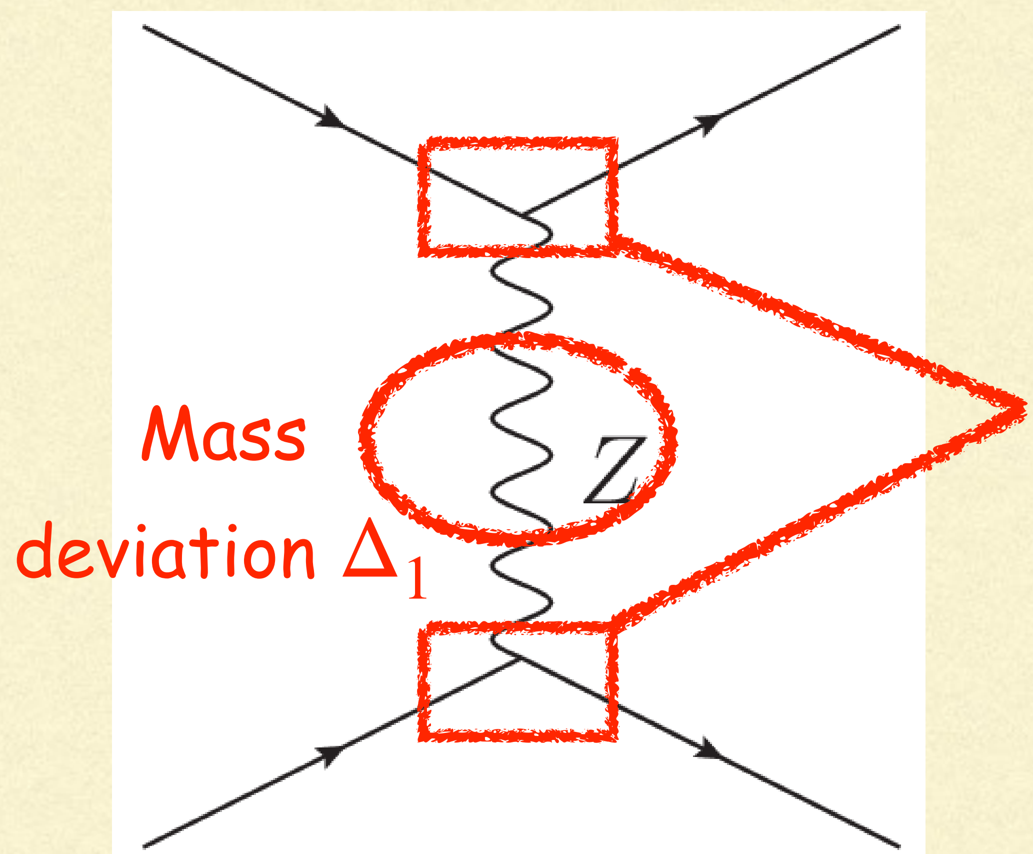
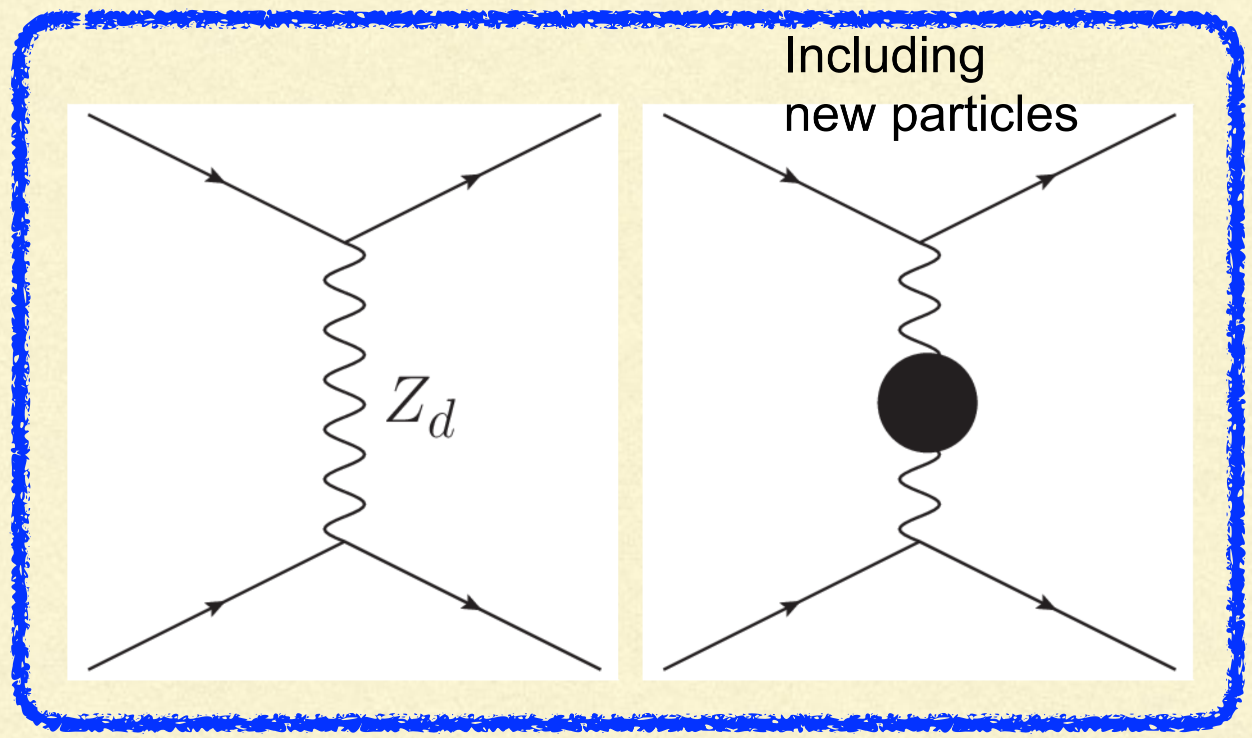


Coupling deviation Δ_2, Δ_3



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

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

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

$r = m_{Z_d}/m_Z$

$s_W = \sin\theta_W$

$c_W = \cos\theta_W$

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

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

EW global fit
(w/ CDF-II result)

$S = 0.06(10)$
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Lu *et al*, 2204.03796

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[Lu *et al*, 2204.03796]

Heavy dark Z bosons and W boson mass anomaly

Using S, T, and U parameters,

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

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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$r^2 < 1 \longrightarrow \Delta m_W^2 < 0$

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Favored by the CDF-II result

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Favored by the CDF-II result

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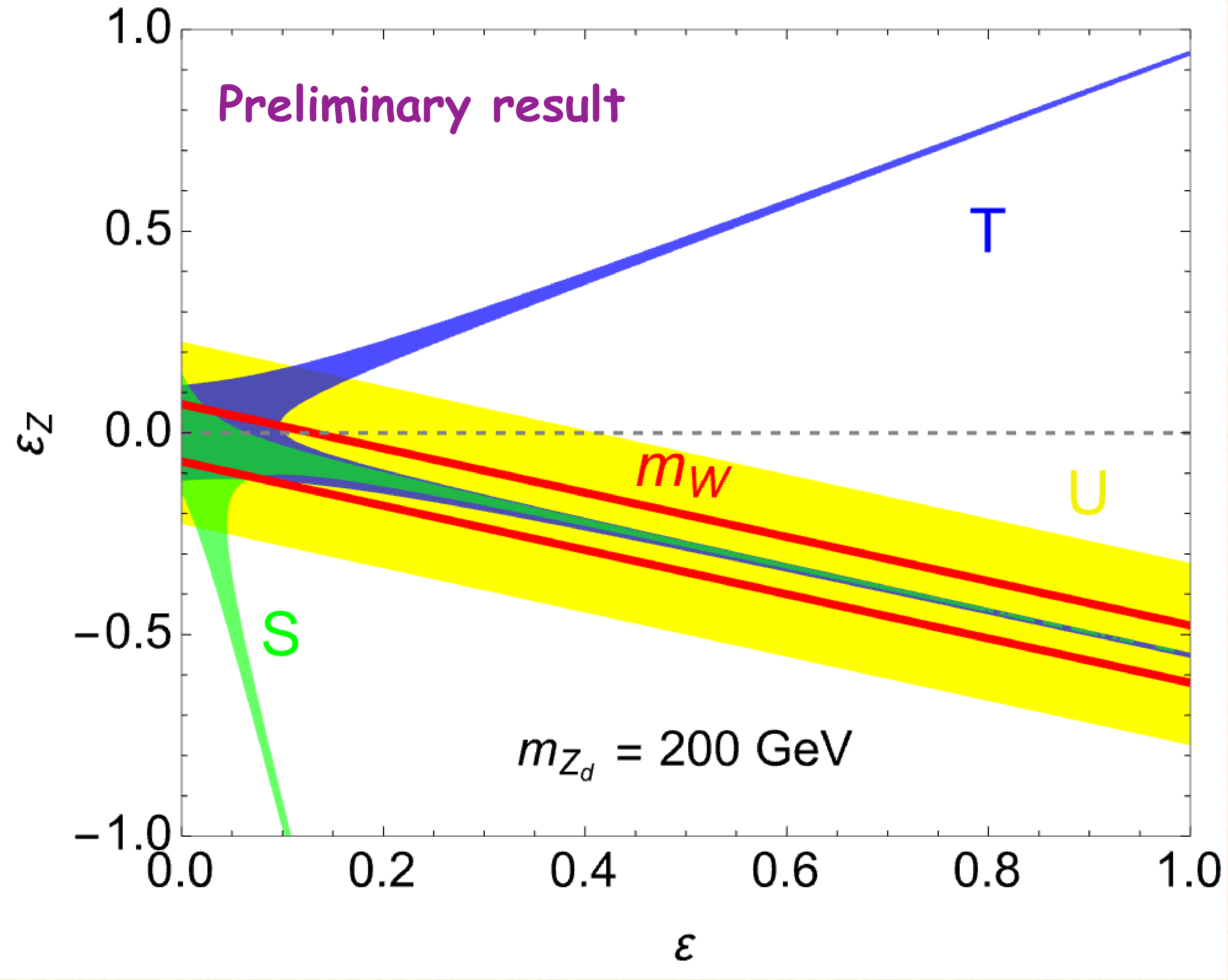
$m_{Z_d} > m_Z$

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

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

W boson mass anomaly & EW global fit



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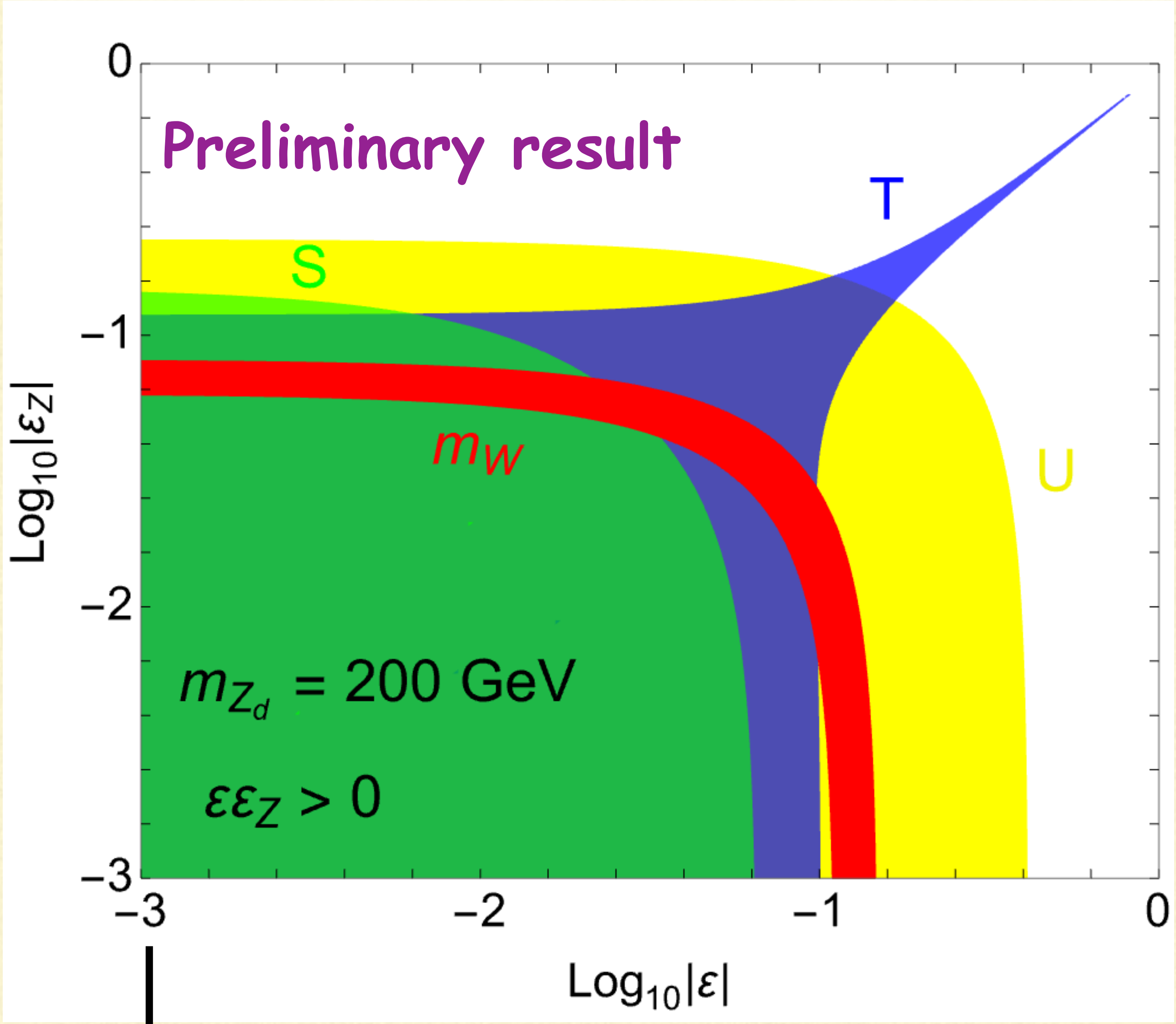

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($\varepsilon_Z = 0$)

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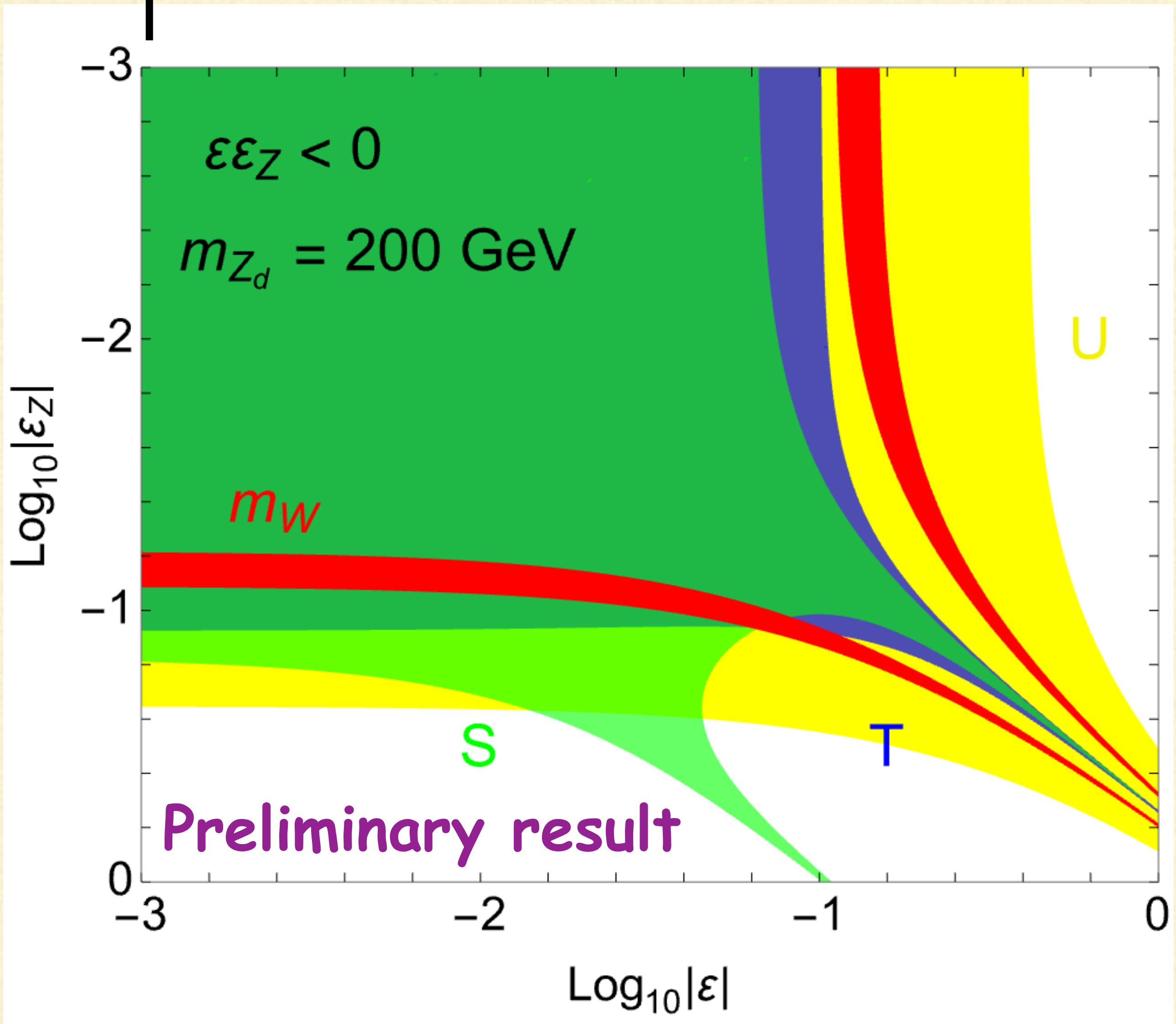

W boson mass anomaly & EW global fit

No overlap region
in dark photon limit

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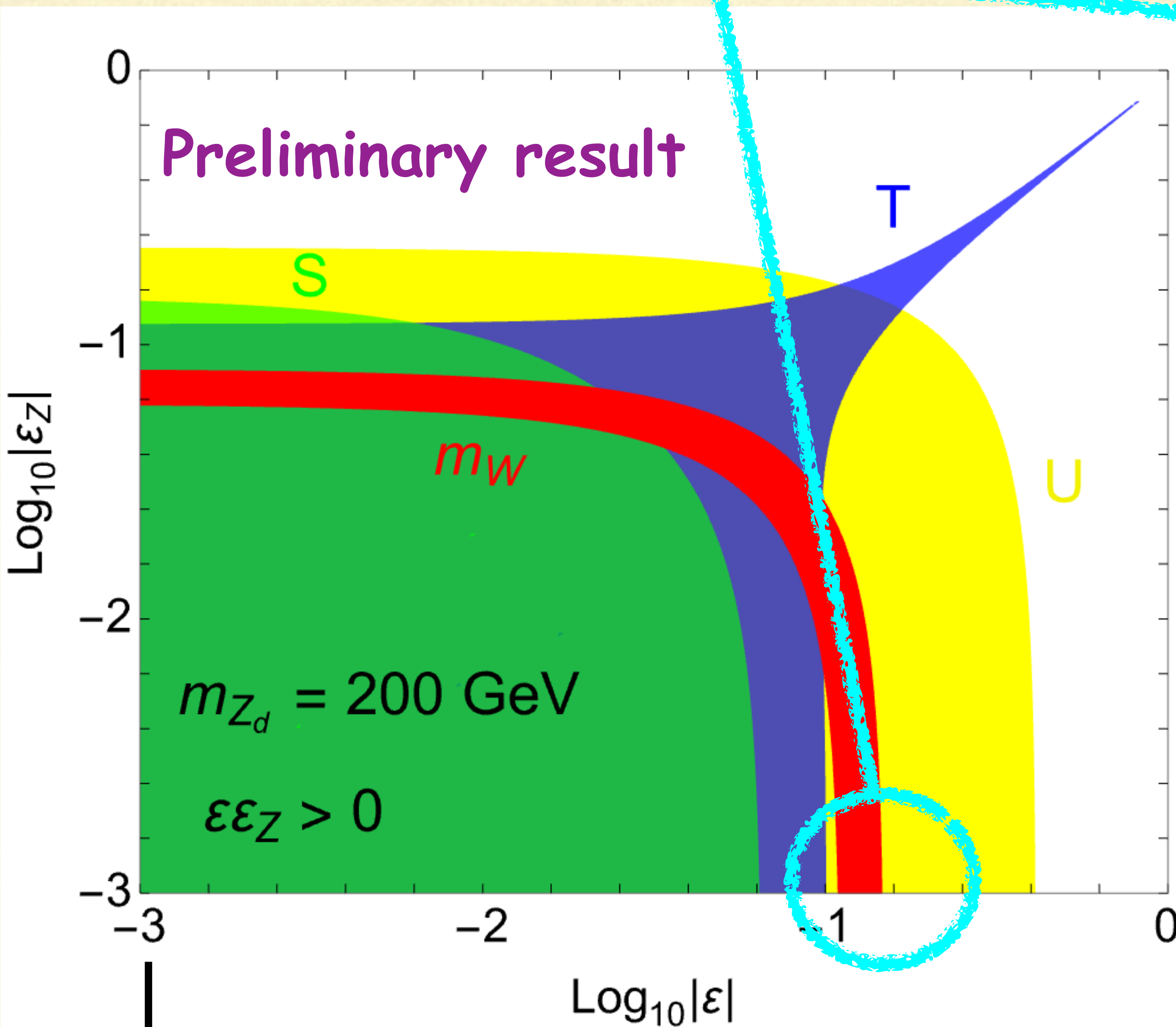
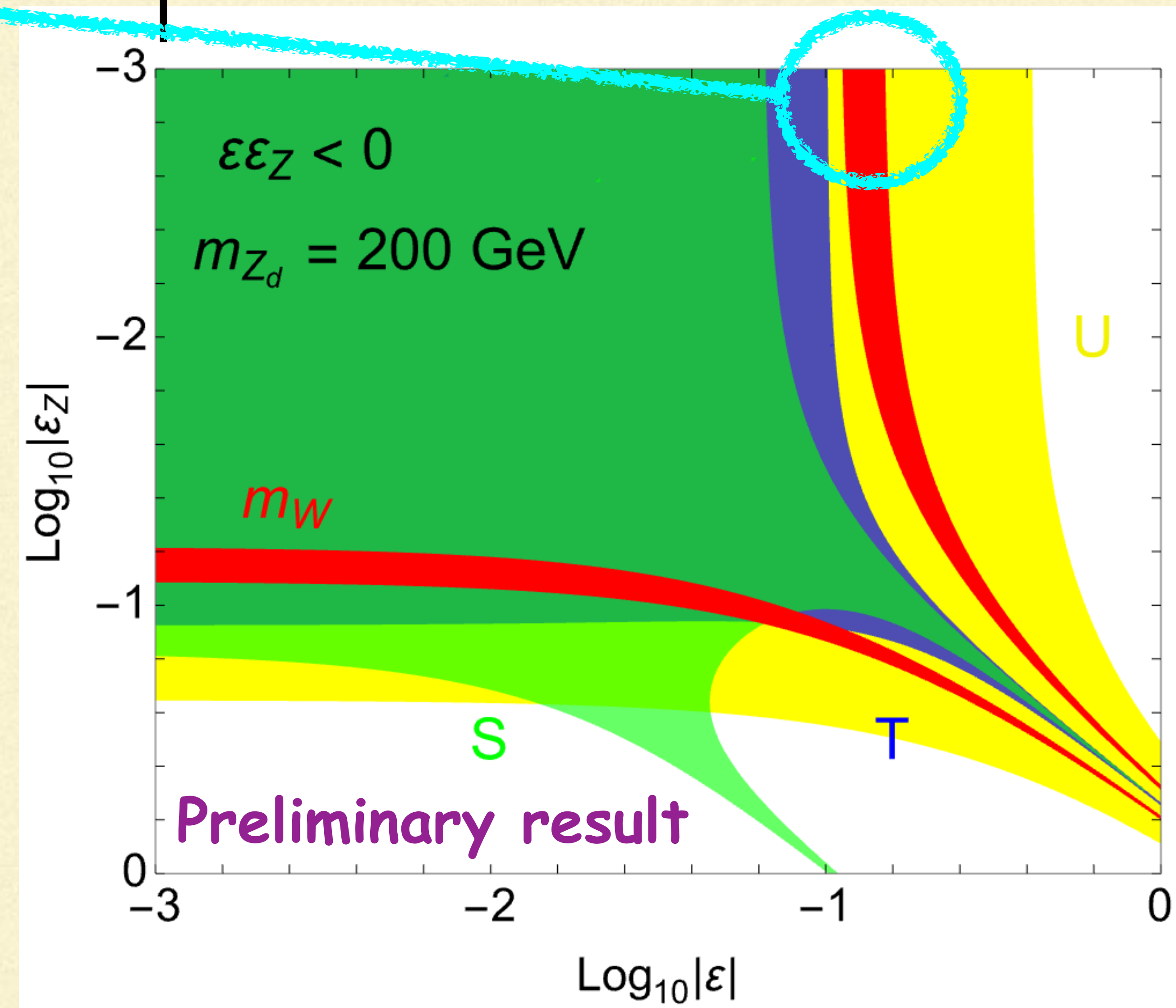
Dark photon limit
($\varepsilon_Z = 0$)





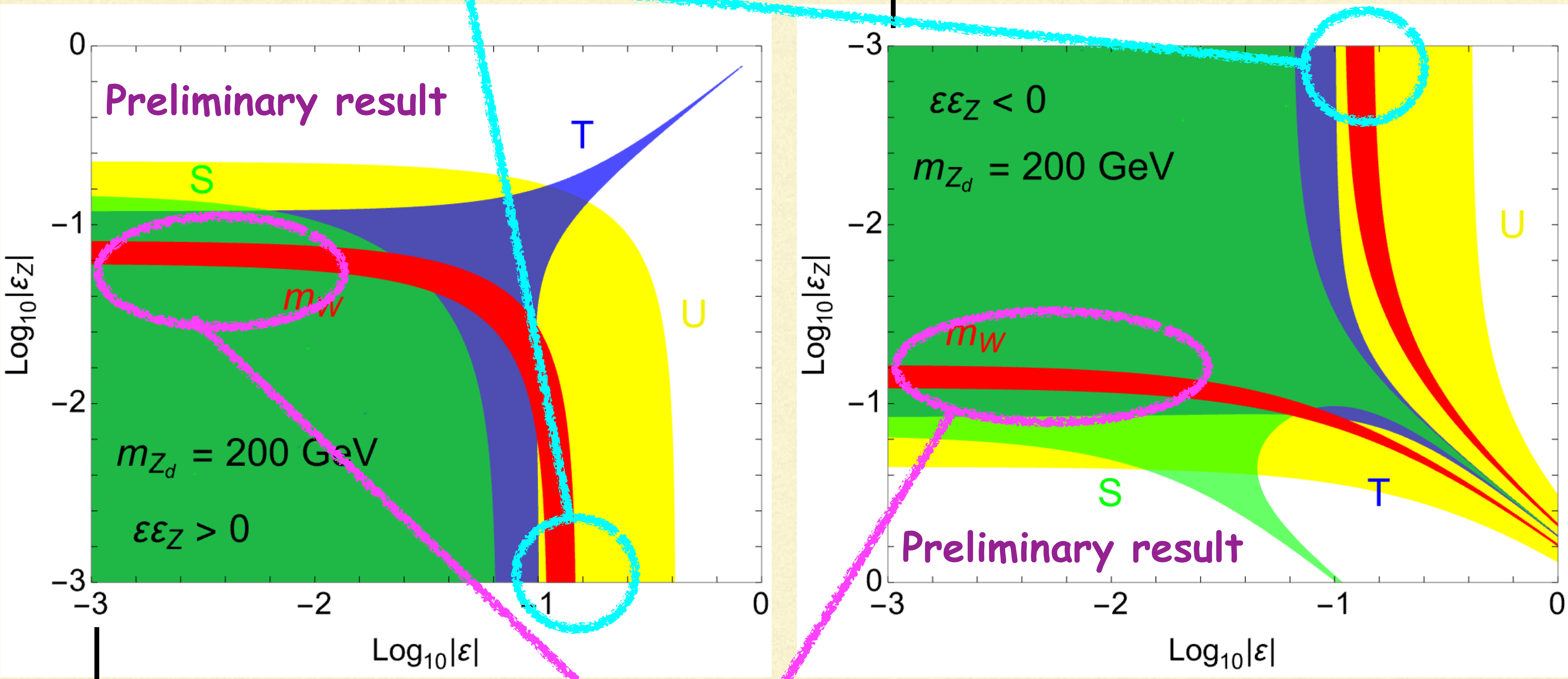
Dark photon limit
($\varepsilon_Z = 0$)

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 ($\varepsilon_Z = 0$)

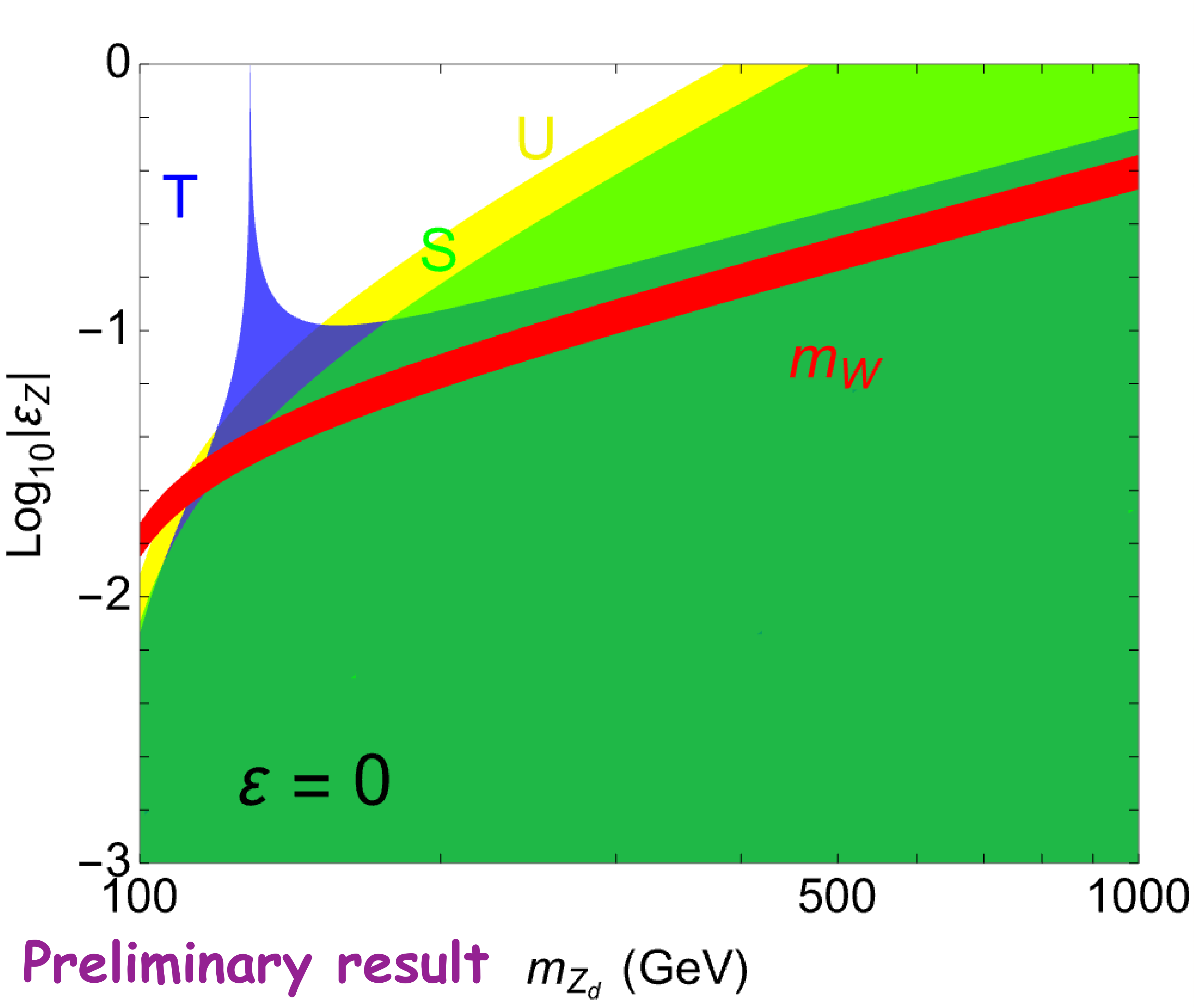


Dark photon limit ($\varepsilon_Z = 0$)

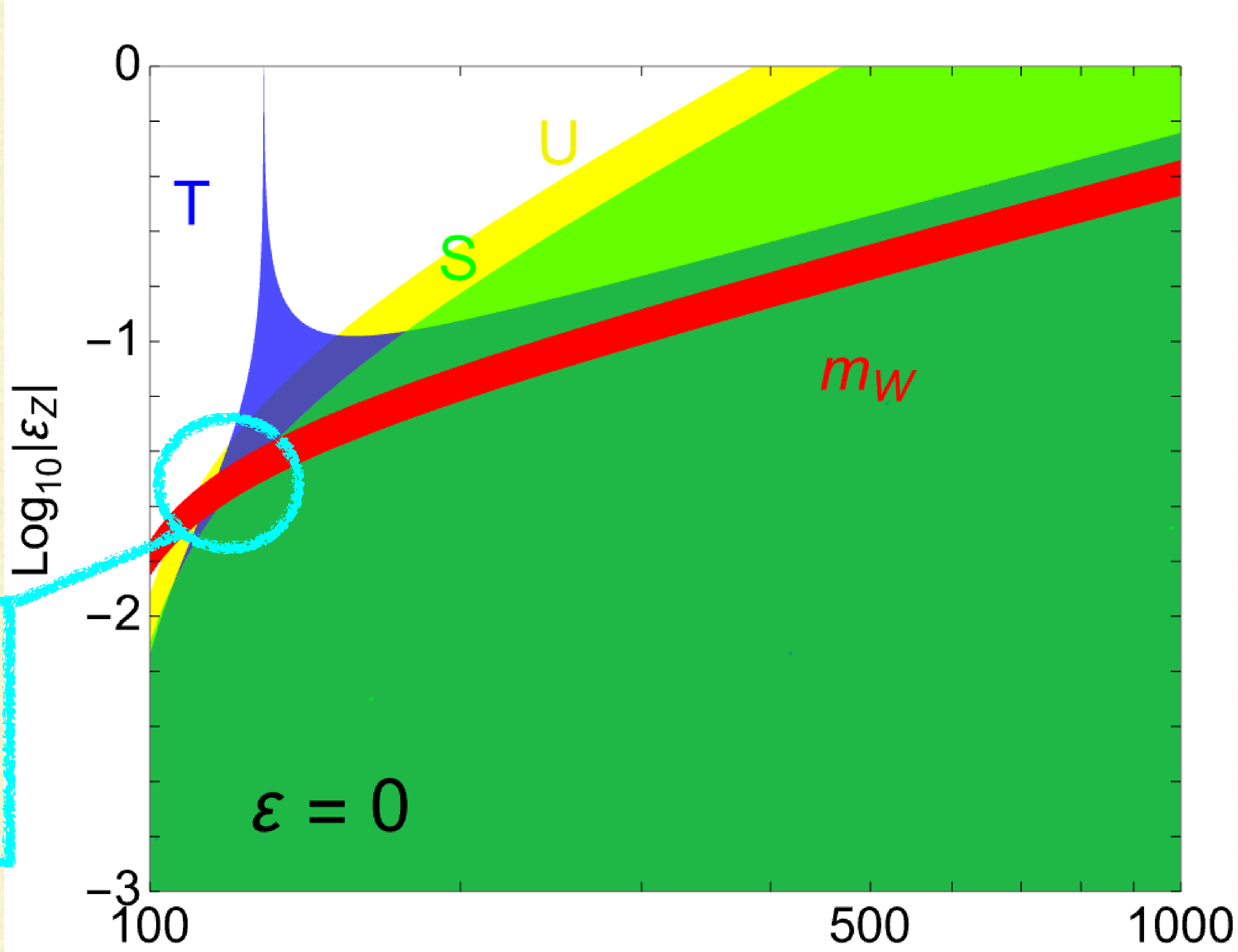
CDF-II result **can be explained**

with $|\varepsilon_Z| = O(0.1)$ and small ε

W boson mass anomaly & EW global fit



W boson mass anomaly & EW global fit



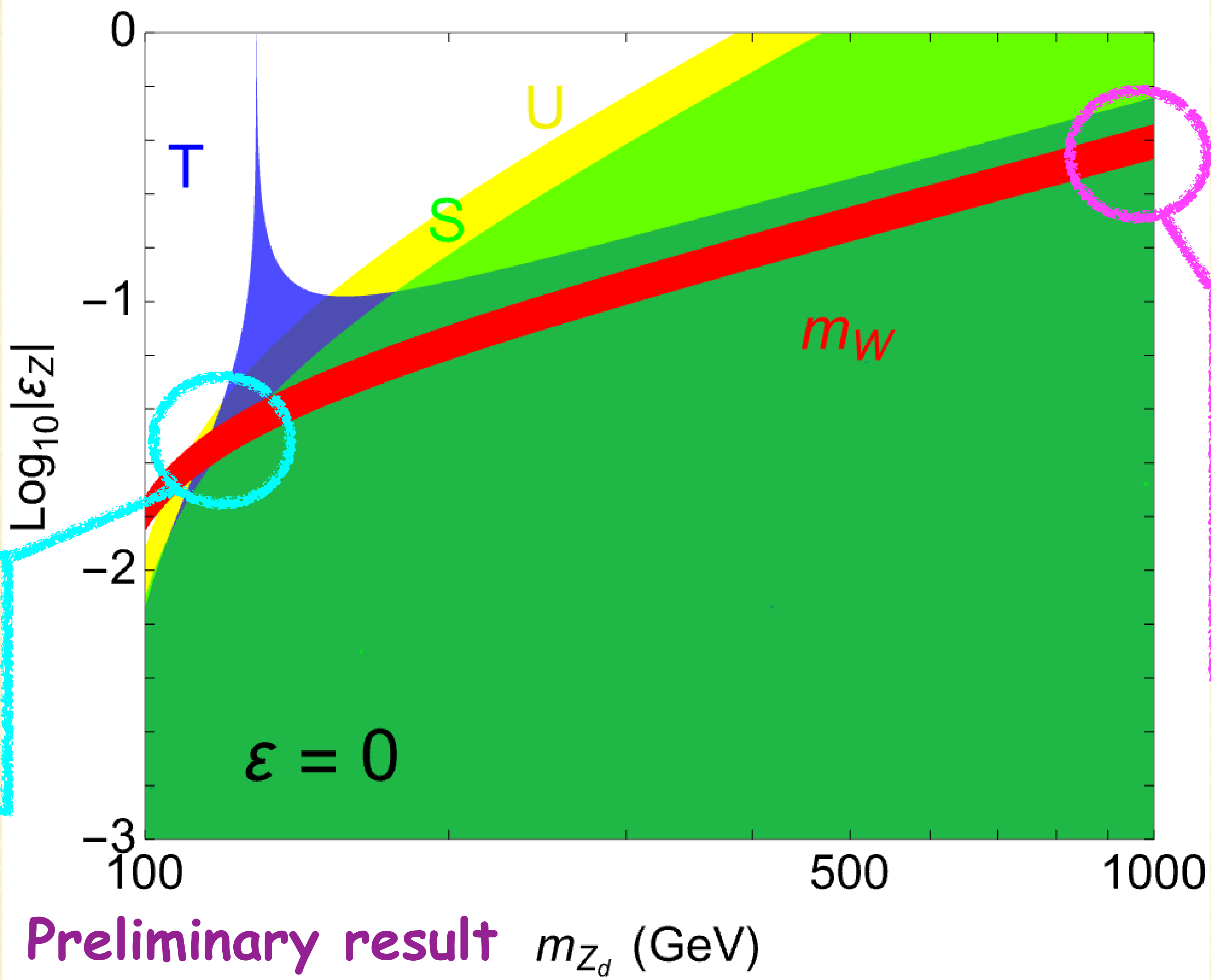
Minimum m_{Z_d}

$m_{Z_d} \simeq 130$ GeV

($|\varepsilon_Z| \simeq 0.03$)

Preliminary result

W boson mass anomaly & EW global fit



Minimum m_{Z_d}
$m_{Z_d} \simeq 130$ GeV
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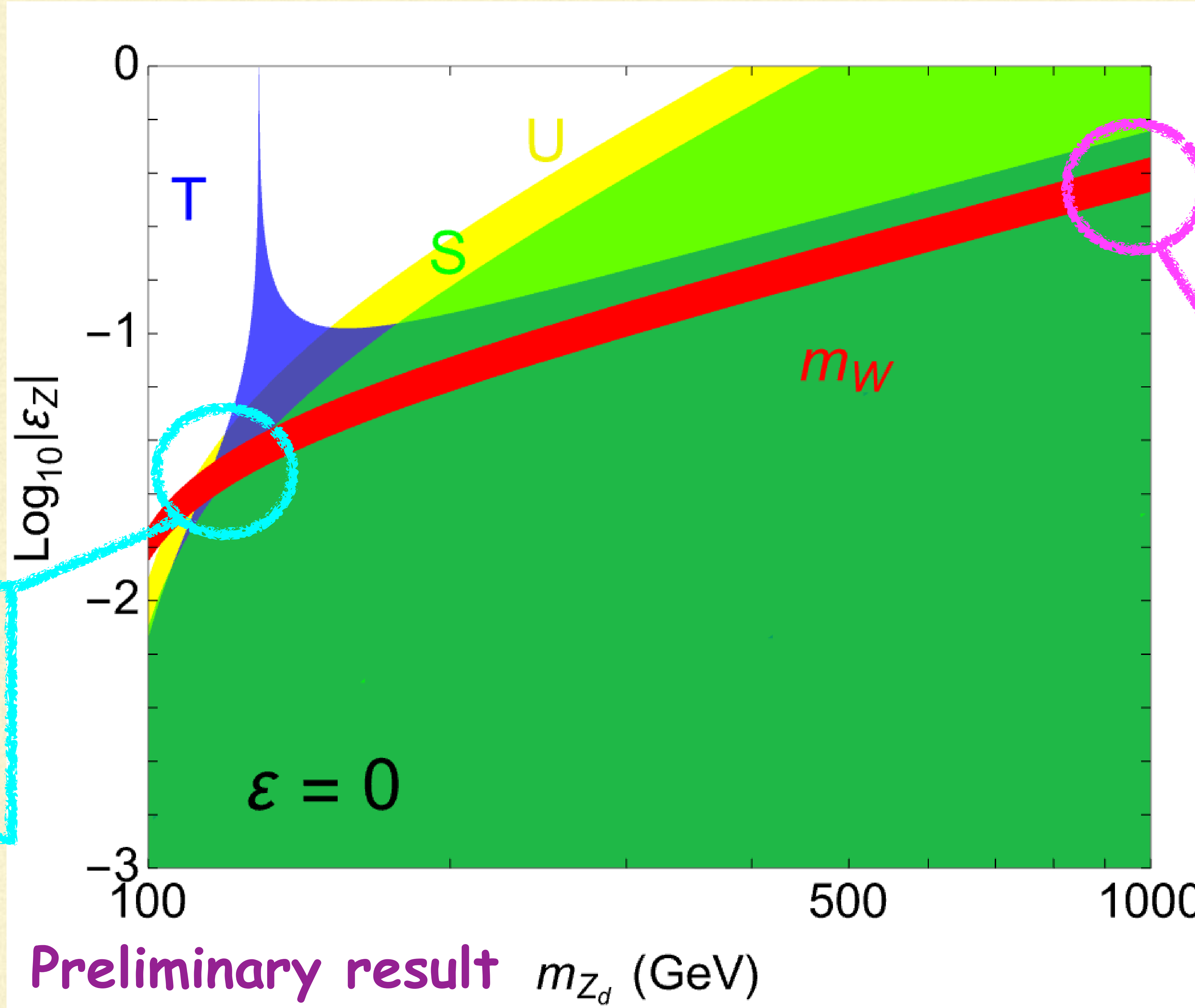
Large ε_Z
for heavier Z_d
||
Perturbation
is not good

Preliminary result

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

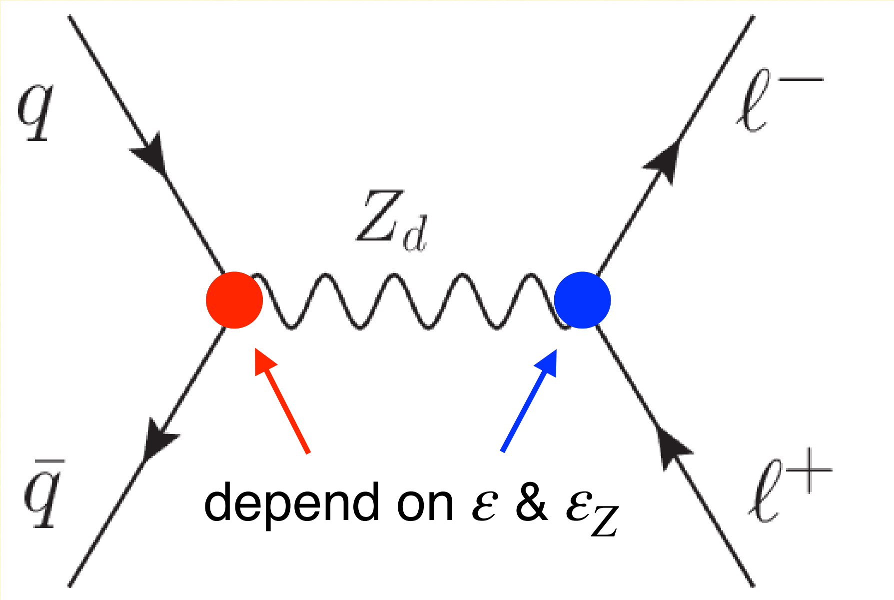
Heavy Z_d ($m_{Z_d} = O(100)$GeV) and relatively large $|\varepsilon_Z|$($\gtrsim 0.03$)

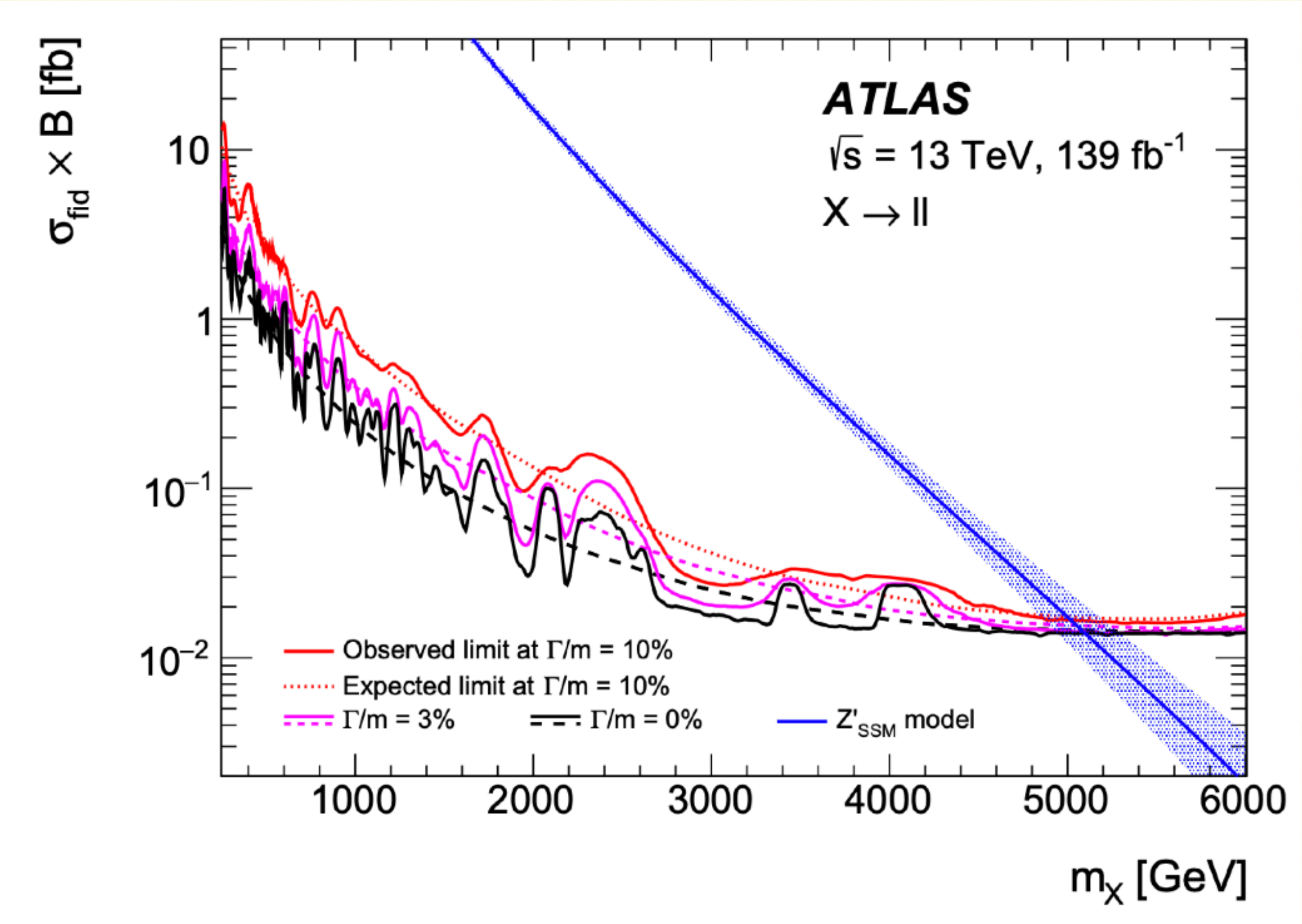
Constraint from direct searches

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

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

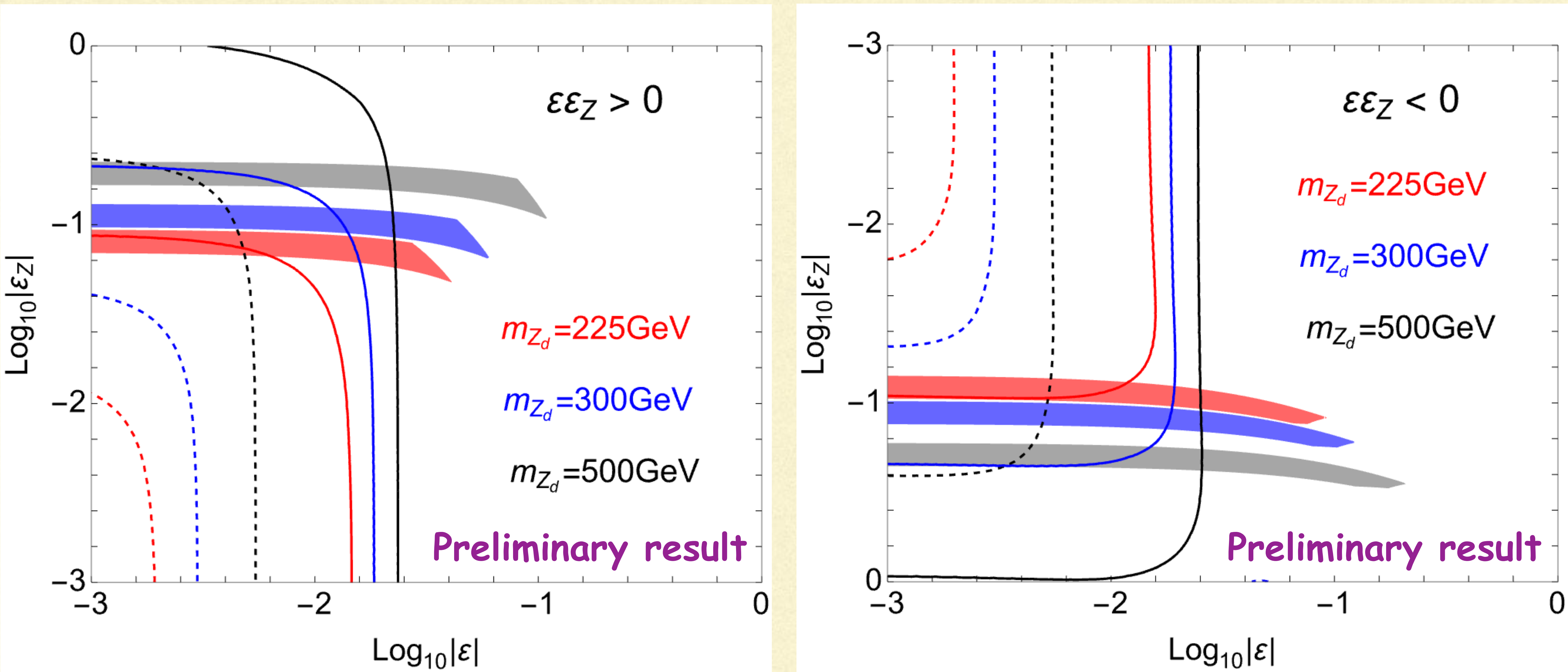
CMS, 1911.03947

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

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.

- Such a parameter region is strongly constrained by dilepton resonant searches unless m_{Z_d} is quite small or large.
  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 $\tilde{Z}_{d\mu}$

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

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

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

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,

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

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

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

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

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