The CDF-II Anomaly and Potential New Physics Explanations

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Outline

- The CDF-II Anomaly
- W Boson Mass in SM
- The Oblique S,T,U Parameters
- New Physics Scenarios
  - Models with Triplet Scalars
  - Models with Doublet Scalars
  - Models with modified Z boson mass

- Conclusions

The CDF-II Anomaly

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  - **Also 7-sigma away from SM prediction !!**

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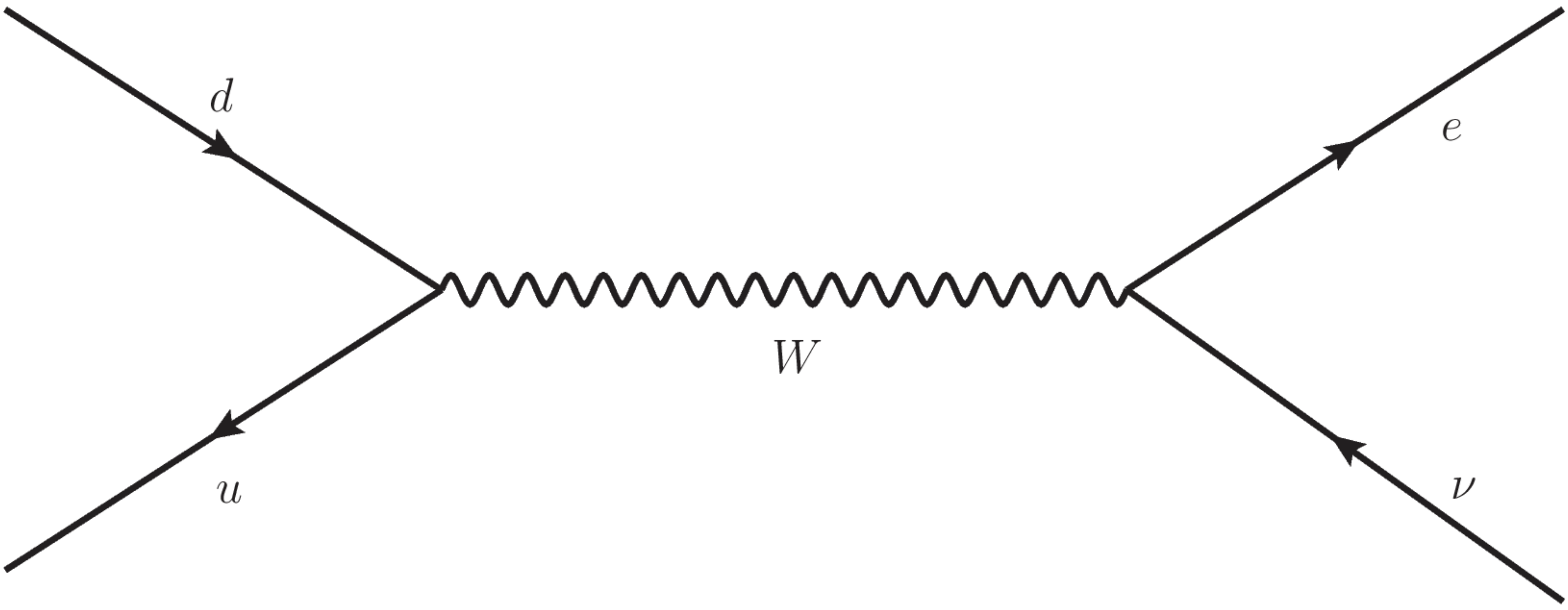

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  - Use the transverse momentum (pT) information of the charged lepton

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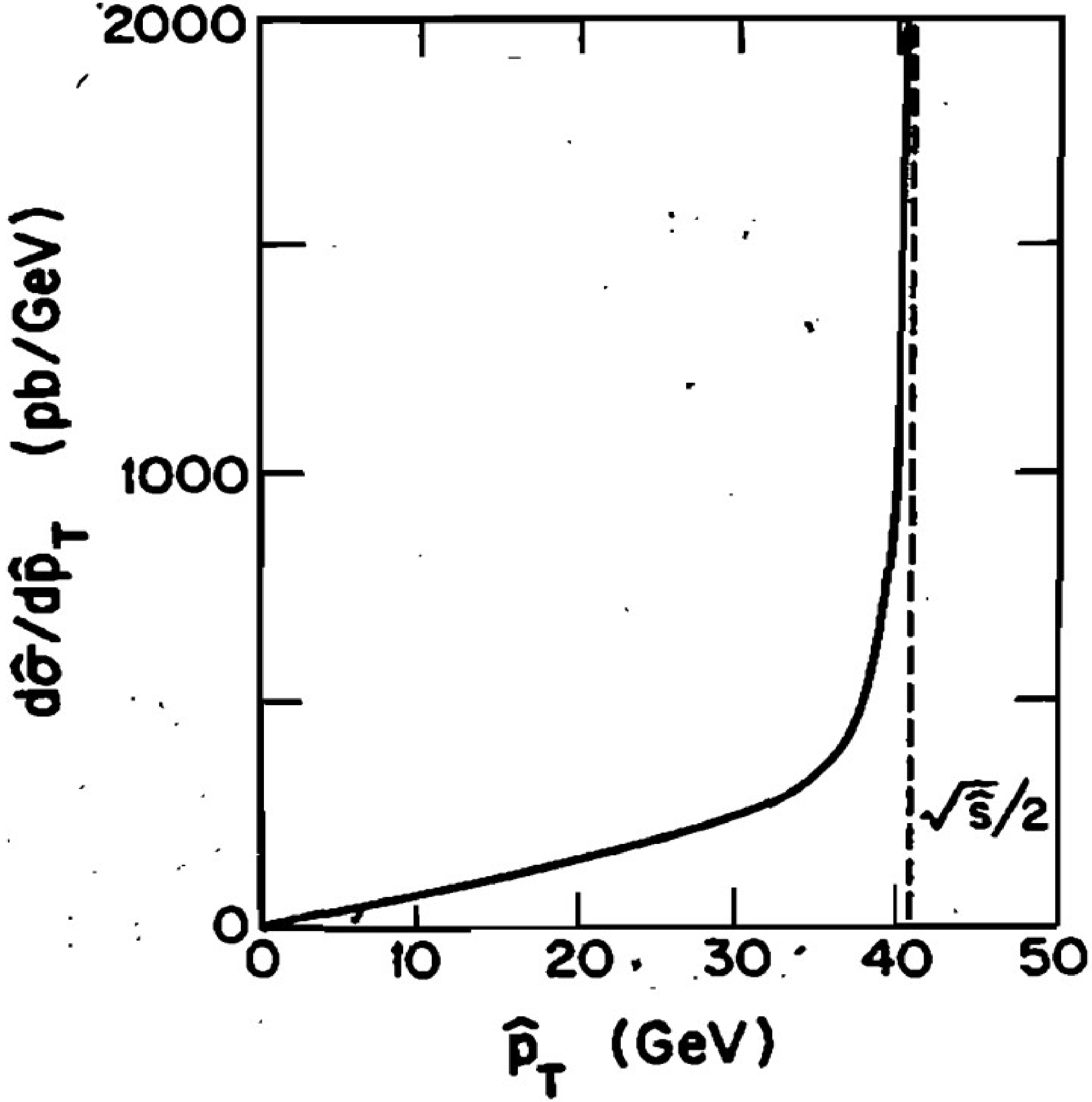

Fig. 8.9. Jacobian peak p_T-distribution in the $u\bar{d} \rightarrow e^+\nu$ subprocess at fixed $\hat{s}$.

Barger and Phillips, Collider Physics

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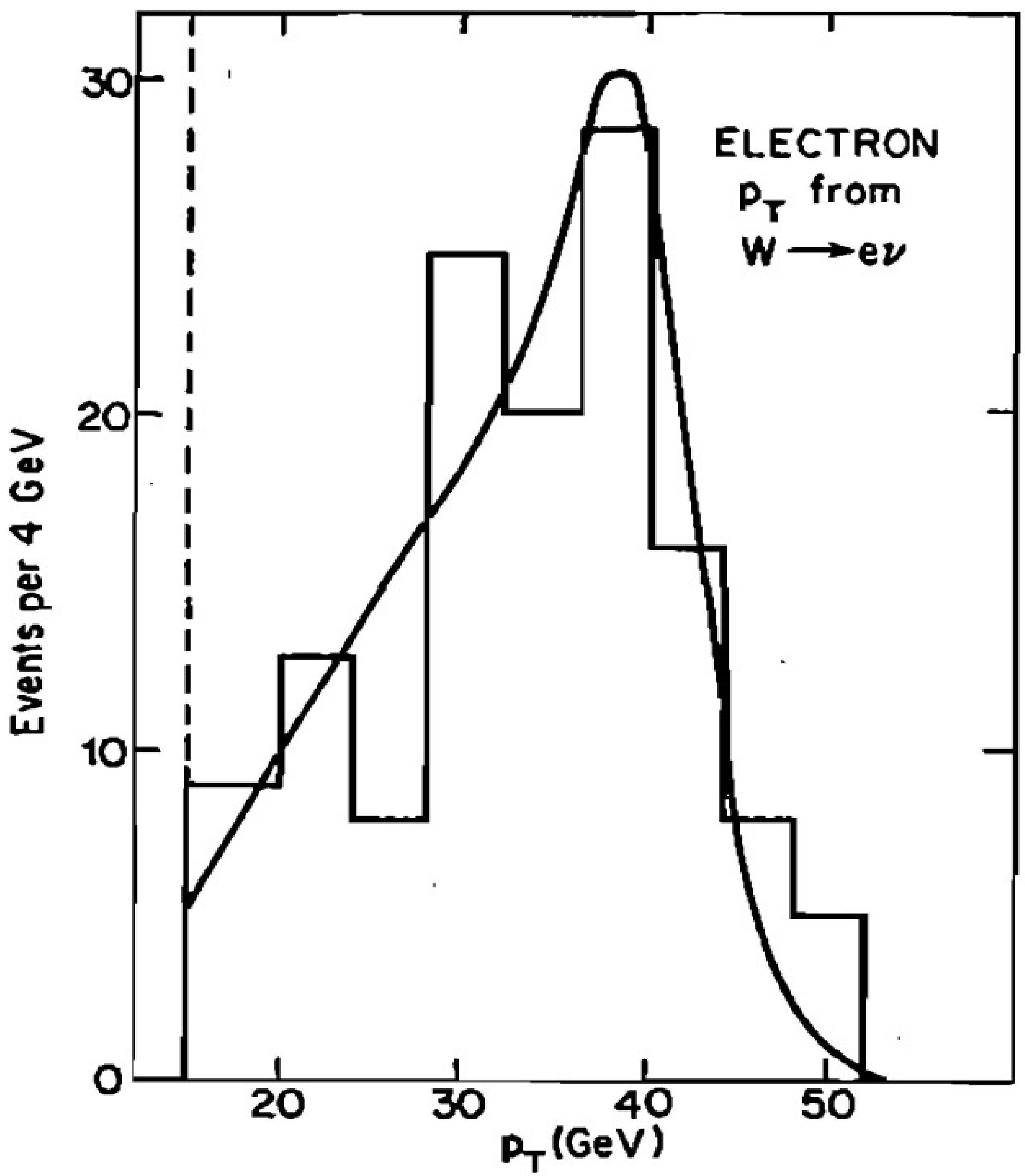

Fig. 8.10. Distribution of electron p_T from $p\bar{p} \to W \to e\nu$ events at $\sqrt{s} = 630$ GeV (UA1 data) compared with a calculation folding in the smearing from $p_T(W)$.

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$$m_T^2(e,\nu) = \left(|\mathbf{p}_{eT}| + |\mathbf{p}_{\nu T}|\right)^2 - \left(\mathbf{p}_{eT} + \mathbf{p}_{\nu T}\right)^2$$

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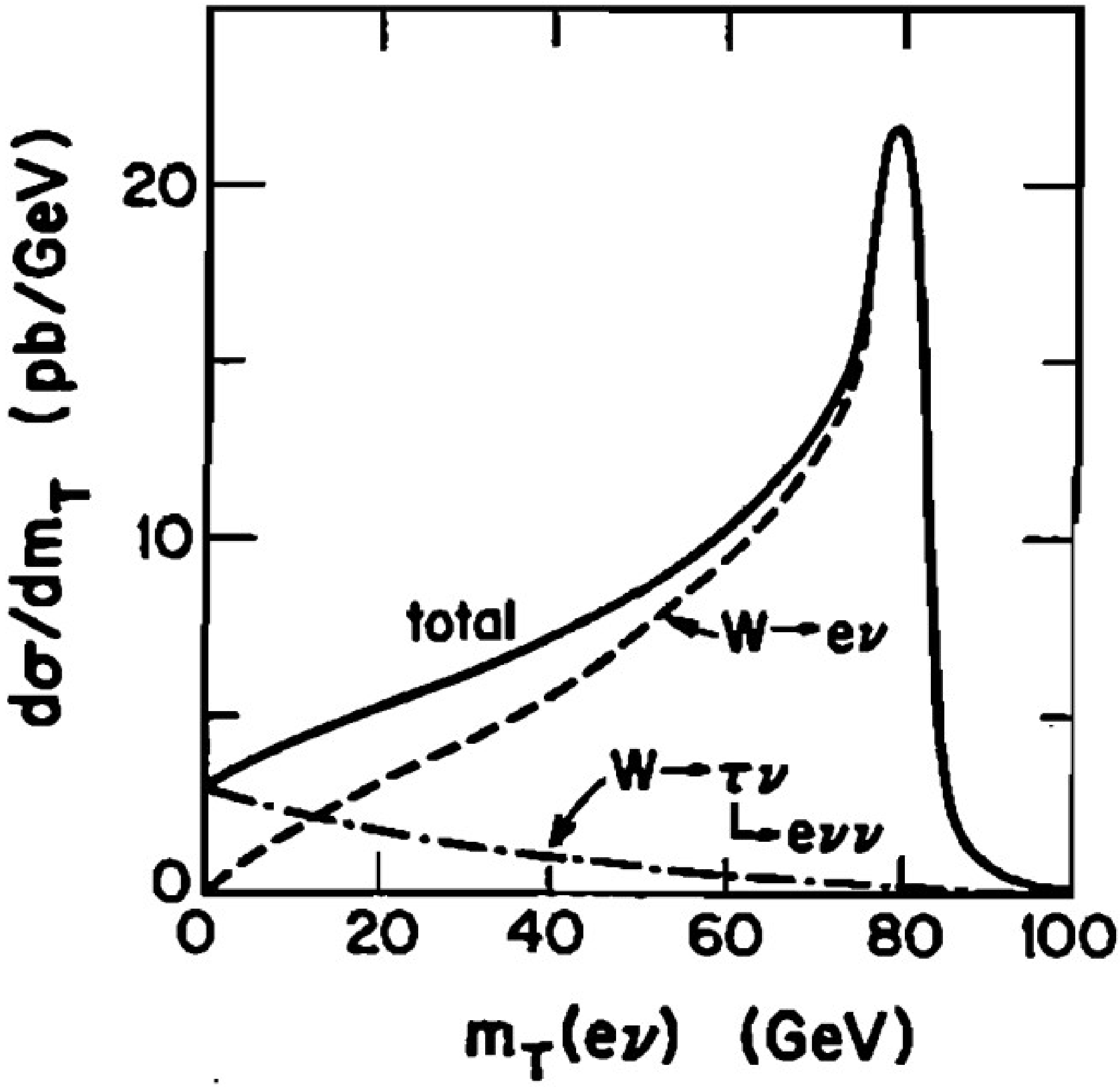

Fig. 8.11. Predicted distribution of transverse mass $m_T(e\nu)$ for $p\bar{p} \to W^{\pm} \to e\nu$ collisions at $\sqrt{s} = 630$ GeV.

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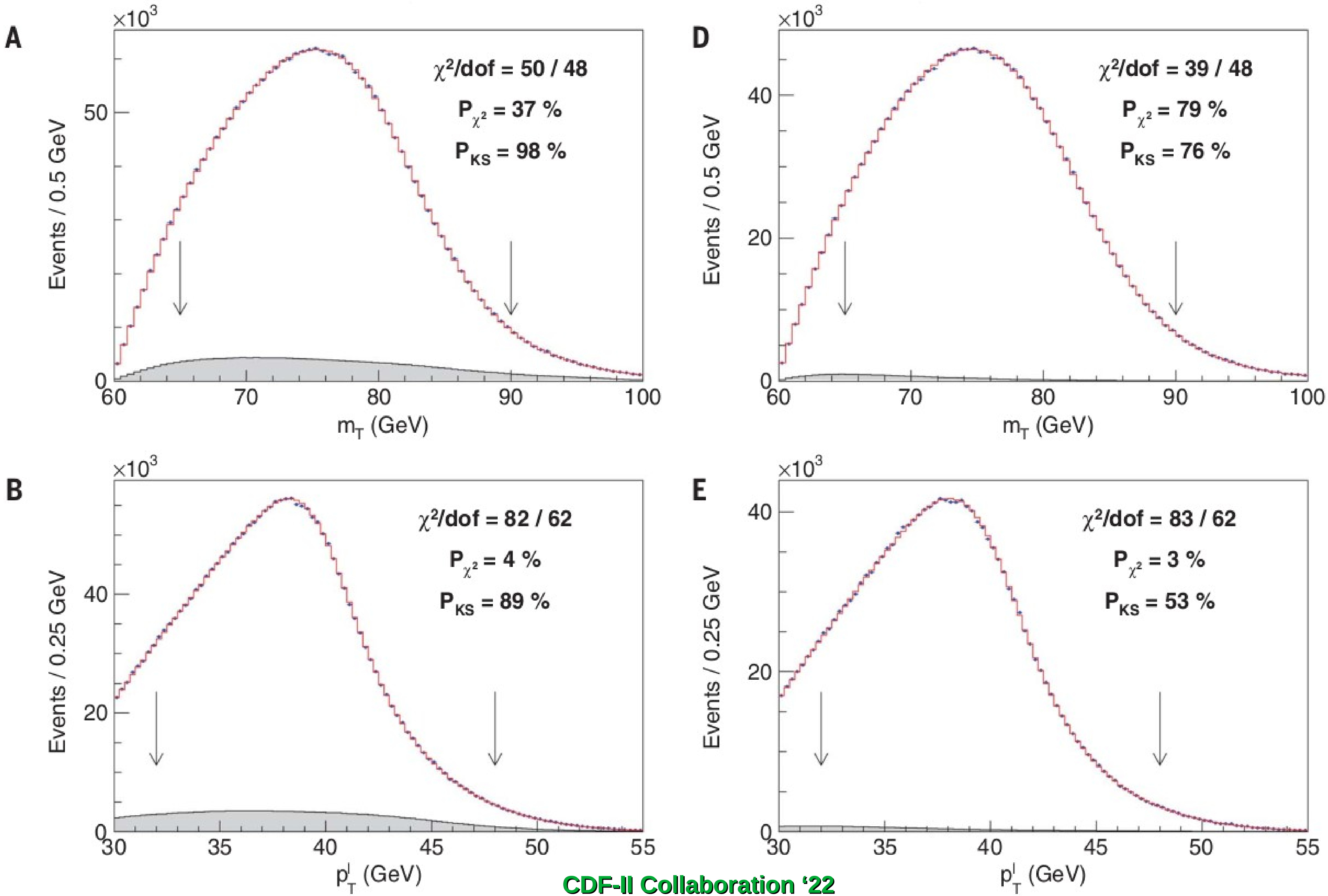
The CDF-II W mass measurement



CDF-II Collaboration '22

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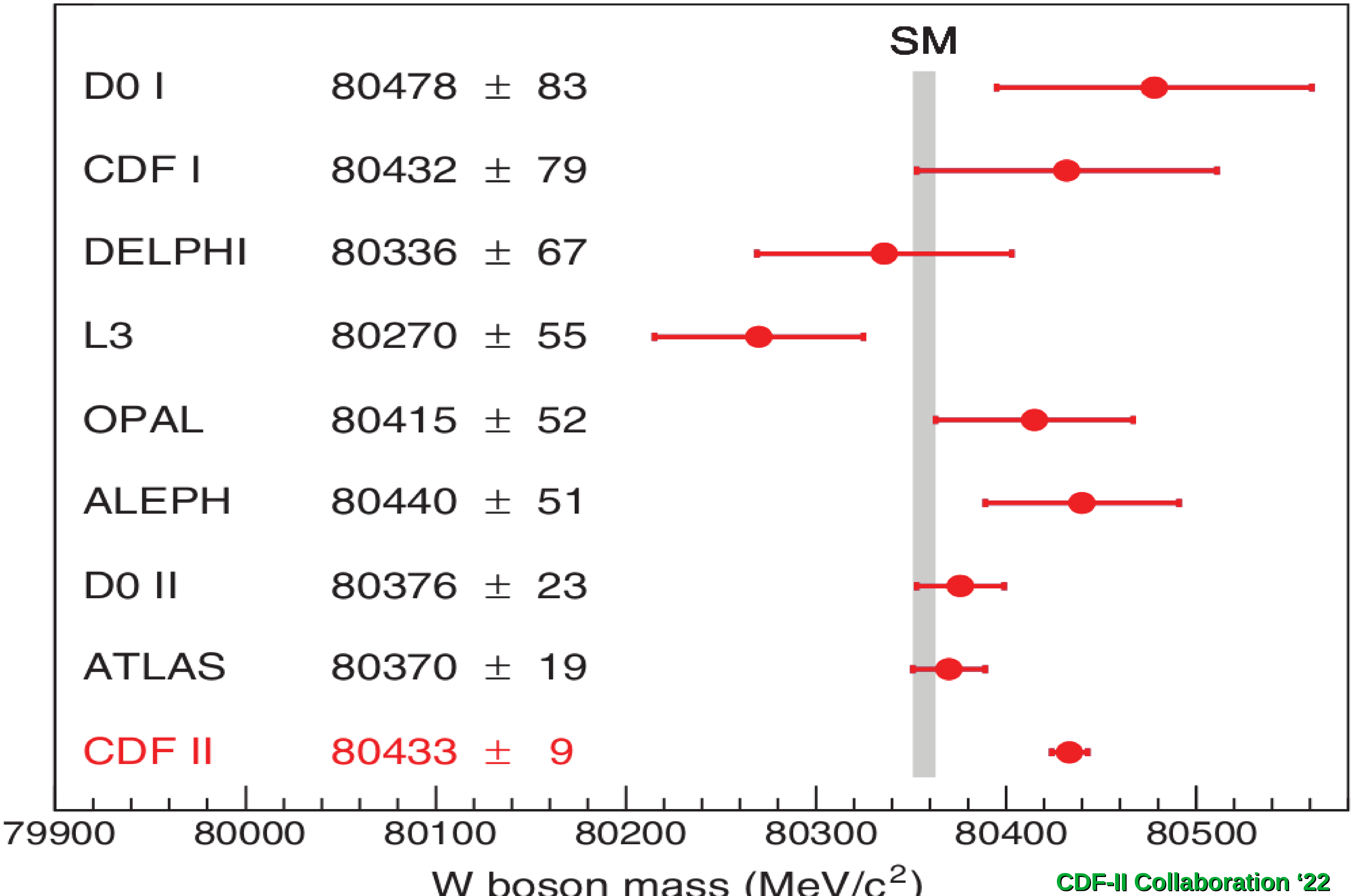

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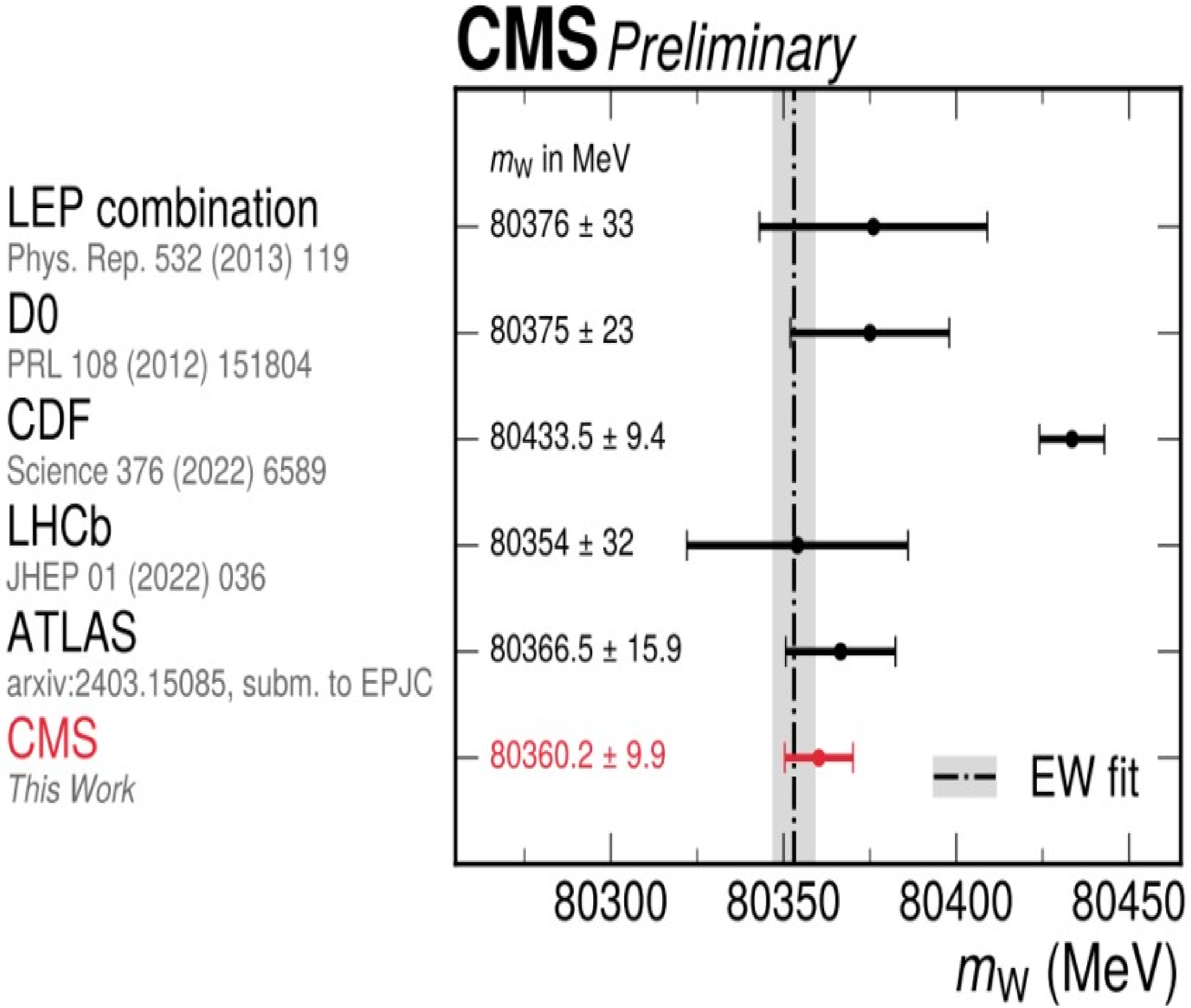
$m_W = 80360.2 \pm 9.9 \text{MeV}$



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  - **I will also discuss their connections to other shortcomings of the SM**

W boson Mass in SM

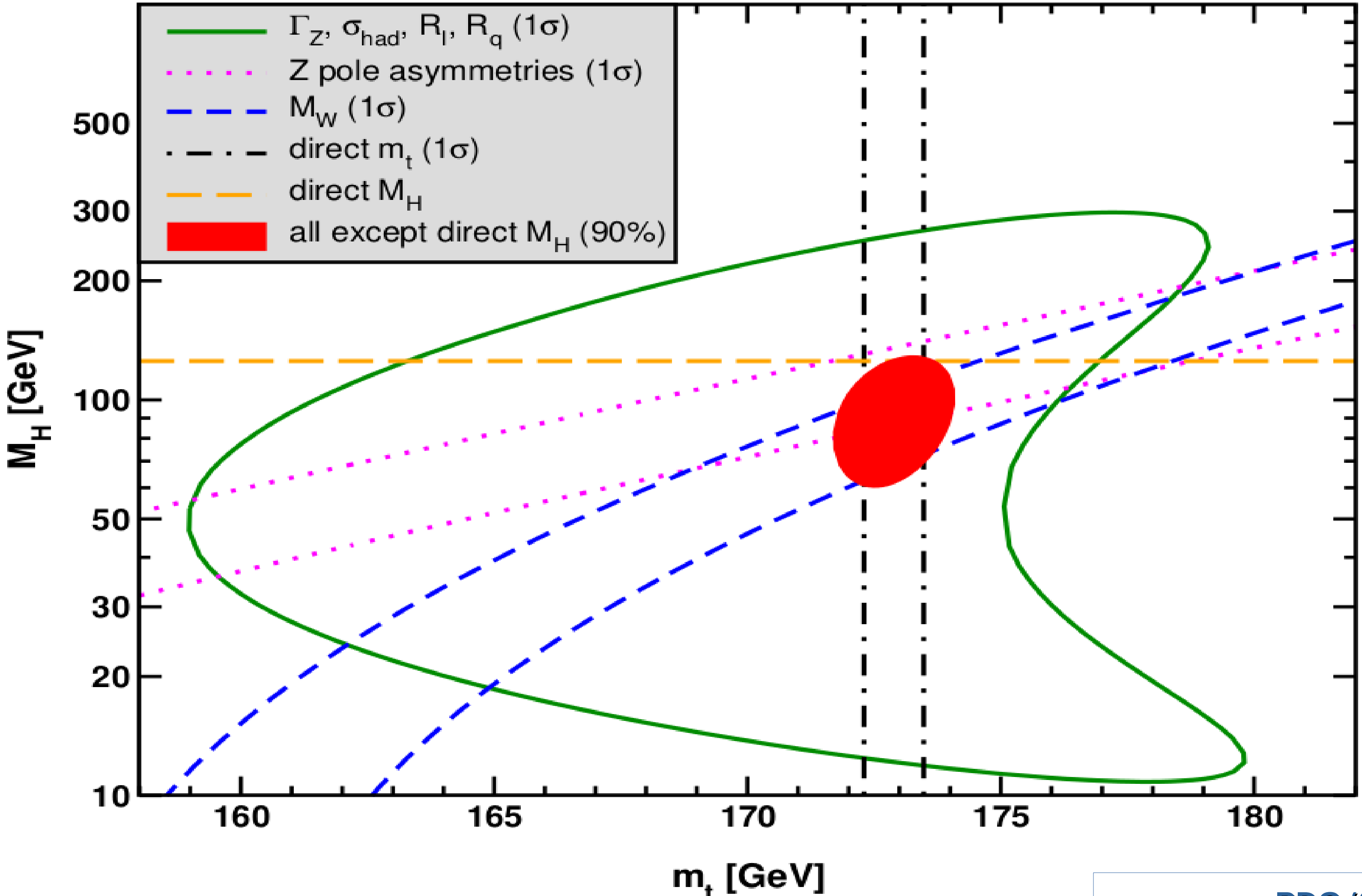
- In SM the W, Z bosons get their mass after SSB via Higgs mechanism
  - The mass of W, Z are proportional to the Higgs vev and the gauge couplings
  - They are also tied together by the rho-parameter (on-shell renomalization scheme)

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \qquad \mathrm{in\,SM}\ :\ \rho = 1$$

- So if you know mass of one gauge boson then you can compute the SM expectation for the other
  - Typically Z mass can be easily and precisely measured
  - Z mass used as input for W mass expectation

SM Global Fit

- You actually do a global fit



PDG '20

The Oblique S, T, U Parameters

- New physics effects can change the SM relations
- Model independent parametrization: The Oblique S, T, U parameters

$$\widehat{\alpha}(M_Z)T \equiv \frac{\Pi_{WW}^{\rm new}(0)}{M_W^2} - \frac{\Pi_{ZZ}^{\rm new}(0)}{M_Z^2} \; ,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}_Z^2\widehat{c}_Z^2}S \equiv \frac{\Pi_{ZZ}^{\rm new}(M_Z^2) - \Pi_{ZZ}^{\rm new}(0)}{M_Z^2} - \frac{\widehat{c}_Z^2 - \widehat{s}_Z^2}{\widehat{c}_Z\widehat{s}_Z}\frac{\Pi_{Z\gamma}^{\rm new}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}^{\rm new}(M_Z^2)}{M_Z^2} \; ,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}_Z^2}(S+U) \equiv \frac{\Pi_{WW}^{\rm new}(M_W^2) - \Pi_{WW}^{\rm new}(0)}{M_W^2} - \frac{\widehat{c}_Z}{\widehat{s}_Z}\frac{\Pi_{Z\gamma}^{\rm new}(M_Z^2)}{M_Z^2} - \frac{\Pi_{\gamma\gamma}^{\rm new}(M_Z^2)}{M_Z^2} \; .$$

Peskin and Takeuchi ‘92

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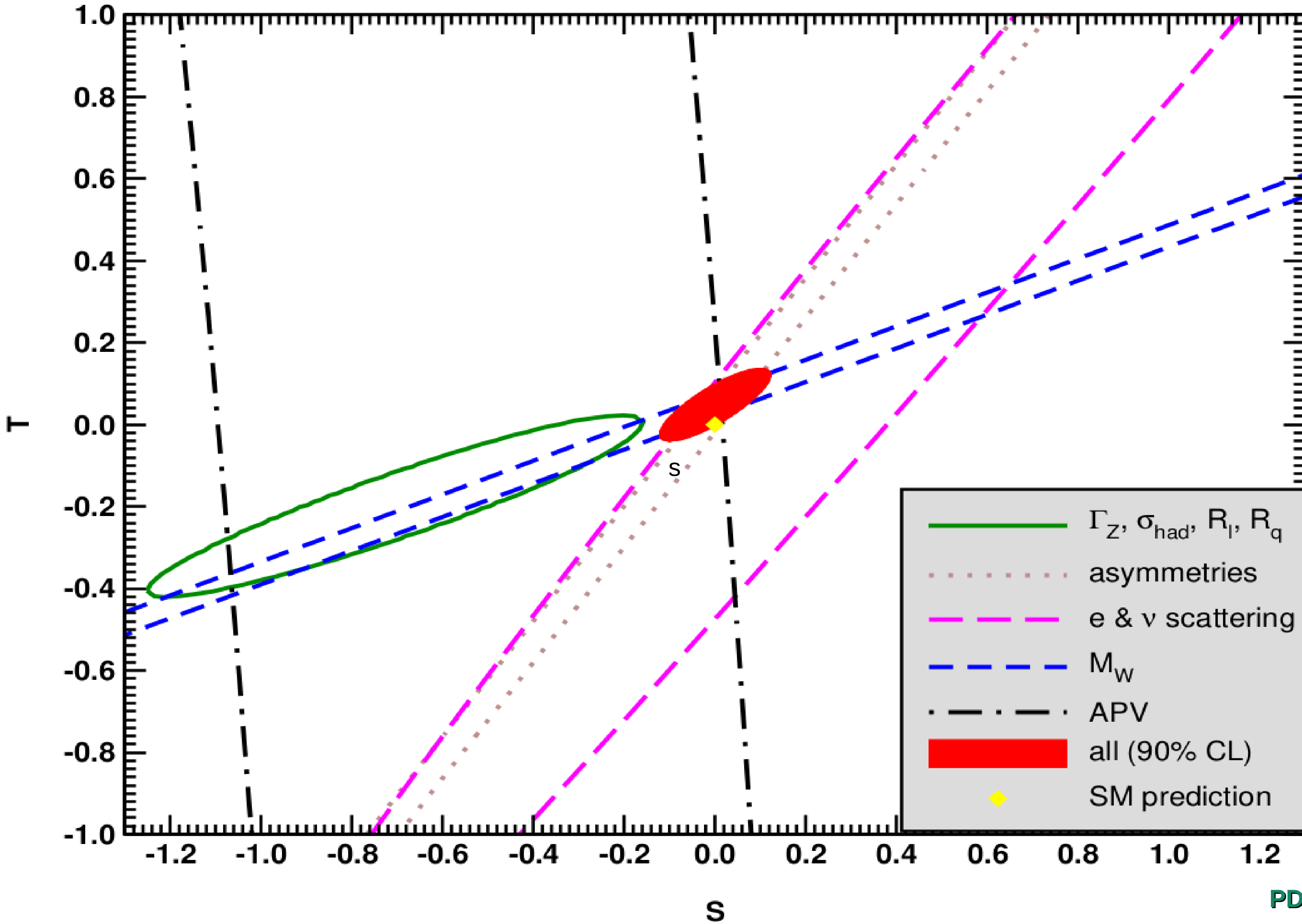

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  - **Triplet scalars changing W-mass at tree level**
  - **Doublet scalars changing W-mass at one loop level**
  - **A new U(1) gauge symmetry and the Z' boson changing Z-boson mass at tree level**

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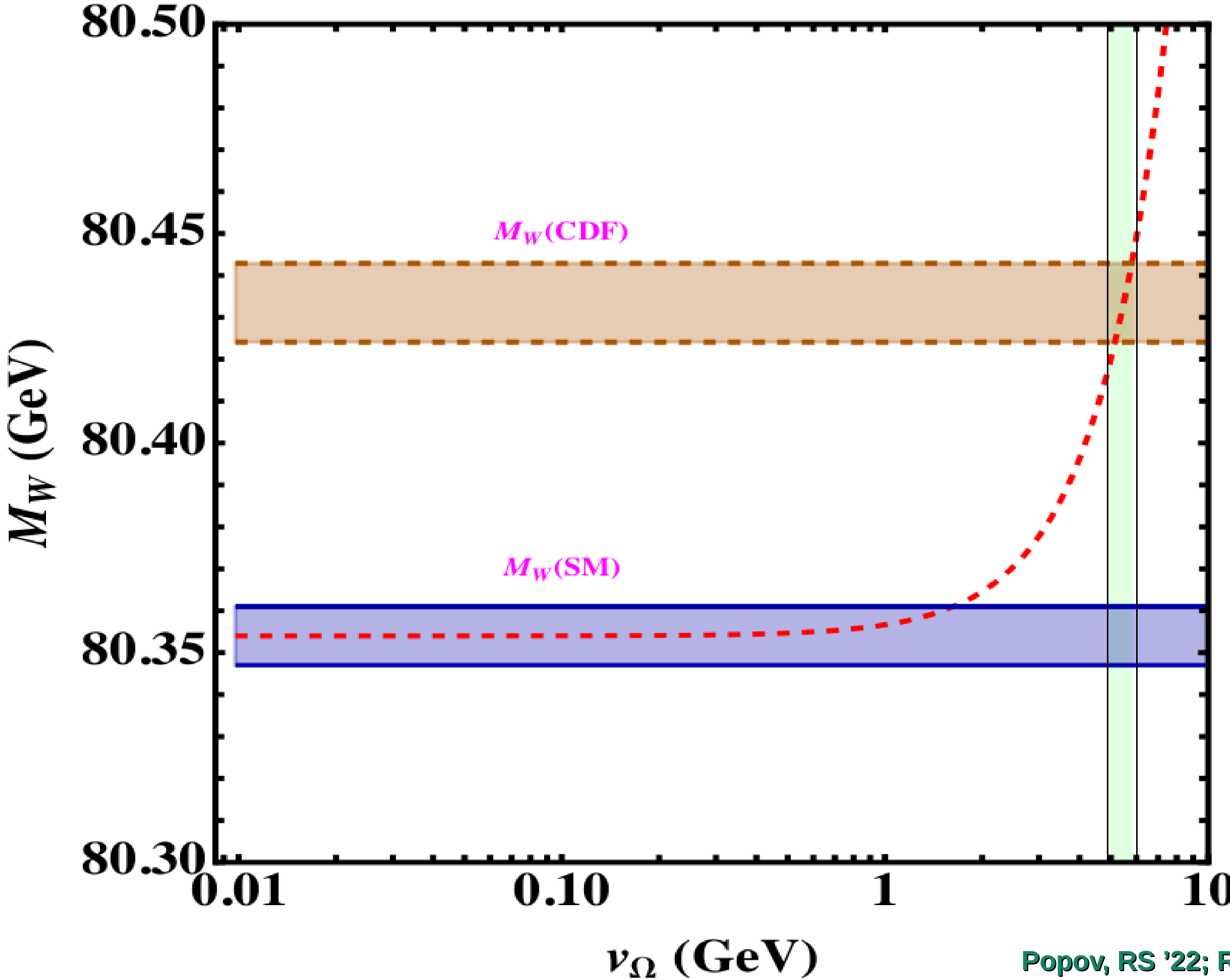
$$\rho = \frac{\sqrt{v_\Phi^2 + 4v_\Omega^2}}{v_\Phi} \approx 1 + 2\frac{v_\Omega^2}{v_\Phi^2} \qquad M_{W,\mathrm{CDF}}^2 - M_{W,\mathrm{SM}}^2 = g^2 v_\Omega^2$$

Triplet Scalars



Popov, RS '22; RS et.al. '22

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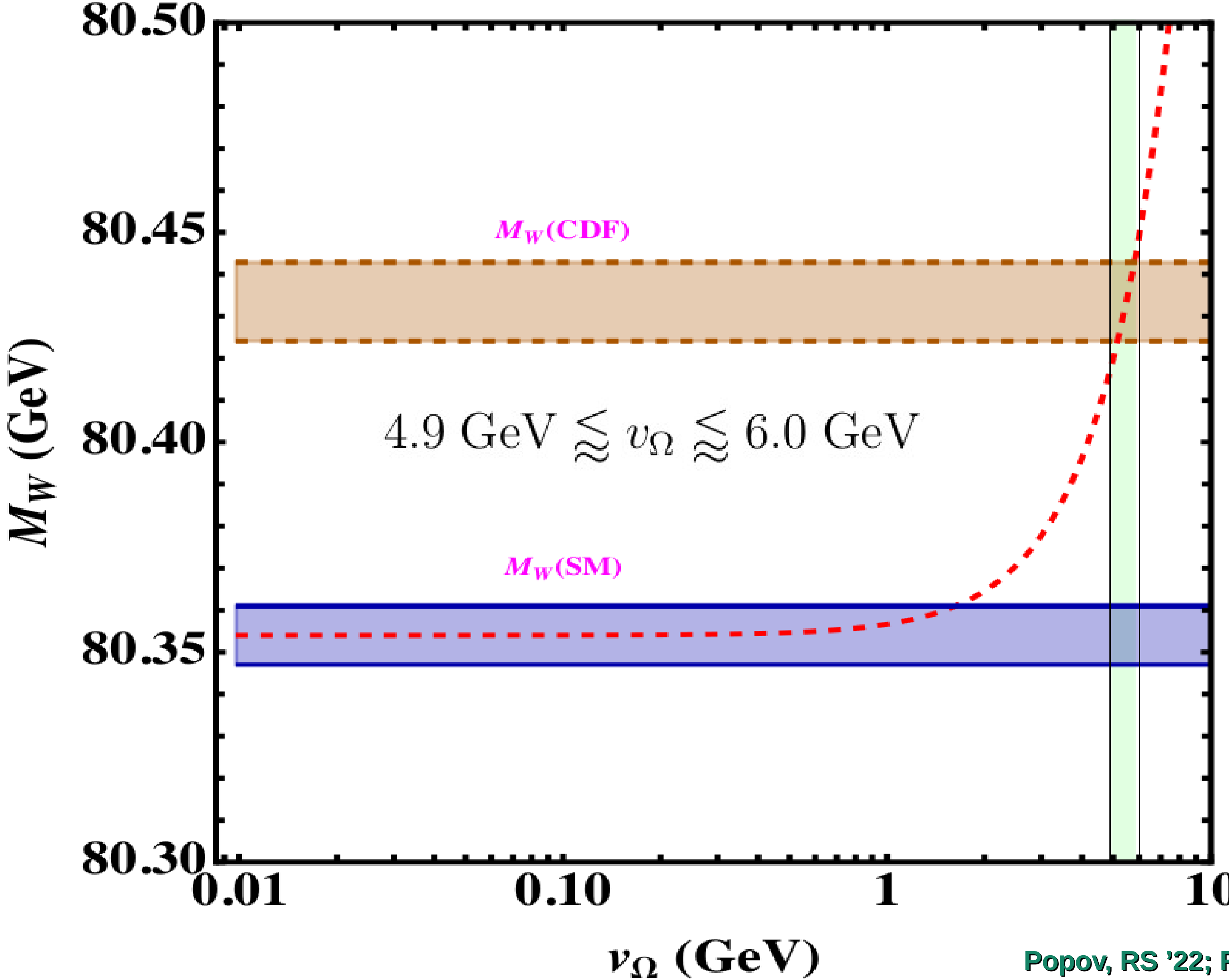

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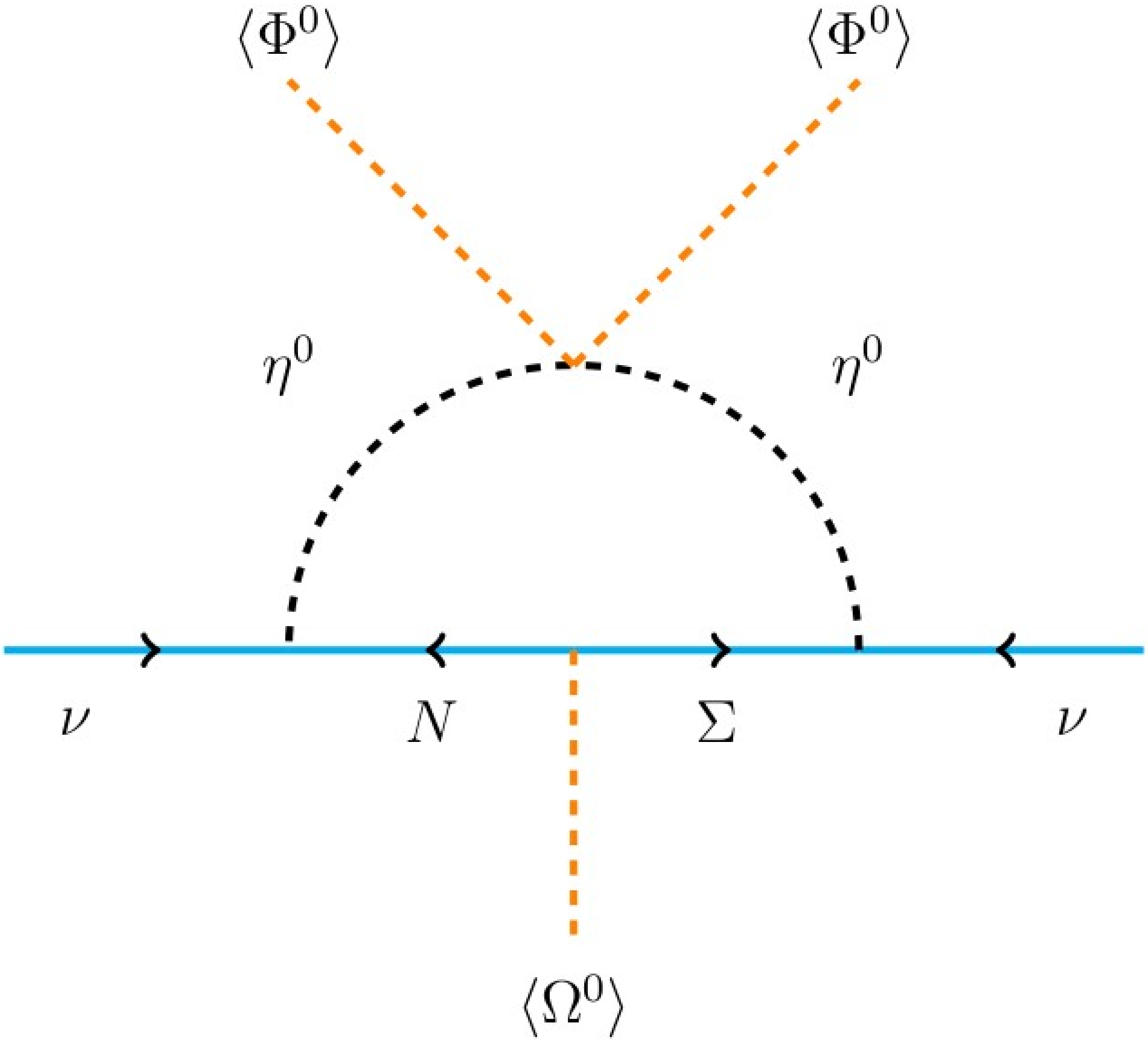
  - Indeed models for neutrino and dark matter already require such scalars **Popov, RS '22; RS et.al. '22**
  - Example: Singlet-Triplet Scotogenic model **[Ma '09, Valle et.al. '09]**

Triplet Scalars

RS et.al. ‘22



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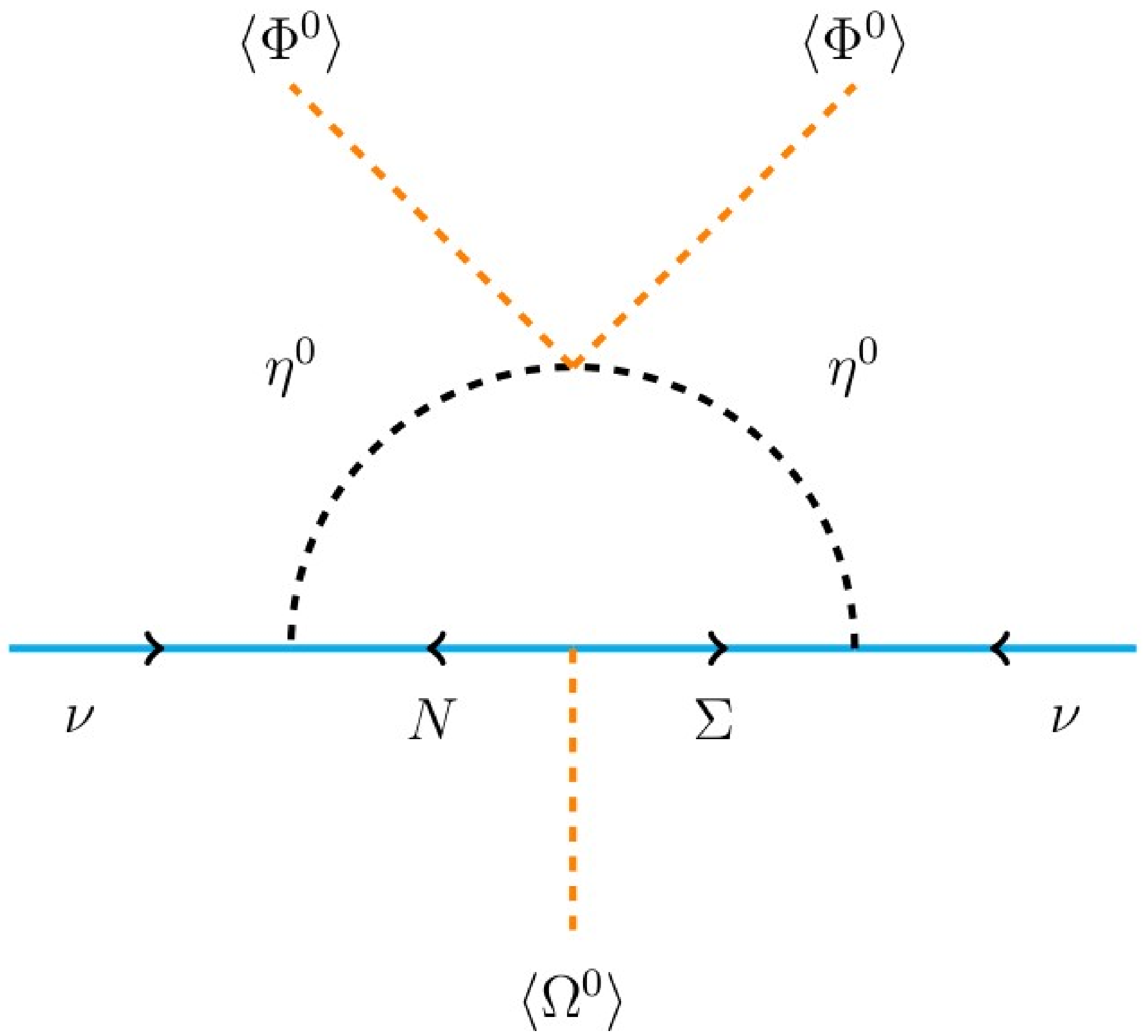

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_{\sigma=1}^{2}\left(\frac{ih_{\alpha\sigma}}{\sqrt{2}}\right)\left(\frac{-ih_{\beta\sigma}}{\sqrt{2}}\right)\frac{m_{\chi_\sigma}}{(4\pi)^2}\left[\frac{m^2_{\eta_R}\ln\left(\frac{m^2_{\chi_\sigma}}{m^2_{\eta_R}}\right)}{m^2_{\chi_\sigma}-m^2_{\eta_R}} - \frac{m^2_{\eta_I}\ln\left(\frac{m^2_{\chi_\sigma}}{m^2_{\eta_I}}\right)}{m^2_{\chi_\sigma}-m^2_{\eta_I}}\right]$$

Triplet Scalars: W mass

- Including loop corrections the W mass: Tree level correction + loop corrections parametrized in terms of S, T, U

Popov, RS ’22; RS et.al. ‘22

$$M_W = M_W^{\rm SM}\Big[\frac{\sqrt{v_\Phi^2 + 4v_\Omega^2}}{v_\Phi} - \frac{\alpha_{\rm em}}{4(c_W^2 - s_W^2)}(S - 1.55T - 1.24U)\Big]$$

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$$S \simeq \underbrace{\frac{1}{12\pi}\log\left(\frac{m_{\eta^0}^2}{m_{\eta^+}^2}\right)}_{\text{Scalar doublet contribution}} + \frac{1}{18\pi}$$

$$T \simeq \underbrace{\frac{1}{6\pi}\frac{1}{\sin^2(\theta_W)\cos^2(\theta_W)}\frac{\Delta M}{M_Z^2}}_{\text{Scalar triplet contribution}} + \underbrace{\frac{2\sqrt{2}G_F}{(4\pi)^2\alpha_{em}}\left[\frac{m_{\eta^0}^2+m_{\eta^+}^2}{2} - \frac{m_{\eta^0}^2 m_{\eta^+}^2}{m_{\eta^+}^2-m_{\eta^0}^2}\log\left(\frac{m_{\eta^+}^2}{m_{\eta^0}^2}\right)\right]}_{\text{Scalar doublet contribution}}$$

$$U \simeq \underbrace{\frac{\Delta M}{3\pi M_H^\pm}}_{\text{Scalar triplet contribution}} \qquad (37)$$

$$+\underbrace{\frac{1}{12\pi}\left[-\frac{5m_{\eta^+}^4-22m_{\eta^+}^2m_{\eta^0}^2+5m_{\eta^0}^4}{3\left(m_{\eta^+}^2-m_{\eta^0}^2\right)^2} + \frac{\left(m_{\eta^+}^2+m_{\eta^0}^2\right)\left(m_{\eta^+}^4-4m_{\eta^+}^2m_{\eta^0}^2+m_{\eta^0}^4\right)}{\left(m_{\eta^+}^2-m_{\eta^0}^2\right)^3}\log\left(\frac{m_{\eta^+}^2}{m_{\eta^0}^2}\right)\right]}_{\text{Scalar doublet contribution}}$$

Triplet Scalars: W mass

- Global fits for S,T, U including CDF-II results:

$$S = 0.06 \pm 0.10, \;\; T = 0.11 \pm 0.12 \;\; \text{and} \;\; U = 0.14 \pm 0.09$$

Lu et.al. ‘22

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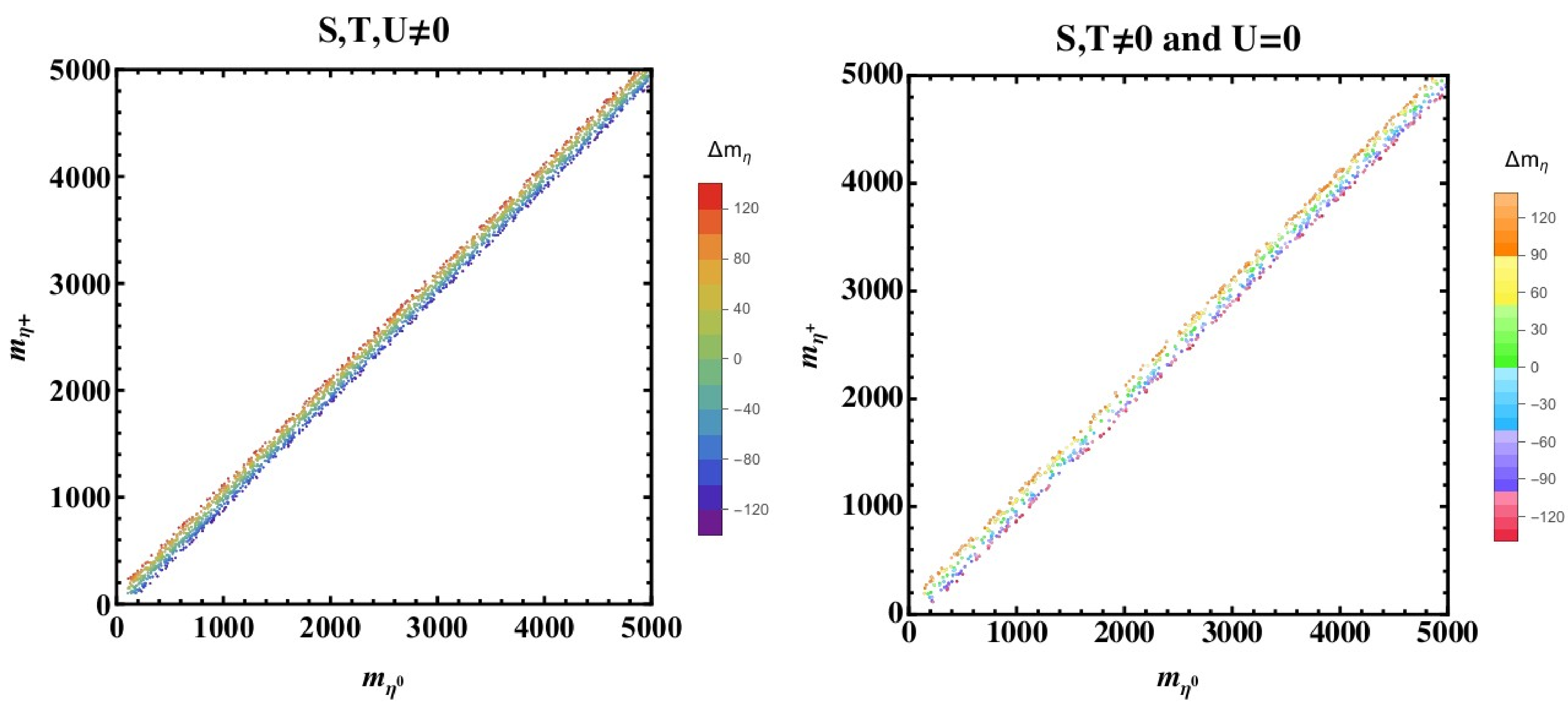
- Compressed spectrum for the scalars in the model

RS et.al. '22



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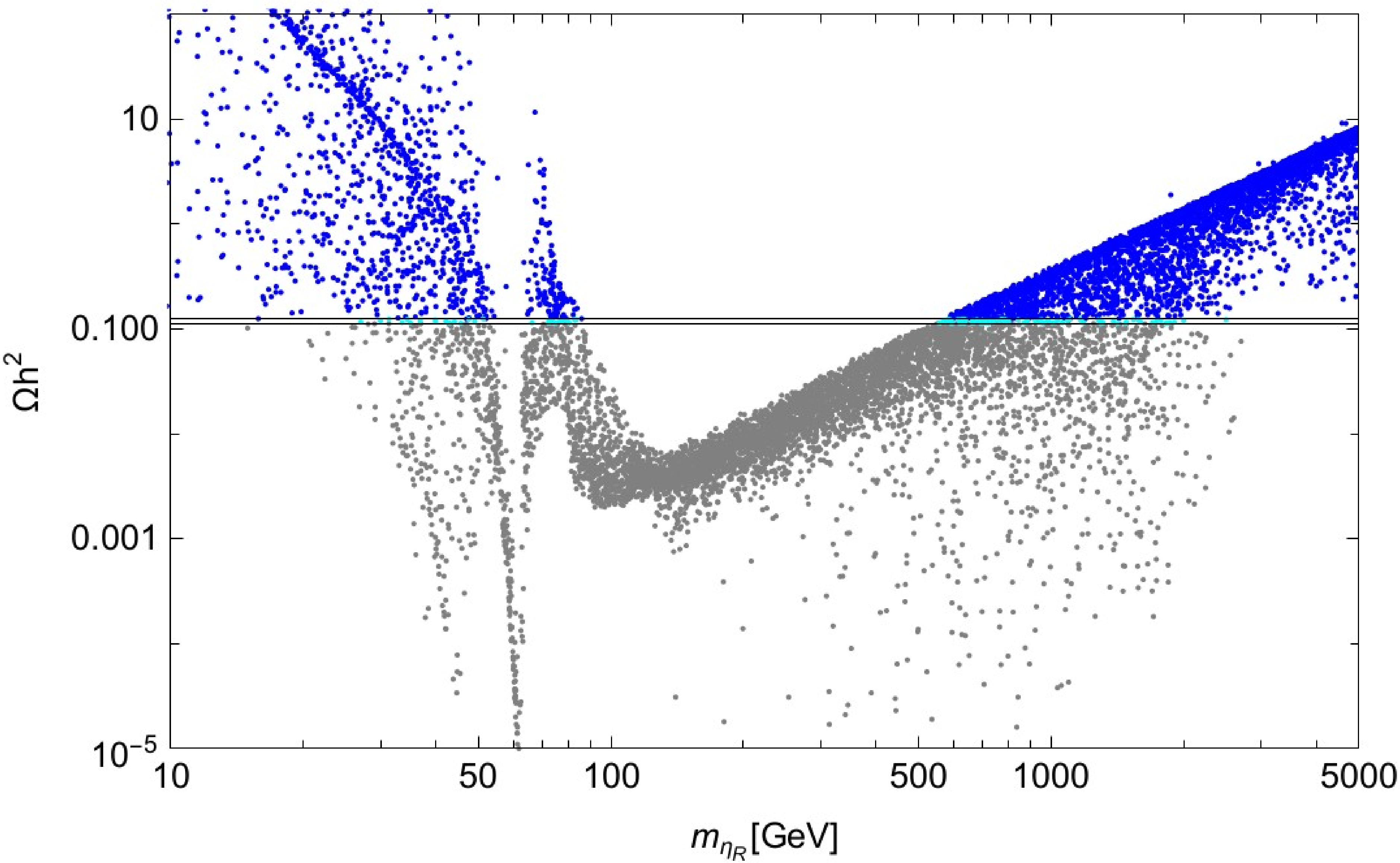

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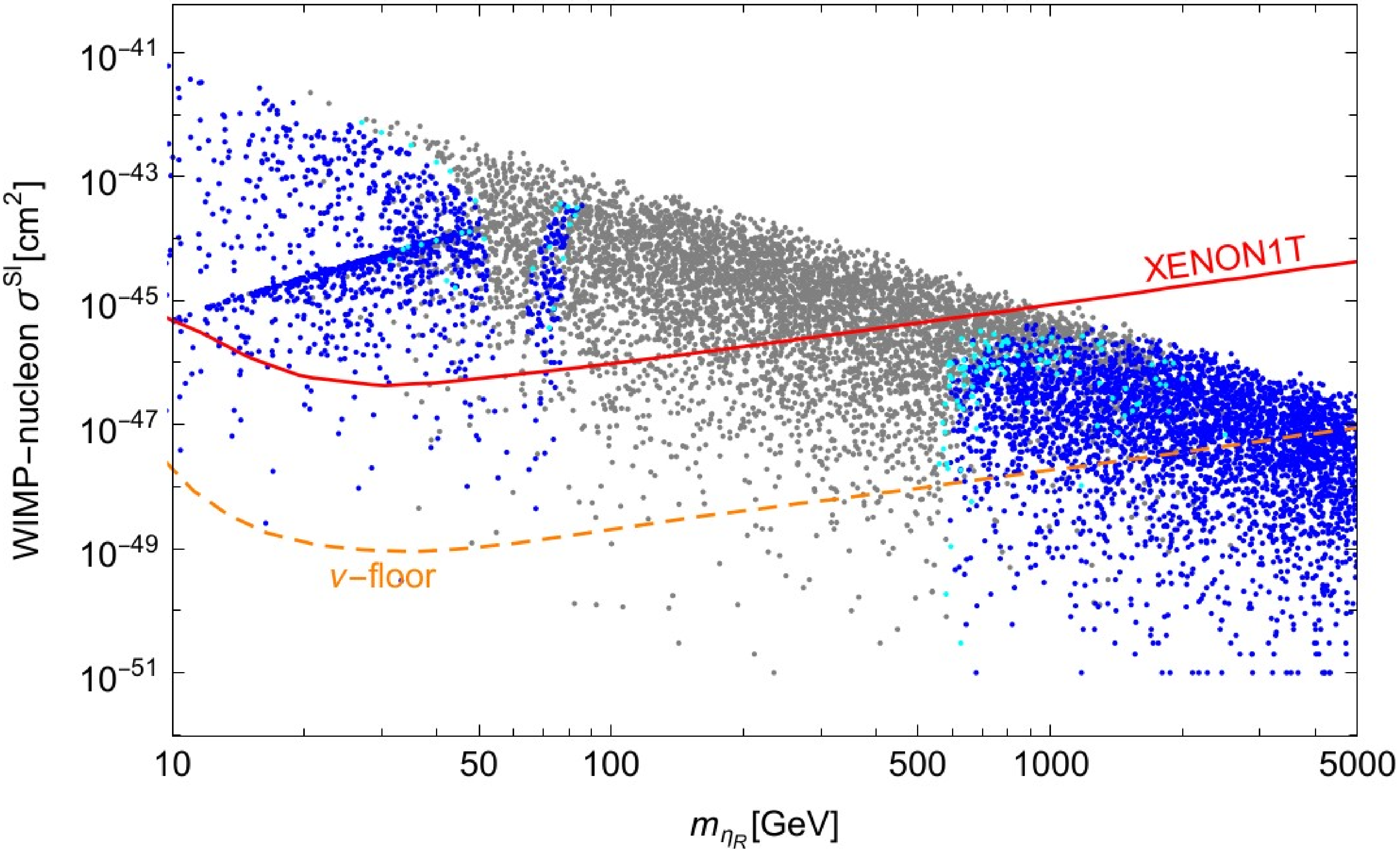

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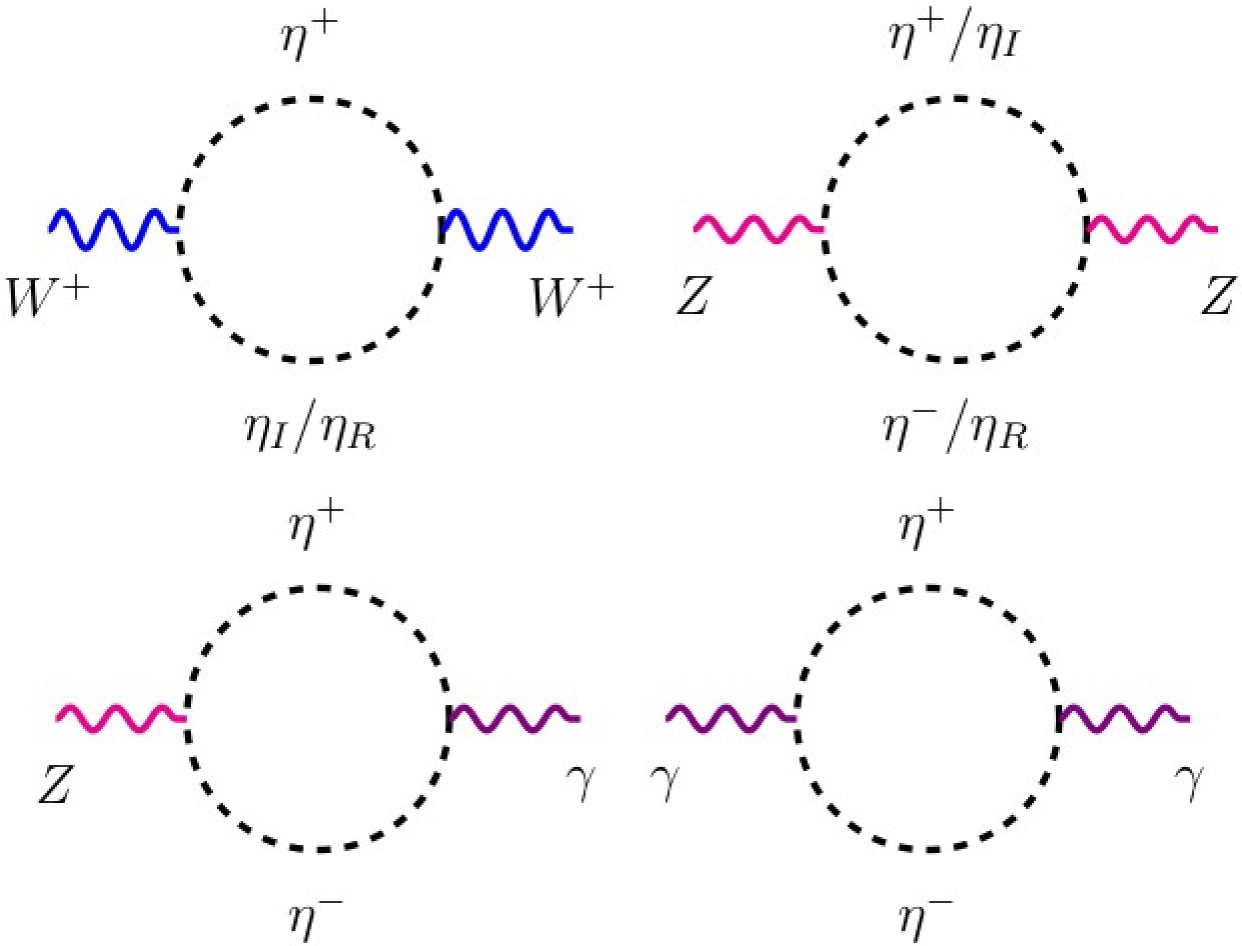

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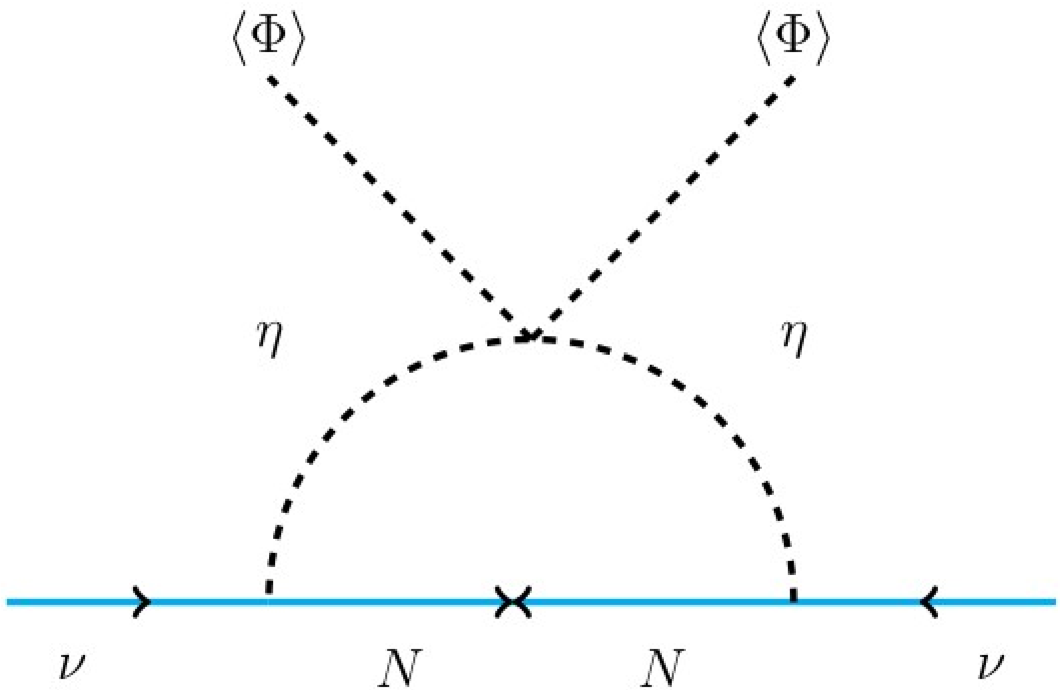

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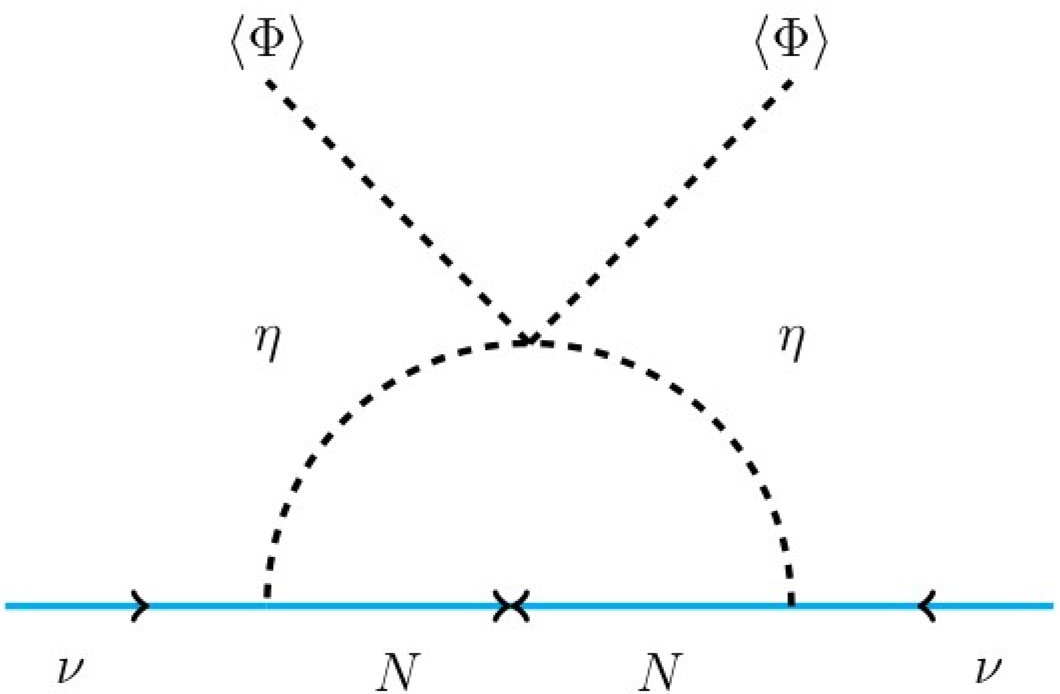
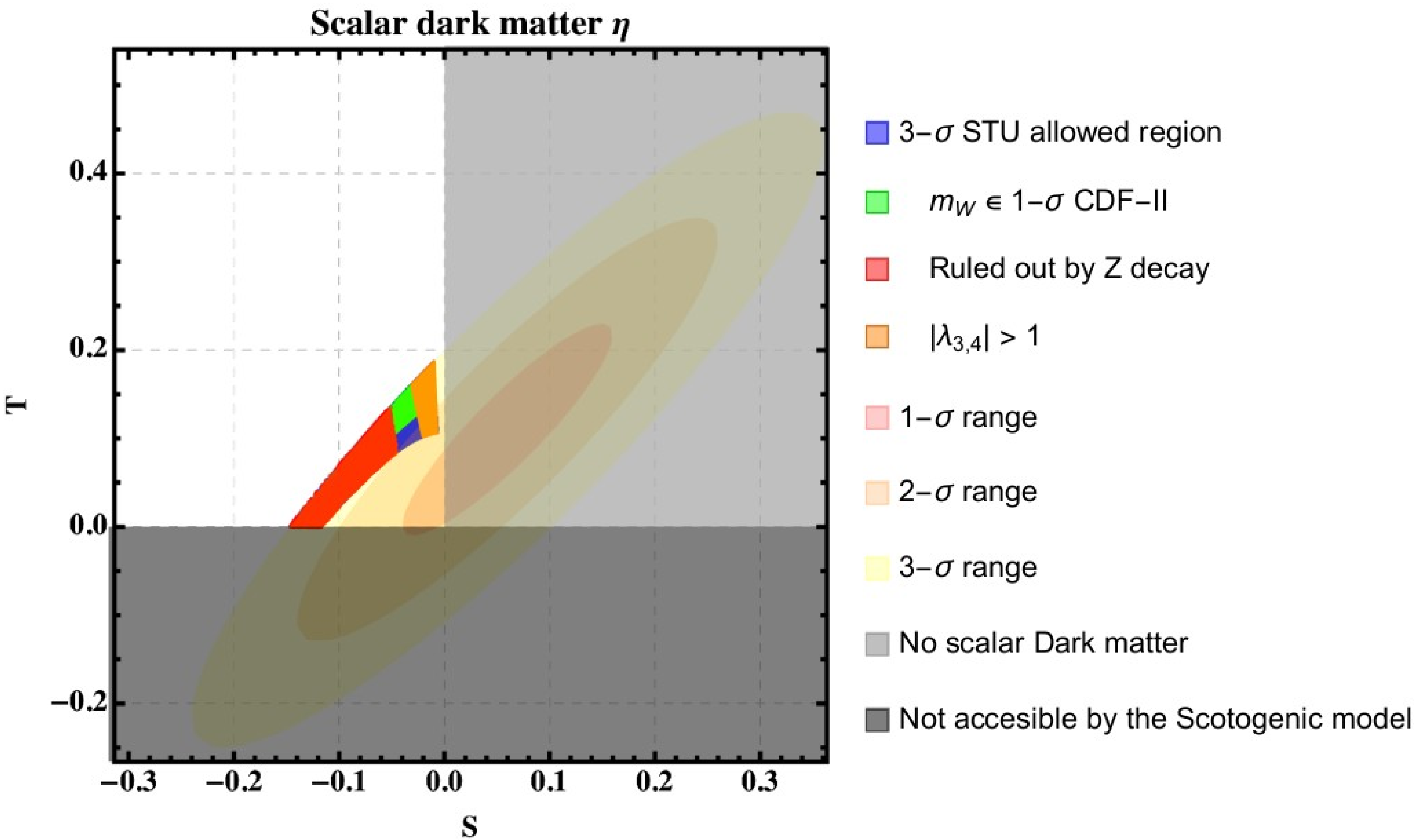


$$\mathcal{M}^{\nu}_{\alpha\beta} = \sum_i \frac{Y^N_{\alpha i} Y^N_{\beta i}}{32\pi^2} m_{N_i} \left[\frac{m^2_{\eta R}}{m^2_{\eta R} - m^2_{N_i}} \log\left(\frac{m^2_{\eta R}}{m^2_{N_i}}\right) - \frac{m^2_{\eta I}}{m^2_{\eta I} - m^2_{N_i}} \log\left(\frac{m^2_{\eta I}}{m^2_{N_i}}\right) \right]$$

Doublet Scalar: W mass

- Doublet scalars lead to loop corrections

RS. et. al. '22, '22, '22



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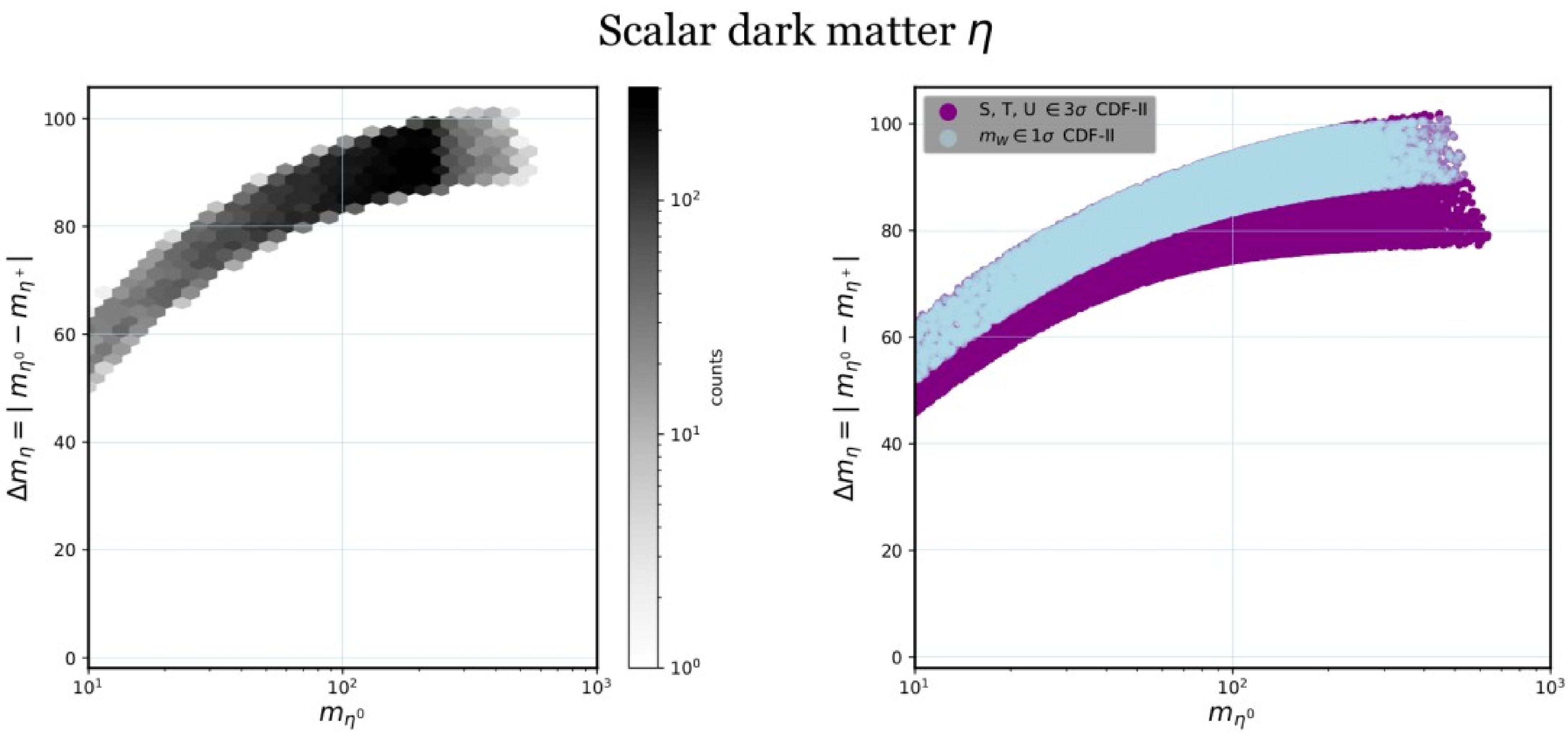
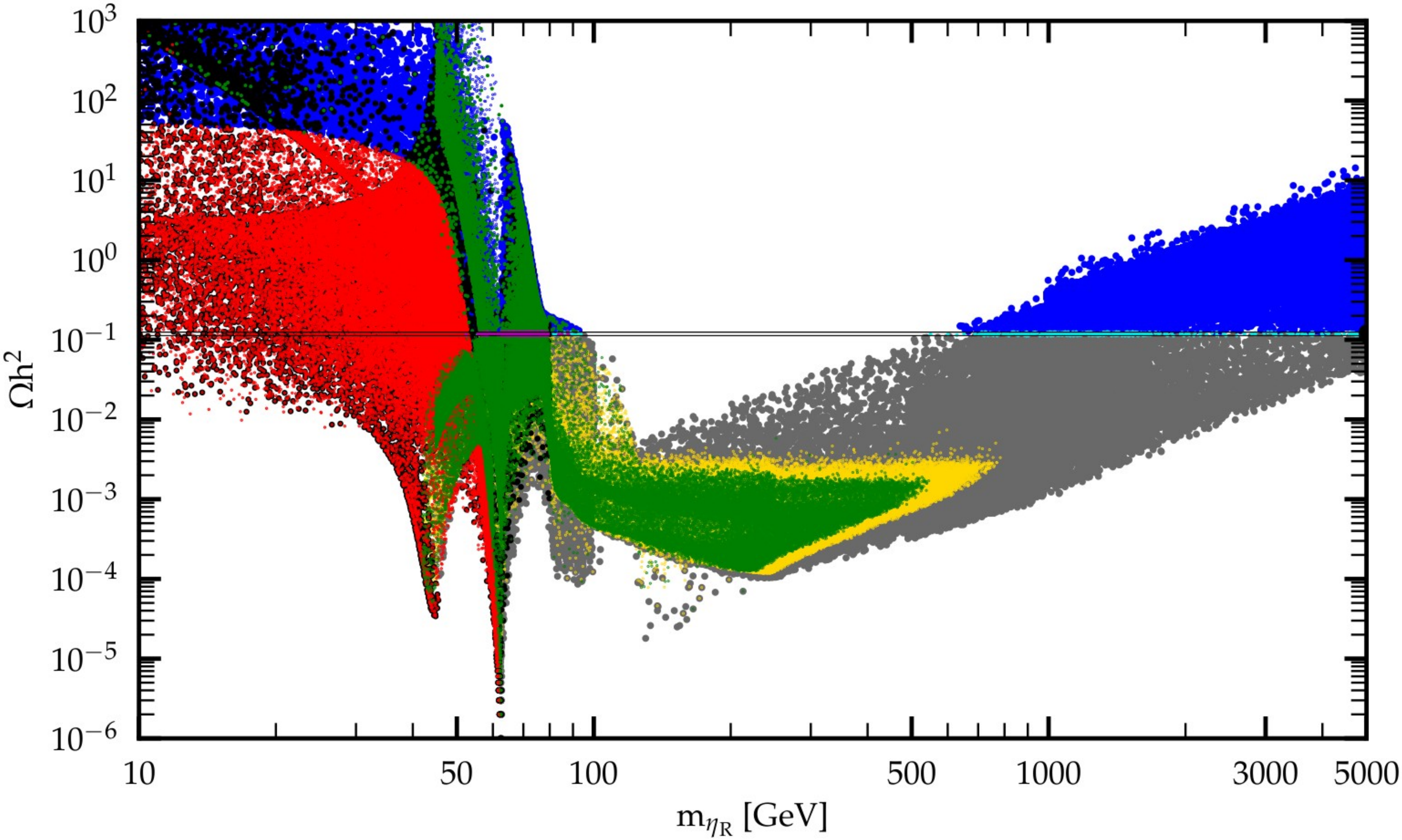


Doublet Scalar Dark Matter

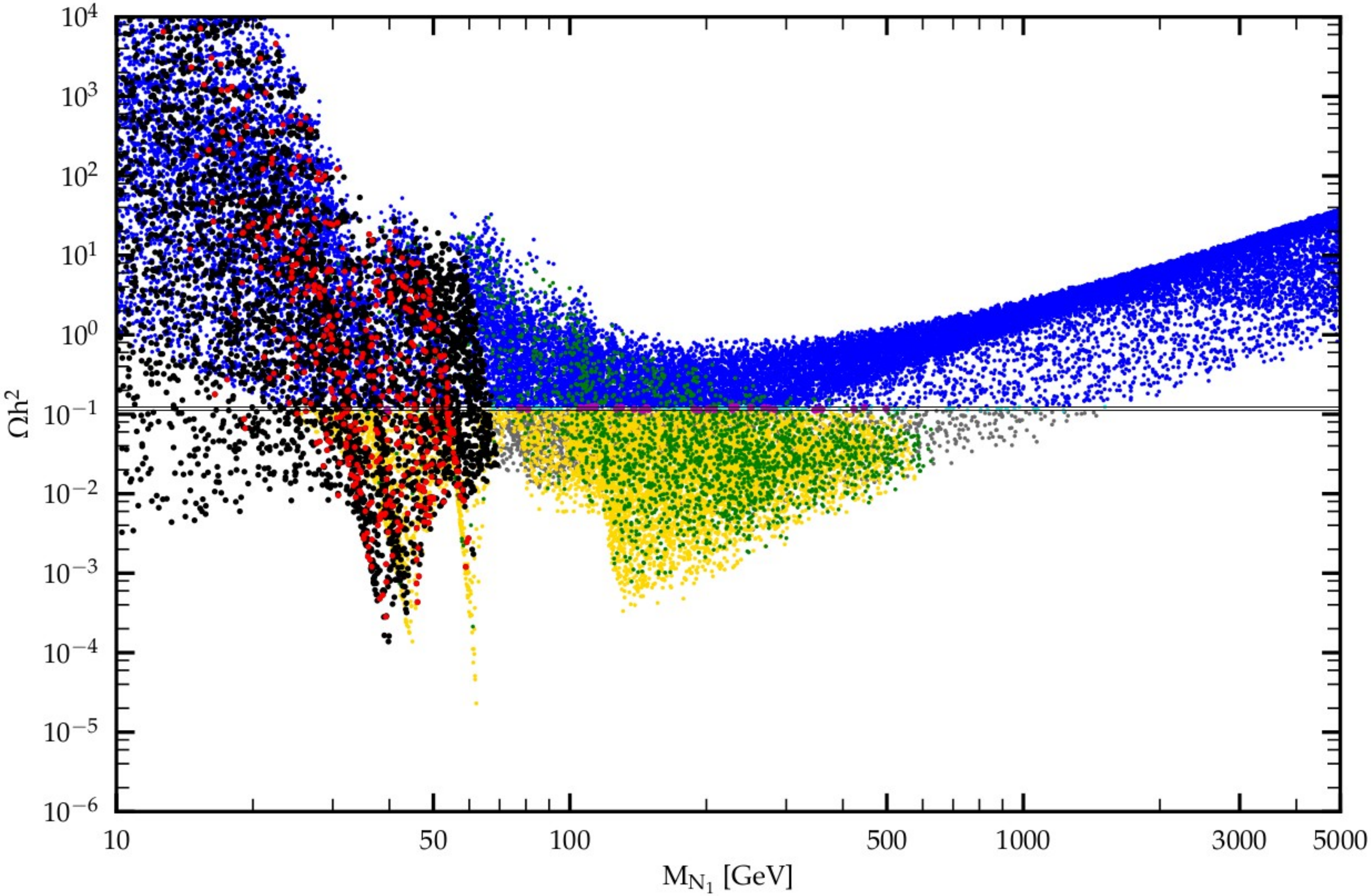
- Doublet scalars can simultaneously be dark matter and satisfy the CDF-II measurement

RS. et. al. '22, '22, '22



Fermionic Dark Matter

- Doublet scalars provide loop correction to W mass while the dark fermion is dark matter   RS. et. al. '22, '22, '22



Z Boson Mass Modification

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- **Presence of a Z' originating from say a new U(1) gauge symmetry can change the Z mass at tree level**

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Fields	($SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{B-L}$)
L_L	$(1, 2, -1/2, -1)$
Q_L	$(3, 2, 1/6, 1/3)$
e_R	$(1, 1, -1, -1)$
u_R	$(3, 1, 2/3, 1/3)$
d_R	$(3, 1, -1/3, 1/3)$
ν_R^1	$(1, 1, 0, 5)$
$\nu_R^{2,3}$	$(1, 1, 0, -4)$
Φ	$(1, 2, 1/2, 0)$
φ	$(1, 2, 1/2, -3)$
σ	$(1, 1, 0, 3)$
χ_d	$(1, 1, 0, 1/2)$

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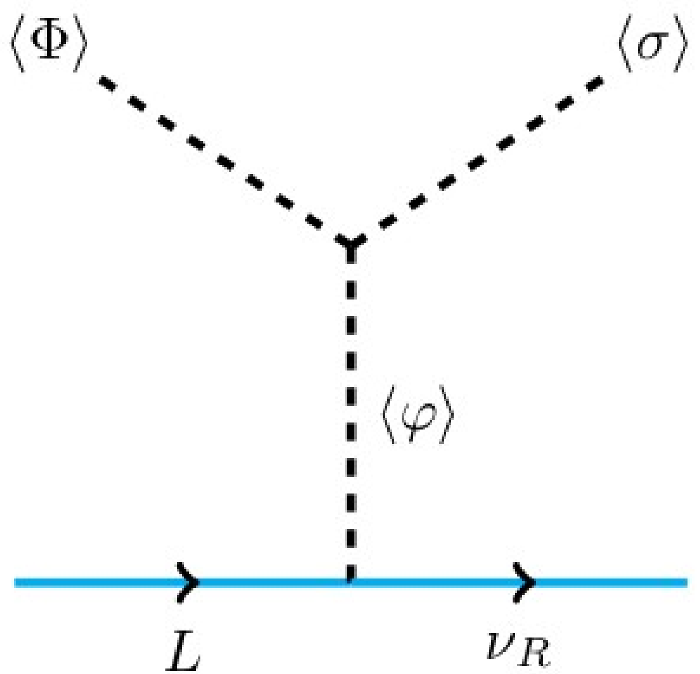

Gauged B-L Symmetry: Z mass

- Due to presence of new Z' the neutral gauge boson mass matrix becomes

Mandal, Prajapati, RS '22

$$\mathcal{M}_V^2 = \frac{v^2}{4}\begin{bmatrix} g'^2 & -gg' & -6u^2 g' g_x \\ -gg' & g^2 & 6u^2 g g_x \\ -6u^2 g' g_x & 6u^2 g g_x & 36 b^2 g_x^2 \end{bmatrix}, \text{ where } u = \frac{v_\varphi}{v}, \text{ and } b^2 = u^2 + \frac{v_\sigma^2}{v^2}$$

- This leads to

$$\begin{bmatrix} A^\mu \\ Z^\mu \\ Z'^\mu \end{bmatrix} = \begin{bmatrix} \cos\theta_w & \sin\theta_w & 0 \\ -\cos\alpha'\cos\theta_w & \cos\alpha'\cos\theta_w & -\sin\alpha' \\ -\sin\alpha'\sin\theta_w & \sin\alpha'\cos\theta_w & \cos\alpha' \end{bmatrix} \begin{bmatrix} B^\mu \\ W_3^\mu \\ X^\mu \end{bmatrix}$$

- Changing the mass of Z as

$$M_A = 0, \; M_Z^2 = \frac{v^2}{8}\left(A' - \sqrt{B'^2 + C'^2}\right) \text{ and } M_{Z'}^2 = \frac{v^2}{8}\left(A' + \sqrt{B'^2 + C'^2}\right),$$

$$\text{where, } A' = 36 b^2 g_x^2 + (g^2 + g'^2), \quad B' = 36 b^2 g_x^2 - (g^2 + g'^2) \text{ and } C' = 12 g_x u^2 \sqrt{g^2 + g'^2}.$$

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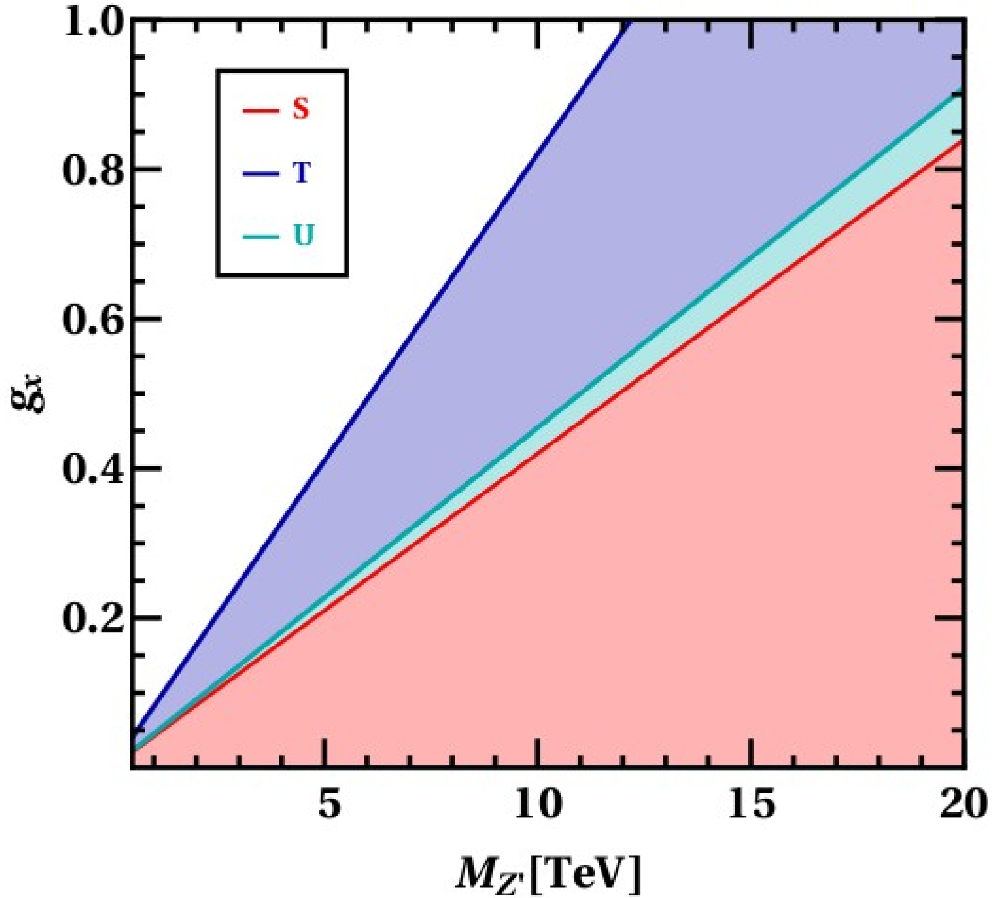

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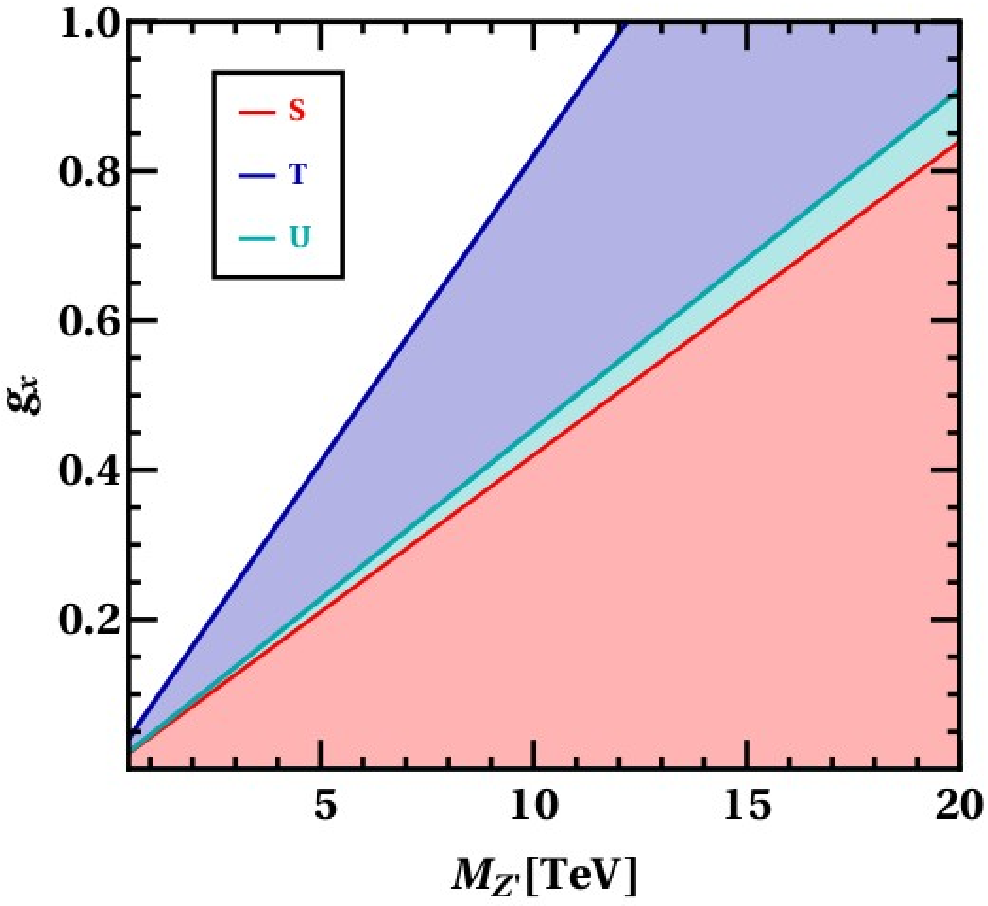

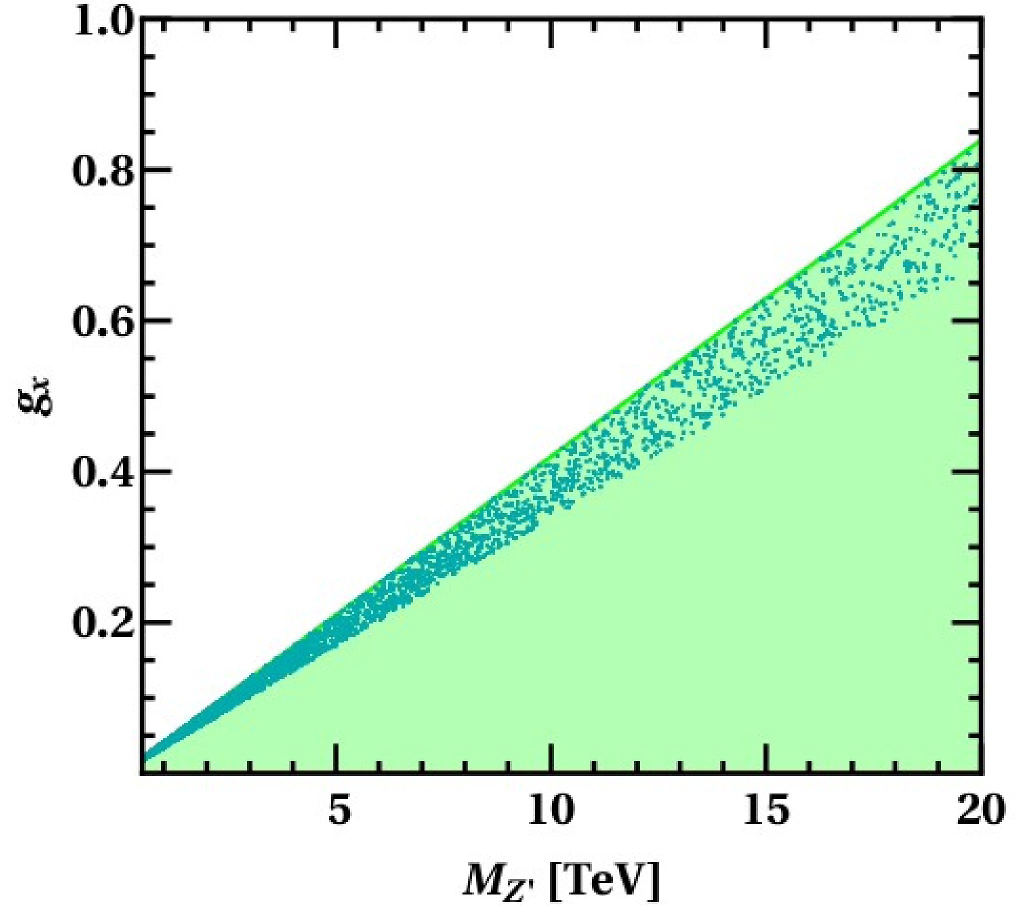

Conclusions

- The CDF-II W mass measurement disagrees with both
  - Other experimental measurements
  - Current SM expectation of W mass
- In my opinion it is too early to say if this is conclusive proof of new physics
- Still, if this is new physics it can be accommodated in several ways. I discussed few such options
  - Triplet scalars modifying W mass at tree level
  - Doublet scalars leading to loop corrections
  - Modification in Z mass leading to W mass anomaly
- Updated ATLAS results and CMS measurements will hopefully clarify the situation

Thank You