HENAN ACADEMY OF SCIENCES

Explaining The New CDF II W-Boson Mass Data In The Georgi-Machacek Extension Models

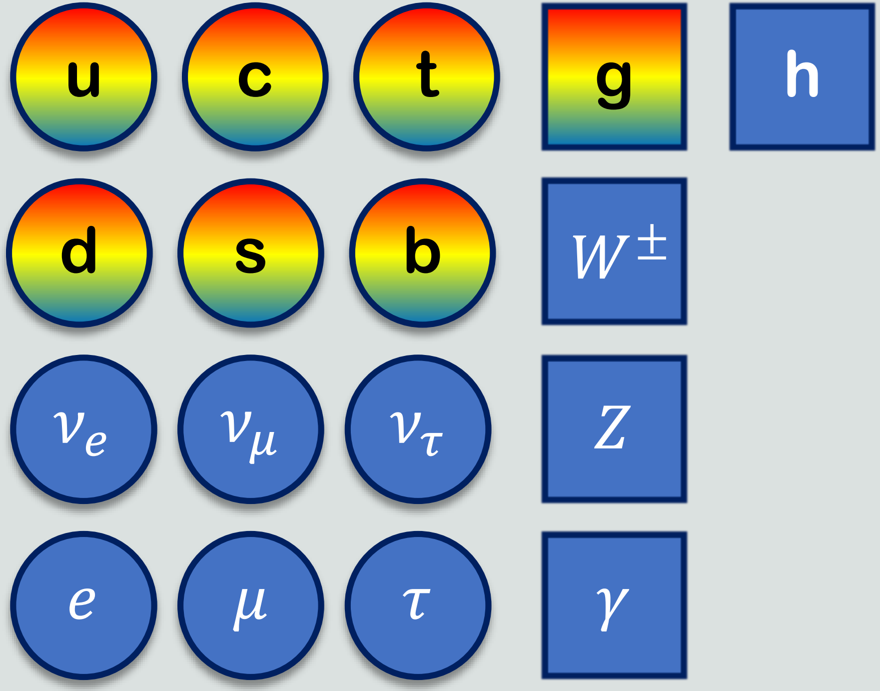
Xiaokang Du(都小康)

8/11/2022

Based on Xiaokang Du, Zhuang Li, Fei Wang, Yingkai Zhang. 2204.05760

CONTENTS

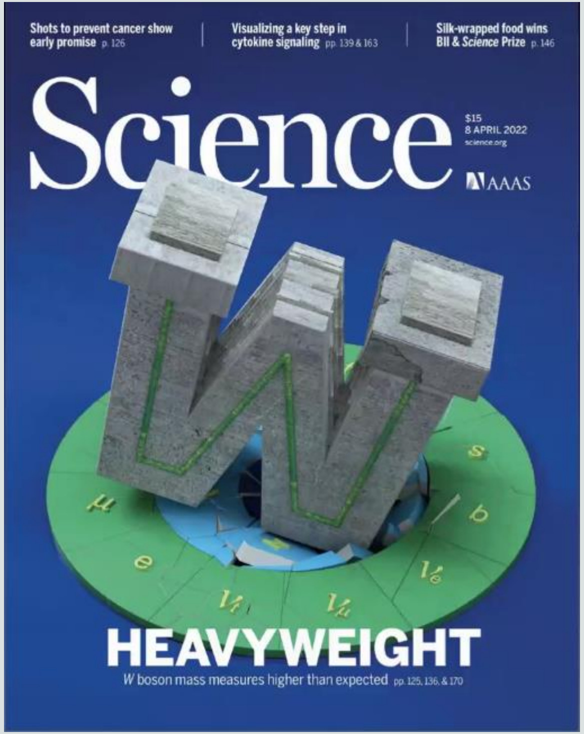
the standard Model



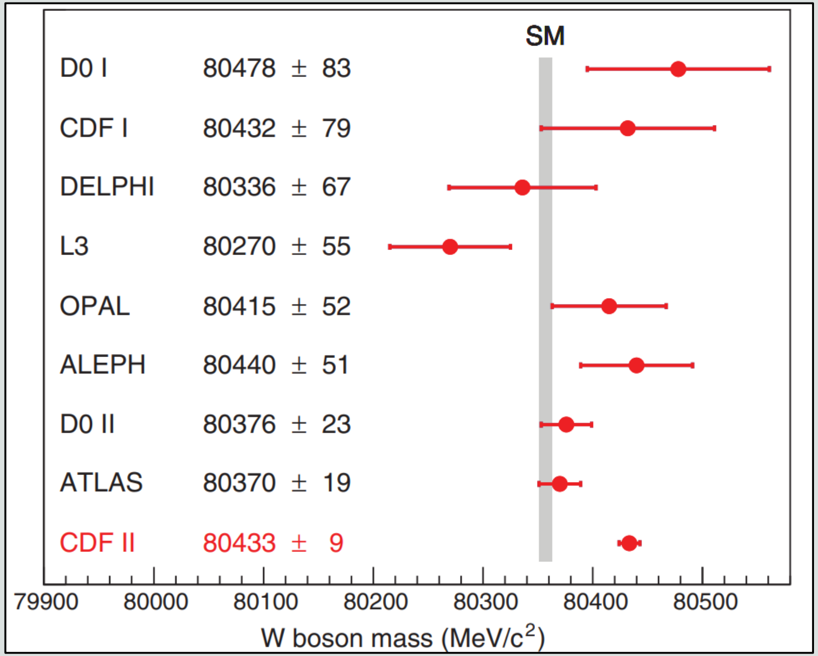
Fields	$U(1)_Y$	$SU(2)_L$	$SU(3)_C$
H	$1/2$	2	1
G^a	0	1	8
W^a	0	3	1
B	0	1	1
$Q_{L_i} = \begin{pmatrix} u_{L_i} \\ d_{L_i} \end{pmatrix}$	$1/6$	2	3
u_{R_i}	$2/3$	1	3
d_{R_i}	$-1/3$	1	3
$L_{L_i} = \begin{pmatrix} \nu_{L_i} \\ E_{L_i} \end{pmatrix}$	$-1/2$	2	1
E_{R_i}	-1	1	1

Nucl.Phys. 22 (1961) 579-588,Phys.Lett. 13 (1964) 168-171,Phys. Rev. Lett.19 (1967) 1264–1266 …

CDF-II Results on W Boson Mass



Science 376, 170-176 (2022)



SM: $M_W = 80357 \pm 6$ MeV

CDF-II: $M_W = 80433.5 \pm 9.4$ MeV

1、CDF-II Results and the Georgi-Machacek Model

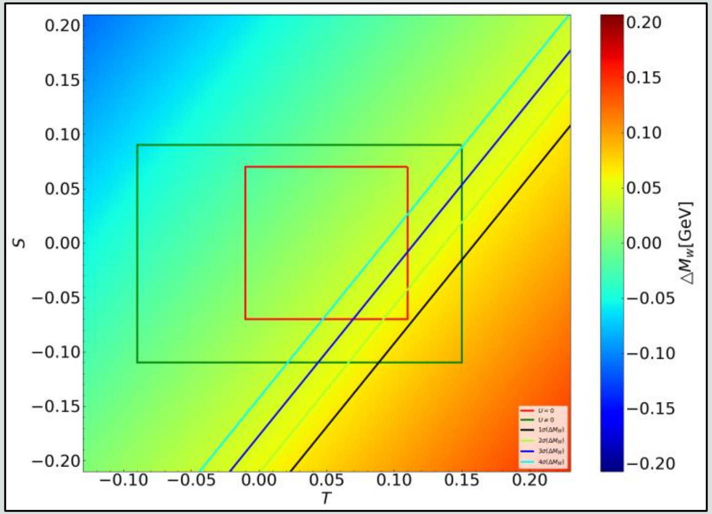
Δm_W ?

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

$$\alpha S = 4 s_W^2 c_W^2\left[\Pi'_{ZZ}(0) - \frac{c_W^2 - s_W^2}{s_W c_W}\Pi'_{Z\gamma}(0) - \Pi'_{\gamma\gamma}(0)\right],$$

$$\alpha T = \frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2},$$

$$\alpha U = 4 s_W^2\left[\Pi'_{WW}(0) - c_W^2\Pi'_{ZZ}(0) - 2 s_W c_W \Pi'_{Z\gamma}(0) - s_W^2\Pi'_{\gamma\gamma}(0)\right]$$



$$S = -0.01 \pm 0.10,\quad T = 0.03 \pm 0.012,\quad U = 0.02 \pm 0.11$$

$$S = 0.00 \pm 0.07,\quad T = 0.05 \pm 0.06,\quad U = 0$$

Phys. Rev. D 46 (1992) 381,PTEP 2020 (2020) 8, 083C01(PDG2020)

The Georgi-Machacek Model

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}$$

Fields	$U(1)_Y$	$SU(2)_L$	$SU(3)_C$
ϕ	1/2	2	1
χ	1	3	1
ξ	0	3	1

$$\mathcal{L}_{GM} = \mathcal{L}_{kin} + \mathcal{L}_Y + \mathcal{L}_\nu - V_H$$

$$\mathcal{L}_\nu \supset h_{ij}\overline{L_L^{ic}} i\tau_2 \chi L_L^j + h.c.$$

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}$$

$$V(\Phi,\Delta) = \frac{1}{2}\mathrm{m}_\Phi^2 \mathrm{tr}[\Phi^\dagger\Phi] + \frac{1}{2}\mathrm{m}_\Delta^2 \mathrm{tr}[\Delta^\dagger\Delta] + \lambda_1\left(\mathrm{tr}[\Phi^\dagger\Phi]\right)^2 + \lambda_2\left(\mathrm{tr}[\Delta^\dagger\Delta]\right)^2$$
$$+\lambda_3 \mathrm{tr}\left[\left(\Delta^\dagger\Delta\right)^2\right] + \lambda_4 \mathrm{tr}[\Phi^\dagger\Phi]\mathrm{tr}[\Delta^\dagger\Delta] + \lambda_5 \mathrm{tr}\left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2}\right] \mathrm{tr}[\Delta^\dagger T^a \Delta T^b]$$
$$+\mu_1 \mathrm{tr}\left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2}\right]\left(P^\dagger \Delta P\right)_{ab} + +\mu_2 \mathrm{tr}[\Delta^\dagger T^a \Delta T^b]\left(P^\dagger \Delta P\right)_{ab}$$

Nucl.Phys.B 262 (1985) 463-477, JHEP 01 (2013) 026, JHEP 01 (2016) 120

1、CDF-II Results and the Georgi-Machacek Model

$$\boldsymbol{SU(2)_L \times SU(2)_R} \xrightarrow[\langle\chi^0\rangle = \langle\xi^0\rangle = v_\Delta]{\langle\phi^0\rangle = v_\phi/\sqrt{2}} \boldsymbol{SU(2)_c}$$

$$v_{EW}^2 = \sum_i \left[4T_i(T_i+1) - Y_i^2\right] |v_i|^2 c_i = v_\phi^2 + 4v_\chi^2 + 4v_\xi^2 = v_\phi^2 + 8v_\Delta^2 = \frac{1}{\sqrt{2}G_F} \approx (246\mathrm{GeV})^2$$

$$c_i = \begin{cases} 1\,, (T,Y) \in complex\ representation \\ 1/2\,, (T, Y=0) \in real\ representation \end{cases}$$

$$\rho_{tree} \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \sum_i \left[4T_i(T_i+1) - Y_i^2\right] |v_i|^2 c_i \Big/ \sum_i 2Y_i|v_i|^2$$

$$\Delta\rho_{tree} \equiv \rho - 1 = \frac{v_\phi^2 + 4v_\chi^2 + 4v_\xi^2}{v_\phi^2 + 8v_\Delta^2} - 1 \approx \frac{4v_\chi^2 - 4v_\xi^2}{\mathrm{v_{EW}^2}}$$

$$\tan\theta = 2\sqrt{2}v_\Delta/v_\phi < 0.2$$

1、CDF-II Results and the Georgi-Machacek Model

$$\mathcal{L}_{type-II} \supset h_{ij}\overline{L_L^{ic}} i\tau_2 \chi L_L^j + \mu_1 \mathrm{tr}\left[\Phi^\dagger \frac{\sigma^a}{2}\Phi\frac{\sigma^b}{2}\right](P^\dagger \Delta P)_{ab}$$

$$\boldsymbol{SU(2)_L \times SU(2)_R} \xrightarrow[\langle\chi^0\rangle = \langle\xi^0\rangle = v_\Delta]{\langle\phi^0\rangle = v_\phi/\sqrt{2}} \boldsymbol{SU(2)_c}$$

$$m_\nu \approx h_{ij} v_\Delta \sim h_{ij} v_\phi^2 \mu_1 / m_\Delta^2 \quad v_\Delta \sim \mathcal{O}(10\mathrm{GeV}) \quad h_{ij} < 10^{-13}$$

Vacuum stability

$$\lambda_1 > 0, \lambda_2 + \lambda_3 > 0, \lambda_2 + \frac{1}{2}\lambda_3 > 0,$$
$$-|\lambda_4| + 2\sqrt{\lambda_1(\lambda_2+\lambda_3)} > 0,$$
$$\lambda_4 - \frac{1}{4}|\lambda_5| + \sqrt{2\lambda_1(2\lambda_2+\lambda_3)} > 0.$$

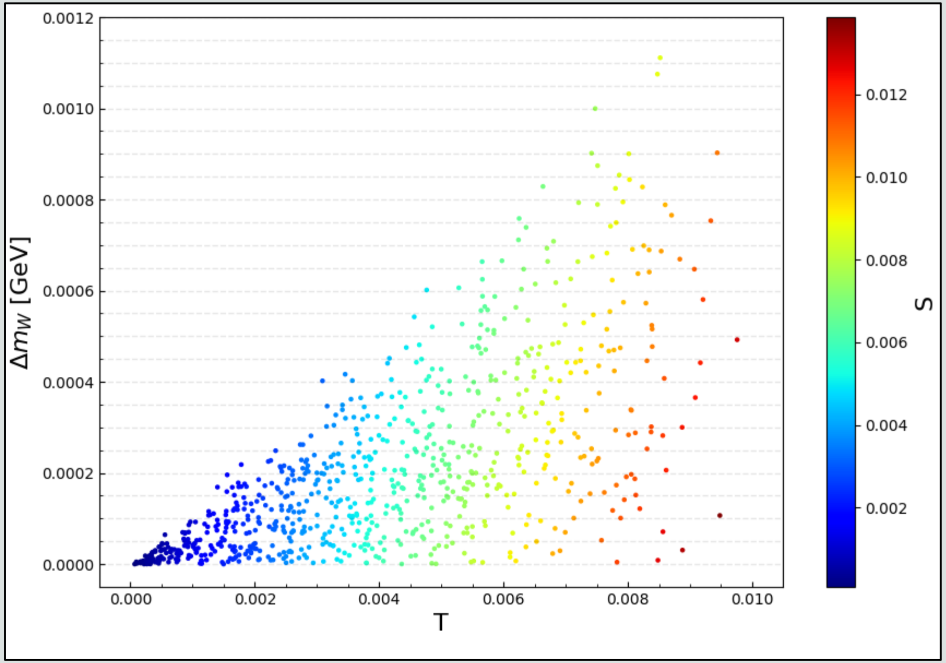
Perturbative unitarity

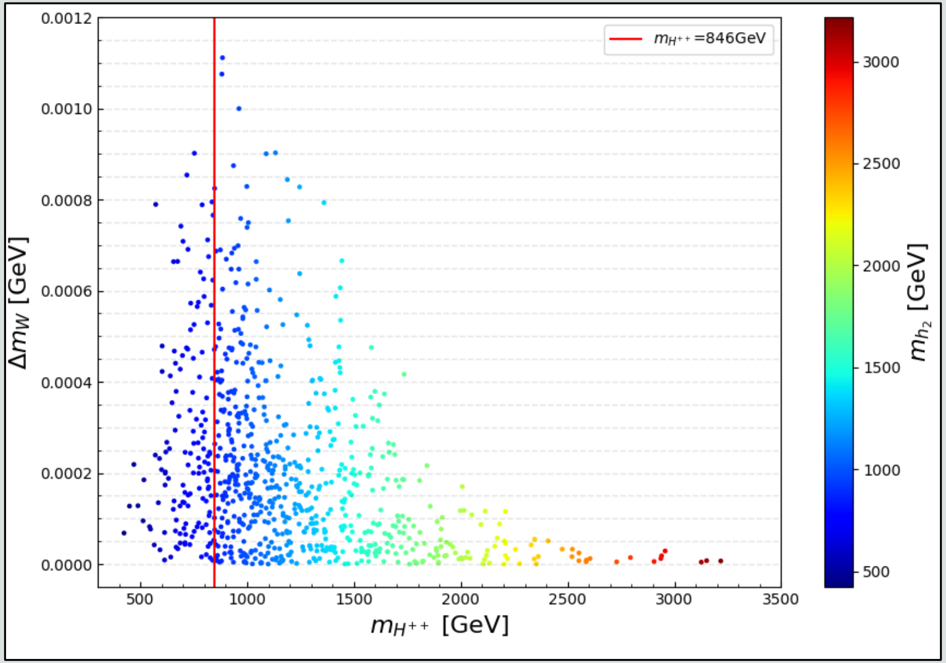
$$|\lambda_4 - \lambda_5| < 2\pi, \qquad |2\lambda_3 + \lambda_2| < \pi,$$
$$|6\lambda_1 + 7\lambda_3 + 11\lambda_2| + \sqrt{(6\lambda_1 - 7\lambda_3 - 11\lambda_2)^2 + 36\lambda_4^2} < 4\pi,$$
$$|2\lambda_1 - \lambda_3 + 2\lambda_2| + \sqrt{(2\lambda_1 + \lambda_3 - 2\lambda_2)^2 + \lambda_5^2} < 4\pi.$$

Nucl.Phys.B 262 (1985) 463-477, *JHEP* 01 (2013) 026, *JHEP* 01 (2016) 120

1 In the Original GM Model

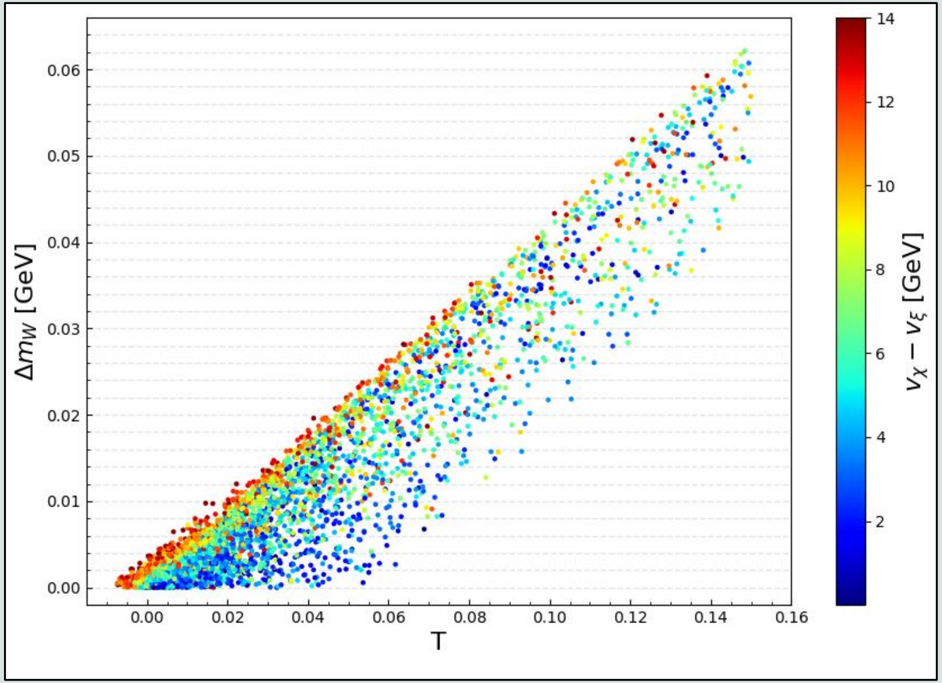
$$SU(2)_L \times SU(2)_R \xrightarrow[\langle\chi^0\rangle = \langle\xi^0\rangle = v_\Delta]{\langle\phi^0\rangle = v_\phi/\sqrt{2}} SU(2)_c$$

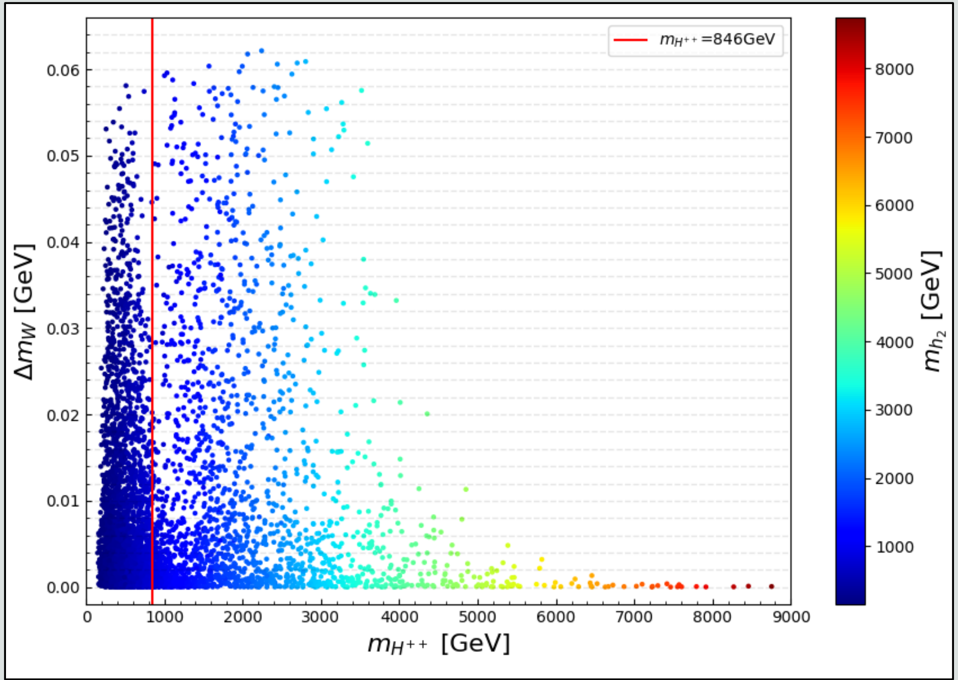




2、Explaining W-Boson Mass In the GM and Extension Models

2 $\Delta v = v_\chi - v_\xi > 0$ → ~~$SU(2)_c$~~ → Δm_W ↑





3 Type-I + Type-II → h_{ij} ↑ → ~~$SU(2)_c$~~ → Δm_W ↑

$$-\mathcal{L}_\nu \supset y_{ij}^N \bar{L}_{L,i}\phi N_{R,j} + \frac{1}{2}(M_R)_{ij} N_{R.i}^T C N_{R,j} + h_{ij}\overline{L_L^{ic}} i\tau_2 \chi L_L^j + h.c.$$

$$M_\nu = \begin{pmatrix} h_{ij} v_\Delta & \left(y_{ij}^N\right)^T v_\phi \\ y_{ij}^N v_\phi & (M_R)_{ij} \end{pmatrix}$$

$M_R \gg v_\phi \gg v_\Delta$

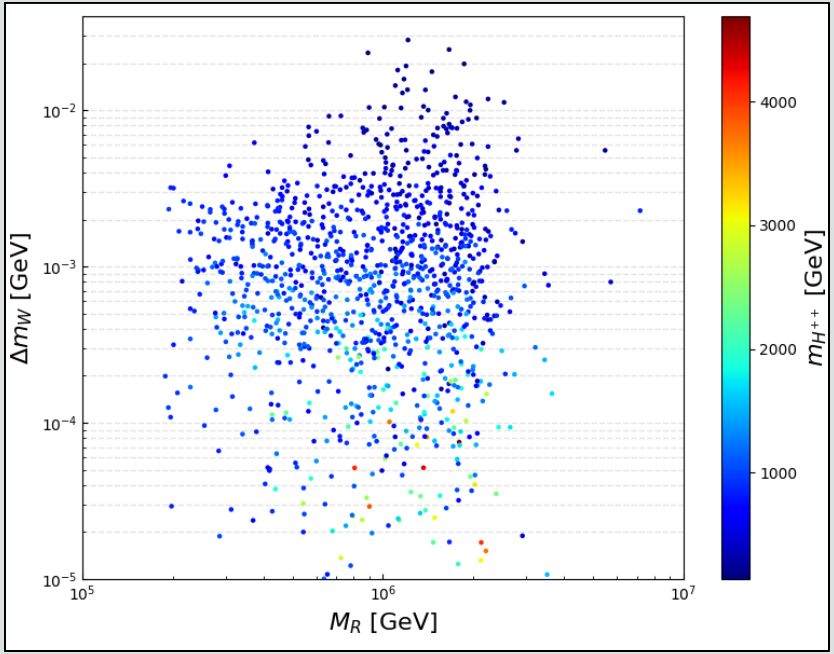
$$m_\nu \approx h_{ij} v_\Delta - v_\phi^2 \left(y_{ij}^N\right)^T M_{R,j}^{-1} \left(y_{ij}^N\right), \qquad h_{ij} v_\Delta \approx \left(y^N v_\phi\right)^2 / M_{R,j}^{-1}$$

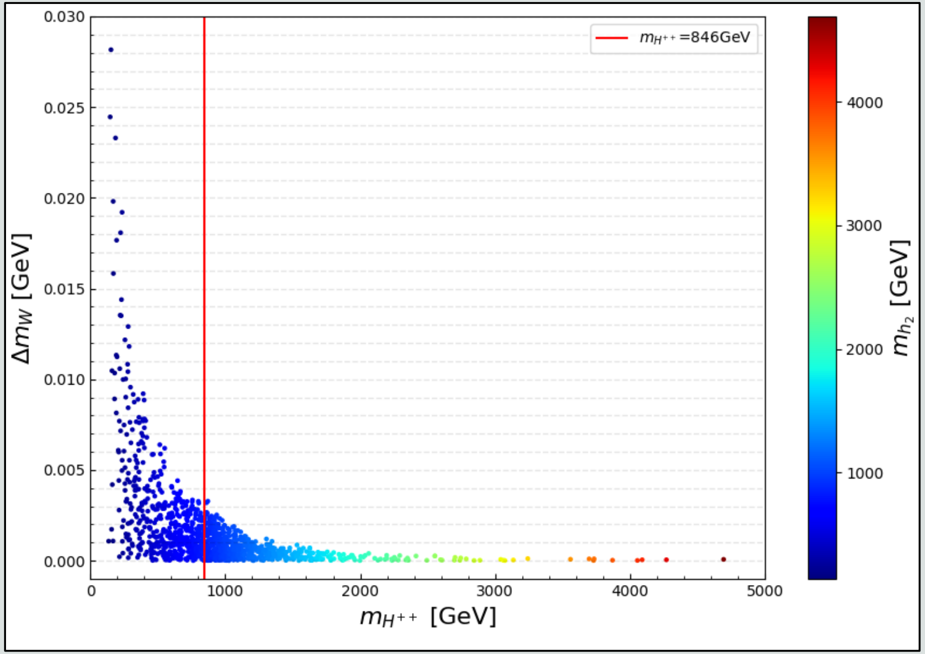
$$h_{ij} = 2\sqrt{2}\left(V_{PMNS}^T\right)^{-1} \left(\frac{v(1 - s_H^2)}{s_H M_{R,i}}\right) \delta_{ij} (V_{PMNS})^{-1}, \qquad y_{ij}^N = (V_{PMNS})^{-1}$$

2、Explaining W-Boson Mass In the GM and Extension Models

$$BR(\mu \to e\gamma) < 4.2 \times 10^{-13}, BR(\mu \to 3e) < 10^{-12}$$

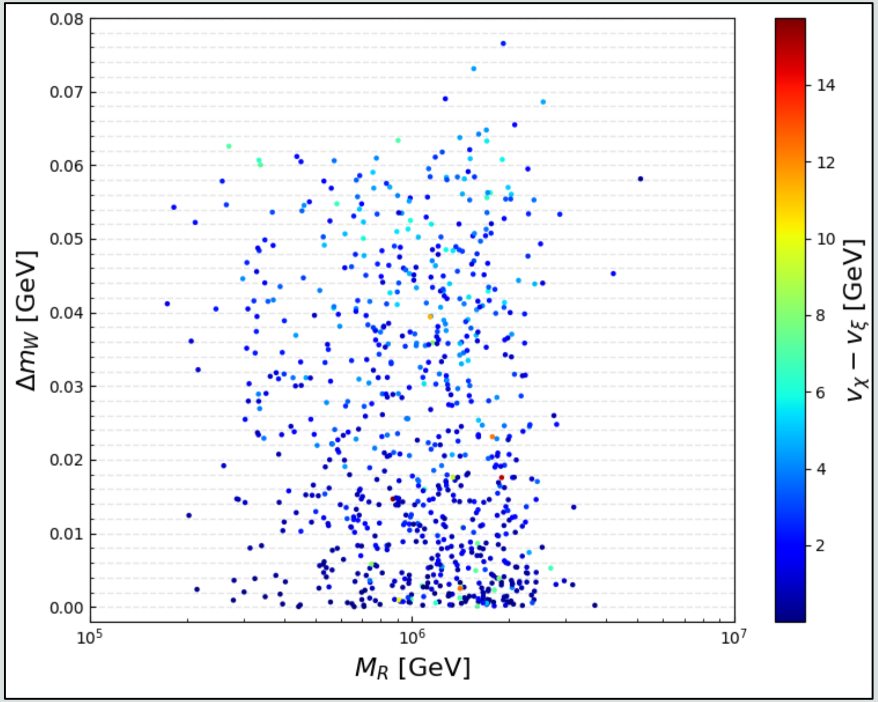
$$BR(\mu \to e\gamma) \sim \frac{\alpha_{EM}}{192\pi} |h_{ij}|^4 \left(\frac{m_W}{M_{H^{++}}}\right)^4 \Rightarrow \quad h_{ij} < 10^{-2}, \quad M_R > 50\text{TeV}$$

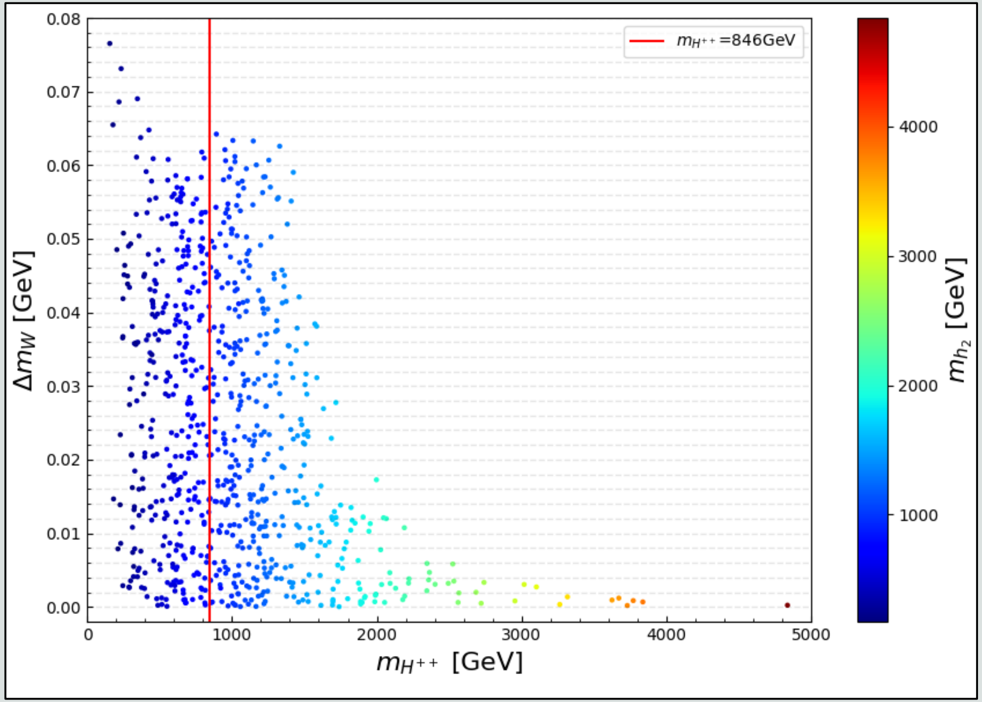




2、Explaining W-Boson Mass In the GM and Extension Models

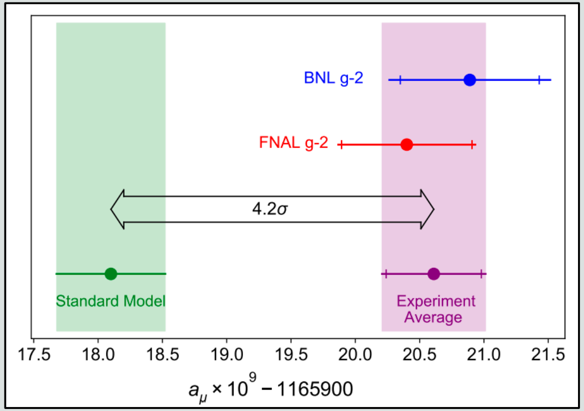
4 $\Delta v = v_\chi - v_\xi > 0$ + Type-I + Type-II



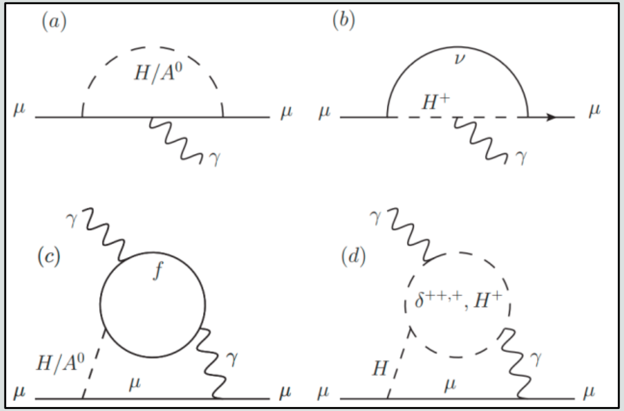


3、What to do Next ?

01 Muon $g-2$ in the GM Model



Phys.Rev.Lett. 126 (2021) 14, 141801



Phys.Rev.D 104 (2021) 5, 055011

02 Leptongenesis in the GM Model

To resolve BAU by the Leptongenesis → Heavy singlet neutrinos with hierarchical mass spectrum → lower bound of about $10^8 \sim 10^9$GeV

Leptonic CP Asymmetry → Mass differences of heavy majorana neutrinos comparable to their decay width; Resonant Effect → lower bound of about ~ TeV

Phys.Rev.D 56 (1997) 5431-5451

1. Taken a general discussion about the contribution to W boson mass in the original GM Model;
2. Explaining CDF-II results in the GM Extension Models. Misalignment among the triplet VEVs and large h_{ij} couplings allowed with RH neutrino sector;
3. Works what to do right now. Try to explain $g_\mu - 2$ and CDF-II results simultaneously, try to understand BAU by leptongenesis in GM model with right hand neutrino extension.

THANKS

Q&A