W Mass Shift in Extended Higgs Sectors

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Based on:

S. Kanemura, KY, 2204.07511 [hep-ph];

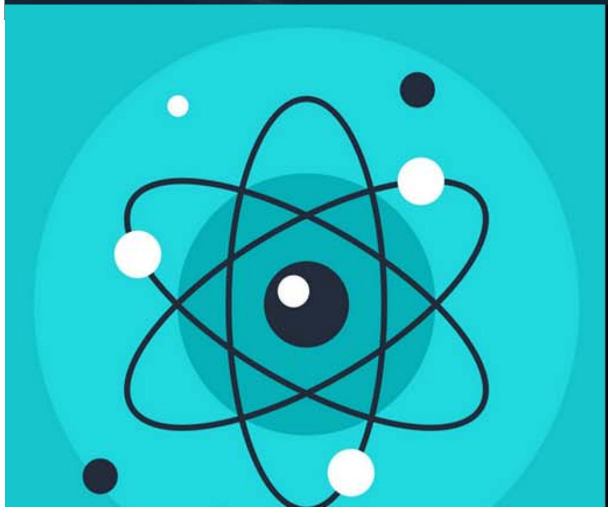
T.-K. Chen, C.-W. Chiang, KY, 2204.12898 [hep-ph]

Rapid Response Workshop on W Boson Mass Anomaly

2022, May 27th, Online

Rapid Response Workshop on Muon g-2

April 30, 2021, National Taiwan University, Taipei



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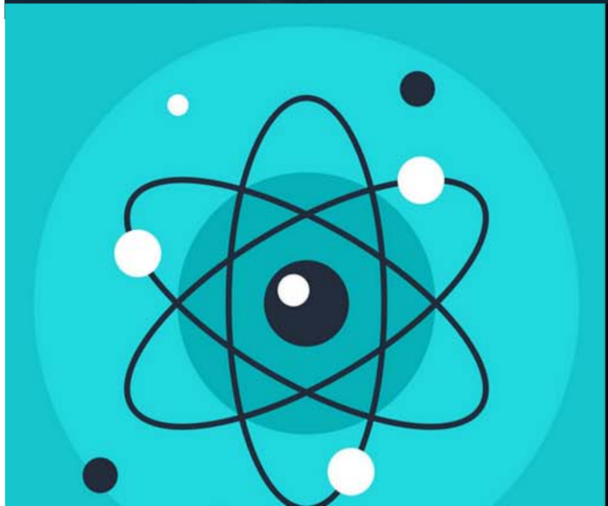


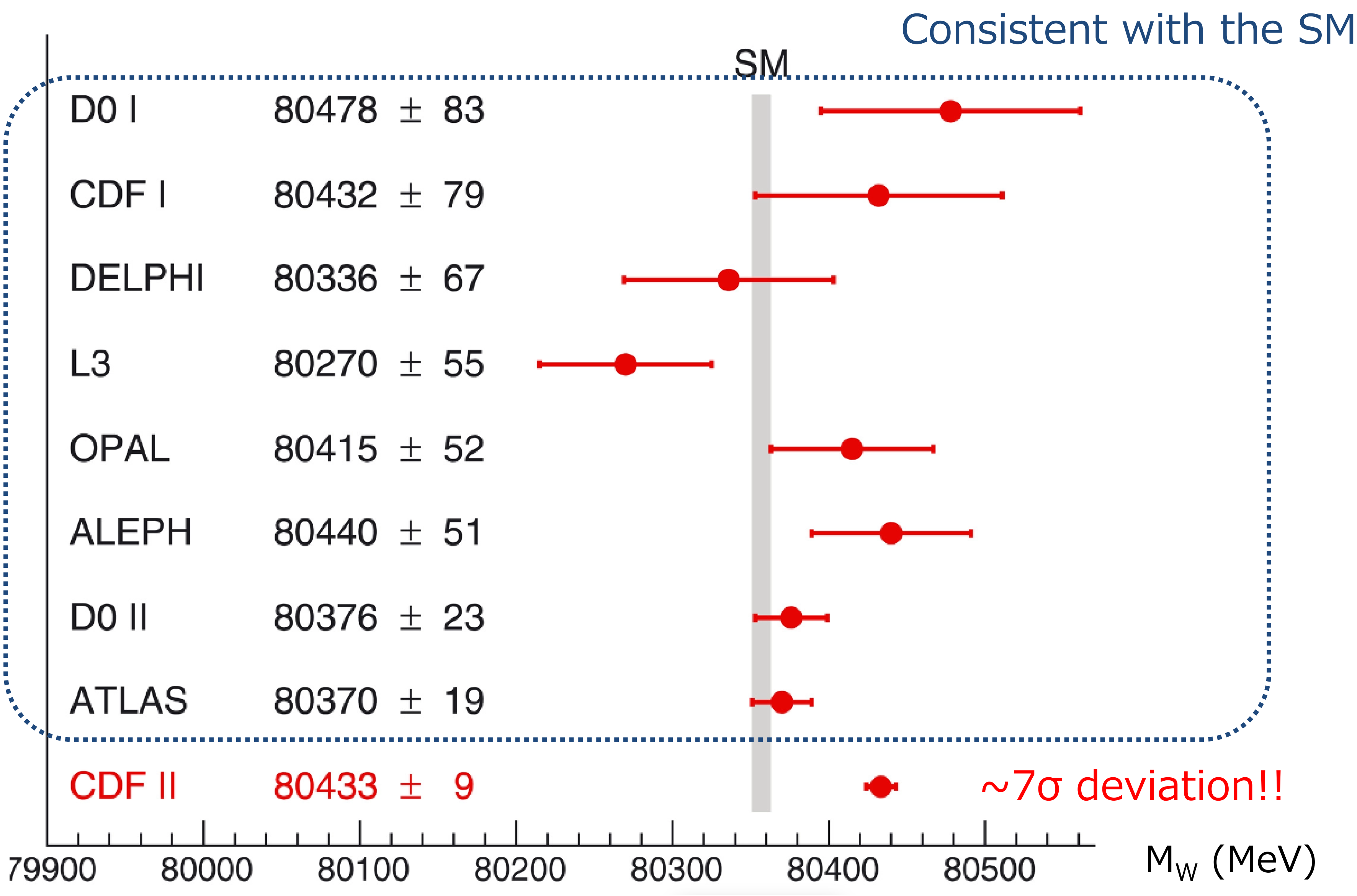
**Rapid Response Workshop on
W Boson Mass Anomaly**

27 May, 2022, Online

Rapid Response Workshop on
XXX Anomaly
2023, Taiwan

CDF II Anomaly

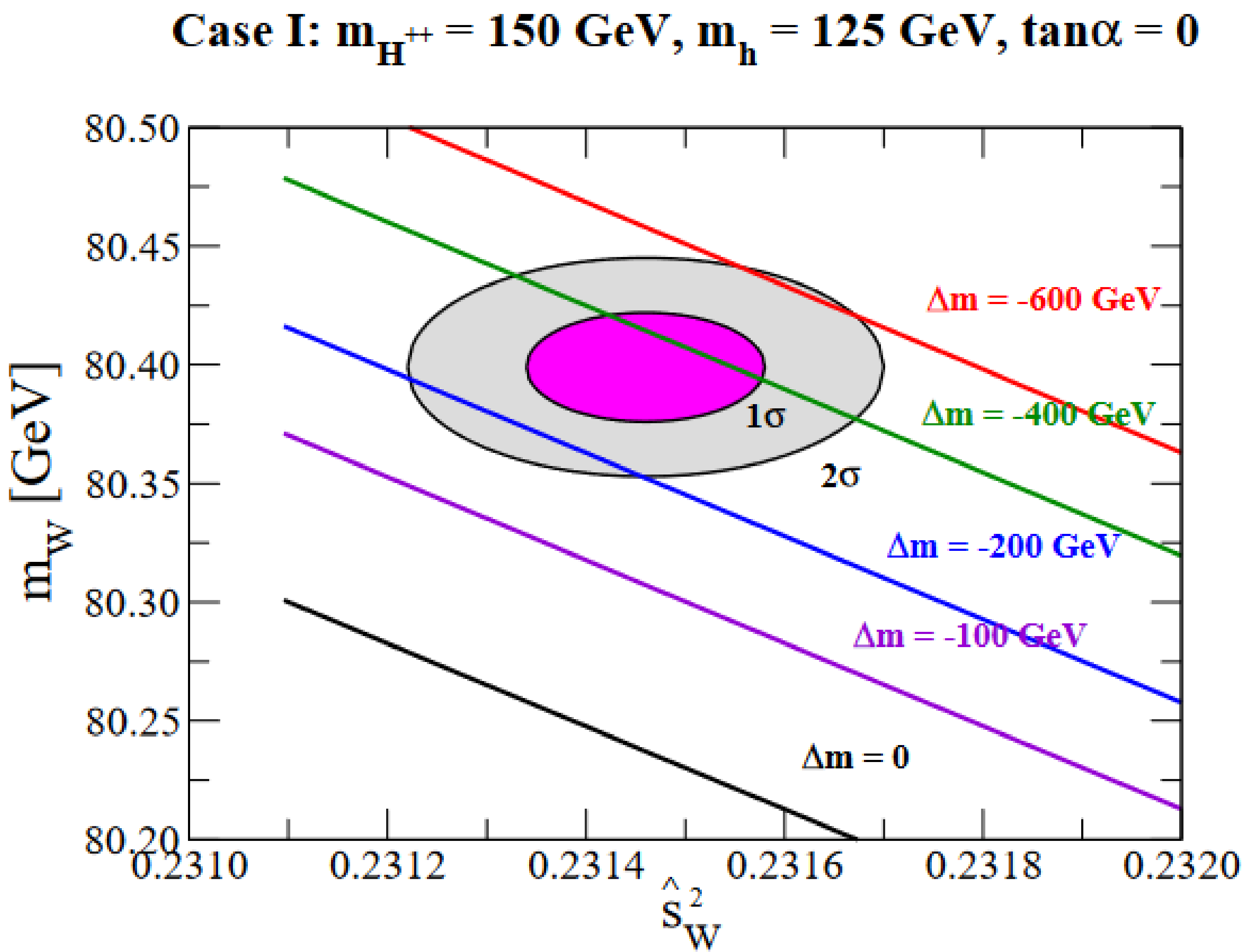
Science 376, 170 (2022)



Typically, we need $\Delta m_W \sim$ 60-100 MeV.

~ 11 years ago

Kanemura, KY (2011)



Content

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II. Electroweak parameters

- Standard model
- Extended Higgs models

III. New physics implication

- Higgs triplet model
- Georgi-Machacek model

IV. Summary

EW parameters in the SM at tree level

- Rho parameter: $$\rho_{\rm tree} = \frac{m_W^2}{m_Z^2 c_W^2} = \frac{\sum_\varphi 2v_\varphi^2[T_\varphi(T_\varphi+1)-Y_\varphi^2]}{\sum_\varphi 4v_\varphi^2 Y_\varphi^2} = 1 \text{ (SM)}$$

VEV for W ($v_W = v$)

VEV for Z (v_Z)

PDG

$$\rho_{\rm exp} = 1.00038 \pm 0.0002$$

- 3 input parameters: $\{g, g', v\} \rightarrow \{\alpha_{em}, G_F, m_Z\}$

- Outputs: $$m_W^2 = \frac{m_Z^2}{2}\left[1+\sqrt{1-\frac{2\sqrt{2}\pi\alpha_{\rm em}}{G_F m_Z^2}}\right] \qquad s_W^2 = \frac{1}{2}\left[1-\sqrt{1-\frac{2\sqrt{2}\pi\alpha_{\rm em}}{G_F m_Z^2}}\right]$$

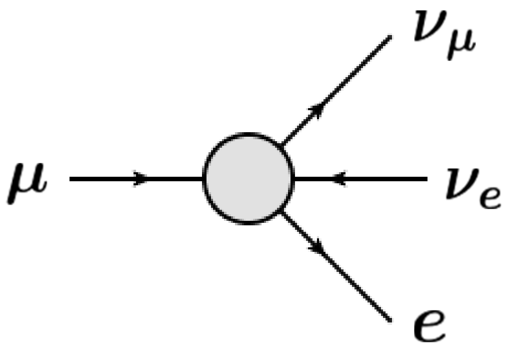
$\alpha_{em} \sim 1/137$, $G_F \sim 1.17\times10^{-5}$ GeV^{-2}, $m_Z \sim 91.2$ GeV

$m_W \sim 80.9$ GeV !? ➡ We need to go to the loop level.

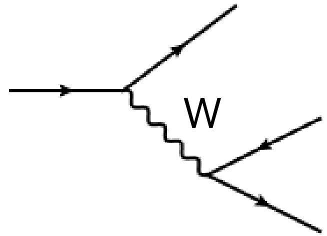
EW parameters in the SM at loop levels

- Shift of the Fermi constant:

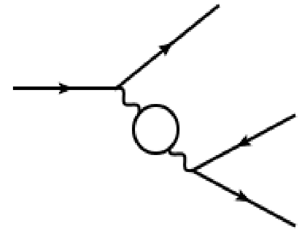
$$G_F \to G_F(1 - \Delta r)$$



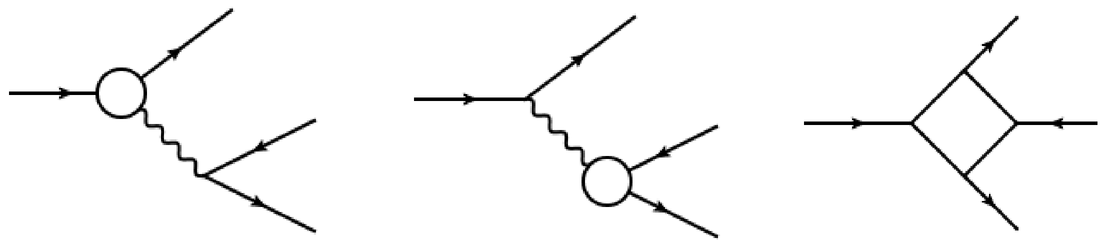
tree



Oblique corrections



Vertex & box corrections



S, U: Peskin-Takeuchi parameter

$\propto \ln m_f$ $\quad\quad$ $\propto m_t^2$

$$\Delta r = \Delta\alpha_{\rm em} - \frac{c_W^2}{s_W^2}\Delta\rho + \frac{\alpha_{\rm em}}{4 s_W^2}\left(2S - \frac{c_W^2 - s_W^2}{s_W^2}U\right) + \delta_{\rm VB} \sim 0.0365$$

PDG

EW parameters in the SM at loop levels

- W mass:

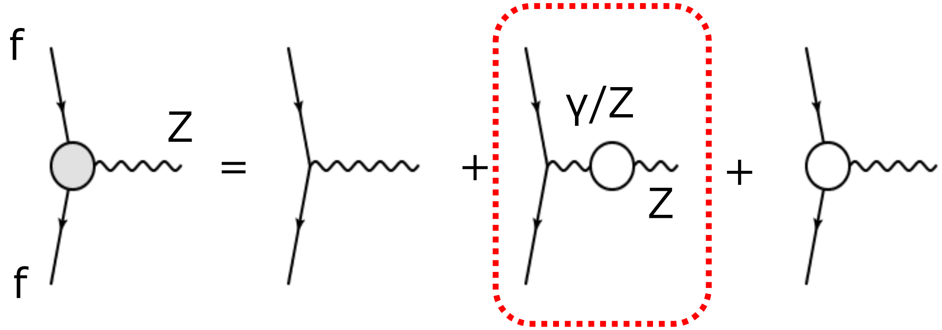
$$(m_W^2)_{\rm ren} = \frac{m_Z^2}{2}\left[1+\sqrt{1-\frac{2\sqrt{2}\pi\alpha_{\rm em}}{G_F m_Z^2 (1-\Delta r)}}\right]$$

$$\simeq m_W^2\left[1+\frac{1}{c_W^2-s_W^2}\left(c_W^2\Delta\rho-\frac{\alpha_{\rm em}}{2}S-s_W^2\Delta\alpha_{\rm em}\right)\right]$$

PDG

➡ m_W (SM) = 80.357 ± 0.006 GeV

- Effective weak mixing angle @ Z pole:



$$\sin^2\theta_{\rm eff}^f \equiv \frac{1}{4|Q_f|}\left[1-{\rm Re}\left(\frac{g_V^f}{g_A^f}\right)\right]_{p^2=m_Z^2}$$

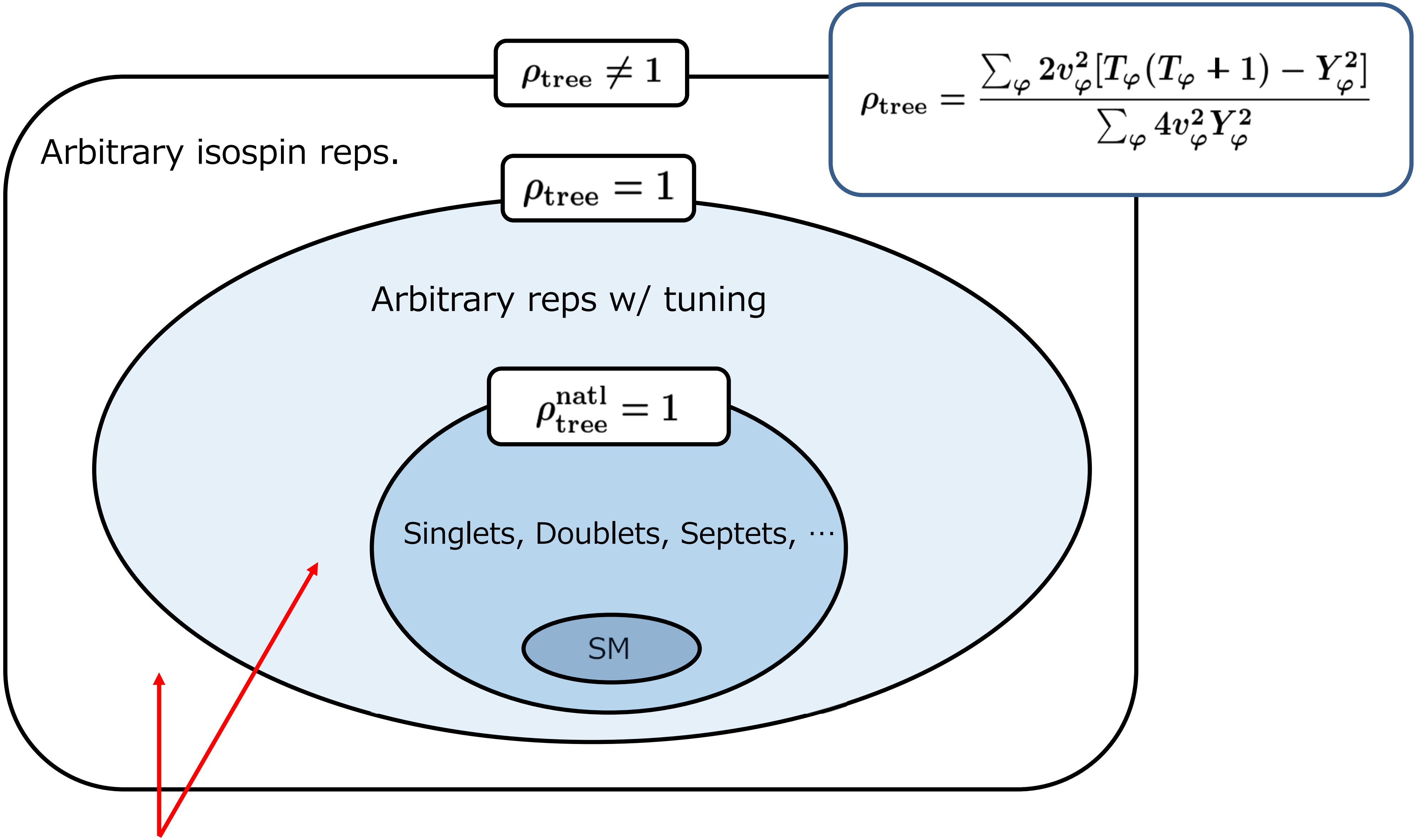
$$\simeq s_W^2+\frac{1}{c_W^2-s_W^2}\left(-c_W^2 s_W^2\Delta\rho+\frac{\alpha_{\rm em}}{4}S+c_W^2 s_W^2\Delta\alpha_{\rm em}\right)$$

PDG

➡ $s_{\rm eff}^2$ (SM) = 0.23153 ± 0.00004 (for f = e, μ)

$s_{\rm eff}^2$ (Exp) = 0.23129 ± 0.00033

Classification of extended Higgs sectors



4 input parameters: $\{g, g', v, v_Z\} \rightarrow \{\alpha_{em}, G_F, m_Z, \rho_{\rm tree}\}$

Extended Higgs with $\rho_{\text{tree}} = 1$

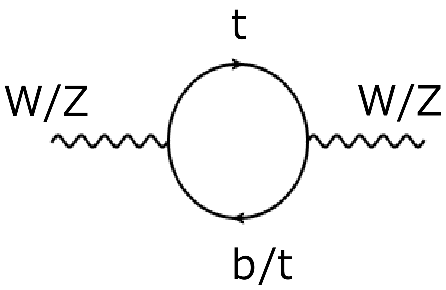
- W mass:

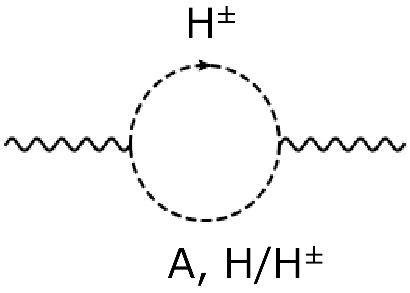
$$m_W^{\text{NP}} \simeq m_W^{\text{SM}} \left[1 + \frac{1}{c_W^2 - s_W^2}\left(\frac{c_W^2}{2}\Delta\rho_{\text{NP}} - \frac{\alpha_{\text{em}}}{4} S_{\text{NP}}\right)\right]$$

$$\simeq m_W^{\text{SM}} \left[1 + 55\ \text{MeV} \times \frac{\Delta\rho_{\text{NP}}}{10^{-3}} - 25\ \text{MeV} \times \frac{S_{\text{NP}}}{0.1}\right]$$

Δρ parameter

$$\Delta\rho = \frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{\Pi_{WW}(0)}{m_Z^2} + \frac{\delta\rho_{\rm tree}}{\rho_{\rm tree}}$$





(Case for the 2HDM, sin(β-α)=1, M_H = M_A)

$$\simeq \frac{1}{16\pi^2 v^2}\left[3m_t^2 + \frac{4}{3}(m_{H^\pm} - m_A)^2\right]$$

$$S_{\rm NP} \simeq -\frac{1}{12\pi}\ln\frac{m_{H^\pm}^2}{m_A^2}$$

$\delta\rho_{\rm tree}$

- =0 for models with $\rho_{\rm tree}^{\rm natl} = 1$
- Determined by an additional renormalization condition

・Zee vertex *Blank, Hollik (1998); Kanemura, KY (2011)*

・Z-A^0 mixing *Aoki, Kanemura, Kikuchi, KY (2013)*

・T parameter *Chiang, Kuo, KY (2017)*

Extended Higgs with $\rho_{\text{tree}} = 1$

- W mass:

$$m_W^{\text{NP}} \simeq m_W^{\text{SM}} \left[1 + \frac{1}{c_W^2 - s_W^2}\left(\frac{c_W^2}{2}\Delta\rho_{\text{NP}} - \frac{\alpha_{\text{em}}}{4}S_{\text{NP}}\right)\right]$$

$$\simeq m_W^{\text{SM}} \left[1 + 55\ \text{MeV} \times \frac{\Delta\rho_{\text{NP}}}{10^{-3}} - 25\ \text{MeV} \times \frac{S_{\text{NP}}}{0.1}\right]$$

- Effective weak mixing angle:

$$s_{\text{eff}}^2|_{\text{NP}} \simeq s_{\text{eff}}^2|_{\text{SM}} + \frac{1}{c_W^2 - s_W^2}\left(-c_W^2 s_W^2 \Delta\rho_{\text{NP}} + \frac{\alpha_{\text{em}}}{4}S_{\text{NP}}\right)$$

$$\simeq s_{\text{eff}}^2|_{\text{SM}} - 2.9 \times 10^{-4}\left(\frac{\Delta\rho_{\text{NP}}}{10^{-3}}\right) + 3.2 \times 10^{-4}\left(\frac{S_{\text{NP}}}{0.1}\right)$$

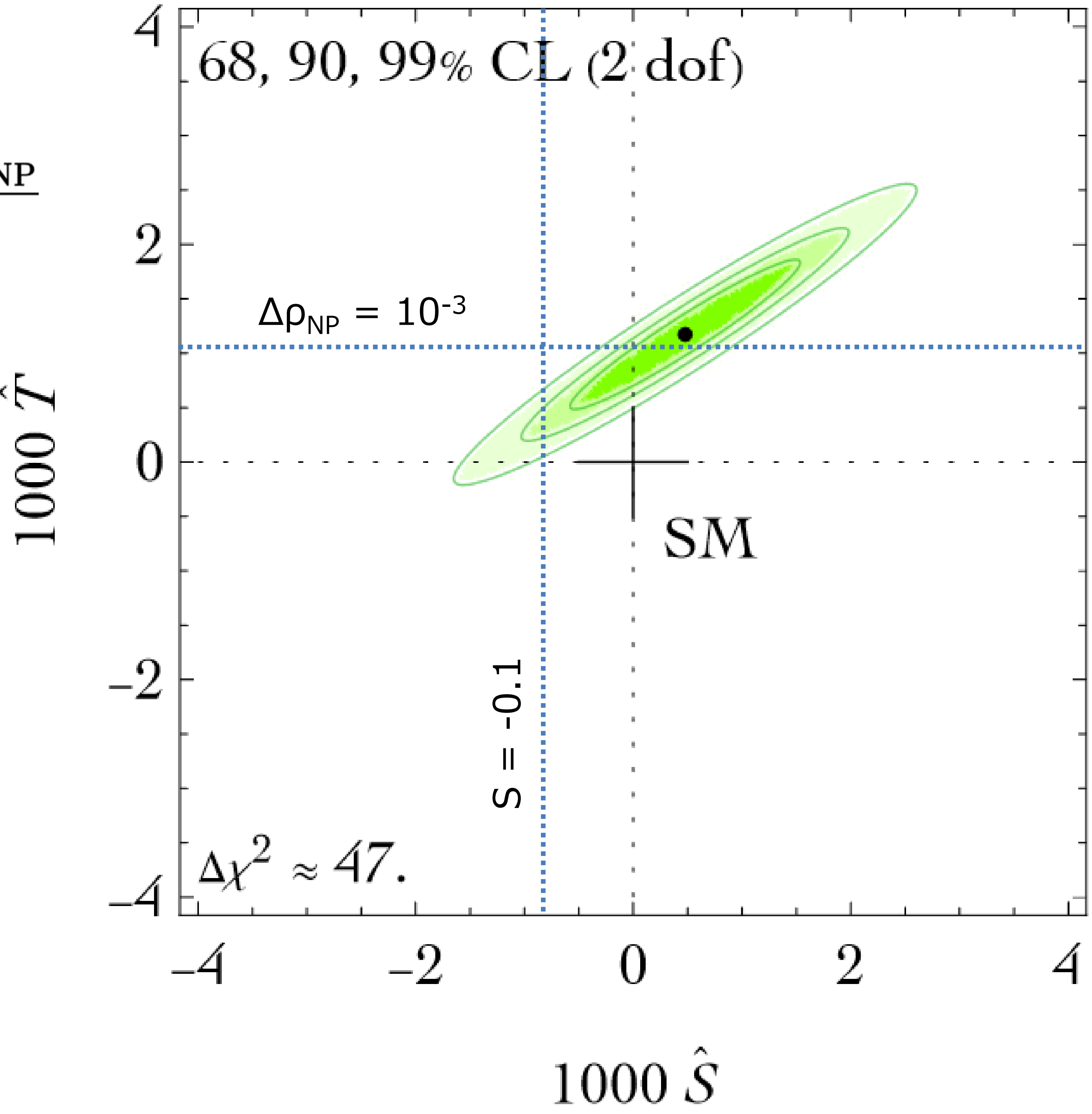
C.f. s_{eff}^2 (Exp) = 0.23129 ± 0.00033

Typically, we need $\Delta\rho_{\text{NP}} = O(10^{-3})$ and/or $S_{\text{NP}} = -O(0.2)$.

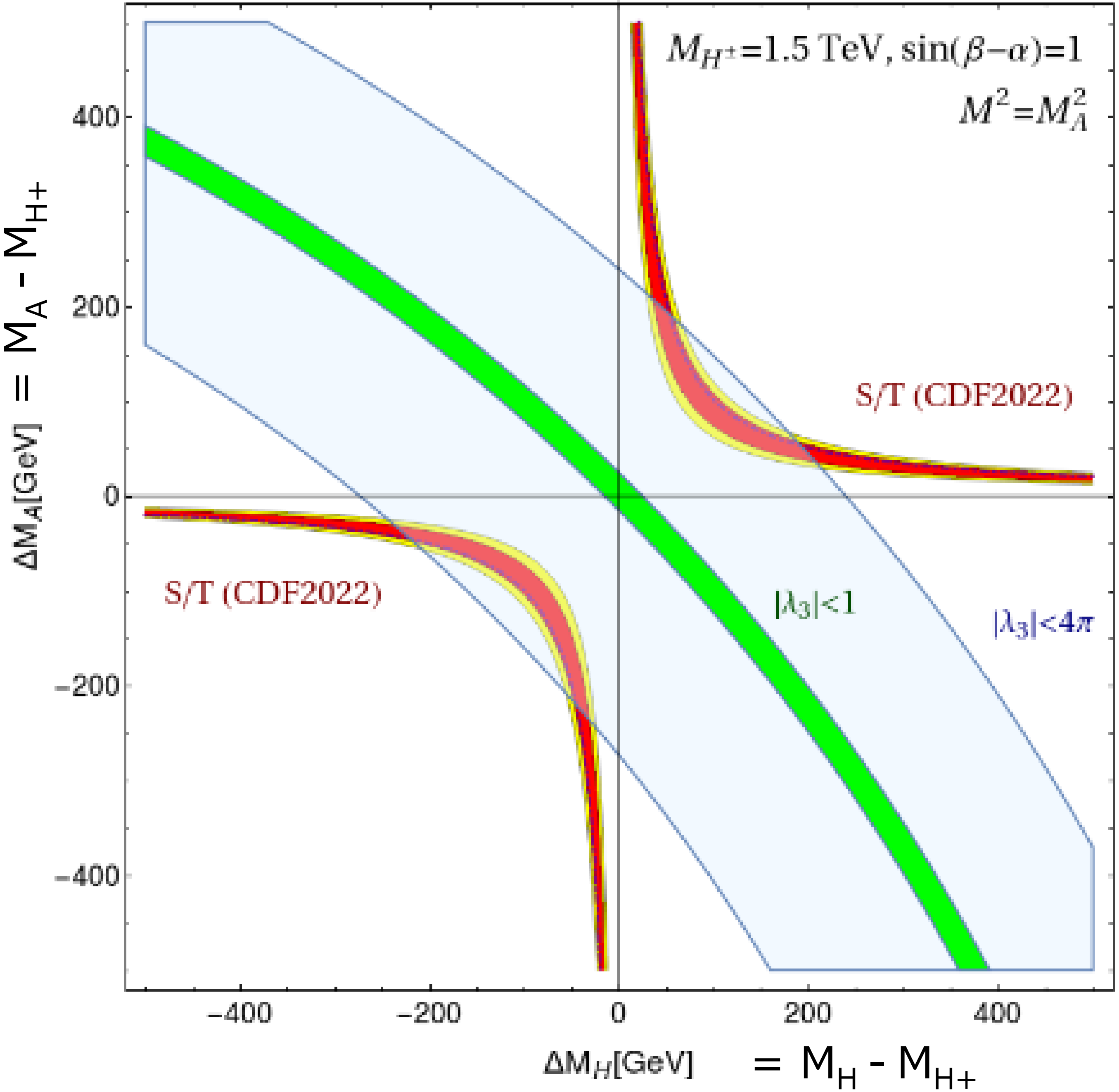
Strumia, 2204.04191 [hep-ph]

$$\hat{T} = \Delta\rho_{\rm NP}$$

$$\hat{S} = \frac{\alpha_{\rm em} S_{\rm NP}}{4 s_W^2}$$



Lee, Cheung, Kim, Lu, Song, 2204. 10338 [hep-ph]



Extended Higgs with $\rho_{tree} \neq 1$

$$\Delta\rho_{\rm tree} = \rho_{\rm tree} - 1$$

- Inputs: $\{\alpha_{em}, G_F, m_Z, \rho_{tree}\}$

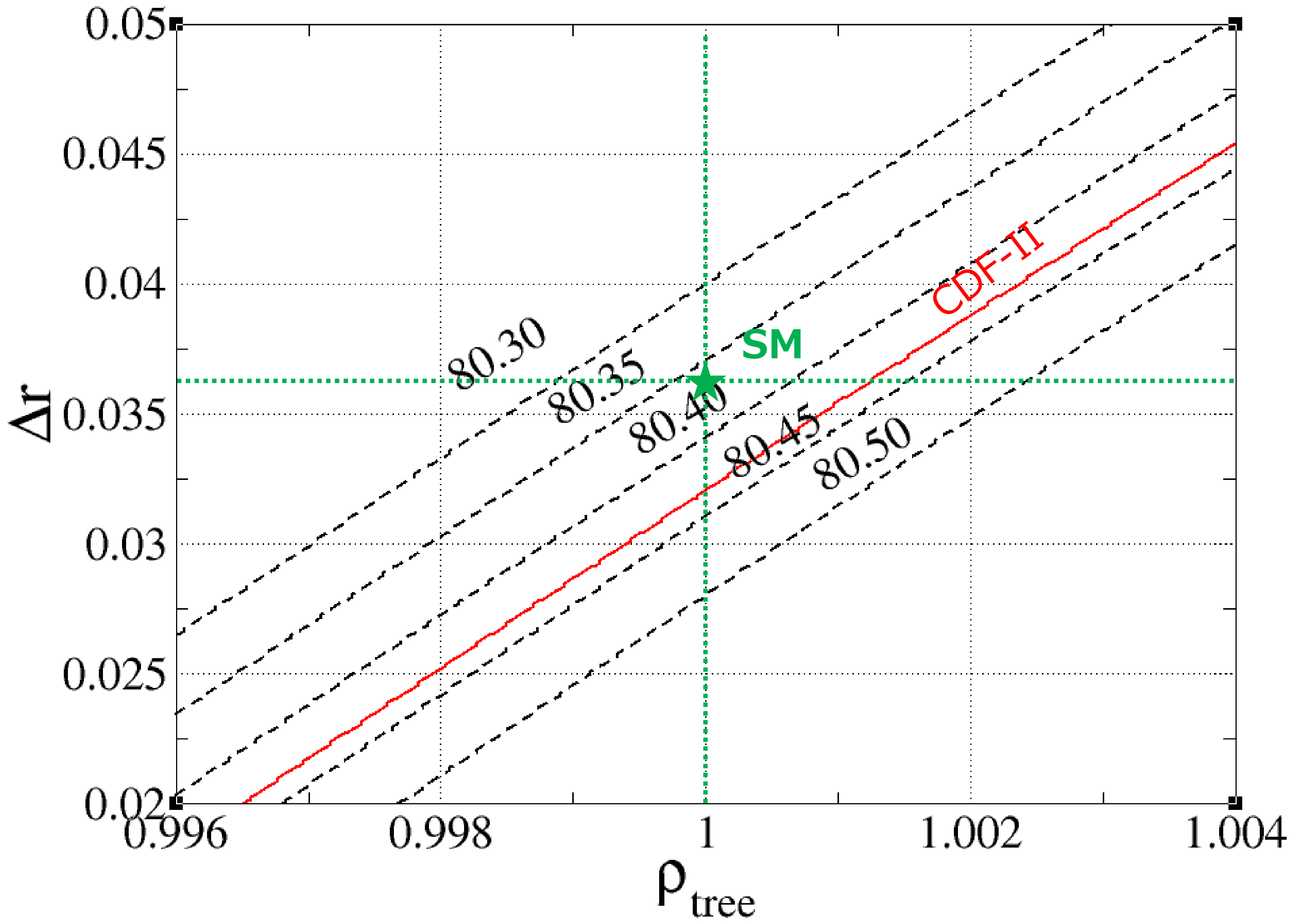
- Outputs: $$m_W^{\rm NP} \simeq m_W^{\rm SM}\left[1 + \frac{1}{c_W^2 - s_W^2}\left[\frac{c_W^2}{2}(\Delta\rho_{\rm tree} + \Delta\rho_{\rm NP}) - \frac{\alpha_{\rm em}}{4}S_{\rm NP}\right]\right]$$

$$s_{\rm eff}^2|_{\rm NP} \simeq s_{\rm eff}^2|_{\rm SM} + \frac{1}{c_W^2 - s_W^2}\left[-c_W^2 s_W^2(\Delta\rho_{\rm tree} + \Delta\rho_{\rm NP}) + \frac{\alpha_{\rm em}}{4}S_{\rm NP}\right]$$

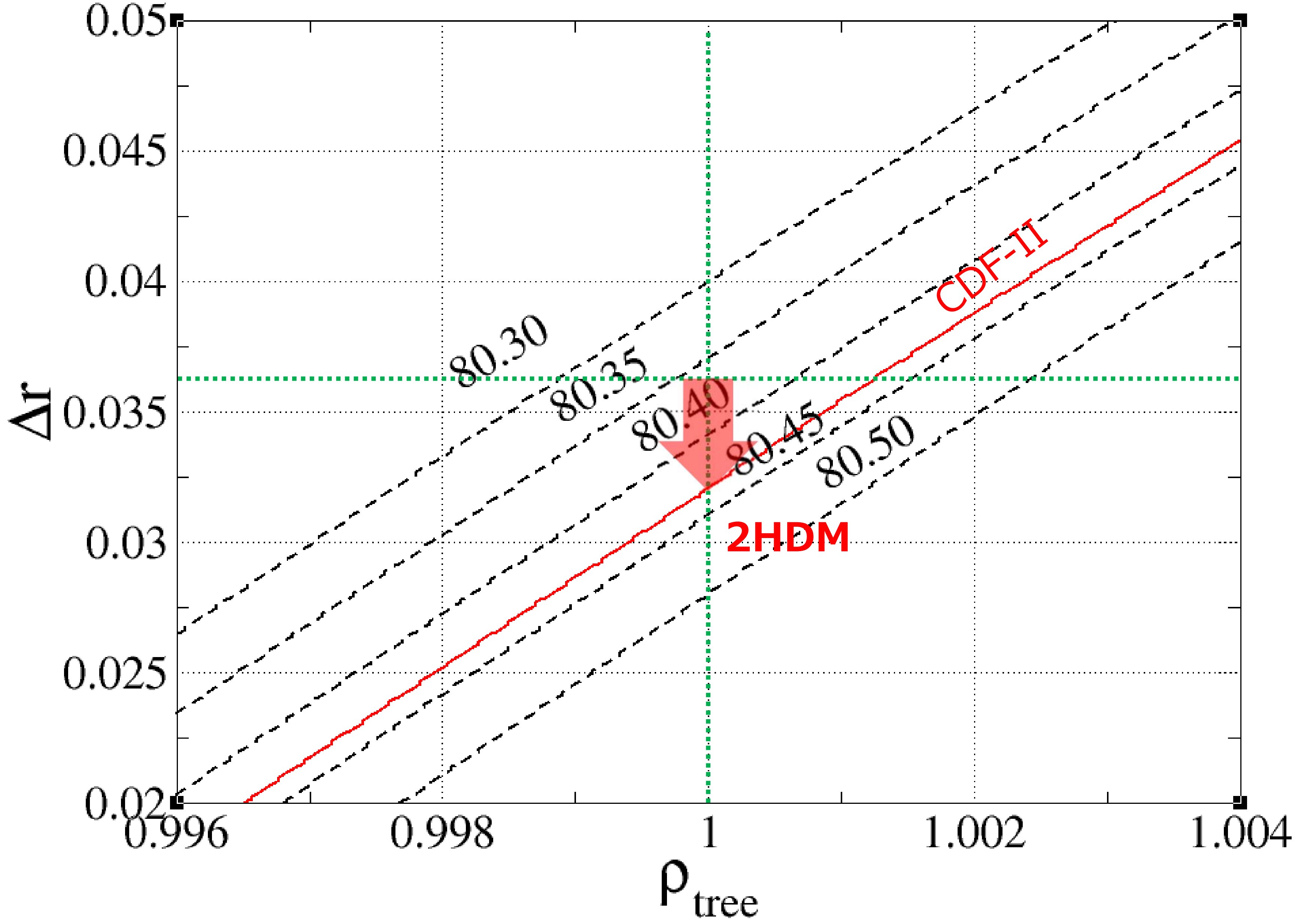
➡ NP contributions to the ρ parameter are given by the tree level part ($\Delta\rho_{tree}$) and the one-loop part ($\Delta\rho_{NP}$) .

- $\Delta\rho_{tree}$ = 0 (Singlets, Doublets)
- $\Delta\rho_{tree}$ > 0 (Triplets with Y = 0)
- $\Delta\rho_{tree}$ < 0 (Triplets with Y =1)

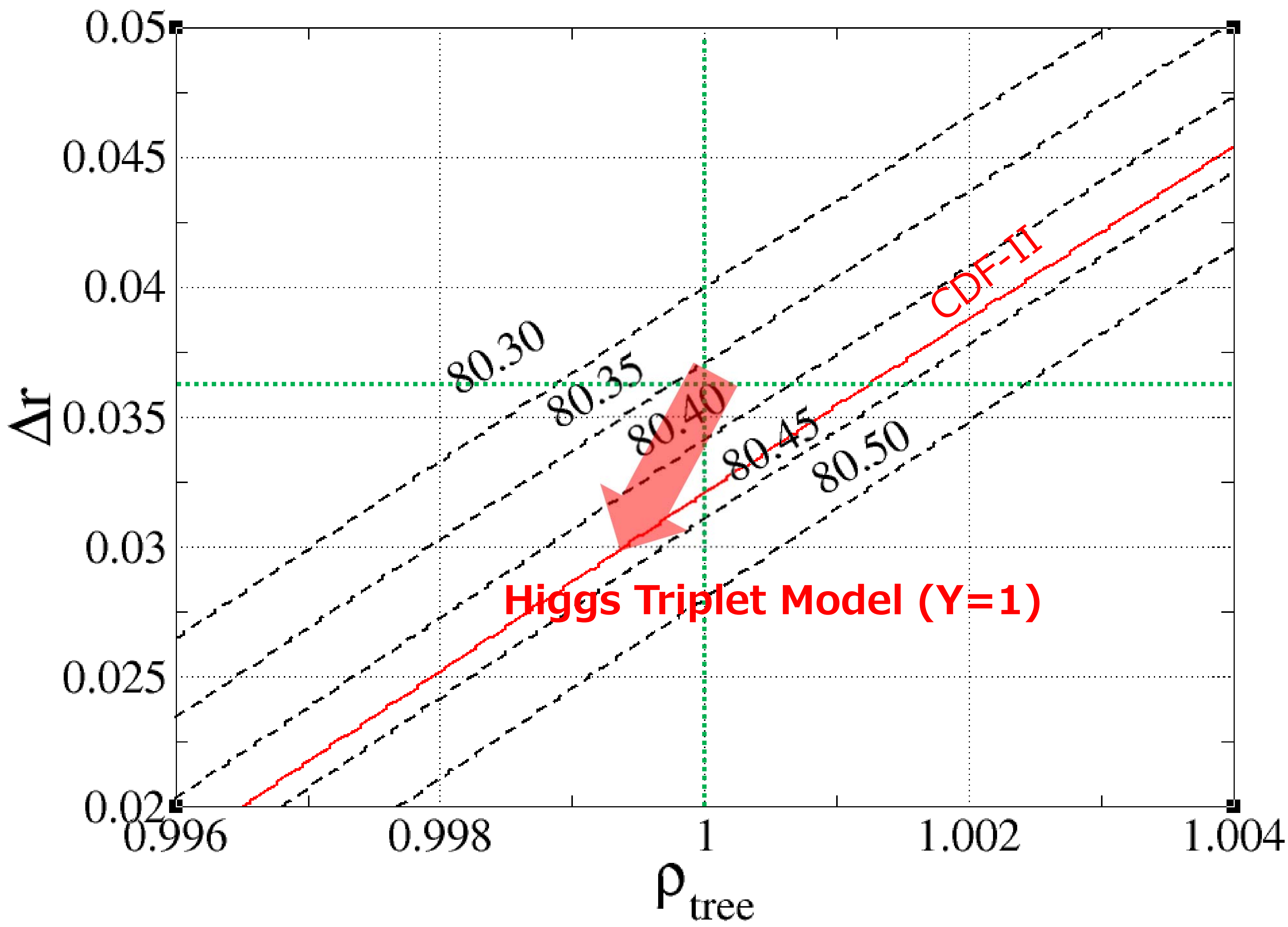
$$\rho_{\rm tree} = \frac{\sum_\varphi 2v_\varphi^2[T_\varphi(T_\varphi + 1) - Y_\varphi^2]}{\sum_\varphi 4v_\varphi^2 Y_\varphi^2}$$



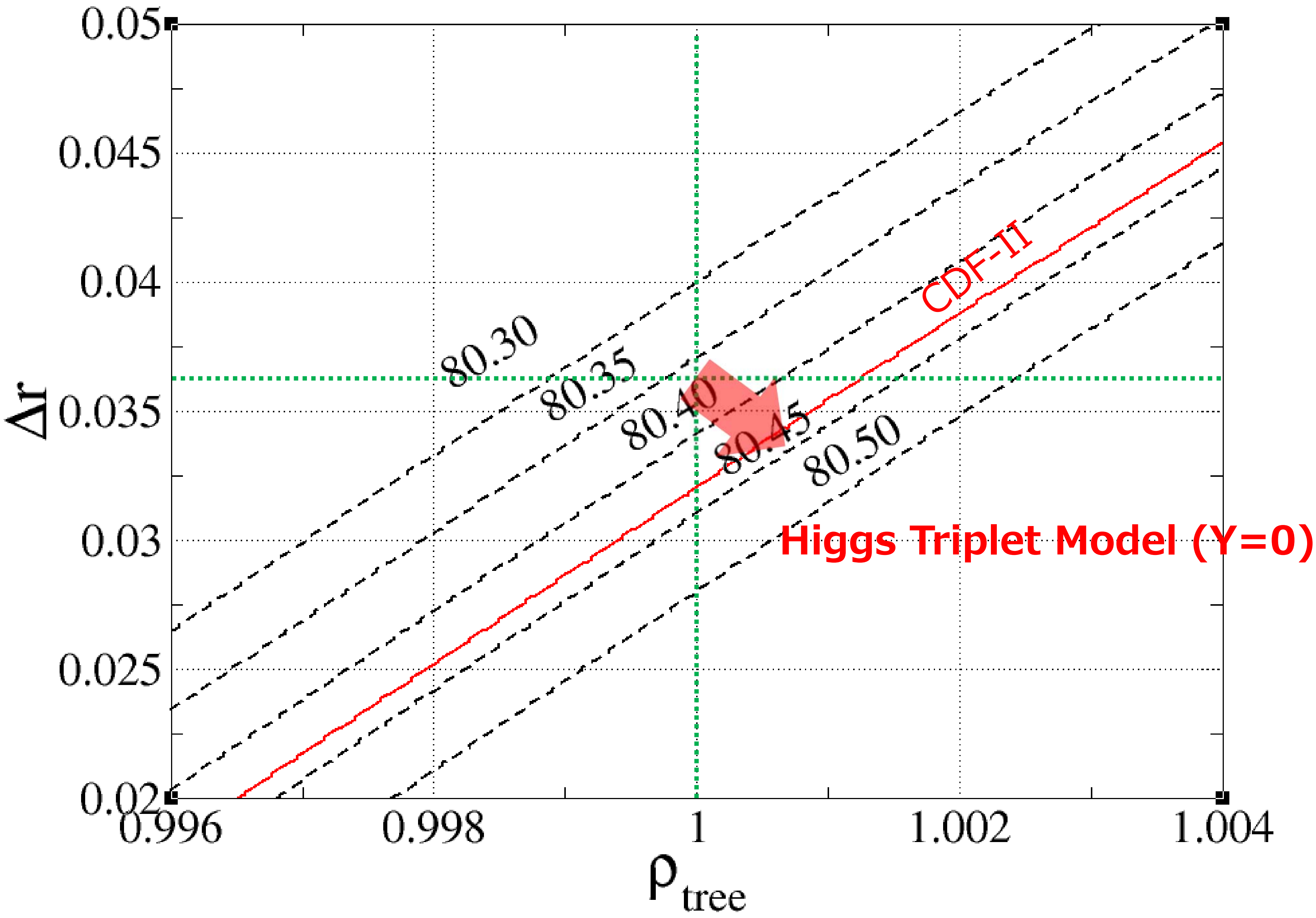
0.05
0.045
0.04
0.035
0.03
0.025
0.02
Δr
0.996
0.998
1
1.002
1.004
ρ tree
80.30
80.35
80.40
80.45
80.50
CDF-II
SM



0.05
0.045
0.04
0.035
0.03
0.025
0.02
Δr
0.996
0.998
1
1.002
1.004
ρ tree
80.30
80.35
80.40
80.45
80.50
CDF-II
2HDM



0.05
0.045
0.04
0.035
0.03
0.025
0.02
Δr
0.996
0.998
1
1.002
1.004
ρ tree
80.30
80.35
80.40
80.45
80.50
CDF-II
Higgs Triplet Model (Y=1)



Higgs Triplet Model (Y=0)
CDF-II
80.30
80.35
80.40
80.45
80.50
Δr
ρ tree
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.996
0.998
1
1.002
1.004

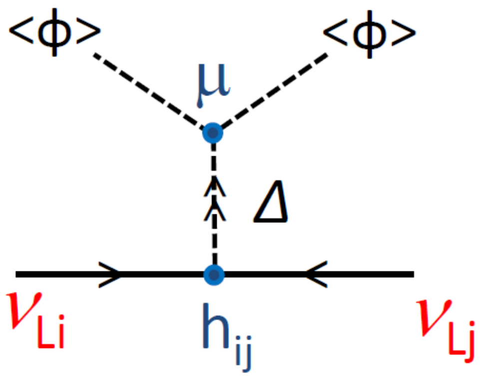
Content

Higgs Triplet Model (HTM)

Cheng, Li (1980);
Schechter, Valle, (1980);
Magg, Wetterich, (1980);
Mohapatra, Senjanovic, (1981)

- Model: Φ (I=1/2, Y=1/2) & Δ (I=1, Y=1) $\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$

- ρ parameter: $\rho_{\mathrm{tree}} = \dfrac{v^2}{v^2 + 2v_\Delta^2} < 1$ $\quad v = \sqrt{v_\Phi^2 + 2v_\Delta^2} \simeq 246\ \mathrm{GeV}$



$$(m_\nu)_{ij} \sim h_{ij} v_\Delta$$

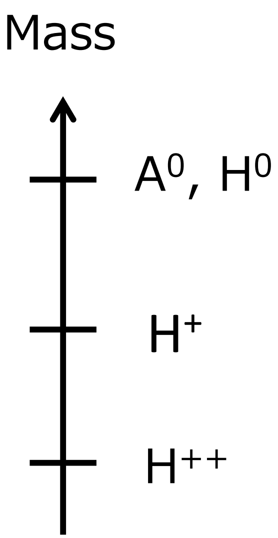
- Type-II seesaw mechanism

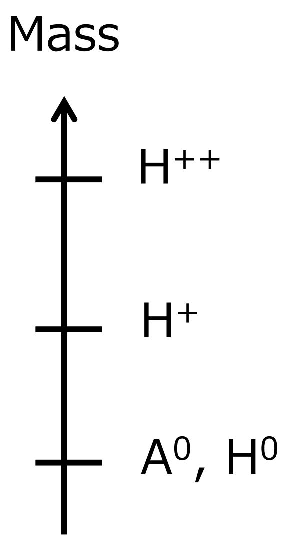
$$\mathcal{L}_{\mathrm{HTM}} = h_{ij} \overline{L_L^{ci}} \cdot \Delta L_L^j + \mu \Phi \cdot \Delta^\dagger \Phi + \cdots$$

- Higgs mass spectrum at $v_\Delta/v \ll 1$

$$m_{H^{\pm\pm}}^2 - m_{H^\pm}^2 = m_{H^\pm}^2 - m_{H^0}^2, \quad m_{H^0}^2 = m_{A^0}^2$$

$$H^{\pm\pm} = \Delta^{\pm\pm}, \;\; H^\pm \sim \Delta^\pm, \;\; \Delta^0 \sim \frac{H^0 + v_\Delta + iA^0}{\sqrt{2}}$$



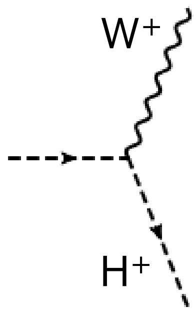


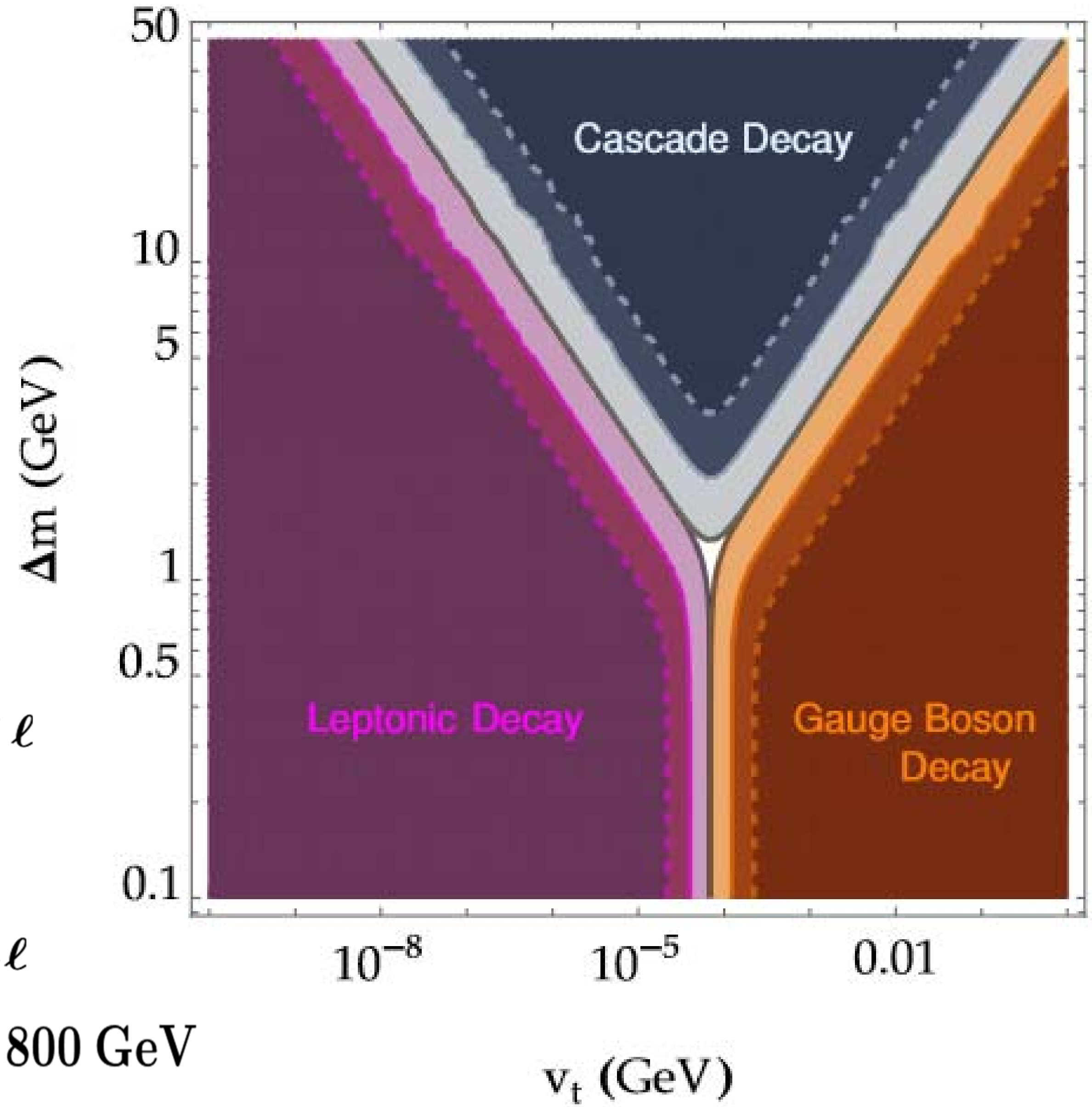
Decay of $H^{\pm\pm}$

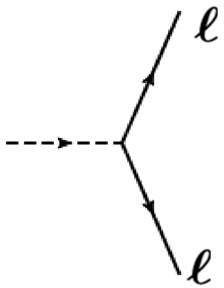
S. Ashanujjaman, K. Ghosh, 2108.10952 (JHEP)

m_{H++} = 500 GeV

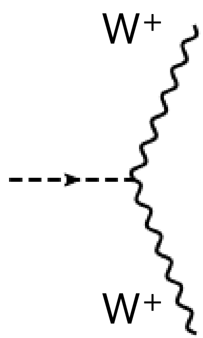
$\Delta m = m_{H++} - m_{H+}$







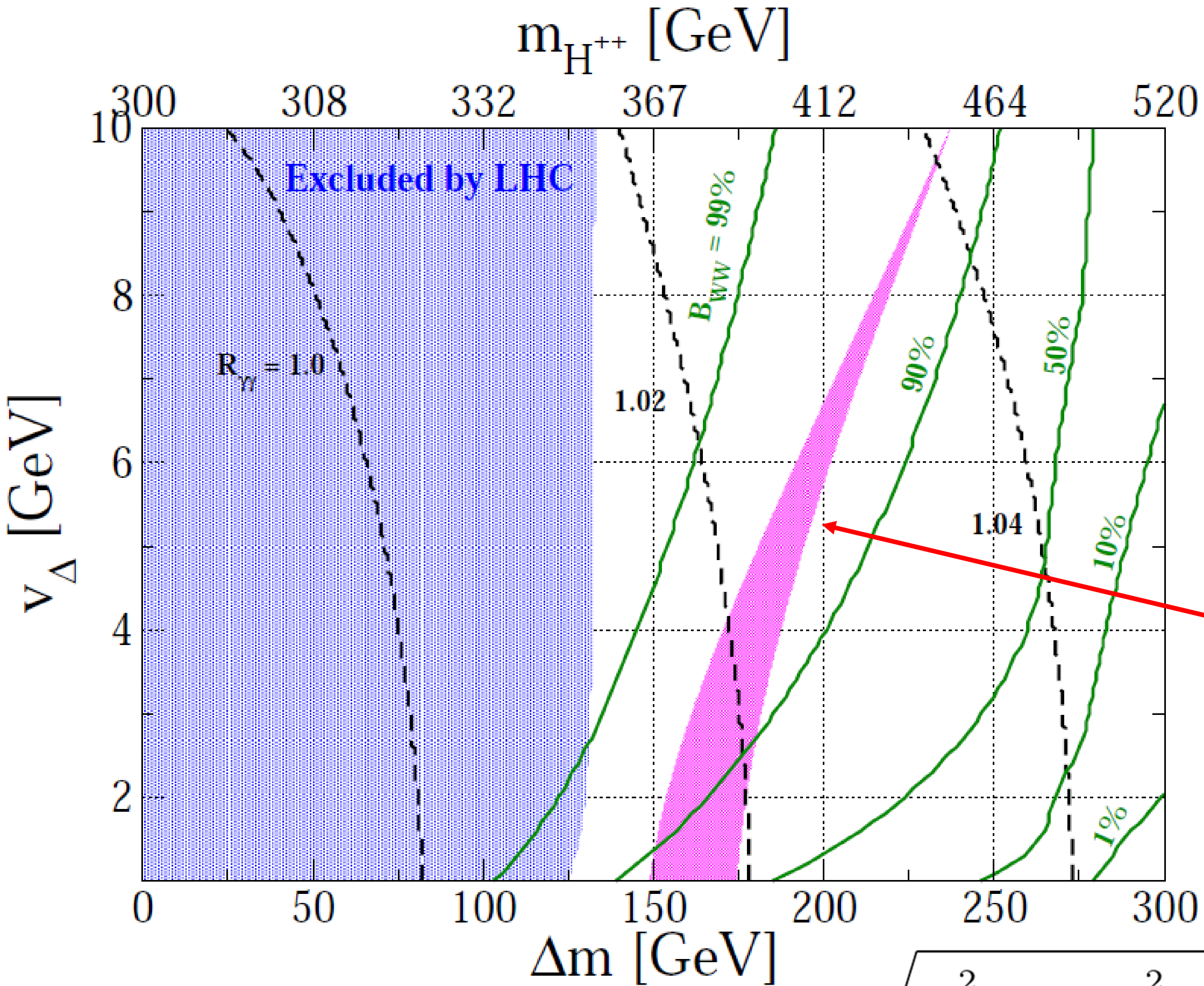
$m_{H^{\pm\pm}} \lesssim 800$ GeV



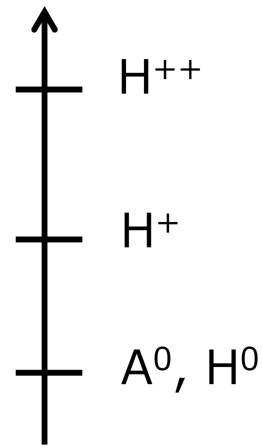
$m_{H^{\pm\pm}} \lesssim 350$ GeV

S. Kanemura, KY, 2204.07511 [hep-ph]

m_{H0} = 300 GeV



$$\equiv \sqrt{m_{H^{\pm\pm}}^2 - m_{H^\pm}^2}$$



m_W (CDF II) at 2σ

under the const. of Δρ,

effective angle, Z decay.

Georgi-Machacek (GM) Model

Georgi, Machacek (1985); Chanowitz, Golden (1985)

- Model: Φ (I=1/2, Y=1/2) & χ (I=1, Y=1) & ξ (I=1, Y= 0)

  - SU(2)$_L$ × SU(2)$_R$ form $\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^- & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^- & \xi^0 & \chi^+ \\ \chi^{--} & -\xi^- & \chi^0 \end{pmatrix}$

- VEV alignment: $\langle\chi^0\rangle = \langle\xi^0\rangle$

  SU(2)$_L$ × SU(2)$_R$ → SU(2)$_V$ (Custodial symmetry) → $\rho_{tree} = 1$

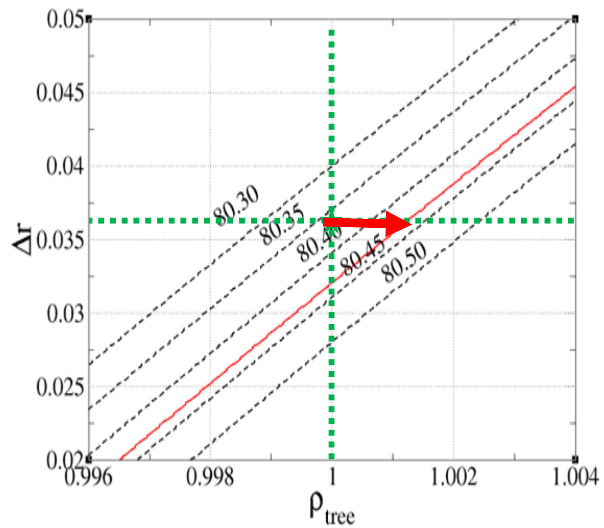
- Misalignment: $\langle\chi^0\rangle \neq \langle\xi^0\rangle$

$$\rho_{\text{tree}} = \frac{v^2}{v^2 - \nu^2}$$

  *SU(2)$_L$ × SU(2)$_R$ → U(1)$_\Delta$

$$\nu^2 = \langle\xi^0\rangle^2 - \langle\chi^0\rangle^2$$

- CDF anomaly: $\nu^2 = 85.4 \pm 10.1\ \text{GeV}^2$ with Δr = Δr (SM)



$$\nu^2 = 85.4 \pm 10.1\ \mathrm{GeV}^2$$

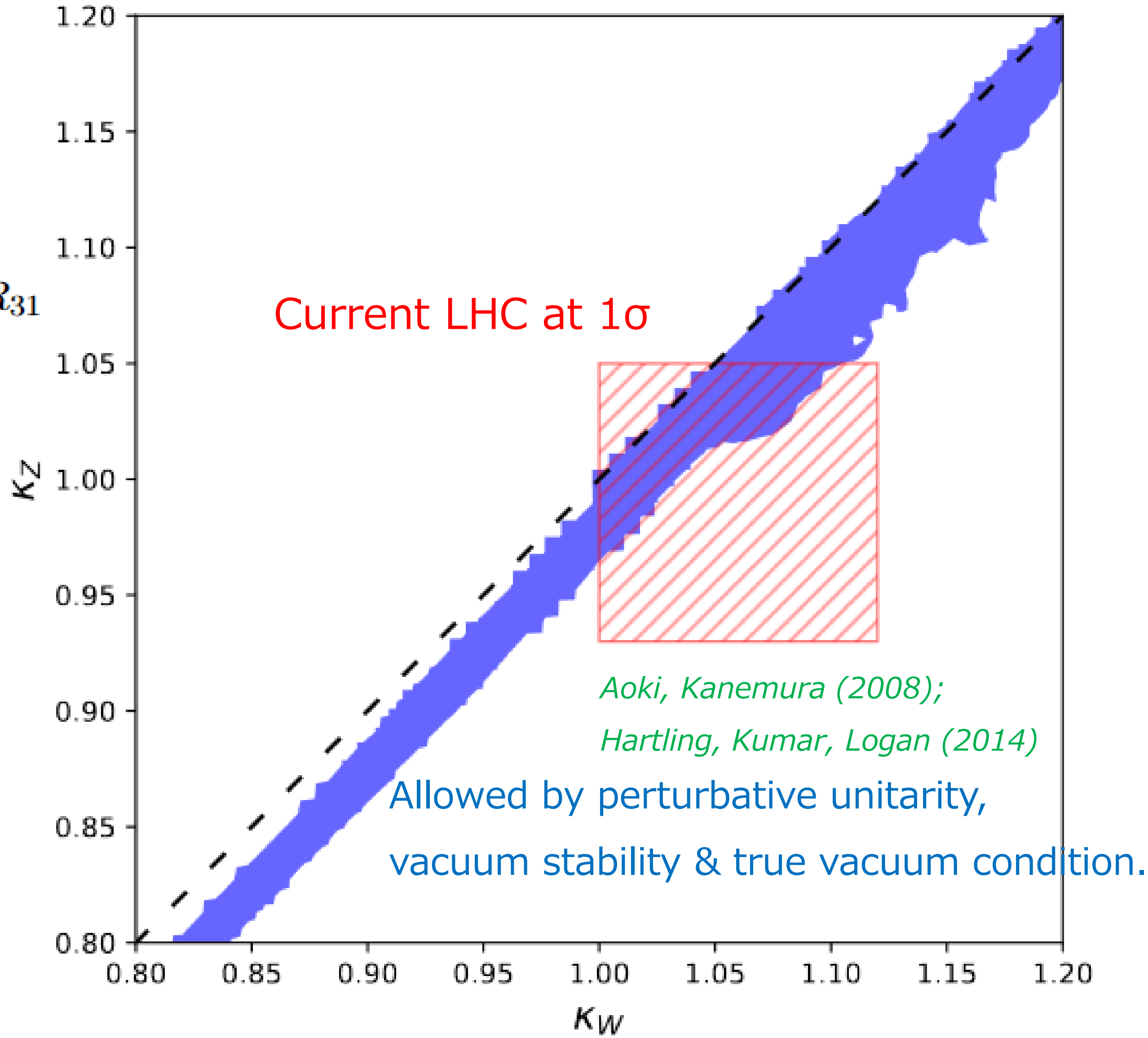
$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}}$$

$$\kappa_W = \frac{v_\Phi}{v} R_{11} + 4\frac{v_\xi}{v} R_{21} + 2\sqrt{2}\frac{v_\chi}{v} R_{31}$$

$$\kappa_Z = \frac{v_\Phi}{v} R_{11} + 4\sqrt{2}\frac{v_\chi}{v} R_{31}$$

$$\begin{pmatrix} h_\phi \\ h_\xi \\ h_\chi \end{pmatrix} = R \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

T.-K. Chen, C.-W. Chiang, KY, 2204.12898 [hep-ph]

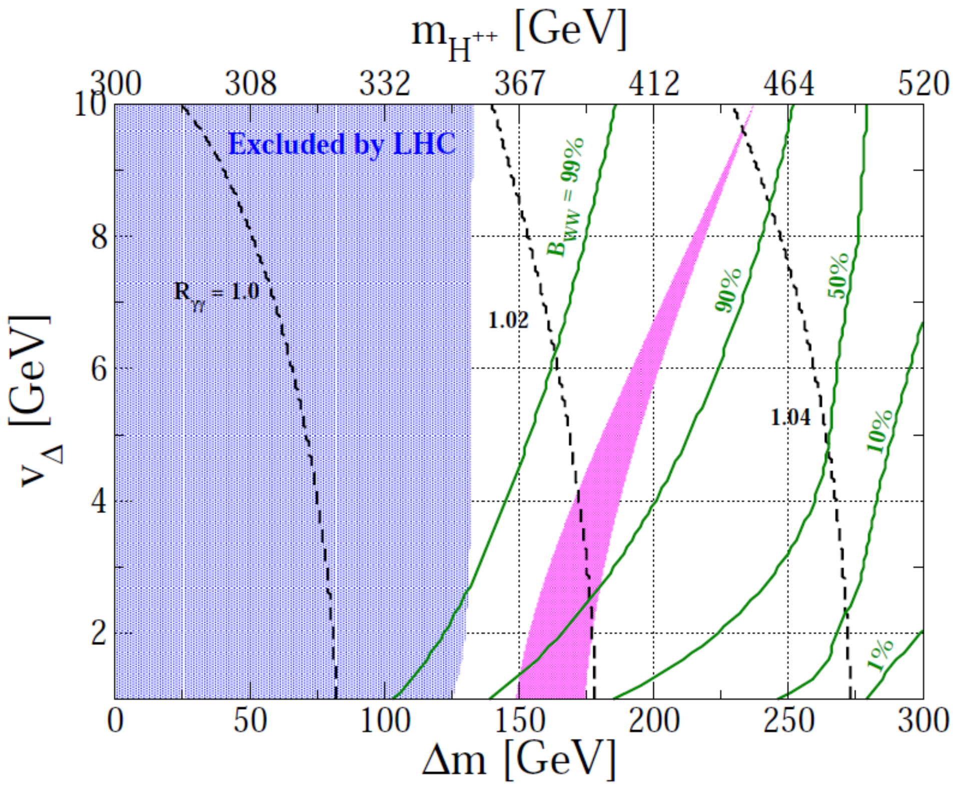


$\kappa_W \gtrsim \kappa_Z$ is predicted, which is favored by the current measurement at LHC.

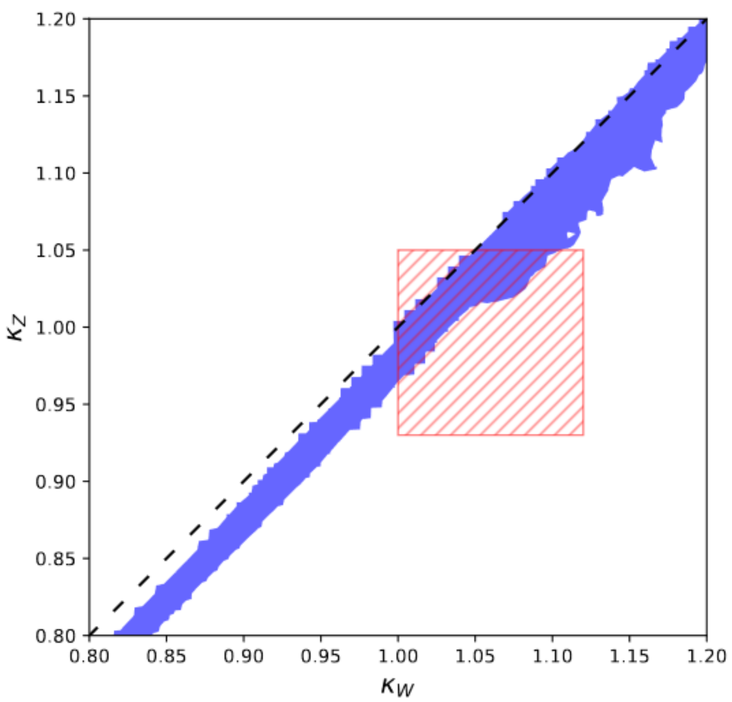
Summary

- W mass anomaly at CDF II can be explained in models with triplets.

Higgs Triplet Model



Georgi-Machacek Model



Backup

Conditions

$$57.7\ \text{MeV} \leq \Delta m_W \leq 95.3\ \text{MeV}.$$

$$|\Delta\rho| \leq 1.8 \times 10^{-3}, \quad |\Delta s^2_{\text{eff}}| \leq 6.6 \times 10^{-4}, \quad |\Delta\Gamma_{\text{lep}}| \leq 0.17\ \text{MeV}.$$

Kanemura, Okada, Taniguchi, Tsumura (2011)

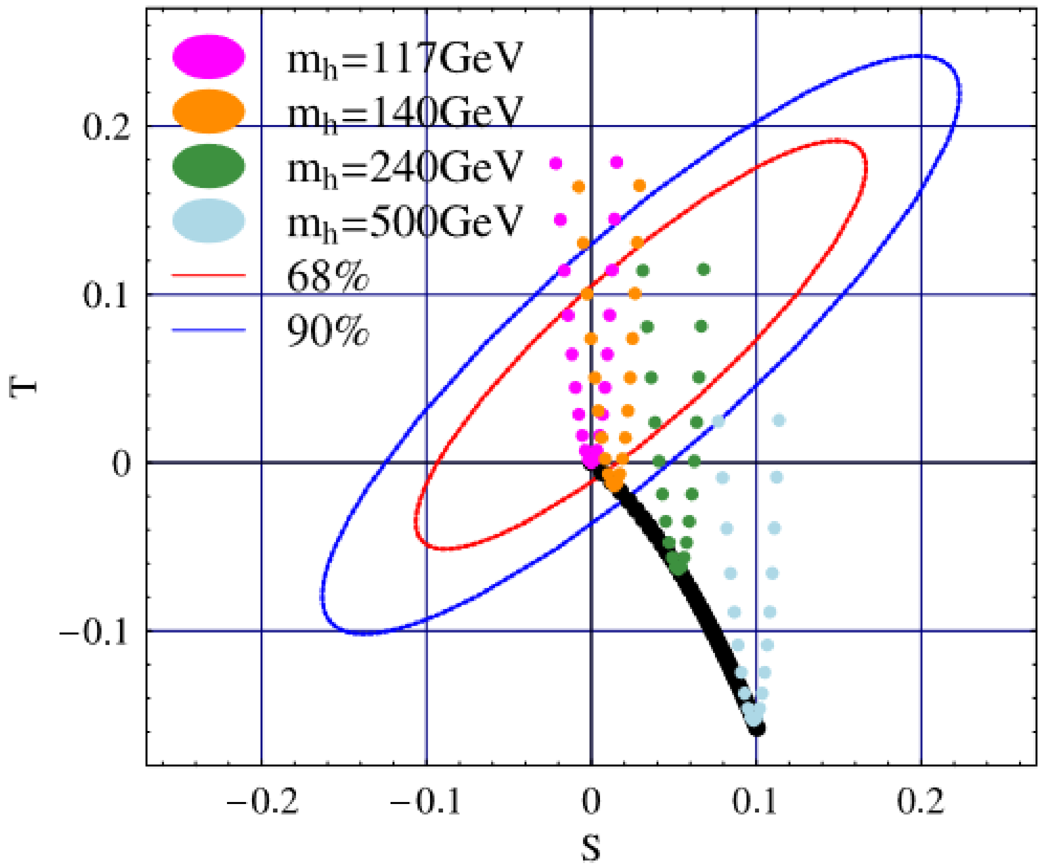


FIG. 1: The χ^2 analysis in the (S, T) plane is shown in the THDM where the SM-like Higgs boson is taken to be 117, 140, 240 and 500 GeV, with the SM-like limit $\sin(\beta - \alpha) = 1$ and $m_{H^\pm} = 300$ GeV. The mass of heavy neutral Higgs bosons $m_A = m_H$ is varied from 200 GeV to 400 GeV by the 10 GeV step (dots: from left to right). Ellipses correspond to electroweak precision limits with 68% ($\sqrt{2.30}\sigma$) and 90% ($\sqrt{4.61}\sigma$) confidence level.

Higgs potential in the HTM

$$V = m^2\Phi^\dagger\Phi + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + [\mu\Phi^T i\tau_2\Delta^\dagger\Phi + \mathrm{h.c.}]$$
$$+\lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\mathrm{Tr}\left[(\Delta^\dagger\Delta)^2\right] + \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi.$$

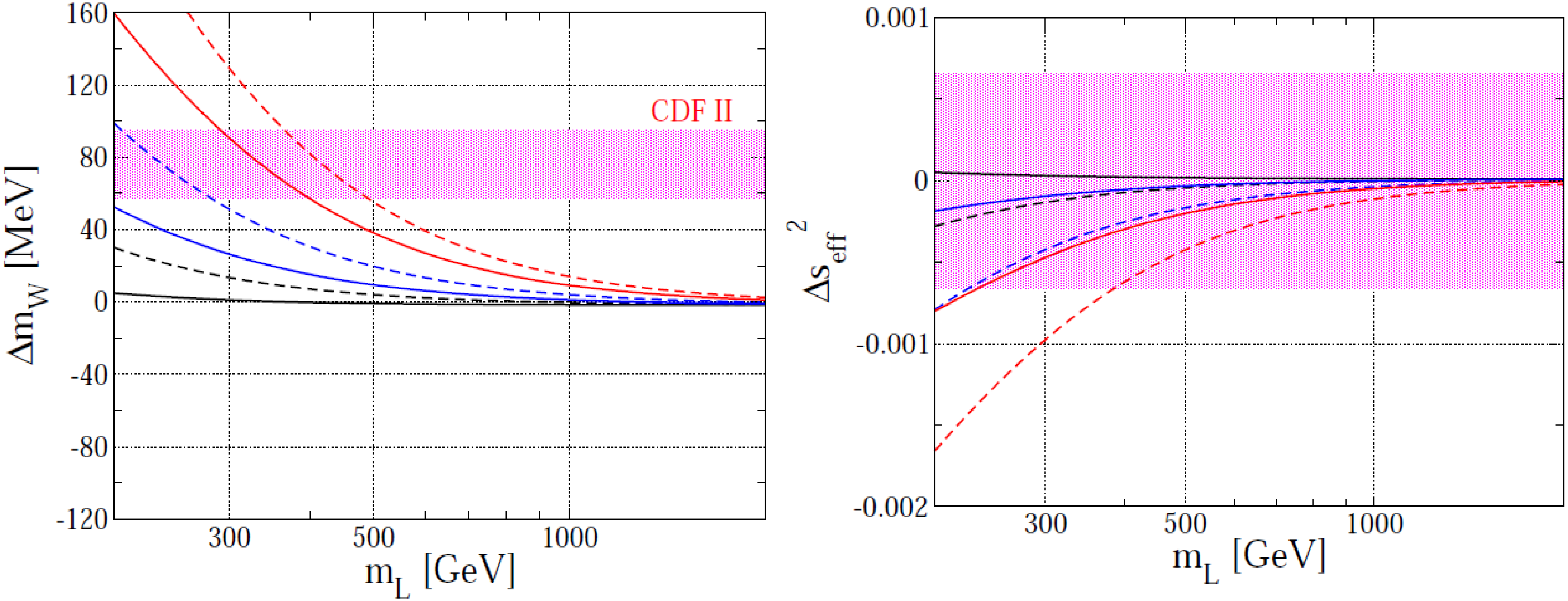
- In the limit $v_\Delta \to 0$ ($\mu \to 0$), a global U(1) symmetry (= lepton #) is restored.
  Then, H^0 and A^0 are degenerate in mass.

- In this case, triplet-like Higgs masses are determined by M and λ_5.
  The masses of H^{++}, H^+, H^0 and A^0 are determined by the squared mass difference and the lightest triplet-like Higgs mass.

$$m^2_{H^{\pm\pm}} - m^2_{H^\pm} = m^2_{H^\pm} - m^2_{H^0} = -\frac{\lambda_5 v^2}{4} \qquad m^2_{H^0} = m^2_{A^0}$$

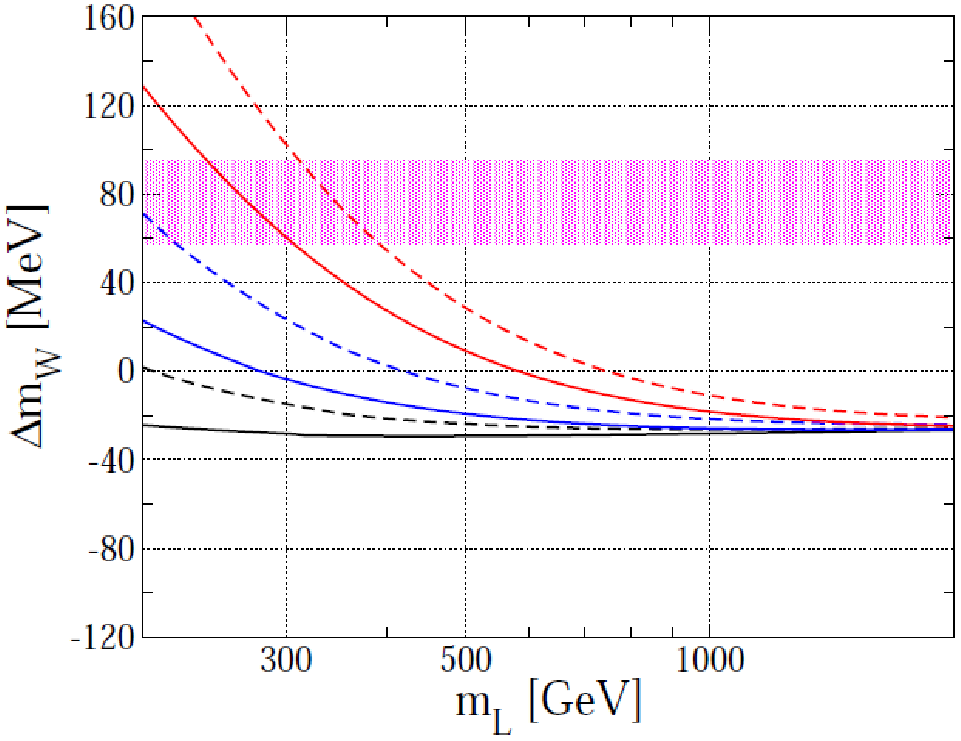
- In the limit $\lambda_5 \to 0$, a global SU(2) symmetry ($\Delta \to U^\dagger\Delta U$) is restored.
  All the triplet-like Higgs bosons are degenerate in mass.

v_Δ = 1 GeV

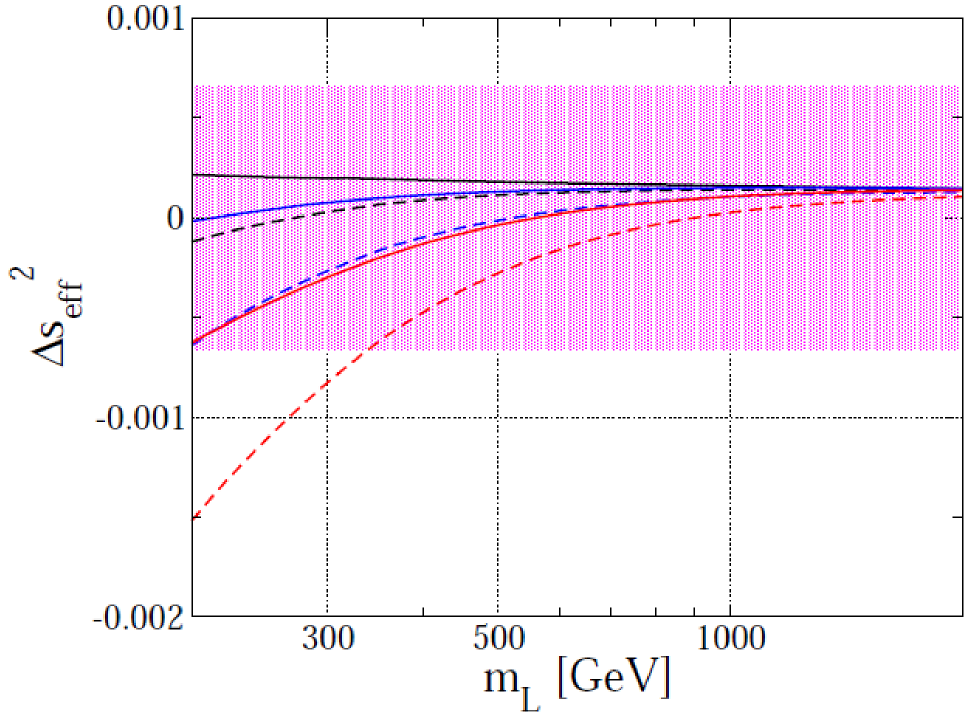


160
120
80
40
0
-40
-80
-120
Δm_W [MeV]
CDF II
300
500
1000
m_L [GeV]
0.001
0
-0.001
-0.002
Δs^2_{eff}
300
500
1000
m_L [GeV]

v_Δ = 4 GeV



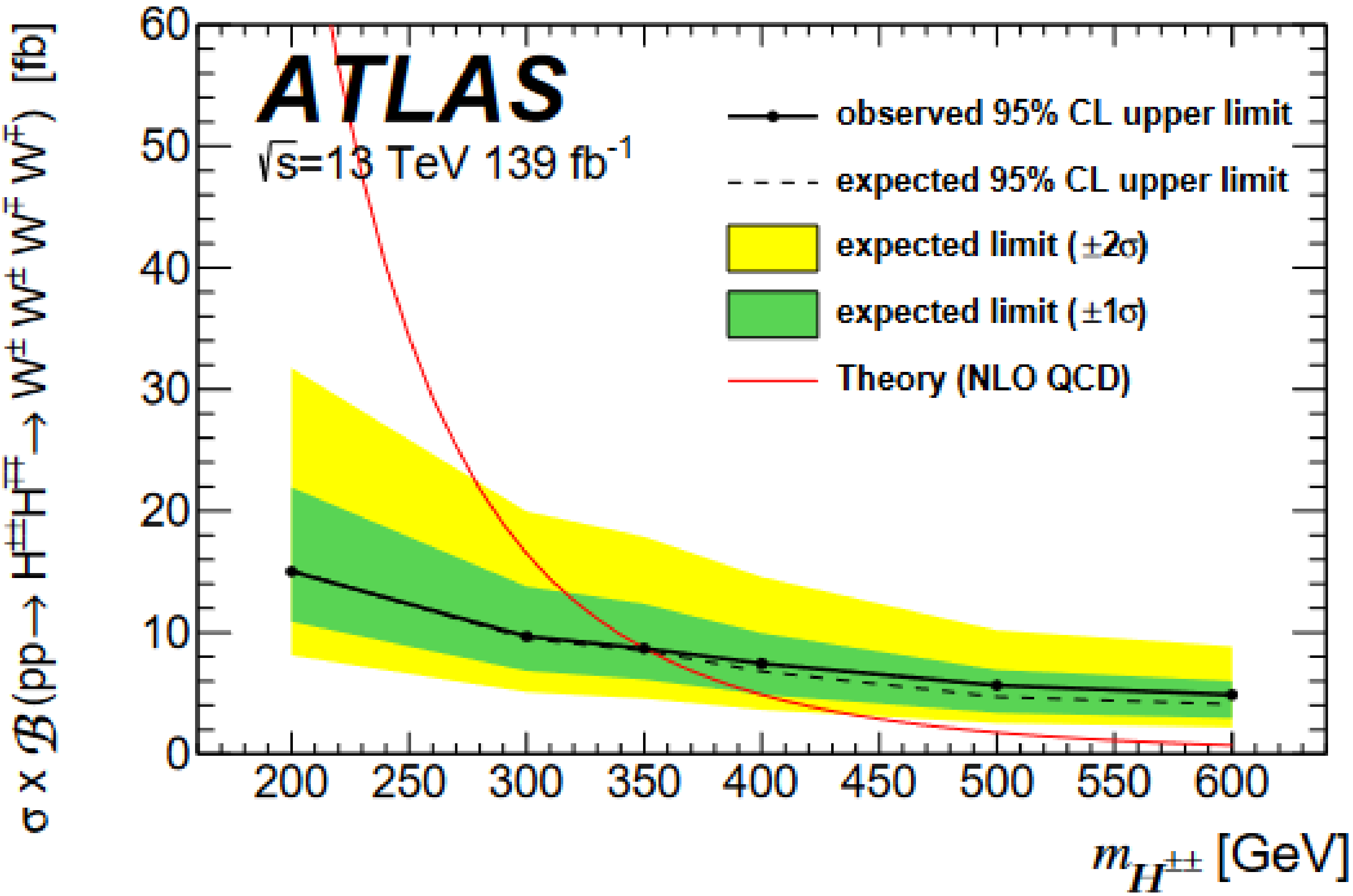
160
120
80
40
0
-40
-80
-120
Δm_W [MeV]
300
500
1000
m_L [GeV]

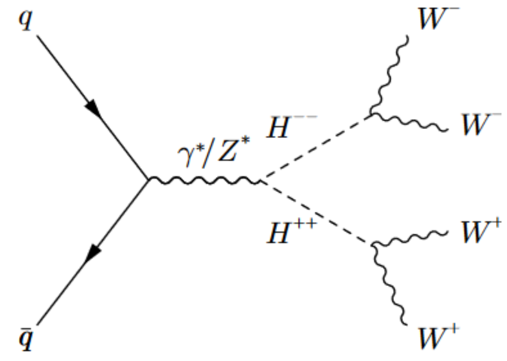


0.001
0
-0.001
-0.002
Δs_eff^2
300
500
1000
m_L [GeV]

Constraint from the diboson decay of $H^{\pm\pm}$

2101.11961 [hep-ex] (ATLAS)



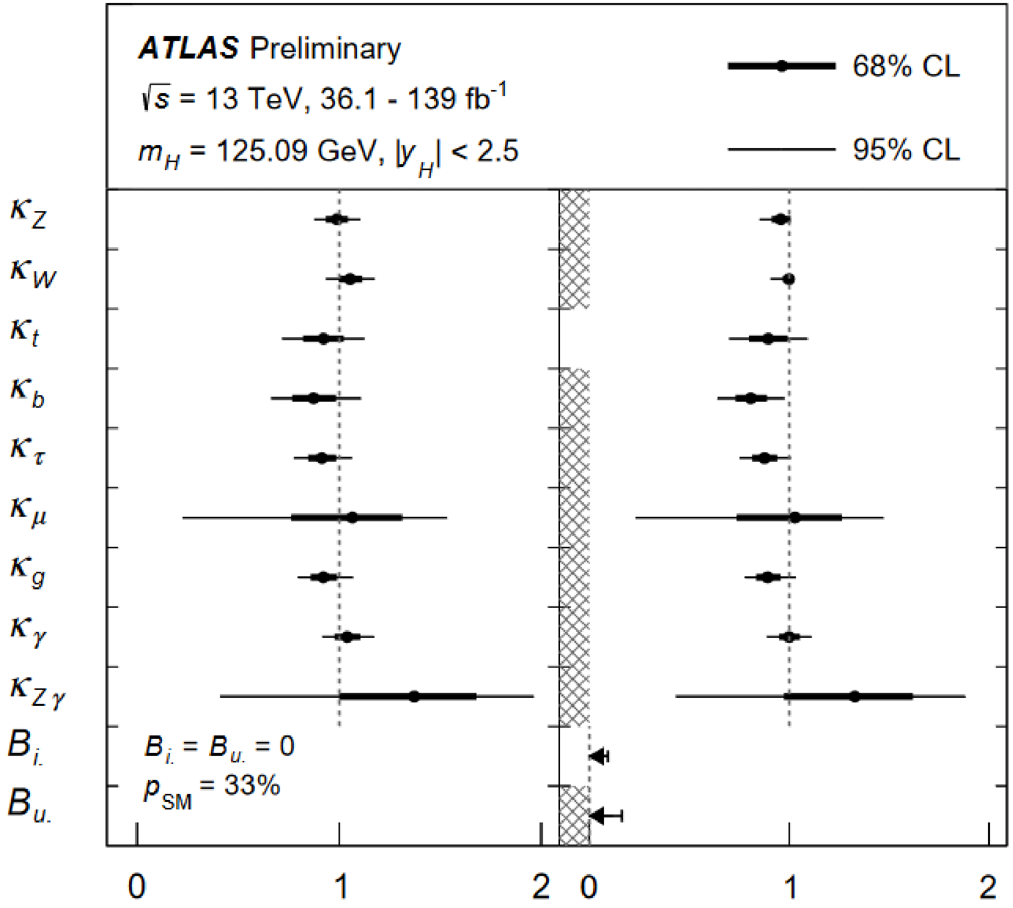


Higgs potential in the GM model

$$
\begin{aligned}
V_{\rm cust} =& m_\Phi^2 {\rm tr}(\Phi^\dagger\Phi) + m_\Delta^2 {\rm tr}(\Delta^\dagger\Delta) + \lambda_1[{\rm tr}(\Phi^\dagger\Phi)]^2 + \lambda_2[{\rm tr}(\Delta^\dagger\Delta)]^2 + \lambda_3{\rm tr}[(\Delta^\dagger\Delta)^2] \\
&+ \lambda_4{\rm tr}(\Phi^\dagger\Phi){\rm tr}(\Delta^\dagger\Delta) + \lambda_5{\rm tr}\left(\Phi^\dagger\frac{\tau^a}{2}\Phi\frac{\tau^b}{2}\right){\rm tr}(\Delta^\dagger t^a\Delta t^b) \\
&+ \mu_1{\rm tr}\left(\Phi^\dagger\frac{\tau^a}{2}\Phi\frac{\tau^b}{2}\right)(P^\dagger\Delta P)^{ab} + \mu_2{\rm tr}\left(\Delta^\dagger t^a\Delta t^b\right)(P^\dagger\Delta P)^{ab},
\end{aligned}
$$

$$
P = \begin{pmatrix} -1/\sqrt{2} & i/\sqrt{2} & 0 \\ 0 & 0 & 1 \\ 1/\sqrt{2} & i/\sqrt{2} & 0 \end{pmatrix}
$$

$$
V = V_{\rm cust}|_{m_\Delta\to 0} + \frac{m_\xi^2}{2}\xi^\dagger\xi + m_\chi^2\chi^\dagger\chi,
$$


ATLAS Preliminary
√s = 13 TeV, 36.1 - 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
68% CL
95% CL
κZ
κW
κt
κb
κτ
κμ
κg
κγ
κZγ
Bi.
Bu.
Bi. = Bu. = 0
pSM = 33%
0
1
2
0
1
2