Consistency of Gauged Two Higgs Doublet Model: Gauge Sector

14th workshop on TeV Physics – NNU Nanjing

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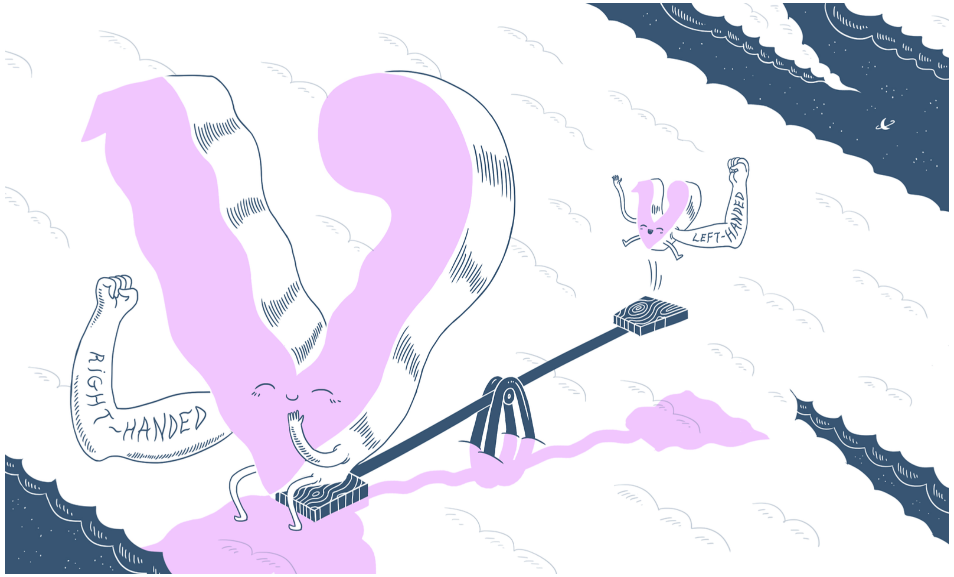
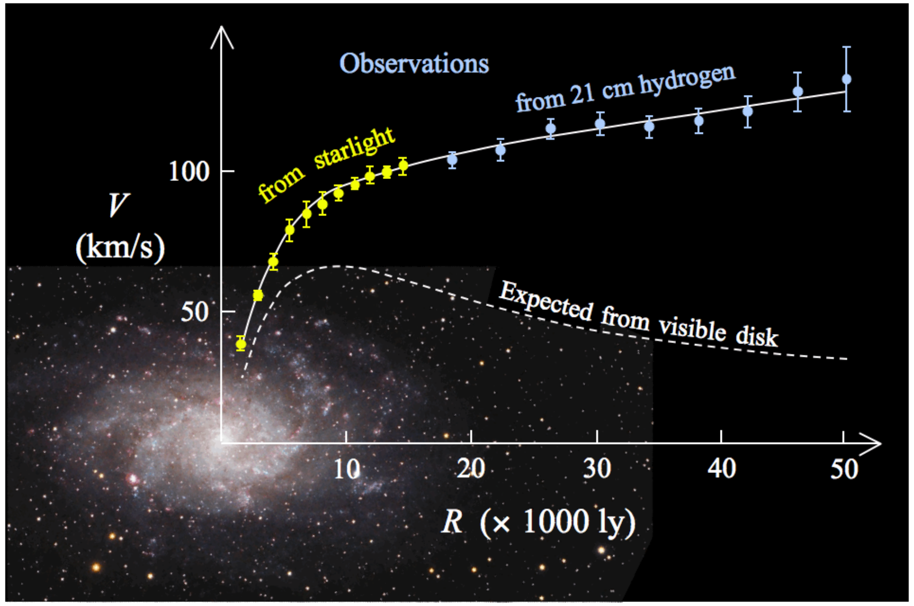
Challenges within SM 

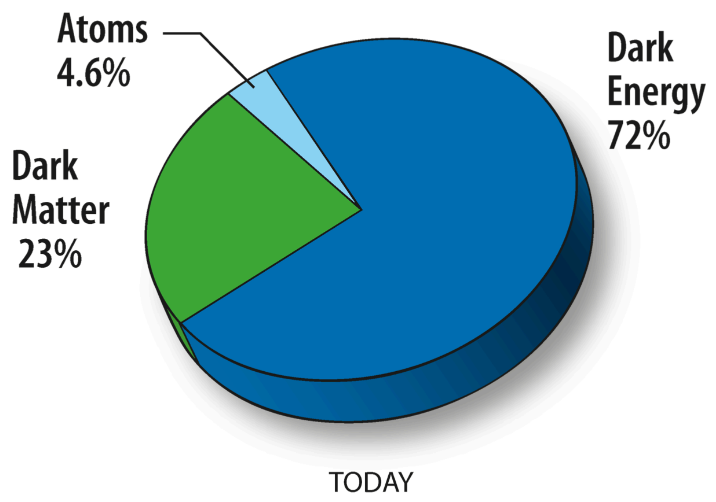
- What is origin of DM?
- What is the origin of neutrino mass?, Why are they so light?
- Etc.



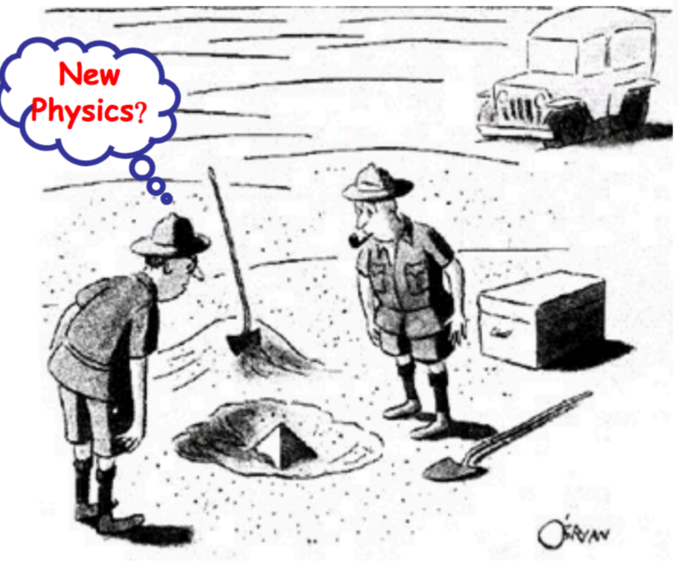
Credit: symmetrymagazine.org



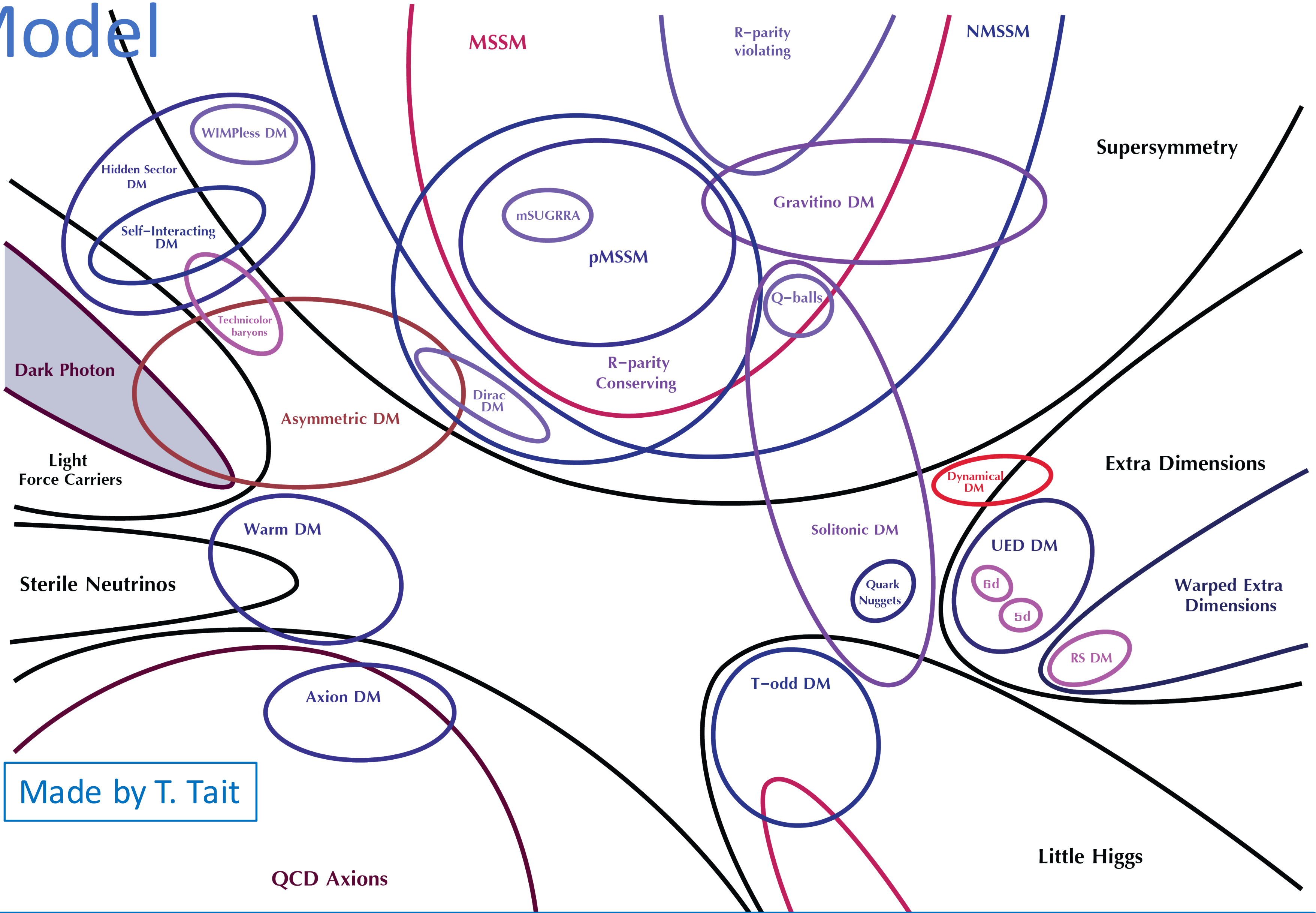
Rotation curve of spiral galaxy M33



New Physics Model



This could be the greatest discovery of the century. Depending, of course, on how far down it goes.



Made by T. Tait

The Gauged Two Higgs Doublet Model (G2HDM) *(Huang et al. 2016)*

Some interesting features of G2HDM

- It was motivated by the iHDM of DM.
- Inert Higgs, DM candidate, is protected by the gauge invariance instead of ad-hoc Z_2 symmetry.
- Neutrino has Dirac mass.
- It is anomaly free and naturally absence of FCNC at tree level.
- Unlike Left-Right symmetric models, the complex vector fields $W'^{(p,m)}$ are electrically neutral.

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Matter content

- H_1, H_2 are embedded into $SU(2)_H$.
- ϕ_H is introduced to gives a Dirac mass to heavy fermions.
- Triplet Higgs Δ_H VEV will contribute to the mass of charge Higgs mass.
- $SU(2)_L$ doublet fermions are singlets under $SU(2)_H$, while $SU(2)_L$ singlet fermions pair up with heavy fermions as $SU(2)_H$ doublets.

Anomaly free!

Matter Fields	$SU(3)_C$	$SU(2)_L$	$SU(2)_H$	$U(1)_Y$	$U(1)_X$
$H = (H_1\,,\,H_2)^T$	1	2	2	1/2	1
$\Phi_H = (\Phi_1\,,\,\Phi_2)^T$	1	1	2	0	1
$\Delta_H = \begin{pmatrix} \Delta_3/2 & \Delta_p/\sqrt{2} \\ \Delta_m/\sqrt{2} & -\Delta_3/2 \end{pmatrix}$	1	1	3	0	0
$Q_L = (u_L\,,\,d_L)^T$	3	2	1	1/6	0
$U_R = (u_R\,,\,u_R^H)^T$	3	1	2	2/3	1
$D_R = (d_R^H\,,\,d_R)^T$	3	1	2	−1/3	−1
u_L^H	3	1	1	2/3	0
d_L^H	3	1	1	−1/3	0
$L_L = (\nu_L\,,\,e_L)^T$	1	2	1	−1/2	0
$N_R = (\nu_R\,,\,\nu_R^H)^T$	1	1	2	0	1
$E_R = (e_R^H\,,\,e_R)^T$	1	1	2	−1	−1
ν_L^H	1	1	1	0	0
e_L^H	1	1	1	−1	0

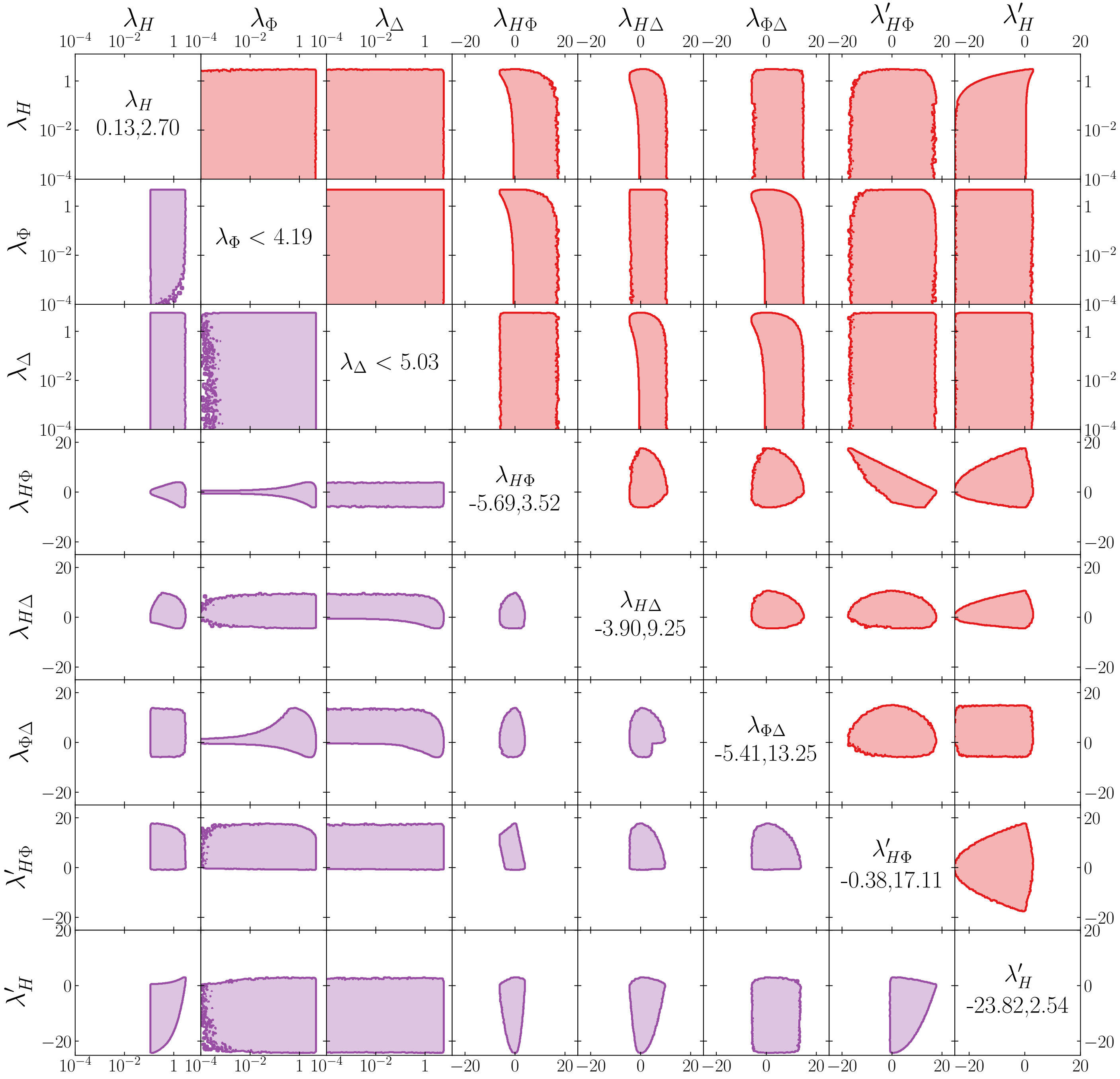
TABLE I. Matter field contents and their quantum number assignments in G2HDM.

Huang, Tsai, Yuan 1708.02355

Consistency of scalar sector

- Vacuum stability (VS),
- Perturbative unitarity (PU)
- Higgs boson mass
- Signal strengths of Higgs boson decays into diphoton and $\tau^+\tau^-$ from the LHC

A. Arhrib, W. C. Huang, R. Ramos, Y. L. S. Tsai & T. C. Yuan 1806.05632



Gauge sector

- New gauge group: $SU(2)_H \otimes U(1)_X$

- The SM W bosons acquire a mass by eating the charged components of H_1 as in the SM since H_2 does not get VEV and other scalars (Φ_H and Δ_H) are neutral.

$$M_{W^\pm} = \frac{1}{2} g v \; ,$$

- $SU(2)_H$ W' bosons receive a mass from all VEVs $\langle H_1 \rangle, \langle \Phi_2 \rangle$ and $\langle \Delta_3 \rangle$.

$$m^2_{W'(p,m)} = \frac{1}{4} g_H^2 \left(v^2 + v_\Phi^2 + 4 v_\Delta^2 \right) \; ,$$

Gauge sector

- $\langle H_1 \rangle$ also gives mass to W'^3 and X boson because of their quantum number. Hence W'^3 and X mix with SM gauge boson W^3 and Y.

$$\mathcal{M}^2_{\text{gauge}} = \begin{pmatrix} \frac{g'^2 v^2}{4} & -\frac{g' g v^2}{4} & \frac{g' g_H v^2}{4} & \frac{g' g_X v^2}{2} \\ -\frac{g' g v^2}{4} & \frac{g^2 v^2}{4} & -\frac{g g_H v^2}{4} & -\frac{g g_X v^2}{2} \\ \frac{g' g_H v^2}{4} & -\frac{g g_H v^2}{4} & \frac{g_H^2 \left(v^2 + v_\Phi^2\right)}{4} & \frac{g_H g_X \left(v^2 - v_\Phi^2\right)}{2} \\ \frac{g' g_X v^2}{2} & -\frac{g g_X v^2}{2} & \frac{g_H g_X \left(v^2 - v_\Phi^2\right)}{2} & g_X^2 \left(v^2 + v_\Phi^2\right) \end{pmatrix}$$

in the interaction basis of (B, W^3, W'^3, X). Here $g_H (g_X)$ is the $SU(2)_H$ ($U(1)_X$) gauge coupling constant and v (v_ϕ) is VEV of H_1 (Φ_H). Their mass eigenstates are denoted as (A, Z, Z', Z'')

- It turns out dark photon has massless which might not be phenomenologically desirable. One can use Stueckelberg Lagrangian to give mass for the dark photon.

$$\mathcal{L}_{\text{Stu}} = +\frac{1}{2}\left(\partial_\mu a + M_X X_\mu + M_Y B_\mu\right)^2 \ ,$$

B. Kors and P. Nath 2004, 2005

Parameter set-up

$$10^{-8} \leq g_H \leq g^{\mathtt{SM}},$$

$$10^{-8} \leq g_X \leq g_1'^{\mathtt{SM}},$$

$$5 \text{ TeV} \leq v_\Phi \leq 200 \text{ TeV} ,$$

$$M_Y = 0 .$$

$$\text{Heavy } M_X : \quad M_X \in [0.1 : 10] \, (\text{TeV}) ,$$

$$\text{Light } M_X : \quad M_X \in \left[10^{-3} : 80\right] (\text{GeV}) .$$

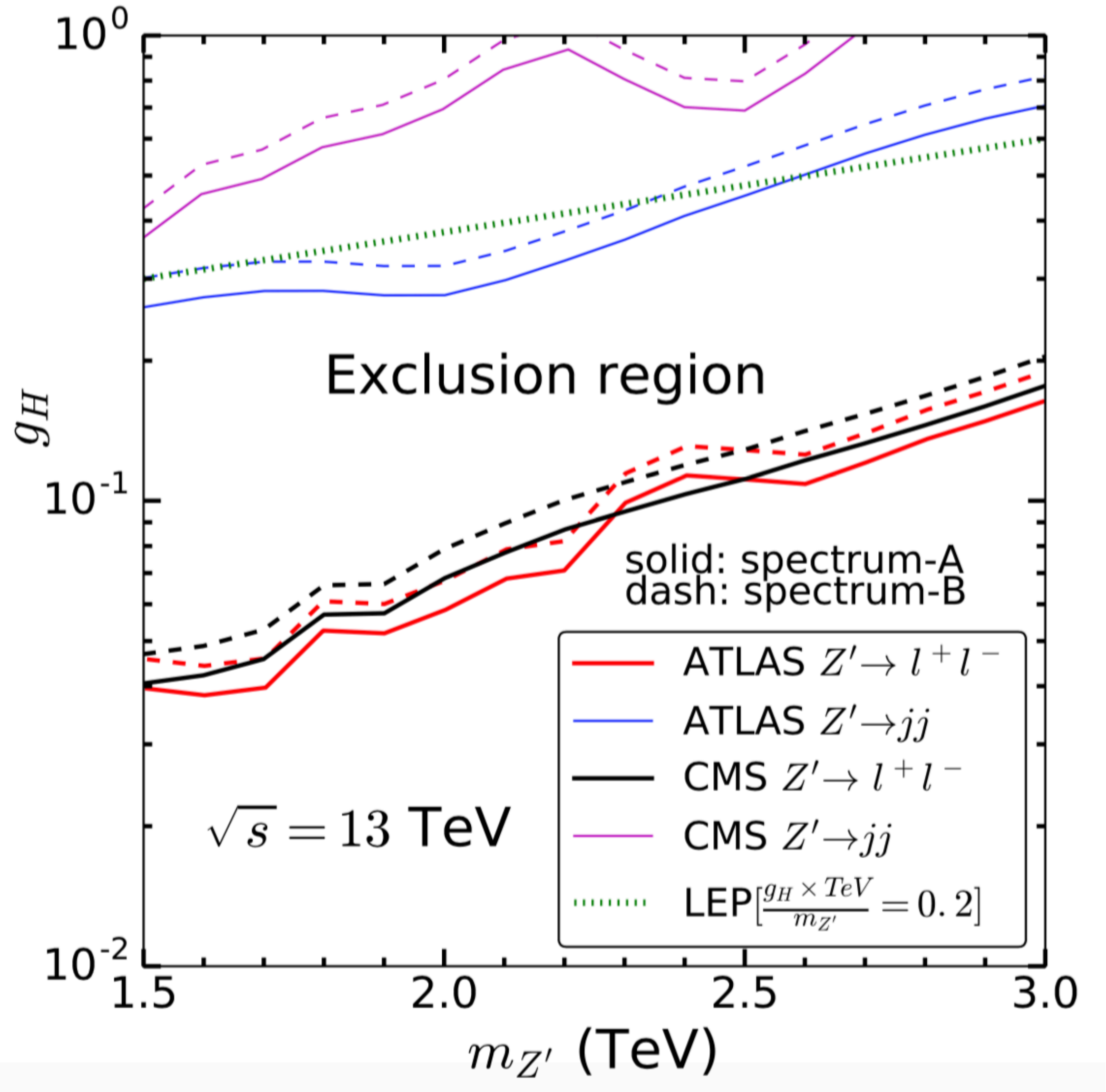
LHC constraint

Direct Z′ resonance search at the ATLAS and CMS 13 TeV.

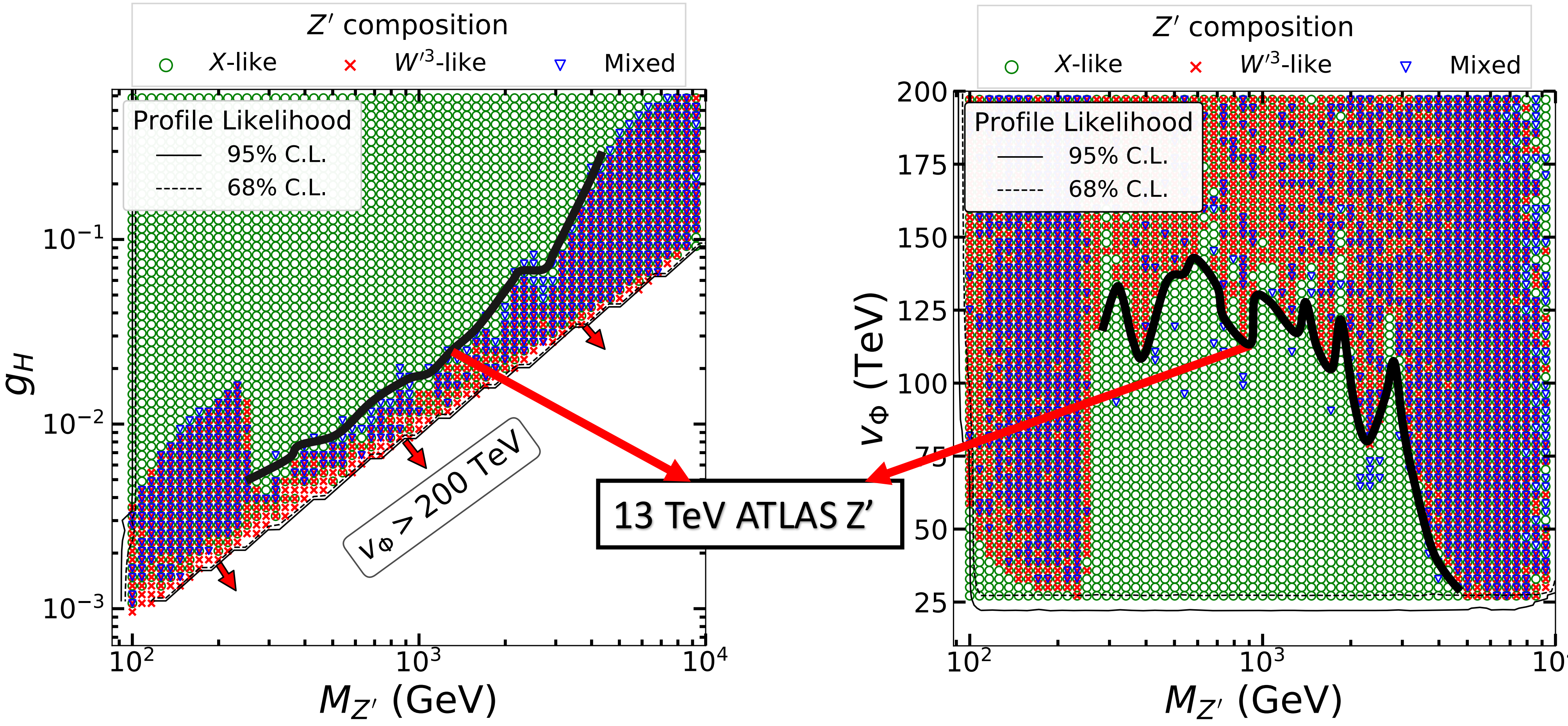
$$m_{Z'}^2 \approx \frac{1}{4} g_H^2 \left(v^2 + v_\Phi^2\right)$$

$$g_H = 0.1 \rightarrow v_\Phi > 50\ TeV$$

W. C. Huang, H. Ishida, C. T. Lu, Y. L. S. Tsai and T. C. Yuan 1708.02355

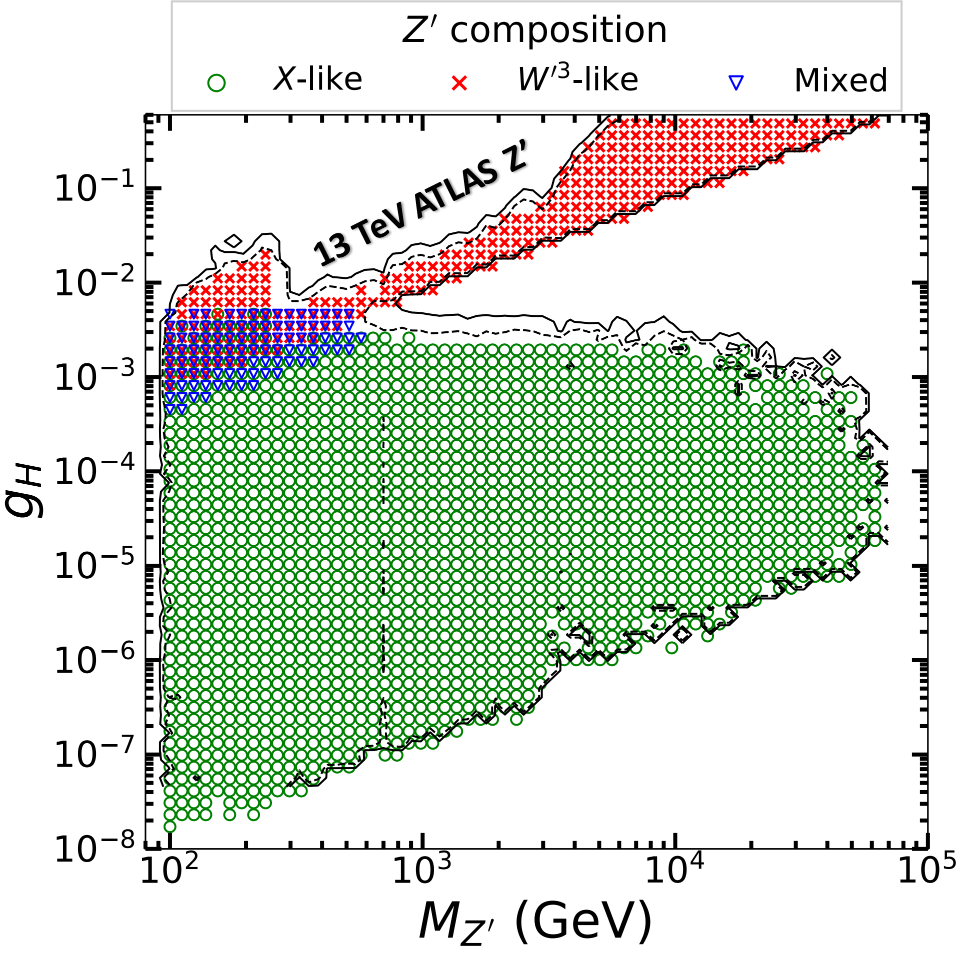


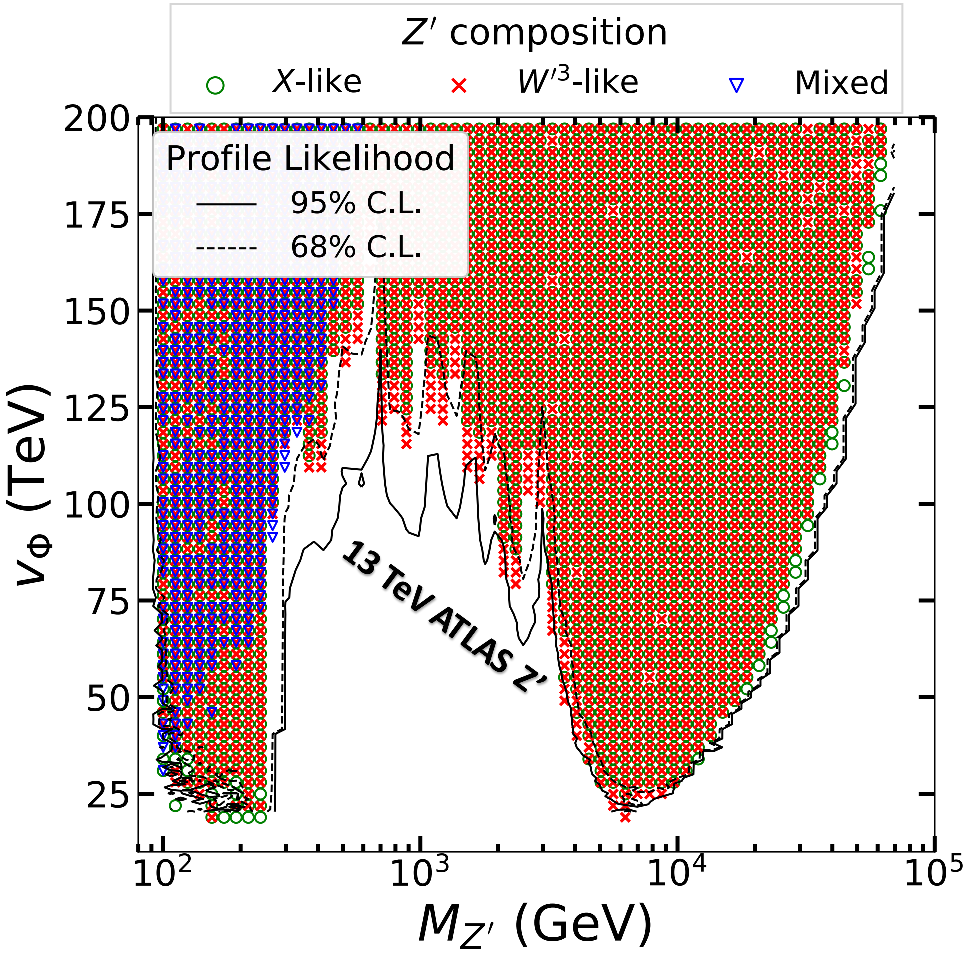
LEP+LHC constraints: Heavy M_X Scenario



- LHC gives the most stringent constraint on g_H and v_ϕ in case of W'^3-like but not X-like.
- It turns out v_ϕ is very sensitive to LEP+LHC data constraints, $v_\phi >$ 23 TeV at 95% CL.

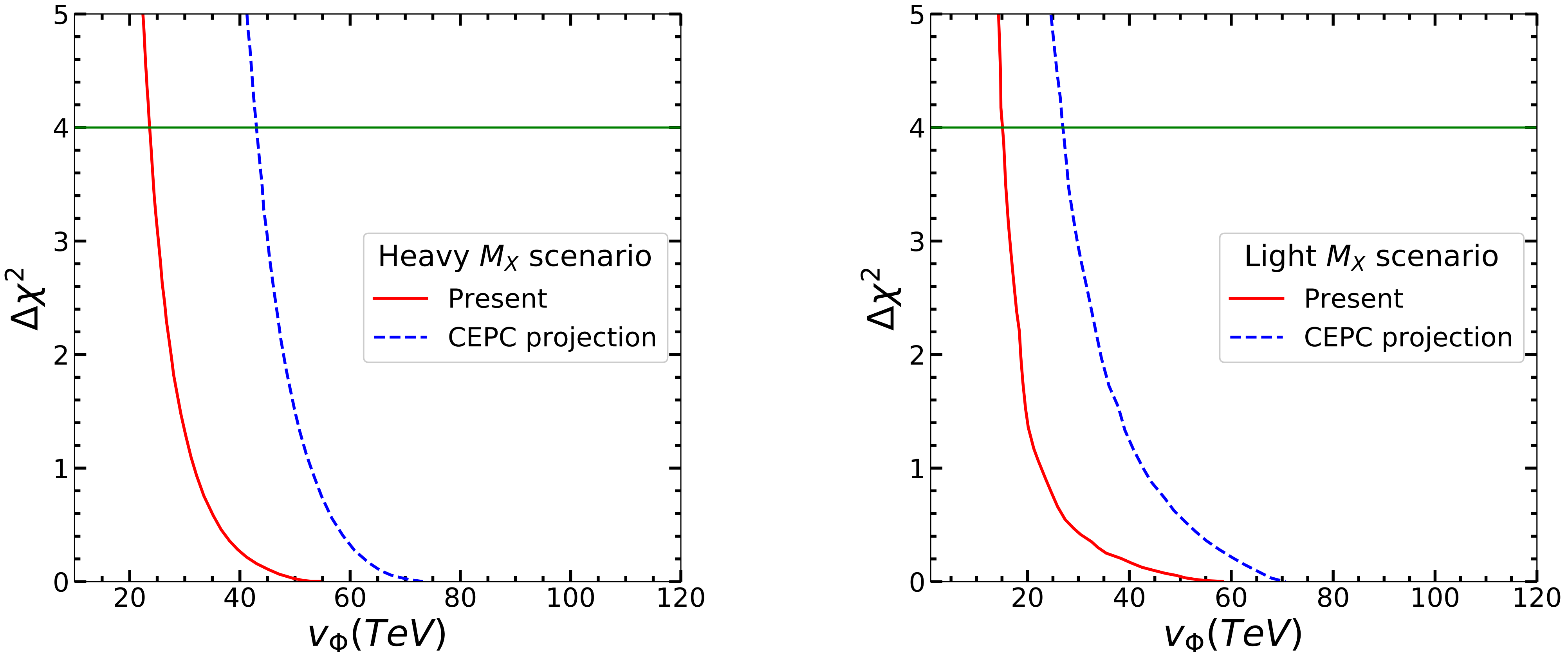
LEP+LHC constraints: Light M_X Scenario





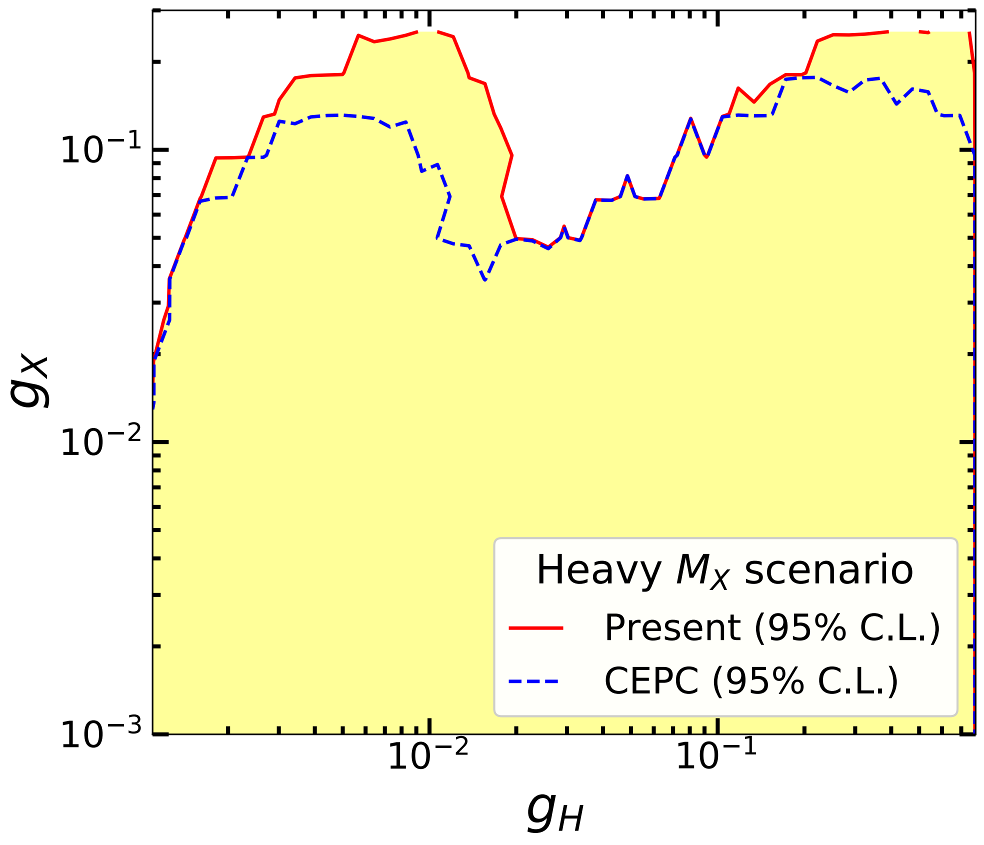
- LHC gives the most stringent constraint on g_H and v_ϕ in both cases of W'^3-like and X-like.

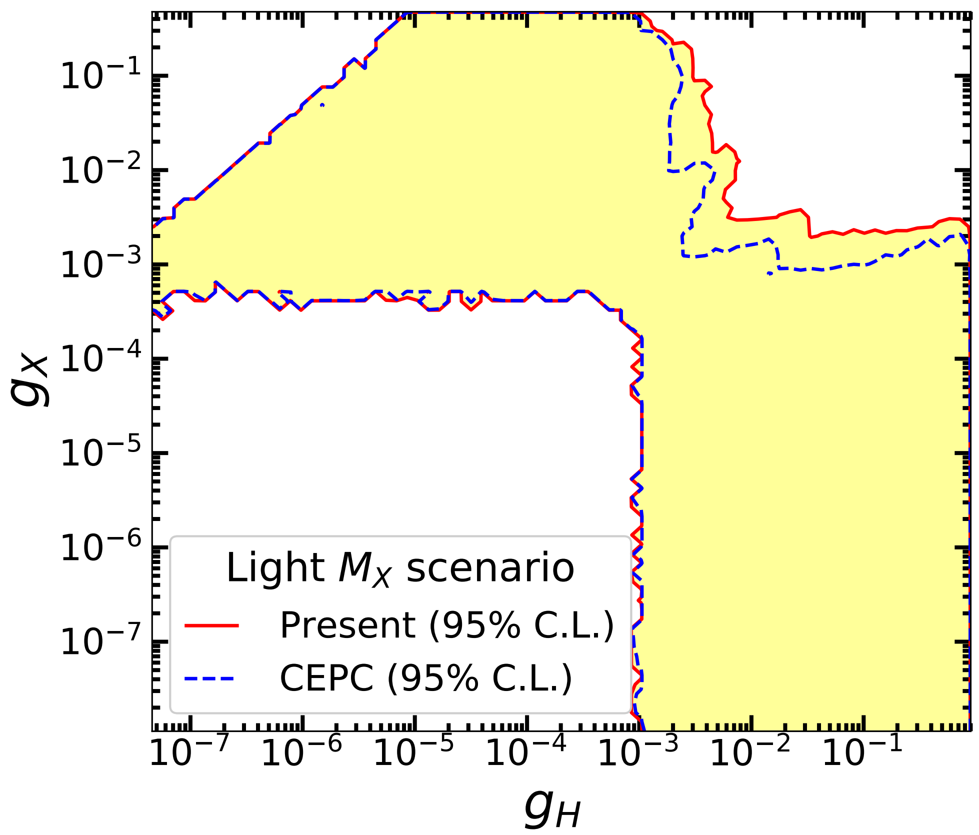
CEPC sensitivity



- CEPC puts a significant improvement on the lower bound of v_ϕ (45 TeV for heavy M_X scenario, 36 TeV for light M_X scenario at 95% CL).
- Heavy M_X scenario is more sensitive than light M_X scenario.

CEPC sensitivity





- New gauge couplings are not really sensitive at CEPC.

Conclusion

- G2HDM not only addresses to the DM but also neutrino mass issue.
- Without resorting to an ad-hoc Z_2 symmetry, an inert Higgs doublet H_2 can be naturally realized, providing a DM candidate.
- The constraints on the new parameters in the gauge sector of G2HDM is studied by using EWPT data collected from LEP at and off the Z-pole as well as current high-mass dilepton resonance search from the LHC.
- Projected sensitivities of the new parameters at the CEPC proposed to be built in China are also discussed.

Thank You

Back up

Yukawa interaction

- SM quarks and lepton obtain their masses from the VEV of H1

$$\mathcal{L}_{\text{Yuk}} \supset + y_d \bar{Q}_L \left(d_R^H H_2 - d_R H_1\right) - y_u \bar{Q}_L \left(u_R \tilde{H}_1 + u_R^H \tilde{H}_2\right) + y_e \bar{L}_L \left(e_R^H H_2 - e_R H_1\right) - y_\nu \bar{L}_L \left(\nu_R \tilde{H}_1 + \nu_R^H \tilde{H}_2\right) + \text{H.c.}\,,$$

SM SM SM

Dirac neutrino mass

Absence of FCNC interactions at tree level naturally!

Higgs potential

The most general Higgs potential which invariant under both $SU(2)_L \times U(1)_Y$ and $SU(2)_H \times U(1)_X$ can be written down as follows

$$V_T = V(H) + V(\Phi_H) + V(\Delta_H) + V_{\text{mix}}(H, \Delta_H, \Phi_H)$$

Where

$$V(H) = \mu_H^2 \left(H^{\alpha i} H_{\alpha i}\right) + \lambda_H \left(H^{\alpha i} H_{\alpha i}\right)^2 + \frac{1}{2}\lambda_H' \varepsilon_{\alpha\beta}\varepsilon^{\gamma\delta}\left(H^{\alpha i} H_{\gamma i}\right)\left(H^{\beta j} H_{\delta j}\right)$$

$$V(\Phi_H) = \mu_\Phi^2 \Phi_H^\dagger \Phi_H + \lambda_\Phi \left(\Phi_H^\dagger \Phi_H\right)^2$$

$$V(\Delta_H) = -\mu_\Delta^2 \mathrm{Tr}\left(\Delta_H^2\right) + \lambda_\Delta \left(\mathrm{Tr}\left(\Delta_H^2\right)\right)^2$$

Higgs potential

$$V_{\text{mix}}(H,\Delta_H,\Phi_H) = +M_{H\Delta}\left(H^\dagger\Delta_H H\right) - M_{\Phi\Delta}\left(\Phi_H^\dagger\Delta_H\Phi_H\right)$$
$$+\lambda_{H\Phi}\left(H^\dagger H\right)\left(\Phi_H^\dagger\Phi_H\right) + \lambda'_{H\Phi}\left(H^\dagger\Phi_H\right)\left(\Phi_H^\dagger H\right)$$
$$+\lambda_{H\Delta}\left(H^\dagger H\right)\mathrm{Tr}\left(\Delta_H^2\right) + \lambda_{\Phi\Delta}\left(\Phi_H^\dagger\Phi_H\right)\mathrm{Tr}\left(\Delta_H^2\right) .$$

Note that term like $\Phi_H^T\epsilon\Delta_H\Phi_H$ is $SU(2)_H$ invariant but forbidden by $U(1)_X$!

Spontaneous symmetry breaking

Let parametrize the fields as

$$H_1 = \begin{pmatrix} G^+ \\ \frac{v+h}{\sqrt{2}} + i\frac{G^0}{\sqrt{2}} \end{pmatrix}, H_2 = \begin{pmatrix} H^+ \\ H_2^0 \end{pmatrix}, \Phi_H = \begin{pmatrix} G_H^p \\ \frac{v_\Phi+\phi_2}{\sqrt{2}} + i\frac{G_H^0}{\sqrt{2}} \end{pmatrix}, \Delta_H = \begin{pmatrix} \frac{-v_\Delta+\delta_3}{2} & \frac{1}{\sqrt{2}}\Delta_p \\ \frac{1}{\sqrt{2}}\Delta_m & \frac{v_\Delta-\delta_3}{2} \end{pmatrix}$$

where v, v_Φ and v_Δ are VEVs to be determined by minimization of the potential. The set $\Psi_G \equiv \{G^0, G^+, G_H^0, G_H^p\}$ are Goldstone bosons.

$$\begin{aligned} V_T(v, v_\Delta, v_\Phi) &= \frac{1}{4}\Big[\lambda_H v^4 + \lambda_\Phi v_\Phi^4 + \lambda_\Delta v_\Delta^4 + 2\left(\mu_H^2 v^2 + \mu_\Phi^2 v_\Phi^2 - \mu_\Delta^2 v_\Delta^2\right) \\ &\quad - \left(M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) v_\Delta + \lambda_{H\Phi} v^2 v_\Phi^2 + \lambda_{H\Delta} v^2 v_\Delta^2 + \lambda_{\Phi\Delta} v_\Phi^2 v_\Delta^2\Big] \end{aligned}$$

Spontaneous symmetry breaking

We will obtain the following equations by minimizing the potential

$$\begin{aligned}
\left(2\lambda_H v^2 + 2\mu_H^2 - M_{H\Delta} v_\Delta + \lambda_{H\Phi} v_\Phi^2 + \lambda_{H\Delta} v_\Delta^2\right) &= 0\,, \\
\left(2\lambda_\Phi v_\Phi^2 + 2\mu_\Phi^2 - M_{\Phi\Delta} v_\Delta + \lambda_{H\Phi} v^2 + \lambda_{\Phi\Delta} v_\Delta^2\right) &= 0\,, \\
4\lambda_\Delta v_\Delta^3 - 4\mu_\Delta^2 v_\Delta - M_{H\Delta} v^2 - M_{\Phi\Delta} v_\Phi^2 + 2 v_\Delta \left(\lambda_{H\Delta} v^2 + \lambda_{\Phi\Delta} v_\Phi^2\right) &= 0\,.
\end{aligned}$$

By solving this set of coupled equations, one can get solutions for v, v_Φ and v_Δ in terms of other parameters in the potential.

Scalar Mass Spectrum

First block in basis of $S = \{h, \phi_2, \delta_3\}$

$$\mathcal{M}_H^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H\Phi} v v_\Phi & \frac{v}{2}\left(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta\right) \\ \lambda_{H\Phi} v v_\Phi & 2\lambda_\Phi v_\Phi^2 & \frac{v_\Phi}{2}\left(M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta\right) \\ \frac{v}{2}\left(M_{H\Delta} - 2\lambda_{H\Delta} v_\Delta\right) & \frac{v_\Phi}{2}\left(M_{\Phi\Delta} - 2\lambda_{\Phi\Delta} v_\Delta\right) & \frac{1}{4v_\Delta}\left(8\lambda_\Delta v_\Delta^3 + M_{H\Delta} v^2 + M_{\Phi\Delta} v_\Phi^2\right) \end{pmatrix}$$

This matrix can be diagonalized by an orthogonal matrix O^H,

$$(O^H)^T \cdot \mathcal{M}_H^2 \cdot O^H = \mathrm{Diag}(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2)$$

- h_1 is identified as 125 GeV SM-like Higgs while h_2 and h_3 are heavier scalars
- Now the 125 GeV SM-like Higgs is mixture of $\{h, \phi_2, \delta_3\}$

Scalar Mass Spectrum

The second block is also 3×3. In the basis of $D = \{G_H^p, H_2^{0*}, \Delta_p\}$, it is given by

$$\mathcal{M}_D^2 = \begin{pmatrix} M_{\Phi\Delta}v_\Delta + \frac{1}{2}\lambda'_{H\Phi}v^2 & \frac{1}{2}\lambda'_{H\Phi}vv_\Phi & -\frac{1}{2}M_{\Phi\Delta}v_\Phi \\ \frac{1}{2}\lambda'_{H\Phi}vv_\Phi & M_{H\Delta}v_\Delta + \frac{1}{2}\lambda'_{H\Phi}v_\Phi^2 & \frac{1}{2}M_{H\Delta}v \\ -\frac{1}{2}M_{\Phi\Delta}v_\Phi & \frac{1}{2}M_{H\Delta}v & \frac{1}{4v_\Delta}\left(M_{H\Delta}v^2 + M_{\Phi\Delta}v_\Phi^2\right) \end{pmatrix} .$$

This matrix can also be diagonalized by an orthogonal matrix O^D

$$(O^D)^T \cdot \mathcal{M}_D^2 \cdot O^D = \mathrm{Diag}(m_{\tilde{G}^p}^2, m_D^2, m_\Delta^2) .$$

- $\tilde{G}^p$ is a Goldstone boson which will be eaten by W'
- D is the dark matter candidate in the model.

Scalar Mass Spectrum

The final one is a 4×4 diagonal block with

$$m_{H^\pm}^2 = M_{H\Delta} v_\Delta - \frac{1}{2}\lambda'_H v^2 + \frac{1}{2}\lambda'_{H\Phi} v_\Phi^2 ,$$
$$m_{G^\pm}^2 = m_{G^0}^2 = m_{G_H^0}^2 = 0 ,$$

- $m_{H^\pm}$ is the mass of charged Higgs
- $m_{G^\pm}$, m_{G^0} and $m_{G_H^0}$ are masses of the four Goldstone boson fields $G^\pm$, G^0 and G_H^0, respectively.

Accidental Z2 symmetry assignment

	$h_1,\ h_2,\ h_3,\ W^{\pm},\ Z,\ Z',\ Z'',\ f^{SM}_{L,R}$	$D,\ \tilde{\Delta},\ H^{\pm},\ W'^{(p,m)},\ f^{H}_{L,R}$
$\mathcal{Z}_2$	$+1$	-1

Mass matrix diagonalization

One can diagonalize the 4 by 4 mass matrix by an orthogonal rotation matrix as follows:

$$\mathcal{O}^{4\times 4}_{M_Y=0} = \begin{pmatrix} c_W & -s_W & 0 & 0 \\ s_W & c_W & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & & & \\ 0 & & \mathcal{O} & \\ 0 & & & \end{pmatrix}$$

Where $\mathcal{O} = \begin{pmatrix} c_\psi c_\phi - s_\theta s_\phi s_\psi & -s_\psi c_\phi - s_\theta s_\phi c_\psi & -c_\theta s_\phi \\ c_\psi s_\phi + s_\theta c_\phi s_\psi & -s_\psi s_\phi + s_\theta c_\phi c_\psi & c_\theta c_\phi \\ -c_\theta s_\psi & -c_\theta c_\psi & s_\theta \end{pmatrix}$,

with $$\tan(\phi) = \frac{(g_H^2 v_\Phi^2 - 2M_{Z_3}^2) v M_{Z^{\rm SM}}}{g_H[(v^2 - v_\Phi^2)M_{Z_3}^2 + v_\Phi^2 (M_{Z^{\rm SM}})^2]},$$

$$\tan(\theta) = \frac{g_H^2[v_\Phi^2(M_{Z^{\rm SM}})^2 - (v^2 + v_\Phi^2)M_{Z_3}^2] + 4M_{Z_3}^2[M_{Z_3}^2 - (M_{Z^{\rm SM}})^2]}{2g_H g_X[(v^2 - v_\Phi^2)M_{Z_3}^2 + v_\Phi^2(M_{Z^{\rm SM}})^2]} \cos\phi ,$$

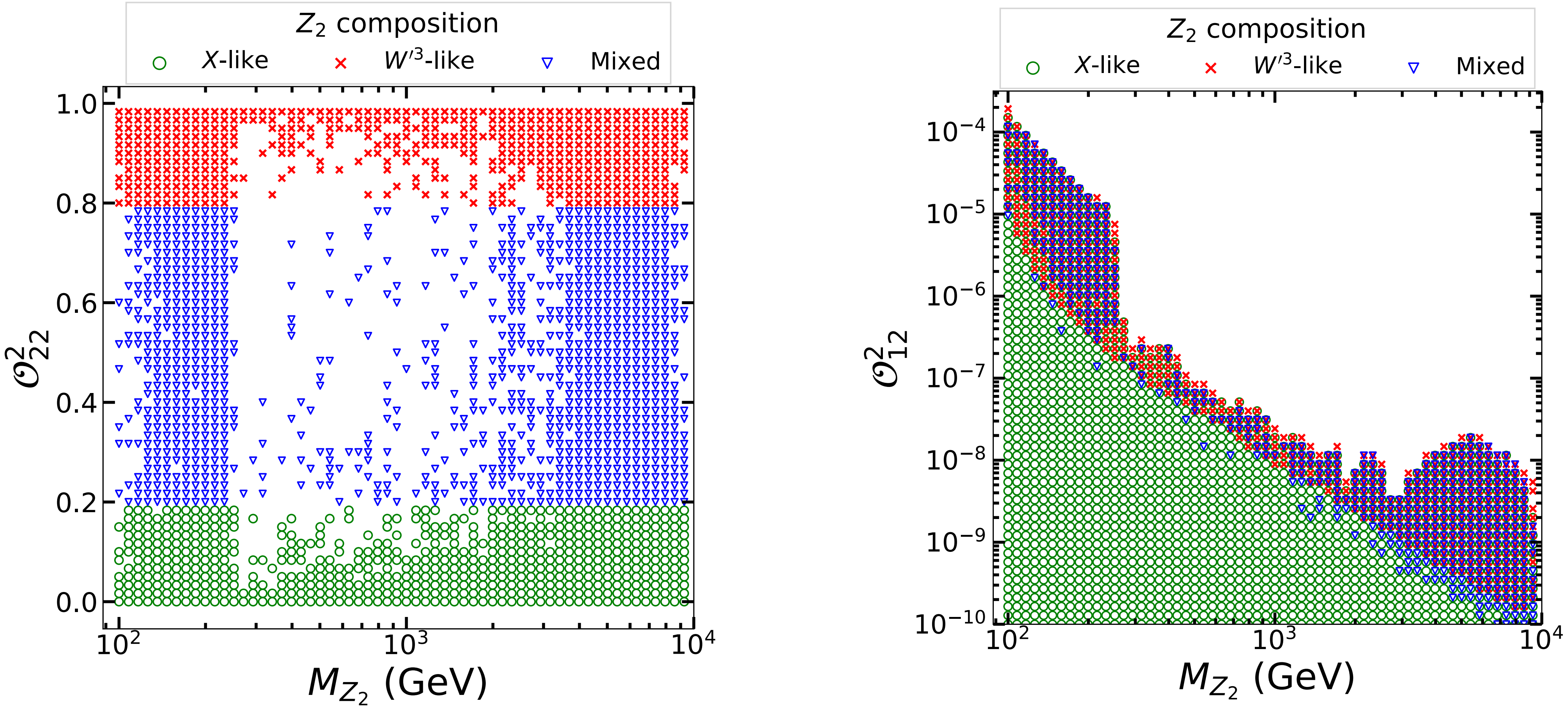
and

$$\cot(\psi) = \frac{g_H(M_{Z_1}^2 - M_X^2 - 2g_X^2 v_\Phi^2)}{g_X(g_H^2 v_\Phi^2 - 2M_{Z_1}^2)} \frac{\cos\theta}{\sin\phi} - \sin\theta \cot\phi .$$

LEP and CEPC observables

Observables	LEP Data	CEPC Precision [23]	Standard Model
M_Z [GeV]	91.1876 ± 0.0021	5×10^{-4}	91.1884 ± 0.0020
Γ_Z [GeV]	2.4952 ± 0.0023	5.06×10^{-4}	2.4942 ± 0.0008
Γ_{had} [GeV]	1.7444 ± 0.0020	—	1.7411 ± 0.0008
Γ_{inv} [MeV]	499.0 ± 1.5	—	501.44 ± 0.04
$\Gamma_{l^+l^-}$ [MeV]	83.984 ± 0.086	—	83.959 ± 0.008
$\sigma_{had}[nb]$	41.541 ± 0.037	—	41.481 ± 0.008
R_e	20.804 ± 0.050	—	20.737 ± 0.010
R_μ	20.785 ± 0.033	0.05%	20.737 ± 0.010
R_τ	20.764 ± 0.045	0.05%	20.782 ± 0.010
R_b	0.21629 ± 0.00066	0.08%	0.21582 ± 0.00002
R_c	0.1721 ± 0.0030	—	0.17221 ± 0.00003
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	—	0.01618 ± 0.00006
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013	—	0.01618 ± 0.00006
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017	—	0.01618 ± 0.00006
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.15%	0.1030 ± 0.0002
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	—	0.0735 ± 0.0001
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	—	0.1031 ± 0.0002
A_e	0.15138 ± 0.00216	—	0.1469 ± 0.0003
A_μ	0.142 ± 0.015	—	0.1469 ± 0.0003
A_τ	0.136 ± 0.015	—	0.1469 ± 0.0003
A_b	0.923 ± 0.020	—	0.9347
A_c	0.670 ± 0.027	—	0.6677 ± 0.0001
A_s	0.0895 ± 0.091	—	0.9356

Z' composition



Here $Z_2 \equiv Z'$