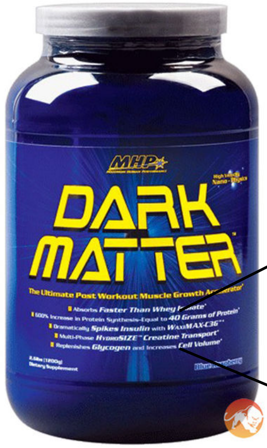
Heidelberg 27/09/2017



Be careful. It contains kaon physics that can harm your model

It contains g-2 which is prejudicial to heavy particles

Use it (dark matter) with care because flavor physics might kill the model

Flavor and Dark Matter Workshop

Dark Matter in a Two Higgs Doublet Model

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Max Planck Institute fur Kernphysik - Heidelberg

Based on: arxiv: 1705.05388, 1710.XXXXX

Dark Matter

WIMPs

Sterile Neutrinos

Axions

Flavor

Minimal Flavor Violation

Rare B decays

R_K

Neutrino Masses

Seesaw type I, II, III

Radiative Seesaw

Inverse Seesaw

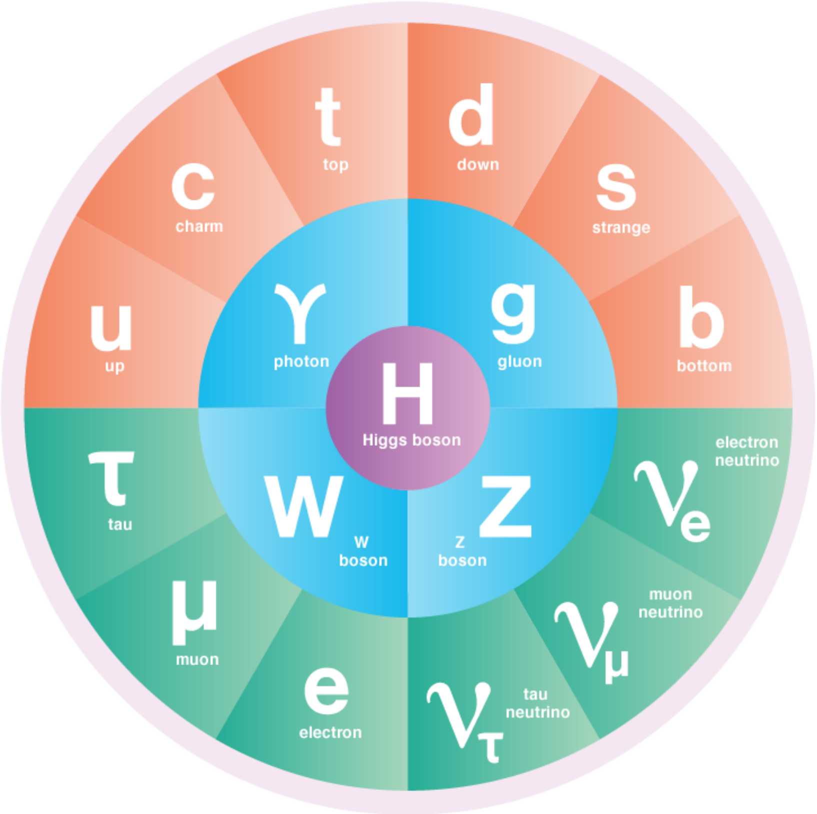
Take Home Message

2HDM guided by Gauge Principles that address:

Dark Matter
Neutrino Masses
Flavor

SM works fine with one Higgs doublet

But, what if there is another higgs doublet in nature...

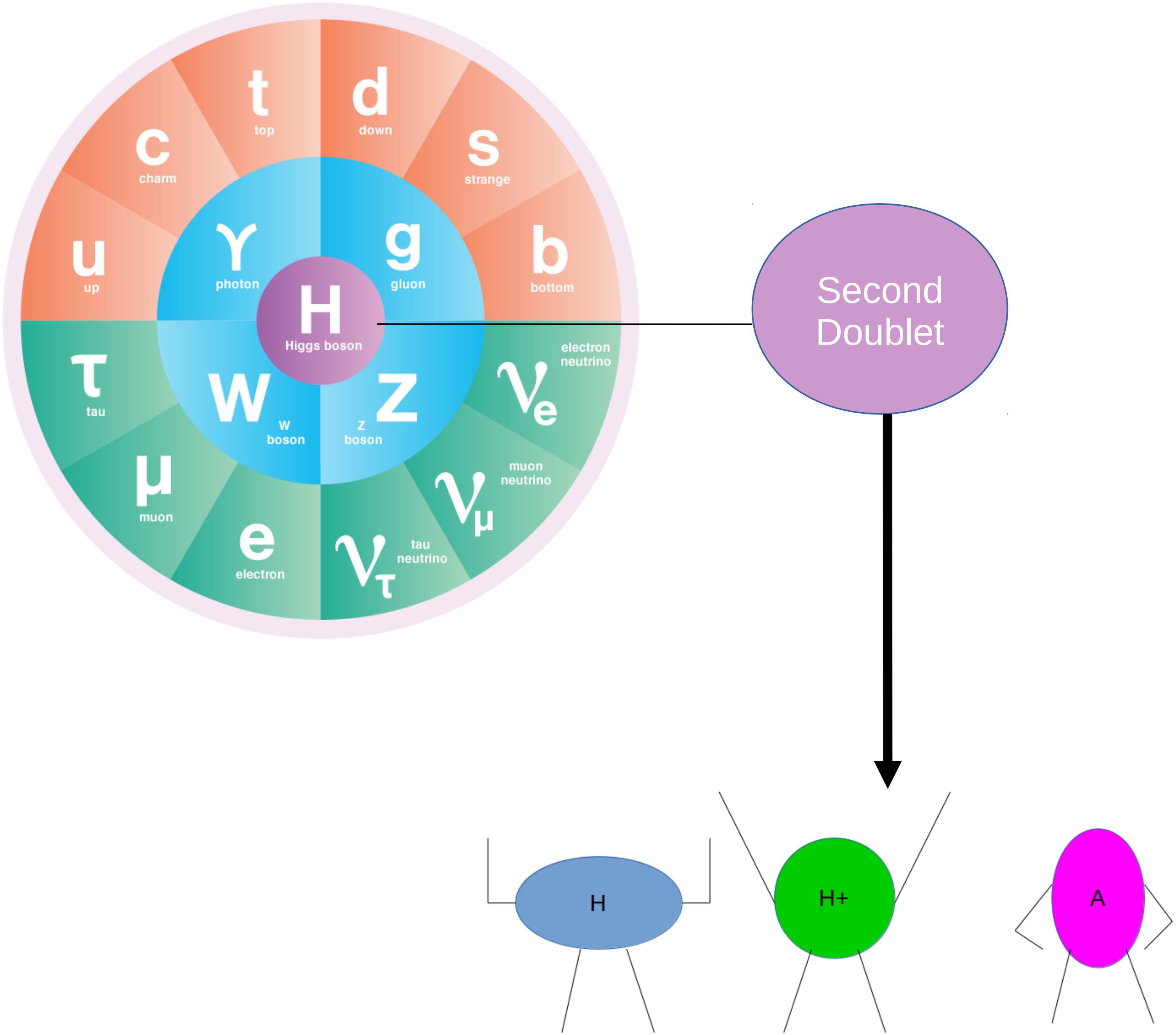


The W and Z masses limit the type of higgs doublets in nature

$$\rho = \frac{\sum_{i=1}^{n} \left[I_i \left(I_i + 1 \right) - \frac{1}{4} Y_i^2 \right] v_i}{\sum_{i=1}^{n} \frac{1}{2} Y_i^2 v_i} \longrightarrow Y = \pm 1$$

SM works fine with one Higgs doublet

But, what if there is another higgs doublet in nature...



General Scalar Potential

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2$$
$$+ \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right)$$
$$+ \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \lambda_6\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_1^\dagger\Phi_2\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + h.c.\right]$$

General Yukawa Lagrangian

$$-\mathcal{L}_{Y_{2HDM}} = y^{1d}\bar{Q}_L\Phi_1 d_R + y^{1u}\bar{Q}_L\widetilde{\Phi}_1 u_R + y^{1e}\bar{L}_L\Phi_1 e_R$$
$$+ y^{2d}\bar{Q}_L\Phi_2 d_R + y^{2u}\bar{Q}_L\widetilde{\Phi}_2 u_R + y^{2e}\bar{L}_L\Phi_2 e_R + h.c.,$$

$$\Phi_1 \to -\Phi_1,\ \ \Phi_2 \to +\Phi_2$$

Ad hoc: to suppress flavor changing Interactions

Can we solve the flavor problem by gauge principles? ✓

Can we generate neutrino masses by gauge principles? ✓

Can we have a plausible dark matter candidate via gauge principles? ✓

Can we have all these at once?

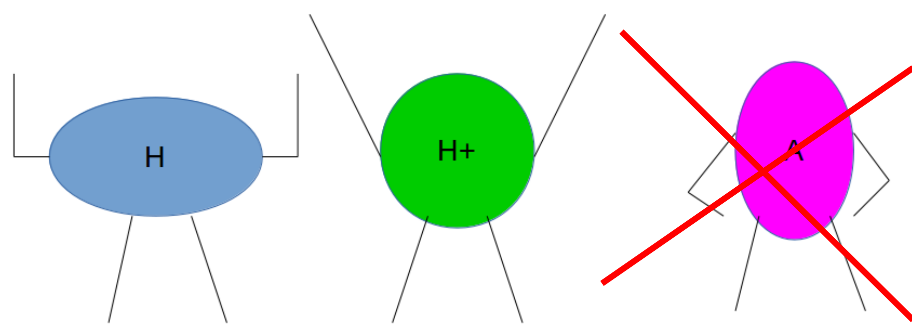
YES WE CAN!

Neutrino masses and absence of FCNI in the 2HDM from Gauge Principles

2HDM + U(1) gauge symmetry

Two Higgs Doublet Models free from FCNI

Fields	u_R	d_R	Q_L	L_L	e_R	N_R	Φ_2	Φ_1
Charges	u	d	$\frac{(u+d)}{2}$	$\frac{-3(u+d)}{2}$	$-(2u+d)$	$-(u+2d)$	$\frac{(u-d)}{2}$	$\frac{5u}{2}+\frac{7d}{2}$
$U(1)_A$	1	-1	0	0	-1	1	1	-1
$U(1)_B$	-1	1	0	0	1	-1	-1	1
$U(1)_C$	$1/2$	-1	$-1/4$	$3/4$	0	$3/2$	$3/4$	$9/4$
$U(1)_D$	1	0	$1/2$	$-3/2$	-2	-1	$1/2$	$5/2$
$U(1)_E$	0	1	$1/2$	$-3/2$	-1	-2	$7/2$	$-1/2$
$U(1)_F$	$4/3$	$2/3$	1	-3	-4	$-8/3$	$1/3$	$17/3$
$U(1)_G$	$-1/3$	$2/3$	$1/6$	$-1/2$	0	-1	$-1/2$	$-3/2$
$U(1)_{B-L}$	$1/3$	$1/3$	$1/3$	-1	-1	-1	0	2
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$-1/2$	-1		$1/2$	$\neq h_2$
$U(1)_N$	0	0	0	0	0		0	$\neq h_2$



Neutrino masses and absence of FCNI in the 2HDM from Gauge Principles

2HDM + U(1) gauge symmetry

Two Higgs Doublet Models free from FCNI

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$U(1)_C$	$1/2$	-1	$-1/4$	$3/4$	0	$3/2$	$3/4$	$9/4$
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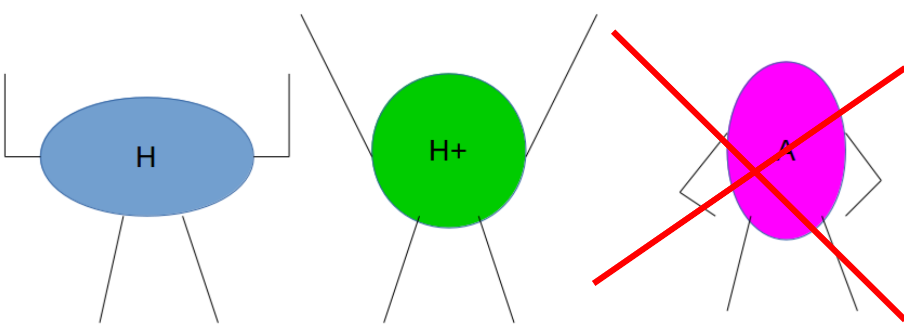
$U(1)_Y$	$2/3$	$-1/3$	$1/6$	$-1/2$	-1		$1/2$	$\neq h_2$
$U(1)_N$	0	0	0	0	0		0	$\neq h_2$

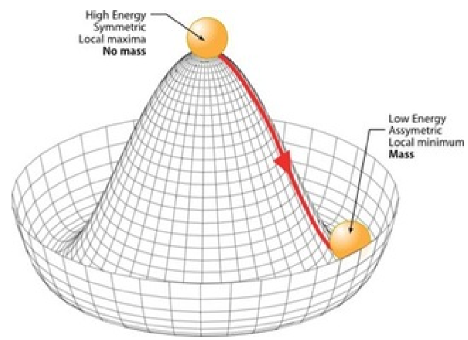
This 2HDM has no pseudoscalar!
This is a key distinction to the canonical 2HDM



***HOW* can we have all these at once?**

Flavor Problem

Discrete Symmetry Generated via U(1) breaking



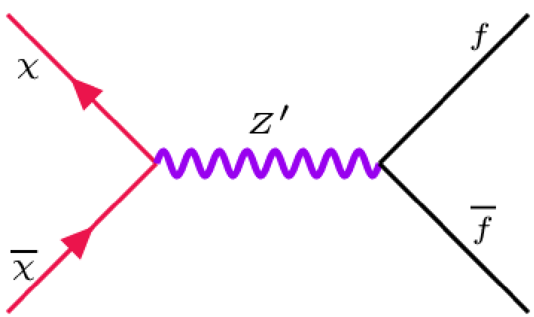
Neutrino Masses

Seesaw mechanism

$$-\mathcal{L} \supset y^{D}_{ij} \bar{L}_{iL} \widetilde{\Phi}_2 N_{jR} + Y^{M}_{ij} \overline{(N_{iR})^c} \Phi_s N_{Rj} \quad \Longrightarrow \quad (\nu \; N) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

Dark Matter

Vector-like fermion under U(1)



Pheno 1

Heavy Higgs Searches

$$m_s^2 = \lambda_s v_s^2,$$

$$m_h^2 = \frac{1}{2}\left(\lambda_1 v_1^2 + \lambda_2 v_2^2 - \sqrt{(\lambda_1 v_1^2 - \lambda_2 v_2^2)^2 + 4(\lambda_3+\lambda_4)^2 v_1^2 v_2^2}\right) \longrightarrow$$

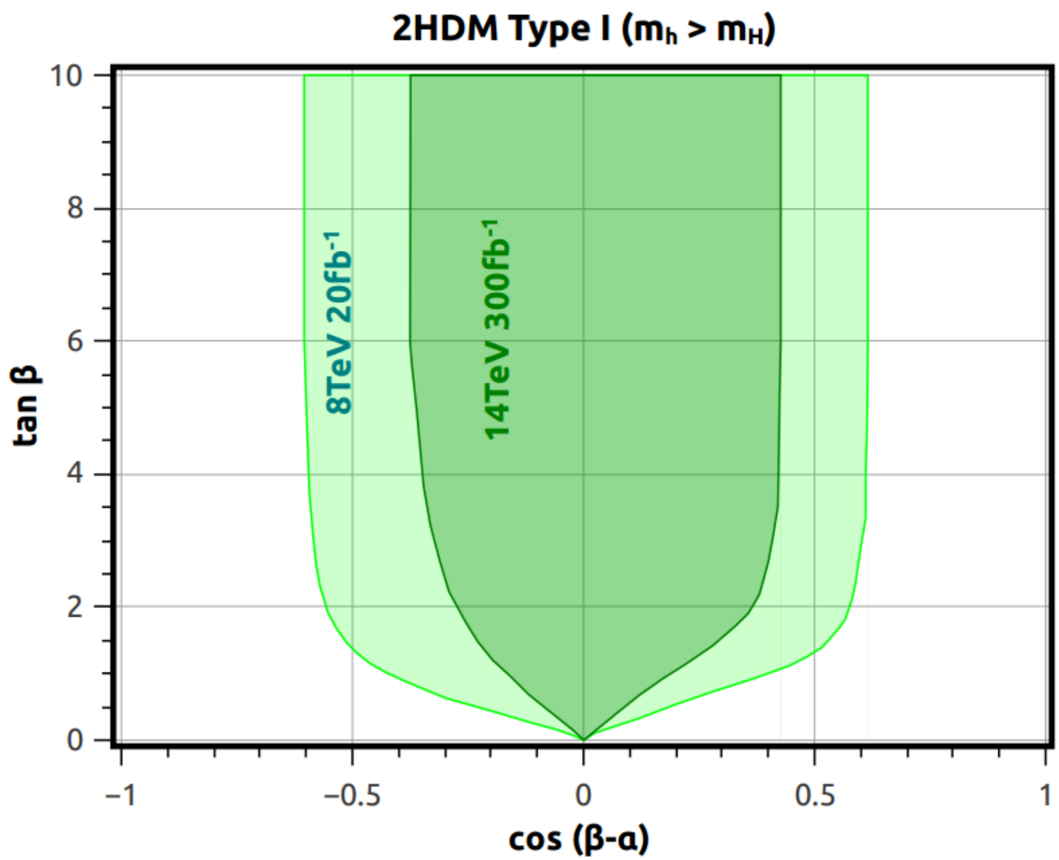
New light scalar lighter than 125GeV

$$m_H^2 = \frac{1}{2}\left(\lambda_1 v_1^2 + \lambda_2 v_2^2 + \sqrt{(\lambda_1 v_1^2 - \lambda_2 v_2^2)^2 + 4(\lambda_3+\lambda_4)^2 v_1^2 v_2^2}\right) \longrightarrow$$

SM Higgs is the heavy scalar!

Usually bounds on 2HDM are expressed with this plot

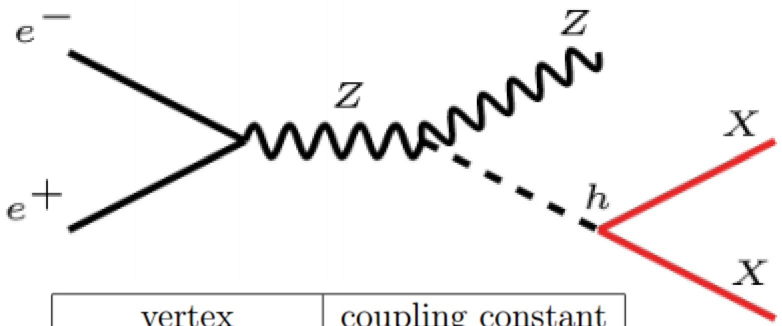
In our model we need much more!



Pheno 2

Light Higgs Searches

Higgs Associated Production at LEP- light higgs searches

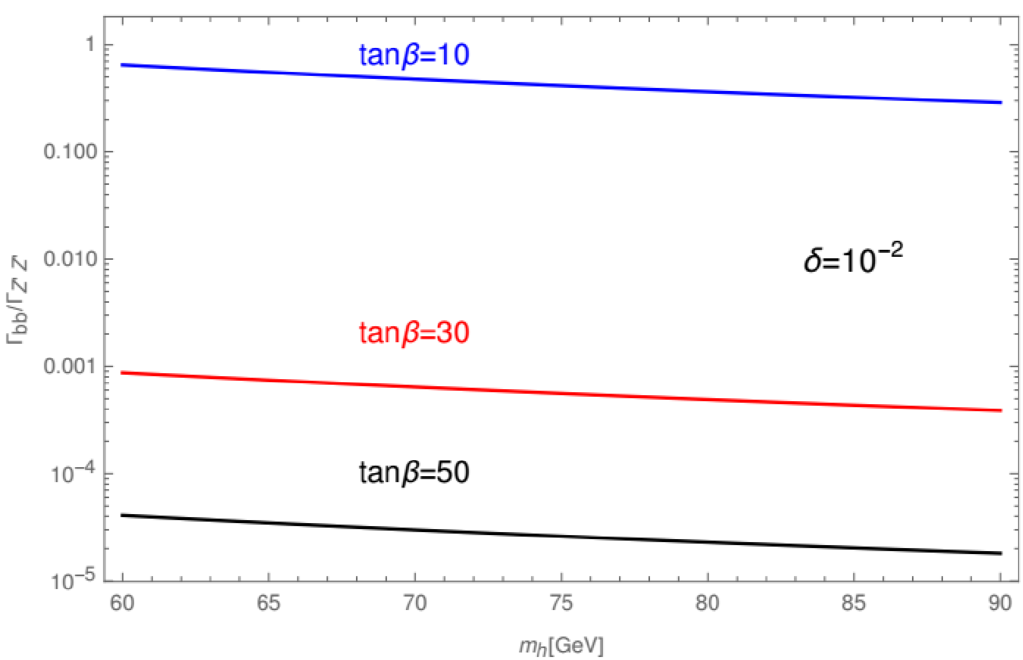


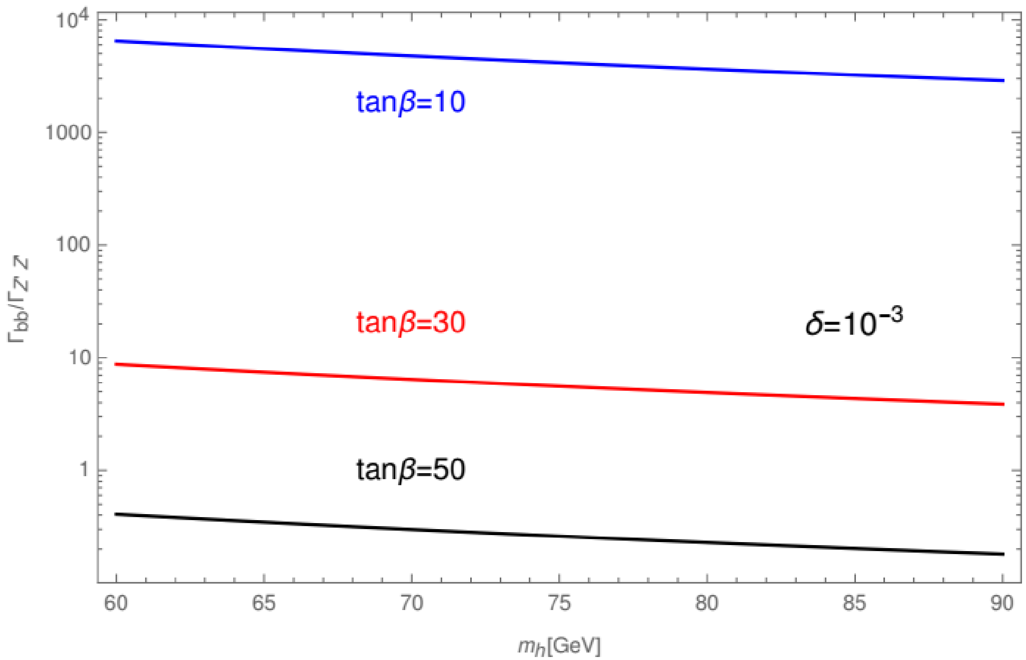
$$\Gamma_{h\to Z'Z'} = \frac{g_Z^2}{128\pi}\frac{m_h^3}{m_Z^2}(\delta\tan\beta)^4\left(\frac{\cos^3\beta\cos\alpha - \sin^3\beta\sin\alpha}{\cos\beta\sin\beta}\right)^2$$

vertex	coupling constant
$H\,t\bar{t}, H\,b\bar{b}, H\,\tau\bar{\tau}$	$\frac{\sin\alpha}{\sin\beta}$
$H\,WW, H\,ZZ$	$\cos(\beta-\alpha)$
$h\,t\bar{t}, h\,b\bar{b}, h\,\tau\bar{\tau}$	$\frac{\cos\alpha}{\sin\beta}$
$h\,WW, h\,ZZ$	$\sin(\beta-\alpha)$

$$\Gamma_{h\to b\bar{b}} = \frac{3m_b^2 m_h}{8\pi v^2}\left(\frac{\cos\alpha}{\sin\beta}\right)^2.$$

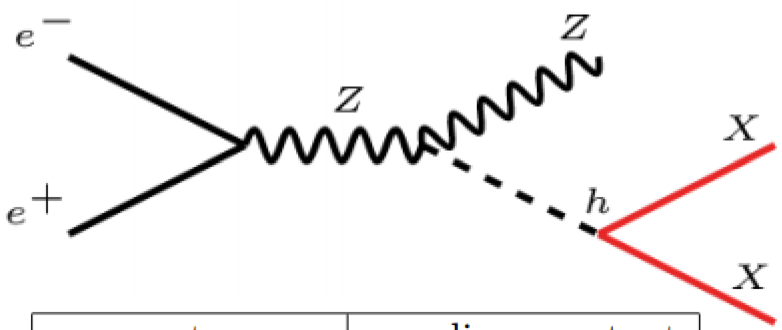
Z' is a gauge boson lighter than the Z





Pheno 2 Light Higgs Searches

Higgs Associated Production at LEP



$$\Gamma_{h\to Z'Z'} = \frac{g_Z^2}{128\pi}\frac{m_h^3}{m_Z^2}(\delta\tan\beta)^4\left(\frac{\cos^3\beta\cos\alpha - \sin^3\beta\sin\alpha}{\cos\beta\sin\beta}\right)^2$$

$$\Gamma_{h\to b\bar{b}} = \frac{3m_b^2 m_h}{8\pi v^2}\left(\frac{\cos\alpha}{\sin\beta}\right)^2 .$$

vertex	coupling constant
$H\,t\bar{t}, H\,b\bar{b}, H\,\tau\bar{\tau}$	$\frac{\sin\alpha}{\sin\beta}$
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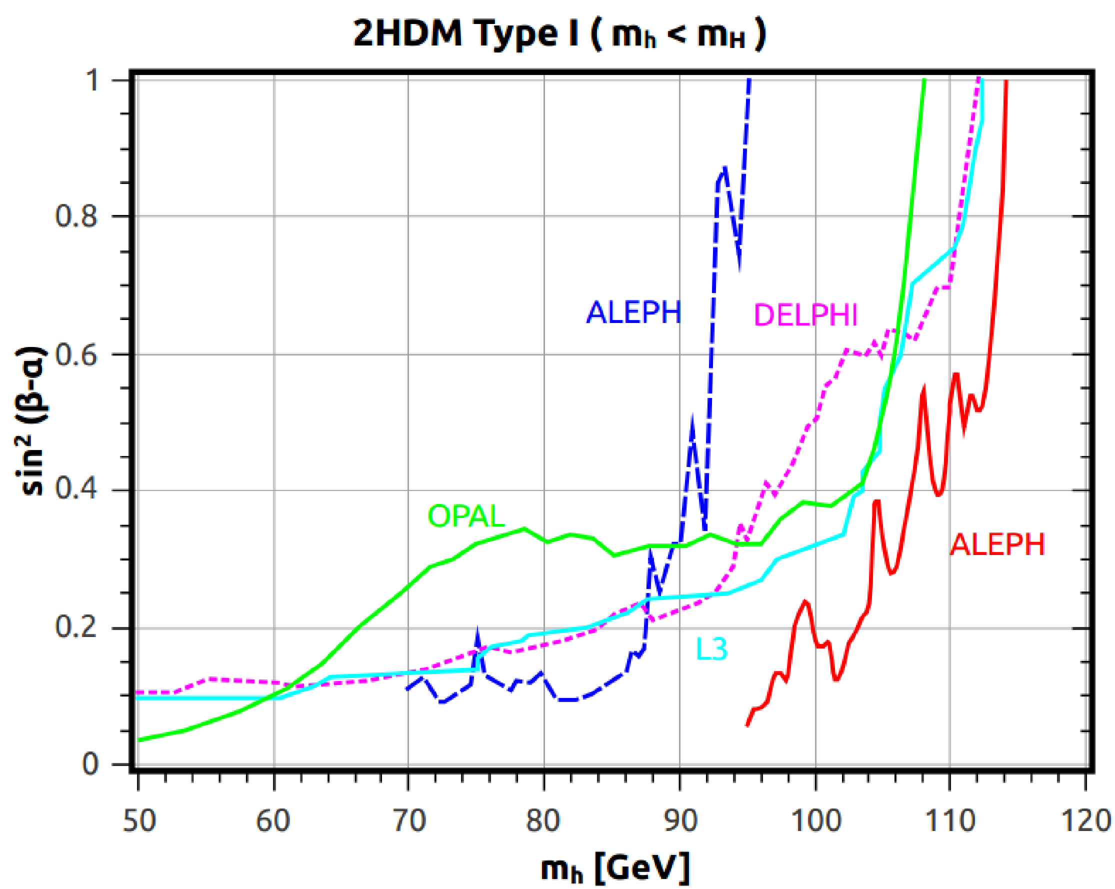


$$\sigma(Zh)/\sigma(ZH_{SM})BR(h\to \text{inv})$$

Pheno 3 Higgs Physics

Higgs Properties as measured by the LHC. Thanks to Higgs Working group!

Higgs decay channel	branching ratio	error
$b\bar{b}$	5.84×10^{-1}	1.5%
$c\bar{c}$	2.89×10^{-2}	6.5%
g g	8.18×10^{-2}	4.5%
ZZ^*	2.62×10^{-1}	2%
WW^*	2.14×10^{-1}	2%
$\tau^+\tau^-$	6.27×10^{-2}	2%
$\mu^+\mu^-$	2.18×10^{-4}	2%
$\gamma\gamma$	2.27×10^{-3}	2.6%
$Z\gamma$	1.5×10^{-3}	6.7%
$ZZ^* \to 4\ell$	2.745×10^{-4}	2%
$ZZ^* \to 2\ell 2\nu$	1.05×10^{-4}	2%

$$\Gamma(H \to ZZ') = \frac{g_Z^2}{64\pi} \frac{(M_H^2 - M_Z^2)^3}{M_H^3 M_Z^2} \delta^2 \tan\beta^2 \sin^2(\beta - \alpha)$$

$$\Gamma(H \to Z'Z') = \frac{g_Z^2}{128\pi} \frac{M_H^3}{M_Z^2} \delta^4 \tan\beta^4 \left(\frac{\cos^3\beta \sin\alpha + \sin^3\beta \cos\alpha}{\cos\beta \sin\beta} \right)^2$$

Z' is a gauge boson lighter than the Z

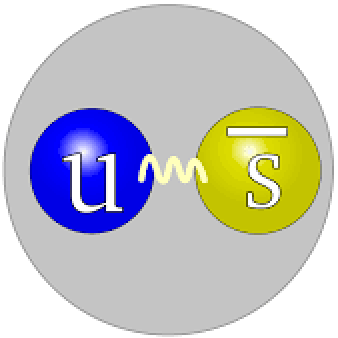
If you have a light Z' that mixes with the Z the precise measurements on the Higgs properties may lead to the strongest bound on the Z-Z' mass mixing

$$\delta^2 \leq \frac{4.6 \times 10^{-6}}{BR(Z' \to l^+ l^-) \sin^2(\beta - \alpha) \tan\beta^2}$$

The Higgs offers a powerful probe to new physics

Pheno 4 Meson Physics

Kaon Decays come into play



$$\mathrm{BR}(K^+ \to \pi^+ e^+ e^-)_{\rm exp} = (3.00 \pm 0.09) \times 10^{-7},$$
$$\mathrm{BR}(K^+ \to \pi^+ \mu^+ \mu^-)_{\rm exp} = (9.4 \pm 0.6) \times 10^{-8},$$
$$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu})_{\rm exp} = (1.7 \pm 1.1) \times 10^{-10}.$$

$$\mathrm{BR}(K^+ \to \pi^+ Z') \simeq 4 \times 10^{-4}\, \delta^2$$

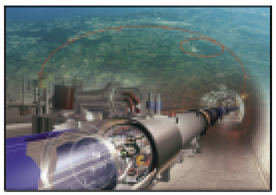
$$\delta \lesssim \frac{2 \times 10^{-2}}{\sqrt{BR(Z' \to l^+ l^-)}},$$
$$\delta \lesssim \frac{7 \times 10^{-4}}{\sqrt{BR(Z' \to \text{missing energy})}}.$$

Very strong Constraint!

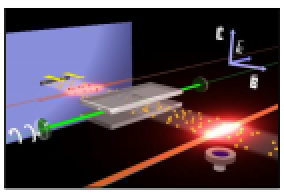
Pheno 5 Atomic Parity Violation

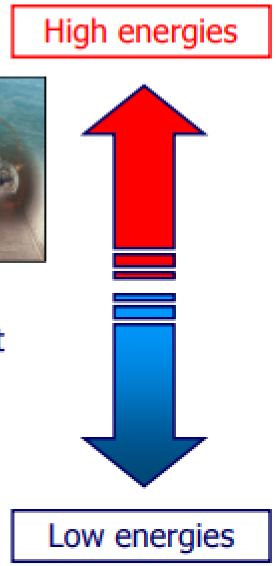
Atomic Parity Violation

Instead of search for new processes or particles directly



Determine weak charge Q_W from atomic parity violation studies and compare the result with Standard Model prediction





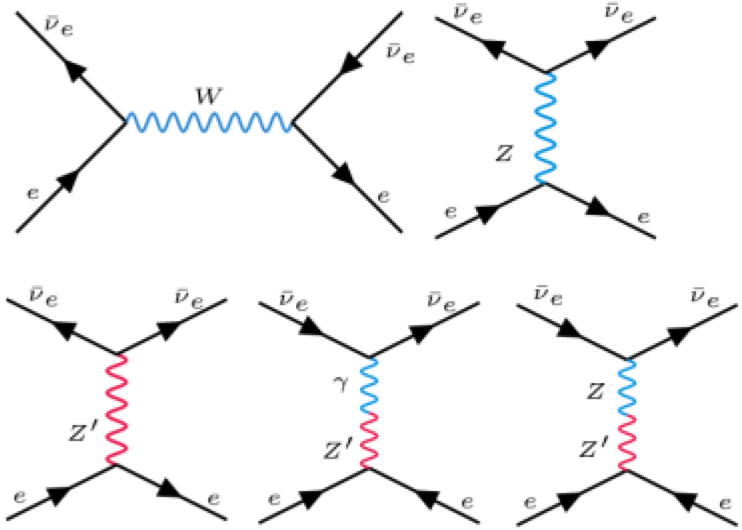
Experiment	$\langle Q \rangle$	$\sin^2\theta_W(m_Z)$	Bound on dark Z (90% CL)
Cesium APV	2.4 MeV	0.2313(16)	$\varepsilon^2 < \frac{39\times10^{-6}}{\delta^2}\left(\frac{m_{Z_d}}{m_Z}\right)^2 \frac{1}{K(m_{Z_d})^2}$
E158 (SLAC)	160 MeV	0.2329(13)	$\varepsilon^2 < \frac{62\times10^{-6}}{\delta^2}\left(\frac{(160\ \mathrm{MeV})^2+m_{Z_d}^2}{m_Z\, m_{Z_d}}\right)^2$
Qweak (JLAB)	170 MeV	±0.0007	$\varepsilon^2 < \frac{7.4\times10^{-6}}{\delta^2}\left(\frac{(170\ \mathrm{MeV})^2+m_{Z_d}^2}{m_Z\, m_{Z_d}}\right)^2$
Moller (JLAB)	75 MeV	±0.00029	$\varepsilon^2 < \frac{1.3\times10^{-6}}{\delta^2}\left(\frac{(75\ \mathrm{MeV})^2+m_{Z_d}^2}{m_Z\, m_{Z_d}}\right)^2$
MESA (Mainz)	50 MeV	±0.00037	$\varepsilon^2 < \frac{2.1\times10^{-6}}{\delta^2}\left(\frac{(50\ \mathrm{MeV})^2+m_{Z_d}^2}{m_Z\, m_{Z_d}}\right)^2$

Master Formula

Kinetic mixing
+
Mass mixing
+
Fermions charged under U(1)

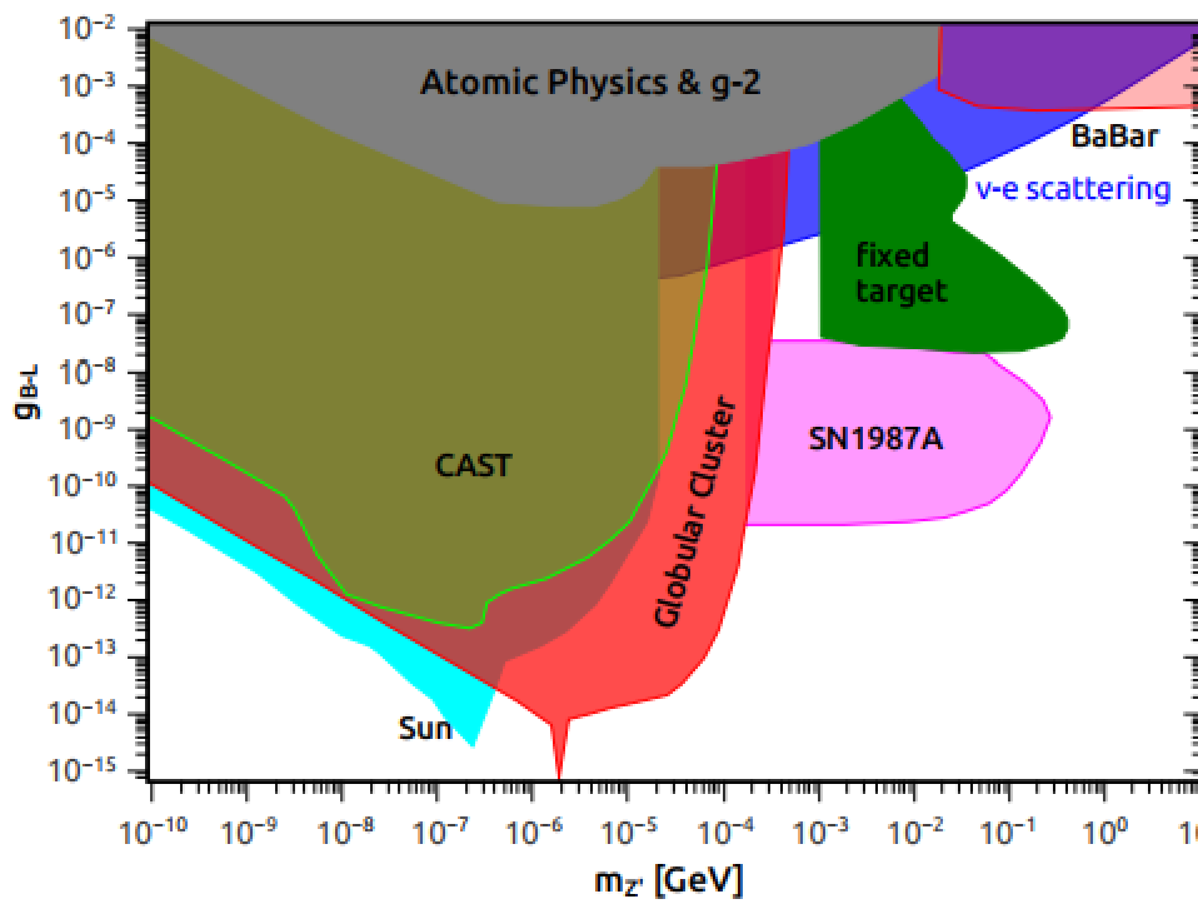
$$\Bigg| 73.16\delta^2 - 220\delta\left(\epsilon\frac{M_Z}{m'_Z}\right)\sin\theta_W\cos\theta_W - \delta^2\frac{188(q+u)}{Q_{x1}\cos^2_\beta + Q_{x2}\sin^2_\beta} - \delta^2\frac{211(q+d)}{Q_{x1}\cos^2_\beta + Q_{x2}\sin^2_\beta}\left(1-\frac{l-e}{Q_{x1}\cos^2_\beta + Q_{x2}\sin^2_\beta}\right)\Bigg| \times K(Cs) < 0.6.$$

Pheno 6 Neutrino-electron Scattering



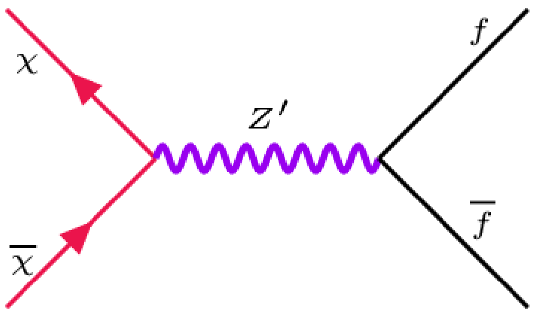
Experiment	Type of neutrino	$\langle E_\nu \rangle$	T
TEXONO-NPCGe [110]	$\bar{\nu}_e$	1−2 MeV	0.35−12 keV
TEXONO-HPGe [111, 112]	$\bar{\nu}_e$	1−2 MeV	12−60 keV
TEXONO-CsI(Tl) [113]	$\bar{\nu}_e$	1−2 MeV	3−8 MeV
LSND [114]	ν_e	36 MeV	18−50 MeV
BOREXINO [115]	ν_e	862 keV	270−665 keV
GEMMA [116]	$\bar{\nu}_e$	1−2 MeV	3−25 keV
CHARM II [117]	ν_μ	23.7 GeV	3-24 GeV
CHARM II [117]	$\bar{\nu}_\mu$	19.1 GeV	3-24 GeV

Bound on the gauge couplings x Z' mass

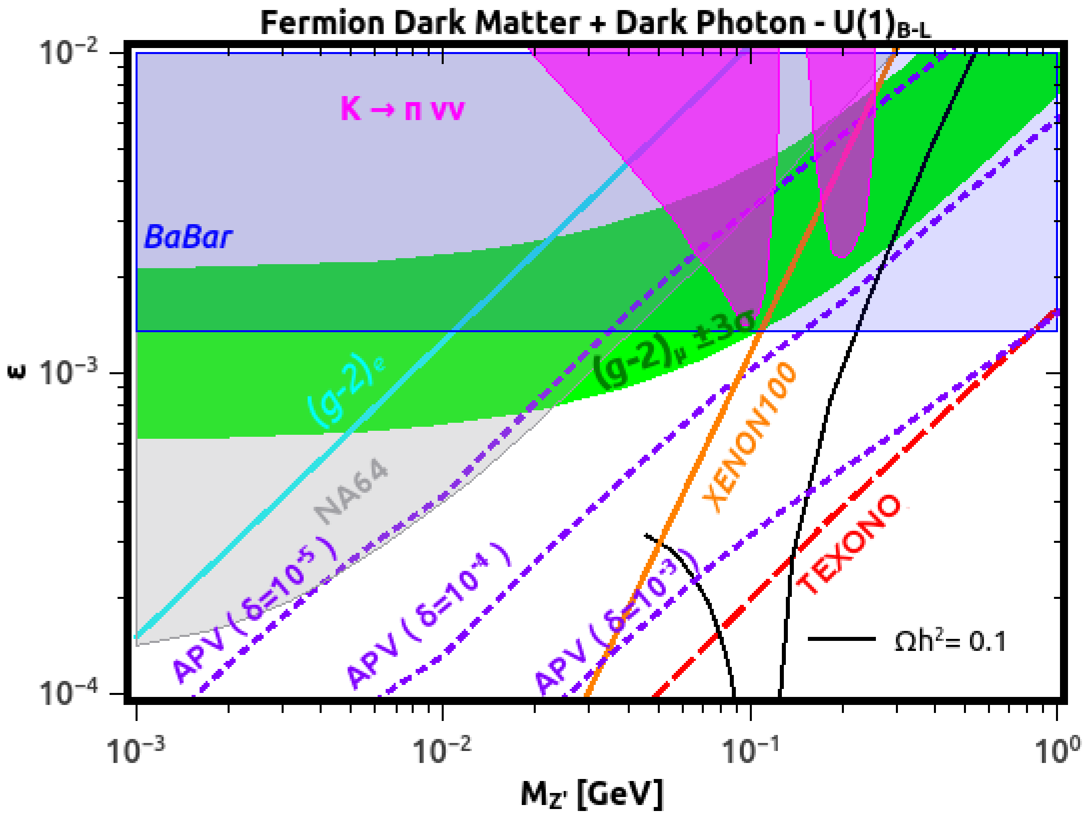


In the context of 2HDM with a B-L symmetry

Pheno 5 Dark Matter in a 2HDM guided by Gauge Principles



50 MeV dark matter, gBL ~1



Relic density: Thermal production

Direct Detection: dark matter-electron scattering

TEXONO: Neutrino-electron scattering

APV: Atomic Parity Violation using Cesium

2HDM amenable to a multitude of constraints while addressing:

Dark matter, neutrino masses, minimal flavor violation