Dark Matter in the Context of 2HDMs with an Extra U(1) Symmetry

Miguel Campos

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arXiv:1712.XXXXX

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Heidelberg Universität

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Outline

- Introduction: 2HDMs
  - The 2HDM Framework
- 2HDMs with $U(1)_X$ Symmetries
  - Theoretical Constraints
  - Interlude: Dark Matter
  - Parameters
  - Experimental Constraints
    - Higgs Physics
    - Other Constraints
    - Dark Matter Constraints

Introduction 1: 2HDMs

Original Motivation

History goes back to 1973, with T. D. Lee. It was an attempt to find new sources of CP Violation.

In 1977 Glashow & Weinberg realize that to avoid tree-level flavor changing neutral interactions (FCNIs), all fermions of a given electric charge can couple to at most one Higgs doublet.

A Theory of Spontaneous T Violation*

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Department of Physics, Columbia University, New York, New York 10027
(Received 11 April 1973)

Natural conservation laws for neutral currents*

Sheldon L. Glashow and Steven Weinberg
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Many top-down attempts at going beyond the SM lead to an enlargement of the Higgs sector. **It is of general interest then to constrain these models.**

Introduction: 2HDMs

Initial Considerations

Two important observational constraints are relevant when considering an enlarged Higgs sector:

- Electroweak Precision Tests

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

Two possibilities to keep this value equal to 1:

- Scalar doublets with Y=±1
- Scalar singlets with Y=0

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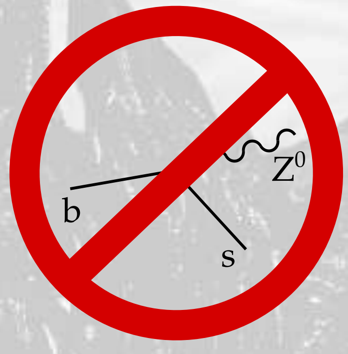
Two possibilities to keep this value equal to 1:

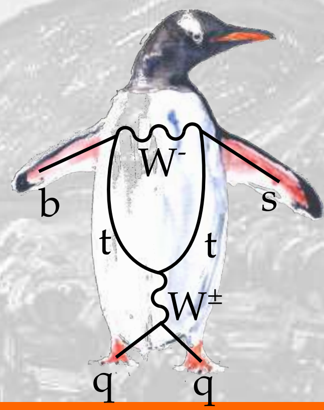
- Scalar doublets with $Y=\pm1$
- Scalar singlets with $Y=0$

- Flavor Changing Neutral Interactions

Not present at tree-level



GIM-suppressed at loop-level



Introduction: 2HDMs

Types of Models

The most general 2HDM Lagrangian produces FCNIs at tree level.

Solution: ad hoc Z_2 symmetry in which

$$\Phi_1 \rightarrow -\Phi_1$$
$$\Phi_2 \rightarrow +\Phi_2$$

The different possible fermion assignments lead to different types of 2HDMs:

Model	Φ_1	Φ_2	u_R	d_R	e_R	Q_L	L_L
Type I	$-$	$+$	$+$	$+$	$+$	$+$	$+$
Type II	$-$	$+$	$+$	$-$	$-$	$+$	$+$
Lepton-specific	$-$	$+$	$+$	$+$	$-$	$+$	$+$
Flipped	$-$	$+$	$+$	$-$	$+$	$+$	$+$

Introduction: 2HDMs

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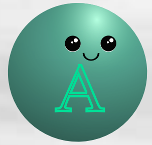
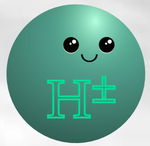
$$\begin{aligned} \Phi_1 &\to -\Phi_1 \\ \Phi_2 &\to +\Phi_2 \end{aligned}$$

Additional particles!





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Model	Φ_1	Φ_2	u_R	d_R	e_R	Q_L	L_L
Type I	−	+	+	+	+	+	+
Type II	−	+	+	−	−	+	+
Lepton-specific	−	+	+	+	−	+	+
Flipped	−	+	+	−	+	+	+

2HDM with $U(1)_X$

The Goal

Explain

- ✓ Absence of flavor violation
- ✓ Neutrino masses
- ✓ Dark matter

via

Gauge principles.

2HDM with $U(1)_X$

Theoretical Constraints

We can explain this Z_2 symmetry from gauge principles as coming from a $U(1)$ abelian symmetry. We demand

- Gauge invariance
- Anomaly cancellation

Again, the fermion charges under $U(1)_X$ define the different models

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

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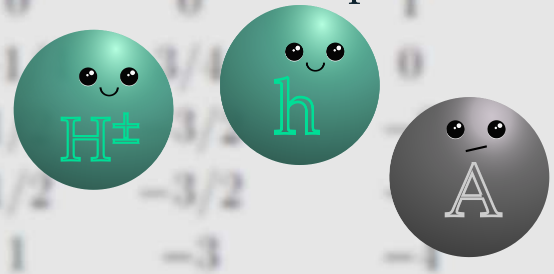
$U(1)_C$	1/2	−1	[illegible]	3/4	0	3/2	3/4	9/4
$U(1)_D$	1	0	[illegible]	[illegible]	[illegible]	−1	1/2	5/2
$U(1)_E$	0	1	1/2	−3/2	[illegible]	−2	7/2	−1/2
$U(1)_F$	4/3	2/3	1	−3	−4	−8/3	1/3	17/3
$U(1)_G$	−1/3	2/3	1/6	−1/2	0	−1	−1/2	−3/2
$U(1)_{B-L}$	1/3	1/3	1/3	−1	−1	−1	0	2

Just 2 additional particles!



2HDM with $U(1)_X$

Neutrino Masses

Additionally, we include neutrino masses through a seesaw type I mechanism, by adding a scalar singlet

$$-\mathcal{L}_\nu \supset y^D_{ij}\bar{L}_{iL}\widetilde{\Phi}_2 N_{jR} + Y^M_{ij}\overline{(N_{iR})^c}\Phi_s N_{Rj}$$

If $\langle\Phi_s\rangle = v_s \sim \mathrm{TeV}$, $y^M \sim 1$ and $y^D \sim 10^{-4}$

then $m_\nu \sim 0.1 \quad \mathrm{eV}$

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$$\mathcal{G} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots?$$

$$\Downarrow ?$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

$$\Downarrow \langle \Phi_s \rangle = v_s$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes Z_2$$

$$\Downarrow \langle \Phi_2 \rangle = v_2$$

$$SU(3)_C \otimes U(1)_{em} \otimes Z_2$$

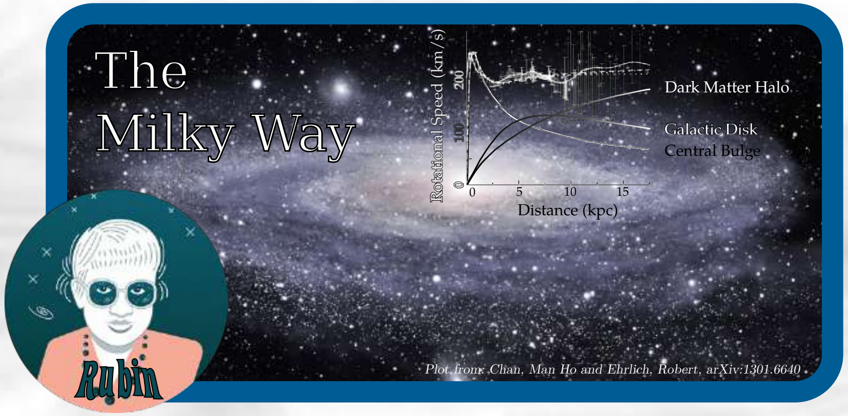
Interlude: Dark Matter

Evidence

The Coma Cluster

Image from: Hubble Space Telescope (NGC 4911 in the Coma Cluster)

Galactic rotation curves



Plot from: Cian, Man Ho and Ehrlich, Robert, arXiv:1301.6640

The CMB spectrum

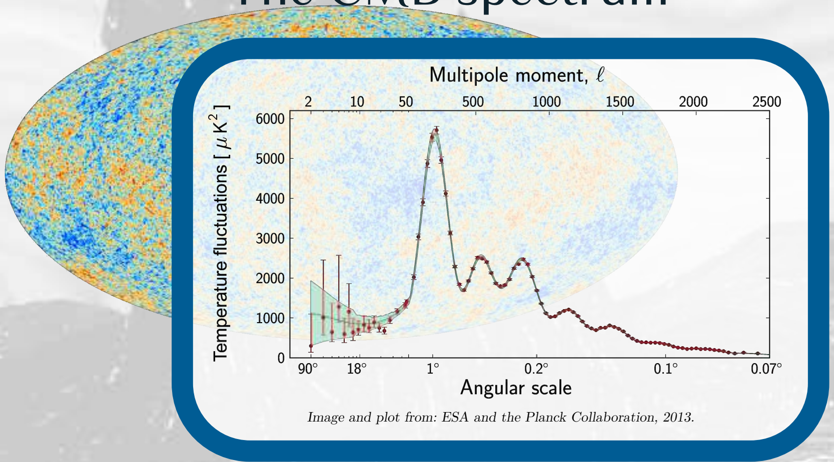


Image and plot from: ESA and the Planck Collaboration, 2013.

The Bullet cluster

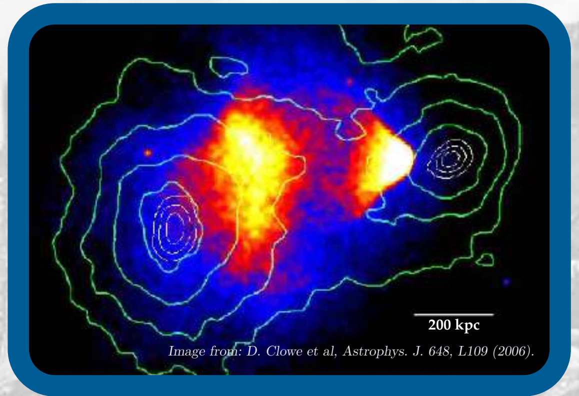
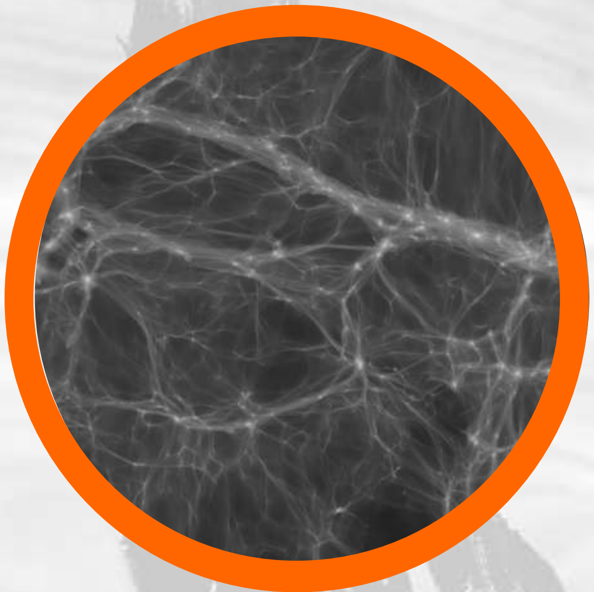


Image from: D. Clowe et al, Astrophys. J. 648, L109 (2006).

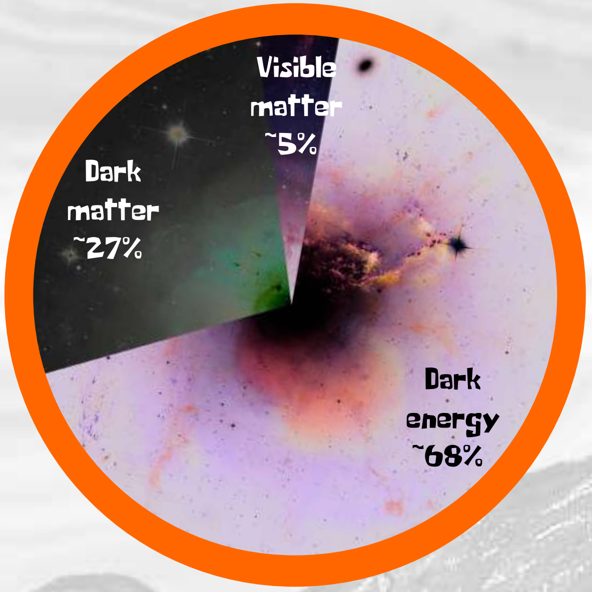
Interlude: Dark Matter

What we know so far:

It is essential for galaxy formation



Its approximate abundance.



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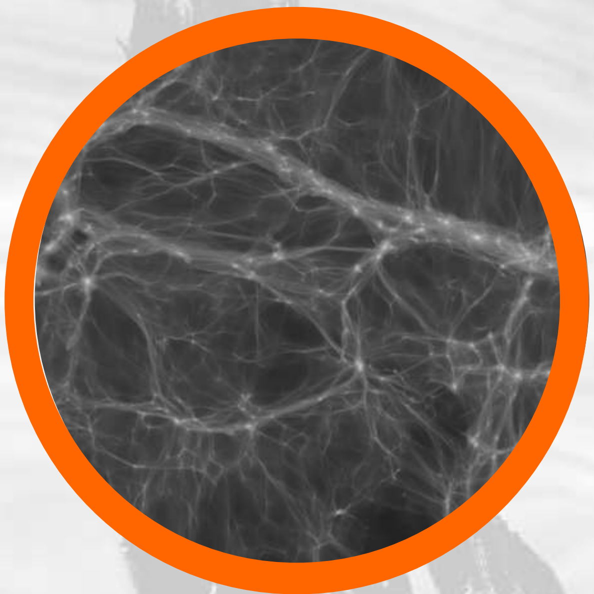

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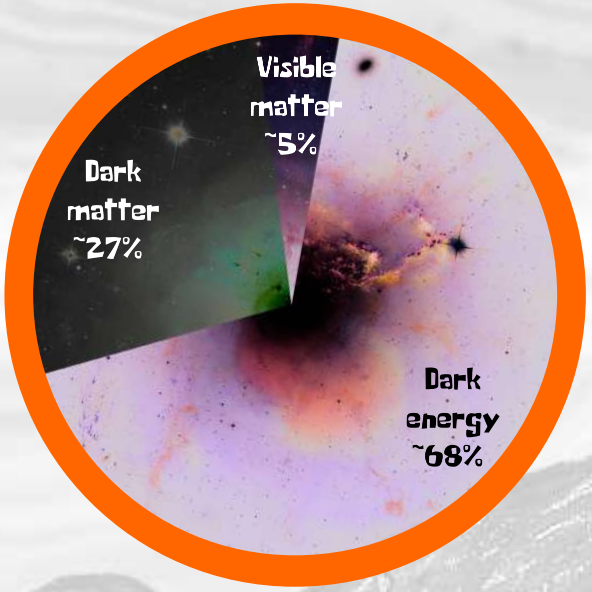
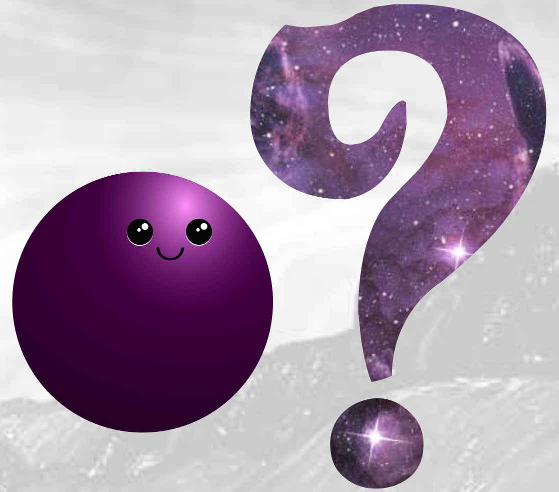


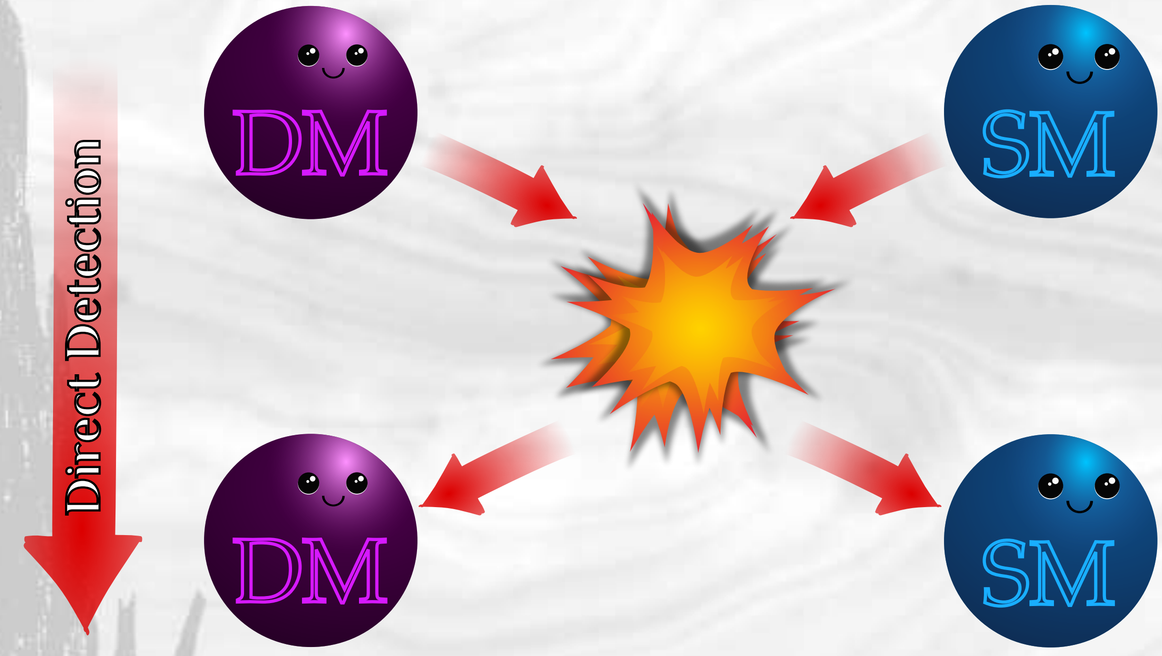
What we don't know:

What it actually is!

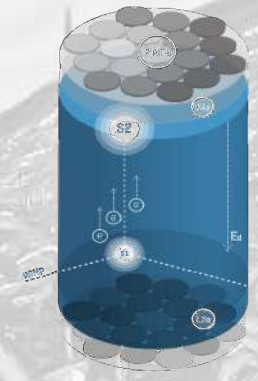


Interlude: Dark Matter

Methods of Detection



Scattering



Interlude: Dark Matter

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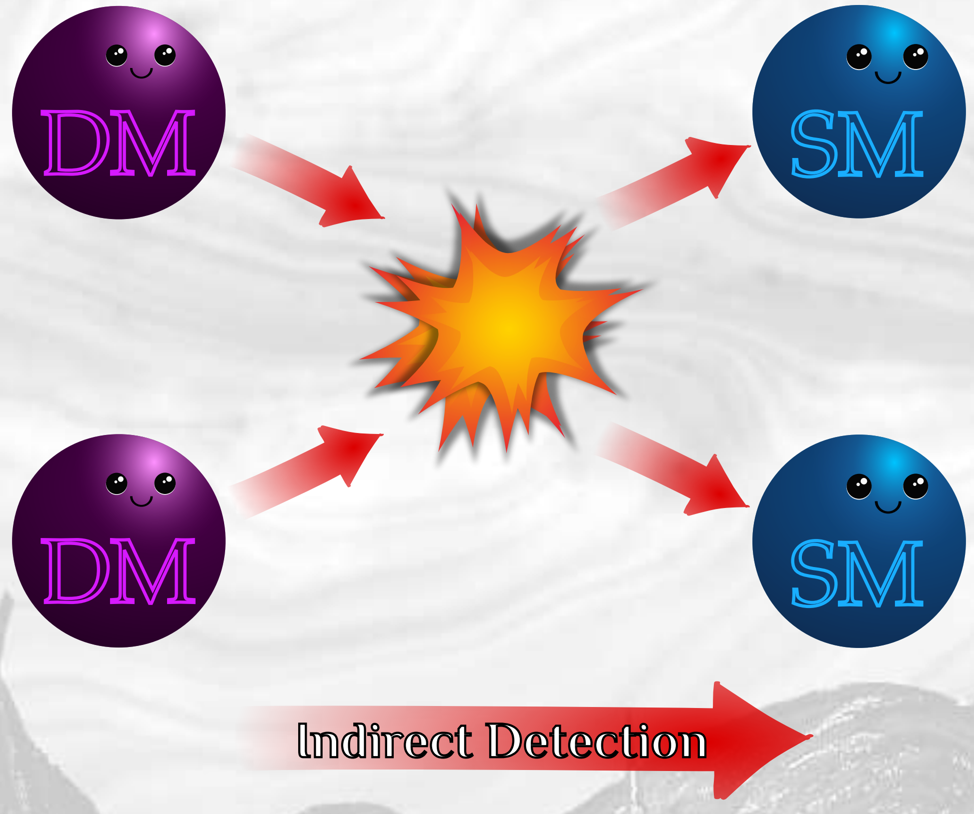
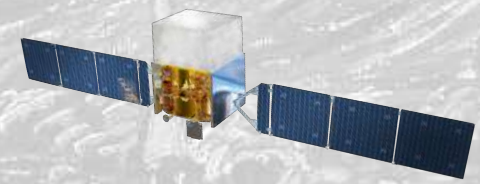


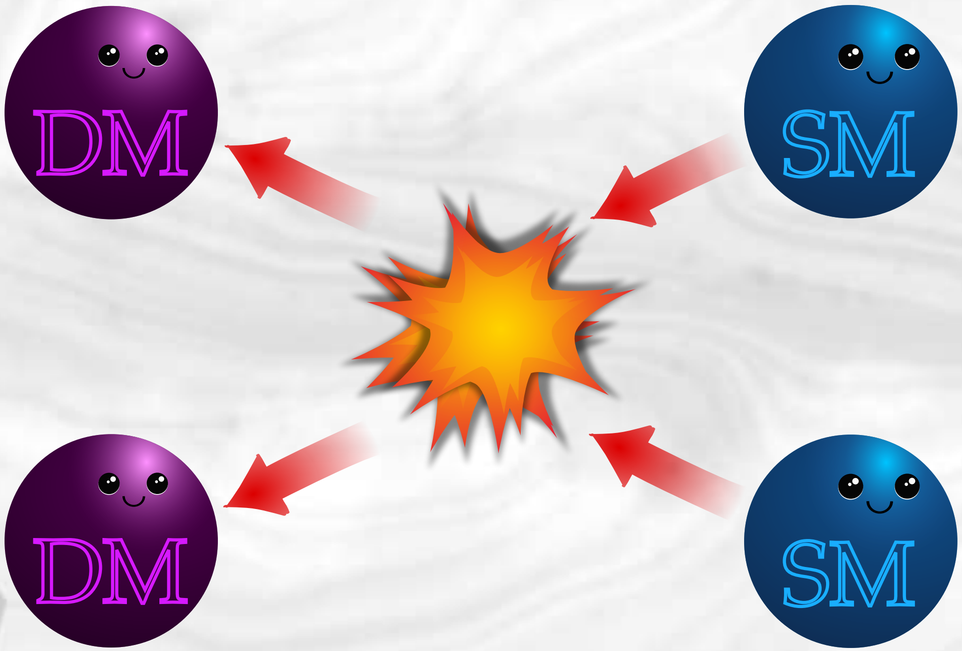
Annihilation



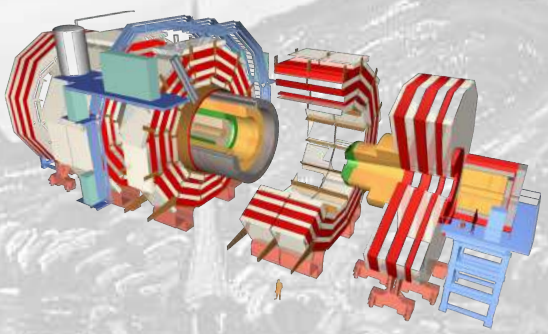
Interlude: Dark Matter

Methods of Detection

Colliders



Production

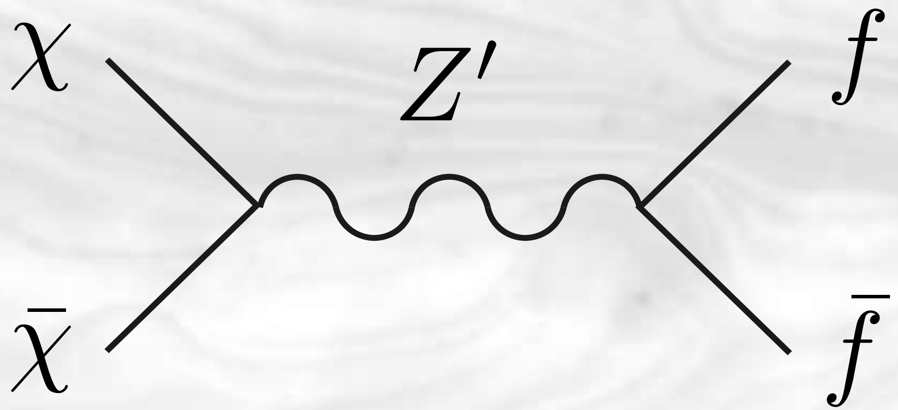


2HDM with $U(1)_X$

Dark Matter

We add a vector-like fermion as a DM candidate charged under $U(1)_X$

In order to maintain the theory anomaly free



It introduces an extra parameter: M_χ

2HDM with $U(1)_X$

Important Parameters

The free parameters of the theory come from...

...the extra scalars

$$\tan\beta := \frac{v_2}{v_1} \qquad v^2 = v_1^2 + v_2^2 = (246 \quad \text{GeV})^2 \qquad v_s$$

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \quad \text{with} \quad \tan 2\alpha = \frac{2(\lambda_3+\lambda_4)v_1 v_2}{\lambda_1 v_1^2 - \lambda_2 v_2^2}$$

2HDM with *U(1)*$_X$

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...the extra gauge boson

kinetic mixing

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} + \frac{\epsilon}{2\, cos\theta_W}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu}$$

$$D_\mu = \partial_\mu + igT^a W_\mu^a + ig'\frac{Q_Y}{2}\hat{B}_\mu + ig_X\frac{Q_X}{2}\hat{X}_\mu$$

coupling constant

$$\delta = \delta(\epsilon_Z)$$

mass mixing

$$M_{Z'} = M_{Z'}(v_s, g_X, \beta) \qquad M_{Z'} \ll M_Z$$

2HDM with *U(1)*$_X$

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...the extra vector-like fermion

$$M_\chi$$

2HDM with $U(1)_X$

Experimental Constraints: Higgs Physics

If we assume that Φ_s does not mix with Φ_1 and Φ_2, the eigenstates masses are given by

$$m_s^2 = \lambda_s v_s^2, \quad \longrightarrow \text{Heavy scalar}$$

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

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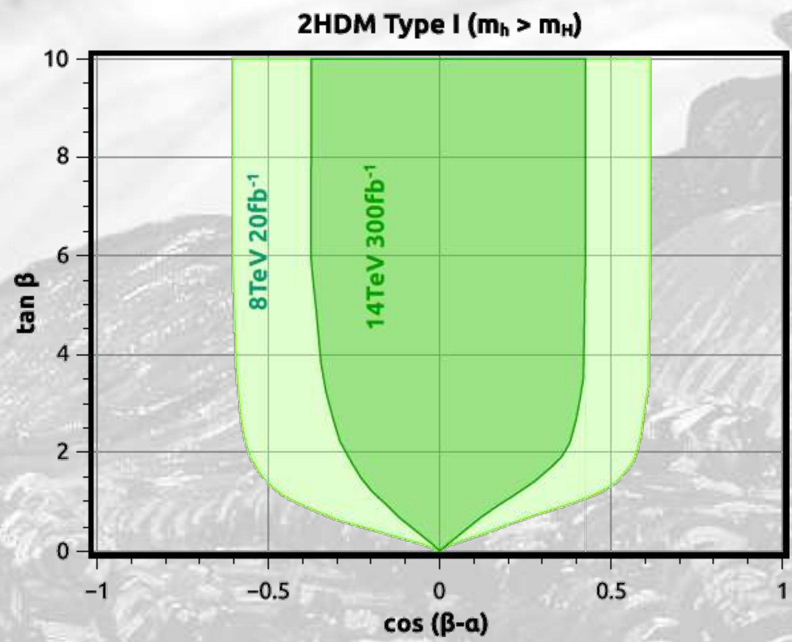
In 2HDMs the limits are usually expressed in terms of this plot, valid for new Higgs more massive than the SM one.
For this **UV complete** family of models we are going to need more, due to the interesting phenomenology.

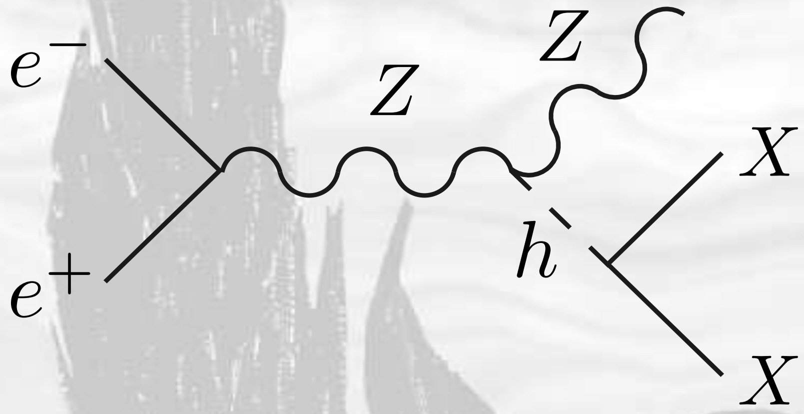


2HDM with $U(1)_X$

Experimental Constraints: Higgs Physics

There were several experiments at LEP looking for $Z+$ scalar decaying into fermions or invisibly.

These searches did not cover fermions with small invariant masses (from a light Z'), so we focus on invisible decays.



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

$BR(h \to \text{inv}) \approx 1$

2HDM with $U(1)_X$

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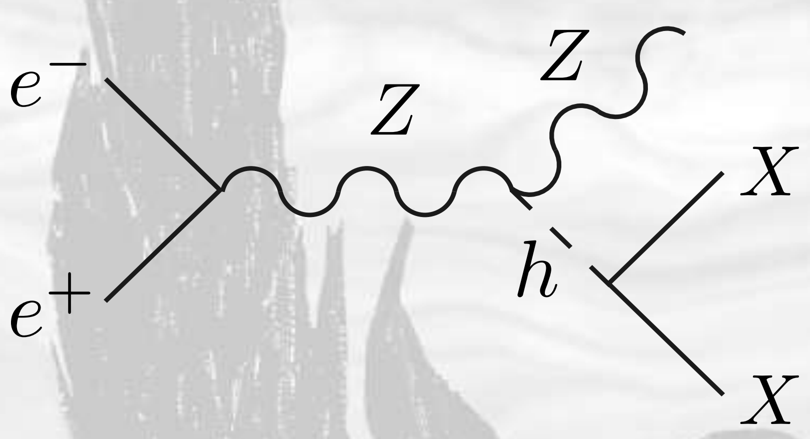

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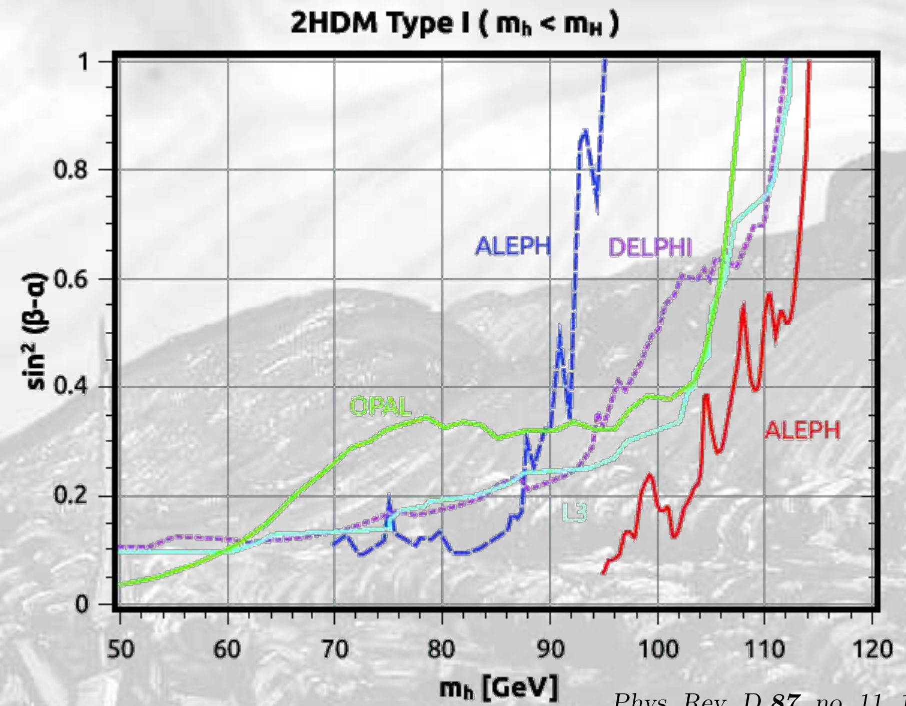

Phys. Rev. D **87**, no. 11, 115009 (2013)

2HDM with $U(1)_X$

Experimental Constraints: Higgs Physics

Thanks to the accurate Higgs branching ratios measurements performed by the Higgs Working Group @ LHC...

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%

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$\tau^+\tau^-$	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%

... we can constrain the parameters of these models

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

enforcing

$$\frac{\Gamma(H \to ZZ' \to 4\ell)}{\Gamma_{\text{total}}} \quad \text{with} \quad \Gamma_{\text{total}} = 4.1\,\text{MeV}$$

to match the measured value within the errors.

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

one needs to choose a model

2HDM with $U(1)_X$

Experimental Constraints: Meson Decays

If kinematically allowed, rare mesons decays can also constrain these models

Rare K Decays

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

$$\delta \lesssim \frac{2 \times 10^{-2}}{\sqrt{BR(Z' \to l^+ l^-)}},$$

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

Rare B Decays

$$BR(B \to K Z') \simeq 0.1 \delta^2$$

$$\delta \lesssim \frac{2 \times 10^{-3}}{\sqrt{BR(Z' \to l^+ l^-)}},$$

$$\delta \lesssim \frac{1.2 \times 10^{-2}}{\sqrt{BR(Z' \to \text{missing energy})}}$$

2HDM with $U(1)_X$

Experimental Constraints: Atomic Parity Violation

While high energy colliders experiments provide a direct observation of new particles, low energy searches provide indirect yet highly precise probes.

2HDM with $U(1)_X$

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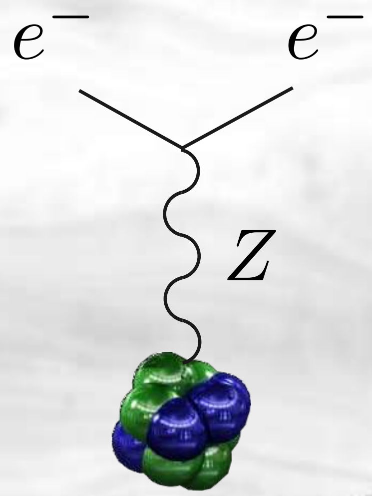
The PNC measurements are interpreted in terms of the weak nuclear charge Q_W

$$Q_W = -N + (1 - 4\sin^2\theta_W)Z + \text{rad. corr.} + \text{New Physics}$$



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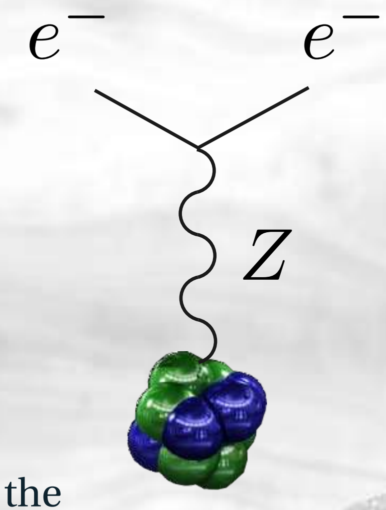

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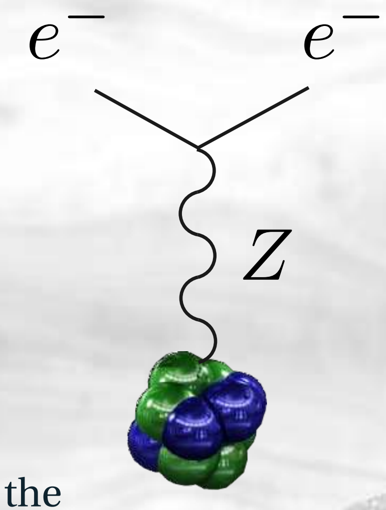

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Because

$$|\Delta Q_W(Cs)| = |Q_W^{\text{exp}} - Q_W^{\text{SM}}| < 0.6$$

we can use the "Master Formula":

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

to impose constraints.

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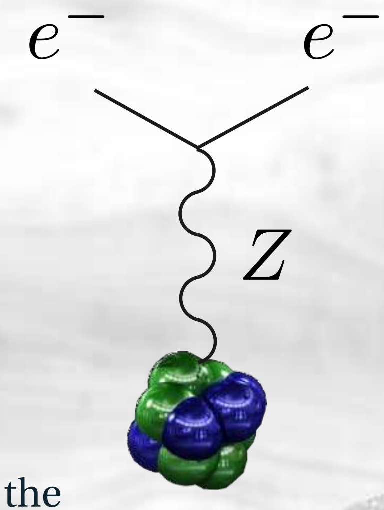

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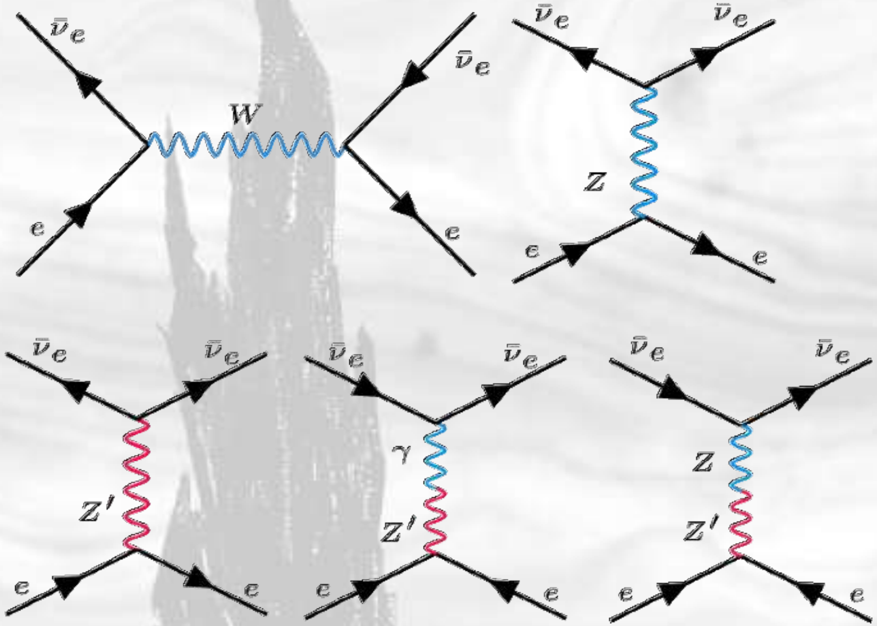
to impose constraints.

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)	$\varepsilon^2 < \frac{62\times10^{-6}}{\delta^2}\left(\frac{(160\text{ MeV})^2+m_{Z_d}^2}{m_Z m_{Z_d}}\right)^2$
Qweak (JLAB)	170 MeV	±0.0007	$\varepsilon^2 < \frac{7.4\times10^{-6}}{\delta^2}\left(\frac{(170\text{ MeV})^2+m_{Z_d}^2}{m_Z m_{Z_d}}\right)^2$
Moller (JLAB)	75 MeV	±0.00029	$\varepsilon^2 < \frac{1.3\times10^{-6}}{\delta^2}\left(\frac{(75\text{ MeV})^2+m_{Z_d}^2}{m_Z m_{Z_d}}\right)^2$
MESA (Mainz)	50 MeV	±0.00037	$\varepsilon^2 < \frac{2.1\times10^{-6}}{\delta^2}\left(\frac{(50\text{ MeV})^2+m_{Z_d}^2}{m_Z m_{Z_d}}\right)^2$

2HDM with $U(1)_X$

Experimental Constraints: Neutrino-Electron Scattering



2HDM with $U(1)_X$

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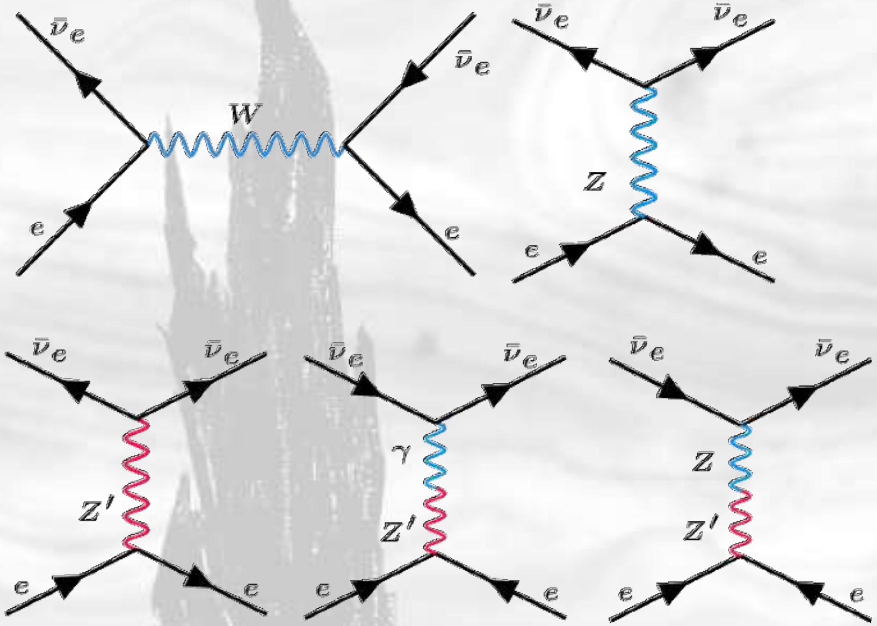

For the case of $U(1)_{B\text{-}L}$

$$\frac{d\sigma}{dE_R} = \frac{g^4_{B-L} m_e}{4\pi E_\nu^2 (m^2_{Z'} + 2 m_e E_R)^2} (2E_\nu^2 + E_R^2 - e E_R E_\nu - m_e E_R)$$

$$\left(\frac{dR}{dE_R}\right)_{NP} = t\, \rho_e \int_{E_\nu^{min}}^{\infty} \frac{d\Phi}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu$$

2HDM with $U(1)_X$

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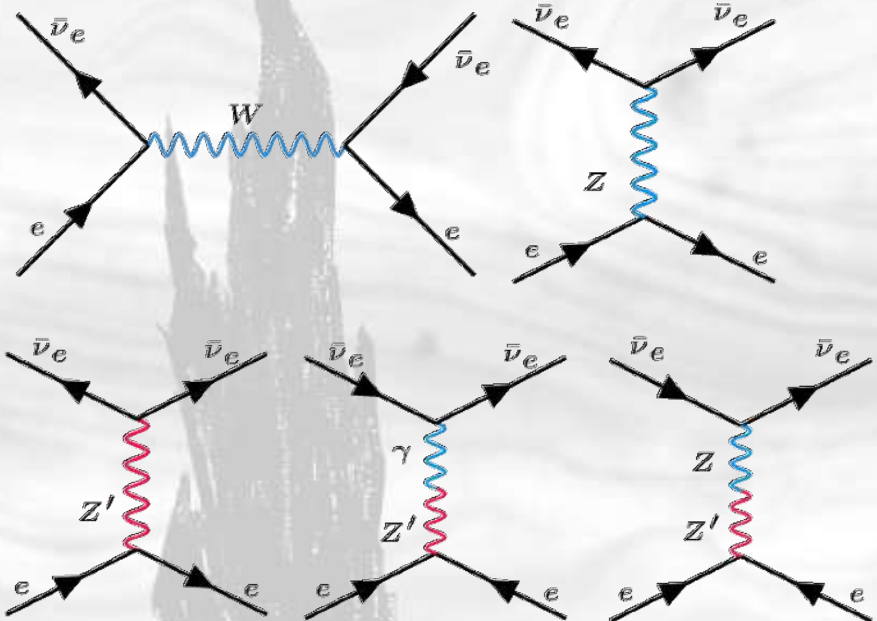

Experiment	Type of neutrino	$\langle E_\nu \rangle$	T
TEXONO-NPCGe [110]	$\bar{\nu}_e$	1–2 MeV	0.35–12 keV
TEXONO-HPGe [111, 112]	$\bar{\nu}_e$	1–2 MeV	12–60 keV
TEXONO-CsI(Tl) [113]	$\bar{\nu}_e$	1–2 MeV	3–8 MeV
LSND [114]	ν_e	36 MeV	18–50 MeV
BOREXINO [115]	ν_e	862 keV	270–665 keV
GEMMA [116]	$\bar{\nu}_e$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

For the case of $U(1)_{B\text{-}L}$

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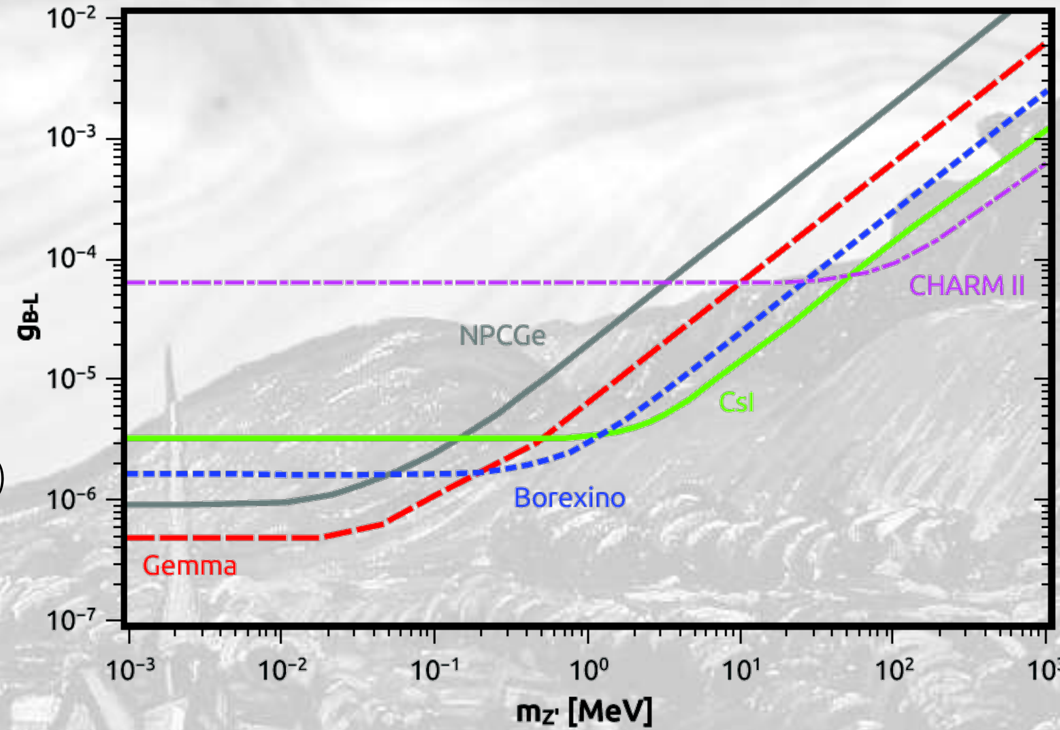
Constraints from neutrino-electron scattering experiments



2HDM with $U(1)_X$

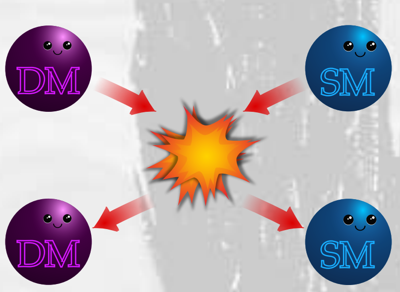
PRELIMINARY

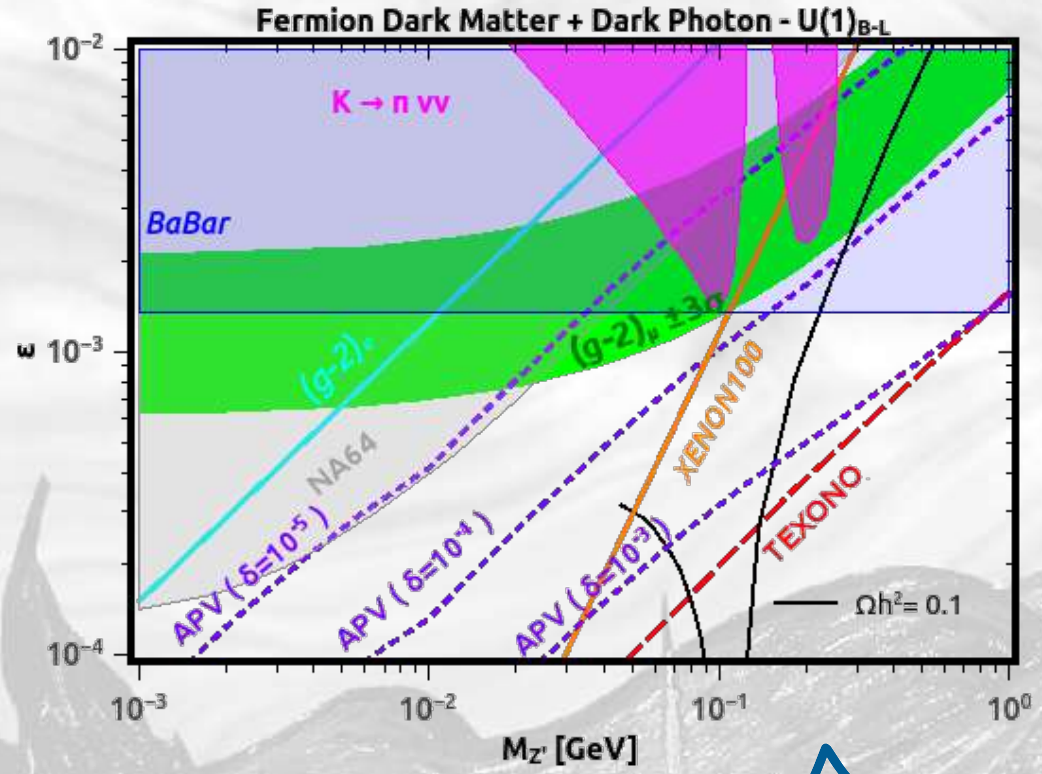
Experimental Constraints: Dark Matter

Example: 50 MeV DM in a 2HDM+$U(1)_{B\text{-}L}$

Relic Density:
Thermally produced

XENON100:
DM-electron scattering





Atomic Parity Violation:
Cesium limits for different
values of mass mixing

TEXONO:
Neutrino-electron scattering

$$g_{B-L} := 1$$

Conclusions

👾 We have shown that it is possible to cure 2HDMs flavor changing interactions from gauge principles while providing neutrino masses through a see-saw mechanism and a dark matter candidate.

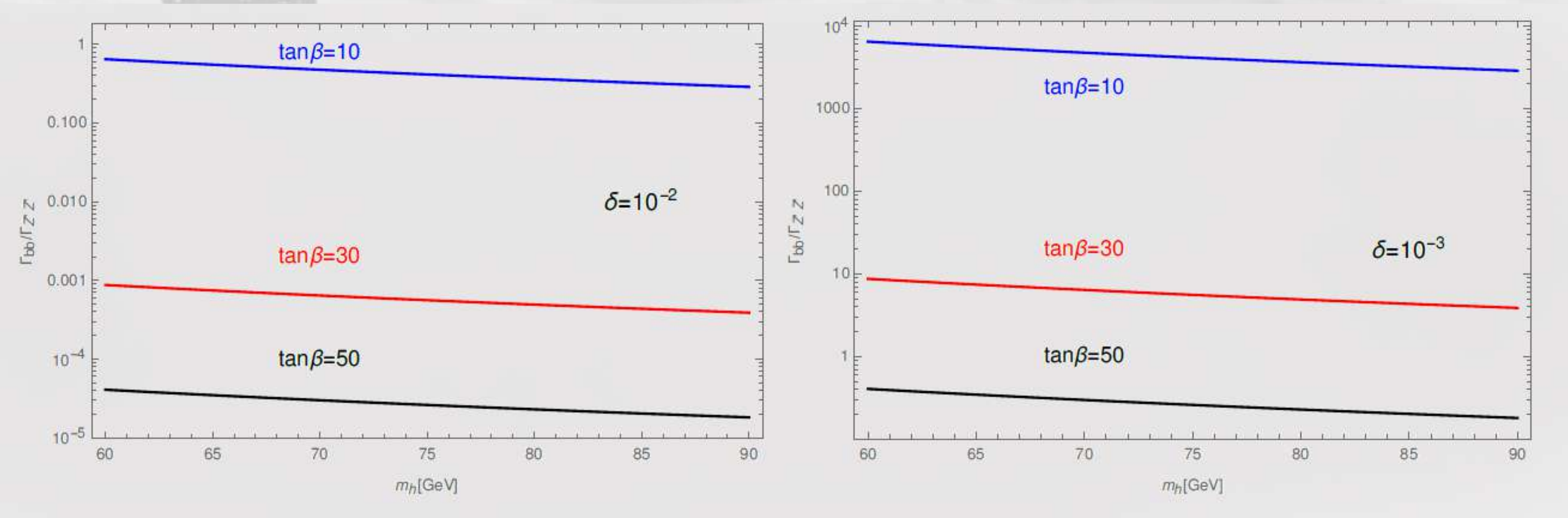
👾 The rich phenomenology that this family of models offer has been explored while trying to remain as general as possible.


Thank you!

Backup Slides

On the robustness of $BR(h \to \text{inv}) \approx 1$

$$\frac{\Gamma_{h\to b\bar{b}}}{\Gamma_{h\to Z'Z'}} = \frac{12m_b^2}{m_h^2}\frac{1}{(\delta\tan\beta)^4}\left(\frac{\cos\beta\sin\beta}{\cos^3\beta\cos\alpha - \sin^3\beta\sin\alpha}\right)^2\left(\frac{\cos\alpha}{\sin\beta}\right)^2$$



Backup Slides

Dark photon searches in comparison with neutrino-electron scattering