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Dissecting a derivative effective operator: 3-loop neutrino masses and their links to dark matter

Maximiliano A. Rivera U*

Universidad Técnica Federico Santa María, Chile

*In collaboration with Michael Gustafsson y José M. No


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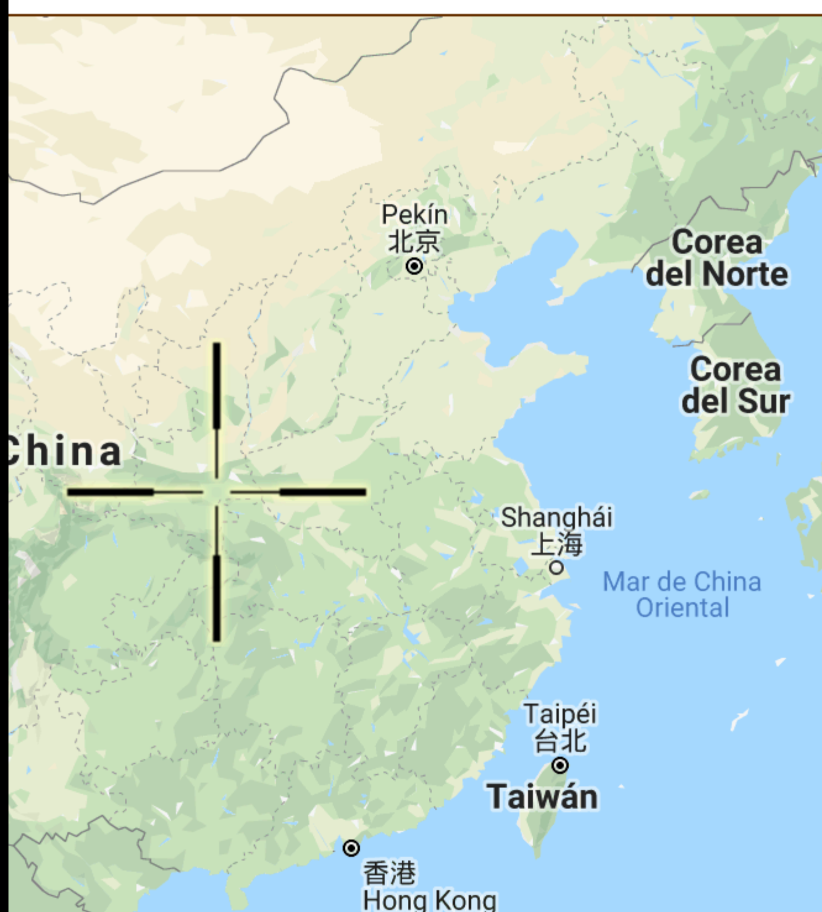
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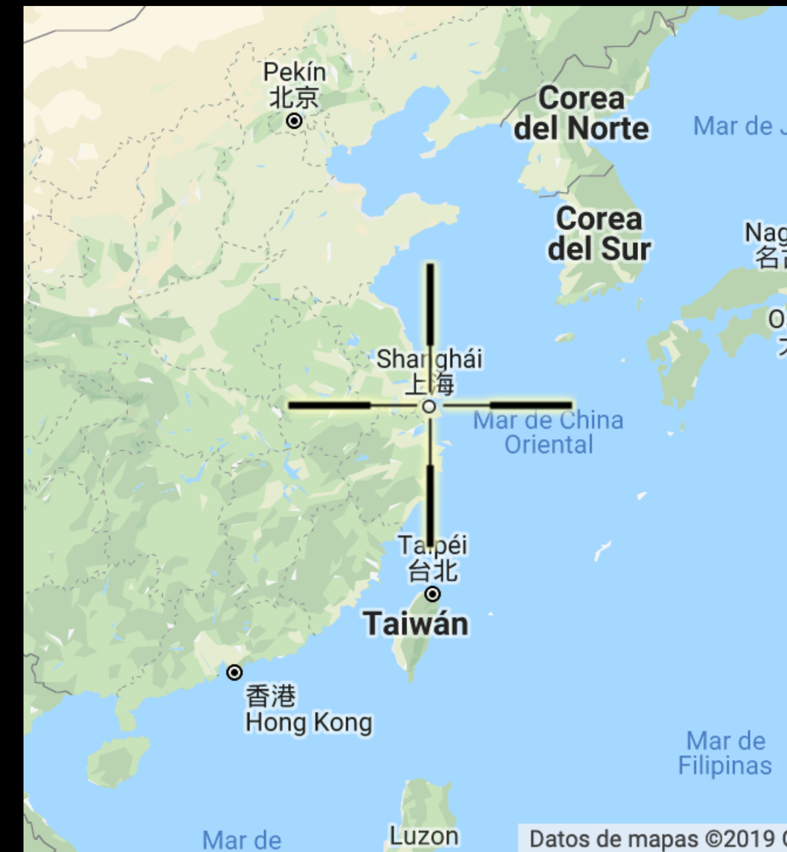
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Open Questions

- What is the mechanism that gives small neutrinos masses?
- What is its particle nature: Dirac or Majorana?
- What is the origin of the flavor mixing structures?

Dark Matter

- What is its nature?
  - Few properties known, but many candidates

How to make a model linking these questions?

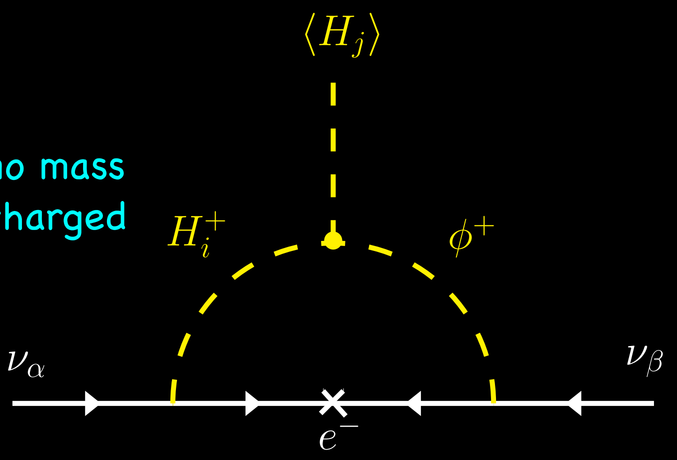
What are its experimental tests/constraints?

History

History

Zee Model

The first radiative neutrino mass mechanism: extra single charged scalar singlet + a doublet



A. Zee, **Phys. Lett. B 93** (1980) 389

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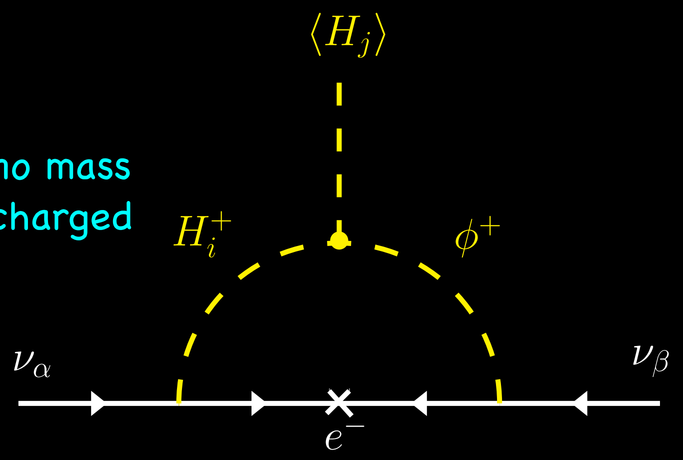

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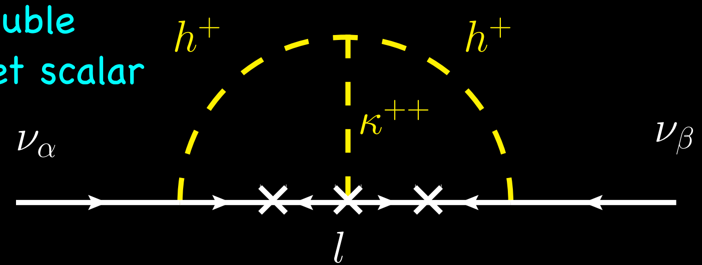
Zee-Babu Model

An extra single and double charged complex singlet scalar



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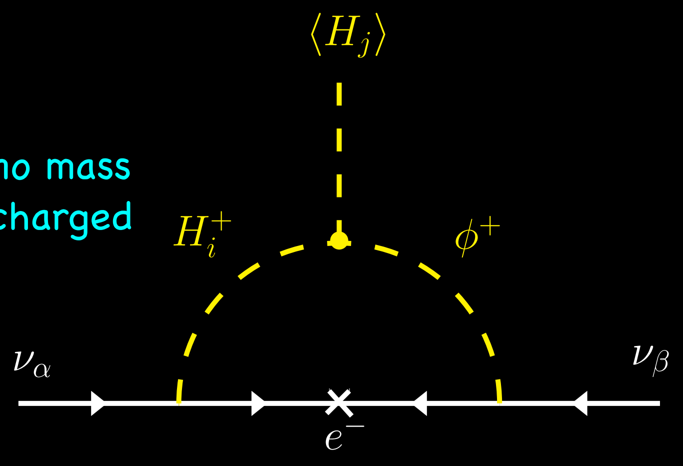

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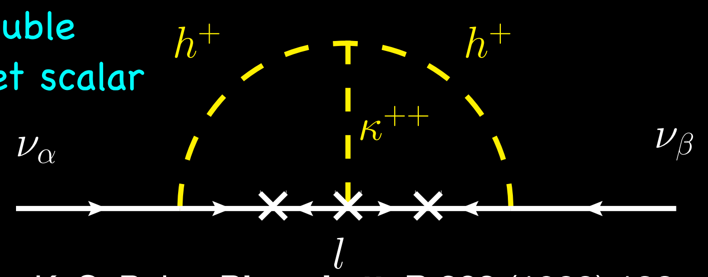

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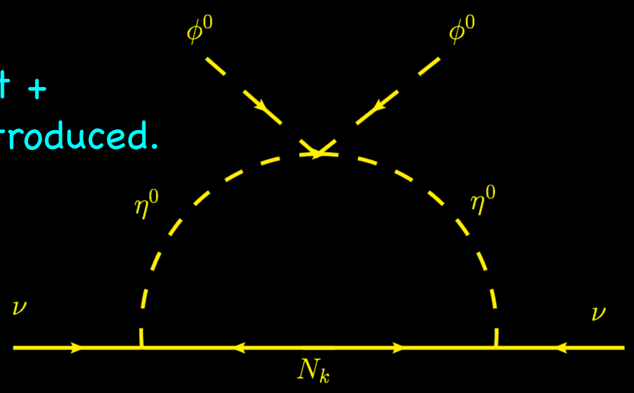
An extra Inert Doublet + RH hevy neutrino is introduced. Scotogenic Model



Ernest Ma, **Phys.Rev. D73 (2006) 077301**

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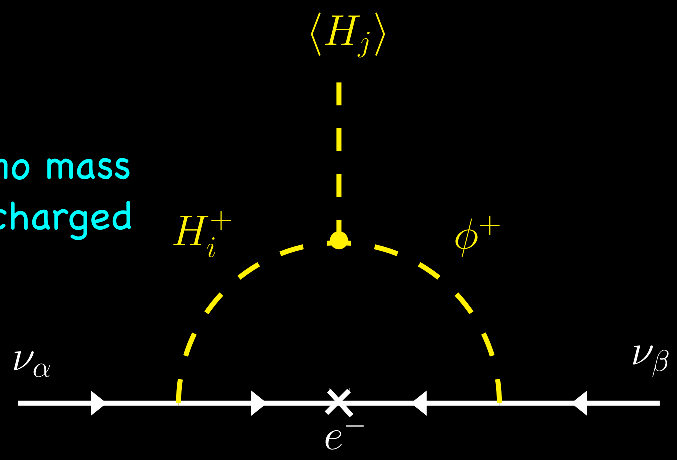

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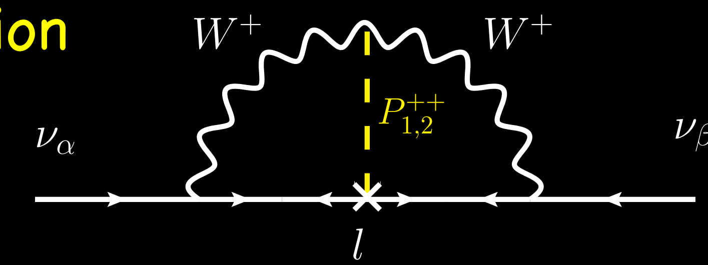
Asiatic Collaboration

A UV completion of a new effective operator is introduced.



C. S. Chen, C. Q. Geng & J. N. Ng, **Phys. Rev. D 75** (2007) 053004

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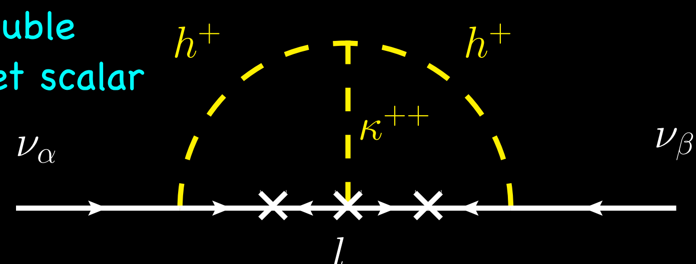

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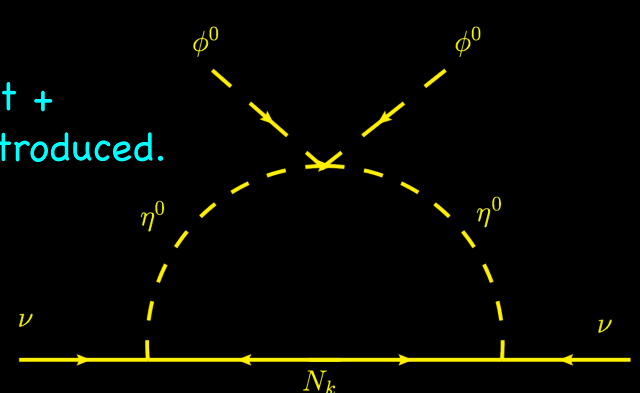

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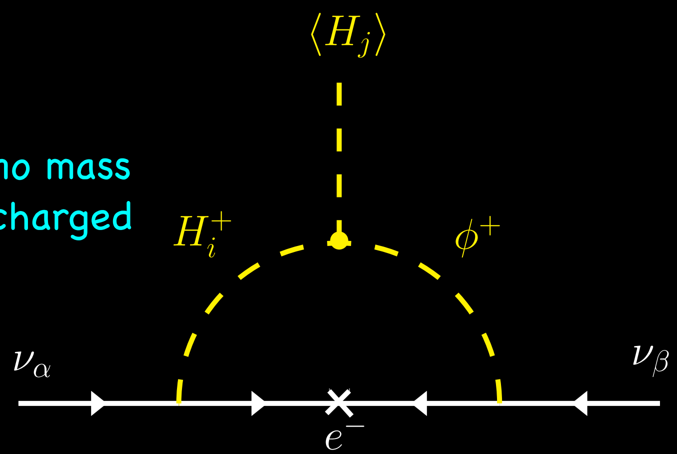

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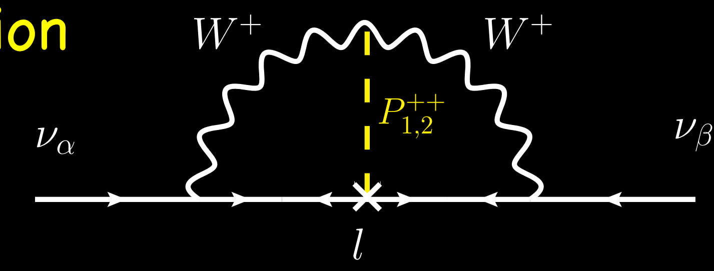

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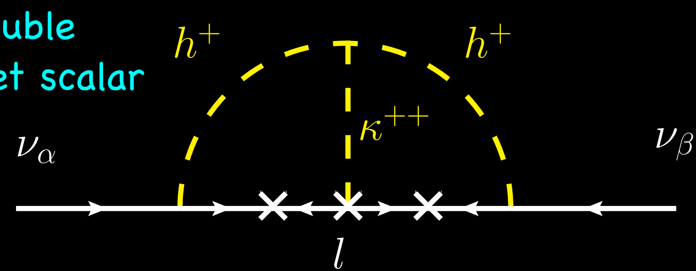

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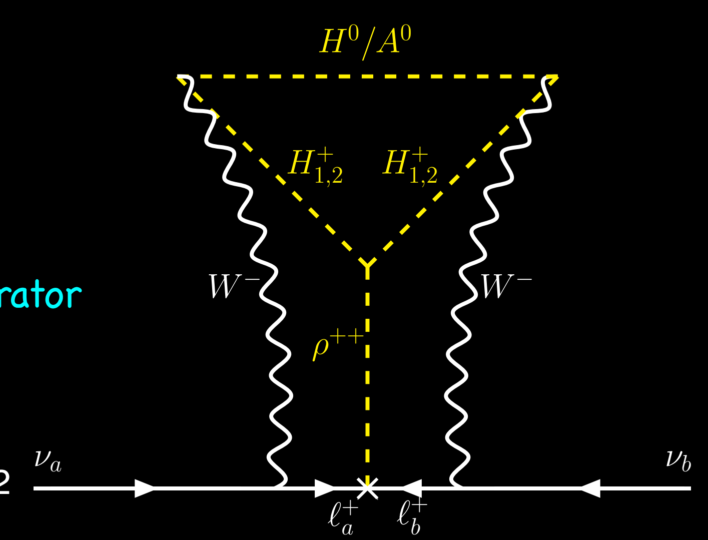
Cocktail Model

A non-trivial realisation of scotogenic model without RH through a non-Weinberg operator



M. Gustafsson, J.M. No, M. Rivera **Phys. Rev. Lett 110** (2013) 211802

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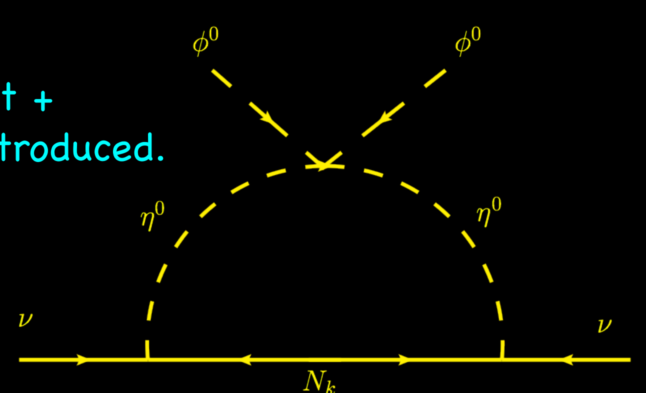

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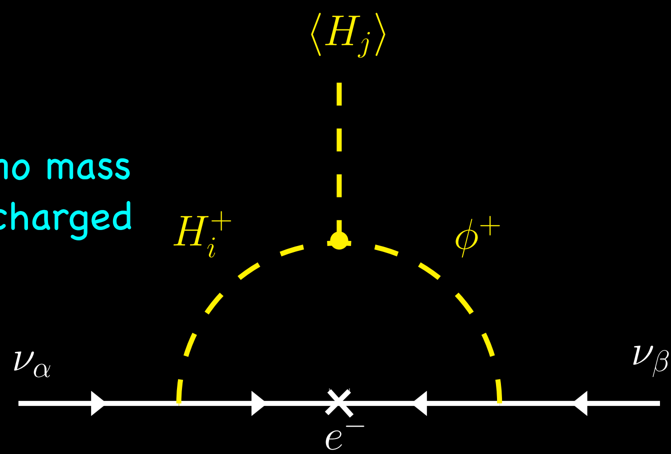

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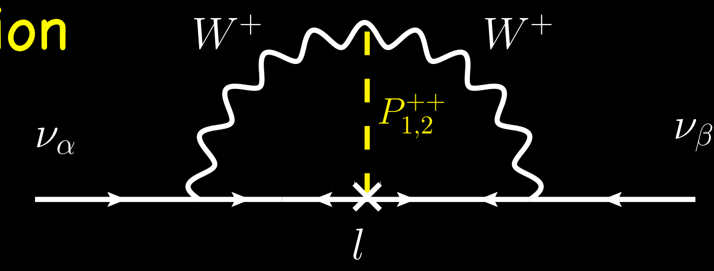

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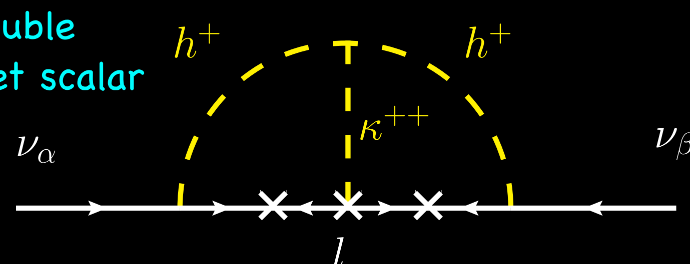

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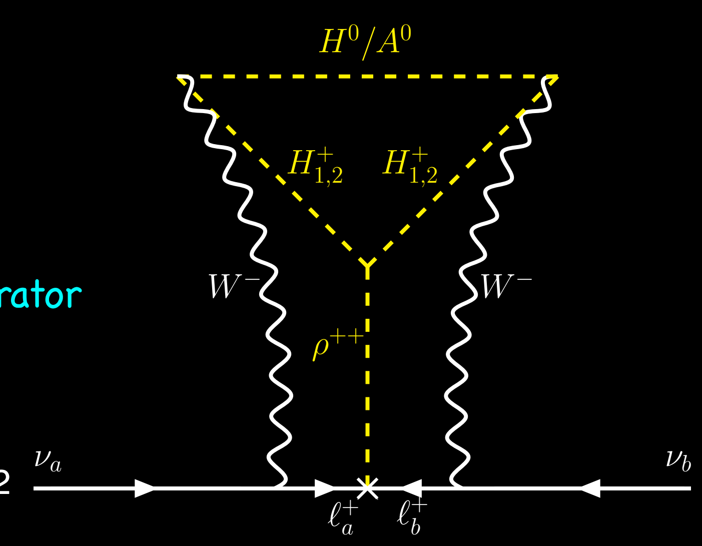

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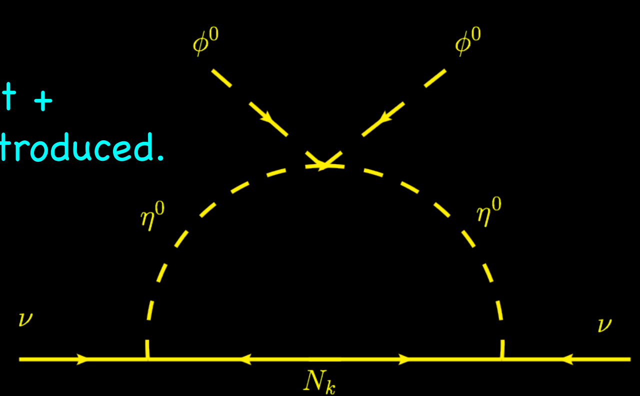
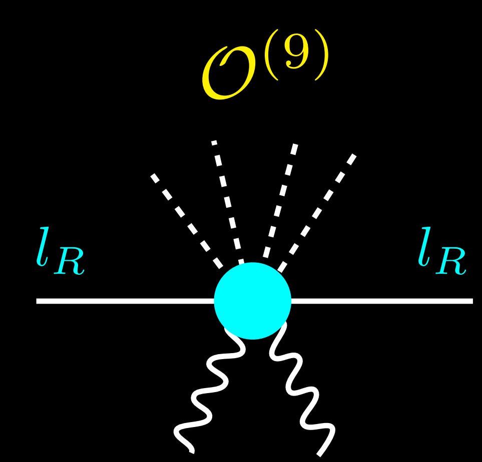


Ernest Ma, **Phys.Rev. D73 (2006) 077301**

Spanish Collaboration

An study of effective operators involve gauge boson is given



Francisco del Aguila, et al
JHEP 1205 (2012) 133

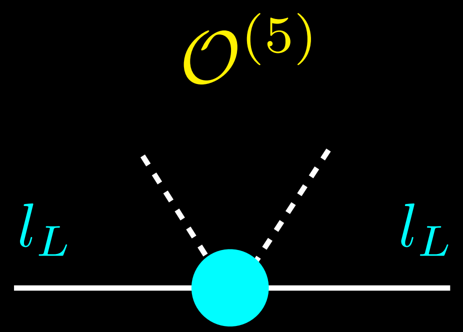
Effective Operator

Neutrino Mass Generation

l_R

Effective Operator

Neutrino Mass Generation



Steven Weinberg
Phys.Rev.Lett 43 (1979) 1566

Tree Level

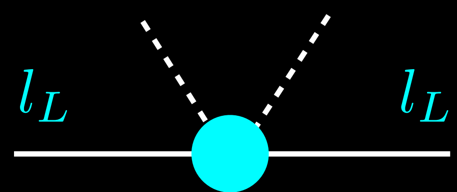
$$(m_\nu)_{ab} \propto \frac{v^2}{\Lambda} C^{(5)}_{ab}$$

l_R

Effective Operator

Neutrino Mass Generation

$\mathcal{O}^{(5)}$



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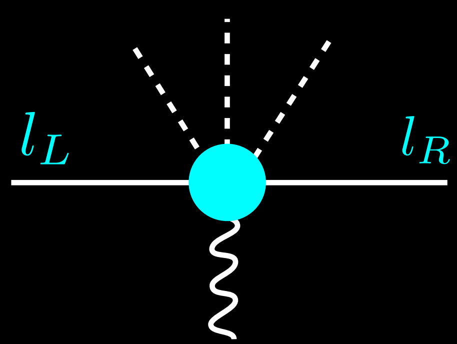
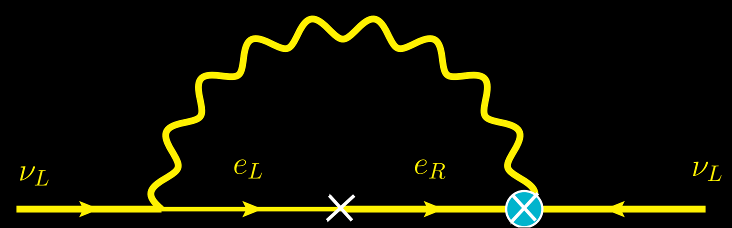




$$(m_\nu)_{ab} \propto \frac{v}{16\pi^2\Lambda}(m_a C^{(7)}_{ab} + m_b C^{(7)}_{ba})$$

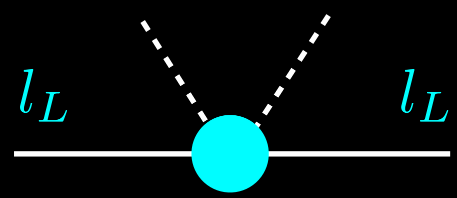
Francisco del Aguila, et al,
JHEP 1206 (2012) 146

l_R

Effective Operator

Neutrino Mass Generation

$\mathcal{O}^{(5)}$



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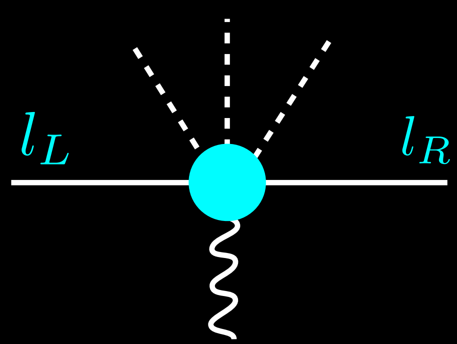

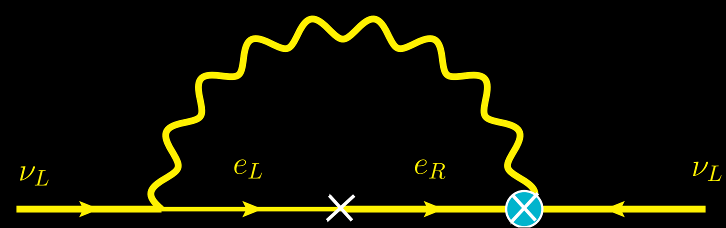

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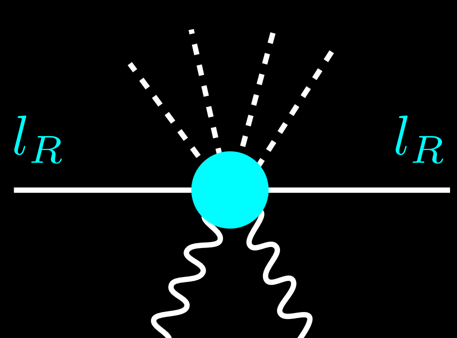
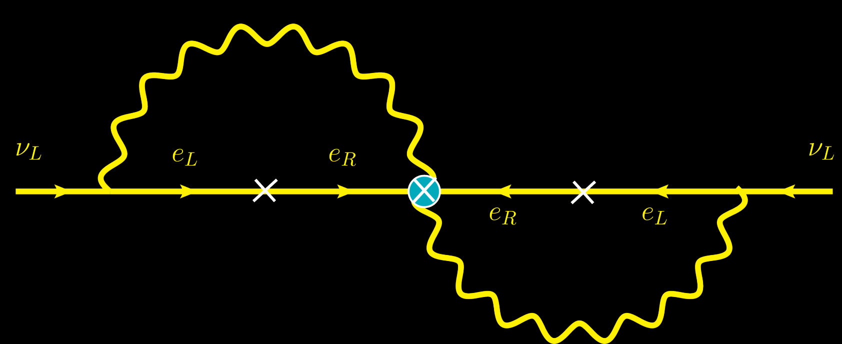
Francisco del Aguila, et al,
JHEP 1206 (2012) 146

$\mathcal{O}^{(9)}$

$$C_{ab} \bar{l^c}_{R_a} l_{R_b} [(D_\mu H)^T i\sigma_2 H]^2$$





$$(m_\nu)_{ab} \propto \frac{1}{(16\pi^2)^2 \Lambda} m_a m_b C^{(9)}_{ab}$$

Mass Matrix Structure <-> Flavour Mixing

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$$U = \text{Diag}\left(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1\right) \times \begin{pmatrix} c_{13}c_{12} & -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} \\ c_{13}s_{12} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} \\ s_{13}e^{-i\delta} & s_{23}c_{13} & c_{23}c_{13} \end{pmatrix}$$

2 Majorana phases	3 Mixing Angles	1 CP phase
α_1, α_2	$\theta_{12}, \theta_{13}, \theta_{23}$	δ

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2 Majorana phases	3 Mixing Angles	1 CP phase
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The neutrino mass matrix, can be diagonalized as follow:

$$m^\nu = U^T\, m_D^\nu\, U$$ with $$m_D^\nu = \mathrm{Diag}\,(m_1, m_2, m_3)$$

$$m_D^\nu = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

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Texture

$$\begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix}$$

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2 Majorana phases α_1, α_2

3 Mixing Angles $\theta_{12}, \theta_{13}, \theta_{23}$

1 CP phase δ

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Mass Matrix Structure <-> Flavour Mixing

$$U = \mathrm{Diag}\left(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1\right) \times \begin{pmatrix} c_{13}c_{12} & -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} \\ c_{13}s_{12} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} \\ s_{13}e^{-i\delta} & s_{23}c_{13} & c_{23}c_{13} \end{pmatrix}$$

2 Majorana phases α_1, α_2

3 Mixing Angles $\theta_{12}, \theta_{13}, \theta_{23}$

1 CP phase δ

The neutrino mass matrix, can be diagonalized as follow:

$$m^\nu = U^T\, m^\nu_D\, U$$ with $$m^\nu_D = \mathrm{Diag}\,(m_1, m_2, m_3)$$

$$m^\nu_D = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Texture

$$\begin{pmatrix} m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\tau\mu} & m_{\tau\tau} \end{pmatrix}$$

$$(m_\nu)_{ab} \propto \frac{v^2}{\Lambda} C^{(5)}_{ab}$$

$$(m_\nu)_{ab} \propto \frac{v}{16\pi^2\Lambda}\left(m_a C^{(7)}_{ab} + m_b C^{(7)}_{ba}\right)$$

$$(m_\nu)_{ab} \propto \frac{1}{(16\pi^2)^2\Lambda} m_a m_b C^{(9)}_{ab}$$

M Gustafsson, José M. No and MR

Phys.Rev. D90 (2014) 013012

$$\begin{pmatrix} 0 & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad \begin{pmatrix} 0 & 0 & \times \\ 0 & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad \begin{pmatrix} 0 & \times & 0 \\ \times & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

Effective Operator

Neutrinoless Double beta Decay

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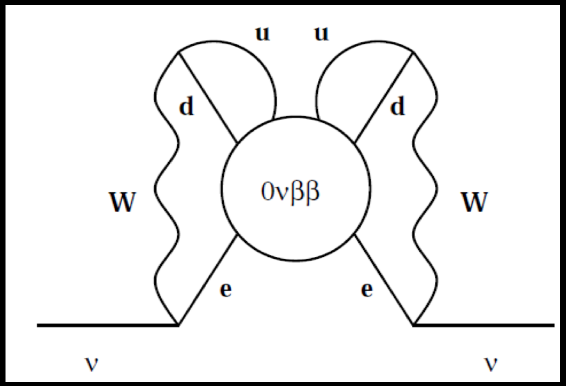
Neutrinoless Double beta Decay

Black box Theorem:

If NLDBD is observed, neutrino has majorana mass

Schechter and J.W.F Valle
Phys.Rev.D 25 (1982) 2951



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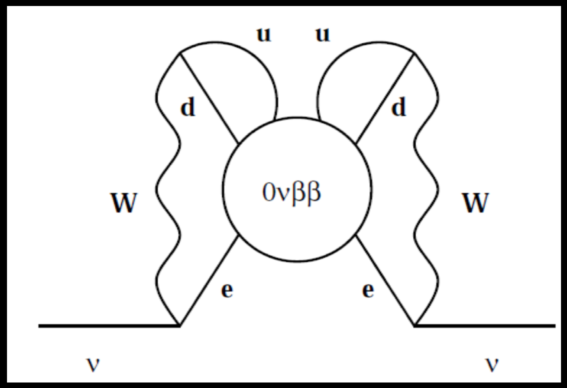

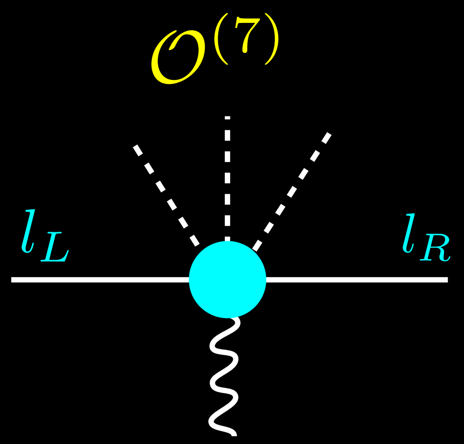

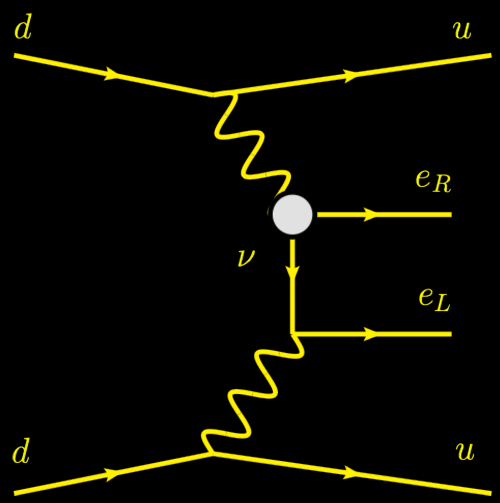

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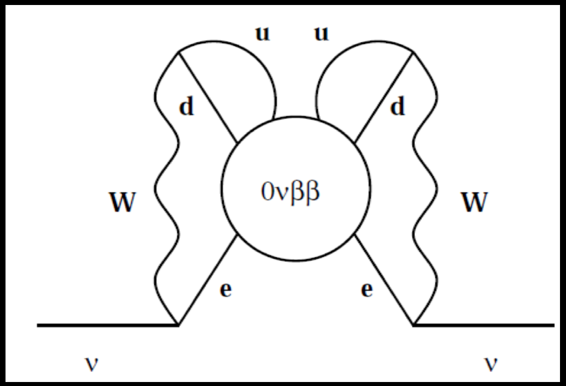

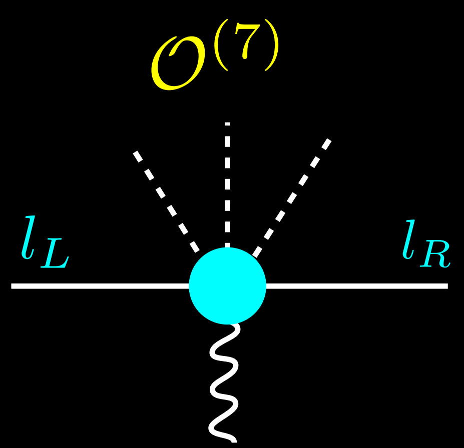

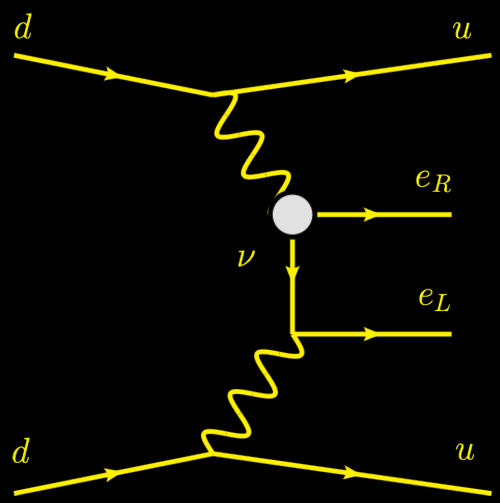

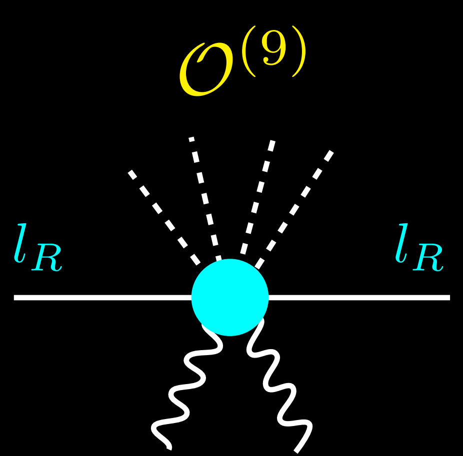

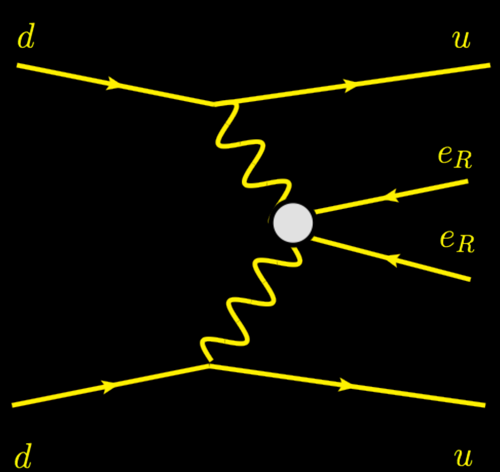

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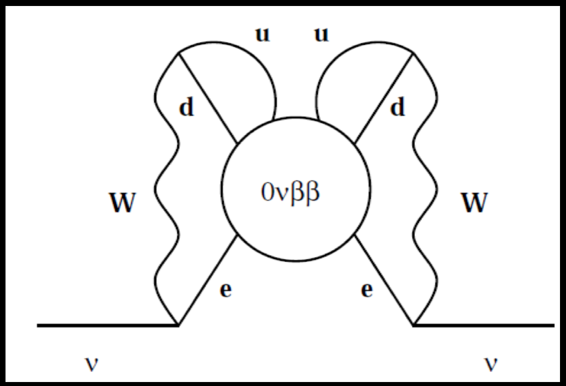
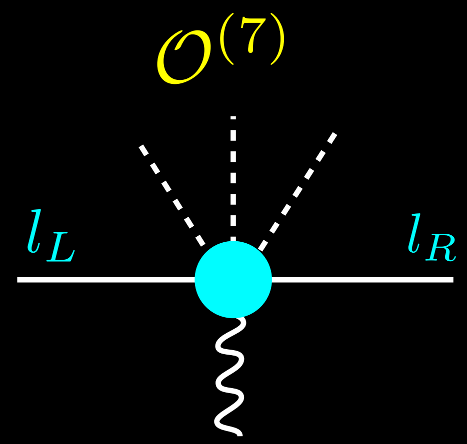
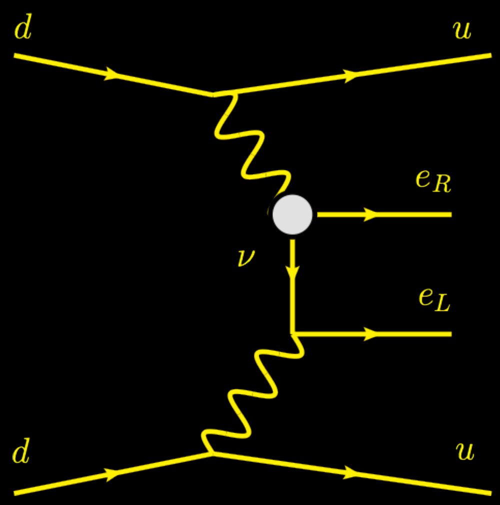
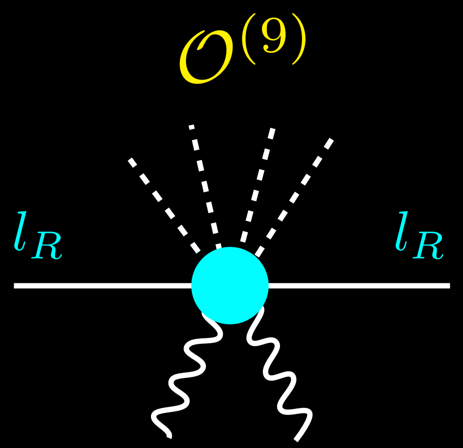
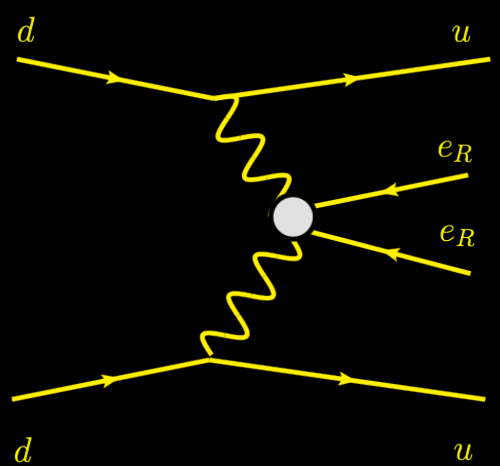






Special Interest:
if polarisation can be measured





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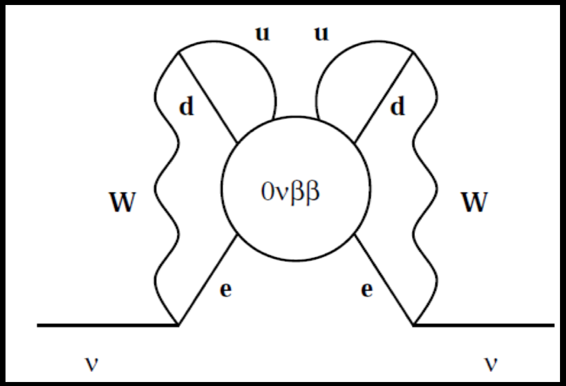

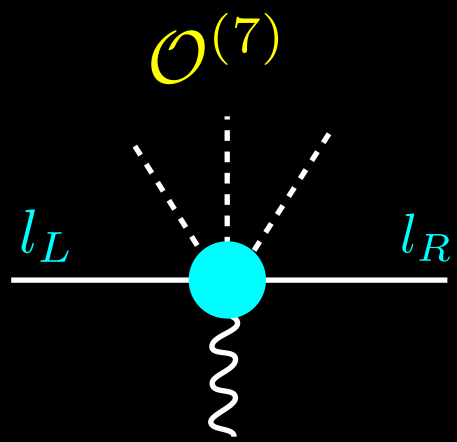

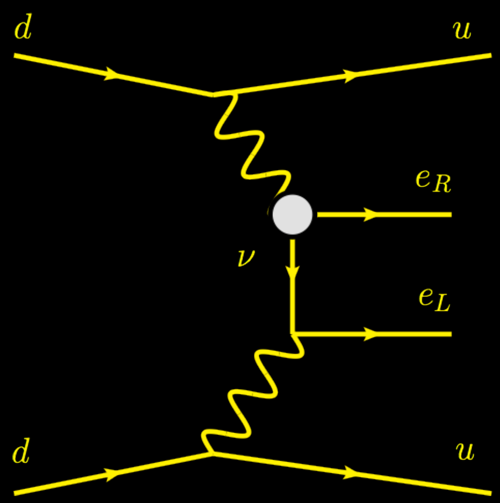

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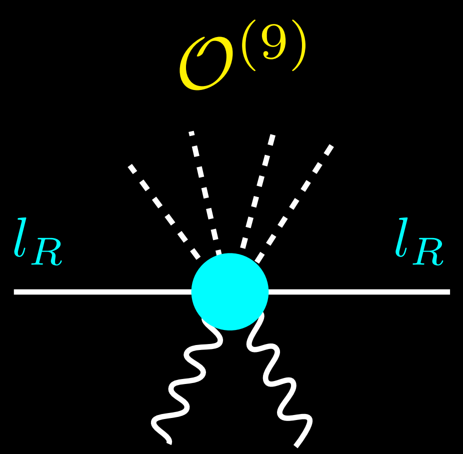

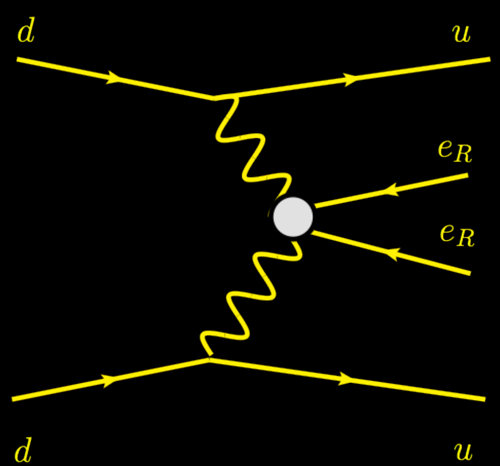

$$\mathcal{A}^{\nu}_{0\nu\beta\beta} \sim \frac{G_F^2}{p_{\text{eff}}^2}|m^{\nu}_{ee}|$$

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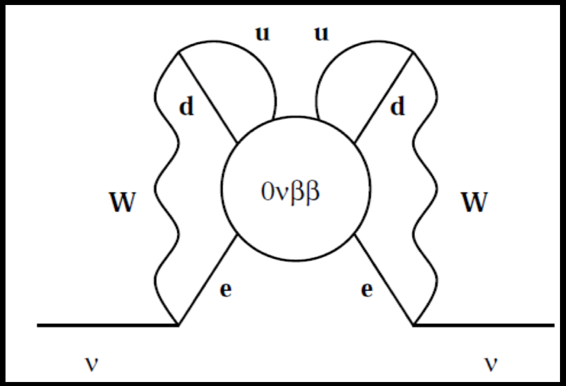
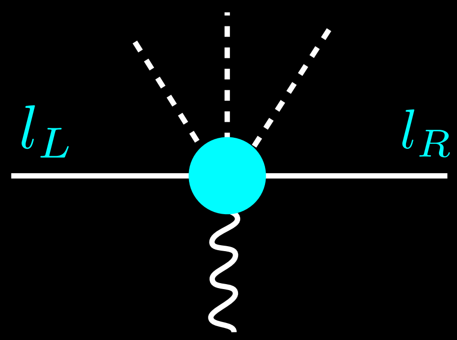
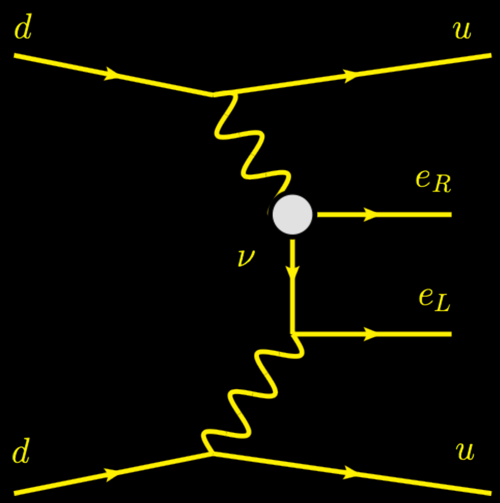
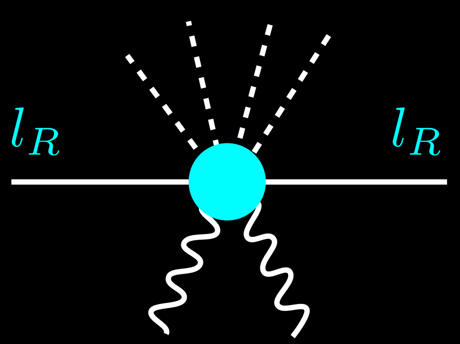


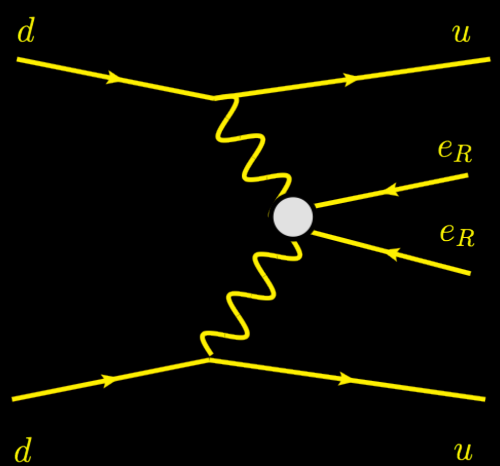
$\mathcal{O}^{(7)}$





$\mathcal{O}^{(9)}$





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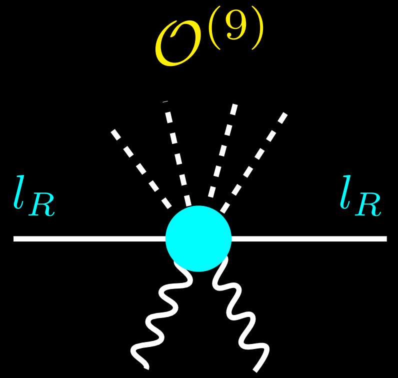
For more details see

Francisco del Aguila, et al,
JHEP 1206 (2012) 146

LFV Operator

$$\mathcal{O}_9 \equiv \overline{\ell^c}_{R_a} \ell_{R_b} \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



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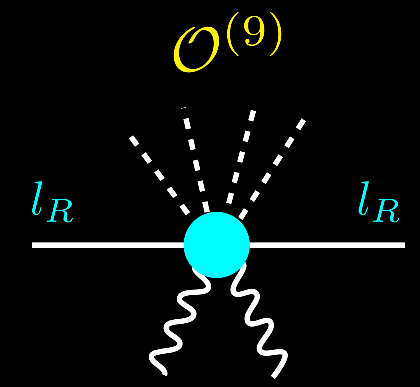

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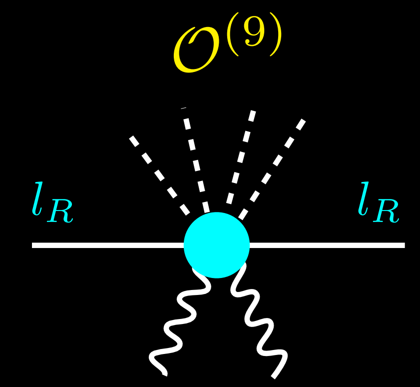

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$$\mathcal{O}^1_{\rm BSM} \equiv \rho \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$

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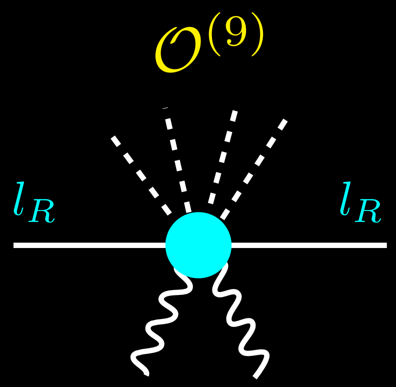

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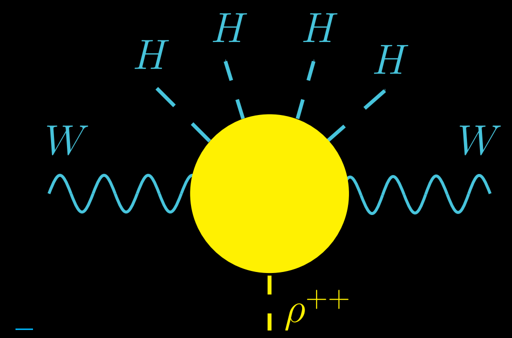

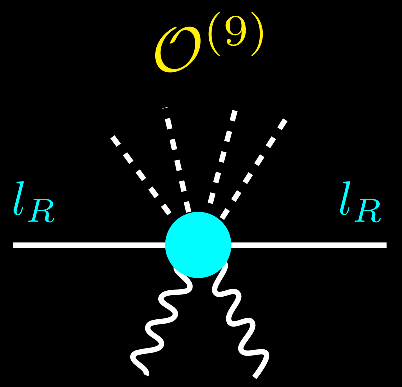

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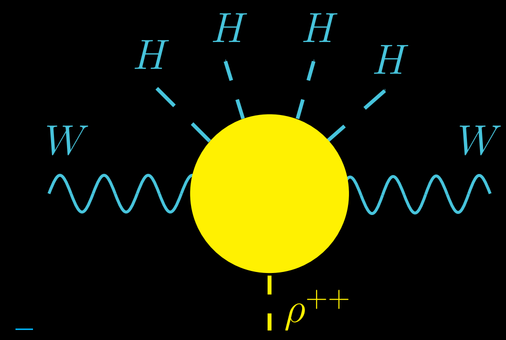

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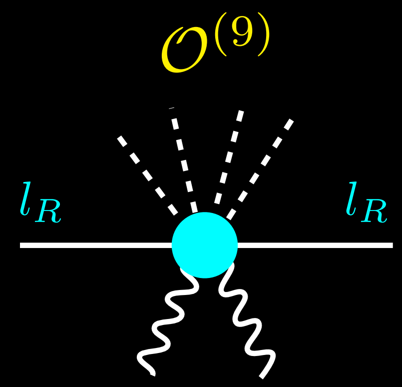

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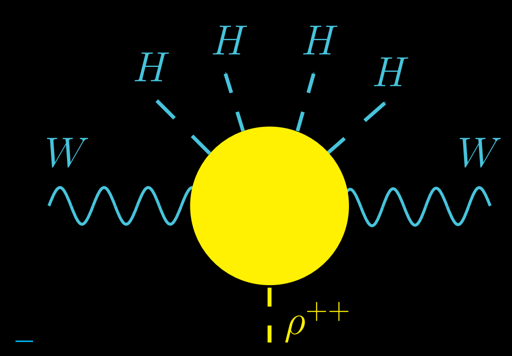

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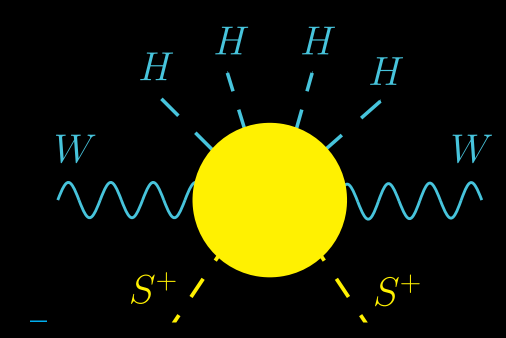

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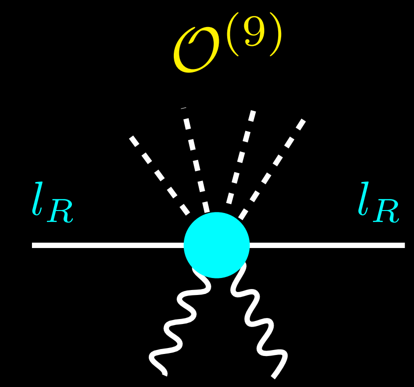

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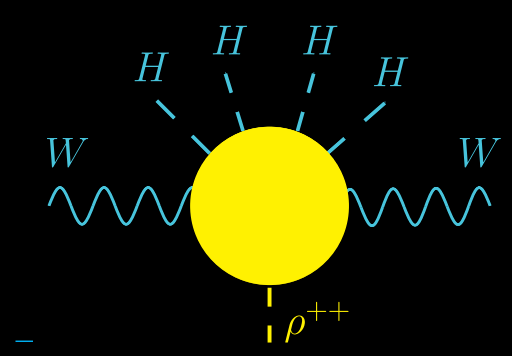

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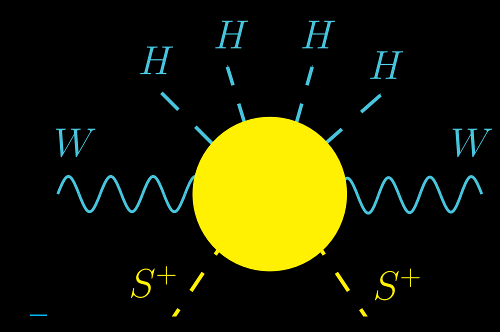

Class 2b

$$\mathcal{O}^{2b}_{\rm BSM} \equiv \bar{\chi}^c \chi \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$

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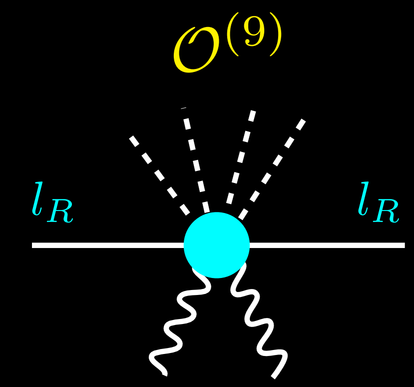

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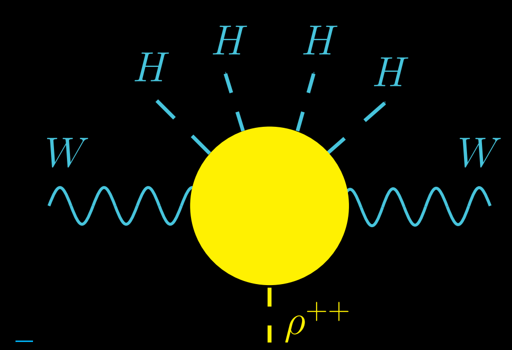

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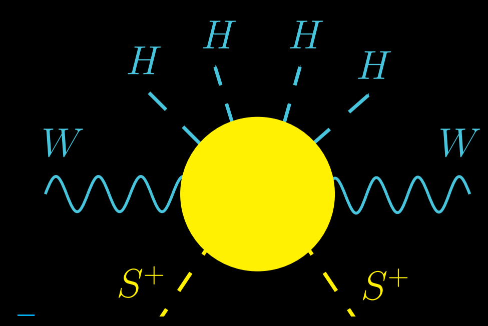

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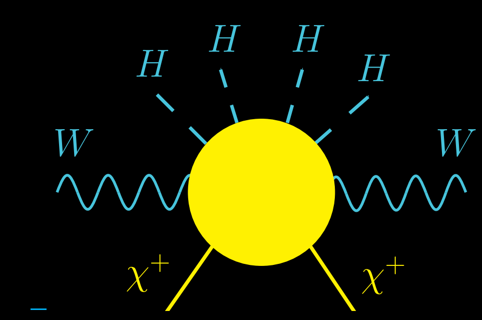

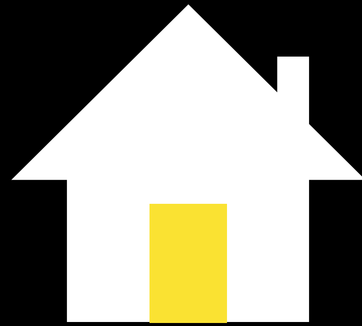

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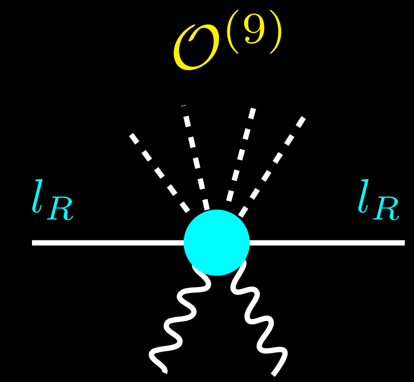

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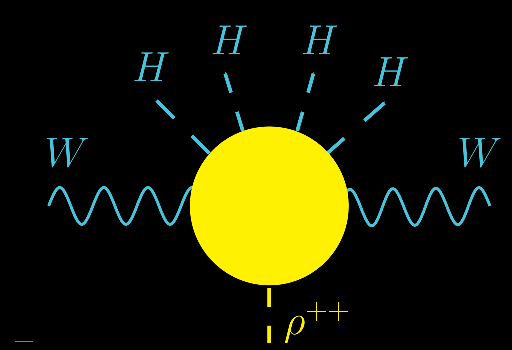

$$C_{ab} \, \overline{\ell^c}_{R_a} \ell_{R_b} \, \rho + \text{h.c.}$$

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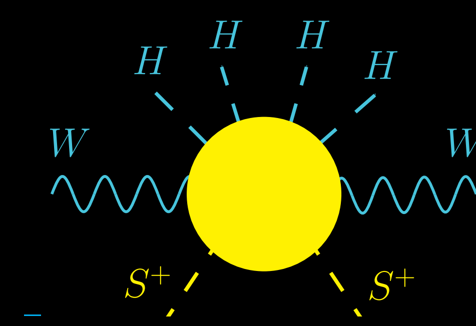

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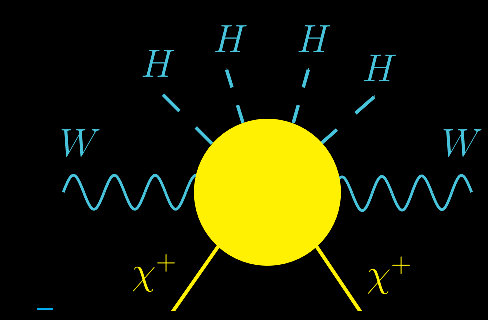

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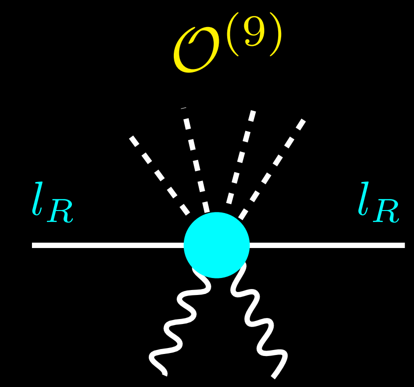

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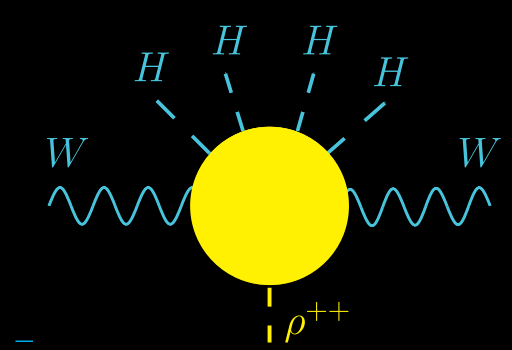

$$C_{ab} \, \overline{\ell^c}_{R_a} \ell_{R_b} \, \rho + \text{h.c.}$$

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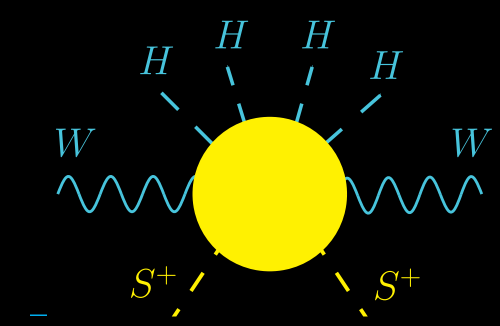

$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$

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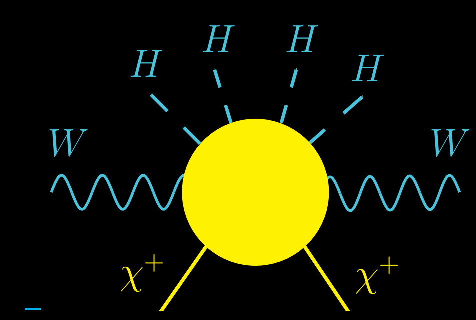
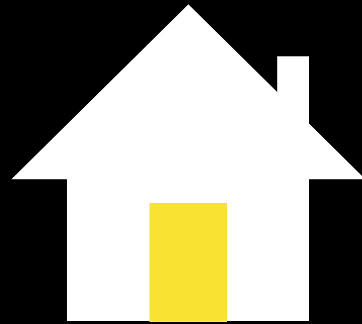
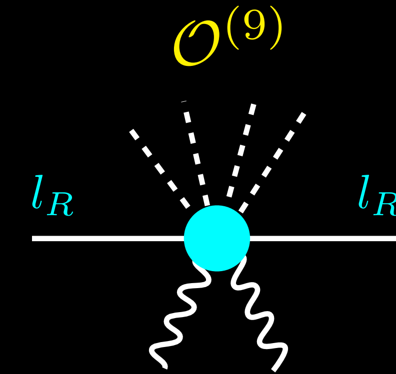
$$\mathcal{O}^{2b}_{\rm BSM} \equiv \bar{\chi}^c \chi \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$





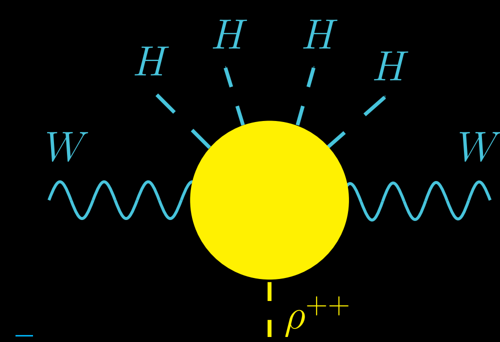
LFV Operator

$$\mathcal{O}_9 \equiv \overline{\ell^c}_{R_a} \ell_{R_b} \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



Class 1

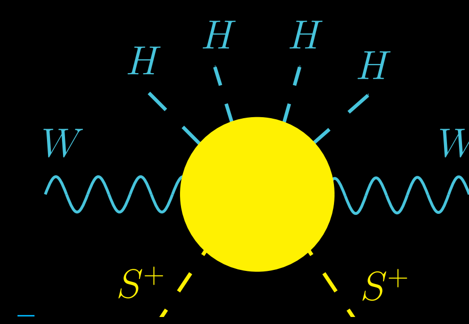
$$\mathcal{O}^1_{\rm BSM} \equiv \rho \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



$$C_{ab} \, \overline{\ell^c}_{R_a} \ell_{R_b} \, \rho + \text{h.c.}$$

Class 2a

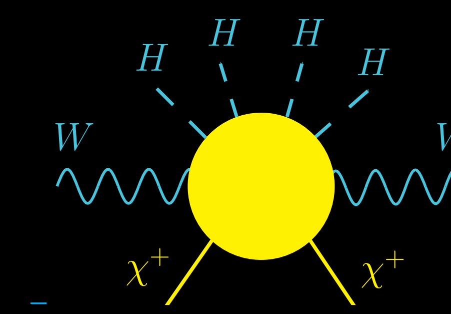
$$\mathcal{O}^{2a}_{\rm BSM} \equiv SS \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$

Class 2b

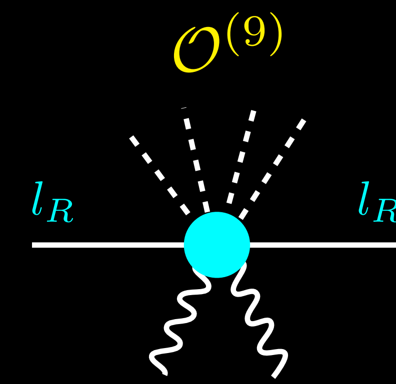
$$\mathcal{O}^{2b}_{\rm BSM} \equiv \bar{\chi}^c \chi \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$

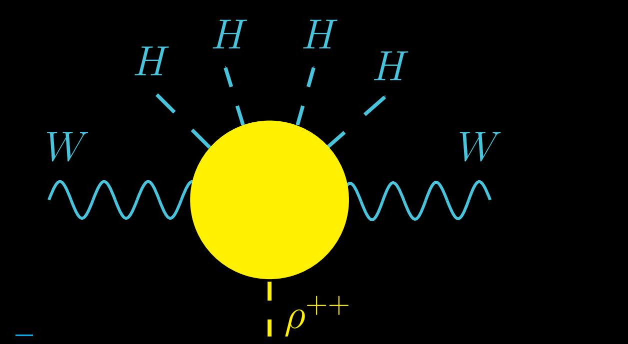
LFV Operator

$$\mathcal{O}_9 \equiv \overline{\ell^c}_{R_a} \ell_{R_b} \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



Class 1

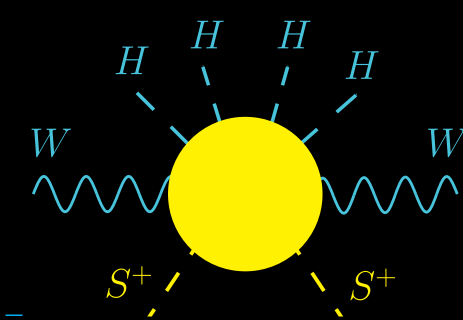
$$\mathcal{O}^1_{\rm BSM} \equiv \rho \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



$$C_{ab} \, \overline{\ell^c}_{R_a} \ell_{R_b} \, \rho + \text{h.c.}$$

Class 2a

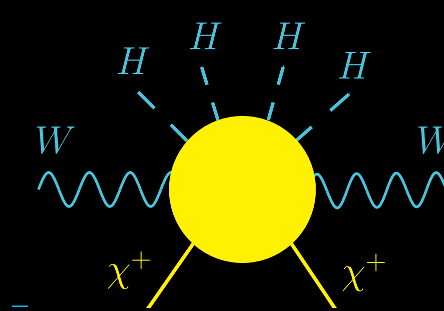
$$\mathcal{O}^{2a}_{\rm BSM} \equiv SS \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



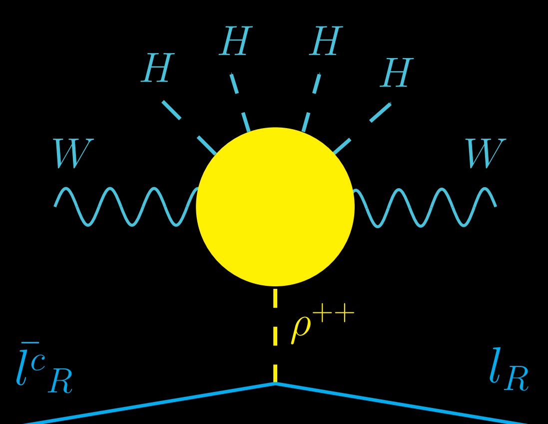
$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$

Class 2b

$$\mathcal{O}^{2b}_{\rm BSM} \equiv \bar{\chi}^c \chi \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$

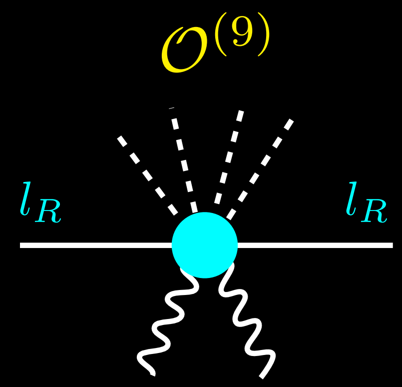


$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$



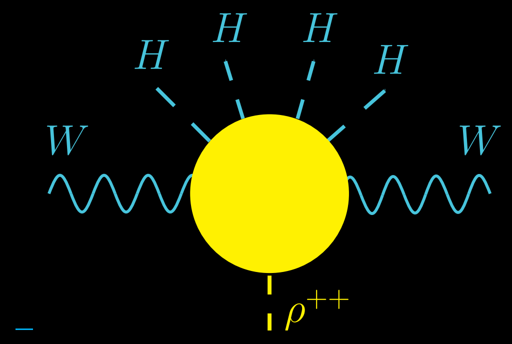
LFV Operator

$$\mathcal{O}_9 \equiv \overline{\ell^c}_{R_a} \ell_{R_b} \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$

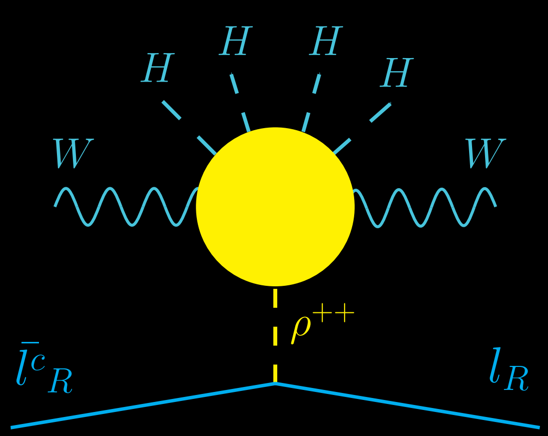


Class 1

$$\mathcal{O}^1_{\rm BSM} \equiv \rho \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$

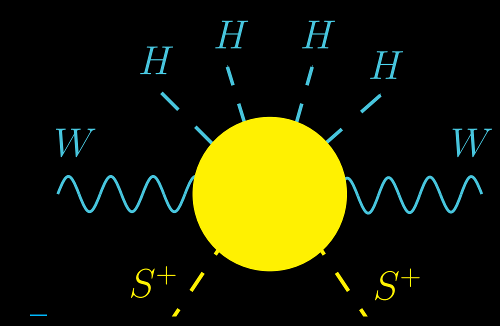


$$C_{ab} \, \overline{\ell^c}_{R_a} \ell_{R_b} \, \rho + \text{h.c.}$$

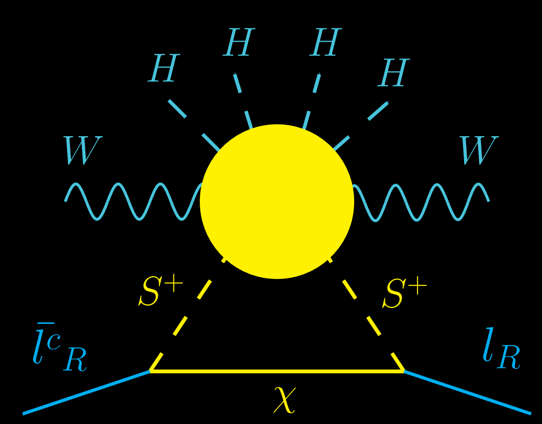


Class 2a

$$\mathcal{O}^{2a}_{\rm BSM} \equiv SS \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$

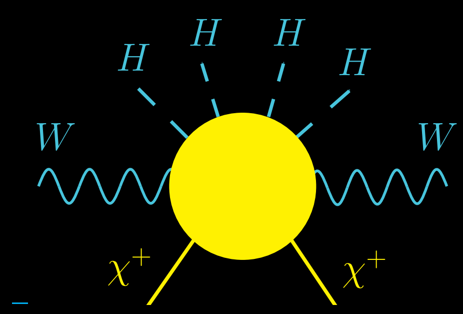


$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$



Class 2b

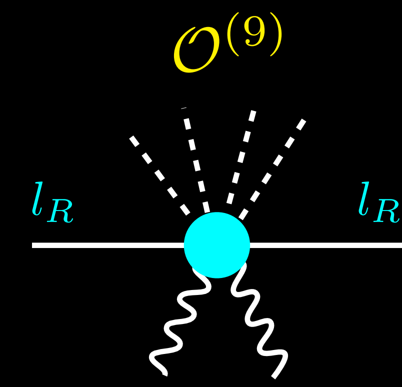
$$\mathcal{O}^{2b}_{\rm BSM} \equiv \bar{\chi}^c \chi \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



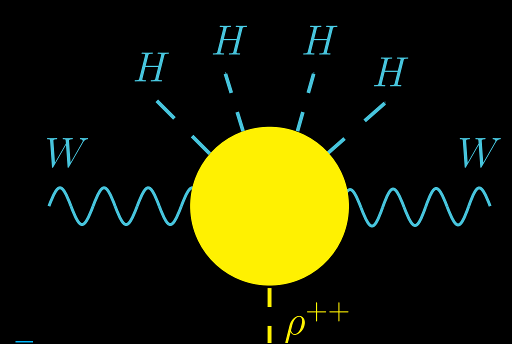
$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$

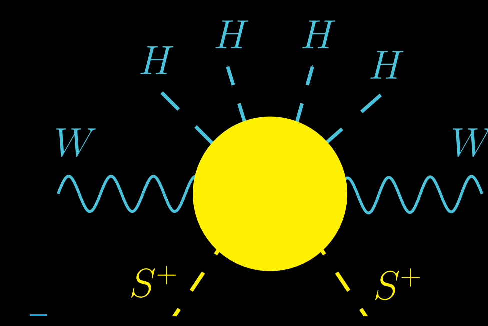
LFV Operator

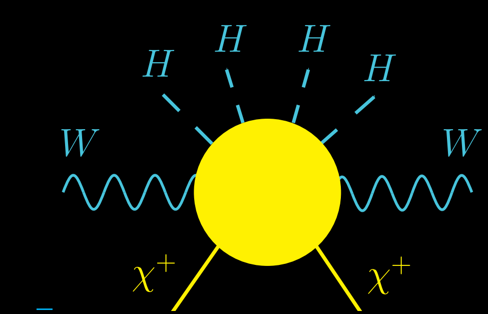
$$\mathcal{O}_9 \equiv \overline{\ell^c}_{R_a} \ell_{R_b} \left[(D_\mu H)^T i\sigma_2 H \right]^2$$



Class 1	Class 2a	Class 2b
$\mathcal{O}^1_{\rm BSM} \equiv \rho \left[(D_\mu H)^T i\sigma_2 H \right]^2$	$\mathcal{O}^{2a}_{\rm BSM} \equiv SS \left[(D_\mu H)^T i\sigma_2 H \right]^2$	$\mathcal{O}^{2b}_{\rm BSM} \equiv \bar{\chi}^c \chi \left[(D_\mu H)^T i\sigma_2 H \right]^2$



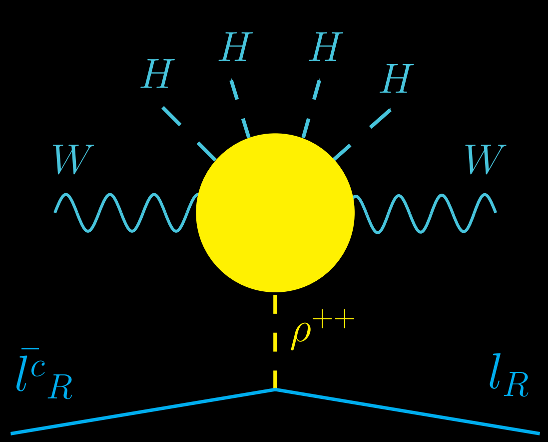


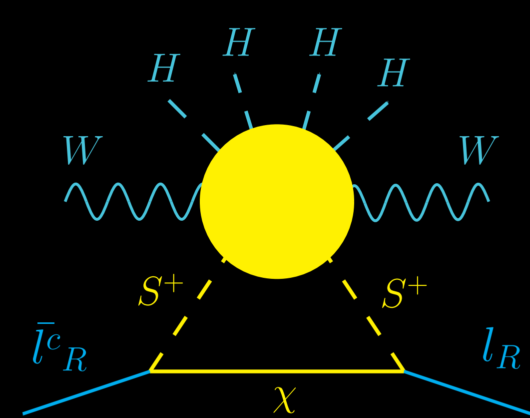


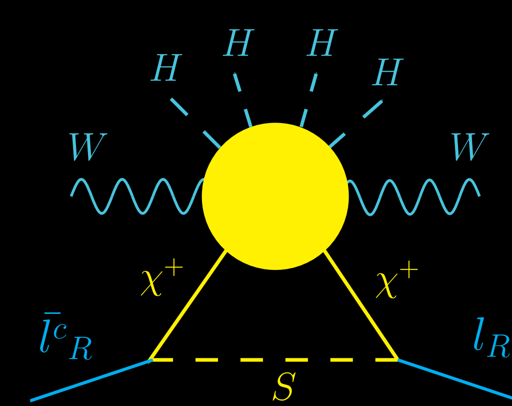
$C_{ab}\, \overline{\ell^c}_{R_a} \ell_{R_b}\, \rho + \text{h.c.}$

$g_a\, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$

$g_a\, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$

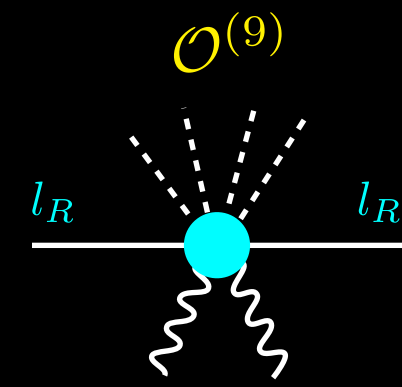






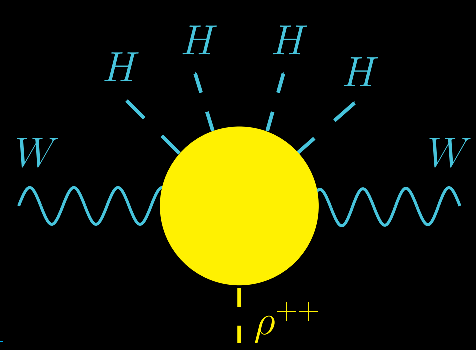
LFV Operator

$$\mathcal{O}_9 \equiv \overline{\ell^c}_{R_a} \ell_{R_b} \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



Class 1

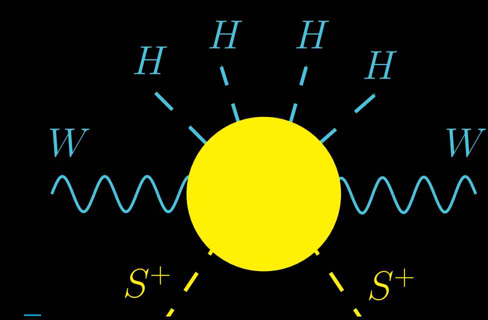
$$\mathcal{O}^{1}_{\text{BSM}} \equiv \rho \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



$$C_{ab} \, \overline{\ell^c}_{R_a} \ell_{R_b} \, \rho + \text{h.c.}$$

Class 2a

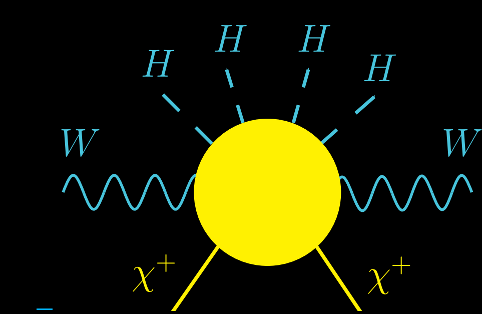
$$\mathcal{O}^{2a}_{\text{BSM}} \equiv SS \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



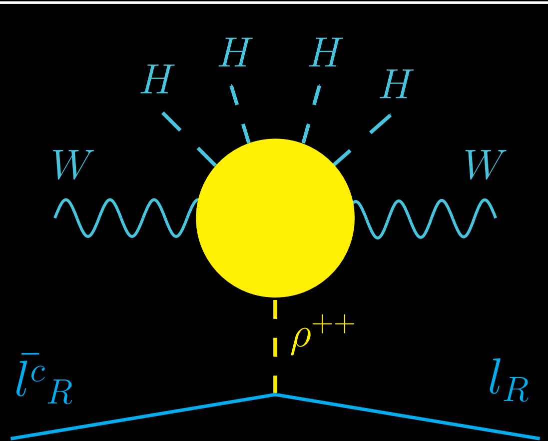
$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$

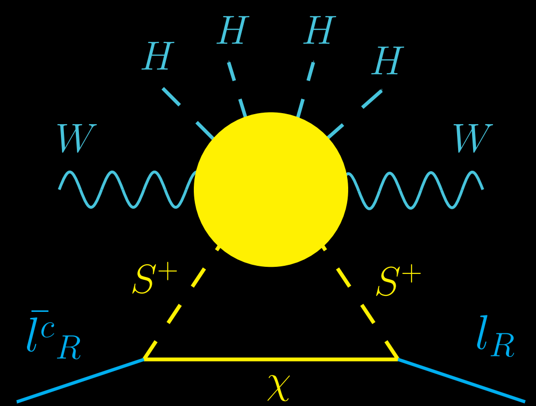
Class 2b

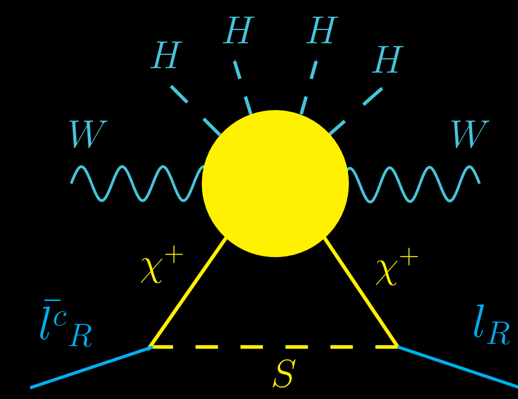
$$\mathcal{O}^{2b}_{\text{BSM}} \equiv \bar{\chi}^c \chi \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$



$$g_a \, \ell_{R_a} (\chi \cdot S) + \text{h.c.}$$

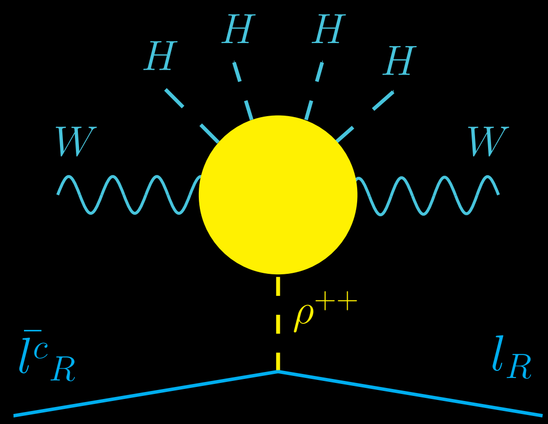




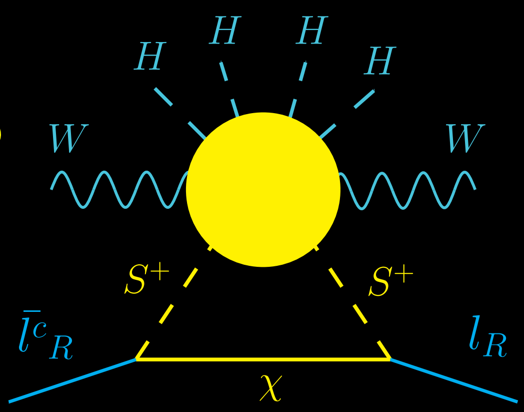


Effective Operator

Differences between Classes



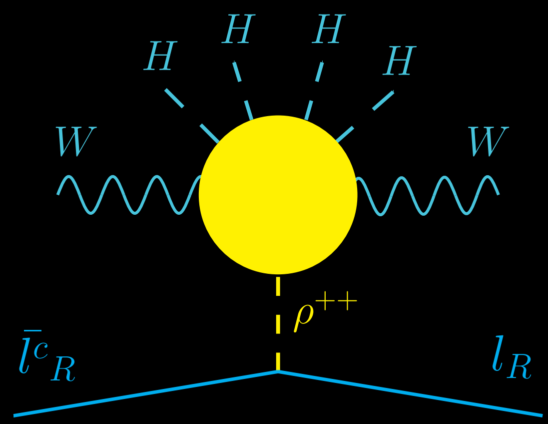
Class 1



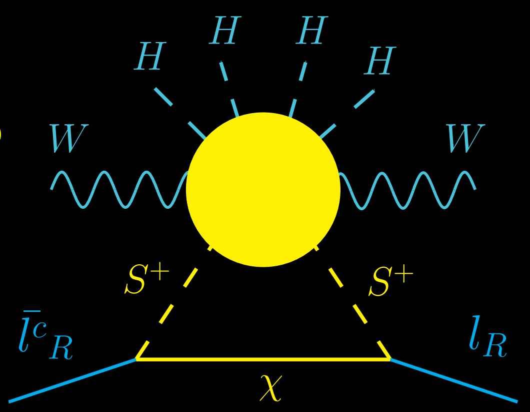
Class 2a

Effective Operator

Differences between Classes

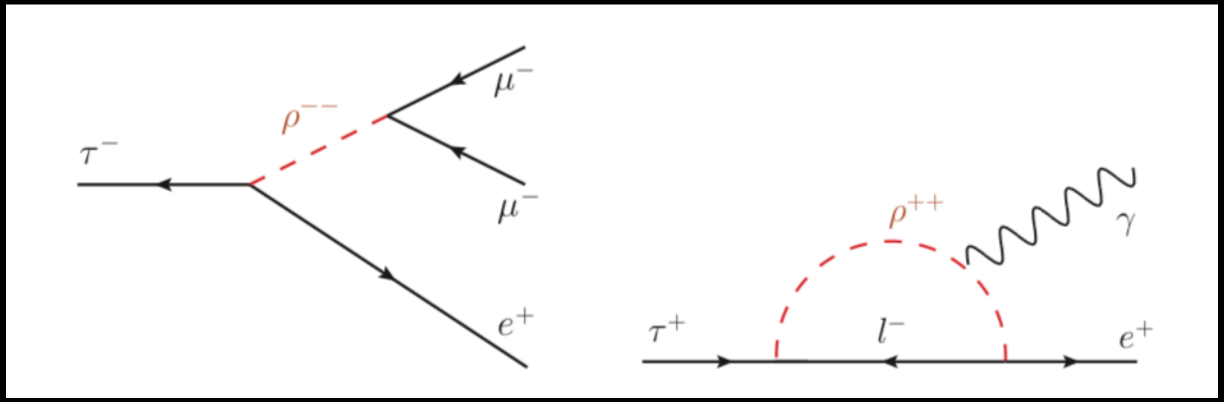


Class 1



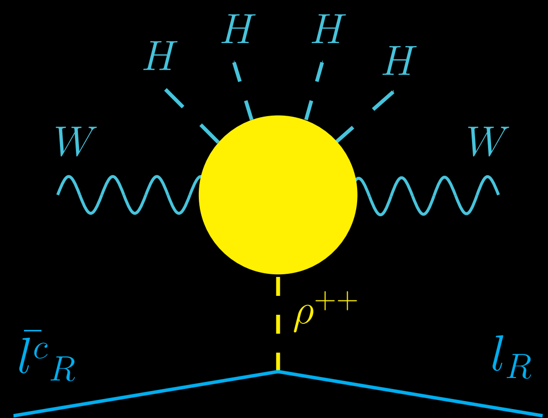
Class 2a

- LFV Processes

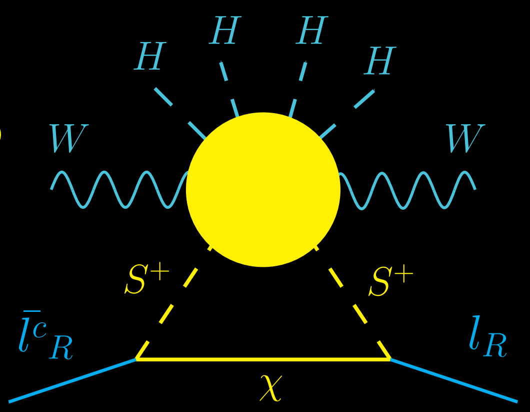


Effective Operator

Differences between Classes

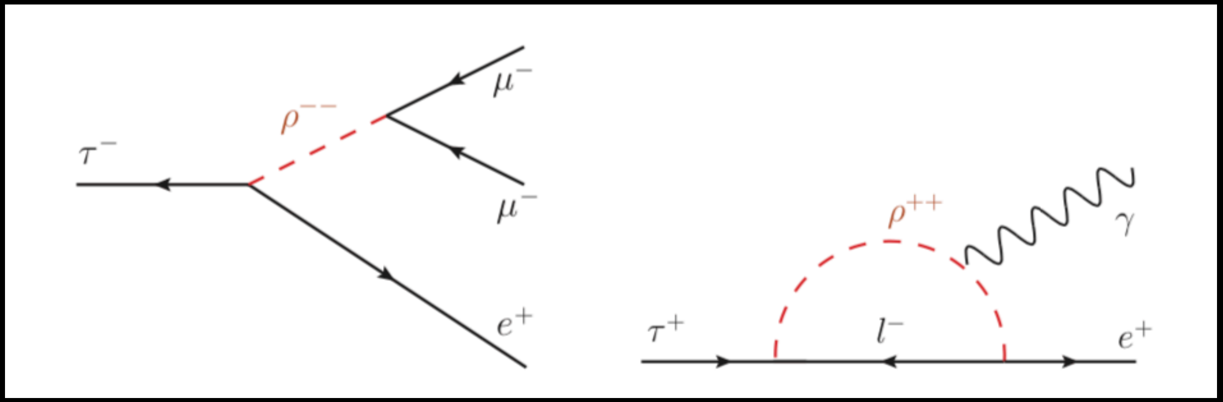


Class 1



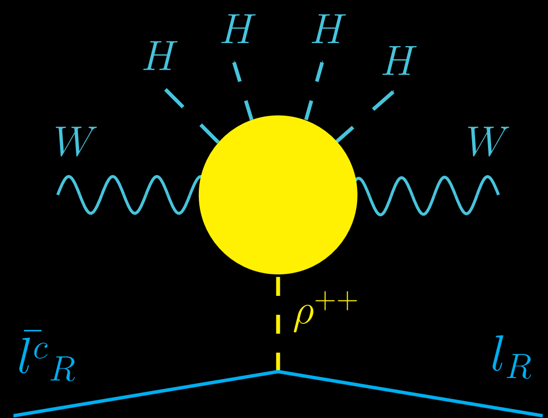
Class 2a

- LFV Processes

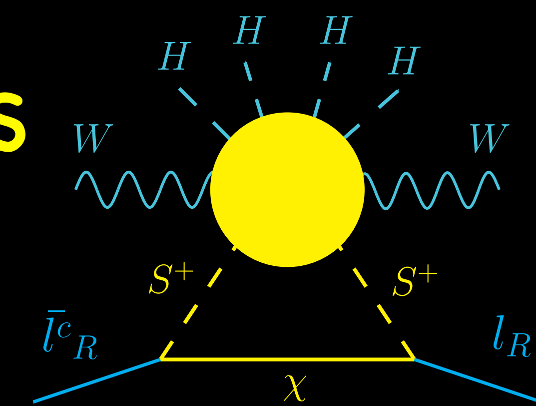


Effective Operator

Differences between Classes

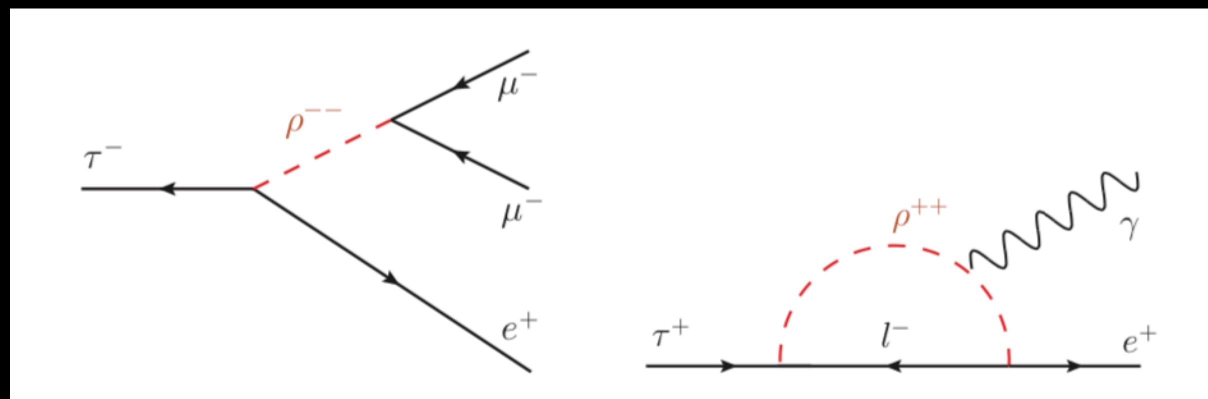


Class 1



Class 2a

- LFV Processes

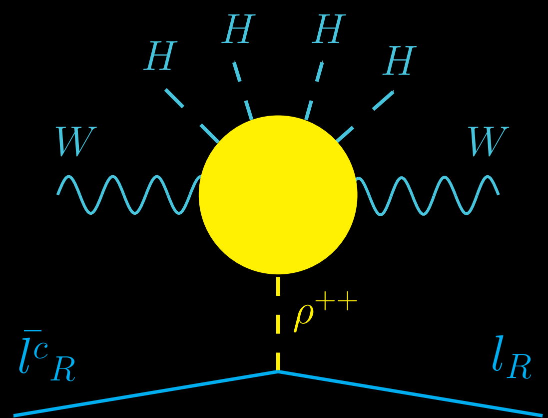


Tree-level and one loop contribution

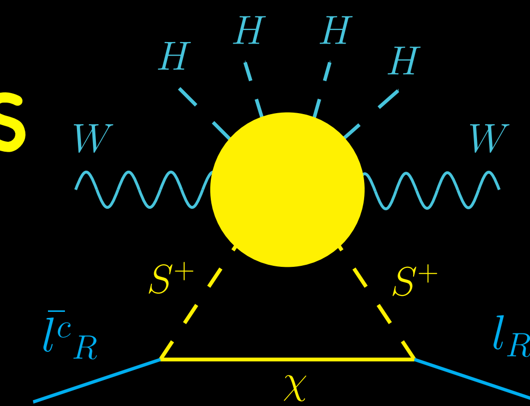
One loop contribution Only

Effective Operator

Differences between Classes

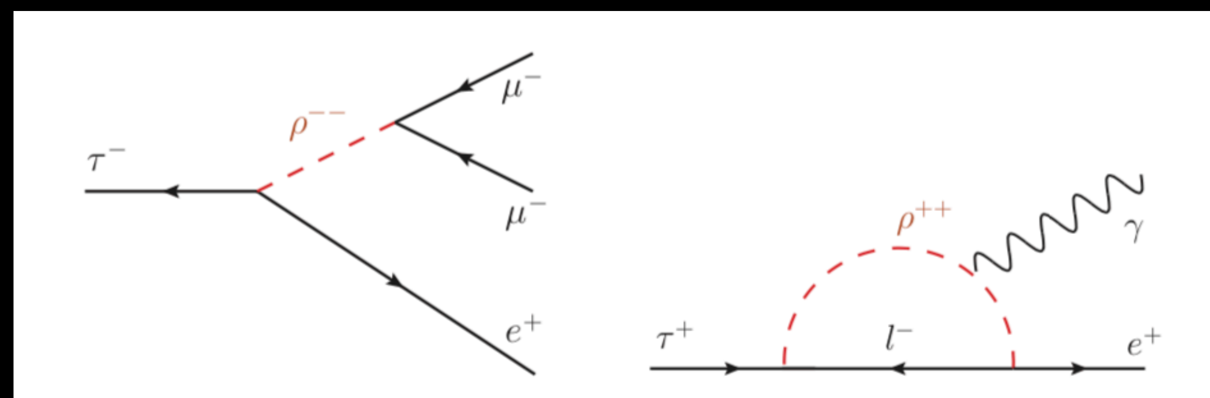


Class 1



Class 2a

- LFV Processes



Tree-level and one loop contribution

$\mu \to e\gamma$

$\tau \to e\mu\mu$

$C_{\mu\mu}/m_\rho \gtrsim 10^{-2}/\mathrm{TeV}$

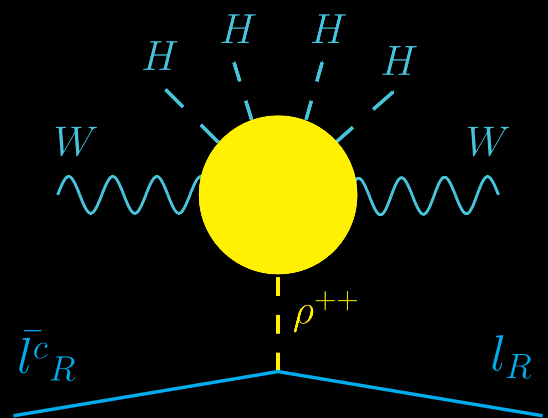
$C_{\mu\tau}/m_\rho \gtrsim 10^{-3}/\mathrm{TeV}$

$C_{e\tau}/m_\rho \gtrsim 0.1/\mathrm{TeV}$

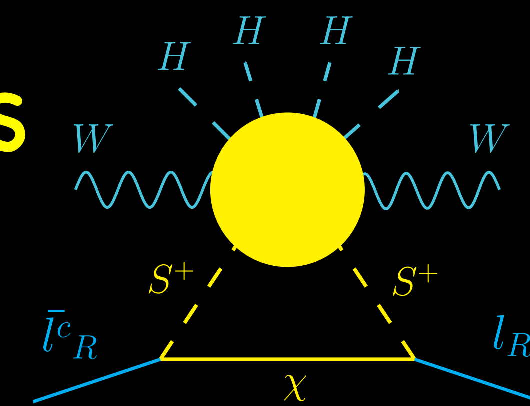
One loop contribution Only

Effective Operator

Differences between Classes

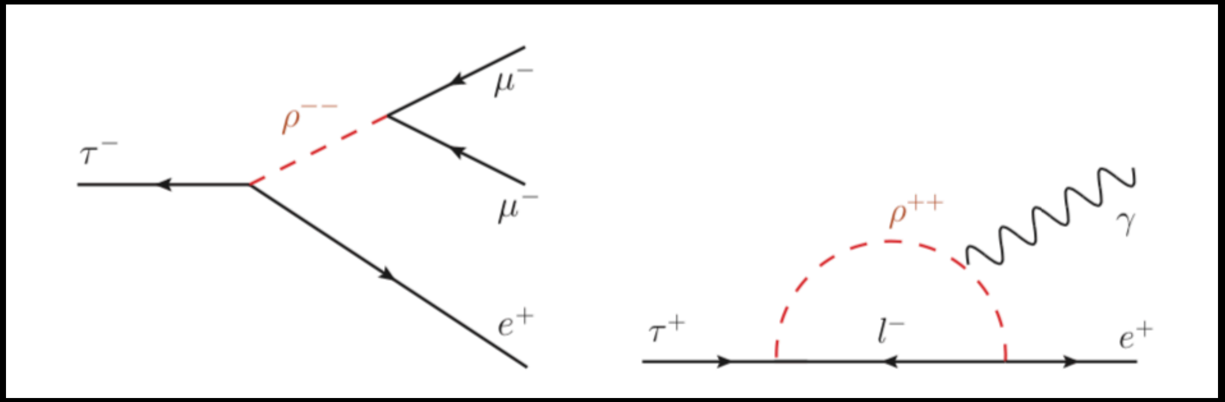


Class 1



Class 2a

- LFV Processes



Tree-level and one loop contribution

One loop contribution Only

$\mu \to e\gamma$

$\tau \to e\mu\mu$

$C_{\mu\mu}/m_\rho \gtrsim 10^{-2}/\mathrm{TeV}$

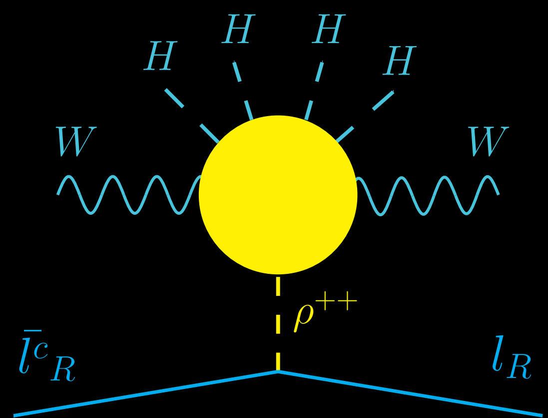
$C_{\mu\tau}/m_\rho \gtrsim 10^{-3}/\mathrm{TeV}$

$C_{e\tau}/m_\rho \gtrsim 0.1/\mathrm{TeV}$

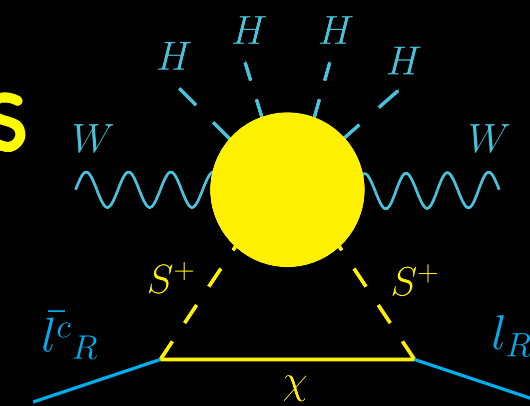
- Neutrino Mass and the Yukawa's structure

Effective Operator

Differences between Classes

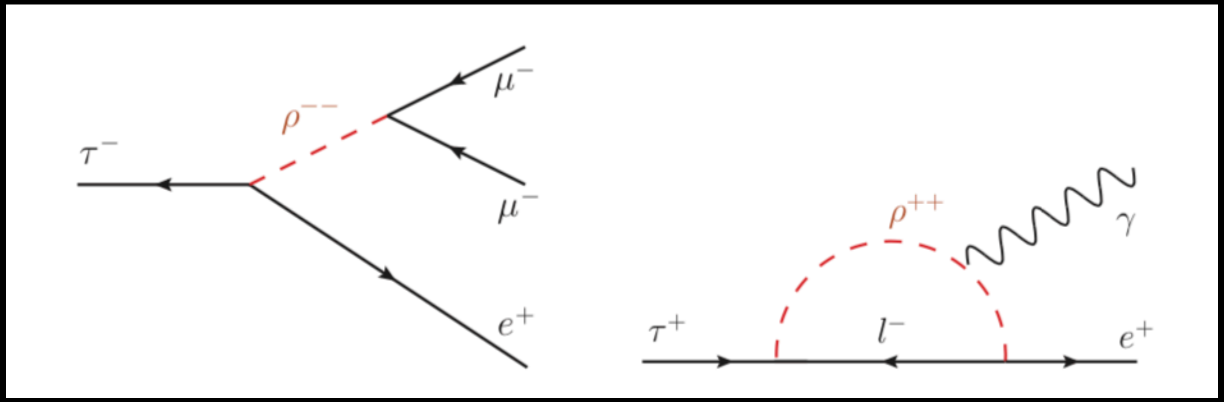


Class 1



Class 2a

- LFV Processes



Tree-level and one loop contribution

$$\mu \to e\gamma$$

$$\tau \to e\mu\mu$$

$$C_{\mu\mu}/m_\rho \gtrsim 10^{-2}/\mathrm{TeV}$$

$$C_{\mu\tau}/m_\rho \gtrsim 10^{-3}/\mathrm{TeV}$$

$$C_{e\tau}/m_\rho \gtrsim 0.1/\mathrm{TeV}$$

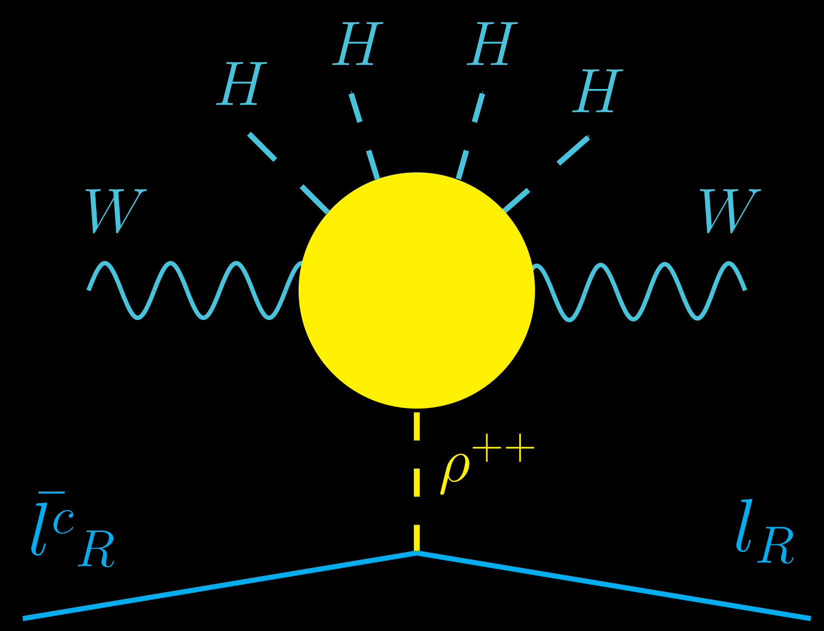
One loop contribution Only

- Neutrino Mass and the Yukawa's structure

$$m^\nu_{ab} = \frac{1}{(16\pi^2)^{L+2}} C_{ab} \frac{m^\ell_a m^\ell_b}{\Lambda}$$

$$m^\nu_{ab} = \frac{1}{(16\pi^2)^{L+3}} g_a g_b \frac{m^\ell_a m^\ell_b}{\Lambda'}$$

UV Completions Class 1



The Cocktail Model:
Inert Doublet

Gustafsson, No and MR.

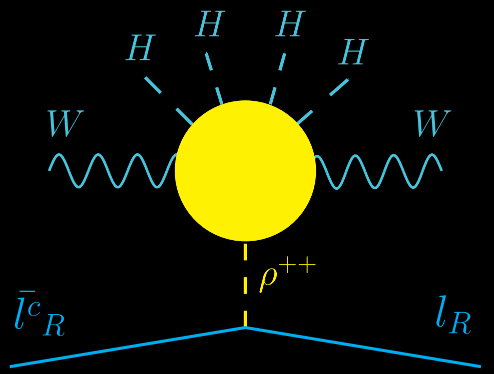
Phys.Rev.Lett. 110 (2013) no.21, 211802

The Lollipop Model:
Inert Triplet

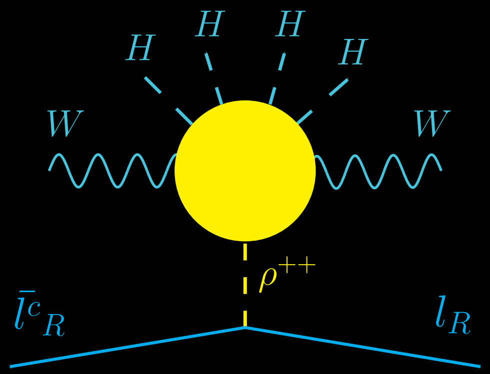
J. Alcaide, D. Das and A. Santamaria,

JHEP 1704, 049 (2017)

The Cocktail Model $1_2 2_2$



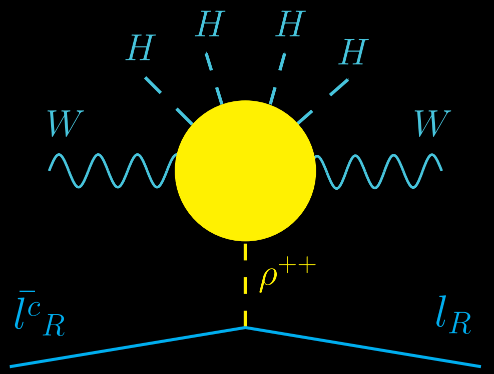
The Cocktail Model $1_2 2_2$



Inert Doublet Model

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{h+iG_0}{\sqrt{2}} + v \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \Lambda^+ \\ \frac{H_0+i\,A_0}{\sqrt{2}} \end{pmatrix}$$

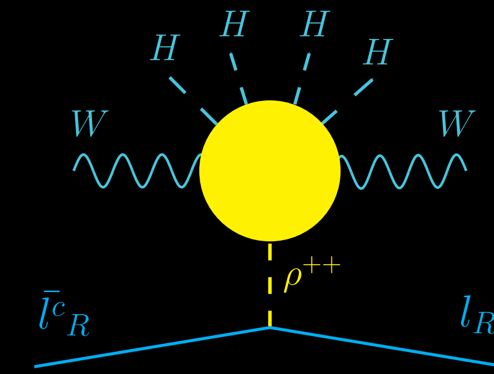
The Cocktail Model $1_2 2_2$



Inert Doublet Model "&" Inspired by Babu/Zee

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{h+iG_0}{\sqrt{2}} + v \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \Lambda^+ \\ \frac{H_0+i\,A_0}{\sqrt{2}} \end{pmatrix} \qquad S^+, \qquad \rho^{++}$$

The Cocktail Model $1_2 2_2$



Inert Doublet Model “&” Inspired by Babu/Zee

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	Φ_1	Φ_2	S^+	ρ^{++}
Z_2	+	-	-	+

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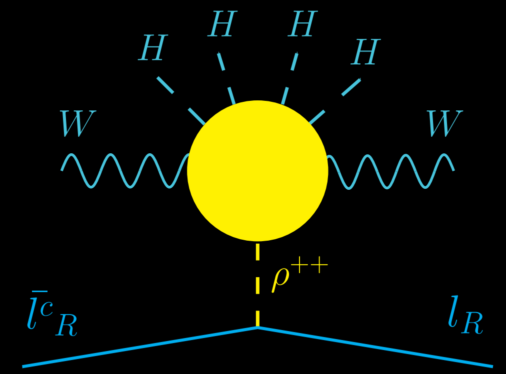

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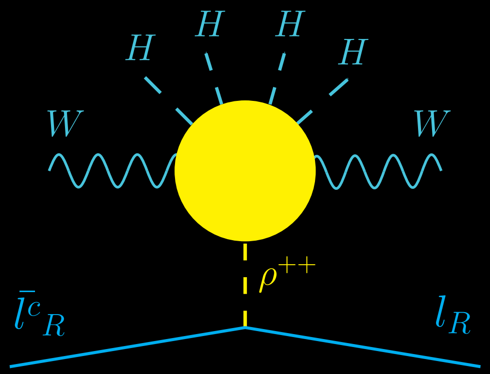
Z_2 +   –   –   +

Field	$SU(2)$	$U(1)_{\mathrm{Y}}$	Z_2
ϕ_1	2	-1/2, 1/2	+
ϕ_2	2	-1/2, 1/2	-
S^+	1	+1	-
ρ^{++}	1	+2	+

The Cocktail Model $1_2 2_2$



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Z_2: + (for Φ_1), − (for Φ_2), − (for S^+), + (for ρ^{++})

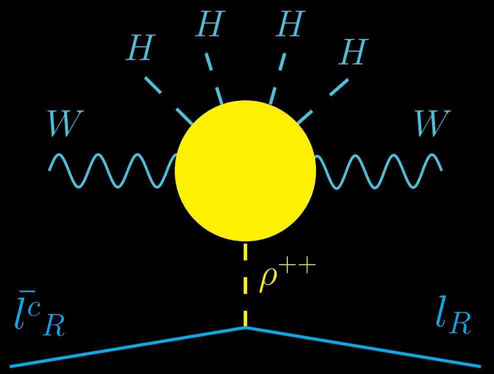
Field	$SU(2)$	$U(1)_Y$	Z_2
ϕ_1	2	-1/2, 1/2	+
ϕ_2	2	-1/2, 1/2	-
S^+	1	+1	-
ρ^{++}	1	+2	+

The Lagrangian

$$\Delta\mathcal{L}_{GNR} = \boxed{\begin{array}{l} -C_{ab}\bar{l^c_{R_a}} l_{R_b}\rho^{++} + \kappa_1 \Phi_2^T i\sigma_2 \Phi_1 S^- \\ +\kappa_2 \rho^{++} S^- S^- + \frac{\lambda_5}{2}(\Phi_1^\dagger \Phi_2)^2 \\ +\lambda_{\rho S}\Phi_2^T i\sigma_2 \Phi_1 S^+ \rho^{--} + h.c. \end{array}}$$

$$+\lambda_4 |\Phi_1^\dagger \Phi_2|^2 + V(|\Phi_1|^2, |\Phi_2|^2, |S|^2, |\rho|^2)$$

The Cocktail Model $1_2 2_2$



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Z_2 + - - +

Field	$SU(2)$	$U(1)_Y$	Z_2
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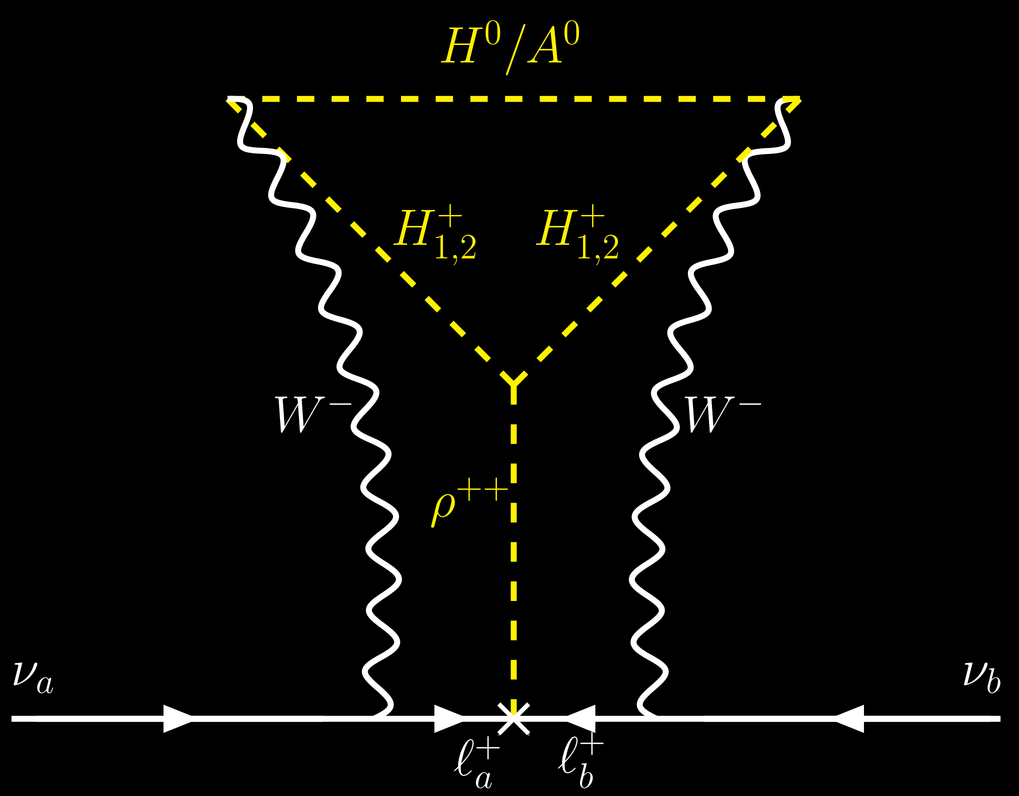
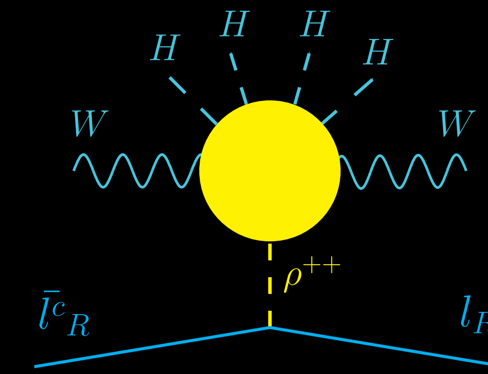


$C_{ab}, \lambda_5 \neq 0$ and two of $\kappa_1, \kappa_2, \lambda_{\rho S} \neq 0$
to break lepton number

The Cocktail Model $1_2 2_2$



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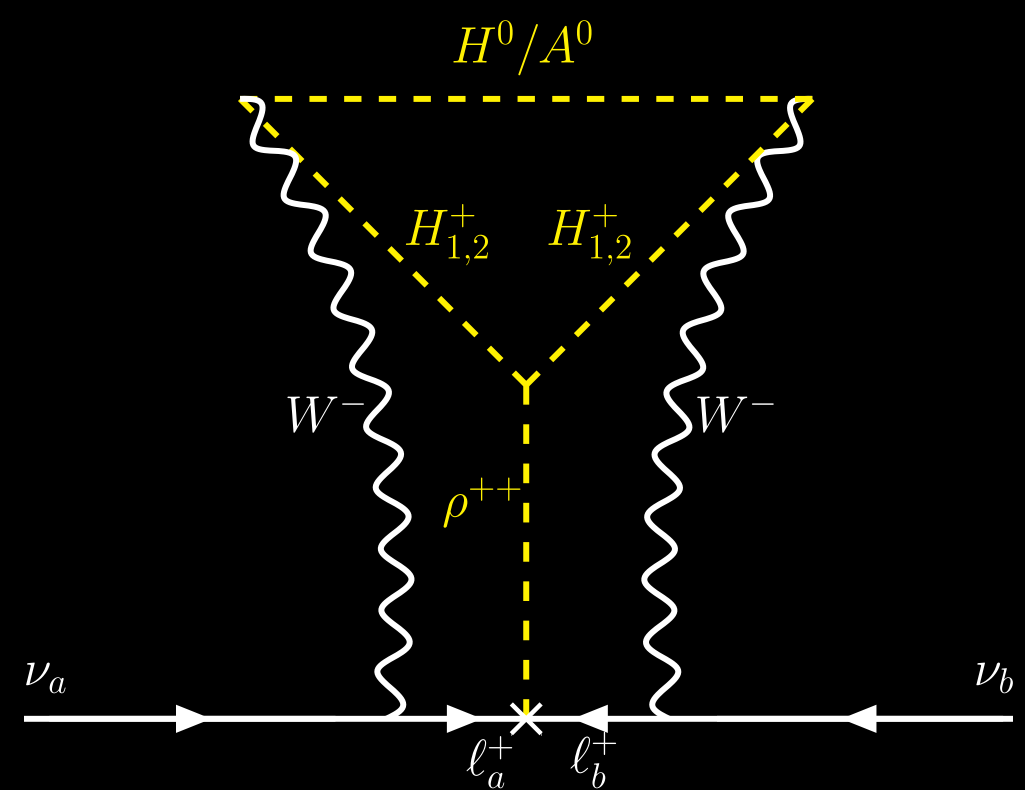


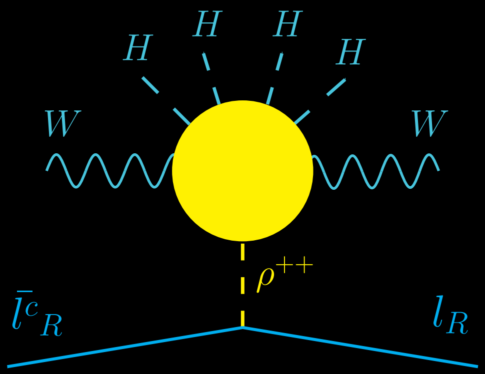
$C_{ab}, \lambda_5 \neq 0$ and two of $\kappa_1, \kappa_2, \lambda_{\rho S} \neq 0$
to break lepton number

$$m^\nu_{ab} = C_{ab} \frac{m^\ell_a m^\ell_b s_{2\beta}}{(16\pi^2)^3 m_\rho} \frac{M_W^4 \Delta m_+^2 \Delta m_0^2}{v^8} (\mathcal{A}_1 \mathcal{I}_1 + \mathcal{A}_2 \mathcal{I}_2)$$

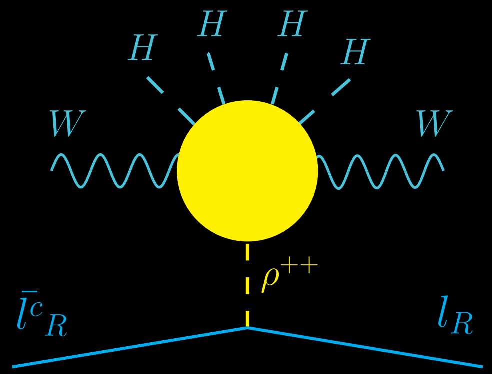
$$\mathcal{A}_1 \simeq \frac{\kappa_2 s_{2\beta} + \xi v c_{2\beta}}{\sqrt{v m_\rho}}, \quad \mathcal{A}_2 \simeq 10\xi$$

The Cocktail Model $1_2 2_2$

Phenomenology



The Cocktail Model $1_2 2_2$



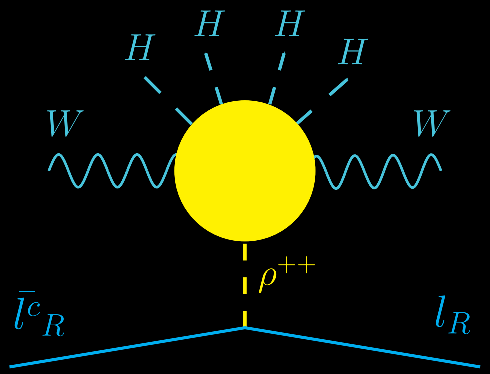
Phenomenology

- EWPT

$$\Delta T = \frac{1}{16\pi m_w^2 s_{\theta_w}^2}\left[c_\beta^2\left(F_{H_1,H_0}+F_{H_1,A_0}\right)+s_\beta^2\left(F_{H_2,H_0}+F_{H_2,A_0}\right)-2c_\beta^2 s_\beta^2 F_{H_1,H_2}-F_{H_0,A_0}\right]$$

$$F_{i,j} = \frac{m_i^2+m_j^2}{2}-\frac{m_i^2 m_j^2}{m_i^2-m_j^2}\ln\frac{m_i^2}{m_j^2}$$

The Cocktail Model $1_2 2_2$



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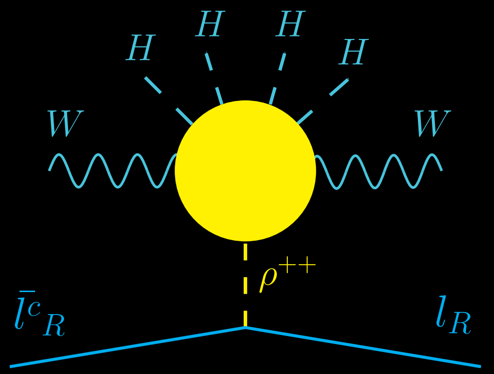
Neutrino mass is proportional to $\Delta m_+^2,\ \Delta m_0^2 \gtrsim v^2$

The Cocktail Model $1_2 2_2$

Phenomenology



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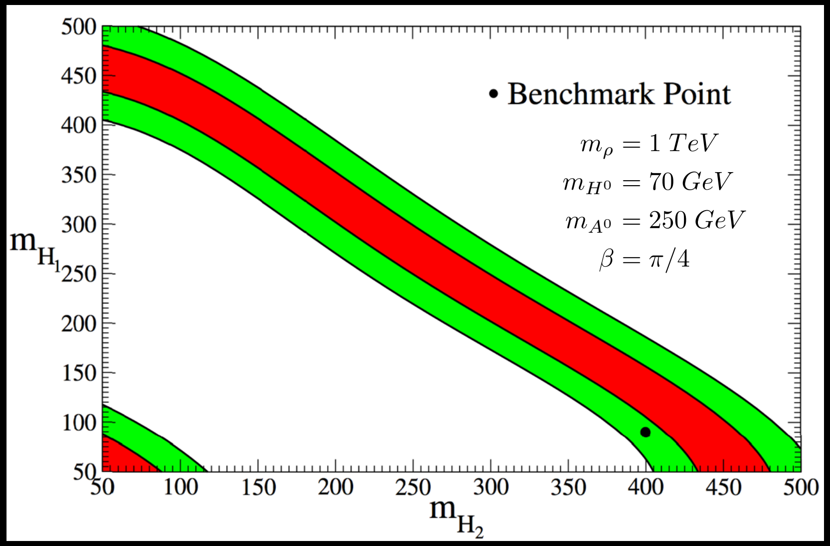
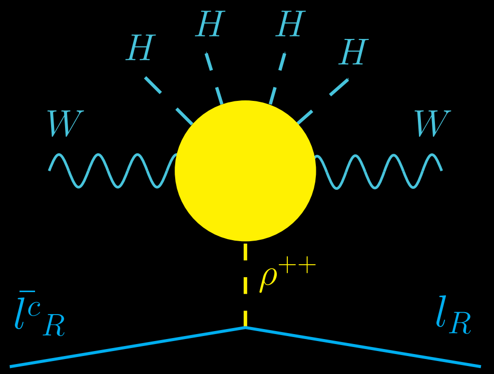


Neutrino mass is proportional to $\Delta m_+^2,\ \Delta m_0^2 \gtrsim v^2$

Mass correlation between new states

$$m_{H_2^+} \gg m_{A_0} \gg m_{H_1^+}, m_{H_0}$$

The Cocktail Model $1_2 2_2$



Phenomenology

- **EWPT**

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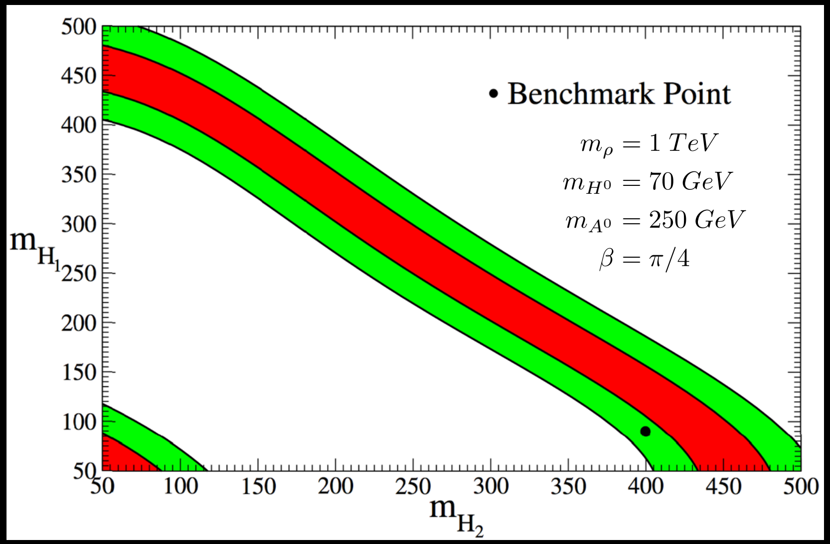

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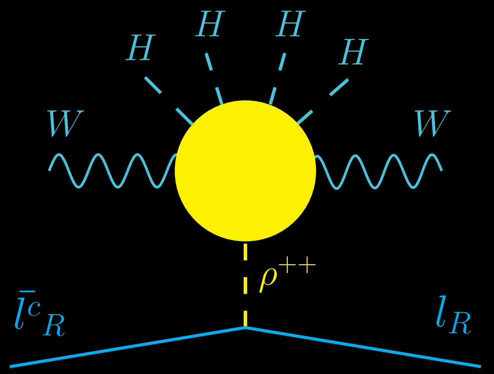
- **Dark Matter**

The Cocktail Model $1_2 2_2$

Phenomenology



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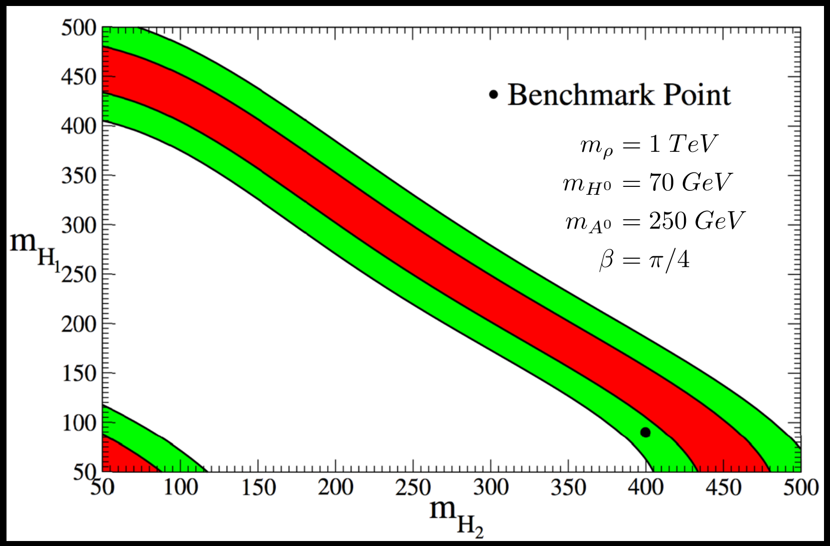

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Mass correlation between new states

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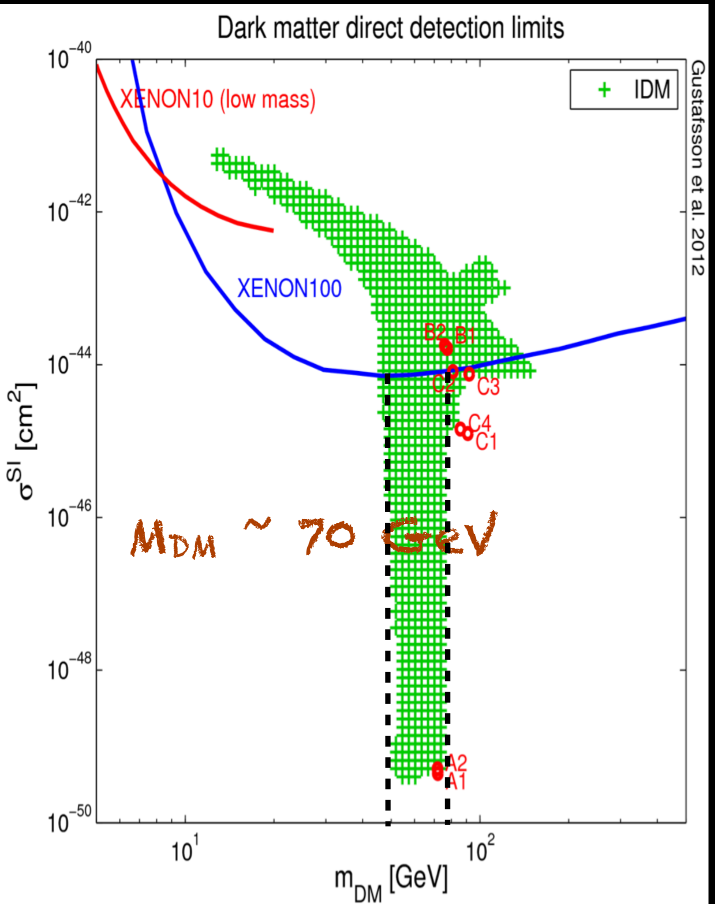
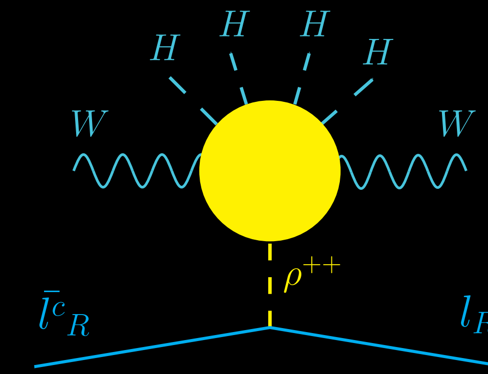
- Dark Matter

Basically 2HDM DM candidate



The Cocktail Model $1_2 2_2$



Phenomenology

- **EWPT**

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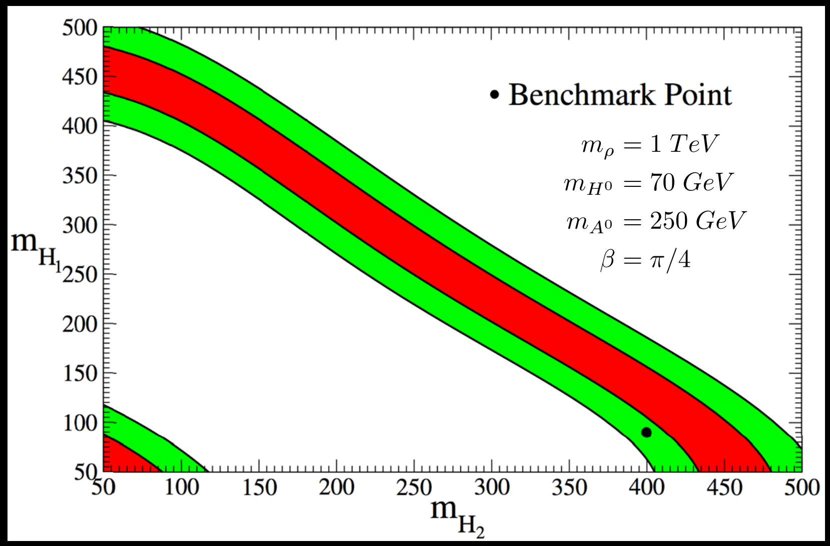

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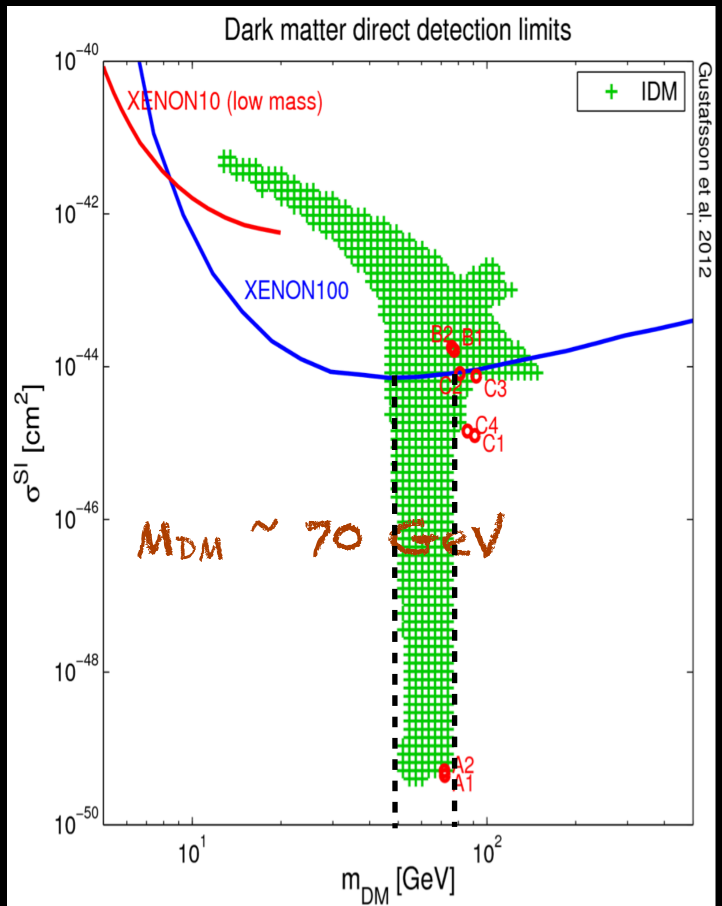
Mass correlation between new states

$$m_{H_2^+} \gg m_{A_0} \gg m_{H_1^+}, m_{H_0}$$

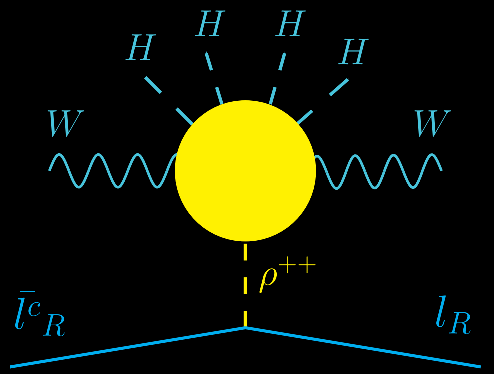
- **Dark Matter**

Basically 2HDM DM candidate

1. Higgs portal (resonance): ~60 GeV
2. Coannihilation with A^0 (gives too small m_ν)
3. H^0H^0 -> WW threshold effect: ~70 GeV (gives striking gamma-ray lines)



The Lollipop Model $1_2 23$



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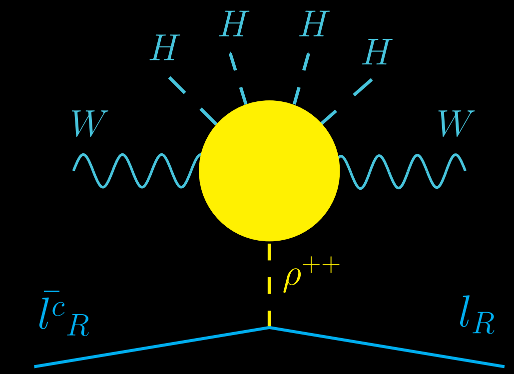
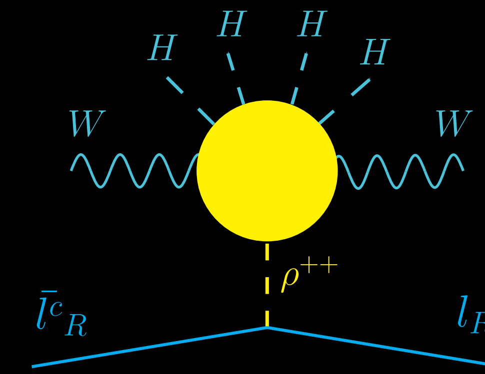


Inert triplet Model "&" Singlets

$$\Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} \Delta^+ & \sqrt{2}\Delta^{++} \\ \Delta^0 + iA^0 & -\Delta^+ \end{pmatrix}, \qquad \sigma, \qquad \rho^{++}$$

Z_2	−	−	+

The Lollipop Model $1_2 23$



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Z_2 −   −   +

The Lagrangian

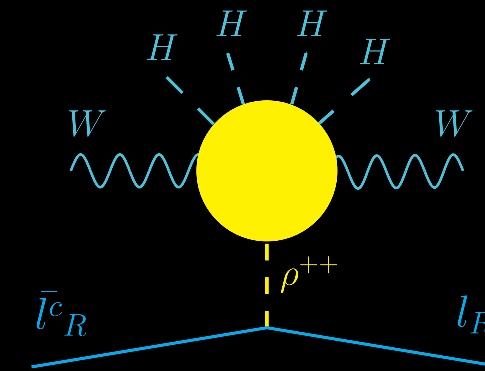
$$\mathcal{L} \supset \mathrm{Tr}[(D_\mu \Delta)^\dagger D^\mu \Delta] + \partial_\mu \sigma\, \partial^\mu \sigma + (D_\mu \rho)^\dagger D^\mu \rho - m_\Delta^2 \mathrm{Tr}[\Delta^\dagger \Delta] - \frac{m_\sigma^2}{2}\sigma^2$$

$$-\lambda_{H\Delta} |H|^2 \mathrm{Tr}[\Delta^\dagger \Delta] - \lambda_{H\sigma} |H|^2 \sigma^2 - \tilde{\lambda}_{H\Delta} H^\dagger \Delta \Delta^\dagger H - \kappa_2 \mathrm{Tr}[\Delta\Delta]\rho^{--}$$

$$-\lambda_6\, \sigma H^\dagger \Delta \tilde{H} - C_{ab}\, \overline{\ell^c}_{R_a} \ell_{R_b}\, \rho^{++} + \mathrm{h.c.}$$

$$+V(\sigma, \rho, H, \Delta)$$

The Lollipop Model $1_2 23$



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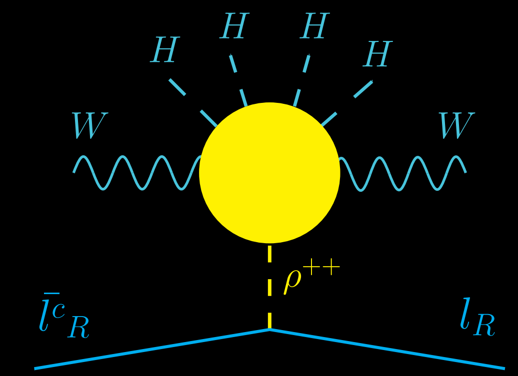
$$-\lambda_{H\Delta} |H|^2 \mathrm{Tr}[\Delta^\dagger \Delta] - \lambda_{H\sigma} |H|^2 \sigma^2 - \tilde{\lambda}_{H\Delta} H^\dagger \Delta \Delta^\dagger H - \kappa_2 \mathrm{Tr}[\Delta\Delta] \rho^{--}$$
$$-\lambda_6\, \sigma H^\dagger \Delta \tilde{H} - C_{ab}\, \overline{\ell^c}_{R_a} \ell_{R_b}\, \rho^{++} + \mathrm{h.c.}$$
$$+V(\sigma, \rho, H, \Delta)$$

$$C_{ab}, \kappa_2, \lambda_6 \neq 0$$
to break lepton number

The Lollipop Model $1_2 23$



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$$-\lambda_6 \, \sigma H^\dagger \Delta \tilde{H} - C_{ab} \, \overline{\ell^c}_{R_a} \ell_{R_b} \, \rho^{++} + \mathrm{h.c.}$$

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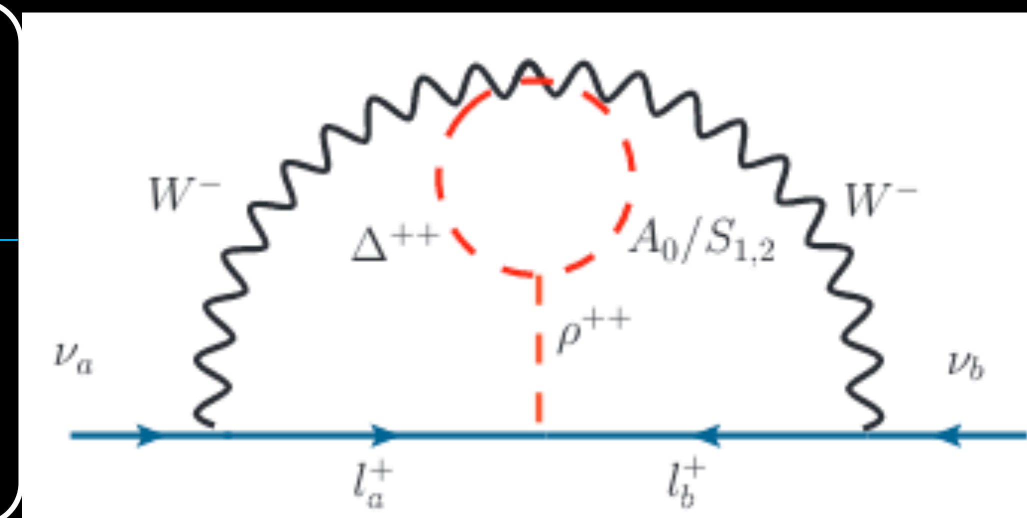

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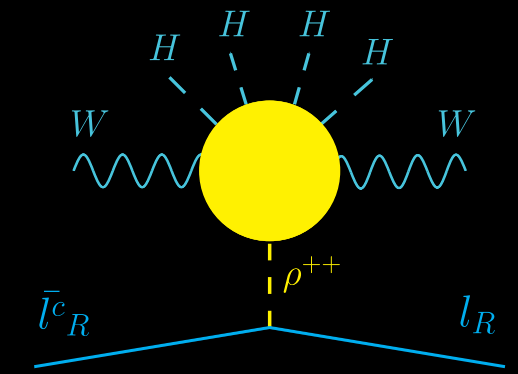

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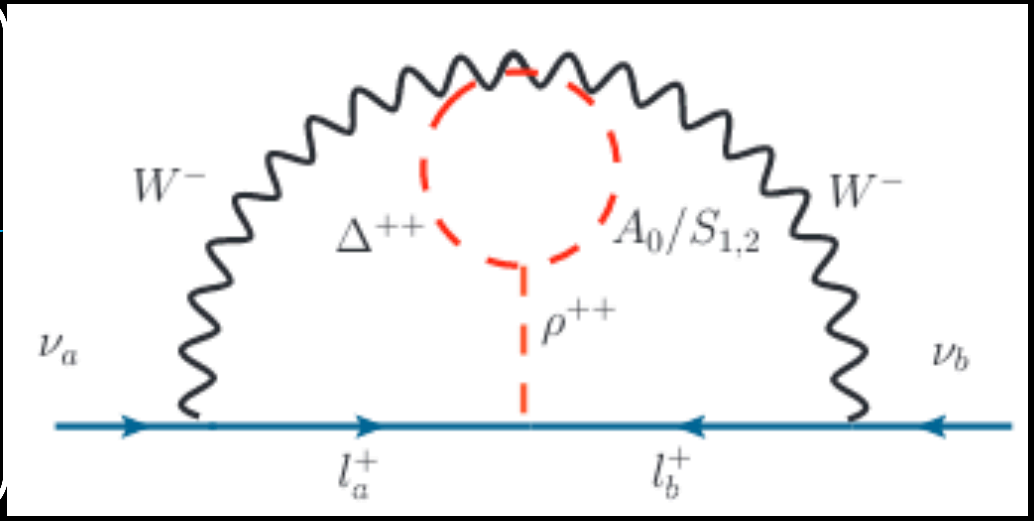
$$-\lambda_6 \, \sigma H^\dagger \Delta \tilde{H} - C_{ab} \, \overline{\ell^c}_{R_a} \ell_{R_b} \, \rho^{++} + \mathrm{h.c.}$$

$$+V(\sigma, \rho, H, \Delta)$$

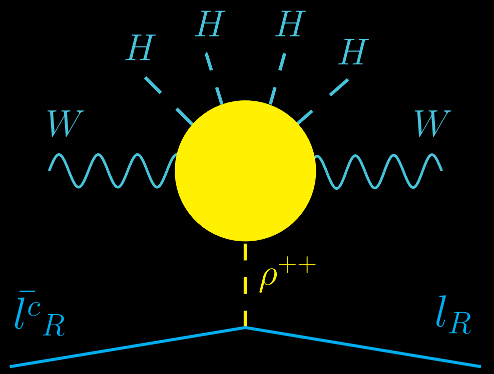


$C_{ab}, \kappa_2, \lambda_6 \neq 0$
to break lepton number

$$m_{ab}^\nu = C_{ab} \frac{m_a^\ell m_b^\ell}{(16\pi^2)^3 \, m_\rho^2} 8\kappa_2 \lambda_6^2 \times \mathcal{I}_\nu$$

The Lolipop Model $1_2 23$

Phenomenology



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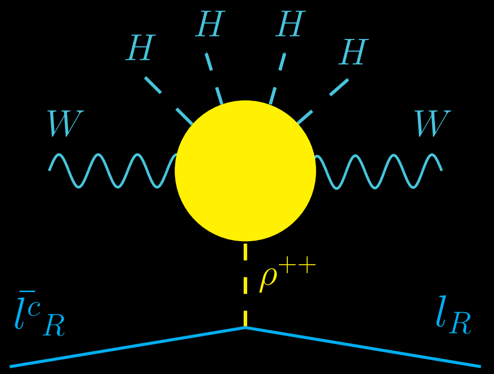

- EWPT

  All Z_2 add fields $\rho^{++}, \Delta^{++}, A_0, S_{1,2}$ Contribuye to S,T, U parameters

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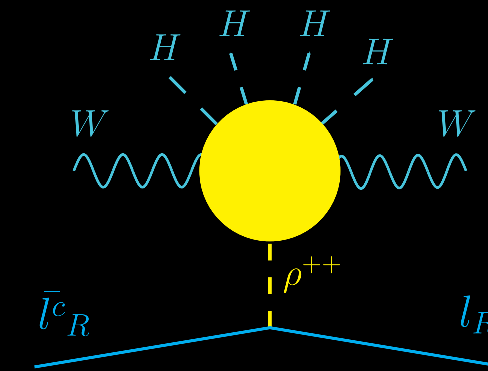

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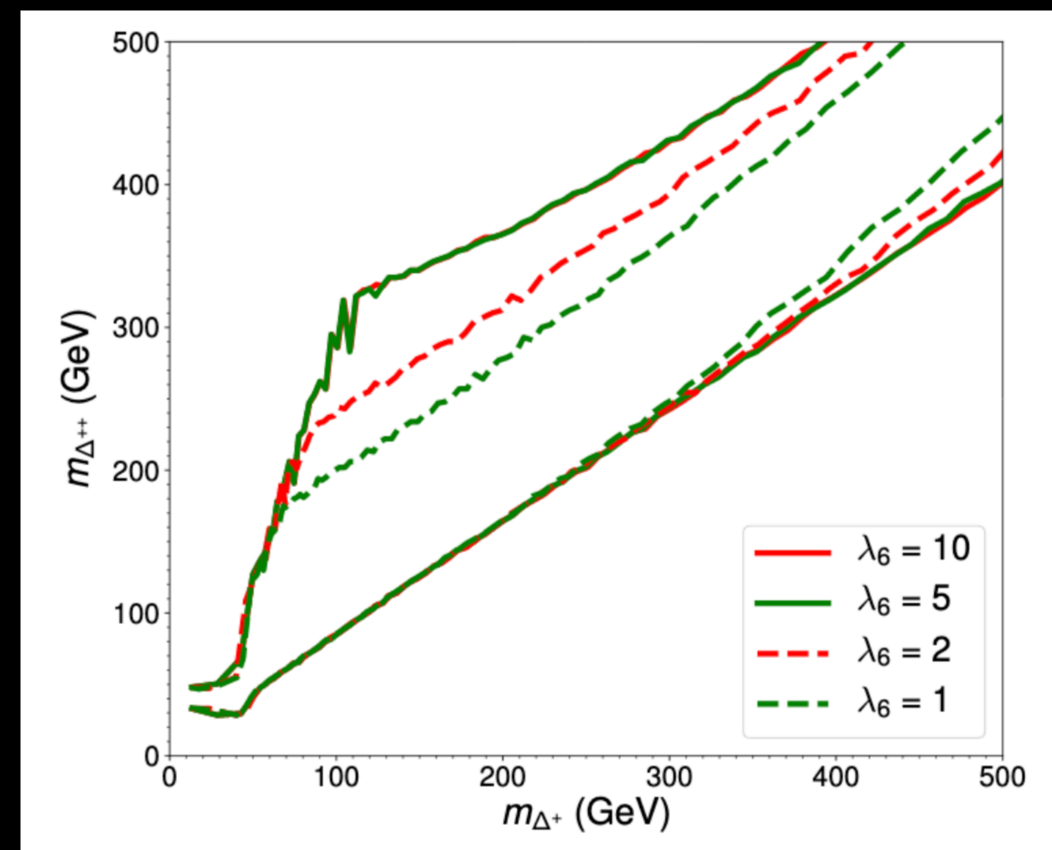
All Z_2 add fields $\rho^{++}, \Delta^{++}, A_0, S_{1,2}$ Contribuye to S,T, U parameters

$$|m_{\Delta^{++}} - m_{\Delta^{+}}| \lesssim 100\,\mathrm{GeV} \quad \text{for } \lambda_6 \lesssim 1$$

$$|m_{\Delta^{++}} - m_{\Delta^{+}}| \lesssim 200\,\mathrm{GeV} \quad \text{for } \lambda_6 \lesssim 4\pi$$



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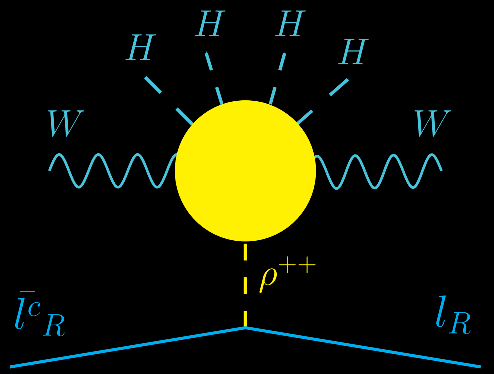

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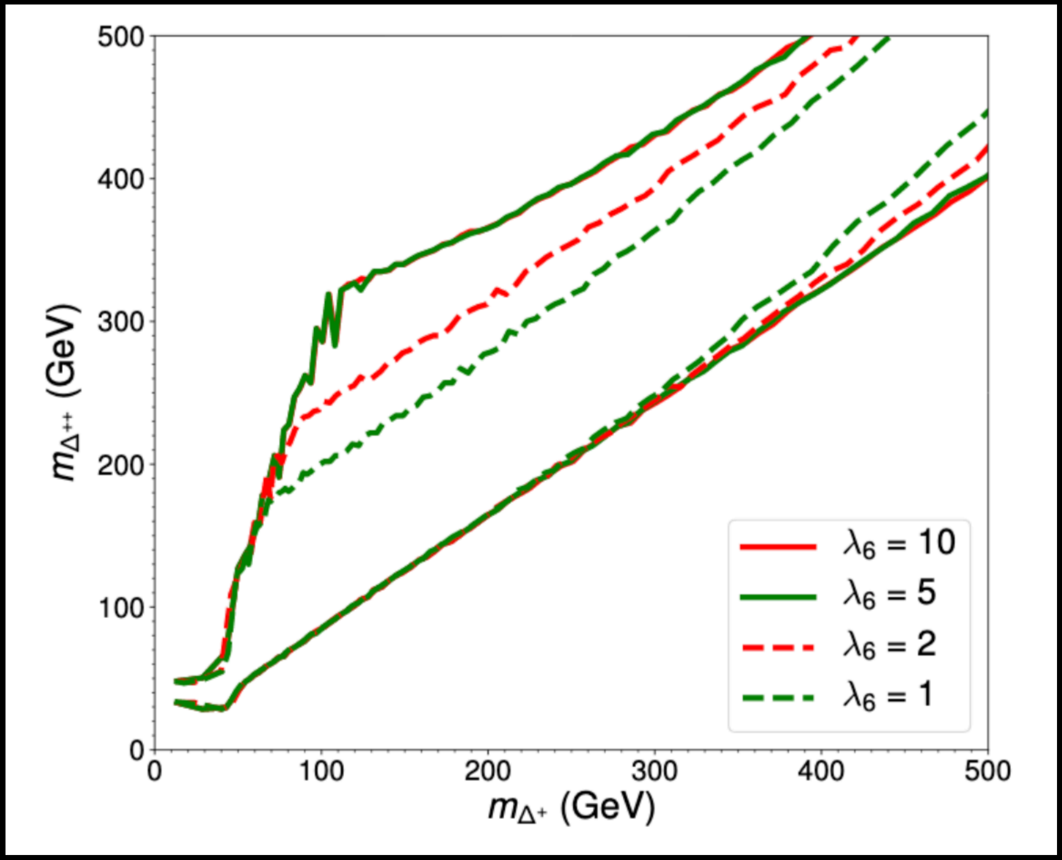

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DM is mainly singlet -> the model resemble Higgs portal singlet scenario

The Lolipop Model $1_2 23$
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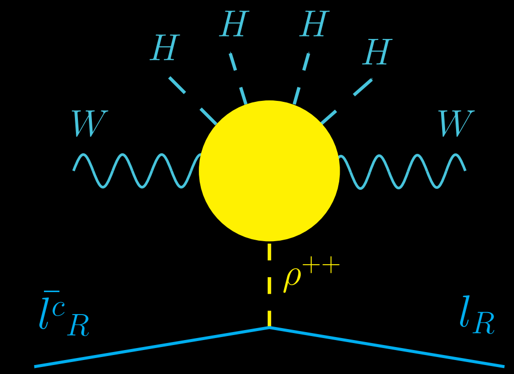

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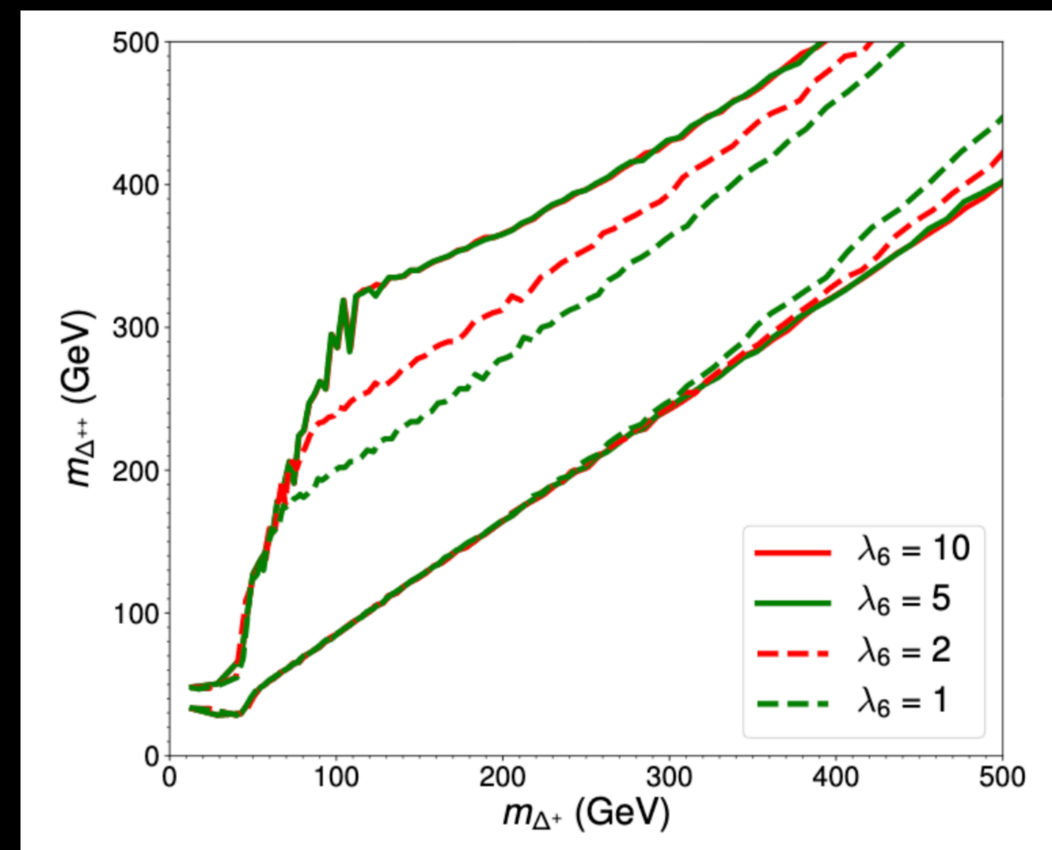

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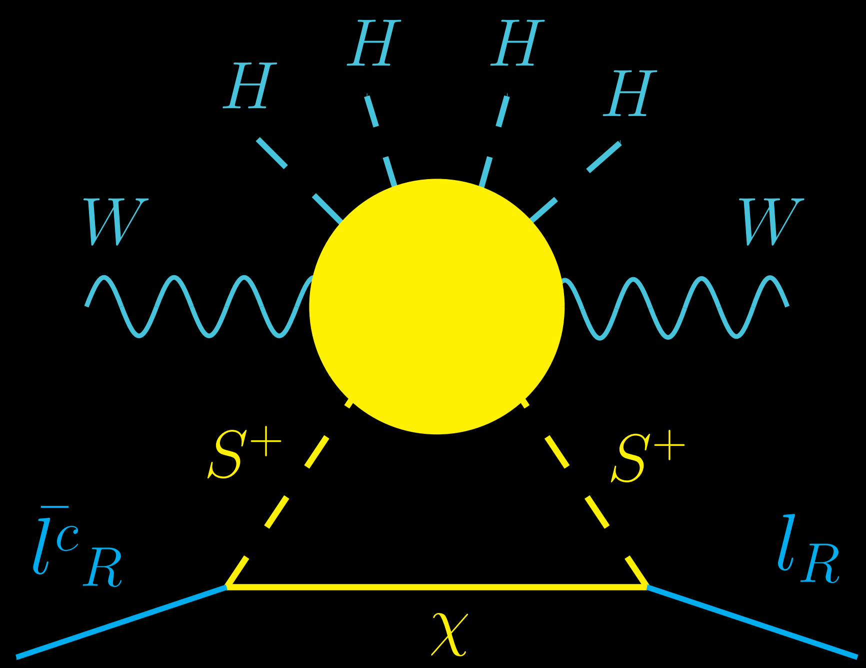
$$\mathcal{L} \supset -\lambda_{S_2} S_2^2 \left(2\sqrt{2} v h + h^2\right)$$

UV Completions Class 2a



$SU(2)_L$ Singlet χ and S

Jin, Li-Gang *et al.* Phys.Lett. B741 (2015) 163-167

Chao-Qiang Geng et al. Phys.Lett. B745 (2015) 56-57

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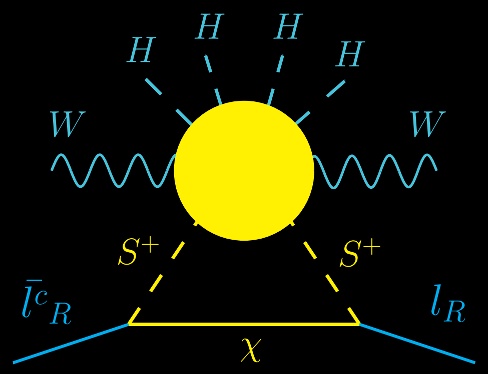

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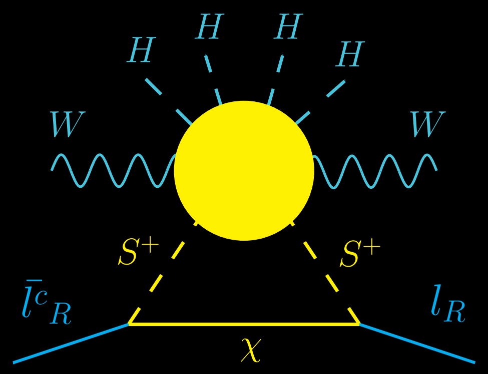
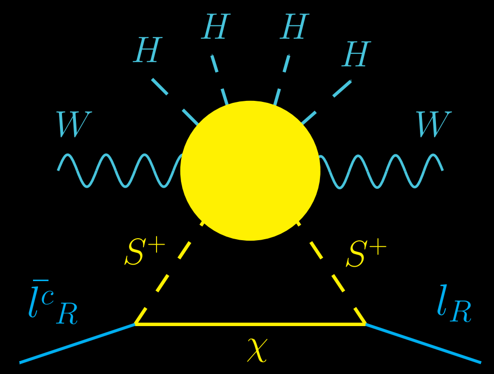


	Singlets		Triplet
	$\chi_i \equiv N_{R_i}$,	S^+,	$\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta_0 & \Delta^+ \\ \Delta^- & -\frac{1}{\sqrt{2}}\Delta_0 \end{pmatrix}$
Z_2	−	−	−



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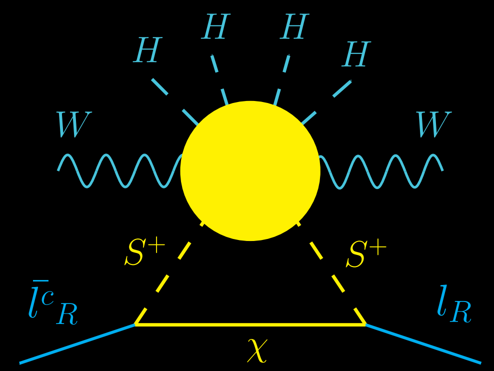
Z_2 −   −   −

The Lagrangian

$$\mathcal{L} = \frac{1}{2}\mathrm{Tr}\left[(D_\mu\Delta)^\dagger (D^\mu\Delta)\right] + (D_\mu S)^* (D^\mu S) + i\overline{N_{R_i}}\partial N_{R_i} - \frac{1}{2}m_{N_i}\overline{N_{R_i}}N^c_{R_i} - g_{ia}\overline{N_{R_i}}\ell^c_{R_a}S^+ + \text{ h.c.}$$

$$+V(S, H, \Delta)$$



$SU(2)_L$ Singlet χ and S

Singlets | **Triplet**

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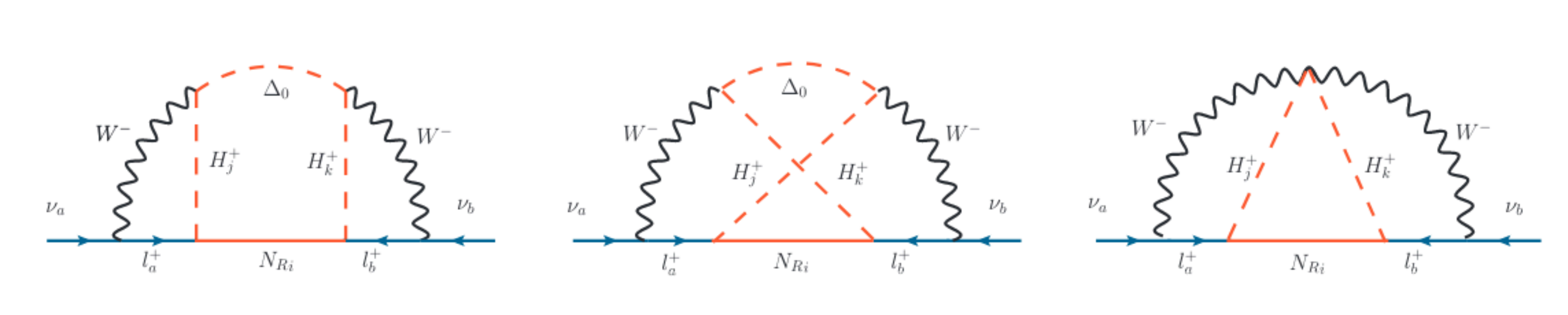
Z_2 –   –   –



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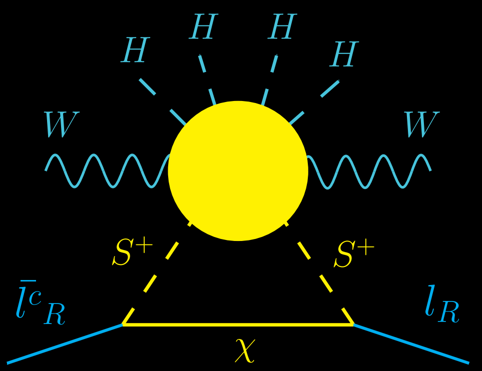

$SU(2)_L$ Singlet χ and S

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Triplet

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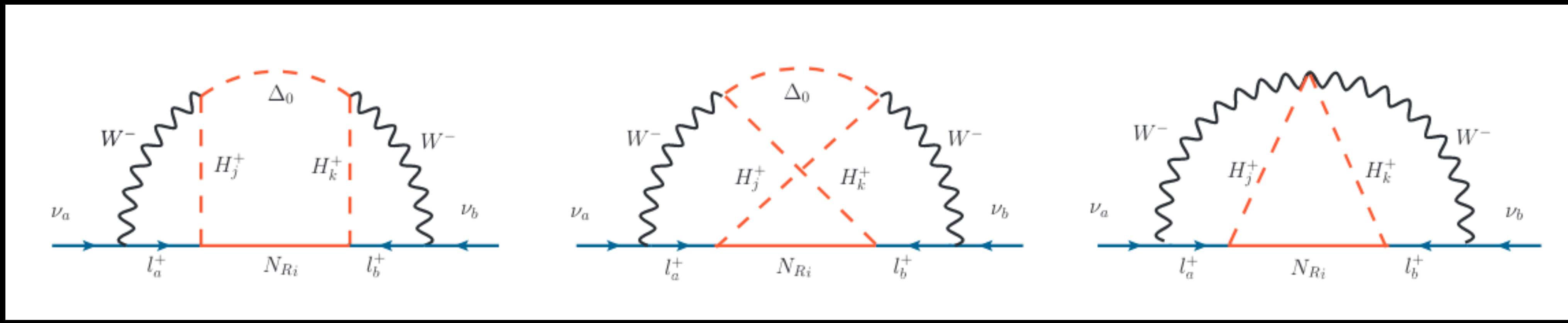
Z_2: $-$ $\quad -$ $\quad -$



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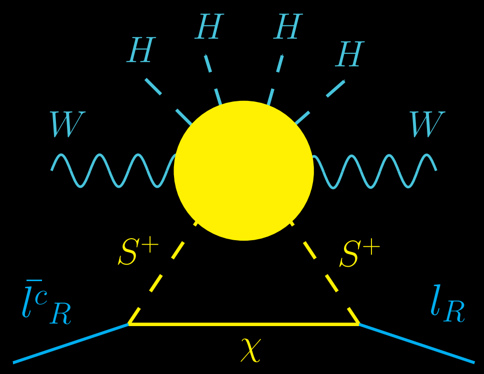
$$+V(S,H,\Delta)$$

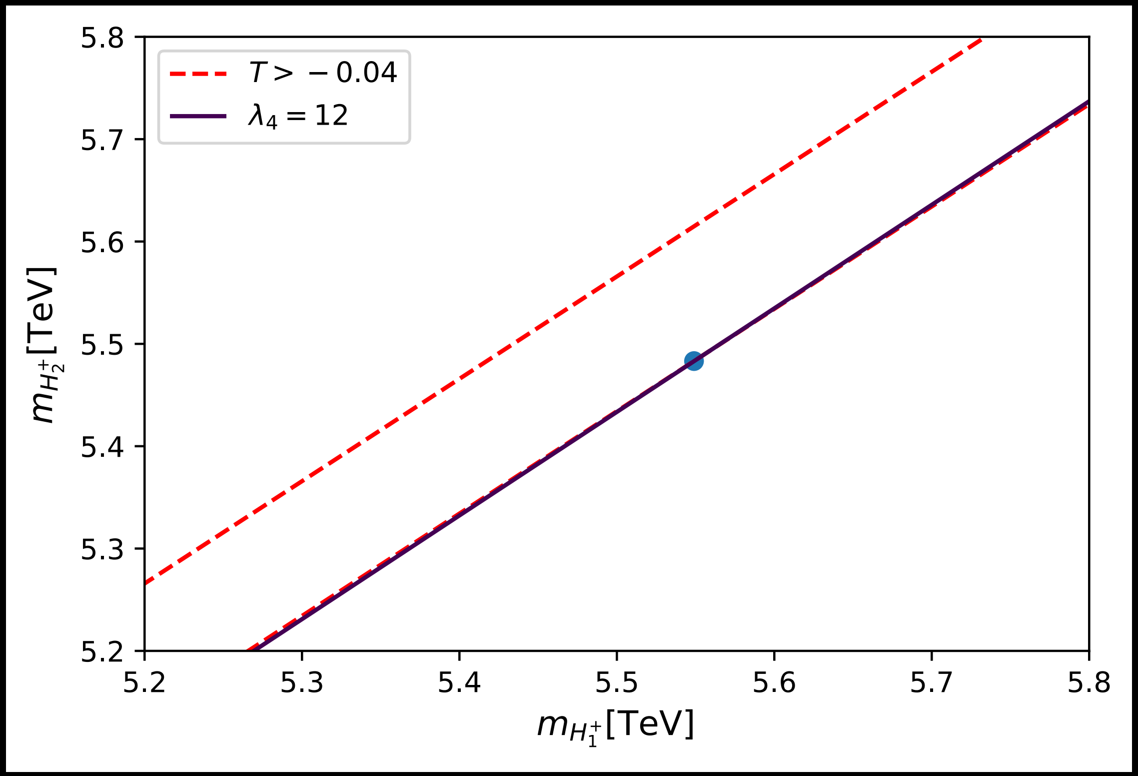
$$m_{ab}^\nu = \frac{m_W^4}{v^4}\frac{m_a^\ell m_b^\ell \sin^2(2\beta)\left(m_{H_1}^2 - m_{H_2}^2\right)^2}{\left(16\pi^2\right)^3} \times \sum_{j=1}^{3}\sum_{i=1}^{n} m_{N_i} g_{ia} g_{ib} I_j\left(m_{N_i}\right)$$

$SU(2)_L$ Singlet χ and S Phenomenology



- EWPT

$$\Delta T = \frac{1}{4\pi s_W^2 m_W^2}\left[c_\beta^2 F_{\Delta^0,H_1} + s_\beta^2 F_{\Delta^0,H_2} - 2 s_\beta^2 c_\beta^2 F_{H_1,H_2}\right]$$

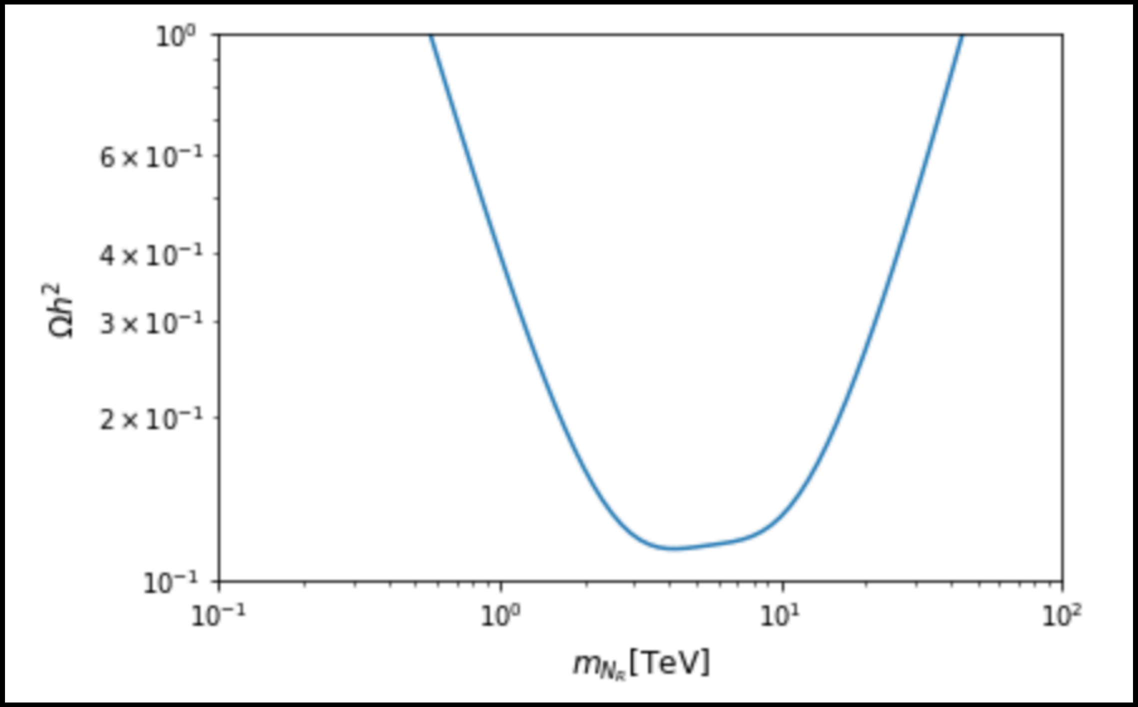


- Dark Matter

$$\sigma v_{\rm rel} = \frac{\sum_{(\alpha,\beta)} |g^*_{1\alpha} g_{1\beta}|^2}{48\pi} m^2_{N_1} F(m_{N_1}, m_{H_1^+}, m_{H_2^+})\, v^2_{\rm rel} = a + b v^2_{\rm rel}$$

$$\Omega_{N_1} h^2 \approx \frac{1.07\times 10^9 {\rm GeV}^{-1}}{M_P} \frac{X_F^2}{\sqrt{g_\star} 3b}$$

$$x_F = \ln\left[\frac{5}{4}\sqrt{\frac{45}{8}}\frac{g}{2\pi^3}\frac{M_P N_{N_1} 6b}{x_F\sqrt{g_\star \chi_F}}\right]$$



Summary

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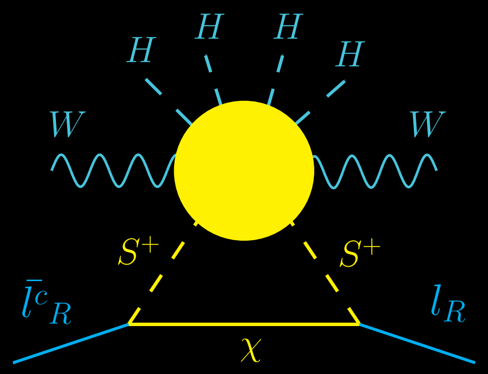
Challenges

- To create a systematic exploration inside the classes , in order to build all UV completions

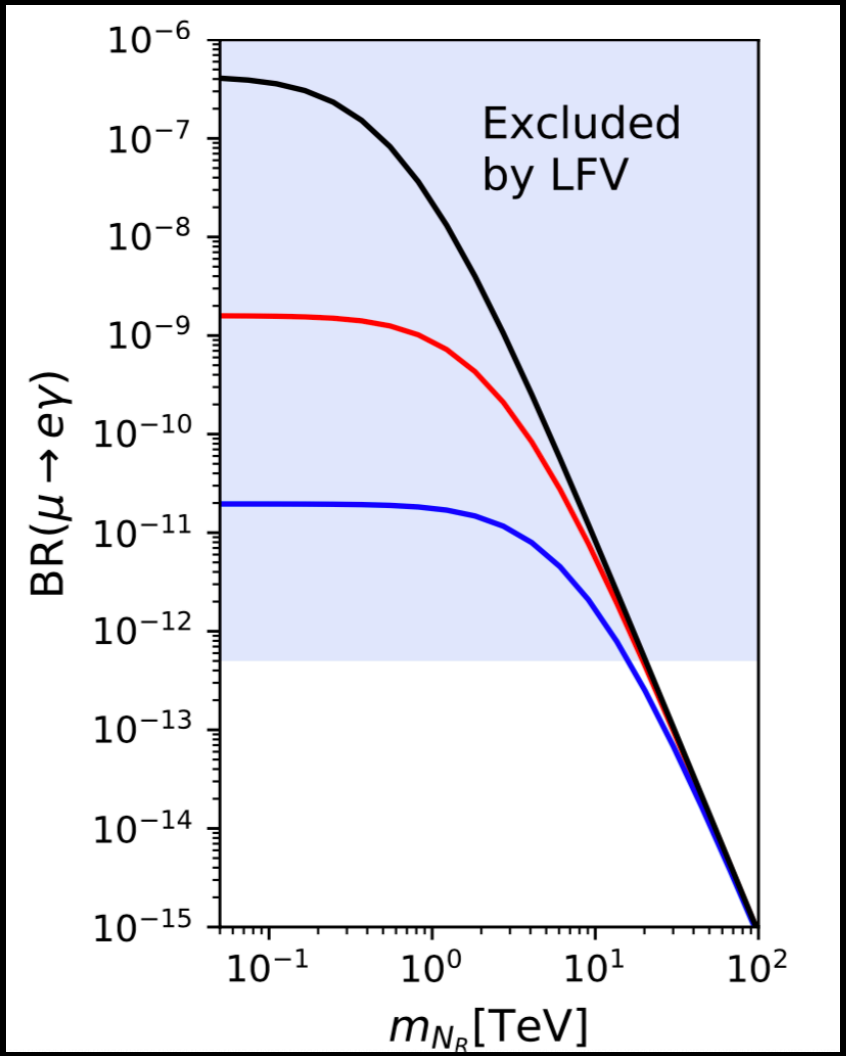
非常感謝

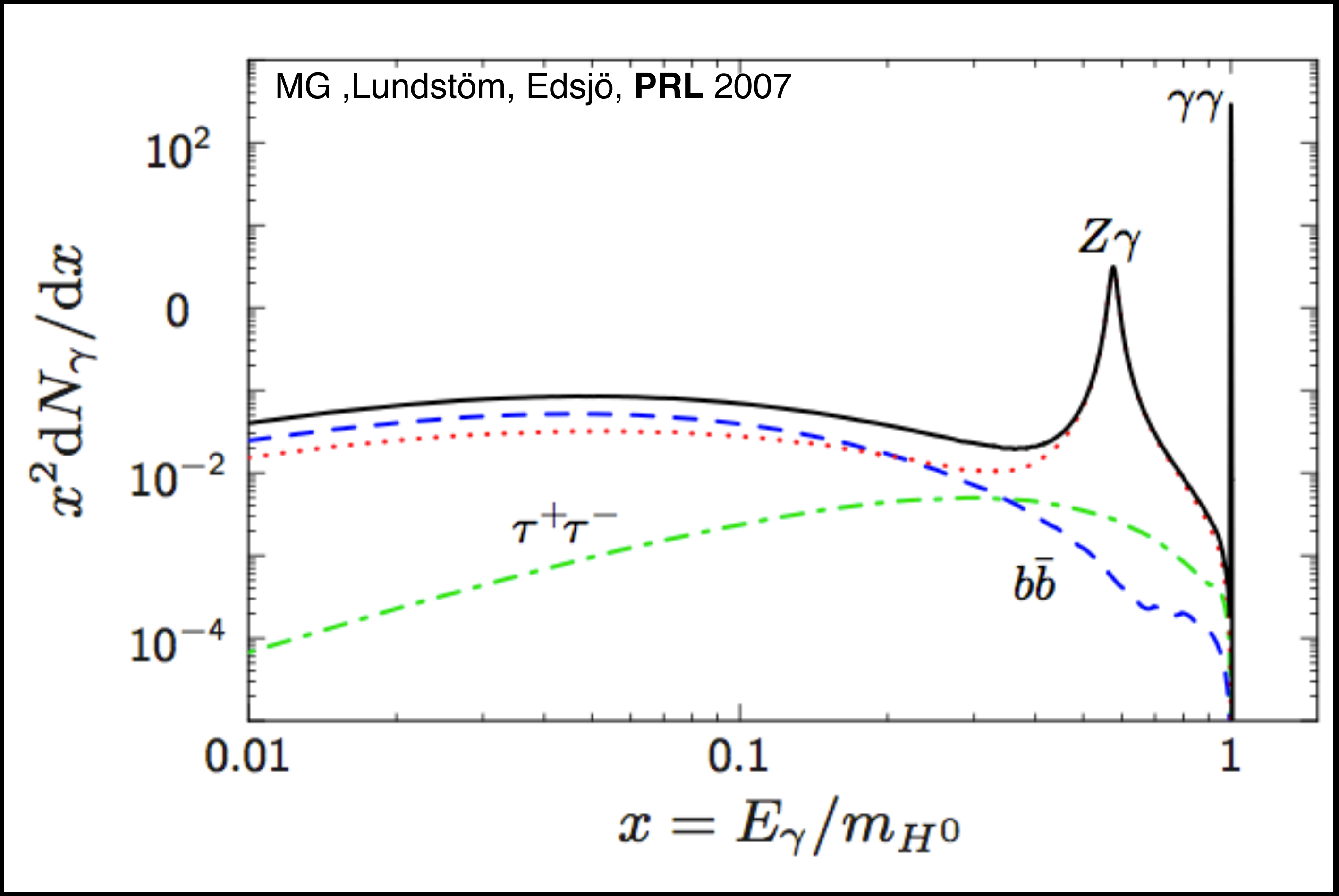
$SU(2)_L$ Singlet χ and S Phenomenology



- LFVP

$$\mathrm{Br}\left(l_\alpha \to l_\beta \gamma\right) = \frac{3\alpha}{64\pi G_F^2} \Big| \sum_{i=1,2} g_{i\alpha}^* g_{i\beta} G(\beta, m_{H_1^+}, m_{H_2^+}) \Big|^2 \mathrm{Br}\left(l_\alpha \to l_\beta v_\alpha \overline{v}_\beta\right)$$




MG ,Lundstöm, Edsjö, PRL 2007
$\gamma\gamma$
$Z\gamma$
$\tau^+\tau^-$
$b\bar{b}$
10^2
0
10^{-2}
10^{-4}
$x^2 \mathrm{d}N_\gamma/\mathrm{d}x$
0.01
0.1
1
$x = E_\gamma/m_{H^0}$