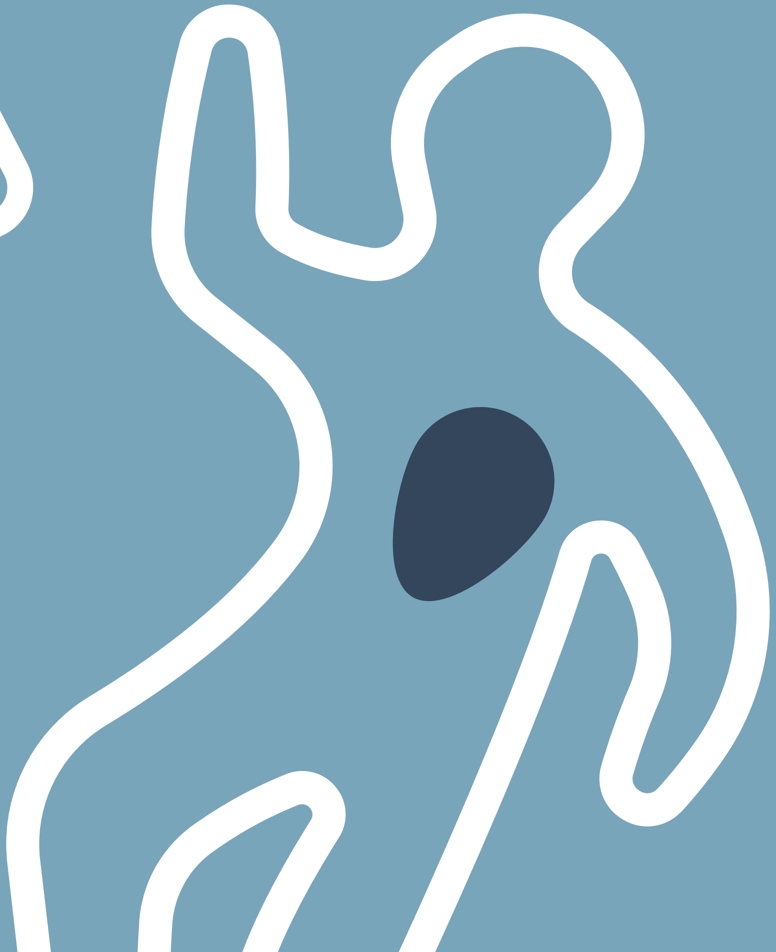
A physics murder mystery

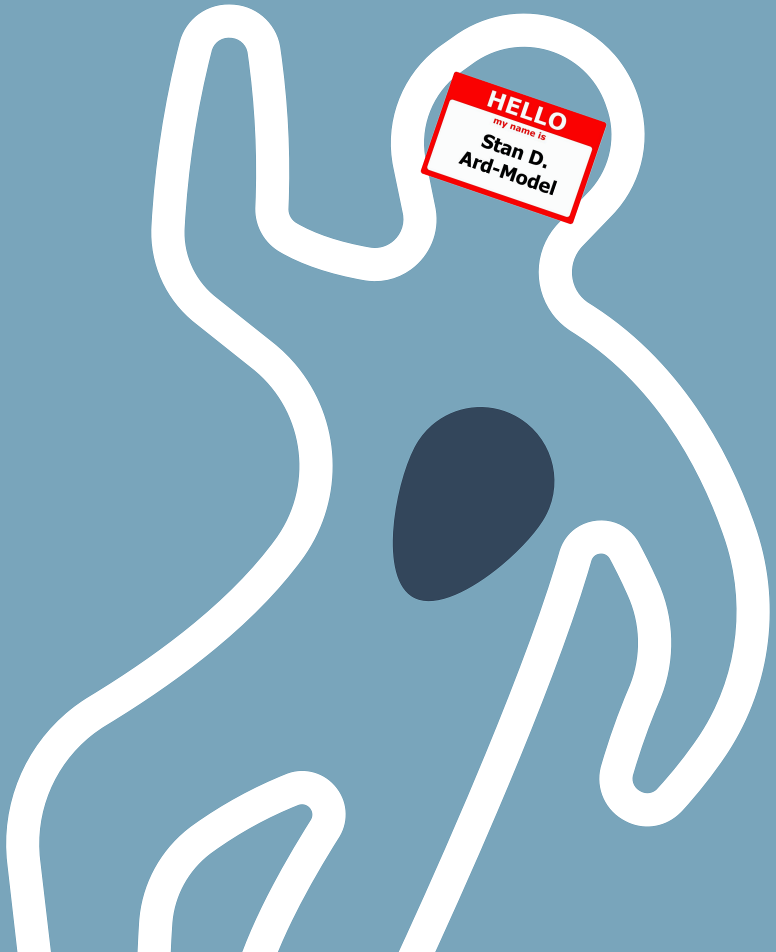
An investigation of neutrinos

Based on 2211.15954, with Michael and Tobias



There's been a murder!

The Standard Model has been found dead in an alleyway!



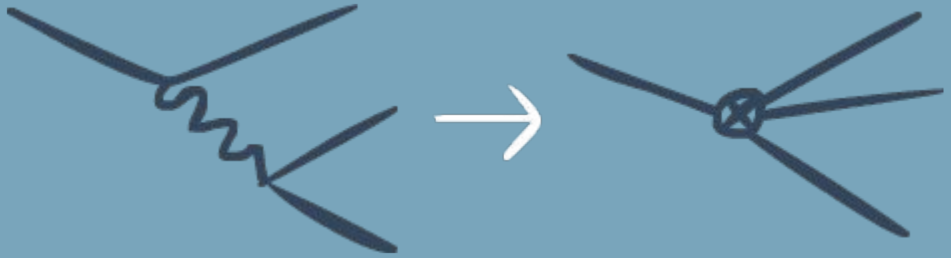
Our best agent is on the case!

Detective inspector **Eugene**
(Effective) Field Theory

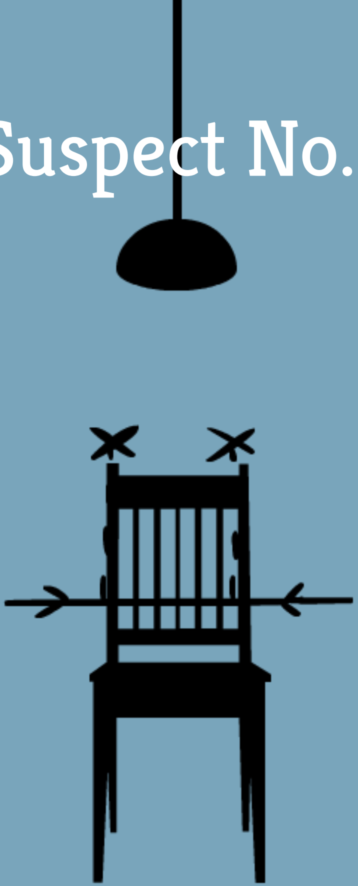
Our best agent is on the case!

Detective inspector **Eugene (Effective) Field Theory**

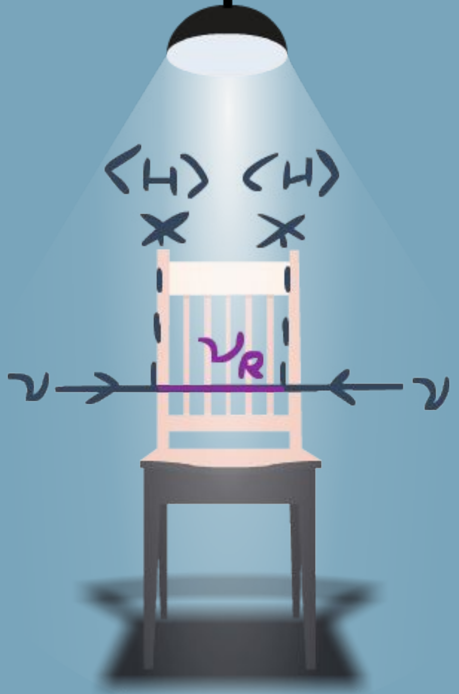
Special skill: Eugene can integrate out the high-energy details, and hone in on the effective results



Suspect No.1



Suspect No.1



TYPE-I SEESAW

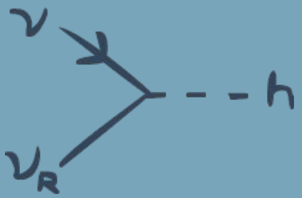
SUSPECT PROFILE: Type-I Seesaw

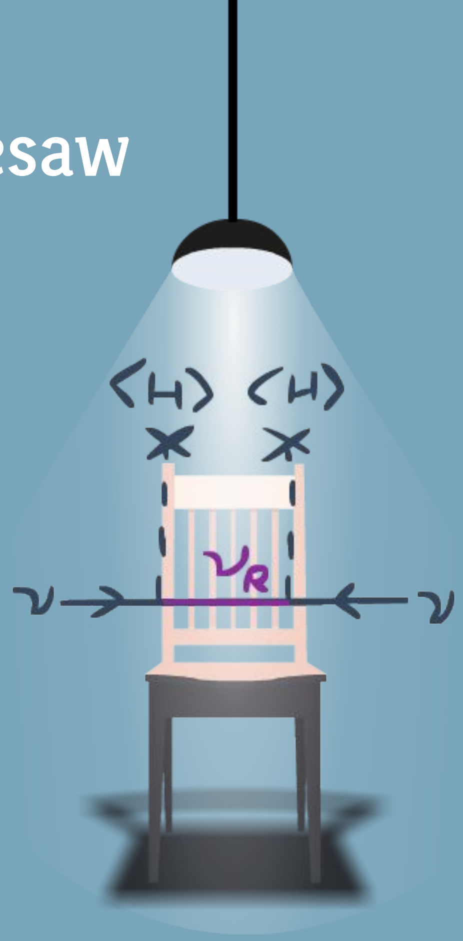
right-handed singlet fermions

Majorana masses

$$\mathcal{L} = \overline{\nu_R} i\partial\!\!\!/ \nu_R - \overline{L} Y \nu_R \widetilde{H} - \frac{1}{2} M \overline{\nu_R^c} \nu_R$$

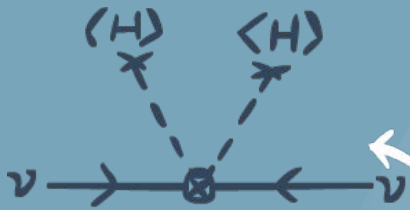
Yukawa interactions



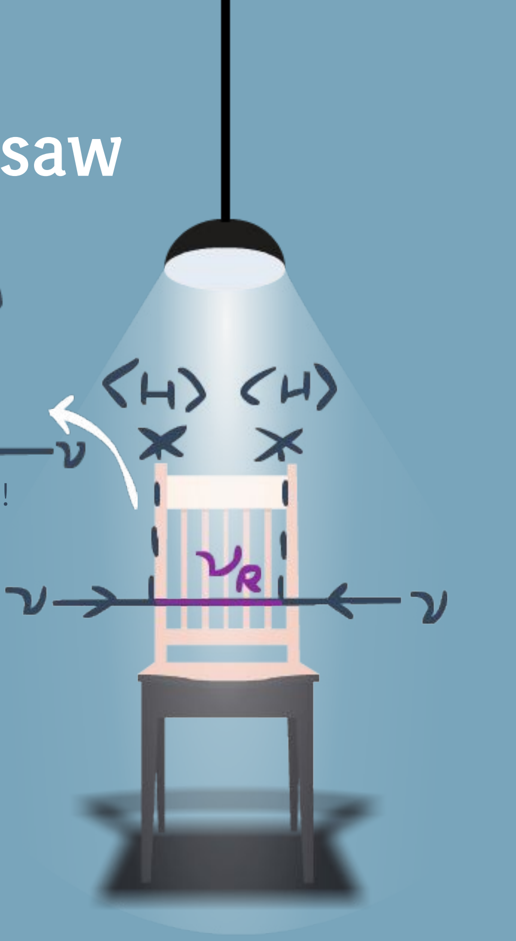


- also caught littering in public

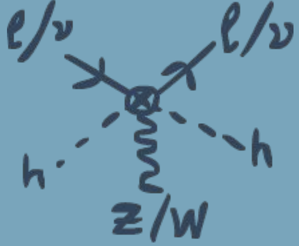
SUSPECT PROFILE: Type-I Seesaw



Neutrino masses!

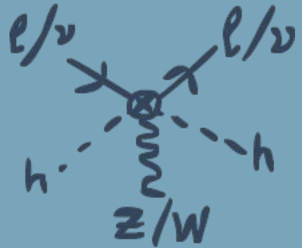


SUSPECT PROFILE: Type-I Seesaw



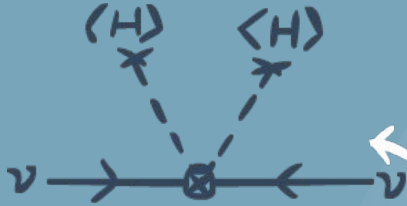
$\mathcal{O}_{HL}^{(1)}$

$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{L}\gamma^\mu L)$

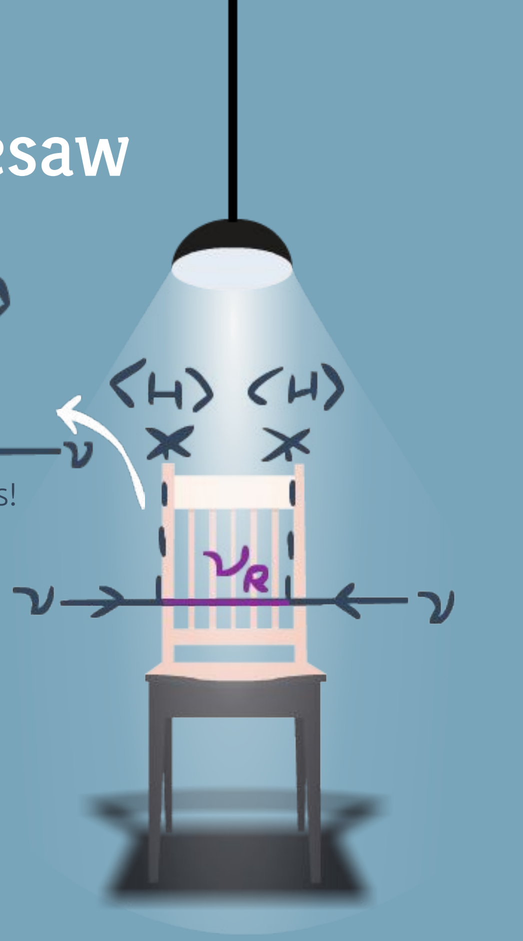


$\mathcal{O}_{HL}^{(3)}$

$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{L}\sigma^a\gamma^\mu L)$

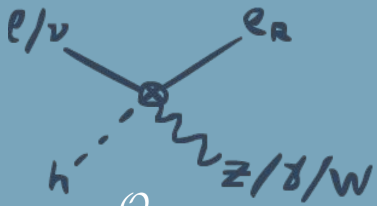


Neutrino masses!



$\mathcal{O}_{eB}$

$(\overline{L}\sigma^{\mu\nu}e_R)HB_{\mu\nu}$



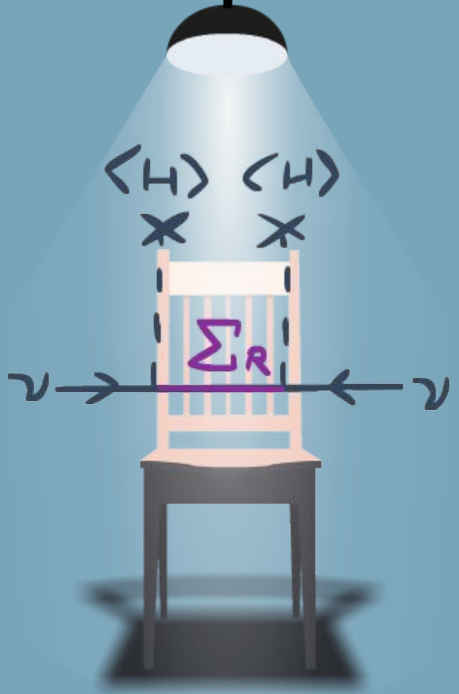
$\mathcal{O}_{eW}$

$(\overline{L}\sigma^{\mu\nu}e_R)\sigma^a HW^a_{\mu\nu}$

+ others...

Suspect No.2

Suspect No.2



TYPE-III SEESAW

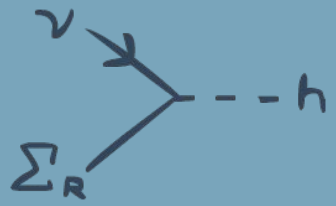
SUSPECT PROFILE: Type-III Seesaw

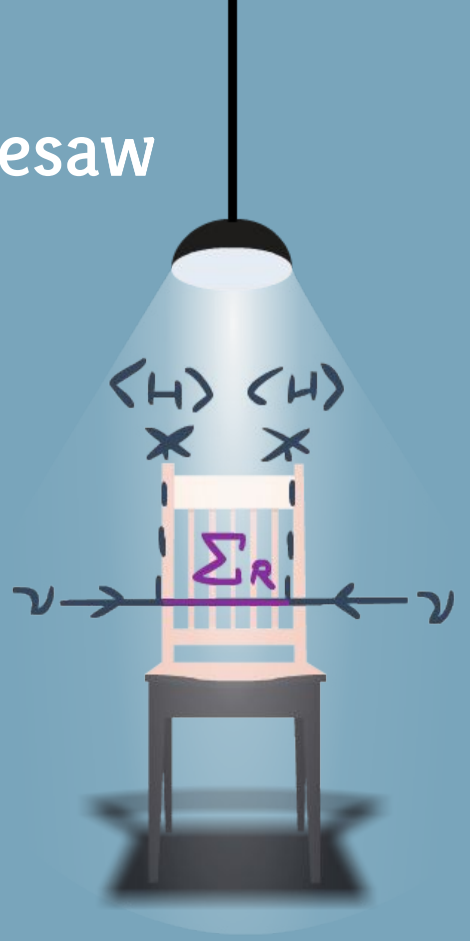
right-handed $SU(2)_W$ triplet fermions

Majorana masses

$$\mathcal{L} = \mathrm{Tr}\left(\overline{\Sigma_R} i \not{D} \Sigma_R\right) - \overline{L} Y \Sigma \widetilde{H} - \frac{1}{2} M \overline{\Sigma_R^c} \Sigma_R$$

Yukawa interactions

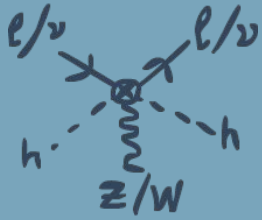




- also caught mooning in a library

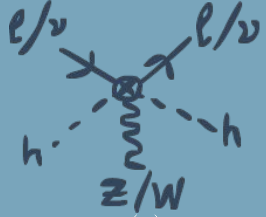
SUSPECT PROFILE: Type-III Seesaw

SUSPECT PROFILE: Type-III Seesaw



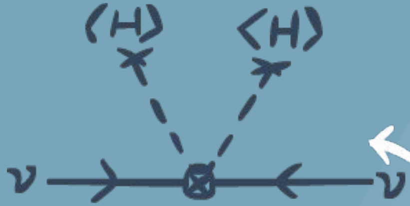
$\mathcal{O}_{HL}^{(1)}$

$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{L}\gamma^\mu L)$

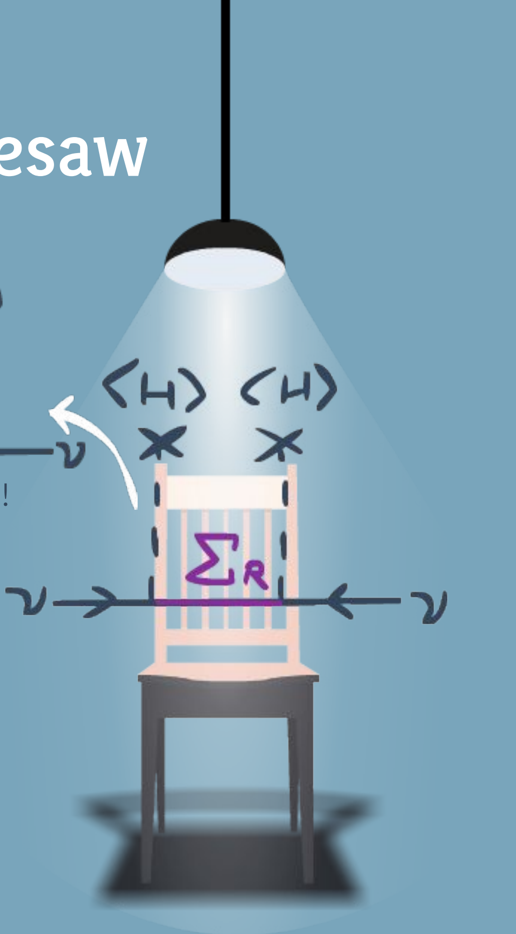


$\mathcal{O}_{HL}^{(3)}$

$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{L}\sigma^a\gamma^\mu L)$



Neutrino masses!



$\mathcal{O}_{eB}$

$(\overline{L}\sigma^{\mu\nu}e_R)HB_{\mu\nu}$

$\mathcal{O}_{eW}$

$(\overline{L}\sigma^{\mu\nu}e_R)\sigma^a HW^a_{\mu\nu}$

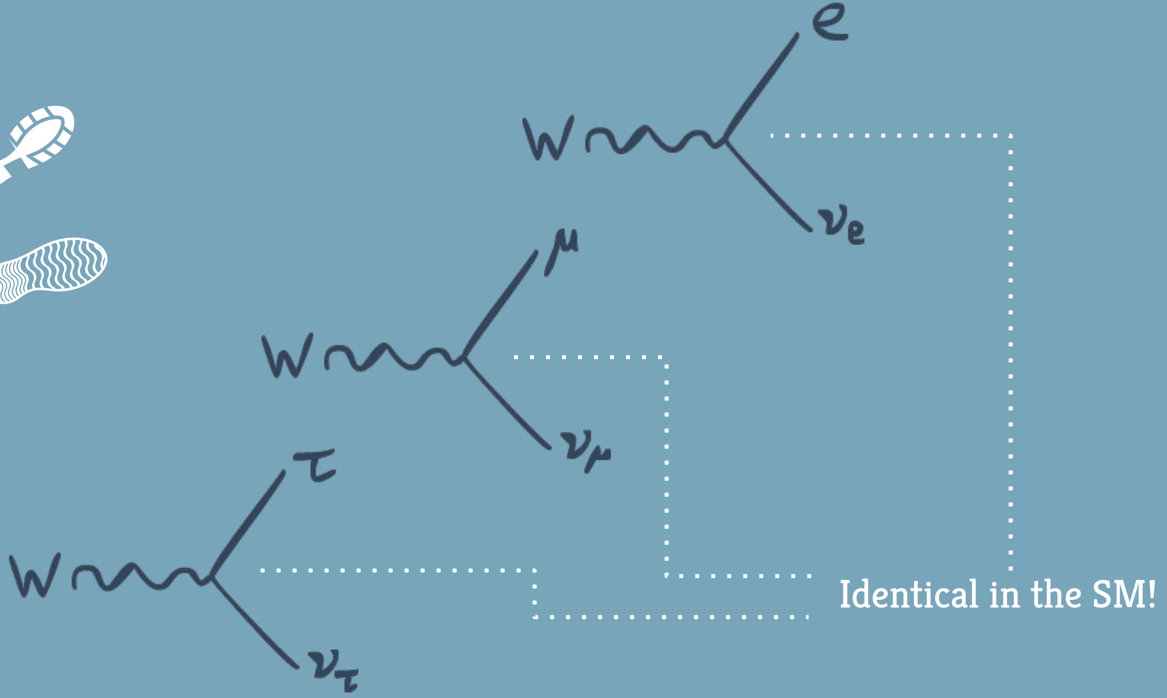
$\mathcal{O}_{eH}$

$(H^\dagger H)(\overline{L}e_R H)$

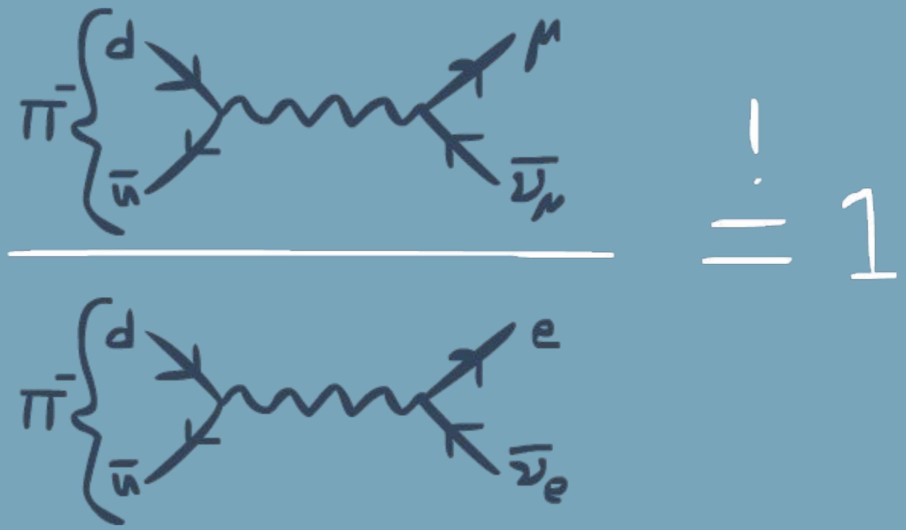
+ others...

THE EVIDENCE

EVIDENCE: Lepton Flavour Universality

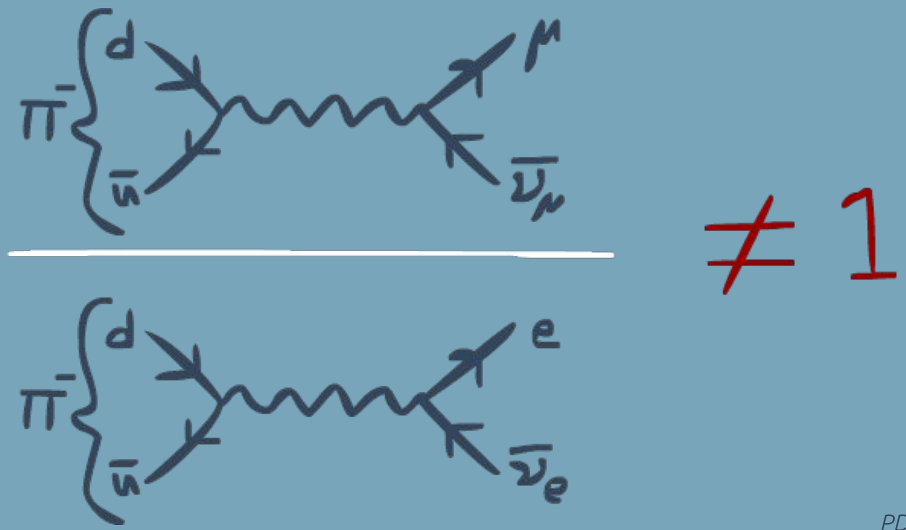


EVIDENCE: Lepton Flavour Universality



Can also look at kaon decays (leptonic & semi-leptonic), tau decays, W decays, etc…

EVIDENCE: Lepton Flavour Universality



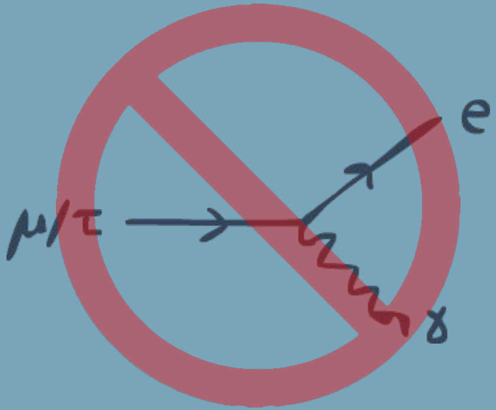
PDG 2002
Pich et. al. 2012.07099
Seng et. al. 2203.05217

Can also look at kaon decays (leptonic & semi-leptonic), tau decays, W decays, etc…

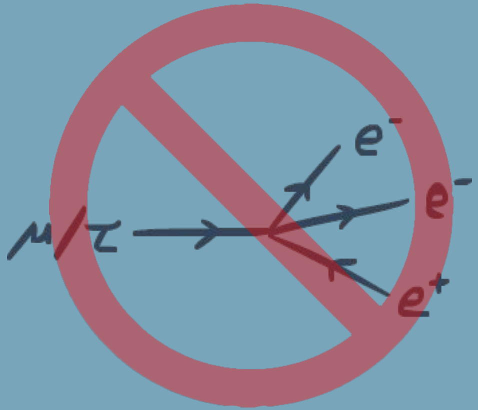
EVIDENCE: Lepton Flavour Universality

The effective couplings in the Seesaw models are <u>not</u> universal!

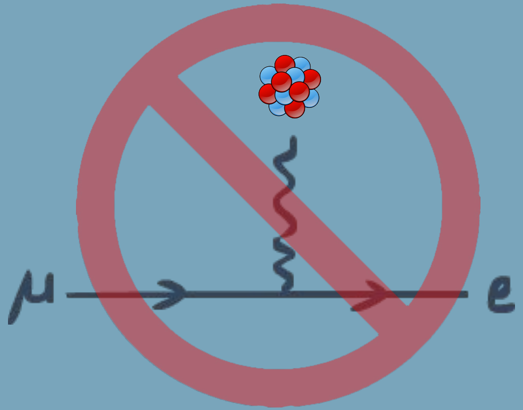
EVIDENCE: Lepton Flavour Violation



RADIATIVE
CHARGED LEPTON
DECAYS



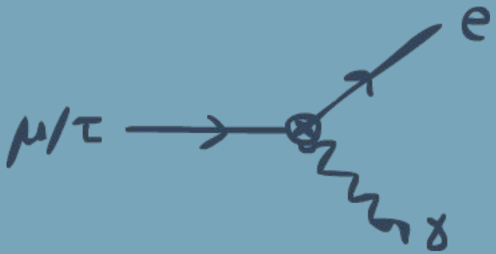
TRILEPTON
DECAYS



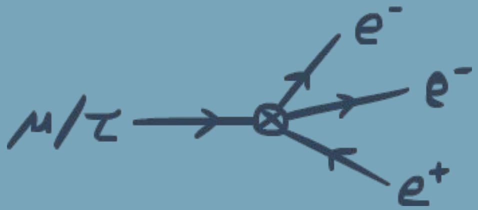
μ-e CONVERSION
IN NUCLEI

Forbidden in the Standard Model!

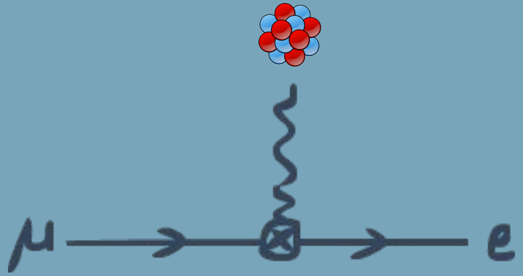
EVIDENCE: Lepton Flavour Violation



RADIATIVE
CHARGED LEPTON
DECAYS



TRILEPTON
DECAYS



μ-e CONVERSION
IN NUCLEI

...allowed by our suspects!

EVIDENCE: Lepton Flavour Violation

Baldini et. al. (MEG) 1605.05081
Bellgardt et. al. (SINDRUM) Nucl. Phys. B
Bertl. et al. (SINDRUM II) Eur. Phys. J. C
Aubert. et al. (BaBar) 0908.2381
Hayasaka. et al. (Belle) 1001.3221

CURRENT STATUS: Not Observed Yet

RADIATIVE CHARGED LEPTON DECAYS

TRILEPTON DECAYS

μ-e CONVERSION IN NUCLEI

<u>...allowed by our suspects!</u>

EVIDENCE: Electroweak Observables

<u>Basic principle:</u> introducing new physics means we have our parameters wrong!

Consider extracting G_F from muon decay:

$$\hat{G}_F = G_F \left[1 + v^2 \left(C^{(3)}_{HL,\mu\mu} + C^{(3)}_{HL,ee} - \frac{1}{2} C_{LL,e\mu\mu e} - \frac{1}{2} C_{LL,\mu e e\mu} \right) \right]$$

EVIDENCE: Electroweak Observables

Basic principle: introducing new physics means we have our parameters wrong!

Consider extracting G_F from muon decay:

$$\hat{G}_F = G_F\left[1 + v^2\left(C^{(3)}_{HL,\mu\mu} + C^{(3)}_{HL,ee} - \frac{1}{2}C_{LL,e\mu\mu e} - \frac{1}{2}C_{LL,\mu e e\mu}\right)\right]$$

⇒ Anything we calculate using G_F as an input parameter will be wrong!

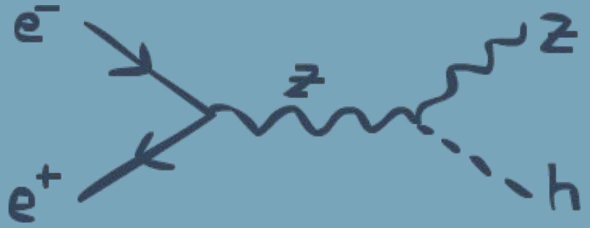
EVIDENCE: Electroweak Observables

Using (α_{EM}, m_Z, G_F) as inputs, we can compute and compare:

Observable	SM Prediction	Measurement
$\sin^2(\theta_W)$	0.231534 ± 0.000030	0.23153 ± 0.00026
m_W [GeV]	80.356 ± 0.006	80.377 ± 0.012

De Blas et. al. 2112.07274
Schael et. al. hep-ex/0509008
PDG 2002

PROSPECTIVE EVIDENCE: Higgsstrahlung



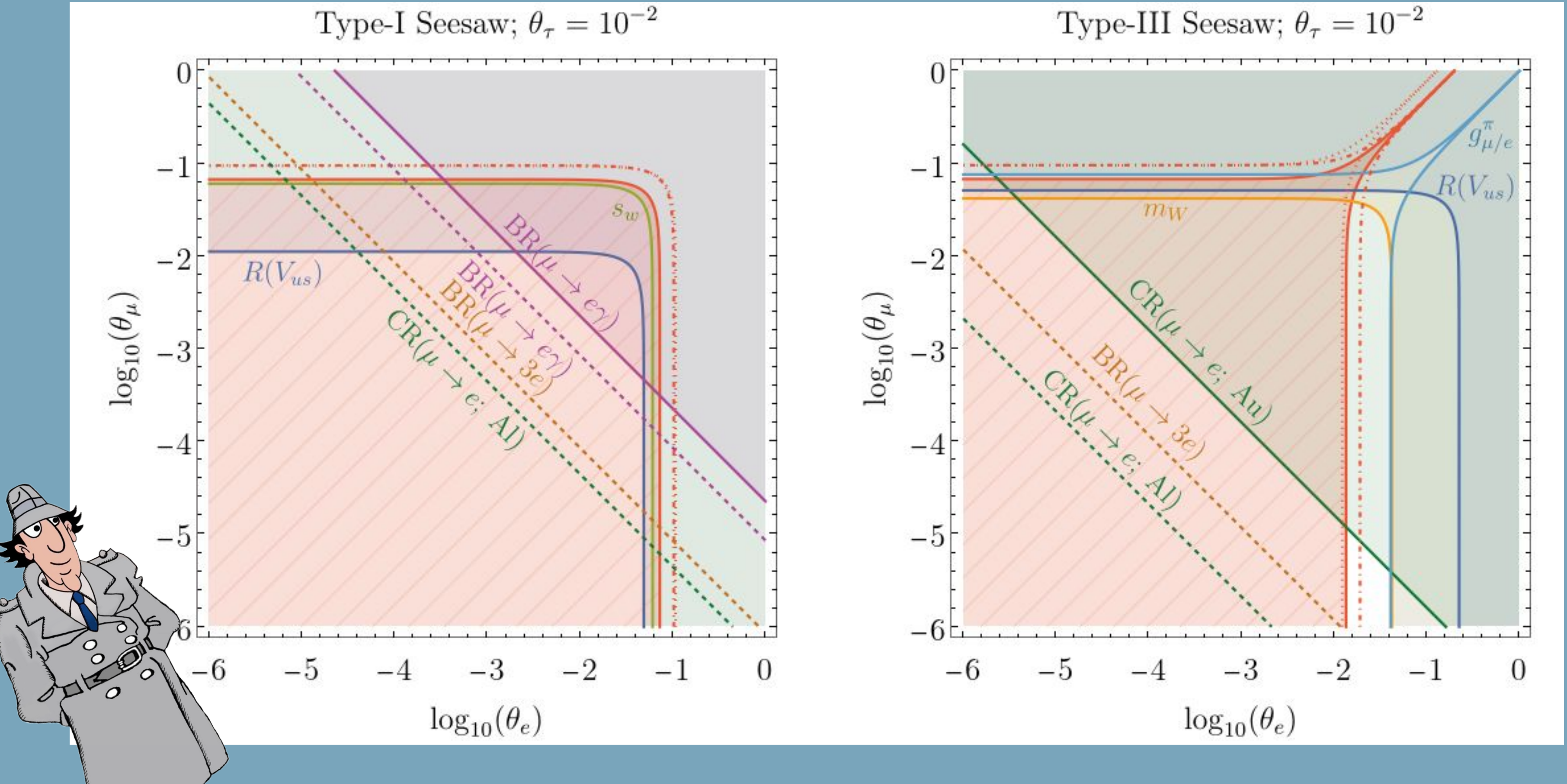
Expected to be measured at ~1% precision at next-generation colliders such as CEPC, FCC-ee, ILC, CLIC.

PROSPECTIVE EVIDENCE: Higgsstrahlung

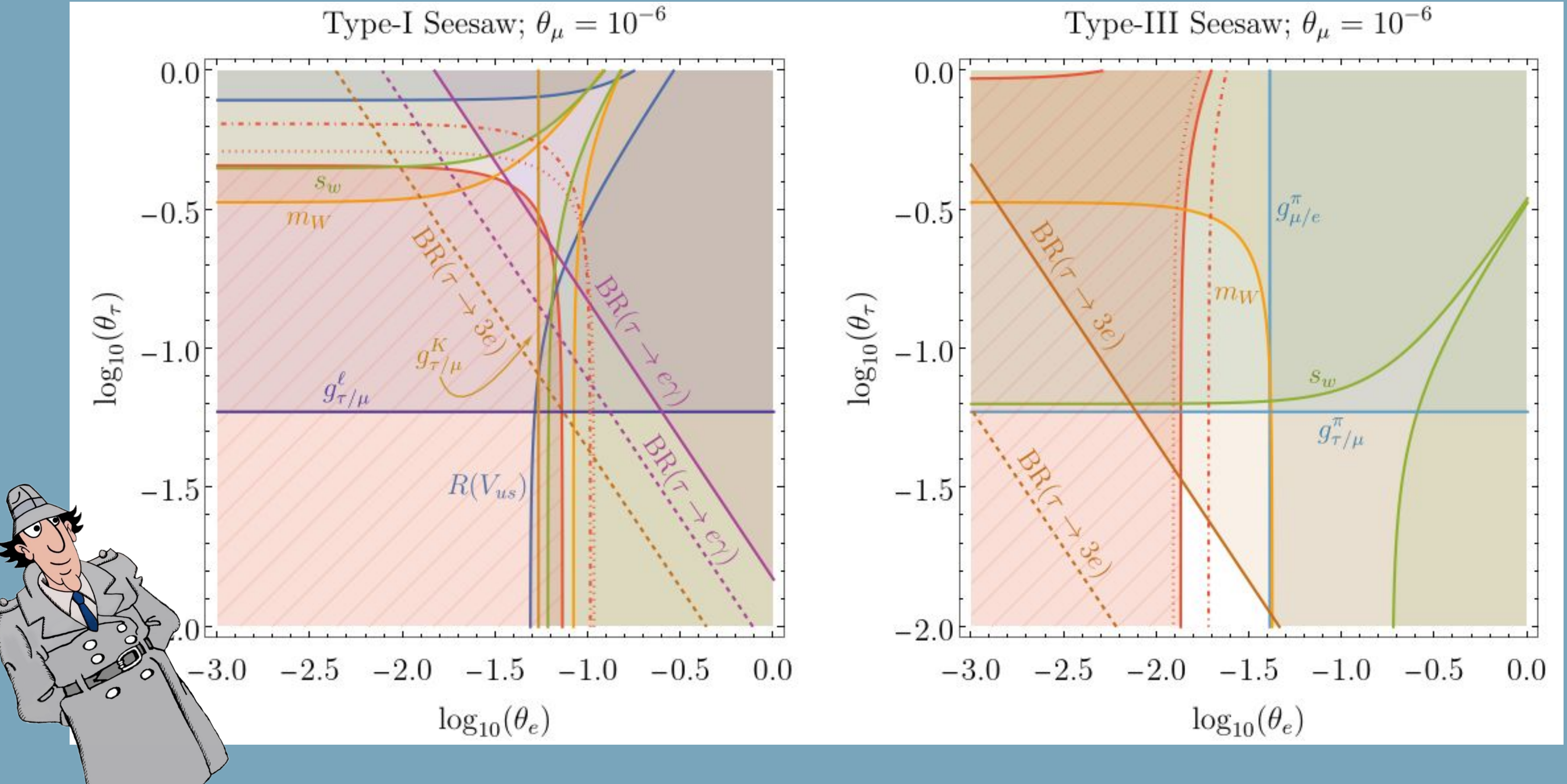
Neutrinos can produce corrections to the SM prediction

⇒ Future source of evidence!

INVESTIGATION FINDINGS



INVESTIGATION FINDINGS



THAT'S ALL

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Backup: Seesaw Mechanism & Mass Matrix

Right-handed neutrinos (Type-I Seesaw)

$$\mathcal{L} = \overline{N} i \partial\!\!\!/ N - \left(\widetilde{Y} \overline{L} \widetilde{H} N + \frac{1}{2} M \overline{N^c} N + \text{h.c.} \right)$$

Mass matrix

$$\mathcal{L}_{\nu\ \text{mass}} = \frac{1}{2} \begin{pmatrix} \overline{\nu} & \overline{N^c} \end{pmatrix} \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} \begin{pmatrix} \nu^c \\ N \end{pmatrix} + \text{h.c.}, \qquad m = \frac{\widetilde{Y} v}{\sqrt{2}}$$

Seesaw masses

$$m_{\text{light}} \approx \frac{m^2}{M}, \qquad m_{\text{heavy}} \approx M$$

Backup: Mass Matrix Texture

We adopt the following texture for the mass matrix:

$$\begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & \theta_e M & 0 \\ 0 & 0 & 0 & \theta_\mu M & 0 \\ 0 & 0 & 0 & \theta_\tau M & 0 \\ \theta_e M & \theta_\mu M & \theta_\tau M & 0 & M \\ 0 & 0 & 0 & M & 0 \end{pmatrix}$$

See e.g. *Abada et. al.* 0707.4058

For concreteness we fix $M = 1\,\text{TeV}$ and explore the parameter space of the **mixing angles** θ_e, θ_μ and θ_τ.

Backup: Wilson Coefficients

Operator	Coefficient	Type-I	Type-III
$(\tilde{H}^\dagger L_i)^T C (\tilde{H}^\dagger L_j)$	$C_{5,ij}$	$\frac{1}{2}\left(\tilde{Y}^* (M^\dagger)^{-1} \tilde{Y}^\dagger\right)_{ij}$	$\frac{1}{2}(\tilde{Y}^* (M^\dagger)^{-1} \tilde{Y}^\dagger)_{ij}$
$(H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{L_i}\gamma^\mu L_j)$	$C^{(1)}_{HL,ij}$	$\frac{1}{4}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger\right)_{ij}$	$\frac{3}{4}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger\right)_{ij}$
$(H^\dagger i \overleftrightarrow{D}^a_\mu H)(\overline{L_i}\sigma^a\gamma^\mu L_j)$	$C^{(3)}_{HL,ij}$	$-\frac{1}{4}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger\right)_{ij}$	$\frac{1}{4}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger\right)_{ij}$
$(H^\dagger H)(\overline{L_i} e_{Rj} H)$	$C_{eH,ij}$	0	$\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$
$(\overline{L_i}\sigma^{\mu\nu} e_{Rj}) H B_{\mu\nu}$	$C_{eB,ij}$	$\frac{1}{16\pi^2}\frac{g_1}{24}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$	$\frac{1}{16\pi^2}\frac{g_1}{8}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$
$(\overline{L_i}\sigma^{\mu\nu}\sigma^a e_{Rj}) H W^a_{\mu\nu}$	$C_{eW,ij}$	$\frac{1}{16\pi^2}\frac{5g_2}{24}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$	$\frac{1}{16\pi^2}\frac{3g_2}{8}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$

Du et. al. 2201.04646, *Zhang & Zhou*, 2107.12133, *Coy & Frigerio*, 2110.09126

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#33465b

#ffffff