THE "DEFORMED"-TYPE II SEESAW MECHANISM

Wrishik Naskar

(based on U. Banerjee, C. Englert, **WN** 2024, 2403.17455)

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Mainz Institute for Theoretical Physics

Extends the SM scalar sector by a complex $SU(2)_L$ triplet (Δ) with $Y_\Delta = 1$.

(Chakrabortty et al. 2016; Primulando et al. 2019; Fuks et al. 2020; Antusch et al. 2019; Águila et al. 2014)

$$\mathcal{L}^{\text{type-II}} = \mathcal{L}_{\text{SM}} + \text{Tr}[D_\mu \Delta^\dagger D^\mu \Delta] - V(\Phi, \Delta) + \mathcal{L}^{\text{BSM}}_{\text{Yukawa}}$$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ (\phi + v_\Phi + i\eta) \end{pmatrix}, \quad \Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} \delta^+ & \sqrt{2}\Delta^{++} \\ (\delta^0 + v_\Delta + i\chi) & -\delta^+ \end{pmatrix}$$

Physical scalars: $h, \Delta^0, A, \Delta^\pm, \Delta^{\pm\pm}$

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$$\mathcal{L}^{\text{BSM}}_{\text{Yukawa}} \supset -(Y_\Delta)_{ij} \bar{\psi}^c_{L_i} \Delta \psi_{L_j} + \text{h.c.}$$

Quintessential in generating non-zero neutrino masses!

TYPE-II SEESAW MECHANISM

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The neutrino mass-mixing matrix (M_ν) is diagonalised by the unitary PMNS matrix,

$$M_\nu = U_{\text{PMNS}}^* \,\text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})\, U_{\text{PMNS}}^\dagger$$

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Yukawa matrix: $Y_\Delta = \dfrac{M_\nu}{\sqrt{2}v_\Delta}$

NUFIT CONSTRAINTS (NORMAL ORDERING)

Parameter	Best-fit
Δm^2_{21} $[10^{-5}\ \mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$
Δm^2_{31} $[10^{-3}\ \mathrm{eV}^2]$	2.50 ± 0.03
$\sin\theta_{12}/0.1$	$3.20^{+0.20}_{-0.16}$
$\theta_{12}/^\circ$	$34.5^{+1.2}_{-1.0}$
$\sin\theta_{23}/0.1$	$5.47^{+0.20}_{-0.30}$
$\theta_{23}/^\circ$	$47.7^{+1.2}_{-1.7}$
$\sin\theta_{13}/0.1$	$2.160^{+0.083}_{-0.069}$
$\theta_{13}/^\circ$	$8.45^{+0.16}_{-0.14}$
δ/π	$1.21^{+0.21}_{-0.15}$
$\delta/^\circ$	218^{+38}_{-27}

Best-fit constraints from the global fit of neutrino oscillation data. (NuFIT 2018)

AN EXAMPLE YUKAWA MATRIX

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\boxed{c_{ij} = \cos\theta_{ij},\ s_{ij} = \sin\theta_{ij}}$$

Plugging in the NuFIT constraints:

$$\boxed{Y_\Delta = \begin{pmatrix} 0.0358 & 0.0018 & 0.0012 \\ 0.0018 & 0.0438 & 0.0069 \\ 0.0012 & 0.0069 & 0.0416 \end{pmatrix}}$$

$$\boxed{v_\Delta = 1\ \text{eV},\ m_{\nu_1} = 0.05\ \text{eV}}$$

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Constraints from neutrino oscillations: U_{PMNS}, Δm^2_{21}, Δm^2_{31}.

(NuFIT 2018)

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Constraints from neutrino oscillations: U_{PMNS}, Δm^2_{21}, Δm^2_{31}.

(NuFIT 2018)

Y_Δ has 2 free-parameters: m_{ν_1}, v_Δ.

Production of $\Delta^{\pm\pm}$: smoking gun signal for the Type-II Seesaw Mechanism at colliders.

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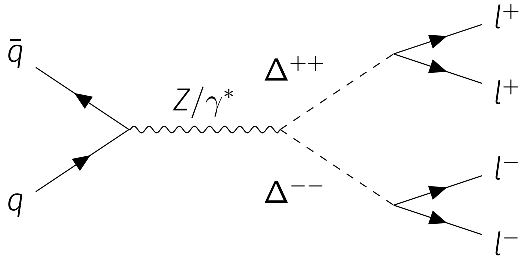
Strongest constraints: $pp \to \Delta^{++}\Delta^{--} \to l^+l^+l^-l^-$ $(l = e, \mu, \tau)$

(ATLAS 2018; ATLAS 2023)

100% branching for $v_\Delta \sim 1$ eV, $m_{\nu_1} \sim 0.05$ eV



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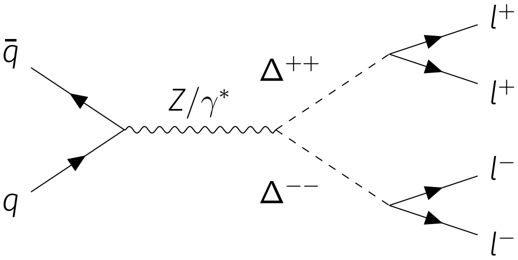
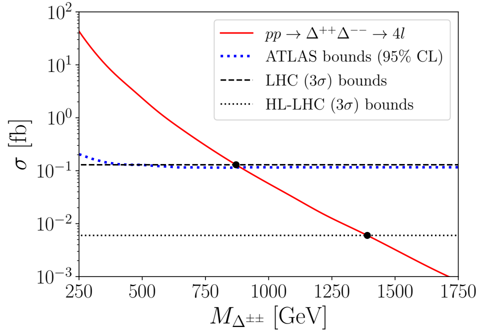


Cuts and methodology: (Anisha, Banerjee, et al. 2022)

Mass exclusions:

LHC: $\gtrsim$ 870 GeV

HL-LHC: $\gtrsim$ 1400 GeV



(ATLAS 2023)

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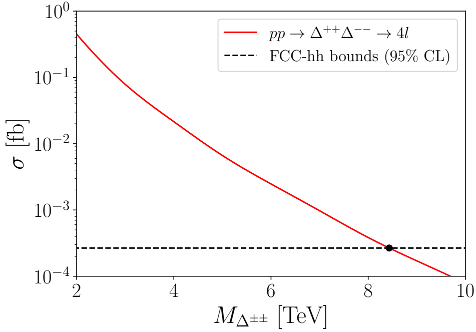
LHC: $\gtrsim$ 870 GeV

HL-LHC: $\gtrsim$ 1400 GeV

FCC-*hh*: $\gtrsim$ 8.5 TeV



THEORETICAL AND EXPERIMENTAL CONSIDERATIONS

- Vacuum stability
- Perturbative Unitarity
- Higgs data
- Electroweak Precision

(Primulando et al. 2019)

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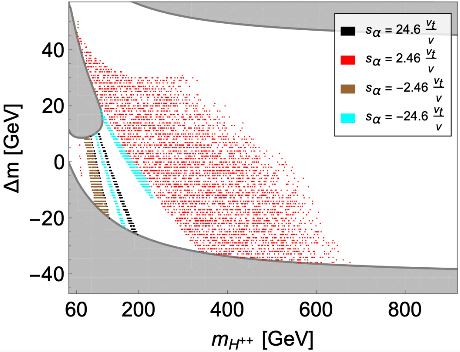

All constraints are within LHC-sensitivity!

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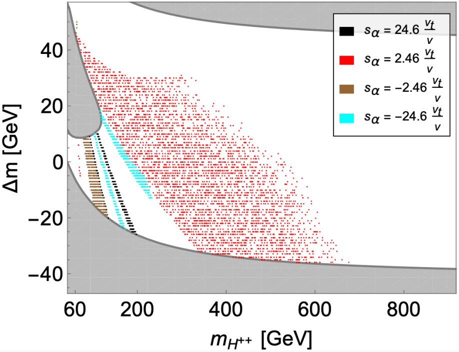

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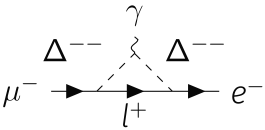
EWP Constraints after FCC-*ee*: $M_{\Delta^{\pm\pm}} \gtrsim 105$ GeV

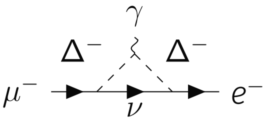
(Fan et al. 2015)

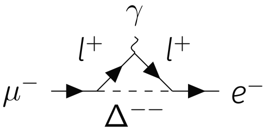
LEPTON-FLAVOUR-VIOLATING (LFV) DECAYS

$$\mathrm{BR}(\mu \to e\gamma) = \frac{\alpha_{\mathrm{EM}} |Y_\Delta^\dagger Y_\Delta|^2_{\mu e}}{192\pi G_F^2} \left(\frac{1}{M^2_{\Delta^\pm}} + \frac{8}{M^2_{\Delta^{\pm\pm}}} \right)^2 \leq 3.1 \times 10^{-13}$$

(MEG 2016; MEG 2024)







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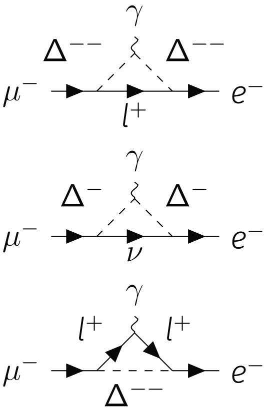
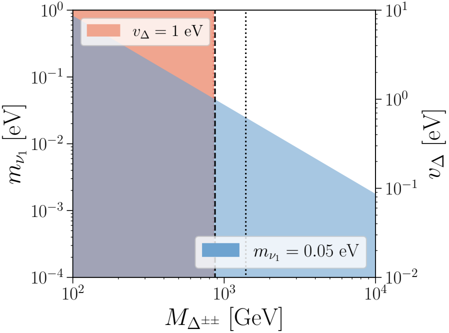
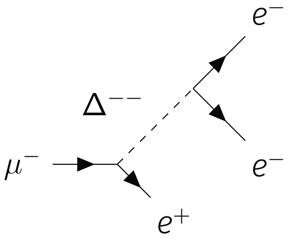




LEPTON-FLAVOUR-VIOLATING (LFV) DECAYS

$$\mathrm{BR}(\mu \to 3e) = \frac{|(Y_\Delta)_{ee}(Y_\Delta)^*_{\mu e}|^2}{4G_F^2 M^4_{\Delta^{\pm\pm}}} \leq 10^{-12}$$

(SINDRUM 1988)



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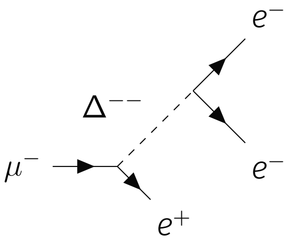

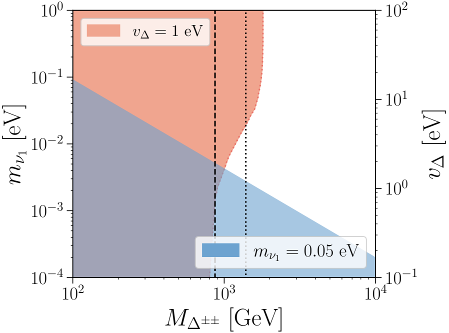

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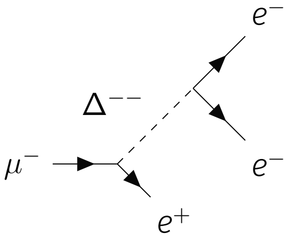

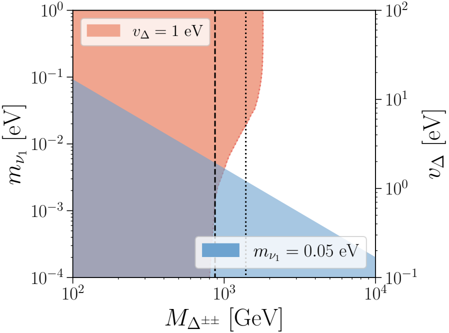

Much of the parameter space sensitive to the HL-LHC is already excluded!

IMPLICATIONS OF EFT-DEFORMATIONS

$$\mathcal{L}^{\text{BSM-EFT}} = \mathcal{L}^{\text{BSM}} + \frac{1}{\Lambda^2} \sum C_i \mathcal{O}_i^{(6)}$$

- **Motivation:** The lightest non-SM particle lies close to the EW scale.
- **Complex singlets:** (Cho et al. 2023; Oikonomou et al. 2024)
- **2HDM:** (Anisha, Biermann, et al. 2022; Anisha, Azevedo, et al. 2024; Ouazghour et al. 2023)
- **Triplet Extensions:** (Padhan et al. 2022; Das et al. 2023)
- **BSM-EFT basis:** (Banerjee et al. 2021)

IMPLICATIONS OF EFT-DEFORMATIONS

$$\mathcal{L}^{\text{BSM-EFT}} = \mathcal{L}^{\text{Type-II}} + \frac{1}{\Lambda^2}\sum C_i \mathcal{O}_i^{(6)}$$

$\mathcal{O}^{(1)}_{L\Phi\Delta,ij}$	$(\bar{\psi}^c_{L_i}\Delta\psi_{L_j})(\Phi^\dagger\Phi)$
$\mathcal{O}^{(2)}_{L\Phi\Delta,ij}$	$\bar{\psi}^c_{L_i,\alpha}\Delta\Phi^\alpha\Phi^\dagger_\beta\psi^\beta_{L_j}$
$\mathcal{O}^{(1)}_{L\Delta,ij}$	$(\bar{\psi}^c_{L_i}\Delta\psi_{L_j})\mathrm{Tr}[(\Delta^\dagger\Delta)]$
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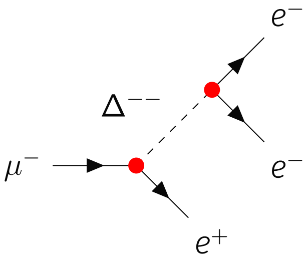

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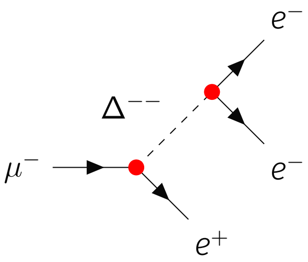
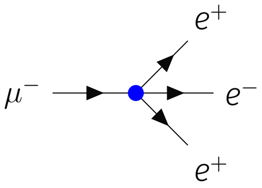
$\mathcal{O}^{(2)}_{L\Delta,ij}$	$\bar{\psi}^c_{L_i} \Delta \Delta^\dagger \Delta \psi_{L_j}$

$\mathcal{O}^{ijkm}_{ll}$	$(\bar{\psi}_{L_i} \gamma_\mu \psi_{L_j})(\bar{\psi}_{L_k} \gamma^\mu \psi_{L_m})$
$\mathcal{O}^{ijkm}_{ee}$	$(\bar{e}_i \gamma_\mu e_j)(\bar{e}_k \gamma^\mu e_m)$
$\mathcal{O}^{ijkm}_{le}$	$(\bar{\psi}_{L_i} \gamma_\mu \psi_{L_j})(\bar{e}_k \gamma^\mu e_m)$





$$\mathcal{L}^{\text{BSM-EFT}} = \mathcal{L}^{\text{Type-II}} + \frac{1}{\Lambda^2}\sum C_i \mathcal{O}_i^{(6)}$$

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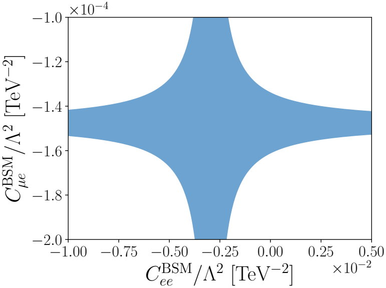
$$(Y^{\text{mod.}}_\Delta)_{ij} = (Y_\Delta)_{ij} - C^{\text{BSM}}_{ij}\frac{v^2}{2\Lambda^2}$$

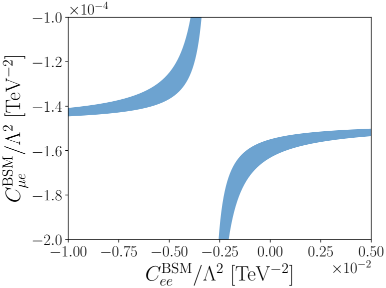
$$\mathrm{BR} \supset |(Y^{\text{mod.}}_\Delta)_{ee}(Y^{\text{mod.}}_\Delta)^*_{\mu e}|^2$$

$$\mathrm{BR} \supset \frac{(C^{\text{SMEFT}}_{ll,le,ee})^2}{\Lambda^4}$$

$C_{\text{SMEFT}} = 0$



$C_{\text{SMEFT}} \neq 0$

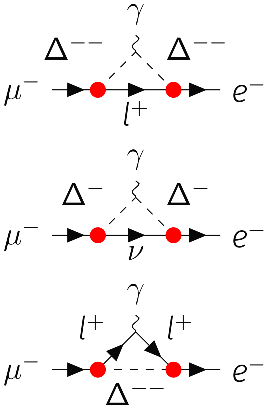


$$C_{L\Phi\Delta,ij} = C_{ij}^{\text{BSM}}$$

Since $(Y_\Delta)_{ee} >> (Y_\Delta)_{\mu e}$, we need bigger cancellations on the diagonal Yukawas compared to the off-diagonal ones.

IMPLICATIONS OF EFT-DEFORMATIONS ($\mu \to e\gamma$)

$\mathcal{O}^{(2)}_{L\Phi\Delta,ij}$	$\bar{\psi}^c_{L_i,\alpha}\Delta\Phi^\alpha\Phi^\dagger_\beta\psi^\beta_{L_j}$



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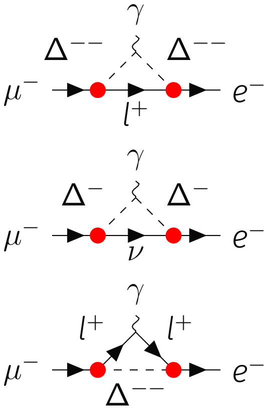
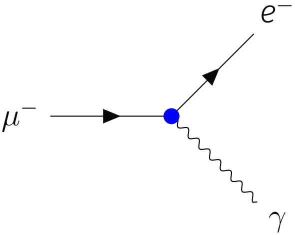
$\mathcal{O}^{(2)}_{L\Phi\Delta,ij}$	$\bar{\psi}^c_{L_i,\alpha}\Delta\Phi^\alpha\Phi^\dagger_\beta\psi^\beta_{L_j}$

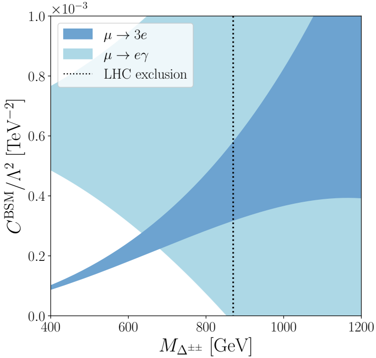
$\mathcal{O}_{eW}$	$(\bar{\psi}_{L_i}\sigma^{\mu\nu}e_j)\tau^\alpha\Phi W^\alpha_{\mu\nu}$
$\mathcal{O}_{eB}$	$(\bar{\psi}_{L_i}\sigma^{\mu\nu}e_j)\Phi B_{\mu\nu}$

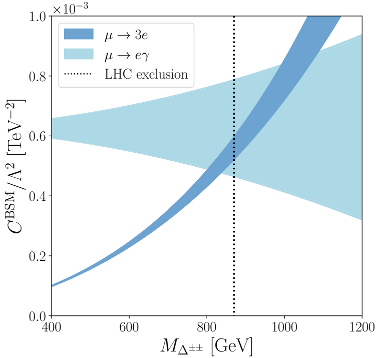




IMPLICATIONS OF EFT-DEFORMATIONS

$C^{\text{SMEFT}} = 0$ $\qquad\qquad$ $C^{\text{SMEFT}} \neq 0$

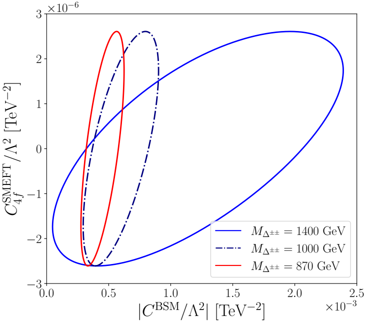




$$C^{(2)}_{L\Phi\Delta,ee} = C^{(2)}_{L\Phi\Delta,\mu e} = C^{\text{BSM}}$$

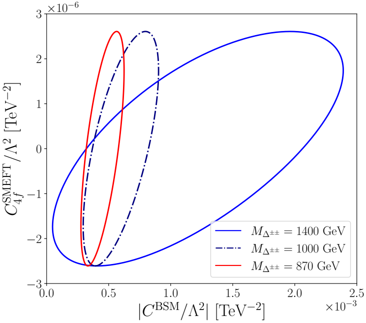
We can probe masses sensitive to the LHC through $\mu \to 3e/e\gamma$.

$$\mu \to 3e$$



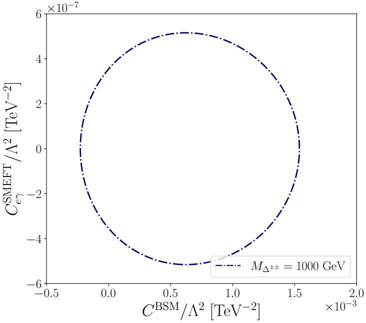
$$C_{ll} = C_{le} = C_{ee} = C_{4f}^{\rm SMEFT}$$

$\mu \to 3e$



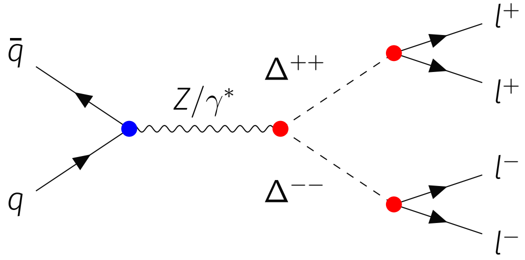
$$C_{ll} = C_{le} = C_{ee} = C_{4f}^{\mathrm{SMEFT}}$$

$\mu \to e\gamma$



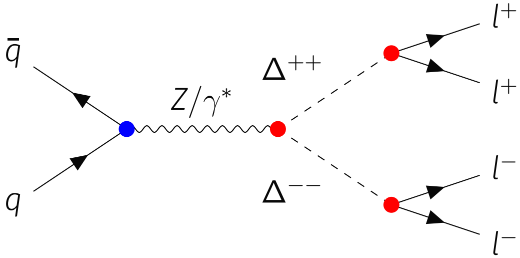
$$C_{eB} = C_{eW} = C_{e\gamma}^{\mathrm{SMEFT}}$$

Hadron Colliders:

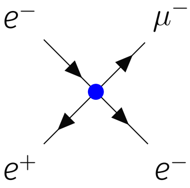


MODIFIED SEESAW AT COLLIDER EXPERIMENTS

Hadron Colliders:



e^+e^--Colliders:



- **FCC**-*ee* (Z-pole, 192 ab^{-1}): $|C_{4f}^{\text{SMEFT}}| \lesssim 10^{-4}$ TeV^{-2}.
- **CLIC** (3 TeV, 5 ab^{-1}): $|C_{4f}^{\text{SMEFT}}| \lesssim 10^{-5}$ TeV^{-2}.

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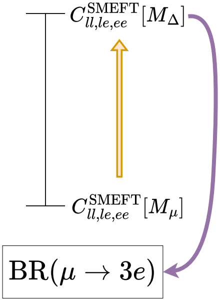
Thank You!

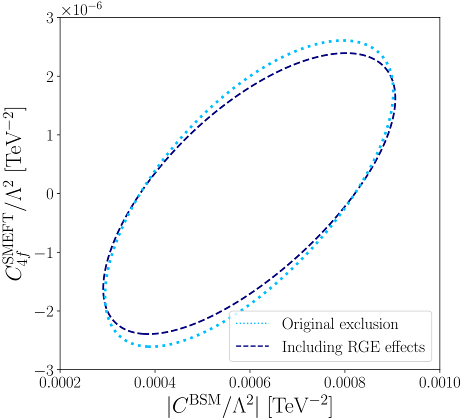
BACKUP SLIDES

RGE-EFFECTS

RGE effects computed for $\boxed{\mu \to 3e}$ using DSixTools.

(Celis et al. 2017; Fuentes-Martin et al. 2021)





RGE effects are small, and don't affect our results considerably.