Matter Unification and Lepton Flavor Violation

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Based on arXiv : 2603.02313 with Pavel Fileviez Perez

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Main Goal

Discuss the possibility to test the idea of

Quark–Lepton Unification at the low scale

through Flavor Experiments.

Flavor Violation in the Standard Model

- V_{CKM} introduces flavor changing interaction in the quark Sector
- As neutrinos are massless, no flavor violation in the leptonic sector.
- Lepton flavor is conserved in SM ($U(1)_e \times U(1)_\mu \times U(1)_\tau$)
- Neutrino Oscillation tells us that Lepton Flavor symmery is not a good symmetry of the nature.

Any Charged Lepton Flavor Violating Signature $\rightarrow$ New Physics.

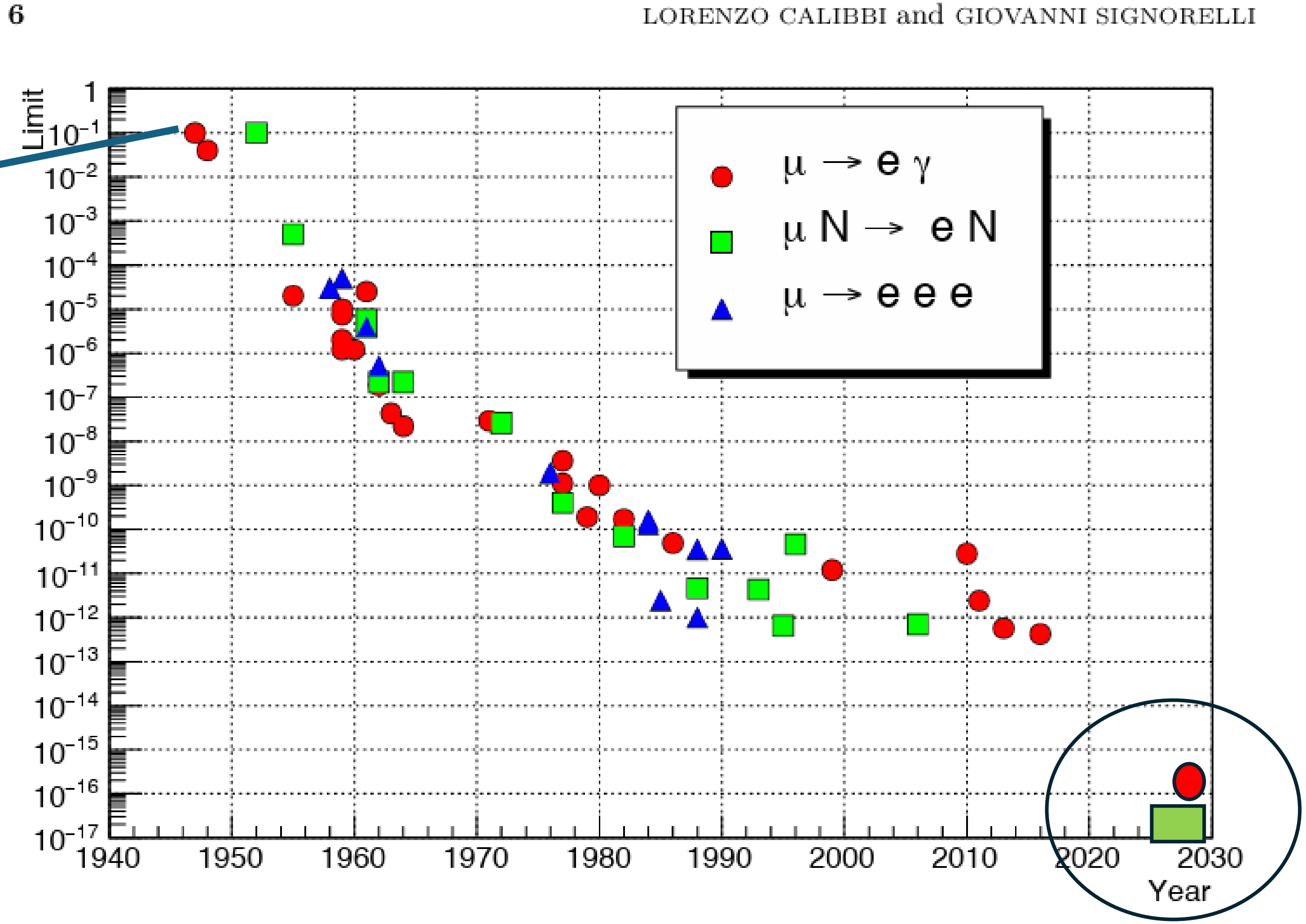
$$\mu \rightarrow e\gamma \;, \quad \mu + N \rightarrow e + N, \; ....$$

History of LFV Searches

Hincks and Pontecorvo (1947)
< 10 %

MEG II

Mu2e (FermiLab)



L.Calibbi , G.Signorelli arXiv : 1709.002942

Quark Lepton Unification

- Why quarks experince strong force but leptons do not ?

Perhaps symmetry between Quarks and Leptons broken at high energy ?

- A mathematically elegant framework ? ⋯

Pati Salam Quark Lepton Unification

- Lepton number as a Fourth color , $SU(4)_c$

Broken at High Scale
$SU(4) \rightarrow SU(3)_c \times U(1)_{B-L}$

SU(4) color →

$$\begin{pmatrix} u_r & u_g & u_b & \nu \\ d_r & d_g & d_b & e \end{pmatrix}_L \qquad (u_r \quad u_g \quad u_b \quad \nu)_R$$

- Right − handed neutinos were first introduced to complete the multiplet.

J. Pati , A. Salam PRD 10(1974)275

Minimal Quark Lepton Unification

$SU(4)_C \times SU(2)_L \times U(1)_R$

Fermionic Fields

$$F_{qL} \sim \begin{pmatrix} u_r & u_g & u_b & \nu \\ d_r & d_g & d_b & e \end{pmatrix}_L \sim (4,2,0)$$

$$F_{u_R} = (u_r \quad u_g \quad u_b \quad \nu)_R \sim (\,4,1,1/2\,)$$

$$F_{d_R} = (d_r \quad d_g \quad d_b \quad e)_R \sim (4,1,-1/2)$$

Higgs Fields

$$\chi = (\chi_r \quad \chi_g \quad \chi_b \quad \chi_0) \sim (4,1,1/2)$$

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \sim (1,2,1/2)$$

$$\Phi = \begin{pmatrix} \Phi_8 & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2 \sim (15,2,1/2)$$

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Minimal Quark Lepton Unification

$SU(4)_C \times SU(2)_L \times U(1)_R$

Gauge Fields

$$V^\mu = \begin{pmatrix} G^\mu & X^\mu/\sqrt{2} \\ (X^\mu)^*/\sqrt{2} & 0 \end{pmatrix} + T_{15}\, V_{15}^\mu \sim (\mathbf{15}, \mathbf{1}, 0),$$

- Gives masses to the Vector Leptoquarks X and Z'

$$M_X^2 = \frac{1}{2} g_4^2 v_\chi^2$$

$$\frac{M_X^2}{M_{Z'}^2} = \frac{2}{3} \cos^2 \theta_s$$

v_χ Matter Unification Scale

Symmetry Breaking

$SU(4)_C \times SU(2)_L \times U(1)_R$

$\downarrow$ $< \chi_0 > = v_\chi/\sqrt{2}$

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

$\downarrow$ $< H_1 >= v_1/\sqrt{2}$, $< H_2 >= v_2/\sqrt{2}$

$SU(3)_C \times U(1)_{EM}$

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Fermion Masses

- The Yukawa interactions for the fermions can be written as

$$-\mathcal{L}_Y = Y_1 \bar{F}_{q_L} i\sigma_2 H_1^* F_{u_R} + Y_2 \bar{F}_{u_R} \Phi^\alpha F_{q_L}^\beta \epsilon_{\alpha\beta} + Y_3 \bar{F}_{q_L} H_1 F_{d_R} + Y_4 \bar{F}_{q_L} \Phi F_{d_R} + \text{H.c.}$$

- The mass matrices for the SM fermions reads as

$$M_U = Y_1 \frac{v_1}{\sqrt{2}} - \frac{1}{2\sqrt{6}} Y_2^\dagger \frac{v_2}{\sqrt{2}}$$

$$M_D = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4^\dagger \frac{v_2}{\sqrt{2}}$$

$$M_E = Y_3 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_4^\dagger \frac{v_2}{\sqrt{2}}$$

Diagonalized

$$U_L^\dagger M_U U_R = M_U^{diag}$$

$$D_L^\dagger M_D D_R = M_D^{diag}$$

$$E_L^\dagger M_E E_R = M_E^{diag}$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} + \frac{3}{2\sqrt{6}} Y_2^\dagger \frac{v_2}{\sqrt{2}}$$

→ Extreme fine tuning needed to generate small neutrino mass

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Neutrino Masses

- To generate small neutrino masses naturally at a low scale, one needs to go beyond the Canonical Seesaw.

Canonical Seesaw Scale $\sim 10^{14-15}$ GeV

- Inverse Seesaw : Introducing three singlet left − handed fermionic fields , $S_L \sim (1,1,0)$

$$\mathcal{L} = Y_5 \overline{F_{Q_L}} \chi S_L + \frac{1}{2} \mu S_L^T C S_L + h.c.$$

- The renormalizable couplings of this model respect a global U(1) fermion matter symmetry.

$$U(1)_F \rightarrow \quad F_{Q_L} = 1 \qquad F_u = F_d = -1 \qquad S_L = 1$$

$\mu S_L^T C S_L$ → Softly Breaks the matter symmetry

Natural to consider this μ parameter much smaller.

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Neutrino Masses

- In this case , the mass matrix for the neutrinos in the basis $(\nu\ \nu^c\ S)$ can be written as

$$(\nu\ \nu^c\ S)\begin{pmatrix} 0 & M_\nu^D & 0 \\ (M_\nu^D)^T & 0 & M_\chi^D \\ 0 & (M_\chi^D)^T & \mu \end{pmatrix}\begin{pmatrix} \nu \\ \nu^c \\ S \end{pmatrix}.$$

$$M_\chi^D = Y_5 v_\chi/\sqrt{2}.$$

$$M_\nu^D = Y_1\frac{v_1}{\sqrt{2}} + \frac{3}{2\sqrt{6}}Y_2^\dagger\frac{v_2}{\sqrt{2}}$$

- In the limit $\mu \ll M_\nu^D \ll M_\chi^D$, the light neutrino mass is given by

$$m_\nu \approx \mu(M_\nu^D)^2/(M_\chi^D)^2$$

- For $\mu \sim O(10^{-2})$ GeV, $M_\nu^D \sim 10^2$ GeV, then $M_\chi^D \sim 10^3$ TeV ← 10^{14-15}GeV

↓

Low Scale Unification

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Minimal Quark Lepton Unification Predictions

$SU(4)_C \times SU(2)_L \times U(1)_R$

- Majorana Neutrinos
- One Vector Leptoquark , X
- Two Scalar Leptoquark doublets , Φ_3 and Φ_4
- A Color Octet Scalar , Φ_8
- An Additional Higgs doublet , H_2

Rich Spectrum of New Fields

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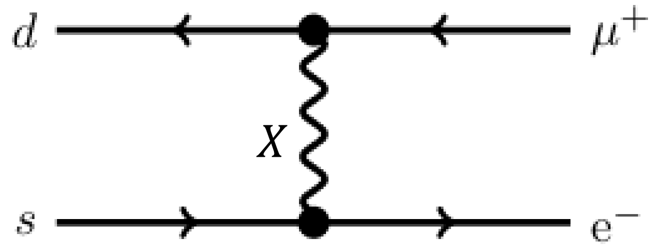
Flavor Violating Meson Decay

$K_L \to \mu^{\pm} e^{\mp}$

- Relevant interaction of vector Leptoquarks

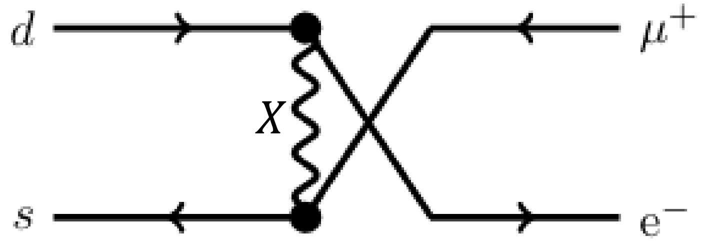
$$\bar{d}_i e_j X_\mu: \quad i g_4/\sqrt{2}\, \gamma^\mu \left(V_L^{ij} P_L + V_R^{ij} P_R \right)$$



- Unknown mixing matrices $V_L = D_L^\dagger E_L$, $V_R = D_R^\dagger E_R$

- The decay width can be written as

$$\Gamma(K_L^0 \to \mu^+ e^-) = \frac{F_K^2\, m_{K_L}}{64\pi} \left(\left| C_S \frac{m_{K_L}^2}{m_d + m_s} - m_\mu\, C_V \right|^2 + \left| C_P \frac{m_{K_L}^2}{m_d + m_s} + m_\mu\, C_A \right|^2 \right) \times \left(1 - \frac{m_\mu^2}{m_{K_L}^2} \right)^2 .$$



- Wilson Coefficients C_S, C_P, C_V, C_A are function of the mixing matrices

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Flavor Violating Meson Decay

$$K_L \to \mu^{\pm} e^{\mp}$$

- Experimental Limit

$$\text{Br}\left(K_L \to \mu^{\pm} e^{\mp}\right) < 4.7 \times 10^{-12}$$

- In the limit $V_L = V_R \sim \mathbb{1}$, $\quad |C_K| = 1$

$$M_X \geq 2400 \text{ TeV}$$

- Freedom in the mixing matix V_L and V_R

Symmetry Breaking scale can be $\mathcal{O}(100)$ TeV

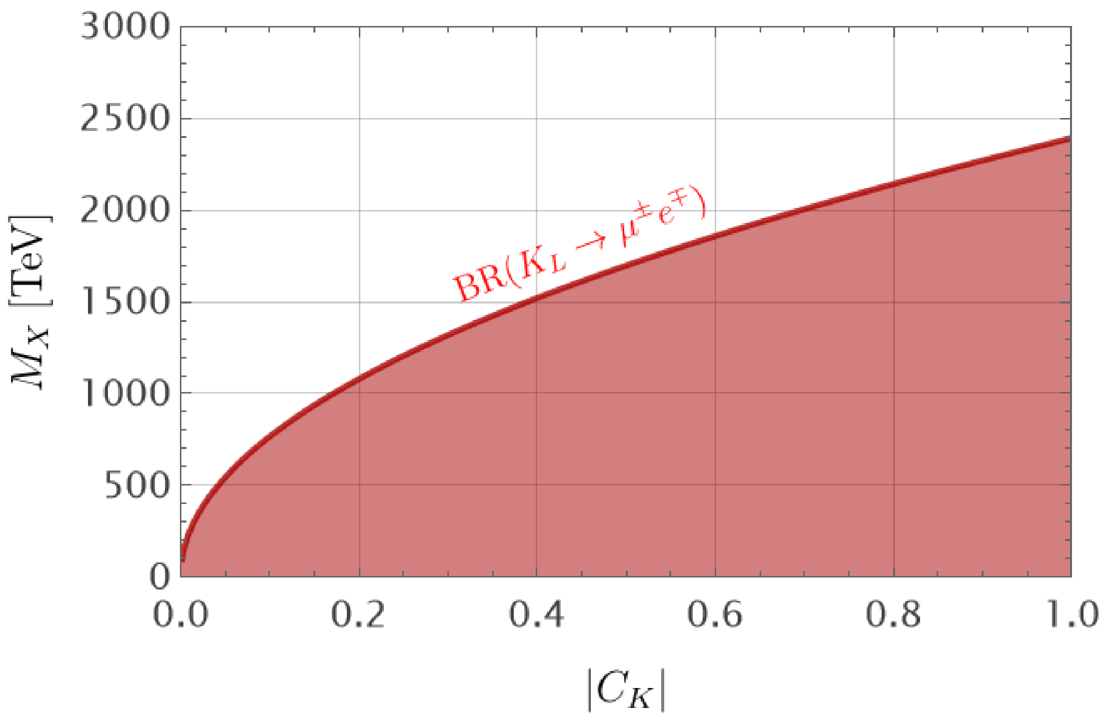

Fig: Red shaded region is excluded

$$C_K = V_{de}^* V_{s\mu} + V_{se}^* V_{d\mu}$$

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Flavor Violating Meson Decay

- General form of V_L and V_R matrix when they are real matrix

$$V_{\rm L,R} = V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix},$$

- Consider four simple scenerios

Case I : $\theta_{13} = \theta_{23} = 0$

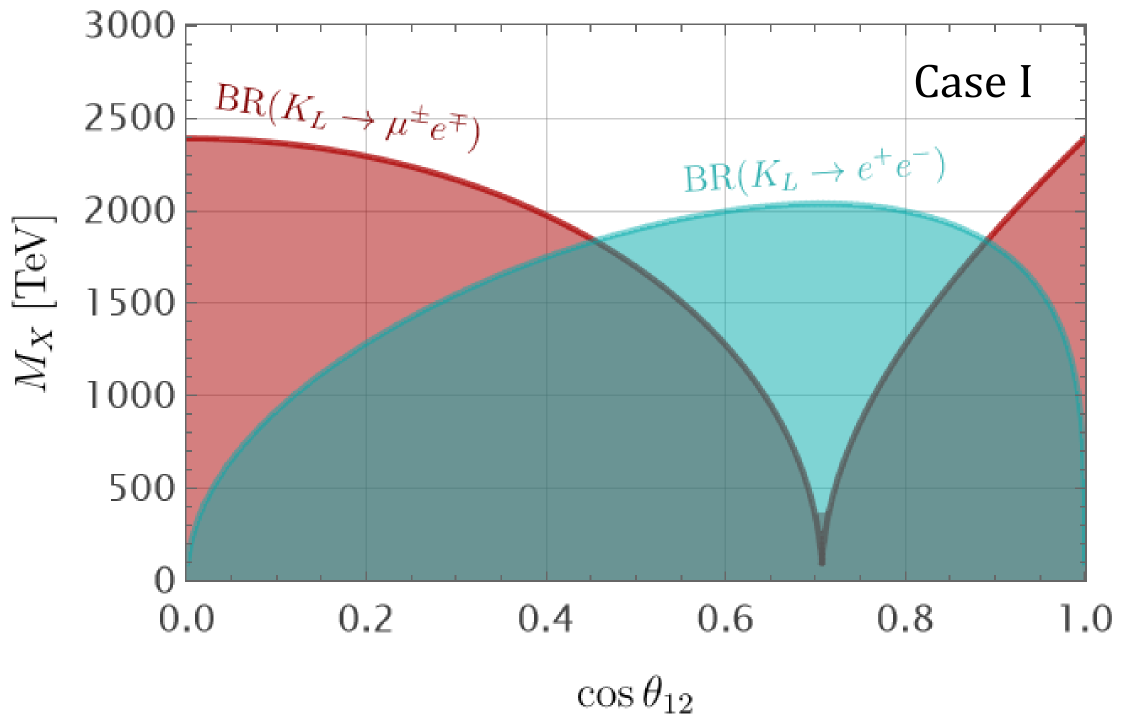
$M_X > 1800$ TeV

Case II : $\theta_{13} = \pi/2\,, \theta_{23} = 0$

Case III : $\theta_{13} = 0, \theta_{23} = \pi/2$

Case IV : $\theta_{13} = \theta_{23} = \pi/2$

$K_L \to \mu^\pm e^\mp, e^\mp e^\pm$ Vanishes



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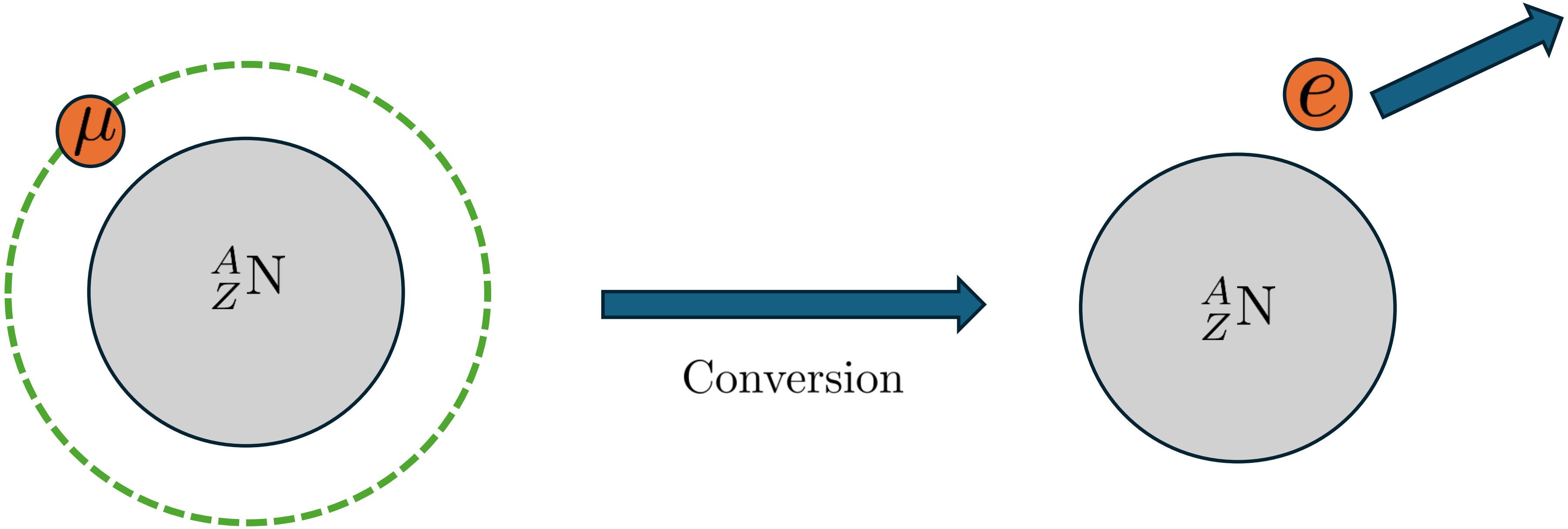
LFV Process (μ → e conversion)

$$\mu^- + N \rightarrow e^- + N$$



1) Captured by the nucleus
2) Decays to $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
3) Converts into an electron

Fig. Schemetic representation of $\mu \rightarrow e$ conversion in Nuclei.

LFV Process (μ → e conversion)

- The muon conversion rate mediated by the vector Leptoquark, X can be written as

$$\Gamma_{\mu\to e} = \frac{m_\mu^5}{16}\Big[\Big|4\left(\tilde{C}_{VR}^{(p)}\ V^{(p)} + \tilde{C}_{VR}^{(n)}\ V^{(n)} + \tilde{C}_{SR}^{(p)}\ S^{(p)} + \tilde{C}_{SR}^{(n)}\ S^{(n)}\right)\Big|^2 + \Big|4\left(\tilde{C}_{VL}^{(p)}\ V^{(p)} + \tilde{C}_{VL}^{(n)}\ V^{(n)} + \tilde{C}_{SL}^{(p)}\ S^{(p)} + \tilde{C}_{SL}^{(n)}\ S^{(n)}\right)\Big|^2\Big],$$

- The Branching ratio can be written as

$$\mathrm{BR}_{\mu\to e}(Z) = \frac{\Gamma_{\mu\to e}(A,Z)}{\Gamma^{\mu}_{capt}(A,Z)}$$

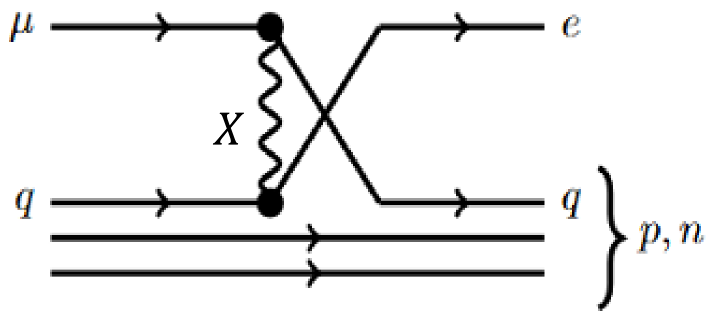


Fig. Feynman graph for μ → e conversion

- The Parameters S and V depend on the Nucleus

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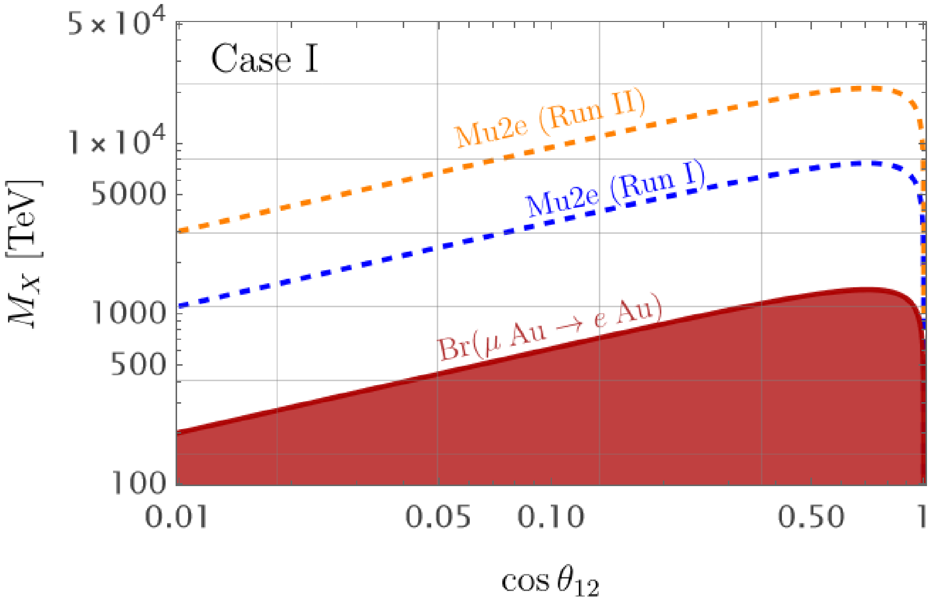
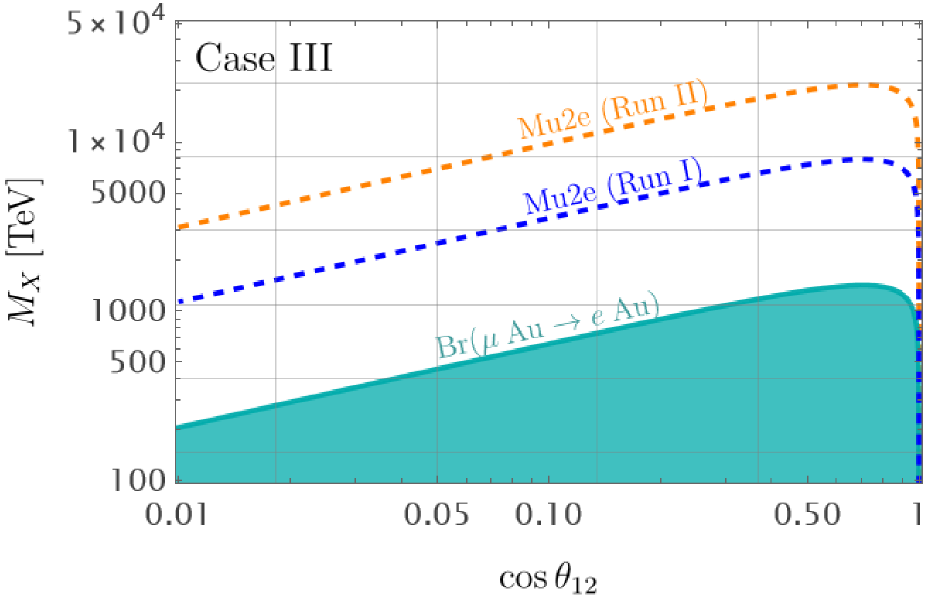
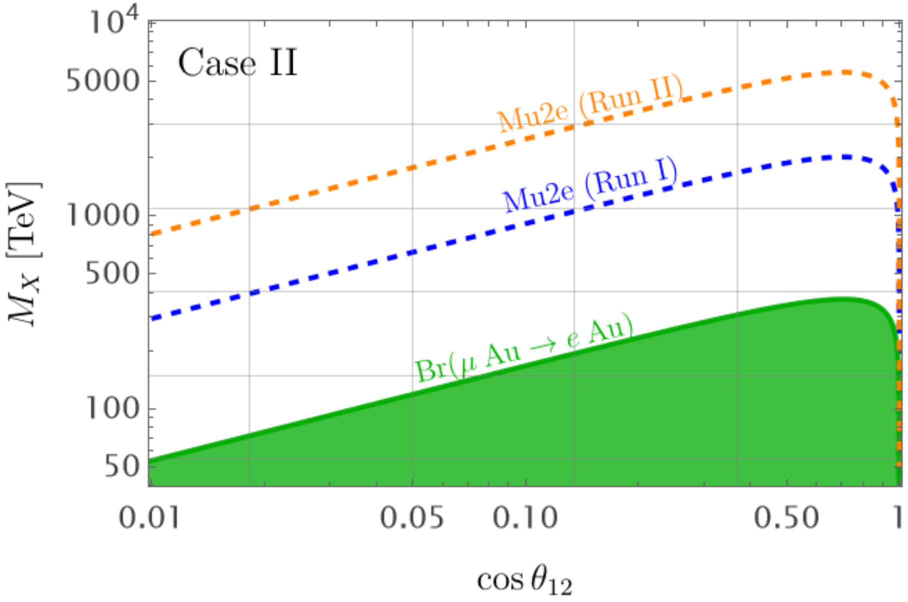
LFV Process (μ → e conversion)



μ → e reach

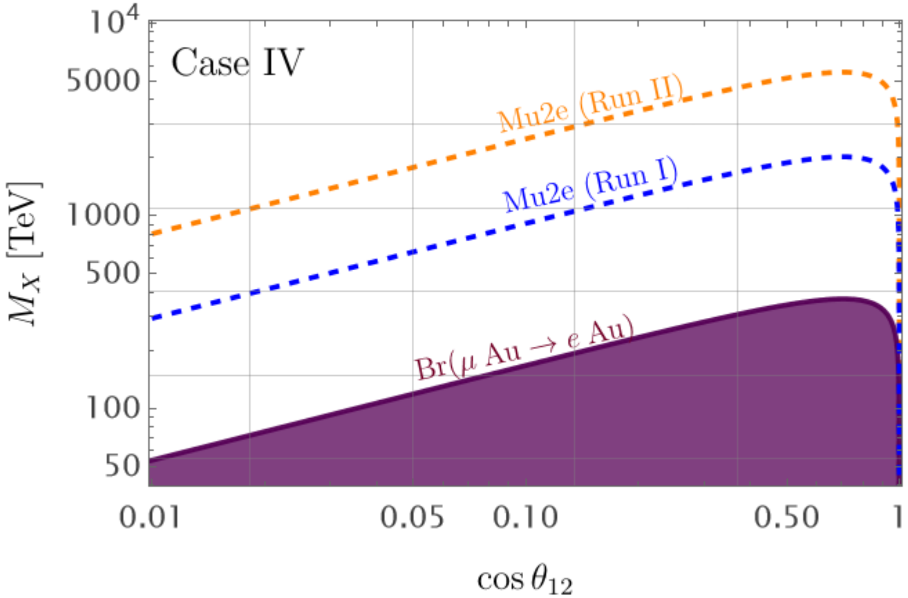
10^4 TeV





μ → e reach

5×10^3 TeV



LFV Processes and Contraints

- Stronger Constraints on M_X or Symmetry Breaking Scale

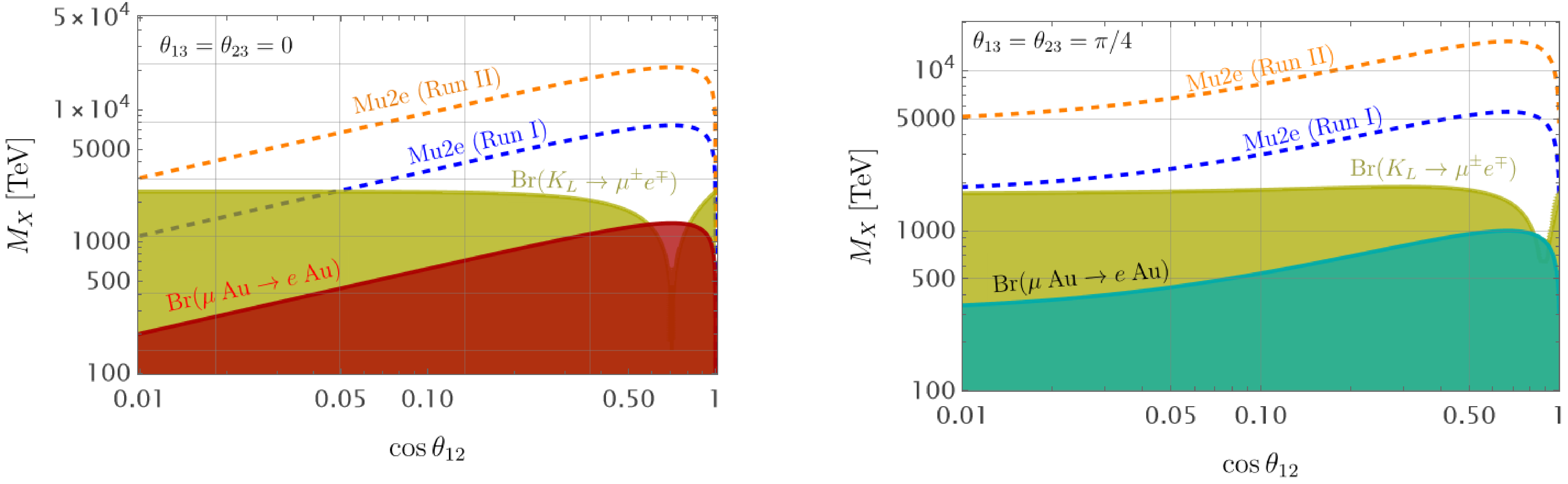


Fig. Limits and Possible reach on Vector Leptoquark , X Mass

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Scalar Leptoquarks

Scalar Fields

$$\Phi = \begin{pmatrix} \Phi_8 & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2$$

$\Phi_3 \sim (\bar{3}, 2, -1/6)_{SM}$ $\Phi_4 \sim (3,2,7/6)_{SM}$

$$\Phi_3 = \begin{pmatrix} \Phi_3^{1/3} \\ \Phi_3^{-2/3} \end{pmatrix} \qquad \Phi_4 = \begin{pmatrix} \Phi_3^{5/3} \\ \Phi_3^{2/3} \end{pmatrix}$$

- Yukawa interaction for Φ_4

$$-\mathcal{L} \supset Y_2 \bar{u}_R \phi_4^{5/3} e_L - Y_2 \bar{u}_R \phi_4^{2/3} \nu_L + Y_4 \bar{u}_L \phi_4^{5/3} e_R + Y_4 \bar{d}_L \phi_4^{2/3} e_R + \text{H.c.}.$$

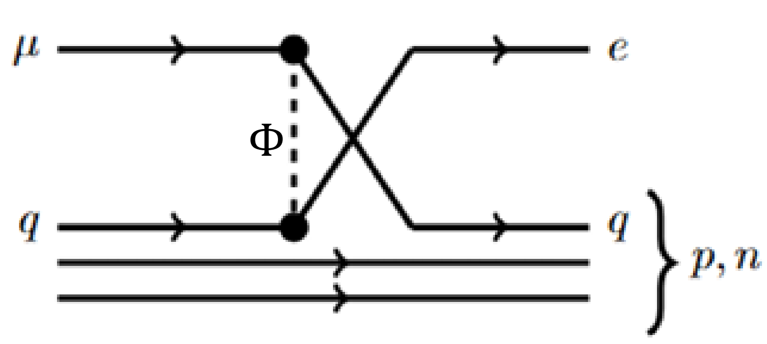

Fig. Feynman graph for μ → e conversion

Dominant contribution to μ → e via the Yukawa interaction of Y_2

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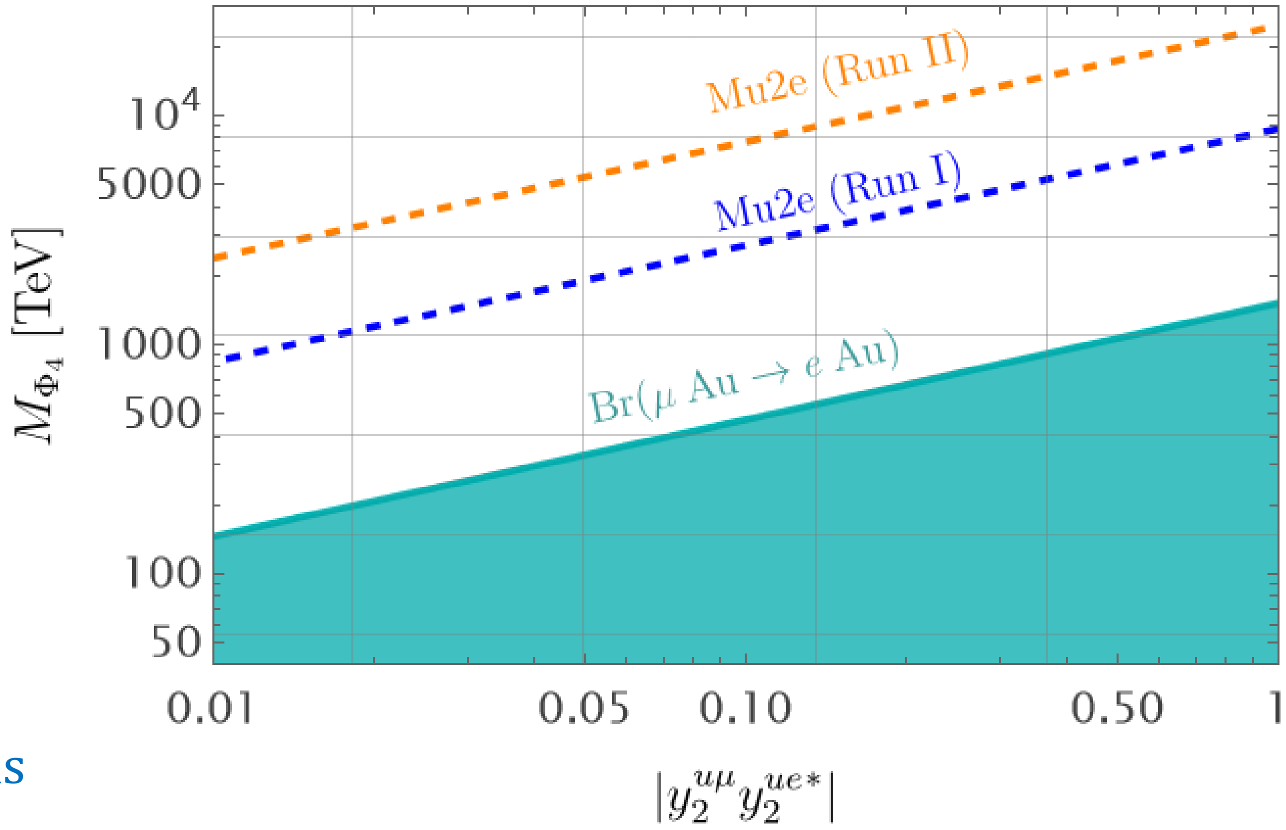
LFV Contraints on Scalar Leptoquarks

- Depending on the Yukawa coupling ,

  μ → e can exclude upto 1000 TeV.

- Mu2e Experiment can reach upto 10^4 TeV .

- Much stronger than the collider bounds



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Summary

- We discuss the idea of Quark Lepton unification at low scale .
- To acheive low scale unification naturally , neutrino masses are generated via inverse seesaw mechanism.
- We discuss the meson decays and show that symmetry breaking scale can be much lower than 10^3 TeV when the freedom of mixing angles are considered.
- It is striking that the Mu2e experiment at Fermilab can test the idea of quark−lepton unification at the low scale .
- Final takeaway : Precision Flavor experiments may provide the first window into the unification of matter.

Backup Slides

Backup Slides

- The SM hypercharge Y is given by $Y = R + \sqrt{6}/3\ T_4$
- $T_4 = \frac{1}{2\sqrt{6}} \mathrm{diag}\,(1,1,1,-3)$, normalized SU(4) generator

Collider Constraints on Scalar Leptoquarks (Φ_3)

- Collider Signatures

$$p\,p \to \phi_3^{1/3}\left(\phi_3^{1/3}\right)^* \to \bar{b}\nu\ (b\bar{\nu}) \qquad p\,p \to \phi_3^{-2/3}\left(\phi_3^{-2/3}\right)^* \to \bar{b}\tau(b\bar{\tau})$$

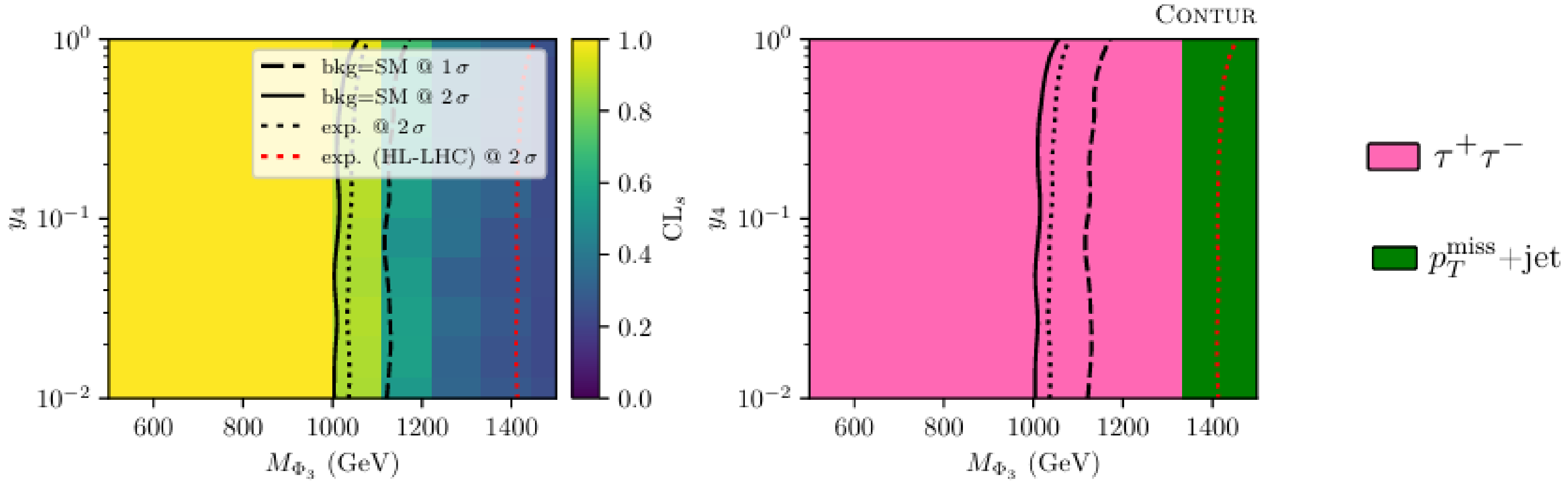


Fig. Exclusion Plot for Φ_3

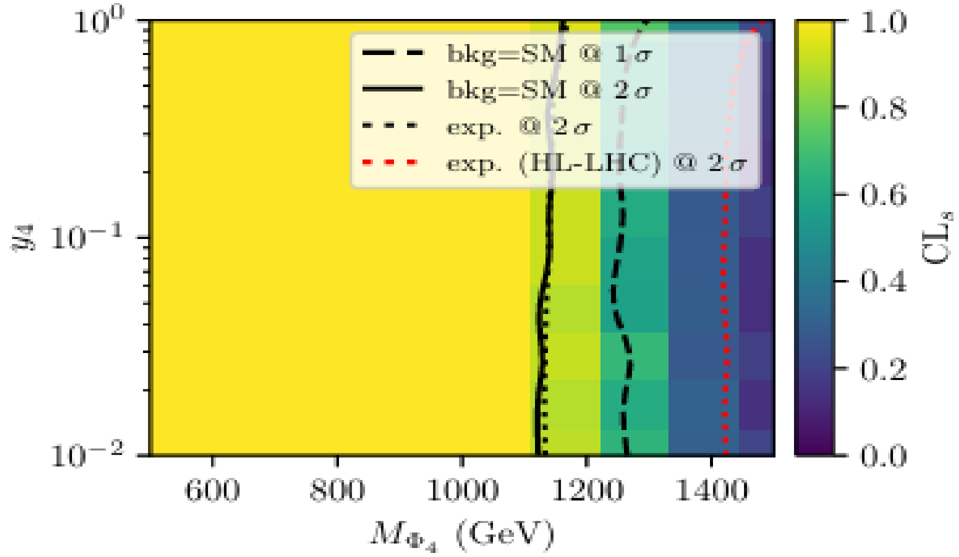
- Exclusion comes from the di − τ measurements $M_{\Phi_3} > 1\text{TeV}$

J. Butterworth , H. Debnath , P. Fileviez Perez , P. Wang arXiv 2512.00143

Collider Constraints on Scalar Leptoquarks (Φ_4)

- Collider Signatures

$$p\,p \to \phi_4^{2/3}\left(\phi_4^{2/3}\right)^* \to \bar{\tau} b\,(\tau \bar{b}) \qquad p\,p \to \phi_4^{5/3}\left(\phi_4^{5/3}\right)^* \to \bar{\tau} t\,(\tau \bar{t})$$



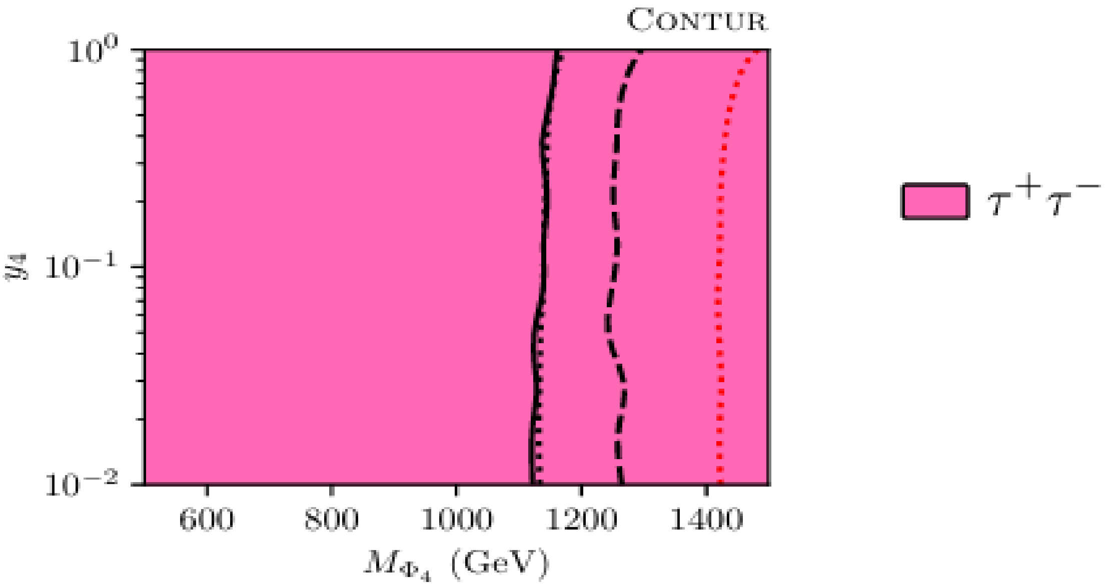


Fig. Exclusion Plot for Φ_4

- Exclusion comes from the di − τ measurements $M_{\Phi_4} > 1.2$ TeV

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Backgrounds for μ → e conversion

- Decay in Orbit (DIO) : $\mu^- \rightarrow e^- \overline{\nu_e} \nu_\mu$
- Radiative π capture : $\pi N \rightarrow \gamma N^*$ and $\gamma \rightarrow e^+ e^-$
- Radiative muon capture
- Cosmic Rays
- … … … … .