Flavour puzzle or Why Neutrinos Are Different?

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The Flavour Puzzle In A Nutshell

✓ **Why three families in the SM?**

- Hierarchical masses + small mixing angles

✓ **Why massive neutrinos?**

- Tiny masses + two large mixing angles

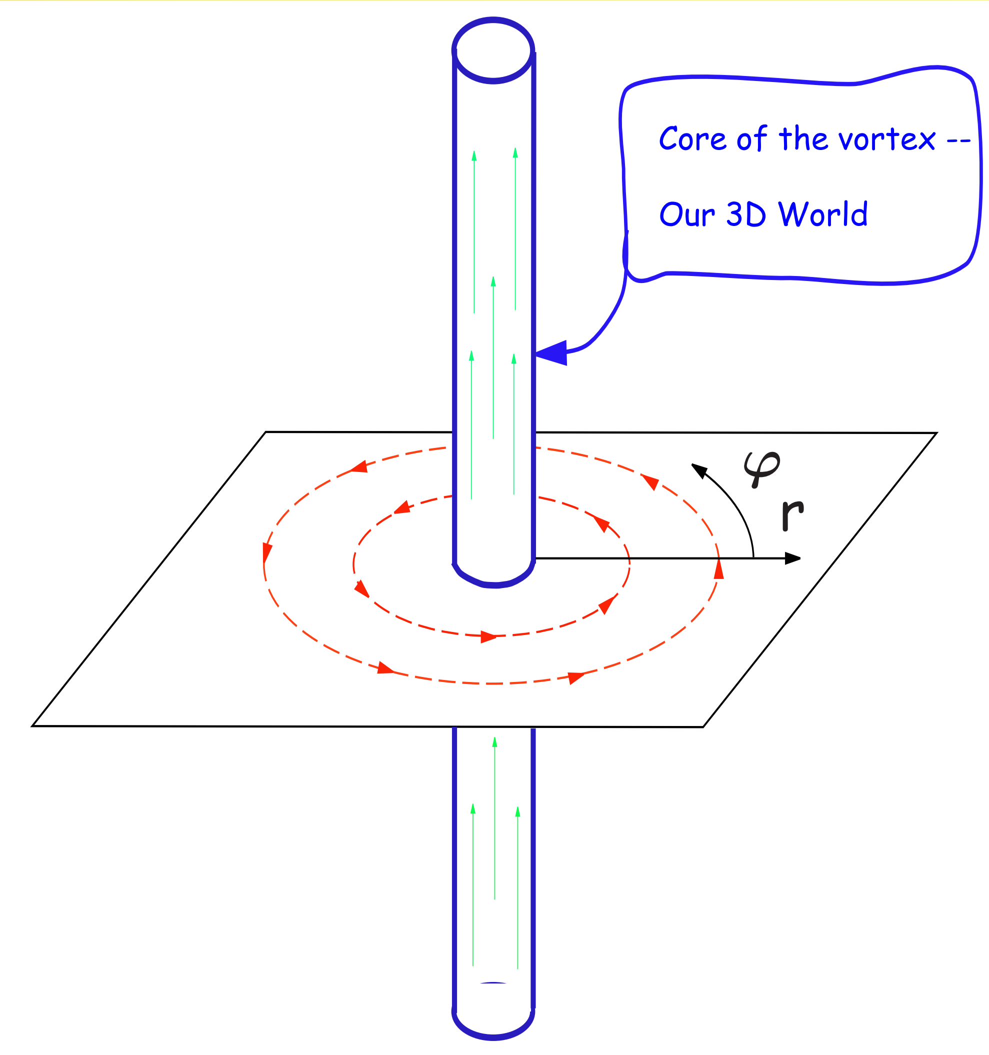
✓ **Why very suppressed FCNC?**

- Strong limits on a TeV scale extension of the SM

Proposed solution:

A model of family replication in 6D

3 Families In 4D From 1 Family In 6D



- Our 3D World is a core of Abrikosov-Nielsen-Olesen vortex:

  $U_g(1)$ gauge field A+scalar Φ

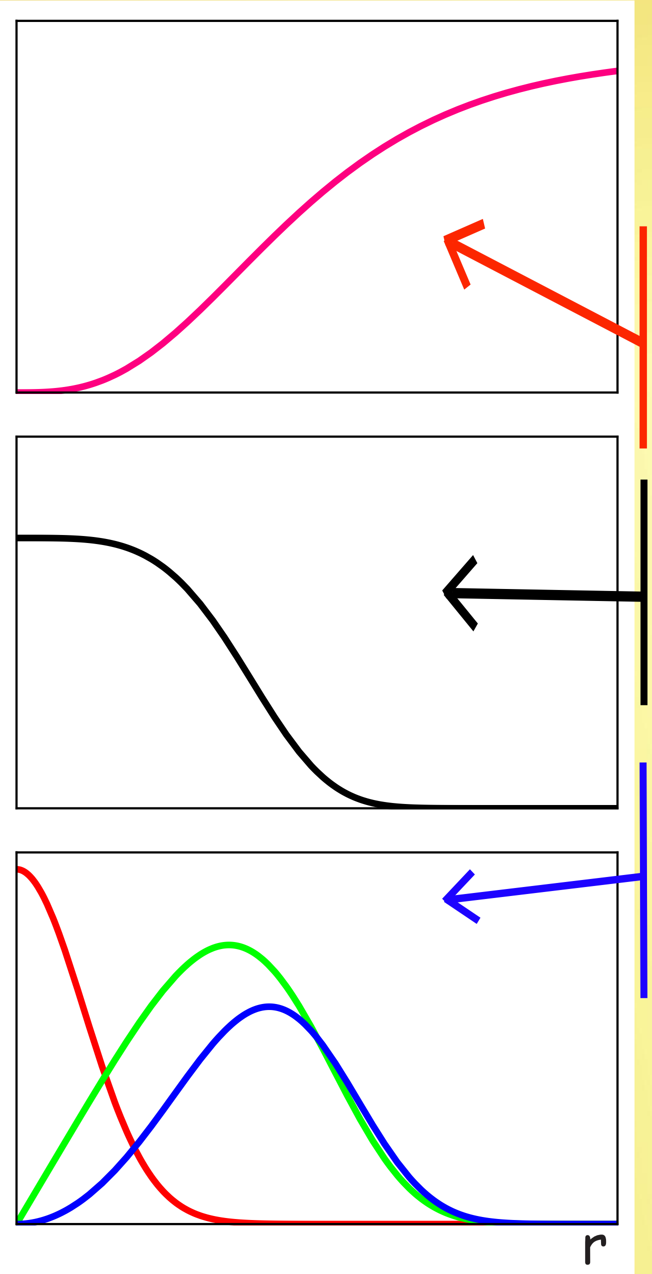
- There is only single vector-like fermionic generation in 6D

- Chiral fermionic zero modes are trapped in the core due to specific interaction with the A and Φ. Specific choise of $U_g(1)$ fermionic gauge charges $\Rightarrow$

  Number of zero modes = 3

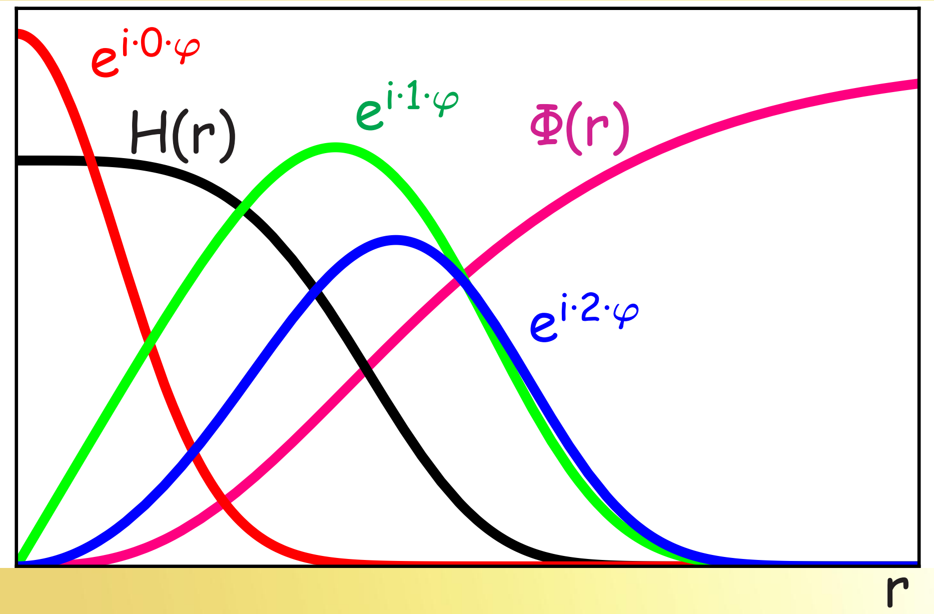
- Zero modes $\Longleftrightarrow$ 4D fermionic families

Field Content



Fields	Profiles	Charges		Representations	
		$U_g(1)$	$U_Y(1)$	$SU_W(2)$	$SU_C(3)$
scalar Φ	$F(r)e^{i\varphi}$ $F(0) = 0,\ F(\infty) = v$	+1	0	1	1
vector A_φ	$A(r)/e$ $A(0) = 0,\ A(\infty) = 1$	0	0	0	0
scalar X	$X(r)$ $X(0) = v_X,\ X(\infty) = 0$	+1	0	1	1
scalar H	$H(r)$ $H_i(0) = \delta_{2i}v_H,\ H_i(\infty) = 0$	--1	+1/2	2	1
fermion Q	3 L zero modes	axial (3,0)	+1/6	2	3
fermion U	3 R zero modes	axial (0,3)	+2/3	1	3
fermion D	3 R zero modes	axial (0,3)	−1/3	1	3
fermion L	3 L zero modes	axial (3,0)	−1/2	2	1
fermion E	3 R zero modes	axial (0,3)	−1	1	1
fermion N	Kaluza-Klein spectrum	0	0	1	1

Hierarchical Dirac Masses



- 3 zero modes have different shapes, and different angular momenta n = 0, 1, 2

$$\hat{J}\Psi_n \equiv -\left(i\partial_\varphi + 3\frac{1+\Gamma_7}{2}\right)\Psi_n = n\Psi_n$$

$$\Psi_n(r \to 0) \sim r^n$$

- $m_{nm} \propto \int_0^{2\pi} d\varphi \int_0^R dr \bar{\Psi}_n \Psi_m HX(\text{or } \Phi) \sim \sigma^{2n(-1)}\delta_{nm(\pm 1)}$

- σ depends on the parameters of the model. Hierarchy arises at $\sigma \sim 0.1$

$$m_2 : m_1 : m_0 \sim \sigma^4 : \sigma^2 : 1 \sim 10^{-4} : 10^{-2} : 1 \qquad U^{CKM} \sim \begin{pmatrix} 1 & \sigma & \sigma^4 \\ \sigma & 1 & \sigma \\ \sigma^2 & \sigma & 1 \end{pmatrix}$$

Generation number ⇔ Angular momentum

✓ The scheme is very constrained, as the profiles are dictated by the equations

Neutrinos masses. Why is it different?

- N -- additional neutral spinor

$\Rightarrow$ Free propagating in the extra dim (up to dist. $R \sim (10 \div 100\,\text{TeV})^{-1}$).

$\Rightarrow$ Majorano-like 6D mass term

$$\frac{M}{2}\bar{N}^c N + \text{h.c.}$$

$\Rightarrow$ Kaluza-Klein tower in 4D (no zero mode)

$\Rightarrow$ Effective 6D couplings with leptons allowed by symmetries

$$\sum_{S_+} \bar{H} S_+ \bar{L} \frac{1+\Gamma_7}{2} N + \sum_{S_-} H S_- \bar{L} \frac{1-\Gamma_7}{2} N + \text{h.c.}$$

$$S_+ = X^*, \Phi^*, X^{*2}\Phi, \ldots$$
$$S_- = X^2, X\Phi, \Phi^2, \ldots$$

Non-zero windings $\Rightarrow$ more composite structure of the mass matrix

$\Rightarrow$ 4D Majorano neutrinos masses are generated by See-saw mechanism

Neutrinos:

$$m^{\nu}_{mn} \sim \int_0^{2\pi} d\varphi \int_0^R dr F(r,\varphi)\, [\bar{L}^c L \propto LL]$$

$$\sim \int_0^{2\pi} d\varphi e^{i(4-n-m+\dots)\varphi} \sim \delta_{4+\dots,m+n}$$

$$\sim \begin{pmatrix} \cdot & \cdot & 1 \\ \cdot & \sigma^2 & \cdot \\ 1 & \cdot & \cdot \end{pmatrix}$$

$$U^{\dagger}_{\nu} m_{\nu} U^{*}_{\nu} \sim \mathrm{diag}(-m, m, m\sigma^2)$$

$$U_{\nu} \sim \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & \sigma \\ \sigma & \sigma & 1 \\ -1/\sqrt{2} & 1/\sqrt{2} & \sigma \end{pmatrix}$$

Charged fermions:

$$m^{charged}_{mn} \sim \int_0^{2\pi} d\varphi \int_0^R dr F(r,\varphi)\, [\bar{\Psi}\Psi \propto \Psi^*\Psi]$$

$$\sim \int_0^{2\pi} d\varphi e^{i(n-m+\dots)\varphi} \sim \delta_{n,m-\dots}$$

$$\sim \begin{pmatrix} \sigma^4 & \cdot & \cdot \\ \cdot & \sigma^2 & \cdot \\ \cdot & \cdot & 1 \end{pmatrix}$$

$$m^{diag}_{charged} \sim \mathrm{diag}(\mu\sigma^4, \mu\sigma^2, \mu)$$

$$U^{CKM} \sim \begin{pmatrix} 1 & \sigma & \sigma^4 \\ \sigma & 1 & \sigma \\ \sigma^2 & \sigma & 1 \end{pmatrix}$$

Consequences of this structure

$$m_\nu \sim \begin{pmatrix} \cdot & \cdot & 1 \\ \cdot & \sigma^2 & \cdot \\ 1 & \cdot & \cdot \end{pmatrix} \qquad m_\nu^{diag} \sim \begin{pmatrix} -m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m\sigma^2 \end{pmatrix}$$

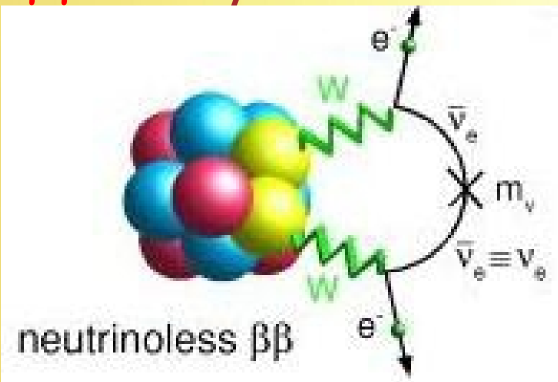
- Inverted hierarchy:

$$\Delta m^2_\odot = \Delta m^2_{12}$$

$$\frac{\Delta m^2_{12}}{\Delta m^2_{13}} \sim \sigma^2$$

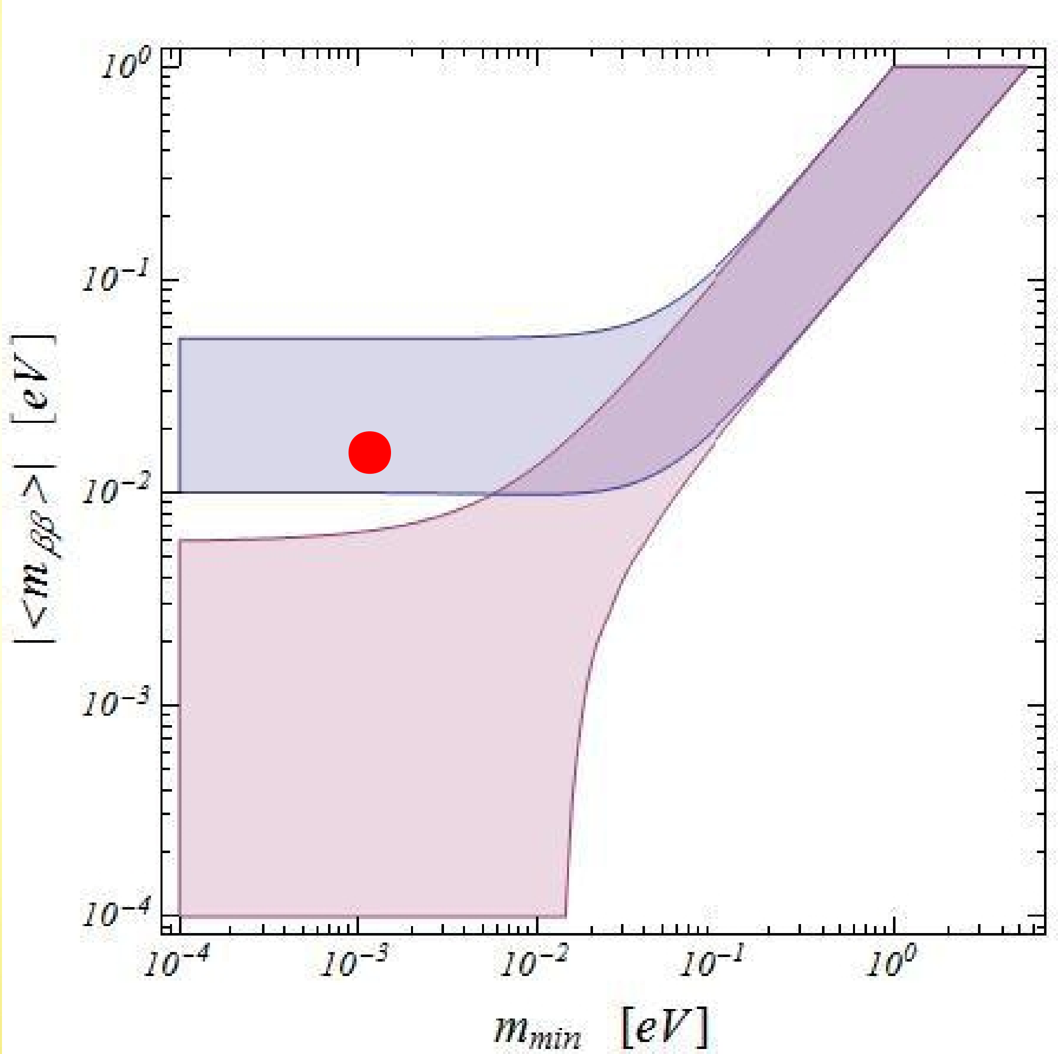
- Pseudo-Dirac structure $\Rightarrow$

  $0\nu\beta\beta$ decay



partial suppression

$$|\langle m_{\beta\beta}\rangle| \simeq \frac{1}{3}\sqrt{\Delta m^2_\oplus}$$



Semi-realistic numerical example

$$m_\nu^{diag} = \begin{pmatrix} -50.03 & 0 & 0 \\ 0 & 50.79 & 0 \\ 0 & 0 & 0.7089 \end{pmatrix} \text{ [meV]}, \quad U_{MNS} = \begin{pmatrix} 0.808 & 0.559 & 0.186 \\ -0.286 & 0.660 & -0.693 \\ -0.514 & 0.502 & 0.696 \end{pmatrix}$$

$$\begin{aligned} \Delta m_{12}^2 &= 7.63 \times 10^{-5} \text{eV}^2 \\ \Delta m_{13}^2 &= 2.50 \times 10^{-3} \text{eV}^2 \end{aligned} \Longrightarrow \frac{\Delta m_{12}^2}{\Delta m_{13}^2} = 3.05\%$$

$$\tan^2\theta_{12} = 0.471 \ \left(0.47^{+0.14}_{-0.10}\right) \qquad \tan^2\theta_{23} = 0.997 \ \left(0.9^{+1.0}_{-0.4}\right)$$

$$\sin^2\theta_{13} = 3.46 \cdot 10^{-2} \ (\leq 0.036)$$

Consequence for $0\nu\beta\beta$ decay

$$|\langle m_{\beta\beta}\rangle| = \left|\sum_i m_i U_{ei}^2\right| = 17.0 \text{ meV}$$

Flavour Violation

- Like in the UED, vector bosons can travel in the bulk of space. From the 4D point of view:

  1 massless vector boson in 6D=

  1 massless vector bozon (zero mode)

  \+ KK tower of massive vector bosons $M_n \sim \frac{n}{R}$

  $\Rightarrow$ FCNC

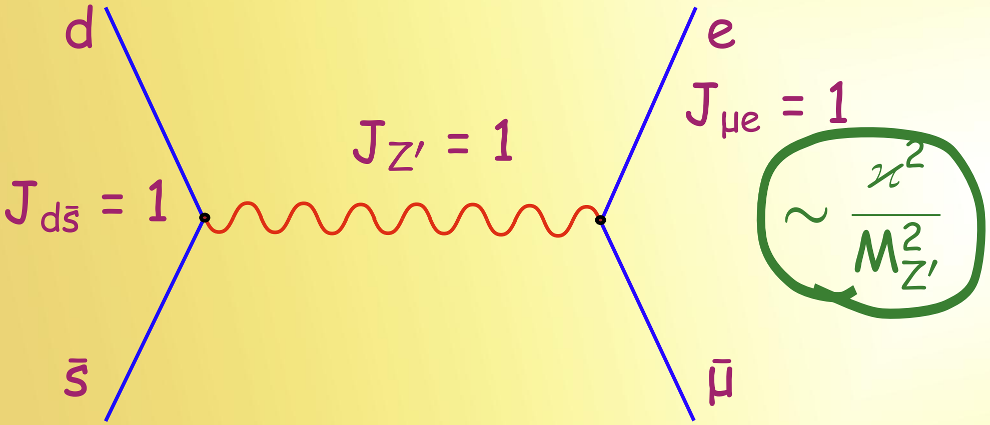
  \+ KK tower of massive scalar bosons in 4D

  $\Rightarrow$ KK scalar modes do not interact with fermion zero modes

- KK vector modes carry angular momentum = family number. In the absence of fermion mixings, family number is an exactly conserved quantity $\Rightarrow$ processes with $\Delta G = \Delta J \neq 0$ are suppressed by mixing.

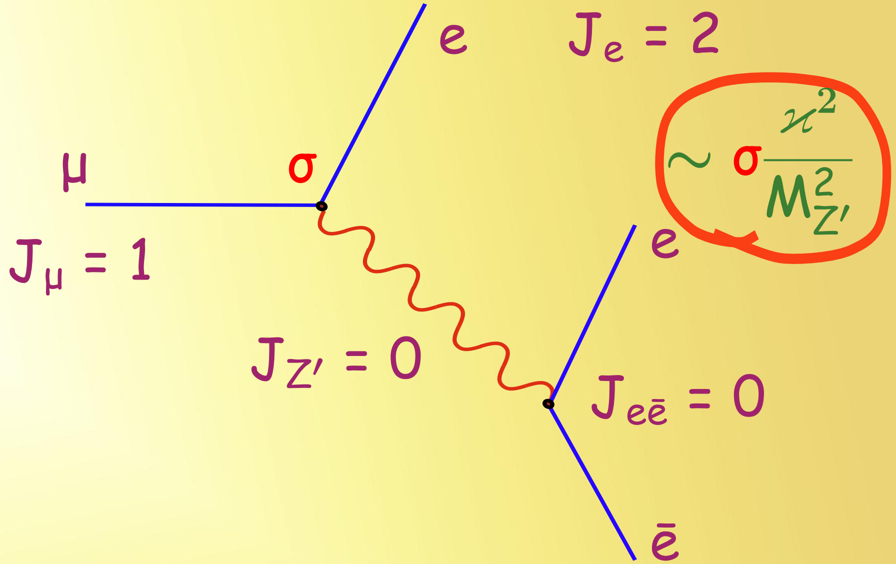
$K_L^0 \to \mu^\pm e^\mp$

$\Delta G = \Delta J = 0$



$\mu \to e e \bar{e}$

$\Delta G = \Delta J = 1$



✓ $\varkappa = 1$ for the particular model, but may be $\ll 1$ for extensions

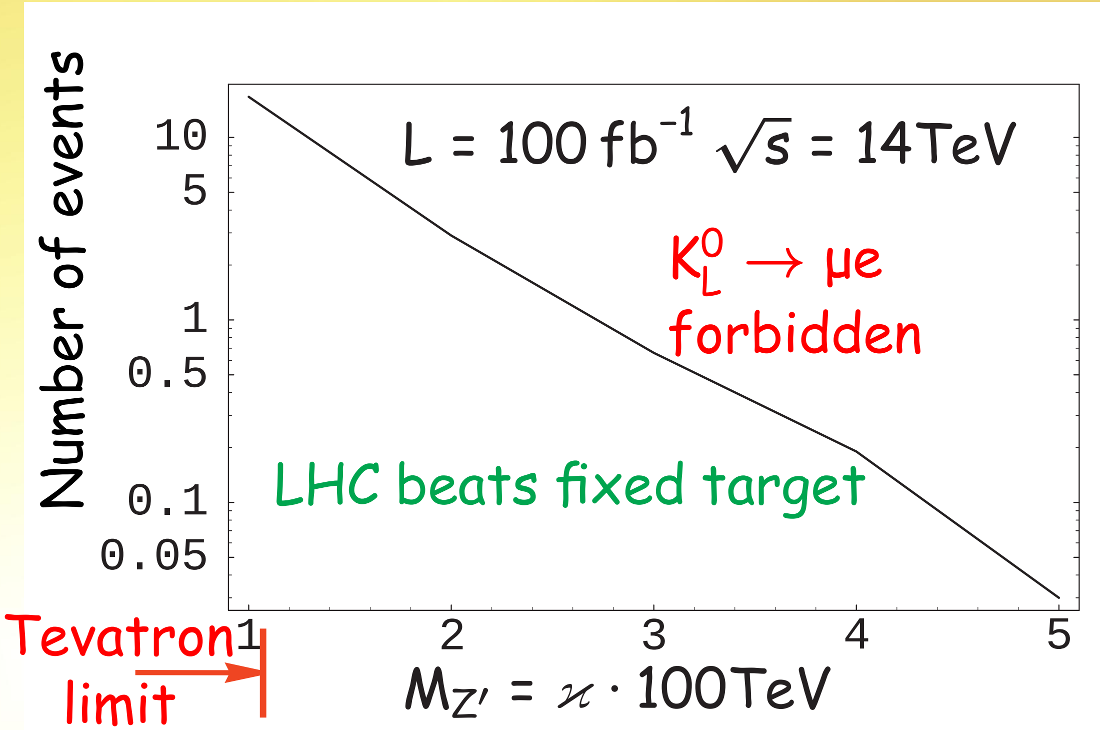
- Rare processes:
  - $\Delta G = 0$: $K_L^0 \to \mu e$, $K^+ \to \pi^+\mu^+e^-$ $\qquad P \sim \sigma^0 \varkappa^4 / M_{Z'}^4$,
  - $\Delta G = 1$: $\mu \to ee\bar{e}$, μe-conversion, $\mu \to e\gamma$ $\qquad P \sim \sigma^2 \varkappa^4 / M_{Z'}^4$,
  - $\Delta G = 2$: mass diference $K_L - K_S$, CP-violation $\qquad P \sim \sigma^4 \varkappa^4 / M_{Z'}^4$,

  Bound on

$$M_{Z'} \gtrsim \varkappa \cdot 100 \cdot \text{TeV}$$

$\mathcal{NB}$: A clear signature of the model would be an observation $K_L^0 \to \mu e$ without observation other FCNC-processes at the same precision level

- Search for an «ordinary» massive $Z'(W', g', \gamma')$
- Search for $pp \to \mu^+ e^- + \ldots$
- Search for $pp \to \mu^- e^+ + \ldots$ --- one order below due to quark content of protons
- Search for $pp \to \bar{t} + c + \ldots$ or $pp \to \bar{b} + s + \ldots$ --- expect a few 1000's events, but must consider background!



LHC thus has the potential (in a specific model) to beat even the very sensitive fixed target $K \to \mu e$ limit!

Conclusions

- Family replication model in 6D: elegant solution to the flavour puzzle
  - Hierarchical Dirac masses + small mixing angles
  - Neutrinos are different: See-saw + Majorano-like mass for the bulk neutral fermion can fit neutrino data
  - Family/lepton number violating FCNC suppressed by small fermion mixings
- Predictions for neutrinos
  - Inverted hierarchy
  - Reactor angle ~ 0.1
  - Partially suppressed neutrinoless $\beta\beta$ decay
- Other predictions
  - $K \to \mu e$ will show up earlier than other FCNC-processes
  - Massive gauge bosons with mass $\sim$ TeV or higher
  - Search for $pp \to \mu^+ e^-$ at LHC can beat fixed target
  - Constraint on B-E-H boson: should be LIGHT