PROTON DECAY

Constraints on New Physics

David EMMANUEL-COSTA

(CFTP/IST-ID, University of Lisbon, Portugal)

in collaboration with **Pedro Carrilho**

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IST-ID TÉCNICO LISBOA CFTP COMPETE FCT Fundação para a Ciência e a Tecnologia QREN QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL

1939: Baryon Number Conservation

E.C.G. Stückelberg observes that protons and neutrons do not decay into any combination of electrons, neutrinos, muons, or their antiparticles. The stability of the proton cannot be explained in terms of energy or charge conservation.

1956: Parity and Charge Conjugation Violation

1964: CP Violation

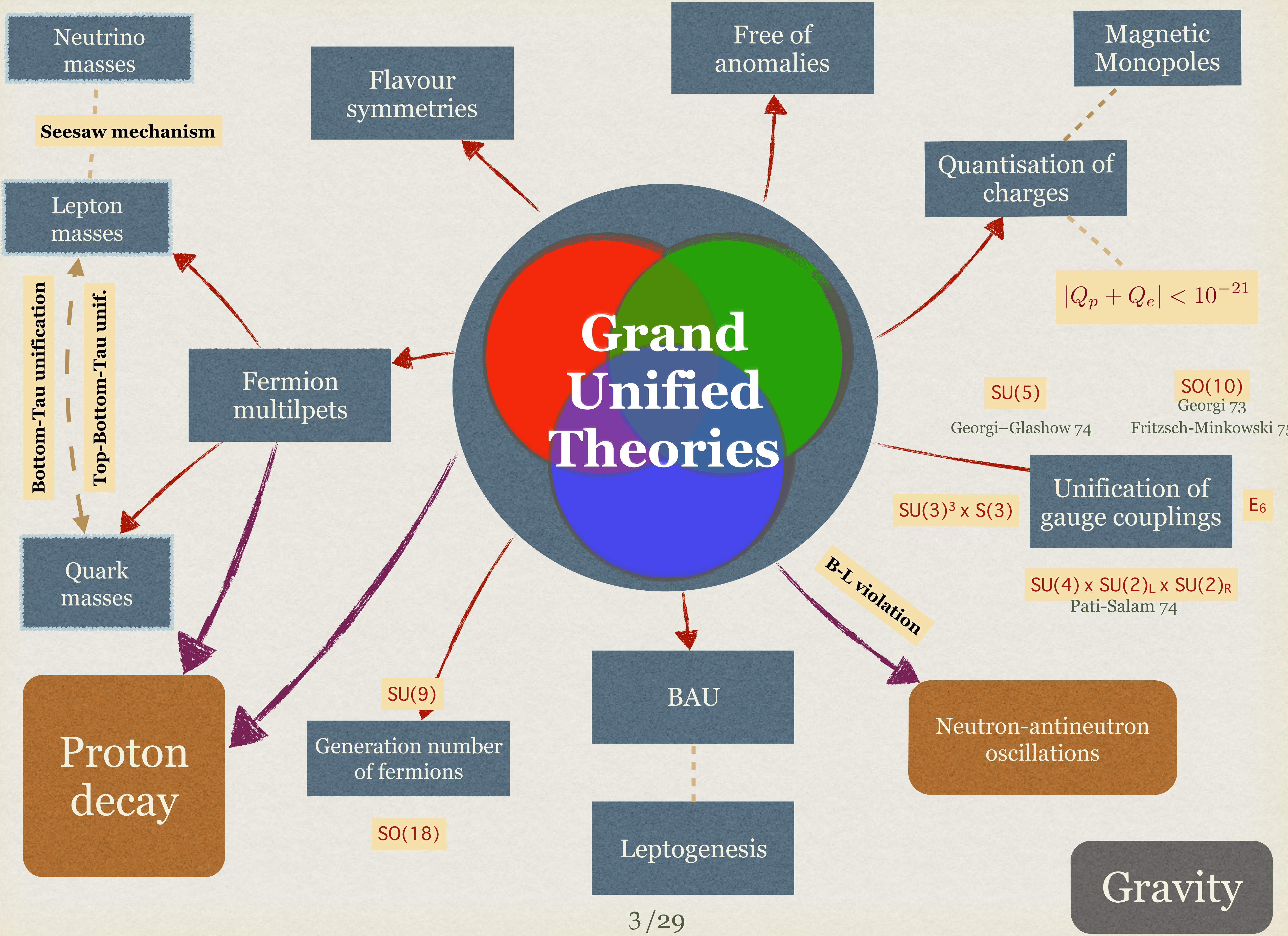
1976: B+L non-conservation

G. 't Hooft showed that in SM instantons induce B+L violation. B-L is still conserved.

1998: Lepton Family Number Violation

Neutrino oscillations are lepton family number violating.

Secular conservation laws: happen to be approx. true, but ultimately violated!


Grand Unified Theories
Neutrino masses
Seesaw mechanism
Lepton masses
Bottom-Tau unification
Top-Bottom-Tau unif.
Quark masses
Flavour symmetries
Free of anomalies
Magnetic Monopoles
Quantisation of charges
$|Q_p + Q_e| < 10^{-21}$
Fermion multilpets
SU(5)
Georgi–Glashow 74
SO(10)
Georgi 73
Fritzsch-Minkowski 75
Unification of gauge couplings
SU(3)³ x S(3)
E6
SU(4) x SU(2)L x SU(2)R
Pati-Salam 74
B-L violation
Proton decay
SU(9)
Generation number of fermions
SO(18)
BAU
Leptogenesis
Neutron-antineutron oscillations
Gravity

EXPERIMENTAL BOUNDS

Super-Kamiokande

22.5 kton fiducial volume

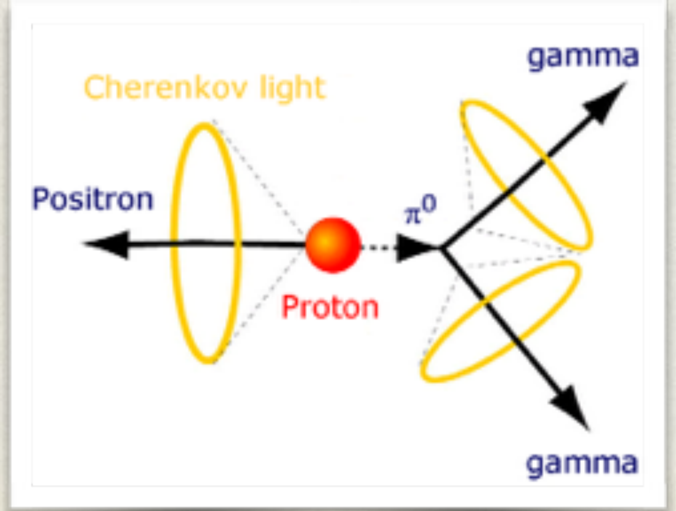
$7.5 \times 10^{33}\, n \;+\; 6 \times 10^{33}\, p$

SK-I: 1996 - 2001
11146 50-cm inner PMTs
40% coverage
1885 20-cm outer PMTs

SK-II: Jan 2003 - Oct 2005
Recovery from accident
5182 50-cm inner PMTs
Acrylic + FRP protective
Outer detector fully restored

SK-III: May 2006 - August 2008
Restored 40% coverage
Outer detector segmented
(top | barrel | bottom)

SK-IV: September 2008 -
SK-IV Replace all electronics – 2008
T2K beam – late 2009
Add gadolinium



$$\tau(p \to e^+\,\pi^0) > 1.01 \times 10^{34} \text{yrs}$$

$$\tau(p \to K^+\,\bar{\nu}) > 4 \times 10^{33}\ \text{yrs}$$

- **Future prospects**

  - Hyper-K (upgraded J-PARC): 20 times larger than Super-K
  - LBNE (liquid Argon): the improvement in sensitivity compared to Super-K is not significant
  - LENA (Liquid-scintillator detector): volume with

for about 10 years it can reach $1.6 \times 10^{34}\, p$ years: $\tau_p \longrightarrow 4 \times 10^{34}$yrs

LAGUNA collaborative scientific project

STANDARD MODEL

- Gauge group (rank 4) :

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

g_s $\quad$ g $\quad$ g'

- Anomaly free theory with exact B-L symmetry
- 3 generations of fermions
- Right-handed neutrinos are absent
- Only one Higgs doublet needed

Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	**Leptons**	$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$
	u_R	u_R	u_R		
	d_R	d_R	d_R		$e^-{}_R$

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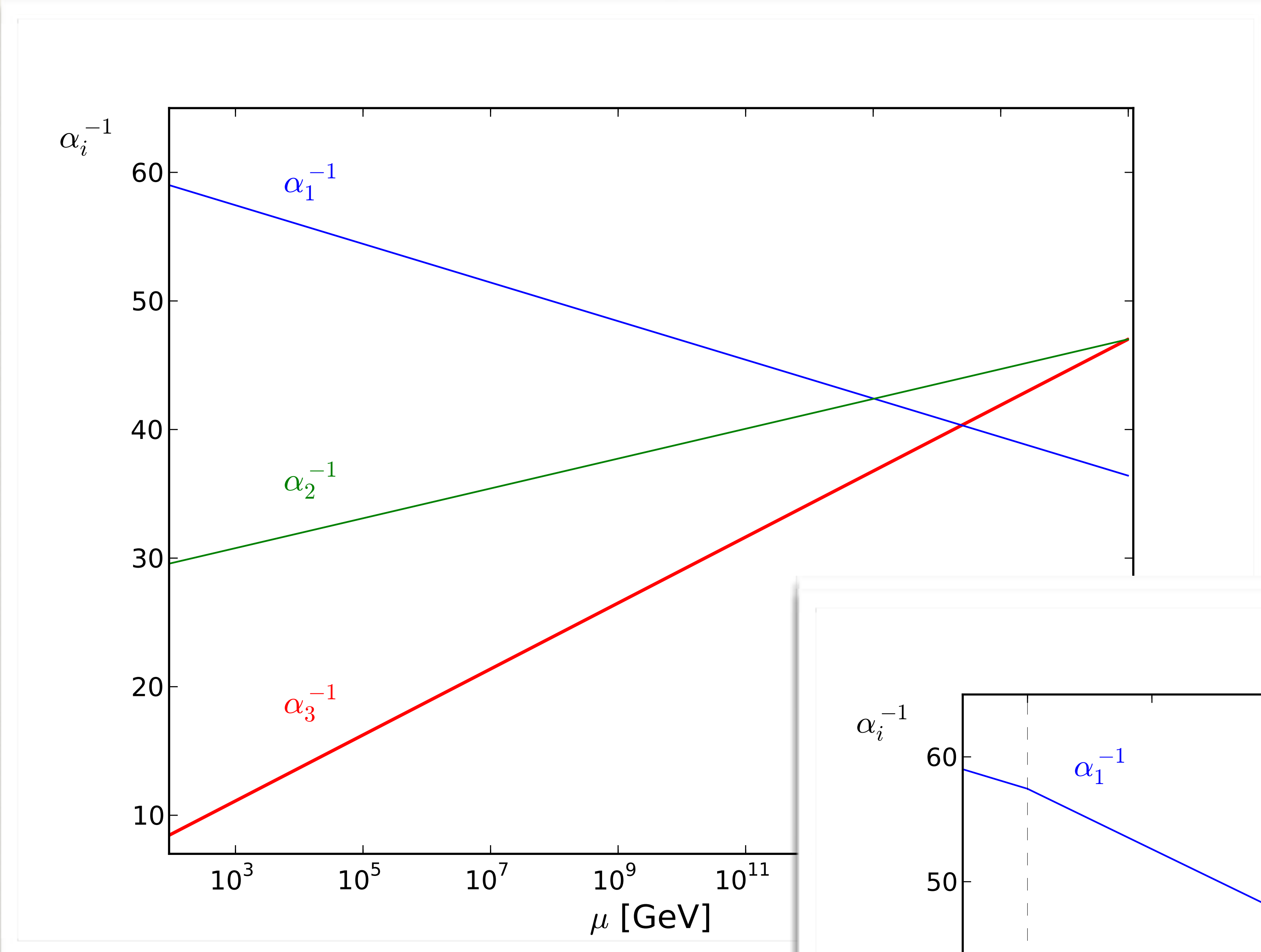
	u^c	u^c	u^c		
	d^c	d^c	d^c		e^+

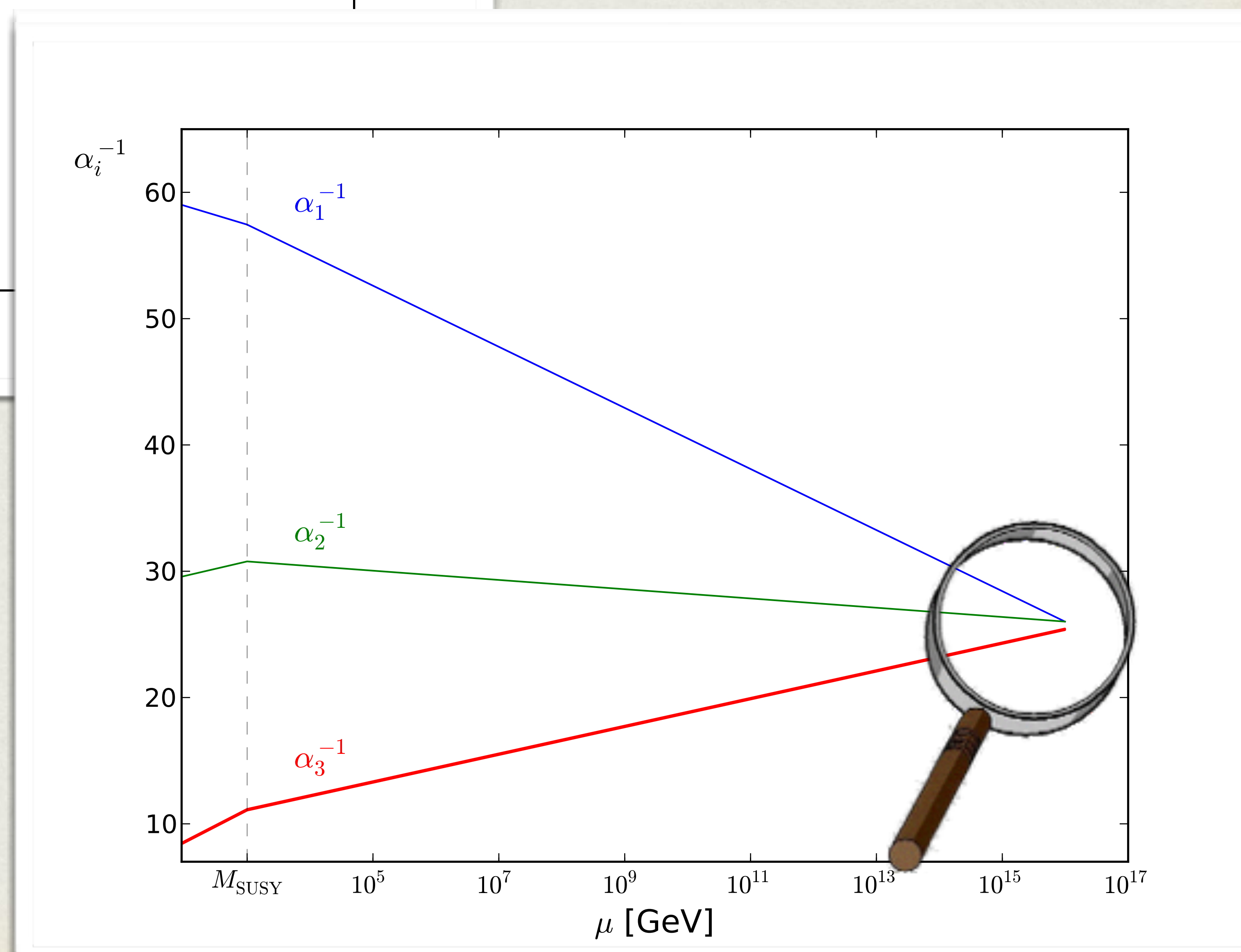
SUPERSYMMETRY

- SUSY GUTs "natural extension of SM"
- Symmetry between fermions and bosons
- Stabilises the masses of the heavy scalar states ()
- Unification of gauge couplings
    - Needs threshold effects:
- Yukawa coupling unification $\Lambda \simeq 2 \times 10^{16}\mathrm{GeV}, \alpha_5^{-1} \simeq 23$
- R-parity → LSP → dark matter candidate



SM

$$\Lambda \simeq 10^{13-15}\text{GeV}$$



MSSM

$$\Lambda \simeq 2 \times 10^{16}\text{GeV}$$

MINIMAL (NON-)SUSY SU(5) GUT

[Georgi and Glashow]

- The simplest GUT group with rank 4
- Anomaly free and B-L conserving
- Contains the SM group $\mathsf{SU}(3)_{\mathrm{C}} \times \mathsf{SU}(2)_{\mathrm{L}} \times \mathsf{U}(1)_{\mathrm{Y}}$

$$5^* = \begin{pmatrix} d^c \\ d^c \\ d^c \\ e^- \\ -\nu \end{pmatrix} \qquad 10 = \begin{pmatrix} 0 & u^c & -u^c & -u & -d \\ -u^c & 0 & u^c & -u & -d \\ u^c & -u^c & 0 & -u & -d \\ u & u & u & 0 & -e^+ \\ d & d & d & e^+ & 0 \end{pmatrix}$$

- Extra heavy gauge bosons X and Y that lead to **proton decay**

$$\alpha_3(\Lambda) = \alpha_2(\Lambda) = \frac{5}{3}\alpha_Y(\Lambda)$$

- **Breaking pattern (Higgs sector)**

  $\Sigma(24)$ Breaks the GUT to the SM group

  $H(5)$ Breaks the SM to QCD +QED

- **Higgs potential**

$$\frac{1}{2}m\mathrm{Tr}\Sigma^2 + \frac{1}{3}a\mathrm{Tr}\Sigma^3 + \frac{1}{4}\lambda_1\mathrm{Tr}\Sigma^4 + \frac{1}{4}\lambda_2(\mathrm{Tr}\Sigma^2)^2\lambda + \overline{H}\left(\Sigma + 3\sigma\right)H$$

$$\langle\Sigma\rangle = \frac{\sigma}{\sqrt{60}}\mathrm{diag}(2,2,2,-3,-3)$$

- **Doublet-triplet-splitting problem**

  Fine-tuning

$$\mathcal{O}(\tfrac{v}{\sigma}) \sim 10^{-13}$$

- **Scalars after the spontaneous breaking**

$$H,\ H_c,\ \Sigma_3,\ \Sigma_8$$

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- **Doublet-triplet-splitting problem**

Missing Partner Mechanism

$$\mathcal{O}(\tfrac{v}{\sigma}) \sim 10^{-13}$$

- **Scalars after the spontaneous breaking**

$$H,\ H_c,\ \Sigma_3,\ \Sigma_8$$

- **Fermion masses**

$$\tfrac{1}{4}\,Y_1^{ij}\,\mathsf{10}_i\,\mathsf{10}_j\,H + \sqrt{2}\,Y_2^{ij}\,\mathsf{10}_i\,\mathsf{5}^*_j\,\overline{H}$$

Neutrinos are massless

$$Y_u^{ij}\,Q_i\,u_j^c\,H_f + Y_d^{ij}\,Q_i\,d_j^c\,\overline{H}_f + Y_e^{ij}\,e_i^c\,L_j\,\overline{H}_f$$
$$+\,\tfrac{1}{2}Y_{qq}^{ij}\,Q_i\,Q_j\,H_c + Y_{ql}^{ij}\,Q_i\,L_j\,\overline{H}_c$$
$$+\,Y_{ue}^{ij}\,u_i^c\,e_j^c\,H_c + Y_{ud}^{ij}\,u_i^c\,d_j^c\,\overline{H}_c$$

$$Y_u = Y_{qq} = Y_{ue} = Y_1 \qquad Y_d = Y_e = Y_{ql} = Y_{ud} = Y_2$$

- **Predictions**

$$M_e = M_d^{\mathsf{T}} \qquad M_u = M_u^{\mathsf{T}}$$

Incompatible with observation extrapolated at GUT scale

$$m_b \approx m_\tau\ , \quad m_s \approx 3\,m_\mu\ , \quad m_d \approx \frac{1}{3}\,m_e$$

- **Fermion masses**

$$\tfrac{1}{4}\, Y_1^{ij}\, \mathsf{10}_i\, \mathsf{10}_j\, H + \sqrt{2}\, Y_2^{ij}\, \mathsf{10}_i\, \mathsf{5}^*_j\, \overline{H}$$

SM

Neutrinos are massless

$$Y_u^{ij}\, Q_i\, u^c_j\, H_f + Y_d^{ij}\, Q_i\, d^c_j\, \overline{H}_f + Y_e^{ij}\, e^c_i\, L_j\, \overline{H}_f$$

$$+ \tfrac{1}{2} Y_{qq}^{ij}\, Q_i\, Q_j\, H_c + Y_{ql}^{ij}\, Q_i\, L_j\, \overline{H}_c$$

$$+ Y_{ue}^{ij}\, u^c_i\, e^c_j\, H_c + Y_{ud}^{ij}\, u^c_i\, d^c_j\, \overline{H}_c$$

$$Y_u = Y_{qq} = Y_{ue} = Y_1 \qquad Y_d = Y_e = Y_{ql} = Y_{ud} = Y_2$$

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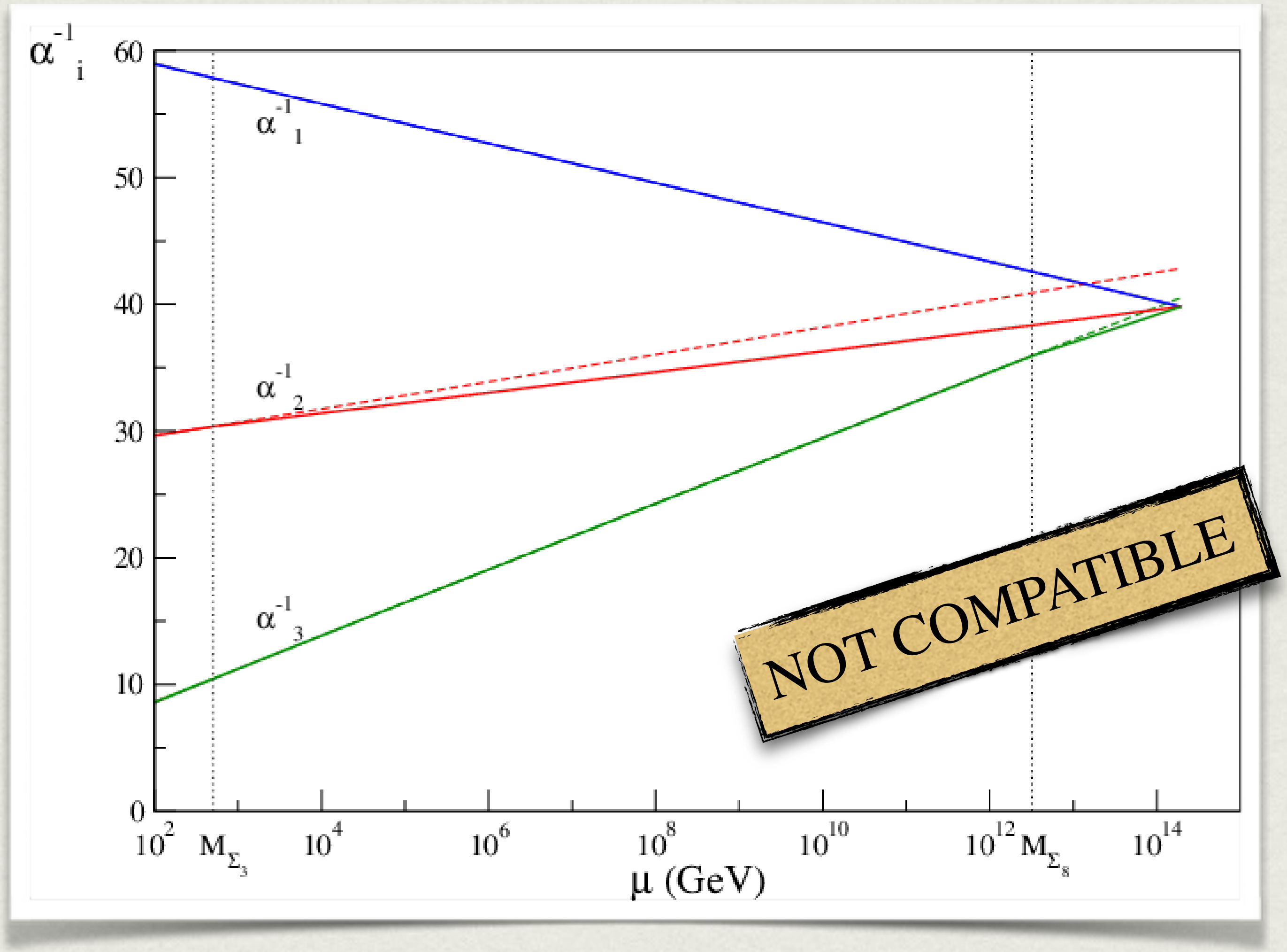
$$M_e = M_d^{\mathsf{T}} \qquad M_u = M_u^{\mathsf{T}}$$

Incompatible with observation extrapolated at GUT scale

$$m_b \approx m_\tau \;, \quad m_s \approx 3\, m_\mu \;, \quad m_d \approx \frac{1}{3}\, m_e$$

[D.E.C, Simões]

- **Unification**



$$1.3 \times 10^{14}\,\mathrm{GeV} \leq \Lambda \leq 2.4 \times 10^{14}$$

$$M_Z \leq M_{\Sigma_3} \leq 1.8 \times 10^{4}\,\mathrm{GeV}$$

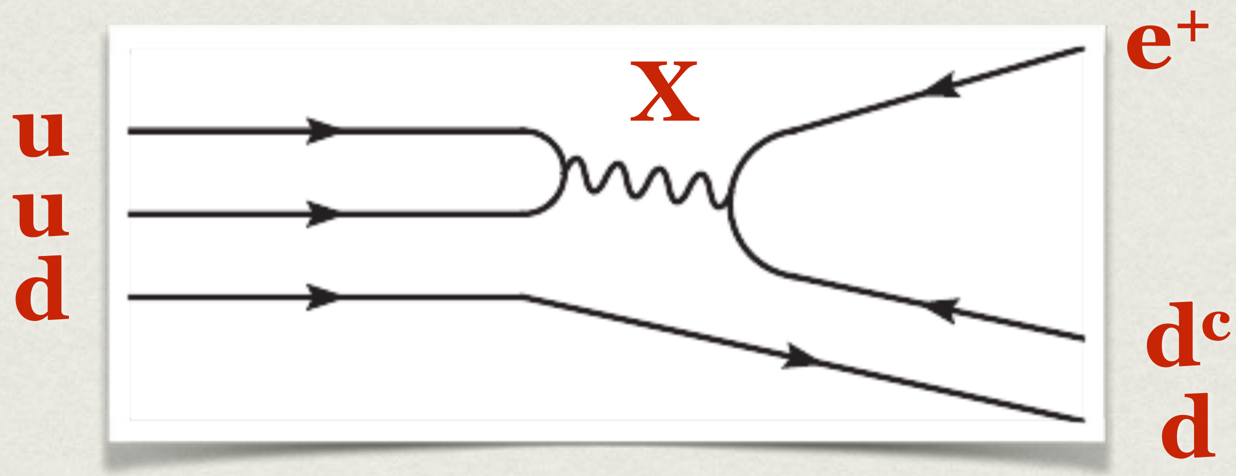
$$5.4 \times 10^{11}\,\mathrm{GeV} \leq M_{\Sigma_8} \leq 1.3 \times 10^{14}\,\mathrm{GeV}$$

- **Heavy gauge bosons X and Y**

$$M_V = \frac{25}{8} g_U^2 \sigma^2$$

- **Dominant contribution**

$$\Gamma \approx \alpha_U^2 \frac{m_p^5}{M_V^4}$$



$$\tau(p \to \pi^0 e^+) > 1.4 \times 10^{34}\,\mathrm{y} \implies M_V > (4.9 - 5.1) \times 10^{15}\,\mathrm{GeV}$$

- **Yukawa coupling contribution is <u>suppressed</u>**

$$\frac{(\Gamma_u)_{ij}\,(\Gamma_d)_{kl}}{M_{H_c}^2} \left[\frac{1}{2}(Q_i Q_j)(Q_k L_l) + (u_i^c e_j^c)(u_k^c d_l^c)\right]$$

CONSISTENT SU(5) MODEL

[Feleviez-Pérez, Senjanovic, Bajc, Dorsner; E.-C., Wiesenfeldt]

- Non-renormalisable
- Fifth dimensional operators to account for the mismatch
- One expects new interactions above GUT scale (e.g. M_{Pl})
- Neutrinos are introduced as singlet fermionic fields
- Splitting between $\Sigma_3,\ \Sigma_8$ is more natural
- Unification issue can only be solved in SUSY

two Higgs doublet needed

$$\sum_{n=1,2} \frac{\sqrt{2}}{\Lambda'} (\Delta_n)_{ij}\ H^*_{n\,a}\, \mathsf{10}^{ab}_i\, \Sigma^c_b\, \mathsf{5}^*_{jc}$$

$$M_d - M_e^\top = 5\,\frac{\sigma}{\Lambda'}(v_1^*\,\Delta_1 + v_2^*\,\Delta_2)$$

ADJOINT SU(5) MODEL

[Georgi, Jarlskog; Feleviez-Pérez; Senjanovic et al.]

- Renormalisable

$$\mathsf{45}_H = S_{(8,2)_{\frac{3}{10}}} \oplus S_{(6^*,1)_{-\frac{1}{5}}} \oplus S_{(3^*,2)_{-\frac{7}{10}}} \oplus S_{(3^*,1)_{\frac{4}{5}}} \oplus \Delta \oplus T_2 \oplus H_2$$

$$\left\langle \mathsf{45}_{H}{}^{\alpha 5}_{\beta} \right\rangle = v_{\mathsf{45}} \left(\delta^{\beta}_{\alpha} - 4\, \delta^{\alpha}_{4} \delta^{4}_{\beta} \right) \ , \alpha,\beta=1,\ldots,4$$

- Neutrinos masses are via a fermionic $\rho(24)$
- Unification is successful
- Solves the mass mismatch

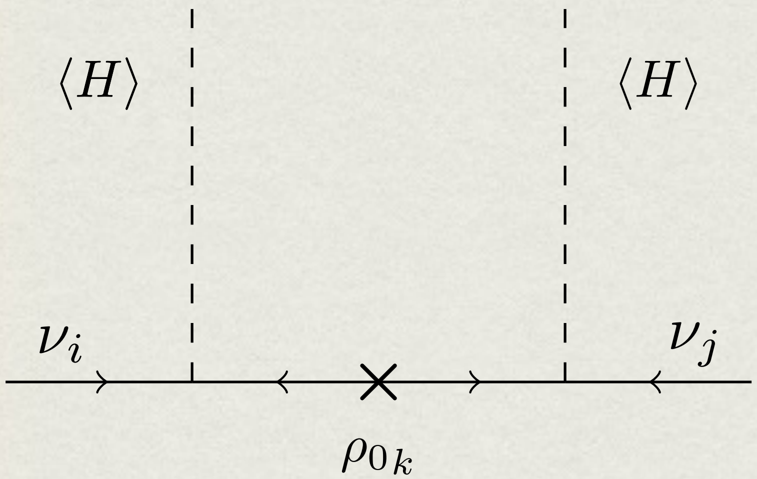
$$M_u = v_{\mathsf{5}}\, \Gamma^1_u + 2\, v_{\mathsf{45}}\, \Gamma^2_u$$

$$M_d = v^*_{\mathsf{5}}\, \Gamma^1_d + 2\, v^*_{\mathsf{45}}\, \Gamma^2_d$$

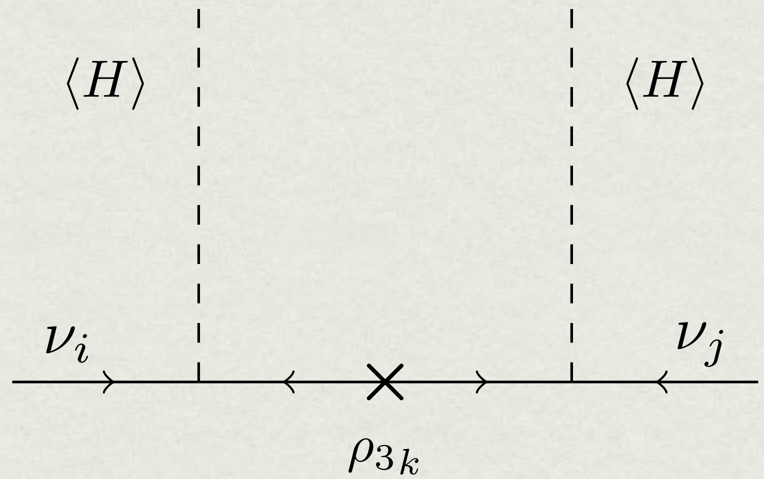
$$M_e^{\mathsf{T}} = v^*_{\mathsf{5}}\, \Gamma^1_d - 6\, v^*_{\mathsf{45}}\, \Gamma^2_d$$

$$M_d - M_e^{\mathsf{T}} = 8\, v^*_{\mathsf{45}}\, \Gamma^2_d$$

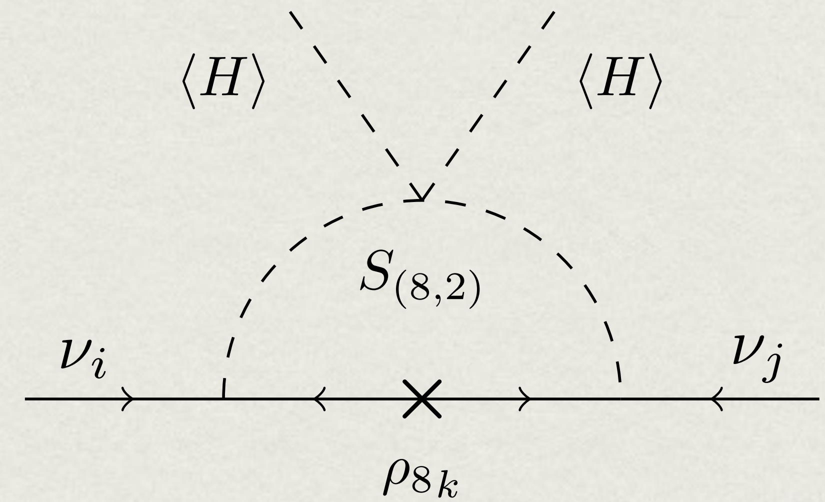
- Neutrino masses (three seesaw mechanisms)



Type I



Type III



Coloured Type

- Proton decay channels

$$\frac{\left(\Gamma_u^1\right)_{ij}\left(\Gamma_d^1\right)_{kl}}{M_{T_1}^2}\left[\frac{1}{2}(Q_iQ_j)(Q_kL_l)\;+\;(u_i^{\mathrm{C}}e_j^{\mathrm{C}})(u_k^{\mathrm{C}}d_l^{\mathrm{C}})\right]$$

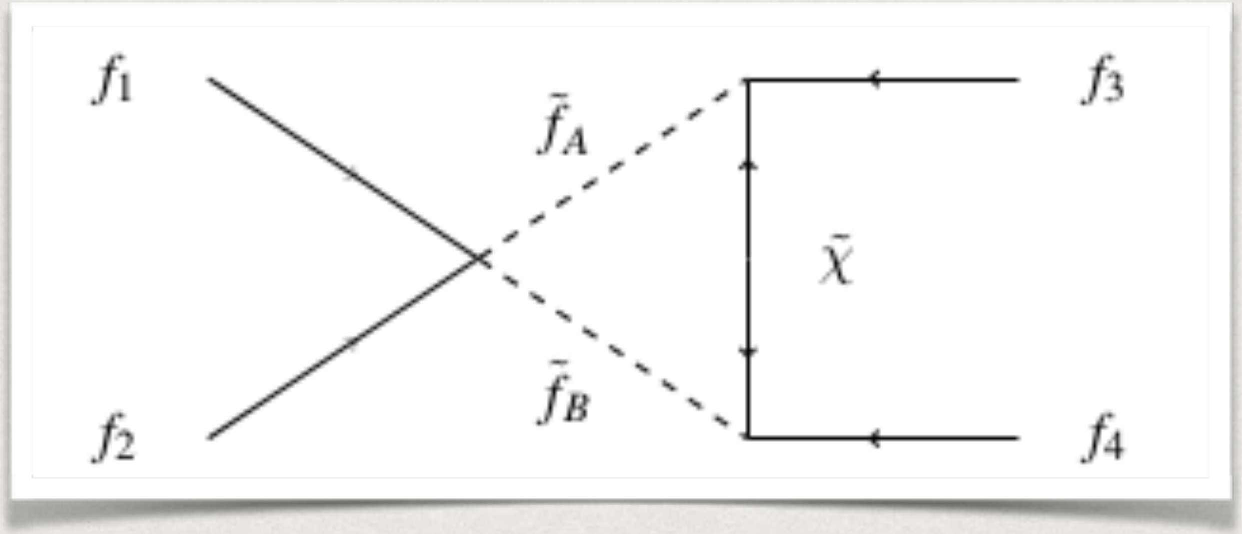
$$\frac{4\left(\Gamma_u^2\right)_{ij}\left(\Gamma_d^2\right)_{kl}}{M_{T_2}^2}(u_i^{\mathrm{C}}e_j^{\mathrm{C}})(u_k^{\mathrm{C}}d_l^{\mathrm{C}})$$

$$\frac{\left(\Gamma_u^2\right)_{ij}\left(\Gamma_d^2\right)_{kl}}{2}\left\{\frac{1}{M_{\boldsymbol{\Delta}^{-1/3}}^2}\Big[(u_id_j)(u_ke_l)\;+\;(u_id_j)(d_k\nu_l)\Big]\;-\;\frac{1}{M_{\boldsymbol{\Delta}^{2/3}}^2}(d_id_j)(u_k\nu_l)\right\}$$

SUSY SU(5) MODEL

**[Dimopoulos, Georgi; Sakai;
Hisano, Murayama, Yanagida;
Goto, Nihei;
D.E.C., Wiesenfeldt]**

- **Higgs triplet exchange is now dominant**



$$\mathcal{M} \sim \frac{1}{M_{H_C}} \tilde{C}_5 g^2 V_{CKM} V_{CKM} |X^{\tilde{f}_A}|^2 |X^{\tilde{f}_B}|^2 V^* U^* f(M_{\tilde{\chi}}, m_A, m_B)$$

Wilson Coefficient

- **Dimension 5 operators**

$$W_{D=5} = -\frac{1}{M_{H_c}} \left[C_{5L}^{ijkl} Q_i Q_j Q_k L_l + C_{5R}^{ijkl} U_i^c E_j^c U_k^c D_l^c \right]$$

- SU(5) **minimal content**

$$C_{5L}^{ijkl} = \frac{1}{2} \left(\tilde{U}_{uL} D_u P \tilde{U}_{uL}^{\top} \right)^{ij} \left(\tilde{U}_{dL} D_d \tilde{U}_{eL}^{\dagger} \right)^{kl}$$

$$C_{5R}^{ijkl} = \left(\tilde{U}_{uR}^{*} D_u V_{CKM}^{*} \tilde{U}_{eR}^{\top} \right)^{ij} \left(\tilde{U}_{uR}^{*} P^{*} V_{CKM} D_d \tilde{U}_{dR}^{\dagger} \right)^{kl}$$

- **Proton decay in** SU(5) **depends on the choice:**

$Y_e = Y_d^{\top}$ **exp.** *or* $Y_d = Y_e^{\top}$ **exp.**

- **Dimension 5 operators**

$$W_{D=5} = -\frac{1}{M_{H_c}}\left[C_{5L}^{ijkl} Q_i Q_j Q_k L_l + C_{5R}^{ijkl} U_i^c E_j^c U_k^c D_l^c\right]$$

- SU(5) **minimal content**

$$C_{5L}^{u} = \frac{1}{2}(D_u P)(V_{CKM} D_d) \quad C_{5L}^{d} = \frac{1}{2}(V_{CKM}^{\dagger} D_u P V_{CKM}^{*})(D_d)$$

$$C_{5R}^{u,d} = (D_u V_{CKM}^{*})(P^{*} V_{CKM} D_d)$$

- **Proton decay in** SU(5) **depends on the choice:**

$Y_e = Y_d^{\mathsf{T}}$ **exp.** *or* $Y_d = Y_e^{\mathsf{T}}$ **exp.**

- **Renormalisation group Factors**

  - *From GUT to SUSY scale the Wilson coefficients are fully evolved with RGE (including all Yukawas) and A_L factors*

$$A_L = \left(\frac{\alpha_3(\mu_{had})}{\alpha_3(m_c)}\right)^{4/9} \left(\frac{\alpha_3(m_c)}{\alpha_3(m_b)}\right)^{12/25} \left(\frac{\alpha_3(m_b)}{\alpha_3(m_Z)}\right)^{12/23}$$

- **Chiral perturbation theory**

$$\mathcal{A}(K^+\bar{\nu}) = A_l \Big\{ [\beta\, \mathcal{M}_{LL}^{usd\nu} + \alpha\, \mathcal{M}_{RL}^{usd\nu}] \frac{2m_p}{3m_B} D \\ + [\beta\, \mathcal{M}_{LL}^{uds\nu} + \alpha\, \mathcal{M}_{RL}^{uds\nu}] \left(1 + \frac{m_p}{3m_B}(3F+D)\right) \\ + [\beta\, \mathcal{M}_{LL}^{dsu\nu} + \alpha\, \mathcal{M}_{RL}^{dsu\nu}] \left(1 - \frac{m_p}{3m_B}(3F-D)\right) \Big\}$$

- **Dependence on** $\tan\beta$

  LLLL contribution $1/\sin^2\beta$

  RRRR contribution $(\tan\beta + \frac{1}{\tan\beta})^2$

- **Decay width**

$$\Gamma(p \to K^+\bar{\nu}) = \frac{(m_p^2 - m_K^2)^2}{32\pi m_p^3 f_\pi^2} \sum_{i=e,\mu,\tau} |\mathcal{A}(K^+\bar{\nu}_i)|^2$$

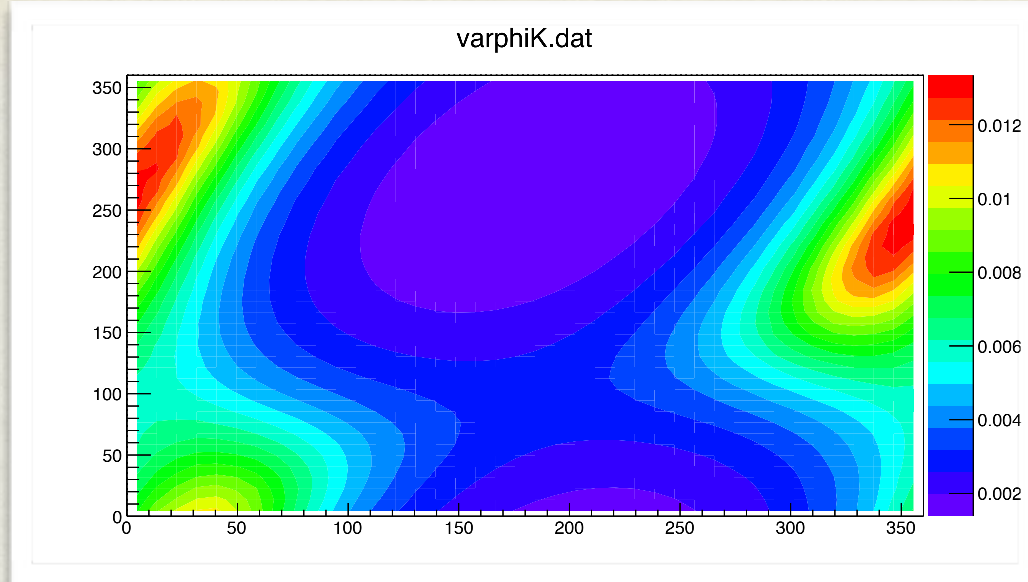
- **All the numerics were made in mSUGRA**

Point	m_0	$m_{1/2}$	A_0	$\tan\beta$	$m_{\tilde{t}}$	$m_{\tilde{\chi}^0}$	$m_{\tilde{\chi}^\pm}$	m_h
1	1000	125	0	2.5	526	47.6	92.2	92.7
2	1472	711	-3157	34.1	920	307	589	124.1
3	7126	595	5968	29.8	4164	244	318	124.7
4	22000	4207	20823	7.3	14176	1949	2744	126.8
5	25000	1200	-20823	7.3	14548	567	1100	127.9
6	20000	115	-19500	7.3	11568	63	131	126.6

- **Coloured Higgs triplet mass**

$$3.5 \times 10^{14}\ \mathrm{GeV} \leq M_{H_C} \leq 3.6 \times 10^{15}\ \mathrm{GeV}$$

NUMERICS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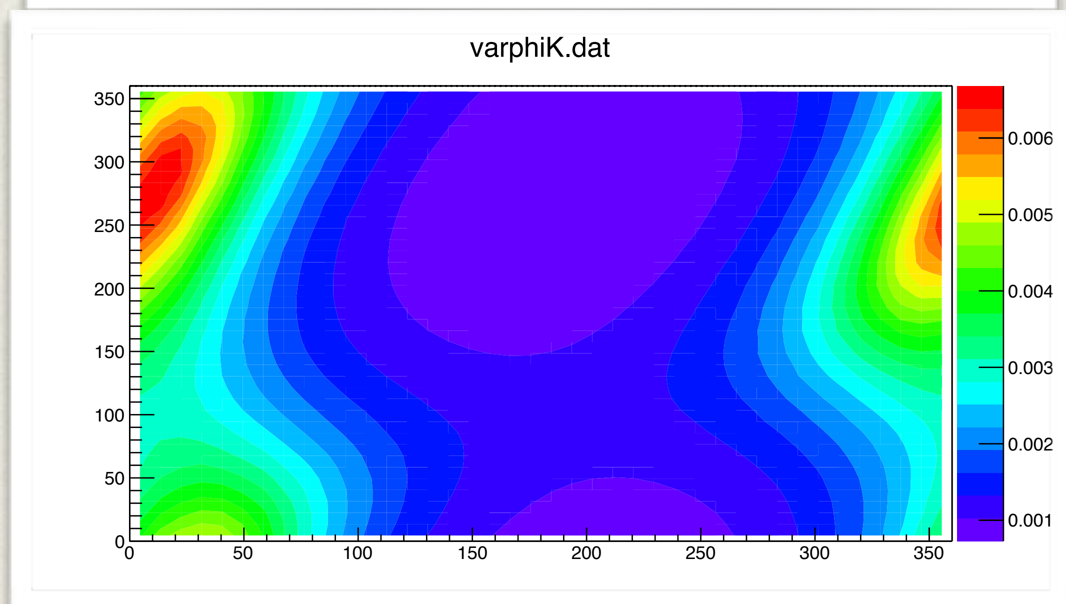
0.012
0.01
0.008
0.006
0.004
0.002
0 50 100 150 200 250 300 350
350 300 250 200 150 100 50 0


varphiK.dat
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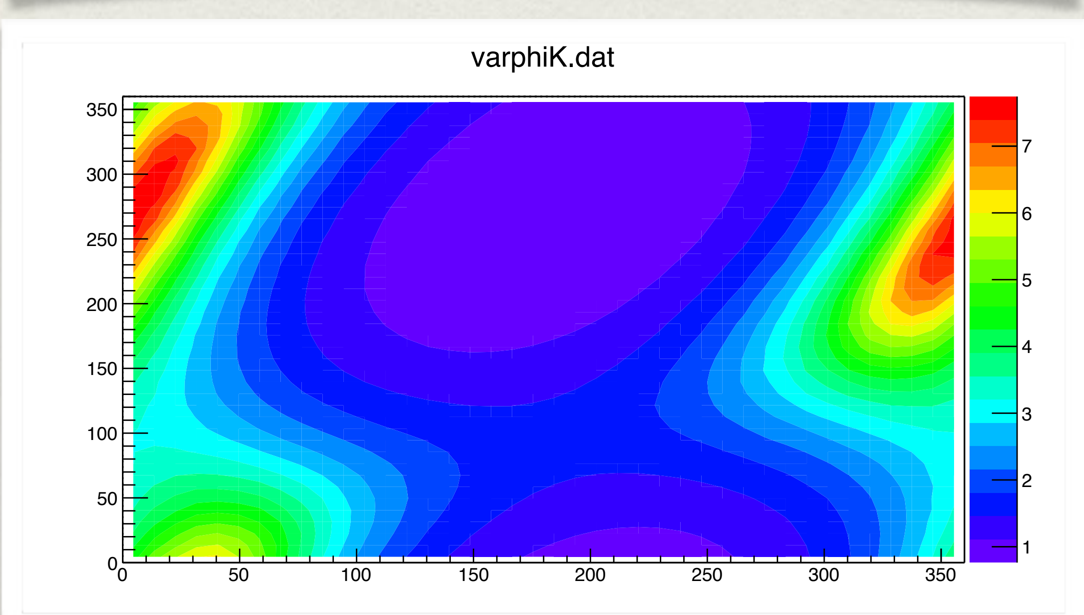
0.005
0.004
0.003
0.002
0.001
0 50 100 150 200 250 300 350
350 300 250 200 150 100 50 0


varphiK.dat
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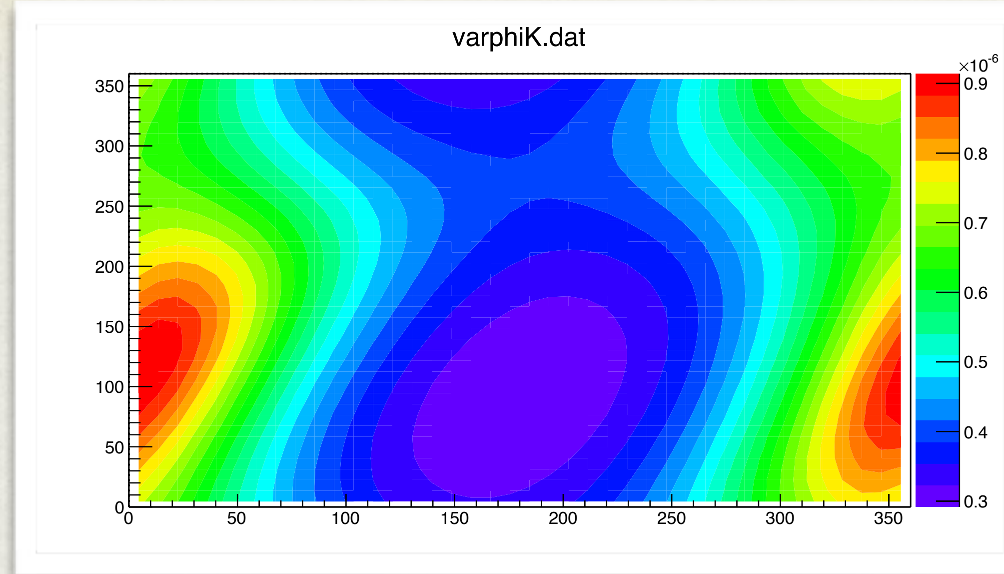
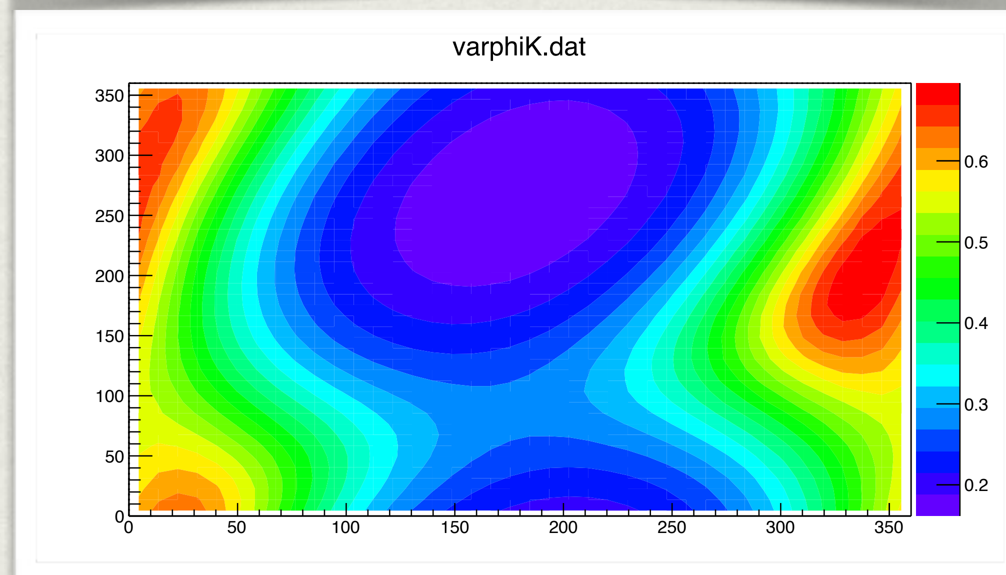
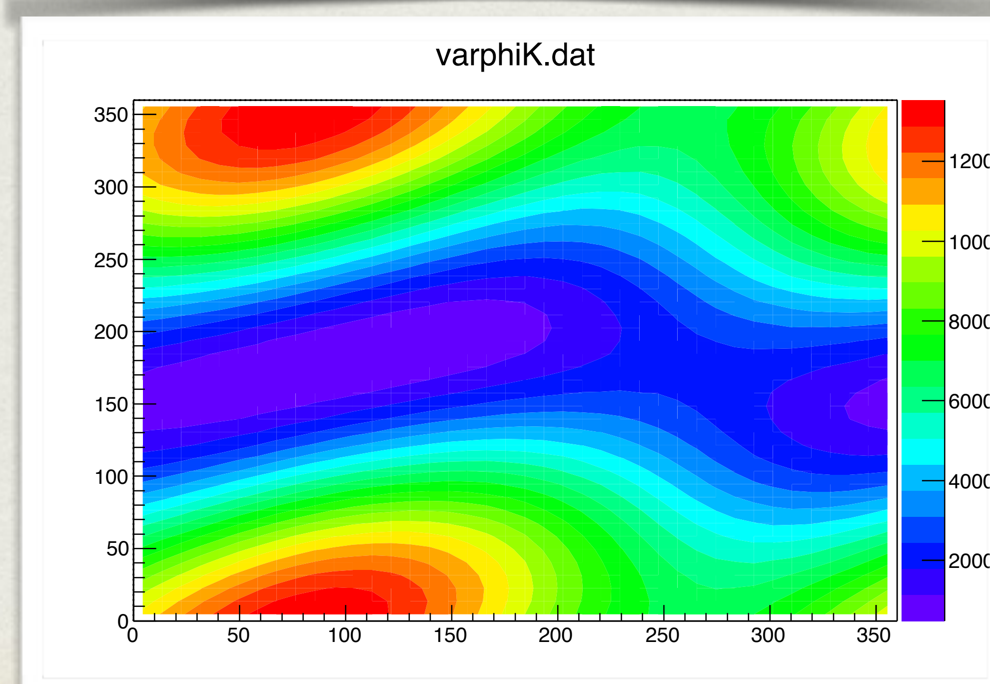
6
5
4
3
2
1
0 50 100 150 200 250 300 350
350 300 250 200 150 100 50 0


varphiK.dat
×10^{-6}
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0 50 100 150 200 250 300 350
350 300 250 200 150 100 50 0

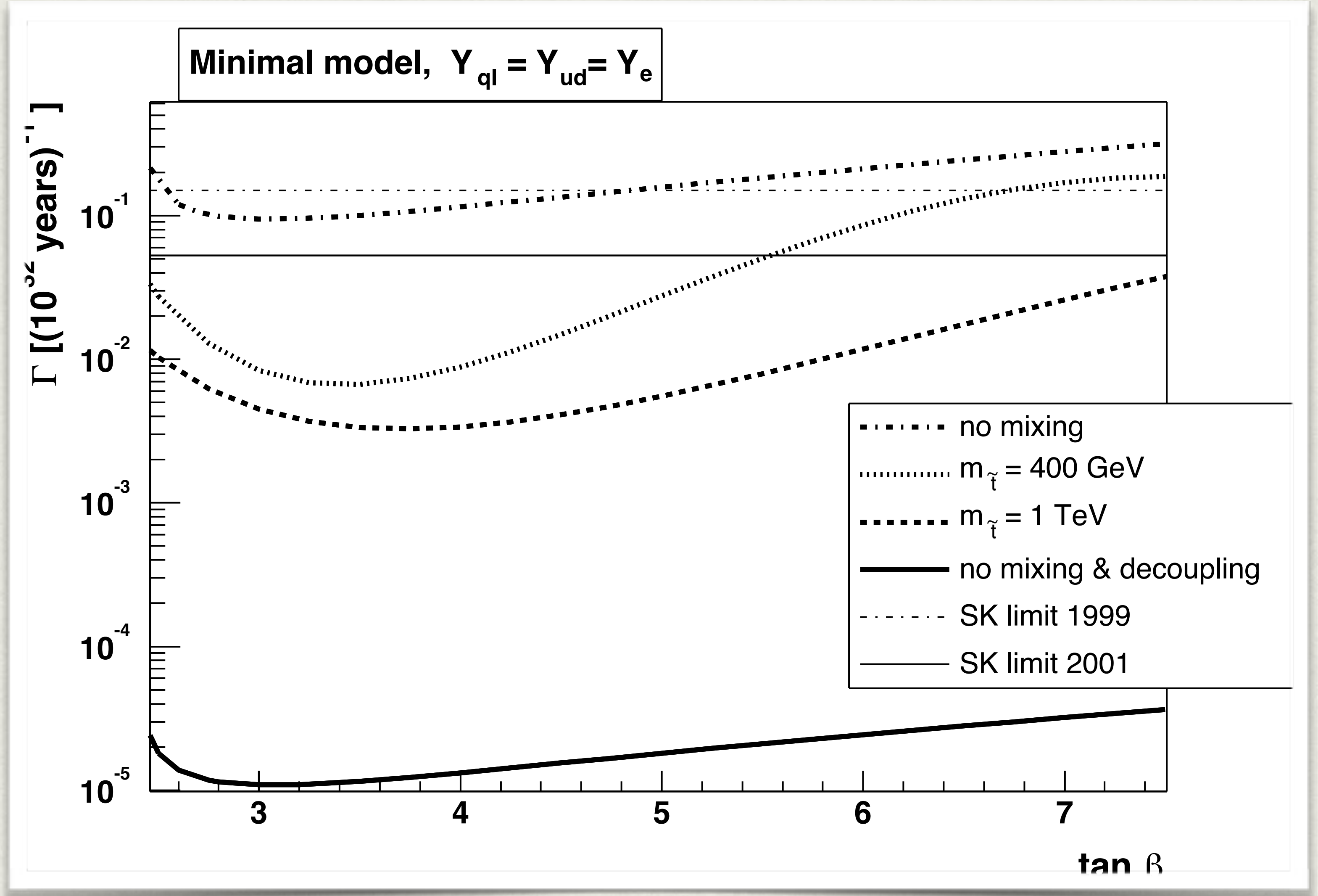

varphiK.dat
0.6
0.5
0.4
0.3
0.2
0 50 100 150 200 250 300 350
350 300 250 200 150 100 50 0


varphiK.dat
1200
1000
8000
6000
4000
2000
0 50 100 150 200 250 300 350
350 300 250 200 150 100 50 0

[D.E.C., Wiesenfeldt]

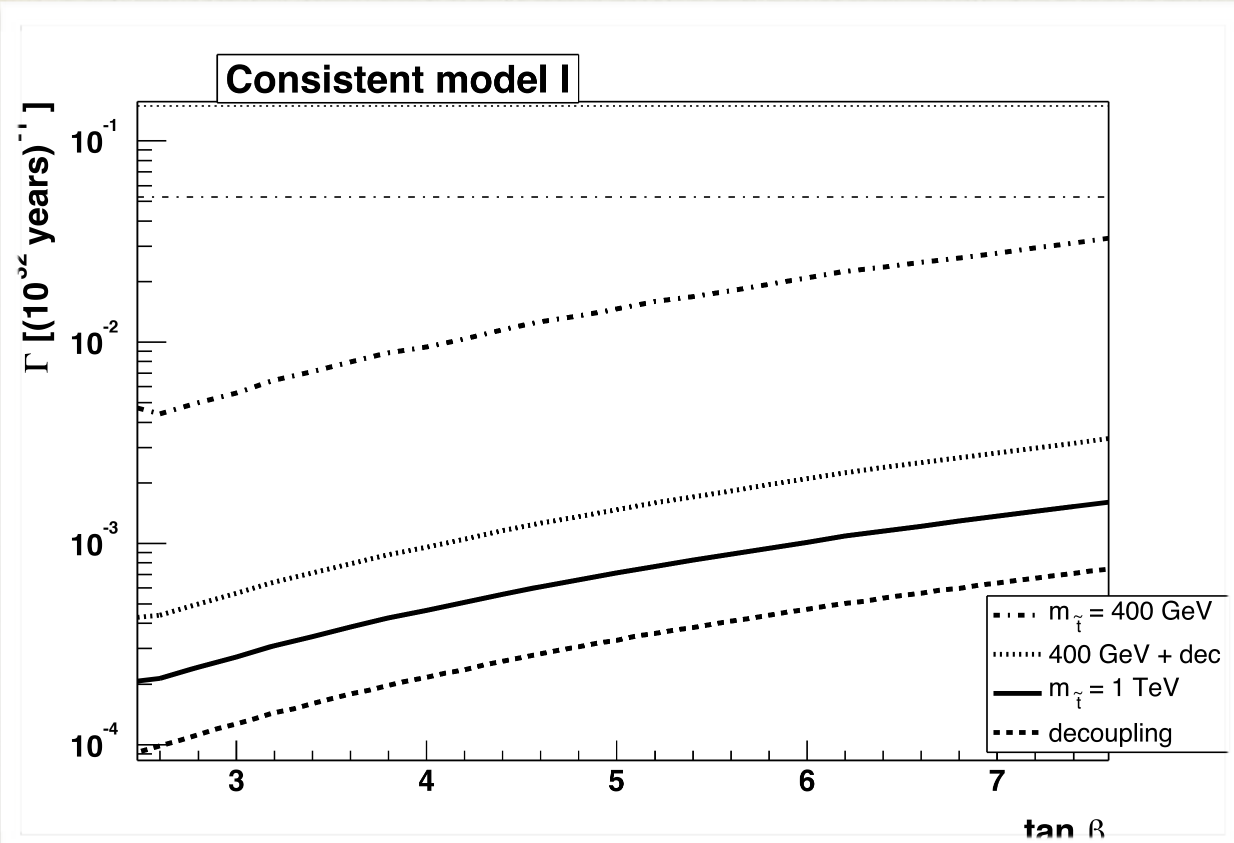
- If we make the other choice:

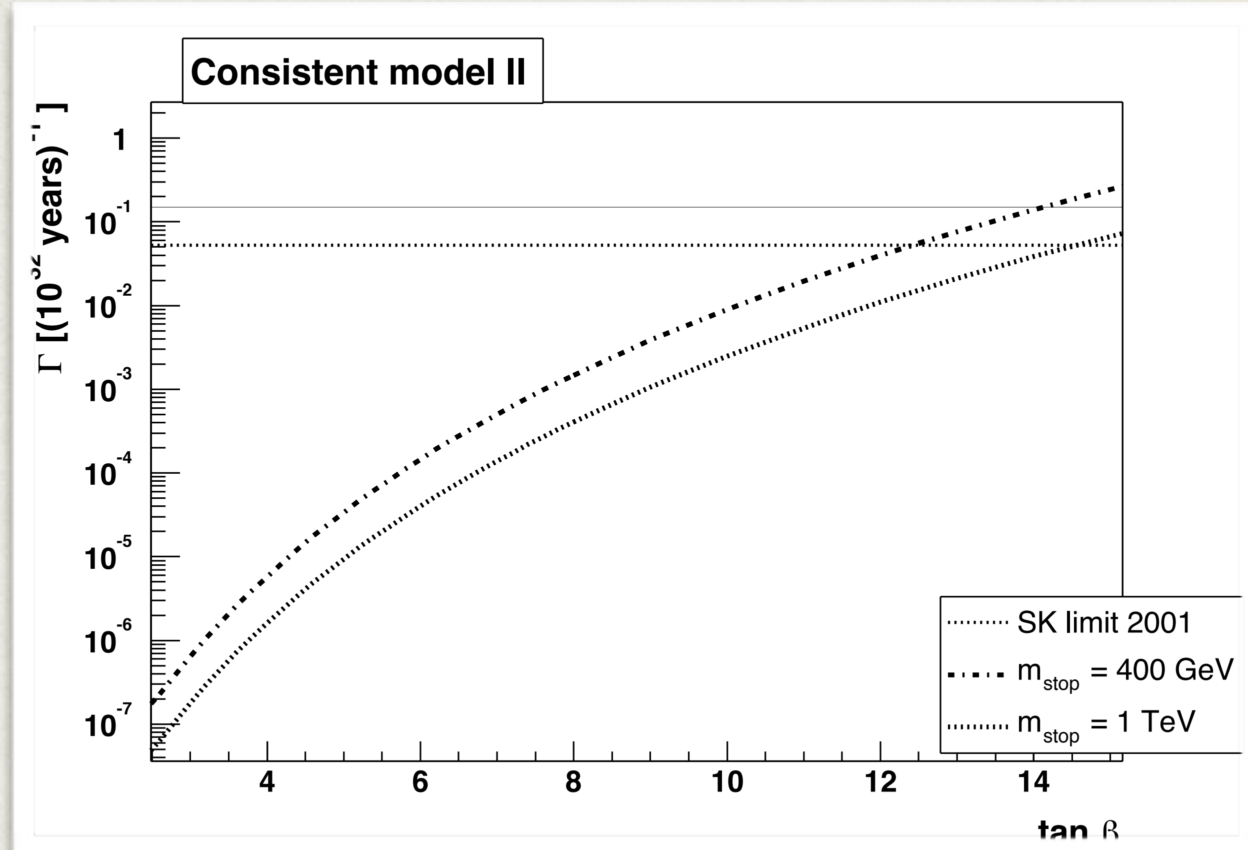
$$Y_d = Y_e^T \quad \text{exp.}$$



[D.E.C., S.Wiesenfeldt]

- **Consistent (non-renormalisable) model examples**





- **Proton decay rate to kaons in the final state**

Model I

$$Y_{qq} = Y_{ue} = \mathrm{diag}(0, 0, \mathrm{y_t})$$
$$Y_{ud} = \mathrm{diag}(0, \mathrm{y_s} - \mathrm{y}_\mu, \mathrm{y_b} - \mathrm{y}_\tau)$$
$$Y_{ql} = \mathrm{diag}(\mathrm{y_e} - \mathrm{y_d}, 0, 0)$$

Model II

$$Y_{qq} = Y_{ue} = \mathrm{diag}(0, 0, \mathrm{y_t})$$
$$Y_{ud} = \mathrm{diag}(\mathrm{y_d} - \mathrm{y_e}, \mathrm{y_s} - \mathrm{y}_\mu, \mathrm{y_b})$$
$$Y_{ql} = \mathrm{diag}(0, 0, \mathrm{y}_\tau)$$

OTHER STRATEGY

[D.E.C, P. Carrilho]

$$H_c \longrightarrow M_{Pl}$$

$$C_{5L}^{ijkl} < 8 \times 10^{-7}$$

$$C_{5R}^{i1kl} < 4.8 \quad C_{5R}^{i2kl} < 0.023 \quad C_{5R}^{i3kl} < 1.4 \times 10^{-3}$$

Point 1

$$C_{5L}^{ijkl} < 2 \times 10^{-7}$$

$$C_{5R}^{i1kl} < 0.6 \quad C_{5R}^{i2kl} < 3 \times 10^{-3} \quad C_{5R}^{i3kl} < 1.7 \times 10^{-4}$$

Point 2

$$C_{5L}^{ijkl} < 9.5 \times 10^{-6}$$

$$C_{5R}^{i1kl} < 34 \quad C_{5R}^{i2kl} < 0.16 \quad C_{5R}^{i3kl} < 9.7 \times 10^{-3}$$

Point 3

$$C_{5L}^{ijkl} < 5.9 \times 10^{-5}$$

$$C_{5R}^{i1kl} < 267 \quad C_{5R}^{i2kl} < 1.3 \quad C_{5R}^{i3kl} < 0.077$$

Point 5

$$C_{5L}^{ijkl} < 1.6 \times 10^{-5}$$

$$C_{5R}^{i1kl} < 190 \quad C_{5R}^{i2kl} < 0.92 \quad C_{5R}^{i3kl} < 0.055$$

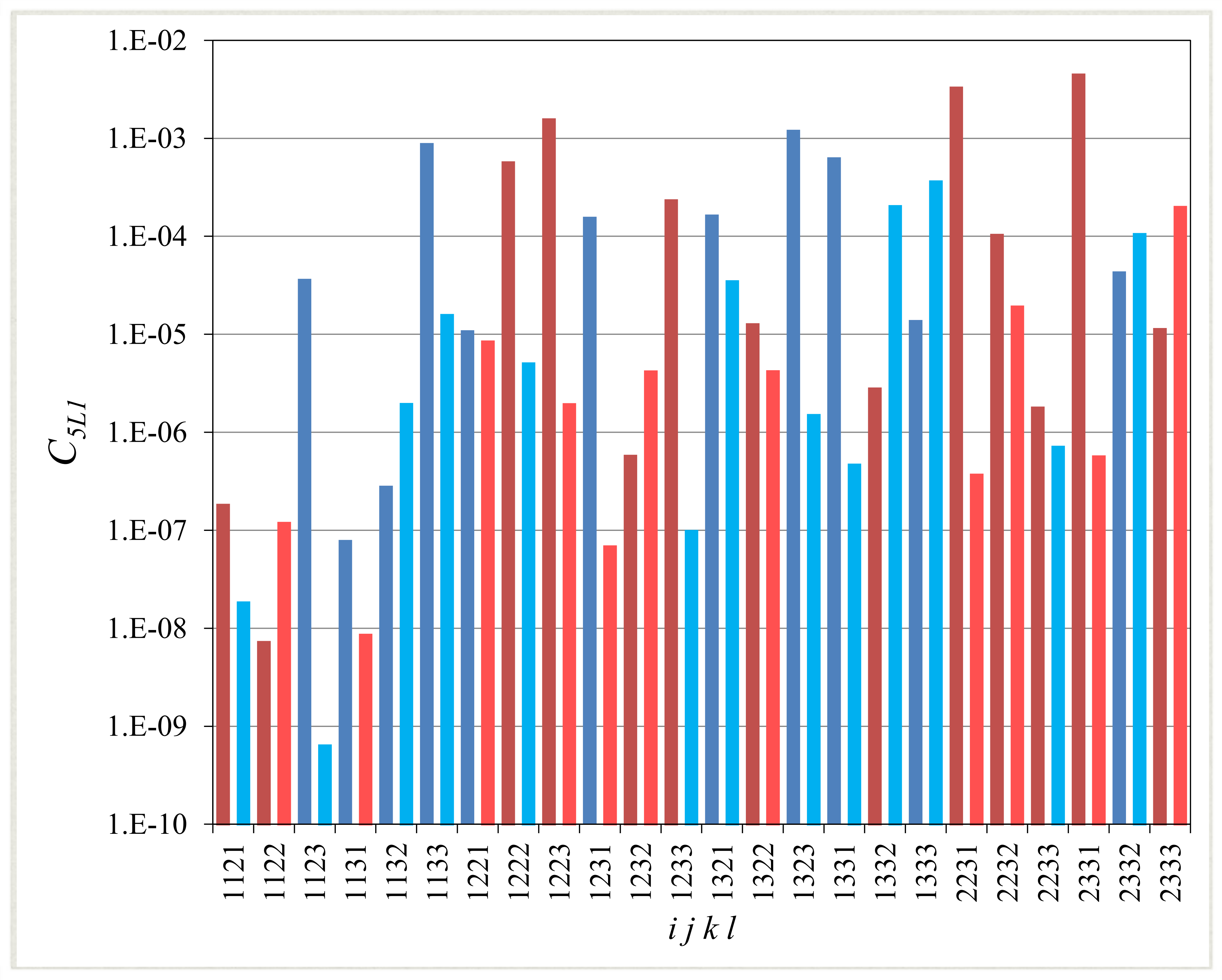
Point 4

$$C_{5L}^{ijkl} < 3.2 \times 10^{-4}$$

$$C_{5R}^{i1kl} < 435 \quad C_{5R}^{i2kl} < 2.1 \quad C_{5R}^{i3kl} < 0.13$$

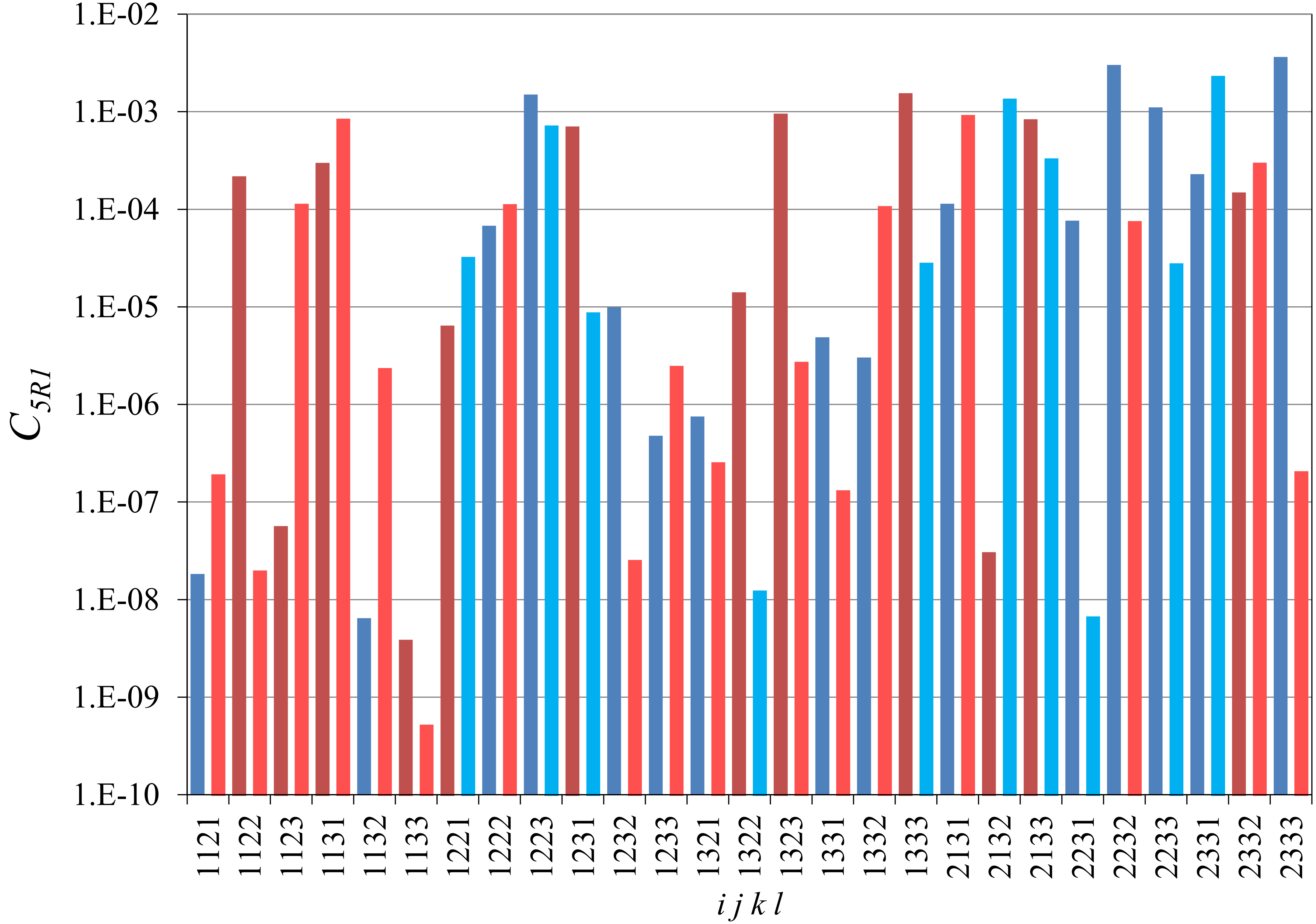
Point 6

[D.E.C, Carrilho]



- **Constraining the 24 independent Wilson coefficients**

[D.E.C, P. Carrilho]



CONCLUSIONS

- **Grand Unified Theories make the bridge between Proton decay and Fermion masses and mixing**
- **Proton decay was not yet discovered and therefore puts constraints on GUT models**
- **Minimal SUSY/ NON-SUSY** SU(5) **is ruled out by the fermion spectrum**
- **The renormalisable Adjoint model solves unification and proton decay**
- **Dangerous** D=5 **operators can be a good discriminator among different Models Beyond SM**

A proton once said,

«I'll fulfill

My long-term belief in free will.

Though theorists (may) say

That I ought to decay

I'm damned if I think that I will».

-David Halliday