Flavour in the Era of LHC

WG3 theory report

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WG3 – Lepton Flavour Violation

- $L$ and $L_i$ conserved in the SM – any experimental FV signal implies physics beyond SM

- Much less experimental data – oscillation measurements, leptogenesis & constraints (LFV, EDMs)

- Physics at low and high scales come together
### Three neutrino analysis

<table>
<thead>
<tr>
<th>$\Delta m^2_{12}$ ($10^{-5}$ eV$^2$)</th>
<th>$\sin^2 \theta_{12}$</th>
<th>$\Delta m^2_{23}$ ($10^{-3}$ eV$^2$)</th>
<th>$\sin^2 \theta_{23}$</th>
<th>$\sin^2 \theta_{13}$ ($10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.9, 7.2, 7.9, 8.7, 9.0</td>
<td>0.24, 0.27, 0.31, 0.36, 0.40</td>
<td>1.5, 1.8, 2.3, 2.9, 3.2</td>
<td>0.31, 0.34, 0.47, 0.63, 0.67</td>
<td></td>
</tr>
</tbody>
</table>

$U^T M_\nu, U=\text{diag } (m_1, m_2, m_3)$

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Seesaw

Why are neutrinos so light?

\[ \frac{1}{2} \nu^c_R M \nu^c_R + \nu^c_R Y_{\nu} L \cdot H_2 \]

\[ M_{\nu} = -m_{D}^{T} M^{-1} m_{D} \]

3+3+3=9 parameters

18 new parameters

M\sim 10^{14} \text{ GeV}

\[ Y_{\nu} = \frac{1}{\nu \sin \beta} D \left( \sqrt{M_i} \right) R D \left( \sqrt{m_j} \right) U^{\dagger} \]
\[
\delta_{RR} \sim (Y_u^+Y_u) \log \frac{M_p}{M_{GUT}}
\]

\[
\delta_{LL} \text{ sleptons} \iff \text{GUT relations} \iff \delta_{RR} \text{ squarks}
\]

\[
\delta_{LL} \sim (Y_\nu^+Y_\nu) \log \frac{M_{GUT}}{M_N}
\]

**SUSY:**

\[
\frac{1}{\Lambda_{LFV}} \to \frac{1}{\tilde{m}_{SUSY}}
\]

\[
\delta_{LL} \quad \delta_{RR} \quad \delta_{LR} \quad \text{for sleptons and squarks}
\]

\[
\mu \to e\gamma \quad b \to s
\]

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Leptogenesis and low energy observables

Gustavo Branco

• Leptogenesis depends on all high-energy seesaw parameters: non-trivial dependence on the low-energy parameters

• Leptogenesis possible also if neutrino Dirac phase is zero

Possible ways to approach

1. Reduce free parameters by means of model building

2. Scan over the full parameter space, predict as many observables as possible and hope that they will be measured
Request for the theory of flavour

What is the origin of quark and lepton masses and mixings?

• Flavour models based on Abelian and non-Abelian flavour symmetries (Oscar Vives)

• Constraints on Yukawa interactions from GUT relations (Borut Bajc, Amon Ilakovac)
U(1) and SU(3) flavour models

• Two concrete examples of flavour models

• Flavour symmetries are broken also in the SUSY sector inducing left-slepton $\delta_{LL}$ and right-down-squark $\delta_{RR}$

• Observable LFV processes and large $b \rightarrow s$ transition
MSSM based on SO(10)

- Minimal Higgs content $10_H + 126_H$
- Predicts $b-\tau$ unification and large $\theta_{atm}$
- Amon Ilakovac: observable $\text{BR}(\mu \rightarrow e\gamma)$

- Borut Bajc: if $126_H$ is missing, $M_N$ can be generated at two loop in split SUSY model

$$M_N \propto m_{\text{SUSY}}$$
Andrea Romanino: In split SUSY EDMs are still observable
Predictive neutrino mass model

Amarjit Soni: a model in which t-quark and N₃ couple to the different Higgs doublet than all other fermions

- Predictions (with normal hierarchy m₃>>m₂>>m₁):
  - a triple t - ν - N seesaw connection:
  - -0.02<θ₁₃ < 0.02 (3σ)
  - 43° < θₐtm <45° (3σ)
  - 28° < θₚ₉ <36° (3σ)
  - Mₙ₁ << Mₙ₂ << Mₙ₃

\[ m_{ν₃} ≈ \frac{m_t^2}{M_{N₃}} \]
Minimal LFV

**Gino Isidori**: Consistent way to reduce free parameters from low energy point of view

\[
\frac{1}{\Lambda_{LN}} \left( L_L^T \right)^i \ g_v^{ik} L_L^k \ \phi^T \phi
\]

Reducible [see-saw type]

\[
g_v \sim \lambda^T \lambda
\]

Triplet Higgs coupling

Heavy neutrino seesaw

\[ H^{++} \rightarrow \mu^+ \mu^+, \mu^+ \tau^+, \tau^+ \tau^+ \]

Background free at LHC
LFV in SUSY particle decays at colliders (I)

- Alejandro Ibarra: gravitino LSP, stau NLSP

\[ \tilde{\tau}_R \times \tilde{\epsilon}_R \quad \begin{array}{c} \psi_{3/2} \\ \hspace{1cm} \left( m^2_{l_R} \right)_{13} \\ e \end{array} \]

- LFV at LC can be probed down to \( \left( m^2_{l_R} \right)_{13}/m^2_1 \lesssim 3 \times 10^{-2} \)
  work for LHC in progress

- Collider experiments probe LFV directly, complementary to rare decays
LFV in SUSY particle decays at colliders (II)

- Reinhold Rückl: $M_N$ degenerate, $R$ real

\[ e^+e^- \rightarrow l_i^+l_j^- + 2\tilde{\chi}_1^0 \]
SUSY points C', G', B', SPS1a, I'

\[ \sqrt{s} = 800 \text{ GeV} \]

\[ Br(\mu \rightarrow e\gamma) > 10^{-12} \quad \text{implies} \quad \sigma(e^+e^- \rightarrow \mu e + 2\tilde{\chi}^0_1) > 0.01 \text{ to } 1 \text{ fb} \]
Higgs mediated LFV

Paride Paradisi: MSSM + non-holomorphic soft terms
R-parity violation

- **Aldo Deandrea**: review on possible collider signatures of R-parity violating couplings

\[
W_{R_p} = \mu_i H_u L_i + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \chi'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \chi''_{ijk} U_i^c D_j^c D_k^c
\]

48 parameters

\[
V_{R_p}^{soft} = \frac{1}{2} A_{ijk} \tilde{L}_i \tilde{L}_j \tilde{L}_k^c + A'_{ijk} \tilde{L}_i \tilde{Q}_j \tilde{d}_k^c + \frac{1}{2} A''_{ijk} \tilde{u}_i^c \tilde{d}_j^c \tilde{d}_k^c \\
+ B_i h_u \tilde{L}_i + \tilde{m}_{d_i}^2 h_d^\dagger \tilde{L}_i + \text{h.c.}
\]

51 parameters

Couplings of the order of $10^{-1}$-$10^{-2}$, could lead to observable effects at high energy colliders
CPV effects in tau decays

• Zbignev Was: discussed CP effects in TAUOLA Monte Carlo generator for $\tau$ decays and tau production processes.

• Tools made available for CLEO, LC, BaBar/Belle and LHC communities
Outlook

• Identify benchmark models for consistent analyses of LFV at colliders and in rare decays (WG1+WG2+WG3)

• Extend LFV studies for LC to LHC (WG1+WG3)

• Applications of Minimal LFV concept

• Connections between soft leptogenesis and EDMs

• T-odd asymmetries in tau->3l, mu->3e decays