Physics beyond the Standard Model

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Contents of Lecture IV

SU(5)

The fermions also magically fit into $SU(5)$ multiplets:

$$\underline{5}^* \equiv \begin{pmatrix} d^c \\ d^c \\ d^c \\ e_L \\ -\nu_{e,L} \end{pmatrix} \qquad \underline{10} \equiv \begin{pmatrix} 0 & u^c & -u^c & u_L & d_L \\ -u^c & 0 & u^c & u_L & d_L \\ u^c & -u^c & 0 & u_L & d_L \\ -u_L & -u_L & -u_L & 0 & e^c \\ -d_L & -d_L & -d_L & -e^c & 0 \end{pmatrix}$$

Here the superscript c denotes antiparticle fields of right–handed fermions.

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- two of the four $SU(3)$ triplets are $SU(2)$ singlets and the other two combine to $SU(2)$ doublets,
- the remaining three colourless fields form a singlet and a doublet with respect to $SU(2)$.

Gauge bosons

There are $5^2 - 1 = 24$ gauge bosons A_μ^a, with 8 gluons, the 3 W-bosons, and the hypercharge boson $A_\mu^{24} = B_\mu$.

The coupling is rescaled as $g_Y =: -\sqrt{\frac{3}{5}} g_1 = -\sqrt{\frac{3}{5}} g$ in terms of the SU(5) coupling g.

Note that the three couplings are equal,

$$g_1 = g_2 = g_3 = g\,,$$

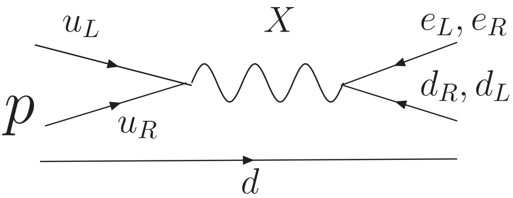
at and above the GUT scale M_{GUT} at which the SU(5) is an unbroken symmetry. The couplings run with energy (renormalisation group evolution) and are very different at the low energies probed by experiment.

The couplings g_1, g_2, g_3 indeed converge and intersect around $M_{\mathrm{GUT}} \approx 10^{15}$ GeV, but the unification is imperfect.

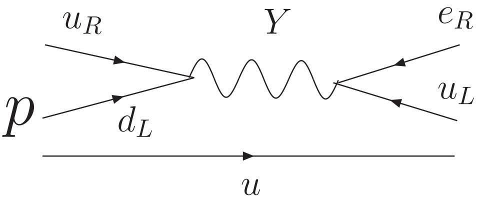
Proton decay

The remaining 12 real gauge bosons form a weak doublet $\begin{pmatrix} X_\mu^a \\ Y_\mu^a \end{pmatrix}, a = 1, 2, 3$ of complex color triplets (just like left-handed quark doublets). The electric charges are $4/3$ for X_μ^a and $1/3$ for Y_μ^a.

An important feature of SU(5) is the possibility of proton decay mediated by the X and Y bosons.



$p \to e^+\pi^0$



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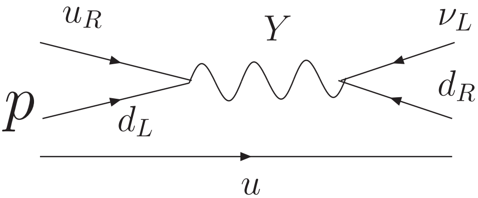

$p \to \overline{\nu}\pi^+$

SO(10)

Even better: The 15 fermion fields of each Standard Model generation and an extra right-handed neutrino field fit into a 16 of

$$SO(10) \supset SU(5)$$

In an $SO(10)$ GUT $U(1)_{B-L}$ is gauged and broken at the $SO(10)$-breaking scale M_{10}.

With appropriate Higgs fields the right-handed neutrino field ν_R gets a Majorana mass of the order of M_{10}. The light neutrino masses come out with (almost) the right size through the see–saw formula:

$$\mathcal{L}_{\rm mass} \supset -(\overline{\nu}_L, \overline{\nu_R^c}) \begin{pmatrix} 0 & Y_D v \\ Y_D^T v & Y_M M_{10} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

Three eigenvalues are $\mathcal{O}(M_{10})$, the other three are $\mathcal{O}(v^2/M_{10})$ and the neutrinos are Majorana fermions.

$SO(10)$

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- neutrino masses: The Majorana mass of the ν_R is roughly equal to the $SO(10)$ breaking scale. Its low energy effect is the desired dimension-5 Majorana mass term.
- $U(1)_{B-L}$ is gauged and broken at the $SO(10)$ breaking scale.
  - $\Rightarrow$ attractive mechanism for leptogenesis and baryogenesis.

Ende GUT - alles GUT?

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

↙ ↘

$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \qquad SU(5)$$

↘ ↙

$$SO(10)$$

$v = 174\,\mathrm{GeV}$ and M_{GUT} are separated by a factor $M_{\mathrm{GUT}}/v \approx 10^{13}$. Quantum corrections of particles with mass M_{GUT} destabilise the electroweak scale, adding a term of order $M_{\mathrm{GUT}}^2/(16\pi^2)$ to v^2 and the Higgs mass M_h^2. Technically, this is no problem, since we can cancel this contribution by a finite counterterm δM_h^2, but this involves fine-tuning of 24 digits. This is the gauge hierarchy problem.

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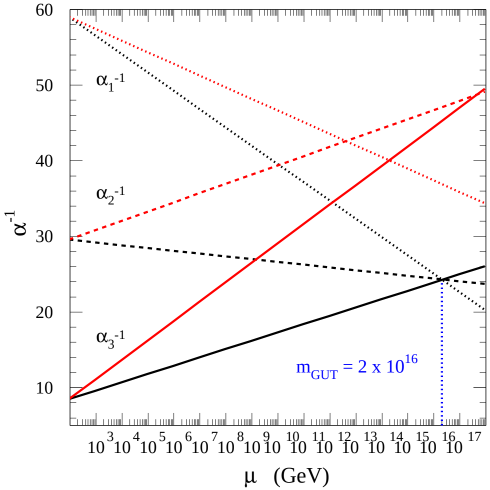
The only known way to solve the fine-tuning problem in a way resulting in a theory valid up to the GUT scale involves supersymmetry.
In supersymmetric theories all Standard-Model fermions have scalar partners, the squarks and sleptons. The superpartners of the bosons are spin-1/2 particles, the gauginos and higgsinos.

Supersymmetry

- tames the quantum corrections to the Higgs mass,
- provides a dark-matter candidate, the lightest supersymmetric particle (LSP),
- improves the unification of gauge couplings required by GUTs,
- can link gravity to the other gauge interactions.

Inverse gauge couplings with and without supersymmetry:



The GUT scale determined from the couplings agrees sufficiently well with the right-handed neutrino mass.

Probing new physics with flavour

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Spectacular: In FCNC transitions of charged leptons the GIM suppression factor is even m_ν^2/M_W^2!

$\Rightarrow$ The SM predictions for charged-lepton FCNCs are essentially zero!

The suppression of FCNC processes in the Standard Model is not a consequence of the $SU(3) \times SU(2)_L \times U(1)_Y$ symmetry. It results from the particle content of the Standard Model and the accidental smallness of most Yukawa couplings. It is absent in generic extensions of the Standard Model.

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Examples:

extra Higgses	$\Rightarrow$	Higgs-mediated FCNC's at tree-level , helicity suppression possibly absent,
squarks/gluinos	$\Rightarrow$	FCNC quark-squark-gluino coupling, no CKM/GIM suppression,
vector-like quarks	$\Rightarrow$	FCNC couplings of an extra Z',
$\mathrm{SU}(2)_{\mathrm{R}}$ gauge bosons	$\Rightarrow$	helicity suppression absent

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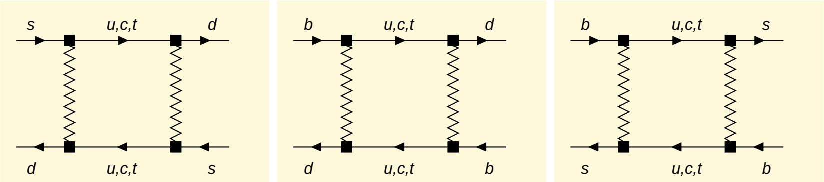
$\mathrm{B_d - \overline{B}_d}$ mixing and $\mathrm{B_s - \overline{B}_s}$ mixing are sensitive to scales up to $\Lambda \sim 100$ TeV.

Meson-antimeson mixing

Important new-physics analysers are the meson-antimeson mixing amplitudes:



$K-\overline{K}$ mixing $B_d-\overline{B}_d$ mixing $B_s-\overline{B}_s$ mixing

Supersymmetry and flavour

The Minimal Supersymmetric Standard Model (MSSM) has many new sources of flavour violation, all in the supersymmetry-breaking sector.

No problem to get big effects in FCNC amplitudes, but rather to suppress the big effects elsewhere.

Squark mass matrix

Diagonalise the Yukawa matrices Y^u_{jk} and Y^d_{jk}

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E.g. Down-squark mass matrix:

$$M^2_{\tilde{d}} = \begin{pmatrix} \left(M^{\tilde{d}}_{1L}\right)^2 & \Delta^{\tilde{d}\,LL}_{12} & \Delta^{\tilde{d}\,LL}_{13} & \Delta^{\tilde{d}\,LR}_{11} & \Delta^{\tilde{d}\,LR}_{12} & \Delta^{\tilde{d}\,LR}_{13} \\ \Delta^{\tilde{d}\,LL\,*}_{12} & \left(M^{\tilde{d}}_{2L}\right)^2 & \Delta^{\tilde{d}\,LL}_{23} & \Delta^{\tilde{d}\,RL\,*}_{12} & \Delta^{\tilde{d}\,LR}_{22} & \Delta^{\tilde{d}\,LR}_{23} \\ \Delta^{\tilde{d}\,LL\,*}_{13} & \Delta^{\tilde{d}\,LL\,*}_{23} & \left(M^{\tilde{d}}_{3L}\right)^2 & \Delta^{\tilde{d}RL\,*}_{13} & \Delta^{\tilde{d}\,RL*}_{23} & \Delta^{\tilde{d}\,LR}_{33} \\ \Delta^{\tilde{d}\,LR\,*}_{11} & \Delta^{\tilde{d}RL}_{12} & \Delta^{\tilde{d}RL}_{13} & \left(M^{\tilde{d}}_{1R}\right)^2 & \Delta^{\tilde{d}\,RR}_{12} & \Delta^{\tilde{d}\,RR}_{13} \\ \Delta^{\tilde{d}\,LR\,*}_{12} & \Delta^{\tilde{d}\,LR*}_{22} & \Delta^{\tilde{d}RL}_{23} & \Delta^{\tilde{d}\,RR\,*}_{12} & \left(M^{\tilde{d}}_{2R}\right)^2 & \Delta^{\tilde{d}\,RR}_{23} \\ \Delta^{\tilde{d}\,LR\,*}_{13} & \Delta^{\tilde{d}\,LR\,*}_{23} & \Delta^{\tilde{d}\,LR\,*}_{33} & \Delta^{\tilde{d}\,RR\,*}_{13} & \Delta^{\tilde{d}\,RR\,*}_{23} & \left(M^{\tilde{d}}_{3R}\right)^2 \end{pmatrix}$$

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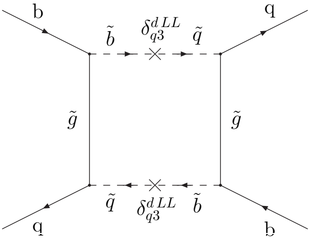
Not diagonal! $\Rightarrow$ new FCNC transitions.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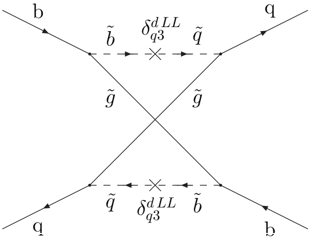
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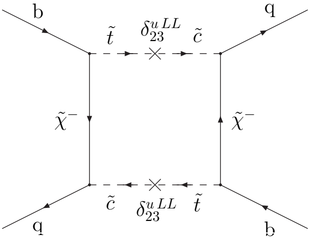
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Model-independent analyses constrain

$$\delta_{ij}^{q\,XY} = \frac{\Delta_{ij}^{\tilde{q}\,XY}}{\frac{1}{6}\sum_s \left[M_{\tilde{q}}^2\right]_{ss}} \qquad \text{with } XY = LL, LR, RR \text{ and } q = u, d$$

using data on FCNC (and also charged-current) processes.

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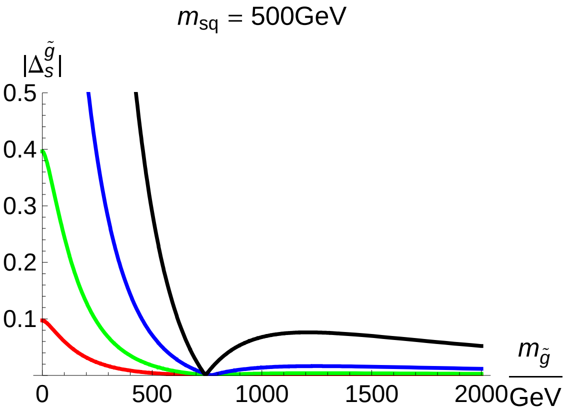
Remarks:

- For $M_{\tilde{g}} \gtrsim 1.5 M_{\tilde{q}}$ the gluino contribution is small for $AB = LL, RR$, so that chargino/neutralino contributions are important.
- To derive meaningful bounds on $\delta_{ij}^{q\,LR}$ chirally enhanced higher-order contributions must be taken into account.

A. Crivellin, UN, 2009

Ratio of gluino and Standard-Model contribution to $B_s - \overline{B}_s$ mixing:



The gluino contribution vanishes for $M_{\tilde{g}} \approx 1.5 M_{\tilde{q}}$, independently of the size of $\Delta_{23}^{d\,LL}$ (curves correspond to 4 different values).

Are there natural ways to motivate sizable new flavour violation in $\mathrm{B_s - \overline{B}_s}$ mixing and $\mathrm{B_d - \overline{B}_d}$ mixing while simultaneous suppressing flavour violation elsewhere?

Flavour and SUSY GUTs

Linking quarks to neutrinos: Flavour mixing:
quarks: Cabibbo-Kobayashi-Maskawa (CKM) matrix
leptons: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

Consider SU(5) multiplets:

$$\mathbf{\overline{5}_1} = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ -\nu_e \end{pmatrix}, \qquad \mathbf{\overline{5}_2} = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ -\nu_\mu \end{pmatrix}, \qquad \mathbf{\overline{5}_3} = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ -\nu_\tau \end{pmatrix}.$$

If the observed large atmospheric neutrino mixing angle stems from a rotation of $\mathbf{\overline{5}_2}$ and $\mathbf{\overline{5}_3}$, it will induce a large $\tilde{b}_R - \tilde{s}_R$-mixing (Moroi; Chang,Masiero,Murayama).

$\Rightarrow$ new b_R–s_R transitions from gluino–squark loops possible.

Key ingredients: Some weak basis with

$$\mathrm{Y}_d = V_{\mathrm{CKM}}^{*} \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} U_{\mathrm{PMNS}}$$

and right-handed down squark mass matrix:

$$\mathrm{m}_{\tilde{d}}^2 (M_Z) = \mathrm{diag}\left(m_{\tilde{d}}^2, m_{\tilde{d}}^2, m_{\tilde{d}}^2 - \Delta_{\tilde{d}}\right).$$

with a calculable real parameter $\Delta_{\tilde{d}}$, typically generated by top-Yukawa RG effects.

Rotating Y_d to diagonal form puts the large atmospheric neutrino mixing angle into $m^2_{\tilde{d}}$:

$$U^\dagger_{\mathrm{PMNS}}\, m^2_{\tilde{d}}\, U_{\mathrm{PMNS}} = \begin{pmatrix} m^2_{\tilde{d}} & 0 & 0 \\ 0 & m^2_{\tilde{d}} - \frac{1}{2}\Delta_{\tilde{d}} & -\frac{1}{2}\Delta_{\tilde{d}}\, e^{i\xi} \\ 0 & -\frac{1}{2}\Delta_{\tilde{d}}\, e^{-i\xi} & m^2_{\tilde{d}} - \frac{1}{2}\Delta_{\tilde{d}} \end{pmatrix}$$

The CP phase ξ affects $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing!

Realistic GUTs involve further dimension-5 Yukawa terms to fix the Yukawa unification in the first two generations. One can use these terms to shuffle a part of the effect from $b_R \to s_R$ into $b_R \to d_R$ transitions. This “leakage” is strongly constrained by $\mathrm{K}-\overline{\mathrm{K}}$ mixing. Trine, Wiesenfeldt, Westhoff 2009

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Similar constraints can be found from $\mu \to e\gamma$.
Borzumati,Yamashita 2009; Girrbach,Mertens,UN,Wiesenfeldt 2009

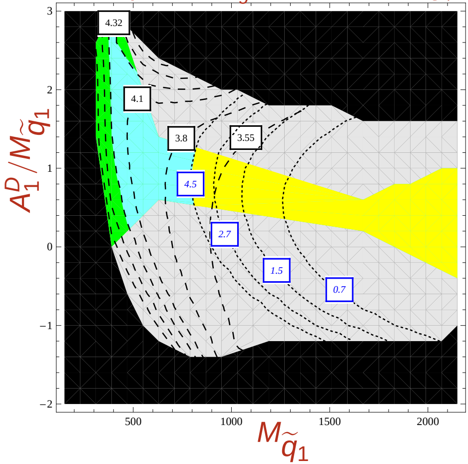
Chang-Masiero-Murayama model

We have considered $B_s - \overline{B}_s$ mixing, $b \to s\gamma$, $\tau \to \mu\gamma$, vacuum stability bounds, lower bounds on sparticle masses and the mass of the lightest Higgs boson.
The analysis involves 7 parameters in addition to those of the Standard Model.

Generic results: Largest effect in $B_s - \overline{B}_s$ mixing
tension with $M_h \geq 114\,\text{GeV}$

J. Girrbach, S. Jäger, M. Knopf, W. Martens, UN, C. Scherrer, S. Wiesenfeldt

Contour plot for $M_{\tilde{g}} = 350\,\text{GeV}$, $\arg\mu = 0$:



Black: negative soft masses^2
Green: excluded by $\tau \to \mu\gamma$ and $b \to s\gamma$
Blue: excluded by $\tau \to \mu\gamma$
Gray: excluded by $B_s - \overline{B}_s$ mixing
Yellow: allowed

dashed lines: $10^4 \cdot Br(b \to s\gamma)$; dotted lines: $10^8 \cdot Br(\tau \to \mu\gamma)$.

Conclusions

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- There is physics beyond the Standard Model: lepton-flavour violation seen in neutrino oscillations, dark matter, the surplus of matter over antimatter in the universe, and gravity.
- The quantum numbers of the Standard-Model fermions point towards grand unification, with preferred gauge group SO(10).
- GUTs explain small but non-zero neutrino masses in a natural way.

Conclusions

- The convergence of the gauge couplings is largely improved in the MSSM, which alleviates the fine-tuning problem induced by the gauge hierarchy. With the LHC lower bounds on squark masses the answer of the MSSM to the fine-tuning problem is imperfect.

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- FCNC processes are sensitive probes of new physics, especially of the supersymmetry-breaking sector. SUSY-GUT models can provide a link between quark and lepton flavour physics.

A pinch of new physics in $B - \overline{B}$ mixing?