THEORY SUMMARY

Mariano Quirós
ICREA/IFAE Barcelona

44th Rencontres de Moriond
Electroweak Session,
La Thuile, March 7-14 2009
OUTLINE

• Strong interactions
• Flavor physics
• Extra dimensions
• Dark Matter
• Baryons
• Perspectives in theory
The Standard Model of strong and electroweak interactions is based on the gauge group

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \]

- \( SU(3)_c \) describes the physics of strong interactions: QCD (see next week conference)
- \( SU(2)_L \times U(1)_Y \) describes the physics of weak and electromagnetic interactions

- It has to be spontaneously broken to QED by the Higgs mechanism
- The Standard Model describes the experimental data with high accuracy
• The theory of strong interactions is well confirmed but the theory becomes non-perturbative at low energies

• It is essential to understand the QCD background at LHC for any discovery: Higgs, new physics,...

• Used techniques are different: pQCD, NRQCD, HQET, chiral Lagrangians, non-perturbative methods (lattice),..., or a combination of all
Prerequisite: factorization

\[
\frac{d\sigma_{pp\to\text{hadrons}}}{dX} = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, \mu_F) f_b(x_2, \mu_F) \times \frac{d\hat{\sigma}_{ab\to\text{partons}}(\alpha_s(\mu_R), \mu_R, \mu_F)}{dX} + O\left(\frac{\Lambda_{\text{QCD}}}{Q^n}\right)
\]

Extracted from data, but evolution is perturbative

Expansion in the coupling constant (LO, NLO, NNLO...)

NB: factorization used in many contexts without proof
Parton densities: recent progress

Recent major progress:

- full NNLO evolution (previous only approximate NNLO)
- full treatment of heavy flavors near the quark mass
  
  [Numerically: e.g. (6-7)% effect on Drell-Yan at LHC]
- more systematic use of uncertainties/correlations
- Neural Network (NN) PDFs

  splitting functions at NNLO: Moch, Vermaseren, A. Vogt ’04
  [+ much related theory progress ’04 -’08]
  Alekhin, CTEQ, MSTW (new MSTW ’09), NN collaboration

Recently on the market: toolkits for NNLO DGLAP evolution of PDFs

  PEGASUS A. Vogt ’04; QCDNUM Botje ’07
  CANDIA Cafarella et al. ’08; HOPPET Salam & Rojo ’08

⇒ Description of PDFs reaching precision, but still some work ahead
Impressive progress in the last years

- precision in parton densities
- higher orders (LO, NLO, NNLO & resummations)
- jets: many new ideas, impressive level of sophistication
- ... [much more, I did not have time to mention]

Progress driven by

- automation/flexibility/public codes
- good communication with experimentalists & common papers

Still many challenges ahead but QCD theory will provide solid basis for a successful physics program at the LHC
The principle

First principle “solution” of QCD

experiments, hadrons

\[
\begin{align*}
  m_p &= 938.272 \text{ MeV} \\
  M_{\pi} &= 139.570 \text{ MeV} \\
  m_K &= 493.7 \text{ MeV} \\
  m_D &= 1896 \text{ MeV} \\
  m_B &= 5279 \text{ MeV}
\end{align*}
\]

- The Lagrangian
- Non-perturbative regulator: lattice with spacing \(a\) fundamental parameters & hadronic matrix elements

\[
\begin{align*}
  \alpha(\mu) \\
  m_u(\mu), m_s(\mu) \\
  m_c(\mu), m_b(\mu) \\
  F_B, F_{B_s}, \xi \ldots
\end{align*}
\]

continuum limit \(a \to 0\)

Rainer Sommer
New perspectives for heavy flavour physics from the lattice
**Some sample results from the literature**

Review of E. Gamiz lattice 2008

examples of results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_c^{\text{MS}}(3 \text{ GeV})$</td>
<td>0.986(10) GeV</td>
<td>HPQCD</td>
</tr>
<tr>
<td>$m_b^{\text{MS}}(m_b)$</td>
<td>4.20(4) GeV</td>
<td>HPQCD</td>
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<tr>
<td>$\xi = \frac{F_{B_s}}{F_B} \sqrt{\frac{m_{B_s}}{m_B}}$</td>
<td>1.211(38)(24)</td>
<td>FNAL/MILC</td>
</tr>
<tr>
<td>$F_{B_s}$</td>
<td>243(11) MeV</td>
<td>FNAL/MILC</td>
</tr>
<tr>
<td>$F_{D_s}$</td>
<td>241(3) MeV</td>
<td>HPQCD</td>
</tr>
</tbody>
</table>

Precision up to 1% is claimed
The challenge

multiple scale problem
always difficult
for a numerical treatment

lattice cutoffs:
\[ \Lambda_{UV} = a^{-1} \]
\[ \Lambda_{IR} = L^{-1} \]

\[ L^{-1} \ll m_\pi, \ldots, m_D, m_B \ll a^{-1} \]

\[ O(e^{-LM_\pi}) \]
\[ \downarrow \]

\[ L \gtrsim 4/M_\pi \sim 6 \text{ fm} \]

\[ L/a \gtrsim 120 \]

beauty not yet accommodated: effective theory, \( \Lambda_{QCD}/m_b \) expansion
$N_f = 2$ QCD: Coordinated Lattice Simulations

Teams

* Berlin (team leader Ulli Wolff)
* CERN (L. Giusti, M. Lüscher)
* DESY-Zeuthen (Rainer Sommer)
* Madrid (Carlos Pena)
* Mainz (Hartmut Wittig)
* Rome (Roberto Petronzio)
* Valencia (Pilar Hernández)

Physics planned at present

* Fundamental parameters up to $M_b$
* Pion interactions
* Baryon physics
* Kaon physics
  also with mixed actions

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$a[\text{fm}]$</th>
<th>lattice</th>
<th>$L[\text{fm}]$</th>
<th>masses</th>
<th>Teams</th>
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<tbody>
<tr>
<td>5.30</td>
<td>0.08</td>
<td>$48 \times 24^3$</td>
<td>1.9</td>
<td>6 masses</td>
<td>CERN, Rome</td>
</tr>
<tr>
<td>5.30</td>
<td>0.08</td>
<td>$64 \times 32^3$</td>
<td>2.6</td>
<td>6 masses</td>
<td>CERN, Rome</td>
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<tr>
<td>5.50</td>
<td>0.06</td>
<td>$64 \times 32^3$</td>
<td>1.9</td>
<td>5 masses</td>
<td>DESY, Berlin, Madrid</td>
</tr>
<tr>
<td>5.70</td>
<td>0.04</td>
<td>$96 \times 48^3$</td>
<td>1.9</td>
<td>2 masses</td>
<td>DESY, Berlin</td>
</tr>
<tr>
<td>5.70</td>
<td>0.04</td>
<td>$128 \times 64^3$</td>
<td>2.6</td>
<td>2 masses</td>
<td>DESY, Berlin, started</td>
</tr>
</tbody>
</table>

Promising for charm (and beauty)
Very good agreement with precision data

**THE ELECTROWEAK SECTOR**

- **usage of latest experimental results:**
  - **Z-pole observables:** LEP/SLD results
    - [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - **M_W** and **Γ_W:** LEP/Tevatron
  - **m_t:** Tevatron
    - [arXiv:0808.1089 [hep-ex]]
  - **Δα_{had}^{(5)}(M_Z^2):** including α_s dependency
  - **m_c, m_b:** world averages
  - **theoretical uncertainties:** M_W (δM_W=4-6GeV), sin^2θ_W (δsin^2θ_W = 4.7·10^{-5})
  - **floating fit parameters:** M_Z, M_H, m_t, Δα_{had}^{(5)}(M_Z^2), α_s(M_Z^2), m_c, m_b
  - **fits are performed in two versions:**
    - **standard fit:** all data except results from direct Higgs searches
    - **complete fit:** all data including results from direct Higgs searches at LEP
      - and Tevatron

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
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<tbody>
<tr>
<td>M_Z [GeV]</td>
<td>91.1875 ± 0.0021</td>
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<tr>
<td>Γ_Z [GeV]</td>
<td>2.4952 ± 0.0023</td>
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<tr>
<td>σ_{had} [mb]</td>
<td>41.540 ± 0.037</td>
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<tr>
<td>R_0^0</td>
<td>20.767 ± 0.025</td>
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<tr>
<td>A_{FB}^{0,c}</td>
<td>0.0171 ± 0.0010</td>
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<tr>
<td>A_t (+)</td>
<td>0.1499 ± 0.0018</td>
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<tr>
<td>A_c</td>
<td>0.670 ± 0.007</td>
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<tr>
<td>A_b</td>
<td>0.923 ± 0.029</td>
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<tr>
<td>A_{FB}^{0,b}</td>
<td>0.0707 ± 0.0015</td>
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<tr>
<td>R_0^0</td>
<td>0.0992 ± 0.0016</td>
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<tr>
<td>R_0^0</td>
<td>0.1721 ± 0.0030</td>
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<tr>
<td>R_0^0</td>
<td>0.21629 ± 0.000066</td>
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<tr>
<td>sin^2θ_W(Q_{FB})</td>
<td>0.2324 ± 0.0012</td>
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<tr>
<td>M_H [GeV]</td>
<td>80.399 ± 0.025</td>
</tr>
<tr>
<td>Γ_H [GeV]</td>
<td>2.008 ± 0.048</td>
</tr>
<tr>
<td>m_c [GeV]</td>
<td>1.25 ± 0.09</td>
</tr>
<tr>
<td>m_b [GeV]</td>
<td>4.20 ± 0.10</td>
</tr>
<tr>
<td>a_Y [GeV^2]</td>
<td>179.4 ± 1.2</td>
</tr>
<tr>
<td>Δα_{had}^{(5)}(M_Z^2) (Δ)</td>
<td>2765 ± 22</td>
</tr>
<tr>
<td>α_s(M_Z^2)</td>
<td>—</td>
</tr>
</tbody>
</table>

† in units of 10^{-5}
Higgs Mass Constraints

- **standard fit:**
  - from MC toy: p-value=0.225±0.004_{-0.02}^{+0.03}
  - Higgs mass
    - central value ±1σ: \( M_H = 80_{-23}^{+30} \) GeV
    - 2σ interval: [39, 155] GeV
    - 3σ interval: [26, 209] GeV

- **green error band**
  - theory uncertainties directly included in \( \chi^2 \) (“flat likelihood”)

- **direct Higgs searches from LEP and Tevatron**
  - resulting contribution added to the \( \chi^2 \) during the fit
pull values of complete fit
- no value exceeds 3σ
- FB asymmetry of bottom quarks → largest contribution to $\chi^2$

$\alpha_s$ from complete fit:

$$\alpha_s(M_Z^2) = 0.1193^{+0.0028}_{-0.0027} \pm 0.0001$$

- including N$^3$LO of the massless QCD Adler function
- first error is experimental fit error
- second error due to missing QCD orders:
  - incl. variation of renorm. scale from $M_Z/2$ to $2M_Z$
  - and massless terms of order/beyond $\alpha_s^5(M_Z)$ and massive terms of order/beyond $\alpha_s^4(M_Z)$
There are a number of problems that the SM cannot resolve and requires **NEW PHYSICS**

- The Higgs sector is sensitive to the UV cutoff: hierarchy problem
  - *Supersymmetry, Warped extra-dimensions*
- No explanation of the **flavor** structure, including the existence of 3 generations
  - No **Dark Matter** candidate
    - No explanations for **baryons**
- No **unification** of strong and electroweak couplings
  - No **unification** with gravity
Solution to the flavor problem is finding a rationale for the structure of masses and mixing angles for quarks and leptons.

Normally it involves introducing a flavor symmetry under which flavor transforms and which breaks at some high scale leaving behind the flavor structure.

An example is the Froggatt-Nielsen mechanism with scalar fields coupled to Yukawa couplings as different powers according to quantum numbers.
Puzzles of the electroweak sector

Matthias Neubert

- Unexplained hierarchies of fermion masses:

- Unexplained hierarchies of fermion mixings (e.g. quark sector):

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]
Beyond SM there is another problem of flavor ...

\[ \mathcal{L}_{\text{EFT}} = \Lambda_{\text{UV}}^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2 + \mathcal{L}_{\text{gauge}}^\text{SM} + \mathcal{L}_{\text{Yukawa}}^\text{SM} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\text{UV}}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\text{UV}}^2} + \ldots \]

- Electroweak symmetry breaking \( \downarrow \) Higgs mass
- Large FCNCs \( \downarrow \) Generic flavor structure

\[ T \quad s \\ h \quad d \quad d \quad s \]

\[ \sim \frac{g_T^2}{16\pi^2} \Lambda_{\text{UV}}^2 \]

\[ \sim \frac{g_X^2}{\Lambda_{\text{UV}}^2} \]

No fine-tuning \( \downarrow \) Bounds on flavor mixing \( \downarrow \)

\[ \Lambda_{\text{Higgs}} \lesssim 1 \text{ TeV} \quad \rightarrow \quad \text{increasing energy scale} \quad \rightarrow \quad \Lambda_{\text{flavor}} \gtrsim 10^3 \text{ TeV} \]

- Solutions to flavor problem explaining \( \Lambda_{\text{Higgs}} \ll \Lambda_{\text{flavor}} \):
  1. \( \Lambda_{\text{UV}} \gg 1 \text{ TeV} \): new particles too heavy to be discovered at LHC
  2. \( \Lambda_{\text{UV}} \approx 1 \text{ TeV} \): quark flavor mixing protected by flavor symmetry
• The global symmetry can give rise to a discrete one
• Much simpler to find models based on discrete groups
• In the quark sector there is strong relation with B-physics:
  • Amarijit Soni finds that several sizable effects in B CP asymmetries are better fitted with a 4th generation and t’ and b’ around 400-600 GeV and a heavy Higgs
  • Aoife Bharucha presented a detailed calculation of the process $B \rightarrow K^* \mu^+ \mu^- \rightarrow K^- \pi^+ \mu^+ \mu^-$ that can probe SM and NP at LHC
• In the leptonic sector the knowledge of neutrino masses and neutrino mixing angles can well fit the tri-bi-maximal texture
2008 Neutrinos & Lepton mixing

\[ \begin{align*}
\Delta m^2_{sol} &= 8.1(7.5 - 8.7) \cdot 10^{-5} \text{eV}^2 \\
\Delta m^2_{atm} &= 2.2(1.7 - 2.9) \cdot 10^{-3} \text{eV}^2 \\
\sin^2 \theta_{12} &= 0.30(0.25 - 0.34) \\
\sin^2 \theta_{23} &= 0.50(0.38 - 0.64) \\
\sin^2 \theta_{13} &= 0(\leq 0.028) \quad (\text{? } \sin \theta_{13} \neq 0 \text{ see Palazzo's talk on friday})
\end{align*} \]

Harrison, Perkins, Scott, PLB530 (2002)

\[ U_{TB}^T M_\nu U_{TB} = M_\nu^{diag} \]

\[ M_l^{diag} \]

\[ U_{TB} = \begin{pmatrix}
\sqrt{2/3} & 1/\sqrt{3} & 0 \\
-1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\
-1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2}
\end{pmatrix} \]

TRI-maximal

BI-maximal

\[ \sin^2 \theta_{12} = 1/3, \sin^2 \theta_{23} = 1/2, \sin^2 \theta_{13} = 0 \]
Discrete flavor symmetries

© LO exact TBM!

Ma & Rajasekaran PRD64, Babu et al. PLB552 (A4)
Ma PLB632 (2006), Hagerdon et al. JHEP 06 042 (S4)

A4

★ even permutations of 4 objects (subgroup of S4, tetraedral symmetries)
★ 4!/2 = 12 elements
★ generated by two basic permutations: S=(4321) & T=(2314)
★ S^2=T^3=(ST)^3=1 → a representation of the group
★ 12 elements belong to 4 equivalence classes
★ 4 inequivalent representations 1, 1', 1'' & 3

S4

★ permutations of 4 objects (tetraedral symmetries)
★ 4! = 24 elements
★ S^4=T^3=1, ST^2S=T → a representation of the group
★ 24 elements belong to 5 equivalence classes
★ 5 inequivalent representations 1_1, 1_2, 2, 3_1, 3_2
A4, S4

\[ G_{Z3}^T M_l M_l^\dagger G_{Z3} = M_l M_l^\dagger \]
(or \[ G_{Z3}^T M_l G_{Z3} = M_l \])

\[ U_{Z3} \]

\[ U_{lep} = U_{Z3}^\dagger U_{Z2} = U_{TB} \]

the group splits differently in charged lepton and neutrino sector not to get trivial mixing!

A4 for SU(5) constructed by Alfredo Urbano (YSF2)
choose a basis for the $A_4, S_4$ generators in which the charged lepton are diagonal

neutrinos can get a mass in different ways

**effective operator (EF)**

\[
\frac{1}{\Lambda} LL h_u h_u
\]

**flavour symmetry**

\[
\frac{1}{\Lambda} LL h_u h_u \frac{\phi_i}{\Lambda_F}
\]

**type I see-saw (SSI)**

\[
M_\nu \sim -m_D M_R^{-1} m^{T_D}
\]

\[
m_D \sim L h_u \nu_c \frac{\phi_i}{\Lambda_F}
\]

**type II see-saw (SSII)**

\[
LL \Phi
\]

\[
M_R \sim \nu_c \nu \phi_i
\]

**type III see-saw (SSIII)**

\[
M_\nu \sim -m_{l\Sigma} M_{\Sigma}^{-1} m^{T_{l\Sigma}}
\]

\[
m_{l\Sigma} \sim L h_u \Sigma \frac{\phi_i}{\Lambda_F}
\]

\[
M_{\Sigma} \sim \Sigma \Sigma \phi_i
\]
Comparing models: A4

**AF-EF**

\[ M_{\nu} = v \begin{pmatrix} a + 2c & -c & -c \\ -c & 2c & a - c \\ -c & a - c & 2c \end{pmatrix} \]

**AF-SSI**

\[ M_{\nu} = v \begin{pmatrix} \frac{1}{3a} + \frac{2}{3} (\frac{1}{3a} + 3c) \\ \frac{1}{3a} - \frac{1}{3} (\frac{1}{3a} + 3c) \\ \frac{1}{3a} - \frac{2}{3} (\frac{1}{3a} + 3c) \end{pmatrix} \]

**HMV**

\[ M_{\nu} = v \begin{pmatrix} \frac{2}{3}a^2 + \frac{1}{3}b^2 \\ \frac{1}{3}a^2 + \frac{1}{3}b^2 \\ \frac{1}{3}a^2 + \frac{1}{3}b^2 \end{pmatrix} \]
• Supersymmetry is the simplest and more elegant solution to the hierarchy problem: quadratic divergences generated by bosons are canceled by fermions.
• In its minimal version (MSSM) the SM-like Higgs mass is very strongly bound and then the theory can be ruled out at the LHC.
• In the MSSM there is a natural candidate for CDM: the lightest neutralino provided R-parity is conserved.
• Gauge coupling unification happens without imposing it.
• Radiative electroweak breaking is a nice feature of minimal SUGRA.
• The stability/triviality problem of the SM are naturally solved by the relation between quartic and gauge coupling.
Gauge coupling unification

Consistently with LEP measurements and if superparticles are at $\sim$ TeV scale gauge couplings unify at a scale $M_{\text{GUT}} \sim 2 \times 10^{16}$ GeV

Stability/triviality problems

- The stability ($\lambda < 0$) and triviality/Landau pole ($\lambda \to \infty$) problems are solved because of the supersymmetric relation
  \[ \lambda = \frac{1}{3} (g^2 + g'^2) \]

- Because the gauge couplings remain perturbative (and positive) up to $M_{\text{GUT}}$ there is no stability and/or triviality problem in the MSSM

- As a consequence: the Higgs mass (unlike in the SM) is NOT a free parameter. For the SM-like Higgs

  \[ m_h^2 \sim M_Z^2 \cos^2 2\beta + \frac{3G_Fm_t^4}{\sqrt{2}\pi^2} \left[ \log \frac{m_t^2}{m_t^2} + \frac{A_t^2}{M_3^2} \left( 1 - \frac{A_t^2}{12M_3^2} \right) \right] \]

- The Higgs mass is a prediction in a supersymmetric theory $\Rightarrow$ theoretical constraints

Electroweak breaking

If soft breaking parameters are generated at $M_{\text{GUT}}$ a tachyonic mass can be triggered by RGE at the weak scale

$m_h$ Vs. $M_{\text{SUSY}}$ [$m_A \sim 1$ TeV, (a,b) $\tan \beta = 15$ $A_t/M_{\text{SUSY}} = (\sqrt{6},0)$; (c,d) $\tan \beta = 2$]
• The key problem in supersymmetric theories is the generation of soft breaking terms: gravity mediation, gauge mediation, gaugino mediation, anomaly mediation.

• In general supersymmetry suffers from the so-called supersymmetric flavor problem: if there is a mismatch between quark and squark diagonalization.

SUSY flavour problem

• Squark mass matrices are not necessarily diagonal in the same basis as the quark mass matrices.

Quark-squark-gluino vertex is flavour-changing in general.

Dangerously large flavour-mixing in FCNC processes involving the strong coupling constant.

Andreas Crivellin
Flavour-changing self energy:

$$-i\Sigma(p)_{fi}^{AB} = \sum_{qA} q_{A_f} \rightarrow p \quad \text{and} \quad q_{B_i} \rightarrow p$$

Mass insertion approximation

$$\Sigma(0)_{fi}^q = g_s^2 \frac{m_g}{6\pi^2} \left( \Delta_{fi}^{LR} P_R + \Delta_{fi}^{RL} P_L \right) C_0 \left( m_\tilde{g}^2, M_{fA}^q, M_{iB}^q \right)$$

Exact diagonalization

$$\Sigma(0)_{fi}^q = g_s^2 \frac{m_g}{6\pi^2} \sum_{s=1}^6 \left( (V_{RL})_{fi}^s P_R + (V_{LR})_{fi}^s P_L \right) B_0 \left( m_\tilde{g}^2, m_{q_s}^2 \right)$$

with

$$\left( V_{LR}^s \right)_{fi} = \sum_{j,k=1}^6 U_{jfi}^{q_L} W_{j,k+3,s}^{q_R} U_{ki}^{q_L} W_{k,s}^{q_R} \quad \text{and} \quad \left( V_{RL}^s \right)_{fi} = \sum_{j,k=1}^6 U_{jfi}^{q_R} W_{j,k+3,s}^{q_L} U_{ki}^{q_R} W_{k,s}^{q_L}$$
### Results and comparison

<table>
<thead>
<tr>
<th>quantity</th>
<th>our bound</th>
<th>bound from FCNC</th>
<th>bound from vacuum stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{12}^{d,LR}$</td>
<td>0.0011</td>
<td>0.006, K mixing</td>
<td>0.00015</td>
</tr>
<tr>
<td>$\delta_{13}^{d,LR}$</td>
<td>0.001</td>
<td>0.15, $B_d$ mixing</td>
<td>0.005</td>
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<tr>
<td>$\delta_{23}^{d,LR}$</td>
<td>0.01</td>
<td>0.06, $b\to s\gamma$</td>
<td>0.05</td>
</tr>
<tr>
<td>$\delta_{13}^{d,LL}$</td>
<td>0.032</td>
<td>0.5, $B_d$ mixing</td>
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<tr>
<td>$\delta_{12}^{u,LR}$</td>
<td>0.0047</td>
<td>0.016, D mixing</td>
<td>0.0012</td>
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<tr>
<td>$\delta_{13}^{u,LR}$</td>
<td>0.027</td>
<td>--</td>
<td>0.22</td>
</tr>
<tr>
<td>$\delta_{23}^{u,LR}$</td>
<td>0.27</td>
<td>--</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Bounds calculated with $m_{\text{squark}}=m_{\text{gluino}}=1000\text{GeV}$
Too many parameters: a simplification is Minimal Flavor Violation
What does MFV imply for SUSY? Simplification!

* The superpotential ($N = 1$, unbroken R-parity) is MFV!
\[ W_{MSSM} = QY_u H_u U + QY_d H_d D + LY_e H_d E + \mu H_d H_u \]

* SUSY-breaking with MFV-generational structure:
\[ \tilde{Q}^\dagger \tilde{m}_Q^2 \tilde{Q} + \tilde{U}^\dagger \tilde{m}_U^2 \tilde{U} + \tilde{D}^\dagger \tilde{m}_D^2 \tilde{D} + (A_u \tilde{Q} H_u \tilde{U}^* + A_d \tilde{Q} H_d \tilde{D}^* + h.c.) \]

\[
\begin{align*}
\tilde{m}_Q^2 &= \tilde{m}^2 (a_1 1 + b_1 Y_u Y_u^\dagger + b_2 Y_d Y_d^\dagger) \\
\tilde{m}_U^2 &= \tilde{m}^2 (a_2 1 + b_5 Y_u^\dagger Y_u) \\
\tilde{m}_D^2 &= \tilde{m}^2 (a_3 1 + b_6 Y_d^\dagger Y_d) \\
A_u &= A(a_4 1 + b_7 Y_d Y_d^\dagger) Y_u \\
A_d &= A(a_5 1 + b_8 Y_u Y_u^\dagger) Y_d
\end{align*}
\]

\[ b_i \equiv 0: \text{SUSY breaking is flavor blind} \]
**MFV Predictions for the MSSM**

* Highly degenerate squarks of 1st and 2nd generation:
  \[ \Delta m/m_0 \sim \lambda_c^2/2; \quad \Delta m < 1 \text{ GeV} \]

* 3rd generation decoupled (via \( V_{CKM} \)).
Another simplification: 1st and 2nd generations heavy

Hierarchical Soft Terms

In the Hierarchical scenario the LL and RR soft terms have the following structure:

\[ \tilde{m}^2 = \begin{pmatrix} h_{11} & h_{12} & a_1 \\ h_{21} & h_{22} & a_2 \\ \bar{a}_1 & \bar{a}_2 & l_3 \end{pmatrix} \]

Where the “h” block is heavy and the remaining entries are much lighter.

The first two families can be naturally heavier with respect to the 3rd one.

Motivations:

- Complementary to degenerate assumption
- If we start with a degenerate condition at very high energy, we end up to a split situation at low energy because of the Yukawa coupling of the 3rd family
- Welcome to alleviate SUSY flavor problem

\[
A(\Delta F = 1) = f(x)\hat{\delta}_{ij} \\
A(\Delta F = 2) = g^{(1)}(x)\hat{\delta}_{ij}^2 \\
x = \frac{\tilde{m}_3^2}{M^2} \\
\hat{\delta}_{ds} \equiv \hat{\delta}_{db} \hat{\delta}_{bs}
\]

Suppression in the 1-2 sector

There are only 4 flavor violating insertions: \( \hat{\delta}_{bd}, \hat{\delta}_{bb}, \hat{\delta}_{dd}, \hat{\delta}_{dd} \)
WARPED EXTRA DIMENSIONS

- It is a solution to the hierarchy problem that involves gravity: it was proposed by Randall and Sundrum

The Randall-Sundrum (RS) idea

Matthias Neubert
Hierarchies from geometry: RS model*

Slice of AdS\(_5\) with curvature \(k\):

\[
ds^2 = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - r^2 d\phi^2, \quad \sigma = kr|\phi|
\]

\[
\epsilon = \frac{M_W}{M_{P1}} = e^{-kr\pi} \approx 10^{-16}, \quad L = -\ln \epsilon \approx 37, \quad M_{KK} = k\epsilon = \text{few TeV}
\]

---

*Randall and Sundrum, hep-ph/9905221, hep-th/9906064
Hierarchies from geometry: RS model

Pattern of gauge-symmetry breaking:

- bulk gauge group $SU(2)_L \times U(1)_Y$ broken by IR brane-localized Higgs to $U(1)_{EM}$
- more complicated patterns (with custodial symmetry) also considered in literature*

RS model: Gauge boson profiles*

Profiles of gauge fields:

- while profiles of photon and gluon are flat, wave functions of heavy gauge bosons and KK modes are peaked near IR brane

\[
\chi_{g,\gamma}(\phi) = \frac{1}{\sqrt{2\pi}}, \quad \chi_{W,Z}(\phi) \approx \frac{1}{\sqrt{2\pi}} \left[ 1 + \frac{m_{W,Z}^2}{M_{KK}^2} \left( 1 - \frac{1}{L} + t^2 \left( 1 - 2L - 2\ln t \right) \right) \right]
\]

*Davoudiasl et al., hep-ph/9911262; Pomarol, hep-ph/9911294; Chang et al., hep-ph/9912498
RS setup allows a “theory of flavor”

RS model: Fermion profiles

Profiles of fermion fields:

- localization of fermion profiles in extra dimension controlled by bulk mass parameters $c_{Q,q} = \pm M_{Q,q}/k$
- top quark lives in IR to generate its large mass, while light fermions live in UV
Quark masses and mixings in RS model*

Scaling laws:

\[ m_{q_i} = \mathcal{O}(1) \frac{v}{\sqrt{2}} F_{cQ_i} F_{c_{q_i}} \]

\[ \lambda = \mathcal{O}(1) \frac{F_{cQ_1}}{F_{cQ_2}} \]

\[ A = \mathcal{O}(1) \frac{F_{cQ_2}^3}{F_{cQ_1}^2 F_{cQ_3}} \]

\[ \bar{\rho} - i\bar{\eta} = \mathcal{O}(1) \]

\[ c_{Q_1} = -0.579, \quad c_{Q_2} = -0.517, \quad c_{Q_3} = -0.473 \]

\[ c_{u_1} = -0.742, \quad c_{u_2} = -0.558, \quad c_{u_3} = +0.339 \]

\[ c_{d_1} = -0.711, \quad c_{d_2} = -0.666, \quad c_{d_3} = -0.553 \]

(+ anarchic Yukawa matrices)

• Hierarchy in quark masses and mixings can be naturally generated from anarchic complex 3×3 matrices \( Y_q = \mathcal{O}(1) \) entering \( Y_q^{\text{eff}} = F_{cQ_i} (Y_q)_{ij} F_{c_{q_j}} \)
Warped-space Froggatt-Nielsen mechanism*

**Bulk fermions in RS:**

\[
(Y_{q}^{\text{eff,RS}})_{ij} \propto (Y_{q})_{ij} e^{-kr\pi(c_{Q_{i}}-c_{q_{j}})}
\]

- bulk parameter \(c_{Q_{i},q_{i}}\)
- warp factor \(\epsilon = e^{-kr\pi}\)

**Froggatt-Nielsen (FN) symmetry:**

\[
(Y_{q}^{\text{eff,FN}})_{ij} \propto (Y_{q})_{ij} \epsilon^{a_{Q_{i}}-b_{q_{j}}}
\]

- \(U(1)_{F}\) charges \(Q_{F} = a_{Q_{i}}, b_{q_{j}}\)
- model parameter \(\epsilon \ll 1\) set by VEVs

- Models with warped spatial extra dimension provide compelling geometrical interpretation of flavor symmetry

**RS is a theory of flavor!**

(to a good extent)

---

*Froggatt and Nielsen, Nucl. Phys, B147 (1979) 277; Casagrande et al., arXiv:0807.4537; Blanke et al., arXiv:0809.1073*
Mixing matrices: Scaling relations

Matthias Neubert

- In all cases one finds:

\[
(\Delta_Q^{(t)})_{ij} \sim F_{cQ_i} F_{cQ_j}, \quad (\delta Q)_{ij} \sim \frac{m_q_i m_q_j}{M_{KK}^2} \frac{1}{F_{cQ_i} F_{cQ_j}} \sim \frac{v^2 Y_q^2}{M_{KK}^2} F_{cQ_i} F_{cQ_j},
\]

\[
(\Delta_q^{(t)})_{ij} \sim F_{cq_i} F_{cq_j}, \quad (\delta q)_{ij} \sim \frac{m_q_i m_q_j}{M_{KK}^2} \frac{1}{F_{cQ_i} F_{cQ_j}} \sim \frac{v^2 Y_q^2}{M_{KK}^2} F_{cQ_i} F_{cQ_j}
\]

Implications of scaling relations:

- all effects are proportional to \( F_{cA_i} F_{cA_j} \), so that all flavor-violating vertices involving light, UV-localized fermions are suppressed

- this suppression of dangerous FCNCs involving light quarks reflects the RS-GIM mechanism

- Flavor-changing tree-level transitions of \( K \) and \( B_s \) mesons particularly interesting as their sensitivity to KK scale extends beyond LHC reach
DARK MATTER

\[ \Omega_{DM} h^2 = 0.105(8) \]

The most popular candidate is a neutral stable weakly interacting massive particle (WIMP)

The WIMP S annihilates and its particle density obeys the Boltzmann equation

\[
\frac{dn_S}{dt} = -3Hn_S - \langle \sigma_{\text{ann}} v \rangle (n_S^2 - n_{S,eq}^2)
\]

\[
n_{S,eq} = T^3 \left( \frac{M_S}{2\pi T} \right)^{3/2} e^{-M_S/T}
\]

Equilibrium distribution

\[
f = \frac{n}{T^3} \quad \frac{df_s}{dT} = \frac{\langle \sigma_{\text{ann}} v \rangle}{H/T^2} \left( f_s^2 - f_{s,eq}^2 \right)
\]
An approximate solution

\[ \frac{M_S}{\hat{T}} = \log \left( \frac{M_S \langle \sigma_{\text{ann}} v \rangle}{H/\hat{T}^2} \right) + \frac{1}{2} \log \left( \frac{8\pi^3 \hat{T}}{M_S} \right) \]

Freeze out temp.

\[ f(T \ll M_S) \approx \frac{H/\hat{T}^2}{\hat{T} \langle \sigma_{\text{ann}} v \rangle} \]

Final particle density

Total energy density of WIMPS at present

\[ T = T_\gamma \]

\[ \Omega_{DM} = \frac{2}{g_* \rho_{\text{crit}}} \frac{M_S n_S(T_\gamma)}{\hat{T} \langle \sigma_{\text{ann}} v \rangle} M_S T_\gamma^3 \]

• Direct searches: elastic scattering of DM off nuclei in a low background detector (recoil energy of nucleus)
• Indirect searches: signals due to DM annihilation in Sun, Earth, where it has been captured and accumulated and in the Galactic Halo
It is relatively easy to have candidates for DM satisfying the energy density constraint.

Some possibilities studied by Fu-Sin Ling:

- Singlet coupled to the Higgs (simplest)
- Inert doublet (Higgs with no VEV)
Constraints on solar system DM has been pointed out in the talks of Stephen Adler and Annika Peter.

**Dark Matter can be gravitationally bound on different scales**

- **Galactic Halo Dark Matter**
  - Mass density \( \rho \sim 0.3 \text{ GeV/c}^2 \text{ cm}^{-3} \)
  - Maxwellian Velocity Distribution

\[
f \propto v^2 e^{-3v^2/2 \bar{v}^2}
\]

\( \bar{v} \sim 270 \text{ km/s} \)

\[
V = V_{\text{dark matter}} + V_0
\]

\( V_0 \) Earth Motion Velocity

Drukier, Freese + Spergel \{Annual Modulation Effect

Freese, Frieman + Gould \} DAMA/LIBRA Signal
SOLAR SYSTEM - BOUND DARK MATTER?

FROM STUDY OF PLANETARY ORBITS -
FRÈRE, LIN, CHEUNG, VERDUNGEN
SEREND + JETZER
IO AND KRAVLOVICH + PITTEVA

$\rho < 10^5 \text{ GeV/} \text{cm}^2 \text{ cm}^{-3}$

COULD PRODUCE A DAILY (SIDEREAL TIME)
MODULATION IN DAMA/LIBRA $\rightarrow$ 24 HOUR PERIOD

EARTH (PLANET-BOUND) DARK MATTER?

IF BOUND WERE ATTAINED, AND IF MASS WERE UNIFORMLY DISTRIBUTED BELOW THE MOON'S ORBIT, DENSITY WOULD BE

$\rho \approx 6 \times 10^{10} \text{ GeV/} \text{cm}^2 \text{ cm}^{-3} \rightarrow \rho_{\text{NANO}}$
Constraints

- Dark matter localized well within Moon orbit and not too near Earth
- Dark matter mass \( \leq 6 \) GeV
- \( \sigma_{\text{ann}} \) high: \( 10^{-23} \text{ cm}^2 \) to \( 10^{-27} \text{ cm}^2 \)
- Dark matter non-self-annihilating and stable in absence of nucleons
POSSIBLE APPLICATIONS OF EARTH AND PLANET-BOUND DARK MATTER (SPECULATIVE!)

- JOVIAN PLANET ANOMALIES

[ADLER PHYS. LETT. B 671 (2009) 203]
ARXIV: 0808.2823

\[ \text{SURFACE HEAT FLUX } H \frac{\text{ergs}}{\text{cm}^2\text{s}} \]

- JUPITER
  - 5440
- SATURN
  - 2010
- URANUS
  - <42
- NEPTUNE
  - 433

? ACCRETION OF PLANET-BOUND DARK MATTER COULD ACCOUNT FOR UNEXPLAINED INTERNAL HEAT PRODUCTION (REQUIRES LOW ENERGY RELEASE EFFICIENCY)

? URANUS AXIS ON ITS SIDE RELATIVE TO ECLIPTIC - COLLISION CAUSING THIS COULD HAVE KNOCKED URANUS OUT OF ITS DARK MATTER CLOUD
**Stephen Adler**

**Flyby Anomaly**

- **Near-Earth Trajectory Can't Be Tracked**
  - **Incoming Asymptote** $v_{in}$
  - **Outgoing Asymptote** $v_{out}$

**Galileo Near Earth (NEAR)**

- **Date**
  - $12/8/92$
  - $1/23/98$

- $\Delta v_{\text{NEAR}} = \frac{\text{km}}{s}$
  - $-4.6$
  - $13.46$

- $\Delta v_{\text{Galileo}} = \frac{\text{km}}{s}$
  - $1.0$
  - $0.01$

**Anderson et al.**

- ARL 100 (2008) 091102
- $v_{out}$ extrapolated from $v_{in}$ does not agree with observation

**Effect is $\sim 10^{-6} v_\infty$ either sign**
The dynamics of dark matter bound to the solar system has been studied by Annika Peter who focussed on standard WIMPs.

Indirect Detection of Dark Matter in the Solar System

- $\nu$’s in the Sun
- $\nu$’s from the Earth
- $\gamma$’s outside the Sun (if time)

All of these probes depend on what happens to the dark matter after it becomes bound to the solar system!
Suppression of the Annihilation Rate
(Standard Halo Model)

Neutrinos from WIMPs in the Sun

Annika Peter

If $m_\chi > 1$ TeV and $\sigma_p^{SD} \lesssim 10^{-38}$ cm$^2$, $\Gamma$ will be heavily suppressed.
One Huge Astrophysical Systematic:
The Dark Disk

• Standard Halo Model (approximate multivariate Gaussian, \( \sigma \approx \frac{v_\odot}{2^{1/2}} \)) based on N-body simulations of dark matter-only galaxies.
• Simulations that include baryons show that the stellar disk drags satellites into the disk plane, where they dissolve.
• This yields a DARK DISK with properties similar to the stellar disk generated by these satellites.
• The dark disk properties are extremely sensitive to the merger history of the Galaxy.
• Typically, speeds wrt to the solar system are MUCH smaller---much easier to capture.

(Read et al. 2008, 2009)
Conclusion

• Indirect detection of WIMPs in the solar system depends sensitively on the bound orbits.

• $\nu$'s from WIMPs in the Sun: suppression in the annihilation rate for $m_X \gtrsim 1 \text{ TeV}$ (this is insensitive to the presence of extra planets). The event rate may be boosted by a factor of $\sim 10$ for the dark disk.

• $\nu$'s from the Earth: for the Standard Halo Model alone, no signal in IceCube. The dark disk boosts the signal by $\sim 1000x$ -- may be observable! Signal sensitive to inner planets.
Question: is the PAMELA positron excess from DM?
This question was dealt with in a DM independent way

Marco Cirelli
The background is an important issue

Are we seeing Dark Matter in cosmic rays?
I don’t know, I fear it’s unlikely
Another possibility for explaining the PAMELA/ATIC positron excess is an astrophysical origin: Tsvi Piran

SNR are the canonical sources of CRs

A new source of electrons & positrons that becomes dominant at ~10 GeV
Consider a Local Source of CR electrons

- Above $E_b \sim 20$ GeV, the electrons will start cooling and disappear.
- Positrons however, form continuously along the way from proton-ISM interactions.
- Therefore the positron/electron ratio will increase

- Primary electron cool and disappear before reaching earth
- Secondary electron/positron form nearer and can reach earth before cooling
The source can be SNR in spiral arm

The Resulting $e^+/(e^+ + e^-)$ ratio

Tsvi Piran
A very general comparison with recent DM experiments

Kathryn Zurek

- PAMELA and ATIC electron/positron excesses
  - This morning’s talks
- 511 keV line
  - No time
- DAMA
  - Focus of this talk
- None suggest ordinary SUSY WIMP DM
- Suggest that DM dynamics may be more complex
Non-standard requirements of PAMELA/ATIC

- Not an ordinary WIMP
- Non-standard annihilation modes $\rightarrow W^+W^-, \bar{b}b, \tau^+\tau^-$
- Non-standard annihilation cross-section $B\langle \sigma_{ann}v \rangle \approx 10^{-23} \text{ cm}^3/\text{s}$
- Anti-protons--would expect an excess
Complex dark sectors

Weak scale states
Higgs, Z’, MSSM states

Dark forces

“Hidden valley”

Standard Model → Dark sector

- Multiple stable states?
- New light forces?

Kathryn Zurek
DAMA and WIMP DM

- New unaccounted for (?) systematic which shifts the threshold: channeling

Only a small fraction of the recoil goes into a mode that DAMA measures. The rest goes into phonons/heat.
Spectral information

<table>
<thead>
<tr>
<th>Energy</th>
<th>$S_i^1$ (cpd/kg/keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – 4 keVee</td>
<td>0.0223 ± 0.0027</td>
</tr>
<tr>
<td>2 – 5 keVee</td>
<td>0.0178 ± 0.0020</td>
</tr>
<tr>
<td>2 – 6 keVee</td>
<td>0.0131 ± 0.0016</td>
</tr>
<tr>
<td>6 – 14 keVee</td>
<td>0.0009 ± 0.0011</td>
</tr>
</tbody>
</table>

Window is not ruled out

DAMA results has inspired low threshold analyses in other experiments, e.g. CDMS and XENON

Savage, Freese, Gondolo, Spolyar
Simple realizations of this solution

Experimentally,

Find mechanism

\[ \Omega_{DM} \approx 5 \Omega_b \]
\[ n_{DM} \approx n_b \]
\[ m_{DM} \approx 5 m_p \]

S.M. Barr, D.B. Kaplan
Farrar, Zaharijas
Kitano, Low
Gudnason, Kouvaris, Sannino
Kitano, Murayam, Ratz
Luty, Kaplan, KZ

\[ W = \frac{X^2 LH}{M} \]

High scale M
Electroweak scale

Standard Model
X sector

Kathryn Zurek
The issue of explaining DAMA results with scalar DM was also addressed by Sarah Andreas (YSF3).

DAMA and WMAP can be satisfied

S. Andreas, T. Hambye, M. H. G. Tytgat

JCAP, 2008, 0810, 034
A “theory” of DM is built by Martti Raidal

- Assume that the initial space-time topology is effectively lower dimensional, e.g., $M^3 \times S^1$ with very small compact space dimension.
- Formulate physics theories consistently in 3-dimensions and lift the result to 4 dimensions.
- Take care of CPT and Lorentz invariance violating effects (photon mass, $S^1$ must be big)
- Use new constraints in 4-dimensional model building

- In 3 dimensions non-Abelian gauge and gravity actions have topological Chern-Simons terms which charges are quantized
- The presence on $N_F$ chiral fermions and $N_G$ gauge bosons induce loop corrections to the actions and the quantization conditions require

$$\frac{1}{16}N_F - \frac{1}{8}N_G = 0$$

- All matter fields come in some representation of SO(10), the U(1) quantum numbers of all of them are well defined
- The $U(1)_X$ is the origin of a discrete $\mathbb{Z}_N$ symmetry needed for DM.

$$P_X \equiv P_M = (-1)^{3(B-L)}$$

- Our scenario generalizes matter parity to non-SUSY models
- Matter parity $P_M$ is an intrinsic property of all matter

Chiral fermions must come in multiples of 16 and there must be odd number of generations
- Experiment: 15 SM fermions + $N$ fit 16 of SO(10), there are $N$ generations
- Number of gauge bosons is $N_G = N_F/2 = 24$
- 24 is an adjoint of SU(5), thus less-dimensions suggest SU(5) GUT and

$$SO(10) \rightarrow SU(5) \times U(1)_X$$
BARYOGENESIS \[ \frac{n_B}{n_{\gamma}} = 6.12(19) \times 10^{-10} \]

The conditions for baryogenesis were stated by Sakharov in 1967 [A.D. Sakharov, JETPL 91B (1967) 24]

- B violation
- C and CP violation
- Departure from thermal equilibrium

All these conditions are fulfilled in the SM

- Baryon number is non-perturbatively violated in the SM: sphalerons at finite temperature
- C and CP violating phases (CKM) are present
- The out-of-equilibrium conditions are present in the bubble walls in a FIRST ORDER PHASE TRANSITION
A mechanism for the generation of the BAU was suggested by Cohen, Kaplan and Nelson in 1993 using CP violating interactions of fermions with the domain wall of a bubble. The reflection and transmission coefficients of fermions and anti-fermions scattering off the CP violating wall are different.

\[ \phi_c = 0 \]

\[ \Gamma_{sphal} = 0 \]

\[ \Delta B = 0 \]

\[ \phi(T_c)/T_c > 1 \]
Although the SM contains all the ingredients for EWBG it fails quantitatively because

- The CP violation provided by the CKM phase is too small to generate the required BAU

\[ \phi(T_c)/T_c \]

\[ u(T_c)/T_c \text{ as a function of } m_H \text{ (in GeV)} \text{ [one-loop]} \]

The phase transition is too weak
• **Leptogenesis generates** \( \Delta L \neq 0 \)

• **Sphalerons** \( \Delta L = \Delta B \) \( \Rightarrow \) \( \Delta B \neq 0 \)

• If right handed neutrinos exist they can do the job

\[
\mathcal{L}_N = M_\alpha N_\alpha N_\alpha + \lambda_{\alpha i} N_\alpha L_i \phi
\]

1. It is impossible to assign a lepton number to the \( N_\alpha \)'s in such a way that \( \mathcal{L}_N \) is \( L \)-conserving: The \( M \)-terms require \( L(N) = 0 \) while the \( \lambda \)-terms require \( L(N) = -1 \). Thus, \( \mathcal{L}_N \) breaks \( L \) and (since it does not break \( B \)) \( B - L \).

2. We can choose the phases of the \( N_\alpha \) fields in a way that makes \( M \) real, but then \( \lambda \) will have physical, irremovable phases. Thus \( \mathcal{L}_N \) violates CP.

3. The Lagrangian \( \mathcal{L}_N \) allows for \( N \) decays via \( N \to L \phi \). If, however, the Yukawa couplings are small enough, the \( N \)-decays occur out of equilibrium.
The Majorana nature of the right-handed neutrino means that any single mass eigenstate can decay both \( L\Phi \), \( \bar{L}\phi \)

\[
\begin{align*}
N_j & \rightarrow H \quad L_i \\
N_j & \rightarrow L \quad H \quad N \\
N_j & \rightarrow H \quad L, \bar{L} \quad L_i
\end{align*}
\]

CP is violated in these decays and CP asymmetry

\[
\epsilon_{N_\alpha} = \frac{\Gamma(N_\alpha \rightarrow \ell H) - \Gamma(N_\alpha \rightarrow \bar{\ell} \bar{H})}{\Gamma(N_\alpha \rightarrow \ell H) + \Gamma(N_\alpha \rightarrow \bar{\ell} \bar{H})}
\]
**Leptogenesis In Greater Depth**

The see-saw model adds to the Standard Model —

\[
\mathcal{L}_{\text{new}} = -\sum_{k=1}^{3} \frac{M_k}{2} N_{kR}^c N_{kR} - \sum_{j, k=1}^{3} y_{jk} \left[ v_{jL} \varphi^0 - \ell_{jL} \varphi^- \right] N_{kR} + h.c.
\]

The Yukawa couplings \( y_{jk} \) cause —

\[ N_k \to \ell_j^+ + \varphi^+ \quad \text{and} \quad N_k \to (\overline{\nu_j}) + \varphi^0. \]
Then, summing over the final lepton flavors, the $\mathcal{CP}$ asymmetry is —

$$
\varepsilon = \frac{\Gamma(N_1 \to L\phi) - \Gamma(N_1 \to \bar{L}\bar{\phi})}{\Gamma(N_1 \to L\phi) + \Gamma(N_1 \to \bar{L}\bar{\phi})}
$$

$$
= \frac{1}{8\pi} \frac{1}{(y^+y)_1} \sum_m \xi_m \left[ \left( (y^+y)_1 \right) \right] \frac{K \left( \frac{M^2_m}{M_1^2} \right)}{}
$$

$$
\varepsilon \sim y^2/10
$$

To explain $n_B/n_\gamma \sim 10^{-9}$ requires $\varepsilon \sim 10^{-6}$. 
\[ M_v \sim \frac{M_D^2}{M_N} \sim \frac{(yv)^2}{M_N} \sim 10^{-1}\text{eV}. \]

For leptogenesis, we required that —

\[ \epsilon \sim \frac{y^2}{10} \sim 10^{-6} \]

Together, these requirements imply that —

\[ M_N \sim 10^9 \text{GeV}. \]

*Leptogenesis requires very heavy neutrinos, far beyond the range of LHC.*
**Electromagnetic Leptogenesis**

(Nicole Bell, B.K., Sandy Law)

Suppose new physics at a high mass scale $\Lambda > M_N$ leads to the electromagnetic $N$ decay mode —

$$N \rightarrow \nu + \gamma \quad \text{Toy Model}$$

or the mode —

$$N \rightarrow L + \varphi + (\gamma \text{ or } Z \text{ or } W)$$

Emitted in standard leptogenesis

More realistic; respects SM conservation laws

Boris Kayser
Q: Could CP in such decays be a successful alternative to the standard leptogenesis scenario?

Q: If so, could it be successful if $M_N \sim 1$ TeV, within range of the LHC, instead of $\sim 10^9$ GeV?

The $N \rightarrow \nu + \gamma$ Toy Model

Transition magnetic and electric dipole moments
An example of tree-loop interference:

\[ N_k \rightarrow \lambda_{jk} \gamma + N_k \rightarrow \lambda_{nk}^* \lambda_{nm} \lambda_{jm} \]

\[ \Gamma(N_k \rightarrow \nu_j + \gamma) - \Gamma(N_k \rightarrow \bar{\nu}_j + \gamma) \propto \Im(\lambda_{jk}^* \lambda_{nk}^* \lambda_{nm} \lambda_{jm}) \]

This model leads to a CP asymmetry \( \varepsilon \) rather similar to the one from standard leptogenesis, with \( y \Rightarrow \lambda \).

The CP phases are now in \( \lambda \).

**EM leptogenesis can succeed.**
Our Two Questions

Q: Could CP in EM decays be a successful alternative to the standard leptogenesis scenario?

A: Yes.

Q: If so, could it be successful if $M_N \sim 1$ TeV, within range of the LHC, instead of $\sim 10^9$ GeV?

A: No.  Boris Kayser
The problem “Can LHC disprove Leptogenesis?” has been reconsidered by Gilles Vertongen

<table>
<thead>
<tr>
<th>Observing $N_R$?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hierarchical $N_R$</td>
</tr>
<tr>
<td>2. Degenerate $N_R$</td>
</tr>
</tbody>
</table>

If not testable, could leptogenesis at least be falsified?
Leptogenesis in Gauge Framework

Proposition:

The observation of $W_R$ @ LHC would disprove Leptogenesis

Why a $W_R$?

1. Majorana neutrinos are naturally present in Grand Unified Theories:

   \[ \text{SO}(10) \to ... \to \text{SU}(3)_C \times \text{SU}(2)_R \times \text{SU}(2)_L \times \text{U}(1)_Y \]

   \[ \text{Left-Right Sym. Model} \]

New gauge fields: $W_R$

\[ \mathcal{L} \equiv \frac{g}{\sqrt{2}} W_R^\mu (\bar{u}_R \gamma_\mu d_R + \bar{N} \gamma_\mu l_R) \]

2. LHC arrival!

   2. Tevatron fixed $m(W_R) > 800$ GeV [CDF Collaboration, note 8747 (2007)]

   3. LHC will probe $m(W_R) < 3-4$ TeV [CERN-LHCC-2006-021]
### Effects of a Low Scale $W_R$

<table>
<thead>
<tr>
<th>Decays</th>
<th>Diagrams</th>
<th>CP Violation</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yukawa</td>
<td><img src="image" alt="Yukawa Diagram" /></td>
<td>$\varepsilon_{CP}^{(0)} \equiv \frac{\Gamma_{N \rightarrow LH} - \overline{\Gamma}<em>{N \rightarrow LH^*}}{\Gamma</em>{tot}}$</td>
<td>$\eta \leq 1$</td>
</tr>
<tr>
<td>Gauge</td>
<td><img src="image" alt="Gauge Diagram" /></td>
<td>$\varepsilon_{CP} = \frac{\Gamma - \overline{\Gamma}}{\Gamma_{tot} + \Gamma_{W_R}}$</td>
<td>$\eta \leq $ $\frac{\Gamma_{tot}^{(l)}}{\Gamma_{tot}^{(l)} + \Gamma_{W_R}}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scatterings</th>
<th>Diagrams</th>
<th>(\Rightarrow) Easier to produce neutrinos @ Reheating</th>
<th>(\Rightarrow) Harder decoupling @ Low $T^o$ (Washout)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge</td>
<td><img src="image" alt="Scatterings Diagram" /></td>
<td>✓</td>
<td>✗</td>
</tr>
</tbody>
</table>

Can LHC disprove Leptogenesis?
**Inclusion in Boltzmann Equations**

**Example of Gauge Effects**

<table>
<thead>
<tr>
<th>Case</th>
<th>Content</th>
<th>$\eta$</th>
<th>$Y_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Standard Leptogenesis</td>
<td>0.5</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>(b)</td>
<td>(a) + $W_R$ decays in $Y_N$</td>
<td>$3 \times 10^{-8}$</td>
<td>$4 \times 10^{-11}$</td>
</tr>
<tr>
<td>(c)</td>
<td>(b) + $W_R$ scatterings in $Y_N$</td>
<td>$2 \times 10^{-10}$</td>
<td>$2 \times 10^{-13}$</td>
</tr>
<tr>
<td>(d)</td>
<td>(c) + $W_R$ scatterings in $Y_L$</td>
<td>$2 \times 10^{-18}$</td>
<td>$2 \times 10^{-21}$</td>
</tr>
<tr>
<td>(e)</td>
<td>(d) + $W_R$ decays in $Y_L$</td>
<td>$2 \times 10^{-18}$</td>
<td>$2 \times 10^{-21}$</td>
</tr>
</tbody>
</table>

Type I Leptogenesis

→ could be disproved if $W_R$ observed @ LHC

→ could work if $m(W_R) > 18 \text{ TeV}$
Another model for TeV Leptogenesis has been considered by Yuji Kajiyama where it is Higgs mediated.

- TeV-scale leptogenesis with $y_\nu \sim 10^{-6}$

\[ \epsilon \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \]

\[ \epsilon \sim \frac{1}{8\pi} \frac{\text{Im} y_\nu^4}{y_\nu^2} \frac{M_1 M_2}{M_1^2 - M_2^2} \sim 10^{-13} \frac{M_1 M_2}{M_1^2 - M_2^2} \sim 10^{-6} \]

\[ \rightarrow \frac{M_2 - M_1}{M_1} \sim 10^{-7} \quad \text{Resonance condition} \]
In this talk, we consider leptogenesis by

\[ \epsilon \sim \frac{1}{16\pi} \frac{\text{Im}[AB^*]C}{|A|^2} \]

can be large if \( A \sim B \sim 10^{-6} \)

We discuss:

1. leptogenesis below EWSB scale \((T < T_c)\)
   without resonance condition,
2. source of CPV is in the Higgs sector.
2. The Model

- Consider a Froggatt-Nielsen type model by Higgs doublets with \( U(1) \) charge assignment
  
  \[
  H_u : 0, \quad H_d : 1, \quad L_i : -3, \quad N_{Ri} : 0
  \]

  \( U(1) \) invariant Yukawa terms are given by

  \[
  \mathcal{L}_\nu = y_{ij}^\nu \bar{N}_{R_i} L_j H_u \left( \frac{H_u H_d}{M^2} \right)^{n_{ij}} + \frac{1}{2} N_{R_i} M_{N_{ij}} N_{R_j} + c.c.
  \]

  where \( (n_{ij}^\nu) = 3 \). Mass hierarchy: \( \left( \frac{v_u v_d}{M^2} \right)^{n_{ij}} \equiv \epsilon^{n_{ij}} = 10^{-2n_{ij}} \)

  \[
  y^\nu \sim \mathcal{O}(1) \text{ and real, } M \sim 1 \text{ TeV}.
  \]

- Higgs potential is given by

  \[
  V = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + \lambda_1 |H_u|^4 + \lambda_2 |H_d|^4 + \lambda_3 |H_u|^2 |H_d|^2 + \lambda_4 |H_u H_d|^2
  \]

  \[
  + \left[ m^2 H_u H_d + \lambda_5 (H_u H_d)^2 + \lambda_6 |H_u|^2 H_u H_d + \lambda_7 |H_d|^2 H_u H_d + c.c. \right]
  \]

  Source of CPV \((m^2, \lambda \text{ are complex.})\)
(1) Leptogenesis occurs below EWSB scale \( (T < T_c) \),

(2) Source of CPV is in the Higgs sector,

(3) Large CP asymmetry \( (0 < \epsilon < 10^{-3}) \) is generated without resonance condition,

(4) Sphaleron converts \( \eta_L \rightarrow \eta_B \) for \( z_c < z < z_d \),

(5) And we can get baryon asymmetry.
Present perspectives

• Using AdS/CFT correspondence some quantities in non-perturbative QCD can be computed: AdS/QCD
• Less-conventional solutions to hierarchy problem
  • Higgs mass protected by global symmetry (pseudo-Goldstone boson): Little Higgs
  • Higgs mass protected by higher dimensional gauge theory: gauge-Higgs unification
• Composite Higgs: using AdS/CFT correspondence
• Higgless models (breaking by boundary condition)
• Higgs in conformal sector (unHiggs): dimension of $H^*H > 2$: quadratic corrections softened

• Unexpected physics: hidden valley models, quirks, unparticles, ..., leaving unexpected signatures
Future perspectives

• They should depend on LHC!

PERHAPS AT MORIOND 2010...