THE ROLE OF PRECISION STUDIES IN THE QUEST FOR NEW PHYSICS

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Fermilab
The Standard Model
Open questions and possible solutions
How to establish new physics
Status of New Physics searches
A journey in supersymmetry
THE STANDARD MODEL
The Standard Model

- The SM is a Quantum Field Theory: fusion of Special Relativity and Quantum Mechanics
- There are three main ingredients:
  - **Forces:** $SU(3)_c \times SU(2)_W \times U(1)_Y$
  - **Matter:** quarks, leptons, gauge bosons
  - **Spontaneous Symmetry Breaking:** mass generation
The SM is a **Quantum Field Theory**: fusion of **Special Relativity** and **Quantum Mechanics**

There are three main ingredients:

- **Forces**: \( SU(3)_c \times SU(2)_{W} \times U(1)_{Y} \)
- **Matter**: quarks, leptons, gauge bosons
- **Spontaneous Symmetry Breaking**: mass generation where the problems begin
Fermion masses

- Transformation properties under $SU(3) \times SU(2) \times U(1)$

\[
\begin{pmatrix}
  u^a_L \\
  d^a_L
\end{pmatrix}
= (3, 2, +1/3)
\]

\[
u^a_R = (3, 1, +4/3)
\]

\[
d^a_R = (3, 1, -2/3)
\]

\[
\begin{pmatrix}
  H^+ \\
  H^0
\end{pmatrix}
= (1, 2, +1)
\]

- Fermion mass terms are forbidden?

$(u_L, d_L)$ are a SU(2) doublet

$u_R$ and $d_R$ are SU(2) singlets

\[m_u \bar{u} L u_R\]
THE HIGGS MECHANISM

• We have a problem with Weak Interactions
  
  Exact $SU(2)$ gauge invariance requires **massless** fermions and vector bosons ($W$ and $Z$)

• Spontaneous Symmetry Breaking:
  
  $SU(3)_s \times SU(2)_W \times U(1)_Y \rightarrow SU(3)_s \times U(1)_{em}$
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Spontaneous Symmetry Breaking:

\[ SU(3)_s \times SU(2)_W \times U(1)_Y \rightarrow SU(3)_s \times U(1)_{em} \]
The Higgs Mechanism

- A scalar SU(2) doublet ($\Phi$) acquires a non-vanishing constant value over the whole space (v.e.v.)
- The $W$ and $Z$ become massive
- A neutral scalar particle of unknown mass emerges ($h$)
The Higgs is a SU(2) doublet with a vev:

\[ \mathcal{L}_Y = \bar{Q}_L Y_d H d_R + \bar{Q}_L Y_u H^\dagger u_R + \text{h.c.} \]

after EWSB

\[ \mathcal{L}_m = \bar{d}_L (\nu Y_d) d_R + \bar{u}_L (\nu Y_u) u_R + \text{h.c.} \]
OPEN QUESTIONS
• General Relativity is hard to quantize:
  • naive approaches fail
  • loop gravity, superstrings theories

• Typical scale associated with gravity:

\[ V = G_N \frac{mM}{r} \sim \frac{mM}{M_{pl}^2} \cdot \frac{1}{r} \]

\[ M_{pl} = G_N^{-1/2} = 1.22 \times 10^{19} \text{ GeV} \]
The strength of the SM interactions depend strongly on the energies ($Q$) of the interacting particles.

$M_{GUT} \sim 10^{16}$ GeV
The strength of the SM interactions depend strongly on the energies (Q) of the interacting particles.

\[ \alpha \sim 10^{16} \text{ GeV} \]

Not quite unified.
\[ \Delta \alpha_{\text{had}}^{(5)} = 0.02758 \pm 0.00035 \]

\[ \Delta \alpha_{\text{had}}^{(5)} = 0.02749 \pm 0.00012 \]

incl. low \( Q^2 \) data

\( m_{\text{Limit}} = 144 \text{ GeV} \)
HIERARCHY PROBLEM

• Embed the SM into a theory that contains very large scales ($M_{pl}$, $M_{GUT}$)

• Quantum fluctuations produce enormous masses for all particles not protected by a symmetry

• Fermions are protected by chirality, Gauge bosons receive masses close to the Higgs vev, the Higgs boson is unprotected:

\[ \delta m_H \sim M_{GUT} \sim 10^{16} \text{ GeV} \]

\[ (m_H)_{fit} \sim 10^2 \text{ GeV} \]
DARK MATTER

WMAP
$\Omega_{DM} h^2 = 0.1047^{+0.007}_{-0.0013}$
• The Gauge part of the SM depends on 4 parameters:

\[ \alpha_1, \alpha_2, \alpha_3, \theta_{\text{QCD}} \]

• Electroweak Symmetry Breaking introduces other 15 parameters:

\[ m_e, m_\mu, m_\tau, m_u, m_d, m_s, m_c, m_b, m_t \]

\[ V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \]

\[ m_H, \langle H \rangle \]
• **Yukawa Lagrangian:** $$\mathcal{L}_Y = \bar{Q}^0_L Y_d H d^0_R + \bar{Q}^0_L Y_u H^\dagger u^0_R + \text{h.c.}$$

• **Gauge interactions:** $$\mathcal{L}_{\text{gauge}} \sim \bar{u}^0_L W d^0_L + \bar{u}^0 Z u^0 + \bar{d}^0 Z d^0$$

• **Quark Mass Eigenstate Basis:**

  $$u_A = U_A u^0_A \quad \text{and} \quad d_A = D_A d^0_A \quad (A=\text{L,R})$$

  $$\mathcal{L}_{\text{gauge}} \sim \bar{u}_L V_{\text{CKM}} W d_L + \bar{u} Z u + \bar{d} Z d \quad \text{with} \quad V_{\text{CKM}} = U_L D_L^\dagger$$

• Of the **four** initial unitary matrices ($U_{\text{L,R}}$ and $D_{\text{L,R}}$), only **one** is observable ($V_{\text{CKM}}$)
• No Flavor Changing Neutral Currents at tree level

• FCNC suppressed also at the loop level (GIM):

\[ \propto V_{ib} V_{is}^* f \left( \frac{m_{ui}^2}{m_W^2} \right) \sim V_{tb} V_{ts}^* \left[ f \left( \frac{m_t^2}{m_W^2} \right) - f(0) \right] \]

• These features have fantastic experimental implications and are a consequence of the (arbitrary) decision of introducing only one Higgs doublet
POSSIBLE SOLUTIONS
Supersymmetry

- Double number of particles (degrees of freedom)
- New symmetry at the TeV scale protects the Higgs mass
- Lightest sparticle provides a dark matter candidate
- Exact unification of electromagnetic, weak and strong interactions
- Relieves the tension between direct and indirect Higgs bounds

Diagram:

- Quarks: $u$, $c$, $t$, $d$, $s$, $b$
- Leptons: $\nu_e$, $\nu_\mu$, $\nu_\tau$, $e$, $\mu$, $\tau$
- gauge bosons: $\gamma$, $W$, $Z$
- Higgs: $H_u$, $H_d$
- Higgsino: $\tilde{H}_u$, $\tilde{H}_d$
- Double number of particles
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• Double number of particles
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• Relieves the tension between direct and indirect Higgs bounds

• indirect
• direct SM
• direct MSSM
OTHER OPTIONS

- **Extra Dimensions**
  - Elimination of the Planck scale
  - Some of the other problems can be tackled

\[ M_{pl} = M_{EW} e^{kr_c \pi} \]

- **Technicolor**
  Higgs as a bound state of a strong force at the TeV scale

- **Little Higgs**
  Higgs as a pseudo-Goldstone boson
  “Modern incarnation of technicolor”
• **Direct detection** at Colliders (Tevatron, LHC)

• **Indirect detection** at $B$ factories (BaBar, Belle), LHCb, super-$B$ factories, rare $K$ decays, Project-X, CLEO-c, LFV experiments (MEG),...

• **Cosmology**: dark matter relic density, direct dark matter detection (CDMS,...)
**COMPLEMENTARITY**

**Direct detection**

Establish new particles

**Indirect detection**

Quantum structure
STATUS OF NEW PHYSICS SEARCHES
**ELECTROWEAK FITS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measurement</th>
<th>Fit</th>
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<tbody>
<tr>
<td>$\Delta \alpha^{(5)}_{\text{had}}(m_Z)$</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
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<tr>
<td>$m_Z$ [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1875</td>
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<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4957</td>
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<td>$\sigma_{\text{had}}$ [nb]</td>
<td>41.540 ± 0.037</td>
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<td>$R_l$</td>
<td>20.767 ± 0.025</td>
<td>20.744</td>
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<td>$A^{0,l}_{tb}$</td>
<td>0.01714 ± 0.00095</td>
<td>0.01645</td>
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<td>$A_l(P^\tau)$</td>
<td>0.1465 ± 0.0032</td>
<td>0.1481</td>
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<td>$R_b$</td>
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<tr>
<td>$R_c$</td>
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<td>0.1722</td>
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<tr>
<td>$A^{0,b}_{tb}$</td>
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<td>$A^{0,c}_{tb}$</td>
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<td>$A_b$</td>
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<td>$A_c$</td>
<td>0.670 ± 0.027</td>
<td>0.668</td>
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<td>$A_l(\text{SLD})$</td>
<td>0.1513 ± 0.0021</td>
<td>0.1481</td>
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<tr>
<td>$\sin^2 \theta_{\text{eff}}(Q_{tb})$</td>
<td>0.2324 ± 0.0012</td>
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<td>$m_W$ [GeV]</td>
<td>80.398 ± 0.025</td>
<td>80.374</td>
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<td>$\Gamma_W$ [GeV]</td>
<td>2.140 ± 0.060</td>
<td>2.091</td>
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<tr>
<td>$m_t$ [GeV]</td>
<td>170.9 ± 1.8</td>
<td>171.3</td>
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</table>
• Unitarity of the CKM matrix implies relations between the various elements

• Focus on the smallest elements

• $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

**Diagram:**
- Unitarity triangle
- Points: $(d_L, s_L, b_L)_k$, $(u_L, c_L, t_L)_i$, $(0,0)$, $(1,0)$
- Relations: $W^-$, $V_{ik}$, $V_{ub}^*$, $V_{td}^*$, $V_{cb}^*$
UNITARITY TRIANGLE

\[ \text{excluded area has CL > 0.95} \]

\[ \sin 2\beta \]

\[ \text{sol. w/ cos}^2 \beta < 0 \]

(excl. at CL > 0.95)

\[ |V_{ub}| \]

\[ \Delta m_s & \Delta m_d \]

\[ \Delta m_d \]

\[ \varepsilon_K \]

\[ \rho \]

\[ \text{Summer 2007} \]
Included area has CL > 0.95

sin2β

Δm_s & Δm_d

ε_K

|V_{ub}|

α

β

γ

Δm_d

ε_K

excluded area has CL > 0.95

sol. w/ cos2β < 0 (excl. at CL > 0.95)

CKM fitter
Summer 2007

V_{ts}

V_{td}

V_{ts}^*

V_{td}^*

K^0

K^0

B^0

B^0

J/ψK_S

V_{tb}

V_{td}

V_{tb}^*

V_{td}^*
HINTS FOR NEW PHYSICS!

• Dark Matter relic density:

\[ \Omega h^2 = 0.1047^{+0.007}_{-0.0013} \rightarrow 80 \sigma \]

• Muon anomalous magnetic moment

\[ a_{\mu}^{\text{exp}} = 11659208(6) \times 10^{-10} \]
\[ a_{\mu}^{\text{SM}}(ee) = 11659178(6) \times 10^{-10} \]
\[ a_{\mu}^{\text{SM}}(\tau) = 11659179(7) \times 10^{-10} \]

\[ \delta a_{\mu} = (29.3 \pm 8.2) \times 10^{-10} \rightarrow 3.6 \sigma \]
The width for $D_s \rightarrow \ell\nu$ is
\[
\Gamma(D_s \rightarrow \ell\nu) = \frac{m_{D_s}}{8\pi} |G_F V_{cs}^* m_\ell| f_{D_s}^2 \left( 1 - \frac{m_\ell^2}{m_{D_s}^2} \right)^2
\]

$f_{D_s}$ is extracted from data and lattice-QCD:

$$(f_{D_s})_{\text{exp}} = (277 \pm 9)\text{MeV} \quad \text{[CLEO]}$$
$$(f_{D_s})_{\text{QCD}} = (241 \pm 3)\text{MeV} \quad \text{[HPQCD]}$$

The discrepancy is at the $3.8\sigma$ level

Requires non-MFV new physics! leptoquarks,...

Independent cross check of the lattice result needed
WHAT DOES THIS MEAN?
TWO SCENARIOS
TWO SCENARIOS

• Decoupling
  • New Physics is very heavy ( \( \gg \) TeV )
  • Arbitrary Flavor Changing couplings
**TWO SCENARIOS**

- **Decoupling**
  - New Physics is very heavy ( >> TeV )
  - Arbitrary Flavor Changing couplings

- **Minimal Flavor Violation**
  - The amazing agreement of $B$ factories measurements with the SM predictions is a *powerful test of the CKM mechanism*
  - Relatively light new particles with CKM-like couplings
  - Correlation between Tevatron/LHC results and low-energy data

*discoveries at LHC* \[\rightarrow\] \[\leftarrow\] *deviations in precision experiments*
We adopt the definition of D’Ambrosio, Giudice, Isidori and Strumia: the only relevant information contained in the quark Yukawa’s are the eigenvalues and the CKM matrix:

\[ Y_U = D_L \, V_{\text{CKM}}^\dagger \, \lambda_u^{\text{diag}} \, U_R , \quad Y_D = D_L \, \lambda_d^{\text{diag}} \, D_R \]

where the matrices \( U_R, D_L \) and \( D_R \) are unphysical.

- Can be implemented as an exact symmetry of the theory (!)
- The structure of Flavor Changing Neutral Currents usually follows the CKM pattern
- If new physics is fairly light (\(< 1 \text{ TeV}\)) deviations are unavoidable
A JOURNEY IN SUSY:
HOW LIGHT CAN THE HIGGS SPECTRUM BE?
**REALISTIC MODELS**

- **R-parity** (dark matter candidate)
- **Grand Unification**

![Graph](image)

- **Radiative ElectroWeak Symmetry Breaking**

\[ \mu > \mu_0 \] \[ \mu < \mu_0 \]

- **Minimal Flavor Violation**
• Any supersymmetric model requires two Higgs doublets ($H_u, H_d$)

• The Higgs spectrum is much richer: three neutral Higgses ($h, H, A$) and one charged Higgs ($H^+$)

• There are two vev’s: one for each doublet

\[
\frac{\langle H^0_u \rangle}{\langle H^0_d \rangle} = \tan \beta
\]
Absence of super-partners degenerate in mass with the SM particles implies that SUSY must be spontaneously broken.

**Supergravity inspired MSSM (SUGRA)**
**Gauge Mediation (GM)**
SOFT BREAKING TERMS

- **Squark mass terms:**
  \[ \mathcal{L}^{\text{squarks}}_{\text{soft}} = \bar{Q}^\dagger M_Q^2 \bar{Q} + \bar{U}^\dagger M_U^2 \bar{U} + \bar{D}^\dagger M_D^2 \bar{D} + \bar{Q} Y_U^A H_u \bar{U} + \bar{Q} Y_D^A H_d \bar{D} \]

- **Sleptons mass terms:**
  \[ \mathcal{L}^{\text{sleptons}}_{\text{soft}} = \bar{\tilde{L}}^\dagger M_L^2 \bar{\tilde{L}} + \bar{\tilde{E}}^\dagger M_E^2 \bar{\tilde{E}} + \bar{\tilde{L}} Y_D^E H_d \bar{\tilde{E}} \]

- **Gauginos mass terms:**
  \[ \mathcal{L}^{\text{gauginos}}_{\text{soft}} = \frac{1}{2} \left( M_1 \bar{\tilde{B}} B + M_2 \bar{\tilde{W}} W + M_3 \bar{\tilde{g}} g \right) \]

- **Higgs mass terms:**
  \[ \mathcal{L}^{\text{higgs}}_{\text{soft}} = \mu B H_1 H_2 + M_1^2 H_1^2 + M_2^2 H_2^2 \]
**MSSM WITH MFV**

- **General** soft-breaking terms:
  \[
  \mathcal{L}_{\text{soft}}^{\text{squarks}} = \bar{Q}^\dagger M_Q^2 Q + \bar{U}^\dagger M_U^2 U + \bar{D}^\dagger M_D^2 D + \bar{Q} Y_U^A H_u U + \bar{Q} Y_D^A H_d D \\
  \mathcal{L}_{\text{soft}}^{\text{sleptons}} = \bar{L}^\dagger M_L^2 L + \bar{E}^\dagger M_E^2 E + \bar{L} Y_D^E H_d E \\
  \mathcal{L}_{\text{soft}}^{\text{gauginos}} = \frac{1}{2} \left( M_1 \bar{B} B + M_2 \bar{W} W + M_3 \bar{g} g \right) \\
  \mathcal{L}_{\text{soft}}^{\text{higgs}} = \mu B H_1 H_2 + M_1^2 H_1^2 + M_2^2 H_2^2
  \]

- **MFV** soft-breaking terms:
  \[
  M_Q^2 = m_Q^2 \left( 1 + b_1 Y_U Y_U^\dagger + b_2 Y_D Y_D^\dagger + b_3 Y_D Y_D^\dagger Y_U Y_U^\dagger + b_4 Y_U Y_U^\dagger Y_D Y_D^\dagger \right) \\
  M_U^2 = m_U^2 \left( 1 + b_5 Y_U^\dagger Y_U \right) \\
  M_D^2 = m_D^2 \left( 1 + b_6 Y_D^\dagger Y_D \right) \\
  A_U = a_U \left( 1 + b_7 Y_D Y_D^\dagger \right) Y_U \\
  A_D = a_D \left( 1 + b_8 Y_U Y_U^\dagger \right) Y_D
  \]
**MSSM WITH MFV**

- **mSugra:**
  
  \[ M_{1/2}, M_0, A_0, \tan \beta, \text{sign}(\mu) \]

- **Non Universal Higgs Mass (NUHM) MSSM:**
  
  \[ M_{1/2}, M_0, M_{H_1}, M_{H_2}, A_0, \tan \beta, \text{sign}(\mu) \]

- **Most general MFV MSSM:**
  
  \[
  (M^2_Q)_{ij} = M^2_Q \delta_{ij}, \quad (M^2_U)_{ij} = M^2_U \delta_{ij}, \quad (M^2_D)_{ij} = M^2_D \delta_{ij}, \\
  (M^2_L)_{ij} = M^2_L \delta_{ij}, \quad (M^2_E)_{ij} = M^2_E \delta_{ij}, \quad M^2_{H_1}, \quad M^2_{H_2}, \\
  (Y^A_U)_{ij} = A_U e^{i \phi_A U} (Y_U)_{ij}, \quad (Y^A_D)_{ij} = A_D e^{i \phi_A D} (Y_D)_{ij}, \\
  (Y^A_E)_{ij} = A_E e^{i \phi_A E} (Y_E)_{ij},
  \]
In the MSSM at large $\tan\beta$ there are tree-level Higgs-mediated FCNC's:

$$\mathcal{L}_Y = -\bar{d}_L Y^d d_R H_1 + \bar{d}_L \left( \Delta Y^d \right) d_R H_2^* + \bar{u}_L Y^u u_R H_2 + \bar{u}_L \left( \Delta Y^u \right) u_R H_1^*$$

For instance the $b_R$-$s_L$-Higgs coupling reads:

$$\mathcal{L}_S = \frac{ig_2}{2M_W} m_b \frac{(\epsilon_{\tilde{\chi}^-_Y} + \epsilon_{\tilde{g}_Y}) V_{ts} \tan^2 \beta}{(1 + \epsilon_0 \tan \beta)^2} \bar{b}_R s_L S + h.c.$$ 

induced from RG running

In SUSY models with Grand Unification and Minimal Flavor Violation:

$$\text{sign} \left( \epsilon_{\tilde{\chi}^-_Y} / \epsilon_{\tilde{g}_Y} \right) < 0$$
The experimental bound and the SM predictions are:

\[ BR(B_s \rightarrow \mu \mu)^{\text{exp}} < 5.8 \times 10^{-8} \text{ at 90\% C.L.} \ [CDF&D0] \]

\[ BR(B_s \rightarrow \mu \mu)^{\text{SM}} = (3.8 \pm 1.0) \times 10^{-9} \]

• In GUT MFV SUSY models the branching ratio reads

\[
BR(B_s \rightarrow \mu^+ \mu^-) \approx \frac{4 \times 10^{-8}}{[1 + 0.5 \times \frac{\tan \beta}{50}]^4} \left[ \frac{\tan \beta}{50} \right]^6 \left( \frac{160 \text{ GeV}}{M_A} \right)^4 \left( \frac{e_{\tilde{t}Y} + e_{\tilde{g}Y}}{4 \times 10^{-4}} \right)^4
\]

• In our models the chargino contribution can easily be \( \sim 3 \times 10^{-3} \). The sum of chargino and gluino is naturally in the few \( \times 10^{-4} \) range.
Other Observables

- Muon Anomalous Magnetic Moment:

\[ \delta a^{\mu} = (29.3 \pm 8.2) \times 10^{-10} \]

- \( B \to \tau \nu \)

\[ R(B \to \tau \nu) \exp = 1.02 \pm 0.40 \]

\[ R(B \to \tau \nu)^{\exp} = 3.6 \sigma \text{ deviation} \]

\[ R(B \to \tau \nu) \exp = 1.02 \pm 0.40 \]

\[ \text{complete agreement} \]
• $B \rightarrow X_s \gamma$

$\mathcal{B}(B \rightarrow X_s \gamma)_{\text{exp}} = (3.55 \pm 0.26) \times 10^{-4}$

$\mathcal{B}(B \rightarrow X_s \gamma)_{\text{SM}} = (2.98 \pm 0.26) \times 10^{-4}$

• Dark Matter relic density

$\Omega h^2 < 0.13$ (99% C.L.)

• $B_s$ mass difference

Not a constraint in these models
MINIMAL SUPERGRAVITY

150 GeV < $M_A$ < 200 GeV

- **green**: direct bounds
- **black**: direct constraints
- **red**: direct constraints

Upper bound on $\Omega h^2$

In the surviving region the $B \rightarrow \tau \nu$ amplitude is negative:

- $R(B \rightarrow \tau \nu)$
We can have light Higgses with smaller $\tan \beta$.

The $B \to \tau\nu$ amplitude can have both signs.
COLLIDER IMPLICATIONS
DIRECT SEARCHES AT COLLIDERS

<table>
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<th>mass (GeV)</th>
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<th>mass (GeV)</th>
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<td>$\chi_1$</td>
<td>130 – 180</td>
<td>$\chi_2$</td>
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<td>$\chi_3$</td>
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<td>$\chi_4$</td>
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<td>$\tilde{\chi}_1^\pm$</td>
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<td>$\tilde{d}_L$</td>
<td>1170 – 1570</td>
<td>$\tilde{\tau}_1$</td>
<td>320 – 860</td>
</tr>
<tr>
<td>$\tilde{\tau}_2$</td>
<td>720 – 1160</td>
<td>$\tilde{e}_R$</td>
<td>900 – 1360</td>
</tr>
<tr>
<td>$\tilde{e}_L$</td>
<td>920 – 1380</td>
<td>$\tilde{\nu}_1$</td>
<td>700 – 1160</td>
</tr>
<tr>
<td>$\tilde{\nu}_3$</td>
<td>920 – 1380</td>
<td>$h$</td>
<td>112.4 – 115.6</td>
</tr>
<tr>
<td>$A$</td>
<td>165 – 200</td>
<td>$H$</td>
<td>165 – 200</td>
</tr>
<tr>
<td>$A^\pm$</td>
<td>150 – 210</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Light Higgs spectrum
- Light gauginos: in particular $m_{\tilde{g}} < m_{\tilde{\chi}_1}$ implies that we can have interesting signatures in 3-body ($\tilde{g} \to t\bar{t}\chi_0$) or loop induced 2-body decays ($\tilde{g} \to g\chi_0$)
**CHARGED HIGGS PRODUCTION**

- **$M_{H^\pm} < M_t$:**

  $p\bar{p} \rightarrow t\bar{t} \rightarrow W^+ b H^- \bar{b} \rightarrow \tau \bar{\nu}, \ell^+ \nu, u\bar{d}$

  \[ \sigma_{t\bar{t}}(Tevatron) \sim 7 \text{ pb} \]

  \[ \sigma_{t\bar{t}}(LHC) \sim 800 \text{ pb} \]

  8x10^6 tt per year (10 fb⁻¹)

- **$M_{H^\pm} > M_t$:**

  $gg \rightarrow t\bar{b} H^- \rightarrow \bar{t}b, \tau \bar{\nu}$

  $gb \rightarrow tH^-$

  \[ \sigma_{t\bar{t}}(LHC) \sim 800 \text{ pb} \]
BRANCHING RATIOS

\begin{align*}
\text{BR}(t \rightarrow H^+ b) & \quad \text{vs} \quad m_{H^+} \text{(GeV)} \\
\text{BR}(H^+ \rightarrow \ell^+ \nu_\ell) & \quad \text{vs} \quad m_{H^+} \text{(GeV)}
\end{align*}
Direct searches at CDF

Dedicated search: $\ell + \tau_h + \not{E}_T + j_b + j$

Interesting region
DIRECT SEARCHES AT CDF

Di-top analysis reinterpretation

**Tauonic Higgs Model**  
CDF Run II Preliminary

- $m_t = 175 \text{ GeV/c}^2$
- $\int L dt = 192 \text{ pb}^{-1}$

$BR(H \rightarrow t \bar{v}) = 1$; $BR(H \rightarrow c \bar{c}) = BR(H \rightarrow t \bar{t}) = BR(H \rightarrow W^+ h^0) = 0$

Interesting region
Di-top analysis reinterpretation: **SUSY analysis**

**CDF Run II Preliminary**

Excluded $95\%$ CL

$m_t = 175$ GeV/c$^2$

$L dt = 192$ pb$^{-1}$

**Theorically inaccessible**

- SM Expected
- SM $\pm 1 \sigma$ Expected
- Excluded CDF Run II
- Excluded LEP

**LEP (ALEPH, DELPHI, L3 and OPAL)**

Assuming $H \rightarrow \tau \nu$ or $H \rightarrow c \bar{c}$ only

- $M_{SUSY} = 1000$ GeV/c$^2$
- $\mu = 500$ GeV/c$^2$
- $A_t = A_b = 2000$ GeV/c$^2$
- $A_\tau = 500$ GeV/c$^2$
- $M_1 = 0.498 M_2$
- $M_2 = M_3 = M_Q = M_U = M_D = M_E = M_L = M_{SUSY}$

**Interesting region**

Direct searches at CDF
DIRECT SEARCHES AT THE LHC

$p\bar{p} \rightarrow t\bar{t} \rightarrow b\bar{b}W(\ell\nu)H(\tau\nu)$

$p\bar{p} \rightarrow t\bar{t} \rightarrow b\bar{b}W(q\bar{q})H(\tau\nu)$
**DIRECT SEARCHES AT THE LHC**

\[ gg \rightarrow tbH(\tau\nu) \]

*The interesting part of the parameter space is covered*
• The most promising indirect channels to look for a light charged Higgs scenario are $B_s \rightarrow \mu \mu$ and $B \rightarrow \tau \nu$

• Another possibility is to look for Lepton Flavor Violation
  - $\ell_i \rightarrow \ell_j \gamma$
  - A supersymmetric see-saw generates lepton flavor violating terms in the slepton sector:

\[
\delta_{LL}^{ij} \approx - \frac{3 + a_0^2}{8 \pi^2} \log \left( \frac{M_X}{M_R} \right) (Y_\nu^\dagger Y_\nu)_{ij}
\]

• There is some degree of freedom in the choice of Yukawas of the neutrinos
We adopt a conservative approach and take $y_{\nu_3} \sim 1$ and assume that the mixing is CKM-like.

There is a strong correlation with the muon $g-2$:

$$B(\ell_i \rightarrow \ell_j \gamma) \approx \left[ \frac{\Delta a_\mu}{20 \times 10^{-10}} \right]^2 \times \left\{ \begin{array}{c} 1 \times 10^{-13} \left[ \frac{\delta_{LL}^{12}}{3 \times 10^{-5}} \right]^2 \\ 1 \times 10^{-9} \left[ \frac{\delta_{LL}^{23}}{6 \times 10^{-3}} \right]^2 \end{array} \right\} \begin{array}{c} [\mu \rightarrow e] \\ [\tau \rightarrow \mu] \end{array}.$$

$\mu \rightarrow e\gamma$ can easily reach the sensitivities of MEG.
A very light Higgs and large tan$\beta$, usually generate too large LFV couplings. In our case, they are under control because of the large gaugino-sfermion mass splitting.
CONCLUSIONS

• The Standard Model provides an excellent description of Nature

• Nevertheless, there are some chinks in its armor:
  • Dark Matter, Muon g-2
  • several theoretical biases (Grand Unification, hierarchies, ...)

• New Physics at the Terascale has to be Minimal Flavor Violating

• The interplay between precision searches and direct detection at colliders will play a critical role in identifying new physics

• In two years the world we know will be shattered and the exploration of the unknown will begin..... stay tuned!
BACKUP SLIDES
• Restore the flavor symmetry group of the SM:
\[ SU(3)_q^3 = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \]

• The Yukawas are replaced by auxiliary fields with a constant background value and with the following transformation properties:
\[ Y_U \sim (3, \bar{3}, 1)_{SU(3)_q^3}, \quad Y_D \sim (3, 1, \bar{3})_{SU(3)_q^3} \]

• Yukawa interactions are now invariant under SU(3)\(^3\):
\[ \mathcal{L}_Y = \bar{Q}_L Y_D D_R H + \bar{Q}_L Y_U U_R H_c + h.c. \]

• Using the SU(3) symmetry we can rotate the background values of the auxiliary fields \( Y_{U,D} \):
\[ Y_U = V_{\text{CKM}}^\dagger \lambda_u^{\text{diag}}, \quad Y_D = \lambda_d^{\text{diag}} \]
**MINIMAL FLAVOR VIOLATION**

- The only flavor changing structure is:

\[
\lambda_{\text{FC}} = \begin{cases} 
  (Y_U Y_U^\dagger)_{ij} & \simeq \lambda_i^2 V_{3i}^* V_{3j} & i \neq j \\
  0 & i = j
\end{cases}
\]

- Generic flavor changing currents:

\[
\bar{Q}_L Y_U Y_U^\dagger Q_L , \quad \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Q_L , \quad \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Y_D D_R
\]

\[
\bar{Q}_L \lambda_{\text{FC}} Q_L , \quad D_R \lambda_d \lambda_{\text{FC}} Q_L , \quad D_R \lambda_d \lambda_{\text{FC}} \lambda_d D_R
\]
• If there are more Higgs doublets:
  - \( \lambda_b \) can be large
  - there is a new source of SU(3) breaking

\[
\lambda_{FC}^d = \begin{pmatrix} Y_D & Y_D^\dagger \end{pmatrix}_{ij} \simeq \frac{2m_b^2}{v^2} \tan^2 \beta \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}
\]

• In principle we have non-holomorphic Higgs interactions

\[
\epsilon_0 Q_L \lambda_d D_R H_U^c \quad \Longrightarrow \quad \delta m_b = m_b \epsilon_0 \tan \beta
\]
(\textit{G-2})_\mu

- Dominated by the chargino-sneutrino diagram:

\[
\delta a_{\chi^\nu}_\mu^+ \simeq \frac{g_2^2}{32\pi^2} \frac{m_\mu^2 \text{Re}(\mu M_2)}{m_\nu^2} \tan \beta
\]

the sign of the SUSY contribution is \textit{sign}(\mu)

- Theoretical predictions are complicated by non-perturbative effects:
  - ✓ light-by-light scattering
  - ✓ hadronic contribution - can be extracted from \(e^+e^-\) and \(\tau\) data (the latter up to \textit{isospin corrections})

- Experimental and theoretical results read:

\[
a_{\mu}^{\text{exp}} = 11659208(6) \times 10^{-10}
\]
\[
a_{\mu}^{\text{SM}}(ee) = 11659178(6) \times 10^{-10}
\]
\[
a_{\mu}^{\text{SM}}(\tau) = 11659179(7) \times 10^{-10}
\]

\[
\Rightarrow \delta a_{\mu} = (29.3 \pm 8.2) \times 10^{-10}
\]

3.6\sigma effect
The experimental measurement is:

\[
\text{BR}(B \to \tau \nu) = \begin{cases} 
(1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})) \times 10^{-4} \\
(1.2 \pm 0.4(\text{stat}) \pm 0.3(\text{bckg}) \pm 0.2(\text{syst})) \times 10^{-4}
\end{cases}
\]

\[
\text{BR}(B \to \tau \nu)^{WA} = (1.42 \pm 0.43) \times 10^{-4}
\]

The SM expectation is (tree-level W exchange):

\[
\text{BR}(B \to \tau \nu) = \frac{G_F^2 m_B m_T^2}{8\pi} \left(1 - \frac{m_T^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B
\]

The supersymmetric corrections interfere destructively with the SM amplitude and are given by

\[
\frac{\text{BR}(B \to \tau \nu)^{\text{SUSY}}}{\text{BR}(B \to \tau \nu)^{\text{SM}}} = \left(1 - \frac{m_B^2}{m_{H^\pm}^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta}\right)^2
\]
\[ B \rightarrow \tau \nu \]

- \( f_B \) and \( V_{ub} \) are the dominant source of error:
  \[
  f_B = (0.216 \pm 0.022) \text{ GeV} \\
  |V_{ub}| = (4.09 \pm 0.26) \times 10^{-3} \quad \text{[HFAG]}
  \]

- The ratio experiment/SM is, therefore:
  \[
  R(B \rightarrow \tau\nu) = 1.02 \pm 0.40
  \]
• The dipole operators are:

\[
H_{Dipole}^{b \to s \gamma} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[ C_7(\mu) \cdot \frac{e m_b}{16\pi^2} \bar{s}_L \sigma_{\mu\nu} b_R F_{\mu\nu} + C_8(\mu) \cdot \frac{g s m_b}{16\pi^2} \bar{s}_L \alpha T^a_{\alpha\beta} \sigma_{\mu\nu} b_R G^{a\mu\nu} \right]
\]

• \(W^+\) and \(H^+\) contributions have the same sign (both negative)

• The sign of the chargino contribution is \(-\text{sign}(A_t \mu)\).
  At the EW scale we have \(A_t \sim -2 \, M_{1/2}\), hence we have destructive and constructive interference for \(\mu > 0\) and \(\mu < 0\), respectively.

• World average: \(\mathcal{B}(B \to X_s \gamma)_{\exp} = (3.55 \pm 0.26) \times 10^{-4}\)

• SM prediction: \(\mathcal{B}(B \to X_s \gamma)_{\text{SM}} = (2.98 \pm 0.26) \times 10^{-4}\)
\( B \rightarrow X_s \gamma \)

- The SM prediction includes NNLO effects

  The charm mass dependence is calculated in the \( m_c \gg m_b/2 \) limit and an extrapolation is used. The exact calculation of the 3-loop matrix element of \( O_2 \) using Mellin-Barnes techniques is being pursued [Boughezal, Czakon, Schutzmeier]

- Becher & Neubert showed that the standard OPE is valid only for cuts on the photon energy of about 1 \( GeV \).

- In order to get a reliable prediction for a more realistic cut of 1.6 \( GeV \), effective theory techniques (SCET RGE) have to be used:

\[
BR(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{GeV}} = 3.15 \times 10^{-4} \quad \text{[normal OPE]}
\]

\[
BR(B \rightarrow X_s \gamma)_{E_\gamma > 1.6 \text{GeV}} = 2.98 \times 10^{-4} \quad \text{[SCET approach]}
\]
$\mathcal{B}(E_\gamma > 1 \text{ GeV}) - \mathcal{B}(E_\gamma > 1.6 \text{ GeV})$

$\mathcal{B}(E_\gamma > 1 \text{ GeV})$

Becher & Neubert
$O(\alpha_s^2)$ partially resummed

$O(\alpha_s^2)$ fixed order

$O(\alpha_s)$ fixed order
For simplicity, let us set $C_i(\mu_b) \to 0$ for $i \neq 7$. Then, in the “fixed order”:

$$\mathcal{B}(E_\gamma > E_0)/\mathcal{B}_{\text{total}} = 1 + \frac{\alpha_s(\mu_b)}{\pi} \phi^{(1)}(E_0) + \left(\frac{\alpha_s(\mu_b)}{\pi}\right)^2 \phi^{(2)}(E_0) + \ldots$$

$$\phi^{(1)}(E_0) = \phi^{(1)}_a(E_0) + \phi^{(1)}_b(E_0)$$

$$\phi^{(1)}_b = \frac{10}{3} \delta + \frac{1}{3} \delta^2 - \frac{2}{9} \delta^3 + \frac{1}{3} \delta (\delta - 4) \ln \delta = \frac{31}{9} - \frac{7}{3} x - \frac{1}{2} x^2 - \frac{1}{9} x^3 - \frac{5}{36} x^4 + \mathcal{O}(x^5)$$

$$x = \frac{2E_0}{m_b}$$

$$\delta = 1 - x$$

$$\phi^{(1)}_a = -\frac{31}{9} - \frac{2}{3} \ln^2 \delta - \frac{7}{3} \ln \delta = -\frac{31}{9} + \frac{7}{3} x + \frac{1}{2} x^2 + \frac{1}{9} x^3 - \frac{1}{36} x^4 + \mathcal{O}(x^5)$$

Terms up to $\mathcal{O}(x^3)$ must cancel out.
The same pattern arises at $O(\alpha_s^2)$:

$$\phi^{(2)}_b \quad x = 2E_0/m_b$$

$$\phi^{(2)}_a \quad \delta = 1 - x$$

It must be the case also at higher orders because:

$$\ln \delta = -x - \frac{1}{2}x^2 - \frac{1}{3}x^3 + O(x^4)$$

However, only “const + logs(δ)” have been included at orders $O(\alpha_s^3)$ and higher in hep-ph/0610067.
**OTHER OBSERVABLES**

- $B_s$ mass difference ($\Delta M_{Bs}$)
  - Proportional to $(\tan \beta)^4$
  - Cancellation $m_H - m_A$ implies $m_s/m_b$ suppression

- Dark matter relic density ($\Omega h^2$)
  - Experimental errors are tiny (4%)
  - Theory uncertainties are much larger
    - Parametric errors (e.g. $M_t$) and uncertainties in the RGE running from the GUT to the EW scales (especially in the large tan$\beta$ region) impact strongly the calculation of $\Omega h^2$
    - Points for which $\Omega h^2$ is too small can be recovered by some other dark matter candidate
  - We impose only a loose upper bound: $\Omega h^2 < 0.13$ (99% C.L.)
\[ m_A^2 = M_{H_d}^2(m_t) - M_{H_u}^2(m_t) - m_Z^2 \]

- The running of \( M_{H_u} \) is driven by the large Yukawa of the top. Hence we always have \( m_{H_u}^2(m_t) < 0 \):

\[ m_{H_u}^2(m_t) \simeq -0.12 M_0^2 - 2.7 M_{1/2}^2 + 0.4 A_0 M_{1/2} - 0.1 A_0^2 \]

- The running of \( M_{H_d} \) depends strongly on \( \tan\beta \)
  - For moderate \( \tan\beta \) (< 10): \( m_{H_d}^2(m_t) > 0 \)
  - For large \( \tan\beta \), the bottom Yukawa plays a more important role until the limiting case \( m_{H_d}^2(m_t) \simeq m_{H_u}^2(m_t) < 0 \)

- Low \( m_A \) can only be achieved at large \( \tan\beta \)
The LSP condition $m_\tilde{\tau} > m_{\tilde{\chi}_0}$ implies a lower bound on $M_0$

- The absence of charge and color breaking minima implies $|A_0| < 3M_0$

- Both $B\to X_s\gamma$ and $B_s\to \mu\mu$, require a small $A_t$

- An approximate formula is: $A_t = 0.25A_0 - 2M_{1/2}$

- We need large $A_0$ and small $M_{1/2}$

- Under these conditions the chargino contribution to $\epsilon_Y$ decreases and the gluino one is increased (i.e. more efficient cancellation)

- We need large $\tan\beta$, large $A_0$, large $M_0$ and small $M_{1/2}$
The soft breaking terms are:

\[ M_i = N \Lambda \tilde{\alpha}_i g(x) \equiv \tilde{M}_i g(x) \]

\[ M_A^2 = 2 N \Lambda^2 \left[ C_3 \tilde{\alpha}_3 + C_2 \tilde{\alpha}_2 + 3/5 Y^2 \tilde{\alpha}_1 \right] f(x) \]

The Higgs mass squared are controlled by RGE effects and are essentially proportional to \( M_3 \); hence:

\[ M_A^2 \simeq M_{H_d}^2 - M_{H_u}^2 \simeq (C_d - C_u) M_3^2 \]

The lower limit on the stau mass, sets a lower limit on \( M_1 \) and hence a stronger lower limit on \( M_3 \):

\[ m_{\tilde{\tau}_1}^2 \sim m_{\tilde{\tau}_R}^2 \sim 6/5 M_1^2 > (100 \text{ GeV})^2 \implies M_3 > 1350 \text{ GeV} \]

\[ M_A < 200 \text{ GeV} \] implies, therefore, the strong fine-tuning \( C_d - C_u \sim 10^{-2} \)
The soft breaking terms are:

\[ M_i = \frac{1}{g_i} \beta_i m_{3/2} \]

\[ M_A^2 = \frac{1}{2} \gamma_A m_{3/2}^2 + m_0^2 Y_A \]

\[ A_A = \beta_{Y_A} m_{3/2} \]

The squared scalar masses tend to be tachyonic and Fayet-Iliopoulos D-terms were added (strong model dependence). As a consequence it is extremely easy to obtain a light \( M_A \). A correct EWSB is obtained only for moderate \( \tan \beta \), therefore the phenomenology of these models (for light \( M_A \)) is less interesting.