SUSY at LHC
connection
to flavor physics

for “flavor physics in the era
of LHC”
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Moving to KEK
from Jan, 2006
Starting from excuses....

Whatever I talk about “flavor physics” can be wrong.
(It might be more useful if you ask numbers you want from LHC directly to me)
Also forgive me about improper references.
Why LHC is related to “flavor physics”

• It sets scale of the new physics

• It measures important parameters. For the case of supersymmetry, it is
  • B physics: charged higgs, sbottom and stop at LHC
  • LFV: determination and slepton masses, direct searches
  • $\mu$, $\tan\beta$

Note: We know nothing about that now
What do we want to know for LFV?

- What we need (for SU(5) GUT)
  - $\tan\beta$: Yukawa coupling
  - $m_R^{(12)}$
  - $M_1, \mu$: neutralino mass matrix

$M_2$ and $m_L$ for SU(5)+$\nu_R$(see-saw)

Distinguish Left and Right sleptons is important
what do we want to know for B physics

- many competing diagrams
- Cancellations.
- Ex: $b \rightarrow s\gamma$: What is charged Higgs mass, stop mass and mixing angle?

if chargino diagram does not exist $m_{H^+} \sim 300\text{GeV}$ is excluded
How to put LHC constraint in the flavor analysis

- Most Flavor studies is performed in the form of scatter plot to show the deviation from SM.

- LHC will come. You may want to put minimum and model independent constraint to your analysis. What are they?

- Most of LHC analysis have been done in a few points in MSUGRA. How generic are they? You confused.
Access to the Flavor structure

We have seen in Franks talk that we might have high sensitivity in squark and slepton masses.
(1% for squarks, and $O(1\text{GeV})$ for slepton mass differences)

What does this means?

Squark sectors

- $M=300\text{GeV}$, soft squark mass
- $m=0$: 734.8
- $m=100$: 741.6 (1%)
- $m=200$: 761.6 (3.6%)

Slepton

- $M=300\text{GeV}$
- $m=0$: 120
- $m=20$: 121.7 (1%)
- $m=30$: 123.7 (3.1%)

The bound from the measured $\Delta m_K$ implies $[25]$

$[10 \text{ TeV}]^2 \left[ \frac{\Delta m_{q_{12}}^2}{m_{\tilde{q}}^2} \right]^2 < 1$.

K bound is not too difficult to satisfy if $m < M$ at GUT scale

gaugino mass dominates the squark masses and it is universal. All fancy flavor effects are reduced.
The effect of non-diagonal scalar mass $m_{ij}$ at GUT scale (but of the order of diagonal scalar mass) will be suppressed at lower scale. $\delta m^2/m^2 < 0.01$ is possible for $m \ll M$.

- LFV is large for $m \sim M$ or $m > M$ regions.

- LHC measurements are good when $m \ll M$. No clean result for the other MSUGRA points.

Hisano and Tobe (2001) $M_2 = 250$ GeV, $\tan \beta = 10$ SUSY sea-saw model $V_{13} = 0.05, Y_t = Y_{\nu \tau}$
SUSY scale determination for $m \gg M$

- Peak position of $M_{\text{eff}}$ reflects $2M_{\text{SUSY}}$, but we have more SM background than originally thought.
- $M_{\text{eff}}$ (One lepton), same strategy but model dependent?
- 3 body decay of gluino. less efficient?
- We only measure gluino masses. squark decays immediately to gluino and hard to reconstruct.

Asai et al

![ATLAS Preliminary](image-url)
Slepton masses and $\tilde{\chi}_2^0$ decay distribution

- $m \gg M$: all 2 body decays into slepton is closed
- virtual process $\tilde{\chi}_2^0 \rightarrow ll\tilde{\chi}_1^0$?

The decay distribution depends on left hand slepton masses in MSUGRA

when $\tilde{l}_R$ is open, virtual $\tilde{l}_L$ contribution appear beyond the two body end points.

$$\frac{\Gamma(\tilde{\chi}_2^0 \rightarrow ll\tilde{\chi}_1^0)}{\Gamma(\tilde{\chi}_2^0 \rightarrow \tilde{l}_R \rightarrow ll\tilde{\chi}_1^0)} = 0.05$$

for SPS1a.
Life with cosmological constraints

A) Bulk region: Bino like.
   Slepton exchange sets $\Omega$

   $$\Omega h^2 \propto \frac{m_i^4}{m_\tilde{\chi}^2}$$

   too large mass density

B) Higgs pole effect near
   $m_H = 2m_\chi$

C) $\tilde{\tau}\tilde{\chi}$ co-annihilation

D) focus point region
   significant higgsino-gaugino mixing
MSUGRA might be too much

- $\mu$ parameter is determined so that $v_H$ is correct.
- So if $m_H$ at GUT scale is much higher than $m_{16}$, MSUGRA prediction for $\mu$ can be evaded. More LSP pair annihilation into $W, h$

$m_H$ can be tuned independently so that higgs pole effect is enhanced.

simultaneously affects LFV through
1) LR mixing of sfermions
2) Higgsino mass insertions

Some recent benchmarks hep-ph 058198 for CMS (light $m_H$)
life with cosmological constraint

What happens if $\mu$ is smaller

- More gaugino component in $\tilde{\chi}_4^0$ if $M_2 \sim \mu$

- mass difference between 1st and 2nd ino smaller

- heavier ino becomes gaugino if $M_2(M_1) > \mu$, longer cascade decay as squark dominantly decay into gaugino (heavier ino)

- several ino signature

Drees et al
PRD63,035008(2001)  
m = 90 GeV  M = 250 GeV  
$\mu$ = 200 GeV  $\tan \beta$ = 10

Not very good example
Example of $\tan\beta$ determination

scalar-muon LR mixing

if $\tilde{\chi}_2^0 \sim \tilde{W}$ then decay width $\Gamma(\tilde{\chi}_2^0 \to \tilde{l}_R l)$ is so suppressed.

Small left component of scalar muon affects decay branching ratios strongly.

$$\tilde{\mu}_1 \sim \tilde{\mu}_R + \epsilon_L \tilde{\mu}_L$$
$$\epsilon_L \sim m_\mu (\mu \tan \beta + A_\mu) / (m_L^2 - m_R^2)$$

$$\Gamma(l) \propto L^2 + R^2$$

$\begin{align*}
L &= g \cos \theta_l N_{\tilde{W}^2} \\
R &= g_Y \sin \theta_l N_{\tilde{B}^2}
\end{align*}$

<table>
<thead>
<tr>
<th>$\tan\beta$</th>
<th>$\text{Br}(e)$</th>
<th>$\text{Br(μ) / Br(e)}$</th>
<th>$S$ (300fb-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>6.3%</td>
<td>1.04</td>
<td>5.6</td>
</tr>
<tr>
<td>20</td>
<td>1.2%</td>
<td>1.17</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Importance of relative branching ratio

\[ \Gamma(\tau) : \Gamma(\mu) : \Gamma(e) \sim (g \cos \theta_\tau N_{\tilde{W}})^2 : (g \cos \theta_\mu N_{\tilde{W}})^2 + (g_Y N_{\tilde{B}})^2 : (g_Y N_{\tilde{B}})^2 \]

Both of them contribute

ignore bino component

ignore selectron mixing

relative branching ratio is important. Note systematics are very different

\[ \mu : \text{clean, outer muon system} \]

\[ e: \text{inner tracking} + E_{\text{cal}} \]

\[ \tau : \text{decay into hadron, jet isolation, } \nu_{\tau} \text{ missing, efficiency} \sim 50\% \]

For 3 body decay and \( \mu > M_2 > M_1 \), left hand slepton dominates....
Left or right??

- at LHC (pp collider) $\sigma$ (squark)$\rightarrow$ $\sigma$(anti-squark)

- MSUGRA case $\tilde{q} \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}lq \rightarrow \tilde{\chi}_1^0 qll$

- wino-like ino produced from left-hand squarks

- wino is polarized (in average). it decays into lepton /anti-lepton equally (Majorana). lepton/anti-lepton correlation to wino(jet) direction is opposite. charge asymmetry.

- NOTE, slepton further decay into lepton. look into the distribution near the jl edge (it may not be end point)
Left or right, simulations

- $m(jl)$ distribution tell us combination of the chirality of squark and slepton in the cascade decays.

\[
\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}_L l q \\
\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow \tilde{l}_R l q \\
m(ql) = 230 \text{ GeV} \\
m(ql) = 380 \text{ GeV}
\]


stau$_1$ behave like left
Flavor violation in slepton decays

- LFV in 2 body decay
- Signal:
  - Edge in $e\mu$ distribution
  - Shoulder in $e\tau$, $\tau\mu$ distribution
- Loop process:
  - GIM like suppression and cancellation among diagrams.

\[
BR(\tau \rightarrow \mu\gamma) \approx 1.1 \times 10^{-6} \left( \frac{\delta}{1.4} \right)^2 \left( \frac{100 \text{ GeV}}{M_\tilde{\ell}} \right)^4
\]

\[
\delta \equiv \frac{M_{\mu\tau}^2}{M_L^2}
\]
$L = 100 \text{fb}^{-1}, \Delta m = 1.2 \text{GeV}, \sin 2\theta = 0.5$

Figure 7: $\sqrt{\Delta \chi^2} = 5$ contours for the LFV discovery. The thick solid line is for $\mu = 1.5M_2$ and $\tan \beta = 10$ in the cMSSM, the thick dashed line for $\mu = M_2$ and $\tan \beta = 20$, and the solid line for $\mu = M_2$ and $\tan \beta = 10$. We fix the $\tilde{\nu}_R - \mu_R$ mixing angle $\theta$ as $\sin 2\theta = 0.5$ and the slepton mass difference $\Delta m = 1.2$ GeV at the GUT scale.
LHC and MSSM Higgs
in connection with B physics

Only one higgs doublet need large luminosity

$m_H \sim 500 \text{GeV}$ is under the hand of LHC

$B_s \rightarrow \tau \nu$ Hazumi’s talk

need large luminosity

Only one higgs doublet
**H/A production**

\[ \text{gg} \rightarrow \text{bbH/A} \rightarrow \tau \tau, \mu \mu, (bb) \]

**signal enhances** \( \propto \tan 2\beta \)

\[ m_A = 130 \text{ GeV}, \tan(\beta) = 30 \quad 20 \text{ fb}^{-1} \]

**Here we are assuming all SUSY particles are heavy. Any loopholes or more information?**
charged higgs searches at LHC

mass can be reconstructed
(with transverse missing momentum)

\[
L = \frac{g}{\sqrt{2m_W}} H^+ (\bar{t} (m_t \cot \beta P_L + m_d \tan \beta P_R) d + m_\tau \tan \beta \bar{\nu} \tau_R) + h c
\]

Assamagan et al hep-ph/0402057

Br?
connection to B physics

- Example $b \rightarrow s \gamma$, large cancellation among diagrams
- You will have an access of the charged higgs mass, branching ratio.
- What can you say about chargino loop contribution? Stop mass and mixings (2-3)

✓ What is the info on stop from LHC??
3rd generation squark

mass matrix

- MSSM parameters $m_{L3}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, A_b, A_t$

\[
\begin{pmatrix}
m^2_{\tilde{b}_L} & -m_b(A_b + \mu \tan \beta) \\
-m_b(A_b + \mu \tan \beta) & m^2_{\tilde{b}_R}
\end{pmatrix}
\]

\[
\begin{pmatrix}
m^2_{\tilde{t}_L} & -m_t(A_t + \mu \cot \beta) \\
-m_t(A_t + \mu \tan \beta) & m^2_{\tilde{t}_R}
\end{pmatrix}
\]

$m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_t, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_b$

In MSUGRA: The 1st and 2nd squark mass are heavier than 3rd due to RGE running and mixings. SUSY events contain many b jets. b tagging efficiency is 60%

Production: direct production from gluon (small) decay from gluino (dominant if open)
non-MSUGRA boundary condition in 3rd generation in B physics

- You may find surprise in B flavor violation process—this may comes from....

- GUT scale neutrino mass assuming $Y_t-Y_{\nu_T}$

- Non universal boundary condition

- stop and sbottom mass may also depends on such thing

Exact treatment for gluino and sbottom reconstruction

Longest cascade decays that can be “solved” event by event even though LSP is missing

\[
\begin{align*}
    m_{\tilde{\chi}}^2 &= p_\chi^2 \\
    m_{\tilde{l}}^2 &= (p_\chi + p_{l_1})^2 \\
    m_{\tilde{\chi}_2}^2 &= (p_\chi + p_{l_1} + p_{l_2})^2 \\
    m_{\tilde{b}_1}^2 &= (p_\chi + p_{l_1} + p_{l_2} + p_{j_1})^2 \\
    m_{\tilde{g}}^2 &= (p_\chi + p_{l_1} + p_{l_2} + p_{j_1} + p_{j_2})^2
\end{align*}
\]

- Assume we know lighter masses
- 3 mass constraints for p(LSP) -> one degree of freedom in 2dim gluino and squark mass space
- 2 events -> mass fixed
- After mass fix, the missing momentum is solved.

Kawagoe et al, PRD71:035008, 2005
sbottom mass reconstruction
(two b jets and two lepton channel)

LHC may address
a) tanβ dependence of sbottom mass
b) size of the LR mixing from Br into $\tilde{\chi}_2^0$ (need to wait LC?)
c) existence of $\tilde{b}_2$?

492±1.2 GeV

$\tilde{b}_2$ contribution

479±2.4 GeV

Kawagoe, MMN, Polesello 04
Flavor violation in sbottom decays at LHC?

- $\epsilon_b=60\%$, not impressive
- Take high $p_T$ jet which comes from LFV sbottom decay + $b$ jet from gluino $\rightarrow b$ sb$_1$ might work (using "mass relation" as cut).
- For $O(1000)$ bbll decay, 360 must be tagged. For full flavor violation it is only 90 events.

<table>
<thead>
<tr>
<th></th>
<th>No flavor violation $\epsilon_b=0.6$</th>
<th>full violation $\epsilon_b=1$</th>
<th>full violation $\epsilon_b=0.6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbll</td>
<td>$0.6\times0.6=0.36$</td>
<td>$0.25$</td>
<td>$0.09$</td>
</tr>
<tr>
<td>jbll</td>
<td>$0.6\times0.4=0.24$</td>
<td>$0.25$</td>
<td>$0.21$</td>
</tr>
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</tr>
<tr>
<td>jjll</td>
<td>$0.4\times0.4=0.16$</td>
<td>$0.25$</td>
<td>$0.49$</td>
</tr>
</tbody>
</table>
scalar top at LHC

- two subsequent cascade decays give \( tb \) end point. It is not dominated by single process.

- hadronic top decay can be reconstructed.

- The \( tb \) end point give you information of stop mass.
Difference between two body and three body

**Biggest branching ratio**

\[ \tilde{g} \rightarrow (t\bar{t} \text{ or } b\bar{b}) \rightarrow tb\tilde{\chi}_1^{\pm} \]

**SPS1a:** edge with \( \Delta M_{tb} \sim 4 \text{GeV} \) for \( 100 \text{fb}^{-1} \)

height \( h \) and edge \( M_{tb} \) may be used to understand stop sector

**SPS2:** (focus points \( M=300 \text{GeV} \))

No edge as expected

Lower bound of stop and sbottom mass?

Limited statistics but distribution may reflect

\[ m_{\tilde{g}} - m_{\tilde{\chi}_2} \sim 480 \text{GeV} \]

\[ m_{\tilde{g}} - m_{\tilde{\chi}_1} \sim 560 \text{GeV} \]

(Hisano et al. PRD68.035007)

1000 fb\(^{-1}\) but cut must be optimized
Endpoint reconstruction

What will we see if we put this constrain to $B$ rare decays?

- weighted end point is reconstructed correctly by the fit over wide region of parameter space.
  
- $A1$ $A2$: a msugra point but $A$ changed maximally ($m=100\text{GeV}$, $M=300\text{GeV}$, $\tan\beta=10$)
  
- $T1$ $T2$ stop mass moved by changed stop$_R$ mass
  
  
- $E1$ $E2$, gluino decays only to stop and top.
From Planck scale to weak scale

Planck scale soft mass

Interactions from GUT scale to weak scale

Light at source

gas in between (line spectrum)

Soft term at weak scale knows everything between GUT to weak
Try together!