BSM at LHC

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On the theories in the market
and how LHC tackle them
LHC is far more important than any experiment in the past

- Expand experimental reach significantly

- Cutting into TeV scale first time. **Last chance** to solve naturalness problem.

- We have solid observational evidence of DM in our Universe. A new particle!

- Future experimental projects are now tied up with “LHC discovery”, ILC, Super B factory, DM searches.... **Huge responsibility to provide correct scientific results quickly.**
New Physics, Clue

Fine tuning in the Higgs sector

\[ \Pi_{\mu\nu} = (g_{\mu\nu} p^2 - p_\mu p_\nu) \Pi \]

Why Higgs vev is $O(200)$ GeV??

Others are reasonable

- $m_f \log \Lambda$ fermion mass
- $SU(2)$ gauge boson loops
- Higgs loop

\[ \begin{align*}
\text{top loop} & : -\frac{3}{8\pi^2} \lambda_t^2 \Lambda^2 \\
\text{top loop} & : -\frac{9}{64\pi^2} g^2 \Lambda^2 \\
\text{Higgs loop} & : \frac{1}{16\pi^2} \lambda^2 \Lambda^2
\end{align*} \]

\[ \sim - (2 \text{ TeV})^2 \]
\[ \sim (700 \text{ GeV})^2 \]
\[ \sim (500 \text{ GeV})^2. \]
New Symmetry → New Particle

- Need control on the radiative correction to the Higgs sector
- ideas
  - chiral symmetry (extended to boson sector)
  - global symmetry (little Higgs model)
  - gauge symmetry (gauge higgs unification)
- Or planck scale is low (Extra dimension model)
- On the other hand, we see no effect of BSM in radiative correction

\[ \delta L = \frac{(h^\dagger D_\mu h)^2}{\Lambda^2} \quad \Lambda > 5 \text{TeV} \]
Classic Solution: Supersymmetry

- exchange boson and fermion. $\phi \leftrightarrow \psi$

- sfermions(0), gaugino(1/2), higgsinos(1/2)

- SUSY change "dimension" (1 for boson 3/2 for fermion), relate mass and couplings

$$\Phi = \frac{1}{g^2} + M\theta^2 \quad \Phi WW = \frac{1}{g^2} F_{\mu\nu} F^{\mu\nu} + M\tilde{g}\tilde{g}$$

- chiral symmetry is extended to boson sector. No quadratic divergence

$$\lambda \psi_L \psi_R H \rightarrow \lambda \phi_L \psi_R \tilde{H} + \lambda \psi_L \phi_R \tilde{H}$$

SUSY breaking scenarios and mass spectrum

- Low energy phenomenology is not the end of the story.

- Hidden sector break supersymmetry. “flavor and CP” problem
  - gravity mediation, gauge mediation, anomaly mediation(string inspired mixed cases), “geometric separation”

- Problems (why alternatives are searched for)
  - Light higgs boson (hope and/or worry) little hierarchy
  - DM constraints
  - gravitino, string moduli.....
Alternative: Extra-dimension

- matter on brane, gravity in the bulk (Arkani-Hamed at al 1998)
  - fundamental gravity scale may be small. gravity effects at colliders

- extra space may not be flat (Randall and Sundrum, 99)

$$ds^2 = e^{-2kr_c\phi} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2$$

$$\Lambda = M_{Pl} e^{-kr_c\pi}$$

- Universal Extra dimension (Appelquist et al 2000)
  - particles also in the bulk, Translation is violated only at the boundary. KK level works as parity. LKK particles is stable

- Black Hole at collider.

- difficulty: divergence (higher dimension), cosmology
Discovery potential

\[ mn = k x_n e^{-k r_c \pi} \]

\[ c < 0.1 \text{ (curvature bound)}, \Lambda < 10 \text{ TeV (hierarchy)} \]

\[ c = \frac{k}{M_{Pl}} \]

\[ \Lambda < 10 \text{ TeV} \]

Region of Interest

see also EPJ C40  Collard et al

Litvin talk in Moriond
Dynamical symmetry breaking?

• Technicolor → Little Higgs model

• Higgs boson is goldstone boson of a large symmetry. $SU(5) \rightarrow SO(5)$

$$\Sigma(x) = e^{i\Pi(x)}/f \Sigma_0 e^{i\Pi^T(x)}/f \quad \frac{f^2}{8} \text{Tr} D_\mu \Sigma (D^\mu \Sigma)^\dagger$$

• Gauge symmetry: $SU(2)_1 \times SU(2)_2 \times U(1)_1 \times U(1)_2$

$$\left(g_1, g_2, g_1', g_2'\right)$$

• quadratic correction to Higgs sector starts from 2 loop

• top sector must be extended (extra top quark). 
  after all top-higgs coupling is the source of fine tuning.

$$\chi = (b_3, t_3, \tilde{t})$$

$$\chi = (b_3, t_3, \tilde{t})$$

$$\tilde{t}, \tilde{t}'$$

$$\frac{1}{2} \lambda_1 f e_{ijk} \epsilon_{xy} \chi_i \Sigma_{jx} \Sigma_{ky} u_3^c + \lambda_2 f \tilde{t} \tilde{t}^c + hc$$

• However it is rather difficult to make simple Little Higgs model and LEP data consistent.
difficulty comes from tree level Heavy-Light mixing

$$L_2 \rightarrow -\frac{g_1 g_2 (g_1^2 - g_2^2)}{4(g_1^2 + g_2^2)} W^a_{\mu L} W^a_{H} h^2 \rightarrow -\frac{g^2 (s^2 - c^2)^2}{8 f^2} W_L W_L h^4$$

$$(W_L^a = s W_1^a + c W_2^a)$$

• Various $v^2/f^2$ corrections, proportional to the coupling difference, $\Delta g = g_1 - g_2$

• $M^2(W_H) = (g_1^2 + g_2^2) f^2/4 \sim (gf/2)^2 > 2.7 \text{TeV}$

• $f > 4 \text{TeV}$ $m(t') > 7 \text{TeV}$, (Hewett et al JHEP, 2003) Fine turning is reintroduced
Little Higgs with T-parity

- gauge groups and matter contents respect T-parity. $SU(2)_1 \equiv SU(2)_2 \ U(1)_1 \equiv U(1)_2$
- T-odd matters are introduced. Looks like SUSY without gluino
- LEP constraint is weaker.
  - Heavy gauge bosons and triplet higgs boson live in T-odd sector. No tree level mixing
- Need more attempts to construct a model including symmetry breaking sector. (cf. the study of SUSY breaking sector.)
- UED has similar nature.
The Lesson is ......

- LEP constraint (small radiative correction)
  - New Physics scale $\Lambda$ is high, suggesting fine tuning.
  - Need symmetry to cancel divergence
  - top partner $\rightarrow$ top must be involved in the symmetry.
- “DM” and “radiative correction” $\rightarrow$ parity structure

LHC signature: strongly interacting particle decay into DM (and flavor sector involving b quark.....)
Basic objects at LHC

- jet and lepton momenta
  \[ p_{j1}, p_{j2}, \ldots, p_{l1}, p_{l2} \ldots \]
- Jet and lepton transverse momenta (to the beam)
  \[ p_{T1}, p_{T2}, p_{T3} \ldots \]
- \( E_{T\text{miss}} \): Sum of the transverse momenta of all particles.
- \( M_{\text{eff}} \): Sum of the transverse energies of first 4 jets + \( E_{T\text{miss}} \)

\[
M_{\text{eff}} \equiv \sum_{i=1,\ldots,4} p_{T_i} + \sum_{\text{leptons}} p_{Tl} + E_{T\text{miss}}
\]
DM and collider signature

- **“SUSY signature”**
  “Models with new colored particles decaying into a stable neutral particle--LSP”

- “New physics” are migrated into SUSY category.
  - Universal extra dimension lightest of first level KK is stable.
  - Little Higgs model with T parity. T parity in the model, T odd sector has stable particle ($B_H$)

- **Signal:**
  Assume mass difference is large
  High $P_T$ jets ($p_{T1}>100\text{GeV}$, $p_{T2,3,4}>50\text{GeV}$)
  $p_{T1}>20\text{GeV}$, $S_T>0.2$
  $E_{T\text{miss}} > \max(100\text{GeV}, 0.2M_{\text{eff}})$
Background and discovery

- The typical number of SUSY events are $10^5$ for 10 fb$^{-1}$, while BG rate is $10^{9-8}$ for W, Z and ttbar productions. $10^{-4}$ rejection of SM process is required.

- Understanding of the distribution is the key issue

- $P_T$ distribution of the jets, $M_{\text{eff}}$ distribution. (theoretical complexities)

- $E_{\text{miss}}$ distributions (Experimental complexities)
Discovery and Recent BG issues

- Bg process $pp \rightarrow W(Z)+X$, ttbar ....

- Lowest order process (ex $gq \rightarrow W q$) + “multiple parton final states” (ex. $gq \rightarrow W+ n$ jet not in soft and collinear region (ME collections, CKKW, Mangano)

- Some generators(ALPGEN, MADevent..) allow to simulate multi-parton final state. Matching between PS and ME is an issue. (Lessons from Tevatron)

- up to ttbar + 3 jet, $W(Z) +6$ jet (!) have been included in BG estimation. Results with full detector simulations are getting ready.
Simulation study of ME corrections

zero lepton channel

- High $P_T$ jets increase drastically when taking into ME.
- $K$ factor is $2 \sim 4$ for large $M_{\text{eff}}$.
- Scale uncertainty still remains (order of $\alpha^n(\mu)$), easily gets factor 2.
- BG is smaller in 1 lepton channel and dominated by $t\bar{t}$bar. calibration is easier

Tune $E_{T\text{miss}}$ cut.

1-lepton channel
**Discovery Potential**

5-sigma discovery potential on $m_0$-$m_{1/2}$ plane

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**100pb$^{-1}$**

$1$-lepton

- $m(\tilde{g}) \sim 1$ TeV
- $m(\tilde{q}) \sim 1$ TeV

**1 fb$^{-1}$**

0-lepton

- $m(\tilde{g}) \sim 1.6$ TeV
- $m(\tilde{q}) \sim 1.5$ TeV

**ATLAS preliminary**

- $m(\tilde{g}) \sim 0.8$ TeV
- $m(\tilde{q}) \sim 1.5$ TeV

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- **Only statistical error is included.**
- **Background** is estimated by Alpgen.
- **0-lepton mode**: More statistics is available.
- **1-lepton mode**: Relatively smaller background uncertainty.
- Major background is $t\bar{t}$ (+njets) is comparatively predictable.

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From Kanay’s Slide in SUSY06
• If both volume modulas T and compensator C contribute to the SUSY breaking,

\[ M_a = \left( \frac{l_a}{R} + \frac{b_a g_{GUT}^2}{16 \pi^2} \right) m_{3/2} \]

• mass spectrum can be quite degenerated. Change FT/FC, MSUGRA → UED like → AM

\[ \alpha = \frac{m_{3/2}(T + T^*)}{F T \log(M_{pl}/m_{3/2})} \]
**SUSY at LHC in degenerated limit**

- Degenerate SUSY = lower $P_T$ jets, small $M_{\text{eff}}$. Discovery gets difficult (no chance if all masses are same).

- "Benchmark" of degenerate scenario

- Need to take into account the background seriously

- $S/N < 1$, discovery is in ?? because of the background uncertainty

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**MSUGRA**

- $m(\text{LSP}) = 0.7M(\text{squark})$

**Kawagoe and Nojiri**

- $1.5 \text{ TeV gluino}$

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*Graphs showing the distributions of $P_T$ and $M_{\text{eff}}$ for different models.*
Little Higgs model with T parity

- fermion partner instead of top partner
- Typical “fermion” top partner production cross section is 0.2 pb at m(T)=800GeV.
- \( \frac{\sigma(\text{boson})}{\sigma(\text{fermion})} = 0.1 \)
- The difference comes from spin structure. Stop production is “mostly” p wave.

from Belyaev et al hep-ph 0609179
Reconstruction of top partners at LHC
(Matsumoto, Nojiri, Nomura.... to appear soon)

Top partner: Key particle of Little higgs model with T parity
\[ gg \rightarrow T_−T^*_−, \quad T_− \rightarrow tB_H \]
\[ \sigma = 0.2\text{pb for } m(T_−) = 800 \text{ GeV} \]
BG is huge \( \sigma(tt) \sim 1\text{nb} \)

- Clue: \( E_{\text{miss}} \) tend to be \( \sim 0.5 \) \( M_{\text{eff}} \) for the events with 2 DM.

- 2 “uncorrelated” top with same energy \( |p_{\text{CM}}| \). Large \( M_{\text{eff}} \) means large \( E_{\text{miss}} \) for fixed \( M(T_−) \).

\( \sigma = 0.2\text{pb for } m(T_−) = 800 \text{ GeV} \)
\( \sigma(tt) \sim 1\text{nb} \)

**Note:**
- \( g \rightarrow T_−T^*_−, T_− \rightarrow tB_H \)
- \( \sigma = 0 \) for \( m(T−) = 800 \text{ GeV} \)
- \( \sigma(tt) \sim 1\text{nb} \)
- \( |p_{\text{CM}}| \)
Top reconstruction

- hemisphere analysis: find two axes in an event

  F. Moortgat and L. Pape, CMS Physics TDR

- algorithm

  - take highest PT jet as seed of an axis. (A)

  - take 2nd jet with max $P_x \Delta R$ from the 1st jet as the seed of the 2nd axis (B)

  - assign jet and lepton activities to the “closer axis”. (C)

  - recalculate “axis=sum of particle in the hemisphere”, repeat. (D,E)

This is an unbiased selection

3 jet invariant mass distribution in a 1st hemisphere

Top peak!
Signal and BG

- Tops are seen in both hemispheres.
- Probability of top reconstruction is small for the $t\bar{t}$ background (because of $E_{T\text{miss}}$ cut).
- Need $b$ tag to make $t\bar{t}$ bar is a dominant background (not applied).
signal distribution & top background

- signal $E_{\text{miss}}$ distribution has a peak near $M_{\text{eff}}/2$
- BG peaks at $E_{\text{miss}} \ll M_{\text{eff}}$
- good margin for discovery due to the bump structure.

no K factor for signal and background
one of $m(jjj)$ is consistent to $m_t$

$m(T-) = 700$ GeV

L = 50fb$^{-1}$

ETmiss (for $M_{\text{eff}} = 1200 - 1400$ GeV)

ETmiss (for $M_{\text{eff}} = 1200 - 1400$ GeV with top)
Sensitivity to the mass

$M(T-) = 600\text{GeV} \quad M(DM) = 100\text{GeV}$

$M_{\text{eff}} > 1000\text{GeV}$

$E_{T\text{miss}} > 400\text{GeV}$

$\sigma = 0.98\text{pb}$

$M(T-) = 700\text{GeV} \quad M(DM) = 125\text{GeV}$

$M_{\text{eff}} > 1100\text{GeV}$

$E_{T\text{miss}} > 450\text{GeV}$

$\sigma = 0.38\text{pb}$

MT$_2$ for $M(B_H) = 150\text{ GeV}$
**SUSY parameter measurement**

**A brief history**

- early 1990
  - **JLC study:** define LC as the machine to measure SUSY parameters, spin, and interaction. check GUT relation $M_1:M_2$
  - **LHC** as a discovery machine.
  - **Snowmass 1996:**
    - **Trying to establish US participation at LHC,** "(ex-)Theorists" (Hinchliffe, Paige, ...) took LC concepts. Techniques for mass reconstruction were established at that time.
    - **ILC:** SUSY coupling measurements ('96 Nojiri et al, Feng et al....): physics point of LC over LHC

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**Image Description:**

- The top image shows a plot with the title "a) $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R$" and parameters such as $\sqrt{s} = 350$ GeV, 20 fb$^{-1}$, $\text{Pol. e}^{-} = +0.95$.
- The bottom image is a graph titled "Measurement of $\tilde{B}_{\tilde{g}}e$ coupling" with parameters $\mu = 300$ GeV, $\tan \beta = 2$.
Mass reconstruction at LHC

- Invariant mass distributions instead of energy distribution
  - Tag particles from a SUSY particle decay chains (jet selections are essential)
  - End point of distributions or distributions near the end point (momentums are aligned)
  - Exact Kinematical relation (long decay chains)
  - $P_T$ of the jets (Peaks at typical scale) $\Rightarrow M_{T2}$

- SUSY distributions" are not correction of the 1 dim distributions. It lives in multi-dimensional space---momentum space of jets and leptons.
determination of the boundary of phase space for mass determination.

Here is the trick!

**LSP**

\[ \widetilde{t}_R \]

\[ \tilde{\chi}_2^0 \]

\[ m(\text{ll}) \]

\[ m(jl) \]

\[ m(jll) \text{ with } m(\text{ll}) > 0.5 m(\text{ll})(\text{max}) \]

\[ \text{ee+}\mu\mu-\mu\mu \text{ subtraction is effective to select single channel} \]

\[ m(\text{jll}) \]

Hinchliffe et al (97)
fermion/boson? Left/Right?

- charge asymmetry in $j\ell(+ \text{ or } -)$ distributions (Barr, Goto et al.... ) in SUSY

- To have this asymmetry
  - $pp$ collider (squark> anti-squark)
  - squark /sleptons are dominantly left or right.

- neutralino is spin $1/2$

- SUSY is the chiral theory, gaugino-$sL-L$ vertex

- Distribution would be different for UED cases (Smillie and Webber, hep-ph 0406317, Alves et al hep-ph/0605067)

- general discussion (by Athanasious et al hep-ph 0605286) for general decays involving 4 new particles

Summary in SPS1a (most lucky case) from LHC/LC study

<table>
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<tr>
<th>particle</th>
<th>mass</th>
<th>error(low)</th>
<th>error(high)</th>
<th>particle mass</th>
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<td>16.3</td>
<td>8.0</td>
<td>bbll</td>
</tr>
<tr>
<td>squark(L)</td>
<td>540</td>
<td>21.2</td>
<td>8.7</td>
<td>jll</td>
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<tr>
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<td>11.8</td>
<td>M_{T2} 10GeV sys</td>
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<td>5.1</td>
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<td>$\tilde{\chi}_2^0$</td>
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<td>13.4</td>
<td>4.7</td>
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<tr>
<td>$\tilde{\chi}_1^0$</td>
<td>96</td>
<td>13.2</td>
<td>4.7</td>
<td></td>
</tr>
</tbody>
</table>

- LSP mass error is large, but mass differences are known precisely
- Access to 3 neutralino mass, information on 3 of (M1,M2,μ, tanβ)
- selectron and smuon mass error is about same to that of N02
- stau mass also can be measured from tau tau end point. many fake tau background. Need more study, but don't be nervous.
Trying to pin down Dark matter nature

- DM density: for SPS1a
  - slepton exchange \((^\wedge)^\nu\)
  - stau co-annihilation \((^\wedge^\wedge)\); not enough in co-annihilation region because dependence is so large. (Discussed in Baltz et al)
  - higgs s-channel exchange \((; ;)\); Heavy higgs is not accessible in many cases.
  - higgsino component \((^\wedge^\wedge)\)

MN, Polesello and Tovey hep-ph/0512204

Figure 17: Spin-independent neutralino-proton direct detection cross section (pb)

**top in SUSY events**

- N(jet)>>7 typically (not as simple as $t\bar{t}$ + missing events.)

Look for jet pairs with $m(jj)\sim M_w$ and $m(bjj)\sim M_t$ (biased analysis)

- Background to $t\rightarrow bW\rightarrow bjj$ is estimated from events in the sideband $m_{jj}<M_w-15\text{GeV}$, $m_{jj}>M_w+15\text{GeV}$.

- Reconstructed top quarks are used to study $tb$ distribution

- Warning about jet background (more high $p_T$ jet) We may have to require leptons.
gluino → stop reconstruction

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

depends on stop mass and mixing angles->edge heights and end point* gives constraints to 3rd generation SUSY breaking, B physics....

\[ M_{tb}^{-w} = \frac{Br(t)M_{tb}(t) + Br(\bar{b})M_{tb}(\bar{b})}{Br(t) + Br(\bar{b})} \]

Uncertainty(QCD): fragmentation (Herwig : Phythia =1.3:1) jet finding algorithm.... How to tune MC?
Thoughts

- New physics at LHC will be in top sector with missing momentum (LEP precision+hierarchy+DM+wish)

  - fermionic top partner -> discovery. Kinematical understanding is necessary. Don’t just count S/B.

  - scalar top (SUSY) -> Other partners...

- Models are increasing. (They will disappear quickly once LHC starts...) How to feed back the theoretical ideas to experimentalists?, especially when we start to see deviation from SM/SUSY.

- Need model independent output from experimentalists (not only MSSM, MSUGRA)

- How to feedback reality to the theorists?: Need quick publication from experimental side in accessible format. Learning from astrophysicists?