Physics at LHC

Junichi Tanaka
ICEPP, University of Tokyo

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Theory meeting on Particle Physics Phenomenology
KEK
Outline

- Introduction
  - What is the LHC?
  - Why is the LHC?
  - ATLAS Detector

- Physics
  - SM Higgs
  - MSSM Higgs
  - SUSY
  - Extra-dimensions

- Summary
What is the LHC?

Proton-Proton (pp) Collider 14TeV

- 27km LHC tunnel
  - Installed in the existing LEP tunnel
- 1232 superconducting dipoles
  with $B = 8.3$ T working at 1.9 Kelvin
- Two general-purpose pp experiments
  ATLAS vs CMS
Large Hadron Collider

LHC tunnel (27km in circumference) (~100m underground)

CERN

ATLAS

CMS

Jura Mountains

Geneva Airport

France side

Swiss side
Time Schedule of LHC

- April, 2007: first beam, commissioning
- **September, 2007**: 7 months with $L=10^{33}$ cm$^{-2}$s$^{-1}$ "Low luminosity" run
  
  **Physics:** $L=10^{fb^{-1}}$ -> Higgs/SUSY?

- 2007~2009: Low luminosity run
- $\sim$2009: $L=10^{34}$ cm$^{-2}$s$^{-1}$ "High luminosity" run

ATLAS Cavern was handled to ATLAS on April 14th, 2003.
Why is the LHC?

**High energy**
- Discovery of SM Higgs
  ~ the last unobserved particle
- Discovery of New Physics

**High luminosity**
Measurement of SM Higgs properties etc.

At the first year 2007~8 (L=10fb⁻¹)

<table>
<thead>
<tr>
<th>Process</th>
<th>Event rate at 2 ⋅ 10³³</th>
<th>2007 L=10fb⁻¹</th>
<th>Comparison (estimation at 2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt</td>
<td>1.6 Hz</td>
<td><strong>10⁷</strong></td>
<td>10⁴ Tevatron-2</td>
</tr>
<tr>
<td>bb: P_T&gt;10GeV</td>
<td>200 KHz (HLT 10Hz)</td>
<td><strong>2 ⋅ 10¹²</strong> (10⁸ inc. di-μ)</td>
<td>5x10⁸ Belle</td>
</tr>
<tr>
<td><strong>Higgs (130GeV)</strong></td>
<td>200/h</td>
<td><strong>5 ⋅ 10⁵</strong></td>
<td>-------</td>
</tr>
<tr>
<td><strong>SUSY (1TeV)</strong></td>
<td>20/h</td>
<td><strong>5 ⋅ 10⁴</strong></td>
<td>-------</td>
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</tbody>
</table>

LHC is Top & B-factory.
LHC can be Higgs & SUSY factory!!!

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1. Inner tracking system: Si, TRT, 2T solenoid magnet
2. Liq. Ar EM calorimeter
3. Muon spectrometer: air-core toroidal magnet

E, P resolution
(P ~ 100 GeV)

\( \mu \sim 2\% \)
\( e, \gamma \sim 1.5\% \)
Jets \sim 8\%

- 40 MHz beam crossing
- Readout channel = 160 M channels
- Raw data = 320 Mbyte/sec (1 TB/hour)
Higgs

The last unobserved particle of SM

and

The most important particle of SM
SM Higgs Production at LHC

Gluon Fusion

Vector Boson Fusion (VBF)

Associated WH, ZHW, Z

Associated ttH, bbH

Excluded by LEP

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SM Higgs Decay

Observation of Higgs by multi modes

Can study Higgs properties in detail.

$114.4 < m_H < 193 \text{ GeV}/c^2 \text{ @95\% C.L.}$

$bb, \tau\tau, \gamma\gamma, WW, ZZ$

are important at the above region.

LEPEWWG Summer 2003

Branching ratios
## Summary of studies for SM Higgs

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>Mass region and purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gluon Fusion</strong></td>
<td>$H \to \gamma\gamma$</td>
<td>110-140GeV</td>
</tr>
<tr>
<td></td>
<td>$H \to ZZ \to 4 \ell$</td>
<td>140-1000 GeV</td>
</tr>
<tr>
<td></td>
<td>$H \to WW$</td>
<td>130-170 GeV</td>
</tr>
<tr>
<td><strong>Vector Boson Fusion</strong></td>
<td>$H \to \tau\tau$</td>
<td>110-140GeV</td>
</tr>
<tr>
<td></td>
<td>$H \to WW$</td>
<td>130-200GeV</td>
</tr>
<tr>
<td></td>
<td>$H \to \gamma\gamma$</td>
<td>110-140GeV</td>
</tr>
<tr>
<td></td>
<td>$H \to bb$</td>
<td>110-140GeV</td>
</tr>
<tr>
<td><strong>ttH</strong></td>
<td>$H \to bb$</td>
<td>110-130GeV</td>
</tr>
<tr>
<td></td>
<td>$H \to \tau\tau$</td>
<td>110-130GeV</td>
</tr>
<tr>
<td></td>
<td>$H \to WW$</td>
<td>130-180GeV</td>
</tr>
<tr>
<td><strong>WH</strong></td>
<td>$H \to WW$</td>
<td>140-170GeV</td>
</tr>
</tbody>
</table>
H → ZZ* → 4leptons

Can observe a peak of SM Higgs because of a better mass resolution $\sigma \sim 1.4$ GeV

M$_H$=130,150,170 GeV
Br(H → WW) ~ 100% at M$_H$=170 GeV

M$_H$=120 GeV

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**VBF** process became major after ATLAS Physics TDR (1999)

1. High Pt jets in forward region
2. Rapidity gap (no color flow)

$\tau^+ \tau^- \rightarrow h \nu_\tau \ell \nu_\tau \ell$  $M_H=120\text{GeV}$  $\tau^+ \tau^- \rightarrow \ell\ell 4 \nu$

- Use missing Et in order to reconstruct $M_{\tau\tau}$.

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Cannot make a peak in case of WW.
Signal shape is similar with background shape but the number of signal is much larger than background with a factor of $>5$. 
Discovery potential of SM Higgs

Can discover Higgs with $L=30\text{fb}^{-1}$ by $>8\sigma$
($(M_H>114\text{GeV}:\text{LEP limit})$)

$M_H < 200\text{GeV}$:
- Light case: VBF $\tau\tau$
- Heavy case: VBF WW
- Can observe Higgs by multi-modes.

$M_H > 200\text{GeV}$:
- $H\rightarrow ZZ\rightarrow 4\text{lepton}$ by $>20\sigma$
Discovery potential of SM Higgs

$\int L \, dt = 10 \text{ fb}^{-1}$

$10\text{fb}^{-1}$ ATLAS

$\sim 5\sigma$ with $L=10\text{fb}^{-1}$

$\rightarrow$ Discovery of Higgs within $\sim 1 \text{ year}$
Higgs Mass

The last unknown parameter in SM

- Accuracy ~ 0.1%
- Main uncertainty comes from calibration.

\[ M_H = 120 \text{GeV}, \ 300 \text{fb}^{-1} \]
\[ \Rightarrow \Delta M_H = 150 \text{MeV} \]
Accuracy of measurement of coupling constant

$g_t, g_\tau, g_Z, g_W : \sim 20\%$

$g_b : \sim 50\%$

$M_H = 115-140\text{GeV}$
MSSM Higgs Sensitivity for $5\sigma$-discovery

2HDM -> 4 Higgs : $h, H^0, A^0, H^+$

We can observe two or more Higgs over most of parameter space.

"Only $h$" and "$h \sim$ SM Higgs"

-> How to disentangle SM/MSSM?
Sensitivity for the $5\sigma$-discovery of MSSM Higgs

MSSM Higgs can be discovered by $L=30\text{fb}^{-1}$. 

$30\text{fb}^{-1}/\text{exp}$

ATLAS+CMS
SUSY

New symmetry: Boson and Fermion

It is broken. -> at ~1TeV

One of candidates to achieve GUT

LSP -> DM?
(\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}) \text{ Production Cross Section at LHC}

\begin{itemize}
  \item Large production X-sec
  \item As mass is larger, high x of pdf is more important.
\end{itemize}

Produced by "strong interaction"

<table>
<thead>
<tr>
<th>Mass of (\tilde{q}, \tilde{g}) (TeV)</th>
<th>X-sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m(\tilde{q}) = m(\tilde{g}) = 0.5)</td>
<td>(\sim 100\text{pb}) main : (\tilde{g}\tilde{g})</td>
</tr>
<tr>
<td>(m(\tilde{q}) = m(\tilde{g}) = 1.0)</td>
<td>(\sim 3\text{pb})</td>
</tr>
<tr>
<td>(m(\tilde{q}) = m(\tilde{g}) = 2.0)</td>
<td>(\sim 20\text{fb}) main : (\tilde{u}\tilde{u}, \tilde{u}\tilde{d})</td>
</tr>
</tbody>
</table>
## Decay of $\tilde{g}, \tilde{q}$

<table>
<thead>
<tr>
<th></th>
<th>$m(\tilde{g}) &lt; m(\tilde{q})$</th>
<th>$m(\tilde{g}) \approx m(\tilde{q})$</th>
<th>$m(\tilde{g}) &gt; m(\tilde{q})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g}$</td>
<td>$q\bar{q}\tilde{B}^0 (\approx 1)$</td>
<td>$\tilde{g} \to q\bar{q}\tilde{B}^0 (\approx 1)$</td>
<td>$\tilde{g} \to q\bar{q}$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{g} \to q\bar{q}\tilde{W}^0 (\approx 2)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$q\bar{q}\tilde{W}^\pm (\approx 4)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{q}_L$</td>
<td>$\tilde{q}_L \to q\tilde{g}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{q}_R$</td>
<td>$\tilde{q}_R \to q\tilde{g}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Decay is mainly determined by the kinematics. Model dependence : small
Event Topology of SUSY

Multi-cascade decay

$\tilde{\chi}_1^0$ remains.

Missing $E_t$

High Pt jets
Event Topology of SUSY

Expected event topology is

- multi leptons
- $E_T$ + High P_T jets + b-jets
- $\tau$-jets

Signal from SUSY

Discovery is easy, since X-sec is large enough.

- BG : tt, QCD, Z+njets, W+njets
- Experimental key-point
  - Measurement of Missing $E_T$
  - Calibration/Correction of high P_T jet

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Discovery potential of mSUGRA

5σ discovery region using Missing Et and Jets

L=300fb⁻¹ : ~2.5TeV

Cold DM candidate: ~1 week

~1year run (L=10fb⁻¹) : ~2TeV

~1month run (L=1fb⁻¹) : \( \tilde{g}, \tilde{q} \) < ~1.5TeV

Search at Lep2/Tevatron-II.

No EWSB
Next step: Detailed study of SUSY

Mass reconstruction

How to?
1. Select decay chain: key point
   - Clean?
   - Other similar decay chain?
   - Cascade chain?
2. Make distributions of mass, $P_T$ and so on.
3. See Edge and endpoint to constraint mass relation of SUSY.

$$M_{\ell\ell}^{\text{max}} = m(\tilde{\chi}_2^0) \sqrt{1 - \left(\frac{m(\tilde{\ell}_R^\pm)}{m(\tilde{\chi}_2^0)}\right)^2} \sqrt{1 - \left(\frac{m(\tilde{\chi}_1^0)}{m(\tilde{\ell}_R^\pm)}\right)^2}$$

[Problem]
- Model dependence: large
- In general, the number of constrains is smaller than that of unknown parameter (mass).

By using SUSY Model, determine mass.
But
- When there are three or more “2body decay chain,” we can determine mass model-independently.
Three “2-body decay chains”

$\tilde{q}$, $\tilde{\chi}_2^0$, $\tilde{\ell}_R^\pm$, $\tilde{\chi}_1^0$

$m(\ell \ell)$ spectrum
- end-point: 109 GeV
- exp. precision $\sim$0.3%

$m(\ell \ell j)^{\text{max}}$ spectrum
- end-point: 272 GeV
- exp. precision $\sim$2 %

$m(\ell \ell j)^{\text{min}}$ spectrum
- end-point: 552 GeV
- exp. precision $\sim$1 %

$m(\ell \ell j)^{\text{max}}$ spectrum
- end-point: 479 GeV
- exp. precision $\sim$1 %

“4 constraints (measurements) $\rightarrow$ 4 unknown mass”
$\rightarrow$ can determine masses model-independently.
(error $\sim$ 3-12% in case of 700-800 GeV squark, gluino)
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Problem of SUSY measurements

- Many many decay chains!
- Can we say that “we use this decay chain!”?
- Model dependent
- SUSY itself becomes background for detailed SUSY studies.

Discovery is easy, But measurement of parameters is difficult.
String theory naturally requires Extra Dimensions.
KK graviton  $gg\rightarrow gG$ (1jet + Missing $E_T$)

$E_T$ distribution

<table>
<thead>
<tr>
<th>$jZ(\nu\nu)$</th>
<th>$jW(\tau\nu)$</th>
<th>$jW(\nu\nu)$</th>
<th>$jW(\mu\nu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>523</td>
<td>151</td>
<td>12</td>
<td>14</td>
</tr>
</tbody>
</table>

Events for HL, 100 fb$^{-1}$

for $E_T^{jet} > 1$ TeV

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>$M_D$ (TeV)</th>
<th>Events</th>
<th>$S_{max} = S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5</td>
<td>1430</td>
<td>61.4</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>366</td>
<td>13.8</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>135</td>
<td>5.1</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>705</td>
<td>26.7</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>131</td>
<td>5.0</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>391</td>
<td>14.8</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>53</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Black Hole

In case of Planck scale ~ TeV:
When impact parameter of initial partons is smaller than Rs, a BH can be produced.

M_{Pl}=1\text{TeV}, \ n=2 \quad M_{BH}=6.3\text{TeV}

(Energetic and spherical event)

\[ \text{M}_{pl} < 5\text{TeV} \quad \text{for } n=2-7 \quad (L=1\text{fb}^{-1}) \]
Summary

- LHC : Start at 2007!
- Higgs
  - SM Higgs can be discovered within 1 year ($L=10\text{fb}^{-1}$).
  - Need a few years to measure Higgs properties.
  - MSSM Higgs : Two or more Higgs observable in many cases.
- SUSY
  - Discovery is easy!
  - Measurement of parameters is difficult.
- Other New Physics
  - **High discovery potential** for them : New physics at “a few TeV” can be discovered.
- Other physics of Standard Model
  - Top, W, b : **Precise** measurements

New Physics is coming soon!