What Will LHC Bring Us: Higgs, SUSY, ---, or Surprises?

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ICEPP (International Center for Elementary Particle Physics)

1. Introduction  
2. LHC Project  
3. Physics Expected at LHC  
4. Summary
1. Introduction
Hadron colliders giving effectively \( \sim 5 \) higher energies than \( e^+e^- \) colliders

\[ E(\text{parton-parton}) \sim \frac{1}{6} \cdot E(\text{proton-proton}) \]

“Highest energy on the Earth”

(10T \( \to \) 20PeV \( \to \) \( E_{cm} \sim 6 \text{TeV} \))
Brief History of Particle Physics in the Last 30 Years


SPEAR                     PEP                                   SLC
J/ψ, τ                    (BNL)               TRISTAN
Υ                        (FNAL)

PEP-II                     KEK-B
ντ                        (FNAL)

SppS
W, Z

Tevatron
ντ (FNAL)

DORIS             PETRA                                         LEP
Pc(χc)          gluon                              Nν, Mt, SM, SUSY-GUT

ICEPP was established

LHC
Higgs
SUSY
??
The Standard Model

SM: checked with <1% accuracy, but
  • Higgs not yet found ("Missing link" of SM)
  • $m_\nu \neq 0$
  • sign of SUSY-GUT
  • Why 3 families?
  • gravity?
  • SM is not an ultimate theory, ---

• Find Higgs
• Look for something beyond SM
2. LHC Project

Accelerator and Detectors
The Large Hadron Collider

14 TeV Proton-Proton Collider At CERN
LHC Experiments

General-purpose pp experiments

ATLAS

CMS

LHCb

pp experiment dedicated to $b$-quark physics
- Single-arm forward spectrometer

ALICE

- Heavy-ion experiment (Pb-Pb collisions)
  - at ~6 TeV/nucleon
  - Quark-gluon plasma studies
**LHC Machine Parameters**

**Proton-Proton Collider**
- Circumference: 26.7 km (using LEP tunnel)
- Beam Energy: **7 TeV** (Injection E: 450 GeV, PS→SPS→LHC)
- 1232 MR dipoles: B=8.33 Tesla, L=14.3m, 1.9K (2-in-1 magnets)
- 368 MR quads: B’=223 T/m, L=3.1m
- No. of Bunches: 2808
- Bunch spacing: 24.95 ns
- Bunch size at IP: 16 µm
- Bunch length at IP: 77 mm
- Half crossing angle: 160 µ rad
- Luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$

**Heavy Ion Collider**
- Pb-Pb $E_{cm}$: 1312 TeV
- Pb-Pb Luminosity: $2 \times 10^{27}$ cm$^{-2}$s$^{-1}$

*Challenging!*
LHC: Proton-Proton Collider at $E_{CM} = 14$ TeV

Many spectator partons $\rightarrow$ large BG

High collision energy $\rightarrow$ New physics
Large BG $\rightarrow$ Analysis is not easy.

Discovery potential 😊

Precision measurement ?
LHC Experimental Challenge

- **High Interaction Rate**
  - 40MHz beam crossing
  - first trigger decision, fast electronics
  - data recorded at ~100 Hz

- **Large Particle Multiplicity**
  - ~20 superposed events in each bunch crossing (min. bias events)
  - ~1000 tracks emerge into the detector every 25 nsec
  - need highly granular detectors, i.e. large number of channels

- **High Radiation Level**
  - neutrons, ☢’s
  - radiation hard detectors and electronics

- **Huge Amount of Data**
  - World-wide computing grid (for data analysis and storage)
Cross Section vs Particle Mass at LHC

Puzzle in the next slide
Find 4 straight tracks.

Challenges for sub-detector system
(Tracking in Inner Detector)

Such an event every 25 nsec without Higgs!

“Searching a needle in a haystack”

(H → ZZ → 4 ℓ )
Answer

Make a “cut” on the transverse momentum of the tracks: \( p_T > 2 \text{ GeV} \)

or

find muon tracks.
Muon Detection and Magnet System

**ATLAS** A Toroidal LHC ApparatuS

**CMS** Compact Muon Solenoid
ATLAS Detector

Toroid Magnets

EM Calorimeter

Muon Spectrometer
(air-core Toroid)

Hadron Calorimeter

Solenoid Magnet

Inner Detector

(Weight = 7000 ton)

42m

23m

ATLAS Collaboration
- 35 countries
- 150 institutions
- 1800 physicists (incl. engineers)
- **Solenoid Magnet** (2T field)
- **Pixel Detectors** $\sigma(\rho\phi) = 12 \mu m$ (1.4 $\times$ $10^8$ channels)
- **Strip Detectors** $\sigma(\rho\phi) = 16 \mu m$ (6 $\times$ $10^6$ channels)
- **Transition Radiation Tracker** $\sigma(\rho\phi) = 170 \mu m$/straw (5 $\times$ $10^5$ channels)

$\Rightarrow \sigma(p_T)/p_T \sim 0.4 \ p_T$ (p_T in TeV)
ATLAS Liq. Ar ECAL

ATLAS HCAL (lead+Scinti.)
Muon Detector

- **Monitored Drift Tubes** (|q| < 2) with a single wire resolution of 80 μm
- **Cathode Strip Chambers** (2 < |q| < 2.7) at higher particle fluxes
- **Resistive Plate Chambers** (|q| < 1.05) with a good time resolution of 1 ns
- **Thin Gap Chambers** (1.05 < |q| < 2.4) at higher particle fluxes
ATLAS Magnet System

5m × 26m barrel s.c. toroid
Activities of ATLAS-Japan Group

15 Institutions (UT/ICEPP, KEK, Tsukuba, TUAT, TMU, Shinshu, Ritsumeikan, Kyoto, KUE, Kobe, NUE, Okayama, Hiroshima, HIT, NIAS)

~50 Staffs (+ Students)

Toroid Magnets (Air-Core)  Hadron Calorimeter  EM Calorimeter  Muon Spectrometer

Inner Detector  Solenoid Magnet

+ DAQ  + Software  + Regional Center
Thin Gap Chambers

for Muon Triggering in Endcap Region (1.05 < |η| < 2.4)

Japanese group is making 1056 / 3600 chambers all the electronics

TDC/TMC for MDT is also a Japanese contribution.
**Japanese Share of the Work**
- 6000/10600 Detectors
- 2500/2500 Hybrid Boards
- 980/2220 Modules

**Production Schedule**
- Sep. 2004 Modules Ready
- End 2004 Cylinders Ready

**Inner Tracker**

**Barrel Silicon Strip Modules**

**Wire-Bonding of the Module**
ATLAS Magnet System

Fe yoke (Calorimeter)

Barrel toroid

End-cap toroid

Central Solenoid
ATLAS raw data:

- 2.8 PB/year
- \(\sim 4 \text{M CD-Rs}\)

For all LHC experiments, need:

- \(\sim 2000\text{k CPU: } 100,000\text{ PCs}\)
- \(2600\text{ TB disk}\)
- \(20\text{ PB tape}\)

Regional Centers

Computing GRID / LCG

\(~2\text{ MB/event}\)

Data Analysis System

Regional centers and world-wide network for LHC data analysis

UT/ICEPP

USA

UK, F, D, I, ---
Low-β Quadrupoles

- **Production in progress**
  - 16 of 18 (incl. 2 spares) Quads. Completed
  - Production to be completed, early 2004

- **Test at KEK**
  - 14 magnets tested
  - Acceptable Training
  - Good field quality and stability

- **Delivery to Fermilab for cryostating**
  - 13 Quads delivered

Tests at KEK Warm measurement
ATLAS Status and Schedule

- Detector parts under construction
- Experimental hall ready (June 2003)
- Detector installation in the pit (by end 2006)
- Detector commissioning (beginning 2007)
- Single beam injection (Apr. 2007)
- Start experiment with pp collisions (from summer 2007)
Tests of 14m magnets

- First beam transfer line magnet installed (Dec. 2003)
- 154 SC dipole magnets (= first octant) delivered (Dec. 2003)

LHC Status and Schedule

- LHC ring closed (end 2006)
- Cooling LHC (beginning 2007)
- Beam commissioning (Apr. 2007)
- Start pp collisions (June 2007)

Test of handling system with the first cryodipole in LHC tunnel (27. Jan. 04)
"CERN/LHC Budget Crisis?"

In 2001, it became apparent:
- cost increase for LHC completion
- tight schedule

In 2002, ERC recommended:
- cut non-LHC activities
- delay the schedule → start-up in 2007

"Old concerns have been overcome:
- the project’s cost is stable and its schedule unchanged, foreseeing first beam in April 2007 with first collisions following in June.” (Council, Dec. 2003)

"LHC is the utmost priority of CERN."
3. Physics Expected at LHC
SM Higgs
What do we know today about it?

• Needed in SM to generate particle masses

• Mass not predicted by theory except that $m_H < 1000$ GeV (from Unitarity)
  $\rightarrow$ tighter constraint from the argument of Landau pole and vacuum stability

• $m_H > 114.4$ GeV from direct searches at LEP

• Indirect limits from fit of SM to:
  -- LEP1/SLD precise measurements at $\sqrt{s} = m_Z$
  -- $m_W$ measurement LEP2/Tevatron
  -- $m_{top}$ measurement at Tevatron

Best fit of SM to data
(minimum $\chi^2$) found for

$m_H = 91^{+58}_{-37}$ GeV

$m_H < 219$ GeV (95% C.L.)

$\Rightarrow$ Higgs could be just around the corner!
Higgs at Tevatron Run-II?

\[ M_H < 120 \text{ GeV at } 3\sigma \text{ by 2007 (?) } \]
Higgs Production at LHC

Gluon Fusion

VBF

Asoc. Prod. with W/Z

Asoc. Prod. with t/b

Excl. by LEP

\[
\sigma(\sqrt{s} \rightarrow H+X) \quad \sqrt{s} = 14 \, \text{TeV}
\]

\[
m_t = 175 \, \text{GeV}
\]

CTEQ4M

Events for $10^5 \, \text{pb}^{-1}$

M. Spiro et al.
NLO QCD

$gg \rightarrow H$

$q\bar{q} \rightarrow Hq\bar{q}$

$q\bar{q} \rightarrow HW$

$gg, q\bar{q} \rightarrow Hbb$

$q\bar{q} \rightarrow HZ$

$M_H (\text{GeV})$

$[0, 1000]$
Observation of multiple decay modes

- Detailed study of Higgs properties

5 important decay modes in the mass region indicated by LEP
## Promising channels for SM Higgs boson ($H<140\text{GeV}$)

### Decay modes

<table>
<thead>
<tr>
<th>Production modes</th>
<th>bb</th>
<th>$\tau\tau$</th>
<th>$\tau\tau$</th>
<th>WW</th>
<th>ZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \to H$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>? ($Y_b$)</td>
<td>Discovery $Y_\tau G_w$</td>
<td>? (Discovery)</td>
<td>Discovery $G_w^2$</td>
<td></td>
</tr>
<tr>
<td>$ttH$</td>
<td>$Y_t Y_b$</td>
<td>$Y_t Y_\tau$</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>WH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- BG too high
- or Br too small

Blue: we can measure couplings and mass
## Promising channels for SM Higgs boson ($H > 140\text{GeV}$)

### Decay modes

<table>
<thead>
<tr>
<th>Production modes</th>
<th>Decay modes</th>
<th>bb</th>
<th>$\bar{b}b$</th>
<th>$\bar{t}t$</th>
<th>$WW$</th>
<th>ZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg $\rightarrow$ H</td>
<td>$bb$</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>Discovery</td>
<td>Discovery</td>
</tr>
<tr>
<td>VBF</td>
<td>$\bar{t}t$</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>Discovery</td>
<td>GwGz</td>
</tr>
<tr>
<td>ttH</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>$GwY_t$ (&lt;180 GeV)</td>
<td>-----</td>
</tr>
<tr>
<td>WH</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>Discovery</td>
<td>-----</td>
</tr>
</tbody>
</table>

- $\square$: BG too high
- -----: $\square$ or Br too small
- Blue: we can measure couplings and mass
H → ZZ* → 4 leptons

CMS

M_H=130GeV

ATLAS

M_H=120GeV
\[ \tau^+ \tau^- \rightarrow h \nu \tau \ell \nu \tau \nu + \ell \ell 4 \nu \]

**Feature of VBF Process:**
- High Pt jet in the forward region
- Higgs decay products observed in the central rapidity gap (no color flow)

\[ M_H = 120 \text{GeV} \]

\[ W^+ W^- \rightarrow \ell \nu \ell \nu \]

\( >5\sigma \text{ for } 140<M_H<200 \text{ GeV with } 10 \text{ fb}^{-1} \)
Discovery Potential of SM Higgs

For the int. lumi. of 30 fb$^{-1}$, 
> 8 $\sigma$ discovery
($M_H > 114$ GeV: LEP limit)

- Light Higgs: VBF
- Heavy Higgs: VBF $\cdot$ WW
- $M_H < 200$ GeV: mult. decay mode
- $M_H > 200$ GeV: $> 20 \sigma$ with
  $H \rightarrow ZZ \rightarrow 4$lepton

SM Higgs would be discovered within one year after LHC start (10 fb$^{-1}$) with $> 5 \sigma$.

$\Rightarrow$ And what’s more?
Measurement of Higgs Mass

ATLAS
300 fb$^{-1}$

$\Delta m_H/m_H \sim 0.1\%$

$H \rightarrow \gamma\gamma$
$H \rightarrow ZZ \rightarrow 4l$

All channels (assuming abs. scale of EM cal. known to 0.1\%)
All channels (if it’s known to 0.02\%)

ATLAS
300 fb$^{-1}$

And its decay width
Higgs Spin and CP

From angular distributions of decay products in $H \rightarrow ZZ \rightarrow 4l$

- Angle between decay planes of two Z’s from Higgs decay

Azimuthal angle distribution of two forward tagging jets in VBF
Measurement of Coupling Constants

Major error source is BG
(10 – 40 %)
→ Need study of QCD/MC

\( y_t, y_b, g_{ZZH}, g_{WWH} \)
will be determined with
\(~20\%\)
accuracy.
\( (M_H = 115 – 140 \text{ GeV}) \)
Super Symmetry

Symmetry between fermions (matter) and bosons (forces)

**Standard Model Particles**

- **Quarks**
  - u, c, t, d, s, b

- **Leptons**
  - ν_e, ν_μ, ν_τ, e, μ, τ

  **3 Generations**

- **Gauge Particles**
  - γ, Z^0, W^±, g

  **GUT?**

**Higgs**

**Not yet found**

**SUSY Particles**

- **Scalar-quarks**
  - ù, ù_c, ù_t

- **Scalar-leptons**
  - ù_e, ù_μ, ù_τ

- **Gauginos**
  - ù_γ, Z^0, W^±, g

- **Higgsinos**
  - ì̄, ì̄_H
Motivations for SUSY

- Solution for the hierarchy problem (protect $m_H$ from divergence)
- Unification of all the forces including gravity
- Provides an important candidate for Dark Matter

Experimental indications:
- Gauge coupling unification (with low E SUSY)
- low mass Higgs

Grand Unified Theories

[Graph showing coupling constants and mass scale]
Minimal Supersymmetric extension of the Standard Model (MSSM) which has minimal particle content (two Higgs doublets)

But still it predicts many new particles and many new parameters! (SUSY is not a perfect symmetry.)

MSSM particle spectrum:

5 Higgs bosons: \( h, H, A, H^\pm \)

- quarks \( \rightarrow \) squarks \( \tilde{u}, \tilde{d}, \text{etc.} \)
- leptons \( \rightarrow \) sleptons \( \tilde{e}, \tilde{\mu}, \tilde{\nu}, \text{etc.} \)
- \( W^\pm \rightarrow \) winos \( \rightarrow \chi^\pm_1, \chi^\pm_2 \) 2 charginos
- \( H^\pm \rightarrow \) charged higgsino \( \rightarrow \chi^{0}_{1,2,3,4} \) 4 neutralinos
- \( \gamma \rightarrow \) photino
- \( Z \rightarrow \) zino
- \( h, H \rightarrow \) neutral higgsino
- \( g \rightarrow \) gluino

\( \chi^0_1 \) is a good candidate of Cold Dark Matter
MSSM Higgs sensitivity at LHC

- $h, H^0, A^0, H^+ -$
- described by 2 parameters
  $(M_A, \tan \beta)$ in tree level
  $(\tan \beta = v_u/v_d)$

- large $\tan \beta \rightarrow$ $bbH/A$ coupling becomes large.
  $H/A \rightarrow bb$

- charged Higgs in $gb \rightarrow tH^-$
  for $\tan \beta > 10$

$h \sim H_{SM}$

Most region will be covered with $30 fb^{-1}$
H/A Production

- Important channel to determine $\tan \beta$

$gg \rightarrow bbH/A \rightarrow \tau\tau, \mu\mu, bb$

$\tan \beta$

$H/A \rightarrow \tau\tau \rightarrow \text{had lep}$

$H/A \rightarrow \mu\mu$

$H \rightarrow ZZ^0 \rightarrow 4\text{ leptons}$

$H/A \rightarrow hh \rightarrow b\bar{b}b\bar{b}$

$A \rightarrow Zh \rightarrow l\bar{b}b\bar{b}$
H^+ - Production

(t,b) Br=90%
(τ,ν) 10%

suppressed at \( \tan \beta \approx \sqrt{m_t / m_b} \)
Mediation of SUSY Breaking

Hidden sector

Gravity int.

SUSY

Gravity mediation (SUGRA)
- $m_0$, $m_{1/2}$, $A_0$, tan$\beta$, sign($\mu$)
- LSP = $\chi^0_1$

m$_0$ : scalar mass
m$_{1/2}$ : gaugino mass
A$_0$ : trilinear coupling const.
$\mu$ : higgsino mass

Messenger

SUSY

Gauge mediation (GMSB)
- M, $\Lambda$, $N_S$, tan$\beta$, sign($\mu$)
- LSP = $\tilde{G}$, NLSP = $\chi^0_1$, $l_R$

10$^{11}$ GeV ?

1 TeV

100 GeV

E

$M_{\text{Planck}}$

$M_{\text{GUT}}$

$100$ TeV ?

SUSY particles

SM particles

Observable sector

Gauge int.
Production cross section of SUSY particles at LHC

mSUGRA model

- $\tilde{g} : 2\text{TeV}$
- $\tilde{q} : 2\text{TeV}$
- $\tilde{g} : 1\text{TeV}$
- $\tilde{q} : 1\text{TeV}$

$(\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q})$ produced via strong processes

- large cross section
- not much dependent on SUSY parameters
\( \tilde{g}, \tilde{q} \) Decay Processes

<table>
<thead>
<tr>
<th>( \tilde{g} )</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} \rightarrow q\bar{q} \tilde{B}^0 ) (≈ 1)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>( \tilde{g} \rightarrow q\bar{q} \tilde{W}^0 ) (≈ 2)</td>
<td></td>
<td></td>
<td>( \tilde{g} \rightarrow q\bar{q} \tilde{W}^0 ) (≈ 2)</td>
</tr>
<tr>
<td>( q\bar{q} \tilde{W}^\pm ) (≈ 4)</td>
<td></td>
<td></td>
<td>( \tilde{g} \rightarrow t\bar{t}_1 b\bar{b}_1 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \tilde{q}_L )</th>
<th>( \tilde{q}_L \rightarrow q\tilde{g} )</th>
<th>( \tilde{q}_L \rightarrow q\tilde{W}^0 ) (≈ 1)</th>
<th>( \tilde{q}_L \rightarrow q\tilde{W}^\pm ) (≈ 2)</th>
</tr>
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<tbody>
<tr>
<td>( \tilde{q}_R )</td>
<td>( \tilde{q}_R \rightarrow q\tilde{g} )</td>
<td>( \tilde{q}_R \rightarrow q\tilde{B}^0 )</td>
<td>( \tilde{q}_R \rightarrow q\tilde{B}^0 )</td>
</tr>
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</table>

**Strong interaction**

**EW interaction**
SUSY Signals

Expected event topology

\[
\begin{align*}
\max(\tilde{g}, \tilde{q}) &\quad \rightarrow (\text{high) } \text{Pt jet} \\
\min(\tilde{g}, \tilde{q}) &\quad \rightarrow \text{lepton} \\
\tilde{\chi}_1^+ &\quad \rightarrow \text{jet} \\
\tilde{\chi}_2^0 &\quad \rightarrow \text{lepton} \\
\tilde{\chi}_1^0 &\quad \rightarrow \text{Higgs}\rightarrow bb
\end{align*}
\]

\[E_T + \text{High } P_T \text{ jets } + \text{b-jets} \]
\[\not\!E_T - \text{jets}\]

- Discovery would be easy.
- To study further details, SUSY itself would become BG.

BG --- tt, QCD, Z+njets, W+njets
Discovery Potential of SUSY (mSUGRA)

10 years (300 fb⁻¹) → ~ 2.5 TeV

1 week run would be sufficient to cover the interesting region for Cold DM.

1 year run (L=10 fb⁻¹) → ~ 2 TeV

1 month run (L=1 fb⁻¹) → ~ 1.5 TeV (5σ)

LEP-II / Tevatron-II search region

No EWSB
What more can one study on SUSY at LHC?

In some cases, ---

- model dependent
- chain of 2-body decays

\[
\begin{align*}
M_{\ell\ell}^{\text{max}} &= m(\tilde{\chi}_2^0) \sqrt{1 - \left( \frac{m(\tilde{\ell}_R^\pm)}{m(\tilde{\chi}_2^0)} \right)^2} \sqrt{1 - \left( \frac{m(\tilde{\chi}_1^0)}{m(\tilde{\ell}_R^\pm)} \right)^2}
\end{align*}
\]

→ Constraint on mass reconstruction
If we are lucky, ---

4 unknowns

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

\[ m(\ell\ell) \text{ spectrum}
\text{end-point : 109 GeV}
\text{exp. precision ~0.3%} \]

\[ m(\ell\ell\ell) \text{ spectrum}
\text{end-point: 479 GeV}
\text{exp. precision ~1%} \]

\[ m(\ell\ell\ell) \text{ min spectrum}
\text{end-point: 552 GeV}
\text{exp. precision ~1%} \]

\[ m(\ell\ell\ell) \text{ max spectrum}
\text{threshold: 272 GeV}
\text{exp. precision ~2%} \]

4 constraints □ We can determine the masses.
(3-12% for 700-800 GeV squark, gluino)
\[ \sigma_E / E = 10 \% / \text{sqrt}(E) \]
\[ \sigma_\theta = 60 \text{ mrad} / \text{sqrt}(E) \]
\[ \sigma_t \sim 100 \text{ ps} \]
A Possible Gauge Mediation Signal

\[ \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \quad \text{ct} \sim O(1m) \]

\[ \tilde{l} \rightarrow l \tilde{\chi}_1^0 \rightarrow l \gamma \tilde{G} \]

\[ m_{\ell}^2 = (p_\gamma + p_{\tilde{G}} + p_\ell)^2 \]
\[ = 2E_\gamma E_{\tilde{G}}(1 - \cos \psi) + 2E_\ell E_{\tilde{G}}(1 - \cos \theta_{\ell \tilde{G}}) \]
\[ + 2E_\ell E_\gamma (1 - \cos \theta_{\ell \gamma}) \]
\[ = \left( 1 + \frac{E_\ell (1 - \cos \theta_{\ell \tilde{G}})}{E_\gamma (1 - \cos \psi)} \right) m_{\tilde{\chi}_1^0}^2 + 2E_\ell E_\gamma (1 - \cos \theta_{\ell \gamma}) \]

\[ \cos \psi = \frac{1 - \xi^2}{1 + \xi^2}, \quad \text{where} \quad \xi = \frac{ct_\gamma - L \cos \alpha}{L \sin \alpha} \]

\(~100\ \text{l}_{\gamma}\ \text{events} \Rightarrow \sigma_{M/M} (\text{slepton, neutralino}) \sim 3\%\)
In some cases ---

\[ \text{NLSP} = \tilde{\tau}_1 \quad \text{and} \quad c\tau \approx 1 \text{ km} \]

\[ \tilde{e}_R \quad \text{and} \quad \tilde{\mu}_R \quad \text{are also long-lived} \]

\[ \rightarrow \text{stable heavy charged leptons} \]

\[ \chi_1 \quad \chi_2 \quad \chi_4 \]

Velocity of \( \tilde{\tau}_R \)

ATLAS MDT \( \rightarrow \sigma_t \approx 1\text{ns} \)

Reconstructed slepton mass

\[ \sigma_M / M \approx 4\% \]
$m_{\text{top}}$ from $t \rightarrow l\nu+J/\psi+X$ decays

Invariant mass $m_{l+J/\psi}$ is correlated to $m_{\text{top}}$

Cuts:
- Isolated lepton: $p_T > 20 \text{ GeV, } |\eta| < 2.4$
- 3 $\mu$ in jet: $p_T > 4 \text{ GeV, } |\eta| < 2.4$
  
  2 $\mu$'s have $m_{\mu\mu} \sim m_{J/\psi}$
- $|m_{t} - m_{Z}| > 10 \text{ GeV, } E_{\text{miss}} > 40 \text{ GeV}$
- 2 additional jets: $p_T > 15 \text{ GeV}$

In 4 years at LHC high lumi ($400 \text{ fb}^{-1}$)
$\sim 4,000 \text{ events expected.}$
stat. error < 0.5 GeV
syst. error < 1 GeV

- possible extensions
  - use $b \rightarrow J/\psi \rightarrow e^+e^-$ as well.
  - use jet-charge method instead of $W \rightarrow e\nu, \mu\nu$.
  - other heavy particle instead of $J/\psi$?
B-physics at ATLAS/LHCb

(1) Measurement of $\sin^2 \theta$ using $B_d \rightarrow J/\psi(\mu^+ \mu^-)K_S^0(\pi^+ \pi^-)$

**ATLAS**

- data rate $\sim 10$Hz ($2 \sigma$, Pt $> 6$GeV)
- reconstruction of $J/\psi$, $K_S^0 \rightarrow B_d$ (S/B=32)
- high statistics: 250k event/30fb$^{-1}$

$\square \square \sin 2 \theta = 0.016$ (stat.) $\pm 0.005$(sys.)
$\sim 2\%$ accuracy (3 years low lumi. run)

**LHCb**

- low Pt trigger
- $\square$, e, $\square$ separation by RICH
- $\sim 2\%$ accuracy with 119k events / 2 fb$^{-1}$
(2) Physics of $B_s$ meson

$\Delta m_s$ from $B_s \rightarrow D_s \pi$ and $B_s \rightarrow D_s a_1$

- detectable up to $30 \text{ps}^{-1}$ (LHCb $58 \text{ps}^{-1}$)
- measurable up to $0.05 \text{ps}^{-1}$ $\Delta m_s \sim 12 \text{ps}^{-1}$

(3) Rare decays

<table>
<thead>
<tr>
<th>Br (SM)</th>
<th>$3.5 \times 10^{-9}$</th>
<th>$1.5 \times 10^{-10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal $B^0_s \rightarrow \mu^+\mu^-$</td>
<td>92</td>
<td>14</td>
</tr>
<tr>
<td>BG</td>
<td>660</td>
<td>93</td>
</tr>
<tr>
<td>Signal $B^0_d \rightarrow \mu^+\mu^-$</td>
<td>27</td>
<td>4</td>
</tr>
</tbody>
</table>

5$\sigma$ signal
Extra Dimensions

Concept of ED is not unfamiliar.

- Kaluza-Klein
- Quantum Gravity
- Superstring
- M-theory

⇒ 10 or 11 dimensional space-time
ED must be compactified. 
→ But how large, and how are ED compactified?

• Various models
• Some ED may be fairly large. (Exp. not excluded)
• If gravity propagates in 4+n dimensions, quantum gravity scale as low as $M_D \approx 1 \text{TeV}$ is possible.
  → No hierarchy problem!
• Graviton becomes massive. (KK excitations)
• Gravity becomes strong.
  → Effects of Q.G./string may be observed at LHC.

Some models:
• Large ED (ADD model) --- $R_C \gg 1 \text{TeV}^{-1}$  ➔ Graviton KK excitations
• Small ED (variation of ADD) --- $R_C \approx 1 \text{TeV}^{-1}$
  ➔ KK excitations of SM gauge bosons
• Warped ED (RS model)  ➔ Gravitons and Graviscalars (radions)
  (Radion $\approx$ SM Higgs; They mix; SM Higgs search at LHC may be confused.)
KK graviton production:

\[ gg \rightarrow gG \]

(mono-jet + missing-\(E_T\))

\[ L = 100 \text{ fb}^{-1} \]

\[ E_{T(jet)} > 1 \text{ TeV} \]
Black Hole Production

If the Planck scale in ~TeV region: can expect Black Hole production

Simulation of a black hole event with $M_{BH} \sim 8$ TeV in ATLAS

$(M_D \sim 1$ TeV, $n=6)$

- Large cross section
- ~Spherical events
- Many high energy jets, leptons, photons etc.

Ecological comment: BH's will decay within $\sim 10^{-26}$ secs, so that the detector (and rest of the world) is safe!
"It might be possible that BH is produced at LHC. It will then disappear immediately by Hawking radiation. And I will get the Nobel Prize."
## Summary of LHC New Physics Reach

<table>
<thead>
<tr>
<th>Phenomena</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Higgs</td>
<td>100 GeV $\sim$ 1 TeV</td>
</tr>
<tr>
<td>MSSM Higgs</td>
<td>covers full $(m_A, \tan \beta)$</td>
</tr>
<tr>
<td>SUSY (squark, gluino)</td>
<td>$&lt; 2$ TeV (100 fb$^{-1}$)</td>
</tr>
<tr>
<td>New gauge bosons ($Z'$)</td>
<td>$&lt; 4.5$ TeV (100 fb$^{-1}$)</td>
</tr>
<tr>
<td>Quark substructure ($\Lambda_C$)</td>
<td>$&lt; 25/40$ TeV (30/300 fb$^{-1}$)</td>
</tr>
<tr>
<td>Large ED ($M_D$ for n=2,4)</td>
<td>$&lt; 6.5/3.4$ TeV (100 fb$^{-1}$)</td>
</tr>
<tr>
<td>Small ED ($M_C$)</td>
<td>$&lt; 9/5.8$ TeV (100 fb$^{-1}$)</td>
</tr>
<tr>
<td>Black holes</td>
<td>$&lt; 5.8$ TeV (100 fb$^{-1}$)</td>
</tr>
<tr>
<td>$M$(top quark)</td>
<td>$&lt; 6 \sim 10$ TeV</td>
</tr>
<tr>
<td>$M_w$</td>
<td>$\sigma_M \sim 1$ GeV ($\sim 0.5 %$)</td>
</tr>
<tr>
<td>$\sigma_M \sim 15$ MeV</td>
<td>$\sigma(sin2\beta) \sim 0.016$ (30 fb$^{-1}$)</td>
</tr>
<tr>
<td>CP-violation in B-decay</td>
<td>$\sim 5\sigma$ (130 fb$^{-1}$)</td>
</tr>
<tr>
<td>Rare B-decay ($B_S \rightarrow \mu\mu$)</td>
<td></td>
</tr>
</tbody>
</table>

Any one of those will change the understanding of our universe!
LHC Looking Down at New Phenomena in the TeV Region

(Original drawing by S.Orito, arranged by T.Mori et al.)