Probing the hierarchy problem with the LHC
Fabiola Gianotti (CERN)
Extra-dimensions
Additional dimensions
$\Rightarrow M_{\text{gravity}} \sim M_{\text{EW}}$
New states at TeV scale

Little Higgs
SM embedded in larger gauge group
New particles at TeV scale, stable $m_H$

Technicolour
New strong interactions break EW symmetry
$\Rightarrow$ Higgs (elementary scalar) removed
New particles at TeV scale

Split SUSY
Accept fine-tuning of $m_H$
(and of cosm. constant)
by anthropic arguments
Part of SUSY spectrum at TeV scale
(for couplings unification and dark matter)

LHC potential for $\sim$all these scenarios demonstrated since long time. Here:
① What can be done at the beginning?
② Signal interpretation and constraints of underlying theory?
What can be done at the beginning?

The first LHC data: from Summer 2007...

\[ 1 \text{ fb}^{-1} (10 \text{ fb}^{-1}) \equiv 6 \text{ months at } 10^{32} (10^{33}) \text{ cm}^{-2}\text{s}^{-1} \text{ at 50\% efficiency} \rightarrow \text{may collect} \]
\[ \text{several fb}^{-1} \text{ per experiment by end 2008} \]

<table>
<thead>
<tr>
<th>Channels (examples...)</th>
<th>Events to tape for 1 fb(^{-1}) (per expt: ATLAS, CMS)</th>
<th>Total statistics from previous Colliders</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W \rightarrow \mu \nu)</td>
<td>(7 \times 10^6)</td>
<td>(\sim 10^4 \text{ LEP, } \sim 10^6 \text{ Tevatron})</td>
</tr>
<tr>
<td>(Z \rightarrow \mu \mu)</td>
<td>(\sim 10^6)</td>
<td>(\sim 10^6 \text{ LEP, } \sim 10^5 \text{ Tevatron})</td>
</tr>
<tr>
<td>(t\bar{t} \rightarrow W b W b \rightarrow \mu \nu +X)</td>
<td>(\sim 10^5)</td>
<td>(\sim 10^4 \text{ Tevatron})</td>
</tr>
<tr>
<td>(\tilde{g}\tilde{g} \quad m = 1 \text{ TeV})</td>
<td>(10^2 - 10^3)</td>
<td>---</td>
</tr>
</tbody>
</table>

With these data:

- **Understand and calibrate detectors in situ using well-known physics samples**
  
  e.g. - \(Z \rightarrow ee, \mu\mu\) tracker, ECAL, Muon chambers calibration and alignment, etc.
  - \(t\bar{t} \rightarrow bl\nu bjj\) jet scale from \(W\rightarrow jj\), b-tag performance, etc.

- **Measure SM physics at \(\sqrt{s} = 14 \text{ TeV}\): \(W, Z, t\bar{t}, \text{QCD jets}...\)** (omnipresent backgrounds to New Physics)

\(\rightarrow\) prepare the road to discovery ....... it will take a lot of time ...
Preparing the detectors to explore the hierarchy problem...

Example: the ATLAS electromagnetic calorimeter

Pb-liquid argon sampling calorimeter with Accordion shape, covering $|\eta| < 2.5$

$H \rightarrow \gamma\gamma$: to observe signal peak on top of huge $\gamma\gamma$ background, need mass resolution of $\sim 1\% \rightarrow$ response uniformity (i.e. total constant term of $E$-resolution) $\leq 0.7\%$ over $|\eta| < 2.5$
**Construction quality**

Thickness of Pb plates must be uniform to 0.5% (~10 μm)

End-cap: 1536 plates

< > ~ 2.2 mm

σ ≈ 9 μm

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**Test-beam measurements**

Scan of a barrel module (Δφ x Δη=0.4x1.4) with high-E electrons

After correction: r.m.s. ≈ 0.57% over ~ 500 spots
3 Cosmics runs:

Measured cosmic $\mu$ rate in ATLAS pit: few Hz
→ $\sim 10^6$ events in $\sim$ 3 months of cosmics runs beginning 2007
→ enough for initial detector shake-down
→ ECAL: check calibration vs $\eta$ to 0.5%

4 First collisions: calibration with $Z \rightarrow e e$ events (rate $\approx 1$ Hz at $10^{33}$)

Use $Z$-mass constraint to correct long-range non-uniformities
(module-to-module variations, effect of upstream material, etc.)
$\sim 10^5 Z \rightarrow e e$ events (few days data taking at $10^{33}$) enough to achieve constant term $c \leq 0.7$

Nevertheless, let's consider the worst (unrealistic?) scenario: no corrections applied
ECAL non-uniformity at construction level, i.e.:
-- no test-beam corrections
-- no calibration with $Z \rightarrow e e$

\[ H \rightarrow \gamma \gamma \] significance \( m_H \approx 115 \text{ GeV} \) degraded by $\sim 25$
→ need 50% more $L$ for discovery
First cosmic muons observed by ATLAS in the pit on June 20th (recorded by hadron Tilecal calorimeter)
Example of initial SM measurement: top signal and top mass
(relevant to New Physics.....)

- Use gold-plated $t\bar{t} \rightarrow bW bW \rightarrow blv bjj$ decay
- Very simple selection:
  -- isolated lepton ($e, \mu$) $p_T > 20$ GeV
  -- exactly 4 jets $p_T > 40$ GeV
  -- no kinematic fit
  -- no b-tagging required (pessimistic, assumes trackers not yet understood)
- Plot invariant mass of 3 jets with highest $p_T$

<table>
<thead>
<tr>
<th>Time</th>
<th>Events at $10^{33}$</th>
<th>Stat. error $\delta M_{top}$ (GeV)</th>
<th>Stat. error $\delta \sigma/\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year</td>
<td>$3 \times 10^5$</td>
<td>0.1</td>
<td>0.2%</td>
</tr>
<tr>
<td>1 month</td>
<td>$7 \times 10^4$</td>
<td>0.2</td>
<td>0.4%</td>
</tr>
<tr>
<td>1 week</td>
<td>$2 \times 10^3$</td>
<td>0.4</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

- Top signal visible in few days also with simple selection and no b-tagging
- Cross-section to $\sim 20\%$
- Top mass to $\sim 7$ GeV (assuming b-jet scale to 10%)
- Get feedback on detector performance: $m_{top}$ wrong $\rightarrow$ jet scale?
- Gold-plated sample to commission b-tagging
- $t\bar{t}$ is background to many searches
What about early discoveries?
Three examples relevant to the hierarchy problem ...

An easy case: a new (narrow) resonance of mass ~ 1 TeV decaying into $e^+e^-$, e.g. a $Z'$ or a Graviton $\rightarrow e^+e^-$ of mass ~ 1 TeV

An intermediate case: SUSY

A difficult case: a light Higgs ($m_H \sim 115$ GeV)
An “easy case”: $G \rightarrow e^+e^-$ resonance with $m \sim 1$ TeV

BR ($G \rightarrow ee \approx 2\%$), $c = 0.01$ (small/conservative coupling to SM particles)

<table>
<thead>
<tr>
<th>Mass (TeV)</th>
<th>Events for 10 fb$^{-1}$ (after all cuts)</th>
<th>$\int L , dt$ for discovery ($\geq 10$ observed events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>$\sim 80$</td>
<td>$\sim 1.2$ fb$^{-1}$</td>
</tr>
<tr>
<td>1.1</td>
<td>$\sim 25$</td>
<td>$\sim 4$ fb$^{-1}$</td>
</tr>
<tr>
<td>1.25</td>
<td>$\sim 13$</td>
<td>$\sim 8$ fb$^{-1}$</td>
</tr>
</tbody>
</table>

- large enough signal for discovery with $\int L \, dt < 10$ fb$^{-1}$ for $m < 1.3$ TeV
- dominant Drell-Yan background small
- signal is mass peak above background

C. Collard

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

F. Gianotti, Lepton-Photon 2005
An “intermediate case” : SUPERSYMMETRY

If SUSY stabilizes \( m_H \rightarrow \) is at TeV scale \( \rightarrow \) could be found quickly .... thanks to:

- large \( \tilde{q}\tilde{q}, \tilde{g}\tilde{g}, \tilde{g}\tilde{g} \) cross-section \( \rightarrow \approx 100 \text{ events/day} \) at \( 10^{33} \) for \( m(\tilde{q}, \tilde{g}) \approx 1 \text{ TeV} \)
- spectacular signatures

\[
\begin{align*}
\sigma_{\text{discovery curves}} \\
\text{~ one year at } 10^{34}: \text{~ up to } \approx 2.5 \text{ TeV} \end{align*}
\]

\[
\begin{align*}
\text{~ one year at } 10^{33}: \text{~ up to } \approx 2 \text{ TeV} \\
\text{~ one month at } 10^{33}: \text{~ up to } \approx 1.5 \text{ TeV}
\end{align*}
\]

Using multijet + \( E_T^{\text{miss}} \) (most powerful and model-independent signature if R-parity conserved)

First/fast determination of SUSY (squark, gluino) mass scale from distribution of \( E_T^{\text{miss}} + \Sigma p_T \) (jets)
A difficult case: a light Higgs ($m_H \sim 115$ GeV) ...

Full GEANT simulation, simple cut-based analyses

<table>
<thead>
<tr>
<th></th>
<th>$H \rightarrow \gamma \gamma$</th>
<th>$ttH \rightarrow ttbb$</th>
<th>$qqH \rightarrow qq\tau\tau$ (ll + l-had)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>130</td>
<td>15</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$B$</td>
<td>4300</td>
<td>45</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$S/\sqrt{B}$</td>
<td>2.0</td>
<td>2.2</td>
<td>$\sim 2.7$</td>
</tr>
</tbody>
</table>

K-factors $\equiv \sigma(\text{NLO})/\sigma(\text{LO}) \approx 2$ not included
Remarks:

Each channel contributes ~ 2σ to total significance → observation of all channels important to extract convincing signal in first year(s)

The 3 channels are complementary → robustness:

- different production and decay modes
- different backgrounds
- different detector/performance requirements:
  - ECAL crucial for $H \rightarrow \gamma\gamma$ (in particular response uniformity) : $\sigma/m \sim 1\%$ needed
  - b-tagging crucial for $ttH$ : 4 b-tagged jets needed to reduce combinatorics
  - efficient jet reconstruction over $|\eta| < 5$ crucial for $qqH \rightarrow qq\tau\tau$ : forward jet tag and central jet veto needed against background

Note: -- all require “low” trigger thresholds

E.g. $ttH$ analysis cuts : $p_T(l) > 20$ GeV, $p_T$ (jets) > 15-30 GeV

-- all require very good understanding (1-10%) of backgrounds
If \( m_H > 180 \text{ GeV} \): early discovery may be easier with \( H \rightarrow 4l \) channel

**Luminosity needed for 5\( \sigma \) discovery (ATLAS+CMS)**

\[ \begin{array}{c}
\text{CMS, 10 fb}^{-1} \\
\text{Signal} \\
\text{Backgr} \\
\end{array} \]

- \( H \rightarrow WW \rightarrow l^+l^-l^+l^- \): high rate (~100 evts/expt) but no mass peak
  - not ideal for early discovery ...
- \( H \rightarrow 4l \) (l=e,\( \mu \)): low-rate but very clean: narrow mass peak, small background

Extra-dimensions (ADD models)

Look for a continuum of Graviton KK states:

\[ q \rightarrow \text{jet(s)} + \text{missing } E_T \]

\[ g \rightarrow G \]

→ topology is jet(s) + missing \( E_T \)

**Cross-section** \[ \approx \frac{1}{M_D^{\delta+2}} \]

\( M_D \) = gravity scale
\( \delta \) = number of extra-dimensions

<table>
<thead>
<tr>
<th>( \delta = 2 )</th>
<th>( \delta = 3 )</th>
<th>( \delta = 4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_D^{\text{max}} )</td>
<td>9 TeV</td>
<td>7 TeV</td>
</tr>
</tbody>
</table>

To characterize the model need to measure \( M_D \) and \( \delta \)

Measurement of cross-section gives ambiguous results: e.g. \( \delta = 2, M_D = 5 \) TeV very similar to \( \delta = 4, M_D = 4 \) TeV

**Solution may be to run at different \( \sqrt{s} \):**

ATLAS, 100 fb\(^{-1}\)

ATLAS

Discriminating between models:
-- SUSY : multijets plus \( E_T^{\text{miss}} \) (+ leptons, ...)
-- ADD : monojet plus \( E_T^{\text{miss}} \)

Good discrimination between various solutions possible with expected <5% accuracy on \( \sigma(10)/\sigma(14) \) for 50 fb\(^{-1}\)
Little Higgs models

Alternative approach to the hierarchy problem predicting heavy top T (EW singlet), new gauge bosons $W_H, Z_H, A_H$ and Higgs triplet $\Phi^0, \Phi^+, \Phi^{++}$

Observation of $T \rightarrow Zt, Wb$ discriminates from 4th family quarks
Observation of $V_H \rightarrow Vh$ discriminates from $W', Z'$

$V_H \rightarrow Vh$
$m_h=120$ GeV

$T \rightarrow Zt \rightarrow ll b\nu$

$ATLAS$
$300$ fb$^{-1}$
Other scenarios ......

Leptoquarks: $lq lq \rightarrow lj lj$

Large number of scenarios studied:
\rightarrow demonstrated detector sensitivity to many signatures
\rightarrow robustness, ability to cope with unexpected scenarios
\rightarrow LHC direct discovery reach (hence exploration of hierarchy problem ... ) up to $m \approx 5-6$ TeV

CMS, 10 fb$^{-1}$
$BR=1.9 \times 10^{-6}$
Reach (30 fb$^{-1}$): $BR < 4 \times 10^{-8}$

Excited leptons: $e^* e, e^* \rightarrow W\nu \rightarrow jj \nu$

ATLAS, 300 fb$^{-1}$

LFV: $W \rightarrow \tau\nu, \tau \rightarrow 3\mu$

F. Gianotti, Lepton-Photon 2005
Constraining the underlying theory ...

Measurements of the SM Higgs parameters

Lot of useful information to constrain the theory (though not competitive with LC precision of e.g. ≈% on couplings)

F. Gianotti, Lepton-Photon 2005
**Higgs self-coupling \( \lambda \)**
- not accessible at LHC
- may be constrained to \( \approx 20\% \) at Super-LHC (L=10^{35})

\[ m_H^2 = 2 \lambda \nu^2 \]

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**Higgs spin and CP**
Promising for \( m_H > 180 \) GeV \((H \rightarrow ZZ \rightarrow 4l)\),
difficult at lower masses

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**Significance for exclusion of \( J^{CP}=0^- \)**

<table>
<thead>
<tr>
<th>( m_H ) (GeV)</th>
<th>( J^{CP} = 1^+ )</th>
<th>( J^{CP} = 1^- )</th>
<th>( J^{CP}=0^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>6.5 ( \sigma )</td>
<td>4.8 ( \sigma )</td>
<td>40 ( \sigma )</td>
</tr>
<tr>
<td>250</td>
<td>20 ( \sigma )</td>
<td>19 ( \sigma )</td>
<td>80 ( \sigma )</td>
</tr>
<tr>
<td>300</td>
<td>23 ( \sigma )</td>
<td>22 ( \sigma )</td>
<td>70 ( \sigma )</td>
</tr>
</tbody>
</table>

Buszello et al. SN-ATLAS-2003-025

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Mass peaks cannot be directly reconstructed \((\chi^0_1 \text{ undetectable})\) → measure invariant mass spectra (end-points, edges,..) of visible particles → deduce constraints on combinations of sparticle masses.

Precise SUSY measurements

\[
\begin{align*}
\text{m (l+\bar{l}−) spectrum} & \quad \text{m (lll)min spectrum} \\
\text{end-point} : 77 \text{ GeV} & \quad \text{end-point: 431 GeV} \\
\text{experim. precision } \sim 0.1\% & \quad \text{experim. precision } \sim 1\%
\end{align*}
\]

\[
m(\tilde{q}_L \chi^0_2 \tilde{\ell}_R \chi^0_1) = (540, 177, 143, 96 \text{ GeV})
\]

ATLAS, 100 fb\(^{-1}\)

mSUGRA Point “SPS1A”

Courtesy B. Gjelsten
Putting all measurements together:

- deduce several sparticle masses: typical precision 1%-20%
  Model-indep. (just kinematics), but interpretation is model-dep.
- from fit of model to all experimental measurements derive
  -- sparticle masses with higher accuracy
  -- fundamental parameters of theory to 1-30%
  -- dark matter \((\chi^0_1)\) relic density and \(\sigma (\chi^0_1 -\text{nucleon})\)

\[
\delta(\Omega h^2) \approx 3\%
\]

ATLAS, 300 fb\(^{-1}\)

mSUGRA, Point “SPS1A”

\(\Omega h^2\)

\(\Omega h^2\)

DAMA

Zepelin, CDMS, Edelweiss
--- present limit
--- projected

LHC data

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
**General strategy toward understanding the underlying theory**  
(SUSY as an example ...)

**Discovery phase:** inclusive searches ... as model-independent as possible

**First characterization of model:** from general features: Large $E_T^{\text{miss}}$? Many leptons? Exotic signatures (heavy stable charged particles, many $\gamma$'s, etc.)? Excess of b-jets or $\tau$'s? ...

**Interpretation phase:**
- reconstruct/look for semi-inclusive topologies, eg:
  -- $h \rightarrow bb$ peaks (can be abundantly produced in sparticle decays)
  -- di-lepton edges
  -- Higgs sector: e.g. $A/H \rightarrow \mu\mu, \tau\tau \Rightarrow$ indication about $\tan\beta$, measure masses
  -- $tt$ pairs and their spectra $\Rightarrow$ stop or sbottom production, gluino $\rightarrow$ stop-top
- determine (combinations of) masses from kinematic measurements (e.g. edges ...)
- measure observables sensitive to parameters of theory (e.g. mass hierarchy)

At each step narrow landscape of possible models and get guidance to go on:
- lot of information from LHC data (masses, cross-sections, topologies, etc.)
- consistency with other data (astrophysics, rare decays, etc.)
- joint effort theorists/experimentalists will be crucial
What the LHC can do and cannot do ….

In general the LHC can (examples ...):
- discover SUSY up to $m(\sim\tilde{q},\tilde{g}) \sim 2.5$ TeV
- measure lightest Higgs $h$ mass to $\sim 0.1$
- derive sparticle masses (typically $\sim\sim, \chi_0^2$) from kinematic measurements
- constrain underlying theory by fitting a model to the data

More difficult or impossible (examples ...):
- disentangle squarks of first two generations
- observe / measure sleptons if $m > 350$ GeV
- measure full gaugino spectrum
- measure sparticle spin-parity and all couplings
- constrain underlying theory in model-indep. way

\[ \frac{1}{M_3} = m(\tilde{g}) \]

complementarity with LC

Ultimate goal: from precise measurements of e.g. gaugino masses at the TeV scale reconstruct high-E theory
Conclusions

• In 2 years from now, particle physics will enter a new epoch, hopefully the most glorious and fruitful of its history.

• Indeed, the hierarchy problem motivates strongly New Physics at the TeV scale

• The LHC will explore this scale in detail with direct discovery potential up to $m \approx 5-6$ TeV
  → if New Physics is there, the LHC will find it
  → it will say final word about many TeV-scale predictions
  → it will tell us which are the right questions to ask, and how to go on
Has Nature prepared a “pleasant” welcome to the TeV-scale (striking signals with limited luminosity and non-ultimate detector performance) or shall we have to sweat through years of data taking and hard work before we can claim a discovery?

Early determination of scale of New Physics would be crucial for planning of future facilities (ILC ? CLIC ? Underground Dark Matter searches ? .... ) The future of our discipline will benefit from a quick feedback on SUSY and the rest .. !

Next challenge: efficient and as-fast-as-possible commissioning of machine and detectors of unprecedented complexity, technology and performance
From E. Fermi, preparatory notes for a talk on "What can we learn with High Energy Accelerators?" given to the American Physical Society, NY, Jan. 29th 1954

For these reasons, clamoring for higher and higher...

Slide 1 - MeV vs. $M_S$ versus time.
Extrapolating to 1994...5 hi 9 Mev or hi est cosmic...170 B$,...preliminary
design...8000 km, 20000 gauss

Slide 2 - 5 hi 17 eV machine.

Why we can learn impossible to guess...main element surprise...some
things look for but see others...Experience on pions...sharpening
knowledge...spin axes and additivity...certainly look for multiple
production...

Fermi's extrapolation to year 1994:
2T magnets, $R=8000$ Km machine
$E_{beam} \sim 5 \times 10^3$ TeV, cost 170 B$

University of Chicago library
(thanks to M.Oreglia)
Many thanks to:

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