FIRST SCHOOL ON LHC PHYSICS

National Centre for Physics
Quaid-i-Azam University Campus
Islamabad

PHYSICS@LHC

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1. Searches for Higgs Boson
2. New Physics or Physics beyond the Standard Model (SM)
3. The Standard Model Physics
4. Physics of Quark-Gluon Plasma
What we want to know from LHC?

The “Quantum Universe” report gives nine key questions in three major areas.

I. Einstein’s dream
1. Undiscovered principles, new symmetries?
2. What is dark energy?
3. Extra space dimensions?
4. Do all forces become the same?

II. The Particle World
5. New particles?
6. What is dark matter?
7. What do neutrinos tell us?

III. Birth of Universe
8. How did the universe start?
9. Where is the antimatter?

The LHC will address at least eight of these.
Expectations of Luminosity Buildup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Phase A</th>
<th>Phase B</th>
<th>Phase C</th>
<th>Nominal</th>
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<td>k / no. bunches</td>
<td>43-156</td>
<td>1 x 1</td>
<td>43 x 43</td>
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<td>Bunch spacing (ns)</td>
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<td>N (10^{11} protons)</td>
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<td>43 x 43</td>
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<td>√(β^<em>/β^</em>_{nom})</td>
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<td>156 x 156</td>
<td>2</td>
<td>9 x 10^{10}</td>
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Early Physics Programme

- Prior to beam: early detector commissioning
  - Readout & trigger tests, runs with all detectors (cosmics, test beams)
- Early beam, up to 10pb⁻¹:
  - Detector synchronization, alignment with beam-halo events, minimum-bias events. Earliest in-situ alignment and calibration
  - Commission trigger, start “physics commissioning”:
    - Physics objects; measure jet and lepton rates; observe W, Z, top
    - And, first look at possible extraordinary signatures...
- Physics collisions, 100pb⁻¹: measure Standard Model, start search
  - $10^6 W \rightarrow l \nu$ ($l = e, \mu$); $2 \times 10^5 Z \rightarrow ll$ ($l = e, \mu$); $10^4 ttbar \rightarrow \mu + X$
    - Improved understanding of physics objects; jet energy scale from $W \rightarrow jj'$; extensive use (and understanding) of b-tagging
    - Measure/understand backgrounds to SUSY and Higgs searches
- Initial MSSM (and some SM) Higgs sensitivity
- Early look for excesses from SUSY & $Z'/jj$ resonances. SUSY hints (?)

- Physics collisions, 1000pb⁻¹: entering Higgs discovery era
  - Also: explore large part of SUSY and resonances at ~ few TeV
Huge stats for Standard Model signals. Rates@10^{33}

~10^8 events/1fb⁻¹ W  (200 Hz)
~10^7 events/1fb⁻¹ Z  (50 Hz)
~10^6 events/1fb⁻¹ tt  (1 Hz)

These will be used as control/calibration samples for searches beyond the Standard Model

They can also be used to scrutinize the Standard Model further.

e.g. top sample is excellent for understanding lepton id. (incl. taus), jet corrections, jet energy scale, b tagging, ….
SM Higgs

Needed $\int L dt \,(fb^{-1})$ per experiment

$\leq 1 \, fb^{-1}$ for 98% C.L. exclusion
$\leq 5 \, fb^{-1}$ for $5\sigma$ discovery over full allowed mass range

ATLAS + CMS preliminary
Standard Model Physics

- **QCD Studies**
  - Jet Studies
  - $\alpha_s$ and its running
  - Inclusive $b$ production
- **Top Quark Physics**
  - Top pair production ($\sigma$, $m_t$, properties of top)
  - Single top ($V_{tb},...$)
- **Electroweak Physics**
  - $W$ & $Z$ cross-section
  - Drell-Yen
  - PDF, TGC
- **Studies of CP Violation:**
  - $B^o \rightarrow J/\psi K^o_s$, $B_c \rightarrow J/\psi \phi$
- **Calibration Channels**
  - $J/\psi \rightarrow \mu^+ \mu^-$, $\psi(2s) \rightarrow \mu^+ \mu^-$
Physics Studies at LHC

• Higgs Searches:
  - $M_H < 140$ GeV $H \rightarrow \gamma\gamma$
  - $140 < M_H < 700$ GeV ($H \rightarrow llll$)
  - $M_H > 500$ GeV ($H \rightarrow lljj$)

• Super-symmetry:
  - SUSY Higgs Boson
  - Sparticles (sleptons, squarks, gluinos ...)

• Exited Quarks
• Lepoquarks
• Monopoles
• Extra-dimensions
• Compositeness
Why a Hadron Collider?

• **Disadvantages:**
  – Hadrons are complex objects
    • High multiplicity of other stuff
    • Energy and type of colliding parton (quark, gluon) unknown
      – Kinematics of events not fully constrained

• **Advantage:**
  – Can access higher energies

**Lepton Collider**
(collision of two point-like particles)  
**Hadron Collider**
(collision of ~ 50 point-like particles)
The Standard Model Lagrangian

\[ L = -\frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu} + i \bar{\psi} D\psi \]

\[ + \psi_i \lambda_{ij} \psi_j h + \text{h.c.} \]

\[ + |D_\mu h|^2 - V(h) \]

\[ + \frac{1}{M} L_i \lambda_{\nu ij} L_j h^2 \text{ or } L_i \lambda_{\nu ij} N_j \]

... and beyond?

- gauge sector
- flavour sector
- EWSB sector
- \( \nu \) mass sector

supersymmetry (many variants)
extra spacetime dimensions
compositeness
strong electroweak symmetry breaking
...
something new?!
Confusion among theorists?

Need experiments to figure out which (if any) represents Nature
At LHC, the total event rate is dominated by huge QCD cross section.

- High Pt QCD jets
- W, Z production
- Gluon-to-Higgs fusion
- Squark, gluinos ($M \sim 1$TeV)
• The Higgs field pervades all of space, interacting with quarks, electrons W, Z etc. These interactions slow down the particles, giving them mass.

• The Higgs field causes the EM and Weak forces to differ at low energy. Three of the four Higgs fields give the longitudinal polarization states required for massive $W^\pm$ and Z. The fourth provides one new particle (the Higgs boson).

The Higgs boson is somewhat like the Bunraku puppeteers, dressed in black to be ‘invisible’, manipulating the players in the drama.
Higgs Decay Rates

Direct:

**Quarks and Leptons**

\[ \Gamma(H \rightarrow q\bar{q}) = 3\Gamma(H \rightarrow l\bar{l}), \text{due to color} \]

\[ \Gamma(H \rightarrow q\bar{q}) = \left[ \frac{\alpha_W}{8} \left( \frac{m_q}{M_W} \right)^2 \right] M_H \]

**Gauge Bosons**

\[ \Gamma(H \rightarrow ZZ) = \Gamma(H \rightarrow WW) / 2 \]

\[ \Gamma(H \rightarrow WW) = \left[ \frac{\alpha_W}{16} \left( \frac{M_H}{M_W} \right)^2 \right] M_H, \text{recall top width} \]

**Loop Decays - Gauge Bosons:**

\[ \Gamma(H \rightarrow gg) \sim \left[ \frac{\alpha_W}{9} \left( \frac{M_H}{M_W} \right)^2 \right] \left[ \frac{(\alpha_s/\pi)^2}{4} |I|^2 / 8 \right] M_H \]

\[ \Gamma(H \rightarrow \gamma\gamma) \sim \left[ \frac{\alpha_W}{9} \left( \frac{M_H}{M_W} \right)^2 \right] \left[ \frac{(\alpha/\pi)^2}{4} |I|^2 / 8 \right] M_H \]

Higgs couples to mass, with no direct \( H_{\gamma\gamma} \) or \( H_{gg} \) coupling
Higgs - Production via gg Fusion

• The formation cross section is,

\[ \frac{d\sigma}{dy} \sim \pi^2 \Gamma(H \rightarrow gg)/(M_H^3)[xg(x)]_{x1}[xg(x)]_{x2} \]

• Using the expression for \( \Gamma(H \rightarrow gg) \) and normalizing the gluon distribution.

\[ \frac{d\sigma}{dy} \sim 49\pi^2\left[ \Gamma(H \rightarrow gg)/(4M_H^3)\right][1 - M_H/\sqrt{s}]^{12} \sim 49\pi^2\Gamma(H \rightarrow gg)/(4M_H^3) \]

\[ \frac{d\sigma}{dy} \sim 49|I|^2 \alpha_s^2 \alpha_W/[288M_W^2]. \]

• Note that the \( M_H^3 \) behavior of \( \Gamma \) cancels the \( 1/M_H^3 \) behavior of \( d\sigma/dy \), leaving a roughly constant cross section,
Higgs Physics in one slide

Production of Higgs:
dominant: $gg \rightarrow H$
subdominant: $HW,HZ,Hqq$

$m_H < 130 \text{ GeV}$: $H \rightarrow bb, \tau\tau$ dominate
Best channels at LHC: $ttH \rightarrow lbbX, H \rightarrow \gamma\gamma$

$m_H > 130 \text{ GeV}$: $H \rightarrow WW(\ast), ZZ(\ast)$ dominate
best search channels at LHC: $H \rightarrow ZZ(\ast) \rightarrow 4l$ (gold-plated), $H \rightarrow WW(\ast) \rightarrow l\nu \bar{l}\nu$

10/23/2009
Higgs Decays

Standard Model Higgs channels considered here:

\[ H \rightarrow \gamma\gamma \]
\[ H \rightarrow WW (*) \rightarrow e\nu\mu\nu \]
\[ H \rightarrow ZZ(*) \rightarrow 4l \ (l = e, \mu) \]
\[ H \rightarrow \tau^+\tau^- \rightarrow ll, lh \]
Higgs discovery?

Gold-plated channel at LHC
Background Free ...

Other channels are more demanding on detectors
Supersymmetry (SUSY)

- SM particles have supersymmetric partners:
  - Differ by 1/2 unit in spin
    - Sfermions (squark, selectron, smuon, ...): spin 0
    - gauginos (chargino, neutralino, gluino,...): spin 1/2
- No SUSY particles found as yet:
  - SUSY must be broken: breaking mechanism determines phenomenology
  - More than 100 parameters even in “minimal” models!
What's Nice about SUSY?

• Symmetry between bosons and fermions
• Unifications of forces possible SUSY changes running of couplings
• Dark matter candidate exists: The Lightest Supersymmetric Particle (LSP)
• No fine-tuning required: Radiative corrections to Higgs acquire SUSY corrections
• Cancellation of fermion and sfermion Loops
• Also consistent with precision measurements of $M_W$ and $M_{\text{top}}$. But may change relationship between $M_W$, $M_{\text{top}}$ and $M_H$
SUSY has many motivations, but the most convincing one are:

→ SUSY has the only possible extension to the Poincare symmetry of space time.

→ The Hierarchy Problem.
  
 If someone ever what to extend the SM by including new physics, we will need to explain why Higgs boson is so light. Super symmetry gives us the answer.

→ Note that the hierarchy problem is not really a problem if you do not include new physics at all.

→ Unification of gauge coupling at GUT scale.

→ SUSY has a good dark matter candidate the Neutralino.
Conserved R-parity requires existence of a lightest stable SUSY particle (LSP). Since no exotic strong or EM bound states (isotopes) have been observed, the LSP should be neutral and colourless WIMP: LSP signature just as heavy neutrino

- The LSP is typically found to be a spin- neutralino, a linear combination of gauginos (in much of the SUSY parameter space the neutralino is a mixture of photino and zino)
- With R-parity: SUSY production in pairs requires energy $2 >$ SUSY mass!

“Typical” SUSY decay chain at the LHC
Experiments evaluate their SUSY discovery potential using some “standard” mSUGRA

D0 & CDF L = 0.3 fb⁻¹ ~ 0.35 TeV
Ultimate (LHC):
L = 300 fb⁻¹ ~ 2.5–3 TeV
1 year 10³⁴ ~ 2.5 TeV
1 year 10³³ ~ 1.8 TeV
1 month 10³³ ~ 1.3 TeV
squark/gluino masses
Luminosity
Time period [cm⁻²s⁻¹]
5 standard deviations discovery contours

<table>
<thead>
<tr>
<th>M_{sp} (GeV)</th>
<th>σ (pb)</th>
<th>Evts/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>100</td>
<td>10⁶–10⁷</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>10⁴–10⁵</td>
</tr>
<tr>
<td>2000</td>
<td>0.01</td>
<td>10²–10³</td>
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</table>

10 fb⁻¹
SUSY Discovery Potential

Discovery potential for squarks and gluinos in the channel

\( n \text{ leptons} + \geq 2 \text{ jets} + \not{E}_T \)

- 300 fb\(^{-1}\) (three years @ high lumi)
- 100 fb\(^{-1}\) (one year @ high lumi)
- 10 fb\(^{-1}\) (one year @ low lumi)
- 1 fb\(^{-1}\) (one month @ low lumi)

mSUGRA: \( A_0 = 0, \tan\beta = 35, \mu > 0 \)
Beyond Supersymmetry

• **Strong theoretical prejudices for SUSY being true**
  – But so far there is a lack of SUSY observation....

• **Need to keep an open eye for e.g.**:
  – **Extra spatial dimensions:**
    • Addresses hierarchy problem: make gravity strong at TeV scale
  – **Extra gauge groups: Z’, W’**
    • Occur naturally in GUT scale theories
  – **Leptoquarks:**
    • Would combine naturally the quark and lepton sector
  – **New/excited fermions**
    • More generations? Compositeness?
  – **Preons:**
    • atom ⇒ nucleus ⇒ proton/neutron ⇒ quarks ⇒ preons?
  – ... ????: something nobody has thought of yet
WHY does quantisation of the electric charge exist?

In 1931 Dirac showed that the existence of single magnetic monopole with magnetic charge $g$ explained the quantization of electric charge $e$ in terms of the Dirac quantization condition

$$ e g = n \frac{\hbar c}{2}, \ n = 0, \pm 1, \pm 2, \ldots \quad (P.A.M. \ Dirac, \ 1931) $$

Besides explaining the quantization of electric charge, the existence of magnetic charges restores the symmetry of the Maxwell’s equations.

Thus, existence of both electric and magnetic charge in the universe requires charge quantization. Since the quantization of electric charge in nature is well established but still mysterious, the discovery of just a single monopole would provide a much wanted explanation.
By a Dirac monopole we mean a particle without electric charge or hadronic interactions and with magnetic charge $g$ satisfying the Dirac quantization condition.

Going from lepton to monopole production we replace

**Two photon s=1/2**

$$e \rightarrow g\beta$$

**Drell-Yan**

Differential cross section

$$d\sigma \sim A \frac{1 + 2\beta^2(1 - \beta^2)(1 - \cos^2 \theta) - \beta^4 \cos^4 \theta}{(1 - \beta^2 \cos^2 \theta)^2}.$$  

As it follows from differential cross section we have all partial waves for two photon production. Thus, we have no any contradiction with unitarity for $\gamma\gamma$ processes.

When we make duality substitution $e \rightarrow g\beta$, the Drell-Yan model satisfy the unitarity relation up to $n\approx 3$. Therefore, we need to use $n=3$ cross section as the unitarity limit for all $n>3$. 

10/23/2009
So, $\gamma\gamma$ production is the leading mechanism for direct monopole searches at LHC.
How can we search monopole at LHC?

If magnetic monopole produced in ATLAS then monopole would be revealed by its unique characteristic.

- Transition Radiation

- The large value of a magnetic charge means that ionization energy losses will be several orders of magnitude greater for monopoles than for electrically charged particle.

- Trapped magnetic monopoles can be drafted by the magnetic field and further registered.
What is Compositeness?

• Quarks may not be fundamental particles; but rather an agglomeration of smaller constituents called “preons.”
• These features are visible above a characteristic energy scale $\Lambda$ below which quarks appear point like.
• $\Lambda$ characterizes both strength of preon coupling and physical size of composite scale
• The Standard Model is an effective theory. The new theory takes over at a scale $\Lambda$ comparable to the Higgs boson mass, i.e. $\Lambda \sim 1$ TeV.
• Possible solution?

**Supersymmetry** : for each SM particle a SUSY partner is introduced. SM and SUSY particle contributions to Higgs mass have opposite sign.

**Extra Dimensions** : Strong gravity at TeV scale. ED already introduced in string theory (theory for describing the gravitation using QFT with 10 or 11 dimensions, in which extra dimensions are compactified).
Direct Searches

Isolated Photon with a large missing transverse energy (non detected G)

Channel which will allow to confirm the discovery in the monojet channel
TeV size X-dimensions at LHC

Variation of the previous model: In addition to the large extra dim, smaller ones are introduced (of TeV-1 size) in which gauge bosons can propagate while fermions are confined on the 4dim brains.

The KK modes of the gauge bosons $\gamma$, $Z$, $W$ are massive and their coupling goes like SM (* $\sqrt{2}$)

**Constraints for $\gamma$ and $Z$:**
- EW Data: $M_{c} > 4$ TeV
- At LHC (mostly from ATLAS):
  - Sensitivity in the peak: $M_{c} \text{ max} = 5.8$ TeV (100 fb-1)
  - From interference study: $M_{c} \text{ max} = 9.5$ TeV (e) for 100 fb-1 and 13.5 TeV for 300 fb-1 (e+$\mu$)
Seeking “SUSY”

- Low-mass SUSY ($M_{sp} \sim 500\text{GeV}$) accessible with $O(10^{-1})\text{ fb}^{-1}$. Some spectacular signatures
- Time to discovery determined by:
  - Time to understand detector performance: $E_T^{\text{miss}}$ tails, jet performance and energy scale, lepton id
  - Time to collect control samples -- e.g. $W$+jets, $Z$+jets, $WW$, top..
Seeking “SUSY”
Extra Dimensions etc: $Z'$

$Z' \rightarrow \mu\mu$ production

Low lumi 0.1 fb$^{-1}$: discovery of 1-1.6 TeV possible
High lumi 100 fb$^{-1}$: extend range to 3.5-4.5 TeV