The Search for New Physics at the LHC

Oliver Buchmüller
CERN

• The “LHC Environment”
  - a real challenge
• Physics Commissioning
  - rediscovery of the SM
• Search for New Physics in the Early Days
  - focus on illustrative examples from ATLAS/CMS

Strings 2008 18/08/2008
The Large Hadron Collider at CERN

- **LHCb/MOEDAL**
  - LHC: 27 km long
  - 100m under ground
  - pp, B-Physics, CP Violation

- **CMS/TOTEM**
  - General Purpose, pp, heavy ions

- **ATLAS/LHCf**
  - Heavy ions, pp

- **ALICE**
  - General Purpose, pp, heavy ions
A Glimpse at the LHC Physics Program

Higgs! (no k-factors)

Extra Dimensions??

Supersymmetry?

Precision Electroweak!

CKM triangle!

Black Holes??

Quark Gluon Plasma?

Physics at a new energy frontier!

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The LHC Environment
Background and Signal

High-$p_T$ QCD jets

W, Z

Top-Top

Higgs

$m_H=100$ GeV

$q, \bar{q}$ pairs, $m \sim 1$ TeV
Background and Signal

Searching for these events is like looking for a needle in a (very) big haystack:

\[ \sigma_{\text{tot}} \approx 100 \text{mb} \]

Jets w. \( E_T > 100 \text{ GeV} \) \( \approx 1 \mu \text{b} \)

\( tt\bar{t} \) \( \approx 800 \text{pb} \)

In order to find the “needle”, we need to understand these processes very well (don’t forget, additional hard jets only cost \( \alpha_s/\pi \approx 0.1 \))
Physics Commissioning with the first collision data
First Phase

“Why”: Measure Charged Particle Density

- W, Z, ttbar cross sections known to ~3 to 10%
- Large uncertainties in minimum bias \( \frac{dN_{ch}}{d\eta} \)
  known to only ~50% (or worse)

Precise knowledge of \( \frac{dN_{ch}}{d\eta} \) very important for MC tuning, understanding underlying event, pile-up etc.
Charged particle multiplicity in pp collisions at \( \sqrt{s} = 10 \) TeV

Abstract

We report on a measurement of the mean charged particle multiplicity in minimum bias events, produced in the central region \(|\eta| < 1\), at the LHC in pp collisions with \( \sqrt{s} = 14 \) TeV, and recorded in the CMS experiment at CERN. The events have been selected by a minimum bias trigger, the charged tracks reconstructed in the silicon tracker and in the muon chambers. The track density is compared to the results of Monte Carlo programs and it is observed that all models fail dramatically to describe the data.

Submitted to *European Journal of Physics*

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Second Phase

Measure Jet Cross Section

- $E_T^{\text{Jet}} > 500 \text{ GeV}$ after a few weeks at $10^{31}\text{cm}^{-2}\text{s}^{-1}$
- Going fast beyond the reach of the Tevatron
- Early sensitivity to compositeness requires understanding of the jet energy scale, PDF’s, …

New Territory

- Tevatron
- LHC
Second Phase

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Contact Interactions - early days

*Discovery Sensitivity (CMS)*

- $10 \text{pb}^{-1} \rightarrow \Lambda \sim 4 \text{ TeV}$
- $100 \text{pb}^{-1} \rightarrow \Lambda \sim 7 \text{ TeV}$
- $1 \text{fb}^{-1} \rightarrow \Lambda \sim 10 \text{ TeV}$
- $10 \text{fb}^{-1} \rightarrow \Lambda \sim 15 \text{ TeV}$

Significant discovery potential:
- e.g. up to $\Lambda \sim 10 \text{ TeV}$
- in 2008/2009

New Territory

Tevatron
LHC

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**Third Phase**

Rediscover the SM

- Reestablish the Standard Model
- Most SM cross sections are significantly higher than at the Tevatron
e.g. \( \sigma_{\text{t\bar{t}}} \) (LHC) \( \approx \) 100 \( \times \) \( \sigma_{\text{t\bar{t}}} \) (Tevatron)
- Crucial for final Detector and Physics Commissioning

THE path to new physics! 14 TeV

**At Luminosity** \( 10^{31} \text{cm}^{-2}\text{s}^{-1} \)

- **bb** production: \( \rightarrow 10^3 \) Hz
- **W**\( \rightarrow \ell \, \nu \): \( \rightarrow 0.1 \) Hz
- **Z**\( \rightarrow \ell \, \ell \): \( \rightarrow 0.01 \) Hz
- **t t** production: \( \rightarrow 0.01 \) Hz
- **SM Higgs** \( \rightarrow 0.0001 \) Hz

At this stage the LHC becomes a real SM Factory!
Third Phase

Rediscover the SM

For $L=10/\text{pb} \ @ \ 10 \ \text{TeV}$
- $W \rightarrow \ell \ \nu$: $\rightarrow 300\text{K Events}$
- $Z \rightarrow \ell \ \ell$: $\rightarrow 30\text{K Events}$
- tt production: $\rightarrow 10\text{K Events}$

Rather large data samples already expected for 2008!

Production Rate: 10 vs.14 TeV:
- W/Z $\sim 70\%$
- ttbar $\sim 50\%$
- Higgs (200) $\sim 50\%$
“Rediscovery” of the Standard Model @ 14 TeV (10 TeV)
Rediscovery of the SM

$J/\phi \rightarrow \mu\mu$ and $Y \rightarrow \mu\mu$

$J/\psi$

Bkg w/o vertex cuts

γ1S

$Z \rightarrow \mu\mu$

$W \rightarrow \mu\nu$

CMS Preliminary @ 10pb$^{-1}$

$t\bar{t} \rightarrow q\bar{q}b b\mu\nu$
New Physics
What to expect?
Good Things Come Early ... and Late

Hadron Collider History

Collider Integrated Luminosity (pb^{-1})

Run IIB Goals
- 8.2 (fb^{+}) With Electron Cooling
- 4.1 (fb^{-}) Without Electron Cooling

UA1 or UA2

Top Discovery (pub.95)

Top Evidence (pub.94)

CDF

W/Z Discovery

Di jets

Tevatron needed to ~match SPS integrated luminosity in order to probe a “new” energy domain

And then discovered top!
**Good Things Come Early ... and Late**

J. Incandela

**Hadron Collider History ... and its potential Future**

Collider Integrated Luminosity (pb⁻¹)

- **Run Iib Goals**: 8.2 (fb⁻¹) With Electron Cooling
- 4.1 (fb⁻¹) Without Electron Cooling

- **2010-2011**: LHC @ 14 TeV ~10/fb
- **Higgs @ 120 GeV ??**

- **SM + X ??**
  - The discovery year?!
  - We will benefit immediately from high energy. Significant sensitivity increase will take lots of statistic increase due to steeply falling parton luminosities

- **LHC will start in a new energy territory**
  - but focus on SM & Commissioning in 2008

- **2008**: LHC @ 10 TeV ~10/fb
  - Top Evidence (pub.94)
  - Top Discovery (pub.95)
  - W/Z Discovery
  - UA1 or UA2

- **2009**: LHC
  - LHC @ 14 TeV few 1/fb

- **1980-2010**: Integrated Luminosity (pb⁻¹)
  - Di Jets
  - W/Z Discovery

**Strin**
Another Way to Look at It …

Many people now ask:

*Will the LHC discover the Higgs boson?*

My answer is …
Another Way to Look at It …

Many people now ask:

Will the LHC discover the Higgs boson?

My answer is …

By the time the LHC discovers the Higgs boson, that discovery will no longer be considered interesting.

M.E. Peskin - Tools 2008
SM + X: New Physics Potential of the LHC

What could make a Higgs discovery “uninteresting”?

Contact Interaction /Excited Quarks?

Supersymmetry?

New Gauge Bosons?

Technicolor?

Extra Dimensions?

Black Holes???

Little Higgs? $T \rightarrow Z^0 \rightarrow llb\bar{b}$

Split Susy?
### New Physics Potential - Early Days

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass reach</th>
<th>Luminosity (fb⁻¹)</th>
<th>Early Systematic Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Interaction</td>
<td>Λ &lt; 3 TeV</td>
<td>0.01</td>
<td>Jet Eff., Energy Scale</td>
</tr>
<tr>
<td>Z⁺</td>
<td>M ~ 1 TeV</td>
<td>0.01-0.1</td>
<td>Alignment</td>
</tr>
<tr>
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<td>0.01</td>
<td>Alignment/MET</td>
</tr>
<tr>
<td>Black Holes</td>
<td>M₀ ~ 2.0 TeV</td>
<td>0.01</td>
<td>MET/ Jet Energy Scale</td>
</tr>
<tr>
<td>Excited Quark</td>
<td>M ~0.7 – 3.6 TeV</td>
<td>0.1</td>
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</tr>
<tr>
<td>Axigluon or Colouron</td>
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<tr>
<td>E6 diquarks</td>
<td>M ~0.7 – 4.0 TeV</td>
<td>0.1</td>
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</tr>
<tr>
<td>Technirho</td>
<td>M ~0.7 – 2.4 TeV</td>
<td>0.1</td>
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</tr>
<tr>
<td>ADD Virtual G_{KK}</td>
<td>M₀ ~ 4.3 - 3 TeV, n = 3-6</td>
<td>0.1</td>
<td>Alignment</td>
</tr>
<tr>
<td>ADD Direct G_{KK}</td>
<td>M₀ ~ 5 - 4 TeV, n = 3-6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SUSY</td>
<td>M ~1.5 – 1.8 TeV</td>
<td>1</td>
<td>MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backg.</td>
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<tr>
<td>Jet+MET+0 lepton</td>
<td>M ~0.5 TeV</td>
<td>0.01</td>
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<td>Jet+MET+1 lepton</td>
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<td>0.1</td>
<td></td>
</tr>
<tr>
<td>mUED</td>
<td>M ~0.3 TeV</td>
<td>0.01</td>
<td>Lepton ID</td>
</tr>
<tr>
<td>M ~ 0.6 TeV</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HSCP</td>
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<td>0.1</td>
<td>TOF, dE/Dx</td>
</tr>
<tr>
<td>RS1 di-jets</td>
<td>M_{G1} ~0.7-0.8 TeV, c=0.1</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
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*Not an exhaustive list!*
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Rather than presenting the generic reach plots for each scenario (we have seen them so many times already), I will discuss a few illustrative examples in more detail.
**Di-lepton Resonances (Example Z’)**

has always been the subject of (clean) searches …

\[ M_{Z’} = 1.5 \text{ TeV} \]

~80 Events in 1fb⁻¹

Main background:
Drell-Yan:
<1 event for \( M > 1.5 \text{ TeV} \) in 1fb⁻¹

\[ Z’ \rightarrow e^+ e^- \text{ Discovery Potential} \]

Very early discovery potential with clean signatures!

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SUSY Searches @ LHC

Huge number of theoretical models
- Very complex analysis; MSSM >100 parameter
- To reduce complexity we have to choose some “reasonable”, “typical” models; use a theory of dynamical SUSY breaking
  - mSUGRA (main model)
  - GMSB (studied in less detail)
  - AMSB (studied in less detail)
- Use models to study different SUSY signatures in the detector.

Clear signatures of large missing energy, hard jets and many leptons! (assume R-Parity)

Could be very spectacular!

For low masses the LHC becomes a real SUSY factory

\[ pp \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}, \tilde{g}\tilde{g} + X \]

LHC: gluino and squark production dominate (strong couplings)

Large production rates at "low mass"

<table>
<thead>
<tr>
<th>( M_{\text{sp}} ) (GeV)</th>
<th>( \sigma ) (pb)</th>
<th>Evts/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>100</td>
<td>( 10^6 - 10^7 )</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>( 10^4 - 10^5 )</td>
</tr>
<tr>
<td>2000</td>
<td>0.01</td>
<td>( 10^2 - 10^3 )</td>
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</table>
Discover Potential for “muli-jet, multi-lepton and missing energy search” is described in the CMSSM.
Both ATLAS and CMS have very similar performance (as expected).
What do we call a “SUSY search”? 

The definition is purely derived from the experimental signature. 
Therefore, a “SUSY search signature” is characterized by 
Lots of missing energy, many jets, and possibly leptons in the final state 

**Missing Energy:**
- from LSP

**Multi-Jet:**
- from cascade decay (gaugino)

**Multi-Leptons:**
- from decay of charginos/neutralinos

RP-Conserving SUSY is a very prominent example predicting this famous signature but …
What is its experimental signature?

... by no means is it the only New Physics model predicting this experimental pattern. Many other NP models predict this genuine signature.

**Missing Energy:**
- Nwimp - end of the cascade

**Multi-Jet:**
- from decay of the Ns (possibly via heavy SM particles like top, W/Z)

**Multi-Leptons:**
- from decay of the N’s

Model examples are Extra dimensions, Little Higgs, Technicolour, etc

but a more generic definition for this signature is as follows.
“SUSY Searches” - What are we searching for?

- Pair-produced new particles N with a colour charge and a mass of O(TeV/2)
- N decays via a cascade into other new particles as well as SM particles like bosons, leptons and quarks
- At the end of the cascade decay is a weakly interacting new particle - i.e. a dark matter candidate

In other words, a “SUSY search” is a search for a weakly interacting (stable) particle that was produced in the cascade decay of a heavy new particle.

Use “SUSY” as a convenient tool to characterize this search!
**Jets + \( E_T^{\text{miss}} \) - Inclusive Search**

- Pair-produced new particles \( N \) with a colour charge and a mass of \( O(\text{TeV})/2 \)
- \( N \) decays via a cascade into other new particles as well as SM particles like bosons, leptons and quarks
- At the end of the cascade decay is a weakly interacting new particle - i.e. a dark matter candidate

*In other words, a “SUSY search” is a search for a weakly interacting (stable) particle that was produced in the cascade decay of a heavy new particle.*

**Big discovery potential**
But requires a very good detector understanding and background control:

**Analysis Strategy:**
- Be brave
- Fight background and noise
- Use data control samples
- Estimate background from data
Data Driven Background Estimations

An illustrative example: $Z \rightarrow \nu \nu + \text{jets}$
Irreducible background for Jets+$E_t^{\text{mis}}$ search

Data-driven strategy:
• define control samples and understand their strength and weaknesses:
Data Driven Background Estimations

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Strength:
• very clean, easy to select

Weakness:
• low statistic: factor 6
  suppressed w.r.t. to $Z \rightarrow \nu\nu$
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$W \rightarrow \mu \nu + \text{jets}$

Strength:
• larger statistic

Weakness:
• not so clean, SM and signal contamination
Data Driven Background Estimations

An illustrative example: \(Z \rightarrow \nu \nu + \text{jets}\)
Irreducible background for Jets+\(E_t^{\text{mis}}\) search

Data driven strategy:
• define control samples and understand their strength and weaknesses:

\[
\begin{align*}
Z & \rightarrow \ell \ell + \text{jets} \\
W & \rightarrow l \nu + \text{jets} \\
\gamma & + \text{jets}
\end{align*}
\]

Strength:
• very clean, easy to select

Weakness:
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\[
\begin{align*}
\nu & \\
\mu & \\
\mu & \\
\nu & \\
\gamma & \\
E_t^{\text{mis}} &
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\mu & \\
\mu & \\
\nu & \\
\gamma & \\
E_t^{\text{mis}} &
\end{align*}
\]

Strength:
• large stat, clean for high \(E_\gamma\)

Weakness:
• not clean for \(E_\gamma < 100\) GeV, possible theo. issues for normalization (u. investigation)

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**W/Z+jets: Estimate Z to invisible**

Measure from $\geq 2$ Jets from Data:

Use:
- $Z(\rightarrow \mu\mu) + \geq 2$ jets
- $Z(\rightarrow ee) + \geq 2$ jets

to estimate directly
- $Z(\rightarrow \nu\nu) + \geq 2$ jets

**W/Z Ratio from data & MC tuning**

- Assume lepton universality
- Measure W/Z ratio as function of N jets

$$\rho \equiv \frac{\sigma(pp \rightarrow W(\rightarrow \mu\nu)+jets)}{\sigma(pp \rightarrow Z(\rightarrow \mu+\mu^-)+jets)}$$

- Tune MC with $\leq 2$ Jets and use it to extrapolate in signal ratio e.g. $\geq 3$ Jets
**γ+jets: Estimate Z to invisible**

**γ+jets selection & properties:**
- $E_\gamma > 150$ GeV
  - clean sample: S/B > 20
  - ratio $\sigma(Z+\text{jet})/\sigma(\gamma+\text{jet})$ constant

**γ+jets: Strategy:**
- remove $\gamma$ from the event:
  - $\gamma$ becomes $E_T^{\text{mis}}$
- take $\sigma(Z+\text{jet})/\sigma(\gamma+\text{jet})$ for $E_\gamma > 200$ GeV from MC or measure in data

---

**Diagrams:**
- Top: $E_\gamma > 150$ GeV
- Bottom: Ratio $\sigma(Z+\text{jet})/\sigma(\gamma+\text{jet})$ vs Boson Pt [GeV/c]

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First Kinematic Measurements

... and if we are a bit lucky we might see such spectacular signals already in the early days!

Look for generic signatures of cascade decays:

Jets + $E_t^{\text{miss}}$ + SFOS di-leptons

Extract: $\tilde{M}_{\ell\ell}^{\text{max}} = M(\tilde{\chi}_2^0) \sqrt{1 - \frac{M^2(\tilde{\ell}_R^0)}{M^2(\tilde{\chi}_1^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{s}^0)}}$

from a fit to the “edge distribution”.

- $\Delta M_{ee}^{\text{max}} = 1.07^{+0.36}_{-0.36} \text{GeV for 1/fb (CMS)}$
- $\Delta M_{\mu\mu}^{\text{max}} = 0.75^{+0.18}_{-0.18} \text{GeV for 1/fb (CMS)}$
- Estimate same flavour top and di-boson bkg directly from $e\mu$ data
- Relatively precise extraction of $M_{ll}^{\text{max}}$ in the first few hundred pb$^{-1}$ is still possible.
SM-like Higgs Boson

Good things come early … and late(r)

Although it may come “late” and therefore may not be the first major discovery of the LHC - we still need to find it (or exclude it).

No reason to discount it … it will be a major event for the LHC & Particle Physics in any case!
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SM-like Higgs Boson

SM: Constrained Phase Space

\[ m_{h(SM)} = 76^{+33}_{-24} \text{ GeV} \]
\[ m_{h(SM)} < 144 \text{ GeV at 95\% CL} \]

SUSY: Accessible Phase Space

- MSSM
- SUGRA
- GMSB
- AMSB
- SM

\[ m_{h(SM)}(\text{SM}) = 76 \pm 33 \text{ GeV} \]

LEP direct search: $>114.5$ GeV

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Higgs Mass below 200 GeV

Low $M_H < 140$ GeV

$H \rightarrow \gamma \gamma$

$2M_w < M_h < 2M_Z$

$H \rightarrow WW(*) \rightarrow 2l$

$130 < M_H < 600$ GeV

$H \rightarrow ZZ(*) \rightarrow 4l$

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SM Higgs Reach

ATLAS Discovery Potential

ATLAS
Preliminary

5\sigma

Average includes:
H\to\gamma\gamma, qqH&H\to\tau\tau, H\to ZZ \to 4l, 
H\to WW \to e\mu, qqH\to qqWW \to qq\mu

Luminosity 1/fb

Significance

CMS, 30 fb^{-1}

M_H, GeV/c^2

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Most difficult part is $M_h \sim 115$ to 120 GeV
ttH→ttbb more difficult than originally expected

Early discovery already possible with 1fb$^{-1}$
$H→WW^{(*)}→2l$
SM Higgs Reach

ATLAS Discovery Potential

Most difficult part is $M_h \sim 115$ to 120 GeV

Early discovery already possible with 1fb$^{-1}$

With 1fb$^{-1}$ of understood data:

- potential to exclude a very large mass range
- potential to discover higgs with $m_h \sim 165$ GeV ($m_h \sim 170$ GeV recently excluded by Tevatron)

LHC will give us an answer!
Summary

- 2008 will be the year of machine, detector, and physics analysis commissioning - i.e. intense preparation for the physics year 2009.
  - Challenge: commissioning of machine and detectors of unprecedented complexity, technology, and performance
  - Re-discover the Standard Model at 10 TeV, understand the “LHC environment”
- The LHC will discover (or exclude) the Higgs by ~2010-2011 [~10/fb].
  - We will get an answer!
  - Large phase space can already be excluded with only ~1fb⁻¹ (i.e. 2009)
- The LHC will discover low energy SUSY (if it exists).
  - 2009 could become the year of “SUSY” but it could also take more time and ingenuity before we can claim a discovery
  - First signals might emerge already in the first data but do we understand them?!
- The LHC will cover a new physics scale of 1-3 TeV.
  - Many new physics models; Black hole, Extra Dimensions,Little Higgs, Split Susy, New Bosons, Technicolour, etc ...

In other words, the next years will be a very exciting time for particle physics . . .
In other words; the next years will be a very exciting time for particle physics.
Many Thanks to:

A. De Roeck, F. Gianotti, G. Giudice, J. Incandela, K. Jakobs and many others…
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A. De Roeck, F. Gianotti, G. Giudice, J. Incandela, K. Jakobs and many others …
The LHC Environment
Collisions at the LHC

7x10^{12} eV
10^{34} cm^{-2} s^{-1}
2835
10^{11}

Beam Energy
Luminosity
Bunches/Beam
Protons/Bunch

Bunch Crossing 4 10^7 Hz
Proton Collisions 10^9 Hz

Parton Collisions

New Particle Production 10^{-5} Hz
(Higgs, SUSY, ...)

Selection of 1 event in 10,000,000,000,000,000

Strings 2008 O. Buchmüller
A very difficult environment ...

20 min bias
events overlap
&
H→ZZ
with Z → 2 muons

: H→ 4 muons:
the cleanest
("golden")
signature

And this (not the
H though…) repeats
every 25 ns…

Reconstructed tracks
with pt > 25 GeV
High Performance Detectors

We don’t know how New Physics will manifest itself

→ detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ....

Very precise vertex reconstruction of secondary particle decays (e.g. b quarks)

Excellent performance over unprecedented energy range: few GeV → few TeV
High Performance Detectors

We don’t know how New Physics will manifest itself.

→ Detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ....
High Performance Detectors

Even for exotic particles like R-Hadrons (if they exist)

We don’t know how New Physics will manifest itself.
→ Detectors must be able to detect as many particles and signatures as possible: e, μ, τ, ν, γ, jets, b-quarks, ....
### LHC Startup

Slide from Mike Lamont

- 1 to N to 43 to 156 bunches per beam
- N bunches displaced in one beam for LHCb
- Pushing gradually one or all of:
  - Bunches per beam
  - Squeeze
  - Bunch intensity

<table>
<thead>
<tr>
<th>Bunches</th>
<th>$\beta^*$</th>
<th>$I_b$</th>
<th>Luminosity</th>
<th>Event rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 x 1</td>
<td>11</td>
<td>$10^{10}$</td>
<td>$\sim 10^{27}$</td>
<td>Low</td>
</tr>
<tr>
<td>43 x 43</td>
<td>11</td>
<td>$3 \times 10^{10}$</td>
<td>$6 \times 10^{29}$</td>
<td>0.05</td>
</tr>
<tr>
<td>43 x 43</td>
<td>4</td>
<td>$3 \times 10^{10}$</td>
<td>$1.7 \times 10^{30}$</td>
<td>0.21</td>
</tr>
<tr>
<td>43 x 43</td>
<td>2</td>
<td>$4 \times 10^{10}$</td>
<td>$6.1 \times 10^{30}$</td>
<td>0.76</td>
</tr>
<tr>
<td>156 x 156</td>
<td>4</td>
<td>$4 \times 10^{10}$</td>
<td>$1.1 \times 10^{31}$</td>
<td>0.38</td>
</tr>
<tr>
<td>156 x 156</td>
<td>4</td>
<td>$9 \times 10^{10}$</td>
<td>$5.6 \times 10^{31}$</td>
<td>1.9</td>
</tr>
<tr>
<td>156 x 156</td>
<td>2</td>
<td>$9 \times 10^{10}$</td>
<td>$1.1 \times 10^{32}$</td>
<td>3.9</td>
</tr>
</tbody>
</table>

After initial commissioning phase 156x156 running of another month could yield $O(10\text{pb}^{-1})$ @ 10 TeV in 2008

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Produced Events in the very First Days

30 days at $3 \times 10^{29}$ with efficiency 20% = 0.15 pb$^{-1}$

Assumed Efficiencies
$\varepsilon(W) = 0.3$  $\varepsilon(Z) = 0.5$  $\varepsilon(t\bar{t}) = 0.02$

Events after one Month
Min Bias : $\sim 10^{10}$
Jet$_{E_T > 25}$ : $\sim 10^{8}$
$W \rightarrow \ell \nu$ : $\sim 10^{3}$
$Z \rightarrow \ell \ell$ : $\sim 10^{2}$
tt$\rightarrow \ell \nu + X$ : $\sim 10^{1}$

Mainly used for general commissioning and detector alignment & calibration.

Strings 2008 O. Buchmüller
Produced Events in the very First Days

30 days at $3 \times 10^{29}$ with efficiency 20% = 0.15 pb$^{-1}$

**Production Rate: 10 vs. 14 TeV:**
- W/Z ~ 70%
- $\text{ttbar}$ ~ 50%
- Higgs (200) ~ 50%

Assumed Efficiencies

$\varepsilon(W) = 0.3 \quad \varepsilon(Z) = 0.5 \quad \varepsilon(\text{ttbar}) = 0.02$

**Events after one Month**
- Min Bias: $\sim 10^{10}$
- $\text{Jet}_{E_T > 25}$: $\sim 10^{8}$
- $W \rightarrow \ell \nu$: $\sim 10^{3}$
- $Z \rightarrow \ell \ell$: $\sim 10^{2}$
- $\text{tt} \rightarrow \ell \nu + X$: $\sim 10^{1}$

14 TeV

*Mainly used for general commissioning and detector alignment & calibration.*

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Production Rates: 14 TeV vs. 10 TeV

Production Rate wrt 14 TeV:
- $W/Z \sim 70\%$
- $t\bar{t} \sim 50\%$
- Higgs (200) $\sim 50\%$

**Graph:**
- Luminosity ratios for parton luminosities at 10 TeV LHC and 14 TeV LHC.
- $gg$ and $\Sigma q\bar{q}$ channels are shown.

**Note:**
- J. Sterling
- PDFs: MSTW2007NLO
LHC will startup in new territory

At 1 TeV constituent com energy
→ gg: 1 fb$^{-1}$ at Tevatron is like 1 nb$^{-1}$ at LHC
→ qq: 1 fb$^{-1}$ at Tevatron is like 1 pb$^{-1}$ at LHC
Early and Late

- Parton Luminosity falls steeply
  - In multi-TeV region, ~ by factor 10 every 600 GeV
- New states produced near threshold
  - Suppose you have a limit on some pair-produced object, M > 1 TeV. How does your sensitivity improve with more data?
    - By ~ (600/2) = 300 GeV = 30% for 10 times more integrated luminosity

Improving sensitivity is tough.... but you can turn evidence into an observation
Good stuff comes early…and late.

- **SPS**
  - 683 GeV com and ~100 GeV mean com partons

- **Tevatron I**
  - 1800 GeV com and ~270 GeV mean com partons

- **SPS & Tevatron Discoveries**
  - SPS turn-on led to quick major discoveries
  - Not true at the Tevatron

- **SPS had a lot of data**
  - Already probed quite a bit higher than the mean constituent com energy (~100 GeV)
  - Tevatron needed to ~match SPS integrated luminosity to in order to probe a “new” energy domain
    - *And then discovered top!*

- **Early discoveries have been followed by other important results at hadron colliders – but these have generally come late**
“Re-discovery” of the Standard Model @ 14 TeV (10 TeV)
**W/Z Production**

Expected rate uncertainties:

<table>
<thead>
<tr>
<th></th>
<th>ATLAS 50/pb</th>
<th>ATLAS 1/fb</th>
<th>CMS 1/fb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>W</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistical:</td>
<td>0.2%</td>
<td>0.04%</td>
<td>0.04%</td>
</tr>
<tr>
<td>Systematic:</td>
<td>3.1% – 5.2%</td>
<td>2.4%</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

Experimental systematic error dominated by missing energy determination

<table>
<thead>
<tr>
<th></th>
<th>ATLAS 50/pb</th>
<th>ATLAS 1/fb</th>
<th>CMS 1/fb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Z</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Statistical:</td>
<td>0.8%</td>
<td>0.2%</td>
<td>0.13%</td>
</tr>
<tr>
<td>Systematic:</td>
<td>3.2% – 3.6%</td>
<td>1.3%</td>
<td>2.3%</td>
</tr>
</tbody>
</table>

W/Z theoretical systematic error dominated by PDFs (1-2%) and boson Pt

Luminosity uncertainty: 10% (at startup), 5% (long-term)

**Use W (Z) production as luminosity reaction:**

- High $Q^2$ – similar to other reactions (tT, SUSY, ...)
- PDF effects cancel to a large extent in ratio of rates
**W/Z Production**

**Inclusive W→lν:**
- Single high-energy lepton (e, μ)
- Missing (transverse) energy (ν)
- Hadronic recoil, possibly jet(s)

**Inclusive Z→μμ:**
- Pair of high-energy leptons of opposite electric charge
- No missing transverse energy
- Hadronic recoil, possibly jet(s)

---

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Example: $J/\phi$, $Y$ and $Z$

$Z \rightarrow \mu\mu$
26K $Z$ and 0.1K backg. @ 50/pb
~200/day $Z \rightarrow \mu\mu$ @ $10^{31}$

$J/\phi \rightarrow \mu\mu$ and $Y \rightarrow \mu\mu$
5000/day $J/\phi$ and
800/day $Y$ @ $10^{31}$

Crucial data samples for the commissioning of the experiments (alignment, momentum scale, efficiencies, etc) but also for physics.
Example: W Production

Starting point for many detailed analyses:
• $p_T$ boson spectrum
• $W$ (and $Z$) + multi-jets (important for searches)
• Asymmetries
• $W$ mass and width
• Calibration candles (in particular $Z$)
• etc

Very rich program of work starting already at day one.
Very relevant for searches!
**Ttbar re-discovery & Ttbar as a tool**

Tag and Lepton study tool

Missing $E_T$ study tool

B tag study tool

**Light quark**

jet energy scale from

$M_W$ constraint

$b$ quark

jet energy scale from

$M_{top}$ constraint

---

3 jets with largest $\Sigma p_T$

4 jets $p_T > 65/40/40/40$ GeV

Isolated muon $p_T > 30$ GeV

NO b-tag !!

Simple and robust tt selection for start-up

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---

CMS Preliminary @ 10pb$^{-1}$

14 TeV

$M3 [\text{GeV/c}^2]$
New Physics
Contact Interactions with Di-jets

New Territory!

New Physics

Signal “over QCD”

Small systematic due to use of ratio:
Di-jet Ratio = N(|h|<0.5) / N(0.5<|h|<1)

Discovery Sensitivity (CMS)
10pb⁻¹ → Λ~4 TeV
100pb⁻¹ → Λ~7 TeV
1fb⁻¹ → Λ~10 TeV
10fb⁻¹ → Λ~15 TeV

Significant discovery potential: e.g. up to Λ~10 TeV in 2008/2009

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New Physics Search with Di-jets

Contact Interaction

Exited Quarks

Significant discovery potential: e.g. up to $\Lambda \sim 10$ TeV in 2008/2009

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Di-lepton Resonances

Because of their clear signature di-lepton resonances have always been the subject of new physics searches. At the LHC they are predicted to arise in many BSM models:

Clear signatures: $\mu^+\mu^-$ and $e^+e^-$ final state

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**Di-lepton Resonances (Example Z’)**

Because of their clear signature di-lepton resonances have always been subject of new physics searches

![Graph showing di-muon channel](image)

- **M_{Z’} = 1.5 TeV**
- **~80 Events in 1fb⁻¹**
- **Main background:**
  - Drell-Yan: <1 event for M > 1.5 TeV in 1fb⁻¹
- **Alignment effects reduce sensitivity by ~50% at the early days (<100pb⁻¹)**

Very early discovery potential with clean signatures!
**SUSY: GMSB**

**SUSY breaking mediated via gauge interactions:**

Experimental Signature:
- lepton and jets
- missing energy from gravitino
- hard photons pointing or non-pointing or long lived staus

Example:
2 Photons & “Standard” SUSY cuts

\[ M=500 \text{ TeV}, \ N=1, \ C_{\text{grav}}=1, \ \text{sgn}(m)=1 \]

\[ \tan \beta \]

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Separate pointing from non-pointing photons by looking at the ECAL cluster shape

Discovery potential already with 1/fb
GMSB

- **Theoretical framework**
  - renormalizable local supersymmetry including gravity
  - SUSY breaking mediated via gauge interactions
  - depends on 6 parameters
  - spin 3/2 gravitino superpartner of the graviton
- **Phenomenological consequences**
  - production as in MSSM
    - can have large cross section (squarks and gluinos produced)
  - decay chains
  - LSP: gravitino, mass<KeV
  - neutralino or stau NLSP decaying to a gravitino ($\chi_1^0 \rightarrow G\gamma$)
    - decay time can be long
- **Final states**:
  - leptons and jets
  - MET from gravitino
  - hard photons (pointing or not-pointing)
    - or
  - long lived stau
**Heavy Stable (Charged) Particles**

- **Heavy:**
  - hundreds of GeV
  - $\beta < 1$
- **Stable:**
  - a few meters
  - can decay in the detector or can cross it
  - we show results about particles crossing the detector
- **Charged:**
  - electrical or colour charge

- **Models:**
  - lepton like particles:
    - GMSB staus
    - Kaluza-Klein tau resonances in UED
  - R-hadrons:
    - long lived stops in SUSY
    - long lived gluino in Split-SUSY

- Many model considered, but model independent analysis
  - no assumption, just observation of a heavy object crossing the detector

### Gluino

**M= 200, 600, 1500 GeV**

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Heavy Stable Particles: GMSB

Gauge Mediated Supersymmetry Breaking. Models for SUSY breaking, alternative to mSUGRA

SUSY breaking transmitted from Hidden sector to visible sector via gauge interactions (“messengers”)

Lightest supersymmetric particle (LSP) is the Gravitino (m≤keV) light, stable and weakly interacting, possible candidate for Dark Matter

<table>
<thead>
<tr>
<th>Par.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$</td>
<td>SUSY breaking scale</td>
</tr>
<tr>
<td>$M_m$</td>
<td>Messenger mass scale</td>
</tr>
<tr>
<td>$\tan\beta$</td>
<td>Ratio of Higgs vev</td>
</tr>
<tr>
<td>$N_m$</td>
<td>Number of SU(5) messenger multiplets</td>
</tr>
<tr>
<td>$\text{sign}(\mu)$</td>
<td>$\mu$ from Higgs sector</td>
</tr>
<tr>
<td>$C_{\text{grav}}$</td>
<td>Sets NLSP lifetime</td>
</tr>
</tbody>
</table>

If $N_m>3$ NLSP is the stau quasi-stable due to the smallness of the coupling constant

- production: ISASUGRA 7.69
  - 2 points from SPS line 7
    - stau(156): $N=3$, $\Lambda=50$ TeV, $M=100$ TeV, $\tan\beta=10$, $\text{sign}(\mu)=1$, $C_{\text{grav}}=10000$
    - stau(247): $N=3$, $\Lambda=80$ TeV, $M=160$ TeV, $\tan\beta=10$, $\text{sign}(\mu)=1$, $C_{\text{grav}}=10000$
  - for both points:
    - larger squark and gluino cross section than direct stau production
    - $\sigma \sim 200$ m
- Generation: PYTHIA 6.409

Table 2: Summary of the slepton NLSP sample. $N_S = 3$, $\tan\beta = 5$, $\text{sign}(\mu) = +$, and no decay of slepton is assumed.

<table>
<thead>
<tr>
<th>name</th>
<th>NLO (LO) $\sigma$ [pb]</th>
<th>$\Lambda$ [TeV]</th>
<th>$M_m$ [TeV]</th>
<th>$M_\tau$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMSB35</td>
<td>21.0 (13.5)</td>
<td>30</td>
<td>250</td>
<td>102.3</td>
</tr>
</tbody>
</table>

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Heavy Stable Particles

- Muon-like signature but:
  - due to particle slowness, trigger and data acquisition efficiency may be affected:

if $\beta \ll 1$ the event may be associated with the wrong bunch crossing

- R-hadrons most demanding case
  - direct pair production $\rightarrow$ must relies on the two R-hadrons only
  - both particles can be slow
  - charge flipping (trajectory modified and neutral R-hadrons not visible)
Heavy Stable Particles: beta

- Drift tubes time resolution (~1 ns in ATLAS and CMS) allows the distinction of relativistic and non-relativistic particles
  - drift time as parameter of the fit
  - realignment of the hits to give an estimate of the delay
- Main bkg:
  - tails in true muons
    - will be estimated with real data using Z\rightarrow\mu\mu
  - cosmics
    - strongly suppressed if DT combined with tracker
Heavy Stable Charged Particles

Predicted by several models:
- lepton like
  - GMSB staus
  - Kaluza-Klein tau’s in UED
- R-Hadrons
  - long lived stop in SUSY
  - long lived gluino in split-susy

Properties:
- \( O(100 \text{ GeV}), \beta < 1 \)
- \( c \tau \) few meters
- electrical or colour charge

Measurement
- momentum in Tracker&Muon
- \( \beta \) TOF in Muon DT & dE/dx in Tracker

ATLAS similar

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Heavy Stable Charged Particles

Predicted by several models:
- **lepton like**
  - GMSB staus
  - Kaluza-Klein tau’s in UED
- **R-Hadrons**
  - long lived stop in SUSY
  - long lived gluino in split-susy

Properties:
- $O(100 \text{ GeV}), \beta<1$
- $c\tau$ few meters
- electrical or colour charge

Measurement
- **momentum in Tracker&Muon**
- **$\beta$ TOF in Muon DT & dE/dx in Tracker**

ATLAS similar

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**Jets + E_t^{miss} + (1,2) l - Inclusive Search**

**Opposite sign di-leptons**

- ATLAS Preliminary
- 1 fb⁻¹
- "Bulk"
- "co-annihilation"

**Same sign di-leptons**

- ATLAS Preliminary
- 1 fb⁻¹
- Almost Background Free

**1 Lepton**

- ATLAS Preliminary
- M(\bar{g}) \approx M(\bar{q}) \approx 1 \text{ TeV},
- L=1 fb⁻¹

**Good discovery potential**

- Lower statistic but cleaner than "0 lepton".

**Analysis Strategy:**
- Still worry about ttbar, W/Z jets and QCD
- Use data control samples
- Get lepton reconstruction/selection under control
SM Background: Jets+MET+(1Lepton)

jets + 0 and 1 lepton channel

Estimate top and W background from data

ATLAS:
control region with $M_T < 100$ GeV
Here we have more SM events than new physics signal

Effective mass distribution in control region can be used to predict distribution in signal region ($M_T > 100$ GeV)

ICH EP08

Sascha Caron
Depending on the SUSY parameter space the \( h \rightarrow bb \) production is possible.

- Separate cascade decay chain in two hemispheres and require two b’s in one.
- 5\( \sigma \) Signal (\( M_h = 115 \) GeV) already with \( \approx 2 \text{fb}^{-1} \)

Could be the first sign of a light higgs but b-tagging is crucial!
Extra space dimensions?

The Gravity force becomes strong!

Signatures
- Eg monojet events
- Monophoton event
- Z' like resonances
- KK excitations

...
Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

$$ds^2 = e^{2k|y|} \eta_{\mu\nu} \ dx^\mu \ dx^\nu - dy^2$$

$$R_5 = -20 \ k^2$$

$$k \sim \text{curvature}$$

$$y = \pi r_c$$

Planck brane

anti-de Sitter space

TeV/SM brane

Study the channel $pp \rightarrow \text{Graviton} \rightarrow \text{e}^+\text{e}^-$

**Phenomenology**

**Sensitivity**

signal + Drell-Yan backgr.
**Quantum Black Holes at the LHC?**

Black Holes are a direct prediction of Einstein’s general theory on relativity.

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

4 dim. : \( R_s \rightarrow \ll 10^{-35} \text{ m} \)
4+n dim. : \( R_s \rightarrow \sim 10^{-19} \text{ m} \)
\( R_S = \text{schwarzschild radius} \)

Quantum Black Holes are harmless for the environment: they will decay within less than \( 10^{-27} \) seconds.

Quantum Black Holes open the exciting perspective to study Quantum Gravity in the lab!

Simulation of a Quantum Black Hole event
Black Holes at LHC:

- With Large Extra Dimensions micro Black Holes (BH) could be produced at LHC energy scale, \( in (4+n) \) dimensional spacetime
  - Schwarzschild radius \( r_{s(4+n)} \) function of the reduced Plank scale \( M_D \)

- BH is formed if the p-p impact parameter is less than \( r_{s(4+n)} \)
  - from semiclassical approach \( \sigma (M_{BH}) = \pi r_{s(4+n)}^2 \)
  - In case of \( M_D \sim \) TeV then \( \sigma (M_{BH}) \sim \) pb

- Could be discovered with 1 fb\(^{-1} \) if \( M_D < 5 \) TeV

- BH with short life time, of the order of \( 10^{-12} \) fs
- BH is expected to evaporate by emission of all particle types
  - source of new particles
  - possibility to probe quantum gravity in lab

- Signature
  - High track multiplicity, hadrons: leptons = 5:1
  - spherical event

1 August 2005

1 Aug 2005

Sphericity
Technicolors: $\rho^+_{TC} \rightarrow W+Z \rightarrow 3l+\nu$

- Dynamical Electroweak Symmetry Breaking
  - QCD-like force which acts on technifermions at a scale of $\sim 250$ GeV
  - Mediated by technimesons
  - $\pi_{TC}$ ($s = 0$), $\rho_{TC}$ and $\omega_{TC}$ ($S = 1$)
  - *No need* for the Higgs boson

- Most promising channel is $\rho_{TC} \rightarrow W+Z \rightarrow 3l+\nu$
  - isolated high $p_T$ leptons + missing $E_T$
  - W and Z kinematics as signature
  - Background from $VV$ ($V=Z,W$), Z bb, tt

1 August 2008
Paolo SPAGNOLO
Higgs
SM-like Higgs Boson

Precision electroweak data tightly constrain the allowed region of $m_h$ in the SM.
Yet, also other important models like mSUGRA are constrained by these data:

mSUGRA fit to flavour, electroweak and cosmology data:

$$m_h(\text{mSUGRA}) = 110^{+8}_{-10} (\text{exp}) \pm 3(\text{theo}) \text{ GeV}$$

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Many of the popular models (e.g. SM or MSSM) require the lightest higgs boson mass to be significantly below 200 GeV.

If the higgs boson really exist, it is probably just around the corner!

Concentrate on SM-like higgs search for $mh<200$ GeV but the LHC covers full phase space up to 1 TeV.

⇒ We will get an answer!

Not covered in this talk:
Search for heavy higgs (e.g. MSSM)
SM Higgs (or lightest Higgs)

Higgs Decay channels

- Higgs couples to $m_f^2$
  - Heaviest available fermion (b quark) always dominates
  - Until WW, ZZ thresholds open
- Low mass: b quarks→ jets; resolution ~ 15%
  - Only chance is EM energy (use $\gamma$ decay mode)
- Once $M_H > 2M_Z$, use this
  - $W$ decays to jets or lepton+neutrino ($E_T^{miss}$)
CMS: Higgs Discovery Potential

Bottom line: We will find the Higgs (or exclude it)!

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SM Higgs Reach - New ATLAS update

For 5σ discovery, one needs

~20 fb\(^{-1}\) to probe down to \(m_H=115\) GeV

10 fb\(^{-1}\) for \(m_H\) range 127 – 440 GeV

3.3 fb\(^{-1}\) for \(m_H\) range 136 – 190 GeV

Just under 2 fb\(^{-1}\) for \(m_H \approx 2m_W\)

For 95% CL exclusion, one needs

2.8 fb\(^{-1}\) for \(m_H = 115\) GeV/c\(^2\)

2 fb\(^{-1}\) for \(m_H\) range 121– 460 GeV

Less than 2 fb\(^{-1}\) to exclude \(m_H \approx 2m_W\)
**Important Higgs Channels**

- $H \rightarrow ZZ^* \rightarrow 4\ell$
  - “early” discovery channels
  - measure Higgs properties (mass, width, xsec) already with 30 fb$^{-1}$ !!

- $H \rightarrow WW^* \rightarrow Inln$
  - significance $> 5(3)$ with 30 fb$^{-1}$ but good comprehension of detector needed (jet, MET, t in lept. and hadr. decay)

- $H \rightarrow gg$ very difficult analysis with still quite unpredictable background

- $ttH \rightarrow ttbb$ at least 60 fb$^{-1}$ (many jets also with low $p_T$ ($<30 \text{ GeV}$) → bad reso/eff)

- other channels (mainly associated production) can help EXCLUDING Higgs (e.g. WH→WWW$^*$→WInln)

<table>
<thead>
<tr>
<th>channel</th>
<th>XS</th>
<th>studied $M_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>5-100 fb</td>
<td>130-500 GeV</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow Inln$</td>
<td>0.5-2.5 pb</td>
<td>120-200 GeV</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow jjln$</td>
<td>200-900 fb</td>
<td>120-250 GeV</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow Inln$</td>
<td>50-250 fb</td>
<td>120-200 GeV</td>
</tr>
<tr>
<td>$H \rightarrow tt$</td>
<td>50-150 fb</td>
<td>115-145 GeV</td>
</tr>
<tr>
<td>$H \rightarrow gg$</td>
<td>50-100 fb</td>
<td>115-150 GeV</td>
</tr>
</tbody>
</table>

**Analysis focusing on**

- improvement of the reconstruction
- backgr. and syst. from data
Photon conversions are important, due to material balance in inner detectors
- 42% in the barrel, 59.5% in the endcap

Energy Resolution
- 0.3% in the barrel, 1% in the endcap

Associated production allows to improve s/b ratio. Both ATLAS and CMS are studying several channels

“Advanced” analyses (NN, Likelihood, categories) allow to improve results with low statistics
Indirect NP Search: $B_S \rightarrow \mu \mu$

LHCb limit on BR at 90% CL (only bkg is observed)

Expected final CDF+D0 limit

Integrated luminosity (fb$^{-1}$)

0.05fb$^{-1}$ to overtake CDF&D0

0.5fb$^{-1}$ for 90% exclusion at SM value

Early discovery possible!

CMS comparable sensitivity (or even a bit better)

Strings 2008 O. Buchmüller
LHC & Strings
String Theory ⇔ LHC

- The LHC can discover
  - Supersymmetry in Nature
  - Extra dimensions at the Terascale
  - Black holes → Study quantum gravity in the lab

- Recent developments
  - String theory inspired models to predict SUSY phenomenology at the LHC
    - $G2$-MSSM models $\Rightarrow$ unusual signatures (B Acharya, G. Kane et al)
    - String/M theory vacua with a visible MSSM sector (Kane, Kumar and Shao arXiv:0709.4259)
  - New models inspired from string theoretical observations e.g. hidden valley models
  - AdS/CFT correspondence to calculate properties in heavy ion collisions
  - Pomeron as a messenger from the string world?

Simultaneous fit of CMSSM parameters $m_0$, $m_{1/2}$, $A_0$, $\tan\beta$ ($\mu>0$) to more than 30 collider and cosmology data (e.g. $M_W$, $M_{\text{top}}$, $g-2$, $\text{BR}(B\to X\gamma)$, relic density)

"CMSSM fit clearly favors low-mass SUSY - Evidence that a signal might show up very early?!"