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 Hardon Collider at CERN

LHCb/MOEDAL
LHC: 27 km long
100m under ground

pp, B-Physics, CP Violation

ATLAS/LHCf

General Purpose,
pp, heavy ions

Heavy ions, pp

CMS/TOTEM

CMS

ALICE
A Glimpse at the LHC Physics Program

Higgs! | Extra Dimensions?? | Black Holes??
---|---|---
Supersymmetry? | CKM triangle! | Quark Gluon Plasma?

Physics at a new energy frontier!

The LHC Environment
Background and Signal

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

$\sigma_{tot} \approx 100mb$

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

$\text{ttar} \approx 800 pb$

In order to find the "needle", we need to understand these processes very well
(don't forget, additional hard jets only cost $\alpha_s/\pi \sim 0.1$)
**Physics Commissioning with the first collision data**

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**First Phase**

“Why”: Measure
Charged Particle Density

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

CDF

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

CMS collaboration

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.

Second Phase

Measure Jet Cross Section

• $E_{T}^{Jet} > 500$ GeV after a few weeks at $10^{31}$ cm$^{-2}$s$^{-1}$
• Going far beyond the reach of the Tevatron
• Early sensitivity to compositeness requires understanding of the jet energy scale, PDF’s, …
**Second Phase**

Measure Jet Cross Section

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

**Contact Interactions - early days**

*Discovery Sensitivity (CMS)*

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

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

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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. $\sigma_{\text{tbar}}$ (LHC) > 100 × $\sigma_{\text{tbar}}$ (Tevatron)
- Crucial for final Detector and Physics Commissioning

**At Luminosity $10^{31}$ cm$^{-2}$s$^{-1}$**

- $bb$ production: → 10$^3$ Hz
- $W \rightarrow \ell \nu$: → 0.1 Hz
- $Z \rightarrow \ell \ell$: → 0.01 Hz
- $t\bar{t}$ production: → 0.01 Hz
- SM Higgs → 0.0001 Hz

At this stage the LHC becomes a real SM Factory!

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Third Phase

Rediscover the SM

For L=10/pb @ 10 TeV

\begin{align*}
  W \rightarrow \ell \nu &: \rightarrow 300\text{K Events} \\
  Z \rightarrow \ell \ell &: \rightarrow 30\text{K Events} \\
  \text{t t production} &: \rightarrow 10\text{K Events}
\end{align*}

Rather large data samples already expected for 2008!

Production Rate: 10 vs.14 TeV:

- $W/Z \sim 70\%$
- $t\bar{t}$ ~50\%
- Higgs (200) ~50\%

“Rediscovery” of the Standard Model @ 14 TeV (10 TeV)
Rediscovery of the SM

New Physics
What to expect?
Good Things Come Early ... and Late

J. Incandela

Hadron Collider History

Collider Integrated Luminosity (pb⁻¹)

- Run I/II Goals
- UA1 or UA2
- Top Discovery (pub. 95)
- Top Evidence (pub. 94)
- W/Z Discovery
- Di jets

Tevatron needed to ~match SPS integrated luminosity in order to probe a "new" energy domain
And then discovered top!

Strins

Year


10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵

Good Things Come Early ... and Late

J. Incandela

Hadron Collider History ... and its potential Future

Collider Integrated Luminosity (pb⁻¹)

- Run I/II Goals
- UA1 or UA2
- Top Discovery (pub. 95)
- Top Evidence (pub. 94)
- W/Z Discovery
- Di jets

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

2008: LHC @ 10 TeV ~10 fb

2009: LHC @ 14 TeV few 1/fb

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 due to steeply falling parton luminosities
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.

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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?
- 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>Δ &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>
<td>W⁺</td>
<td>M = 1 TeV</td>
<td>0.01</td>
<td>Alignment/MET</td>
</tr>
<tr>
<td>Black Holes</td>
<td>M₂⁺ = 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>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>Axigluon or Colouron</td>
<td>M = 0.7 – 3.5 TeV</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>E6 diquarks</td>
<td>M = 0.7 – 4.0 TeV</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>Technirho</td>
<td>M = 0.7 – 2.4 TeV</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td>ADD Virtual G_{XX}</td>
<td>M₂⁺ = 4.3 – 3 TeV, n = 3-6</td>
<td>0.1</td>
<td>Alignment</td>
</tr>
<tr>
<td></td>
<td>M₂⁺ = 5 – 4 TeV, n = 3-6</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>ADD Direct G_{XX}</td>
<td>M₂⁺ = 1.5-1.8 TeV, n = 3-6</td>
<td>0.1</td>
<td>MET, Jetphoton Scale</td>
</tr>
<tr>
<td>SUSY</td>
<td>M = 1.5 – 1.8 TeV</td>
<td>0.1</td>
<td>MET, Jet Energy Scale, Multi-Jet backgrounds, Standard Model backgr.</td>
</tr>
<tr>
<td>Jet+MET+0 lepton</td>
<td>M = 0.5 TeV</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Jet+MET+1 lepton</td>
<td>M = 0.5 TeV</td>
<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></td>
<td>M = 0.6 TeV</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>HSCP</td>
<td>M = 0.3 TeV</td>
<td>0.1</td>
<td>TOF, dE/Dx</td>
</tr>
<tr>
<td></td>
<td>M = 1.0 TeV</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>RS1</td>
<td>M_{dijets} = 0.7-0.8 TeV, c=0.1</td>
<td>0.1</td>
<td>Jet Energy Scale</td>
</tr>
<tr>
<td></td>
<td>M_{di-muons} = 0.8-2.3 TeV, c=0.01-0.1</td>
<td>1</td>
<td>Alignment</td>
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“Not an exhaustive list!”

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<td>0.1</td>
<td>MET, Jet/Photon Scale</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</td>
</tr>
<tr>
<td>Jet+MET+0 lepton</td>
<td>M = -0.5 TeV</td>
<td>0.01</td>
<td>MET backgrounds</td>
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<td>MET backgrounds</td>
</tr>
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<td>mUED</td>
<td>M = -0.3 TeV</td>
<td>0.01</td>
<td>Lepton ID</td>
</tr>
<tr>
<td></td>
<td>M = - n TeV</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Not an exhaustive list!

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.

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**Di-lepton Resonances (Example Z')**

has always been the subject of (clean) searches ...  

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

- \( \sim 80 \) Events in 1fb⁻¹
- \( M_{Z'} = 1.5 \text{ TeV} \)
- \( \sqrt{s} = 2.3 \text{ TeV} \)

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

Very early discovery potential with clean signatures!

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Very early discovery potential with clean signatures!
**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.

<table>
<thead>
<tr>
<th>$M_{3/2}$ (GeV)</th>
<th>$\sigma$ (pb)</th>
<th>Evts/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>100</td>
<td>$10^3$-10$^4$</td>
</tr>
<tr>
<td>1000</td>
<td>1</td>
<td>$10^2$-10$^5$</td>
</tr>
<tr>
<td>2000</td>
<td>0.01</td>
<td>$10^2$-10$^3$</td>
</tr>
</tbody>
</table>

For low masses the LHC becomes a real SUSY factory

**SUSY Discovery Potential - CMSSM**

Discover Potential for “multi-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

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: $Z \to \nu \nu + \text{jets}$
Irreducible background for Jets+$E_{t}^{\text{mis}}$ search

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

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**Data Driven Background Estimations**

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

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

$Z \to \mu \mu + \text{jets}$

**Strength:**
- very clean, easy to select

**Weakness:**
- low statistic: factor 6
  suppressed w.r.t. to $Z \to \nu \nu$

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**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:

  - $Z \rightarrow \mu \mu + \text{jets}$
  - $W \rightarrow \mu + \text{jets}$

  **Strength:**
  - very clean, easy to select
  - low statistic: factor 6 suppressed w.r.t. to $Z \rightarrow \nu \nu$

  **Weakness:**
  - not so clean, SM and signal contamination

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**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:

  - $Z \rightarrow \ell \ell + \text{jets}$
  - $W \rightarrow \nu + \text{jets}$
  - $\gamma + \text{jets}$

  **Strength:**
  - very clean, easy to select
  - low statistic: factor 6 suppressed wrt. to $Z \rightarrow \nu \nu$

  **Weakness:**
  - not so clean, SM and signal contamination

**Strength:**
- large stat, clean for high $E_T$

**Weakness:**
- not clean for $E_T<100$ GeV, possible theo. issues for normalization (u. investigation)

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W/Z+jets: Estimate Z to invisible

Measure from ≥ 2 Jets from Data:
Use:
- Z(→μμ) + ≥2 jets
- Z(→ee) + ≥2 jets
to estimate directly
- Z(→νν) + ≥2 jets

W/Z Ratio from data & MC tuning
- Assume lepton universality
- Measure W/Z ratio as function of N jets
\[ \rho \equiv \frac{\sigma(pp\rightarrow W(\rightarrow\muν)+jets)}{\sigma(pp\rightarrow Z(\rightarrow\mu±\mu∓)+jets)} \]
- Tune MC with <=2 Jets and use it to extrapolate in signal ratio e.g. =>3Jets

γ+jets: Estimate Z to invisible

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

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

\[ \text{Jets + } E_{\text{miss}} \text{ +SFOS di-leptons} \]

Extract:

from a fit to the “edge distribution”:

- \( \Delta M_{ee}^{\text{max}} = 1.07_{-0.36}^{+0.36} \text{ GeV for 1/\text{fb}} \) (CMS)
- \( \Delta M_{\mu\mu}^{\text{max}} = 0.75_{-0.18}^{+0.18} \text{ GeV for 1/\text{fb}} \) (CMS)
- Estimate same flavour top and di-boson bkg directly from \( e\mu \) data
- Relatively precise extraction of \( M_{\chi_1^0}^{\text{max}} \) in the first few hundred \( \text{pb}^{-1} \) 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!
**SM-like Higgs Boson**

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**SM-like Higgs Boson**

SM: Constrained Phase Space

\[ m_h(\text{SM}) = 76^{+33}_{-24} \text{ GeV} \]

\[ m_h(\text{SM}) < 144 \text{ GeV} @ 95\% \text{ CL} \]

SUSY: Accessible Phase Space

- MSSM
- SUGRA
- GMSB
- AMSB

**LEP direct search: >114.5 GeV**

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**Higgs Mass below 200 GeV**

Low $M_H < 140$ GeV  
$2M_W < M_H < 2M_Z$  
$130 < M_H < 600$ GeV

$H \rightarrow \gamma \gamma$  
$H \rightarrow WW^{(*)} \rightarrow 2l$  
$H \rightarrow ZZ^{(*)} \rightarrow 4l$

**SM Higgs Reach**

**ATLAS Discovery Potential**

$5\sigma$

**CMS, 30 fb$^{-1}$**

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

H→ttb more difficult than originally expected

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

$H\rightarrow WW^{(*)} \rightarrow 2l$

SM Higgs Reach

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 . . .

Timeline: Near-term Prediction

- Higgs discovery sensitivity ($M_H=130$-$500$ GeV)
- Explore SUSY to $m \sim$ TeV
- Precision SM measurements
- Sensitivity to 1-1.5 TeV resonances $\rightarrow$ lepton pairs
- Understand SUSY and Higgs background from SM
- More accurate alignment & EM/Jet/ETmiss calibration
- Test beam, cosmic runs, pre-alignment & calibration,
- extensive simulations ...
- Search for very striking new physics signature
- Use SM processes as "standard candles"
- Initial detector & trigger synchronisation,
  commissioning, calibration & alignment, material

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**Timeline: Long-term Guess**

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**Many Thanks to:**

A. De Roeck, F. Gianotti, G. Giudice, J. Incandela, K. Jakobs and many others …

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Backup

The LHC Environment
Collisions at the LHC

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pp collisions at 14 TeV at $10^{34}$ cm$^{-2}$s$^{-1}$

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...
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: $e$, $\mu$, $\tau$, $\nu$, $\gamma$, jets, $b$-quarks, ....

Muon spectrometer

Hadron calorimeter

Inner tracker

Electromagnetic calorimeter

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

Excellent performance over unprecedented energy range:
  few GeV $\rightarrow$ few TeV

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**High Performance Detectors**

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

![Diagram of high performance detectors](image)

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

→ Detectors must be able to detect as many particles and signatures as possible: $e, \mu, \tau, \nu, \gamma, \text{jets}, \text{b-quarks}$, ....

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**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>
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<th>$\beta^*$</th>
<th>$L_\text{b}$</th>
<th>Luminosity</th>
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<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 $O(10^{10})@10$ TeV in 2008*
**Produced Events in the very First Days**

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

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

**Events after one Month**
- Min Bias: $\sim 10^{10}$
- $\text{Jet}_{\text{E}>25}$: $\sim 10^{8}$
- $W \to \ell v$: $\sim 10^{3}$
- $Z \to \ell\ell$: $\sim 10^{2}$
- $t\bar{t} \to \ell\ell + X$: $\sim 10^{1}$

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

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---

**Produced Events in the very First Days**

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

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

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

**Events after one Month**
- Min Bias: $\sim 10^{10}$
- $\text{Jet}_{\text{E}>25}$: $\sim 10^{8}$
- $W \to \ell v$: $\sim 10^{3}$
- $Z \to \ell\ell$: $\sim 10^{2}$
- $t\bar{t} \to \ell\ell + X$: $\sim 10^{1}$

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

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**Production Rates: 14 TeV vs. 10 TeV**

![Graph showing ratios of parton luminosities at 10 TeV LHC and 14 TeV LHC](image)

**Production Rate wrt 14 TeV:**
- W/Z ~70%
- ttbar ~50%
- Higgs (200) ~50%

---

**LHC will startup in new territory**

![Graph comparing gg and qq luminosity at LHC and Tevatron](image)

**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

---

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"Re-discovery" of the Standard Model @ 14 TeV (10 TeV)

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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>W</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Statistical</td>
<td>0.2%</td>
<td>0.04%</td>
</tr>
<tr>
<td></td>
<td>Systematic</td>
<td>3.1% – 5.2%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Z</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Statistical</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>Systematic</td>
<td>3.2% – 3.6%</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Experimental systematic error dominated by missing energy determination

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 extend 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→l⁺l⁻:**
- Pair of high-energy leptons of opposite electric charge
- No missing transverse energy
- Hadronic recoil, possibly jet(s)

---

**Example: J/φ, Y and Z**

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

---

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**Example: W Production**

Starting point for many detailed analyses:
- \( p_T \) boson spectrum
- \( W (\text{and } Z) + \) 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 \( M_{\text{top}} \) constraint

4 jets \( p_T > 65/40/40 \) GeV

Isolated muon \( p_T > 30 \) GeV

3 jets with largest \( \Sigma p_T \)

NO b-tag!!

Simple and robust tt selection for start-up

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**New Physics**

**Contact Interactions with Di-jets**

**Signal “over QCD”**

- **ATLAS:**
  - Probe $\Lambda > 20$ TeV already with 30fb$^{-1}$

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

**Discovery Sensitivity (CMS):**
- 10pb$^{-1}$ → $\Lambda \sim 4$ TeV
- 100pb$^{-1}$ → $\Lambda \sim 7$ TeV
- 1fb$^{-1}$ → $\Lambda \sim 10$ TeV
- 10fb$^{-1}$ → $\Lambda \sim 15$ TeV

**Significant discovery potential:**
e.g. up to $\Lambda \sim 10$ TeV in 2008/2009
New Physics Search with Di-jets

Contact Interaction

Exited Quarks

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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:

\( \gamma'^*Z'^* \) (TeV\(^{-1}\) Extra Dimensions)

\( Z' \) new gauge boson

\( G'^* \) (Randall Sundrum)

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.

**Di-muon channel**

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:**

<table>
<thead>
<tr>
<th align="left">Experimental Signature:</th>
</tr>
</thead>
<tbody>
<tr>
<td align="left">• lepton and jets</td>
</tr>
<tr>
<td align="left">• missing energy from graviton</td>
</tr>
<tr>
<td align="left">• hard photons pointing or non-pointing or long lived staus</td>
</tr>
</tbody>
</table>

**Example:**

2 Photons & “Standard” SUSY cuts

\[ \tan \beta \]

\[ \chi^0_{NLSP} \]

\[ \Lambda \] [TeV]

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---
SUSY: GMSB

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 (ν→Gν)
    - decay time can be long
- Final states:
  - leptons and jets
  - MET from gravitino
  - hard photons (pointing or not-pointing)
  - long lived stau

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Heavy Stable (Charged) Particles

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

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

---

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 (mskeV)
- light, stable and weakly interacting, possible candidate for Dark Matter

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

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

- production: ISASUGRA 7.69
  - 2 points from SPS line 7
    - stau(155): N=3, $\Lambda=50$ TeV, $M=100$ TeV, $\tan\beta=10$, sign(\mu)=1, $C_{\text{prod}}=10000$
    - stau(247): N=3, $\Lambda=80$ TeV, $M=160$ TeV, $\tan\beta=10$, sign(\mu)=1, $C_{\text{prod}}=10000$
  - for both points:
    - larger squark and gluino cross section than direct stau production
    - cc ~ 260 m
- Generation: PYTHIA 6.409

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

<table>
<thead>
<tr>
<th>name</th>
<th>NLO (LO) $\sigma$ (pb)</th>
<th>$\Lambda$ [GeV]</th>
<th>$M_{\tilde{m}}$ [TeV]</th>
<th>$M_{\tilde{m}}$ [GV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMSB5</td>
<td>21.0 (15.5)</td>
<td>30</td>
<td>150</td>
<td>102.5</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 $\beta < 1$ 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 ($\sim 1$ 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 $Z=\mu\mu$
  - 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:

• $O(100 \text{ GeV}), \beta<1$
• $\sim$ 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**$+E_{T}^{\text{miss}}+(1,2)$ I - Inclusive Search

### Opposite sign di-leptons

- ATLAS Preliminary
- $1fb^{-1}$
- "Bulk"
- "co-annihilation"

### Same sign di-leptons

- ATLAS Preliminary
- $1fb^{-1}$
- Almost Background Free

**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)**

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)**

---

*ICHEP08*
“Low Mass $M_h$” in SUSY Decays

Depending on the SUSY parameter space the $h\to bb$ production is possible

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

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

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---

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)

\[ ds^2 = e^{-2k(y)} \eta_{\mu\nu} \, dx^\mu \, dx^\nu + dy^2 \]

Planck brane

\[ y = 0 \]

TeV/SM brane

\[ y = \pi R_c \]

\[ R_S = -20 \, k^2 \]

\[ k \sim \text{curvature} \]

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

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 \( \sim \text{TeV} \) region: can expect Quantum Black Hole production

4 dim. : \( R_S \rightarrow \ll 10^{-35} \text{ m} \)

4+n dim. : \( R_S \rightarrow \sim 10^{-19} \text{ m} \)

\( R_S = \text{schwartzschild radius} \)

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!
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 \( M_0 \)
- BH is formed if the p-p impact parameter is less than \( r_s(4+n) \)
  - from semiclassical approach \( \sigma(M_{\text{BH}}) = \pi r_s^2(4+n) \)
  - In case of \( M_0 \sim \text{TeV} \) then \( \sigma(M_{\text{BH}}) \sim \text{pb} \)
- Could be discovered with 1 fb\(^{-1}\) if \( M_0 < 5 \text{ TeV} \)
- BH with short life time, of the order of \( 10^{-12} \text{ fs} \)
- 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

Technicolors: \( \rho^{\pm}_{\text{TC}} \rightarrow W+Z \rightarrow 3l+\nu \)

- **Dynamical Electroweak Symmetry Breaking**
  - QCD-like force which acts on technifermions at a scale of \( \sim 250 \text{ GeV} \)
  - Mediated by technimesons
  - \( \pi_{\text{TC}}(s=0) \), \( \rho_{\text{TC}} \) and \( \omega_{\text{TC}}(s=1) \)
  - **No need** for the Higgs boson
- **Most promising channel** is \( \rho_{\text{TC}} \rightarrow W+Z \rightarrow 3l+\nu \)
  - isolated high \( p_T \) leptons + missing \( E_T \)
  - W and Z kinematics as signature
  - Background from VV (V=Z,W), Z bb, tt
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:

\begin{align*}
\text{mSUGRA fit to flavour, electroweak and cosmology data:}
\end{align*}

$m_h(m_{\text{SUGRA}}) = 110^{+8}_{-10} \text{ (exp)} \pm 3 \text{ (theo)} \text{ GeV}$
SM-like Higgs Boson

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 \( m_h < 200 \text{ GeV} \) 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\( \rightarrow \) 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 (\( E_t^{\text{miss}} \))

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**CMS: Higgs Discovery Potential**

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

---

**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 \(m_H = 2m_W\)

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 \(m_H = 2m_W\)
**Important Higgs Channels**

- **H → ZZ⁺→4l** “early” discovery channels
- **H → WW⁺→lnln** measure Higgs properties (mass, width, xsec) already with 30 fb⁻¹ !
  - **H → WW⁺→jljl / lnln in VBF** significance > 5(3) with 30 fb⁻¹
  - **H → tt in VBF** but good comprehension of detector needed (jet, MET, t in lept. and hadr. decay)
- **H → gg** very difficult analysis with still quite unpredictable background
- **ttH → ttbb** at least 60 fb⁻¹ (many jets also with low pₜ (<30 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 Mₜ</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ZZ⁺→4l</td>
<td>5-100 fb</td>
<td>130-500 GeV</td>
</tr>
<tr>
<td>H → WW⁺→lnln</td>
<td>0.5-2.5 pb</td>
<td>120-200 GeV</td>
</tr>
<tr>
<td>H → WW⁺→jljl</td>
<td>200-900 fb</td>
<td>120-250 GeV</td>
</tr>
<tr>
<td>H → WW⁺→lnln</td>
<td>50-250 fb</td>
<td>120-200 GeV</td>
</tr>
<tr>
<td>H → tt</td>
<td>50-150 fb</td>
<td>115-145 GeV</td>
</tr>
<tr>
<td>H → 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

**H → γγ**

- **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: $B_S \rightarrow \mu\mu$**

*Early discovery possible!*

---

**LHC & Strings**

---

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String Theory ⇔ LHC

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

2. Recent developments
   - String theory inspired models to predict SUSY phenomenology at the LHC
     - G2-MSSM models ⇒ 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?

Preferred CMSSM Parameter Space

"LHC Weather Forecast"

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. $M_W$, $M_H$, g-2, $BR(B\to X\gamma)$, relic density)

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