Challenges for early discovery in ATLAS and CMS

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Rencontres de Moriond 2007
Electroweak interactions and Unified theories
Often remarked: LHC can make discoveries with one month of data. Maybe correct. But not the first month of data...

pp at 14 TeV, ATLAS and CMS: new territory. Need to find the north, make a map, firm ground under our feet.

Plan to illustrate this with 4 examples of possible discoveries with ~1 fb\(^{-1}\) of data (Moriond 2009?):

- QCD jets and dijets at high \(E_T\)
- High mass lepton pairs
- Higgs \(\rightarrow WW \rightarrow ll\nu\nu\)
- Low mass supersymmetry

By no means a complete list. In fact: searches must be general

On the way: we need to “rediscover” the Standard Model
Establish its validity in specific corners and tails: data + theory
Many more challenges not related to early discovery: no time to cover
First challenge: get the LHC operational

Still on course for engineering run fall 2007:
- system commissioning
- single beam operations at 450 GeV
- collisions at 450 x 450 GeV, no ramp, no squeeze
  → low luminosity: ATLAS/CMS commissioning

First collisions at 14 TeV: June 2008?
after system and beam commissioning
  26 weeks of proton-proton physics run in 2008
- phase 1: 43 bunches, $L \sim 5 \times 10^{30}$
- phase 2: 75 ns, $L \sim 2.5 \times 10^{31} \rightarrow 1 \times 10^{32}$
- phase 3: 25 ns, $L \sim 4 \times 10^{32} \rightarrow 1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

Integrated luminosity end of 2008: 0.5 - 1 fb$^{-1}$?
(e.g.: 1 fb$^{-1}$ = 120 effective days @ $10^{32} \text{ cm}^{-2}\text{s}^{-1}$)
And the experiments too: huge challenge

Getting the subdetectors built, tested and installed. Power and signal cables, detector control and monitoring. Cooling pipes, cryogenic installations, magnets...

**CMS:** lowered central part (YB0) February 28th, rest soon will run in 2007 without ECAL endcap and pixels rest going well

**ATLAS:** on a tight schedule to run almost complete in 2007. No TRT at high $|\eta|$, some muon chambers missing

Both will have reduced trigger/DAQ capabilities initially
Getting the data flowing…

First individual detectors, then combined
Commissioning the DAQ system with cosmics
Single beam in LHC: beam halo

Use: debug cabling errors
initial alignment
first intercalibration: uniformity to few %

Data processing: Grid, Tier-1, Tier-2 etc

Challenge: get processing of HUGE quantities of data going
Data Challenges, Calibration Challenges,
Computing System Commissioning (ATLAS 2007)

ATLAS: CSC exercise should lead to notes
CMS: published physics TDR in summer 06
Use of 2007 data (at 900 GeV)

100 nb\(^{-1}\) ? No W,Z; few J/ψ; mostly minimum bias, some jets

CMS ECAL intercalibration:

~ 1.5% calibration uniformity achievable in central barrel with 18 million minimum-bias (few days of data taking in 2007)

Commissioning of tracking:

~ 15 days of data taking in 2007 enough to cover up to \(p_T\) (leading jet) ~ 40 GeV
What do we expect to see at 14 TeV?

Low $p_T$ hadronic events ("minimum bias")

Modeled in various generators, but big uncertainties

Probably the first CMS/ATLAS measurements!
Charged particle multiplicities vs $p_T$ and $\eta$
Particles away from jet regions (No time to cover here)
What do we expect to see at 14 TeV?

@10^{32} \text{ cm}^{-2}\text{s}^{-1}

QCD jets, jets and more jets

Standard candles: W, Z, top

SM Higgs

Perhaps new physics

Jet cross section
Example 1 of possible early discovery: anomalies in high \( E_T \) QCD jets, di-jet masses

1 fb\(^{-1} \): jets up to 3-3.5 TeV, di-jet masses up to 6 TeV: **new territory!**
Example 1 of possible early discovery: anomalies in high $E_T$ QCD jets, di-jet masses

1 fb$^{-1}$: jets up to 3-3.5 TeV, di-jet masses up to 6 TeV: new territory!
Sensitive to substructure, contact interactions, high mass resonances

Challenges: Jet energy scale, Parton density functions (PDF) (notably: gluon at high $x$), underlying event, trigger, scale variation, hadronization

Deviations from SM for various compositeness scales, 30 fb$^{-1}$
Challenge: Parton Density Function uncertainties

Uncertainty on the gluon pdf, and can LHC jet data help?:

Further pdf information from W, Z production: no info on high x gluon pdf information from $\gamma^* + \text{jet}$ does help.

Does PDF fitting sweep new physics under the rug? Measure over large kinematic range: new physics central, PDF everywhere

Beyond 1 fb$^{-1}$: needs reduction of systematics: jet energy scale
**Challenge: Jet energy scale**

Validation of the energy of a jet is a **BIG challenge**

Startup: uncertainty ~10% , from test beam, calibration, cosmics
First data: embark on data-driven JES derivation

\[ E_{\text{cor}} = \frac{E_{\text{raw}} - \text{offset}}{F_{\eta} \cdot \text{response} \cdot \text{showering}} \]

Using $\gamma$+jet and dijet events

CMS and ATLAS: 10% initially $\rightarrow$ 2-3% above 20 GeV after 1-10 fb$^{-1}$
and 1% eventually? Ambitious!

Using: $\gamma$+ jet events
$Z$ + jet events
\{ Needs EM scale first \}

light jets and b-jets!

top-pair events: 2 jets from W
Expected sensitivity for new physics:

Discovery potential with 1 fb\(^{-1}\): excited quarks up to 3.4 TeV
E\(_6\) diquarks up to 3.7 TeV
Contact interactions scale 7.7 TeV
Example 2: high mass di-lepton pairs

High mass: sensitive to $Z'$, graviton resonances, etc.
Also: large extra dimensions: deviations from SM spectrum

Challenges: lepton momentum scale: alignment, calibration
knowledge of efficiencies, fakes, misreconstruction
SM predictions at high mass, K-factors
MC generators for new physics
Challenge: tracker alignment

At start-up: hardware based-alignment, plus cosmics
\[ \rightarrow 20-200 \, \mu m \text{ accuracy at startup} \]

- e.g. ATLAS: frequency scanning interferometry in silicon strip detector

CMS: laser alignment

842 grid line lengths measured precisely
\[ \rightarrow \text{measures structure shapes, not sensors} \]
\[ \rightarrow \text{monitor movements over } \sim \text{hours} \]

Track-based alignment using minimum bias, \( Z \rightarrow ee, \mu \mu \)

Few days of data taking: sufficient statistics.

Challenge: \(<10 \, \mu m\) precision, \(120000\) parameters (CMS)
\[ \rightarrow 36000\) parameters (ATLAS) \]
Challenge: tracker alignment

Track-based alignment using minimum bias, $Z \rightarrow ee$, $\mu\mu$

CMS plots:

- $\sigma(p_T)/p_T$ vs $\eta$, $p_T = 100$ GeV/c
- $\sigma(d_{ca})$ vs $\eta$, $p_T = 100$ GeV/c

Initial:

- $p_T$ distribution
- $d_{ca}$ distribution

After few fb$^{-1}$:

- $N_{SEC}/N_{EV} = 0.964$, $\sigma = 0.0373 \pm 0.0004$
- $N_{SEC}/N_{EV} = 0.967$, $\sigma = 0.1080 \pm 0.0014$
- $N_{SEC}/N_{EV} = 0.965$, $\sigma = 0.0445 \pm 0.0007$
Lepton energy/momentum scale calibration

**Electrons: \( Z \rightarrow ee \)**

CMS: intercalibration with single electrons, min bias
uniformity 0.4 – 2.0% (from 4% at day-1)
absolute scale from \( Z \): 0.05 – 0.1%

ATLAS: uniformity 1.0 → 0.4%, scale < 0.1%

**Challenge:** disentangle many effects with \( Z \) sample:
B-field, material, non-uniformity, alignment, response...
(so: also need top, \( J/\psi \), \( \Upsilon \), minimum bias,...)

**Challenge:** extrapolate \( Z \) calibration to high lepton \( p_T \)
Need accurate MC modeling of all effects

**Muons: \( Z \rightarrow \mu\mu \)**

3 days of data taking at \( 10^{33} \)
(or 1 month at \( 10^{32} \)):
>\( 10^5 \) muon pairs

Momentum scale < 0.1%
Mystery of dark matter in the universe solved: it’s in front of CMS/ATLAS ECAL...

Affects electrons and photons: energy loss, conversions
Some more challenges

**Challenge: selection and trigger efficiency**

- Cannot rely on MC
- Use data: redundant triggers
- prescaled triggers

**W,Z cross sections → Juan Alcaraz talk**

- redundant reconstruction methods
  - e.g. muons in inner detector, calorimeter, muon system

- tag-and-probe: $Z \rightarrow \mu \mu$ one $\mu$ tight, look at other

**Challenge: uncertainties in SM prediction: scale, pdf**

- EW corrections?
- corners of phase space

Use control samples in data
But cannot always cover tails, corners of phase space

→ MC remains important, must describe data control samples
Sensitivities for various new physics models

**ADD-type extra dimensions**

- 2-2.8 TeV
- 6 TeV scale

**Randall-Sundrum gravitons**

- 1 fb
- 10 fb
- 100 fb
- 300 fb

**CMS**

- Int. luminosity (fb⁻¹)
- Z' mass (TeV)
- Graviton Mass, GeV/c²

**CMS**

- n=3
Example 3: a SM Higgs boson with a mass of 165 GeV

\[ H \rightarrow WW \rightarrow l\ell\nu\nu \]
(see talk Alexey Drozdetskiy)

No mass peak: counting experiment

**Challenge: extremely good knowledge of background needed**

Backgrounds: \( qq \rightarrow WW, \, gg \rightarrow WW, \, tt \rightarrow WWbb, \, tWb \rightarrow WWb(b), \, ZW \rightarrow lll, \, ZZ \rightarrow ll, \nu\nu \)

Get background from data itself: control samples: \( tt, \, WW, \, WZ \)

**Challenge: understanding of control samples control of systematics keep theory uncertainties small**
Final example: SUSY in (lepton+)jets+$E_T^{\text{miss}}$ final state

Large cross section for gluinos, squarks

Inclusive searches:
- high $p_T$ jets
- large $E_T^{\text{miss}}$
- optional: high $p_T$ lepton(s)

SUSY could show up in:
- $E_T^{\text{miss}}$
- $H_T$
- $M_{\text{eff}}$ “fat” events

Challenge: extract backgrounds from data
don’t be fooled by detector mishaps
be generic, yet efficient
busy events: reconstruction affected

Backgrounds: QCD, top-pair, W, Z production
Missing transverse energy: $E_T^{\text{miss}}$

Escaping particles: momentum balance upset
But: - detector effects (holes, noise...)
- finite resolution
- QCD jets can have real $E_T^{\text{miss}}$

**Difficult!**

Day-1: poor resolution
Data-driven calibration needed

$E_T^{\text{miss}}$ spectrum contaminated by cosmics, beam-halo, machine/detector problems, etc.

**Challenge:** detector effects $E_T^{\text{miss}}$ in QCD events

Punch-through at very high $E_T$
Object reconstruction in busy events,
Samples of b-jets
$E_T^{\text{miss}}$ calibration
Jet energy scale calibration

**Top-pair events!**

**ATLAS: try early sample without b-tagging:**

- 3 jets with largest $\sum p_T$
- 4 jets $p_T > 40$ GeV
- 2 jets $M(jj) \sim M(W)$
- Isolated lepton $p_T > 20$ GeV
- $E_T^{\text{miss}} > 20$ GeV

Observe with $30 \text{ pb}^{-1}$
$\sigma(\text{tt})$ to 20%: $100 \text{ pb}^{-1}$
$M(t)$ to 7-10 GeV

- $b$ jets
- $E_T^{\text{miss}}$ calibration
- Hadronic $W$’s
- $p_T$ (top) studies

If $b$-tag works, cleaner selection

100 pb$^{-1}$
$\sigma(\text{tt})$ to 20%: 100 pb$^{-1}$
$M(t)$ to 7-10 GeV
Background estimation: as much as possible from data

Main sources: Z+jets, W+jets, top-pair production

Can select control samples: Z→μμ, W→μν, semileptonic top pairs

Top: can select clean control sample with mass reconstruction normalize at low \(E_T^{\text{miss}}\), extrapolate to SUSY signal region
mSUGRA reach

Fairly robust discovery potential with 1 fb⁻¹

More general searches also performed

Challenge: if we see something: what is it?
Maybe nature has some REAL SURPRISES in store...

Large extra dimensions, Planck scale ~ EW scale

Possible micro black hole production; decay via Hawking radiation into photons, leptons, jets...

CMS and ATLAS might see this with 1-100 pb⁻¹!
Some final thoughts and general challenges

LHC eagerly awaited by large community, theorists...
Pressure for early results
→ But must not compromise quality!

Blind analyses: desirable, but practical?

Look at $10^7$ bins, see three $5\sigma$ peaks even if no new physics!

Learn from the Tevatron. Still lots to be learned on $W,Z$ production, particularly with associated jets, $b$-quarks...
Understanding the detectors will be a MAJOR task.

Backup
What data samples in 2007?

ATLAS preliminary \( \sqrt{s} = 900 \text{ GeV}, \ L = 10^{29} \text{ cm}^{-2} \text{ s}^{-1} \)

- Jets \( p_T > 15 \text{ GeV} \)
- Jets \( p_T > 50 \text{ GeV} \)
- Jets \( p_T > 70 \text{ GeV} \)
- \( \Upsilon \to \mu \mu \)
- \( W \to e \nu, \mu \nu \)
- \( J/\psi \to \mu \mu \)
- \( Z \to ee, \mu \mu \)

F. Gianotti

- Start to commission triggers and detectors with collision data (minimum bias, jets, ..) in real LHC environment
- Maybe first physics measurements (minimum-bias, underlying event, QCD jets, ..)?
- Observe a few \( W \to l \nu, \ Upsilon \to \mu \mu, \ J/\psi \to \mu \mu \)?

30% data taking efficiency included (machine plus detector)
Trigger and analysis efficiencies included

+ 1 million minimum-bias/day
The inevitable first measurements: soft hadronic stuff

- Your average inelastic collision: “minimum bias”
- The “rest of the event” for a hard scattering: underlying event

Probably very first measurement in 14 TeV (and 900 GeV) data:
- central charged particle multiplicity
- “transverse” charged particle density in di-jet, DY events

400 MeV tracks: reach end of TRT
With the first collision data (1-100 pb\(^{-1}\)) at 14 TeV

Understand detector performance in situ in the LHC environment, and perform first physics measurements:

- Measure particle multiplicity in minimum bias (a few hours of data taking …)
- Measure QCD jet cross-section to \(\sim 30\%\) ?
  (Expect \(>10^3\) events with \(E_T(j) > 1\) TeV with 100 pb\(^{-1}\))
- Measure W, Z cross-sections to 10% with 100 pb\(^{-1}\)?
- Observe a top signal with \(\sim 30\) pb\(^{-1}\)
- Measure \(t\bar{t}\) cross-section to 20% and \(m(\text{top})\) to 7-10 GeV with 100 pb\(^{-1}\) ?
- Improve knowledge of PDF (low-\(x\) gluons !) with W/Z with \(O(100)\) pb\(^{-1}\) ?
- First tuning of MC (minimum-bias, underlying event, \(t\bar{t}\), W/Z+jets, QCD jets,…)

And, more ambitiously:

- Discover SUSY up to gluino masses of \(\sim 1.3\) TeV ?
- Discover a Z\(^{'}\) up to masses of \(\sim 1.3\) TeV ?
- Surprises ?
Assumed selection efficiency:
\[ W \rightarrow l\nu, Z \rightarrow ll : 20\% \]
\[ t\bar{t} \rightarrow l\nu + X : 1.5\% \text{ (no b-tag, inside mass bin)} \]

+ lots of minimum-bias and jets (10^7 events in 2 weeks of data taking if 20% of trigger bandwidth allocated)

\[ 100 \text{ pb}^{-1} \equiv \text{few days at } 10^{32}, \varepsilon=50\% \]
\[ 1 \text{ fb}^{-1} \equiv 6 \text{ month at } 10^{32}, \varepsilon=50\% \]
EM Calorimeter, \( \sigma/E \approx 3\%/\sqrt{E \text{(GeV)}} \oplus 0.5\% 

Hadron Calorimeter, \( \sigma/E \approx 100\%/\sqrt{E \text{(GeV)}} \oplus 5\% 

Muon Spectrometer, \( \sigma/p_T \approx 5\% \text{ at } 1 \text{ TeV/c (from Tracker)} \)
**A Toroidal LHC AppartuS (ATLAS) DETECTOR**

**EM Calorimeters**, \( \sigma/E \approx 10\%/\sqrt{E} \text{(GeV)} \oplus 0.7\% 

excellent electron/photon identification
Good \( E \) resolution (e.g., \( H \to \gamma\gamma \))

**Full coverage for \(|\eta|<2.5\)**

**Precision Muon Spectrometer**, 
\( \sigma/p_T \approx 10\% \) at 1 TeV/c
Fast response for trigger
Good \( p \) resolution
(e.g., \( A/Z' \to \mu\mu, \ H \to 4\mu \))

**Hadron Calorimeters**, 
\( \sigma/E \approx 50\%/\sqrt{E} \text{(GeV)} \oplus 3\% 

Good jet and \( E_T \) miss performance
(e.g., \( H \to \tau\tau \))

**Inner Detector:**
Si Pixel and strips (SCT) &
Transition radiation tracker (TRT)
\( \sigma/p_T \approx 5 \times 10^{-4} \ p_T \oplus 0.001 

Good impact parameter res.
\( \sigma(d_0)=15\mu m@20\text{GeV} \) (e.g. \( H \to bb \))

**Magnets:**
Solenoid (Inner Detector) 2T, air-core toroids (Muon Spectrometer) \( \sim 0.5T \)
<table>
<thead>
<tr>
<th>Selected figure-of-merit</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rec. Eff. Muons with $p_T=1\text{GeV}$</td>
<td>97%</td>
<td>97%</td>
</tr>
<tr>
<td>Rec. Eff. Pions $p_T=1\text{GeV}$</td>
<td>84%</td>
<td>80%</td>
</tr>
<tr>
<td>Rec. Eff. El. $p_T=5\text{GeV}$</td>
<td>90%</td>
<td>85%</td>
</tr>
<tr>
<td>$\sigma_{p_T}$ for $p_T=1\text{GeV} \eta=0$</td>
<td>1.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>$\sigma_{p_T}$ for $p_T=100\text{GeV} \eta=0$</td>
<td>3.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Transverse $\sigma_{i.p.}$ for $p_T=1\text{GeV}$</td>
<td>75µm</td>
<td>90µm</td>
</tr>
<tr>
<td>Longitudinal $\sigma_{i.p.}$ for $p_T=1\text{GeV}$</td>
<td>150µm</td>
<td>125µm</td>
</tr>
</tbody>
</table>

- CMS tracker has better momentum resolution (larger field and lever arm)
- However impact of material on efficiencies
- Similar impact parameter resolution

<table>
<thead>
<tr>
<th>Trigger type</th>
<th>ATLAS (GeV) Threshold</th>
<th>CMS (GeV) Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive isolated e/γ</td>
<td>25</td>
<td>29</td>
</tr>
<tr>
<td>Two electrons/Two photons</td>
<td>15</td>
<td>17</td>
</tr>
<tr>
<td>Inclusive isolated muon</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Two muons</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Inclusive τ-jet</td>
<td>-</td>
<td>86</td>
</tr>
<tr>
<td>Two τ-jet</td>
<td>-</td>
<td>59</td>
</tr>
<tr>
<td>τ-jet and E_{miss}^T</td>
<td>25 and 30</td>
<td>-</td>
</tr>
<tr>
<td>1-jet, 3-jets, 4-jets</td>
<td>200, 90, 65</td>
<td>177, 86, 70</td>
</tr>
<tr>
<td>Jet and E_{miss}^T</td>
<td>60 and 60</td>
<td></td>
</tr>
<tr>
<td>Electron and Jet</td>
<td></td>
<td>21 and 45</td>
</tr>
<tr>
<td>Electron-Muon</td>
<td>15*10</td>
<td>-</td>
</tr>
<tr>
<td>+calibration, monitoring, etc…</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goals for Physics</td>
<td>Expected Day 0</td>
<td></td>
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<tr>
<td>------------------</td>
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<td></td>
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<tr>
<td></td>
<td>ECAL uniformity</td>
<td>Lepton energy scale</td>
</tr>
<tr>
<td></td>
<td>~ 1% ATLAS</td>
<td>0.5—2%</td>
</tr>
<tr>
<td></td>
<td>~ 4% CMS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt; 1%</td>
<td></td>
</tr>
</tbody>
</table>

0.5—2% Lepton energy scale

ECAL uniformity

HCAL uniformity

Jet energy scale

Tracker alignment

< 1%
**Standard Model**
- \( \text{Br}(B^0_s \to \mu^+ \mu^-) \approx 3.5 \times 10^{-9} \)
- \( \text{Br}(B^0_d \to \mu^+ \mu^-) \approx 10^{-10} \)

**Eg ATLAS (yes, “staged” ATLAS for early running)**
- Trigger: \( p_T(\mu) > 6 \text{ GeV} \) for \( |\eta(\mu)| < 2.5 \)
- Analysis optimized for \( S/\sqrt{B} \)
- \( \sigma(B \to \mu \mu) \approx 80 \text{ MeV} \)

<table>
<thead>
<tr>
<th>Integral LHC Luminosity</th>
<th>ATLAS upper limit at 90% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 pb(^{-1})</td>
<td>(&lt; 1.0 \times 10^{-7})</td>
</tr>
<tr>
<td>1 fb(^{-1})</td>
<td>(&lt; 1.5 \times 10^{-8})</td>
</tr>
<tr>
<td>10 fb(^{-1})</td>
<td>(&lt; 5.5 \times 10^{-9})</td>
</tr>
</tbody>
</table>
### NLO wishlist

<table>
<thead>
<tr>
<th>process</th>
<th>relevant for</th>
</tr>
</thead>
<tbody>
<tr>
<td>( pp \to V V + \text{jet} )</td>
<td>( t\bar{t}H ), new physics</td>
</tr>
<tr>
<td>( pp \to H + 2 \text{ jets} )</td>
<td>( H ) production by vector boson fusion (VBF)</td>
</tr>
<tr>
<td>( pp \to t\bar{t} b\bar{b} )</td>
<td>( t\bar{t}H )</td>
</tr>
<tr>
<td>( pp \to t\bar{t} + 2 \text{ jets} )</td>
<td>( t\bar{t}H )</td>
</tr>
<tr>
<td>( pp \to V V b\bar{b} )</td>
<td>( \text{VBF}\to H \to VV ), ( t\bar{t}H ), new physics</td>
</tr>
<tr>
<td>( pp \to V V + 2 \text{ jets} )</td>
<td>( \text{VBF}\to H \to VV )</td>
</tr>
<tr>
<td>( pp \to V + 3 \text{ jets} )</td>
<td>various new physics signatures</td>
</tr>
<tr>
<td>( pp \to V V V )</td>
<td>SUSY trilepton searches</td>
</tr>
</tbody>
</table>

**Table 2.** The wishlist of processes for which a NLO calculation is both desired and feasible in the near future.

(from Campbell, Huston and Stirling, hep-ph/0611148)
Challenge: W/Z/top + jets backgrounds

Large cross sections

Difficult to model: match ME and PS in generators

no-lepton vs one-lepton searches:

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