Super-LHC: The Experimental Program

James W. Rohlf
Boston University
Machine

Detectors
  - Tracker
  - Calorimetry
  - Muon
  - Trigger/DAQ

Electronics

Computing

Who and When

Conclusions

Observations

References
Pt. 1: ATLAS

Pt. 5: CMS

\[ f_{\text{orbit}} = 11.245 \text{ kHz} \]

\[ T = 88.924 \mu s \]
The gaps are important for synchronization!
LHC/PS = 42.4
(39 PS fill) (72 bunches/PS fill)
= 2808 bunches

\[ \Delta t = \frac{88924 \text{ ns}}{3564 \text{ ns}} = 24.95 \text{ ns} \]

“Abort gap”
= 3 \( \mu \text{s} \)
used for fast reset

Rohlf/SLHC – p.4/69
How do we get there?

\( N_b = \) protons per bunch

\( f = \) collision frequency

\( \sigma^* = \) transverse beam size at IP

\( \sigma_z = \) bunch length

\[
L = \frac{N_b^2 f}{4\pi \sigma^*^2} \frac{1}{\sqrt{1 + \frac{\theta_c^2 \sigma_z^2}{4\sigma^*^2}}}
\]

circular beams crossing at angle \( \theta_c \)

Phase 0: **no hardware upgrades**

- ATLAS and CMS only, 9 T in dipoles
- \( \rightarrow 2.3 \times 10^{34} \text{ cm} \)
- \( \sqrt{s} = 15 \text{ TeV} \)

Phase 1: **no changes to LHC arcs**

- SLHC: lower beta, increase \( N_b \), 12.5 ns
- \( \rightarrow 9.2 \times 10^{34} \text{ cm} \)
- \( \sqrt{s} = 15 \text{ TeV} \)

Phase 2: **major hardware upgrades**

- EDLHC: new magnets and injector
- \( \rightarrow 2 \times 10^{35} \text{ cm} \)
- \( \sqrt{s} = 25 \text{ TeV} \)

O. Brüning et al., LHC Luminosity and Energy Upgrade: A Feasibility Study
## Nominal vs Phase 0

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal</th>
<th>Phase 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of bunches</td>
<td>$n_b$</td>
<td>2808</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>$\Delta t$</td>
<td>25 ns</td>
</tr>
<tr>
<td>protons per bunch</td>
<td>$N_b$</td>
<td>$1.1 \times 10^{11}$</td>
</tr>
<tr>
<td>average beam current</td>
<td>$I_{\text{ave}}$</td>
<td>0.56 A</td>
</tr>
<tr>
<td>r.m.s. bunch length</td>
<td>$\sigma_z$</td>
<td>7.55 cm</td>
</tr>
<tr>
<td>beta at IP1 &amp; IP5</td>
<td>$\beta^*$</td>
<td>0.5 m</td>
</tr>
<tr>
<td>r.m.s. crossing angle</td>
<td>$\theta_c$</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>luminosity</td>
<td>$L$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>Nominal</td>
<td>Phase 1</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>number of bunches</td>
<td>$n_b$</td>
<td>$n_b$</td>
</tr>
<tr>
<td></td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>$\Delta t$</td>
<td>25 ns</td>
</tr>
<tr>
<td>protons per bunch</td>
<td>$N_b$</td>
<td>$1.1 \times 10^{11}$</td>
</tr>
<tr>
<td>average beam current</td>
<td>$I_{\text{ave}}$</td>
<td>0.56 A</td>
</tr>
<tr>
<td>r.m.s. bunch length</td>
<td>$\sigma_z$</td>
<td>7.55 cm</td>
</tr>
<tr>
<td>beta at IP1 &amp; IP5</td>
<td>$\beta^*$</td>
<td>0.5 m</td>
</tr>
<tr>
<td>r.m.s. crossing angle</td>
<td>$\theta_c$</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>luminosity</td>
<td>$L$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>
The superbunch option is not synchronization-friendly!

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>Superbunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of bunches</td>
<td>$n_b$</td>
<td>2808</td>
</tr>
<tr>
<td>bunch spacing</td>
<td>$\Delta t$</td>
<td>25 ns</td>
</tr>
<tr>
<td>protons per bunch</td>
<td>$N_b$</td>
<td>$1.1 \times 10^{11}$</td>
</tr>
<tr>
<td>average beam current</td>
<td>$I_{ave}$</td>
<td>0.56 A</td>
</tr>
<tr>
<td>r.m.s. bunch length</td>
<td>$\sigma_z$</td>
<td>7.55 cm</td>
</tr>
<tr>
<td>beta at IP1 &amp; IP5</td>
<td>$\beta^*$</td>
<td>0.5 m</td>
</tr>
<tr>
<td>r.m.s. crossing angle</td>
<td>$\theta_c$</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>luminosity</td>
<td>$L$</td>
<td>$10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>
Expensive and less clear

- Equip SPS with superconducting magnets to inject at 1 TeV
  - Gives a factor of 2 in luminosity
  - First step for energy upgrade
- Install new dipoles to run at 15 T
  - Magnets could exist by 2015
  - Upgraded machine by 2020, $\sqrt{s} = 25$ TeV

But... this may be the fastest path to study multi-TeV constituent collisions
Charged particles

15 TeV

25 TeV

10
9
8
7
6
5
4
3
2
1
0
0.5
1
1.5
2
2.5
dN/dη (charged particles)

10^4
10^3
10^2
10
1
0
2
4
6
8
10
p_T (charged particles)

ID
Entries
Mean
RMS
100
193346
0.6054
0.5790

100
223535
0.6425
0.6535

25 TeV
### LHC/SLHC Comparison

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>SLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pp c.m. energy</strong></td>
<td>14 TeV</td>
<td>15 TeV</td>
</tr>
<tr>
<td><strong>luminosity</strong></td>
<td>$10^{34} \text{ cm}^{-2}\text{s}^{-1}$</td>
<td>$10^{35} \text{ cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td><strong>collision rate</strong></td>
<td>1 GHz</td>
<td>10 GHz</td>
</tr>
<tr>
<td><strong>W/Z^0 rate</strong></td>
<td>1 kHz</td>
<td>10 kHz</td>
</tr>
<tr>
<td><strong>bunch spacing</strong></td>
<td>25 ns</td>
<td>12.5 ns</td>
</tr>
<tr>
<td><strong>interactions per crossing</strong></td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>$\frac{dN_{\text{ch}}}{d\eta}$ <strong>per crossing</strong></td>
<td>150</td>
<td>750</td>
</tr>
<tr>
<td><strong>track flux @ 1 m</strong></td>
<td>$10^5 \text{ cm}^{-2}\text{s}^{-1}$</td>
<td>$10^6 \text{ cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td><strong>calorimeter pileup noise</strong></td>
<td>nominal</td>
<td>$\times 2$-$3$</td>
</tr>
<tr>
<td><strong>rad. dose @ 1 m for 2500 fb$^{-1}$</strong></td>
<td>1 kGy</td>
<td>10 kGy</td>
</tr>
</tbody>
</table>
SLHC Detectors overview

- tracking in B field
- EM calorimetry
- had. calorimetry
- muon detectors

A Toroidal Large hadron collider
AparatuS (ATLAS) 7 kTons
0.5 T toroid, 2 T solenoid
25 m × 46 m

Compact Muon Solenoid (CMS) 14 kTons
4 T solenoid
15 m × 22 m
**ATLAS**

Large magnet cost (40%)
- good stand-alone muon resolution ($BL^2$)
- less resources spent on ECAL and tracking

**CMS**

Lower magnet cost (25%)
- high-resolution tracker
- high-performance ECAL
## Detector technology

<table>
<thead>
<tr>
<th>Component</th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tracking:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>inner barrel</td>
<td>pixels</td>
<td>pixels</td>
</tr>
<tr>
<td>endcap</td>
<td>silicon strips</td>
<td>silicon strips / straw tubes</td>
</tr>
<tr>
<td></td>
<td>silicon strips</td>
<td>silicon strips / straw tubes</td>
</tr>
<tr>
<td><strong>ECAL:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>barrel</td>
<td>crystals (PbWO₄)</td>
<td>liquid argon / Pb</td>
</tr>
<tr>
<td>end cap</td>
<td>crystals (PbWO₄)</td>
<td>liquid argon / Pb</td>
</tr>
<tr>
<td><strong>HCAL:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>barrel</td>
<td>scintillator / brass</td>
<td>scintillator / Fe</td>
</tr>
<tr>
<td>end cap</td>
<td>scintillator / brass</td>
<td>liquid argon / Cu</td>
</tr>
<tr>
<td>forward</td>
<td>quartz / Fe</td>
<td>liquid argon / Cu-W</td>
</tr>
<tr>
<td><strong>Muon:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>barrel</td>
<td>drift chambers + resistive plate</td>
<td>drift tubes + resistive plate</td>
</tr>
<tr>
<td>end cap</td>
<td>cathode strip + resistive plate</td>
<td>cathode strip + thin gap</td>
</tr>
</tbody>
</table>
solid red = ATLAS tile calorimeter
CMS superimposed on ATLAS:
solid red = ATLAS tile calorimeter, blue lines = CMS HCAL
neutron flux at

\[ L = 10^{35} \text{ cm}^{-2} \text{s}^{-1} \]

dose (Gy)

2500 fb\(^{-1}\)
### SLHC Tracker

**ATLAS: silicon + straws**

- **pixels**: 80M ch, 2 m²
- **strips**: 6M ch, 60 m²
- **trt straws**: 420k ch.

**CMS: silicon**

- **pixels**: 50M ch, 1 m²
- **strips**: 10M ch, 220 m²

---

Rohlf/SLHC – p.19/69
• Occupancy
  need to keep low to preserve:
    reconstruction efficiency
    momentum resolution
    b/tau tagging

• Radiation
  need to survive a fluence of $10^{15} \text{ cm}^{-2}$
\[ O \sim \frac{L \Delta t \Delta A}{r^2} \]

\( L \) = luminosity, \( \Delta t \) = sensitive time, \( \Delta A \) = cell area, \( r \) = distance

For a silicon strip (10 cm × 100\( \mu \)m), \( r = 20 \) cm, at LHC design luminosity with 25 ns crossing, the occupancy is 3%.

For SLHC with 12.5 ns crossing, this goes to 15%.

Can make work by being smaller or further away, and clocking at 80 MHz.
\[ D \sim \frac{L \tau}{r^2} \]

\( L = \) luminosity, \( \tau = \) exposure time, \( r = \) distance

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>Flux ( \text{cm}^{-2}\text{s}^{-1} )</th>
<th>Dose (kGy) for 2500 ( \text{fb}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5 \times 10^8</td>
<td>4200</td>
</tr>
<tr>
<td>11</td>
<td>10^8</td>
<td>940</td>
</tr>
<tr>
<td>22</td>
<td>3 \times 10^7</td>
<td>350</td>
</tr>
<tr>
<td>75</td>
<td>3.5 \times 10^6</td>
<td>35</td>
</tr>
<tr>
<td>115</td>
<td>1.5 \times 10^6</td>
<td>9.3</td>
</tr>
</tbody>
</table>
SLHC Tracking implications

• Silicon can work at $r > 60$ cm.
  six layers with pitches of 80-160 $\mu$m will preserve performance
  need to exploit 12-inch wafer technology
  need to operate at $\times 2$ higher fluences than tested for LHC

• Pixels can work at $20$ cm < $r$ < 60 cm.
  need cells that are $\times 10$ larger than current pixels and
    $\times 10$ small than current Si strips (macro-pixel)

• New technology is needed at $r < 20$ cm.
  need 50 $\mu$m $\times$ 50 $\mu$m feature size.
  ideas include CVD diamond, monolithic pixels, cryogenic Si
<table>
<thead>
<tr>
<th></th>
<th>res. @ 50 GeV</th>
<th>material in front</th>
<th>thickness</th>
<th>$\Delta \eta \times \Delta \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td>1.5%</td>
<td>2-4 $\chi_0$</td>
<td>21-36 $\chi_0$</td>
<td>front $0.003 \times 0.1$</td>
</tr>
<tr>
<td></td>
<td>0.8%</td>
<td>0.4-1.3 $\chi_0$</td>
<td>25-27 $\chi_0$</td>
<td>middle $0.025 \times 0.025$</td>
</tr>
<tr>
<td><strong>CMS</strong></td>
<td>0.0174 $\times 0.0174$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**ATLAS**: liquid argon / Pb

**CMS**: crystal (PbWO$_4$)
\[ \Delta \phi = 0.0245 \]
\[ \Delta \eta = 0.025 \]
\[ 37.5\text{mm}/8 = 4.69\text{ mm} \]
\[ \Delta \eta = 0.0031 \]
\[ \Delta \phi = 0.0245 \]
\[ x_4 = 46.8\text{ mm} \]
\[ x_4 = 147.3\text{ mm} \]

\[ |\eta| < 1.5 \]

\[ 1.4 < |\eta| < 3.2 \]

\[ ATLAS \]

\[ CMS \]

\[ |\eta| < 1.5 \]

\[ 1.5|\eta| < 3 \]

\[ ATLAS LA detail \]
• Radiation dose
  Dominated by photons in electromagnetic showers
  \[ D \sim \frac{L}{r^2 \sin \theta} \]
  \( L = \) luminosity, \( r = \) distance, \( \theta = \) polar angle
  15 kGy for barrel, 200 kGy for end-cap

• Detector limits
  space charge for ATLAS liquid argon
  leakage current noise for CMS photodetectors

• Pileup noise
  gets worse by \( \sqrt{5} \) to \( \sqrt{10} \) (depends on readout speed)

• Isolation for electron ID
critical density
**Signal Shapes**

- 2000V
- 1800V
- 1600V
- 1400V
- 1200V
- 1000V
- 815V
- 615V
- 400V
- 200V

**Equation**

\[ I_{\text{norm}} = a_1 e^{-\frac{t}{\tau_1}} + a_2 e^{-\frac{t}{\tau_2}} + a_3 e^{-\frac{t}{\tau_3}} \]

- \( a_1 = 244 \); \( \tau_1 = 5.1 \text{ ns} \)
- \( a_2 = 78 \); \( \tau_2 = 14 \text{ ns} \)
- \( a_3 = 11 \); \( \tau_3 = 110 \text{ ns} \)
Liquid argon and crystals can work in the barrel sampling at 40 MHz with BCID

ATLAS study with full simulation:
- electron efficiency is maintained (81% → 78%)
- jet rejection decreases ×1.5 (10^4 → 7 × 10^3)

Both ATLAS and CMS end caps need redesign
### ATLAS: scintillator / Fe

- **Extended barrel**
  - $|\eta| < 1.0$
  - $0.8 < |\eta| < 1.7$
  - Coverage: 8%
  - Thickness: 8-10 $\lambda$
  - Front: $0.1 \times 0.1$
  - Back: $0.2 \times 0.1$

### CMS: scintillator / brass

- **Barrel**
  - $|\eta| < 1.4$
  - Coverage: 10%
  - Thickness: 11-15 $\lambda$
  - $0.087 \times 0.087$
### ATLAS: liq. argon / Cu

<table>
<thead>
<tr>
<th>coverage</th>
<th>res. @ 100 GeV</th>
<th>thickness</th>
<th>$\Delta \eta \times \Delta \phi$</th>
</tr>
</thead>
</table>
| $1.5 < |\eta| < 3.2$     | 8%           | $9 \, \lambda$ | $1.5 < |\eta| < 2.5 \quad 0.1 \times 0.1$
|                   |                |           | $2.5 < |\eta| < 3.2 \quad 0.2 \times 0.1$          |

### CMS: scintillator / brass

<table>
<thead>
<tr>
<th>coverage</th>
<th>res. @ 100 GeV</th>
<th>thickness</th>
<th>$\Delta \eta \times \Delta \phi$</th>
</tr>
</thead>
</table>
| $1.4 < |\eta| < 3.0$     | 10%          | $11 \, \lambda$ | $1.4 < |\eta| < 1.7 \quad 0.087 \times 0.087$
|                   |                |           | $1.7 < |\eta| < 3.0 \quad 0.087 \times 0.17$          |
### ATLAS: liquid argon / Cu-W

<table>
<thead>
<tr>
<th>coverage</th>
<th>$\pi$ res. @ 300 GeV</th>
<th>thickness</th>
<th>$\Delta\eta \times \Delta\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$3.1 &lt;</td>
<td>\eta</td>
<td>&lt; 4.9$</td>
</tr>
<tr>
<td>CMS</td>
<td>$3.0 &lt;</td>
<td>\eta</td>
<td>&lt; 5.0$</td>
</tr>
</tbody>
</table>

### CMS: quartz / Fe

Rohlf/SLHC – p.33/69
Dose at shower max in calorimetry for $2500 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>ECAL (kGy)</th>
<th>HCAL (kGy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1.5</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>2.9</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>3.5</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5000</td>
<td></td>
</tr>
</tbody>
</table>

The dose rate in the barrel at SLHC is comparable to that expected in the endcap at LHC.
**SLHC Calorimetry**

Pulse structure vs. time

- Scintillator time constants: 8, 10, 29 ns
- HPD time constant: 4 ns
- Preamp time constant: 5 ns

[Graph showing pulse structure over time with time constants and energy levels]
scintillator time constants: 8, 10, 29 ns

HPD time constant: 4 ns
preamp time constant: 5 ns
shift 40 MHz clock edge w.r.t. event time in 1 ns steps

energy vs. time (25 ns per bin)
SLHC Calorimetry

CMS HCAL pulse measurement

QIE pulse e 30 GeV (1ns)

![Graph showing the pulse measurement of CMS HCAL for an electron of 30 GeV, with time (ns) on the x-axis and signal intensity on the y-axis.](image)
Signal fraction in 1 timeslice

0.35 0.4 0.45 0.5 0.55 0.6 0.65 0.7 0.75 0.8

Signal fraction in 2 timeslices

0.74 0.76 0.78 0.8 0.82 0.84 0.86 0.88 0.9

$e 30 \text{ GeV}$
SLHC Calorimetry

225 GeV pion muon

LHC bunch spacing

Rohlf/SLHC – p. 40/69
225 GeV pion

Entries  531
Mean   -0.000251
RMS    0.6069

SLHC bunch spacing

Rohlf/SLHC – p.40/69
Replace CMS endcap scintillator with quartz?

Test beam results with production HF wedges, Aug. 2003

Issues:

- fitting in existing geometry
- photodetector (4 T field)
New scintillators R&D to make fast, rad. hard., eff.

Pulses from tiles read with multiclad WSF

R. Ruchti et al., COMO 2003.

Graph of relative efficiency of scintillators after 1 Mrad exposure to $^{60}$Co

Data Set DSB1
Data Set 2: BDOC
Data Set 3: Y11
Data Set 4: DSB2

Pulse Height (arbitrary units)

12.5 ns
• ATLAS and CMS scintillating tiles can work in the barrel; BC ID is essential; faster is better.

• Both ATLAS and CMS end caps need redesign

• Forward calorimetry needs to be upgraded
  Can give up some rapidity coverage to get out of most severe radiation zone \((3 < |\eta| < 4.2 \text{ instead of } 3 < |\eta| < 5.0 \text{ keeps dose constant})\).
### Muon Barrel design

#### ATLAS, $|\eta| < 1.0$

- **stations**: 3, 50 $\mu$m
- **trigger**: 3 RPC
- **resolution @ 100 GeV**
  - stand-alone: $\frac{\Delta p_T}{p_T} = 0.2 - 1\%$

#### CMS, $|\eta| < 1.3$

- **stations**: 4, 100 $\mu$m
- **trigger**: 4 DT+6 RPC
- **resolution @ 100 GeV**
  - stand-alone: $\frac{\Delta p_T}{p_T} = 2 - 4\%$
  - global: $\frac{\Delta p_T}{p_T} = 0.6 - 1.7\%$

---

---
**ATLAS**

- 30 mm diameter
- $\sigma = 100 \, \mu m$

**CMS**

- 42 mm $\times$ 13 mm
- $\sigma = 300 \, \mu m$
LHC radiation rates \((\gamma, n)\): \(9 \sim 100 \text{ cm}^{-2}\text{s}^{-1}\)

Resolution is degraded due to space charge effects.

Beam test with large chamber:

100 GeV muons and Cs\(^{137}\) source.
**SLHC**

**Muon End cap**

**cathode strip chambers**

---

**ATLAS**

- **coverage**: $1 < |\eta| < 2.7$, 4 disks
- **space res.**: 60 $\mu$m
- **time res.**: 7 ns

**CMS**

- **coverage**: $1 < |\eta| < 2.4$, 4 disks
- **space res.**: 75-150 $\mu$m
- **time res.**: 4.5

---

Rohlf/SLHC – p.47/69
Muon End cap

CMS CSC design

Cathode Strip Chambers

Wire spacing ~3mm

Gas: Ar(40%) + CO2 (50%) + CF4 (10%)

HV wires ~ 3.6 kV

Induced charge

Gas gap 9.5mm avalanche

Wires orthogonal to strips
(except for ME1/1 rotated 25° to compensate Lorentz Effect)

Precise Φ measurement (75-150 µm)

Radial cathode strips

Precise timing measurement (BX).

Coarse measurement of the radial position.

Chamber: ~4.5ns

16-54mm

(5-15 wires readout together)

Trapezoidal chambers (10° or 20° in Φ). 6 layers

Muon Shielding

\[ L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

present shielding

\[ L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \]

extra shielding
• Extra shielding at high $\eta$ needed

• ATLAS and CMS drift tubes MAY work in the barrel if not, can replace with CSC

• Both ATLAS and CMS cathode strip chambers can work in the region $|\eta| < 2$
  • The rates in the strips will reach 700 KHz. Electronics will need to be upgraded to allow larger storage buffer to keep dead-time reasonable.
  • Radiation levels may exclude FPGAs because of SEU.
Trigger issues

- Occupancy: pileup & increased event size affects electron, muon, jet, missing $E_T$
  
  cone of size $\sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.5$
  
  has 70 pion pileup $E_T = 42$ GeV

- Rates
  
  \[\Rightarrow \text{increase thresholds}\]

- Radiation
  
  single event upsets in on-detector electronics

- High-Level Trigger \(100 \text{ kHz} \rightarrow 100 \text{ Hz}\)
  
  10,000 CPUs needed
LHC event size is 1 MByte.
Level-1 trigger rate is 100 kHz.
Number of CMS data links is 500.
Average data rate on DAQ link (with large fluctuations!):

\[ R = \frac{(10^6 \text{ Bytes})(10^5 \text{ s}^{-1})}{500} = 200 \text{ MBytes/s} \]

This is dominated by tracker data \( \rightarrow \times 10 \) at SLHC.
An order of magnitude increase in bandwidth is needed.
Current Algorithms

- Sliding window centered on all ECAL/HCAL trigger tower pairs
- Fine Grain
- Electron
  - 2-tower $\Sigma E_T + H/E$
- Isolated Electron
  - 2x5-crystal strips > 90% energy in 5x5 (Fine Grain)
  - Neighbor EM + Had Quiet
- Jet or $\tau E_T$
  - 12x12 trig. tower $\Sigma E_T$ sliding in 4x4 steps w/central 4x4 > rest
  - $\tau$ algorithm (isolated narrow energy deposits)
  - Call Jet $\tau$ if all 9 4x4 region $\tau$-vetoes off
  - $\tau$-veto: Patterns of E or H towers in 4x4
• Jets
  granularity $\Delta \eta \times \Delta \phi = 0.37 \times 0.37 \rightarrow 0.087 \times 0.087$

• Missing $E_T$
  granularity $\Delta \phi = 0.37 \rightarrow 0.087$

• Electron
  $\pi^0$ veto and track match

• Tau
  isolation $\Delta \eta \times \Delta \phi = 1 \times 1 \rightarrow 0.5 \times 0.5$

$\Rightarrow$ increased data sharing, adders, and memory
**SLHC Trigger implications**

- 80 MHz level-1 pipeline is essential.
- BC ID is for each subsystem.

**Level-1 thresholds (GeV)**

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>SLHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>inclusive muon</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>muon pair</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>inclusive isolated $e/\gamma$</td>
<td>34</td>
<td>55</td>
</tr>
<tr>
<td>isolated $e/\gamma$ pair</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>inclusive jet</td>
<td>250</td>
<td>350</td>
</tr>
<tr>
<td>jet $\cdot E_T$</td>
<td>113.70</td>
<td>150.80</td>
</tr>
</tbody>
</table>

*See CMS DAQ TDR estimate.*
• Next generation deep sub-micron technology
  • Radiation hardness (total dose and SEU)
  • Low noise analog systems
• System design (on detector processing vs. links)
• Advanced data link technology
• Communication techniques (tracker in L1 trigger?)
• Power systems (reduce tracker mass)
**SLHC Data Links**

Example: CMS HCAL

- **Front end**
  - TTC trigger timing & control
  - GOL 3k links
  - 16 bits @ 80 MHz

- **Readout Module**
  - LVDS 200 links
  - 32 bits @ 40 MHz
  - Vitesse 500 links
  - 1.2 Gbit/s

- **Data Concentrator**
  - SLINK 32 links
  - 64 bits @ 100 MHz

- **Level-1 Trigger**
LHC now uses 0.25\(\mu\text{m}\) technology. In 2010, the microelectronics industry will be using 40 nm. SLHC can look at 130 nm now and 65 nm in 2008-9. This would give \(\times 16\) more gates.

Fabrication on 12-inch wafers implies complex software for layout.

Present links use 1-2.5 Gbits/s. Industry now uses 10 Gbits/s and R&D is on 40 Gbits/s. SLHC needs the bandwidth of these fast links.

Use wireless for communication to reduce material in tracker.

see P. Sharp, LECC 2003 for more detailed list.
CPU comparisons

Collaboration Size vs. CPU

- Earth Simulator
- LHC Exp.
- Grey Wave
- Current accelerator Exp.
- Nuclear Exp.
- Astronomy
- Atmospheric Chemistry Group

From J. Huth (Harvard/ATLAS) Sept., 03
“Expected” Performance summary

- **Tracking**
  - b tagging rejection $190 \rightarrow 27$ ($p_T = 80 \text{ GeV}/c$)

- **Electron Identification**
  - $\times 5$-$10$ pileup $\Rightarrow \times 2$-$3$ noise

- **Muon Identification**
  - reduced rapidity coverage ($|\eta| < 2$) due to increased shielding needs

- **Jets**
  - forward jet tag and central jet veto degraded

- **Trigger**
  - higher thresholds for inclusive processes
How should we organize this R&D?

CMS Management Board

CMS Electronics R&D Review Board

Electronics R&D Proposals to Upgrade CMS for Super LHC

Tracker  ECAL  HCAL  Muons  Trigger  DAQ
Dear Jim,

I don’t have a transparency for the ATLAS procedures concerning the SLHC. However, all major issues pass through the Executive Board, and it is usual that an expert Review Panel would look at technical issues, whereas the upgrade strategy itself will be a broader issue, involving also the Collaboration Board.

Of course I must also say that at this stage we are not so much concerned about upgrades for a SLHC, our main worry is to get ATLAS (and LHC) become a reality first...

Cheers... Peter
The LHC has first collisions planned for April 2007, with an initial run of 3 months. This “shakedown” run will undoubtedly reveal many detector problems.

There will likely be a shutdown for about 3 months, followed by the first “physics” run at low luminosity ($2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$).

Sometime in 2008, the luminosity is projected to reach design ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$).

At design luminosity, we can expect about 100 fb$^{-1}$ per year.

Some where around 2012, the time to double the size of the data set will be approximately 4-5 years. This is the natural time for the upgrade to take place.

Since the preparation is expected take 10 years, the time to start is NOW.
Conclusions

- Tracking needs complete replacement! Although new technology will be needed for $R < 20$ cm, the biggest challenge will be electronics and system integration.
- End-cap and forward calorimetry needs to be significantly upgraded.
- Muon detectors will work up to $\eta < 2$ with additional shielding installed.
- The level-1 trigger needs to be upgraded to sample at 80 MHz.
SLHC ZZ → 4 lepton event

$10^{33} \text{ cm}^{-2}\text{s}^{-1}$

$10^{34} \text{ cm}^{-2}\text{s}^{-1}$

$10^{35} \text{ cm}^{-2}\text{s}^{-1}$
It seems all too easy to extrapolate operation of ATLAS and CMS at $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ when it is sure to be a huge challenge to make the detectors work at “low” luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ just four years from now... however...
It seems all too easy to extrapolate operation of ATLAS and CMS at $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ when it is sure to be a huge challenge to make the detectors work at “low” luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ just four years from now... however...

The SLHC luminosity upgrade seems to be a “no brainer,” “bang for the buck” and critically important for the future of CERN and particle physics.
It seems all too easy to extrapolate operation of ATLAS and CMS at $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ when it is sure to be a huge challenge to make the detectors work at “low” luminosity of $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ just four years from now... however...

The SLHC luminosity upgrade seems to be a “no brainer,” “bang for the buck” and critically important for the future of CERN and particle physics.

It is inconceivable that any result from the LHC or SLHC could indicate that we do NOT want to increase the energy. The EDLHC may be the fastest route for this. It seems that people are too quick to forget *why* the SSC was designed for 40 TeV!
Physics will not go as planned...

\[ a \neq \frac{v^2}{r} \]
LHC Progress Dashboard

Dipole cold masses

Equivalent dipoles

01-Jan-01  01-Jan-02  01-Jan-03  01-Jan-04  01-Jan-05  01-Jan-06  01-Jan-07

Updated 30 Sep 2003

Data provided by P. Lienard AT-MAS


