Super-LHC: The Experimental Program

James W. Rohlf
Boston University
experimental overview

- Machine
- Detectors
  - Tracker
  - Calorimetry
  - Muon
  - Trigger/DAQ
- Electronics
- Computing
- Who and When
- Conclusions
- Observations
- References
$f_{\text{orbit}} = 11.245 \ \text{kHz}$

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

Δt = \frac{88924 \text{ ns}}{3564 \text{ ns}}
= 24.95 \text{ ns}

“Abort gap”
= 3 \mu s
used for fast reset

Rohlf/SLHC – p.4/69
### SLHC Super LHC

reaching for $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ and beyond

How do we get there?

$N_b =$ protons per bunch

$f =$ collision frequency

$\sigma^* =$ transverse beam size at IP

$\sigma_z =$ bunch length

---

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

---

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
<th>Luminosity $L$</th>
<th>Energy $\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 0:</td>
<td><strong>no hardware upgrades</strong></td>
<td>$2.3 \times 10^{34}$ cm</td>
<td>15 TeV</td>
</tr>
<tr>
<td>ATLAS and CMS only, 9 T in dipoles</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 1:</td>
<td><strong>no changes to LHC arcs</strong></td>
<td>$9.2 \times 10^{34}$ cm</td>
<td>15 TeV</td>
</tr>
<tr>
<td>SLHC</td>
<td>lower beta, increase $N_b$, 12.5 ns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 2:</td>
<td><strong>major hardware upgrades</strong></td>
<td>$2 \times 10^{35}$ cm</td>
<td>25 TeV</td>
</tr>
<tr>
<td>EDLHC</td>
<td>new magnets and injector</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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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>$I_{ave}$</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>
### Phase 1

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>Phase 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of bunches</td>
<td>$n_b$</td>
<td>2808</td>
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<td>$\theta_c$</td>
<td>300 $\mu$rad</td>
</tr>
<tr>
<td>lumininosity</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>
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</tr>
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<td>beta at IP1 &amp; IP5</td>
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<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

Rohlf/SLHC – p.10/69
<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>$\frac{dN_{\text{ch}}}{d\eta}$ per crossing</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>$\times 2\text{-}3$</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>
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

- tracking in B field
- EM calorimetry
- had. calorimetry
- muon detectors
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></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 end cap</td>
<td>crystals ((\text{PbWO}_4))</td>
<td>liquid argon / Pb</td>
</tr>
<tr>
<td></td>
<td>crystals ((\text{PbWO}_4))</td>
<td>liquid argon / Pb</td>
</tr>
<tr>
<td><strong>HCAL:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>barrel end cap</td>
<td>scintillator / brass</td>
<td>scintillator / Fe</td>
</tr>
<tr>
<td>forward</td>
<td>scintillator / brass</td>
<td>liquid argon / Cu</td>
</tr>
<tr>
<td></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 end cap</td>
<td>drift chambers</td>
<td>drift tubes</td>
</tr>
<tr>
<td></td>
<td>+ resistive plate</td>
<td>+ resistive plate</td>
</tr>
<tr>
<td></td>
<td>cathode strip</td>
<td>cathode strip</td>
</tr>
<tr>
<td></td>
<td>+ resistive plate</td>
<td>+ thin gap</td>
</tr>
</tbody>
</table>
solid red = ATLAS tile calorimeter

8 m

4 m

Rohlf/SLHC – p.17/69
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)
$2500 \text{ fb}^{-1}$
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
SLHC Tracker geometry

50 – 110 cm

20 – 50 cm

$r < 20$ cm
Tracking issues

• Occupancy
  need to keep low to preserve:
    reconstruction efficiency
    momentum resolution
    b/tau tagging

• Radiation
  need to survive a fluence of $10^{15}$ cm$^{-2}$
Tracking occupancy

\[ O \sim \frac{L \Delta t \Delta A}{r^2} \]

\( L \) = 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 is goes to 15%.

Can make work by being smaller or further away, and clocking at 80 MHz.
The ionization dose is given by:

\[ D \sim \frac{L\tau}{r^2} \]

where:
- \( L \) = luminosity,
- \( \tau \) = exposure time,
- \( r \) = distance.

### Table: Dose for Different Radii

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>Flux ( \text{cm}^{-2}\text{s}^{-1} )</th>
<th>Dose (kGy) for 2500 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>
• Silicon can work at $r > 60 \text{ cm}$.  
  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 $20 \text{ cm} < r < 60 \text{ cm}$.  
  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 $r < 20 \text{ cm}$.  
  need 50$\mu$m$\times$50$\mu$m feature size.  
  ideas include CVD diamond, monolithic pixels, cryogenic Si
## ECAL

### ATLAS: liquid argon / Pb

- **res. @ 50 GeV:** 1.5%
- **material in front:** 2-4 $\chi_0$
- **thickness:** 21-36 $\chi_0$
- **$\Delta \eta \times \Delta \phi$:**
  - front: $0.003 \times 0.1$
  - middle: $0.025 \times 0.025$
  - back: $0.05 \times 0.025$

### CMS: crystal (PbWO$_4$)

- **res. @ 50 GeV:** 0.8%
- **material in front:** 0.4-1.3 $\chi_0$
- **thickness:** 25-27 $\chi_0$
- **$\Delta \eta \times \Delta \phi$:** $0.0174 \times 0.0174$
SLHC ECAL geometry

ATLAS

\[ |\eta| < 1.5 \]

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

CMS

\[ |\eta| < 1.5 \]

\[ 1.5 |\eta| < 3 \]

ATLAS LA detail
- Radiation dose
  Dominated by photons in electromagnetic showers

\[ D \sim \frac{L}{r^2 \sin \theta} \]

- 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
Liquid argon space charge

critical density

![Graph showing the critical density of liquid argon](image)
ATLAS liquid argon

CMS crystal

Signal Shapes

\[ I_{\text{norm}} = a_1 e^{-t/t_1} + a_2 e^{-t/t_2} + a_3 e^{-t/t_3} \]

- \( a_1 = 244 \); \( t_1 = 5.1 \text{ ns} \)
- \( a_2 = 78 \); \( t_2 = 14 \text{ ns} \)
- \( a_3 = 11 \); \( t_3 = 110 \text{ ns} \)
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 $\times 1.5$ ($10^4 \rightarrow 7 \times 10^3$)

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

- **Extended barrel**
  - $|\eta| < 1.0$
  - $0.8 < |\eta| < 1.7$

- **ATLAS coverage**
  - $|\eta| < 1.0$

- **CMS**: scintillator / brass

### Coverage and Performance

<table>
<thead>
<tr>
<th></th>
<th>coverage</th>
<th>res. @ 100 GeV</th>
<th>thickness</th>
<th>$\Delta \eta \times \Delta \phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.0$</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>$0.8 &lt;</td>
<td>\eta</td>
<td>&lt; 1.7$</td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.4$</td>
<td>10%</td>
</tr>
</tbody>
</table>
### ATLAS and CMS HCAL End Cap

ATLAS uses liquid argon / Cu while CMS uses scintillator / brass.

### Coverage, Resolution, and Thickness

<table>
<thead>
<tr>
<th></th>
<th>Coverage</th>
<th>Resolution @ 100 GeV</th>
<th>Thickness</th>
<th>$\Delta \eta \times \Delta \phi$</th>
</tr>
</thead>
</table>
| **ATLAS**      | $1.5 < |\eta| < 3.2$ | 8%                    | $9 \lambda$ | $1.5 < |\eta| < 2.5$ : $0.1 \times 0.1$  
                  |            |                       |           | $2.5 < |\eta| < 3.2$ : $0.2 \times 0.1$         |
| **CMS**        | $1.4 < |\eta| < 3.0$ | 10%                   | $11 \lambda$ | $1.4 < |\eta| < 1.7$ : $0.087 \times 0.087$  
                  |            |                       |           | $1.7 < |\eta| < 3.0$ : $0.087 \times 0.17$   |
### ATLAS: liquid argon / Cu-W

- **Coverage**: $3.1 < |\eta| < 4.9$
- **$\pi$ Resolution at 300 GeV**: 8%
- **Thickness**: $9 \lambda$
- **$\Delta \eta \times \Delta \phi$**: $0.2 \times 0.2$

### CMS: quartz / Fe

- **Coverage**: $3.0 < |\eta| < 5.0$
- **$\pi$ Resolution at 300 GeV**: 20%
- **Thickness**: $10 \lambda$
- **$\Delta \eta \times \Delta \phi$**: $0.17 \times 0.17$
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.
Calorimetry

Pulse structure vs. time

- scintillator time constants: 8, 10, 29 ns
- HPD time constant: 4 ns
- preamp time constant: 5 ns

Diagram:
- Graph showing pulse structure over time with energy (E) on the y-axis and time (t) on the x-axis.
- Time intervals marked: 0, 25, 50, 75 ns.
Pulse structure vs. time

- 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)
QIE pulse e 30 GeV (1ns)

Time [ns]
SLHC Calorimetry

12.5 ns

Signal fraction in 1 time bucket

Signal fraction in 2 time buckets

Signal fraction in 3 time buckets

12.5 ns Time Slice

0 ns

12 ns

S. Abdullin 29/09/2003

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SLHC Calorimetry time resolution

225 GeV pion

LHC bunch spacing

muon

Rohlf/SLHC – p.40/69
225 GeV pion

SLHC bunch spacing
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

12.5 ns

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

R. Ruchti et al., COMO 2003.
• 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 ($3 < |\eta| < 4.2$ instead
  of $3 < |\eta| < 5.0$ keeps dose constant).
### ATLAS, $|\eta| < 1.0$

**SLHC Muon Barrel design**

![ATLAS Muon Barrel Design](Image)

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

**CMS-TS-00079**

![CMS Muon Barrel Design](Image)

### Table:Muon Barrel Performance

<table>
<thead>
<tr>
<th></th>
<th>stations</th>
<th>trigger</th>
<th>resolution @ 100 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS</strong></td>
<td>3, 50 µm</td>
<td>3 RPC</td>
<td>stand-alone $\frac{\Delta p_T}{p_T} = 0.2 - 1%$</td>
</tr>
<tr>
<td><strong>CMS</strong></td>
<td>4, 100 µm</td>
<td>4 DT+6 RPC</td>
<td>stand-alone $\frac{\Delta p_T}{p_T} = 2 - 4%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>global $\frac{\Delta p_T}{p_T} = 0.6 - 1.7%$</td>
</tr>
</tbody>
</table>
SLHC Muon Barrel drift tubes

ATLAS

30 mm diameter
\( \sigma = 100 \ \mu m \)

CMS

42 mm \( \times \) 13 mm
\( \sigma = 300 \ \mu m \)
LHC radiation rates \((\gamma, n)\): \(9 - 100 \text{ cm}^{-2}\text{s}^{-1}\)
Resolution is degraded due to space charge effects.

Beam test with large chamber:
100 GeV muons and Cs\(^{137}\) source.
### Muon End cap cathode strip chambers

#### ATLAS

<table>
<thead>
<tr>
<th>coverage</th>
<th>space res.</th>
<th>time res.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 &lt;</td>
<td>\eta</td>
<td>&lt; 2.7$, 4 disks</td>
</tr>
</tbody>
</table>

#### CMS

<table>
<thead>
<tr>
<th>coverage</th>
<th>space res.</th>
<th>time res.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 &lt;</td>
<td>\eta</td>
<td>&lt; 2.4$, 4 disks</td>
</tr>
</tbody>
</table>

Rohlf/SLHC – p.47/69
Muon End cap CMS CSC design
Muon Shielding

Present shielding

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

Extra shielding

\[ L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \]
• Extra shielding at high $\eta$ needed

• ATLAS and CMS drift tubes MAY work in the barrel
  LHC design has 3-5 safety factor
  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.
**SLHC** 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**
  ⇒ increase thresholds

- **Radiation**
  single event upsets in on-detector electronics

- **High-Level Trigger** (100 kHz → 100 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

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

SLHC Trigger CMS calorimeter
• 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
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>
• 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)

Peter Sharp
LECC Amsterdam
Oct. 3, 2003
**Data Links** example: CMS HCAL

- **GOL**: 3k links, 16 bits @ 80 MHz
- **LVDS**: 200 links, 32 bits @ 40 MHz
- **Vitesse**: 500 links, 1.2 Gbit/s
- **SLINK**: 32 links, 64 bits @ 100 MHz

**Front end** → **Readout Module** → **Data Concentrator** → **Level-1 Trigger**

**TTC**
- Trigger timing & control
SLHC Electronics technology

- LHC now uses $0.25\mu m$ 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.
**“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?
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.
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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...

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


