Preparing for the LHC (Physics Commissioning)

Darin Acosta
University of Florida
Who I am

- Associate Professor
  Physics Department
  University of Florida

- Have worked on:
  - e+e- experiment (CLEO)
  - ep experiment (ZEUS)
  - p\bar p experiment (CDF)
  - pp experiment (CMS)

- Currently working as
  - Deputy commissioning coordinator of CMS
    (still learning the job ☺️)

- Past experience with
  - Designing electronics
  - Muon detectors, calorimeters
  - Various physics groups
9 June 2007
Commissioning lecture

World's Biggest Science Project Aims to Unlock 'God Particle'

By Paul Henley
BBC News

"We are embarking on an experiment that cannot be done without Virdee, at Imperial College.

"We must speak.'

Over a £6 billion, sprawling complex situated at the French-Swiss border, physicists are now working towards the world's most ambitious engineering projects - the Large Hadron Collider.

Various magnets of the magnetically named Compact Muon Solenoid experiment are moved into position at the Large Hadron Collider facility deep under the French-Swiss border.

In the 1st 10 days of operation of the machine, there will be 50,000 collisions of particles.

LARGE HADRON COLLIDER
Location: Border of France and Switzerland
Price Tag: £6 billion

The realms of the inconceivably huge and the unimaginably tiny will be united later this year in the countryside near Geneva, when the world's most massive physics experiment gets underway within a 17-mile ring spanning the French-Swiss border. Inside the Large Hadron Collider, the energies are so great that the creation of a new universe is possible.
The Large Hadron Collider of Cern (European Organization for Nuclear Research)

In a tunnel 300 feet below Switzerland and France, scientists are putting the final touches on a 16.8-mile long particle accelerator that will smash protons together in an attempt to create forces and particles that existed shortly after the Big Bang and rarely, if ever, today.

Source: Cern, Physics World, Sept. 2004; Lawrence Berkeley National Laboratory

Graham Roberts, David Constantine, Mika Grindstaff, Erin Acinero/ The New York Times
So you want to discover…

- The Higgs boson
- Supersymmetry
- Extra dimensions
- New gauge bosons
- All of the above!

- What does it take to prepare?
Timeline of an Experiment

- Generic detector R&D
- Experiment proposed (Collaboration forms)
- More detector R&D and system design
- Construction
- Testing
  - Installation
  - Commissioning
  - Operations
  - Analysis
- Publication!

This set of lectures

9 June 2007
# Outline of Lectures

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<th>Lecture 3</th>
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<td>What is commissioning?</td>
<td>Detector performance</td>
<td>Operating the Experiment</td>
</tr>
<tr>
<td>Scale of the problem</td>
<td>Temporal alignment (synchronization)</td>
<td>What it takes to run a large experiment</td>
</tr>
<tr>
<td>Commissioning activities</td>
<td>Spatial alignment</td>
<td>Data quality monitoring</td>
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<td>Test beam programs</td>
<td>Material budget</td>
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<tr>
<td>Detector &quot;Slice Tests&quot;</td>
<td>Calibration</td>
<td></td>
</tr>
<tr>
<td>Magnetic field measurements</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Test beam programs
- Detector "Slice Tests"
- Magnetic field measurements
- Temporal alignment (synchronization)
- Spatial alignment
- Material budget
- Calibration
- What it takes to run a large experiment
- Data quality monitoring

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Outline, Cont’d

Lecture 3

Preparing for physics measurements
- Luminosity measurement & beam conditions
  - Impact of pile-up
- Understanding the detector performance from data
  - Impact of instrumental issues (noisy/dead channels, zero suppression) on basic physics objects
  - Missing Transverse Energy – catch-all of instrumental problems
  - Jet Energy scale

Early LHC physics measurements
- Underlying event
- Calibrating the Standard Model backgrounds
  - e.g. QCD jet production, Electroweak measurements, Top quark measurements

Lecture 4

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Commissioning lecture
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What is Commissioning?

- Bring the detectors, electronics, power, cooling, safety and monitoring systems into nominal operation
- Prepare the experiment for efficient data-taking operations and expected detector performance
  - Synchronize, calibrate, and align detectors
  - Monitor the detector performance
  - Achieve efficient and reproducible data operations
- “Physics commissioning”
  - Calibrate Standard Model processes
  - Understand and remove instrumental and beam backgrounds
Scale of the problem

“Nope, there’s no scale” – Apollo program
## Scale: LHC Collaboration sizes

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Institutes</th>
<th>Countries</th>
<th>Collaborators</th>
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</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>104</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>ATLAS</td>
<td>164</td>
<td>35</td>
<td>1900</td>
</tr>
<tr>
<td>CMS</td>
<td>155</td>
<td>37</td>
<td>1940</td>
</tr>
<tr>
<td>LHCb</td>
<td>48</td>
<td>15</td>
<td>680</td>
</tr>
<tr>
<td>TOTEM</td>
<td>11</td>
<td>8</td>
<td>80</td>
</tr>
</tbody>
</table>
Go where no one has gone before…

<table>
<thead>
<tr>
<th></th>
<th>Tevatron / CDF</th>
<th>LHC / CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>1 TeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>Inst. Lumi.</td>
<td>$10^{32}$</td>
<td>$10^{34}$</td>
</tr>
<tr>
<td>Electronic channels</td>
<td>1M</td>
<td>80M</td>
</tr>
<tr>
<td>Bunch xing freq</td>
<td>2.5 MHz (7.6 MHz clk)</td>
<td>40 MHz</td>
</tr>
<tr>
<td>L1 output rate</td>
<td>25 kHz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>L2 output / HLT input</td>
<td>400 Hz</td>
<td>100 kHz</td>
</tr>
<tr>
<td>L3 output rate</td>
<td>90 Hz</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Event size</td>
<td>0.2 MB</td>
<td>1 MB</td>
</tr>
<tr>
<td>Filter Farm</td>
<td>250 nodes</td>
<td>O(1000) nodes</td>
</tr>
</tbody>
</table>

More particle occupancy, thus more granularity in detectors

Complexity in electronics and computing increases
The “Compact” Muon Solenoid (CMS) Experiment

More about detectors in Dr. Froidevaux’s lectures

4T solenoid

Muon chambers

Silicon Tracker (200 m²)

PbWO₄ Crystals γ/ e detection

Hadronic calorimeter

Jets, missing $E_T$ ($\nu$)
CMS: Preassembled on surface, in final installation underground

Muon chambers
Solenoid
Hadronic calorimeter
CMS Silicon Tracker

Barrel and Forward Pixels

Inner Barrel & Disks (TIB & TID)

Outer Barrel (TOB)

End Caps (TEC)

2.4 m

5.4 m

volume 24.4 m³
running temperature - 20 °C
CMS Silicon Tracker

- Strip Tracker
  - 200 m² coverage
  - 10μm precision measurements
  - 9.6M electronic channels
  - For comparison, CDF inner vertex detector < 1M

- Inner Pixel tracking system (not shown)
  - 66M channels!
CMS Muon Systems

- 3 technologies:
  - drift-tubes, cathode strip chambers, resistive plate chambers
- 25000 m² of active detection planes
  - 100μm precision on position
- About 1M electronic channels
  - For comparison, the CDF muon system has "only" 8K channels
ATLAS

- **ATLAS detector:**
  - diameter 25 m, length 46 m, mass 7,000 tons, $10^8$ channels, 3,000 km cables
  
  - muon spectrometer  
  - toroid magnets  
  - tile calorimeter  
  - liquid argon calorimeter

- solenoid magnet  
- transition radiation tracker  
- silicon tracker  
- pixel detector
ATLAS Tracking Detectors

- Transition Radiation Tracker
  - Straw tubes, 0.4M channels
- Strip Tracker
  - 6M electronic channels
- Pixel system (not shown)
  - 80M channels
  - Assembly almost complete

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ATLAS Tracking installation and commissioning

Cosmic-ray recorded in tests on surface
Scale: Software

- Extensive amount of software is required for controlling electronic hardware, monitoring, and data acquisition and storage
  - Load firmware, download settings, spy on error counters, log data to mass storage, etc.

- Moreover, an even greater amount of software is required to process raw data, e.g.
  - Convert ADC counts $\rightarrow$ energy deposition
  - Cluster neighboring energy deposits into a single shower $\rightarrow$ electron energy
  - Convert TDC counts $\rightarrow$ drift time $\rightarrow$ hit position
  - Associate hits $\rightarrow$ particle trajectory $\rightarrow$ momentum (from curvature)
Software, 2

- The process of converting logged raw data into useable objects for physics analysis is referred to as “reconstruction”
  - Detector-specific local reconstruction and clustering, tracking algorithms, vertex reconstruction, muon identification, jet reconstruction, electron reconstruction, etc.

- Software is also needed to simulate collisions and the detector response in order to understand data in an analysis
  - e.g. efficiency determination, mass resolution

- Finally, you must write your own software to take reconstructed or simulated data and perform data analysis!
Modern collider experiments require more than 1M lines of code for offline software.

CMS:
- Lines of SW in last 1.5 years
- ~300 developers
- C++ language

Though tempting, nowadays you cannot write all the software you need on a modern collider experiment.
- Take your rate of writing code and determine your graduation date!
- Must rely on others, but you should understand it all!

SW needs commissioning too (thorough validation!)
Scale: The LHC Distributed Computing Model

WLCG

CMS Experiment

Tier 0

Tier 1

Tier 2

Tier 3

Tier 4

Online System

CERN T0

Korea T1

Italy T1

Russia T1

FNAL T1

Physics caches across Tier 2

2.5-10 Gb/s

>10 Gb/s

0.1 - 1.5 GB/s

10-40 Gb/s

2500 physicists, 40 countries

10s of Petabytes/yr by 2008

1000 Petabytes in < 10 yrs?

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## Scale: CMS 25% Scale Test in 2006 (CSA06)

### Tier-1: 7 centres

<table>
<thead>
<tr>
<th>Site</th>
<th>CPU[kS12k]</th>
<th>CPU[#]</th>
<th>Disk[TB]</th>
<th>Network[Gb/s]</th>
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<td>228</td>
<td>140</td>
<td>48+(36)</td>
<td>2</td>
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<tr>
<td>CNAF</td>
<td>225</td>
<td>300</td>
<td>40</td>
<td>10+(10)</td>
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<tr>
<td>FNAL</td>
<td>2200</td>
<td>1800</td>
<td>700</td>
<td>11</td>
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<tr>
<td>GridKa</td>
<td>220+(220)</td>
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<td>10</td>
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<tr>
<td>IN2P3</td>
<td>250</td>
<td>70</td>
<td>10</td>
<td></td>
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<tr>
<td>PIC</td>
<td>150</td>
<td>120</td>
<td>50</td>
<td>1</td>
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<tr>
<td>RAL</td>
<td>200</td>
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### Tier-2: 27 centres

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<th>Network[Gb/s]</th>
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<td>Bari</td>
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<td>5</td>
<td>1</td>
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<td>25</td>
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<tr>
<td>Belgium_UCL</td>
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<td>256</td>
<td>55</td>
<td>10</td>
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<td>4</td>
<td>1</td>
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<tr>
<td>DESY</td>
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<td>10</td>
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<td>JINR</td>
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<tr>
<td>London_IC</td>
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<td>1</td>
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<td>1</td>
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<tr>
<td>Nebraska</td>
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<td>252</td>
<td>21</td>
<td>0.6</td>
</tr>
<tr>
<td>Pisa</td>
<td>76</td>
<td>76</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Purdue</td>
<td>228+(256)</td>
<td>30+(170)</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Rome</td>
<td>48</td>
<td>48</td>
<td>5+(10)</td>
<td>1</td>
</tr>
<tr>
<td>SINP</td>
<td>24</td>
<td>24</td>
<td>1</td>
<td></td>
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<td>SPRACE</td>
<td>311</td>
<td>242</td>
<td>28</td>
<td>1</td>
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<tr>
<td>Taiwan</td>
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<td>6</td>
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<tr>
<td>UCSD</td>
<td>150</td>
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<td>10</td>
<td>10</td>
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<tr>
<td>Wisconsin</td>
<td>547</td>
<td>428</td>
<td>90</td>
<td>10</td>
</tr>
</tbody>
</table>

### Tier-0 (CERN):

- 1400 CPUs

### Scale by 4X for 2008 physics operation

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Commissioning lecture

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Commissioning

Everything is installed, let’s just turn it on!
(i.e. What’s the problem?)
Why an Experiment is not a Monte Carlo generator

- Are all the cables connected properly?
- Are all electronic channels working, and boards functioning properly?
- Are the power supplies and cooling systems working reliably, and are the monitoring and safety systems working to protect your priceless detectors and electronics?
- Do all data fragments correspond to the same beam crossing?
- Are the detectors where you think they are, or at least where your software thinks they are?
- Has the software been debugged?
- Are the detectors delivering their expected performance?
  - e.g. are mass peaks showing up where they should be?
It all has to work!

Commissioning is a big job...
And still waiting for this book to come out

Dummy’s Guide to Commissioning
ATLAS Combined Testbeam, 2004

Dedicated test of a complete slice of the ATLAS experiment in a test beam at CERN
Purpose of a Combined System Test

☐ Study the performance of a slice of the experiment
  - Collect a lot of data
  - Make comparisons between data and Monte Carlo simulation

☐ Calibrate the detectors (calorimeters)

☐ Gain experience with many commissioning issues in a global way
  - Integration of many complex subsystems
  - Experience with software (and subsequent debugging, improvements)
  - Test data handling system (the computing model)
H8 Beam line

- Particles: e, π, μ, γ
- Energies: 1 – 350 GeV
- Area spans 50m!

Calorimeters and particle identification  Muon system
CMS Magnet Test and Cosmic Challenge (MTCC)

Aug. – Nov. 2006

Operates world’s most energetic magnet! (2.7 GJ)

Operating a vertical slice of CMS:
- Muon Detectors (6–8%):
  - Drift-tubes
  - Cathode strip chambers
  - Resistive plate chambers
- Barrel Hadron Calorimeter (22%)
- Barrel electromagnetic calorimeter (5%)
- Tracker (~1%)
- DAQ and Trigger

Two Phases:
- Phase 1: all detector elements participate, B=0, 3.8T
- Phase 2: remove tracker+ECAL, and insert B field mapper

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Operates world’s most energetic magnet! (2.7 GJ)
Valuable Experience Installing and Closing CMS on the Surface, before Commissioning Underground

As well as integrating services (cabling, cooling, safety systems) and operations (calibration, alignment)

HB Insertion: First one took two weeks, while plus side took three days

EB Insertion
The Magnet Worked!

Author: Austin Ball, Austin.Ball@cern.ch
Type: 
Subject: Ramping towards 3 T. Fringe field effects visible.

Balcony barrack shielding not very effective.
Air conditioner already stopped...switched off.
60 G at RPC PS's.
Take care with opening and closing rack doors!!!
Why it was a non-trivial result
The Detectors, Trigger and DAQ worked

- Recorded ~200M cosmic muon events from Aug. – Nov. 2006
- Trigger rate up to 200 Hz

Run 2605/Event 3981
B=3.8 Tesla
27 August 2006
A Golden Cosmic Muon Event

- Cosmic muon through CSC and DT muon systems, triggered through Global Muon Trigger, and read out by central DAQ
Muon Spectra Measured in 4T Field (CMS MTCC)

Cosmic muons data normalised to Monte Carlo simulation

Reasonable agreement between data and simulation.

Almost every aspect of final CMS from detector to CMSSW had to work to produce these plots.
Some of the Experience Gained at MTCC

- Identification and replacement of magnetic components (ferrite inductors)
  - Part of alignment system
- Measurement of scintillator brightening effect in B-field for in-situ calorimeter
  - 10% effect
- Observation that some photodetectors are not aligned with B field
  - Hybrid Photodetector (HPD) relies on alignment of B field with tube axis – calculation was off for those connected to the outer hadron barrel detector (25º difference)
  - Result is large pixel-to-pixel cross talk
- Observation of high rate of electrical discharges in hybrid photodetector (HPD) elements in hadron calorimeter, especially at certain field strengths (1-2 T)

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HPD Noise Effect

- Discovered that the hybrid photodetectors used to read out the scintillation light from the barrel hadron calorimeter suffered significantly increased noise around 1-2T
- Cannot operate well at those field strengths (but 4T is nominal pt.)
Magnetic Field Measurements

- Precise knowledge of the magnetic field map is crucial to track reconstruction
  - Momentum measurement depends on charged particle bending
  - More information in second lecture
- Detailed calculations followed by probe measurements
Mapping of CMS Magnetic Field

Field mapped at: 2.0, 3.0, 3.5, 3.8(twice) & 4.0 T with 0T references.
statistical precision of $10^{-4}$ achieved
Hall probe and NMR probe

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4T = 19.140kA: stable operation confirmed
Temp stability margin 0.6 K

Field Mapper carriage insertion and test
Magnetic Maps

- Sort of data collected: $B_z$, $B_r$, $B_\phi$
- Analysis ongoing
ATLAS Map – Even more complicated

- Barrel toroid
- Endcap toroid
- Central solenoid 2T
CMS Tracker Integration and Analysis Facility

- 20% of the silicon strip tracker connected and readout from January – June 2007 in dedicated surface facility
  - About 2M channels, more than CDF silicon vertex detector
- Gain operational experience, alignment studies, detector performance studies
  - >1M cosmic muon tracks collected
Track reconstruction and event display
Other Commissioning Slice Tests:
CMS Drift Tubes on surface (awaiting lowering)

Commissioning detectors, calibration, alignment
Unanticipated Roadblocks in Commissioning

- Don’t underestimate the low-tech problems that get in your way, such as access to cooling water for electronics

- Cannot yet operate this nice disk of muon chambers underground,
- Because some cooling water valves that need to be opened are blocked by other disks and wheels of iron, because we needed space for this scaffolding

Just didn’t think of it before closing detectors…
The giant caverns are actually tight!
Computing Commissioning

- CMS Combined Computing, Software, and Analysis Challenge
  - A 50 million event exercise to test the workflow and dataflow associated with the data handling model of CMS at 25% scale

- Major components:
  - Preparation of large simulated datasets
  - Prompt reconstruction at Tier-0 (CERN):
    - Reconstruction at 40 Hz (create tracks, electrons, muons, …)
    - Application of calibration constants from an offline database
    - Splitting of a trigger-tagged sample into 10 streams
  - Distribution of data to all 7 participating Tier-1s @ 150 MB/s
  - “Skim jobs” at some Tier-1s with secondary datasets copied to Tier-2 centers (e.g. University of Florida)
  - Physics jobs at Tier-2s and Tier-1s on data (50K jobs/day!)
CSA06 Summary in a Nutshell

- CSA was launched on October 2, 2006
- Operations lasted ~6 weeks until mid-November
  - Everything on previous page has been successfully tested!
  - Tier-0 prompt reconstruction of 207M events including application of calibration constants via database
  - Total network transfers exceeded 1 PB = $10^{15}$ B !
  - Sustained >150 MB/s
  - T0$\rightarrow$T1 transfers

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Figure 14: The rate of data transferred between the Tier-0 to the Tier-1 centers in MB per second.
Commissioning & Run Coordination

- What I think my job duties are

- Coordinate commissioning efforts across detector subsystems, trigger, DAQ, and offline data handling
- Facilitate problem-solving across subsystems
- Schedule and prioritize global data-taking activities
- Ensure adequate monitoring, diagnostics, and logging of essential events
- Ensure efficient, reproducible, and well-documented procedures for data-taking
- Oversight on achieving the expected detector performance at the level of basic detector objects
- Shift organization

In other words, provide the “glue”, but not the parts, to prepare an experiment for physics
Summary of Commissioning Exercises

- You always learn something!
  - Expect the unexpected (electronics failures, detector noise, …)
- It is important to test slices of the complete system for functionality (vertical slice tests), and the portions of the full system for scale (horizontal slice tests)
- Because of the importance of the LHC turn-on, and the possibility of new discoveries right at the beginning, we are trying to pre-commission as much as we can before beams
- But this implies trade-offs:
  - Commissioning exercises vs. installation activities
  - Global data-taking exercises vs. subsystem commissioning
- It’s a “chicken-or-egg” problem:
  - If we wait for installation to be over, we have not pre-commissioned in time
  - We can’t commission until we are installed
Performance

Success in commissioning will be judged quantitatively by achieving the design performance from the detector subsystems.
Credits

- ATLAS
- CDF
- CMS
- Christoph Amelung
- Paolo Bartalini
- Adolf Bornheim
- Rick Cavanaugh
- Sergio Cittolin
- Pawel De Barbaro
- Domenico Giordano
- Slawek Tkaczyk
- Jim Virdee