Did the LHC Detectors meet our Expectations?

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Did the LHC Detectors meet our Expectations?

• YES
  – Although #Interactions/bunch crossing higher than foreseen, experiments coped with that:
    • Comparisons of performance of tracking detectors for μ’s are presented for the various experiments.
    • Comparisons of performance of calorimeters for e’s are presented for the various experiments.
    • Comparisons of performance for jets and Missing Et are presented for the various experiments.
    • Comparison of Particle ID of the various experiments

• BUT
  – Many unforeseen problems with industrial products:
    • Various problems will be shown, not expected from Industry and possible lessons to be learned.
  – Surprises due to radiation effects, as well as ambient conditions:
    • Various problems will be shown and possible lessons to be learned.
  – Very limited expertise and new people hired are not necessarily involved in running the experiments
    • Who will get the LHC experiments back into operation in 2015?
The LHC and its 4 Experiments
Although the final LHC Luminosity has not been achieved, Collisions/crossing higher than foreseen. Experiments perform well under conditions above the expectation. Even for higher multiplicities in HI collisions.

Although peak Lumi 30% bellow max foreseen, #collisions/crossing 80% higher due to 20MHz running.

ATLAS 2\(\mu\) event with 25 reconstructed vertices.

CMS 2\(\mu\) Event with 78 Reconstructed vertices.
Very complex Experiments (with ~100M channels); it is hard to keep all of them running.

- For the large experiments >95% of the channels (mostly >98%) are working.
- During collisions >98% of the subsystems are operational.
- This has been possible due to the continuous work of a relatively small number of scientists, whose constant dedication has allowed the LHC experiments to outperform any expectation.
Clearly one should not compare the large Experiments with specialized ones, since the emphasis on the Physics is different.
Experiments have different methods to achieve their good \( \mu \) momentum resolution (3 using their ID capabilities + outside trigger, one (ATLAS) using a combination of ID and \( \mu \) Spectrometer.

**ATLAS Barrel:**
- **MS needed at very high** \( P_t \)
- **ID better up to** \( P_t \approx 80 \) GeV

**ATLAS Endcap:**
- **ID better up to** \( P_t \approx 20 \) GeV
- **MS as Barrel up to** \( |\eta| \approx 2.7 \) thanks to forward TOROID’s
Barrel Muon Stations

- Basic tracking elements are Drift-Tubes, where the wire is placed to within 10 microns; tube assembly is placed to within 20 microns, and deformation of the assembly is followed with a local alignment system.

- Precision chambers are (mainly) Al-Monitored Drift Tubes

- Hit resolution
  - Average $\approx 80\mu m$
  - 6/8 layers per station $\approx 40\mu m$
  - Align 3-stations (up to 10m) at $\approx 40\mu m$
Tag-and-probe from Z

Inefficiency at $\eta \sim 0$ can be recovered with calorimetric-tag muons. MC reproduces data within 1%.
Muon Resolution at high P

ATLAS Preliminary
Data 2011 (\sqrt{s} = 7 TeV)

\[ \int L \, dt = 560 \, \text{pb}^{-1} \]

\( (q_{\text{T}})_{1S} - (q_{\text{T}})_{\text{L}} + \text{sector offset} \, [\text{TeV}^{-1}] \)

\( \eta \)

\( \pm 0.3 \, \text{TeV}^{-1} \)

- Towers BI-BM-BO
- Towers CS-EM-EO
- Towers EI-EM-EO

**Official numbers** 2011

<table>
<thead>
<tr>
<th>Region</th>
<th>( \sigma_{\text{ali}} , [\text{TeV}^{-1}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0.130 ( \pm ) 0.05</td>
</tr>
<tr>
<td>Endcap MDT</td>
<td>0.174 ( \pm ) 0.05</td>
</tr>
<tr>
<td>Endcap CSC</td>
<td>0.146 ( \pm ) 0.05</td>
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</tbody>
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- From these two methods constrains on the alignment contribution to P resolution derived
- difference between the two estimates taken as systematic error
- GOOD enough for high-PT physics

**Quite close to design value** 40 \( \mu \text{m} \rightarrow 0.08 \, \text{TeV}^{-1} \):

**Very close to achieve the final performance**
Trigger is a crucial element in LHC Physics

- The MUON trigger philosophy is based on opening a cone (which defines a given $p(t)$ threshold) around a point in a pivot plane (that contains non-overlapping geometry).
- The barrel includes a 3-out-of-4 trigger logic for low $p(t)$, combined with a 1-out-of-2 confirmation logic for high $p(t)$.
- The end-cap requires a 3-out-of-4 logic combined with a 2-out-of-3 logic in the inner layer. The low $p(t)$ is obtained by a non-linear combination in the inner layer, while linear for the high $p(t)$.
- The end-cap has a more robust logic, due to the higher background conditions, combined with the fact that the stations are located in a non-magnetic region.
ATLAS Muon trigger & Reconstruction

• **1st Level (2 μs) 40MHz → 75 KHz**
  - On chamber trigger matrix performs time coincidence of signals in trigger roads:
    - Low Pt Barrel 6 GeV ~ 25 cm (8 strips)
    - High Pt Barrel 20 GeV ~30 cm (10 Strips)
  - From hits time: Choose collision BX
  - RPC and TGC have good time resolution: BX efficiency > 99%

• **2nd Level (10 ms): → 3 KHz**
  - Look to ID + MS tracks in ROI
  - Better Pt resolution: sharpen threshold

• **3rd Level-EF (few s): → 200 Hz**
  - Full detector granularity
  - Offline Reconstruction Software
  - Sharp P threshold and Calorimetric isolation

• **Reconstruction efficiency independent of the number of int/crossing**
More than 97% of the RPC towers are fully operational. Efficiency of individual layers and of coincidence is reaching its expected level. Good matching between tracking and trigger chambers for finding the tracks.

- 98.8% of the chambers are fully operational.
- Chamber efficiencies at the expected level
- Problems with low momentum P background due to n interactions (to be discussed at the end of presentation)
Other 3 LHC Experiments base μ momentum measurement on ID, while trigger performs rough P cut

• CMS:
  – The field is weaker in the return yoke than in the solenoid. Also due to the Fe slabs, it does not need very good position resolution.
  – Barrel Trigger: DT+RPC
  – End Cap Trigger: CSC+RPC
CMS μ Spectrometer performance

- 468 CSC chambers in the End-Caps, with position resolutions ranging 56-140μm (some small failure in one of the End-Caps).
- 250 DT in the barrel with achieved position resolution of 250μm.
- 480 (barrel) + 432(End-Cap) RPC chambers, that help to improve the μ-trigger efficiency.
Like CMS, in LHCb μ P measurement determined by internal and external tracking devices. Tracking (M1-M5) through μ filter for P>6GeV sets trigger.

- M1 is made out of GEM’s. M2-M5 use CSC with a projective tower arrangement.
- The trigger requirement is to have hits in each of the 5 stations, which requires individual station efficiencies >99%.
- None of the 1380 chambers had a permanent failure.
LHCB $\mu$ trigger system efficiency

- Only significant inefficiency is in a small region of the M1 layer equipped with GEM’s, where the rates are substantially higher.
ALICE $\mu$ Spectrometer is similar (trigger and accurate tracking) to ATLAS, but in a very small solid angle.

- Acceptance limited to high rapidity (-4.0 to -2.5) and acceptance limited to $J/\psi$ and $\Upsilon$ with relatively low p (above 0.5GeV/c).
- Tracking via 10 planes of CSC’s using pads located in 5 stations. Achieved resolution in bending plane 70μm.
- Trigger performed by 2 double planes of RPC’s (140m²).
- Achieved resolution on $J/\psi$ (for low P) width: 83+/−4MeV, slightly (6MeV) larger than the expectations.
Add Central tracking for $\mu$ reconstruction

- ATLAS: PIX, Si, TRT; Solenoidal field: 2T

- CMS: PIX; Si; Solenoidal field 3.8T

- LHCB: Si inside vacuum (VELO) + Si before magnet Si + Straw tracker after magnet: 4Tm

- ALICE: main tracker (not related to $\mu$’s), made of ITS (PIX, Si-drift, Si), TPC, TRD inside a Solenoidal field of 0.5T
ATLAS Tracking Detector Performance

• **Pixel**: very high efficiency with good resolution. Some problem with optical modules.

• **SCT**: very high efficiency with the achieved resolution. Over 99% operational.

• **TRT**: occupancy is reasonable even with high Number of vertices.
ATLAS inner detector performance

- Major effort was made to align the detector and understanding the various materials.
- The outcome can be checked at high momentum by reconstructing the $Z \rightarrow 2\mu$ mass bias and resolution.
- Impressive to see that also radiative $Z \rightarrow 4\mu$ can be clearly seen (candle for Higgs mass reconstruction), obtained by combining inner detector with MUON Spectrometer.
CMS inner detector performance

- **PIXEL Tracker**: very good single hit efficiency.

- **SCT Tracker**: even for all modules, hit efficiency is very high.

- **Overall tracking efficiency**: The high magnetic field allows for an excellent momentum resolution and a high efficiency for high momentum $\mu$, but reduced efficiency for low momentum (track bending). High efficiency for isolated $\mu$ independent of int/crossing.
CMS inner tracker performance

• Due to the high magnetic field, very good mass resolution for $Z \rightarrow \mu^+ \mu^-$ (almost natural width).
• Also good resolution for the candle process $Z \rightarrow 4\mu$. 
LHCb Tracking performance

- **VELO**: 0.5% non-operational channels. Superb position resolution. Due to the movements, need to control its alignment: OK within 5\(\mu\)m.

- **Si Tracker**: efficiency >99%; point resolution: 50-60\(\mu\)m.

Straw tubes resolution for the Tracker is 211\(\mu\)m, while the efficiency for tracks away from edges of tube is 99.2%.
LHCb tracking performance

- Due to need to measure B states very close to each other, the mass resolution of the LHCb detector is excellent. A few examples are given below for 2-μ’s

\[ \hat{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9} \]

Compared to TH predictions

\[ (3.54 \pm 0.30) \times 10^{-9} \]
Tracking performance of ALICE

- Very complex detector to disentangle single tracks in a very complex environment ($dN/d\eta \sim 6,000$). The excellent performance of the TPC is a crucial element for the high efficiency. The performance shown are based on MC expectations.
- A typical example of expected mass reconstruction is shown for $D_s$ production in p-p interactions.
Electron and γ identification and measurement at LHC

- **ATLAS**: LAr calorimeter (with pre-shower) + TRT + E/p matching.

- **CMS**: Crystals + Pre-shower + E/p matching.

- **LHCb**: Pb-Scintillator with WS. Pre-shower (Sc+WS fiber) + Shashlik +E/p.

- **ALICE**: Pb-Tungstate crystals +TRD
ATLAS e-γ identification and measurement

- Very good granularity +pointing helps to reject π⁰ and point to relevant vertex.
- TRT helps in reducing π/e miss. ID, however some of this can be also done with shower shape.
- Pointing helps for very good matching between track and calorimeter for Z->ee.
- Energy scale corrections (based on Z->ee) are small.
- Not very high dependence on # of int/crossing for various e-ID.
- Very nice resolution for Z-peak
CMS electron-\(\gamma\) identification and measurement

- Crystals allow for a superb energy resolution. Very clearly seen in the \(Z^{\rightarrow}\)ee mass reconstruction (1.6\% mass resolution in Barrel).
- Inter-calibration using a laser monitor plays a crucial role, in particular for the crystals in the End-Cap.
- This is also done to keep a constant trigger threshold.
LHCb electron-γ identification and measurement

- Good results on the mass resolution over a large range of masses, by controlling $J/\psi$, $\Upsilon$ and $Z$.
- Good photon and $\pi^0$ resolution are needed to reconstruct B final states containing $\Upsilon$.
Performance of the large LHC experiments for Jets and Missing $E_T$

• Large rapidity ($\eta<5$) coverage for both experiments.
  – ATLAS
   • makes use of its very good lateral granularity of its calorimeters, combined with longitudinal sampling, to disentangle the EM and Hadronic component of showers (like H1) and perform compensation.
   • Due to high pile-up, corrections are made using # vertices.
   • For low energy jets, different corrections are needed depending on jet type, as well as on charge multiplicity.
  – CMS
   • Good granularity but lacking longitudinal segmentation, uses a simplified weighting method.
   • Making use of the high magnetic field that gives a good charge particle separation, has developed an Energy Flow algorithm that gives excellent resolution for jets, and by doing it for individual vertices, provides results that are relatively immune to pile-up effects.

• As usual, at the end, both experiments are comparable.
• Missing $E_T$ correction due to number of Primary vertices and corresponding improvement in the resolution.

• Jet correction differences for light $q$ and gluon jets, jet energy dependence on #charge tracks and jet resolution ($R<0.6$) as function of Energy, by comparing 2 jets.
• Improvement in jet energy reconstruction using Energy flow as compared to pure calorimetric energy and its response as function of rapidity. Correction as a function of #vertices for 2012 data.

• Typical Missing energy distribution for $Z\rightarrow\mu^+\mu^-$

• Missing $E_T$ resolution as a function of # VTX for $Z\rightarrow\mu\mu$ events.

One could benefit from longitudinal sampling in the HCAL
Particle ID ($\pi$/K separation)

- LHCb: 2 gas Cerenkov detectors + 1 Aerogel.
- Good angular resolution resulting in mass peaks.

- ALICE: 6 Si layers (dE/dx), TPC (dE/dx) + TOF (MRPC) + RICH (in limited acceptance) for P<5GeV.
- Very good separation, in particular for low P particles, ranging from 0.1 to 3.0GeV, in a very harsh environment (Pb-Pb), with very low systematic errors.
Did the LHC Detectors meet our Expectations?

• The answer is clearly yes, with all the Experiments producing beautiful results, with the different sub-systems having failure rates of 1-5%, running at \#int/crossing 2-4 (LHCb) higher than foreseen.

• This is due to a relatively small number of dedicated Physicists that keep these large experiments running (and do not have the time to produce results on detector performance). Without the dedication of these people such results would not be possible, and I hope that new ones can be formed to re-start the experiments in 2015.

• But claiming that everything went smoothly in constructing and running the experiments would be a great exaggeration; many problems occurred (some will be fixed in future upgrades) and one should learn from these problems/failures.
Some of the problems during construction and lessons to be learned

• CMS crystals:
  – when going into a new technology, try to qualify more than one (not always very stable) firms to do the job.
• ATLAS (here I am more aware of problems):
  – Non-adhesiveness of the of Cu electrodes to Capton.
  – Non-adhesiveness of Al lines in Capton foils.
  – Non-controlled impedance in Capton transmission lines.
  – Change of quality during production of MDT tubes.
  – Even when a firm has large production capabilities with many products, a small change with respect to the regular line depends on 1-2 experts that are not always available, make sure that you are there with these experts to produce your “small change” to the product.
Even when you qualified a Standard product of a known firm, you have to check every batch, since if the firm is large, it might have subcontracted the work. Keep track of every batch that you get, since you might need to replace it.

- Some optical fibers assembled in Israel were found to be non-radiation hard.
- As a result of that a full series of radiation tests were started at Weizmann (and also BNL) to characterize the various batches.
- The fiber manufactures were contacted, and DRAKA confirmed the radiation characteristics of their products, while after a lot of pressure, Corning responded (via one of their senior Engineers) with the following statement:
  - Although the paper features SMF the results can equally apply to MMF. Our multimode fibre products do not contain Phosphorous. I hope this helps, let me know if you have any further questions.
- Following a chemical analysis of the radiation damaged fiber, the report was send to Corning, confirming the P contamination, the answer was slightly different:
  - I have checked with our speciality fibre group and we are not able to offer a radiation hardened multimode fibre solution or allude to any minimum performance specification of any of our standard fibres when used in applications needing resistance to radiation exposure.
Some problems during operation due to humidity conditions

- ATLAS VCSELs laser deterioration with humidity:
  - Normally many electronic devices are tested at 85DEG/85%RH without powering.
  - Normally single VCSELs are sealed hermetically with either glass or metal=> not possible for large arrays, which are sealed with S-based substances that can have pin-holes.
  - Testing at 85/85 under power produces immediate failures due to corrosion.
- Non being reachable every channel in the ATLAS Si strips has to 2 VCSELs=>no problem in >99% of channels.
- In PIX, following the qualifications, only 1 VCSEL/readout channel=>5% failure; to be replaced during shut-down.
- Lesson:
  - test every element under the real conditions you are going to use it (without caring about the specs).
  - In un-accessible places try to avoid being dependent on single failures
- CMS (possible LHCb ?) fast deterioration of HPD’s (to be replaced by SiPM):
  - For any product try to perform accelerated tests
Neutrons do not always behave the way one expects

• CMS crystal deterioration in the high rapidity region has probably a neutron component:
  – It would be very nice to have a few MeV neutron source as part of the new GIF++ facility.

• ATLAS high $\mu$ Trigger rate in the forward region is related to low energy neutrons giving a recoil $P$ outside the magnetic field. The inner $\mu$ layer coincidence will reduce the rate by 30% (it was foreseen but will be implemented in this shut-down);
  – If you can add an additional condition to your trigger, without reducing much your efficiency, do it, since you never know when you will need it.
With the success comes the appetite

• There is a clear Physics interest to accumulate an integrated Luminosity of $3,000 \text{fb}^{-1}$ for the large LHC experiments (max needed inst. Lumi $<10$ times present Lumi).
• This requires new ID with Si technology at the edge of what can be achieved.
• Major modifications for the various triggers, in order to keep a relatively low $P_T$ single lepton trigger, a low missing $E_T$ trigger (to be achieved by making use of the fine granularity and longitudinal sample of the modified (CMS) or present calorimeters, as well as more powerful processors).
• This requires a major R&D process that has already started, and hopefully this will allow to form new detector people, which is crucial for the future of the field, and in particular if we want the present LHC success to continue after 2015, to ensure that

• **We can get the LHC detectors back into operation in 2015.**
Conclusions

• Did the LHC Detectors meet our Expectations?
  – With experiments that have 60-80M channels operating with ~1-2% failures, the answer is that the LHC Experiments are doing very well.
  – The expected performance of the various sub-systems is very close to those that were originally proposed.
  – It is crucial that we form new people to keep on developing, improving and maintaining the performance of these Experiments.
Did the LHC Detectors meet our Expectations?

The answer is clearly yes.