LHC Upgrades
Accelerator
&
Experiments

10th Hiroshima Symposium
Application of Semiconductor
Tracking Detectors,
Xi'an, China

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RAL/Oxford
UK

25/09/2015
**Timeline to Upgrades**

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
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<tbody>
<tr>
<td>2010</td>
<td></td>
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<tr>
<td>2015</td>
<td></td>
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<tr>
<td>2020</td>
<td></td>
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<tr>
<td>2025</td>
<td></td>
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<tr>
<td>2035</td>
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</tbody>
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**LHC-Run-1: History**

- Proton-proton (p-p) centre-of-mass energy 7 - 8 TeV
- Bunch spacing 50ns *(some tests at 25ns, mainly used for scrubbing)*
- Number of p-p interactions per beam crossing: Pile-up $\langle \mu \rangle$ 20-30
- Maximum instantaneous luminosity $6-7 \times 10^{33} \text{ cm}^2\text{s}^{-1}$
- Integrated luminosity for General Purpose Detectors (ATLAS and CMS) $\sim 30 \text{ fb}^{-1}$
- LHCb p-p: collect around $3.36 \text{ fb}^{-1}$
- ATLAS-CMS-ALICE: (pb-pb): 0.15 nb$^{-1}$
- All experiments p-Pb 30nb$^{-1}$

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High Luminosity LHC plan beyond 2015, updated according to the CERN MTP for 2016-2020, CERN Council June 2015

These slides rely heavily on presentations made at the two ECFA workshops in 2013 and 2014.
Timeline to Upgrades

LHC-Long-Shutdown-1 (LS1 or Phase-0)

LHC

Consolidation of the LHC – splice repairs, Improved collimation, R2E project ... see next slide.

ALICE, ATLAS, CMS, LHCb

Different levels of upgrade discussed in the slides
**Timeline to Upgrades**

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**LHC-Run-2 : The Present**

- Proton-proton centre-of-mass energy 13-14 TeV, bunch spacing reduced to 25ns, 2808 bunches
- Maximum instantaneous luminosity $1-2 \times 10^{34}$ cm$^2$s$^{-1}$
- Number of p-p interactions per beam crossing: Pile-up: $<\mu>$ 25-50
- Integrated luminosity for GPD's (ATLAS and CMS) 150fb$^{-1}$ at end of run.
- Extended Year End Technical Stop (EYETS) **16-17** CMS install new pixel detector
- LHCb p-p: collect around 7fb$^{-1}$
- ATLAS-CMS-ALICE: (pb-pb): 1 nb$^{-1}$
- All experiments p-Pb $\sim$100nb$^{-1}$
Timeline to Upgrades

LHC-Long-Shutdown-2 (LS2 or Phase-1)

LHC

Injector upgrade Linac-4, cryogenics at point-4, Civil engineering at P1-P5
A new SPS injection kicker system with a 50ns rise time
Collimators with dispersion suppression regions close to experimental points to avoid quenches and excessive radiation load.

ALICE, ATLAS, CMS and LHCb all have upgrades (see slides below)
For ALICE and LHCb these are the Major upgrades
### LHC-Run-3

- Proton-proton centre-of-mass energy 14 TeV at bunch spacing 25ns
- Maximum instantaneous luminosity $\sim \geq 2 \times 10^{34} \text{ cm}^2\text{s}^{-1}$
- Integrated luminosity for GPD’s (ATLAS and CMS) 300fb$^{-1}$
- Heavy Ion luminosity goes from $1 \times 10^{27} \text{ cm}^2\text{s}^{-1}$ to $\sim 7 \times 10^{27} \text{ cm}^2\text{s}^{-1}$
- LHCb p-p: 2020 to end of program aim to collect around 50fb$^{-1}$

This marks the end of phase I
Timeline to Upgrades

LHC-Long Shutdown 3 (LS3 or Phase-2)

LHC, ATLAS & CMS

All have major upgrades (details in the slides below)
30 months in total.
ATLAS and CMS upgrades cost ~270MCHF.
Timeline to Upgrades

HL-LHC-Run-4 and beyond ... *The Future*

proton-proton centre-of-mass energy 14 TeV, bunch spacing 25ns

Maximum available instantaneous luminosity $\sim 2.0 \times 10^{35} \text{ cm}^2\text{s}^{-1}$

Use levelled instantaneous luminosity up to a peak of $7.5 \times 10^{34} \text{ cm}^2\text{s}^{-1}$

Number of p-p interactions per beam crossing: $<\mu> 200$

Integrated luminosity for GPD’s (ATLAS and CMS) $3,000 \text{fb}^{-1}$, $(300 \text{fb}^{-1} \text{yr}^{-1})$

ATLAS-CMS-ALICE: (pb-pb) : $10 \text{ nb}^{-1}$
After Run-3 : Getting to HL-LHC
from 300fb\(^{-1}\) to 3,000fb\(^{-1}\) (300fb\(^{-1}\)yr\(^{-1}\))

Number of bunches
50ns - 25ns

Number of particles per bunch

\[ L = γ \left( \frac{f_{rev}}{4\pi} \right) \frac{n_b \cdot N_b^2}{e_n \cdot β^*} F(φ, β^*, ε, σ_s) \]

- maximize bunch intensities → Improve upgrade accelerator complex
- minimize beam size (constant beam power) → Focusing quadrupoles at Interaction points
- maximize number of bunches (beam power) → 25ns operation
- minimize the beam emittance
- compensate for geometric factors → Crab cavities
- Improve machine ‘up-time’ → Minimize unscheduled aborts
## Getting to the HL-LHC luminosity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal LHC (design report)</th>
<th>HL-LHC 25ns (standard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy in collision [TeV]</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>(N_b)</td>
<td>1.15E+11</td>
<td>2.2E+11</td>
</tr>
<tr>
<td>(n_b)</td>
<td>2808</td>
<td>2748(^1)</td>
</tr>
<tr>
<td>Number of collisions at IP1 and IP5</td>
<td>2808</td>
<td>2736</td>
</tr>
<tr>
<td>beam current [A]</td>
<td>0.58</td>
<td>1.09</td>
</tr>
<tr>
<td>x-ing angle [(\mu)rad])</td>
<td>285</td>
<td>590</td>
</tr>
<tr>
<td>beam separation [(\sigma))</td>
<td>9.4</td>
<td>12.5</td>
</tr>
<tr>
<td>(\beta^*) [m]</td>
<td>0.55</td>
<td>0.15</td>
</tr>
<tr>
<td>(\varepsilon_n) [(\mu)m]</td>
<td>3.75</td>
<td>2.50</td>
</tr>
<tr>
<td>(\varepsilon_L) [eVs]</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>Geometric loss factor R0 without crab-cavity</td>
<td>0.836</td>
<td>0.305</td>
</tr>
<tr>
<td>Geometric loss factor R1 with crab-cavity</td>
<td>(0.981)</td>
<td>0.829</td>
</tr>
<tr>
<td>beam-beam / IP without Crab Cavity</td>
<td>3.1E-03</td>
<td>3.3E-03</td>
</tr>
<tr>
<td>beam-beam / IP with Crab cavity</td>
<td>3.8E-03</td>
<td>1.1E-02</td>
</tr>
<tr>
<td>Peak Luminosity without crab-cavity [cm(^{-2}) s(^{-1})]</td>
<td>1.00E+34</td>
<td>7.18E+34</td>
</tr>
<tr>
<td>Virtual Luminosity with crab-cavity: (L_{\text{peak}})*R1/R0 [cm(^{-2}) s(^{-1})]</td>
<td>(1.18E+34)</td>
<td>19.54E+34</td>
</tr>
<tr>
<td>Events / crossing without levelling w/o crab-cavity</td>
<td>27</td>
<td>198</td>
</tr>
<tr>
<td>Levelled Luminosity [cm(^{-2}) s(^{-1})]</td>
<td>-</td>
<td>5.00E+34</td>
</tr>
<tr>
<td>Events / crossing (with levelling and crab-cavities for HL-LHC)</td>
<td>27</td>
<td>138</td>
</tr>
<tr>
<td>Peak line density of pile up event [evt/mm] (max over stable beam)</td>
<td>0.21</td>
<td>1.25</td>
</tr>
<tr>
<td>Levelling time [h] (assuming no emittance growth)</td>
<td>-</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Without upgrading machine (using continuous evolution) luminosity limited to 1,000fb\(^{-1}\)

The HL-LHC Project

- New IR-quads Nb$_3$Sn (inner triplets-focussing)
- New 11 T Nb$_3$Sn (short) dipoles (allow collimation)
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- ...

Major intervention on more than 1.2 km of the LHC
Crab Cavities, compensation

Aim: reduce the effect of the finite crossing angle

Without crabbing

New crossing strategy under study mitigate the pile-up density: some new of the new schemes have interesting potential as “crab-kissing”

- 3 proto types available
- Cavity tests are on-going
- Test with beam in SPS foreseen in 2015-2016
- Beam test in LHC foreseen in 2017
Luminosity Levelling at HL-LHC

- High peak luminosity ... not that useful
- Levelling minimizes pile-up in experiments and provide “constant” luminosity
- Schemes to minimize pile-up density in Z.
  - Crab Kissing

Obtain about 3 - 4 fb\(^{-1}\)/day (40% stable beams)
The LHCb Upgrade Program

LHCb Phase 1
LHCb Overview

- High-precision b-physics experiment devoted to and the search for new physics.
  - Studying
    - CP violation and rare decays in the b and c-quark sector
    - Search for deviations from the SM due to new particles in loop diagrams
    - Maintaining sensitivity to new physics above the TeV scale

- Run-1
  - Excellent performance of all sub-detectors
  - running at levelled luminosity of $\sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, pile-up $\langle \mu \rangle \sim 1$
  - first level hardware trigger running at $\sim 1 \text{ MHz}$
  - Trigger by looking for displaced vertices
  - Record data at $\sim 3\text{ -} 5 \text{ kHz}$

- LS2 and beyond
  - increase luminosity to a levelled $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, pile-up $\langle \mu \rangle \sim 5$
  - Now send data to fully flexible & efficient software trigger farm at 40MHz
  - 20kHz to storage
  - Plan to integrate $\geq 50 \text{ fb}^{-1}$ of data over 10 years.
  - Installation takes about 18 months
LHCb full readout at 40 MHz

- Upgrade all of the sub-systems to 40 MHz Front-End readout
- Replace complete sub-systems with embedded legacy electronics
- Redesign sub-systems to increased occupancies and maintain excellent performance at the higher rates
The Challenges:

- withstand increased, non-uniform, radiation up to $8 \times 10^{15} \text{n}_{eq}\text{cm}^{-2}$
- high data volume at 40 MHz
- Increased acceptance
- Reduce the inactive material
- Move first layer closer to the beam 5.5mm → 3.5mm

Design and Technology Choices:

- 55x55 µm$^2$ pixel sensors
- 40 MHz VELOPIX (130 nm technology to sustain ~400 Mrad) (VELOPIX which is an evolution of the TIMEPIX)
- Thickness of foil between primary and secondary vacua from 300µm to 150µm
- Micro channel CO$_2$ cooling
RICH Upgrade

40 MHz readout → need to replace HPDs due to embedded FE (1MHz limitation)
- Change to 64 channel Multi-Anode PMTs
- 40 MHz Front-End

- Adapting to higher occupancy
  - Remove aerogel radiator
  - modify optics of RICH1 to spread out Cherenkov rings (optimise gas enclosure without modifying B-shield)

New photo-detector readout module
Tracking System Upgrade

- Excellent mass resolution
- Very low background

- TT silicon
- IT silicon
- OT straw tubes

- TT - Si-Strips
  - p-in-n change to n-in-p
  - 5cm to 10cm long silicon strips
  - 180 → 90 µm pitch
  - ATLAS IBL like structures (Ca foam)

- Ti Stations
  - Fibre Tracker away from beam
  - Scintillating fibres MAT
  - Si-PM array to read out
  - Excellent position resolution
  - Cooling challenges (-40ºC)

See talks by Mark Tobin, Olaf Steinkamp
ATLAS and CMS
ATLAS and CMS Upgrades

- Technical/Design issues/choices that apply to both experiments

  - High radiation field within the detector (operation, installation and maintenance)
  - Radiation tolerant sensors for the pixel and strip detectors up to $2 \times 10^{16} \text{n}_{\text{eq}} \text{cm}^{-2}$
  - Radiation tolerant, low power, small feature size ASIC developments
  - Radiation tolerant powering schemes for High and Low Voltage (Serial Power or POL DC-DC)
  - Radiation tolerant high-bandwidth and optical data transmission (GBT, VL projects...)
  - High density, high reliability, low cost interconnects
  - Efficient trigger selection and getting from 40,000kHz to $\sim 1,000$kHz to 10kHz (incl Track Tigger)
  - Fast processors for track-triggers
  - Light mechanical structures, detector assemblies
  - Radiation tolerant crystals, photo-detectors and fibres for calorimeters
  - Radiation hard High rate gas chambers
  - Possibility of using high precision timing in calorimeter pre-sampling
  - Handling BIG DATA
  - ...

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LHC Upgrades : McMahon : Xi'an 2015
Pile up in the GPD’s

$Z \rightarrow \mu \mu$ event from 2012 data with 25 vertices

Nominal with 25ns beam

50ns beam
ATLAS and CMS Upgrades

• Performance Issues
  
  – Performance of detectors must not be significantly degraded in the presence of highest pile-up
  – Extensions of the rapidity coverage of all detectors towards $|\eta| = 4$
  – The possibility of using fast timing signals in the calorimeters to mitigate the effects of pile-up
  – Keeping the thresholds of trigger objects down while respecting the available bandwidth limitations
  – Using tracking in the earliest stages of triggering.
  – ....
ATLAS Phase 0

Points to draw your attention to..
EM Calorimeter in central region is LAr
Had-Calorimeter Scintillator
Forward Calorimeter LAr
ATLAS Phase-0 upgrades

• Insertable B-Layer to 4 layer Pixel
  - Add additional measurement/layer point close to I.P.
  - Better impact parameter resolution
  - Installation IBL in spring 2014
  - Important ingredient for low mass, rad-hard
  - construction: 2x2 cm FE-I4 Pixel Chip, 130 nm CMOS
  - Will stay up-to Phase-II

• Pixel Detector
  - new service panels – recover non-functional channels, better access, increased bandwidth

• Pixel + SCT Detectors
  - New thermoshipon cooling system

• Muon spectrometer
  - Install Muon End-cap Extension (EE) chambers to improve coverage at $1.0 < |n| < 1.3$
ATLAS Phase 1
Phase 1: New Small Wheel

- Replace existing Small Wheels with New Small Wheels
  - Cover the region in rapidity between 1.3 and 2.7
  - Improved tracking and trigger capabilities
  - Position resolution < 100 μm
  - IP-pointing segment in NSW with $\sigma_0 \sim 1$ mrad
  - Meets Phase-II requirements
    - Compatible with $\langle \mu \rangle = 200$
    - Luminosities up to $L \sim 7 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  - Technology: Micro-Megas and s-TGC’s
- Large reduction of muon L1 trigger rate
  - Especially in forward direction which is dominated by fakes
  - Coincidences with outer layers of Tile Calorimeter removes peak of muon fakes
Phase 1: New Small Wheel

- Replace existing Small Wheels with **New Small Wheels**
  - Cover the region in rapidity between 1.3 and 2.7
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- Large reduction of muon L1 trigger rate
  - Especially in forward direction
  - which is dominated by fakes
  - Coincidences with outer layers of Tile Calorimeter
    - removes peak of muon fakes

\[ \sqrt{s} = 14 \text{ TeV} \quad L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

- Extrapolation without NSW
  - $|\eta| > 1.05$
  - $|\eta| < 1.05$
- Extrapolation with NSW

**ATLAS Preliminary**
Fast TracK Trigger (FTK)

- Dedicated, hardware-based track finder
  - Runs after L1, on duplicated Si-detector read-out links (strip and pixel)
  - Provides tracking input for L2 for the full event, fast customized electronics
  - Finds and fits tracks (~ 25 μs) in the ID silicon layers at an “offline precision”
  - Processing performed in two steps

1. hit pattern matching to pre-stored patterns (coarse)

2. subsequent linear fitting in FPGAs (precise)
ATLAS Phase 2
New Tracking detector

- Current Inner Detector (ID)
  - Designed to operate for 10 years at $L = 1 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
    with $\langle \mu \rangle = 23$, @25 ns, $L_1 = 100 \text{kHz}$
- Limiting factors at HL-LHC
  - Bandwidth saturation (Pixels, SCT)
  - Occupancy limits (TRT, SCT)
  - Radiation damage (Pixels (SCT) designed for $400 \ (700) \text{ fb}^{-1}$)

LoI layout new (all Si) ATLAS Inner Tracker for HL-LHC

New 130nm prototype strip ASICs in design
- incorporates L0/L1 logic
- Able to read out at 1Mhz L0

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ATLAS Silicon Strip Tracker

- Outer tracker is a silicon strip detector with n-in-p sensors
- Double-sided layers with implemented stereo angle (40 mrad)
  - Short (23.8 mm) & long strips (47.8 mm) 74.5 μm pitch in barrel
  - End-Cap with radial strips of different pitch (6 different module)
- Stave/petal one object; top and bottom side read out separately

- Silicon Modules directly glued to a carbon fibre plate with embedded cooling.
- Services integrated into face sheet including power control and data transmission.
ATLAS Pixel Tracker

- Module development well advanced
- Final Layout and mechanical design still under active review
- Inner and Outer Cylinders for Barrel region (*inner cylinders are replaceable*)
  - Not necessarily the same technology in inner and outer barrels
- HV/HR CMOS “smart” sensors are still an attractive option for the outer layers

Quad Pixel Module Prototype

*See talks (x 6) by Branislav Ristic, Toko Hirono Anna Macchiolo, Nobu Unno, Giovanni Calderini, Simon Viel*
New Tracking detector cont.

- Studies with LOI layout
  - Robust tracking
  - Low Occupancy <1% for $<\mu>=200$
  - Reduced material wrt current ID
  - Comparable / better tracking performance at $<\mu>=200$ as current ID at $<\mu>=0$
  - Latency margins

- Solid baseline design
  - Now working on optimisation, final Q1 2016
  - Will include a rapidity extension
Trigger system architecture

- New design for Phase II
  - 2-level system, Phase-I L1 becomes Phase-II L0, new L1 includes tracking
  - Requires changes to detector FE electronics feeding trigger system
  - **Level-0**: Rate \(\sim 1,000\ kHz\), Lat. \(\sim 10\ \mu s\) : Muon + Calorimeter
  - **Level-1**: Rate \(\sim 400\ kHz\), Lat. \(\sim 30\ \mu s\): Muon + Calorimeter + Tracks

End of Run-3
Trigger system architecture

- New design for Phase II
  - 2-level system, Phase-I L1 becomes Phase-II L0, new L1 includes tracking
  - Requires changes to detector FE electronics feeding trigger system
- Level-0: Rate ~ 1,000 kHz, Lat. ~10 μs: Muon + Calorimeter
- Level-1: Rate ~400 kHz, Lat. ~30 μs: Muon + Calorimeter + Tracks

Start of Run-4

Track Trigger at Level-1 (L1)
- Move part of High Level Trigger reconstruction into L1
- Goal: keep thresholds on $p_T$ of triggering leptons and L1 trigger rates low
CMS Phase 0
CMS Phase-0 upgrades

- Completion/consolidation of the detector for $1 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
  - Muon end-cap system
    - ME1/1 electronics (un-ganging), ME4/2 complete stations & shielding
  - Si Tracker
    - Prepare for cold operation (-20°C coolant)

- Issues identified during Run 1
  - HF photo-dectors
    - Reduce beam-related background
  - HO photo-dectors
    - replaced with Silicon Photo-Multipliers (Si-PM)

- Preparatory work for Phase 1 Upgrades
  - New beam pipe and “pilot blade” installation for the Pixel Upgrade
  - New HF backend electronics - ahead of HCAL frontend upgrade
  - Splitting for L1-Trigger inputs to allow commissioning new trigger in parallel with operating present trigger
CMS Phase 1
Phase 1 – Pixel Detector

- 4 layers central and 3 disks forward
  - 1 more space point, closer to beam at 3cm
  - Improved track resolution and efficiency
  - Tolerate up to 100 PU and survive to 500 fb\(^{-1}\), with exchange of innermost layer

- New readout chip
  - Recovers inefficiency at high rate and Pile-up

- Less material
  - CO2 cooling, new cabling and powering scheme (DC-DC)

See talk by Simon Spannagel

Ready to install EYETS 2016-2017
Runs to 2023
CMS Phase 2
**Phase 2 Tracker: Conceptual design**

- **Outer tracker**
  - High granularity for efficient track reconstruction beyond 140 PU
  - Two sensor “$P_T$ modules” to provide trigger information at 40 MHz for tracks with $P_T \geq 2$ GeV
  - Improved material budget

- **Pixel detector**
  - Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to $|\eta| = 4$
  - Thin sensors 100 μm; smaller pixels 30 x 100 μm

See talks by Thomas Bergauer,
CMS Outer Tracker

2S Strip Sensor modules
3 layers at R>60cm
2 x 1016 strips : 5cm x 90μm
Power ~ 5W
90cm² active area
Spacing 1.8mm and 4.0mm

PS Pixel + Strip Sensor modules
2 layers at R>20cm
2 x 960 strips : 2.5cm x 100μm
32 x 960 pixels : 1.5mm x 100μm
Power ~ 7W
45cm² active area
Spacing 1.6mm, 2.6mm and 4.0mm
Operates at ~-20°C, set point -30°C

Modules discriminate low-p_T tracks in the FE electronics. data for track reconstruction at L1
Hybrid is key element: Wire-bonds from the sensors to the hybrid connect two sides
Overall 216 m² with 47 M strips, 215M long pixels
Triggering Using Outer Tracker

Two sensor “Pt-modules” to provide trigger information at 40 MHz for tracks with $Pt \geq 2\text{GeV}$

L1 tracking acceptance is limited to $|\eta| < 2.5$
CMS Tracker : Hits and Material

[Graphs showing data for Phase-1 and Phase-2 trackers]
CMS Muon System

- Investigating increase of the muon coverage beyond $|\eta| < 2.4$ with GEM tagging station (ME0) coupled with extended pixel (depending on HE upgrade)
- Concept under study to complete muon stations at $1.6 < |\eta| < 2.4$
  - GEM in 2 first stations (Pt resolution)
  - Glass-RPC in 2 last stations (timing resolution to reduce background)
The ALICE Upgrade Program

ALICE Phase 1
ALICE Overview

- Major upgrade of ALICE detector to process Pb-Pb collisions at high rates and improve vertex reconstruction capabilities at low transverse momentum capabilities (rare probes).
- Read out all Pb-Pb interactions at a maximum rate of 50kHz (L > 6x10^{27} cm^{-1} s^{-1}), with a minimum bias trigger (currently limited to 0.5kHz)
- Online data reduction based on reconstruction of clusters and tracks
- Aim to record 10nb^{-1} of Pb-Pb and > 50nb^{-1} of p-Pb (factor 100 in statistics to 2018)

Key elements of the upgrade programme are:
- New Inner Tracking System - ITS (7 layers, ~11m^2)
  - Built on the experience from STAR vertex detector See talk by Giacomo Contin
- Replace TPC endplates with new electronics for continuous readout
- New 5-plane muon silicon telescope in forward region in front of hadron absorber in the acceptance of the muon Spectrometer
- Readout rate upgrade of all other ALICE sub-detectors to 50kHz
- All data written to tape, processed (reconstructed) data
ALICE ITS
Replaces existing detector

7 layers of MAPS

Radial coverage
22 – 406 mm

700 krad/ $1 \times 10^{13}$ 1 MeV $n_{eq}$
Includes safety factor 10

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LHC Upgrades : McMahon : Xi'an 2015
New ITS Design goals

- Impact parameter resolution improved by a factor of about 3
- Get closer to Impact Point 39mm → 22mm (1 MRad and $10^{13}$ n cm$^{-1}$)
- Material budget at inner layers: $X/X_0 : \sim 1.14\% \rightarrow \sim 0.3\%$
- Reduce pixel size: 50µm x 425µm → 20µm x 20µm (50µm thick)
- Number of layers 6 → 7 (25Gpixels of MAPS at 50kHz)

Readout of Pb-Pb interactions at > 50 kHz and pp interactions at ~ 1 MHz
Resolutions: $\sigma_{r\phi} = 4$ µm, $\sigma_z = 4$ µm for all layers.
Replace wire chambers with quadruple-GEM chambers

Increase rate limitation from 3.5kHz to 50kHz
Gas Electron Multiplier gain ~2k
Conclusions

- The next 20 years will include a very exciting program of measurements at the highest energy frontier the HLHC.

- The LHC will go from 300 fb\(^{-1}\) at the end of phase I to 3000 fb\(^{-1}\) at the end of phase II and will be a unique facility for particle physics.

- The physics program will certainly include precise measurements of Higgs properties and the search of new particles.

- All four experiments have exciting and vigorous upgrade programs. These are challenging technically and are leading us to push our understanding and developments to the limits.

Back Up Slides
This means I could not fit in these slides for lack of time.
Less relevant for this Symposium

*Please look at these at your leisure*
Cost per year of upgrades
The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections
Complete reconstruction of 1500 of these splices
Consolidation of the 10170 13kA splices, installing 27,000 shunts
Installation of 5000 consolidated electrical insulation systems
300,000 electrical resistance measurements
10170 orbital welding of stainless steel lines

18,000 electrical Quality Assurance tests
10170 leak tightness tests
4 quadrupole magnets to be replaced
15 dipole magnets to be replaced
Installation of 612 pressure relief devices to bring the total to 1344
Consolidation of the 13 kA circuits in the 16 main electrical feedboxes
Calorimeter and Muon Upgrades

MWPC

5 stations
M1 to M5

Inner ECAL modules around beam-pipe replaced

Radiation damage and occupancies
- Calorimeter stays
- Pre-shower and SPD removed
- HCAL modules ok up to ~50 fb\(^{-1}\)
- Irradiation tests show that ECAL modules resist up to ~20 fb\(^{-1}\) → LS3

- Remove station M1 due to too high occupancies
- Keep on-detector electronics already at 40 MHz readout
- New off-detector electronics readout
- Production of spare MWPC for installation in LS3 in hottest regions
Trigger Towers $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$
- Used to calculate core energy, isolation

Better granularity, energy resolution same threshold at acceptable rates

Without the upgrade Run-1 trigger menu at $L_{\text{inst}}=3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ the total rate for EM triggers would be **270 kHz** (Total L1 bandwidth is 100kHz)
Calorimeter electronics

• Tile Calorimeters
  – No changes required to the detector
  – Full replacement of electronics (FE and BE)
    • New read-out architecture: Full digitisation of data at 40MHz and transmission to off-detector system

• LAr Calorimeter
  – Replace FE and BE electronics
    • Aging, radiation limits
    • 40 MHz digitisation, inputs to L0/L1
    • Natural evolution of Phase-I trigger boards
  – Replace Forward calorimeter (FCal) if required
    • Install new sFCAL in cryostat or miniFCAL in front of cryostat if significant degradation in current FCAL
Muon system upgrade

Upgrade FE electronics
  – accommodate L0/L1 scheme parameters

- Improve L1 $p_T$ resolution
  – Use MDT information possibly seeded by trigger chambers ROIs (RPC/TGC)
  – Another option: add higher precision RPC layer at inner MDT station

Match angle measurement in end-cap MDTs to precision measurement in NSW
Phase 1 – HCAL

- New readout chip (QIE10) with TDC
  - Timing: improved rejection of beam-related backgrounds, particularly HF

- Replace HPDs in HB and HE with SiPMs
  - Small radiation tolerant package, stable in magnetic field
  - PDE improved x3, lower noise
  - Allows depth segmentation for improved measurement of hadronic cluster rejection of backgrounds, and re-weighting for radiation damage

- Segmentation for TDR

  Quadrant of HB and HE showing depth segmentation with Si-PM readout
Silicon pixel tracker in the acceptance of the Muon Spectrometer placed between the Interaction Point and the Hadron Absorber to track back to the IP (also MAPS)