ATLAS Run-2 status and performance

F. Pastore (Royal Holloway, University of London)
on behalf of the ATLAS Collaboration

- ATLAS improvements and expectations
- LHC restarts: Run2 is on
- ATLAS commissioning and status

Montpellier, June 29th 2015
Acknowledgments

ATLAS Collaboration
226 institutes, 5206 current members, 38 countries

...and many thanks to the LHC operators
Success of ATLAS during Run-1

LHC provided during Run-1 (2010-2012):
- Integrated L: ~ 5 fb$^{-1}$ @ 7 TeV, ~21 fb$^{-1}$ @ 8 TeV

ATLAS recorded 94% (data taking efficiency) of all the p-p collisions, and certified 95% as good data

This ended up in physics papers
- 428 published papers
- more than 600 conference notes and conference talks
Higgs mass and couplings

- Combined signal strength $\mu = 1.18^{+0.15}_{-0.14}$, consistent with SM. Precision mass in combination with CMS at 0.2%. Coupling strengths measured with and without model dependent assumptions.
- Improved studies on spin/parity, consistent with SM.
- First $ttH$ measurements (important for t-H Yukawa).

Top physics: precision mass and charge asymmetry, top is a good probe for searching New Physics ($t\bar{t}$ resonances, simultaneous measurements of mass/JES/bJES).

Summary of the ATLAS direct $m_{top}$ measurements

- Search of New Physics at 95% CL for: electroweak production of charginos and neutralinos, squark pair production and variety of inclusive SUSY searches; as well as narrow resonances at high mass (di-boson)…

To continue with more data and Energy.
After two years of shutdown, LHC is starting to collide protons at un-precedent CM Energy: 13 TeV

Initial LHC commissioning progressed quite fast (no single source of problems): foreseen 57 weeks

April 5th: Beam splashes (injection tests)
May 5th: 900 GeV collisions: recorded ~7x10^6 min-bias events, “quiet beam” mode
May 20th: 13 TeV collisions: recorded (0.3-0.4) nb^-1, ~21x10^6 min-bias events, ”quiet beam” mode
June 3rd: 13 TeV collisions with “stable beam” started

Foreseen proton physics: ~30 weeks at 50ns, and ~70 at 25ns

Run-2
\[ \sqrt{s} = 13 \text{ TeV} \]
\[ L_{\text{int}} = 100-150 \text{ fb}^{-1} \]
\[ L_{\text{peak}} = 1.3-1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} (\mu \sim 40) \]

Summer is dedicated to 50ns→25ns bunch spacing transition
No restrictions visible at high energy

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Schedule from LHC
PROTON PHYSICS: STABLE BEAMS

Energy: 6500 GeV  \( I(B1): 2.92 \times 10^{11} \)  \( I(B2): 2.94 \times 10^{11} \)

FBCT Intensity and Beam Energy

Instantaneous Luminosity


the LHC is back in business!
(all IPs optimized)

BIS status and SMP flags

- Link Status of Beam Permits
  - B1: false, B2: false
- Global Beam Permit
  - B1: true, B2: true
- Setup Beam
  - B1: false, B2: false
- Beam Presence
  - B1: true, B2: true
- Moveable Devices Allowed In
  - B1: true, B2: true
- Stable Beams
  - B1: true, B2: true

AFS: Single_3b_2_2_2_with_nc_probes

PM Status B1: ENABLED
PM Status B2: ENABLED
Number of bunches: 50
Number of colliding bunches (ATLAS/CMS): 38
Peak luminosity: $1.45 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
Integrated luminosity: $3.8 + 3.5 \text{ pb}^{-1}$

Peak <Events>/BC: ~27
| Energy  | 6500 GeV | L(B1):  | 2.87e+11 | L(B2):  | 2.87e+11 |
What’s new in ATLAS?

During two-year Long- Shutdown-1 (LS1), ATLAS performed consolidation tasks
- and more eco–friendly: CO2 cooling for new components, repair leaks, less radiation (additional shielding and Al beam pipes)

Infrastructure:
- Change of components to increase up-time of the detector (electrical and power network, vacuum loop, magnets operations, He compressors, cooling and ventilation)

Detector (described in detail later):
- Consolidation and increase of robustness against high radiation level
- Completion of the detector installation, as described in the Technical Design Report
- New components, like Pixel Insertable-B-Layer (IBL), and new TDAQ infrastructure

Computing and software: new data management and analysis tools
Pixel-detector panel construction

ATLAS calorimeters

The IBL enters its support tube

Detector vacuuming

Drift-tubes inspection

Big-wheels separation

Thin-gap-chamber replacement

LUCID and beam-pipe installation

Small Wheel to surface in 2013

Point-1 ATLAS cavern was hive of activity for more than two years
Integration of all detectors started in February 2014

- Full shift crew and millions of cosmic ray data collected, for alignments of Inner Detectors and muon system
- Cosmic rays and beam splashes used for internal timing alignment, need to align at BC level all the detectors and adjust LHC clock phase (new Central Trigger Processor distributes the signals)

Gradual integration during the Milestone weeks

<table>
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<th>M2</th>
<th>M3</th>
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<th>M5</th>
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Minimum Bias Scintillators aligned in time @BC, with first collisions

Alignment between upward and downward tracks from cosmic rays

Δq/pt, difference between top and bottom tracks

ATLAS Preliminary Δ(Up-Down) Tracks
Cosmic ray data
2015 data

ATLAS Preliminary
Δ(Up-Down) Tracks

Leading Edge Trigger Offset [BC]

Minimum Bias Scintillators aligned in time @BC, with first collisions

ATLAS Preliminary

Δq/pt, difference between top and bottom tracks

Before Alignment
μ=9.38 TeV⁻¹
FWHM/2.35=4.9 TeV⁻¹
February Alignment
μ=0.07 TeV⁻¹
FWHM/2.35=2.0 TeV⁻¹
March Alignment
μ=0.02 TeV⁻¹
FWHM/2.35=1.2 TeV⁻¹

Number of tracks / 16.8 TeV⁻¹

ATLAS Preliminary

Leading Edge Trigger Offset [BC]
Overall detector readiness (from Apr. 2015)

<table>
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<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
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<tr>
<td>Pixels</td>
<td>92 M</td>
<td>99.0%</td>
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<tr>
<td>SCT Silicon Strips</td>
<td>6.3 M</td>
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<td>350 k</td>
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<td>100%</td>
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<td>Forward LAr calorimeter</td>
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<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.1%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>99.8%</td>
</tr>
</tbody>
</table>
Muon Spectrometer in LS1

- Increase the acceptance, with new or repaired chambers
  - **Repaired or replaced** almost 30 Thin-Gap-Chambers (TGC) and inactive Cathode-Strip-Chambers (CSC) using specially designed lifting devices
  - **Completion of the spectrometer** with new Resistive-Plate-Chambers (RPC) in the Barrel holes (+2.8% acceptance) and Extra Endcap chambers

- **Reduce the L1 trigger rate in the Endcap region (η>1.05)**, dominated by slow particles not coming from the interaction region

- **Significant improving of muon purity expected (30% rate reduction)** by adding coincidences with the inner layers and with the external Hadronic/Tile calorimeter
Combined muon system in Run2

- **All system timed-in and aligned**

- Toroid magnet was off during first collisions to facilitate final commissioning of new muon stations (feet in sectors, and elevator chambers). New alignment sensors calibrating

- New readout of the cathode strip chambers (CSC) fully operational, can reach 100 kHz

- **J/ψ candidates** seen in p-p collisions at 13 TeV. The data were taken during "quiet beams" delivered as part of the LHC beam commissioning period in May 2015

The di-muon invariant mass distribution of $J/\psi \rightarrow \mu+\mu$-candidates observed in $\sqrt{s} = 13$ TeV pp collisions. The data are fitted with a Gaussian signal PDF and a constant background, the fitted mean value of the signal is **consistent with the world average J/ψ mass**.
Display of a proton-proton collision event recorded by ATLAS on 21 May 2015 at a collision energy of 13 TeV. Tracks reconstructed from hits in the inner tracking detector are shown as arcs curving in the solenoidal magnetic field and the green bars indicate hits in the Muon spectrometer. In this event two muons are identified, and their invariant mass is consistent with that of a J/Psi meson.
Calorimeters after LS1

- **Strategy during LS1**: increase reliability of the detectors with
  - new on-detectors power supplies
  - consolidated electronics
  - improved data and power transmission
- It will result in smaller systematics uncertainties, including for the jet energy scale and resolution

- **Hadronic Calorimeter (Fe/Sci Tile)**: consolidation of electronics, new LV power supplies and Cs calibration system
  - Status: greatly recovered readout channels

- **Liquid Argon Calorimeter (LAr)**: HW consolidation (LV PS, FE boards), new FE demonstrator for future run-3
  - Status: 100% ready

- **More flexible L1 trigger paths (ASIC->FPGA)**: for example signal processing for missing-\(E_T\) with dynamic pedestal subtraction based on global cell occupancy and in-bunch train positions, to increase resolution
  - Status: under final commissioning
Calorimeters observed beam splashes

Average LAr cell energy sums obtained during beam splashes on April 7, 2015:

ATLAS Preliminary LAr Barrels
Run 260466 Tue Apr 7 2015
Composite Average of 63 Splash Events

Average LAr cell energy sums obtained during beam splashes on April 7, 2015:

ATLAS Preliminary LAr Endcap C
Run 260466 Tue Apr 7 2015
Average of 30 A-Side Splash Events

ATLAS Preliminary LAr Endcap A
Run 260466 Tue Apr 7 2015
Average of 33 C-Side Splash Events

LAr barrel FE board timing aligned

with time-of-flight corrections to account for splash events originating away from the interaction point and traveling nearly parallel to the beam axis.
Calorimeters calibrations at 13 TeV

**Di-photon** spectrum, without data-driven energy scale corrections applied

**Jet $p_T$ spectrum** measured with topological clusters, calibrated with the EM+JES scheme and selected with $p_T > 20$ GeV requirement

**Missing Energy resolution**, measured with topological clusters using LCW (Local Cluster Weighting) and selecting a good vertex
Display of a proton-proton collision event recorded by ATLAS on 21 May 2015 at a collision energy of 13 TeV. Tracks reconstructed from hits in the inner tracking detector are shown as arcs curving in the solenoidal magnetic field and green bars are proportional to the energy deposited in the electromagnetic calorimeter. A high energy electron and positron are identified with an invariant mass consistent with that of a Z boson candidate.
Inner Trackers: TRT, SCT,...

**Transition Radiation Tracker (TRT)**
- Operates at limit in high radiation environment, crucial for reducing fake electrons and photon conversions, orthogonal to calorimeter
- To cope with gas leaks (abundant during Run-1 due to ageing corrosion of outflow pipes), strategy is **changing Xe as active gas with Argon** (less expensive) when needed, with x10 reduced absorption of TR. Added remote gas regulation
- **New readout** mechanism for operation at higher collision rates

**Semiconductor Tracker (SCT)**
- **New faster electronics**, with improved optical transmitters
- Increased readout bandwidth

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### Position residuals for low momentum tracks $p_T > 0.5\text{GeV}$, with TRT straws filled with Argon

- **ATLAS Preliminary**
- 2015 Data, $\sqrt{s}=900$ GeV
- $\sigma = 130 \, \mu m$

- Tracking performance in TRT not affected by the change of active gas (Ar)

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### SCT timing scan during 13TeV collisions

- **ATLAS SCT Preliminary**
- Module -2.1.18.0
- Mean = $-4.8 \pm 0.2$ ns

- SCT fully operational and timed-in
The original 3-layer Pixel detectors made more robust against optical link failures with a new service panel, at easy access

- Big repairing effort (with extraction of the detector)

Insertable B-Layer (IBL): new 4th inner layer, mounted on the beam-pipe, greatly increases the efficiency of reconstructing tracks/vertices (b-tagging) and ensures good performance against radiation damage

- Installed with > 99.9% live channels
- Routinely readout in cosmic ray runs and first collisions

The IBL has been the most challenging project for ATLAS LS1, its installation drove all the cavern activities

- Installation, anticipated by almost 2 years, suffered from wire-bonds corrosion, so new modules were produced in record time
- Since first cosmic runs, observed a larger than expected thermally-induced r-φ “twisting” of IBL staves, at the level of few μm/K: it might require refinements to operating procedures, with careful temperature control at the level of ~ 0.2 K

<table>
<thead>
<tr>
<th>Disk</th>
<th>Layer 2</th>
<th>Layer 1</th>
<th>Layer 0</th>
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<td>4.5%</td>
<td>7.0%</td>
<td>1.9%</td>
<td>6.3%</td>
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<tr>
<td>3.5%</td>
<td>2.0%</td>
<td>1.2%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

Distribution of Time Over Threshold (ToT) corrected to normal incidence for IBL Clusters

ATLAS Preliminary 2015 √s = 13 TeV

- IBL Planar
- IBL 3D

Three different technology sensors now in the Pixel detector

Threshold =2650 electrons
Temperature =-10° C.
Planar Bias Voltage = 80 V
3D Bias Voltage = 20 V
Display of a proton-proton collision event recorded by ATLAS on 3 June 2015, with the first LHC stable beams at a collision energy of 13 TeV.

Tracks reconstructed by the tracking detector are shown as light blue lines, and hits in the layers of the silicon tracking detector are shown as colored filled circles. The four inner layers are part of the silicon pixel detector and the four outer layers are part of the silicon strip detector. The layer closest to the beam, called IBL, is new for Run 2. In the view in the bottom right it is seen that this event has multiple pp collisions. The total number of reconstructed collision vertices is 17 but they are not all resolvable on the scale of this picture.
Tracking monitoring with quiet beams

**Optimised vertex algorithms** monitored during first collisions

**Tracker “radiography”:** the radial position of vertices, reconstructed with multiple tracks having >5σ transverse impact parameter significance, show hadronic interactions in the new beam-pipe and IBL.

Due to impact parameter cuts, the efficiency depends on the radius.
Forward detectors and Luminosity

- **New Minimum Bias Trigger Scintillators (MBTS)**, useful for low energy/low interaction rate runs, such as first collisions, calibration scans and heavy ion runs.

- **New LUCID (Luminosity Cherenkov Integrating Detector)** for high quality luminosity measurements, suitably rad-hard.

- **Upgraded ALFA-system (4 Roman Pots on each side)**, with a new heat protection system and additional horizontal Roman Pots to improve acceptance.

- **Pre-calibration with mini Van Der Meer scan, testing detectors**
  - First measurements: $L_{\text{inst}} \sim 5 \times 10^{28} \text{ cm}^{-2} \text{ s}^{-1}$, $<\mu> \sim 0.35$

**Ultimate Luminosity precision at the 2-3% level, with combined effort from different detectors**

- Monitor of average number of pp-interactions per bunch crossing measured by LUCID.

ATLAS Preliminary

\[ s=13 \text{ TeV} \]
Run2 T/DAQ architecture

- Increase L1 rate (100 kHz)
- Merged HLT
- Increase Readout bandwidth
- Increase HLT rate (1 kHz)
- Unified network

- New architecture tested successfully
- L1 output limit will be decided by detector occupancy
The trigger and data acquisition system had a major upgrade during LS1, prepared to deal with trigger rate increased by a factor x5: factor ~x2 due to energy increase (higher for high $p_T$ jets) and factor x2-3 due to luminosity.

- Improvements needed to reduce trigger rates to acceptable levels, while maintaining or even improving efficiencies in the challenging conditions (limited upgrade of the electronics).
- Enriched with more sophisticated/flexible algorithms, in hardware and software.

**Level-1 upgrades:**

- **New topological processor**, to select specific signatures at low energy thresholds, mainly final states with missing-$E_T$, jets and $\tau$s ($ZH \to $ννbb and $H\to\tau\tau$).
- **New Central Trigger Processor** to increase number of L1 items.

**Level-1 status:** all systems used first collisions for timing adjustments of the new components. New systems are under final commissioning.
**Reduced number of trigger levels:** two high-level triggers merged into one, with x2.5 reduced data transfer and improved trigger algorithms

- **DAQ system** simplified and significantly upgraded (software/hardware): single network and single farm, increased bandwidth on the Readout System

- Same **Region-of-Interest approach**, but with flexible event-building: more offline algorithms can be used online, easily maintenance, more algorithms shared

**Run-2 trigger menu validation on-going**

- More flexibility with larger number of L1 (~300) and HLT (~1000) selections and more dedicated multi-object selections

- First collisions recorded with L1 triggers, with calibrations and monitoring running smoothly

- Detailed studies of latency and deadtime needed to protect detectors (expected % deadtime at 100 kHz)

**Expected by the end of this year, first installation of the Fast Tracker (FTK), an hardware processor that will enable tracking feature extractions in less than 100 µs**
Computing, software, analysis

- Computing resources do not scale accordingly with the new Run-2 challenges:
  - Higher pile-up (30→40) and more complex events
  - Higher trigger rate (~1 kHz=1.5GB/s)

- During LS1, big effort to ensure more flexibility and less artificial boundaries
  - New computing model, production system and data management tools
  - New analysis data model: new analysis tools and reduced analysis dataset types

- Tier-0 processing under commissioning, ready for new data-taking:
  - Latest release more robust high pile-up, with factor x4 gain in CPU resources (20% gain for full simulation)
  - 48-hours calibration loop started after first 13TeV collisions: 3/4 days for AODs available, 4/6 days for derived
  - Monte Carlo production running at full speed, for simulated events at 50 ns, while 25 ns sample is underway

Great optimisations in the tracking algorithms
Conclusions

After two years of hard activities to improve the detector and the full experiment infrastructure, ATLAS is ready to explore new energy and luminosity scenarios offered by the LHC proton-proton collisions in Run-2, with improved discovery potential.

Millions of cosmic rays, beam splashes and first collisions at 13 TeV used to tune the full infrastructure, and confirm that ATLAS is performing as expected, starting from the detector operation to data processing and analysis.

We are preparing many candidates for easy cross-section measurements with first 1/fb @13 TeV, recorded during the 50ns intensity ramp during Summer.

... and expecting rapid LHC luminosity raising in first few weeks of September, with target 5 to 10 /fb for 2015.

100 /fb planned for Run2 useful to:

- establish Higgs decays into fermions (ττ and bb) and observe rare decays (H→μμ)
- explore the TeV scale, while using precision Standard Model measurements as discovery tools...

...and the hunt continues!
Back-up slides
First Luminosity measurements

Can these be shown?

Inner Trackers: Transition Radiation Tracker (TRT)

- Operates at limit in high radiation environment, crucial for reducing fake electrons and photon conversions, orthogonal to calorimeter
  - Maintaining low-threshold electron trigger
  - Many analyses with low-pT electrons and/or with sizeable contributions from fakes (from Higgs, EW measurements, like W+jet, to SUSY searches)
- Run1 leaks in the gas outflow pipes, due to ageing corrosion, minimised by tuning the gas flow
  - No impact on performance, but high cost for Xenon losses (∼200 liter/day ≡ 50 kCHF/month)
- Run2: strategy to cope with evolution of the gas leaks, changing active gas with Argon, with x10 reduced absorption of TR, but small impact expected in tracking performance
  - No impact on spatial resolution observed in first collisions
- Run2: gas system modified significantly with a remote regulation system
- Run2: New readout driver firmware for operation at higher collision rates. New thresholds optimised

![Position residuals for low momentum tracks $p_t > 0.5\text{GeV}$, with TRT straws filled with Argon gas](image)

- $\sigma = 130\ \mu\text{m}$

![Time residuals for low momentum tracks $p_t > 0.5\text{GeV}$, with TRT straws filled with Argon gas](image)

- $\mu = 0.5\ \text{ns}$
- $\sigma = 2.6\ \text{ns}$
Inner Trackers: Semiconductor Tracker (SCT)

- Installed and commissioned new faster electronics, with improved optical transmitters (more robust against humidity)
- More efficient data taking with increased number of Readout modules
- Observed drop in leakage currents due to 15 months annealing at room temperature. The noise levels at the start of Run2 are comparable with the values at the end of Run1
- Timing scan done during first 13 TeV collisions
  - Trigger to the front end modules was delayed in 5ns steps ranging from -20ns to +20ns relative to nominal timing (3 consecutive BCs samples)

Maximum sustainable L1 trigger rate for data transfer from FE chip to RODm as a function of the mean number of interactions per bunch crossing, $\mu$. 

\begin{align*}
\text{Maximum sustainable rate [kHz]} \\
\mu \\
\end{align*}
The full trigger tau reconstruction time for 14 TeV ttbar Monte Carlo with a mean of 46 interactions per bunch crossing, measured on a 2.4 GHz Intel Xeon CPU. The timing is dominated by track finding - only 36 ms is spent in calorimetry. Shown are the times for two strategies; in the first, “One-step”, strategy, tracks are reconstructed within a tau candidate Region of Interest (RoI) of size $\Delta \eta \times \Delta \phi = 0.4 \times 0.4$ pointing to a calorimeter cluster, and with a spread along the beamline of $|z_0| < 225$ mm, corresponding to the size of the interaction region. There is a mean of approximately 3 tau candidates per event. In the second (“Two-step”) trigger strategy, tracks are first reconstructed within a small RoI of size $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ with the same $z_0$ extent. Further tracks are then reconstructed in a wider (in $\eta$ and $\phi$) RoI with $\Delta \eta \times \Delta \phi = 0.4 \times 0.4$, centred on the leading (highest-pT) track from the previous step. This RoI is constrained to $|\Delta z_0| < 10$ mm with respect to the perigee of the leading track. Splitting the tracking into these two steps reduces the non-linear dependence of the tracking on occupancy with minimal effect on efficiency.
Large shape distortions induced by temperature changes seen in Cosmic rays results.

Due to difference of thermal expansion coefficients of different materials in IBL

Task force studied effects on Physics and Mechanical integrity, preliminary reports show:

Very little effect on physics, manageable with on/offline corrections, temperature during fills is very stable (<0.2 K)

Mechanical distortions are elastic, but large stress are induced on structures, not yet definitive answer on long term stability

Final report is due during the summer
Run-2 LHC Plans & Conditions

LHC / HL-LHC Plan

- $\sqrt{s} = 7$ (8) TeV
- 50ns bunch spacing
- $L_{\text{int}} \approx 30 \text{ fb}^{-1}$
- $L_{\text{peak}} \approx 7.5 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- \sim 1400 bunches total
- Bunch charge: $\sim 1.6 \cdot 10^{11} \text{ p/b}$
- $\mu \sim 30$
- $\beta^* = 0.6 \text{ m}$

Run-1

- $\sqrt{s} = 13$ TeV
- 25 ns bunch spacing
- $L_{\text{int}} \approx 100 - 150 \text{ fb}^{-1}$ -- 10 fb$^{-1}$ in 2015
- $L_{\text{peak}} \approx 1.3 - 1.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- \sim 2800 bunches total
- Bunch charge $\sim 1.15 \cdot 10^{11} \text{ p/b}$
- Small emittance/bright beams with BCMS (batch compression, merging, split) scheme (2.4 \rightarrow 1.3 \mu m)
- $\mu \sim 40$
- $\beta^* = 0.55 \text{ m nominal, 0.8 m in 2015}$

Run-2