Beauty 2014

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14th – 18th July 2014

The B-Physics Programme of ATLAS in LHC Run-II and in HL-LHC

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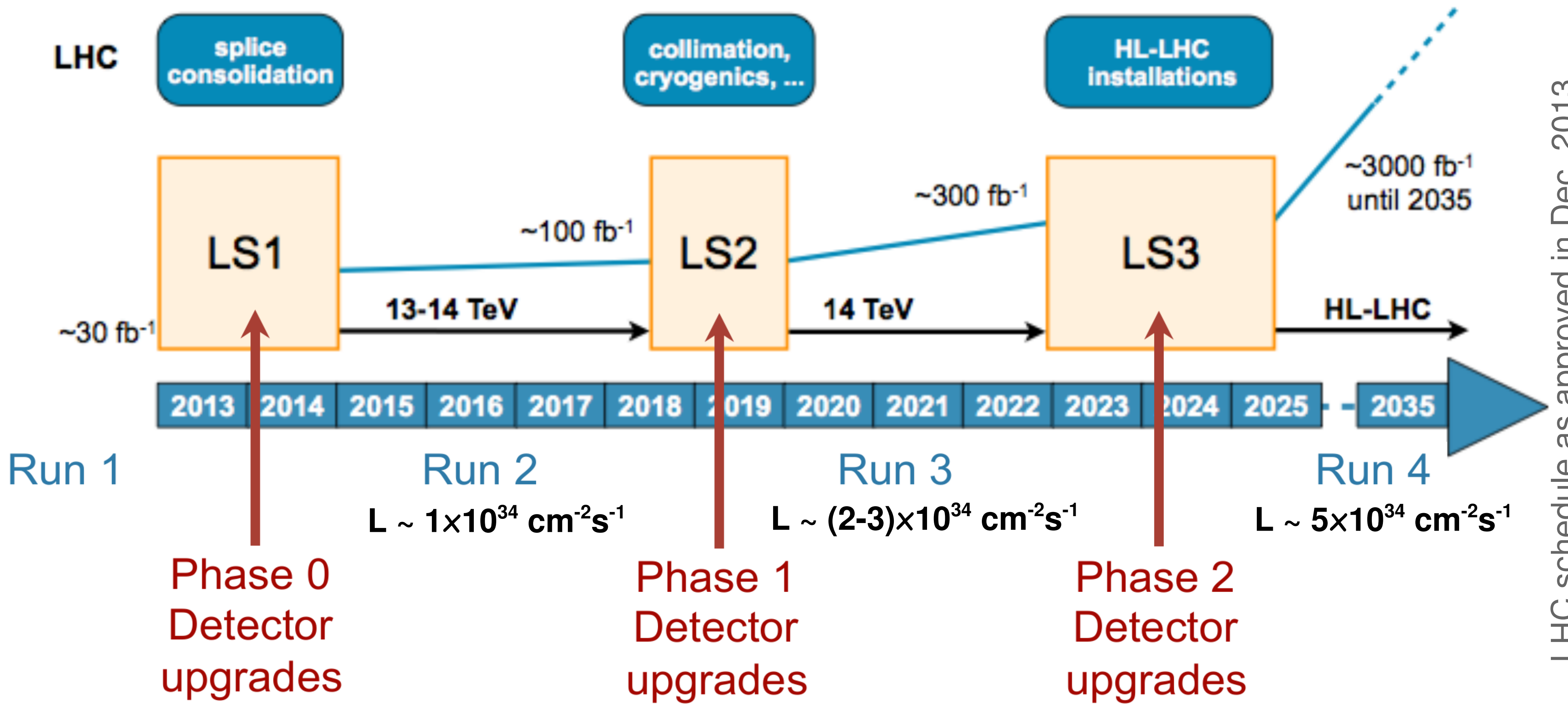
on behalf of the ATLAS collaboration

The LHC Roadmap

- LHC and its experiments are doing very well, providing data at the energy frontier



- $\sqrt{s}$ = 14 TeV, high luminosity & pile-up =>
  - increased detector occupancy; saturation of the bandwidth
  - challenging for triggers to maintain sensitivity to physics
  - increased radiation damage and activation of the materials

B-Physics Programme

- **The B-physics programme in Run 2 and beyond will follow the current Run 1 approach:**
  - Precision measurements and rare processes that most benefit from high integrated luminosity and/or are inaccessible at B-factories. Focus on those with potential in beyond-SM effects
    - $B_s \to J/\psi\phi$, $\Lambda_b \to J/\psi\Lambda$, …, $B_{(s)} \to \mu\mu$, $b \to s\mu\mu$
  - Heavy flavour production at 14TeV
    - B-hadron production x-section, prompt/non-prompt quarkonia production
  - Heavy flavour production in association with other physics objects
    - $W+J/\psi$ etc.
  - Searches for new/exotic states and new decay modes
    - χ_b, B_c decays, $B_c(2S)$
- Trigger still ties us to muonic final states

B-Physics Programme cont.

- The Run 1 of LHC experiments showed: in B-physics a sensitivity to potential effects **beyond SM** is only possible if the measurements are accomplished at unprecedentedly high precision => **need the future LHC Runs**

- To make that possible and keep similar or better performance, we need:
  - **trigger strategies** and
  - **detector upgrades** (namely tracking)

  able to face the harsher environment of the future Runs

- 2nd part of the talk => study of the impact of the detector & trigger changes on $B_s \to J/\psi\phi$ measurement precision

Current ATLAS Detector

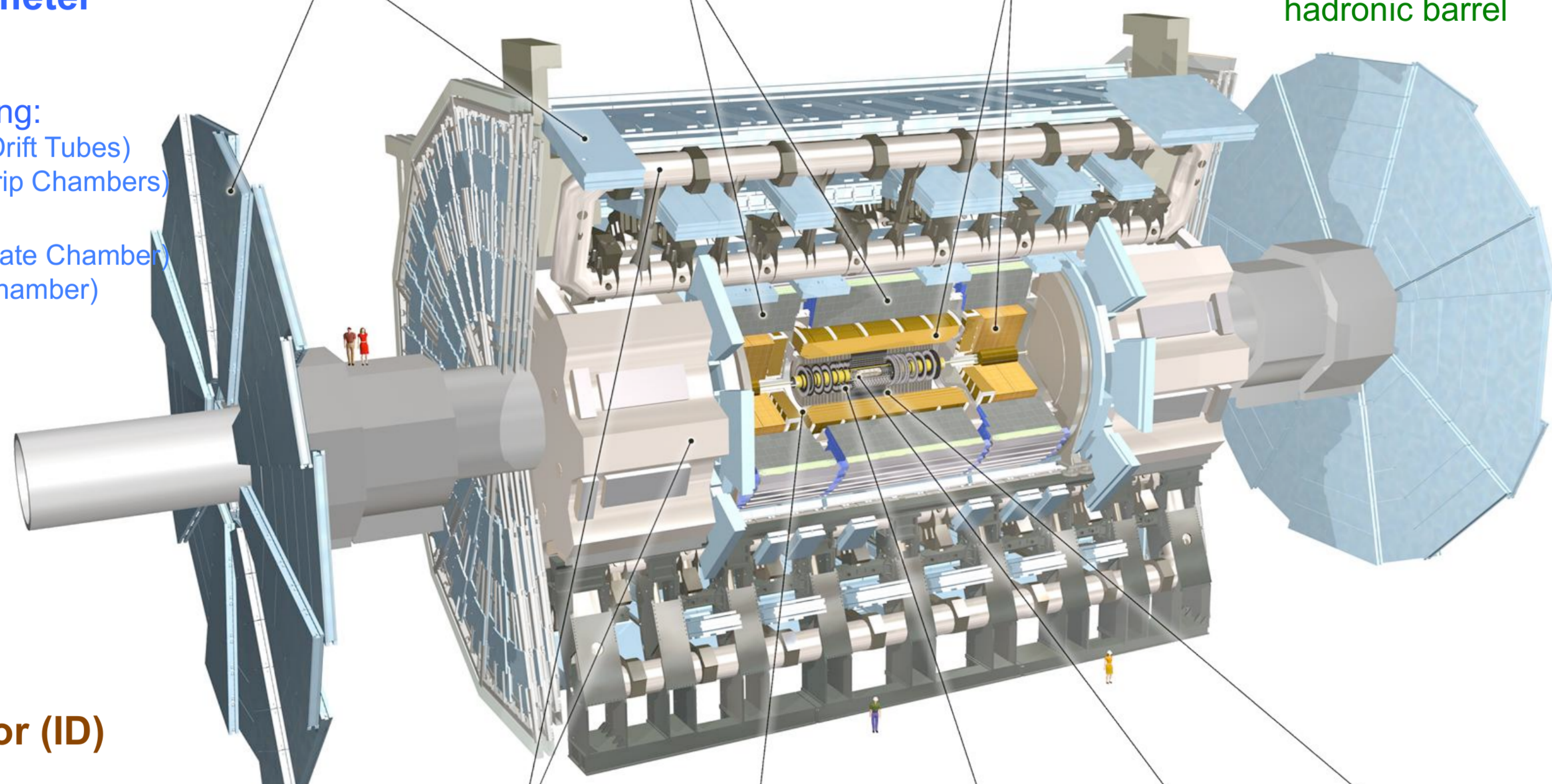
Calorimeter System

EM and Hadronic energy
- LAr EM barrel and EC
- LAr Had. Barrel
- Tile Calorimeter (Fe-Scin.) hadronic barrel

Muon Specrometer

Toroid Magnets
Precision μ tracking:
- MDT (Monitored Drift Tubes)
- CSC (Cathode Strip Chambers)

Trigger:
- RPC (Resistive Plate Chamber)
- TGC (Thin Gas Chamber)

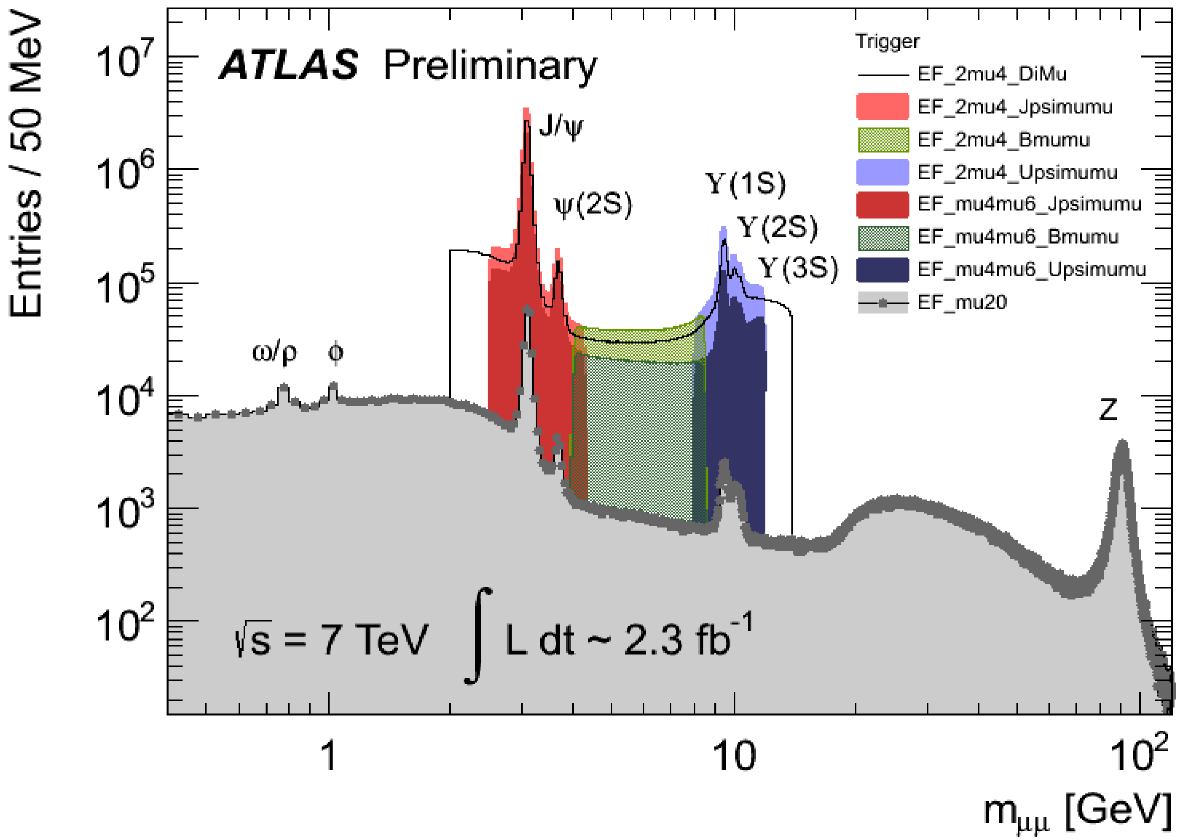


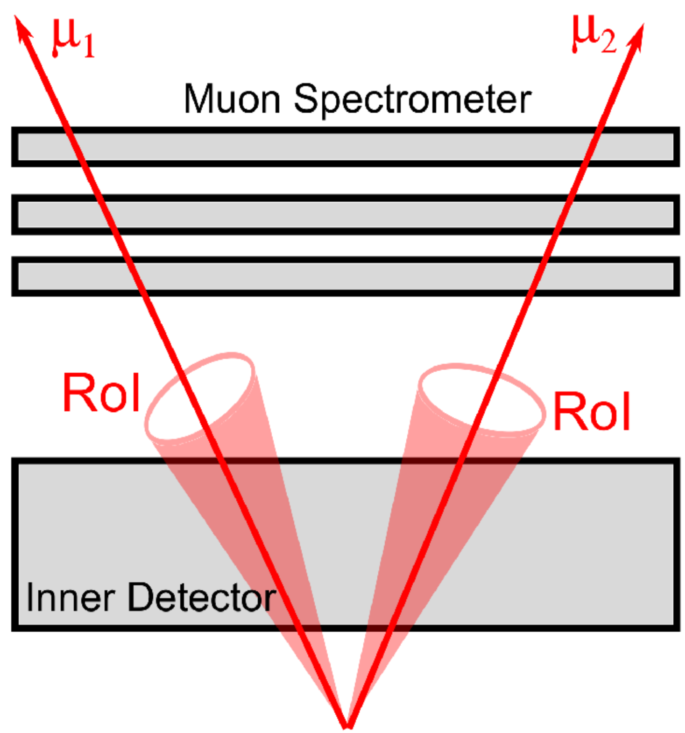
Inner Detector (ID)

Tracking
2T Solenoid Magnet
- Silicon Pixels, 50x400 μm^2
- Silicon Strips (SCT), 80 μm stereo
- Transition Ratiation Tracker (TRT) 36 points/track

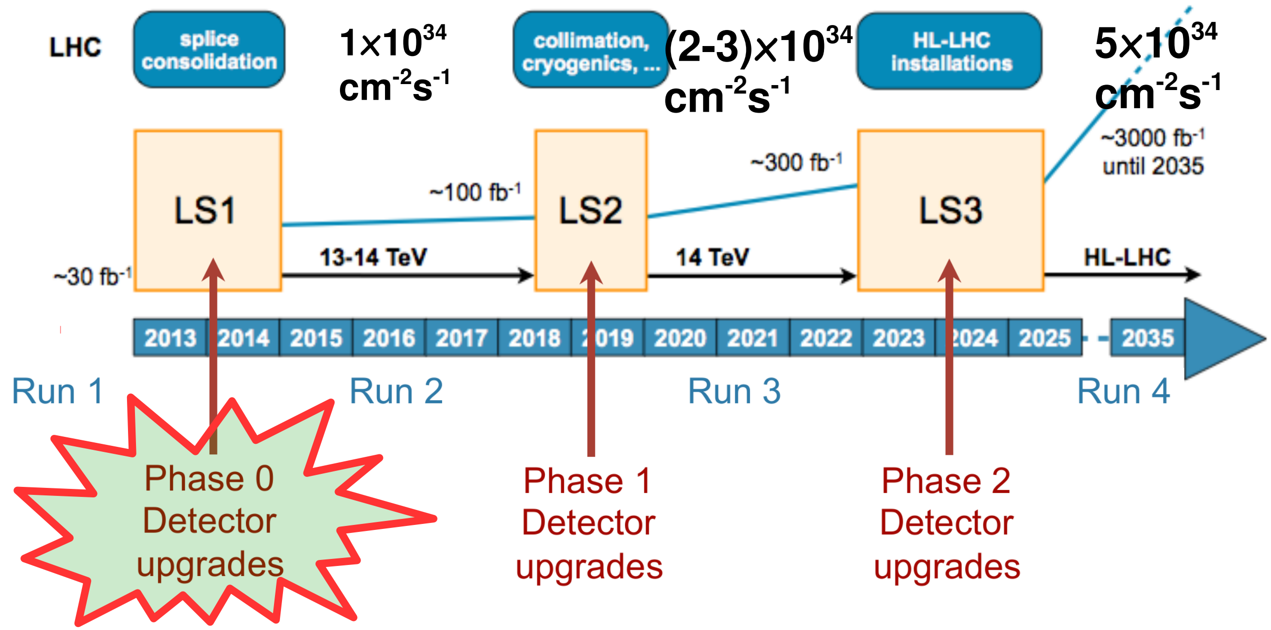
Current (Run 1) B-Physics Triggers

- Mostly based on **di-muon** signature (e/γ or hadronic B-decays lost in background), some analyses using **single-muon** based or **multi-muon** triggers
- Whole trigger chain 3-level based:
  - Level1 (L1) – HW based, fast muon detectors, di-muons with $p_T > 4$ GeV
  - Level2 (L2)/Event Filter (EF) – SW based, precise confirmation of the muons by Inner Detector tracks reconstruction, di-muon vertex construction (inv. mass cut), and possibly search for other hadronic tracks of requested B-decays

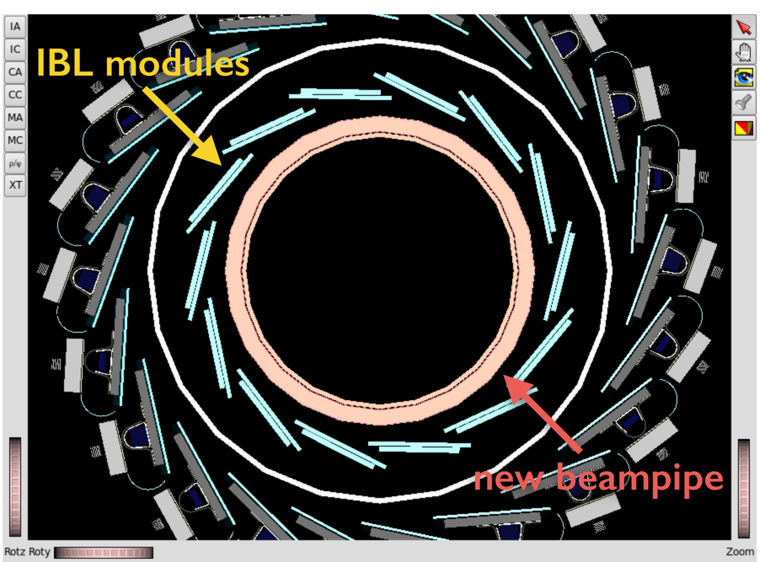




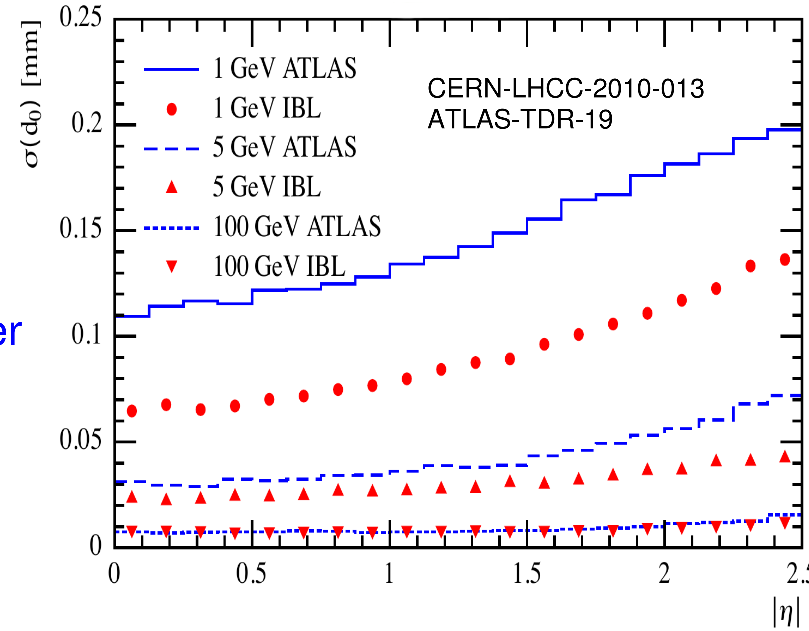
Detector & Trigger Upgrades - Phase 0



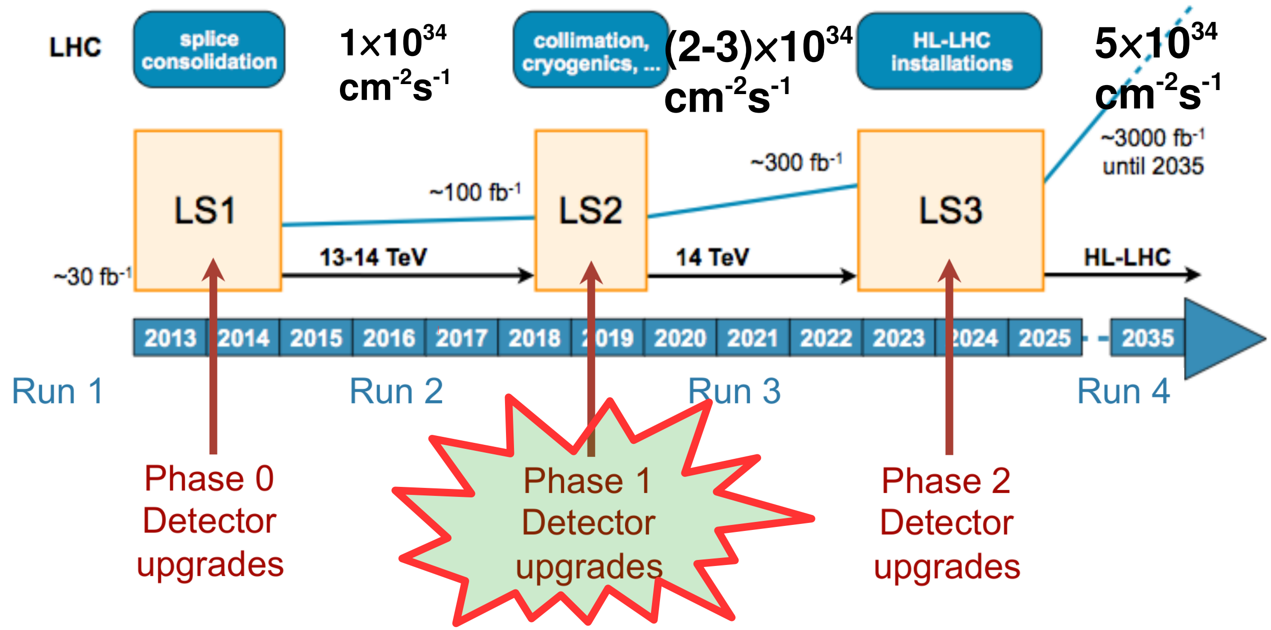
- Long Shutdown (LS) 1 almost over, LHC starts providing physics data in Spring 2015
- **Additional Pixel Layer (IBL)** and Be small radius beam pipe
- **Topological L1 trigger**
- Improved coverage of Muon spectrometer ($1.0 < |\eta| < 1.3$)
- Diamond Beam Monitor, consolidation of some parts of the detector (cooling etc.)



- Small radius (32-38 mm; current B-layer at 50.5 mm), small material budget
- 4[th] pixel layer => more robust track reconstruction, better impact parameter d_0 and z_0 resolution
- Better θ and ϕ resolution at low $p_T \sim 1$ GeV



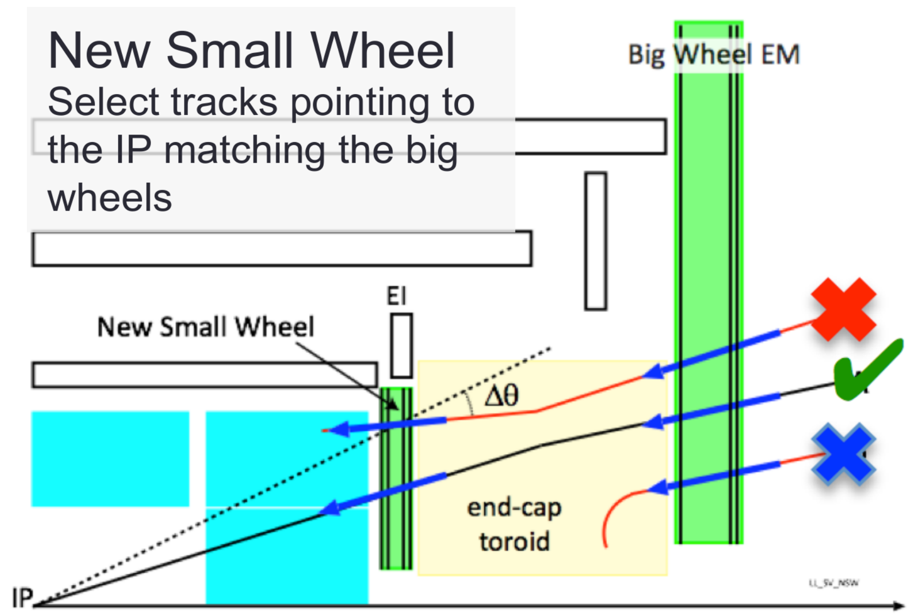
Detector & Trigger Upgrades – Phase 1



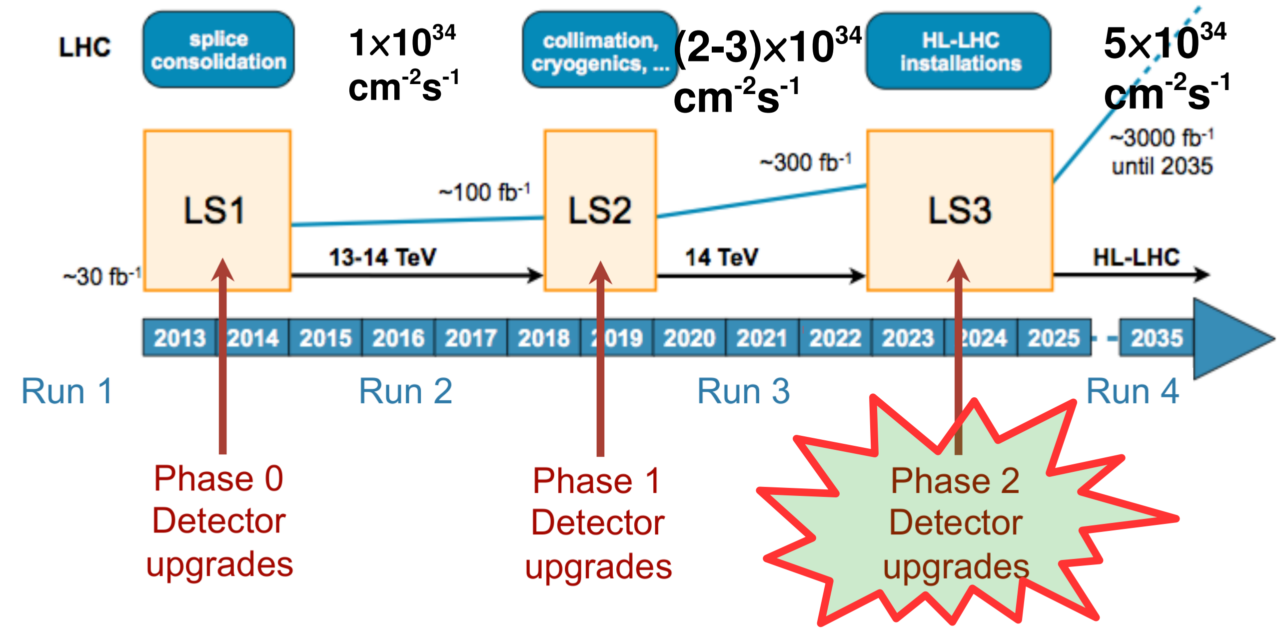
- Goal: no loss of performance when going above LHC nominal luminosity
- **New small muon wheel**
- **New fast-tracking (FTK) at trigger level 1.5. Gradually implemented already during Run 2**
- Higher granularity and precision L1 trigger for calorimeter
- TDAQ improved performance

Fast tracking trigger:

- HW based track finder in the Inner Detector silicon layers at "offline precision"
- Provides tracks already before the L2 trigger (first SW based trigger layer)
- Two-step processing: hit pattern matching & subsequent linear fitting in FPGAs

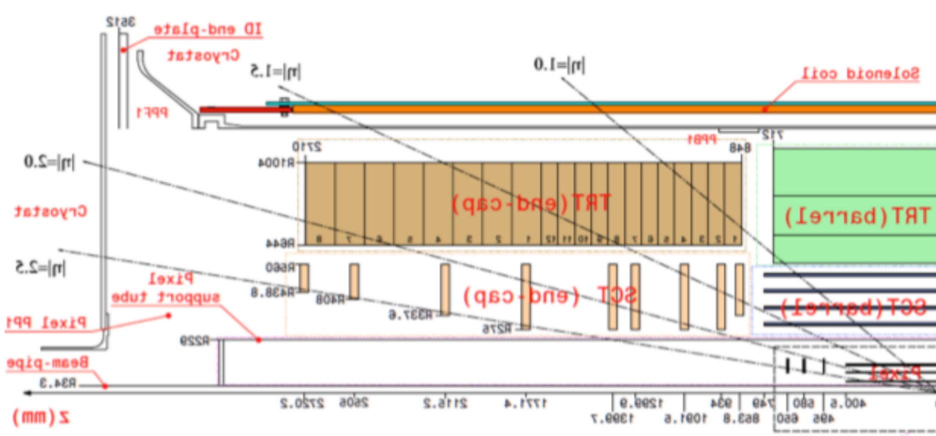


Detector & Trigger Upgrades – Phase 2

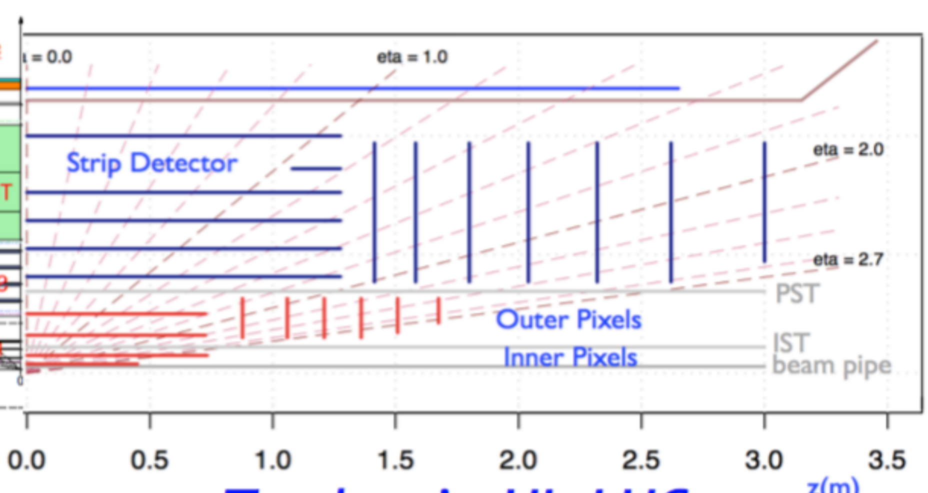


- Goal: maintain/improve performance despite high lumi.
- **Completely new Si based tracking (ITK)**
- New trigger system – possibly will include HW-based L1 track trigger
- Full granularity calorimetry information
- Upgrade part of the muon systems, fast trigger

Phase 2 Inner Tracker: current ID will become inefficient due to radiation damage; too high occupancy in TRT; high granularity (~4× better) required to cope with high pileup (~up to 200)



ATLAS Today



Tracker in HL-LHC

Triggering B-Physics in Run 2 and Beyond

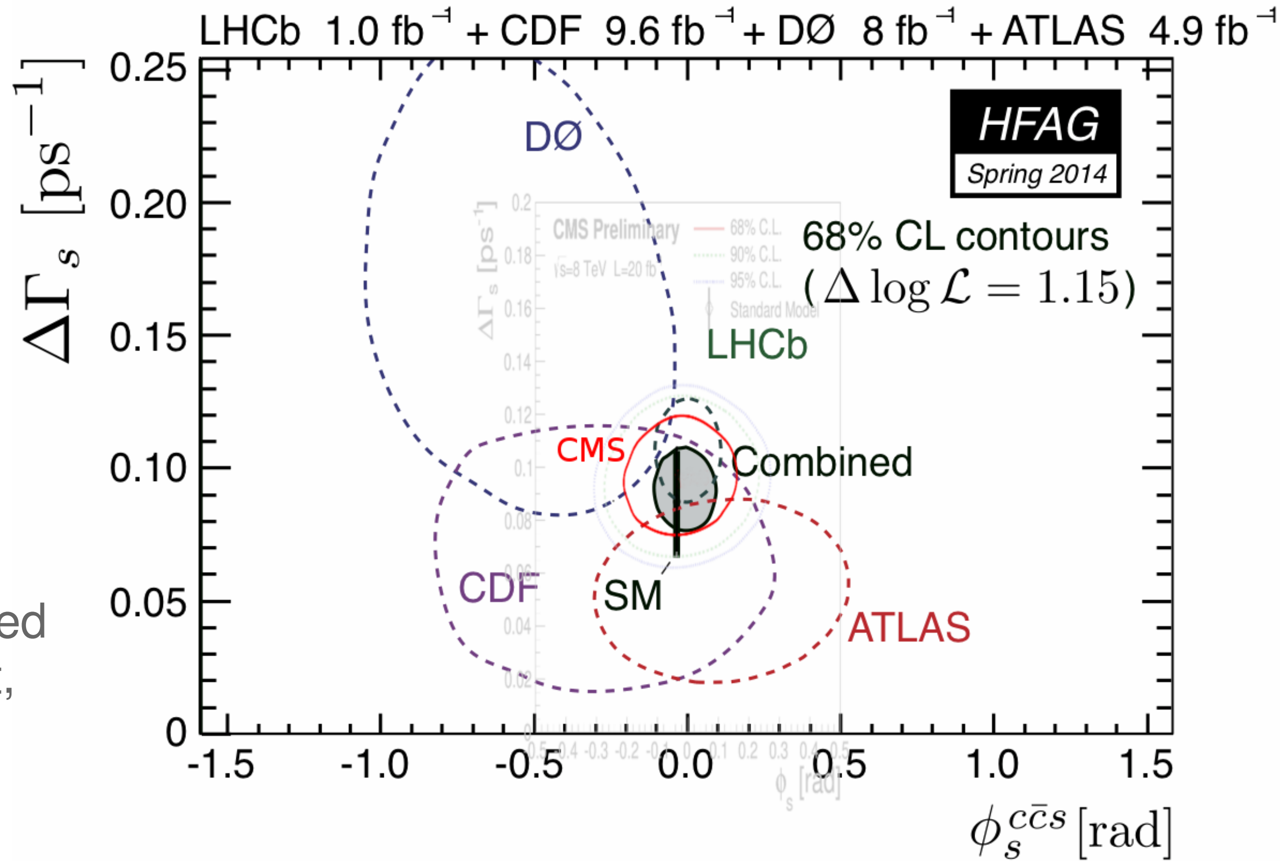
- Triggers remain based on single/di/multi-muon signatures, but can be combined with other objects (e.g. hadronic tracks)
- The rates of the passing events needs to be within the limits of the trigger system at each stage:
  - Run 1: the total maximum output rates from the L1, L2 and EF: 75 kHz, 6-7kHz, 400 Hz
- Run 1 limitations on B-physics triggers mainly from the restriction on the L1 rate
- In upcoming runs, both HW-based L1 and SW-based L2+EF will have to be tightened to fit within the allowed limits
- Level 1 trigger rate control:
  - Increasing the **muon p_T thresholds** or **barrel-only** events (Run 1 approach) $\rightarrow$ significant signal loss
  - In future runs, additional **topological selections** will be possible at HW level, (rough selections based on di-muon opening angle or invariant mass)
- Level 2 trigger & Event Filter rate control:
  - The available tools allow offline-analysis like selections. Can thus reconstruct complicated objects (**whole B-decay trees**) and make selections based on that
  - CPU resources will be saved by the **Fast Tracking Trigger**

Future Potential for CPV Measurement in $B_s \rightarrow J/\psi\phi$ Decay

ATL-PHYS-PUB-2013-010
(prepared for ECFA High Luminosity LHC Experiments Workshop in 2013)

Physics Motivation

- Latest 2D sensitivity plot: CPV phase ϕ_s w.r.t. $\Delta\Gamma$ – full Tevatron data and the LHC measurements:
  - LHCb (1 fb^{-1}),
  - ATLAS (4.9 fb^{-1}),
  - CMS (20 fb^{-1})
    - fresh result, superimposed on the official HFAG plot, not included in the combination



- ATLAS result 3rd best. Analysis on the way for 8TeV data with 4x bigger statistics
- Measurements consistent with SM so far, but the SM ϕ_s = -0.0368 ± 0.0018 with very small uncertainty → any deviation would prove effects beyond SM
- LHC experiments will need Runs 2,3 and HL-LHC phase to achieve this sensitivity

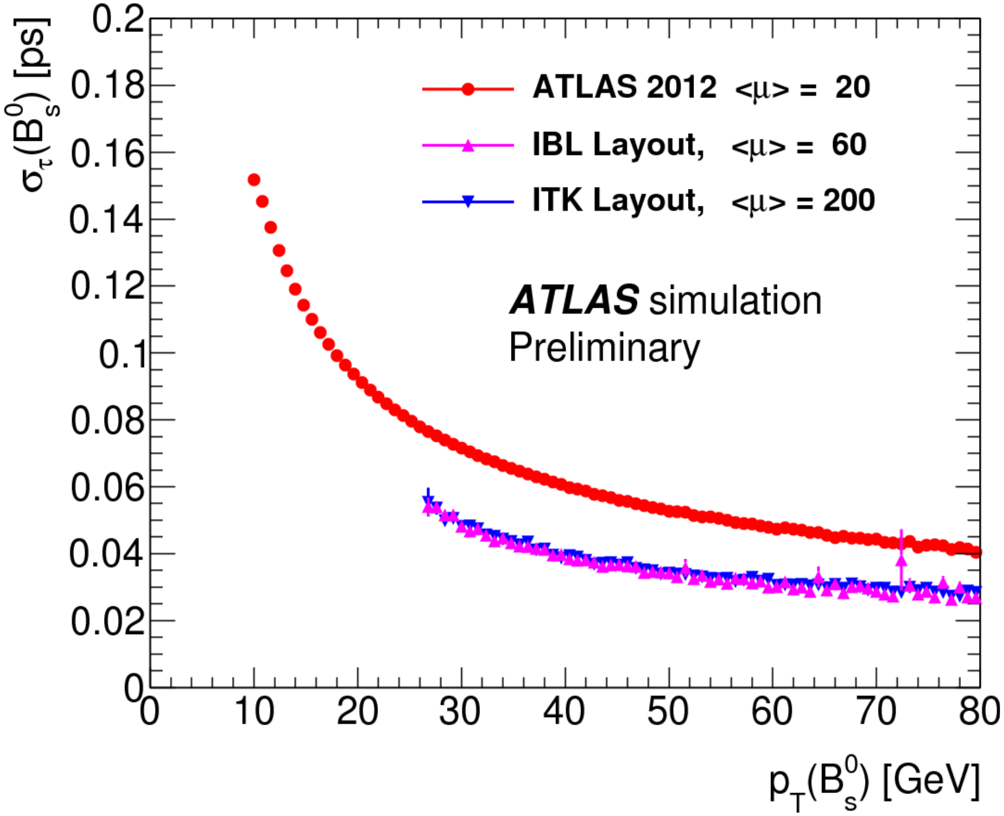
Potential for Run 2,3 and HL-LHC

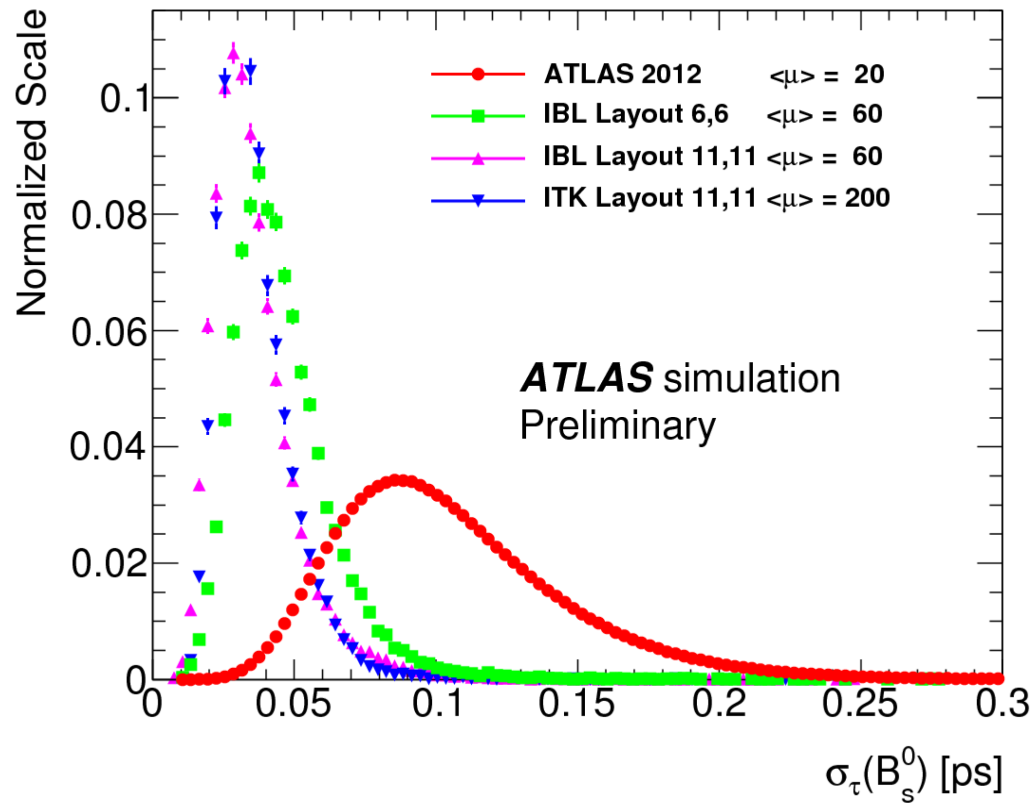
- Key factors with new detectors and high luminosity:
  - Lifetime precision: namely time resolution σ_τ – with new Inner Detectors
  - Performance stability in high pileup
  - Statistics: efficiency decrease is unavoidable; higher trigger thresholds, stronger track selections. Compensation: bigger cross-section at 14 TeV (~2 times) and high integrated luminosity at HL-LHC

Process	MC cuts	Geometry	$<\mu>$	MC events
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 3.5$ GeV	2012	20	$40 \cdot 10^6$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 6$ GeV	IBL	60	$50 \cdot 10^3$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 11$ GeV	IBL	60	$50 \cdot 10^3$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$	$p_T(\mu^\pm) > 11$ GeV	ITK	200	$50 \cdot 10^3$

  - Future ATLAS J/ψ trigger not finalized yet, however having reasonable working model: MC events simulated with di-muon thresholds:
    - p_T **6+6 GeV** or **11+11 GeV** for Run 2
    - p_T **11+11 GeV** for Run 3 and HL-LHC

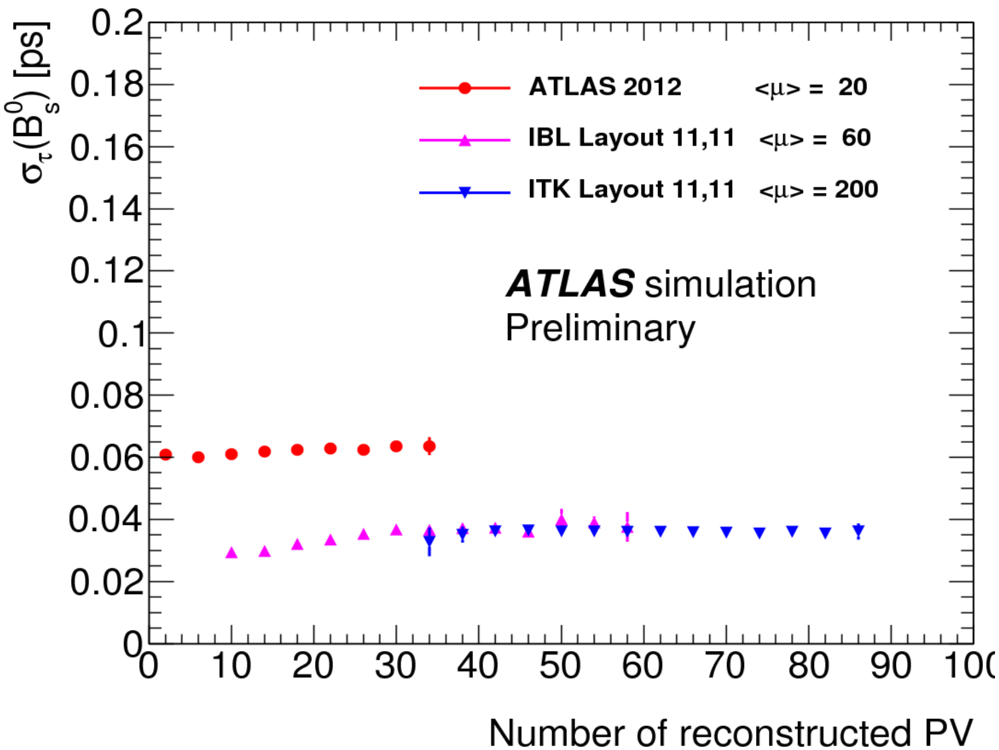
Time Resolution: ITK, IBL w.r.t Run 1

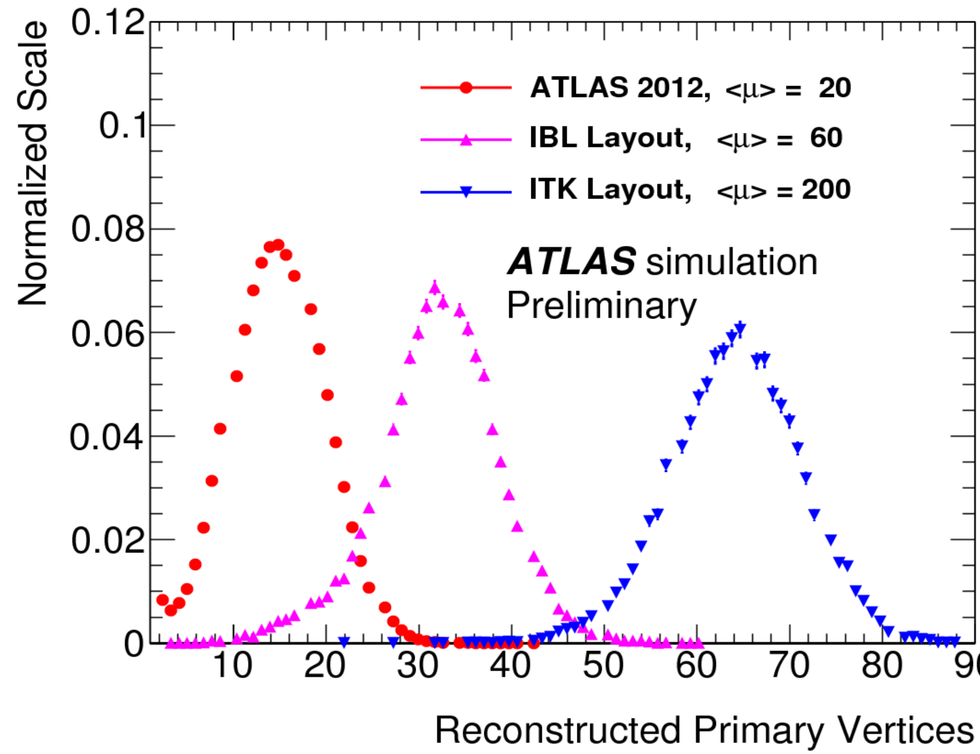




- Time resolution is important for precise measurement of CPV of fast oscillating B_s mesons
  - in 2011 data taking the LHCb $\langle\sigma_\tau\rangle$ ~40 fs^{-1}, ATLAS $\langle\sigma_\tau\rangle$ ~100 fs^{-1}
  - with equal statistics @ 2011: LHCb $\sigma(\phi_s)$ = 0.10 rad, ATLAS $\sigma(\phi_s)$ = 0.25 rad
- New ID layouts IBL and ITK improve σ_τ by factor of 30% compared to Run 1 performance (for the same p_T values)
- Higher p_T in future runs improves further σ_τ and signal purity on the account of lower efficiency

Time Resolution: Stability with #PV





- Concern: time resolution σ_τ may deteriorate with increasing number of primary vertices (#PV)
  - B_s decay time $\tau = L_{xy}M_B/p_T(B)$ where L_{xy} is displacement in xy plane of B_s vertex from PV
  - Best PV candidates chosen by a minimal 3D distance of $p_T(B)$ direction vector to PV
- Run 1: 8TeV (2012 data): high resolution σ_τ was low ~100 fs and dominated by material due to low p_T $\rightarrow$ σ_τ not sensitive to #PV
- IBL and ITK: high resolution σ_τ ~ 35 fs and also higher p_T used $\rightarrow$ σ_τ slightly grows (by ~14%) between #PV 10-40; then with ITK layout σ_τ becomes stable over all #PV range 40-90

Precision on CPV Phase ϕ_s from MC

	2011 *)	2012	2015-17		2019-21	2023-30+
Detector	current	current	IBL		IBL	ITK
Average interactions per BX $<\mu>$	6-12	21	60		60	200
Luminosity, fb^{-1}	4.9	20	100		250	3 000
Di-μ trigger p_T thresholds, GeV	4 - 4(6)	4 - 6	6 - 6	11 - 11	11 - 11	11 - 11
Signal events per fb^{-1}	4 400	4 320	3 280	460	460	330
Signal events	22 000	86 400	327 900	45 500	114 000	810 000
Total events in analysis	130 000	550 000	1 874 000	284 000	758 000	6 461 000
MC $\sigma(\phi_s)$ (stat.), rad	0.25	0.12	0.054	0.10	0.064	0.022

- *) 2011 **Toy-MC fit driven by** 2011 **data**, result is consistent with real 2011 data analysis (arXiv:1407.1796, W. Dearnaley talk on Monday), background estimates from **2012 data sidebands**
- 2012 is also a result of Toy-MC model, driven by 2012 data
- Muon p_T thresholds 11+11 GeV substantially (7x) decrease number of signal events per fb^{-1} w.r.t. 6+6 GeV thresholds
- Hence a potential in Runs 2 and 3 would depend on muon trigger thresholds applied
- Two given ϕ_s precision values for Run 2: **0.054 rad** (11+11 GeV) and **0.10 rad** (6+6 GeV) represent an optimistic and a rather conservative options

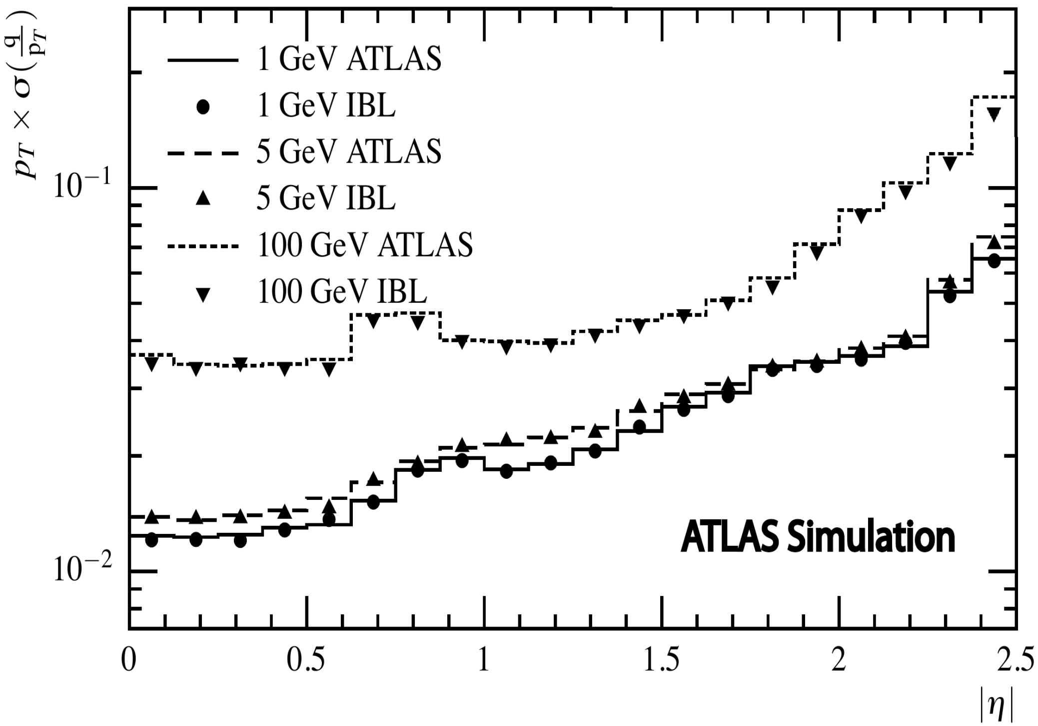
Conclusions

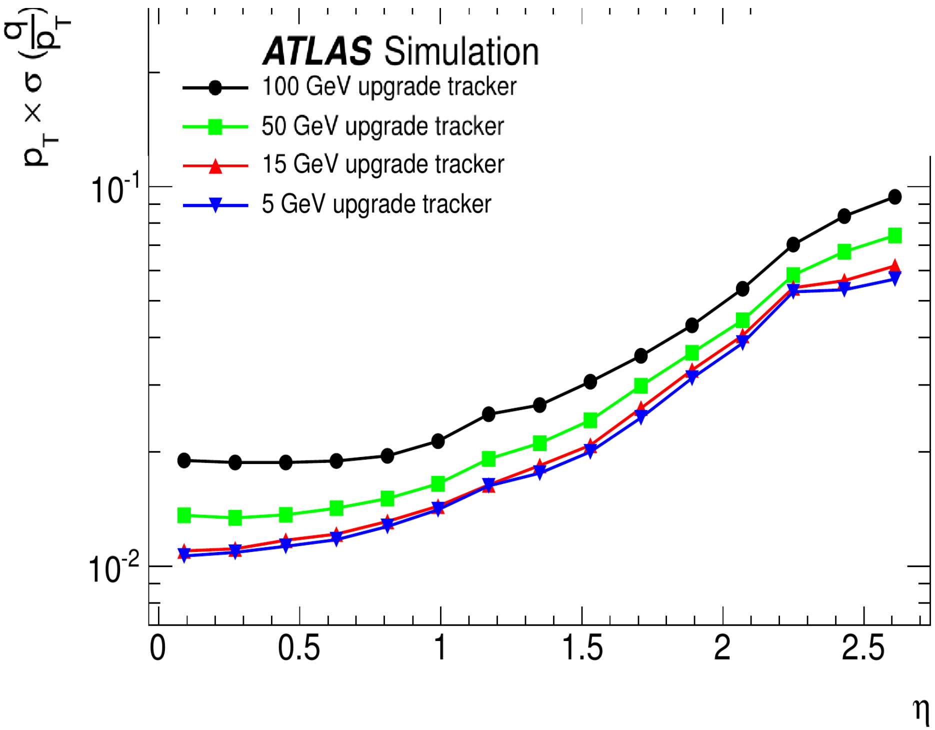
- ATLAS will continue its B-physics program in the Run 2,3 and the HL-LHC era, focusing on precision measurements, rare decays and heavy flavour production and spectroscopy
- Detector upgrades (namely in **tracking** and **muon system**) and new **trigger strategies** and tools will help to cope with the high-luminosity environment and achieve precision needed to examine possible beyond-SM effects in the heavy-flavour production and decays
- Pilot study of $B_s \to J/\psi\phi$ CPV analysis:
  - shown improvements in the precision coming from the tracking detectors upgrade (already those for Run 2)
  - demonstrated strong dependence of the precision on the trigger thresholds/configurations
  - indicated weak effect on the analysis by the expected pile-up conditions in future LHC Runs

Backup

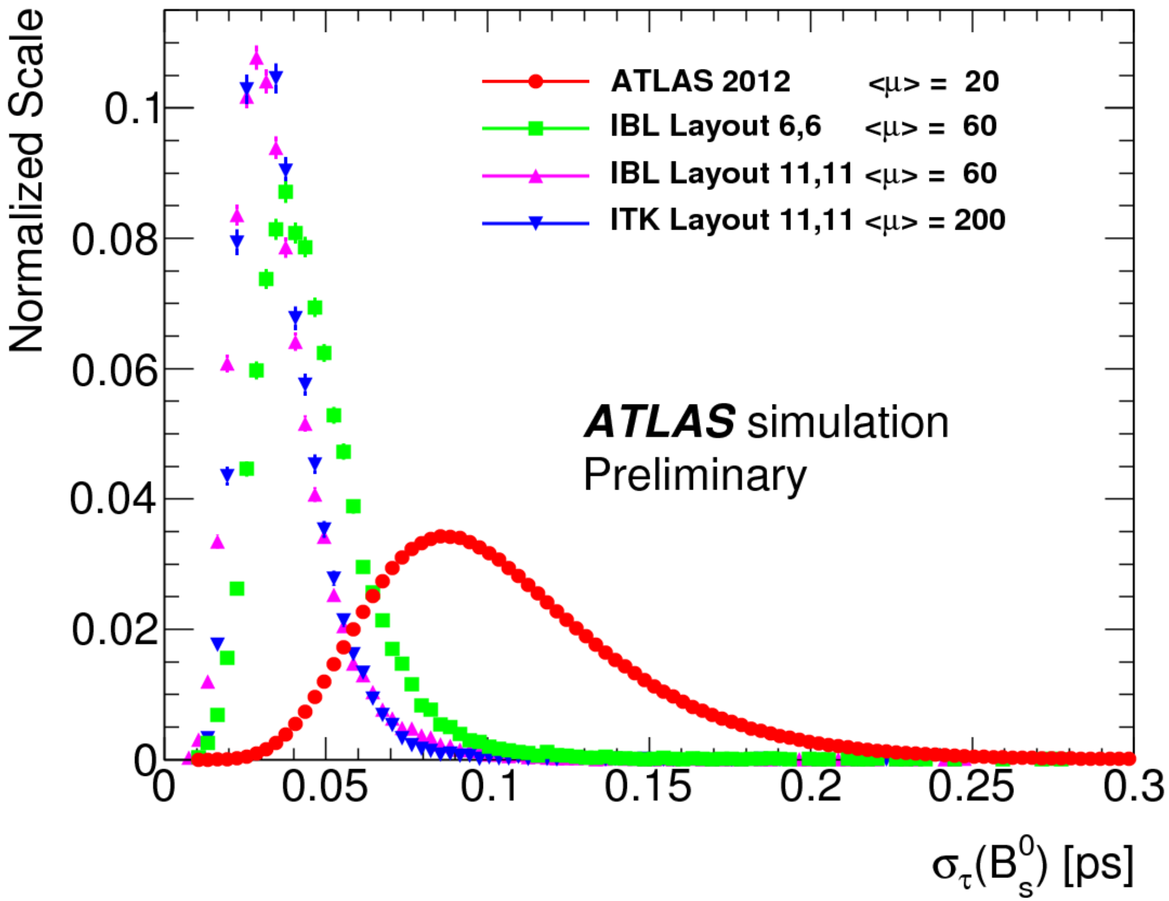
IBL & ITK p_T Resolution

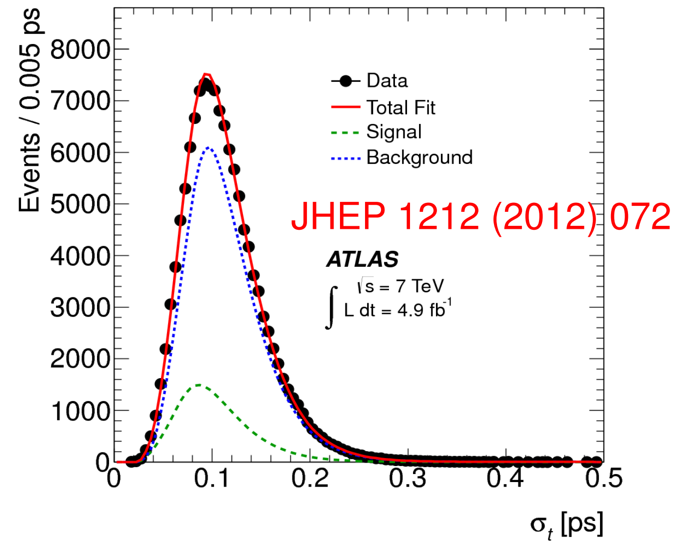
CERN-LHCC-2012-022 ; LHCC-I-023

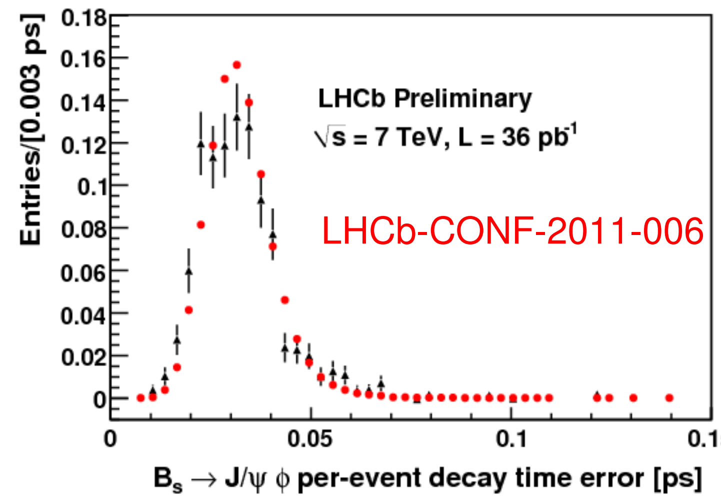




Time Resolution: ITK, IBL w.r.t Run 1







- Improvement of an average time resolution $\langle\sigma_\tau\rangle$ in future runs will also be connected with increased p_T thresholds
- On the other side, the increase of the thresholds will reduce efficiency with improved trigger purity

Measurement Precision Using Toy-MC

- Performance parameters extracted from fully simulated signal events were used as input to Toy-MC to estimate precision on physics parameters of the B_s decay
- Background full simulation not done (too high rejection), so background properties derived from mass-sidebands of 2012 data; for future layouts after applying muon $p_T > 6$ GeV or $p_T > 11$ GeV cuts
- Generated Toy-MC events were then fit by the same program as used for real data
- Toy-MC model was validated against 2011 data conditions and the results on sensitivity to physics parameters found consistent with real data analysis