HL-LHC and B Physics with the ATLAS detector

Adam Barton on behalf of ATLAS

Beauty 2020

Motivation for High Luminosity-LHC

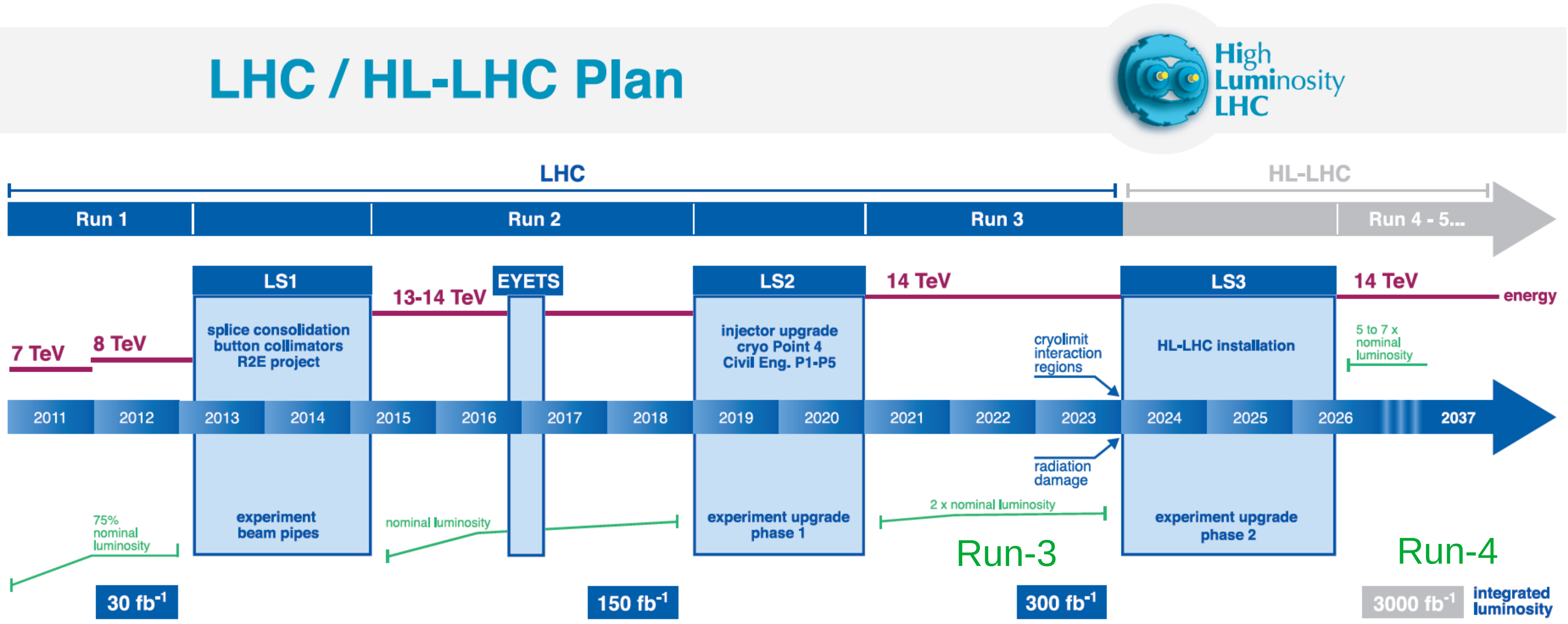
- LHC Experiments started data taking in 2010, since then much has been achieved:
  - Higgs Boson was discovered in 2012
  - Several rare decays discovered (e.g. $B_s \rightarrow \mu^+\mu^-$)
  - Measurements of CP violation in B sector
    - No violations of the standard model yet
- Puzzles remaining:
  - Dark Matter
  - Supersymmetry
  - Flavour or CP anomalies

LHC development

- The LHC is already running at L peak = 2.06 x 10 34 $cm^{-2}s^{-1}$. Which is 2x the design specification
  - In run 3: probably only linear improvements
- E_{CMS} = 14 TeV is expected for Run 3. Which is the full design specification

HL-LHC Timeline and Core Parameters

[CERN-2017-007-M]

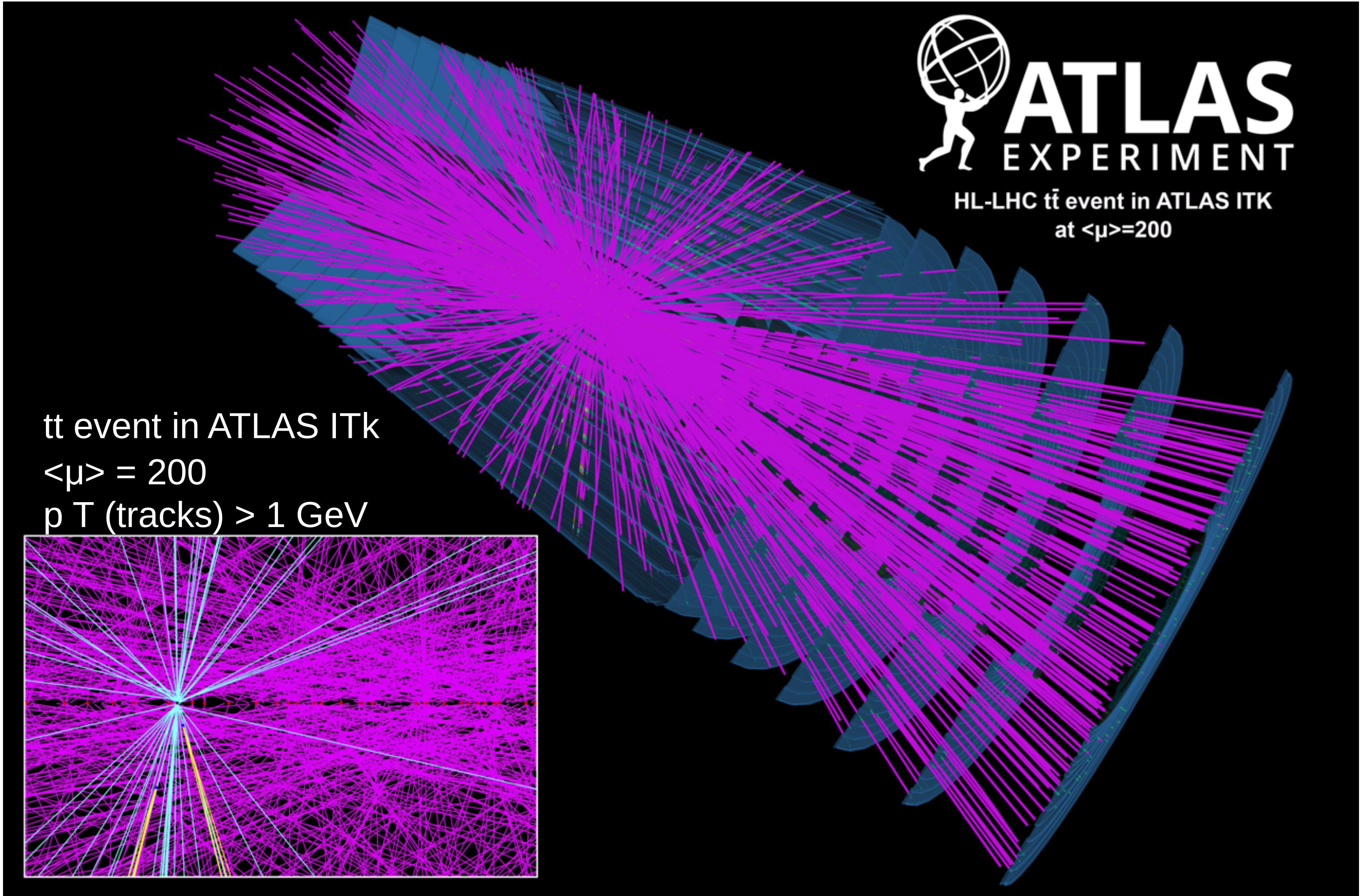


Run-4 aims to have 10x the luminosity of run-3 with peak luminosity between 5 and 7.5 x 10^{34} $cm^{-2}s^{-1}$

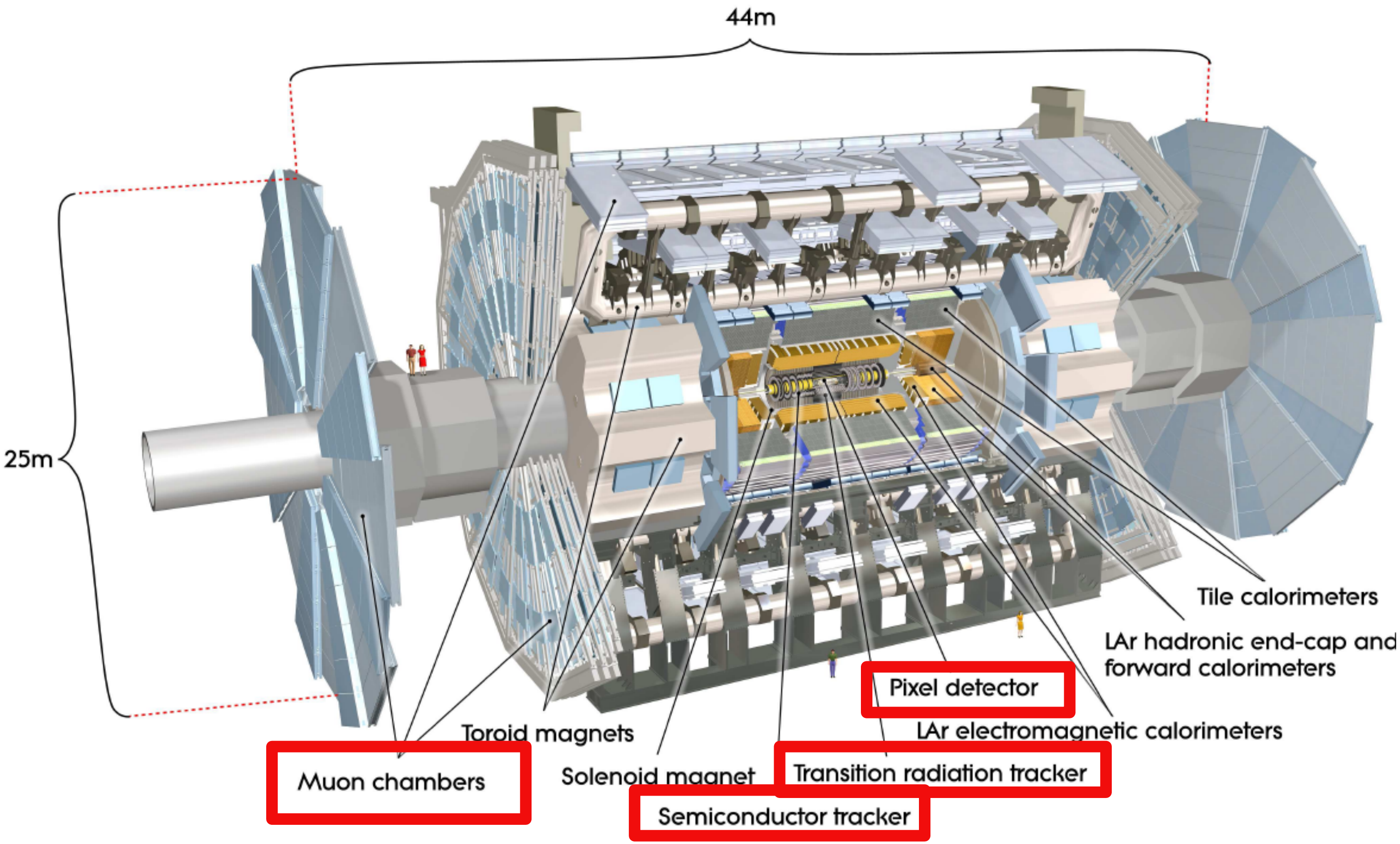
<μ> = 140 ... 200 pp interactions, every 25 ns

High pile-up and event rates, need upgraded detectors

tt event in ATLAS ITk
<μ> = 200
p T (tracks) > 1 GeV



A Toroidal LHC ApparatuS (ATLAS)



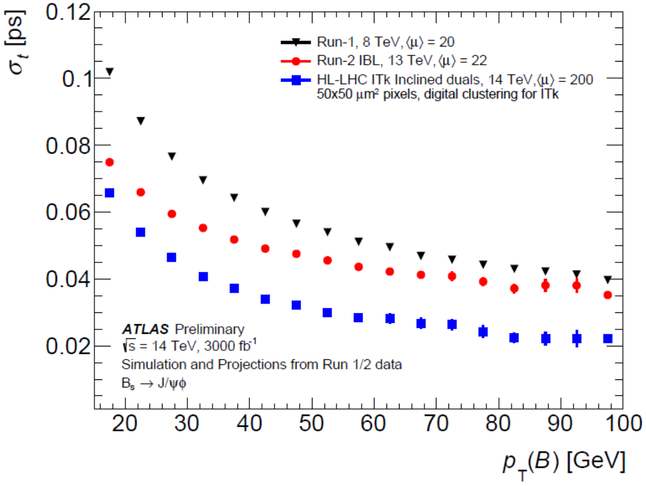
ATLAS Upgrade Program

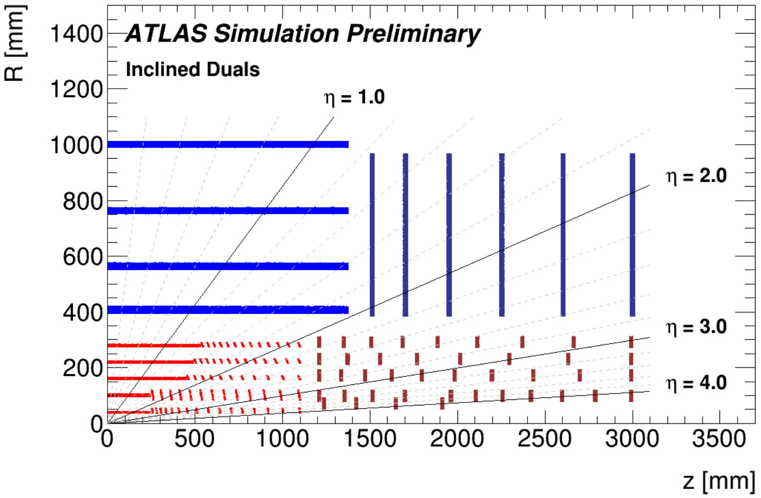
System	Phase0/ run 2	Phase 1/run 3	Phase 2 / run 4
Pixel	IBL at R=34 mm, new cooling, new services		Replaced by ITk pixel
SCT			Replaced by ITk strips
TRT			Decommissioned
Lar + Tile	New power supplies	New L1 trigger electronics	New readout electronics (input to L0Calo), 40 MHz streaming, High Granularity Timing Detector (HGTD)
Muon	Gas leak repairs	BMG and BIS78 detectors in acceptance gaps New small wheel detectors	New chambers in inner barrel Replace front-end electronics
Trigger	New L1Topo, Upgraded CTP, Partial FTK L2 + EF → HLT	New FEX, New muon-CTP interface HLT: multi-threading, offline-like algorithms	L0 (Calo, Muons) 1 MHz, 10 μs latency optional: L1 (L0 at 4 MHz, L1Track) 800 kHz, 35 μs latency

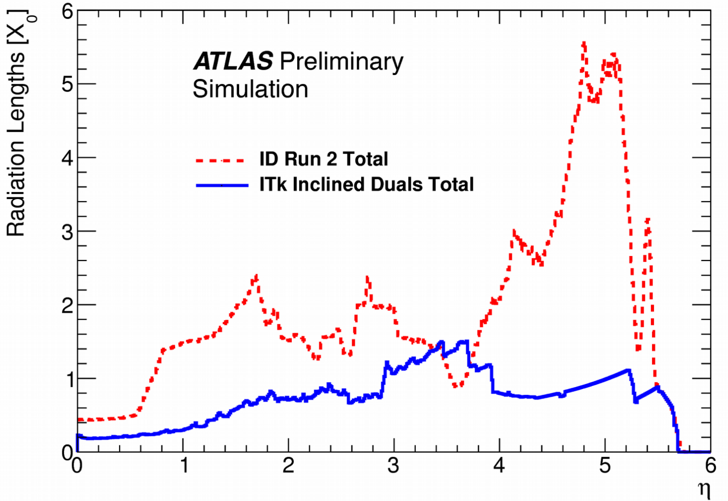
[LHCC-I-023, CERN-LHCC-2015-020]

ATLAS Inner Tracker (ITk) Upgrade

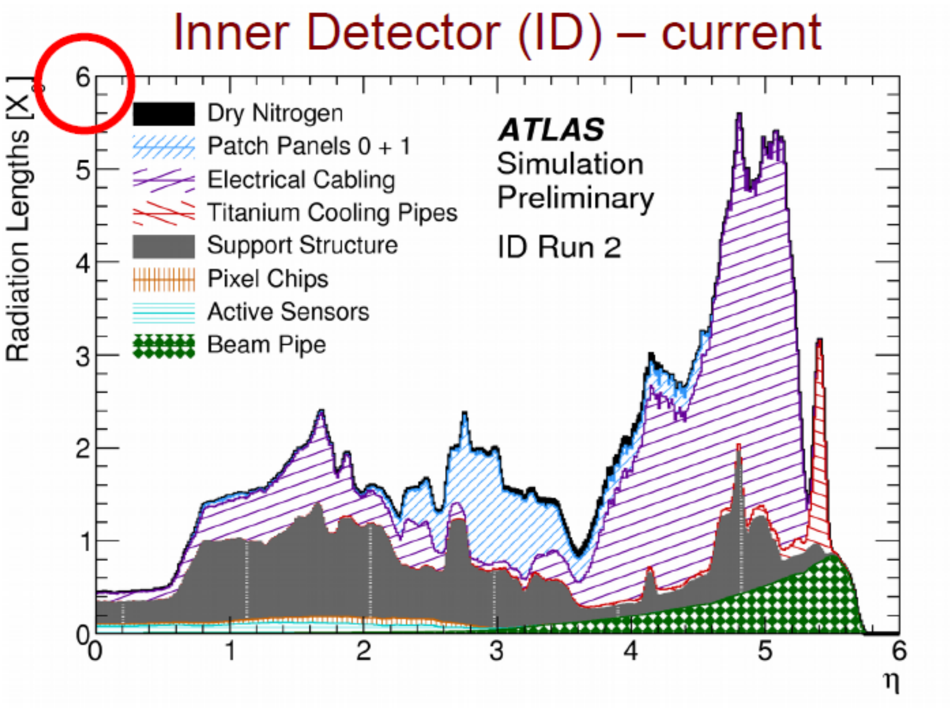
- New all-silicon detector:
- ITk pixel (13 m^2):
  - Eta max = 4.0 (now 2.5)
  - 5 barrel, 5 EC layers (with rings)
  - Innermost layer at 36mm
  - ~580 M channels (80 M now)
- ITk strips (160 m^2):
  - 4 barrel layers, 6 EC rings
  - ~ 50 M channels (6 M now)
  - Strip occupancy < 1%
- The ITk has considerably less material than the existing detector leading to:
  - Improved tracking efficiency
  - Better mass resolution

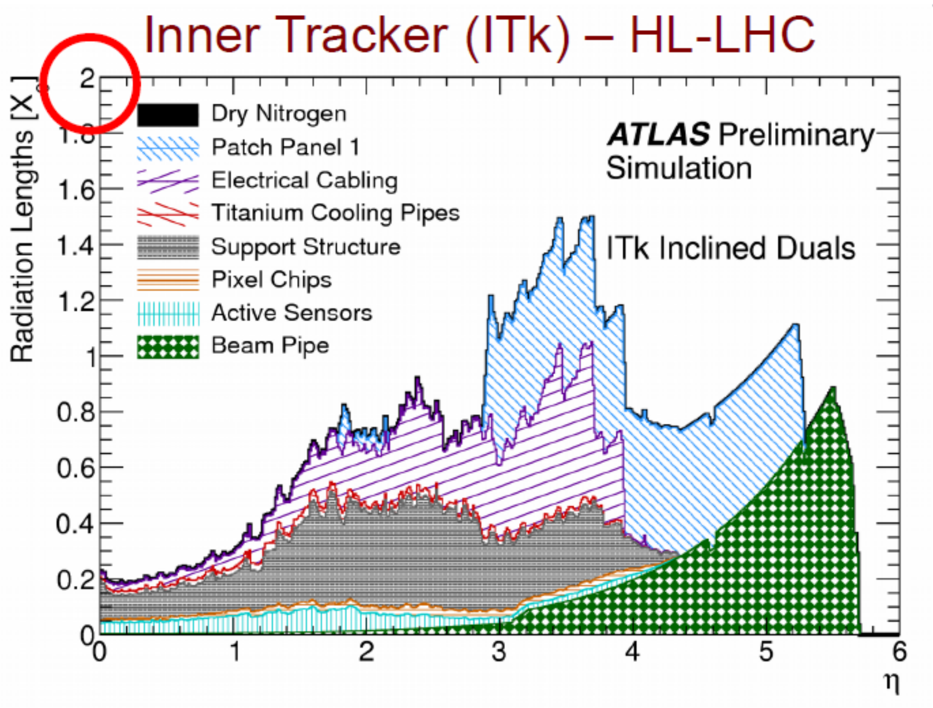






ATLAS ID and ITk Material Budgets



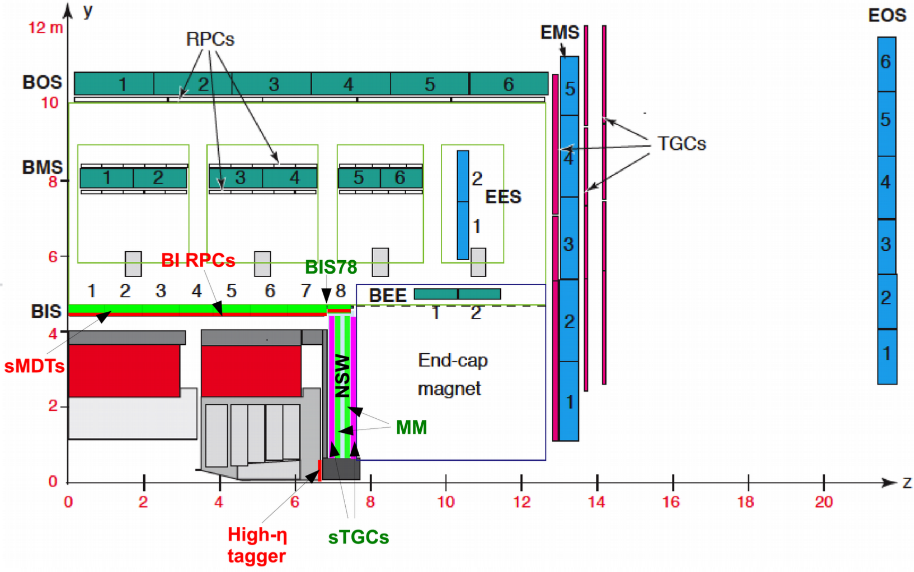


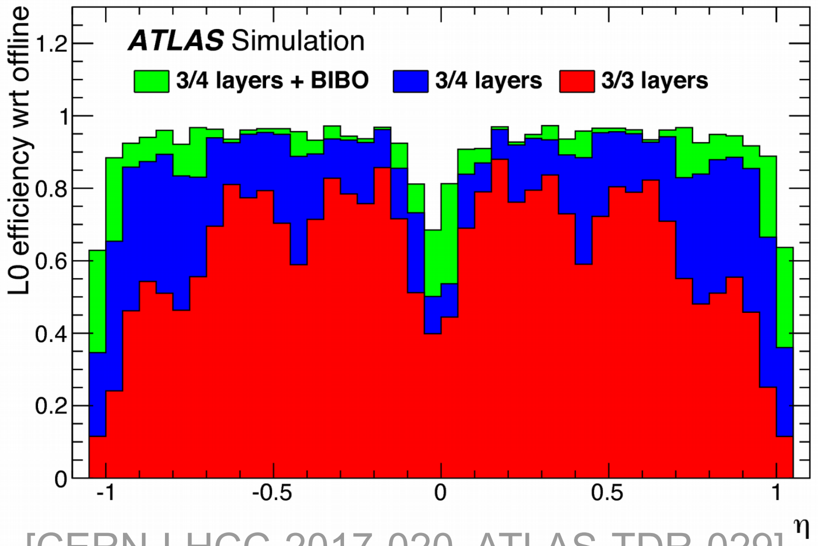
Material budget of ITk is greatly reduced.

[CERN-LHCC-2017-017, ATLAS-TDR-026]

ATLAS Muon System Upgrade

- New Small Wheel (NSW):
  - Small trip Thin Gap Chambers (sTGC) – Fast L1 trigger
  - MicroMegas (MM) – precision muon tracks
  - Covers 1.3 < |η| < 2.7 – reduce fake rates
- New inner barrel (BI) RPCs:
  - L0 triggers acceptance for combined muons |η| < 1.05 increases 78% → 96%
  - Improves worse case (reduced RPC HV) from 57% - 75% → 92%



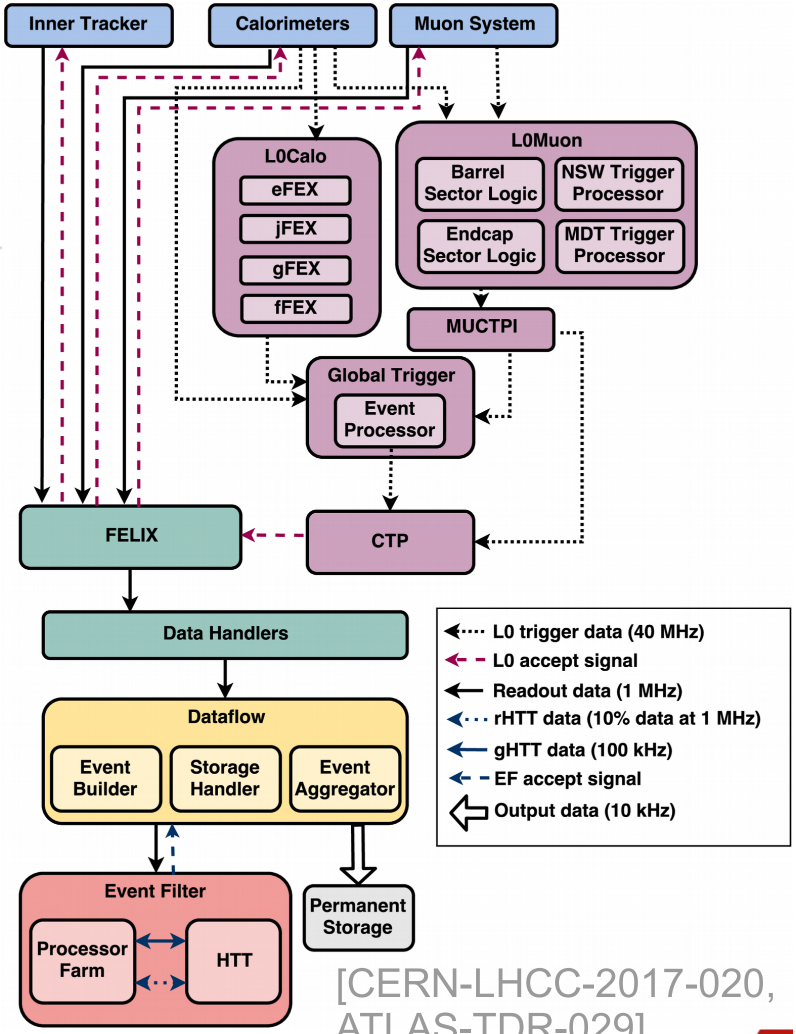


[ATLAS-PUB-2016-026]

[CERN-LHCC-2017-020, ATLAS-TDR-029]

ATLAS Trigger and Data Acquisition Upgrades

- L0 trigger – A hardware trigger based on calorimeter and muon information
  - MDT precision available
  - Global event processor refines objects
  - 1 MHz rate at 10 μs latency
- Possible Dual L0/L1 trigger
  - 4 Mhz at 10 μs latency
  - Suppresses pileup
- Data Acquisition, new Front End link eXchange (FELIX) and storage Handler
- Event Filter: Hardware Track Trigger (HTT) 400 kHz then HLT software 10 kHz



[CERN-LHCC-2017-020, ATLAS-TDR-029]

B-Physics HL-LHC Prospects at ATLAS

- Makes use of high luminosity to make precise measurements or find rare processes
  - Improved lifetime and mass resolution can be exploited
  - Rare processes require complex trigger strategies
- Lepton Flavor Violation (LFV) and Lepton Flavor Universality (LFU)
- Heavy flavor production
  - B-hadron, Quarkonia production to test QCD predictions
  - Heavy Flavour in association with other objects (double quarkonia, double parton scattering)
  - Searching for exotic states or new decay modes B_c decays, $B_c(2S)$, heavy baryons, tetra/pentaquarks

$B_s^0 \rightarrow J/\psi\phi$
$\Lambda_b^0 \rightarrow J/\psi\Lambda^0$
$B_s^0 \rightarrow \mu^+\mu^-$

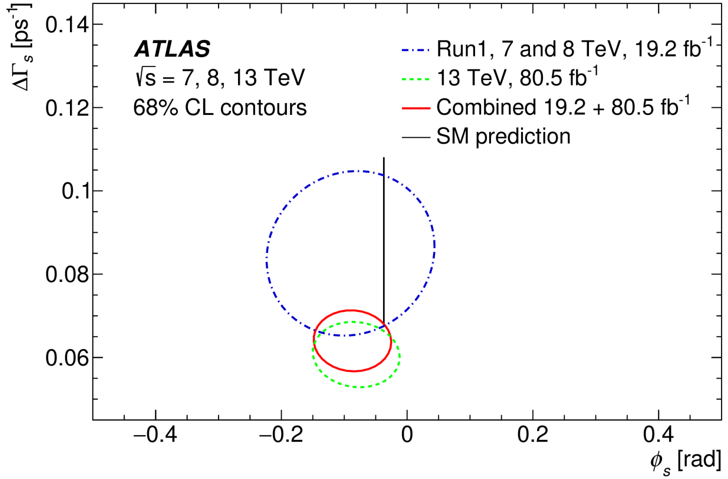
$\tau \rightarrow 3\mu$
$B_s \rightarrow e\,\mu$
$B \rightarrow K^* e^+ e^-$

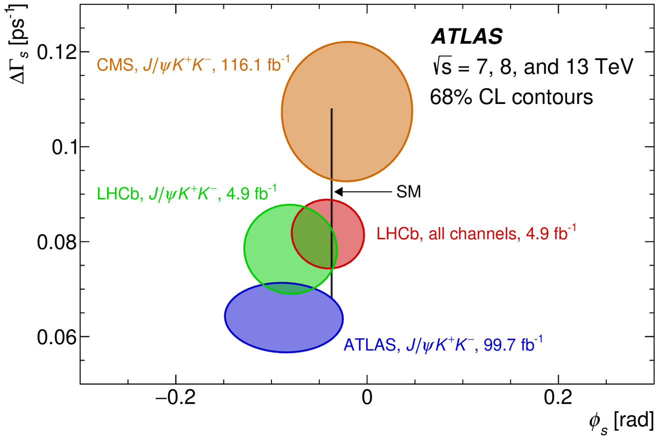
arXiv:2001.07115

$B_s^0 \to J/\psi\varphi$: CP Violation

- $B_s^0 \to J/\psi\phi$ with $J/\psi \to \mu\mu$, $\phi \to KK$
  - Agrees with SM
  - Consistent with other experiments
  - Potentially new Physics as uncertainty shrinks

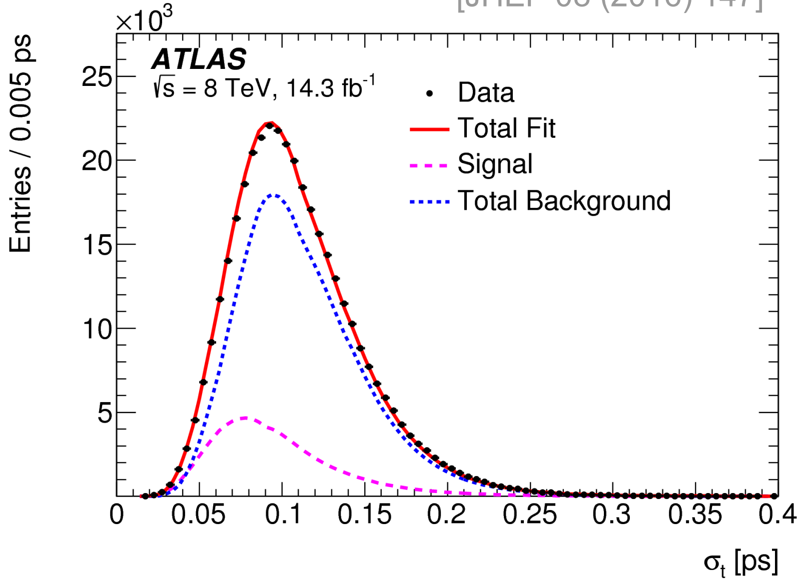
$$\phi_s = -0.087 \pm 0.036 \text{ (stat.)} \pm 0.019 \text{ (syst.) rad}$$
$$\Delta\Gamma_s = 0.0641 \pm 0.0043 \text{ (stat.)} \pm 0.0024 \text{ (syst.) ps}^{-1}$$
$$\Gamma_s = 0.6697 \pm 0.0014 \text{ (stat.)} \pm 0.0015 \text{ (syst.) ps}^{-1}$$





$B_s^0 \to J/\psi\phi$ – Proper decay Time

[JHEP 08 (2016) 147]



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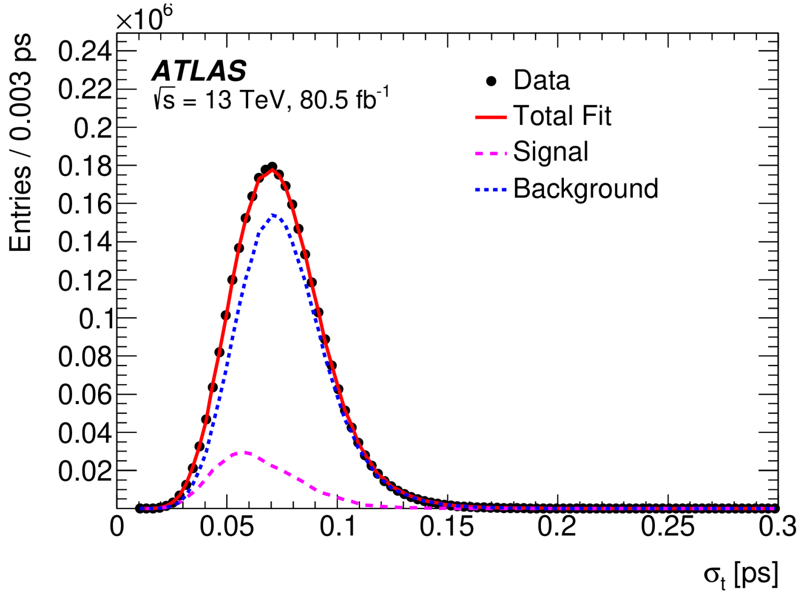
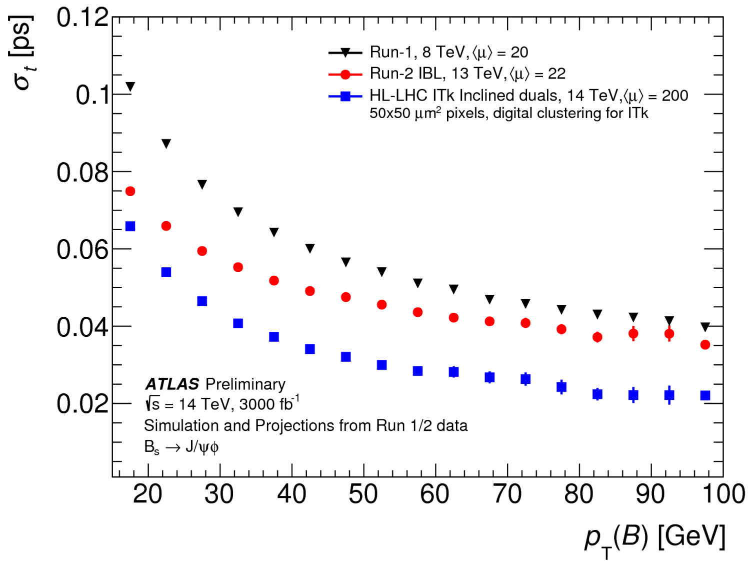
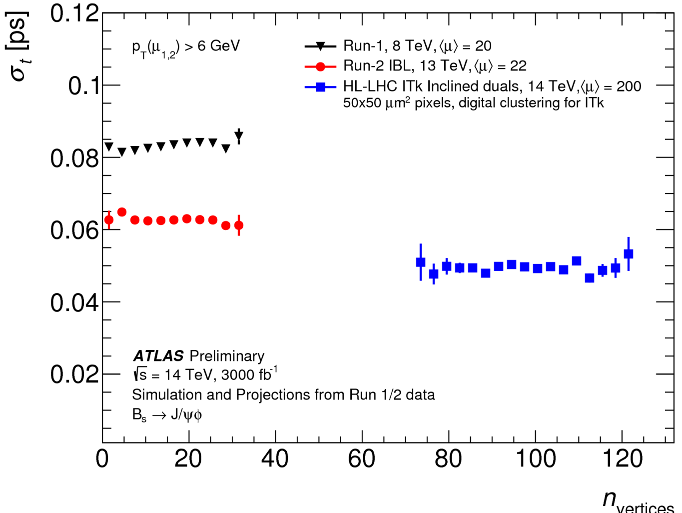


- The Insertable B Layer (IBL) added in Run 2:
  - Precision improves by 30%
  - Further improvement by ITk

Prospects for Bs→ J/ψφ at HL-LHC (1)

- Dedicated signal MC samples:
  - L_{inst} = 7 x 10^{34} $cm^{-2}s^{-1}$ @ 14 TeV
    <μ>=200 pile-up events
    Preliminary ITk design: innermost pixel layers at 39 mm and 80 mm: 50 x 50 μm^2 pixels
  - Samples generated with muon p_T > 5.5 GeV
- Candidate selection is same as the Run 1 paper
- σ_τ resolution improves over run2 IBL, improves with p_T
- Could improve further with analogue digital pixel clustering





Prospects for Bs→ J/ψφ at HL-LHC (2)

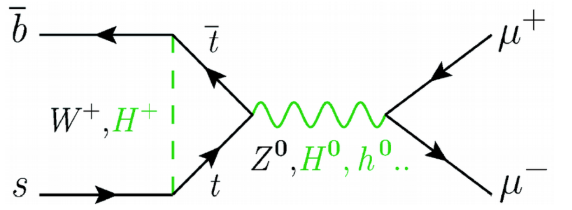
- ECFA 2018 study (3000 fb^{-1}) based on Run 1, signal from MC and background from data side-bands
- Pseudo-experiments & fits
- Systematic errors are based on conservative assumptions and should improve

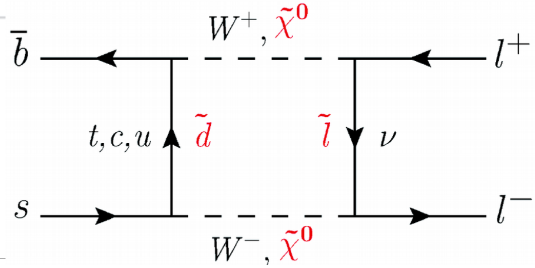
B_s flavour tagging calibration
Likelihood fit model description
Trigger efficiency
ID alignment

Period	L_{int} [fb^{-1}]	N_{sig}	f_{sig}	Tag Power [%]	$\sigma(\tau)$ [ps]	$\delta^{stat}_{\phi_s}$ [rad] measured (extrapolated)	$\delta^{stat}_{\Delta\Gamma_s}$ [ps^{-1}] measured (extrapolated)
2012	14.3	73693	0.20	1.49	0.091	0.082	0.013
2011	4.9	22690	0.17	1.45	0.100	0.25 (0.22)	0.021 (0.023)
						$\delta^{stat}_{\phi_s}$ [rad] extrapolated	
HL-LHC	3000						
Trigger μ6μ6		$9.72 \cdot 10^6$	0.17	1.49	0.048	0.004	0.0011
Trigger μ10μ6		$5.93 \cdot 10^6$	0.17	1.49	0.044	0.005	0.0014
Trigger μ10μ10		$1.75 \cdot 10^6$	0.15	1.49	0.038	0.009	0.003

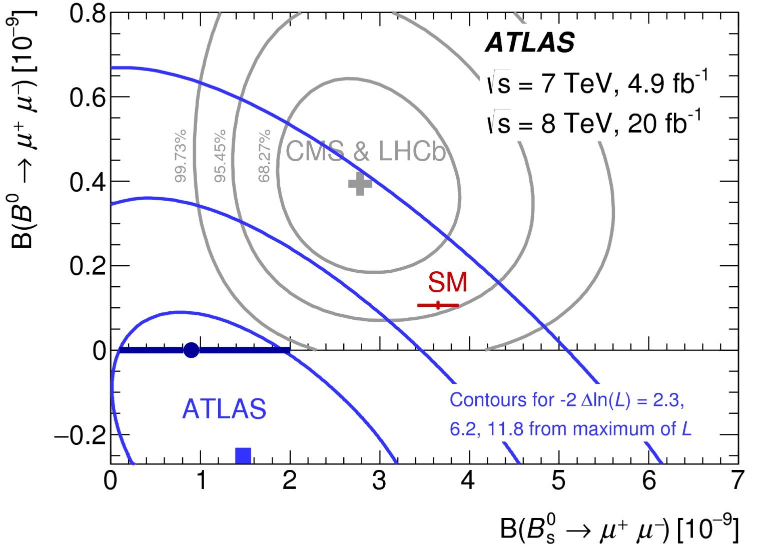
[Eur. Phys. J. C76 (2016) 513]

B(s) → $\mu^+\mu^-$ – Run 1





- BR($B_{(s)} \rightarrow \mu^+\mu^-$) w.r.t. BR($B^\pm \rightarrow J/\psi\ K^\pm$) can identify New Physics arising via loop diagrams
- Compatible with SM at 2σ
- Lower in both BRs compared to combined CMS & LHCb result
- In run 4 we expect better mass separation and increased statistics



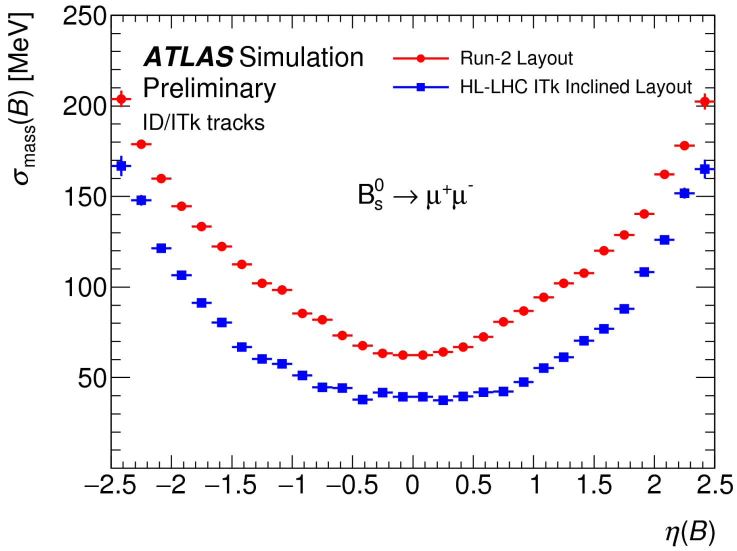
Prospects for B(s) → $\mu^+\mu^-$ – Mass Separation

[CERN-LHCC-2017-021, ATLAS-TDR-030]

- Dedicated signal MC samples:
  - L_{inst} = 7 x 10^{34} $cm^{-2}s^{-1}$ @ 14 TeV

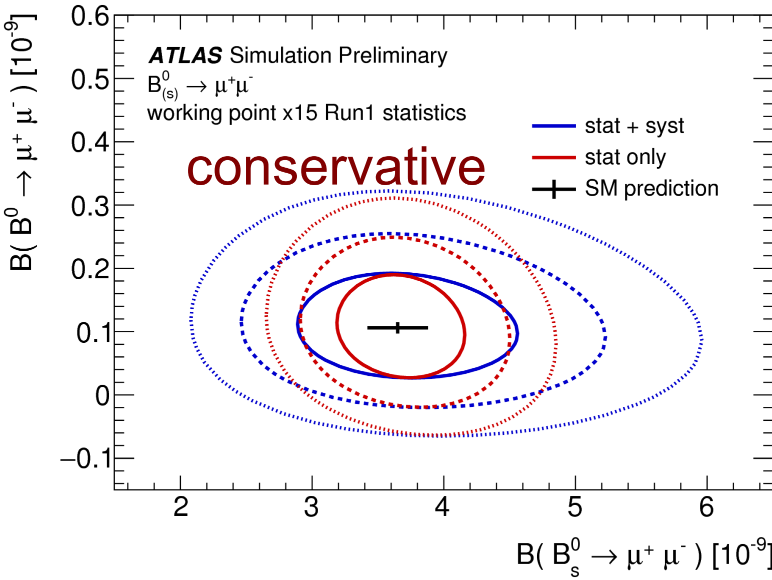
    <μ>=200 pile-up events

    Preliminary ITk design: inclined design up to|η|<4 and 80 mm: 50 x 50 μm^2 pixels
- Improved mass resolution of Itk:
  - Barrel by x 1.65: 1.4σ (Run 1)→ 2.3σ
  - End-Caps by x 1.5: 0.85σ (Run 1)→ 1.3σ

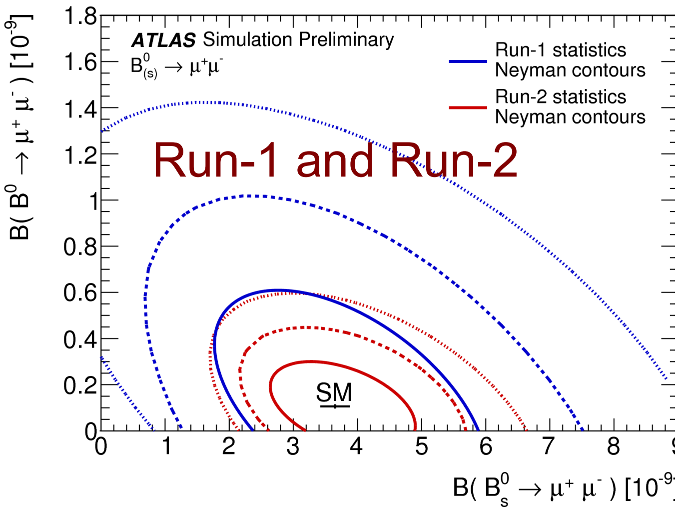


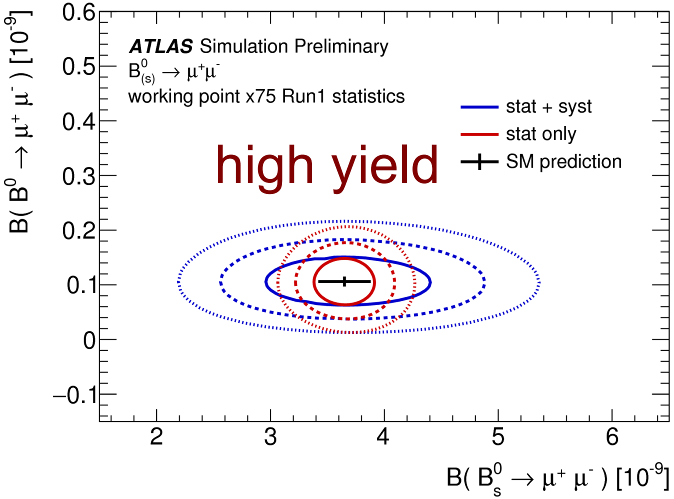
[ATL-PHYS-PUB-2016-026]

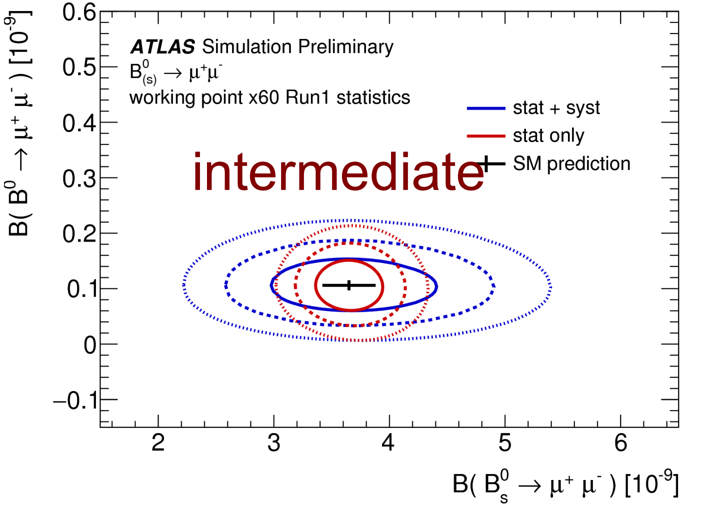
Prospects for $B_{(s)} \rightarrow \mu^+\mu^-$ – Prospects – HL-LHC



- Three trigger scenarios:
  - 2MU10 $\rightarrow$ 15 x N_{Run1}
  - MU6_MU10 $\rightarrow$ 60 x N_{Run1}
  - 2MU6 $\rightarrow$ 75 x N_{Run1}
- Pseudo experiments based on Run-1 analysis
- Conservative assumptions about systematic

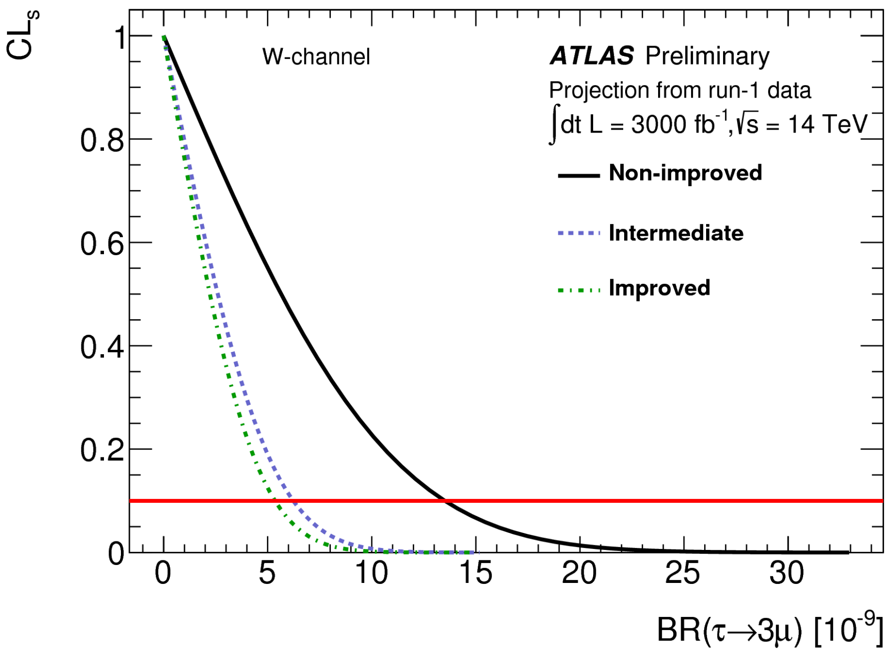






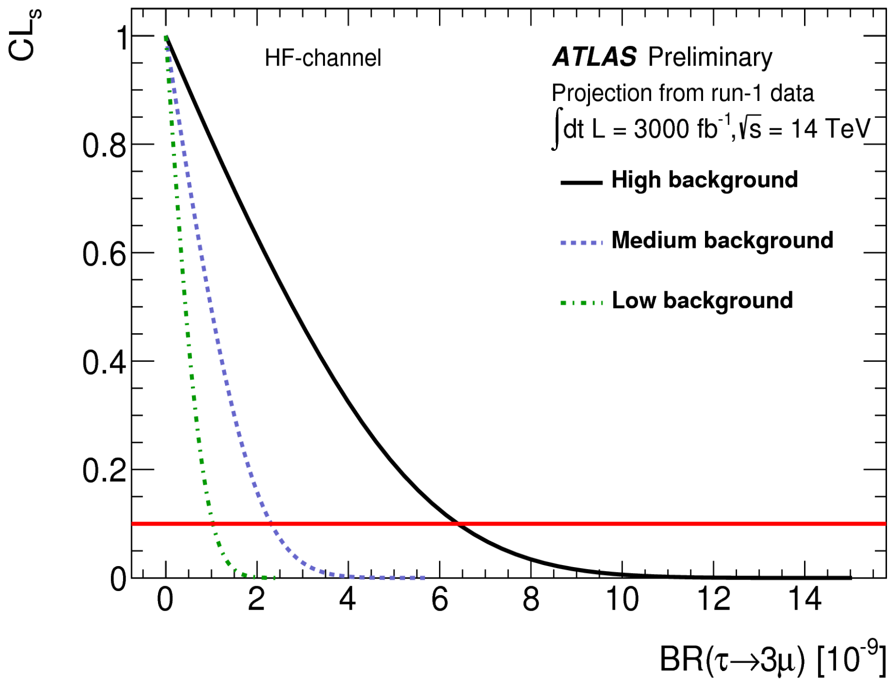
τ→ 3μ at ATLAS HL-LHC (W channel)

- This decay can be used to look for flavor violations. This extrapolation is based on a run-1 analysis which searched the channel W→τν.
- MC signal (3000 fb^{-1}) is produced and tested under 3 scenarios:
  - Non-improved: Same as Run-1 but scaled luminosity and production cross-section
  - Intermediate: Run-2 trigger and reconstruction improvements. This increases the signal yield x2.2
  - Improved: Search window in tightened by expect ITK resolution improvements.



τ→ 3μ at ATLAS HL-LHC (HF channel)

- HF Flavor channels are less clean but potentially accessible. Not tried at ATLAS yet but an estimation is presented
  - High background – assume background is an order larger than run-1 W-channel
  - Medium background – HF background channel is 3x larger than the W-channel
  - Low background – Assume HF background is the same as W-channel

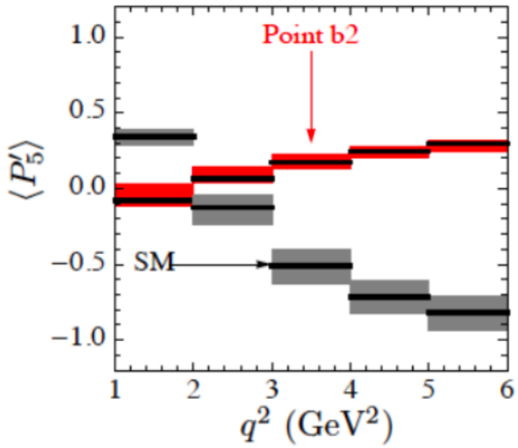


$B_d \rightarrow K^{*0}\ \mu\mu$

- ATLAS has angular analyses of the $B_d \rightarrow K^{*0}\ \mu\mu$ decay.
- Uses MC (3000 fb^{-1}) simulated with the HL-LHC layout and method and q^2 binning from Run-1.
- Three trigger scenarios are considered mu6mu6, mu10mu6 and mu10mu10.

LHC phase	q^2 [GeV^2]	$N_{sig} \pm \delta^{stat}_{N_{sig}}$	$\delta^{stat}_{F_L}$	$\delta^{stat}_{P_1}$	$\delta^{stat}_{P'_4}$	$\delta^{stat}_{P'_5}$	$\delta^{stat}_{P'_6}$	$\delta^{stat}_{P'_8}$
Run 1	[0.04, 2.0]	128 ± 22	0.08	0.30	0.40	0.26	0.21	0.48
	[2.0, 4.0]	106 ± 23	0.11	0.51	0.31	0.31	0.28	0.41
	[4.0, 6.0]	114 ± 24	0.13	0.43	0.33	0.35	0.27	0.42
HL-LHC μ6μ6	[0.04, 2.0]	15800 ± 190	0.007	0.025	0.030	0.024	0.018	0.038
	[2.0, 4.0]	15200 ± 180	0.007	0.055	0.030	0.028	0.020	0.037
	[4.0, 6.0]	14000 ± 200	0.009	0.063	0.031	0.034	0.027	0.039
HL-LHC μ10μ6	[0.04, 2.0]	10000 ± 160	0.009	0.036	0.040	0.029	0.022	0.049
	[2.0, 4.0]	9700 ± 150	0.010	0.071	0.039	0.034	0.027	0.045
	[4.0, 6.0]	8900 ± 170	0.012	0.084	0.039	0.042	0.033	0.050
HL-LHC μ10μ10	[0.04, 2.0]	3200 ± 90	0.017	0.065	0.072	0.052	0.040	0.090
	[2.0, 4.0]	3100 ± 90	0.017	0.13	0.069	0.063	0.048	0.080
	[4.0, 6.0]	2800 ± 100	0.022	0.16	0.074	0.075	0.060	0.088

The precision in measuring a representative P'_5 parameter is expected to improve by factors of ∼9×,∼8×,∼5×

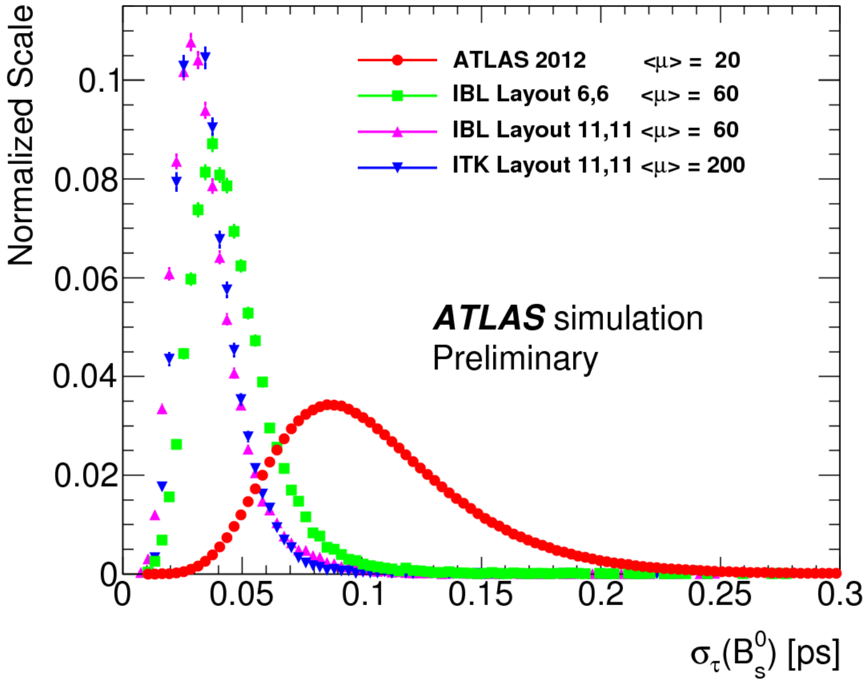


Conclusions

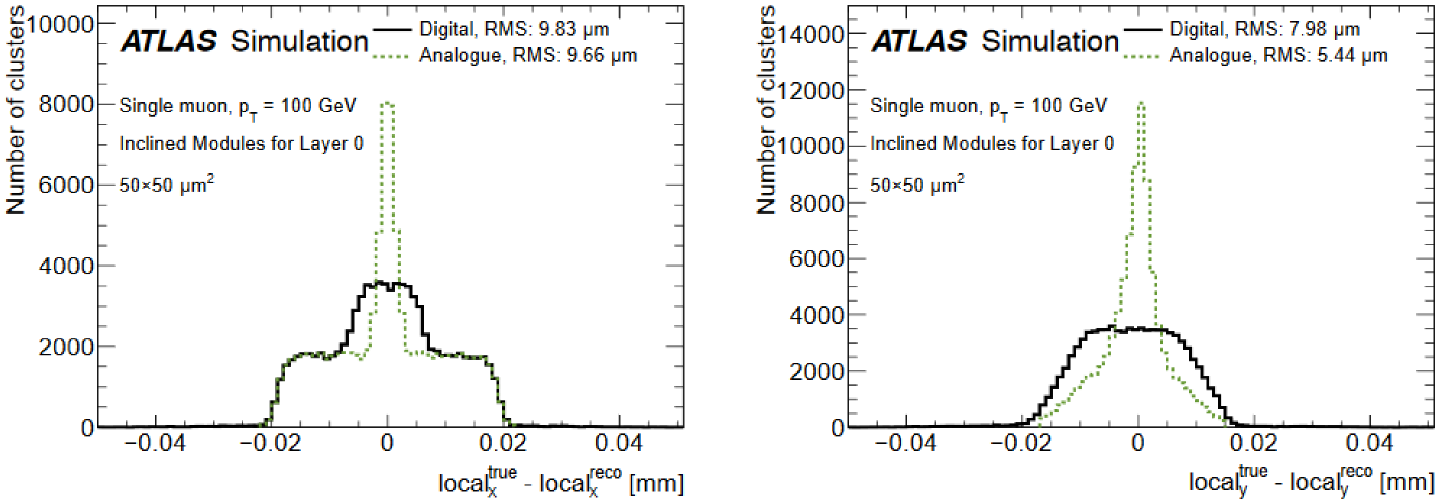
- Extensive upgrade program for LHC & ATLAS:
  - HL-LHC: 5x LHC peak luminosity (7.5 x 1034 cm-2s-1)
  - Detector upgrades: (ITk, NSW, sRPCs, L0/L1 hardware trigger, EF software trigger)
  - ATLAS B physics program continues in Run 3 and for HL-LHC
    - May add additional triggers for electron decays or cascade decays
  - Can expected improved measurements based on estimations presented

Supporting Material

$B_s^0 \rightarrow J/\psi\phi$



Muon Resolutions – Digital vs. Analogue Clusters



- Clear improvement with analogue cluster
- Expect better vertexing

B(s) → μ+μ- - mass separation