ATLAS Plans for the High-Luminosity LHC

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on behalf of the ATLAS collaboration

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Center for Particle Physics Siegen

FSP 103 ATLAS

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Motivation for High Luminosity-LHC

Many physics achievements by LHC & experiments

- Higgs boson found (2012++)
- Several rare decays discovered (e.g. $B_s^0 \rightarrow \mu^+\mu^-$, …)
- CP violation in B sector (e.g. $B_s^0 \rightarrow J/\psi\ \phi$)
- Standard Model is describing measurements well

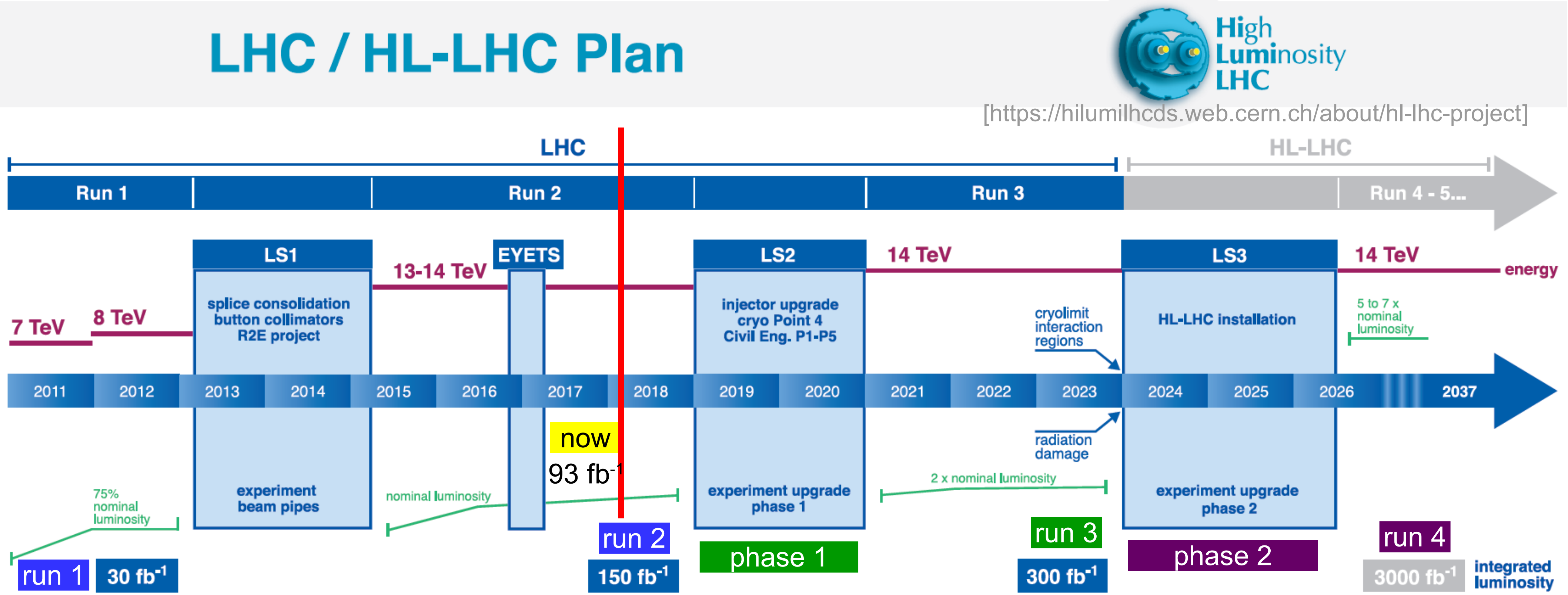
Many puzzles remaining

- Dark matter → New type(s) of particles?
- Supersymmetry: Does it exist?
- Flavor anomalies: LFV, LFU violation?
- Matter-antimatter asymmetry
  → How to explain it? CP violation only?

LHC at or above design performance

- Already at $L_{peak} = 2.06 \times 10^{34}$ cm^{-2}s^{-1} (2 x design)
- E_{CMS} = 14 TeV expected for Run 3
- ➔ Expect only linear increase in $\int L\, dt$ after Run 3
- Need more to improve measurements
- ➔ Upgrade LHC and experiments to High-Luminosity (HL) phase

HL-LHC Timeline and Core Parameters

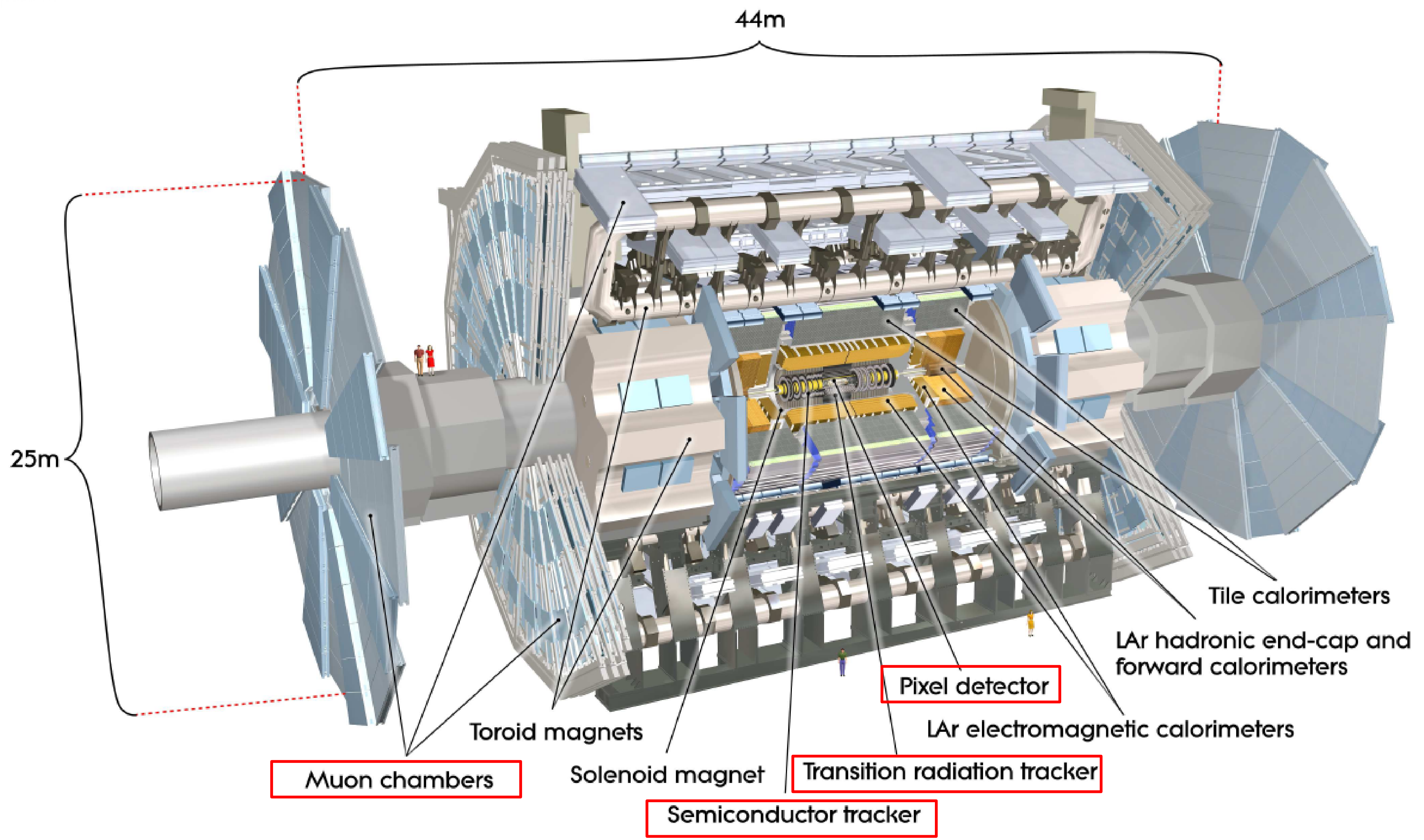


Study Higgs in detail and enhance discovery potential

[CERN-2017-007-M]

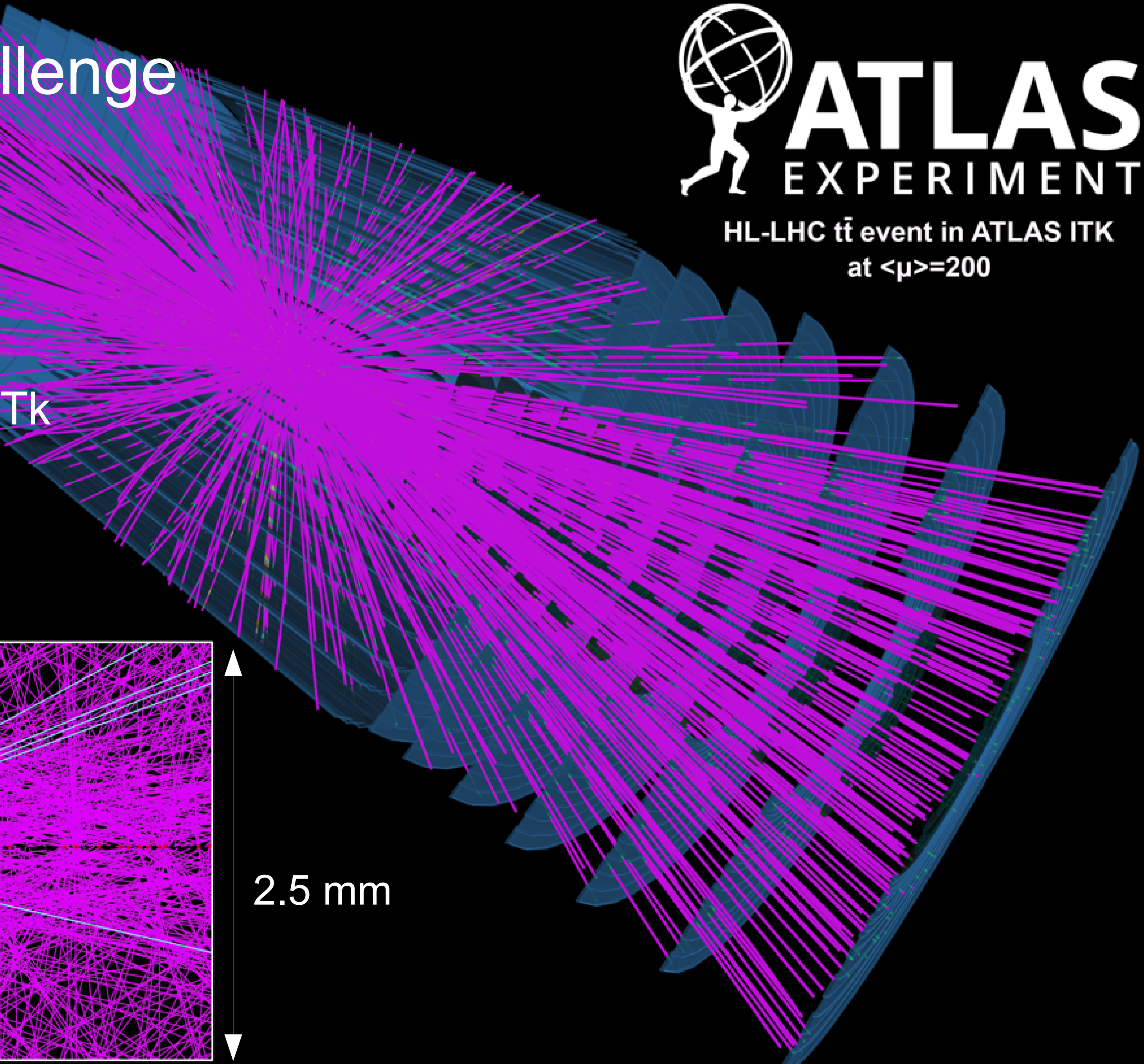
- Aim: > 10 x $\int L dt$ of LHC → 3 000 – 4 000 fb^{-1}
- Peak L_{inst} ~ 5 ... 7.5 x 10^{34} cm^{-2} s^{-1}
- <μ> = 140 … 200 pp interactions, every 25 ns
- ➔ Unprecedented pileup, huge event rates → upgrade detectors!

A Toroidal LHC ApparatuS (ATLAS)

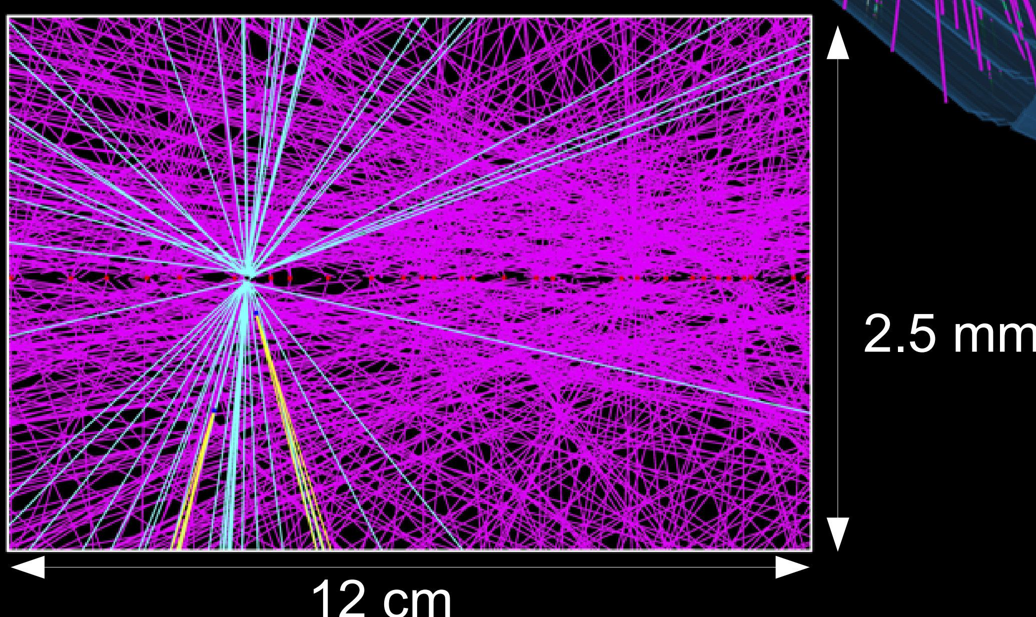


Inner detector and muon chambers most important for B physics

HL-LHC Challenge



- $t\bar{t}$ event in ATLAS ITk
- $\langle\mu\rangle = 200$
- p_T(tracks) > 1 GeV



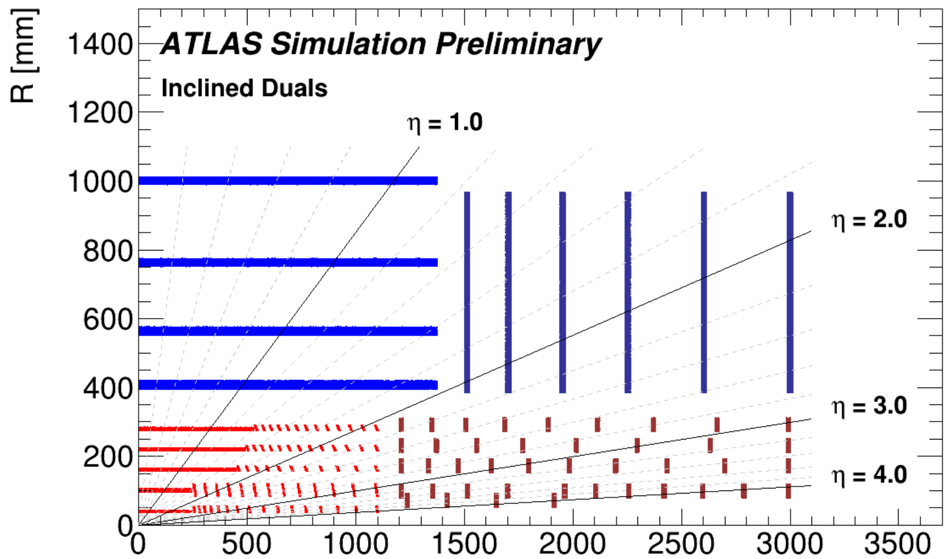
ATLAS Upgrade Program

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	all new power supplies	new L1 trigger electronics	new readout electronics (input to L0Calo), 40 MHz streaming, High Granularity Timing Detector (HGTD)
Tile	new low voltage power supplies		readout electronics, 40 MHz streaming, improved drawer mechanics, new HV power supplies
RPC	gas leak repairs	BMG (sMDT) in acceptance gaps, BIS78 chambers between barrel and end-caps	new chambers in inner barrel
TGC		New Small Wheel (sTGC + MicroMegas)	new front-end electronics, forward tagger (option)
MDT			replace all front-end electronics
Trigger	new L1Topo, upgraded CTP, partial FTK L2 + EF → HLT	new FEX, full FTK, 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
DAQ	custom hard-/firmware	FELIX for some systems	FELIX for all systems

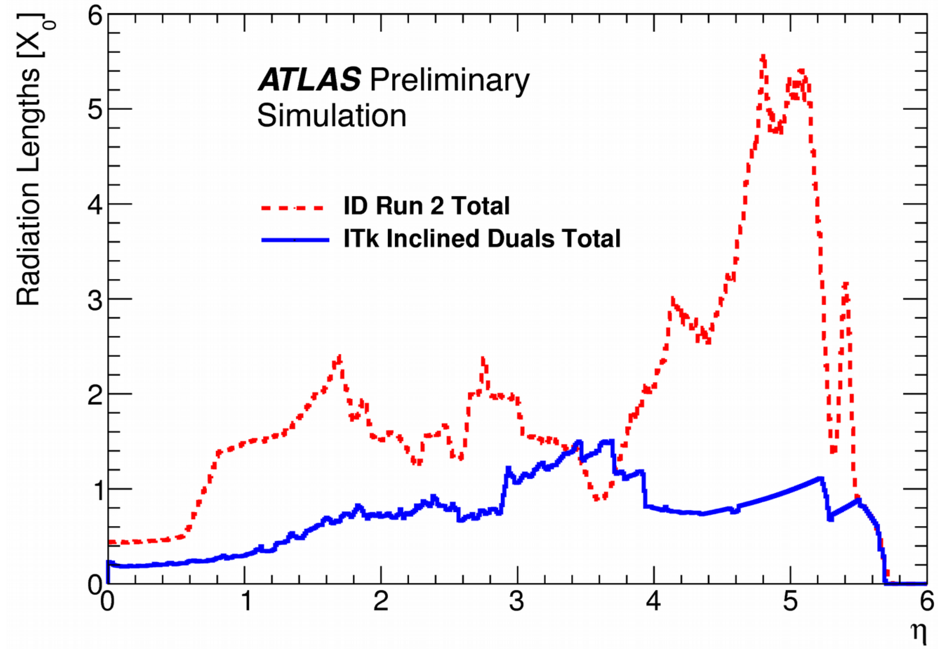
ATLAS Inner Tracker (ITk) Upgrade

New all-silicon detector:

- ITk pixel (13 m^2):
  - 5 barrel, 5 EC layers (with rings)
  - Inclined sensors
  - Extends to $\eta_{max} = 4.0$ (2.5 now)
  - Innermost layer at 36 mm
  - ~ 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%
- ITk material considerably less than current ID
  - Improved tracking efficiency
  - Better mass resolution



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

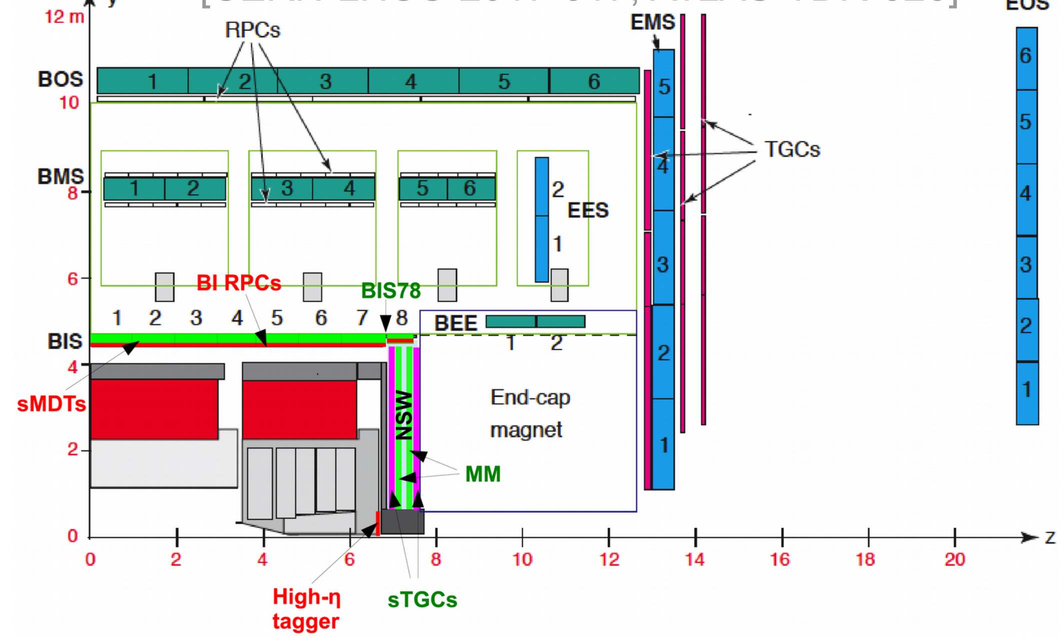


ATLAS Muon System Upgrade

New Small Wheel (NSW):

- Phase 1 upgrade
- Small strip Thin Gap Chambers (sTGC)
  → high efficiency for fast L1 trigger
- MicroMegas (MM)
  → (mostly) precision muon tracks
- Covers 1.3 < |η| < 2.7
  → reduce fake tracks in high radiation background region

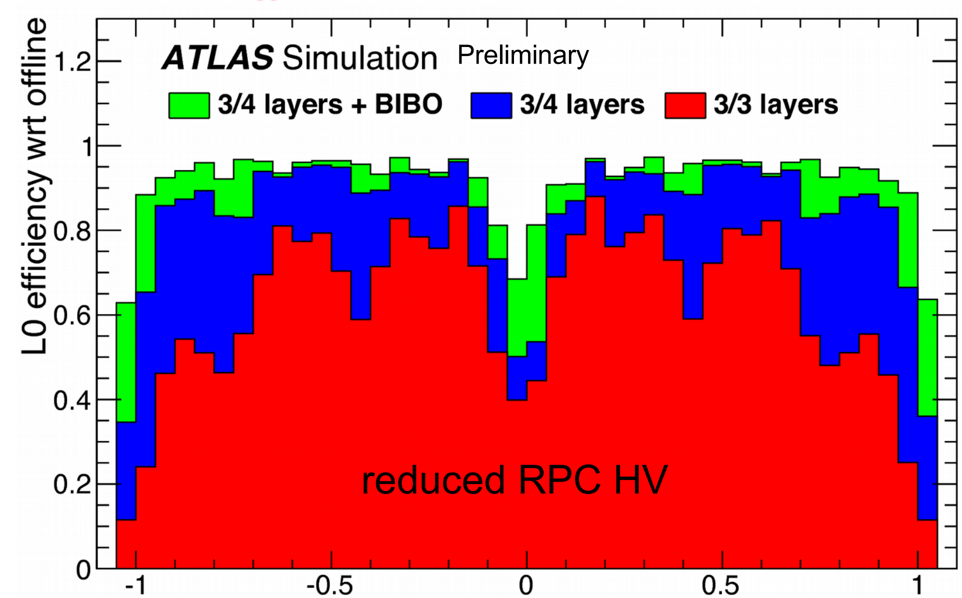
[CERN-LHCC-2017-017, ATLAS-TDR-026]



New inner barrel (BI) RPCs:

- L0 trigger acceptance for reco'd combined muons
  within |η| < 1.05 increases
  from 78% → 96%
- "Worst 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 (baseline):

- Hardware trigger based on calorimeter and muon information
- MDT precision information available
- Global event processor refines e, γ, τ, jet and E_T^{miss} objects
- 1 MHz rate at 10 μs latency

Option: dual L0/L1 trigger:

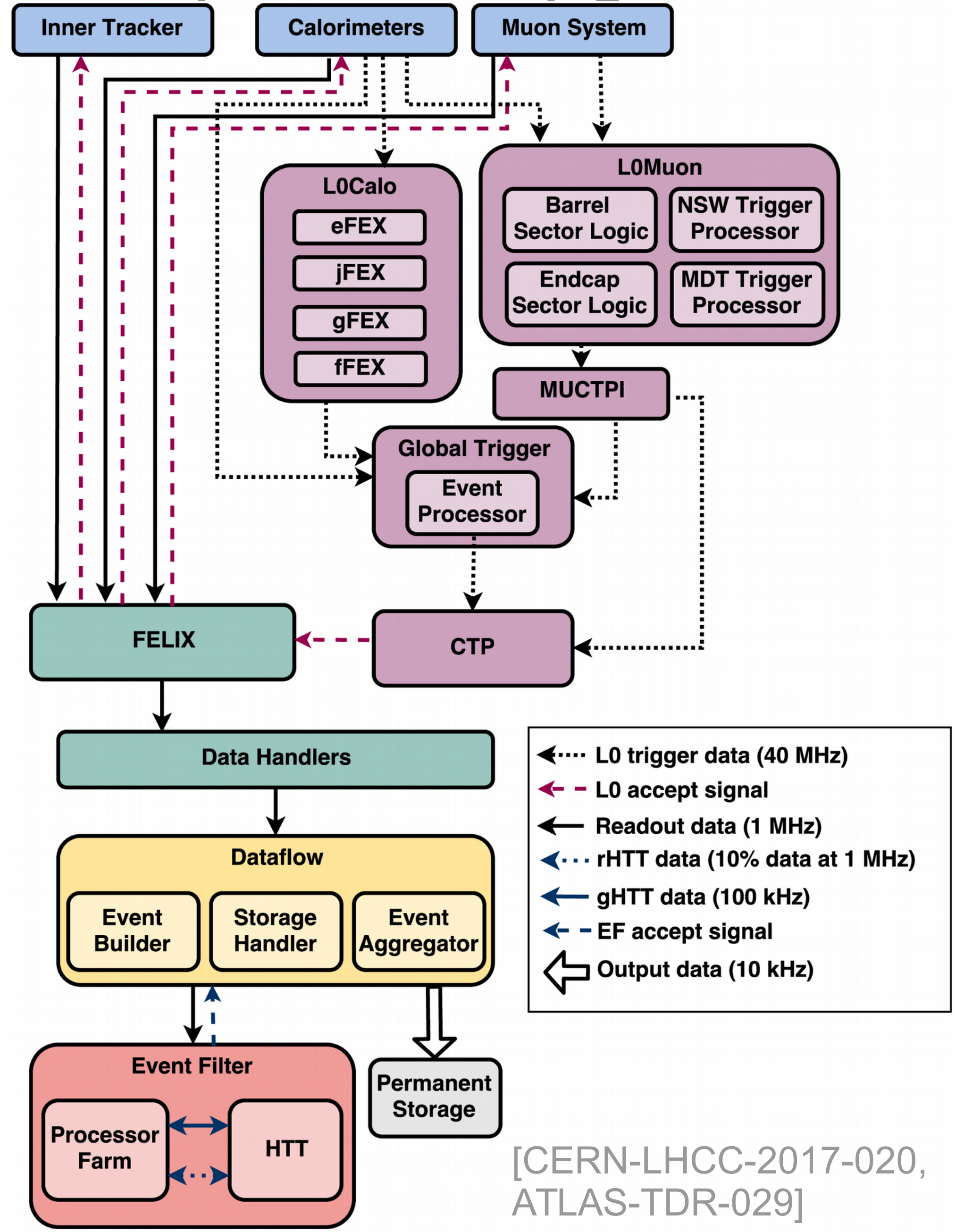
- 4 MHz rate at 10 μs latency
- Hardware tracking (L1track) $\rightarrow$ pileup suppression

Data Acquisition:

- Front End LInk eXchange (FELIX)
- New Storage Handler

Event Filter:

- Hardware Track Trigger (HTT) $\rightarrow$ 400 kHz
- High-Level-Trigger (HLT) in software $\rightarrow$ 10 kHz



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

B-Physics HL-LHC Prospects at ATLAS

Precision measurements, rare processes

- $B_s^0 \rightarrow J/\psi\,\phi$, $\Lambda_b^0 \rightarrow J/\psi\,\Lambda^0$, …, $B_{(s)}^0 \rightarrow \mu^+\mu^-$, $b \rightarrow s\,\mu^+\mu^-$
  - Potential for beyond-SM effects
  - Make use of high $\int L\,dt$
  - Exploit improved detector performance
  - Rare processes require complex trigger stategies

Lepton Flavor Violation (LFV) and Lepton Flavor Universality (LFU)

- $\tau \rightarrow 3\,\mu$, $B_s^0 \rightarrow e\,\mu$, $B^0 \rightarrow K^{*0}\,e^+e^-$ / $B^0 \rightarrow K^{*0}\,\mu^+\mu^-$

Heavy flavor production

- B-hadron, prompt/non-prompt quarkonia production
  - Test of QCD predictions
- Heavy flavor in association with other objects
  - W/Z + J/ψ, double quarkonia, …
  - Double parton scattering
- Searches for new/exotic states, new decay modes
  - χ_b, B_c decays, $B_c(2S)$, heavy baryons, tetra/pentaquarks

$B_s^0 \to J/\psi\ \phi$: CP Violation and $\Delta\Gamma_s$ – Run 1

$B_s^0 \to J/\psi\ \phi$ with $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$

- Sensitive to CPV phase ϕ_s

Combined Run-1 result:

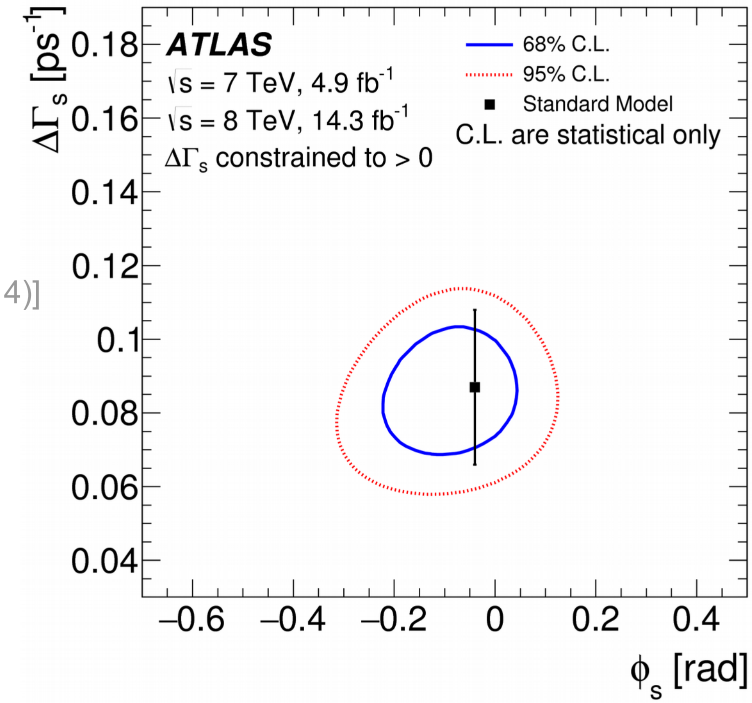
[Phys. Rev. D 90, 052007 (2014)]
[JHEP 08 (2016) 147]

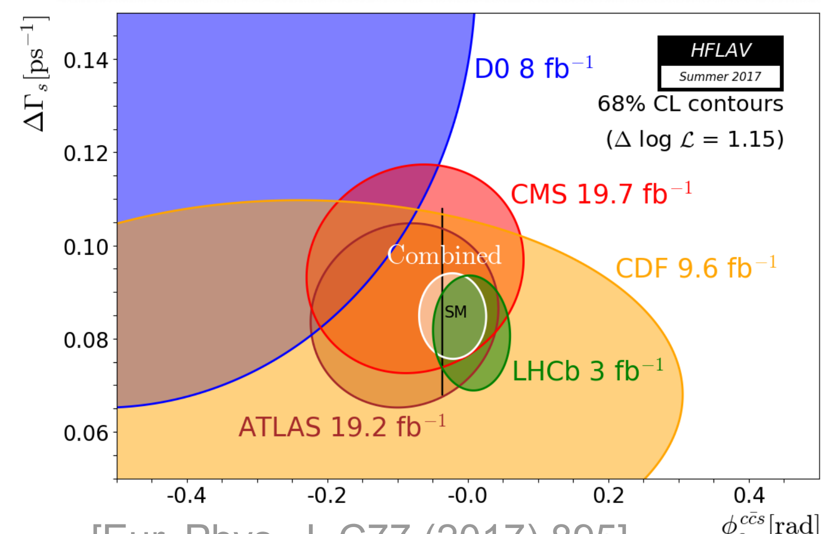
- ϕ_s = -0.090 ± 0.078 (stat) ± 0.041 (syst) rad
- $\Delta\Gamma_s$ = 0.085 ± 0.011 (stat) ± 0.007 (syst) ps^{-1}

- Agrees with SM
- Consistent with other experiments
- Still room for New Physics in CPV

Expected upgrade improvements:

- Better decay time resolution
- Lower uncertainties due to higher statistics
  (also for systematic uncertainties)

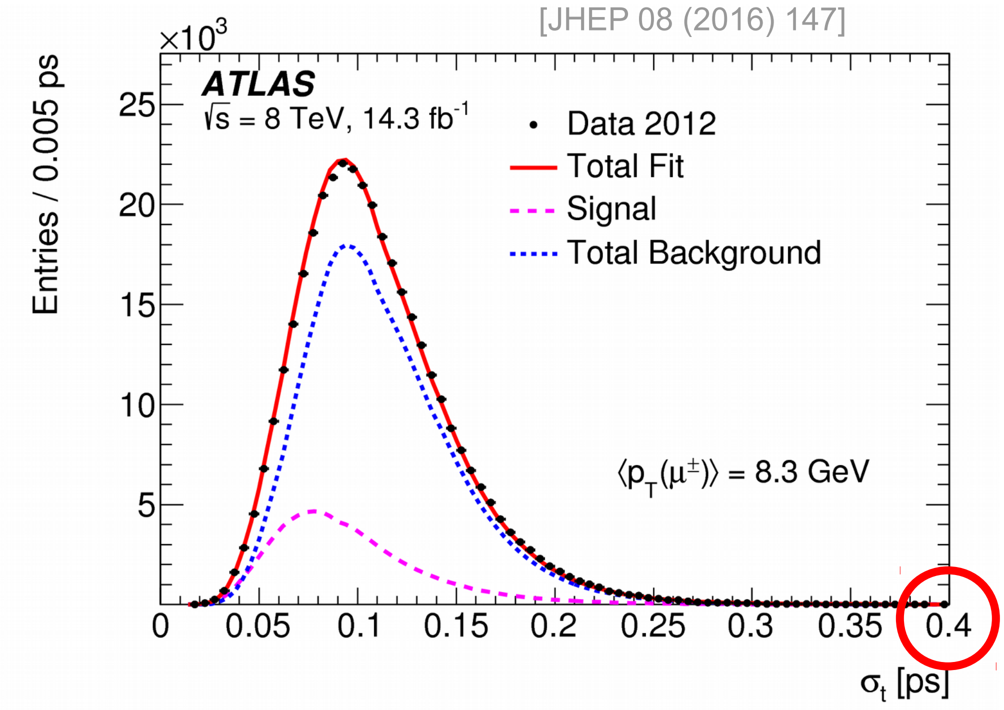




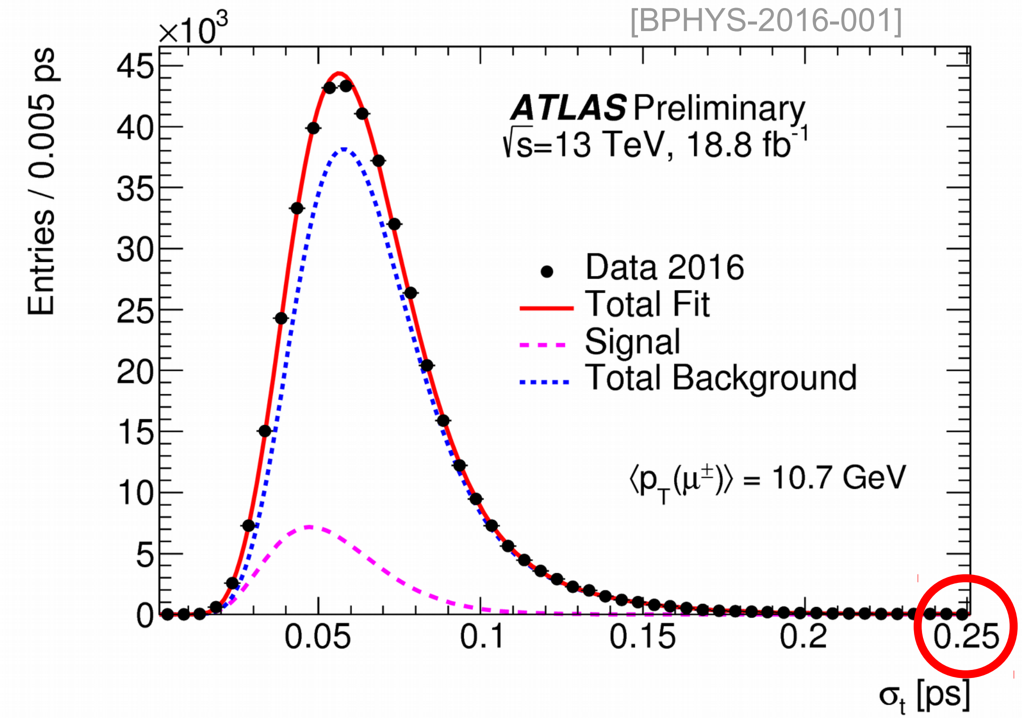
[Eur. Phys. J. C77 (2017) 895]

$B_s^0 \to J/\psi\ \phi$ Proper Time Resolution – Run 2

Run 1 – 2012 data



Run 2 – 2016 data

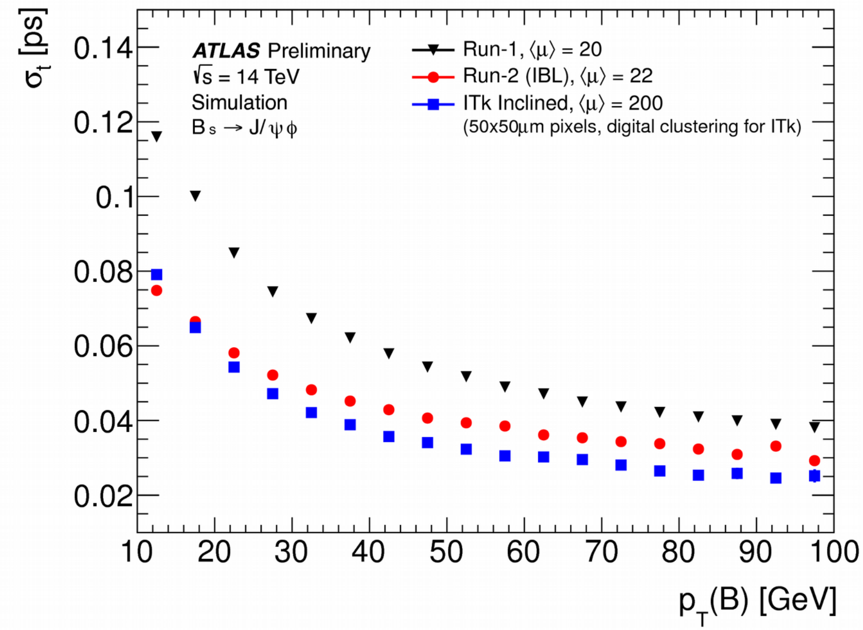


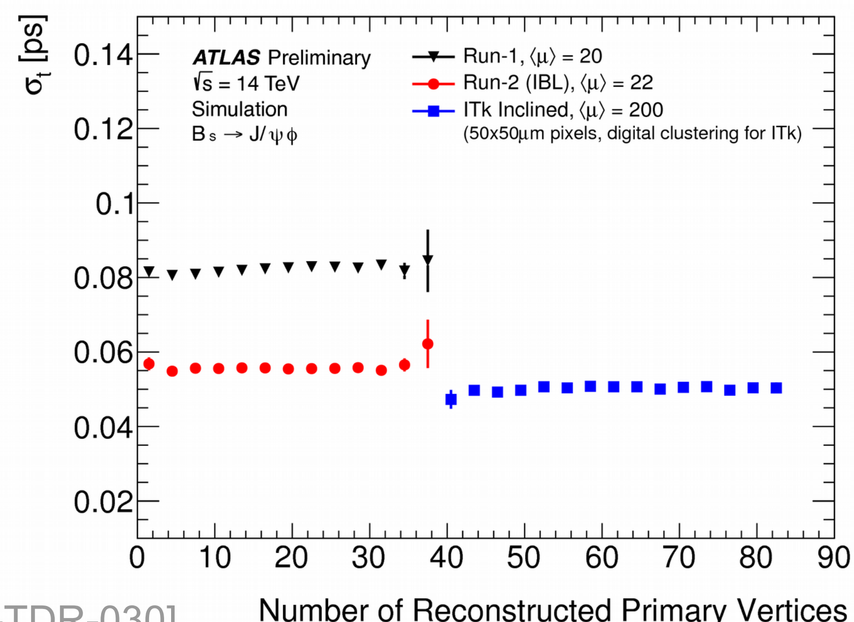
Insertable B Layer (IBL) added in Run 2:

- σ_t improves by ~ 30%
- Further improvement expected for ITk layout

Prospects for $B_s^0 \to J/\psi\ \phi$ at HL-LHC (1)

- Dedicated signal MC samples:
  - $L_{inst} = 7 \times 10^{34}\ cm^{-2}s^{-1}$ @ 14 TeV
    $\langle\mu\rangle = 200$ pile-up events
  - ITk: innermost pixel layers at 39 mm and 80 mm; 50 x 50 μm^2 pixels
  - $p_T(\mu^{\pm}_{1,2}) > 5.5$ GeV
- Candidate selection ~ Run 1
- Extrapolation of σ_τ resolution:
  - Run 2: 30% gain w.r.t. Run 1 (IBL)
  - further improvement at higher $p_T(B)$ for ITk
  - ~ stable with $\langle\mu\rangle$
- Analogue instead of digital pixel clustering
  $\longrightarrow$ additional gain expected





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

Prospects for $B_s^0 \to J/\psi\, \phi$ at HL-LHC (2)

ECFA 2013 study (3 000 fb^{-1})

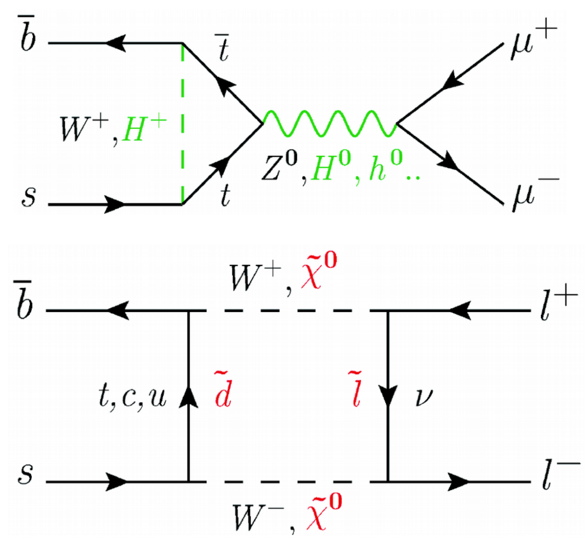
- Based on Run 1 analysis
  - Signal from MC
  - Background from sidebands
- Pseudo-experiments & fits:
  - Mass
  - Time and angular distributions
  - Flavor tagging
- Conservative!
  - $\sigma(\phi_s)$ (syst) < 0.04 rad

- Syst. uncertainties expected to improve with statistics:
  - B_s^0 flavor tagging calibration
  - Likelihood fit model description
  - Fit to $B^0 \to J/\psi\, K^{*0}$ component
  - Trigger efficiency
  - ID alignment
- Later study: [ATL-PHYS-PUB-2016-026]
  - Statistics x ~3 by topological μ trigger (lower p_T thresholds, same bandwidth)

[ATL-PHYS-PUB-2013-010]	2011	2012	2015-17		2019-21	2023-30+
Detector	Run 1	Run 1	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

achieved: 0.078 (2011/12)

$B_{(s)}^0 \to \mu^+\mu^-$ – Run 1



BR($B_{(s)}^0 \to \mu^+\mu^-$) w.r.t. BR($B^\pm \to J/\psi K^\pm$)

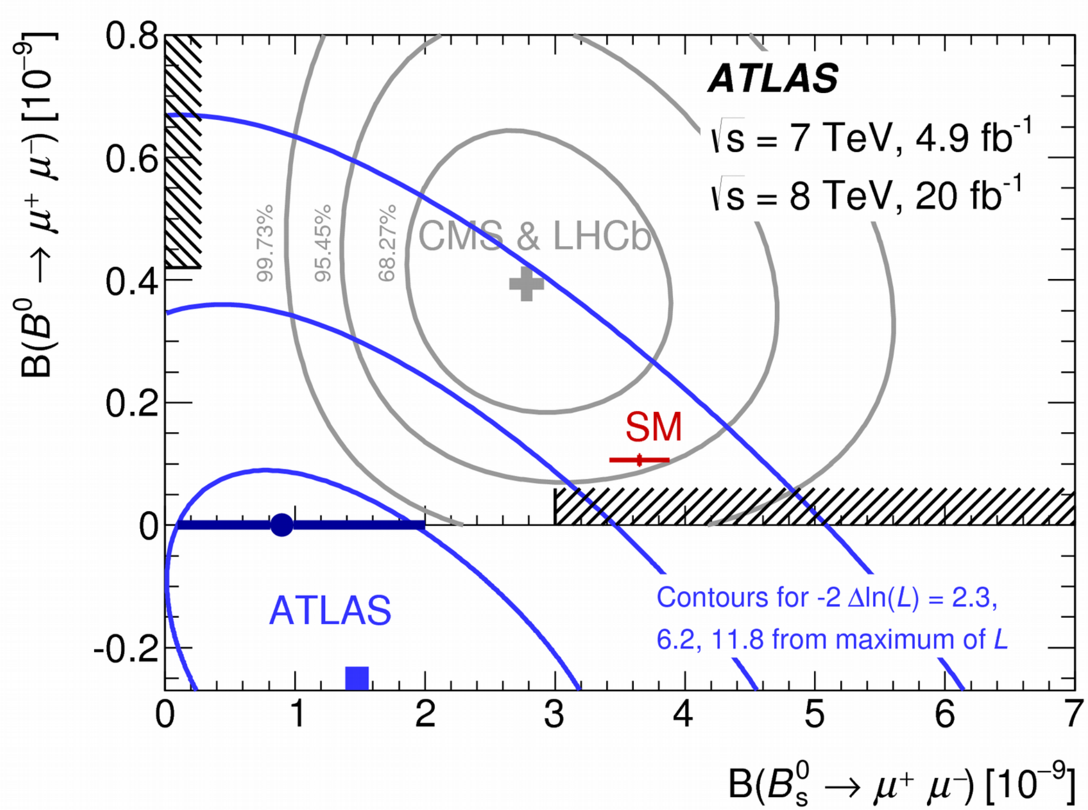
- Sensitive to New Physics in decay via loop diagrams

Run 1 result:

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

- BR($B^0_s \to \mu^+\mu^-$) = $0.9\,^{+1.1}_{-0.8} \times 10^{-9}$
- BR($B^0 \to \mu^+\mu^-$) < 4.2×10^{-10} at 95% CL

- Compatible with SM at ~ 2σ
- Lower in both BRs compared to combined CMS&LHCb result



Expected upgrade improvements:

- Better mass separation
- Increased statistics

Prospects for $B_{(s)}^0 \to \mu^+\mu^-$ – Mass Separation

Dedicated $B_s^0 \to \mu^+\mu^-$ MC:

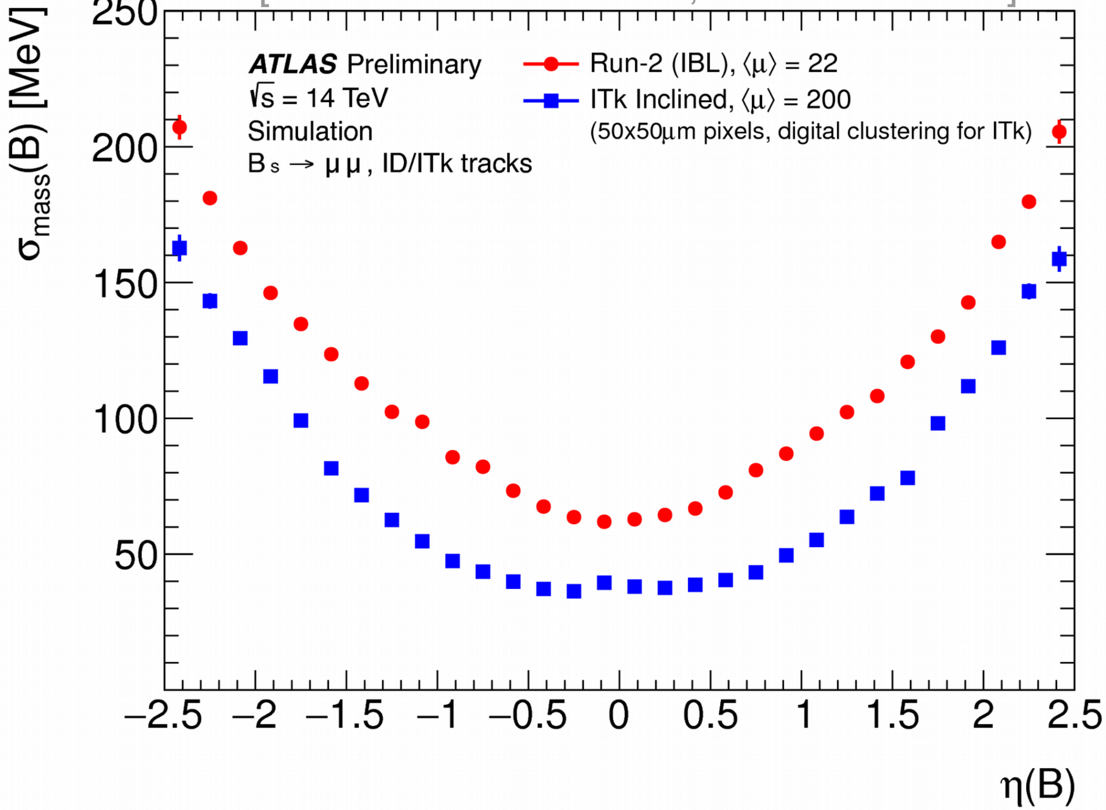
- Run 2 conditions like 2015
- HL-LHC & HL-ATLAS:
  - $L_{inst} = 7.5 \times 10^{34}$ cm^{2}s^{-1} at 14 TeV CME $\langle\mu\rangle = 200$ pile-up events
  - ITk: inclined design, up to $|\eta| < 4$, $50 \times 50\ \mu m^2$ pixels

Candidate selection ~ Run 1

- B_s^0: oppositely charged $\mu^\pm$, $p_T(\mu^\pm_{1,2}) > 5.5$ GeV
- Two-track vertex fit
- $m(B_s^0)$ from ID/ITk-only tracks

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

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



Separation of $m(B_s^0)$ and $m(B^0)$:

- Barrel by x 1.65: 1.4 σ (Run 1) → 2.3 σ
- End-Caps by x ~1.5: 0.85 σ (Run 1) → 1.3 σ

[ATL-PHYS-PUB-2016-026]

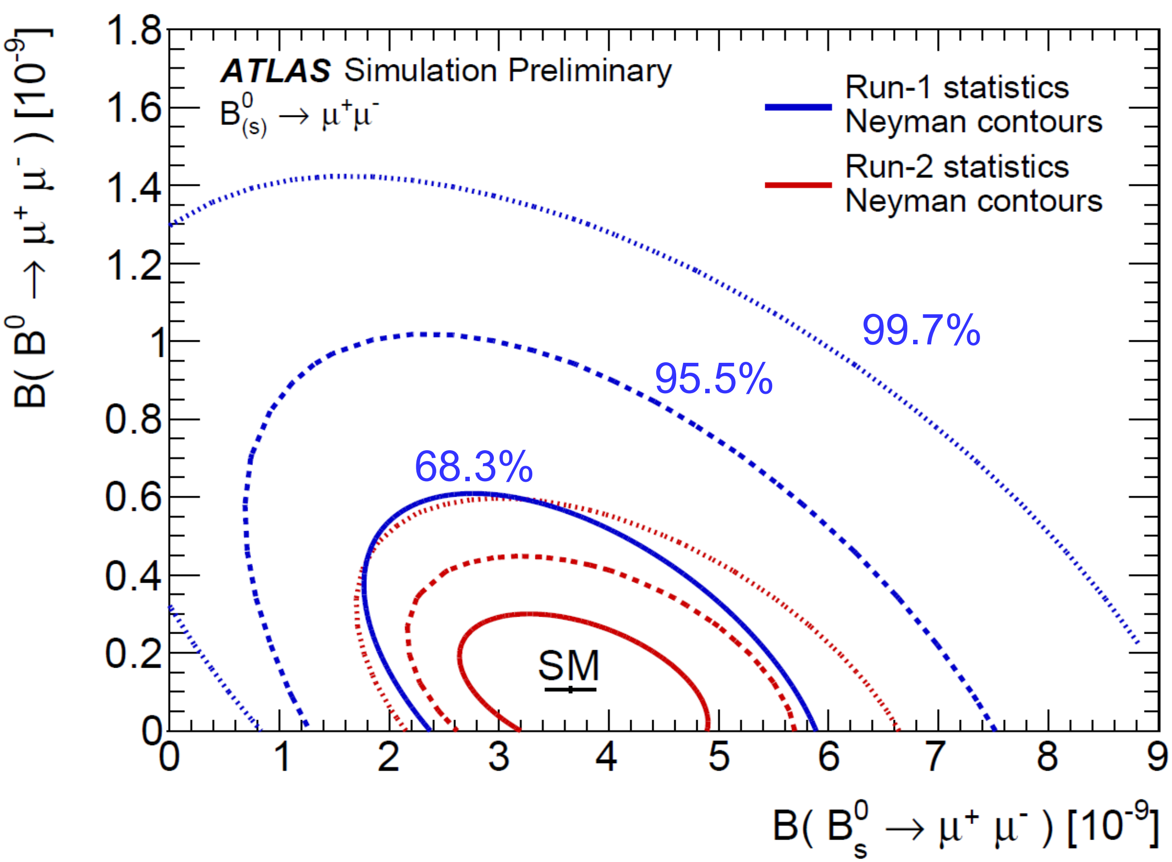
$BR(B_{(s)}^0 \rightarrow \mu^+\mu^-)$ Prospects – Run 2 (130 fb^{-1})

Signal statistics estimate:

- Based on Run 1 result
- Full Run 2 → $\int L\,dt \sim 130\ fb^{-1}$
- σ_{bb}: 8 TeV → 13/14 TeV : factor ~1.7
- 2MU6 || MU6_MU4 topological triggers

➔ total: $N_{Run2} \sim 7 \times N_{Run1}$

[ATL-PHYS-PUB-2018-005]



Pseudo-MC experiments

- 2D Neyman construction
- Based on Run 1 likelihood

Systematic uncertainties

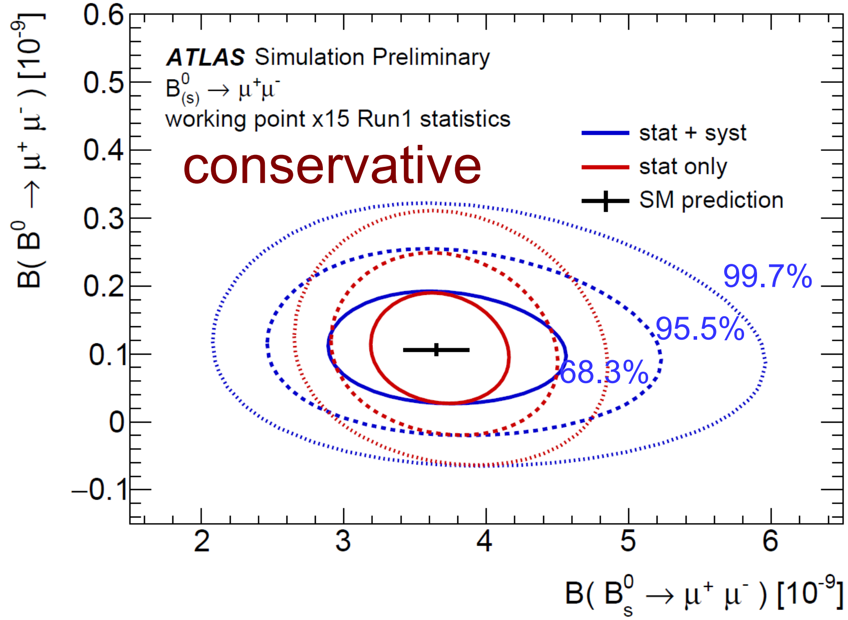
- External:
  f_s/f_d, $BR(B^\pm \rightarrow J/\psi K^\pm)$
  → keep as in Run 1
- Internal:
  fit shapes, efficiencies, …
  → scale with statistics

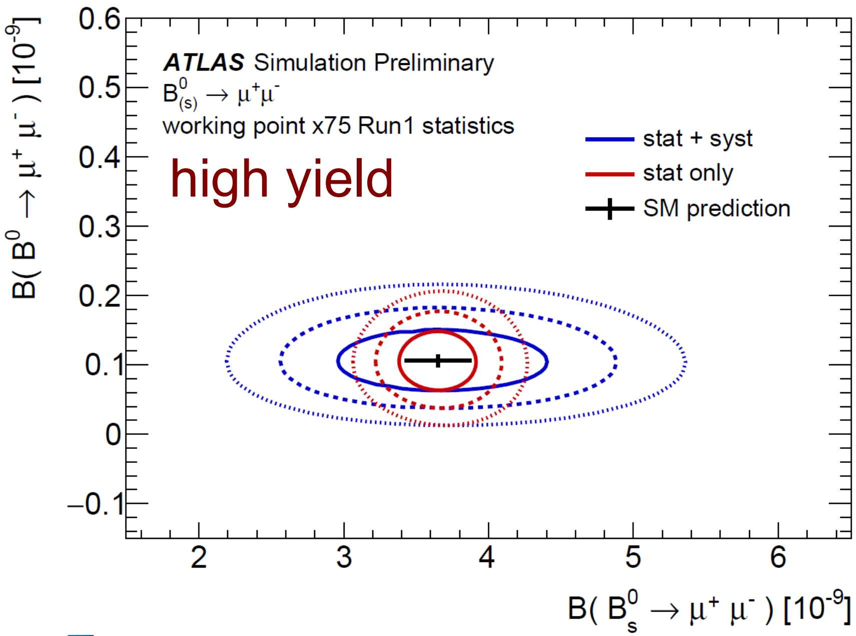
BR($B_{(s)}^0 \rightarrow \mu^+\mu^-$) Prospects – HL-LHC (3 ab^{-1})

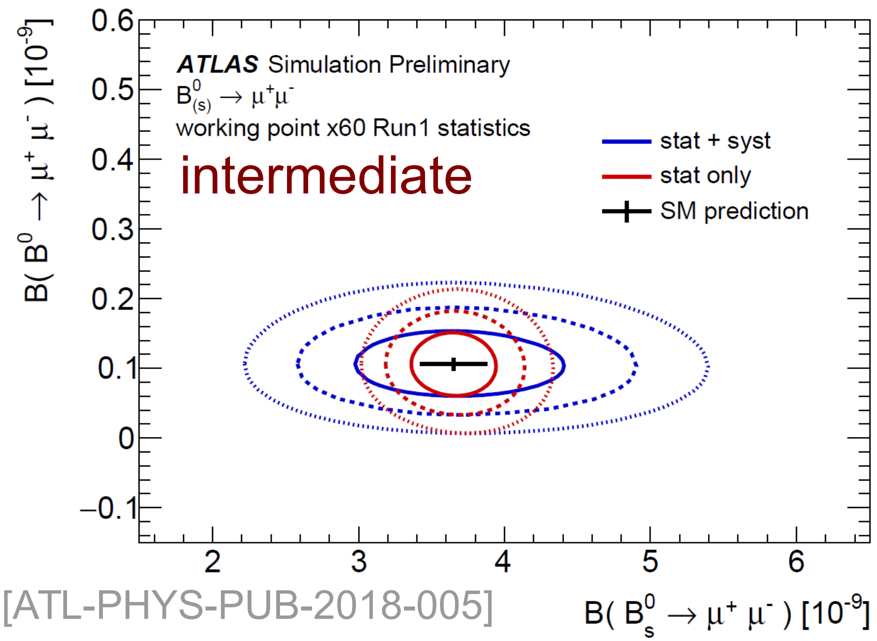
Three trigger scenarios:
- 2MU10 $\rightarrow$ 15 x N_{Run1}
- MU6_MU10 $\rightarrow$ 60 x N_{Run1}
- 2MU6 $\rightarrow$ 75 x N_{Run1}

Pseudo-MC experiments
- Profile likelihood contours
- Based on Run 1 likelihood

Dominant systematics:
- $\sigma(f_s/f_d)$ ~ 8.3% "conservative"







[ATL-PHYS-PUB-2018-005]

Conclusions

Extensive upgrade program for LHC & ATLAS:

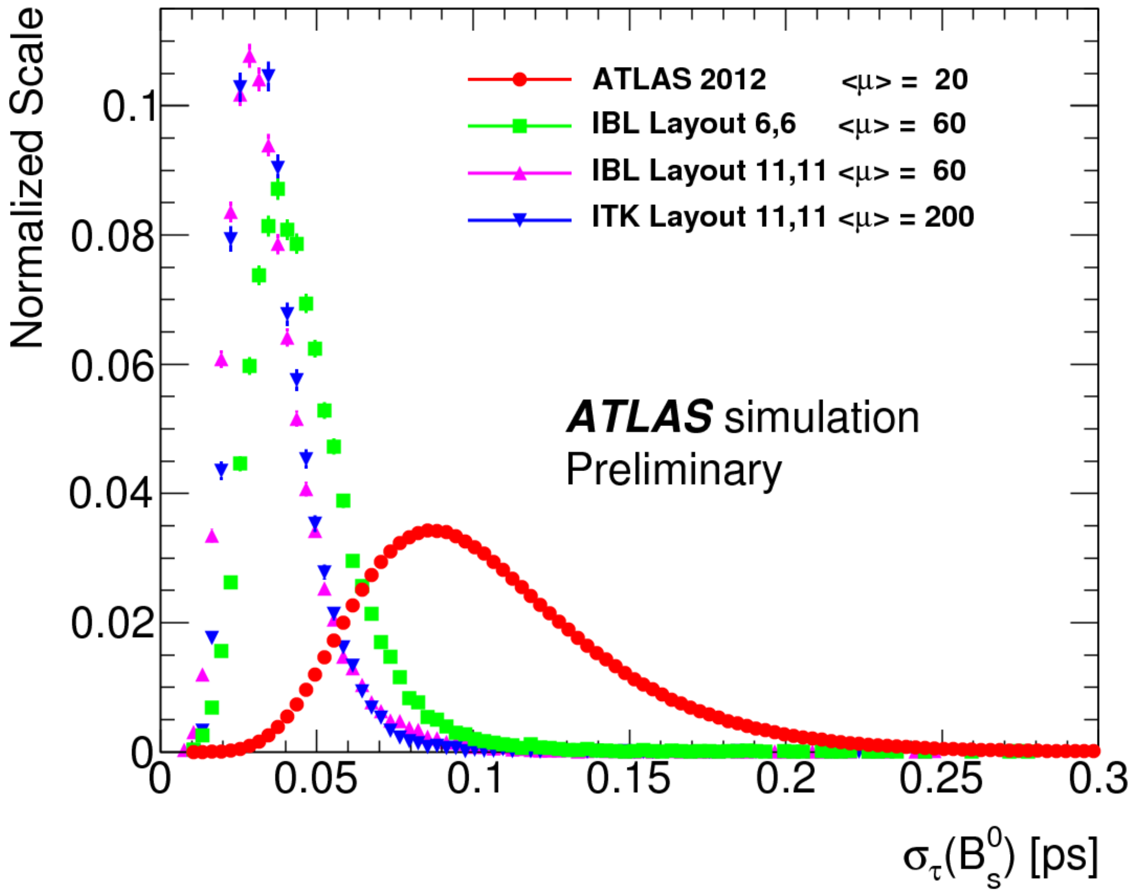
- HL-LHC: 5x LHC peak luminosity (7.5 x 10^{34} $cm^{-2}s^{-1}$)
- ATLAS detector upgrades
  (ITk, NSW, sRPCs, L0/L1 hardware trigger, EF software trigger)
- ATLAS B physics program continues in Run 3 and for HL-LHC
  - Similar focus as in Run 1 and Run 2
  - Possibly add final states with electrons (needs trigger)
- Exploit detector upgrades, esp. of ITk and muon system
  - Improved secondary vertex reconstruction
  - Better invariant mass resolution
  - Develop topological L0/L1 triggers to keep low lepton p_T thresholds
- Use increased statistics for measurements and searches, e.g.:
  - $B_s^0 \to J/\psi\ \phi$: CP violation
  - $B_{(s)}^0 \to \mu^+\mu^-$: rare decays

Supporting Material

$B_s^0 \to J/\psi\, \phi$ at HL-LHC (Backup 1)

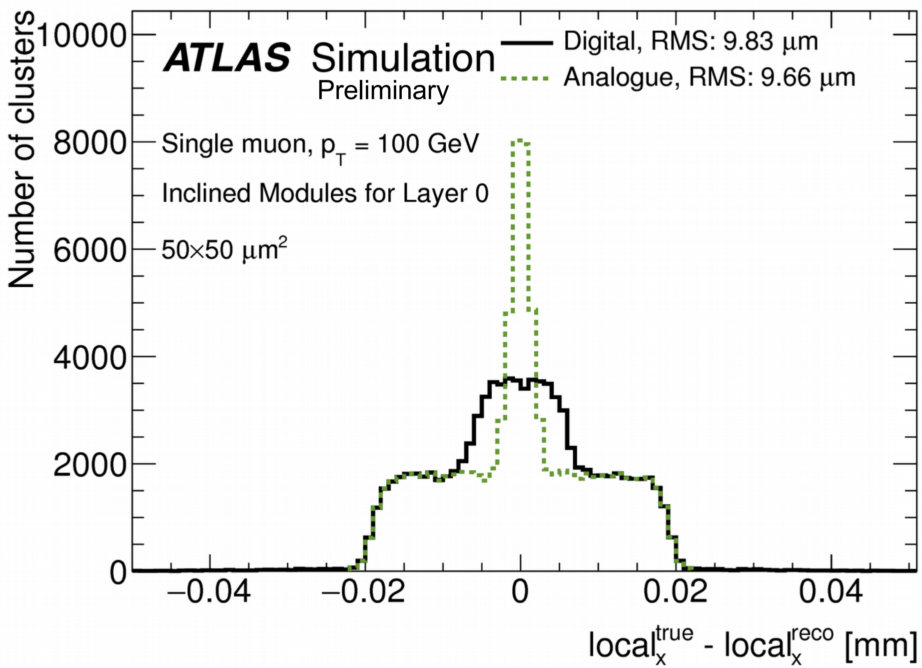
[ATL-PHYS-PUB-2013-010]

- Proper-time resolution σ_τ simulated for :
  - ATLAS 2012 layout (p_T(trigger $\mu^\pm$) > 4 GeV)
  - IBL layout (p_T(trigger $\mu^\pm$) > 6 GeV)
  - IBL layout (p_T(trigger $\mu^\pm$) > 11 GeV)
  - ITK layout (p_T(trigger $\mu^\pm$) > 11 GeV)

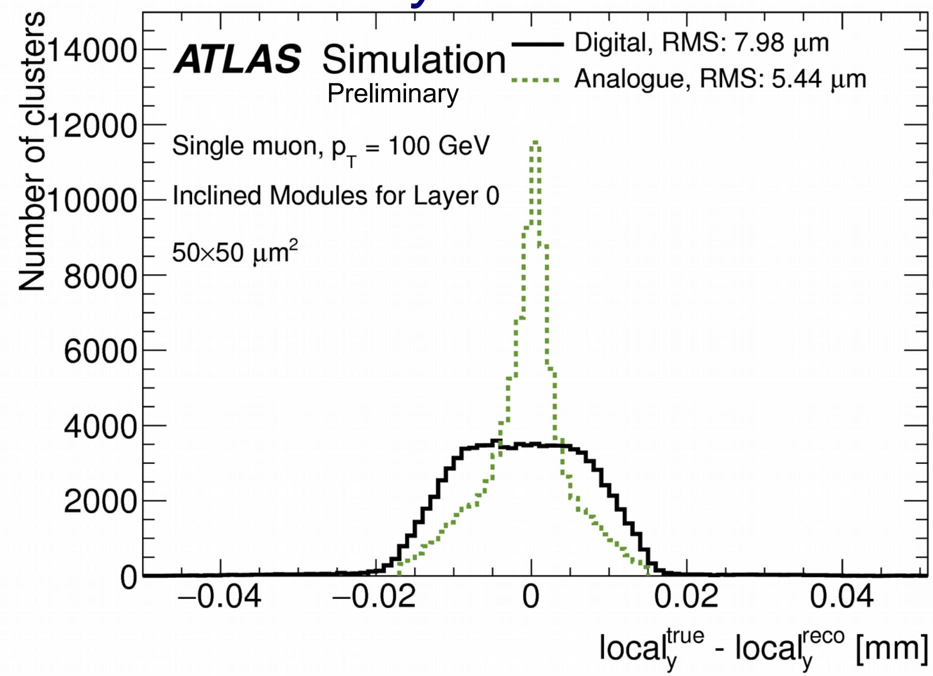


Muon Resolutions – Digital vs. Analogue Clusters

Local *x* resolution



Local *y* resolution



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

- Resolutions for single μ tracks (p_T = 100 GeV) for:
  - 50 x 50 μm² pixels with **digital** clustering
  - 50 x 50 μm² pixels with **anlogue** clustering
- Clear improvement in both coordinates for analogue clustering
- ➜ Expect improved vertexing resolution

Prospects for $B_{(s)}^0 \to \mu^+\mu^-$ – Mass Separation

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

Dedicated $B_s^0 \to \mu^+\mu^-$ MC:

- Run 2 conditions like 2015
- HL-LHC & HL-ATLAS:
  - $L_{inst} = 7.5 \times 10^{34}$ cm^{2}s^{-1} at 14 TeV CME $\langle\mu\rangle = 200$ pile-up events
  - ITK: inclined design, up to $|\eta| < 4$, 50 x 50 μm^2 pixels

Candidate selection ~ Run 1

- B_s^0: oppositely charged $\mu^\pm$, $p_T(\mu^\pm) > 5.5$ GeV
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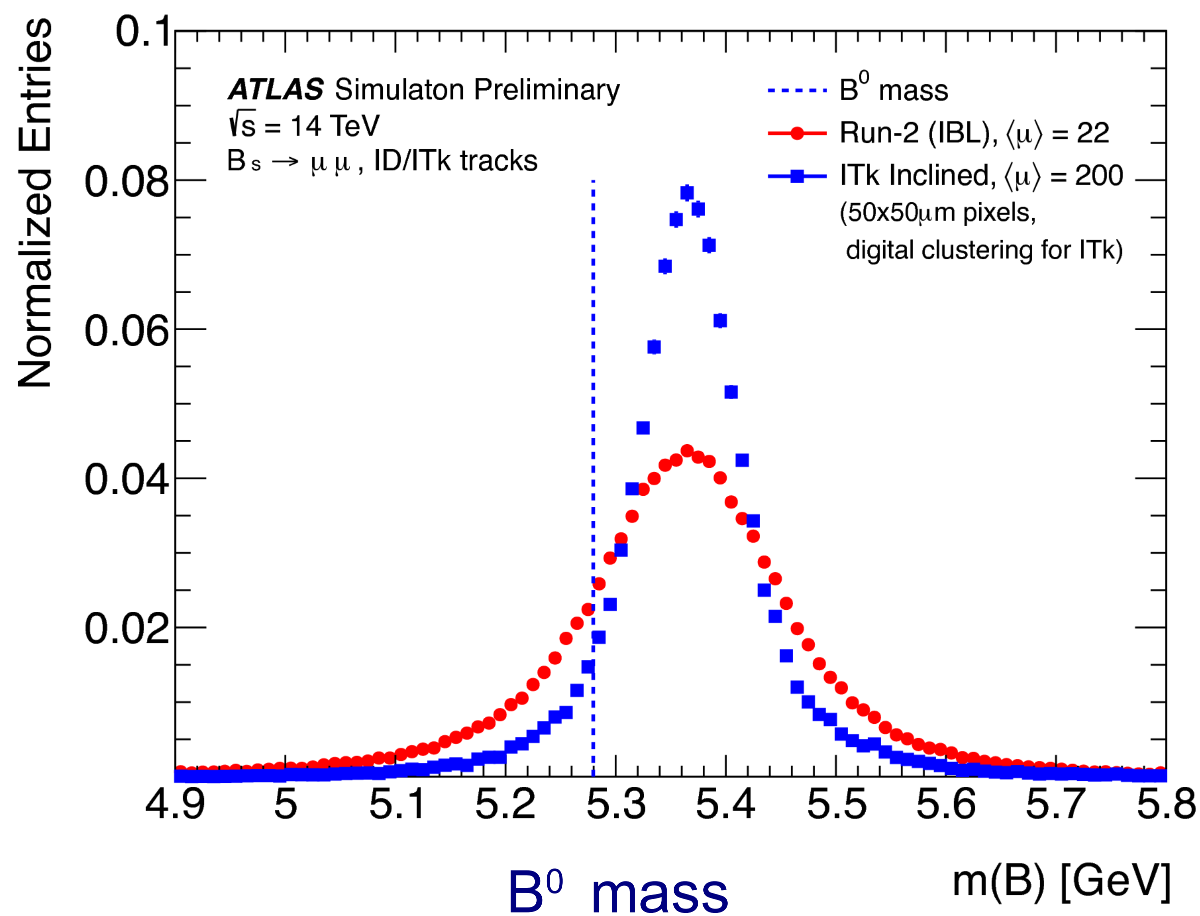
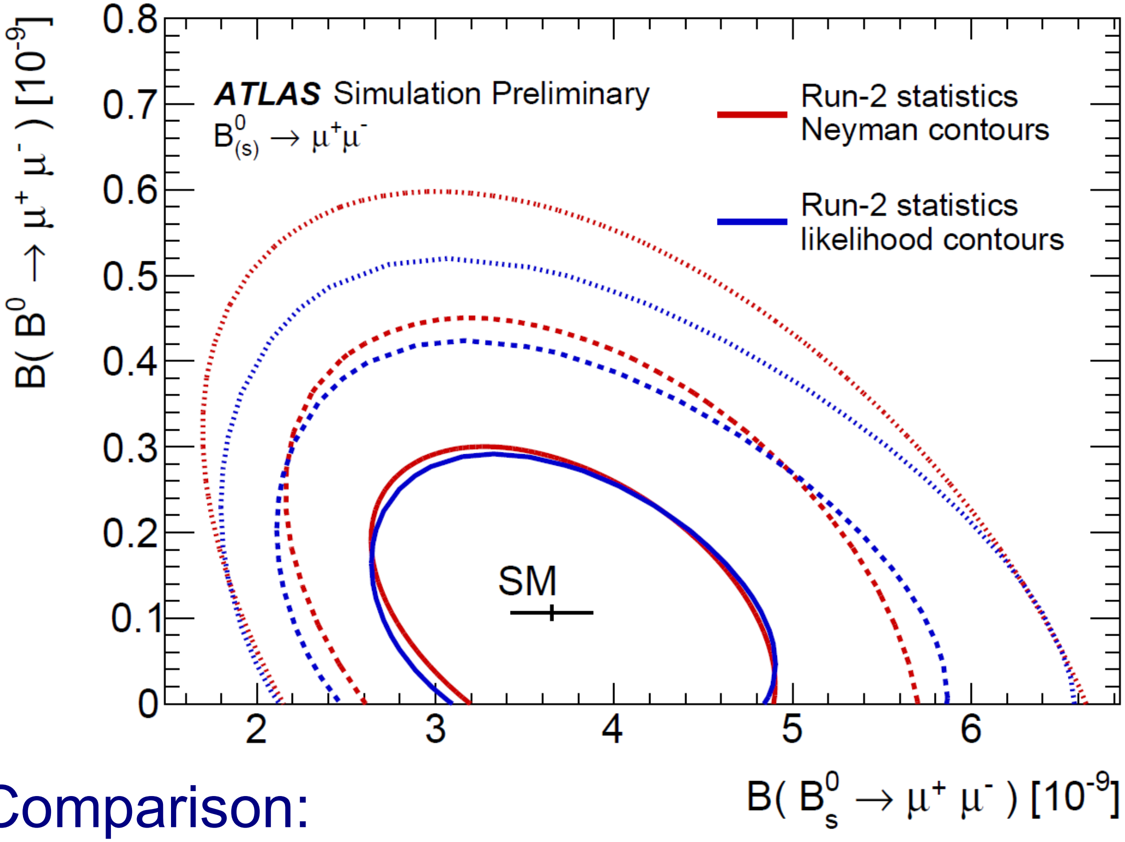


B^0 mass

$B_{(s)}^0 \to \mu^+\mu^-$ – Contour Comparison for Run 2

[ATL-PHYS-PUB-2018-005]



Comparison:

- Confidence regions for 2D Neyman belt construction
- Profile likelihood contours at constant $\Delta \log L$

- Contours are reasonably consistent for 68.3%
- Divergences for larger areas because of non-Gaussian contributions to likelihood

BR($B_{(s)}^0 \rightarrow \mu^+\mu^-$) Prospects – Run 2 & HL-LHC

Uncertainties on BR($B_s^0 \rightarrow \mu^+ \mu^-$) and BR($B^0 \rightarrow \mu^+ \mu^-$): [ATL-PHYS-PUB-2018-005]

		$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$		$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$	
		stat $[10^{-10}]$	stat + syst $[10^{-10}]$	stat $[10^{-10}]$	stat + syst $[10^{-10}]$
Run 2	7x N_{R1}	7.0	8.3	1.42	1.43
HL-LHC: Conservative	15x N_{R1}	3.2	5.5	0.53	0.54
HL-LHC: Intermediate	60x N_{R1}	1.9	4.7	0.30	0.31
HL-LHC: High-yield	75x N_{R1}	1.8	4.6	0.27	0.28

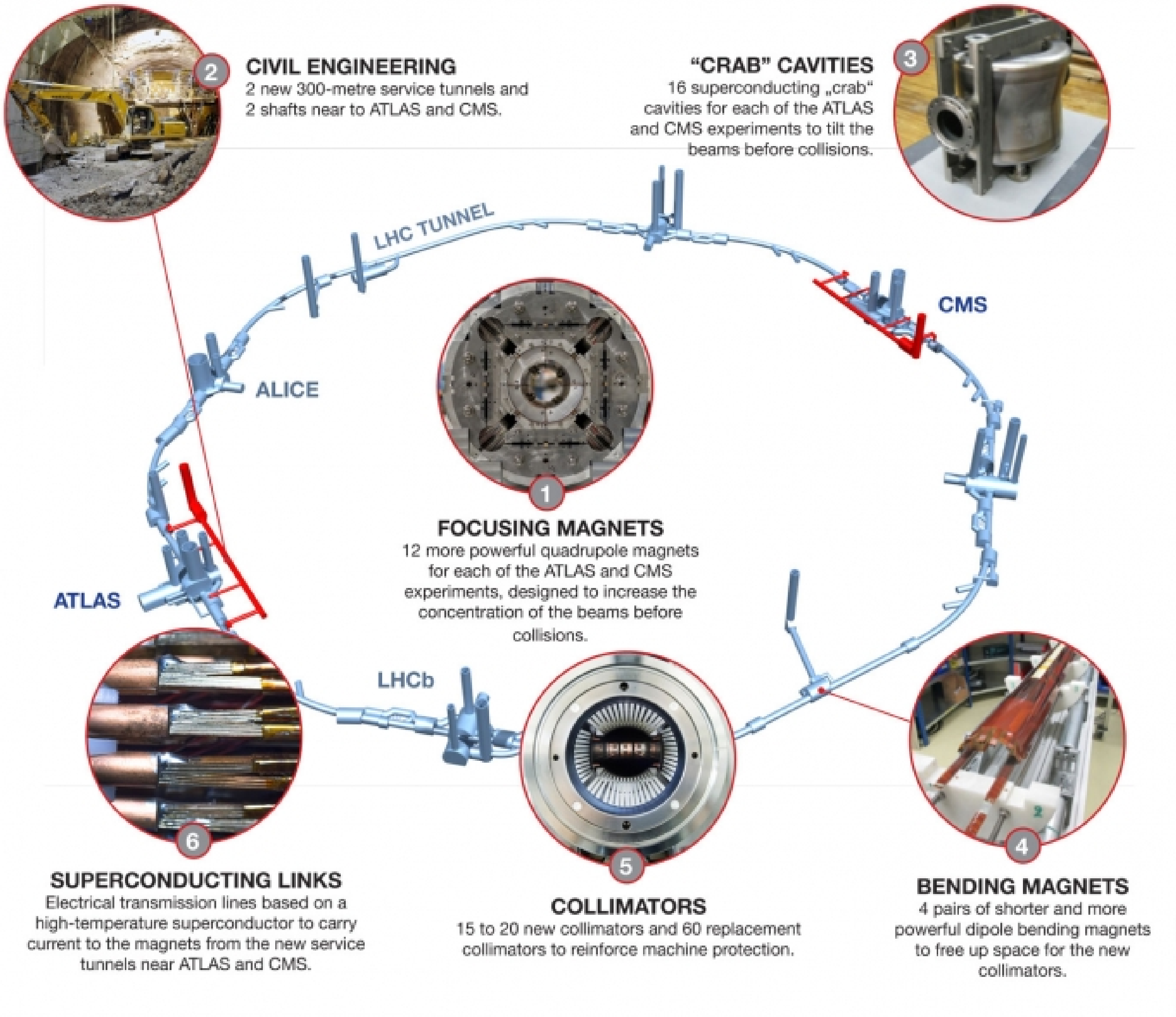
CMS & LHCb combined (Run 1): [Nature 522 (2015) 68]

- BR($B_s^0 \rightarrow \mu^+ \mu^-$) = $2.8^{+0.7}_{-0.6}$)x10^{-9}, BR($B^0 \rightarrow \mu^+ \mu^-$) = ($3.9^{+1.6}_{-1.4}$)x$10^{-10}$

LHCb (2015+2016):

- BR($B_s^0 \rightarrow \mu^+ \mu^-$) = $3.0 \pm 0.6^{+0.3}_{-0.2}$)x$10^{-9}$ [Phys. Rev. Let. 118 (2017) 191801]

Machine Upgrades for HL-LHC



[CERN-2017-007-M]

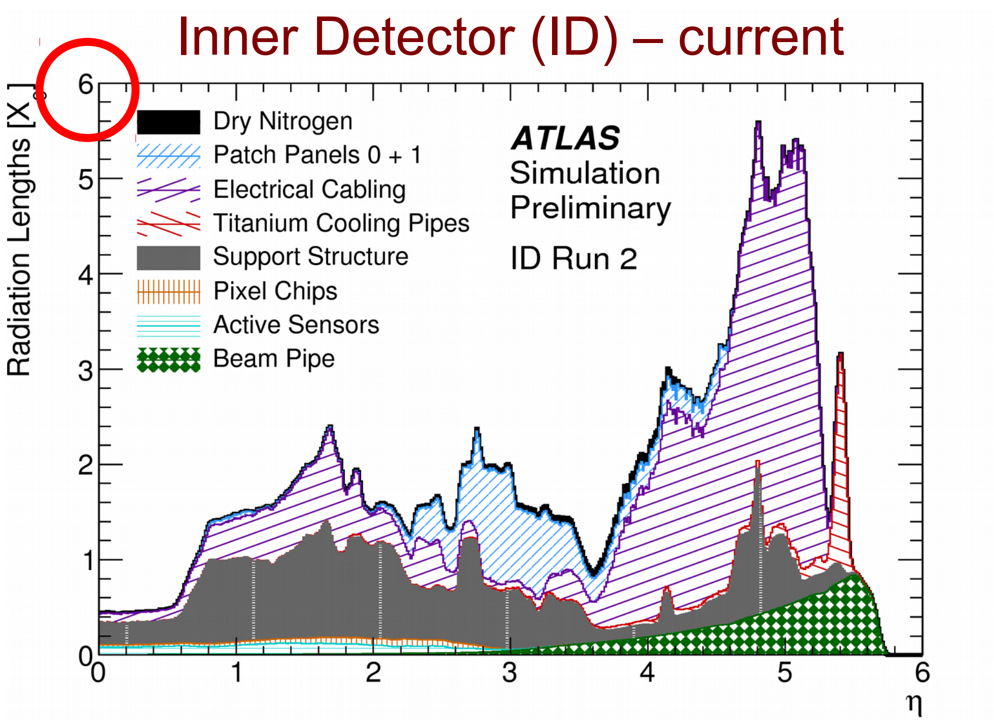
New SC magnets (4 + 12):
- Nb_3Sn → 12 – 13 T
  → 2x aperture for dipole and quadrupole magnets

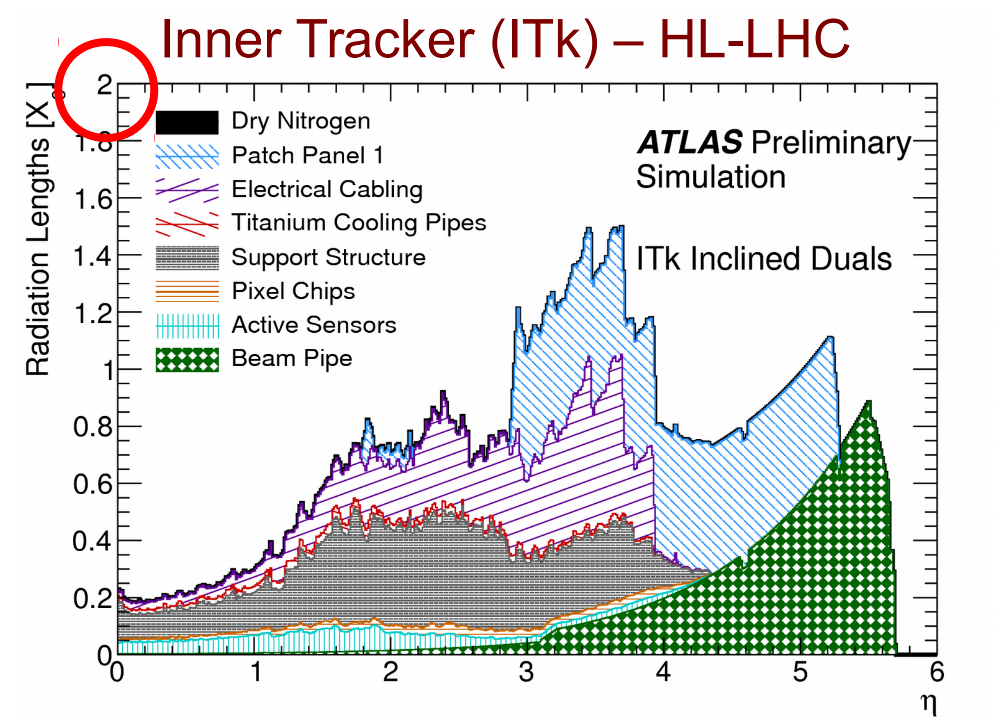
Crab cavities:
- Increase luminosity
- Reduce beam-beam effects

New SC cables (MgB_2):
- Sustaining 100 kA
  → power converters into service gallery
- 1.2 km (~5%) of LHC ring with new components

Pre-accelerators:
- LINAC4 (2020)
  → 2x beam brightness
- Improvements for PS Booster, PS, SPS

ATLAS ID and ITk Material Budgets



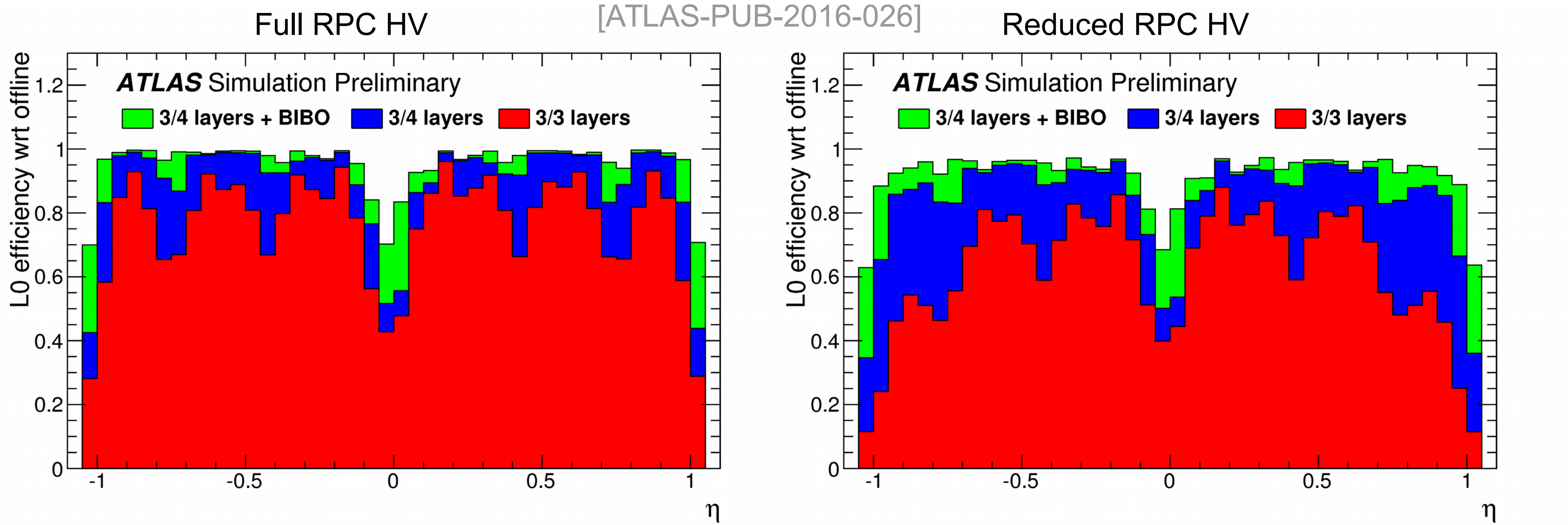


[CERN-LHCC-2017-020, ATLAS-TDR-029]

- Material budget of ITk is greatly reduced.

ATLAS Muon L0 Trigger with new BI RPCs (1)

[ATLAS-PUB-2016-026]

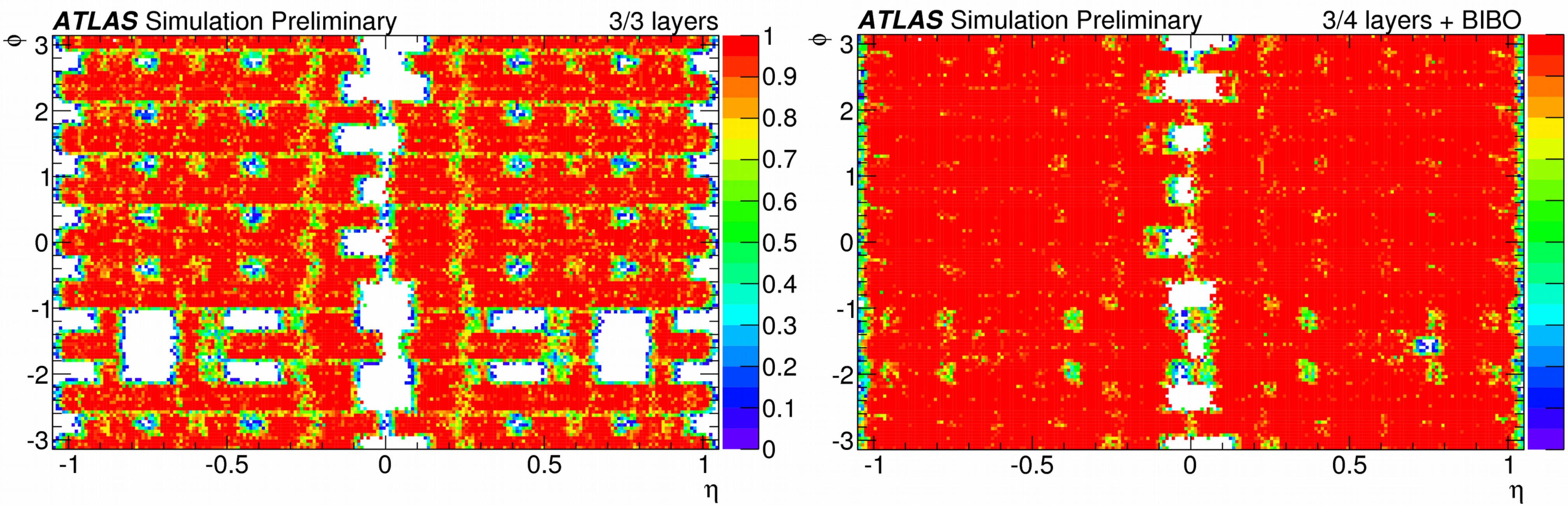


- L0 trigger acceptance for reco'd combined muon tracks within $|\eta| < 1.05$ increases from 78% → 96%

- L0 trigger acceptance for reco'd combined muon tracks within $|\eta| < 1.05$ increases from 57 … 75% → 92%
- "worst case" szenario

ATLAS Muon L0 Trigger with new BI RPCs (2)

[ATLAS-PUB-2016-026]

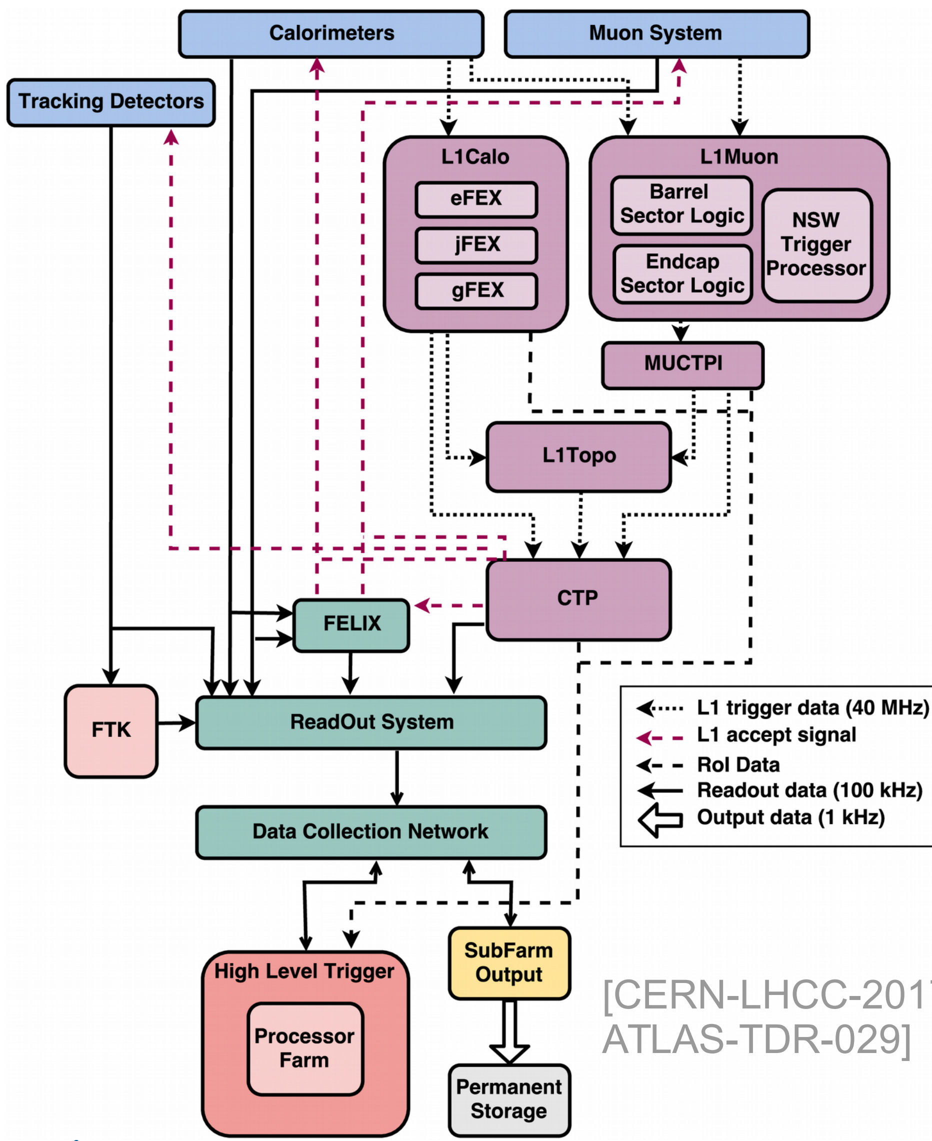


- L0 trigger acceptance for reco'd combined muon tracks
- with present trigger setup

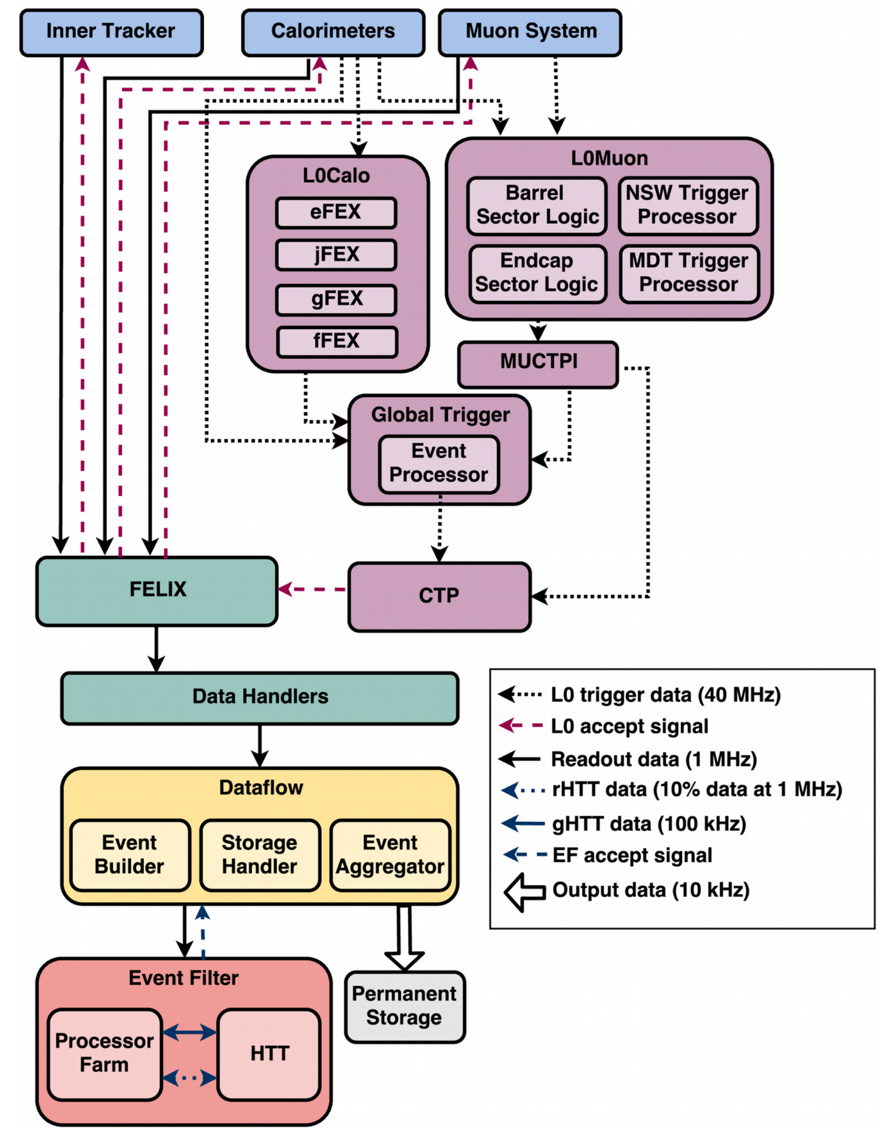
- L0 trigger acceptance for reco'd combined muon tracks
- with optimal L0 trigger setup

ATLAS Trigger Upgrades

L1 trigger (phase 1, Run 3)



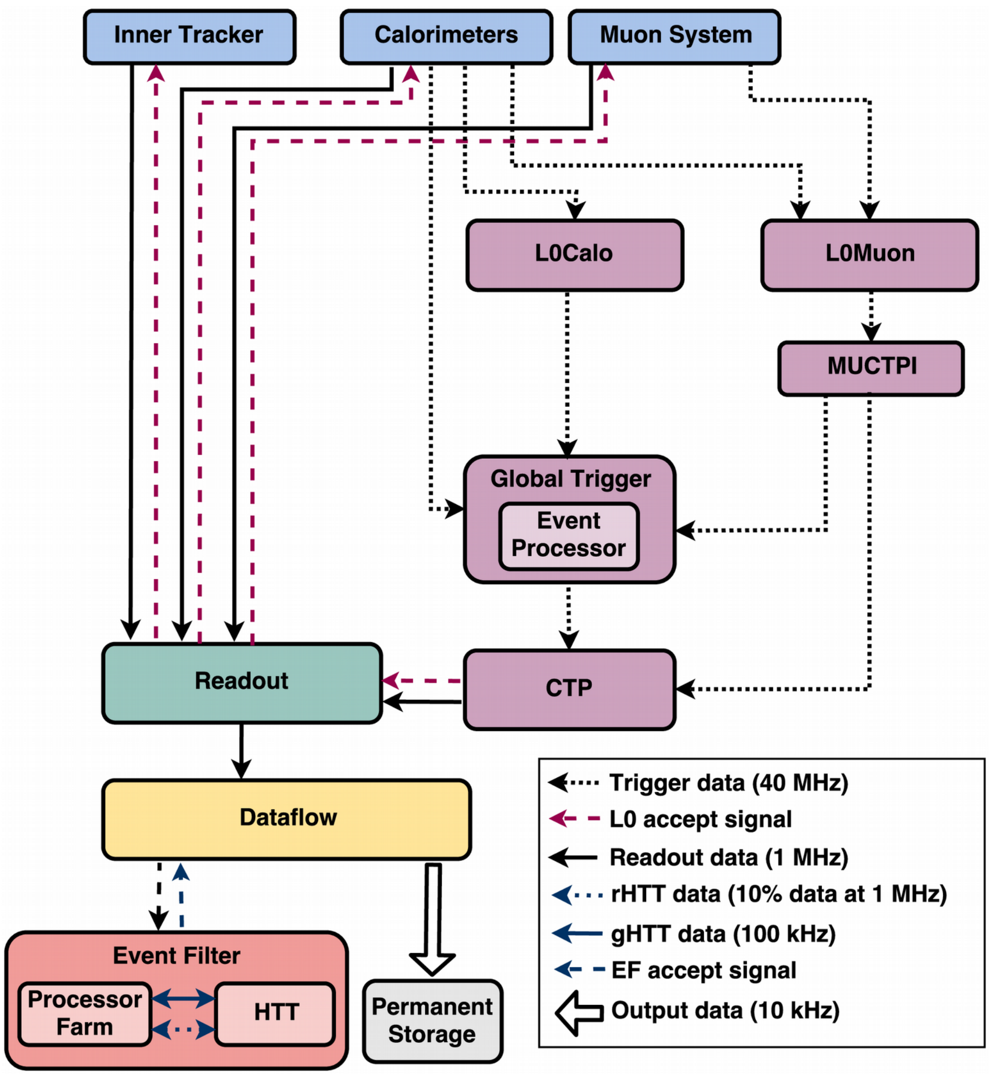
L0 trigger (phase 2, baseline)



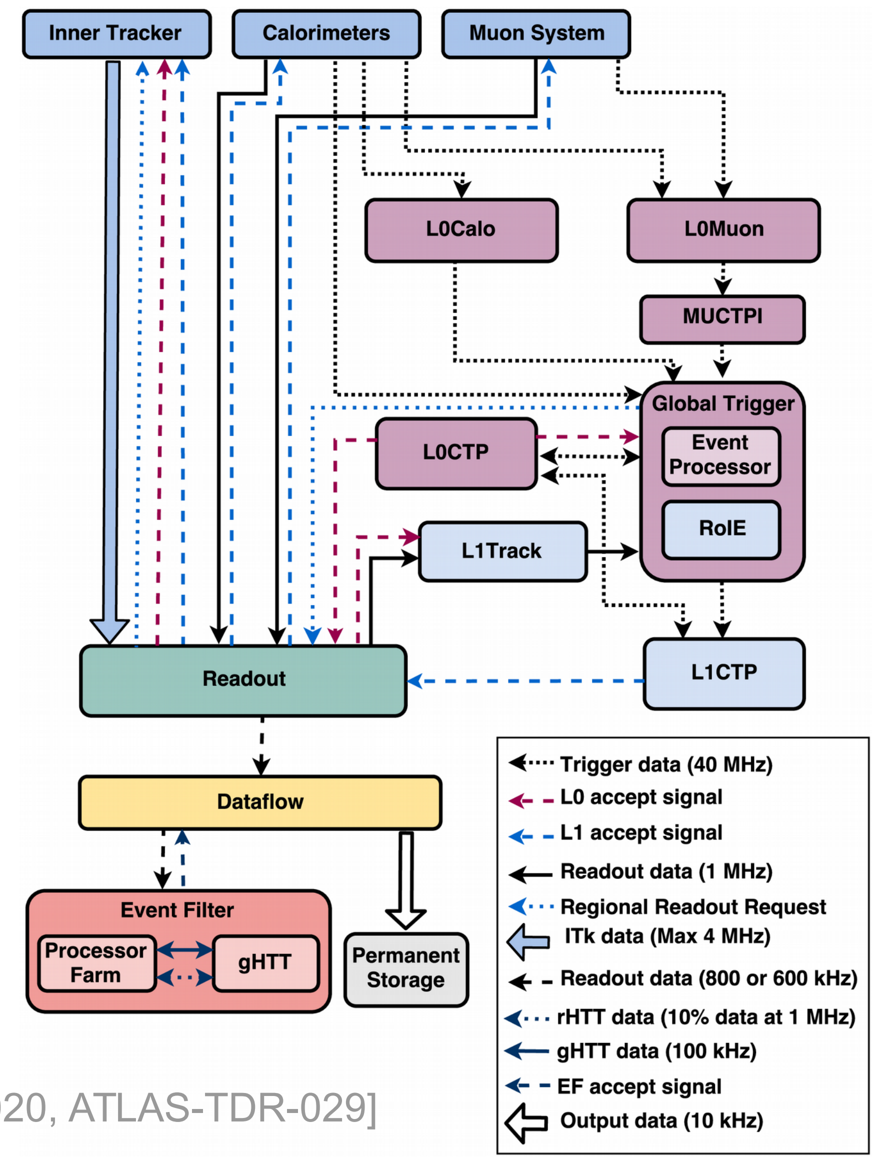
[CERN-LHCC-2017-020, ATLAS-TDR-029]

ATLAS HL-LHC Trigger Upgrade Options

L0 trigger (baseline)

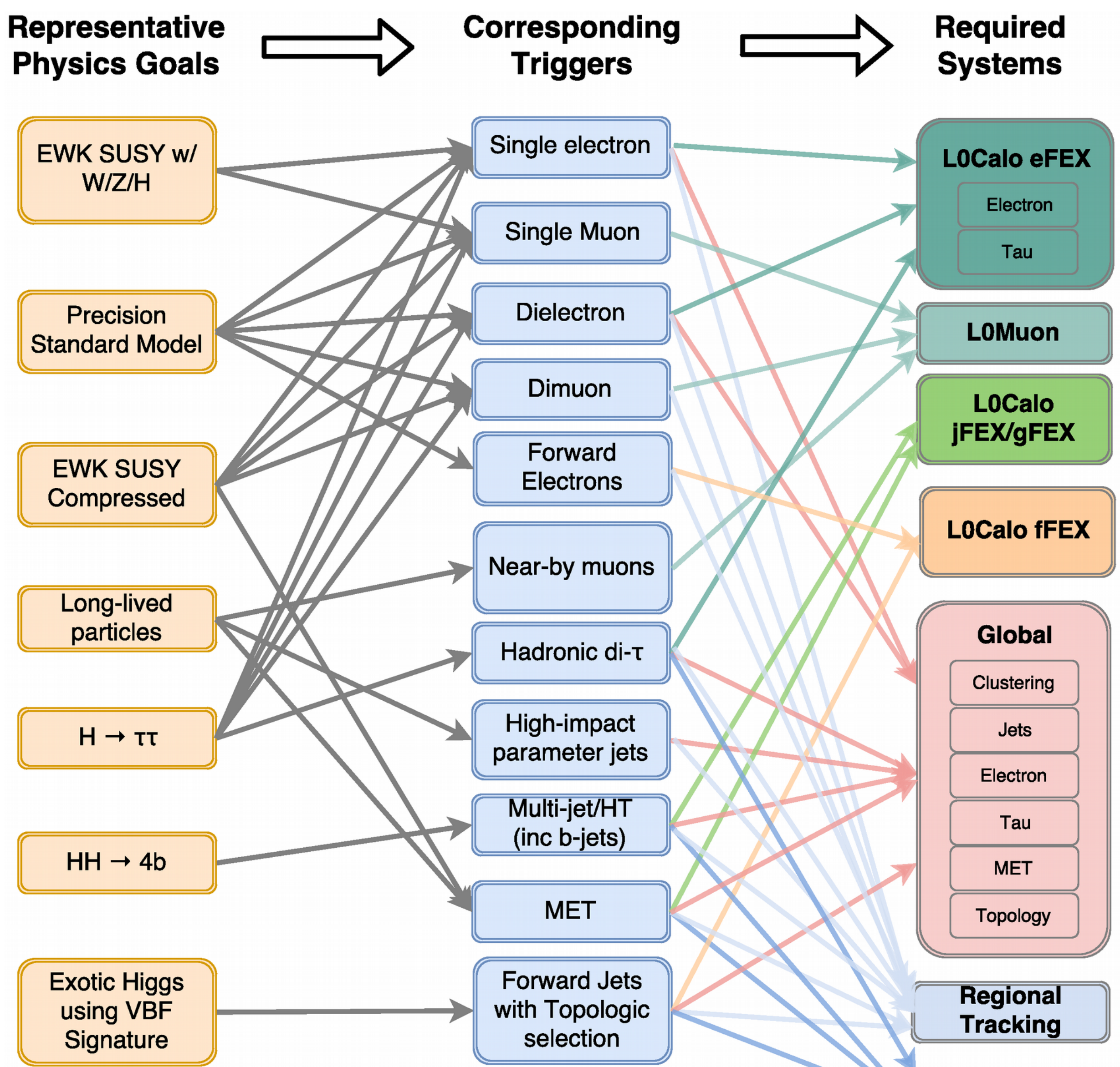


Dual L0 & L1 trigger



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

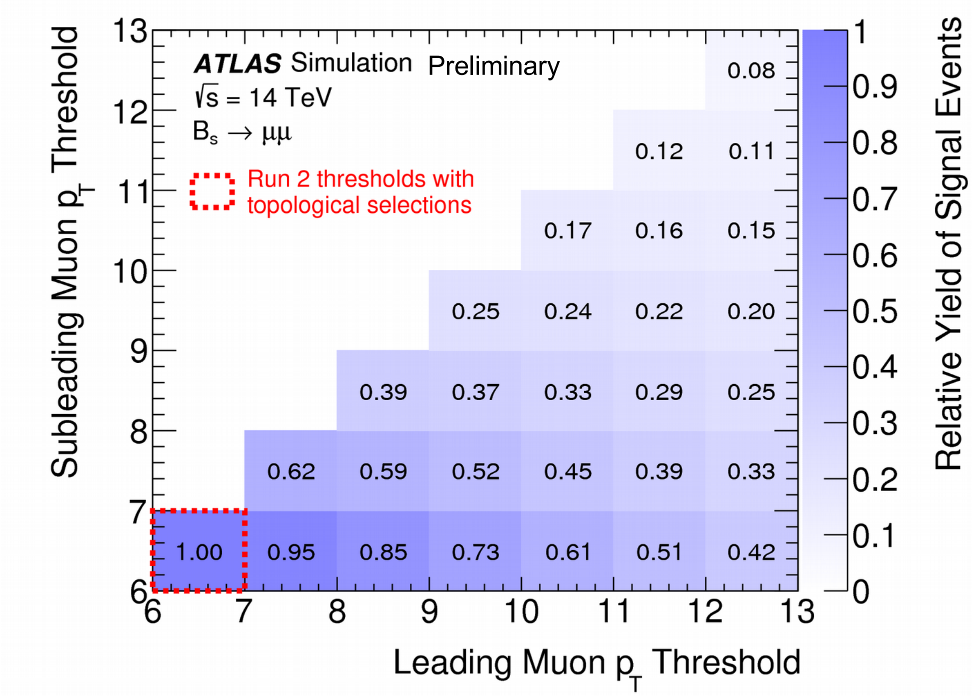
ATLAS HL-LHC Trigger and Physics Goals



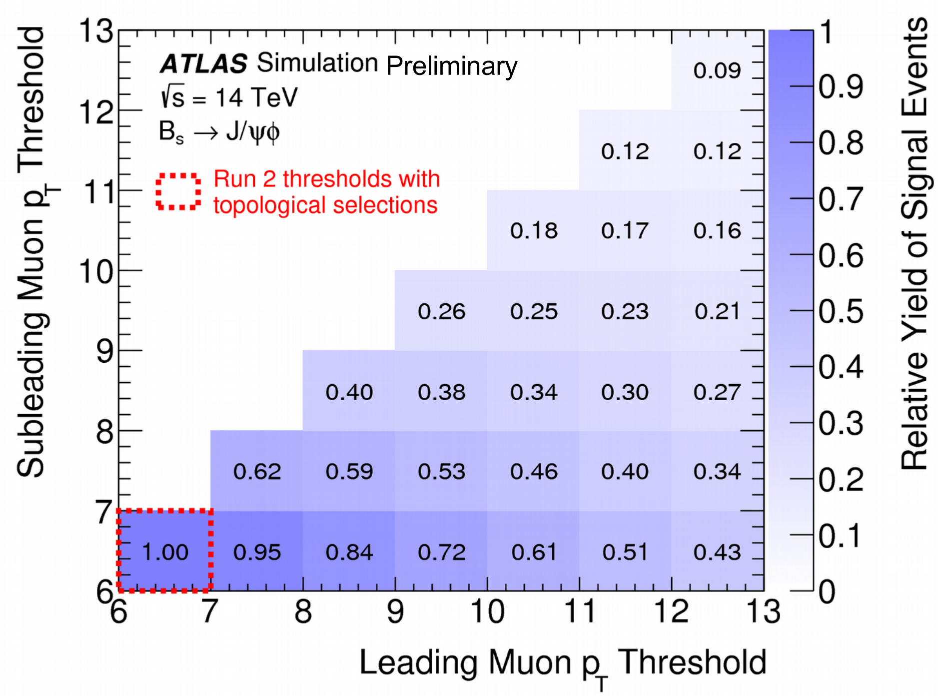
[CERN-LHCC-2017-020, ATLAS-TDR-029]

Relative Yield vs. $(p_T(\mu_1),p_T(\mu_2))$ Threshold

$B_s^0 \rightarrow \mu^+\mu^-$



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

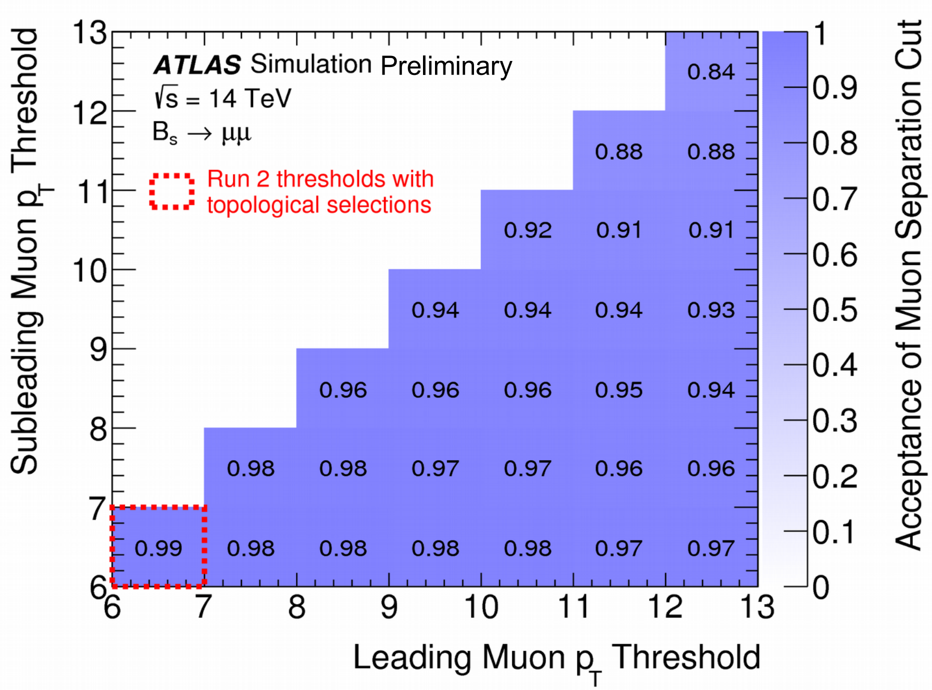


[CERN-LHCC-2017-020, ATLAS-TDR-029]

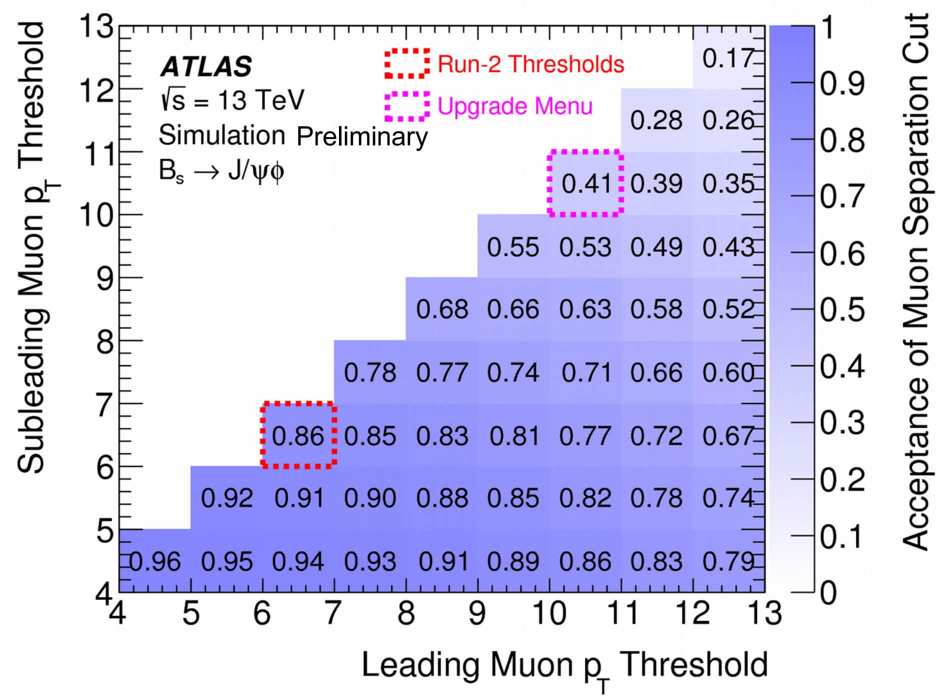
- Normalized to $p_T(\mu_1) > 6$ GeV & $p_T(\mu_2) > 6$ GeV (lowest unprescaled di-μ trigger in Run 2)
- Run ½ baseline offline cuts applied

Relative Yield with Topological Selection

$B_s^0 \to \mu^+\mu^-$



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



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

- Separation of muons by either $|\Delta\eta(\mu^+,\mu^-)| > 0.2$ rad or $|\Delta\phi(\mu^+,\mu^-)| > 0.2$ rad (typical L1 muon trigger granularity)
- Normalized to $p_T(\mu_1) > 6$ GeV & $p_T(\mu_2) > 6$ GeV
- Run ½ baseline offline cuts applied
- Work ongoing to improve trigger acceptance for near-by muons