ATLAS Measurements of CP Violation and Rare Decays in Beauty Mesons

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on behalf of the ATLAS collaboration

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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

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FSP 103 ATLAS

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Introduction

New Physics beyond the Standard Model in B meson decays:

- Branching fractions in rare decays:
  $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
  - ATLAS result with 36.2 fb^{-1} (effectively 26.3 fb^{-1}) of 13 TeV LHC data (Run 2, 2015-2016) + combination with 25 fb^{-1} of 7-8 TeV LHC data (Run 1)
    [JHEP04 (2019) 098]
- CP violation parameters ϕ_s and $\Delta\Gamma_s$
  $B_s^0 \to J/\psi\, \phi$
  - ATLAS result with 80.5 fb^{-1} of 13 TeV LHC data (Run 2, 2015-2017) + combination with 19.2 fb^{-1} of 7-8 TeV LHC data (Run 1)
    [ATLAS-CONF-2019-009]

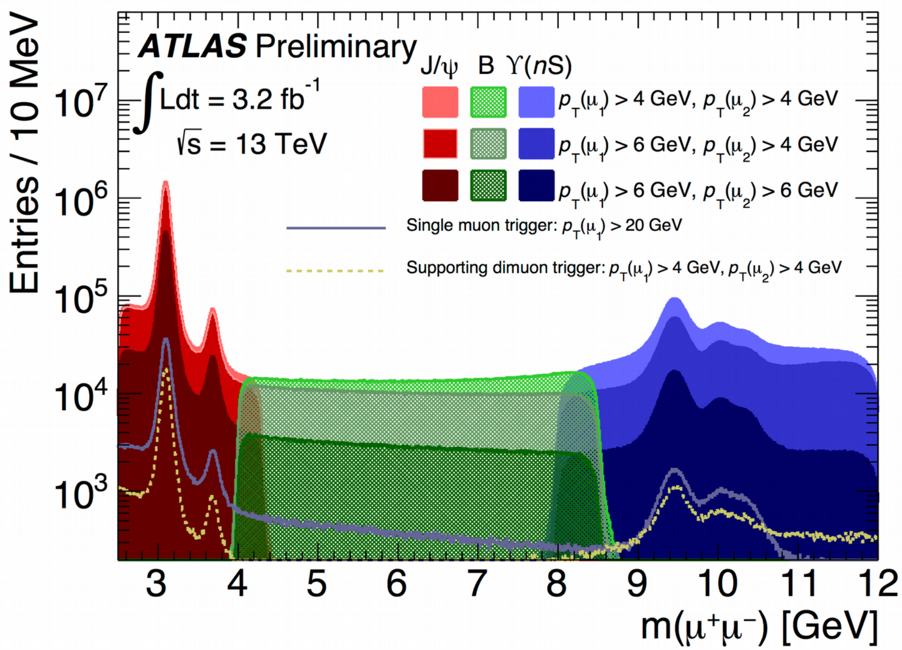
Prospects at the HL-LHC:

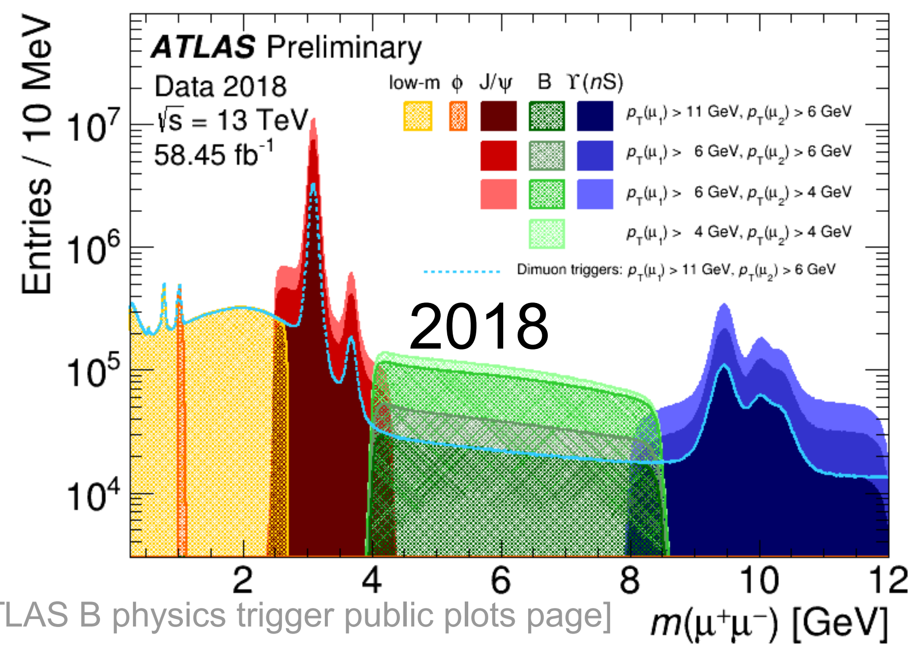
- $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
  [ATL-PHYS-PUB-2018-005]
- $B_s^0 \to J/\psi\, \phi$
  [ATL-PHYS-PUB-2018-041]

ATLAS B Physics Triggers

Mostly based on di-muon triggers

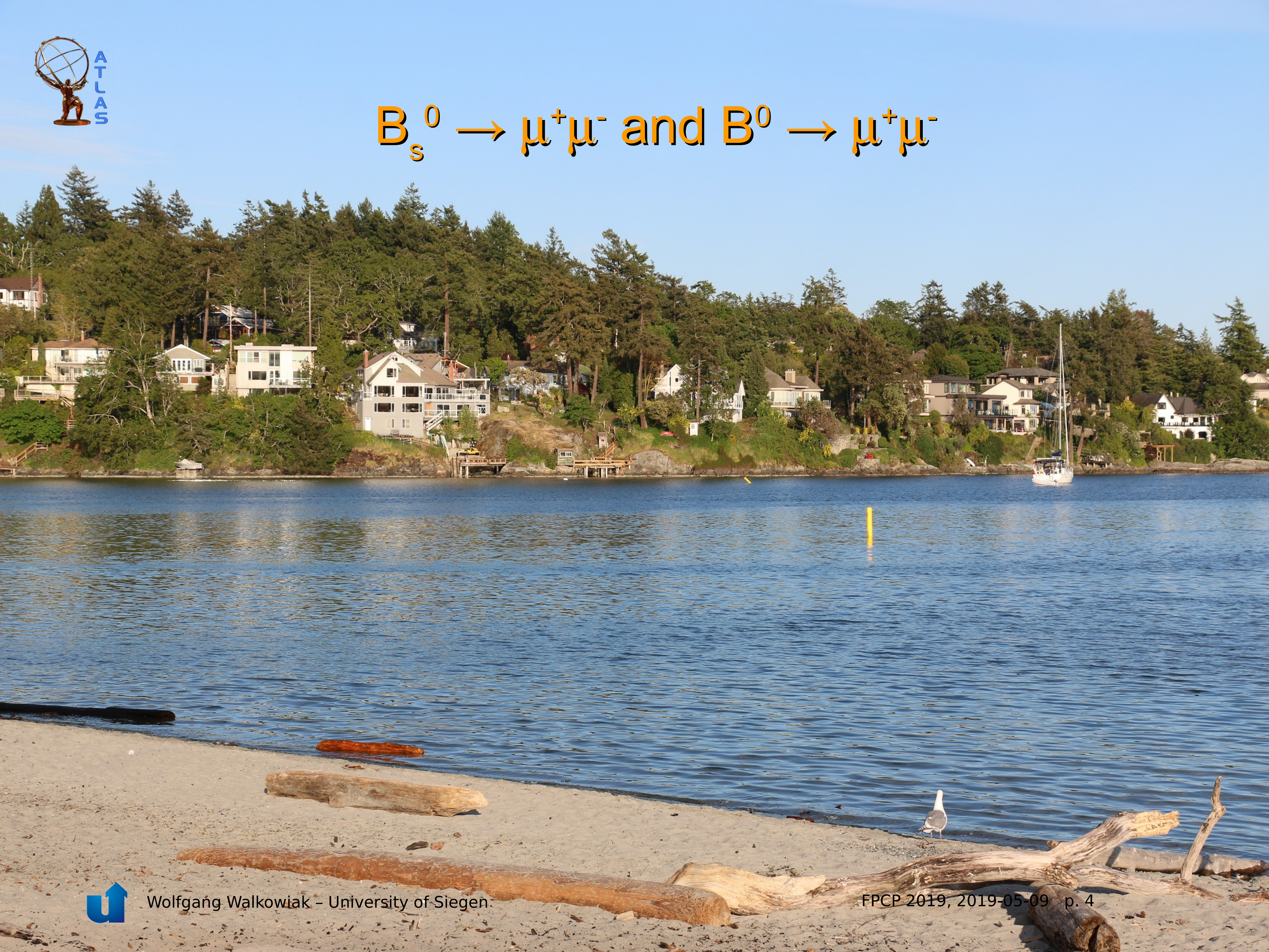
- $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ analysis (Run 2, 2015-2016)
  - two muons with $p_{T,1} > 6$ GeV, $p_{T,2} > 4$ GeV in $|\eta| < 2.5$, 4 GeV < $m_{\mu\mu}$ < 8.5 GeV, $L_{xy} > 0$ (2016)
- $B_s^0 \rightarrow J/\psi\, \phi$ analysis (Run 2, 2015-2017)
  - $J/\psi \rightarrow \mu^+\mu^-$ decays with μ-p_T thresholds of either 4 GeV or 6 GeV (combination of multiple triggers)



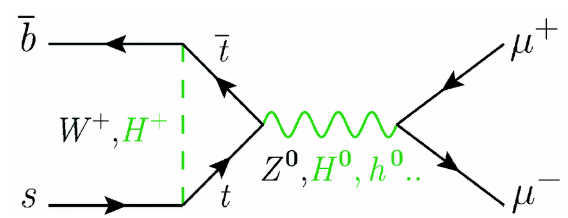


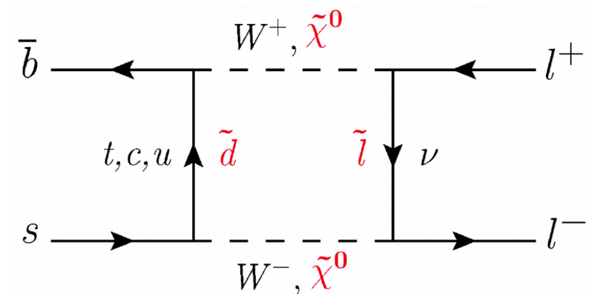
[ATLAS B physics trigger public plots page]

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



$B_{(s)}{}^0 \to \mu^+\mu^-$ – Run 1





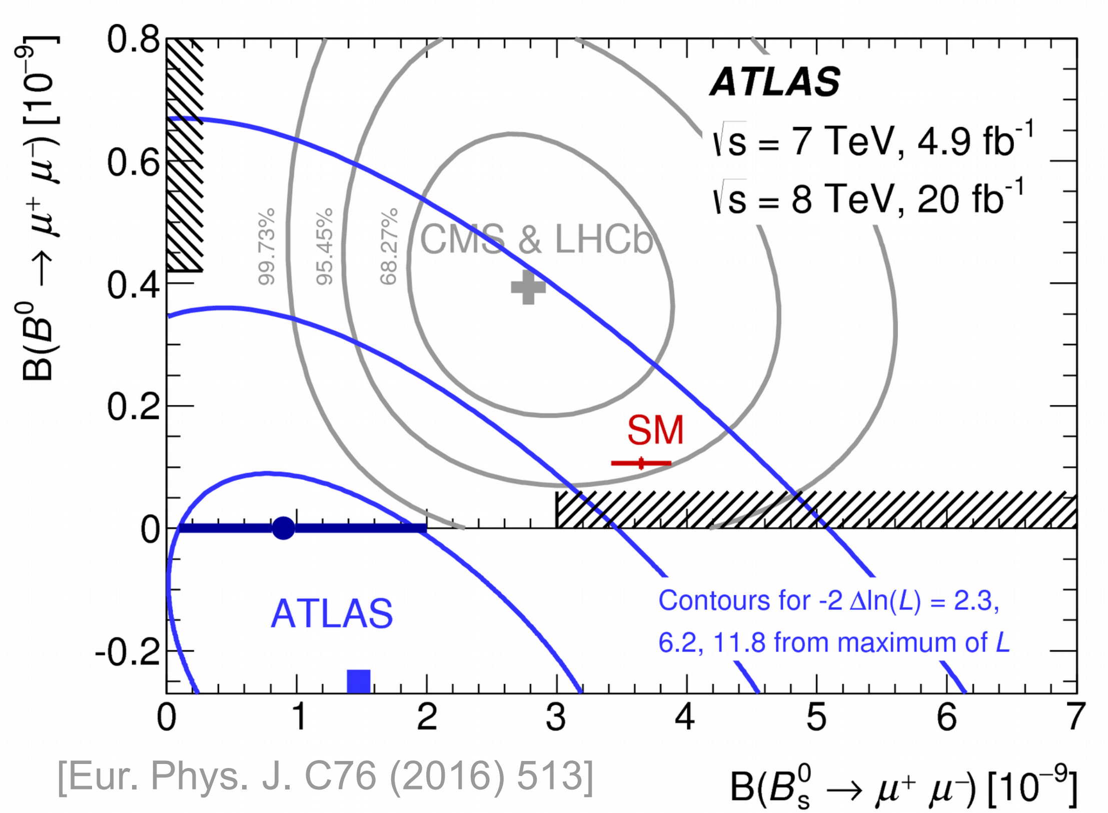
BR($B_{(s)}{}^0 \to \mu^+\mu^-$) w.r.t. BR($B^\pm \to J/\psi\ K^\pm$)

- Sensitive to New Physics in decay via loop diagrams

Run 1 result:

- 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 BR compared to CMS&LHCb Run 1 combined
- Tension in B^0 reduced with LHCb Run 2 measurement

BR($B^0 \to \mu^+\mu^-$) < 3.4×10^{-10} at 95% CL
[PRL 118 (2017) 191801]

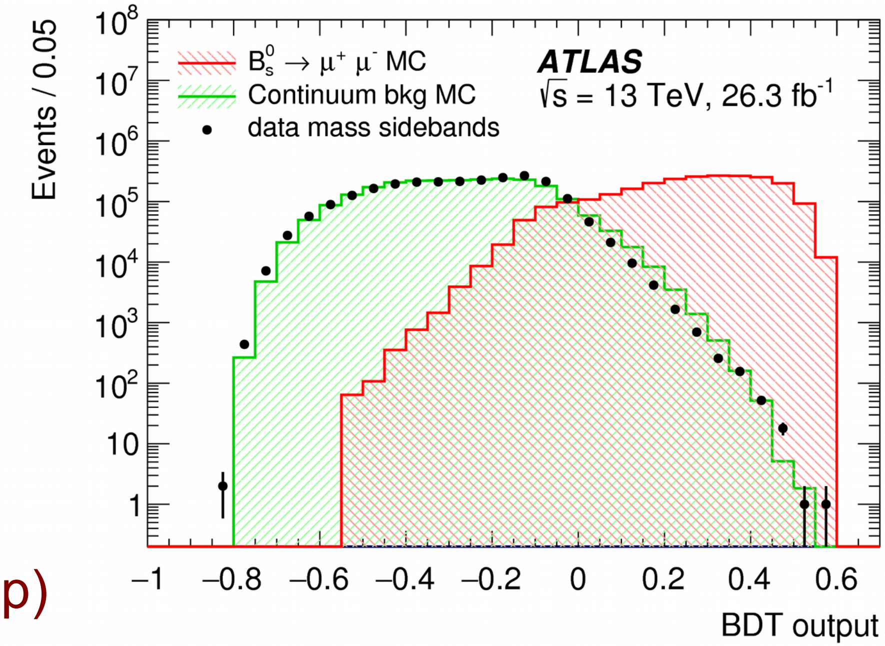


[Eur. Phys. J. C76 (2016) 513]

$B_{(s)}^0 \rightarrow \mu^+\mu^-$ – Backgrounds

Combinatorial $(b \rightarrow \mu X) \times (\bar{b} \rightarrow \mu X)$ pairs

- 15-variable BDT to reject dominant background
- Trained and tested on data sidebands and simulated signal events

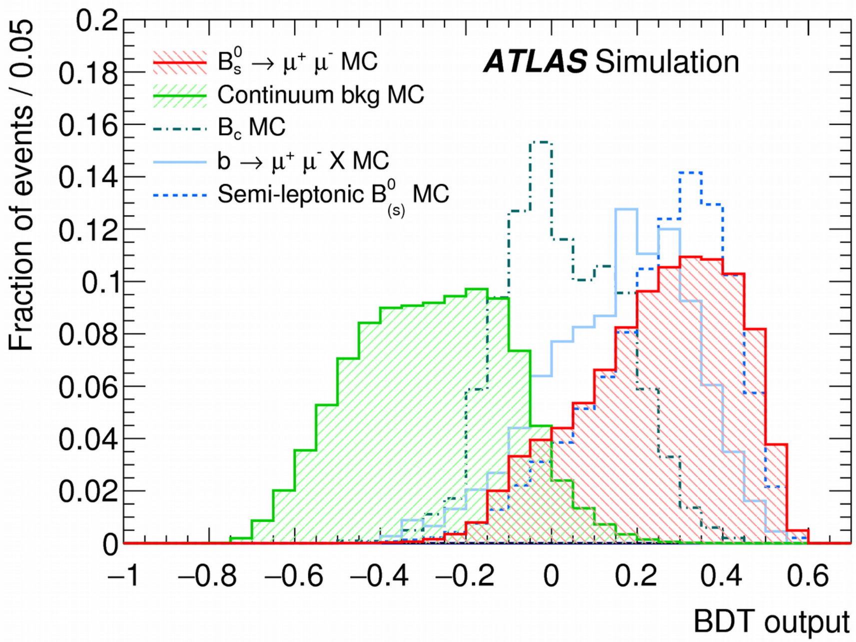


Partially reconstructed $(b \rightarrow \mu\mu X)$

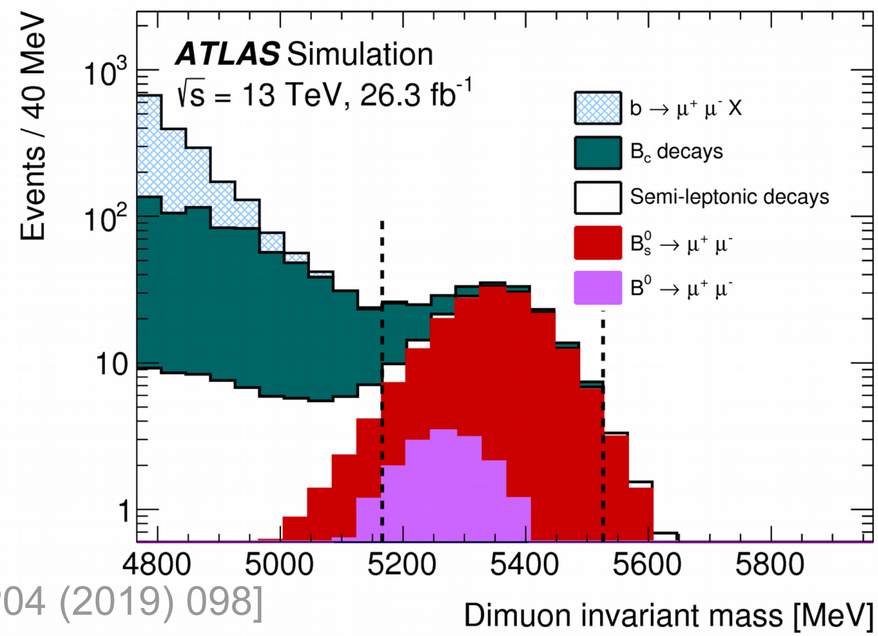
- Real di-muons at low $m_{\mu\mu}$

$B \rightarrow \mu\mu X$, $B \rightarrow c\mu X \rightarrow s(d)\mu\mu X$, $B_c \rightarrow J/\psi\, \mu\nu$

Semi-leptonic decays $(B_{(s)}/\Lambda_b^0 \rightarrow h\mu\nu$, $h = \pi, K, p)$



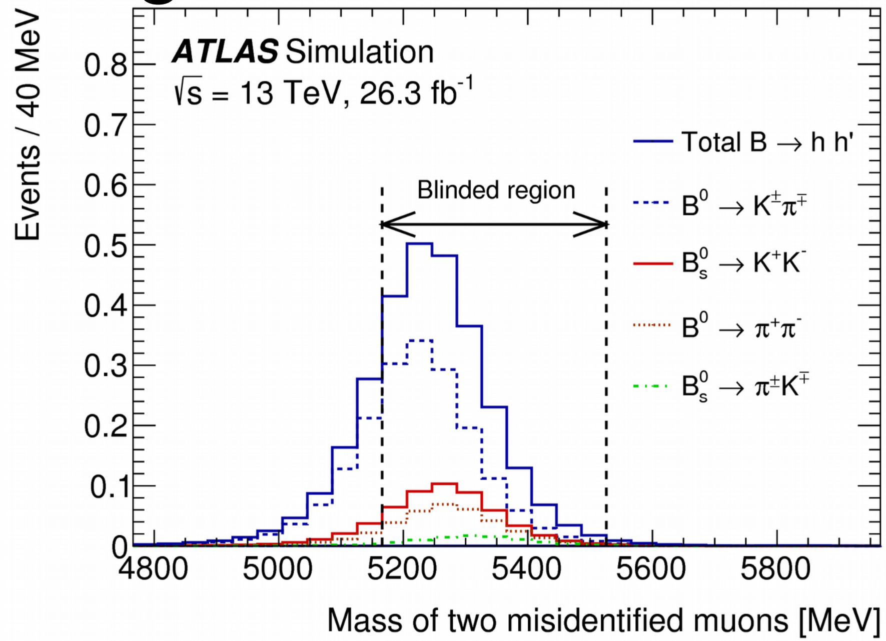
[JHEP04 (2019) 098]



$B_{(s)}^0 \rightarrow \mu^+\mu^-$ – Peaking Background

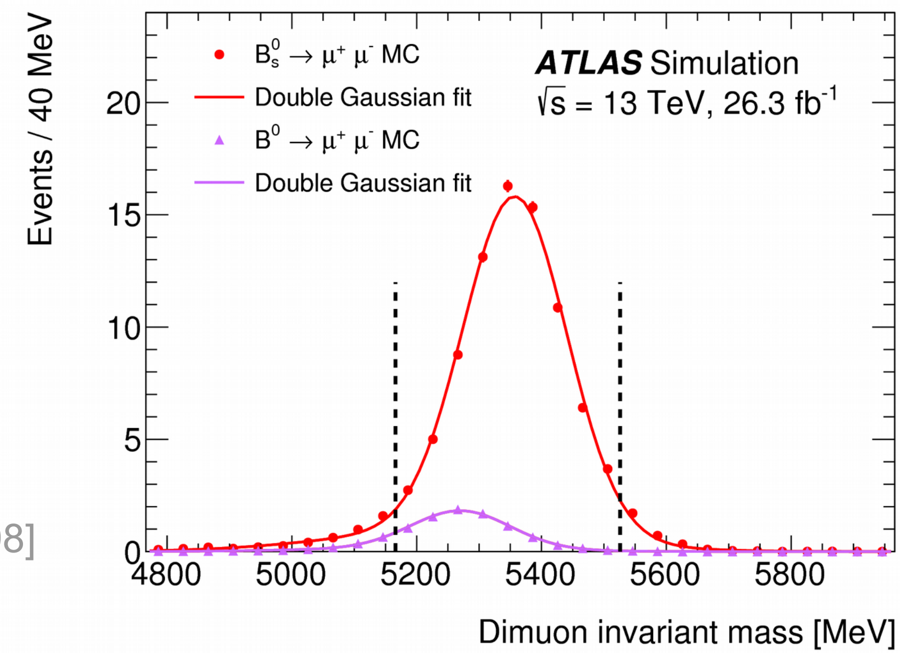
B → hh' (h = $\pi^\pm$, $K^\pm$)

- Superimposed to signal
- Small contribution
- Studied with MC
- Validated in data control regions
- Fake rates with "tight" μ selection:
  - π: 0.1%
  - K: 0.08%
  - p: < 0.01%
  - ➔ reduces mis-ID by 0.39^2
  - ➔ in SR: 2.9 ± 2.0 events



Limited mass resolution:

- Overlap of B^0_s and B^0 peaks
- ➔ statistically separated by fit



[JHEP04 (2019) 098]

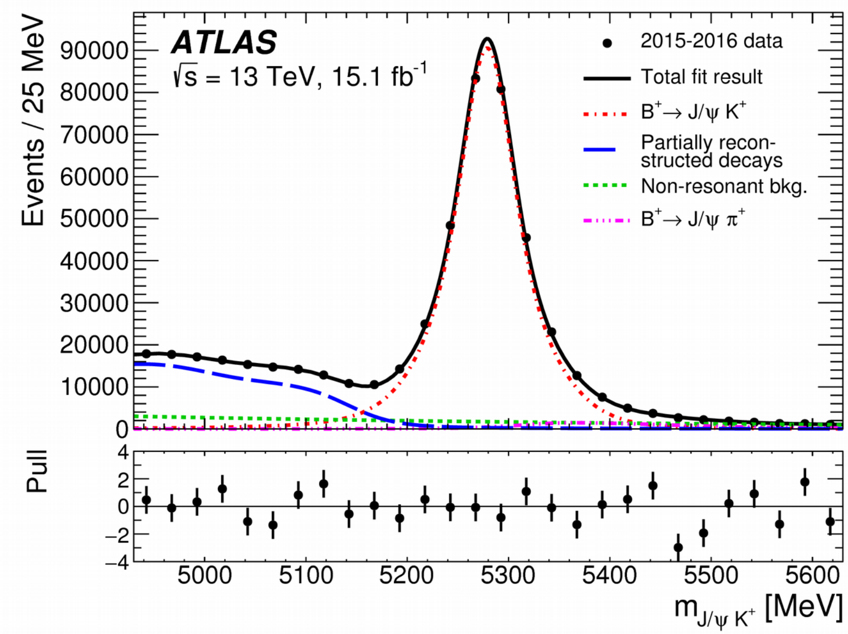
$B_{(s)}^0 \to \mu^+\mu^-$ – Normalization Channel

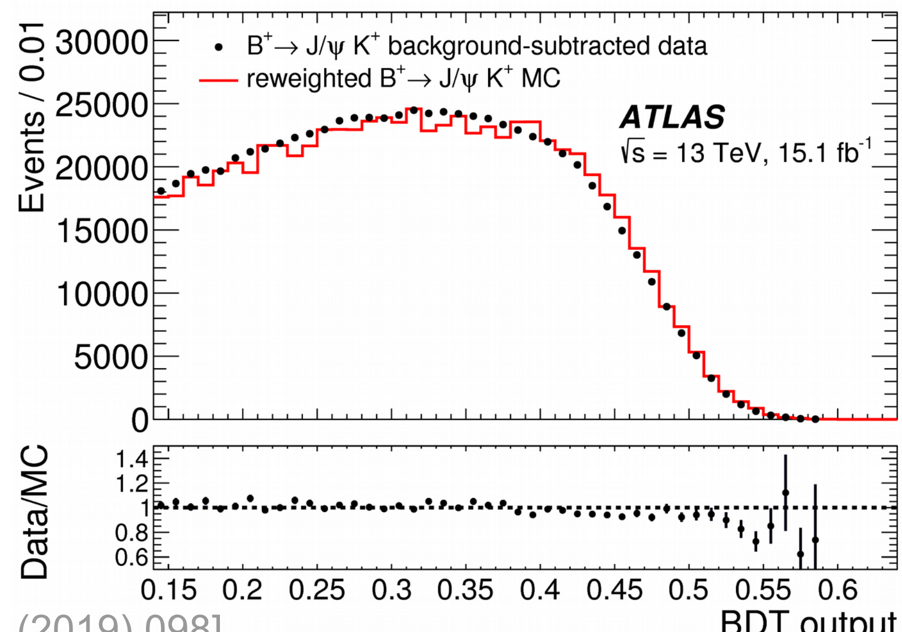
$B^\pm \to J/\psi\, K^\pm$ yield:

- unbinned ML fit to $m_{J/\psi K}$

Efficiency relative to $B^0_{(s)} \to \mu^+\mu^-$:

- Extracted from MC
- Fiducial volume:
  $p_T(B) > 8$ GeV, $|\eta_B| < 2.5$
- Data-MC discrepancies
  $\to$ systematic uncertainties
- Effective B_s^0 lifetime
  $\to$ 2.7% correction





R_ε uncertainties

Source	Contribution [%]
Statistical	0.8
BDT input variables	3.2
Kaon tracking efficiency	1.5
Muon trigger and reconstruction	1.0
Kinematic reweighting (DDW)	0.8
Pile-up reweighting	0.6

$R_\varepsilon = \varepsilon_{J/\psi K}/\varepsilon_{\mu\mu} = 0.1176 \pm 0.0009\ (\text{sys}) \pm 0.0047\ (\text{stat})$

[JHEP04 (2019) 098]

$B_{(s)}^0 \to \mu^+\mu^-$ – Signal Yield

Unbinned ML fit to $m_{\mu\mu}$ in 4 BDT bins

- Signals and $B \to hh'$
  3 double-Gaussians with common mean
- Combinatorial background
  1[rst] order polynomial
- $b \to \mu\mu X$,
  exponential
- Semi-leptonic background
  absorbed in exponential

data-driven shape parameters and normalizations

Extracted yields:

- $N_s = 80 \pm 22$ $N_d = -12 \pm 20$

Consistent with SM expectations:

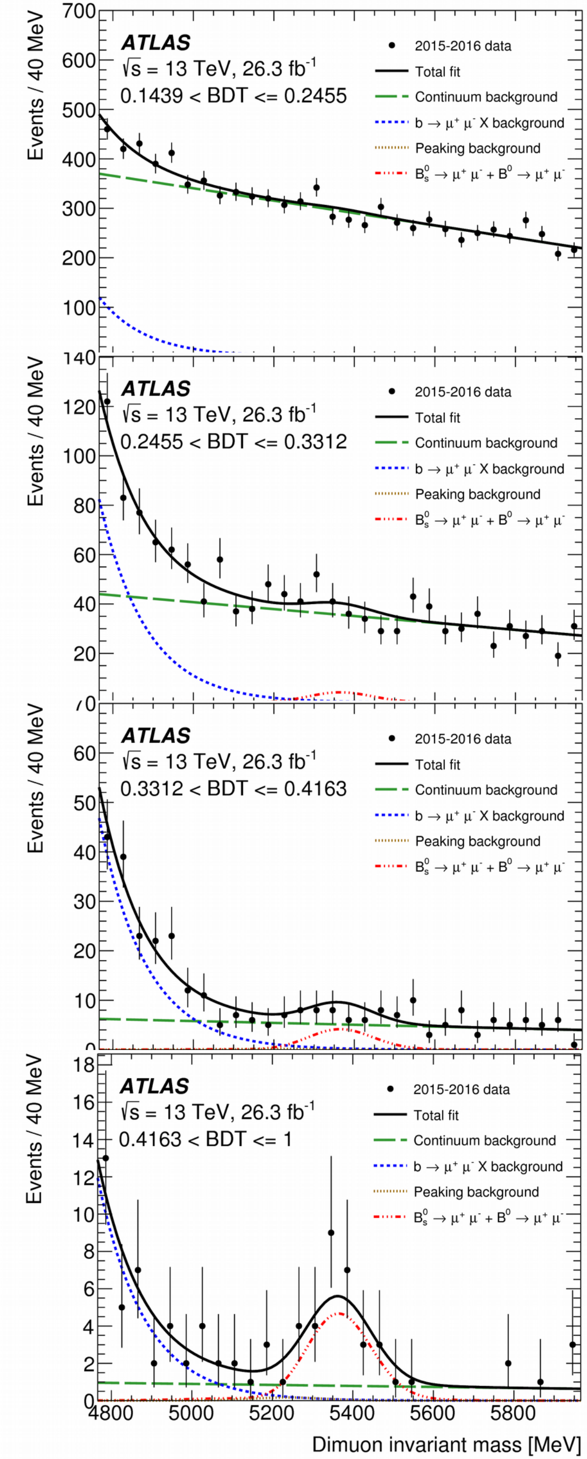
- $N_s = 91$ $N_d = 10$

Branching fraction (Neyman construction):

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9}$$

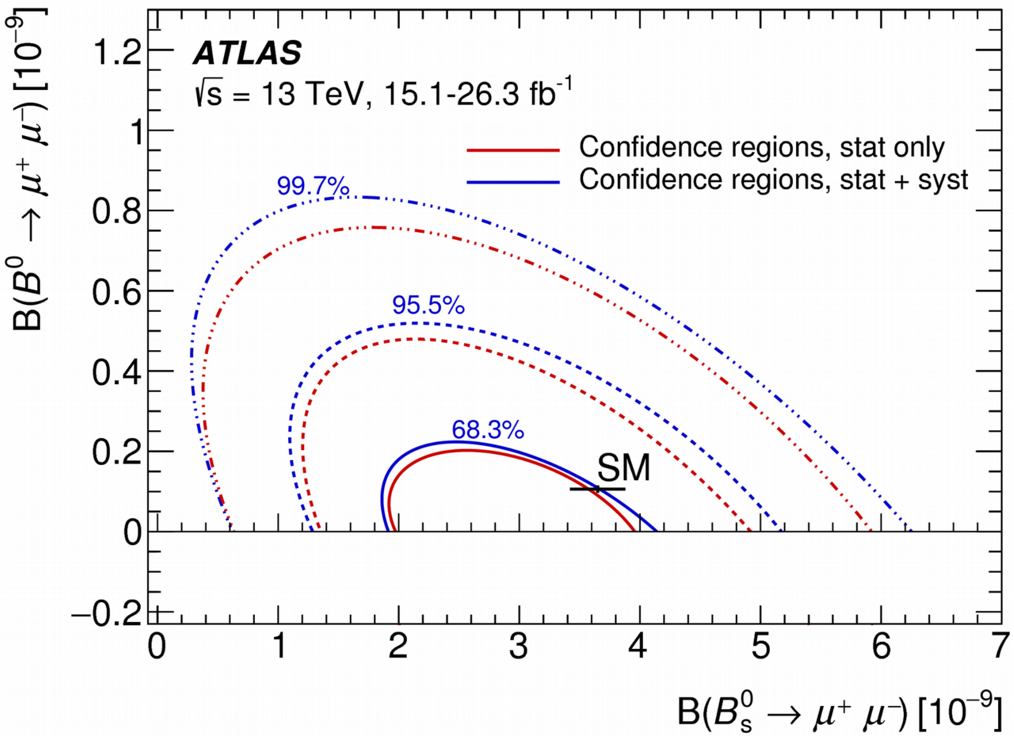
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$$ @ 95% CL

[JHEP04 (2019) 098]

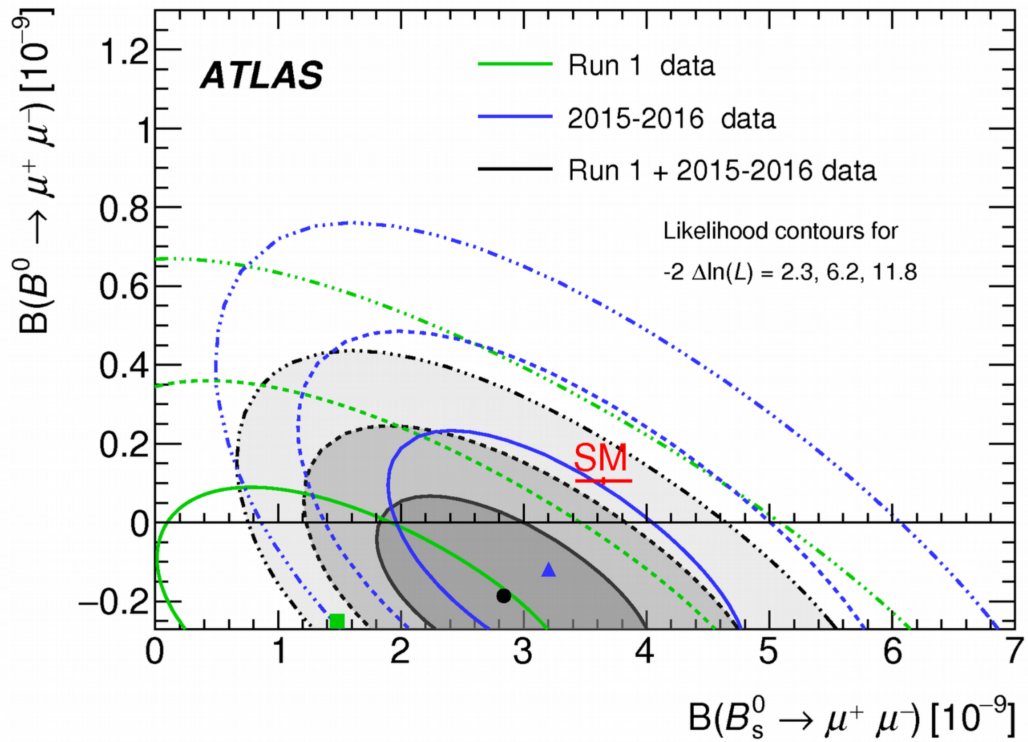


$B_{(s)}^0 \rightarrow \mu^+\mu^-$ – Results: Run 2 and Combination

Run 2 (2015/16) only



Run 1 + Run 2 (2015/16)



Neyman contours:

- $BR(B^0_s \rightarrow \mu^+\mu^-) = (3.2\ ^{+1.1}_{-1.0}) \times 10^{-9}$
- $BR(B^0 \rightarrow \mu^+\mu^-) < 4.3 \times 10^{-10}$ at 95% CL

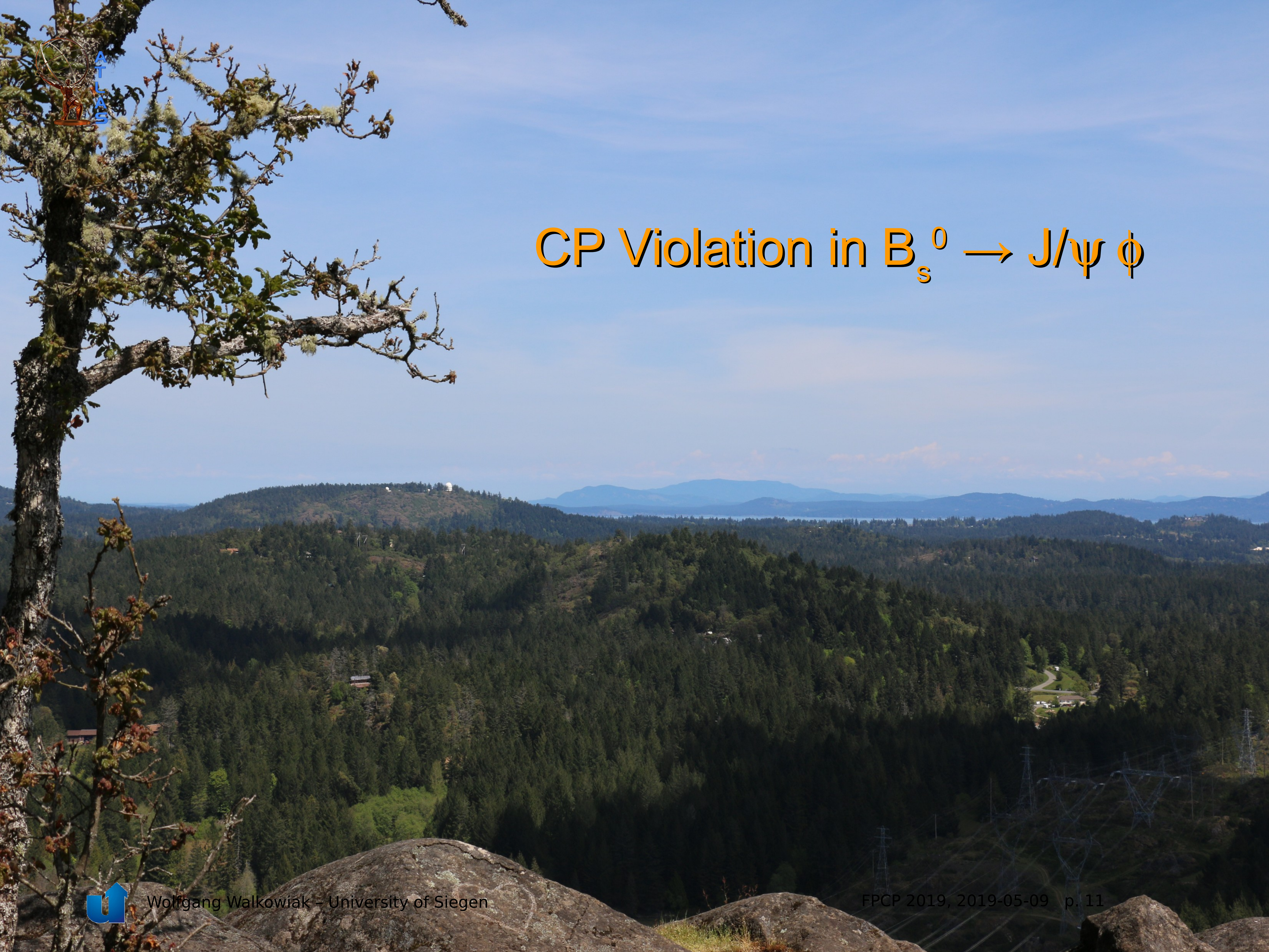
Combination (likelihood contours):

- $BR(B^0_s \rightarrow \mu^+\mu^-) = (2.8\ ^{+0.8}_{-0.7}) \times 10^{-9}$
- $BR(B^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 95% CL

Compatible with SM at 2.4 σ

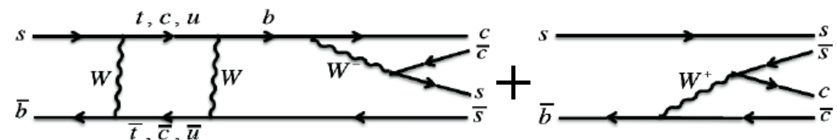
[JHEP04 (2019) 098]

CP Violation in $B_s^0 \rightarrow J/\psi\ \phi$



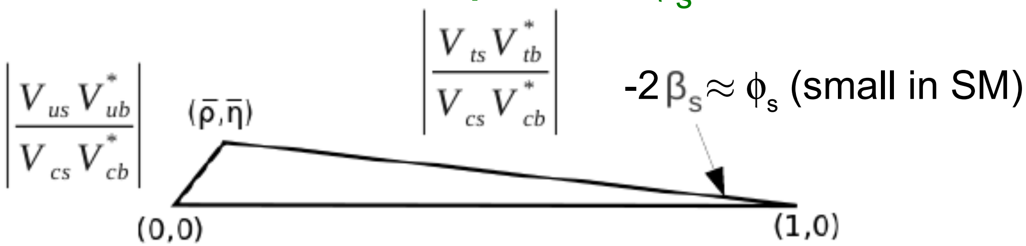
$B_s^0 \rightarrow J/\psi\,\phi$: CP Violation and $\Delta\Gamma_s$ – Run 1

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

$\Gamma_s \sim \Big|$  $\Big|^2$

Decay amplitude with mixing — Direct decay amplitude

- Sensitive to CPV phase ϕ_s

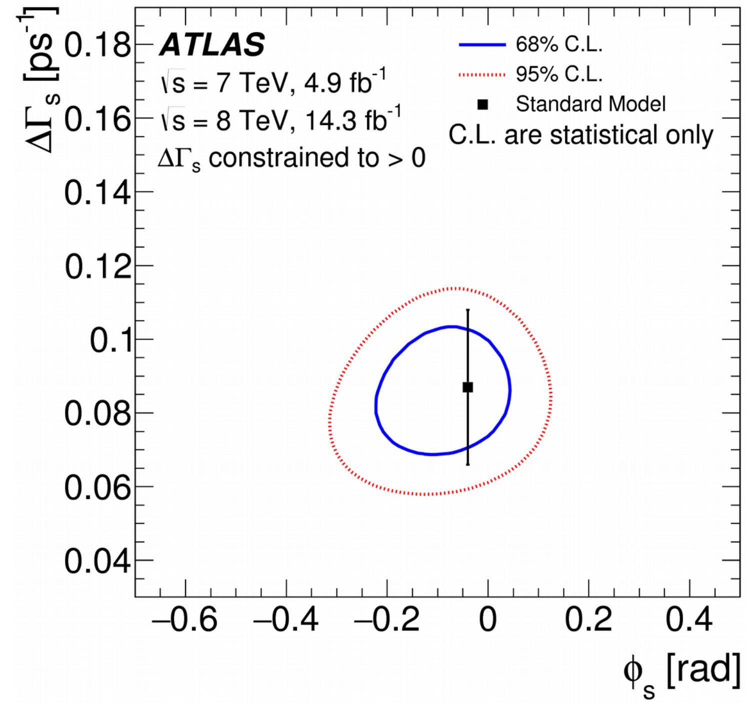


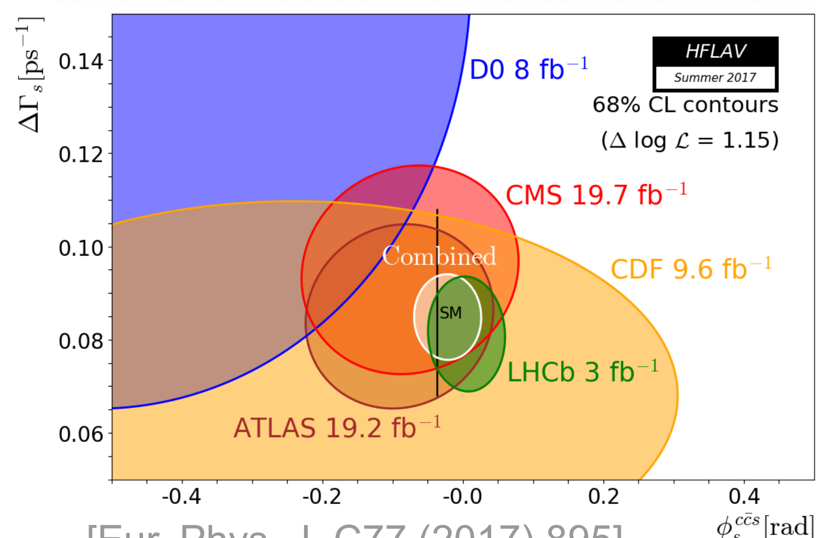
ATLAS Run-1 result:

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

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

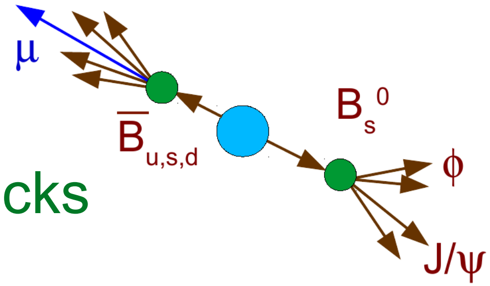
- Agrees with SM
- Consistent with other experiments
- Still room for New Physics in CPV





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

$B_s^0 \to J/\psi\ \phi$: Run 2 B_s^0 Flavor Tagging

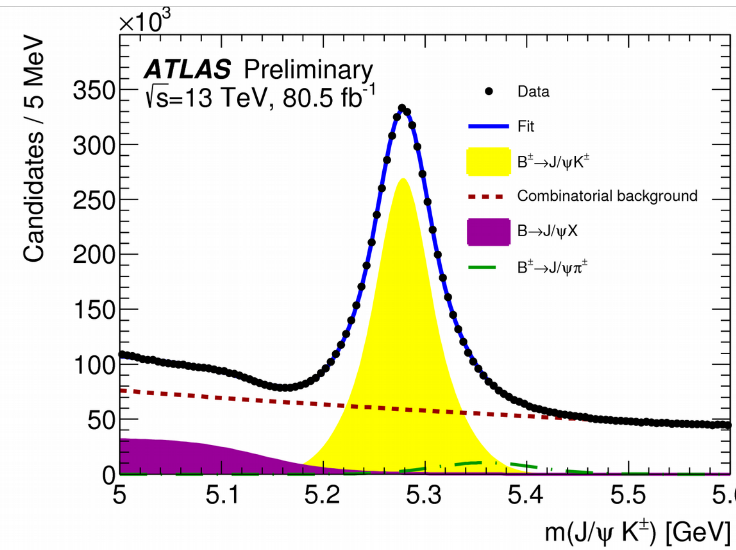


Opposite-side taggers:

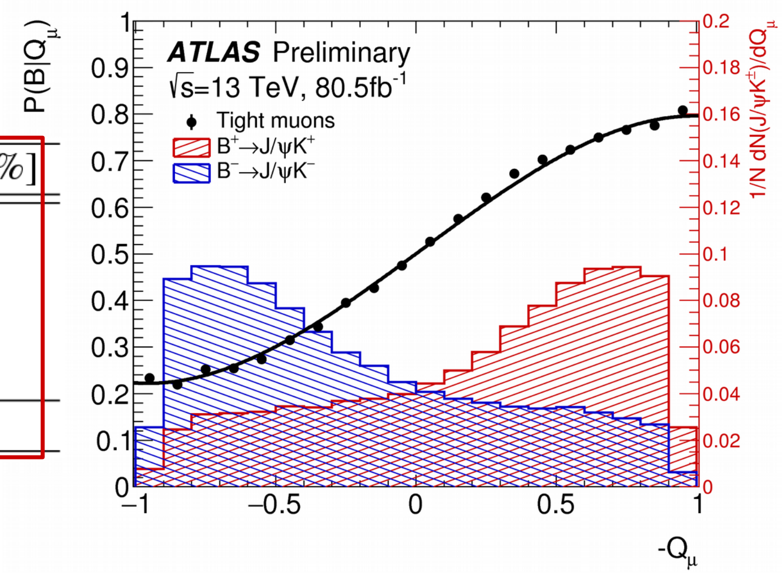
- p_T-weighted charge of tracks in cone around
  - electron
  - muon
  - b-jet

$$Q_x = \frac{\sum_i^{N \text{ tracks}} q_i \cdot (p_{\mathrm{T}i})^\kappa}{\sum_i^{N \text{ tracks}} (p_{\mathrm{T}i})^\kappa}$$

- calibrated on self-tagged $B^\pm \to J/\psi K^\pm$ events



[ATLAS-CONF-2019-009]

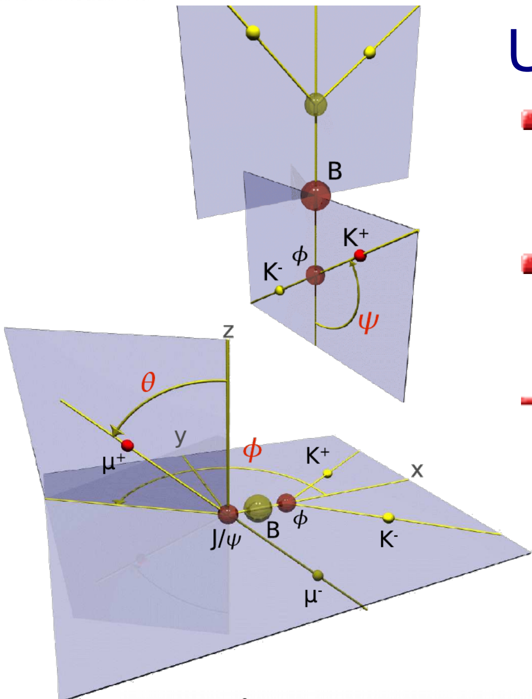


Tag method	Efficiency [%]	Effective Dilution [%]	Tagging Power [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_{T} muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	5.54 ± 0.01	20.4 ± 0.1	0.231 ± 0.005
Total	14.74 ± 0.02	33.4 ± 0.1	1.65 ± 0.01

Dilution $\mathcal{D}(Q_x) = 2P(B|Q_x) - 1$

Tagging power $T_x = \sum_i \epsilon_{x\,i} \cdot (2P(B|Q_{x\,i}) - 1)^2$

$B_s^0 \to J/\psi\ \phi$: Run 2 Unbinned ML Fit



Unbinned maximum likelihood fit:

- B_s^0 properties

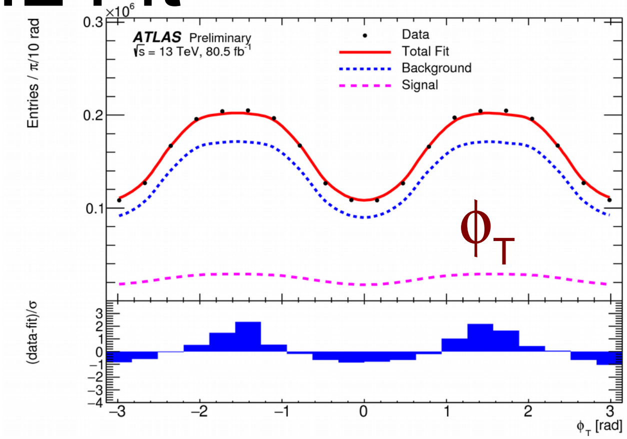
  m_i, σ_{mi}, t_i, σ_{ti}, p_{Ti}, $p_i(B|Q_x)$
- transversity angles

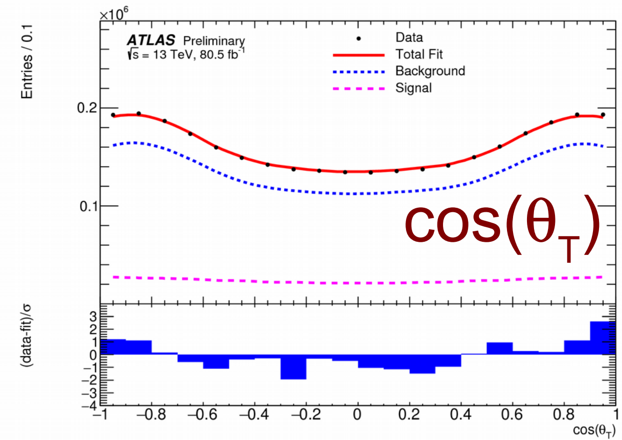
  $\Omega_i\ (\theta_{Ti}, \phi_{Ti}, \psi_{Ti})$
- signal parameters:

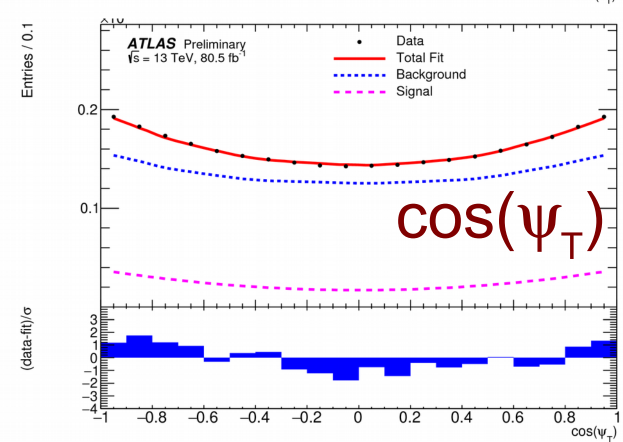
  ϕ_s, $\Delta\Gamma_s$, Γ_s, $|A_0(0)|^2$, $|A_\parallel(0)|^2$,

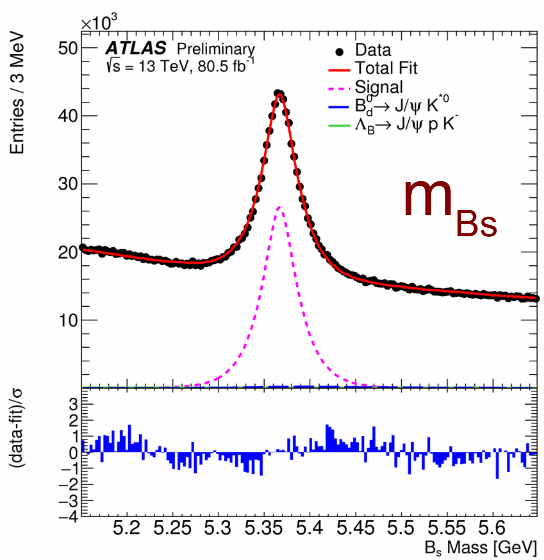
  $\delta_\parallel$, $\delta_\perp$, $|A_s(0)|^2$, $\delta_\perp$-δ_S

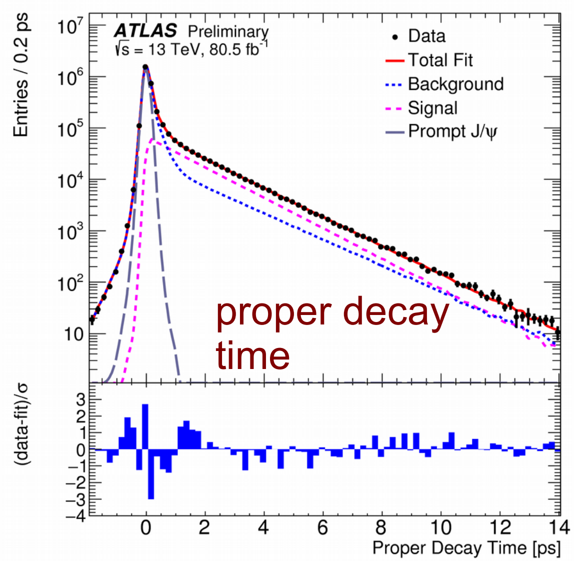
[ATLAS-CONF-2019-009]









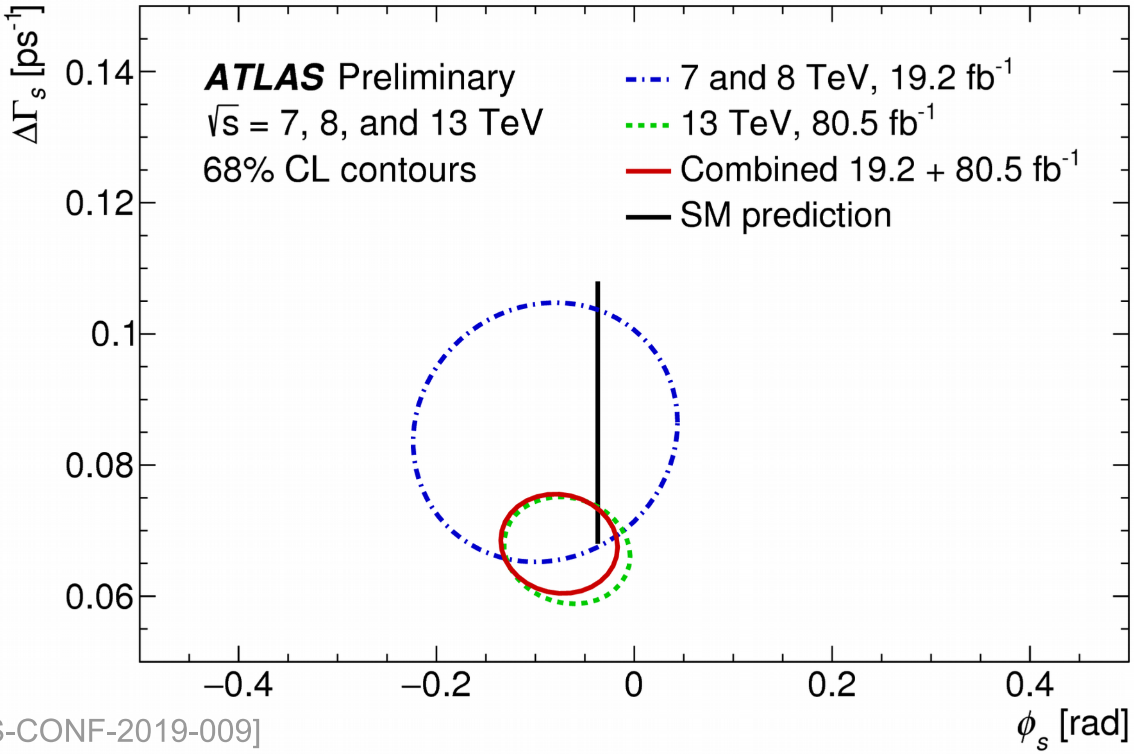


$B_s^0 \to J/\psi\, \phi$: ATLAS CPV Results (1)

Run 2 only (80.5 fb^{-1}):

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	–0.068	0.038	0.018
$\Delta\Gamma_s$[ps^{-1}]	0.067	0.005	0.002
Γ_s[ps^{-1}]	0.669	0.001	0.001
$\lvert A_{\parallel}(0)\rvert^2$	0.219	0.002	0.002
$\lvert A_0(0)\rvert^2$	0.517	0.001	0.004
$\lvert A_S(0)\rvert^2$	0.046	0.003	0.004
$\delta_\perp$ [rad]	2.946	0.101	0.097
$\delta_\parallel$ [rad]	3.267	0.082	0.201
$\delta_\perp - \delta_S$ [rad]	–0.220	0.037	0.010

Run 1 (19.2 fb^{-1}) & Run 2 (80.5 fb^{-1}):



[ATLAS-CONF-2019-009]

$B_s^0 \to J/\psi\ \phi$: ATLAS CPV Results (2)

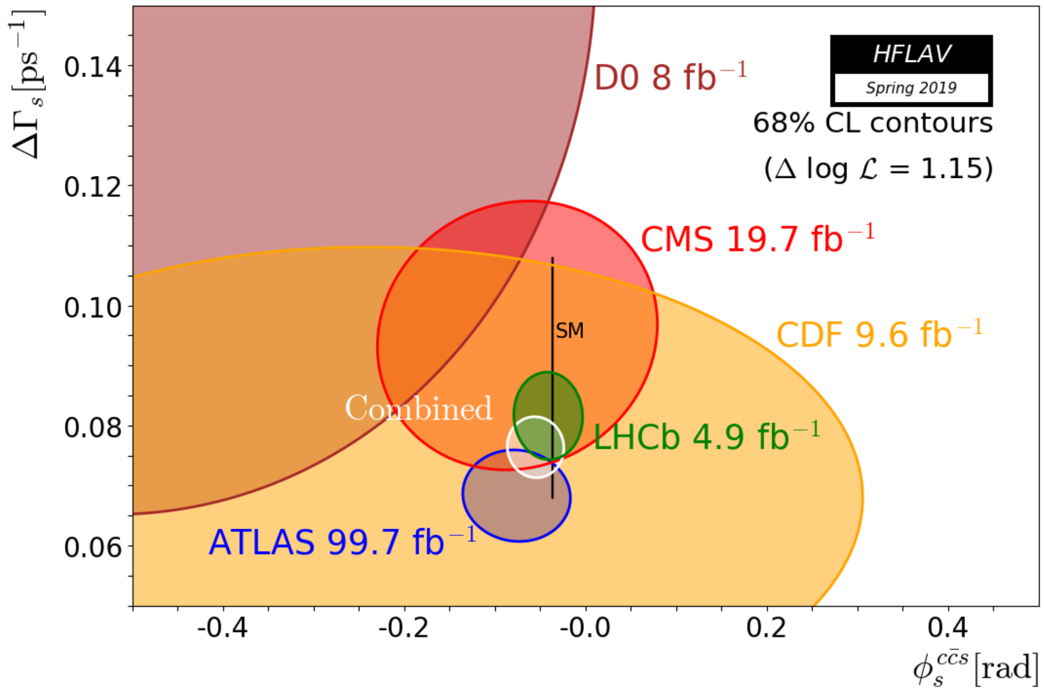
ATLAS Run 1 & Run 2 combined
(19.2 fb^{-1} + 80.5 fb^{-1})

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	–0.076	0.034	0.019
$\Delta\Gamma_s[\mathrm{ps}^{-1}]$	0.068	0.004	0.003
$\Gamma_s[\mathrm{ps}^{-1}]$	0.669	0.001	0.001
$\lvert A_{\parallel}(0)\rvert^2$	0.220	0.002	0.002
$\lvert A_0(0)\rvert^2$	0.517	0.001	0.004
$\lvert A_S\rvert^2$	0.043	0.004	0.004
$\delta_\perp$ [rad]	3.075	0.096	0.091
$\delta_\parallel$ [rad]	3.295	0.079	0.202
$\delta_\perp - \delta_S$ [rad]	–0.216	0.037	0.010

[ATLAS-CONF-2019-009]

Comparison with CMS & LHCb:

[Preliminary HFLAV average, F. Dordei, CERN seminar 2019-05-07]



- Consistent with results from CMS, LHCb and Standard Model
- Stringent single measurement of ϕ_s, $\Delta\Gamma_s$, Γ_s and helicity function parameters
- Still to add 60 fb^{-1} of 2018 data

Preliminary HFLAV average:

ϕ_s = -0.055 ± 0.021 rad

$\Delta\Gamma_s = 0.0764^{+0.0034}_{-0.0033}\ \mathrm{ps}^{-1}$

$B_{(s)}^0 \to \mu^+\mu^-$ and $B_s^0 \to J/\psi\,\phi$ at the High-Luminosity LHC

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

All-Si Inner Tracker (ITk):

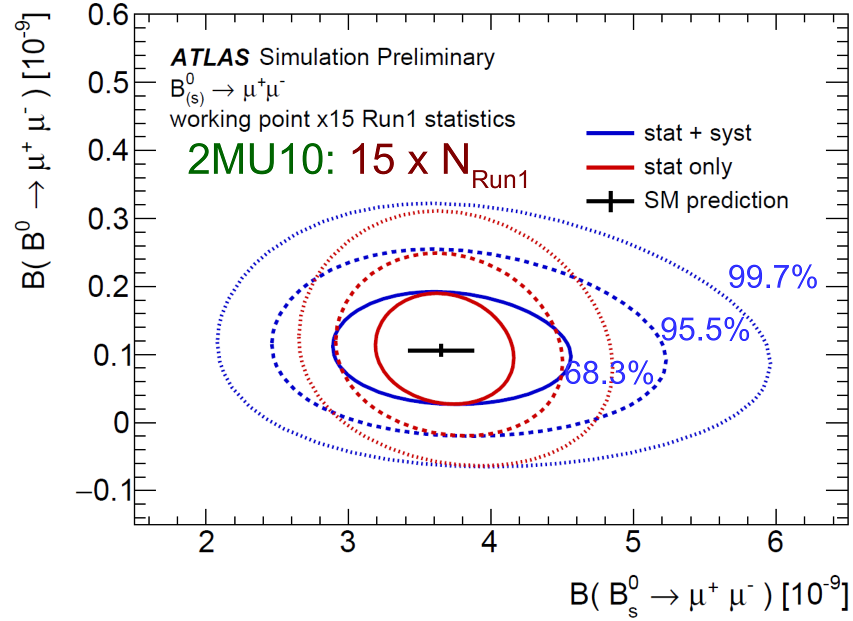
- improves:
  - B mass resolution σ_{mB}
  - proper time resolution σ_t

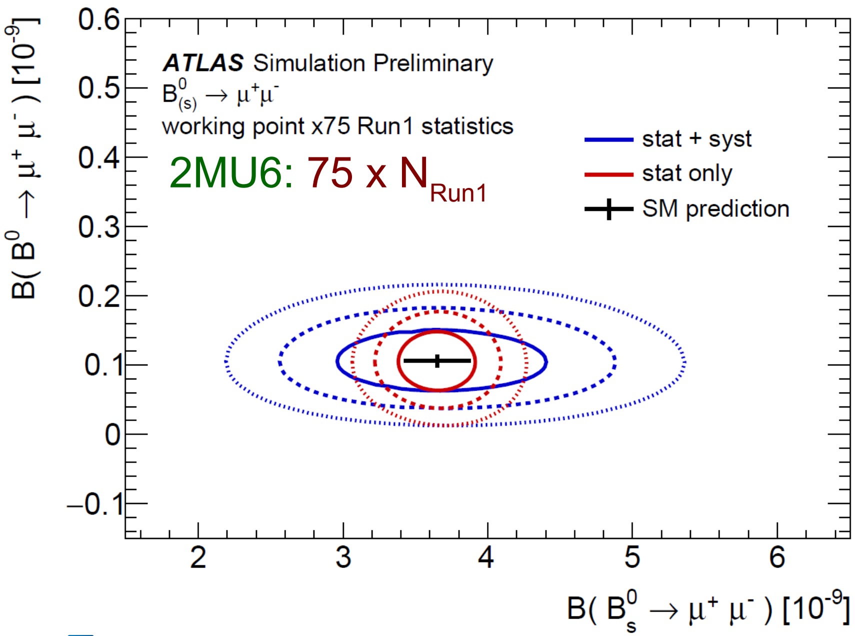
Pseudo-MC experiments

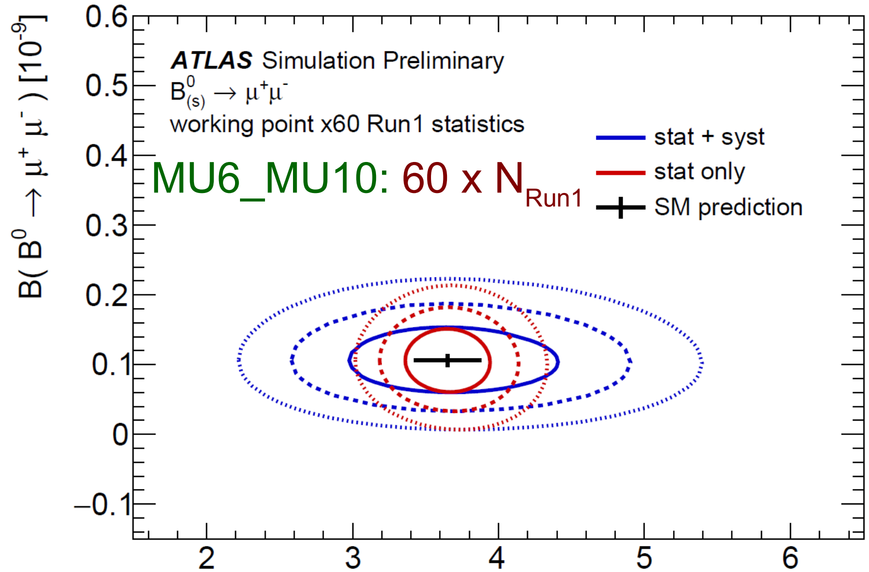
- Profile likelihood contours
- Based on Run 1 likelihood

Dominant systematics:

- $\sigma(f_s/f_d)$ ~ 8.3% “conservative”







[ATL-PHYS-PUB-2018-005]

$B_s^0 \rightarrow J/\psi\ \phi$ CPV Prospects – HL-LHC (3 ab^{-1})

Three trigger scenarios:

- 2MU10 $\rightarrow$ 18 x N_{Run1}
- MU6_MU10 $\rightarrow$ 60 x N_{Run1}
- 2MU6 $\rightarrow$ 100 x N_{Run1}

$\delta_{\phi s}^{stat}$ calculated w.r.t. 2012 data:

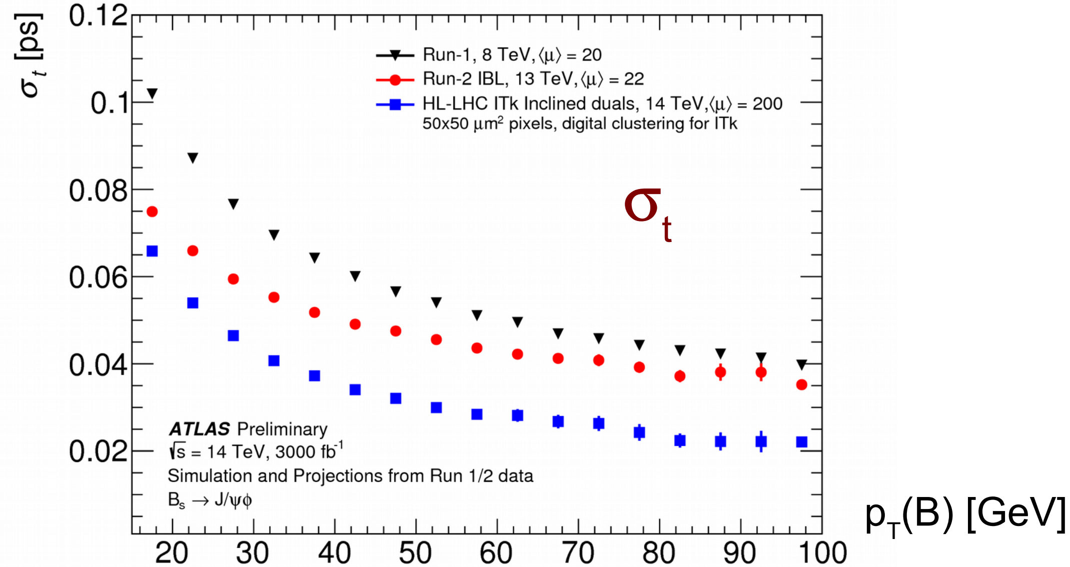
- N_{sig}, σ_t scale with statistics
- tag power not scaled

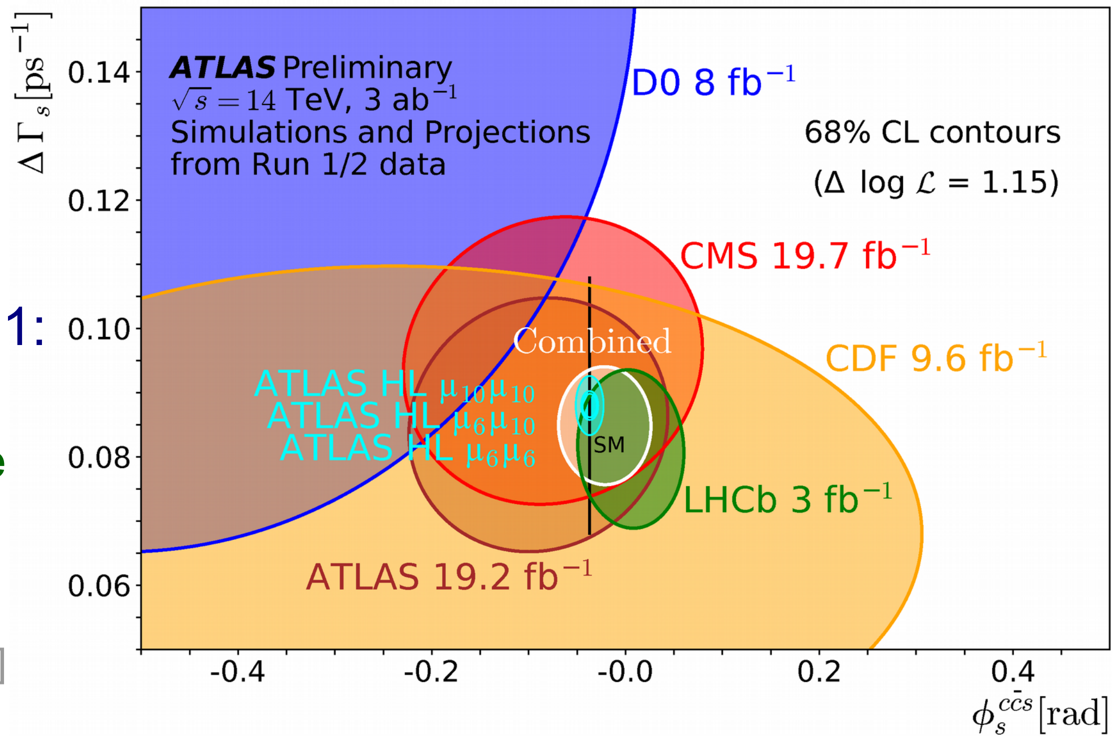
Systematics expected to improve with statistics:

- $\delta_{\phi s}^{syst} \sim 0.003$ rad
- $\delta_{\Delta\Gamma s}^{syst} \sim 0.0005\ ps^{-1}$

Expected improvements w.r.t. Run 1:

- $\delta_{\phi s}^{stat}$: factor 9x to 20x
  $\rightarrow$ up to 7x smaller than SM ϕ_s value
- $\delta_{\Delta\Gamma s}^{stat}$: factor 4x to 10x





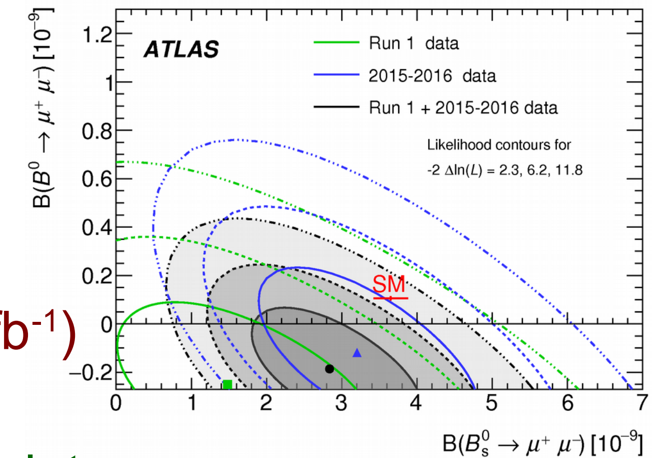
[ATL-PHYS-PUB-2018-041]

Conclusions

ATLAS measurements of rare decays and CPV:

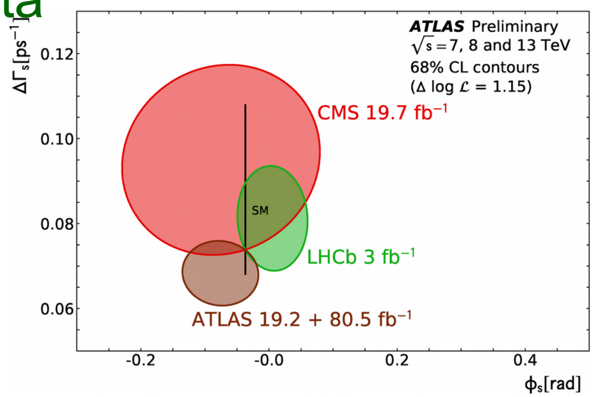
- $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ with 36.2 fb^{-1} of Run 2 data
  - Agrees with SM and other measurements
  - No sign for $B^0 \to \mu^+\mu^-$ in ATLAS data
  - Data taken in 2017 + 2018 still to be added (~107 fb^{-1})

  [JHEP04 (2019) 098]



- CPV: ϕ_s and $\Delta\Gamma_s$ in $B_s^0 \to J/\psi\, \phi$ with 80.5 fb^{-1} of Run 2 data
  - Single measurement precision comparable to LHCb
  - Reaching sensitivity to test SM prediction
  - Data taken in 2018 still to be added (~ 60 fb^{-1})

  [ATLAS-CONF-2019-099]

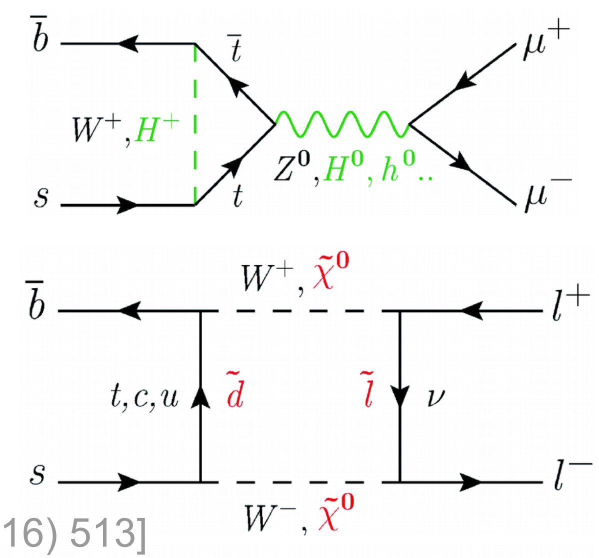


- Both channels will profit from HL-LHC
  - Considerably increased statistics
  - Improved m_B resolution
  - Improved σ_t resolution
  - Promising to test SM

  [ATL-PHYS-PUB-2018-005, ATL-PHYS-PUB-2018-041]

Supporting Material

$B_{(s)}{}^0 \rightarrow \mu^+\mu^-$ – Run 1



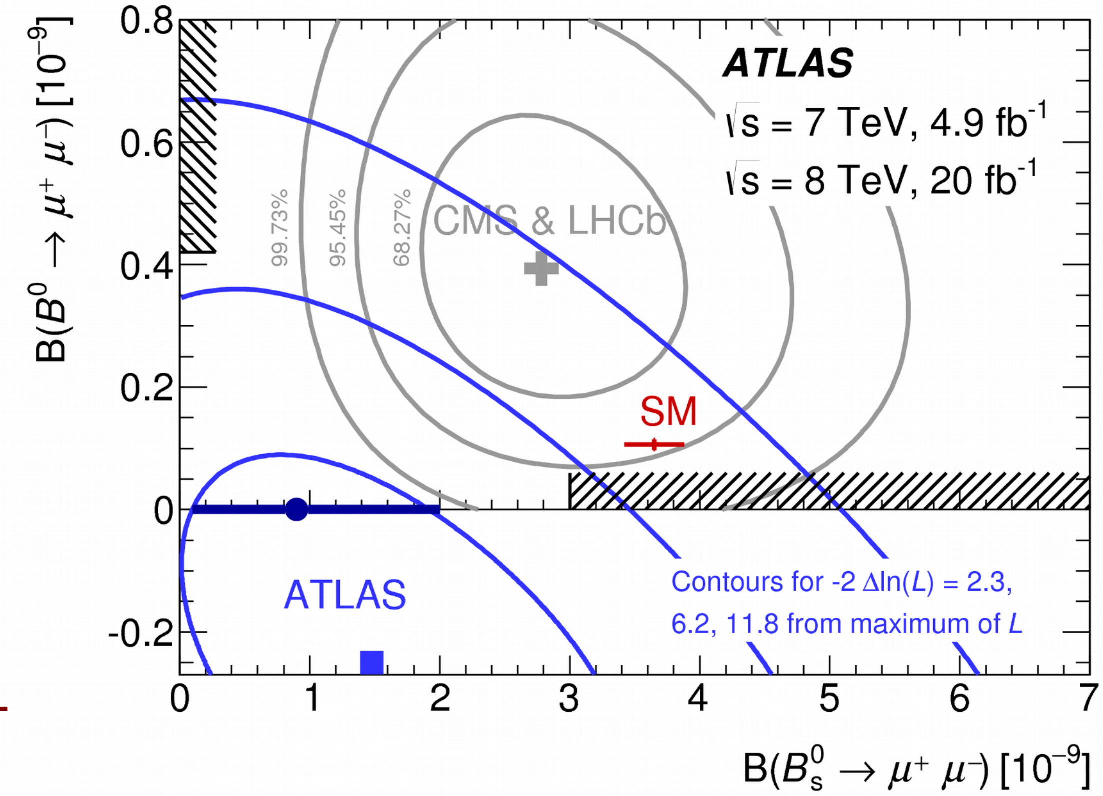
BR($B_{(s)}{}^0 \rightarrow \mu^+\mu^-$) w.r.t. BR($B^\pm \rightarrow J/\psi\, K^\pm$)

- Sensitive to New Physics in decay via loop diagrams

Run 1 result:

- BR($B^0_s \rightarrow \mu^+\mu^-$) = $(0.9\ ^{+1.1}_{-0.8})\mathrm{x}10^{-9}$
- BR($B^0 \rightarrow \mu^+\mu^-$) < $4.2\mathrm{x}10^{-10}$ at 95% CL

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



Compatible with SM at ~ 2σ:

- BR($B^0_s \rightarrow \mu^+\mu^-$) = $(3.65 \pm 0.23)\mathrm{x}10^{-9}$
- BR($B^0 \rightarrow \mu^+\mu^-$) = $(1.06 \pm 0.09)\mathrm{x}10^{-10}$

[PRL 112 (2014) 101801]

CMS&LHCb Run 1 combined:

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

[Nature 522 (2015) 68]

LHCb Run 1 + partial Run 2:

- BR($B^0_s \rightarrow \mu^+\mu^-$) = $3.0 \pm 0.6\ ^{+0.3}_{-0.2}$ x 10^{-9}
- BR($B^0 \rightarrow \mu^+\mu^-$) < 3.4 x 10^{-10} at 95% CL

[PRL 118 (2017) 191801]

$B_{(s)}^0 \to \mu^+\mu^-$ – Master Formula

Measurement w.r.t. $B^\pm \to J/\psi\, K^\pm$ with $J/\psi \to \mu^+\mu^-$

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{d(s)}}{\varepsilon_{\mu^+\mu^-}} \times \left[\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right] \frac{\varepsilon_{J/\psi K^+}}{N_{J/\psi K^+}} \times \frac{f_u}{f_{d(s)}}$$
$$= N_{d(s)} \frac{\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{D}_{\mathrm{ref}}} \times \frac{f_u}{f_{d(s)}}\,, \qquad (1.1)$$

with

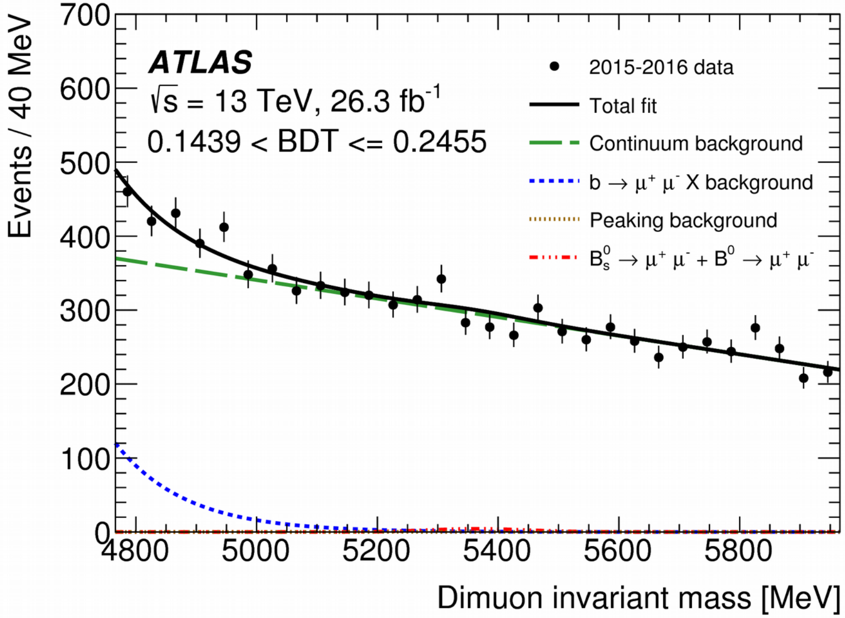
- $\mathcal{D}_{\mathrm{ref}} = N_{J/\psi K^+} \times (\varepsilon_{\mu^+\mu^-}/\varepsilon_{J/\psi K^+})$
- $N_{d(s)}$: $B^0(s) \to \mu^+\mu^-$ signal yields
- $N_{J/\psi K}$: $B^\pm \to J/\psi\, K^\pm$ reference channel yield
- $\varepsilon_{\mu+\mu^-}$ and $\varepsilon_{J/\psi K}$: acceptance times efficiency
- $f_u/f_{d(s)}$: ratio of hadronization probabilities of b-quark into $B^\pm$ and $B^0_{(s)}$
  = 0.256 ± 0.013 [PRD 98 (2018) 03001]
- $B(B^+ \to J/\psi\, K^+)$ x $B(J/\psi \to \mu^+\mu^-)$
  = (1.010 ± 0.029)x10-3 x (5.961 ± 0.033)% [PRD 98 (2018) 03001]

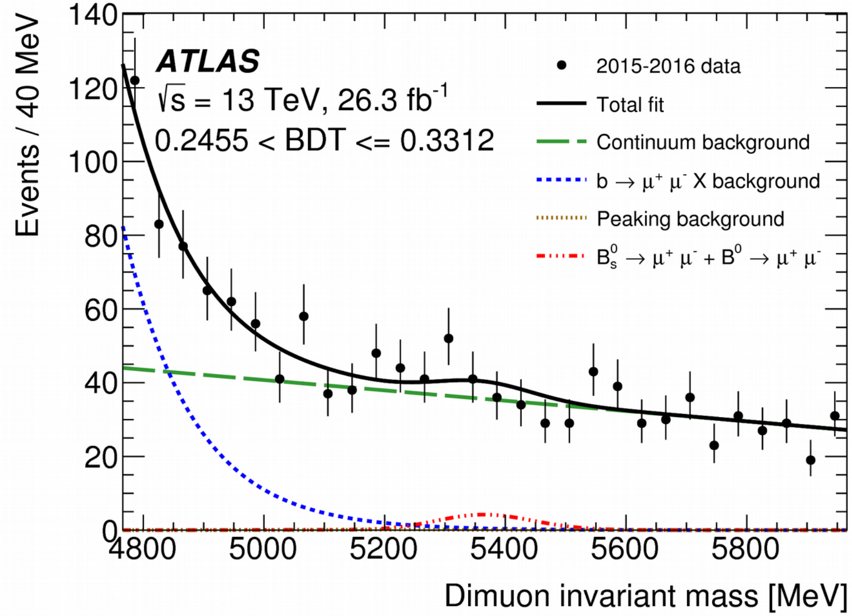
$B_{(s)}^0 \to \mu^+\mu^-$ – BDT Input Variables

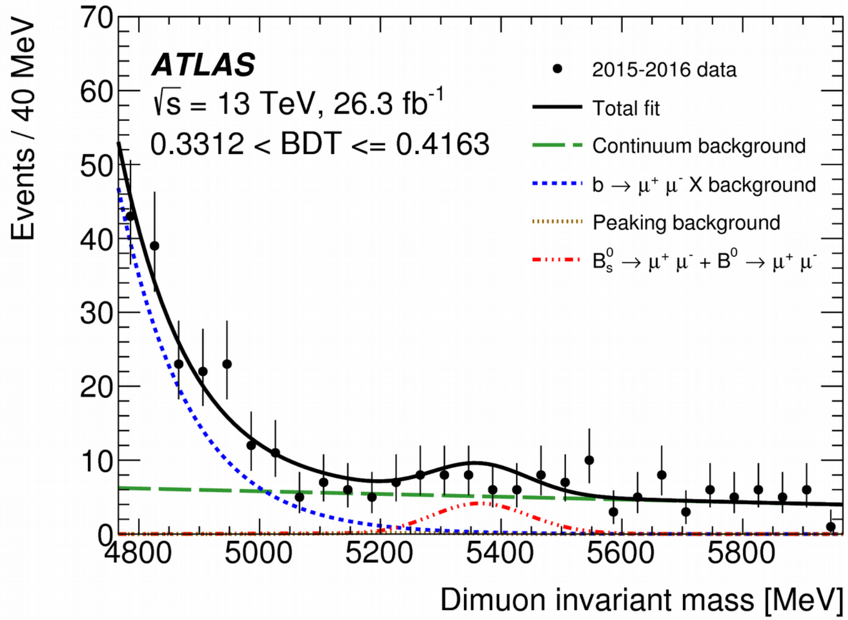
Variable	Description
p_{T}^{B}	Magnitude of the B candidate transverse momentum $\overrightarrow{p_{\mathrm{T}}}^{B}$.
$\chi^2_{\mathrm{PV,DV}\ xy}$	Compatibility of the separation $\overrightarrow{\Delta x}$ between production (i.e. associated PV) and decay (DV) vertices in the transverse projection: $\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \Sigma^{-1}_{\overrightarrow{\Delta x}_{\mathrm{T}}} \cdot \overrightarrow{\Delta x}_{\mathrm{T}}$, where $\Sigma_{\overrightarrow{\Delta x}_{\mathrm{T}}}$ is the covariance matrix.
$\Delta R_{\mathrm{flight}}$	Three-dimensional angular distance between $\overrightarrow{p}^{B}$ and $\overrightarrow{\Delta x}$: $\sqrt{\alpha_{2\mathrm{D}}{}^2 + (\Delta\eta)^2}$
$\lvert\alpha_{2\mathrm{D}}\rvert$	Absolute value of the angle in the transverse plane between $\overrightarrow{p_{\mathrm{T}}}^{B}$ and $\overrightarrow{\Delta x}_{\mathrm{T}}$.
L_{xy}	Projection of $\overrightarrow{\Delta x}_{\mathrm{T}}$ along the direction of $\overrightarrow{p}_{\mathrm{T}}^{B}$: $(\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \overrightarrow{p_{\mathrm{T}}}^{B})/\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$.
$\mathrm{IP}_B^{3\mathrm{D}}$	Three-dimensional impact parameter of the B candidate to the associated PV.
$\mathrm{DOCA}_{\mu\mu}$	Distance of closest approach (DOCA) of the two tracks forming the B candidate (three-dimensional).
$\Delta\phi_{\mu\mu}$	Azimuthal angle between the momenta of the two tracks forming the B candidate.
$\lvert d_0\rvert^{\max}$-sig.	Significance of the larger absolute value of the impact parameters to the PV of the tracks forming the B candidate, in the transverse plane.
$\lvert d_0\rvert^{\min}$-sig.	Significance of the smaller absolute value of the impact parameters to the PV of the tracks forming the B candidate, in the transverse plane.
$P_{\mathrm{L}}^{\min}$	The smaller of the projected values of the muon momenta along $\overrightarrow{p_{\mathrm{T}}}^{B}$.
$I_{0.7}$	Isolation variable defined as ratio of $\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$ to the sum of $\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$ and the transverse momenta of all additional tracks contained within a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$ around the B direction. Only tracks matched to the same PV as the B candidate are included in the sum.
$\mathrm{DOCA}_{\mathrm{xtrk}}$	DOCA of the closest additional track to the decay vertex of the B candidate. Only tracks matched to the same PV as the B candidate are considered.
$N_{\mathrm{xtrk}}^{\mathrm{close}}$	Number of additional tracks compatible with the decay vertex (DV) of the B candidate with $\ln(\chi^2_{\mathrm{xtrk,DV}}) < 1$. Only tracks matched to the same PV as the B candidate are considered.
$\chi^2_{\mu,\mathrm{xPV}}$	Minimum χ^2 for the compatibility of a muon in the B candidate with any PV reconstructed in the event.

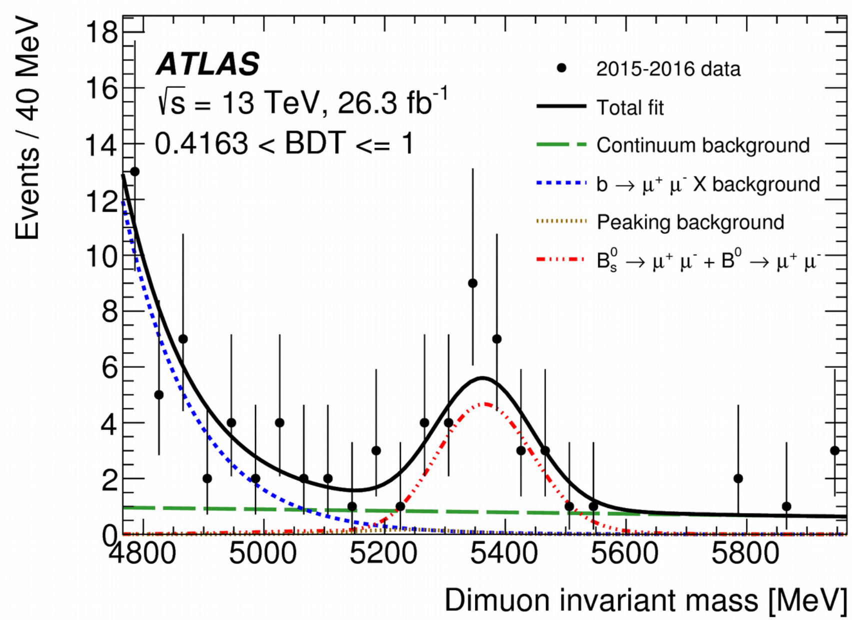
[JHEP04 (2019) 098]

$B_{(s)}^0 \to \mu^+\mu^-$ – Signal Yield









[JHEP04 (2019) 098]

$B_{(s)}^0 \to \mu^+\mu^-$ – Systematic Uncertainties

Expected uncertainties on BR($B^0_{(s)} \to \mu^+\mu^-$):

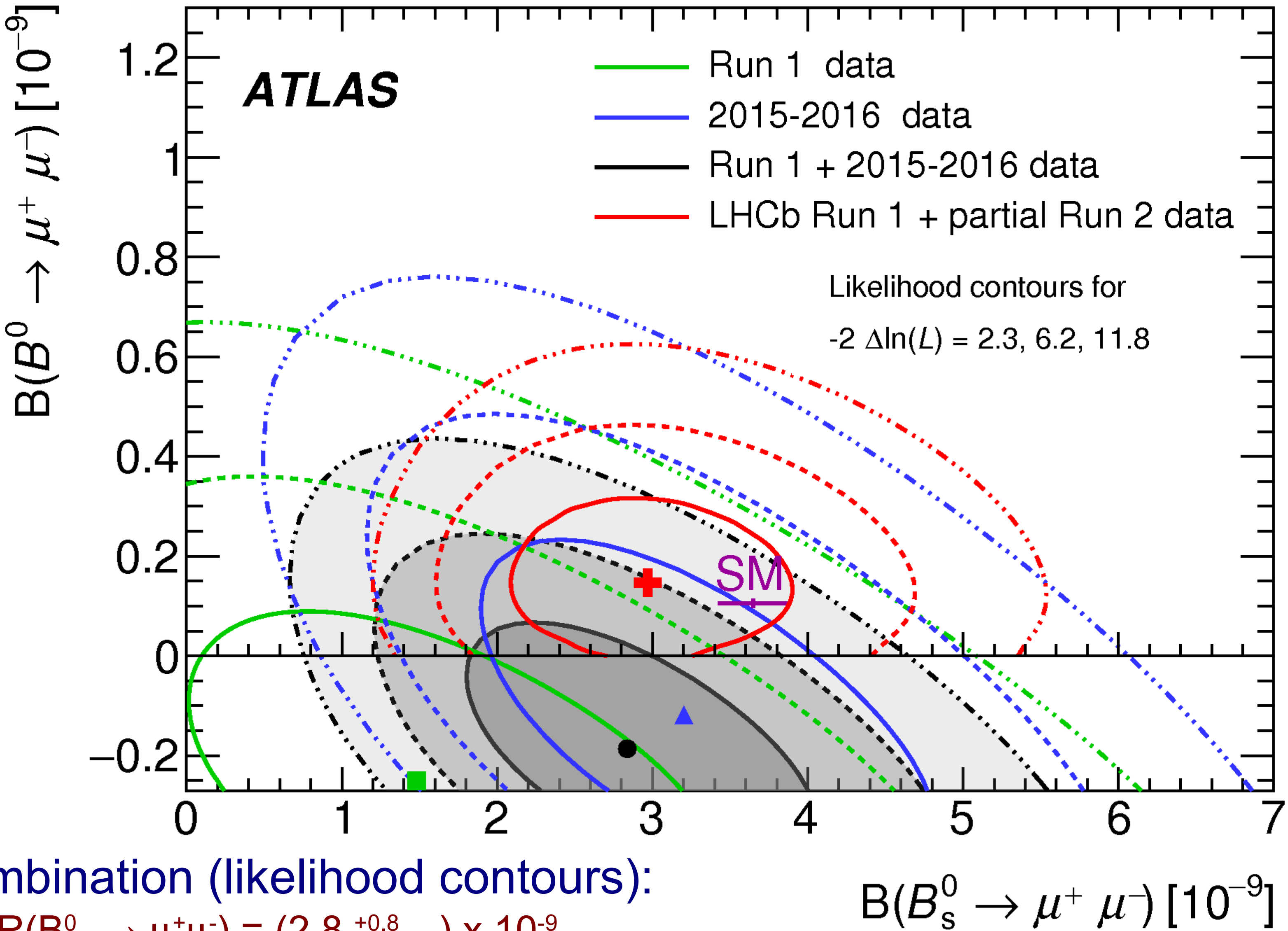
Source	B_s^0 [%]	B^0 [%]
f_s/f_d	5.1	-
B^+ yield	4.8	4.8
R_ε	4.1	4.1
$\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)$	2.9	2.9
Fit systematic uncertainties	8.7	65
Stat. uncertainty (from likelihood est.)	27	150

[JHEP04 (2019) 098]

- Dominated by statistical uncertainties
- Main fit systematic uncertainties:
  - Mass scale uncertainty
  - Parametrization of the b $\to \mu^+\mu^-$X background

[JHEP04 (2019) 098]

$B_{(s)}{}^0 \rightarrow \mu^+\mu^-$ – Run 1 +Run 2 (2015-2016)



Combination (likelihood contours):

- $BR(B^0_s \rightarrow \mu^+\mu^-) = (2.8\ ^{+0.8}_{-0.7}) \times 10^{-9}$
- $BR(B^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 95% CL

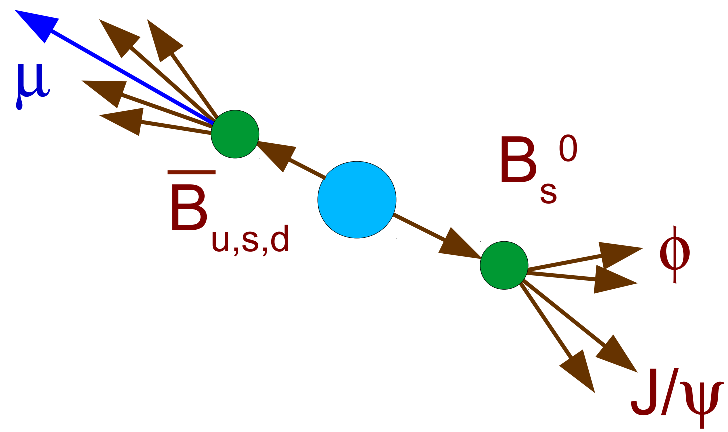
Compatible with SM at 2.4 σ

$B_s^0 \to J/\psi\ \phi$: Run 2 Analysis Strategy

Signal in interference of B_s^0 mixing and decay

$\rightarrow$ proper decay time and flavor tagging!

[ATLAS-CONF-2019-009]



Proper decay time (t_i):

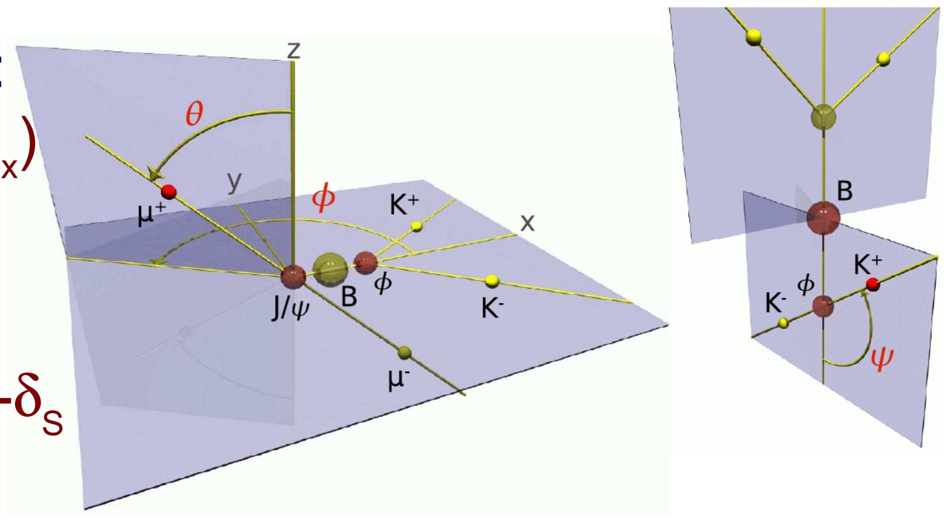
$$t = \frac{L_{xy}\, m_B}{p_{T_B}}$$

$B_s^0/\overline{B}_s^0$ flavor at production

- Three oppposite-side taggers (M_i)

Unbinned maximum likelihood fit using:

- B_s^0 properties m_i, σ_{mi}, t_i, σ_{ti}, p_{Ti}, $p_i(B|Q_x)$
- transversity angles Ω_i (θ_{Ti}, ϕ_{Ti}, ψ_{Ti})
- signal parameters: ϕ_s, $\Delta\Gamma_s$, Γ_s, $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $\delta_\parallel$, $\delta_\perp$, $|A_s(0)|^2$, $\delta_\perp$-δ_S



$B_s^0 \to J/\psi\ \phi$: Systematic Uncertainties

[ATLAS-CONF-2019-009]

Summary of systematic uncertainties assigned to physical parameters of interest

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	1.7×10^{-2}	0.4×10^{-3}	0.3×10^{-3}	0.2×10^{-3}	0.2×10^{-3}	2.3×10^{-3}	1.9×10^{-2}	2.2×10^{-2}	2.2×10^{-3}
Acceptance	0.7×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.8×10^{-3}	0.7×10^{-3}	2.4×10^{-3}	3.3×10^{-2}	1.4×10^{-2}	2.6×10^{-3}
ID alignment	0.7×10^{-3}	0.1×10^{-3}	0.5×10^{-3}	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	1.0×10^{-2}	7.2×10^{-3}	$<10^{-4}$
S–wave phase	0.2×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.3×10^{-3}	$<10^{-4}$	0.3×10^{-3}	1.1×10^{-2}	2.1×10^{-2}	8.3×10^{-3}
Background angles model:									
Choice of fit function	1.8×10^{-3}	0.8×10^{-3}	$<10^{-4}$	1.4×10^{-3}	0.7×10^{-3}	0.2×10^{-3}	8.5×10^{-2}	1.9×10^{-1}	1.8×10^{-3}
Choice of p_T bins	1.3×10^{-3}	0.5×10^{-3}	$<10^{-4}$	0.4×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	7.2×10^{-3}	1.0×10^{-3}
Choice of mass interval	0.4×10^{-3}	0.1×10^{-3}	0.1×10^{-3}	0.3×10^{-3}	0.3×10^{-3}	1.3×10^{-3}	4.4×10^{-3}	7.4×10^{-3}	2.3×10^{-3}
Dedicated backgrounds:									
B_d^0	2.3×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.2×10^{-3}	3.1×10^{-3}	1.4×10^{-3}	1.0×10^{-2}	2.3×10^{-2}	2.1×10^{-3}
Λ_b	1.6×10^{-3}	0.4×10^{-3}	0.2×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.8×10^{-3}	1.4×10^{-2}	2.9×10^{-2}	0.8×10^{-3}
Fit model:									
Time res. sig frac	1.4×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.5×10^{-3}	0.6×10^{-3}	0.6×10^{-3}	1.2×10^{-2}	3.0×10^{-2}	0.4×10^{-3}
Time res. p_T bins	3.3×10^{-3}	1.4×10^{-3}	0.1×10^{-2}	$<10^{-4}$	$<10^{-4}$	0.5×10^{-3}	6.2×10^{-3}	5.2×10^{-3}	1.1×10^{-3}
Total	1.8×10^{-2}	0.2×10^{-2}	0.1×10^{-2}	0.2×10^{-2}	0.4×10^{-2}	0.4×10^{-2}	9.7×10^{-2}	2.0×10^{-1}	0.1×10^{-1}

$B_s^0 \to J/\psi\ \phi$: Tagging Method Fractions

[ATLAS-CONF-2019-009]

Fraction of events f_{+1} and f_{-1} with cone charges of +1 and -1, respectively, for signal and background events and for the different tag methods. The remaining fraction, $1 - f_{+1} - f_{-1}$, is the fraction of events from the continuous part of the distributions, and not explicitly shown in the table. Only statistical uncertainties are quoted.

Tag method	Signal		Background	
	f_{+1} [%]	f_{-1} [%]	f_{+1} [%]	f_{-1} [%]
Tight muon	6.9 ± 0.3	7.5 ± 0.3	4.7 ± 0.1	4.9 ± 0.1
Electron	20 ± 1	19 ± 1	16.8 ± 0.2	17.3 ± 0.2
Low-p_T muon	10.9 ± 0.5	11.7 ± 0.5	7.0 ± 0.1	7.6 ± 0.1
Jet	4.51 ± 0.15	4.58 ± 0.16	3.76 ± 0.03	3.86 ± 0.03

Relative fractions of signal and background events tagged using different tag methods. The efficiencies include both the continuous and the discrete contributions. Only statistical uncertainties are quoted.

Tag method	Signal efficiency [%]	Background efficiency [%]
Tight muon	4.00 ± 0.06	3.16 ± 0.01
Electron	1.87 ± 0.04	1.48 ± 0.01
Low-p_T muon	2.91 ± 0.05	2.64 ± 0.01
Jet	14.4 ± 0.1	11.96 ± 0.02
Untagged	76.7 ± 0.3	80.77 ± 0.05

$B_s^0 \to J/\psi\ \phi$: Correlations of Fit Parameters

[ATLAS-CONF-2019-009]

Fit correlations between the physical parameters of interest.

	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp} - \delta_S$
ϕ_s	−0.111	0.038	0.000	−0.008	−0.015	0.019	−0.001	−0.011
$\Delta\Gamma$	1	−0.563	0.092	0.097	0.042	0.036	0.011	0.009
Γ_s		1	−0.139	−0.040	0.103	−0.105	−0.041	0.016
$\lvert A_{\parallel}(0)\rvert^2$			1	−0.349	−0.216	0.571	0.223	−0.035
$\lvert A_0(0)\rvert^2$				1	0.299	−0.129	−0.056	0.051
$\lvert A_S(0)\rvert^2$					1	−0.408	−0.175	0.164
$\delta_{\parallel}$						1	0.392	−0.041
$\delta_{\perp}$							1	0.052

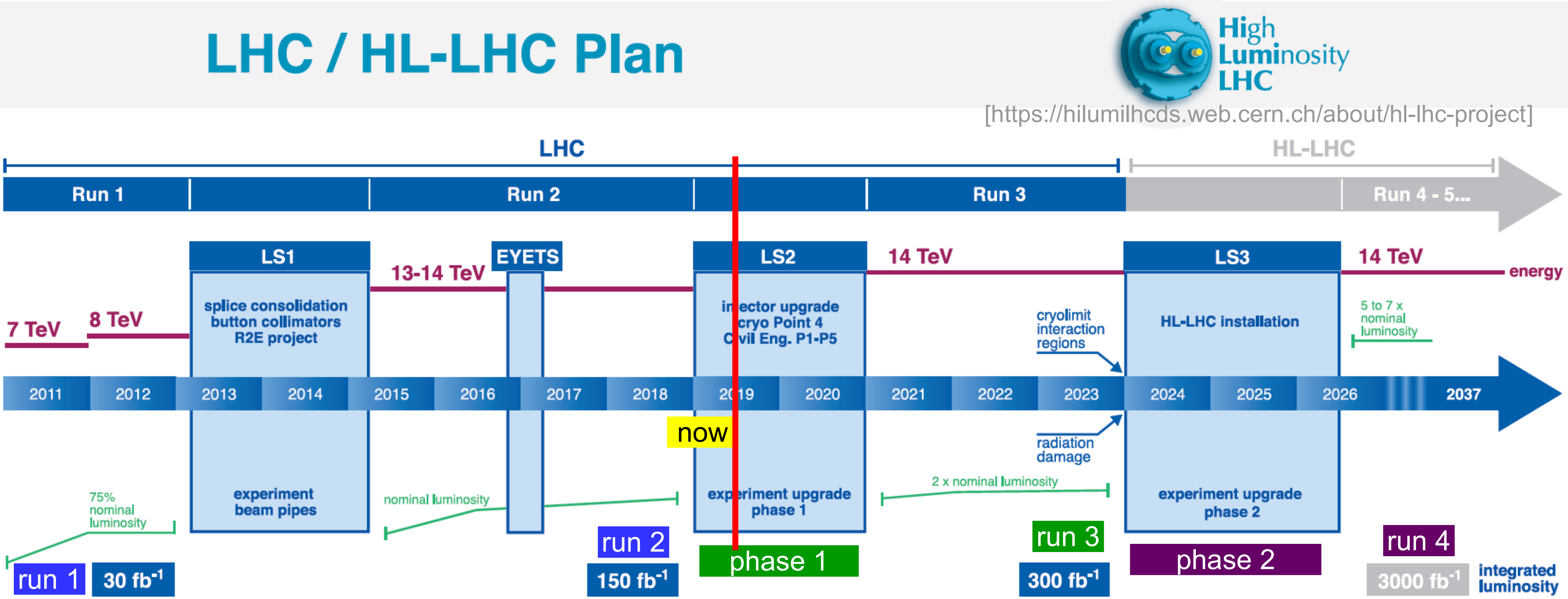
$B_s^0 \rightarrow J/\psi\,\phi$: Results Overview ϕ_s

ϕ_s [rad]	Value	Stat. uncertainty	Syst. uncertainty	Reference
ATLAS Run 2 (80.5 fb^{-1})	-0.068	0.038	0.018	ATLAS-CONF-2019-009
ATLAS Run 1 (19.2 fb^{-1})	-0.090	0.078	0.041	JHEP 08 (2016) 147
ATLAS Run 1+Run 2 (19.2 + 80.5 fb^{-1})	-0.076	0.034	0.019	ATLAS-CONF-2019-009
Standard Model	-0.0363	$^{+0.0016}_{-0.0015}$		Phys. Rev. D 84 (2011) 033005
CMS Run 1 (19.7 fb^{-1})	-0.075	0.097	0.031	Phys. Lett B 757 (2016) 97
LHCb Run 1 ($B_s^0 \rightarrow J/\psi\,\phi$, 3.0 fb^{-1})	-0.058	0.049	0.006	Phys. Rev. Lett. 114 (2015) 041801
LHCb Run 1 ($B_s^0 \rightarrow \psi(2S)\,\phi$, 3.0 fb^{-1})	0.23	$^{+0.29}_{-0.28}$	0.02	Phys. Lett B 762 (2016) 253
LHCb Run 2 ($B_s^0 \rightarrow J/\psi\pi^+\pi^-$, 1.9 fb^{-1})	-0.057	0.060	0.011	arXiv:1903.05530
LHCb Run 2 ($B_s^0 \rightarrow J/\psi K^+K^-$, 1.9 fb^{-1})	-0.080	0.041	0.006	LHCB-PAPER-2019-013
LHCb Run 2 ($B_s^0 \rightarrow J/\psi\, K^+K^-$, $\pi^+\pi^-$ combined, 1.9 fb^{-1})	-0.040	0.025		LHCB-PAPER-2019-013 arXiv:1903.05530 Moriond: K. Govorkova

$B_s^0 \to J/\psi\,\phi$: Results Overview $\Delta\Gamma_s$

$\Delta\Gamma_s$ [ps^{-1}]	Value	Stat. uncertainty	Syst. uncertainty	Reference
ATLAS Run 2 (80.5 fb^{-1})	0.067	0.005	0.002	ATLAS-CONF-2019-009
ATLAS Run 1 (19.2 fb^{-1})	0.085	0.011	0.007	JHEP 08 (2016) 147
ATLAS Run 1+Run 2 (19.2 + 80.5 fb^{-1})	0.068	0.004	0.003	ATLAS-CONF-2019-009
Standard Model	0.087	0.021		arXiv:1102.4274
CMS Run 1 (19.7 fb^{-1})	0.095	0.013	0.007	Phys. Lett. B 757 (2016) 97
LHCb Run 1 ($B_s^0 \to J/\psi\,\phi$, 3.0 fb^{-1})	0.0805	0.0091	0.0032	Phys. Rev. Lett. 114 (2015) 041801
LHCb Run 1 ($B_s^0 \to \psi(2S)\,\phi$, 3.0 fb^{-1})	0.066	+0.041 -0.044	0.007	Phys. Lett B 762 (2016) 253
LHCb Run 2 ($B_s^0 \to J/\psi K^+K^-$, 1.9 fb^{-1})	0.0772	0.0077	0.0026	LHCB-PAPER-2019-013
LHCb Run 2 ($B_s^0 \to J/\psi\, K^+K^-$, $\pi^+\pi^-$ combined, 1.9 fb^{-1})	0.0813	0.0048		LHCB-PAPER-2019-013 arXiv:1903.05530 Moriond: K. Govorkova

HL-LHC Timeline and Core Parameters



[https://hilumilhcds.web.cern.ch/about/hl-lhc-project]

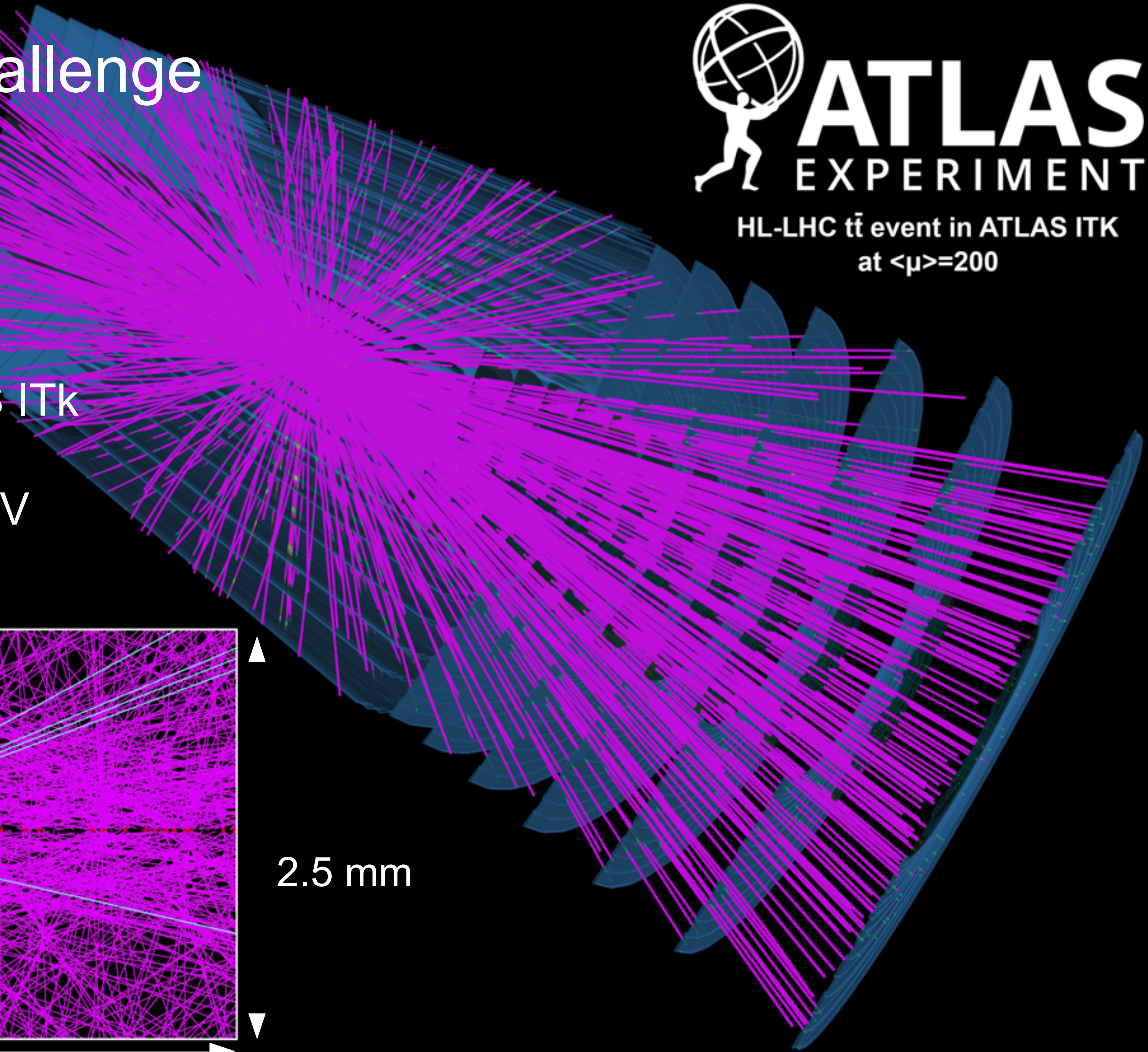
HL-LHC parameters: [CERN-2017-007-M]

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

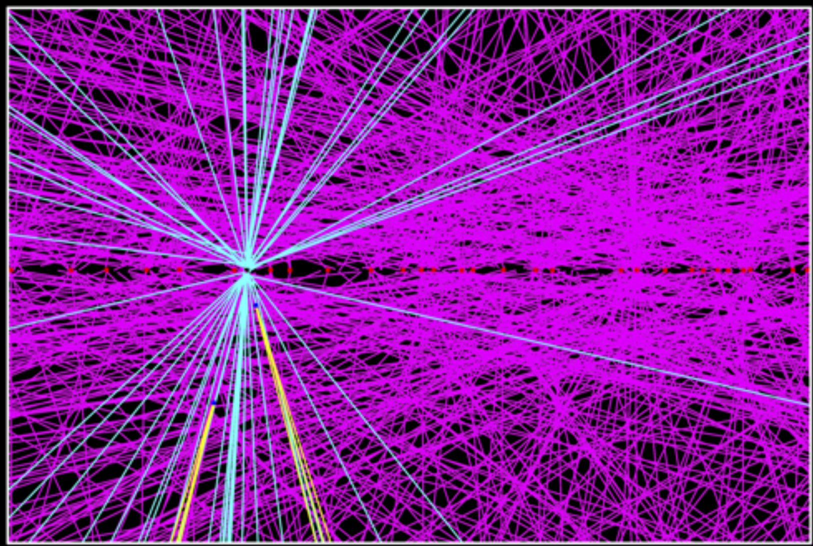
ATLAS upgrades:

- Detector & trigger, esp. new all-Si Inner TracKer (ITK)
- improves
  - B mass resolution σ_{mB}
  - proper time resolution σ_t

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

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

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

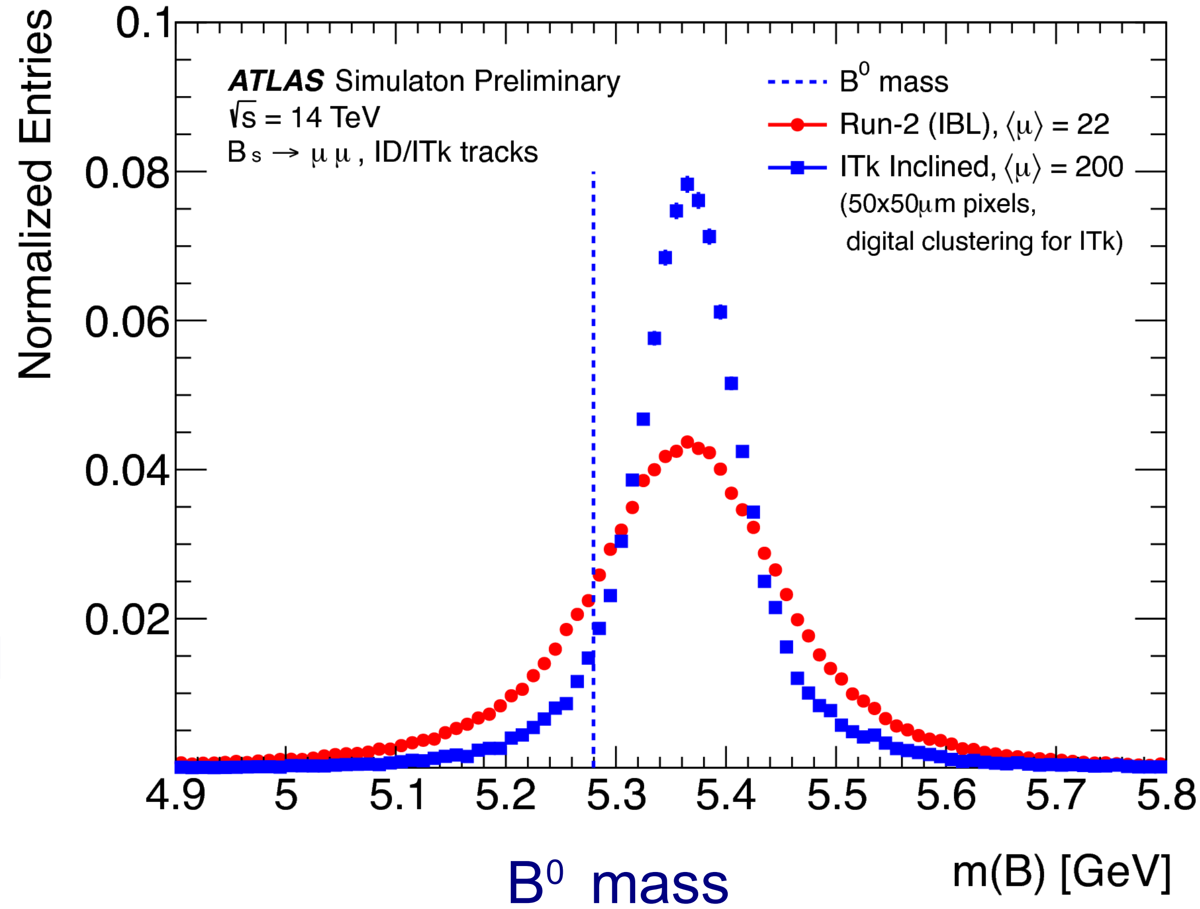
Dedicated $B_s^0 \to \mu^+\mu^-$ MC:

- 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 x 50 μm^2 pixels

Candidate selection ~ Run 1

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

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



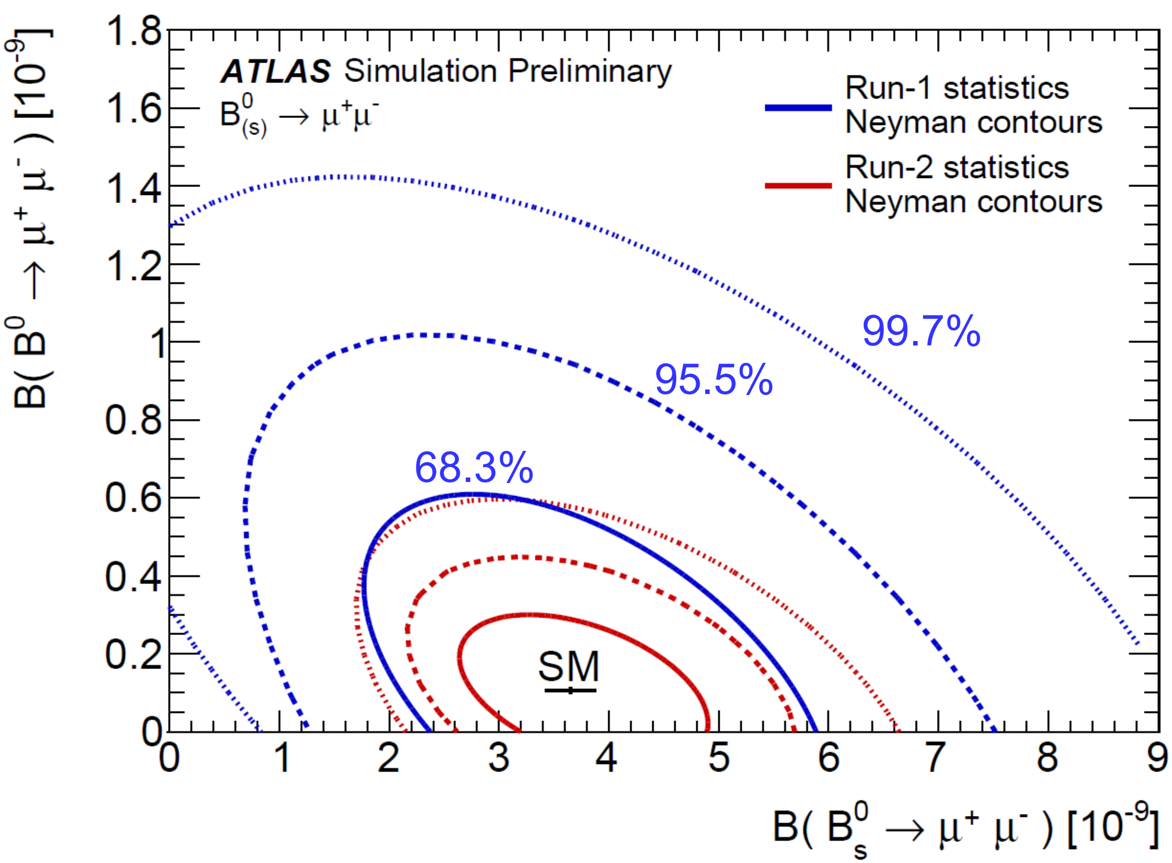
BR($B_{(s)}^0 \to \mu^+\mu^-$) Prospects – Run 2 (130 fb^{-1})

Signal statistics estimate:

- Based on Run 1 result
- Full Run 2 $\to$ $\int L\, dt \sim 130$ fb^{-1}
- σ_{bb}: 8 TeV $\to$ 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($B^\pm \to J/\psi K^\pm$)
  $\to$ keep as in Run 1
- Internal:
  fit shapes, efficiencies, …
  $\to$ scale with statistics

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]

		$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$		$\mathcal{B}(B^0 \to \mu^+\mu^-)$	
		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($B^0 \rightarrow \mu^+ \mu^-$) = $(3.9^{+1.6}_{-1.4})\text{x}10^{-10}$

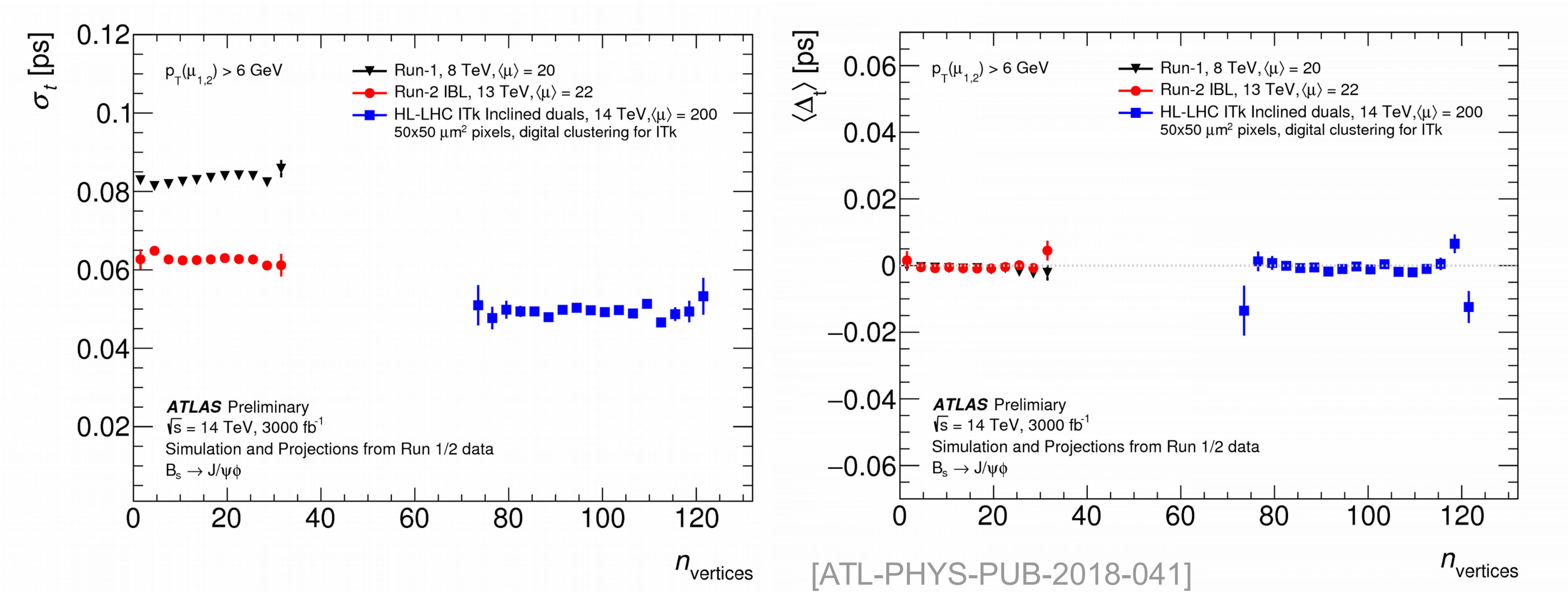
LHCb (2015+2016):

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

$B_s^0 \rightarrow J/\psi\,\phi$ Pileup Stability for HL-LHC (3 ab^{-1})

Dependence of the MC-true based proper decay time resolution (left) and bias of the the proper decay time reconstruction (right) of the $B_s^0 \rightarrow J/\psi\,\phi$ on the number of reconstructed primary vertices.

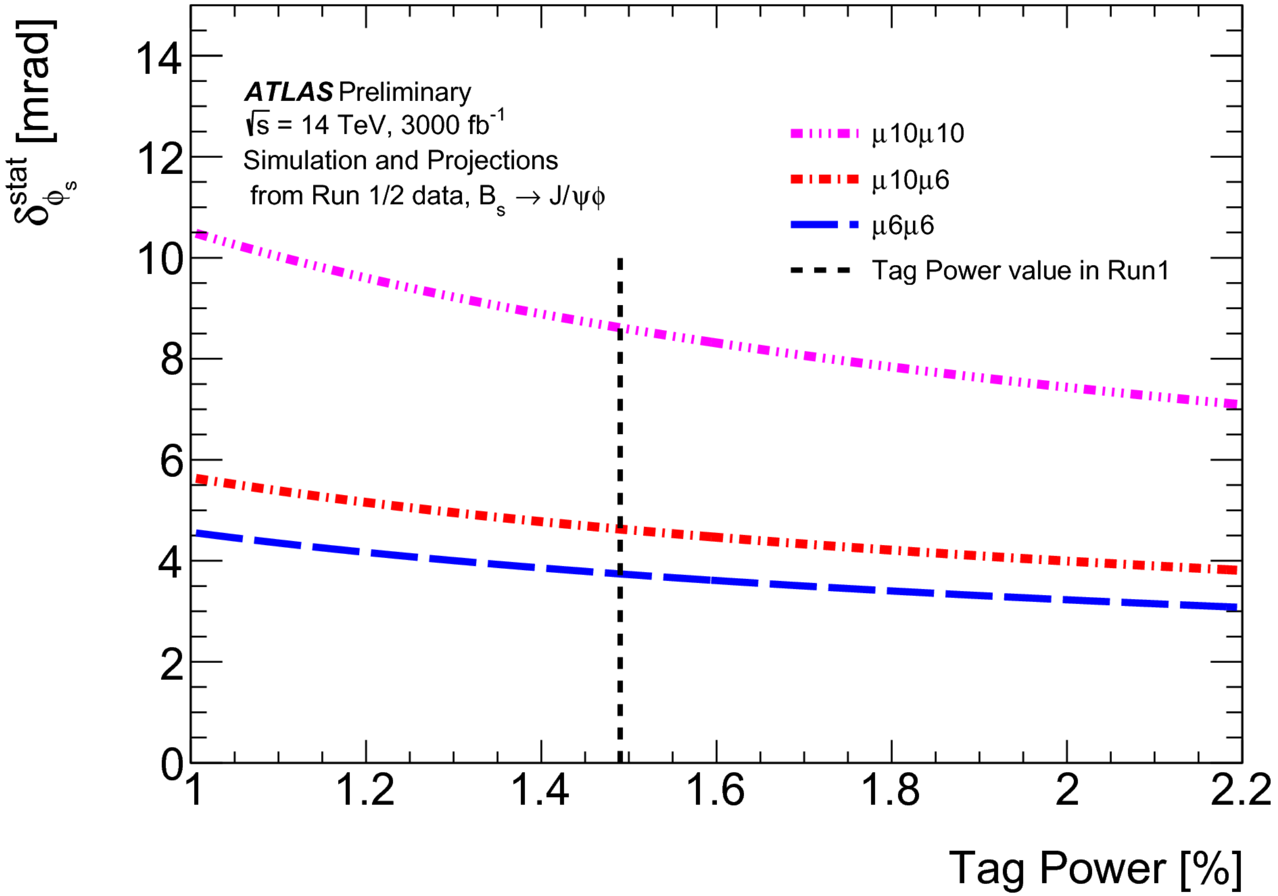
All samples use 6 GeV muon p_T cuts.



[ATL-PHYS-PUB-2018-041]

$B_s^0 \rightarrow J/\psi\, \phi$ Tag Power for HL-LHC (3 ab^{-1})

Dependence of the ϕ_s precision, $\delta_{\phi s}$, on Tag Power (TP), for a broad range of TP values for each of the upgrade trigger threshold scenarios.



[ATL-PHYS-PUB-2018-041]

$B_s^0 \to J/\psi\ \phi$ Predictions for HL-LHC (3 ab^{-1})

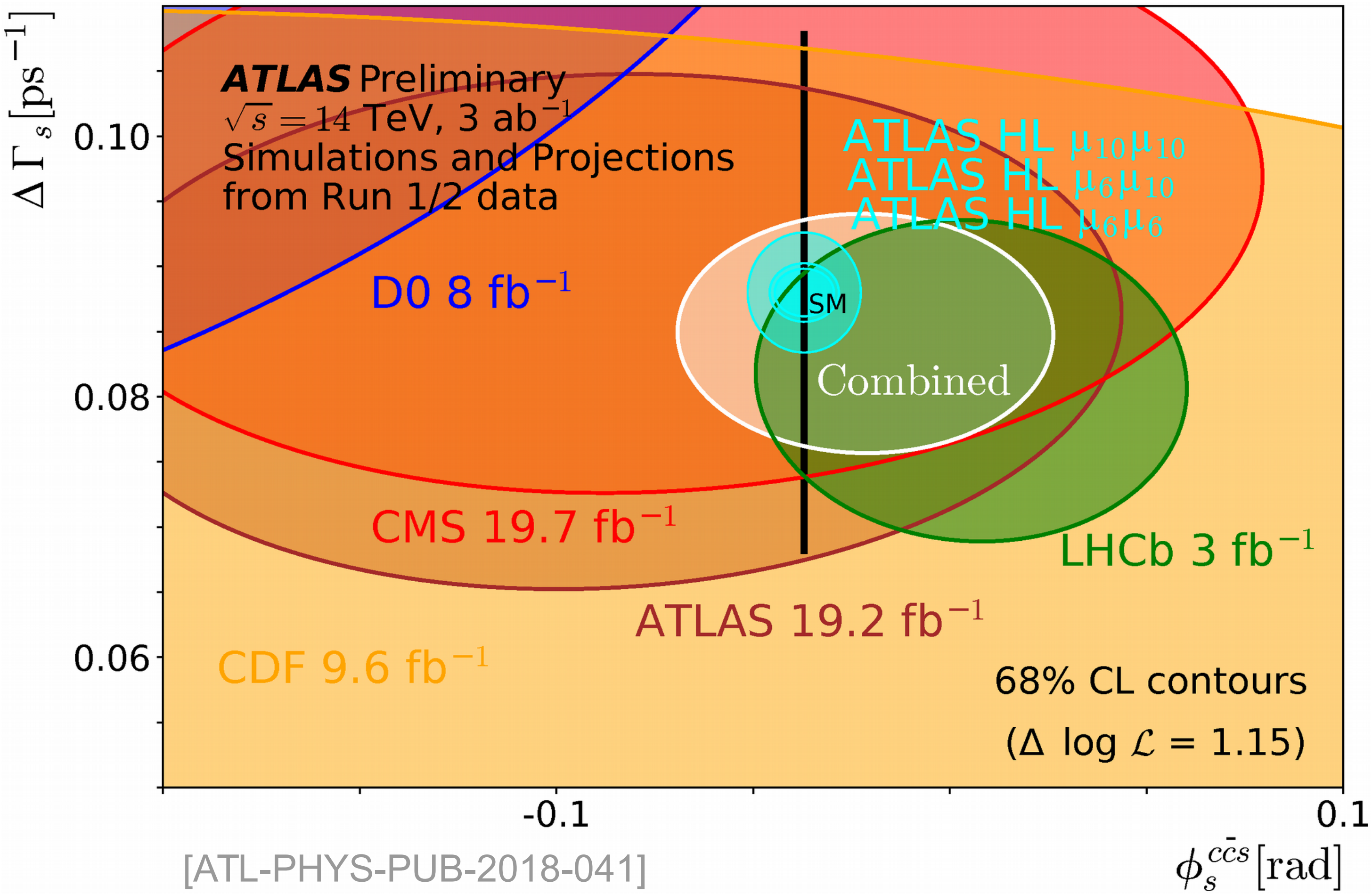
Summary of $B_s^0 \to J/\psi$ performance for existing data and predictions for HL-LHC. The precision on ϕ_s is statistical only.

Period	L_{int} [fb^{-1}]	N_{sig}	f_{sig}	Tag Power [%]	$\sigma(\tau)$ [ps]	$\delta^{\text{stat}}_{\phi_s}$ [rad] measured (extrapolated)	$\delta^{\text{stat}}_{\Delta\Gamma_s}$ [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)
						$\delta^{\text{stat}}_{\phi_s}$ [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

[ATL-PHYS-PUB-2018-041]

$B_s^0 \to J/\psi\, \phi$ CPV Prospects – HL-LHC (3 ab^{-1})

Experimental summary of the ϕ_s measurements with superimposed ATLAS HL-LHC extrapolations, including both the projected statistical and systematic uncertainties.

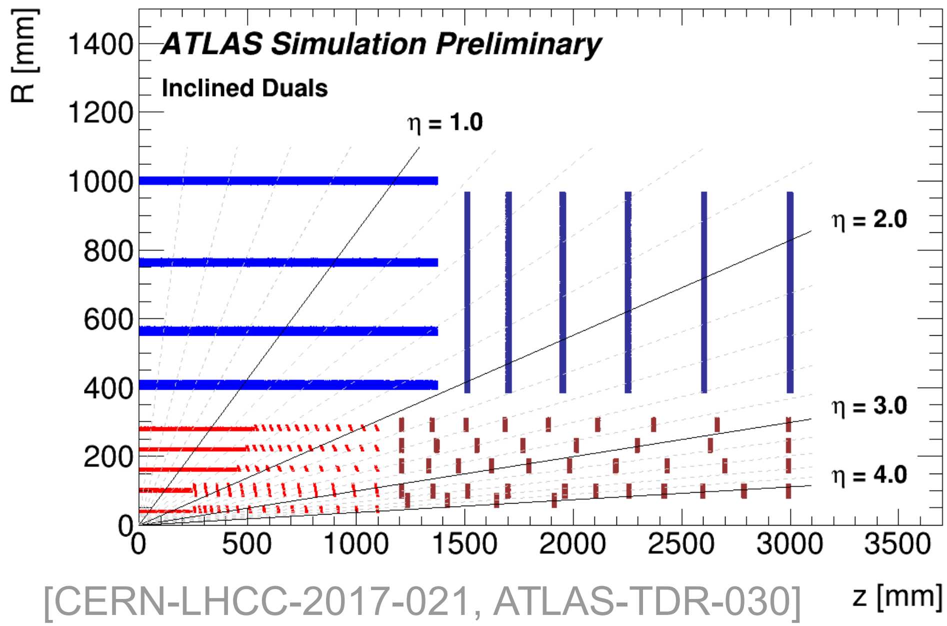


[ATL-PHYS-PUB-2018-041]

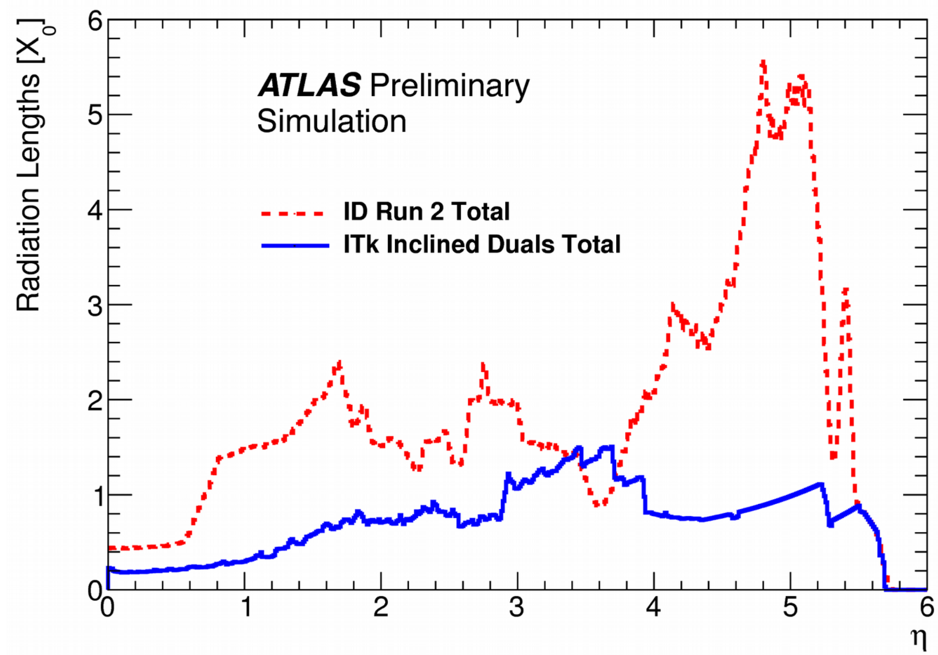
ATLAS Inner Tracker (ITk) Upgrade

New all-silicon detector:

- ITk pixel (13 m²):
  - 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 m²):
  - 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



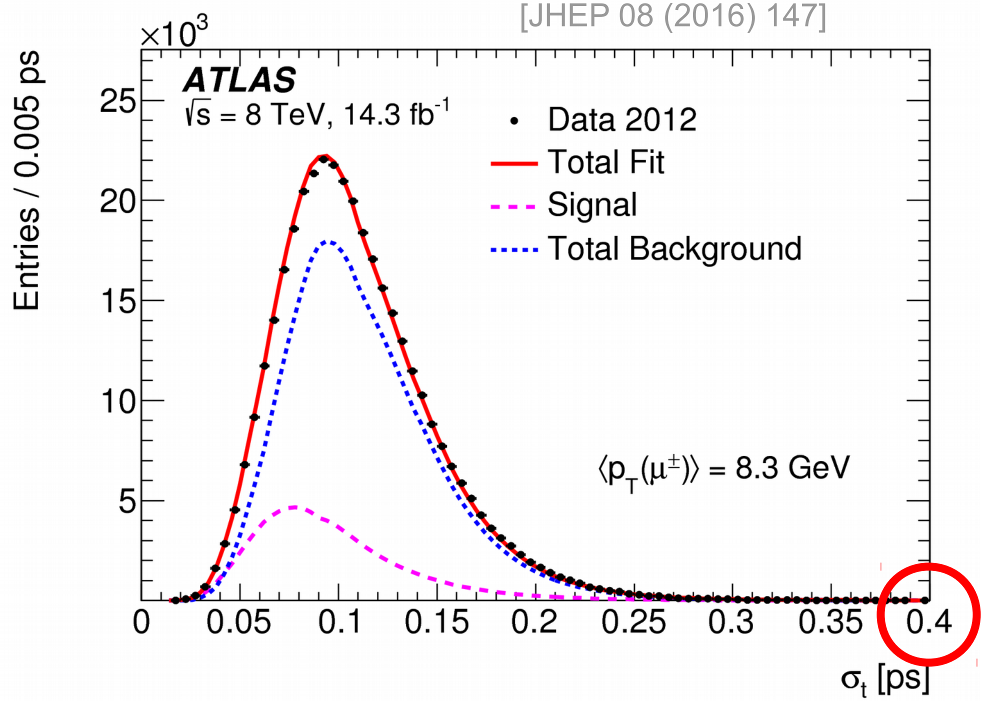
[CERN-LHCC-2017-021, ATLAS-TDR-030]



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

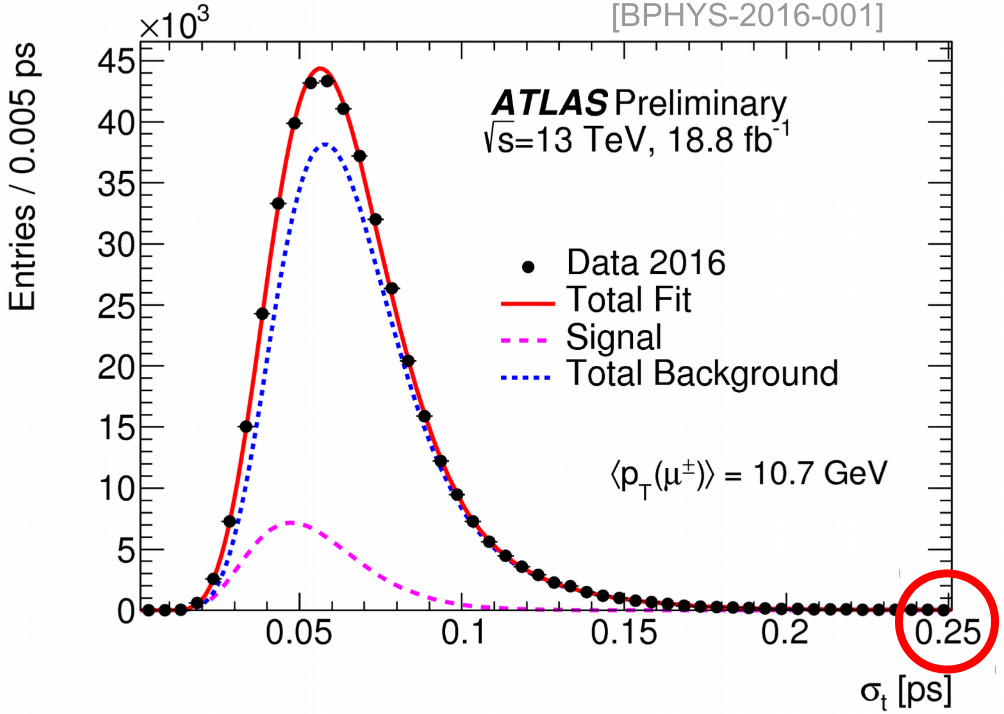
Run 1 – 2012 data

[JHEP 08 (2016) 147]



Run 2 – 2016 data

[BPHYS-2016-001]



Insertable B Layer (IBL) added in Run 2:

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

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

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

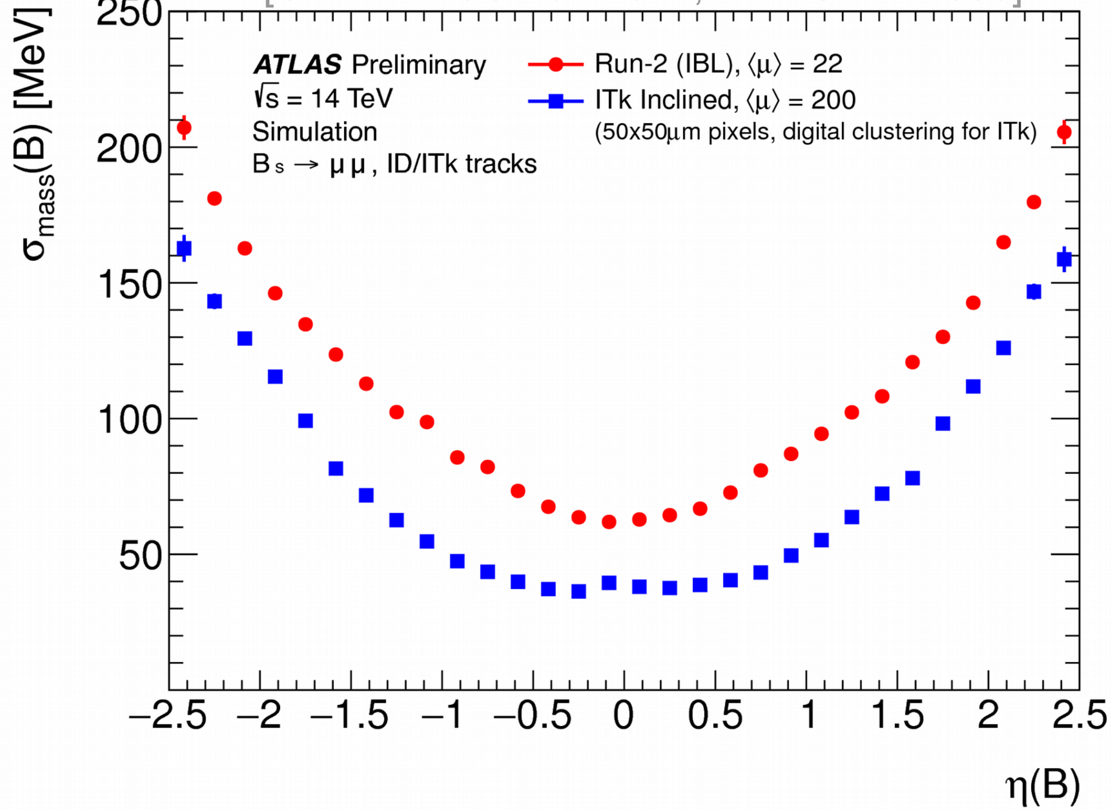
- Run 2 conditions like 2015
- HL-LHC & HL-ATLAS:
  - $L_{inst} = 7.5 \times 10^{34}\ cm^2s^{-1}$ at 14 TeV CME $<\mu> = 200$ pile-up events
  - ITk: inclined design, up to $|\eta| < 4$, 50 x 50 μm^2 pixels

Candidate selection ~ Run 1

- B_s^0: oppositely charged $\mu^\pm$, $p_T(\mu^\pm_{1,2}) > 5.5$ 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]



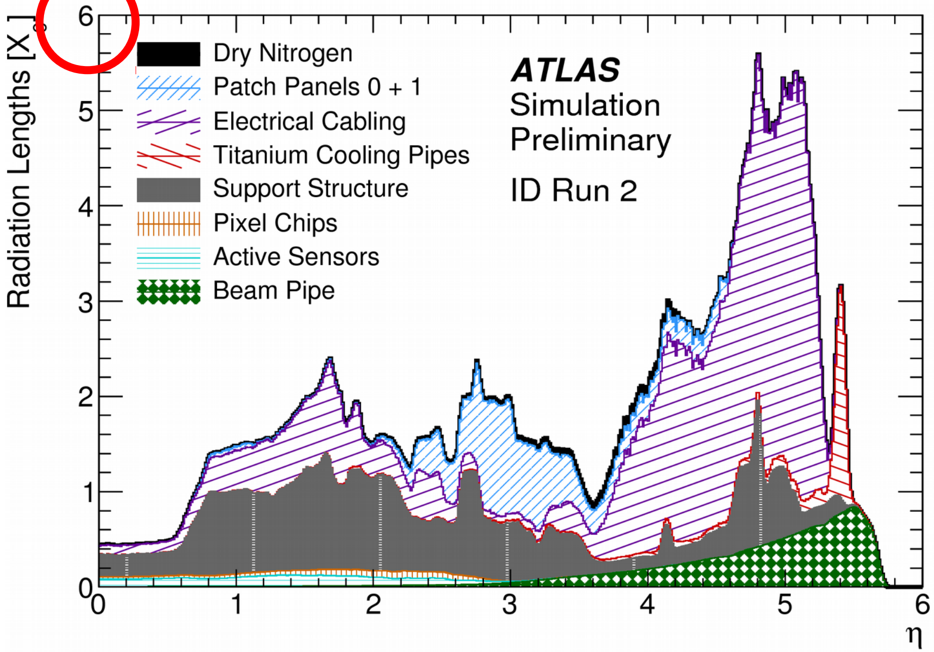
Separation of $m(B_s^0)$ and $m(B^0)$:

- 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

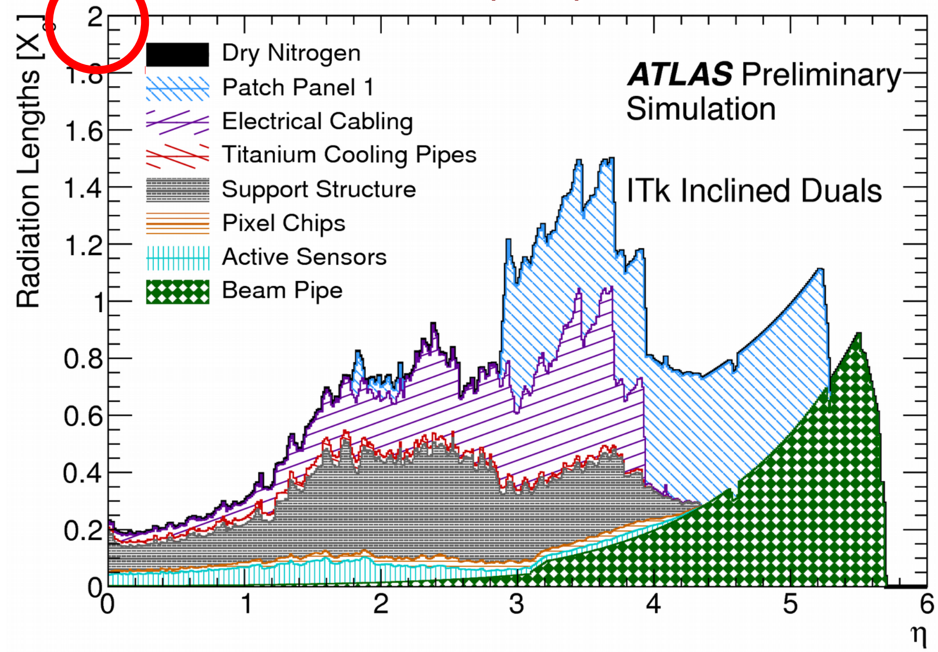
[ATL-PHYS-PUB-2016-026]

ATLAS ID and ITk Material Budgets

Inner Detector (ID) – current



Inner Tracker (ITk) – HL-LHC



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

- Material budget of ITk is greatly reduced.