Rare and Semi-rare Decays of Beauty Mesons in ATLAS

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on behalf of the ATLAS collaboration

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Introduction

New Physics beyond the Standard Model in B meson decays:

- Angular analysis of semi-rare decays:
  $B^0 \to K^{*0} \mu^+\mu^-$
  - ATLAS result with 20.3 fb^{-1} of 8 TeV LHC data (Run 1, 2012)
    [JHEP10 (2018) 047]
- 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]

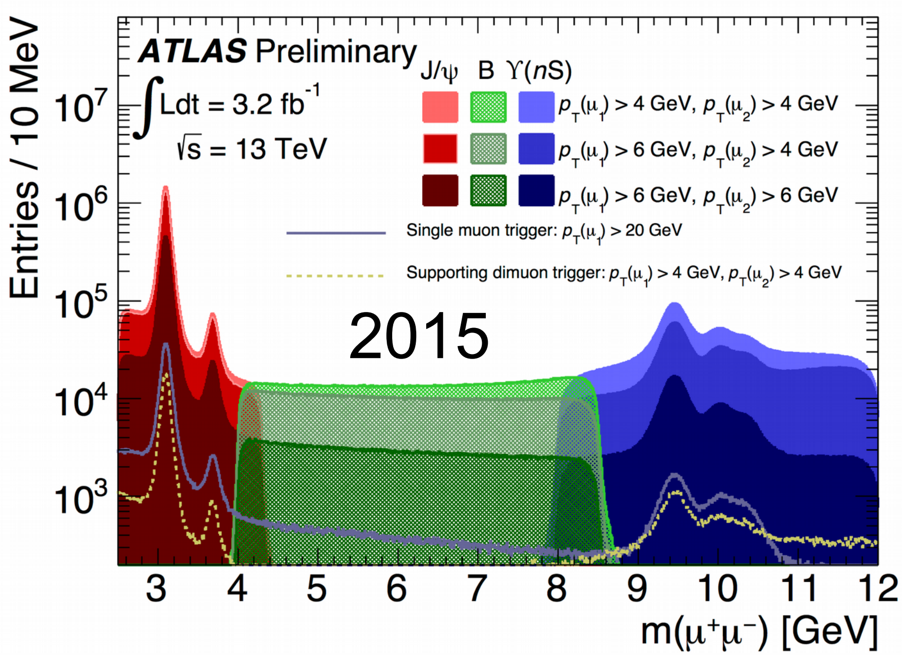
Prospects at the HL-LHC:

- $B^0 \to K^{*0} \mu^+\mu^-$
  [ATL-PHYS-PUB-2019-003]
- $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$
  [ATL-PHYS-PUB-2018-005]

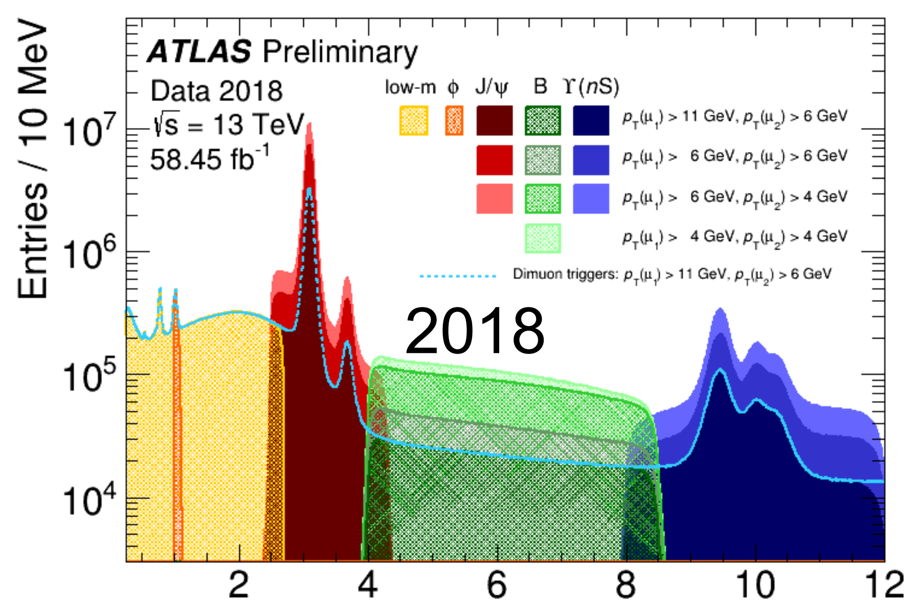
ATLAS B Physics Triggers

Mostly based on di-muon triggers

- $B^0 \to K^{*0} \mu^+\mu^-$ analysis (Run 1, 8 TeV, 2012)
  - combination of 19 trigger chains (1μ, 2μ or 3μ)
  - largest multi-μ contribution from 2μ with $p_{T,1} > 6$ GeV, $p_{T,2} > 4$ GeV
- $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ analysis (Run 2, 13 TeV, 2015-2016)
  - two μ 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)



[ATLAS B physics trigger public plots page]

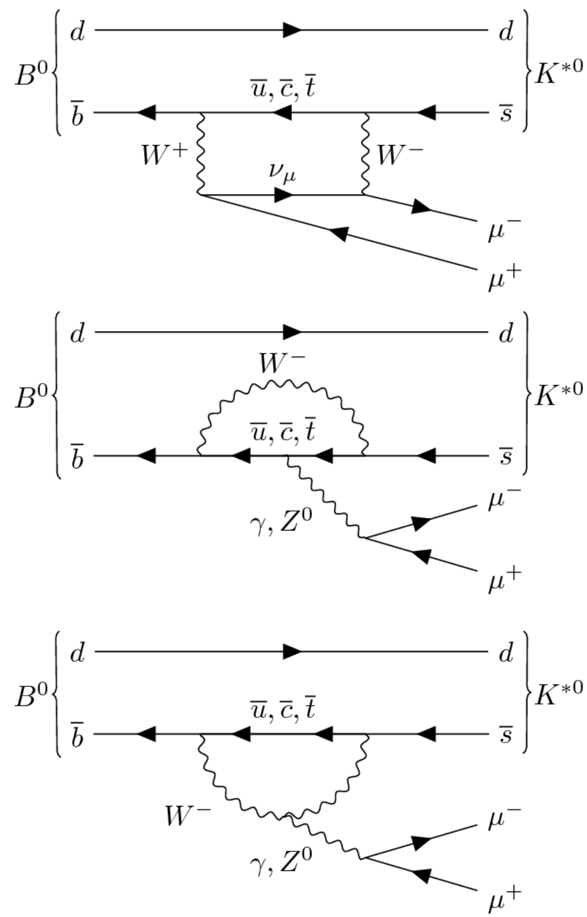


$B^0 \rightarrow K^{*0} \mu^+\mu^-$

$B^0 \rightarrow K^{*0}\, \mu^+\mu^-$ – Overview

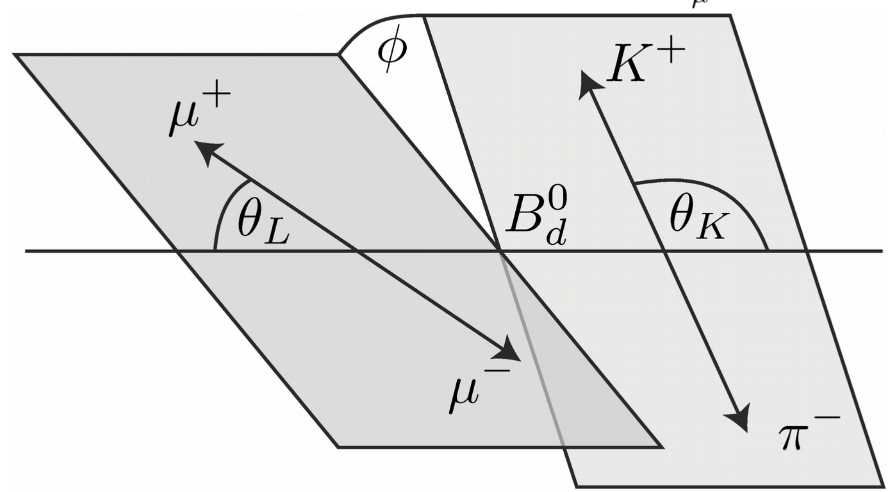
$B^0 \rightarrow K^{*0}\, \mu^+\mu^-$: loop-suppressed FCNC decay

- Sensitive to New Physics: differential decay rates and angular distributions
- $BR(B^0 \rightarrow K^{*0}\, \mu^+\mu^-) \sim (1.03 \pm 0.06) \times 10^{-6}$
- LHCb: up to 3.4σ deviation from SM



Analysis of angular distributions of θ_L, θ_K and ϕ in $q^2 = [m(\mu^+\mu^-)]^2$ bins

- Fit to $m_{K\pi\mu\mu}$, $\cos\theta_K$, $\cos\theta_L$ and ϕ distributions
  → F_L (K^{*0} longitudinal polarization)
  → S_i (angular parameters)
- $S_i \rightarrow P_j^{(')}$: reduce theory uncertainties
- low statistics
  → trigonometric folding
  → 4 x 3-parameter fits (F_L, S_3, $S_{i=4,5,7,8}$) per q^2 bin



[JHEP10 (2018) 047]

$B^0 \to K^{*0} \mu^+\mu^-$ – Signal Selection

$B^0 \to K^{*0} \mu^+\mu^-$ with $K^{*0} \to K^+\pi^-$ cuts:

- $p_T(\mu,\pi,K) > (3.5, 0.5, 0.5)$ GeV, $|\eta| < 2.5$
- $m(K\pi) \in [846, 946]$ MeV
- $m(K\pi\mu\mu) \in [5110, 5700]$ MeV
  - left SB reduced: suppress $B \to \mu\mu X$ PRDs
- $q^2 \leq 6\ \mathrm{GeV}^2$: suppress $J/\psi[\to J/\psi\gamma]K^*$ radiative tail

Suppress combinatorial background:

- $p_T(K^{*0}) > 3$ GeV, $t/\sigma_t > 12.75$, $\cos\Theta > 0.999$, $\chi^2/\mathrm{n.d.f}(B^0) < 2$

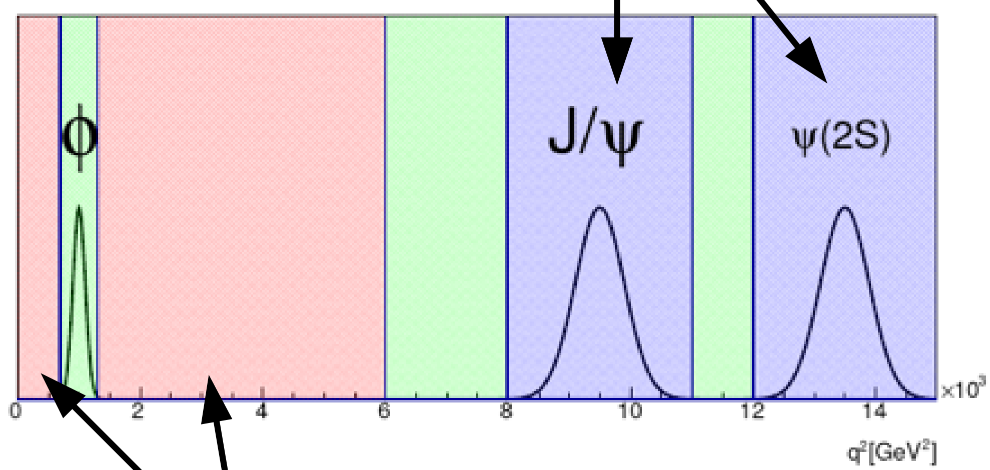
Other backgrounds:

- at $\cos\theta_L \sim 0.7$: $B \to D^0/D^+_{(s)}X \to K\pi X, KK\pi X$
  $\to$ veto $D^0/D^+_{(s)}$ mass ranges
- at $\cos\theta_K \sim 1$: fake K^* (comb. $K\pi$) and $B^+ \to K^+/\pi^+\mu^+\mu^-$
  $\to$ difference fitting [-1, 1] vs [-1, 0.9], veto B^+ mass range
  $\to$ systematic uncertainties

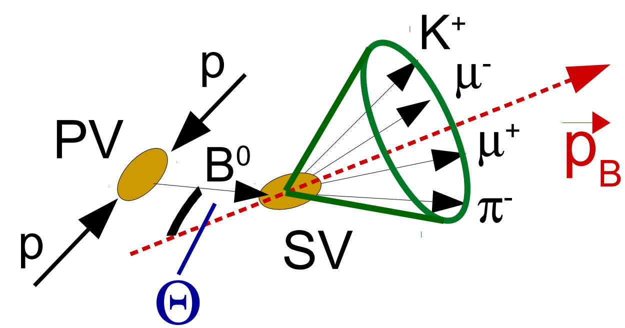
Multiple $K\pi\mu\mu$ candidates (12% of events):

- best $\chi 2$ or smallest $|m(K\pi) - m_{PDG}(K^{*0})| / \sigma(m(K\pi))$
  $\to$ residual mis-tag fraction ~ 11% ($S_{4,5}$ dilution) $\to$ post-fit correction

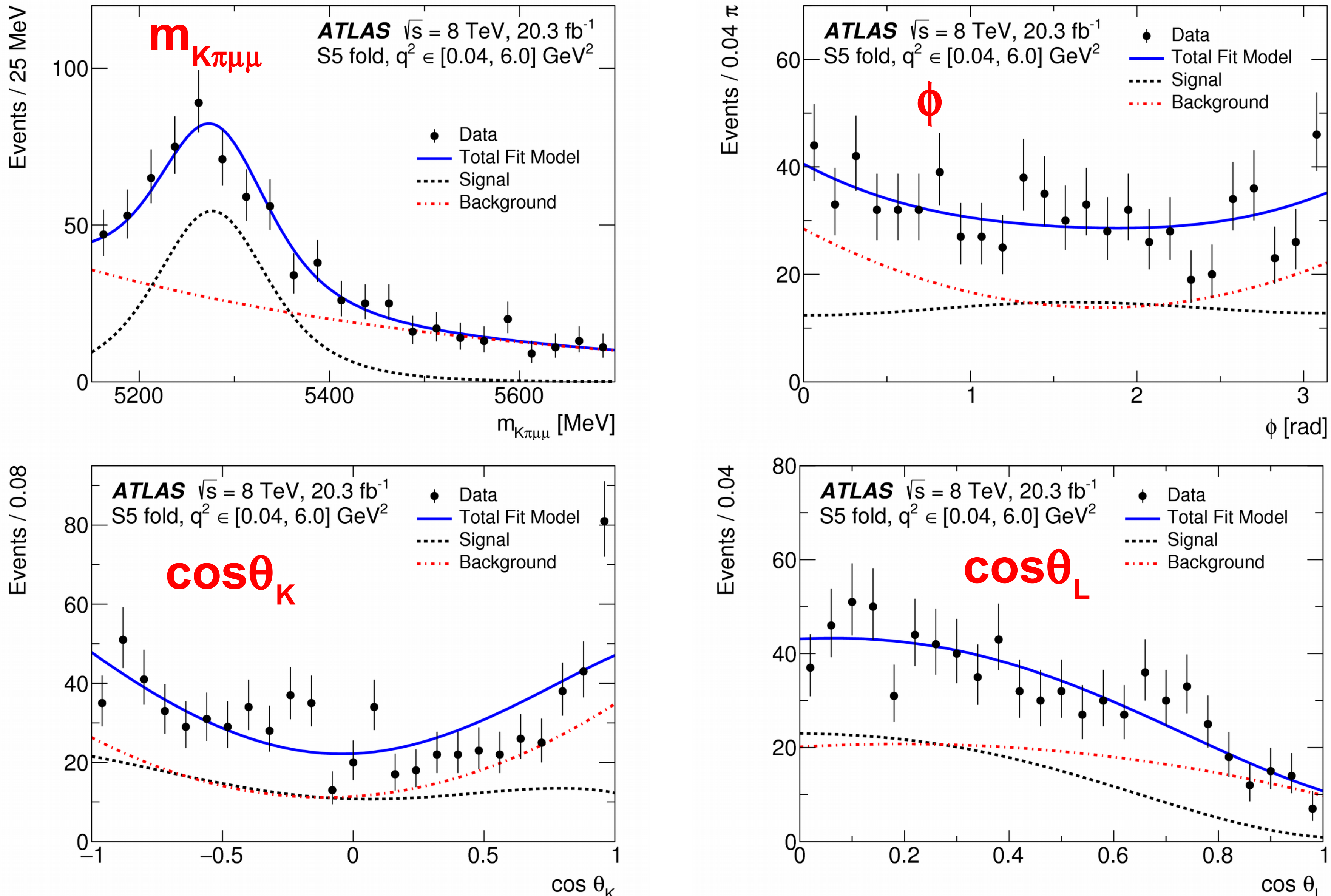
control regions
(→ mass peak parameters)



signal regions (787 events)
$q^2 \in [0.04, 6]$ excl. $[0.98, 1.1]\ \mathrm{GeV}^2$



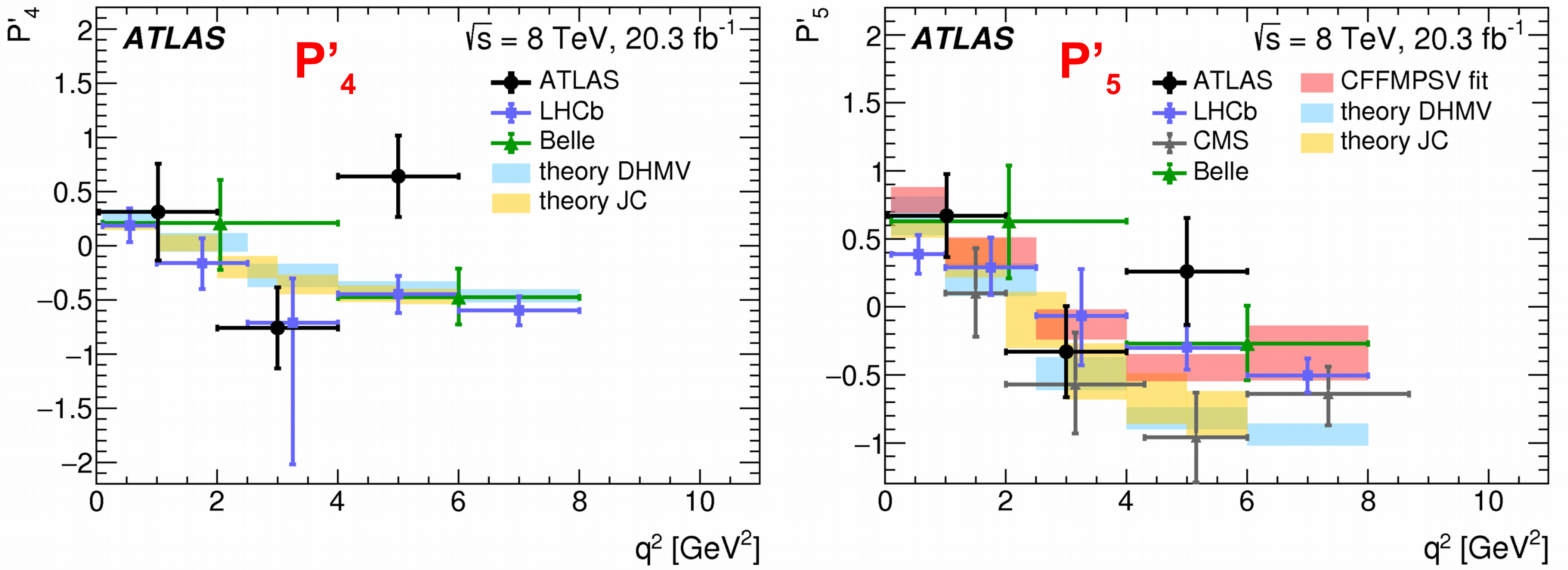
$B^0 \to K^{*0} \mu^+\mu^-$ – Fit Results for $q^2 \in [0.04, 6.0]$ GeV



- Example with S_5 folding scheme applied

[JHEP 10 (2018) 047]

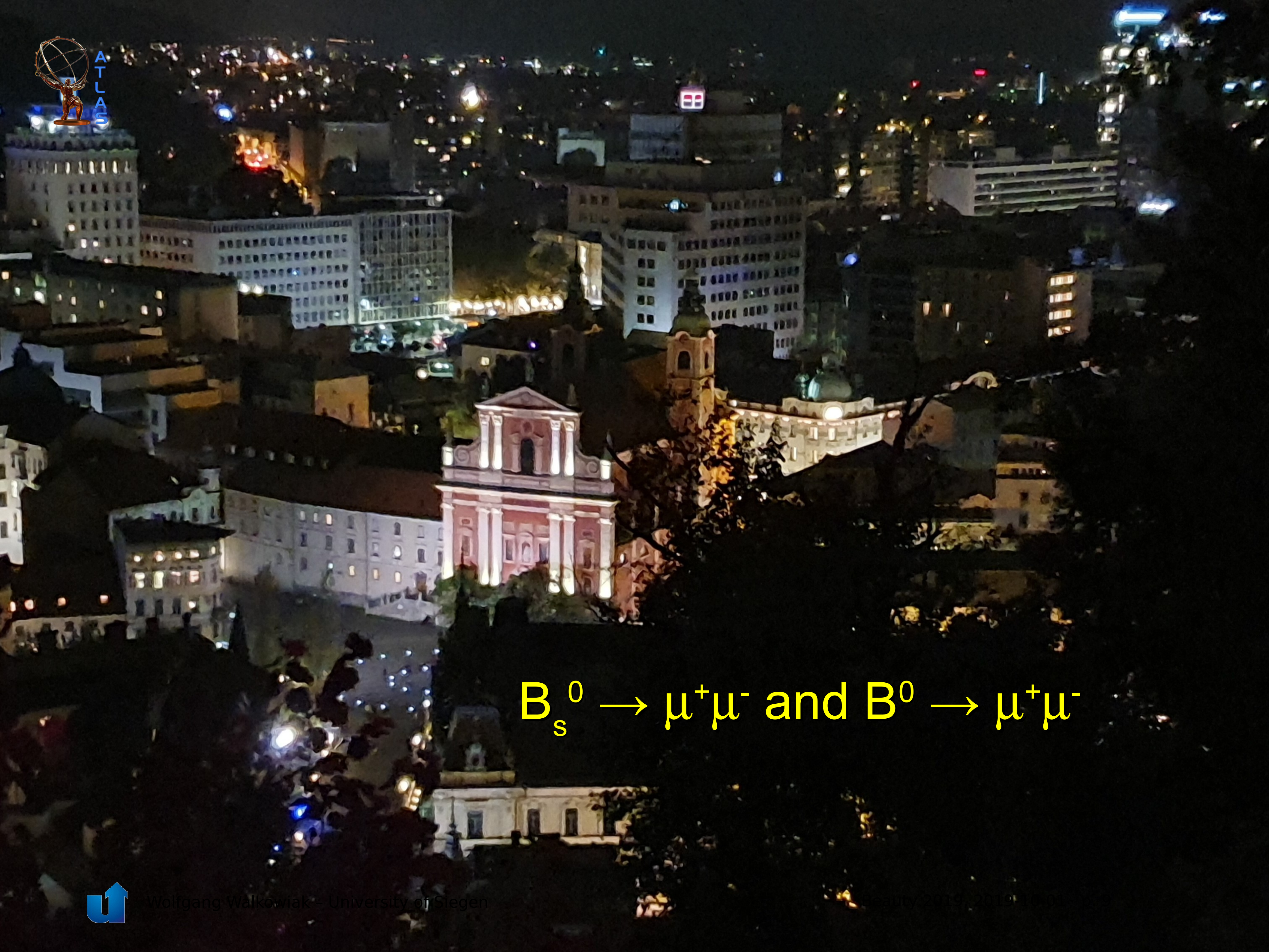
$B^0 \to K^{*0} \mu^+\mu^-$ – Results



- Largest deviation: ~ 2.7σ from DHMV for P'_4 and P'_5 in $q^2 \in [4, 6]$ GeV^2
- Consistent with other experiments
  → P'_5 deviation coherent with LHCb

[JHEP 10 (2018) 047]

→ see backup for all comparison plots and references

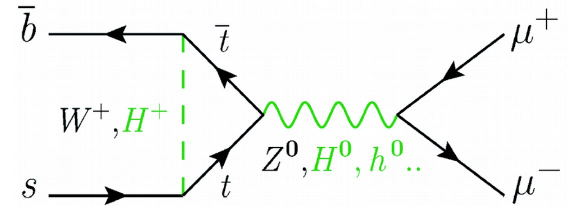


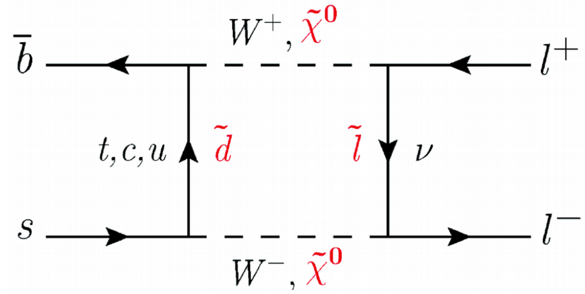
$B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$

$B_{(s)}^0 \to \mu^+\mu^-$ – Run 1

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

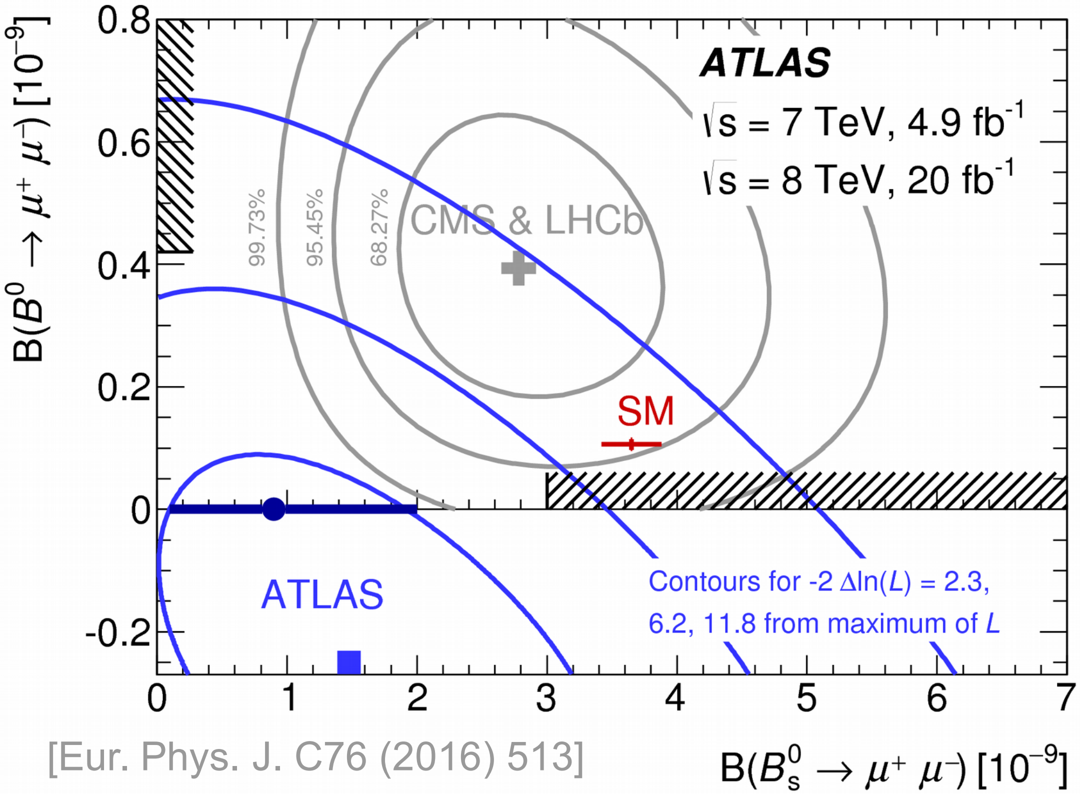
- Sensitive to New Physics in decay via loop diagrams





Run 1 result:

- $BR(B^0_s \to \mu^+\mu^-) = (0.9\ ^{+1.1}_{-0.8}) \times 10^{-9}$
- $BR(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ 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
  $BR(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ at 95% CL
  [PRL 118 (2017) 191801]
  and very recent (2019) CMS Run 1 + partial Run 2 result
  $BR(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ at 95% CL
  [CMS PAS BPHY-16-004, 2019-08-04]



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

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

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

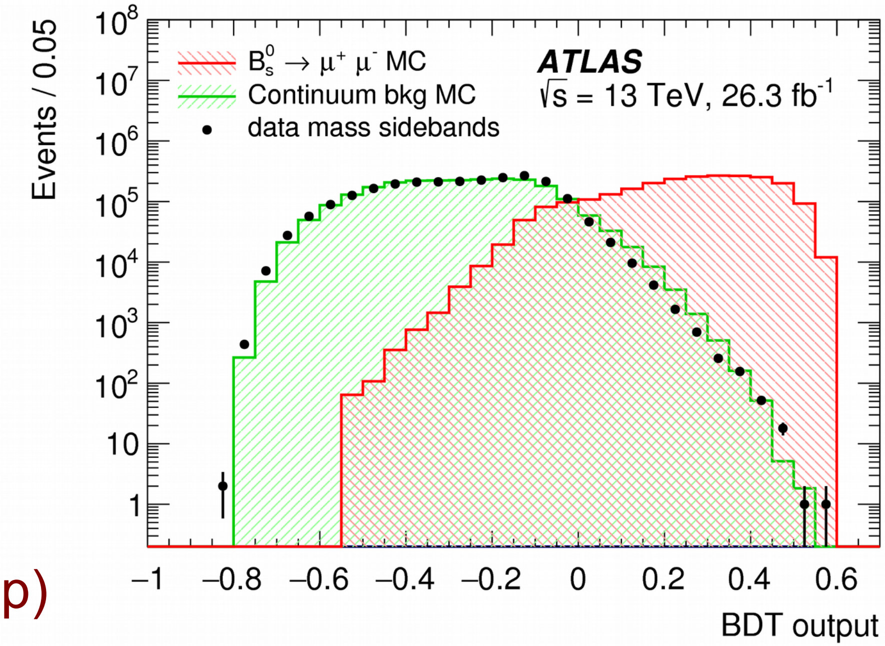
- 15-variable BDT to reject dominant background
- Trained and tested on data mass sidebands and simulated signal events

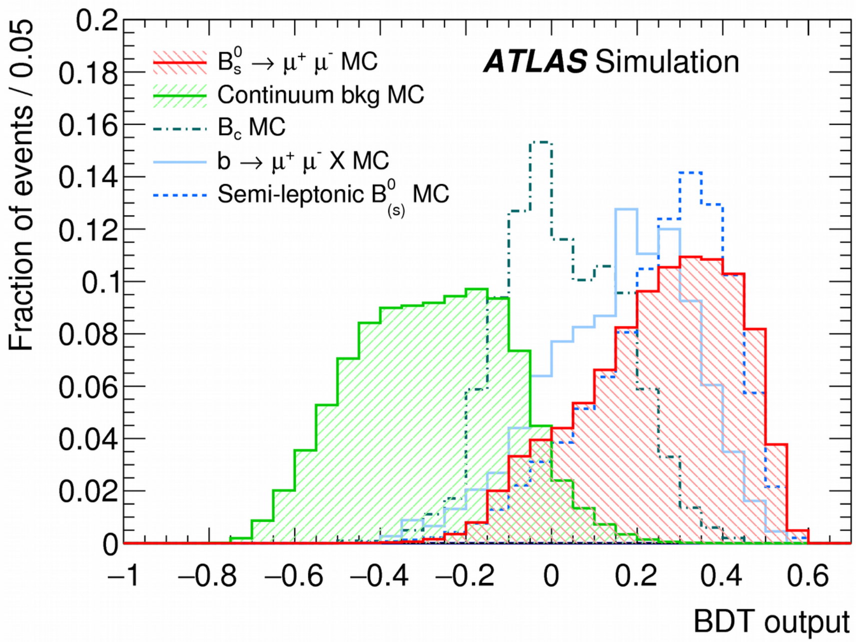
Partially reconstructed ($b \rightarrow \mu\mu X$)

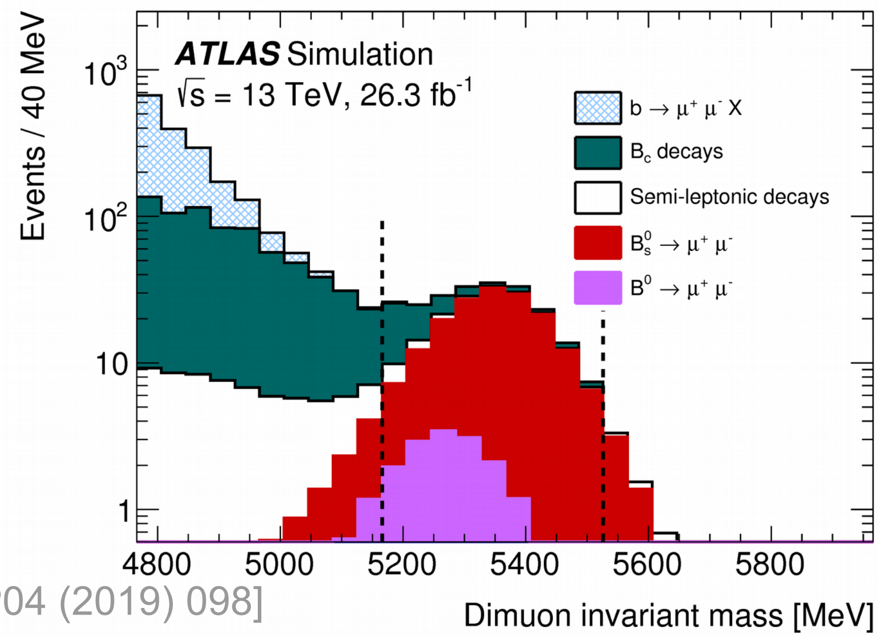
- Real di-muons at low $m_{\mu\mu}$

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

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





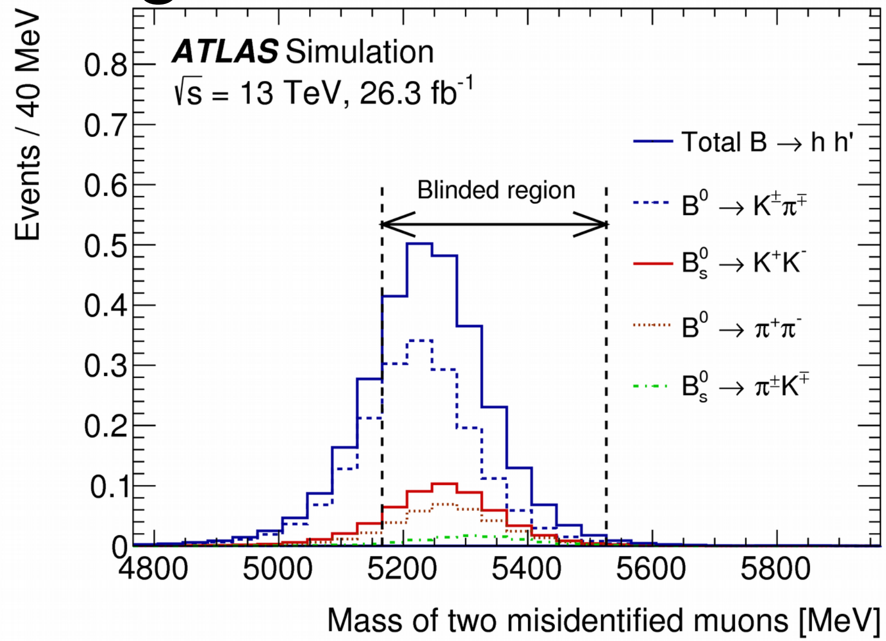


[JHEP04 (2019) 098]

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

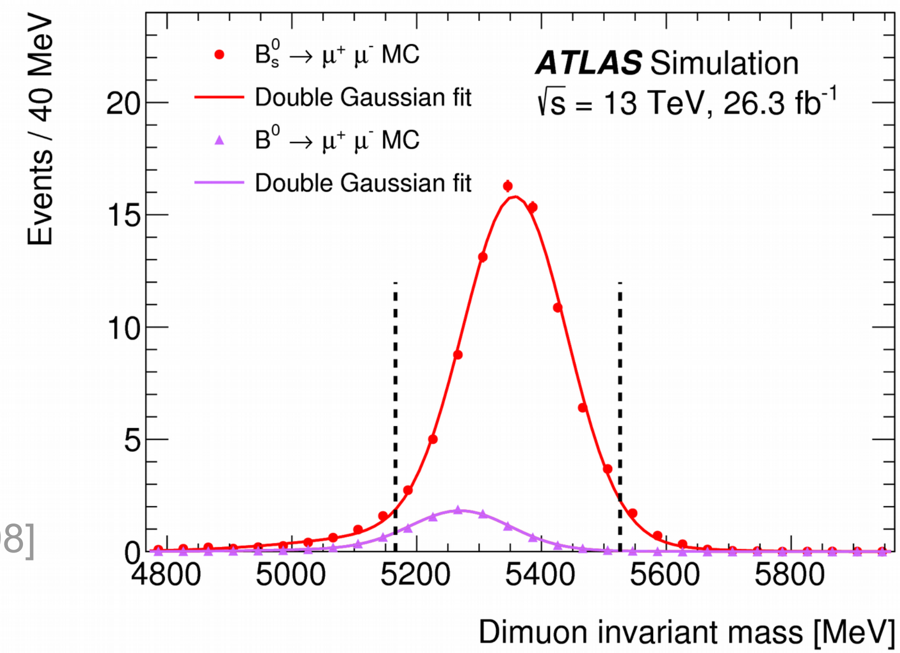
$B \rightarrow hh'$ ($h = \pi^\pm, K^\pm$)

- 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 blinded region: 2.9 ± 2.0 events



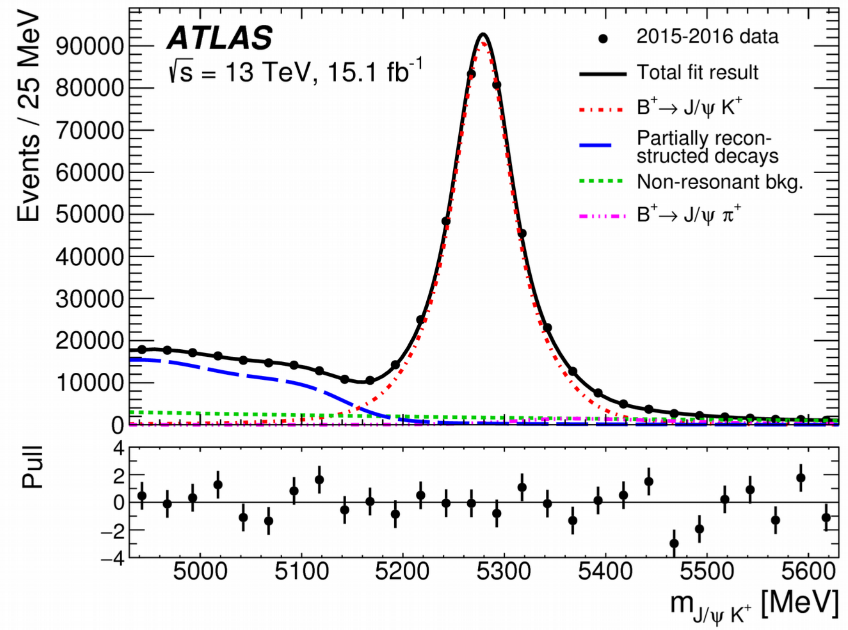
Limited mass resolution:

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



[JHEP04 (2019) 098]

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

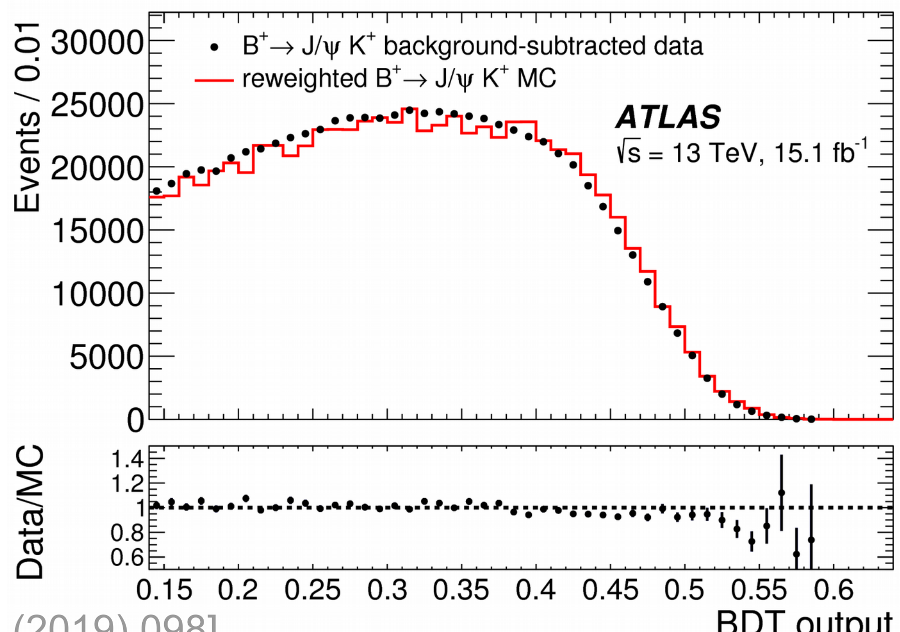


$B^\pm \to J/\psi\, K^\pm$ yield:

- 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 → systematic uncertainties
- Effective B_s^0 lifetime → 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

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

[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 means
- 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:

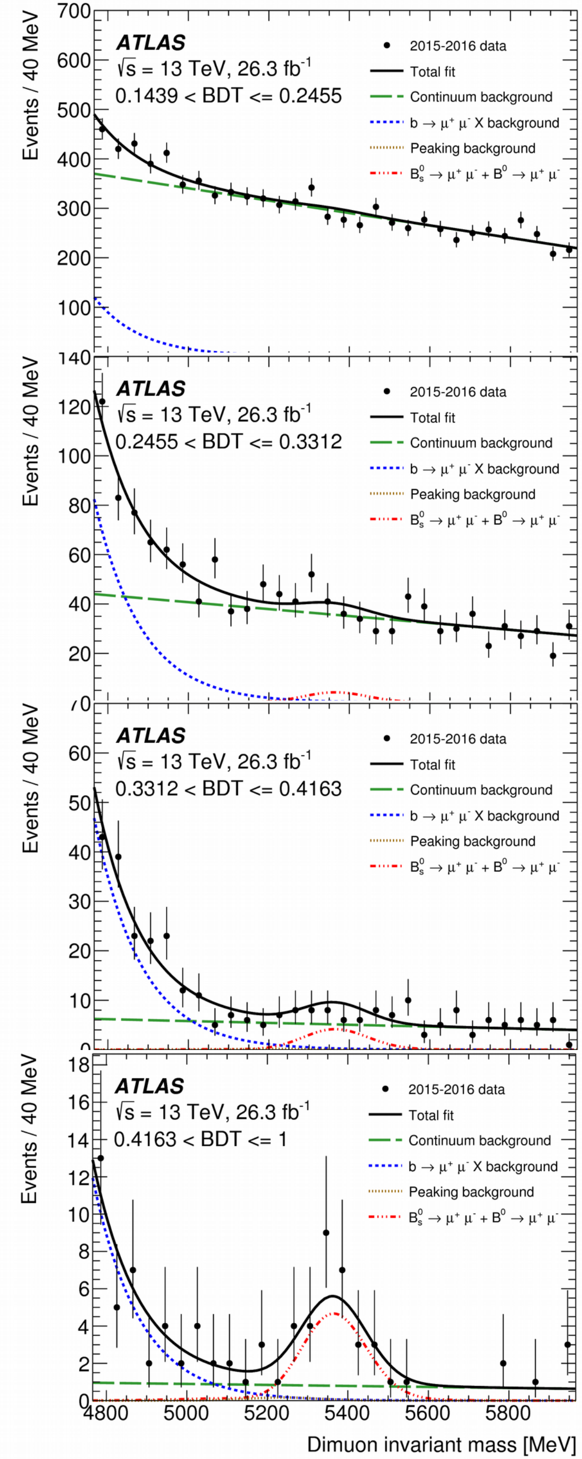
- $N_s = 91$ $N_d = 10$

Branching fraction (Neyman construction):

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

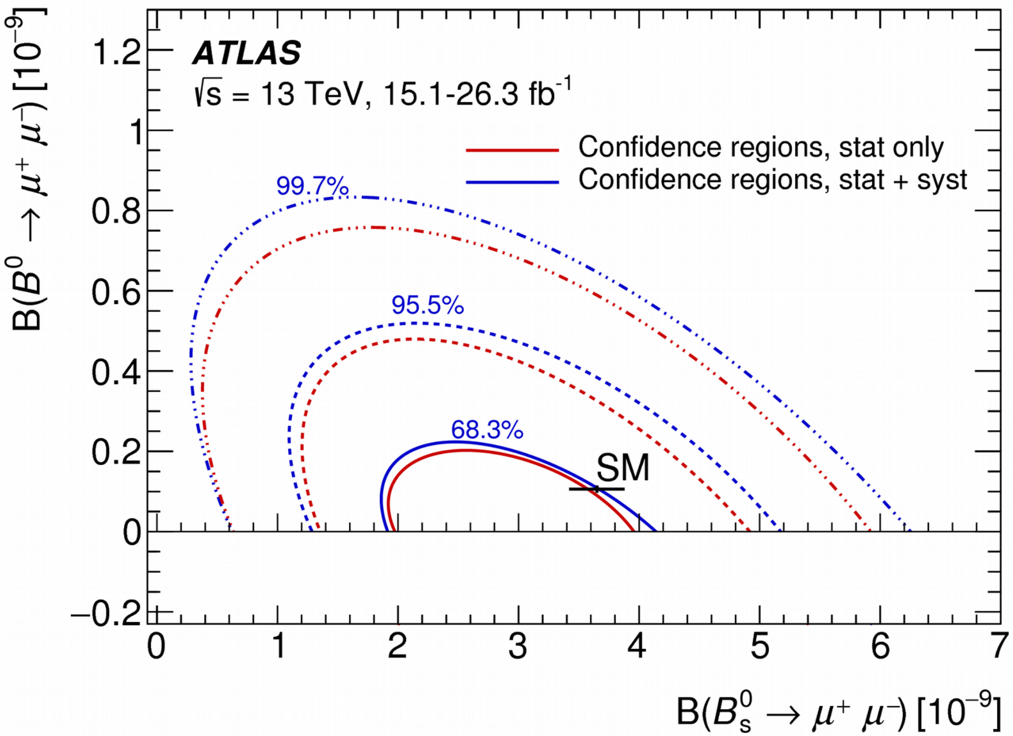
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$$ @ 95% CL

[JHEP04 (2019) 098]

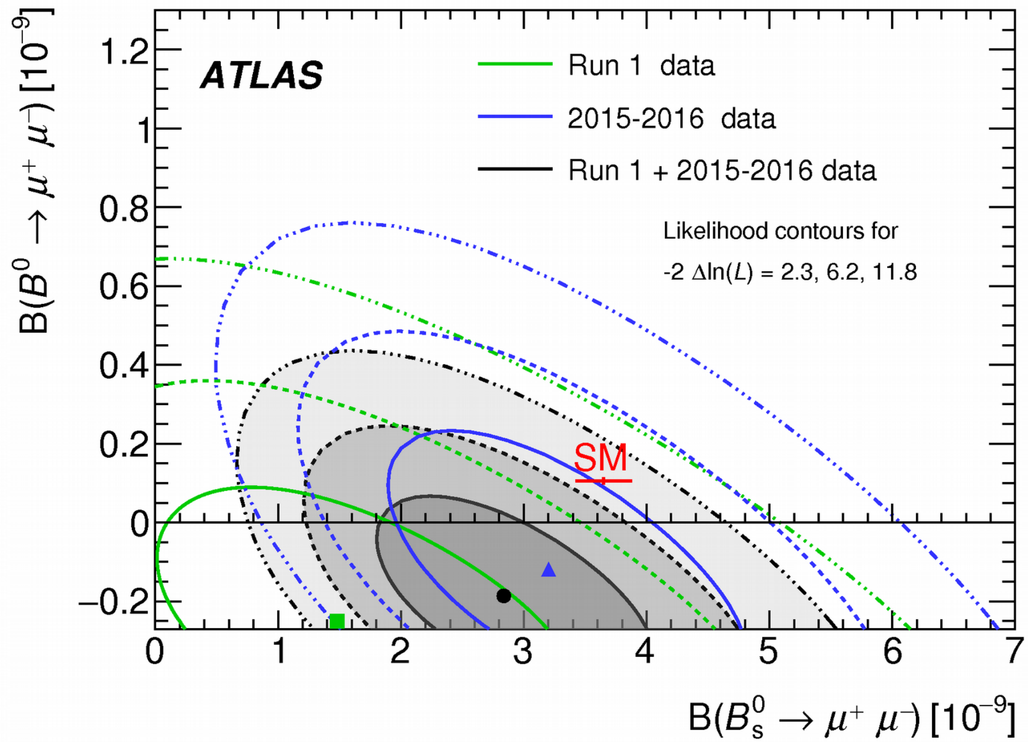


$B_{(s)}^0 \to \mu^+\mu^-$ – Results: Run 2 and Combination

Run 2 (2015/16) only



Run 1 + Run 2 (2015/16)



Neyman contours:

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

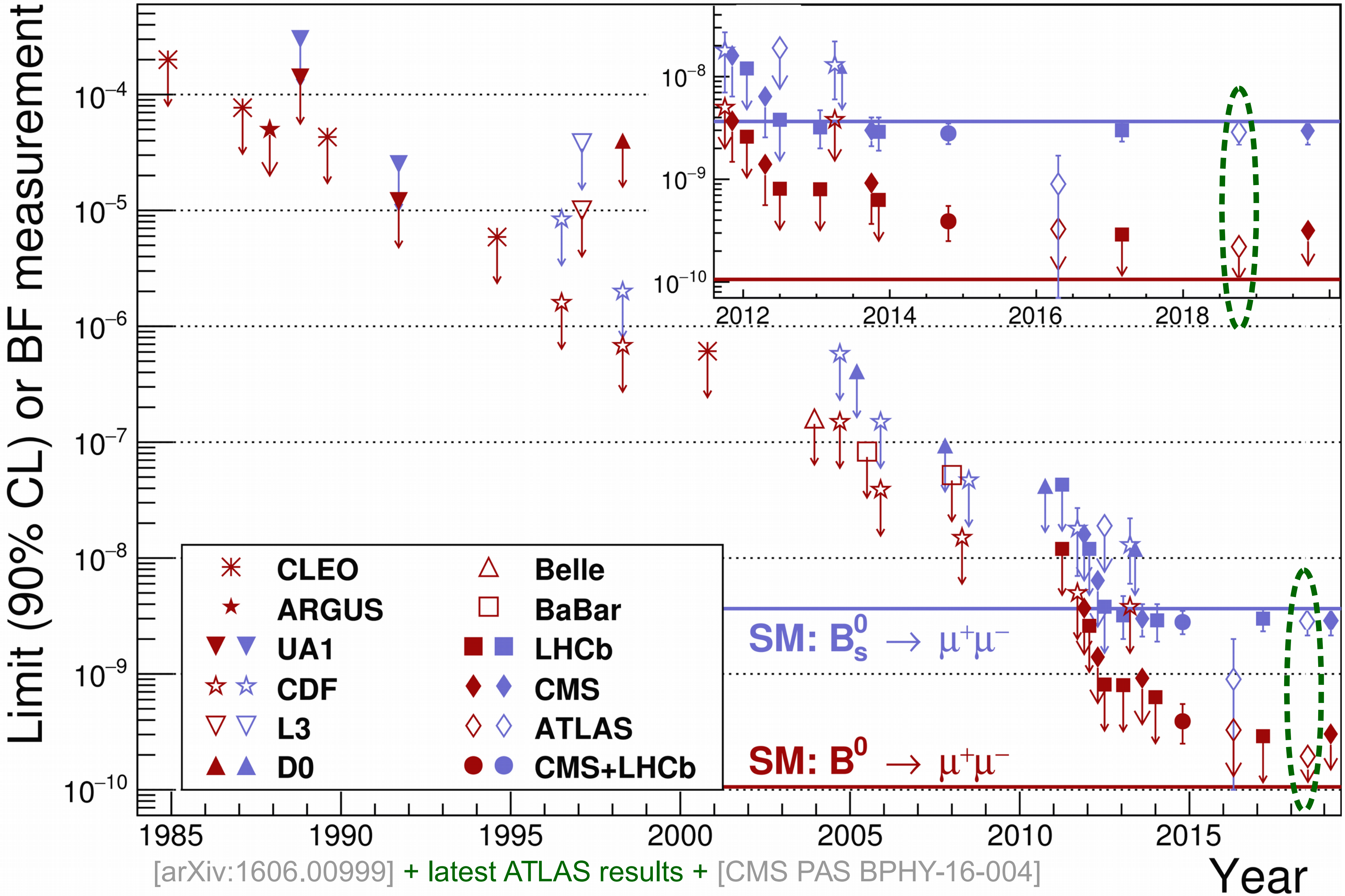
Combination (likelihood contours):

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

Compatible with SM at 2.4 σ

[JHEP04 (2019) 098]

$B_{(s)}^0 \to \mu^+\mu^-$ – BR-Evolution with Time



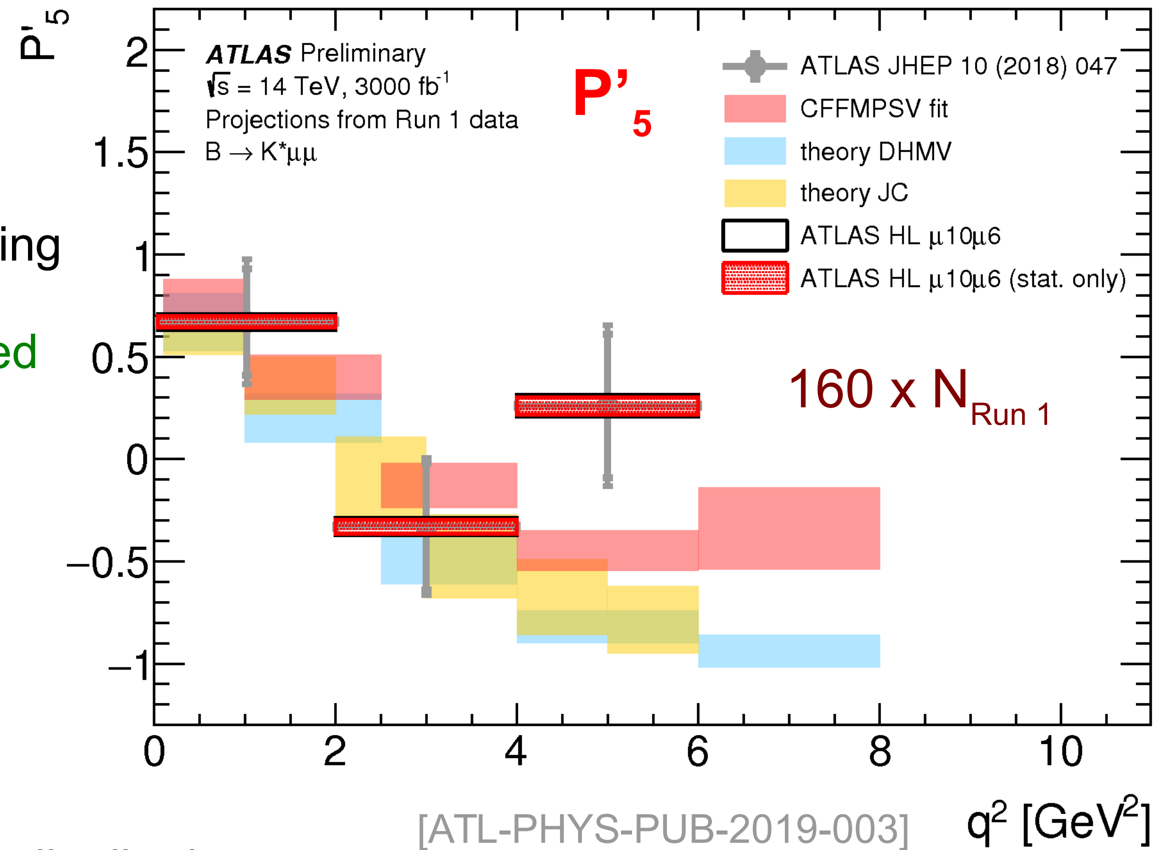
[arXiv:1606.00999] + latest ATLAS results + [CMS PAS BPHY-16-004]

$B^0 \to K^{*0} \mu^+\mu^-$ and $B_{(s)}^0 \to \mu^+\mu^-$ at the High-Luminosity LHC

$B^0 \to K^{*0} \mu^+\mu^-$ – HL-LHC Prospects (3 ab^{-1})

Expected improvements:

- $\sigma(m_{K\pi\mu\mu}) = 0.7\text{x}\ \sigma(m_{K\pi\mu\mu}^{\text{Run 1}})$
  → better S/B separation
- $\sigma_{bb} \sim 1.7\text{x}\ \sigma_{bb}^{\text{Run 1}}$ (8 TeV → 14 TeV)
- Improved fit model and understanding of exclusive backgrounds
  → corresponding systematics scaled by ~ $1/\sqrt{L_{int}}$



[ATL-PHYS-PUB-2019-003]

Three trigger scenarios:

- 2MU10 → ~ 50 x $N_{\text{Run 1}}$
- MU6_MU10 → ~ 160 x $N_{\text{Run 1}}$
- 2MU6 → ~ 250 x $N_{\text{Run 1}}$

Pseudo-MC experiments

- Run 1 signal & background angular distributions
- Same Run 1 fitting procedure
  → P'_5 precision improves by ~ 9x, ~ 8x, ~ 5x
- Expected to be still dominated by statistical uncertainties

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

All-Si Inner Tracker (ITk):

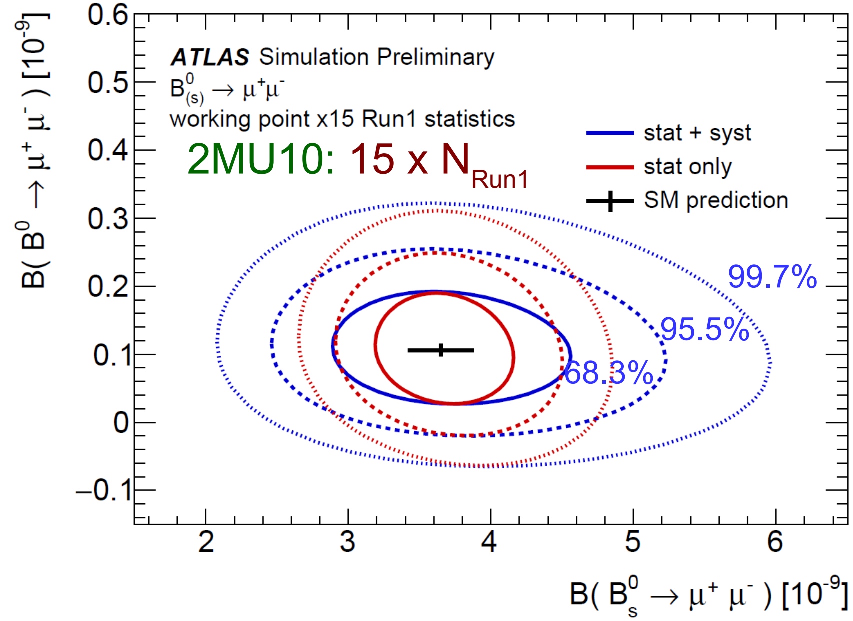
- improves:
  - B mass resolution σ_{mB}
  - proper time resolution σ_t

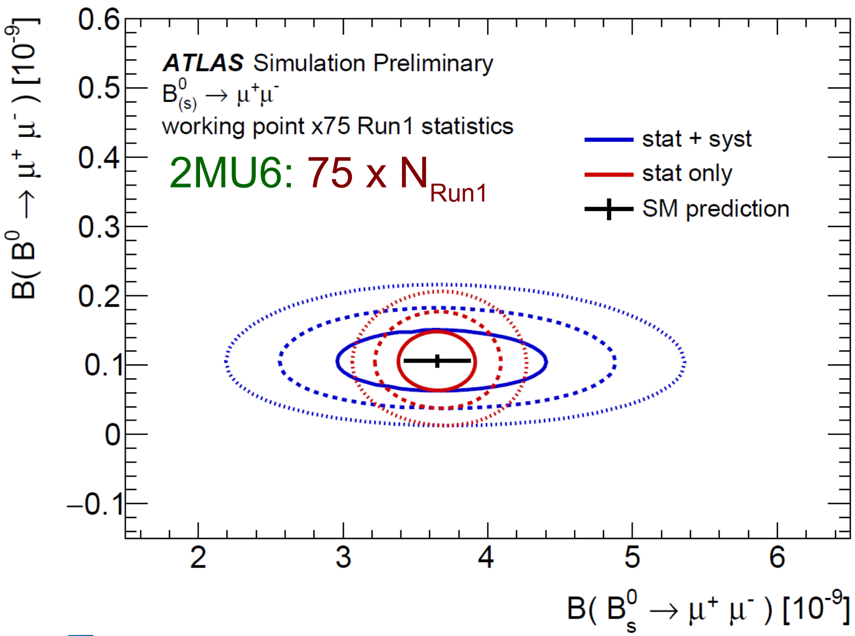
Pseudo-MC experiments

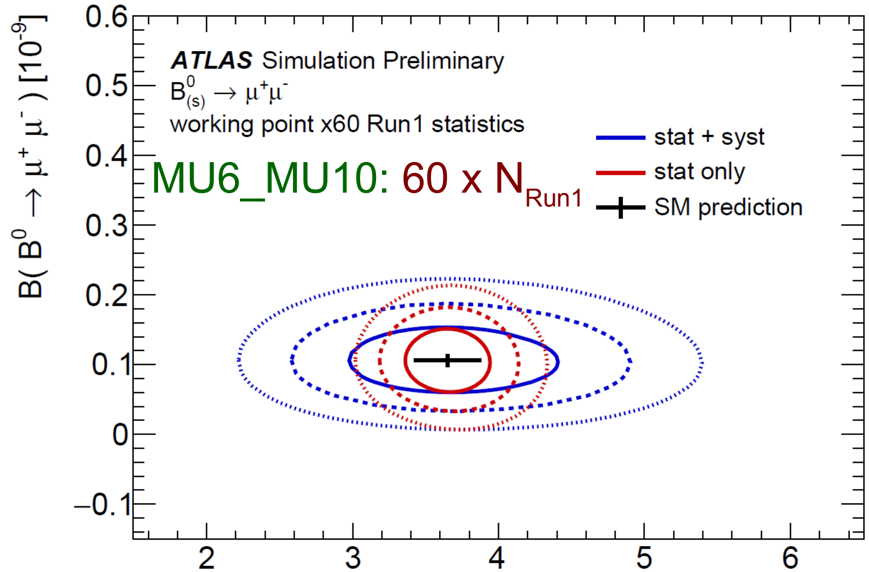
- Profile likelihood contours
- Based on Run 1 likelihood

Dominant systematics:

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







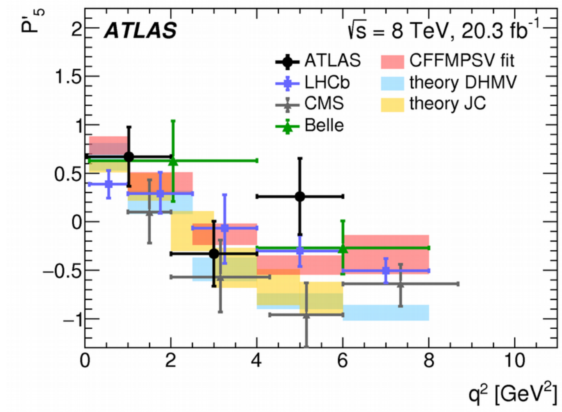
[ATL-PHYS-PUB-2018-005]

Conclusions

ATLAS measurements of semi-rare and rare decays:

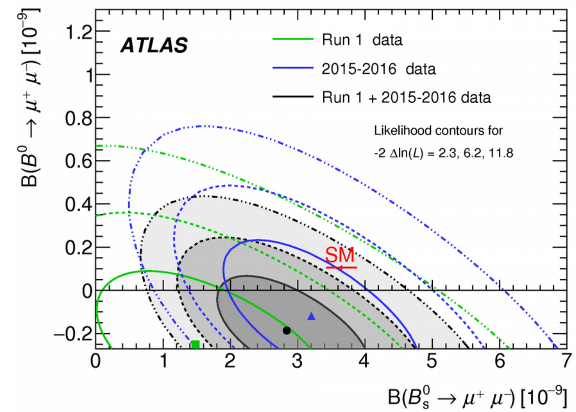
- Angular analysis of $B^0 \rightarrow K^{*0} \mu^+\mu^-$ with 20.3 fb^{-1} of Run 1 data
  - Results compatible with SM and other experiments
  - Data taken in Run 2 to be analyzed (~ 140 fb^{-1})

    [JHEP10 (2018) 047]



- $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ with 36.2 fb^{-1} of Run 2 data
  - Agrees with SM and other measurements
  - No sign for $B^0 \rightarrow \mu^+\mu^-$ in ATLAS data
  - Data taken in 2017 + 2018 still to be added (~105 fb^{-1})

    [JHEP04 (2019) 098]

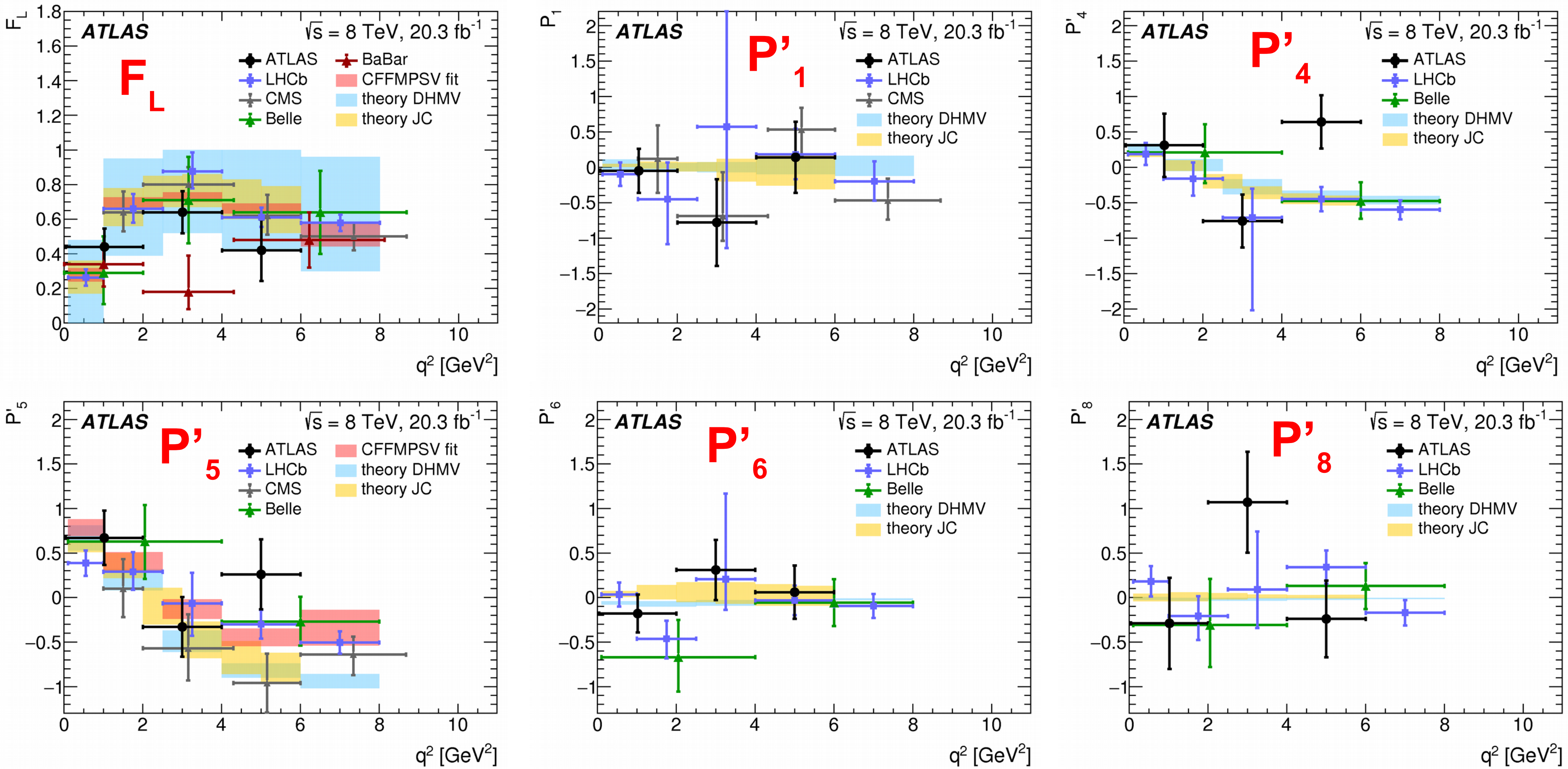


- Both channels will profit from HL-LHC
  - Considerably increased statistics
  - Improved m_B resolution
  - Improved σ_t resolution
  - Promising to test SM

    [ATL-PHYS-PUB-2018-005, ATL-PHYS-PUB-2019-003]

Supporting Material

$B^0 \to K^{*0} \mu^+\mu^-$ – Results: Theory vs. Experiments



CFFMPSV: M. Ciuchini et al., JHEP 06 (2016) 116
DHMV: S. Descotes-Genon et al., JHEP 01 (2013) 048; JHEP 05 (2013) 137; JHEP 12 (2014) 125
JC: S. Jäger and J. Martin Camalich, JHEP 05 (2013) 043; Phys. Rev. D 93 (2016) 014028
LHCb Collaboration, JHEP 02 (2016) 104
CMS Collaboration, Phys. Lett. B 753 (2016) 424
Belle Collaboration, Phys. Rev. Lett. 103 (2009) 171801
BaBar Collaboration, Phys. Rev. D 93 (2016) 052015

[JHEP 10 (2018) 047]

$B^0 \to K^{*0} \mu^+\mu^-$ – Systematic Uncertainties

[JHEP 10 (2018) 047]

Source	F_L	S_3	S_4	S_5	S_7	S_8
Combinatoric $K\pi$ (fake K^*) background	0.03	0.03	0.05	0.04	0.06	0.16
D and B^+ veto	0.11	0.04	0.05	0.04	0.01	0.06
Background pdf shape	0.04	0.04	0.03	0.03	0.03	0.01
Acceptance function	0.01	0.01	0.07	0.01	0.01	0.01
Partially reconstructed decay background	0.03	0.05	0.02	0.08	0.05	0.06
Alignment and B field calibration	0.02	0.04	0.05	0.04	0.04	0.04
Fit bias	0.01	0.01	0.02	0.03	0.01	0.05
Data/MC differences for p_T	0.02	0.02	0.01	0.01	0.01	0.01
S-wave	0.01	0.01	0.01	0.01	0.01	0.03
Nuisance parameters	0.01	0.01	0.01	0.01	0.01	0.01
Λ_b, B^+ and B_s background	0.01	0.01	0.01	0.01	0.01	0.01
Misreconstructed signal	0.01	0.01	0.01	0.01	0.01	0.01
Dilution	–	–	-	< 0.01	–	< 0.01

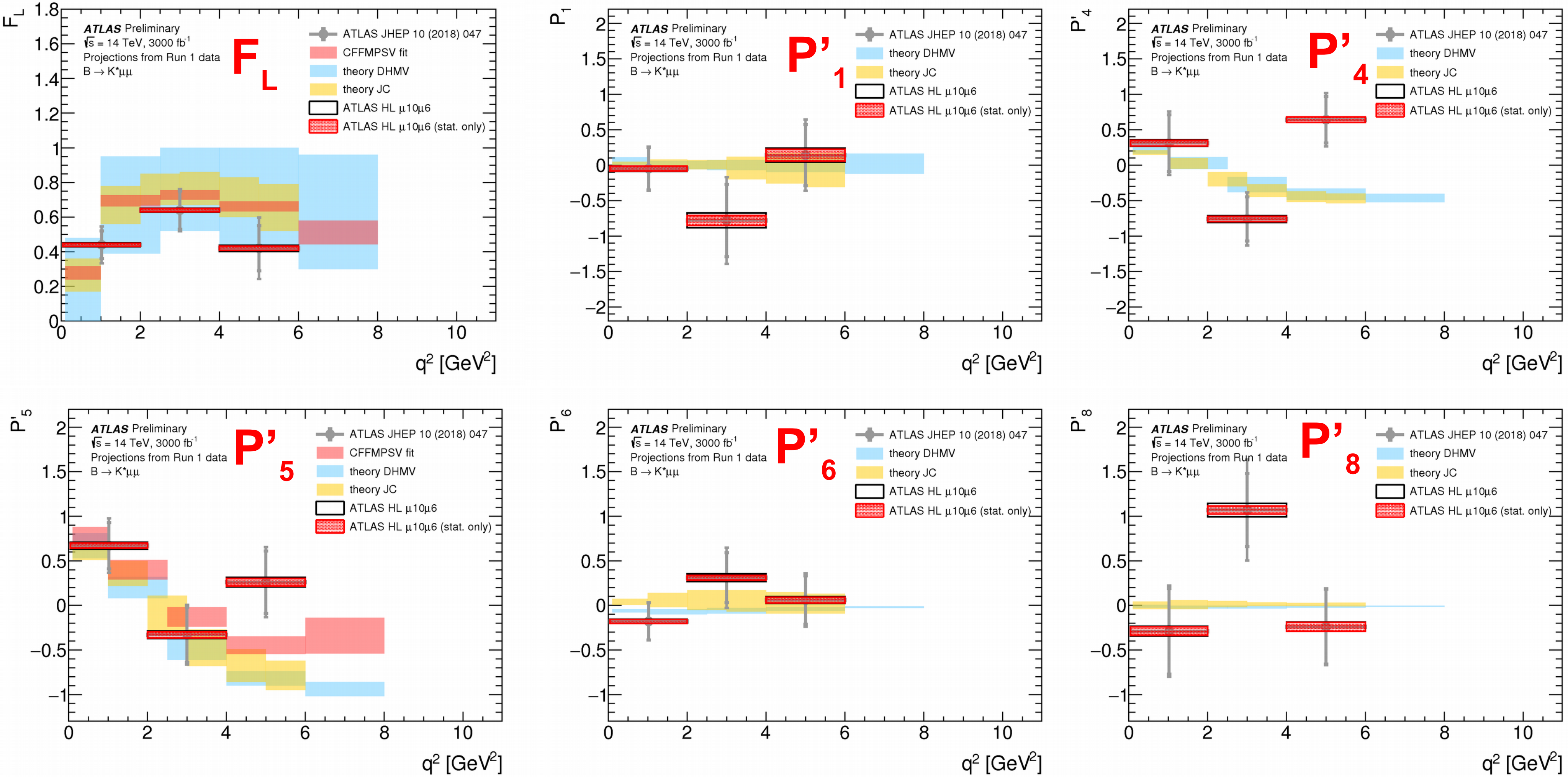
Transformations $S_i \to P_i(')$:

$$P_1 = \frac{2S_3}{1 - F_L}$$

$$P'_{j=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}$$

Table entries:
largest value of systematic uncertainties across all q^2 bins;
uncertainties vary between q^2 bins

$B^0 \to K^{*0} \mu^+\mu^-$ – HL-LHC Prospects ($3\ ab^{-1}$)



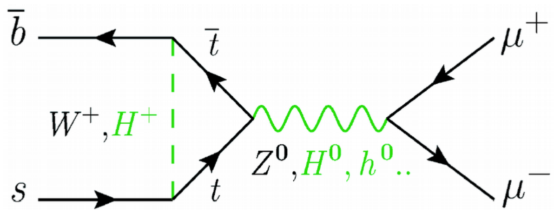
[ATL-PHYS-PUB-2019-003]

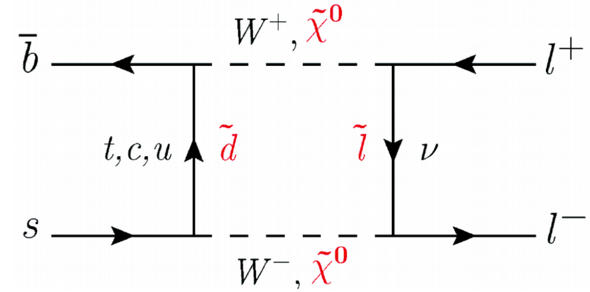
CFFMPSV: M. Ciuchini et al., JHEP 06 (2016) 116
DHMV: S. Descotes-Genon et al., JHEP 01 (2013) 048; JHEP 05 (2013) 137; JHEP 12 (2014) 125
JC: S. Jäger and J. Martin Camalich, JHEP 05 (2013) 043; Phys. Rev. D 93 (2016) 014028

$B_{(s)}^0 \to \mu^+\mu^-$ – 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:

- $BR(B^0_s \to \mu^+\mu^-) = (0.9\ ^{+1.1}_{-0.8})\times10^{-9}$
- $BR(B^0 \to \mu^+\mu^-) < 4.2\times10^{-10}$ at 95% CL

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

Recent theory update:

- $BR(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14)\times10^{-9}$
- $BR(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.15)\times10^{-10}$

[arXiv:1909.07011]

Compatible with SM at ~ 2σ:

- $BR(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23)\times10^{-9}$
- $BR(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09)\times10^{-10}$

[PRL 112 (2014) 101801]

CMS&LHCb Run 1 combined:

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

[Nature 522 (2015) 68]

LHCb Run 1 + partial Run 2:

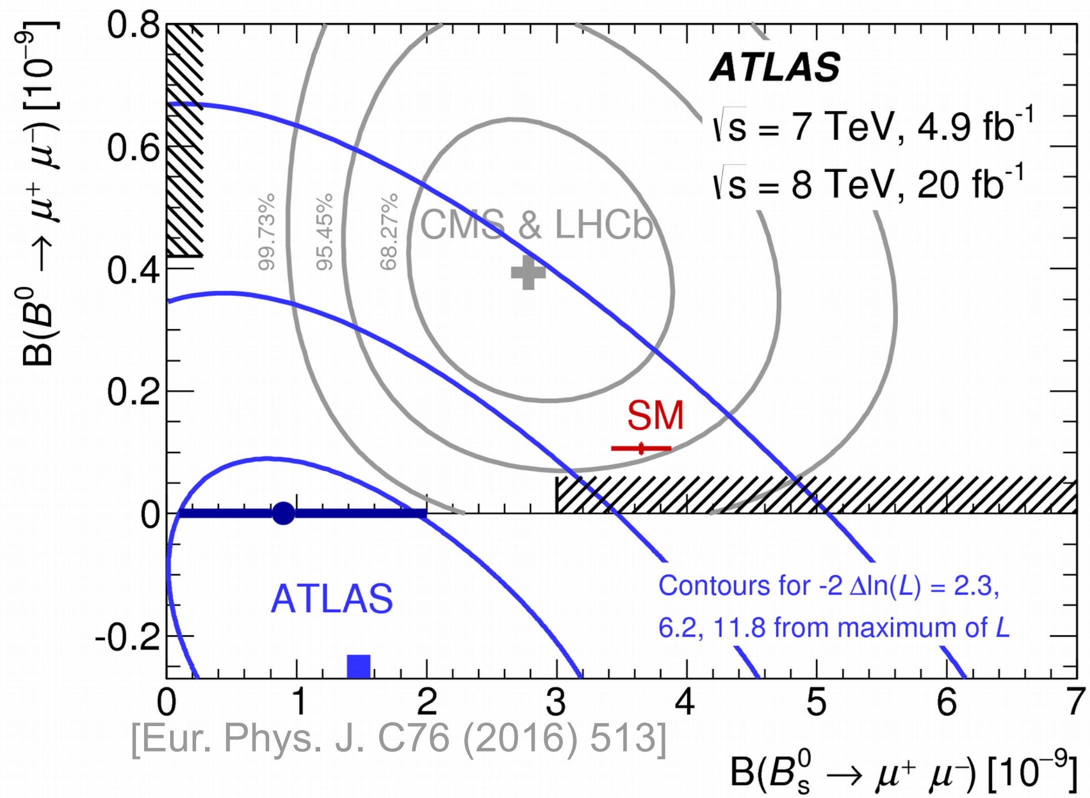
- $BR(B^0_s \to \mu^+\mu^-) = (3.0\ ^{+0.7}_{-0.6} \pm 0.2) \times 10^{-9}$
- $BR(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$ at 95% CL

[PRL 118 (2017) 191801]

CMS Run 1 + partial Run 2:

- $BR(B^0_s \to \mu^+\mu^-) = (2.9 \pm 0.6\ ^{+0.3}_{-0.2}) \times 10^{-9}$
- $BR(B^0 \to \mu^+\mu^-) < 3.6 \times 10^{-10}$ at 95% CL

[CMS PAS BPHY-16-004, 2019-08-04]



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

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

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

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

$$= N_{d(s)} \frac{\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{D}_{\text{ref}}} \times \frac{f_u}{f_{d(s)}}, \qquad (1.1)$$

with

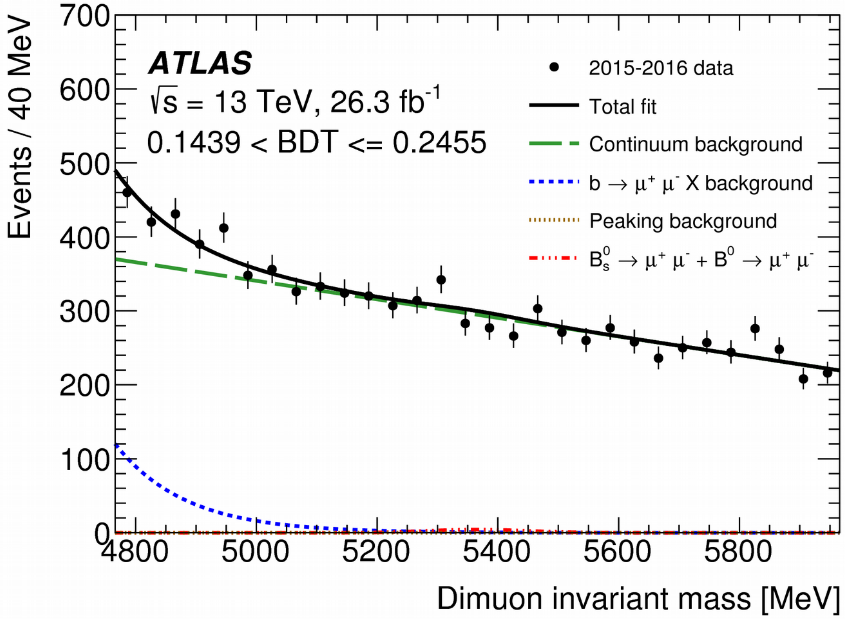
- $\mathcal{D}_{\text{ref}} = N_{J/\psi K^+} \times (\varepsilon_{\mu^+\mu^-}/\varepsilon_{J/\psi K^+})$
- $N_{d(s)}$: $B^0(s) \to \mu^+\mu^-$ signal yields
- $N_{J/\psi K}$: $B^\pm \to J/\psi\, K^\pm$ reference channel yield
- $\varepsilon_{\mu+\mu^-}$ and $\varepsilon_{J/\psi K}$: acceptance times efficiency
- $f_u/f_{d(s)}$: ratio of hadronization probabilities of b-quark into $B^\pm$ and $B^0_{(s)}$
  $= 0.256 \pm 0.013$ [PRD 98 (2018) 03001]
- $B(B^+ \to J/\psi\, K^+) \times B(J/\psi \to \mu^+\mu^-)$
  $= (1.010 \pm 0.029) \times 10^{-3} \times (5.961 \pm 0.033)\%$ [PRD 98 (2018) 03001]

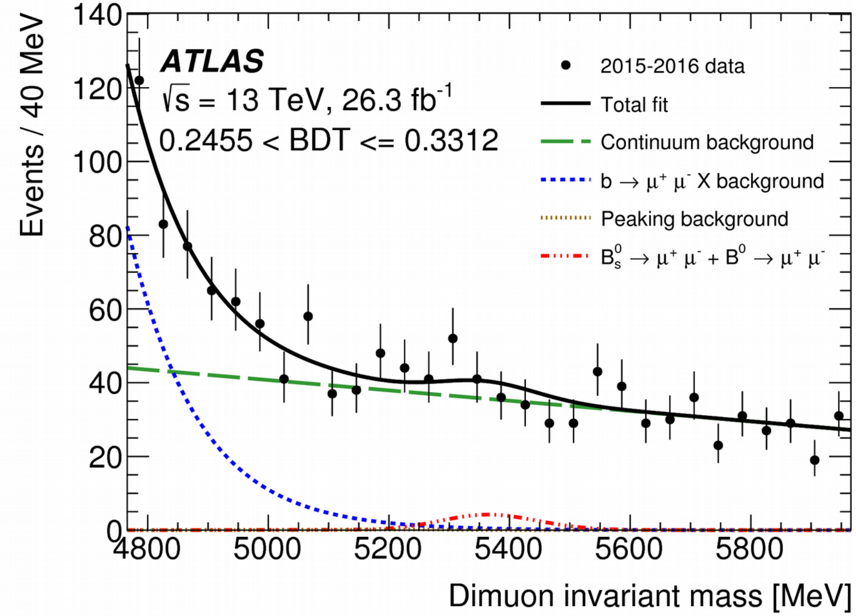
$B_{(s)}^0 \to \mu^+\mu^-$ – BDT Input Variables

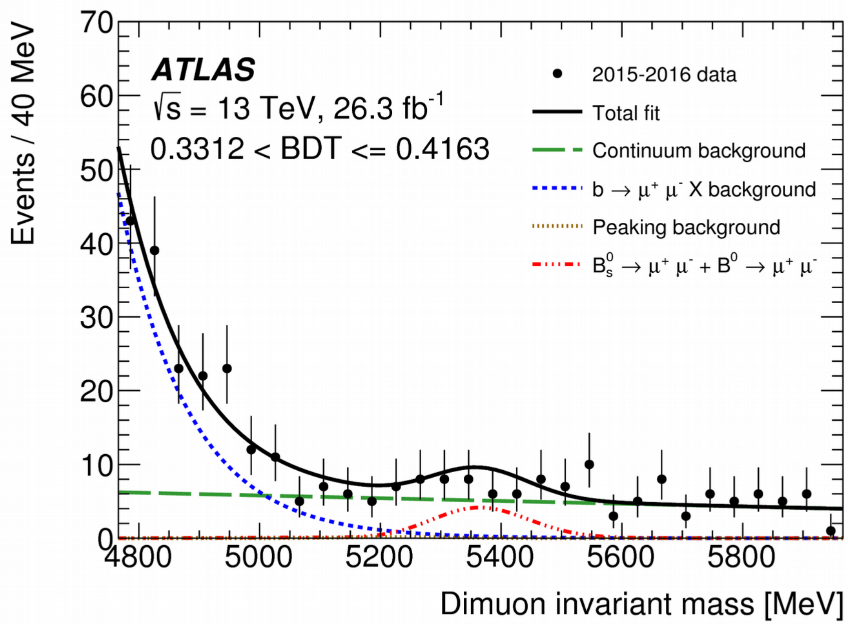
Variable	Description
p_{T}^{B}	Magnitude of the B candidate transverse momentum $\vec{p_{\mathrm{T}}}^{B}$.
$\chi^2_{\mathrm{PV,DV}\ xy}$	Compatibility of the separation $\overrightarrow{\Delta x}$ between production (i.e. associated PV) and decay (DV) vertices in the transverse projection: $\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \Sigma^{-1}_{\overrightarrow{\Delta x}_{\mathrm{T}}} \cdot \overrightarrow{\Delta x}_{\mathrm{T}}$, where $\Sigma_{\overrightarrow{\Delta x}_{\mathrm{T}}}$ is the covariance matrix.
$\Delta R_{\mathrm{flight}}$	Three-dimensional angular distance between $\vec{p}^{B}$ 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 $\vec{p_{\mathrm{T}}}^{B}$ and $\overrightarrow{\Delta x}_{\mathrm{T}}$.
L_{xy}	Projection of $\overrightarrow{\Delta x}_{\mathrm{T}}$ along the direction of $\vec{p}_{\mathrm{T}}^{B}$: $(\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \vec{p_{\mathrm{T}}}^{B})/\lvert\vec{p_{\mathrm{T}}}^{B}\rvert$.
$\mathrm{IP}_{B}^{3\mathrm{D}}$	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 $\vec{p_{\mathrm{T}}}^{B}$.
$I_{0.7}$	Isolation variable defined as ratio of $\lvert\vec{p_{\mathrm{T}}}^{B}\rvert$ to the sum of $\lvert\vec{p_{\mathrm{T}}}^{B}\rvert$ 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.

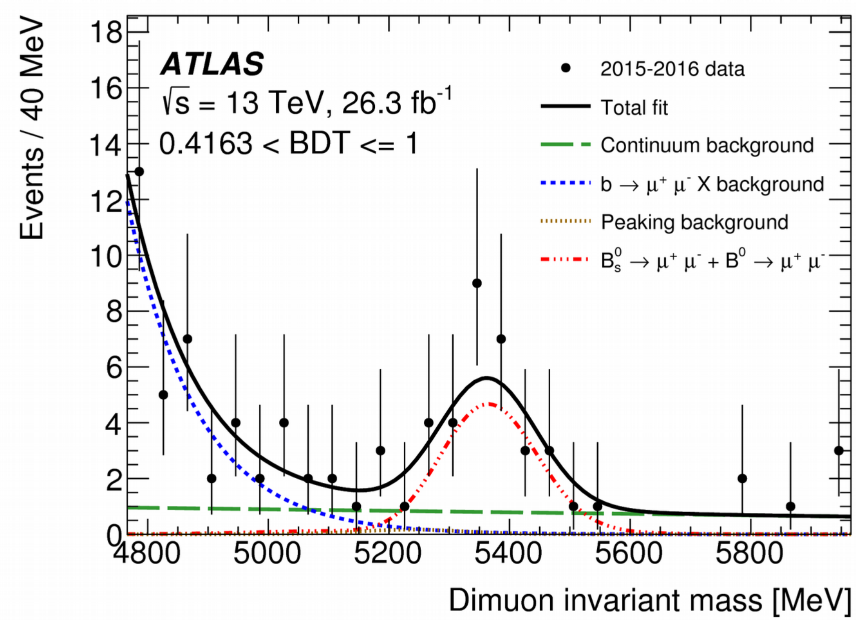
[JHEP04 (2019) 098]

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









[JHEP04 (2019) 098]

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

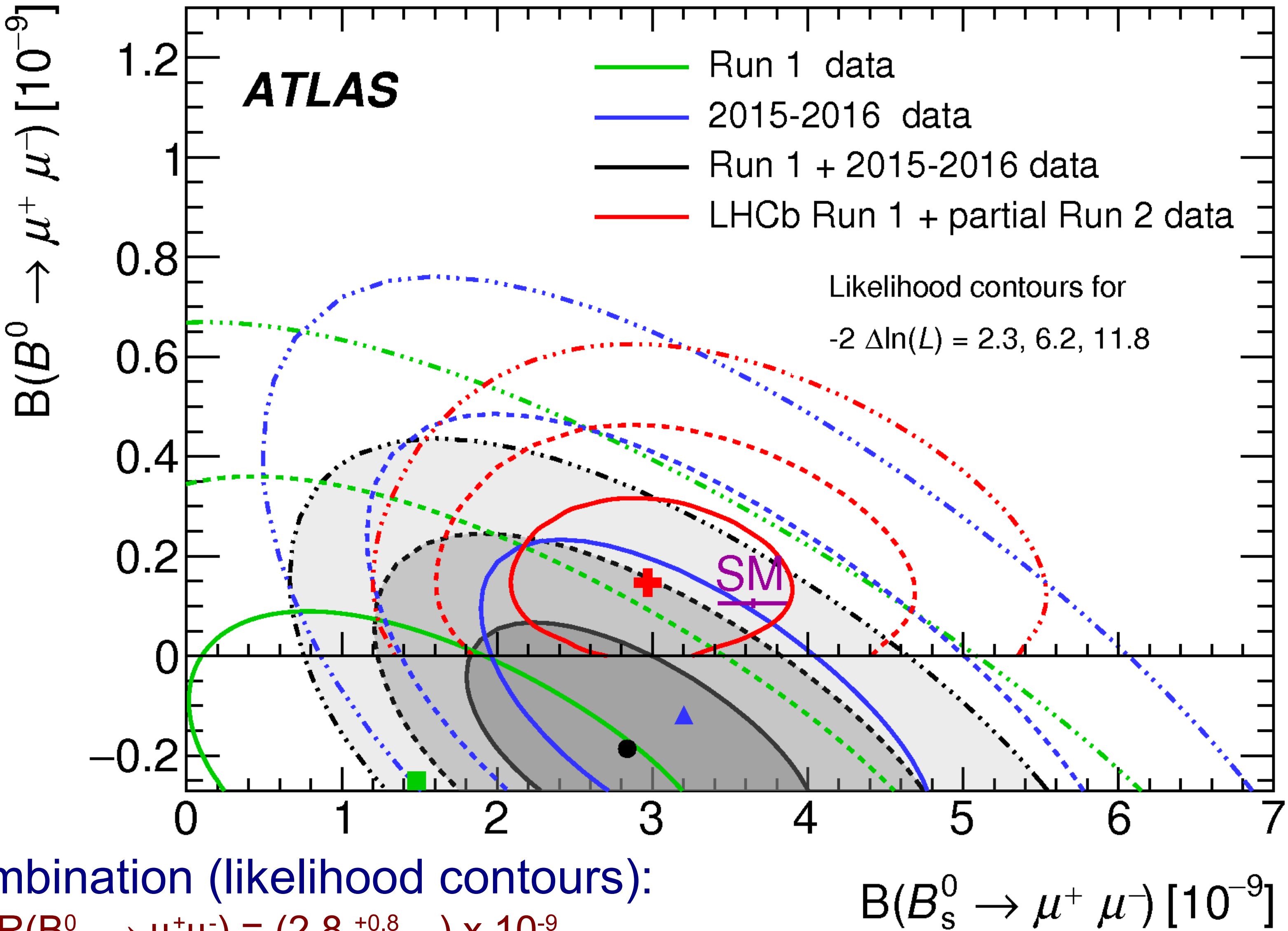
Expected uncertainties on BR($B^0_{(s)} \to \mu^+\mu^-$):

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

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



Combination (likelihood contours):

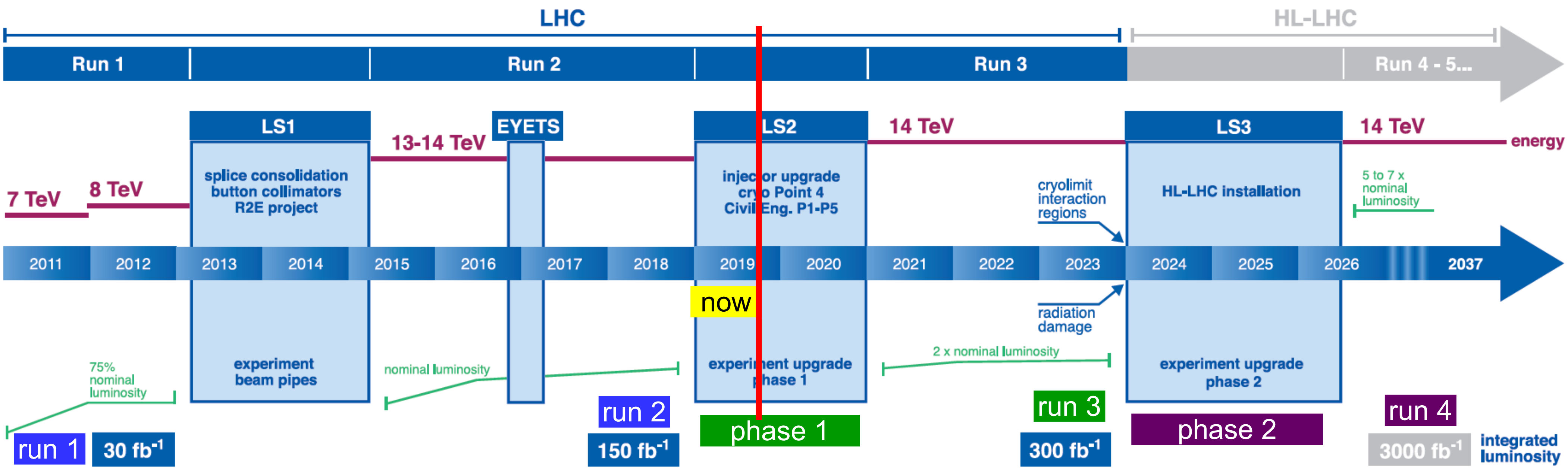
- $BR(B^0_s \rightarrow \mu^+\mu^-) = (2.8\,^{+0.8}_{-0.7}) \times 10^{-9}$
- $BR(B^0 \rightarrow \mu^+\mu^-) < 2.1 \times 10^{-10}$ at 95% CL

Compatible with SM at 2.4 σ

HL-LHC Timeline and Core Parameters

LHC / HL-LHC Plan

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



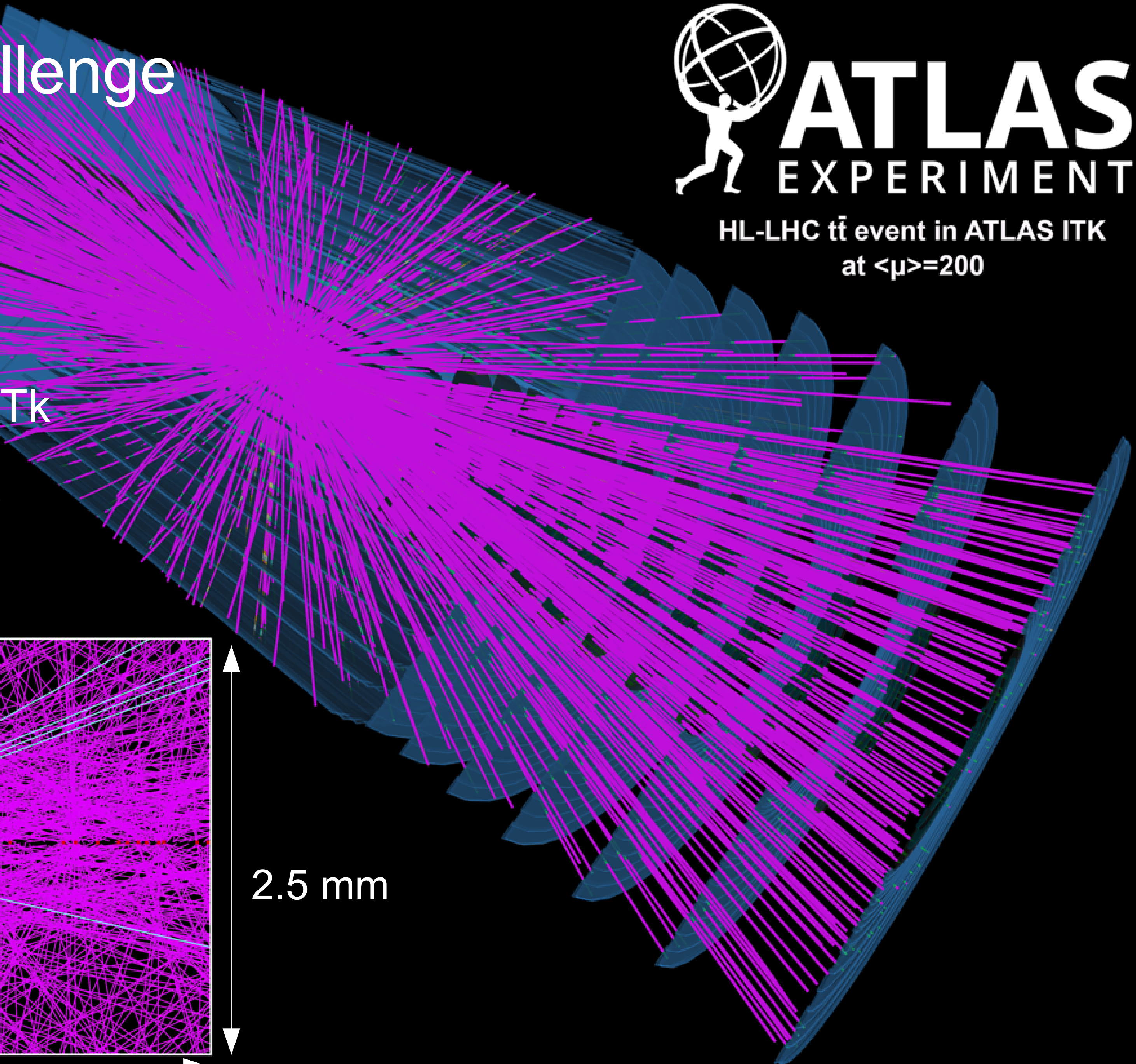
HL-LHC parameters: [CERN-2017-007-M]

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

ATLAS upgrades:

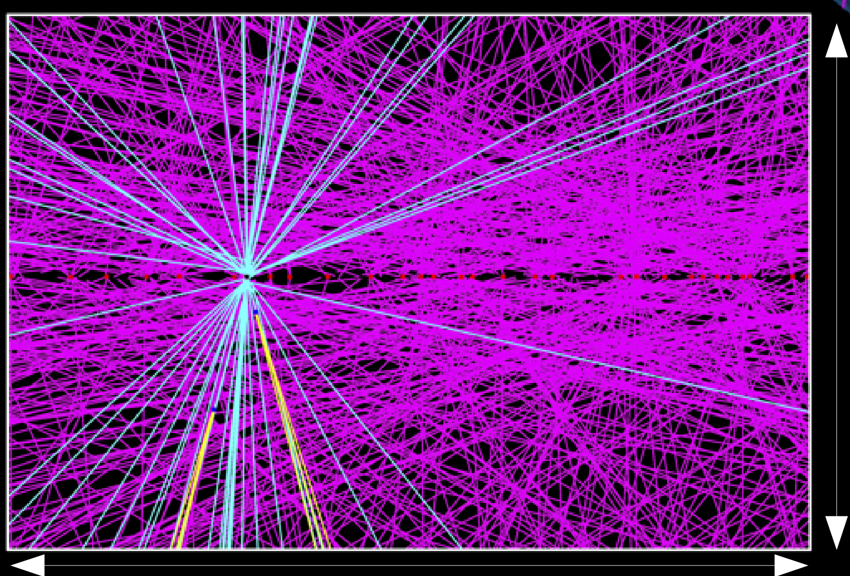
- Detector & trigger, esp. new all-Si Inner TracKer (ITK)
- → improves
  - B mass resolution σ_{mB}
  - proper time resolution σ_t

HL-LHC Challenge



HL-LHC $t\bar{t}$ event in ATLAS ITK
at $\langle\mu\rangle$=200

- $t\bar{t}$ 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 $B_{(s)}^0 \rightarrow \mu^+\mu^-$ – Mass Separation

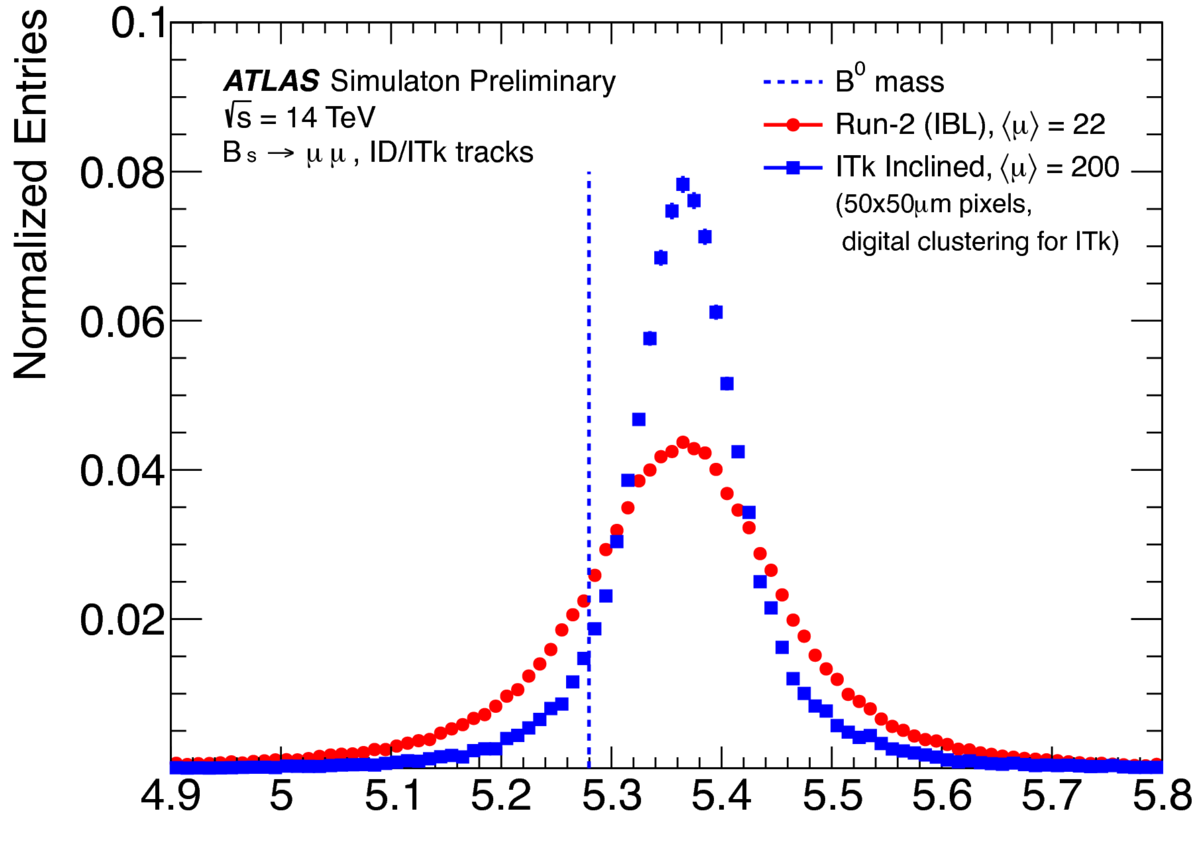
Dedicated $B_s^0 \rightarrow \mu^+\mu^-$ MC:

- Run 2 conditions like 2015
- HL-LHC & HL-ATLAS:
  - $L_{inst} = 7.5 \times 10^{34}\ cm^2s^{-1}$ at 14 TeV CME <μ> = 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 $\mu^\pm$, $p_T(\mu^\pm) > 5.5$ GeV
- Two-track vertex fit
- $m(B_s^0)$ from ID/ITK-only tracks

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



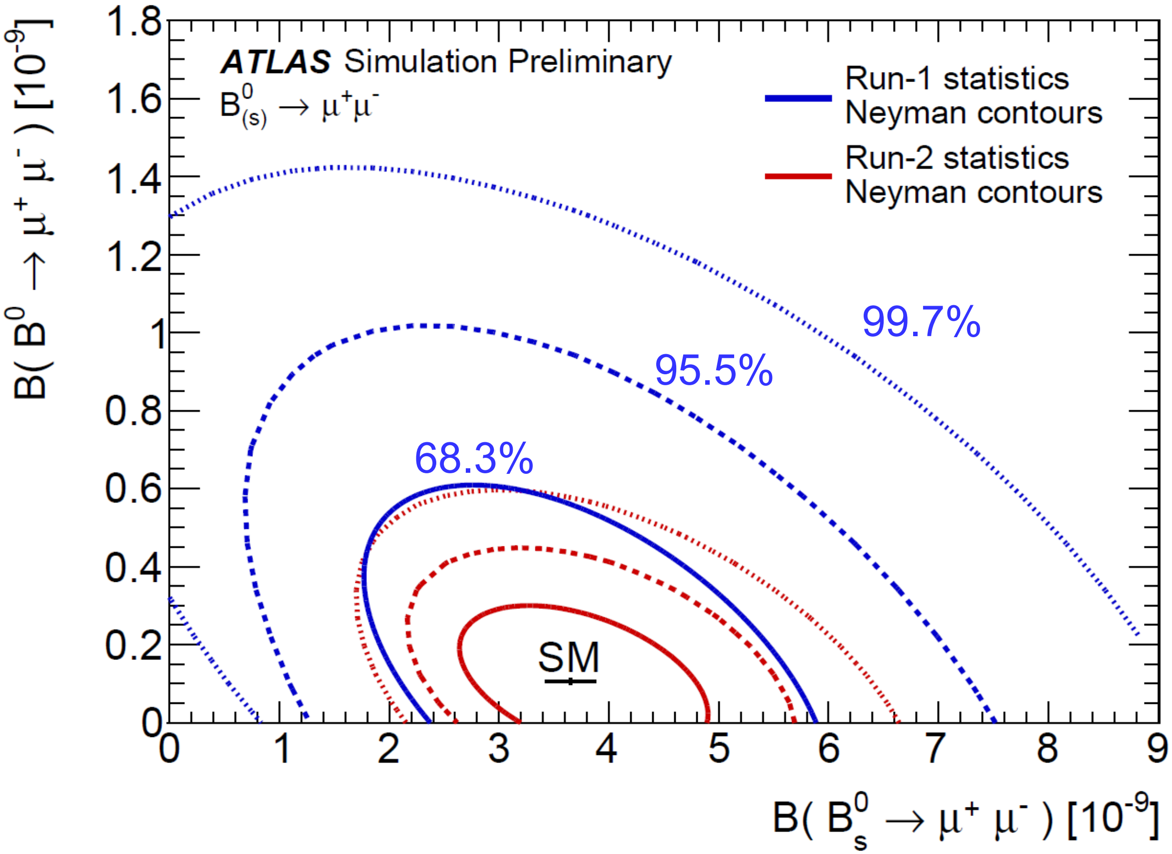
B⁰ mass

BR($B_{(s)}^0 \to \mu^+\mu^-$) 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($B^\pm \to J/\psi K^\pm$)
  → keep as in Run 1
- Internal:
  fit shapes, efficiencies, …
  → scale with statistics

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

Uncertainties on BR($B_s^0 \to \mu^+ \mu^-$) and BR($B^0 \to \mu^+ \mu^-$): [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($B_s^0 \to \mu^+ \mu^-$) = $2.8^{+0.7}_{-0.6}$)x10^{-9}, BR($B^0 \to \mu^+ \mu^-$) = ($3.9^{+1.6}_{-1.4}$)x10^{-10}

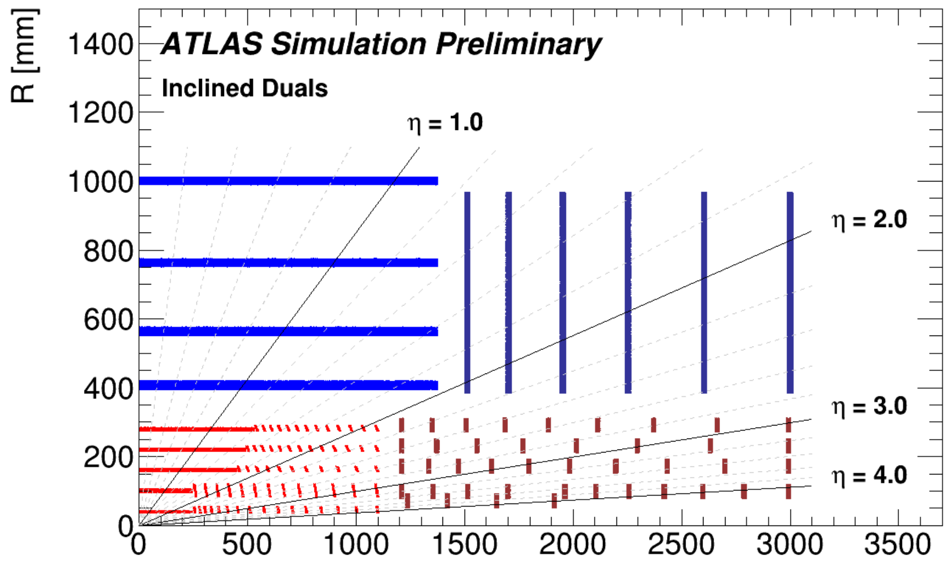
LHCb (2015+2016):

- BR($B_s^0 \to \mu^+ \mu^-$) = 3.0 ± $0.6^{+0.3}_{-0.2}$)x10^{-9} [Phys. Rev. Let. 118 (2017) 191801]

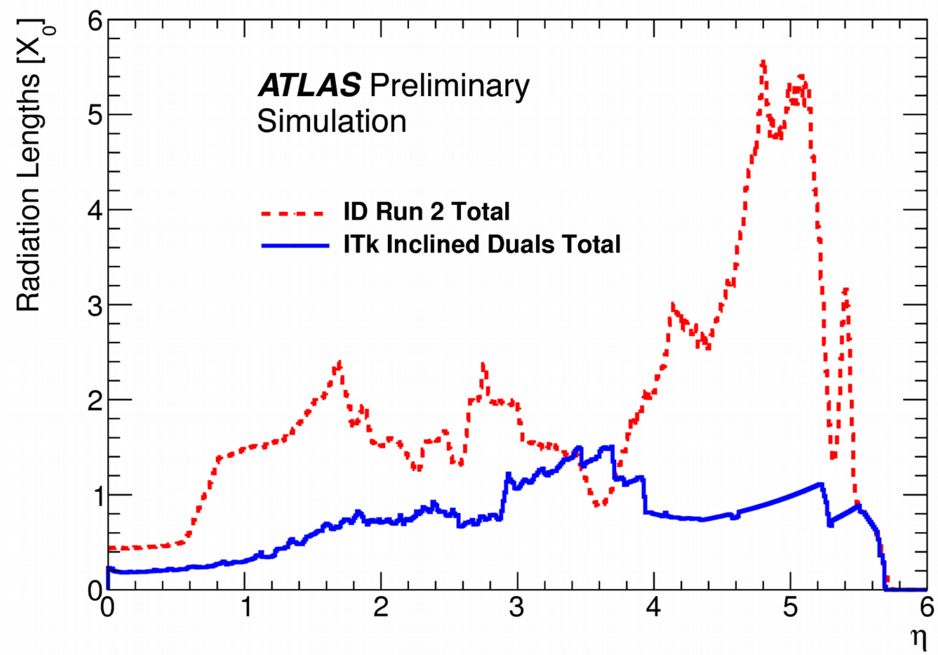
ATLAS Inner Tracker (ITk) Upgrade

New all-silicon detector:

- ITk pixel (13 m²):
  - 5 barrel, 5 EC layers (with rings)
  - Inclined sensors
  - Extends to η_{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

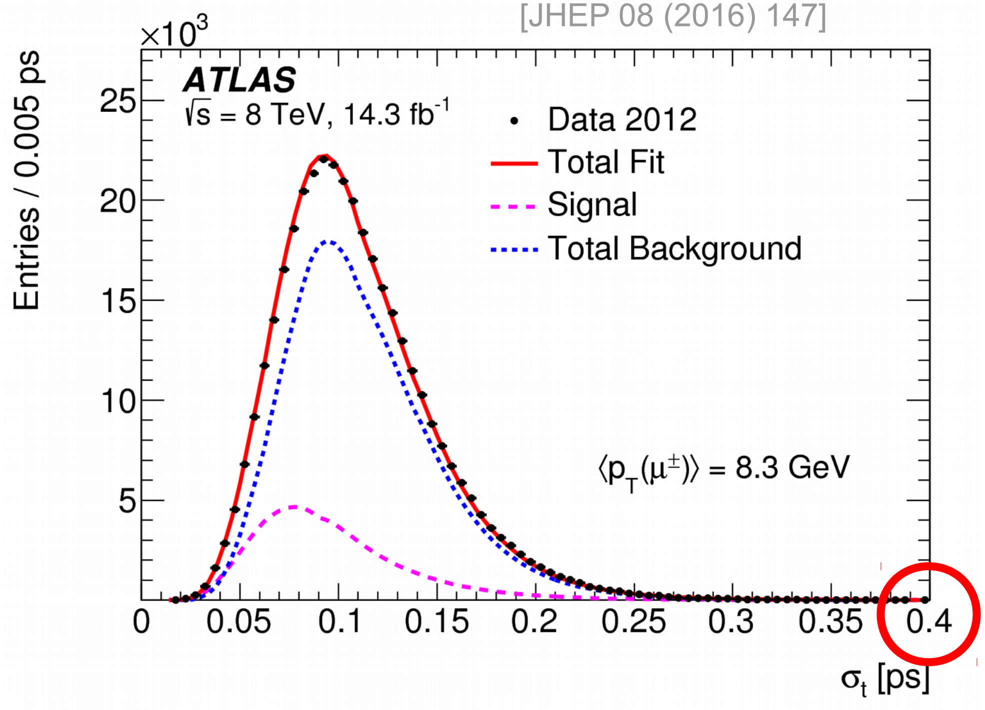


[CERN-LHCC-2017-021, ATLAS-TDR-030]

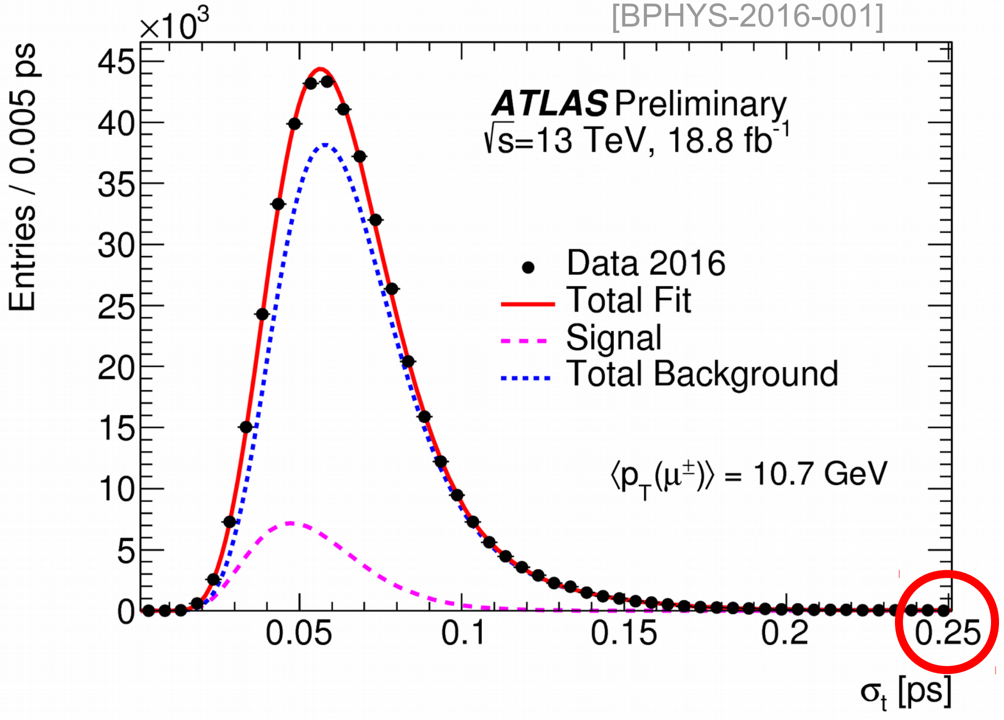


$B_s^0 \to J/\psi\ \phi$ Proper Time Resolution – Run 2

Run 1 – 2012 data



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

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

- Run 2 conditions like 2015
- HL-LHC & HL-ATLAS:
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Candidate selection ~ Run 1

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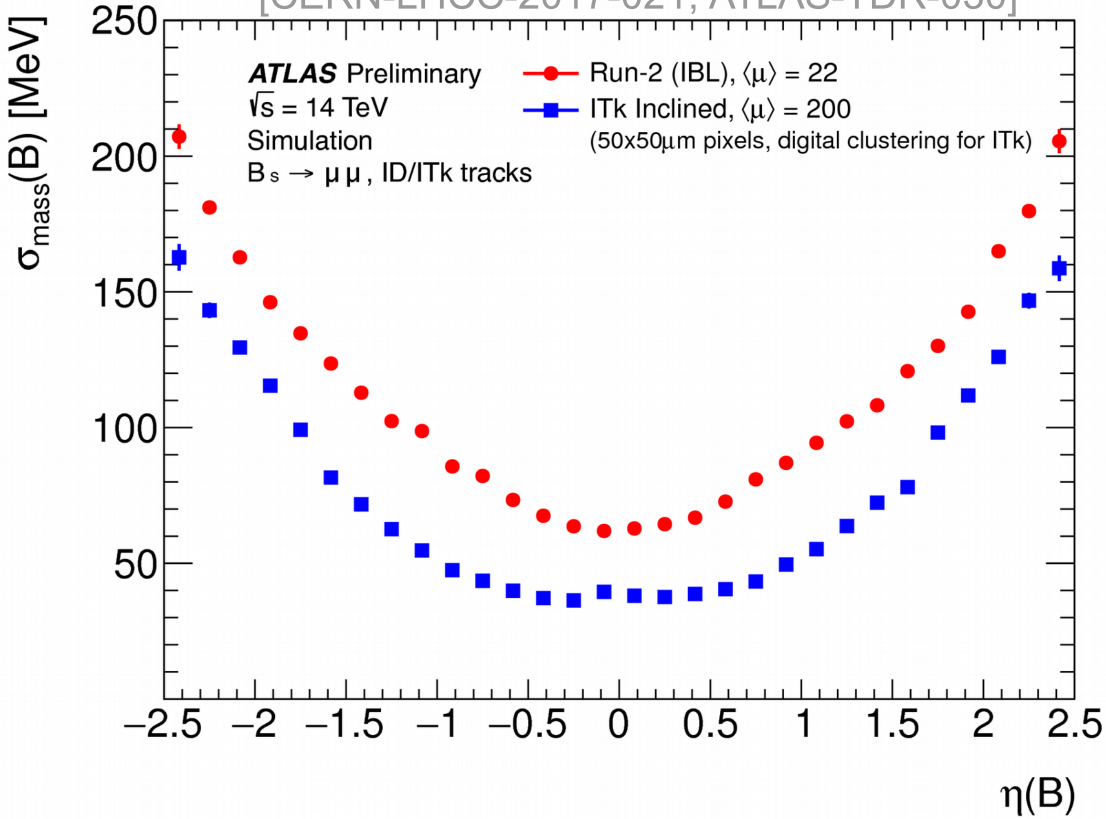
- Two-track vertex fit
- $m(B_s^0)$ from ID/ITk-only tracks

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

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



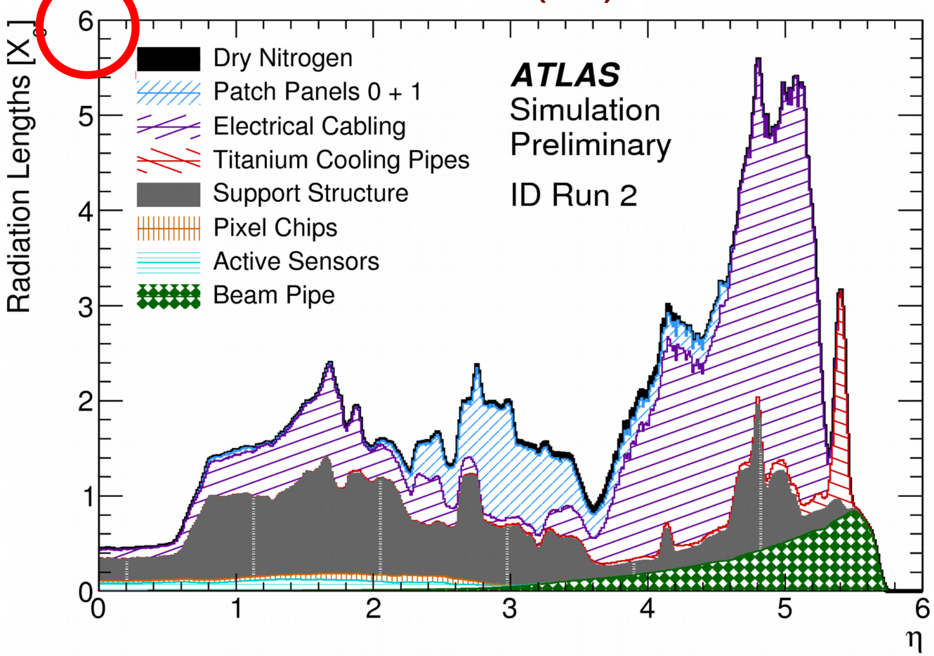
Separation of $m(B_s^0)$ and $m(B^0)$:

- 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

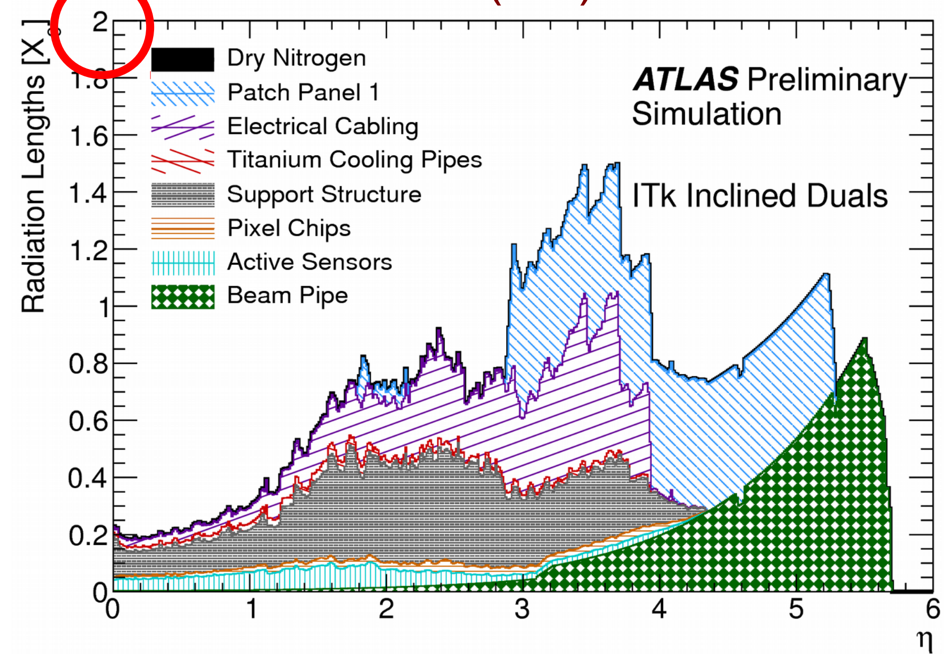
[ATL-PHYS-PUB-2016-026]

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.