

Rare and Semi-rare Decays in ATLAS

Iskander Ibragimov



UNIVERSITÄT
SIEGEN



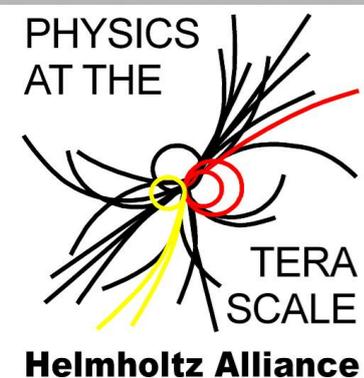
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High Energy Physics

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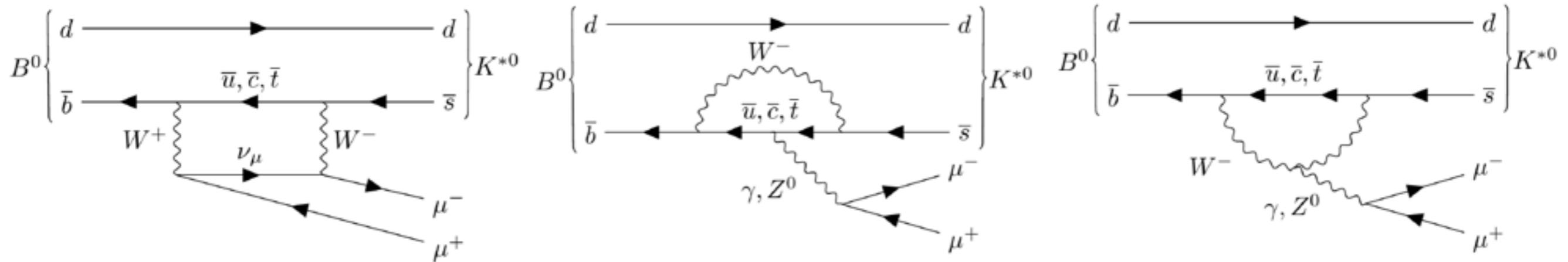




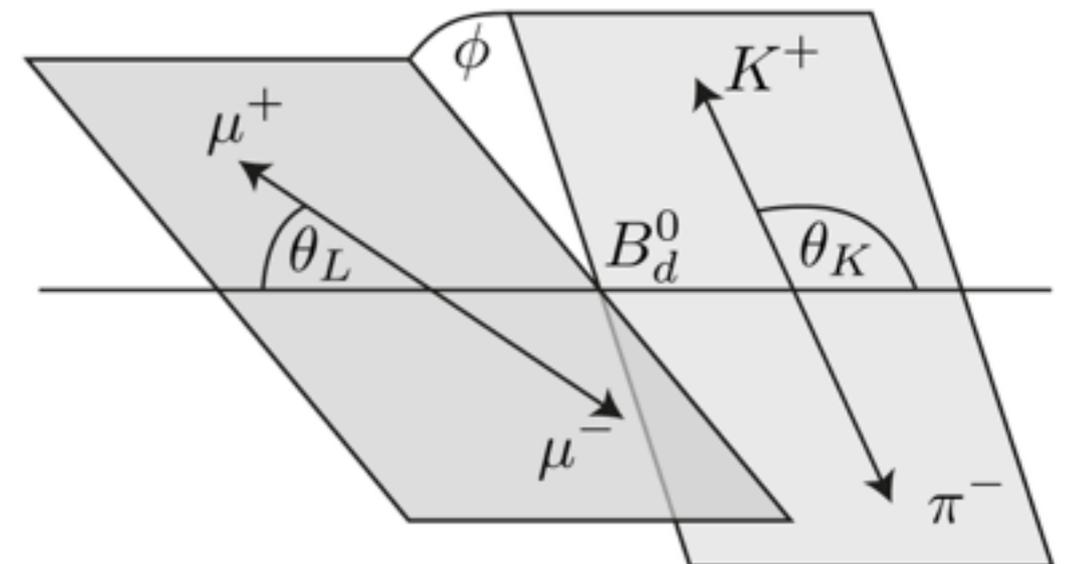
Outline



- Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay [[JHEP 10 \(2018\) 047](#)]
- HL-LHC prospects for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay [[ATL-PHYS-PUB-2019-003](#)]
- $B^0_{(s)} \rightarrow \mu^+ \mu^-$ analysis with 2015 and 2016 data [[JHEP04 \(2019\) 098](#)]
- $B^0_{(s)} \rightarrow \mu^+ \mu^-$ prospects for HL-LHC [[ATL-PHYS-PUB-2018-005](#)]
- Summary



- forbidden in SM at tree level, loop-suppressed FCNC decay
 - BR $\sim (1.03 \pm 0.06) \times 10^{-6}$
 - differential decay rates and angular distributions sensitive to NP
 - LHCb reports up to 3.4σ deviation from SM
- angular distribution is analysed in bins of $q^2 = [m(\mu^+ \mu^-)]^2$ as a function of θ_L , θ_K and ϕ
- K^{*0} longitudinal polarisation fraction F_L and angular parameters S_i are extracted from the fit to distributions of $m_{K\pi\mu\mu}$, $\cos\theta_K$, $\cos\theta_L$ and ϕ
- reduce theoretical uncertainties with $S_i \rightarrow P_j^{(\prime)}$ transformations
- low statistics \rightarrow use trigonometric folding (e.g. for F_L , S_3 , S_5 , P'_5 : $\phi \rightarrow -\phi$ for $\phi < 0$, $\theta_L \rightarrow \pi - \theta_L$ for $\theta_L > \pi/2$) \rightarrow 4 sets of fits for 3 parameters (F_L , S_3 and one of $S_{i=4,5,7,8}$) for each q^2 bin

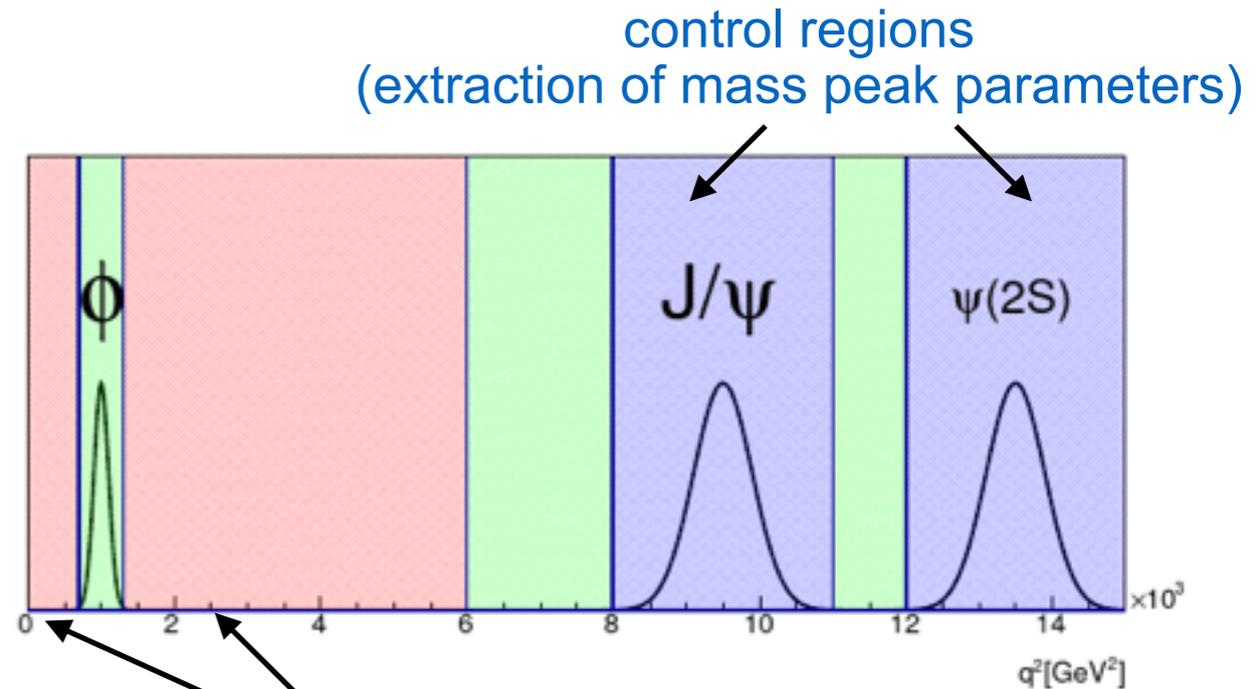




$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: Signal Selection

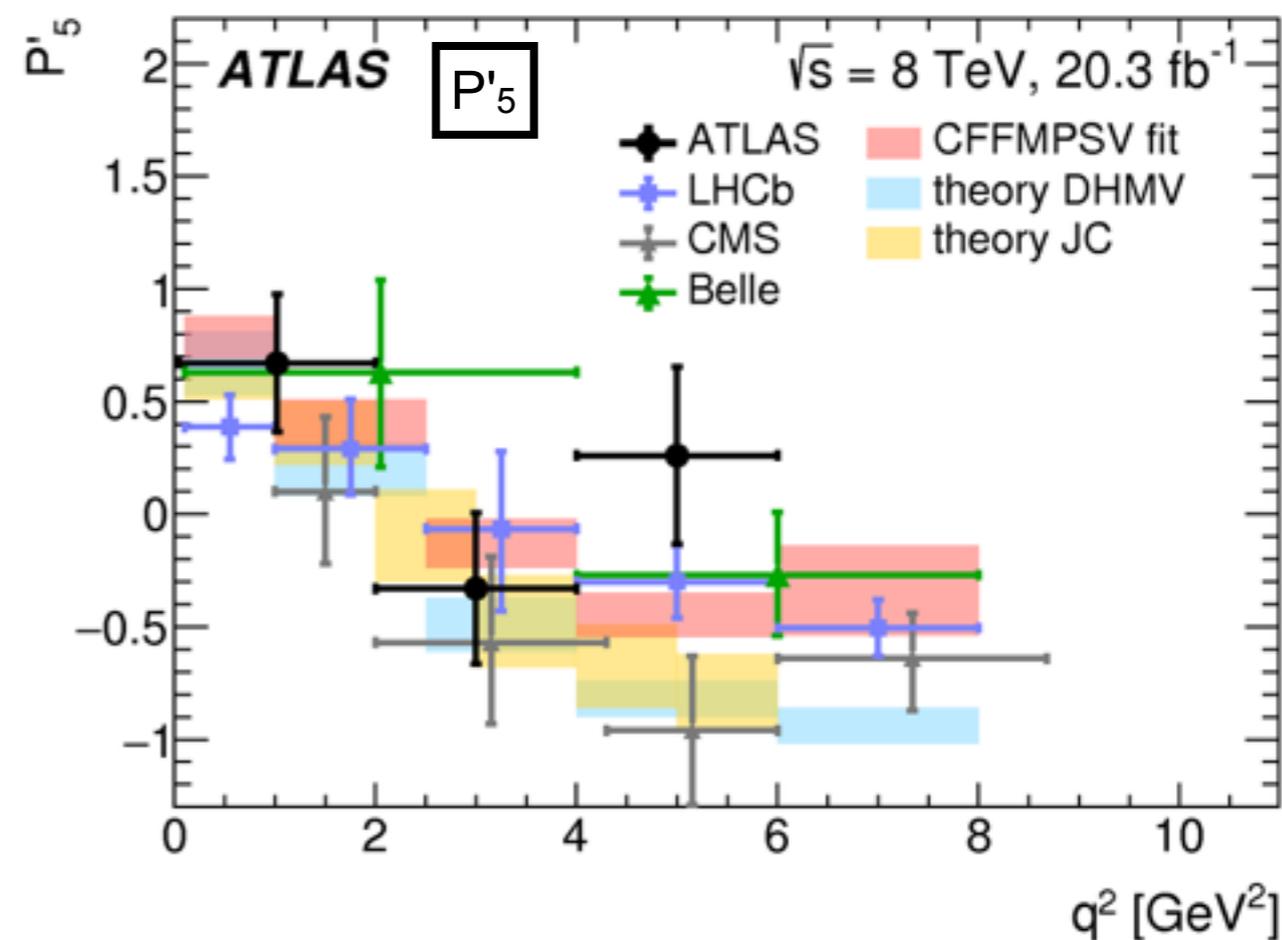
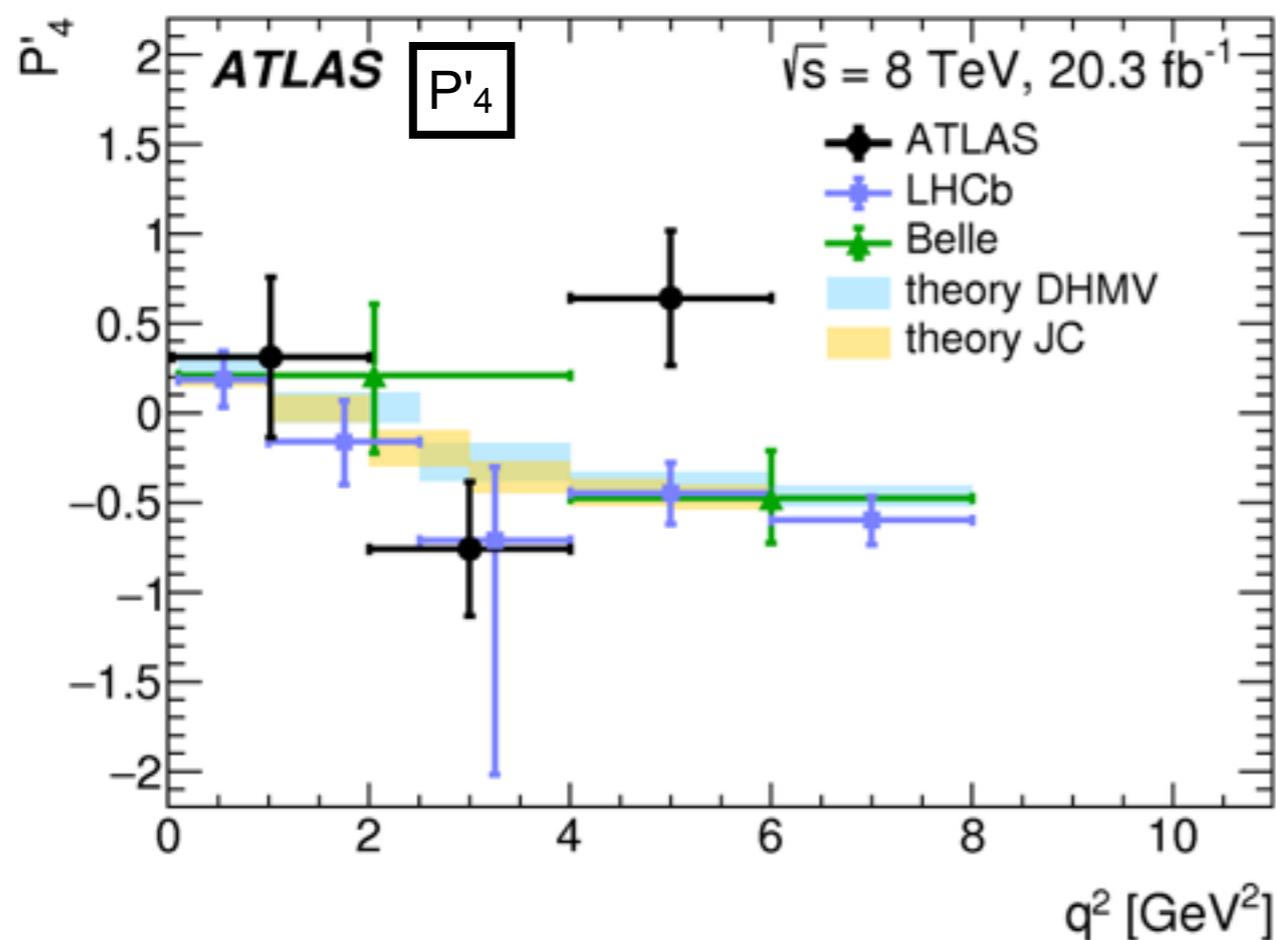
- full 2012 data - 20.3 fb⁻¹ Run 1 $\sqrt{8}$ TeV
- single, di-, and tri- μ triggers
- acceptance and mass cuts
 - $p_T(\mu, \pi, K) > (3.5, 0.5, 0.5)$ GeV, $|\eta| < 2.5$
 - $m(K\pi) \in [846, 946]$ MeV
 - $m(K\pi\mu\mu) \in [5150, 5700]$ MeV

- shorter left SB to cut out $B \rightarrow \mu\mu X$ PRD
- $q^2 \leq 6$ GeV²: radiative tail of $J/\psi \rightarrow J/\psi\gamma K^*$ above



$q^2 \in [0.04, 6] \setminus [0.98, 1.1]$ GeV² – signal region (787 events)

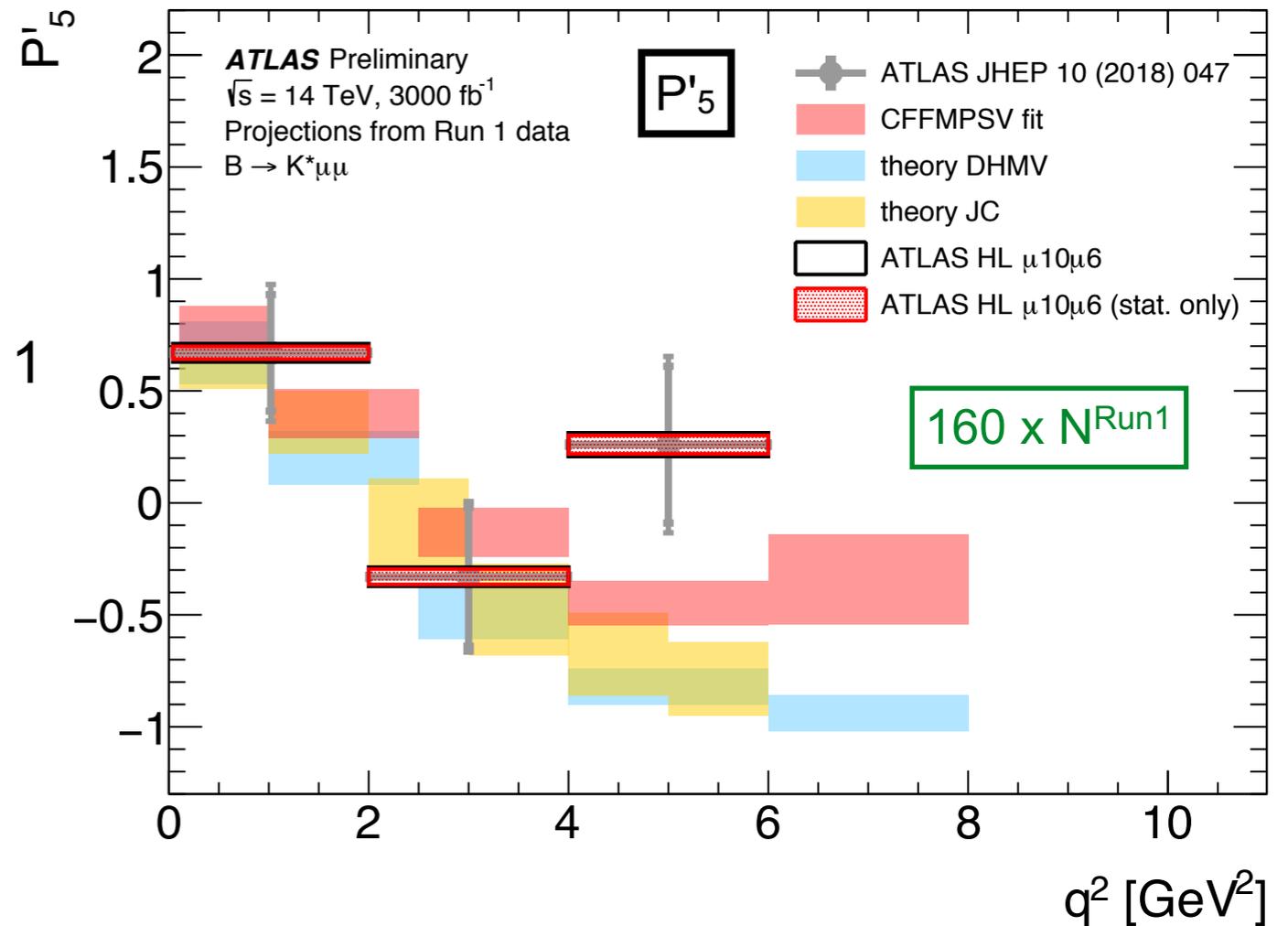
- combinatorial background suppression:
 - $p_T(K^{*0}) > 3$ GeV, $\tau/\sigma_\tau > 12.75$, $\cos\theta > 0.999$, $\chi^2/n.d.f.(B^0) < 2$
- other backgrounds
 - at $\cos\theta_L \sim 0.7$: $B \rightarrow D^0/D^+_{(s)} X \rightarrow K\pi, KK\pi$ (\rightarrow veto around $D^0/D^+_{(s)}$ masses)
 - at $\cos\theta_K \sim 1$: fake K^* (combinatoric $K\pi$) candidates and $B^+ \rightarrow K^+/\pi^+ \mu^+ \mu^-$
 - systematics: difference when fitting $[-1, 1]$ vs $[-1, 0.9]$, veto around B^+ mass
- handling of multiple candidates
 - best χ^2 or smallest $|m(K\pi) - m_{PDG}(K^{*0})| / \sigma(m(K\pi))$
 - residual mis-tag fraction $\sim 11\%$ (**S**_{4,5,9} dilution), corrected post-fit



- largest deviation $\sim 2.7\sigma$ from DHMV model for in P'_4 and P'_5 in $q^2 \in [4, 6] \text{ GeV}^2$ bin
- results consistent with other experiments
 - deviation in P'_5 coherent with LHCb measurement

[all comparison plots incl. references in the backup]

- $\sigma(m_{K\pi\mu\mu}) = 0.7 \times \sigma(m_{K\pi\mu\mu}^{\text{Run 1}})$ expected \rightarrow improvement in S/B separation
- $\sigma_{bb} \sim 1.7 \times \sigma_{bb}^{\text{Run 1}}$ ($8 \text{ TeV} \rightarrow 14 \text{ TeV}$)
- 3 trigger scenarios considered:
 - 2MU10 $\rightarrow \sim 50 \times N^{\text{Run1}}$
 - MU6_MU10 $\rightarrow \sim 160 \times N^{\text{Run1}}$
 - 2MU6 $\rightarrow \sim 250 \times N^{\text{Run1}}$
- pseudo-MC experiments based on Run 1 signal and background angular distributions
- same fitting procedure as in Run 1
- better fit model and knowledge of exclusive backgrounds expected
 - scaled corresponding systematics by $\sim 1/\sqrt{L_{\text{int}}}$
- precision in measuring P'_5 improves by $\sim 9x$, $\sim 8x$ or $\sim 5x$
- expected to be still dominated by statistics





$B^0_{(s)} \rightarrow \mu^+ \mu^-$ analysis with
2015 and 2016 data

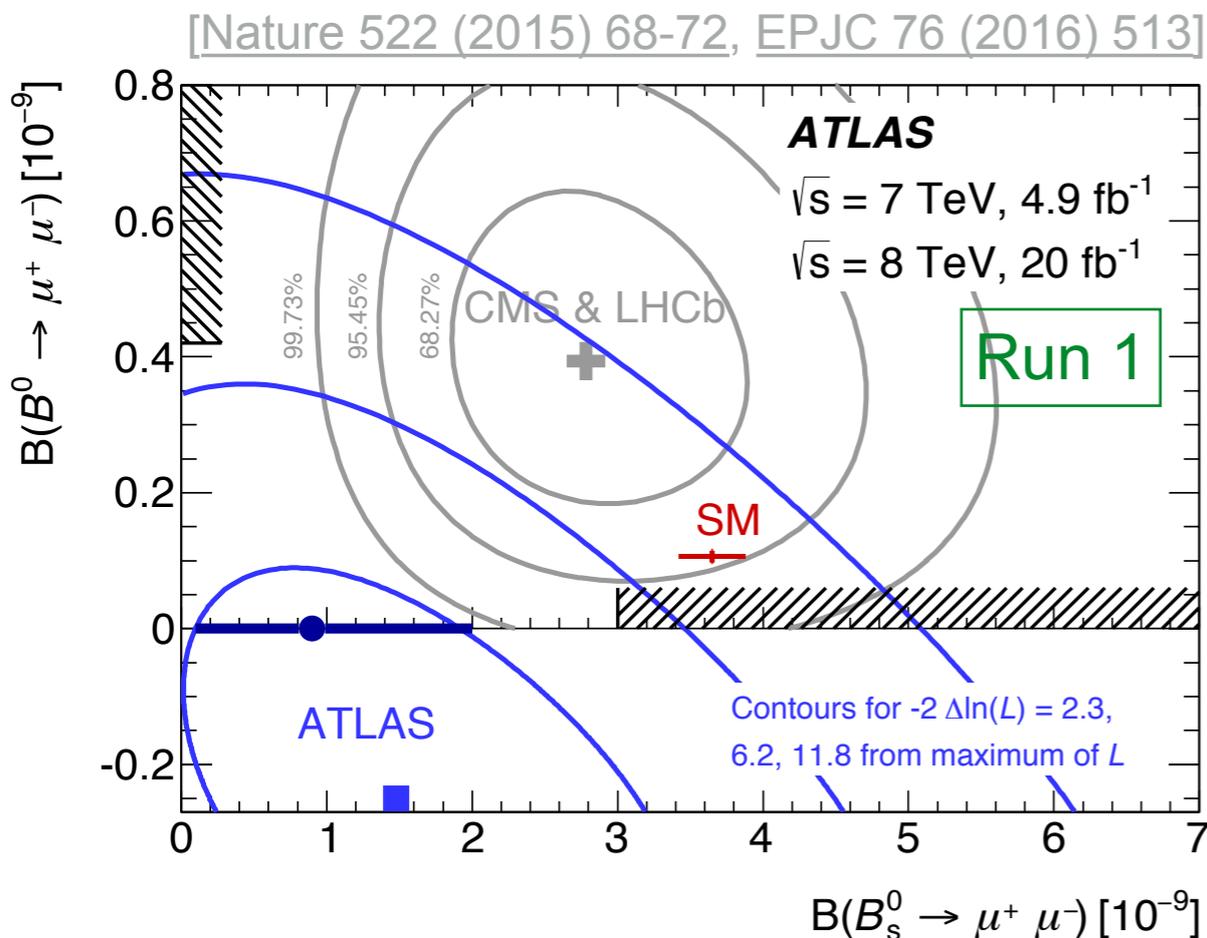


$B^0_{(s)} \rightarrow \mu^+ \mu^-$: Introduction

- strongly suppressed and precisely calculated in the SM:

- $BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.57 \pm 0.17) \times 10^{-9} (*)$ [PRL 120(2018) 011801]
- $BR(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ [PRL 112(2014) 101801]

→ powerful indirect search for New Physics



- Run 1 CMS & LHCb combination

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

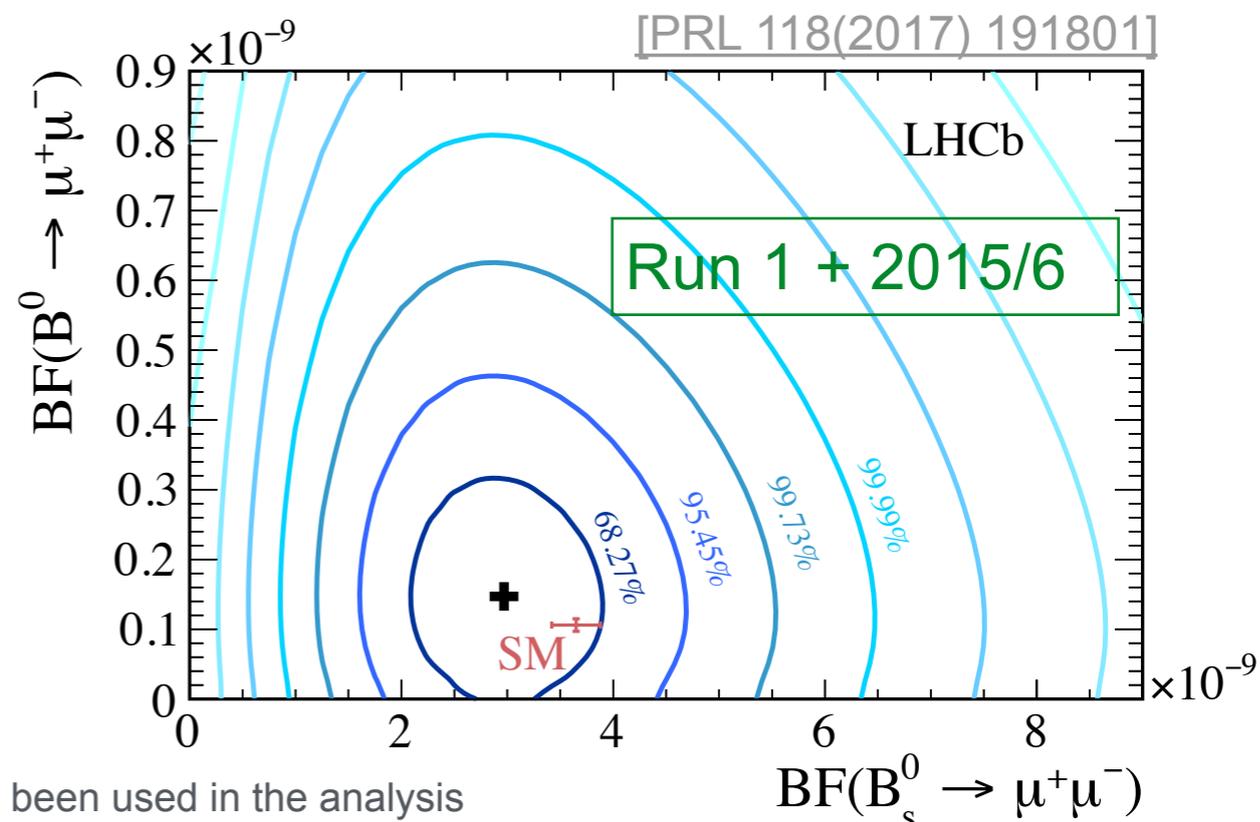
- ATLAS Run 1 result

- $BR(B^0_s \rightarrow \mu^+ \mu^-) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$
- $BR(B^0 \rightarrow \mu^+ \mu^-) < 4.2 \times 10^{-10}$ (at 95% CL)
- compatible with SM at $\sim 2\sigma$

- Run 1 + 2015/6 LHCb result

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

all LHC results consistent with SM (so far)

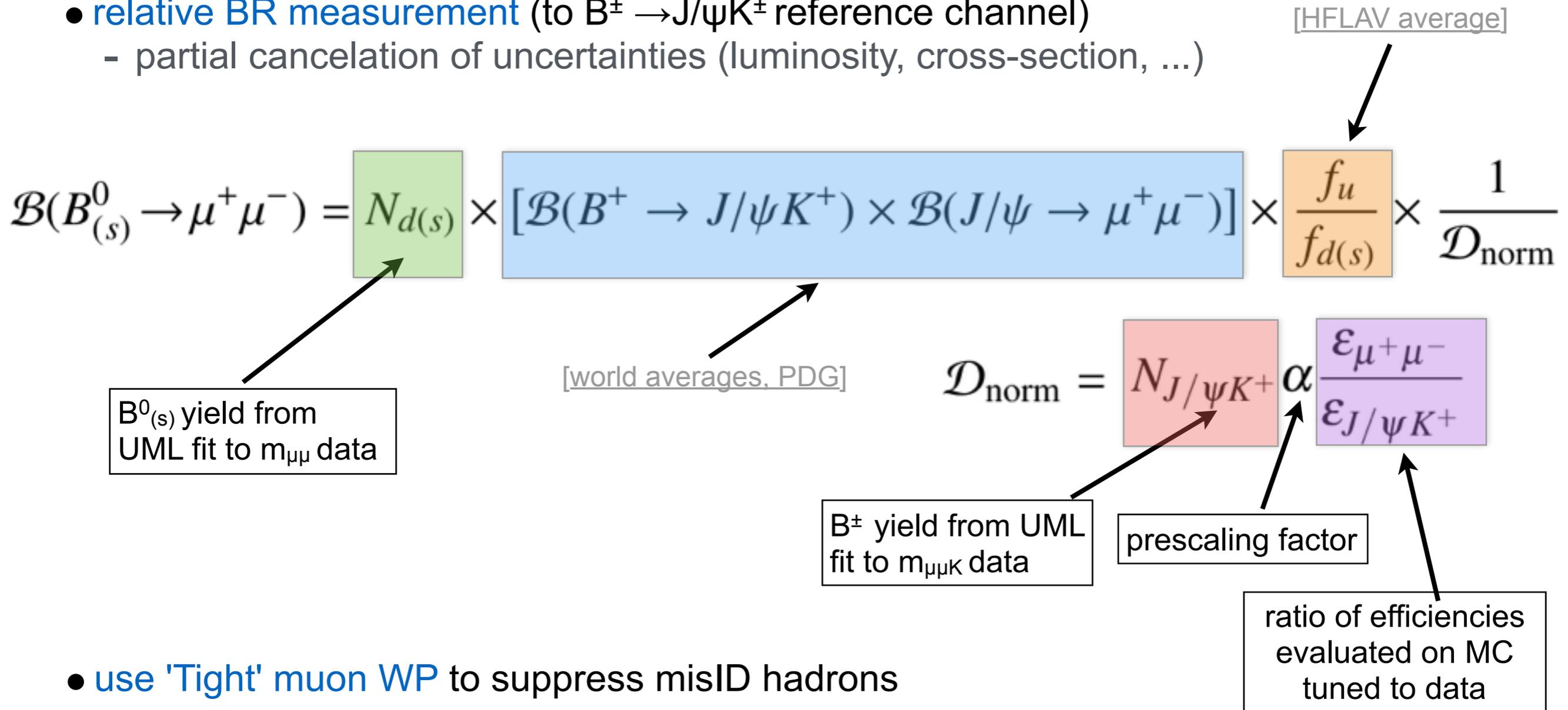


(*)value $BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ [PRL 112(2014) 101801] has been used in the analysis



$B^0_{(s)} \rightarrow \mu^+ \mu^-$: Analysis Strategy

- **relative BR measurement** (to $B^\pm \rightarrow J/\psi K^\pm$ reference channel)
 - partial cancelation of uncertainties (luminosity, cross-section, ...)



- use 'Tight' muon WP to suppress misID hadrons
- blind $m_{\mu\mu}$ mass range [5166, 5526] MeV
- use BDT against combinatorial background
- check Data/MC agreement on $B^\pm \rightarrow J/\psi K^\pm$ and $B^0_s \rightarrow J/\psi \phi$, $\phi \rightarrow K^+ K^-$
- **signal extraction** with ML fit over $m_{\mu\mu}$ in four intervals of BDT
- use **Neyman construction** to improve statistical treatment of the result

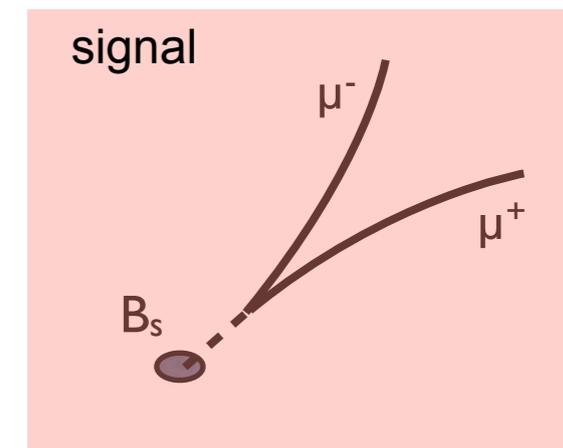
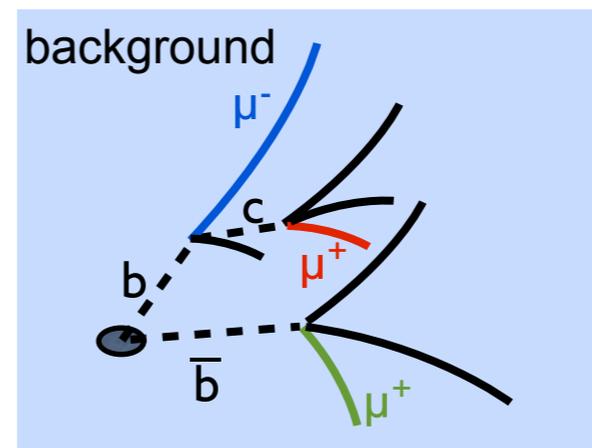


$B^0_{(s)} \rightarrow \mu^+ \mu^-$: Non-resonant Background

- combinatorial from real muons

- dominant source
- mostly from $b\bar{b} \rightarrow \mu^+ \mu^- X$
- modelled with dedicated MC

small mass dependence over entire search region



- partially reconstructed $B \rightarrow \mu\mu X$ decays

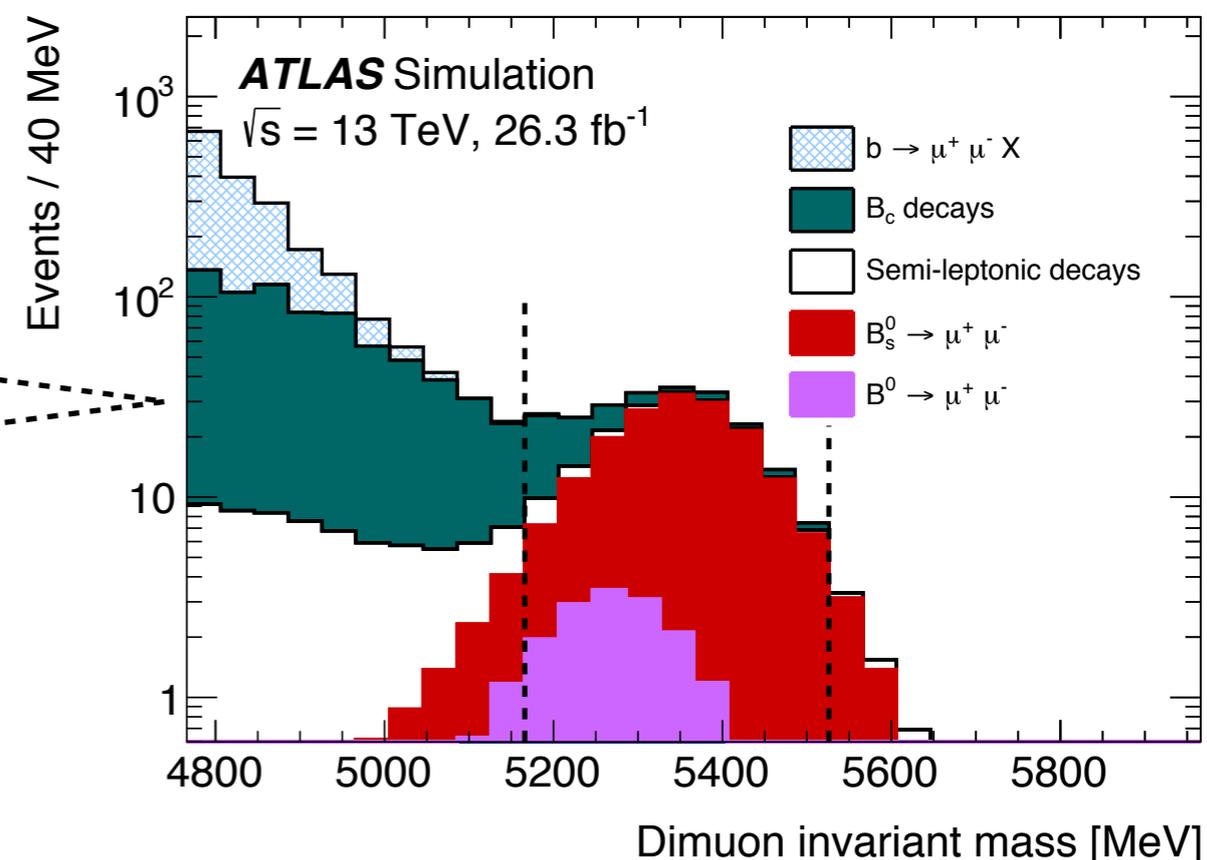
- same vertex, e.g. $B^0 \rightarrow K^* \mu\mu$
- semi-leptonic decay cascades
 $b \rightarrow c \mu \nu \rightarrow s(d) \mu \mu \nu$
- $B^{\pm}_c \rightarrow J/\psi \mu^{\pm} \nu \rightarrow \mu^{\pm} \mu^+ \mu^- \nu$ decays

- semi-leptonic $B_{(s)} \rightarrow \mu h \nu$

- hadron misidentified as muon
- $B^0 \rightarrow \pi^- \mu^+ \nu$, $B^0_s \rightarrow K^- \mu^+ \nu$, $\Lambda_b \rightarrow p \mu^- \bar{\nu}$

populate mainly left sideband

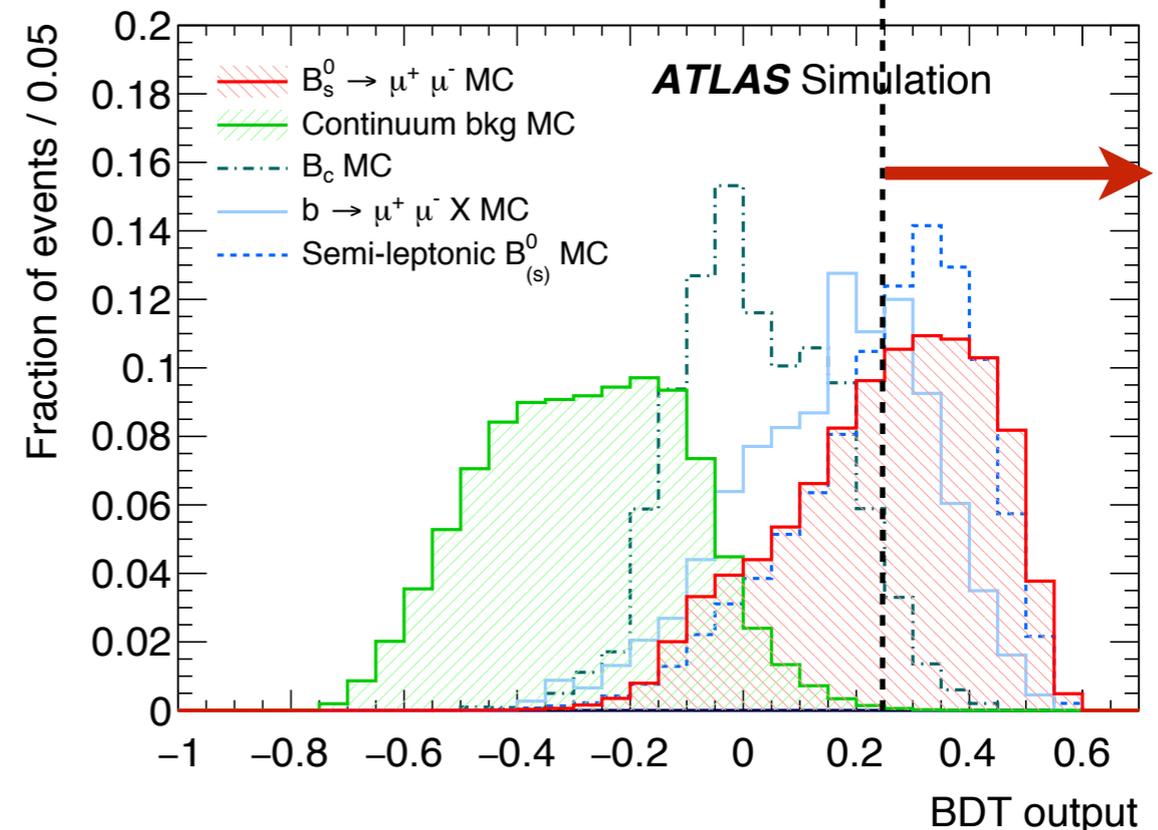
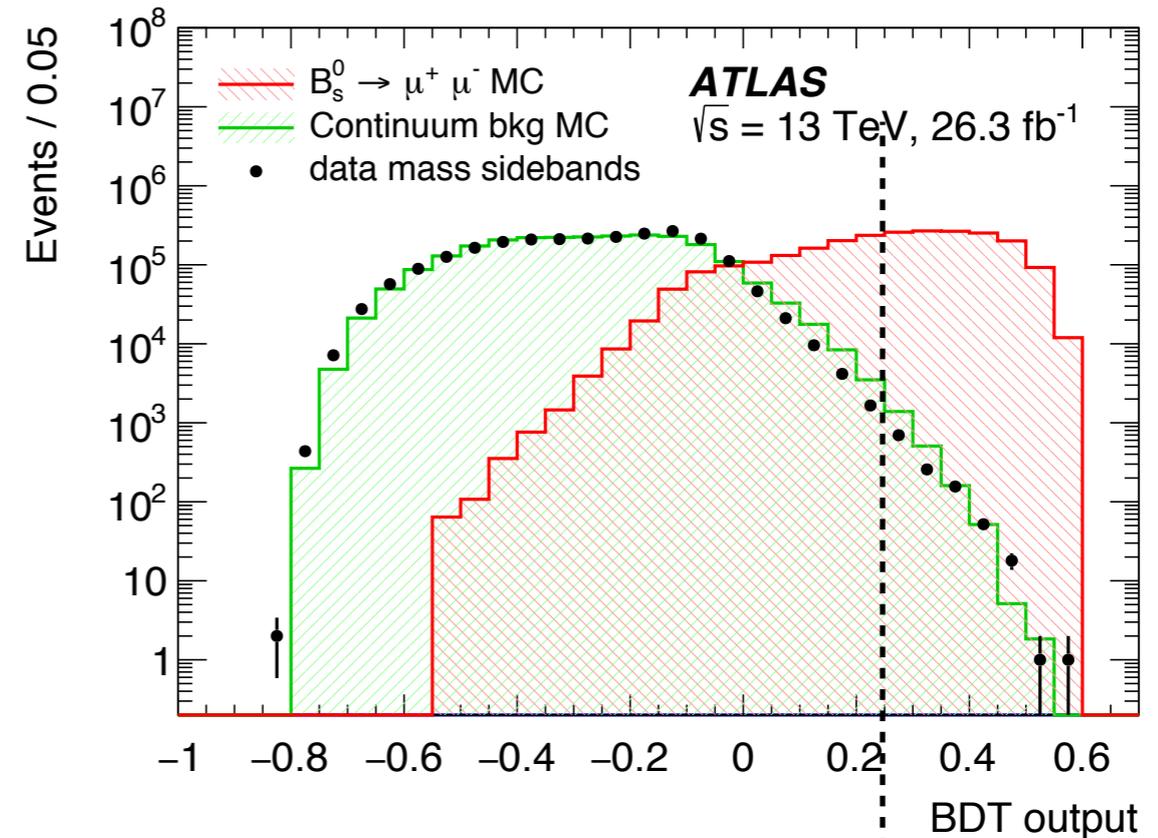
expectation based on PDG' BRs and integrated luminosity:



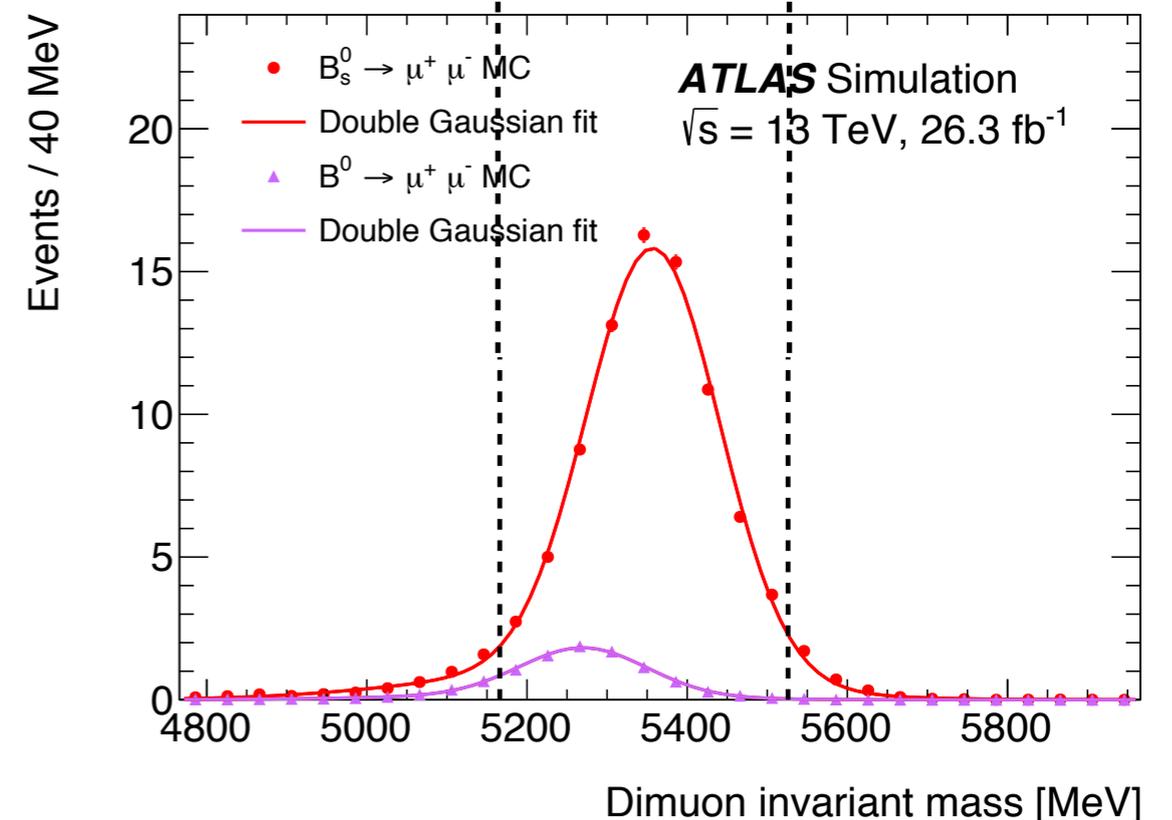
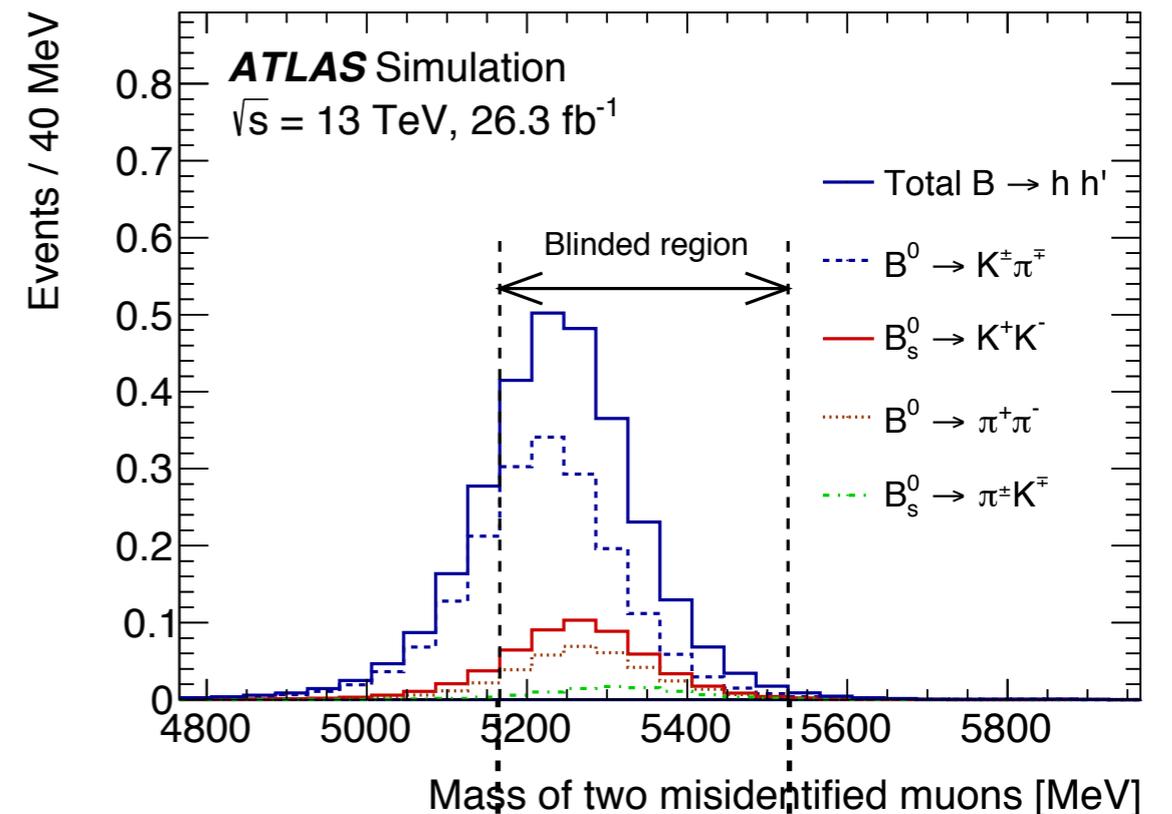


$B^0_{(s)} \rightarrow \mu^+ \mu^-$: BDT Discriminant

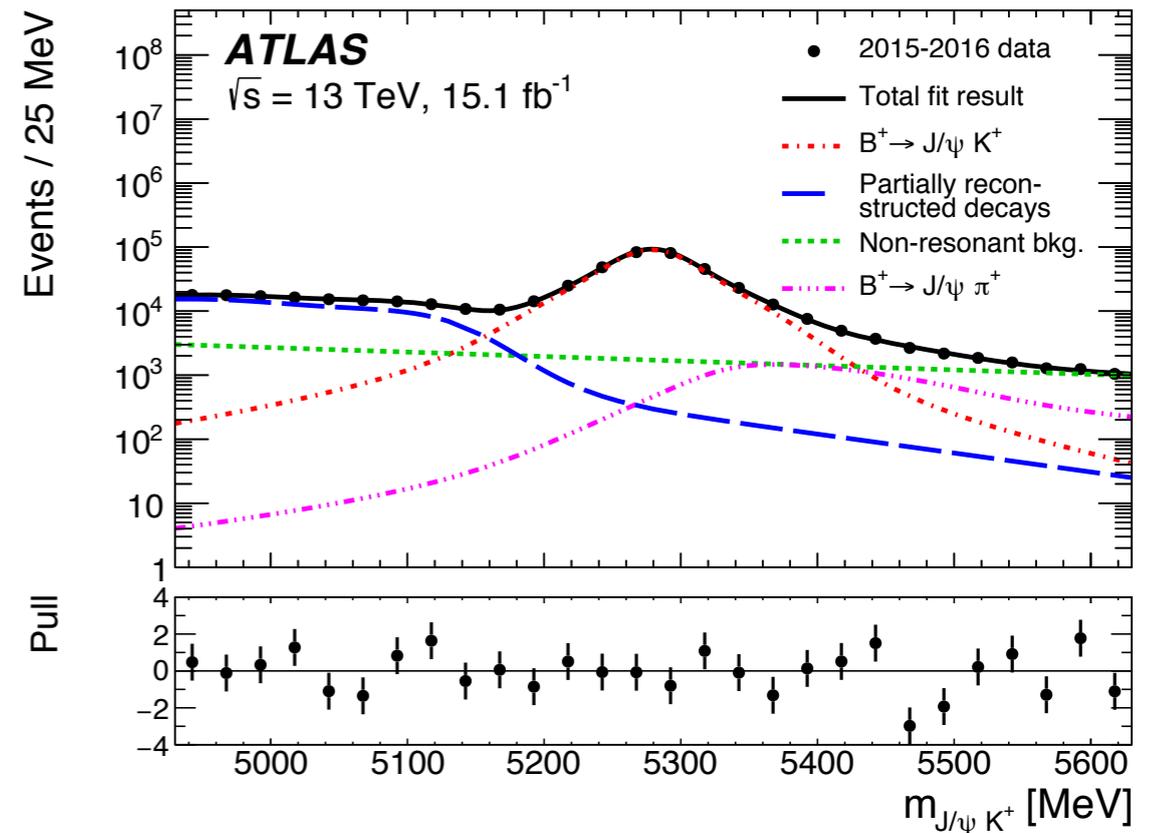
- against combinatorial background
- 15 variables used for training
 - topology of reconstructed B-decay
 - properties of muons
 - underlying event
- split mass sidebands into 3 subsets
 - unbiased training/evaluation of 3 independent BDT's
 - similar performance of BDT's
- signal sensitive region $BDT > 0.25$
 - $\epsilon_{sig} = 54\%$, $\epsilon_{bkg} = 0.03\%$
- suppresses other background components as well



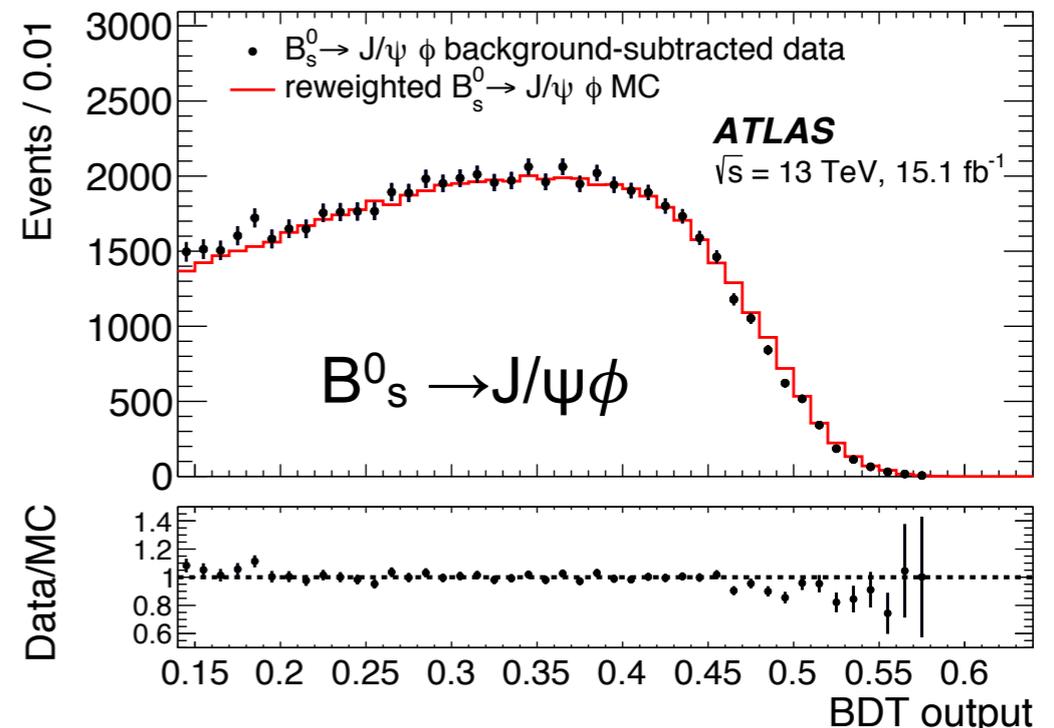
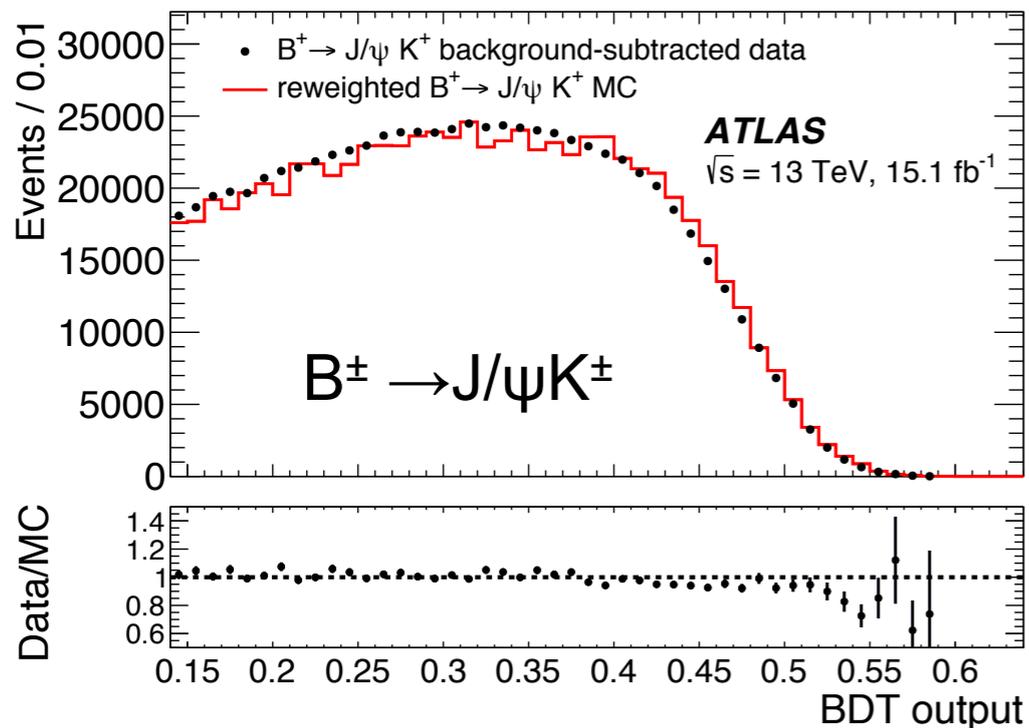
- both h reconstructed as μ mainly due to decays in flight
- from simulation studies:
 $B^0_s \rightarrow K^+K^-$, $B^0 \rightarrow K^\pm\pi^\pm$, $B^0_s \rightarrow \pi^+\pi^-$ decays
- low rate but $B^0 \rightarrow \mu^+\mu^-$ -like topology
- use 'Tight' μ working point: misID reduction by $\times 0.39^2$ with $\epsilon_\mu = 90\%$
- final $P(\text{misID}) = 0.08\%$ (K^\pm), 0.1% (π^\pm), $<0.01\%$ (p)
- signal region yield obtained inverting 'Tight' μ selection: $N_{\text{peak bkg}} = 2.9 \pm 2.0$ events
 - cross-checked with simulation
 - split equally among 3 BDT bins in the signal fit



- B^\pm yield from UML fit of $m_{\mu\mu K}$ distributions
 - shape parameters obtained from simultaneous fit to data and MC samples of sig. and bkg.
- data/MC discrepancies dominate systematic uncertainty on $\varepsilon_{\mu\mu}/\varepsilon_{\mu\mu K}$ ratio (3.2% out of the total 4.1%)

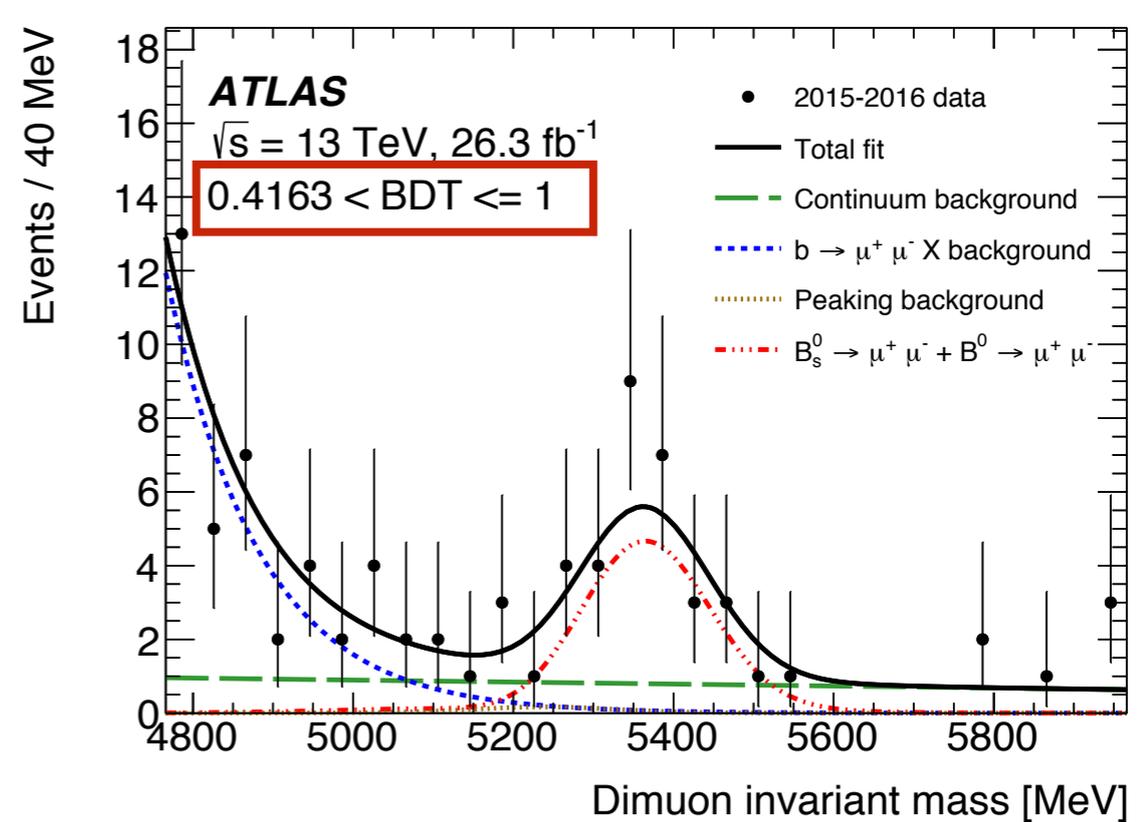
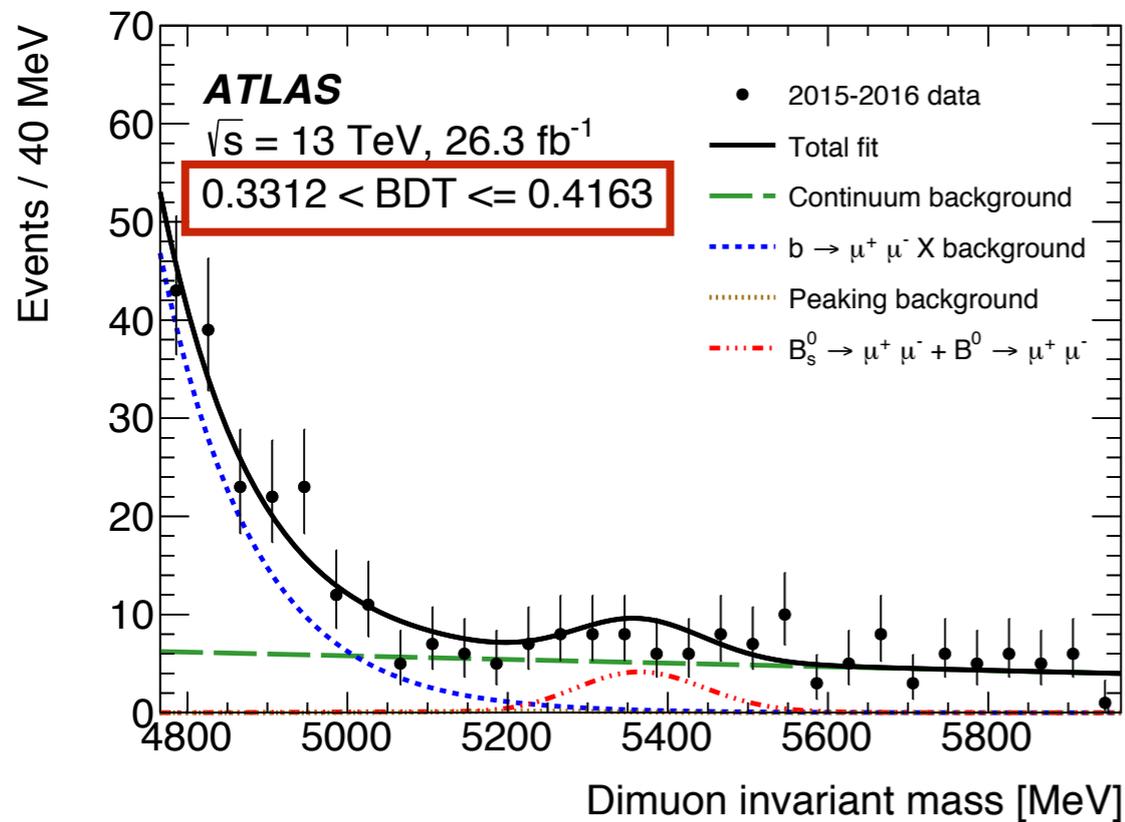
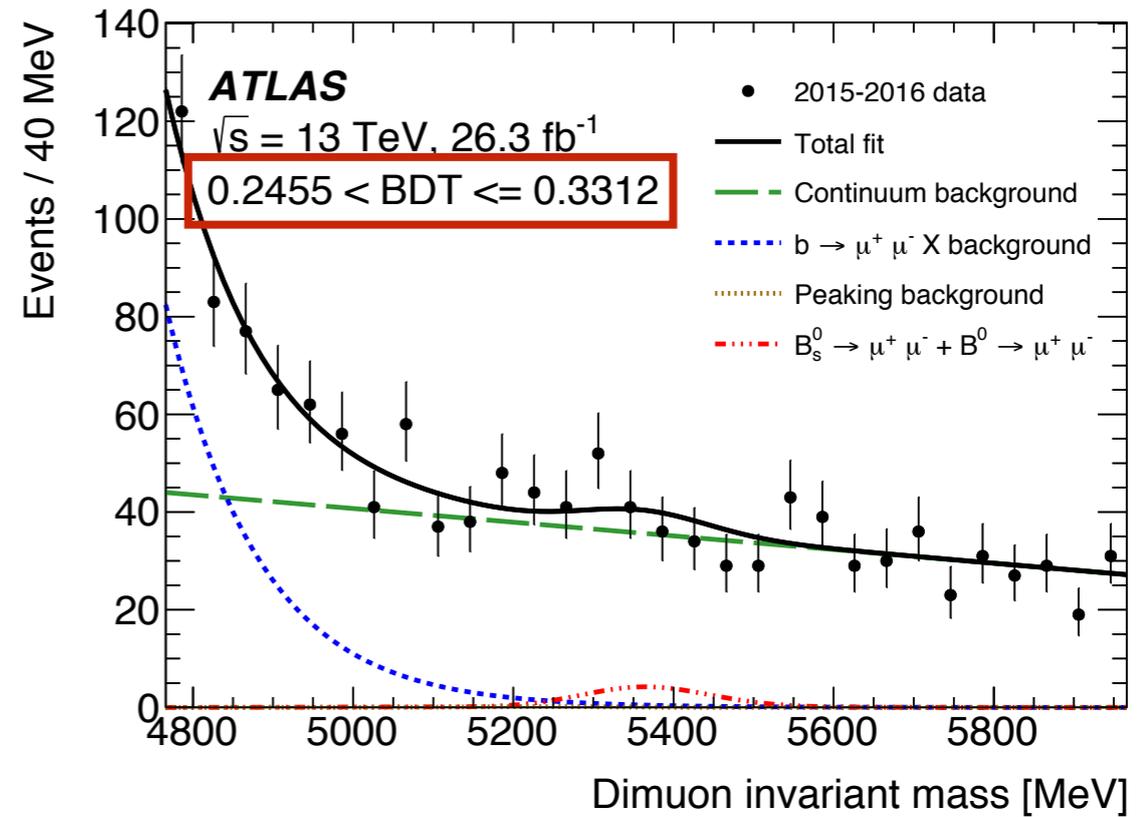
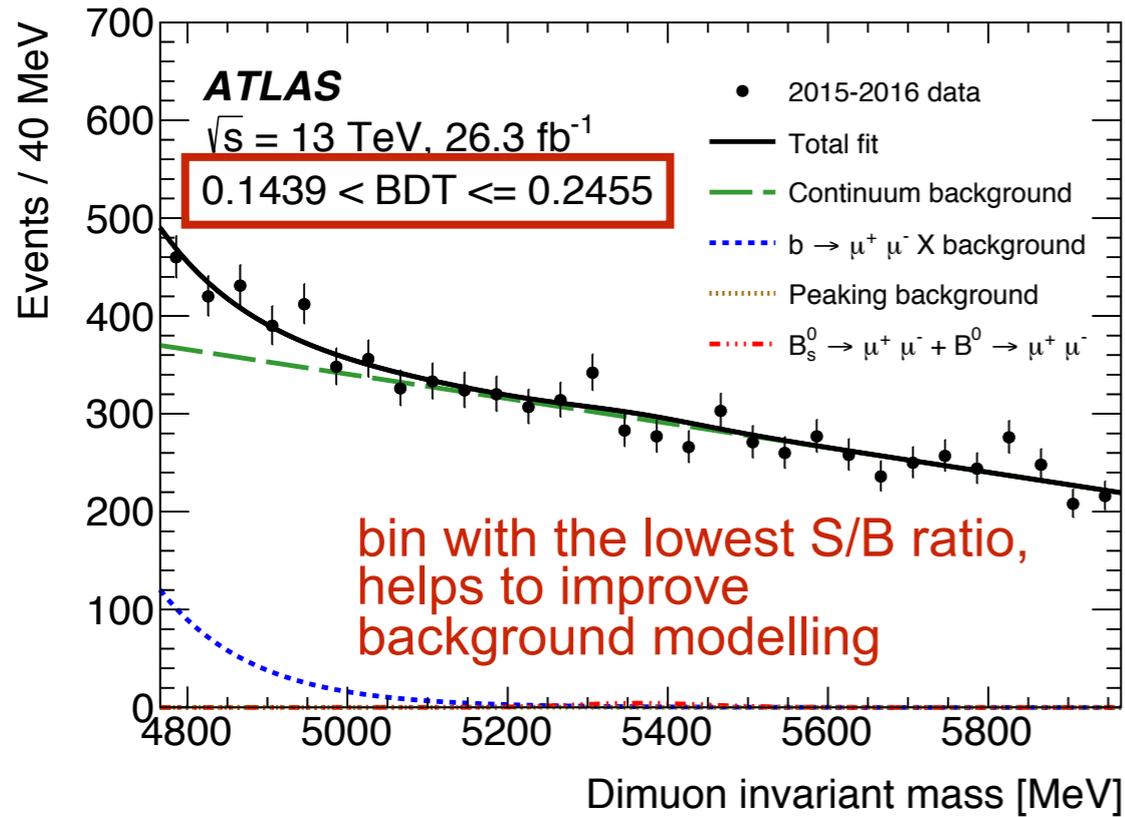


Data/MC agreement in the most sensitive BDT range:





$B^0_{(s)} \rightarrow \mu^+ \mu^-$: Signal Yield Extraction

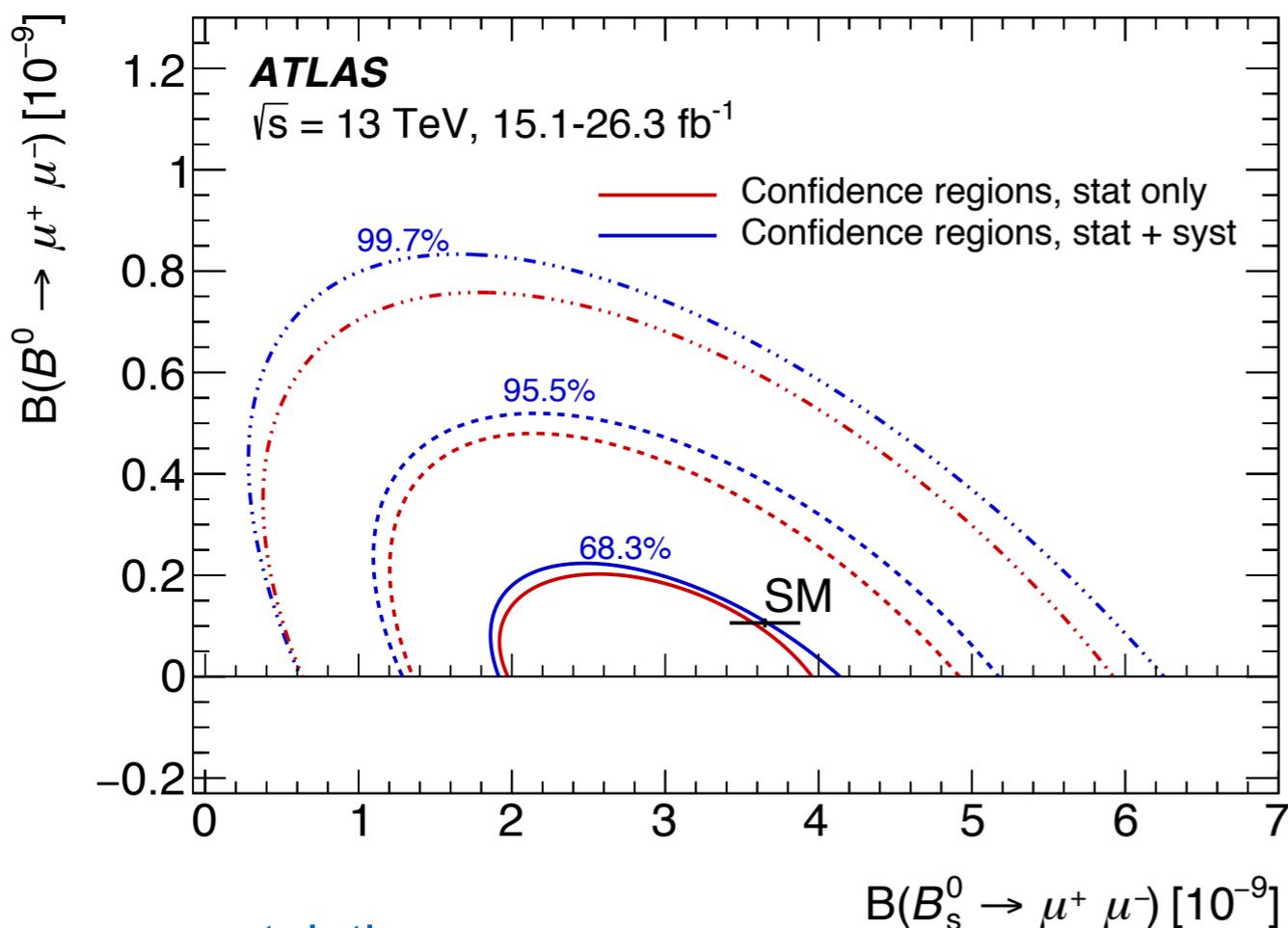




$B^0_{(s)} \rightarrow \mu^+ \mu^-$: Results with 2015/16 Data



- extracted (expected in SM) signal yields:
 - $N_s = 80 \pm 22$ (91) and $N_d = -12 \pm 20$ (10) events \rightarrow consistent with expectations



uncertainties:

Source	B^0_s (%)	B^0 (%)
f_s/f_d	5.1	-
B^+ Yield	4.8	4.8
R_ϵ	4.1	4.1
$\mathcal{B}(B^+ \rightarrow J/\psi K^+) \times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$	2.9	2.9
Fit Systematic Uncertainties	8.7	65
Stat. Uncertainty (from Likelihood est.)	27	150

total fit systematic uncertainties:

$$\sigma_{\text{syst}}^{N_s} = 3 + 0.05N_s$$

$$\sigma_{\text{syst}}^{N_d} = 2.9 + 0.05N_s + 0.05N_d$$

correlation coefficient: $\rho_{\text{syst}} = -0.83$

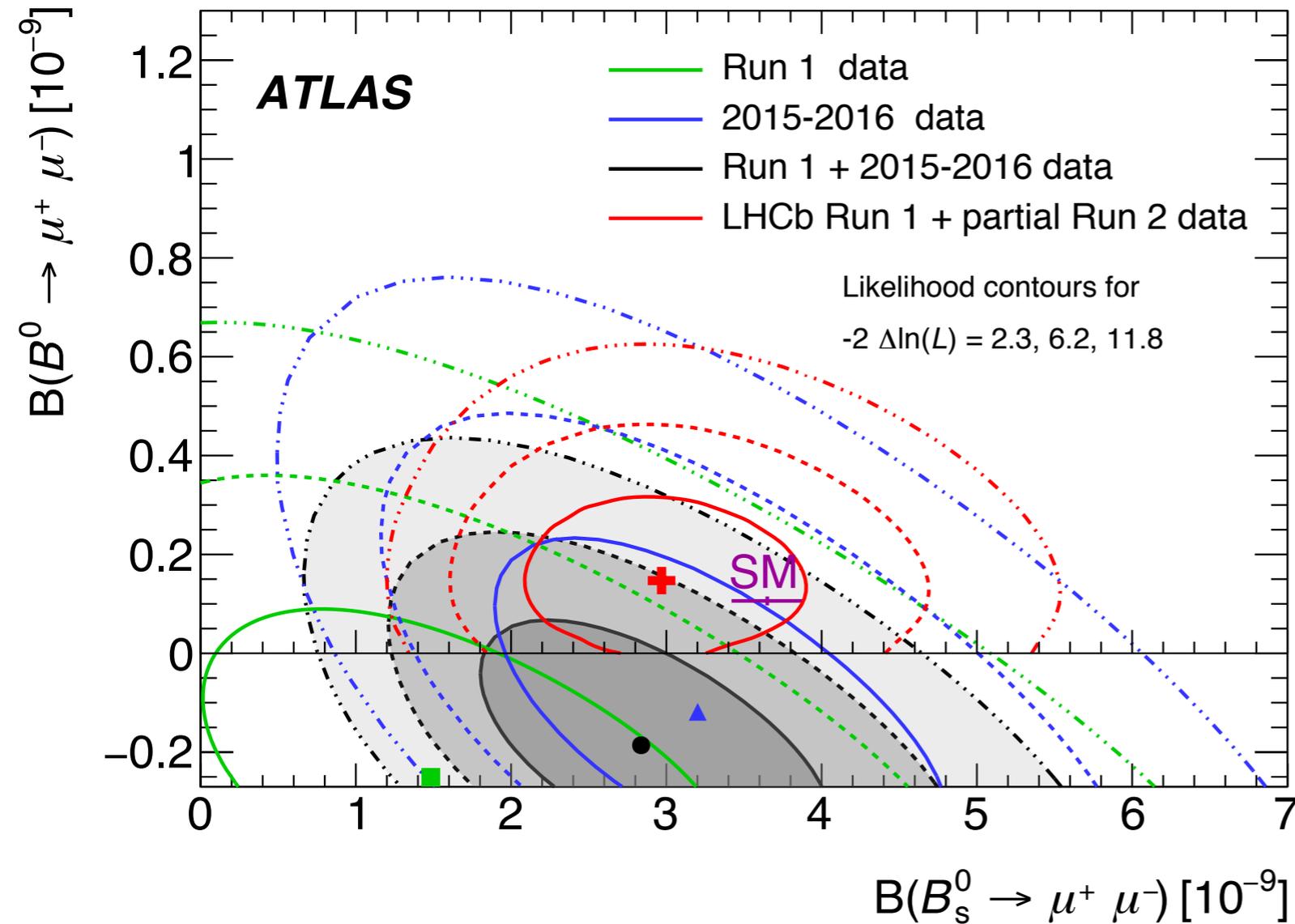
- likelihood maximum:
 - $BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.9) \times 10^{-9}$
 - $BR(B^0 \rightarrow \mu^+ \mu^-) = (-1.3 \pm 2.1) \times 10^{-10}$
- result from Neyman 2D contours:
 - $BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.21^{+0.96}_{-0.91} {}^{+0.49}_{-0.30}) \times 10^{-9}$
 - $BR(B^0 \rightarrow \mu^+ \mu^-) < 4.3 \times 10^{-10}$ at 95% CL
- expected result in SM hypothesis:
 - $BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.6^{+1.1}_{-1.0}) \times 10^{-9}$
 - $BR(B^0 \rightarrow \mu^+ \mu^-) < 7.1 \times 10^{-10}$ at 95% CL

statistical uncertainties dominate

[JHEP04 (2019) 098]



$B^0_{(s)} \rightarrow \mu^+ \mu^-$: Combination with Run 1



- likelihood maximum:

$$BR(B^0_s \rightarrow \mu^+ \mu^-) = (2.8 \pm 0.7) \times 10^{-9}$$

$$BR(B^0 \rightarrow \mu^+ \mu^-) = (-1.9 \pm 1.6) \times 10^{-10}$$

- result from likelihood contours:

$$BR(B^0_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$$

$$BR(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10} \text{ at 95\% CL}$$

- expected result in SM hypothesis:

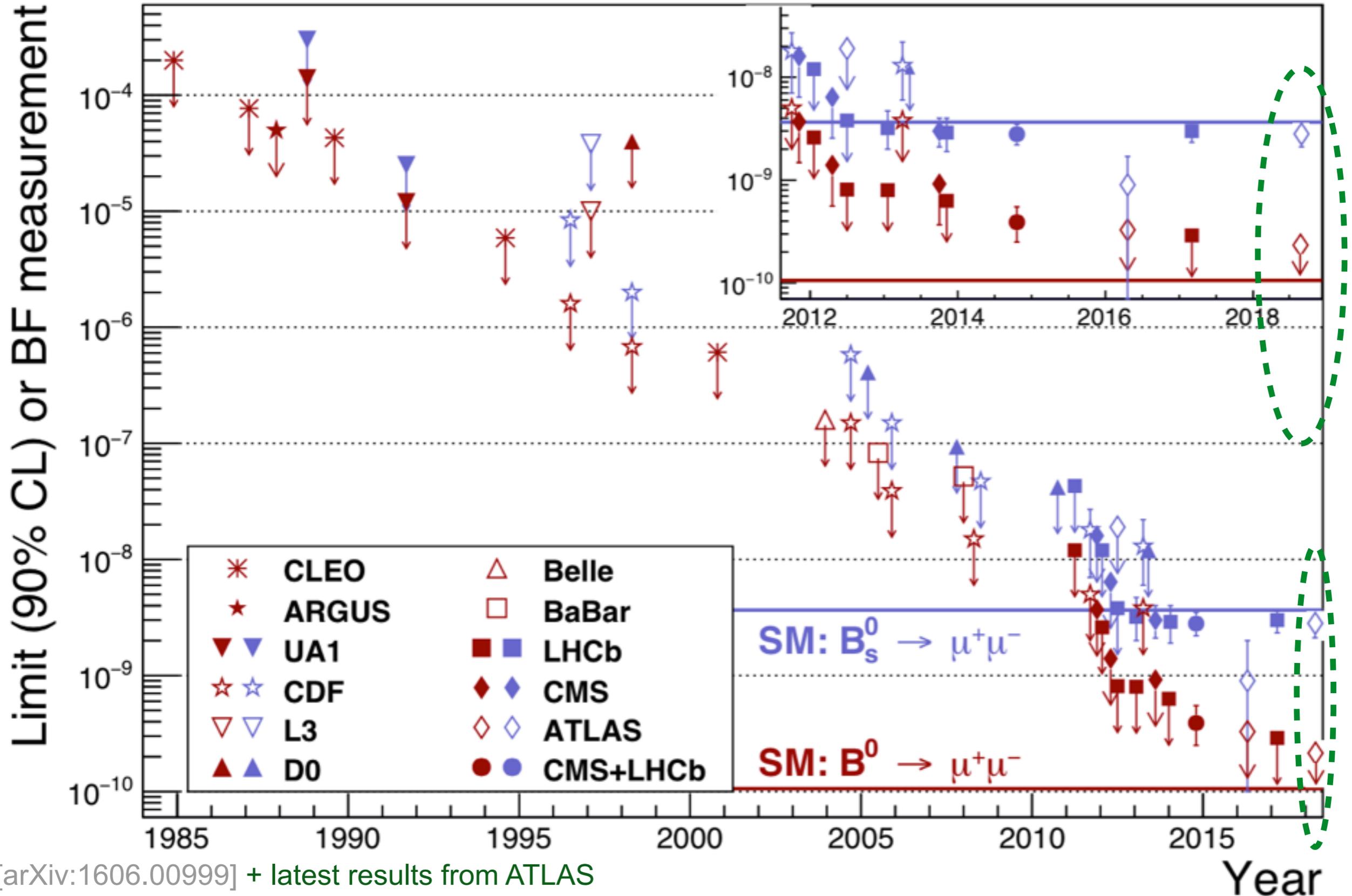
$$BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.6^{+0.9}_{-0.8}) \times 10^{-9}$$

$$BR(B^0 \rightarrow \mu^+ \mu^-) < 5.6 \times 10^{-10} \text{ at 95\% CL}$$

- compatible with SM at $\sim 2.4\sigma$
- combined significance for $B^0_s \rightarrow \mu^+ \mu^- \sim 4.6\sigma$
- $BR(B^0 \rightarrow \mu^+ \mu^-)$ limit most stringent to date



BR($B^0_{(s)} \rightarrow \mu^+\mu^-$) Evolution



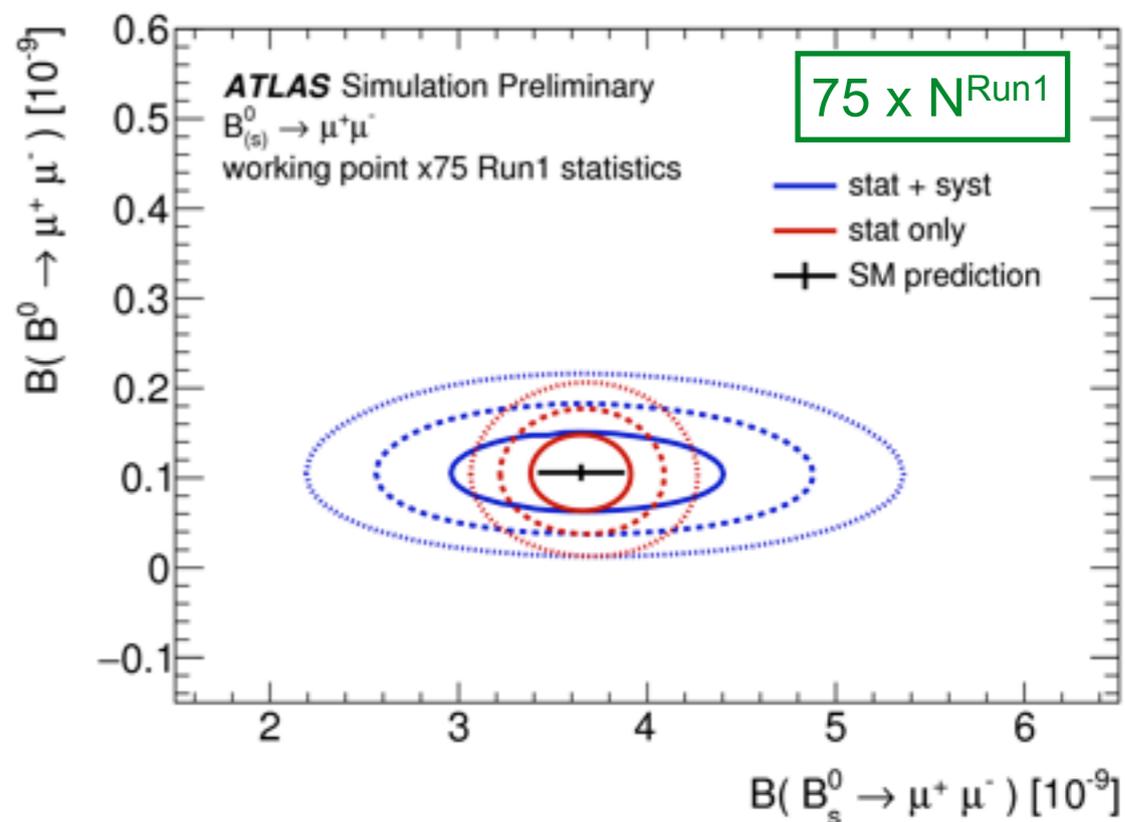
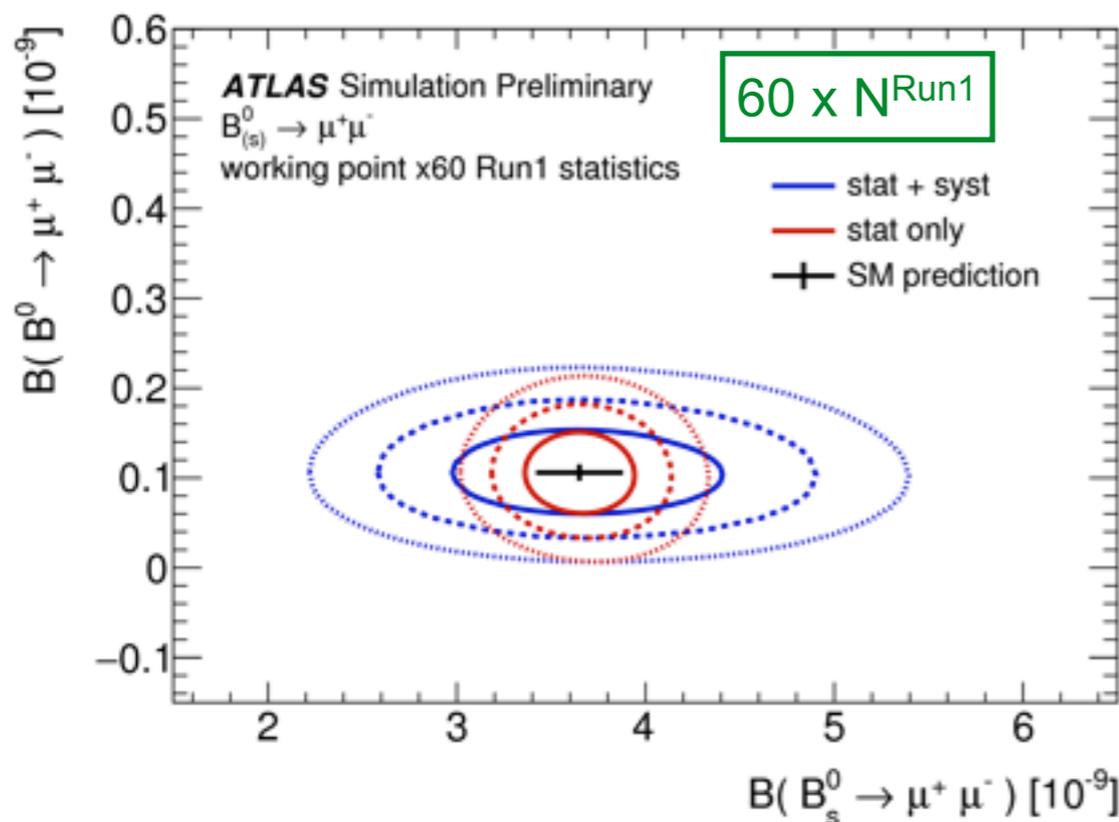
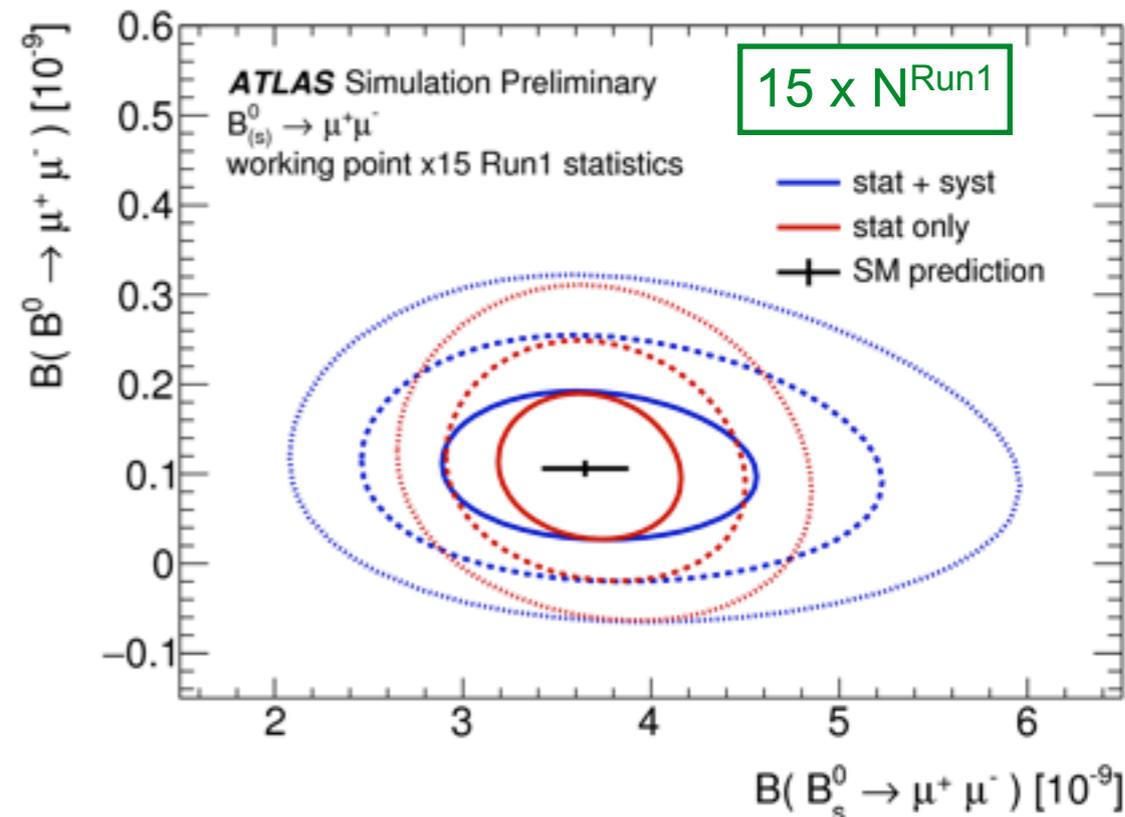
[arXiv:1606.00999] + latest results from ATLAS



$B^0_{(s)} \rightarrow \mu^+ \mu^-$: HL-LHC Prospects (3 ab^{-1})



- better $\sigma(m_{\mu\mu})$ expected \rightarrow improvement of $m(B^0_s)$ and $m(B^0)$ separation
- 3 trigger scenarios considered:
 - 2MU10 $\rightarrow 15 \times N^{\text{Run1}}$
 - MU6_MU10 $\rightarrow 60 \times N^{\text{Run1}}$
 - 2MU6 $\rightarrow 75 \times N^{\text{Run1}}$
- pseudo-MC experiments based on Run 1 likelihood
- dominant systematics:
 - $\sigma(f_s/f_d) \sim 8.3\%$ ("conservative")





Summary & Outlook

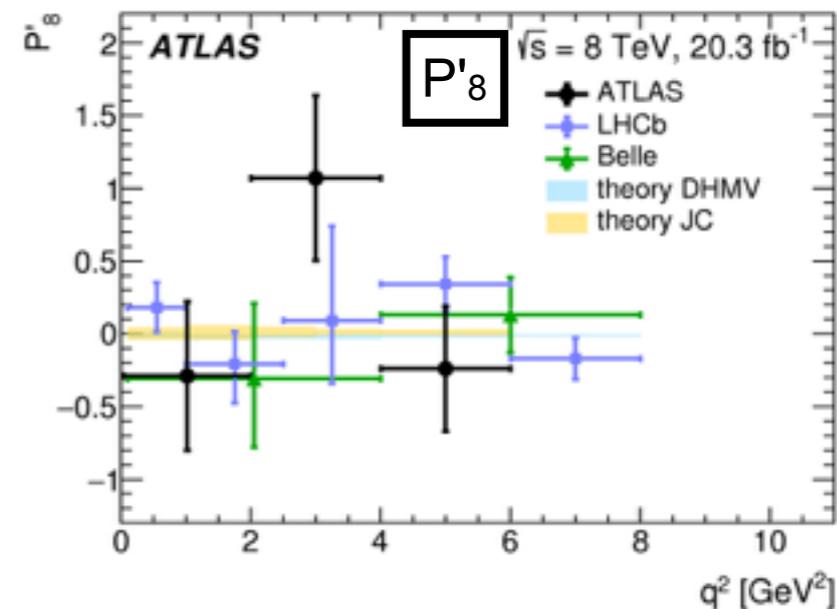
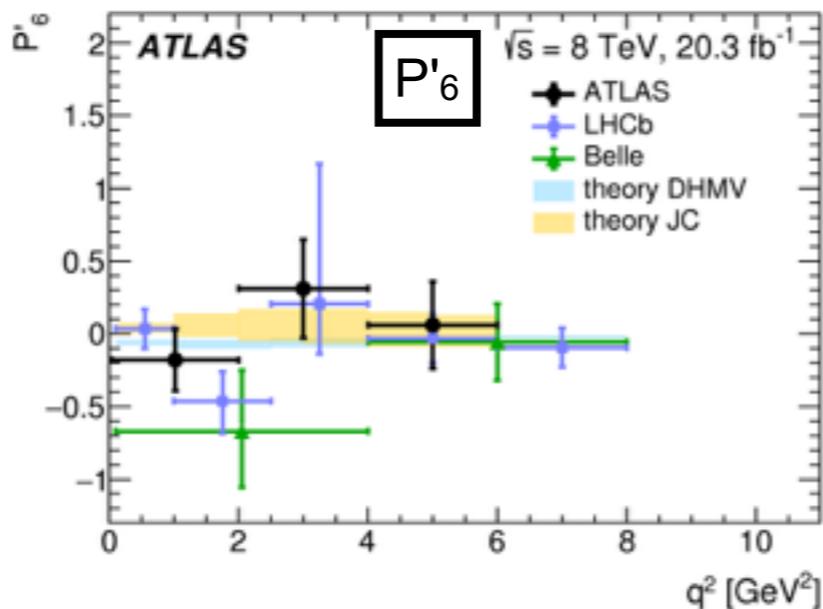
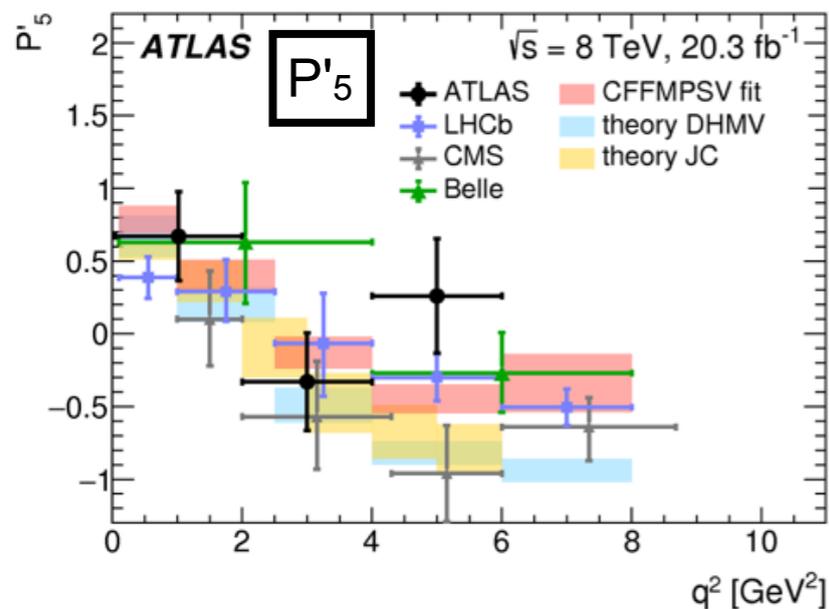
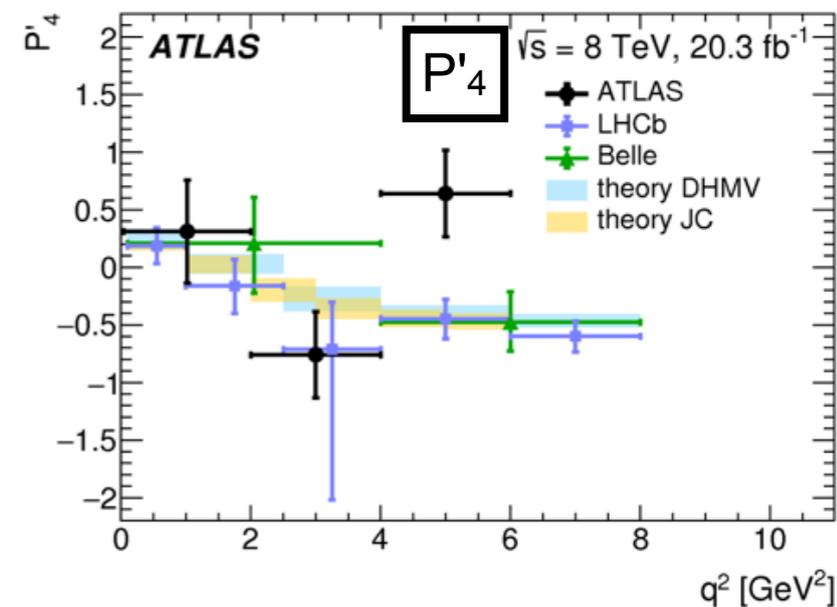
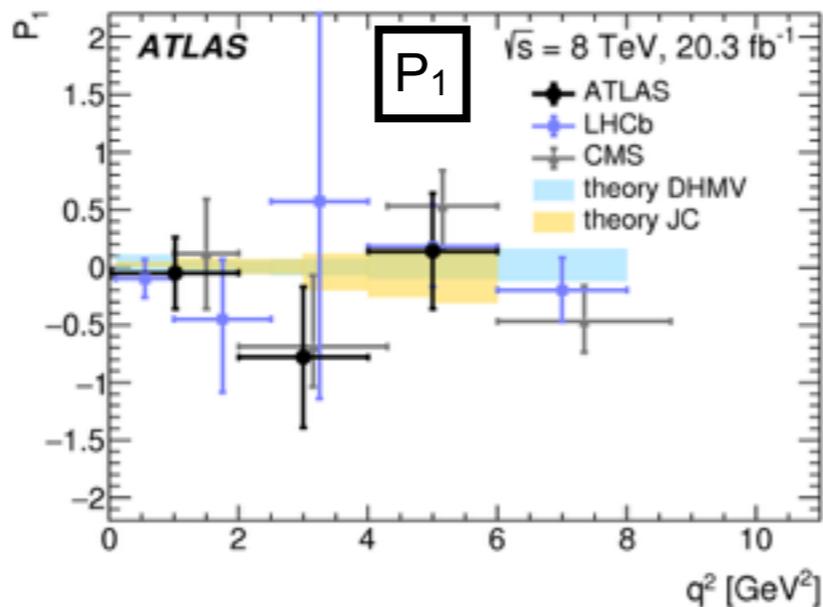
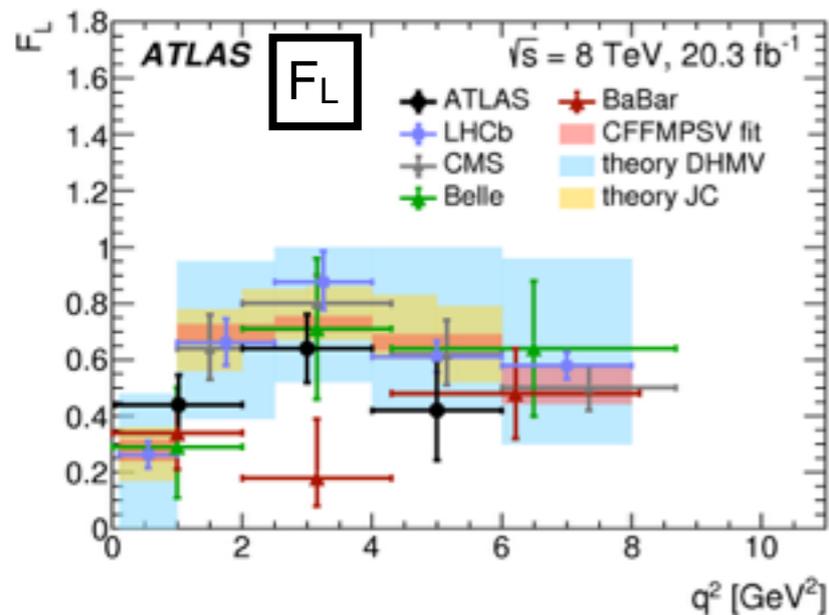
- angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay with Run 1 data shown
 - results compatible with SM and other experiments
- $B^0_{(s)} \rightarrow \mu^+ \mu^-$ analysis with 2015/16 data presented
 - $BR(B^0_s \rightarrow \mu^+ \mu^-) = (3.2^{+1.1}_{-1.0}) \times 10^{-9}$
 - $BR(B^0 \rightarrow \mu^+ \mu^-) < 4.3 \times 10^{-10}$ at 95% CL
- combination with Run 1 result yields
 - $BR(B^0_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$
 - $BR(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10}$ at 95% CL
 - results compatible with SM at 2.4σ
- reach for expected HL-LHC statistics for $B^0_{(s)} \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ presented
- 140 fb^{-1} of full Run 2 data being analysed - stay tuned for new results!



BACKUP



$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: Results vs Theory/Experiments



CFFMPSV: Ciuchini et al.; JHEP 06 (2016) 116; arXiv:1611.04338

DHMV: Descotes-Genon et al.; JHEP 01 (2013) 048; JHEP 05 (2013) 137; JHEP 12 (2014) 125

JC: Jäger-Camalich; JHEP 05 (2013) 043; Phys. Rev. D93 (2016) 014028

LHCb Collaboration, JHEP 02 (2016)

CMS Collaboration, Phys. Lett. B 781 (2018) 517 [P'_i plots], Phys. Lett. B 753 (2016) 424 [F_L plot]

Belle Collaboration, arXiv:1604.04042 [P'_i plots], Phys. Rev. Lett. 103 (2009) 171801 [F_L plot]

BaBar Collaboration, Phys. Rev. D 93 (2016) 052015



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

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

transformation of systematics $S_i \rightarrow P_i^{(')}$

$$P_1 = \frac{2S_3}{1 - F_L} \quad P'_{j=4,5,6,8} = \frac{S_{i=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}$$



$B^0(s) \rightarrow \mu^+ \mu^-$: BDT Input Variables

Variable	Description
p_T^B	Magnitude of the B candidate transverse momentum \vec{p}_T^B .
$\chi_{PV,DV}^2$	Compatibility of the separation $\vec{\Delta x}$ between production (<i>i.e.</i> associated PV) and decay (DV) vertices in the transverse projection: $\vec{\Delta x}_T \cdot \Sigma_{\vec{\Delta x}_T}^{-1} \cdot \vec{\Delta x}_T$, where $\Sigma_{\vec{\Delta x}_T}$ is the covariance matrix.
ΔR	three-dimensional opening between \vec{p}^B and $\vec{\Delta x}$: $\sqrt{\alpha_{2D}^2 + \Delta\eta^2}$
$ \alpha_{2D} $	Absolute value of the angle between \vec{p}_T^B and $\vec{\Delta x}_T$ (transverse projection).
L_{xy}	Projection of $\vec{\Delta x}_T$ along the direction of \vec{p}_T^B : $(\vec{\Delta x}_T \cdot \vec{p}_T^B) / \vec{p}_T^B $.
IP_B^{3D}	three-dimensional impact parameter of the B candidate to the associated PV.
$DOCA_{\mu\mu}$	Distance of closest approach (DOCA) of the two tracks forming the B candidate (three-dimensional).
$\Delta\phi_{\mu\mu}$	Difference in azimuthal angle between the momenta of the two tracks forming the B candidate.
$ d_0 ^{\max}\text{-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.
$ d_0 ^{\min}\text{-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_L^{\min}	Value of the smaller projection of the momenta of the muon candidates along \vec{p}_T^B .
$I_{0.7}$	Isolation variable defined as ratio of $ \vec{p}_T^B $ to the sum of $ \vec{p}_T^B $ and of the transverse momenta of all additional tracks contained within a cone of size $\Delta R < 0.7$ around the B direction. Only tracks matched to the same PV as the B candidate are included in the sum.
$DOCA_{\text{trk}}$	DOCA of the closest additional track to the decay vertex of the B candidate. Tracks matched to a PV different from the B candidate are excluded.
$N_{\text{trk}}^{\text{close}}$	Number of additional tracks compatible with the decay vertex (DV) of the B candidate with $\ln(\chi_{\text{trk},DV}^2) < 1$. The tracks matched to a PV different from the B candidate are excluded.
$\chi_{\mu,xPV}^2$	Minimum χ^2 for the compatibility of a muon in the B candidate with any PV reconstructed in the event.

[ATLAS-CONF-2018-046]



Systematic uncertainties on $\epsilon_{\mu\mu}/\epsilon_{\mu\mu K}$ ratio



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

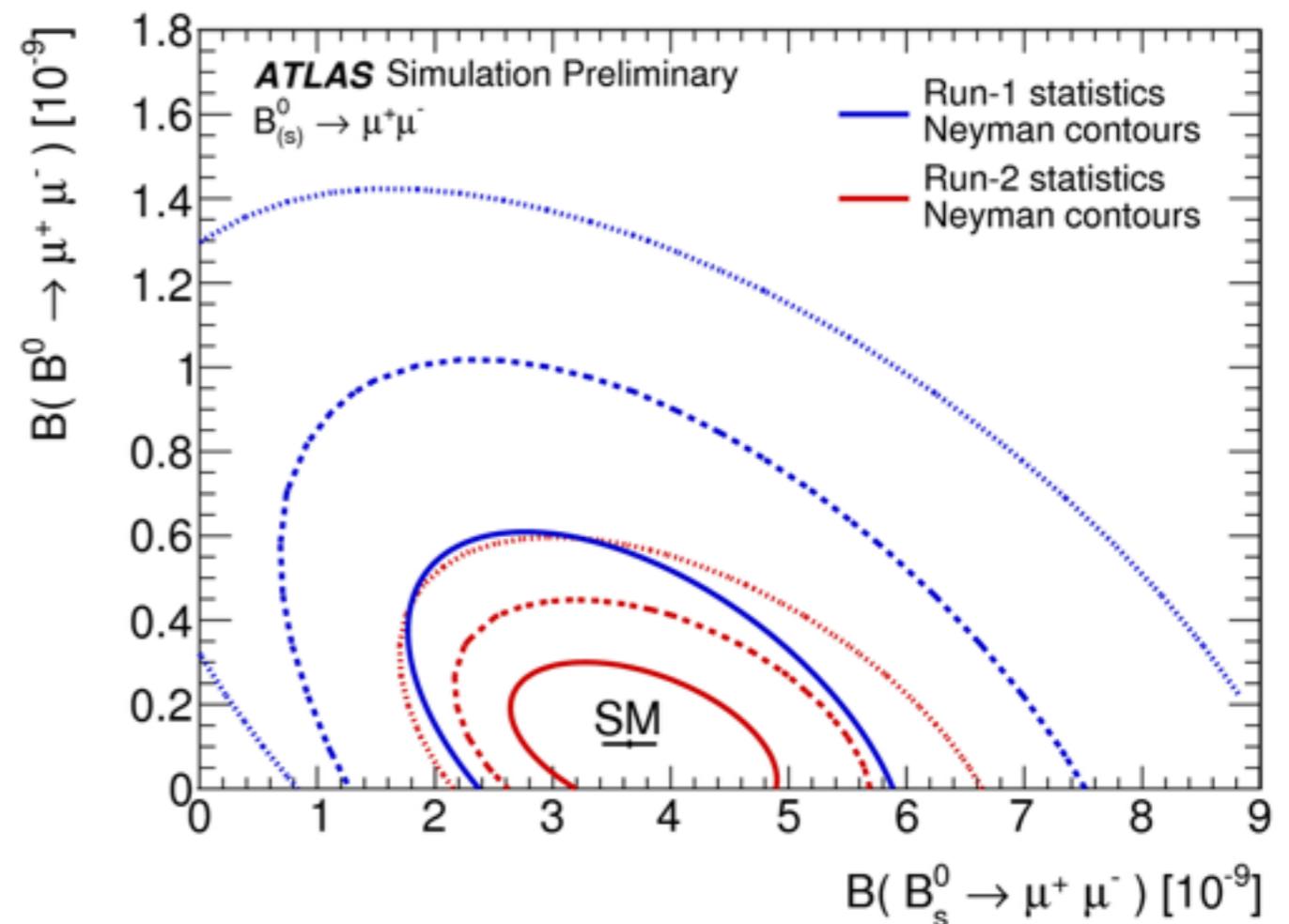
[ATLAS-CONF-2018-046]



- pseudo-MC experiments **based on Run 1** measurement
- 2D Neyman belt construction to estimate CL contours
 - total statistics is scaled in the likelihood
 - $\sigma_{bb} \sim 1.7x$ Run 1 (8 TeV \rightarrow 13 TeV)
 - 2MU6 || MU6_MU4 topological triggers
 - \Rightarrow **estimated to $\sim 7x$ Run 1**
 - same S/B ratio as in Run 1 - "conservative" as background suppression expected to improve due to IBL

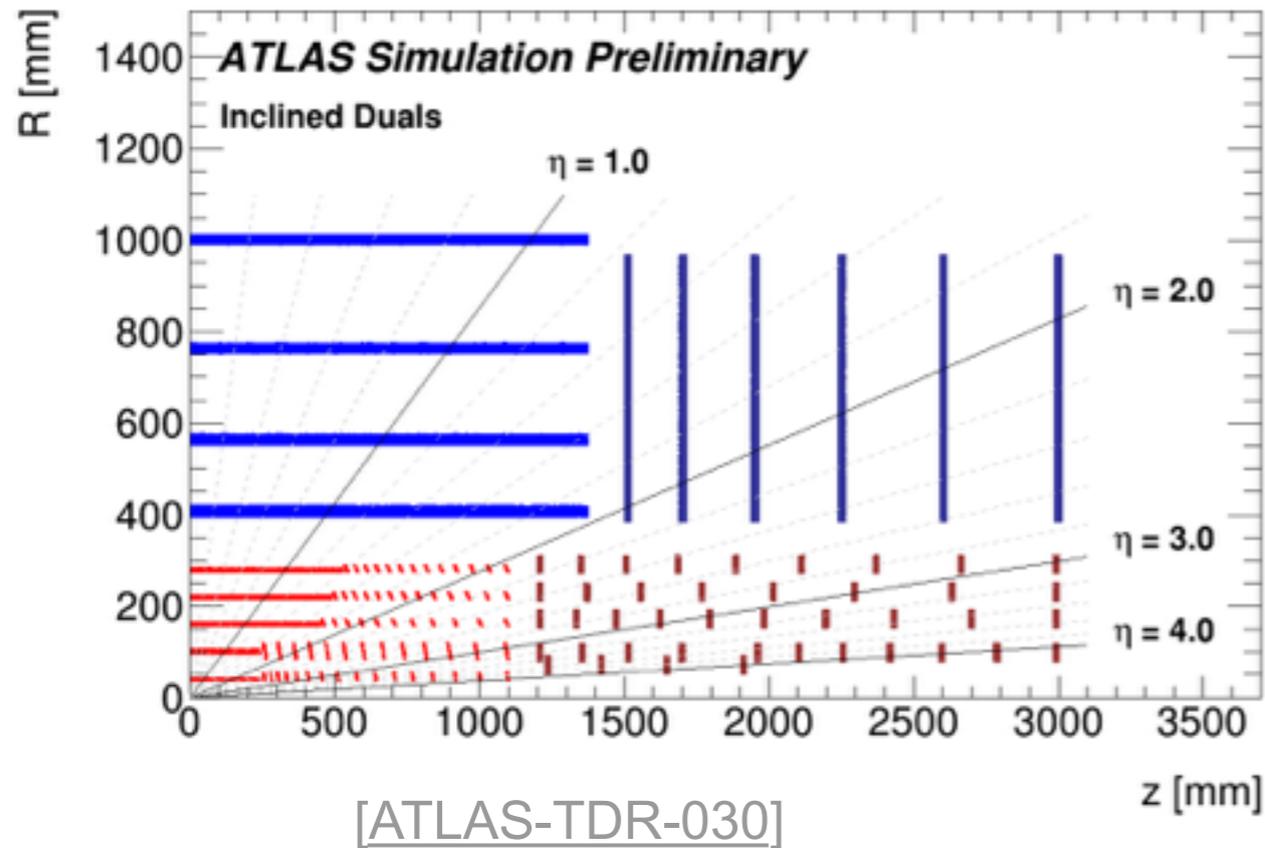
Systematic uncertainties: (30% of Run 1 total error)

- external: f_s/f_d , $\text{BR}(B^\pm \rightarrow J/\psi K^\pm)$
 - kept as in Run 1
- internal: efficiencies, fit shapes, background extrapolation, trigger modelling,...
 - scaled with statistics



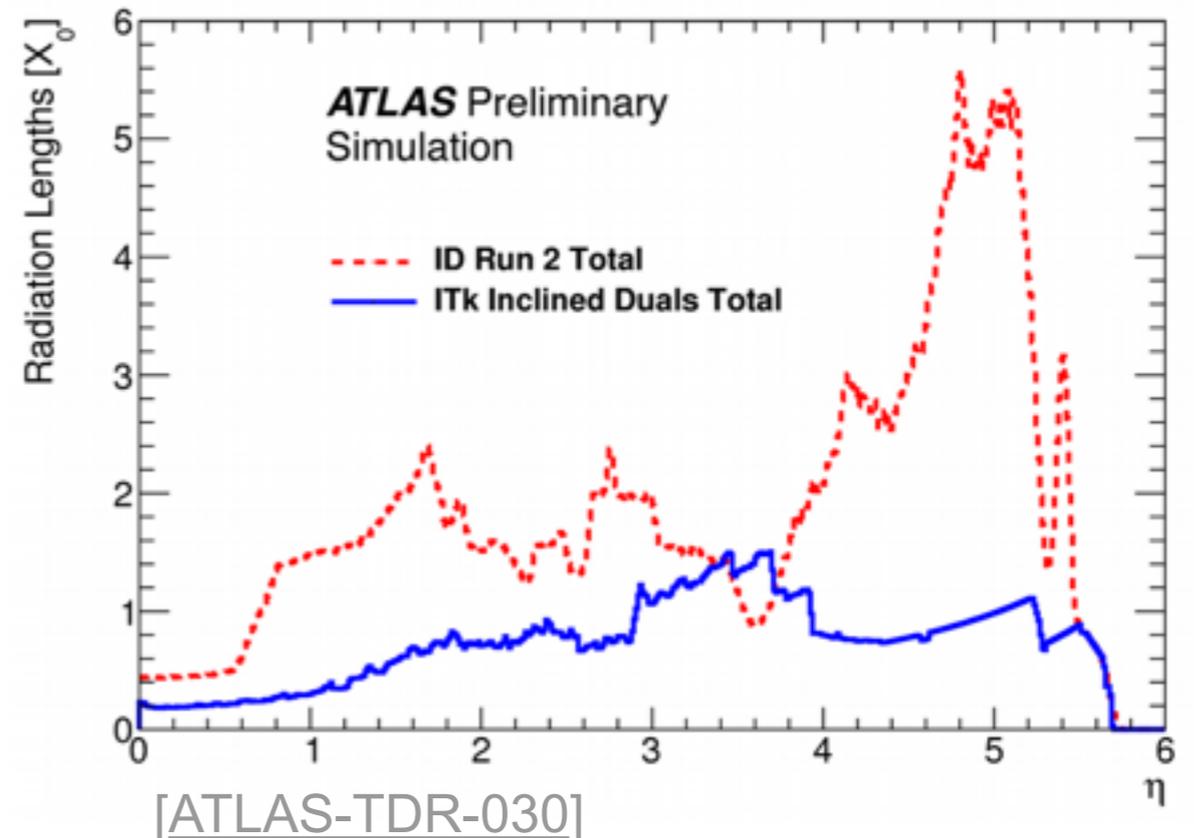


ATLAS Inner Tracker (ITk) Upgrade



- ITk Pixel (13 m²):
 - 5 barrel, 5 EC layers (with rings)
 - inclined design, $|\eta_{\max}| < 4$ (2.5 now)
 - innermost layer at 36 mm
 - ~580 M channels (~92 M now)
- ITk Strips (160 m²):
 - 4 barrel layers, 6 EC rings
 - ~50M channels (6M now)

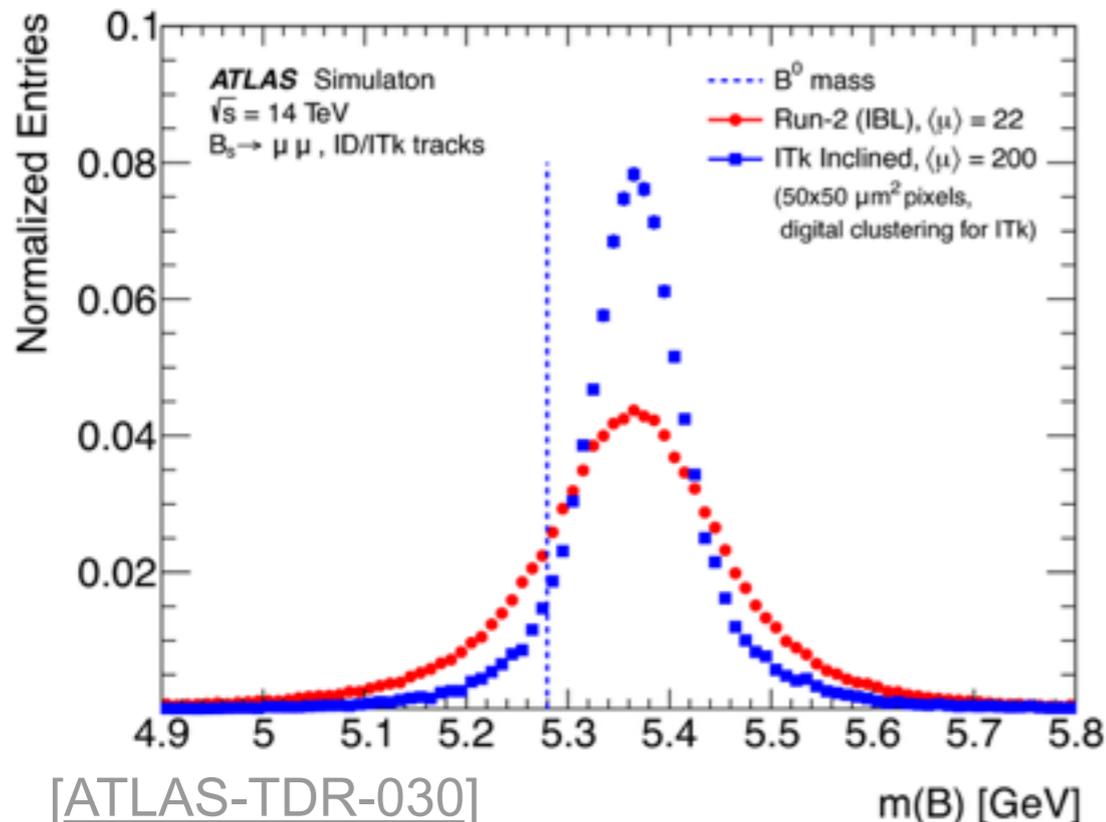
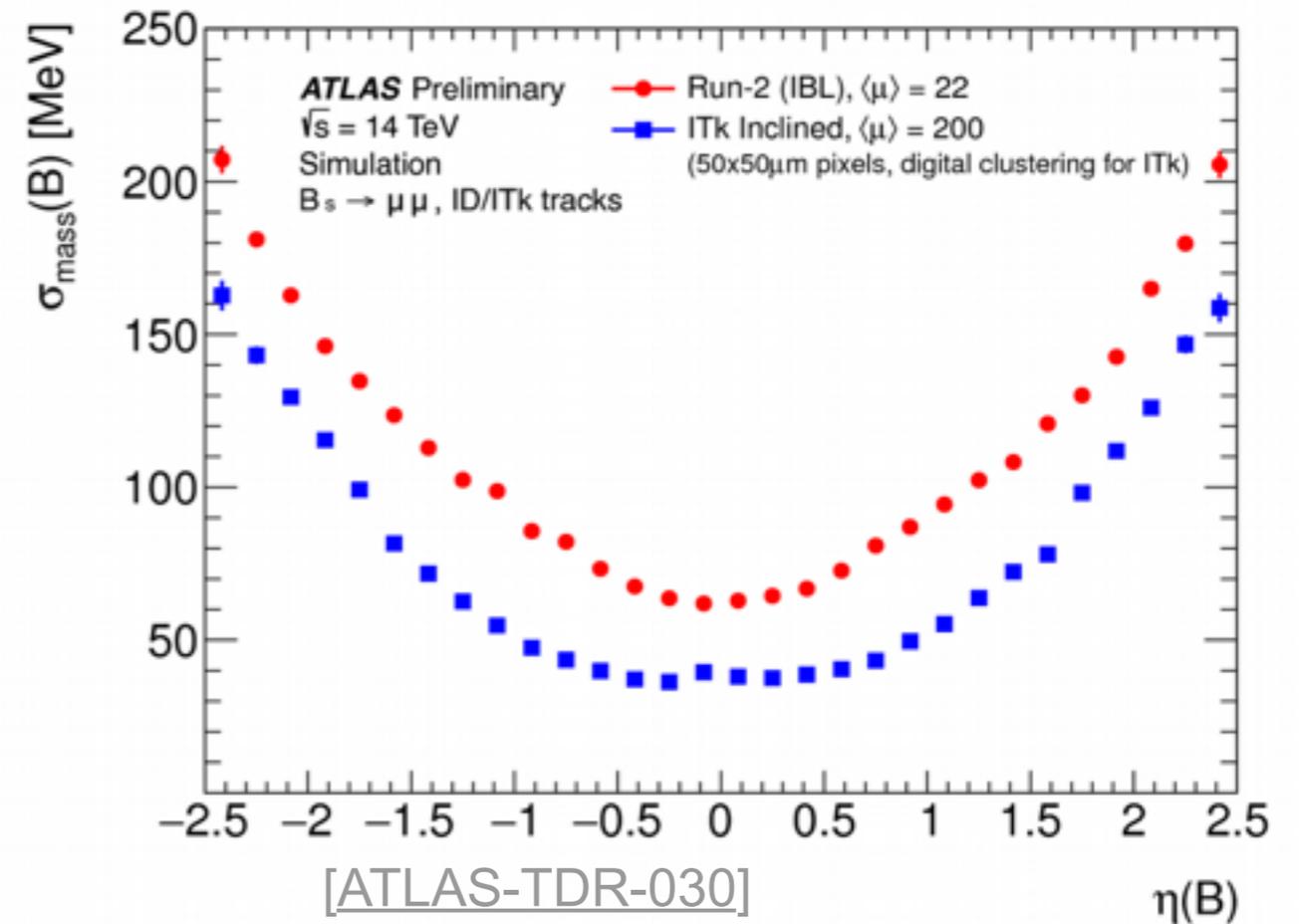
- ITk material considerably less than current ID:
 - better tracking efficiency
 - better mass resolution





Mass Resolution with HL-ATLAS

- dedicated $B^0_s \rightarrow \mu^+\mu^-$ MC:
 - Run 2 (2015) conditions
 - new tracker: ITk, inclined design, $|\eta| < 4$, $50 \times 50 \mu\text{m}^2$ pixels
- candidate selection ~Run 1:
 - B^0_s from $\mu^+\mu^-$ pairs with $p_T(\mu^\pm) > 5.5 \text{ GeV}$
 - two-track vertex fit
 - $m(B^0_s)$ from ITk-only tracks



improvement of $m(B^0_s)$ and $m(B^0)$ separation:

- barrel by x 1.65:
 - 1.4σ (Run 1) \rightarrow 2.3σ
- end-caps by x ~1.5:
 - 0.85σ (Run 1) \rightarrow 1.3σ

[ATL-PHYS-PUB-2016-026]