Search for new physics in rare decays of B-mesons at ATLAS

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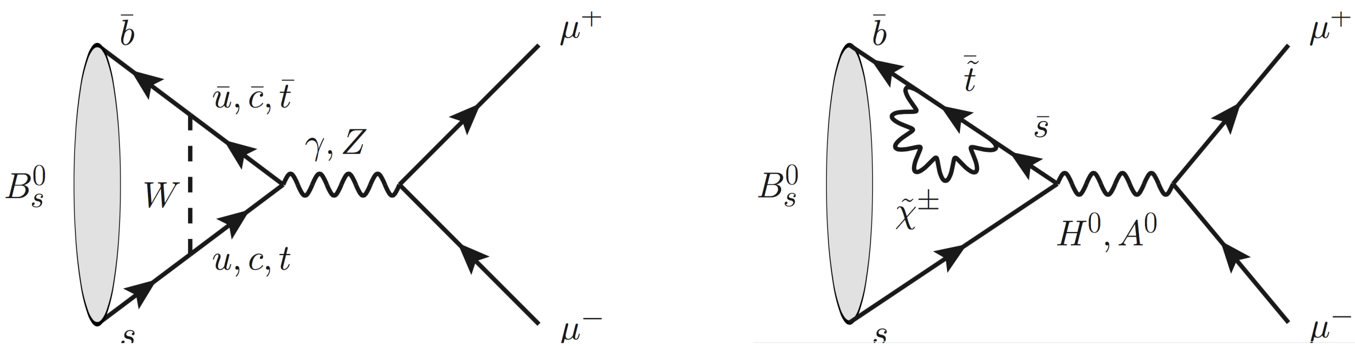
Introduction and motivations

Decays of $B^0_{(s)} \rightarrow \mu^+\mu^-$ must proceed via flavour changing neutral currents:

- Loop and helicity suppressed decay
- Very sensitive to New Phenomena:
  both constructive/destructive interference possible



Purely leptonic final state:
theoretically and experimentally very clean

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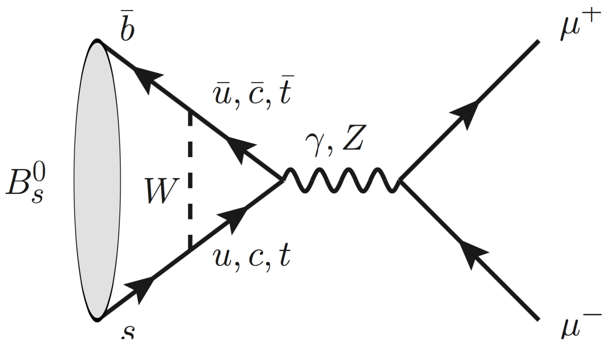

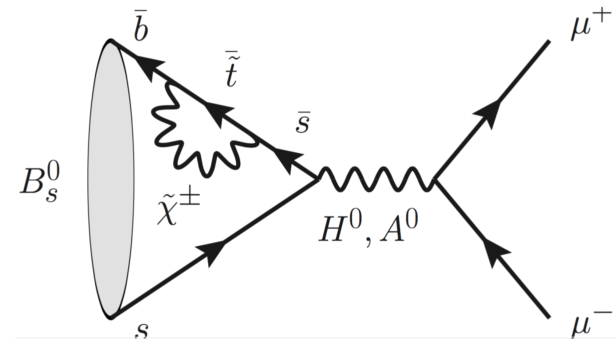

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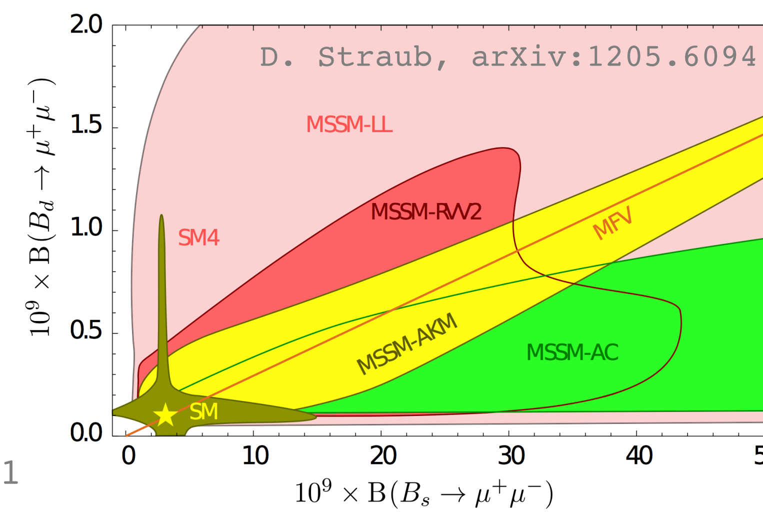
SM predictions:

$Br(B^0_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$Br(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

C. Bobeth et al., PRL 112 (2104) 101801



Introduction and motivations

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- Loop and helicity suppressed decay
- Very se… both …

CMS and LHCb combined result:

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

$Br(B^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$

Nature 522 (2015) 68-72

Today, present results from ATLAS with full Run-1 dataset

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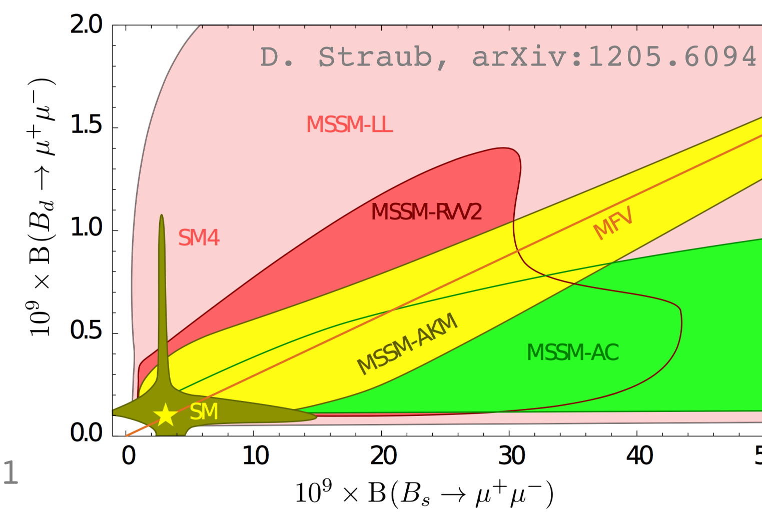

Analysis overview

- Trigger events based on di-muon signature: $p_T(\mu)>4\ (4,\ 6)$ *GeV*

- Select well-reconstructed di-muon candidate events in invariant mass range 4766–5966 MeV.
  *Range [5166–5526] MeV **blinded** until entire analysis chain defined*
  $m(B^0_s)$=5367 MeV, $m(B^0)$=5280 MeV

- Extract signal yield from data using unbinned maximum likelihood fit (UBML)
  Multivariate analysis using two distinct BDTs trained for background suppression
  Data-driven control regions for cross-checks and background modelling

- Normalise signal to $B^{\pm}\rightarrow J/\psi(\rightarrow\mu^{+}\mu^{-})K^{\pm}$ signal
  Reference signal decay provides partial systematics cancellation

Measurement strategy

Measure $B^0_s \to \mu^+\mu^-$ with respect to $B^\pm \to J/\psi(\to\mu^+\mu^-)K^\pm$ reference channel:

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{N_{B_{d(s)}}}{\varepsilon_{\mu^+\mu^-}} \times \frac{\varepsilon_{J/\psi K^\pm}}{N_{J/\psi K^\pm}}$$

Extract yields of signal and reference from UBML fits
Correct each channel for efficiencies

Measurement strategy

Measure $B^0_s \to \mu^+\mu^-$ with respect to $B^\pm \to J/\psi(\to \mu^+\mu^-)K^\pm$ reference channel:

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

Correct for hadronisation probability differences

Use ATLAS measurement = 0.240±0.020 and isospin symmetry

PRL 11 (2015) 262001, arXiv:1507.08925

Measurement strategy

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

Account for reference channel branching fractions

Measurement strategy

Modify previous formula slightly to account for changing trigger conditions:

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{B_{d(s)}} \times \frac{f_u}{f_{d(s)}} \times \frac{1}{\mathcal{D}_{norm}} \times \left[\mathcal{B}(B^\pm \to J/\psi K^\pm) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right]$$

$$\mathcal{D}_{norm} = \sum_k N^k_{J/\psi K^\pm} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^\pm}}\right)_k$$

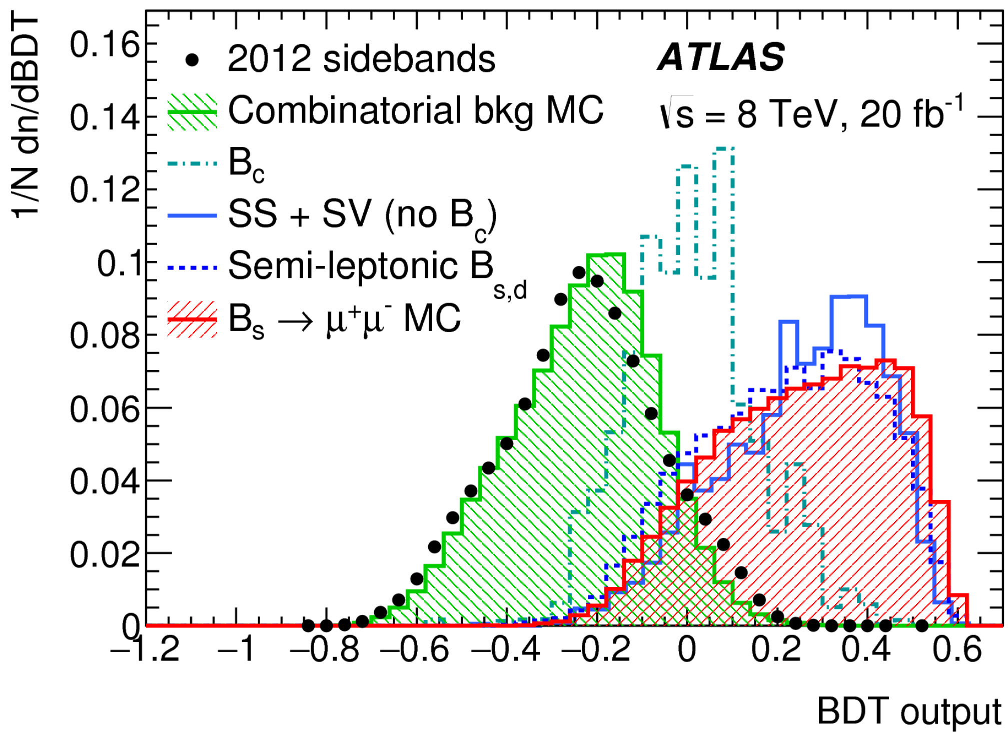
Above term captures changing reference channel yields and efficiency ratios for different trigger streams across 7 and 8 TeV data-taking

Combinatorial background

Signal separated from uncorrelated b(→c)→μ background with MVA classifier

Background x10^3 larger than next largest (semi-leptonic) background

Use 15 variables related to B candidate, muons, tracks in event



Signal efficiency = 54%, for a 5x10^3 background rejection

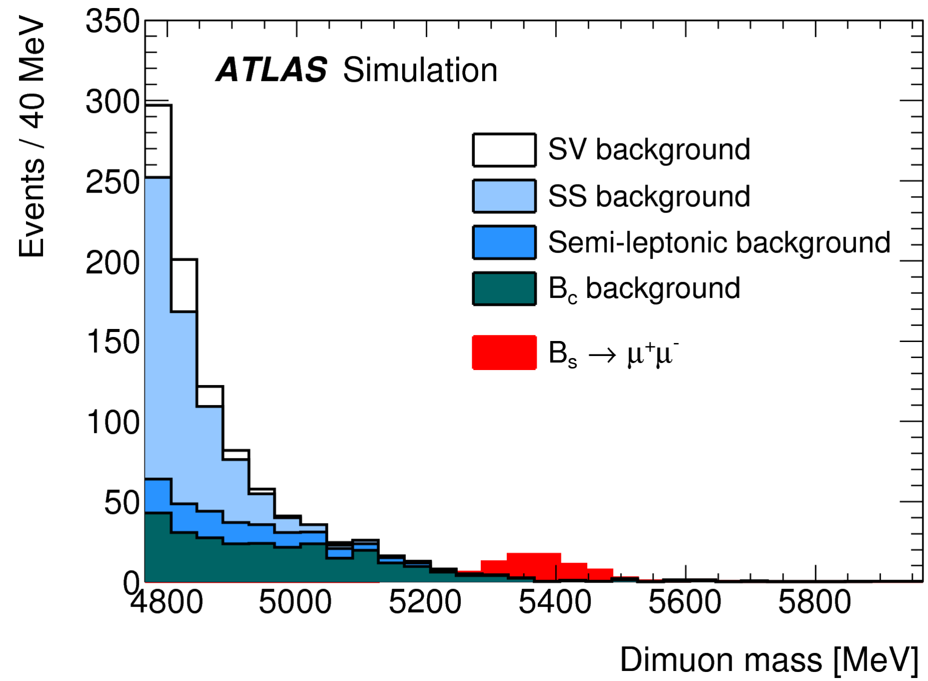
Partially-reconstructed B decays

B-decays with two real muons look like signal but accumulate at low mass:
modelled with Monte Carlo simulations

Same-vertex (SV) backgrounds
$B_d \to K^* \mu^+ \mu^-$, $B_c \to J/\psi(\to \mu^+ \mu^-) \mu^+ \nu$

Same-side (SS) backgrounds
$b \to \mu^- c(\to \mu^+ X')X$

Semi-leptonic
$B \to \mu h \nu$



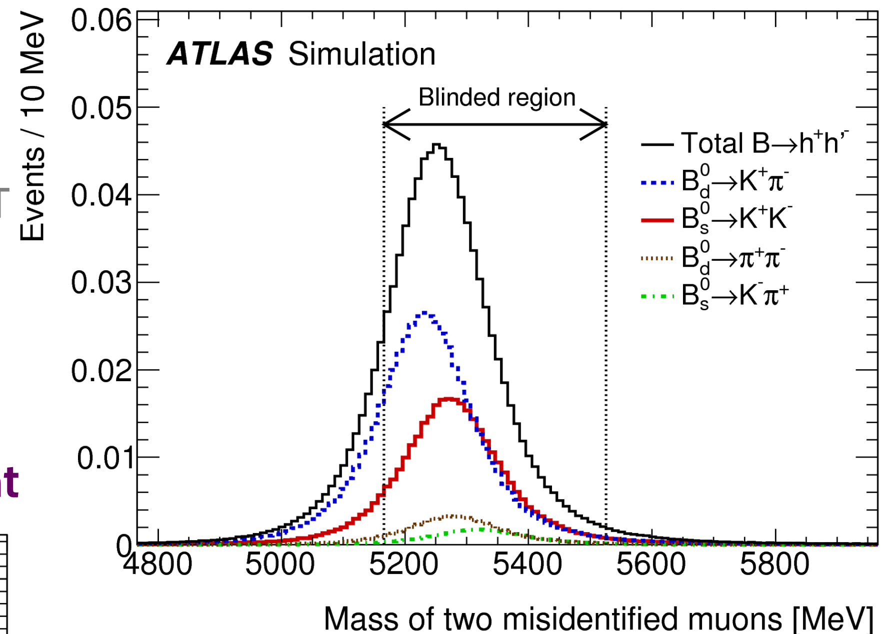
Background from misidentified hadrons

Train dedicated fake BDT classifier against hadron misidentification

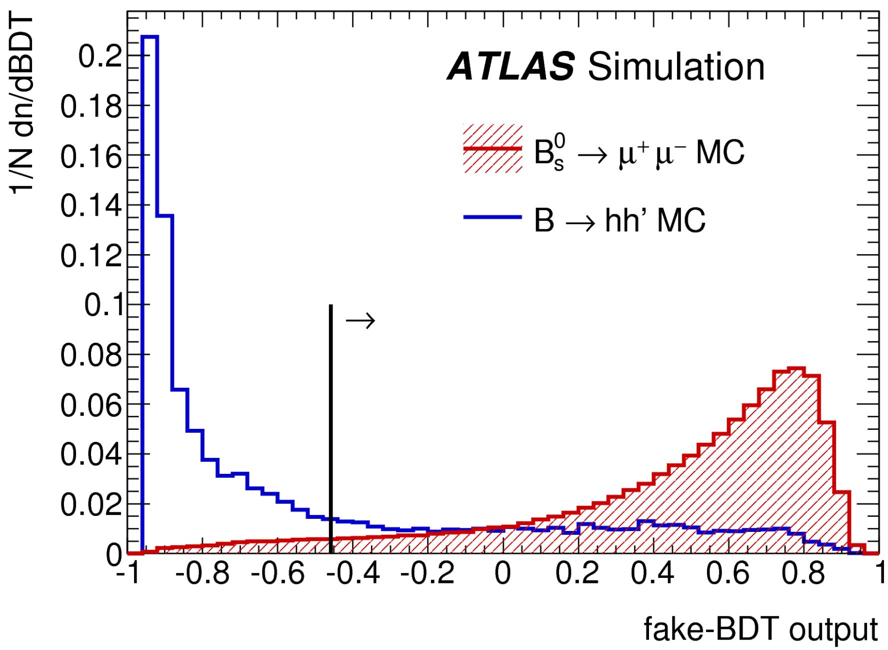
Studied with MC signal $B_s \to \mu^+\mu^-$, $B \to hh'$ and $\Lambda_b \to ph$ backgrounds

Validated with $\phi \to K^+K^-$, $B^\pm \to J/\psi K^\pm$, inverted BDT $B_s \to \mu^+\mu^-$ data

P(misID) = <0.01% (p), 0.4% (K), 0.2% (π)



Background rejection 40% (x7 on 7 TeV) for 95% prompt muon efficiency working point

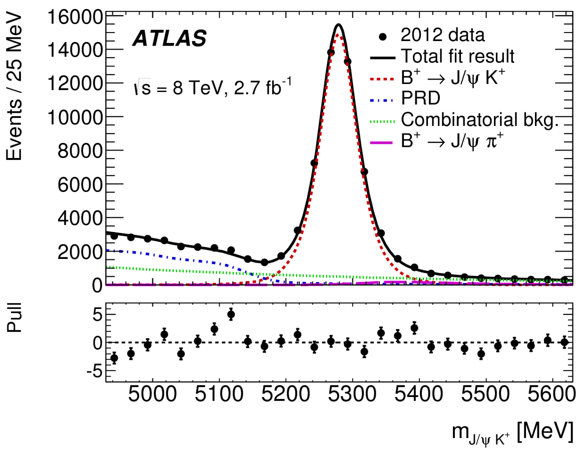


Total number of B→hh' contributing to signal region 1.0±0.4

Reference channel: B± yield extraction

UBML fit applied to J/ψK± and J/ψπ± data simultaneously

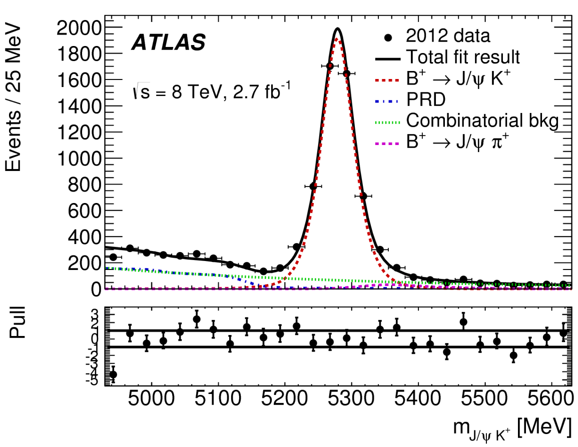
- Four-component fit for PRDs, combinatorial background, K±/π± signal
- Continuum BDT and fake BDT selections applied to B± reference

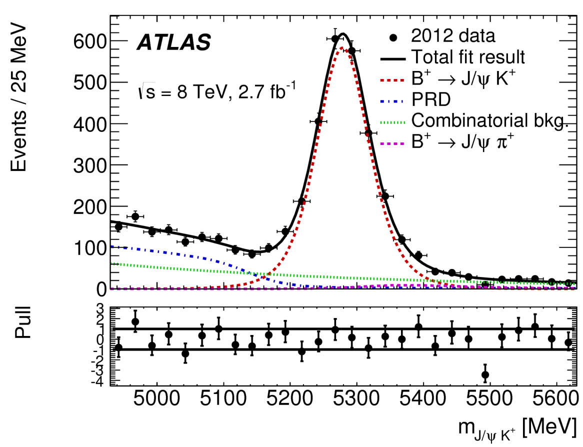


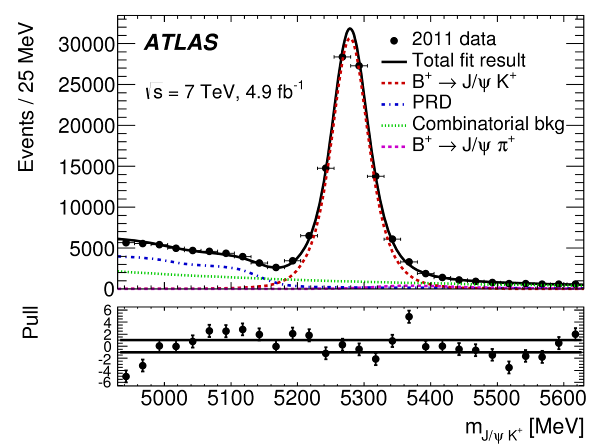
Measure π±/K± relative branching ratio:

$$\rho_{\pi/K} = \frac{\mathcal{B}(B^{\pm} \to J/\psi\pi^{\pm})}{\mathcal{B}(B^{\pm} \to J/\psi K^{\pm})} = 0.035 \pm 0.003^{stat} \pm 0.012^{syst}$$

LHCb: 0.0383±0.0011±0.0007
BaBar: 0.0537±0.0045±0.0011





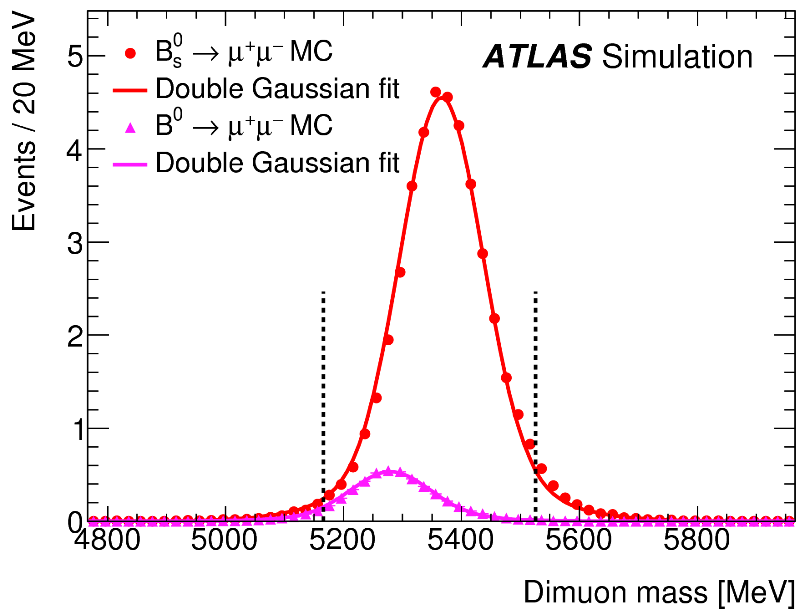


$B_{(s)}$ signal yield extraction

Signal yield extracted from UBML fit to dimuon invariant mass distribution

Extracted simultaneously in three categories in three continuum BDT ranges (each with constant signal efficiency = 18%)

BDT ranges: [0.242–0.351], [0.351-0.454], [0.454-1.0]



Fit results

Expected signal yield:

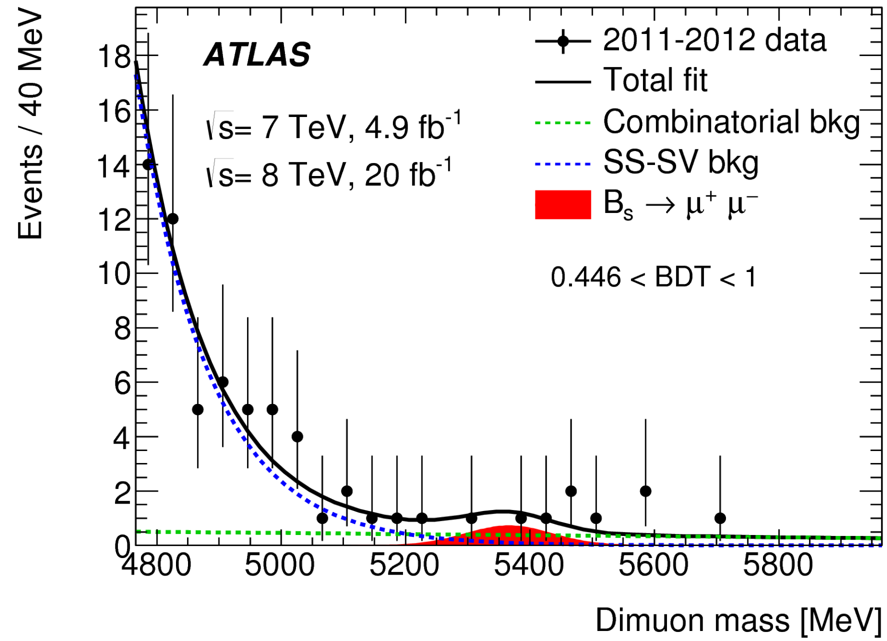
$N(B_s)$ = 41, $N(B)$ = 5

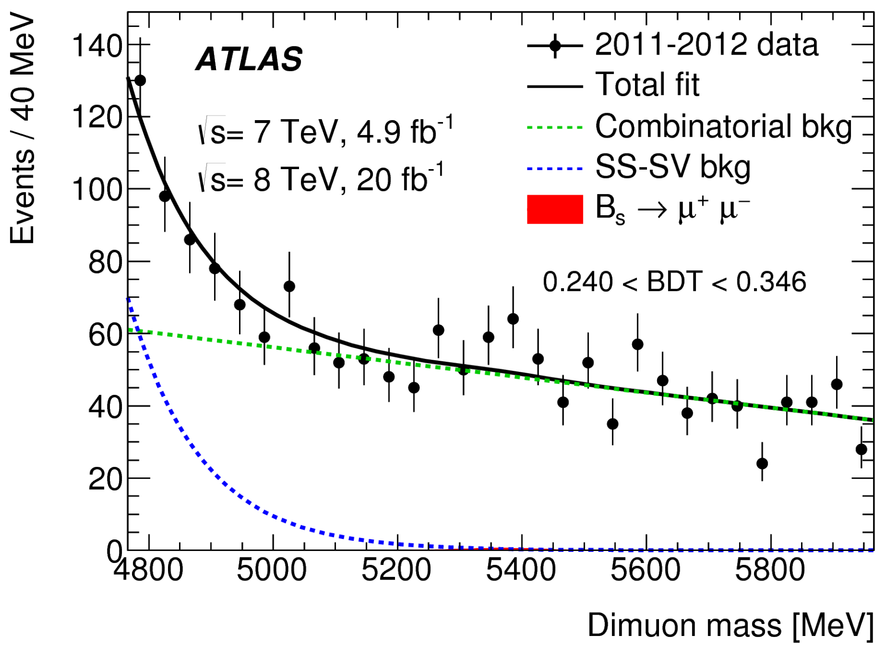
(Exp. significance B_s=3.1σ, B_d=0.2σ)

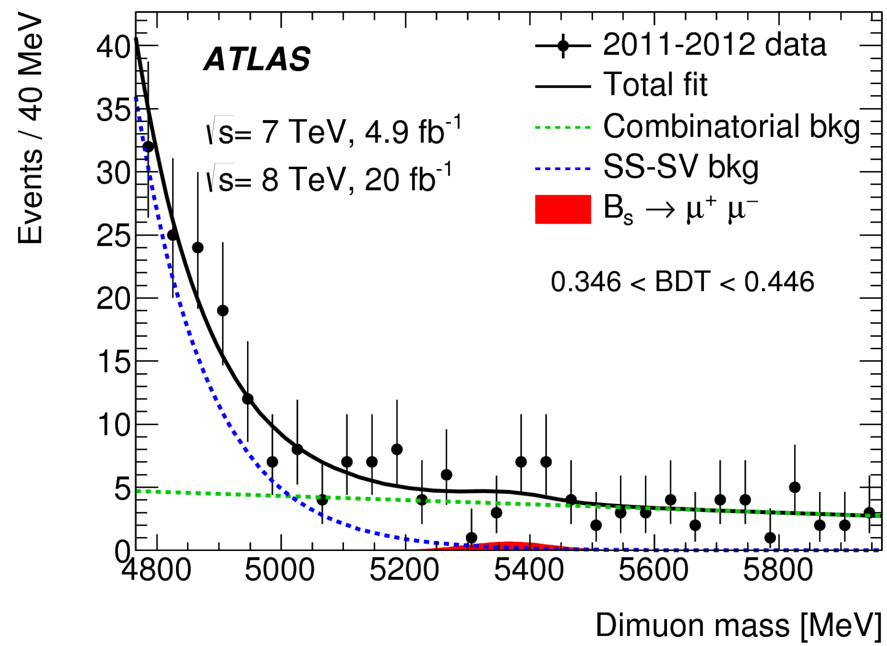
Observed fitted signal yield:

$N_{obs}(B_s)$ = 16±12, $N_{obs}(B)$ = -11±9

$N_{obs}(B_s)$ = 11, $N_{obs}(B)$ = 0 when constraining N≥0







$B^0_s \to \mu^+\mu^-$ branching fraction measurement

Determine branching fraction with non-negative boundary condition

Uncertainties obtained with Neyman construction of frequentist confidence belt including statistical and systematic uncertainties (σ_{syst}=±0.3x10^{-9})

$Br(B^0_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8})\times 10^{-9}$

Upper limits from CL_s approach:

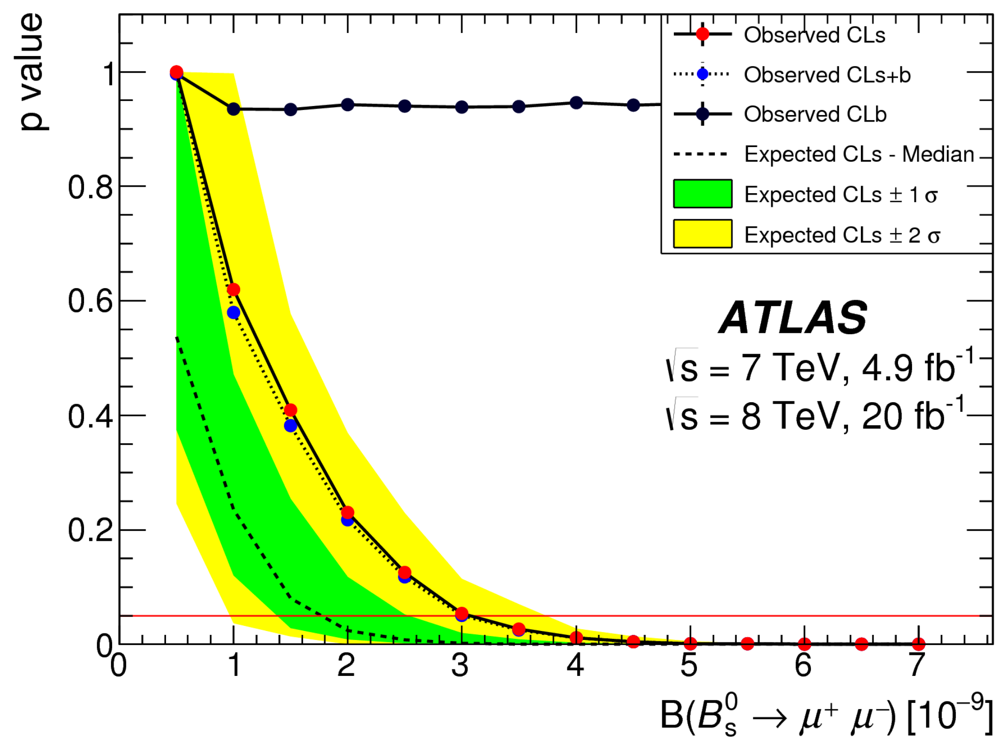
$Br(B^0_s \to \mu^+\mu^-) < 3.0\times 10^{-9}$ at 95% CL

Observed compatibility with null (background-only) hypothesis:

p=0.08 (1.4 σ)

Expectation for SM signal:

p=0.0011 (3.1 σ)



$B^0_d \to \mu^+\mu^-$ branching fraction measurement

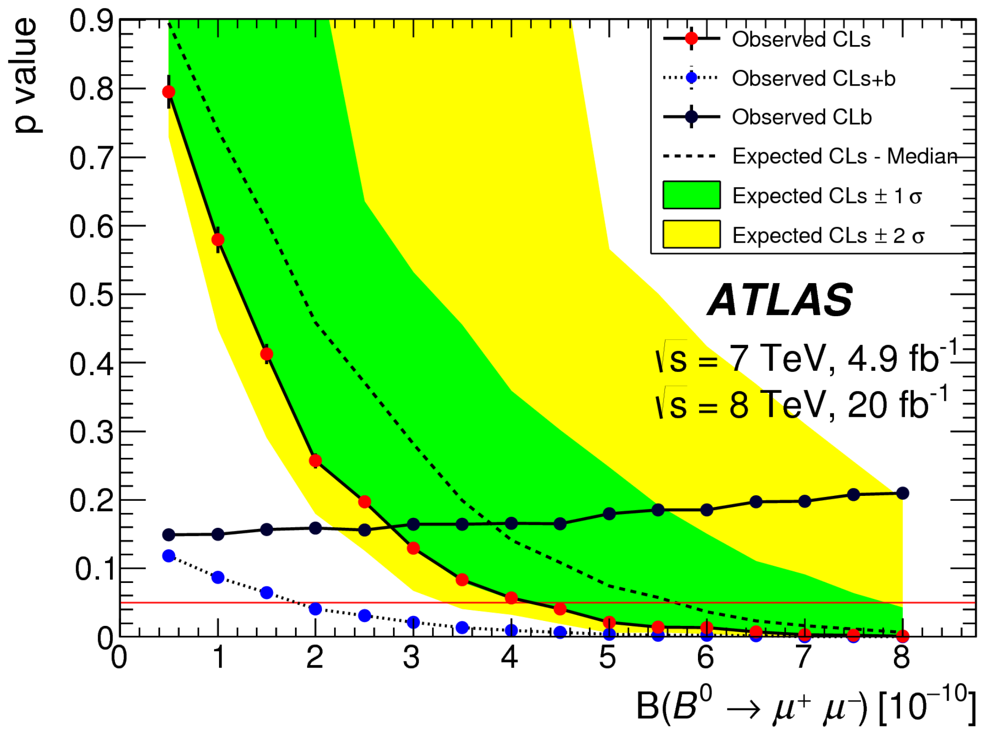
Upper limit on branching fraction for B_d determined using CL_s technique:

$Br(B^0_d \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ at 95% CL

Expected limit $< 5.7^{+2.1}_{-1.2} \times 10^{-10}$

In conjunction with B_s results is compatible with the SM at:

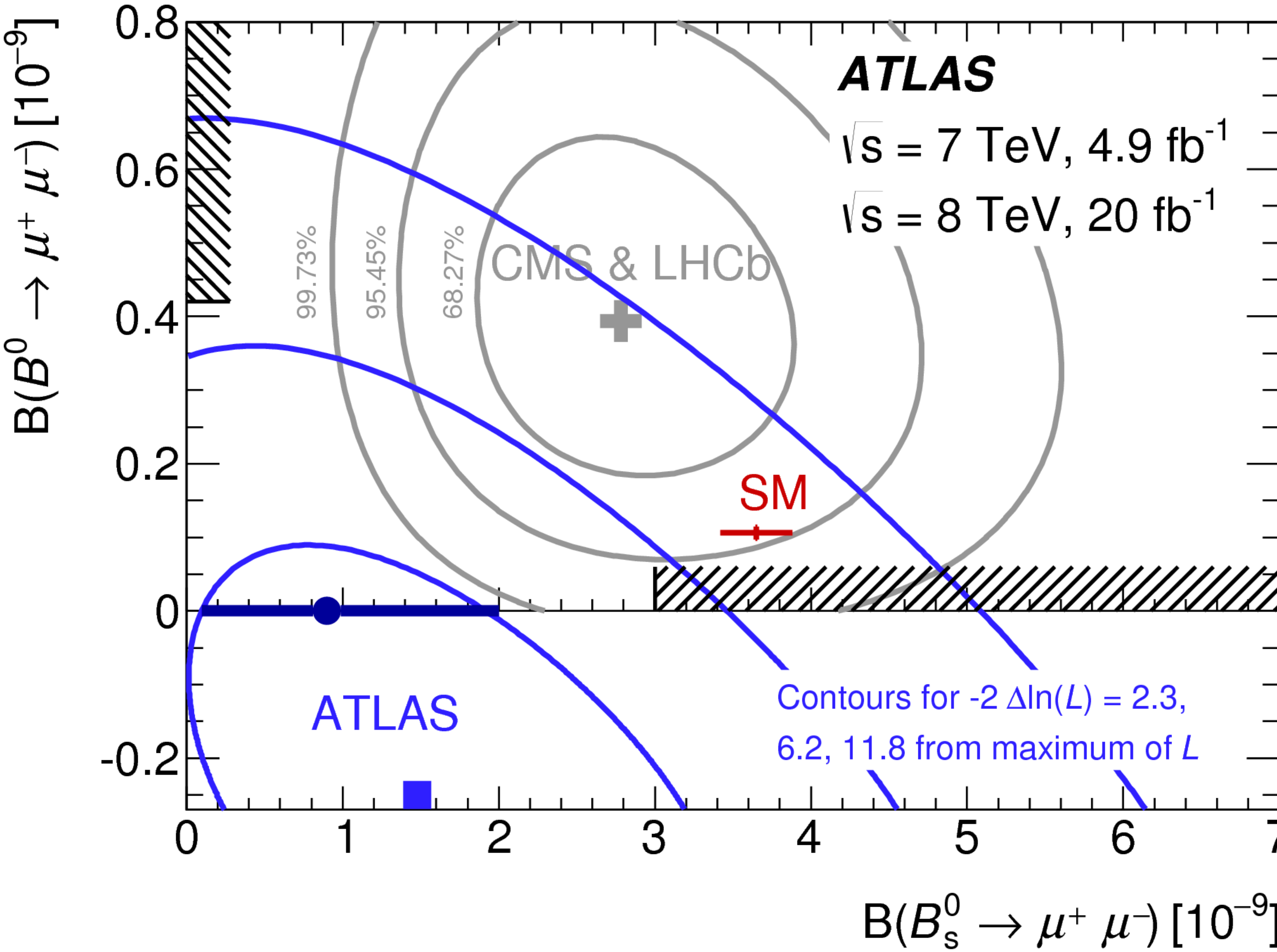
$p = 0.048\ (2.0\sigma)$



Results: $B^0_s \rightarrow \mu^+\mu^-$ vs. $B^0_d \rightarrow \mu^+\mu^-$ contour

CERN-EP-2016-064, arXiv:1604.04263, Submitted to EPJC

Likelihood contours without imposing natural boundaries



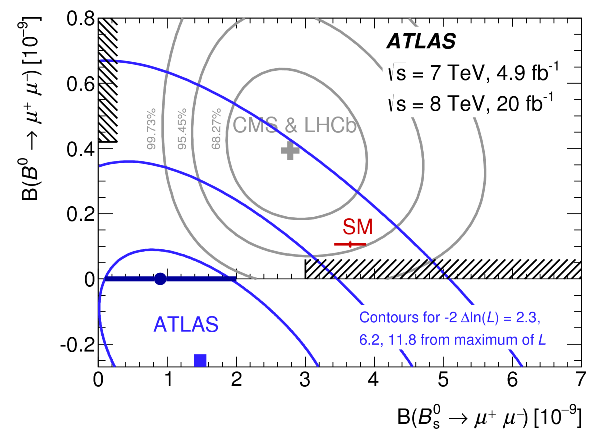
CERN-EP-2016-064, arXiv:1604.04263, Submitted to EPJC

Using the data collected during Run-1 of the LHC, ATLAS has new results on the rare decays B^0_s and B^0 into muon pairs

Uncertainties competitive with CMS and LHCb

Observe the following results:

$$Br(B^0_s \to \mu^+\mu^-) = (0.9^{+1.1}_{-0.8})\times10^{-9}$$
$$< 3.0\times10^{-9} \text{ at } 95\% \text{ CL}$$
$$Br(B^0_d \to \mu^+\mu^-) < 4.2\times10^{-10} \text{ at } 95\% \text{ CL}$$



lower than the SM prediction

$$Br_{SM}(B^0_s \to \mu^+\mu^-) = (3.65\pm0.23)\times10^{-9}$$
$$Br_{SM}(B^0 \to \mu^+\mu^-) = (1.06\pm0.09)\times10^{-10}$$

Compatibility with the SM is 2.0 σ in the simultaneous fit, leaving room for destructive interference from NP to the SM rate.

Analysis of Run-2 data (~100 fb^{-1}) expected to significantly enhance sensitivity.

Backup

Trigger and event selection

- Minimum p_T thresholds on muons driven by trigger:

  7 TeV data: *$p_T(\mu)>4$ GeV, $|\eta(\mu)|<2.5$*

  8 TeV data split into three exclusive categories:

  8 TeV (T1): *One muon $p_T(\mu)>6$ GeV, other $p_T(\mu)>4$ GeV, $|\eta(\mu)|<2.5$*

  8 TeV (T2): *Both $p_T(\mu)>4$ GeV and at least one in $|\eta(\mu)|<1.05$*

  8 TeV (T3): *Both $p_T(\mu)>4$ GeV and $1.05\leq|\eta(\mu)|<2.5$*

- Both selected muons must be *Combined*
  (Inner Detector and Muon Spectrometer muon track reconstruction)

- $B^0_{(s)}\rightarrow\mu^+\mu^-$ signal, and $B^\pm\rightarrow J/\psi(\rightarrow\mu+\mu-)K^\pm$, $B_s\rightarrow J/\psi(\rightarrow\mu+\mu-)\phi(K^+K^-)$ reference:
  - Di-muon vertex fit
  - Association to primary vertex
  - Fiducial region: $p_T(B)>8$ GeV, $|\eta(B)|<2.5$

Background modelling

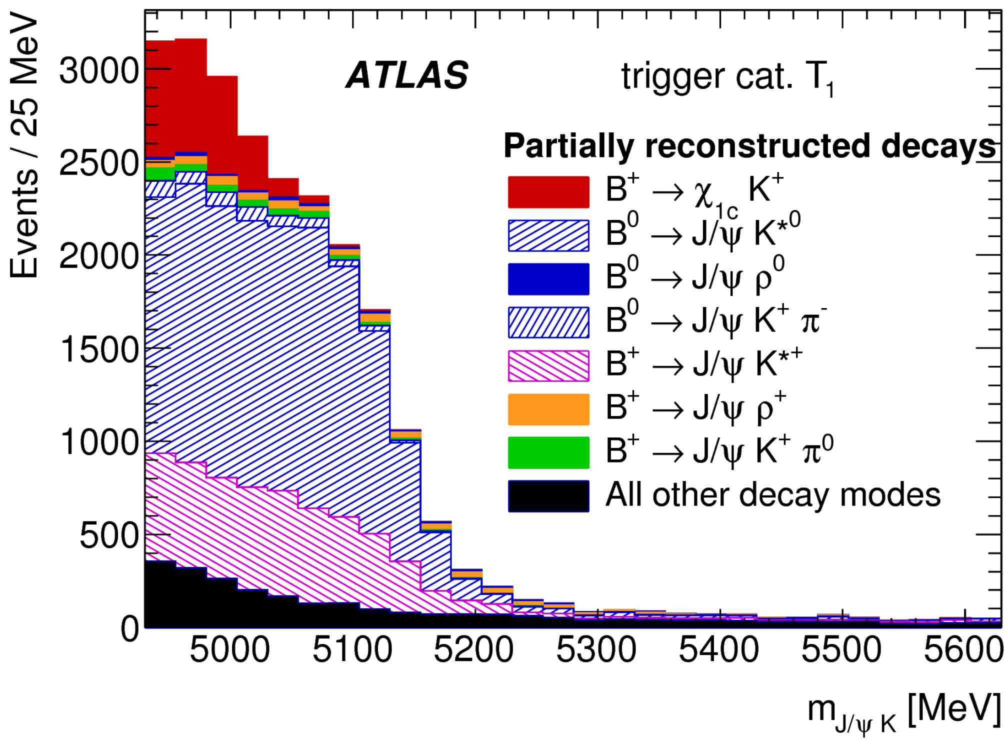
Background contributions to search (in decreasing size):

1. Combinatorial background
   Real muons from uncorrelated b(→c)→μ decays

2. Partially-reconstructed B decays
   Real muons coming from B→μμ+X decays
   Single pion/kaon misidentified as muon (semi-leptonic B and B_s decays)

3. Peaking backgrounds
   B_s/B_d→hh' (h=π/K/p). Small component, but dangerous as overlaid on signal!

Partially-reconstructed decays for $B^{\pm}$ reference channel



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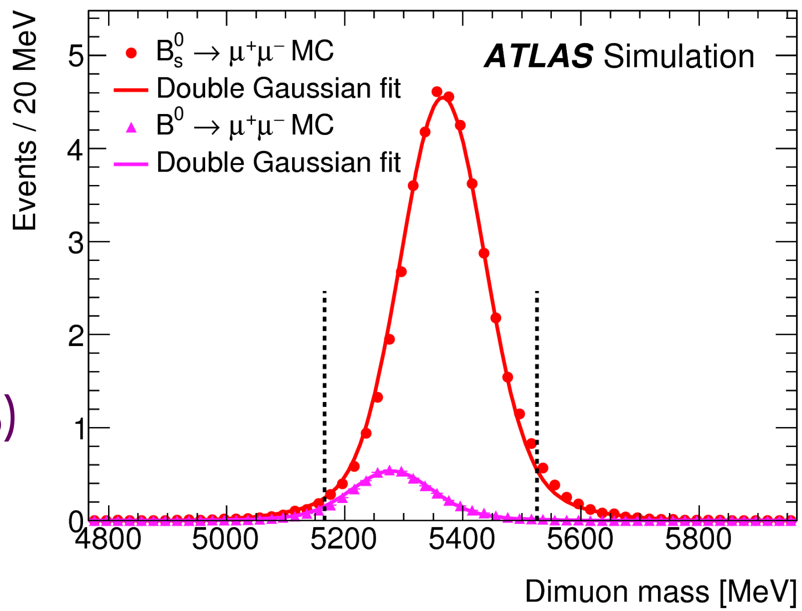


Signal:

Two superimposed Gaussians;

Common mean, avg. with 80 MeV, shape constrained across BDT

Low mass background:

Exponential with mass (SS+SV)

Shape constrained across BDT, normalisation independent

Continuum background:

Linear with mass: small correlation with BDT interval consistent with sidebands/MC

Peaking background:

Gaussian; equal amplitude in each BDT bin, constrained to 1.0±0.4 total

Efficiency correction

Reference-to-signal efficiency correction determined per dataset / trigger category $\left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^\pm}}\right)$

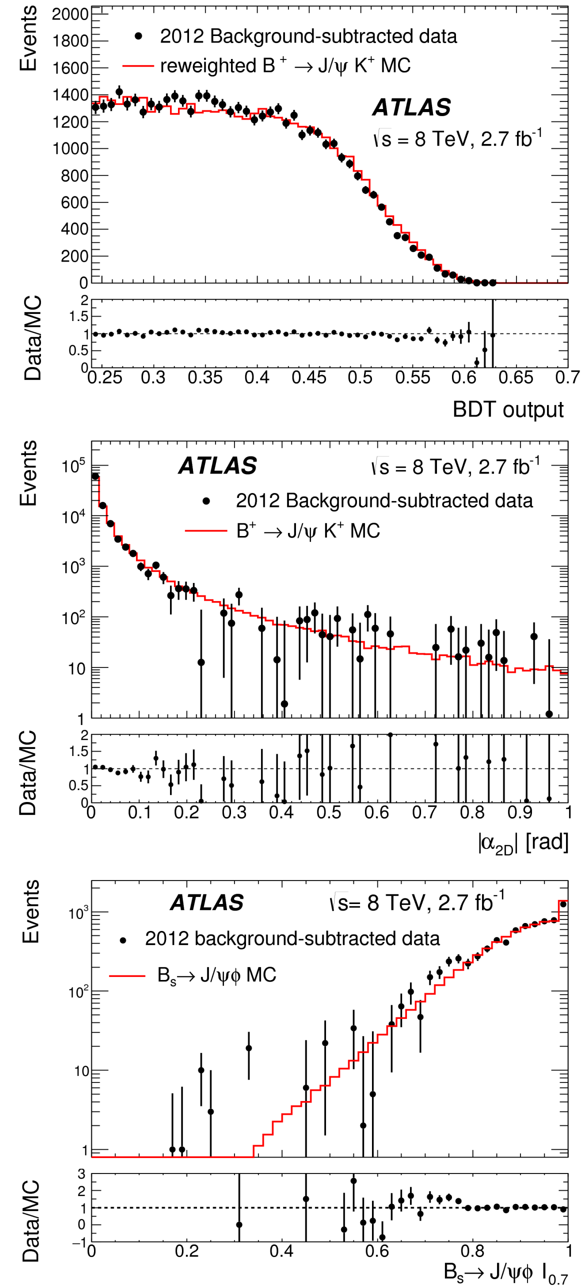
- $p_T - \eta$ spectra tuned on reference channels
- Trigger efficiency from data-driven tag-and-probe

MC-data comparison on discriminating variables in BDT
- only isolation needs tuning for $B^\pm$ mode
- for $B_{(s)}$ additional correction due to lifetime needed

Correction to ratio ~+3–4% for B^0, -0.6% for B^0_s

Total systematic uncertainty from efficiency = 5.9%

(includes effect of reweighting all 15 variables entering cBDT with $B^\pm$ data, trigger efficiency, $p_T - \eta$ reweighting, uncertainties on $B^\pm$ and $K^\pm$ reconstruction)

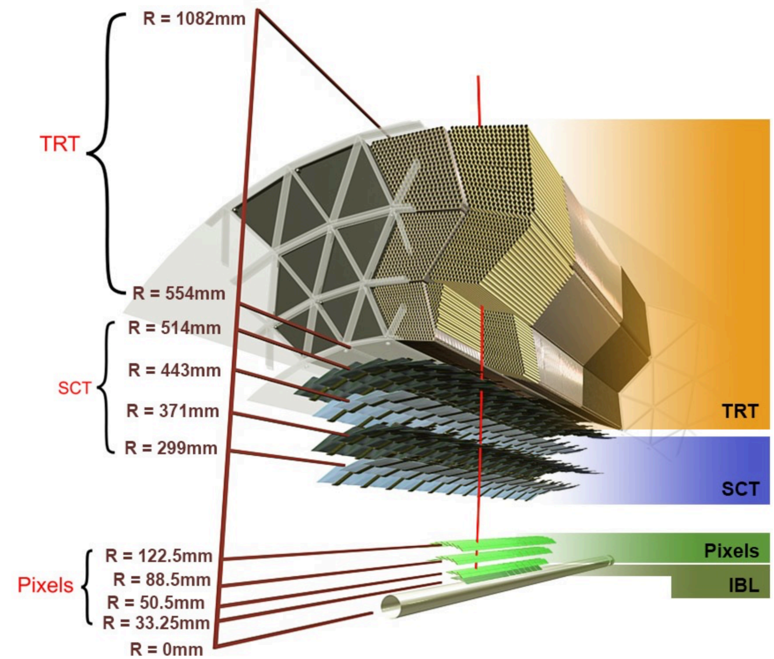


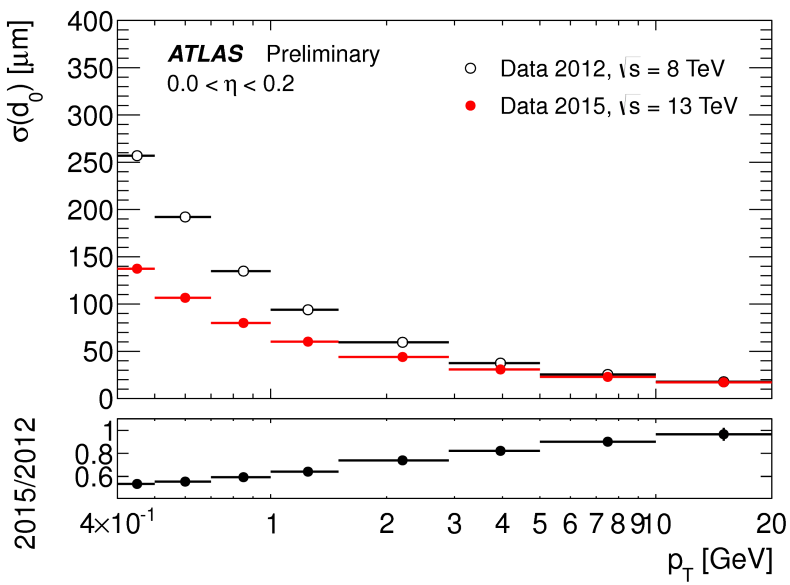
CERN-LHCC-2010-013

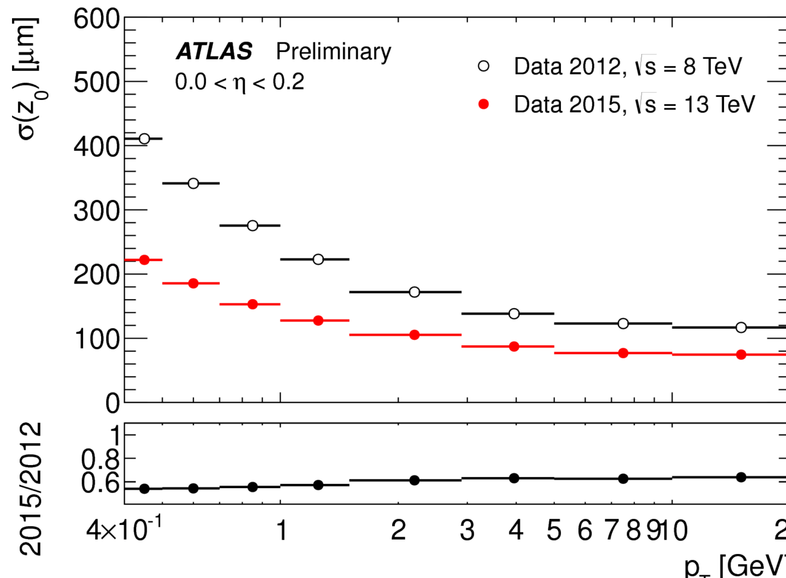
Inner B-Layer (IBL) upgrade for Run-2

Additional pixel layer, small radius: 33.25 mm (current B-layer at 50.5 mm)

Fourth pixel layer provides improved d_0 and z_0 resolution, and θ and ϕ resolution at low p_T (~ 1 GeV)







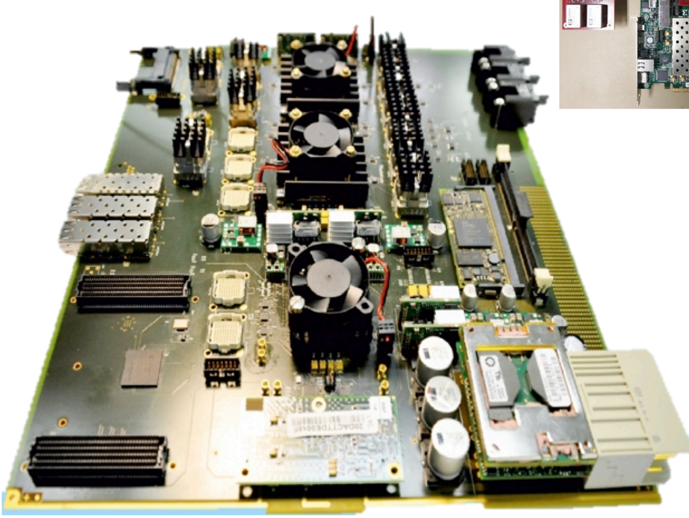
ATLAS L1 topological triggers

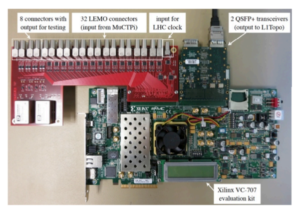
Level-1 'topological' triggers introduced to ATLAS for Run-2

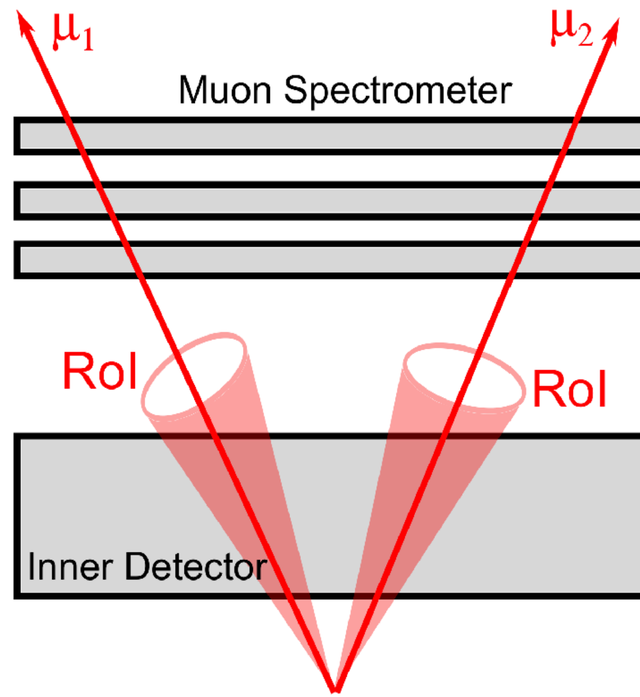
New on-board algorithms allow trigger rate reduction of 2–5 at Level-1

Coarse topological RoI information added to di-muon signatures

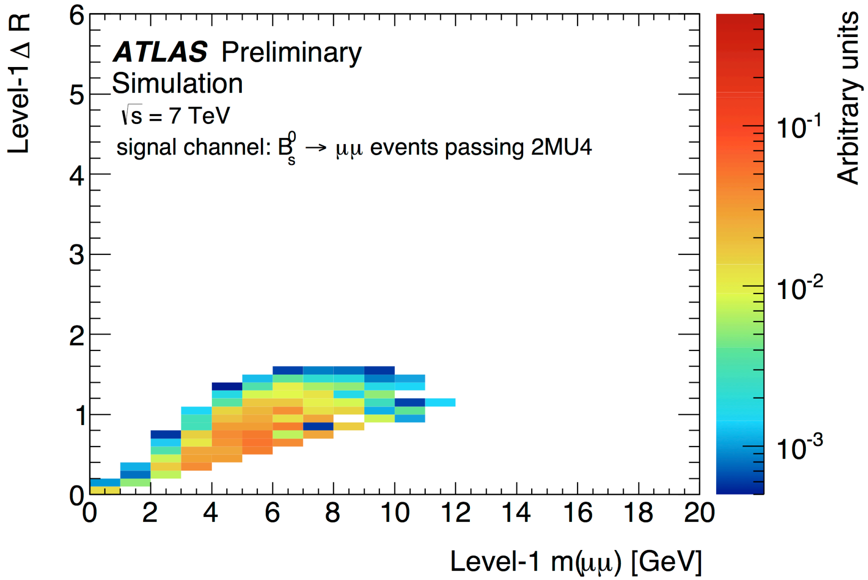
Parameters such as $\Delta\phi$, $\Delta\eta$, ΔR, invariant mass of muon pairs can be selected to optimise signal selection / background rejection

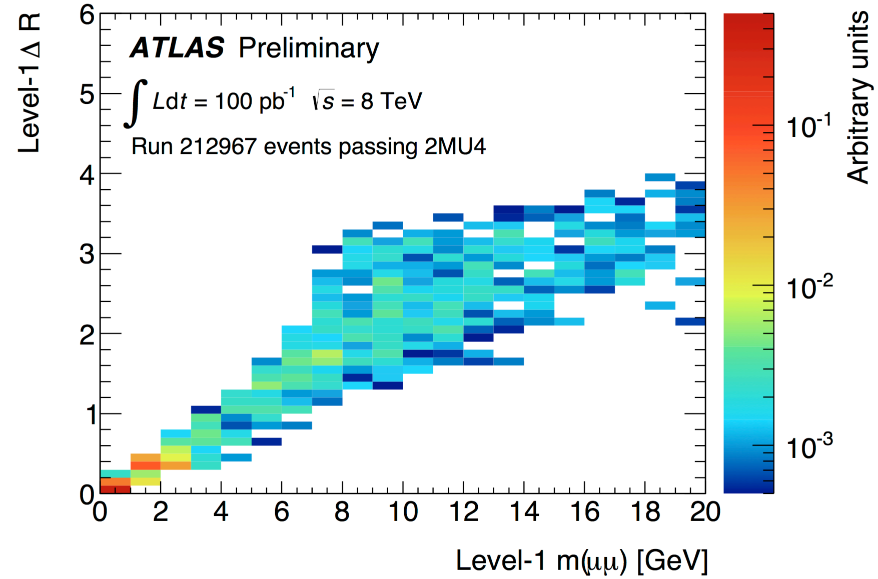






ATLAS B-Physics L1topo menu

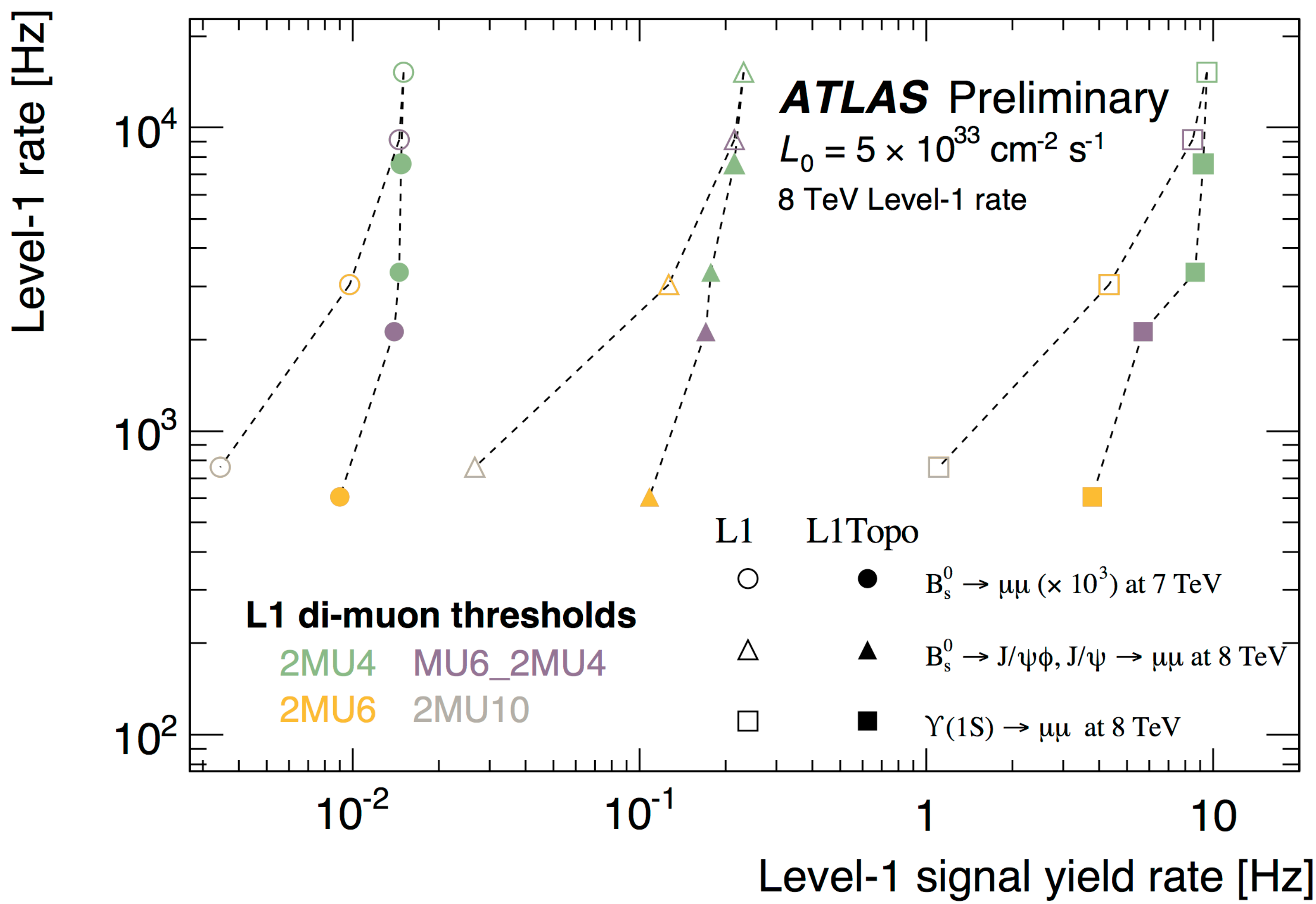




Level-1 muon thresholds	Topo cut		Background rejection	Signal efficiencies		
	$m(\mu\mu)$ [GeV]	ΔR		$B_s^0 \to \mu\mu$	$B_s^0 \to J/\psi\phi, J/\psi \to \mu\mu$	$\Upsilon(1S) \to \mu\mu$
2MU4	–	–	0.00 (baseline)	1.00	1.00	1.00
MU6_2MU4	–	–	0.40	0.97	0.93	0.89
2MU4	1–19	0–3.4	0.50	0.98	0.93	0.97
2MU4	2–8 7–14	0–1.5 0–2.4	0.78	0.97 –	0.77 –	– 0.75
2MU6	–	–	0.80	0.65	0.55	0.46
MU6_2MU4	2–8 8–13	0.0–1.5 0.0–2.2	0.86	0.93 –	0.74 –	– 0.60
2MU10	–	–	0.95	0.23	0.17	0.12
2MU6	2–9 8–13	0.2–1.5 0–2.2	0.96	0.60 –	0.47 –	– 0.40

ATLAS B-Physics L1topo menu

Significant signal gain for fixed L1 trigger rates from L1topo implementation

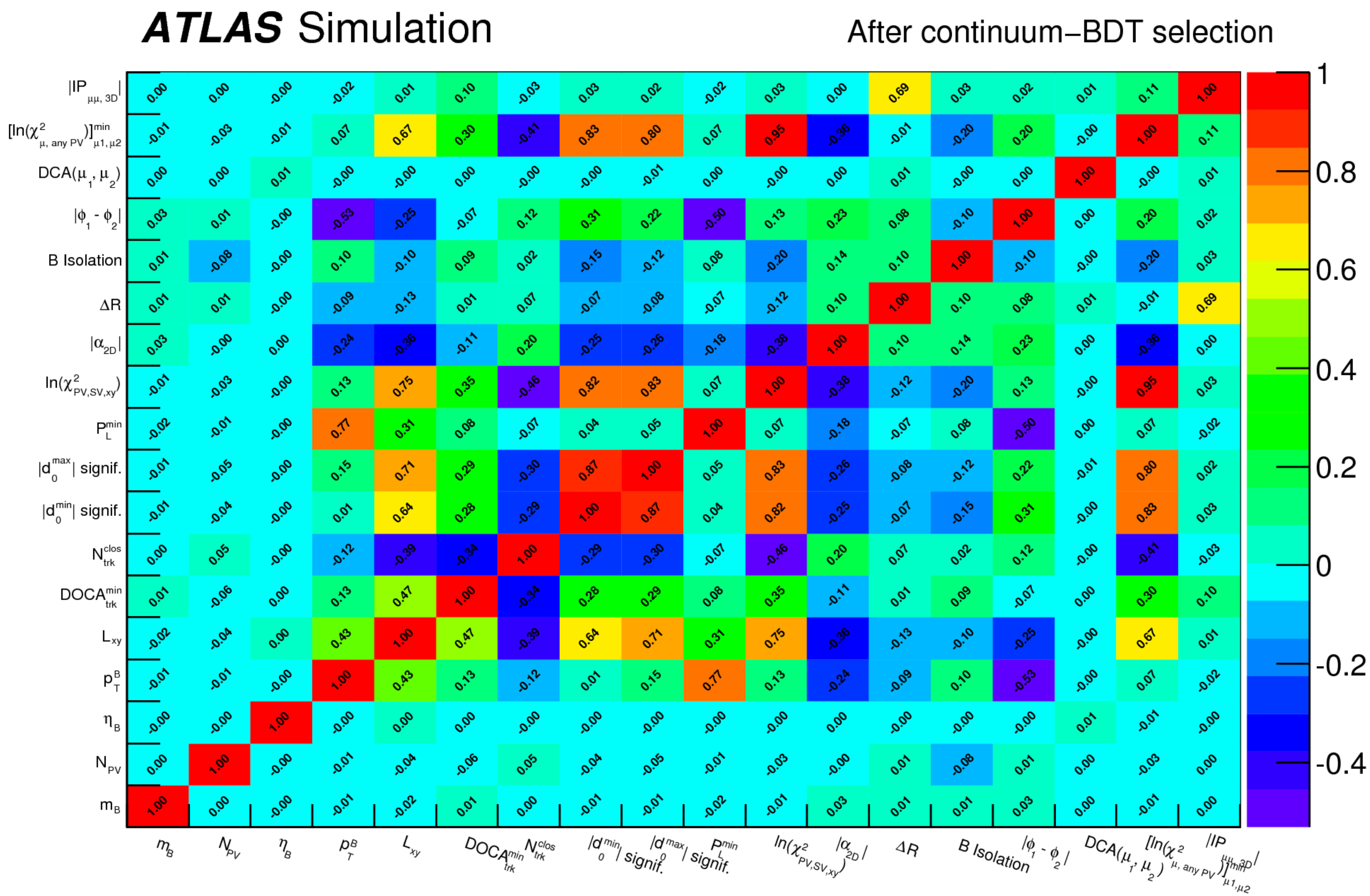


Detailed description of c-BDT variables

Variable	Description
p_{T}^{B}	Magnitude of the B candidate transverse momentum $\overrightarrow{p_{\mathrm{T}}}^{B}$.
$\chi^2_{\mathrm{PV,DV}\ xy}$	Significance 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.
ΔR	three-dimensional opening between $\overrightarrow{p}^{B}$ and $\overrightarrow{\Delta x}$: $\sqrt{\alpha_{\mathrm{2D}}{}^2 + \Delta\eta^2}$
$\lvert\alpha_{\mathrm{2D}}\rvert$	Absolute value of the angle between $\overrightarrow{p_{\mathrm{T}}}^{B}$ and $\overrightarrow{\Delta x}_{\mathrm{T}}$ (transverse projection).
L_{xy}	Projection of $\overrightarrow{\Delta x}_{\mathrm{T}}$ along the direction of $\overrightarrow{p}^{B}_{\mathrm{T}}$: $(\overrightarrow{\Delta x}_{\mathrm{T}} \cdot \overrightarrow{p_{\mathrm{T}}}^{B})/\lvert\overrightarrow{p_{\mathrm{T}}}^{B}\rvert$.
$\mathrm{IP}_{B}^{\mathrm{3D}}$	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).
$\Delta\phi_{\mu\mu}$	Difference in azimuthal angle between the momenta of the two tracks forming the B candidate.
$\lvert d_0\rvert^{\mathrm{max}}$-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.
$\lvert d_0\rvert^{\mathrm{min}}$-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.
$P_{\mathrm{L}}^{\mathrm{min}}$	Value of the smaller projection of the momenta of the muon candidates 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 of the transverse momenta of all additional tracks contained within a cone of size $\Delta R < 0.7$ around the B direction. Only tracks with $p_{\mathrm{T}} > 0.5$ GeV and 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. Tracks matched to a PV different from the B candidate are excluded.
$N^{\mathrm{close}}_{\mathrm{xtrk}}$	Number of additional tracks compatible with the decay vertex (DV) of the B candidate with $\ln(\chi^2_{\mathrm{xtrk,DV}}) < 1$. The tracks matched to a PV different from the B candidate are excluded.
$\chi^2_{\mu,\mathrm{xPV}}$	Minimum χ^2 for the compatibility of a muon in the B candidate with a PV different from the one associated with the B candidate.

BDT correlations

Correlations on discriminating variables entering the continuum BDT



Systematic uncertainties

Systematic uncertainties entering branching fraction extraction

	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	$\mathcal{B}(B^0 \to \mu^+\mu^-)$
Scale uncertainties		
$\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu\mu)$ branching fractions	3.1%	3.1%
$B^0{}_{(s)}/B^+$ production ratio	8.3%	0
B^+ yield and $B^0{}_{(s)}/B^+$ efficiency ratio	5.9%	5.9%
Relative efficiency of continuum-BDT intervals	9%	9%
Signal and background model	6%	0
Total scale uncertainty	16%	11%
Offset uncertainties		
Signal and background model	0.2×10^{-9}	0.7×10^{-10}