Results on the search for the $B_s \to \mu\mu$ decay in the ATLAS experiment using 4.9 fb^{-1}of integrated luminosity

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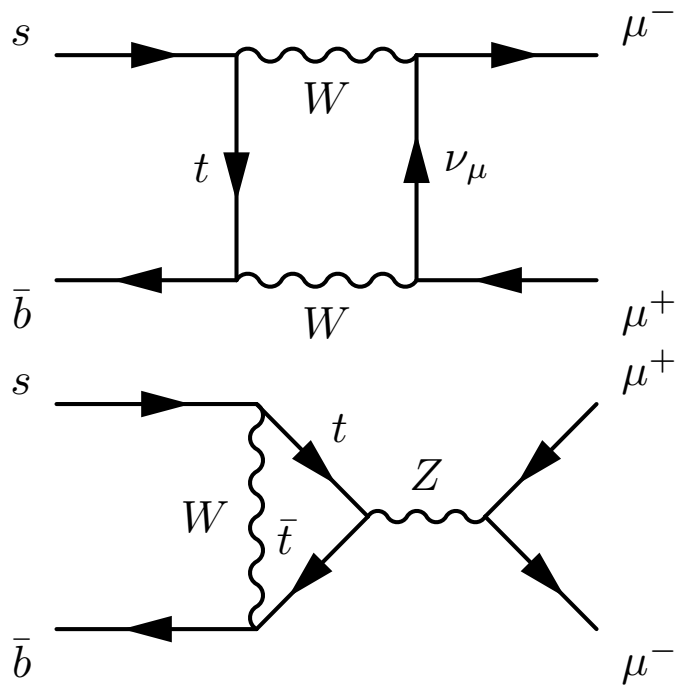
Introduction

- The decay $B_s \to \mu^+\mu^-$ is forbidden at tree level in the Standard Model (FCNC)
- Occurs via "box" and "penguin" diagrams in the SM:
- Standard Model predicts branching ratios
  $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.56 \pm 0.30) \times 10^{-9}$,
  $\mathscr{B}(B_d^0 \to \mu^+\mu^-) = (1.07 \pm 0.10) \times 10^{-10}$
- Might be substantially enhanced by non-SM contributions



- Search was earlier performed by CDF, D0, CMS, LHCb
- CMS and LHCb had an evidence of the decay:
  - LHCb: $\mathscr{B} = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$
  - CMS: $\mathscr{B} = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
- ATLAS previously published an analysis of 2.4 fb^{-1} (half 2011 data): $\mathscr{B}(B_s \to \mu\mu) < 2.2 \times 10^{-8}$ @ 95 % C.L.
- Here, the update on full 2011 data is presented – ATLAS-CONF-2013-076

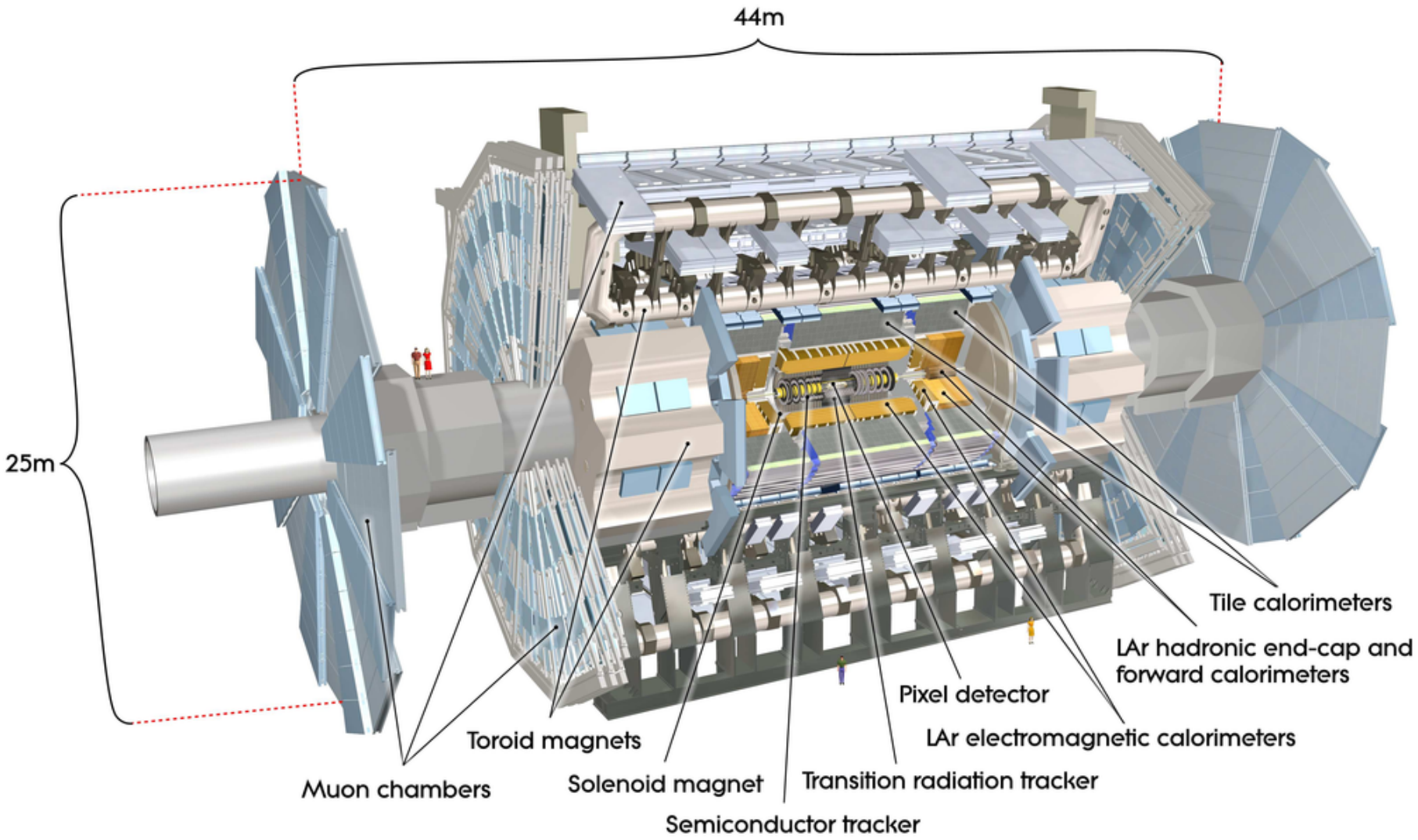
Analysis in a nutshell

- Normalization to the reference channel $B^+ \to J/\psi(\mu^+\mu^-)K^+$

$$\mathscr{B}(B_s \to \mu^+\mu^-) = \mathscr{B}(B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+) \times \frac{f_u}{f_s} \times \frac{N_{\mu^+\mu^-}}{N_{J/\psi K^+}} \times \frac{A_{J/\psi K^+}}{A_{\mu^+\mu^-}} \frac{\epsilon_{J/\psi K^+}}{\epsilon_{\mu^+\mu^-}}$$

- $N_{\mu^+\mu^-}$ is a number of observed signal events, $N_{J/\psi K^+}$ is taken from the reference decay mode fit
- $\frac{A_{J/\psi K^+}}{A_{\mu^+\mu^-}} \frac{\epsilon_{J/\psi K^+}}{\epsilon_{\mu^+\mu^-}}$ obtained from simulation
- 4.9 fb^{-1} of pp data collected in 2011 at 7 TeV are used
- Signal candidate selection based on multivariate technique (BDT) with 13 input variables
- Upper limit on $\mathscr{B}(B_s \to \mu^+\mu^-)$ obtained using CL$_s$ method
- "Blind" analysis: the signal mass region [5066, 5666] MeV is not used until the analysis procedure is finalized and frozen

ATLAS detector



Trigger and data preselection

Trigger

- Dedicated di-muon trigger used to select events online
- Two opposite-side muons with $p_T > 4$ GeV required at LVL1 (hardware) trigger
- They are confirmed at High-Level Trigger and fit to a common vertex
- Same trigger for both signal and reference decay mode

Data events preselection (before BDT training)

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

- $p_T(B_s) > 8$ GeV, $|\eta(B_s)| < 2.5$
- $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.5$
-
- $\chi^2(\mu^+\mu^-) < 2.0$
-

$B^+ \to J/\psi K^+$

- $p_T(B_s) > 8$ GeV, $|\eta(B_s)| < 2.5$
- $p_T(\mu) > 4$ GeV, $|\eta(\mu)| < 2.5$
- $p_T(K) > 2.5$ GeV, $|\eta(K)| < 2.5$
- $\chi^2(\mu^+\mu^- K^+) < 6.0$
- $2.915 < m(\mu^+\mu^-) < 3.175$ GeV

Background composition and multivariate selection

Two main sources of background

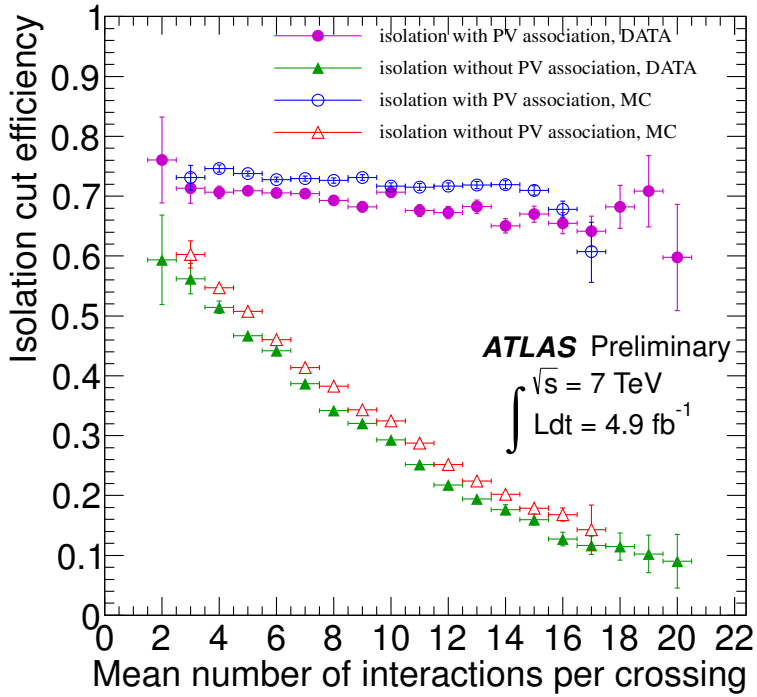
- Combinatorial background (continuum)
  - Smooth mass spectrum
  - BDT classifier is trained to suppress this background
  - $b\bar{b} \to \mu^+\mu^- X$ provides a good description
- Resonant background from $B \to h^+h'^-$ decays, $h = \pi$ or K
  - π and K can be misidentified as muons (at $2.1/4.1/3.3 \times 10^{-3}$ for $\pi/K^+/K^-$ respectively)
  - Peaks in the signal mass region
  - Irreducible background, shown to be small w.r.t. the continuum

Multivariate classifier based on Boosted Decision Trees (BDT) technique is used for signal selection

- Training with $b\bar{b} \to \mu^+\mu^- X$ MC as background and $B_s \to \mu^+\mu^-$ MC as signal
- Optimizing by maximization of $P = \epsilon_{sig}/(1 + \sqrt{N_{bkg}})$
- Half of the data sidebands are used for N_{bkg} in optimization, other half for evaluation of the expected background

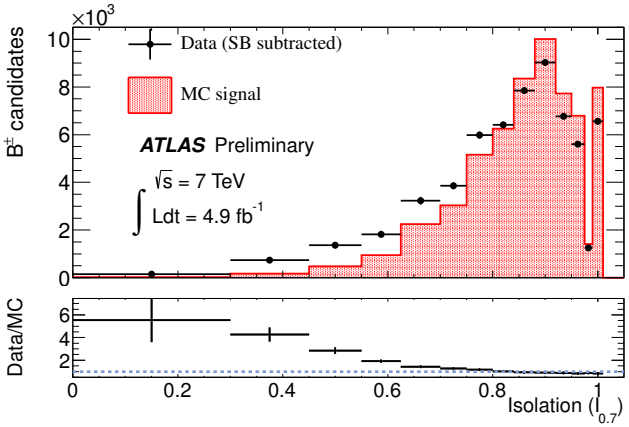
Multivariate selection

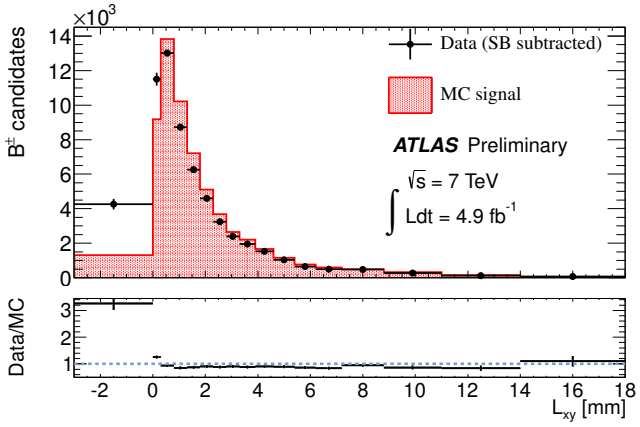
Variable	Description
L_{xy}	Scalar product in the transverse plane of $(\Delta\vec{x} \cdot \vec{p}^B)/\lvert\vec{p}_T^B\rvert$
$I_{0.7}$ isolation	Ratio of $\lvert\vec{p}_T^B\rvert$ to the sum of $\lvert\vec{p}_T^B\rvert$ and the transverse momenta of all tracks with $p_T > 0.5$ GeV within a cone $\Delta R < 0.7$ from the B direction, excluding B decay products
$\lvert\alpha_{2D}\rvert$	Absolute value of the angle in the transverse plane between $\Delta\vec{x}$ and $\vec{p}^B$
p_L^{min}	Minimum momentum of the two muon candidates along the B direction
p_T^B	B transverse momentum
ct significance	Proper decay length $ct = L_{xy} \times m_B/p_T^B$ divided by its uncertainty
χ_z^2, χ_{xy}^2	Significance of the separation between production (PV) and decay vertex (SV) $\Delta\vec{x}^T \cdot \left(\sigma_{\Delta\vec{x}}^2\right)^{-1} \cdot \Delta\vec{x}$, in z and (x, y), respectively
$\lvert D_{xy}\rvert^{min}$, $\lvert D_z\rvert^{min}$	Absolute values of the minimum distance of closest approach in the xy plane or along z of tracks in the event to the B vertex
ΔR	Angle $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ between $\Delta\vec{x}$ and $\vec{p}^B$
$\lvert d_0\rvert^{max}$, $\lvert d_0\rvert^{min}$	Absolute values of the maximum and minimum impact parameter in the transverse plane of the B decay products relative to the primary vertex

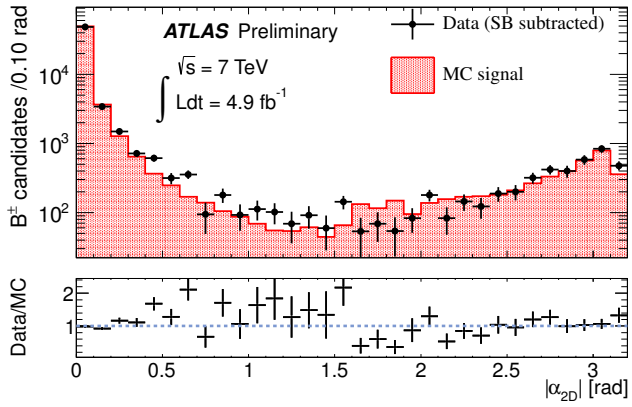


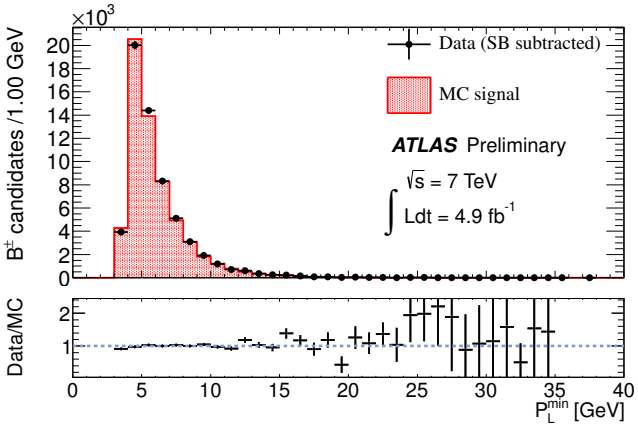
- Isolation variable $I_{0.7}$ is redefined using PV association to eliminate the impact of pile-up
- All MC samples have been reweighted using the B^+ sideband-subtracted data to compensate the data-MC discrepancies
  - Signal and reference decay MC reweighted in terms of p_T and η of B meson
  - Continuum background MC also reweighted similarly using B_s sideband events
  - The residual discrepancies are moderate and accounted for in systematics

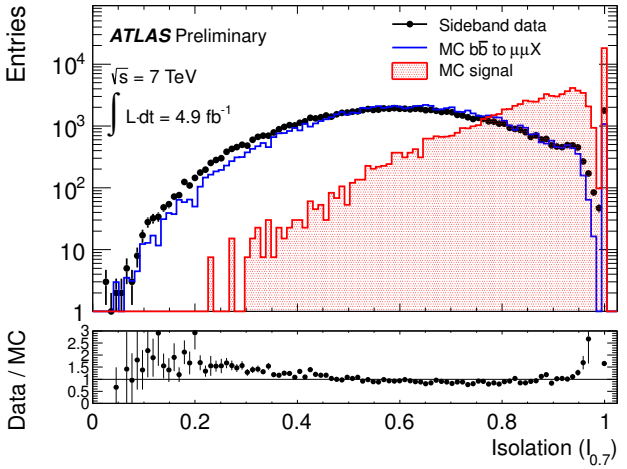
Data – MC comparison

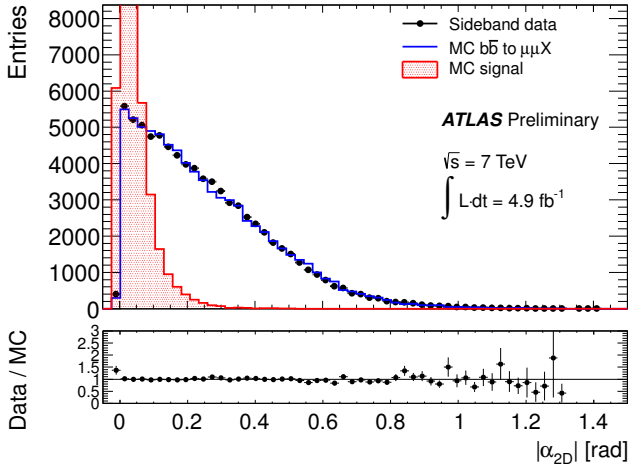






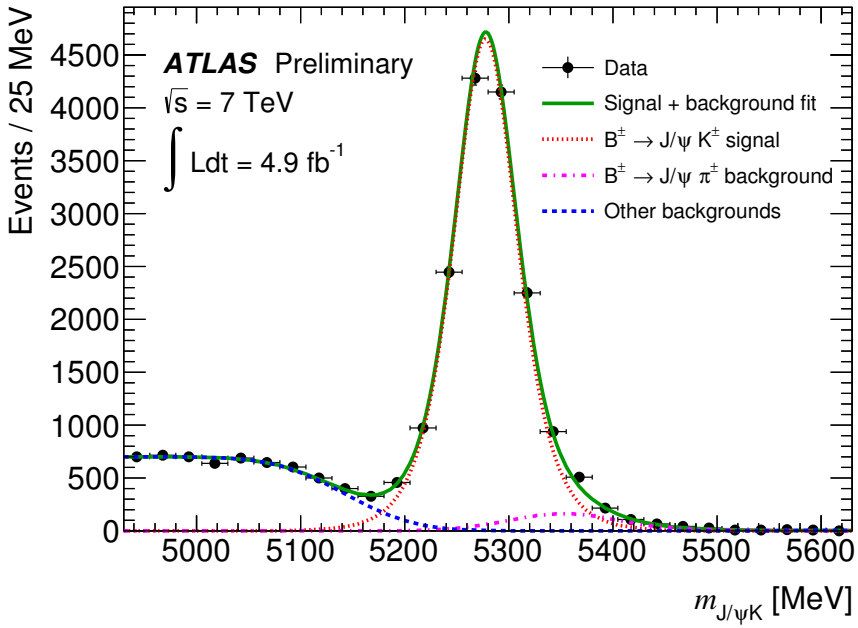


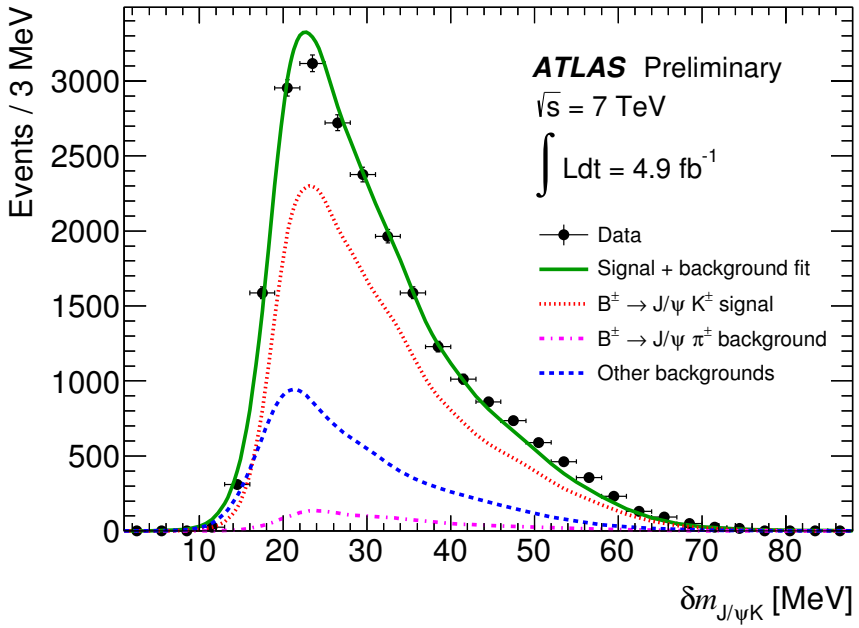




B^+ signal yield extraction

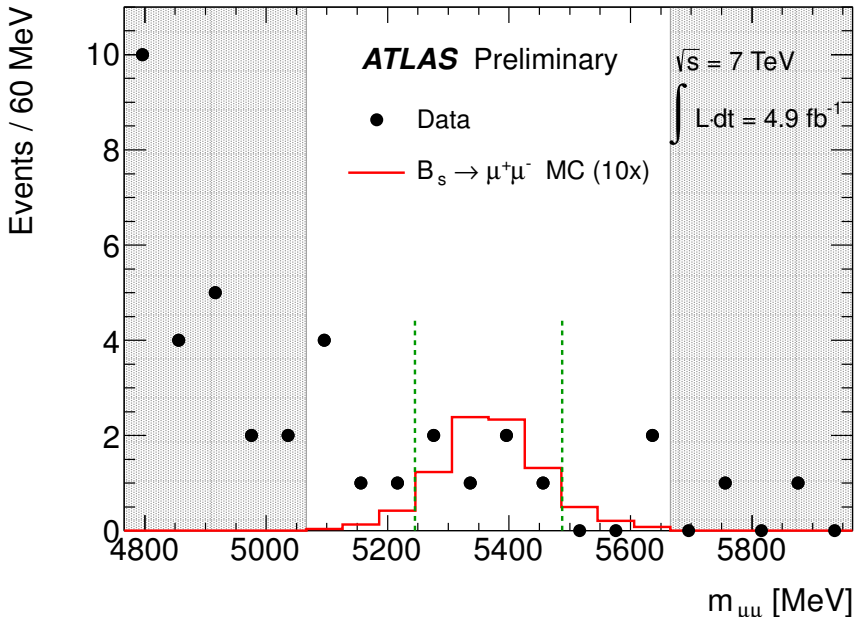
- Same BDT selection is applied to the reference channel
- Two-dimensional extended unbinned ML fit to $m_{\mu^+\mu^-K^+}$ and $\delta m_{\mu^+\mu^-K^+}$ distribution
  - Either single or double gaussian for signal mass
  - Exponential for combinatorial background
  - Complementary error function for partially reconstructed decays
  - Crystal Ball for $B^+ \to J/\psi\pi^+$ contribution
  - $\delta m_{\mu^+\mu^-K^+}$ is described using kernel estimate
- Totally 15214 events with $\pm 1.1\,\%$ stat. and $\pm 2.4\,\%$ syst.



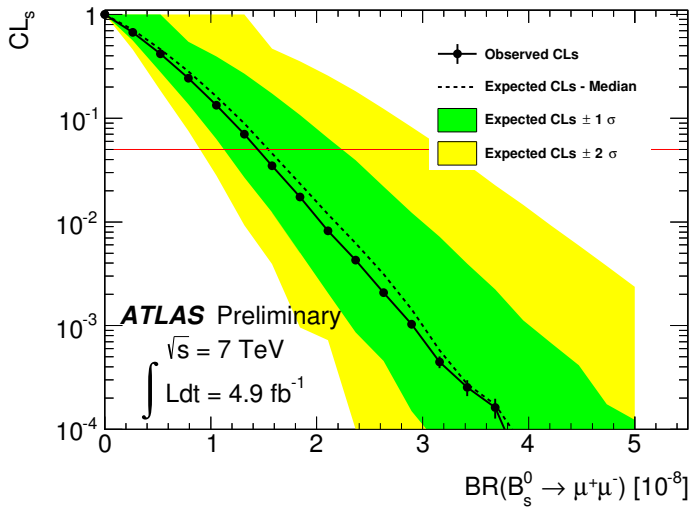


Systematics and results

description	contribution
PDG branching fractions and f_s/f_d	8.5%
$K^{\pm}$ tracking efficiency	5%
vertexing efficiency	2%
$K^{\pm}$ charge asymmetry. in $B^{\pm} \to J/\psi K^{\pm}$	1%
$B^{\pm} \to J/\psi K^{\pm}$ yield	2.4%
$R_{A\epsilon}$	6.9%
total (comb. in quadrature)	12.5%



- The observed upper limit is
  $\mathscr{B}(B_s \to \mu^+\mu^-) < 1.5(1.2) \times 10^{-8}$ @ 95 (90) % C.L.
- The expected limit was
  $\mathscr{B}(B_s \to \mu^+\mu^-) < 1.6^{+0.7}_{-0.4}(1.3^{+0.7}_{-0.4}) \times 10^{-8}$ @ 95 (90) % C.L.



Conclusion

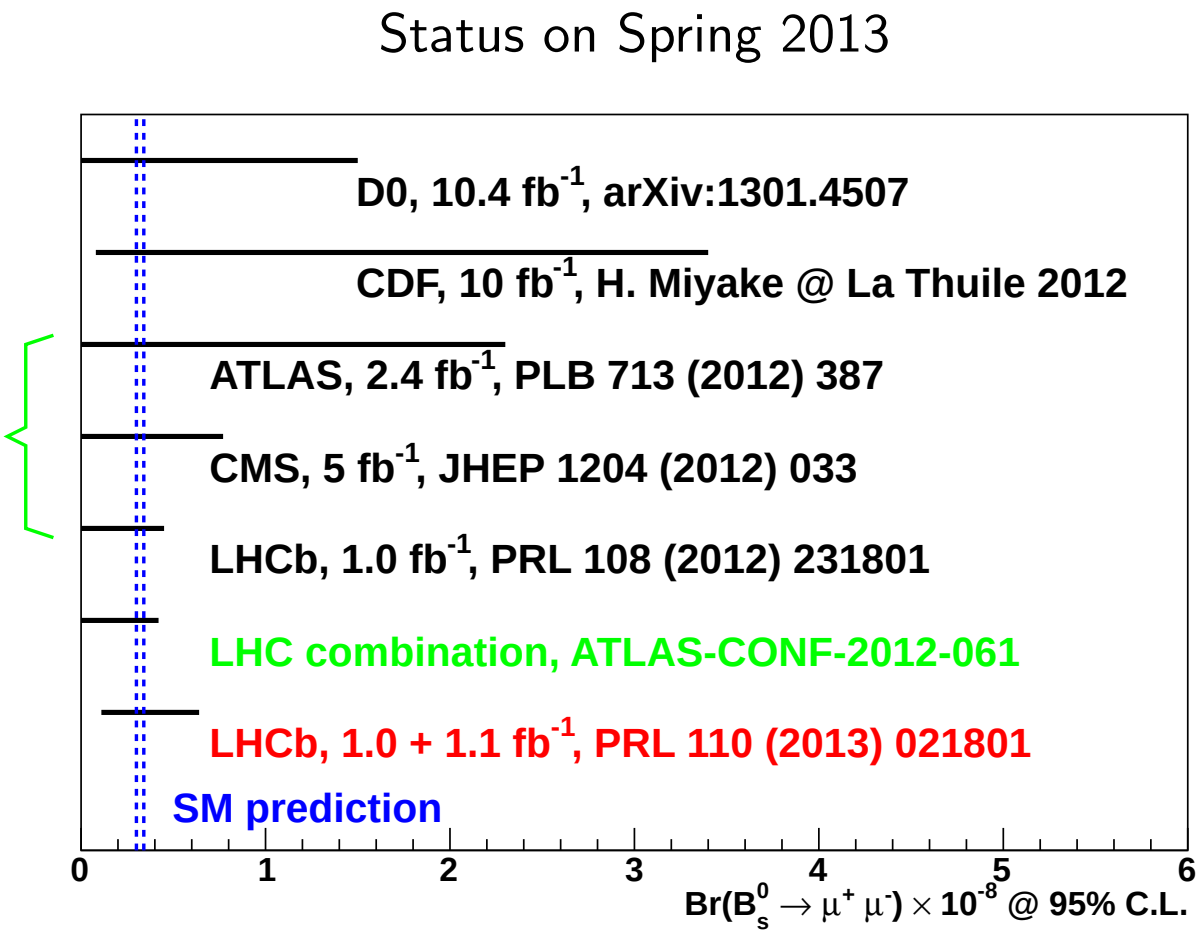
- Using 4.9 fb^{-1} of pp data collected in 2011 ATLAS has set an upper limit on $B_s \to \mu^+\mu^-$ decay branching ratio

$$\mathscr{B}(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8} \text{ @ 95 \% C.L.}$$

- The analysis on 2012 data (20 fb^{-1}) is on-going
- A number of new ideas to be implemented
- We hope to be competitive with CMS and LHCb after processing the full Run I statistics

Backup slides

Other experiments results



Links to the most recent papers with observation:

- CMS – PRL 111 (2013) 101804, arXiv:1307.5025
- LHCb – PRL 111 (2013) 101805, arXiv:1307.5024

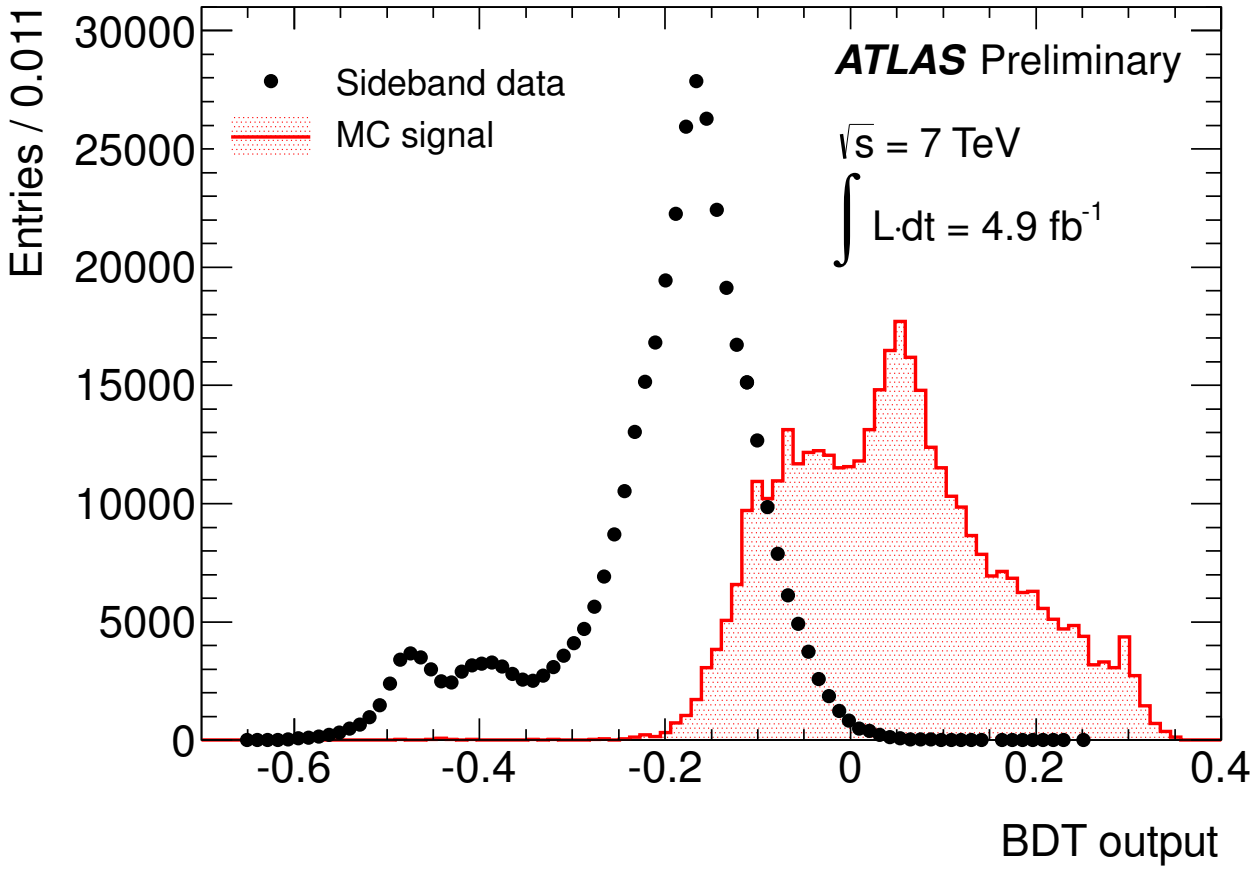
Likelihood and numbers

$$\mathcal{L} = \text{Poisson}(N_{SR}^{obs}|\epsilon\,\mathcal{B} + N_{bkg} + N_{B\to hh})\,\text{Poisson}(N_{bkg,SB}^{obs}|R_{bkg}\,N_{bkg}) \times \text{Gauss}(\epsilon^{obs}|\epsilon, \sigma_\epsilon)\,\text{Gauss}(R_{bkg}^{obs}|R_{bkg}, \sigma_{R_{bkg}})$$

Channel	$A \times \epsilon$	$R_{A\epsilon}$
B^+	$1.317 \pm 0.008\%$ (stat)	$0.267 \pm 1.8\%$ (stat) $\pm 6.9\%$ (syst)
B_s^0	$4.929 \pm 0.084\%$ (stat)	

quantity	value
$N_{J/\psi K^\pm}$	$15\,214 \pm 1.10\% \pm 2.39\%$
$R_{A\epsilon}$	$0.267 \pm 1.8\% \pm 6.9\%$
SES	$(2.07 \pm 0.26) \cdot 10^{-9}$
R_{bkg}^{obs}	1.240 ± 0.050
N_{SR}^{exp} | N_{SR}^{obs}	6.75 | 6
$N_{bkg,SB}^{obs}$	8
$N_{B\to hh}$	0.30

BDT shape



Optimized cuts:

- BDT > 0.118
- $|\Delta m| < 121$ MeV