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Heavy Quarks and Leptons

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$B_{D/s} \rightarrow \mu^+ \mu^-$ in ATLAS

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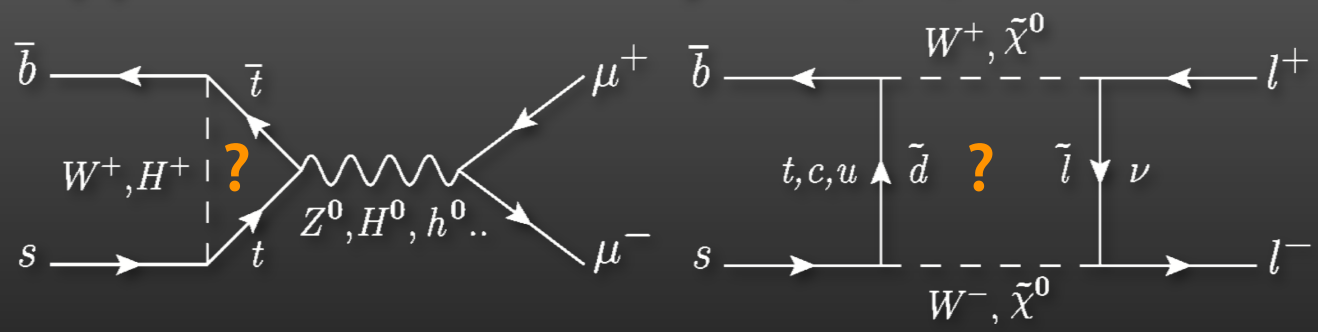
on behalf of the ATLAS Collaboration

Outline

- $B_{d/s} \rightarrow \mu^+\mu^-$ physics motivation
- The ATLAS detector and data taking
- $B_{d/s} \rightarrow \mu^+\mu^-$ analysis overview
- Backgrounds
- $B^\pm \rightarrow J/\Psi\, K^\pm$ yield extraction
  - $(J/\Psi\, \pi^\pm)$ / $(J/\Psi\, K^\pm)$ ratio measurement
- Signal $B_{d/s} \rightarrow \mu^+\mu^-$ yield extraction
- Results of BR($B_{d/s} \rightarrow \mu^+\mu^-$) measurement

Motivation

- accurate SM prediction - helicity suppressed FCNC
- observation of decay rate enhancement / suppression → New Physics (NP)



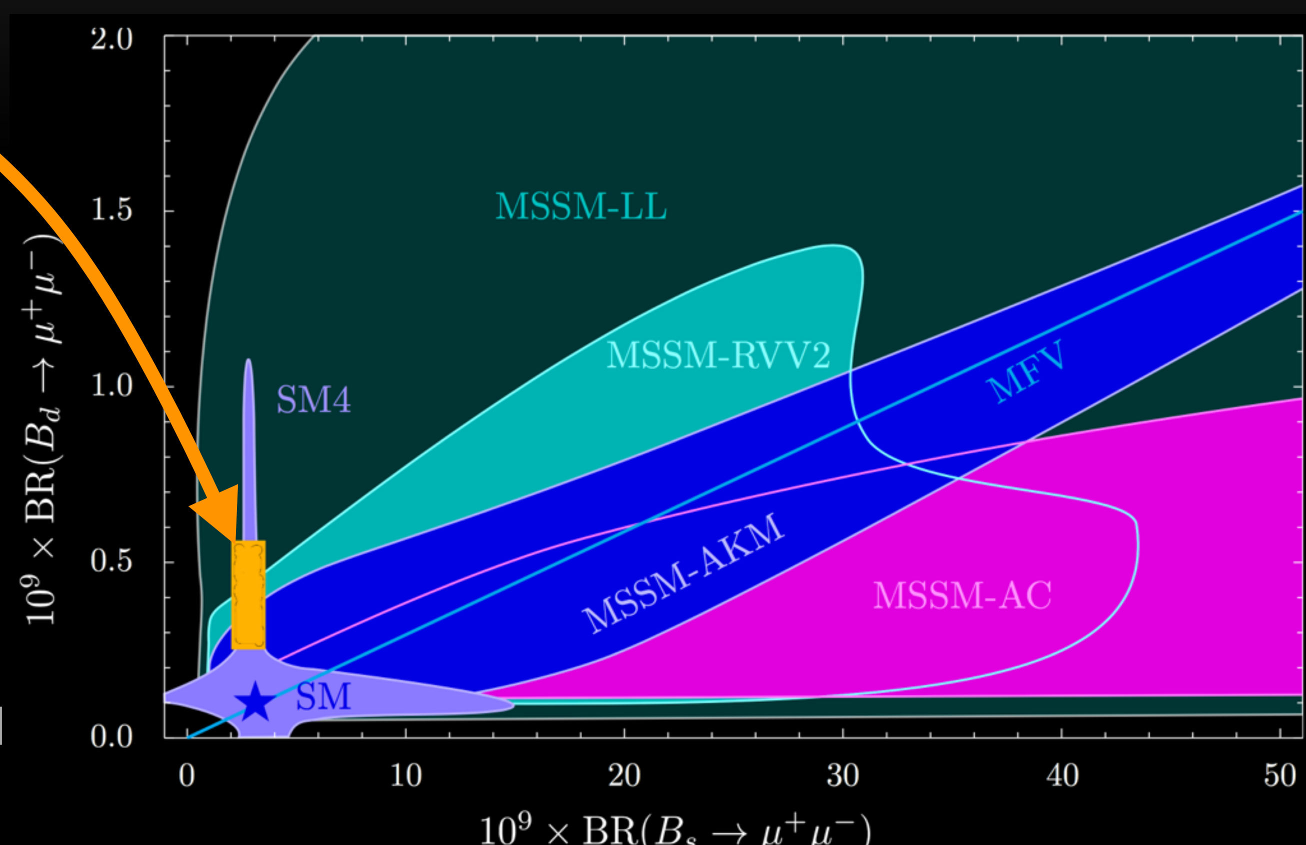
- strong QCD-free constraint on NP
- genuine probe of Yukawa interactions
- EW precision test (wrt. Z penguin)

Evidences of CMS+LHCb combined [1]

- $BR(B_s \rightarrow \mu^+\mu^-) = (2.8 + 0.7 - 0.6) \times 10^{-9}$
- $BR(B_d \rightarrow \mu^+\mu^-) = (3.9 + 1.6 - 1.4) \times 10^{-10}$

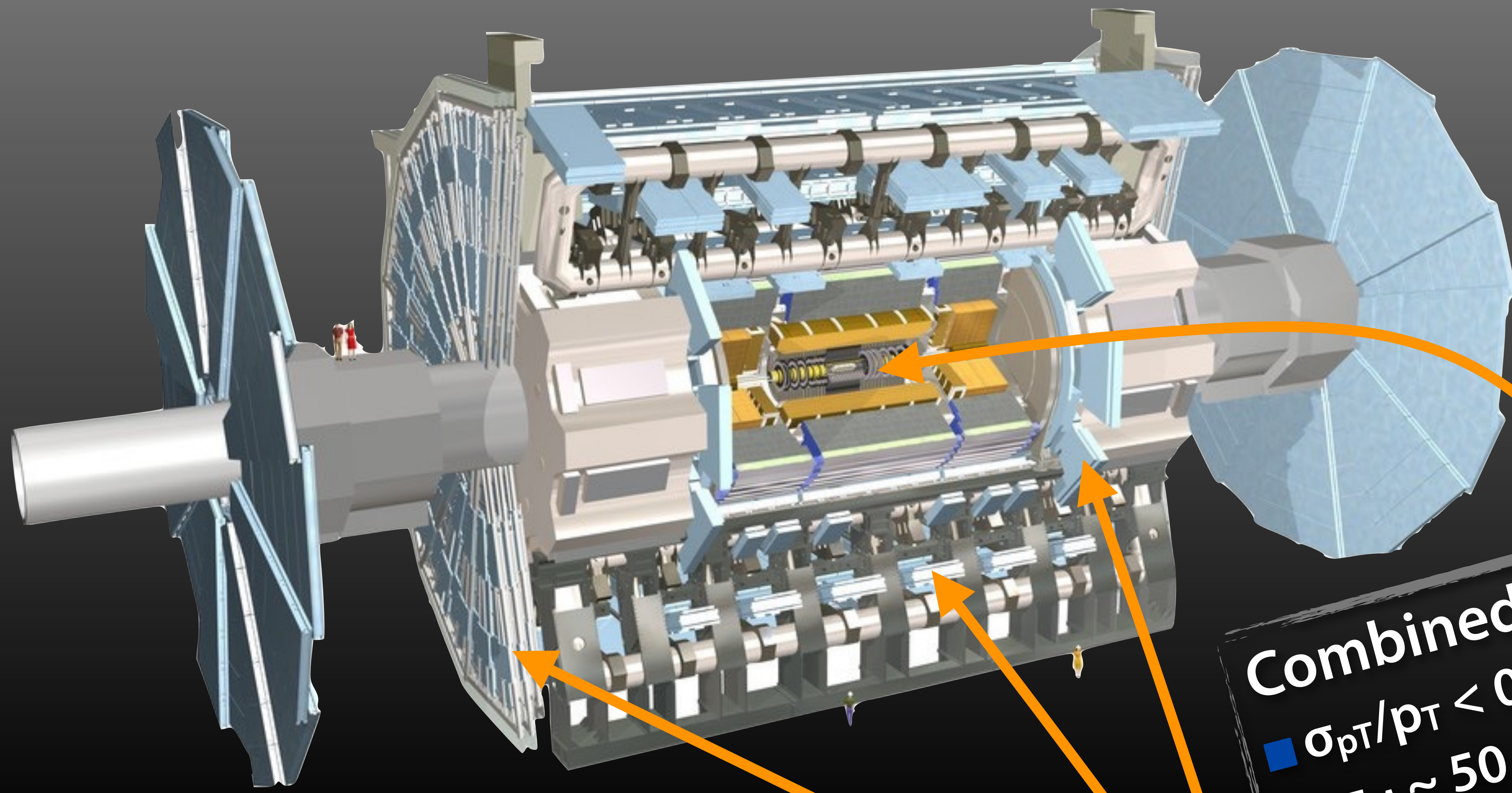
Standard Model [2]

- $BR_{SM}(B_s \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
- $BR_{SM}(B_d \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$



[1] Nature 522 (2015) 68-72
[2] C. Bobeth et al., Phys. Rev. Lett. 112 (2014) 101801
[3] Buras et al., Eur.Phys.J. C72 (2012) 2172

The ATLAS Detector



Combined Tracking ($|\eta| < 2.5$)
- $\sigma_{p_T}/p_T < 0.05\%\ p_T$ (up to 5 GeV) $\oplus$ 1.5%
- $\sigma_M \sim 50$ (J/ψ), 150 (Υ) MeV

Inner Detector ($|\eta| < 2.5$)
- silicon pixel, strip & transition rad. tracker
  - Impact parameter resolution $\approx 10\ \mu m$
  - 2T solenoidal field

Muon Spectrometer ($|\eta| < 2.7$)
- Trigger chambers (RPC, TGC),
- Tracking chambers (MDT, CSC)
- 0.5-2 T air-core toroids
- $\sigma_p/p \sim 10\%$

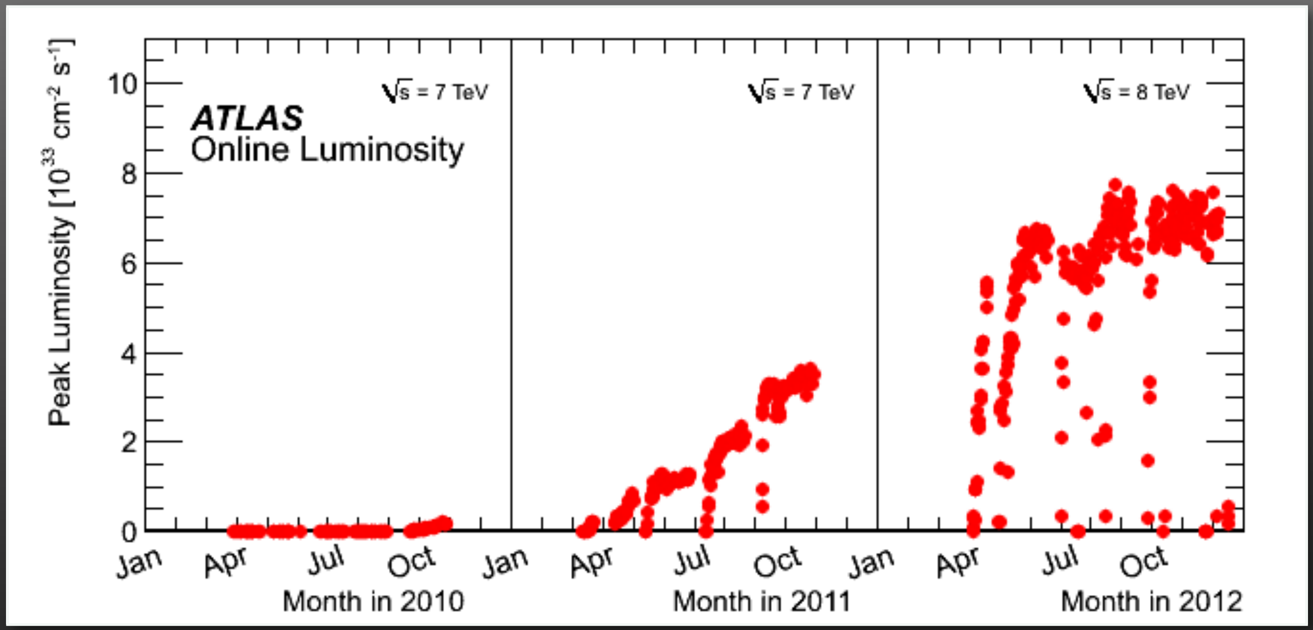
Run I Data Taking

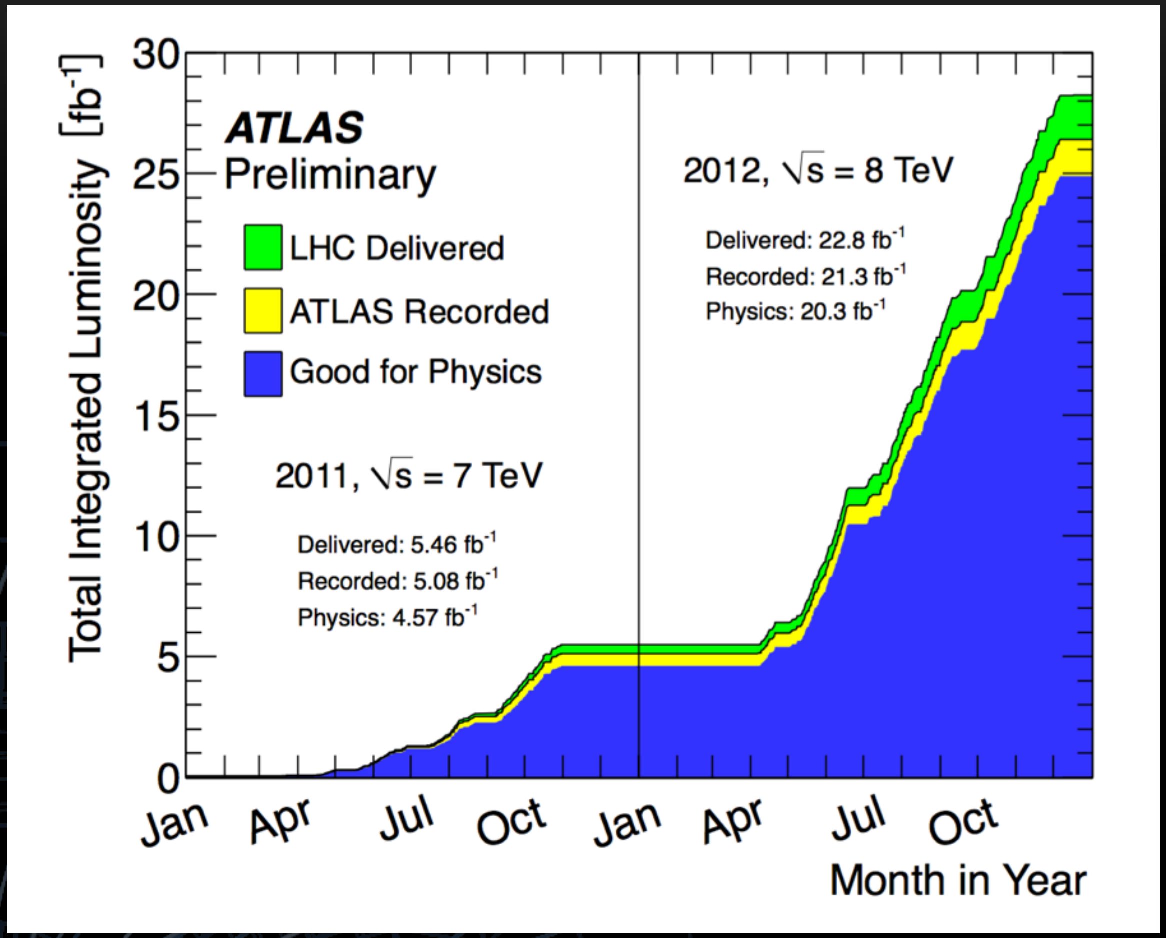
2011 ~ 4.6 fb^{-1}

- instantaneous luminosity & pile-up steadily increasing

2012 ~ 20.4 fb^{-1}

- Flatter instantaneous luminosity profile
- Challenging pile-up conditions !



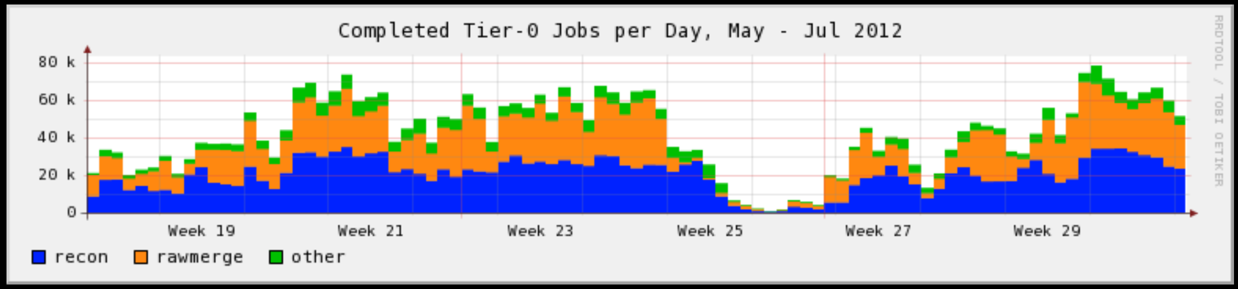


di-muon trigger event selection

↓

Tier-0 processing

- ~24 PB of RAW and derived data
- Up-to 80k Tier-0 jobs completed/day



$B_{D/s} \to \mu^+\mu^-$ strategy @ ATLAS

Analysis Features

- Blind analysis technique: exclude mass region $5166 < m(\mu^+\mu^-) < 5526$ MeV
- Multivariate analysis - 2 BDTs for background suppression
  data control samples used for x-checks & bkg understanding
- Relative branching ratio measurement
  - reference signal decay $B^\pm \to J/\Psi K^\pm \to \mu^+\mu^- K^\pm$ (large stat.)
  - partial cancelation of systematics (on luminosity, cross-sec., efficiencies, trigger)
  - $BR(B^\pm \to J/\Psi\pi^\pm)/BR(B^\pm \to J/\Psi K^\pm)$ = natural parallel measurement

$$\mathcal{BR}(B_{d(s)} \to \mu^+\mu^-) = \mathcal{BR}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) \times \boxed{\frac{f_u}{f_{d(s)}}} \times \boxed{N_{\mu^+\mu^-}} \times \boxed{\left[\sum_j \left(\boxed{N^j_{J/\Psi K^\pm}} \times \boxed{\alpha_j} \times \boxed{\left(\frac{\epsilon_{\mu^+\mu^-}}{\epsilon_{J/\Psi K^\pm}}\right)_j}\right)\right]^{-1}}$$

Hadronisation probabilities

Yields from likelihood mass fits

Trigger and luminosity weight factors

(Acceptance x Efficiency) ratio of signal/ref. channel

$\mathcal{D}_{norm}$ Normalisation term $j \in$ (4 event categories)

$B_{D/S} \to \mu^+\mu^-$ strategy @ ATLAS

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

PDG, ATLAS (f_s/f_d ; assuming f_u/f_d =1)

Data

$$\times \quad N_{\mu^+\mu^-} \times \Big[\sum_j (N^j_{J/\Psi K^\pm} \times \alpha_j$$

- $N_{\mu+\mu-}$ - unbinned extended ML fit simultaneously in 3 bins of c-BDT classifier
- $N_{J/\Psi K\pm}$ - 4 unbinned extended ML fits (data + MC fit simultaneously)

Simulation - (efficiency x acceptance) terms ε_x

$$\times \left(\frac{\epsilon_{\mu^+\mu^-}}{\epsilon_{J/\Psi K^\pm}} \right)_j \Big]^{-1}$$

- "calibrated" on data
- systematics from Data/MC discrepancies

Event Selection

4 mutually exclusive trigger categories

(to avoid efficiency loss)

- 2011 data
  1. 2011 : 2 μ, each with $p_T > 4$ GeV (22%)
- 2012 data
  2. T1 : 2 μ, with $p_{T,\mu1} > 6$ GeV & $p_{T,\mu2} > 4$ GeV (68%)
  3. T2 : 2 μ, each with $p_T > 4$ GeV & at least one in $|\eta| < 1.05$ (6%)
  4. T3 : 2 μ, each with $p_T > 4$ GeV & both in $|\eta| > 1.05$ (4%)

Cuts

- $m(\mu\mu) \in [4766,5966]$GeV
- Kaons, Muons, B mesons : $|\eta| < 2.5$
- $p_T(\mu) > 4$ GeV
- $p_T(K) > 1$ GeV
- $p_T(B) > 8$ GeV

Additional cuts for all channels

(~5% loss in signal, reduce bkg. by a factor ~0.4)

- $\Delta R < 1.5$
- $\alpha 2D < 1.0$
- $Lxy > 0$

ID+MS combined tracking

mass resolution in end-caps better by 30% wrt. 7 TeV analysis

Improved Primary Vertex (PV) identification → 99.8 % efficient

selected PV has min. distance (in z) to a point of closest approach of p(B) direction (3D) extrapolated to beam line.

$B_{d/s} \to \mu^+\mu^-$ Backgrounds

Combinatorial Background

- $b\bar{b} \to \mu^+\mu^-$ reduced by c-BDT trained on MC

in B_s fit: 1st order polynomial

Partially reconstructed decays

- Same-vertex (SV)

e.g. : $B^0_d \to K\mu^+\mu^-$, $B_c \to J/\psi(\mu^+\mu^-)\mu^+\nu$

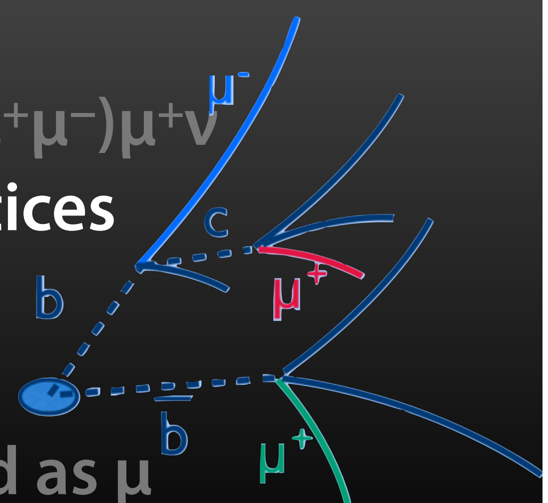
- Same-side (SS) different vertices

$b \to \mu^- c(\to \mu^+ X')X$

- Semi-leptonic

e.g. : $B \to \mu h \nu$, h mis-identified as μ

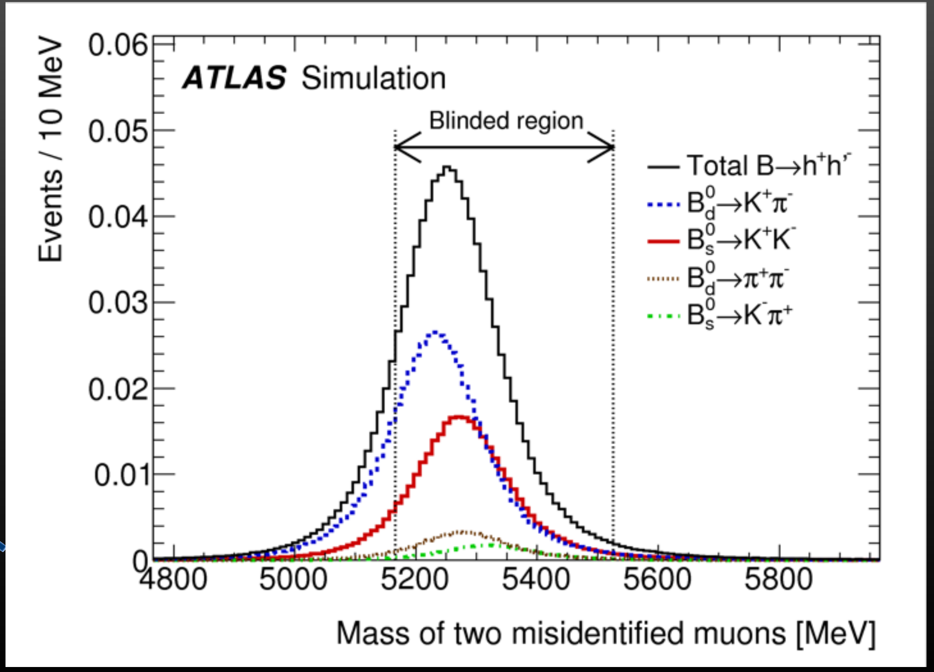
in B_s fit: exponential

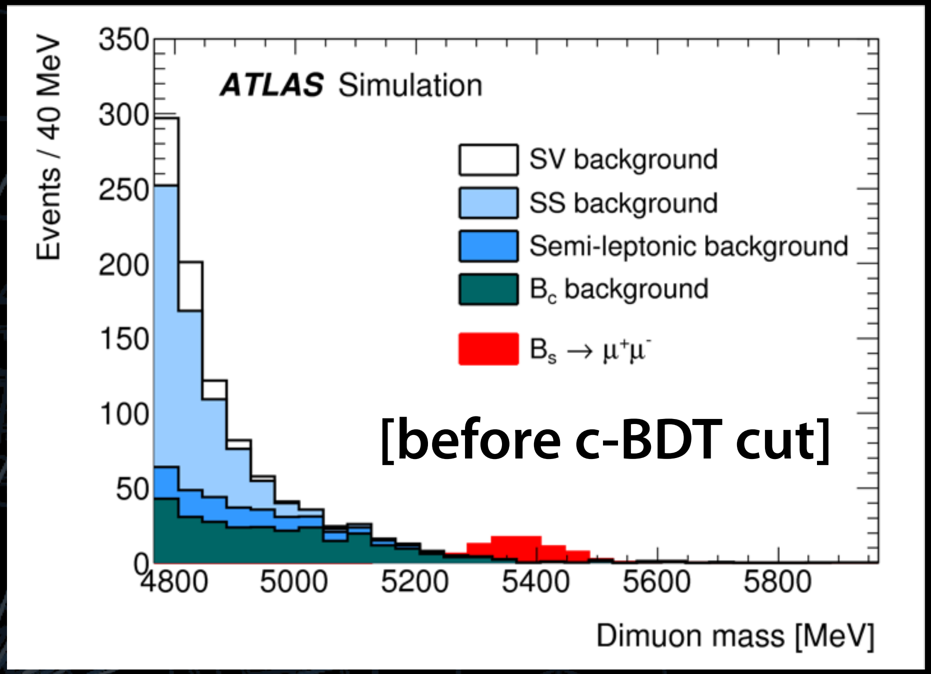


Peaking background

- $B \to hh'$, $h = \pi, K, p$ mis-identified as μ
- dangerously mimicks the signal

in B_s fit: signal-like PDF





f-BDT trained on MC

- reduced bkg. from h mis-identified as μ
- performance validated on data

(fake K from $\Phi \to K^+K^-$, $B^\pm \to J/\Psi K^\pm$)

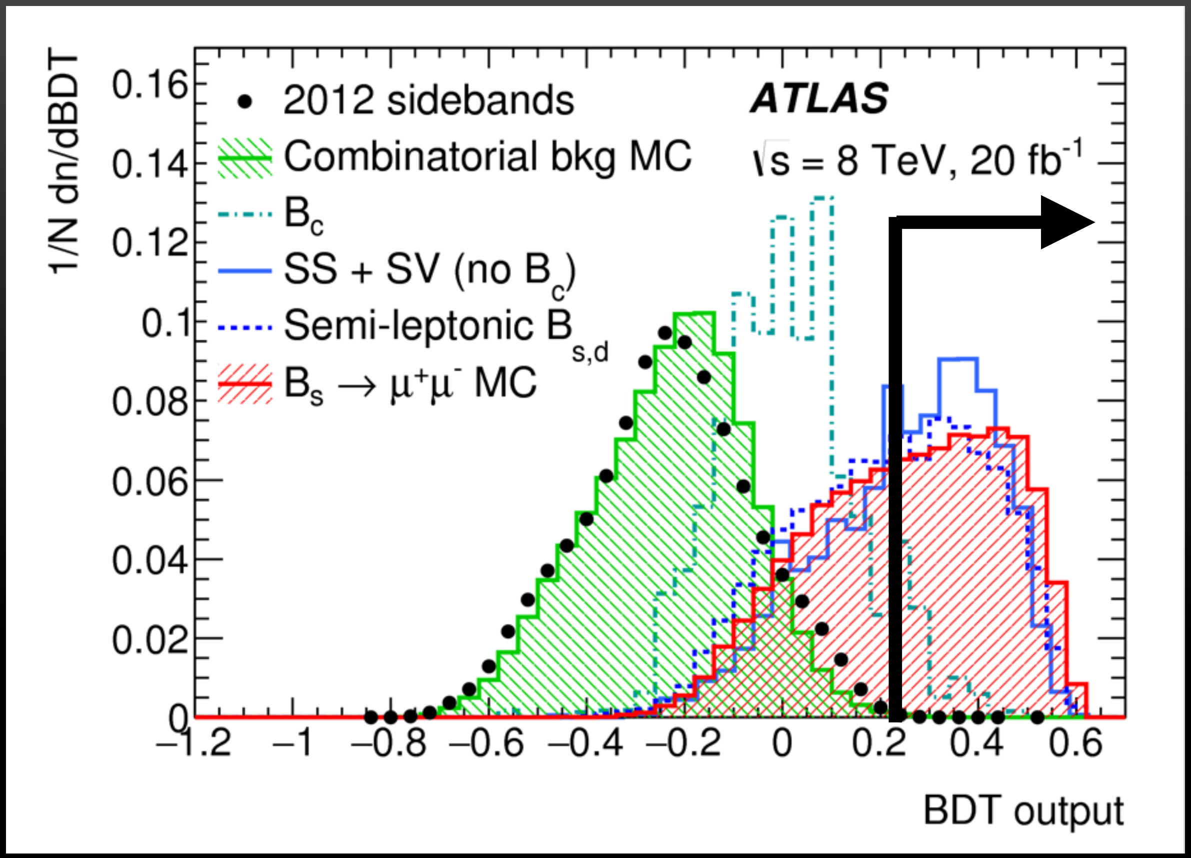
- rejection 7 times > wrt. 7 TeV analysis
- $B_{d/s} \to \mu\mu$ signal eff. set to 95% :

expect 1.0 ± 0.4 (MC) fake events [0.2 ± 1.0 (data)]

(x-check on signal data w reverse f-BDT cut)

Combinatorial Background Discrimination

- Largest Background component
  (2000 x higher in data than SS+SV)
- Boosted Decision Tree classifier applied for suppression (c-BDT)
  - 15 input variables exploiting :
    B-meson kinematic
    Good PV-SV separation Δx (cτ ~ 450μm)
    Collinearity between Δx and P(μμ)
    None or few additional tracks around the SV
    μ prop., X^2 wrt. other vertices, B isolation…



- Trained on 1.4G MC
  events with μ from b/c quark decays
  MC has 8 x > stat. than in sideband data
  left sideband used for c-BDT validation

- Combinatorial bkg reduced ~1000 x
- Signal efficiency 54%

- Data/MC validated on control samples
  $B^\pm \to J/\Psi K^\pm$, $B_s \to J/\Psi\ \Phi$
- Data/MC discrepancies
  accounted for as systematic error.

Reference Channel Yield

Unbinned extended maximum likelihood (ML) fits

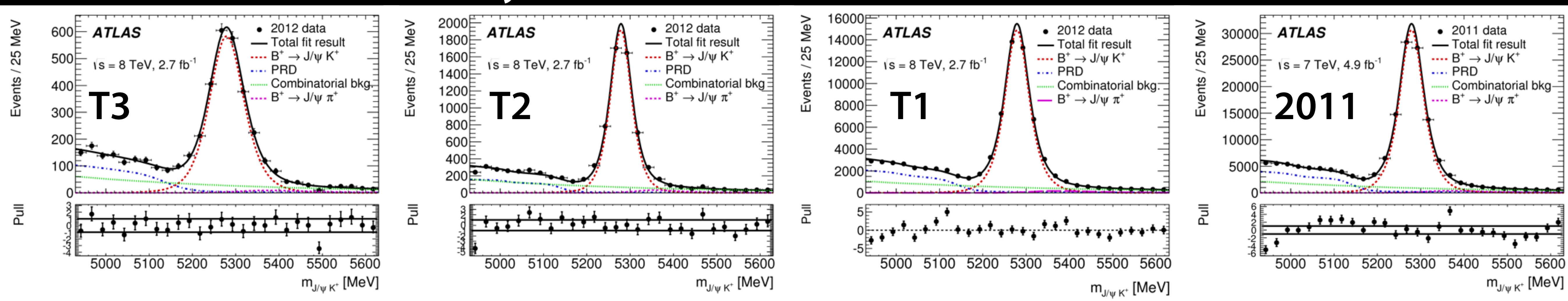
- $m(\mu^+\mu^-K^\pm)$ Data mass distribution fitted (simultaneously with MC)
- Extract yields of $B^\pm \to J/\Psi\,\pi^\pm$ & $B^\pm \to J/\Psi\,K^\pm$ at the same time ("+" sign plot notation)
- Several parameters are free to vary
  - Normalisations
  - mass scale & resolution
  - slope of combinatorial bkg.

- 4- component fit
  - partially reconstructed decays (PRD)
  - combinatorial bkg,
  - $J/\Psi\,\pi^\pm$ & $J/\Psi\,K^\pm$
- shapes sim. constrained by MC

Main systematics

- Combinatorial model
- MC modelling of PRD
- Signal charge asymmetry (K^- reconstructed less efficiently)

Total contribution to $\mathcal{D}_{\mathrm{norm}}$ systematics ± 0.8%



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

- LHCb (0.0383 + 0.0011 + 0.0007)
- BABAR (0.0537 + 0.0045 + 0.0011)

(Acceptance x Efficiency) ratio of signal/ref. channel

Extracted from simulation (MC samples)

- separately for each channel and category ($p_T(B) > 8$ GeV, $|\eta(B)| < 2.5$)
- corrections from B^+ or $B_s \to J/\Psi\ \Phi$ data on :
  $p_T(B)$ and $\eta(B)$ spectra
  $B_s \to \mu^+\mu^-$ lifetime and B isolation
  trigger efficiencies corrected using J/ψ and Y data (tag & probe studies)

Main Systematic Uncertainty

- vertexing (B_s vs $B^\pm$) & track reconstruction K^+
- Residual Data/MC discrepancy on the c-BDT variables (±3.2%)
- Total systematic uncertainty contribution from $B^\pm$ yield and $B_s/B^\pm$ acc. x eff. ratio ± 5.9%

Statistical uncertainty in simulation	0.5%
p_T, η reweighting and trigger efficiency	1.3%
Data to MC discrepancy in discriminating variables	4.2%
K^+ and B^+ reconstruction	3.6%
Residual trigger efficiency systematic uncertainty	1.5%
B^+ yield	0.8%
Total uncertainty	5.9%

Expected Signal Yield

$$\sum_k N^k_{\mu\mu} = \frac{f_s}{f_u} \times \frac{\mathcal{BR}(B^0_{(s)} \to \mu^+\mu^-)}{\mathcal{BR}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm)} \times \sum_k \frac{N^k_{J/\Psi K}\alpha_k}{R^k_{A\epsilon}}$$

Estimate expected $B_s \to \mu^+\mu^-$ signal yield

- Assuming :
  - SM branching ratios
  - c-BDT and f-BDT was applied
  - reference channel yield measured
  - $R^k_{A\varepsilon}$ was evaluated

then all the inputs are known :

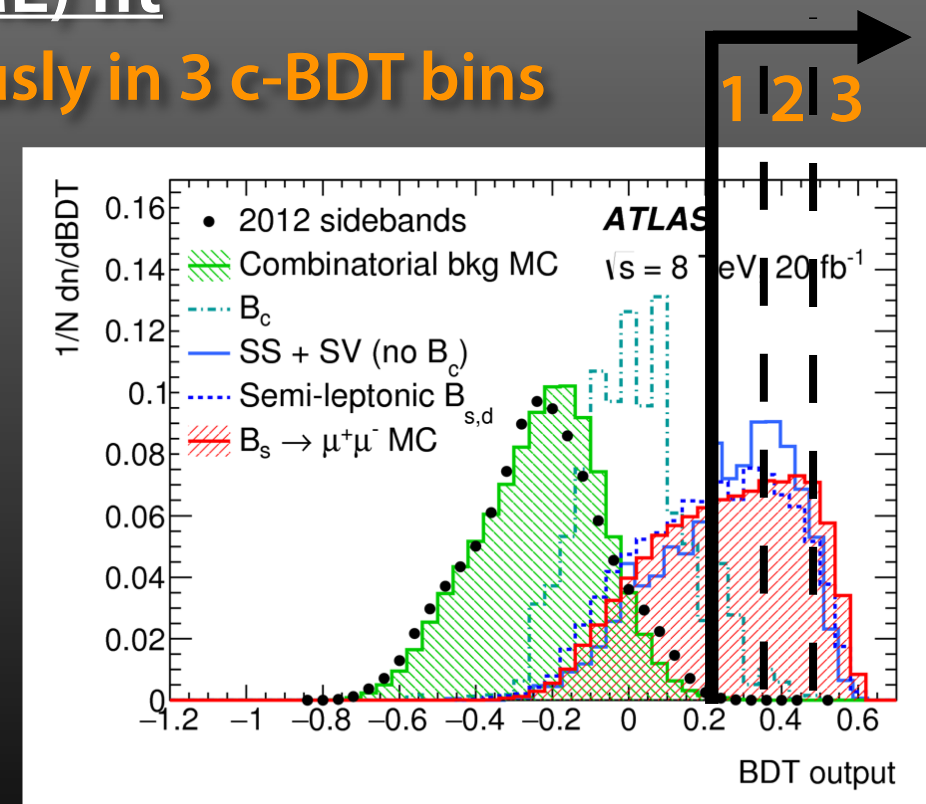
Data Category (k)	$R^k_{A\varepsilon} = \varepsilon_{J/\psi K\pm} / \varepsilon_{\mu+\mu-}$	$N^k_{J/\psi K\pm}$	α_k	f_s/f_d ($f_{u/d}$=1)	$N_{Bs \to \mu+\mu-}$
T1	0.180 ± 0.001 ±0.009	46 860 ± 290 ± 280	7.23	0.240 ± 0.020 ATLAS arXiv:1507.08925	27
T2	0.226 ± 0.004 ±0.014	5 200 ± 84 ± 100	7.28		2.4
T3	0.189 ± 0.005 ±0.022	2 512 ± 91 ± 42	7.29		1.4
2011	0.156 ± 0.002 ±0.009	95 900 ± 420 ± 1 100	1		8.8

- Expect 41 B_s and 5 B_d events in the signal region
- N_{Bs} contains +4% correction on $B_s \to \mu+\mu-$ efficiency (due to diff. lifetime of B_s and $B_H^{(s)}$)

$B_{d/s} \to \mu^+\mu^-$ signal fit

Unbinned extended maximum likelihood (ML) fit

- $m(\mu^+\mu^-)$ Data mass distribution fitted **simultaneously in 3 c-BDT bins** w different S/B ratio to constrain the bkg.
- Extract N_{Bs} and N_{Bd}
- Each bin has 18% signal efficiency



Basic fit configuration

- Background models: **independent bkg yields and rel. fractions in each bin**
  - Combinatorial bkg - 1st order Chebychev slopes extracted independently in each bin
  - Same side/vertex bkg - Exponential constrained to same shape in all bins
  - Peaking bkg - signal-like PDF w fixed shape (MC), yield 1.0 ± 0.4, and rel. fractions
  - Semi-leptonic bkg: no additional PDF (Gaussian tail in low-mass added only for systematics)
- Signal:
  - 2 Double Gaussian shapes from MC B_s / B_d sample
  - signal fractions in each bin constrained to exp. equal signal efficiency
  - **2 normalisation parameters N_{Bs} and N_{Bd}**

$B_{D/s} \to \mu^+\mu^-$ Fit Sensitivity & Systematics

MC Toy Experiments

- SM expected significance:

  $s_{B_s \to \mu^+\mu^-} = 3.1\,\sigma$, $s_{B_d \to \mu^+\mu^-} = 0.2\,\sigma$

  (Toys w mean $N_{B_s \to \mu^+\mu^-} = 41$, $N_{B_d \to \mu^+\mu^-} = 5$ & imposing $N_{B_{s/d} \to \mu^+\mu^-} > 0$)

- Dominant Systematics:

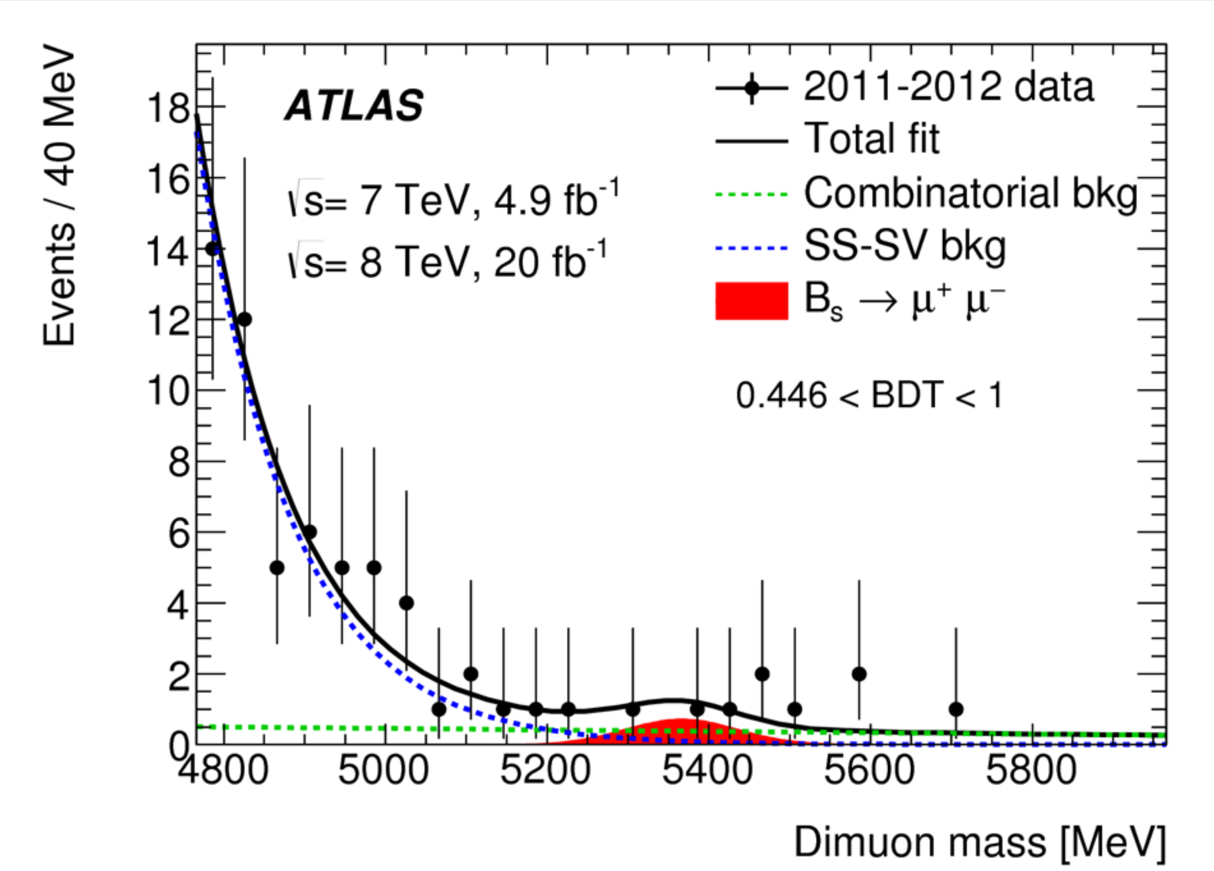
  Uncertainty in the relative efficiencies of the 3 c-BDT bins

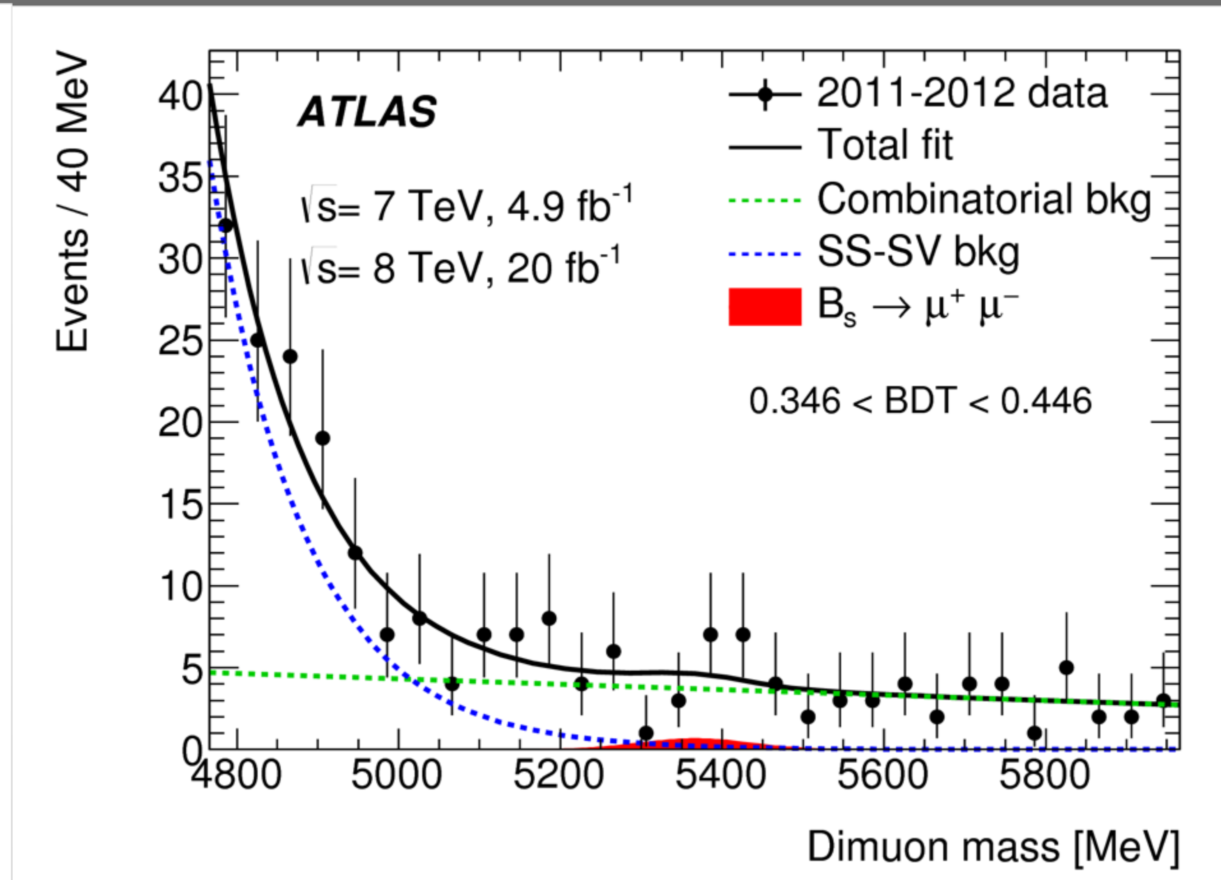
  Alternative signal and background models

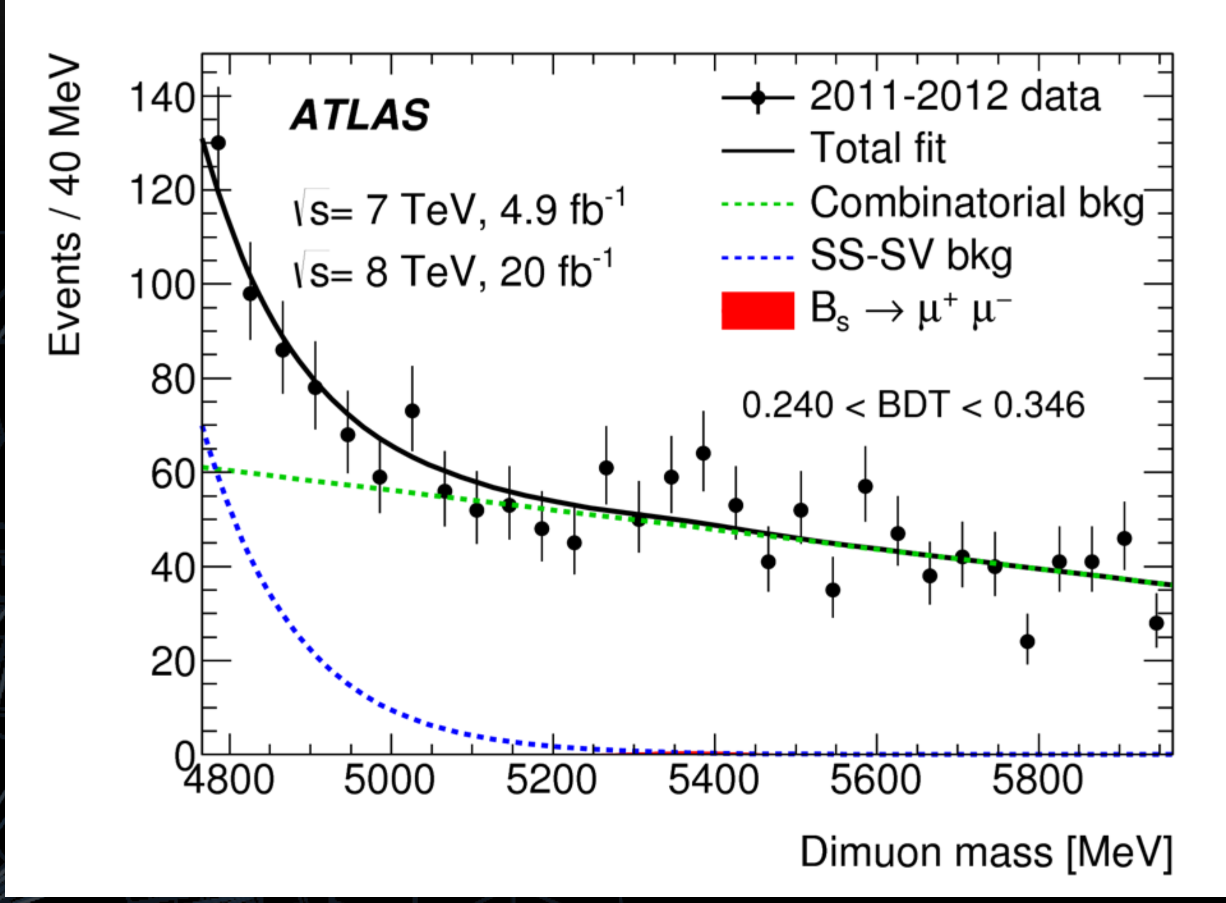
	$\mathcal{B}(B^0_s \to \mu^+\mu^-)$	$\mathcal{B}(B^0 \to \mu^+\mu^-)$
Scale uncertainties		
$\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu\mu)$ branching fractions	3.1%	3.1%
$B^0{}_{(s)}/B^+$ production ratio	8.3%	0
B^+ yield and $B^0{}_{(s)}/B^+$ efficiency ratio	5.9%	5.9%
Relative 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}

Statistically limited measurement

$B_{D/s} \rightarrow \mu^+\mu^-$ fit result







Yields

- $N_{Bs \rightarrow \mu+\mu-} = 16 \pm 12$
- $N_{Bd \rightarrow \mu+\mu-} = -11 \pm 9$

lower than expected !

$S_{Bs \rightarrow \mu+\mu-} = 1.4\,\sigma$

$B_{d/s} \to \mu^+\mu^-$ Branching Ratios

Branching ratio extraction

- Central BR value:
  looking at minimum of the likelihood imposing $N_{Bs/d \to \mu+\mu-} > 0$ ($N_{Bd} = 0$; $N_{Bs} = 11$)
  $BR(B_d \to \mu^+\mu^-) = 0$, $BR(B_s \to \mu^+\mu^-) = 0.9 \times 10^{-9}$

- Uncertainties:
  Neyman construction of frequentist confidence belt (MC Toy experiments)
  include both statistical (dominant) and systematic uncertainties
  $\sigma_{syst.} = \pm 0.3 \times 10^{-9}$

- Upper limits set @ 95 % CL using CLs technique

Results	SM Expected
$BR(B_s) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$	$BR_{SM}(B_s) = (3.65 \pm 0.23) \times 10^{-9}$
$BR(B_s) < 3.0 \times 10^{-9}$ @ 95 % CL	
$BR(B_d) < 4.2 \times 10^{-10}$ @ 95 % CL	$BR_{SM}(B_d) = (1.06 \pm 0.09) \times 10^{-10}$

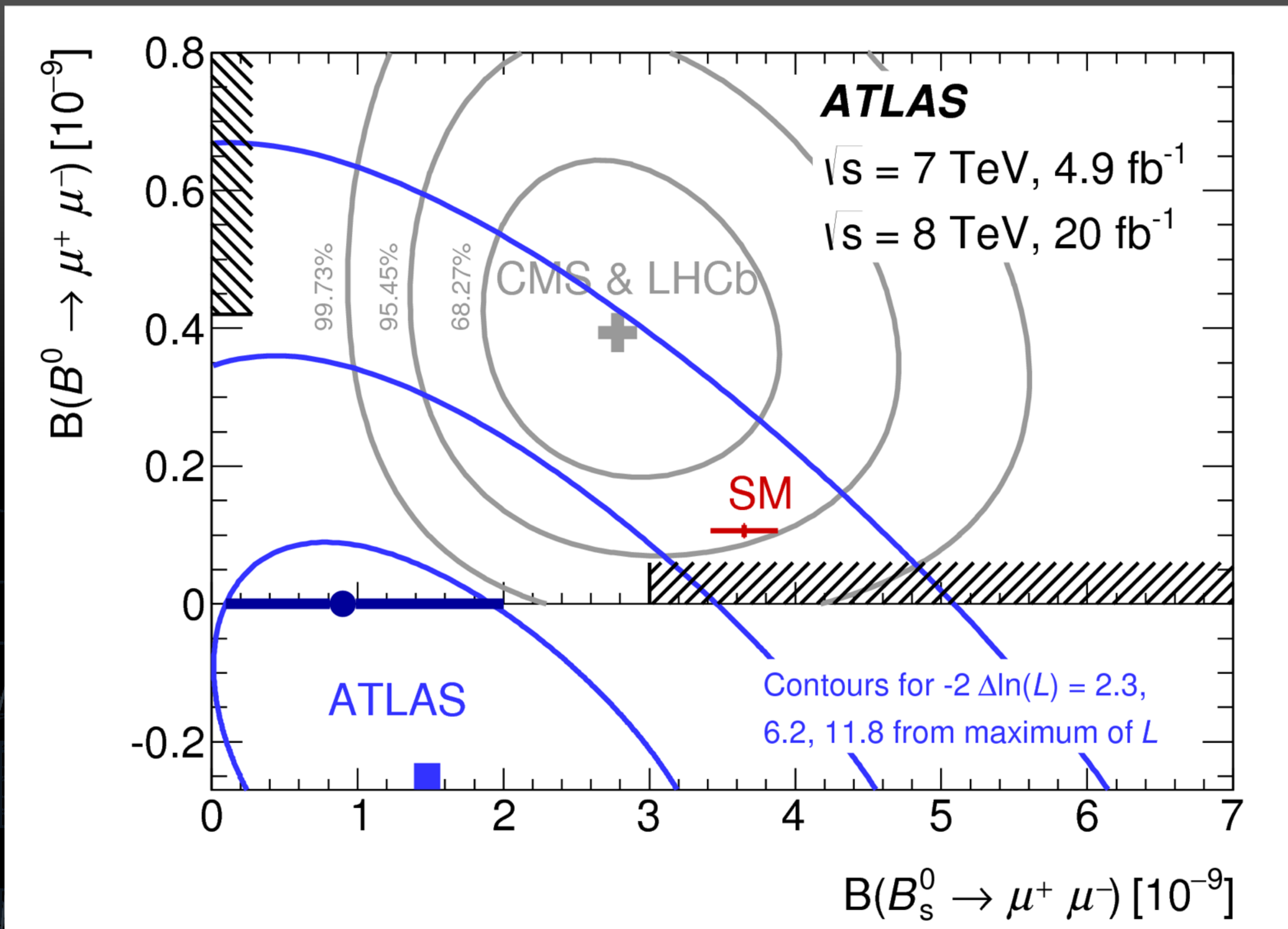
- ATLAS precision comparable with CMS and LHCb
  despite their (by construction) better $m(\mu^+\mu^-)$ resolution (~1.5x for CMS; ~3x for LHCb)

Result

Result compatible (lower than) SM p-value = 0.048 (2.0σ)

(obtained by profile likelihood ratio)

Possibility of destructive interference of NP with the SM



CERN-EP-2016-064

arXiv:1604.04263

Submitted to EPJC

Summary

- Presented results of the ATLAS search for $B_{d/s} \rightarrow \mu^+ \mu^-$ decays on full Run I data from LHC
- Significant improvement in analysis techniques
- Results compatible with (lower than) CMS and LHCb
- 2.0 σ compatibility with the SM prediction (SM higher) w room for destructive interference of NP with SM
- Planning analysis of Run2 (~100 fb^{-1}) data

$BR(B_s \rightarrow \mu^+\mu^-) = (0.9 +1.1 - 0.8) \times 10^{-9}$

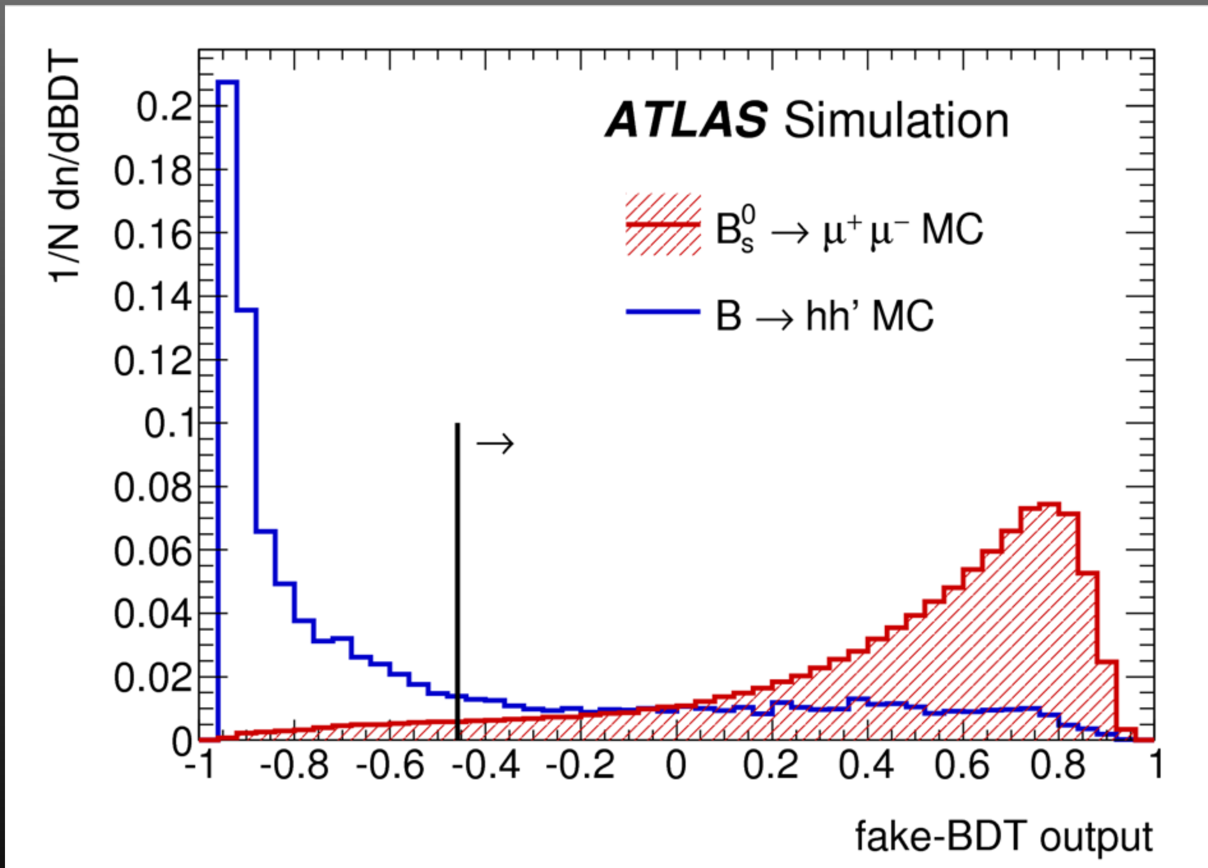
$BR(B_s \rightarrow \mu^+\mu^-) < 3.0 \times 10^{-9}$ @ 95 % CL

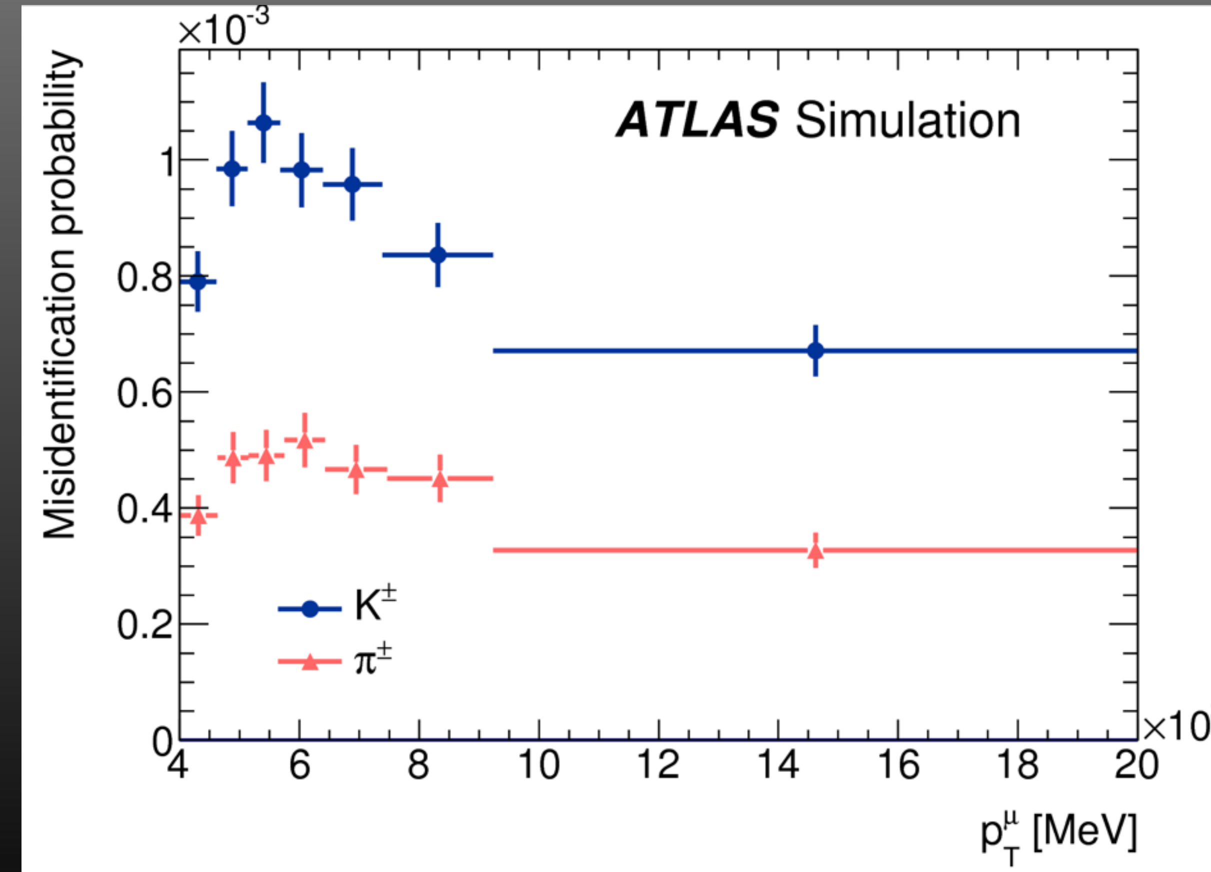
$BR(B_d \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-10}$ @ 95 % CL

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

BACKUP

F-BDT



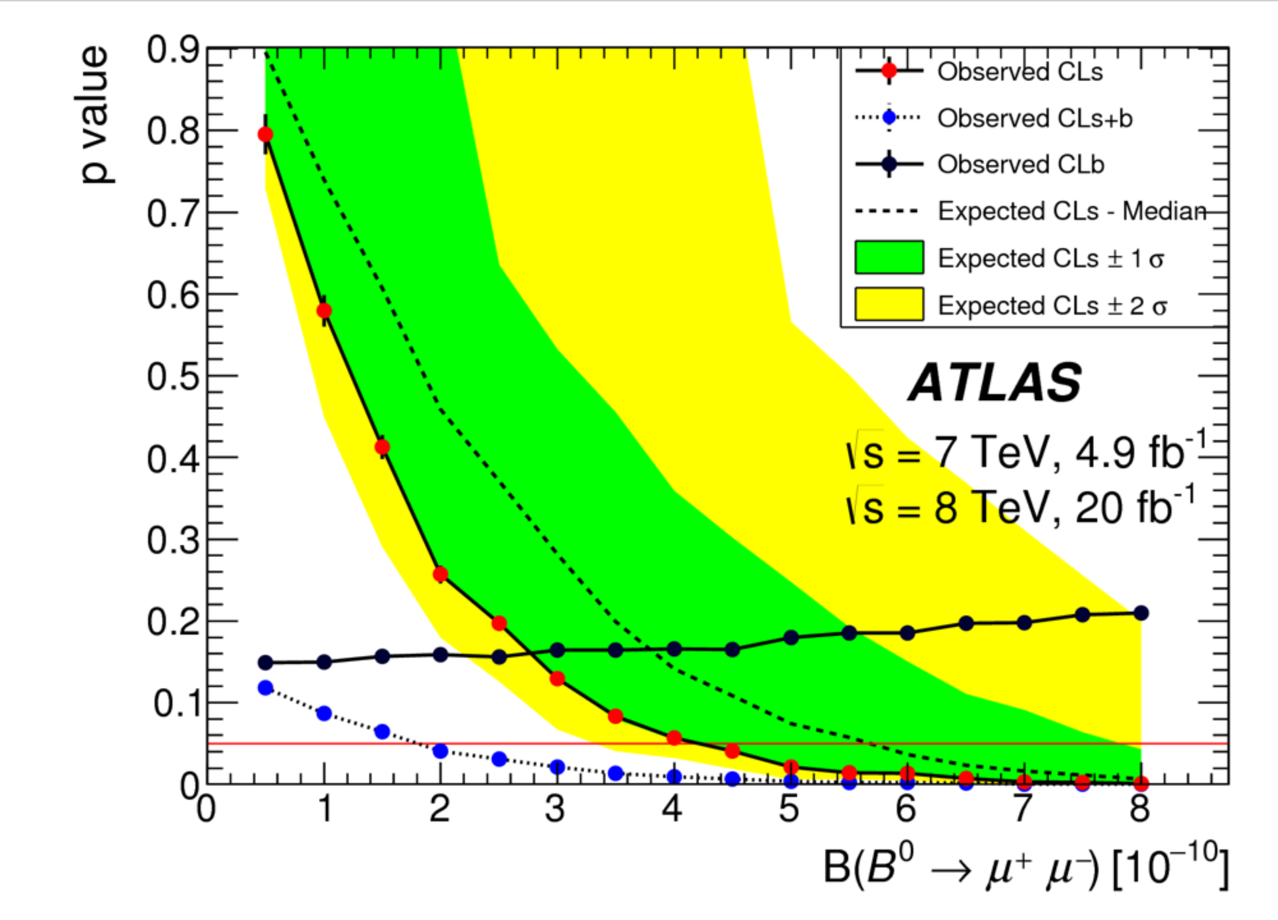


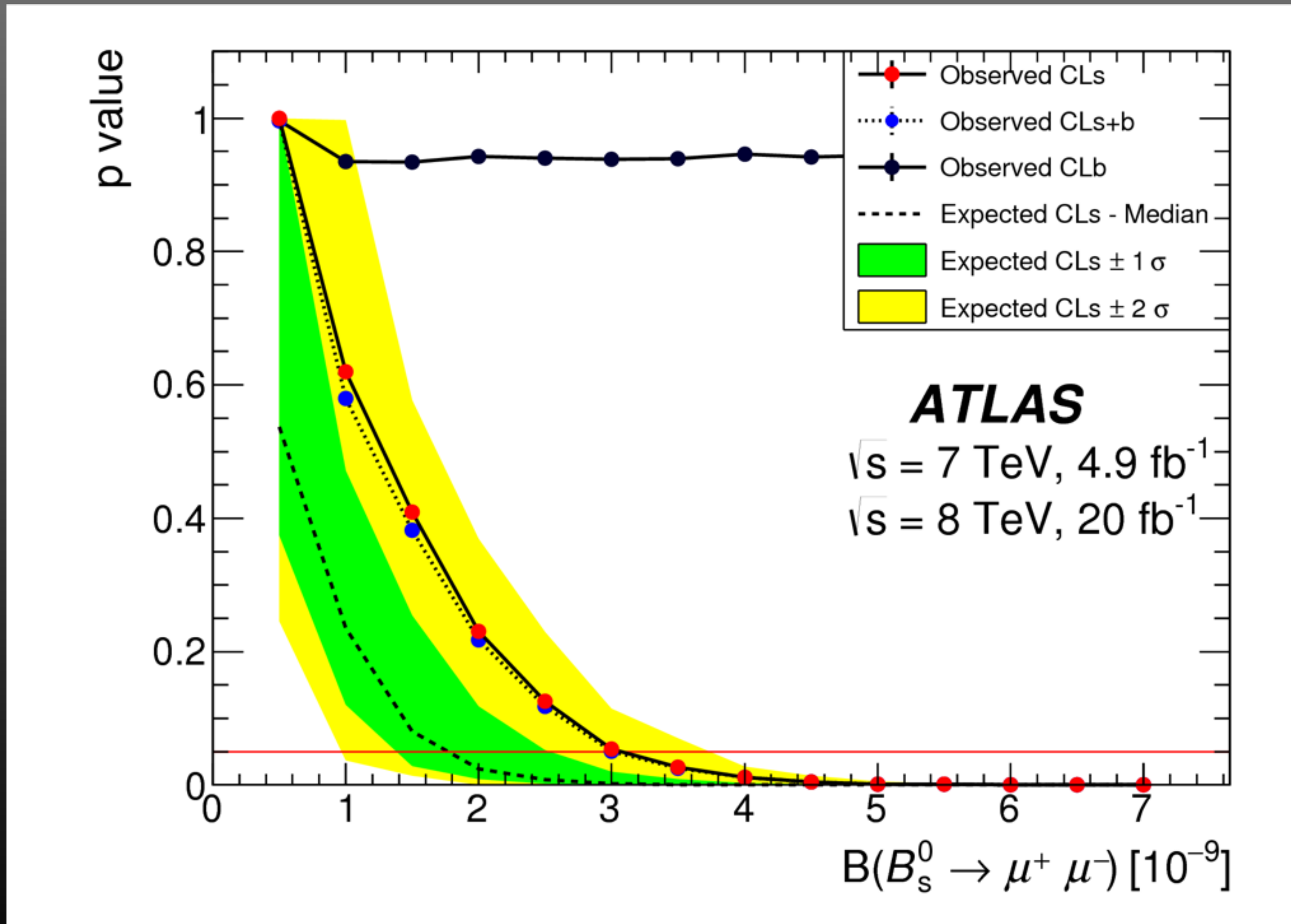
Critical aspect of the analysis

- **hadrons mis-identified as muons fake signal and can destroy sensitivity to NP**
- **f-BDT reduces mis-identification probability to 0.09%/0.04%/<0.01% for K/π/p.**
- **Punch through 3% (8%) level for K (π).**

1. Absolute value of the track rapidity measured in the ID.
2. Ratio q/p (charge over momentum) measured in the MS.
3. Scattering curvature significance: maximum variation of the track curvature between adjacent layers of the ID.
4. χ^2 of the track reconstruction in the MS.
5. Number of hits used to reconstruct the track in the MS.
6. Ratio of the values of q/p measured in the ID and in the MS, corrected for the average energy loss in the calorimeter.
7. χ^2 of the match between the tracks reconstructed in the ID and MS.
8. Energy deposited in the calorimeters along the muon trajectory obtained by combining ID and MS tracks.

CLs limits





Results

- $BR(B_s) = (0.9^{+1.1}_{-0.8}) \times 10^{-9}$
- $BR(B_s) < 3.0 \times 10^{-9}$ @ 95 % CL
- $BR_{MCToys}(B_s) < 1.8^{+0.7}_{-0.4} \times 10^{-9}$ @ 95 % CL
  (from MC Toys; no signal; background as in data)

- $BR(B_d) < 4.2 \times 10^{-10}$ @ 95 % CL
- $BR_{MCToys}(B_d) < 5.7^{+2.1}_{-1.5} \times 10^{-10}$ @ 95 % CL
  (from MC Toys; no signal; background as in data)

SM Expected

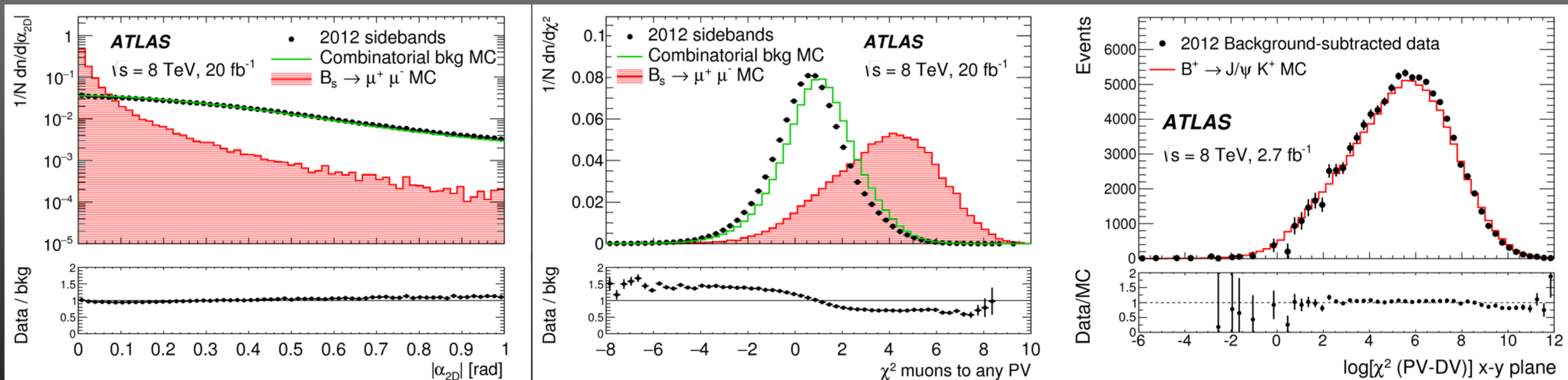
$BR_{SM}(B_s) = (3.65 \pm 0.23) \times 10^{-9}$

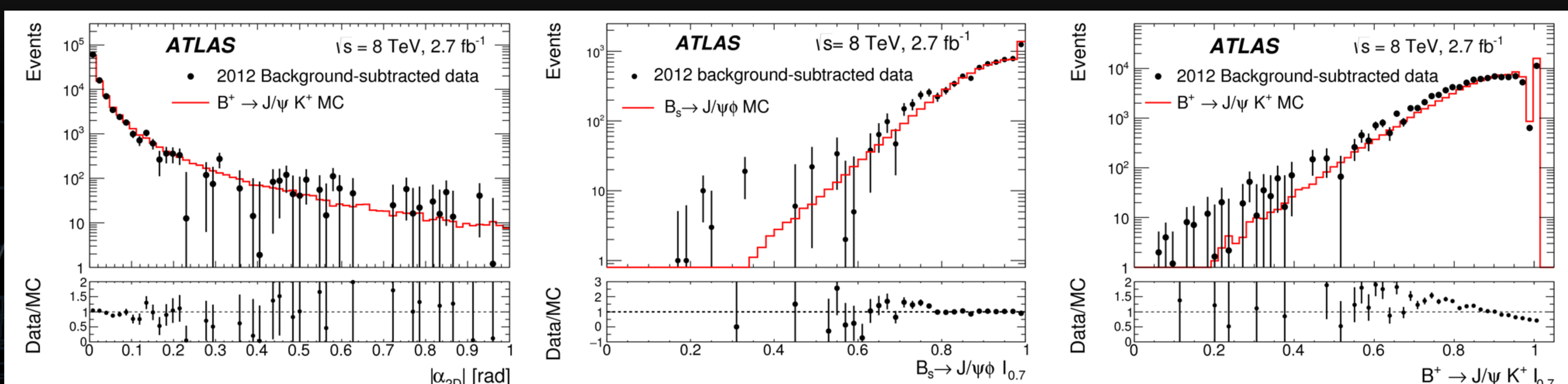
$BR_{SM}(B_d) = (1.06 \pm 0.09) \times 10^{-10}$

c-BDT

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.

Data/MC comparison





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