Study of rare B decays on Run1 at ATLAS

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(QMUL)
on behalf of the ATLAS Collaboration

Rare B decays, Theory and Experiment 2016
Barcelona, Spain
April 18th, 2016

- off-topic reflection on Barcelona and Gaudi
- probably a unique case in which tourists hear about hyperbolic functions while visiting a church!

B physics in ATLAS

- very limited *(wo)*man power
  - but a good variety of analyses
  - *delivered more or less timely :)*
- recent results (in the last year):
  - quarkonia production cross sections:
    - J/ψ and $\psi(2S)$: to appear in EPJC, arXiv:1512.03657
  - branching fractions:
    - Λ_b: PLB, arXiv:1507.08202, B_c: EPJC, arXiv:1507.07099
  - $J/\psi\phi$ angular analysis: submitted to JHEP, arXiv:1601.03297
  - fragmentation fraction f_s/f_d: PRL, arXiv:1507.08925
  - rare B decays: $B_{(s)} \to \mu^+\mu^-$:
    - submitted to EPJC, arXiv:1604.04263

Ratio of b fragmentation fractions f_s/f_d

ATLAS, PRL 115, 262001 (2015), arXiv:1507.08925

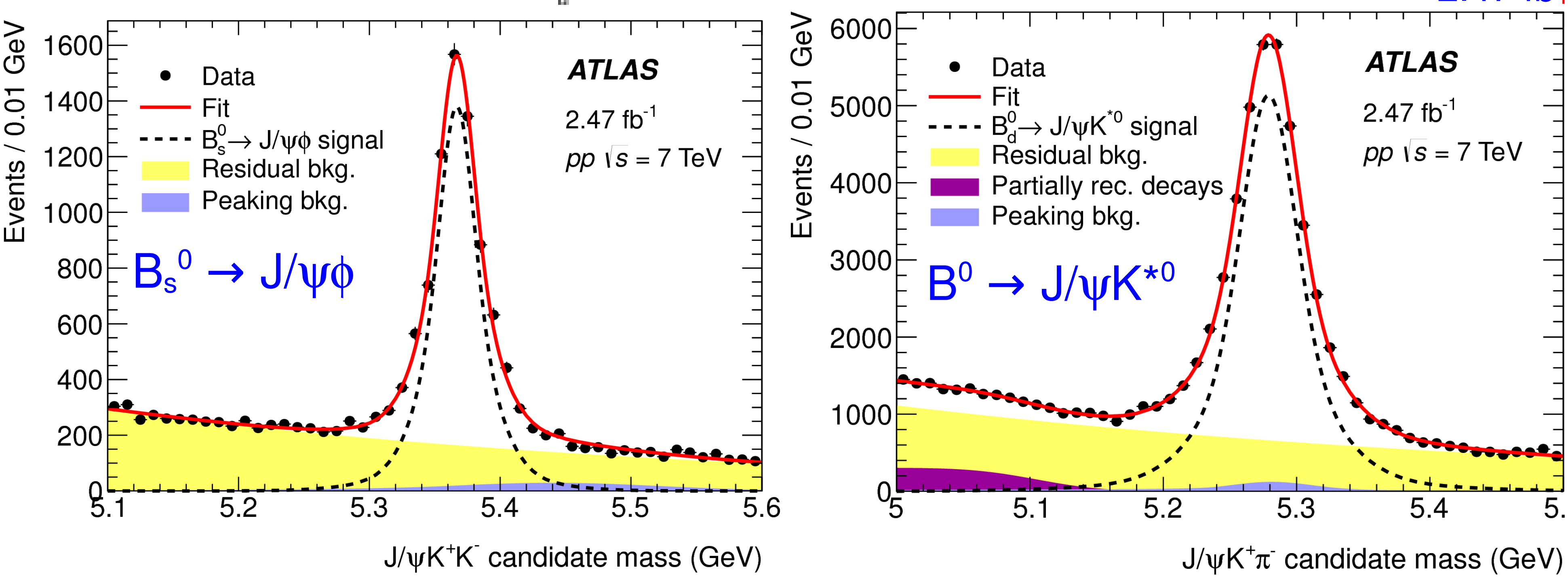
$B_s^0 \rightarrow J/\psi\phi$ and $B^0 \rightarrow J/\psi K^{*0}$ used to determine the ratio of fragmentation fractions f_s/f_d

The ratio is extracted from measured signal yields, converted into B meson yields by correcting for the different efficiencies and by the decay branching ratios

- yields from unbinned maximum likelihood fit to invariant mass spectra
- correction for acceptance and selection efficiency ratios in the two modes

$$\frac{f_s}{f_d} = \frac{N_{B_s^0}}{N_{B_d^0}} \frac{\mathcal{B}(B_d^0 \rightarrow J/\psi K^{*0})}{\mathcal{B}(B_s^0 \rightarrow J/\psi\phi)} \frac{\mathcal{B}(K^{*0} \rightarrow K^+\pi^-)}{\mathcal{B}(\phi \rightarrow K^+K^-)} \mathcal{R}_{\text{eff}}$$

2.47 fb-1



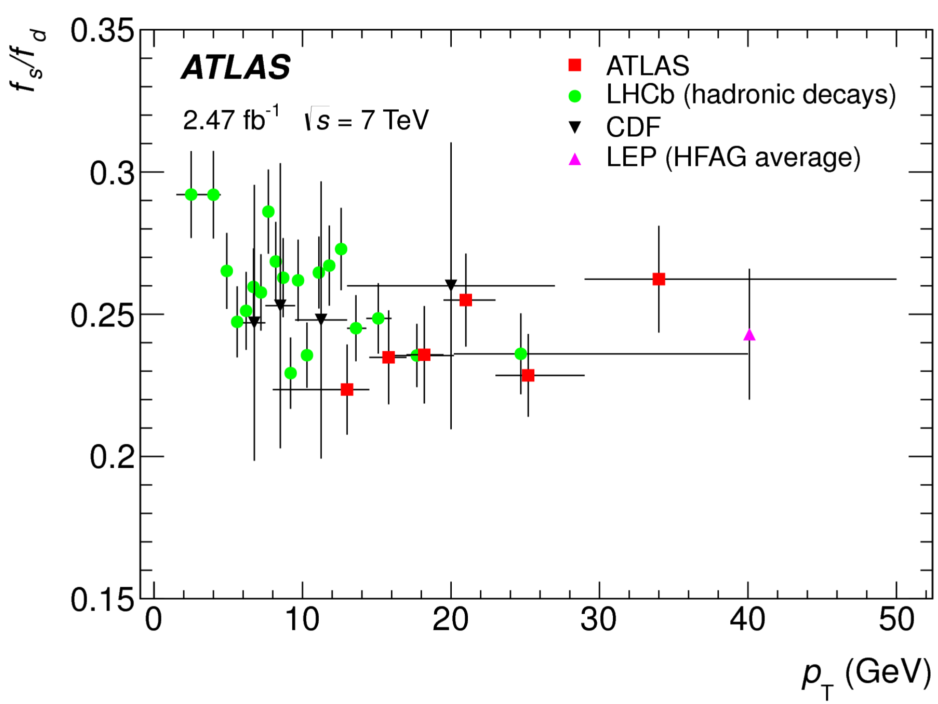
Ratio of b fragmentation fractions f_s/f_d

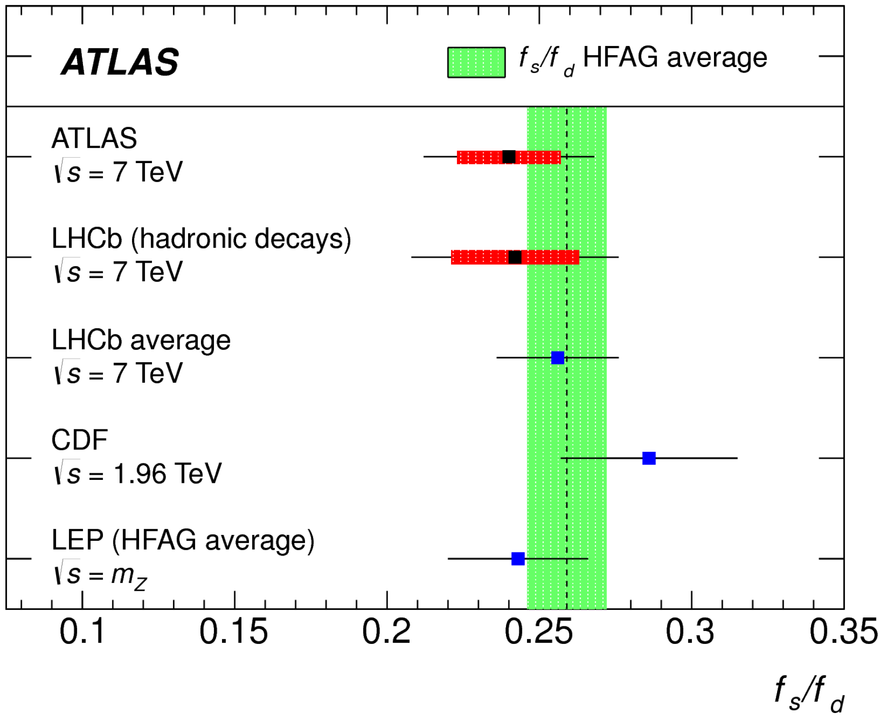
ATLAS, PRL 115, 262001 (2015), arXiv:1507.08925

Final measurement:

$$f_s/f_d = 0.240 \pm 0.004(\text{stat}) \pm 0.010(\text{sys}) \pm 0.017(\text{th})$$

- Uses perturbative QCD calculation of branching fractions ratio [arXiv:1309.0313]
- Measurement in p_T and pseudorapidity intervals: no visible dependence
- Results compared to previous experimental results
  → historical tension between LEP/CDF
- Good agreement with recent LHCb results. Improving the world average
- Fundamental input for the rare decay $B_s \to \mu^+\mu^-$





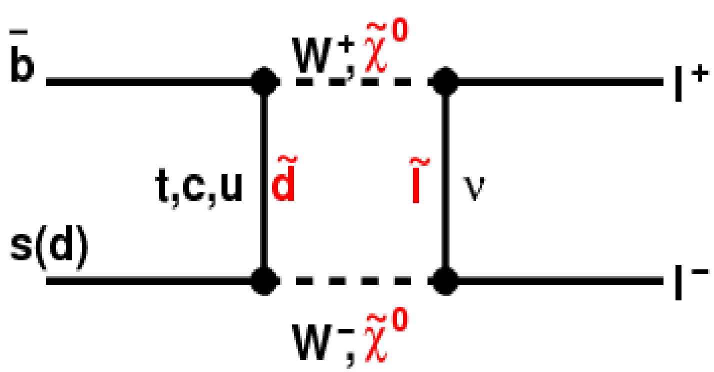
Motivations, predictions and previous results

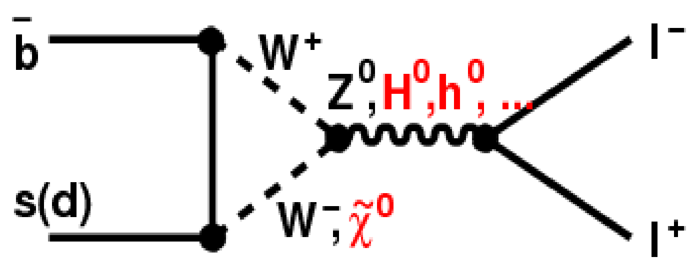
- Decays of B^0 and B^0_s into two muons have to proceed through Flavour Changing Neutral Currents (FCNC)
  → they are suppressed in the SM
- In addition, they are CKM and helicity suppressed.
- However, within the SM, they can be calculated with small theoretical uncertainties of order 6-8%
  - latest determination includes NLO EM and NNLO QCD corrections

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

Bobeth et al., PRL 112 (2104) 101801

- Perfect ground for indirect new physics searches:
  - virtual new physics particles can contribute to the loop
  - both enhancement and suppression effects are possible





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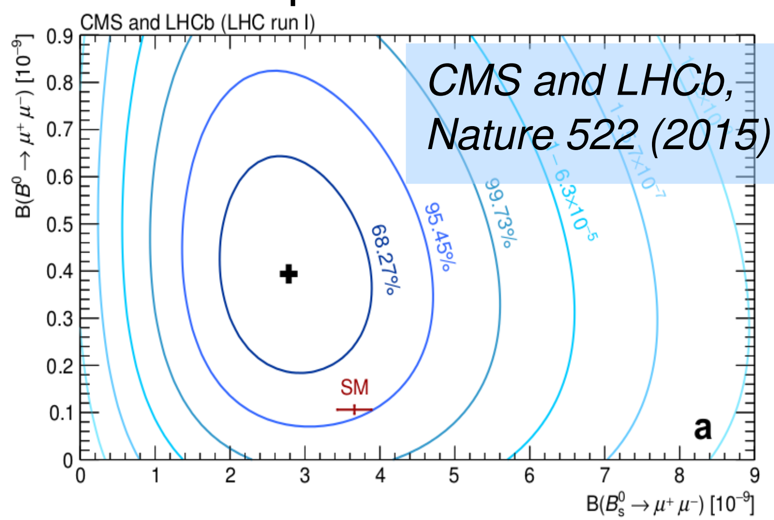
- Combination from CMS and LHCb:
  - 6σ observation for the B^0_s channel:

    $$\mathbf{B(B^0_s \rightarrow \mu^+\mu^-) = (2.8^{+0.7}_{-0.6})\ 10^{-9}}$$
  - 3σ evidence for the B^0 channel:

    $$\mathbf{B(B^0 \rightarrow \mu^+\mu^-) = (3.9^{+1.6}_{-1.4})\ 10^{-10}}$$
  - some tension with the SM



CMS and LHCb, Nature 522 (2015) 68--72

ATLAS analysis on full Run 1 data

ATLAS, submitted to EPJC, arXiv:1604.04263

- ATLAS study on 25 fb^{-1} of Run 1 data:
  - 4.9 fb^{-1} of 7 TeV data taken in 2011
  - 20 fb^{-1} of 8 TeV data taken in 2012

- Improved analysis strategy:
  - dimuon triggers:
    - symmetric trigger requiring two muons with $p_T > 4$ GeV
      → good for 2011
      → prescaled in 2012, so three trigger categories
      merging asymmetric triggers *($p_T > 4$ and 6 GeV)*
      and central events *(one barrel muon with $|\eta| < 1.05$)*
  - both the inner detector and the muon spectrometer used for better mass resolution in the end-cap region.
  - background fighting with MVA classifiers:
    - *continuum-BDT* for reducing the combinatorial background
    - *fake-BDT* for reducing the hadron misidentification as muons
  - signal extraction with a *UML fit* to the dimuon invariant mass
  - normalisation with $B^{\pm} \to J/\psi K^{\pm}$ channel:
    yield, fragmentation and efficiency ratios

Analysis strategy: normalisation channel

- normalisation with $B^{\pm} \to J/\psi\ K^{\pm}$ channel:

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

$$\times \left[\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right]$$

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- correction for the efficiencies of the two channels
- correction for the different hadronisation probabilities for B^0_S and B^0 vs $B^{\pm}$
- include the $B^{\pm}$ and J/ψ branching fractions

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- Modify the above formula to take into account the three trigger categories and 2011 data
  - normalisation channel yield evaluated in each trigger and data category
  - same for the efficiency ratio

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$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \times \frac{f_u}{f_{d(s)}} \times \frac{1}{\mathcal{D}_{\text{norm}}}$$

$$\times \left[\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right]$$

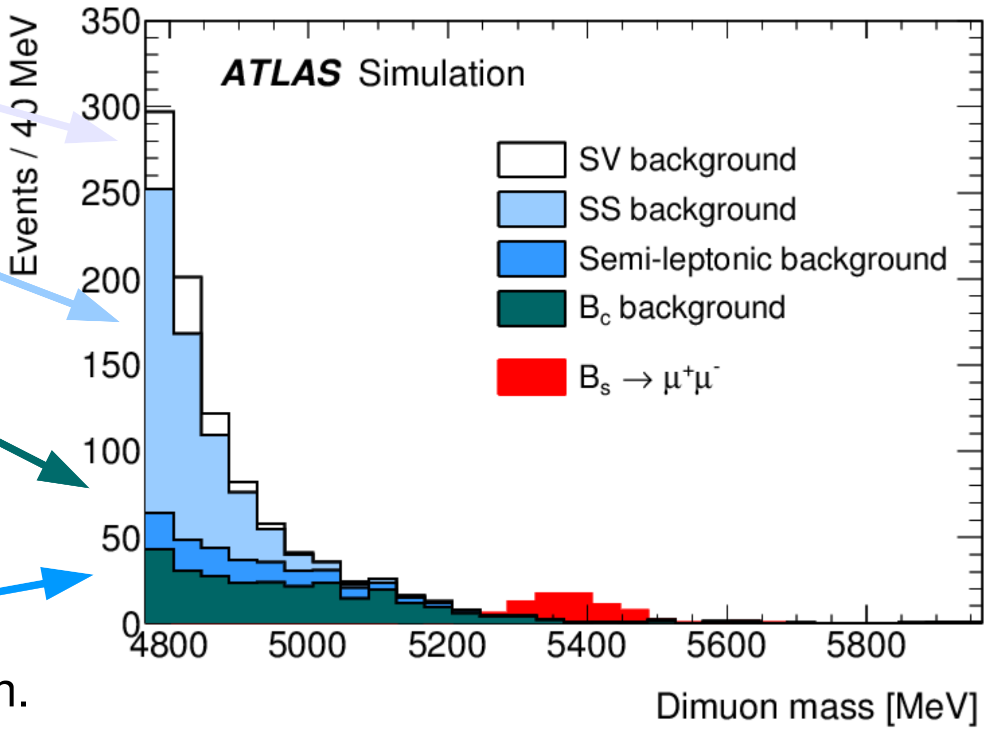
$$\mathcal{D}_{\text{norm}} = \sum_k N^k_{J/\psi K^+} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}}\right)_k$$

- index *k* runs on the trigger and data categories
- α_k takes into account the prescaling factors

Background contributions

In order of relative amplitude:

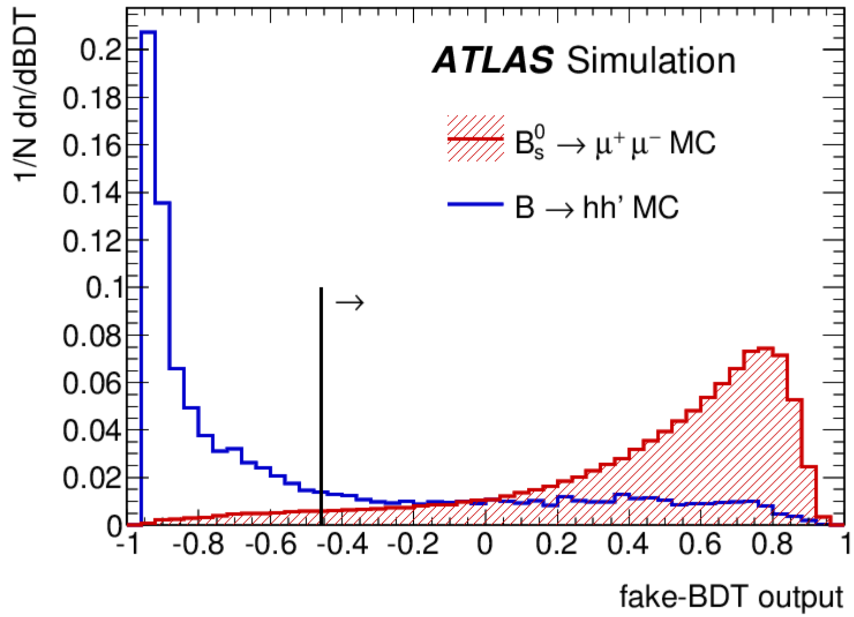
- combinatorial background from opposite-side muons:
  - dominant component
  - with smooth distribution across the dimuon invariant mass range
- partially reconstructed B decays:
  - Same Vertex (SV):
    $B \to \mu\mu X$ decays like $B \to K^*\mu\mu$
  - Same Side (SS):
    semileptonic decay cascades
    ($b \to c\mu\nu \to s(d)\mu\mu\nu\nu$)
  - B_c decays: like $B_c \to J/\psi\ \mu\nu$
  - all these accumulate at low values of the dimuon invariant mass
  - constituted by real muons



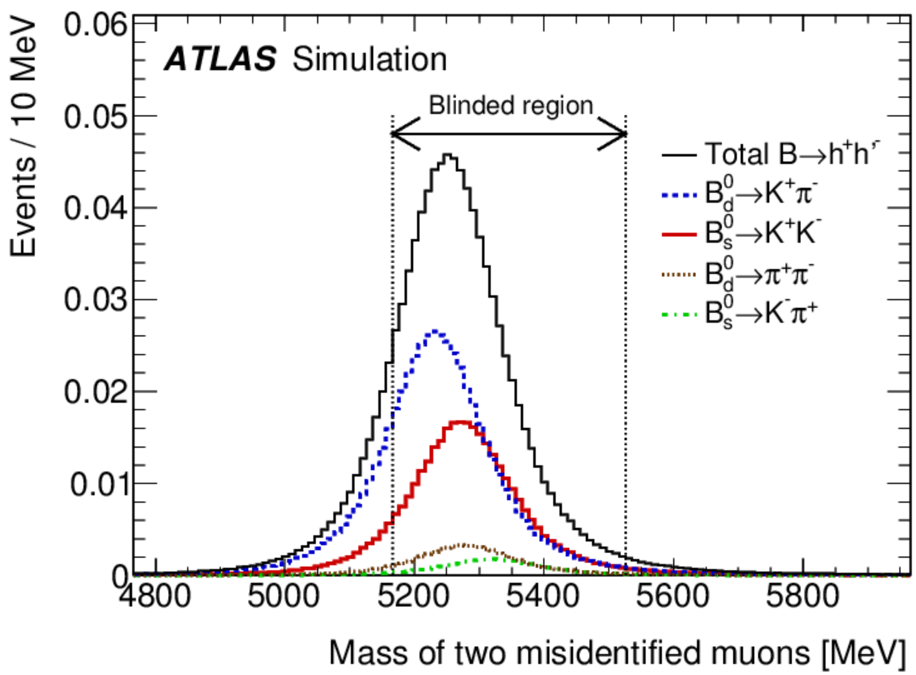
- semileptonic B and B_S decays:
  - one real muon and a charged hadron.
- peaking background from charmless hadronic $B_{(S)}$ decays:
  - B decays into two hadrons h (kaons and pions): $B^0_{(S)} \to hh'$
  - smaller component, but perfectly overlaid with the signal in dimuon invariant mass

Fake-BDT against hadron misidentification

- studied on simulated samples of $B \to hh'$, signal $B \to \mu\mu$, and $\Lambda_b \to ph$
- validated with data from $\phi \to KK$ and $B^{\pm} \to J/\psi K^{\pm}$ decays.
- the probability of misidentification of protons is negligible (< 0.01%)
- the probability of misidentification is about 0.28% for kaons and 0.12% for pions.



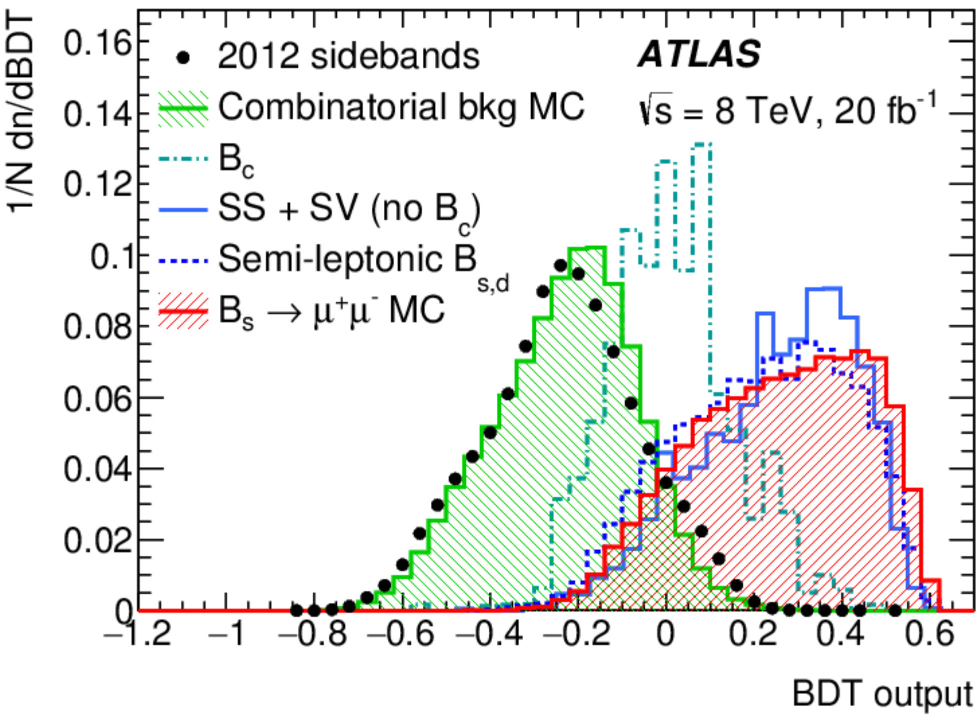
reduced of 0.4 with a dedicated *fake-BDT* with efficiency of prompt muons set at 95%



Use $B^{\pm} \to J/\psi K^{\pm}$ yield and efficiency ratio to normalise $B \to hh'$ (like for the signal): the total number of peaking-background events feeding into our events is 1.0±0.4

Continuum-BDT against combinatorial bkg

- combinatorial background: muon pairs from uncorrelated decays of hadrons produced in the hadronisation of b and $\bar{b}$ quarks (or c and $\bar{c}$ quarks).
- separated from signal with a MVA classifier:
- 15 variables related to the B candidate, to the muons from the B candidate, to the other tracks from the same collision and to pile-up vertices.

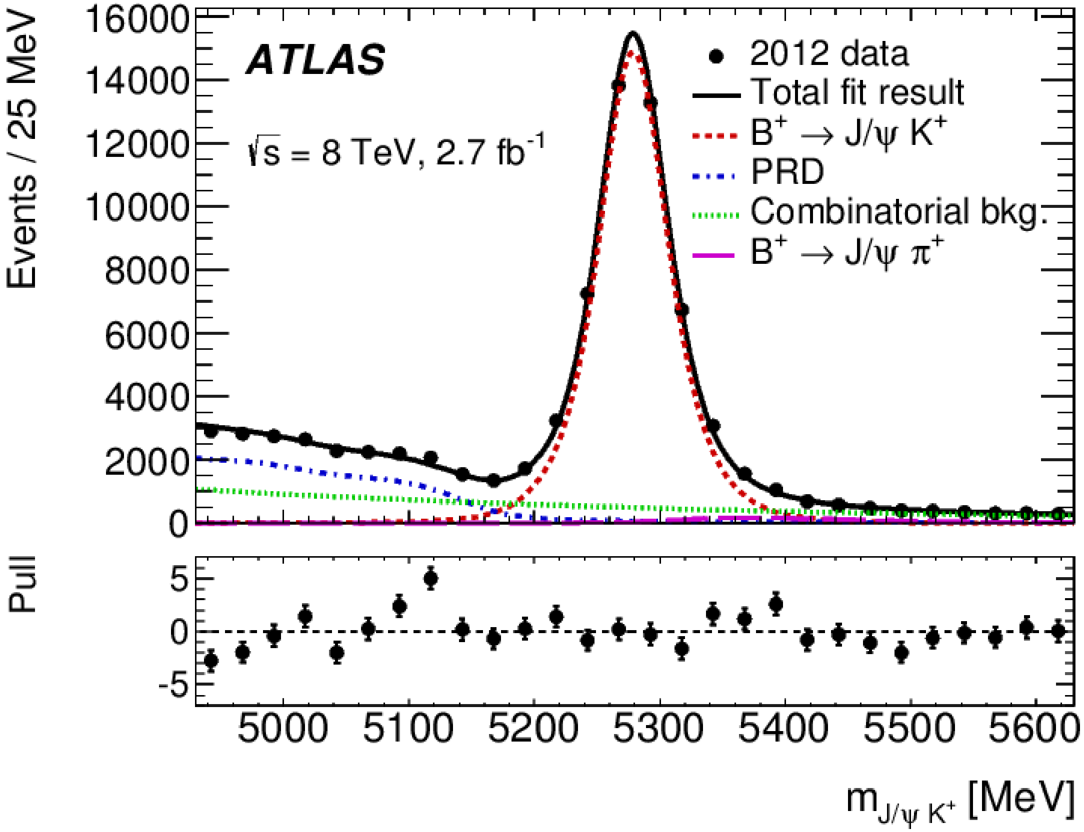


- training of the continuum-BDT done on a large MC sample of uncorrelated b (c) and $\bar{b}$ ($\bar{c}$) hadrons with forced decays into final states containing muons: 1.4G MC events
- tested on high-mass sideband data: not perfect data-MC agreement, but sample good enough for training, which is the sole use of this sample.
- B-related backgrounds behave like signal: SS-SV, semileptonic decays, peaking background

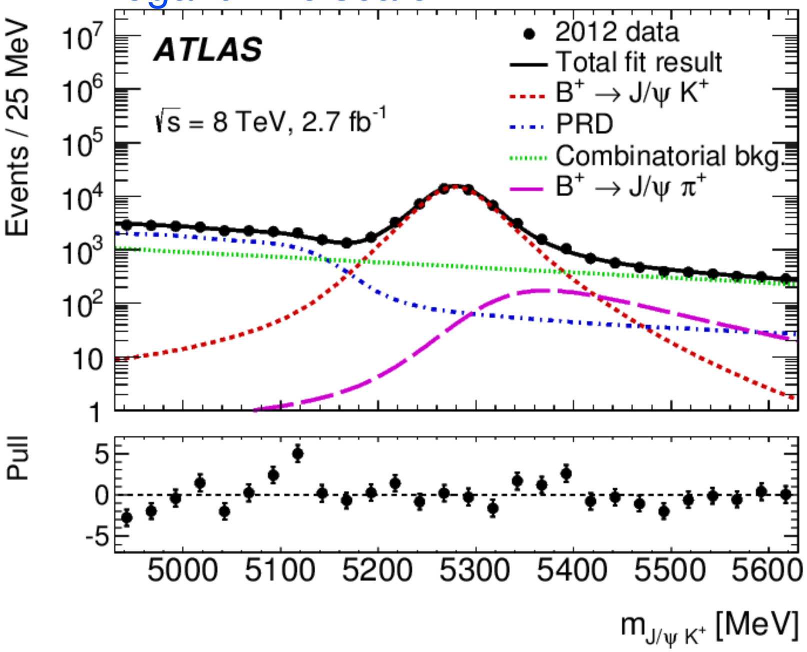
Normalisation B yield extraction

- applied fake-BDT and continuum-BDT selections (optimised for signal)
- yields extracted separately in the 4 categories:
  three trigger categories for 2012 and 2011 data
- unbinned maximum likelihood fit of the invariant mass $m_{J/\psi K} \rightarrow m_{\mu\mu K}$
- measurement of $J/\psi\pi$ over $J/\psi K$ ratio $\rho_{\pi/K} = 0.035 \pm 0.003 \pm 0.012$

example for one 2012 trigger category



logarithmic scale



Efficiency ratio $\varepsilon_{\mu\mu}/\varepsilon_{J/\psi K}$

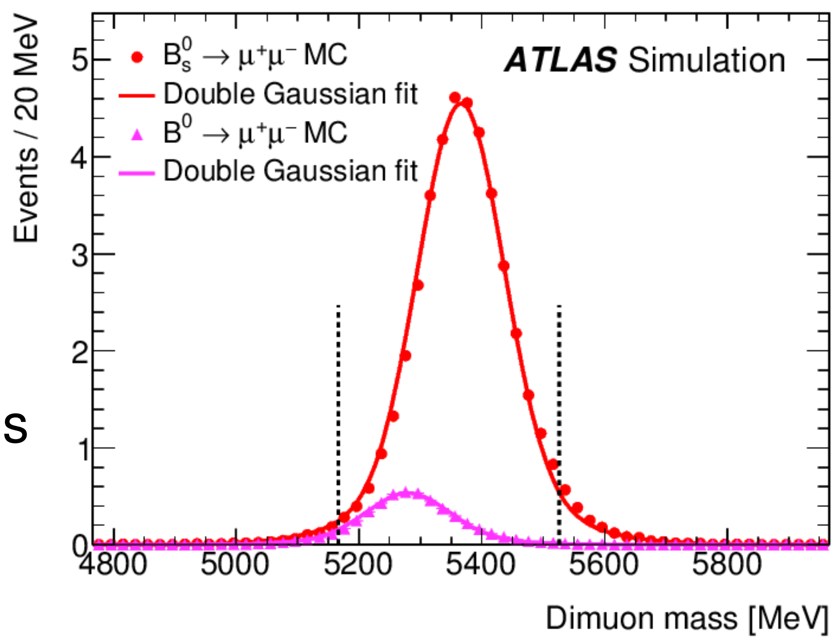
$$\mathcal{D}_{\rm norm} = \sum_k N^k_{J/\psi K^+} \alpha_k \left(\frac{\varepsilon_{\mu^+\mu^-}}{\varepsilon_{J/\psi K^+}}\right)_k$$

- in each category (k) the efficiency ratio is obtained from MC
- p_T and η MC spectra are tuned on data from the reference channels:
- residual trigger efficiency differences from tag&probe studies on J/ψ and Υ
- systematic uncertainty from data-MC discrepancies:
  assessed from the data-MC comparisons of the discriminating variables used in the continuum-BDT: dominant systematic contribution to D_{norm}
  - isolation requires tuning in the $B^{\pm}$ mode:
  - central value of the efficiency ratio corrected with this tuning
- For B^0_S:
  - correction for lifetime difference between the B^0_S mass eigenstates: lifetime from SM prediction and efficiency correction (+4%) from MC

Total correction to the central value of the efficiency ratio:
+3% for B^0 and -1% for B^0_S (including the lifetime correction)

Total systematic uncertainty ±5.9% on the normalisation term D_{norm}

Signal yield extraction



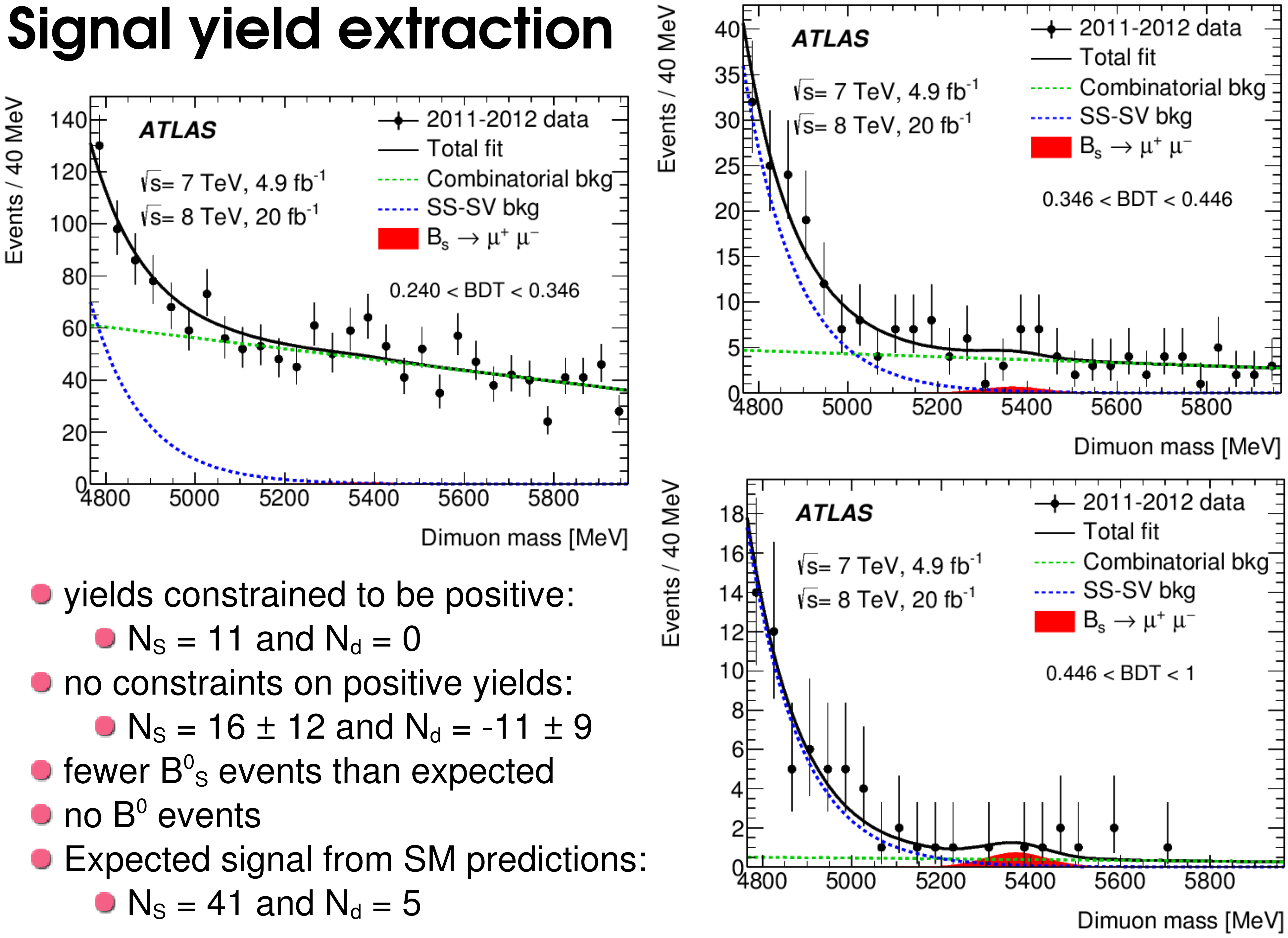
- signal yields (N_d and N_S) extracted with a unbinned maximum likelihood fit to the dimuon invariant mass distribution
- fit performed simultaneously in the categories corresponding to three continuum-BDT bins with constant signal efficiency (18%)

- *signal*: two Gaussian distributions with common mean, shape constrained across continuum-BDT bins and fixed to the MC shapes, varied for systematic uncertainty
- *SS-SV background*: exponential distribution, parameters floated in the fit, shape constrained across the continuum-BDT bins, independent normalisations.
- *peaking background*: two Gaussian distributions constrained across continuum-BDT bins and fixed to the MC shapes, normalisation fixed to 1.0±0.4 total events
- *continuum background*: first order polynomial, parameters floated in the fit, shape loosely constrained across the continuum-BDT bins, independent normalisations

- systematics obtained by varying all the above:

  $\sigma_{syst}(N_S) = \sqrt{2^2 + (0.06 \times N_S)^2}$ and $\sigma_{syst}(N_d) = 3$ events

Signal yield extraction



- yields constrained to be positive:
  - N_S = 11 and N_d = 0
- no constraints on positive yields:
  - N_S = 16 ± 12 and N_d = -11 ± 9
- fewer B^0_S events than expected
- no B^0 events
- Expected signal from SM predictions:
  - N_S = 41 and N_d = 5

Branching fraction extraction

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \times \frac{f_u}{f_{d(s)}} \times \frac{1}{\mathcal{D}_{\rm norm}}$$

$$\times \left[\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to \mu^+\mu^-)\right]$$

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

The normalization includes:

- $B^{\pm}$ branching fraction (world averages)
- the fragmentation fraction f_u/f_S from the ATLAS measurement of f_S/f_d performed in the same p_T, η range: 0.240 ± 0.020 (8% systematic)
- the efficiency ratios and $B^{\pm}$ yields in the D_{norm} term
- The total uncertainty in the normalisation is
  - ±11% for BR($B^0_S \to \mu^+\mu^-$)
  - ± 7% for BR($B^0 \to \mu^+\mu^-$)

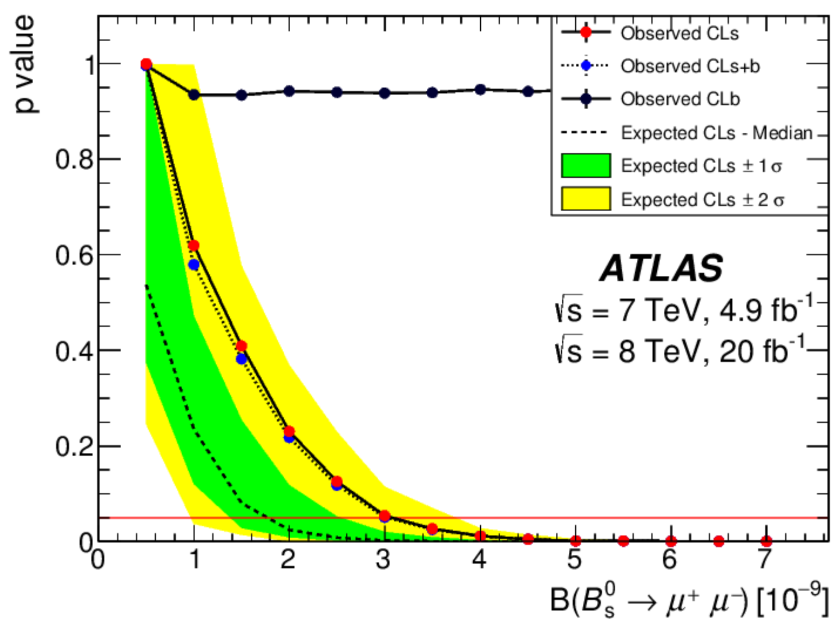
ATLAS PRL 115 (2015) 262001

Result for the B^0_s branching fraction

- central value obtained with non-negative branching fractions
- the errors obtained by a frequentist belt, using pseudo-MC experiments and include both statistic and systematic uncertainties.
- the systematic uncertainty is
  - $\sigma_{syst} = \pm\, 0.3 \times 10^{-9}$

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

- the upper limit from CLs is
  - $B(B^0_s \to \mu^+\mu^-) < 3.0 \times 10^{-9}$ at 95% CL
- the observed compatibility with the null hypothesis (only background) has
  - $p = 0.08\ (1.4\sigma)$
- the expectation for a SM signal is
  - $p = 0.0011\ (3.1\sigma)$

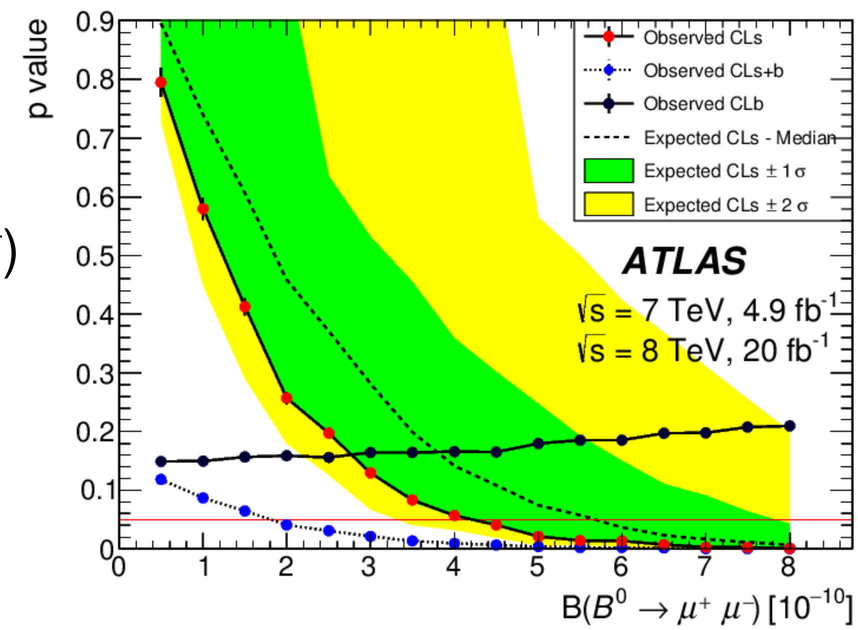


Result for the B^0 branching fraction

- upper limit set using CLs technique

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

- no signal, $B(B^0_S \to \mu^+\mu^-)$ left free to be determined in the fit
- CL_b is ≈ 0.15 for $B(B^0 \to \mu^+\mu^-)$ near 0:
  - -1σ fluctuation of background
- expected limit $< 5.7^{+2.1}_{-1.2} \times 10^{-10}$
- the limit is higher than the SM prediction
  - $B(B^0)_{SM} = (1.06 \pm 0.09) \times 10^{-10}$
- the expected significance for $B(B^0 \to \mu^+\mu^-)$ assuming the SM branching fraction is 0.2σ



Likelihood contours

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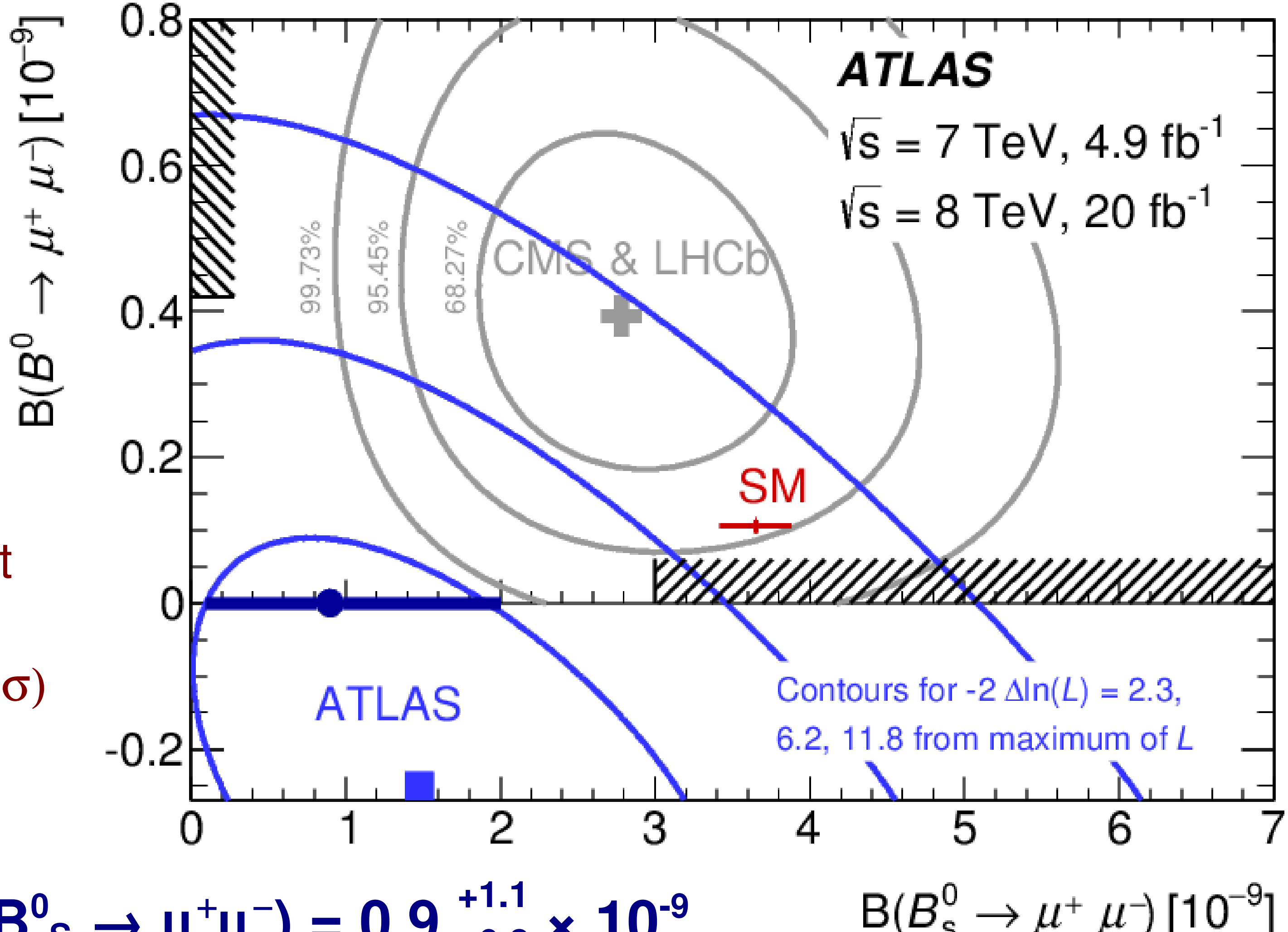

compatibility
of the simultaneous fit
with the SM:
p-value = 0.048 (2.0σ)

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

Few words on $K^*\mu\mu$ at 8 TeV at ATLAS

- ongoing work on 20 fb^{-1} of 8 TeV data
- completely revisited analysis
- thorough study of background contributions
  - with exclusive MC samples produced
  - vetoed or included in the mass and angular fits
- the J/ψ control region is exploited to test the selections and the fits
- aim at perform the angular analysis
- as usual: very limited in (wo)man power
  - so no official word on the possible time line :)

Conclusions

- Run 1 study on rare B decays into muons just submitted to the journal:

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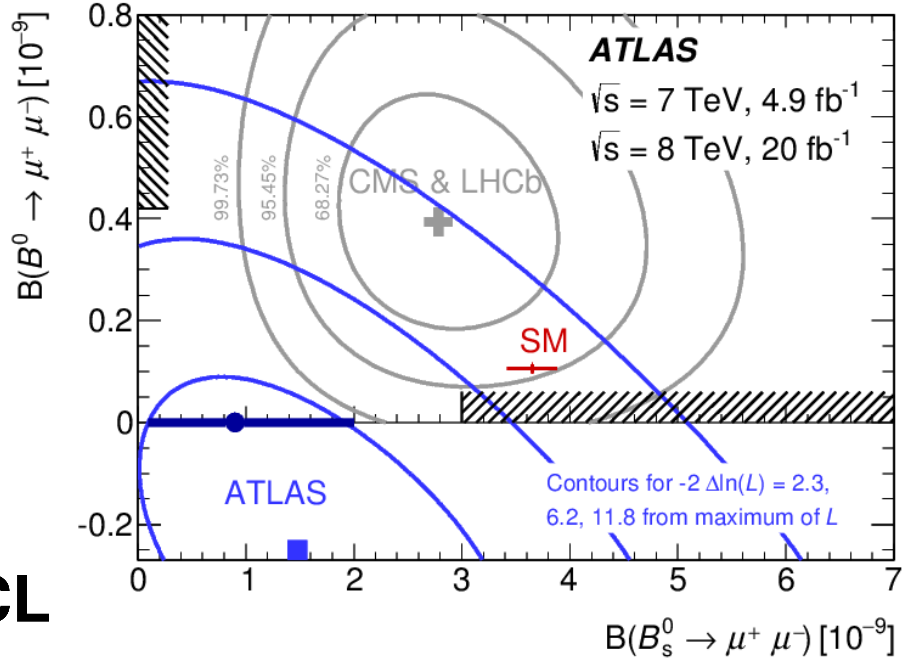
$B(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$ at 95% CL



- compatibility of the simultaneous fit with the SM: p-value = 0.048 (2.0σ)
- a possible LHC average will slightly increase the tension with the SM for the B_s branching fraction

- ATLAS is working on K*μμ angular analysis on 20 fb^{-1} of 8 TeV data with better background understanding and improved fit strategy

- B physics in ATLAS is healthily challenging and very much alive.

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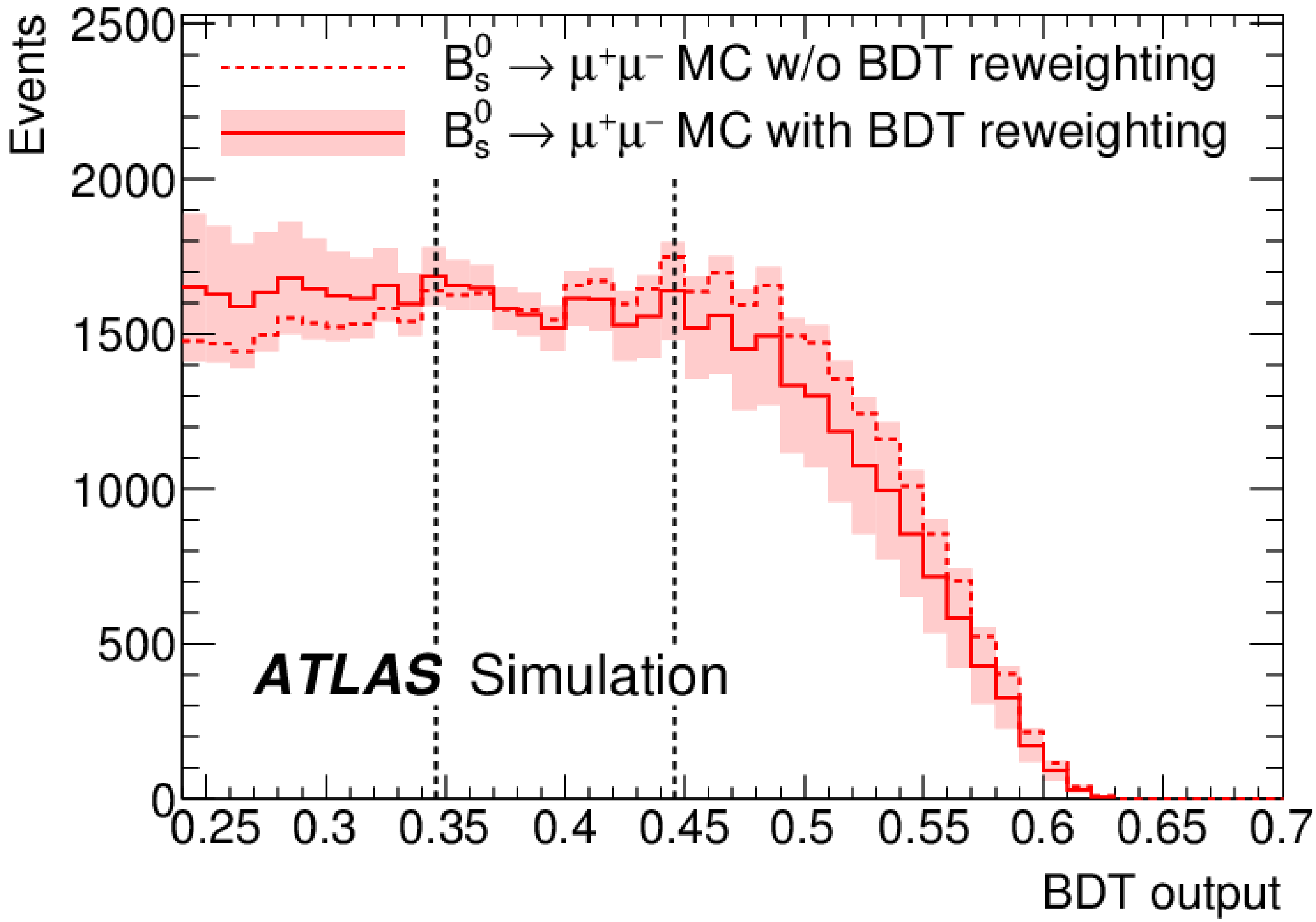
back-up slides

Continuum-BDT bins



Total systematics on the BR 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}

Normalisation B yield extraction:

- yields extracted separately in the 4 categories:
  three trigger categories for 2012 and 2011 data
- unbinned maximum likelihood fit of the invariant mass $m_{J/\psi K} \rightarrow m_{\mu\mu K}$
- detailed study on partially reconstructed decays (PRD)

example for one 2012 trigger category