Latest B $\rightarrow$ $\mu^+\mu^-$ results with the ATLAS detector

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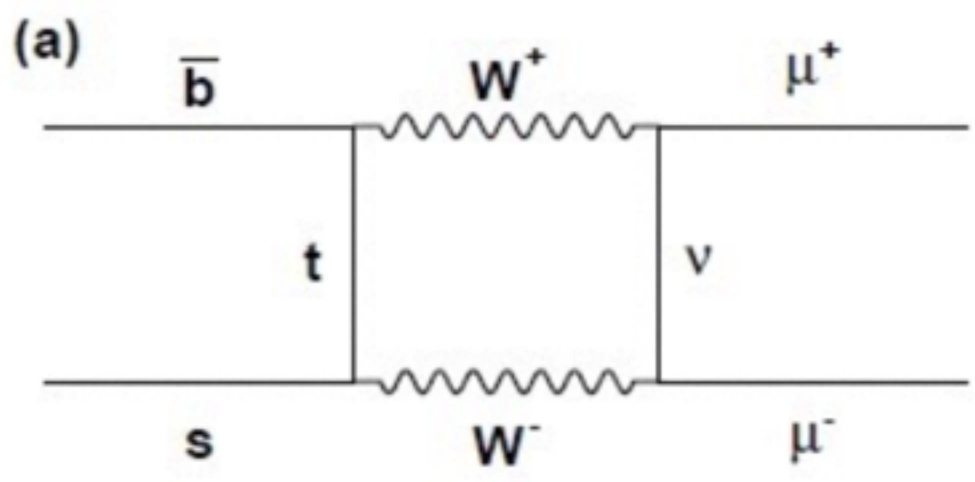
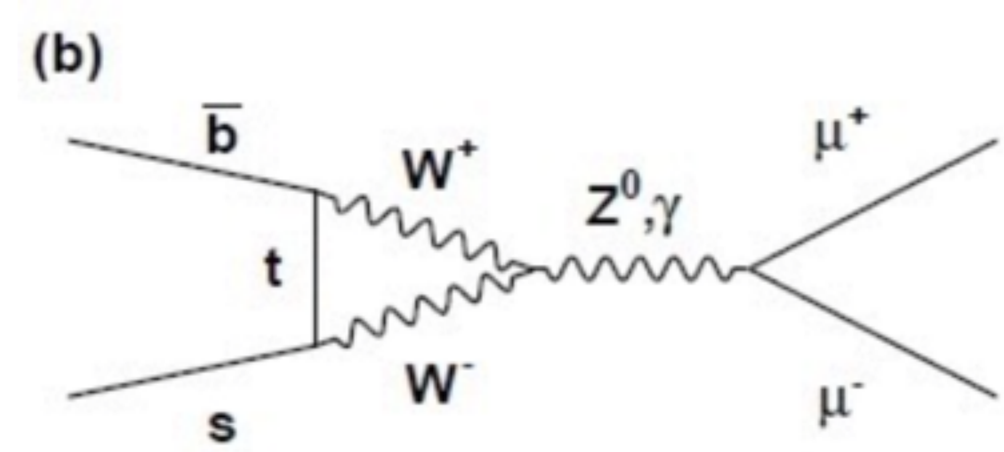
Outline

- Introduction: BSM searches in B-physics
- 2015/16 B —> $\mu^+\mu^-$ analysis
- B —> $\mu^+\mu^-$ Run 2 and HL-LHC projections

FNCN BSM searches in B-physics

- Some B-physics rare and semi-rare processes are mediated by flavour changing neutral current (FCNC)
  - No tree-level SM Feynman diagrams





- Suppressed SM amplitudes
  - Sensitive to small effects from NP loop contributions
  - We can indirectly search for new physics at scales beyond the reach of the LHC
  - **Sensitive probe for beyond standard model physics**

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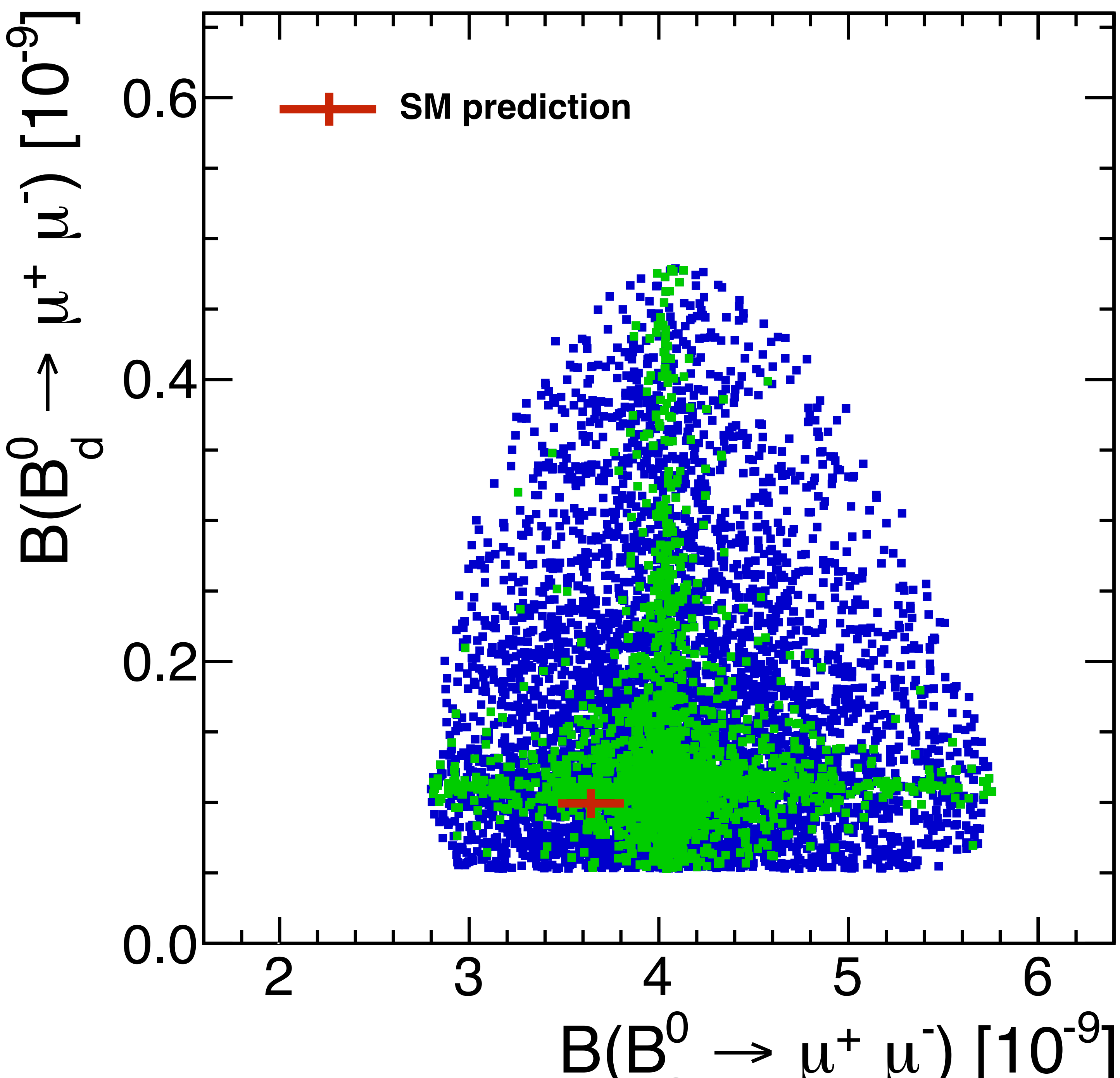
BSM searches in B-physics

- green and blue points show the possible effects of new physics on BR($B_d \rightarrow \mu^+\mu^-$) - BR($B_s \rightarrow \mu^+\mu^-$)



- new physics based on Phys. Rev. D 91, 095011 (2015)
- potential large effects with respect to SM prediction uncertainty
- measured NP effects on FCNC would translate into hints of NP scale

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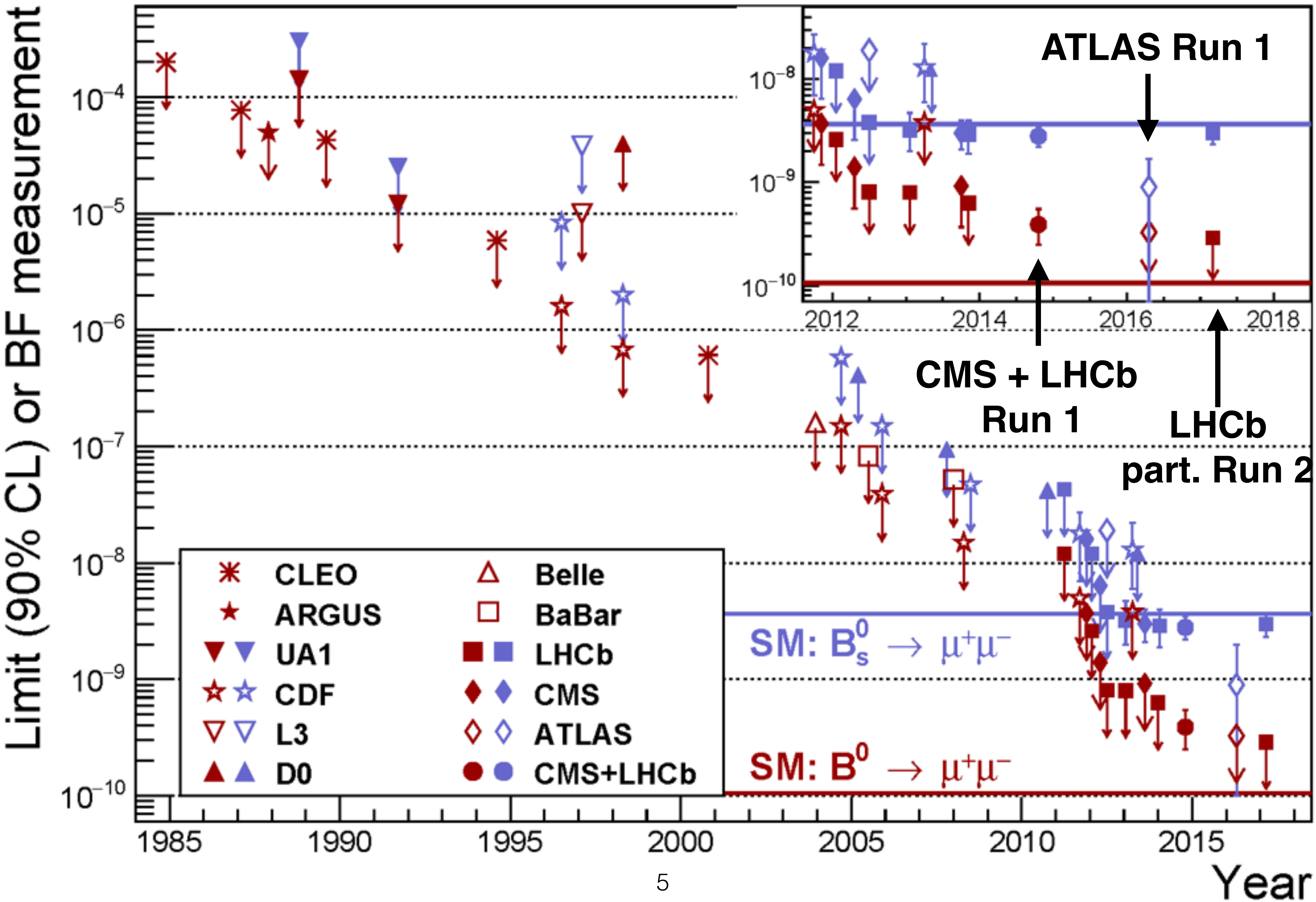
B → $\mu^+\mu^-$ state of the art

(as in August 2018)



$B \to \mu^+\mu^-$ analysis strategy

- New ATLAS analysis on 2015 / 16 data
- Measurement relative to $B^+ \longrightarrow J/\Psi\, K^+$ (normalisation channel)

$$\mathcal{B}(B_x^0 \to \mu^+\mu^-) = \frac{f_u}{f_x} \times \mathcal{B}(B^+ \to J/\psi\, K^+, \psi \to \mu^+\mu^-) \times \frac{N_x}{N_{J/\psi K^+}} \times \frac{\varepsilon_{J/\psi K^+}}{\varepsilon_x}$$

x = s / d

Relative production of B^0_x and B^+ (HFLAV world average)

Reference channel BR (PDG)

Signal yields, extracted from mass fit on data

relative efficiency, extracted from MC

- Blind analysis, mass region around signal peaks blinded

- Overwhelming non-resonant dimuon background
  - BDT trained for bb background reduction

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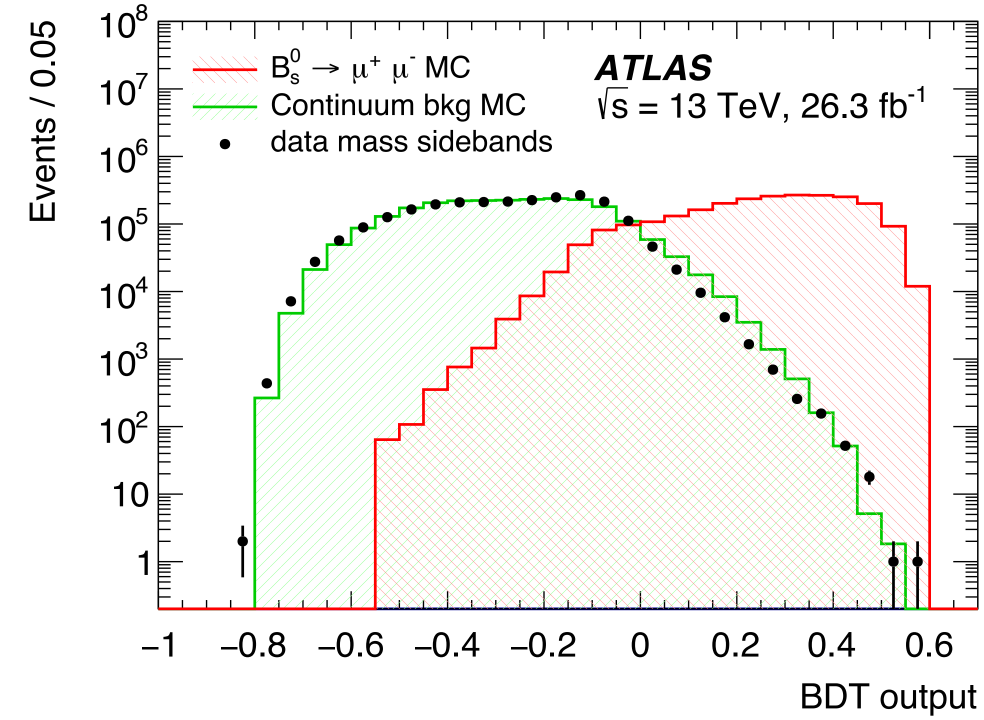
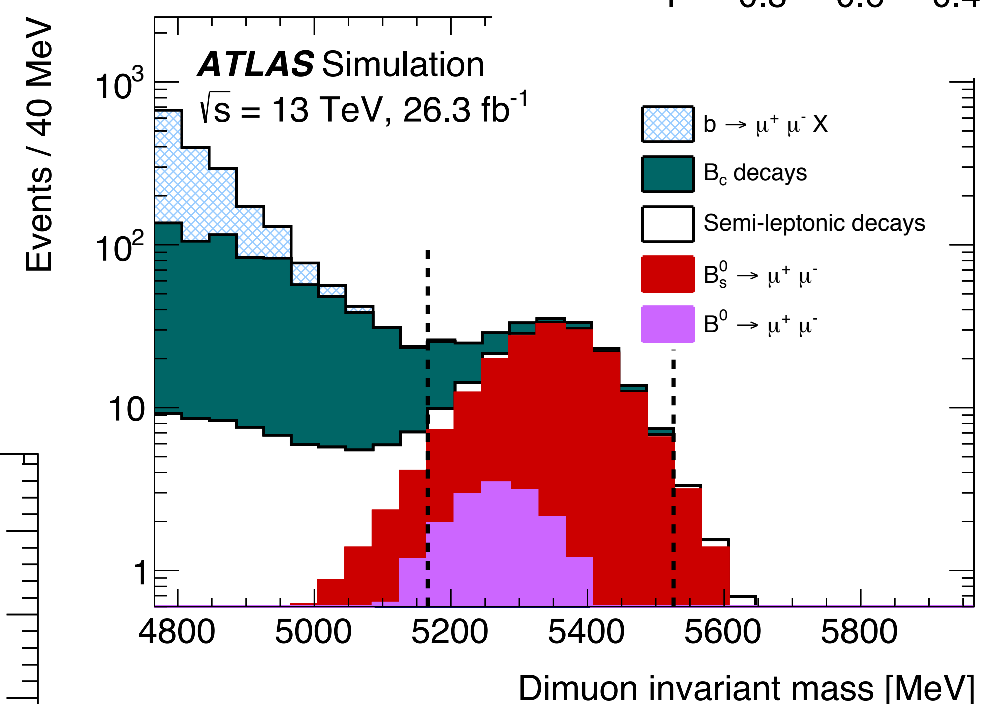
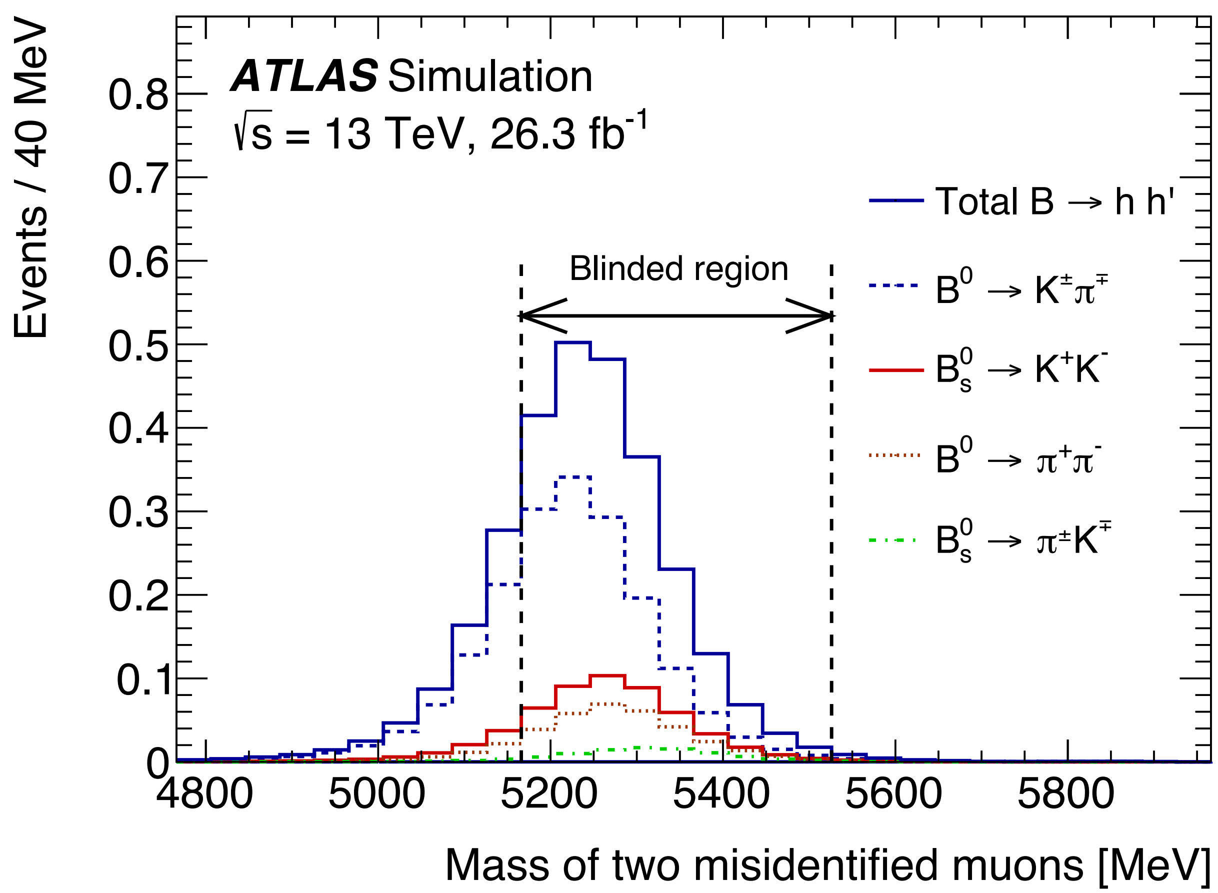
B → μ⁺μ⁻ backgrounds



- Three main background sources
  - **Continuum**:
    - Main background
    - Highly reduced with BDT
  - **Partially reconstructed**:
    - include several sources
    - Accumulate at low mass





- **Peaking background**:
  - B—>hh' with two fake mu
  - Small but superimposed with signal
  - Mis-identification reduced using tight muons

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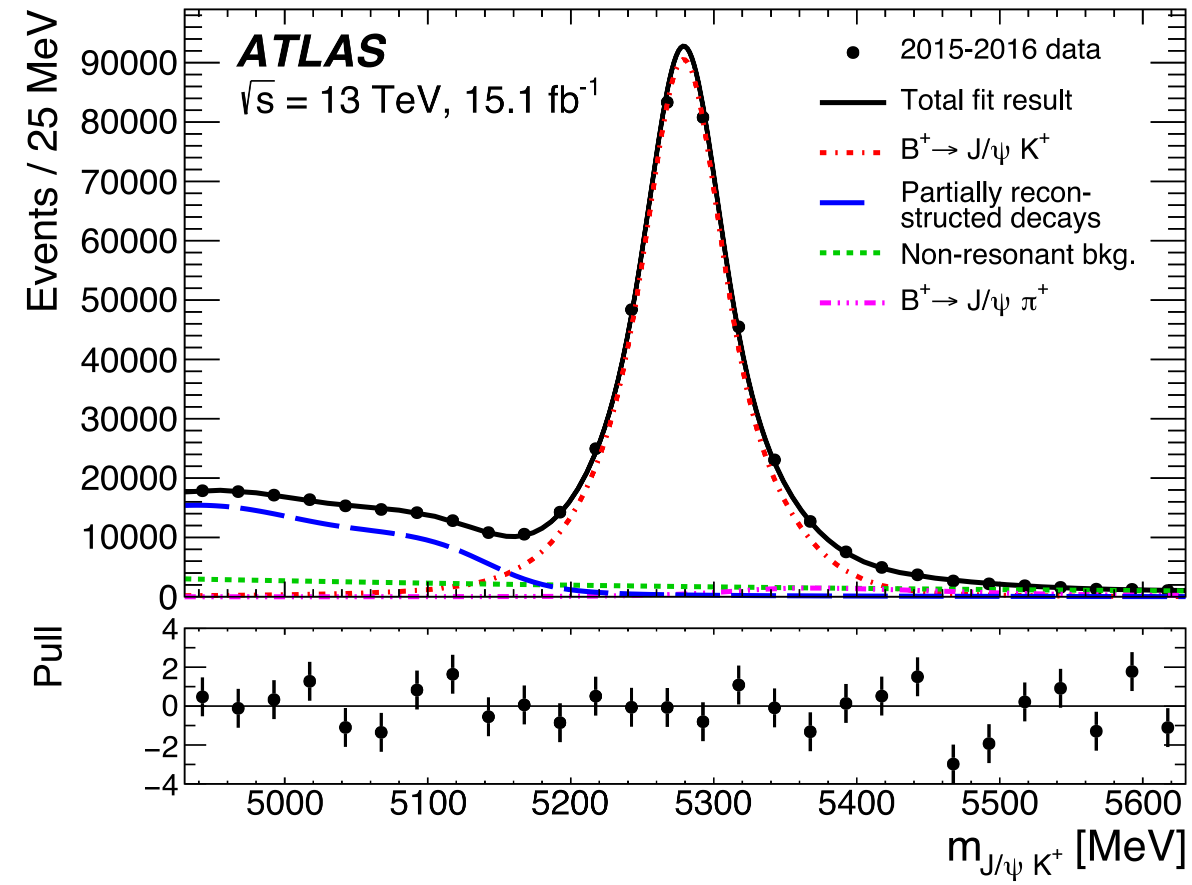
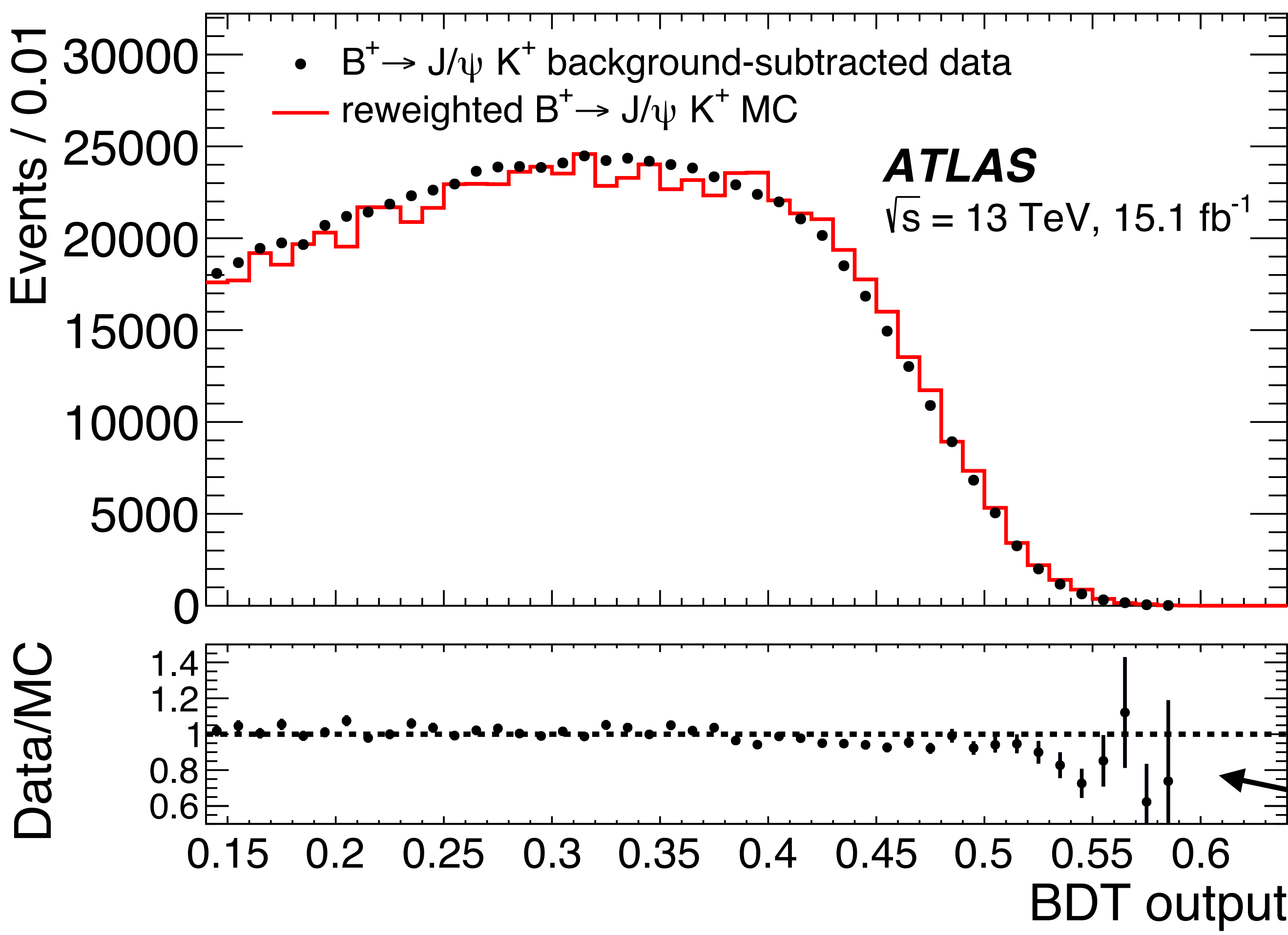
CERN-EP-2018-291

Normalisation channel

- Extended unbinned maximum likelihood fit on B^+ mass distribution from data
- $N(B^+) = 334351 \pm 0.3\%$ stat $\pm$ 4.8% syst





- Efficiency relative to $B_s \longrightarrow \mu^+\mu^-$ signal
  - Extracted from MC
  - Corrected with data driven methods
    - based on $B^+ \longrightarrow J/\Psi K^+$ and $B_s \longrightarrow J/\Psi \Phi$ data
  - Residual data-MC discrepancies fed into systematics

Signal yield extraction

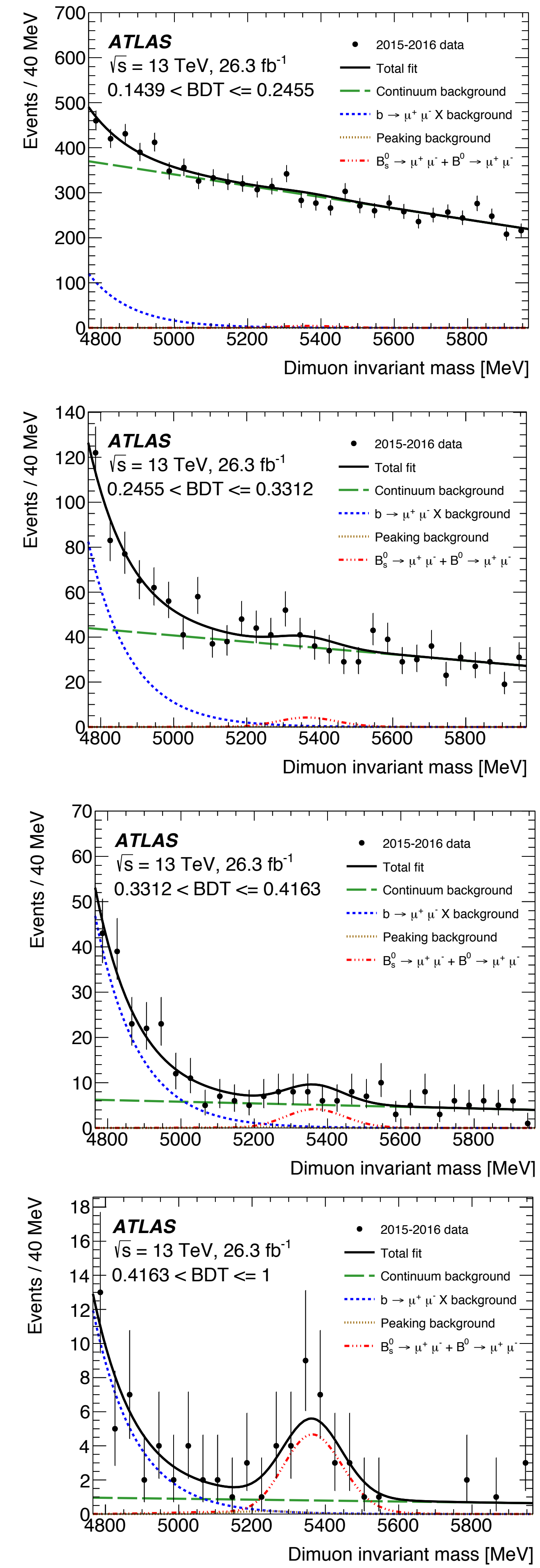
- Simultaneous extended ML fit on 4 BDT bins
- Models:
  - Signal, B—>hh: double gaussian

    → fixed shape, data-driven normalisation

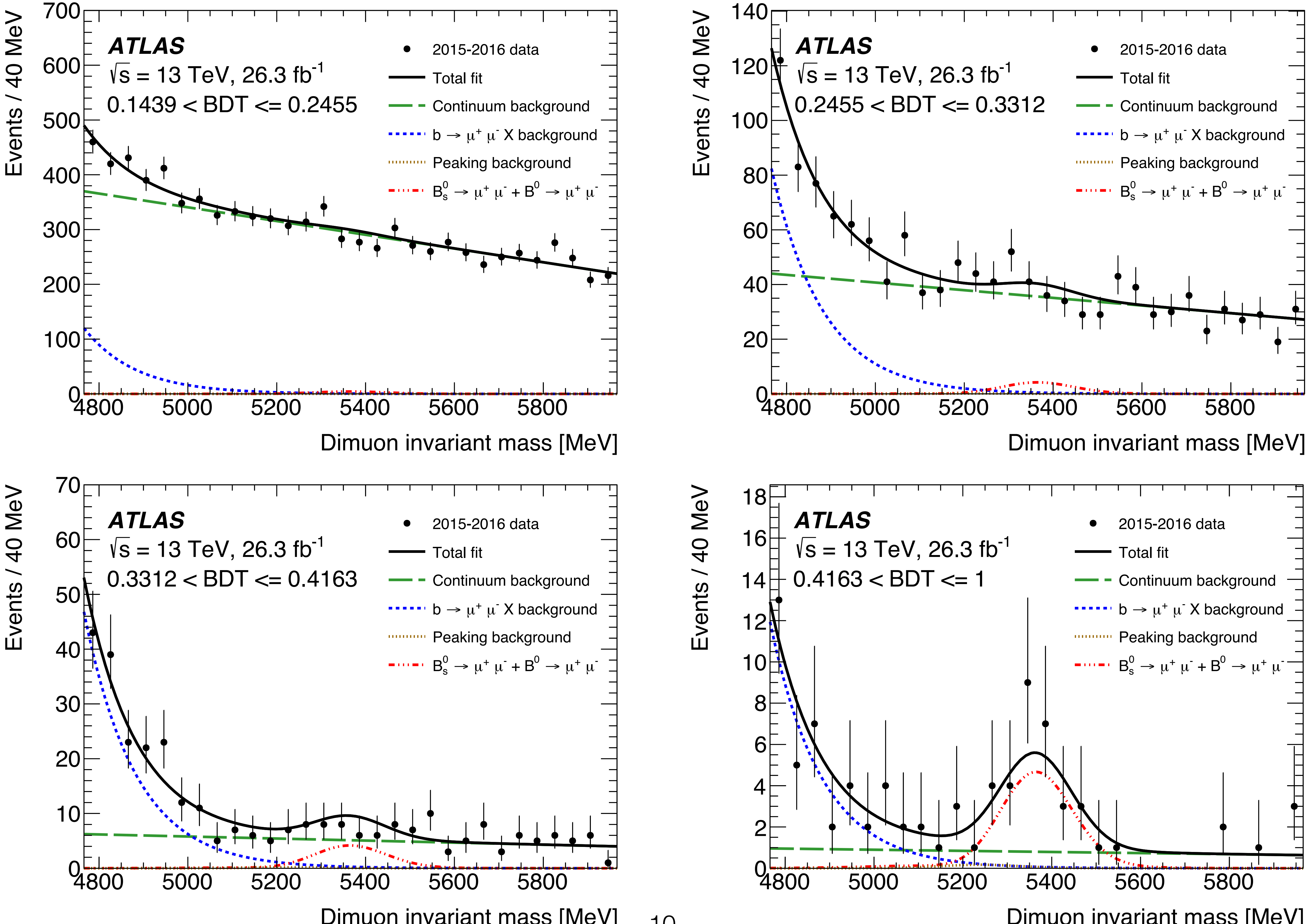
  - partially reconstructed: exponential
  - Continuum bkg: pol1

    → data-driven shape and normalisation

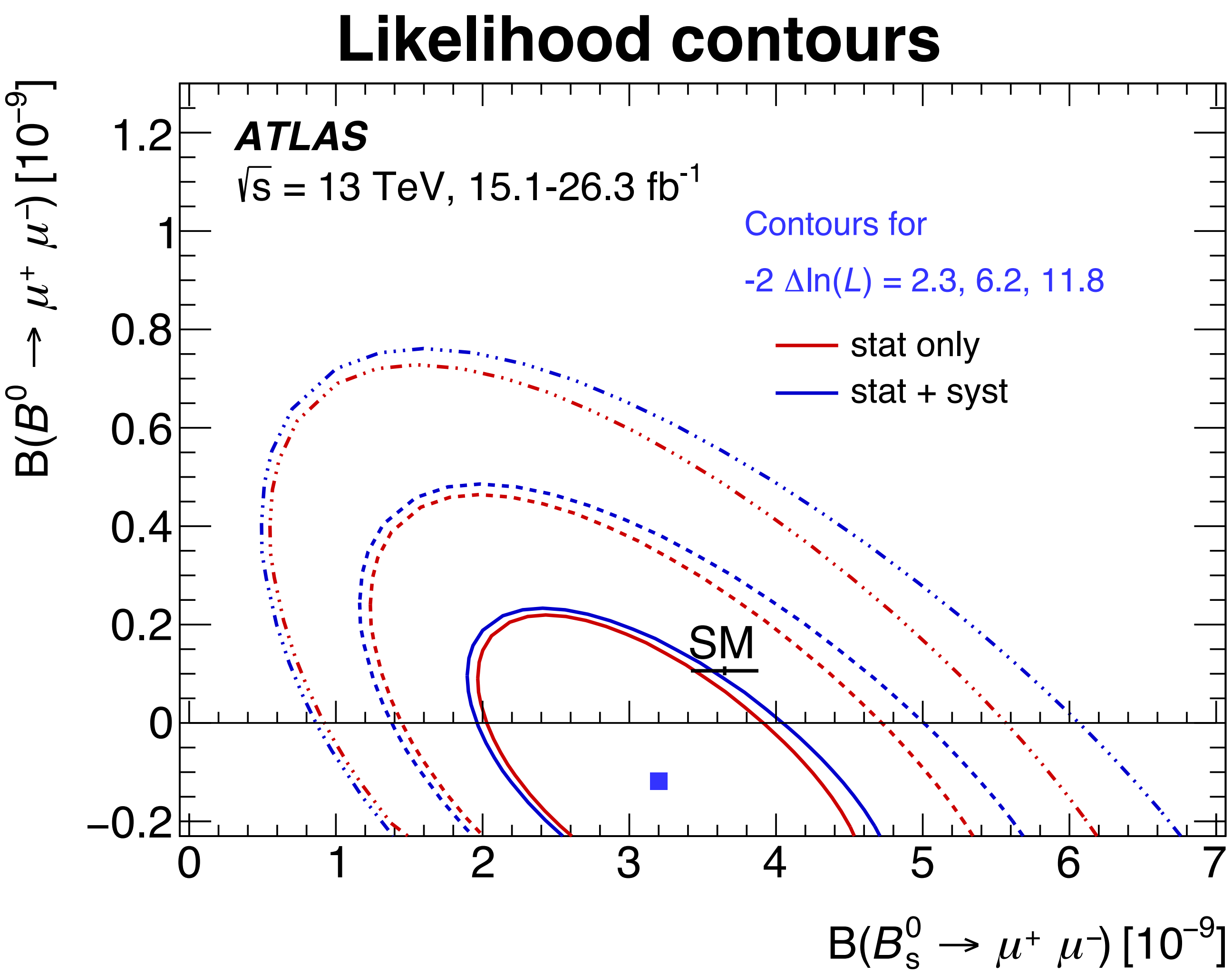
- Signal yield:
  - Expected: $N(B_s) = 91$, $N(B_d) = 10$
  - Found: $N(B_s) = 80 \pm 22$, $N(B_d) = -11 \pm 19$

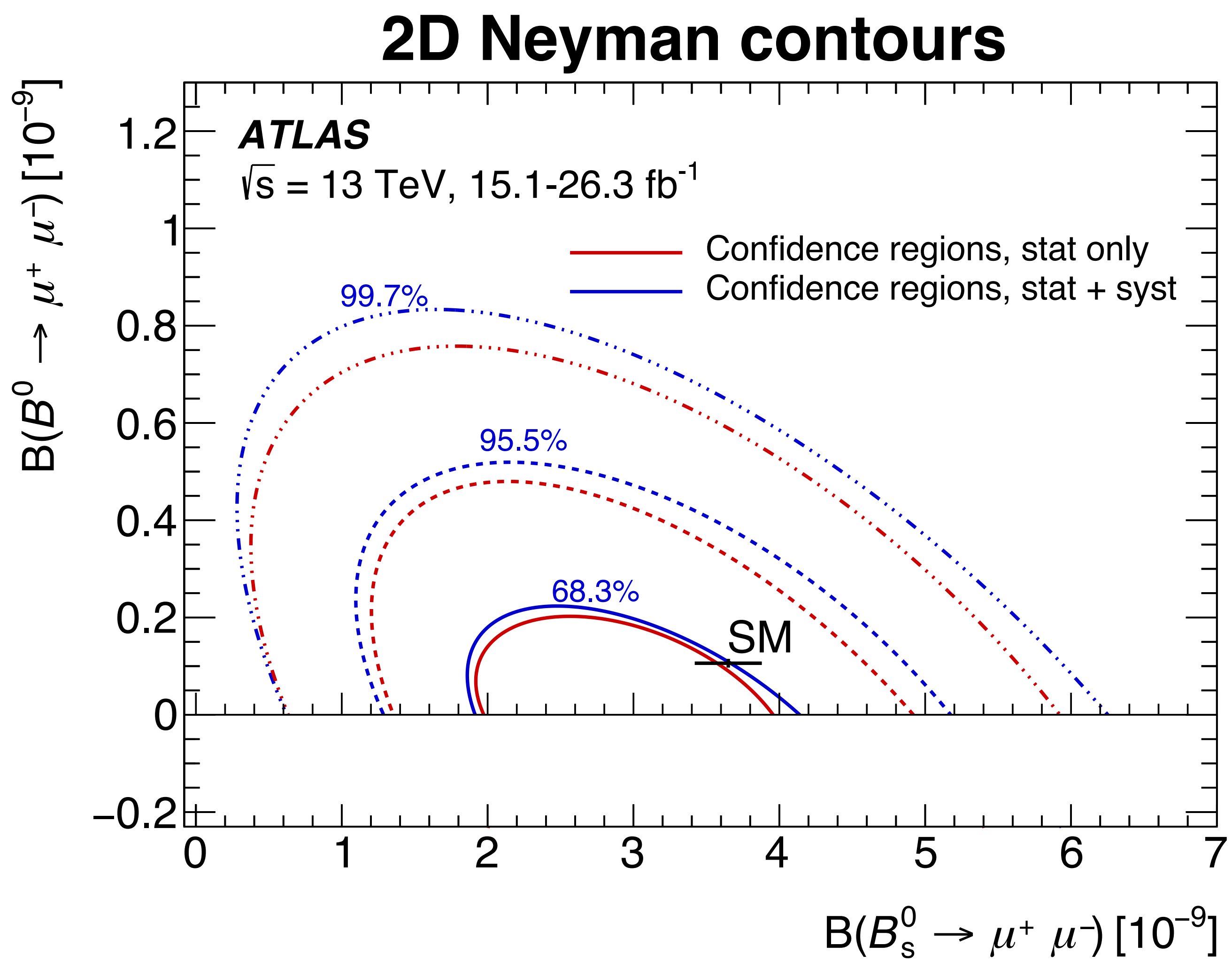


Signal yield extraction



BR extraction





- Using the Neyman frequentist approach, including systematics:

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9} = \left(3.2^{+1.1}_{-1.0}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 4.3 \times 10^{-10} \text{ at 95\% CL}$$

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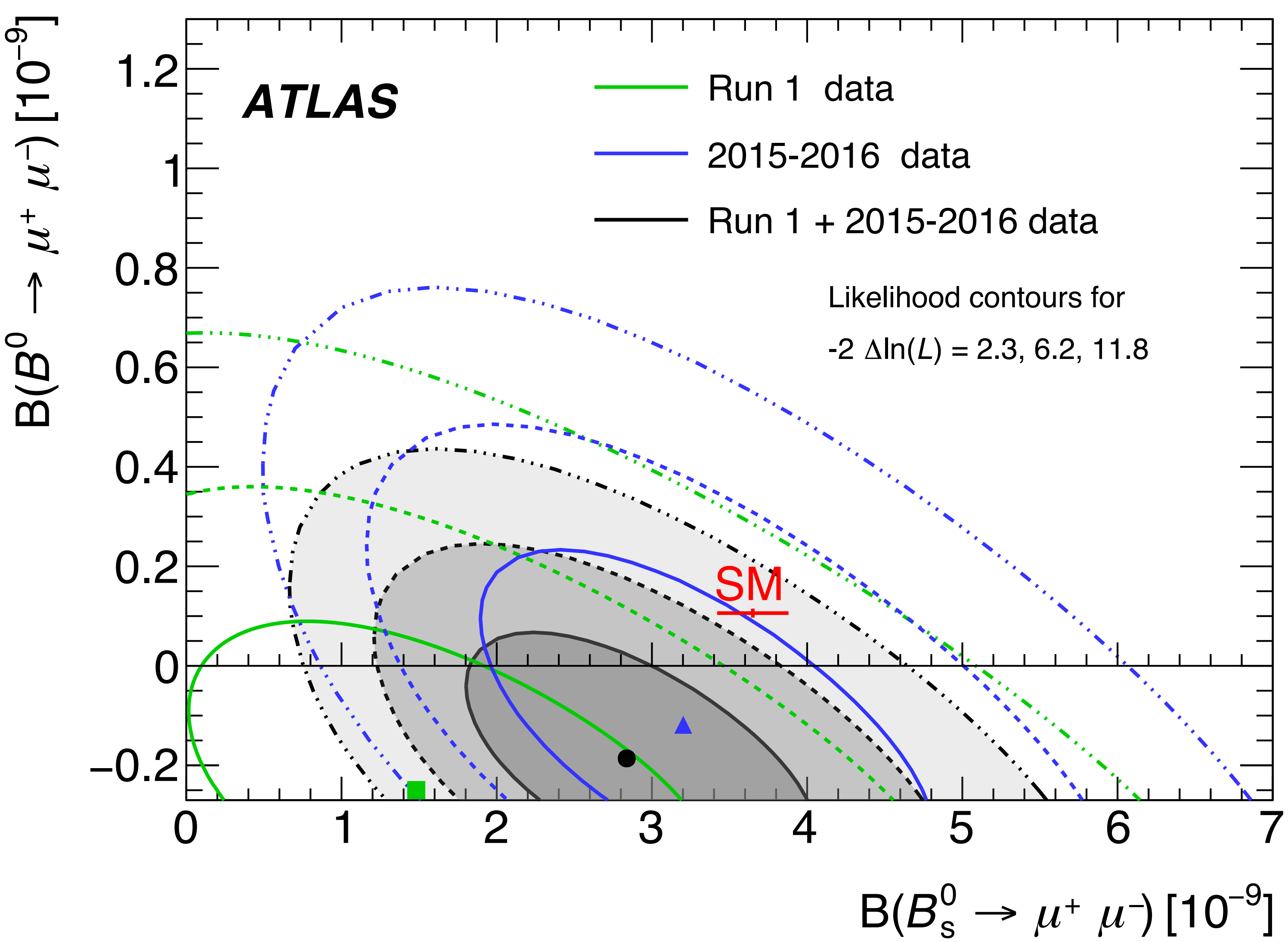
Combination with Run 1

- Combine Run 1 and 2015/16 likelihoods
  - Common parameters:
    - Reference channel BR
    - Hadronisation probability



- Exploiting Neyman construction:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

<u>Most stringent upper limit on the market!!!!</u>

- B^0_s—>μμ combined significance: 4.6 sigma

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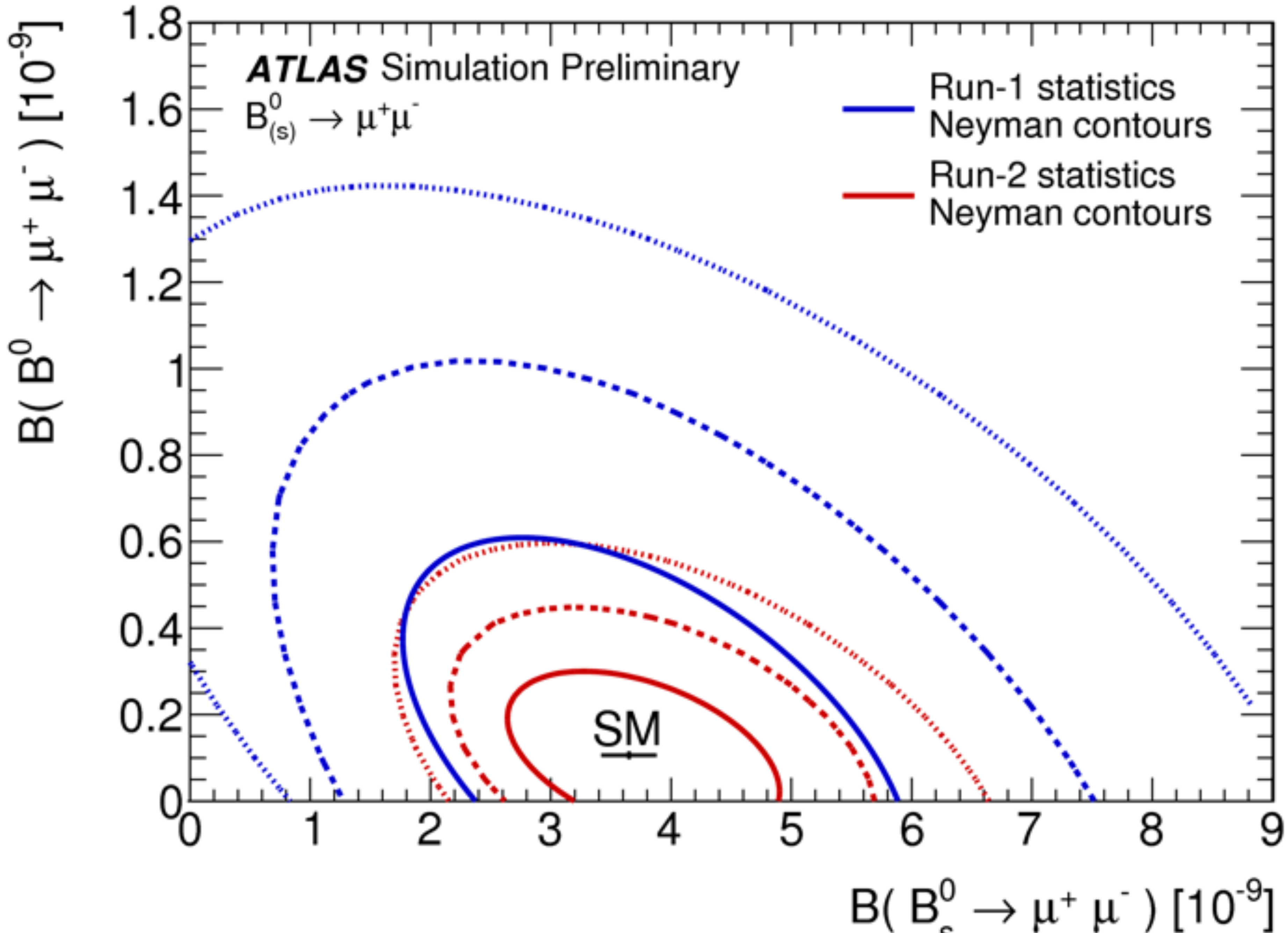
B —> $\mu^+\mu^-$: Run 2 and HL-LHC

Run 2 projection

- Based on Run 1 analysis (projection precedes 2015-2016 result)
- Increased b production X-sec w.r.t Run 1
- Integrated luminosity: 130 fb^{-1}
- Consider a mixture of different triggers, in order to maximise the statistics



- Expected **~x7 Run 1 statistics**
- Systematic uncertainties assumed to behave as in Run 1 analysis

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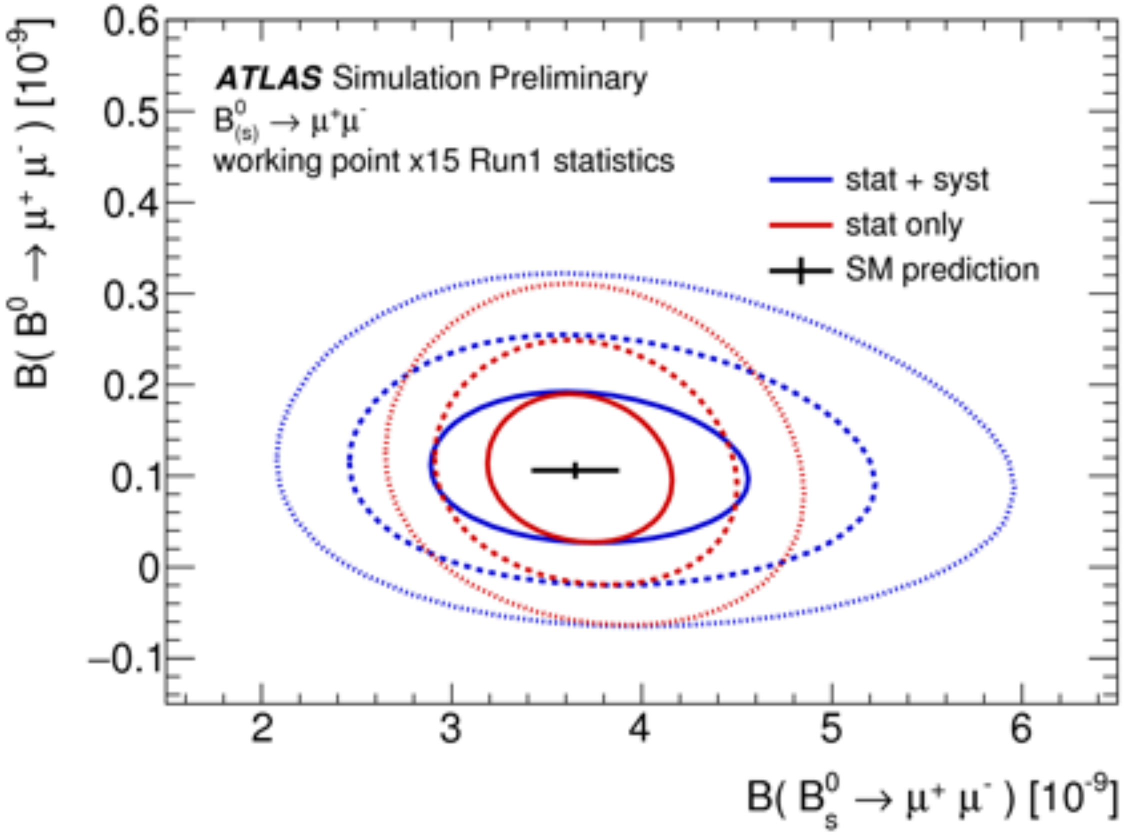
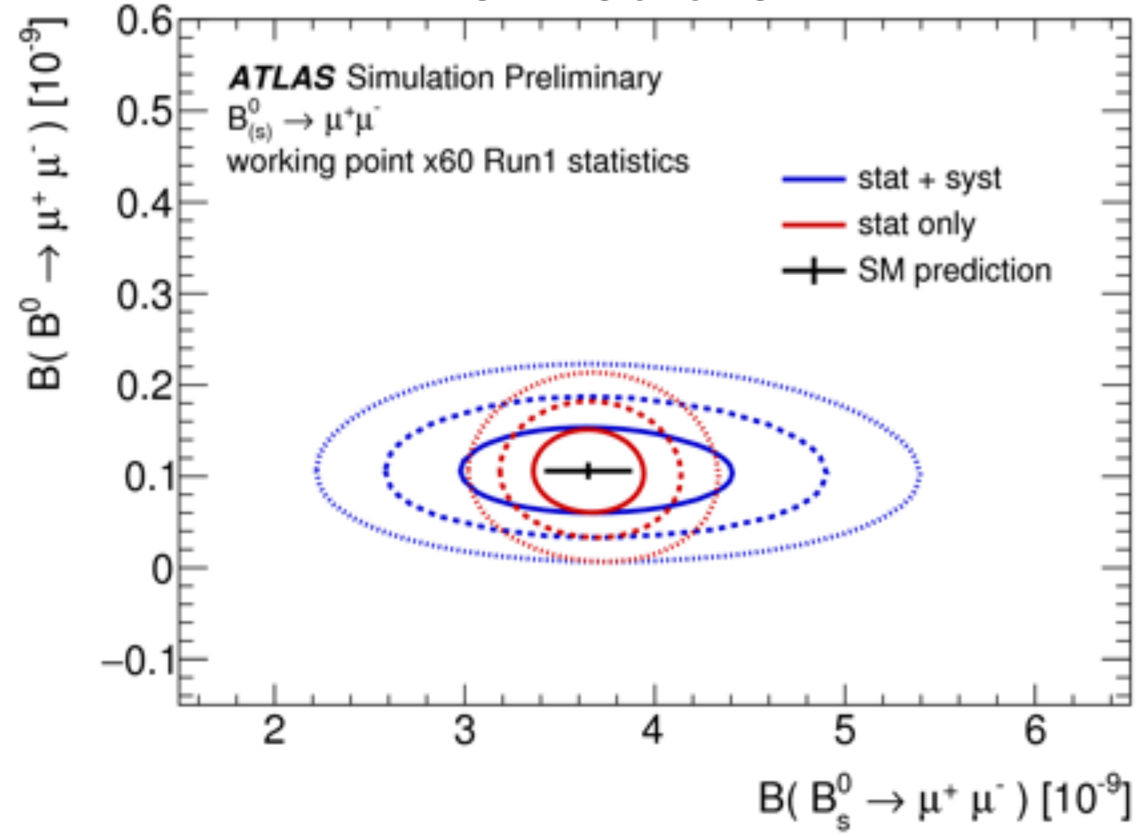
HL-LHC projections

ATL-PHYS-PUB-2018-005

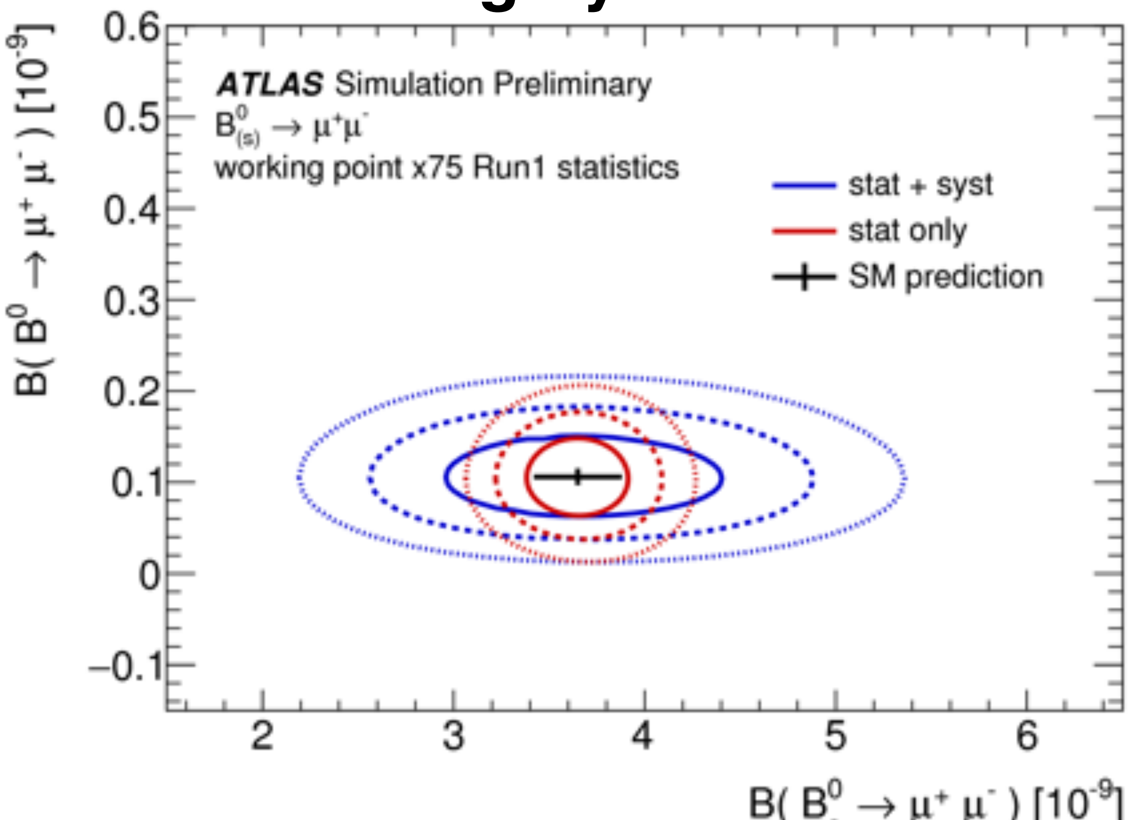
conservative



intermediate



high-yield



- Integrated luminosity: 3 ab^{-1}
- Increased b production X-sec w.r.t Run 1
- Trigger scenarios considered:
  - **Conservative**: mu10_mu10
  - **Intermediate**: mu10_mu6
  - **High-yield**: mu6_mu6

- Systematic uncertainties assumed to behave as in Run 1 analysis
- same pile-up robustness as Run 1 analysis
  - backgrounds due to $b\bar{b}$ events

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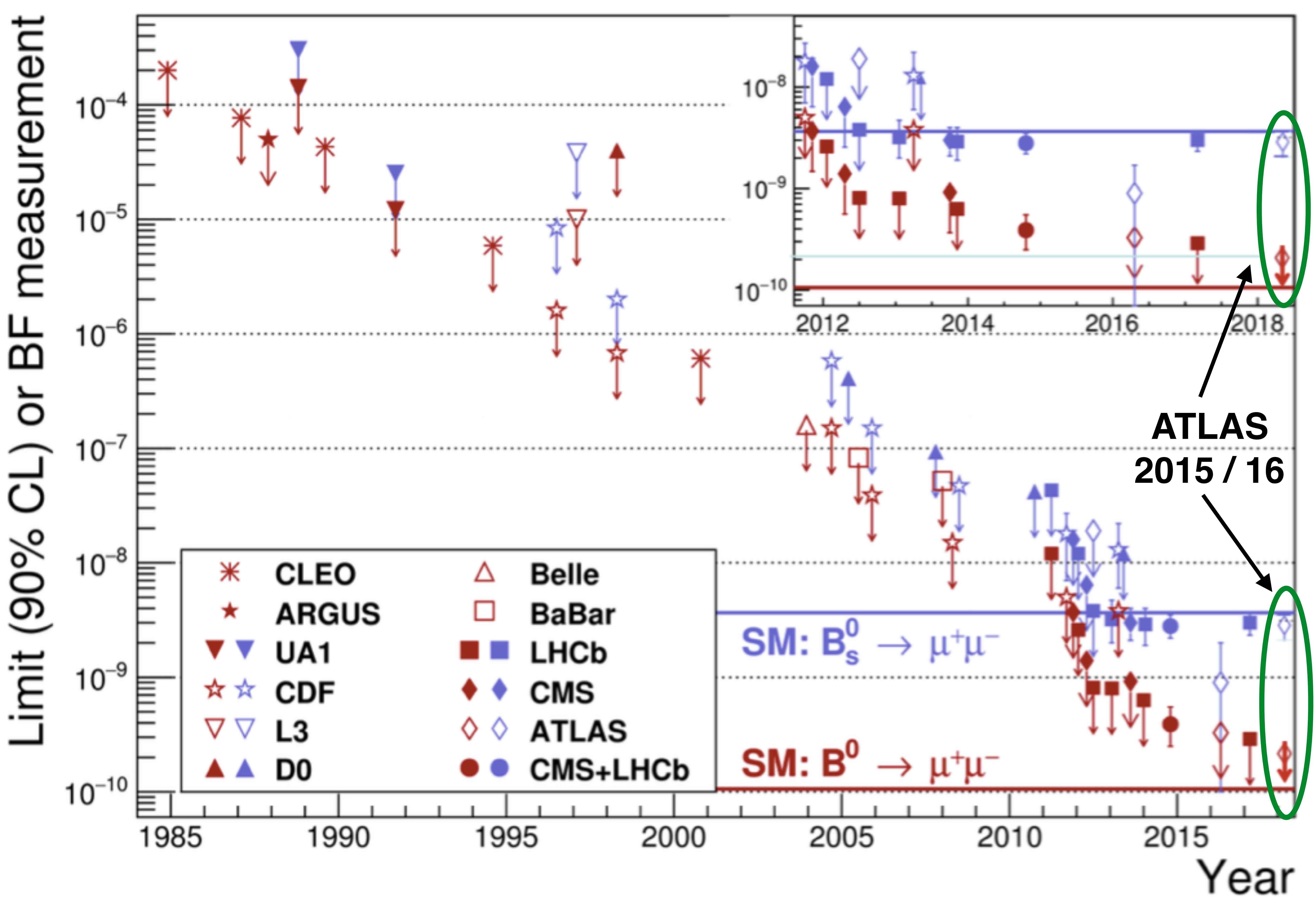
conclusions

- B-physics searches can provide important hints on new physics beyond the reach of the LHC, overcoming the limits of direct production

- 2015/16 B —> $\mu^+\mu^-$ analysis:
  - Combined with Run 1 result
  - Most stringent BR(B —> $\mu^+\mu^-$) upper limit on the market
  - Compatible with SM expectation

- Future B —> $\mu^+\mu^-$:
  - Projections available for Run 2 and HL-LHC
  - Several scenarios explored



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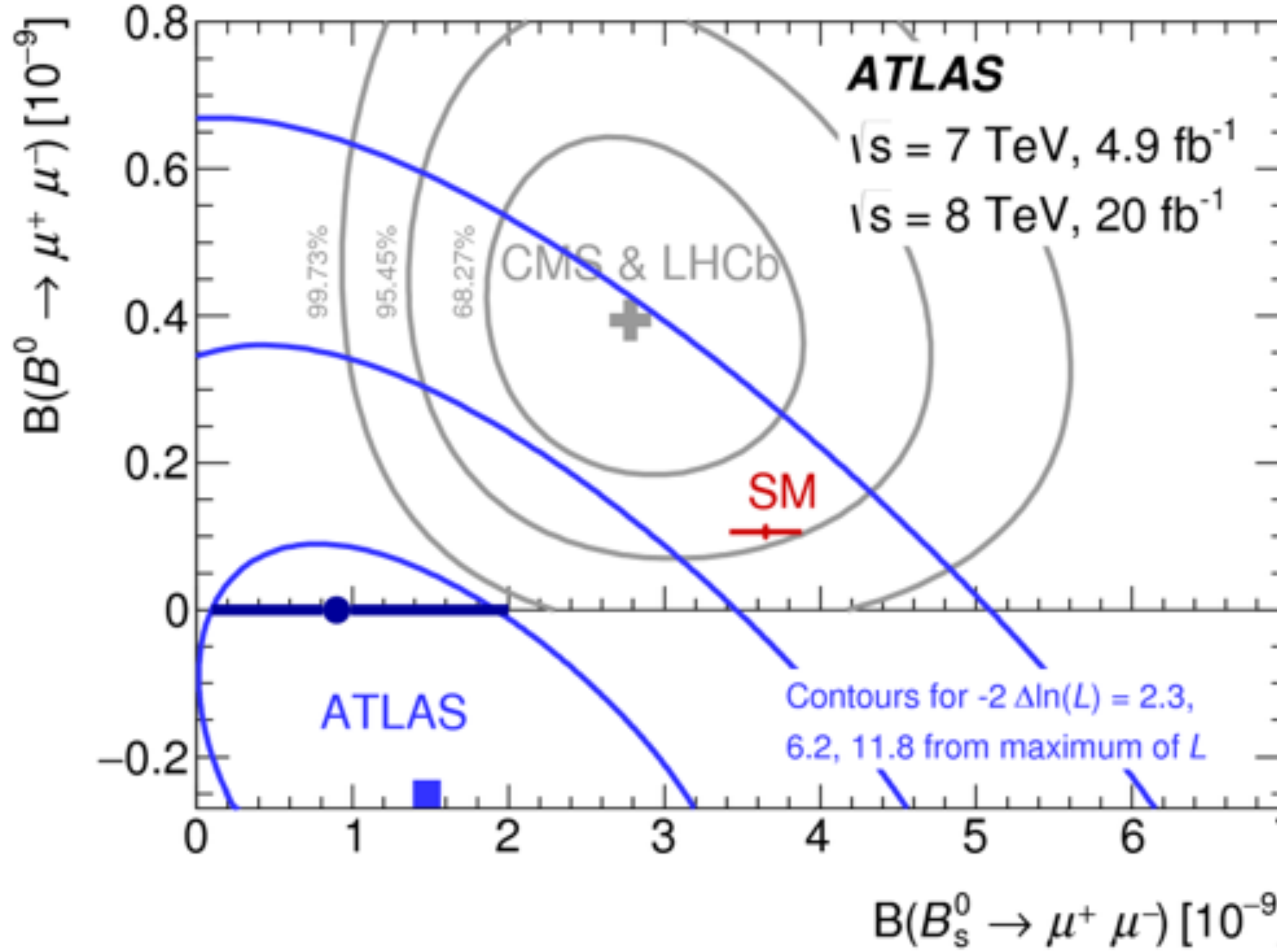
BACKUP

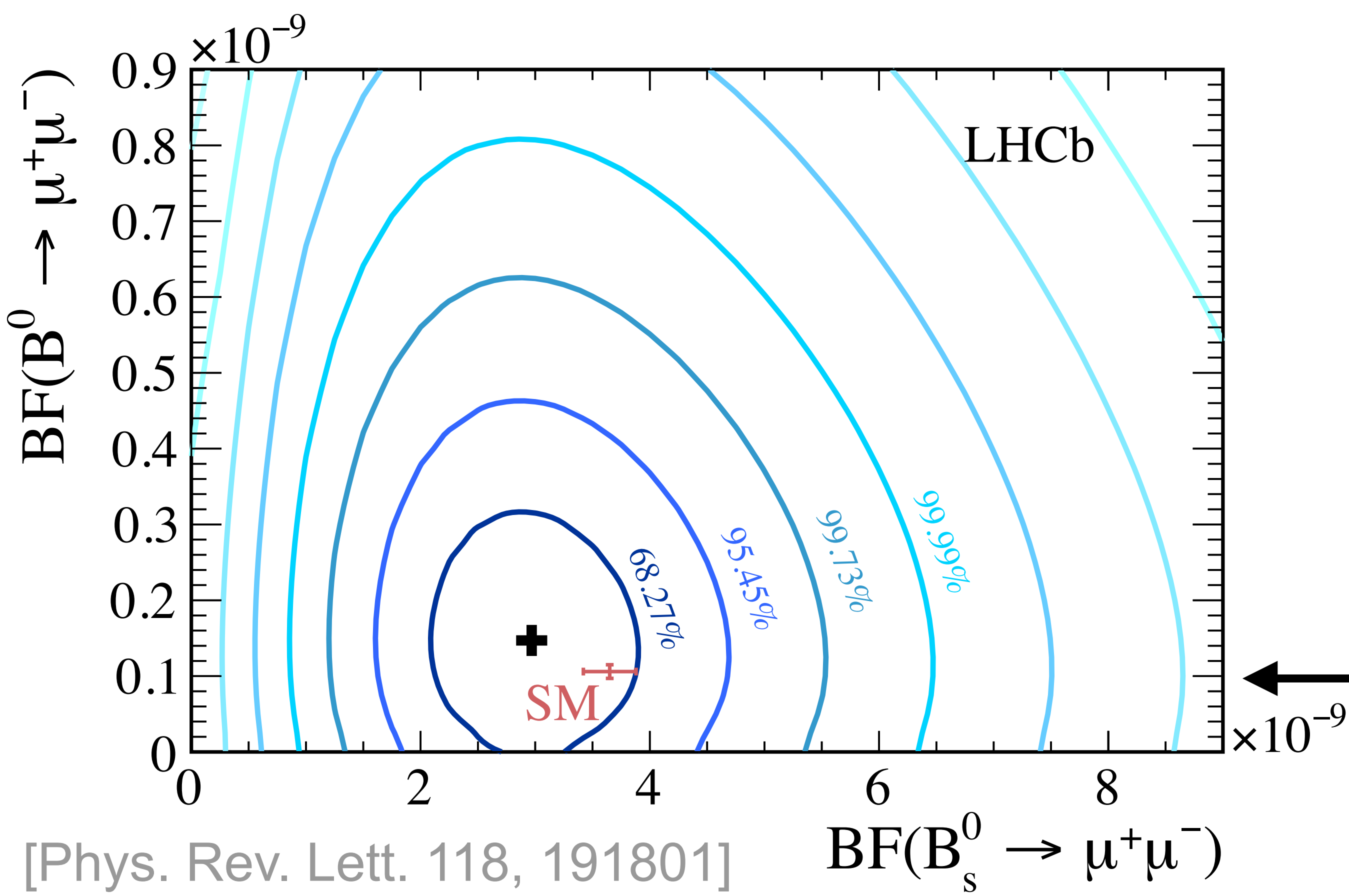
$B_s \rightarrow \mu^+\mu^-$ at the LHC

from Run1:

- ATLAS: blue contours
- CMS + LHCb combination: grey contours

[Eur. Phys. J. C76 (2016) 513]





[Phys. Rev. Lett. 118, 191801]

from Run2:

- LHCb (Run1 + 2016 data)

no significant deviations from SM (so far)

- keep searching

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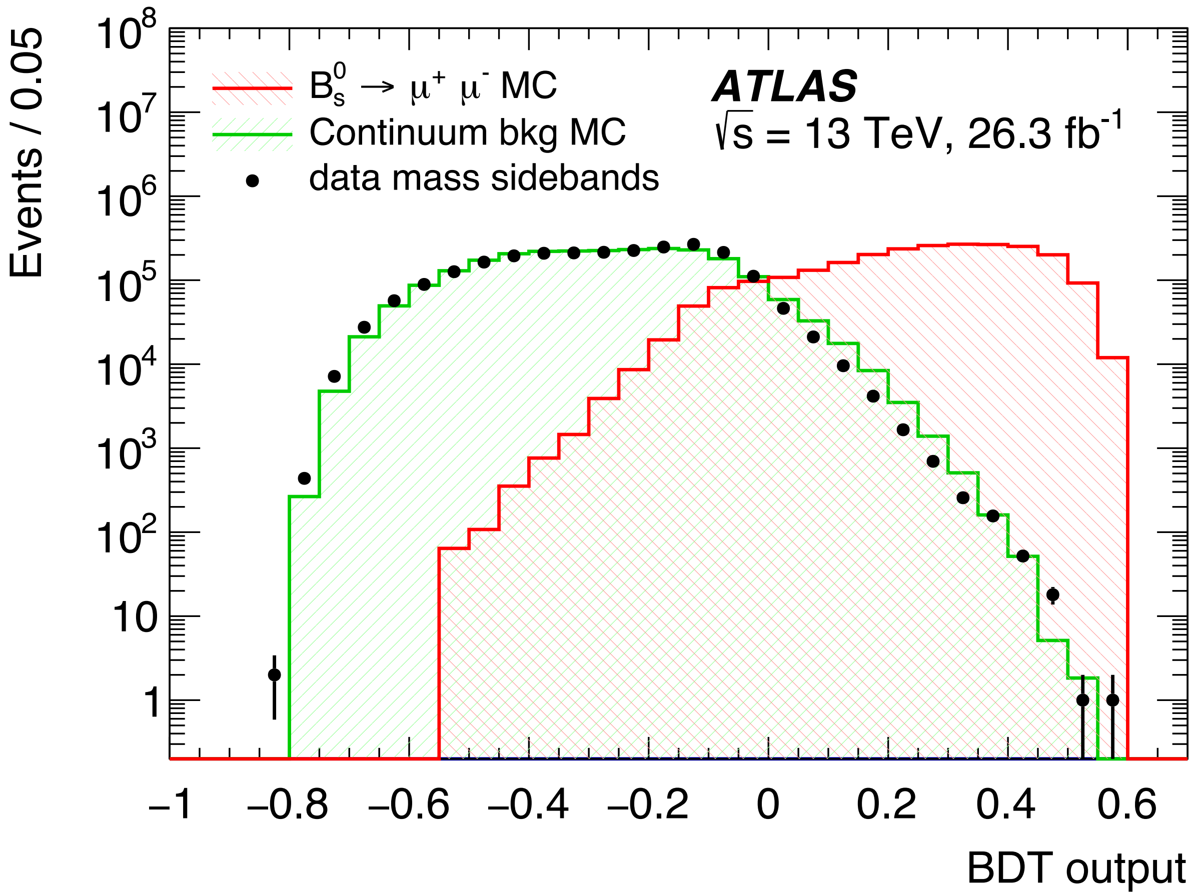
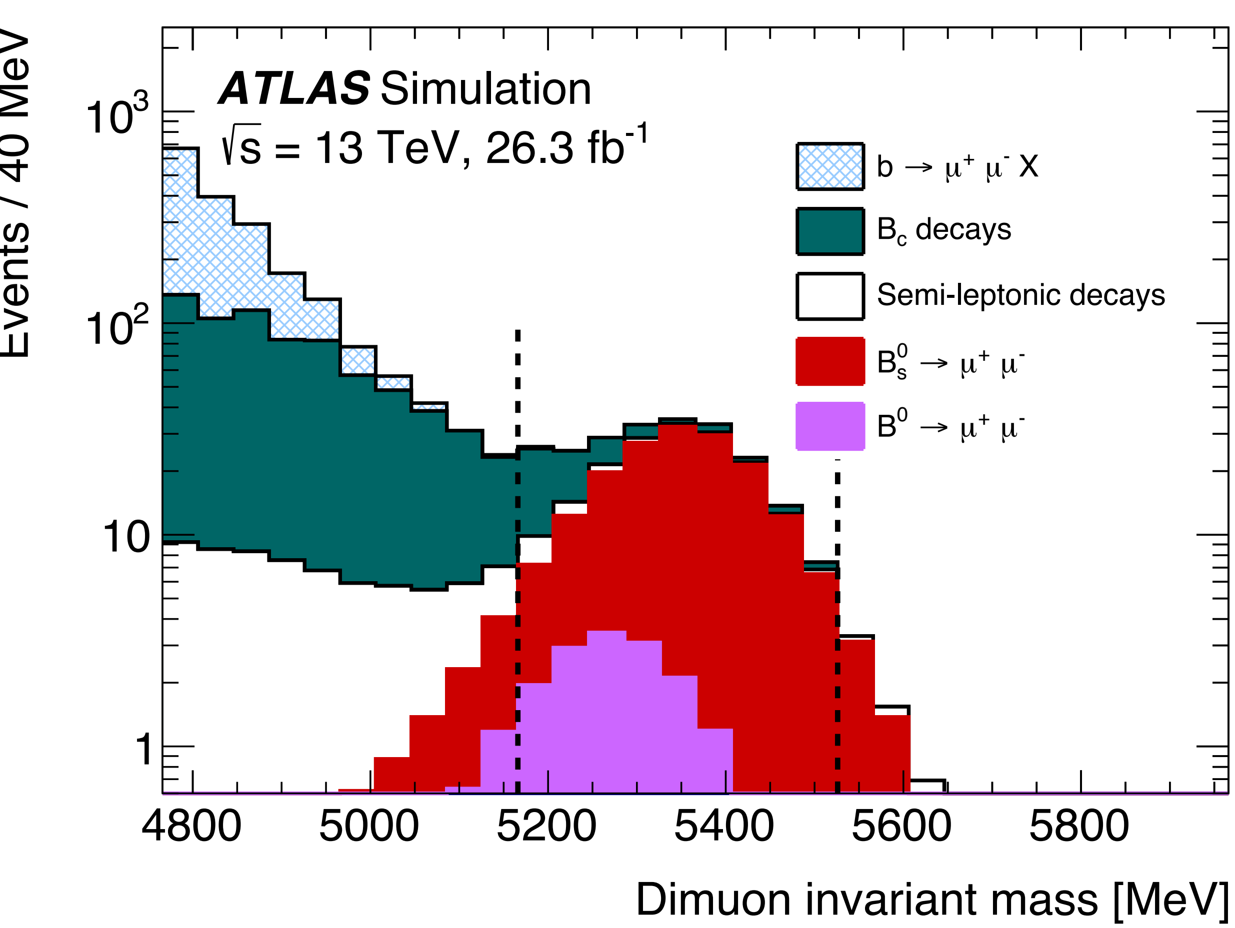
B → μ⁺μ⁻ backgrounds





- Three main background sources
  - **Continuum**:
    - Main background
    - Highly reduced with BDT
  - **Partially reconstructed**:
    - Include several sources
    - Accumulate at low mass
  - **fake mu background**:
    - Semileptonics included in partially reconstructed
    - Peaking background
      - Next slide

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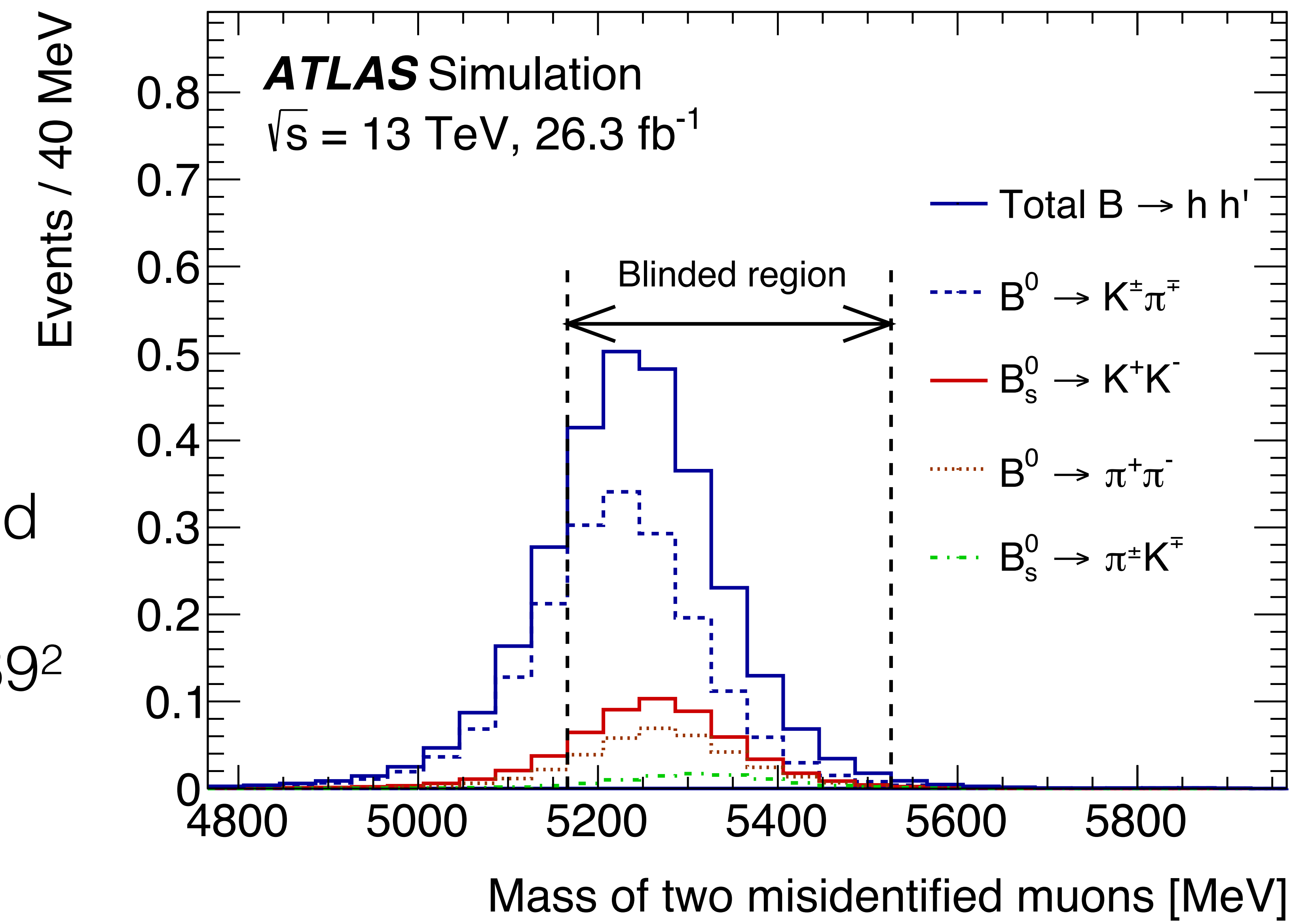
B → μ⁺μ⁻ backgrounds - peaking background

- B—>hh' with two fake μ
- Small but superimposed with signal
- Mis-identification reduced using tight muons
  - Improved of factor 0.39^2 with respect to loose muons



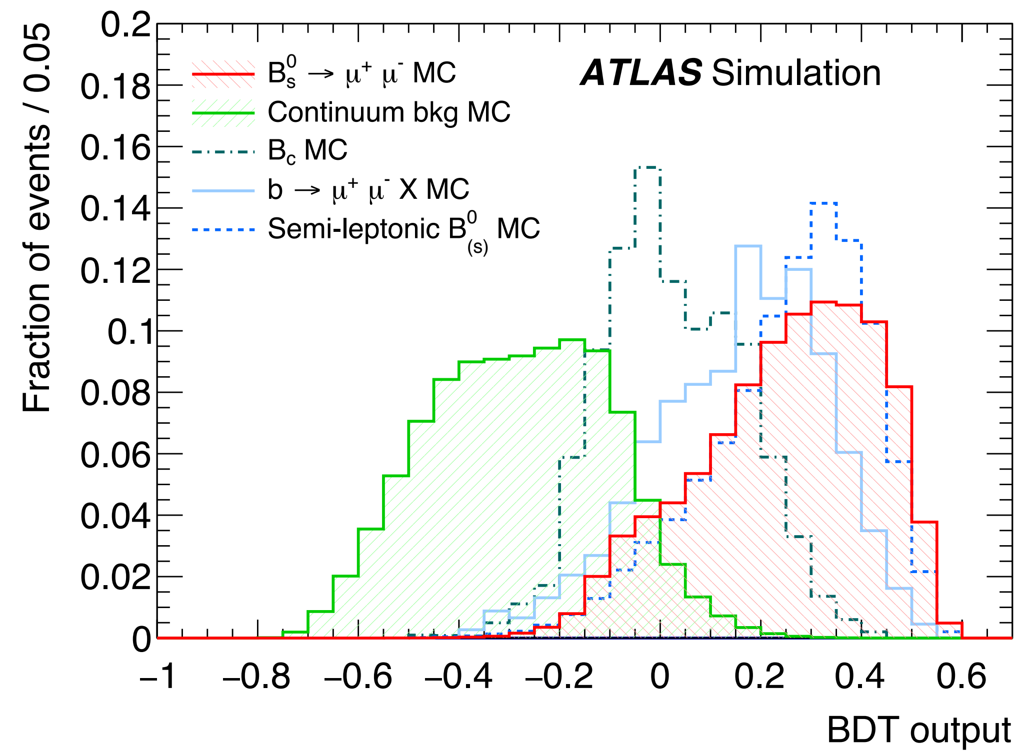
- Number of expected events = 2

$B_s \rightarrow \mu^+\mu^-$ BDT

- MVA based discriminating variable, to enhance continuum background reduction
  - Boosted Decision Tree (BDT)

Variable	Description
p_T^B	Magnitude of the *B* candidate transverse momentum $\vec{p_T}^B$.
$\chi^2_{PV,DV\,xy}$	Compatibility of the separation $\vec{\Delta x}$ between production (*i.e.* associated PV) and decay (DV) vertices in the transverse projection: $\vec{\Delta x}_T \cdot \Sigma^{-1}_{\vec{\Delta x}_T} \cdot \vec{\Delta x}_T$, where $\Sigma_{\vec{\Delta x}_T}$ is the covariance matrix.
ΔR_{flight}	three-dimensional angular distance between $\vec{p}^B$ and $\vec{\Delta x}$: $\sqrt{\alpha_{2D}{}^2 + \Delta\eta^2}$
$\lvert\alpha_{2D}\rvert$	Absolute value of the angle in the transverse plane between $\vec{p_T}^B$ and $\vec{\Delta x}_T$.
L_{xy}	Projection of $\vec{\Delta x}_T$ along the direction of $\vec{p}^B_T$: $(\vec{\Delta x}_T \cdot \vec{p_T}^B)/\lvert\vec{p_T}^B\rvert$.
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.
$\lvert d_0\rvert^{max}$-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.
$\lvert d_0\rvert^{min}$-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_L^{min}	The smaller of the projected values of the muon momenta along $\vec{p_T}^B$.
$I_{0.7}$	Isolation variable defined as ratio of $\lvert\vec{p_T}^B\rvert$ to the sum of $\lvert\vec{p_T}^B\rvert$ and of the transverse momenta of all additional tracks contained within a cone of size $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.7$ around the *B* direction. Only tracks matched to the same PV as the *B* candidate are included in the sum.
$DOCA_{xtrk}$	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_{xtrk}^{close}	Number of additional tracks compatible with the decay vertex (DV) of the *B* candidate with $\ln(\chi^2_{xtrk,DV}) < 1$. The tracks matched to a PV different from the *B* candidate are excluded.
$\chi^2_{\mu,xPV}$	Minimum χ^2 for the compatibility of a muon in the *B* candidate with any PV reconstructed in the event.

- same 15 input variables as Run 1
- trained and tested on data sidebands
  - randomly divide sample in three equal sub-samples
  - use sub-samples in turns to train, test and evaluate the BDT performance
- final selection: 54% signal efficiency (same as in Run 1)



acceptance X efficiency ratio

- takes into account relative differences in acceptance, efficiency, integrated luminosity and selection used for signal and normalisation channel
- calculation based on MC

$$\frac{\varepsilon_x}{\varepsilon_{J/\psi K^+}} = 0.1144 \pm 0.8\% \text{ (stat)} \pm 4.0\% \text{ (syst)}$$

- systematics:

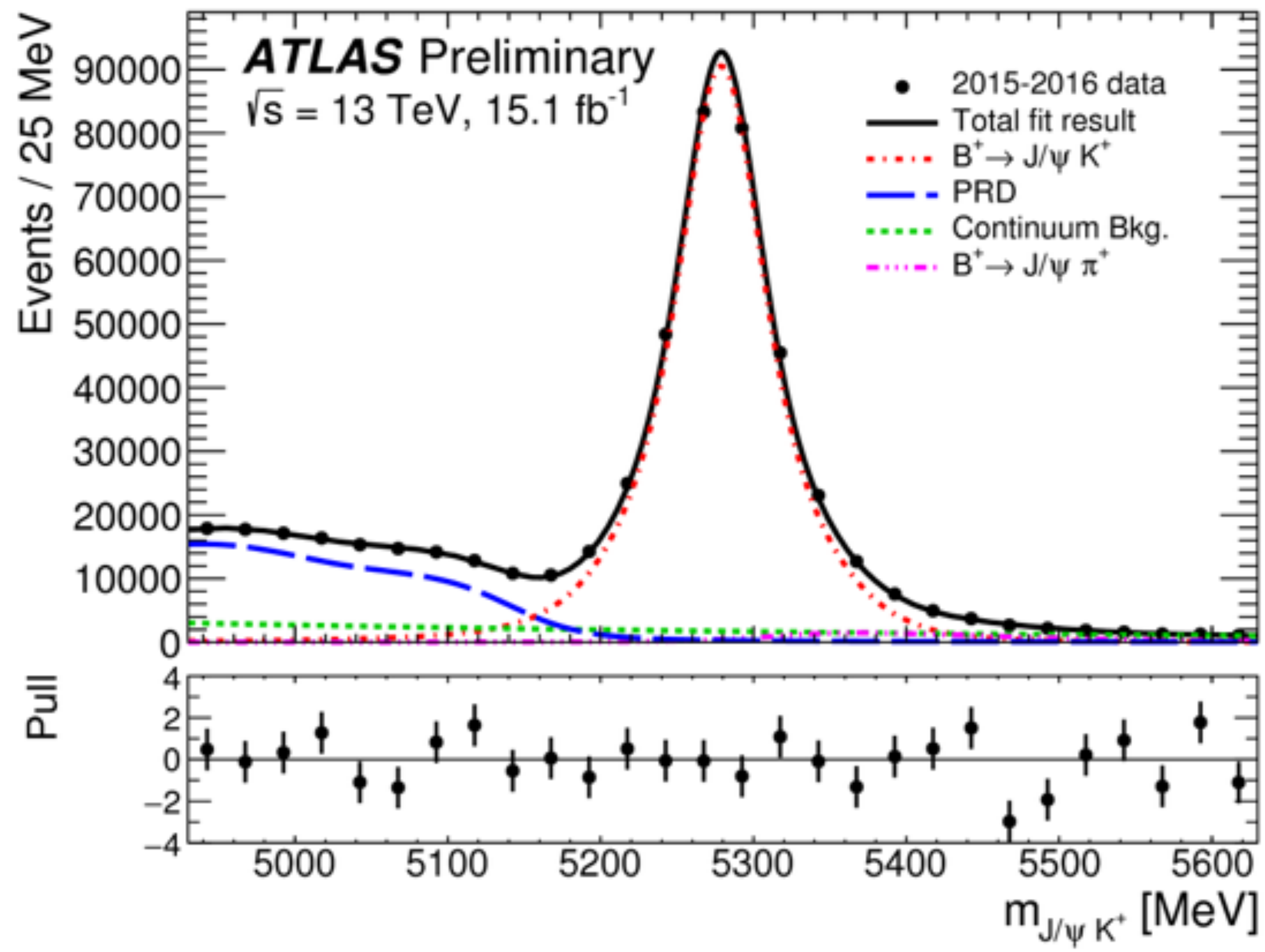
Source	Contribution (%)
Statistical	0.8
BDT Input Variables	3.2
Kaon Tracking Efficiency	1.5
Muon trigger and reconstruction	1.0
Kinematic Reweighting (DDW)	0.8
Pile-up Reweighting	0.6

$B^+ \rightarrow J/\Psi\ K^+$ yield extraction

- extended unbinned maximum likelihood fit on B^+ mass distribution from data
  - complex MC driven models due to high statistics

- systematics:

Source of systematics	Value[%]
PRD1 parametrization	+1.7
PRD2 parametrization	-3
PRD3 parametrization	+1
Combinatorial parametrization	+1.7
Use B^+ signal sample	+2.2
Use B^- signal sample	+1.4
Weights	+0.7
Starting point	±1.4
PRD composition	+2.4
Combined	4.8



- fit result: $N(B^+) = 334351 \pm 0.3\%$ stat $\pm 4.8\%$ syst

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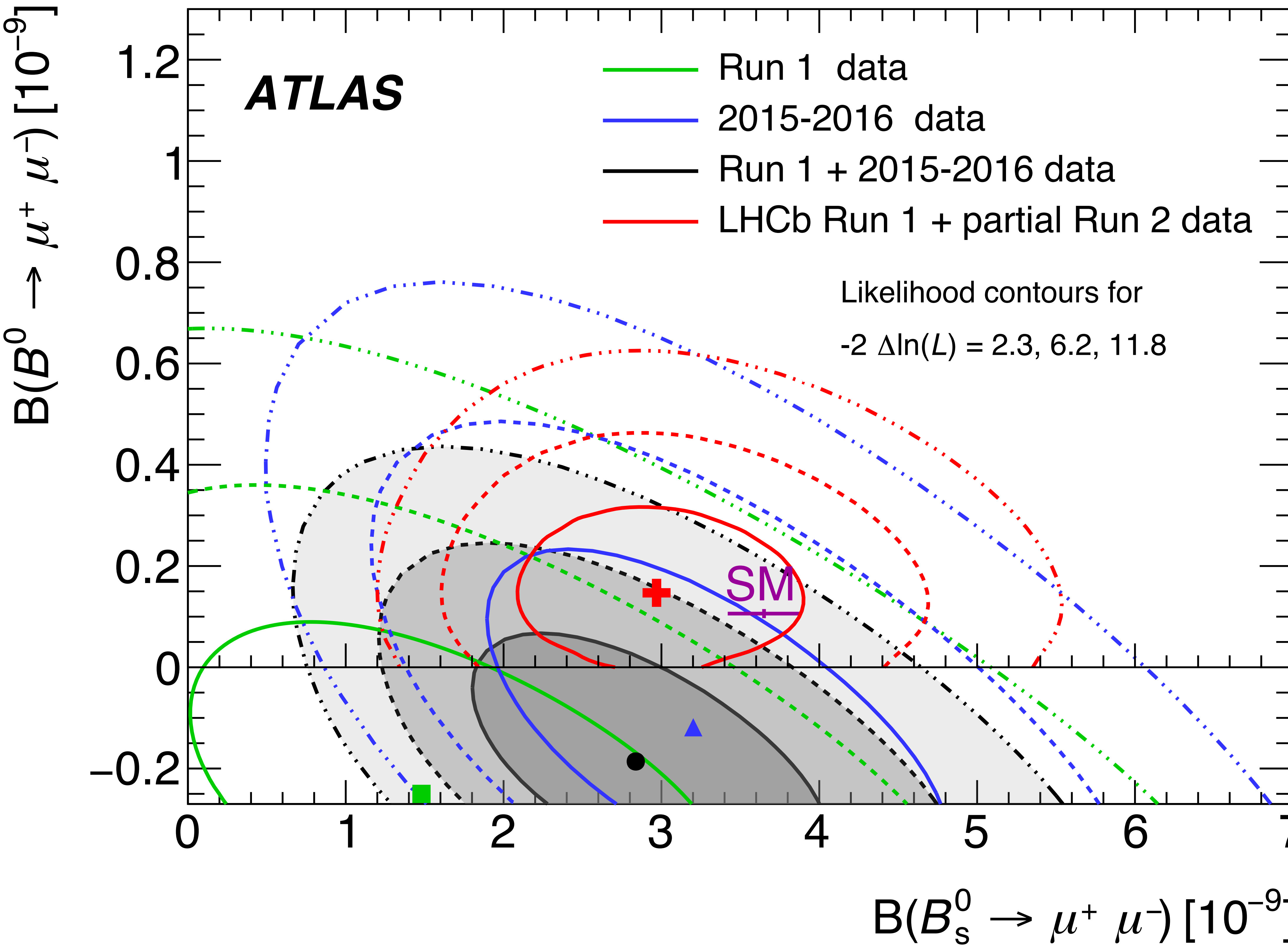
B —> mumu - combination with Run 1



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B → $\mu^+\mu^-$ projection

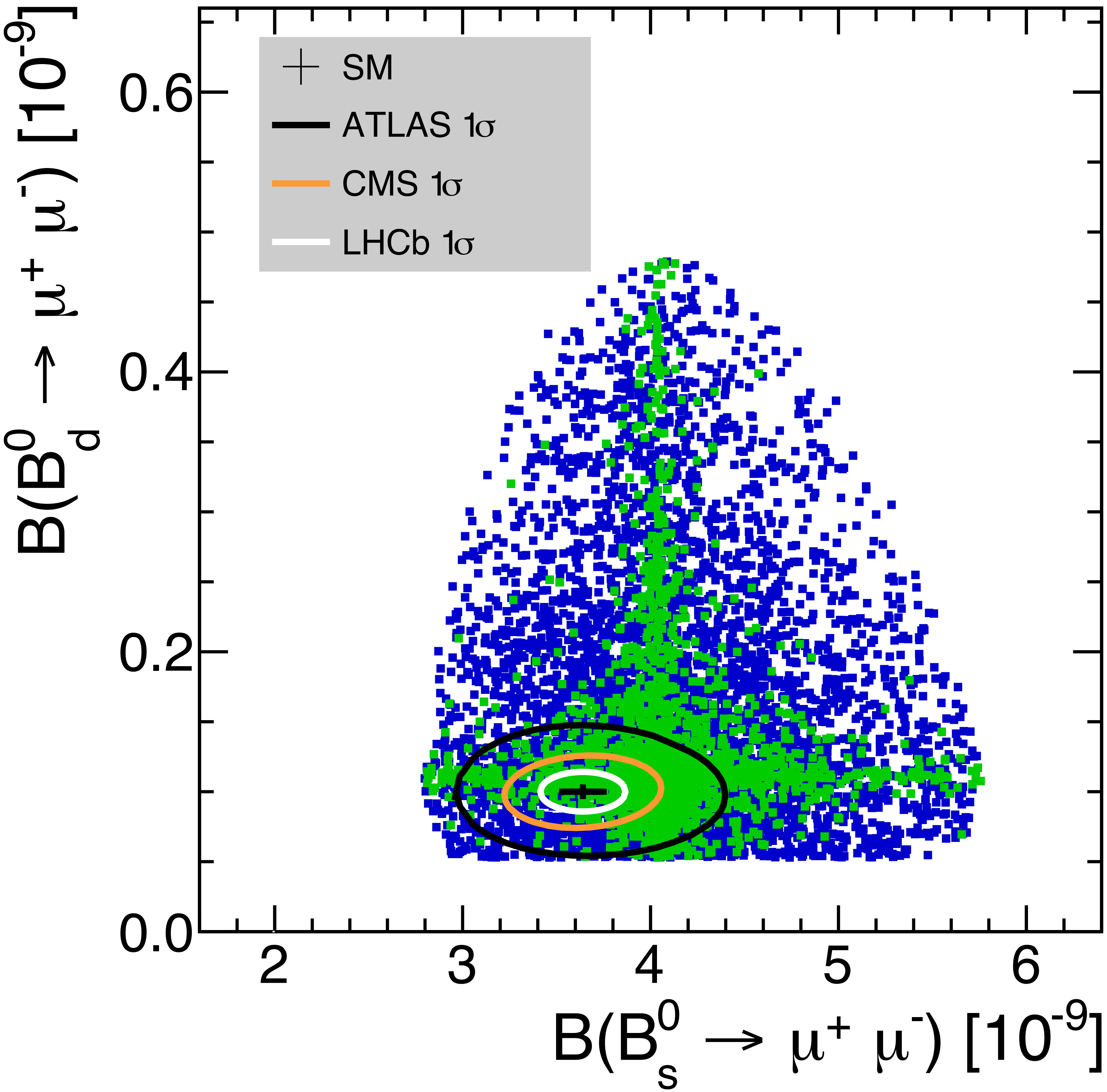
- uncertainty on BRs obtained from projections:

	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$		$\mathcal{B}(B^0 \to \mu^+\mu^-)$	
	stat $[10^{-10}]$	stat + syst $[10^{-10}]$	stat $[10^{-10}]$	stat + syst $[10^{-10}]$
Run 2	7.0	8.3	1.42	1.43
HL-LHC: Conservative	3.2	5.5	0.53	0.54
HL-LHC: Intermediate	1.9	4.7	0.30	0.31
HL-LHC: High-yield	1.8	4.6	0.27	0.28

- systematic uncertainties become relevant in B_S measurement
  - expected improvement, but hard to estimate

- expected analysis reach:
  - comparable to CMS and LHCb's
  - complementary to B-factory experiments (Belle II)

$B \to \mu^+\mu^-$ projections



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