Rare B Decays: Results and Prospects in ATLAS

Heavy Quarks & Leptons

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for the ATLAS collaboration

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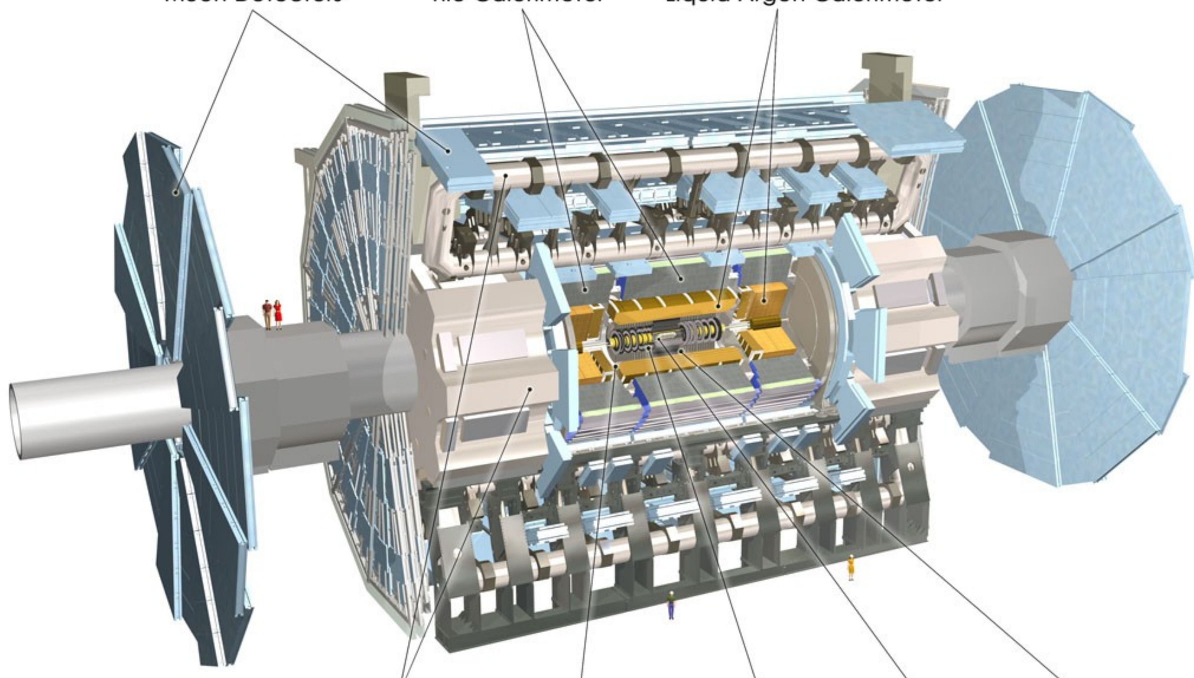
ATLAS detector

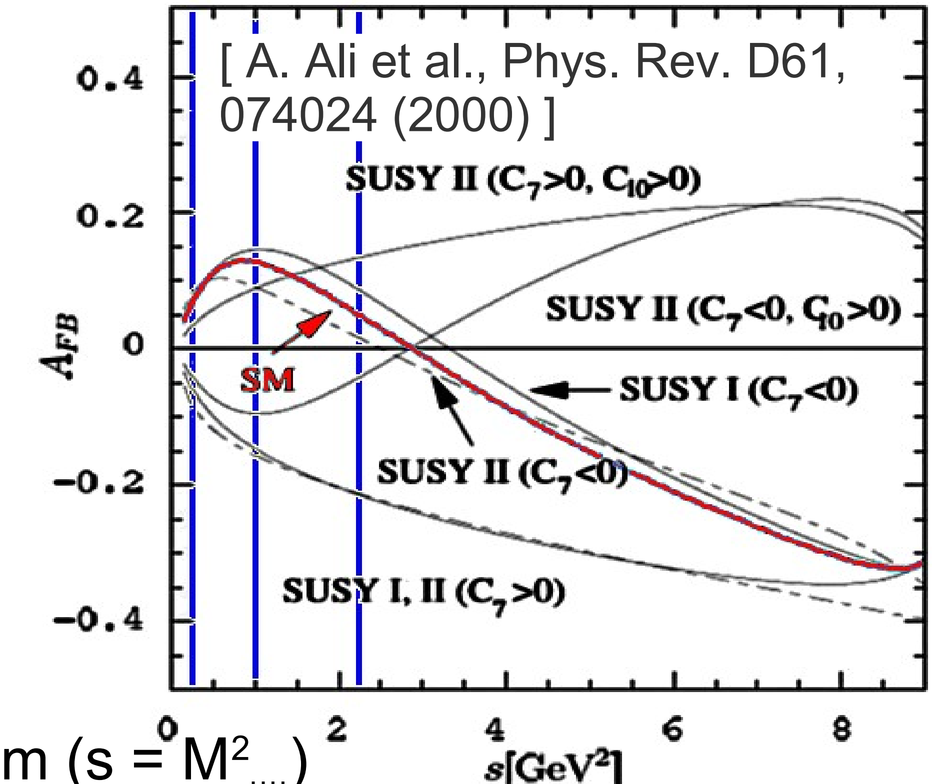


- **Inner Detector (ID)**
  (high granularity tracking detector)
  - Pixel Detector: point resolution of 10 μm (R-ϕ) and 110 μm (z)
  - SCT – Si strip detector: point resolution of 17 μm (R-ϕ) and 580 μm (z)
  - TRT – transition radiation tracker: point resolution of 130 μm
- **Muon Spectrometer (MS)**
  - Precision tracking chambers: MDT, CSC (~40 μm space resolution)
  - Fast trigger chambers: RPC, TGC (~ 10 ns time resolution)

Precise measurements of muons (MS+ID) important for rare B decays!

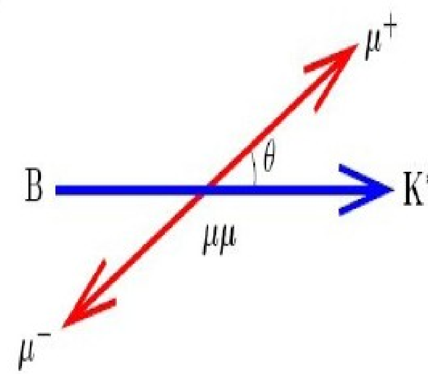
Motivation: b → sμ⁻μ⁺ transitions

- $b \to s\,\mu^+\mu^-$ transitions
  - BR ~ 10^{-6}
  - Channels of interest:
    - $B_d^0 \to K^{0*}\mu^+\mu^-$
    - $B_s^0 \to \phi\mu^+\mu^-$
    - $\Lambda_b \to \Lambda^0\mu^+\mu^-$
    - $B^+ \to K^+\mu^+\mu^-$
    - $B^+ \to K^{+*}\mu^+\mu^-$



- Studied distributions:
  - Di-muon invariant mass spectrum ($s = M^2_{\mu\mu}$)
  - Forward-backward asymmetry (A_{FB}):

$$A_{FB}(s)=\frac{\int_0^1 d\cos\theta\,\frac{d\Gamma(s,\cos\theta)}{ds\,d\cos\theta}-\int_{-1}^0 d\cos\theta\,\frac{d\Gamma(s,\cos\theta)}{ds\,d\cos\theta}}{\int_{-1}^1 d\cos\theta\,d\frac{\Gamma(s,\cos\theta)}{ds\,d\cos\theta}}$$



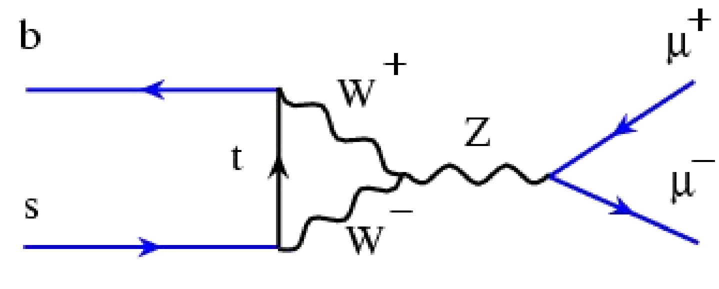
  - **$A_{FB}(s)$ sensitive to extensions of the Standard Model**

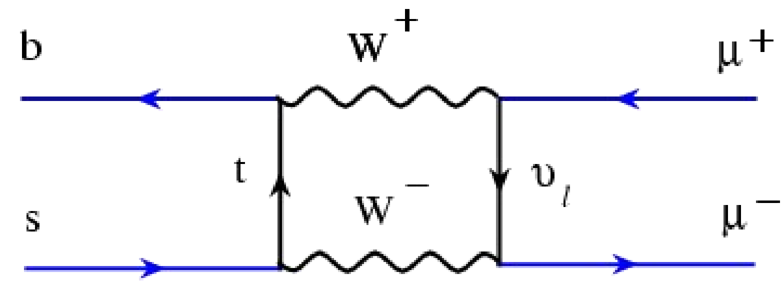
Motivation: di-muonic B decays

- Very rare decays $B^0_{s(d)} \to \mu^+\mu^-$
- Suppressed at tree level
- SM predicted BR ~ $(3.6 \pm 0.3) \times 10^{-9}$

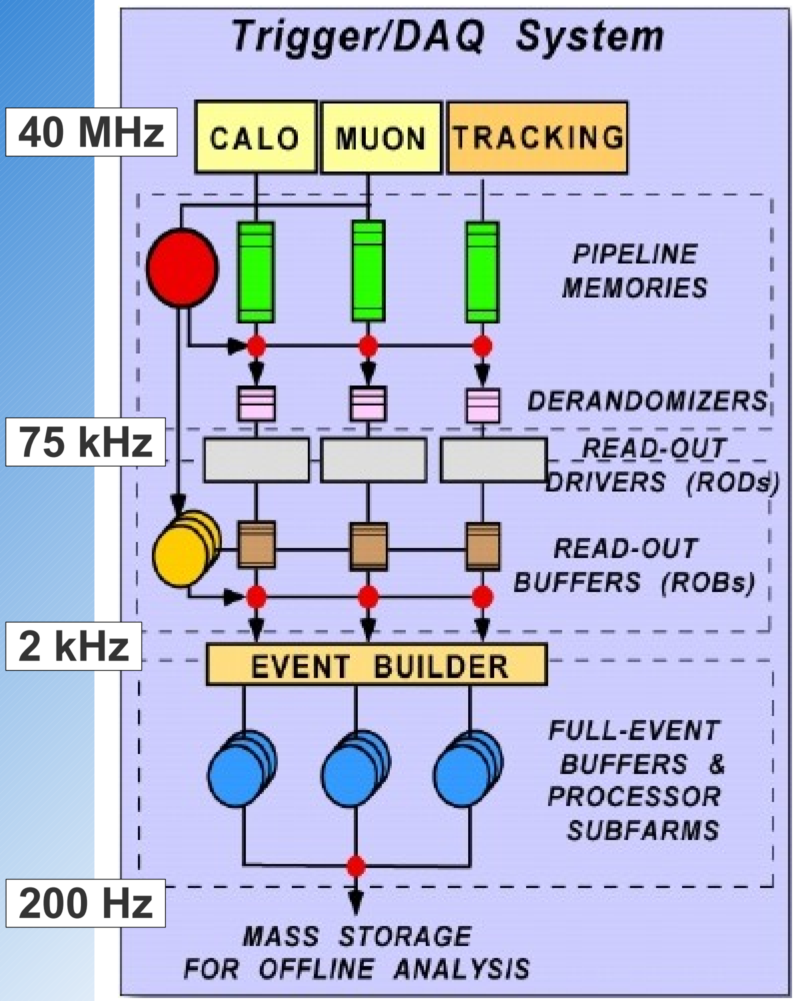
[A. J. Buras, Prog. Theor. Phys. 122 (2009), 145]

- **Branching ratio very sensitive to New Physics effects:**
  - **MSSM: BR ~ $\tan^6\beta$ ($\to$ BR ~10^{-9} – 10^{-7})**
- Clear experimental signature
- Current best experimental measurements:
  - CDF: **BR** < 4.3×10^{-8} @ 95% CL [ICHEP2010]
  - D0: **BR** < 5.1×10^{-8} @ 95% CL [ICHEP2010]





ATLAS trigger system design

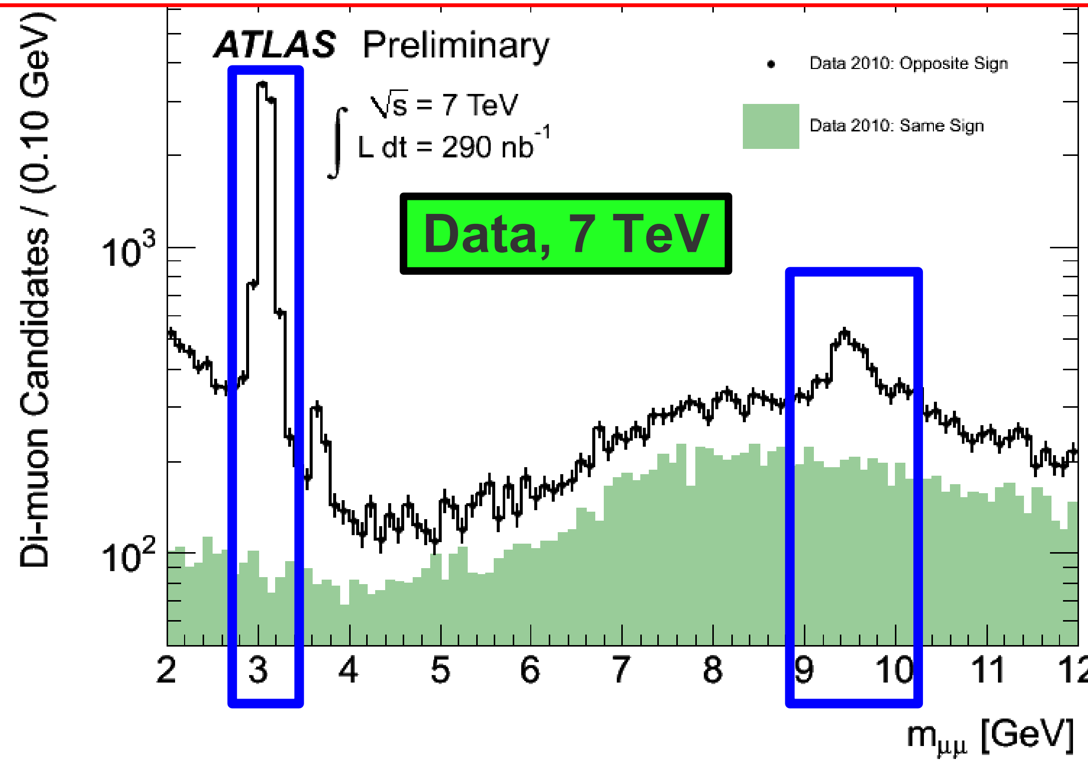


- Level 1 (LVL1)
  - Hardware based
  - Detect muon signatures using dedicated fast tracking chambers
  - Identify Regions of Interest (RoI)
  - Reduce input rate from maximum 40 MHz (bunch crossing rate) to 75 kHz
- Level 2 (LVL2)
  - Software based
  - Confirm LVL1 signatures using precision detectors
  - Extrapolate muon tracks to ID and refit inside RoI
  - Output rate 2 kHz
- Event Filter (EF)
  - Software based
  - Refine LVL2 decision using offline-like algorithms
  - Further selection possible using vertexing, decay length, angular distributions
  - Output rate 200 Hz (~5-10% available for B Physics)

Di-muon signatures considered

- Di-muon (common vertex) events
- Di-muon invariant mass spectrum should include:
  - Heavy quarkonia (J/ψ, Υ...) decaying to $\mu^+\mu^-$

Selection not optimised for $B_s^0 \to \mu^+\mu^-$ searches



- Events recorded if either one of the following triggers fired:
  - LVL1 muon trigger, no cut on min p_T
  - Minimum bias trigger
- Offline selection: $p_T(\mu_1) > 2.5$ GeV, $p_T(\mu_2) > 4$ GeV
- Corresponding to: $L = 290$ nb^{-1}

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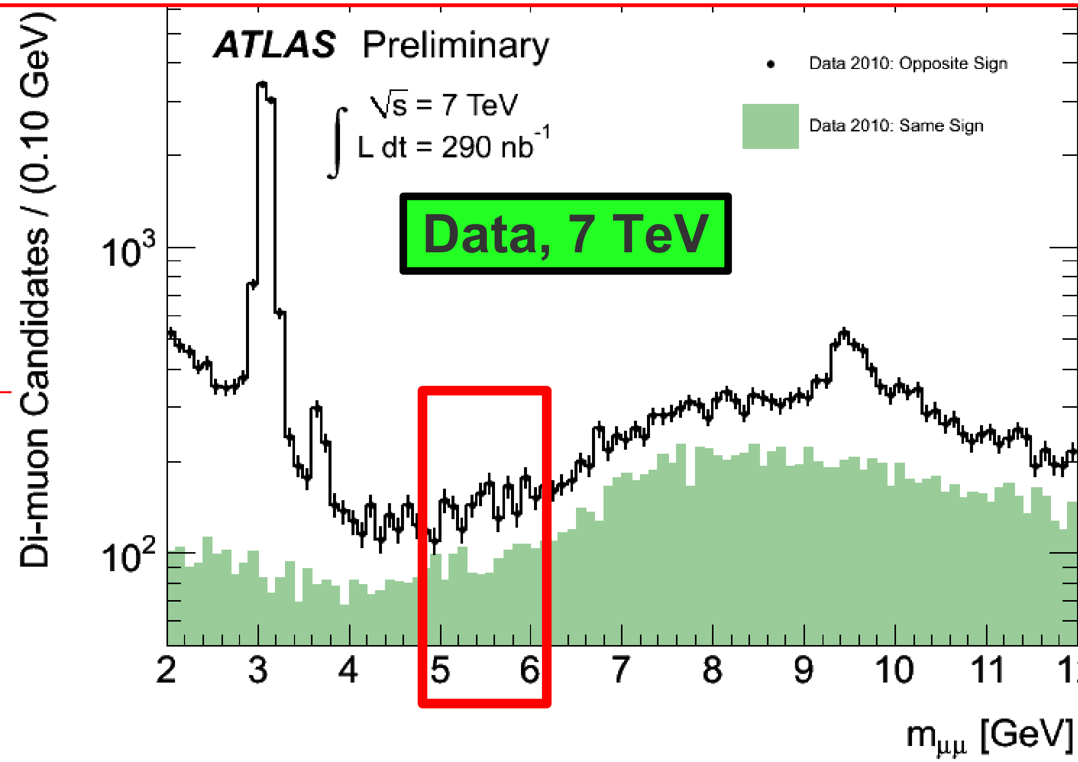

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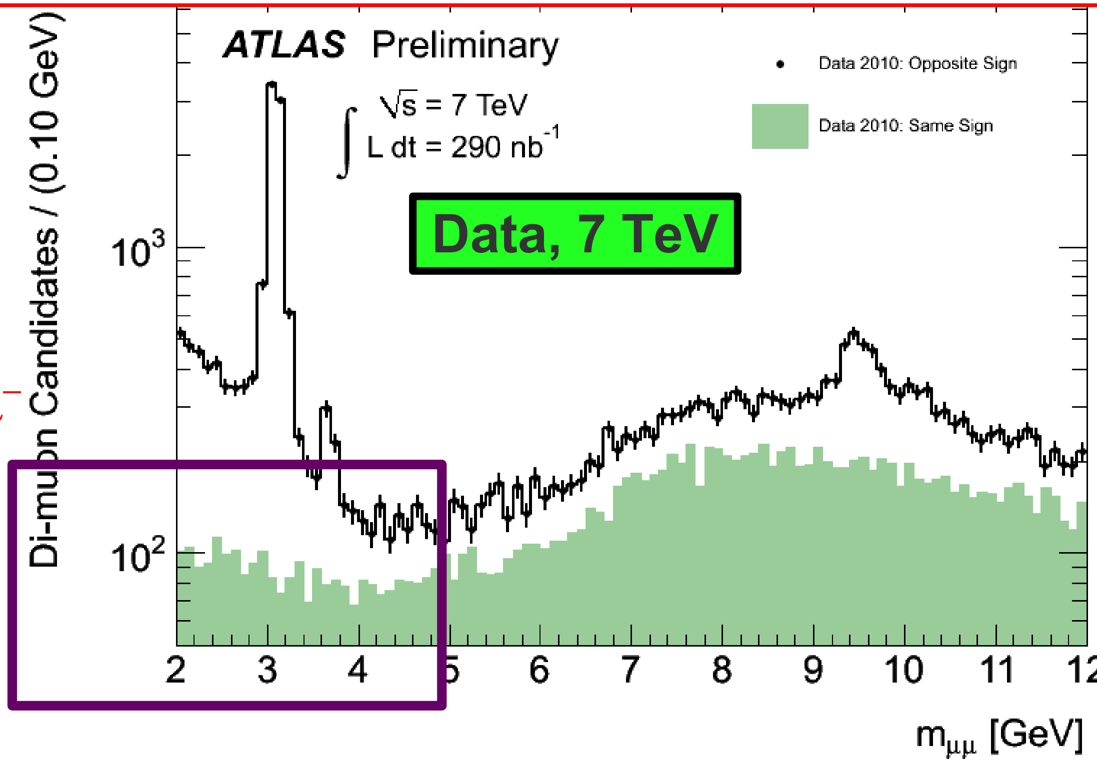

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  - Very rare decays: $B_s^0 \to \mu^+\mu^-$
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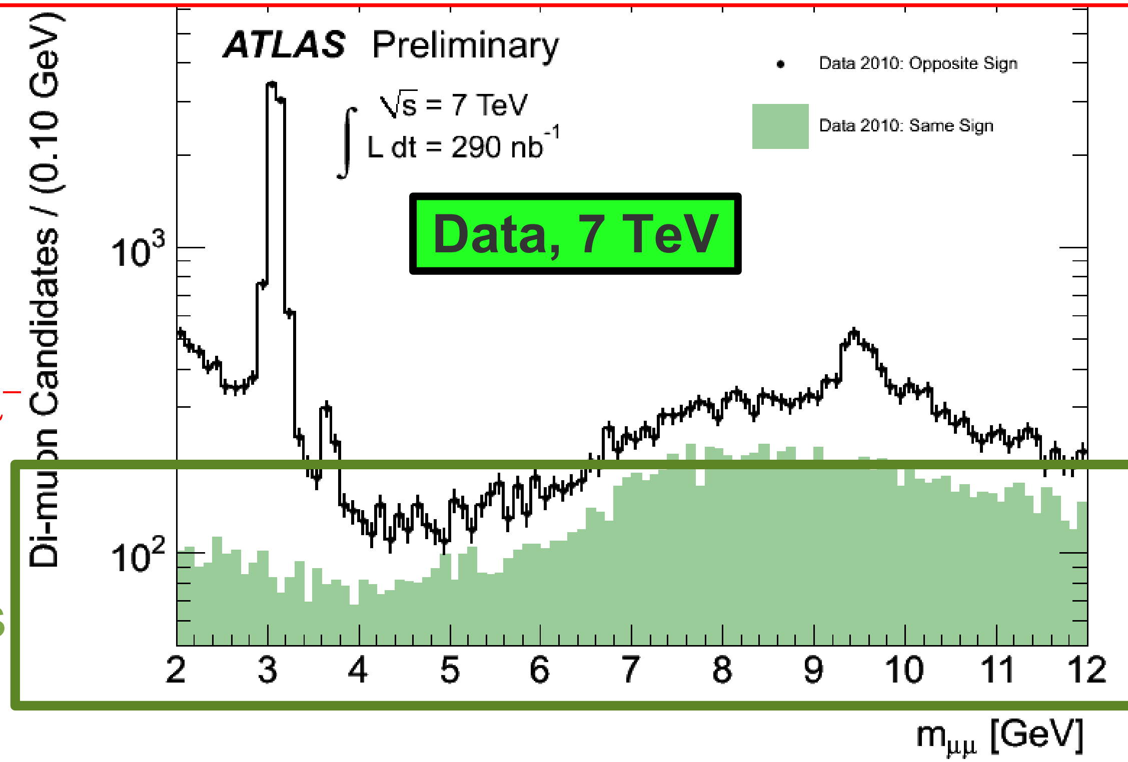
  - Continuum in di-muon mass spectrum (Drell-Yan)
- Invariant mass range to trigger: $0 < M(\mu\mu) < 13$ GeV



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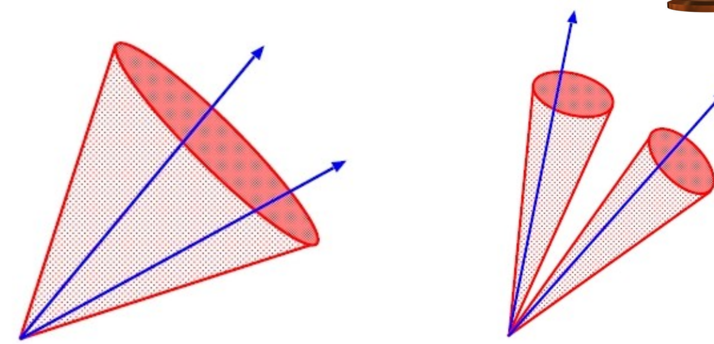
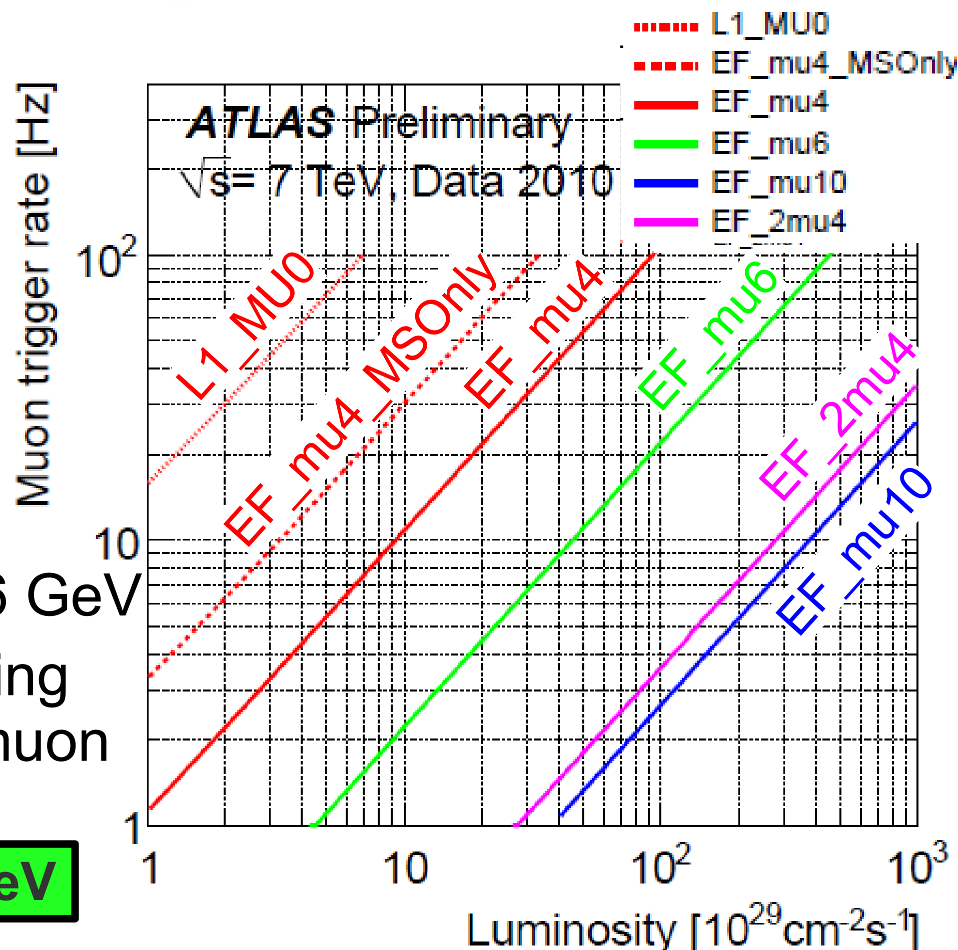
Di-muon HLT trigger for rare B decays

- Single muon trigger
  - Seeded by 1 LVL1 muon
  - Confirm muon at LVL2
  - Search for the second muon inside a large RoI around the LVL1 muon
  - Mass and vertex cuts at EF
- Di-muon trigger
  - Seeded by two LVL1 muons
  - Confirm muons at LVL2
  - Refit tracks inside small RoI
  - Mass and vertex cuts at EF
- Single muon trigger feasible only at low luminosity
- Lowest muon p_T thresholds: 4 GeV, 6 GeV
- Higher luminosity will require increasing the p_T threshold and/or using the di-muon trigger



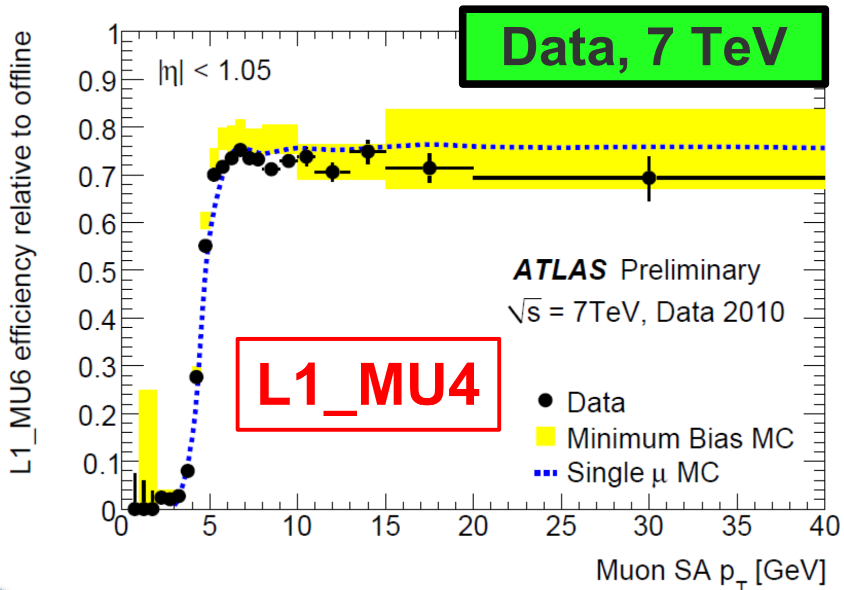


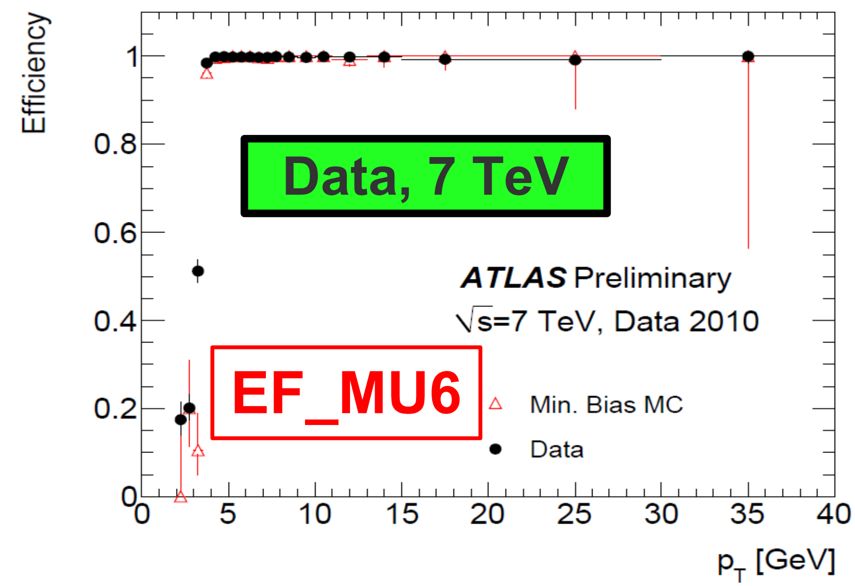
Data, 7 TeV

Single muon trigger performance

- Performance determined by comparing the number of events passing a certain trigger w.r.t. offline muons (offline matching criteria $\Delta R < 0.5$)
- Efficiency at plateau determined after fitting with:

$$f = \frac{A}{1 + e^{\frac{-(x-B)}{C}}}$$

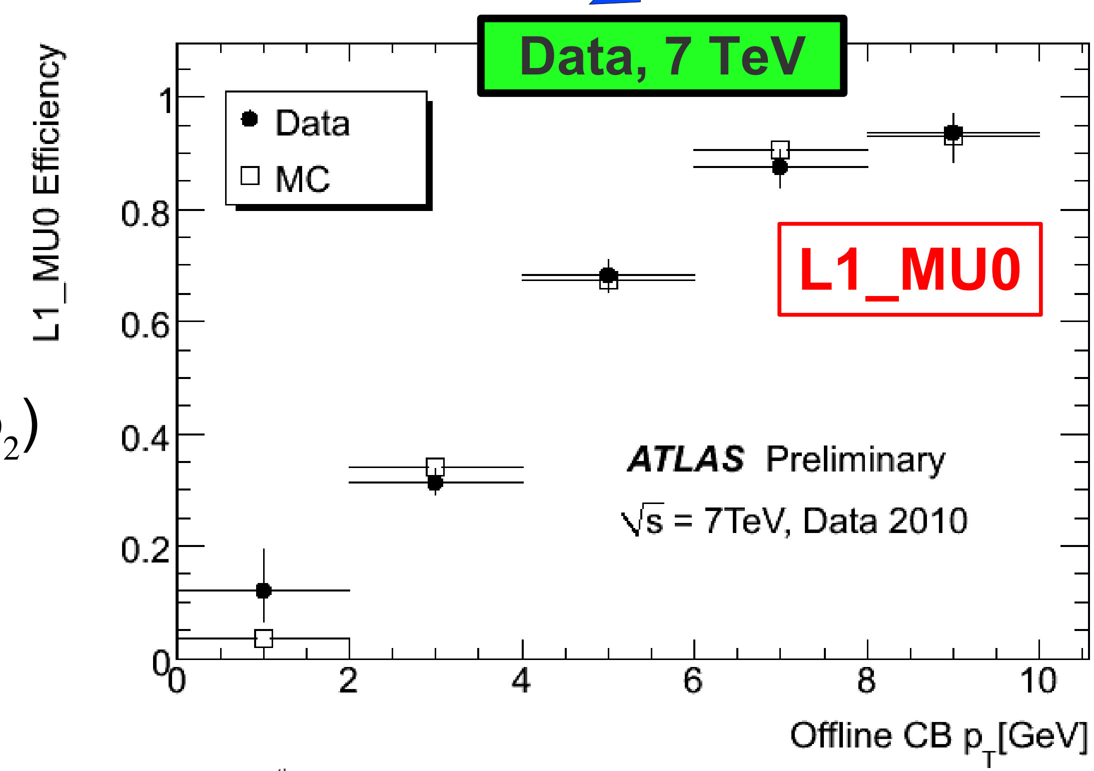




- Efficiency value at plateau is:
  - LVL1_MU4 (barrel): ~76% – from a max. of 82% (due to geometrical acceptance)
  - LVL1_MU4 (endcap): ~94% (~100% geometrical acceptance)
  - LVL2_MU6: ~97% – w.r.t. LVL1
  - EF_MU6: ~99% – w.r.t. LVL2

Di-muon trigger performance

- Determine single muon trigger efficiency using "tag and probe" method using di-muon final states (e.g. J/ψ)
  - Select sample of $J/\psi \rightarrow \mu^+\mu^-$ candidates unbiased by trigger
  - "tag" muon – matched to an offline reconstructed muon
  - "probe" muon – check if muon fired trigger
  - Single muon efficiency map: $\varepsilon_{\mu 1}(p_{T1}, \eta_1, \phi_1)$



- Di-muon efficiency determined from single muon efficiencies:
  $\varepsilon_{\mu\mu}(p_{T\mu\mu}, \eta_{\mu\mu}, \phi_{\mu\mu}) \sim$
  $\varepsilon_{\mu 1}(p_{T1}, \eta_1, \phi_1) \cdot \varepsilon_{\mu 2}(p_{T2}, \eta_2, \phi_2)$

Strategy for $B_s^0 \to \mu^+\mu^-$

- Perform search for the decays
- Interested in determining the branching ratio
  - Normalized to a well determined reference channel:

    $B^+ \to J/\psi\ (\mu^+\mu^-)\ K^+$
  - Systematic errors for signal and normalization channels nearly cancel each other

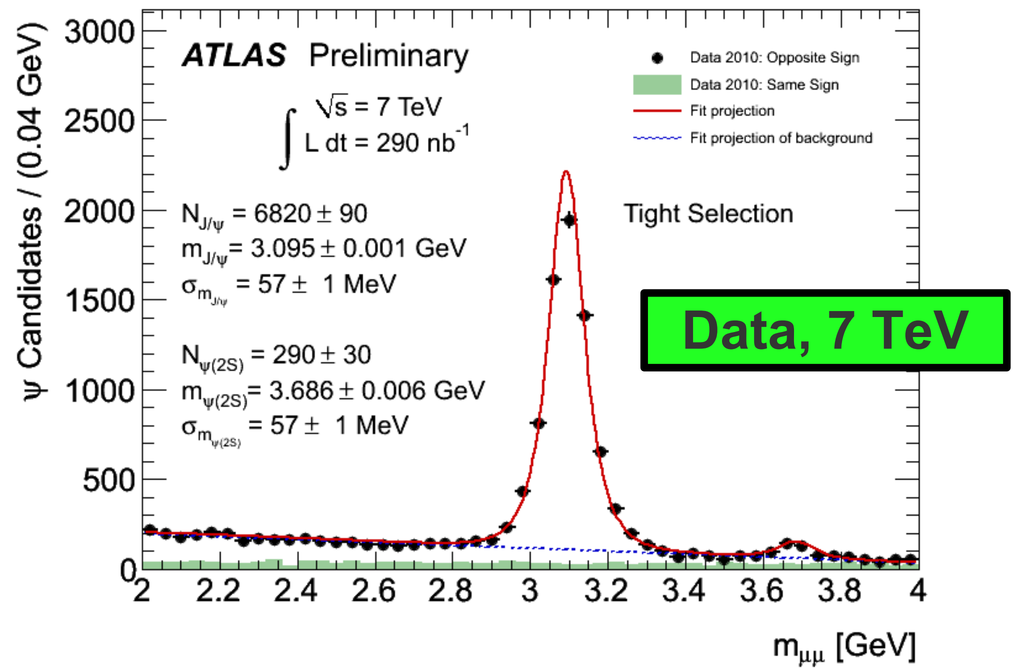
$$BR(B_s \to \mu^+\mu^-) = \frac{N_{B_s}}{N_{B^+}} \cdot \frac{\alpha_{B^+}}{\alpha_{B_s}} \cdot \frac{\varepsilon_{B^+}}{\varepsilon_{B_s}} \cdot \frac{f_u}{f_s} \cdot BR(B^+ \to J/\psi\, K^+) \cdot BR(J/\psi \to \mu^+\mu^-)$$

  - N_{Bs} (N_B^+) – no. of events after selection
  - α_{Bs} (α_B^+) – geometric and kinematic acceptance
  - ε_{Bs} (ε_B^+) – total efficiency
  - f_u, f_s – b-quark fragmentation probabilities

Reference channel

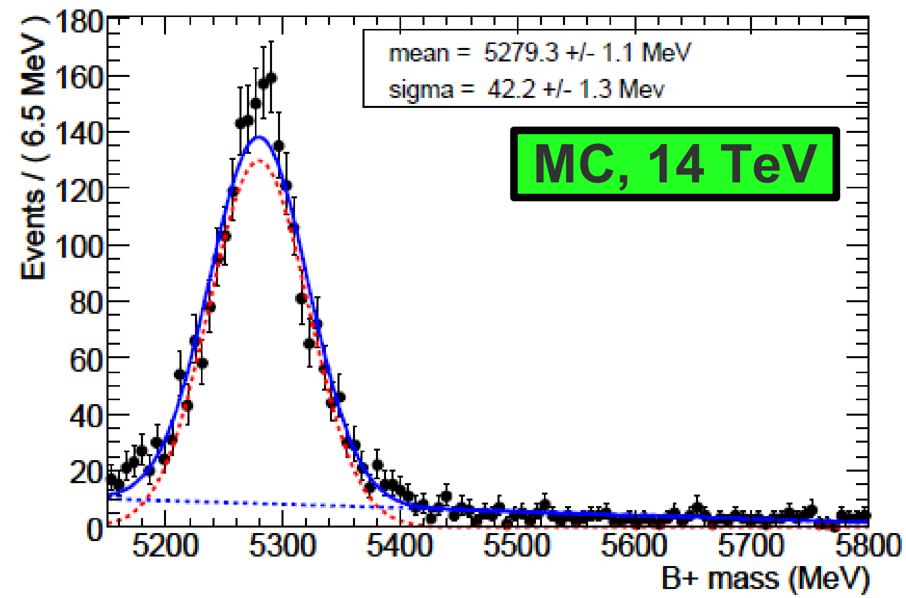
$J/\Psi \rightarrow \mu^+\mu^-$

- Events recorded with either one of the following triggers:
  - LVL1 muon trigger, no cut on minimum p_T
  - Minimum bias trigger
- Offline selection:
  $p_T(\mu_1) > 2.5$ GeV,
  $p_T(\mu_2) > 4$ GeV



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

- Based on simulated data
- Selection cuts used for the $B_s^0 \rightarrow \mu^+\mu^-$ selection not included here
- Mass resolution: ~ 42 MeV



Backgrounds

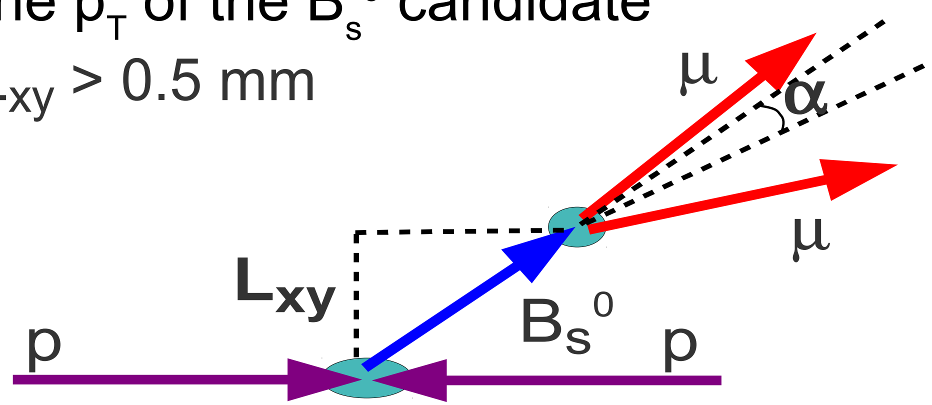
- Exclusive decays of B mesons:
  - Hadron misidentification ($B_{s(d)}^0 \to h_1^- h_2^+$, $B_{s(d)}^0 \to h^- \mu^+ \nu_\mu$) e.g.:

Decay channel	Branching ratio
$B^0 \to K^+\pi^-$	$(1.82 \pm 0.08) \times 10^{-5}$
$B^0 \to \pi^+\pi^-$	$(4.6 \pm 0.4) \times 10^{-6}$
$B_s^0 \to \pi^+K^-$	$< 2.1 \times 10^{-4}$ @ 90% CL
$B_s^0 \to K^-\mu^+\nu$	$\sim 1.32 \times 10^{-4}$

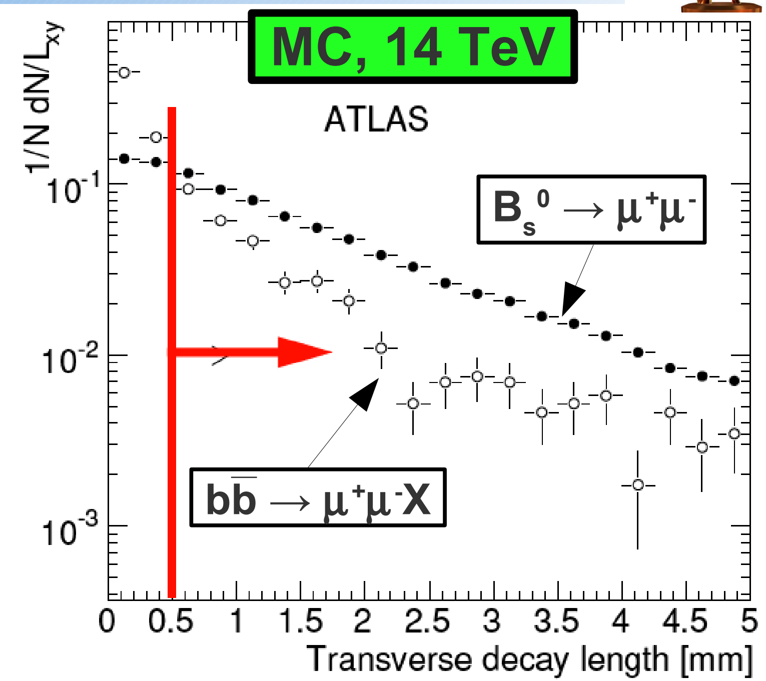
  - Four lepton decays ($B^+ \to \mu^+\mu^- l^+ \nu_l$)
- Combinatorial background:
  - $b\bar{b} \to \mu^+\mu^- X$
- Sources of prompt $\mu\mu$ pairs (J/ψ, Drell-Yan)
- In flight decays and material interactions

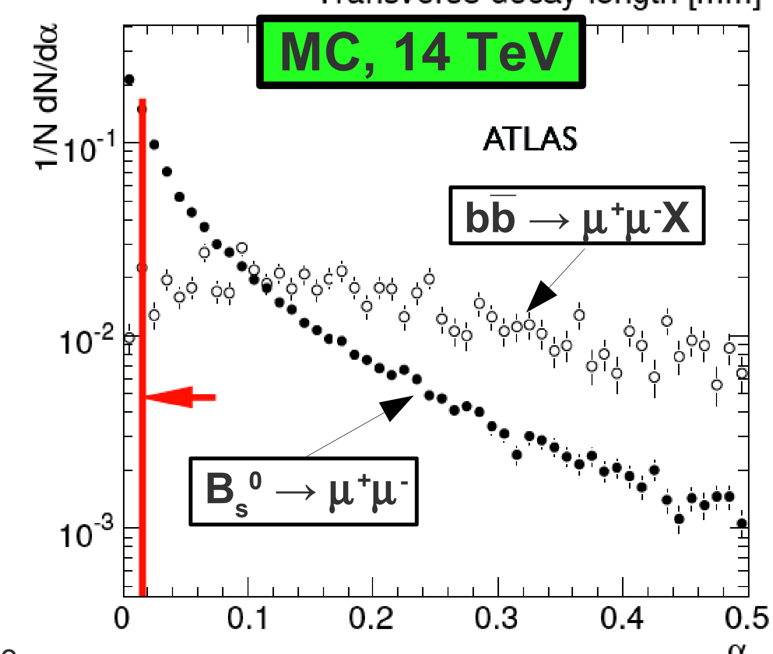
Selection cuts (1)

- **Preselection**
  - Quality cuts on the μμ vertex
- **Transverse decay length**
  - Distance between the primary vertex and the decay vertex projected on the p_T of the B_s^0 candidate
  - $L_{xy} > 0.5$ mm



- **Pointing angle**
  - Between B_s^0 flight direction and direction of decay vertex as seen from primary vertex
  - $\alpha < 0.017$ rad

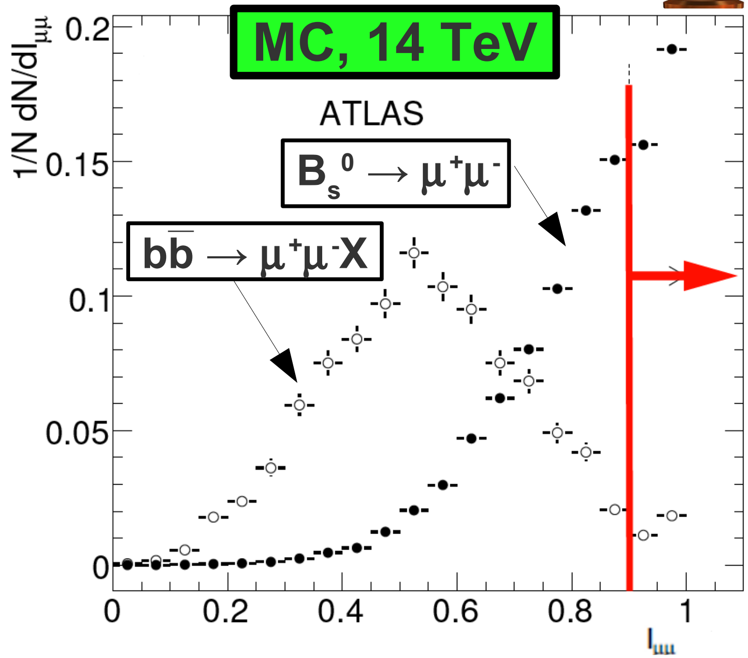




Selection cuts (2)

Track isolation

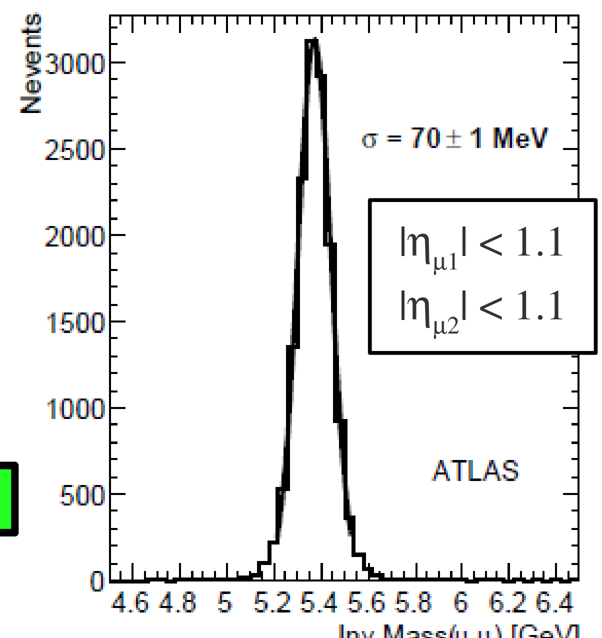
- $$I_{\mu\mu} = \frac{p_T(B_s)}{p_T(B_s) + \sum_i p_T(track_i)}$$
  with track p_T > 1 GeV inside cone $\Delta R < 1$
- $I_{\mu\mu} > 0.9$ $\qquad \Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$

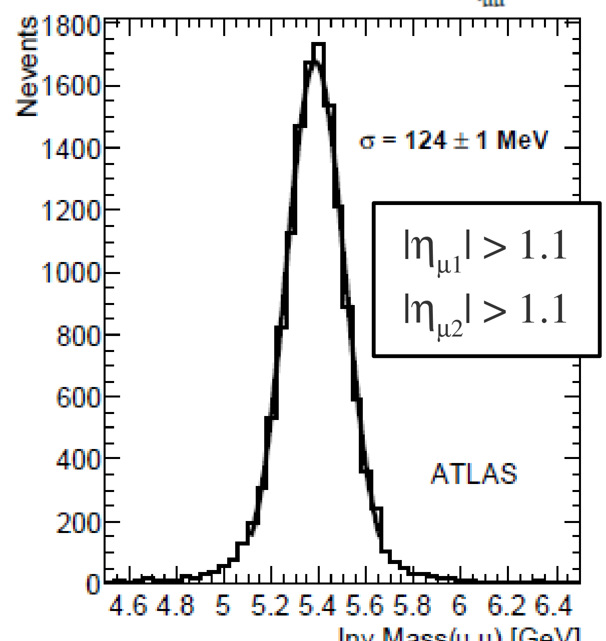


Invariant mass

- Window cut:
- $M(\mu\mu) \in [M_{B_s}$-70 MeV, M_{B_s}+140 MeV]
- Asymmetric cuts chosen in order to minimize overlapping with B_d^0 mass
- Mass resolution:
  - ~70 MeV ($|\eta_\mu| < 1.1$)
  - ~124 MeV ($|\eta_\mu| > 1.1$)

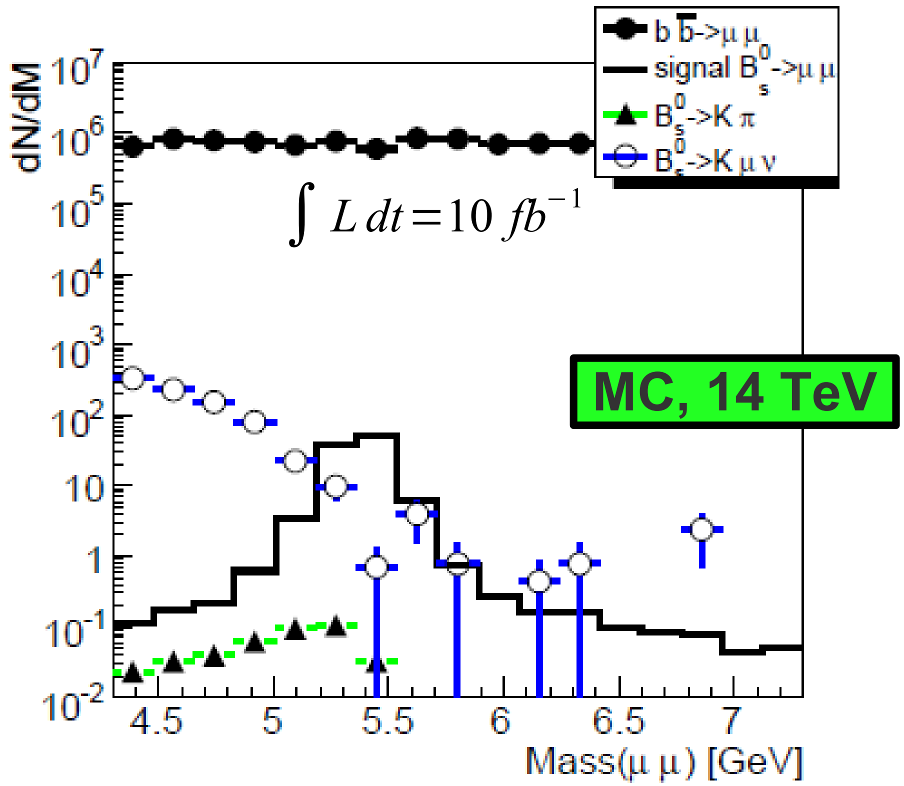
MC, 14 TeV



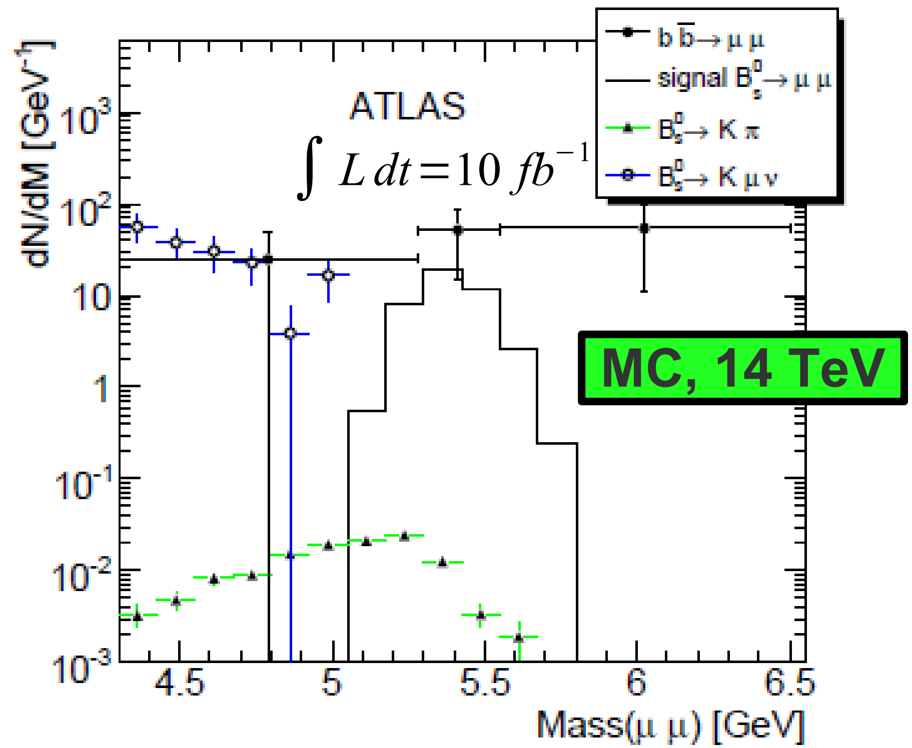


Background rejection

Before cut selection



After all cuts



- Exclusive channels well suppressed in the B_s^0 mass region
- Major contribution remaining from combinatorial background

Efficiency & event yield

Selection cut	$B_s^0 \to \mu^+\mu^-$	$b\bar{b} \to \mu^+\mu^- X$	
$I_{\mu\mu} > 0.9$	0.24	$(2.6 \pm 0.3) \times 10^{-2}$	
$L_{xy} > 0.5$ mm	0.26	$(1.4 \pm 0.1) \times 10^{-2}$	$(1.0 \pm 0.7) \times 10^{-3}$
$\alpha < 0.017$	0.23	$(8.5 \pm 0.2) \times 10^{-3}$	
$M(\mu\mu)$	0.76	0.079	
Total efficiency	0.04	0.24×10^{-6}	$(2.0 \pm 1.4) \times 10^{-6}$
Events (10 fb^{-1})	$\boxed{5.7}$		$\boxed{14^{+13}_{-10}}$

- Cut factorisation applied: $\varepsilon_{total} = \varepsilon_{I_{\mu\mu}} \cdot \varepsilon_{M_{\mu\mu}} \cdot \varepsilon_{L_{xy},\alpha}$
- Low correlations between variables, except L_{xy} and α
- Expected events for 10 fb^{-1}:
  - 5.7 signal
  - 14 background

Summary

- Rare (semi-)muonic decays of B mesons may give an indirect evidence of New Physics:
  - $b \rightarrow s\ \mu^+\mu^-$ transitions (forward-backward asymmetry),
  - $B_s^0 \rightarrow \mu^+\mu^-$ (branching ratio).

- Single muon trigger performance was determined from data, with efficiencies at plateau:
  - LVL1: ~76% (barrel), ~94% (endcap),
  - LVL2: ~97%,
  - EF: ~99%.

- Efficiency map $\varepsilon(p_T)$ obtained using “tag and probe” for LVL1 single muon trigger. This is used in determining the di-muon trigger efficiency.

- Expected number of events for 10 fb^{-1} using the $B_s^0 \rightarrow \mu^+\mu^-$ analysis:
  - 5.7 (signal),
  - 14 (background).

Back-up slides

Event selection

μ pairs (μ^+, μ^-)
Kinematic cuts (p_T, η)

preselection

$M(\mu\mu) \in [4300\ \mathrm{MeV}, 7000\ \mathrm{MeV}]$
$\mu\mu$ vertex $\chi^2/\mathrm{ndf} < 10$,
B_s^0 candidate

$M(\mu\mu) = M_{PDG}(J/\psi) \pm 150$ MeV

$M(K\mu\mu) \in [4300\ \mathrm{MeV}, 7000\ \mathrm{MeV}]$,
$K\mu\mu$ vertex $\chi^2/\mathrm{ndf} < 10$,
B^+ candidate

selection cuts

$L_{xy} > 0.5$ mm

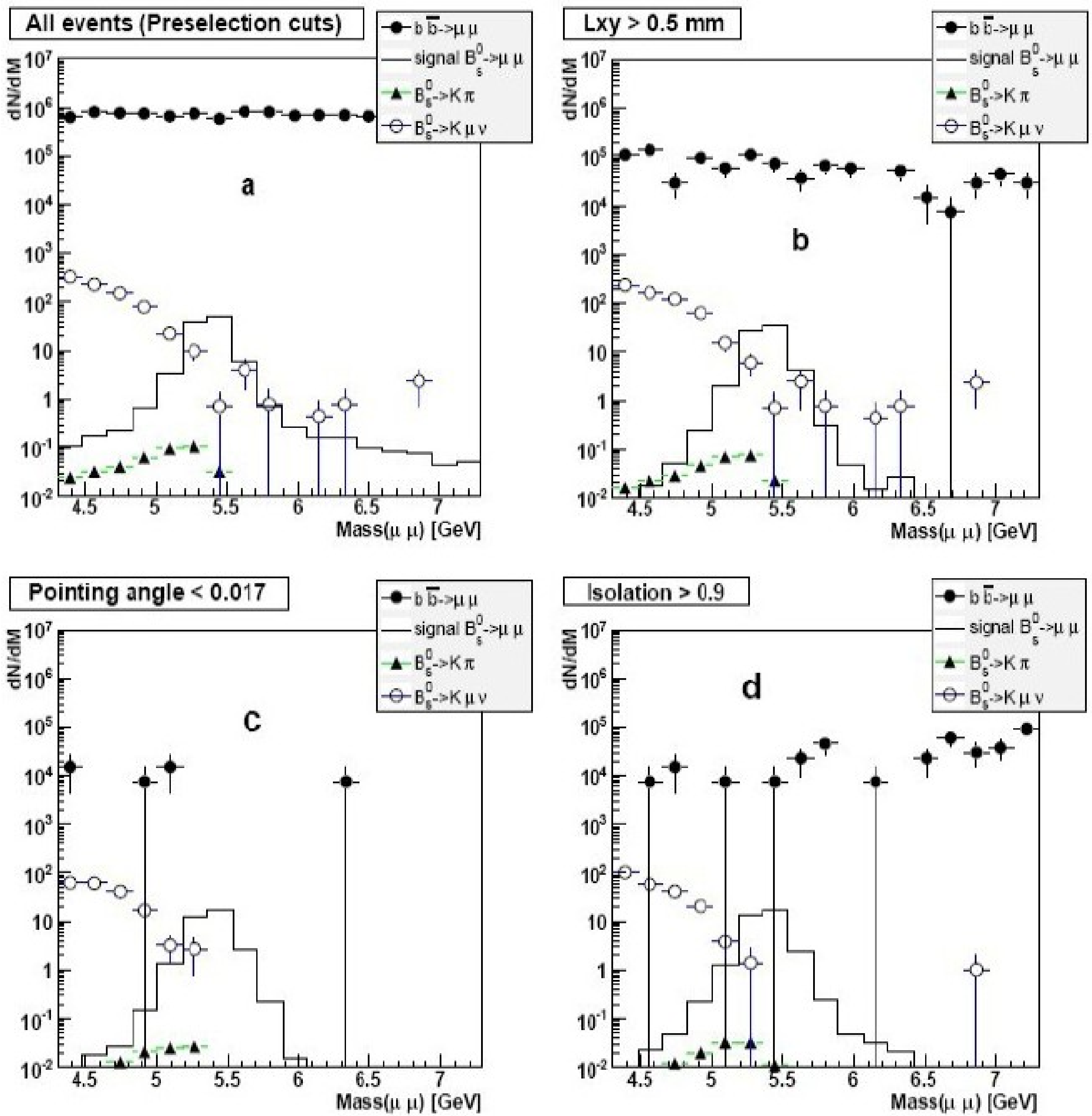
$\alpha < 0.017$ rad

$I_{\mu\mu} > 0.9$

$M(B_s) = M_{PDG}(B_s)^{+140\ \mathrm{MeV}}_{-70\ \mathrm{MeV}}$

$M(B^+) = M_{PDG}(B^+)^{+70\ \mathrm{MeV}}_{-140\ \mathrm{MeV}}$

Background rejection



- **Cuts shown separately**

MC, 14 TeV