Search for $B^0_s \to \mu^+\mu^-$ and exclusive B decays with the ATLAS detector

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On behalf of the
ATLAS Collaboration

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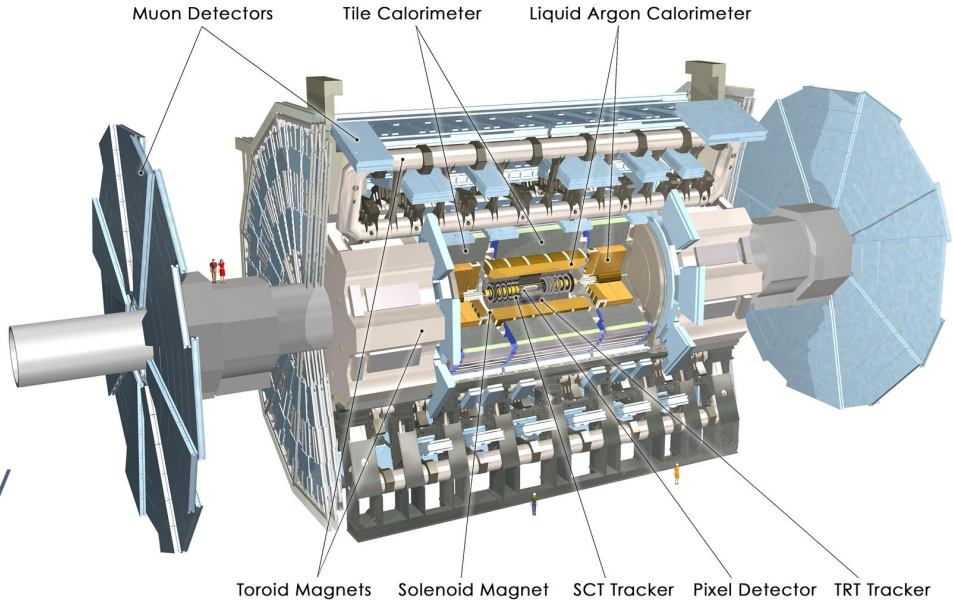
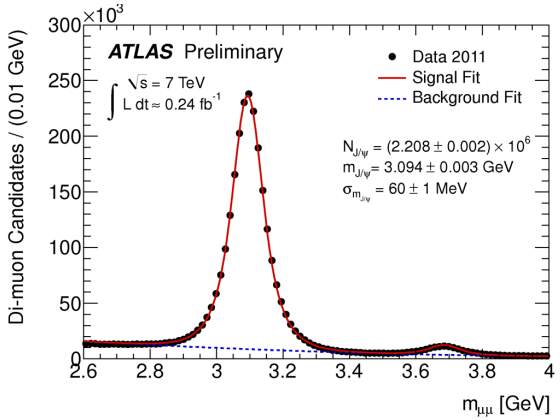
Outline

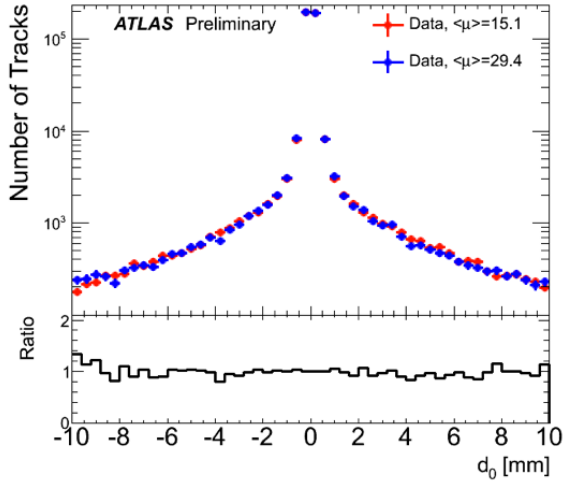
- The ATLAS experiment
  - Detector
  - Trigger for B Physics
- Exclusive B decays with $J/\psi \rightarrow \mu^+\mu^-$
  - $B_c^{\pm} \rightarrow J/\psi(\mu^+\mu^-)\pi^{\pm}$
  - $B_d \rightarrow J/\psi(\mu^+\mu^-)K^{*0}$
  - $B_s \rightarrow J/\psi(\mu^+\mu^-)\phi$
- Search for Rare decay
  - $B_s \rightarrow \mu^+\mu^-$
    ($B^{\pm} \rightarrow J/\psi(\mu^+\mu^-)K^{\pm}$ as reference channel)

The ATLAS Detector

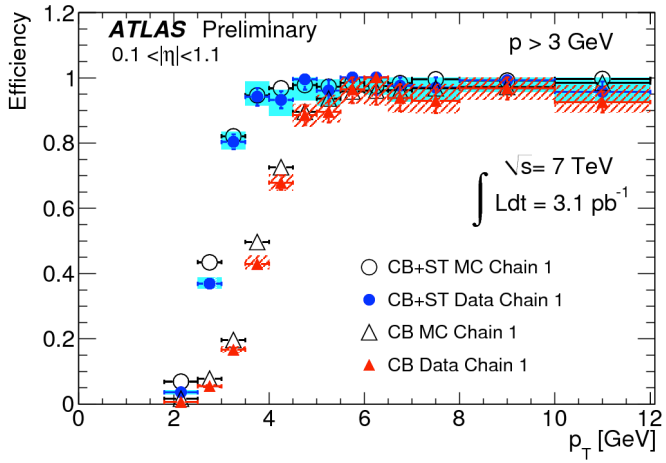
- Inner Detector
  - Good mass resolution
    - S/B discrimination
    - Limited PID: K/pi separation only for p<1GeV
  - Good vertex resolution even with high pile-up
    - Precise B measurements



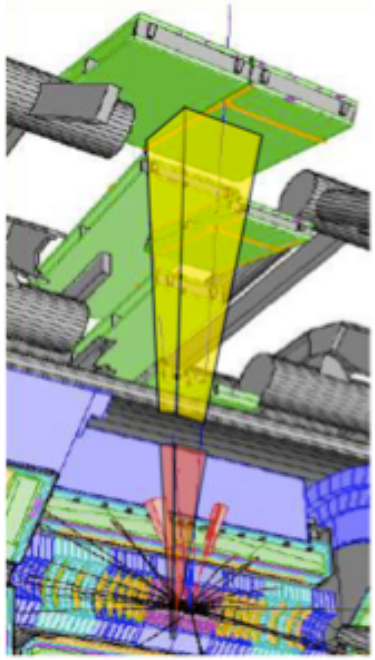




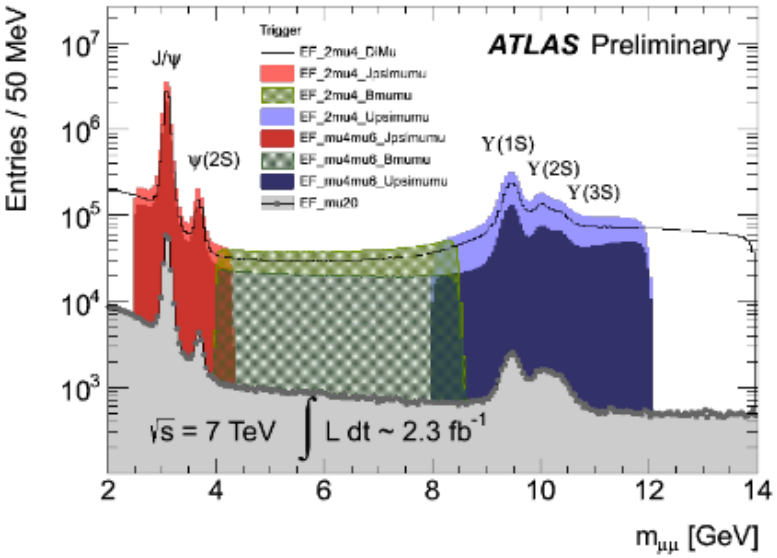
- Muon Spectrometer
  - Trigger performance for low-p_T muons as expected

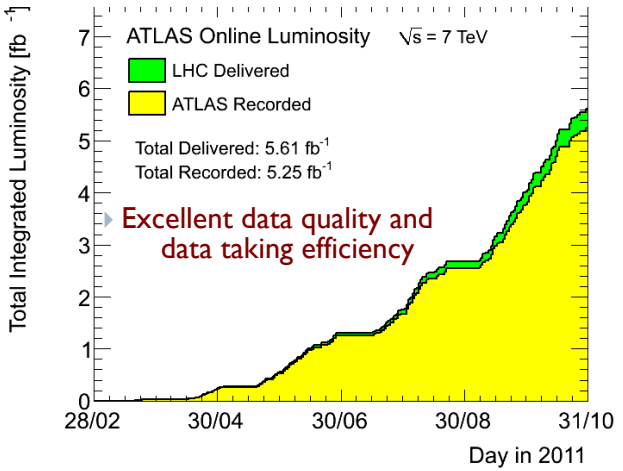


Trigger for B Physics



- ATLAS trigger
  - Output rate ~300Hz
  - Three levels of selection
  - Based on Regions-of-Interest
- B-Trigger
  - High p_T trigger priority for general-pourposes experiment (Higgs, SUSY etc.)
  - Keep low p_T trigger thresholds at high luminosity
  - Total bandwidth is the main limitation
- Di-muon trigger is the key
- ~10fb^{-1} in 2011+2012
  - bb-production mostly at large $|\eta|$
  - In 10fb^{-1} expected about
    - 300G B^0 pairs
    - 60M $B^0_s \rightarrow J/\psi\,\phi$

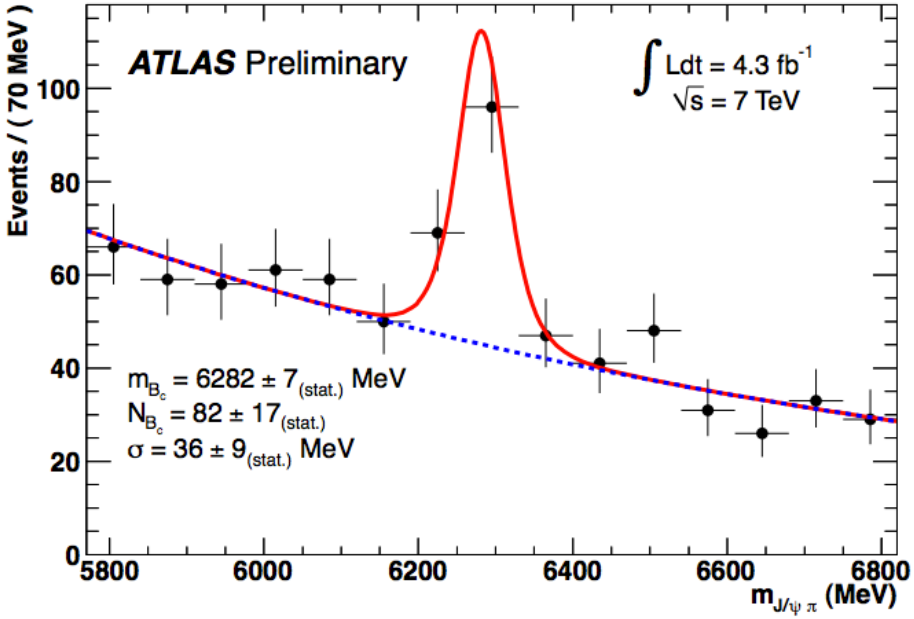




$B_c^{\pm} \rightarrow J/\psi(\mu^+\mu^-)\pi^{\pm}$

- B_c bound state of heaviest quarks (c,b)→
  - Test of non relativistic potential models, perturbatve QCD, lattice calculations

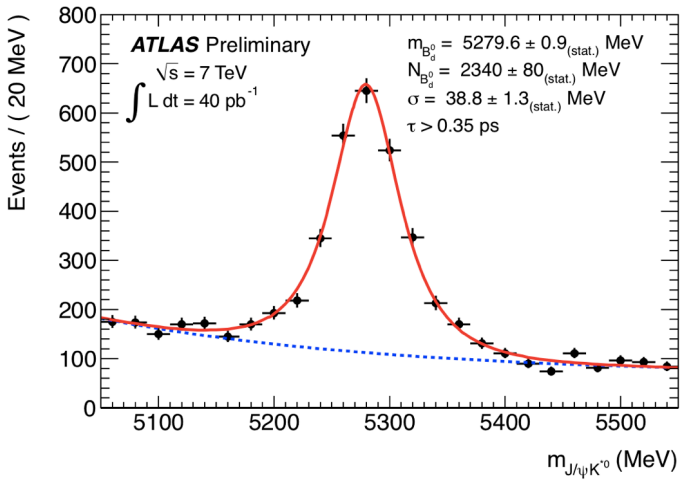
- Trigger:
  - Single muon p_T> 6 GeV
  - Di-muon $p_T(\mu_1)$> 4 (6)GeV, $p_T(\mu_2)$> 4 GeV
- Selection cuts:
  - J/psi:
    - $p_T(\mu)^{max}$> 6 GeV, $p_T(\mu)^{min}$> 4 GeV
    - Muon vertex fit χ^2/N_{dof}<15
    - $|M(\mu\mu)-M(J/\psi)|$ < 180 MeV
  - Pion:
    - >1Pixel hit > 6 SCT hits
    - $p_T(\pi^{\pm})$ > 4 GeV
  - $B_c^{\pm}$:
    - $\mu\mu\pi$ vertex fit χ^2/N_{dof}<2
    - $p_T(B_c)$ > 15 GeV
- Signal+Bkg unbinned maximum likelihood fit



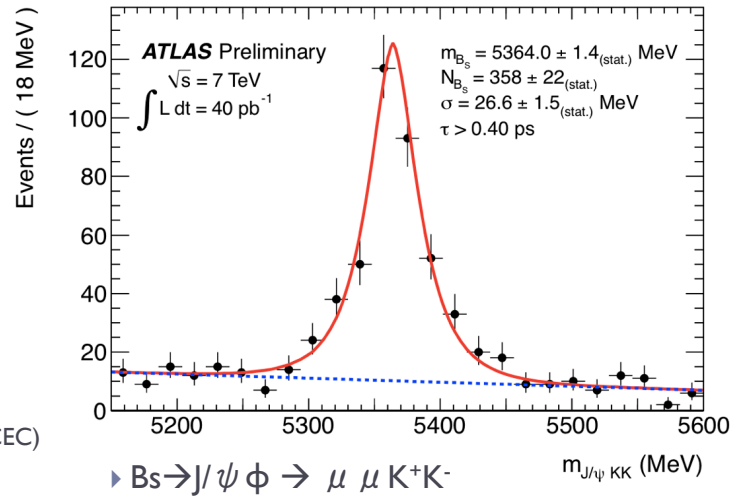
M_{Bc} (fit) = 6282±7(stat) MeV
M_{Bc} (PDG) = 6277±6 MeV

Good agreement→ p_T scale well understood down to low p_T values

$B_d \rightarrow J/\psi K^{*0}$ and $B_s \rightarrow J/\psi \phi$



- B hadron mass signal measured in exclusive decays with $J/\psi(\mu\ \mu)$ (2010 and 2011)
- Good consistency with PDG values
- Two early examples showed here
  - Very low pile-up ('relaxed analysis')

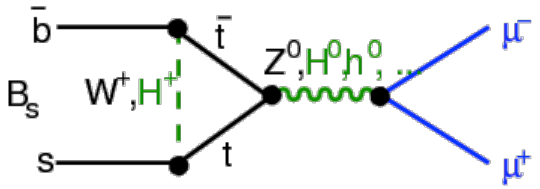


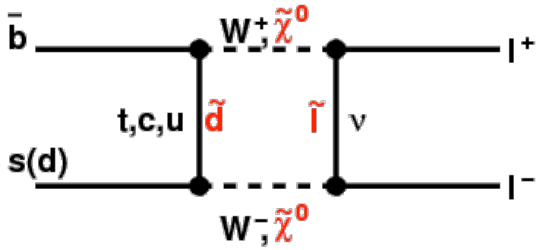
- J/ψ (common)
  - 2 muon candidates p_T>3GeV
  - $\mu\ \mu$ vertex fit χ^2/N_{dof}<10
  - $|M(\mu\ \mu)-M(J/\psi)|$ < 270/360/480 MeV (BarrelBarrel/BarrelEndCap/ECEC)
- Bd→$J/\psi K^{*0}$→ $\mu\ \mu\ K^+\pi^-$
  - 2 not-muon opposite charge tracks with p_T>0.5 GeV
  - M(Kπ) in [846-946] MeV
  - $p_T(K^{*0})$>2.5 GeV
  - $\mu\ \mu$ Kπ vertex fit χ^2/N_{dof}<2.5
  - τ >0.35 ps
- Bs→$J/\psi\phi$ → $\mu\ \mu\ K^+K^-$
  - 2 not-muon opposite charge tracks with p_T>0.5 GeV
  - $p_T(K^+)$,$p_T(K^-)$>1GeV
  - M(K^+K^-) in [1009-1031] MeV
  - $\mu\ \mu$ KK vertex fit χ^2/N_{dof}<2.0
  - τ >0.40 ps

$B^0_s \to \mu\ \mu$: Physics Motivation

- $B^0_s \to \mu^+\mu^-$
  - Process sensitive to FCNC
  - Highly suppressed in Standard Mode
  - Powerful probe for New Physics

New Physics could increase (but even decrease) $Br(B^0_s \to \mu^+\mu^-)$

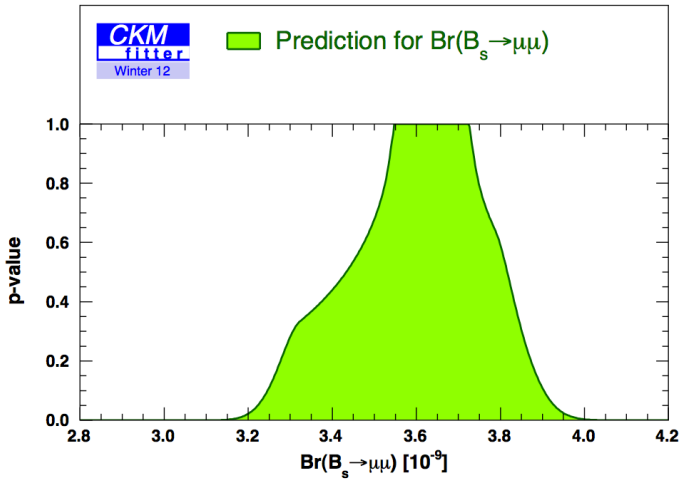




Current status:

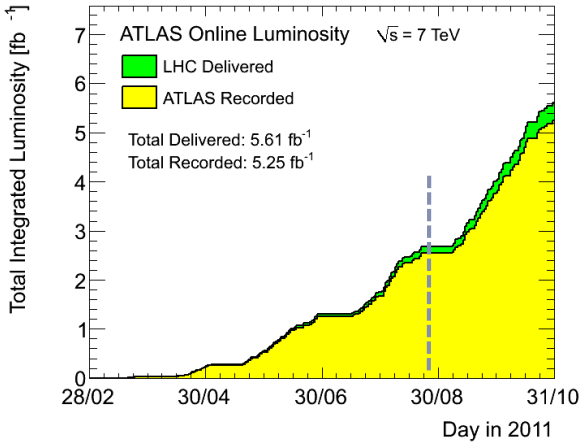
SM prediction:
$Br(B^0_s \to \mu^+\mu^-) = 3.2 \pm 0.2\ 10^{-9}$

SM fit (CKMfitter):
$Br(B^0_s \to \mu^+\mu^-) = 3.64^{+0.21}_{-0.32}\ 10^{-9}$



$B^0_s \to \mu\ \mu$: analysis overview

- Result on 2.4fb^{-1}
  - collected up to July 2011 with homogeneous trigger
- Relative measurement
  - Partial cancellation of systematics
  - Reference channel: $B^{\pm} \to J/\psi\, K^{\pm}$
    - High yield with similar final state



$$BR(B_s \to \mu\mu) = \frac{N_{B_s \to \mu\mu}}{N_{J/\psi K^{\pm}}} \cdot \frac{\alpha_{J/\psi K^{\pm}} \varepsilon^{tot}_{J/\psi K^{\pm}}}{\alpha_{B_s \to \mu\mu} \varepsilon^{tot}_{B_s \to \mu\mu}} \cdot \frac{f_u}{f_s} \cdot BR(B^{\pm} \to J/\psi K^{\pm})$$

$B^0_s \to \mu\ \mu$: analysis overview

- Unbiassed
  - Blind analysis
    - signal region (±300MeV around B^0_s mass) blinded
    - Use MC to model data
  - Background data in sidebands split in two
    - 50% to optimize selection cuts
    - 50% to measure the bkg yield after cuts optimization
- Signal/Background discrimination
  - Multivariated analysis
    - BDT based on 14 variables
  - Data sample split in three mass resolution categories according to the pseudorapidity value of the muon with higher $|\eta|$ (η^{max})
- Signal extraction
  - Event count in signal region
  - Background estimation from sidebands
- Limit extraction with CLs method

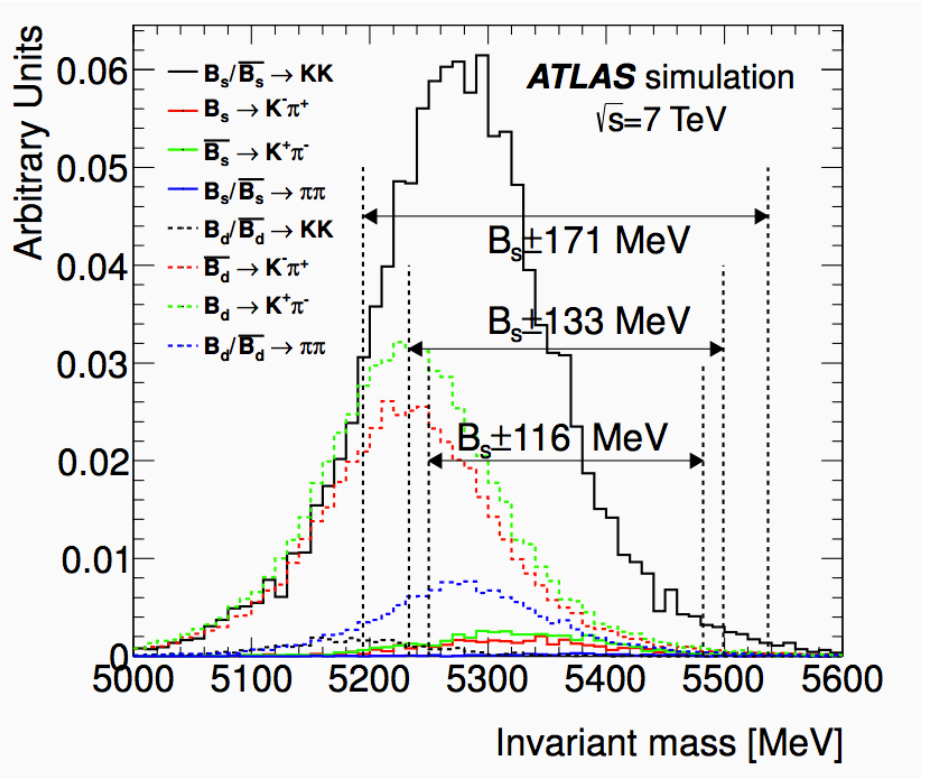
Channel	Signal Region	Sideband Regions
$B^0_s \to \mu^+\mu^-$	[5066,5666] MeV	[4766,5066] MeV [5666,5966] MeV
$B^\pm \to J/\psi K^\pm$	[5180,5380] MeV	[4930,5130] MeV [5430,5630] MeV

η^{max}	Detector region	Mass resolution (MeV)
1.0	Barrel	60
1.5	Transition	80
2.5	Endcap	110

Background Composition

- Real muons (continuum):
  - bb→μμX dominant background
  - Modeled using data in sidebands
- "Fake" muons (decays in flight, punch-throughs):
  - B→hh (KK, Kπ, ππ)
    - "quasi irreducible" due to close topology
    - BRx(fake rate) ≈ 10^{-9}, close to SM B_s→μμ
    - Contribution estimated with MC: almost negligible
- Single muon + "fake" (e.g. B→μKν)
  - Negligible contribution, outside our search windows

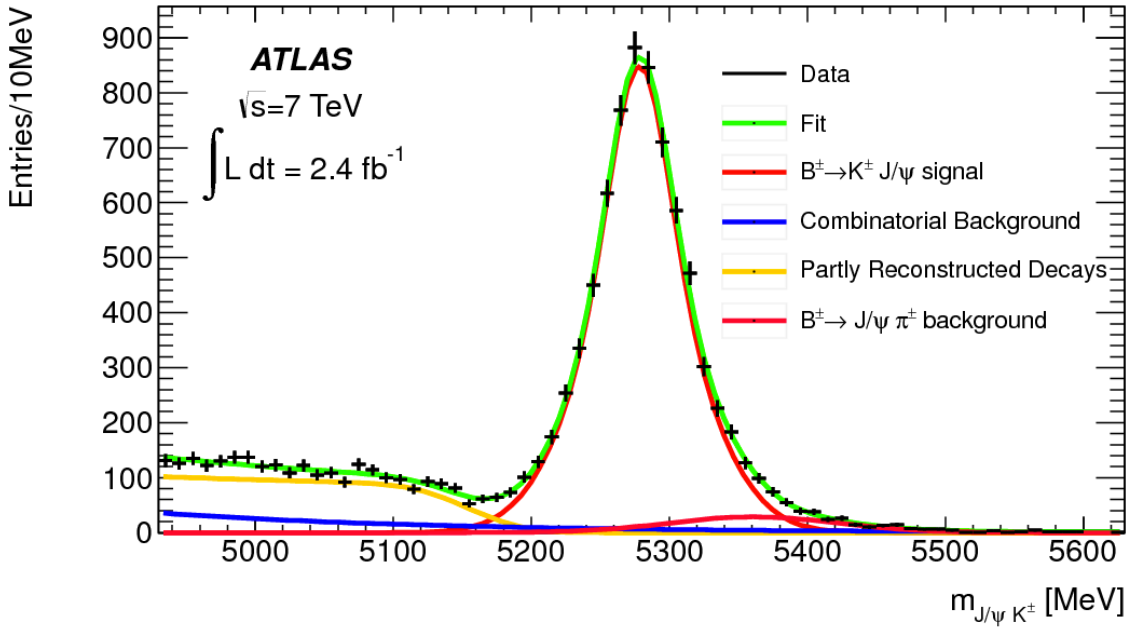
B→hh reconstructed as $\mu\ \mu$



$B^{\pm} \rightarrow J/\psi K^{\pm}$ Yield

$$BR(B_s \rightarrow \mu\mu) = N_{B_s \rightarrow \mu\mu} \left[\frac{\alpha_{J/\psi K^{\pm}} \varepsilon^{tot}_{J/\psi K^{\pm}}}{\alpha_{B_s \rightarrow \mu\mu} \varepsilon^{tot}_{B_s \rightarrow \mu\mu}} \cdot \frac{1}{N_{J/\psi K^{\pm}}} \cdot \frac{f_u}{f_s} \cdot BR(B^{\pm} \rightarrow J/\psi K^{\pm}) \right]$$

- BDT trained for B_s used also on $B^{\pm}$, in order to minimize selection sistematics
- Yield uncertainties
  - Statistical
  - Systematic
    - Vary binning
    - Signal/background models
    - Binned/un-binned fit



$\lvert\eta_{max}\rvert$ Range	0-1.0	1.0-1.5	1.5-2.5
$B^{\pm} \rightarrow J/\psi K^{\pm} \rightarrow \mu^+\mu^- K^{\pm}$	4300	1410	1130
statistical uncertainty	±1.6%	±2.8%	±3.0%
systematic uncertainty	±2.9%	±7.4%	±14.1%

Single Event Sensitivity

- SES (single event sensitivity)=$B_s \rightarrow \mu\ \mu$ Br which would give 1 signal event in the data sample

$$BR(B_s \rightarrow \mu\mu) = N_{B_s \rightarrow \mu\mu} \left[\frac{\alpha_{J/\psi K^\pm} \varepsilon^{tot}_{J/\psi K^\pm}}{\alpha_{B_s \rightarrow \mu\mu} \varepsilon^{tot}_{B_s \rightarrow \mu\mu}} \right] \frac{1}{N_{J/\psi K^\pm}} \cdot \frac{f_u}{f_s} \cdot BR(B^\pm \rightarrow J/\psi K^\pm)$$

- Efficiency and acceptance estimated on MC

$\lvert\eta_{max}\rvert$ Upper limit	$R^i_{A\epsilon}$	Δ % Stat.	Δ % Syst.
1.0	0.27	3.1	3.1
1.5	0.20	4.8	5.5
2.5	0.14	5.3	5.9

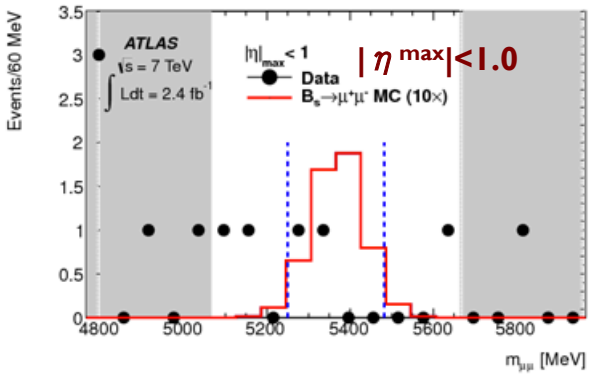
- $1/(4.45 \pm 0.38) 10^{-3}$
  - from PDG+LHCb(Phys.Rev.D85(2012)032008)
  - Dominant systematic uncertainty

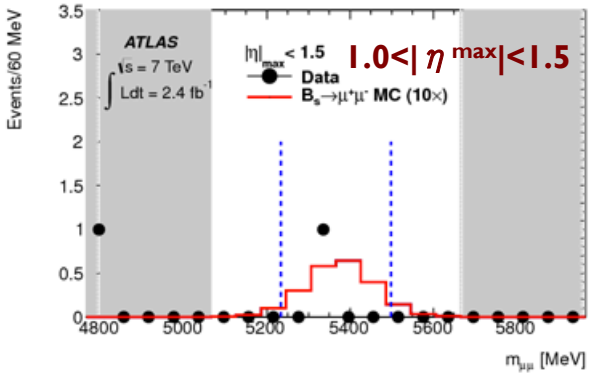
- Additional systematic uncertainties:
  - Data-MC absolute K efficiency: 5%
  - Vertex reconstruction efficiency: 2%
  - K^+/K^- asymmetry: 1%

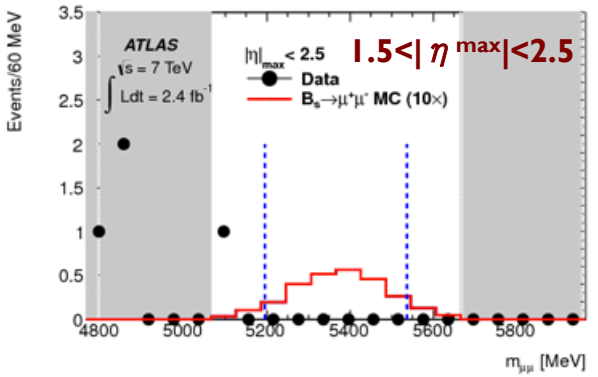
Signal box opening

- Mass window width (dashed lines) for signal region (SR) optimized in each mass resolution bin

	Mass Resolution bins		
	$\|\eta\|<1.0$	$1.0<\|\eta\|<1.5$	$1.5<\|\eta\|<2.5$
Events in sidebands (unbiassed)	**5**	**0**	**2**
Events in sidebands (biassed)	**1**	**1**	**1**
Expected bkg event in SR	**3.86**	**0**	**2.28**
Expected resonant bkg	**0.1**	**0.06**	**0.8**
Observed events in SR	**2**	**1**	**0**





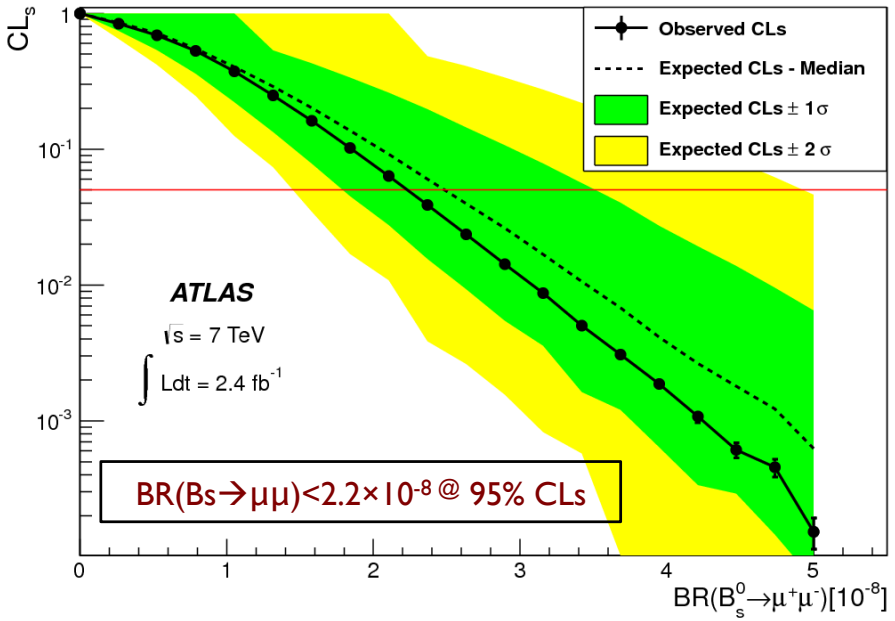


Limit extraction:

- Upper limit extracted with modified frequentist (CLs) approach
- Limit expectation at 95% CL
  - Even sidebands (unbiassed): 2.3×10^{-8}
  - Odd sidebands (biassed): 1.7×10^{-8}
  - All mass resolution bins merged (for comparison): 2.9×10^{-8}
- **Observed limit at 95% CL (unbiassed): 2.2×10^{-8}**

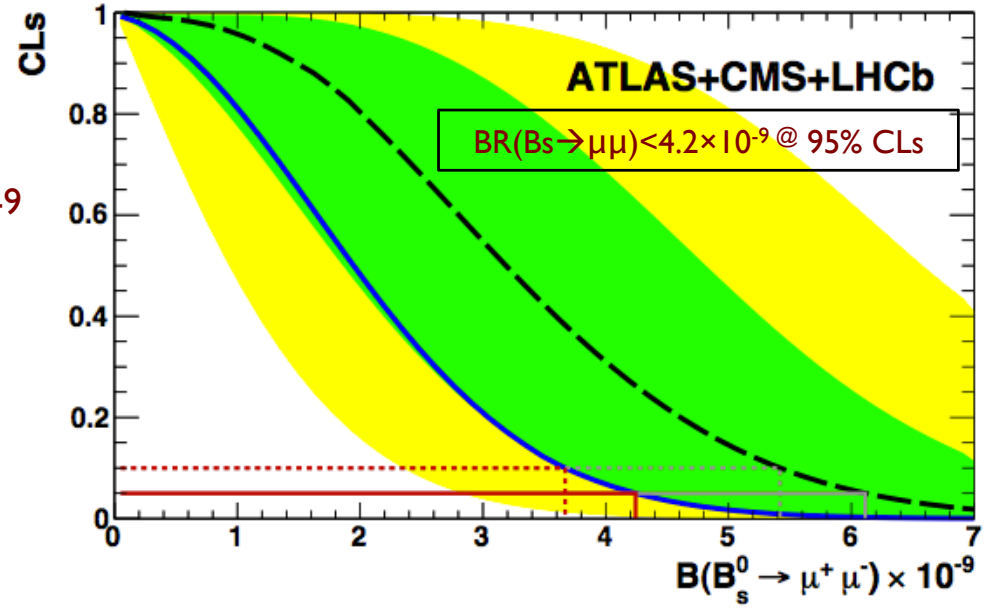
$$\mathcal{L} = \mathrm{Gauss}(\epsilon_{\mathrm{obs}}|\epsilon,\sigma_\epsilon)\times\mathrm{Gauss}(R^{\mathrm{bkg}}_{\mathrm{obs}}|R^{\mathrm{bkg}},\sigma_{R^{\mathrm{bkg}}})\times \prod_{i=1}^{N_{\mathrm{bin}}}\mathrm{Poisson}(N_i^{\mathrm{obs}}|\epsilon\,\epsilon_i\mathrm{BR}+N_i^{\mathrm{bkg}}+N_i^{B\to hh})\times \mathrm{Poisson}(N^{\mathrm{bkg}}_{\mathrm{obs},i}|R^{\mathrm{bkg}}\,R_i^{\mathrm{bkg}}N_i^{\mathrm{bkg}})\times \mathrm{Gauss}(\epsilon_{\mathrm{obs},i}|\epsilon_i,\sigma_{\epsilon_i})\,.$$

- Next steps:
  - Full 2011 (and 2012) statistics
  - Use spectrometer information to improve mass resolution in forward regions
  - MC-based continuous background model
  - Mass fit for signal yield extraction
- Expect improvements better than $\sqrt{L}$



$B^0_s \to \mu\ \mu$ LHC combination

- ATLAS result combined with CMS and LHCb
- Observed limit at 95% CL: 4.2×10^{-9}
- Most recent up-to-date result
- Compatible with SM signal within $1\,\sigma$ ($1\text{-}CL_{s+b}$=84%)
- p-value bkg-only hypotesis ($1\text{-}CL_b$): 5%



SM value for Br (3.2×10^{-9}) is becoming close

Mode	Limit	ATLAS	CMS	LHCb 2010	LHCb 2011	Combined
$B^0_s \to \mu^+\mu^-$ (10^{-9})	Bkg Only	23	(3.6)	65	3.4	2.3
	Bkg+SM		8.4		7.2	6.1
	Obs	22	7.7 (7.2)	56	4.5	4.2

Conclusions

- Rich B-Physics program with ATLAS
  - Event selection strategy mainly based on di-muon trigger
  - Benchmarks channels with $J/\psi \rightarrow \mu\ \mu$ well assessed
    - p_T scale well under control down to few GeV even with high pile-up
  - More additional interesting results
    - See talks by: K. Toms and S. Palestini
  - Search for rare $B_s \rightarrow \mu\ \mu$ decay with $2.4 fb^{-1}$
    - $Br(B_s \rightarrow \mu\ \mu) < 22\ 10^{-9}$
    - Extension to $5 fb^{-1}$ with several analysis improvements in preparation
  - LHC combination (ATLAS+CMS+LHCb) gives the best up-to-date limit:
    - $Br(B_s \rightarrow \mu\ \mu) < 4.2\ 10^{-9}$
    - SM value is getting close!

Supporting material

Reconstruction and event selection

- 2- (B^0_s) or 3- ($B^{\pm}$) prong vertex constraint
- Primary vertex selection:
  - The closest in z to the B candidate
  - Re-fit excluding B daughters
- Tracks:
  - At least 1 pixel, 6 SCT and 9 TRT hits
  - $|\eta|$<2.5 and p_T>4 (2.5) GeV for muons (kaons)
  - ID tracks matching tracks in Muon Spectrometer for muons
- B candidates
  - p_T>8 GeV and $|\eta|$<2.5
- Signal/Bkg discrimination
  - Boost Decision Tree on 14 variables
  - Optimize P with a=2 for 95% CL.
  - Most powerful discriminating characteristics:
    - Distance PV-SV (Lxy, ct-significance,)
    - Symmetry of final state (pointing angle alpha2D, d0 …)
    - Full reconstruction (pointing angle, Dmin)
    - B hadronization features (Isolation, pT of reconstructed B)

$$\mathcal{P} = \frac{\epsilon_{\mathrm{sig}}}{\frac{a}{2} + \sqrt{N_{\mathrm{bkg}}}}$$