Flavour Physics Results from ATLAS

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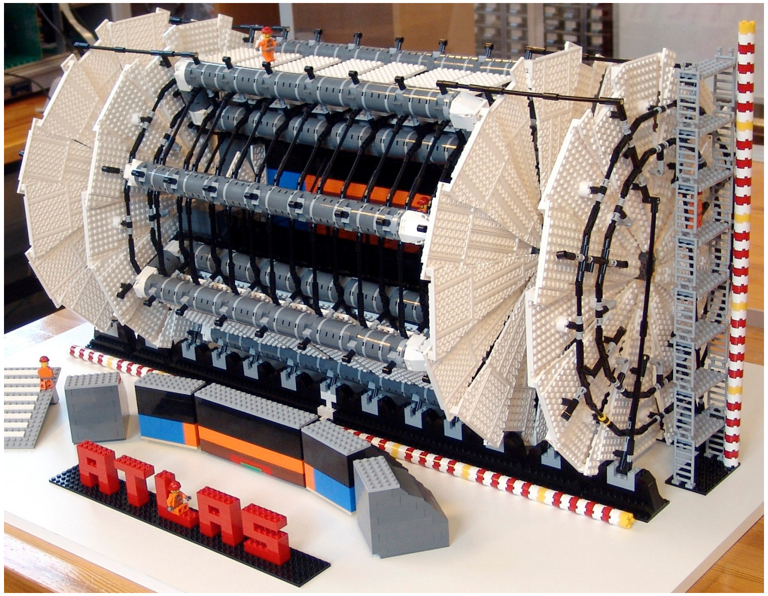


4th Capri Workshop on Flavour Physics

Capri, Italy
June 13th, 2012

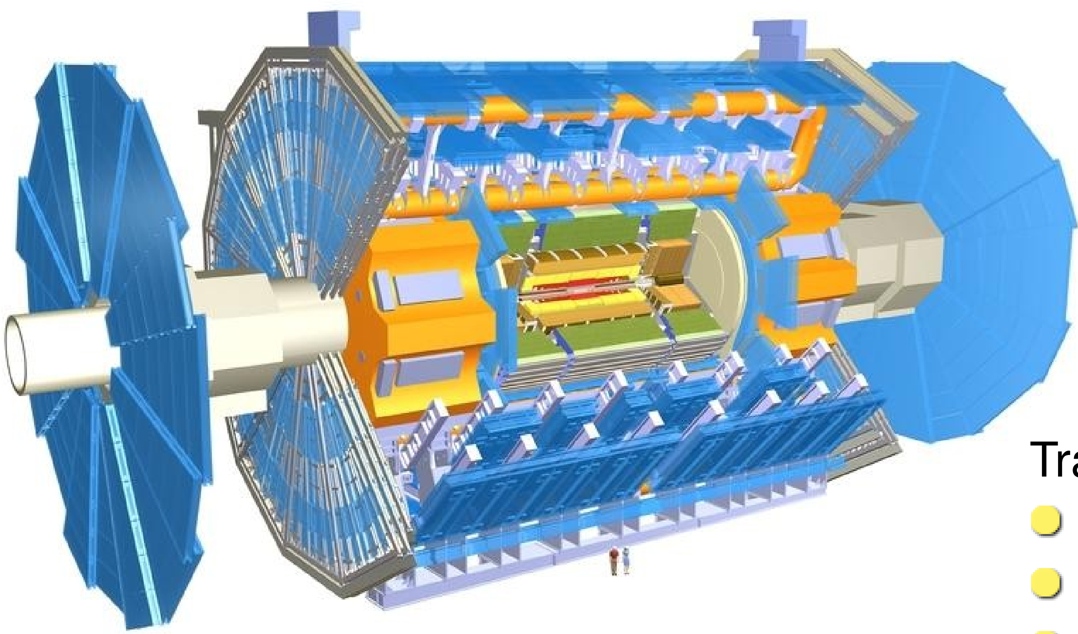
outline

- ATLAS data, detector and triggers
- detector performances
- B meson mass and lifetime measurements
- search for B rare decays: B_s to $\mu\mu$

speaker's selection from B physics programme, but there is more:

- observation of D, J/ψ, Υ(2s) and Υ
  ATLAS-CONF-2010-034, ATLASCONF-2010-045
- D^*, $D^\pm$, D_s cross sections
  ATLAS-CONF-2010-017
- J/ψ differential cross section and prompt/non-prompt separation
  Nucl. Phys. B, Vol. 850, 387-444 (2011)
- Υ production cross-section
  Phys. Lett. B705, 9-27 (2011)
- χ_b and χ_b(3P) observation: new structure at 10.5 GeV (>6σ)
  Phys. Lett. B705, 9-27 (2011)

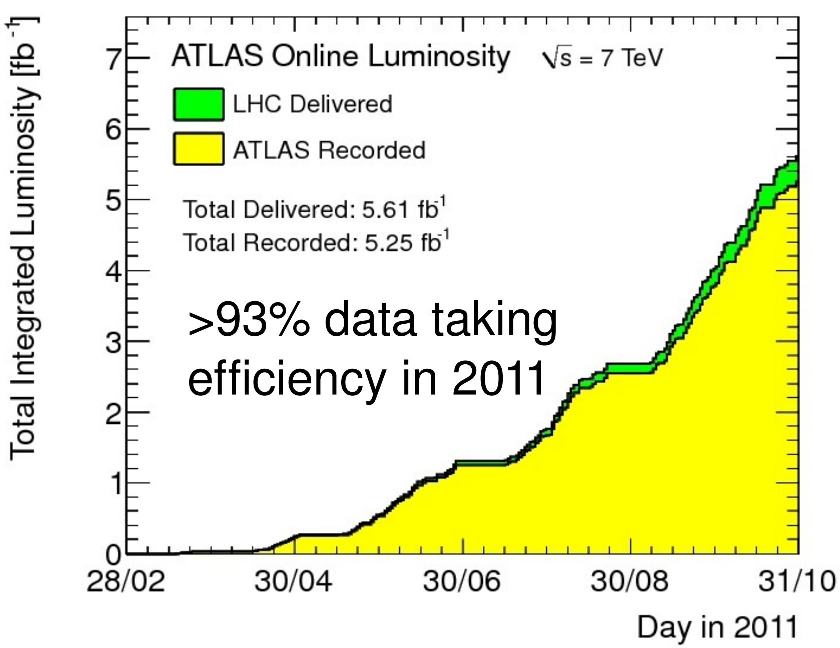
ATLAS



- *Tracking*
  - Silicon (Pixel+Semiconductor tracker) and Transition Radiation Tracker
  - 2T solenoidal field
- *Muon identification:*
  - Dedicated tracking chambers
  - 0.5-2 T toroidal field

Tracking performances:

- 10 μm Impact Parameter resolution
- $\sigma\, p_T/p_T \sim 0.05\%\, p_T\, (+)\, 1.5\%$
- σ m(J/ψ-Y)~60-120 MeV (ID dominated)



- >5 fb-1 recorded in 2011: Instantaneous luminosity and pile-up steadily increasing
- bb-production mostly at large η

ATLAS sensitive to |η| < 2.5 region

- expect about ~150G B^0–pairs
- ~30M $B_s \to J/\psi\phi$ events for $5fb^{-1}$

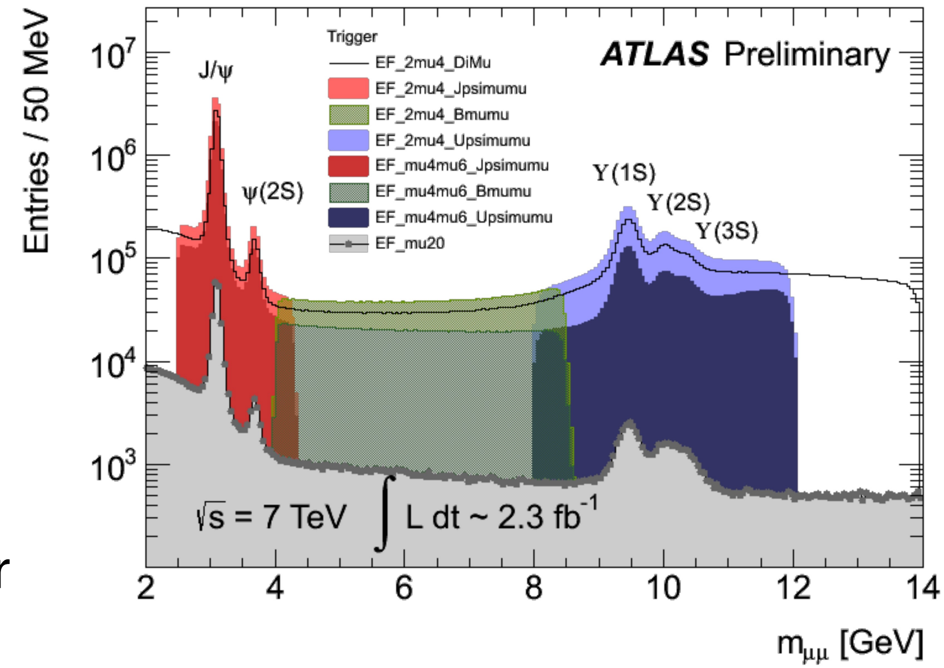
ATLAS: triggers

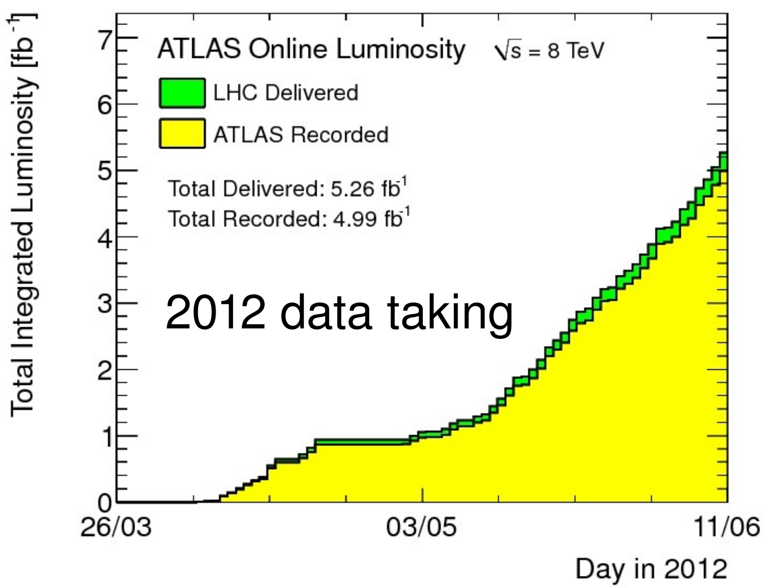
di-lepton triggers are our main tool

- High luminosity (2011): di-muon triggers
- As luminosity increases, bandwidth requirements are more stringent
- Potentially forced to higher pT

L1 4 GeV selections have been made cleaner:

- we managed to run with constant trigger thresholds for B physics all across 2011





~ 5 fb^{-1} of data already collected in 2012

- trigger revisited to reduce the rates
- higher muon p_T thresholds would affect the efficiency for B physics
- specific di-muon selections with Barrel/Endcap logic
- 4 p_T di-muon triggers collected but processed later in time (2013 shutdown)

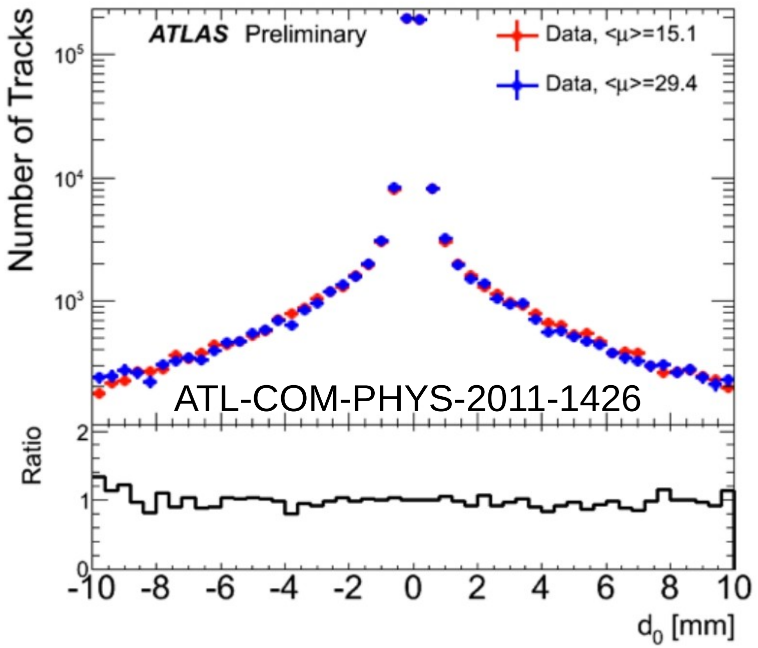
tracking-vertexing performance in pile-up

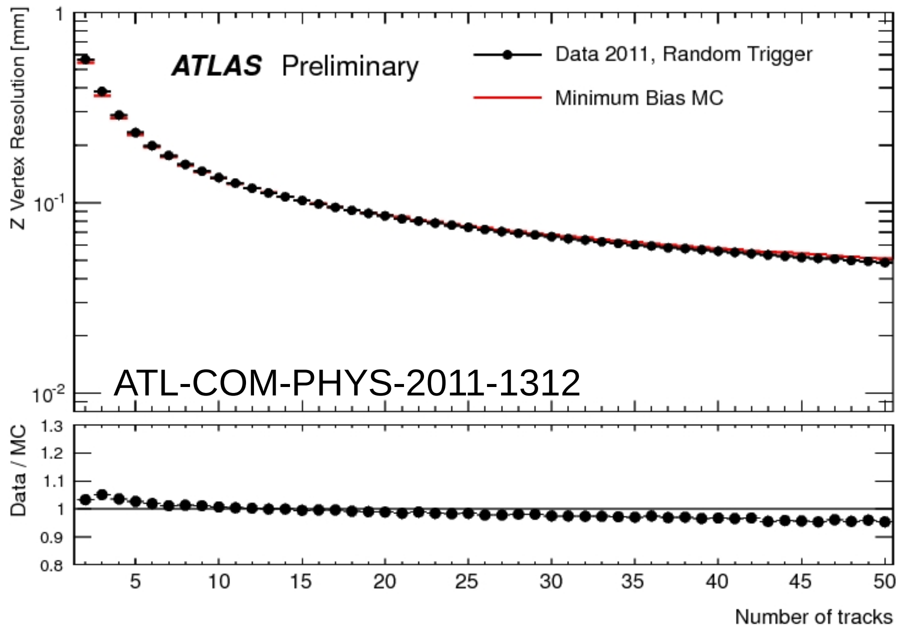
- Vertex resolution important for precision B-physics measurements: lifetime, CPV, rare decays.

- Quality of vertexing monitored over 2011 as pileup increased

- d_0 (top plot) of the reconstracted tracks with respect to the PV for 2 different number of pileups:
  - The tails are sensitive to the rate of secondaries and fakes. No significant increase in the fake rate observed.

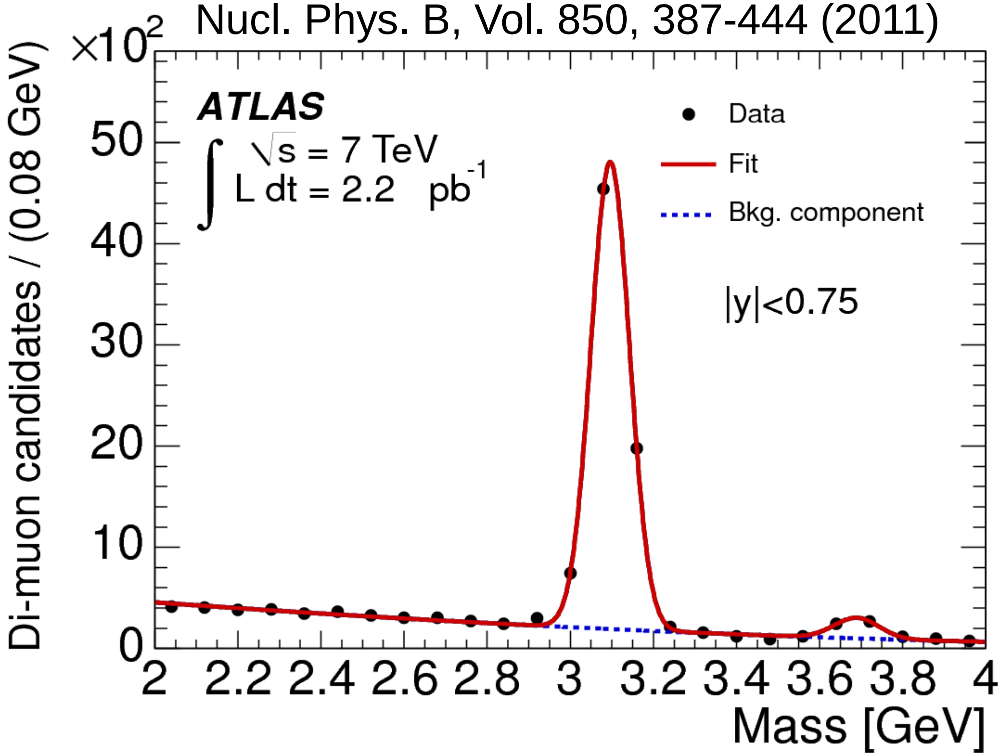
- Good z-resolution of primary vertex important at high luminosities



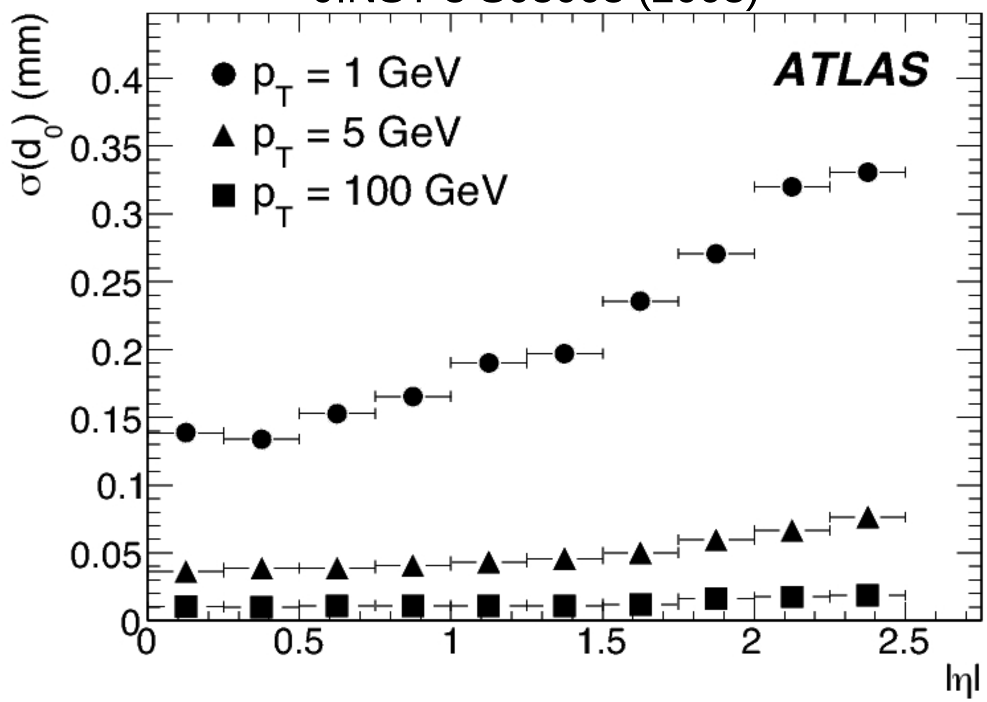


performances

Nucl. Phys. B, Vol. 850, 387-444 (2011)



JINST 3 S08003 (2008)



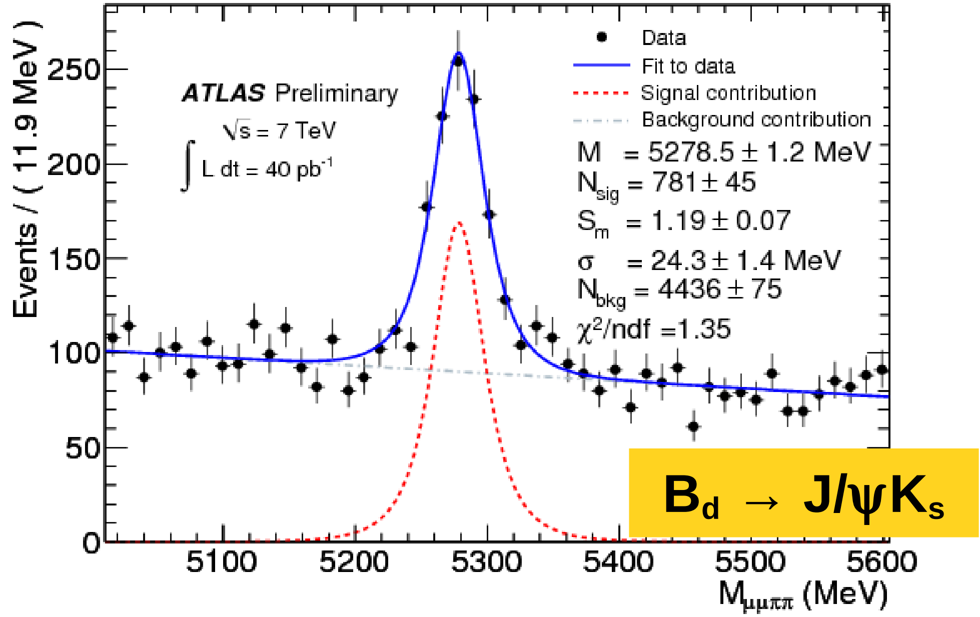
- good mass resolution required for good S/B performance
  - limited particle ID: only for p_T < 1GeV/c K/π separation possible
- good impact parameter resolution required for lifetime measurements

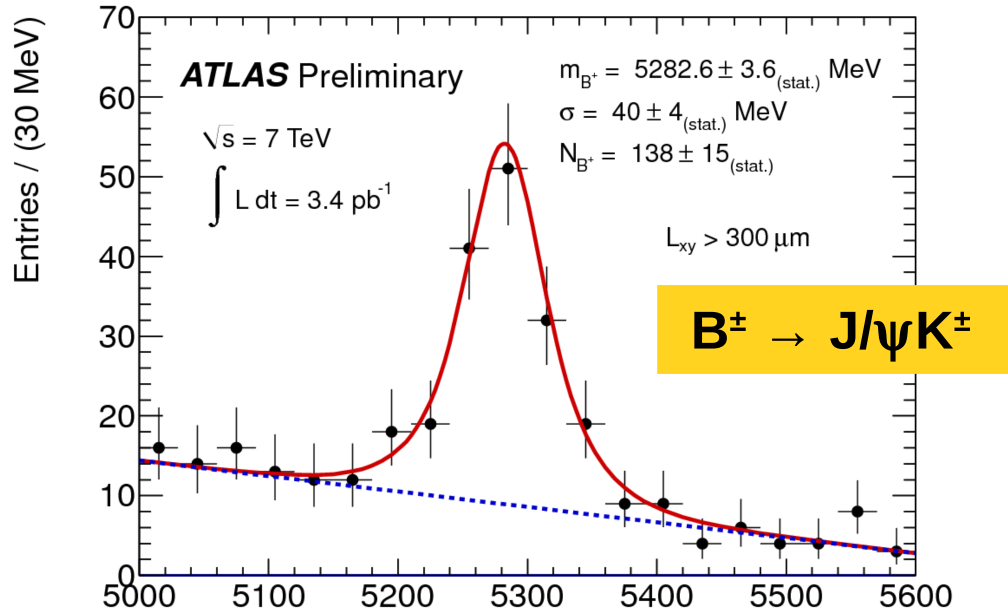
B-hadrons mass signals, updates 2011

- in the first data (2010-2011) masses of all B-hadrons measured in exclusive decays with $J/\psi(\mu\mu)$
- Consistency with PDG - showed that p_T scale well understood also down to low p_T values
- Latest updates using 2011 data shown here for Λ_b and B_c

The solid line is the projection of the results of the unbinned maximum likelihood fits

ATLAS-CONF-2011-105





ATLAS-CONF-2010-098

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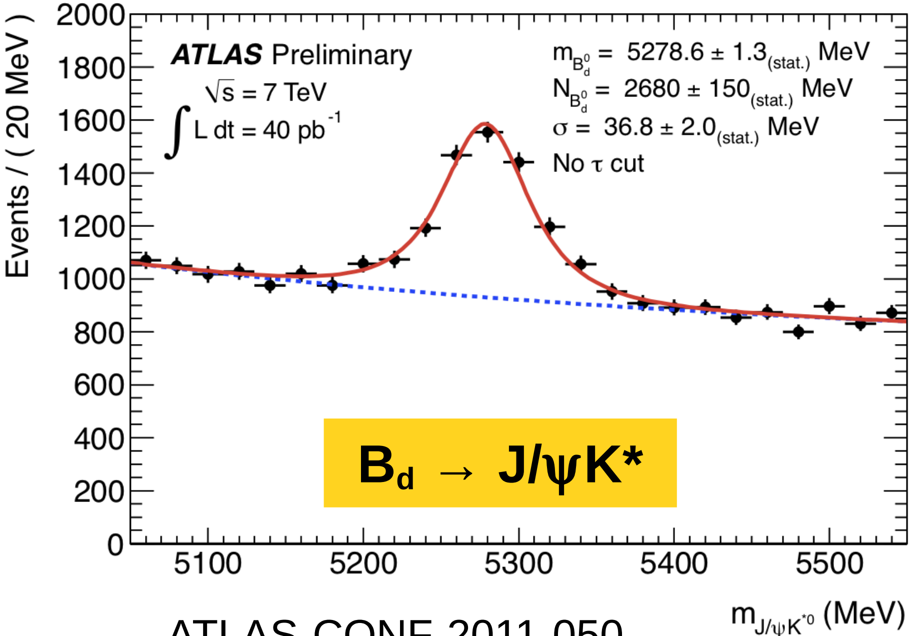
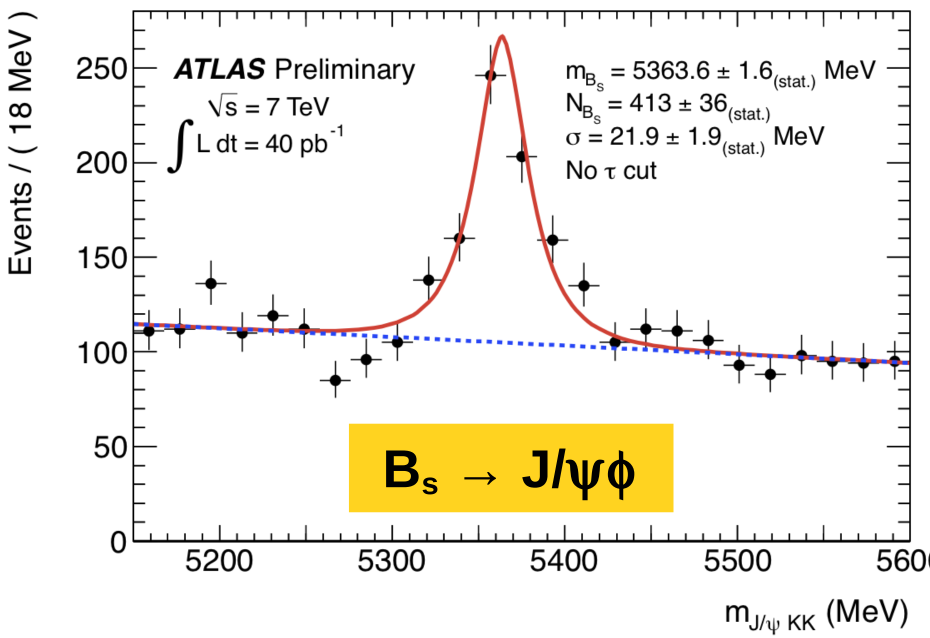


ATLAS-CONF-2011-050



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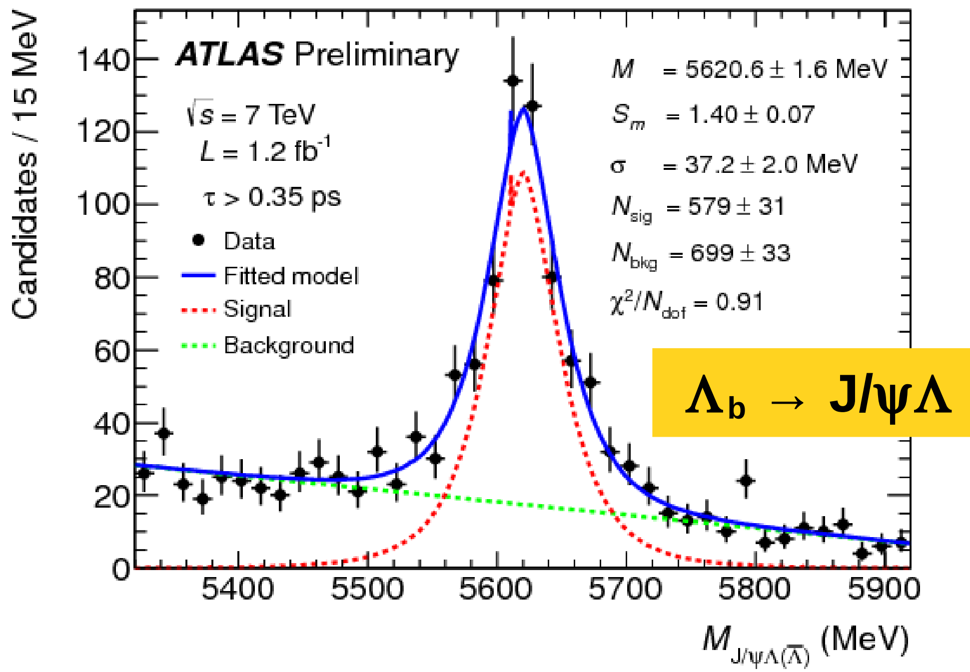
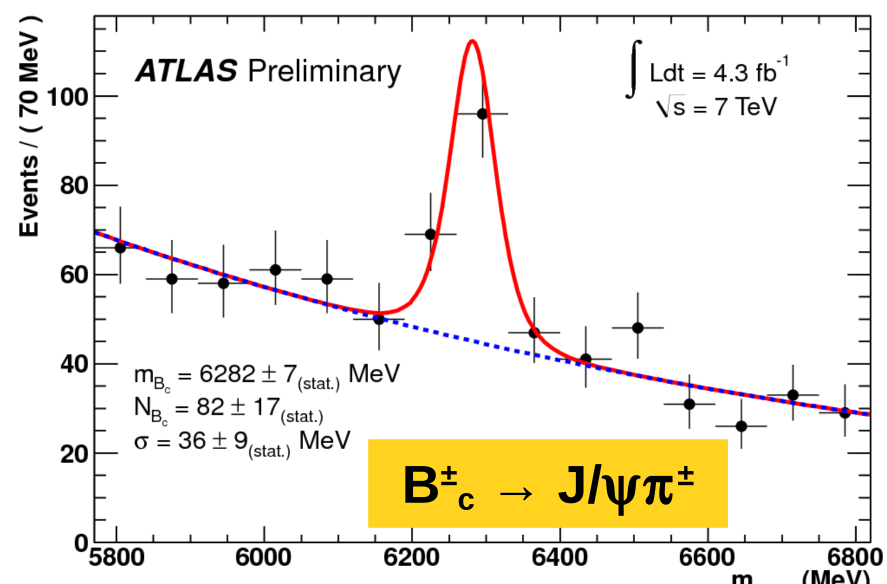
ATLAS-CONF-2011-124



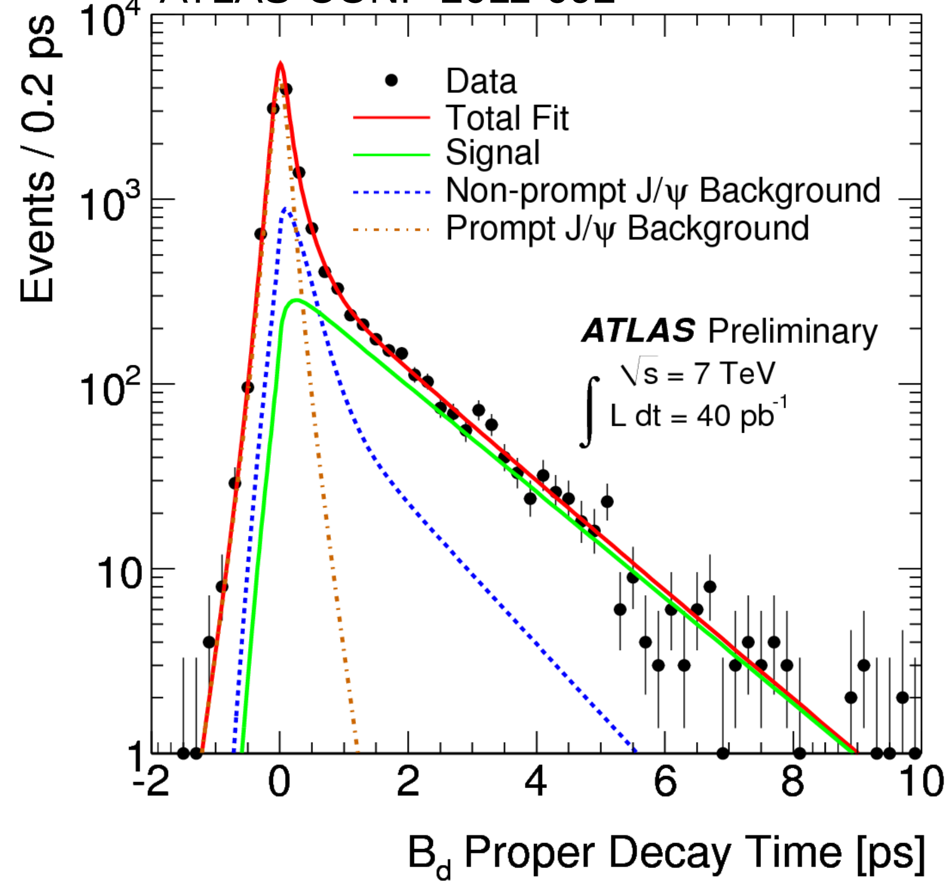


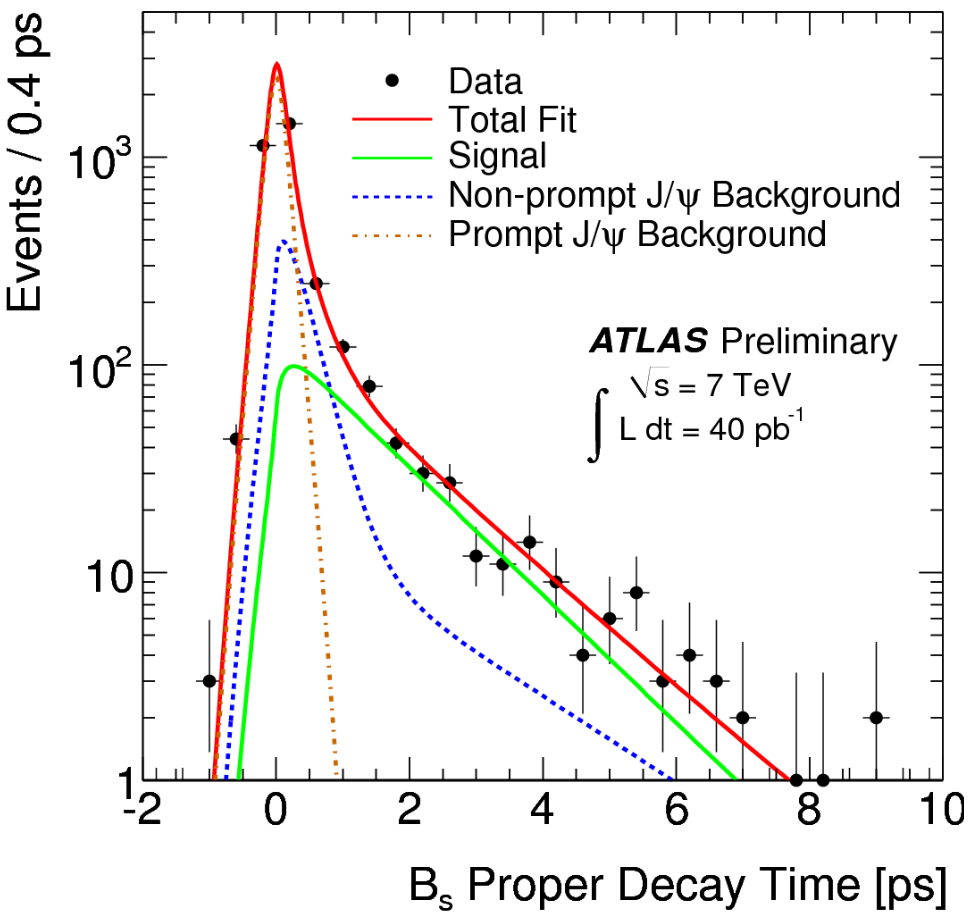
ATLAS-CONF-2012-028

B-lifetime measurements

- lifetimes measurements are the foundation for more complex measurements and selections (oscillations, mixing, $\Delta\Gamma$, β_s, rare decays etc.)

ATLAS-CONF-2011-092



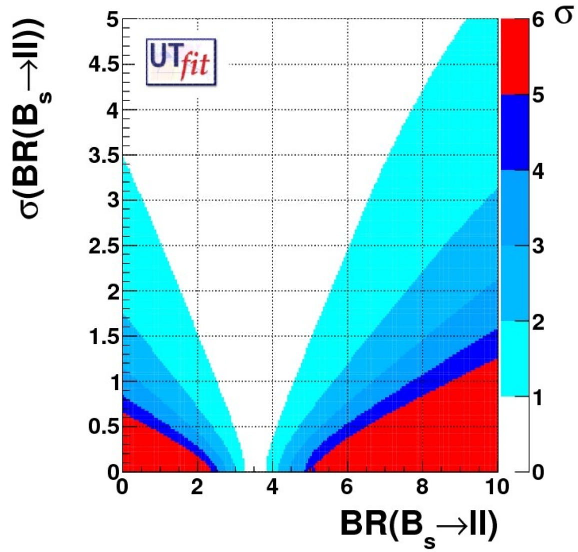


consistent with PDG

$$m_{B_d} = (5279.0 \pm 0.8)\,\mathrm{MeV}$$
$$\sigma_m = (34.3 \pm 0.9)\,\mathrm{MeV}$$
$$\tau_{B_d} = (1.51 \pm 0.04 \pm 0.04)\,\mathrm{ps}$$

$$m_{B_s} = (5363.7 \pm 1.2)\,\mathrm{MeV}$$
$$\sigma_m = (24.8 \pm 1.2)\,\mathrm{MeV}$$
$$\tau_{B_s} = (1.41 \pm 0.08 \pm 0.05)\,\mathrm{ps}$$

search for rare decays: $B_{(s)} \rightarrow \mu\mu$



- flavour changing neutral currents (FCNC) are highl suppressed in the Standard Model
  - expected Bs mumu SM branching ratio:

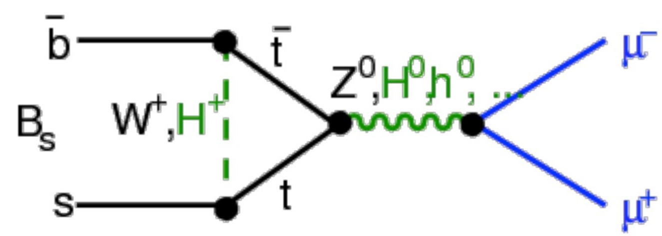
    $(3.2 \pm 0.2)\ 10^{-9}$

    Buras et al., Phys.Lett. B694 (2011) 402

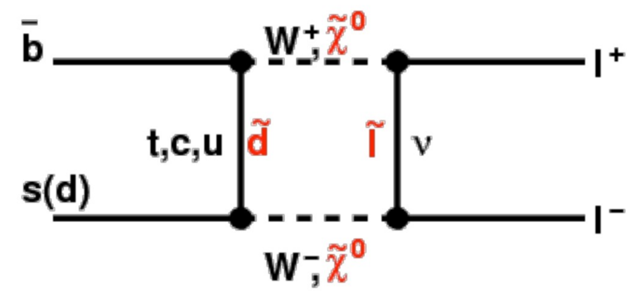
    $(3.5 \pm 0.3)\ 10^{-9}$

    UTfit prediction

- B to $\mu\mu$ branching ratio might be substantially enhanced by coupling to non-SM particles
  - being the SM well under control this channel provides a powerful method to peek into NP

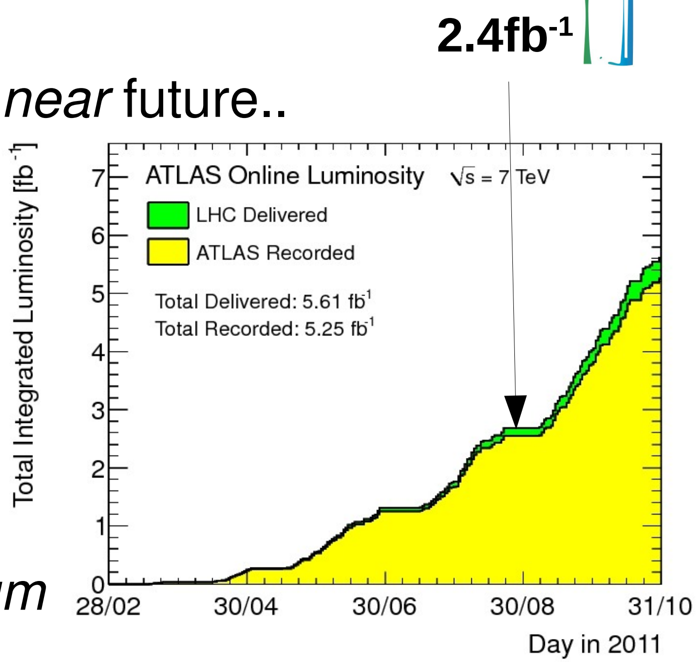


- orthogonal search for physics beyond the standard model
  - can reach higher scales wrt to the direct search



$B_{(s)} \rightarrow \mu\mu$ @ ATLAS:

- ATLAS profits from large luminosity:
  - integrated luminosity 2.4 fb-1 used for this result
  - already a lot more on tape to be analysed in the *near* future..



- expected mass resolution on B's
  - ~60 MeV (for muons in the barrel)
  - ~110 MeV (for muons in the forward region)

- main background sources:
  - *dominant background contribution from continuum*
    - real muons, flattish di-muon invariant mass
    - estimated from mass sidebands
  - *resonant contribution from mis-reconstructed decays: B to hh (h=K, π)*
    - quasi-irreducible background
    - estimated with MC
    - very small contribution within the current analysis

no dedicated particle identification in ATLAS

analysis strategy @ ATLAS:

- **Relative BR measurement:**
  - partial cancelation of uncertainties: on luminosity, cross-section, ..
  - reference channel ($B^{\pm} \rightarrow J/\psi K^{\pm}$, $J/\psi \rightarrow \mu^+\mu^-$)
  - blind analysis: signal region ± 300 GeV around B_s mass blinded
  - limit placed using CLs method

$$BR(B_s \rightarrow \mu\mu) = \boxed{N_{B_s\rightarrow\mu\mu}\frac{1}{N_{B^{\pm}\rightarrow J/\psi K^{\pm}}}} BR(B^{\pm} \rightarrow J/\psi K^{\pm})\frac{f_u}{f_s}\ \frac{\varepsilon_{B^{\pm}\rightarrow J/\psi K^{\pm}}}{\varepsilon_{B_s\rightarrow\mu\mu}}\frac{A_{B^{\pm}\rightarrow J/\psi K^{\pm}}}{A_{B_s\rightarrow\mu\mu}}$$

- **Signal extraction:**
  - event count in “signal region”
  - “subtraction” of sidebands: interpolation taken from 50% of sidebands
- **Signal-background discrimination:**
  - selection based on 14 variables
  - multivariate analysis (BDT)
  - 50% of sidebands to model background

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- **Efficiencies & acceptances**
  - Derived from simulation ("calibrated" on data)

$$\varepsilon \cdot A = (N_{\text{reconstructed and selected}}/N_{\text{generated}})$$

  - Reference channel ($B^{\pm} \to J/K^{\pm}$) selected with as-close-as-possible selection
- **BR of the reference channel and relative production rate f_u/f_s**
  - taken from PDG and the latest LHCb results

analysis strategy @ ATLAS:

Relative BR measurement:

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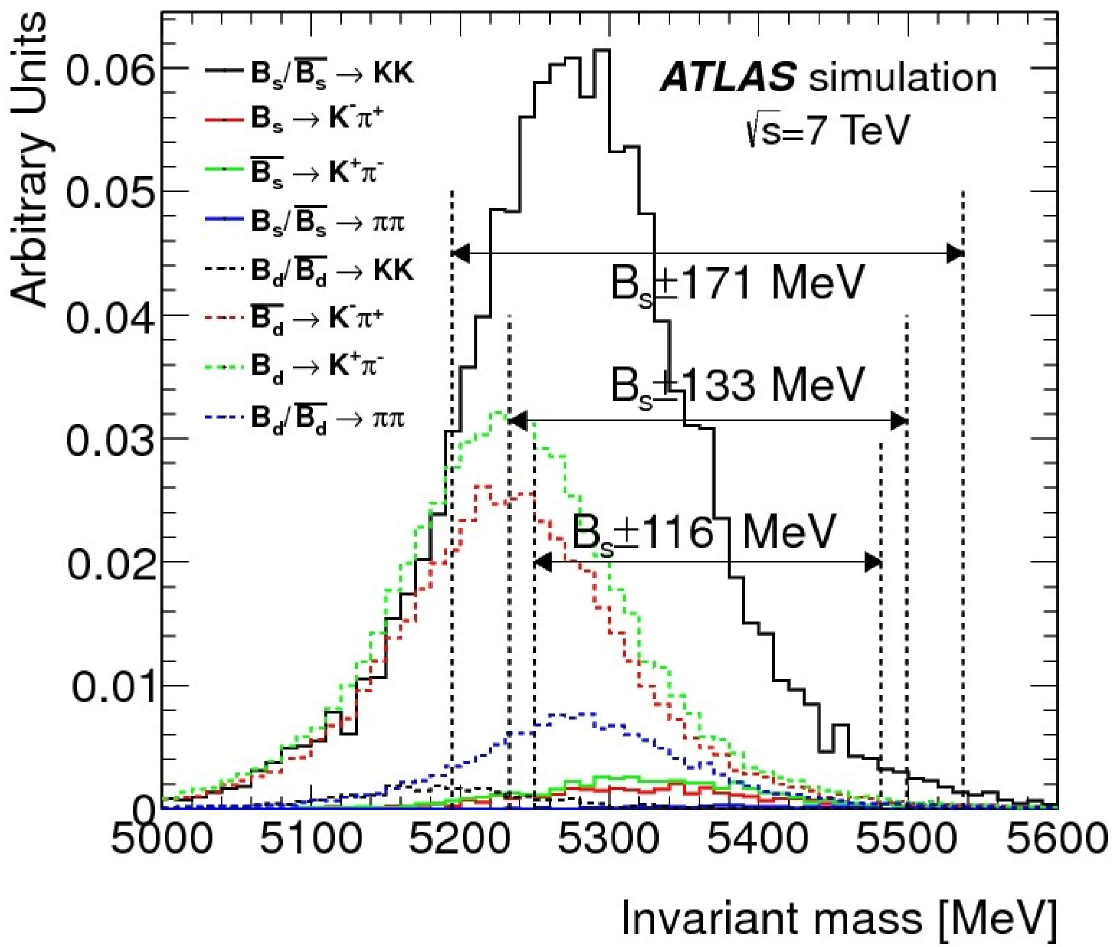
Single Event Sensitivity (SES)

corresponds to the $B_s \to \mu^+\mu^-$ branching fraction which would yield one observed signal event in the data sample.

background composition

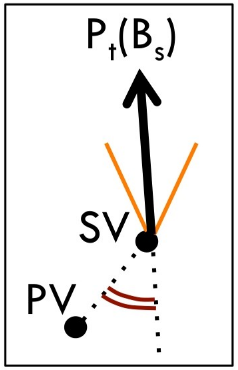
- **continuum:**
  - dominated by non-resonant bb production with μμX final states
  - real muons
  - smooth shape in the di-muon mass
  - limited MC statistics available in ATLAS
  - measured by interpolation from sideband data into the signal region



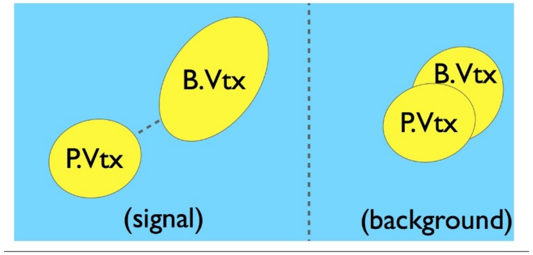
- **resonant**:
  - B → hh, with hadrons misidentified as muons
  - mainly B → $K^+\pi^-/\pi^+\pi^-$ decays
  - BR x (fake rate) ≈ 10^{-9} close to the SM B_s to μμ BR
  - similar decay topology → hard to suppress
  - contribution estimated from MC: currently still quite small

recontruction and event selection

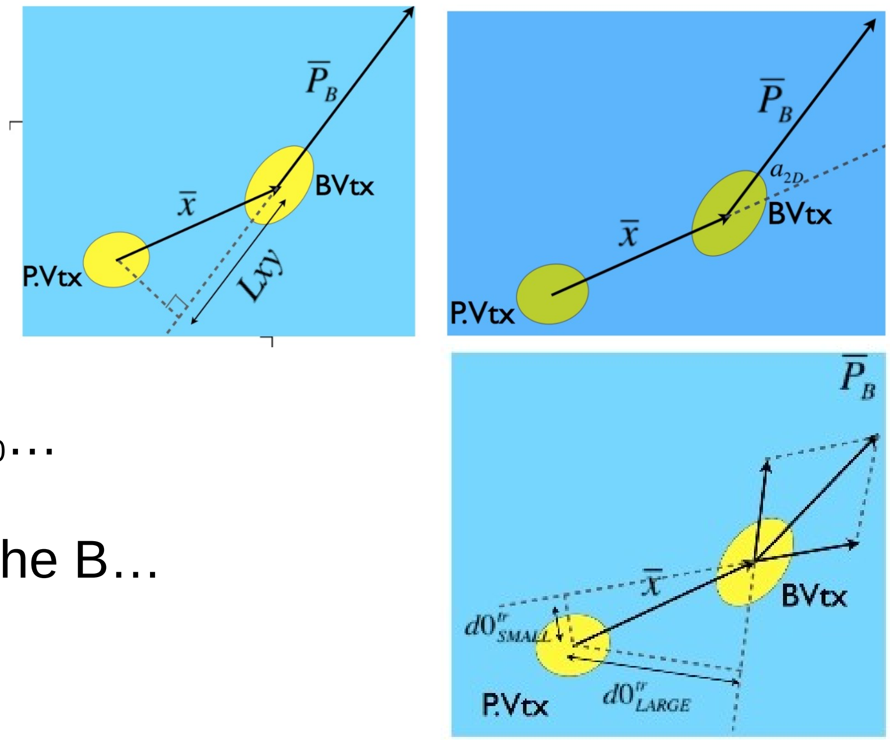
- 2, 3 or 4 prong vertex constraint depending on decay topology
- Primary Vertex selection:
  - the closest in z to the B candidate
  - Re-fit excluding B daughters
- Tracks:
  - At least 1 pixel, 6 SCT and 9 TRT hits (*good tracks*)
  - $|\eta| < 2.5$ and $p_T > 4$ (2.5) GeV for muons (kaons)
  - tracks from the tracking systems matched to muon spectrometer tracks
- B candidates: $p_T > 8$ GeV and $|\eta|<2.5$



- select events based on their decay topology
- discriminating variables to distinguish between B and continuum events
- 14 variables identified and used in a boosted decision tree (BDT):
  - not correlated with invariant mass
  - highest discriminating power
  - highly correlated variables excluded

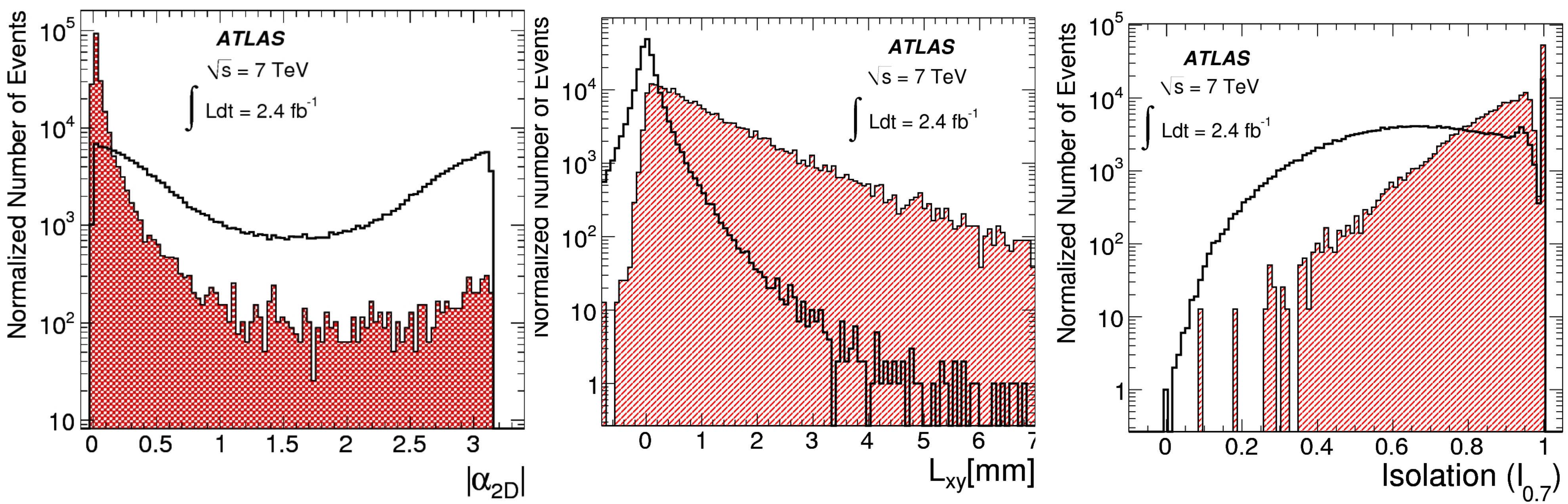


discriminating variables



Exploit:

- Primary Vertex-Secondary Vertex separation: L_{xy}, $c\tau$ significance
- Symmetry of final state: pointing angle, d_0…
- Full reconstruction: pointing angle, D_{min}…
- B hadronization features: Isolation, p_T of the B…

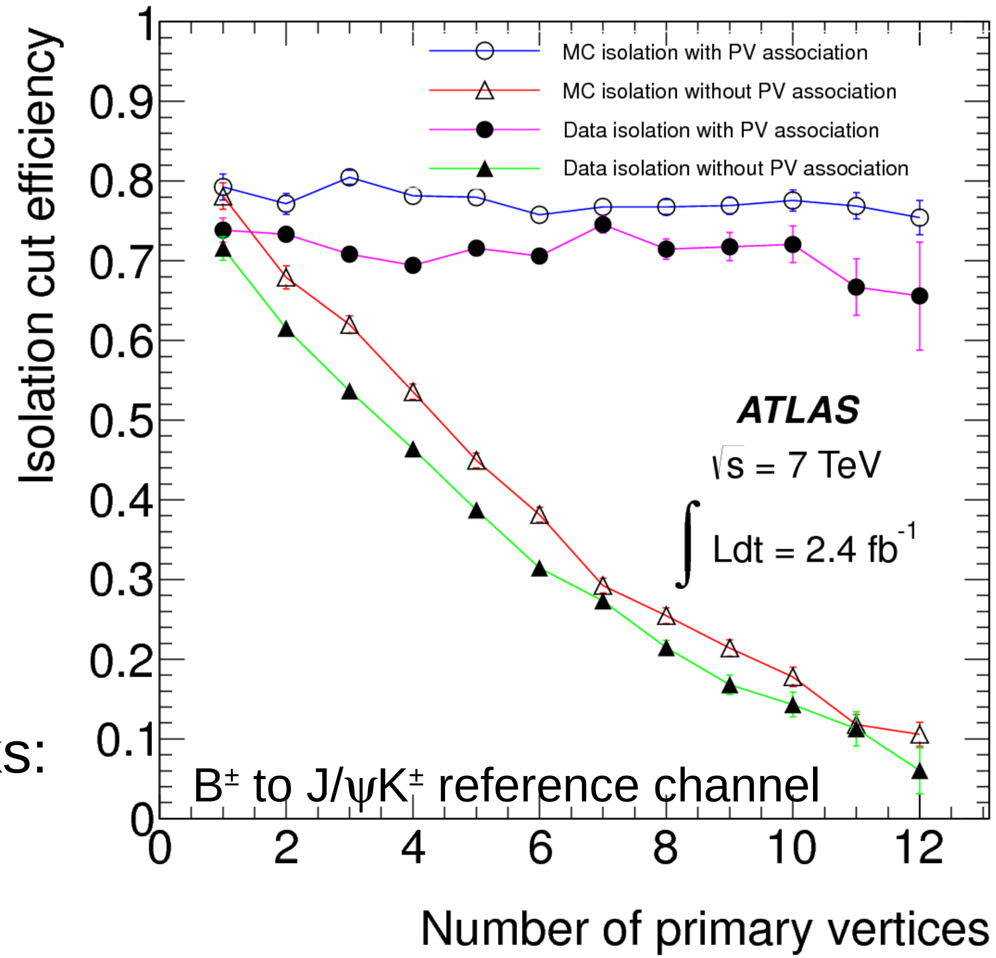


isolation and pile-up

- Isolation variable:

$$I^{\Delta R} = \frac{P_T^B}{P_T^B + \sum_i^{\Delta R} p_T^i}$$

tracks with $p_T > 0.5$ GeV excluding B daughters in the cone $\Delta R < 0.7$, where $\Delta R = \mathrm{sqrt}((\Delta\eta)^2+(\Delta\phi)^2)$



- Solution: PV association of tracks:
  - gets rid of the interference from the other interactions
  - isolation cut efficiency is now pile-up independent

Boosted Decision Tree (BDT)

- Multivariate techniques used to combine the separation power of the 14 discriminating variables chosen.

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

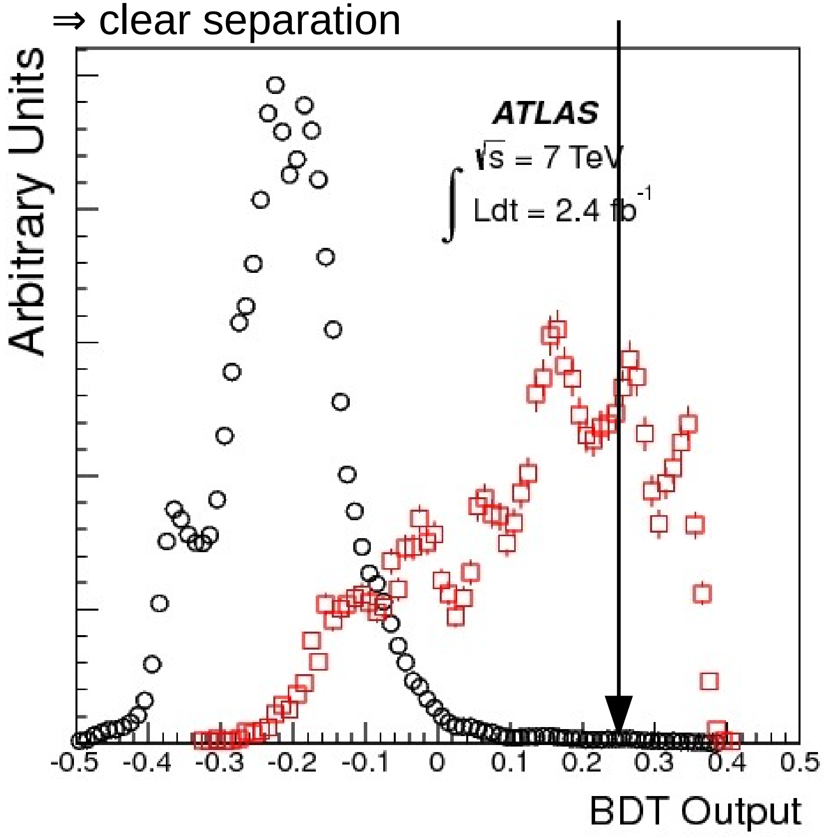
(a=2 for 95% CL limit)

- among the classifiers tested, BDT is the best performing
- trained using $B_s \to \mu^+\mu^-$ signal MC and data from sidebands (50% of the events)
- then BDT cut and mass search window optimized by maximizing the estimator above

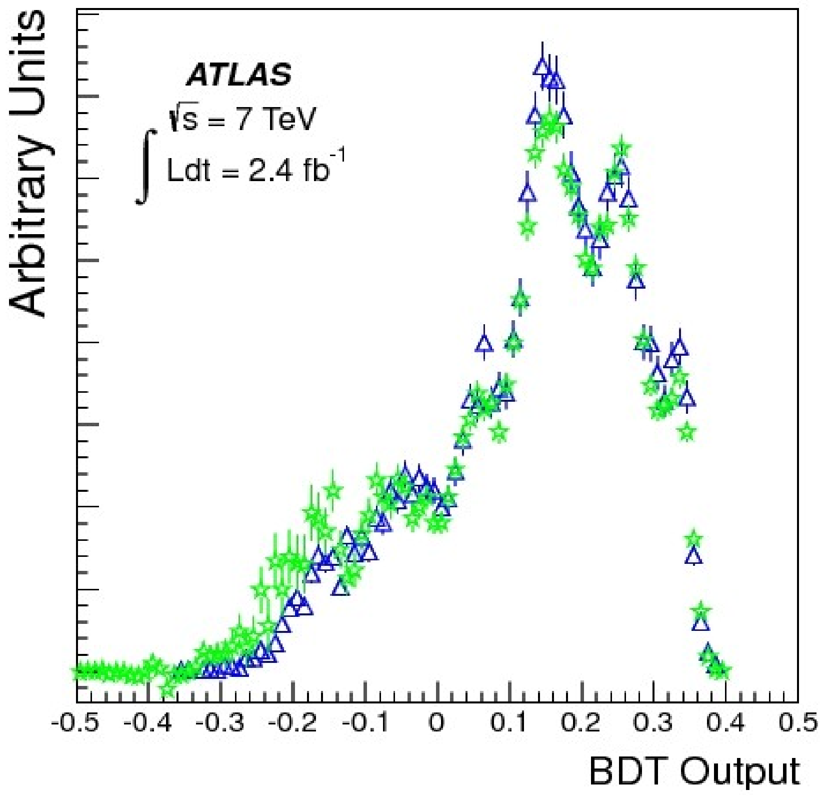
Boosted Decision Tree (BDT)

- Multivariate techniques used to combine the separation power of the 14 discriminating variables chosen.

B_s signal (MC) vs **background (sidebands)**
⇒ clear separation



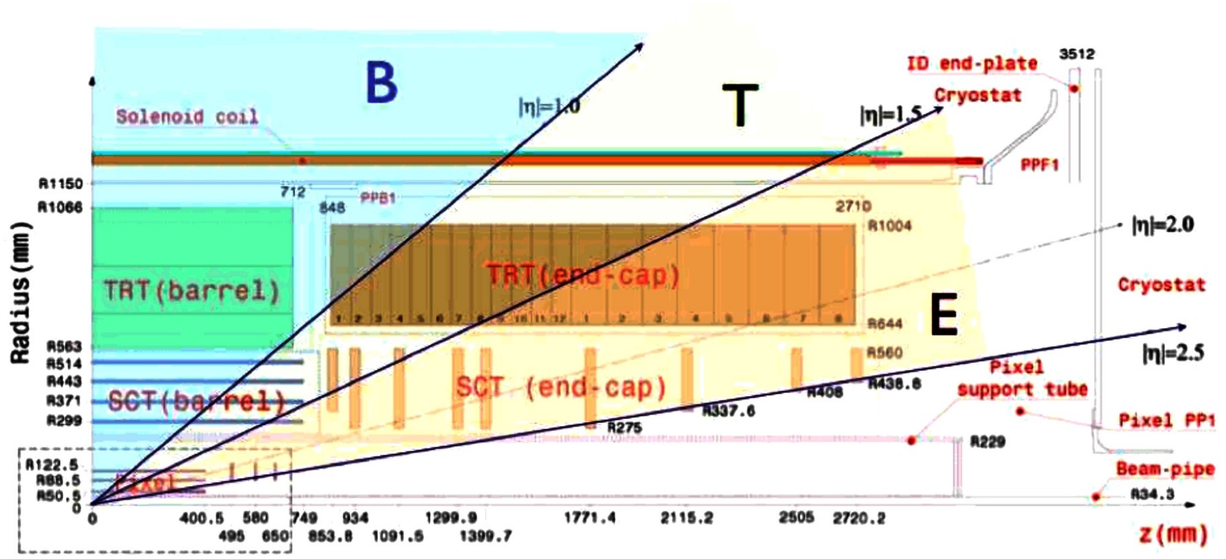
$B^{\pm}$ data (sideband subtracted)
vs **MC (weighted)** ⇒ good agreement



- optimal cut at ~0.25
- good S/B separation
- MC reproduces response on data pretty well!

mass resolution categories

- Three mass resolution categories are defined according to the η of the muons in the final state

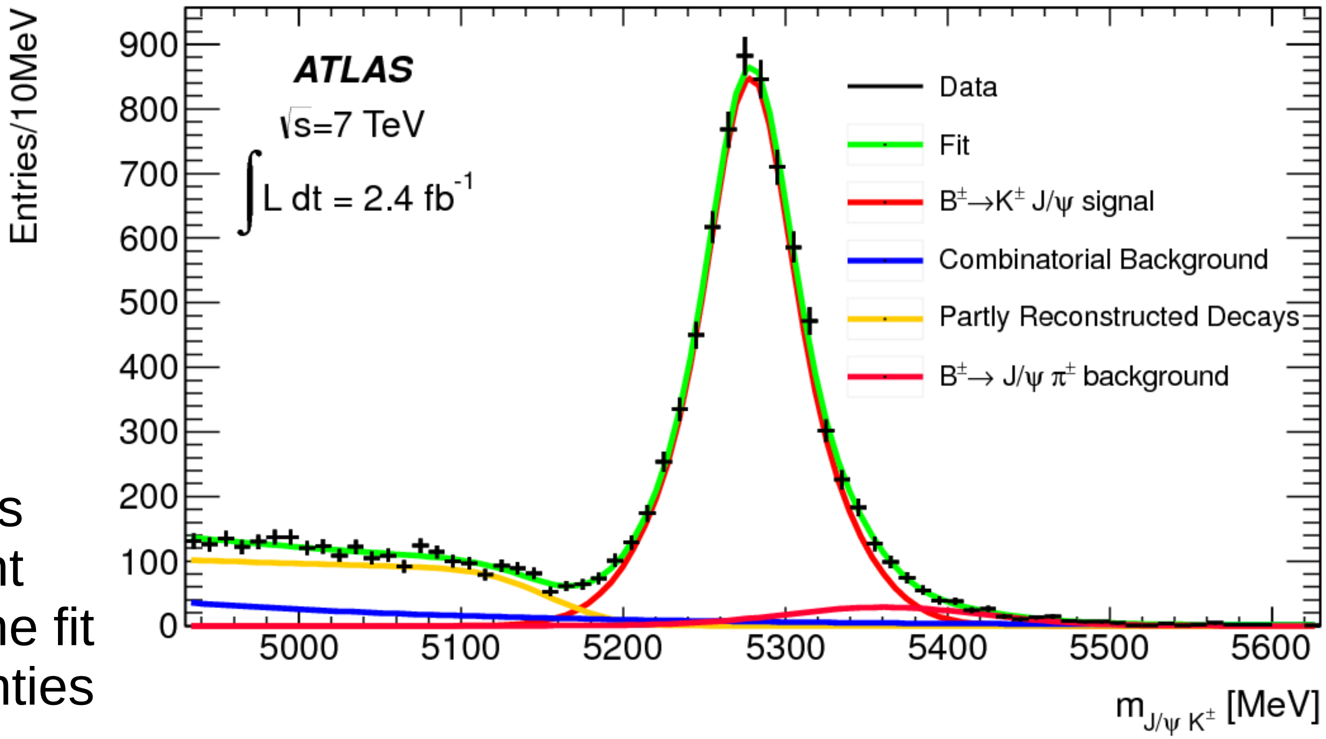


- Mass resolution for di-muon candidates changes substantially between barrel and end-cap detectors

$\lvert\eta_{max}\rvert$	1.0	1.5	2.5
σ_m [MeV]	60	80	110
Relative fraction [%]	51	24	25
invariant mass window [MeV]	±116	±133	±171
BDT output threshold	0.234	0.245	0.270

reference channel yield

- keep selection as close to Bs as possible
- BDT trained for B_s used also on B^+, in order to minimize selection systematics
- inclusion of per-event mass resolution in the fit
- Systematic uncertainties on the yield
  - Vary binning
  - Signal/background models
  - Binned/un-binned fit



$B^{\pm}$ yield measurement only on even-numbered events
odd-numbered events used for MC re-weighting

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

ingredient for the limit extraction

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$\lvert\eta_{max}\rvert$ Range	$R^i_{A\epsilon}$	Δ % Stat.	Δ % Syst.
0-1.0	0.274	3.1	3.1
1.0-1.5	0.202	4.8	5.5
1.5-2.5	0.143	5.3	5.9

$$BR(B_s \to \mu\mu) = N_{B_s\to\mu\mu} \frac{1}{N_{B^\pm\to J/\psi K^\pm}} BR(B^\pm \to J/\psi K^\pm) \frac{f_u}{f_s} \frac{\varepsilon_{B^\pm\to J/\psi K^\pm}}{\varepsilon_{B_s\to\mu\mu}} \frac{A_{B^\pm\to J/\psi K^\pm}}{A_{B_s\to\mu\mu}}$$

$1/(4.45\pm0.38)\times10^3$

[PDG + LHCb]

Additional sources of systematics:

- vertex reconstruction efficiency in data/MC
- absolute $K^\pm$ reconstruction efficiency
- asymmetry in detector response to K^+/K^-

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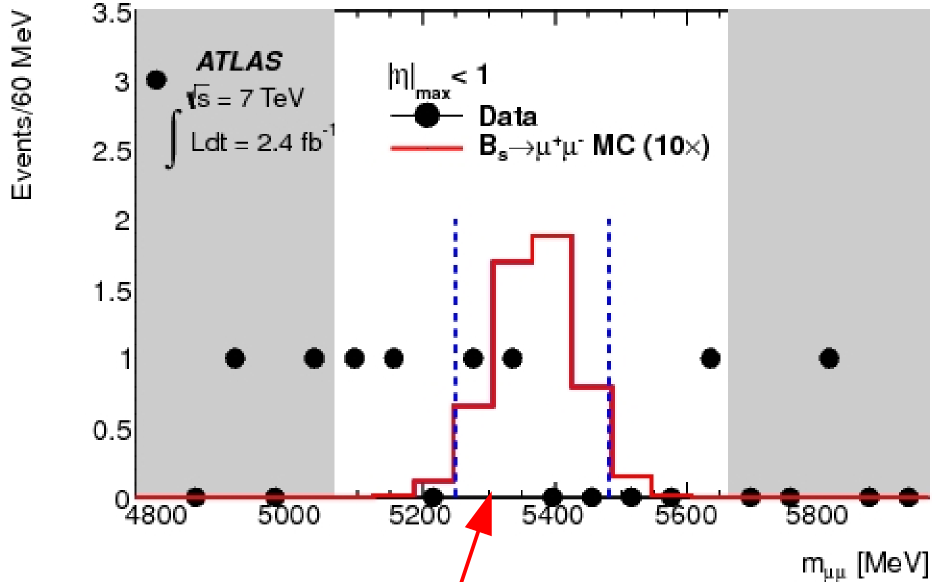
$1/(4.45\pm0.38)\times10^3$

[PDG + LHCb]

$\lvert\eta\rvert_{max}$ Range	0–1.0	1.0–1.5	1.5–2.5
SES= $(\epsilon\epsilon_i)^{-1}$ $[10^{-8}]$	0.71	1.6	1.4

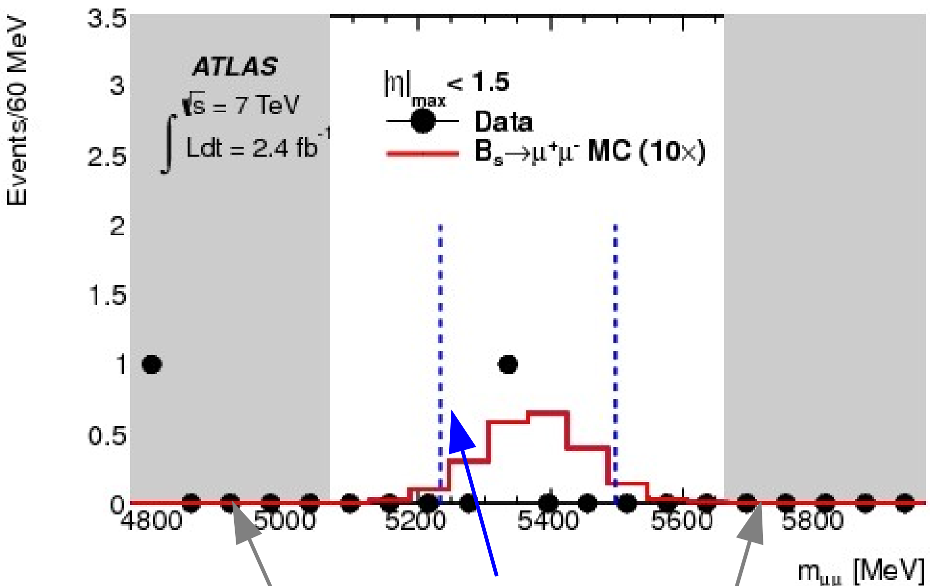
opening the box

60 MeV resolution



signal peak 10 times enhanced

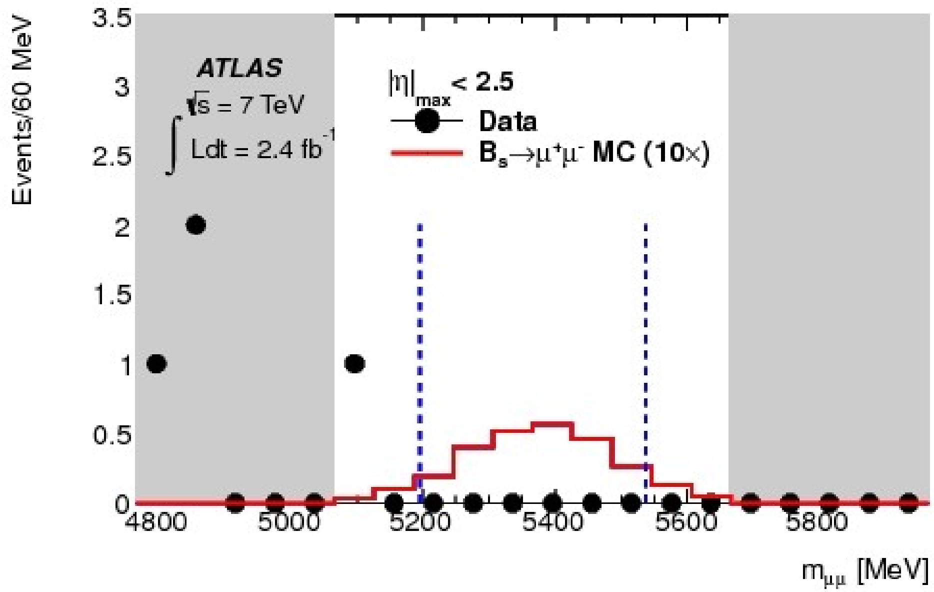
80 MeV resolution



optimized search window

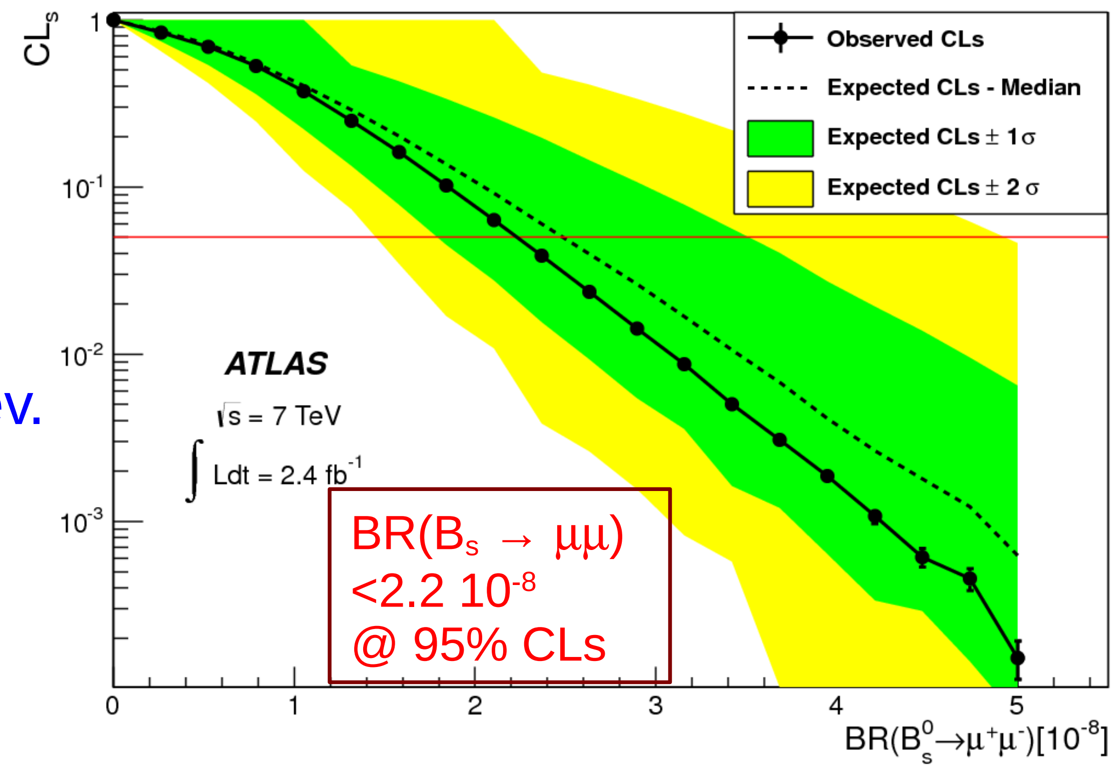
sidebands

110 MeV resolution



event counting and limit

- observed events: 2+1+0
- Sidebands:
  - Even: 5/0/2 [un-biased]
  - Odd: 1/1/1 [biased]
- Continuous background
  - interpolation: 6.1 ev.
- Resonant background: 0.24 ev.
- 95% CLs limit expectations:
  - Even sidebands: 2.3 10^{-8} (68% of toys in range 1.8-3.3 10^{-8})
  - Odd sidebands: 1.7 10^{-8} [biased]
  - All bins merged: 2.9 10^{-8} [for comparison]



Future improvements:

- Use of spectrometer information to improve mass resolution (forward muons)
- MC-based continuous background model
- Full 2011 (and 2012) statistics
- Mass fit for the signal yield extraction

Expect improvements better than sqrt(Lumi)

conclusions

- B physics in ATLAS is alive and kicking:
  - Event selection strategy mainly based on di-muons
  - Benchmarks and standard-candles well assessed
  - First rare decays analysis

    but still a lot of space for improving!

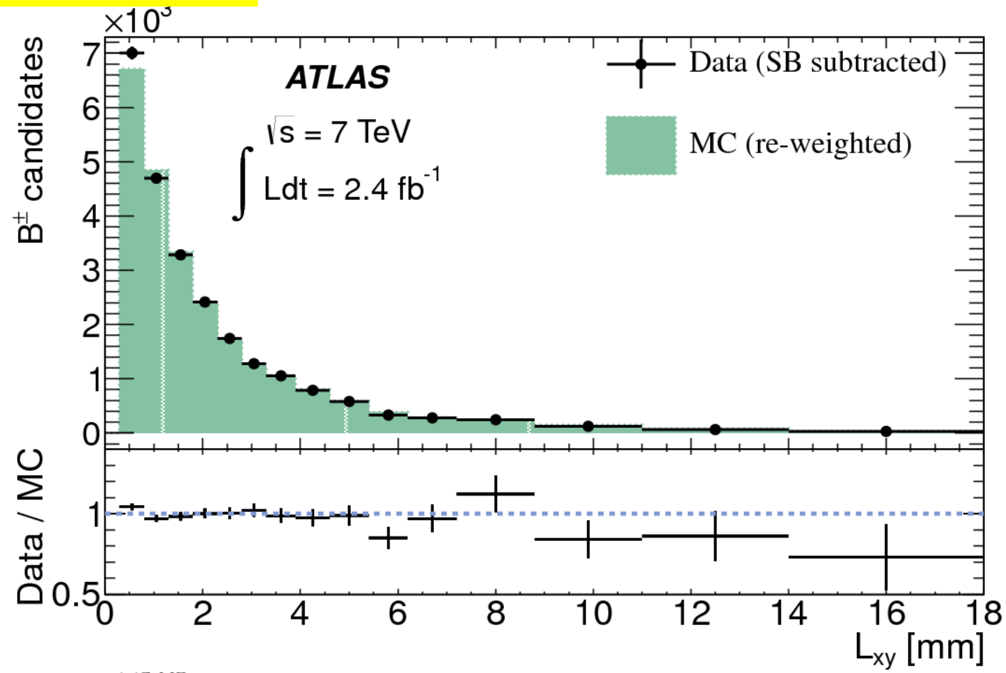
- Many more results in progress and/or around the corner:
  - Polarizations
  - Production cross-sections
  - B_s to $J/\psi\phi$ mixing and CP violation

backup

data-MC comparison for B to μμ

B meson kinematic variables weighted in MC to match distributions in data

Agreement verified on B± data (sideband subtracted):



Residual deviations for some variables
→ accounted for in systematics

Isolation variable cross-checked on $B_s \to J/\psi\phi$ control sample
→ no discrepancies between data and MC found