Exclusive and rare B decays in ATLAS

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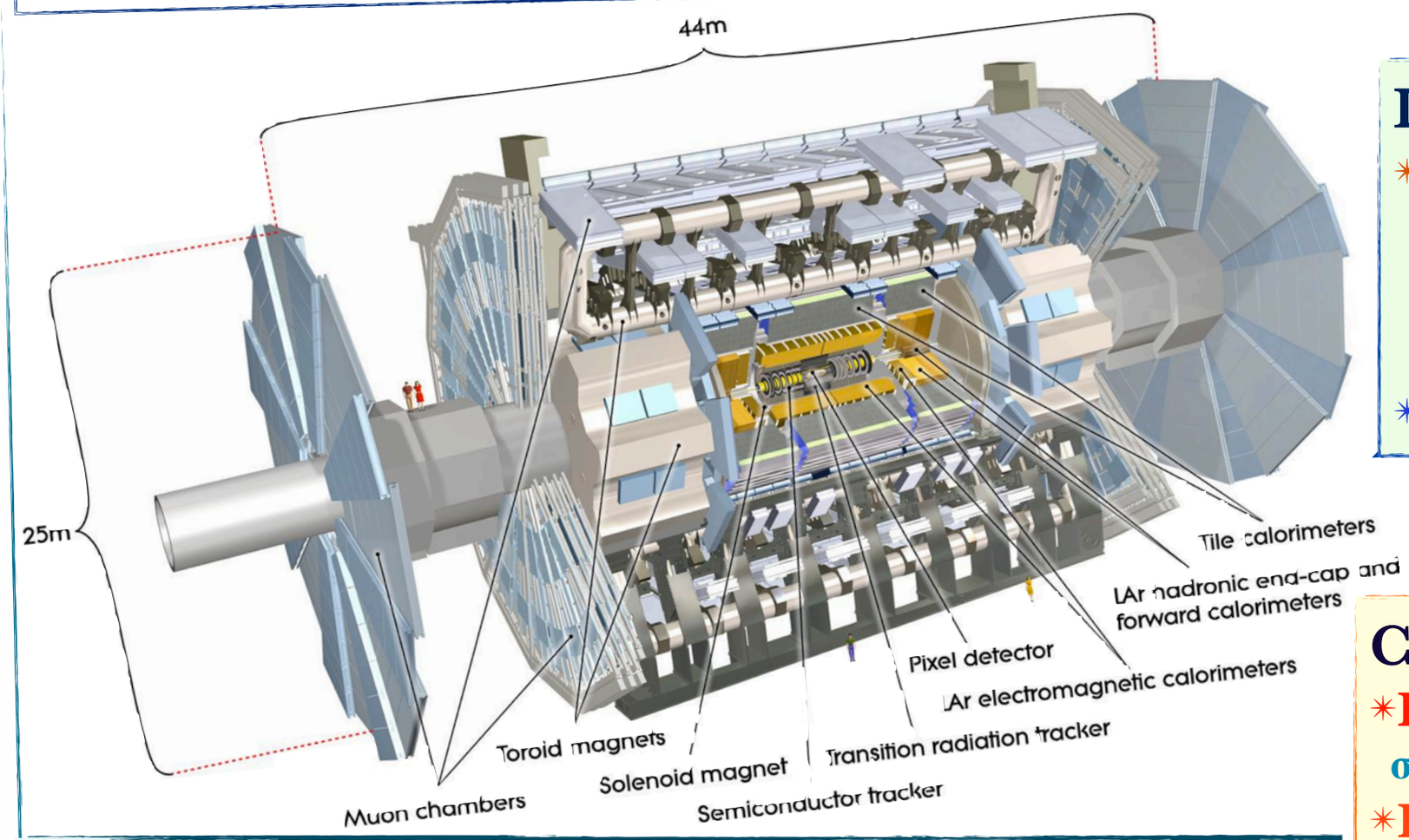
(*) University of Naples "Federico II" & INFN

Outline

- *ATLAS @LHC:*
  - *detector*
  - *2010/2011 data taking*
  - *B-Physics measurements requirements:*
    - *performance & trigger*
- *Exclusive B-decays overview*
- *Rare B decays:*
  - $B^0_s \rightarrow \mu^+\mu^-$

The ATLAS detector

A T*oroidal* LHC A*pparatu*S



Inner detector (|η| < 2.4):

- Silicon pixel and strip, Transition Radiator Tracker
  - $\sigma p/p \approx$ 3-5 %
  - Impact parameter resolution~ 10 μm
- 2T Solenoidal field

Calorimeters (|η| < 5):

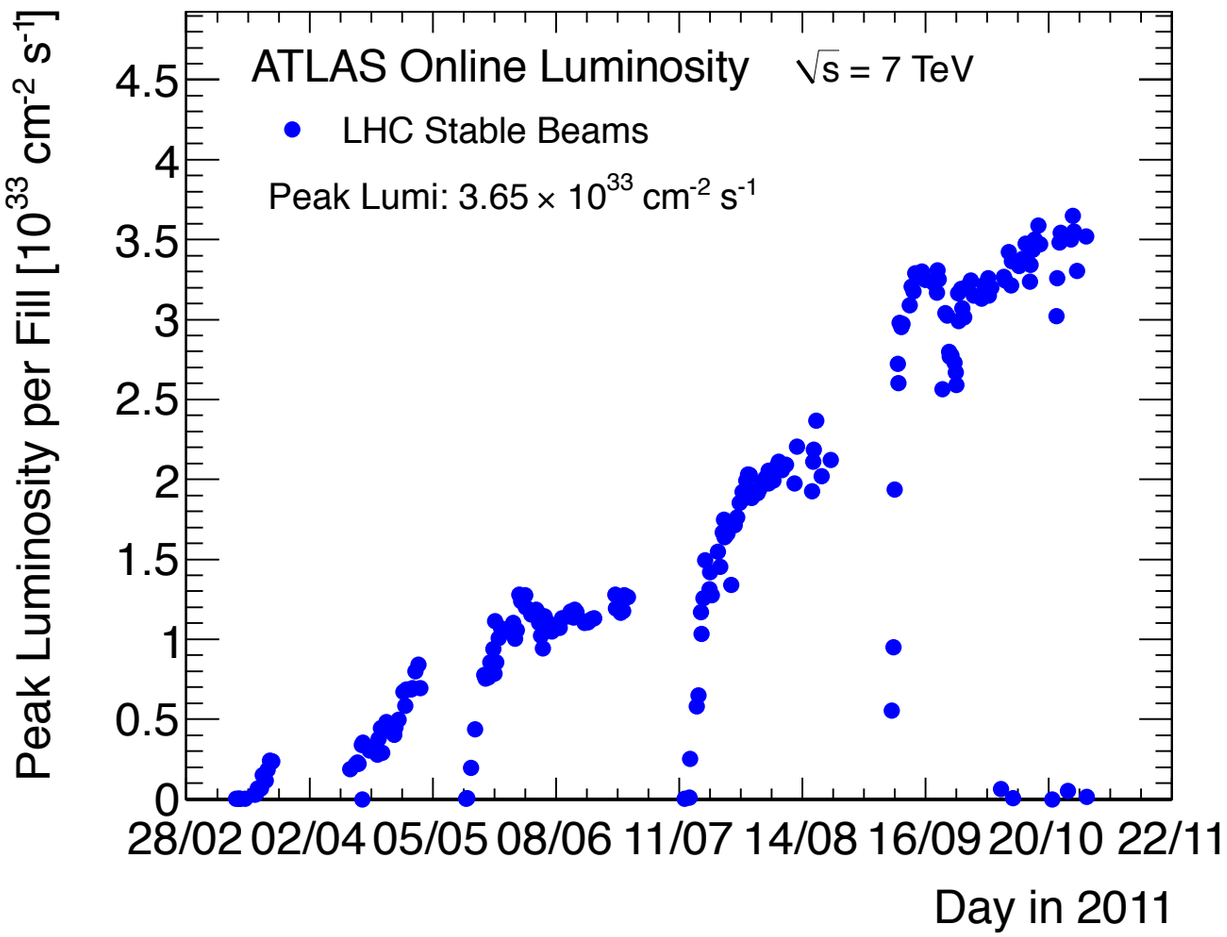
- EM: Pb-LAr
  - $\sigma/E \approx 10\%/\sqrt{E(GeV)} \oplus 0.7\%$
- HADRONIC: Iron/Scintillator Tiles
  - $\sigma/E \approx 50\%/\sqrt{E(GeV)} \oplus 3\%$

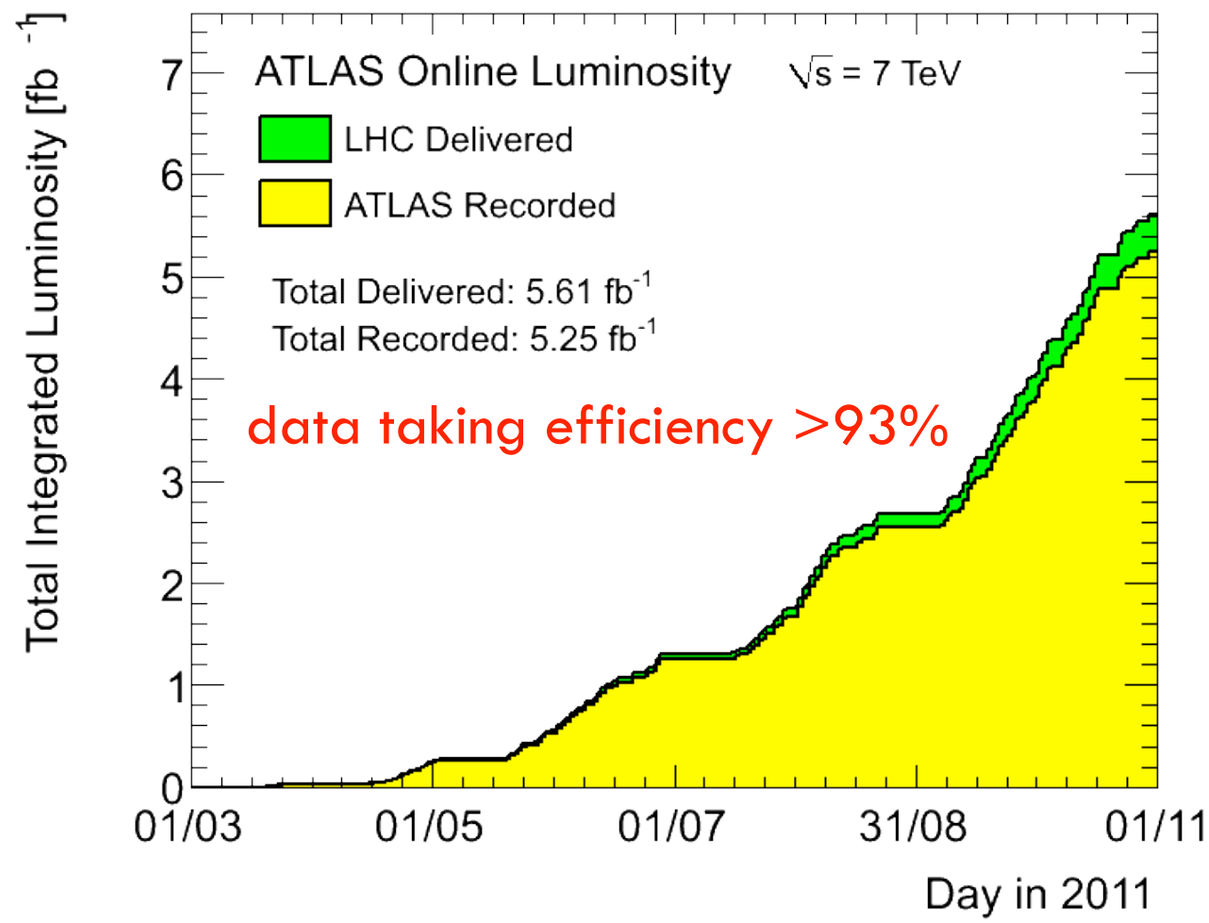
Muon Spectrometer (|η| < 2.7):

- Trigger chambers: RPC and TGC
- 0.5 - 2 T Toroidal field
- Coordinate Measurements Chambers: MDT and CSC
  - $\sigma/p \sim 5\%$ (for p_T = (10-100) GeV/c)

The ATLAS data-taking

ATLASLuminosityPublicResults





Instantaneous luminosity:

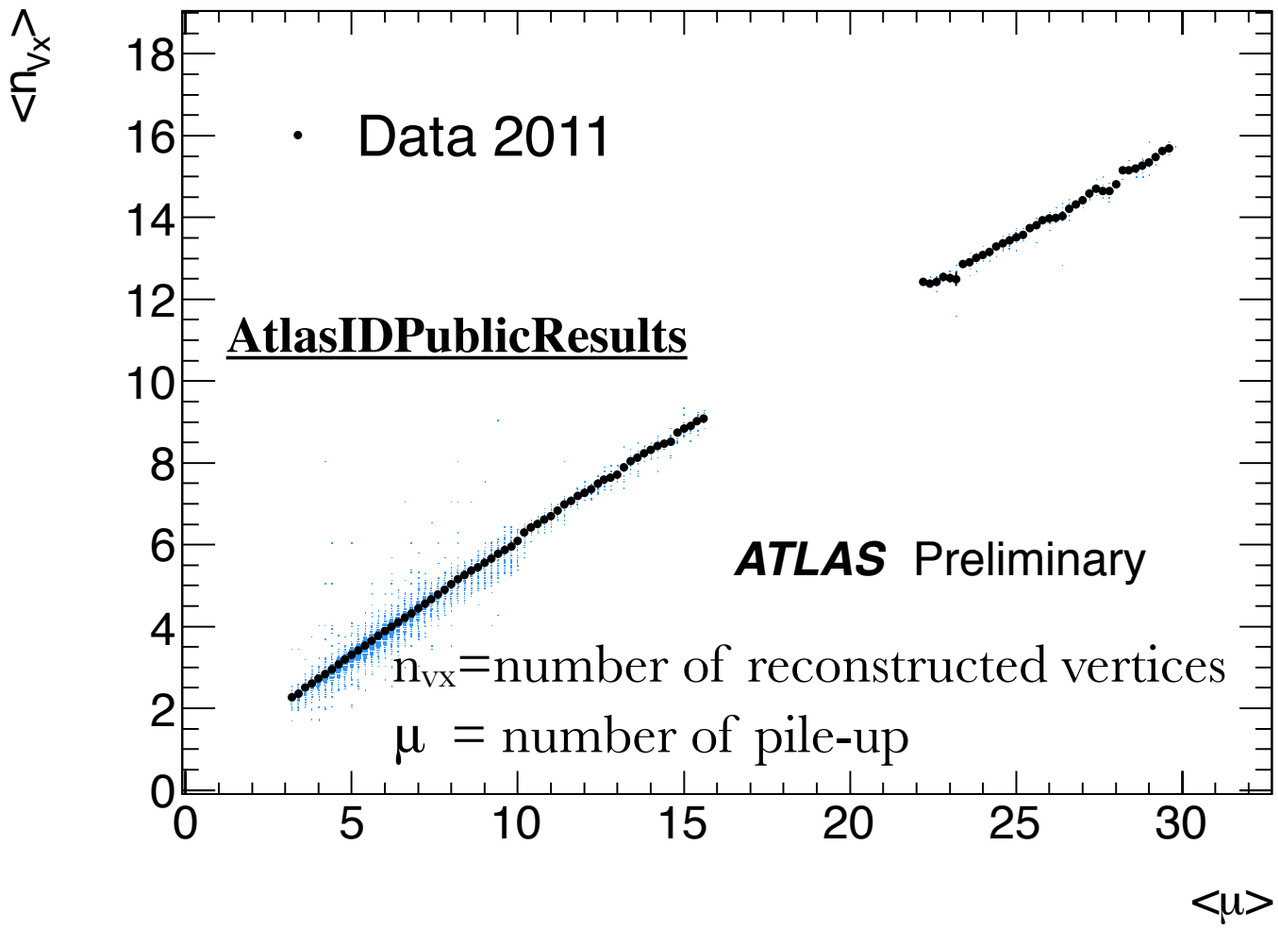
- 2010: $2.1*10^{32}$ cm^{-2} s^{-1}
- 2011: $3.65*10^{33}$ cm^{-2} s^{-1}

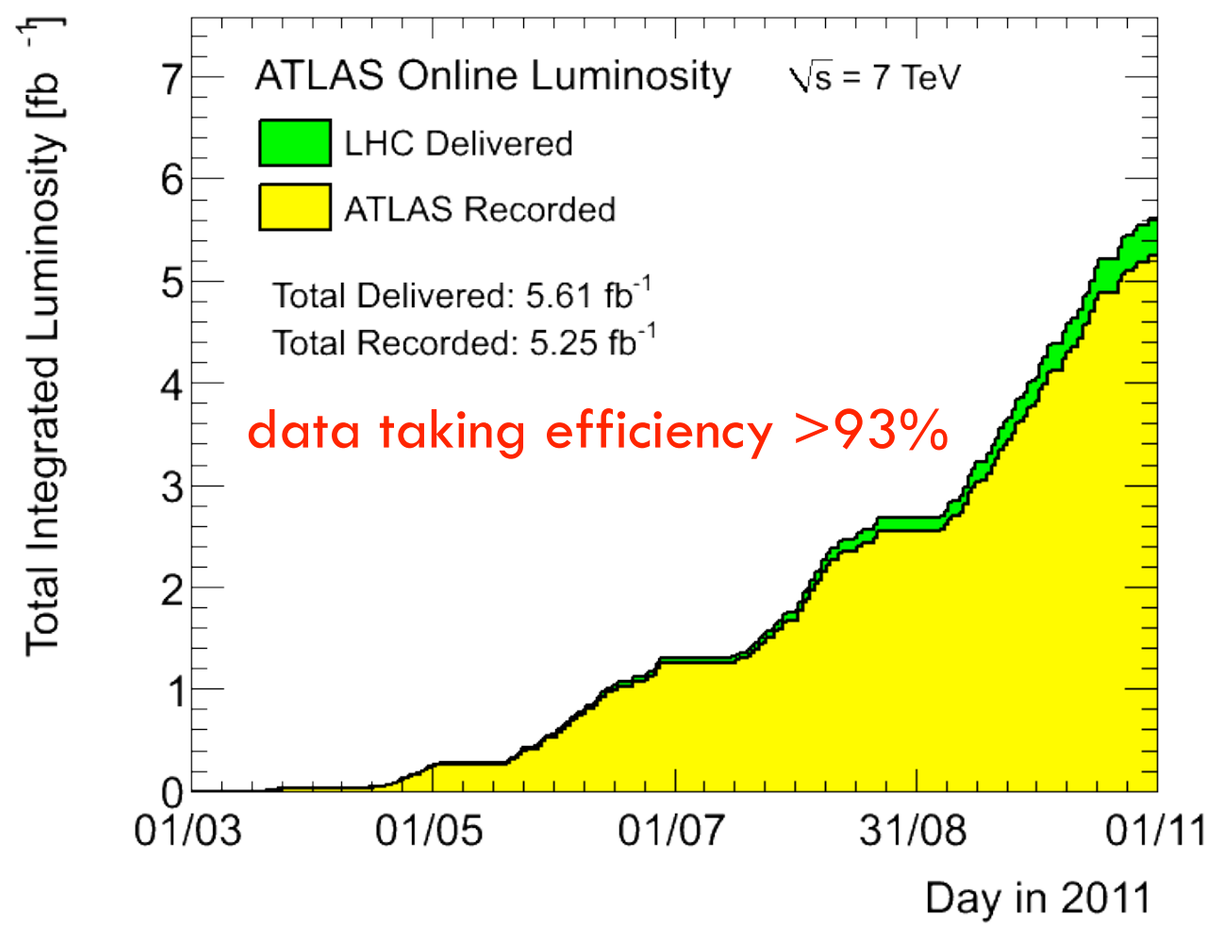
Integrated luminosity delivered to ATLAS:

- 2010: ~ 40 pb^{-1}
- 2011: 5.6 fb^{-1}

The ATLAS data-taking

ATLASLuminosityPublicResults





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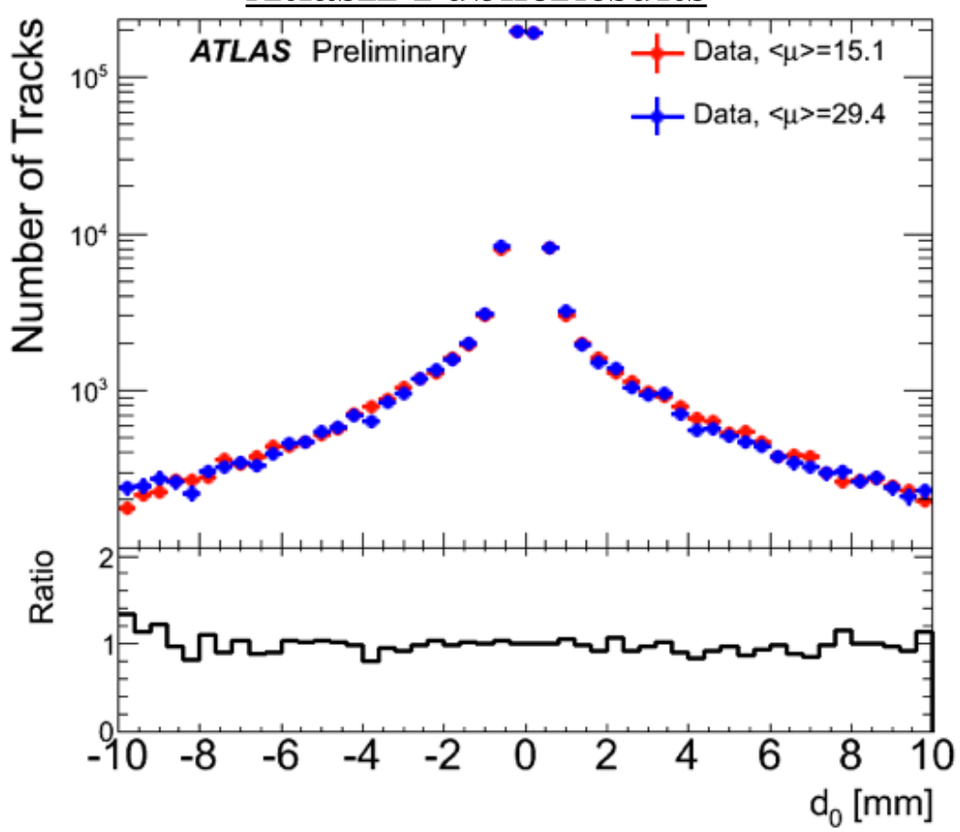
Pile-up is the challenge at high LHC luminosity!

Performance

B-Physics measurements rely on good muon reconstruction

- Good Inner Detector Vertexing/Traking performance for precision measurements/ muon momentum resolution

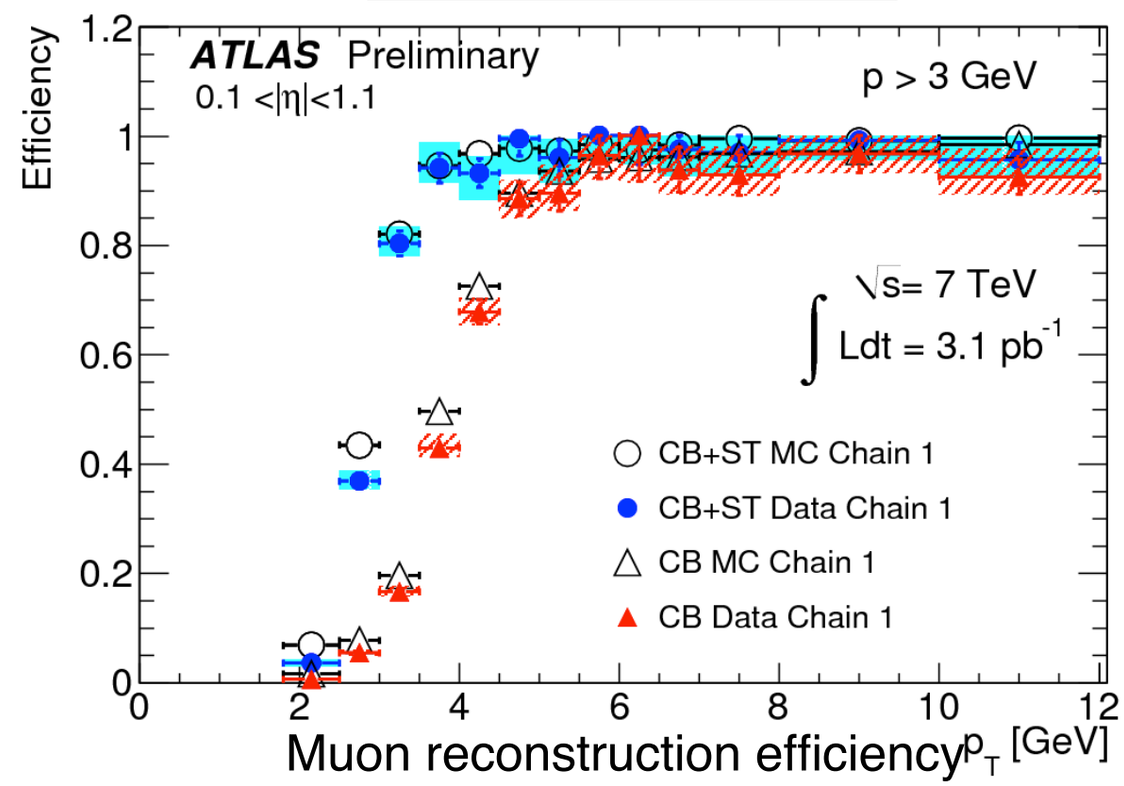
AtlasIDPublicResults



Transverse impact parameter at two different pile-up conditions

- Good Muon Spectrometer performance for muon trigger and identification

ATLAS-CONF-2011-021



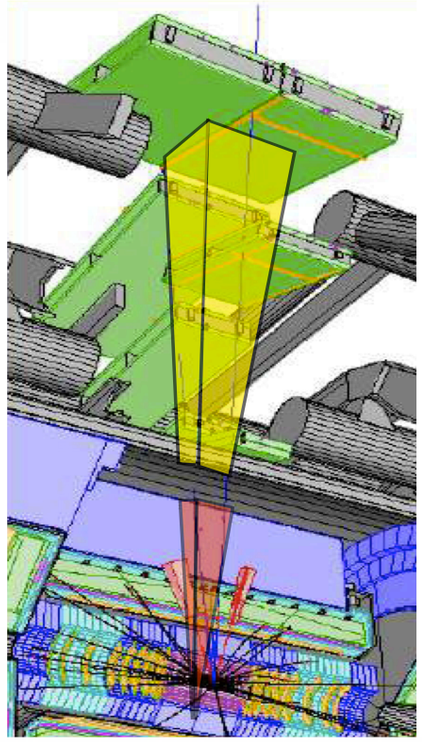
Muon reconstruction efficiency using J/ψ decays

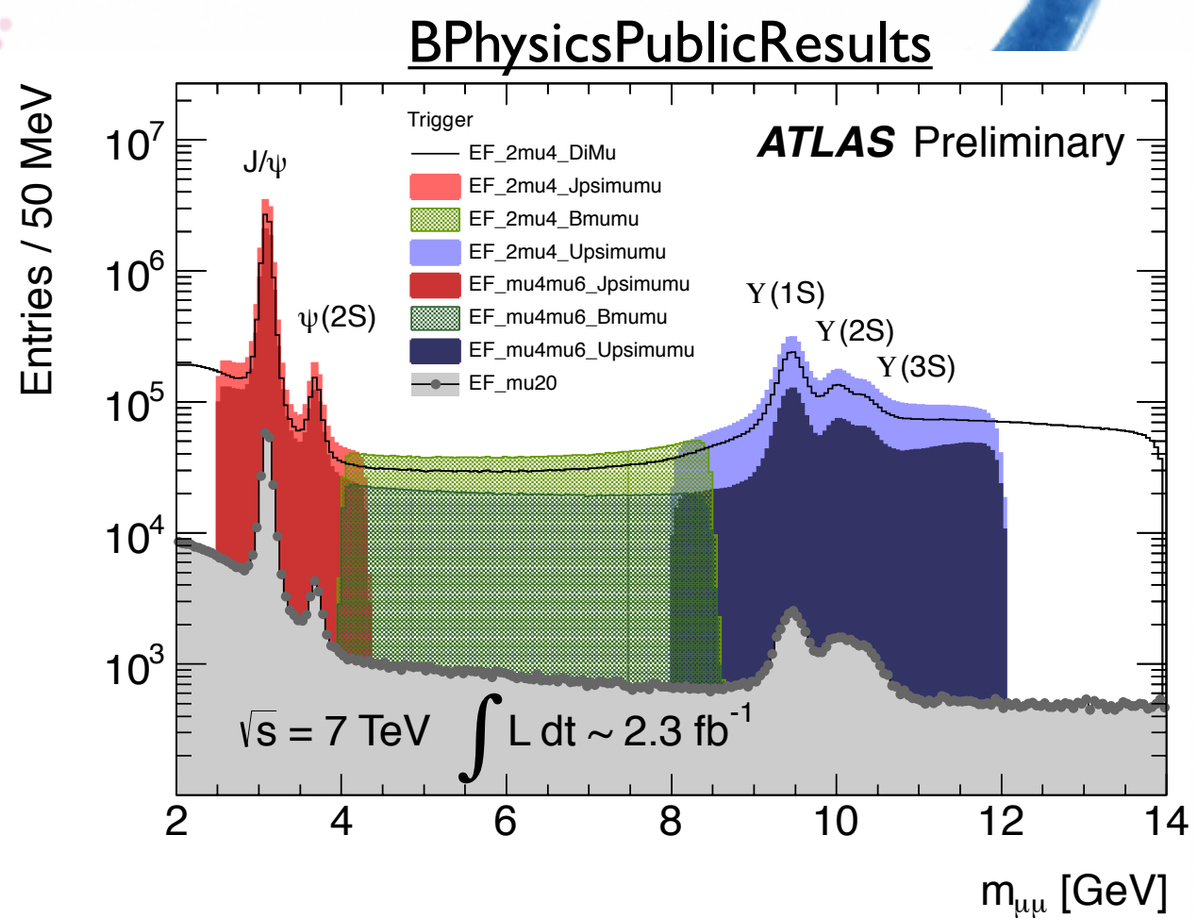
CB= ID and MS track matched
ST= ID track and MS segment matched
Chain 1= One of the two ATLAS muon reconstruction algorithms

Mass resolutions: $\sigma_m(J/\psi - \Upsilon) \sim (60 - 120)$ MeV (ID dominated)

Trigger & B-Physics

ATLAS trigger:
- **Output rate~300 Hz**
- **three levels of event selection**
- **based on Region of Interests**





Exclusive and rare B decays selections based on:

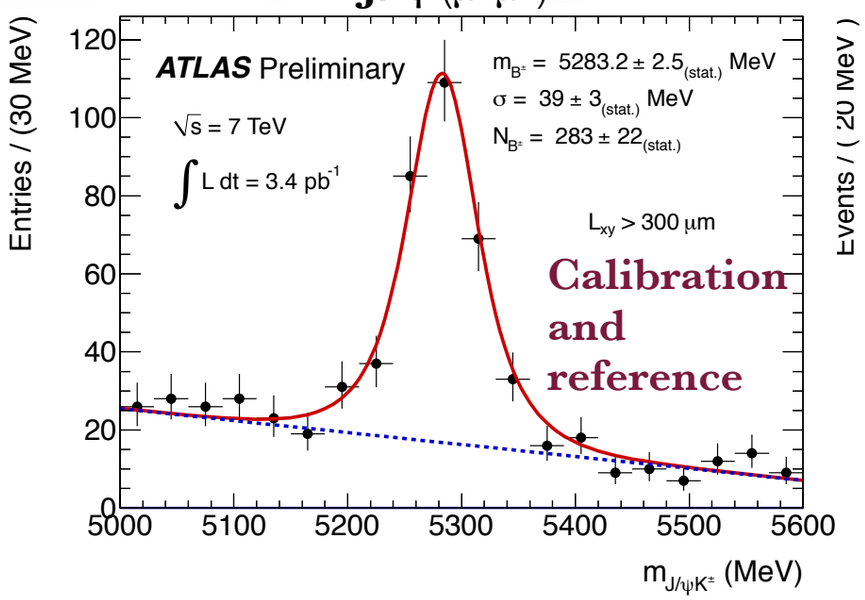
- **Single muon triggers in 2010 (low luminosity)**
- **Di-muons triggers (+pre-scaled single muon) in 2011 (high luminosity)**

B-Physics trigger thresholds kept un-prescaled during 2011 despite the increasing instantaneous luminosity

Exclusive B decays overview

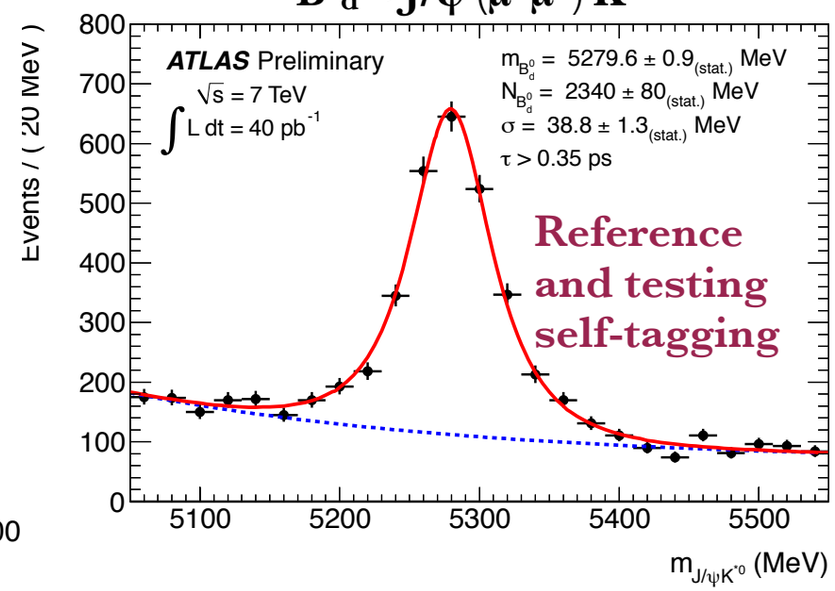
ATLAS-CONF-2010-098

$B^{\pm} \to J/\psi\,(\mu^+\mu^-)K^{\pm}$

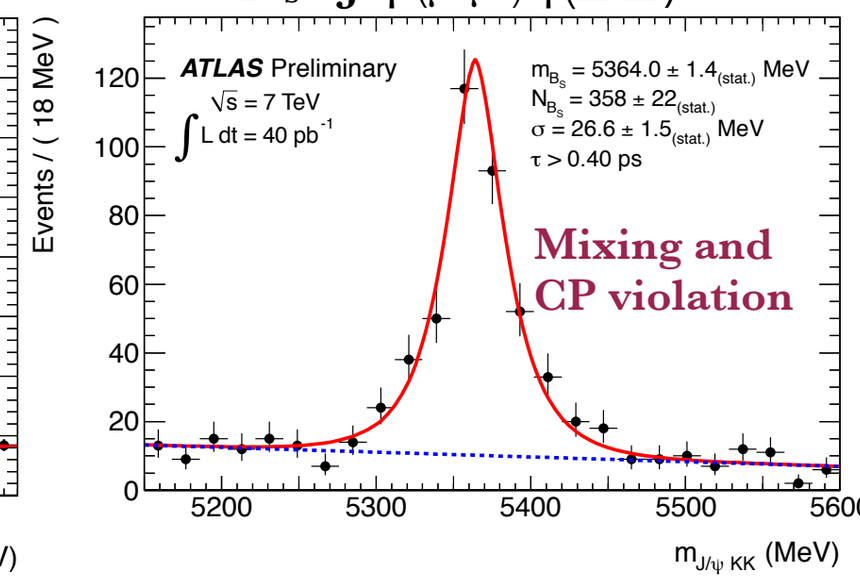


ATLAS-CONF-2011-050 & ATLAS-CONF-2011-092

$B^0_d \to J/\psi\,(\mu^+\mu^-)\,K^{*+}$

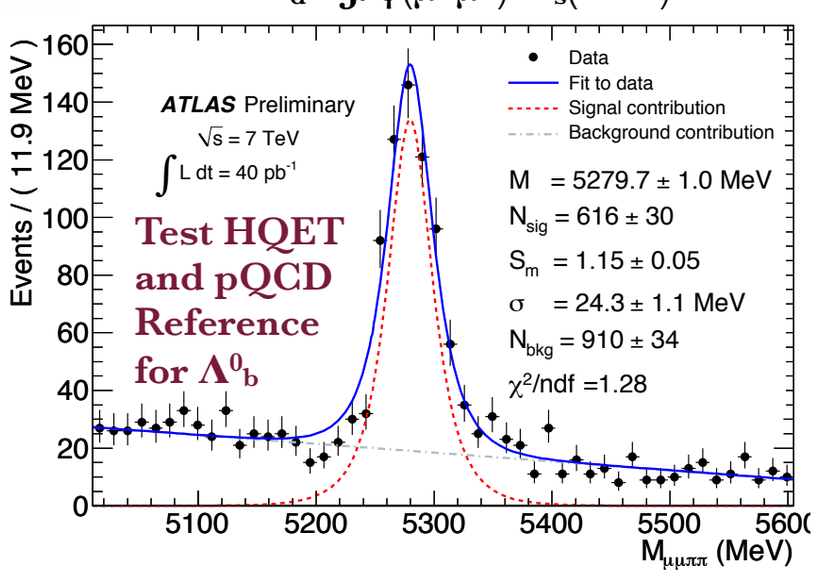


$B^0_s \to J/\psi\,(\mu^+\mu^-)\,\phi(K^+K^-)$



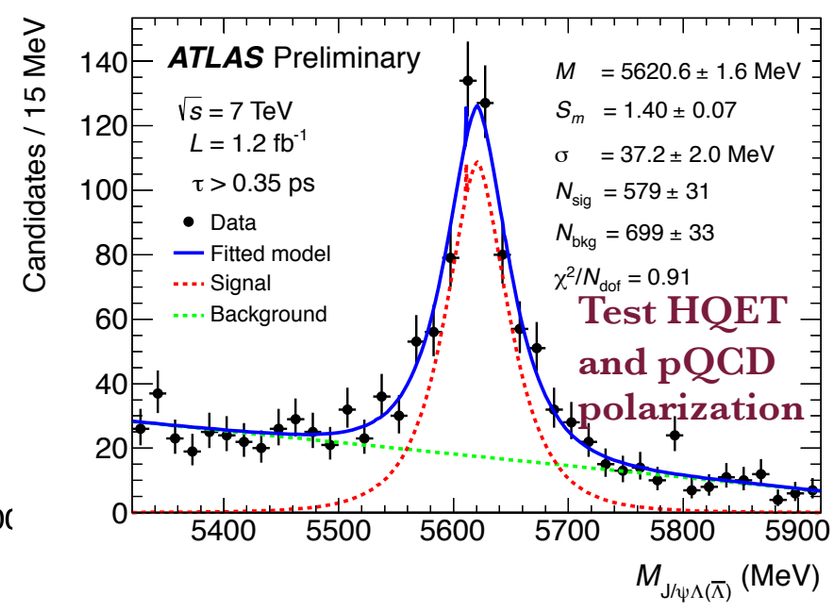
ATLAS-CONF-2011-105

$B^0_d \to J/\psi(\mu^+\mu^-)K^0_s(\pi^+\pi^-)$



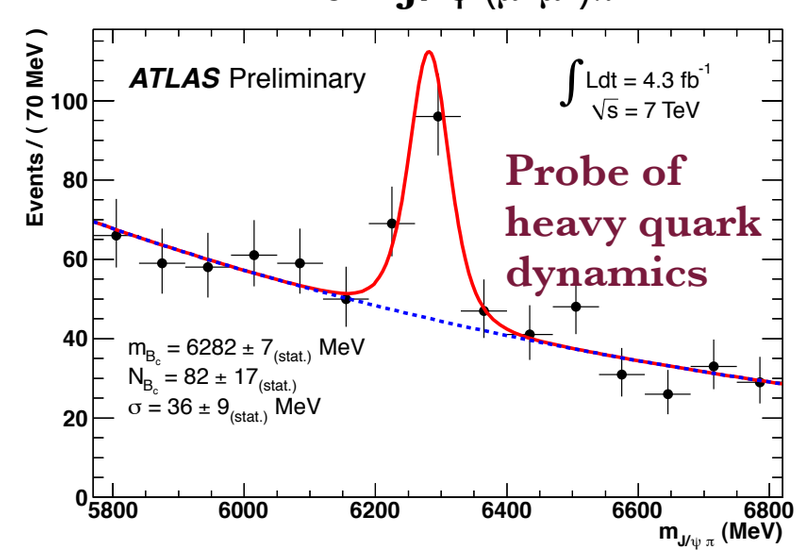
ATLAS-CONF-2011-124

$\Lambda^0_b \to J/\psi(\mu^+\mu^-)\Lambda^0(p^+\pi^-)$



ATLAS-CONF-2012-028

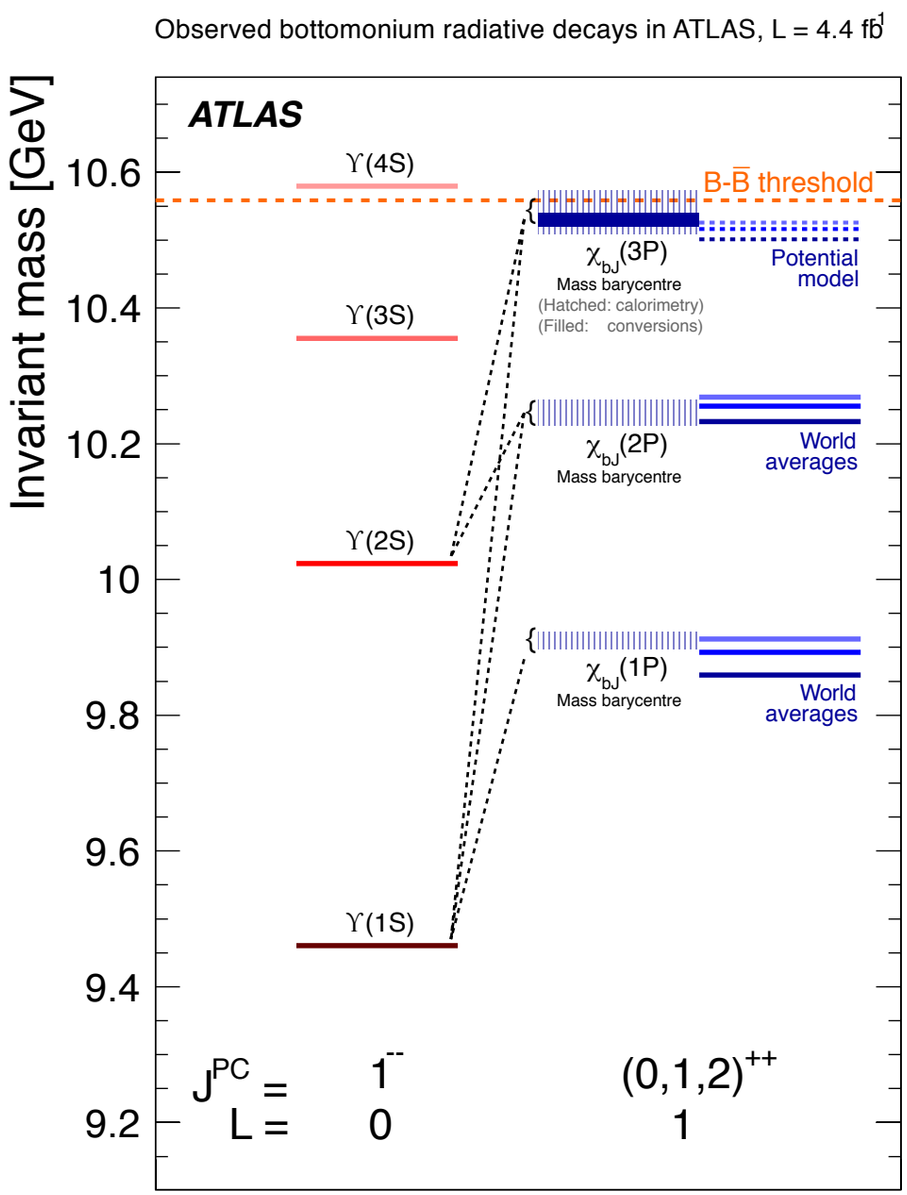
$B^{\pm}c \to J/\psi\,(\mu^+\mu^-)\pi^{\pm}$

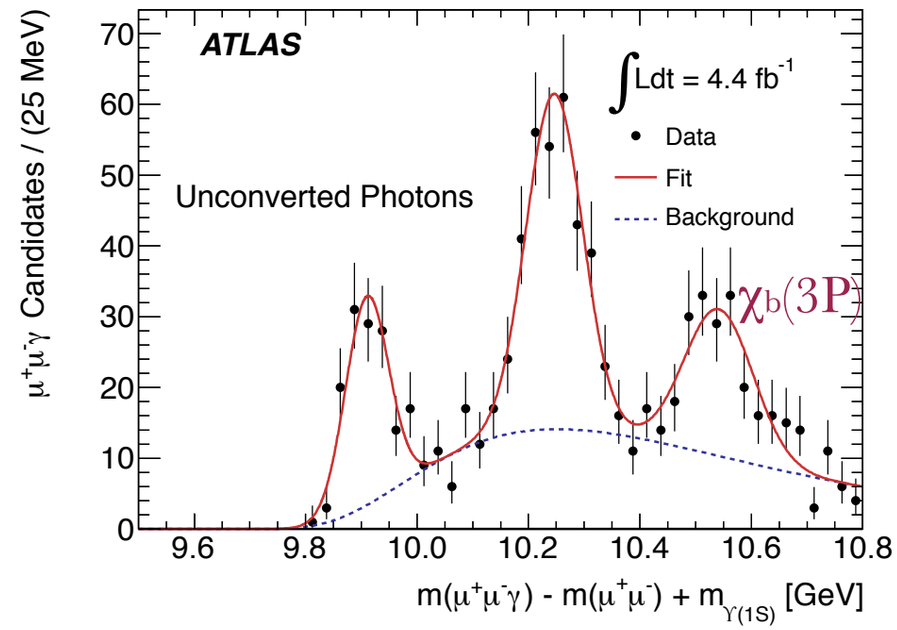


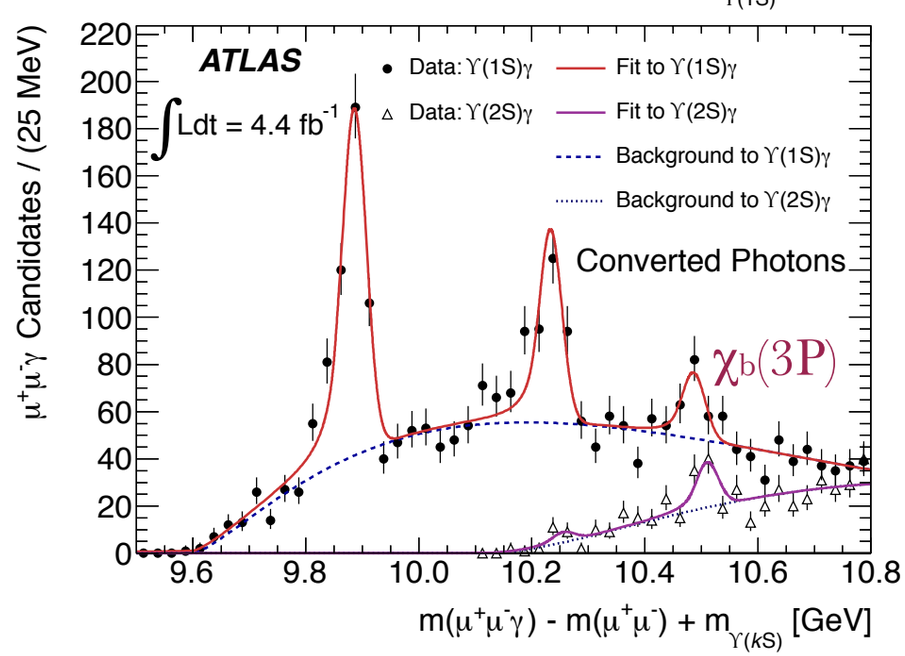
All mass measurements agree with PDG values

Exclusive B decays overview

A recent result: $\chi_b(3P) \rightarrow \Upsilon(1S,2S)\gamma$ **arxiv: 1112.5154**







$M[\chi_b(3P)]=10.530\pm0.005\ (stat)\pm0.009\ (syst)$ GeV

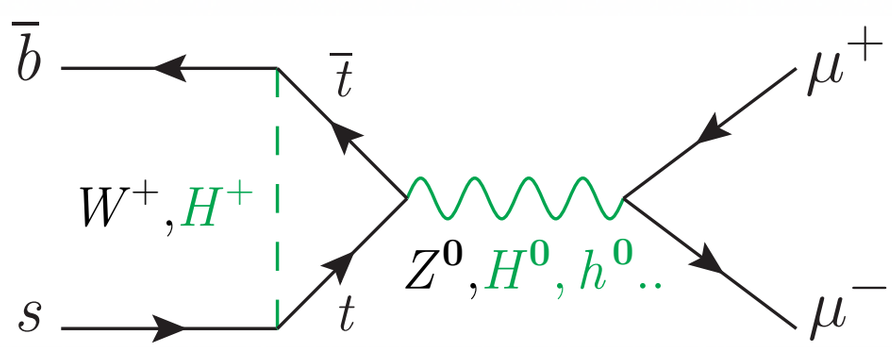
compatible with computation based on potential model for quarkonia states

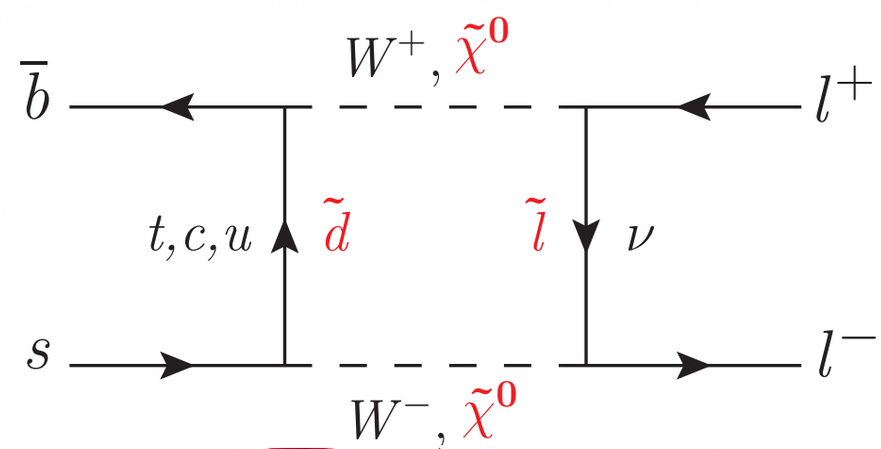
The $B^0_s \rightarrow \mu^+\mu^-$ decay

ATLAS-CONF-2012-010

Motivations

Flavor Changing Neutral Current processes highly suppressed in the Standard Model (SM).
Deviations wrt SM predictions in several New Physics models.





Analysis strategy (1/2)

- **Luminosity: 2.4 fb^{-1} of data, collected up to July 2011 (before a major change in the trigger)**
- **Reduced systematic uncertainties:**
  - ✦ **high-yield reference channel with a similar final state:**

$$\mathrm{BR}\left(B_s^0 \to \mu^+\mu^-\right) = N_{\mu^+\mu^-} \times \frac{1}{N_{J/\psi K^\pm}} \times \frac{A_{J/\psi K^\pm}\,\varepsilon_{J/\psi K^\pm}}{A_{\mu^+\mu^-}\,\varepsilon_{\mu^+\mu^-}} \times \mathrm{BR}\left(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm\right) \times \frac{f_u}{f_s}$$

Single Event Sensitivity

From data

Yield of $B^\pm \to J/\psi K^\pm$ used as reference channel

Acceptances and efficiencies from Monte Carlo, $R_{A\varepsilon}$

From other measurements:

$\mathrm{BR}\left(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm\right) = (6.01 \pm 0.21) \times 10^{-5}$ [PDG]

$f_u/f_s = 0.267 \pm 0.021$ [LHCb(1,2)]

  - ✦ **Monte Carlo (MC) samples re-tuned using data-driven per event weights**

(1) "Averages of b-hadron, c-hadron, and τ-lepton Properties" - 2011; 1010.1589.
(2) " Measurement of b hadron production fractions in 7 TeV collisions"- 2011;1111.2357

Analysis strategy (2/2)

- **Avoid possible sources of `a-priori' bias:**
  - ✦ **blind the signal region (5066 MeV < $m_{\mu\mu}$ < 5666 MeV): use MC to model signal**
  - ✦ **no optimization bias: data in sidebands**

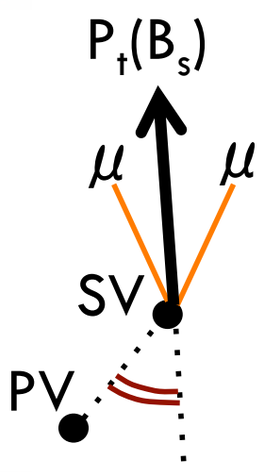
    (4766 MeV < $m_{\mu\mu}$ < 5066 MeV ∪ 5666 MeV < $m_{\mu\mu}$ < 5966 MeV) split in :
    - ✦ **odd numbered events, to optimize cuts**
    - ✦ **even numbered events channel, to estimate the yields after the cuts optimization**
- **Improve signal/background separation:**
  - ✦ **samples split in three mass resolution categories (~ 60 / 80 / 110 MeV) depending on muons pseudorapidity ($|\eta_{max}|$<1.0/1.5/2.5)**
  - ✦ **multivariate analysis (MVA) used to combine the separation power of different variables**

Signal/background discrimination

Background Composition:

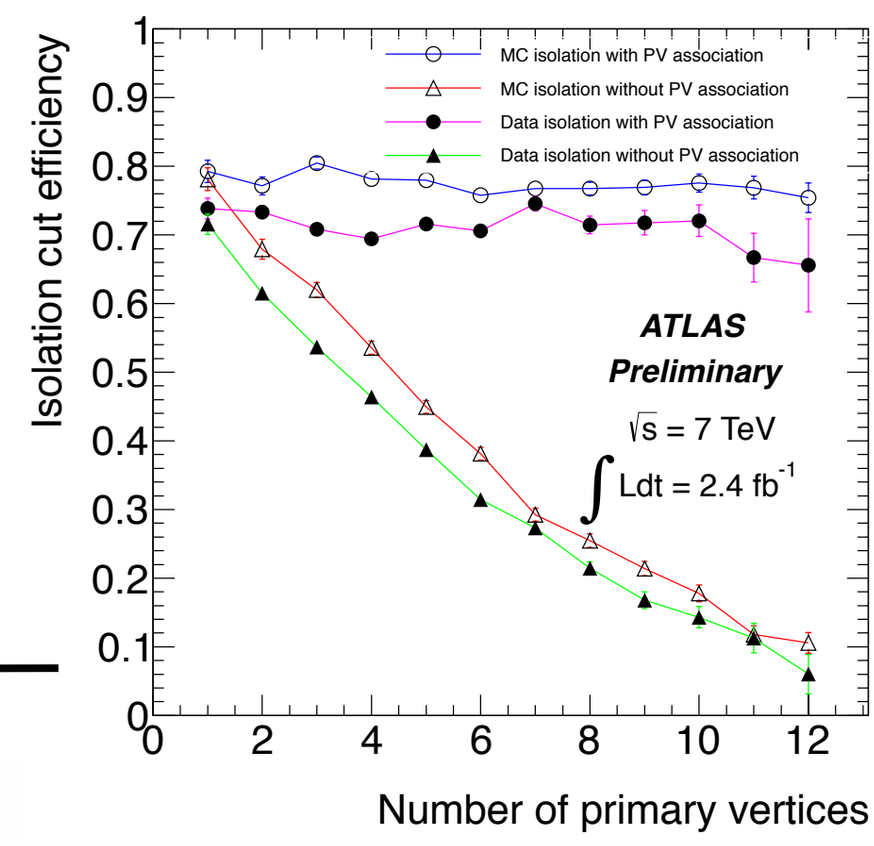
- **continuum: $bb \to \mu^+\mu^- X$ modeled using data in sidebands, main contribution**
- **'resonant': $B \to hh$ (KK, Kπ, ππ), "fake muons" from decays in flight, punch-throughs)**
  BRx(fake rate) ≈ 10^{-9}, close to SM branching ratio for signal, accounted in the upper limit extraction
- **'mixed': $bb \to \mu^+ h^- X$, single muon +"fake muon", negligible contribution**

Discriminating variables used in the multivariate classifier:



- **14 selected:**
  - **for their discriminating power**
  - **avoiding using correlated variables**
- **exploit signal features, like:**
  - **PV-SV separation: L_{xy}, ct significance...**
  - **Symmetry of final state: pointing angle, d_0...**
  - **B hadronization features: Isolation, $P_T(B_s)$...**

track based,
pile-up independent

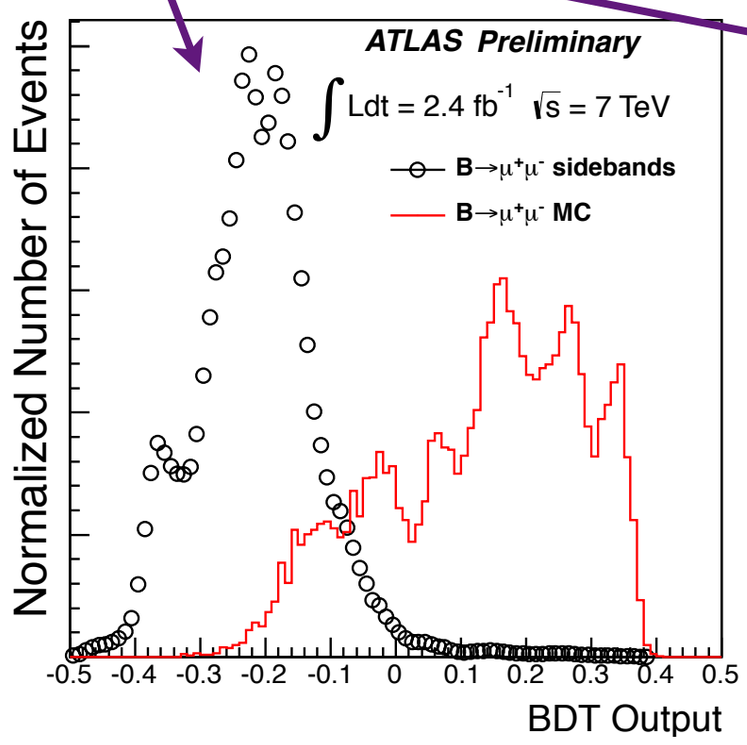


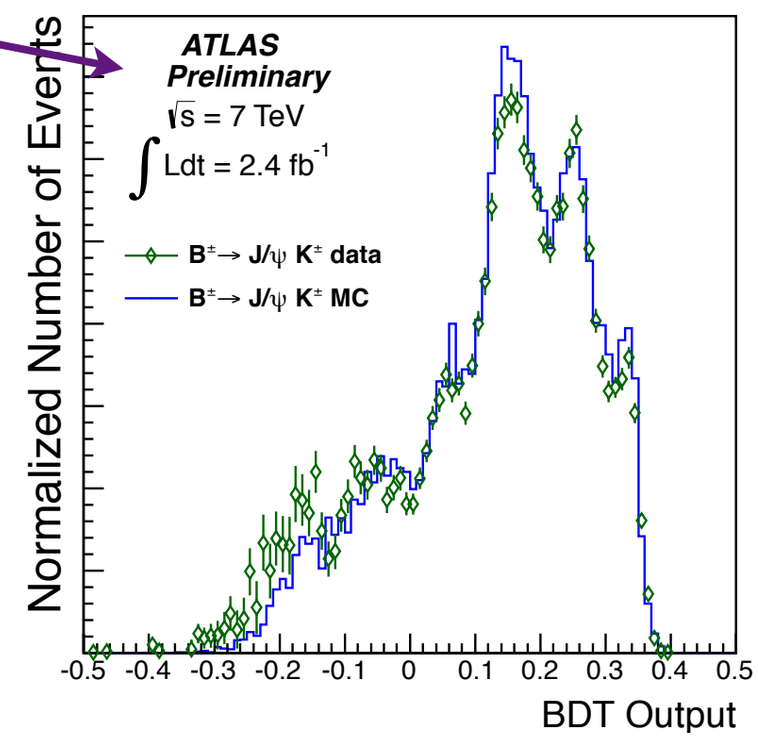
Selection optimization

Optimize the estimator(*) $\mathcal{P} = \dfrac{\epsilon_{\rm sig}}{\frac{a}{2} + \sqrt{N_{\rm bkg}}}$ **(a=2 for 95% CL limit)**

- **for the three mass resolution categories**
- **as a function of the width of search window in mass and the lower cut on BDT output**

- Ranked as best classifier
- correlation with the mass checked with a test signal at 6.5 GeV





(*)G. Punzi,
"Sensitivity of searches for new signal and its optimization", tech. rep., SLAC, Stanford, CA, 2003.

Inputs to Single Event Sensitivity

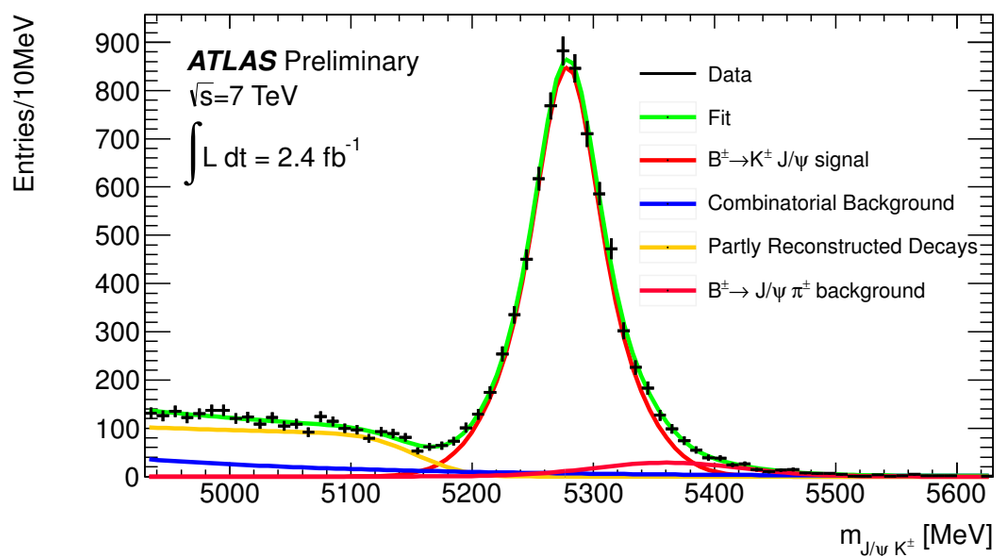
$$\mathrm{SES} = \frac{1}{N_{J/\psi K^\pm}} \times \frac{A_{J/\psi K^\pm}\,\varepsilon_{J/\psi K^\pm}}{A_{\mu^+\mu^-}\,\varepsilon_{\mu^+\mu^-}} \times \mathrm{BR}\left(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm\right) \times \frac{f_u}{f_s}$$

data

MC

$1/(4.45\pm0.38)\times10^3$
[PDG + LHCb]

Reference channel yield



After selection cuts, even events only!

Resolution category	$\lvert\eta_{max}\rvert$ <1.0	$\lvert\eta_{max}\rvert$ <1.5	$\lvert\eta_{max}\rvert$ <2.5
$B^\pm \to J/\psi K^\pm$ yield	4298	1407	1126
Stat. uncertainty	±1.6%	±2.8%	±3.0%
Syst. uncertainty	±2.9%	±7.4%	±14.1%

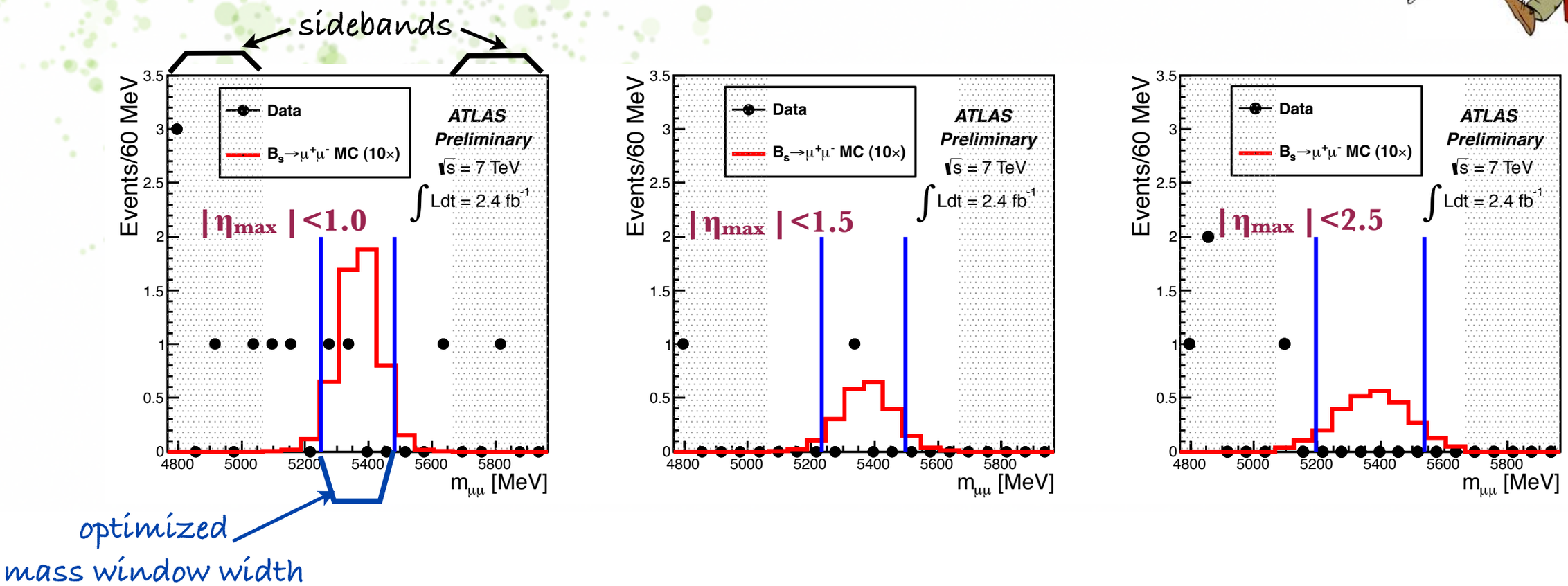
εA ratio

Resolution category	$\lvert\eta_{max}\rvert$	$R_{A\varepsilon}$	$\Delta R_{A\varepsilon}/R_{A\varepsilon}$ % Stat.	Syst.
$\lvert\eta_{max}\rvert$<1.0	1.0	0.27	3.1	3.1
$\lvert\eta_{max}\rvert$<1.5	1.5	0.20	4.8	5.5
$\lvert\eta_{max}\rvert$<2.5	2.5	0.14	5.3	5.9

Output:

Resolution category	$\lvert\eta_{max}\rvert$ <1.0	$\lvert\eta_{max}\rvert$ <1.5	$\lvert\eta_{max}\rvert$ <2.5
SES [x 10^{-8}]	0.71	1.6	1.4

Unblinding



	Resolution category		
Background Events	$\lvert\eta_{max}\rvert<1.0$	$\lvert\eta_{max}\rvert<1.5$	$\lvert\eta_{max}\rvert<2.5$
Even	5	0	2
Odd (biased)	1	1	1

Continuous background interpolation: 6.1 ev.

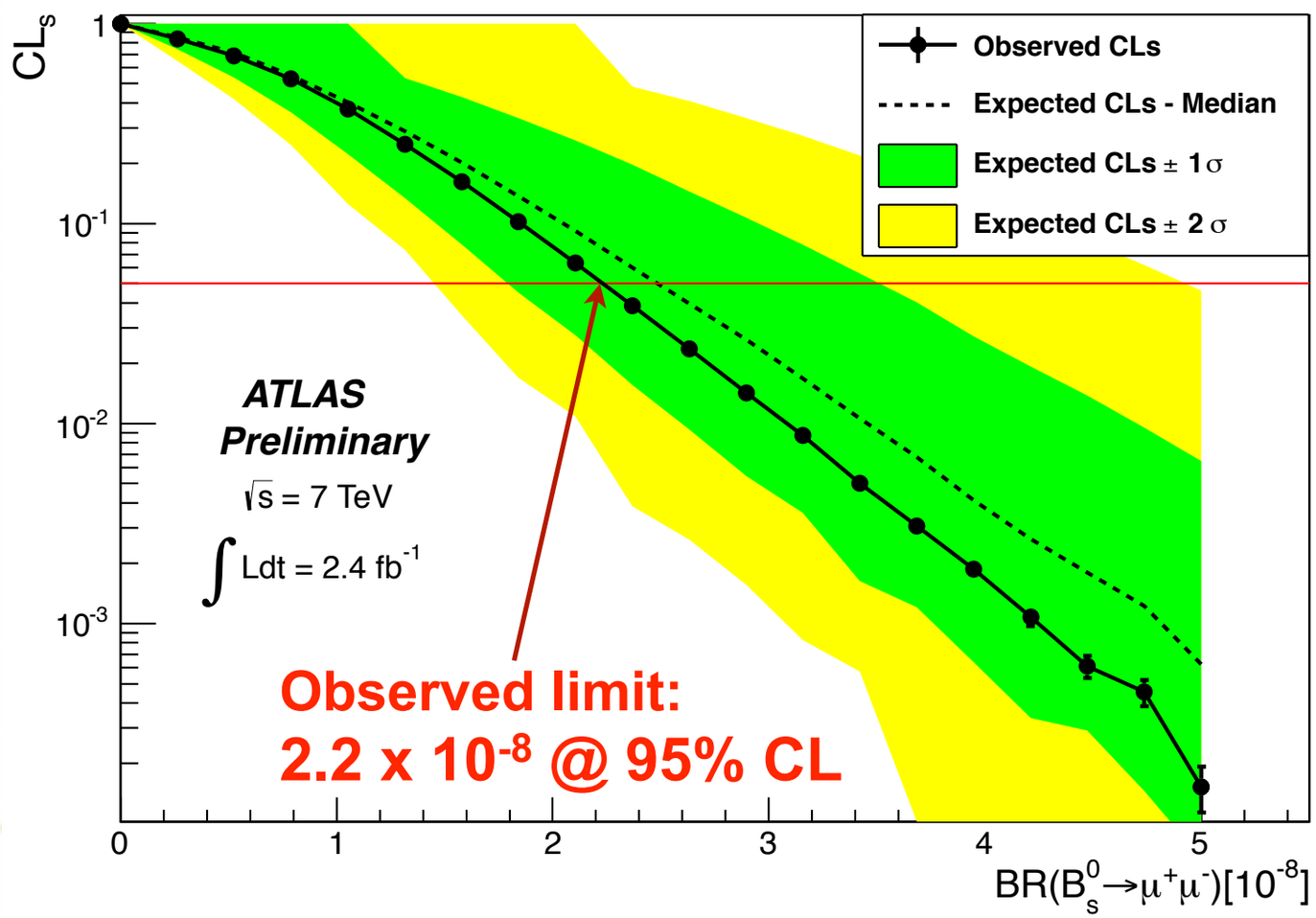
Note: expected 'resonant' background : 0.24 events (η bins merged)

Upper Limit

Before the unblinding.....

	95% CLs limit expectations
Even sidebands	2.3×10^{-8}
Odd sidebands	1.7×10^{-8}
All bins merged	2.8×10^{-8}

.....after the unblinding



Next steps:

- Use of spectrometer information to improve mass resolution for forward muons
- MC-based continuous background model - remove statistical uncertainty on event count in sidebands
- Use Full 2011 (and 2012) statistics

Expect improvements better than sqrt(Lumi)!

Summary & plans

- **ATLAS made several interesting measurements on B decays channels:**
  - ✓ **Observation of B-hadrons and lifetimes**
  - ✓ **First observation of a new state at LHC: $\chi_b(3P)$**
  - ✓ **Upper Limit on BR($B^0_s \to \mu^+\mu^-$)**

- **On the horizon:**
  - **B-hadrons decays:**
    - **CP violation and mixing with $B^0_s \to J/\psi\ \phi$**
    - **Λ_b , B^+_c , B^0_s physics**
  - **Rare Decays:**
    - **BR($B^0_s \to \mu^+\mu^-$) upper limit update with full statistics**
    - **$B^0_s \to \mu^+\mu^-\phi$, $B^0_d \to \mu^+\mu^-K^*$**

Back-up

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Performance

ATLAS Detector Status

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.9%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	99.5%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	100%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	97.7%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	99.7%

All subsystems maintain high performance!

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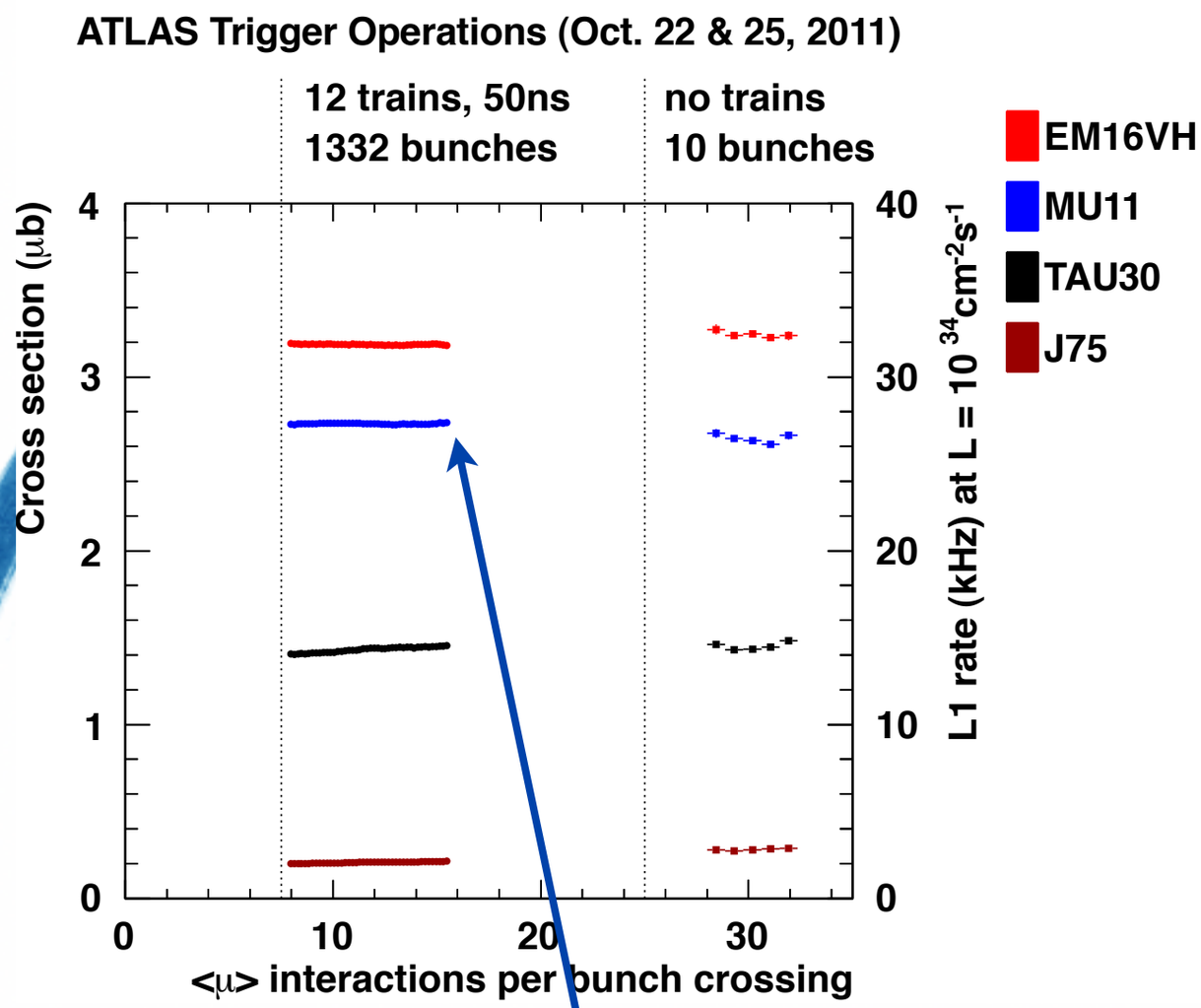
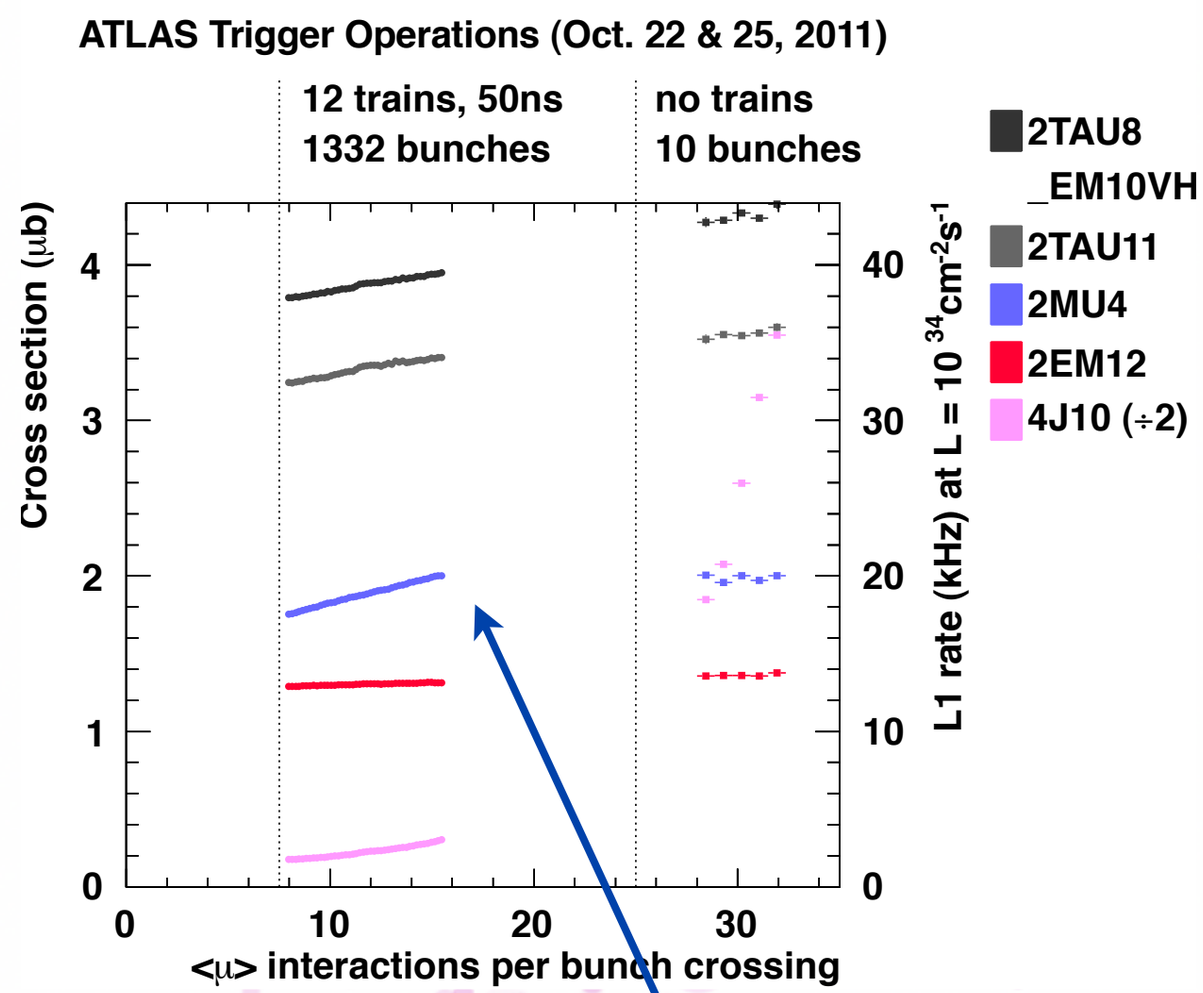
Muon trigger ad pile-up

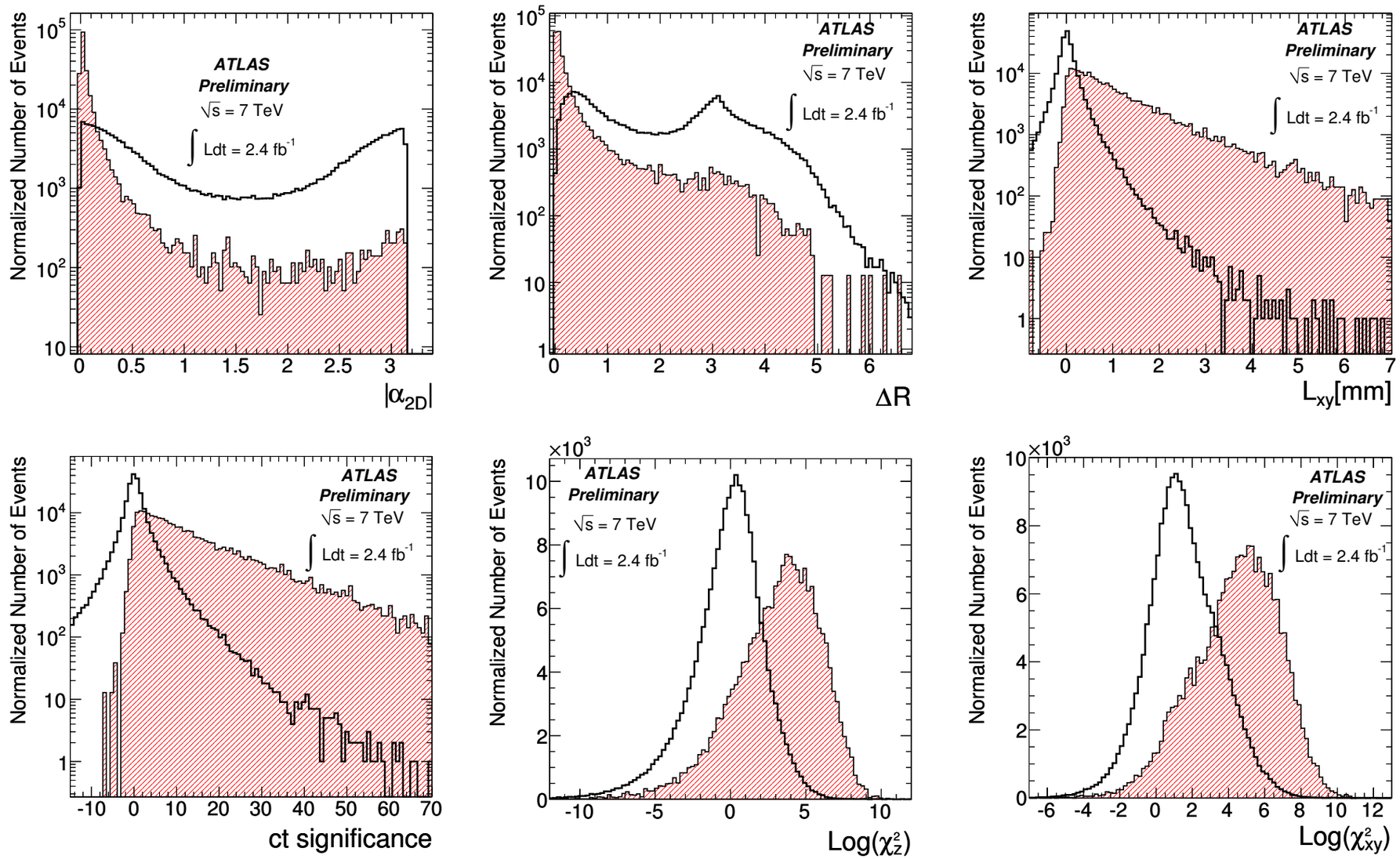


high p_T
stable wrt pile-up



low p_T
affected by fake rate;
tighter selections used

Discriminating variables (1/2)



Variable	Description
$\lvert\alpha_{2D}\rvert$ pointing angle	Absolute value of the angle in the transverse plane between $\Delta\vec{x}$ and $\vec{p}^B$
ΔR	Angle $(\Delta\phi^2 + \Delta\eta^2)^{1/2}$ between $\Delta\vec{x}$ and $\vec{p}^B$
L_{xy}	Scalar product in the transverse plane of $(\Delta\vec{x} \cdot \vec{p}^B)/\lvert\vec{p}_T^B\rvert$
ct significance	Proper decay length $ct = L_{xy} \times m_B/p_T^B$ divided by its uncertainty
χ^2_{xy}, χ^2_z	χ^2 computed between the measured PV and SV positions in (x, y) and z, respectively

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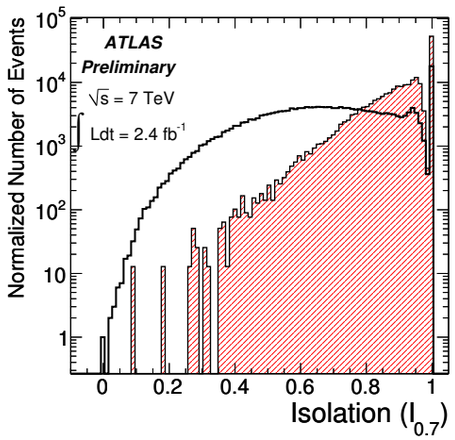
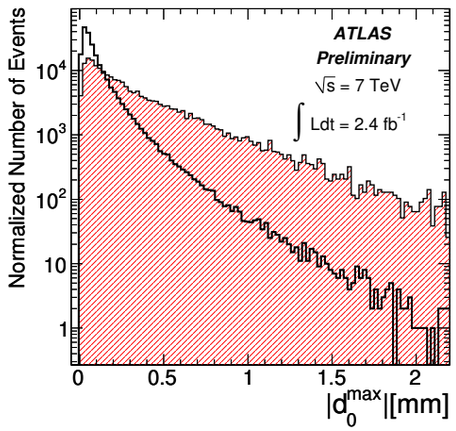
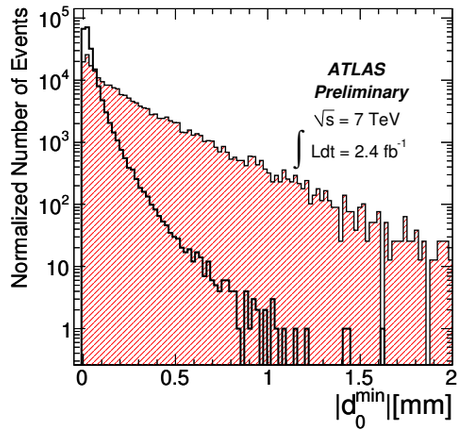
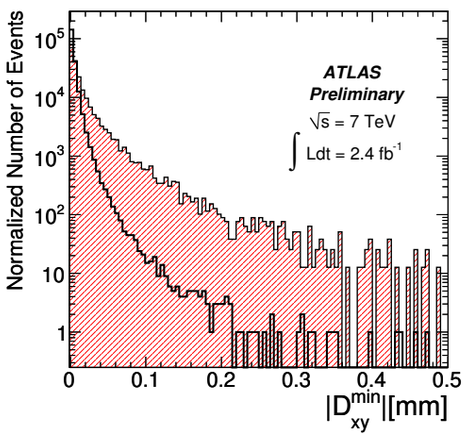
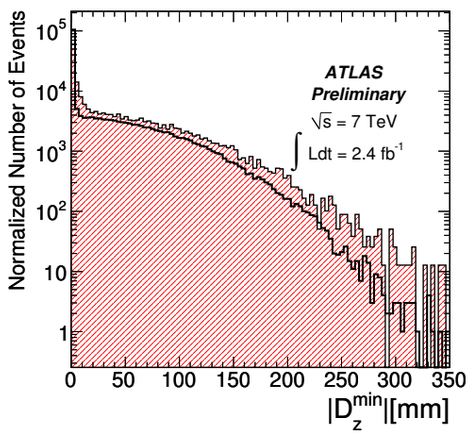
Discriminating variables (2/2)

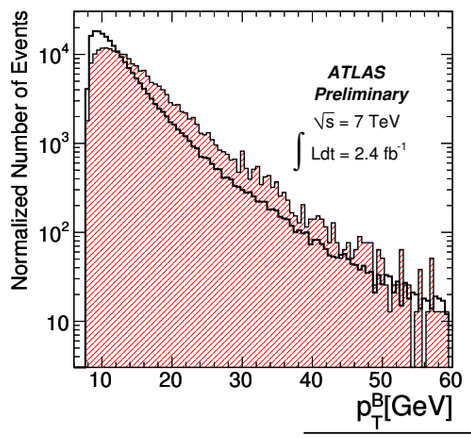


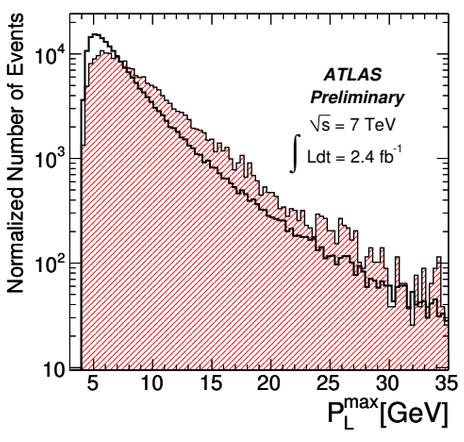


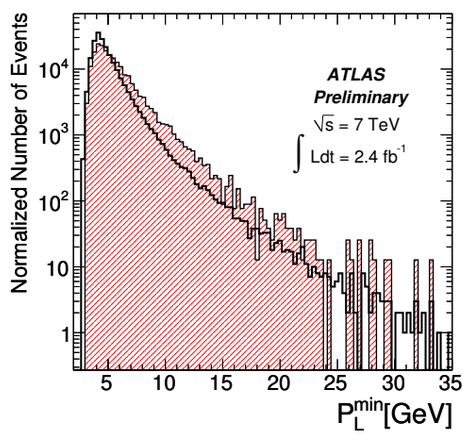












Variable	Description
$I_{0.7}$ Isolation	Ratio of $\lvert\vec{p}_T^B\rvert$ over the sum of $\lvert\vec{p}_T^B\rvert$ and the transverse momenta of all tracks of $p_T > 0.5$ GeV within a cone $\Delta R < 0.7$ from the B direction, excluding B decay products
$\lvert d_0^{\max}\rvert$, $\lvert d_0^{\min}\rvert$	Absolute values of the maximum and minimum impact parameter in the transverse plane of the B decay products relative to the primary vertex
$\lvert D_{xy}^{\min}\rvert$, $\lvert D_z^{\min}\rvert$	Absolute values of the minimum distance of closest approach in the xy plane (or along z) between the B vertex and tracks in the event
p_{T}^B	B transverse momentum
$p_L^{\max}$, $p_L^{\min}$	Maximum and minimum momentum of the two muon candidates along the B direction

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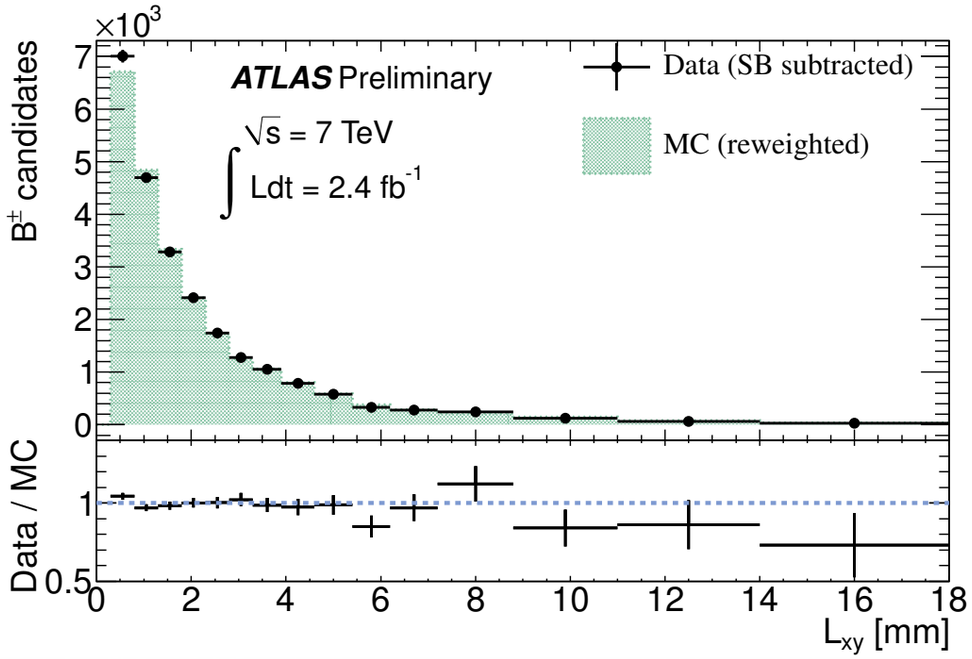
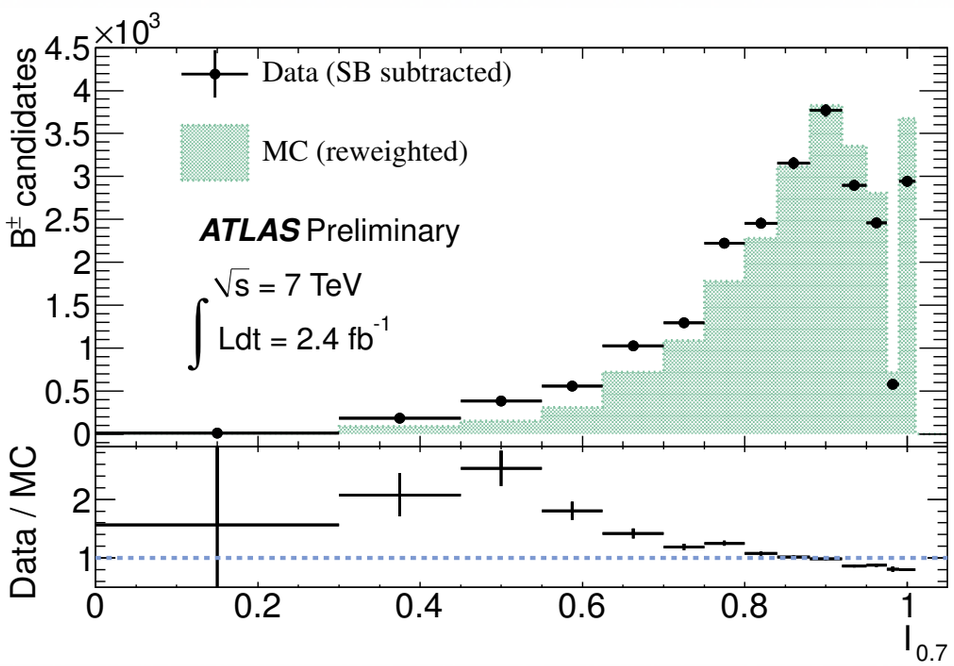
Data/MC comparison





Derived MC corrections weights to account for:

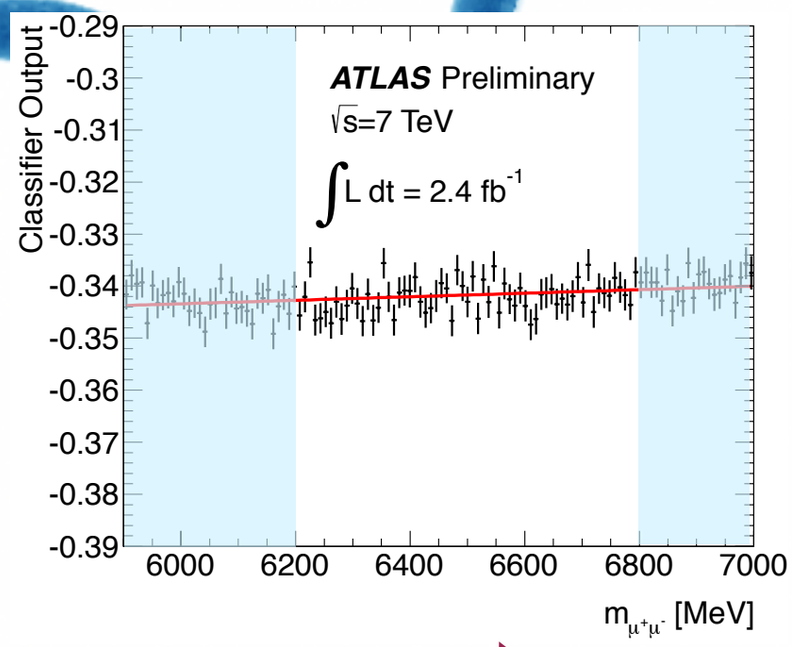
- **Final-state selections on MC, different between B^+ and B_s : residual differences due to different b-quark hadronization have been assessed by using $B^0_s \rightarrow J/\psi\ \phi$ control sample**

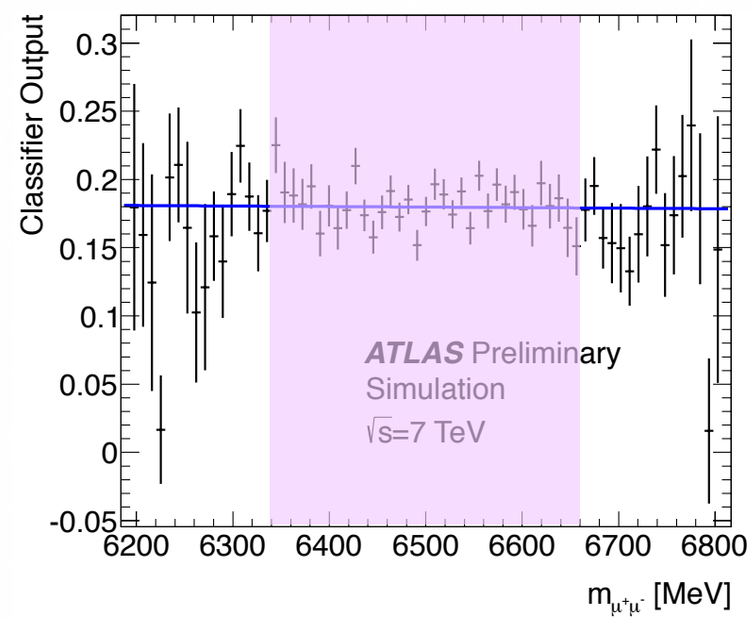
- **Differences between MC and data, primarily in B kinematics (p_T,η)**

After corrections still differences observed on some discriminating variables: taken as systematic uncertainties in the εA ratio

BDT independence test

Fake signal at 6.5 GeV





No mass dependence of the TMVA selection

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