ATLAS $B_s \to \mu\mu$

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on behalf of the ATLAS Collaboration

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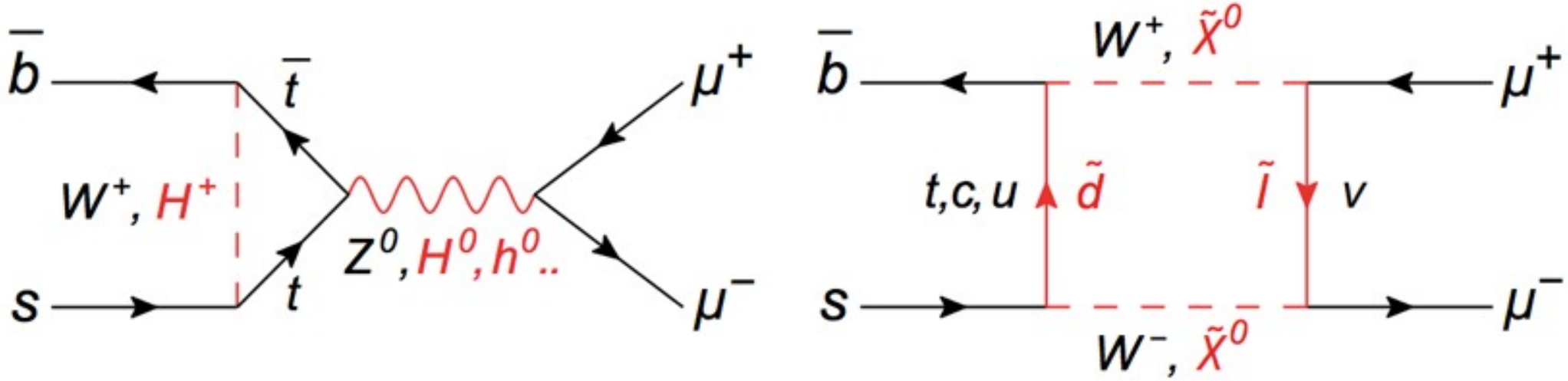
Beauty2013

Introduction

- Bs→μμ : Flavor Changing Neutral Current (FCNC)
  - strongly suppressed in the SM, BR(theo) = $(3.5\pm0.2)\times10^{-9}$
  - can be enhanced by new physics



- First measurement of the BR by LHCb is:
  $BR(Bs\rightarrow\mu\mu) = (3.2\ ^{+1.5}\ _{-1.2}) \times 10^{-9}$
  Phys. Rev. Lett. **110**, 021801 (2013), LHCb-TALK-2012-306

- Sufficient precise measurement of the BR can allow to claim the new physics
  => <u>combination of ATLAS, CMS and LHCb</u>

- This talk will present current status & future plans of the ATLAS experiment

Strategy

- Features of this analysis:

1. **Triggering** data efficiently;
2. **Blind analysis**;
3. **Multivariate analysis** with Boosted Decision Trees (BDT);
   ※ In order to avoid bias, half of sideband events (odd-numbered) are used for BDT training and cut optimization, and the other half (even-numbered) for background estimation.
4. **CLs** approach for limit setting.

- ATLAS obtains the branching fraction by using the following formula

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

- BR($B^\pm \to J/\psi K^\pm \to \mu\mu K^\pm$) : BR of reference channel:= $(6.01 \pm 0.21)\times 10^{-5}$ (PDG)
- f_u/f_s : Relative production probability of $B^0/B_s := 0.267 \pm 0.021$

[LHCb, Phys. Rev. D 85 (2012)032008]

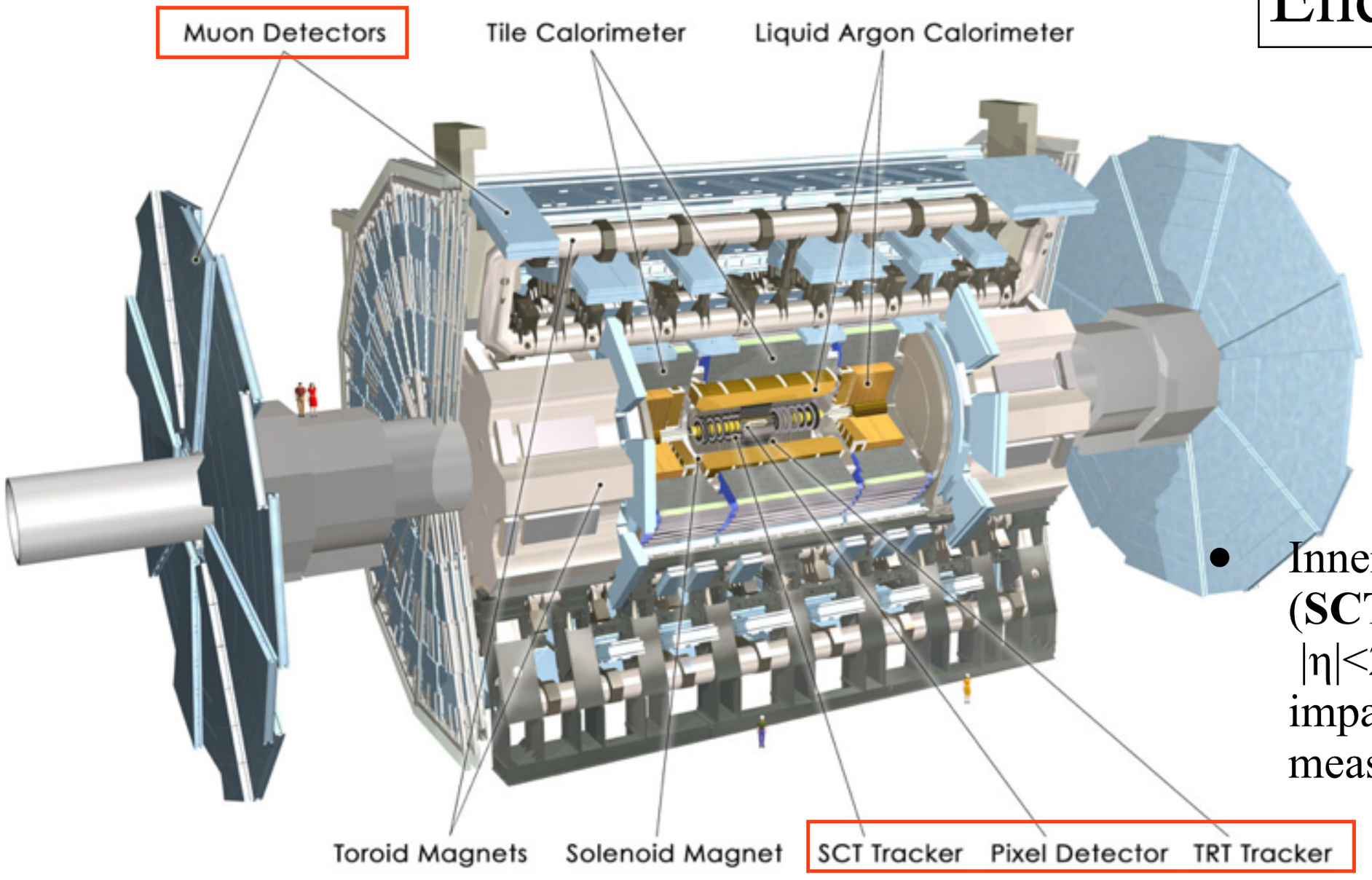
- N_{XX} : Number of events observed in each channel
- A_{XX} : Selection acceptance for each channel
- ε_{XX} : Overall efficiency for each channel

(We can suppress common syst. uncertainties to signal and reference channels)

The ATLAS detector

- **Muon Detectors**
- Precise muon chamber: $|\eta|<2.7$, resolution of ~40μm
- Trigger muon chamber: synchronized with the LHC clock

Barrel: $|\eta|<1$
Endcap: $|\eta|>1$



- Inner detector (ID) (**SCT** + **Pixel** + **TRT**) $|\eta|<2.5$, Resolution on impact parameter measurement ~10μm

After combination ID + Muon, $\sigma_{pT}/p_T \sim 0.05\%/p_T$ [GeV] (ID dominant)

ATLAS muon & B-phys trigger

- Triggering objects i.e. e/γ, jets, muon, etc. by 3-step chain
- 2012: lowest un-prescaled single muon and e/γ trigger: p_T>24GeV
- For low-p_T physics process, special trigger configurations were prepared

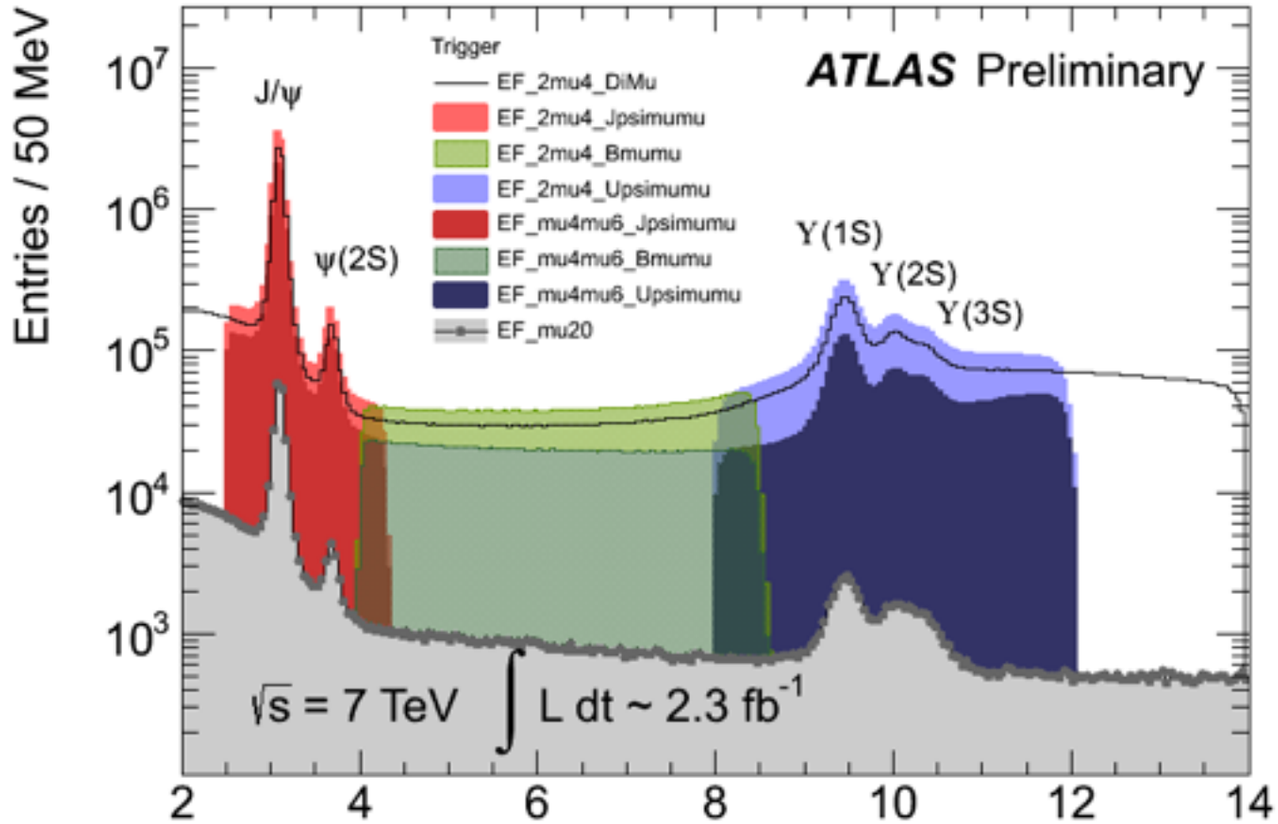
Special trigger chain for B-phys

LVL.1: Fast triggering using custom-made hardware.
Require **two muon candidates**

LVL.2: Software reconstruction using precise muon detector
Faster reconstruction by using LVL.1 info.

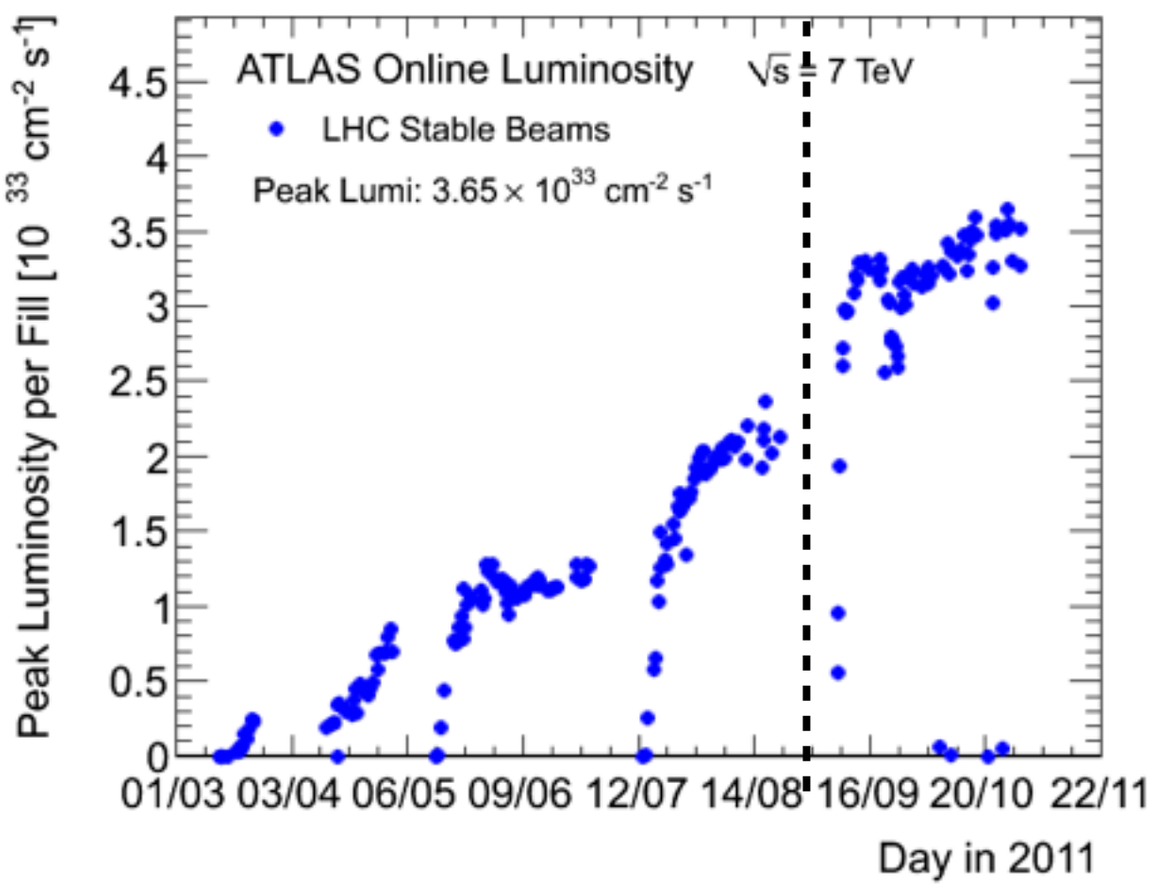
Event Filter: Full track reconstruction
Muon p_T>4GeV
loose invariant mass window cut and vertex cut

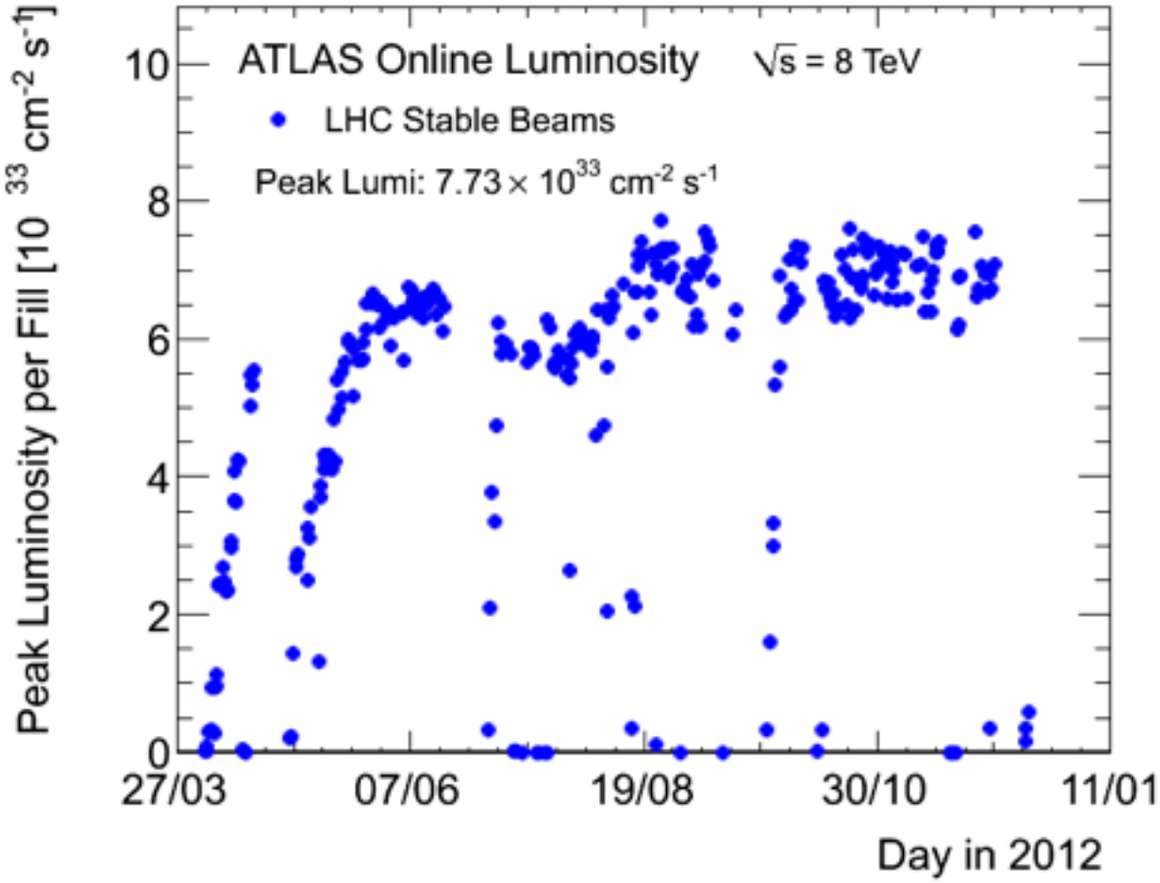
RECORD



	mass window@trigger level
Bs trigger	[4000, 8000] MeV
J/ψ trigger	[2500, 4300] MeV

B-phys trigger operation in 2011/2012





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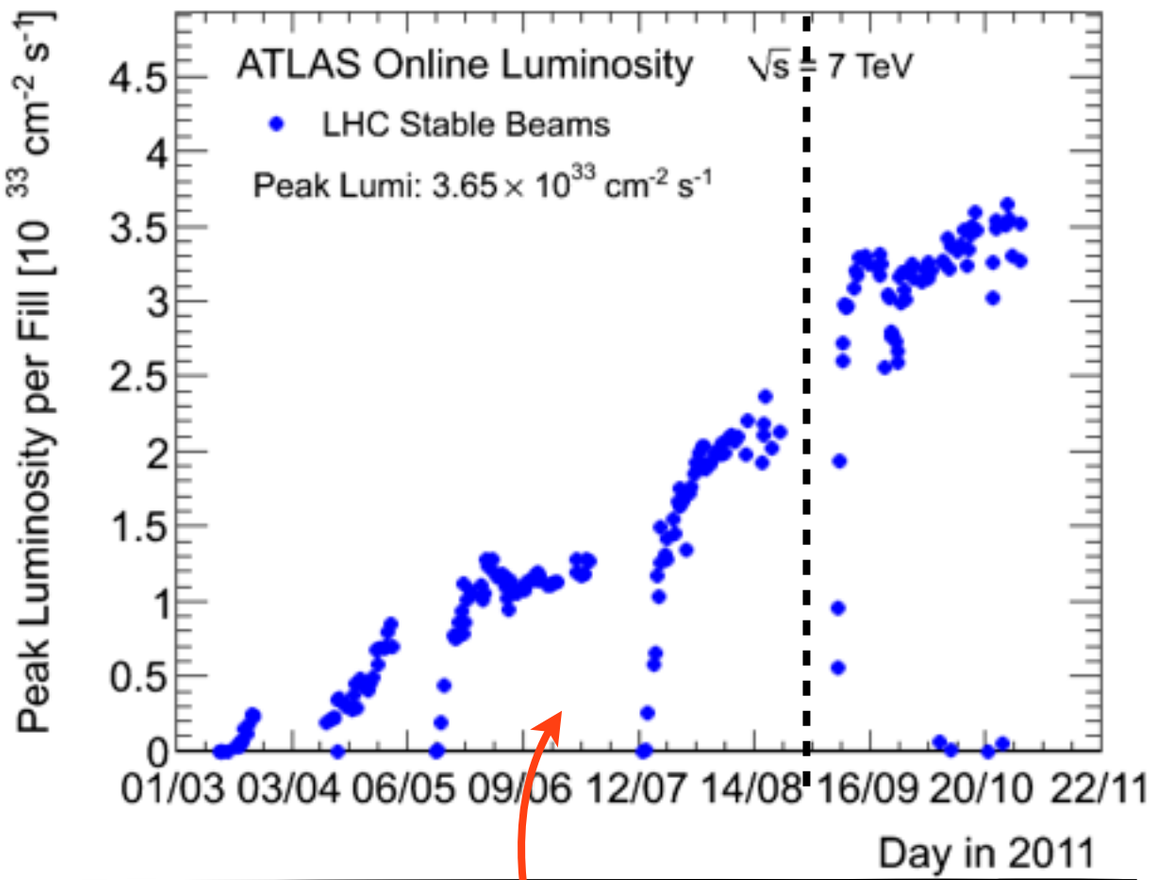

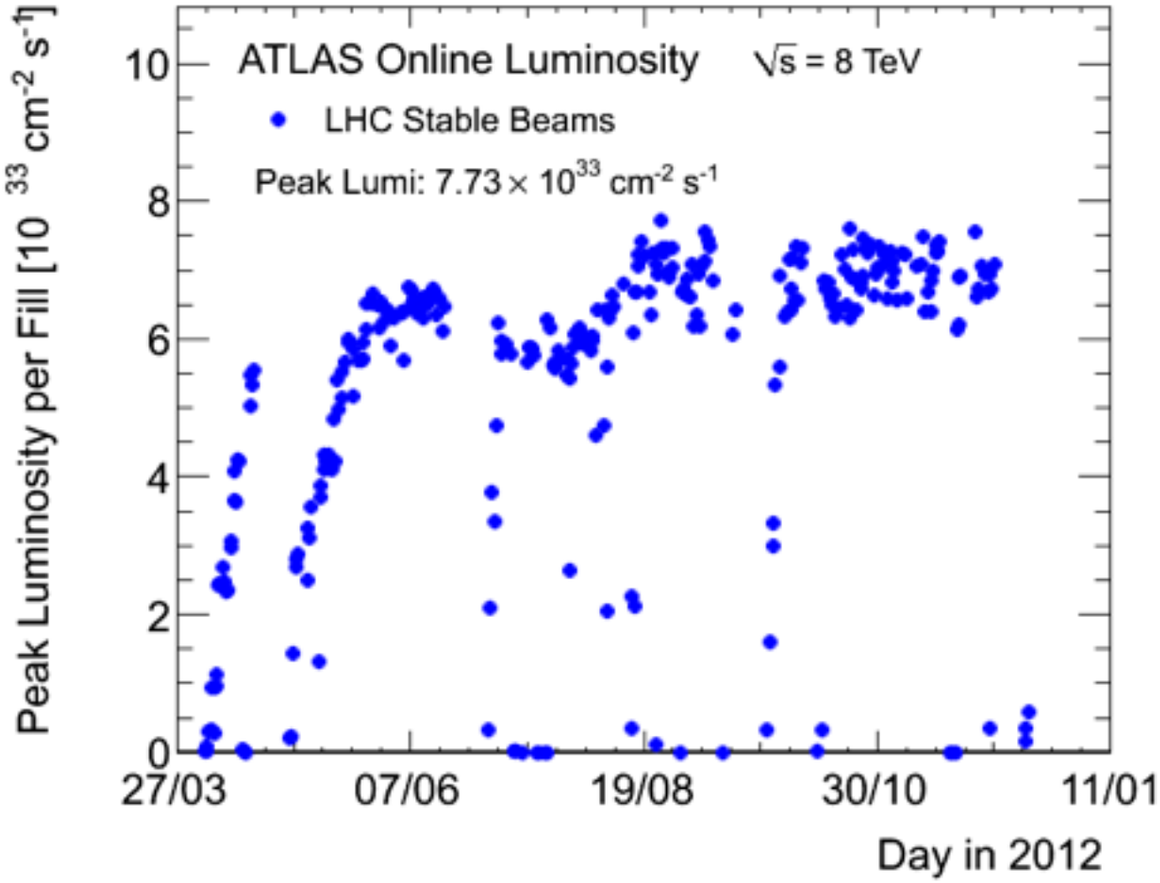

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Keep nominal Bs and J/ψ triggers
=> Bs→μμ result was already published and I will show it today

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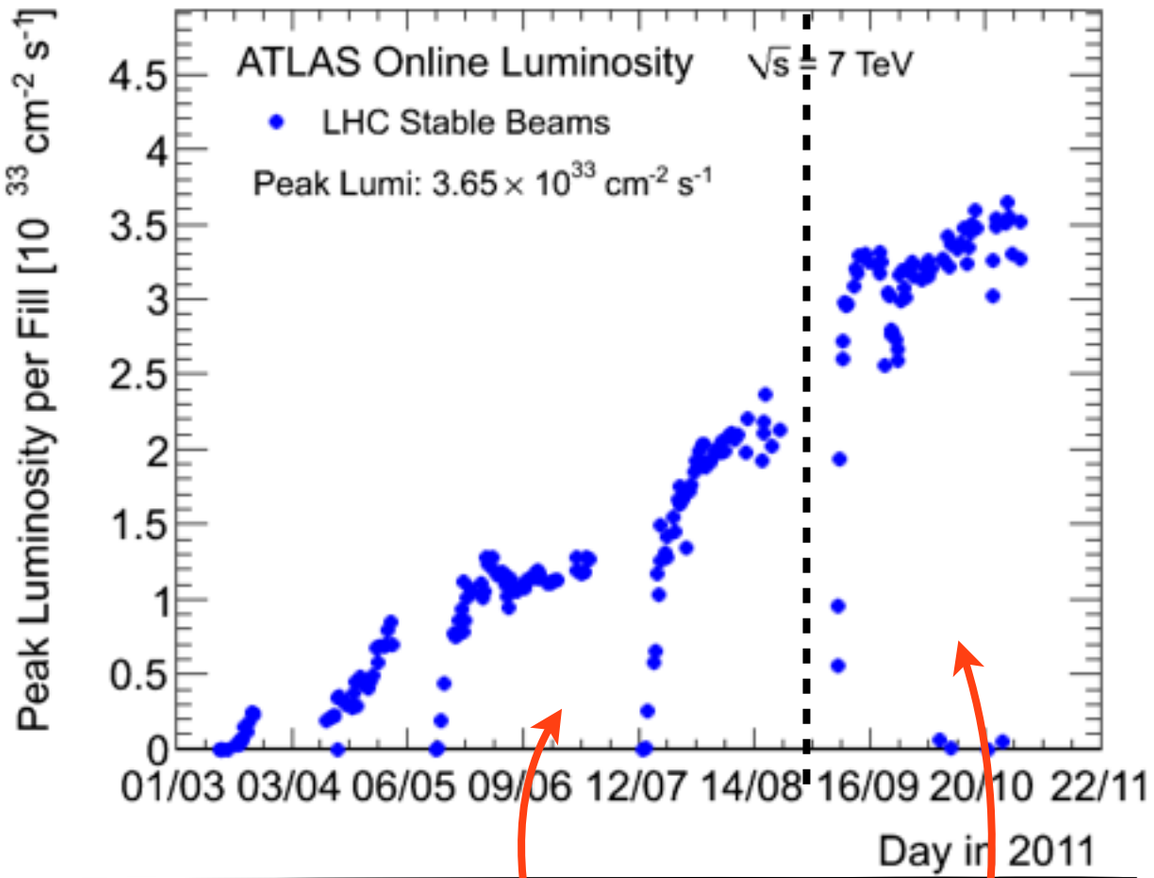

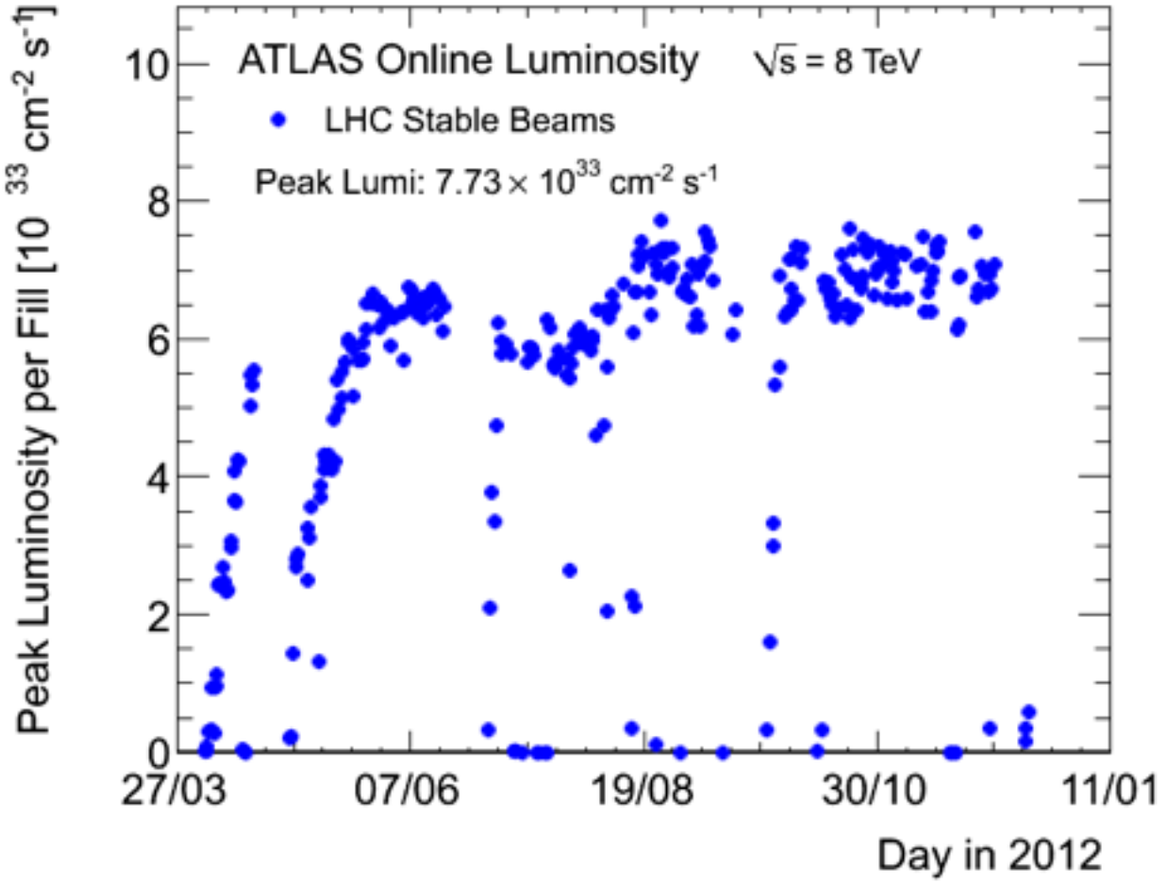

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LHC luminosity was increased (>3×10^{33} cm^{-2}s^{-1}).
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=> Analysis with these data is in progress and will be published shortly

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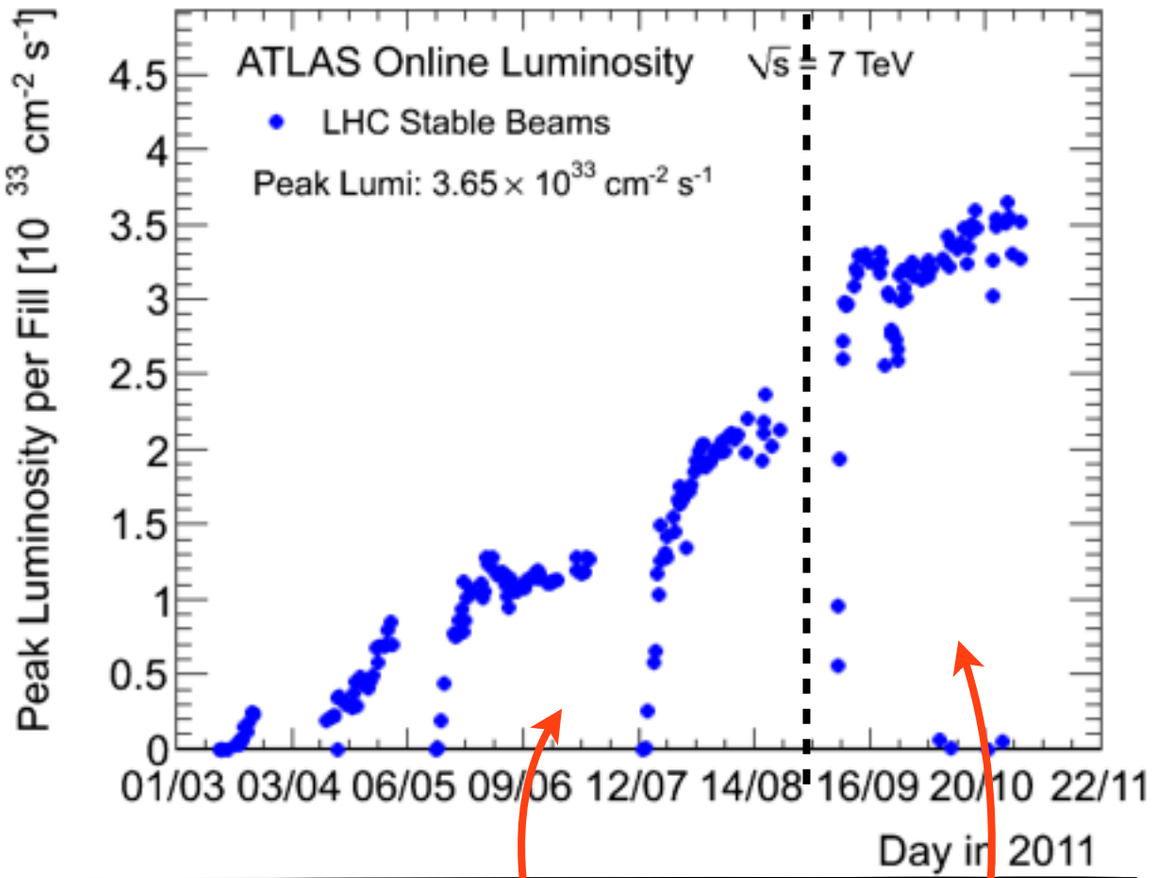

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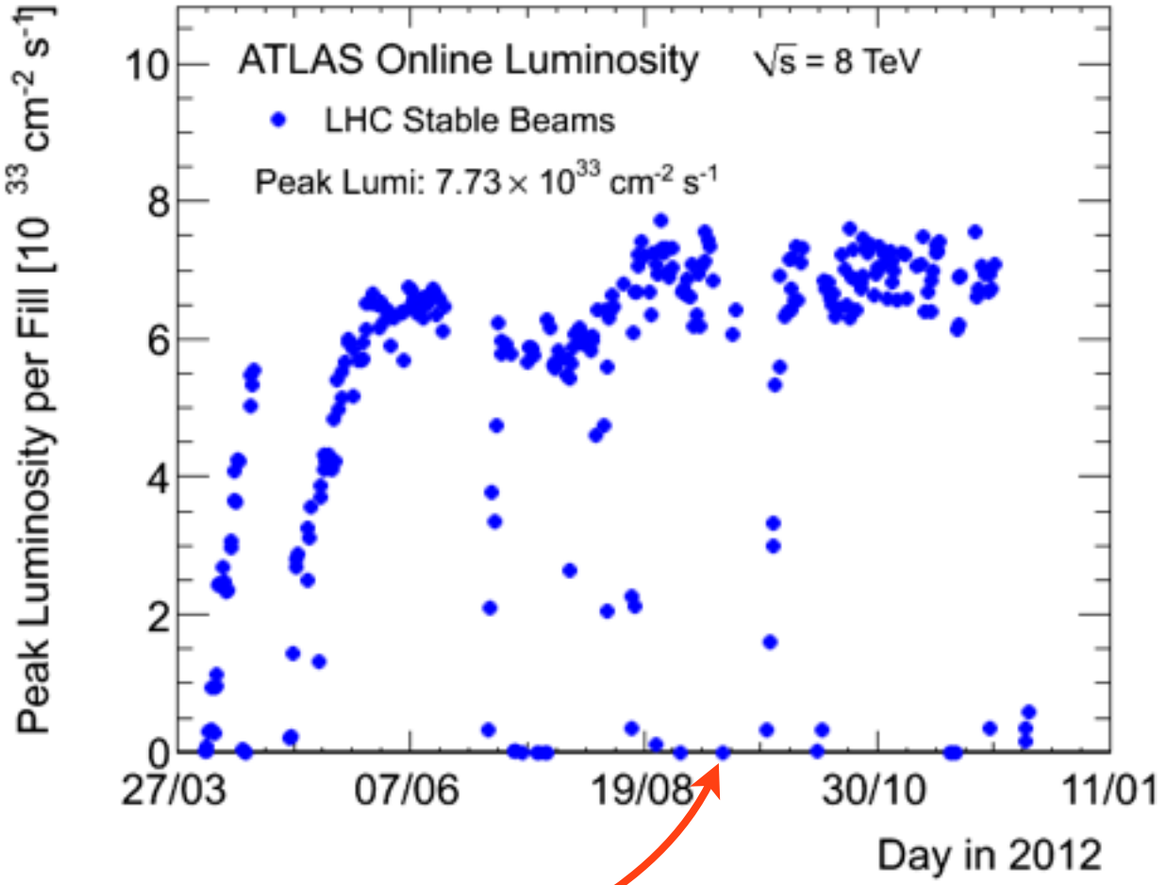

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New LVL.1 firmware configuration implemented and Barrel only trigger (both muon candidates are at barrel region) was prepared

This sample will be analyzed

Trigger performance is under investigation (designed to keep >90% efficiency at barrel region w.r.t. 2011 run)

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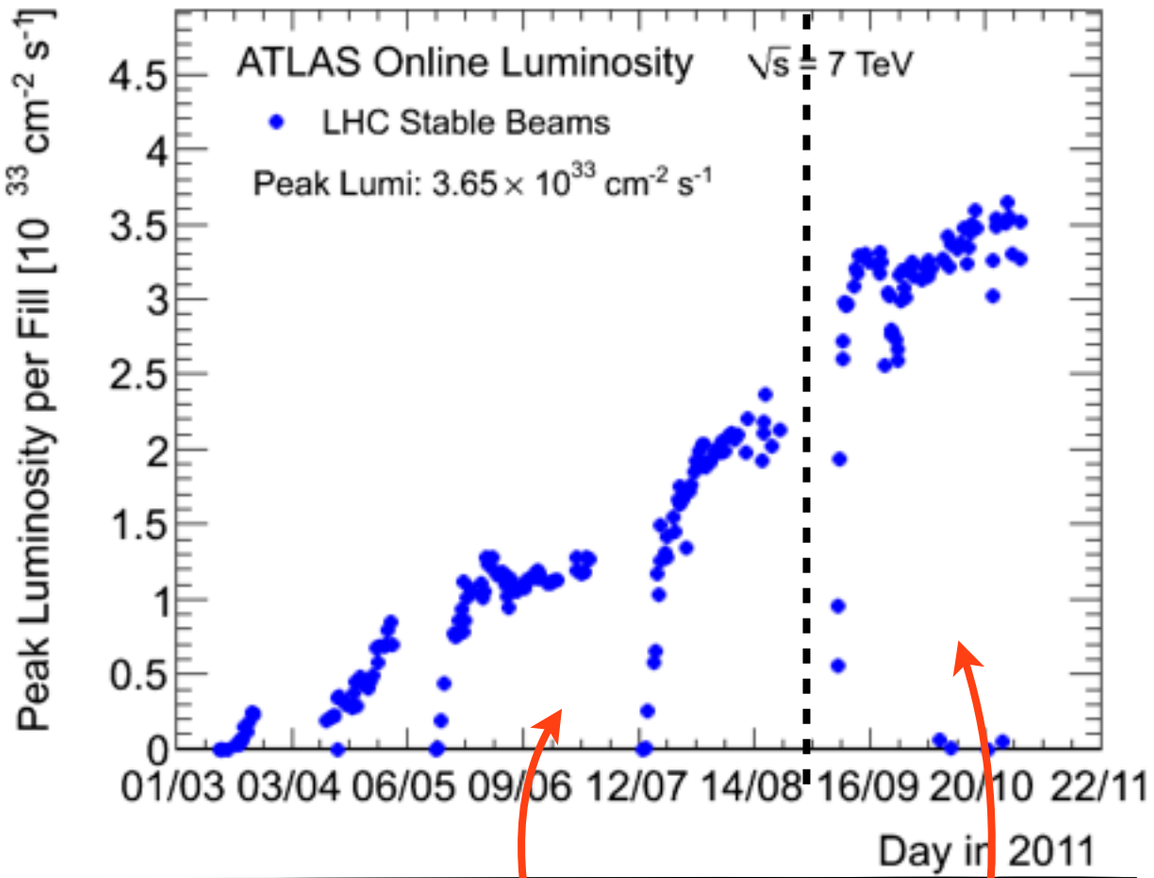

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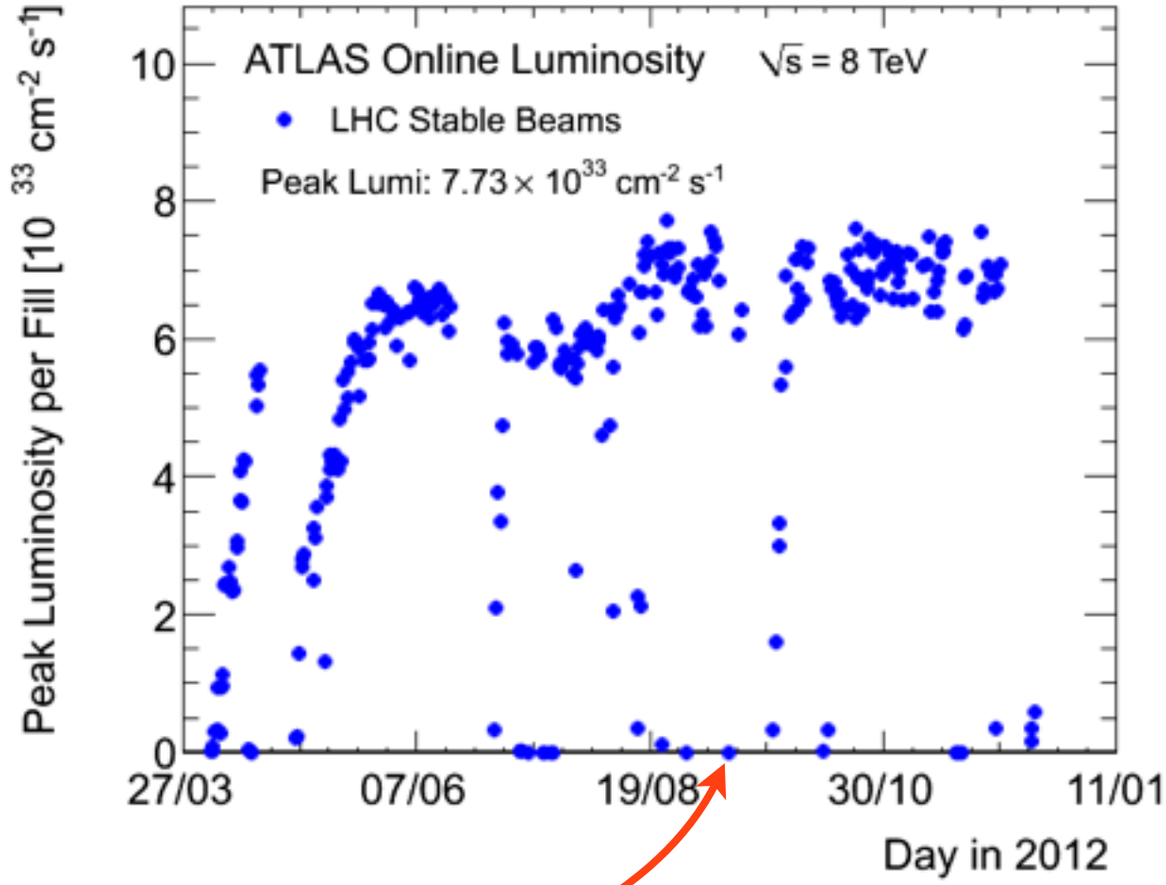

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We have dataset of ~5fb^{-1}@7TeV and ~20fb^{-1}@8TeV(barrel only)

Background modeling

- Two categories of background were considered:

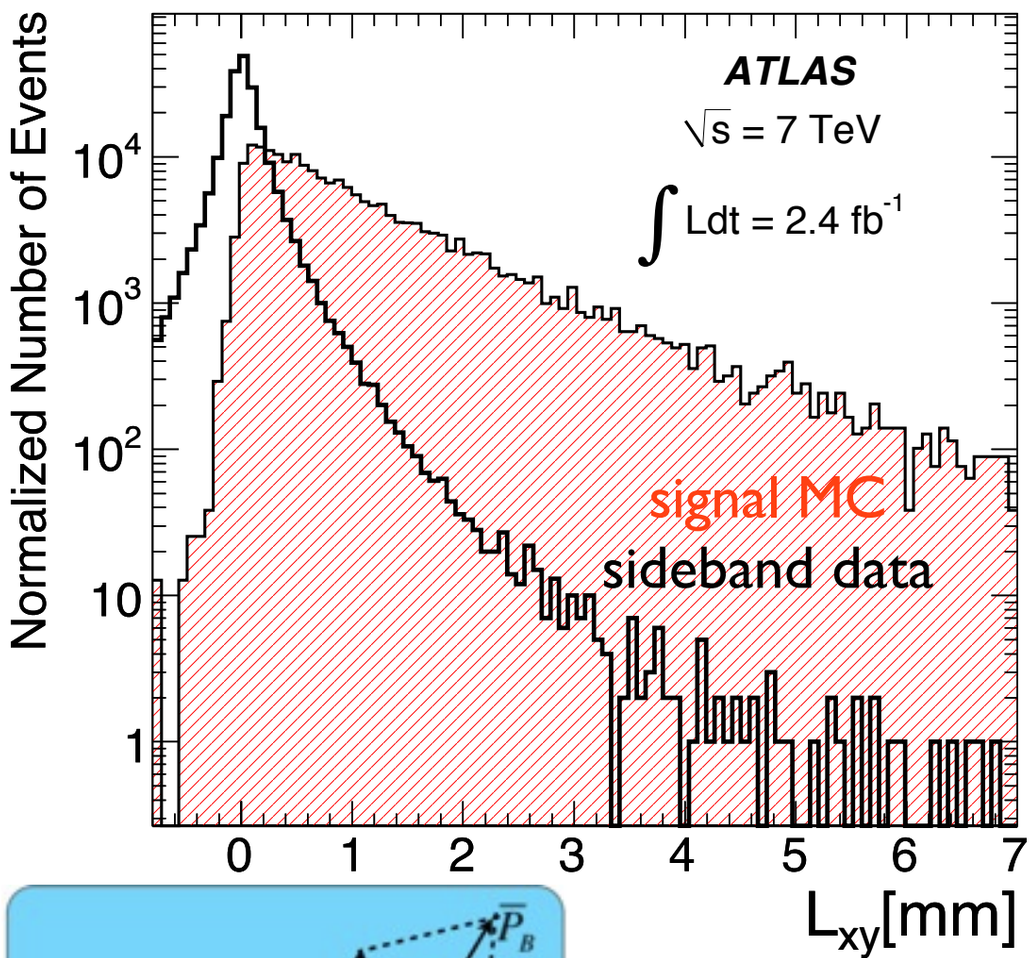
1. **Combinatorial b.g.**
   - Interpolated from sideband data (4% syst. uncertainty on scaling factor)
   - Distribution was confirmed to be reasonable by $bb \rightarrow \mu\mu X$ MC.
   - <u>Suppressed by BDT discrimination</u>

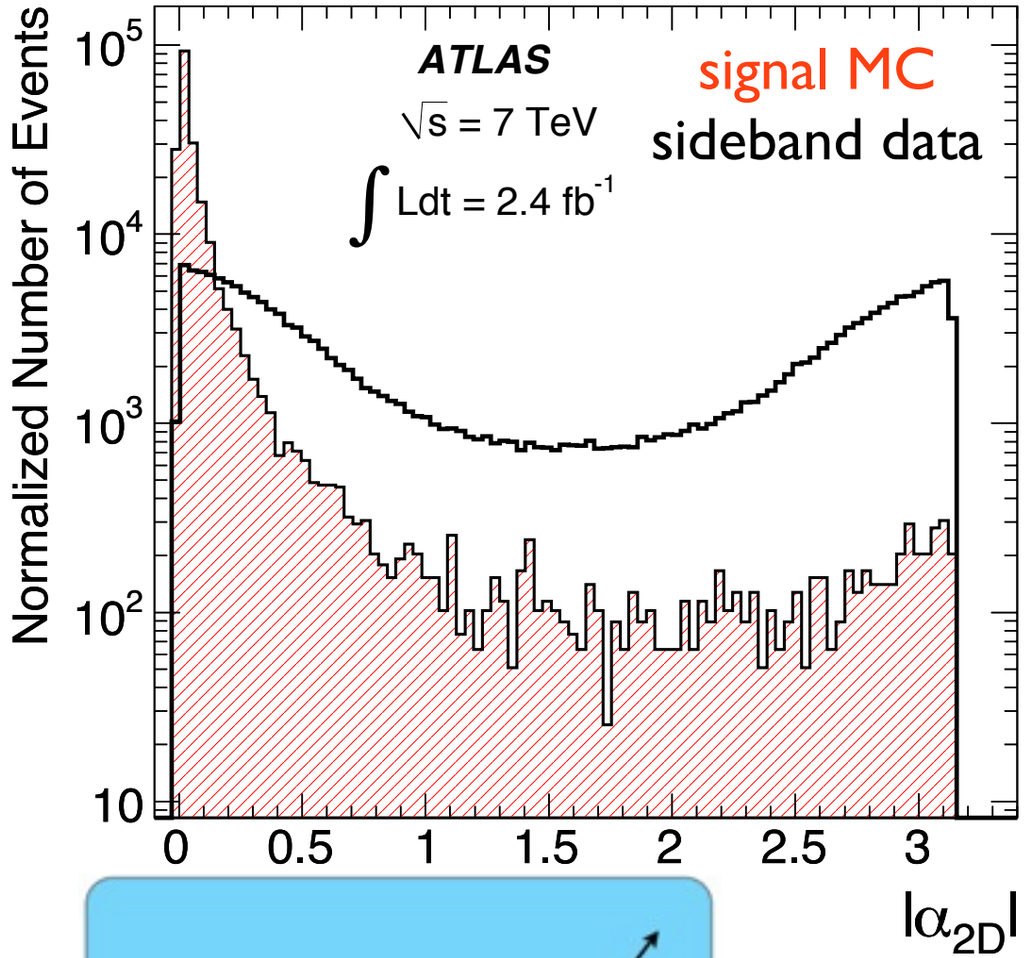
2. **Peaking b.g.**
   - mainly *B* decays with double mis-identified muons

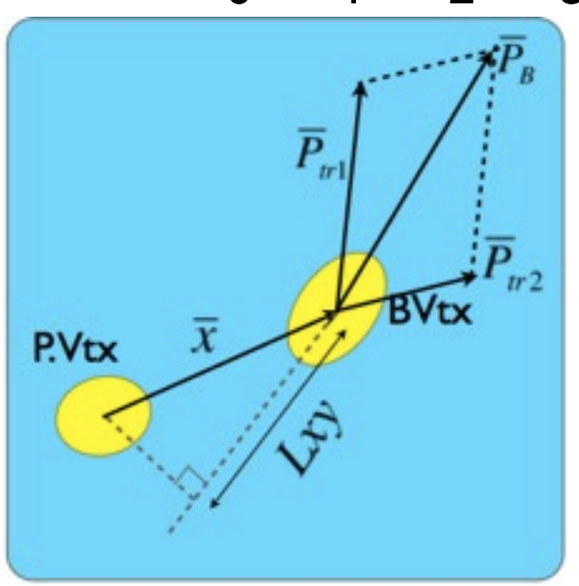
     e.g. $Bs \rightarrow K^+\mu^-\nu$, $Bs \rightarrow K^+\pi^-$, etc.
   - The probability to mis-identify hadrons to di-muon:
     4 (2)% for Kaon (pion) (20% relative uncertainty)
   - <u>Topology is very similar to signals</u>
     => not expect BDT discrimination
   - MC-base estimation (acceptance × efficiency × fake probability)

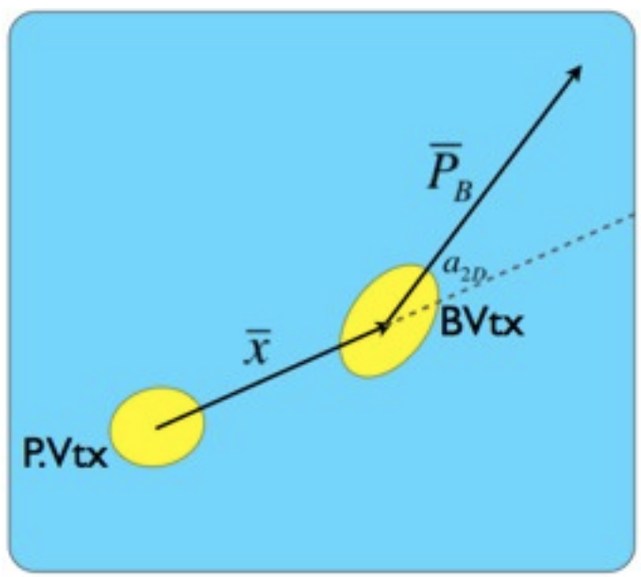
BDT inputs

- After pre-selection (brief kinematic cut on backup slide), 14 discriminating variables are selected as BDT inputs



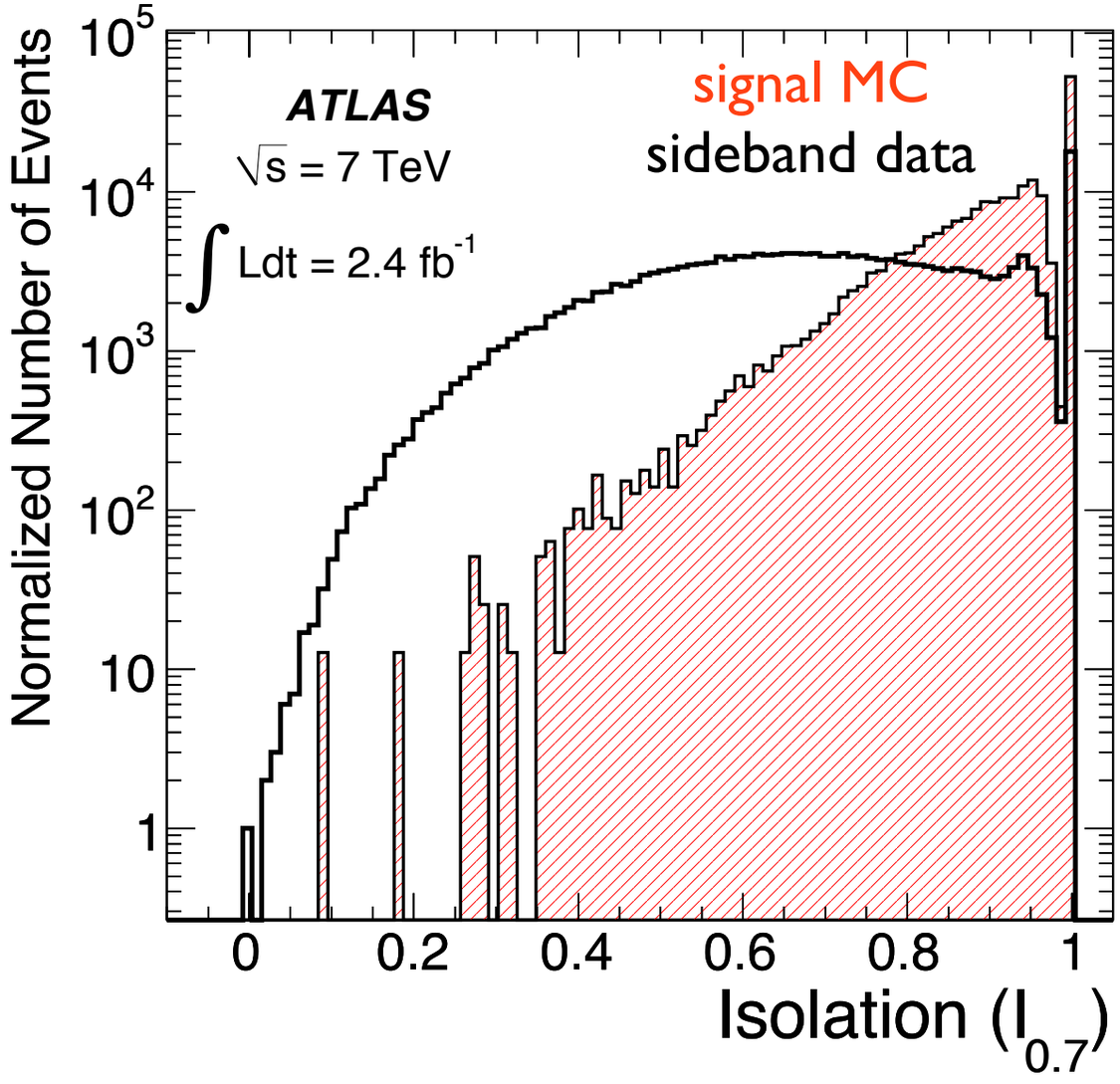




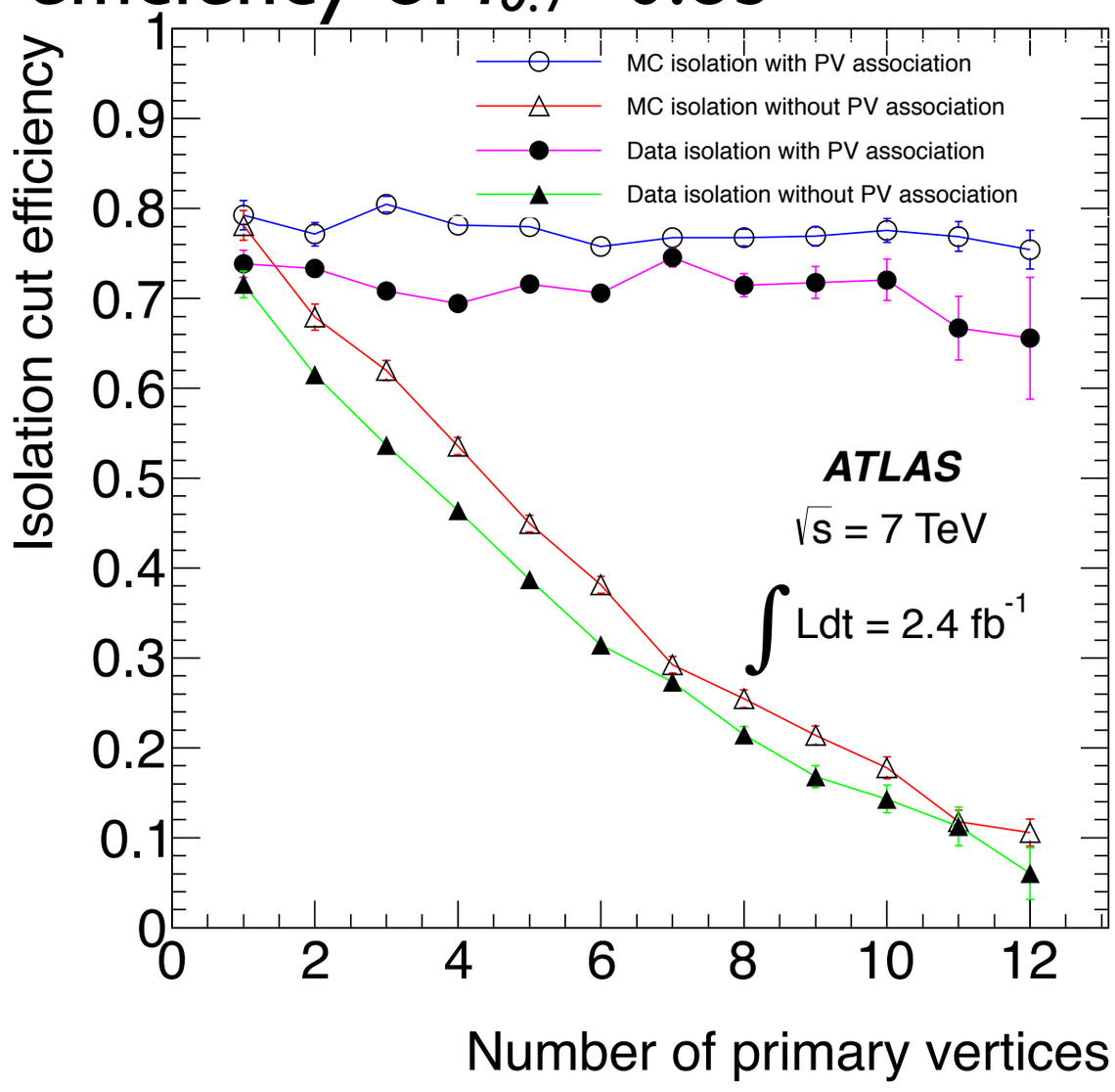


BDT inputs (cont'd)

- Isolation (ratio of B-p_T and sum of track-p_T in dR<0.7) has a largest pile-up dependency, so definition of $I_{0.7}$ is restricted only to use tracks from the primary vertex associated with B decay



efficiency of $I_{0.7}$>0.83

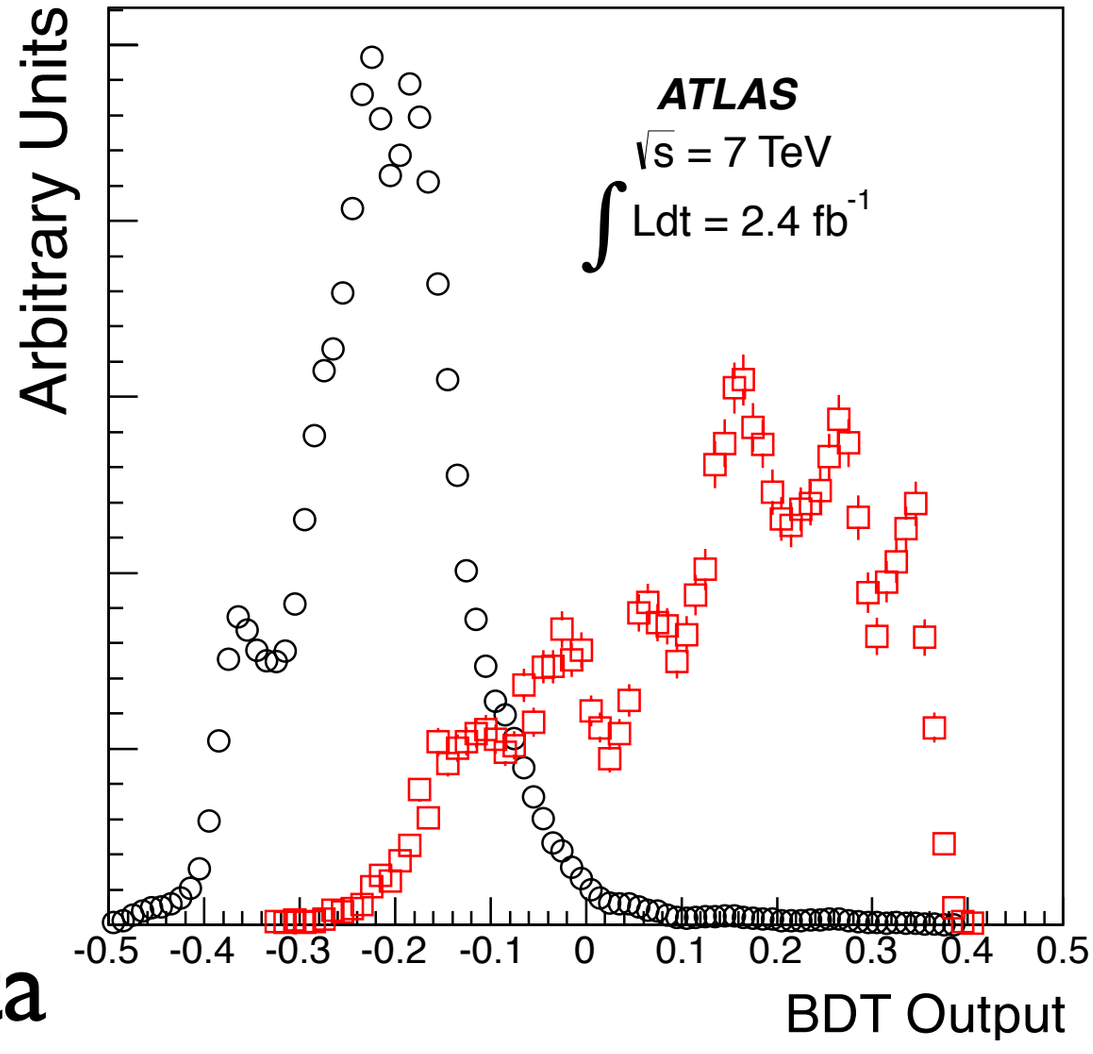


BDT output

- Three categories w.r.t. $|\eta|_{\max}$ (maximum pseudo-rapidity of muon candidate) according to difference of the mass resolutions
- Mass window and BDT thresholds: optimized **simultaneously** to maximize the sensitivity: $P = \frac{\epsilon_{\mathrm{sig}}}{1+\sqrt{N_{\mathrm{bkg}}}}$

$\lvert\eta\rvert_{\max}$ Range	0–1.0	1.0–1.5	1.5–2.5
invariant mass window [MeV]	±116	±133	±171
BDT output threshold	0.234	0.245	0.270

- BDT output is confirmed not depending on the invariant mass by using sideband data



signal MC

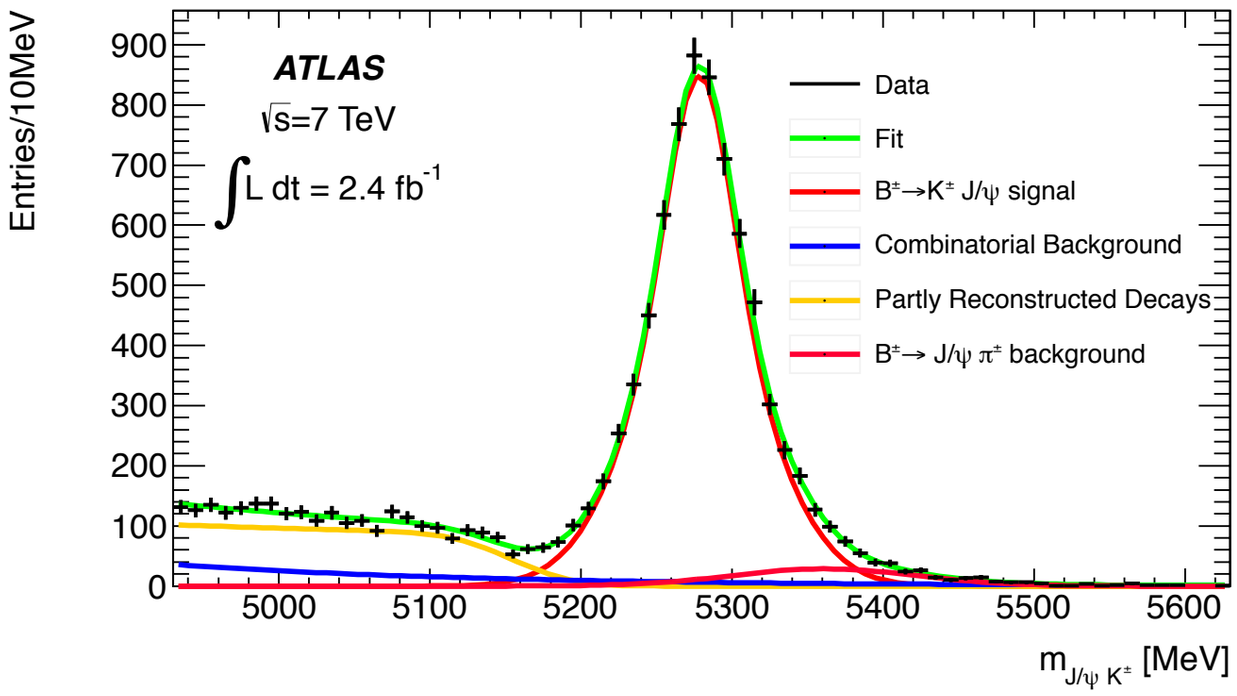
sideband data

$B^{\pm} \to J/\psi K^{\pm} \to \mu\mu K^{\pm}$ yield

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

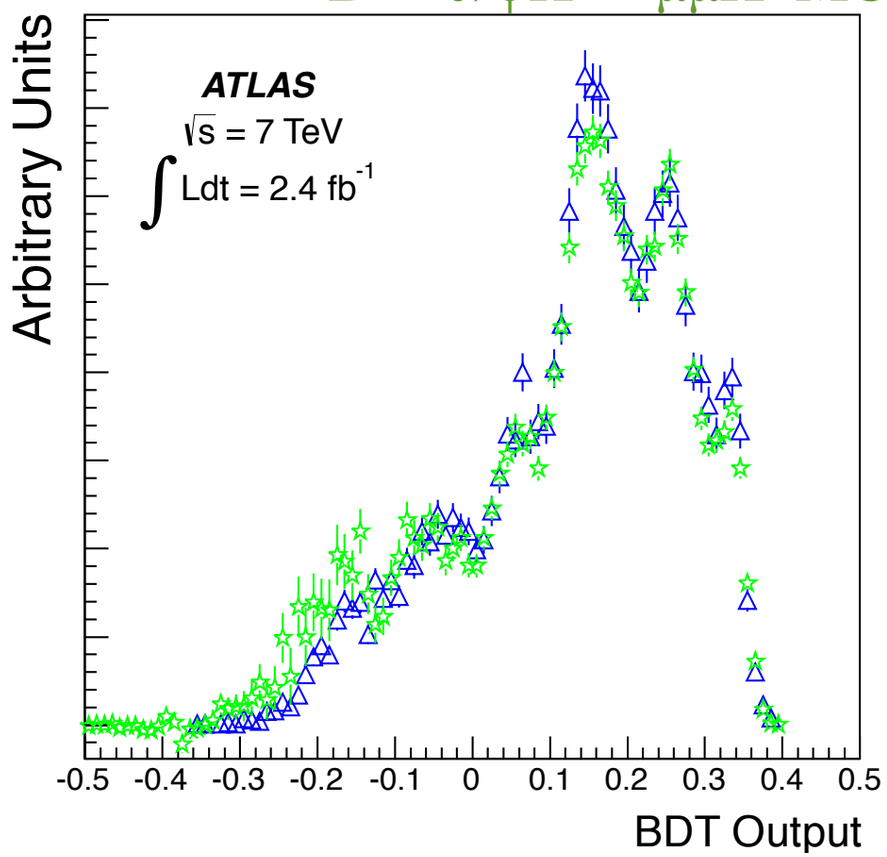
- Backgrounds for the reference channel: combinatorial b.g., partly reconstructed decays and $B^{\pm} \to J/\psi\pi^{\pm}$
- Apply binned likelihood fit and subtract them

$\lvert\eta\rvert_{\max}$ 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%



$B^{\pm} \to J/\psi K^{\pm} \to \mu\mu K^{\pm}$ yield after b.g. subtraction

$B^{\pm} \to J/\psi K^{\pm} \to \mu\mu K^{\pm}$ MC



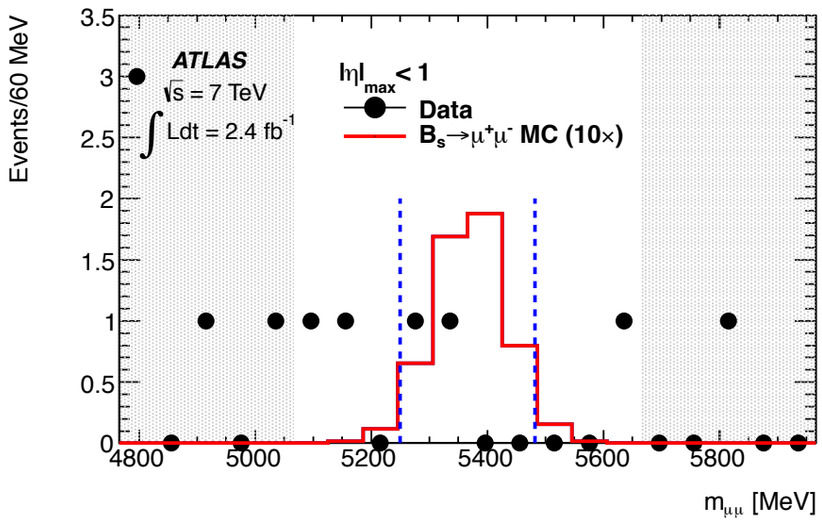
Acceptance and efficiency

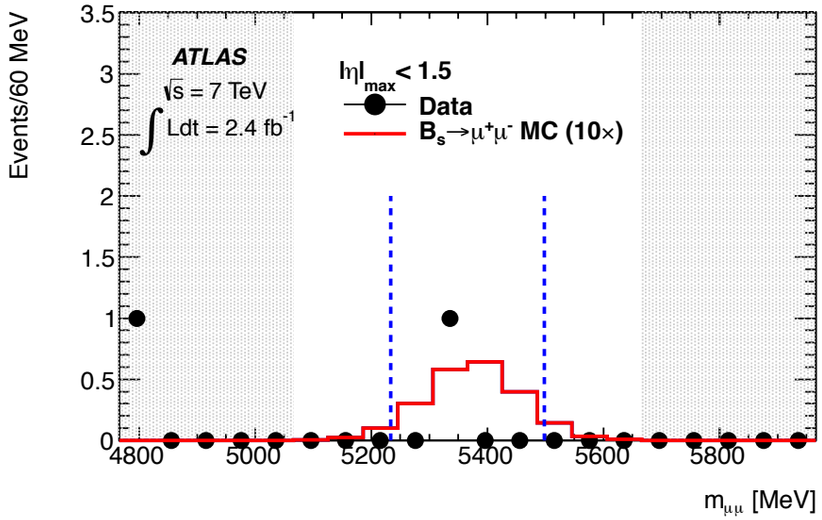
$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B^\pm \to J/\psi K^\pm \to \mu^+\mu^- K^\pm) \times \frac{f_u}{f_s} \times \frac{N_{\mu^+\mu^-}}{N_{J/\psi K^\pm}} \times \frac{A_{J/\psi K^\pm}}{A_{\mu^+\mu^-}} \frac{\epsilon_{J/\psi K^\pm}}{\epsilon_{\mu^+\mu^-}}, \quad (1)$$

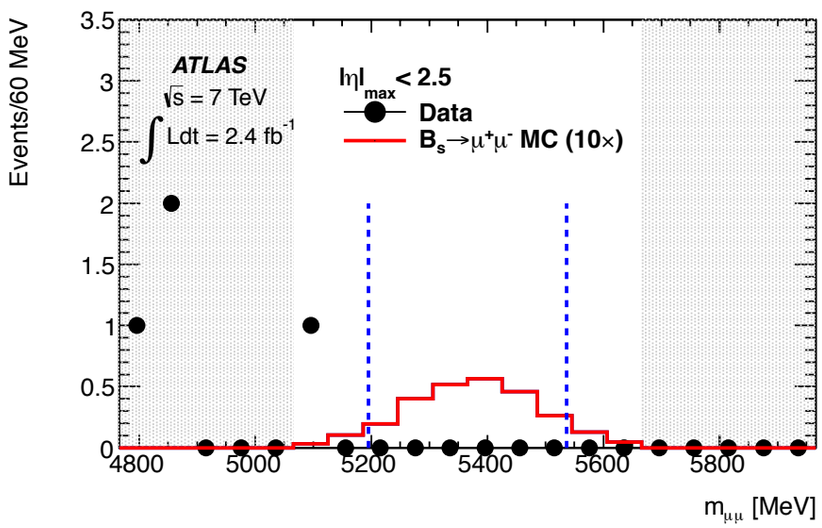
- $R_{A\varepsilon} = (A\varepsilon_{J/\psi K})/(A\varepsilon_{\mu\mu})$
  - relative acceptance × efficiency of ref. channel to signal channel
  - estimated by MC
  - Main systematic uncertainty comes from data/MC difference on BDT output (10-20% depending on mass resolution category)

$\lvert\eta\rvert_{\max}$ 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

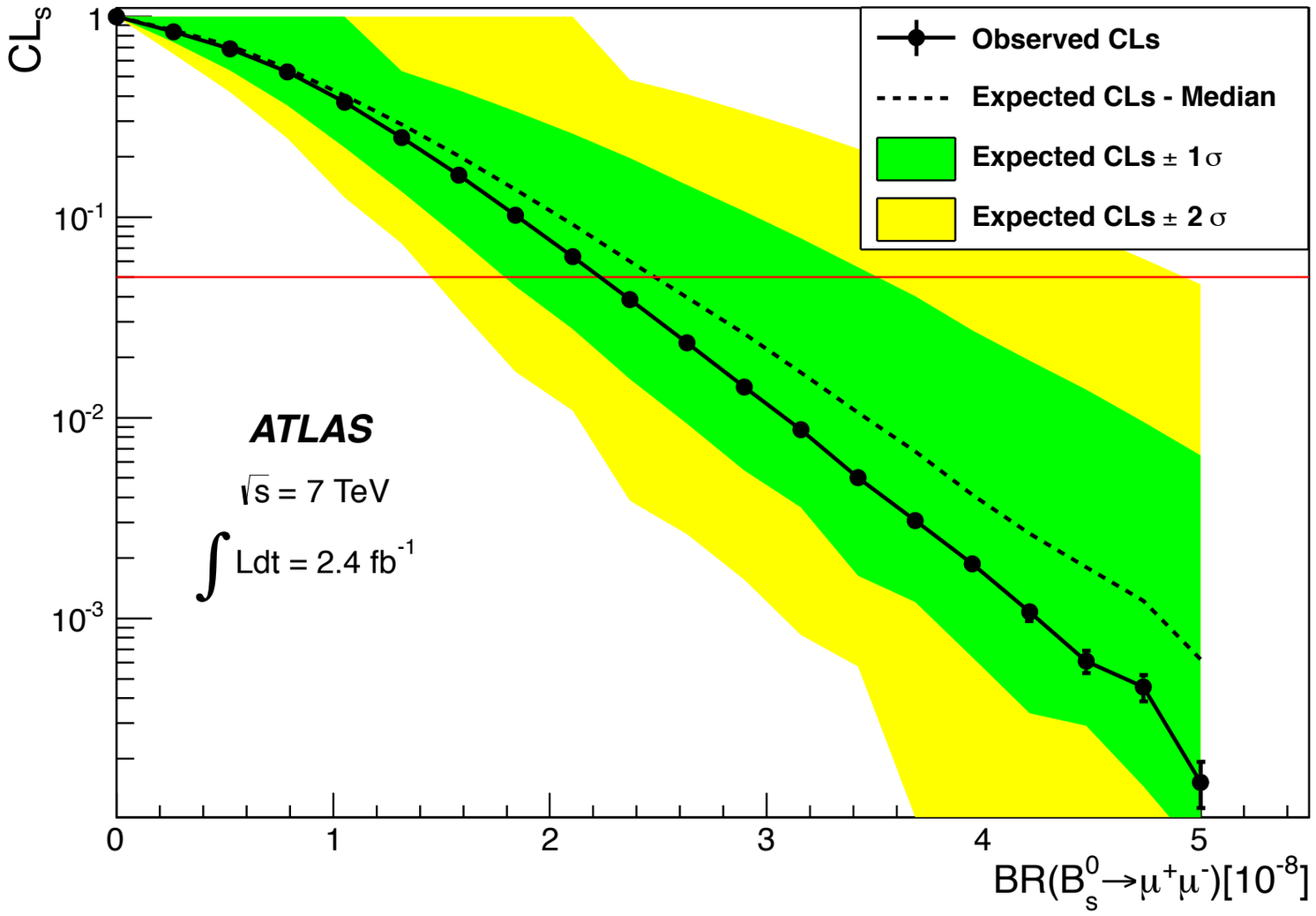
Results





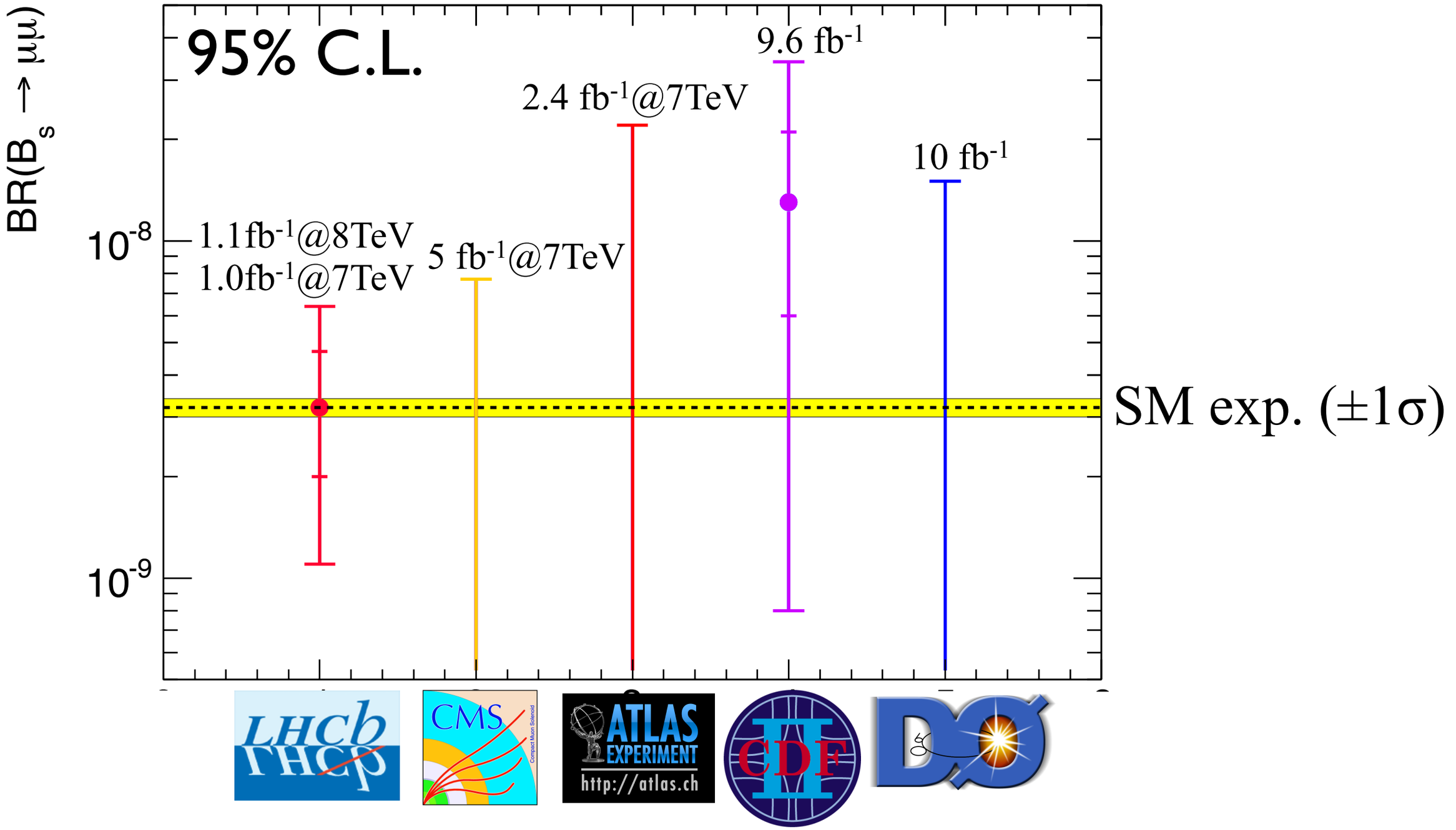


- Set limit on BR using CLs approach
- BR(Bs→μμ) < 2.2 × 10^{-8} (95% C.L.)



Comparison with the other experiments

- Current combine limit of ATLAS (2.4fb^{-1}), CMS(5fb^{-1}) and LHCb (1.0fb^{-1}) : $<4.2\times10^{-9}$



Summary

- The precise measurement of the branching ratio of Bs→μμ is a very sensitive for new physics
- BR(Bs→μμ) was measured with data corresponding to 2.4fb^{-1} collected with the ATLAS
- The measured upper limit on the branching fraction was 2.2×10^{-8} at 95% C.L.
- We will publish full-statistic analysis result of 7 TeV run (~5fb^{-1}) as soon as possible
- We collected ~20fb^{-1} un-prescaled sample of enriched barrel at 8 TeV run

backup

Pre-selection

- Trigger selection (Bs or J/ψ trigger including loose mass cut)
- Inner detector quality cut
- Both muons satisfy $|\eta_{trk}| < 2.5$ and $p_{T,trk}>4$ GeV; Kaon track in the reference channel satisfy $|\eta_{trk}| < 2.5$ and $p_{T,trk}>2.5$ GeV.
- Vertex fitting $\chi^2/ndf<2.0$ for $Bs\rightarrow\mu\mu$ candidate and <6.0 for the other channel
- $p_{T,B} > 8$GeV and $|\eta_B|<2.5$
- $(2915 < m_{J/\psi} < 3175$ MeV)
- The primary vertex was reconstructed by fitting tracks without B decay daughters (if multiple primary vertex are found, the closest one in *z*-axis with decay vertex is selected)

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

N_{events} after preselection

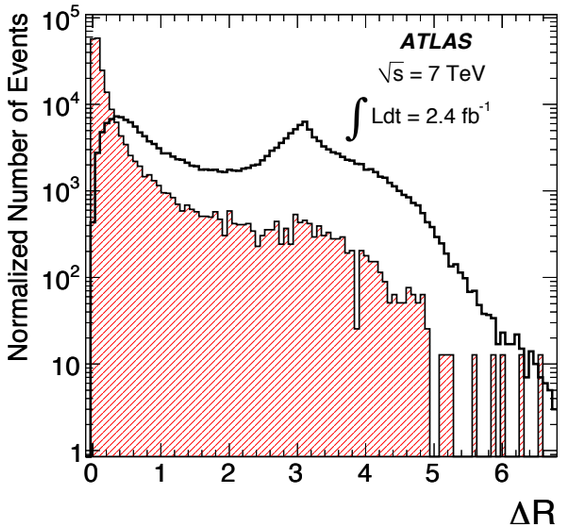
2×10^5

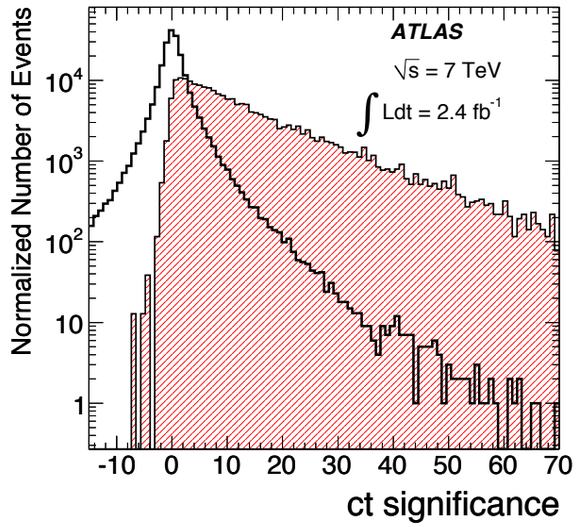
1.4×10^5

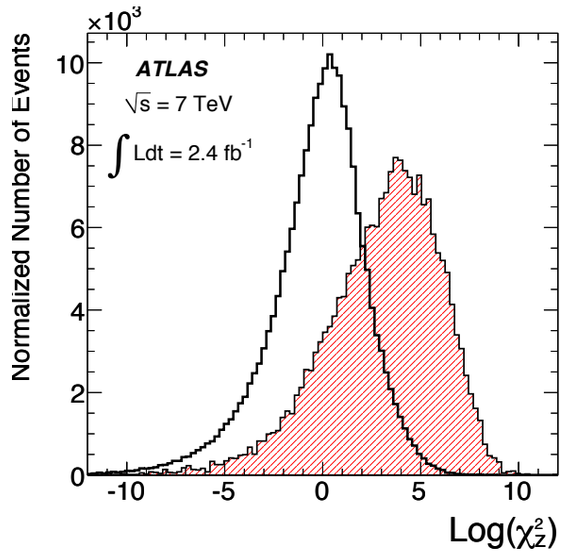
BDT input details

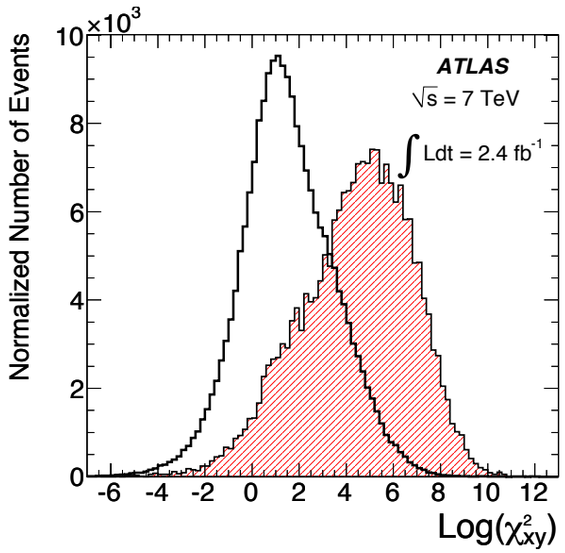
Variable	Description
$\lvert\alpha_{\mathrm{2D}}\rvert$ pointing angle	Absolute value of the angle in the transverse plane between $\Delta\vec{x}$ and $\vec{p}^{B}$
ΔR	Angle $\sqrt{(\Delta\phi)^2+(\Delta\eta)^2}$ between $\Delta\vec{x}$ and $\vec{p}^{B}$
L_{xy}	Scalar product in the transverse plane of $(\Delta\vec{x}\cdot\vec{p}^{B})/\lvert\vec{p}^{B}_{\mathrm{T}}\rvert$
ct significance	Proper decay length $ct = L_{\mathrm{xy}}\times m_B/p^{B}_{\mathrm{T}}$ divided by its uncertainty
χ^2_{xy}, χ^2_{z}	Vertex separation significance $\Delta\vec{x}^{\,T}\cdot\left(\sigma^2_{\Delta\vec{x}}\right)^{-1}\cdot\Delta\vec{x}$ in (x,y) and z, respectively
$I_{0.7}$ isolation	Ratio of $\lvert\vec{p}^{B}_{\mathrm{T}}\rvert$ to the sum of $\lvert\vec{p}^{B}_{\mathrm{T}}\rvert$ and the transverse momenta of all tracks with $p_{\mathrm{T}} > 0.5$ GeV within a cone $\Delta R < 0.7$ from the B direction, excluding B decay products
$\lvert d_0^{\mathrm{max}}\rvert$, $\lvert d_0^{\mathrm{min}}\rvert$	Absolute values of the maximum and minimum impact parameter in the transverse plane of the B decay products relative to the primary vertex
$\lvert D^{\mathrm{min}}_{\mathrm{xy}}\rvert$, $\lvert D^{\mathrm{min}}_{\mathrm{z}}\rvert$	Absolute values of the minimum distance of closest approach in the xy plane (or along z) of tracks in the event to the B vertex
p^{B}_{T}	B transverse momentum
$p^{\mathrm{max}}_{\mathrm{L}}$, $p^{\mathrm{min}}_{\mathrm{L}}$	Maximum and minimum momentum of the two muon candidates along the B direction

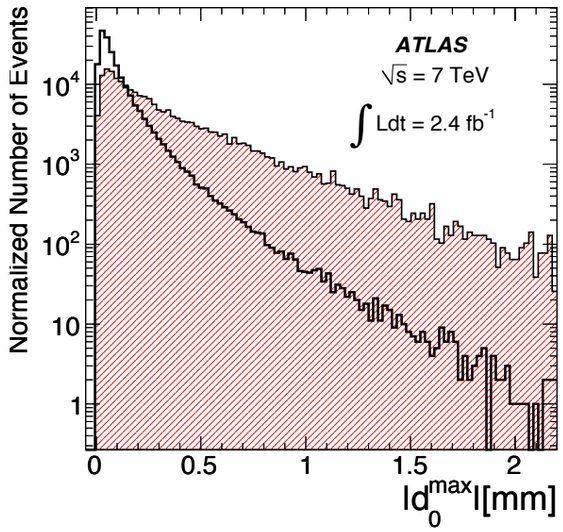
The other distributions for BDT input

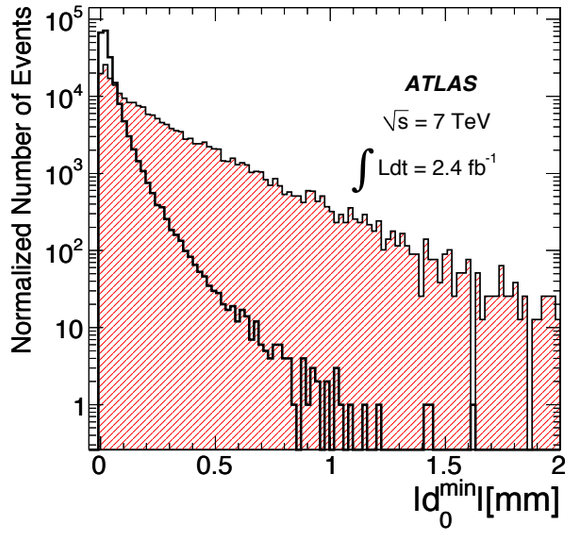


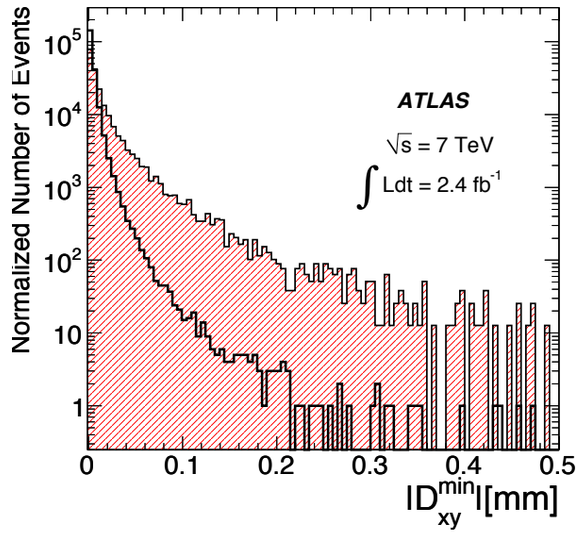


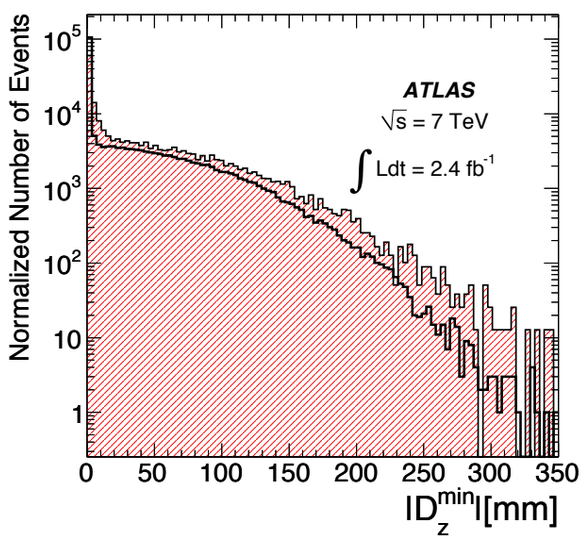


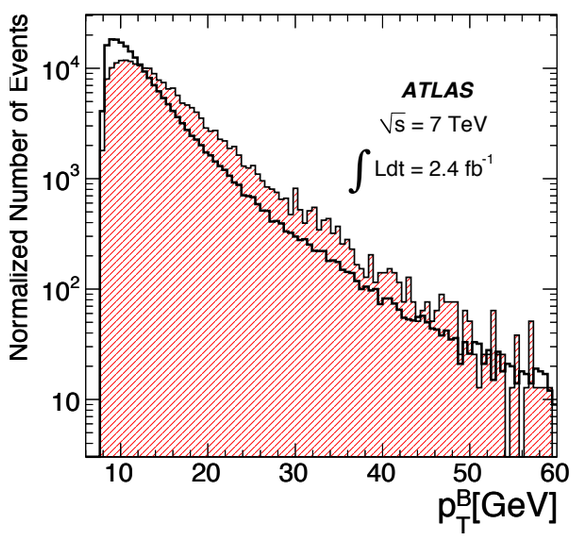


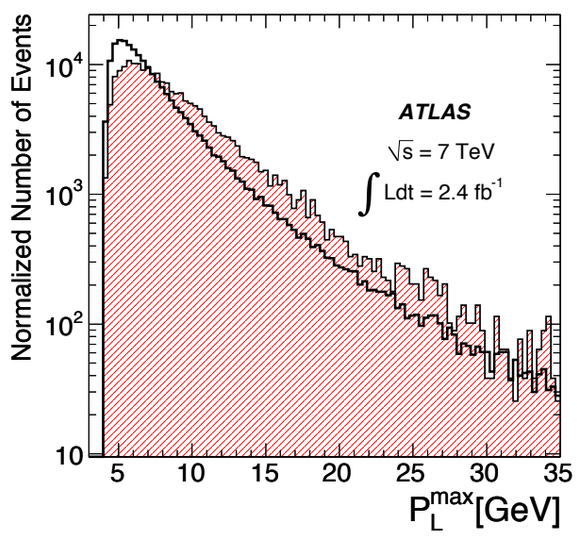


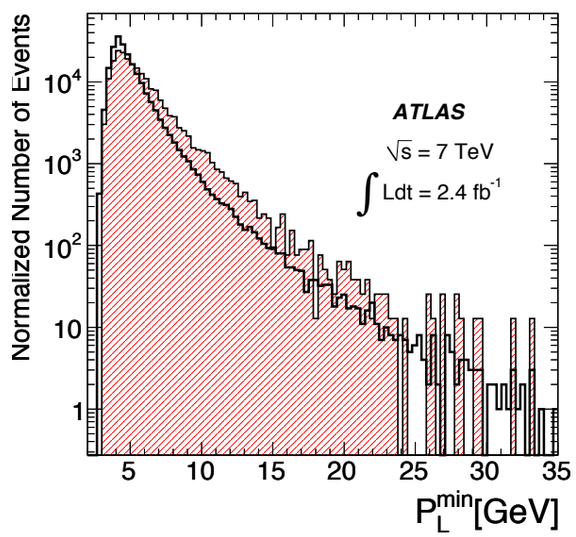






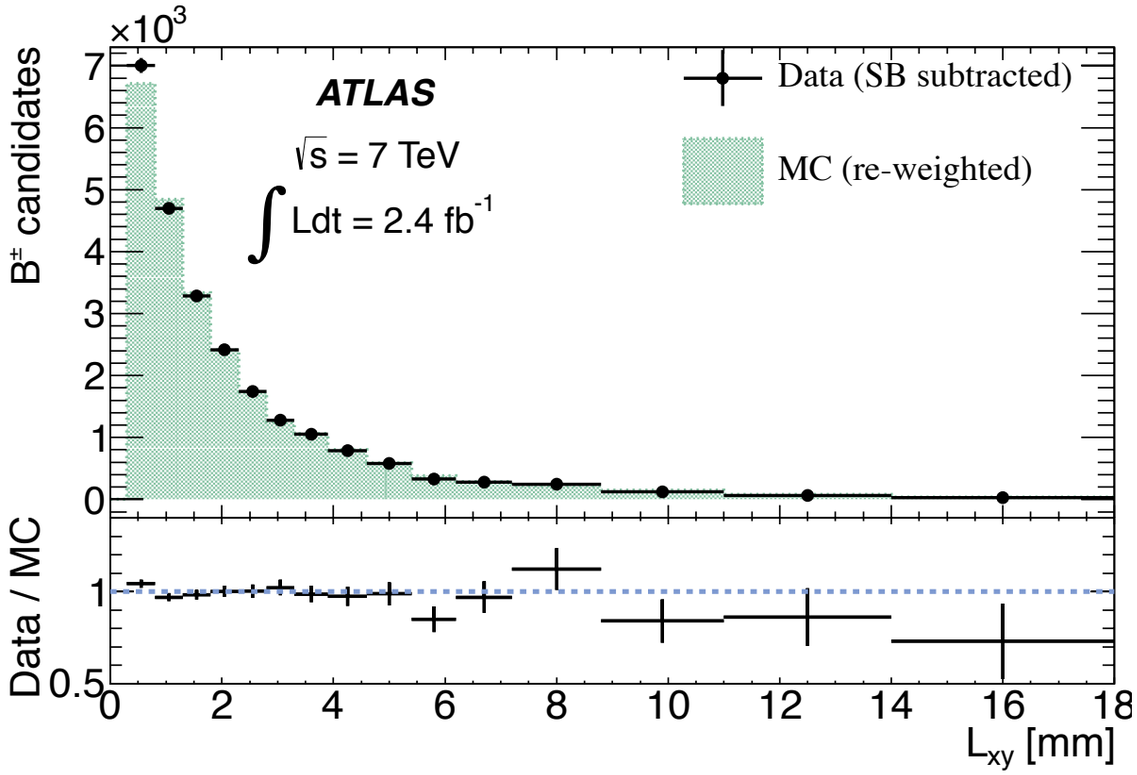


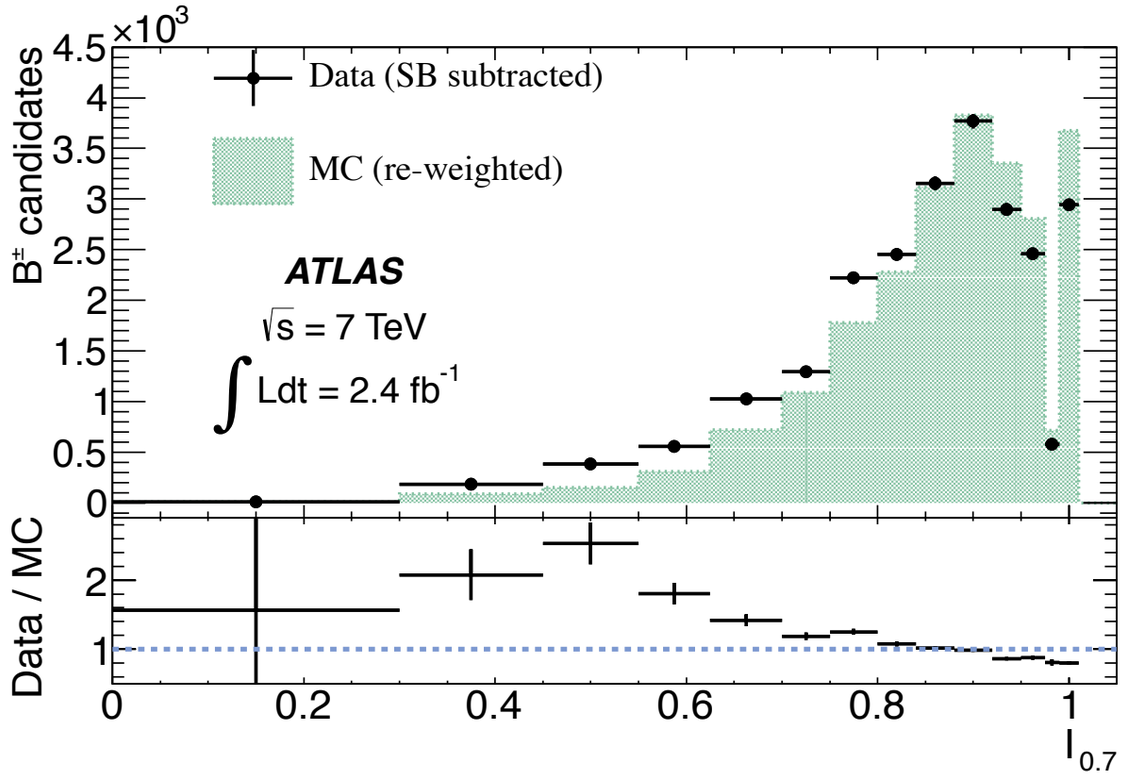




MC re-weighting

- Generator level + Data-driven reweighting





Likelihood for CLs calculation

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

Comparison with the other experiments

		$BR\left(B^0 \to \mu^+\mu^-\right)$	$BR\left(B_s^0 \to \mu^+\mu^-\right)$
LHCb	1.1 fb^{-1}(8TeV) 1.0 fb^{-1}(7TeV)	<9.4×10^{-10}	[1.1, 6.4]×10^{-9} $(3.2^{+1.5}_{-1.2})\times10^{-9}$
CMS	5 fb^{-1}(7TeV)	<1.8×10^{-9}	<7.7×10^{-9}
ATLAS	2.4 fb^{-1}(7TeV)	-	<2.2×10^{-8}
CDF	9.6 fb^{-1}	<4.6×10^{-9}	[0.8, 34]×10^{-9} $(1.3^{+0.9}_{-0.7})\times10^{-8}$
DØ	10 fb^{-1}	-	<1.5×10^{-8}
BELLE	78fb^{-1}	<1.6×10^{-8}	-
BABAR	347fb^{-1}	<8.3×10^{-9}	-

Current combine limit of ATLAS(2.4fb^{-1}),
CMS(5fb^{-1}) and LHCb (1.0fb^{-1}) : <4.2×10^{-9}