Rare *B* decays and processes with the ATLAS detector

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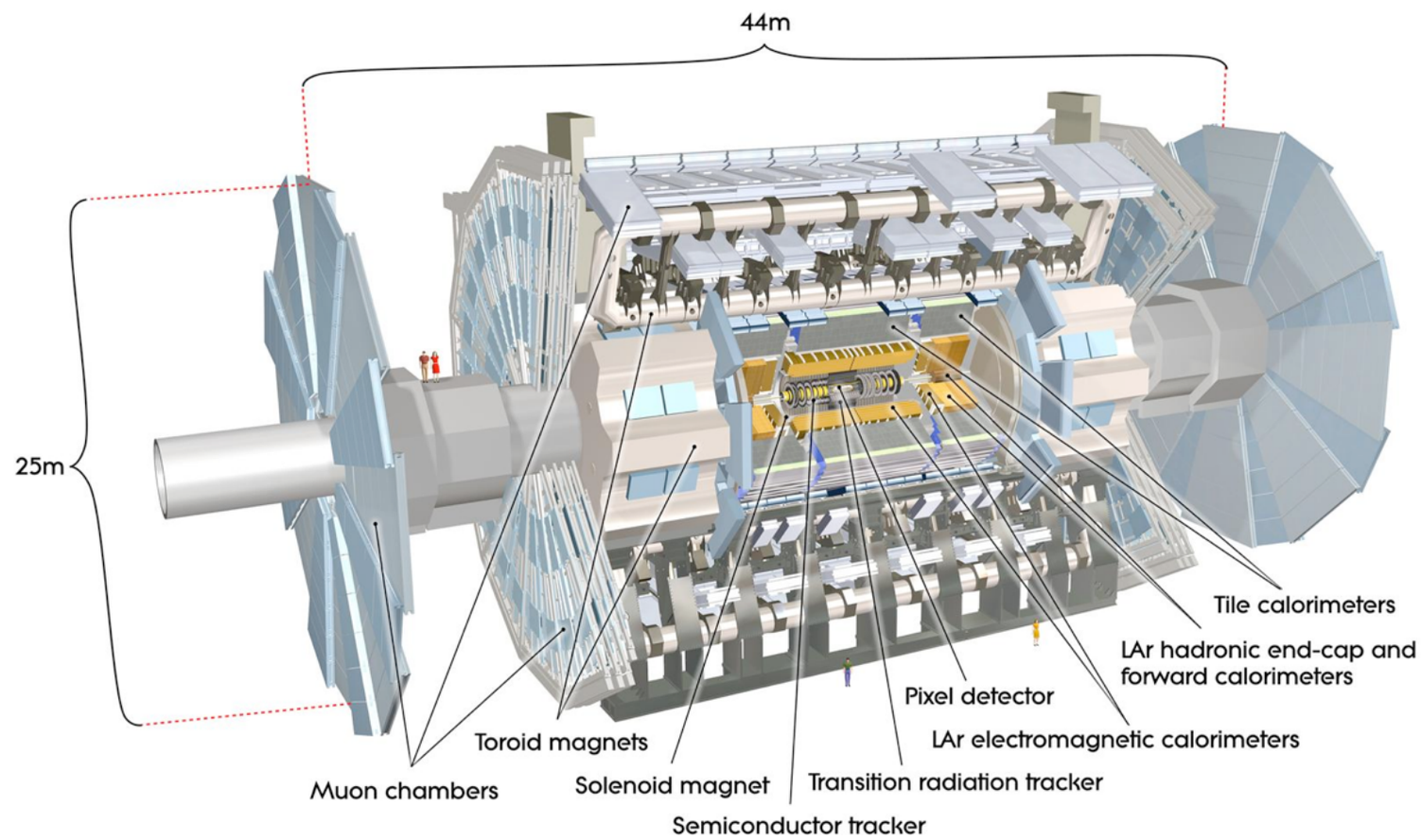
Outline

- ATLAS detector
- First measurement of associated vector boson plus prompt charmonium production at the ATLAS experiment
- Search for $B_s \rightarrow \mu^+\mu^-$ rare decay
- Conclusions

The ATLAS detector

- General purpose detector at the LHC
  - Tracking
    - Silicon (Pixel+SemiConductor Tracker) and Transition Radiation Tracker
    - 2 T solenoidal field
- Muon identification:
  - Dedicated tracking chambers
  - 0.5-2T toroidal field



- Neutrinos
  - Not detected
  - Imbalance of transverse momentum

Associated vector boson plus prompt charmonium production

Introduction

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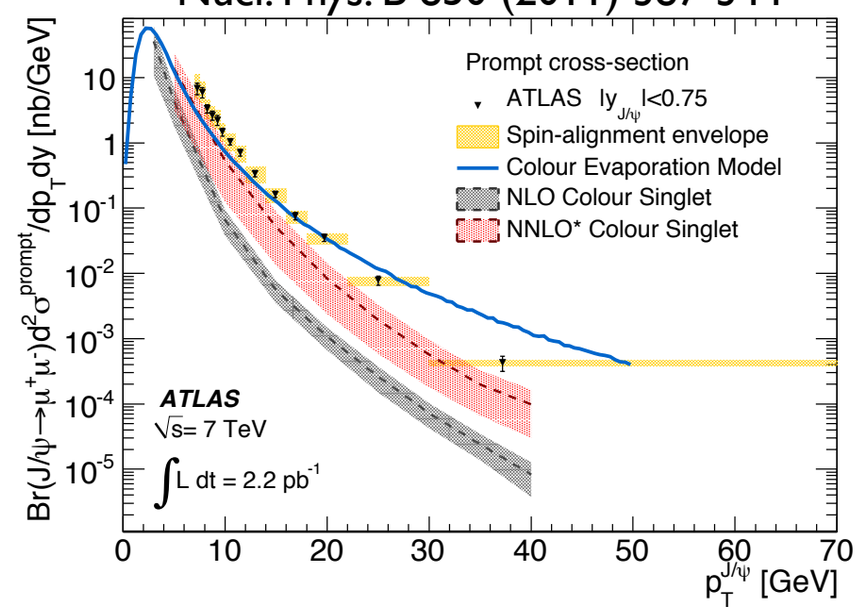
- J/ψ meson is a bound state of $c\bar{c}$
- Production mechanism of prompt J/ψ not well understood
- Production mechanisms:
  - Colour singlet process (CS): quarkonia produced is determined by the state of the original quarks
  - Colour octet process (CO): proposes that the quark pairs produced by the hard process are not produced with the quantum numbers of the physical quarkonia but evolve into the quarkonia state through radiation of soft gluons.

Nucl. Phys. B 850 (2011) 387-344



- $W^\pm$ + prompt J/ψ is a quark-initiated process with different production mechanisms than the inclusive J/ψ
- Possible scenarios considered prior to ATLAS measurement
  - being dominated by CO processes → test of NRQCD (Phys.Rev. D66 (2002) 114002)
- First measurement of the associated production of $W^\pm$ + prompt J/ψ (arxiv.org/1401.2831)
  - $W^\pm \to \mu\nu_\mu$ and $J/\psi \to \mu\mu$ with ATLAS detector at $\sqrt{s}$ = 7 TeV

Associated vector boson plus prompt charmonium production

Data analysis

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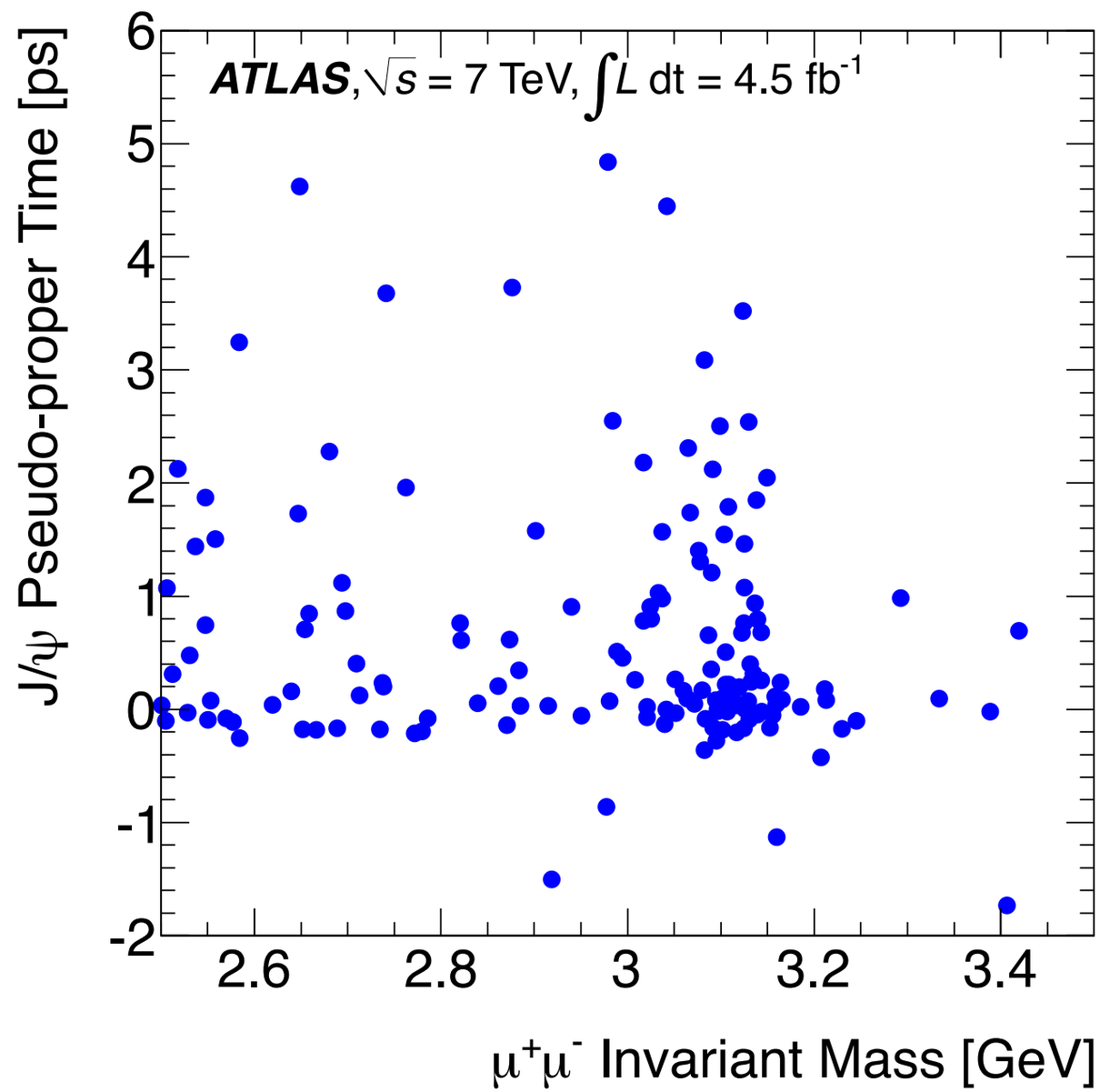
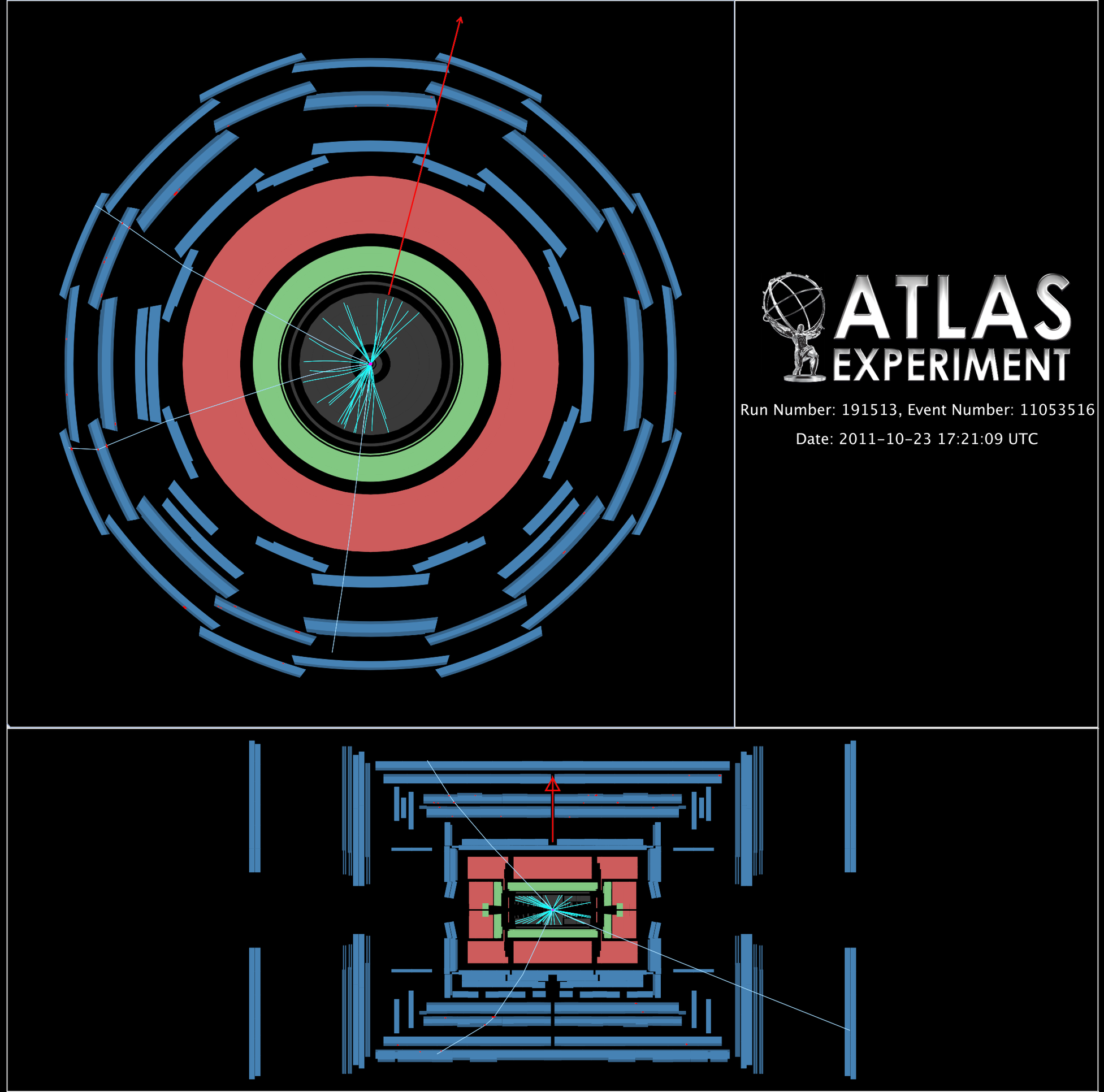
- 2011 dataset, 4.5 fb^{-1} of $\sqrt{s}$ = 7 TeV pp collisions
- Single muon trigger p_T>18 GeV
- $J/\psi \rightarrow \mu^+\mu^-$
  - p_T^{μ} >3.5 (2.5) GeV with $|\eta|$<1.3 (>1.3)
  - common vertex
  - invariant mass 2.5 < $m_{\mu\mu}$ < 3.5 GeV
  - 8.5 < $p_T^{J/\psi}$ < 30 GeV and $|y_{J/\psi}|$<2.1
- $W^{\pm} \rightarrow \mu\nu_{\mu}$
  - isolated muon p_T > 25 GeV and $|\eta|$<2.4
  - missing transverse energy > 20 GeV
  - transverse mass of the $W^{\pm}$ boson > 40 GeV
- Closest distance of the W muon to the PV to be within 1mm in z
- W decay muon to have transverse impact parameter significance $d0/\sigma(d_0)$<3
- Remove events with $|m_{\mu\mu}-m_z|$<10 GeV




ATLAS
EXPERIMENT
Run Number: 191513, Event Number: 11053516
Date: 2011-10-23 17:21:09 UTC

Associated vector boson plus prompt charmonium production

Extraction of prompt J/ψ component

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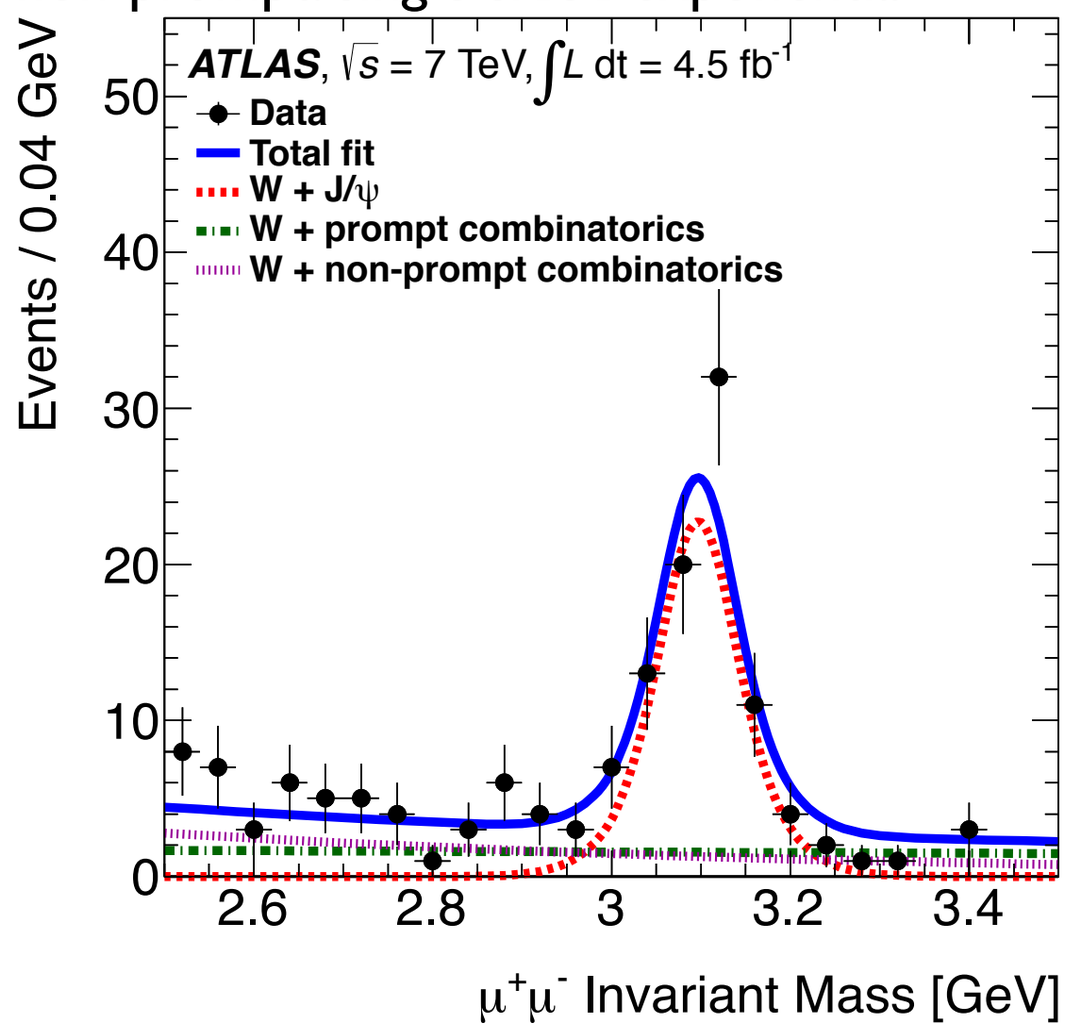
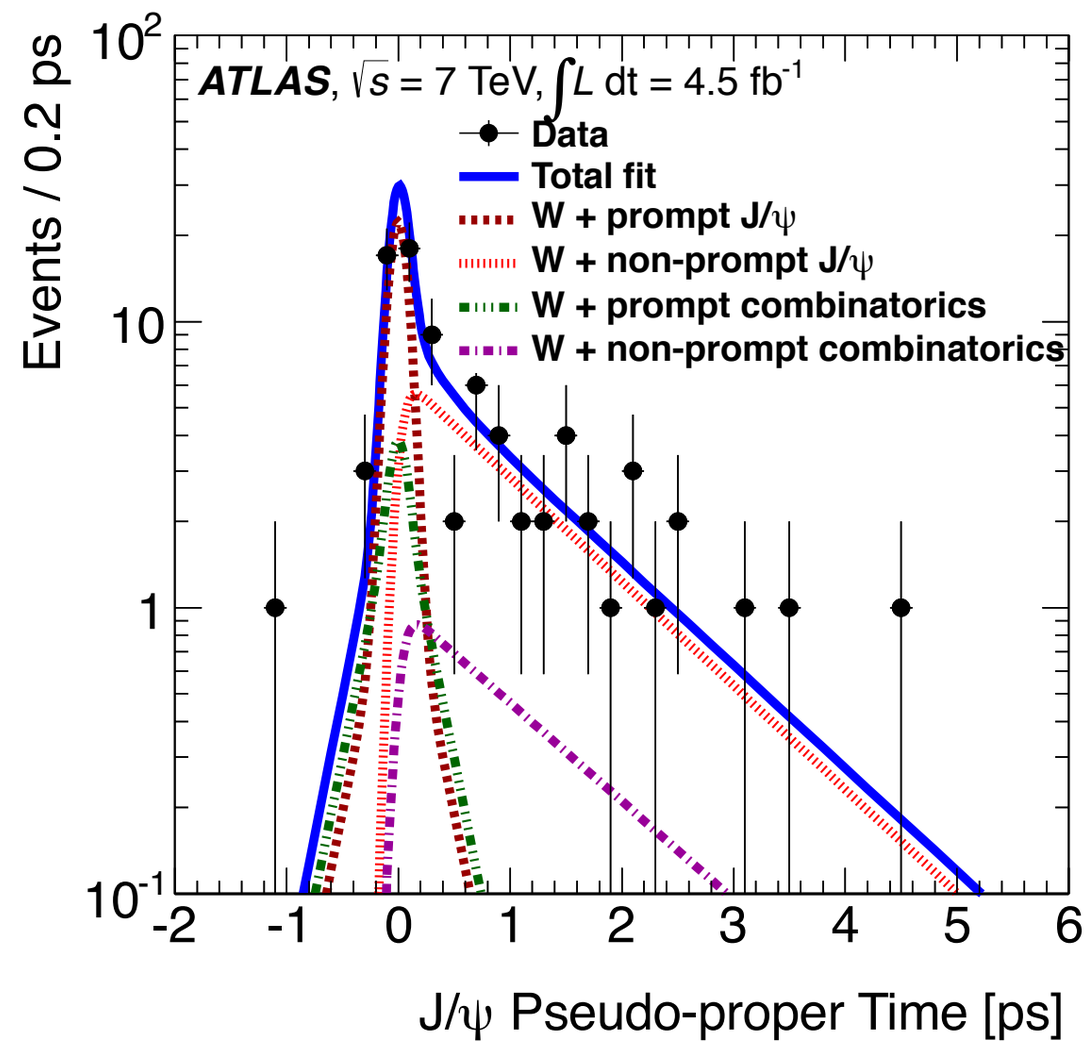
- 2D unbinned maximum likelihood fit in J/ψ invariant mass and pseudo-proper time
- Mass
  - signal: gaussian
  - background: exponential
- Pseudo-proper time
  - prompt: gaussian + double sided exponential
  - non-prompt: single sided exponential

shape parameters taken from a fit in an inclusive J/ψ sample from data





Associated vector boson plus prompt charmonium production

Extraction of prompt J/ψ component

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Yields from two-dimensional fit			
Process	Barrel	Endcap	Total
Prompt J/ψ	$10.0^{+4.7}_{-4.0}$	$19.2^{+5.8}_{-5.1}$	$29.2^{+7.5}_{-6.5}(*)$
Non-prompt J/ψ	$27.9^{+6.5}_{-5.8}$	$13.9^{+5.3}_{-4.5}$	$41.8^{+8.4}_{-7.3}$
Prompt background	$20.4^{+5.9}_{-5.1}$	$18.8^{+6.3}_{-5.3}$	$39.2^{+8.6}_{-7.3}$
Non-prompt background	$19.8^{+5.8}_{-4.9}$	$19.2^{+6.1}_{-5.1}$	$39.0^{+8.4}_{-7.1}$
p-value	8.0×10^{-3}	1.4×10^{-6}	2.1×10^{-7}
Significance (σ)	2.4	4.7	5.1

extract m_T^W events based on the prompt J/ψ yield using sPlot

p-value evaluated with pseudo-experiments with B-only hypothesis to determine how often it fluctuates to S+B hypothesis

Associated vector boson plus prompt charmonium production

$W^{\pm}$ events associated with prompt J/ψs

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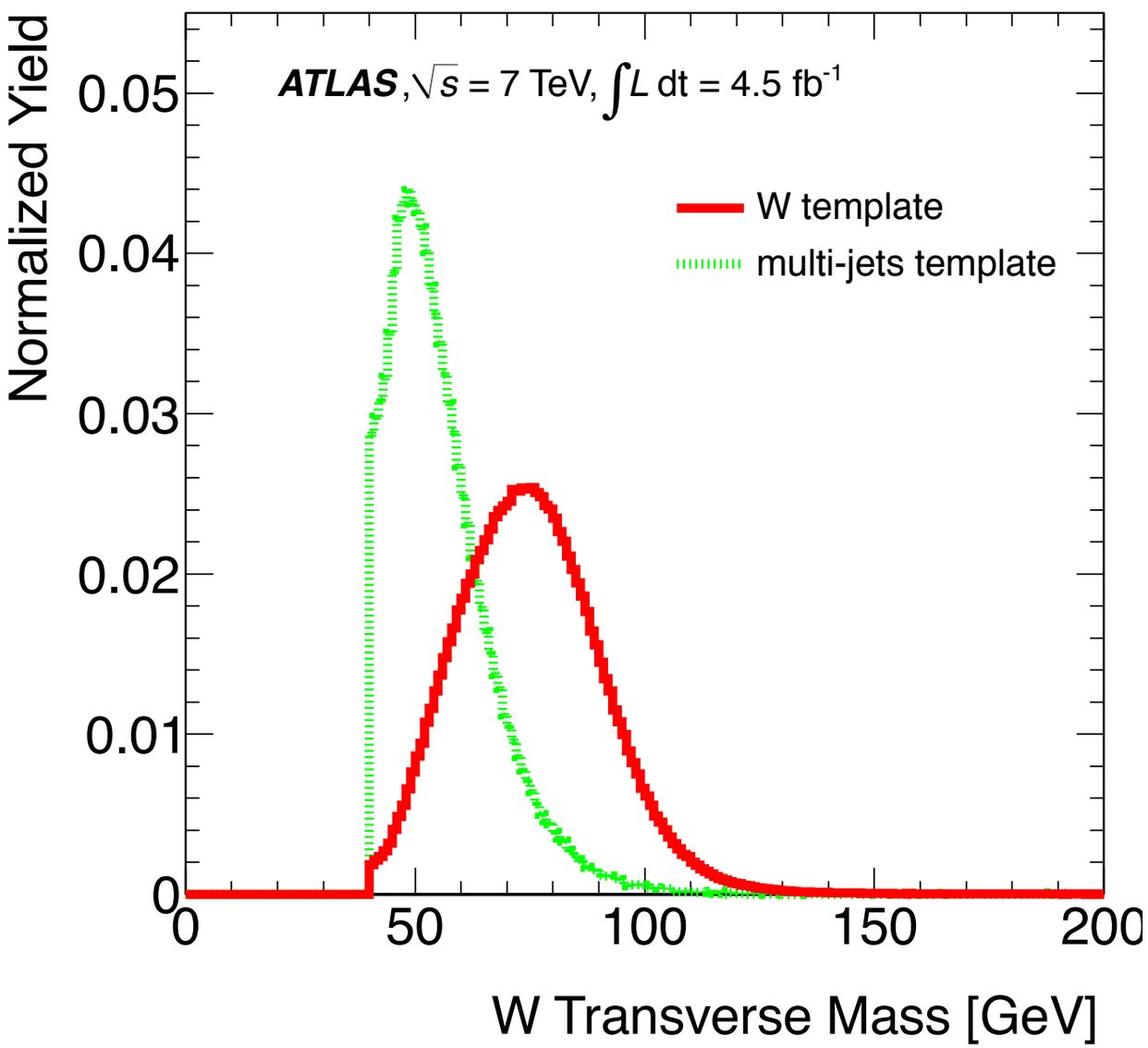
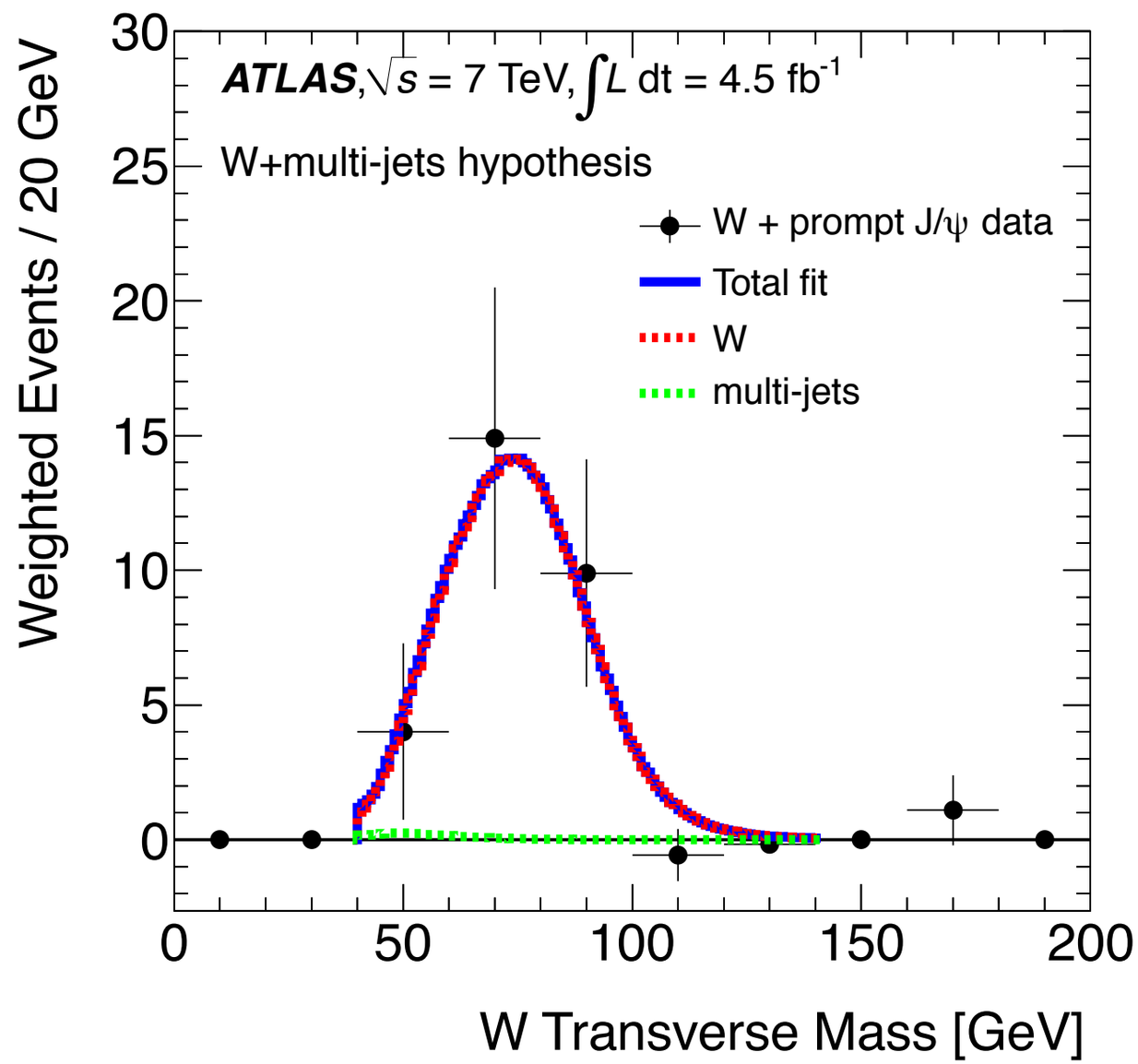
- Confirming the $W^{\pm}$
- Weighted $W^{\pm}$ transverse mass distribution using J/ψ signal yield compared with
  - $W^{\pm}$ signal template
  - data-driven multi-jet template
- Multi-jet yield < 0.3 events at 95% credibility





Backgrounds

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- $W^{\pm}$ + b
  - rejected from the fit
- $B_c \rightarrow J/\psi \mu^{\pm} \nu_{\mu} X$
  - check the three-muon invariant mass below 12 GeV
- Z+jets
  - $|m_{\mu\mu} - m_z| < 10$ GeV
- Pileup
  - $W^{\pm}$ + J/ψ candidates might be produced in different pp collisions of the same bunch crossing
  - $N = N^{extra}_{vtx} \times P_{J/\psi} \times N_{W^{\pm}}$
    - N^{extra}_{vtx}: Number of extra vertices near the $W^{\pm}$
    - $P_{J/\psi}$: Probability of producing a J/ψ meson
    - $N_{W^{\pm}}$: number of $W^{\pm}$ candidates in fiducial region
  - Estimated ~ 1.8 ± 0.2 events (subtracted from the cross section measurement)

Associated vector boson plus prompt charmonium production

Double parton scattering

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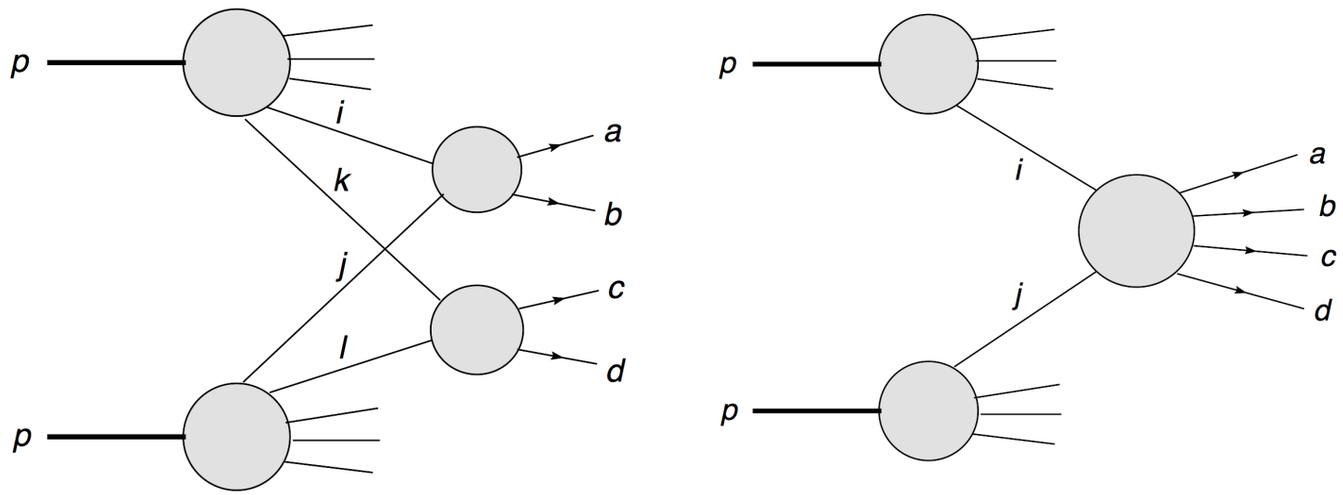
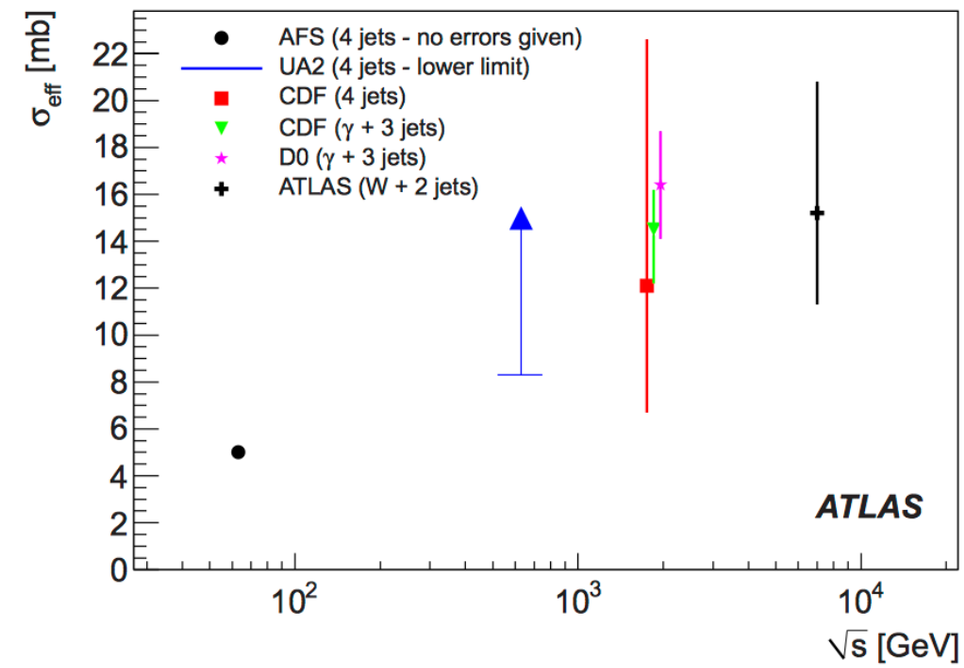
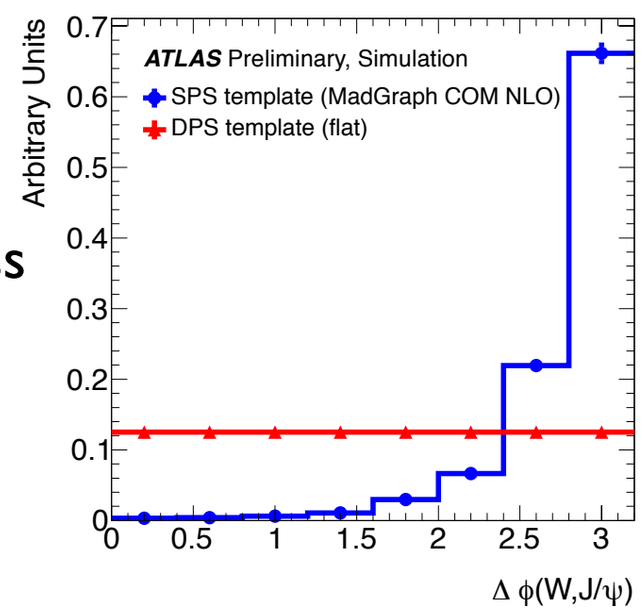
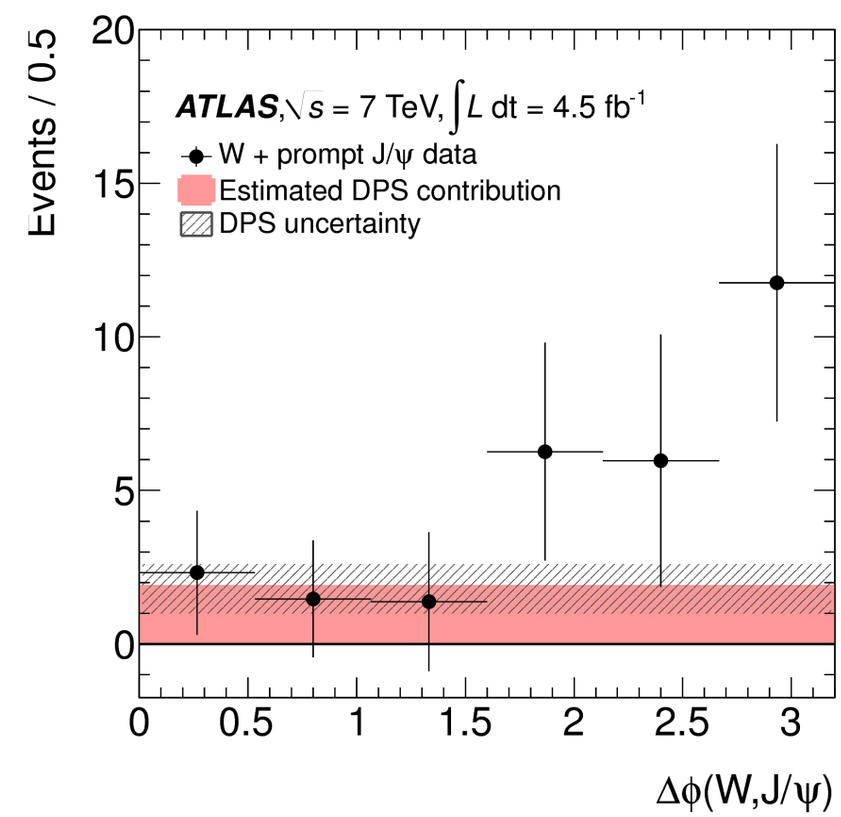
- $W^{\pm}$ and J/ψ candidates originate from two different parton interactions in the same pp collision





- $N_{DPS} = P_{J/\psi|W^{\pm}} N_{W^{\pm}}$
  - $P_{J/\psi|W^{\pm}} = \sigma_{J/\psi}/\sigma_{eff}$
    - Probability of an additional process to occur (along with the J/ψ)
    - $\sigma_{eff} = 15+3^{+5}_{-3}$ mb (ATLAS measurement arXiv:1301.6872)
  - $N_{W^{\pm}}$: number of $W^{\pm}$ candidates in fiducial region
- $N_{DPS} = 11 \pm 4$





Efficiency - acceptance corrections

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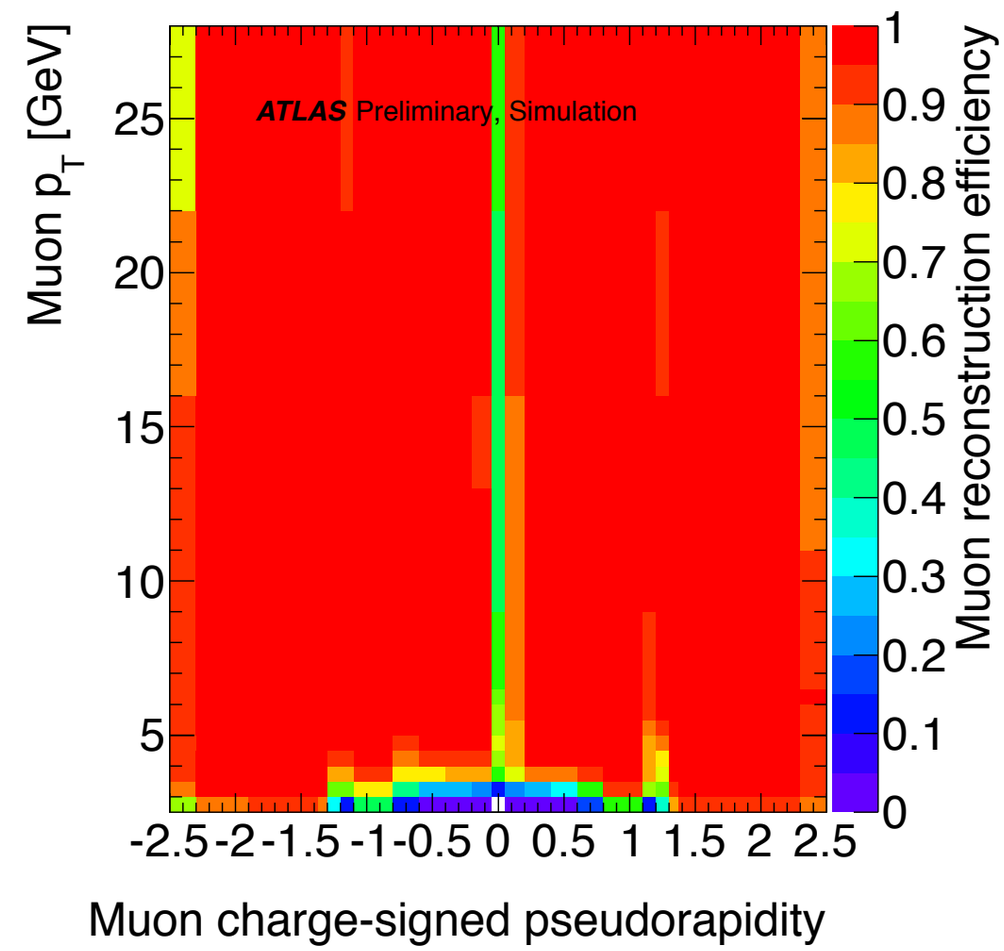
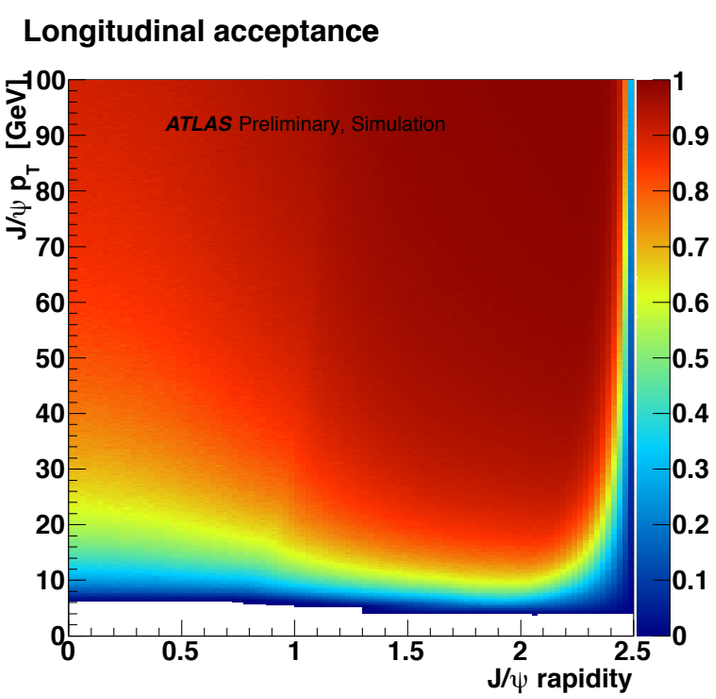
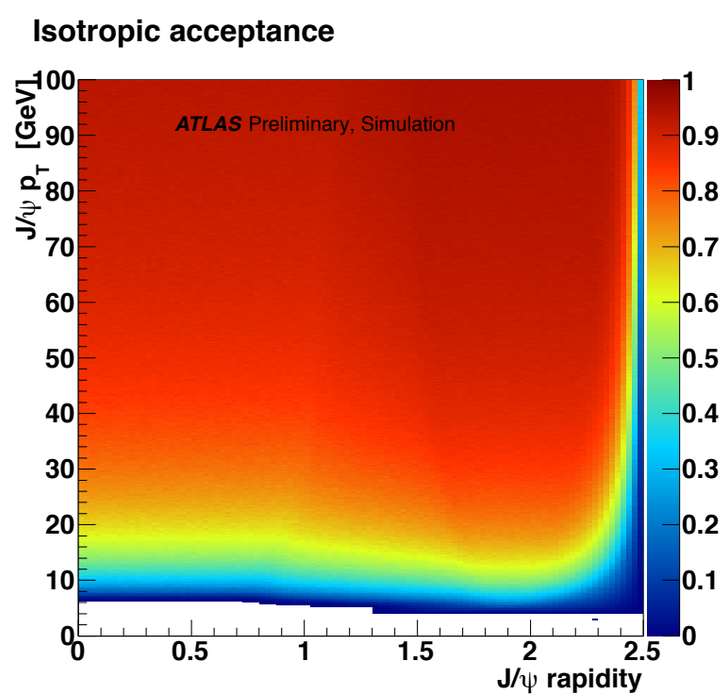
$$\frac{\sigma(pp \to W + \text{prompt} \quad J/\psi)}{\sigma(pp \to W)} = \frac{\frac{N^{W+J/\psi}}{\epsilon^{J/\psi} \cdot \alpha^{J/\psi} \cdot \cancel{\epsilon^{W}} \cdot \cancel{\mathcal{L}}}}{\frac{N^{W}}{\cancel{\epsilon^{W}} \cdot \cancel{\mathcal{L}}}}$$

- Muon reconstruction efficiencies calculated using J/ψ "tag-and-probe" method
- Decay muons can follow different paths (depending on the spin-alignment)
- The efficiency for these muons to fall in the fiducial region - acceptance
  - Following different J/ψ spin-alignment scenarios







Associated vector boson plus prompt charmonium production

Inclusive cross section ratio

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- Inclusive differential cross section
- Rare process
- Estimation for DPS contribution
  - 40% of the total signal
- SPS dominated low $p_T^{J/\psi}$ production rate

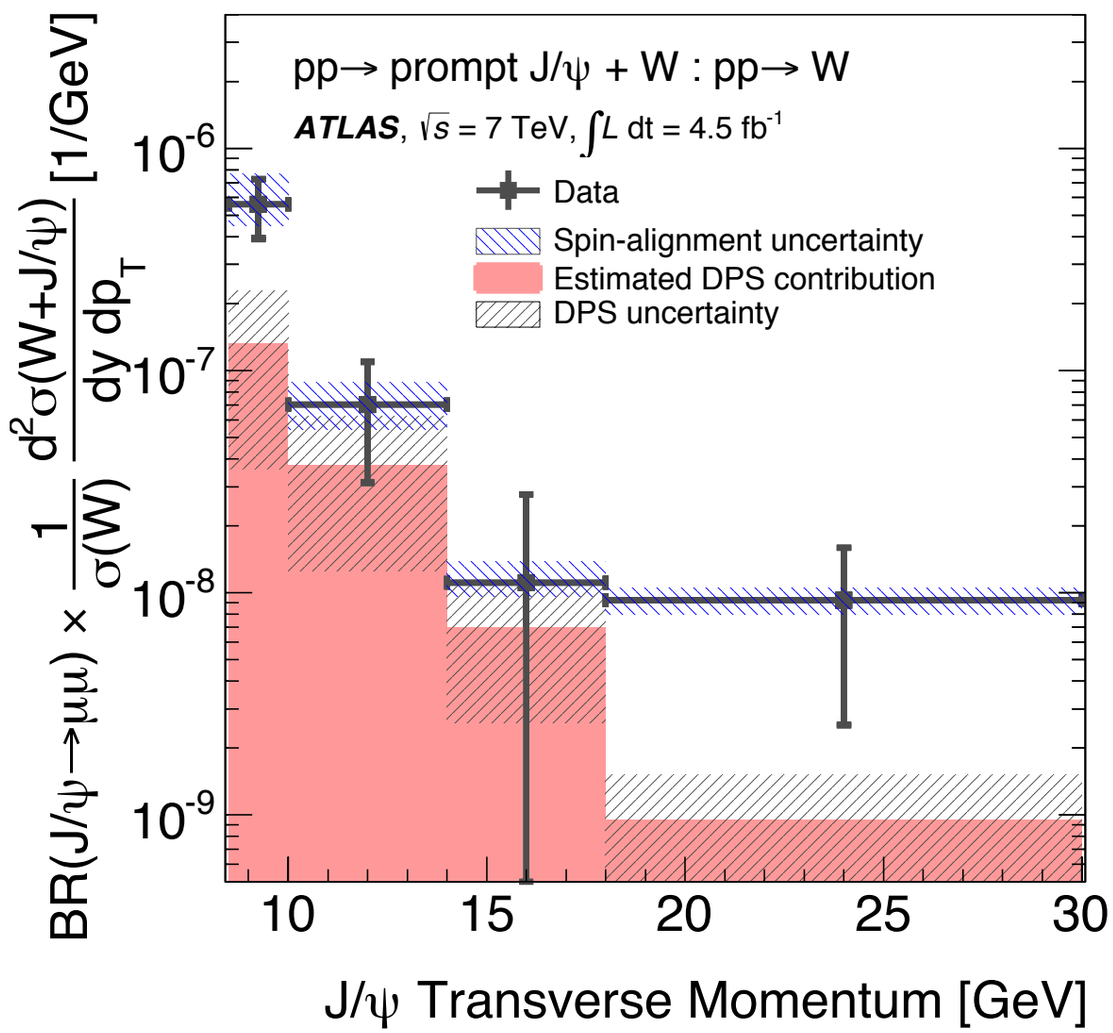
$R_{J/\psi}^{fid} = (51 \pm 13 \pm 4) \times 10^{-8}$

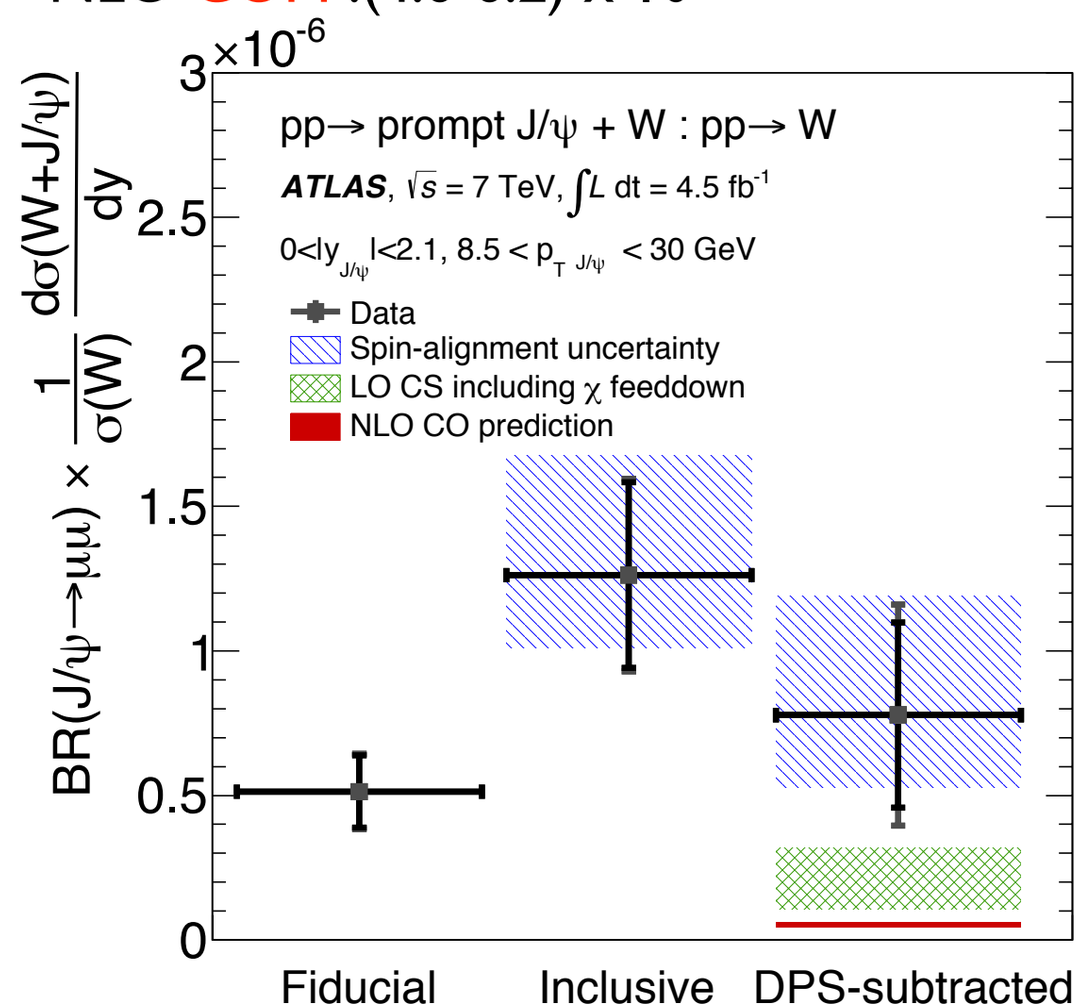
$R_{J/\psi}^{incl} = (126 \pm 32 \pm 9) \times 10^{-8}$

$R_{J/\psi}^{DPS\ sub} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8}$

LO CSM : $(10\text{-}32) \times 10^{-8}$

NLO COM : $(4.6\text{-}6.2) \times 10^{-8}$



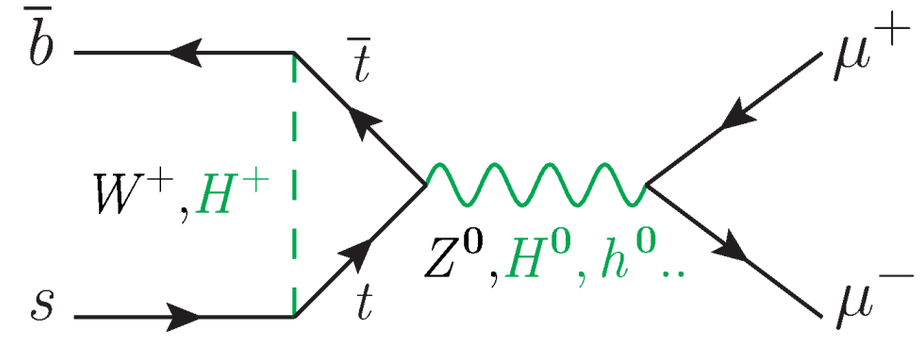


Search for $B_s \to \mu^+\mu^-$ rare decay

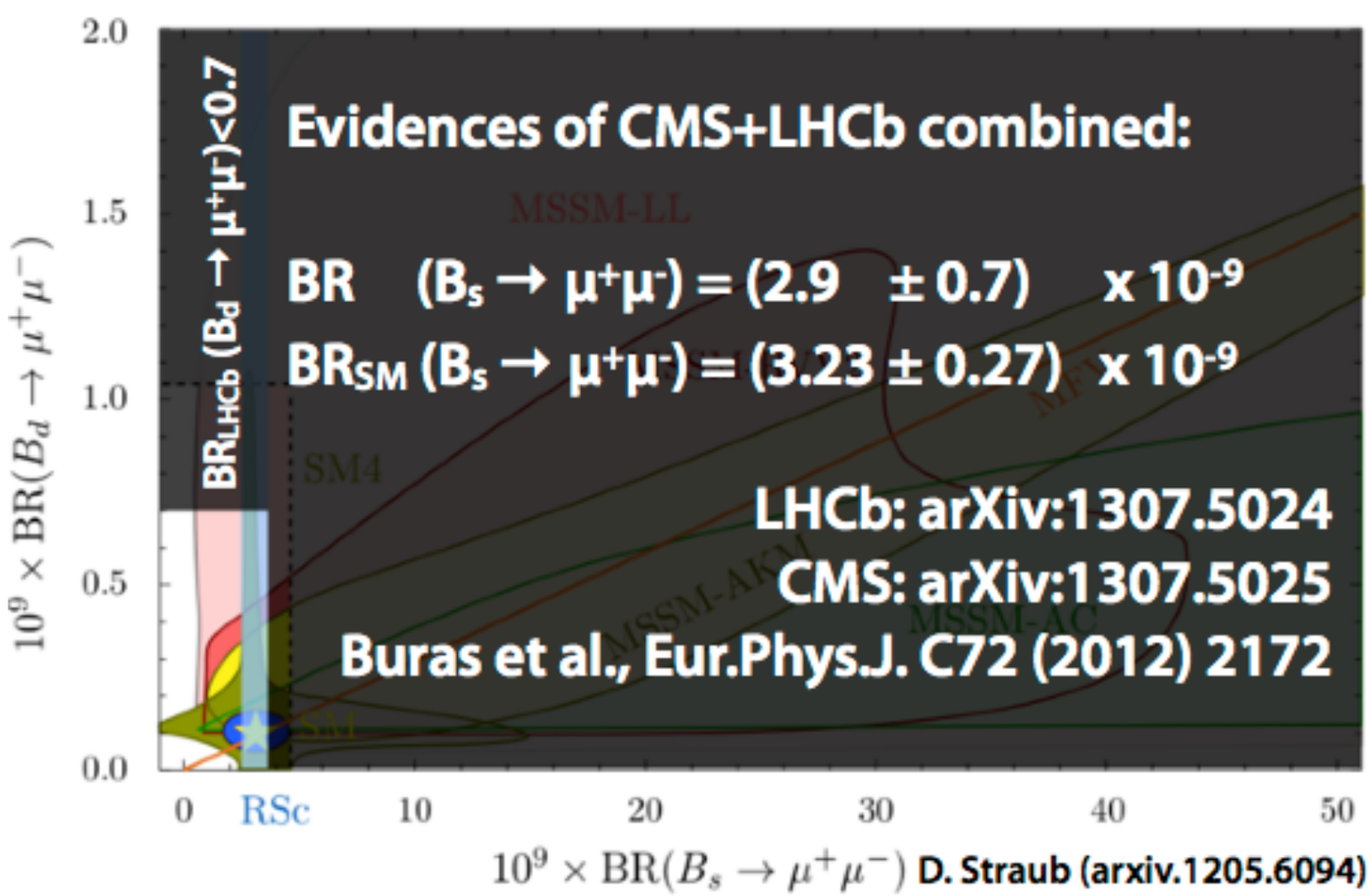
Introduction

ATLAS-CONF-2013-076

- Indirect probe for new physics
  - Very small standard model branching ratio
- Sensitive to FCNC



- Recent results from CMS (25 fb^{-1}) and LHCb (3 fb^{-1}) consistent with SM expectations
- New physics can increase (decrease) the Br



- 2011 dataset, 4.5 fb^{-1} of $\sqrt{s}$ = 7 TeV pp collisions
- muons
  - p_T > 4 GeV with $|\eta|$<2.5
- B_s
  - p_T > 8 GeV with $|\eta|$<2.5
- $B^\pm$
  - p_T > 8 GeV with $|\eta|$<2.5
  - p^K_T > 2.5 GeV with $|\eta^K|$<2.5
- J/ψ
  - 2.915 < $m_{\mu\mu}$ < 3.275 GeV
- Triggers
  - B_s: EF_2mu4(T)_Bmumu
  - $B^\pm$: EF_2mu4(T)_Jpsimumu

Analysis overview

ATLAS-CONF-2013-076

- (First) blind analysis
  - signal region (±300 MeV around the B_s mass) blinded
  - weighted MC is used for modelling the data
- Background events in sidebands are split in two
  - 50% to optimise selection cuts
  - 50% to measure the background yield after cuts optimisation
- Signal/Background discrimination
  - multivariate analysis
  - BDT based on 13 variables
- Signal extraction
  - event count in signal region
  - background estimation from sidebands

Efficiency and acceptance derived from simulations calibrated on data

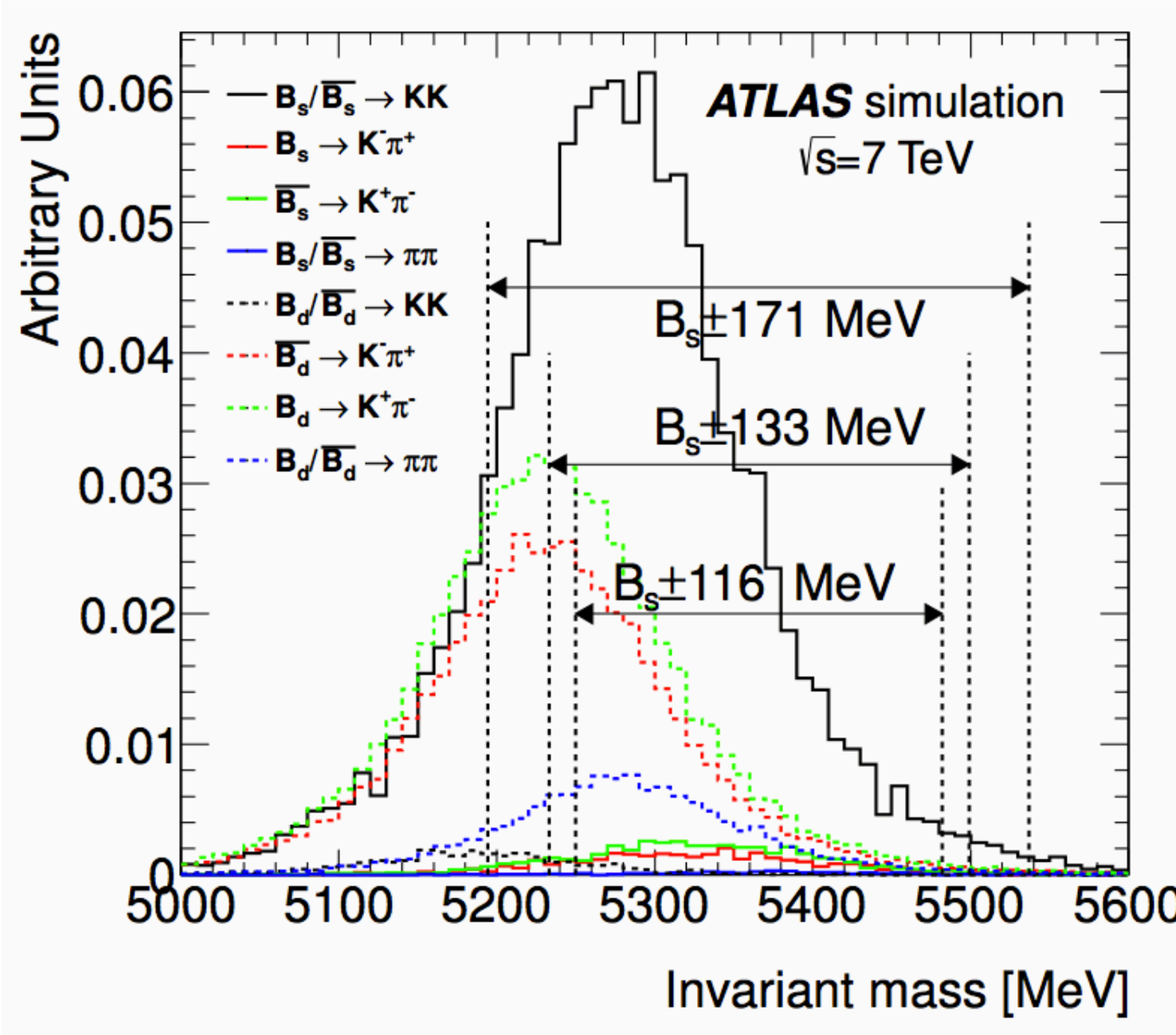
from PDG + LHCb

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

Background composition

ATLAS-CONF-2013-076

- Real muons (continuum):
  - $bb \to \mu\mu X$ dominant background
  - modelled using data in sidebands
- "Fake" muons (decays in flight, punch-throughs):
  - $B \to hh$ ($h=K,\pi$)
    - semi-irreducible due to close topology
    - BR x (fake rate) $\approx 10^{-9}$, close to SM $B_s \to \mu\mu$
    - contribution estimated with MC: negligible
- Single muon + "fake" (like $B \to \mu K \nu$)
  - negligible contribution
  - outside our search windows



Background discrimination and BDT selection

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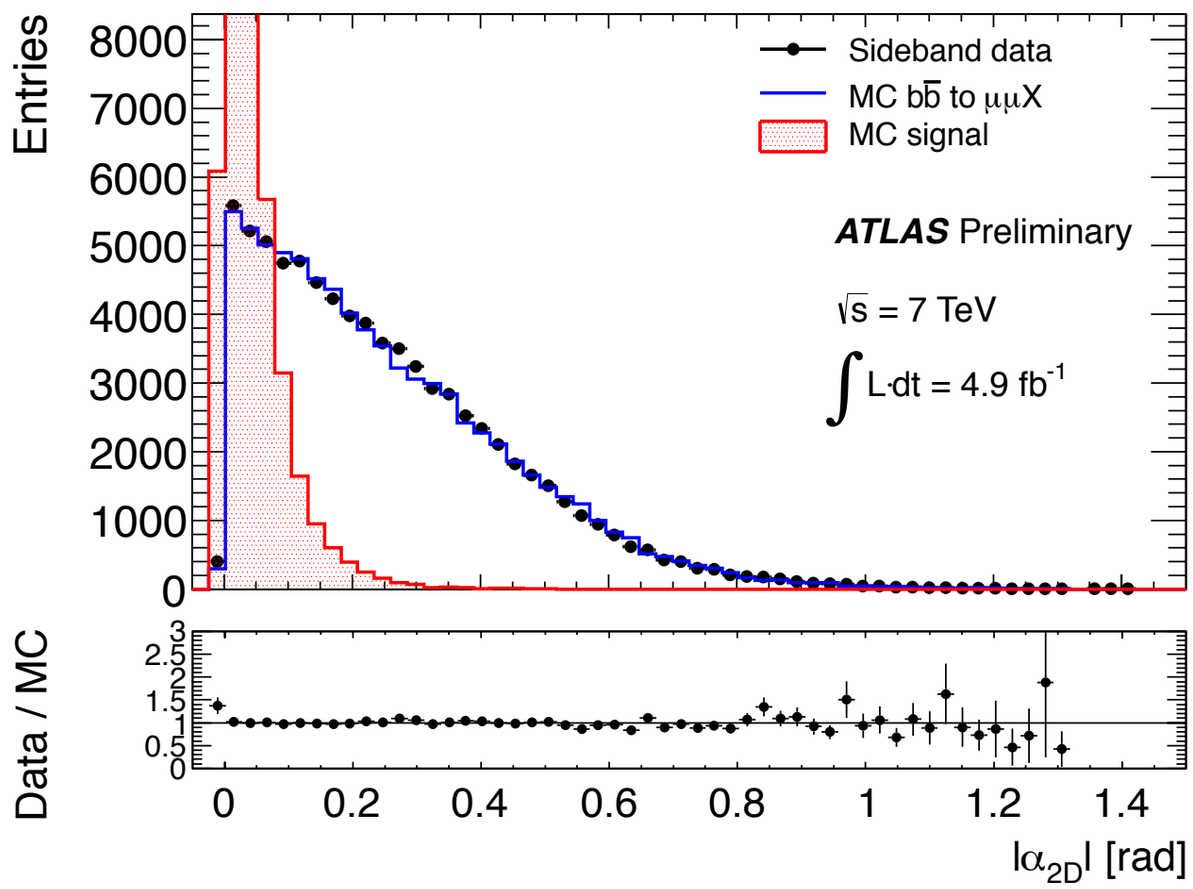
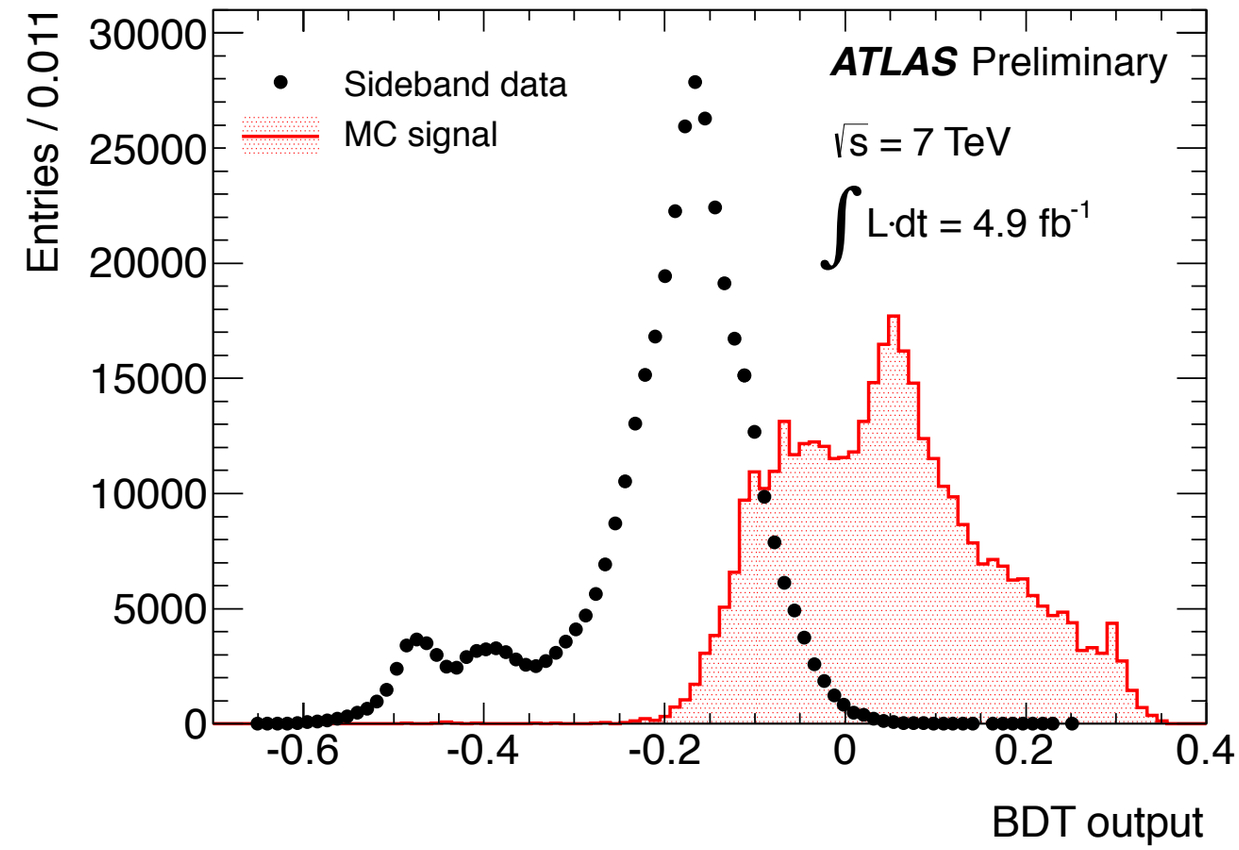
- Signal to background discrimination
  - 13 best performing discriminating variables chosen by MVA
  - PV-SV separation (L_{xy})
  - B hadronisation featured (p_T^B)
  - full reconstruction (α_{2D})
  - good Data/MC agreement



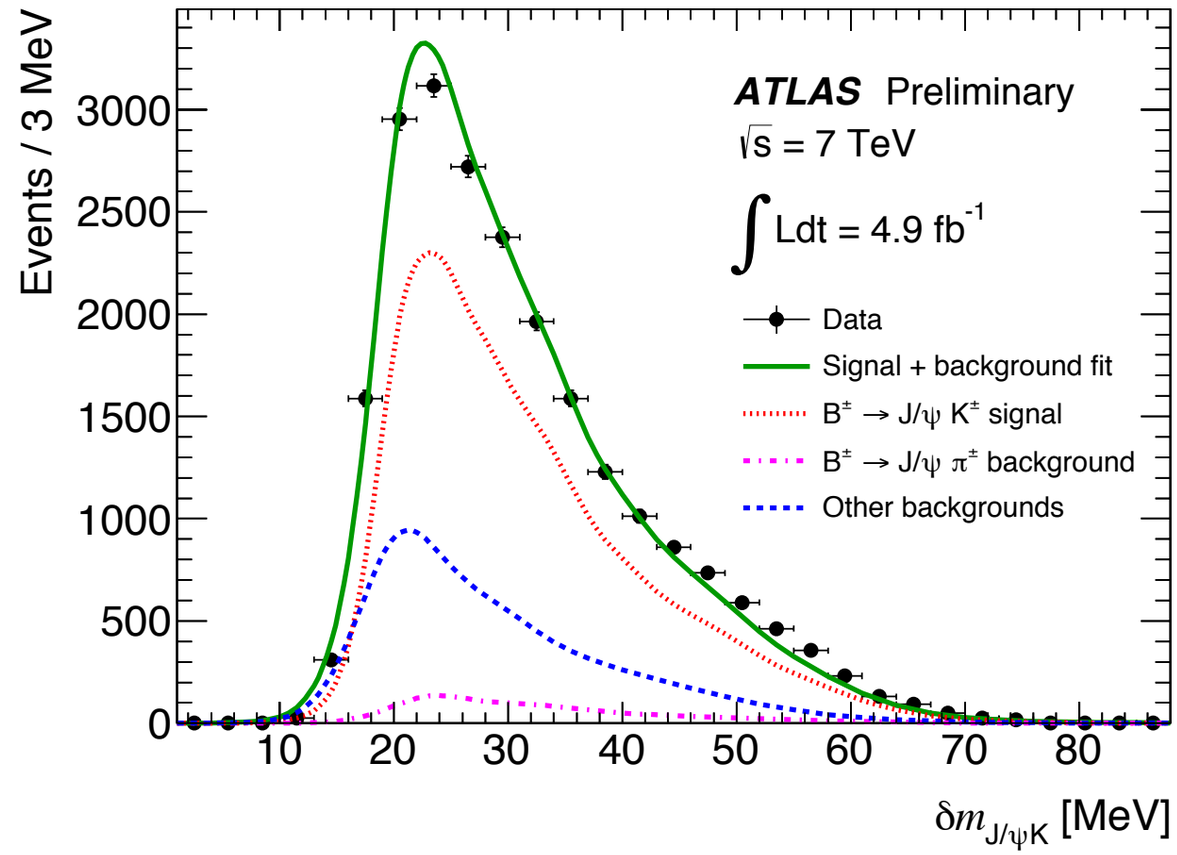


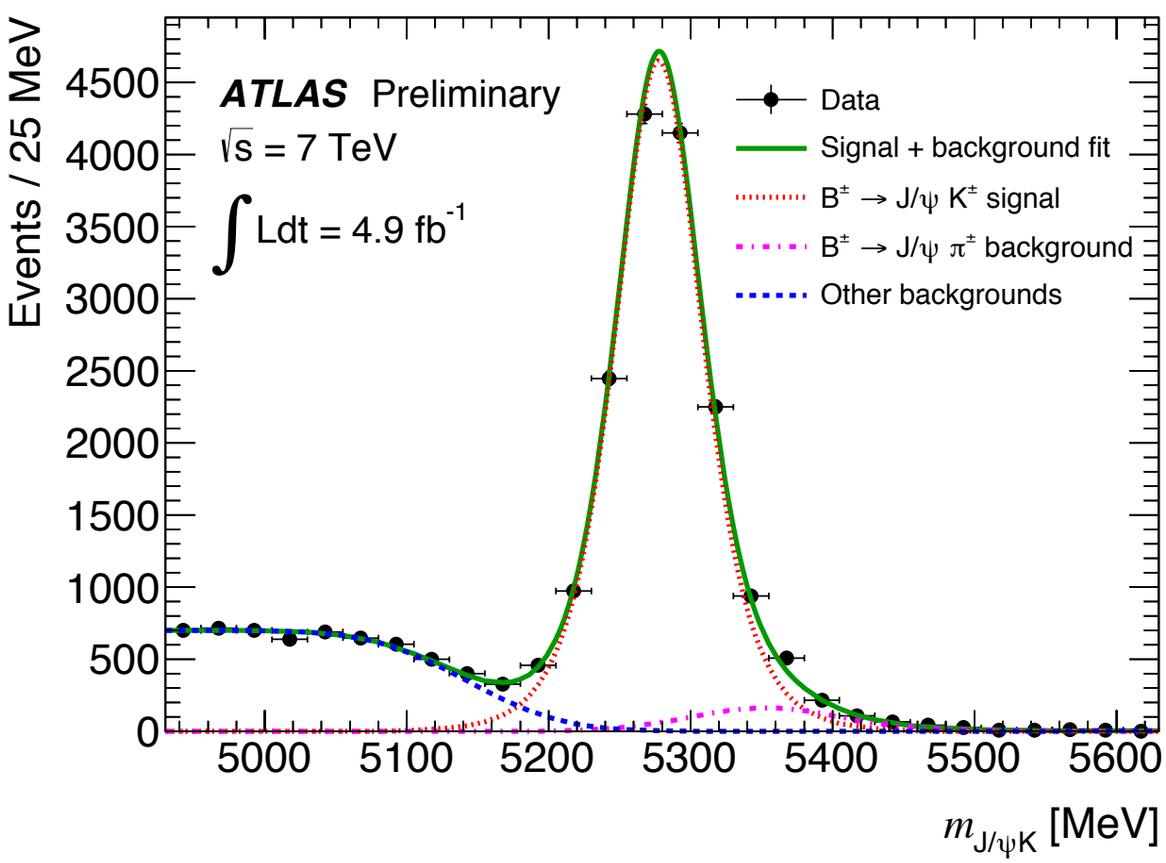
- Selection optimised in (Δm, q) space
  - Δm: signal mass window range
  - q: BDT output
- Maximize the estimator
  $P = \varepsilon_{sig}/(1\sqrt{N_{bckg}})$
- max P = 0.0145
- q>0.118 and Δm<121 MeV

Reference channel

ATLAS-CONF-2013-076

- BDT trained for B_s also applied on $B^\pm$
- Signal yield extracted
  - 2 different models, both featuring
    - unbinned maximum likelihood fit
    - per-event mass resolution
  - combination of the results





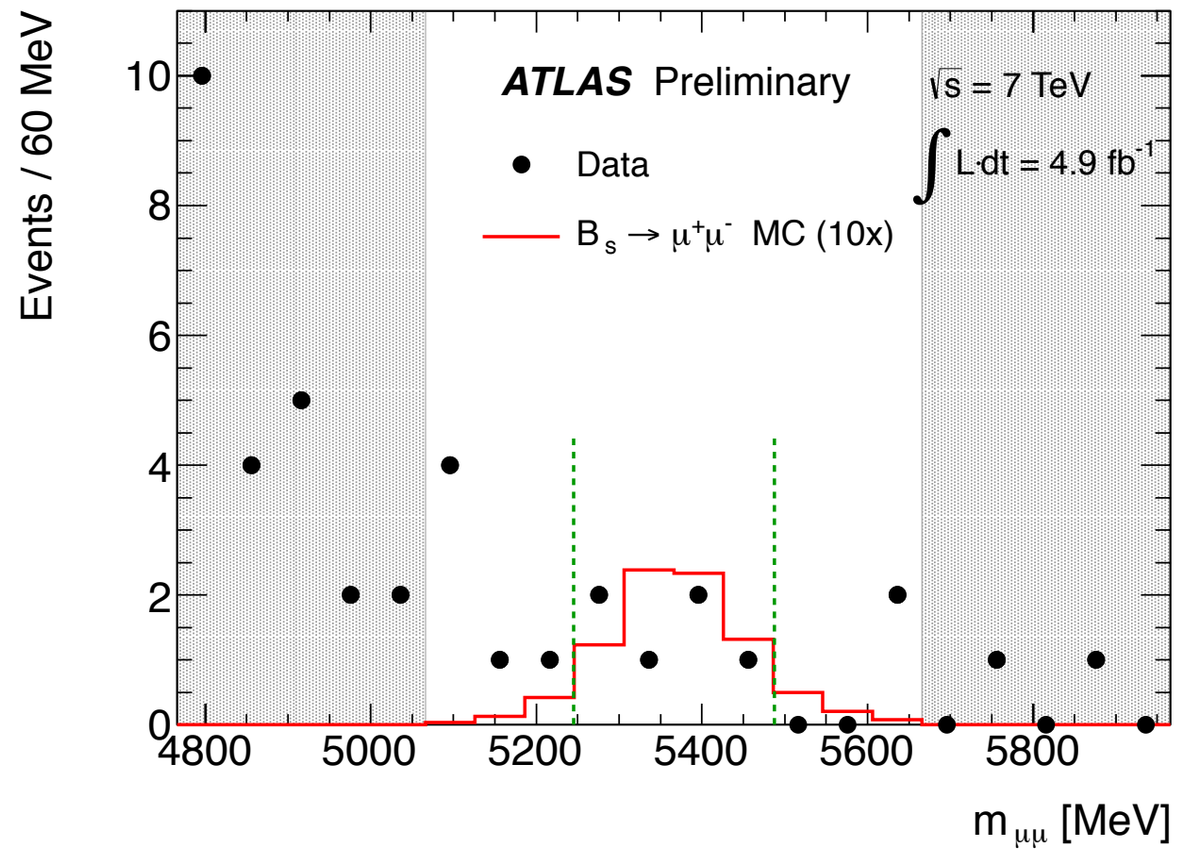
$N(B^\pm \rightarrow J/\psi K^\pm) = 15214 \pm 1.1\%\ (stat) \pm 2.4\%\ (syst)$

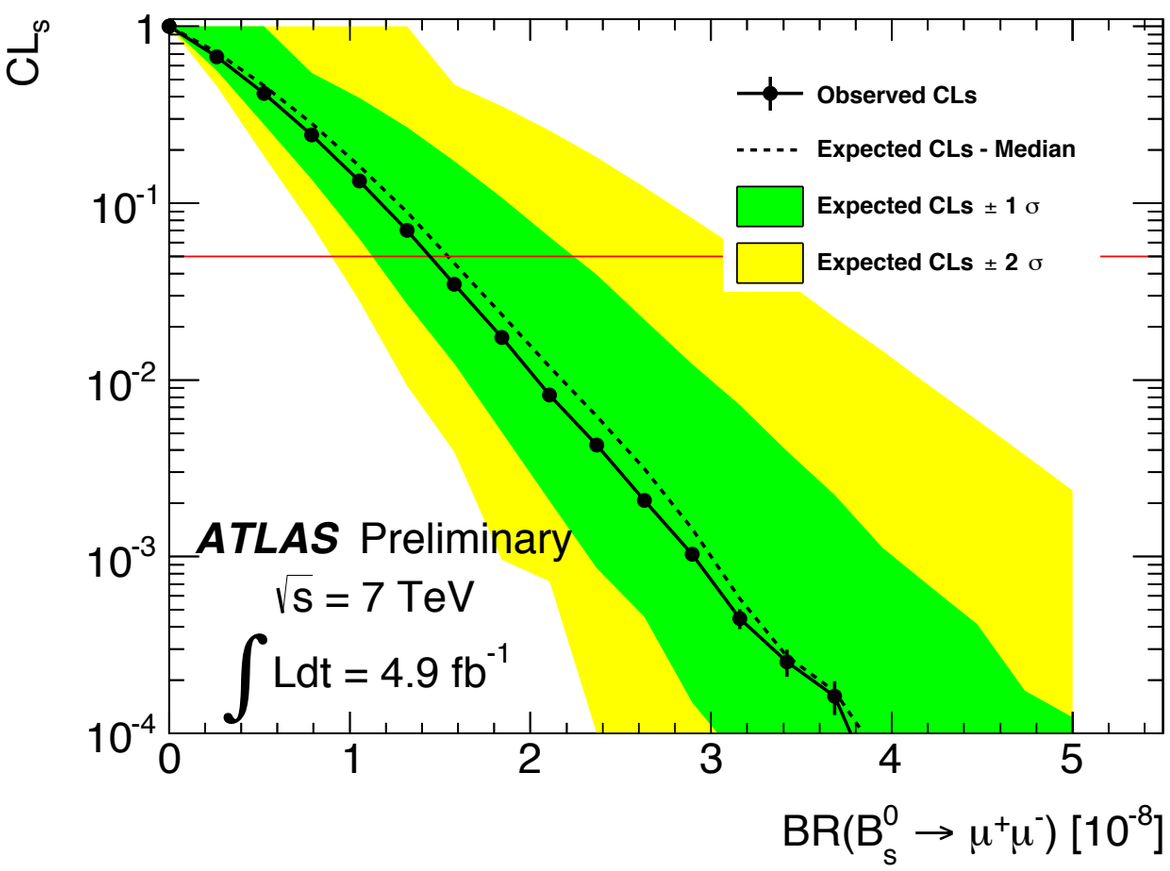
Search for $B_s \to \mu^+\mu^-$ rare decay

Limit on $Br(B_s \to \mu^+\mu^-)$

ATLAS-CONF-2013-076

- SES = (2.07 ± 26% (stat) ± 12.5% (syst)) x 10^{-9}
- N_{bkg} expected in signal windows = 6.75
- N_{obs} in signal window = 6
- Upper limit extracted with modified frequentist approach (CLs method)





$<1.5 \times 10^{-8}$ @ 95% CL

Conclusions

- Very successful ATLAS B physics program
- Consistent data-collection strategy for 2011 and 2012 data taking periods, with good signal collection efficiencies

- First observation of charmonium + vector boson production with a statistical significance of 5.1σ
- Measurement of cross-section ratio $W^{\pm}+J/\psi : W^{\pm}$
- CSM theories revisited
  - CSM contributions larger than COM

- Search for the rare decay $B_s \rightarrow \mu^+\mu^-$
  - limit is set using 2011 data
  - process of 2012 data is ongoing - results coming soon

20+ fb^{-1} more data to analyze

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