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
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.

$W^\pm$ + prompt J/ψ is a quark-initiated process with different production mechanisms than the inclusive J/ψ

Possible scenarios considered prior to ATLAS measurement

- First measurement of the associated production of $W^\pm$ + prompt J/ψ (arxiv.org/1401.2831)
  - $W^\pm \rightarrow \mu\nu_\mu$ and J/ψ → $\mu\mu$ with ATLAS detector at $\sqrt{s} = 7$ TeV
• 2011 dataset, 4.5 fb\(^{-1}\) of \(\sqrt{s} = 7\) TeV pp collisions
• Single muon trigger \(p_T > 18\) GeV
• \(J/\psi \rightarrow \mu^+\mu^-\)
  • \(p_T > 3.5\) (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 \(|y_{J/\psi}| < 2.1\)
• \(W^\pm \rightarrow \mu\nu\)
  • 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 1 mm in \(z\)
• \(W\) decay muon to have transverse impact parameter significance \(d0/\sigma(d0) < 3\)
• Remove events with \(|m_{\mu\mu} - m_z| < 10\) GeV
Extraction of prompt $J/\psi$ component

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

ATLAS, $\sqrt{s} = 7$ TeV, $\int L dt = 4.5$ fb$^{-1}$

shape parameters taken from a fit in an inclusive $J/\psi$ sample from data
## Extraction of prompt $J/\psi$ component

### Yields from two-dimensional fit

<table>
<thead>
<tr>
<th>Process</th>
<th>Barrel</th>
<th>Endcap</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt $J/\psi$</td>
<td>$10.0^{+4.7}_{-4.0}$</td>
<td>$19.2^{+5.8}_{-5.1}$</td>
<td>$29.2^{+7.5}_{-6.5}$ (*)</td>
</tr>
<tr>
<td>Non-prompt $J/\psi$</td>
<td>$27.9^{+6.5}_{-5.8}$</td>
<td>$13.9^{+5.3}_{-4.5}$</td>
<td>$41.8^{+8.4}_{-7.3}$</td>
</tr>
<tr>
<td>Prompt background</td>
<td>$20.4^{+5.9}_{-5.1}$</td>
<td>$18.8^{+6.3}_{-5.3}$</td>
<td>$39.2^{+8.6}_{-7.3}$</td>
</tr>
<tr>
<td>Non-prompt background</td>
<td>$19.8^{+5.8}_{-4.9}$</td>
<td>$19.2^{+6.1}_{-5.1}$</td>
<td>$39.0^{+8.4}_{-7.1}$</td>
</tr>
<tr>
<td>$p$-value</td>
<td>$8.0 \times 10^{-3}$</td>
<td>$1.4 \times 10^{-6}$</td>
<td>$2.1 \times 10^{-7}$</td>
</tr>
<tr>
<td>Significance ($\sigma$)</td>
<td>2.4</td>
<td>4.7</td>
<td>5.1</td>
</tr>
</tbody>
</table>

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

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extract $m_T^{\text{W}}$ events based on the prompt $J/\psi$ yield using sPlot
• Confirming the $W^\pm$
• Weighted $W^\pm$ transverse mass distribution using $J/\psi$ signal yield compared with
  • $W^\pm$ signal template
  • data-driven multi-jet template
• Multi-jet yield < 0.3 events at 95% credibility
• $W^\pm + b$
  • rejected from the fit
• $B_c \rightarrow J/\psi \mu^\pm \nu_\mu X$
  • check the three-muon invariant mass below 12 GeV
• $Z + \text{jets}$
  • $|m_{\mu\mu} - m_Z| < 10$ GeV
• Pileup
  • $W^\pm + J/\psi$ candidates might be produced in different $pp$ collisions of the same bunch crossing
  • $N = N_{\text{extra}}^{\text{vtx}} \times P_{J/\psi} \times N_{W^\pm}$
    • $N_{\text{extra}}^{\text{vtx}}$: Number of extra vertices near the $W^\pm$
    • $P_{J/\psi}$: Probability of producing a $J/\psi$ meson
    • $N_{W^\pm}$: number of $W^\pm$ candidates in fiducial region
  • Estimated $\sim 1.8 \pm 0.2$ events (subtracted from the cross section measurement)
- $W^\pm$ and $J/\psi$ candidates originate from two different parton interactions in the same pp collision

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

\[
\frac{\sigma(pp \rightarrow W + \text{prompt } J/\psi)}{\sigma(pp \rightarrow W)} \frac{N^{W+J/\psi}}{\epsilon^{J/\psi} \cdot \alpha^{J/\psi} \cdot \epsilon^W \cdot L} \frac{N^W}{\epsilon^W \cdot L}
\]

- Longitudinal acceptance
- Isotropic acceptance

Muons

ATLAS Preliminary, Simulation

Preliminary, Simulation

ATLAS Preliminary, Simulation
- Inclusive differential cross section
- Rare process
- Estimation for DPS contribution
  - 40% of the total signal
- SPS dominated low $p_T$ production rate

\[ R_{J/\psi}^{\text{fid}} = (51 \pm 13 \pm 4) \times 10^{-8} \]
\[ R_{J/\psi}^{\text{incl}} = (126 \pm 32 \pm 9) \times 10^{-8} \]
\[ R_{J/\psi}^{\text{DPS sub}} = (78 \pm 32 \pm 41 \pm 25) \times 10^{-8} \]

LO CSM : \((10-32) \times 10^{-8}\)
NLO COM : \((4.6-6.2) \times 10^{-8}\)
Search for $B_s \rightarrow \mu^+ \mu^-$ rare decay

Introduction

- 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 $|\eta^K| < 2.5$
- $J/\psi$
  - $2.915 < m_{\mu\mu} < 3.275$ GeV
- Triggers
  - $B_s$: EF_2mu4(T)_Bmumu
  - $B^\pm$: EF_2mu4(T)_Jpsimu
Analysis overview

- (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

\[
BR(B_s \rightarrow \mu\mu) = \frac{N_{B_s \rightarrow \mu\mu}}{N_{J/\psi K^\pm}} \cdot \frac{\alpha_{J/\psi K^\pm}}{\alpha_{B_s \rightarrow \mu\mu}} \cdot \frac{f_{J/\psi K^\pm}^{\text{tot}}}{f_{B_s \rightarrow \mu\mu}} \cdot \frac{BR(B^\pm \rightarrow J / \psi K^\pm)}{f_{J/\psi K^\pm}}
\]

Efficiency and acceptance derived from simulations calibrated on data from PDG + LHCb
Search for $B_s \rightarrow \mu^+ \mu^-$ rare decay

Background composition

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

![ATLAS simulation with invariant mass distribution](image)
Background discrimination and BDT selection

• 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 (\alpha_{2D})
  • good Data/MC agreement

• Selection optimised in (\Delta m, q) space
  • \Delta m: signal mass window range
  • q: BDT output
  • Maximize the estimator
    \[ P = \frac{\epsilon_{\text{sig}}}{\sqrt{N_{\text{bckg}}}} \]
    • max P = 0.0145
    • q>0.118 and \Delta m<121 \text{ MeV}
Reference channel

- 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

\[
N(B^\pm \rightarrow J/\psi K^\pm) = 15214 \pm 1.1\% \text{ (stat)} \pm 2.4\% \text{ (syst)}
\]
Limit on $\text{Br}(B_s \rightarrow \mu^+\mu^-)$

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

\begin{tabular}{c|c|c|c|c|c|c}
\hline
\text{Observed CLs} & \text{Expected CLs} - Median & \text{Expected CLs} \pm 1 \sigma & \text{Expected CLs} \pm 2 \sigma \\
\hline
\hline
\end{tabular}

\begin{align*}
\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) [10^{-8}] &< 1.5 \times 10^{-8} \text{ @ 95\% CL}
\end{align*}
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