Rare decays: ATLAS / CMS

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on behalf on the ATLAS and CMS collaborations

HL-LHC workshop

18 June 2018
Outline

• why rare decays?
• HL-LHC studies from ATLAS and CMS
• ATLAS and CMS projections for $B(s) \rightarrow \mu^+\mu^-$
• conclusions
why study rare decays?

- B-physics rare and semi-rare processes are mediated by flavour changing neutral current (FCNC)

- suppressed SM amplitudes → sensitive to small effects from NP loop contributions
- We can indirectly search for new physics at scales beyond the reach of the LHC
- **sensitive probe for beyond standard model physics**

- HL-LHC will be a powerful test bench for B physics predictions
  - high collected luminosity → study rare processes at a sensitivity level never reached before
  - simple projection: $10^{15}$ $b\bar{b}$ pairs in 3000 fb$^{-1}$ (HL-LHC)
  - possibility to cover new interesting channels —> $B \rightarrow \tau\mu$, $B \rightarrow \mu e$, $B \rightarrow \tau\tau$
B $\rightarrow$ K$^*$ $\mu^+\mu^-$ from ATLAS and CMS

- new physics entering the loop can be detected by looking at the angular distributions of the decay
- Run 1 ATLAS and CMS analysis public

ATLAS $\rightarrow$ deviation in $P_{4}'$ and $P_{5}'$
CMS $\rightarrow$ in agreements with SM
LHCb $\rightarrow$ deviation in $P_{5}'$

ATLAS and CMS show great potential in this hot topic

$B \rightarrow K^* \mu^+\mu^-$ $\rightarrow$ expected HL-LHC studies from ATLAS and CMS
\[ B(s) \rightarrow \mu^+\mu^- \text{ from ATLAS and CMS} \]

- \( B(s) \rightarrow \mu^+\mu^- \):
  - studies published from both ATLAS and CMS
  - use these processes as benchmark for flavour physics at HL-LHC
  - additional studies on effective lifetime estimate from CMS ongoing

- LHCb studies also available
  - see Christoph’s talk
$B_{(s)} \rightarrow \mu^+\mu^-$ state of the art

[Scholarpedia 11 (2016) 32643]
\( B(s) \to \mu^+\mu^- \) projections to Run 2/3 and HL-LHC

- similar strategy for ATLAS and CMS
  - studies based on latest published result \( \rightarrow \) Run1 analyses
  - do not consider improvements in analysis strategy \( \rightarrow \) conservative approach
  - maintain same PDFs and S/B ratio
    - scale yields with available statistics
    - modify PDFs parameters if needed
- common choices:
  - production X-section and signal BRs as predicted by the SM
- total collected luminosity:
  - Run 2:
    - ATLAS: 130 fb\(^{-1}\)
    - CMS: 100 f fb\(^{-1}\)
  - Run 3:
    - CMS: 300 fb\(^{-1}\)
  - HL-LHC: 3 ab\(^{-1}\) (3000 fb\(^{-1}\))

- trigger strategy
  - crucial in HL-LHC environment
  - different strategies from ATLAS and CMS \( \rightarrow \) next slides
ATLAS $B(s) \rightarrow \mu^+\mu^-$ studies

- assumptions:
  - $\sigma_{bb}$ and BR based on SM predictions

- collected luminosity $\rightarrow$ Run2 130 fb$^{-1}$, HL-LHC 3 ab$^{-1}$

- di-muon trigger efficiencies $\rightarrow$ various scenarios

- Run2
  - admixtures of di-muon triggers with different thresholds
    - 2mu6, mu6_mu4, their topological variations

- HL-LHC
  - 3 scenarios studied:
    - 2mu6 $\rightarrow$ high-yield
    - mu10_mu6 $\rightarrow$ intermediate
    - 2mu10 $\rightarrow$ conservative
ATLAS $B_{(s)} \rightarrow \mu^+\mu^-$ studies

• assumptions:
  • $\sigma_{bb}$ and BR based on SM predictions
  • collected luminosity $\rightarrow$ Run2 130 fb$^{-1}$, HL-LHC 3 ab$^{-1}$
  • di-muon trigger efficiencies $\rightarrow$ various scenarios
  • dimuon mass resolution $\rightarrow$ improvement in phase 2

[ATLAS Simulation $\sqrt{s} = 14$ TeV $B_s \rightarrow \mu\mu$, ID/ITk tracks]

[CERN-LHCC-2017-021, ATLAS-TDR-030]
ATLAS $B(s) \rightarrow \mu^+\mu^-$ studies

• assumptions:
  • $\sigma_{b\bar{b}}$ and BR based on SM predictions

• collected luminosity $\rightarrow$ Run2 130 fb$^{-1}$, HL-LHC 3 ab$^{-1}$

• di-muon trigger efficiencies $\rightarrow$ various scenarios

• dimuon mass resolution $\rightarrow$ improvement in phase 2

• systematics $\rightarrow$ conservative approach

• external systematics:
  • e.g. $f_s/f_d$, BR($B^\pm \rightarrow J/\psi K^\pm$)
  • same as Run1

• internal systematics:
  • e.g. data-MC discrepancies, triggering modelling, background extrapolation, …
  • scale with statistics
ATLAS Run 2

• test of extrapolation procedure with Full Run 2 statistics prediction
• projected Run2 statistics: ~x7 Run1 statistics

• stat+syst contours based on 2D Neyman belt construction
• depending on statistical regime:
  • “low statistics”: full-fledged Neyman belt approach
  • asymptotically: likelihood contours
• Neyman contours close to likelihood ones already for expected run 2 statistics —> approximate HL extrapolations with likelihood

[ATL-PHYS-PUB-2018-005]
ATLAS HL-LHC

- 3 trigger scenarios:
  - 2mu10
    - conservative: ~x15 Run1 stat
  - mu6_mu10
    - intermediate: ~x60 Run1 stat
  - 2mu6
    - high yield: ~x75 Run1 stat
- profiled likelihood contours
  - red: stat only
  - blue: stat + syst
- dominant systematic on BR(Bs): $f_s/f_d$

ATLAS Simulation Preliminary
$B^0_{(s)} \rightarrow \mu^+\mu^-$
working point x15 Run1 statistics

ATLAS Simulation Preliminary
$B^0_{(s)} \rightarrow \mu^+\mu^-$
working point x60 Run1 statistics

ATLAS Simulation Preliminary
$B^0_{(s)} \rightarrow \mu^+\mu^-$
working point x75 Run1 statistics

[ATL-PHYS-PUB-2018-005]
CMS $B_s \rightarrow \mu^+\mu^-$ studies

- assumptions:
  - \( \sigma_{bb} \) and BR based on SM predictions

- **collected luminosity** —> Run2 100 fb\(^{-1}\), Run3 300 fb\(^{-1}\), HL-LHC 3 ab\(^{-1}\)

- **di-muon trigger** —> L1 track trigger for Phase 2

- Phase I: standard di-muon trigger
- Phase 2: L1 track trigger
  - invariant mass resolution at L1: 70 MeV
  - preliminary rate estimates: few hundred Hz at L1

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CMS Simulation

Scaled to L = 3000 fb\(^{-1}\)

- 10^8
- 10^7
- 10^6
- 10^5
- 10^4
- 10^3
- 10^2
- 10
- 1

Events / (0.02 GeV)

\( m_{\mu\mu} \) (GeV)

- L1TrkMu (PhaseII) Trigger
  - \( p_T(\mu) > 3 \) GeV
  - \( |h_l(\mu)| < 2 \)
  - \( p_T(\mu\mu) > 4 \) GeV
  - \( |h_{(\mu\mu)}| < 2 \)
  - \( |\Delta \cdot d_{(\mu\mu)}| < 1 \) cm
  - \( 3.9 < m(\mu\mu) < 6.9 \) GeV

- \( B_s \rightarrow \mu^+\mu^- \)
- \( B_d \rightarrow \mu^+\mu^- \)
- Background
- Total signal

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[CMS-PAS-FTR-14-015]

University of Sussex
CMS \(B(s) \rightarrow \mu^+\mu^-\) studies

- assumptions:
  - \(\sigma_{bb} \) and BR based on SM predictions
  - collected luminosity \(\rightarrow\) Run2 100 fb\(^{-1}\), Run3 300 fb\(^{-1}\), HL-LHC 3 ab\(^{-1}\)
  - di-muon trigger \(\rightarrow\) L1 track trigger for Phase 2
  - pile-up effects \(\rightarrow\) impact on discriminating variables

- due to high HL-LHC luminosity
- efficiency loss in discriminating variables due to pile-up
- tighter \(\mu\) cuts to maintain fake rate as Run1
- overall efficiency loss: 30%
- conservative estimation
CMS $B_{(s)} \rightarrow \mu^+\mu^-$ studies

- assumptions:
  - $\sigma_{bb}$ and BR based on SM predictions
  - collected luminosity $\rightarrow$ Run2 100 fb$^{-1}$, Run3 300 fb$^{-1}$, HL-LHC 3 ab$^{-1}$
  - di-muon trigger $\rightarrow$ L1 track trigger for Phase 2
  - pile-up effects $\rightarrow$ impact on discriminating variables
  - dimuon mass resolution $\rightarrow$ improvement in phase 2

- improve bkg rejection and $B_s$-$B_d$ separation
CMS $B_{(s)} \rightarrow \mu^+\mu^-$ studies

- assumptions:
  - $\sigma_{b\bar{b}}$ and BR based on SM predictions
  - **collected luminosity** $\rightarrow$ Run2 100 fb$^{-1}$, Run3 300 fb$^{-1}$, HL-LHC 3 ab$^{-1}$
  - **di-muon trigger** $\rightarrow$ L1 track trigger for Phase 2
  - **pile-up effects** $\rightarrow$ impact on discriminating variables
  - **dimuon mass resolution** $\rightarrow$ improvement in phase 2
  - **systematics** $\rightarrow$ scale with statistics

<table>
<thead>
<tr>
<th></th>
<th>Run I</th>
<th>Phase I</th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_s/f_d$</td>
<td>9%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>norm yield</td>
<td>5%</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>peaking bkg</td>
<td>60%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>semileptonic decays</td>
<td>50%</td>
<td>25%</td>
<td>20%</td>
</tr>
</tbody>
</table>
CMS Run 3 and HL-LHC

[Scaled to L = 300 fb⁻¹]

**Uncertainty on BRs**

<table>
<thead>
<tr>
<th>( \mathcal{L} ) (fb⁻¹)</th>
<th>( \delta \text{BR}(B_s) )</th>
<th>( \delta \text{BR}(B_d) )</th>
<th>BR( (B_d) ) sign.</th>
<th>( \delta [\text{BR}(B_s) / \text{BR}(B_d)] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>14%</td>
<td>63%</td>
<td>0.6-2.5σ</td>
<td>66%</td>
</tr>
<tr>
<td>300</td>
<td>12%</td>
<td>41%</td>
<td>1.5-3.5σ</td>
<td>43%</td>
</tr>
<tr>
<td>300 (barrel)</td>
<td>13%</td>
<td>48%</td>
<td>1.2-3.3σ</td>
<td>50%</td>
</tr>
<tr>
<td>3000 (barrel)</td>
<td>11%</td>
<td>18%</td>
<td>5.6-8.0σ</td>
<td>21%</td>
</tr>
</tbody>
</table>

uncertainty on BRs

BR\( (B_d) \) statistical significance

uncertainty on BRs ratio
ATLAS - CMS comparison at HL-LHC

- compare ATLAS and CMS expected uncertainties on signal BRs
  - ATLAS uncertainties from: ATL-PHYS-PUB-2018-005
  - CMS uncertainties derived from: CMS-PAS-FTR-14-015
  - including systematics

<table>
<thead>
<tr>
<th></th>
<th>$\sigma( \text{BR}(B_s) )$ [10^{-9}]</th>
<th>$\sigma( \text{BR}(B_d) )$ [10^{-9}]</th>
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<tbody>
<tr>
<td>CMS</td>
<td>0.40</td>
<td>0.019</td>
</tr>
<tr>
<td>ATLAS high-yield</td>
<td>0.46</td>
<td>0.028</td>
</tr>
<tr>
<td>ATLAS intermediate</td>
<td>0.47</td>
<td>0.031</td>
</tr>
<tr>
<td>ATLAS conservative</td>
<td>0.55</td>
<td>0.054</td>
</tr>
</tbody>
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SM predictions: $\text{BR}(B_s) = (3.65 \pm 0.23) \times 10^{-9}$, $\text{BR}(B_d) = (1.06 \pm 0.09) \times 10^{-10}$

- on $B_s$ CMS slightly better than ATLAS intermediate and high-yield
  - ATLAS systematics conservatively over-estimated

- on $B_d$ CMS shows smaller uncertainty than ATLAS

- both experiments have great potential
  - possibility to measure both BRs at 5 sigma
conclusions

• HL-LHC will be a powerful test bench for B physics predictions
• ongoing HL-LHC studies on several processes
  • $B \to K^* \mu^+\mu^-$ (P5' parameter)
  • $B_{(s)} \to \mu^+\mu^-$ studies ready
• projections to Run2/3 and HL-LHC performed by ATLAS and CMS
  • rather conservative assumptions
  • increment in luminosity and B production X-section
  • major detector improvements considered
• both ATLAS and CMS show great potential
  • possibility to measure $BR(B_{(s)} \rightarrow \mu^+\mu^-)$ at 5 sigma
BACKUP
# ATLAS - CMS comparison at HL-LHC

- compare ATLAS and CMS expected uncertainties on signal BRs
- ATLAS uncertainties from: ATL-PHYS-PUB-2018-005
- CMS uncertainties calculated from: CMS-PAS-FTR-14-015

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<tr>
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SM predictions: \( BR(B_s) = (3.65 \pm 0.23) \times 10^{-9} \), \( BR(B_d) = (1.06 \pm 0.09) \times 10^{-10} \)
ATLAS di-muon trigger yields

- Run 1/2 baseline offline cuts applied

- separation of muons by either
  $|\Delta \eta(\mu^+,\mu^-)| > 0.2 \text{ rad}$ or
  $|\Delta \phi(\mu^+,\mu^-)| > 0.2 \text{ rad}$
  (typical L1 muon trigger granularity)

- normalized to $p_T(\mu_1) > 6 \text{ GeV} \& p_T(\mu_2) > 6 \text{ GeV}$ (lowest unprescaled di-\(\mu\) trigger in Run 2)

- work ongoing to improve trigger acceptance for near-by muons
Comparison of the 68.3% (solid), 95.5% (dashed) and 99.7% (dotted) stat.+syst. confidence regions for the extrapolated Run 2 statistics. Red contours are obtained exploiting the 2D Neyman belt construction based on pseudo-MC experiments, while blue contours are drawn at constant $\Delta \log L$ in the gaussian maximum approximation. The Run 2 pseudo-MCs reproduce the expected signal mass resolution and have been scaled with respect to their Run 1 counterpart according to the triggers available in Run 2, the different integrated luminosity and the different B production cross section. The black point shows the SM theoretical prediction and its uncertainty.