Rare Decays and other Electroweak $b$-physics Measurements at ATLAS and CMS

P. Ronchese - CMS/ATLAS collaborations

University and INFN Padova

50$^{\text{th}}$ Rencontres de Moriond - EW 2015

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Mars 14-21, 2015
Introduction

Rare decays:
- $\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+ \mu^-)$ measurement
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular analysis

CP violation:
- $B_s^0$ lifetime difference and CPV phase in $B_s^0 \rightarrow J/\psi \phi$
- $B_s^0 \rightarrow J/\psi f_0$ propaedeutic studies

Conclusions
Motivations to study HF physics at CMS & ATLAS

Look for indirect evidence or constraints to new physics beyond SM

- Tree level $W$ exchange hardly modified by NP processes
- Exploit the sensitivity of some processes to loop diagrams at high mass scales
- Rare FCNC decays branching ratios modified by new degrees of freedom in the loops
- Angular analysis to probe specific terms in effective lagrangian
- Measure CP violation to investigate NP contributions to mixing processes
ATLAS and CMS experiments

Data samples

- $\sqrt{s} = 7 \text{ TeV}, \mathcal{L} \sim 5 \text{ fb}^{-1}$ (2011 run)
- $\sqrt{s} = 8 \text{ TeV}, \mathcal{L} \sim 20 \text{ fb}^{-1}$ (2012 run)

All shown results involve dimuons
Dedicated triggers developed for analyses
Selections: dimuon mass, $p_T$, displaced vertex, pointing angle
Outline

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$B(B_{d,s}^0 \rightarrow \mu^+ \mu^-)$: SM predictions

- $B_{d,s}^0 \rightarrow \mu^+ \mu^-$ highly suppressed in the SM
  - FCNC: only at higher order processes (box, penguin)
  - Cabibbo suppressed: $|V_{ts(td)}|^2$
  - Helicity suppressed: $(m_{\mu}/m_B)^2$
  - Internal annihilation: $(f_B/m_B)^2$

New NLO-EW and NNLO-QCD corrections

C. Bobeth et al., PRL 112 (2014) 101801

- $\mathcal{B}(B_{s}^0 \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.65 \pm 0.23) \times 10^{-9}$
- $\mathcal{B}(B_{d}^0 \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}$
$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+ \mu^-)$: beyond SM

Significant deviations predicted by theories beyond SM

- New degrees of freedom are present
- Discrimination among BSM theories from $\mathcal{R} \equiv \mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$ ratio
- $\mathcal{R}$ prediction by BSM theories with minimal flavour violation equal as in SM

**BSM processes**

**NUHM**
J.R. Ellis et al., JHEP 05 (2006) 063

**MCPMFV**
J.R. Ellis et al., PRD 76 (2007) 115011

**Leptoquarks**
S. Davidson et al., JHEP 11 (2010) 073

**MSSM with large $\tan \beta$**

P. Ronchese - CMS/ATLAS
$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+\mu^-) : \text{search/measurement}$

$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+\mu^-) \text{ determined by comparison with another channel}$

$$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+\mu^-) = \frac{N_{\text{sig}} \epsilon_{\text{nrm}} f_u}{N_{\text{nrm}} \epsilon_{\text{sig}} f_{d,s}} \mathcal{B}(B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+\mu^- K^\pm)$$

- Combinatorial (from sidebands)
- Non-peaking: semileptonic $b$-decays
- Peaking: $(B_{d,s}^0, \Lambda_b^0) \rightarrow hh'$ (from simulation)

**Background:**

- Combinatorial (from sidebands)
- Non-peaking: semileptonic $b$-decays
- Peaking: $(B_{d,s}^0, \Lambda_b^0) \rightarrow hh'$ (from simulation)

**ATLAS($\sqrt{s} = 7$ TeV)**

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8} @ 95\% \text{ C.L.} \]

**CMS($\sqrt{s} = 7, 8$ TeV)(*)**

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.8^{+1.0}_{-0.9}) \times 10^{-9} \]

\[ \mathcal{B}(B_d^0 \rightarrow \mu^+\mu^-) = (4.4^{+2.2}_{-1.9}) \times 10^{-10} \]

(*) Changed vs. previously published on PRL

More infos at frame 28
**B(B_{d,s}^0 \rightarrow \mu^+ \mu^-)**: updates & CMS+LHCb combination

<table>
<thead>
<tr>
<th>Updated quantity</th>
<th>old</th>
<th>new</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_u/f_s</td>
<td>3.91 ± 0.31</td>
<td>3.86 ± 0.22</td>
</tr>
<tr>
<td>B(\Lambda_b^0 \rightarrow p\mu^-\nu)</td>
<td>(6.50 ± 6.50) \times 10^{-4}</td>
<td>(4.94 ± 2.19) \times 10^{-4} event by event weights</td>
</tr>
</tbody>
</table>

Time dependent corrections:
- Decay time dependent selection: time dependent efficiency
- Superposition of different mass eigenstates: time dependent width

**CMS+LHCb**

arXiv:1411.4413

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}
\]

\[
\mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}
\]

More info at frames 28, 29
$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+\mu^-)$: evolution

- Higher energy (up to $\sqrt{s} = 14$ TeV):
  - higher cross-section
- Higher luminosity (up to $L = 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$):
  - larger events sample
  - higher pile-up (up to 140)

CMS evolution
- Improved muon system (for Run2, limited effect)
- Improved tracker (after LS2 & for HL-LHC)
- Improved trigger

Vertexing efficiency loss
Tracking efficiency loss

- $f_u/f_s$ improved
  - Background estimation improved

CMS expectations

<table>
<thead>
<tr>
<th>$\mathcal{L}(\text{fb}^{-1})$</th>
<th>$\delta \mathcal{B}/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$</th>
<th>$\delta \mathcal{B}/\mathcal{B}(B_d^0 \rightarrow \mu^+\mu^-)$</th>
<th>$\delta R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>13%</td>
<td>48%</td>
<td>50%</td>
</tr>
<tr>
<td>3000</td>
<td>11%</td>
<td>18%</td>
<td>21%</td>
</tr>
</tbody>
</table>

$\delta R$ (at Run 300 GeV) = 33% ± 0.3%
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  - $B_s^0$ lifetime difference and CPV phase in $B_s^0 \rightarrow J/\psi \phi$
  - $B_s^0 \rightarrow J/\psi f_0$ propaedeutic studies
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Rare decays
CP violation
Conclusions
Backup

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$, $K^{*0} \rightarrow K^+ \pi^-$ angular analysis

Possible BSM physics effects through contributions in Wilson coefficients $C_7$, $C_9$ and $C_{10}$

Differential branching ratio

- Kinematic variables:
  - $\theta_L$, $\theta_K$, $\phi$ angles
  - $q^2 = m^2(\mu^+ \mu^-)$
- Parameters:
  - $A_{FB}$: muon forward/backward asymmetry
  - $F_L$: $K^{*0}$ longitudinal polarization
  - $F_S$, $A_S$: $K^+ \pi^-$ S-wave contribution and interference
- Form-factor independent observables

- Events divided in $q^2$ bins
- $B^0 \rightarrow K^{*0}(J/\psi, \psi')$ regions removed
- $\phi$ angle integrated out

2011 data

More infos at frame 32
**ATLAS**

ATLAS-CONF-2013-038

Sequential fit:
- Yields from mass fit
- $A_{FB}$, $F_L$ from angles fit
- $F_S$ from BaBar

**CMS**

PLB 727 (2013) 77

Simultaneous fit:
- $A_{FB}$, $F_L$, $F_S$, $A_S$
- $d\beta/dq^2$ by comparison with $B^0 \rightarrow K^{*0} J/\psi$

More infos at frames 32,33
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay parameters compatible with other experiments

Parameters dependence on $q^2$ compatible with SM predictions at low and high $q^2$

Waiting for $\sqrt{s} = 8$ TeV results

Looking for form-factor independent observables
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$B^0_s \rightarrow J/\psi \phi$ : lifetime difference and CPV phase

Flavoured initial state: admixture of $B_L$ and $B_H$

- Unflavoured final state:
  - direct and mixing-mediated decays
  - interference: phase $\phi_s \simeq -2\beta_s$
- Non-definite CP final state:
  - admixture of CP odd and even
  - components disentangled by time-dependent angular analysis: $\Theta = \theta, \varphi, \psi$

$|\Phi_s| < 0.05$ in MFV models

G.Isidori, arXiv:1302.0661

Reduced sensitivity of $\Delta \Gamma_s$ to physics beyond SM

J.Charles et al., PRD 84 (2011) 033005

$2\beta_s^{(SM)} = 0.0363^{+0.0016}_{-0.0015}$ rad

A.Lenz and U.Nierste, arXiv:1102.4274

$\Delta \Gamma_s^{(SM)} = 0.087 \pm 0.021$ ps$^{-1}$
**Introduction**

**Rare decays**

**CP violation**

**Conclusions**

**Backup**

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**$B_s^0 \to J/\psi\phi$: decay width parameters**

### Differential decay width

\[
\frac{d^4\Gamma(B_s^0(t))}{d\Theta dt} = f(\Theta, \alpha, ct) \propto \sum_{i=1}^{10} O_i(\alpha, ct) \cdot g_i(\Theta)
\]

\[
O_i(\alpha, ct) = N_i e^{-t/\tau} \left[ a_i \cosh\left(\frac{1}{2} \Delta \Gamma_s ct\right) + b_i \sinh\left(\frac{1}{2} \Delta \Gamma_s ct\right) \right. \\
\left. \pm c_i \cos(\Delta m_s ct) \pm d_i \sin(\Delta m_s ct) \right]
\]

$N_i, a_i, b_i, c_i, d_i$ terms depending on $\alpha$ parameters: \& $\Phi_s$ in $b_i, d_i$

- $A_\perp, A_0, A_\parallel, A_S$: P-wave and S-wave amplitudes
- $\delta_\perp, \delta_0, \delta_\parallel, \delta_S$: wave phases
- $|\lambda|$: direct CP violation
- $+(c_i, d_i)$ for $B_s^0$, $-(c_i, d_i)$ for $\bar{B}_s^0$

### Parameters fit

- $\delta_0 = 0$, $|\lambda| = 1$ fixed
- $\delta_{S\perp} = \delta_S - \delta_\perp$
- $\Delta m_s$ from PDG

### $B_s^0 - \bar{B}_s^0$ discrimination

Other $b$ flavour tagging

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**P. Ronchese - CMS/ATLAS**

EW measurements with $b$ at ATLAS and CMS - 17
**$B_s^0 \rightarrow J/\psi\phi$: flavour tagging**

- $B_s^0/\bar{B}_s^0$ flavour at production inferred from charge of decay products of the second $b$
- Charge-flavour correlation diluted (cascade, oscillations, ...)

**ATLAS ($\sqrt{s} = 7$ TeV)**

- combined muon charge
- combined jet charge

\[
\epsilon_{\text{tag}} = (32.1 \pm 0.01(\text{stat}))\% \\
P_{\text{tag}} = (1.45 \pm 0.05(\text{stat}))\%
\]

**CMS ($\sqrt{s} = 8$ TeV)**

- muon charge
- electron charge

\[
\epsilon_{\text{tag}} = (7.67 \pm 0.04(\text{stat}))\% \\
P_{\text{tag}} = (0.97 \pm 0.03(\text{stat}))\%
\]

Performances measured with $B^+ \rightarrow J/\psi K^+$ events

P. Ronchese - CMS/ATLAS

EW measurements with $b$ at ATLAS and CMS - 18
$B_s^0 \rightarrow J/\psi\phi$ : results

Unbinned maximum likelihood fit including per-event resolution and tagging probability terms

<table>
<thead>
<tr>
<th>ATLAS ($\sqrt{s} = 7$ TeV)</th>
<th>CMS ($\sqrt{s} = 8$ TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Gamma_S [\text{ps}^{-1}]$</td>
<td>$0.053 \pm 0.021 \pm 0.010$</td>
</tr>
<tr>
<td>$\phi_S [\text{rad}]$</td>
<td>$0.12 \pm 0.25 \pm 0.05$</td>
</tr>
</tbody>
</table>

Results compatible with world averages and SM expectations

More infos at frame 34
$B^0_s \rightarrow J/\psi \phi$ : evolution

$\phi_s$ error much bigger than theoretical uncertainty:
- more data needed...
- more difficult environment with increasing luminosity

**ATLAS evolution**

Tracker improvements:
- fourth pixel layer (for Run2)
- reduced pixel size (for HL-LHC)

Limited trigger bandwidth:
harder $p_T,\mu$ cuts with increasing luminosity

- 6 GeV at Phase-1
- 11 GeV at Phase-2

**Higher tracker performances**
- better vertex reconstruction
- proper decay time resolution improved by $\sim 30\%$

More infos at frame 35
$B_s^0 \to J/\psi \phi$ : evolution

Estimated PU
- 60 at Phase-1
- 200 at Phase-2
No significant effect on time resolution

Signal yield estimated from 2012 data by applying muon $p_T$ cuts and rescaling for efficiencies and luminosities

<table>
<thead>
<tr>
<th>ATLAS expectations</th>
<th>Expectations validated with 2011 measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}(fb^{-1})$</td>
<td>100</td>
</tr>
<tr>
<td>$p_T \mu$ cut [GeV]</td>
<td>6</td>
</tr>
<tr>
<td>$\sigma(\phi_s)$(stat)[rad]</td>
<td>0.054</td>
</tr>
</tbody>
</table>

More infos at frame 35
Outline

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  - $B^0_s \rightarrow J/\psi f_0$ propaedeutic studies
- Conclusions
$B_s^0 \rightarrow J/\psi f_0$: study motivations

Alternative channel to measure $\phi_s$

- $f_0$ is a scalar ($J^{PC} = 0^{++}$)
- The final state is a CP-odd eigenstate
- No need to disentangle two components
- Angular analysis no more needed

$$\Gamma(B_s^0/\bar{B}_s^0 \rightarrow J/\psi f_0) = \mathcal{N} e^{-\Gamma_{st}} \left\{ e^{\Delta \Gamma_{st}/2} (1 + \cos \phi_s) + e^{-\Delta \Gamma_{st}/2} (1 - \cos \phi_s) \right\}$$

Hadronic structure of $f_0(980)$

- quark-antiquark
- tetraquark
- $K\bar{K}$ molecule

Critical hadronic corrections

$B_s^0$ flavour at production

Tagged analysis

- Same technique used as for $B_s^0 \rightarrow J/\psi \phi$
- Tagging info added to $\sin \phi_s$
\[ B_s^0 \rightarrow J/\psi f_0 : \text{BR measurement} \]

**Propaedeutic studies**

- \( \mathcal{B}(B_s^0 \rightarrow J/\psi f_0) \mathcal{B}(f_0 \rightarrow \pi^+\pi^-) / \mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \mathcal{B}(\phi \rightarrow K^+K^-) \) has been measured.
- Lifetime and CPV measurement to come.

**Event selection:**

- \( J/\psi \) : dimuon originating from a displaced vertex
- \( f_0 \) : Two opposite-charge \( \pi \)
  \( |m_{\pi\pi} - 974 \text{ MeV}| < 50 \text{ MeV} \)
- \( \Phi \) : Two opposite-charge \( K \)
  \( |m_{KK} - 1020 \text{ MeV}| < 10 \text{ MeV} \)
$B^0_s \rightarrow J/\psi f_0 : \text{results}$

**BR ratio measurement: systematic uncertainties cancellation**

\[
R_{f_0/\phi} = \frac{\mathcal{B}(B^0_s \rightarrow J/\psi f_0)\mathcal{B}(f_0 \rightarrow \pi^+\pi^-)}{\mathcal{B}(B^0_s \rightarrow J/\psi \phi)\mathcal{B}(\phi \rightarrow K^+K^-)} = \frac{N_{f_0}^{\text{obs}}}{N_{\phi}^{\text{obs}}} \times \frac{\epsilon_{f_0}}{\epsilon_{\phi}}
\]

- Yield from unbinned max likelihood fit
- Efficiency from MC

**CMS($\sqrt{s} = 7$ TeV) arXiv:1501.06089**

\[
R_{f_0/\phi} = 0.140 \pm 0.013 \pm 0.018
\]

More infos at frame 27
ATLAS and CMS have produced significant EW results in HF physics

\( \mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) \) have been measured

An angular analysis of \( B^0 \rightarrow K^{*0}\mu^+\mu^- \) have been performed

The CP violation phase \( \phi_s \) in \( B_s^0 \rightarrow J/\psi\phi \) decay has been measured

The study of the \( B_s^0 \rightarrow J/\psi f_0 \) decay begun

All results are, up to now, compatible with SM predictions

...but there’s still room to squeeze it further
Extra informations

BACKUP
$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+\mu^-)$: additional material

Signal and background discriminated by mean of a multivariate analysis (BDT):

- **ATLAS:**
  - cut on BDT output
- **CMS:**
  - events divided in 12 categories
  - dimuon invariant mass fitted simultaneously in all categories

Background from $\Lambda_b^0 \rightarrow p\mu^-\nu$ (CMS):

- mis-reconstruction probability strongly dependent on $q^2 = m_{\mu\nu}^2$
- simulated distribution different from the predicted one (other predictions now available)
- weight defined as the ratio of the two distributions

A.Khodjamirian et al., JHEP 09 (2011) 106
$\mathcal{B}(B_{d,s}^0 \to \mu^+\mu^-)$: additional material

\[
\Gamma(B_S^0 \to \mu^+\mu^-) = (R_H + R_L)e^{-\Gamma_{st}}\left[\cosh\frac{y_st}{\tau_{B_S^0}} + A_{\Delta\Gamma}\sinh\frac{y_st}{\tau_{B_S^0}}\right]
\]

\[
y_s = (\Gamma_L - \Gamma_H)/(\Gamma_L + \Gamma_H) = 0.0615 \pm 0.0085 \text{ (from HFAG)}
\]

\[
A_{\Delta\Gamma} = (R_H - R_L)/(R_H + R_L) = 1.0 \text{ (from SM)}
\]

- Time dependent quantities used in the selection (e.g. impact parameters)
- Time integrated efficiency dependent on the decay rate

Y. Amhis et al., arXiv:1207.1158
K. De Bruyn et al., PRL 109 (2012) 041801
\[ \mathcal{B}(B_{d,s}^0 \rightarrow \mu^+\mu^-) : \text{additional material} \]

Only muons in the barrel

<table>
<thead>
<tr>
<th>Phase-1</th>
<th>Phase-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass resolution ( \approx 42 \text{ MeV} )</td>
<td>Mass resolution: ( \approx 28 \text{ MeV} )</td>
</tr>
<tr>
<td>Uncertainties:</td>
<td>Uncertainties:</td>
</tr>
<tr>
<td>( B^+ ) : 5%</td>
<td>on ( B^+ ) : 3%</td>
</tr>
<tr>
<td>on peaking bg: 20%</td>
<td>on peaking bg: 10%</td>
</tr>
<tr>
<td>on semileptonic bg: 25%</td>
<td>on semileptonic bg: 20%</td>
</tr>
<tr>
<td>on ( f_s/f_u ) : 5%</td>
<td>on ( f_s/f_u ) : 5%</td>
</tr>
<tr>
<td>Trigger &amp; PU: same as ( \sqrt{s} = 8 \text{ TeV} )</td>
<td>Trigger &amp; PU: reduced efficiency</td>
</tr>
<tr>
<td></td>
<td>35% signal and normalization</td>
</tr>
<tr>
<td></td>
<td>30% backgrounds</td>
</tr>
</tbody>
</table>
$\mathcal{B}(B^0_{d,s} \rightarrow \mu^+ \mu^-) :$ additional material
**CMS parametrization**

\[
\frac{1}{\Gamma} \frac{d^3\Gamma}{d \cos \theta_K d \cos \theta_L dq^2} = \frac{9}{16} \left\{ \left[ \frac{2}{3} F_S + \frac{4}{3} A_S \cos \theta_K \right] (1 - \cos^2 \theta_L) + (1 - F_S) \left[ 2 F_L \cos^2 \theta_K (1 - \cos^2 \theta_L) + \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta_L) + \frac{4}{3} A_{FB} (1 - \cos^2 \theta_K) \cos \theta_L \right] \right\}
\]

\( F_S, A_S \) constrained from \( B^0 \to K^{*0} J/\psi \) and \( B^0 \to K^{*0} \psi' \)

\[
\frac{d\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{dq^2} = \frac{\epsilon_N}{\epsilon_S} \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi)}{Y_N} \frac{dY_S}{dq^2}
\]

**ATLAS parametrization**

\[
\frac{1}{\Gamma} \frac{d^2\Gamma}{d \cos \theta_L dq^2} = \frac{3}{4} F_L (1 - \cos^2 \theta_L) + \frac{3}{8} (1 - F_L) (1 + \cos^2 \theta_L) + A_{FB} \cos \theta_L
\]

\[
\frac{1}{\Gamma} \frac{d^2\Gamma}{d \cos \theta_K dq^2} = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L) (1 - \cos^2 \theta_K)
\]
$B^0 \rightarrow K^{*0} \mu^+\mu^-$, $K^{*0} \rightarrow K^+\pi^-$: additional material
### Introduction

Rare decays

CP violation

Conclusions

Backup

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### Rare decays

**CP violation**

**Conclusions**

**Backup**

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### Additional Material

**$B_s^0 \rightarrow J/\psi \phi$ : additional material**

<table>
<thead>
<tr>
<th>ATLAS ($\sqrt{s} = 7$ TeV)</th>
<th>CMS ($\sqrt{s} = 8$ TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$</td>
<td>A_S</td>
</tr>
<tr>
<td>$</td>
<td>A_\perp</td>
</tr>
<tr>
<td>$</td>
<td>A_\parallel</td>
</tr>
<tr>
<td>$\delta_\parallel [\text{rad}]$</td>
<td>[3.04, 3.23]</td>
</tr>
<tr>
<td>$\delta_\perp [\text{rad}]$</td>
<td>3.89 ± 0.47 ± 0.11</td>
</tr>
<tr>
<td>$\delta_S - \delta_\perp [\text{rad}]$</td>
<td></td>
</tr>
<tr>
<td>$\delta_\perp - \delta_s [\text{rad}]$</td>
<td>[3.02, 3.25]</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$[1/(0.677 \pm 0.007 \pm 0.004)]$ ps</td>
</tr>
</tbody>
</table>

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**Back to main frame 19**
$B_s^0 \rightarrow J/\psi \phi$: additional material

$\sigma(pp \rightarrow J/\psi)$ at $\sqrt{s} = 14$ TeV assumed to be twice as at $\sqrt{s} = 7$ TeV