Recent Heavy Flavour results from CMS

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on behalf of CMS collaboration

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Introduction

B-physics at CMS

- In addition to high $p_T$ physics (SM, Higgs, searches) CMS can give significant contribution to beauty and heavy flavour physics
- in some field able to compete with a dedicated experiment as LHCb
- Key elements:
  - large production cross-section at LHC
  - excellent tracking and muon id performances
  - flexible trigger system able to collect data at high luminosity and large pile up

This presentation

I will report some of the (not-so) recent results for the CMS collaboration in Heavy Flavour: focus on most recent results, not a complete review, personal bias in place.
More complete information about HF-physics results can be found at CMS public results webpage
Outline

1 CMS performance
2 Quarkonia production
   • Single quarkonium production
   • Prompt Double $\Upsilon$ observation
3 Properties
   • Lifetime measurement
   • $\Lambda_b$ polarization
4 Spectroscopy
   • Search for $X^+(5568) \rightarrow B^0_s \pi^+$
5 Rare decays and angular analysis
   • $B^0_s \rightarrow \mu \mu$
   • $b \rightarrow s \mu \mu$
6 Summary
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Experimental setup: dedicated HF triggers

Experimental setup: trigger optimised for different analysis

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5 (prompt) quarkonia states \( J/\psi, \psi(2S), \Upsilon(1s, 2s, 3s) \)
\( \sqrt{s} = 13 \text{ TeV}, \ L = 2.4(2.7) \text{ fb}^{-1}, \ |y_{\mu\mu}| < 1.2 \)

\[
\frac{d^2\sigma}{dp_T dy} \cdot B(q\bar{q} \to \mu\mu) = \frac{N(q\bar{q})(p_T, y)}{\mathcal{L} \Delta p_T \Delta y} \cdot \left\langle \frac{1}{(\varepsilon A)(p_T, y)} \right\rangle
\]

\[
\varepsilon_{\mu\mu}(p_T, y) = \varepsilon_{\mu}(p_{T1}, \eta_1) \cdot \varepsilon_{\mu}(p_{T2}, \eta_2) \cdot \rho(p_T, \eta) \cdot \varepsilon_{\text{trk}}^{2}
\]

from tag & probe \quad \text{correlation} \quad \text{Tracking}

\[
A = \frac{N_{\text{kin}}^{\text{gen}}(p_T, y)}{N_{\text{gen}}^{\text{gen}}(p_T, y)} \text{ from MC simulation}
\]
Cross section results

Shape vs $p_T$ consistent for all quarkonia states across rapidity regions
Comparison with NLO NRQCD prediction and 7 TeV results

**J/ψ, ψ(2S)**

**CMS**

| y | < 1.2
|---|---|
| | 2.3 − 2.7 fb⁻¹ (13 TeV)

\[
\sigma_{\text{data}} \times B_{\text{theory}}
\]

**Γ(1S), Γ(2S), Γ(3S)**

**CMS**

| y | < 1.2
|---|---|
| | 2.7 fb⁻¹ (13 TeV)

\[
\sigma_{\text{data}} \times B_{\text{theory}}
\]

Good agreement

- NRQCD under(over)estimates J/ψ (ψ(2S)), within uncert.
- Ratio 13/7 TeV changing slowly with \( p_T \), expected from evolution of pdf

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HF-physics at CMS

Cracow 09/01/2018 8 / 31
Prompt Double $\Upsilon$ observation 8 TeV

Double $J/\psi$ already seen

- HLT: $3\mu$: 1 pair with $8.5 < M_{\mu\mu} < 11$ GeV
- $p_T^{\mu} > 3.5$ GeV, $|\eta| < 2.4$
- vertexing (on $2\mu$ & $4\mu$);
- fiducial region: $|y^\Upsilon| < 2.0$

Signal extracted with 2D ext-UML of $M^{(1)}_{\mu\mu}$ and $M^{(2)}_{\mu\mu}$

- $M^{(1)}_{\mu\mu}$ ($M^{(2)}_{\mu\mu}$) higher (lower)-mass $\Upsilon$ candidate
  - if $(\Upsilon(1S) \Upsilon(2S))$: $\Upsilon(2S)$ appears in $M^{(1)}_{\mu\mu}$
- $N_{\Upsilon(1S)\Upsilon(1S)} = 38 \pm 7$ ($\gg 5\sigma$)
- $N_{\Upsilon(1S)\Upsilon(2S)} = 13^{+6}_{-5}$ ($\sim 2.6\sigma$)

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Fiducial and effective cross section

Fiducial cross section, assuming isotropical decay of both $\Upsilon(1S)$:

$$\sigma_{\text{fid}} = \frac{N_{\Upsilon(1S)\Upsilon(1S)}}{\mathcal{L}B^2(\Upsilon(1S) \rightarrow \mu\mu) \langle A_\varepsilon \rangle} = 68.8 \pm 12.7(\text{stat}) \pm 7.4(\text{syst}) \pm 2.8(B) \text{ pb}$$

with different extreme polarization $\sigma_{\text{fid}} =^{+36\%}_{-38\%}$.

$A_\varepsilon$ on a event-by-event basis, using measured $\Upsilon$ and $\mu$ momenta (data embedding into simulation)

Effective cross-section (with additional Double Parton Scattering process)

$$\sigma_{\text{eff}} = \frac{1}{2} \frac{\sigma^2_{\Upsilon(1S)}}{\sigma_{\text{DPS}}} = \frac{1}{2} \frac{\sigma^2_{\Upsilon(1S)}}{f_{\text{DPS}} \sigma_{\text{fid}} B^2(\Upsilon(1S) \rightarrow \mu\mu)}, \quad \sigma_{\Upsilon(1S)} \text{ form} \quad [\text{CMS, PLB 749(2015) 14}]$$

- $2.2 < \sigma_{\text{eff}} < 6.6 \text{ mb}$
  - corresponding to $f_{\text{DPS}} \approx 10 - 30\%$ from residual of SPS prediction
  - not enough stats to measure $f_{\text{DPS}}$ from $\Delta y_{\Upsilon(1S)\Upsilon(1S)}$.

✓ heavy quarkonia measurement $(2 - 8 \text{ mb})$ (mostly from $gg$)

✗ smaller than that from multi-jet studies $12 - 20 \text{ mb}$ (mostly from $q\bar{q}$ and $qg$)

might indicate distance between g’s smaller than that of q’s or q-g
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6 Summary
Motivation:

- Precision lifetime measurement play important role in non-perturbative QCD
  - description by Heavy Quark Expansion (HQE) model
  - perturbative expansion of interaction of single heavy quark with light ones
- $B^+_c$ weak decay through either b or c decay (shorter $\tau$) or via annihilation (predicted to contribute 10% of decay width)
  - lifetime measurement can be used to test its decay model
  - some discrepancies between $\tau_{B^+_c}$: LHCb > Tevatron.

CMS measured lifetime of b-hadrons decaying to $J/\psi(\rightarrow \mu\mu) + X$: 8 TeV, 19.7 fb$^{-1}$

- States considered:
  - $B^0 \rightarrow J/\psi K^*$, $B^0 \rightarrow J/\psi K^0_S$
  - $B^0_s \rightarrow J/\psi \pi \pi$, $B^0_s \rightarrow J/\psi \phi$
  - $\Lambda_b \rightarrow J/\psi \Lambda$
  - $B^+_c \rightarrow J/\psi K^+$
  - Reference channel $B^+ \rightarrow J/\psi K^+$
Methods: \( ct \) proper decay length

- b-hadron lifetime from proper decay length:
  \[ ct = \frac{L}{(\beta\gamma c)} = \frac{L_{xy}}{(\beta\gamma)_{T}} = \frac{M}{T} \]

- UML of \( ct \), \( \sigma_{ct} \) (per-event), and \( M_{b-had} \)

- efficiency distortion corrected from simulation

- turn-on region discarded \( ct > 200 \mu m \) (100 \( \mu m \) \( B_c^{+} \))
Results: $B^0$ lifetime

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>CMS Results</th>
<th>PDG2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow J/\psi K^*$</td>
<td>$c\tau_{B^0} = 453.0 \pm 1.6,(\text{stat}) \pm 1.5,(\text{syst})$</td>
<td>$455.7 \pm 1.2\ \mu m$</td>
</tr>
<tr>
<td>$B^0 \rightarrow J/\psi K^0_S$</td>
<td>$c\tau_{B^0} = 457.8 \pm 2.7,(\text{stat}) \pm 2.7,(\text{syst})$</td>
<td></td>
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</table>

Good agreement between the two final states and with world average
Results: \( B_s^0 \) lifetimes

\[ B_s^0 \rightarrow J/\psi \phi \]

- **Decay mode**
  - \( B_s^0 \rightarrow J/\psi \pi \pi \)
  - \( B_s^0 \rightarrow J/\psi \phi \)

\[ \begin{array}{c|c|c}
\text{Decay mode} & \text{CMS results} & \text{PDG2016} \\
\hline
B_s^0 \rightarrow J/\psi \pi \pi & \tau_H = 504.3 \pm 10.5 \text{(stat)} \pm 3.7 \text{(syst)} & 509 \pm 12 \text{ \( \mu \)m} \\
B_s^0 \rightarrow J/\psi \phi & \tau_{\text{eff}} = 443.9 \pm 2.0 \text{(stat)} \pm 1.2 \text{(syst)} & 443 \pm 2.4 \text{ \( \mu \)m} \\
\end{array} \]

- **J/\psi \pi \pi** dominated by \( B_s^0 \rightarrow J/\psi f(980) \): CP-odd \( \tau_H \)
- **J/\psi \phi** mixture of CP-odd and even, effective lifetime \( \tau_{\text{eff}} \)
  - Complementary to measurement of weak mixing phase \( \varphi_S \) [CMS, PLB 757(2016)97]
- Combination of \( \tau_H \) and \( \tau_{\text{eff}} \) gives: \( c \tau_L = 419 \pm 6.4 \text{ \( \mu \)m} \), compatible with WA
Results: $\Lambda_b$ lifetime

- $c\tau = 442.1 \pm 8.2\text{(stat)} \pm 2.7\text{(syst)} \mu m$
- good agreement with previous CMS results and with world average ($439.8 \pm 3.0 \mu m$)
- follow the tendency for longer lifetime

$\Lambda_b \to J/\psi \Lambda^0$

$\sigma(\text{Fit}) / \sigma(\text{Data}) = 3 - 2 - 1 - 0 1 2 3$

$\Lambda_b$ lifetime measurement

Data vs. Fit

 CMS (2017, 19.5 fb$^{-1}$), $J/\psi \Lambda$
 LHCb (2015, 3.0 fb$^{-1}$), $J/\psi \Lambda$
 LHCb (2012, 1.0 fb$^{-1}$), $J/\psi \Lambda$
 ATLAS (2013, 4.9 fb$^{-1}$), $J/\psi \Lambda$
 CDF (2011, 4.3 fb$^{-1}$), $J/\psi \Lambda$
 CMS (2013, 5.0 fb$^{-1}$), $J/\psi \Lambda$
 DØ (2012, 10.4 fb$^{-1}$), $J/\psi \Lambda$

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HF-physics at CMS
**B⁺c lifetime measurement method**

- for B⁺c used $\Delta \Gamma$ (LHCb approach$^{[PLB \ 742(2015) \ 29]}$);
  - difference of total width $B⁺c \to J/\psi \pi^+$ and $B⁺ \to J/\psi K^+$
  - $c\tau_{B⁺} = 490 \pm 0.8$(stat) $\mu$m PDG2016: $491.4 \pm 1.2\mu$m
- large background, smaller lifetime: the ratio method reduces syst uncert, as the resolution cancel out.

$$R(t) = \frac{N_{B⁺c}}{N_{B⁺}} = \frac{e^{-t/\tau_{B⁺c}} \otimes G(t) \varepsilon_{B⁺c}}{e^{-t/\tau_{B⁺}} \otimes G(t) \varepsilon_{B⁺}} \approx R_\varepsilon(t)e^{-\Delta \Gamma t} \text{ with } \Delta \Gamma = 1/\tau_{B⁺c} - 1/\tau_{B⁺}$$
$\Delta \Gamma$ extracted via a binned $\chi^2$-fit to $R(t)$, corrected for efficiency ratio, with an exponential function.

Results is converted to $\tau_{B_c^+}$ using WA $\tau_{B^+}$

$c \tau_{B_c^+} = 162.3 \pm 8.2\text{(stat)} \pm 4.7\text{(syst)} \pm 0.1(\tau_{B^+}) \mu$m

- In agreement with recent LHCb results and world average
- higher than Tevatron results
Λ_b polarization

- HQET predicts large fraction of b polarization to be retained after hadronization [hep-ph/0702191.]
- Λ_b polarization P measured in decay Λ_b → J/ψ(→ μμ)Λ(→ pπ−)
  - both prompt and non-prompt decay;
  - 7(8) TeV with 5.2(19.8) fb⁻¹
  - both Λ_b and Λ̄_b decay: from CP P = −P

  - α₁ parity-violating decay asymmetry
  - α₂ longitudinal polarization of Λ
  - γ₀ related to J/ψ polarization
  - αΛ is the asym parameter of Λ → pπ⁻ decay
    (fixed to 0.642 ± 0.013)
  - α₁, α₂, γ₀ related to T_{ij} helicity amplitudes of Λ
    and J/ψ [Kramer-Sima, NPB 50 (1996) 125]

5 angles describe the decay: Ω = (θ_Λ, θ_p, φ_p, θ_μ, φ_μ) integrating over φ_μ and φ_p simplify the pdf (i_{max} = 19 → 8)

Helicity formalism:

\[
\frac{d^5Γ}{dΩ_5}(Ω) ≈ \sum_{i=1}^{8} u_i(α_1, α_2, γ_0) v_i(P, α_Λ) w_i(Ω).
\]
\( \Lambda_b \) polarization results

- UML fit to 7 and 8 TeV, \( \Lambda_b \) and \( \bar{\Lambda}_b \)
  - \( \theta_{\Lambda_p, \mu} \) and \( M_{J/\psi \Lambda} \)
  - background from \( M \) side bands
  - 3D efficiency from simulation
  - \( N_{\Lambda_b} = 984 \pm 41(2114 \pm 57) \) 7(8) TeV
  - \( N_{\bar{\Lambda}_b} = 919 \pm 45(2021 \pm 57) \) 7(8) TeV

\[
\begin{align*}
P &= 0.00 \pm 0.06 \text{ (stat)} \pm 0.06 \text{ (syst)}, \\
\alpha_1 &= 0.14 \pm 0.14 \text{ (stat)} \pm 0.10 \text{ (syst)}, \\
\alpha_2 &= -1.11 \pm 0.04 \text{ (stat)} \pm 0.05 \text{ (syst)}, \\
\gamma_0 &= -0.27 \pm 0.08 \text{ (stat)} \pm 0.11 \text{ (syst)},
\end{align*}
\]

- Good agreement with LHCb [PLB 724 (2013) 27] and ATLAS [PRD 89 (2014) 092009]
- \( P \) consistent with pQCD prediction 10% [PLB 649 (2007) 152], but disfavour \( P \sim 20\% \) [PLB 614 (2005) 165]
- \( \alpha_1 \) predicted 0.78 from HQET [arXiv:hep-ph/0412116] disfavoured, other models ok \( \sim [−0.2, −0.1] \)
- \( \alpha_2 \): positive helicity for \( \Lambda \) suppressed, as predicted [PRD 88 (2013) 114018]
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Search for $X^+(5568) \rightarrow B_s^0 \pi^+$

Observation by D0 [PRL 117 (2016) 022003] with $L=10.4 \text{ fb}^{-1}$, $\approx 5.5k \ B_s^0$ reported 5.1$\sigma$

"first instance of a hadronic state with valence quarks of four different flavors."

Not confirmed by LHCb [PRL 117 (2016) 152003] with $3 \text{ fb}^{-1}$, $(30+14)k \ B_s^0 \rightarrow (J/\psi \phi + D_s^- \pi^+)$

Search performed at CMS [CERN-EP-2017-287, sub. to PRL] based on $\sim 50k \ B_s^0 \rightarrow J/\psi \phi$ decays

- Signal: 2 gaussian
- background: exponential
- signal region, side bands
Search for $X^+(5568)$: invariant mass scan

- Search for structures in the $M_{B_s^0 \pi^\pm}$
  - $B_s^0 \rightarrow J/\psi \phi$
    - $2 \mu, p_T^{\mu\mu} > 4$ GeV, $p_T^{\mu\mu} > 7$ GeV
    - 2 tracks ($K^{\pm}$), $p_T^K > 0.7$ GeV, $|M_{KK} - M_\phi| < 10$ MeV
    - fit $\mu\mu KK$ to common vertex
    - $p_T > 10$ GeV, $D_{xy}/\sigma > 3$, pointing to primary vtx
  - $X(5568)^\pm \rightarrow B_s^0 \pi^\pm$
    - $p_T^\pi > 0.5$ GeV, no $\Delta R(B_s^0, \pi)$ cut
  - $M^\Delta_{B_s^0 \pi^\pm} = M_{J/\psi KK \pi} - M_{J/\psi KK} + M_{B_s^0}$
    - strong correlation between $M_{J/\psi KK \pi}$ and $M_{J/\psi KK}$
  - Comparison $M^\Delta_{B_s^0 \pi^\pm}$ in $B_s^0$ signal and side bands
    - removing $M_{KK}$ cut, lower/higher SB
    - from higher SB: $B_{1,2}^{(*)} \rightarrow B_s^0(\pi^\pm), \text{with } B_s^0 \rightarrow J/\psi K^+ \pi^-$
Search for $X^+(5568)$: impact of $\Delta R$ cut and results

**Cone cut** $\Delta R(B_s^0, \pi) = \sqrt{\Delta \eta^2 + \Delta \phi^2}$, strongly affect $M$ distribution

\[
\rho_x = \frac{N_X(5568)}{N_{B_s^0} \varepsilon_{B_s^0} \varepsilon_{X(5568)}} \varepsilon_{B_s^0} < 1.1(1.0)\% \text{ at } 90\% \text{ CL}
\]

for $p_T > 10(15) \text{ GeV}$

$\rho_x(D0) = 8.6 \pm 2.6 \pm 1.6\%$

$\Gamma_{D0} \sim 20 \text{ MeV}$

**UML fit with BW$\otimes 3G$:**

\[
N_X = -85 \pm 160 \text{ events}
\]

$\rho_x$ for different width $\Gamma$

$\Gamma_D \sim 20 \text{ MeV}$

D0 used $\Delta R < 0.3$
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B → µµ: CMS results

**CMS results for B(B_{s,d} → µµ)**

**Run I results** [PRL 111 (2013) 101804]

L = (5 + 20) fb⁻¹ @ 7&8 TeV

\[ B(B_s^0) = 3.0^{+0.9}_{-0.8} \text{(stat.)}^{+0.6}_{-0.4} \text{(syst.)} \times 10^{-9} \quad 4.3\sigma \quad (4.8 \text{ exp}) \]

\[ B(B_d^0) < 1.1 \times 10^{-9} \quad 95\% \ CL \]

\[ B = 3.5^{+2.1}_{-1.8} \text{(stat. + syst.)} \times 10^{-10} \quad 2.0\sigma \]
B → μμ: Projection for Run2

- ‘Simple’ scaling of current analysis in CMS-FTR-13-022
  - not including ‘better’ methodology

<table>
<thead>
<tr>
<th>L (fb⁻¹)</th>
<th>No. of B⁺</th>
<th>No. of B⁰</th>
<th>δB/B(B⁺ → μ⁺μ⁻)</th>
<th>δB/B(B⁰ → μ⁺μ⁻)</th>
<th>δB/B(B⁺ → τ⁺τ⁻)</th>
<th>δB/B(B⁰ → τ⁺τ⁻)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>16.5</td>
<td>2.0</td>
<td>35%</td>
<td>&gt;100%</td>
<td>0.0–1.5σ</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>100</td>
<td>144</td>
<td>18</td>
<td>15%</td>
<td>66%</td>
<td>0.5–2.4σ</td>
<td>71%</td>
</tr>
<tr>
<td>300</td>
<td>433</td>
<td>54</td>
<td>12%</td>
<td>45%</td>
<td>1.3–3.3σ</td>
<td>47%</td>
</tr>
<tr>
<td>3000</td>
<td>2096</td>
<td>256</td>
<td>12%</td>
<td>18%</td>
<td>5.4–7.6σ</td>
<td>21%</td>
</tr>
</tbody>
</table>

- Trigger will be crucial (p_{⊥} resolution at L1 for dimuons)
  - E.g. L1 track trigger!

B → μμ new analysis:
- improved muon ID
- improved pileup studies
- effective lifetime determination
- in-situ dimuon trigger/reconstruction bias determination
- not a "search analysis" any more
$B^0 \rightarrow K^* \mu \mu$: introduction

- $B^0 \rightarrow K^* \mu \mu$ FCNC process
- Fully described by: $\theta_\ell, \theta_K, \varphi$ and $q^2 = M_{\mu\mu}^2$;
- $B^0 (\bar{B}^0)$ identified by K and $\pi$ charges;
- First analysis [PLB 753 (2016) 424] 8 TeV, 20 fb$^{-1}$:
  - measured $A_{FB}$, $F_L$, and $dB/dq^2$ vs $q^2$.
  - Signal Yield $\sim$ 1400 events
- Use same dataset to measure $P'_5$ and $P_1$ with CMS data
Final state $K^+\pi^-\mu^+\mu^-$ has contribution from \textbf{P-wave ($K^*$)} and \textbf{S-wave}.

In total, PDF has 14 parameters: fold around $\varphi = 0$ and $\theta_{\ell} = \pi/2$ to reduce them.

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\varphi d\cos \theta_{\ell} d\cos \theta_K} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left( F_S + A_s \cos \theta_K \right) \left( 1 - \cos^2 \theta_{\ell} \right) + A^5_s \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_{\ell} \cos \Phi} \right. \\
+ (1 - F_S) \left[ 2F_L \cos^2 \theta_K \left( 1 - \cos^2 \theta_{\ell} \right) + \frac{1}{2} \left( 1 - F_L \right) \left( 1 - \cos^2 \theta_K \right) \left( 1 + \cos^2 \theta_{\ell} \right) \right] \\
+ \frac{1}{2} P_1 (1 - F_L)(1 - \cos^2 \theta_K)(1 - \cos^2 \theta_{\ell}) \cos 2\Phi \\
+ 2P'_5 \cos \theta_K \sqrt{F_L (1 - F_L)} \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_{\ell} \cos \Phi} \left\} \right.
\]

6 parameters left: statistics not enough to perform a fully floating fit.

$F_L$, $F_S$, and $A_s$ fixed from previous CMS measurement.

$P_1$ and $P'_5$ measured, $A^5_s$ nuisance parameter.
$B^0 \rightarrow K^* \mu \mu$: Signal Pdf

- Final state $K^+ \pi^- \mu^+ \mu^-$ has contribution from $P$-wave ($K^*$) and $S$-wave
- In total, PDF has 14 parameters: fold around $\varphi = 0$ and $\theta_\ell = \pi/2$ to reduce them

$$\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 \, d \cos \theta_i \, d \cos \theta_K \, d \phi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[ (F_S + A_S \cos \theta_K) (1 - \cos^2 \theta_i) + A_5 \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_i} \cos \phi \right] 
+ (1 - F_S) \left[ 2F_L \cos^2 \theta_K (1 - \cos^2 \theta_i) + \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta_i) \right] 
+ \frac{1}{2} P_1 (1 - F_L)(1 - \cos^2 \theta_K)(1 - \cos^2 \theta_i) \cos 2\phi 
+ 2P'_5 \cos \theta_K \sqrt{F_L (1 - F_L) \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_i} \cos \phi} \right\}$$

- 6 parameters left: statistics not enough to perform a fully floating fit
- $F_L$, $F_S$, and $A_s$ fixed from previous CMS measurement
- $P_1$ and $P'_5$ measured, $A_5^s$ nuisance parameter
**B^0 → K^*μμ: Signal Pdf**

- Final state $K^+π^−μ^+μ^−$ has contribution from P-wave ($K^*$) and S-wave
- in total, PDF has 14 parameters: fold around $φ = 0$ and $θ_ℓ = π/2$ to reduce them

\[
\frac{1}{dΓ/dq^2} \frac{d^4Γ}{dq^2 d cos θ_i d cos θ_K d φ} = \frac{9}{8π} \left\{ \frac{2}{3} \left( FS + As cos θ_K \right) \left( 1 - cos^2 θ_i \right) + A_5^S \sqrt{1 - cos^2 θ_K} \sqrt{1 - cos^2 θ_i cos φ} \right\} + \left( 1 - FS \right) \left[ 2F_L cos^2 θ_K \left( 1 - cos^2 θ_i \right) + \frac{1}{2} \left( 1 - F_L \right) \left( 1 - cos^2 θ_K \right) \left( 1 + cos^2 θ_i \right) \right] + \frac{1}{2} P_1 (1 - F_L) (1 - cos^2 θ_K) (1 - cos^2 θ_i) cos 2φ + 2P'_5 cos θ_K \sqrt{F_L (1 - F_L)} \sqrt{1 - cos^2 θ_K} \sqrt{1 - cos^2 θ_i cos φ} \right\}
\]

- 6 parameters left: statistics not enough to perform a fully floating fit
- $F_L$, $F_S$, and $A_s$ fixed from previous CMS measurement
- $P_1$ and $P'_5$ measured, $A_5^S$ nuisance parameter
$B^0 \rightarrow K^* \mu \mu$: Signal Pdf

- Final state $K^+\pi^-\mu^+\mu^-$ has contribution from P-wave ($K^*$) and S-wave
- In total, PDF has 14 parameters: fold around $\varphi = 0$ and $\theta_\ell = \pi/2$ to reduce them

\[
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{dq^2 d\cos \theta_i d\cos \theta_K d\phi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left( F_S + A_S \cos \theta_K \right) \left( 1 - \cos^2 \theta_i \right) + A_S^5 \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_i} \cos \phi \right\}
+ (1 - F_S) \left[ 2F_L \cos^2 \theta_K \left( 1 - \cos^2 \theta_i \right) + \frac{1}{2} (1 - F_L) \left( 1 - \cos^2 \theta_K \right) \left( 1 + \cos^2 \theta_i \right) \right]
+ \frac{1}{2} P_1 (1 - F_L) (1 - \cos^2 \theta_K) (1 - \cos^2 \theta_i) \cos 2\phi
+ 2P_5' \cos \theta_K \sqrt{F_L (1 - F_L)} \sqrt{1 - \cos^2 \theta_K} \sqrt{1 - \cos^2 \theta_i} \cos \phi \right\}
\]

- 6 parameters left: statistics not enough to perform a fully floating fit
- $F_L$, $F_S$, and $A_s$ fixed from previous CMS measurement
- $P_1$ and $P_5'$ measured, $A_s^5$ nuisance parameter
\[ p.d.f. \left( m, \cos \theta_K, \cos \theta_l, \phi \right) = Y_S^C \cdot \left( S_i^R (m) \cdot S_i^a (\cos \theta_K, \cos \theta_l, \phi) \cdot \epsilon_i^R (\cos \theta_K, \cos \theta_l, \phi) \right) \]
\[ + \frac{f_i^M}{1 - f_i^M} \cdot S_i^M (m) \cdot S_i^a (- \cos \theta_K, - \cos \theta_l, - \phi) \cdot \epsilon_i^M (\cos \theta_K, \cos \theta_l, \phi) \]
\[ + Y_B \cdot B_i^m (m) \cdot B_i^{\cos \theta_K} (\cos \theta_K) \cdot B_i^{\cos \theta_l} (\cos \theta_l) \cdot B_i^{\phi} (\phi). \]
p.d.f. \( (m, \cos \theta_K, \cos \theta_l, \phi) = Y^C_S \cdot \left( S^R_i(m) \cdot S^a_i(\cos \theta_K, \cos \theta_l, \phi) \cdot \epsilon^R_i(\cos \theta_K, \cos \theta_l, \phi) \right) \\
+ \frac{f^M_i}{1 - f^M_i} \cdot S^M_i(m) \cdot S^a_i(- \cos \theta_K, - \cos \theta_l, -\phi) \cdot \epsilon^M_i(\cos \theta_K, \cos \theta_l, \phi) \\
+ Y_B \cdot B^m_i(m) \cdot B^\cos \theta_K_i(\cos \theta_K) \cdot B^\cos \theta_l_i(\cos \theta_l) \cdot B^\phi_i(\phi) \)
p.d.f. \((m, \cos \theta_K, \cos \theta_l, \phi) = Y^C_S \cdot (S^R_i(m) \cdot S^a_i(\cos \theta_K, \cos \theta_l, \phi) \cdot \epsilon^R_i(\cos \theta_K, \cos \theta_l, \phi) \cdot S^M_i(m) \cdot S^a_i(-\cos \theta_K, -\cos \theta_l, -\phi) \cdot \epsilon^M_i(\cos \theta_K, \cos \theta_l, \phi) + Y_B \cdot B^m_i(m) \cdot B^c_i(\cos \theta_K(\cos \theta_l) \cdot B^c_i(\cos \theta_l) \cdot B^\phi_i(\phi).}
\[ p.d.f.(m, \cos \theta_K, \cos \theta_l, \phi) = Y_S^C \cdot (S_i^R(m)) \cdot S_i^a(\cos \theta_K, \cos \theta_l, \phi) \cdot \epsilon_i^R(\cos \theta_K, \cos \theta_l, \phi) \]

\[ + \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos \theta_K, -\cos \theta_l, -\phi) \cdot \epsilon_i^M(\cos \theta_K, \cos \theta_l, \phi) \]

\[ + Y_B \cdot B_i^m(m) \cdot B_i^{\cos \theta_K}(\cos \theta_K) \cdot B_i^{\cos \theta_l}(\cos \theta_l) \cdot B_i^\phi(\phi). \]
p.d.f. \( (m, \cos \theta_K, \cos \theta_l, \phi) = Y_S^C \cdot \left( S_i^R(m) \cdot S_i^a \left( \cos \theta_K, \cos \theta_l, \phi \right) \cdot \epsilon_i^R \left( \cos \theta_K, \cos \theta_l, \phi \right) \right) \)

\[
3D \text{ Efficiency} \quad \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a \left( - \cos \theta_K, - \cos \theta_l, - \phi \right) \epsilon_i^M \left( \cos \theta_K, \cos \theta_l, \phi \right) 
\]

\[+\ Y_B \cdot B_i^m(m) \cdot B_i^{\cos \theta_K} \left( \cos \theta_K \right) \cdot B_i^{\cos \theta_l} \left( \cos \theta_l \right) \cdot B_i^\phi(\phi).\]
Full PDF, including mis-tagged events and background

\[ p.d.f. (m, \cos \theta_K, \cos \theta_l, \phi) = Y_S^n \cdot \left( S_i^R(m) \cdot S_i^a(\cos \theta_K, \cos \theta_l, \phi) \cdot \epsilon_i^R(\cos \theta_K, \cos \theta_l, \phi) \right) + \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(- \cos \theta_K, - \cos \theta_l, - \phi) \cdot \epsilon_i^M(\cos \theta_K, \cos \theta_l, \phi) \] 

+ \ Y_B \cdot B_i^m(m) \cdot B_i^{cos \theta_K}(\cos \theta_K) \cdot B_i^{cos \theta_l}(\cos \theta_l) \cdot B_i^\phi(\phi). \]

- Fit performed for 7 (+2 CR) different \( q^2 \) bins
- Fit \( m \) side bands to determine the background shape;
- Fit whole mass spectrum with 5 floating parameters;
- Used unbinned extended maximum likelihood estimator
  - discretize \( P_1, P_5' \) space
  - maximize \( \mathcal{L}(Y_S, Y_B, A_5^5) \)
  - fit \( \mathcal{L} \) with 2D-gaussian
  - find abs max of \( \mathcal{L} \) inside the physically allowed region
- Stat uncert using FC construction along the 1D profiled \( \mathcal{L} \)
### Systematics

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>$P_1(10^{-3})$</th>
<th>$P_5'(10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation mismodeling</td>
<td>1–33</td>
<td>10–23</td>
</tr>
<tr>
<td>Fit bias</td>
<td>5–78</td>
<td>10–119</td>
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<tr>
<td>MC statistical uncertainty</td>
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<td>31–112</td>
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<td>Efficiency</td>
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<td>$K\pi$ mistagging</td>
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<td>6–66</td>
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<tr>
<td>Background distribution</td>
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<tr>
<td>Mass distribution</td>
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<td>Feed-through background</td>
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<td>3–24</td>
</tr>
<tr>
<td>$F_L$, $F_S$, $A_S$ uncertainty propagation</td>
<td>0–126</td>
<td>0–200</td>
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<td>Angular resolution</td>
<td>2–68</td>
<td>0.1–12</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>60–220</td>
<td>70–230</td>
</tr>
</tbody>
</table>

- Comparing fit results on MC (high stat) with input (**simulation mismod**)
- **Fit bias** with cocktail signal MC + toy background from data side-bands;
- **MC stat** due to limited statistics in efficiency shape evaluation
- Comparing $F_L$ on CR wrt PDG (**efficiency**)
- **$K\pi$ mistag** evaluated in $J/\psi$ control region and propagated to all bins;

#### Propagation of $F_L$, $F_S$, and $A_S$ uncertainties:

- generate pseudo experiments, with $x100$ events, for each $q^2$ bin;
  - Fit with $F_L$, $F_S$, $A_S$ free to float and with $F_L$, $F_S$, $A_S$ fixed;
  - ratio of stat. uncert. on $P_1$ and $P_5'$ with free and fixed fit used to estimate syst uncertainties.
- check bias vs statistics of toy MC and validated on control channels
Results: fit projection for second bin: $2.0 < q^2 < 4.3$ GeV$^2$
Results vs SM prediction and LHCb/Belle measurements

**SM-DHMV** is computed using soft form factors in addition with parametrised power corrections and with the hadronic charm-loop contribution derived from calculations [JHEP 01 (2013) 048, JHEP 05 (2013) 137]

**SM-HEPfit** uses full QCD computation of the form factors and derives the hadronic contribution from LHCb data [JHEP 06 (2016) 116, arXiv:1611.04338]

No significant deviation wrt SM prediction, more compatible with **SM-DHMV**

Uncertainties are not small
Outline

1. CMS performance
2. Quarkonia production
   - Single quarkonium production
   - Prompt Double $\Upsilon$ observation
3. Properties
   - Lifetime measurement
   - $\Lambda_b$ polarization
4. Spectroscopy
   - Search for $X^+(5568) \rightarrow B_s^0 \pi^+$
5. Rare decays and angular analysis
   - $B_s^0 \rightarrow \mu \mu$
   - $b \rightarrow s \mu \mu$
6. Summary
Although designed for high $p_T$ physics, CMS can provide interesting results on flavour physics.

- results shown:
  - single and double quarkonia production
  - lifetime measurement for $B^0, B^0_s, B^+_c, \Lambda_b$
  - $\Lambda_b$ polarization
  - search for $X(5568)$
  - $B^0_s \rightarrow \mu\mu$
  - $B^0 \rightarrow K^*\mu\mu$ angular analysis has been extended to measure $P_1$ and $P'_5$ parameters:

- Large dataset at 13 TeV still being analyzed
- trigger is performing well also for this low $p_T$ physics
- expect interesting results and updated in the future.
Additional or backup slides
Yield extraction

Quarkonium yield extracted with a extended-UML to $M_{\mu\mu}$.
- Pdf used:
  - $J/\psi$: Crystal ball + Guassian
  - $\psi$(2S): Crystal ball
  - $\Upsilon$ (1s,2s,3s): Crystal ball
  - Background: exponential
- for $J/\psi$, $\psi$(2S) non prompt-component from b-hadrons decay.
  - use 2D UML using also decay length of $J/\psi,\psi$(2S): pdf
    - prompt component: double gaussian (per-event resolution)
    - non-prompt: exponential×gaussian
    - background: double gaussian
Fraction of non-prompt $J/\psi$ and $\psi(2S)$ (from b-hadrons) as a function of $p_T$, and for 7 TeV ($|y| < 0.9$) and 13 TeV ($|y| < 0.3$).

CMS Preliminary

$2.4 \text{ fb}^{-1}$ (13 TeV)

$2.7 \text{ fb}^{-1}$ (13 TeV)
B$^+$ production

$\sqrt{s} = 13$ TeV, $L = 48.1 \text{ pb}^{-1}$ with 50 $\text{ns}$ bunch spacings

Decay mode: $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^- \mu^+ K^+$

$$\frac{d\sigma(pp \rightarrow B^+ X)}{dx^B} = \frac{n_{\text{sig}}(x^B)}{2 A(x^B) \varepsilon(x^B) B \mathcal{L} \Delta x^B}$$

$x = p_T^B, y^B$

Selection:

**L1**
- $2\mu \mid \eta \mid < 1.6$
- $2\mu \mid \eta \mid < 2.4$ and $1\mu \ p_T > 10 \text{ GeV}$

**HLT**
- $2\mu \mid \eta \mid < 2.4$, $p_T > 4 \text{ GeV}$,
  - $2.9 < M_{\mu\mu} < 3.3 \text{ GeV}$, $P_{\text{vtx}}^{\mu\mu} > 10\%$
- $J/\psi \ p_T > 8 \text{ GeV}$
- $K$ charged track $p_T > 1 \text{ GeV}$

- factor 2: $\sigma$ for single charge $B^+$
- $n_{\text{sig}}(p_T, \mid y \mid)$ from UML fit
- $B = B(B^+ \rightarrow J/\psi K^+) \cdot B(J/\psi \rightarrow \mu\mu)$
- $\Delta p_T, \Delta y = 2\Delta \mid y \mid$ are bin widths
- $A, \varepsilon$ from MC, evaluated for each bin
Signal yield extraction

- Signal extracted with extended UML to $M_{J/\psi K^+}$ distribution in different bin of $p_T$ and $y$
- 9 bins in $p_T^B \in [10 - 100] \text{ GeV}$
  - $|y^B| < 1.45(2.1)$ for $p_T^B < 17(100) \text{ GeV}$
- 8 bins in $|y^B|$
  - $p_T^B \in [10 - 100] \text{ GeV}$
- pdf:
  - signal: 3 gaussian
  - combinatorial background: exponential
  - $B^+ \rightarrow J/\psi \pi^+$: 3 gaussian
  - $B \rightarrow J/\psi + h's$: error function

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HF-physics at CMS
Cracow 09/01/2018 5 / 30
Comparison with FONLL [JHEP 03 (2001) 006] and PYTHIA prediction, for 7 and 13 TeV. Reasonable agreement in shape and normalization.
Ratio of $\sigma$ measurement at 13 and 7 TeV prefer higher valued compared to FONLL and PYTHIA prediction
The measurement of quarkonium pair production in pp collisions provides further insight into the underlying mechanism of particle production. It probes specific mechanism of $c\bar{c}c\bar{c}$ & $b\bar{b}b\bar{b}$ systems production & transformation to two mesons, namely it probes the distribution of gluons in a proton since their production should be dominated by gluon-gluon interactions as well.

According to the description by parton models production in QCD, in a single hadron-hadron collision 2 partons often undergo a single interaction (Single Parton Scattering : SPS).

The SPS mechanism can be described by NRQCD.

At the parton level the two $J/\psi$ mesons are either produced as CS states or CO states that turn into color-singlets after emitting soft gluons. CO contributions play a greater role as $p_T$ increases.

Non-trivial contributions should come from Next-to-Leading Order (NLO) SPS. Models released recently begin to approach NLO (and NNLO).
Double Quarkonia Production: DPS

> It is also possible that multiple distinct parton interaction (MPIs) occur, the simplest case being the **Double Parton Scattering (DPS)**: 2 distinct parton-parton collisions (still in the same pp interaction)

> Because of the high parton flux and the high center-of-mass energy @ the LHC, **the pair production can be potentially sensitive to DPS**. These non-trivial contribution expected from DPS cannot be modeled by current NRQCD predictions: difficult to be addressed within perturbative QCD framework.

> **Pair production in pp collisions via DPS** is assumed to **result from 2 independent SPS occurrences**

> Several DPS production processes, including final states with quarkonia and with associated jets are described by an **effective cross section** $\sigma_{eff}$ that characterizes the transverse area of the hard partonic interactions, expected to be **independent of the final states** (assuming PDFs not correlated).

It depends on the **DPS fraction** which is usually estimated either …
1) as a residual of the SPS prediction, or …
2) as the result of a fit to the rapidity or azimuthal angle difference between pairs

Strong correlation of the two $J/\psi$'s produced via SPS interaction should result in small values of the absolute rapidity difference $|\Delta y|$: **large $|\Delta y|$ values are possible for DPS production**

**X-section measurement of quarkonium pair production crucial to understand SPS & DPS contributions**

> Pair production phase space @CMS nicely complements LHCb and gives access to high $p_T$ regime
\[ \sigma_{\text{eff}} \] comparison

![Graph showing \( \sigma_{\text{eff}} \) comparison across different experiments.](image)
Double Quarkonia Production: systematics and polarization

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<th>λ_θ_1</th>
<th>+1</th>
<th>+1</th>
<th>+0.5</th>
<th>-0.5</th>
<th>+0.5</th>
<th>-1</th>
<th>+1</th>
<th>-0.5</th>
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<td>+0.5</td>
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<td>-1</td>
<td>-0.5</td>
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<td>-1</td>
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<tr>
<td>Change (%)</td>
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<td>+26</td>
<td>+18</td>
<td>-2</td>
<td>-3</td>
<td>-9</td>
<td>-9</td>
<td>-19</td>
<td>-29</td>
<td>-38</td>
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<table>
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<th>Component</th>
<th>Uncertainty (%)</th>
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<td>Integrated luminosity</td>
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</tr>
<tr>
<td>Total</td>
<td>10.7</td>
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</table>
**Lifetime: b-hadrons reconstruction**

- **Signal extraction:**
  - Trigger: muon pairs compatible with $J/\psi$ mass & $p_T \geq 8 GeV$
  - High quality offline charged tracks attached to $J/\psi$ (or tertiary) vertex $[p_T \geq 0.5 GeV]$; additional kinematical requirements according to channel.
  - Intermediate neutral resonances [$K^0, K^0_s, \phi, \Lambda^0$] reconstructed by pairs of opposite charged tracks from a common vertex; $2\sigma$ mass-window around nominal masses; cross-channel contamination removed.
  - Tertiary vertex displacement requirements (for $K^0, \Lambda^0$).
  - $b$-hadron candidates: vertex quality criteria & $p_T \geq 13 GeV$ [except $B_c^+ (p_T \geq 10 GeV)$ & $J/\psi\phi$ (no req.)]; candidates fit with mass constraint for $J/\psi, K^0_c, \Lambda^0$
  - Production vertex selected by **smallest pointing angle $\alpha$** (fitted from reco tracks using the **beamspot as a constraint**)

- **Reference channel:**
  - $B^+ \rightarrow J/\psi K^+$ ($p_T(K) \geq 1.0 GeV$): the simplest decay mode with the highest yield
  - Used for overall calibration & specific systematic studies
Lifetime measurement: UML fit

Unbinned Maximum Likelihood fit with a set of 3 input observables (per candidate):

$$L = \prod_j \left[ n_{SIG} L_{SIG}(\Phi_j) + n_{BKG} L_{BKG}(\Phi_j) \right]$$

where

$$L(\Phi_j) = L(m_j) \cdot L(ct_j) \cdot L(\sigma_{ct}^j)$$

- SIG: Gaussian sum
- BKG: Exponential
- SIG: distribution from SB-subtracted region
- BKG: from SideBands

SIG: Gaussian sum

$$L_{SIG}(ct_j | \sigma_{ct}^j ; \tau) = \left[ e^{-ct_j} \otimes G(t_j - t_j^c ; \sigma_{ct}^j) \right] \cdot \varepsilon(ct_j) \int L_{SIG}(t) dt$$

- the exponential decay distribution (with lifetime [*]) is
- smeared with a per-candidate resolution function $\sigma_{ct}^j$
- corrected by reconstruction/selection biases
described by the relative efficiency $\varepsilon(ct)$

[*] effective lifetime for $B^0 \rightarrow J/\psi \phi$ (discussed later)

BKG: Exponential

$$L_{BKG}(ct_j | \sigma_{ct}^j) = \left[ \sum_k e^{-ct_j / \tau_k} \otimes G(t_j - t_j^c ; \sigma_{ct}^j) \right] \int L_{BKG}(t) dt$$

- t-model given by an heuristic sum of decay functions
Lifetime: $B_s^0$ effective lifetime

- $B_s$ mesons undergo rapid spontaneous transitions between particle and antiparticle states; the system is described by heavy/light, $B_H / B_L$, mass eigenstates characterized by sizable differences:

$$\Delta m_s = m_H - m_L \equiv 17.76 \pm 0.02 \text{ ps}^{-1} \quad \Delta \Gamma / \Gamma \equiv \frac{\Gamma_H - \Gamma_L}{(\Gamma_H + \Gamma_L)/2} \equiv -0.12 \pm 0.01$$

In absence of sizable CPV in the $B_s$ system, heavy/light eigenstates correspond to CP-odd/even resp.

- $B_s^0 \to J/\psi \pi^+ \pi^-$: the final state is dominated by $f_s(980)$, making it a CP-odd state [PRD 89 (2014) 092006]
  - the measured lifetime gives direct access to $\Gamma_H$ (thus $\tau_H$)

- $B_s^0 \to J/\psi \phi$: the final state is an admixture of 1 CP-odd and 2 CP-even eigenstates
  - the measured lifetime is an effective lifetime $\tau_{\text{eff}}$ (the distribution consists in 2 exponentials)
    - that is a weighted average of $\tau_H$ & $\tau_L$ (note: average lifetime is for equal admixtures) (details @backup)

- This is complementary to the weak mixing phase $\phi_s$ analysis CMS, PLB 757 (2016) 97 where the CP-odd/even components are disentangled by an angular analysis (details @backup)

- The bias caused by the contamination of nonresonant $B_s^0 \to J/\psi KK$ decays is considered as a systematic uncertainty.
  - The S-wave fraction is assigned the value ($f_s = 1.2^{+0.1,-0.07}$) measured in CMS, PLB 757 (2016) 97, after the needed correction [to account for different trigger & selection criteria in the 2 analyses].

- The $B_H / B_L$ relative fraction evolves in time $ct > 200 \text{ \mu m}$ modifies the relative composition & $ct_{\text{eff}}$ must be properly corrected
B_s^0 system: mixing and decay

- B_s mesons mix via box diagrams [with relatively large decay width difference between the mass eigenstates]

When B_s^0 & B_s^0 decay to a CP eigenstate (as in flavor-blind B_s^0 \rightarrow J/ψφ) the weak phase ϕ_s arises from the interference between direct decays & decays with mixing.

Theoretically clean decay mode: tiny CPV ruled by \( ϕ_s^{SM} = \beta_s - 0.0363^{+0.016}_{-0.015} \) rad [β_s = arg(-V_{ts} V_{ts}^*)] [PRD 84 (2011) 033005]

- Sensitivity to NP in mixing: many NP scenarios predict enhanced values of ϕ_s.

J/ψφ final state: admixture of CP-odd and CP-even eigenstate to be disentangled by angular analysis.

- The different CP components in the \( B_s^0 \rightarrow J/ψφ \) decay are accessed in another already published CMS analysis, performed as a time-dependent, tagged, angular analysis (using the same 8TeV dataset).

It implies the detailed characterization of the system & the simultaneous extraction of weak phase ϕ_s & width difference \( ΔΓ_s \) (and the measurement of the average decay width \( Γ_s \)).

- \( ΔΓ_s \) is confirmed to be non-zero

- These accurate measurements are in good agreement with SM predictions and with previous ones (that of ϕ_s is statistically limited; to be done with Run-II)
In the heavy quark effective theory (HQET) predicts a large fraction of the tranverse b-quark polarization to be retained after hadronization. http://arxiv.org:hep-ph/0702191. In the particular $\Lambda_b$ baryons the b-quark combines with a spin-0 $ud$ pair, so all of the $\Lambda_b$ spin resides on the valence b-quark and we expect b-polarization to become $\Lambda_b$ polarization.

A previous LHCb measurement in 2013 is published in Physics Letters B 724 (2013) 27. The reported value cannot exclude a transverse polarization at the order of 10%, however a polarization of 20% at level of ± 2.7sigma is discarded.

Also, the asymmetry parameter in $\Lambda_b \rightarrow \Lambda V$ decays has been calculated in many publications. Most predictions lie in the range from -21% and -10%, while HQET obtains a large positive value arXiv:hep-ph/0412116.

Method | Value
---|---
Factorisation | -0.1
Factorisation | -0.18
Covariant oscillator quark model | -0.208
Perturbative QCD | -0.17 to -0.14
Factorisation (HQET) | 0.777
Light front quark model | -0.204

To summary, a measurement of the polarization provides a test of HQET and information about heavy baryon hadronization and nonperturbative corrections to spin transfer in fragmentation.
Λ_b polarization systematics

- We consider the following systematics sources:
  - **Fit Bias.** From Toy MC we take the difference between the input values and the mean of the fitted values as systematic.
  - **Asymmetry parameter.** The maximum difference when we vary the value of this parameter within ±sigma of its measured value is taken as systematic.
  - **Background mass model.** We use an exponential instead of a first order polynomial, also we vary bkg parameters ±sigma.
  - **Background angular model.** We change the model to estimate the shape of the angular background. The difference with the nominal result is taken as systematic.
  - **Signal mass model.** This uncertainty is estimated by varying the parameters within their uncertainties and taking into account the correlations. The difference with the nominal result is taken as systematic.
  - **Angular efficiency.** The values of the Chebyshev coefficients are varied ±sigma. The maximum difference with respect to the nominal fit is taken as systematic.
  - **Angular resolution.** The measurement resolution of the angular observables is considered. First, we determine angular resolution from MC, the resulting Gaussian models are used to generate random numbers that are added to the 3 polar angles of MC events at gen-level. The difference between the parameters obtained from fits using events with/out random terms added is quoted as systematic.
  - **Azimuthal efficiency.** The non-uniformity of the azimuthal efficiency shape is investigated from Toy MC. We generate 500 pseudo-experiments, using the 5D angular distribution (3 polar & 2 azimuthal angles) multiplied by the polar and azimuthal efficiency shape (from full MC simulation). Then we fit them with the 3D nominal model. Difference of the mean values with respect to the input values are taken as systematic.
  - **Reweighting procedure.** We apply a procedure where weights are varied in each iteration. The histograms of MC distribution are varied ±sigma(bin error) and then compute the weight per event. We take the largest difference with respect to the nominal value as systematic.
  - **Possible reco-bias.** Possible unaccounted reconstruction bias is considered. In order to estimate this systematic uncertainty, we generate a MC sample with input values of the helicity amplitudes and polarization similar to the observed values in data, we fit the MC sample and take the differences between input and fit values for every angular parameter and the polarization. Since we are considering the Full MC, we subtract the sum in quadrature of the systematic sources involved in the fit from those observed differences, finally we take the square root of this subtraction as the estimation of the systematic.
Λ_b polarization systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>$P \times 10^{-2}$</th>
<th>$\alpha_1 \times 10^{-2}$</th>
<th>$\alpha_2 \times 10^{-2}$</th>
<th>$\gamma_0 \times 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular Efficiency</td>
<td>0.1</td>
<td>0.3</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Azimuthal Efficiency</td>
<td>0.1</td>
<td>1.0</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Fit Bias</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>1.0</td>
<td>0.1</td>
<td>2.6</td>
<td>0.8</td>
</tr>
<tr>
<td>Background mass model</td>
<td>0.01</td>
<td>0.5</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Background angular model</td>
<td>0.4</td>
<td>0.5</td>
<td>0.9</td>
<td>5.0</td>
</tr>
<tr>
<td>Signal mass model</td>
<td>0.01</td>
<td>0.3</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Asymmetry parameter $\alpha_A$</td>
<td>0.4</td>
<td>0.7</td>
<td>2.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Reweight procedure</td>
<td>0.1</td>
<td>1.3</td>
<td>0.4</td>
<td>2.0</td>
</tr>
<tr>
<td>Reconstruction bins</td>
<td>5.6</td>
<td>10.0</td>
<td>5.1</td>
<td>9.1</td>
</tr>
<tr>
<td>Total(sqrt of the quadratic sum)</td>
<td>5.8</td>
<td>10.0</td>
<td>5.1</td>
<td>11.1</td>
</tr>
</tbody>
</table>

† The contributions from the different uncertainty sources are assumed to be independent

† The total systematic uncertainty is calculated as the square root of the quadratic sum of all uncertainties.
Λ_b polarization results

\[ \alpha_1 \equiv \left| T_{++} \right|^2 - \left| T_{+0} \right|^2 - \left| T_{-0} \right|^2 - \left| T_{--} \right|^2, \]
\[ \alpha_2 \equiv \left| T_{++} \right|^2 + \left| T_{+0} \right|^2 - \left| T_{-0} \right|^2 - \left| T_{--} \right|^2, \]
\[ \gamma_0 \equiv \left| T_{++} \right|^2 - 2 \left| T_{+0} \right|^2 - 2 \left| T_{-0} \right|^2 + \left| T_{--} \right|^2, \]

\[ P = 0.00 \pm 0.06(stat) \pm 0.06(syst), \]
\[ \alpha_1 = 0.14 \pm 0.14(stat) \pm 0.10(syst), \]
\[ \alpha_2 = -1.11 \pm 0.04(stat) \pm 0.05(syst), \]
\[ \gamma_0 = -0.27 \pm 0.08(stat) \pm 0.11(syst) \]

\[ \left| T_{-0} \right|^2 = 0.52 \pm 0.03(stat) \pm 0.04(syst), \]
\[ \left| T_{+0} \right|^2 = -0.10 \pm 0.04(stat) \pm 0.04(syst), \]
\[ \left| T_{--} \right|^2 = 0.53 \pm 0.04(stat) \pm 0.04(syst), \]
\[ \left| T_{++} \right|^2 = 0.04 \pm 0.04(stat) \pm 0.04(syst). \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CMS result</th>
<th>LHCb result</th>
<th>difference</th>
<th>ATLAS result</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>\left</td>
<td>T_{-0} \right</td>
<td>^2</td>
<td>0.52 \pm 0.03</td>
<td>0.57 \pm 0.06</td>
<td>0.31 \sigma</td>
</tr>
<tr>
<td>\left</td>
<td>T_{+0} \right</td>
<td>^2</td>
<td>-0.10 \pm 0.04</td>
<td>0.01 \pm 0.04</td>
<td>1.45 \sigma</td>
</tr>
<tr>
<td>\left</td>
<td>T_{--} \right</td>
<td>^2</td>
<td>0.53 \pm 0.04</td>
<td>0.51 \pm 0.05</td>
<td>0.13 \sigma</td>
</tr>
<tr>
<td>\left</td>
<td>T_{++} \right</td>
<td>^2</td>
<td>0.04 \pm 0.04</td>
<td>-0.10 \pm 0.04</td>
<td>1.98 \sigma</td>
</tr>
</tbody>
</table>
**Signal (BDT selection)**
- a good, isolated $\mu^\pm$ pair from displaced vertex
- momentum aligned along flight direction;
- invariant mass peaking at $M(B_s^0, B_d^0)$
- $B(B_s^0 \rightarrow \mu \mu) = N_s \cdot \frac{B(B^\pm \rightarrow J/\psi K^{\pm})}{N(B^\pm \rightarrow J/\psi K^{\pm})} \cdot \frac{\epsilon(B^\pm)}{\epsilon(B_s^0)} \cdot \frac{f_u}{f_s}$
- $\epsilon$ include acceptance, trigger, and selection
- $f_s/f_u$ B-factorization

**Background**
- combinatorial (semileptonic decay): side bands
- rare decays
  - non peaking $B_s^0 \rightarrow K^\pm \mu \nu$, $\Lambda_b \rightarrow p \mu \nu$ (MC)
  - peaking $B^0 \rightarrow KK, K\pi, \pi\pi$: absolute yield evaluated on independent single-$\mu$ trigger
- $\mu$ quality, good sec. vertex, isolation, pointing angle, and $M_{\mu\mu}$ resolution: → powerful background suppression

Normalization channel $B^\pm \rightarrow J/\psi K^{\pm} \rightarrow \mu \mu K^{\pm}$, calibration $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu \mu KK$
- UML symultaneous fit to Bs and Bd
- several categories based on event classification (BDT) and region (Barrel-Endcap)
$B_s^0 \rightarrow \mu\mu$

Observed significances (expected)

$B_s^0 \rightarrow \mu^+\mu^- : 6.2\sigma (7.4\sigma)$

$B^0 \rightarrow \mu^+\mu^- : 3.2\sigma (0.8\sigma)$
$B_s^0 \rightarrow \mu^+ \mu^-$: overview

- **Signal** $B_s^0 \rightarrow \mu^+ \mu^-$
  - two muons from one decay vertex
  - well reconstructed secondary vertex
  - momentum aligned with flight direction
  - isolated, mass around $m_{B_s^0}$

- **Background**
  - combinatorial (from sidebands)
    - two semileptonic ($B$) decays (gluon splitting)
    - one semileptonic ($B$) decay and one misidentified hadron
  - rare single $B$ decays (from MC simulation)
    - non-peaking, e.g. $B_s^0 \rightarrow K^+ \mu^+ \nu$, $B_s \rightarrow p \mu^+ \nu$
    - peaking, e.g. $B_s^0 \rightarrow K^+ K^-$

- **Blind analysis**
  - Critical issues
    - optimized selection
    - muon misidentification probability
    - pileup (isolation)
$B^0_s \rightarrow \mu^+ \mu^-$: methodology

- Measurement of $B^0_s \rightarrow \mu^+ \mu^-$ relative to normalisation channel:
  - $B^+ \rightarrow J/\psi K^+$, with well-known branching fraction
  - (nearly) identical selection to reduce systematic uncertainties

\[
\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = \frac{n_{\text{obs}}^{B^0_s}}{\varepsilon_{B^0_s} N_{B^0_s}} = \frac{n_{\text{obs}}^{B^0_s}}{\varepsilon_{B^0_s} \mathcal{L} \sigma(pp \rightarrow B^0_s)}
\]

\[
= \frac{n_{\text{obs}}^{B^0_s}}{N(B^+ \rightarrow J/\psi K^+)} \frac{A_{B^+}}{A_{B^0_s}} \frac{\varepsilon_{B^0_s}^{\text{trig}}}{\varepsilon_{B^+}^{\text{trig}}} \frac{\varepsilon_{B^+}^{\mu}}{\varepsilon_{B^0_s}^{\mu}} \frac{f_B}{f_{B^+}} \mathcal{B}(B^+ \rightarrow J/\psi [\mu^+ \mu^-]K)
\]

- Reconstructed exclusive decays
  - $B^+ \rightarrow J/\psi K^+$: normalization and studies
  - $B^0_s \rightarrow J/\psi \phi$: $B^0_s$ signal MC validation
    alternative normalization
  - $J/\psi, \Upsilon(1S) \rightarrow \mu^+ \mu^-$: mass calibration

- Divide data into channels
  - better sensitivity
  - add more data
\( B_s^0 \rightarrow \mu\mu: \) systematics

- Hadronization probability ratio \( f_s / f_u \) from LHCb \cite{JHEP 04, 001 (2013)}
  - additional 5% systematics for possible \( p_\perp \) or \( \eta \) dependence
  - in-situ studies show no \( p_\perp \) dependence
    - ratio of \( B^+ \rightarrow J/\psi K^+ \) vs \( B_s^0 \rightarrow J/\psi \phi \)

- Rare decays
  - hadron to muon misidentification probability
    - \( K_S^0 \rightarrow \pi^+\pi^- \), \( \Lambda \rightarrow p\pi \), and \( D^{**} \rightarrow D^0 (K^-\pi^+)\pi^+ \)
    - 50% uncertainty, pions/kaons/protons uncorrelated
  - branching fraction uncertainties
  - \( \Lambda_b \rightarrow p\mu\bar{\nu} \):
    - large range of predictions in literature (w/o \( \text{JHEP, 1109, 106} \))
    - take average \( (6.5 \times 10^{-4}) \) and assign 100% uncertainty
      - note that invariant mass covers \( B_s^0 \) signal region, using \text{EvtGen} 'phase space' model for decay

- Normalization
  - 5%, varied functional forms and mass-constrained fits
Dataset selection

**Trig** Dedicated HLT trigger path:
- **Low pt dimuon, displaced, low invariant mass**
  \[ h \ p_T^h > 0.8 \text{ GeV}, |M(K\pi) - M_{K^*}| < 90 \text{ MeV}, M_{KK} > 1.035 \text{ (}\phi\text{ veto), displaced } DCA/\sigma > 2 \]
  \[ \mu \ p_T^\mu > 3.5 \text{ GeV}, p_T^{\mu\mu} > 6.9 \text{ GeV}, 1 < M_{\mu\mu} < 4.8 \text{ GeV, displaced } L/\sigma > 3 \]
  \[ B^0 \ p_t > 8 \text{ GeV, } |\eta| < 2.2, \text{ displaced } (L/\sigma > 12), \cos \alpha > 0.9994, |M - M_{B^0}| < 280 \text{ MeV} \]
  - Both \( B^0 \) and \( \bar{B}^0 \) considered, if more than one candidate, take the one with best \( B^0 \) vtx CL
  - anti radiation cut against feed-down of \( J/\psi /\psi' \)

**CR** signal and control sample \( J/\psi \) and \( \psi' \) treated same way.

CMS has no PID capability to distinguish K from \( \pi \)
- CP state assignment based on which hypothesis \( M(K^+\pi^- - K^-\pi^+) \) is closer to \( M_{K^*}(PDG) \):
  - mistag rate 14% (MC)
Background considered

- Partially reconstructed $B^0$ decay might pollute left $M_{B^0}$ side bands
  - restrict left s.b. ($5.1 < M < 5.6$ GeV, default $5 < M < 5.6$ GeV)
  - redo fit: change in $P_1$ and $P'_5$ within the systematics uncertainties.

- $B^\pm \rightarrow K^\pm \mu\mu$ plus and additional random $\pi^\mp$:
  - distribution ends at $M > 5.4$ GeV, further reduced by $\cos\alpha$ cut, and BR similar to $B^0 \rightarrow K^* \mu\mu$

- $\Lambda_b \rightarrow pKJ/\psi(\mu^+\mu^-)$
  - look at event in the $M_{K\pi\mu\mu} \approx M_{B^0}$ peak, reconstruct them using p, K mass hypothesis: no peak seen.

- $B^0 \rightarrow DX$, with $D \rightarrow hh$ and h mis-id as $\mu$
  - requires two mis-id: $P_{\text{misId}} \sim 1 \cdot 10^{-3}$: given BR $\sim 1 \cdot 10^{-3}$ negligible.

- $B^0 \rightarrow J/\psi(\mu\mu)K^*(K\pi)$, with one h and one $\mu$ switched
  - $P_{\text{misId}} \cdot (1 - \varepsilon_\mu) \sim 1 \cdot 10^{-4}$, $Y_{B^0 \rightarrow J/\psi \mu\mu} \sim 1.6 \cdot 10^5$: few events in bin close to $J/\psi$
  - $J/\psi$ feed contamination in close bin included in the fit model
extensive fit validation with MC: used as **systematics**
- compare fit results with MC input values (**sim mismodeling**)  
- compare with data-like MC (**fit bias**)
  - signal only correct tag
  - signal correct+wrong tag
  - signal + background
- Data control channel (J/ψ and ψ′), comparing fit results with PDG (F_L) (**efficiency**)  
- compare P₁ and P₅′ on J/ψ and ψ′ w/ and w/o F_L fixed: no bias

\[
\frac{\mathcal{B}(B^0 \to K^{*} \psi')} {\mathcal{B}(B^0 \to K^{*} J/\psi)} \equiv \frac{Y_{\psi'}} {Y_{J/\psi}} \cdot \frac{\mathcal{B}(J/\psi \to \mu^+ \mu^-)} {\mathcal{B}(\psi' \to \mu^+ \mu^-)} = 0.480 \pm 0.008(\text{stat}) \pm 0.055(\text{R}_{\psi'})
\]

vs PDG 0.484 \pm 0.018(\text{stat}) \pm 0.011(\text{syst}) \pm 0.012(\text{R}_{\psi'})
Several validation steps are performed with **simulation**:

- with statistically precise MC signal sample: compare fit results with input values to the simulation (**simulation mismodeling**)
- with 200 data-like MC signal+background samples: compare average fit results with fit to the statistically precise MC signal sample (**fit bias**)
- with pseudo-experiments

**B^0 \to K^{*0} J/\psi**

Validation with **data** control channels:

- Fit performed with $F_L$ free to vary
- The difference of $F_L$ with respect to PDG value is propagated to the signal $q^2$ bins as systematic uncertainty (**efficiency**)
The decay rate can become negative for certain values of the angular parameters \((P_1, P_5', A^5_5)\).

The presence of such a physically allowed region greatly complicates the numerical maximisation process of the likelihood by MINUIT and especially the error determination by MINOS, in particular next to the boundary between physical and unphysical regions.

The **best estimate** of \(P_1\) and \(P_5'\) is computed by:

- discretise the bi-dimensional space \(P_1-P_5'\)
- maximise the likelihood as a function of \(Y_s\), \(Y_B\), and \(A^5_5\) at fixed values of \(P_1\), \(P_5'\)
- fit the likelihood distribution with a 2D-gaussian function
- the maximum of this function inside the physically allowed region is the best estimate

To ensure correct coverage for the **uncertainties** of \(P_1\) and \(P_5'\), the Feldman-Cousins method is used in a simplified form: the confidence interval’s construction is performed only along two 1D paths determined by profiling the 2D-gaussian description of the likelihood inside the physically allowed region.

![Diagram](image.png)
To ensure correct coverage for the uncertainties of $P_1$ and $P_5$, the Feldman-Cousins method is used in a simplified form: the confidence interval's construction is performed only along the two 1D paths determined by profiling the 2D-gaussian description of likelihood inside the physically allowed region:

- generate 100 pseudo-experiments for each point of the path
- fit and rank according to the likelihood-ratio
- confidence interval bound is found when data likelihood-ratio exceeds the 68.3% of the pseudo-experiments

Due to the limited number of pseudo-experiments, statistical fluctuations are present

To produce a robust result, the ranking of the data likelihood-ratio is plotted for several scan points

The intersection is then computed using a linear fit