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 x-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 Υ observation
3. Properties
   - Lifetime measurement
   - Λ_b polarization
4. Spectroscopy
   - Search for $X^+(5568) \to B_s^0\pi^+$
5. Rare decays and angular analysis
   - $B_s^0 \to \mu\mu$
   - $b \to s\mu\mu$
6. Summary

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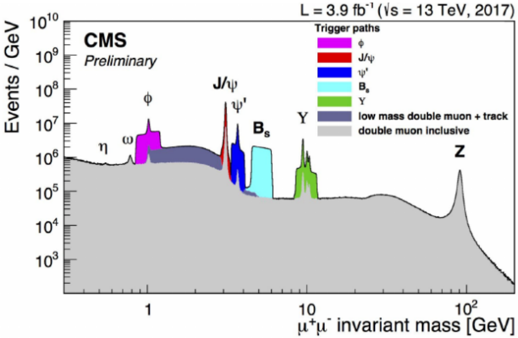
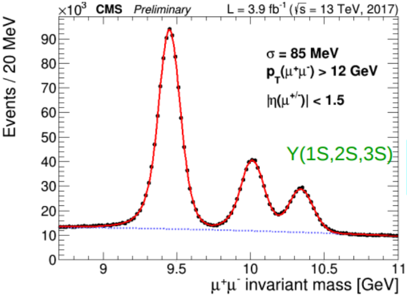
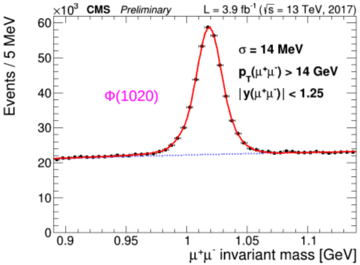
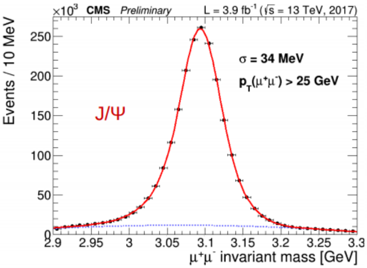


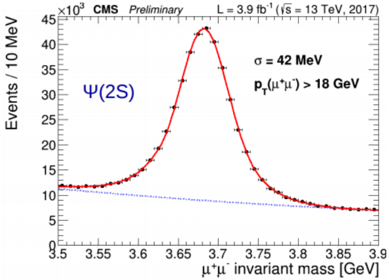


Experimental setup: dedicated HF triggers

Using 2017 data: CMS-DP-2017-029







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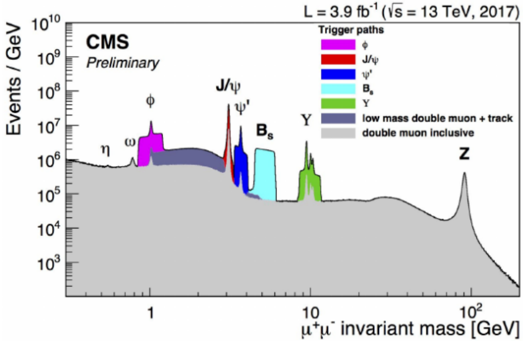
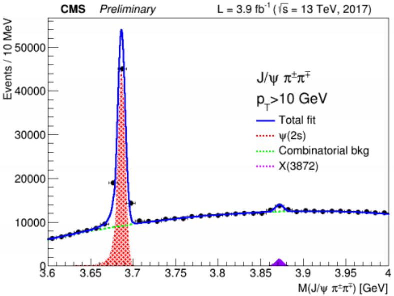
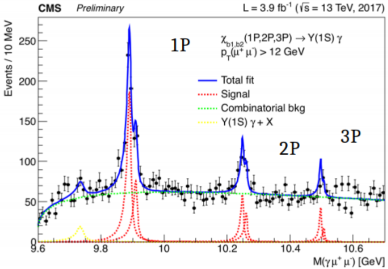
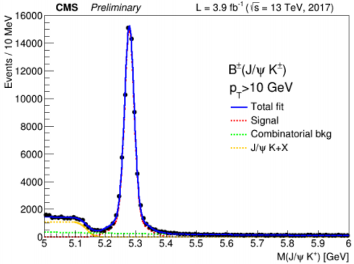


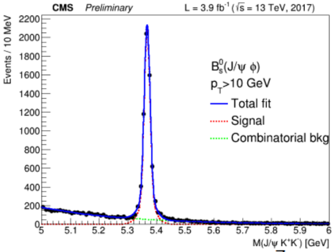


Experimental setup: trigger optimised for different analysis

Using 2017 data: CMS-DP-2017-029







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Outline

Quarkonia production

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

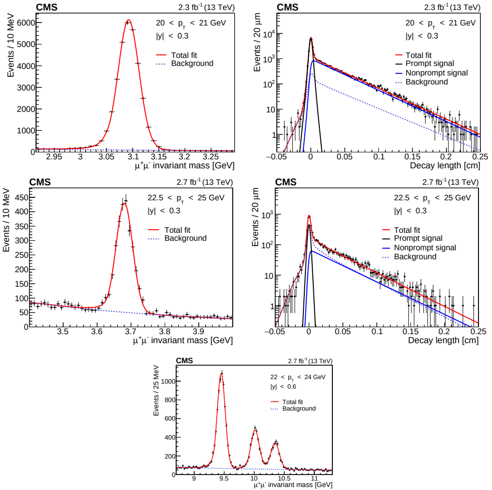
$$\frac{d^2\sigma}{dp_T dy} \cdot \mathcal{B}(q\bar{q} \to \mu\mu) = \frac{N^{(q\bar{q})}(p_T, y)}{\mathcal{L}\Delta p_T \Delta y} \cdot \left\langle \frac{1}{(\varepsilon\mathcal{A})(p_T, y)} \right\rangle$$

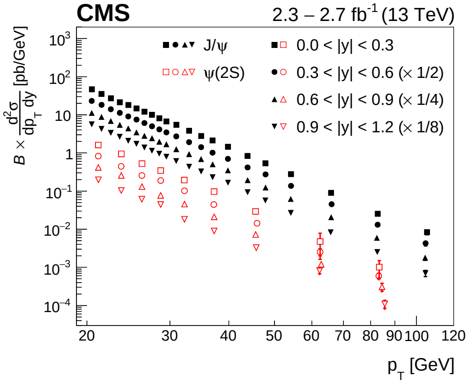
$$\varepsilon_{\mu\mu}(p_T, y) = \varepsilon_\mu(p_{T1}, \eta_1) \cdot \varepsilon_\mu(p_{T2}, \eta_2) \cdot \rho(p_T, \eta) \cdot \varepsilon^2_{trk}$$

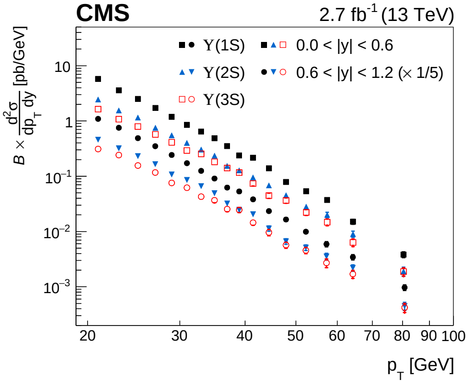
from tag & probe — correlation for $\mu\mu$ — Tracking efficiency

$$\mathcal{A} = \frac{N^{gen}_{kin}(p_T, y)}{N^{gen}(p_T, y)}$$ from MC simulation

$N^{(q\bar{q})}_{\text{prompt}}$ in a 2D bin (p_T, y) from UML fit of $M_{\mu\mu}$ (and $c\tau$ for ψ).

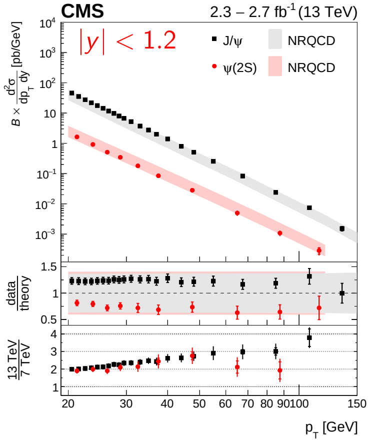




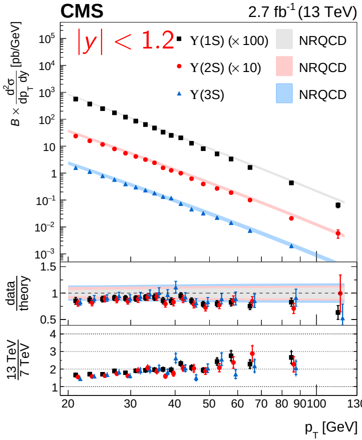


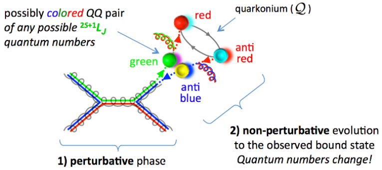
Shape vs p_T consistent for all quarkonia states across rapidity regions

$J/\psi, \psi(2S)$



$\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$





good agreement

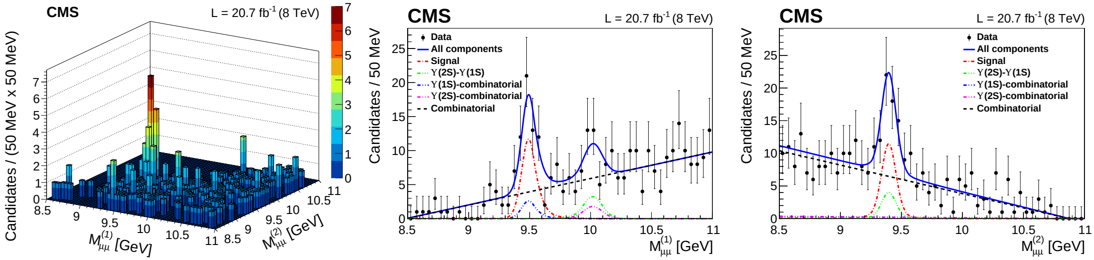
- NRQCD under(over)estimates J/ψ ($\psi(2S)$), within uncert.
- ratio 13/7 TeV changing slowly with p_T, expected from evolution of pdf

Prompt Double Υ observation 8 TeV [JHEP 05 (2017) 013]

Double J/ψ already seen [LHCb: PLB 707 (2012) 5259, ATLAS: EPJ C 77 (2017) 76, CMS: JHEP 09 (2014) 094], double Υ not yet

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

- Signal extracted with 2D ext-UML of $M_{\mu\mu}^{(1)}$ and $M_{\mu\mu}^{(2)}$
  - $M_{\mu\mu}^{(1)}$ ($M_{\mu\mu}^{(2)}$) higher (lower)-mass Υ candidate
    - if ($\Upsilon(1S)\ \Upsilon(2S)$): $\Upsilon(2S)$ appears in $M_{\mu\mu}^{(1)}$
- $N_{\Upsilon(1S)\Upsilon(1S)} = 38 \pm 7$ ($\gg 5\sigma$)
- $N_{\Upsilon(1S)\Upsilon(2S)} = 13^{+6}_{-5}$ ($\sim 2.6\sigma$)



Fiducial and effective cross section

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

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

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

$\mathcal{A}\varepsilon$ on a event-by-event basis, using measured Υ and μ momenta (data embedding into simulation)

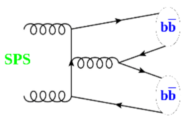
Effective cross-section (with additional Double Parton Scattering process)

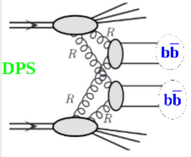
$$\sigma_{eff} = \frac{1}{2}\frac{\sigma^2_{\Upsilon(1S)}}{\sigma_{DPS}} = \frac{1}{2}\frac{\sigma^2_{\Upsilon(1S)}}{f_{DPS}\sigma_{fid}\mathcal{B}^2_{\Upsilon(1S)\to\mu\mu}}, \qquad \sigma_{\Upsilon(1S)} \text{ form [CMS, PLB 749(2015) 14]}$$

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

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

  ✗ smaller than that from multi-jet studies $12 - 20\ mb$ (mostly from $q\bar{q}$ and qg)
- might indicate distance between g's smaller than that of q's or q-g





Outline

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 τ) 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 $J/\psi(\to \mu\mu) + X$: $8\,\text{TeV}$, $19.7\,\text{fb}^{-1}$
- States considered:

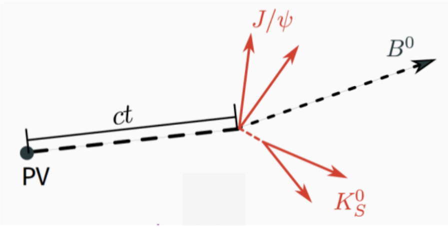
B^0 $B^0 \to J/\psi K^*$, $B^0 \to J/\psi K^0_S$
B^0_s $B^0_s \to J/\psi \pi\pi$, $B^0_s \to J/\psi \phi$
Λ_b $\Lambda_b \to J/\psi \Lambda$
B_c^+ $B_c^+ \to J/\psi \pi$

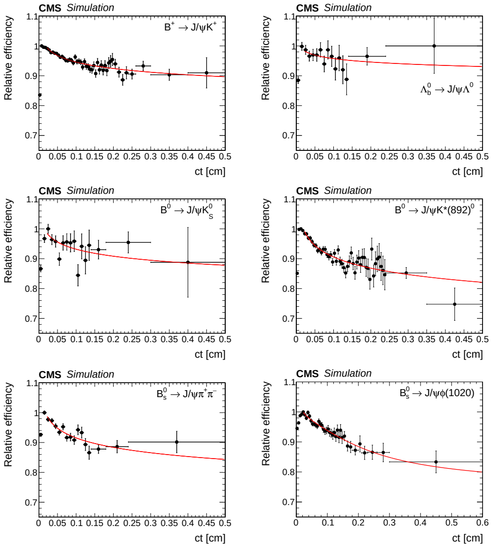
  - Reference channel $B^+ \to J/\psi K^+$

- b-hadron lifetime from proper decay length:

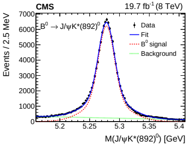
$$ct = \frac{L}{(\beta\gamma c)} = \frac{L_{xy}}{(\beta\gamma)_T} = L_{xy}\frac{M}{p_T}$$

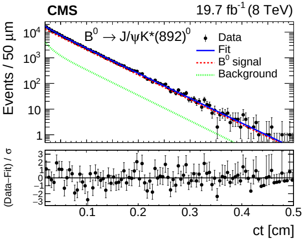
- UML of ct, σ_{ct} (per-event), and M_{b-had}
- efficiency distortion corrected from simulation
- turn-on region discarded $ct > 200\,\mu$m ($100\,\mu$m B_c^+)

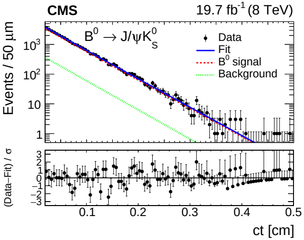




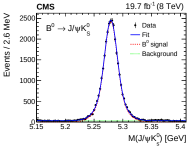
$B^0 \to J/\psi K^*$







$B^0 \to J/\psi K^0_S$

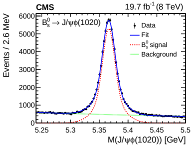


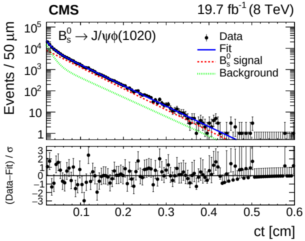
decay mode	CMS results	PDG2016
$B^0 \to J/\psi K^*$	$c\tau_{B^0} = 453.0 \pm 1.6(\text{stat}) \pm 1.5(\text{syst})$	$455.7 \pm 1.2\ \mu m$
$B^0 \to J/\psi K^0_S$	$c\tau_{B^0} = 457.8 \pm 2.7(\text{stat}) \pm 2.7(\text{syst})$	

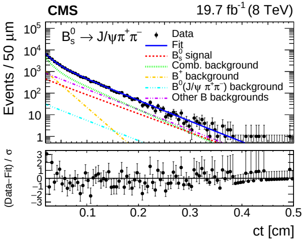
Good agreement between the two final states and with world average

Results: B_s^0 lifetimes

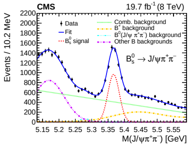
$B_s^0 \to J/\psi\phi$





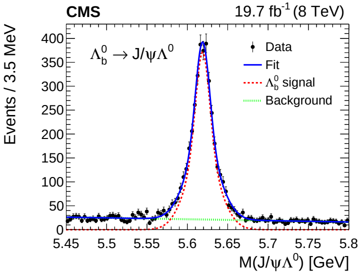


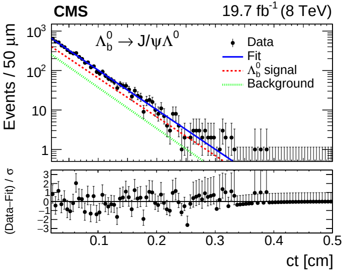
$B_s^0 \to J/\psi\pi\pi$



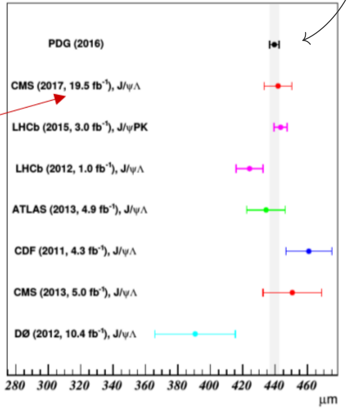
decay mode	CMS results	PDG2016
$B_s^0 \to J/\psi\pi\pi$	$\tau_H = 504.3 \pm 10.5(\text{stat}) \pm 3.7(\text{syst})$	$509 \pm 12\ \mu$m
$B_s^0 \to J/\psi\phi$	$\tau_{eff} = 443.9 \pm 2.0(\text{stat}) \pm 1.2(\text{syst})$	$443 \pm 2.4\ \mu$m

- $J/\psi\pi\pi$ dominated by $B_s^0 \to J/\psi f(980)$: CP-odd τ_H
- $J/\psi\phi$ mixture of CP-odd and even, effective lifetime τ_{eff}
  - complementary to measurement of weak mixing phase φ_s [CMS, PLB 757(2016)97]
- combination of τ_H and τ_{eff} gives: $c\tau_L = 419 \pm 6.4\ \mu$m, compatible with WA



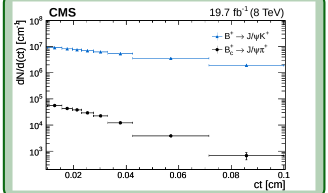


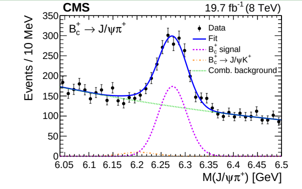
- $c\tau = 442.1 \pm 8.2(\text{stat}) \pm 2.7(\text{syst})\ \mu\text{m}$
- good agreement with previous CMS results and with **world average ($439.8 \pm 3.0\ \mu$m)**
- follow the tendency for longer lifetime

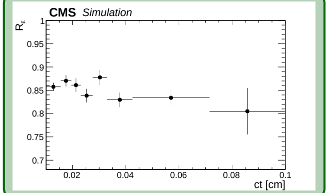


- for B_c^+ used $\Delta\Gamma$ (LHCb approach[PLB 742(2015) 29]);
  - difference of total width $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$
  - $c\tau_{B^+} = 490 \pm 0.8(\text{stat})\,\mu\text{m}$ PDG2016: $491.4 \pm 1.2\,\mu\text{m}$
- large background, smaller lifetime: the ratio method reduces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

$$\mathcal{R}(t) = \frac{N_{B_c^+}}{N_{B^+}} = \frac{e^{-t/\tau_{B_c^+}} \otimes G(t)}{e^{-t/\tau_{B^+}} \otimes G(t)} \frac{\varepsilon_{B_c^+}}{\varepsilon_{B^+}} \approx \mathcal{R}_\varepsilon(t) e^{-\Delta\Gamma t} \text{ with } \Delta\Gamma = 1/\tau_{B_c^+} - 1/\tau_{B^+}$$

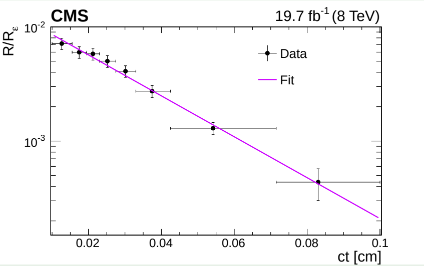






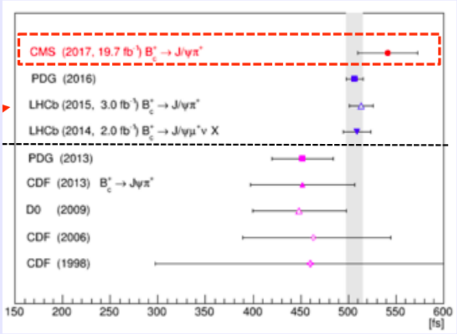
B_c^+ lifetime results

$\Delta\Gamma$ extracted via a binned χ^2-fit to $\mathcal{R}(t)$, corrected for efficiency ratio, with an exponential function.



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

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



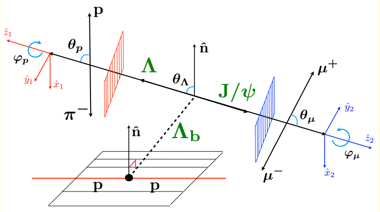
- In agreement with recent LHCb results and world average
- higher than Tevatron results

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 $\Lambda_b \to J/\psi(\to \mu\mu)\Lambda(\to p\pi^-)$
  - both prompt and non-prompt decay;
  - 7(8) TeV with 5.2(19.8) fb^{-1}
  - both Λ_b and $\overline{\Lambda_b}$ decay: from CP $P = -\overline{P}$

α_1 parity-violating decay asymmetry
α_2 longitudinal polarization of Λ
γ_0 related to J/ψ polarization
α_Λ is the asym parameter of $\Lambda \to p\pi^-$ decay (fixed to 0.642 ± 0.013)

- $\alpha_1, \alpha_2, \gamma_0$ related to T_{ij} helicity amplitudes of Λ and J/ψ [Kramer-Sima, NPB 50 (1996) 125]



5 angles describe the decay: $\Omega = (\theta_\Lambda, \theta_p, \varphi_p, \theta_\mu, \varphi_\mu)$ integrating over φ_μ and φ_p simplify the pdf ($i_{max} = 19 \to 8$)

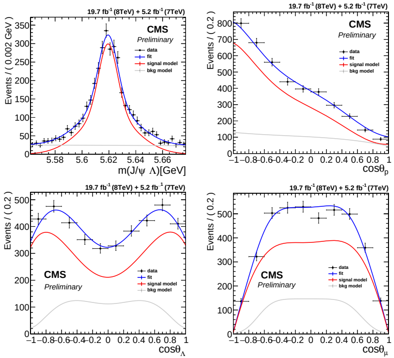
helicity formalism:

$$\frac{d^5\Gamma}{d\Omega_5}(\Omega) \approx \sum_{i=1}^{8} u_i(\alpha_1, \alpha_2, \gamma_0)\, v_i(P, \alpha_\Lambda)\, w_i(\Omega)\,.$$

Λ_b polarization results

- UML fit to 7 and 8 TeV, Λ_b and $\overline{\Lambda_b}$
  - $\theta_{\Lambda,p,\mu}$ 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
  - $N_{\overline{\Lambda_b}} = 919 \pm 45 (2021 \pm 57)$ 7(8) TeV

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

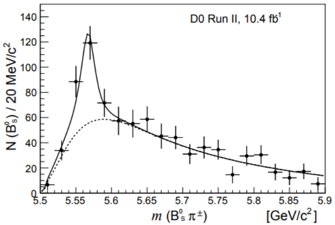


- Good agreement with LHCb[PLB 724 (2013) 27] and ATLAS[PRD 89 (2014) 092009]
- P consistent with pQCD prediction 10% [PLB 649 (2007) 152], but disfavour $P \sim 20\%$[PLB 614 (2005) 165]
- α_1 predicted 0.78 from HQET [arXiv:hep-ph/0412116] disfavoured, other models ok $\sim [-0.2, -0.1]$
- α_2: positive helicity for Λ suppressed, as predicted[PRD 88 (2013) 114018]

Outline

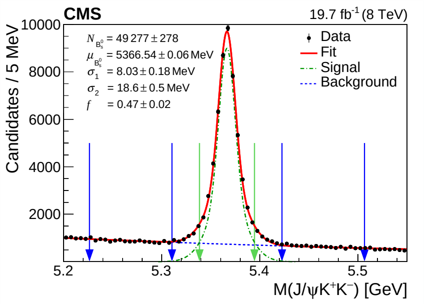
Observation by D0 [PRL 117 (2016) 022003]
with $L=10.4\,fb^{-1}$, $\approx 5.5k$ B_s^0
reported 5.1σ

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



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

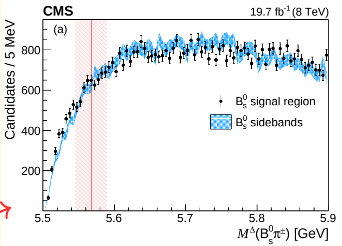
Search performed at CMS [CERN-EP-2017-287, sub. to PRL]
based on $\sim$50k $B_s^0 \to J/\psi\phi$ decays

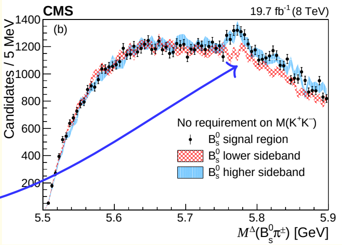


- Signal: 2 gaussian
- background: exponential
- signal region, side bands

Search for $X^+(5568)$: invariant mass scan

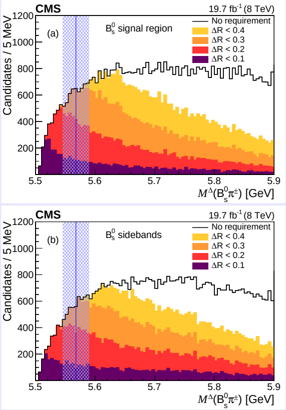
- Search for structures in the $M_{B_s^0\pi^\pm}$
- $B_s^0 \to J/\psi\phi$
  - 2μ, $p_T^{mu} > 4$ GeV, $p_T^{\mu\mu} > 7$ GeV
  - 2 tracks ($K^\pm$), $p_T^K > 0.7$ GeV, $|M_{KK} - M_\phi| < 10$ MeV
  - fit $\mu\mu$KK to common vertex
  - $p_T^{B_s^0} > 10$ GeV, $D_{xy}/\sigma > 3$, pointing to primary vtx
- $X(5568)^\pm \to B_s^0\pi^\pm$
  - $p_T^\pi > 0.5$ 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: $B_{1,2}^{(*)} \to B_s^{0(*)}\pi$, with $B_s^0 \to J/\psi K^+\pi^-$





Search for $X^+(5568)$: impact of ΔR cut and results

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



D0 used $\Delta R < 0.3$

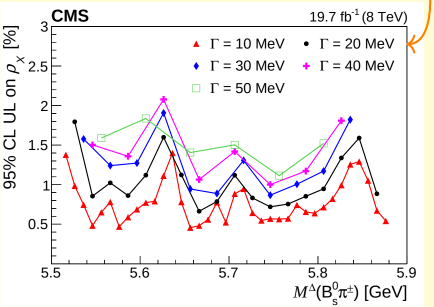
UML fit with BW⊗3G: $N_X = -85 \pm 160$ events

$$\rho_X = \frac{N_{X(5568)}}{N_{B_s^0}} \frac{\varepsilon_{B_s^0}}{\varepsilon_{X(5568)}} < 1.1(1.0)\% \text{ at } 90\% \text{ CL}$$

for $p_T^{B_s^0} > 10(15)$ GeV

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

$\Gamma_{D0} \sim 20$ MeV



ρ_X for different width Γ

Outline

$B \to \mu\mu$: CMS results

CMS results for $\mathcal{B}(B_{s,d} \to \mu\mu)$

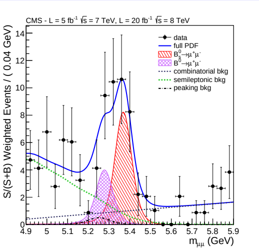
Run I results [PRL 111 (2013) 101804]

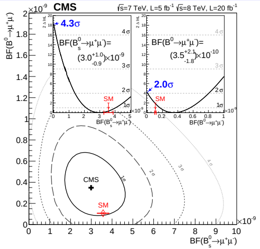
$L = (5 + 20)\,\mathrm{fb}^{-1}$ @ 7&8 TeV

$\mathcal{B}(B^0_s) = 3.0^{+0.9}_{-0.8}(\mathrm{stat.})^{+0.6}_{-0.4}(\mathrm{syst.}) \cdot 10^{-9}$ 4.3σ (4.8 exp)

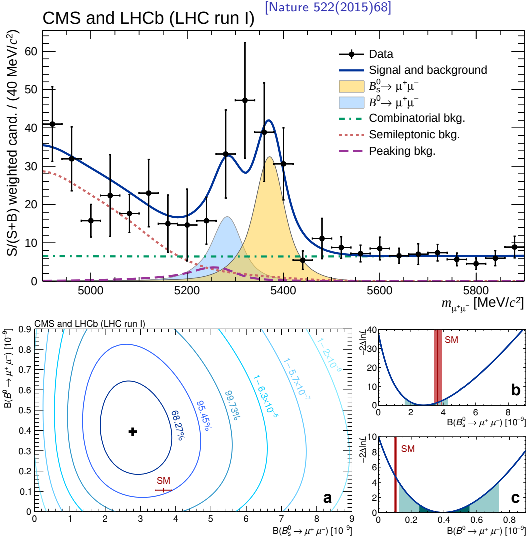
$\mathcal{B}(B^0_d) < 1.1 \cdot 10^{-9}$ 95% CL

$\mathcal{B} = 3.5^{+2.1}_{-1.8}(\mathrm{stat.} + \mathrm{syst.}) \cdot 10^{-10}$ 2.0σ





[Nature 522(2015)68]



$B \to \mu\mu$: Projection for Run2

[CMS-FTR-13-002]

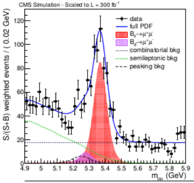
[CMS-TDR-15-002]

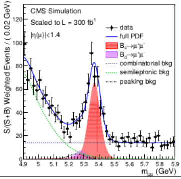
[CMS-TDR-17-001]

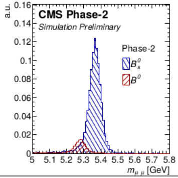
- 'Simple' scaling of current analysis in CMS-FTR-13-022
  - ▷ not including 'better' methodology

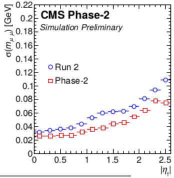
L (fb^{-1})	No. of $\mathrm{B_s^0}$	No. of $\mathrm{B^0}$	$\delta\mathcal{B}/\mathcal{B}(\mathrm{B_s}^0 \to \mu^+\mu^-)$	$\delta\mathcal{B}/\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-)$	$\mathrm{B^0}$ sign.	$\delta\frac{\mathcal{B}(\mathrm{B^0}\to\mu^+\mu^-)}{\mathcal{B}(\mathrm{B_s^0}\to\mu^+\mu^-)}$
20	16.5	2.0	35%	>100%	0.0–1.5 σ	>100%
100	144	18	15%	66%	0.5–2.4 σ	71%
300	433	54	12%	45%	1.3–3.3 σ	47%
3000	2096	256	12%	18%	5.4–7.6 σ	21%

- Trigger will be crucial ($p_\perp$ resolution at L1 for dimuons)
  - ▷ E.g. L1 track trigger!





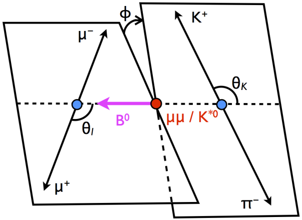


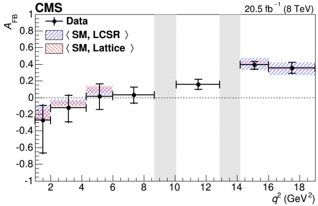


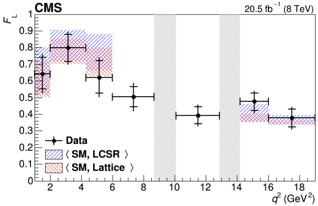
$B \to \mu\mu$ new analysis:

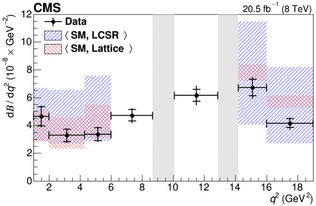
- improved muon ID
- improved pileup studies
- effective lifetime determination
- in-situ dimuon trigger/reconstruction bias determination
- not a "search analysis" any more

- $B^0 \to K^* \mu\mu$ FCNC process
- Fully described by: $\theta_\ell, \theta_K, \varphi$ and $q^2 = M^2_{\mu\mu}$;
- B^0 ($\overline{B}^0$) identified by K and π 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









$B^0 \to K^*\mu\mu$: 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

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\mathrm{d}\cos\theta_l\mathrm{d}\cos\theta_\mathrm{K}\mathrm{d}\phi} = \frac{9}{8\pi}\left\{\frac{2}{3}\left[(F_\mathrm{S} + A_\mathrm{S}\cos\theta_\mathrm{K})\left(1-\cos^2\theta_l\right) + A_\mathrm{S}^5\sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right.$$
$$+ (1-F_\mathrm{S})\left[2F_\mathrm{L}\cos^2\theta_\mathrm{K}\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_\mathrm{L})\left(1-\cos^2\theta_\mathrm{K}\right)\left(1+\cos^2\theta_l\right)\right.$$
$$+ \frac{1}{2}P_1(1-F_\mathrm{L})(1-\cos^2\theta_\mathrm{K})(1-\cos^2\theta_l)\cos 2\phi$$
$$\left.\left. + 2P_5'\cos\theta_\mathrm{K}\sqrt{F_\mathrm{L}\,(1-F_\mathrm{L})}\sqrt{1-\cos^2\theta_\mathrm{K}}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

- 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

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$$+ (1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right)\right.$$
$$+ \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi$$
$$\left.\left. +2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

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$$+ (1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right)\right.$$
$$+ \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi$$
$$\left.\left. +2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

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$$+ (1-F_S)\left[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right)\right.$$
$$+ \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi$$
$$\left.\left. + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\right]\right\}$$

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- F_L, F_S, and A_s fixed from previous CMS measurement
- P_1 and P_5' measured, A_s^5 nuisance parameter

Full PDF, including mis-tagged events and background

$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi)$$

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

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

Full PDF, including mis-tagged events and background

$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi)$$
$$+ \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_K, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(\cos\theta_K, \cos\theta_l, \phi) \Big)$$
$$+ Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_K}(\cos\theta_K) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).$$

Correct-Tag

Wrong-Tag

Background

Full PDF, including mis-tagged events and background

$$
\begin{aligned}
\text{p.d.f.}(m, \cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) = Y_S^C \cdot \Big(& \boxed{S_i^R(m)} \cdot S_i^a(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_{\mathrm{K}}, \cos\theta_l, \phi) \\
& + \frac{f_i^M}{1 - f_i^M} \boxed{S_i^M(m)} \cdot S_i^a(-\cos\theta_{\mathrm{K}}, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(\cos\theta_{\mathrm{K}}, \ldots \\
& + Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_{\mathrm{K}}}(\cos\theta_{\mathrm{K}}) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).
\end{aligned}
$$

Mass Shape
(double gauss)

Full PDF, including mis-tagged events and background

$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi)$$
$$+ \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_K, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(\cos\theta_K, \cos\theta_l, \phi) \Big)$$
$$+ Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_K}(\cos\theta_K) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).$$

Signal pdf

Full PDF, including mis-tagged events and background

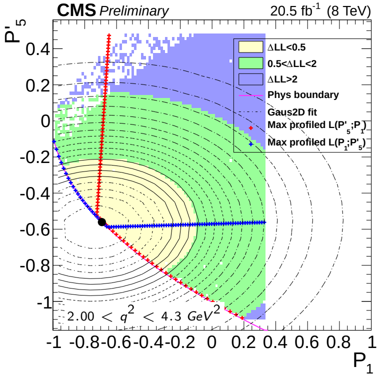
$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi) + \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_K, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(\cos\theta_K, \cos\theta_l, \phi) \Big) + Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_K}(\cos\theta_K) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).$$

3D Efficiency

Full PDF, including mis-tagged events and background

$$\text{p.d.f.}(m, \cos\theta_K, \cos\theta_l, \phi) = Y_S^C \cdot \Big(S_i^R(m) \cdot S_i^a(\cos\theta_K, \cos\theta_l, \phi) \cdot \epsilon_i^R(\cos\theta_K, \cos\theta_l, \phi)$$
$$+ \frac{f_i^M}{1 - f_i^M} \cdot S_i^M(m) \cdot S_i^a(-\cos\theta_K, -\cos\theta_l, -\phi) \cdot \epsilon_i^M(\cos\theta_K, \cos\theta_l, \phi) \Big)$$
$$+ Y_B \cdot B_i^m(m) \cdot B_i^{\cos\theta_K}(\cos\theta_K) \cdot B_i^{\cos\theta_l}(\cos\theta_l) \cdot B_i^{\phi}(\phi).$$

- 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 $\mathcal{L}(Y_S, Y_B, A_s^5)$
  - 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

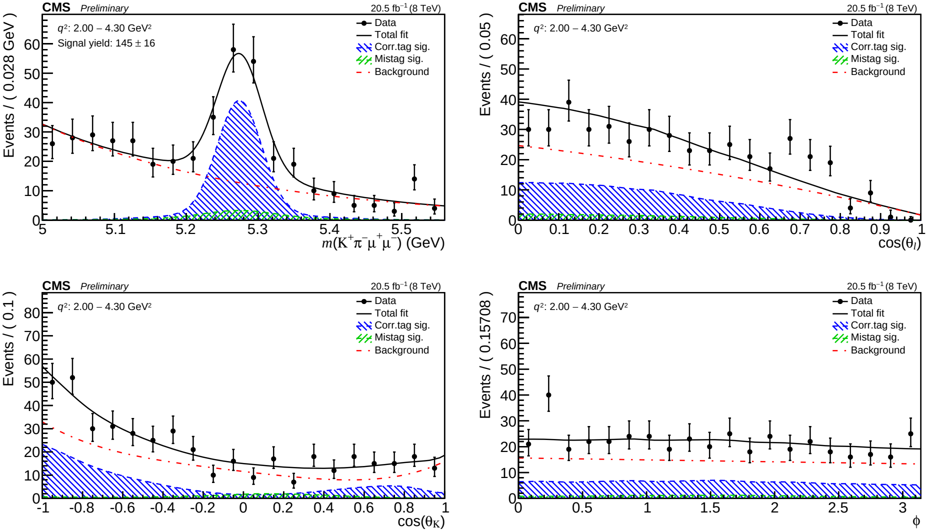
Systematic uncertainty	$P_1(10^{-3})$	$P'_5(10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–119
MC statistical uncertainty	29–73	31–112
Efficiency	17–100	5–65
$K\pi$ mistagging	8–110	6–66
Background distribution	12–70	10–51
Mass distribution	12	19
Feed-through background	4–12	3–24
F_L, F_S, A_S uncertainty propagation	0–126	0–200
Angular resolution	2–68	0.1–12
Total systematic uncertainty	60–220	70–230

- 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/ψ control region and propagated to all bins;

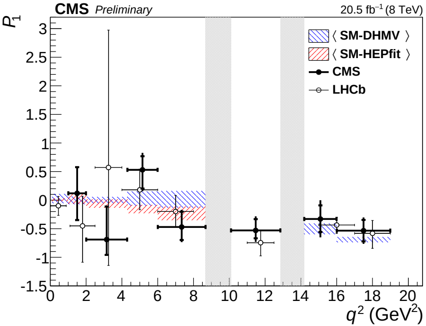
Propagation of F_L, F_S, and A_s uncertainties:

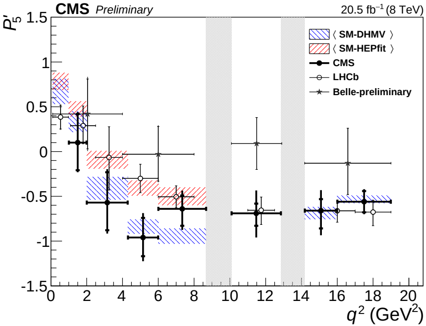
- generate pseudo experiments, with x100 events, for each q^2 bin;
  - Fit with F_L, F_S, A_s free to float and with F_L, F_S, A_s fixed;
  - ratio of stat. uncert. on P_1 and P'_5 with free and fixed fit used to estimate syst uncertainties.
- check bias vs statistics of toy MC and validated on control channels

Results: fit projection for second bin: $2.0 < q^2 < 4.3\,\text{GeV}^2$



Results vs SM prediction and LHCb/Belle measurements





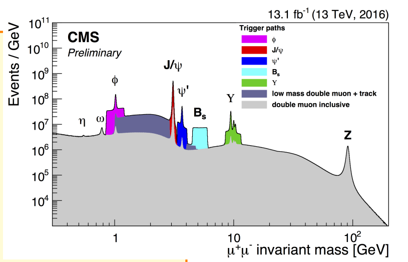
LHCb [JHEP 02 (2016) 104], Belle [PRL 118 (2017) 111801], ATLAS results not shown [ATLAS-CONF-2017-023]

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

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, Λ_b
  - Λ_b polarization
  - search for $X(5568)$
  - $B^0_s \to \mu\mu$
  - $B^0 \to K^*\mu\mu$ 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.

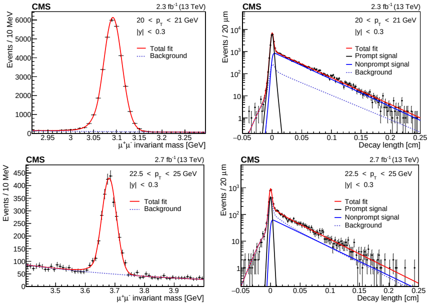
Additional stuff

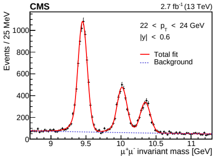
Additional or backup slides

Yield extraction

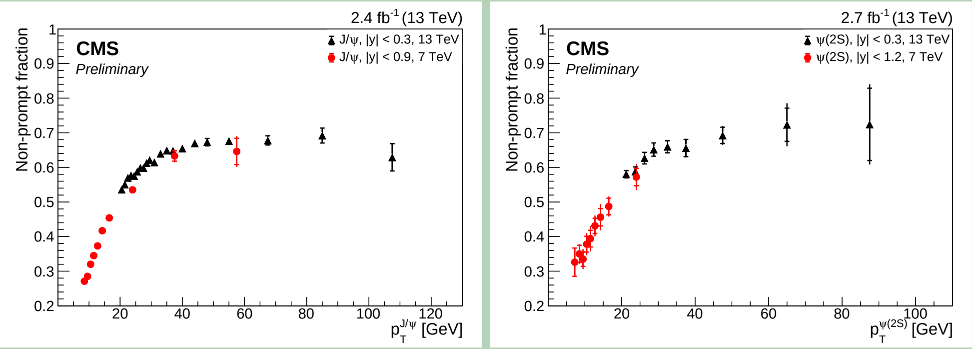
Quarkonium yield extracted with a extended-UML to $M_{\mu\mu}$.

- Pdf used:
  - J/ψ: Crystal ball + Guassian
  - ψ(2S): Crystal ball
  - Υ (1s,2s,3s): Crystal ball
  - Background: exponential
- for J/ψ, ψ(2S) non prompt-component from b-hadrons decay.
  - use 2D UML using also decay lenght of J/ψ,ψ(2S): pdf
    - prompt component: double gaussian (per-event resolution)
    - non-prompt: exponential$\otimes$gaussian
    - background: double gaussian





J/ψ and $\psi(2S)$ fraction from b-hadrons decay



Fraction of non-prompt J/ψ and $\psi(2S)$ (from b-hadrons) as a function of p_T, and for 7 TeV ($|y| < 0.9$) and 13 TeV ($|y| < 0.3$)

B^+ production

Phys. Lett. B 771 (2017) 435

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

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

$$\frac{d\sigma(pp \to B^+X)}{dx^B} = \frac{n_{sig}(x^B)}{2\,\mathcal{A}(x^B)\,\varepsilon(x^B)\,\mathcal{B}\,\mathcal{L}\,\Delta x^B} \qquad x = p_T^B, y^B$$

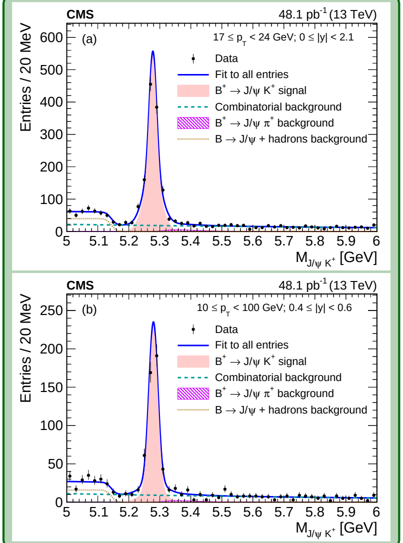
Selection:

- L1: 2μ $|\eta| < 1.6$ or 2μ $|\eta| < 2.4$ and 1μ $p_T > 10\,\text{GeV}$
- HLT: 2μ $|\eta| < 2.4$, $p_T > 4\,\text{GeV}$, $2.9 < M_{\mu\mu} < 3.3\,\text{GeV}$, $P_{vtx}^{\mu\mu} > 10\%$
- J/ψ: $p_T > 8\,\text{GeV}$
- K: charged track $p_T > 1\,\text{GeV}$

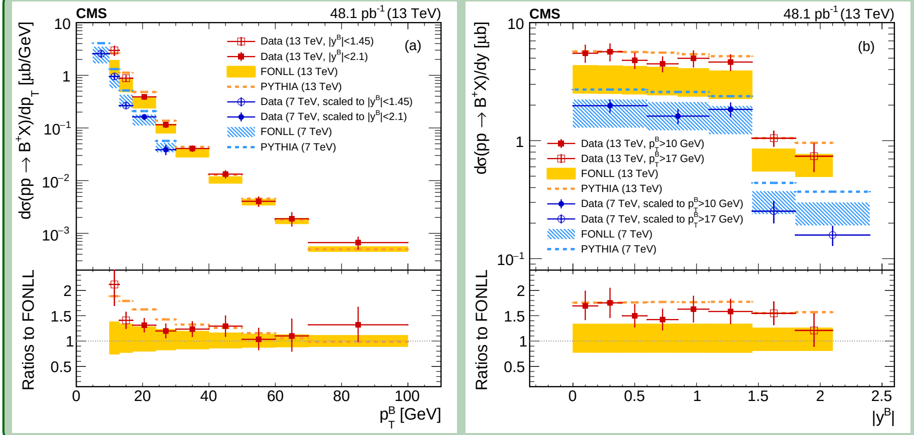
- factor 2: σ for single charge B^+
- $n_{sig}(p_T, |y|)$ from UML fit
- $\mathcal{B} = \mathcal{B}(B^+ \to J/\psi K^+) \cdot \mathcal{B}(J/\psi \to \mu\mu)$
- Δp_T, $\Delta y = 2\Delta|y|$ are bin widths
- $\mathcal{A}, \varepsilon$ from MC, evaluated for each bin

Signal yield extraction

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

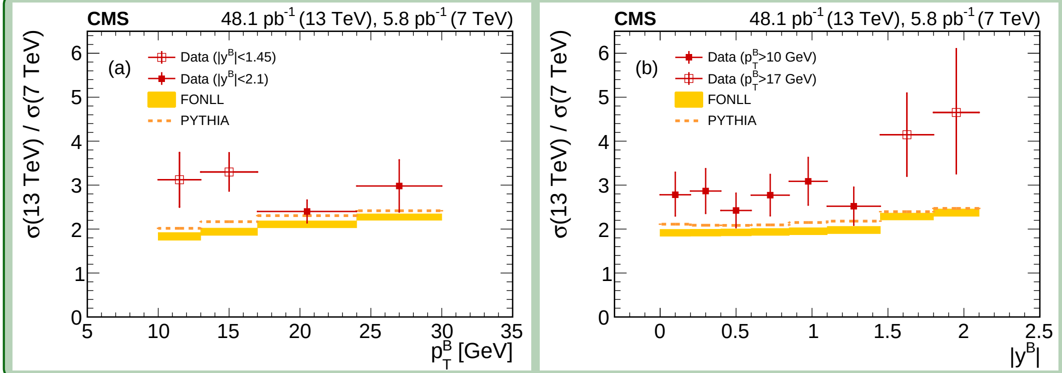


B^+ cross-section results: 13 and 7 TeV



Comparison with FONLL [JHEP 03 (2001) 006] and PYTHIA prediction, for 7 and 13 TeV. Reasonable agreement in shape and normalization

Cross section ratio: 13/7 TeV



Ratio of σ measurement at 13 and 7 TeV prefer higher valued compared to FONLL and PYTHIA prediction

Double Quarkonia Production: SPS

- 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/ψ 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 occurances**

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

[more on this later!]

It depends on the **DPS fraction** which is usually estimated either ...

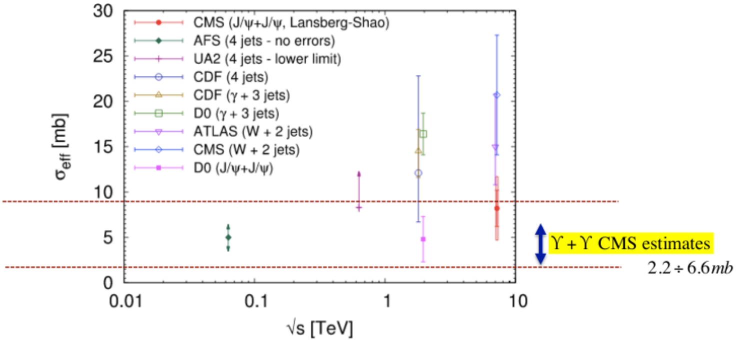
1) as a residual of the SPS prediction, or ...

2) as the result of a fit to the rapidity or azimuthal angle difference between pairs

Strong correlation of the two J/ψ 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

Xsection 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



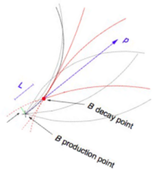
CMS (J/ψ+J/ψ, Lansberg-Shao)
AFS (4 jets - no errors)
UA2 (4 jets - lower limit)
CDF (4 jets)
CDF (γ + 3 jets)
D0 (γ + 3 jets)
ATLAS (W + 2 jets)
CMS (W + 2 jets)
D0 (J/ψ+J/ψ)
σ_eff [mb]
√s [TeV]
0
5
10
15
20
25
30
0.01
0.1
1
10
ϒ + ϒ CMS estimates
2.2 ÷ 6.6mb

$\lambda_{\theta 1}$	+1	+1	+0.5	−0.5	+0.5	−1	+1	−0.5	−0.5	−1
$\lambda_{\theta 2}$	+1	+0.5	+0.5	+0.5	−0.5	+1	−1	−0.5	−1	−1
Change (%)	+36	+26	+18	−2	−3	−9	−9	−19	−29	−38

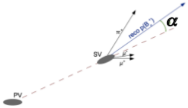
Component	Uncertainty (%)
Resonance shape	7.9
Simulation	4.9
Efficiency	3.7
Acceptance	2.8
Integrated luminosity	2.6
Total	10.7

Signal extraction:

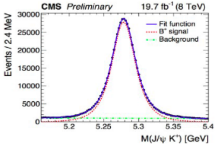
- Trigger: muon pairs compatible with J/ψ mass & $p_T \geq 8GeV$
- High quality offline charged tracks attached to J/ψ (or tertiary) vertex [$p_T \geq 0.5GeV$]; additional kinematical requirements according to channel.
- Intermediate neutral resonances [$K^{*0}, K_s^0, \phi, \Lambda^0$] reconstructed by pairs of opposite charged tracks from a common vertex; 2σ mass-window around nominal masses; cross-channel contamination removed. Tertiary vertex displacement requirements (for K_s^0, Λ^0).



- b-hadron candidates: vertex quality criteria & $p_T \geq 13GeV$ [except B_c^+ ($p_T \geq 10GeV$) & $J/\psi\phi$ (no req.)]; candidates' fit with mass constraint for $J/\psi, K_s^0, \Lambda^0$
- *Production* vertex selected by **smallest *pointing angle* α** (fitted from reco tracks using the **beamspot as a constraint**)



Reference channel:



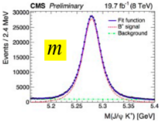
$B^+ \rightarrow J/\psi K^+$ ($p_T(K) \geq 1.0GeV$) : the simplest decay mode with the highest yield

- used for overall calibration & specific systematic studies

Lifetime measurement: UML fit

Unbinned Maximum Likelihood fit with a set of **3 input observables** (per candidate): $\Phi_j = (m_j,\ ct_j,\ \sigma^j_{ct})$

$$L = \prod_j \left[n_{SIG} L_{SIG}(\Phi_j) + n_{BKG} L_{BKG}(\Phi_j) \right] \quad \textbf{where} \quad L(\Phi_j) = L(m_j)\cdot L(ct_j|\sigma^j_{ct})\cdot L(\sigma^j_{ct})$$

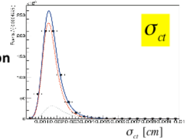


SIG: Gaussian sum

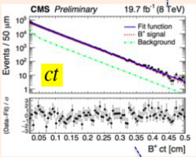
BKG: Exponential

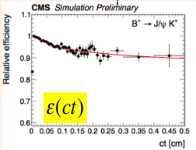
SIG: distribution from SB-subtracted region

BKG: from SideBands



SIG: $L_{SIG}(ct_j|\sigma^j_{ct};\tau) = \left[e^{-ct'_j/\tau} \otimes G(t_j - t'_j;\sigma^j_{ct}) \right]\cdot \varepsilon(ct_j) \Big/ \int L_{SIG}(t)\,dt$





: the exponential decay distrib. (with *lifetime* [*]) is

- smeared with a per-candidate resolution function σ_{ct}

- corrected by reconstruction/selection biases described by the relative efficiency $\varepsilon(ct)$

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

BKG: $L_{BKG}(ct_j|\sigma^j_{ct}) = \left[\sum_k e^{-ct'_j/\tau_k} \otimes G(t_j - t'_j;\sigma^j_{ct}) \right] \Big/ \int L_{BKG}(t)\,dt$ **: *t*-model given by an heuristic sum of decay functions**

- ***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:

$$\Delta m_S \equiv m_H - m_L \cong 17.76 \pm 0.02 ps^{-1} \qquad \Delta\Gamma/\Gamma \equiv \frac{\Gamma_H - \Gamma_L}{(\Gamma_H + \Gamma_L)/2} \cong -0.12 \pm 0.01$$

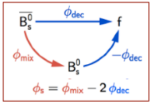
In absence of sizable CPV in the ***B**$_s$* system, heavy/light eigenstates correspond to CP-odd/even resp.

- $B_s^0 \to J/\psi\pi^+\pi^-$: the final state state is dominated by $f_0(980)$, making it a CP-odd state [PRD 89 (2014) 092006]
  - the measured lifetime gives direct access to Γ_H (thus τ_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*** τ_{eff} (the distribution consists in 2 exponentials) that is a weighted average of τ_H & τ_L [**note**: *average* lifetime is for equal admixtures] (details @backup)
  - This is **complementary to** the weak mixing phase ϕ_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 ($f_S = 1.2^{+0.9}_{-0.7}\%$) 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 ⇨ the cut $ct > 200\mu m$ modifies the relative composition & $c\tau_{eff}$ 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 & $\bar{B}_s^0$ decay to a *CP* eigenstate (as in flavor-blind $B_s^0 \to J/\psi\phi$) the weak phase ϕ_s arises from the interference between direct decays & decays with mixing



Theoretically clean decay mode: tiny CPV ruled by $\phi_S^{SM} \approx -2\beta_S = -0.0363^{+0.0016}_{-0.0015} rad$ $[\beta_S = \arg(-V_{ts}V_{tb}^* / V_{cs}V_{cb}^*)]$ [PRD 84 (2011) 033005]

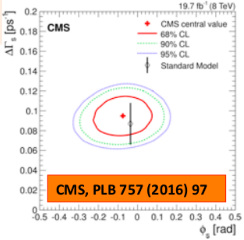
⇨ Sensitivity to NP in mixing: many NP scenarios predict enhanced values of ϕ_S

$J/\psi\phi$ final state : admixture of CP-odd and CP-even eigenstate to be disentangled by angular analysis

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

It implies the detailed characterization of the system & the simultaneous extraction of *weak phase* ϕ_S & *width difference* $\Delta\Gamma_S$ (and the measurement of the *average decay width* Γ_S)

  - $\Delta\Gamma_S$ 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)



Λ_b polarization

- 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 Λ_b baryons the b-quark combines with a spin-0 *ud* pair, so all of the Λ_b spin resides on the valence b-quark and we expect b-polarization to become Λ_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 asymetry parameter in Λ_b —> Λ 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

LHCb

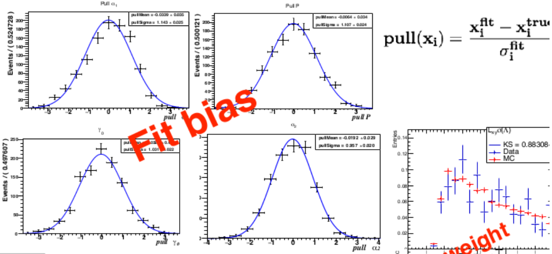
- To summary, a measurement of the polarization provides a test of HQET and information about heavy baryon hadronization and nonperturbative corrections to spin transfer in fragmentation.

Λ_b polarization systematics

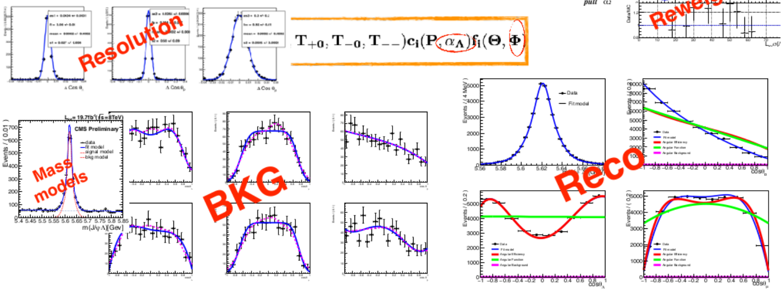
- We consider the following systematics sources:
  - **Fit Bias**. From Toy MC we take the difference between the input values and the mean of the fitted values as systematic
  - **Asymmetry parameter**. The maximum difference when we vary the value of this parameter within ±sigma of its measured value 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 systemati

Λ_b polarization systematics

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



- 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

$$\alpha_1 \equiv |T_{++}|^2 - |T_{+0}|^2 + |T_{-0}|^2 - |T_{--}|^2,$$
$$\alpha_2 \equiv |T_{++}|^2 + |T_{+0}|^2 - |T_{-0}|^2 - |T_{--}|^2,$$
$$\gamma_0 \equiv |T_{++}|^2 - 2|T_{+0}|^2 - 2|T_{-0}|^2 + |T_{--}|^2,$$

i	η_i	c_i	f_i
1	1	1	1
2	α_2	α_Λ	$\cos\theta_p$
3	$-\alpha_1$	P	$\cos\theta_\Lambda$
4	$-(1+2\gamma_0)/3$	$\alpha_\Lambda P$	$\cos\theta_\Lambda \cos\theta_p$
5	$\gamma_0/2$	1	$(3\cos^2\theta_\mu - 1)/2$
6	$(3\alpha_1 - \alpha_2)/4$	α_Λ	$\cos\theta_p (3\cos^2\theta_\mu - 1)/2$
7	$(\alpha_1 - 3\alpha_2)/4$	P	$\cos\theta_\Lambda (3\cos^2\theta_\mu - 1)/2$
8	$(\gamma_0 - 4)/6$	$\alpha_\Lambda P$	$\cos\theta_\Lambda \cos\theta_p (3\cos^2\theta_\mu - 1)/2$

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

↓

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

Parameter	CMS	LHCb		ATLAS	
		result	difference	result	difference
$\lvert T_{-0}\rvert^2$	$0.52 \pm 0.03 \pm 0.04$	$0.57 \pm 0.06 \pm 0.03$	0.71σ	$0.35^{+0.07}_{-0.08} \pm 0.04$	1.60σ
$\lvert T_{+0}\rvert^2$	$-0.10 \pm 0.04 \pm 0.04$	$0.01 \pm 0.04 \pm 0.03$	1.45σ	$0.03^{+0.04}_{-0.06} \pm 0.03$	1.48σ
$\lvert T_{--}\rvert^2$	$0.53 \pm 0.04 \pm 0.04$	$0.51 \pm 0.05 \pm 0.02$	0.13σ	$0.62^{+0.06}_{-0.08} \pm 0.02$	1.00σ
$\lvert T_{++}\rvert^2$	$0.04 \pm 0.04 \pm 0.04$	$-0.10 \pm 0.04 \pm 0.03$	1.98σ	$0.01^{+0.02}_{-0.01} \pm 0.01$	0.65σ
P	$0.00 \pm 0.06 \pm 0.06$	$0.06 \pm 0.07 \pm 0.06$	0.47σ	—	

$B_s^0 \to \mu\mu$ Analysis in a nutshell

PRL 111 (2013) 101804

Signal (BDT selection)

- a good, isolated $\mu^\pm$ pair from displaced vertex
- momentum aligned along flight direction;
- invariant mass peaking at $M(B_s^0, B_d^0)$

$$\mathcal{B}(B_s^0 \to \mu\mu) = N_s \cdot \frac{\mathcal{B}(B^\pm \to J/\psi K^\pm)}{N(B^\pm \to J/\psi K^\pm)} \cdot \frac{\varepsilon(B^\pm)}{\varepsilon(B_s^0)} \frac{f_u}{f_s}$$

- ε include acceptance, trigger, and selection
- f_s/f_u B-factorization

Background

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

---

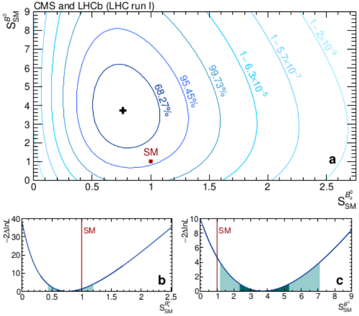
- Normalization channel $B^\pm \to J/\psi K^\pm \to \mu\mu K^\pm$, calibration $B_s^0 \to J/\psi\phi \to \mu\mu KK$
- UML symultaneous fit to Bs and Bd
- several categories based on event classification (BDT) and region (Barrel-Endcap)

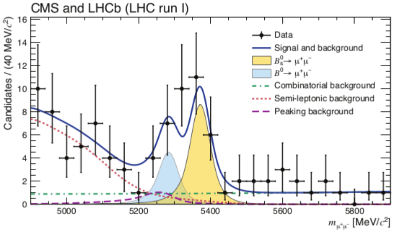
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

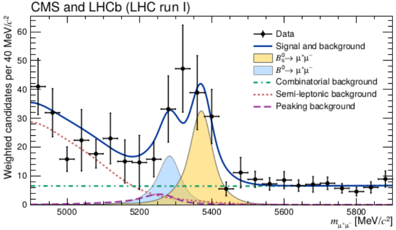
Observed significances (expected)

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

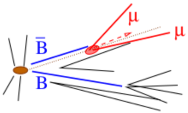
$B^0 \to \mu^+\mu^-$: $3.2\sigma(0.8\sigma)$



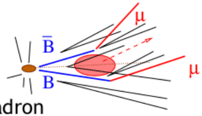




- Signal $B_s^0 \to \mu^+\mu^-$
  - two muons from one decay vertex
    - well reconstructed secondary vertex
    - momentum aligned with flight direction
    - isolated, mass around $m_{B_s^0}$



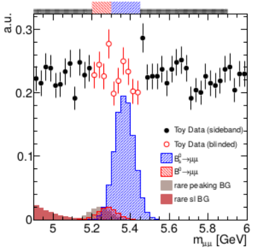
- Background
  - combinatorial (from sidebands)
    - two semileptonic (B) decays (gluon splitting)
    - one semileptonic (B) decay and one misidentified hadron



  - rare single B decays (from MC simulation)
    - non-peaking, e.g. $B_s^0 \to K^-\mu^+\nu$, $\Lambda_b \to p\mu^+\nu$
    - peaking, e.g. $B_s^0 \to K^+K^-$

- Blind analysis

⇒ Critical issues
  - optimized selection
  - muon misidentification probability
  - pileup (isolation)



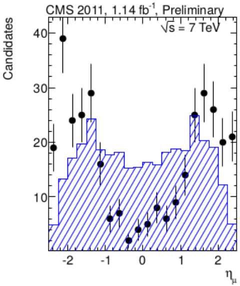
$B_s^0 \to \mu\mu$: methodology

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

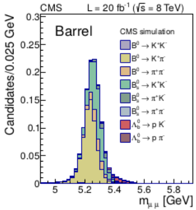
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \frac{n^{\rm obs}_{B_s^0}}{\varepsilon_{B_s^0} N_{B_s^0}} = \frac{n^{\rm obs}_{B_s^0}}{\varepsilon_{B_s^0} \mathcal{L}\, \sigma(pp \to B_s^0)}$$

$$= \frac{n^{\rm obs}_{B_s^0}}{N(B^+ \to J/\psi\, K^+)} \frac{A_{B^+}}{A_{B_s^0}} \frac{\varepsilon^{ana}_{B^+}}{\varepsilon^{ana}_{B_s^0}} \frac{\varepsilon^{\mu}_{B^+}}{\varepsilon^{\mu}_{B_s^0}} \frac{\varepsilon^{trig}_{B^+}}{\varepsilon^{trig}_{B_s^0}} \frac{f_u}{f_s} \mathcal{B}(B^+ \to J/\psi\,[\mu^+\mu^-]K)$$

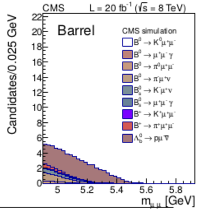
- Reconstructed exclusive decays
  - $B^+ \to J/\psi\, K^+$: normalization and studies
  - $B_s^0 \to J/\psi\, \phi$: B_s^0 signal MC validation, alternative normalization
  - $J/\psi\, , \Upsilon(1S) \to \mu^+\mu^-$: mass calibration
- Divide data into channels
  - better sensitivity
  - add more data



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



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



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

Trig Dedicated HLT trigger path:
Low pt dimuon, displaced, low invariant mass

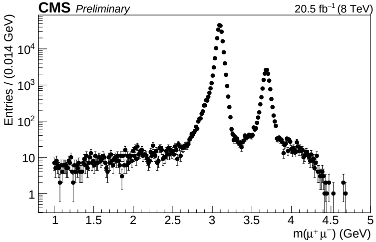
h $p_T^h > 0.8\,\mathrm{GeV}$, $|M(\mathrm{K}\pi) - M_{\mathrm{K}^*}| < 90$ MeV, $M_{\mathrm{KK}} > 1.035$ (ϕ veto), displaced $DCA/\sigma > 2$

μ $p_T^\mu > 3.5\,\mathrm{GeV}$, $p_T^{\mu\mu} > 6.9$ GeV, $1 < M_{\mu\mu} < 4.8\,\mathrm{GeV}$, displaced $L/\sigma > 3$

B^0 $p_t > 8\,\mathrm{GeV}$, $|\eta| < 2.2$, displaced $(L/\sigma > 12)$, $\cos\alpha > 0.9994$, $|M - M_{\mathrm{B}^0}| < 280$ MeV

- Both B^0 and $\overline{\mathrm{B}}^0$ considered, if more than one candidate, take the one with best B^0 vtx CL
- anti radiation cut against feed-down of $\mathrm{J}/\psi/\psi'$

CR signal and control sample J/ψ and ψ' treated same way.



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

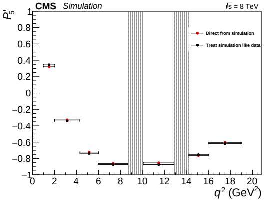
Background considered

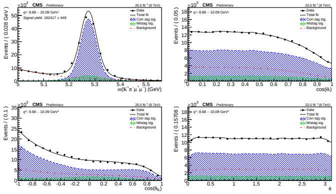
- Partially reconstructed B^0 decay might pollute left M_{B^0} side bands
  - restrict left s.b. $(5.1 < M < 5.6\,\text{GeV}$, default $5 < M < 5.6\,\text{GeV})$
  - redo fit: change in P_1 and P_5' within the systmatics uncertainties.
- $B^\pm \to K^\pm \mu\mu$ plus and additional random $\pi^\mp$:
  - distribution ends at $M > 5.4\,\text{GeV}$, further reduced by $\cos\alpha$ cut, and BR similar to $B^0 \to K^*\mu\mu$
- $\Lambda_b \to pKJ/\psi(\mu^+\mu^-)$
  - 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.
- $B^0 \to DX$, with $D \to hh$ and h mis-id as μ
  - requires two mis-id: $P_{misId} \sim 1 \cdot 10^{-3}$: given $BR \sim 1 \cdot 10^{-3}$ negligible.
- $B^0 \to J/\psi(\mu\mu)K^*(K\pi)$, with one h and one μ switched
  - $P_{misId\ \mu} \cdot (1 - \varepsilon_\mu) \sim 1 \cdot 10^{-4}$, $Y_{B^0 \to J/\psi\mu\mu} \sim 1.6 \cdot 10^5$: few events in bin close to J/ψ
  - J/ψ feed contamination in close bin included in the fit model

Fit validation

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 P_1 and P_5' on J/ψ and ψ' w/ and w/o F_L fixed: no bias



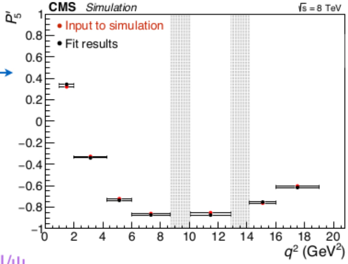


$$\frac{\mathcal{B}(B^0 \to K^* \psi')}{\mathcal{B}(B^0 \to K^* J/\psi)} == \frac{Y_{\psi'}}{\epsilon_{\psi'}} \frac{\epsilon_{J/\psi}}{Y_{J/\psi}} \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi' \to \mu^+\mu^-)} = 0.480 \pm 0.008(\mathrm{stat}) \pm 0.055(\mathrm{R}_{\psi}^{\mu\mu})$$

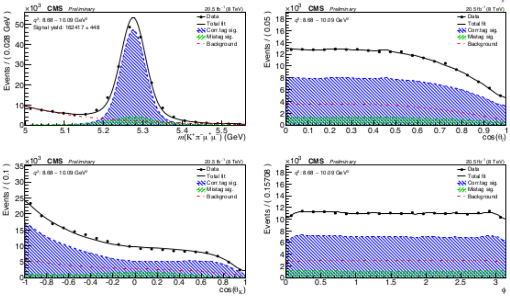
vs PDG $0.484 \pm 0.018(\mathrm{stat}) \pm 0.011(\mathrm{syst}) \pm 0.012(\mathrm{R}_{\psi}^{ee})$

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



$B^0 \rightarrow K^{*0} J/\psi$

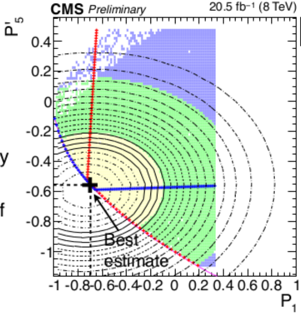


Validation with data control channels:

- Fit performed with $\mathbf{F_L}$ free to vary
- The difference of $\mathbf{F_L}$ with respect to PDG value is propagated to the signal q^2 bins as systematic uncertainty (**efficiency**)

Fit procedure

- The decay rate can become negative for certain values of the angular parameters (**P_1**, **P_5'**, **A^5_s**)
- 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_s** 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



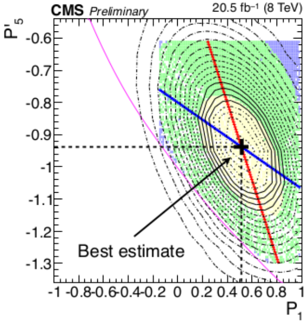
2nd q^2 bin

Color code Log Likelihood (LL):
- yellow = 0 to 0.5 LL
- green = 0.5 to 2 LL

Coloured paths:
- Profile likelihood for P_1
- Profile likelihood for P_5'

FC stat uncertainties determination

- 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