Heavy quark physics

LaThuile 2015: XXIX Rencontres de Physique de la Vallee d'Aoste

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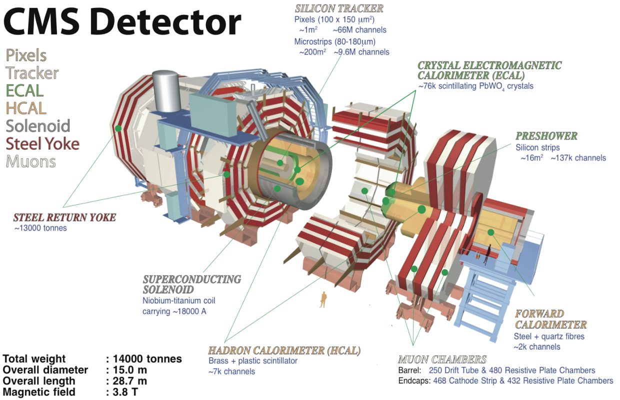
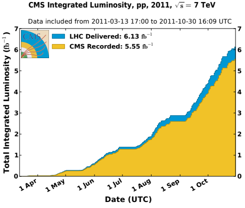
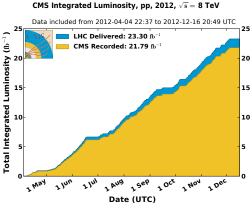
March 3,2015







- 2010: $L=10^{32}\ cm^{-2}s^{-1}$
- 2011: $L=4 \cdot 10^{33}\ cm^{-2}s^{-1}$
- 2012: $L=7.5 \cdot 10^{33}\ cm^{-2}s^{-1}$

- Dimuon mass resolution: 32 MeV (barrel) and 75 MeV (endcap)
- Impact parameter resolution: 10 μm @ 100 GeV and 20 μm @ 10 GeV

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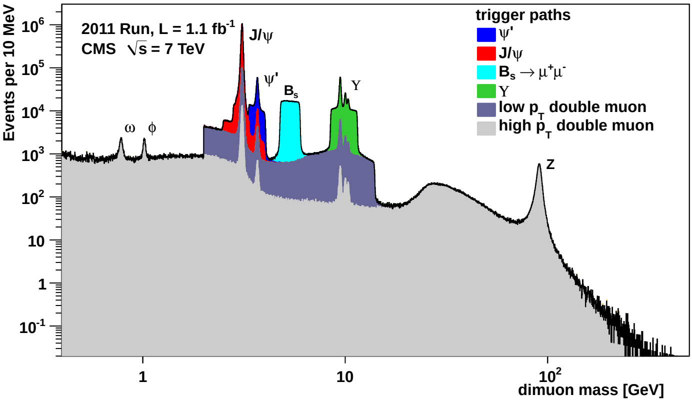
Heavy flavour physics triggers



Trigger selection

- Muon kinematics
- Dimuon kinematics and vertex probability
- Flight length significance and pointing angle

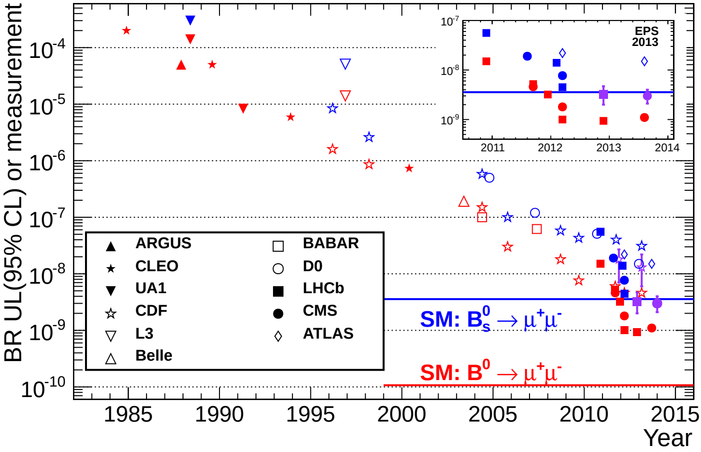
Outline

Recent results on physics of beauty and charm quarks in proton-proton collisions at CMS:

- Search for physics beyond the standard model (by the mean of indirect evidence)
  - Search for $\mathrm{B_{s,d}} \to \mu\mu$ decays at CMS
  - CP-violating phase ϕ_s using $\mathrm{B_s} \to \mathrm{J}/\psi\phi(1020)$ channel
- Study of standard model of particle physics, test of QCD and particle properties
  - $\mathrm{B}^+ \to \psi(2\mathrm{S})\phi\mathrm{K}^+$ rare decay
  - $\mathrm{B_c}$ decays
  - $\mathcal{B}(\mathrm{B_s} \to \mathrm{J}/\psi \mathrm{f}_0(980))/\mathcal{B}(\mathrm{B_s} \to \mathrm{J}/\psi\phi(1020))$ ratio
  - J/ψ, $\psi(2\mathrm{S})$, $\Upsilon(nS), and \chi_{bn}$ production

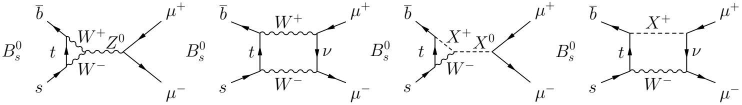
Search for $\mathrm{B_{s,d}} \to \mu\mu$ decays at CMS

$B_{s,d} \to \mu\mu$ search history



$B_{s,d} \to \mu\mu$ motivation

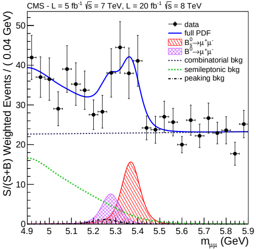
Standard Model　　　　Beyond SM

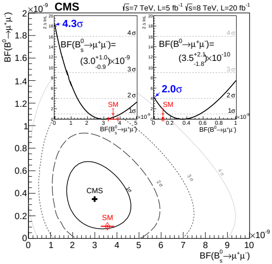


- Highly suppressed decay in SM
  - Forbidden ar tree level $\to$ FCNC transitions only possible through penguin or box diagram
  - Cabibbo $|V_{td}| < |V_{ts}|$ and helicity suppressed
- SM predictions
  - $\mathcal{B}(B_s \to \mu\mu)$=$(3.66 \pm 0.23) \cdot 10^{-9}$ (PRL112, 101801, 2014)
  - $\mathcal{B}(B_d \to \mu\mu)$=$(1.06 \pm 0.10) \cdot 10^{-10}$ (PRL112, 101801, 2014)
- Sensitivity to NP
  - 2HDM and $m(H^+)$
  - MSSM tan β
  - Leptoquarks
  - 4^{th} generation top

$\mathrm{B_{s,d}} \to \mu\mu$ CMS measurement [PRL 111 (2013) 101804]

- Selections:
  - BDT muon selection $\to$ low muon fake rate
  - Selection done using a BDT with 12 input variables for B candidates
  - Trained with MC signals sample and with data sidebands
  - Same BDT for $\mathrm{B}^{\pm} \to \mathrm{J}/\psi \mathrm{K}^{\pm}$ normalisation and $\mathrm{B_s} \to \mathrm{J}/\psi\phi(1020)$ control channels
  - No pile-dependence, no $\mathrm{B_s}$ mass dependence
- BDT categories:
  - BDT response divided in multiple bins depending on data period 2012(4) or 2011(2)
  - Two further categories: barrel and endcap regions (different mass resolution)
- Unbinned ML fit with per-event resolution:
  - Signal: fit of both $\mathrm{B_s}$ and B^0 shapes
  - Peaking backgrounds ($\mathrm{B}^0 \to \mathrm{K}\pi$, $\mathrm{B}_s \to \mathrm{KK}$)
  - Combinatorial and semileptonic BG

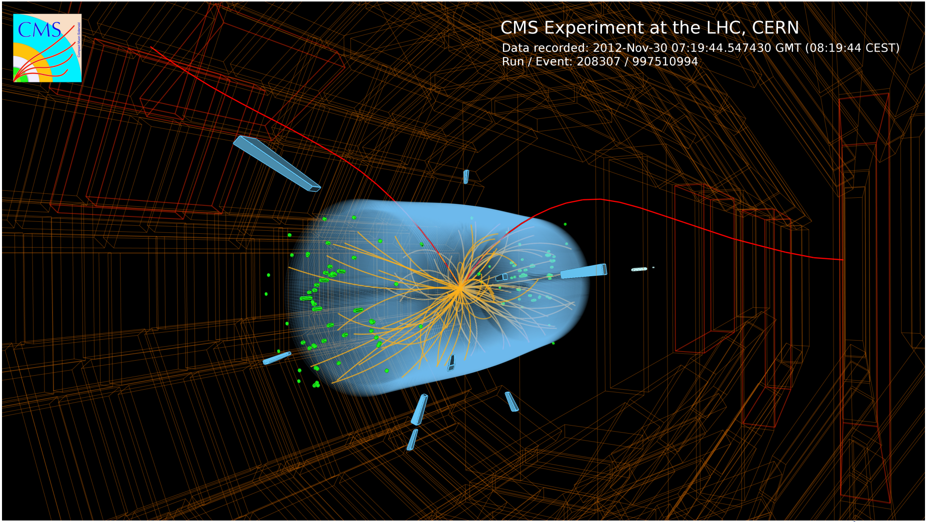




$\mathcal{B}(\mathrm{B_s} \to \mu\mu)=(3.0^{+0.9}_{-0.8}(stat.)^{+0.6}_{-0.4}(syst.)) \cdot 10^{-9}$ S=4.3σ (Exp. 4.8)

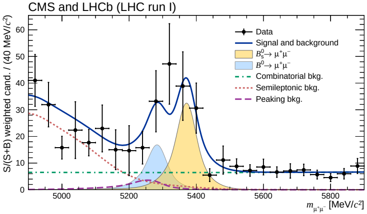
$\mathcal{B}(\mathrm{B_d} \to \mu\mu) < 1.1 \cdot 10^{-9}$ (95% C.L.)

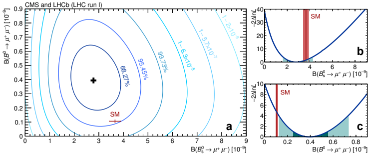
$B_{s,d} \to \mu\mu$ Event display



$B_{s,d} \to \mu\mu$ CMS + LHCb meas. [arXiv:1411.4413 Sub. to Nature]

- Data: 25 fb^{-1} (CMS) and 3 fb^{-1} (LHCb)
- Selection: BDT with 20 categories, 12 CMS categories which depend on $\sqrt{s}$, detector region, and BDT ranges + 8 LHCb categories which depend on BDT ranges
- Common parameters: hadronisation fraction f_d/f_s, $\mathcal{B}(B^{\pm} \to J/\psi K^{\pm})$
- Improvement of the CMS analysis: $\Lambda_b \to p\mu\nu$ branching ratio updated to the last prediction





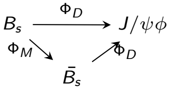
$\mathcal{B}(B_s \to \mu\mu) = (2.8^{+0.7}_{-0.6}) \cdot 10^{-9}$ S=6.2σ (Exp: 7.4σ)

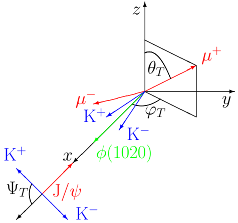
$\mathcal{B}(B_d \to \mu\mu) = (3.9^{+1.6}_{-1.4}) \cdot 10^{-10}$ S=3.0σ (Exp: 0.8σ)

CP-violating phase ϕ_s using $\mathrm{B_s} \rightarrow \mathrm{J}/\psi\phi(1020)$ channel

$B_s \rightarrow J/\psi\phi(1020)$ ϕ_s motivation

- The B_s meson decays into a final state $J/\psi\phi(1020)$, which is a mixture of two CP eigenstates (odd/even);
- Interference between direct $B_s \rightarrow J/\psi\phi(1020)$ decay and decay via mixing gives rise to a CP violation phase $\phi_s \approx -2\beta_s = -0.0363^{+0.0016}_{-0.0015}$ *rad* (SM), where $\beta_s = arg(-V_{ts}V^*_{tb}/V_{cs}V^*_{cb})$;
- If the ϕ_s differs w.r.t. the SM prediction, then New Physics might contribute in the mixing box diagram.





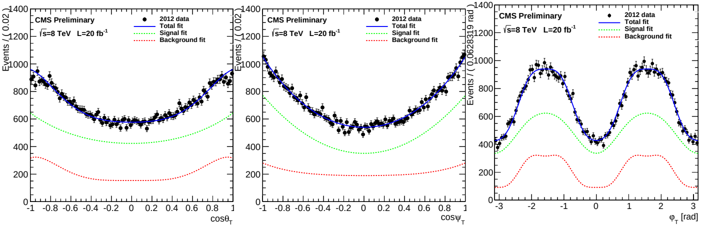
- We measure the weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ by disentangling the two CP final states of the B_s with a tagged angular analysis;
- Opposite side lepton tagging is used to define the flavour at production time.

$B_s \to J/\psi\phi(1020)$ ϕ_s measurement

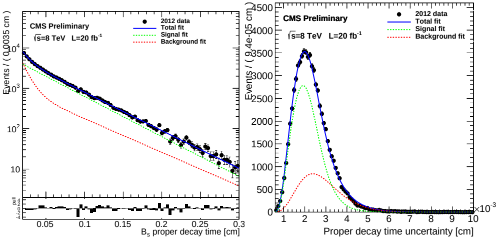
$$\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = X(\Theta, \alpha, t) = \sum_{i=1}^{10} O_i(\alpha, t).g_i(\Theta),$$

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

- b_i and d_i depend on $\sin\phi_s$ and $\cos\phi_s$
- $\Delta\Gamma_s > 0$: we use previous LHCb results
- α physics parameters $(\Delta\Gamma_s, \phi_s, c\tau, |A_0|^2, |A_S|^2, |A_\perp^2|, \delta_\parallel, \delta_{S\perp}, \delta_\perp)$
- Averaged performance of the combined (μ and e) tagger: $\omega = 32.2 \pm 0.3\%$, $\epsilon_{tag} = 7.67 \pm 0.04\%$, $P_{tag} = 0.97 \pm 0.04\%$;



- Fit of the tagged model on the 2012 data, with a gaussian constraint of Δm_s to the PDG value $17.69 \pm 0.08\ \hbar/ps$
- Extended maximum-likelihood fit

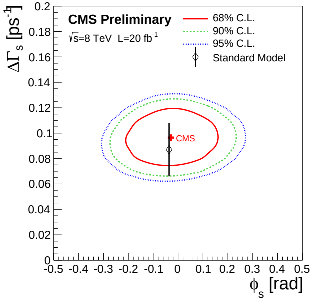


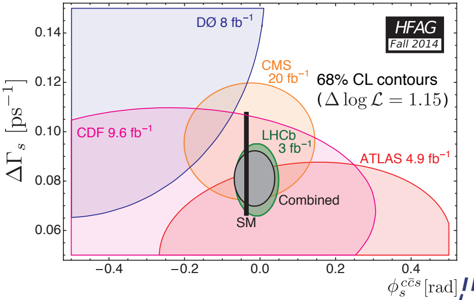
Parameter	Fit results
$\vert A_0\vert^2$	0.511 ± 0.006
$\vert A_S\vert^2$	0.015 ± 0.016
$\vert A_\perp\vert^2$	0.242 ± 0.008
$\Delta\Gamma_s\ [ps^{-1}]$	0.096 ± 0.014
$\delta_\parallel\ [rad]$	3.48 ± 0.09
$\delta_{S\perp}\ [rad]$	0.34 ± 0.24
$\delta_\perp\ [rad]$	2.73 ± 0.36
$\phi_s\ [rad]$	-0.03 ± 0.11
$c\tau\ [\mu m]$	447 ± 3

- Analysing the 2012 CMS data (20.0 fb^{-1}), we selected 49k B_s signal events. We obtain:

$$\phi_s = -0.03 \pm 0.11\ (stat.) \pm 0.03\ (syst.)\ rad$$
$$\Delta\Gamma_s = 0.096 \pm 0.014\ (stat.) \pm 0.007\ (syst.)\ ps^{-1}$$

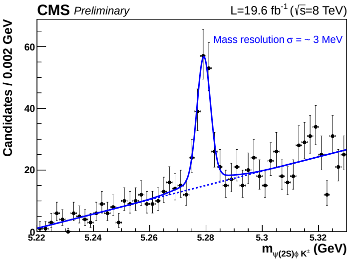
- Contour plot (stat. only), constraining $\Delta\Gamma_s > 0$:



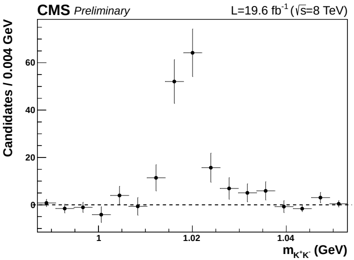


$B^+ \to \psi(2S)\phi K^+$ rare decay

Resonant peak



Background subtracted plot KK mass

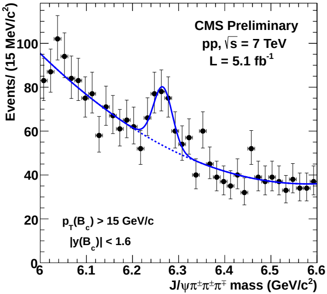


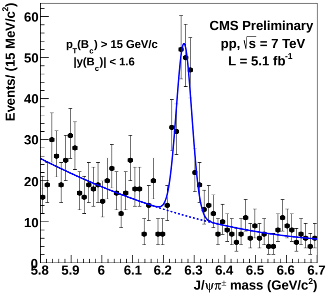
- Resonand structure due to $B^+ \to \psi(2S)\phi K^+$ decay has been found
- About 144 events identify as signal
- Next step: branching fraction measurement

$\mathrm{B_c}$ decays

$\mathrm{B_c}$ decays [JHEP 01 (2015) 063]

The $\mathrm{B_c^\pm} \to \mathrm{J}/\psi\pi^\pm$ and $\mathrm{B_c^\pm} \to \mathrm{J}/\psi\pi^\pm\pi^\pm\pi^\pm$ decay modes are studied in CMS in the kinematic region where the transverse momentum of the $B_c^\pm$ meson is greater than 15 GeV/c and within the central rapidity region $|y| < 1.6$.





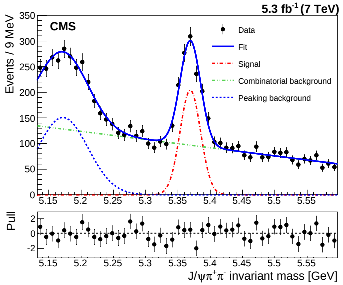
$$R_{\mathrm{B_c}} = \frac{\mathcal{B}(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp)}{\mathcal{B}(B_c^\pm \to J/\psi\pi^\pm)} = 2.55 \pm 0.80(stat) \pm 0.33(syst)^{+0.04}_{-0.01}(\tau_{B_c})$$

$$R_{c/u} = \frac{\sigma(B_c^\pm)\times\mathcal{B}(B_c^\pm \to J/\psi\pi^\pm)}{\sigma(B^\pm)\times\mathcal{B}(B^\pm \to J/\psi K^\pm)} = (0.48 \pm 0.05(stat) \pm 0.03(syst) \pm 0.05(\tau_{B_c})) \times 10^{-2}$$

$$\frac{\mathcal{B}(\mathrm{B_s} \to \mathrm{J}/\psi \mathrm{f_0}(980))}{\mathcal{B}(\mathrm{B_s} \to \mathrm{J}/\psi \phi(1020))}$$

ratio

$\frac{\mathcal{B}(\mathrm{B_s}\to \mathrm{J}/\psi \mathrm{f_0}(980))}{\mathcal{B}(\mathrm{B_s}\to \mathrm{J}/\psi \phi(1020))}$ ratio [arXiv:1501.06089 Sub. to PLB]



$$R_{\mathrm{f_0}/\phi} = \frac{\mathcal{B}(\mathrm{B_s} \to \mathrm{J}/\psi \mathrm{f_0})\mathcal{B}(\mathrm{f_0} \to \pi\pi)}{\mathcal{B}(\mathrm{B_s} \to \mathrm{J}/\psi \phi)\mathcal{B}(\phi \to \mathrm{KK})} = \frac{N^{\mathrm{f_0}}_{\mathrm{obs}}}{N^{\phi}_{\mathrm{obs}}} \times \epsilon^{\phi/\mathrm{f_0}}_{\mathrm{reco}} = 0.140 \pm 0.013(stat) \pm 0.018(syst)$$

- $N^{\mathrm{f_0}}_{\mathrm{obs}}$=873 and N^{ϕ}_{obs}=8377
- Consistent with predictions (PRD 79 (2009) 074024)
- Consistent with previous measurements

Systematics	Uncert.
Fit model	2.1%
$\mathrm{f_0}$ mass window width	6.4%
MC simulation ($\mathrm{f_0}$ natural width)	8.6%
Decay model in MC generation	6.2%

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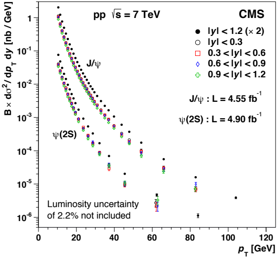
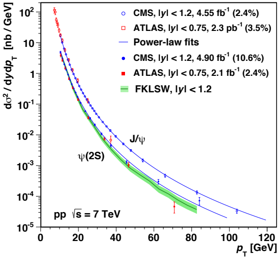
J/ψ, ψ(2S), Υ(nS), and χ_{bn} production

J/ψ, $\psi(2S)$ production [arXiv:1502.04155 Sub. to PRL]

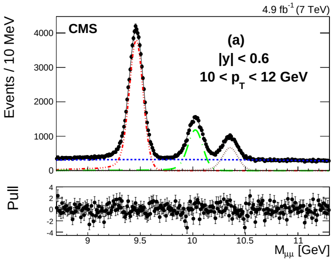
- Double differential prompt J/ψ and $\psi(2S)$ cross section and rapidity integrated ($|y| < 1.2$) differential cross section (assuming umpolarised scenario)
- 2011 data with extended p_T range up to 120 GeV (J/ψ) and 100 GeV ($\psi(2S)$)
- Acceptance measured for different polarisation scenario

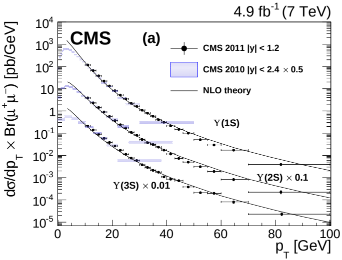




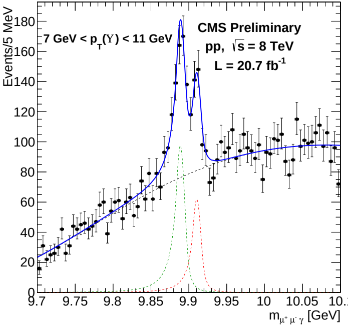
Υ(1S,2S,3S) production (S-wave)[arXiv:1501.07750 Sub. to PLB]

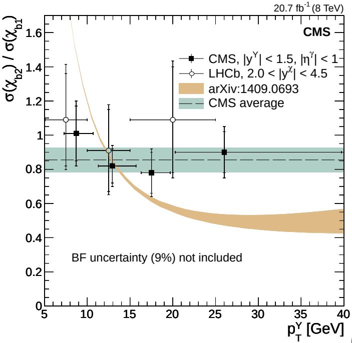
- Differential prompt Υ(1S,2S,3S)$\rightarrow \mu\mu$ production as function of p_T in the rapidity range $|y| < 1.2$
- NLO calculations from [Gong, et al.] extended by the authors to cover the range $p_T < 100$ GeV
- The measurements show a transition from an exponential to a power-law behavior at $p_T \approx$ 20 GeV for the three Υ states





- Use of converted photons to reconstruct $\Upsilon(1S)+\gamma$ final states in four bins
- Cross section ratio $\sigma(\chi_{b2})/\sigma(\chi_{b1})$ shows no evident p_{T} dependence
- Not completely in agreement with the NRQCD model predictions



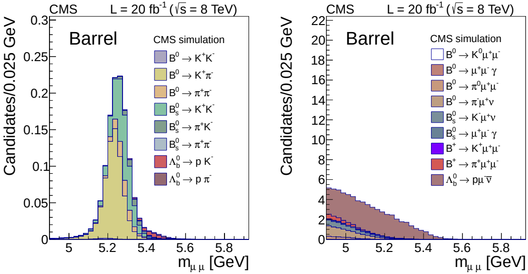


Summary

- CMS take advantage of its performance in the reconstruction of high p_{T} muon to measure the cross section of charmonion and bottomium states at unprecedented p_{T} range
- Good muon reconstruction permits CMS to be competitive in the search for $\mathrm{B_s} \to \mu\mu$ first observation
- Rare decays of $\mathrm{B_c}$ and $\mathrm{B^+}$ mesons are reconstructed and can be used in next analyses (e.g. cross section and lifetime measurement)
- CP-violating phase ϕ_s measurement can take advantage of $\mathrm{B_s} \to \mathrm{J}/\psi \mathrm{f_0}(980)$ reconstruction

Additional slides

$B_{s,d} \to \mu\mu$ rare backgrounds



$$\mathcal{B}(B_s \to \mu\mu) = \frac{N_{B_s}}{N_{\rm norm}} \frac{f_d}{f_u} \frac{\epsilon_{\rm norm}}{\epsilon_{B_s}} \mathcal{B}_{\rm norm} \quad (1)$$

$\frac{\mathcal{B}(\mathrm{B_s}\to \mathrm{J}/\psi \mathrm{f_0}(980))}{\mathcal{B}(\mathrm{B_s}\to \mathrm{J}/\psi \phi(1020))}$ ratio non-resonant BG

- $\mathrm{f}_0 \to \pi\pi$ invariant mass restricted to 50 MeV
- Assumption that $\pi\pi$ non-resonant component negligible component
- Assumption confirmed by PRD 89 029006
- Dedicated systematics:
  - varying the assumed width of the f_0 (50 MeV) in the MC simulation by $\pm$20%, which is within the 90% CL of our measured f_0 mass model
  - varying the f_0(890) mass window up to $\pm$100 MeV to account for possible backgrounds (basically f_0(1500) and f_2(1270))

$\mathrm{B_s} \to \mathrm{J}/\psi\phi(1020)$ ϕ_s signal model

We use the same notations as LHCb [arXiv:1304.2600]:

$$\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = X(\Theta, \alpha, t) = \sum_{i=1}^{10} O_i(\alpha, t).g_i(\Theta),$$

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

i	$g_i(\theta_T, \psi_T, \phi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\phi_T$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\sin\phi_T$	$\lvert A_0(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}(1-\sin^2\theta_T\cos^2\phi_T)$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$	$\lvert A_S(0)A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$	$\lvert A_S(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$	$\lvert A_S(0)A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \qquad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2}$$

$|\lambda|$ includes possible contribution from CP violation in direct decay, we assume $|\lambda| = 1$ and we assign a systematics.

$\Delta\Gamma_s > 0$: we use previous LHCb results. α physics parameters ($\Delta\Gamma_s$, ϕ_s, $c\tau$, $|A_0|^2$, $|A_S|^2$, $|A_\perp^2|$, $\delta_\parallel$, $\delta_{S\perp}$, $\delta_\perp$)

$B_s \to J/\psi\phi(1020)$ ϕ_s systematics table

Source of uncertainty	$\lvert A_0\rvert^2$	$\lvert A_S\rvert^2$	$\lvert A_\perp\rvert^2$	$\Delta\Gamma_s$ ps^{-1}	$\delta_\parallel$ rad	$\delta_{S\perp}$ rad	$\delta_\perp$ rad	ϕ_s rad	$c\tau$ μm
Statistical uncertainty	0.0058	0.016	0.0077	0.0138	0.092	0.24	0.36	0.109	3.0
Proper time efficiency	0.0015	-	0.0023	0.0057	-	-	-	0.002	1.0
Angular efficiency	0.0060	0.008	0.0104	0.0021	0.674	0.14	0.66	0.016	0.8
Model bias	0.0008	-	-	0.0012	0.025	0.03	-	0.015	0.4
Proper decay resolution	0.0009	-	0.0008	0.0021	0.004	-	0.02	0.006	2.9
BG mistag modelling	0.0021	-	0.0013	0.0018	0.074	1.10	0.02	0.002	0.7
Flavour tagging	-	-	-	-	-	-	0.02	0.005	-
PDF modelling assumpt.	0.0016	0.002	0.0021	0.0021	0.010	0.03	0.04	0.006	0.2
$\lvert\lambda\rvert$ as a free parameter	0.0001	0.005	0.0001	0.0003	0.002	0.01	0.03	0.015	-
Kaon p_T re-weighting	0.0094	0.020	0.0041	0.0015	0.085	0.11	0.02	0.014	1.1
Total systematics	0.0116	0.022	0.0117	0.0073	0.685	1.12	0.66	0.032	3.5

- The systematic uncertainties from the proper decay time efficiency and the kaon p_T distribution originate from residual differences between data and simulation;
  - For the proper decay time efficiency, the statistical uncertainty of the efficiency model is propagated to the results
  - For the kaon p_T, the discrepancy between the data and the simulation is taken into account as a systematic uncertainty
- The model bias systematic comes from the biases of the observables obtained with toy pseudo-experiments of the fitted model;
- We left $\lvert\lambda\rvert$ as a free parameter to evaluate the effect of possible other contributions in the weak phase.