B^{+} and Onia cross section at 13 TeV at CMS

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University and INFN Padova

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Outline

- Introduction
- $B^{\pm}$ production
- Quarkonia production
- Conclusions

Motivations

Motivations to study HF physics at CMS

- Probe the underlying QCD processes:
  - measure production cross section,
  - measure quarkonia polarization,
  - look for new and exotic states.
- Look for effects of new physics beyond the Standard Model (not treated here):
  - study lifetime and decay properties of B hadrons,
  - look for new physics effects in rare decays.

Results from 2015 data taking at $\sqrt{s} = 13$ TeV :

- $B^{\pm}$ production cross section
- Quarkonia production cross sections

Motivations

Motivations to study HF physics at CMS

- Probe the underlying QCD processes:
  - measure production cross section,
  - measure quarkonia polarization,
  - look for new and exotic states.
- Look for beyond
  - stud
  - look

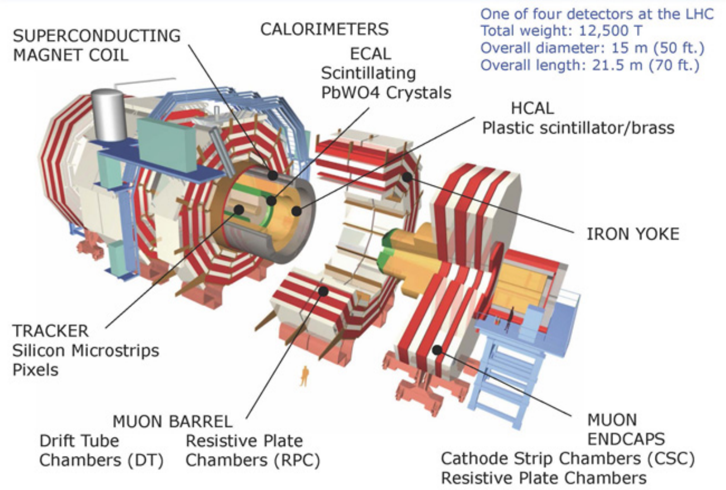
- reference or ingredient for searches and measurements of rarer or new processes
- baseline for associated production of HF and other objects

Results from 2015 data taking at $\sqrt{s} = 13$ TeV :

- $B^{\pm}$ production cross section
- Quarkonia production cross sections

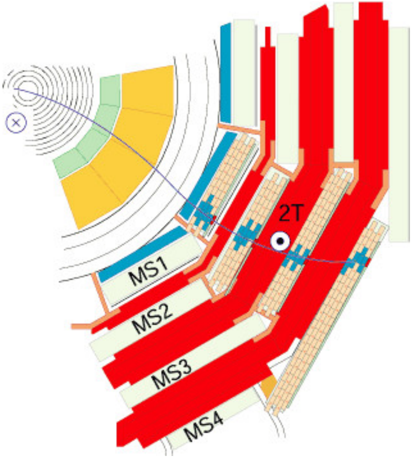
Experiment

The CMS experiment



JINST 03 (2008) S08004

Muon reconstruction



- 3 detectors dedicated to muon trigger and reconstruction
- Stand-alone reconstruction capability by muon detectors
- Tracker-muon match:
  - inside-out: more efficient at low p_T
  - outside-in: more efficient at high p_T

Performances

JINST 7 (2012) P10002

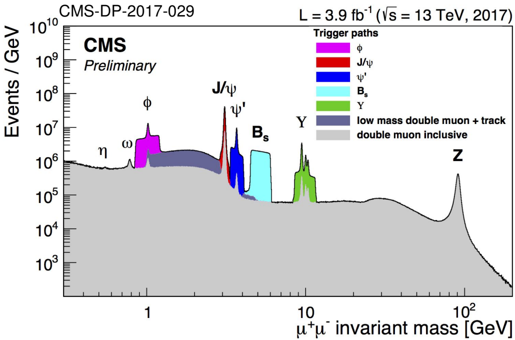
- Misidentification probability $P_{\mathrm{mis}} < 1\%$
- Momentum resolution $\sigma(p_T) \sim 1 \div 6\%$ for $p_t < 100$ GeV

Trigger

- High luminosity
- Limited bandwidth

$\Rightarrow$ Di-muon triggers possibly plus other tracks

- L1: hardware (fast, rate $\sim$ 100 kHz)
- HLT: software (full track reconstruction, rate $\sim$ 1 kHz)



Specific triggers developed for different analyses

Cuts on
- transverse momentum, (pseudo)rapidity
- vertex χ^2 and displacement
- di-muon mass & pointing angles

"Legacy" results from Run-1: ($\sqrt{s} = 7, 8$ TeV)

B mesons & baryons

$\sigma(pp \to B^+X)$	PRL 106 (2011) 112001
$\sigma(pp \to B_0X)$	PRL 106 (2011) 252001
$\sigma(pp \to B_sX)$	PRD 84 (2011) 052008
$B_c^{\pm} \to J/\psi\pi^{\pm}(\pi^+\pi^-)$	JHEP 01 (2015) 063
Λ_b^0 polarization	arXiv:1802.04867

Quarkonia

$\sigma(pp \to (J/\psi\ , \psi(2S), \Upsilon(nS))X)$	JHEP 02 (2012) 011, PRL 114 (2015) 191802, PLB 727 (2013) 101
$(J/\psi\ , \psi(nS), \Upsilon(nS))$ polarization	PLB 727 (2013) 381, PRL 110 (2013) 081802
$\Upsilon(nS)$ polarizations & production ratios vs. multiplicity	PLB 761 (2016) 31, CMS-PAS-BPH-14-009
$\sigma(\chi_{c2})/\sigma(\chi_{c1})$, $\sigma(\chi_{b2})/\sigma(\chi_{b1})$	EPJC (2012) 72:2251, PLB 743 (2015) 383

Double quarkonia & exotica

Double J/ψ production	JHEP 09 (2014) 094
Double Υ production	JHEP 05 (2017) 013
$X(3872)$ production	JHEP 04 (2013) 154
Observation of $B^{\pm} \to \psi(2S)\phi K^{\pm}$	PLB 764 (2017) 66
Search for $X_b \to \Upsilon(1S)\pi^+\pi^-$	PLB 727 (2013) 57
Search for the $X(5568)$ state in $B_s^0\pi^{\pm}$ decays	CMS-PAS-BPH-16-002

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$\sigma(pp \to B^{+}X)$ cross-section

Measured at $\sqrt{s} = 13$ TeV

extended p_T range

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$\sigma(pp \to (J/\psi, \psi(2S), \Upsilon(nS))X)$ cross-section

Measured at $\sqrt{s} = 13$ TeV

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$B^{\pm}$ production cross-section

$$B^{\pm} \to J/\psi K^{\pm} \, , J/\psi \to \mu^{+}\mu^{-}$$

- Studies of *b*-hadron production at the higher energies
  $\Rightarrow$ new important test of theoretical calculations
- First $B^{\pm}$ production cross-section measurement at $\sqrt{s} = 13$ TeV

$\mathcal{L} = 48.1\ \mathrm{pb}^{-1}$, $|y_B| < 2.1$, $10\ \mathrm{GeV} < p_{T,B} < 100\ \mathrm{GeV}$ PLB 771 (2017) 435

Differential cross-section, vs. transverse momentum and rapidity

$$\frac{d\sigma(pp \to B^{+}X)}{dz} = \frac{n_{\mathrm{sig}}(z)}{2 \cdot \mathcal{B} \cdot A \cdot \epsilon(z) \cdot \mathcal{L} \cdot \Delta z}$$

z	=	$p_{T,B}$, $\|y_B\|$	$n_{\mathrm{sig}}(z)$	=	signal yield
2	=	account for	A	=	acceptance
		B charge symmetry	$\epsilon(z)$	=	efficiency
$\mathcal{B}$	=	$\mathcal{B}(B^{\pm} \to J/\psi K^{\pm})$	$\mathcal{L}$	=	integrated luminosity
		$\cdot\mathcal{B}(J/\psi \to \mu^{+}\mu^{-})$	Δz	=	bin width

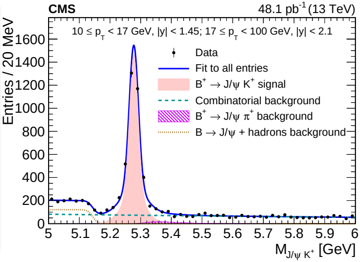
$B^{\pm}$ signal extraction

Event selection

- Muon quality: match chamber segment with extrapolated track
- J/ψ candidate quality: invariant mass and vertex fit χ^2
- $B^{\pm}$ candidate quality: common vertex, flight distance and direction

$B^{\pm} \to J/\psi K^{\pm}$ invariant mass distributions

- $p_{T,B}$ and $|y_B|$ bins
- Unbinned max likelihood fit:
  - Sum of 2 gaussians (signal)
  - exponential (background)
  - error function (mis-reconstructed $B^{\pm} \to J/\psi KX$)



$B^{\pm} \rightarrow J/\psi K^{\pm}$ acceptance and efficiency

Overall $A \cdot \epsilon$ estimation

- Simulated events with $|y_B| < 2.1$, $10\text{ GeV} < p_{T,B} < 100\text{ GeV}$
- Selected event fraction:
  - 0.78% ($10\text{ GeV} < p_{T,B} < 13\text{ GeV}$) ; 20% ($70\text{ GeV} < p_{T,B} < 100\text{ GeV}$)
  - 3.6% ($0 < |y_B| < 0.2$) ; 1.4% ($1.8 < |y_B| < 2.1$)

Trigger and muon-reconstruction efficiency

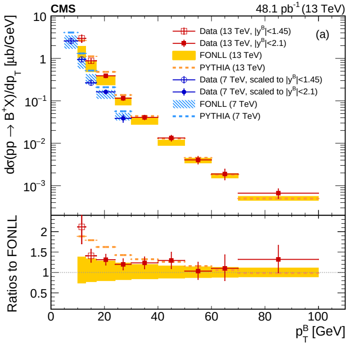
- Inclusive $J/\psi \rightarrow \mu^+\mu^-$ data sample
- Tag-and-probe method
  - one muon satisfying stringent quality requirements
  - second muon identified only with tracker or muon system
- Efficiency compared with simulation, difference included in systematic uncertainties

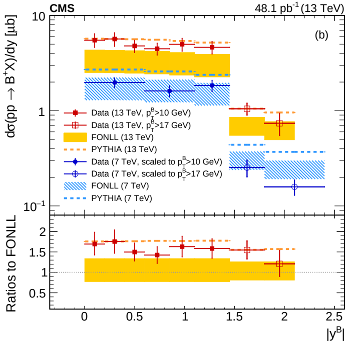
$B^{\pm}$ production: results

Differential cross-section vs. $p_{T,B}$, $|y_B|$

- Left: $d\sigma/dp_{T,B}$ (integrated over [$|y_B| < 1.45$] or [$|y_B| < 2.1$])
- Right: $d\sigma/d|y_B|$ (integrated over [10 GeV $< p_{T,B} <$ 100 GeV] or [17 GeV $< p_{T,B} <$ 100 GeV])
- Comparison with FONLL and PYTHIA

M.Cacciari *et al.*, JHEP 05 (1998) 007 , JHEP 03 (2001) 006 , JHEP 10 (2012) 137
T. Sjöstrand *et al.*, CPC 178 (2008) 852



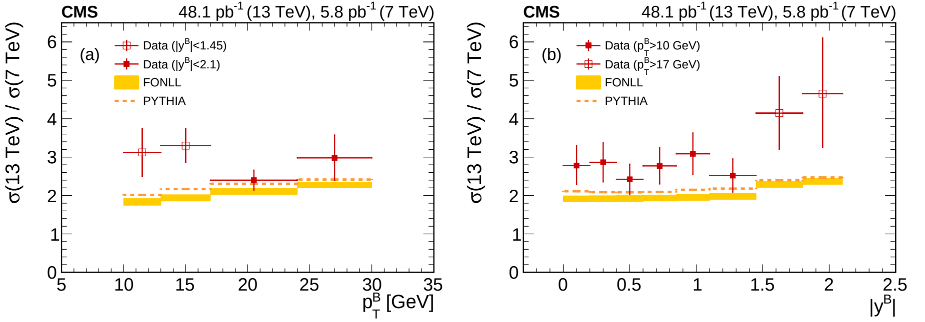


$B^{\pm}$ production: results

Differential cross-section ratios vs. $p_{T,B}$, $|y_B|$

- Left: $R(d\sigma/dp_{T,B})$ (integrated over [$|y_B| < 1.45$] or [$|y_B| < 2.1$])
- Right: $R(d\sigma/d\,|y_B|)$ (integrated over [10 GeV $< p_{T,B} <$ 100 GeV] or [17 GeV $< p_{T,B} <$ 100 GeV])
- Reduced sensitivity to scale uncertainty, constraint to gluon PDF

M.Cacciari *et al.*, arXiv:1507.06197



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Quarkonia production cross-section

J/ψ , $\psi(2S)$, $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$

- Test factorization and NRQCD
  G.T.Bodwin *et al.*, PRD 51 (1995) 1125 , PRD 55 (1997) 5853
  P.Cho and A.K.Leibovich, PRD 53 (1996) 150 , PRD 53 (1996) 6203
- 2 phases:
  B. Gong *et al.*, PRL 112 (2014) 032001 , Z.-B. Kang *et al.*, PRD 91 (2015) 014030
  - perturbative generation of $Q\bar{Q}$ pair (singlet/octet)
  - hadronization producing bound state (LDME)
- Different center of mass energies:
  - perturbative calculations appropriate for energy
  - same LDME
  P.Faccioli *et al.*, PLB 736 (2014) 98
  G.T.Bodwin *et al.*, PRL 113 (2014) 022001
- Higher energy and higher cross-section: extended p_T reach

$\mathcal{L} = 2.3 - 2.7\ \text{fb}^{-1}$, $|y_{\mu^+\mu^-}| < 1.2$, $p_{T,\mu^+\mu^-}$ up to 120 GeV PLB 780 (2018) 251

Double-differential cross-section,
vs. transverse momentum and rapidity

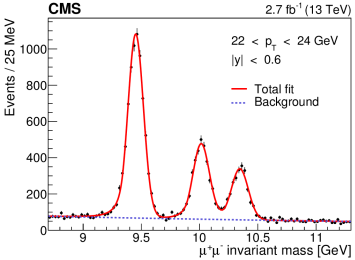
$$\mathcal{B}(Q\bar{Q} \to \mu^+\mu^-) \cdot \frac{d^2\sigma(pp \to Q\bar{Q}X)}{dp_T dy} = \frac{N_{Q\bar{Q}}(p_T, y)}{\mathcal{L} \cdot \Delta p_T \cdot \Delta y} \cdot \left\langle \frac{1}{A(p_T, y) \cdot \epsilon(p_T, y)} \right\rangle$$

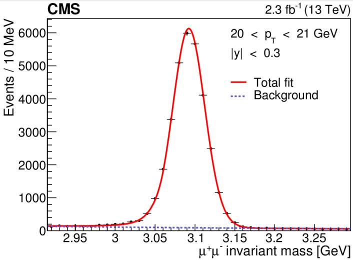
Quarkonia signal extraction

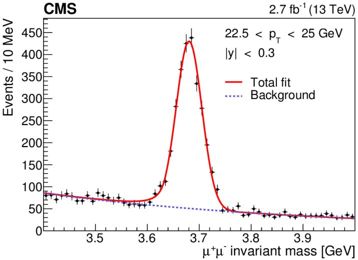
$Q\bar{Q}$ invariant mass distributions

- Muon & vertex quality selection
- Unbinned max likelihood fit in $p_{T,Q\bar{Q}}$ and $|y_{Q\bar{Q}}|$ bins
  - Crystal Ball function (signal)
  - exponential (background)

> Parameters constrained to p_T-integrated fit result



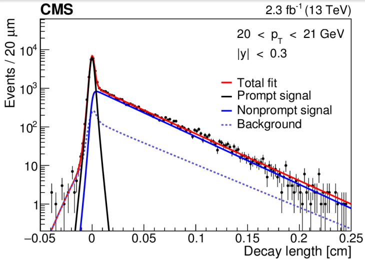


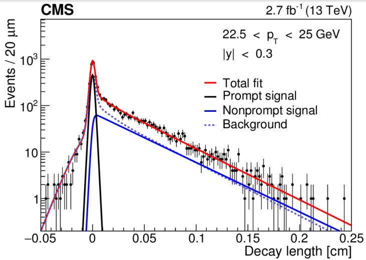


Prompt/non-prompt components

Chamonium sources

- Production in primary *pp* interaction: prompt
- Production in *b*-hadron decay: non-prompt





Simultaneous fit to mass and “pseudo proper decay length”:

- prompt: resolution function
- non-prompt: exponential convolved with resolution function
- background: gaussian plus exponential

$Q\bar{Q} \to \mu^+\mu^-$ acceptance and efficiency

Acceptance

Generated $Q\bar{Q}$ events, decay to $\mu^+\mu^-$ simulated with PYTHIA8

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

- $N^{\text{gen}}(p_T, y)$: generated events
  $N^{\text{gen}}_{\text{kin}}(p_T, y)$: events passing selection
- Acceptance stored in finely binned histograms
- Unpolarized production assumed

Efficiency

- Tag-and-probe method
- dimuon efficiency: product of two efficiencies multiplied by a correction factor accounting for correlation

Acceptance and efficiency calculated event-by-event

$Q\bar{Q} \rightarrow \mu^+\mu^-$ acceptance and efficiency

Acceptance

Generat... th PYTHIA8

- $N^{\text{gen}}(p$...
  $N^{\text{gen}}_{\text{kin}}(p$...
- Acceptance stored in finely binned histograms
- Unpolarized production assumed

Polarization

- Compatible with measurements
- Results directly comparable with other experiments
- Factors for different polarization assumptions provided

Efficiency

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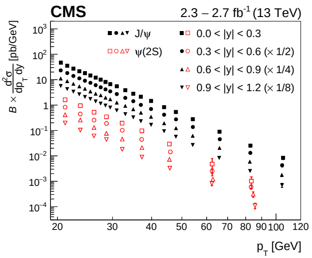
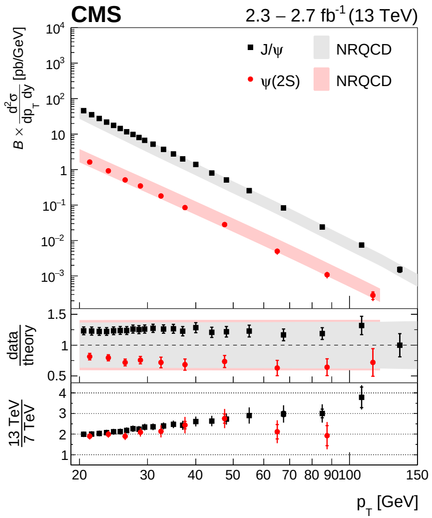
Acceptance and efficiency calculated event-by-event

J/ψ , $\psi(2S)$: results

Double-differential cross-section

- Plot vs. p_T in 4 $|y|$ bins
- p_T up to:
  - 120 GeV(J/ψ)
  - 100 GeV($\psi(2S)$)
- Extended p_T range for the integrated range $|y| < 1.2$

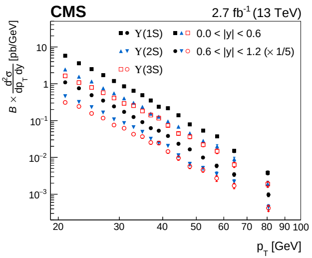


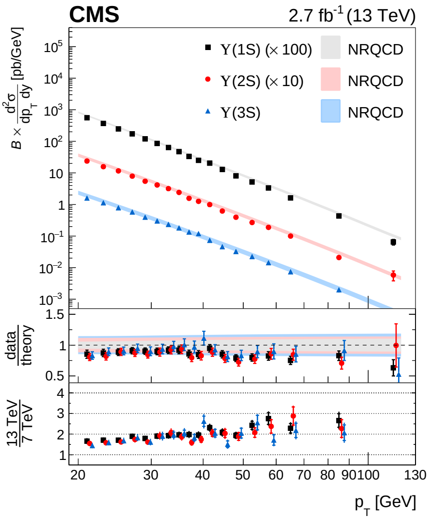


$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$: results

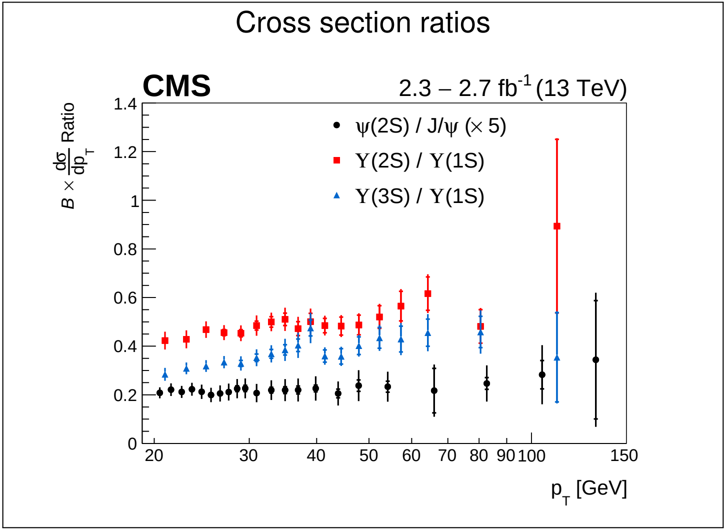
Double-differential cross-section

- Plot vs. p_T in 2 $|y|$ bins
- p_T up to 100 GeV
- Extended p_T range for the integrated range $|y| < 1.2$





Quarkonia production: production ratios



Conclusions

- Differential cross section for B^+ production at $\sqrt{s} = 13$ TeV has been measured up to 100 GeV in p_T. A reasonable agreement with FONLL calculations and with PYTHIA has been found.
- The double differential production cross sections at $\sqrt{s} = 13$ TeV for J/ψ , $\psi(2S)$, $\Upsilon(nS)$ have been measured. These results shall contribute to consolidate the underlying hypotheses of NRQCD and provide further input to constrain the theory parameters.

Extra informations

BACKUP

$B^{\pm}$ production: systematic uncertainties

Signal yield

- Different mass modeling functions:
  - signal: 3 gaussians or gaussian + CB
  - background: 2nd order polynomial
  - $B^{\pm} \to J/\psi KX$ events: mass shift
- Include the rare decay $B^{\pm} \to J/\psi\pi^{\pm}$
- p_T , $|y|$ bin to bin migration due to finite resolution

Other sources

- Luminosity: 2.3%
- $\mathcal{B}(B^{\pm} \to J/\psi K^{\pm} \to \mu^{+}\mu^{-}K^{\pm})$: 3.1%

Quarkonia production: systematic uncertainties

Signal yield

Different mass fits:

- changes in CB function parameters
- fixed/free mean masses
- exponential/linear function for background

Non-prompt fraction

- Decay length from:
  - average interaction point
  - nearest primary vertex along beam direction
- Different functions for background modeling
- Changes in parameter constraints