Heavy flavor results from CMS

P. Ronchese - CMS collaboration

University and INFN Padova

25th International Workshop on
Deep Inelastic Scattering and Related Topics

Birmingham, UK
April 3-7, 2017

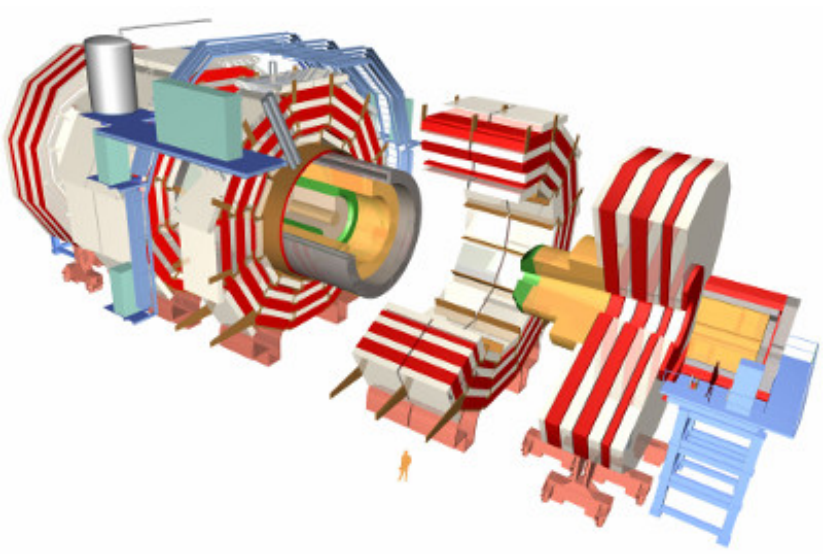
Outline

- Introduction
- Recent results for B hadrons production and decays
- Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$
- Conclusions

Motivations

- 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:
  - study lifetime and decay properties of B hadrons,
  - look for new physics effects in rare decays.

CMS experiment



Data samples

- $\sqrt{s} = 7$ TeV , $\mathcal{L} \sim 5$ fb^{-1} (2011 run)
- $\sqrt{s} = 8$ TeV , $\mathcal{L} \sim 20$ fb^{-1} (2012 run)
- $\sqrt{s} = 13$ TeV , $\mathcal{L} \sim 2.7$ fb^{-1} (2015 run)

All shown results involve two (at least) muons
Dedicated triggers developed for analyses
Selections: dimuon mass, p_T, displaced vertex, pointing angle

Production cross-section, polarization and decays

B mesons & baryons

$\sigma(pp \to B^+X)$	PRL 106 (2011) 112001, arXiv:1609.00873
$\sigma(pp \to B^0X)$	PRL 106 (2011) 252001
$\sigma(pp \to B_s \to J/\psi\phi)$	PRD 84 (2011) 052008
$B_c^\pm \to J/\psi\pi^\pm(\pi^+\pi^-)$	JHEP 01 (2015) 063
Λ_b^0 polarization	CMS-PAS-BPH-15-002

Quarkonia

$\sigma(pp \to (J/\psi\ ,\psi(2S),\Upsilon(nS))X)$	JHEP 02 (2012) 011, PRL 114 (2015) 191802, PLB 727 (2013) 101, CMS-PAS-BPH-15-005
$(J/\psi\ ,\psi(nS),\Upsilon(nS))$ 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, CMS-PAS-BPH-13-005

Double quarkonia & exotica

Double J/ψ production	CMS-PAS-BPH-11-021
Double Υ production	arXiv:1610.07095
$X(3872)$ 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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Not covered in the list

- $B^0_{d,s} \to \mu^+\mu^-$
- CP violation
- ...

$\sigma(pp \to (J/\psi\ ,\psi(2S), \Upsilon$	
JHEP	101, CMS-PAS-BPH-15-005
$(J/\psi\ ,\psi(nS), \Upsilon(nS))$ p	81, PRL 110 (2013) 081802
$\Upsilon(nS)$ polarizations & p	31, CMS-PAS-BPH-14-009
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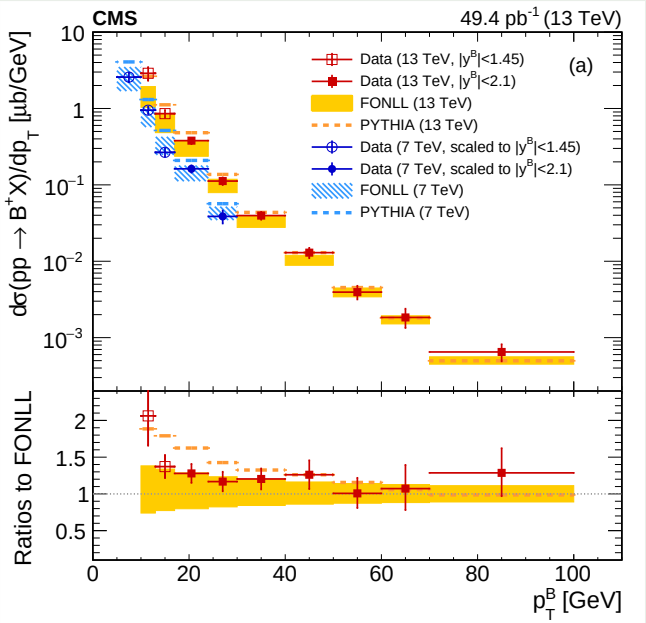
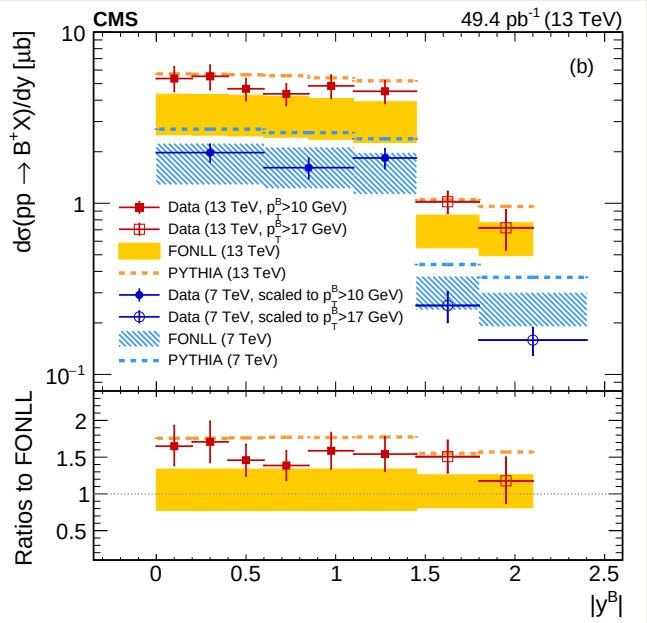
B^+ production cross-section

$\sigma(pp \to B^+X)$ differential cross-section vs. $p_{T,B}$, $|y_B|$





00, arXiv:1609.00873
RL 106 (2011) 252001
PRD 84 (2011) 052008
JHEP 01 (2015) 063
CMS-PAS-BPH-15-002

CMS-PAS-BPH-15-005
RL 110 (2013) 081802
CMS-PAS-BPH-14-009
CMS-PAS-BPH-13-005

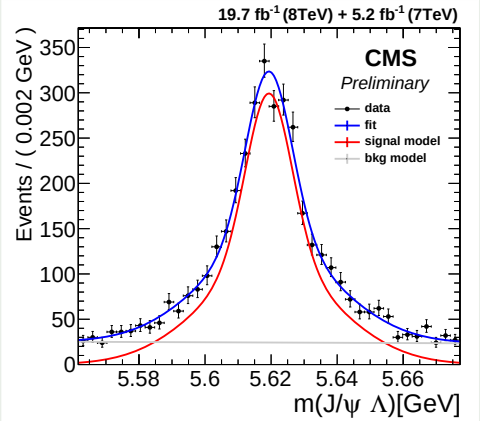
$B^\pm \to J/\psi K^\pm$, $J/\psi \to \mu^+\mu^-$

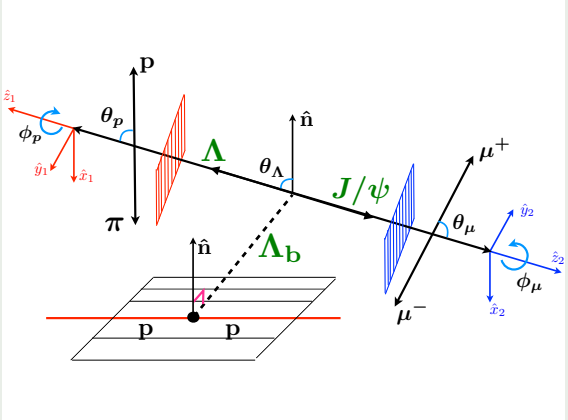
- Left: $d\sigma/dp_{T,B}$ (integrated over $|y_B| < 2.1$)
- Right: $d\sigma/d\,|y_B|$ (integrated over 10 GeV $< p_{T,B} <$ 100 GeV or 17 GeV $< p_{T,B} <$ 100 GeV)
- Comparison with FONLL and PYTHIA

M.Cacciari *et al.*, JHEP 05 (1998) 007 , JHEP 03 (2001) 006 , JHEP 10 (2012) 137 , arXiv:1507.06197

Λ_b^0 polarization: $\Lambda_b^0 \to J/\psi\Lambda^0$

UML fit of invariant mass and decay angles





$$P = 0.00 \pm 0.06 \pm 0.02$$

12001, arXiv:1609.00873
PRL 106 (2011) 252001
PRD 84 (2011) 052008
JHEP 01 (2015) 063
CMS-PAS-BPH-15-002

CMS-PAS-BPH-15-005
, PRL 110 (2013) 081802

HQET & previous measurements

- Large fraction of transverse *b*-quark polarization retained after hadronization
  A.F.Falk and M.E.Peskin, PRD 49 (1994) 3320
  G. Hiller *et al.*, PLB 649 (2007) 152, Z.J.Ajaltouni *et al.*, PLB 614 (2005) 165
- Measured at LEP, but different production mechanism
  ALEPH Collaboration, PLB 365 (1996) 437
  OPAL Collaboration, PLB 444 (1998) 539
  DELPHI Collaboration, PLB 474 (2000) 205
- Measured at LHCb: $P = 0.06 \pm 0.07 \pm 0.02$
  LHCb Collaboration, PLB 724 (2013) 27
  (parity-violating asymmetry and helicity amplitudes for $\Lambda_b^0 \to J/\psi\Lambda^0$, ATLAS Collaboration, PRD 89 (2014) 092009)

Quarkonia production cross-section

Test factorization and NRQCD

- 2 phases:
  - 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

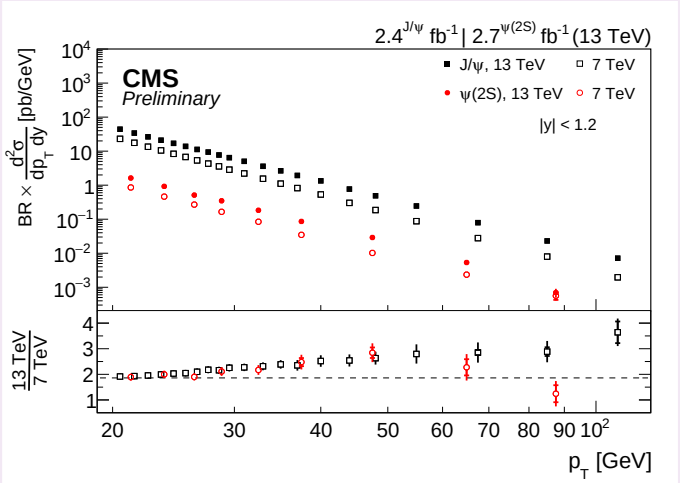
P.Faccioli *et al.*, PLB 736 (2014) 98
G.T.Bodwin *et al.*, PRL 113 (2014) 022001

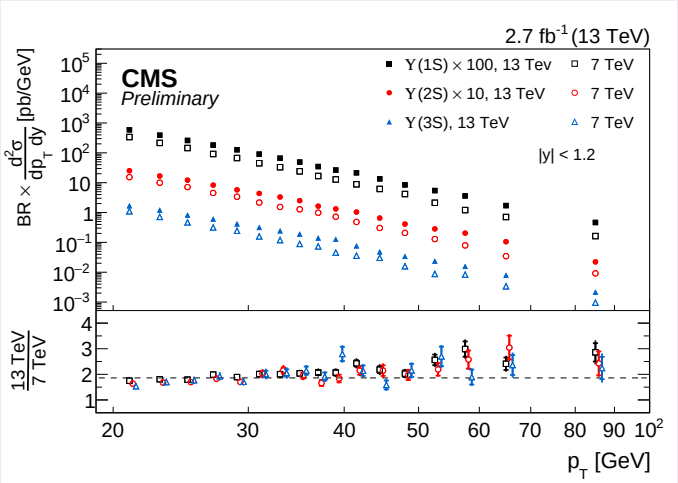
(2011) 112001, arXiv:1609.00873
PRL 106 (2011) 252001
PRD 84 (2011) 052008
JHEP 01 (2015) 063
CMS-PAS-BPH-15-002

JHEP 02 (2012) 011, PRL 114 (2015) 191802, PLB 727 (2013) 10, CMS-PAS-BPH-15-005
PRL 110 (2013) 081802
CMS-PAS-BPH-14-009
CMS-PAS-BPH-13-005

CMS-PAS-BPH-11-021
arXiv:1610.07095
JHEP 04 (2013) 154
PLB 764 (2017) 66
PLB 727 (2013) 57
CMS-PAS-BPH-16-002

Cross-section ratio vs. p_T





Prompt/non-prompt components

B mesons & baryons

(2011) 112001, arXiv:1609.00873
PRL 106 (2011) 252001
PRD 84 (2011) 052008
JHEP 01 (2015) 063
CMS-PAS-BPH-15-002

Chamonium sources

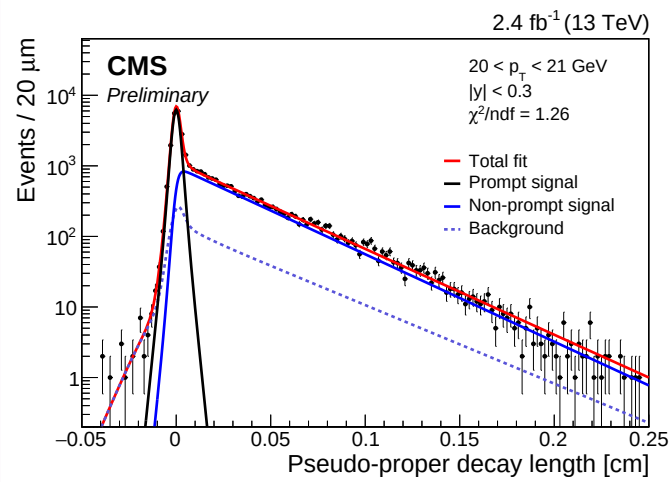
- Production in primary *pp* interaction: prompt
- Production in *b*-hadron decay: non-prompt
- Simultaneous fit to mass and "pseudo proper decay length"

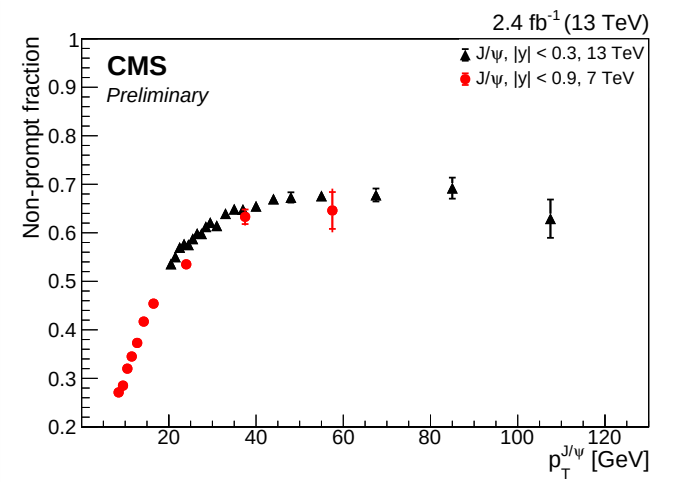
Quarkonia

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

JHEP 02 (2012) 011, PRL 114 (2015) 191802, PLB 727 (2013) 10, CMS-PAS-BPH-15-005
PRL 110 (2013) 081802
CMS-PAS-BPH-14-009
CMS-PAS-BPH-13-005

Decay length fit and cross-section ratio





CMS-PAS-BPH-11-021
arXiv:1610.07095
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PLB 764 (2017) 66
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CMS-PAS-BPH-16-002

ϒ production ratios vs. multiplicity

Heavy-quark pair evolution to quarkonium state

- Different numbers of particles associated with each of the quarkonium states: feed-down processes, soft gluon fragmentation
- Quarkonia yield increase with associated track multiplicity observed at LHC: hint of new phenomena

T.Lang and M.Bleicher, PRC 87 (2013) 024907

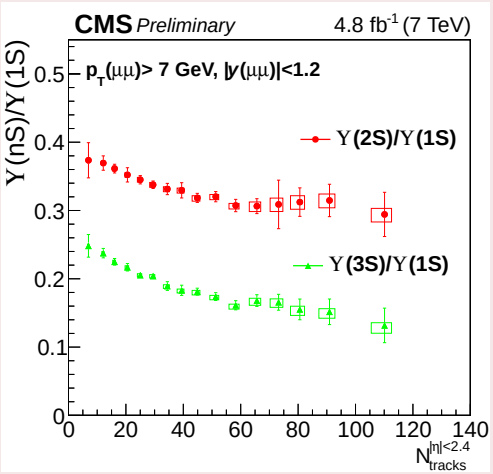
E.G.Ferreiro and C.Pajares, PRC 86 (2012) 034903

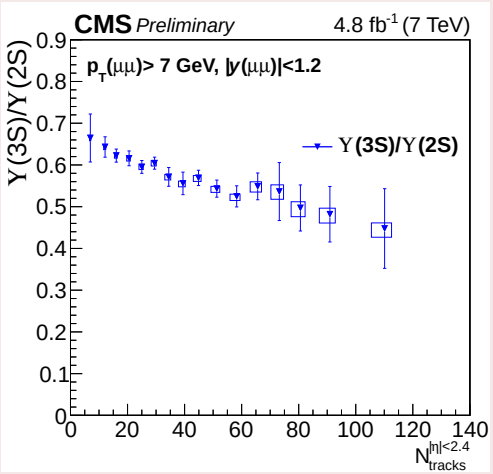
- Angular correlations interpreted as signals of collective effects

R.Campanini and G.Ferri, PLB 703 (2011) 237

K.Dusling *et al.*, IJMPE (2016) 1630002

Signal fit and ϒ(*n*S) yield extraction





$$< N_{\text{tracks}}^{|\eta|<2.4} >_{\Upsilon(1S)} = 34.14 \pm 0.04$$

$$< N_{\text{tracks}}^{|\eta|<2.4} >_{\Upsilon(2S)} = 33.17 \pm 0.05$$

$$< N_{\text{tracks}}^{|\eta|<2.4} >_{\Upsilon(3S)} = 32.10 \pm 0.05$$

81, PRL 110 (2013) 081802
, CMS-PAS-BPH-14-009
1, CMS-PAS-BPH-13-005

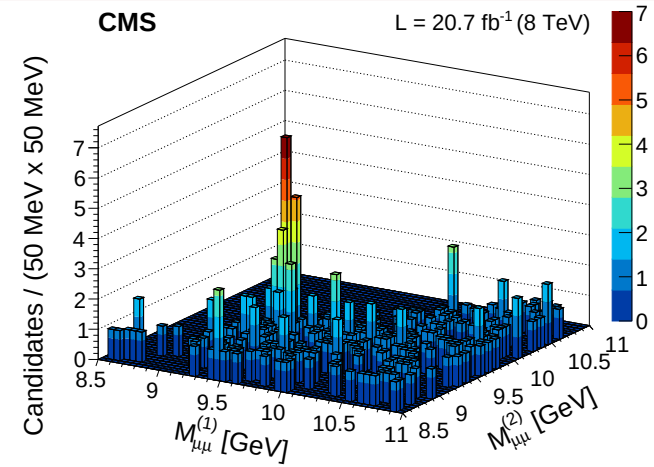
CMS-PAS-BPH-11-021
arXiv:1610.07095
JHEP 04 (2013) 154
PLB 764 (2017) 66
PLB 727 (2013) 57
CMS-PAS-BPH-16-002

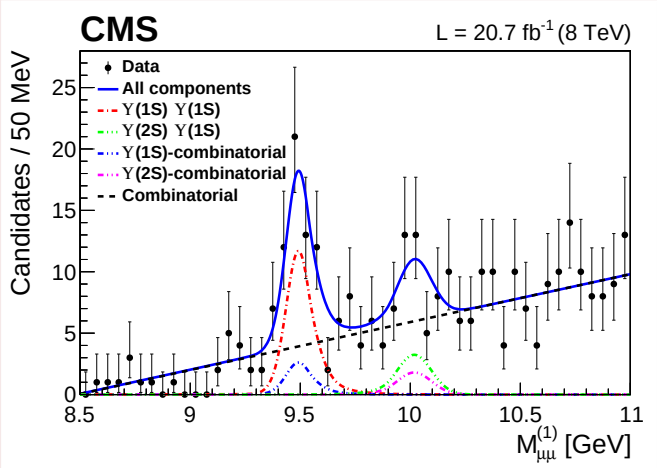
Double $\Upsilon(1S)$ production cross-section

Quarkonium pair production mechanism

- High parton densities in *pp* collisions: single/double parton scattering (SPS/DPS) — S.Baranov *et al.*, PLB 705 (2011) 116
- Color singlet/octet: dominant at low/high p_T — P.Ko *et al.*, JHEP 01 (2011) 070
- Possibly produced in decays of tetra-quarks — A.V.Berezhnoy *et al.*, PRD 86 (2012) 034004

Signal fit and total cross-section





$$\sigma_T = (68.8 \pm 12.7(\text{stat}) \pm 7.4(\text{syst}) \pm 2.8(\text{BR}))\text{pb}$$

Υ polarization uncertainty: -38%/+36% variation

1, CMS-PAS-BPH-15-005
, PRL 110 (2013) 081802
1, CMS-PAS-BPH-14-009
1, CMS-PAS-BPH-13-005

CMS-PAS-BPH-11-021
arXiv:1610.07095
JHEP 04 (2013) 154
PLB 764 (2017) 66
PLB 727 (2013) 57
CMS-PAS-BPH-16-002

Observation of $B^{\pm} \to \psi(2S)\phi K^{\pm}$ decay

Structures in $J/\psi\phi$ mass spectrum in $B^{\pm} \to J/\psi\phi K^{\pm}$

Reported by several experiments

- Study naturally extended to $\psi(2S)\phi$ mass spectra
- Branching ratio measured by comparison:

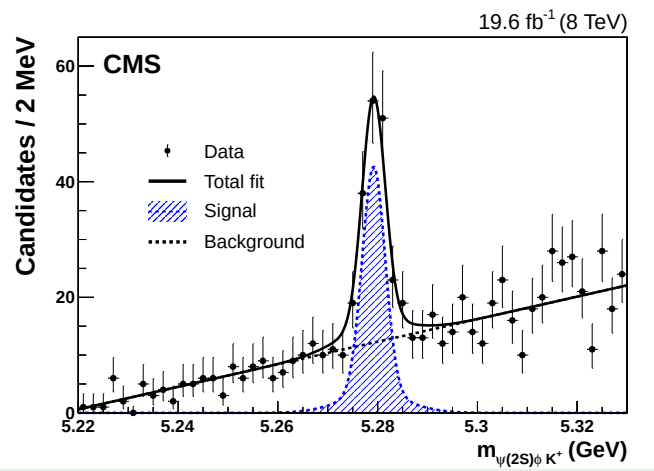
$$\mathcal{B}(B^{\pm} \to \psi(2S)\phi K^{\pm}) = \frac{N_{B^{\pm}\to\psi(2S)\phi K^{\pm}}\,\mathcal{B}_R(B^{\pm}\to\psi(2S)K^{\pm})}{N_{B^{\pm}\to\psi(2S)K^{\pm}}\,\epsilon_{\rm rel}\,\mathcal{B}(\phi\to K^+K^-)}$$

CDF Collaboration, PRL 102 (2009) 242002
D0 Collaboration, PRD 89 (2014) 012004
BaBar Collaboration, PRD 91 (2015) 012003
LHCb Collaboration, arXiv:1606.07895
CMS Collaboration, PLB 734 (2014) 261

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

1, CMS-PAS-BPH-15-005
, PRL 110 (2013) 081802
1, CMS-PAS-BPH-14-009
1, CMS-PAS-BPH-13-005

Invariant mass distribution & branching ratio



$$\mathcal{B}(B^{\pm} \to \psi(2S)\phi K^{\pm}) = (4.0 \pm 0.4(\text{stat}) \pm 0.6(\text{syst}) \pm 0.2(\mathcal{B}_R))\cdot 10^{-6}$$

CMS-PAS-BPH-11-021
arXiv:1610.07095
JHEP 04 (2013) 154
PLB 764 (2017) 66
PLB 727 (2013) 57
CMS-PAS-BPH-16-002

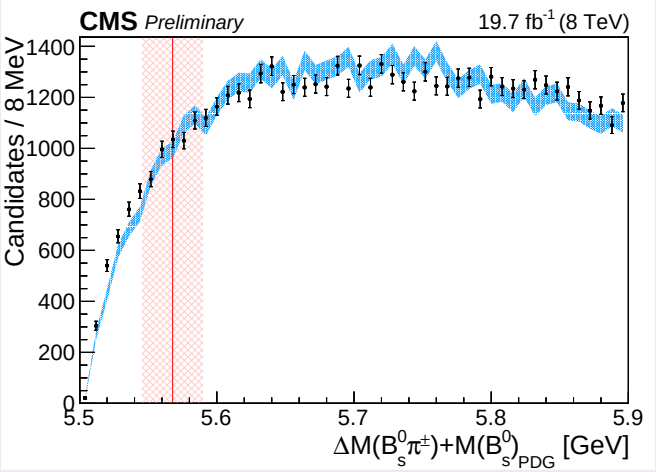
Search for the $X(5568)$ state in $B_s^0\pi^{\pm}$ decays

Search for $X(5568)$

Evidence of a new $B_s^0\pi^\pm$ state?

- Reported by D0 collaboration — D0 Collaboration, PRL 117 (2016) 022003
- Possibly composed of four different flavors of quarks (b, s, u, d), but difficult interpretation — F.K.Guo *et al.*, CTP 65 (2016) 5, 593; T.J.Burns and E.S.Swanson, arXiv:1603.04366
- No significant signal observed by LHCb — LHCb Collaboration, arXiv:1608.00435

$B_s^0\pi^\pm$, $B_s^0 \to J/\psi\phi$ invariant mass distribution



$$M^\Delta = M_{B_s^0} + M_{J/\psi K^+K^-\pi^\pm} - M_{J/\psi K^+K^-}$$

- black points with bars: B_s^0 signal
- blue band: B_s^0 sidebands

$\rho_X < 3.9\%$@95%C.L

1, CMS-PAS-BPH-15-005
, PRL 110 (2013) 081802
1, CMS-PAS-BPH-14-009
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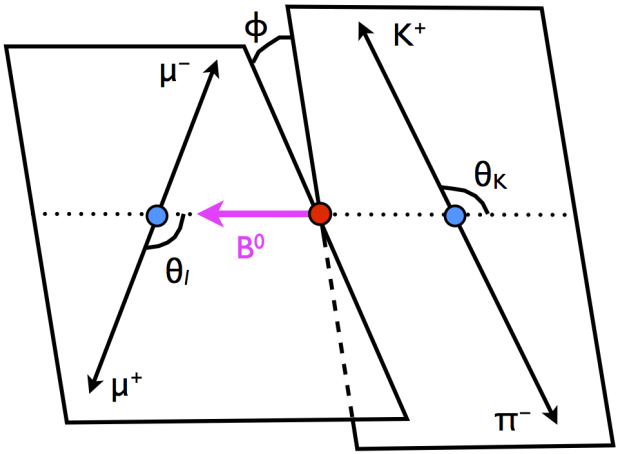
Search for the $X(5568)$ state in $B_s^0\pi^\pm$ decays

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



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

Differential branching ratio

- Kinematic variables:
  - θ_l , θ_K , ϕ angles
  - $q^2 = m^2(\mu^+\mu^-)$
- Parameters:
  - A_{FB} : muon forward/backward asymmetry
  - F_L : K^{*0} longitudinal polarization
  - F_S , A_S : $K^+\pi^-$ S-wave contribution and interference
  - P_1, P_5', A_{5S}: ϕ dependence

Predictions & previous measurements

- First measurement by LHCb — LHCb Collaboration, JHEP 02 (2016) 104
- Discrepancy with SM prediction — Descotes-Genon *et al.*, JHEP 06 (2016) 092
- New HEPfit predictions — M.Ciuchini *et al.*, JHEP 06 (2016) 116, arXiv:1611.04338,

Angular analysis, first step: ϕ integrated out

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

Angular distribution fitted in q^2 bins

Unbinned Maximum Likelihood fit

PDF components:

- correctly tagged signal events
- mistagged signal events
- background

- Variables: invariant mass, θ_K, θ_l
- Free parameters: mass parameters, yields, A_{FB} , F_L , F_S , A_S
- Fixed: background angular parameters

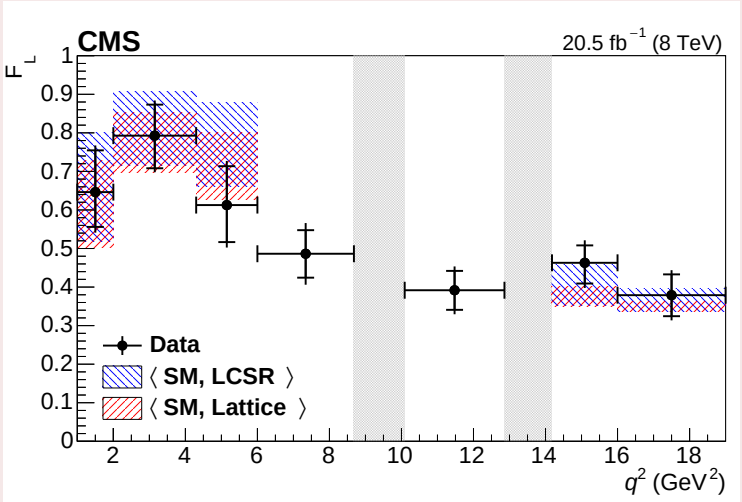
background from sidebands ; $\frac{d\mathcal{B}(B^0\to K^{*0}\mu^+\mu^-)}{dq^2} = \frac{Y_S}{Y_N}\frac{\epsilon_N}{\epsilon_S}\frac{\mathcal{B}(B^0\to J/\psi K^{*0})}{\Delta q^2}$

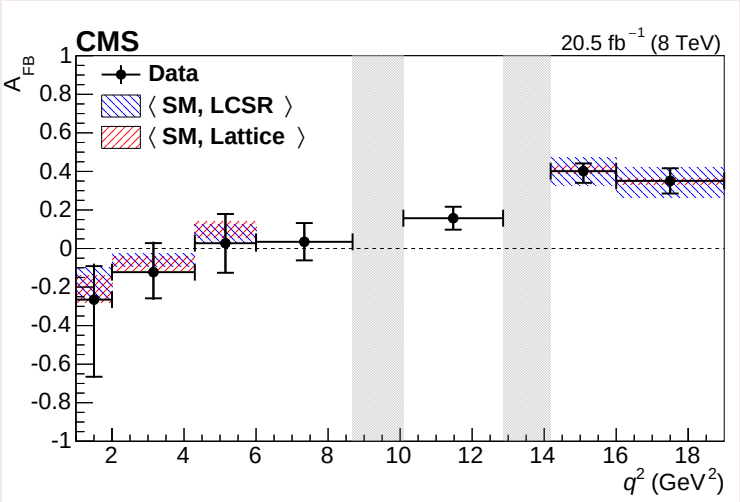
$B^0/\bar{B}^0$ discrimination: K/π assignment on invariant mass basis

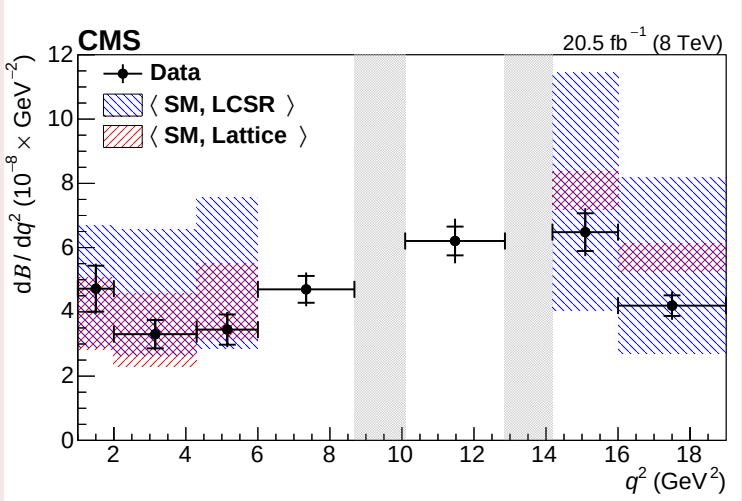
Angular analysis, first step: ϕ integrated out

Results & comparisons (predictions)

PLB 753 (2016) 424







Light-cone sum rules

A.Khodjamirian *et al.*, JHEP 09 (2010) 089

A.Khodjamirian *et al.*, JHEP 02 (2013) 010

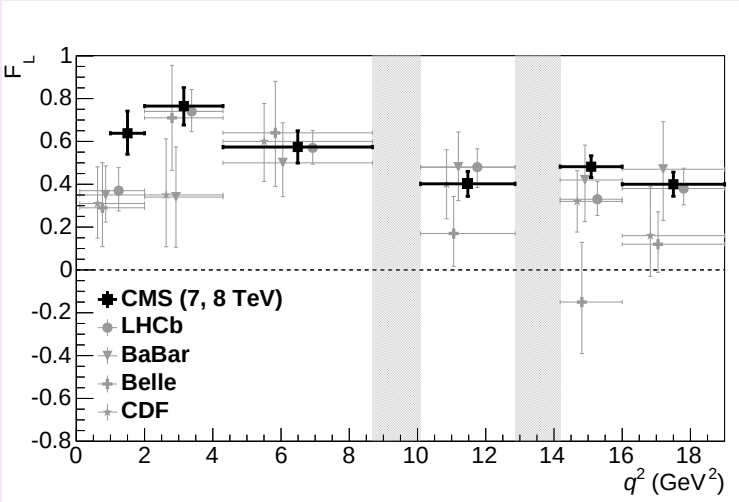
Lattice

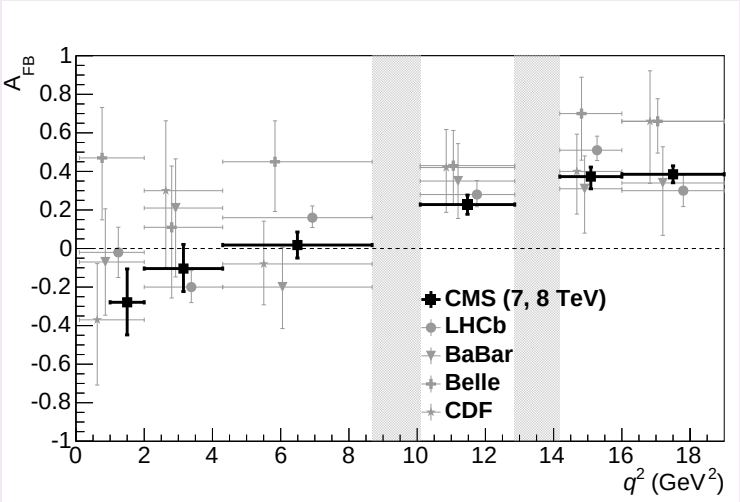
R.R.Horgan *et al.*, PRD 89 (2014) 094501

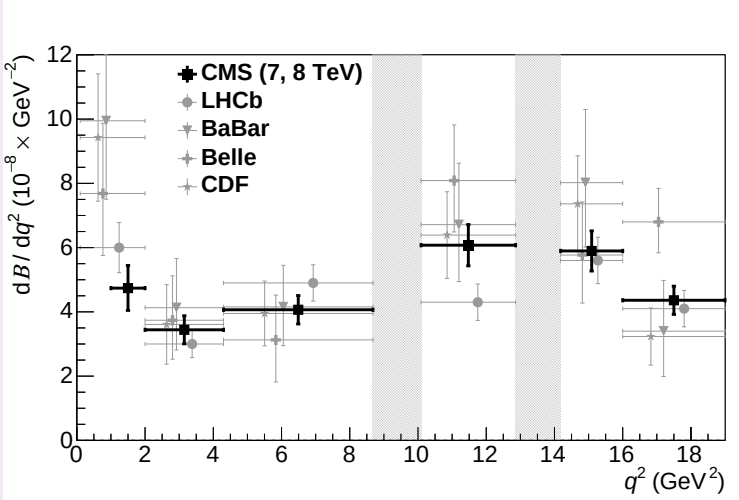
Angular analysis, first step: ϕ integrated out

Results & comparisons (other measurements)

PLB 727 (2013) 77, PLB 753 (2016) 424







BaBar Collaboration, PRD 86 (2012) 032012

Belle Collaboration, PRL 108 (2012) 081807

CDF Collaboration, PRL 106 (2011) 161801

LHCb Collaboration, JHEP 08 (2013) 131

Angular analysis, second step: ϕ & θ_l folded around 0 & $\pi/2$

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

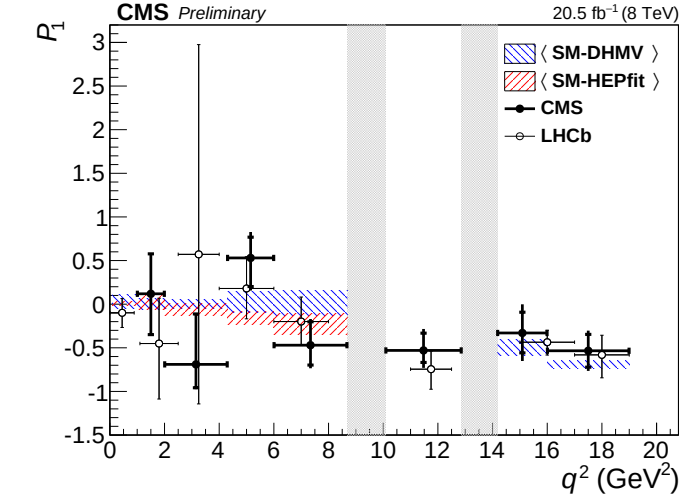
Unbinned Maximum Likelihood fit

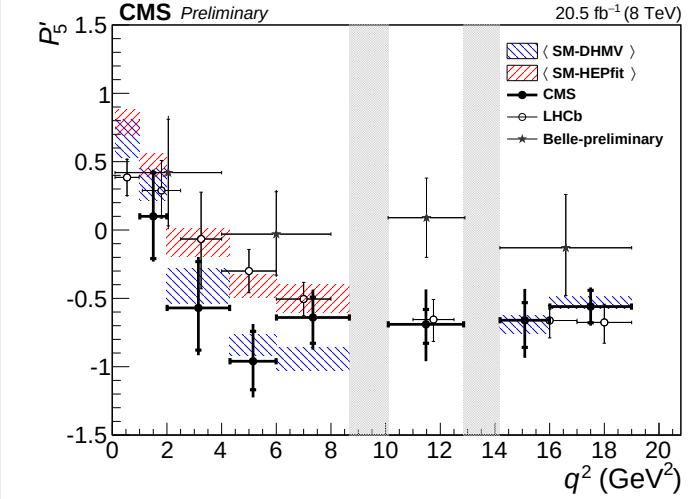
- F_L , F_S , A_S fixed to previous result (effect included in systematic error)
- Blind procedure:
  - fit on simulation, stability checked with toys
  - fit on control regions ($B^0 \to J/\psi K^{*0}$, $B^0 \to \psi' K^{*0}$)
- Statistical errors computed from a 2D Feldman-Cousins scan

Angular analysis, second step: ϕ & θ_l folded around 0 & $\pi/2$

Results & comparisons

CMS-PAS-BPH-15-008





Descotes-Genon *et al.*, JHEP 05 (2014) 137

M.Ciuchini *et al.*, arXiv:1611.04338

LHCb Collaboration, JHEP 02 (2016) 104

Belle Collaboration, arXiv:1612.05014

not shown: ATLAS Collaboration, ATLAS-CONF-2017-023

Conclusions

- CMS has produced new results about B mesons and quarkonia production cross-section and polarization; some previous measurements have been extended to $\sqrt{s} = 13$ TeV
- New results from studies of exotic states and decays have been also produced, double Υ production and $B^{\pm} \to \psi(2S)\phi K^{\pm}$ decay have been observed
- An angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ has been performed, results have been compared to predictions and measurements from other experiments

Extra informations

BACKUP

$B^{\pm}$ 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

$\mathcal{L} = 50.8\ \text{pb}^{-1}$, $|y_B| < 2.1$, $10\ \text{GeV} < p_{T,B} < 100\ \text{GeV}$ arXiv:1609.00873

Differential cross-section, vs. transverse momentum and rapidity

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

z	=	$p_{T,B}$, $\lvert y_B \rvert$	$n_{\text{sig}}(z)$	=	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

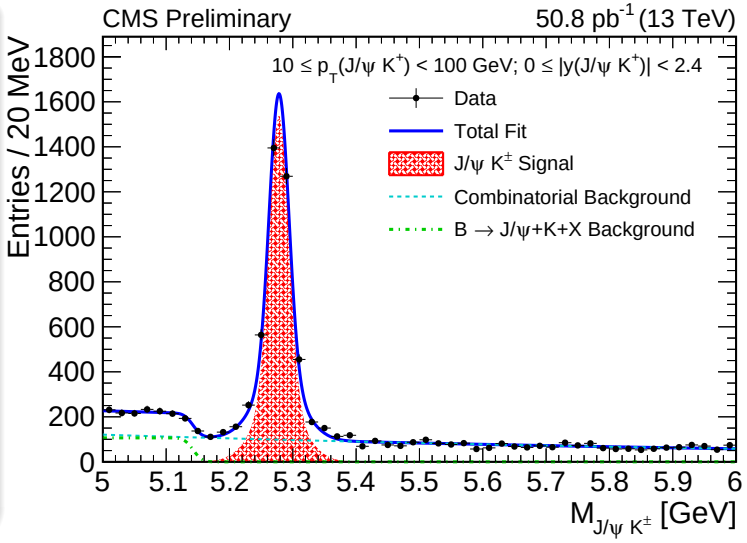
$B^{\pm}$ signal extraction

Event selection

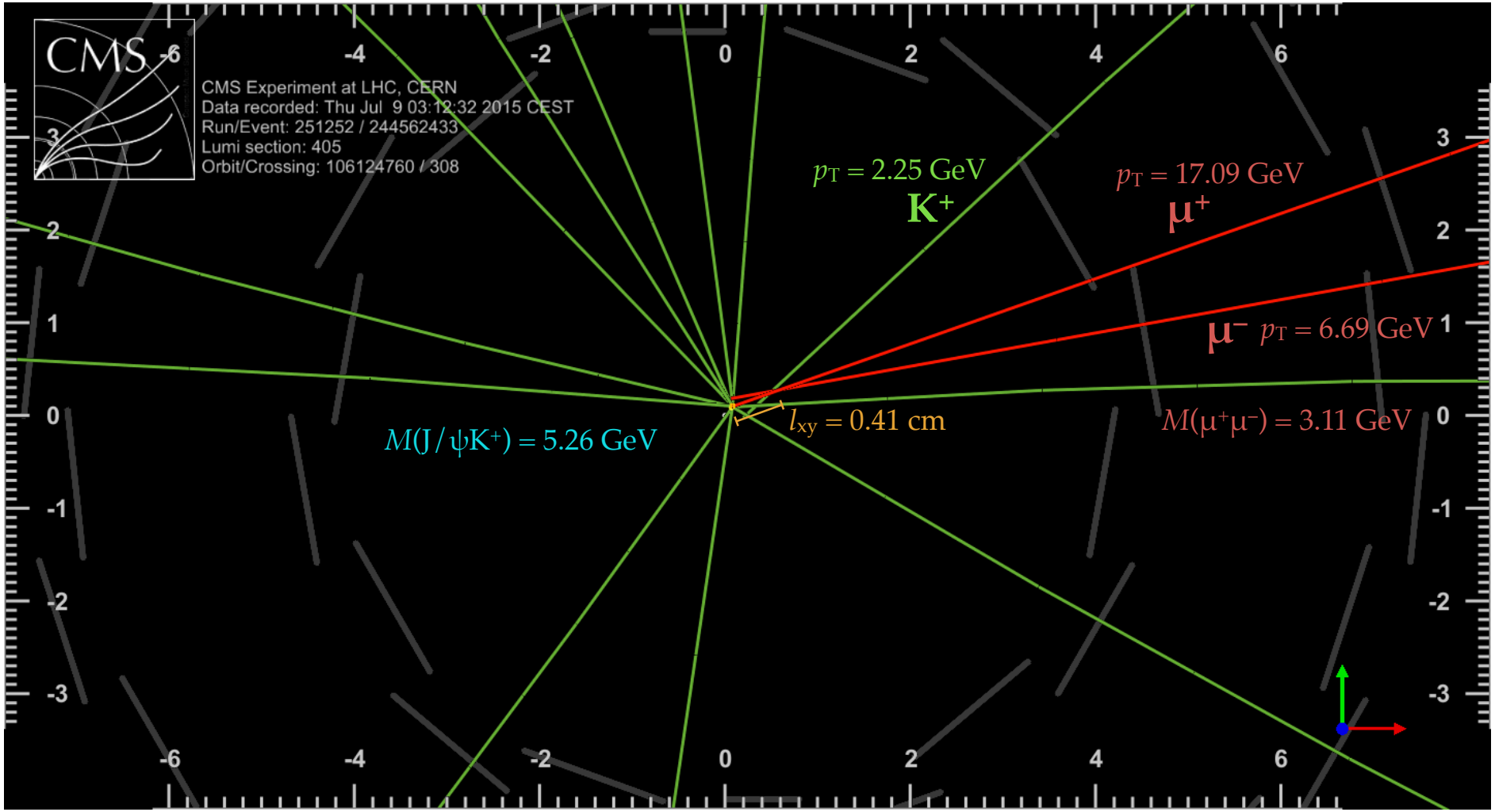
- Muon quality: match chamber segment with extrapolated track
- J/ψ candidate quality: invariant mass and vertex fit χ^2
- $B^{\pm}$ candidate quality: common vertex, flight distance and direction

$B^{\pm} \to J/\psi K^{\pm}$ 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 $B^{\pm} \to J/\psi KX$)



$B^{\pm} \to J/\psi K^{\pm}$ event



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

Overall $A \cdot \epsilon$ estimation

- Simulated events with $|y_B| < 2.4$, 10 GeV $< p_{T,B} <$ 100 GeV
- Selected event fraction:
  - 0.5% ($p_{T,B} \sim$ 10 GeV) ; 19% (70 GeV $< p_{T,B} <$ 100 GeV)
  - 4% ($|y_B| \sim 0$) ; 0.4% ($1.8 < |y_B| < 2.4$)

Trigger and muon-reconstruction efficiency

- Inclusive $J/\psi \to \mu^+\mu^-$ 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: systematic uncertainties

Signal yield

- Different mass modeling functions:
  - signal: 3 gaussians
  - background: 2nd order polynomial
  - $B^{\pm} \to J/\psi KX$ events: gaussian, 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: 4.8%
- $\mathcal{B}(B^{\pm} \to J/\psi K^{\pm} \to \mu^{+}\mu^{-}K^{\pm})$: 3.1%

Λ_b^0 polarization: $\Lambda_b^0 \to J/\psi\Lambda^0$ selection

J/ψ selection

- $p_{T,\mu} > 4$ GeV
- $|\eta_\mu| < 2.2$
- $p_{T,\mu\mu} > 8$ GeV
- $|m_{\mu\mu} - m_{J/\psi}| < 150$ MeV
- $\text{Prob}_{\text{vtx}} > 0.15$
- $\cos\alpha > 0.95$
- $L_{xy} > 3\sigma$

Λ_0 selection

- $N_{\text{hit}} \geq 6$, $\chi^2/N_{\text{d.o.f.}} < 5$
- $p_{T,\pi} > 0.3$ GeV , $p_{T,p} > 1.0$ GeV
- $p_{T,p\pi} > 1.3$ GeV
- $|m_{p\pi} - m_{\Lambda^0}| < 9$ MeV
- $|m_{\pi\pi} - m_{K_S^0}| > 20$ MeV
- $d_{xy} > 2\sigma_{\text{vtx}}$, $\text{Prob}_{\text{vtx}} > 0.02$
- $D_{\text{BS-vtx}} > 3\sigma_{\text{vtx}}$

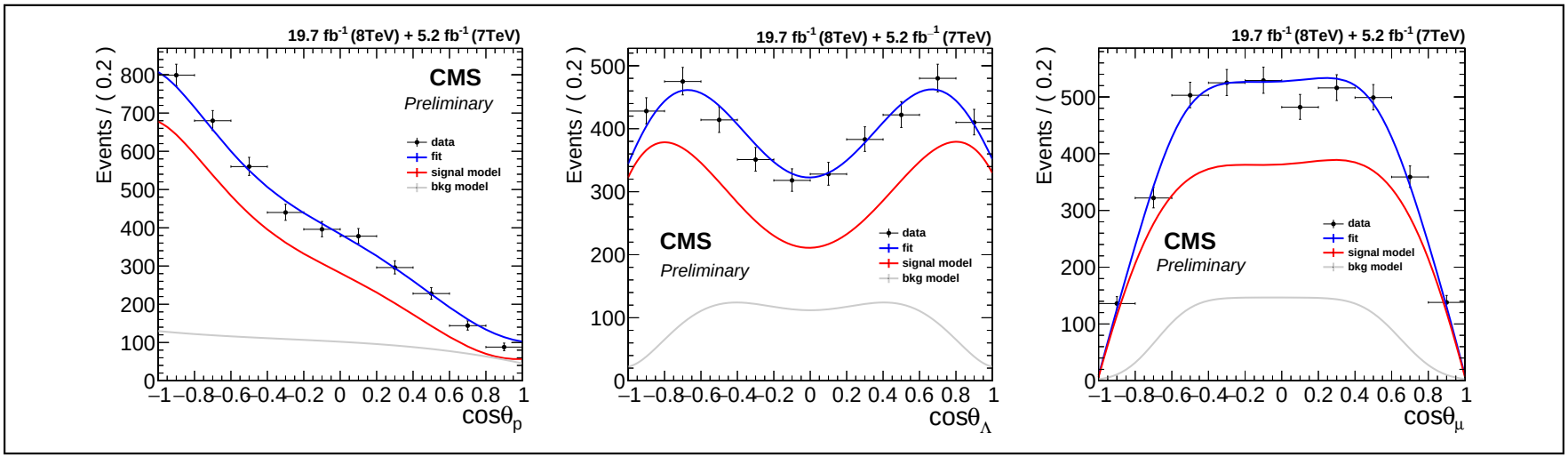
- p, π masses assigned according to p_T : $p_{T,p} > p_{T,\pi}$
- $p_{T,\Lambda_b^0} > 10$ GeV
- $\text{Prob}_{J/\psi\tilde{}0} > 0.03$
- 5.40 GeV $< m_{\Lambda_b^0} < 5.84$ GeV

Λ_b^0 polarization: angular distribution

$$\frac{d\Gamma}{d\Omega_3} = \Sigma_{i=1}^{8} \eta_i c_i f_i$$

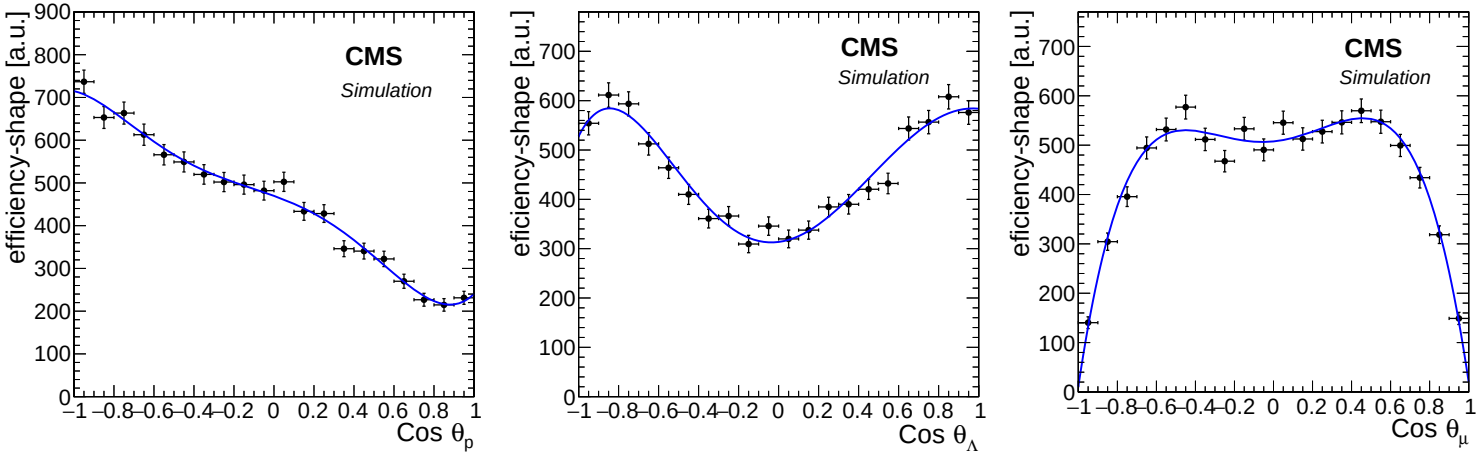
i	η_i	c_i	f_i
1	1	1	1
2	α_2	α_Λ	$\cos\theta_p$
3	$-\alpha_1$	P	$\cos\theta_\Lambda$
4	$-(1+2\gamma_0)/3$	$\alpha_\Lambda P$	$\cos\theta_\Lambda \cos\theta_p$
5	$\gamma_0/2$	1	$(3\cos^2\theta_\mu - 1)/2$
6	$(3\alpha_1 - \alpha_2)/4$	α_Λ	$\cos\theta_p (3\cos^2\theta_\mu - 1)/2$
7	$(\alpha_1 - 3\alpha_2)/4$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

$$\begin{aligned} P &= 0.00 \pm 0.06 \pm 0.02 \\ \alpha_1 &= 0.12 \pm 0.13 \pm 0.06 \\ \alpha_2 &= -0.93 \pm 0.04 \pm 0.04 \\ \gamma_0 &= -0.46 \pm 0.07 \pm 0.04 \end{aligned}$$

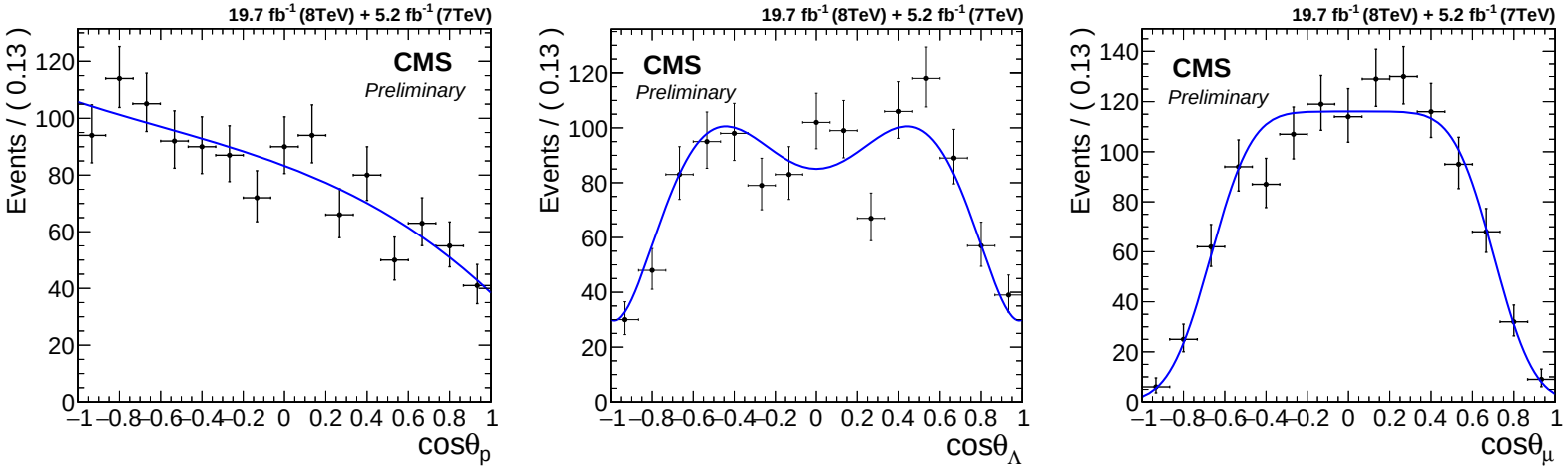


Λ_b^0 polarization: efficiency & background

efficiency



background



Quarkonia production cross-section

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

- Test factorization and NRQCD
- 2 phases:
  - 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
- Higher energy and higher cross-section: extended p_T reach

G.T.Bodwin *et al.*, PRD 51 (1995) 1125
G.T.Bodwin *et al.*, PRD 55 (1997) 5853
P.Cho and A.K.Leibovich, PRD 53 (1996) 150
P.Cho and A.K.Leibovich, PRD 53 (1996) 6203

P.Faccioli *et al.*, PLB 736 (2014) 98
G.T.Bodwin *et al.*, PRL 113 (2014) 022001

$\mathcal{L} = 2.4\ \text{fb}^{-1}$, $|y_{\mu^+\mu^-}| < 1.2$, $p_{T,\mu^+\mu^-}$ up to 120 GeV CMS-PAS-BPH-15-005

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

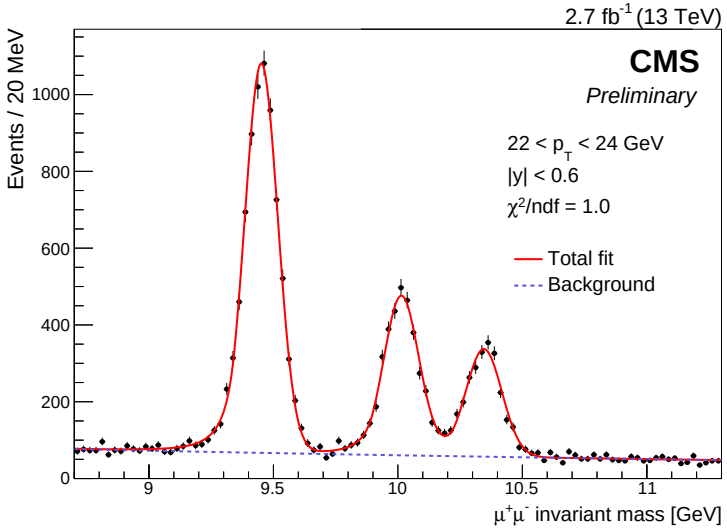
$$\mathcal{B}(Q\bar{Q} \to \mu^+\mu^-) \cdot \frac{d^2\sigma(pp \to Q\bar{Q}X)}{dp_T dy} = \frac{N_{Q\bar{Q}}(z)}{\mathcal{L} \cdot \Delta z} \cdot \langle \frac{1}{A(p_T, y) \cdot \epsilon(p_T, y)} \rangle$$

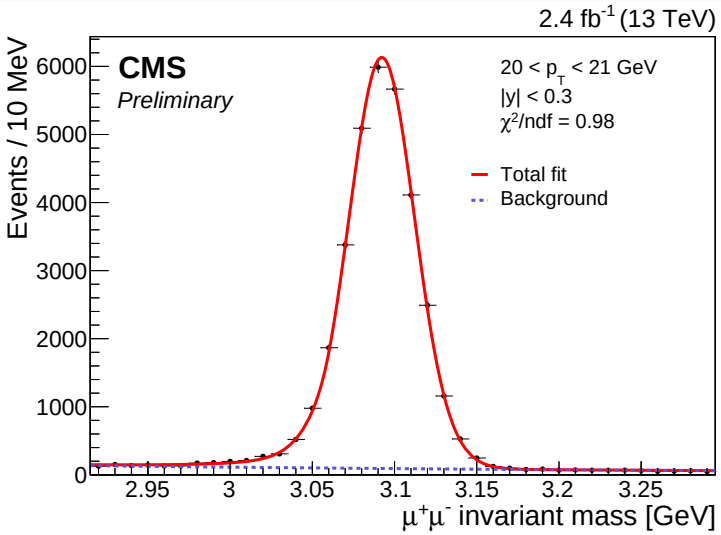
Quarkonia signal extraction

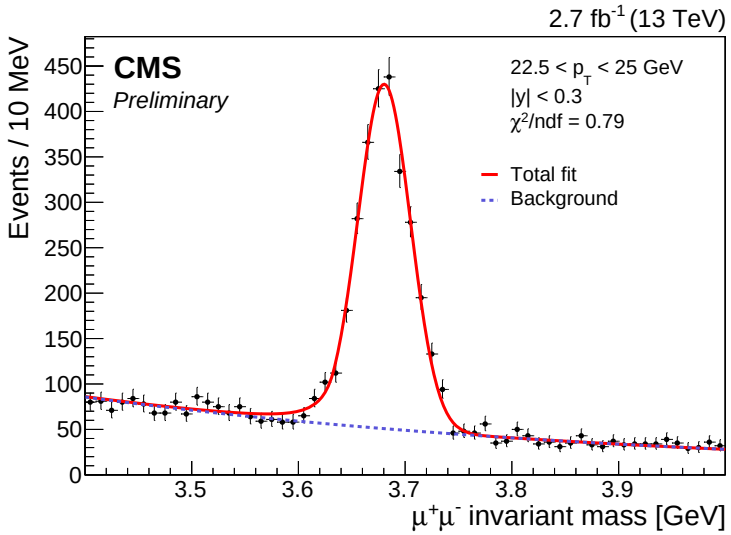
$Q\bar{Q}$ invariant mass distributions

- 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



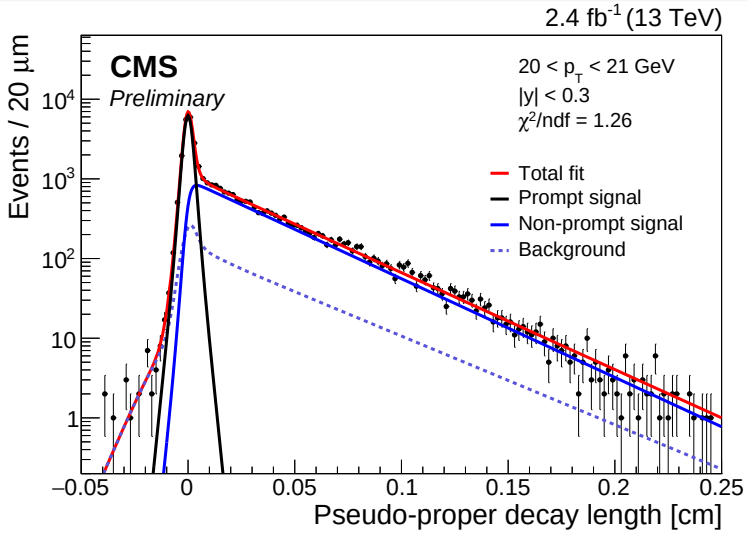


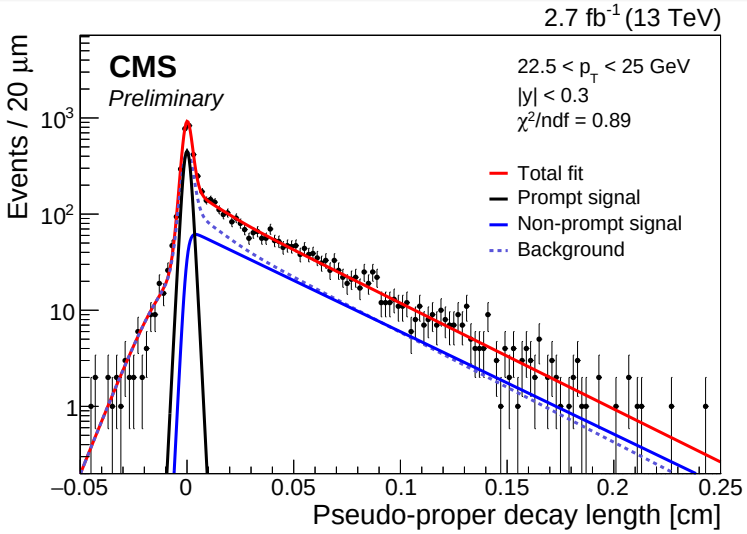


Prompt/non-prompt components

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 convoluted 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

Quarkonia production: systematic uncertainties

Signal yield

Different mass fits:

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

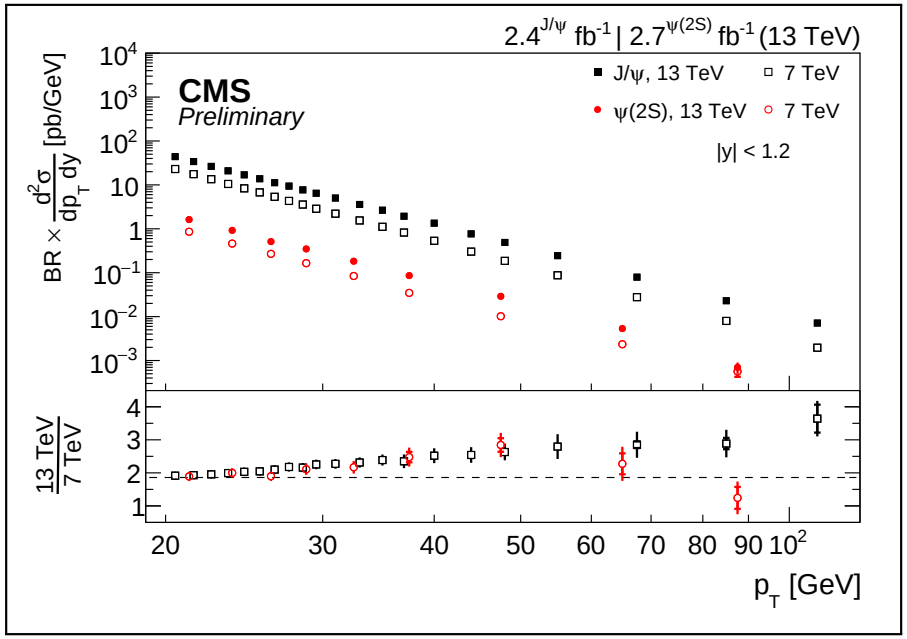
Non-prompt fraction

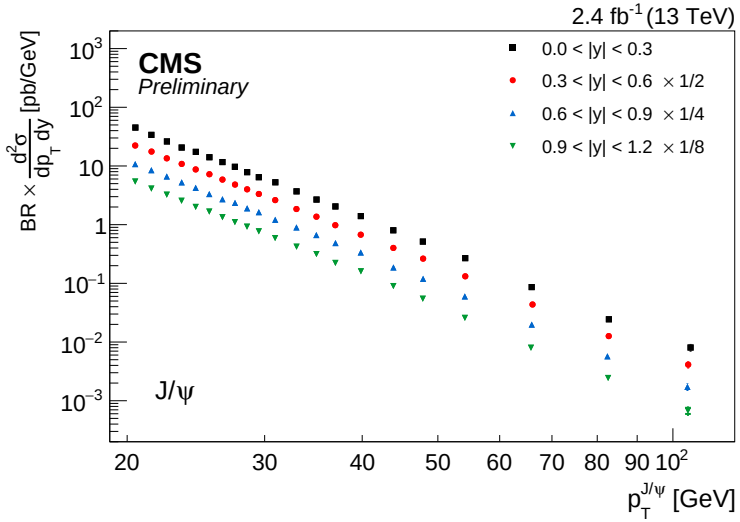
- Decay length from:
  - average interaction point
  - nearest primary vertex along beam direction
- Different functions for background modeling: right, left or double-sided exponential
- Changes in parameter constraints

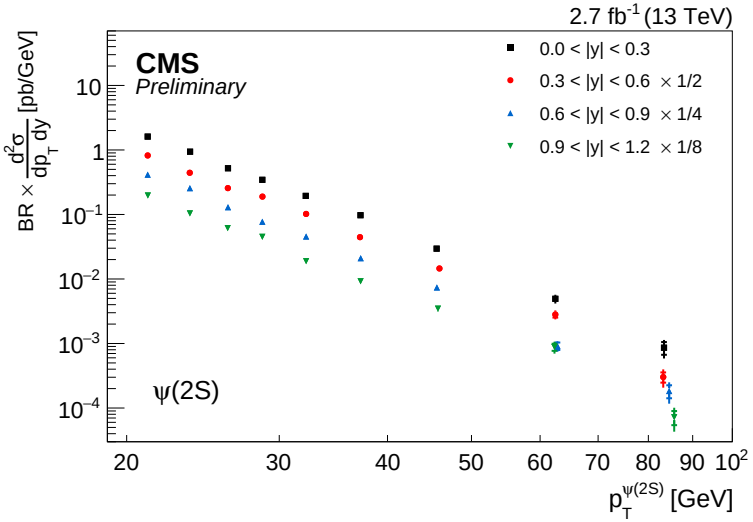
J/ψ , $\psi(2S)$: results

Double-differential cross-section

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

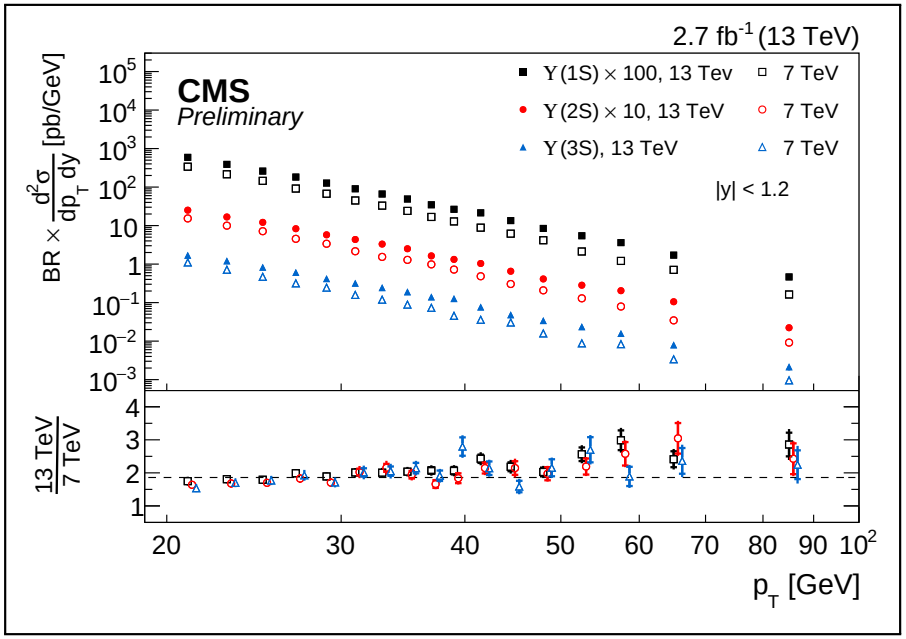


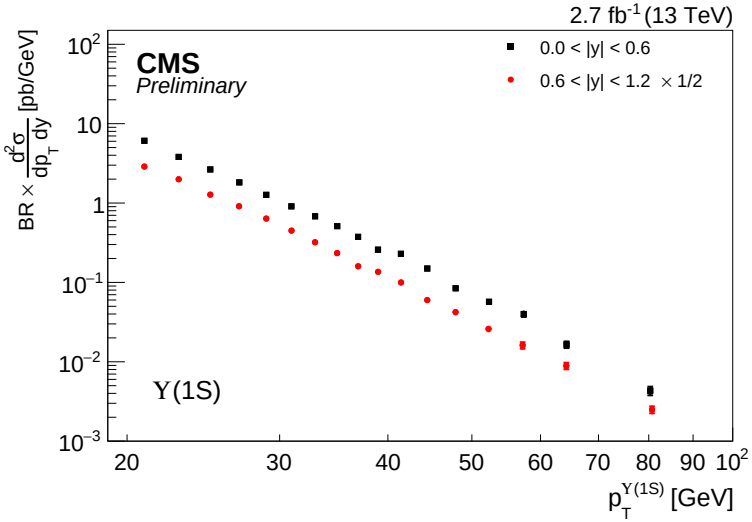


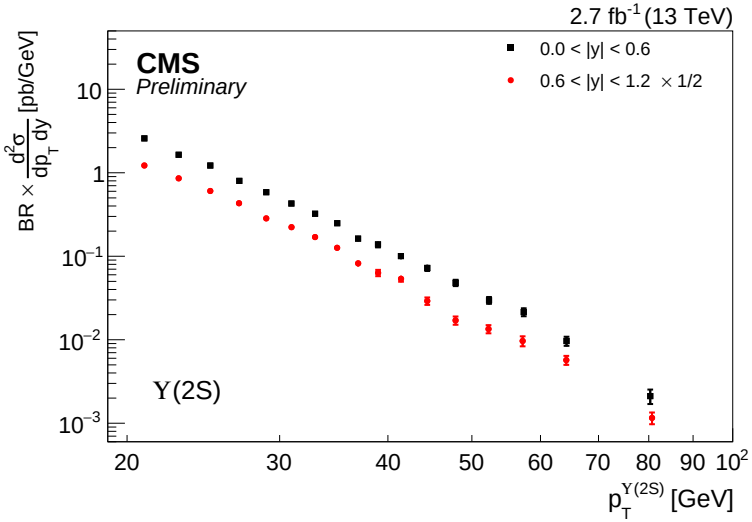


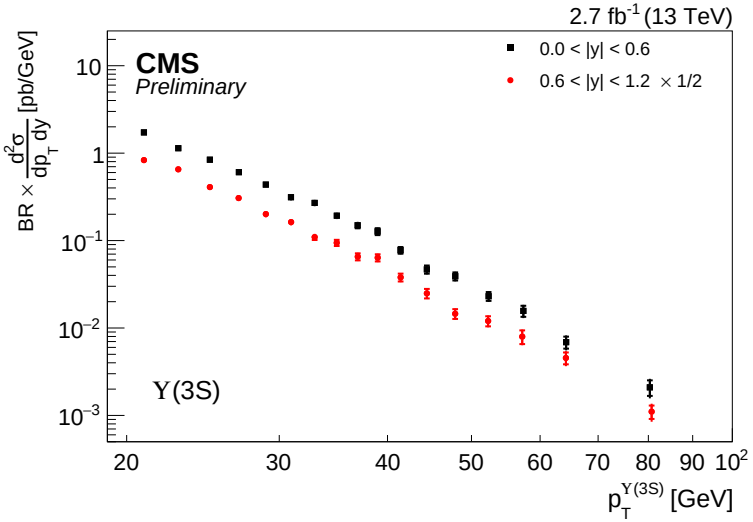
$\Upsilon(1S)$,$\Upsilon(2S)$,$\Upsilon(3S)$: results

Plot vs. p_T in 2 $|y|$ bins



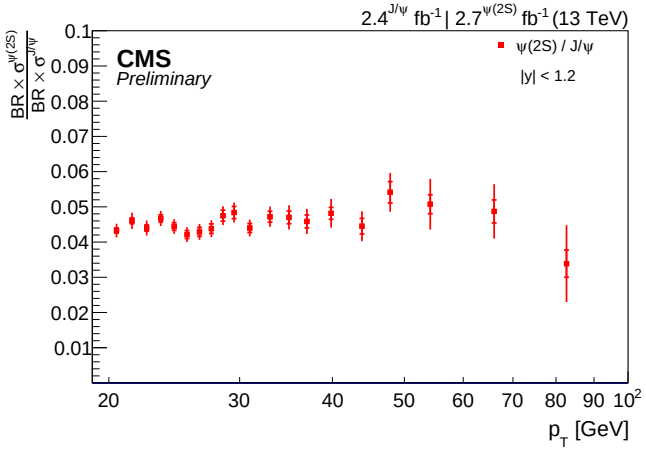


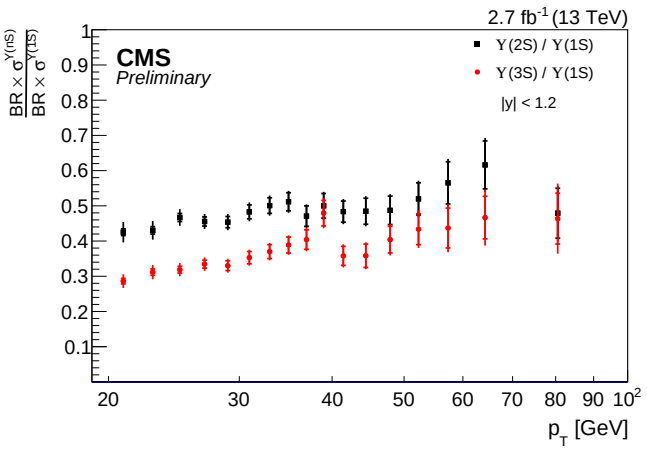




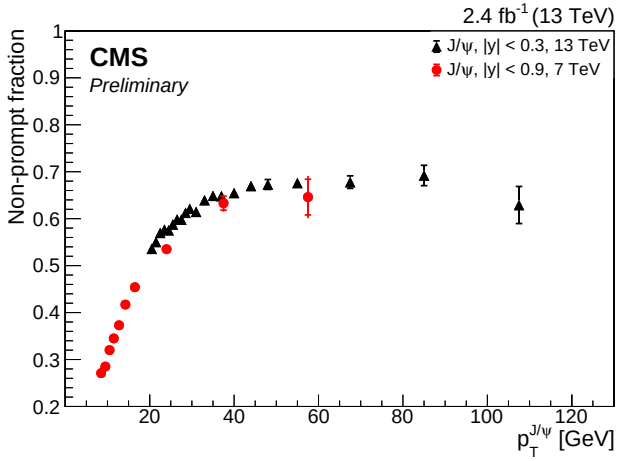
Quarkonia production: production ratios

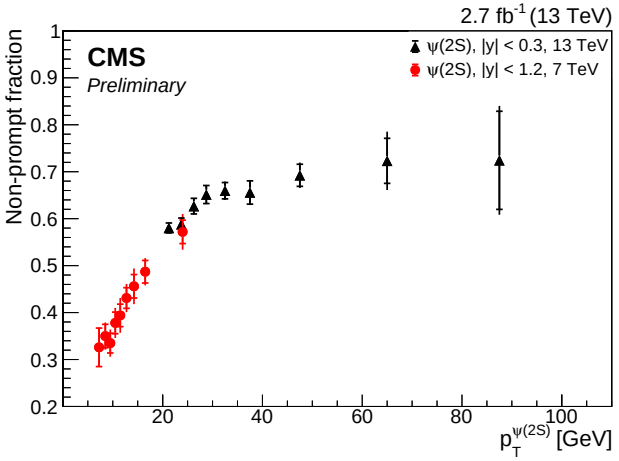
Cross section ratios



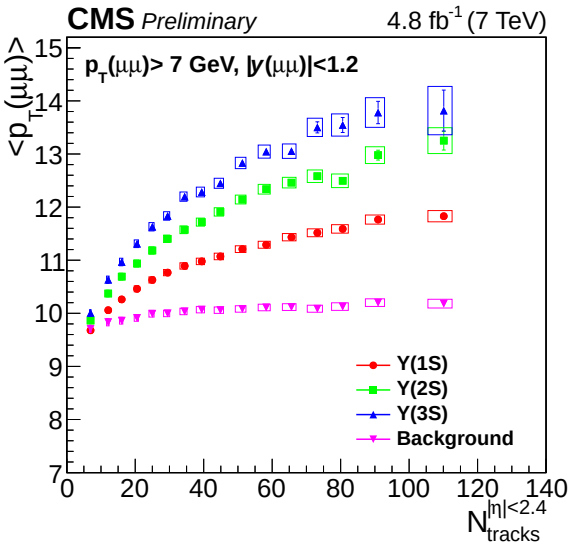


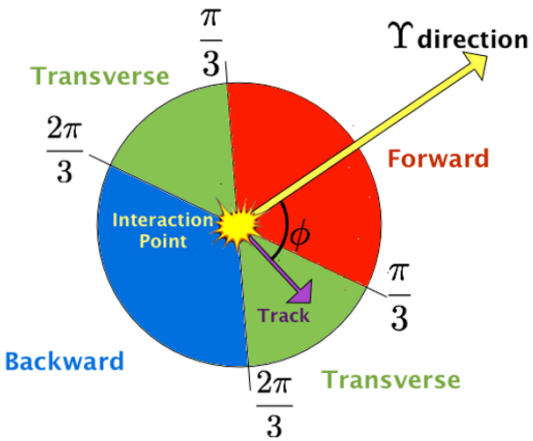
Non-prompt fractions

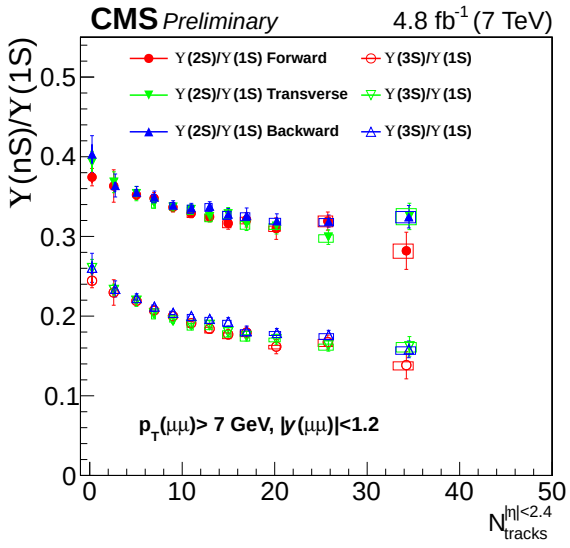




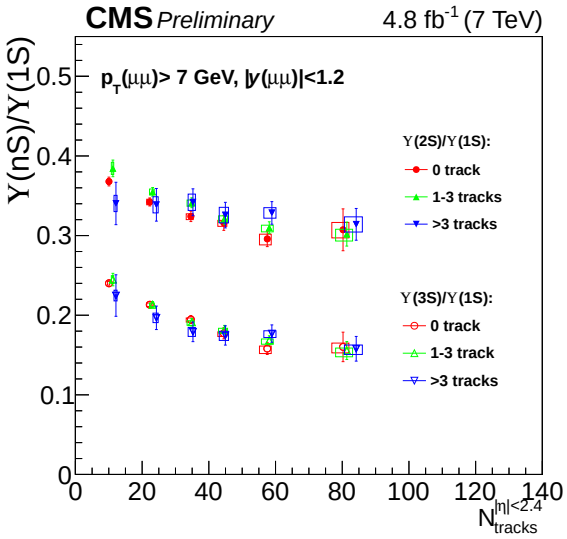
ϒ production ratios vs. multiplicity

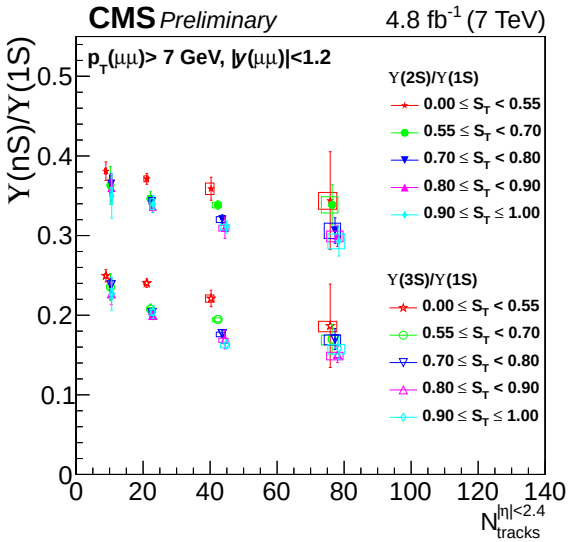






$\Delta R < 0.5$





Double ϒ production

High parton densities in *pp* collisions

- Single parton scattering (SPS):
  - assumed to dominate
  - strongly correlated pairs, small $|\Delta y|$
- Double parton scattering (DPS):
  - multiple heavy-flavour production,
  - large $|\Delta y|$ values

S. Baranov,*et al.*, PLB 705 (2011) 116-119 , C.H.Kom *et al.*, PRL 107 (2011) 082002

Quarkonium pair production mechanism

- Color singlet: dominant at low p_T
- Color octet: important at high p_T

P. Ko *et al.*, JHEP01(2011)070 , J.Campbell *et al.*, PRL 98 (2007) 252002

Possibly produced in decays of tetra-quarks

A.V.Berezhnoy, *et al.*, PRD 86 (2012) 034004

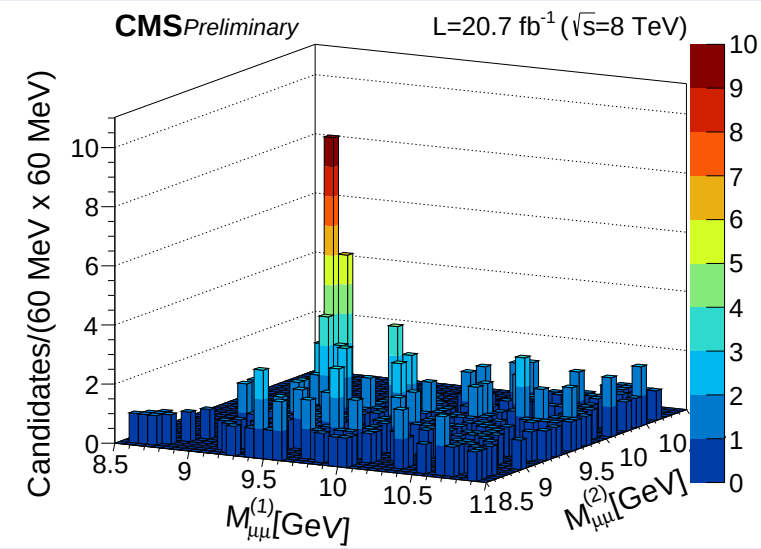
Double ϒ selection & signal extraction

Event selection

- Muon quality:
  - hits in tracker and pixel detector
  - match chamber segment with extrapolated track
- $p_{T,\mu} > 3.5$ GeV , $|\eta_\mu| < 2.4$
- $p_{T,\Upsilon} < 50$ GeV , $|y_\Upsilon| < 2.0$

} uniform muon acceptance region

- Multiple ϒ events discarded
- Non-prompt production negligible



Invariant mass distributions

- ϒ(1S)ϒ(1S) and ϒ(1S)ϒ(2S) yield estimated,
- no visible signal for ϒ(3S)
- 2*D* unbinned max likelihood fit, 5 components

Double Υ selection & signal extraction

Event selection

- Muon quality:
  - hits in tracker and pixel detector
  - match chamber segment with extrapolated track
- $p_{T,\mu} > 3.5$ GeV , $|\eta_\mu| < 2.4$
- $p_{T,\Upsilon} < 50$ GeV , $|y_\Upsilon| < 2.0$

  } uniform muon acceptance region
- Multiple $\Upsilon\Upsilon$ events discarded
- Non-prompt production negligible

Invariant mass distributions

- $\Upsilon(1S)\Upsilon(1S)$ and $\Upsilon(1S)\Upsilon(2S)$ yield estimated,
- no visible signal for $\Upsilon(3S)$
- $2D$ unbinned max likelihood fit, 5 components

{
- CB function (signal)
- 1st Chebyshev polynomial (bg)

{
- $\Upsilon(1S)\Upsilon(1S)$, $\Upsilon(1S)\Upsilon(2S)$
- $\Upsilon(1S)/\Upsilon(2S)$-combinatorial
- combinatorial-combinatorial

Double Υ production cross-section

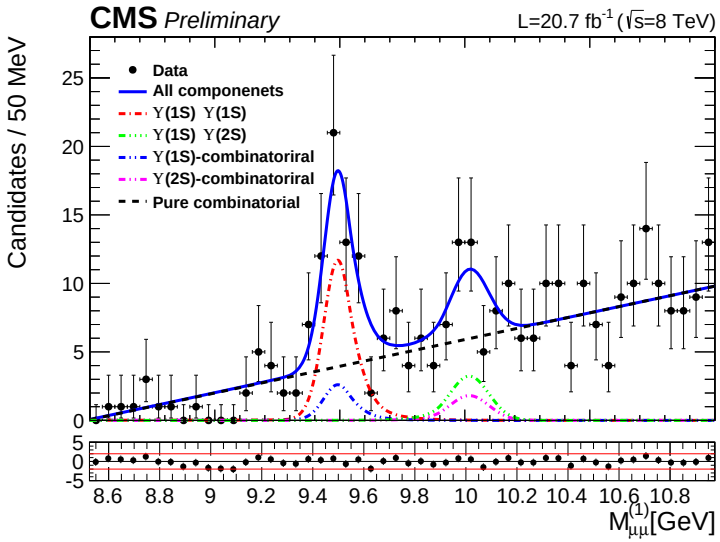
$$\sigma_T = \frac{n_{sig} \cdot \bar{\omega}}{\mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)^2 \cdot \mathcal{L}}$$

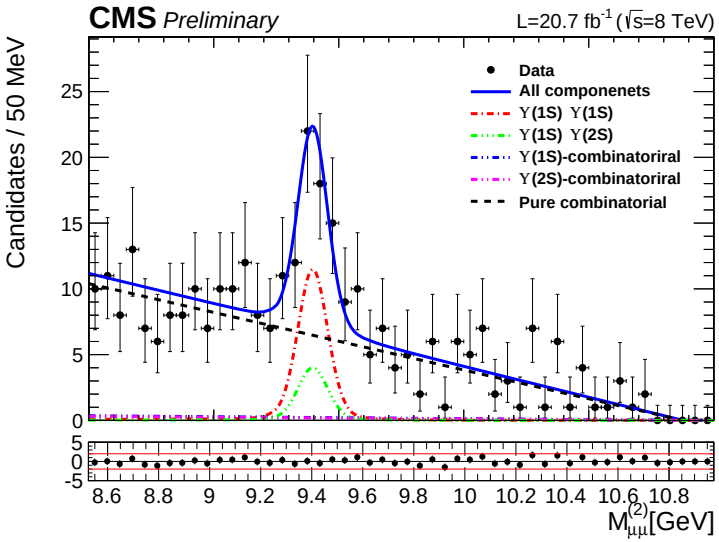
n_{sig} = $\Upsilon(1S)\Upsilon(1S)$ signal yield

$\mathcal{L}$ = integrated luminosity

$\bar{\omega}$ = acceptance & efficiency factor

- Acceptance and efficiency computed event-by-event on a MC sample
- Υ mesons assumed to decay isotropically





Double Υ production: results

$\sqrt{s} = 8$ TeV , $\mathcal{L} = 20.7$ fb^{-1} CMS-PAS-BPH-14-008

$$\sigma_T = (68.8 \pm 12.7(\text{stat}) \pm 7.4(\text{syst}) \pm 2.8(\text{BR}))\text{pb}$$

Systematic uncertainties

- Signal/background shapes
- Acceptance and efficiency
- Integrated luminosity

Υ polarization

- Acceptance computed assuming unpolarized production compared with full longitudinal/transverse polarization hypotheses
- -38%/+36% variation found

Observation of $B^{\pm} \to \psi(2S)\phi K^{\pm}$ decay: event selection

$\psi(2S)$ selection

- $p_{T,\mu\mu} > 4.9$ GeV
- $|m_{\mu\mu} - m_{\psi(2S)}| < 5\ \sigma_{M,\psi}$

ϕ selection

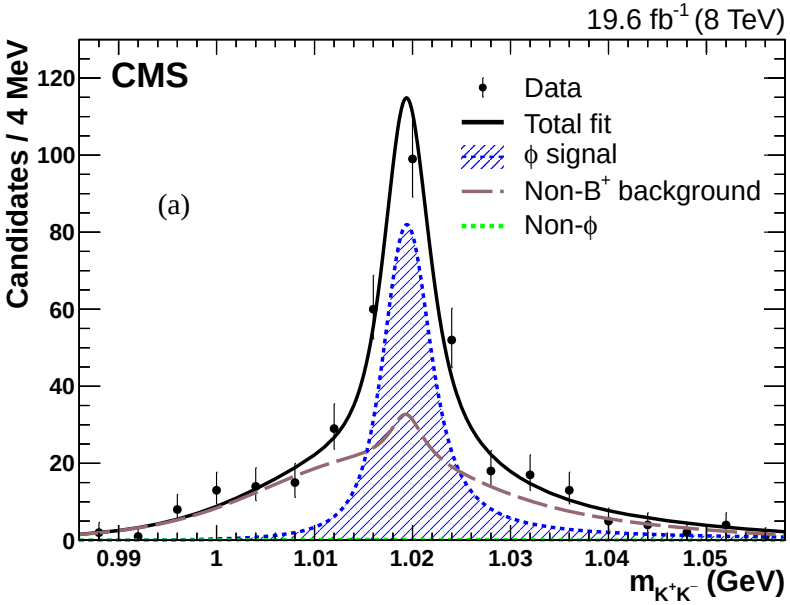
- High-quality tracks
- $p_{T,K} > 1.0$ GeV

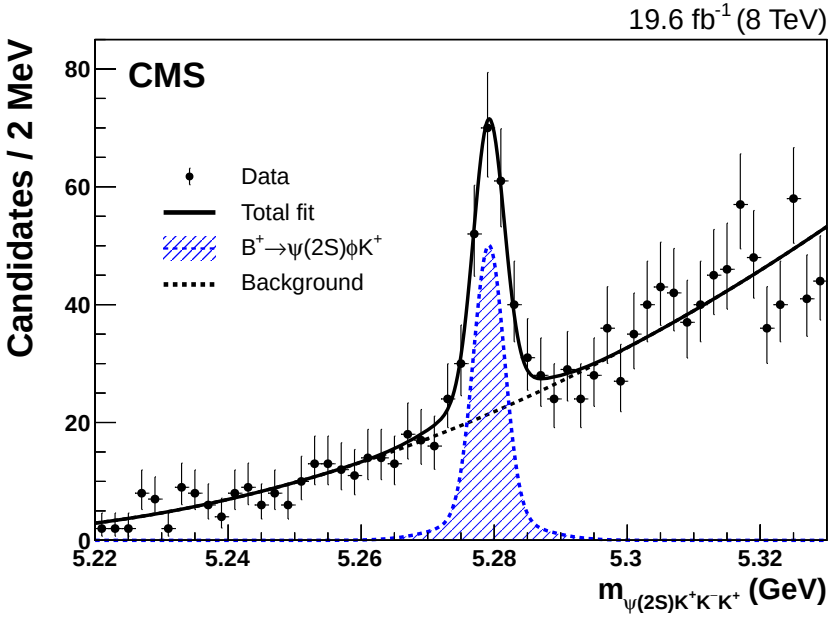
- 3D kinematic fit with $\psi(2S)$ mass constraint
- $|m_{\text{cand}} - m_{B^+}| < 5\ \sigma_{M,B}$
- $\text{Prob}_{\text{vtx}} > 0.10$
- $L_{xy} > 4\sigma$
- $\cos\alpha > 0.99$
- $p_{T,\mu\mu} > 7$ GeV
- $|m_{KK} - m_{\phi}| < 8$ MeV

Observation of $B^{\pm} \to \psi(2S)\phi K^{\pm}$ decay: systematic uncertainties

Main systematic sources

- B^{+} mass shape for signal mode
- Charged particle track reconstruction efficiency
- Modeling of p_T dependence of B^{+} efficiency
- ϕ purity





Search for $X(5568)$: event selection

J/ψ selection

- $p_{T,\mu} > 4$ GeV
- $|\eta_\mu| < 2.2$
- $p_{T,\mu\mu} > 7$ GeV
- 3.04 GeV $< m_{\mu\mu} < 3.15$ GeV
- $\text{Prob}_{\text{vtx}} > 0.10$
- $\cos\alpha > 0.9$
- $L_{xy} > 3\sigma$

ϕ selection

- High-quality tracks
- $p_{T,K} > 0.7$ GeV
- $|m_{KK} - m_\phi| < 10$ MeV

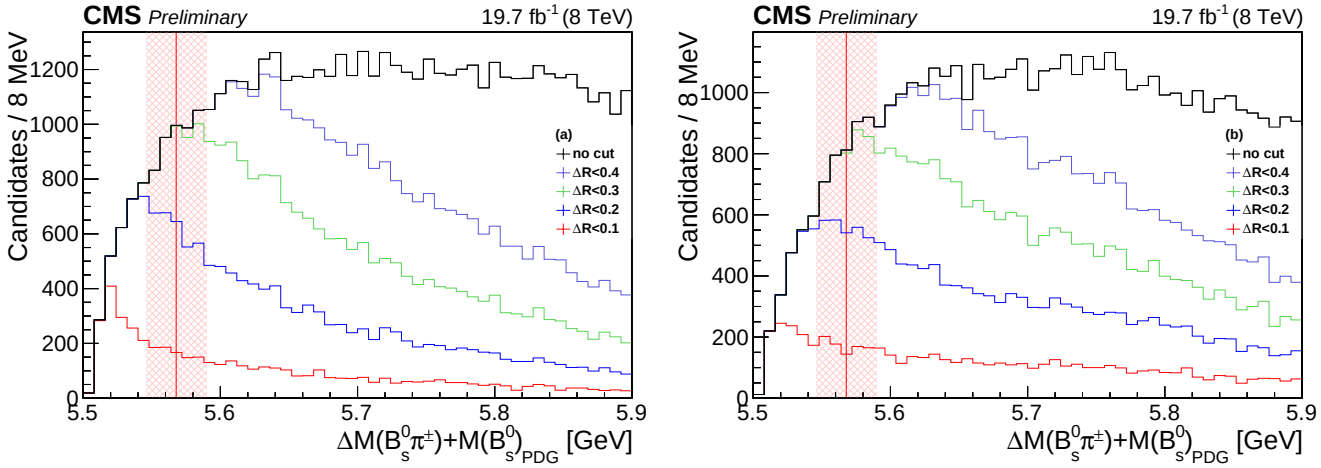
$\pi^\pm$ selection

- High-quality tracks
- From Primary vertex
- $p_{T,\pi} > 0.5$ GeV

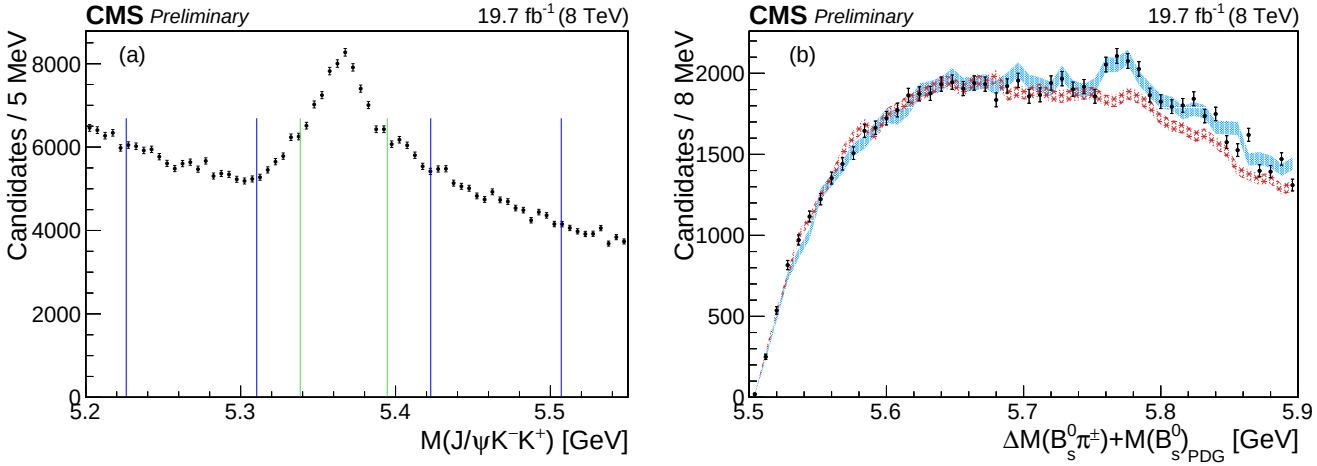
- 3D kinematic fit with $\psi(2S)$ mass constraint
- 5.20 GeV $m_{J/\psi\phi} < 5.55$ GeV
- $\text{Prob}_{\text{vtx}} > 0.01$, $\cos\alpha > 0.99$
- $p_{T,\mu\mu} > 7$ GeV

Search for $X(5568)$: different cuts

Cone cut



No m_{KK} cut

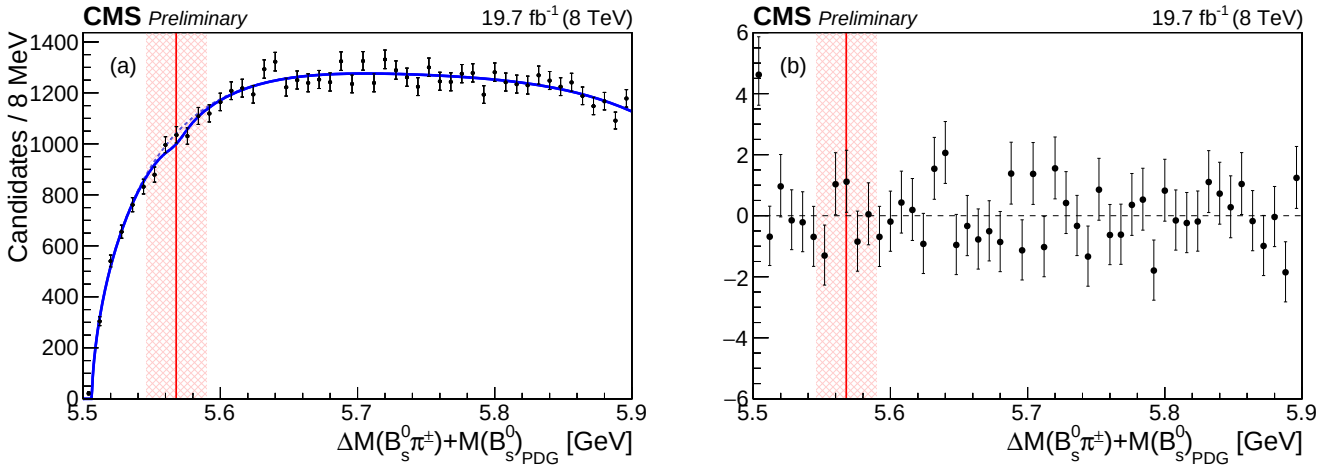


Search for $X(5568)$: fit & checks

- UML fit: $(x - x_0)^{\alpha} \times \mathrm{Pol}n(x)$ + Breit-Wigner: yield = -175 ± 134
- separate bg/signal fit: yield = -235 ± 93
- fit in $[m_X - 2.5\Gamma_X : m_X + 2.5\Gamma_X]$: yield = 4 ± 94
- different functions & parameters

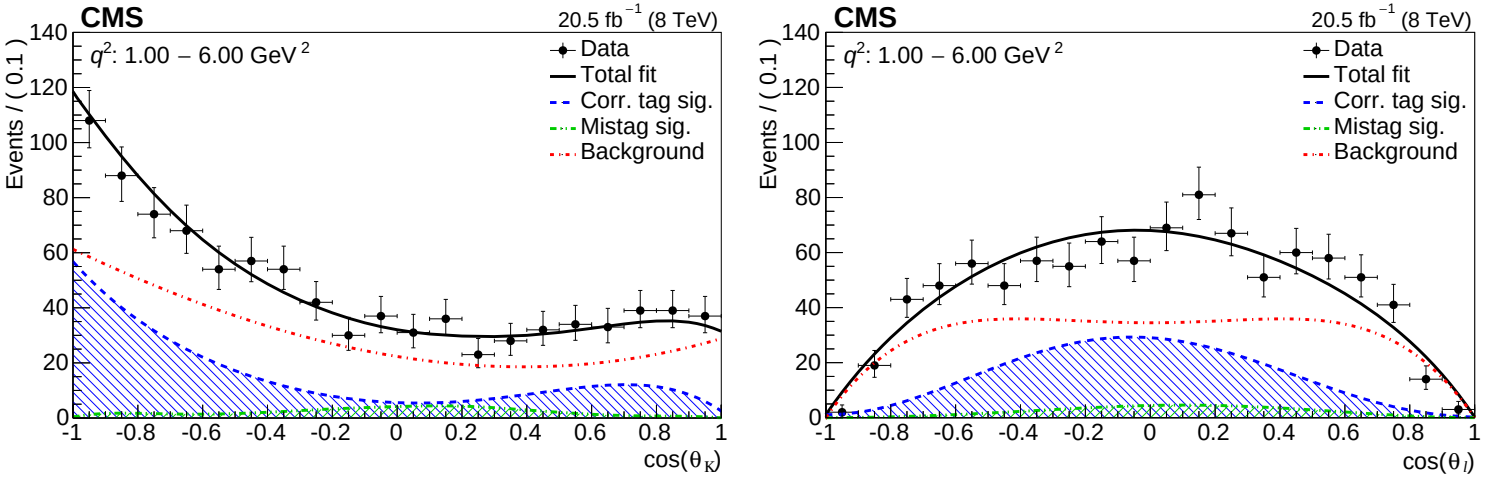
Upper limit: 198

$$\rho_X \equiv \frac{\sigma(pp \to X(5568) + \mathrm{any}) \times \mathcal{B}(X(5568) \to B_s^0 \pi^{\pm})}{\sigma(pp \to B_s^0 + \mathrm{any})} = \frac{N_{X(5568)}}{N_{B_s^0}} \frac{\epsilon_{B_s^0}}{\epsilon_{X(5568)}}$$

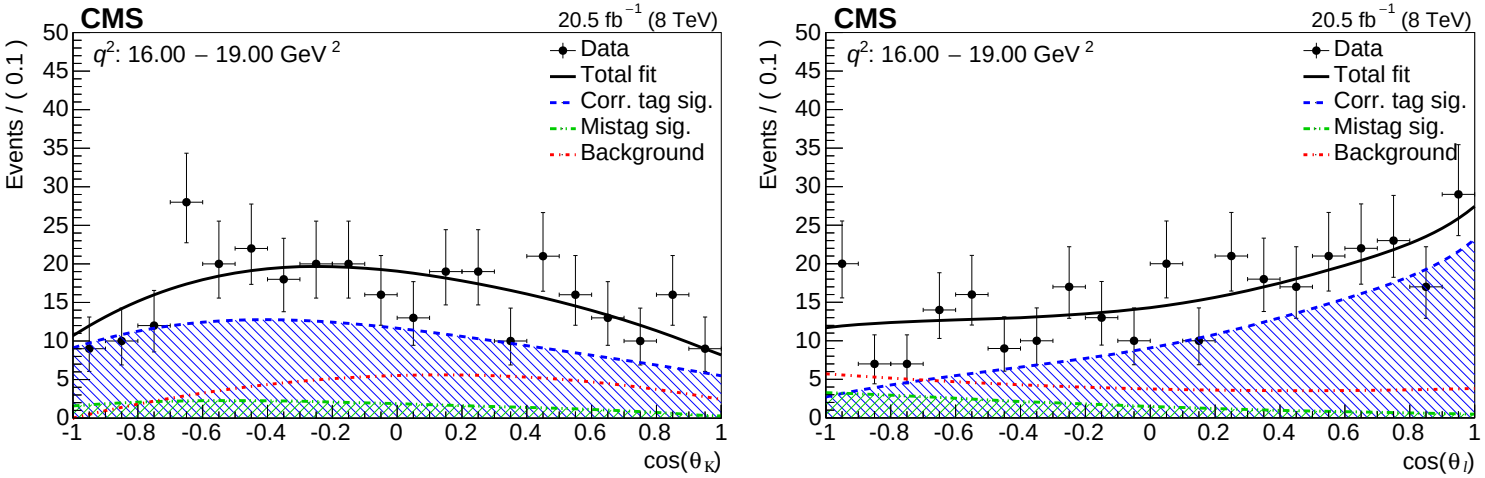


Angular analysis, ϕ integrated out: θ_K & θ_l

Low q^2



High q^2



Angular analysis, ϕ integrated out: parameters by bin

q^2 (GeV^2)	Signal yield	F_L	A_{FB}	$d\mathcal{B}/dq^2$ ($10^{-8}\,\mathrm{GeV}^{-2}$)
1.00–2.00	85 ± 11	$0.65^{+0.11}_{-0.09} \pm 0.05$	$-0.27^{+0.17}_{-0.40} \pm 0.07$	$4.7 \pm 0.7 \pm 0.3$
2.00–4.30	145 ± 16	$0.79 \pm 0.08 \pm 0.04$	$-0.12^{+0.15}_{-0.14} \pm 0.05$	$3.3 \pm 0.4 \pm 0.2$
4.30–6.00	119 ± 15	$0.61 \pm 0.10 \pm 0.05$	$0.03 \pm 0.15 \pm 0.03$	$3.4 \pm 0.5 \pm 0.3$
6.00–8.68	253 ± 21	$0.49 \pm 0.06 \pm 0.05$	$0.04 \pm 0.10 \pm 0.02$	$4.7 \pm 0.4 \pm 0.3$
10.09–12.86	362 ± 25	$0.39 \pm 0.05 \pm 0.04$	$0.16 \pm 0.06 \pm 0.01$	$6.2 \pm 0.4 \pm 0.5$
14.18–16.00	225 ± 16	$0.46 \pm 0.05 \pm 0.04$	$0.40^{+0.04}_{-0.06} \pm 0.01$	$6.5 \pm 0.6 \pm 0.5$
16.00–19.00	239 ± 18	$0.38 \pm 0.05 \pm 0.04$	$0.35 \pm 0.07 \pm 0.01$	$4.2 \pm 0.3 \pm 0.3$

Angular analysis, ϕ integrated out: comparisons

Experiment	F_L	A_{FB}	$d\mathcal{B}/dq^2$ (10^{-8} GeV^{-2})
CMS (7 TeV)	$0.68 \pm 0.10 \pm 0.02$	$-0.07 \pm 0.12 \pm 0.01$	$4.4 \pm 0.6 \pm 0.4$
CMS (8 TeV, this analysis)	$0.72 \pm 0.05 \pm 0.04$	$-0.15^{+0.10}_{-0.08} \pm 0.03$	$3.6 \pm 0.3 \pm 0.3$
CMS (7 TeV + 8 TeV)	0.71 ± 0.06	$-0.12^{+0.07}_{-0.08}$	3.8 ± 0.4
LHCb	$0.65^{+0.08}_{-0.07} \pm 0.03$	$-0.17 \pm 0.06 \pm 0.01$	$3.4 \pm 0.3^{+0.4}_{-0.5}$
BaBar	—	—	$4.1^{+1.1}_{-1.0} \pm 0.1$
CDF	$0.69^{+0.19}_{-0.21} \pm 0.08$	$0.29^{+0.20}_{-0.23} \pm 0.07$	$3.2 \pm 1.1 \pm 0.3$
Belle	$0.67 \pm 0.23 \pm 0.05$	$0.26^{+0.27}_{-0.32} \pm 0.07$	$3.0^{+0.9}_{-0.8} \pm 0.2$
SM (LCSR)	$0.79^{+0.09}_{-0.12}$	$-0.02^{+0.03}_{-0.02}$	$4.6^{+2.3}_{-1.7}$
SM (Lattice)	$0.73^{+0.08}_{-0.10}$	$-0.03^{+0.04}_{-0.03}$	$3.8^{+1.2}_{-1.0}$

Angular analysis, ϕ integrated out: systematic errors

Systematic uncertainty	$F_L(10^{-3})$	$A_{FB}(10^{-3})$	$d\mathcal{B}/dq^2$ (%)
Simulation mismodeling	1–17	0–37	1.0–5.5
Fit bias	0–34	2–42	—
MC statistical uncertainty	3–10	5–18	0.5–2.0
Efficiency	34	5	—
$K\pi$ mistagging	1–4	0–7	0.1–4.1
Background distribution	1–9	0–6	0.0–1.2
Mass distribution	3	1	3.2
Feed-through background	0–27	0–5	0.0–4.0
Angular resolution	6–24	0–5	0.2–2.1
Normalization to $B^0 \to K^{*0}J/\psi$	—	—	4.6
Total systematic uncertainty	36–54	10–68	6.4–8.6

Angular analysis, ϕ & θ_l folded: fitted distributions