

CMS results on flavour physics

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University and INFN Padova

CAPRI2014
Theory, Phenomenology and Experiments
in Flavour Physics

Naples, Villa Orlandi, Anacapri, May 23-25, 2014



Motivations

Several motivations to study HF physics at CMS

- Advance b,c spectroscopy
- Test QCD and effective theories
- Look for indirect evidence or constraints to new physics
- Improve environment description in NP searches



Outline

- Old results:

B^+ , B^0 , B_s , prompt-nonprompt J/ψ , $\psi(2S)$, $\Upsilon(nS)$ production

- Mesons:

- $\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+ \mu^-)$
- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay angles
- B_s^0 lifetime difference
- $B_c \rightarrow J/\psi \pi / 3\pi$ production and B.R.

- Baryons:

- Λ_b production and lifetime
- Observation of $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$

- Quarkonia:

- Double J/ψ production
- J/ψ , $\psi(2S)$, $\Upsilon(nS)$ polarization
- χ_c , χ_b production

- Exotica:

- $X(3872)$ production
- Search for $X_b \rightarrow \Upsilon(1S) \pi^+ \pi^-$
- Observation of peaks in $B^\pm \rightarrow J/\psi \phi K^\pm$



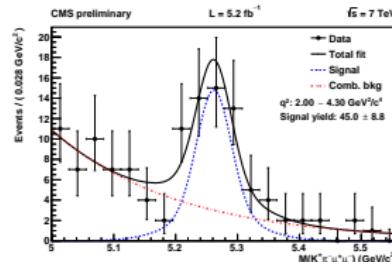
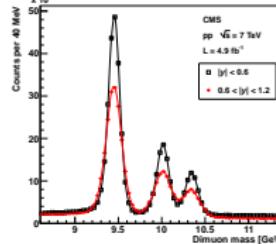
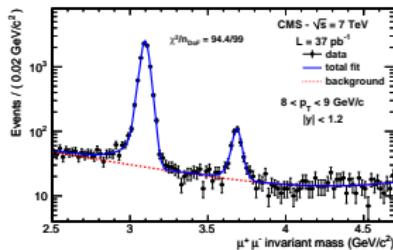
Compact Di-Muon Solenoid?

Data samples

- $\sqrt{s} = 7\text{TeV}$, $\mathcal{L} = 5\text{fb}^{-1}$ (2011 run)
- $\sqrt{s} = 8\text{TeV}$, $\mathcal{L} = 20\text{fb}^{-1}$ (2012 run)
- Oldest results obtained with part of the statistic or 2010 data

All shown results involve di-muons

- With definite invariant mass (J/ψ , Υ) ...

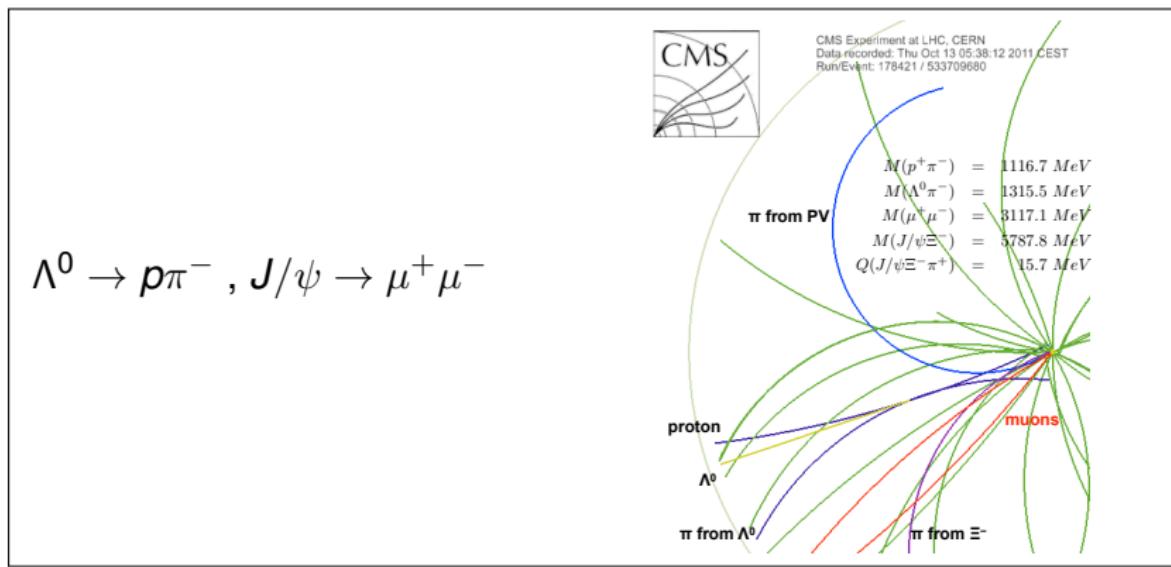


- ...or not ($B^0 \rightarrow K^{*0} \mu^+ \mu^-$)
- Useful to reduce trigger rate

Secondary vertices

Secondary vertices reconstruction in event selection

- Reject background
- Discriminate prompt vs. non-prompt dimuons



“Legacy” results from 2010 run ($\sqrt{s} = 7\text{TeV}$, $\mathcal{L} \sim 40\text{pb}^{-1}$)

B meson production

 $B^+ \rightarrow J/\psi K^+$

PRL 106 (2011) 112001

 $p_{TB} > 5\text{GeV}$, $|y_B| < 2.4$ $\sigma(pp \rightarrow B^+) = (28.1 \pm 2.4 \pm 2.0)\mu\text{b}$ $B^0 \rightarrow J/\psi K_S^0$

PRL 106 (2011) 252001

 $p_{TB} > 5\text{GeV}$, $|y_B| < 2.2$ $\sigma(pp \rightarrow B_0) = (33.2 \pm 2.5 \pm 3.5)\mu\text{b}$ $B_s \rightarrow J/\psi \phi$

PRD 84 (2011) 052008

 $8 < p_{TB} < 50\text{GeV}$, $|y_B| < 2.4$ $\sigma(pp \rightarrow B_s \rightarrow J/\psi \phi) = (6.9 \pm 0.6 \pm 0.6)\text{nb}$

Quarkonia production

 $pp \rightarrow (J/\psi, \psi(2S))X$

JHEP 02 (2012) 011

Prompt, non-prompt

 $pp \rightarrow \Upsilon(nS)X$

PLB 727 (2013) 101

 $|y_\Upsilon| < 2.4$, $p_{T\Upsilon} < 50\text{GeV}$ 

More infos at slides 30,39,42

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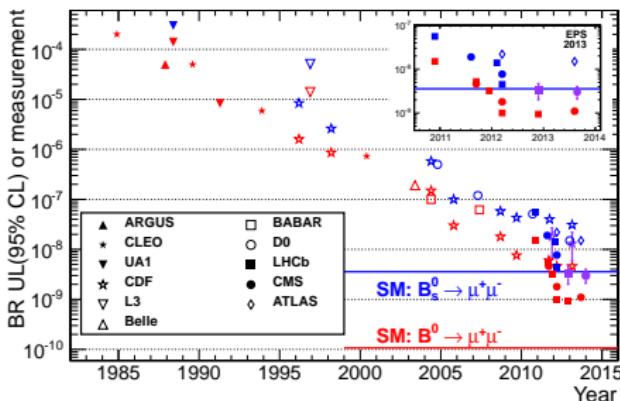
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$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+ \mu^-)$

- Very rare decay
- B.R. increased by NP processes
- Studied since a very long time



- B.R. determined by comparison with other channels
 - $B^+ \rightarrow J/\psi K^+$ used as normalization
 - $B_s^0 \rightarrow J/\psi \phi$ used as control
- Signal/background discriminated by BDT
 - Invariant mass fit in BDT-output event categories to extract $B_s^0 \rightarrow \mu^+ \mu^-$ yield
 - BDT-output cut to estimate $B_d^0 \rightarrow \mu^+ \mu^-$ yield or upper limit



More infos at slide 31

$$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+ \mu^-)$$

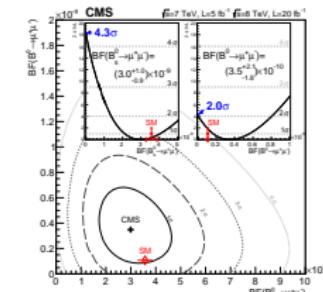
Results (full sample)

PRL 111 (2013) 101804

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$$

$$\mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-) < 1.1 \times 10^{-9} @ 95\% \text{ C.L.}$$

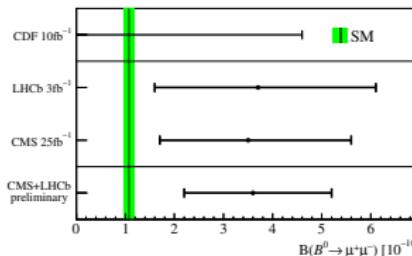
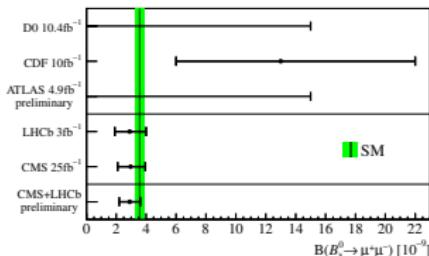


Combination with LHCb (preliminary)

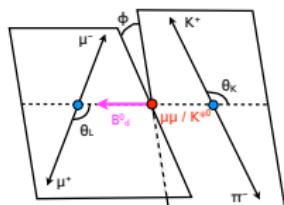
CMS PAS BPH-13-007

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9} (\text{rescaled})$$

$$\mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$



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

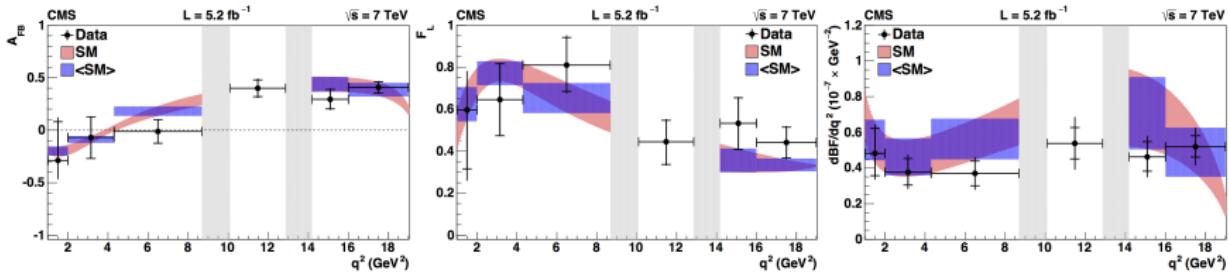


- A_{FB} : muons forward-backward asymmetry
- F_L : K^{*0} longitudinal polarization
- $d\mathcal{B}/dq^2$: differential branching fraction
- Deviations in q^2 -dependence can point to NP

PDF fit ($\sqrt{s} = 7$ TeV)

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- Events divided in q^2 bins, $B^0 \rightarrow K^{*0}(J/\psi, \psi')$ regions removed
- Unbinned max-likelihood fit to $K\pi\mu\mu$ mass, ϑ_μ , ϑ_K

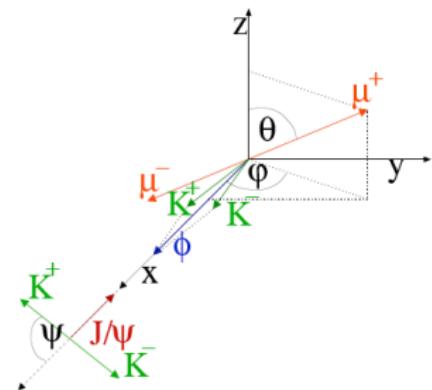


More infos at slide 32



B_s^0 lifetime difference in $B_s^0 \rightarrow J/\psi\phi$

- B_s^0, \bar{B}_s^0 flavour eigenstates are mixtures of mass eigenstates
- Lifetime difference obtained by a fit to differential decay rates
- $\frac{d^4\Gamma(B_s(t))}{d\Theta dt} = f(\Theta, t; \alpha)$
- $\Theta = \vartheta, \varphi, \psi$
- $\alpha = \Gamma_s, \Delta\Gamma_s +$ amplitudes and phases
- Mixing phase $\phi_s = 0$ assumed (effect included in systematics)



Results ($\sqrt{s} = 7\text{TeV}$)

CMS-PAS-BPH-11-006

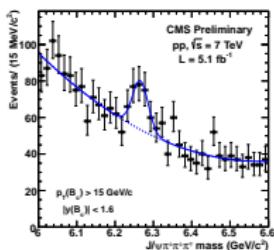
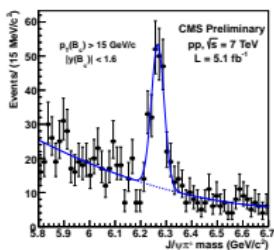
$$\begin{aligned}\tau_{B_s} &= (0.0450 \pm 0.00059 \pm 0.00022)\text{cm} \\ \Delta\Gamma_s &= (0.048 \pm 0.024 \pm 0.003)\text{ps}^{-1}\end{aligned}$$



More infos at slide 34

$B_c^\pm \rightarrow J/\psi \pi^\pm (\pi^+ \pi^-)$: production and decay

- B_c^\pm carries two heavy flavours:
- Cross-section and b.r. measurements:



- Higher-order processes at production
- c and b quark competing in decay
- Help understanding process
- Propaedeutic for more refined investigations

Unbinned max. likelihood fit

Results ($\sqrt{s} = 7$ TeV)

CMS-PAS-BPH-12-011

$$\frac{\sigma(B_c^\pm) \times \mathcal{B}(B_c^\pm \rightarrow J/\psi \pi^\pm)}{\sigma(B^\pm) \times \mathcal{B}(B^\pm \rightarrow J/\psi K^\pm)} = \\ (0.48 \pm 0.05 \pm 0.04^{+0.05}_{-0.03}(\tau_{B_c})) \times 10^{-2}$$

$$\frac{\mathcal{B}(B_c^\pm \rightarrow J/\psi \pi^\pm \pi^+ \pi^-)}{\mathcal{B}(B_c^\pm \rightarrow J/\psi \pi^\pm)} = 2.43 \pm 0.76^{+0.05}_{-0.03}$$



More infos at slide 35

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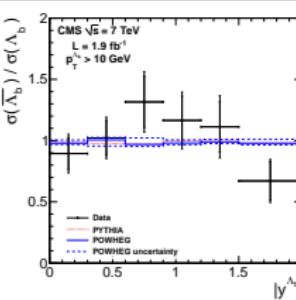
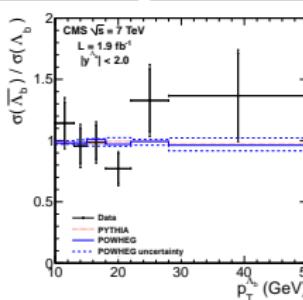
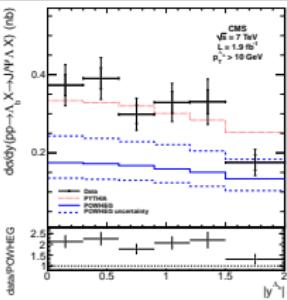
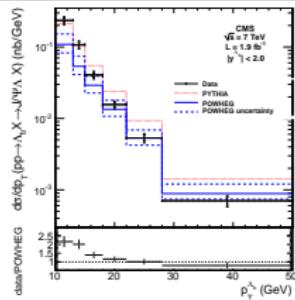
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Λ_b^0 production

- Baryon/meson production comparison: test differences in the hadronization process
- $\bar{\Lambda}_b^0$ to Λ_b^0 production ratio: test baryon transport models

Decay channel: $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$, $\Lambda^0 \rightarrow p\pi^-$ $p_{T\Lambda_b} > 10\text{GeV}$, $|y_{\Lambda_b}| < 2.0$ Results ($\sqrt{s} = 7\text{TeV}$, $\mathcal{L} = 1.9\text{fb}^{-1}$)

PLB 714 (2012) 136

$$\sigma(pp \rightarrow \Lambda_b^0 X) \times \mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda^0) = (1.16 \pm 0.06 \pm 0.12)\text{nb}$$

$$\frac{\sigma(pp \rightarrow \bar{\Lambda}_b^0 X)}{\sigma(pp \rightarrow \Lambda_b^0 X)} = 1.02 \pm 0.07 \pm 0.09$$

2.2% (luminosity) and 1.3% (J/ψ , Λ^0 B.R.s) errors not included

More infos at slide 36



Λ_b^0 lifetime

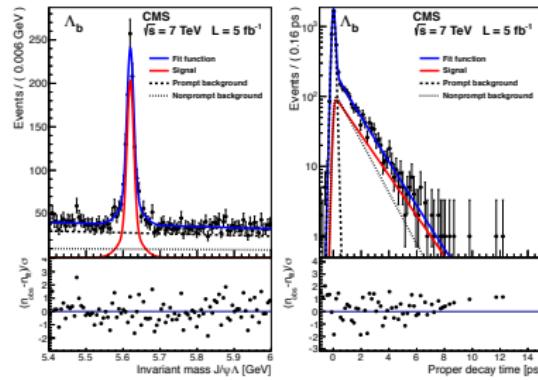
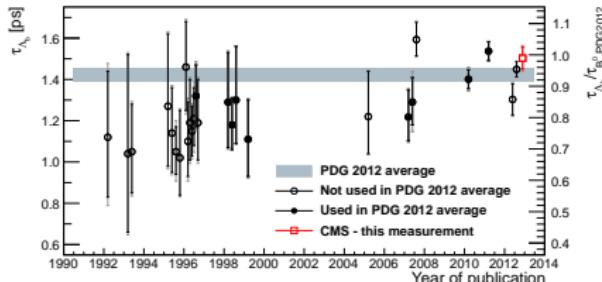
- Early predictions:
 $\tau(\Lambda_b^0)/\tau_{B^0} > 0.90$
- Initial measurements:
lower results
- \Rightarrow more refined calculations

Decay channel: $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$, $\Lambda^0 \rightarrow p \pi^-$

- Simultaneous UML fit
on mass and proper time
- $B^0 \rightarrow J/\psi K_s^0$, $K_s^0 \rightarrow \pi^+ \pi^-$
used as cross-check

Results ($\sqrt{s} = 7$ TeV) JHEP 07 (2013) 163

$$\tau_{\Lambda_b^0} = (1.503 \pm 0.052 \pm 0.031) \text{ ps}$$

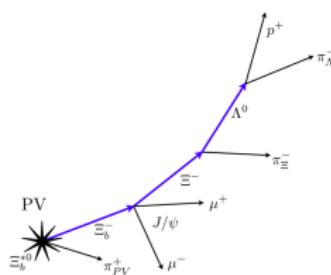


More infos at slide 37

$$\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$$

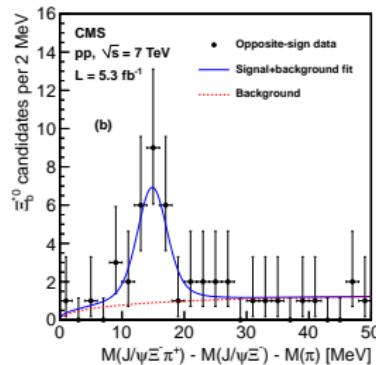
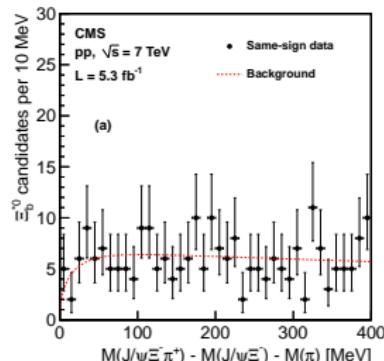
- $m_{\Xi_b'} - m_{\Xi_b^-}$
expected smaller than m_π
- $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$ decay
expected to be allowed

- $\Xi_b^- \rightarrow J/\psi \Xi^-$
- $\Xi^- \rightarrow \Lambda^0 \pi^-$
- $\Lambda^0 \rightarrow p \pi^-$



Mass fit ($\sqrt{s} = 7 \text{ TeV}$) PRL 108 (2012) 252002

$$Q = (14.84 \pm 0.74 \pm 0.28) \text{ MeV}$$



More infos at slide 38

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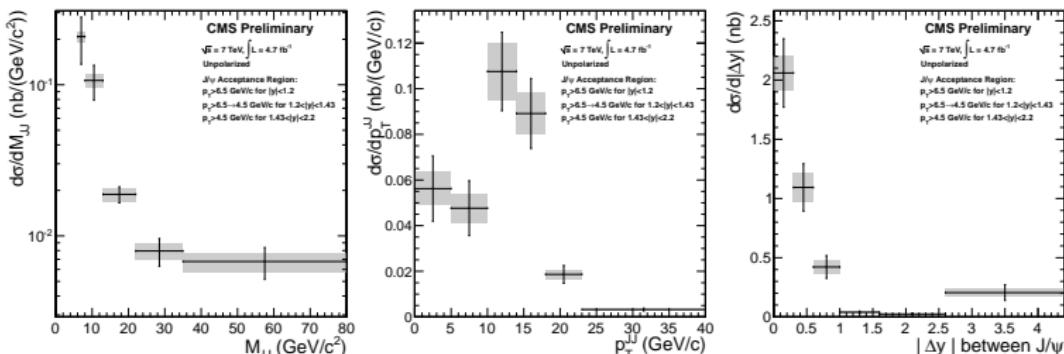
Double J/ψ production

Production of J/ψ pairs:

- double-parton scattering
- color-octet states

Cross section measured vs:

- $J/\psi J/\psi$ invariant mass
- $J/\psi J/\psi$ total p_T
- Δy



No excess in η_b mass region; DPS hint at $\Delta y > 2.6$

Total cross section ($\sqrt{s} = 7 \text{ TeV}$) CMS-PAS-BPH-11-021

$$\sigma(pp \rightarrow J/\psi J/\psi X) = (1.49 \pm 0.07 \pm 0.14) \text{ nb}$$

More infos at slide 45

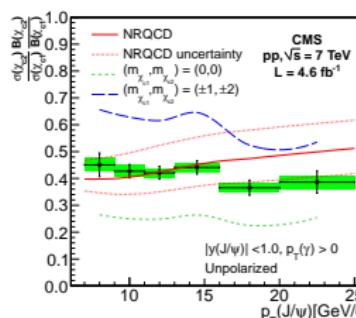
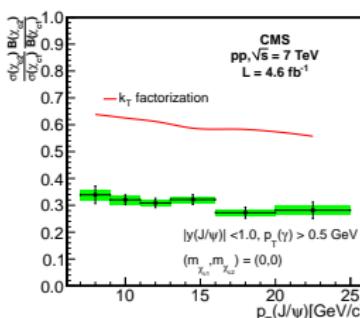
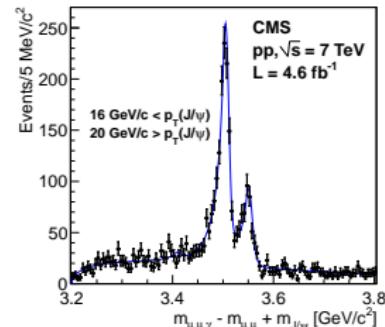
χ_{c2} vs χ_{c1} relative production

P-wave charmonia:

- feed-down contribution to J/ψ production
- relative production sensitive to singlet/octet production mechanisms
- reconstructed in the channel $\chi_c \rightarrow J/\psi\gamma$ followed by the photon conversion

$\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ($\sqrt{s} = 7\text{TeV}$) EPJ C (2012) 72:2251

Measured vs. $p_{TJ/\psi}$ for $|y_{J/\psi}| < 1.0$



- Prompt J/ψ selected by flight distance
- Different polarization scenarios assumed

- k_T factorization: predicts trend, factor 2 higher
- NRQCD: compatible

More infos at slide 46

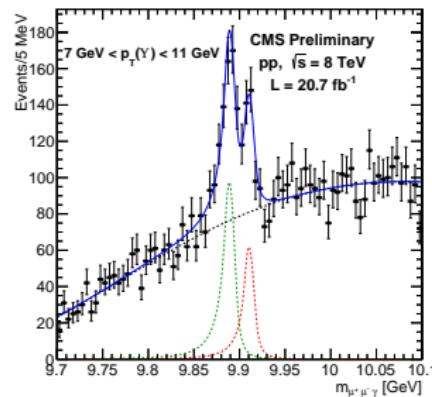
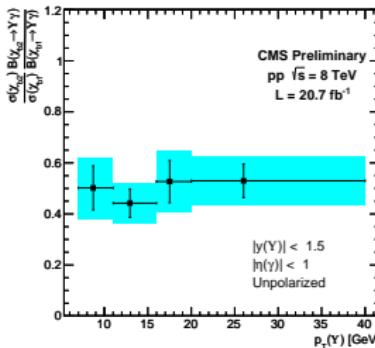
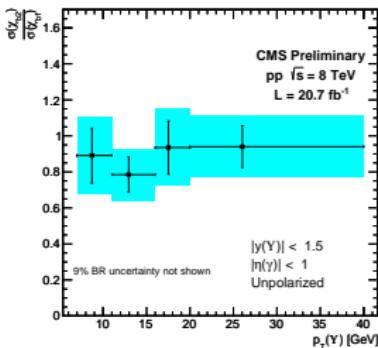


$\chi_{b2}(1P)$ vs $\chi_{b1}(1P)$ relative production

Very challenging measurement ($m_{\chi_{b2}} - m_{\chi_{b1}} = 19.4\text{MeV}$)

$\sigma(\chi_{b2})/\sigma(\chi_{b1})$ ($\sqrt{s} = 8\text{TeV}$) CMS-PAS-BPH-13-005

Same technique used for $\sigma(\chi_{c2})/\sigma(\chi_{c1})$
 $|y_{\gamma(1s)}| < 1.5$, $|\eta_\gamma| < 1.0$



No significant p_T dependence observed

Quarkonia polarization

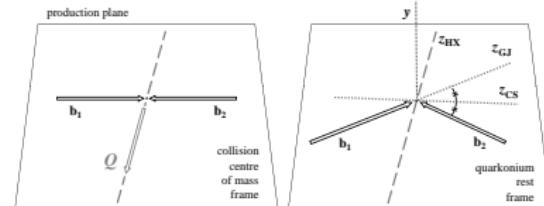
- Quarkonium production in hadron collisions not yet fully settled
- J/ψ polarization description in NRQCD:
 - purely perturbative color-singlet production
 - nonperturbative transitions from coloured quark pairs
- S-wave states predicted to be transversely polarized
- Small longitudinally polarized observed by CDF

$$W(\cos \vartheta, \varphi | \vec{\lambda}) = \frac{3}{4\pi(3+\lambda_\vartheta)} (1 + \lambda_\vartheta \cos^2 \vartheta + \lambda_\varphi \sin^2 \vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos \varphi)$$

Polarization frames: HX(helicity), CS(Collins-Soper), PX

“Invariant polarization parameter”:

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$$

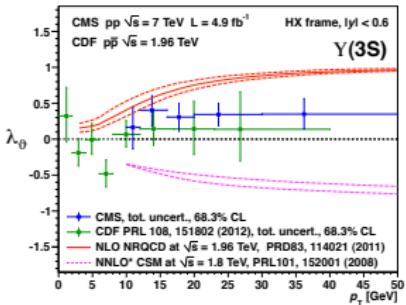
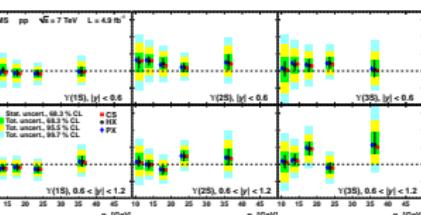
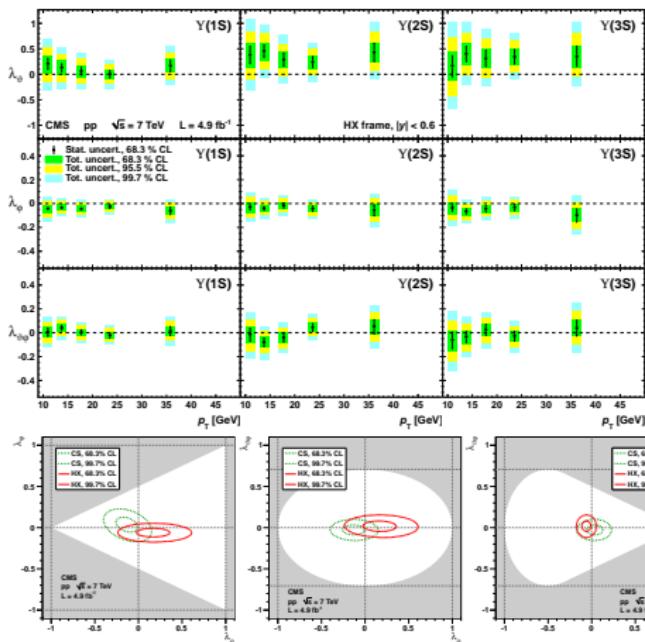


$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarization

Parameters fit($\sqrt{s} = 7\text{TeV}$)

PRL 110 (2013) 081802

Events divided in p_T and rapidity (y) bins: $|y| < 0.6$, $0.6 < |y| < 1.2$



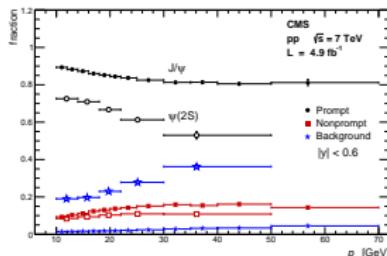
More infos at slide 47

Prompt J/ψ and $\psi(2S)$ polarization

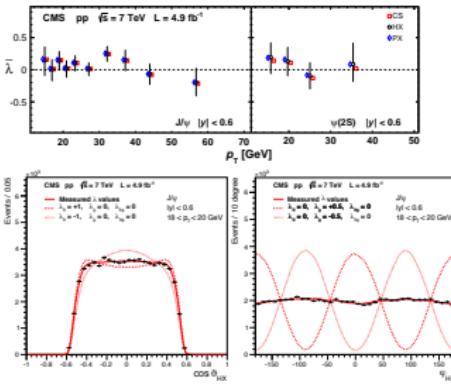
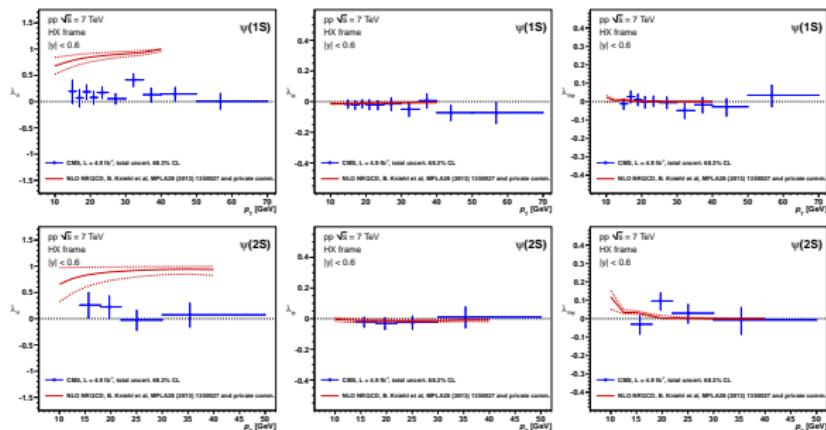
Parameters fit($\sqrt{s} = 7\text{TeV}$)

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- Analysis similar to bottomonium
- Charmonium from B decay separated by flight distance



HX frame:



More infos at slide 50

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Heavy flavour exotic states

Unexpected heavy charmonium states

- $X(3872)$ first observed in $B^+ \rightarrow J/\psi K^+ \pi^+ \pi^-$ decay
- Their nature is not well understood
- Interpreted as tetraquark or hadronic molecules
- Bottomonium partners are looked for



X(3872) production

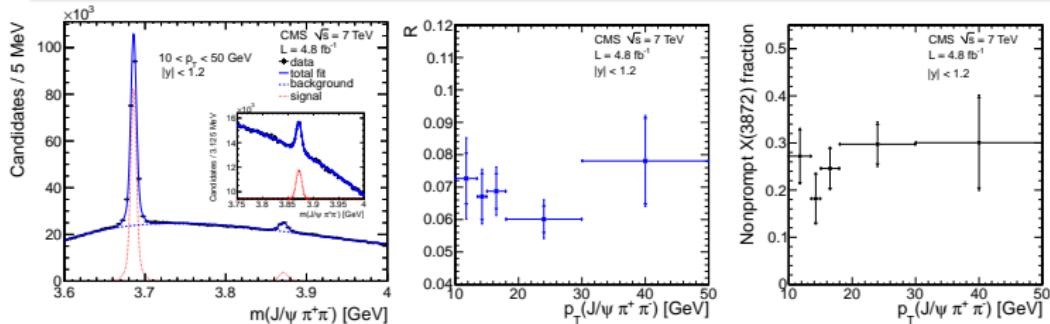
- X(3872) first exotic charmonium seen
- Reconstructed at CMS in the channel $X(3872) \rightarrow J/\psi \pi^+ \pi^-$
- Cross section measured as ratio to $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$
- Prompt-nonprompt components separated by flight distance

Mass fit ($\sqrt{s} = 7\text{TeV}$)

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Unpolarized $J^{PC} = 1^{++}$ state assumed

$$R = \frac{\sigma(pp \rightarrow X(3872) + \text{any}) \times \mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\sigma(pp \rightarrow \psi(2S) + \text{any}) \times \mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = 0.0656 \pm 0.0029 \pm 0.0065$$



More infos at slide 54



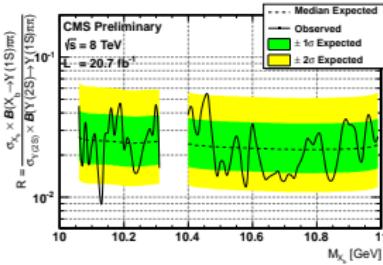
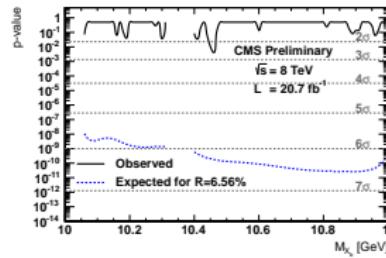
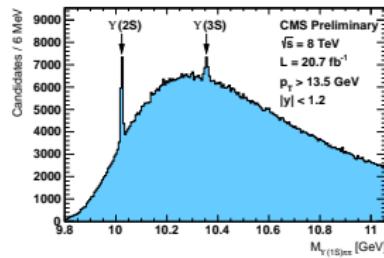
Search for $X_b \rightarrow \Upsilon(1S)\pi^+\pi^-$

- Bottomonium-state looked for in the final state $\Upsilon(1S)\pi^+\pi^-$ as a counterpart of $X(3872) \rightarrow J/\psi\pi^+\pi^-$
- $\Upsilon(1S)$ combined with 2 opposite charged tracks
- Common vertex reconstructed

Results ($\sqrt{s} = 8\text{TeV}$)

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$$\frac{\sigma(pp \rightarrow X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)} < (0.9 \div 5.4)\% @ 95\% \text{C.L.}$$



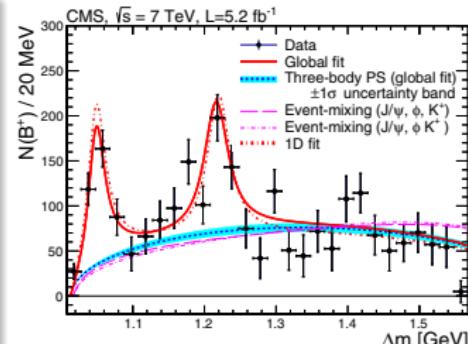
Peaks in $B^\pm \rightarrow J/\psi \phi K^\pm$

- $Y(4140)$ evidence reported by CDF in $B^\pm \rightarrow J/\psi \phi K^\pm$ decay
- J/ψ reconstructed and combined with 3 charged tracks with total charge $\sum_i q_i = \pm 1$
- Lowest-mass K^+K^- pair compatible with ϕ
- Fit $\Delta_m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ distribution

Results ($\sqrt{s} = 7\text{TeV}$)

arXiv:1309.6920

	yield	$\Delta m(\text{MeV})$
low	310 ± 70	1051.3 ± 2.4
high	418 ± 170	1217.1 ± 5.3
	$m(\text{MeV})$	$\Gamma(\text{MeV})$
low	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$
high	$4313.8 \pm 5.3 \pm 7.3$	$38^{+30}_{-15} \pm 16$



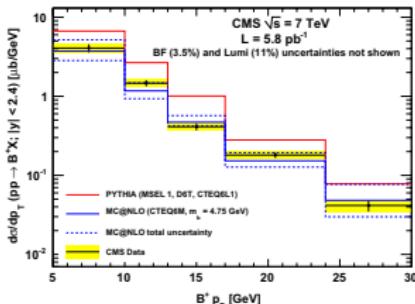
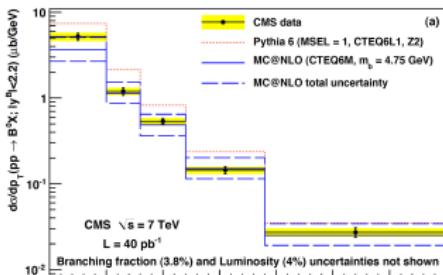
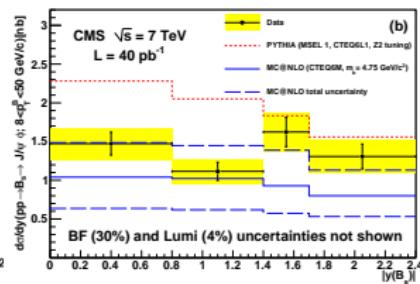
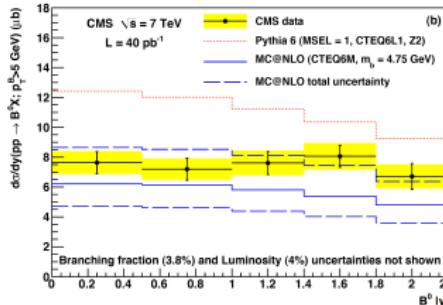
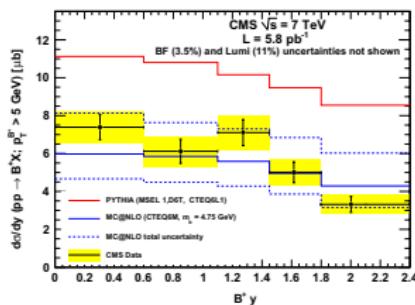
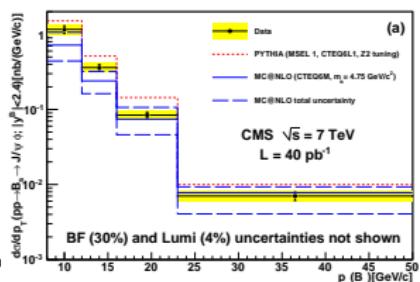
More infos at slide 55

Conclusions

- CMS has produced several results in HF physics
- B_s^0 decay to $\mu^+\mu^-$ has been observed
- Angular analysis in $B_{s,d}^0$ decays performed to probe for NP
- Baryon production, lifetime and spectroscopy give information about HF hadron properties
- Heavy quarkonia cross sections and polarizations give informations about production mechanisms
- Study of exotic heavy quarkonia is going on



B^+ , B^0 , B_s production

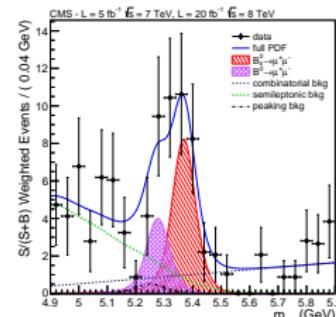
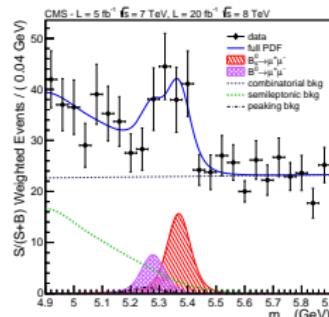
 B^+  B^0  B_s 

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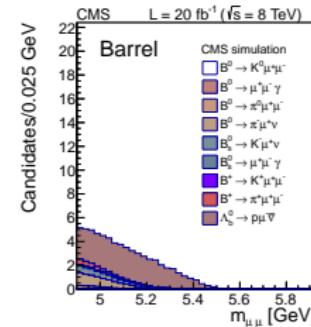
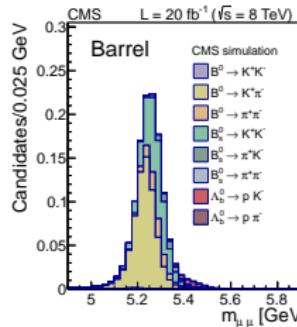
$$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+ \mu^-)$$

$$\mathcal{B}(B_{d,s}^0 \rightarrow \mu^+ \mu^-) = \frac{N_{\text{sig}}}{N_{\text{nrm}}} \frac{\epsilon_{\text{nrm}}}{\epsilon_{\text{sig}}} \frac{f_u}{f_{d,s}} \mathcal{B}(B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm)$$

Reconstructed invariant mass



Background:
peaking + non-peaking



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

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

A_S , F_S : parameters describing $K^+ \pi^-$ system S-wave contribution and interference

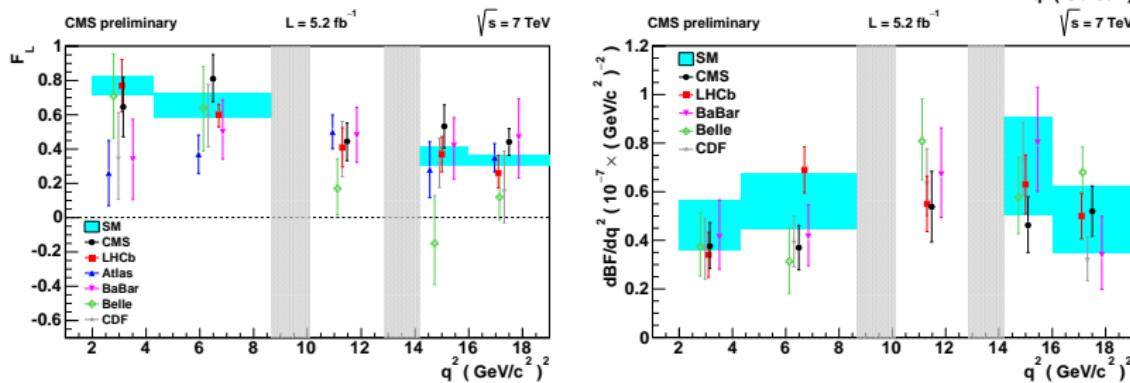
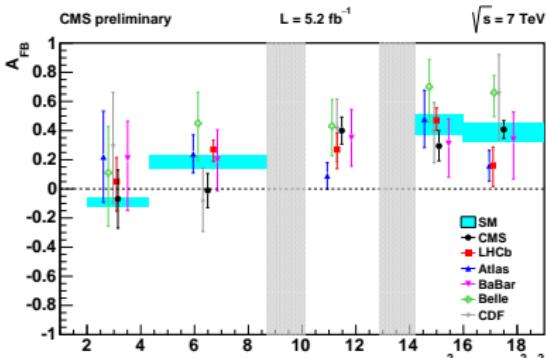
Differential B.R. determined by taking $\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi)$ as normalization:

$$\frac{d\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{dq^2} = \frac{Y_S \epsilon_N}{Y_N \epsilon_S} \frac{d\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi)}{dq^2}$$



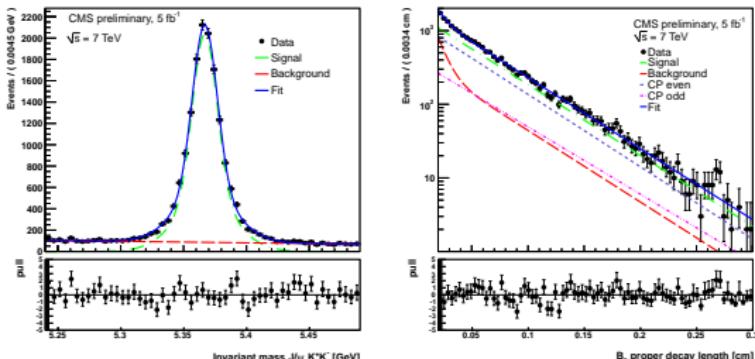
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$B^0 \rightarrow K^{*0} \mu^+ \mu^-$, $K^{*0} \rightarrow K^+ \pi^-$ angular analysis

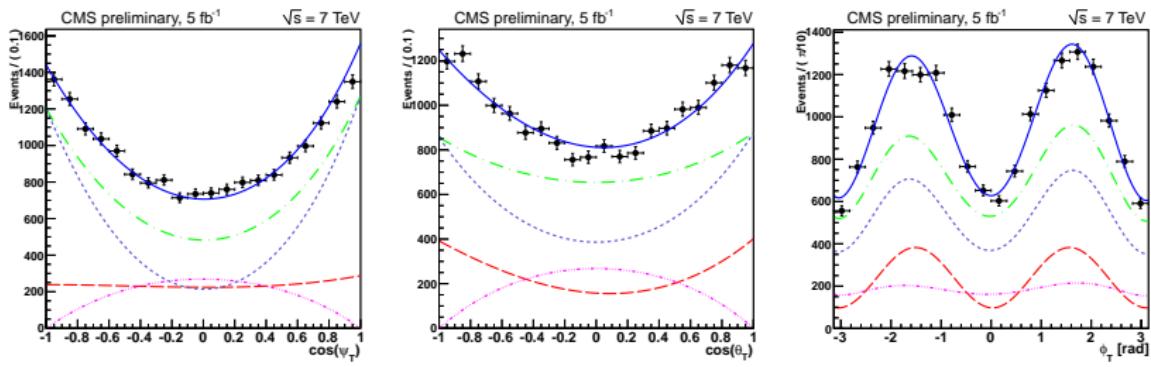
 Comparison with
other experiments

[Back to main slide 10](#)


B_s^0 lifetime difference in $B_s^0 \rightarrow J/\psi\phi$

Reconstructed invariant mass and decay length



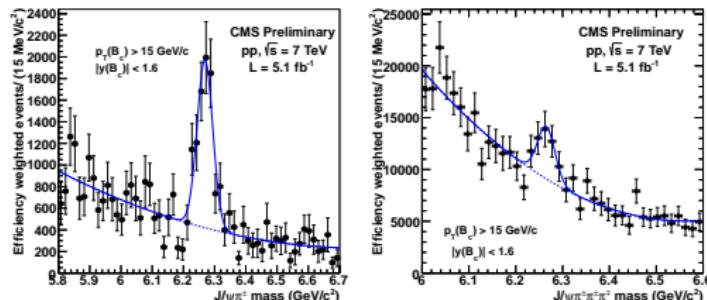
Decay angles:



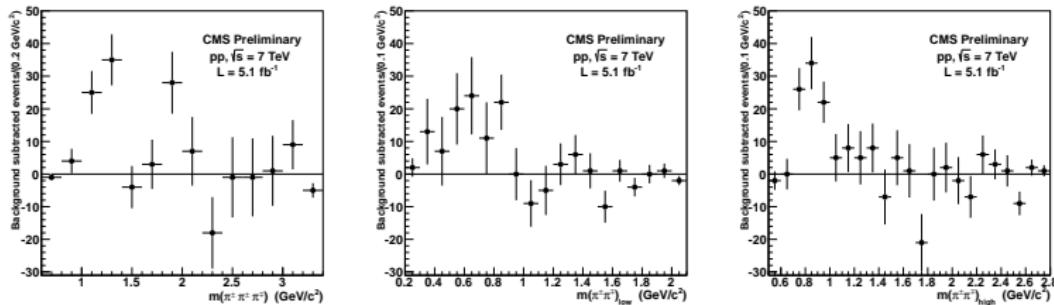
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$B_c^\pm \rightarrow J/\psi \pi^\pm (\pi^+ \pi^-)$: production and decay

Efficiency corrected yield
 $\tau_{B_c} = 0.452 \pm 0.032\text{ps}$



$\pi^\pm \pi^+ \pi^- (a_1(1260)?), \pi^+ \pi^- (\rho_0(770)?)$ mass projections

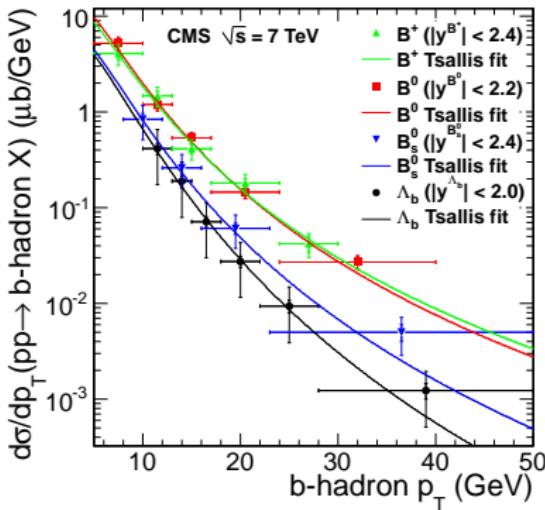


Events simulated with BCVEGPY interfaced with PYTHIA

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Λ_b production

$$\text{Tsallis function: } \frac{1}{N} \frac{dN}{dp_T} = C_{p_T} \left[1 + \frac{\sqrt{p_T^2 + m^2} - m}{nT} \right]^{-n}$$



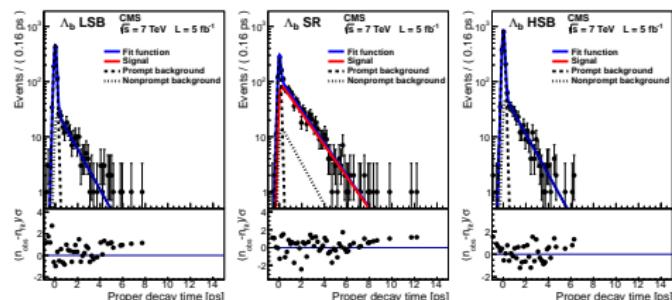
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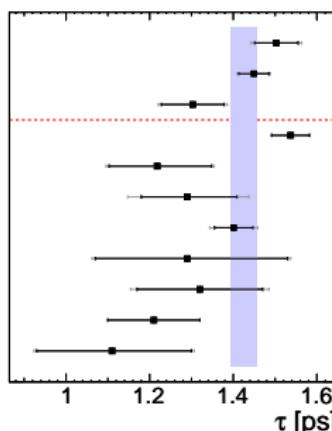
Λ_b^0 lifetime

Comparison with other experiments

Sidebands fits:



Λ_b lifetime



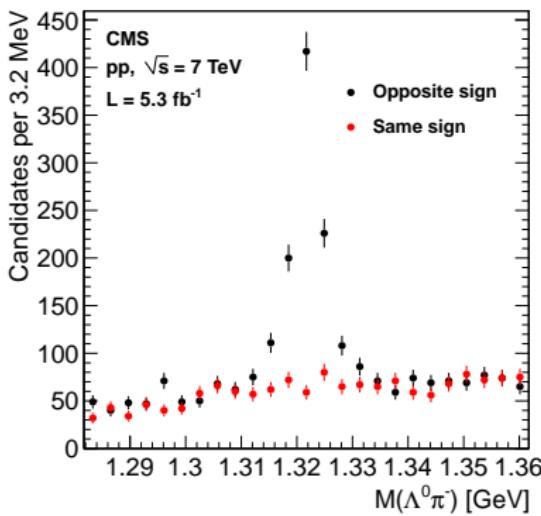
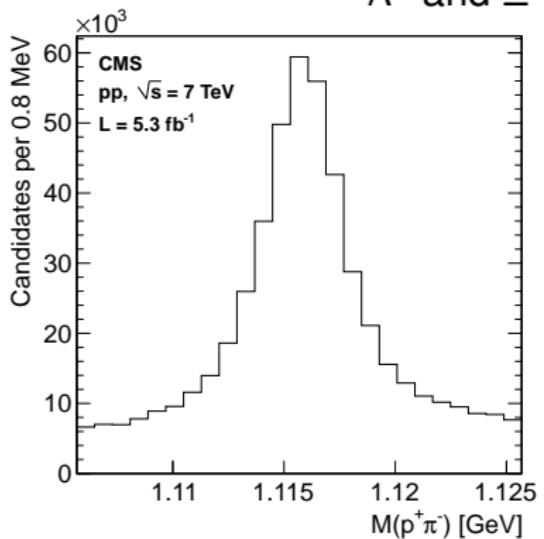
CMS. (2011) $J/\psi \Lambda$
 ATLAS (2011) $J/\psi \Lambda$
 D0 (02-11) $J/\psi \Lambda$
 CDF2 (02-09) $J/\psi \Lambda$
 D0 (02-06) $J/\psi \Lambda$
 D0 (02-06) $\Lambda_c^* \mu$
 CDF2 (02-06) $\Lambda_c^* \pi$
 OPAL (90-95) $\Lambda_c^* l, \Lambda' l$
 CDF1 (91-95) $\Lambda_c^* l$
 ALEPH (91-95) Λl
 DELPHI (91-94) $\Lambda_c^* l$
errors in black: statistical only
 errors in grey: syst. added in quadrature
 band: current best value (PDG)
 ----- values below used for best value
 J. Beringer et al. (Particle Data Group)
 Phys. Rev. D86, 010001 (2012)

	N_{sig}	$m(\text{MeV})$	$\tau(\text{ps})$
Λ_b^0	1013 ± 40	5619.7 ± 0.5	1.503 ± 0.052
B^0	6772 ± 87	5278.9 ± 0.2	1.526 ± 0.019

$$\mathcal{L} = \prod_i \left[N_{\text{sig}} \cdot G_2(m_i; m_{\text{sig}}, \sigma_{m1}, \sigma_{m2}, f) \cdot e^{-t/\tau_{\text{sig}}} \otimes G(t_i; \mu, S \cdot \sigma_{t,i}) \right. \\ \left. + N_{\text{prompt}} \cdot P(m_i; a) \cdot G(t_i; \mu, S \cdot \sigma_{t,i}) \right. \\ \left. + N_{\text{nonprompt}} \cdot P(m_i; a) \cdot e^{-t/\tau_{\text{sig}}} \otimes G(t_i; \mu, S \cdot \sigma_{t,i}) \right]$$



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Ξ_b^{*0} Λ^0 and Ξ^- masses:

$$\Xi_b^{*0} \text{ width: } \Gamma_{\Xi_b^{*0}} = 2.1 \pm 1.7 (\text{stat})$$



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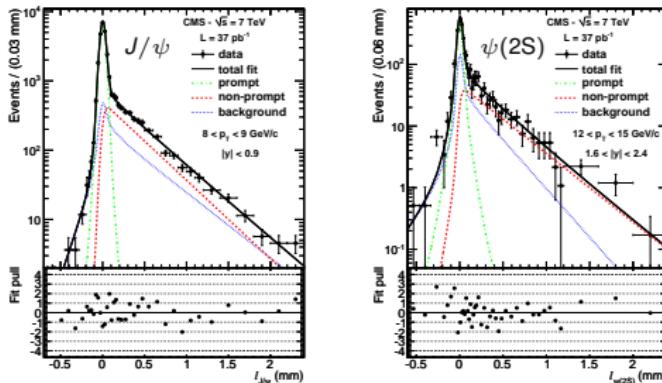
J/ψ , $\psi(2S)$ production

Charmonium sources:

- prompt-direct
- prompt-indirect
- non-prompt

prompt: NRQCD

non-prompt: FONLL



- Simultaneous fit to invariant mass and flight distance in p_T, y bins
- Acceptance computed in unpolarized scenario

muon acceptance

$|\eta_\mu| < 1.2 : p_{T\mu} > 4.0 \text{ GeV}$

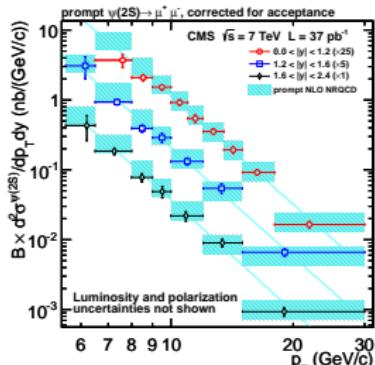
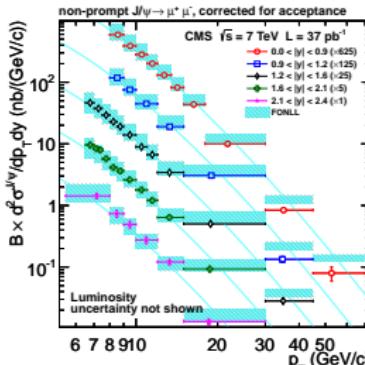
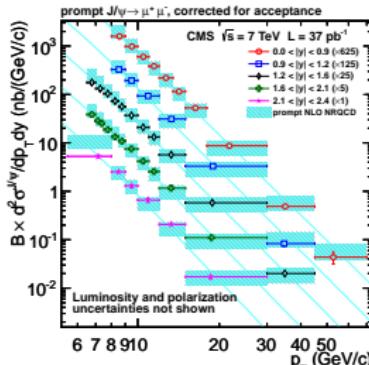
$1.2 < |\eta_\mu| < 2.4 : p_{T\mu} > 3.3 \text{ GeV}$

J/ψ , $\psi(2S)$ cross section
integrated over $|y_{\psi(nS)}| < 2.4$
 $5.5 \div 8.0 < p_{T\psi(nS)} < 30 \div 70 \text{ GeV}$



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J/ψ , $\psi(2S)$ acceptance-corrected cross sections

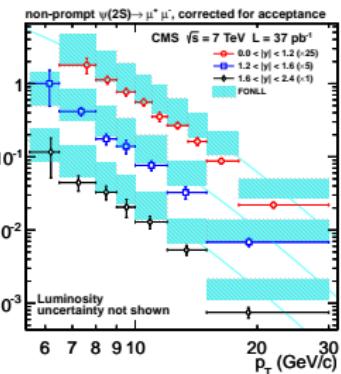


$$\sigma(pp \rightarrow \text{prompt } J/\psi X) \times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = (54.5 \pm 0.3 \pm 2.3 \pm 2.2) \text{ nb}$$

$$\sigma(pp \rightarrow bX \rightarrow J/\psi X) \times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = (20.2 \pm 0.2 \pm 0.8 \pm 0.8) \text{ nb}$$

$$\sigma(pp \rightarrow \text{prompt } \psi(2S) X) \times \mathcal{B}(\psi(2S) \rightarrow \mu^+ \mu^-) = (3.53 \pm 0.26 \pm 0.32 \pm 0.14) \text{ nb}$$

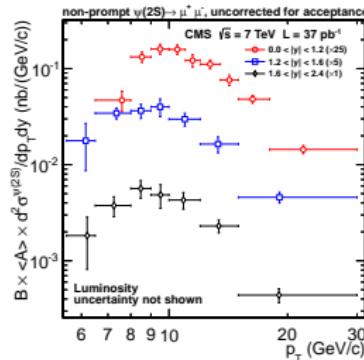
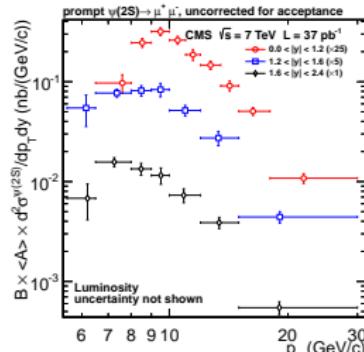
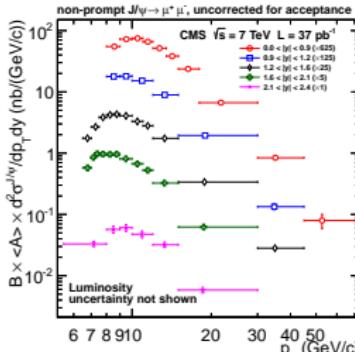
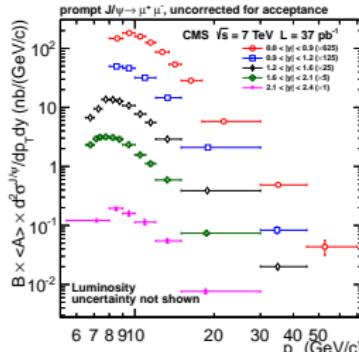
$$\sigma(pp \rightarrow bX \rightarrow \psi(2S) X) \times \mathcal{B}(\psi(2S) \rightarrow \mu^+ \mu^-) = (1.47 \pm 0.12 \pm 0.13 \pm 0.06) \text{ nb}$$



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J/ψ , $\psi(2S)$ fiducial cross sections



$$\sigma(pp \rightarrow \text{prompt } J/\psi X) \times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = (9.83 \pm 0.03 \pm 0.38 \pm 0.39) \text{ nb}$$

$$\sigma(pp \rightarrow bX \rightarrow J/\psi X) \times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) = (4.67 \pm 0.02 \pm 0.17 \pm 0.19) \text{ nb}$$

$$\sigma(pp \rightarrow \text{prompt } \psi(2S) X) \times \mathcal{B}(\psi(2S) \rightarrow \mu^+ \mu^-) = (0.410 \pm 0.009 \pm 0.023 \pm 0.016) \text{ nb}$$

$$\sigma(pp \rightarrow bX \rightarrow \psi(2S) X) \times \mathcal{B}(\psi(2S) \rightarrow \mu^+ \mu^-) = (0.235 \pm 0.006 \pm 0.013 \pm 0.009) \text{ nb}$$



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

- Similar analysis as J/ψ , $\psi(2S)$
- Simultaneous fit for $n = 1, 2, 3$

muon acceptance

$|\eta_\mu| < 0.8 : p_{T\mu} > 3.75 \text{ GeV}$

$0.8 < |\eta_\mu| < 1.6 : p_{T\mu} > 3.5 \text{ GeV}$

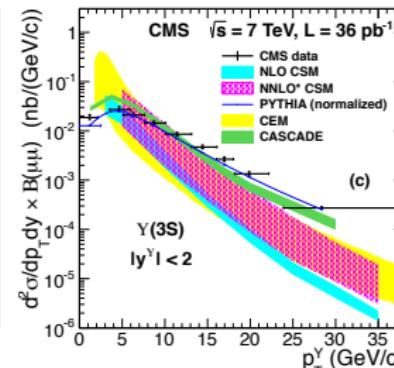
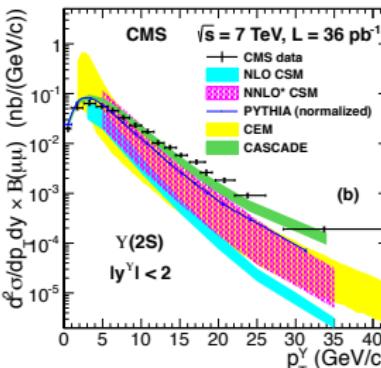
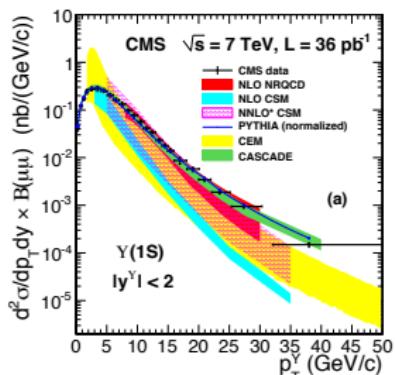
$1.6 < |\eta_\mu| < 2.4 : p_{T\mu} > 3.0 \text{ GeV}$

$\Upsilon(nS)$ cross section integrated over $|y_\Upsilon| < 2.4$, $p_{T\Upsilon} < 50 \text{ GeV}$

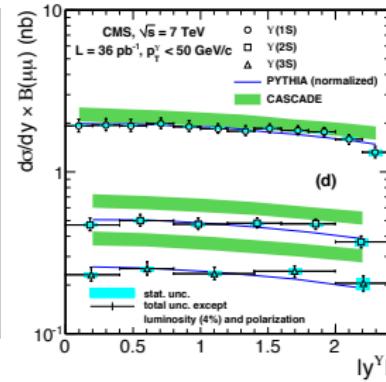


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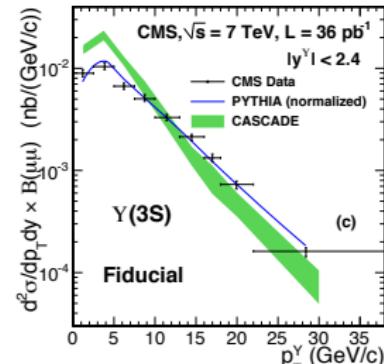
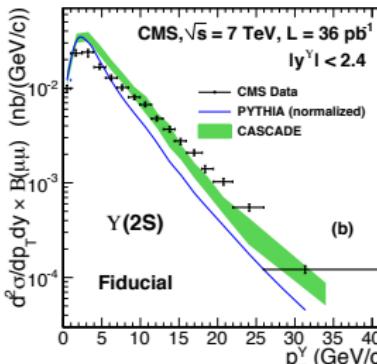
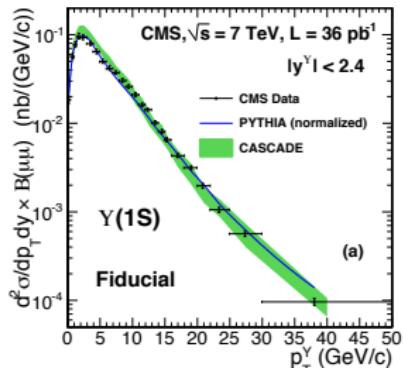
$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ acceptance-corrected cross sections



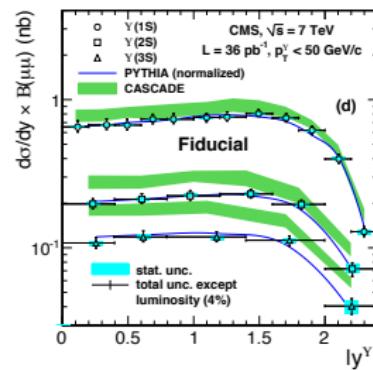
$$\begin{aligned} \sigma(pp \rightarrow \Upsilon(1S)X) \times \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-) &= \\ (8.55 \pm 0.05^{+0.56}_{-0.50} \pm 0.34) \text{ nb} \\ \sigma(pp \rightarrow \Upsilon(2S)X) \times \mathcal{B}(\Upsilon(2S) \rightarrow \mu^+\mu^-) &= \\ (2.21 \pm 0.03^{+0.16}_{-0.14} \pm 0.09) \text{ nb} \\ \sigma(pp \rightarrow \Upsilon(3S)X) \times \mathcal{B}(\Upsilon(3S) \rightarrow \mu^+\mu^-) &= \\ (1.11 \pm 0.02^{+0.10}_{-0.08} \pm 0.04) \text{ nb} \end{aligned}$$


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$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ fiducial cross sections



$$\begin{aligned} \sigma(pp \rightarrow \Upsilon(1S)X) \times \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+ \mu^-) &= (3.06 \pm 0.02^{+0.20}_{-0.18} \pm 0.12) \text{ nb} \\ \sigma(pp \rightarrow \Upsilon(2S)X) \times \mathcal{B}(\Upsilon(2S) \rightarrow \mu^+ \mu^-) &= (0.910 \pm 0.011^{+0.055}_{-0.046} \pm 0.036) \text{ nb} \\ \sigma(pp \rightarrow \Upsilon(3S)X) \times \mathcal{B}(\Upsilon(3S) \rightarrow \mu^+ \mu^-) &= (0.490 \pm 0.010^{+0.029}_{-0.029} \pm 0.020) \text{ nb} \end{aligned}$$

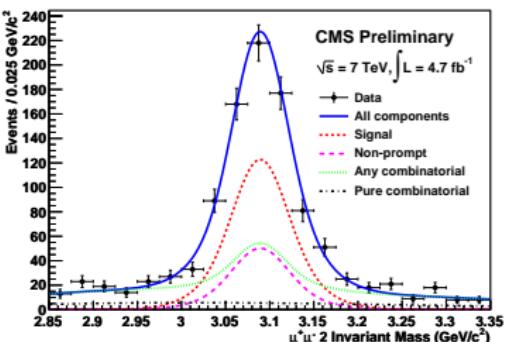
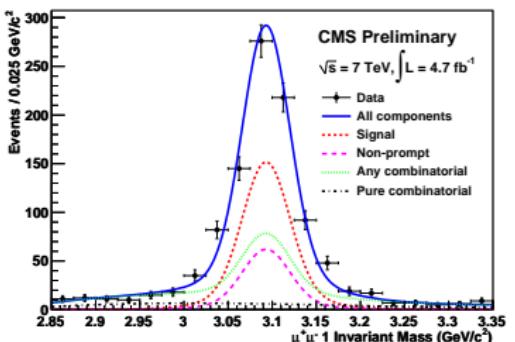


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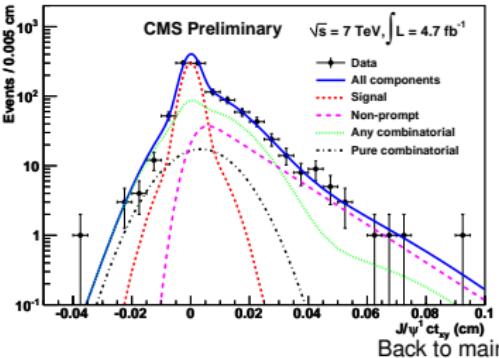


Double J/ψ production

J/ψ invariant masses



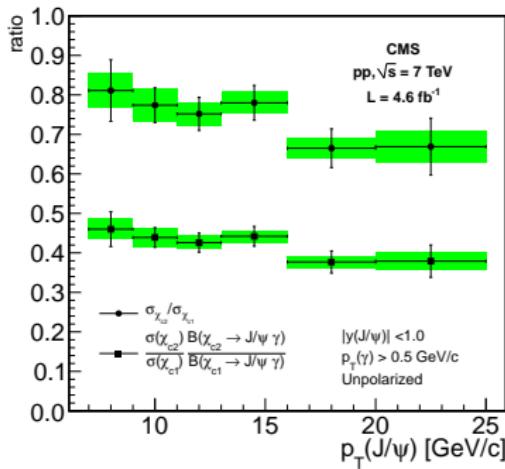
J/ψ decay length



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χ_{c2} vs χ_{c1} relative production

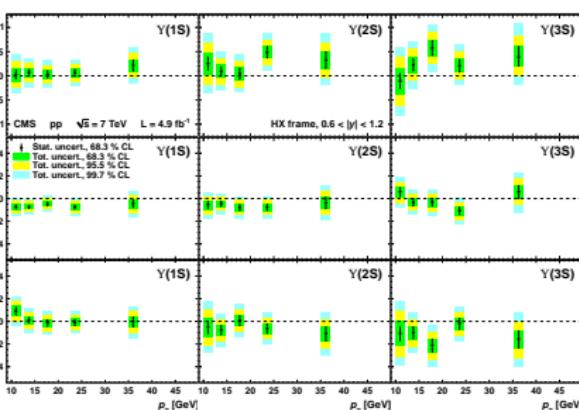
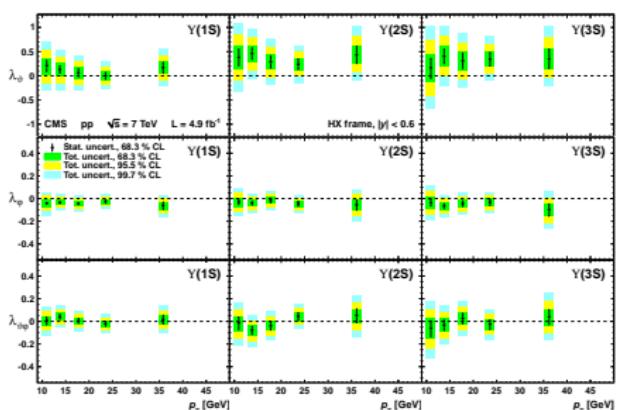
“Pure” cross-sections (divided by B.R.),
assuming unpolarized production



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

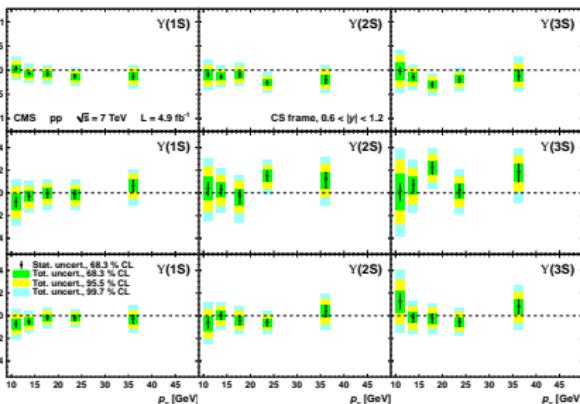
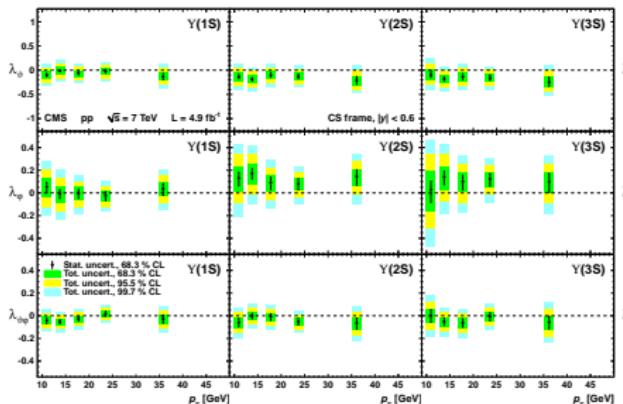
HX frame



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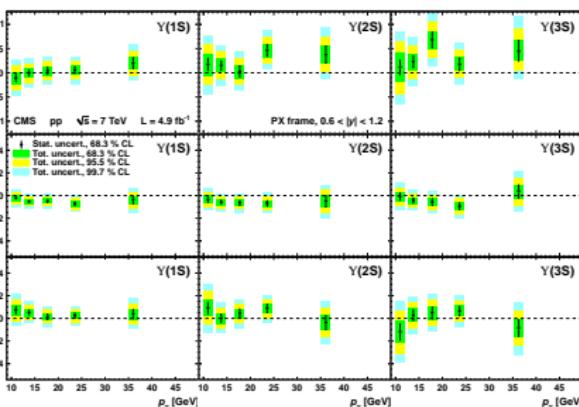
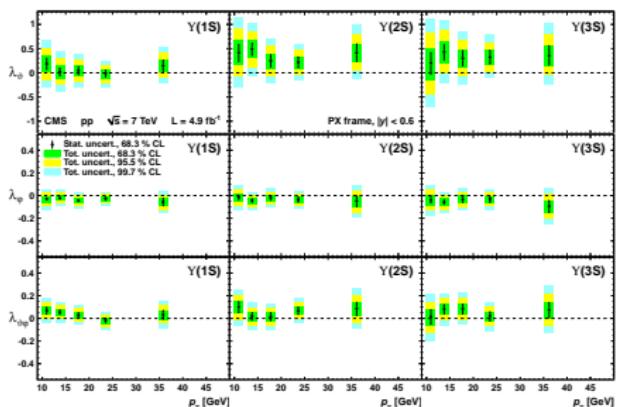
$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarization

CS frame



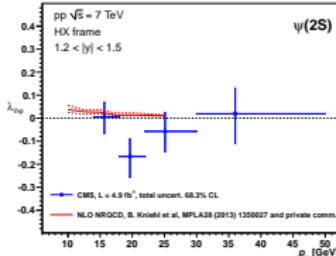
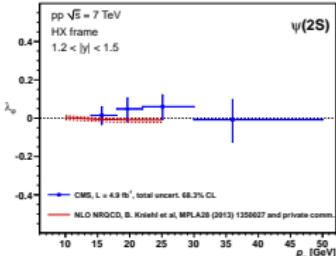
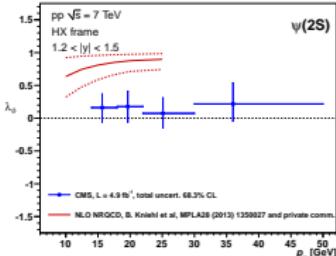
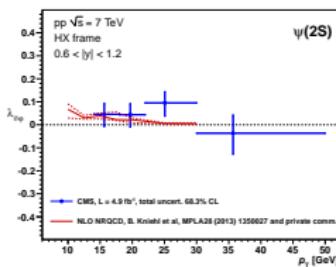
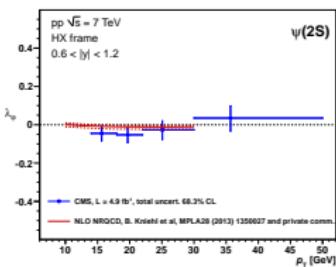
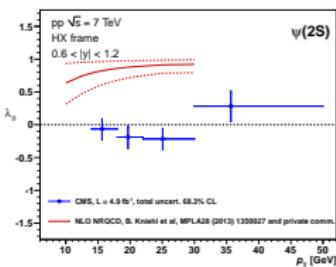
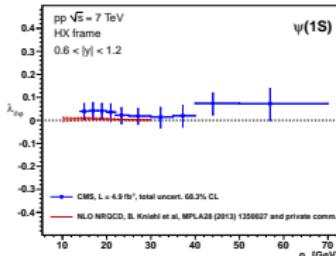
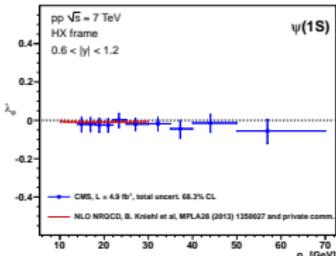
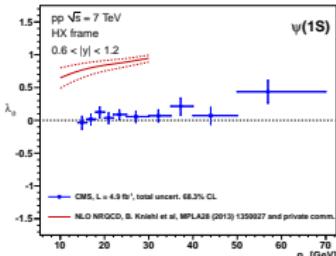
$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ polarization

PX frame



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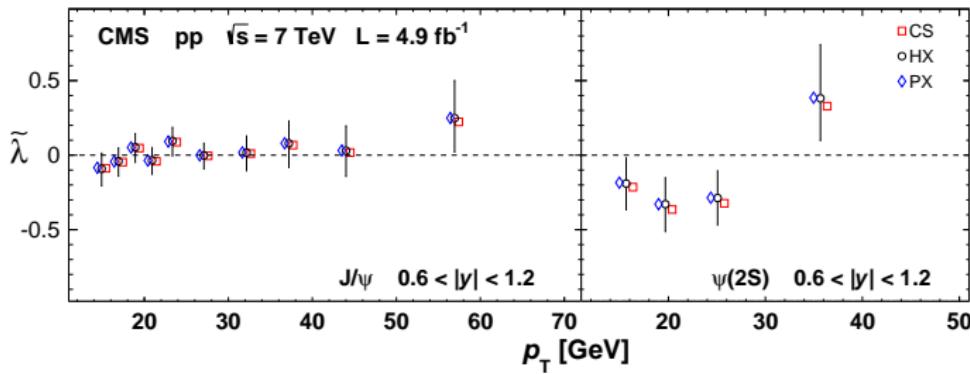
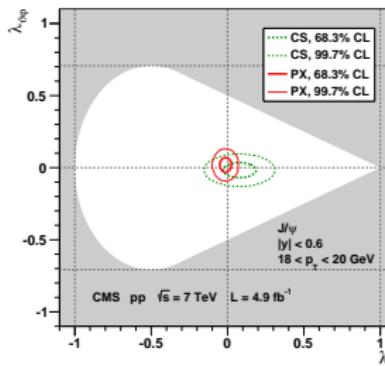
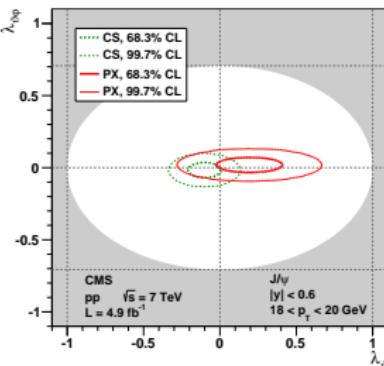
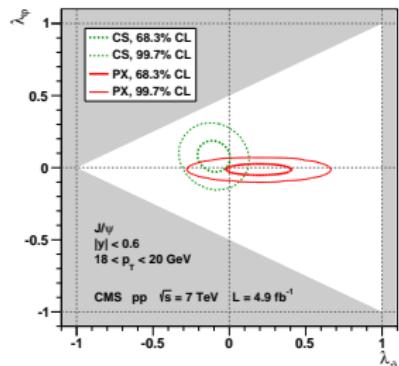
Prompt J/ψ and $\psi(2S)$ polarization



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Prompt J/ψ and $\psi(2S)$ polarization



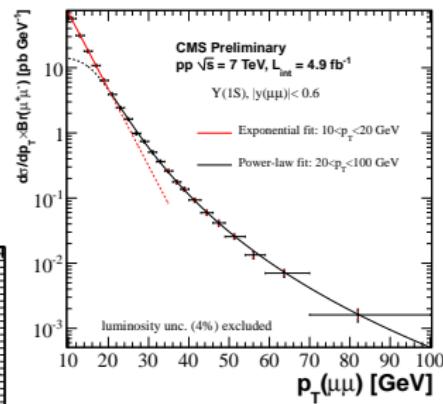
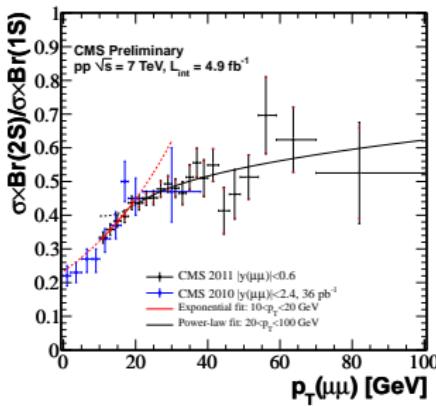
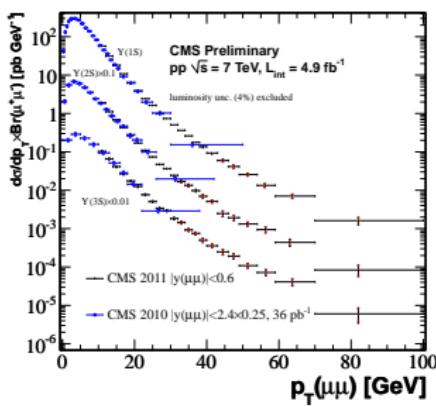
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$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ production

Bottomonium cross-sections:
acceptance computed according to measured polarization

Cross section fit ($\sqrt{s} = 7\text{TeV}$) CMS-PAS-BPH-12-006

- exponential for $10 < p_T < 20\text{GeV}$
- $\frac{A}{C + \left(\frac{p_T}{p_0}\right)^\alpha}$ for $p_T > 20\text{GeV}$



$\Upsilon(nS)$ cross section integrated over $|y_\Upsilon| < 0.6$



More infos at slide 53

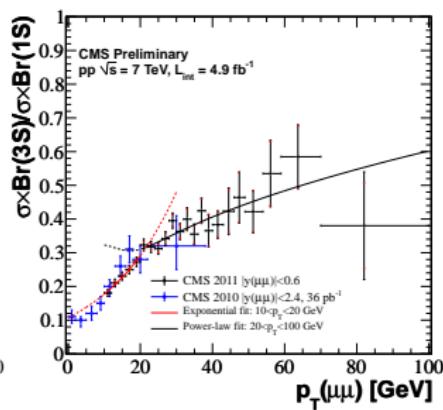
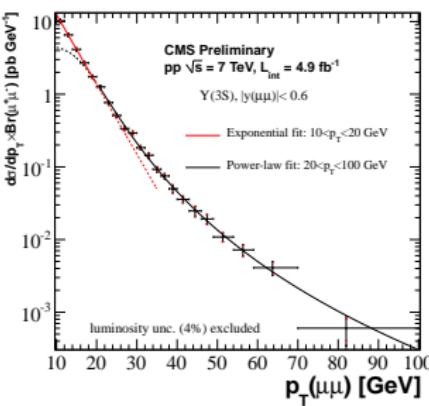
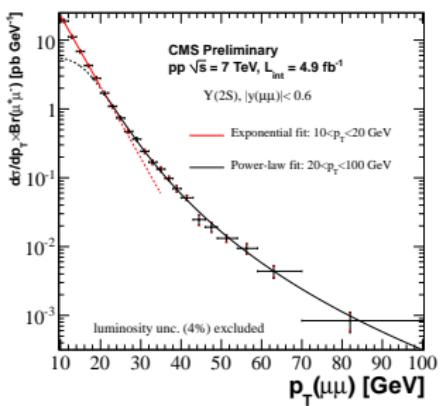
$\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ production

$|\eta_\mu| < 1.2 : p_{T\mu} > 4.5 \text{ GeV}$

$1.2 < |\eta_\mu| < 1.4 : p_{T\mu} > 3.5 \text{ GeV}$

$1.4 < |\eta_\mu| < 1.6 : p_{T\mu} > 3 \text{ GeV}$

$\Upsilon(nS)$ cross section integrated over $|y_\Upsilon| < 0.6$



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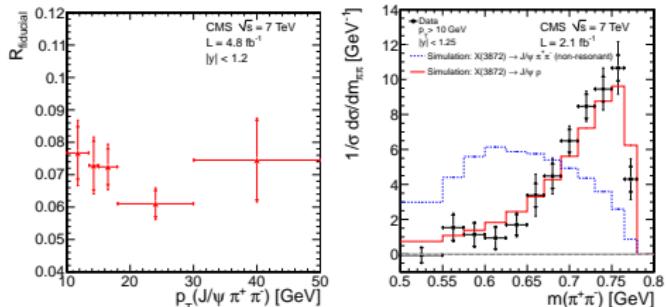
$X(3872)$ fiducial cross section

$$\begin{aligned} |\eta_\mu| < 1.2 : p_{T\mu} > 4.0 \text{ GeV} \\ 1.2 < |\eta_\mu| < 2.4 : p_{T\mu} > 3.3 \text{ GeV} \end{aligned}$$

Cross section integrated over

$$\begin{aligned} |y_{J/\psi}| &< 1.25 \\ p_{TJ/\psi} &> 7 \div 10 \text{ GeV} \\ |y_X| &< 1.2 \\ 10.0 \div 13.5 &< p_{TX} < 50.0 \text{ GeV} \end{aligned}$$

$$R = \frac{\sigma(pp \rightarrow X(3872) + \text{any}) \times \mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\sigma(pp \rightarrow X(3872) + \text{any}) \times \mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = 0.0694 \pm 0.0029 \pm 0.0036$$



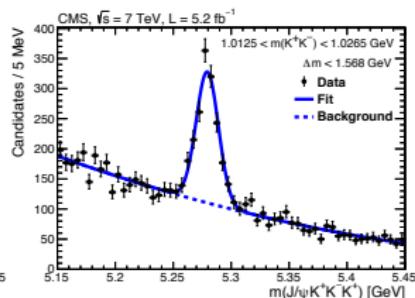
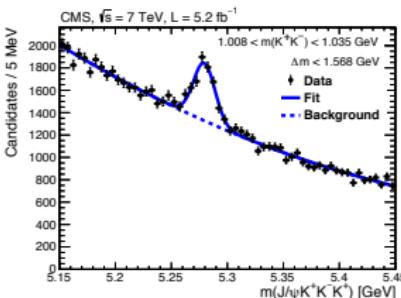
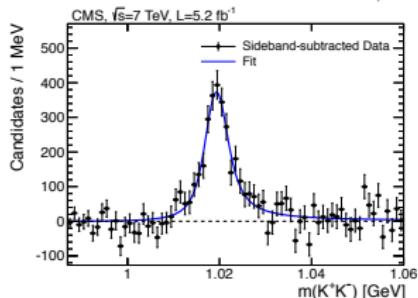
Dipion mass compatible
with an intermediate ρ^0



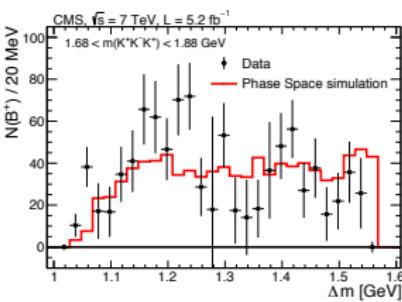
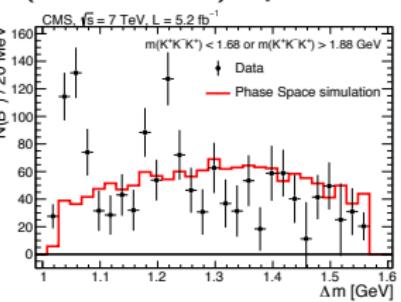
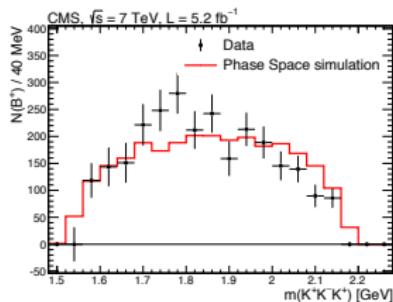
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Peaks in $B^\pm \rightarrow J/\psi \phi K^\pm$

m_ϕ , m_{B^+} (loose and tight cuts):



$m(K^+K^-K^+)$ spectrum:



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