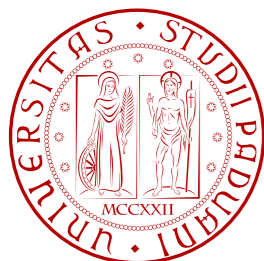


XXVII Rencontres de Physique de la Vallée d'Aoste

# Heavy-flavor production and spectroscopy at CMS

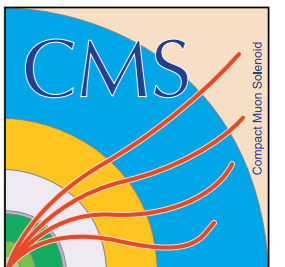
Nicola Pozzobon

on behalf of the CMS Collaboration



Sezione di  
Padova

Università degli Studi di Padova  
INFN - Sezione di Padova



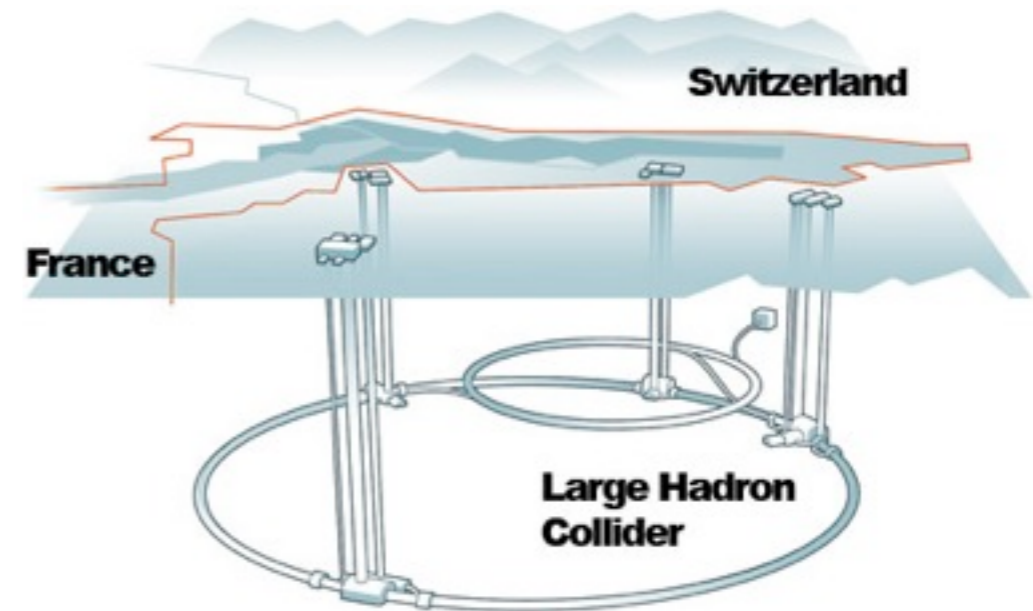
- measurements of heavy-flavor (HF) production provide a testing ground for QCD calculations in a new energy regime
- NLO contributions dominate at LHC, large uncertainties remain due to factorization and renormalization scales
- $b$ -flavor identification is crucial in many searches
  - SM backgrounds must be understood
  - measurements of  $b$ -hadron properties provide important tests of the SM: any deviation would be indirect indication of New Physics
- this contribution will report on the most recent results in the field of HF measurements with the CMS experiment
  - measurement of  $X(3872)$  production cross section
  - measurement of  $\Lambda_b$  lifetime
  - observation of  $B_c^+ \rightarrow J/\psi \pi^+$  and  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$
  - observation of structures in  $B^+ \rightarrow J/\psi \phi K^+$
  - observation of a new  $\Xi_b$  baryon

# The Large Hadron Collider

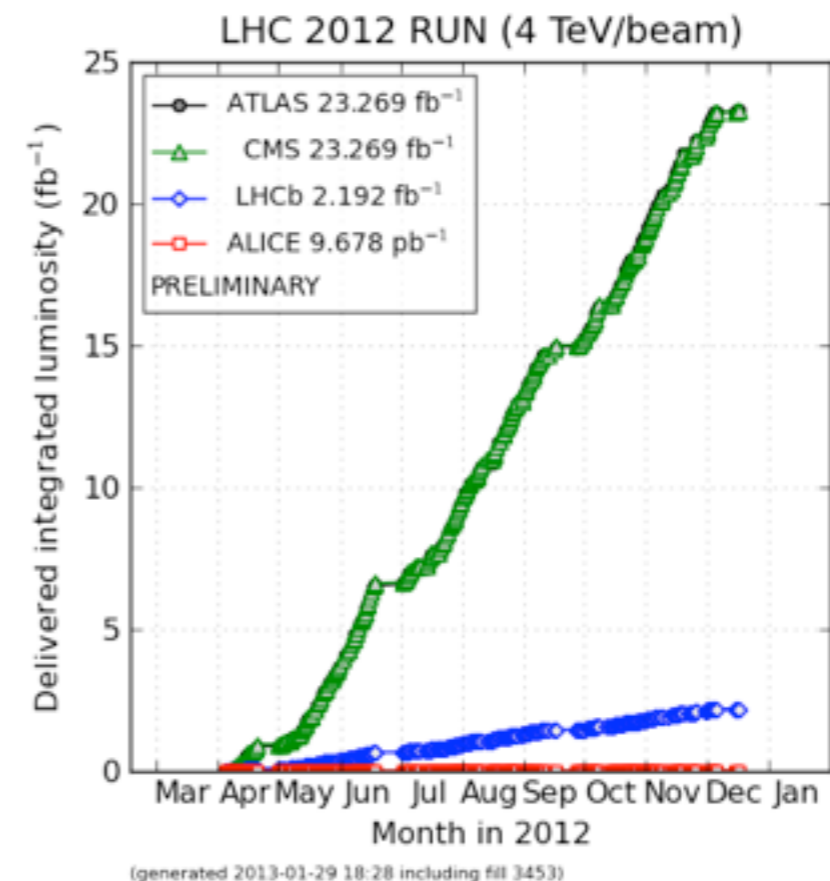
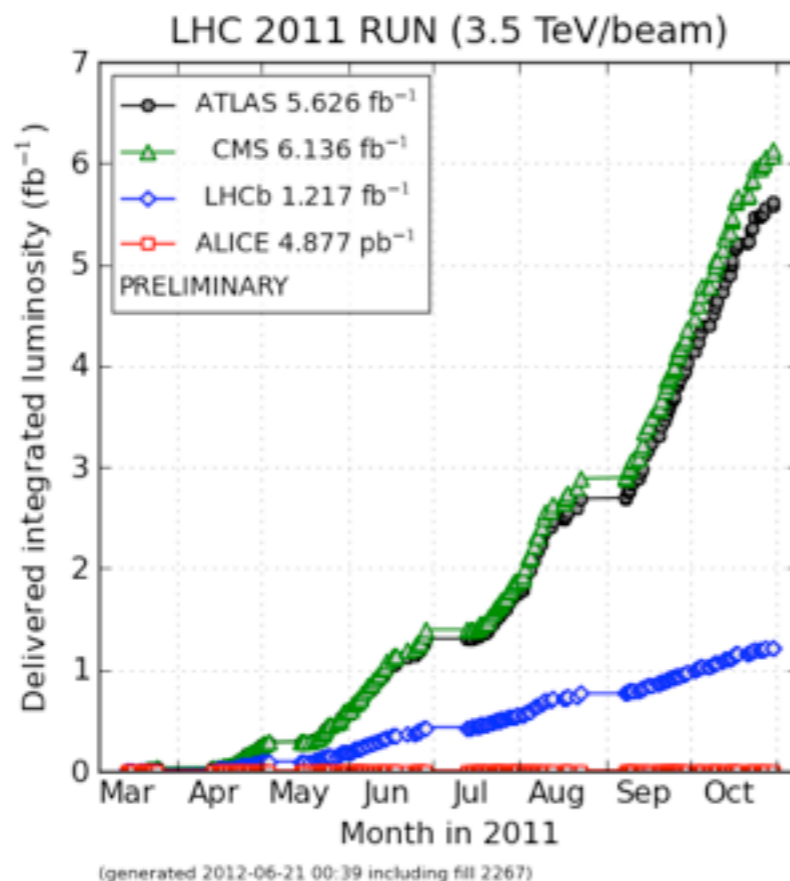
## proton-proton collisions

- ▶ 2009:  $\sqrt{s} = 0.9, 2.76$  TeV
- ▶ 2010, 2011:  $\sqrt{s} = 7$  TeV
- ▶ 2012:  $\sqrt{s} = 8$  TeV

## dedicated Pb-Pb and p-Pb runs



<http://lpc.web.cern.ch/lpc/>



# The CMS Experiment

1. Pixel Detector
2. Silicon Strip Tracker
3. Electromagnetic Calorimeters  $|\eta| < 3$
4. Hadronic Calorimeters  $|\eta| < 5$
5. 3.8 T Superconducting Solenoid
6. Muon Detectors  $|\eta| < 2.4$ 
  - Muon + Track  
 $p_T$  resolution  $< 1.5\%$   
( $p_T < 100$  GeV)

**excellent performance  
in data taking and  
reconstruction**

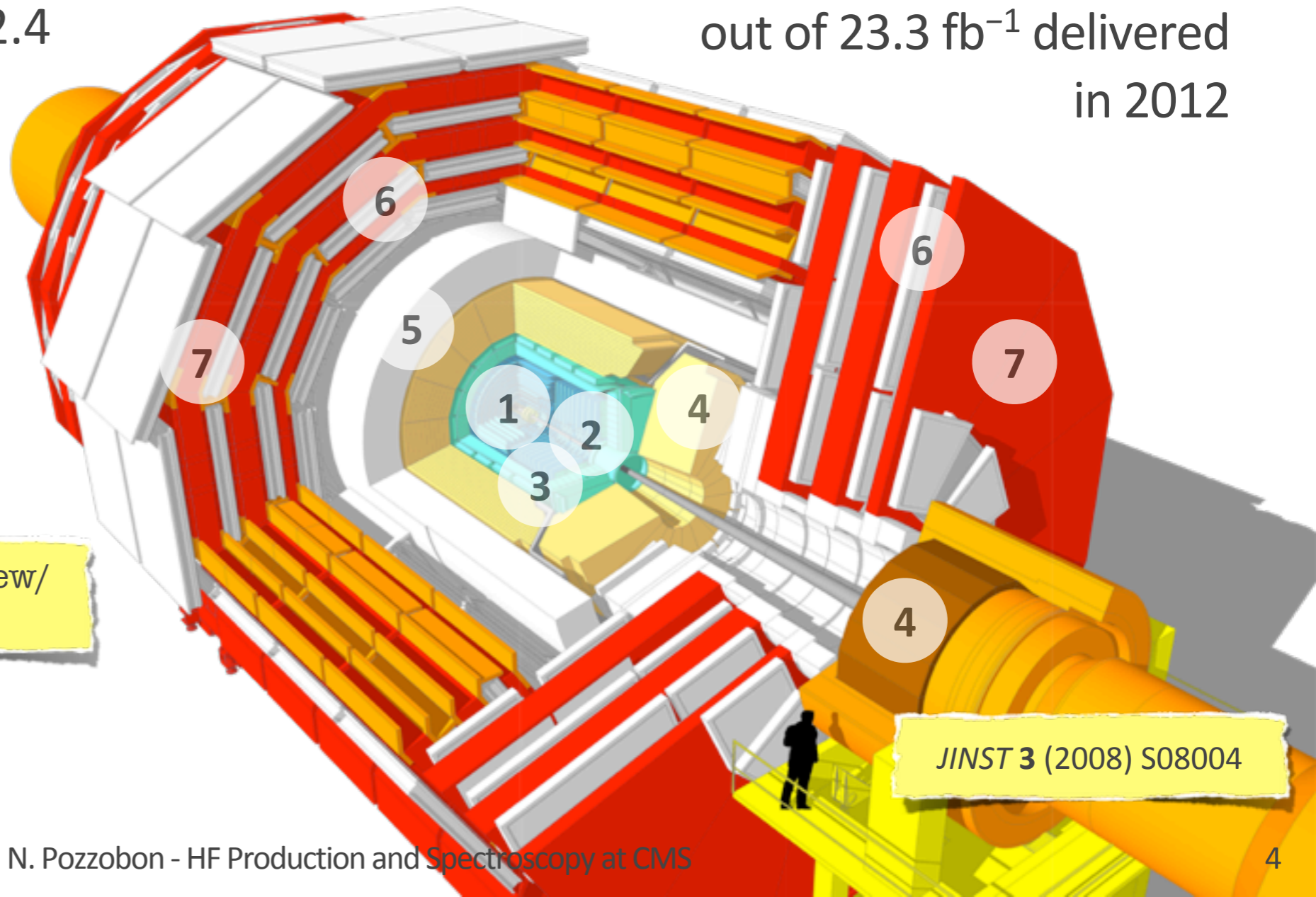
recorded  $21.79 \text{ fb}^{-1}$   
out of  $23.3 \text{ fb}^{-1}$  delivered  
in 2012

submitted to *JINST*  
arXiv:1206.4071

CMS-PAS-TRK-10-005

[https://twiki.cern.ch/twiki/bin/view/  
CMSPublic/DPGResultsTRK](https://twiki.cern.ch/twiki/bin/view/CMSPublic/DPGResultsTRK)

## 7. Return Yoke



*JINST* 3 (2008) S08004

# $X(3872)$ production cross section

## introduction and previous studies

- ▶ first observation in 2003 at Belle
- ▶ the first spectroscopy puzzle: unexpected charmonium candidate, picture still unclear about its nature
- ▶ observed in several decay channels also at BaBar, CDF, D0 and LHC experiments
- ▶ angular analysis favors  $J^{PC} = 1^{++}$  or  $2^{-+}$
- ▶ produced promptly and in  $B$ -decays, quantitative predictions in NRQCD *in the hypothesis that  $X(3872)$  is standard charmonium*

## data sample

- ▶ 4.8 fb<sup>-1</sup> of 2011 pp collision data at  $\sqrt{s} = 7$  TeV
- ▶ prompt  $J/\psi$  dimuon triggers

## event selection

- ▶  $X(3872) \rightarrow J/\psi \pi^+ \pi^-$
- ▶  $J/\psi \rightarrow \mu^+ \mu^-$
- ▶ opposite-sign muon-pair with central rapidity, consistent with  $J/\psi$  mass
- ▶ track selection: stringent quality criteria
- ▶  $p_T(J/\psi \pi^+ \pi^-)$  in (10, 50) GeV range,  $|\eta(J/\psi \pi^+ \pi^-)| < 1.2$
- ▶ 4-track vertex refit with common vertex and dimuon mass constraints

submitted to *JHEP*  
arXiv:1302.3968

# $X(3872)$ production cross section

## analysis

- ▶ signal yield from unbinned maximum-likelihood fit for each resonance (Gaussian signal + polynomial background) in 5 different  $p_T(J/\psi \pi^+ \pi^-)$  bins
- ▶ cross section  $\times$  BR measured by comparison with analogous  $\psi(2S)$  decay:  $R = N_{X(3872)} A_{\psi(2S)} \epsilon_{\psi(2S)} / N_{\psi(2S)} A_{X(3872)} \epsilon_{X(3872)}$
- ▶ corrections and efficiency factors calculated from MC assuming unpolarized resonance and  $J^{PC} = 1^{++}$

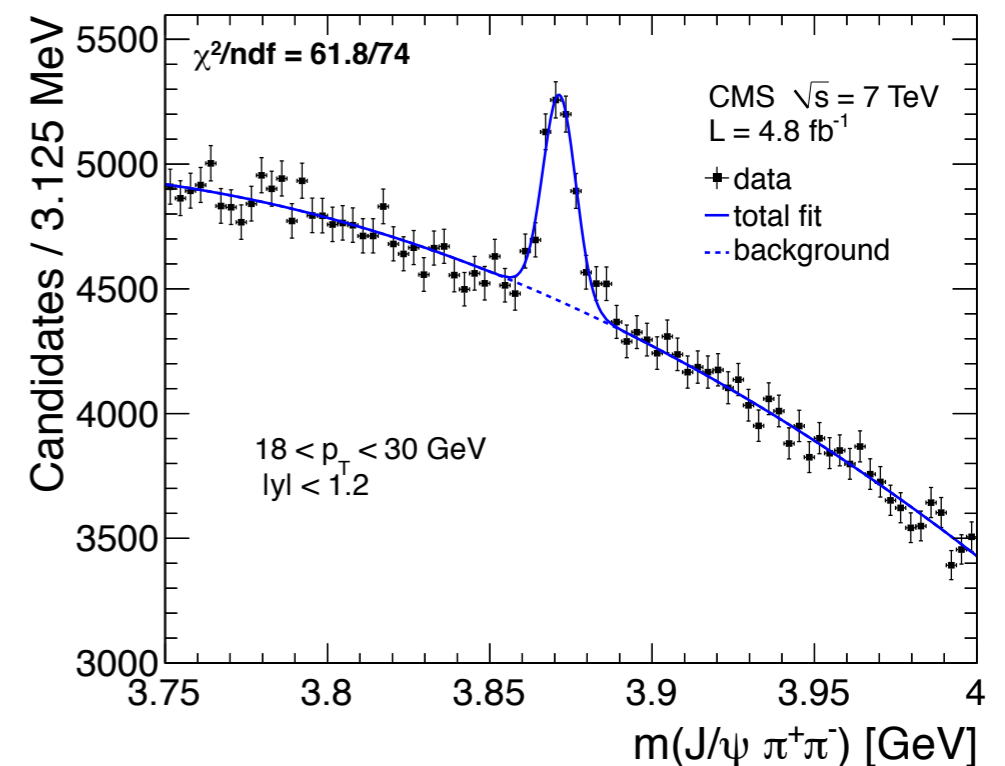
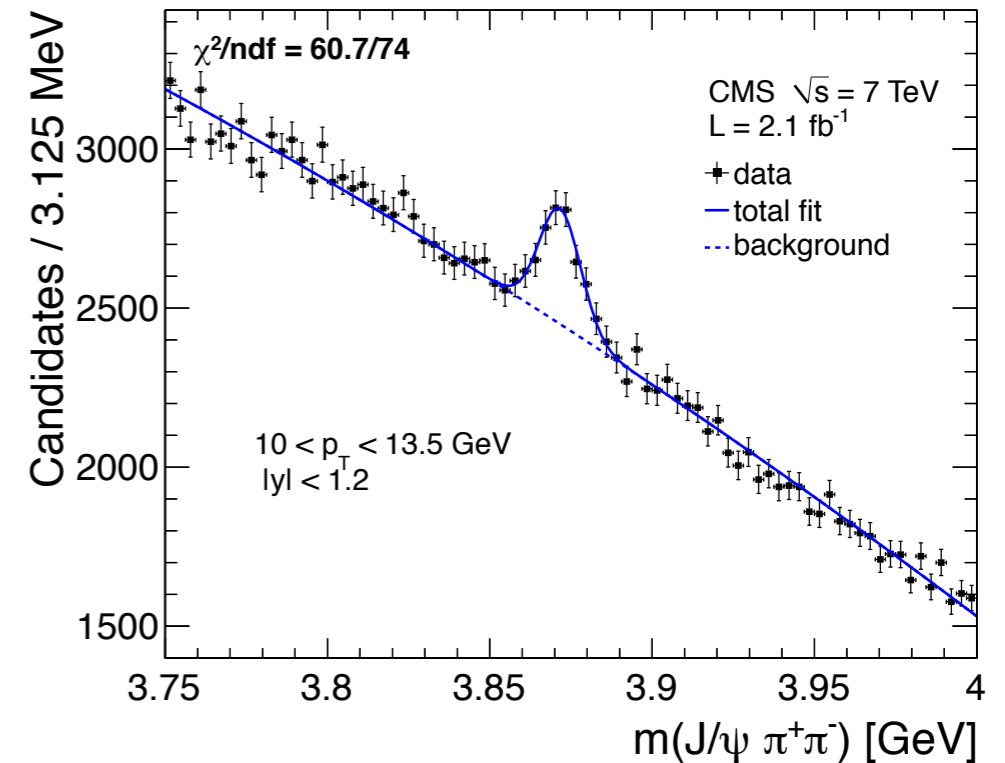
## backgrounds

- ▶ random track combinatorial background is reduced with  $\Delta R(J/\psi, \pi) < 0.55$
- ▶ good primary vertex selection  $\rightarrow$  result is not sensitive to pileup

## major systematics

- ▶ pion-pair efficiency: taken from different yields in  $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$  and  $\psi(2S) \rightarrow \pi^+ \pi^-$ , 1 % to 5 % with decreasing pion-pair  $p_T$
- ▶  $X(3872)$   $p_T$  spectrum: 1-7 % to 11 % with decreasing  $p_T$
- ▶  $\psi(2S)$   $p_T$  spectrum: 1-7 % to 11 % with decreasing  $p_T$
- ▶ dimuon efficiencies tend to cancel in the ratio:  $< 1\%$

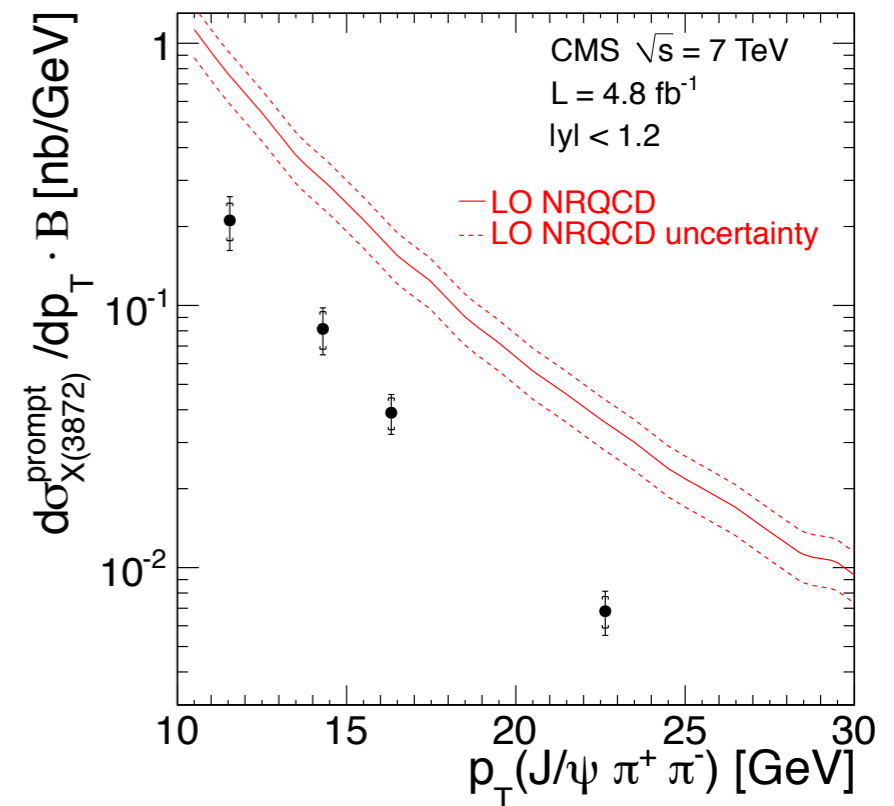
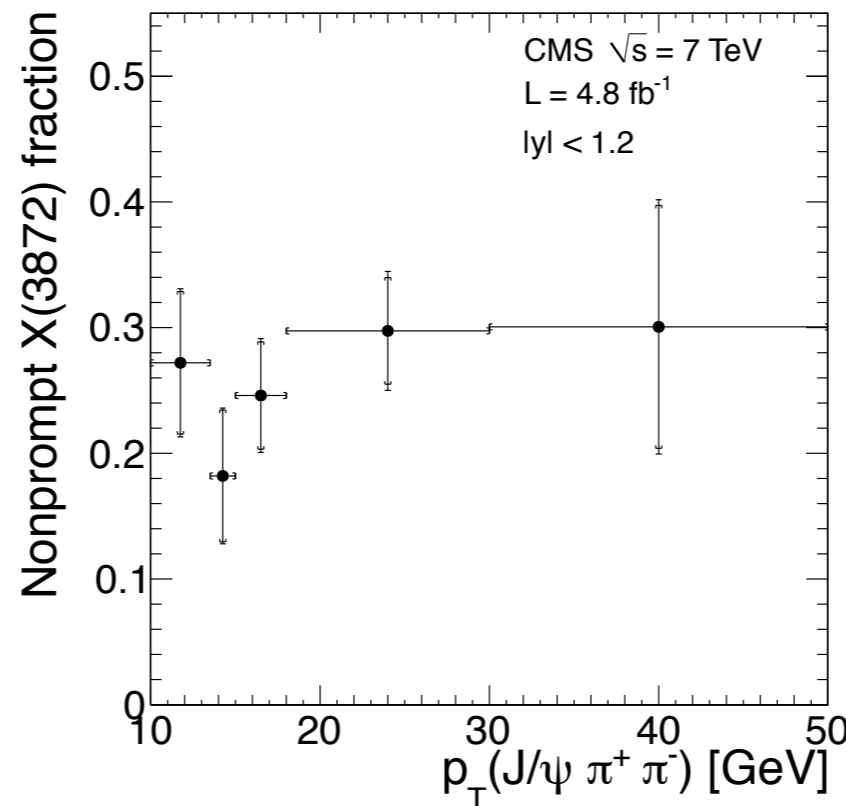
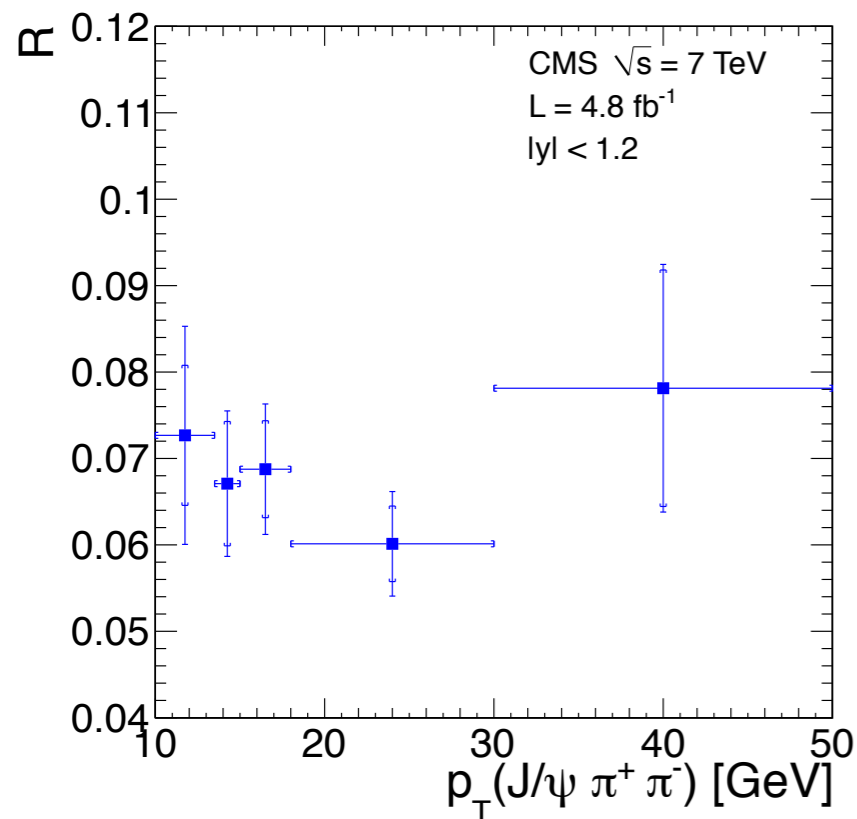
example: signal yield from fit to invariant mass in two  $p_T$  bins



# X(3872) production cross section

## results

- ▶ differential cross section ratio R as a function of the X(3872)  $p_T$
- ▶  $R = N_{X(3872)} A_{\psi(2S)} \epsilon_{\psi(2S)} / N_{\psi(2S)} A_{X(3872)} \epsilon_{X(3872)}$
- ▶ measurement of non-prompt fraction: pseudo-proper decay-length larger than 0.1 mm retains 80 % of non-prompt X(3872) while contamination from prompt candidates is less than 0.1 %
- ▶ measurement of prompt X(3872) production cross section from R and prompt  $\psi(2S)$  cross section



- ▶ such a difference from predicted values means this is not standard charmonium

# $\Lambda_b$ lifetime

## introduction

- ▶ complementary to cross section measurement to understand the models behind HF production
- ▶ lifetime predicted by non-perturbative models
- ▶ topology similar to  $B \rightarrow J/\psi K_S^0 (\pi^+\pi^-)$
- ▶ accurate measurement of  $B$  lifetime used to validate the procedure

## data sample

- ▶  $5.0 \text{ fb}^{-1}$  of 2011 pp collision data at  $\sqrt{s} = 7 \text{ TeV}$
- ▶ displaced-vertex  $J/\psi$  dimuon trigger in central region

BPH-11-013, presented at HCP 2012

## event selection

- ▶  $\Lambda_b \rightarrow J/\psi \Lambda$
- ▶  $J/\psi \rightarrow \mu^+ \mu^-$
- ▶ opposite-sign muon-pair with central rapidity, consistent with  $J/\psi$  mass, high-quality track
- ▶  $\Lambda \rightarrow p \pi^-$
- ▶  $\Lambda$  from opposite-sign charged tracks, “proton” hypothesis assigned to the highest momentum track in the pair
- ▶  $K_S^0 (\pi^+\pi^-)$  hypothesis is tested and event is rejected, if candidate mass is close to  $m(K_S^0)$
- ▶  $J/\psi$  and  $\Lambda$  candidates common vertex refit, dimuon mass constraint, proton-pion mass constraint



# $\Lambda_b$ lifetime

## analysis

- ▶  $\Lambda_b$  lifetime and mass simultaneously extracted from unbinned maximum-likelihood fit
- ▶  $B$  lifetime and mass as a control measurement

## backgrounds

- ▶ prompt background (combinatorial)
- ▶ non-prompt background: different  $b$  hadrons with wrong mass assumptions for tracks, incompletely reconstructed decays

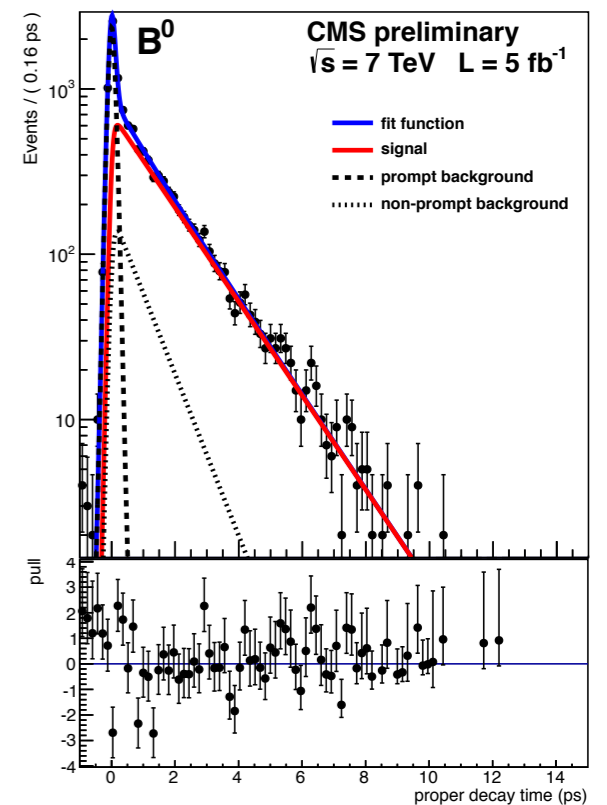
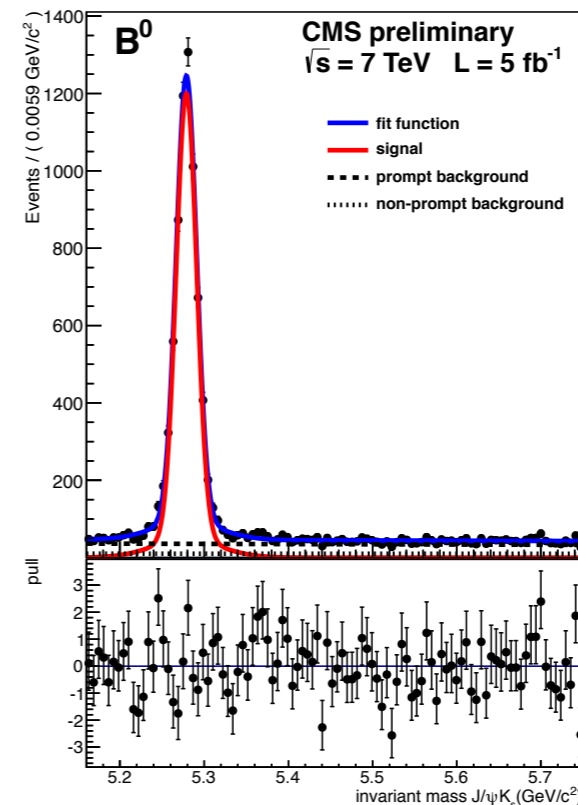
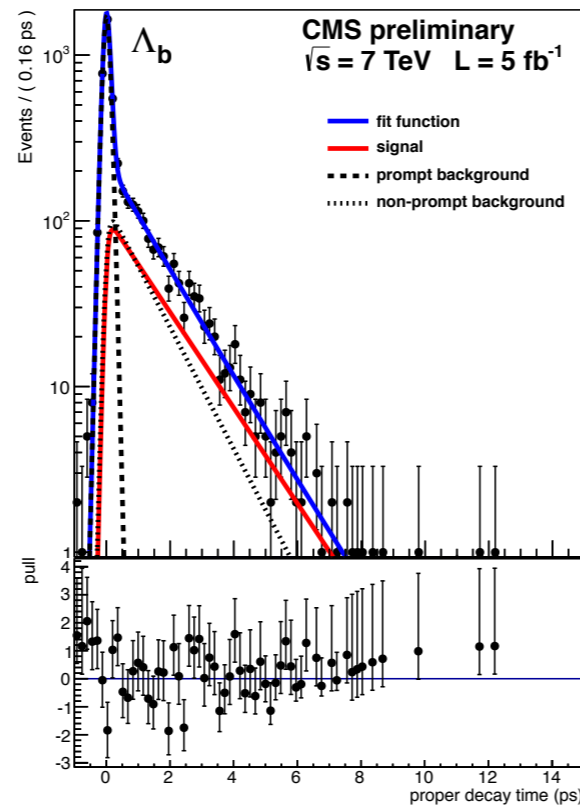
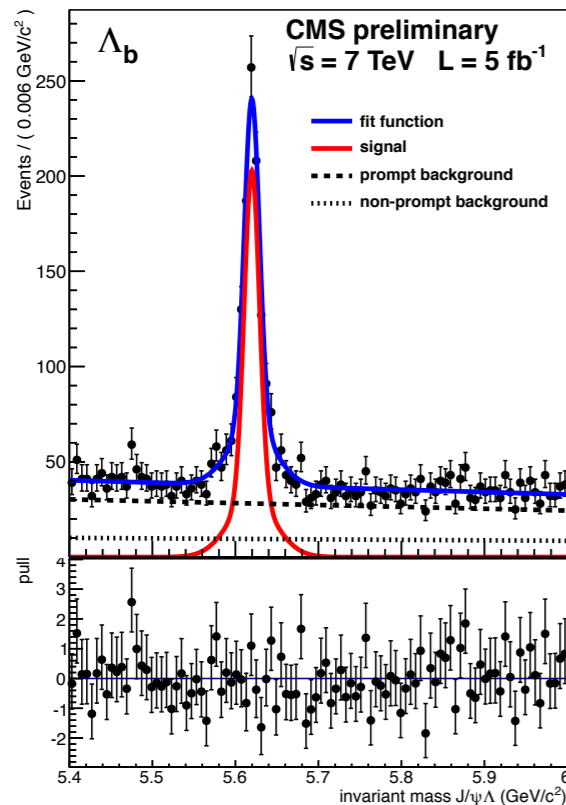
## main systematics

- ▶ detector alignment
- ▶ efficiency as a function of proper decay time
- ▶ fit model

## results

- ▶  $\Lambda_b$  lifetime =  $1.503 \pm 0.052$  (stat)  $\pm 0.031$  (syst) ps
- ▶ world average value:  $1.425 \pm 0.032$  ps
- ▶  $B$  lifetime:  $1.526 \pm 0.019$  ps

$\Lambda_b$  and  $B$  signal yield from fit to invariant mass and lifetime from fit to pseudo-proper decay time



# Observation of $B_c^+ \rightarrow J/\psi \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$

## introduction and previous studies

- ▶ unique probe for heavy-quark dynamics not accessible to  $b\bar{b}$  or  $c\bar{c}$  bound states
- ▶ ground state of two different bound heavy quarks with competing decay modes
- ▶ measurement of lifetime and branching fraction would help in understanding the decay dynamics
- ▶  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$  first observed at LHCb, CMS measurement is the only experimental confirmation so far

## data sample

- ▶ 4.7 fb<sup>-1</sup> of 2011 pp collision data at  $\sqrt{s} = 7$  TeV
- ▶ displaced-vertex  $J/\psi$  dimuon triggers

## event selection

- ▶  $B_c^+ \rightarrow J/\psi \pi^+$ ,  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$
- ▶  $J/\psi \rightarrow \mu^+ \mu^-$
- ▶ opposite-sign muon-pair with central rapidity, consistent with  $J/\psi$  mass, high-quality track
- ▶ 1 or 3 additional tracks, assumed to be pions
- ▶ largest- $p_T$   $B_c^+$  candidate retained
- ▶  $p_T(B_c^+) > 10$  GeV,  $|\eta(B_c^+)| < 1.6$
- ▶  $B_c^+ \rightarrow J/\psi \pi^+$  and  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$  specific based on 3D secondary-vertex significance

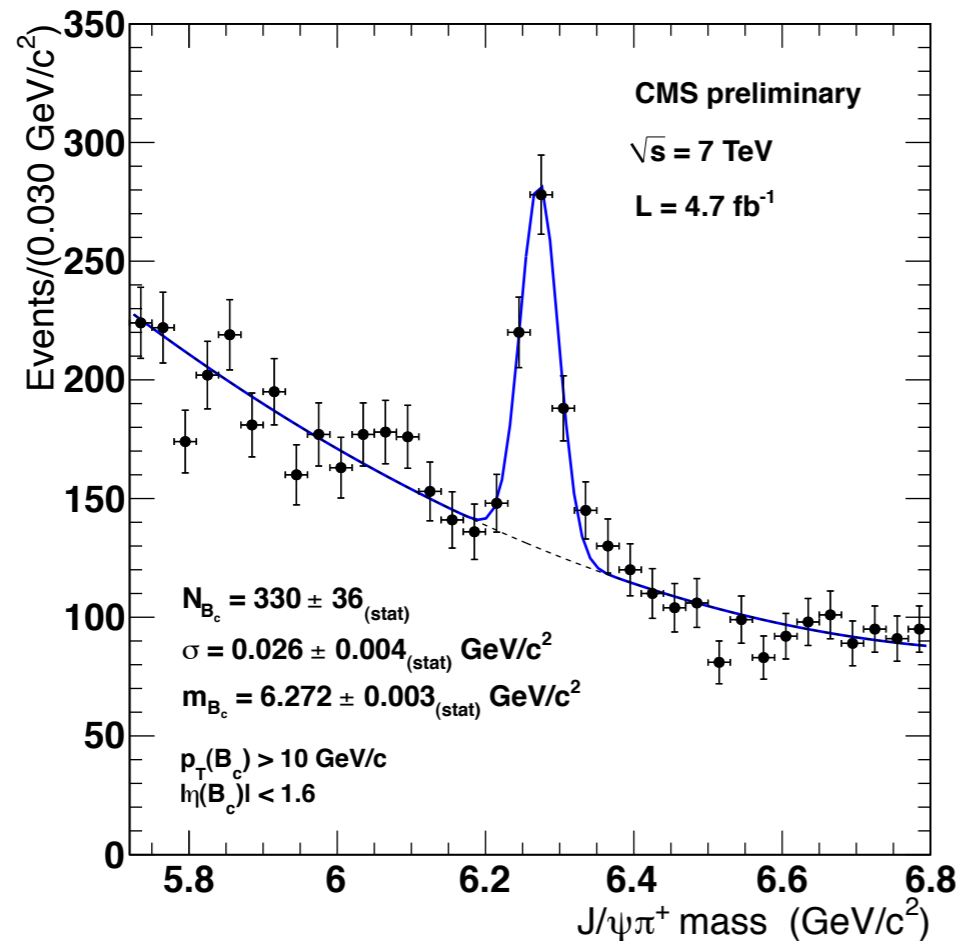
CMS-PAS-BPH-11-003

# Observation of $B_c^+ \rightarrow J/\psi \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$

## analysis

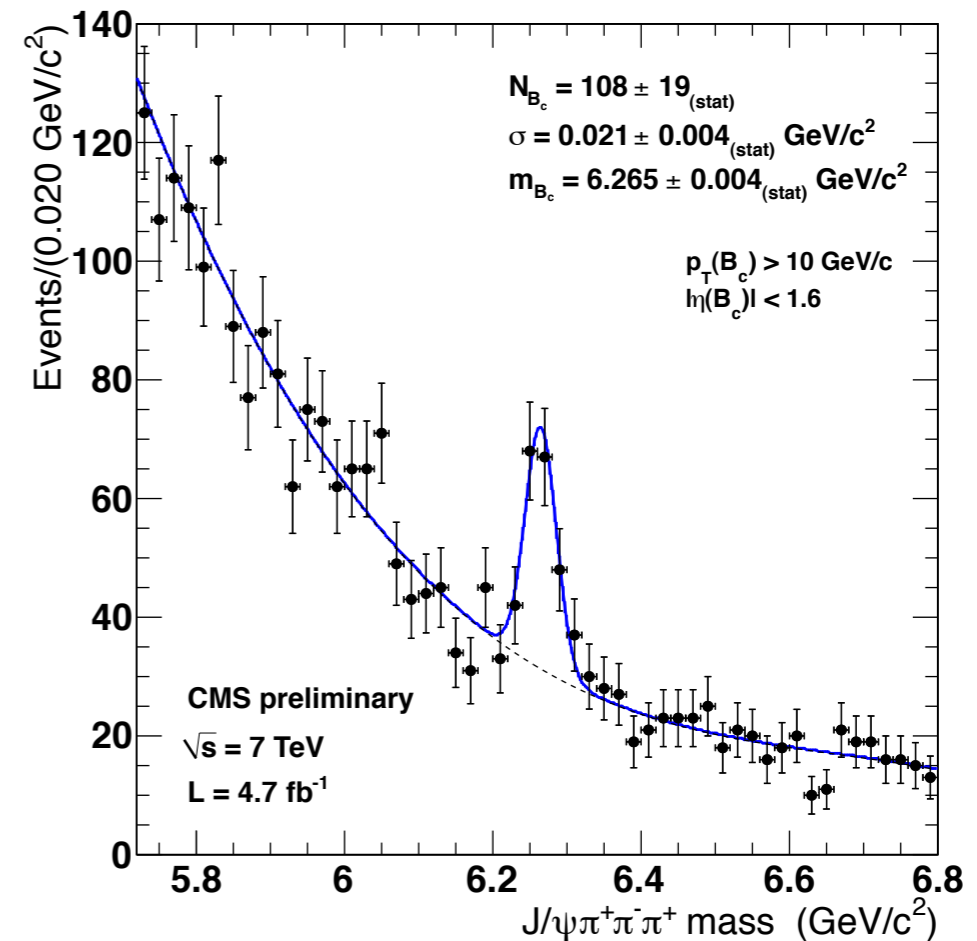
- ▶ signal yield from binned maximum-likelihood fit to invariant-mass distributions

signal yield from fit to invariant mass for the 1-pion and 3-pions decay modes



## results

- ▶ number of observed decays (measured yields)
  - ▶  $B_c^+ \rightarrow J/\psi \pi^+$ :  $330 \pm 36$  (stat)  $\pm 23$  (syst),  $S/\sqrt{S+B} = 10.5$
  - ▶  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ :  $108 \pm 19$  (stat)  $\pm 14$  (syst),  $S/\sqrt{S+B} = 6.1$



# Structures in $J/\psi \phi$ spectrum from $B^+ \rightarrow J/\psi \phi K^+$

## introduction and previous studies

- ▶ conventional quark model is unable to explain charmonium-like states discovered over last decade
- ▶ charmed hybrids? tetraquarks? molecular states?
- ▶ CDF studied  $B^+ \rightarrow J/\psi \phi K^+$  in 2009
- ▶ narrow structure near  $J/\psi$  threshold with  $5 \sigma$  significance:  **$Y(4140)$**   
 $m = 4143.4^{+2.0}_{-3.0} \text{ (stat)} \pm 1.2 \text{ (syst)} \text{ MeV}$ ,  
 $\Gamma = 15.3^{+10.4}_{-6.1} \text{ (stat)} \pm 2.5 \text{ (syst)} \text{ MeV}$
- ▶ exotic state candidate
- ▶ analogous searches at Belle (inconclusive, but found another structure around 4.38 GeV) and LHCb (in conflict with CDF)
- ▶ independent results may clarify the status

## event selection

- ▶  $B^+ \rightarrow J/\psi \phi K^+$
- ▶  $J/\psi \rightarrow \mu^+ \mu^-$
- ▶  $\phi \rightarrow K^+ K^-$
- ▶ muon pair combined with three additional tracks with total charge  $\pm 1$  and kaon mass assigned
- ▶  $\phi$  candidate is the lowest-mass opposite-sign pair (if mass is compatible with the  $\phi$  mass)

## data sample

- ▶  $5.2 \text{ fb}^{-1}$  of 2011 pp collision data at  $\sqrt{s} = 7 \text{ TeV}$
- ▶ displaced-vertex  $J/\psi$  dimuon triggers

BPH-11-026, presented at HCP 2012

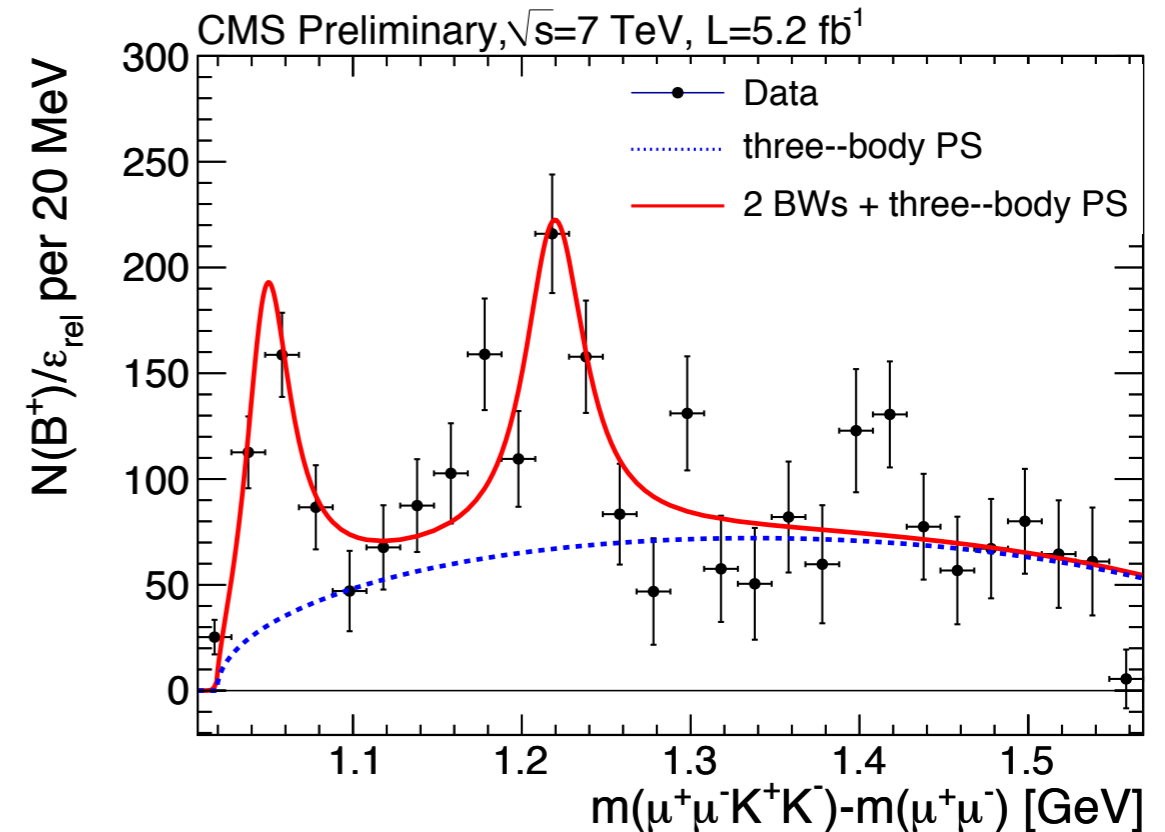
# Structures in $J/\psi \phi$ spectrum from $B^+ \rightarrow J/\psi \phi K^+$

## analysis

- ▶  $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$  as sensitive variable
- ▶  $\Delta m$  distributions must be corrected for phase-space effects
- ▶ observed structures are modeled by S-wave relativistic Breit-Wigner functions (convolved with Gaussian resolution, width constrained to value from simulation)

## backgrounds

- ▶ misidentified  $B^+ \rightarrow J/\psi f^0(980) K^+$  is negligible
- ▶ non-resonant  $B^+ \rightarrow J/\psi K^+ K^- K^+$  is negligible
- ▶ combinatorial from misidentified  $B^0_s \rightarrow \psi(2S) \phi \rightarrow J/\psi \pi^+ \pi^- \phi$  is rejected with  $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-) > 1.568$  GeV cut



## results

- ▶ confirmation of CDF result with structure 1
- ▶ angular analysis would help in understanding the nature of these structures

# Observation of a new $\Xi_b$ baryon

## introduction and previous studies

- ▶ several predicted baryons with beauty and strange valence quarks
  - ▶  $\Xi_b$  ground state:  $J^P = 1/2^+$
  - ▶  $\Xi'_b$ :  $J^P = 1/2^+$
  - ▶  $\Xi_b^*$ :  $J^P = 3/2^+$
  - ▶ two states with negative P
- ▶  $\Xi_b$  candidates observed at the Tevatron
  - ▶ quantum numbers not probed yet

## data sample

- ▶  $5.3 \text{ fb}^{-1}$  of 2011 pp collision data at  $\sqrt{s} = 7 \text{ TeV}$
- ▶ displaced-vertex  $J/\psi$  dimuon triggers

## event selection

- ▶ decays reconstructed with quality criteria as in previously described measurements
- ▶  $\Xi_b^{*0} \rightarrow \Xi_b^- \pi^+$
- ▶  $\Xi_b^- \rightarrow J/\psi \Xi^-$ 
  - ▶  $J/\psi \rightarrow \mu^+ \mu^-$
  - ▶  $\Xi^- \rightarrow \Lambda \pi^-$ 
    - ▶  $\Lambda \rightarrow p \pi^-$
- ▶ three secondary vertices in the full event reconstruction
- ▶  $K_S$  contamination removed with invariant-mass constraints

*Phys. Rev. Lett.* **108** (2012) 252002

# Observation of a new $\Xi_b$ baryon

## analysis

- ▶ signal yield from unbinned maximum-likelihood fit to  $Q = m(J/\psi \Xi^- \pi^+) - m(J/\psi \Xi^-) - m(\pi^+)$
- ▶ combinatorial background modeled with wrong-sign pion and  $\Xi_b^-$  candidates
- ▶ measured distributions are used to generate uncorrelated momenta of same-sign candidates to calculate  $Q$
- ▶ simulation of exclusive decays of  $b$  hadrons to evaluate the impact of partially reconstructed decays

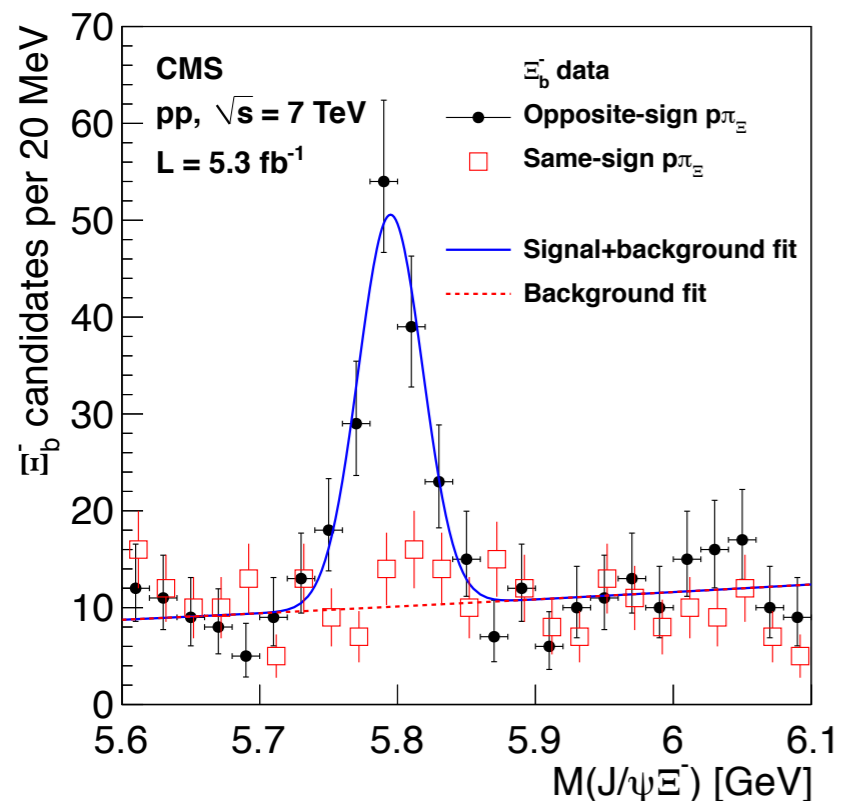
## systematics

- ▶ background evaluation from wrong-sign candidates: different parameterizations of measured distributions are used

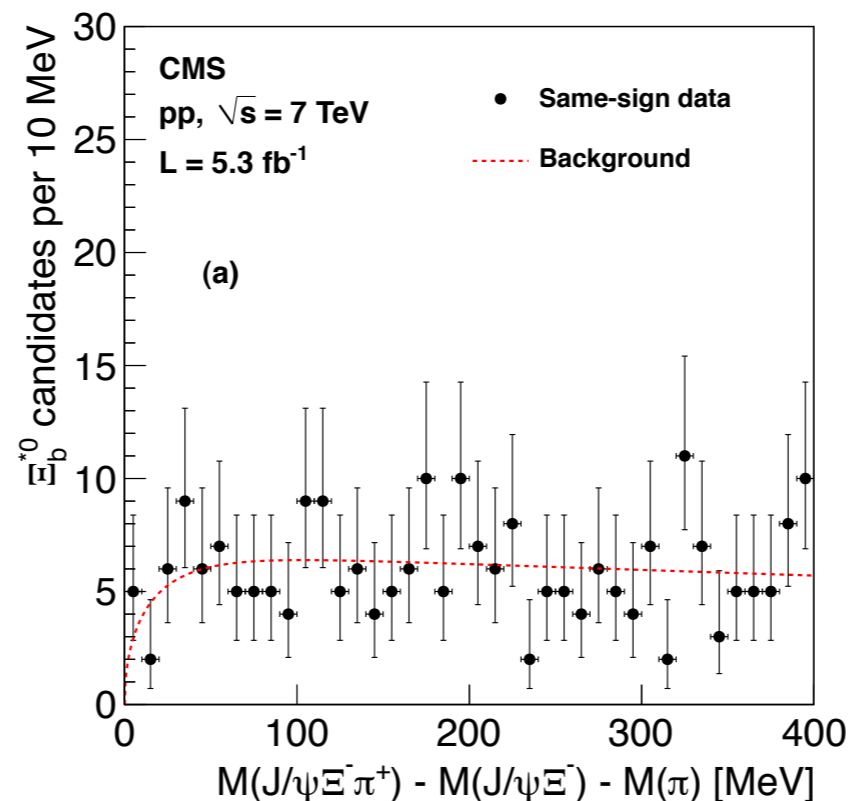
## results

- ▶ first observation: **6.9  $\sigma$**  significance
- ▶  $m = 5945.0 \pm 0.7$  (stat)  $\pm 2.7$  (PDG  $\Xi_b^-$  mass) MeV
- ▶ given mass and decay mode, this baryon is a candidate  $\Xi_b^*$  with  $J^P = 3/2^+$

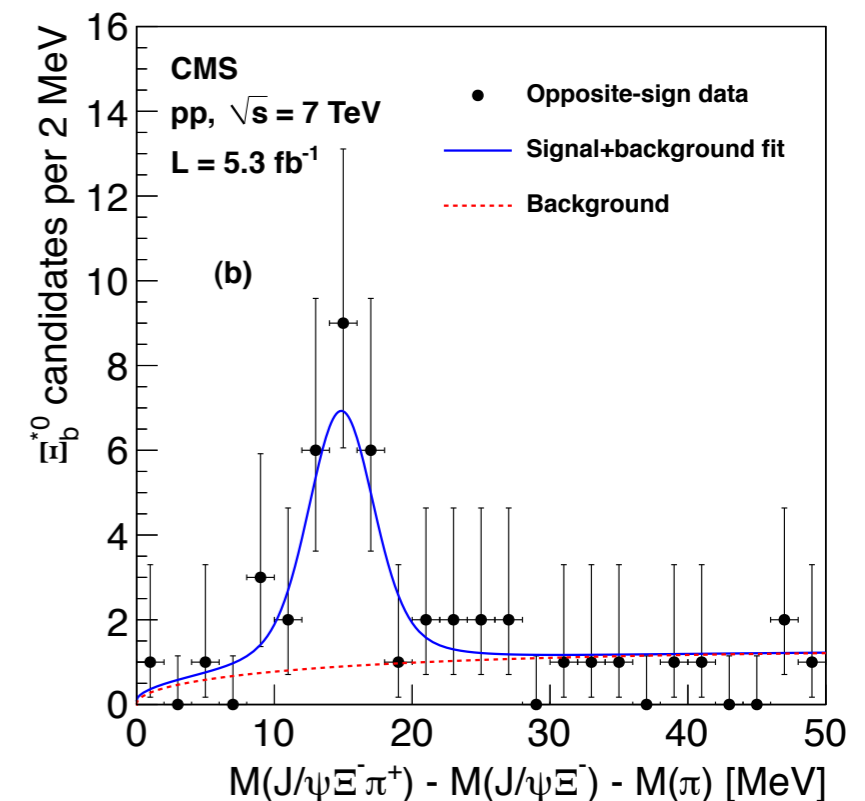
reconstruction of  $\Xi_b^-$  candidate



$Q$ : background from wrong-sign pion and  $\Xi_b^-$  candidates



$Q$ : signal and background



# concluding remarks

- the LHC excellent performance in 2010 and 2011 allowed CMS and the other LHC experiments to perform high-quality studies in heavy-flavor physics
- excellent performance of CMS tracker and muon detectors was crucial in studying heavy-flavor physics in fully reconstructed decays of  $b$  hadrons
- new results in exotic quarkonia:  $X(3872)$
- new results in properties of  $b$  hadrons:  $\Lambda_b$  and  $B_c^+$
- observation of new hadrons and structures:  $\Xi_b^*$  and  $B^+ \rightarrow J/\psi \phi K^+$

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH>



**backup**

# references

- ❖  $X(3872)$  production
  - ✓ presented at HCP 2012, submitted to *JHEP*, preprint available at *arXiv:1302.3968*
- ❖  $\Lambda_b$  lifetime
  - ✓ presented at HCP 2012
- ❖ observation of  $B_c^+ \rightarrow J/\psi \pi^+$  and  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$ 
  - ✓ presented at ICHEP 2012, CMS public analysis summary available at CERN Document Server as CMS-PAS-BPH-11-003
- ❖ observation of structures in  $B^+ \rightarrow J/\psi \phi K^+$ 
  - ✓ presented at HCP 2012
- ❖ observation of a new  $\Xi_b$  baryon
  - ✓ presented at FPCP 2012, *Phys. Rev. Lett.* **108** (2012) 252002

# $\Lambda_b$ production cross section

## introduction and previous studies

- ▶ first measurement of the production cross section of a  $b$  baryon, from fully reconstructed  $J/\psi \Lambda$  decays
- ▶ predictions from perturbative QCD at NLO
- ▶ understanding the production rates for  $b$  hadrons: essential for accurate estimates of HF backgrounds for various searches (H, SUSY, etc.)
- ▶ pp initial state at the LHC allows tests of baryon transport models, which predict rapidity-dependent antibaryon/baryon asymmetries, in contrast to baryon-antibaryon pair production

## data sample

- ▶ 1.9 fb<sup>-1</sup> of 2011 pp collision data at  $\sqrt{s} = 7$  TeV
- ▶  $J/\psi$  dimuon trigger with dimuon  $p_T > 7$  GeV
- ▶ displaced  $J/\psi$  vertex at trigger level

## event selection

- ▶  $\Lambda_b \rightarrow J/\psi \Lambda$
- ▶  $J/\psi \rightarrow \mu^+ \mu^-$ 
  - ▶ single muon  $p_T > 3.5$  GeV,  $|\eta| < 2.2$
  - ▶ track selection based on stringent quality criteria
  - ▶  $J/\psi \rightarrow \mu^+ \mu^-$  vertex and mass constraints
- ▶  $\Lambda \rightarrow p \pi^-$ 
  - ▶  $\Lambda$  from opposite-sign charged tracks
  - ▶ “proton” hypothesis assigned to the higher momentum track in the pair,  $p_T > 1.0$  GeV
  - ▶  $\Lambda \rightarrow p \pi^-$  vertex and mass constraints
- ▶  $J/\psi$  and  $\Lambda$  candidates common vertex refit, dimuon mass constraint, proton-pion mass constraint
- ▶  $p_T(J/\psi p \pi^-) > 10$  GeV,  $|\gamma(J/\psi p \pi^-)| < 2.0$

✓ presented at Moriond 2012, *Phys. Lett. B* **714** (2012) 136-157

# $\Lambda_b$ production cross section

## backgrounds

- ▶ dominated by non-prompt  $J/\psi$  production in  $B$  decays, rejected with  $J/\psi$   $\Lambda$  invariant mass constraints

## analysis

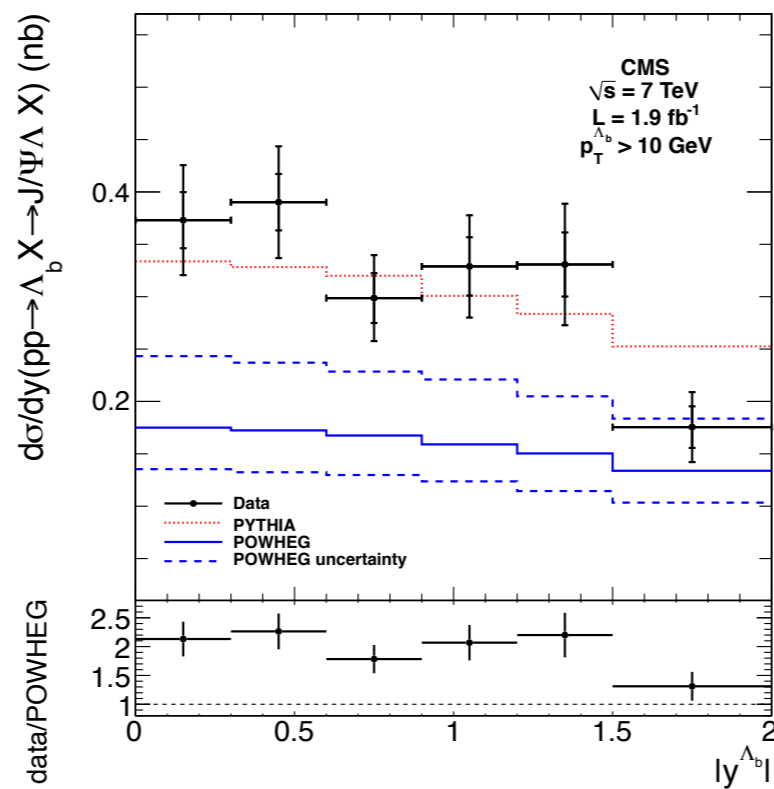
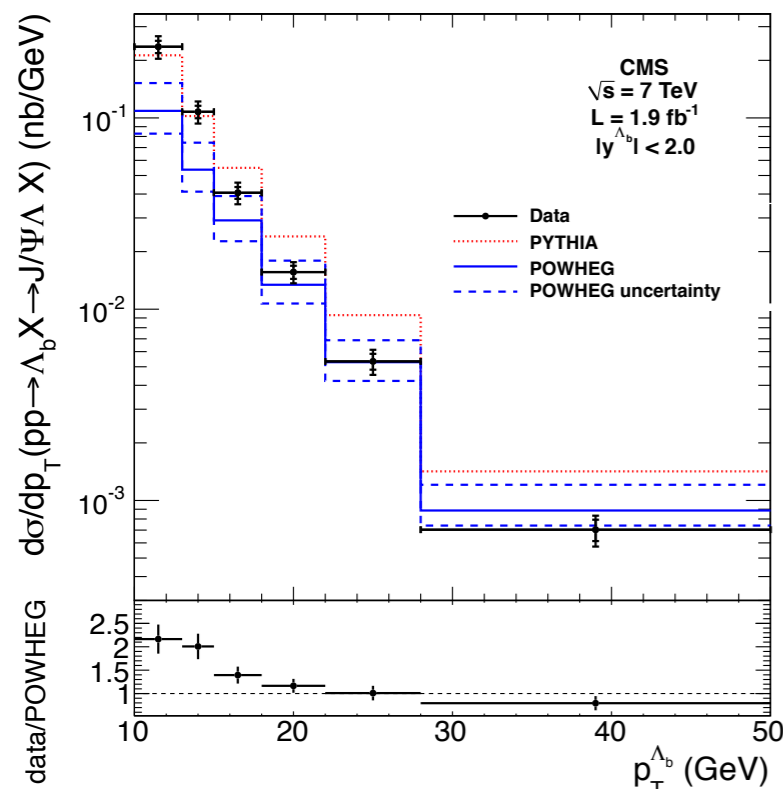
- ▶ particle-antiparticle separation with proton-pion charge
- ▶ separate selection efficiencies
- ▶ yields are extracted from unbinned extended maximum-likelihood fits to  $J/\psi$   $\Lambda$  invariant mass in bins of  $p_T$  and  $|y|$

## systematics

- ▶ relevant for both cross section and cross section ratio
- ▶ signal-shape uncertainty
- ▶ background-shape uncertainty
- ▶ G4 simulation of antiproton interaction
- ▶ detector material
- ▶ simulated sample size

- ▶ relevant only for cross section

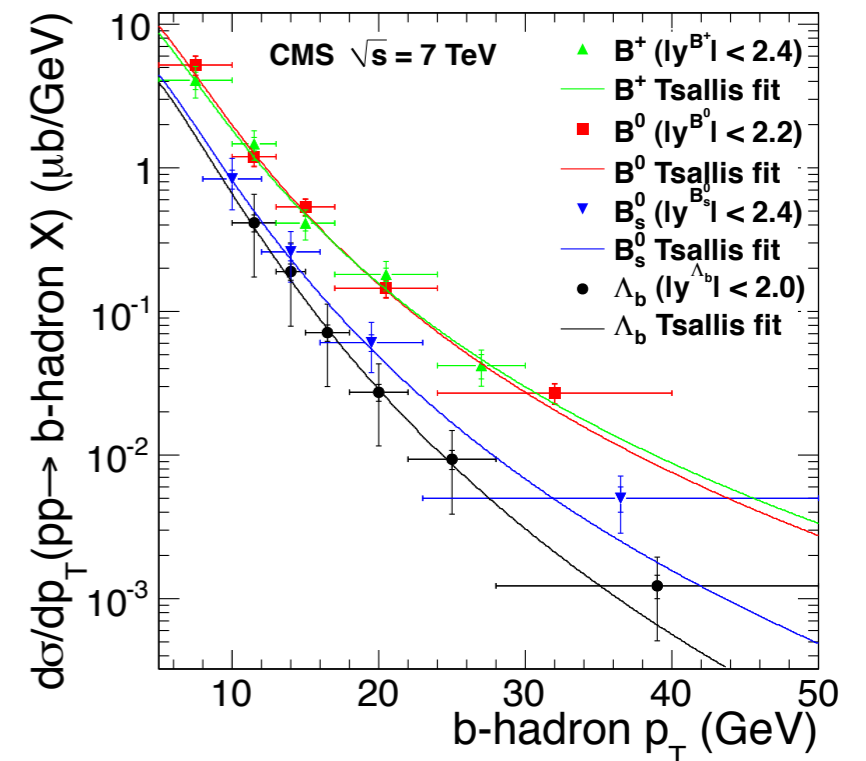
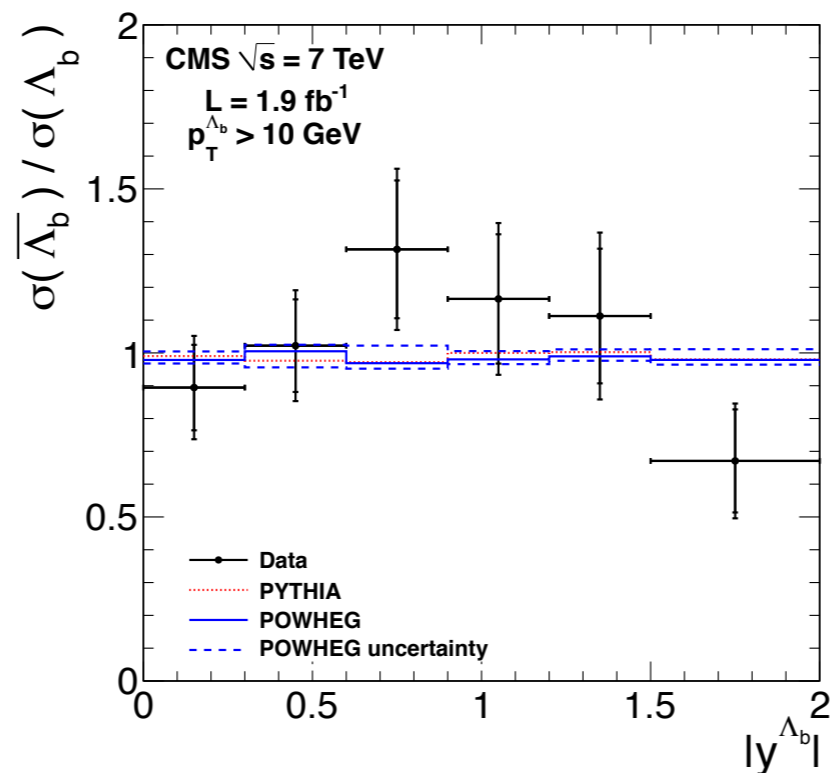
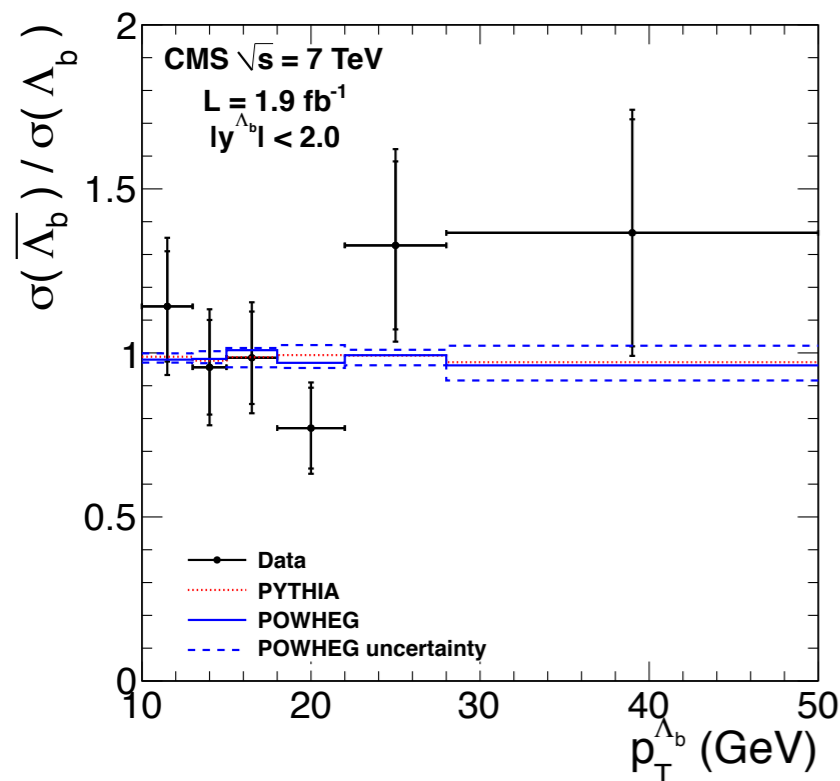
- ▶ reconstruction and selection efficiencies
- ▶  $\Lambda_b$  kinematics and polarization
- ▶ pileup
- ▶ luminosity
- ▶  $p_T$  and  $|y|$  bin size



# $\Lambda_b$ production cross section

## additional comments

- ▶ cross section measurement is complemented by cross section ratio between baryon and anti-baryon
- ▶ comparison with measured  $p_T$  spectra of  $B$  mesons
- ▶ comparison with LO and NLO predictions
- ▶ the measured  $\Lambda_b$  spectrum decreases faster than both the prediction and the measured  $p_T$  spectra of  $B$  mesons



# $b$ -hadron $p_T$ spectra

- ▶ comparison of CMS results for  $b$ -hadron production versus  $p_T$ : data are fit to the Tsallis function ( $C$  = normalization,  $T$  and  $n$  = shape,  $m$  = hadron mass)
- ▶  $T$  dominates at low  $p_T$  (exponential) and is fixed to the mean value from fit to  $B^+$  and  $B^0$
- ▶  $n$  dominates at high  $p_T$  (power law)
- ▶ larger  $n$  value for  $\Lambda_b$ : more steeply falling  $p_T$  distribution than observed for the mesons
- ▶ this suggests that the production of  $\Lambda_b$  baryons, relative to  $B$  mesons, varies as a function of  $p_T$ , with a larger  $\Lambda_b/B$  ratio at lower  $p_T$

$$\frac{1}{N} \frac{dN}{dp_T} = Cp_T \left[ 1 + \frac{\sqrt{p_T^2 + m^2} - m}{nT} \right]^{-n}$$

