BEAUTY2013 Bologna, 8-12 Apr

Heavy Flavor Spectroscopy and Production in CMS

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on behalf of the CMS Collaboration

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CMS Compact Muon Solenoid

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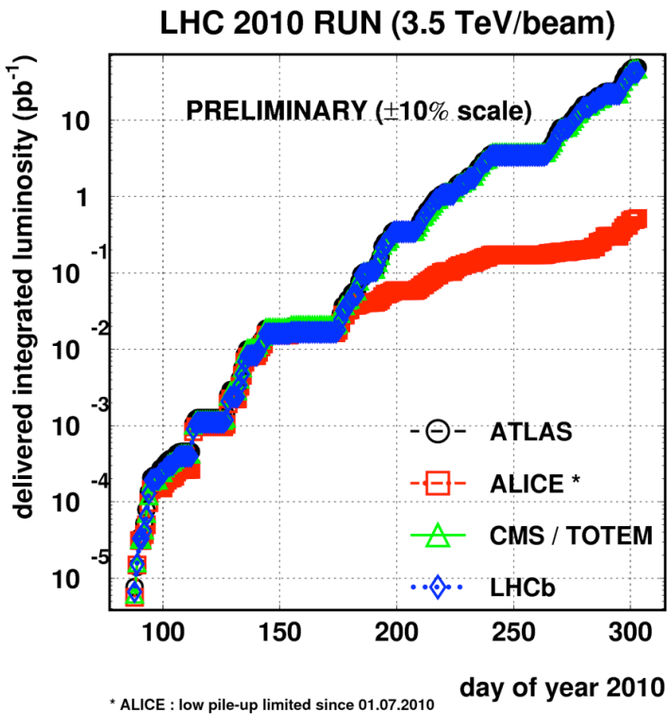
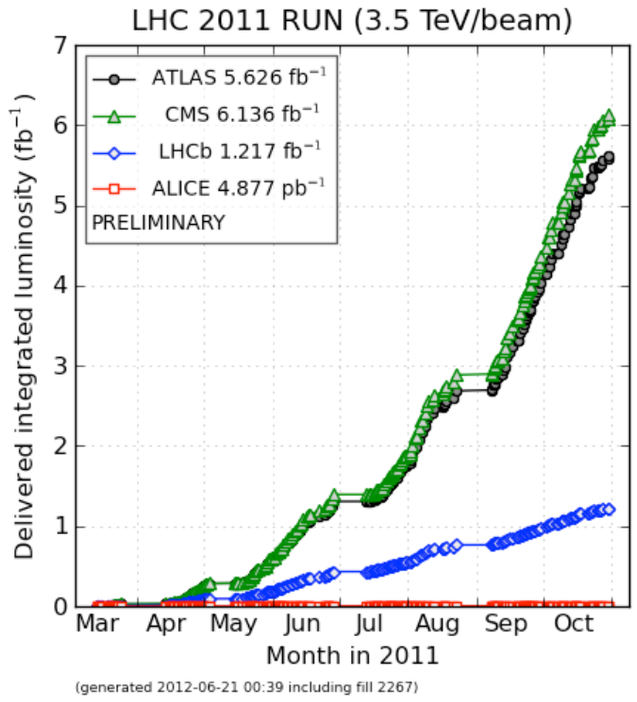
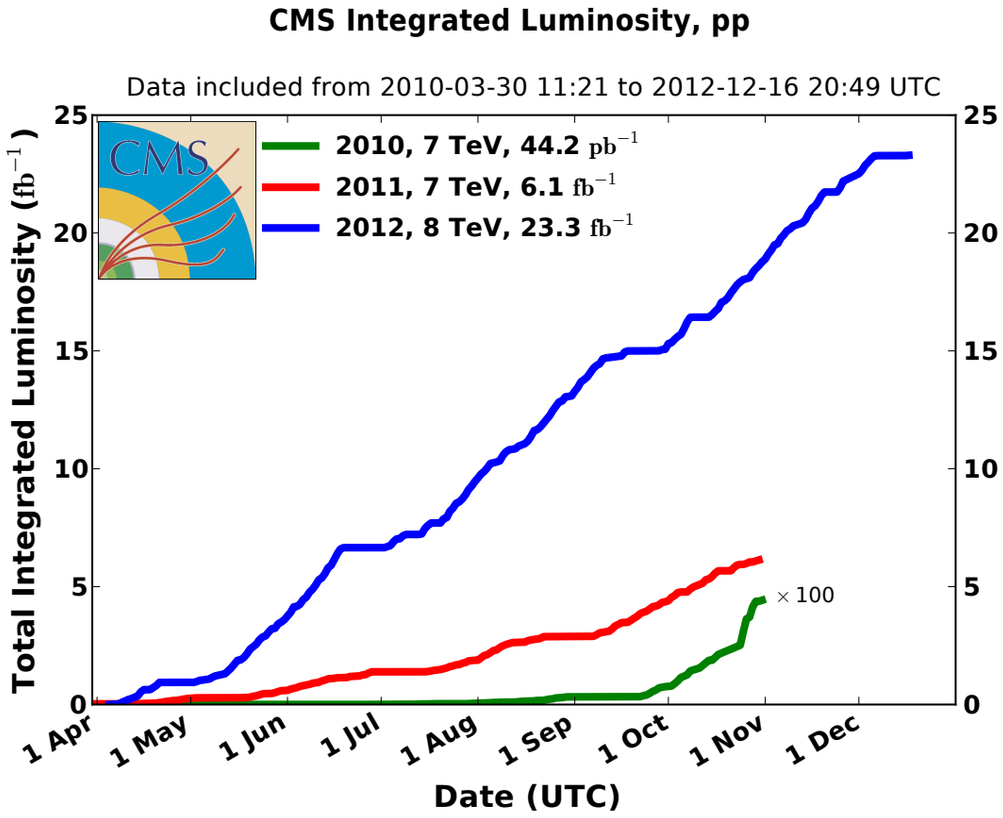
Introduction

- Measurement of **heavy flavor production** is crucial to test QCD models and predictions
  - b-hadron properties provide important tests of the SM → any deviation would be indirect indication of New Physics
  - plenty of heavy hadrons produced at hadron colliders→ chance to study still not well-known particles
- Knowledge of b-flavored **background** needed by New Physics studies
- **Outline** of the talk
  - measurement of the X(3872) production cross section
  - observation of structures in the $J/\psi\phi$ spectrum
  - observation of a new Ξ baryon and observation of the B_c meson
  - measurement of beauty di-jet angular correlation 

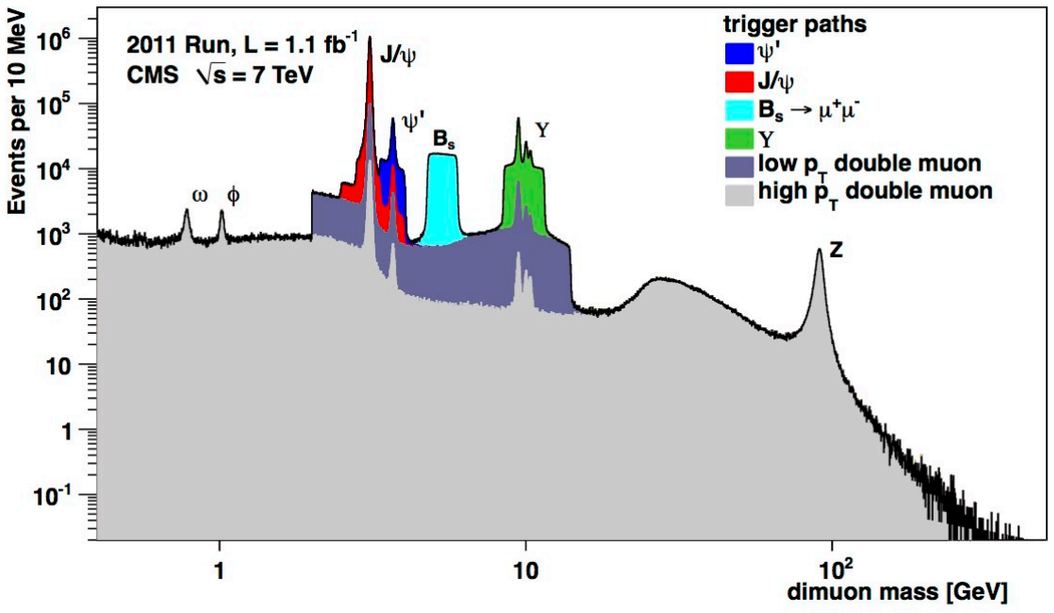
LHC and CMS performance







Results presented in this talk are based on proton proton data collected in 2010 or in 2011 @7 TeV



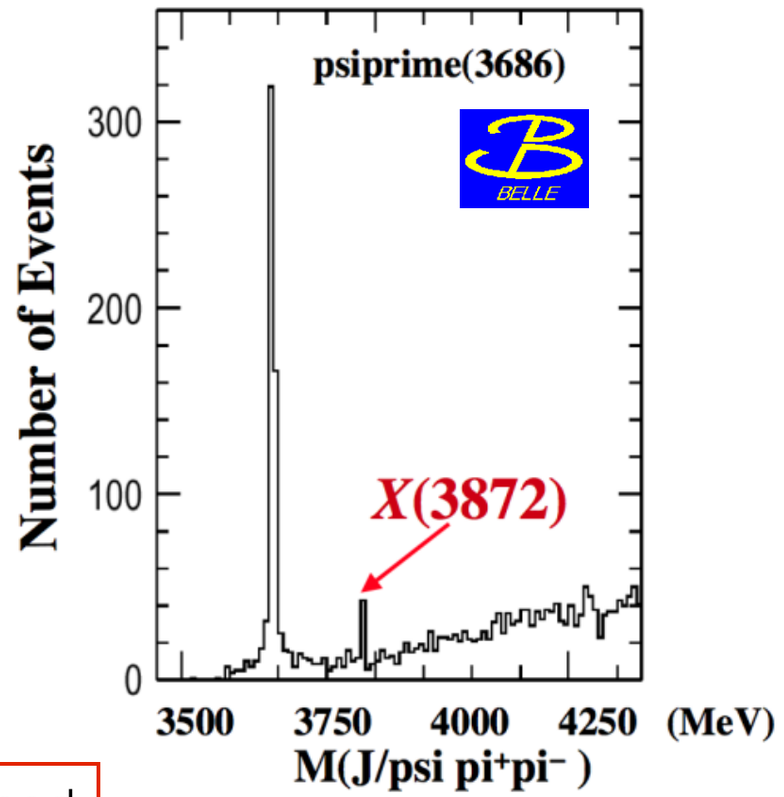
CMS dimuon triggers

X(3872) production cross section

- The X(3872) was discovered by Belle in 2003

  Phys.Rev.Lett.91, 262001 (2003)

  - Later confirmed by BaBar, D0 and CDF
  - **Its nature still remains unclear. Possibilities:**
    - a $c\bar{c}$ state
    - a multi-quark molecule: loosely bound state of D^0 and D^{*0}
    - a tetra-quark: bound state of diquark and anti-diquark



- Angular analysis favors $J^{PC}=1^{++}$ or 2^{-+}
  - In March 2013, LHCb measured $J^{PC}=1^{++}$

    arXiv:1302.6269

CMS results are obtained with the assumption that $J^{PC}=1^{++}$

- Produced both in prompt and B→X(3872) feed-down processes
- Prompt production of quarkonium states usually described by NRQCD
  - Measurement of the prompt production rate @LHC can test such predictions

see poster from M. Dall'Osso for CMS

X(3872) production cross section

arXiv:1302.3968, acc. for pub. in JHEP

- Use the decay X(3872)→J/ψ $\pi^+\pi^-$ (J/ψ → μμ) in the kinematic range 10 < p_T < 50 GeV and |y| < 1.2

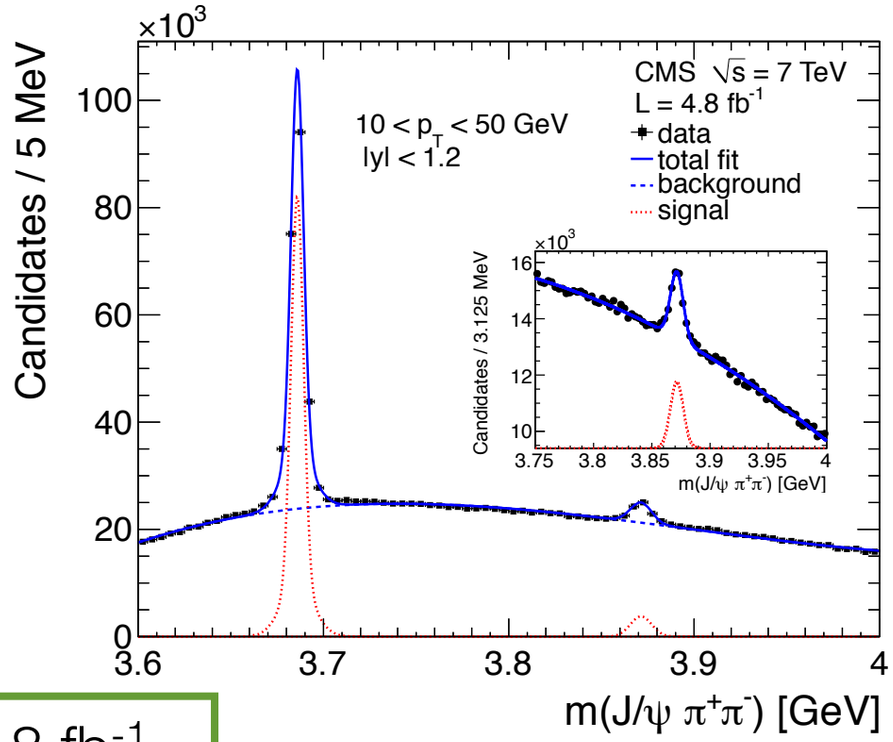
- Cross section measured by determining the ratio of X(3872) and ψ(2S) cross sections

$$R = \frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \epsilon_{\psi(2S)}}{N_{\psi(2S)} \cdot A_{X(3872)} \cdot \epsilon_{X(3872)}}$$

signal yield determined from unbinned ML fit in 5 pT bins

acceptance

efficiency



2011 data, 4.8 fb^{-1}

Event selection:

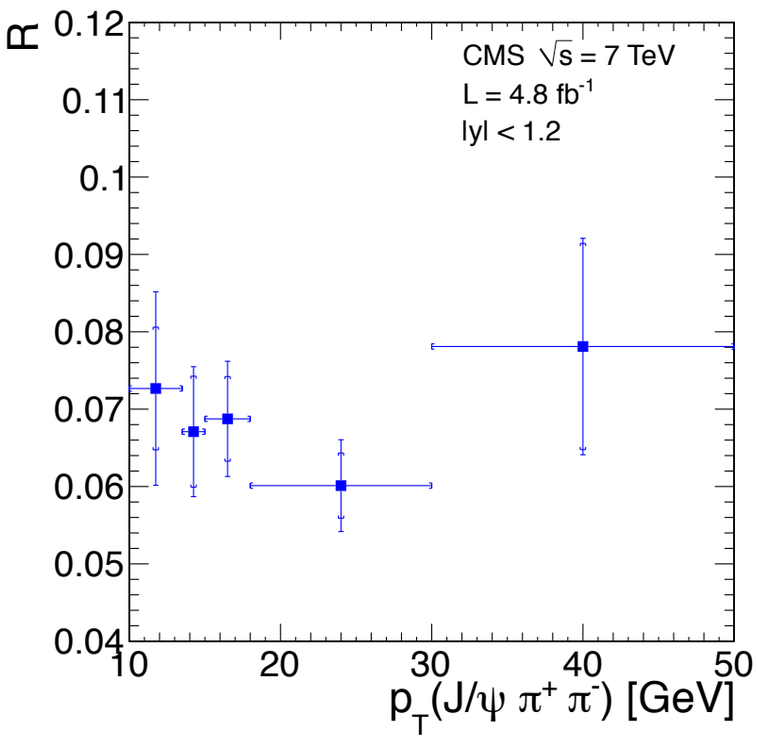
- prompt J/ψ dimuon trigger with p_T(J/ψ) threshold (7 or 10 GeV)
- opposite sign dimuon pair in the central region |y($\mu^+\mu^-$)| < 1.25 and with invariant mass in a 75 MeV window from the J/ψ mass
- p_T threshold for each muon depending on |η|
- candidate J/ψ associated to 2 opposite sign tracks assumed to be pions
- kinematic vertex fit constraining the J/ψ mass
- tracks refit (pion p_T > 0.6GeV)
- ΔR(J/ψ,π)<0.55 to reduce combinatorial bkg
- Q value < 300 MeV

see poster from M. Dall'Osso for CMS

X(3872) production cross section

R = X(3872)/ψ(2S) cross section ratio as a function of p_T

- X(3872) and ψ(2S) unpolarized in the simulation
  - different polarization scenarios can induce a variation up to 90%

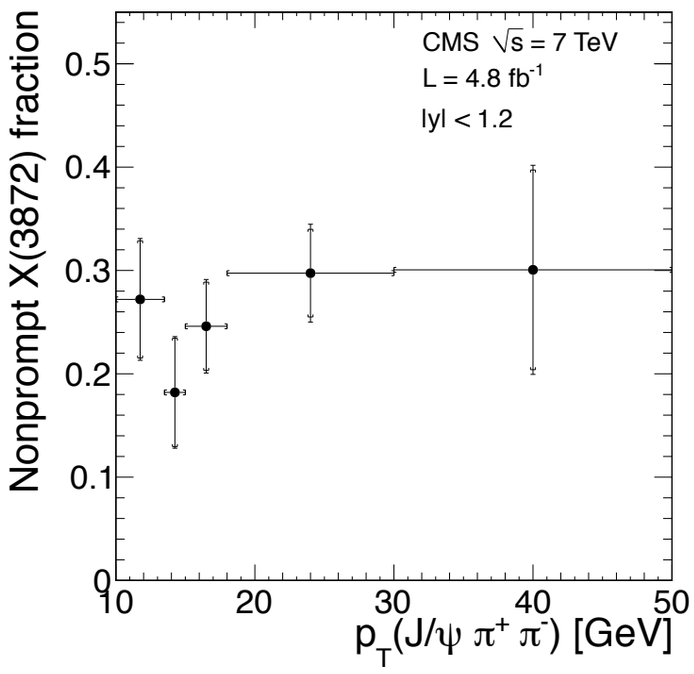


no significant dependence on p_T

Non Prompt Fraction as a function of p_T

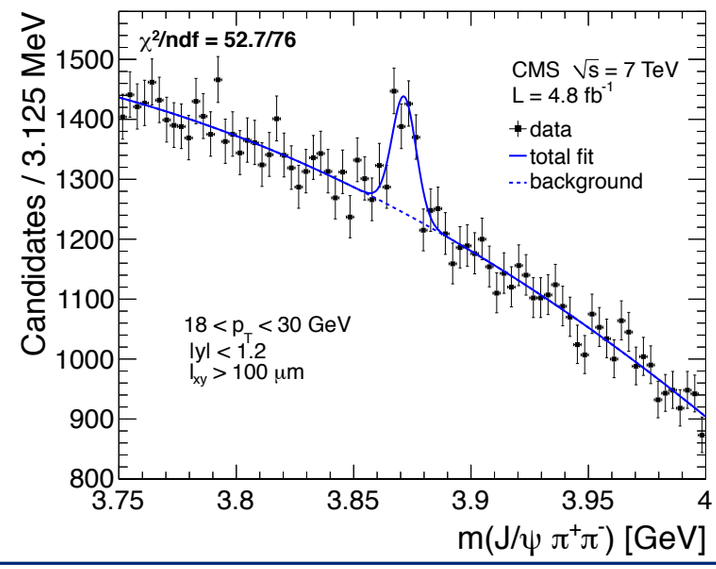
Discrimination based on transverse decay length $l_{xy}^{X(3872)} = \frac{L_{xy}^{X(3872)} \cdot m_{X(3872)}}{p_T}$

- Events with X(3872) from B decays selected by requiring l_{xy} > 100 μm
  - contribution from prompt X(3872) is negligible (< 0.1%)
  - method cross-checked with a 2D fit to the invariant-mass vs l_{xy}



$$nonpromptFraction = \frac{N(X(3872)_{fromB})}{N(X(3872))}$$

- measurement dominated by statistics



see poster from M. Dall'Osso for CMS

X(3872) production cross section

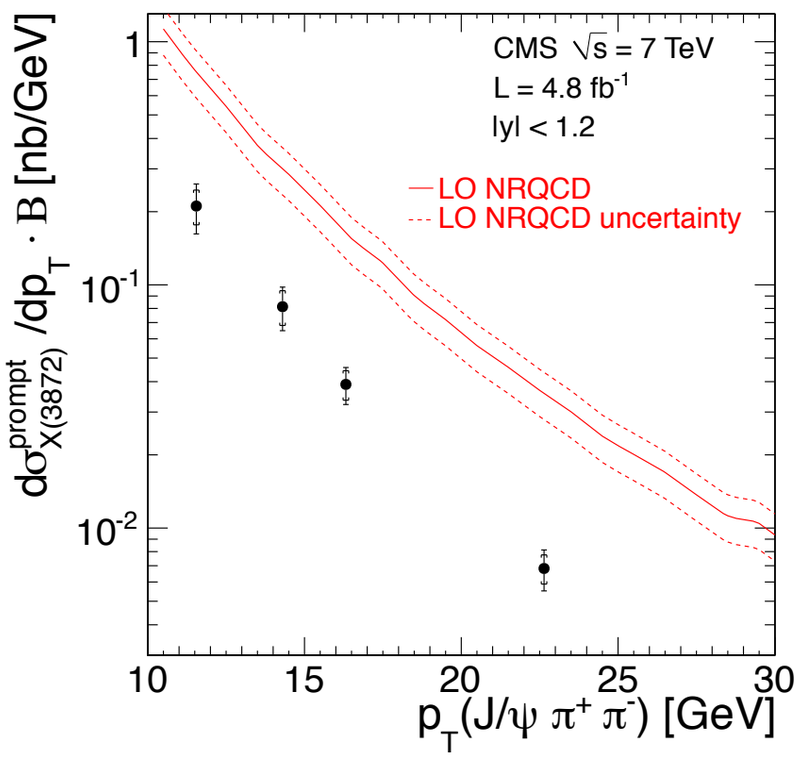
Prompt Xsection

- combining the x-section ratio and non-prompt fraction results with previous CMS measurement of the prompt ψ(2S) x-section

  JHEP 02 (2012) 011

- compared to NRQCD theoretical prediction

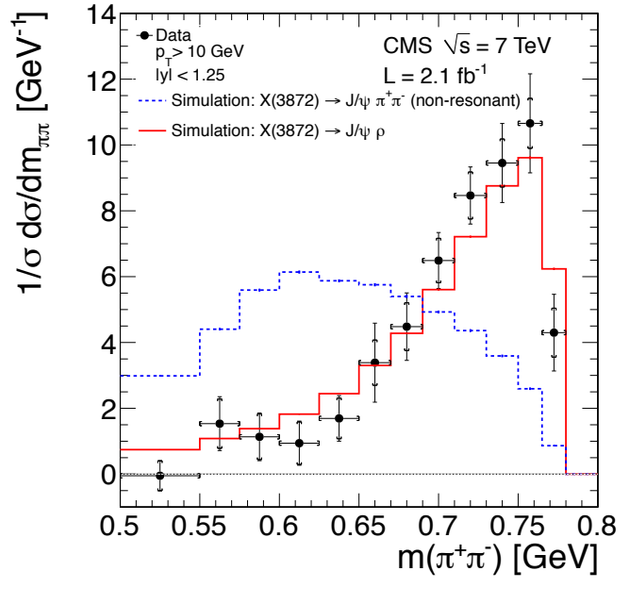
  Phys Rev D81 114018



- NRQCD predictions significantly exceed the measured value, while p_T dependence is reasonably well described

Dipion invariant mass

- $\pi^+\pi^-$ invariant mass distribution studied to investigate decay properties of X(3872)
  - event sample divided in intervals of dipion invariant mass
  - $\pi^+\pi^-$ mass spectrum extracted from signal yields from the fits to data in each bin, after correction for detector acceptance and efficiencies
- data distribution compared to simulations with and w/o intermediate ρ^0 in the $J/\psi\ \pi^+\pi^-$ decay



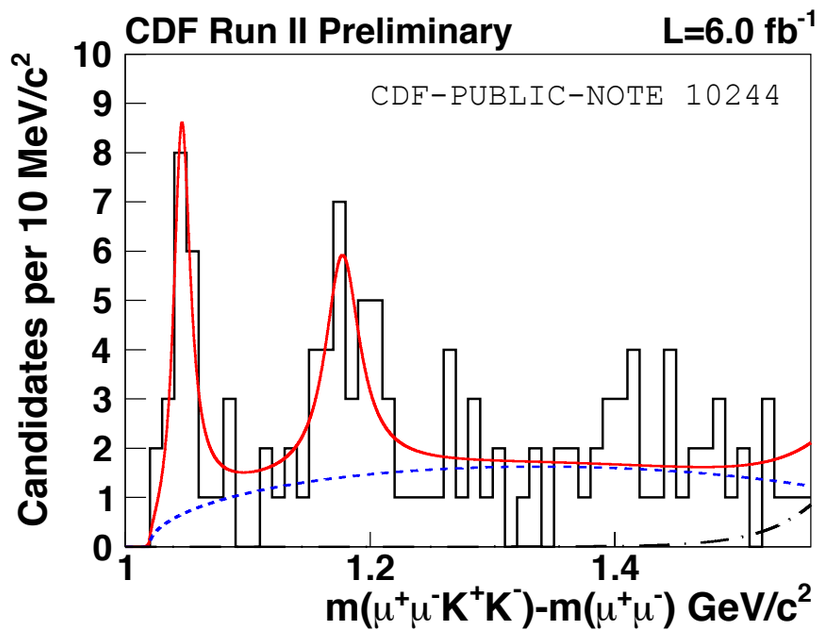
- The assumption of intermediate ρ^0 decay gives better agreement with data

Observation of substructures in the J/ψϕ spectrum

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11026

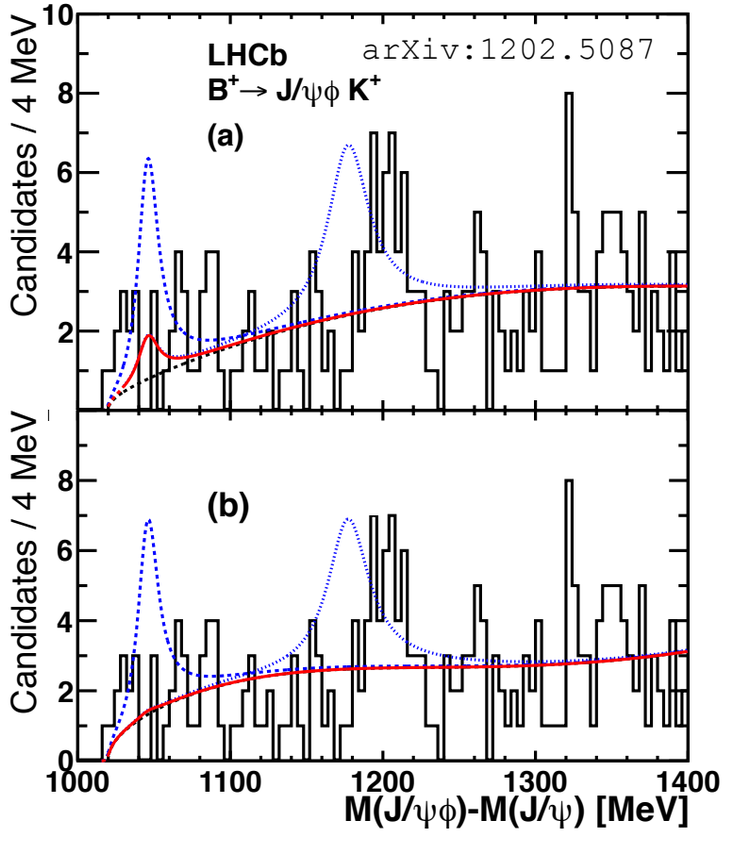
- Discovery of new quarkonium-like states over the last decade, not foreseen in the conventional quark model
  - nature of these entities is still a puzzle (charmed hybrids? tetraquarks? molecular states?)

- CDF reported evidence for a narrow structure Y(4140) with mass $4143.4^{+2.9}_{-3.0}\pm1.2_{(syst)}$ MeV and width $15.3^{+10.4}_{-6.1}\pm 2.5_{(syst)}$ MeV



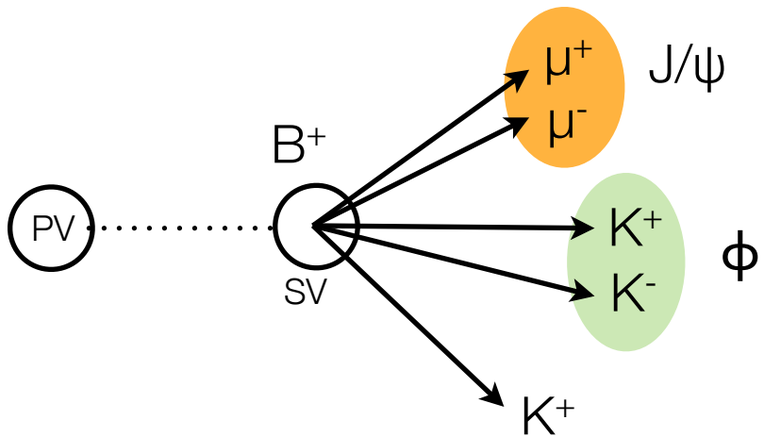
- if confirmed, candidate for an exotic meson
  - Belle could not confirm it
  - LHCb did not confirm the existence of Y(4140) and put an upper limit on its production

- useful to have an independent result
  - **CMS studies the J/ψϕ mass spectrum from exclusive $B^+ \to J/\psi\phi K^+$ decays**



see poster from A. Pompili for CMS

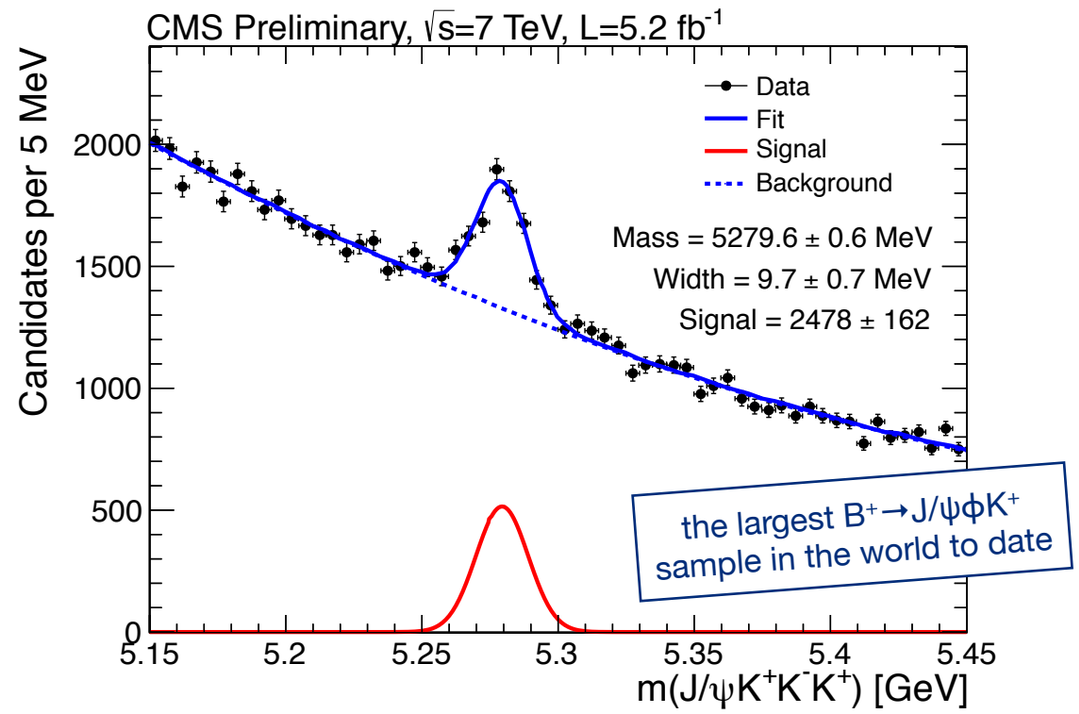
Observation of substructures in the J/ψϕ spectrum

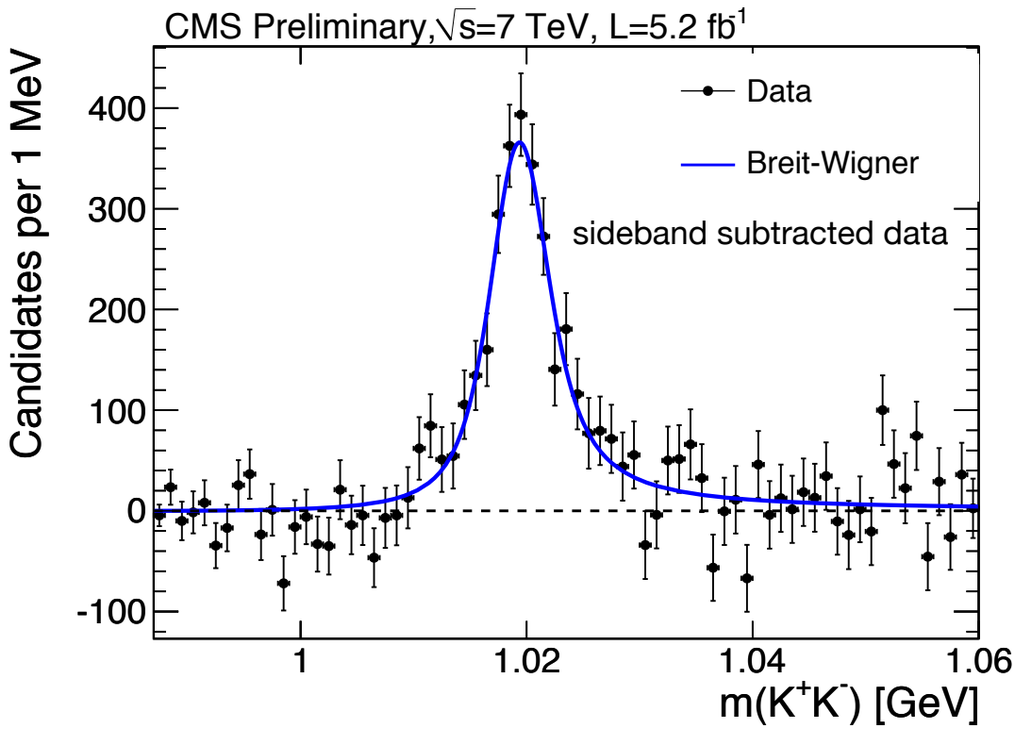


Event selection:

- displaced J/ψ dimuon trigger with p_T(J/ψ) threshold (7 GeV)
- run dependent p_T threshold for each muon
- candidate J/ψ associated to 3 additional charged tracks
- vertex constraining J/ψ mass
- K^+K^- pair with lower mass considered as ϕ
  - must lie in ϕ mass window

2011 data: 5.2 fb^{-1}





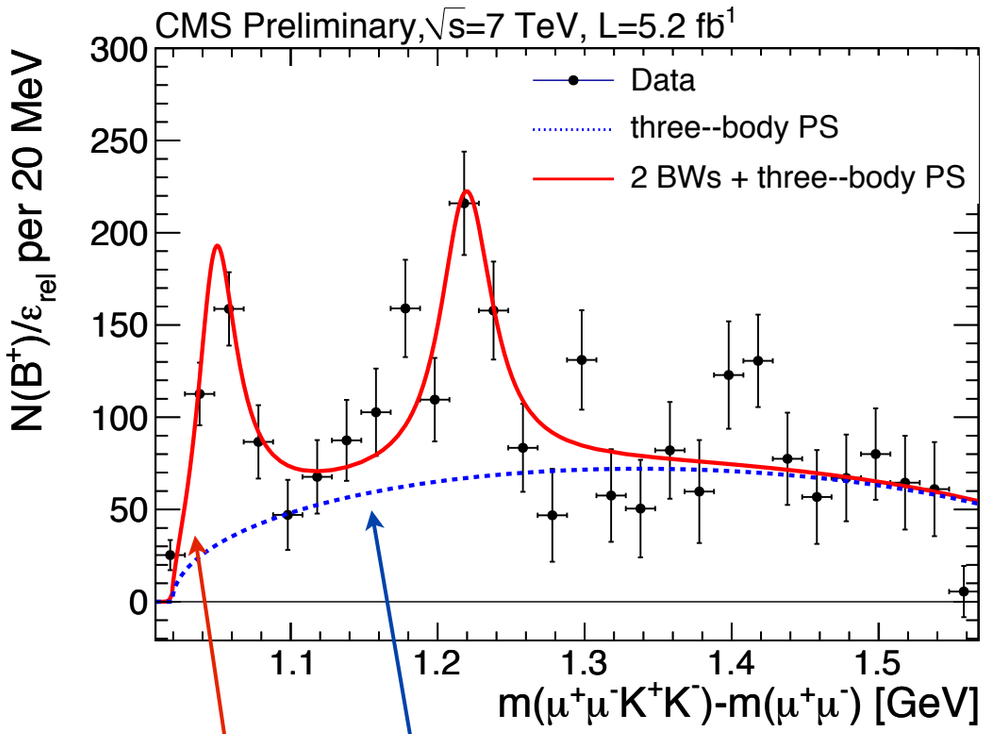
see poster from A. Pompili for CMS

Observation of substructures in the J/ψϕ spectrum

Presence of possible structures investigated using the $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ spectrum.

Δm spectrum obtained by:

- dividing the dataset in 20MeV Δm bins
- extracting the number of B signal in each Δm bin by fitting the J/ψϕK spectrum
- plotting the B^+ yield corrected by relative efficiency



	Yield	Mass
1st structure	355 ± 46	$4148.2 \pm 2.0_{(stat)} \pm 4.6_{(syst)}$ MeV
2nd structure	445 ± 83	$4316.7 \pm 3.0_{(stat)} \pm 7.3_{(syst)}$ MeV

CMS confirmed a structure at 4148 MeV with a significance greater than 5σ and saw an evidence for a second structure in the same mass spectrum

Angular analysis would help elucidate the nature of these 2 structures

Observation of a new Ξ_b baryon

Phys. Rev. Lett. 108 (2012) 252002

- Several predicted baryons with one *s* and one *b* quark:

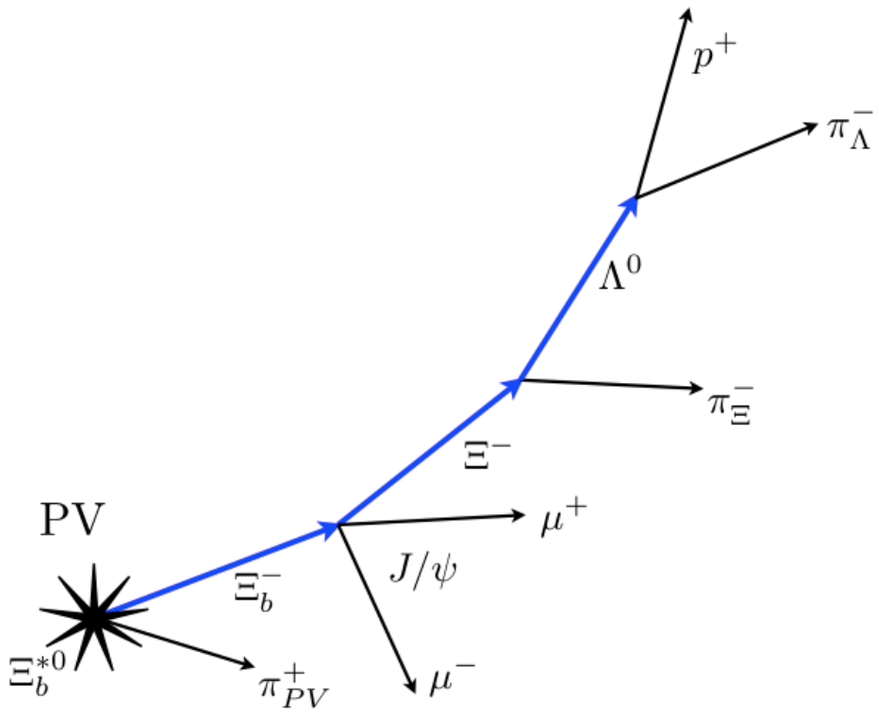
Ξ_b ground state $J^P=1/2^+$	Ξ'_b $J^P=1/2^+$	Ξ^*_b $J^P=3/2^+$	two states with negative P

  - @Tevatron baryons with masses and decay modes consistent with the theoretical predictions for the ground state Ξ_b baryons have been observed, although quantum number not yet established

CMS looks for $\Xi^{*0}_b \rightarrow \Xi^-_b\pi^+$
2011 data: 5.3 fb^{-1}

Event selection:

- Identify the Ξ^-_b and then associate one opposite sign π to form the Ξ^{-*}_b
- J/ψ triggers with p_T(J/ψ) threshold
- 3 secondary vertices in the full event reconstruction
  - K_s and Ω^- mass vetoes applied

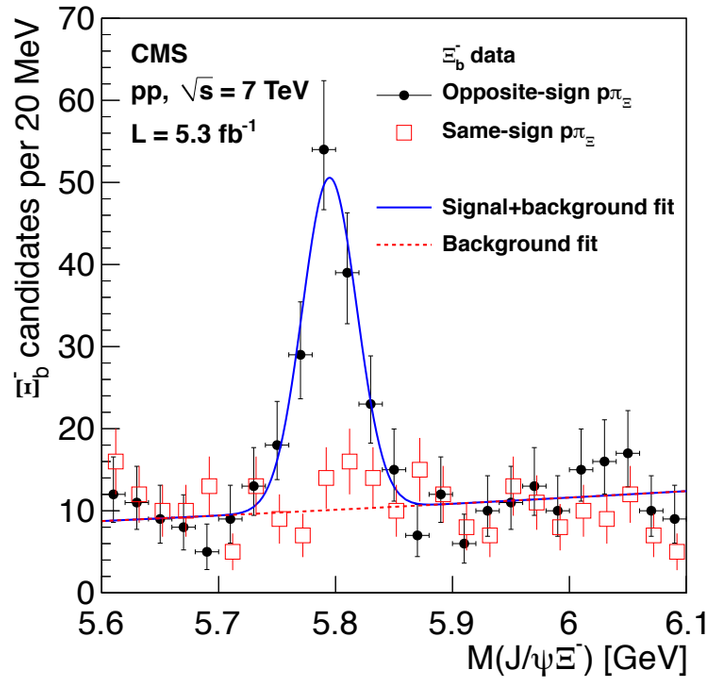


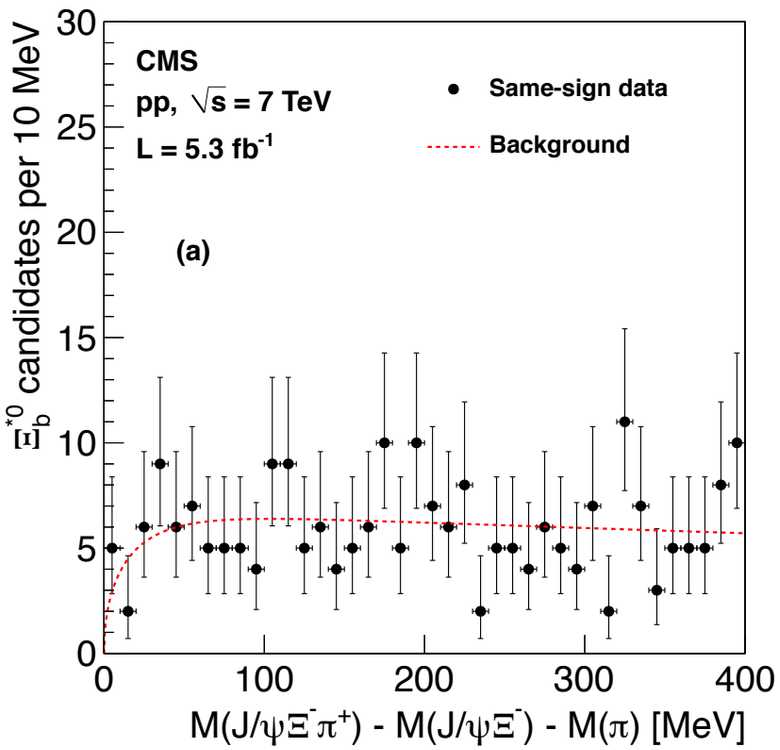
Observation of a new Ξ_b baryon

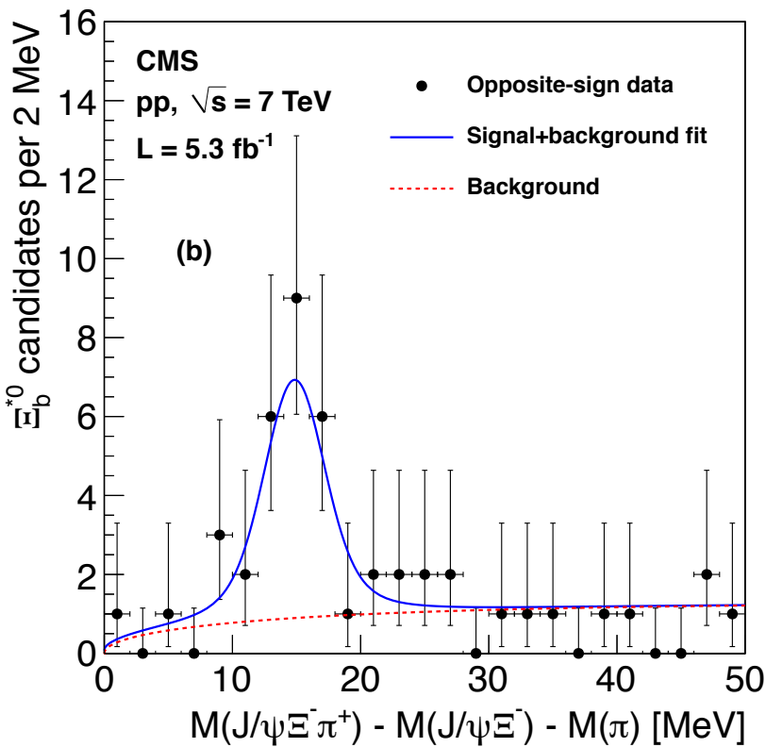
- Ξ^*_b search in the Q value domain
  - Need reliable bkg shape
    - Model built using same sign data to generate randomly uncorrelated values to calculate a Q value for predicting the combinatorial background distribution

$m = 5945.0 \pm 0.7_{(stat)} \pm 0.3_{(syst)} \pm 2.7_{(PDG)}$ MeV

$\Gamma_{BW} = 2.1 \pm 1.7_{(stat)}$ MeV







Signal significance = 6.9σ

No evidence for a similar peak when studying partially reconstructed B hadron decays in MC

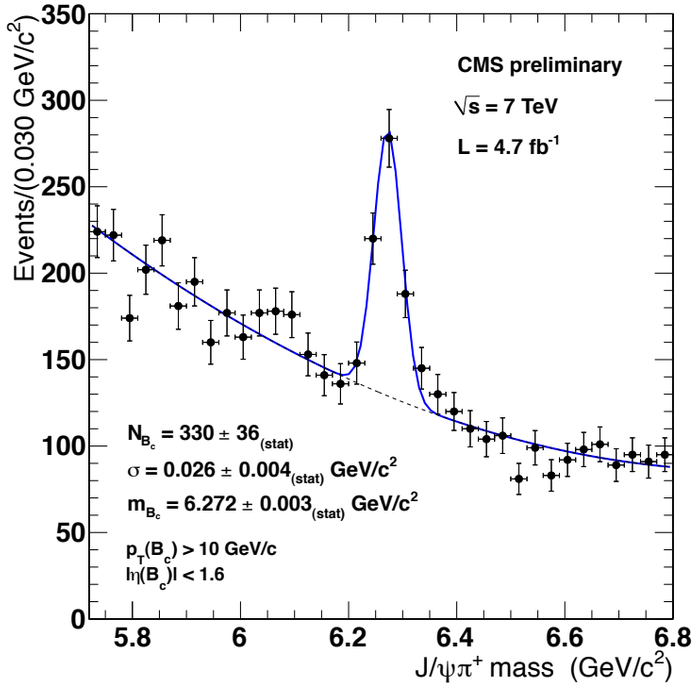
Systematic uncertainties: background model, Q value measurement

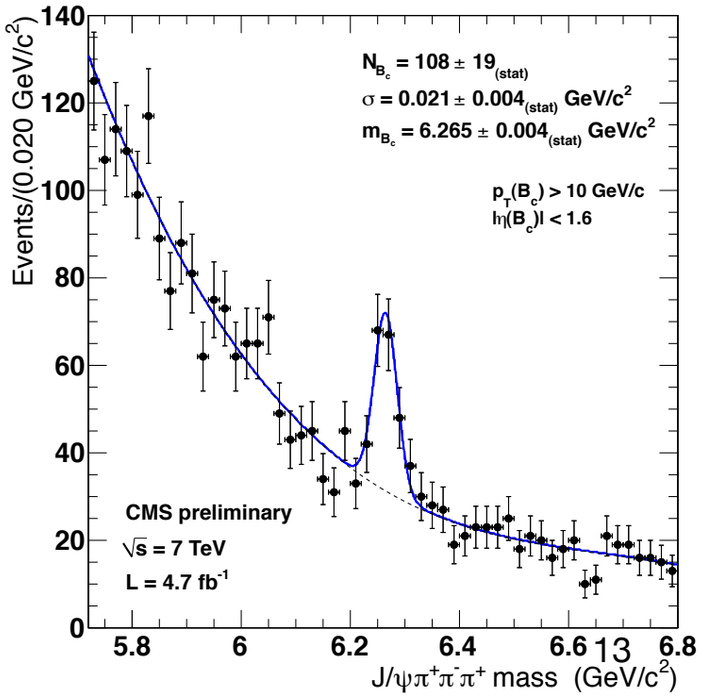
Observation of the B_c meson

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11003

- Unique probe for heavy-quark dynamics since carries two different heavy flavors
  - Both quarks compete in the decay
- Experimental knowledge still rather poor (only produced at hadron colliders)
  - Only few decay channels have been observed so far

2011 data: 4.7 fb^{-1}





Event selection:

- displaced J/ψ dimuon trigger with p_T(J/ψ) threshold (7 GeV)
- kinematic vertex fit to the dimuon candidate + 1 (3) tracks constraining the J/ψ mass
- consider kinematic range $p_T(B_c)>10$ and $|\eta(B_c)|<1.6$

@CMS observed in 2 decay channels:

- $B^+_c \to J/\psi\pi^+$ $\quad S/\sqrt{S+B} = 10.5$
- $B^+_c \to J/\psi\pi^+\pi^-\pi^+$: $\quad S/\sqrt{S+B} = 6.1$

  observed @LHCb for the first time, CMS is the only experimental confirmation so far

LHCb-PAPER-2011-044

Measurement of beauty di-jet angular correlation

- **Studying the hadroproduction of beauty quark pairs allows for a test pQCD**
  - At lowest order, b and b_{bar} quarks emitted back to back
  - At higher order, subprocesses with additional emitted gluons give rise to different topologies in the final state
  - Measurements of beauty di-jet angular correlations provide information on production subprocesses
- Hadroproduction of beauty di-jet expected to be a dominant background for many BSM processes
- Complementary measurement to CMS previous publication JHEP03 136 (2011)
  - B-hadrons have large semileptonic BR → Use of low-p_T single-muon trigger
    - Allows for a larger probe of beauty di-jet phase space than jet triggers
  - Measurements of the **differential cross sections wrt $\Delta\phi$ and ΔR**

Measurement of beauty di-jet angular correlation

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH10019

NEW

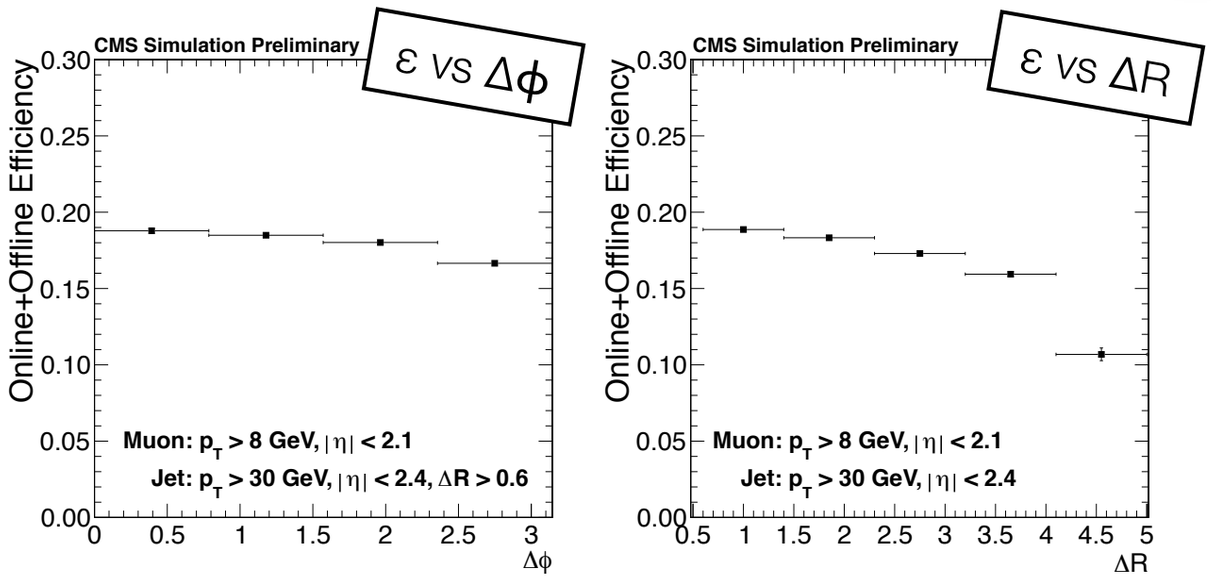
Event selection:

- low-transverse-momentum single-muon trigger and requiring $p_T(\mu) > 8$ GeV and $|\eta(\mu)| < 2.1$
- Jets from ParticleFlow candidates using infrared and collinear safe anti-kt algorithm
  - $p_T > 30$ GeV and $|\eta| < 2.4$
  - classified as mu-jets or non-mu-jets
- at least one mu-jet having an associated tight muon and at least one non-mu-jet
- b-tagging using Track Counting algorithm and applying medium (tight) purity requirements for the mu(non-mu)-jet
- veto on events with 3 or more jets passing this selections (0.7%)

Systematics uncertainties:

- shape of selection efficiencies
- selection purity
- trigger efficiency
- b-tagging scale factors
- integrated lumi
- muon reconstruction scale factor
- jet energy scale and resolution
- fragmentation and pdf

- Selection efficiency from MC



- beauty di-jet signal in data determined by bin-by-bin purity correction to selected events
  - fractional flavor content of the di-jet extracted from a system of 4 equations solved with pseudo experiments and fitting the resulting distributions
  - overall signal purity from data: $0.933 \pm 0.017_{(stat)}$

Measurement of beauty di-jet angular correlation

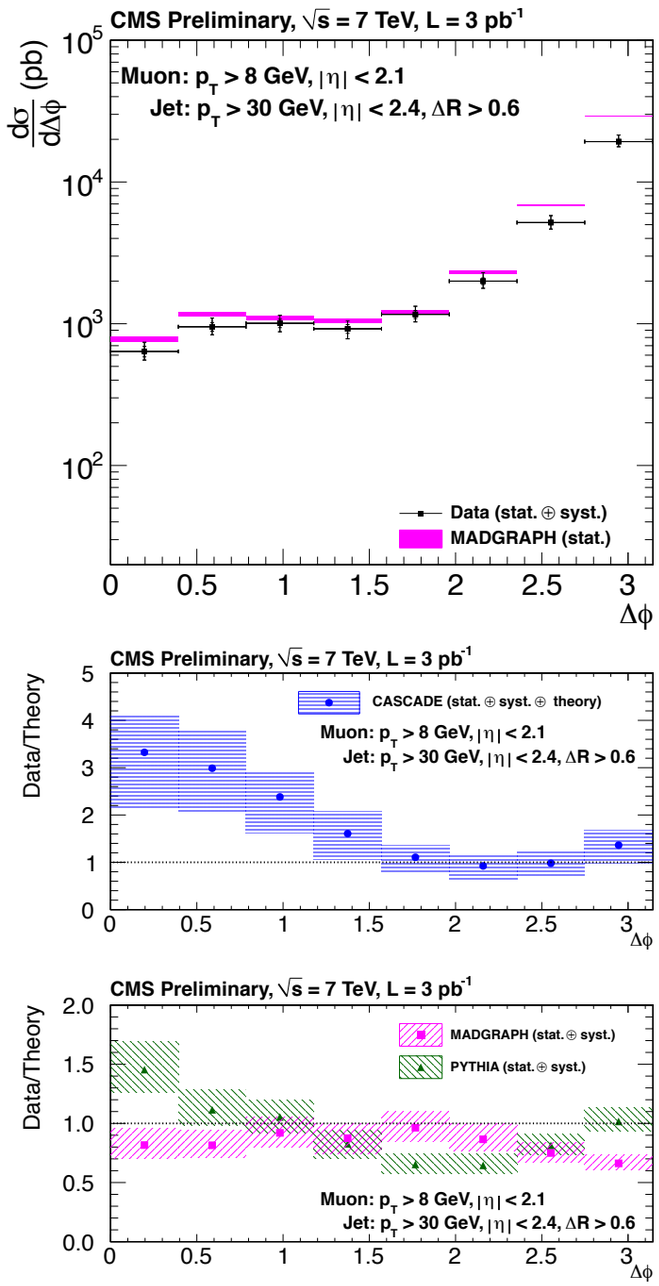
NEW

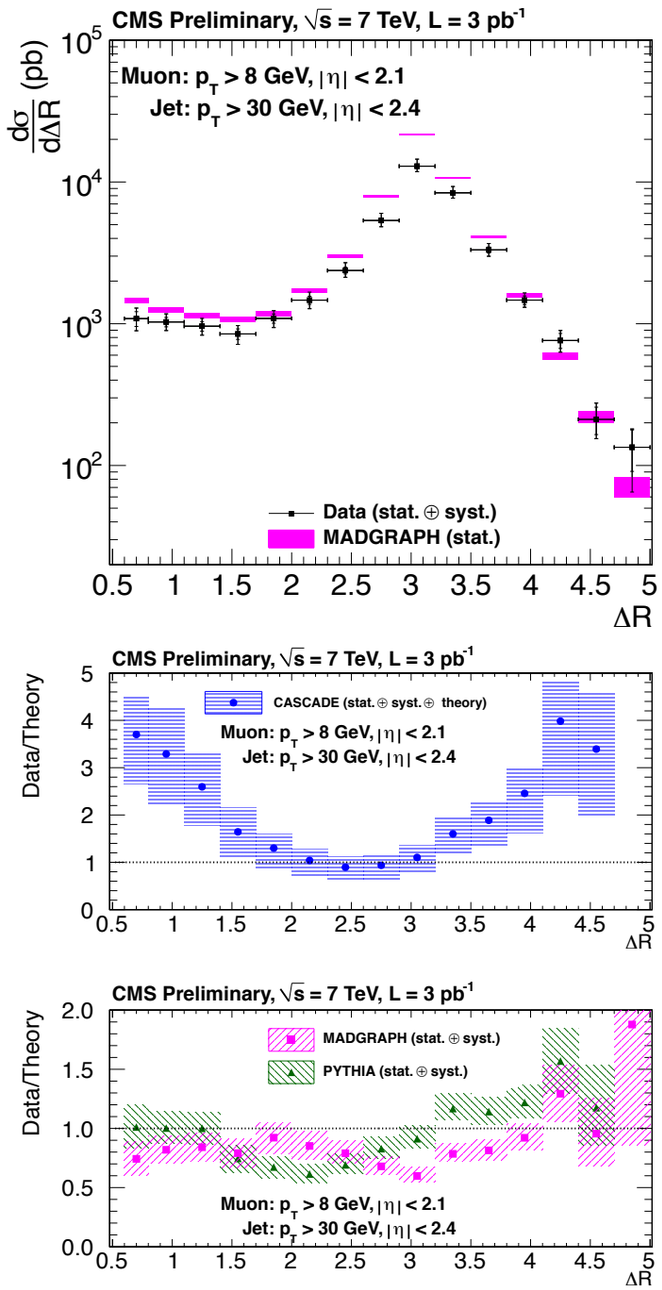
- Experimental cross section per bin of ΔA (ΔA = Δϕ or ΔR)

$$\left(\frac{d\sigma}{d\Delta A}\right)_i = \frac{N^{Data} P_{B\overline{B}}}{\mathcal{L}\Delta A \epsilon_{B\overline{B}}^{Total}}$$

BB_{bar} purity for the i^{th} bin

selection efficiency for the i^{th} bin





Data are compared to theoretical predictions from PYTHIA, MADGRAPH and CASCADE

Simulated predictions are not normalized to data

Total cross section

Data	PYTHIA
$12.2 \pm 0.2\,(\text{stat.})^{+1.6}_{-1.2}\,(\text{syst.})$	$13.18 \pm 0.02\,(\text{stat.})$

MADGRAPH	CASCADE
$17.1 \pm 0.1\,(\text{stat.})$	$9.48 \pm 0.04\,(\text{stat.})^{+1.93}_{-2.65}\,(\text{syst.})$

PYTHIA: disagreement in low Δϕ region while best describing absolute normalization

CASCADE: region of disagreement in both Δϕ and ΔR and underestimates absolute normalization

MADGRAPH: best description of the shape in the low angular region but overestimates absolute normalization

Conclusions

- Thanks to the excellent LHC and CMS performances, important studies have been carried out in the Heavy Flavor physics sector on 2010 and 2011 data

  - Production cross section measurements (X(3872))
  - Observation of new hadrons (Ξ^*_b) and new decay modes ($B_c \rightarrow J/\psi\pi\pi\pi$)
  - Observation of structures in the $J/\psi\phi$ spectrum
  - Measurements of beauty di-jet angular correlations

- **Stay tuned for new results with 2011 and 2012 data!**

All CMS B-Physics results are available at
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

Other CMS contributions @Beauty2013

Ilse Kraetschmer, "Quarkonium polarization from CMS and Tevatron"
Mon, 16:40 - 17:00, Heavy Flavour Production (I)

Torsten Dahms, "Upsilon melting in CMS / ALICE"
Tue, 9:30 - 9:50, Heavy Flavour Production (II)

Marco de Mattia, "Bs --> mu mu in CMS"
Tue, 14:30-14:50, Rare B Decays (I)

Mauro Dinardo, "Measurement of B --> K*0 mu mu in CMS"
Tue, 16:35 - 16:55, Rare B Decays (II)

Luigi Guiducci, "ATLAS, CMS and LHCb Trigger/DAQ systems for flavour physics"
Wed, 14:40 - 15:10, Aspects of LHC Data Taking

Poster session:

Alexis Pompili, "Observation of two structures in the J/psi phi mass spectrum of exclusive B+ --> J/psi phi K+ decays in CMS"

Martino Dall'Osso, "Measurement of the X(3872) production cross section via decays to J/psi pi pi"

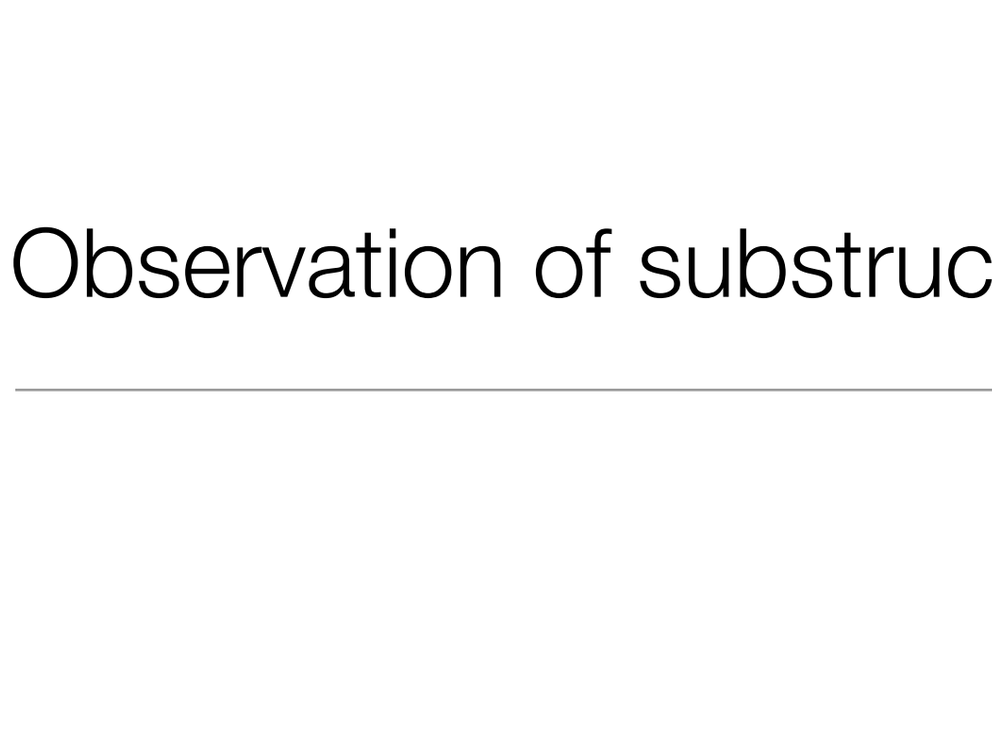
Backup

Bibliography

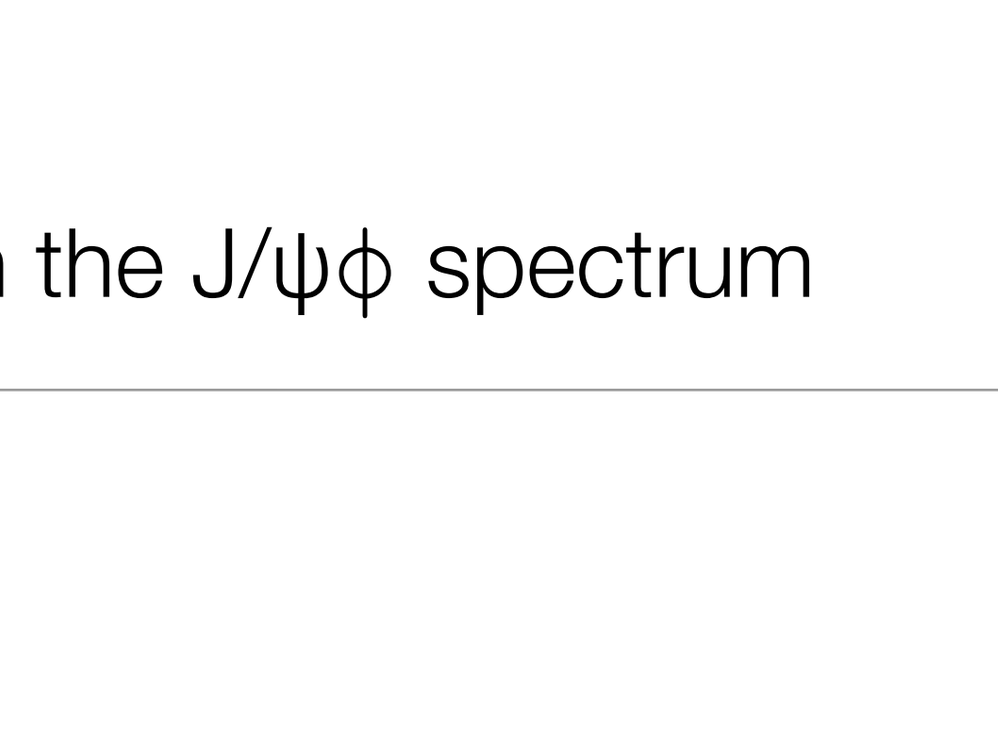
- **X(3872) cross section** *arXiv:1302.3968, accepted for publication by JHEP*
- **Observation of Ξ^{*0}_b** *Phys. Rev. Lett. 108 (2012) 252002*
- **Observation of B_c** *CMS-PAS-BPH-11-003*
- **Structures in J/ψϕ spectrum** *presented @HCP2012*
- **Measurement of beauty di-jet angular correlation** *CMS-PAS-BPH-10-019*

Observation of substructures in the J/ψϕ spectrum

Fit with only bkg hypothesis



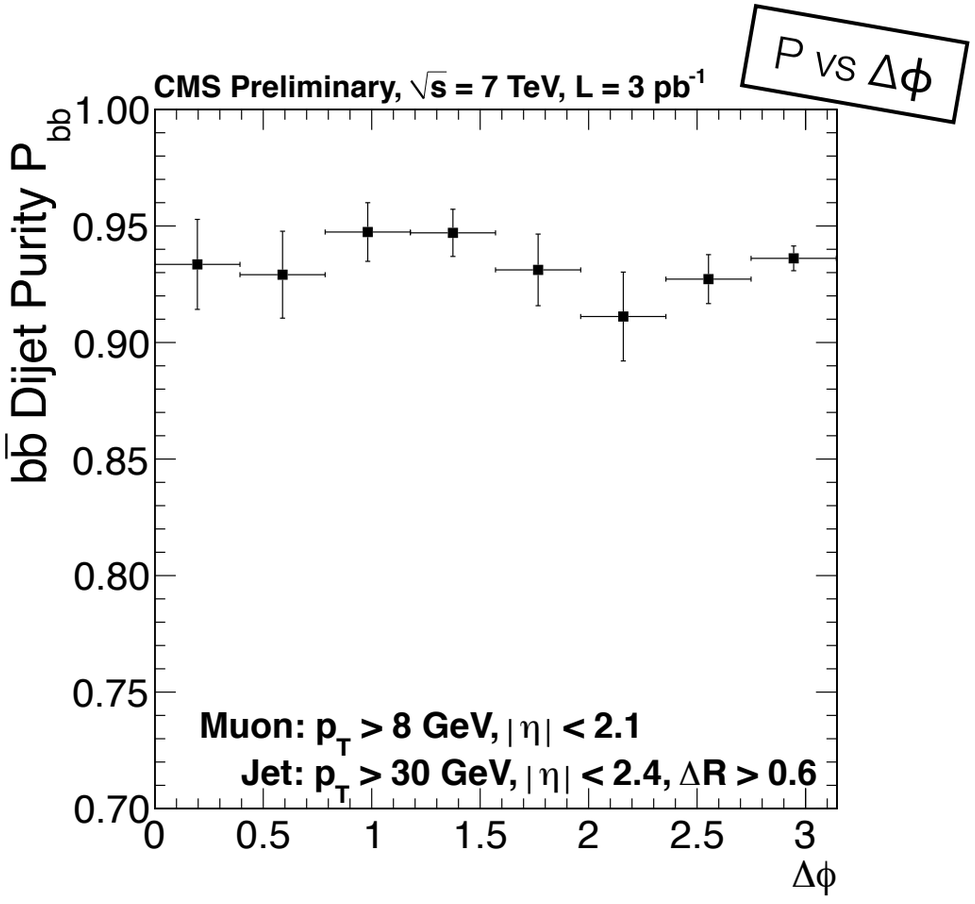
Fit with only one signal hypothesis

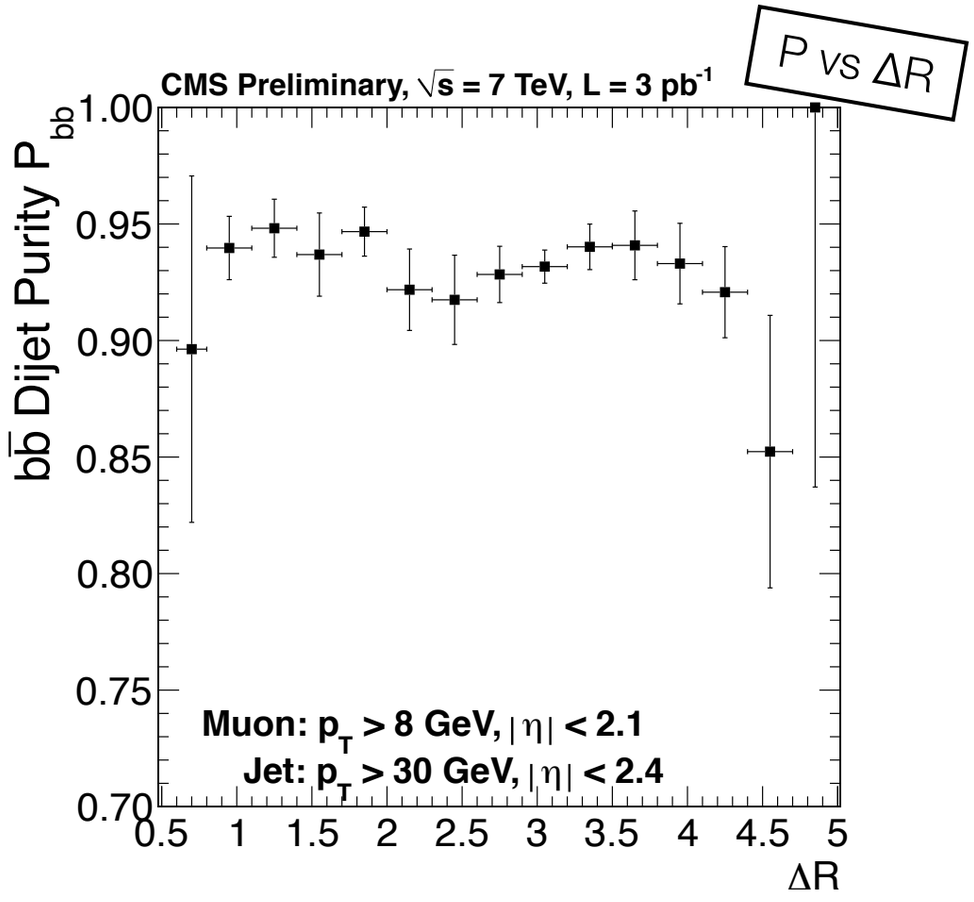


Measurement of beauty di-jet angular correlation

- The overall purity is calculated by taking the Integral of raw dN/dA plots from data before and after the purity correction

$$P_{Overall} = \frac{\sum_i N_i^{Data} \cdot P_{BB_i}}{\sum_i N_i^{Data}}$$

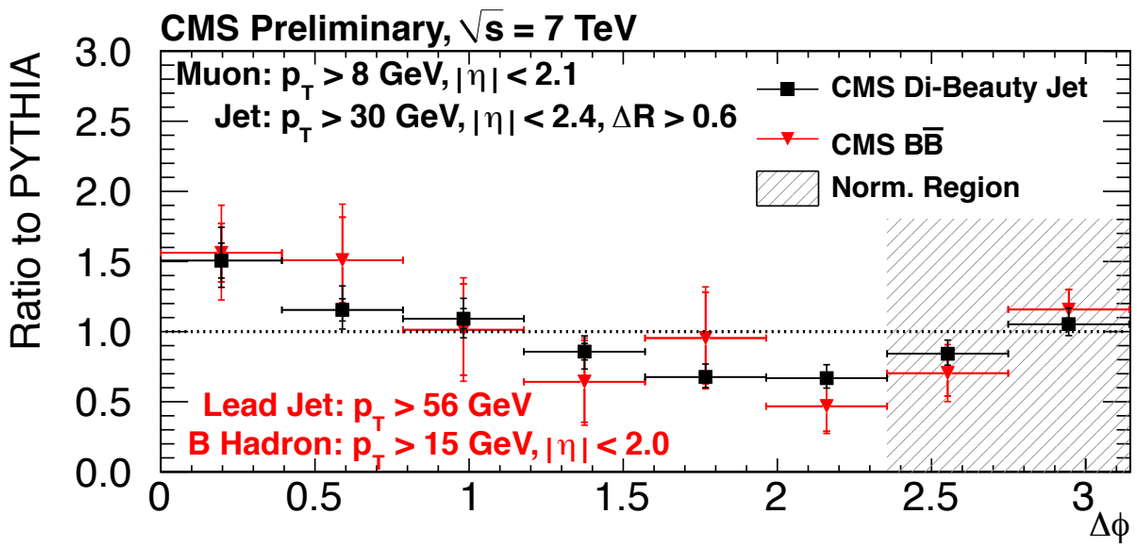




Measurement of beauty di-jet angular correlation

Comparison of the data ratio to PYTHIA differential production cross section with results from previous CMS Collaboration results published in JHEP 1103 (2011) 136.

The PYTHIA theoretical prediction was normalized to data in the region $\Delta\phi > 6\pi/8$ prior to forming the ratio.



The PYTHIA theoretical prediction was normalized to data in the region $2.4 < \Delta R < 4.4$ ($2.3 < \Delta R < 4.4$) for the down triangles (squares) prior to forming the ratio.