# Bottom Production, Spectroscopy and Lifetimes

Physics in Collision 2012

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# Introduction and Overview

- The topics of Heavy Flavor **production**, **spectroscopy** and **lifetimes** are vast.
- Experiments are providing a plethora of results.
- Not only it is impossible to describe them all, but even attempting a categorization is not trivial ! Limited here to hadron (and ep) colliders. I apologize for not mentioning your favored result.

**Production**:

- the area with the largest number of measurements
- overview : importance of studying HF production, theoretical framework
- we will try to group measurements and provide one/two examples for each group

**Spectroscopy**:

- quick introduction
- description of the latest findings in HF spectroscopy and precision measurements

**Lifetimes**:

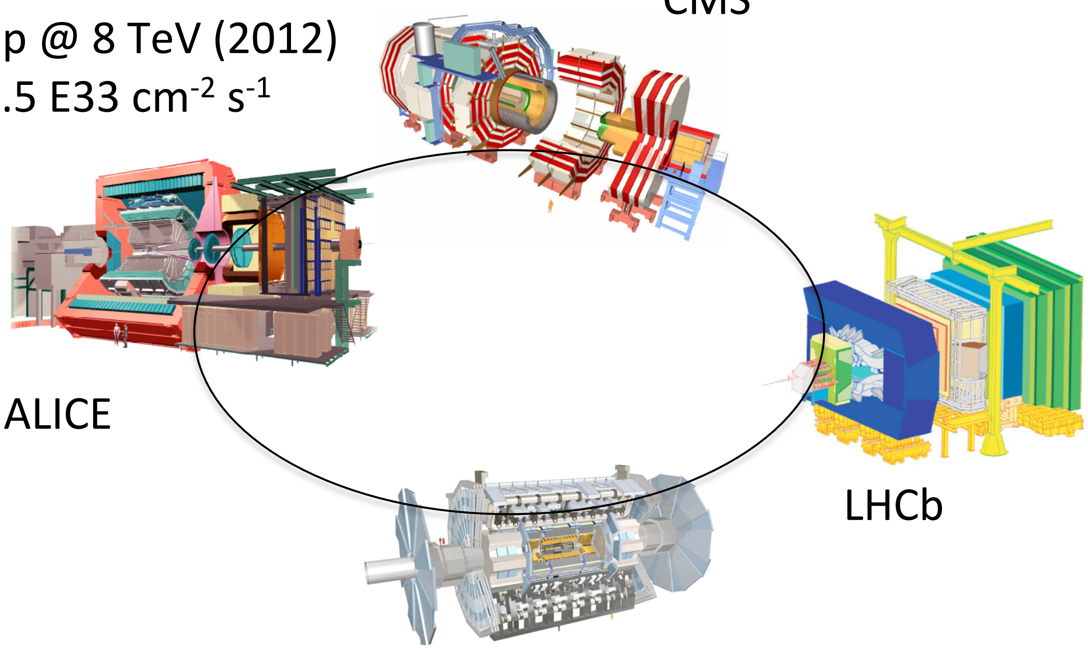
- why measure lifetimes ?
- the $\Lambda_b$ case
- the $B_s$ case

# Instruments

# Instruments

**LHC**
pp @ 8 TeV (2012)
7.5 E33 $cm^{-2}$ $s^{-1}$

CMS



ALICE

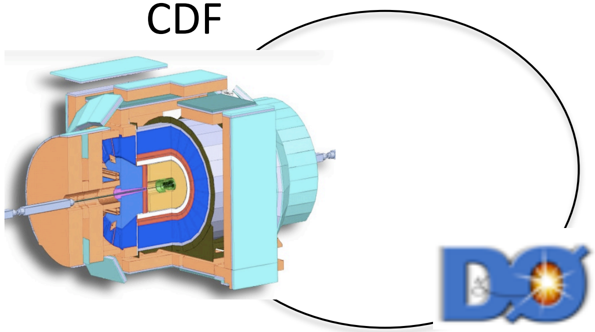
LHCb

ATLAS

**Tevatron**

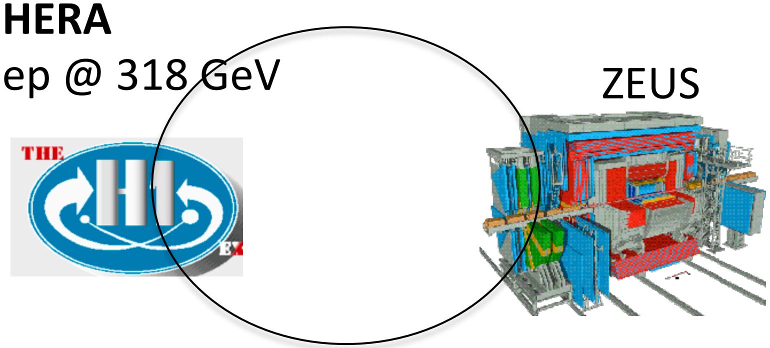
ppbar @ 1.96 TeV
4 E32 $cm^{-2}$ $s^{-1}$

CDF




**HERA**
ep @ 318 GeV

ZEUS

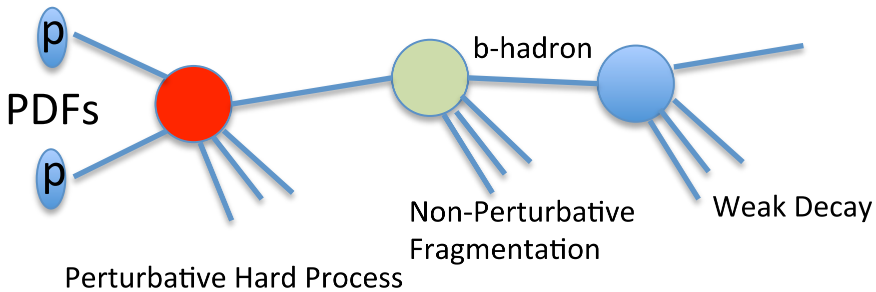



ATLAS and CMS tightened their **trigger** requirements in 2011/2012 runs leaving relatively less space for HF physics (with notable exceptions). Also high pileup makes measurements more difficult.

# b (Heavy Flavor) Production

# Understanding b  (Heavy Flavor) Production

- HF production is one of the **ultimate tests of QCD**, allowing to probe our understanding of the fundamental constituents  of matter and their interactions.




PDFs
Hard scattering
Fragmentation
Decay

$$\frac{d\sigma(b \to B \to J/\psi)}{dp_T} = \frac{d\sigma(b)}{d\hat{p}_T} \otimes f(b \to B) \otimes g(B \to J/\psi)$$

from Cacciari

- When things seemed obvious, the community was hit by the x50 discrepancy in J/ψ  production at Tevatron,  x3 discrepancy in B production: a lesson of humility !

  - Most cited  theoretical frameworks include :

FONLL, MC@NLO, POWHEG    for **b hadron production**

NRQCD    for **quarkonia**

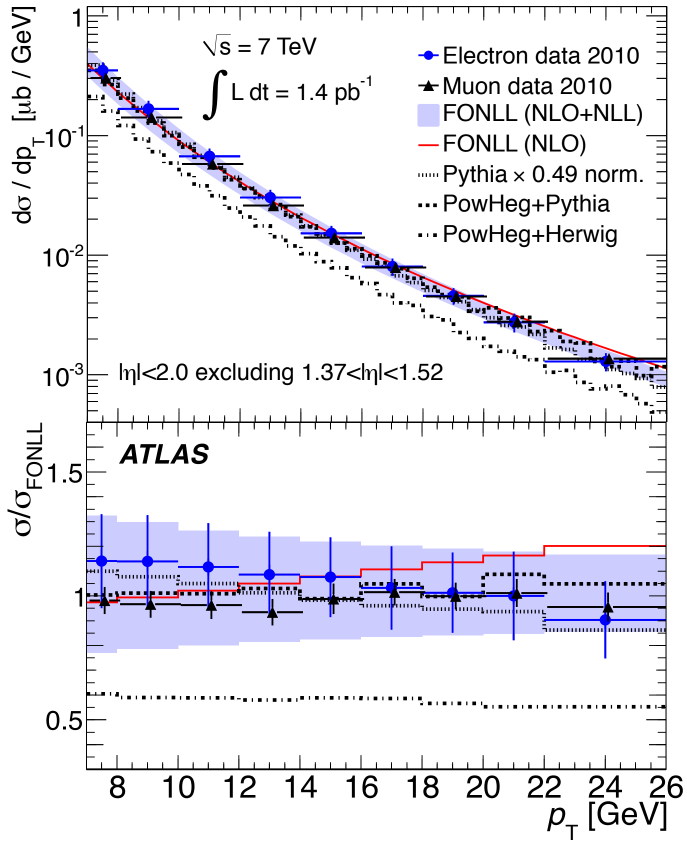
# Measuring b (Heavy Flavor) Production

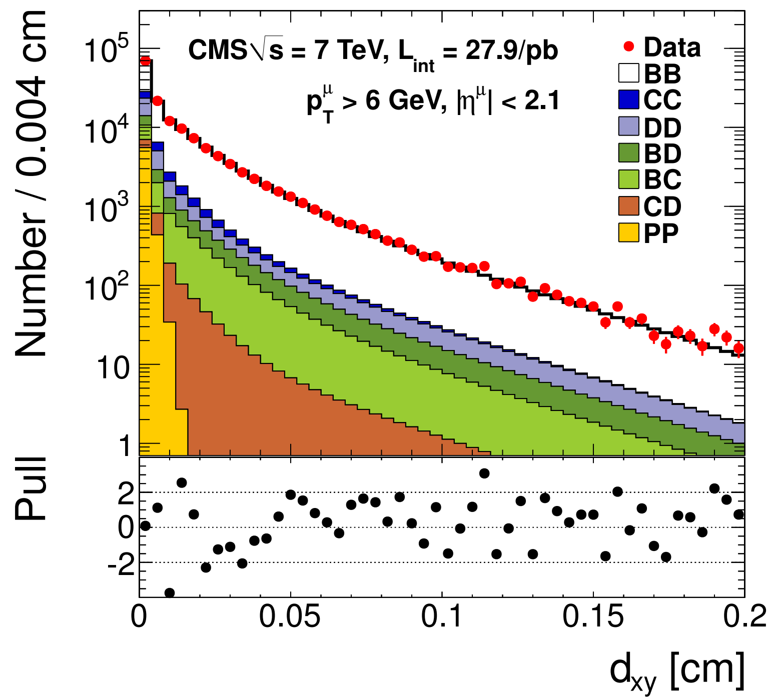
HF production can be studied in several ways :

- **Inclusive** measurements with **e/μ** in the final states
  *e.g. pp → bb+X → μμ+X*
- **Inclusive** measurements HF + X
  *e.g. pp → displaced J/Ψ + X*
- HF in association with **jets, b-jets**
  *e.g. D* in jets*
- **Exclusive** production ($B^+$, $B^0$, $B_s$, $\Lambda_b$)
  *e.g. pp → $B^+$ + X → J/Ψ + $K^+$ +X*
- **Onia** production (prompt and non-prompt J/ψ and ψ(2S), Υ(nS), ratios, polarization)
- HF in association with **vector bosons**
  *e.g. pp → Z,W + b talk by Bob Hirosky*
- **Double J/ψ** , multi-c final states *talk by Ellie Dobson*

# Inclusive e/μ cross sections from HF decays

PLB 707(2012) 438 (ATLAS)
JHEP 06 (2012) 110 (CMS)




CMS: $d_{xy}$ used to select b component

ATLAS: W/Z/γ* contributions are subtracted, leaving only contributions from HF
Excellent agreement with FONLL.

$$\sigma(\mathrm{pp} \to \mathrm{b\bar{b}X} \to \mu\mu\mathrm{X}', p_\mathrm{T} > 4\,\mathrm{GeV}, |\eta| < 2.1) =$$
$$26.4 \pm 0.1\ (\mathrm{stat.})\ \ \pm 2.4\ (\mathrm{syst.})\ \ \pm 1.1\ (\mathrm{lumi.})\ \ \mathrm{nb}$$

Compatible with MC@NLO

# Inclusive b production cross section at 7 TeV (ATLAS)

Nucl. Phys. B 864 (2012) 341

$H_b \rightarrow D^{*+} \mu^- X$

↳ $\pi^+ D^0 (\rightarrow K^- \pi^+)$

Compared with

LHCB ($D0\mu\nu X$) Phys. Lett. B 694 (2010) 209

($J/\psi$ X) Eur. Phys. J. C 71 (2011) 1645

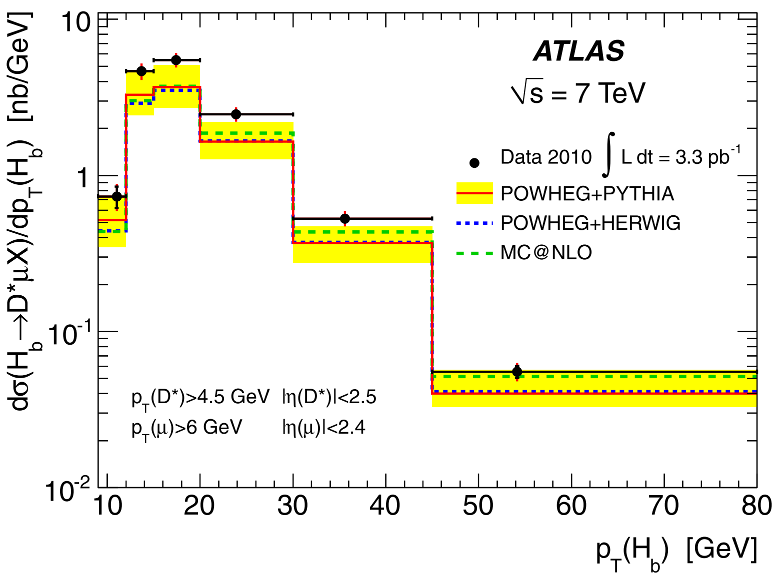
ALICE ($J/\psi$ X) arXiv:1205.5880v1

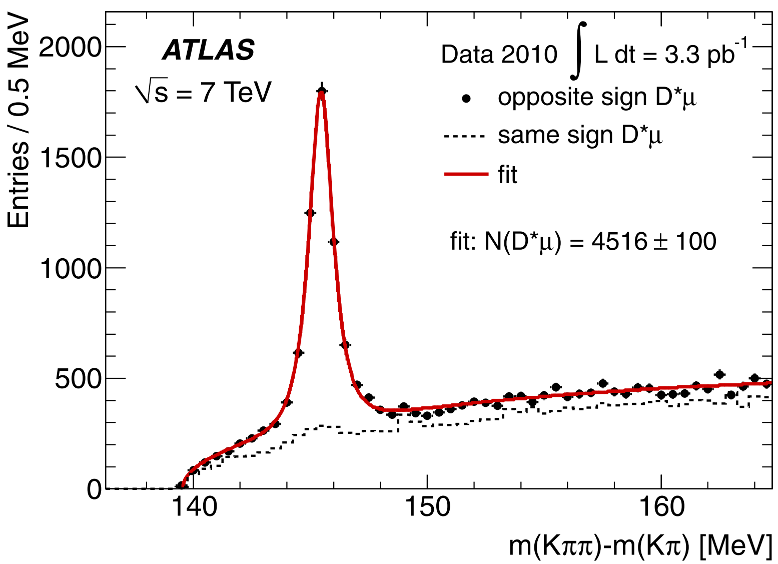
$H_b$ : hadron containing a b quark (mostly $B^0$)

$p_T(H_b) > 9$ GeV, $|\eta(H_b)| < 2.5$

Higher than predictions, but consistent within uncertainties

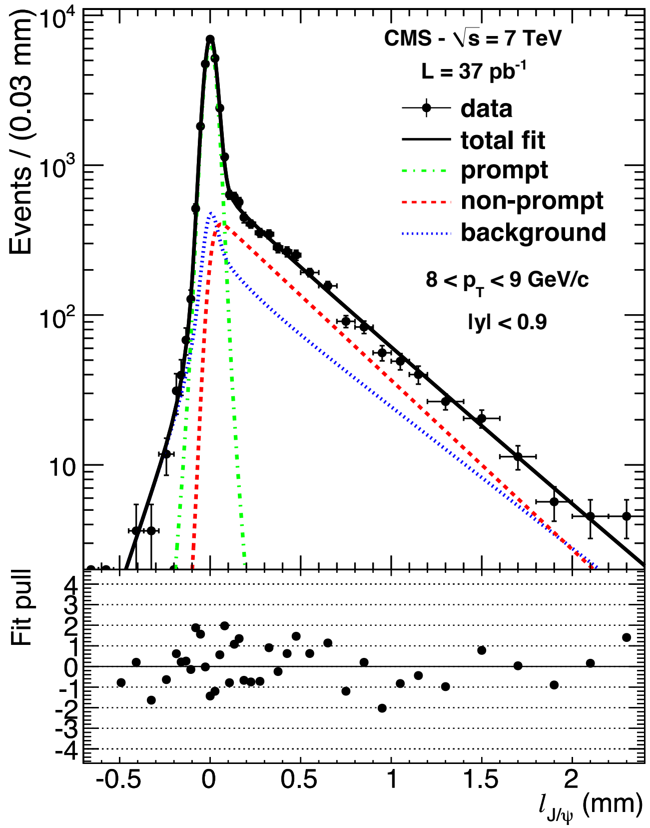
Complemented by a similar measurement in the c sector : D* in jets Phys. Rev. D 85 052005(2012) which shows a x2/x3 discrepancy with the models considered

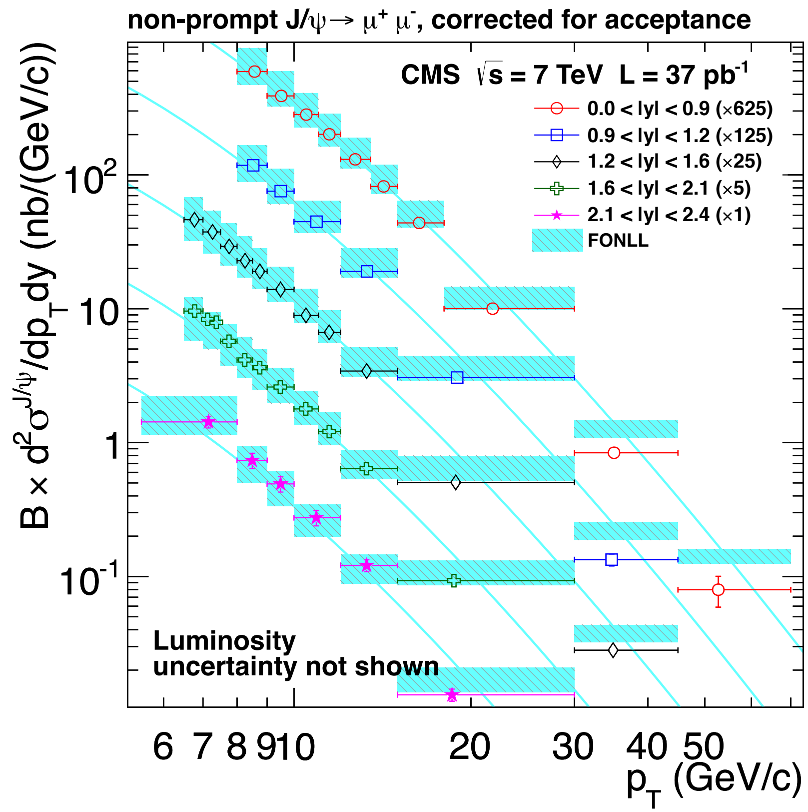


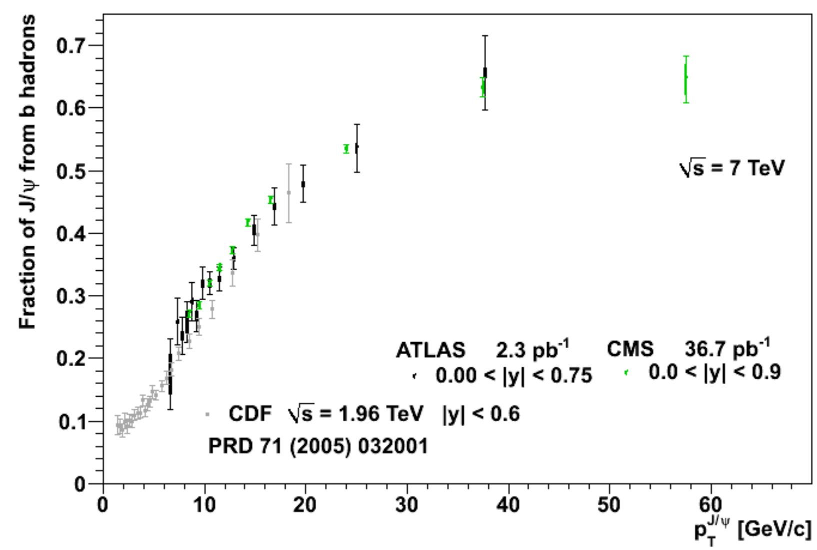
# Inclusive J/ψ X production

*JHEP 02 (2012) 011*




$$\ell_{J/\psi} = L_{xy} \cdot m_{J/\psi} / p_T$$




- Technique: 2D fits to mass and lifetime, per event ε corrections.
- Good agreement with NLO NRQCD (prompt) and FONLL (non-prompt)

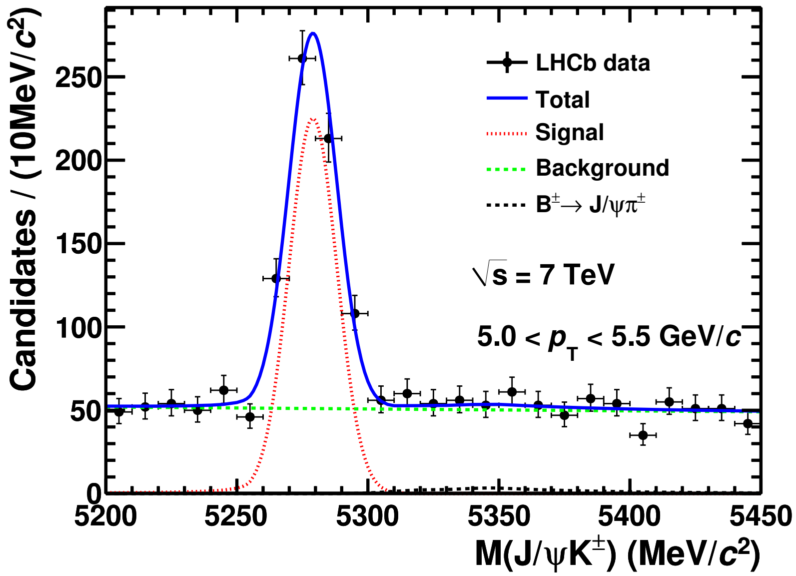
# $B^{\pm}$ production cross section at 7 TeV (LHCb)

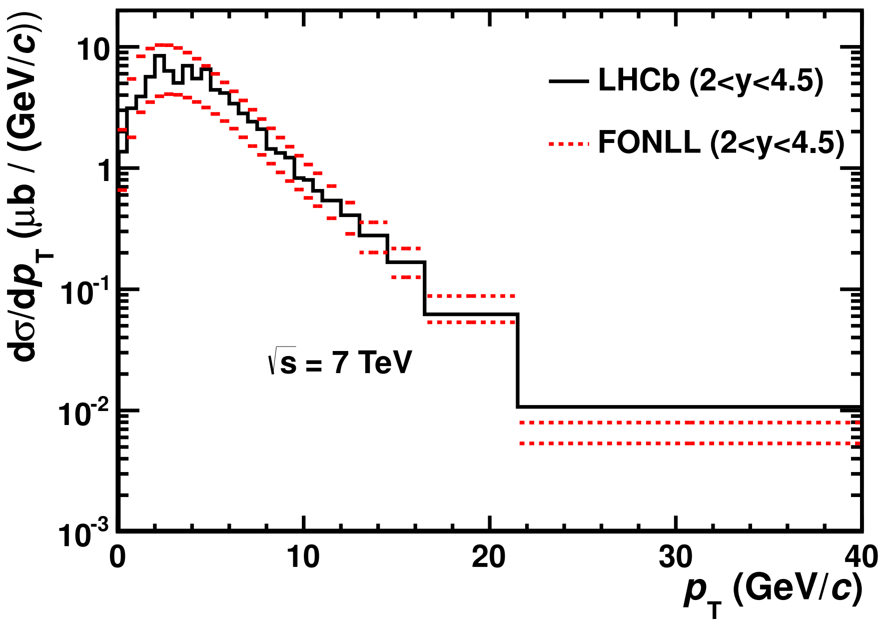
JHEP 04(2012) 093

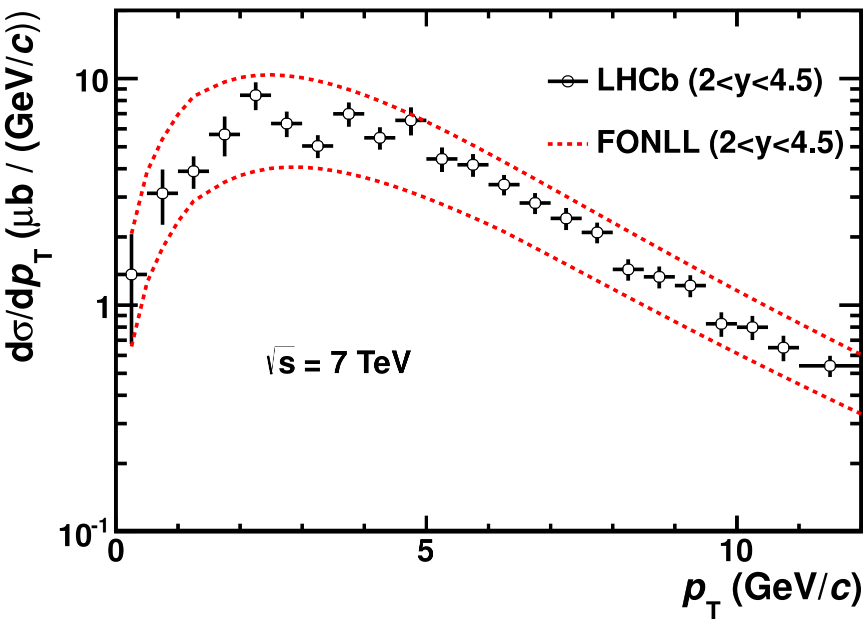
Exclusive study :

$B^{\pm} \rightarrow J/\psi\, K^{\pm}$ , 35 $pb^{-1}$

- $0 < p_T(B) < 40$ GeV, $2.0 < y < 4.5$
- $\sigma = 41.4 \pm 1.5 \pm 3.1$ μb
- Good agreement with FONLL within uncertainties
- First measurement in the forward region
- Updates planned



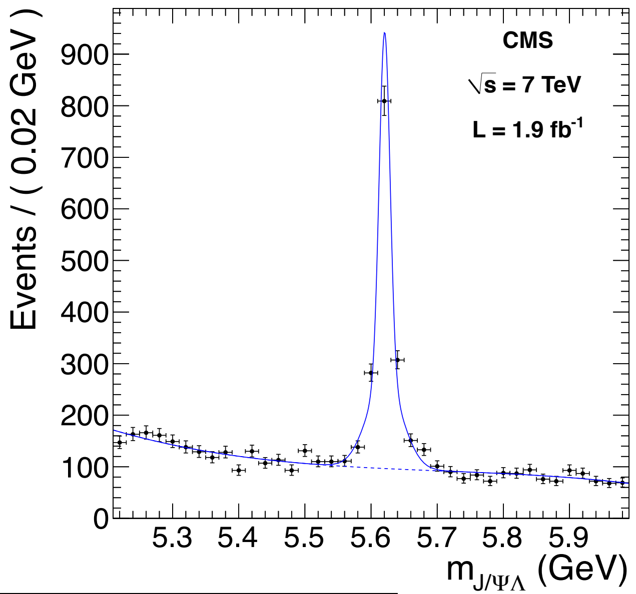
Phys. Lett. B714 (2012) 136

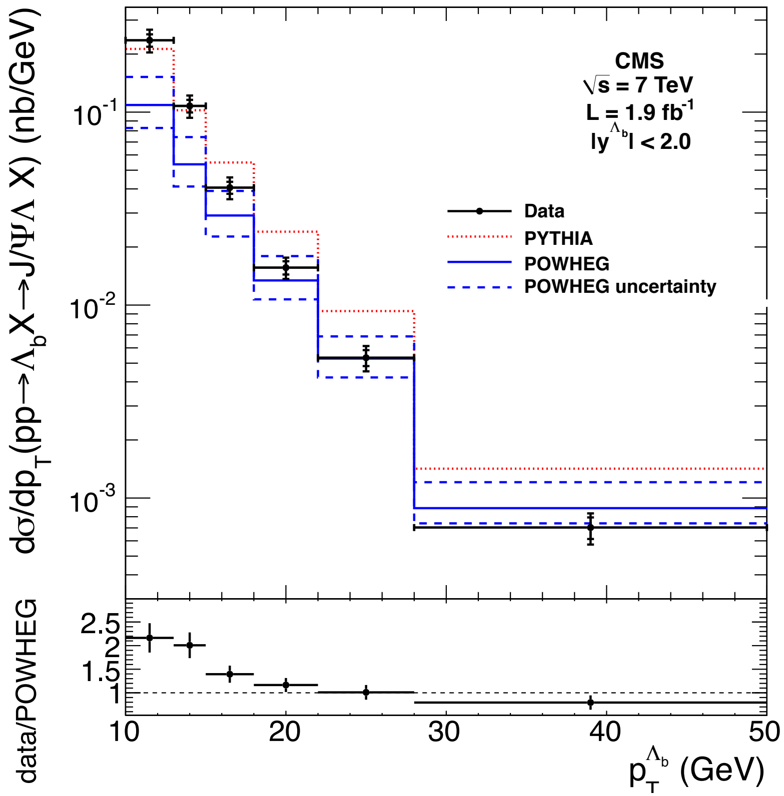
# $\Lambda_b$ differential cross section and asymmetries

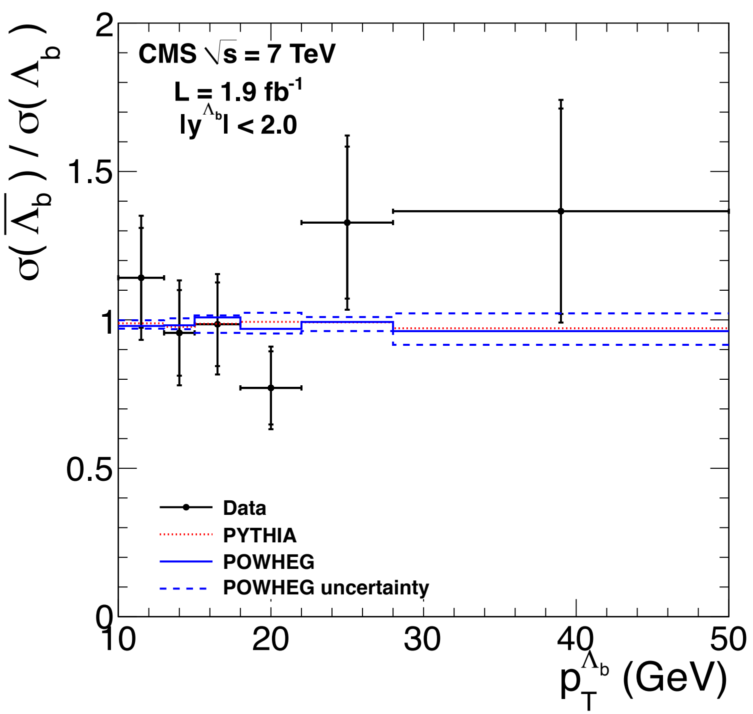
$$\Lambda_b \to J/\psi \Lambda^0 \to \mu\mu p \pi^-$$

Displaced J/Ψ trigger

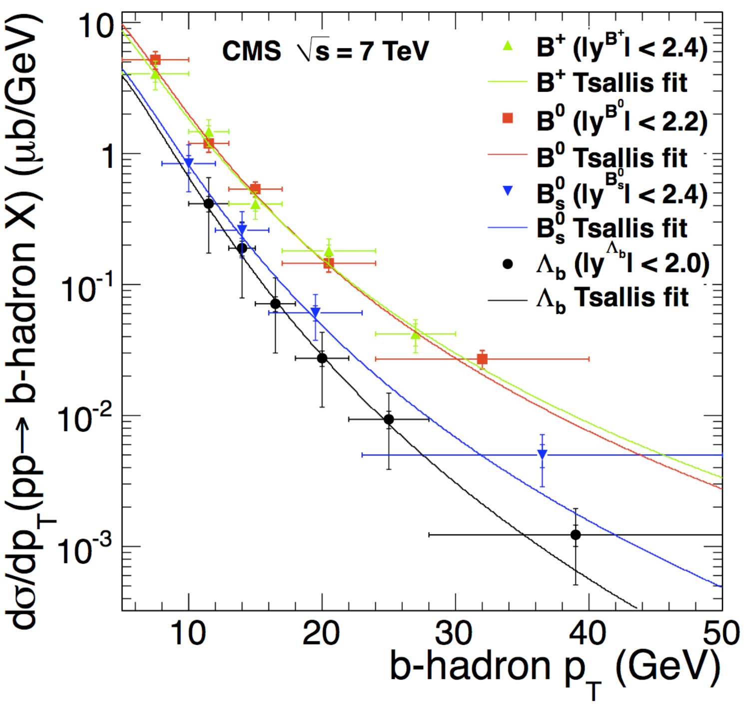
- Spectrum slightly steeper than expected
- No evidence of asymmetries

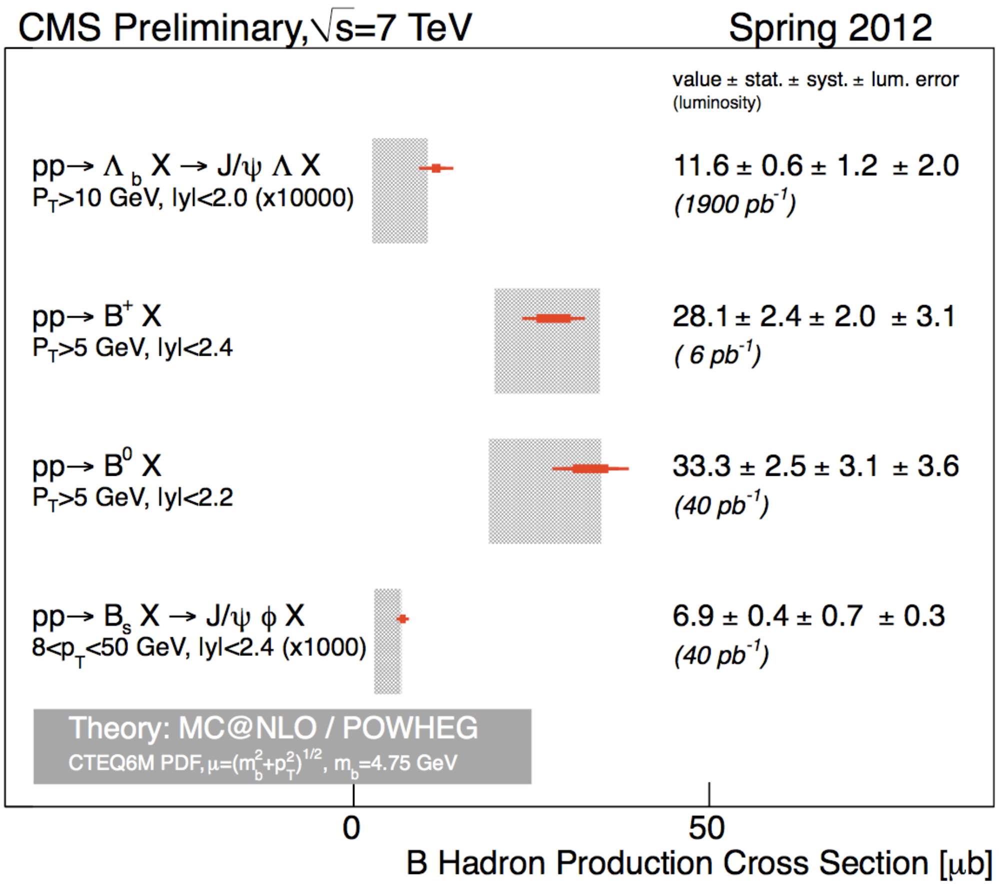


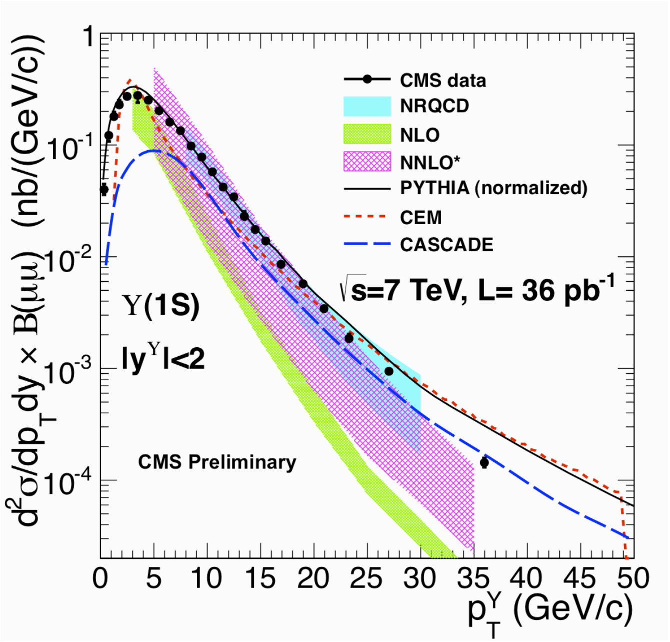



# CMS exclusive b-hadron production summary

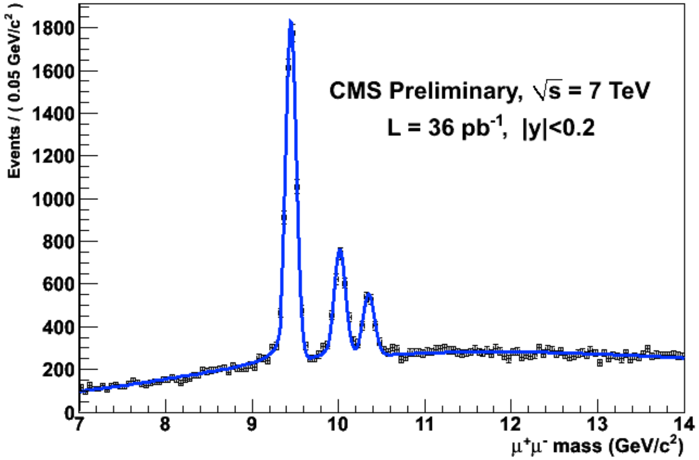


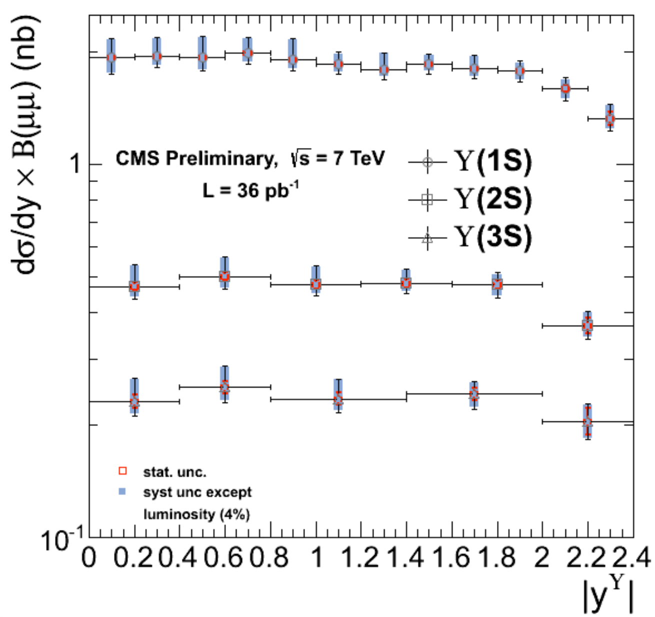



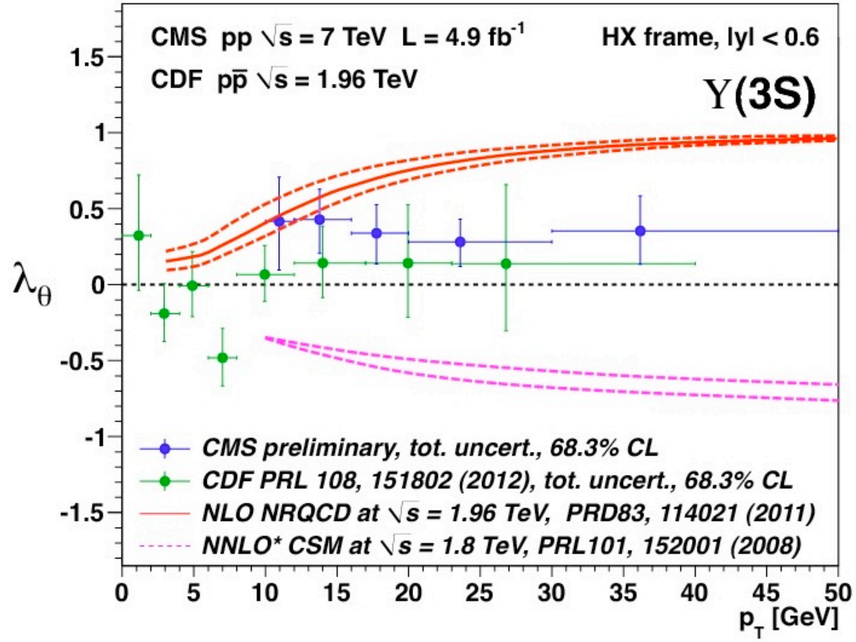
# Υ Production and Polarization




CMS BPH-11-001
CMS BPH-11-023




Υ production in agreement with NRQCD
No polarization for Υ(1,2,3S) !

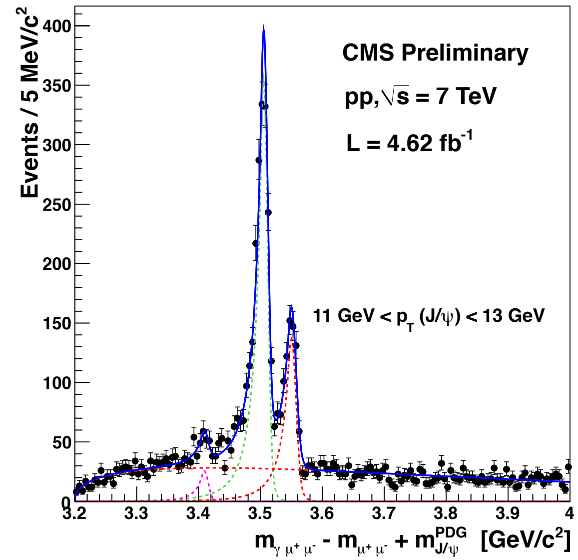
# Onia: $\chi_{c2} / \chi_{c1}$ prompt production ratio

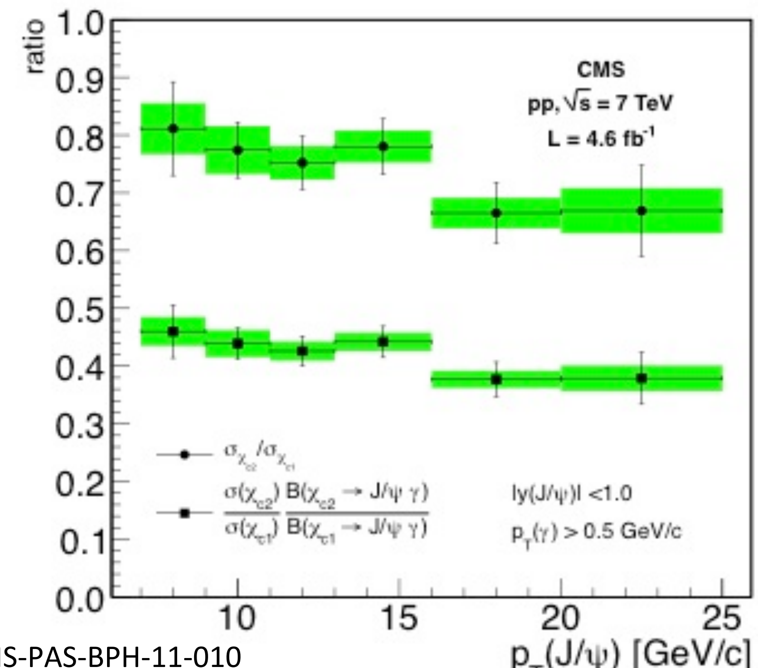
A nice quantity to measure because many experimental and theoretical uncertainties cancel

$$\chi_c \rightarrow J/\psi + \gamma$$

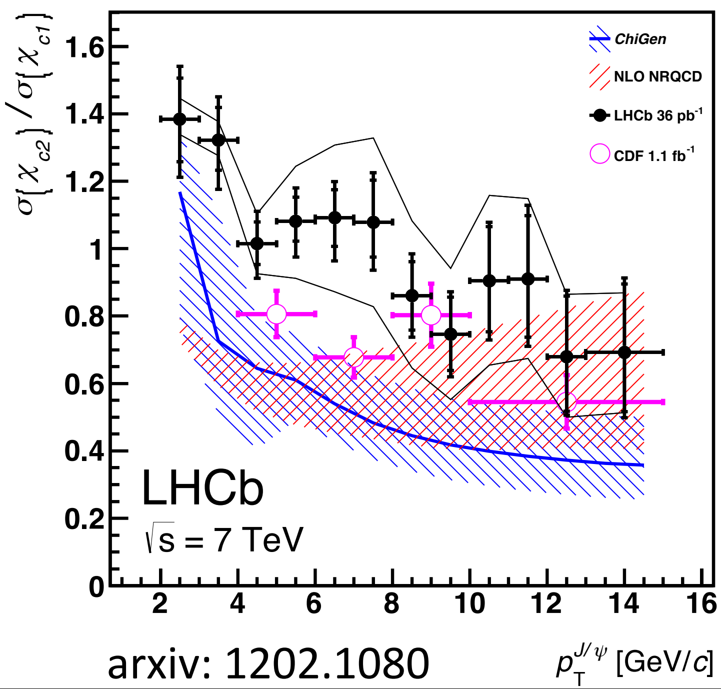
Using converted $\gamma$ allows good mass resolution

Good agreement of CMS measurement with NRQCD



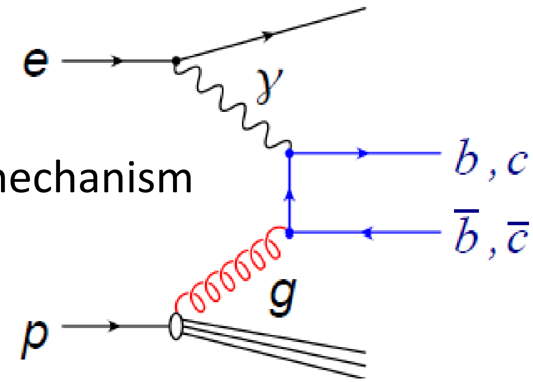




CMS-PAS-BPH-11-010

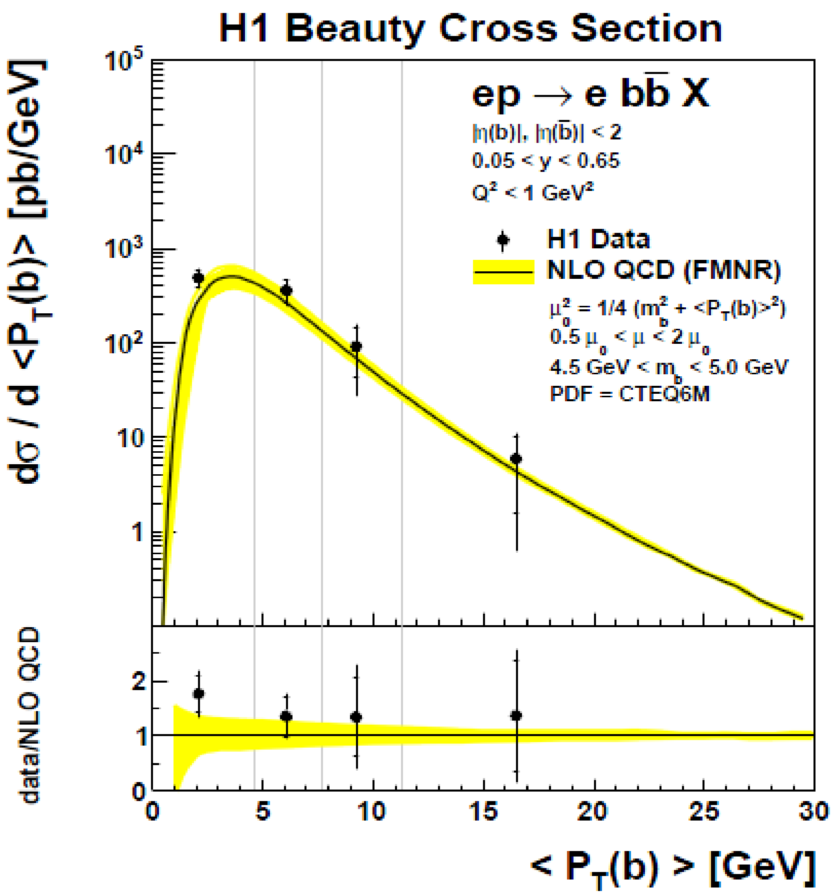


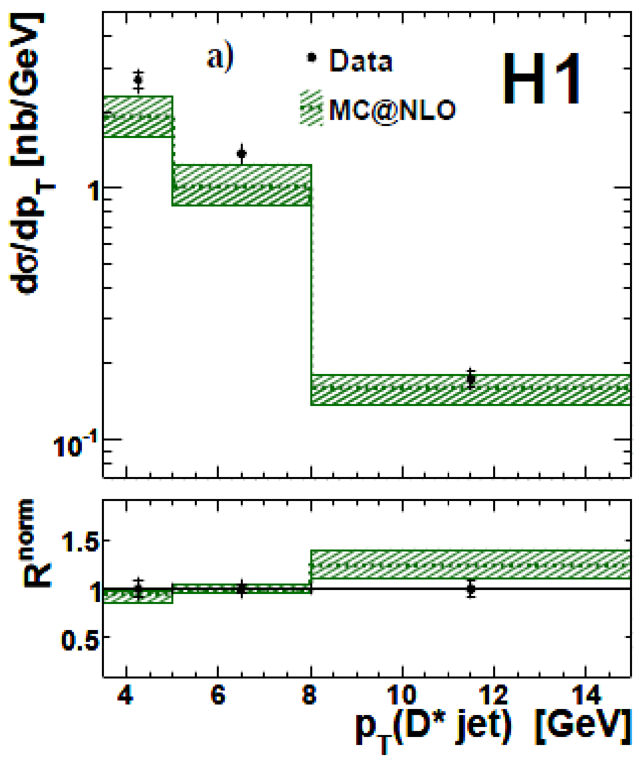

arxiv: 1202.1080

# HERA : HF photoproduction

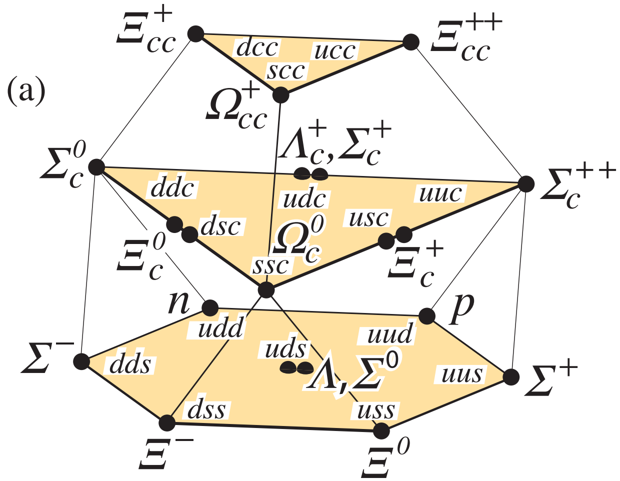



Boson-gluon fusion is the dominant mechanism

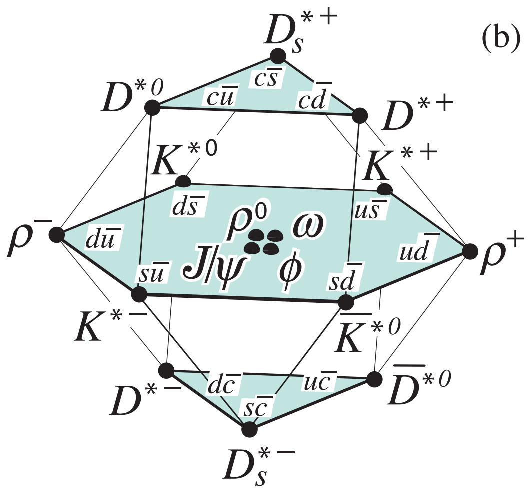



charm in photoproduction with D* and D jets Eur. Phys, J C72 (2012) 1995 H1
beauty with di-electrons ep -> ebbbar X -> eee X' DESY-12-072 H1
beauty with dijets and muons ep-> ebbarX -> e jj mu X DESY 12 059 H1
charm jets from inclusive sescondary vertices in DIS ZEUS-prel-12-002
charm from D+ and Λ+ in DIS Eur. Phys. (2012) 009




# Spectroscopy



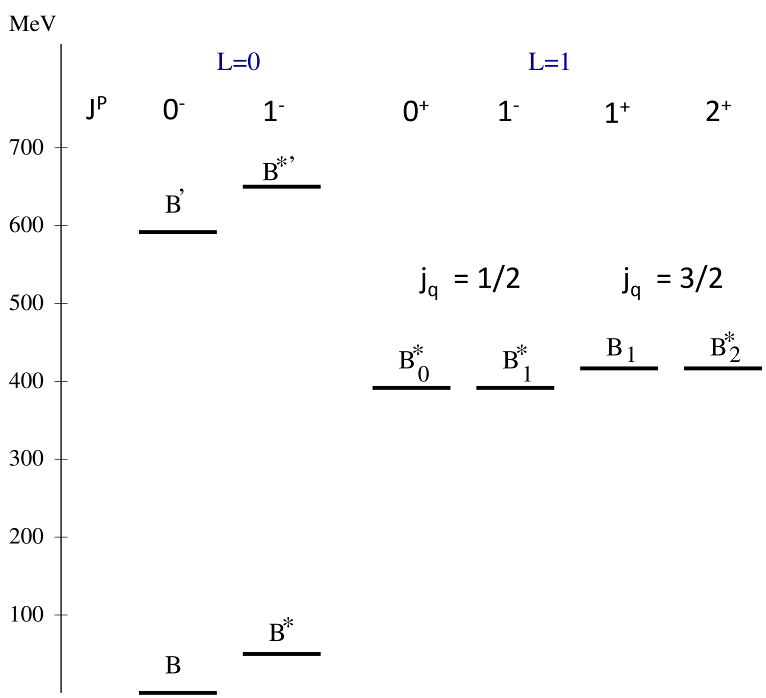
# Spectroscopy

**b meson** : the hydrogen atom of QCD
**b baryon** : the helium atom of QCD

Spectra predicted f.i. by Heavy Quark Effective Theory , in which the heavy quark is viewed as a static color source in the hadron. The spin of the heavy quark is decoupled.

*Example for the  b-ubar b-dbar case:*
States characterized by three quantum numbers :

| | |
|---|---|
| L | orbital angular momentum of the system |
| $j_q$ = $\lvert L \pm ½ \rvert$ | angular momentum of the light quark |
| J = $\lvert j_q \pm ½ \rvert$ | total angular momentum |




PDG notation : $B_{(s)J}^{(*)}$ , (*) = 0+, 1-, 2+
For L=1 : 4 states, collectively called $B^{**}_{(s)}$
Two narrow and two broad resonances

$B_1(5721)^0$ and the $B_2{*}(5747)^0$ seen at Tevatron but missing their charged isospin partners until recently

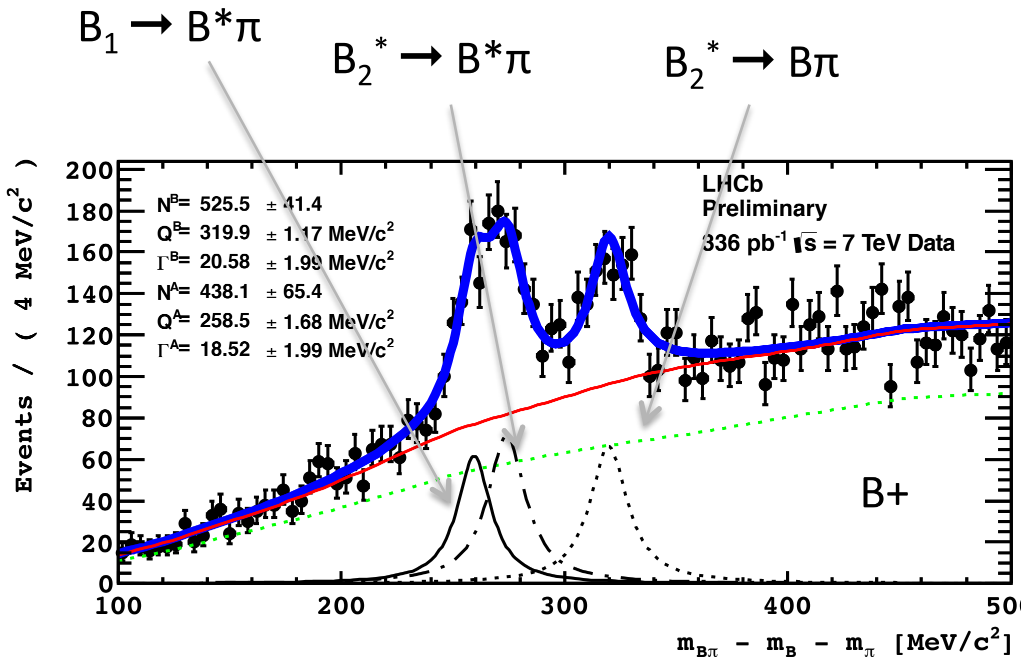
# LHCb: $B_{(s)}^{**}$

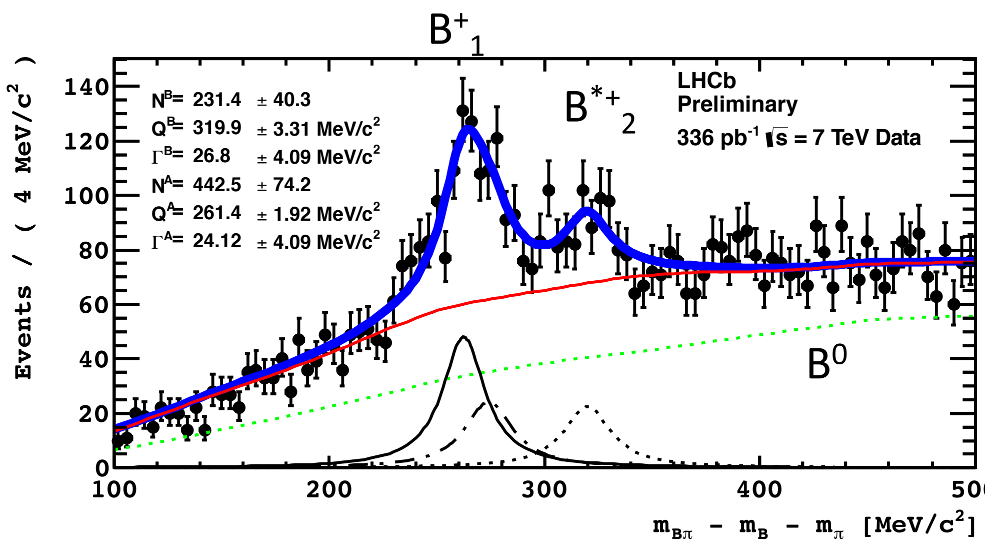
*LHCb-CONF-2011-053*

First observation of orbitally excited $B^{+}_{1}$ and $B^{*+}_{2}$

Search performed in the $B\pi$ invariant mass spectrum, with the B reconstructed in various modes: $J/\Psi K$, $D\pi$, $D3\pi$.

336 pb $^{-1}$




$M(B^{+}_{1}) = 5726.3 \pm 1.9\,(\text{stat}) \pm 3.0\,(\text{sys}) \pm 0.5(m_B)$ MeV

$M(B^{+*}_{2}) = 5739.0 \pm 3.3\,(\text{stat}) \pm 1.6\,(\text{sys}) \pm 0.3(m_B)$ MeV

# $B_c$ : new decay mode

*arXiv:1204.0079*

CMS-PAS-BPH-11-003

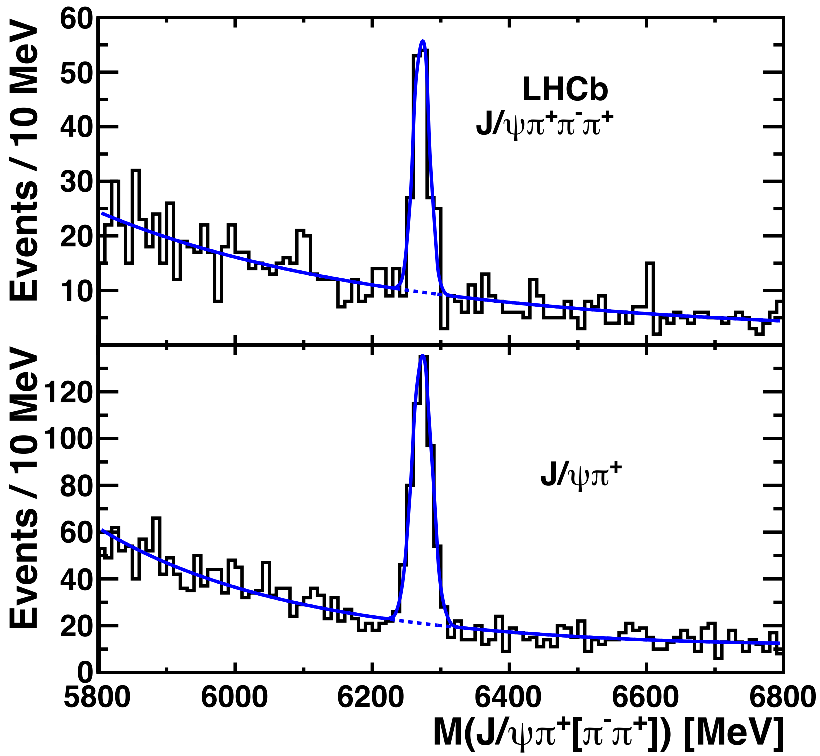
meson with two heaviest quarks

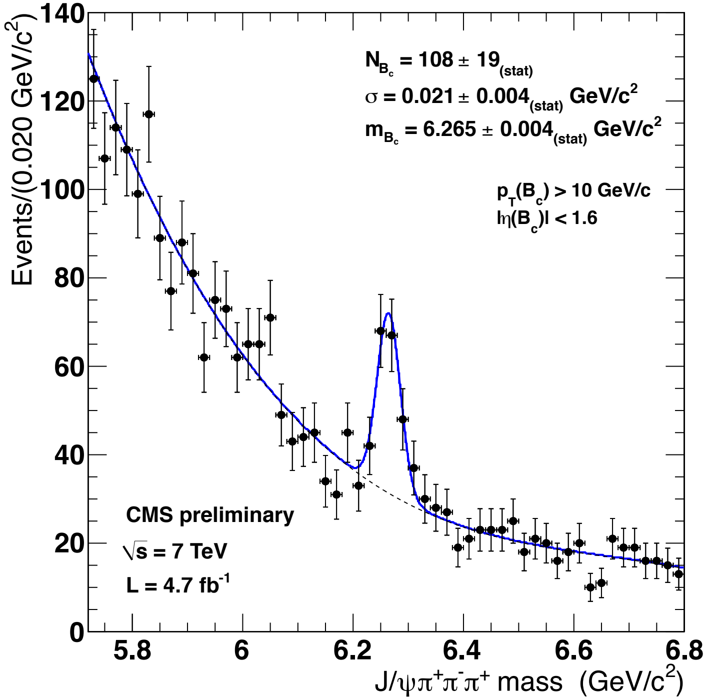
LHCb makes first observation of

$$B_c \rightarrow J/\psi\ \pi^+\pi^-$$

soon confirmed by CMS

Mass and production x section measurement (LHCb)




$$BR(J/\psi\ 3\pi)/\ BR(J/\psi\ \pi) = 2.41 \pm 0.30 \pm 0.33$$

# Heavy Baryons : New observation : $\Lambda_b^{0*}$

Observed by LHCb and confirmed by CDF

arXiv:1205:3452 ,

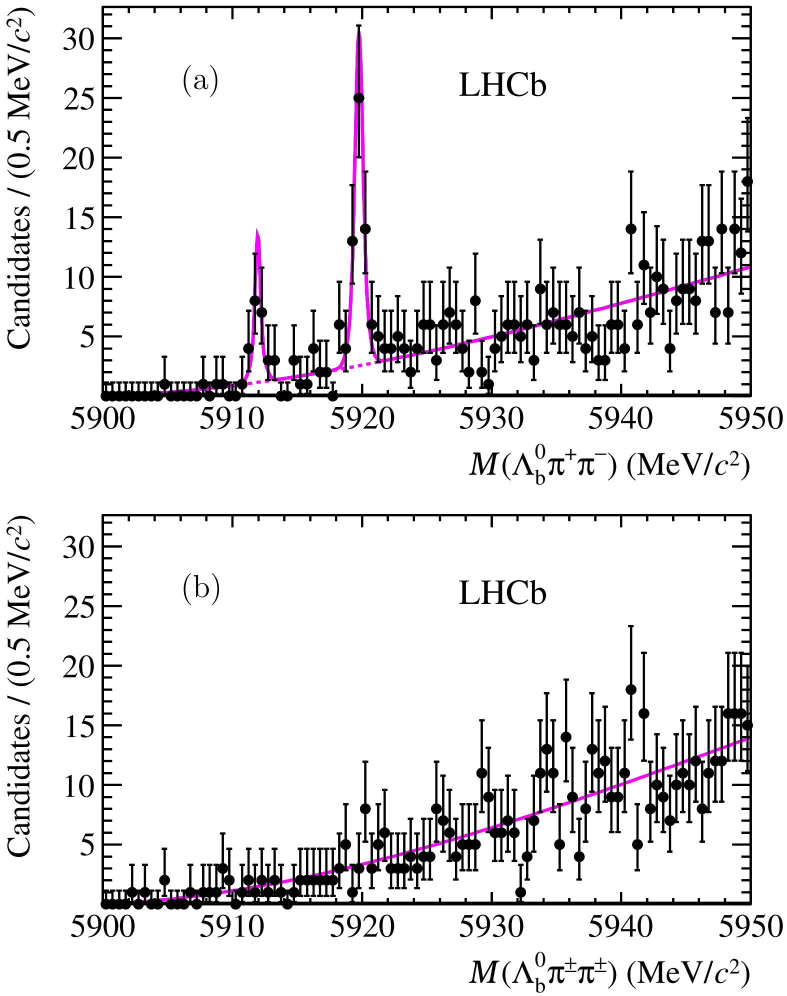
CDF Public Note 10900

Observation of two narrow states in the

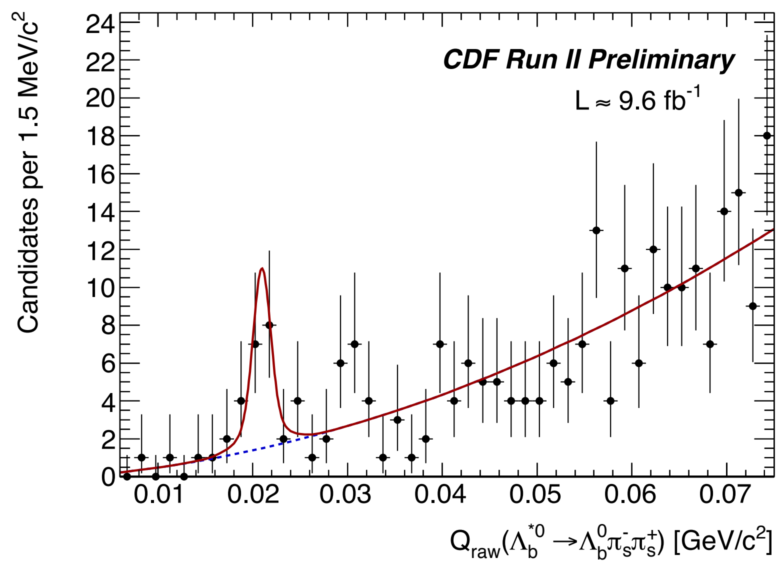
$\Lambda_b^0 \pi\pi$ spectrum

$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi$

$\Lambda_c^+ \rightarrow pK\pi$ expected at $J^P = 1/2^-$ and $3/2^-$. Orbitally excited $\Lambda_b$ 's [udb]



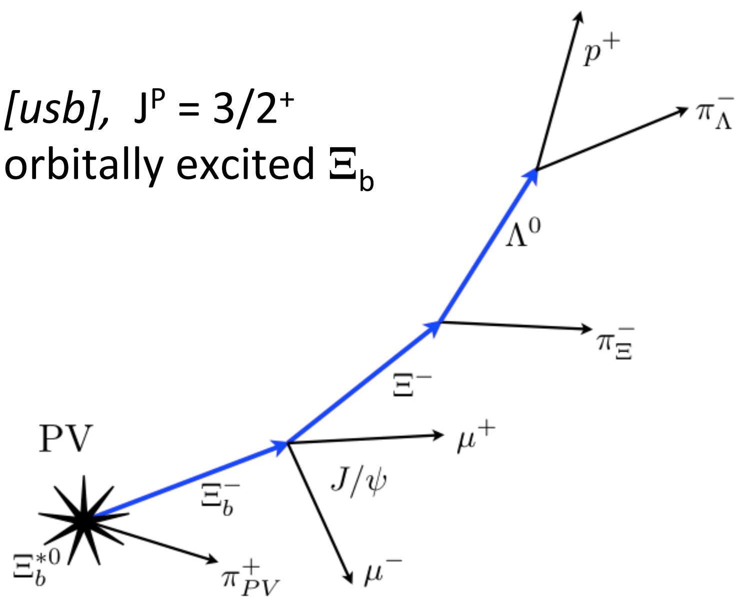

$$M_{\Lambda_b^{*0}(5912)} = 5911.95 \pm 0.12 \pm 0.03 \pm 0.66\,\mathrm{MeV}/c^2,$$
$$M_{\Lambda_b^{*0}(5920)} = 5919.76 \pm 0.07 \pm 0.02 \pm 0.66\,\mathrm{MeV}/c^2,$$

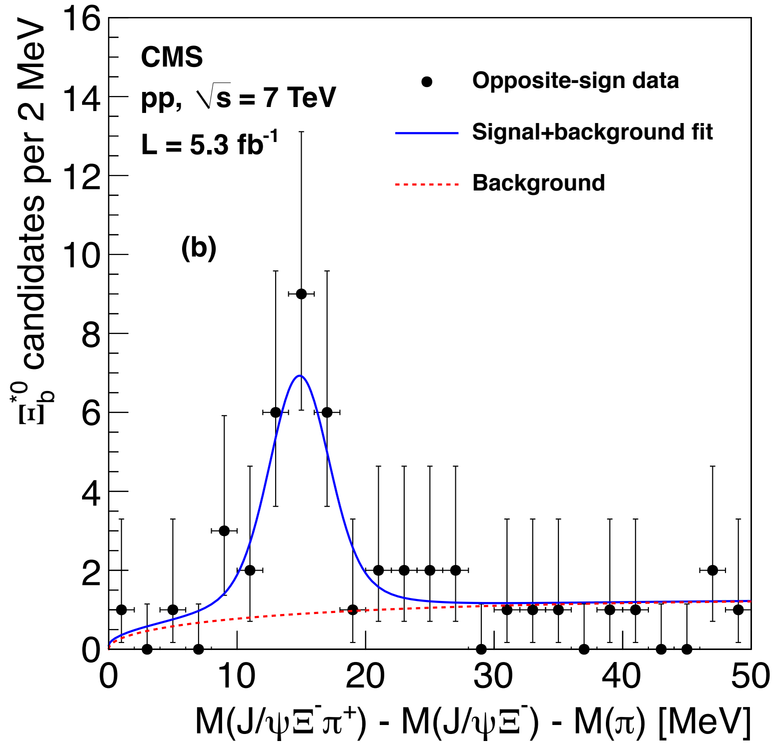


# New Observation: $\Xi_b^{0*}$

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

*[usb],* $J^P = 3/2^+$
orbitally excited $\Xi_b$




Complicated cascade that challenges detector and reconstruction capabilities
>5σ evidence

21 candidates observed, expected background : 3

$$Q = M(\mathrm{J}/\psi\Xi^-\pi^+) - M(\mathrm{J}/\psi\Xi^-) - M(\pi)\ :\ 14.84 \pm 0.74\,(\mathrm{stat.}) \pm 0.28\,(\mathrm{syst.})\,\mathrm{MeV}$$

$m_{\Xi b^*}$ = 5945.0 ± 0.7(stat) ± 0.3(sys) ± 2.7(PDG) MeV

# $\Sigma_b^{\pm}$, $\Sigma_b^{\pm *}$

Phys. Rev. D 85, 092011 (2012)

Two [*udb*], S-wave isospin triplets with $J^P = 1/2^+$ and $J^P = 3/2^+$ , $S^P_{[ud]} = 1^+$

CDF provides most precise determination of masses and widths

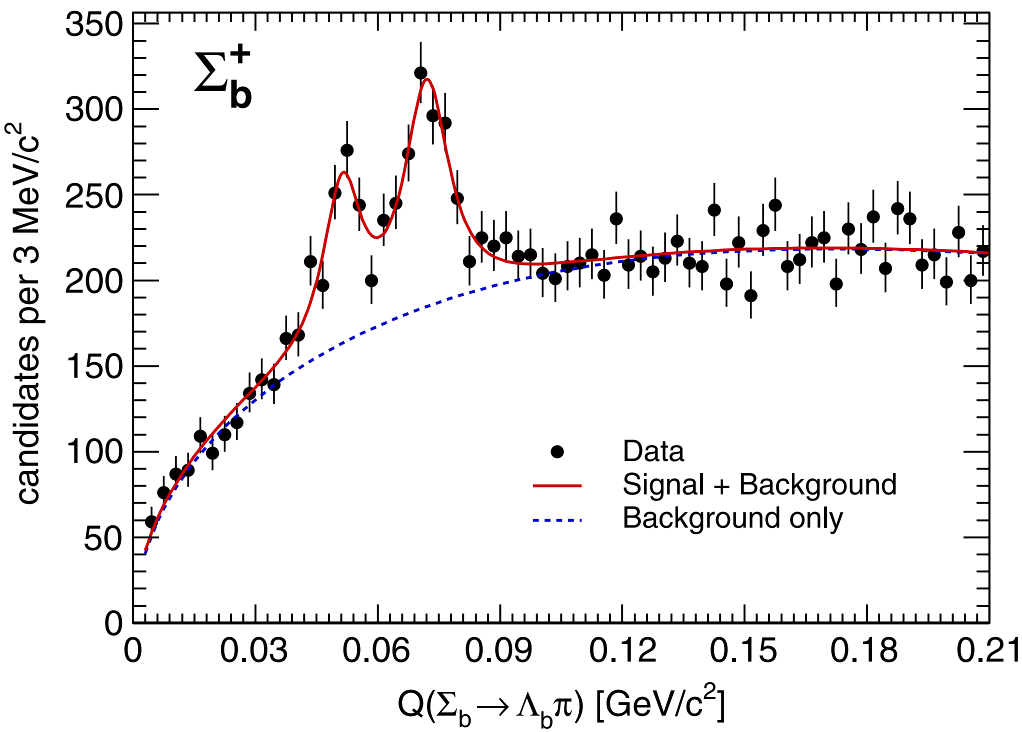
$\Sigma_b \rightarrow \Lambda_b^0 \pi$

$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi$

$\Lambda_c^+ \rightarrow pK\pi$

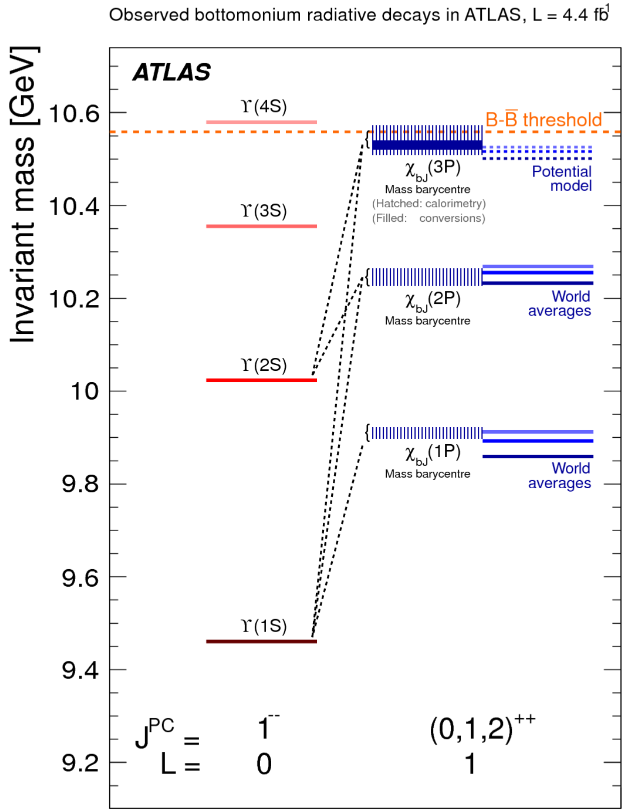
TABLE III. Summary of the results of the fits to the $Q = M(\Lambda_b^0 \pi^{\pm}) - M(\Lambda_b^0) - m_\pi$ spectra. The statistical uncertainties are returned by the unbinned maximum-likelihood fits.

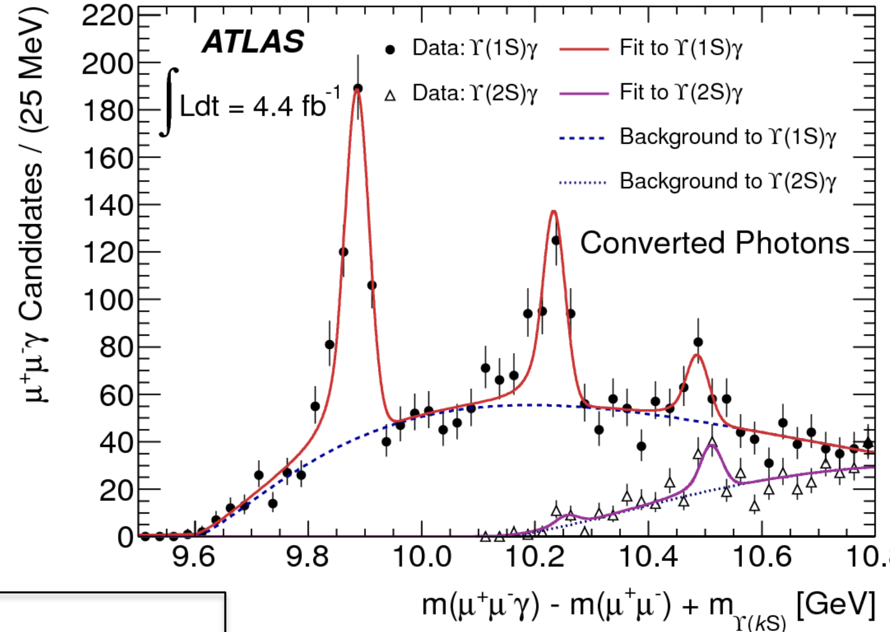
| State | $Q_0$ value, MeV/$c^2$ | Natural width, $\Gamma_0$, MeV/$c^2$ | Yield |
|---|---|---|---|
| $\Sigma_b^-$ | $56.2^{+0.6}_{-0.5}$ | $4.9^{+3.1}_{-2.1}$ | $340^{+90}_{-70}$ |
| $\Sigma_b^{*-}$ | $75.8 \pm 0.6$ | $7.5^{+2.2}_{-1.8}$ | $540^{+90}_{-80}$ |
| $\Sigma_b^+$ | $52.1^{+0.9}_{-0.8}$ | $9.7^{+3.8}_{-2.8}$ | $470^{+110}_{-90}$ |
| $\Sigma_b^{*+}$ | $72.8 \pm 0.7$ | $11.5^{+2.7}_{-2.2}$ | $800^{+110}_{-100}$ |



# New bottomonium states : $\chi_b(3P)$

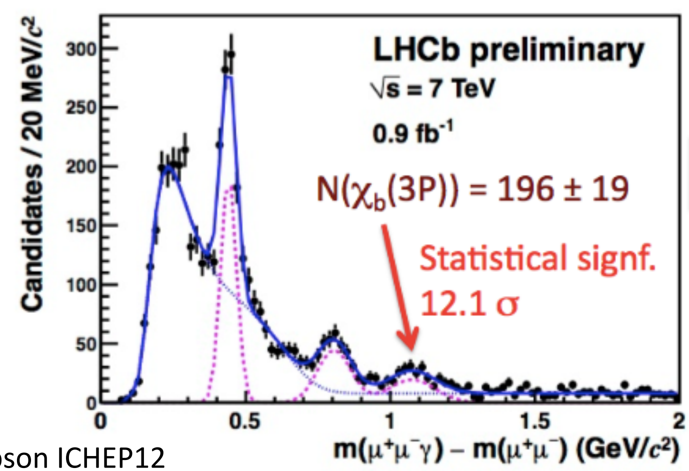
PRL 108, 152001 (2012)



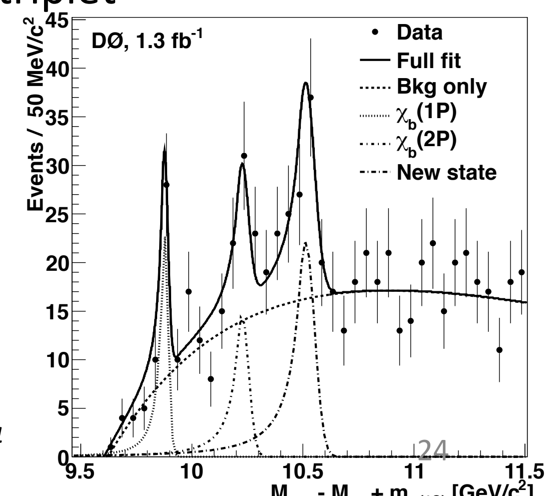

$$\chi_b(nP) \rightarrow \Upsilon(nS) + \gamma$$

Each peak represents a J=(0),1,2 triplet




D0 confirms...

*arXiv:1203.6034*




V. Gibson ICHEP12

# Lifetimes

# The importance of measuring HF hadron lifetimes

**spectator model** of HF decay : in this simple picture
all b mesons and baryons would have the same lifetime, but this is modified by the strong  interaction with the other quarks and gluons.

The study of b-hadron lifetimes can teach us about the interplay between strong and weak interactions.

$$\Gamma_B \sim |V_{CKM}|^2 \sum_n c_n(\mu) \left(\frac{1}{m_b}\right)^n \langle H_b | O_n | H_b \rangle.$$

Heavy Quark Expansion

$c_n(\mu)$ → short distance effects

$\langle H_b | O_n | H_b \rangle$ → np long distance effects

$\mathcal{O}(1/m_b^3)$ baryon/meson

$\mathcal{O}(1/m_b^4)$ spectator effects ($B_s$, $B^+$, $B^0$)

$$\frac{\tau(B^+)}{\tau(B^0)} = 1.06 \pm 0.02, \qquad \frac{\tau(B_s^0)}{\tau(B^0)} = 1.00 \pm 0.01, \qquad \frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.88 \pm 0.05.$$

# $\Lambda_b$ lifetime and mass

Discrepancy CDF/CDF, CDF/D0

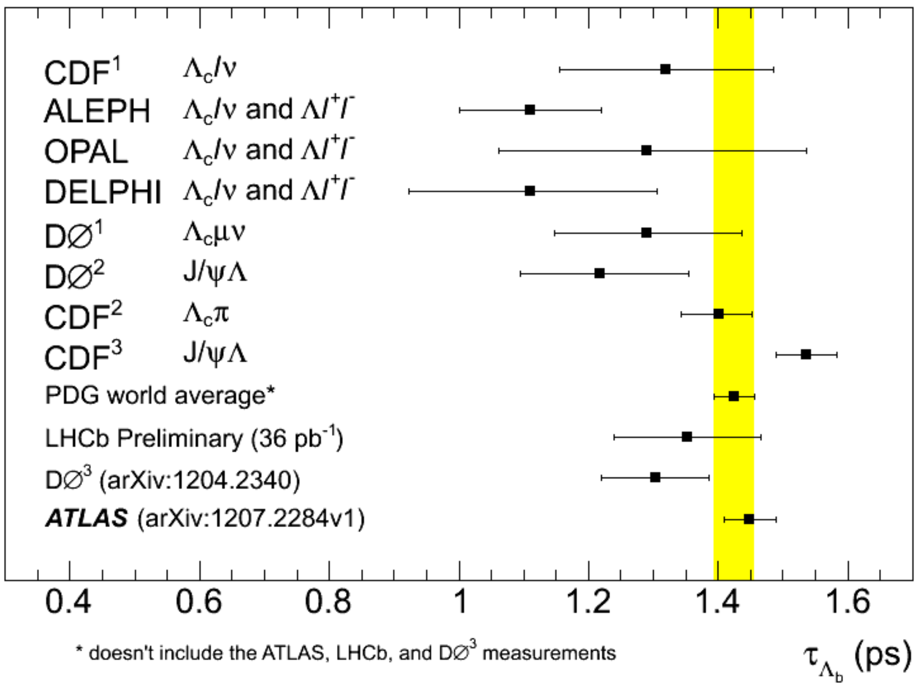
ATLAS: $m(\Lambda_b) = 5619.7 \pm 0.7(stat) \pm 1.1(syst) MeV$

N ($\Lambda_b$) = 2184 ± 57

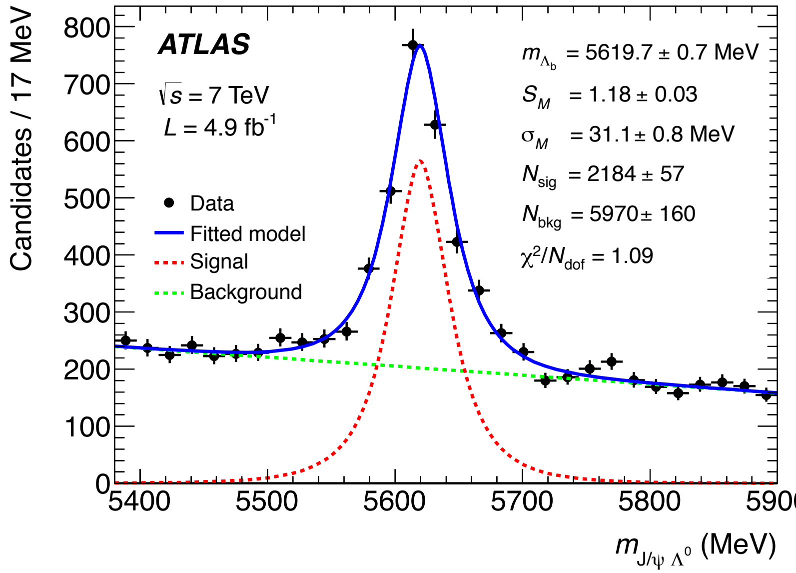
$\tau(\Lambda_b) = 1.499 \pm 0.036(stat) \pm 0.017(syst) ps$

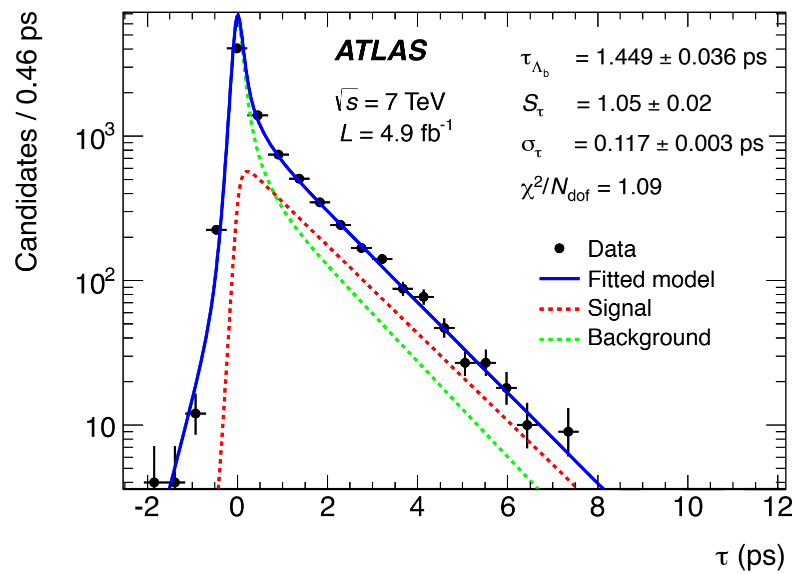
PDG(2012): $\tau(\Lambda_b) = 1.425 \pm 0.032$ ps

courtesy of N. Panikashvili




D0[3] :Phys. Rev. D **85**, 112003 (2012)



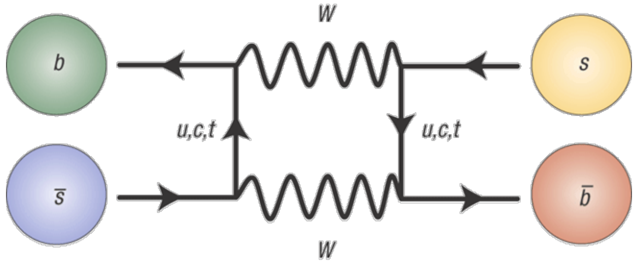




arxiv 1207.2284

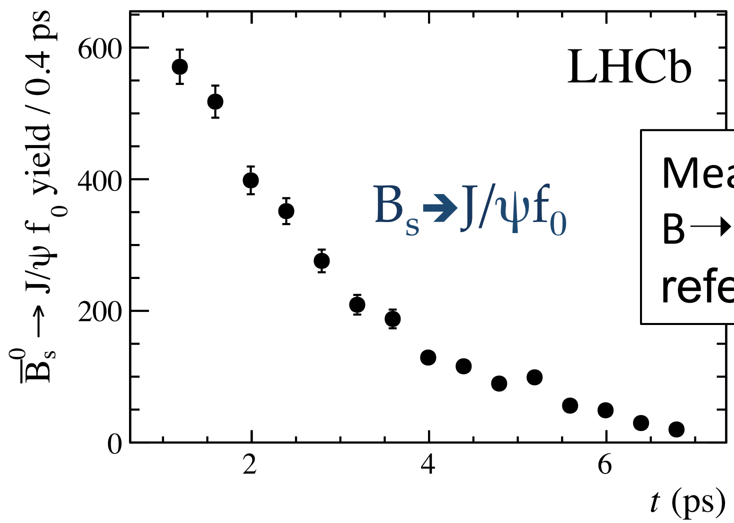
# $B_s$ lifetime

PRL 108 (2012) 241801
arXiv: 1207.0878
LHCb-PAPER-2012-013
CDF Phys. Rev. D85 (2012) 072002
D0 Phys. Rev. D85 (2012) 032006

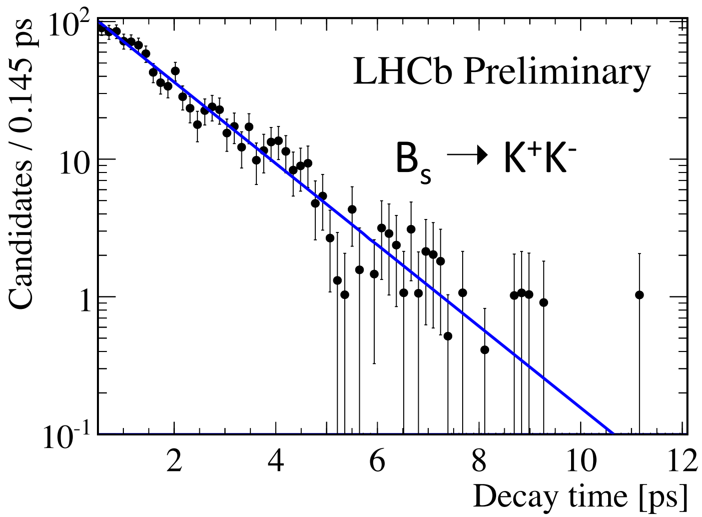
Because of mixing, there are two mass eigenstates ($m_H$, $m_L$) with separate lifetimes and widths $\Gamma_H$ $\Gamma_L$,




$\Gamma_s = (\Gamma_H + \Gamma_L)/2$ is the effective lifetime, obtained by describing the untagged decay time distribution with a single exponential: $\Delta\Gamma_s = \Gamma_L - \Gamma_H$




Measured with $B \to J/\psi K^{*0}$ as reference




From $B_s \to J/\psi f_0(980)$: $\Gamma_H = 0.588 \pm 0.017\ \text{ps}^{-1}$
CP odd
[LHCB-PAPER-2012-017]

From $B_s \to J/\psi \Phi$ : $\Gamma_s = 0.6580 \pm 0.0085\ \text{ps}^{-1}$
mixture
$\Delta\Gamma_s = 0.116 \pm 0.019\ \text{ps}^{-1}$
[LHCB-CONF-2012-002]

From $B_s \to K^+K^-$ , assuming no CPV
CP even
$\Gamma_L = 0.681 \pm 0.021\ \text{ps}^{-1}$
[LHCB-PAPER-2012-013]

# Conclusions

An impressive number of new measurements in the HF sector in 2012 concerning production, spectroscopy and lifetimes and many more in the oven

HF **production**: cross section measurements in exclusive and inclusive decays, in association with jets, vector bosons, etc. Apologies for not mentioning your favored measurement !

**Spectroscopy**: discovery of new mesons ($B^{+}_{1}$, $B^{*+}_{2}$, $\chi_b(3P)$ ) and baryons ($\Lambda_b^*$, $\Xi_b^*$)

**Lifetimes**: $\Lambda_b$ , $B_s$

Theoretical tools that were rigged and tuned at Tevatron are working remarkably well at LHC. On the other side, we are still using several **effective theories** ! Also, theoretical uncertainties often larger than experimental uncertainties.

# Extras

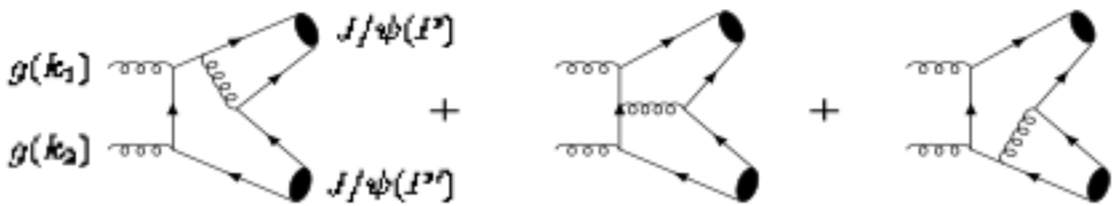
# multiple Charm production

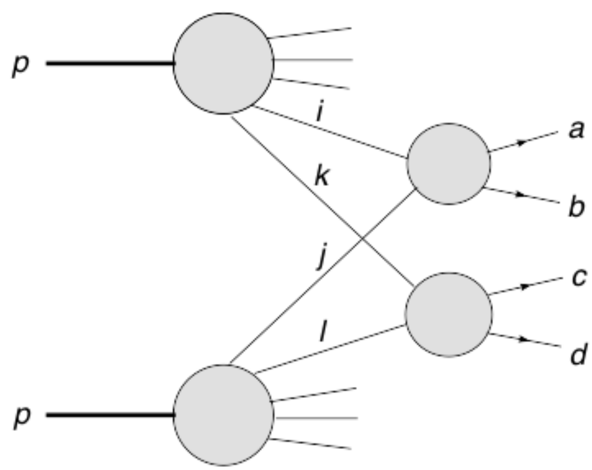
Can originate from several processes:

1. LO gg → J/ψ ccbar

2. Double Parton Scattering

3. sea quarks

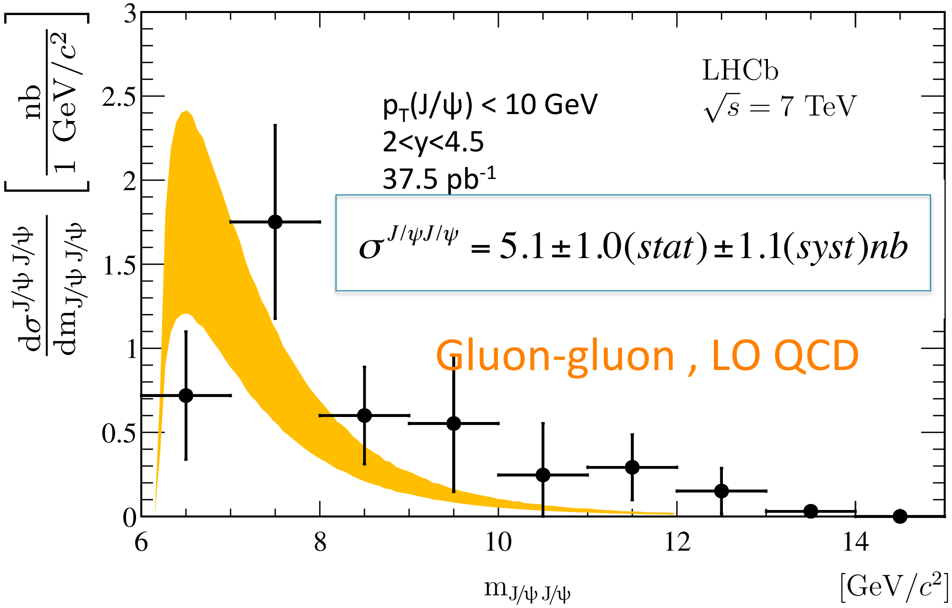


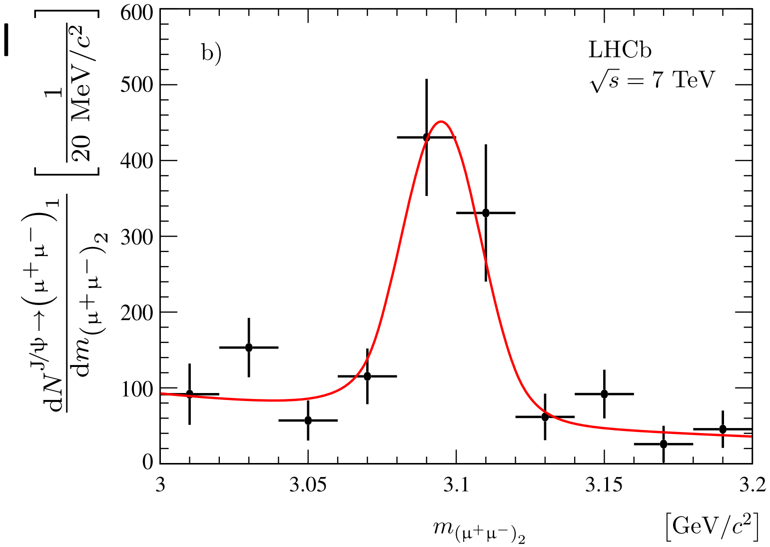



# Double J/ψ production

Physics Letters B 707 (2012) 52–59

two prompt J/ψ reconstructed in the μμ channel

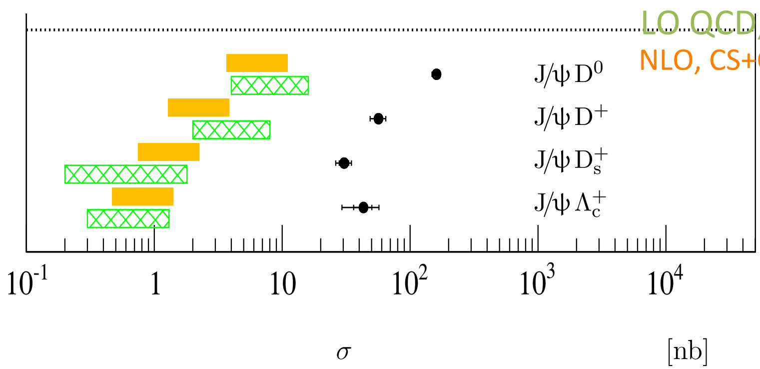


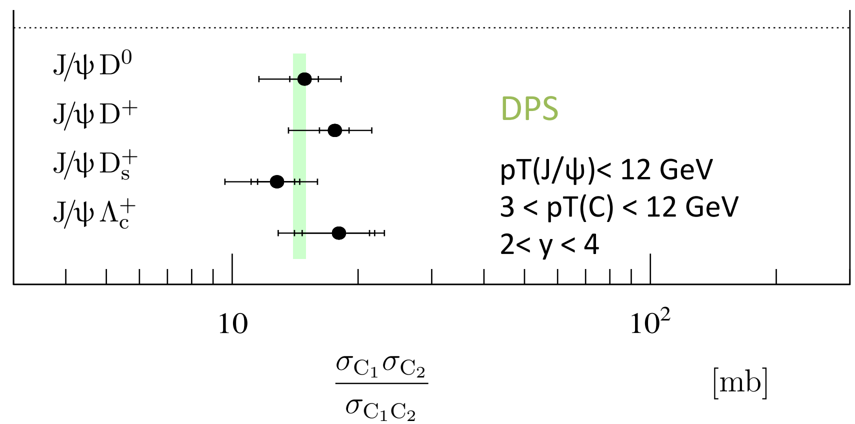




To be compared with LO QCD
σ(J/ψJ/ψ) = 4.1 ±1.2 (arXiv:1101.5881)

Integrated cross section compatible with LO, but DPS could still play a role …

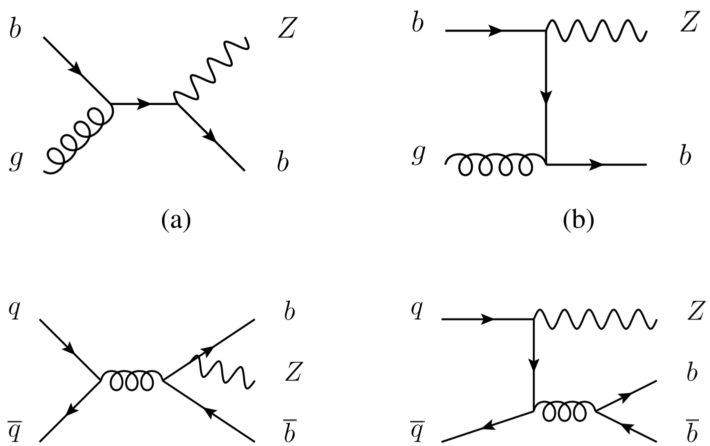
J/ψ + open charm mesons and 2 open charm

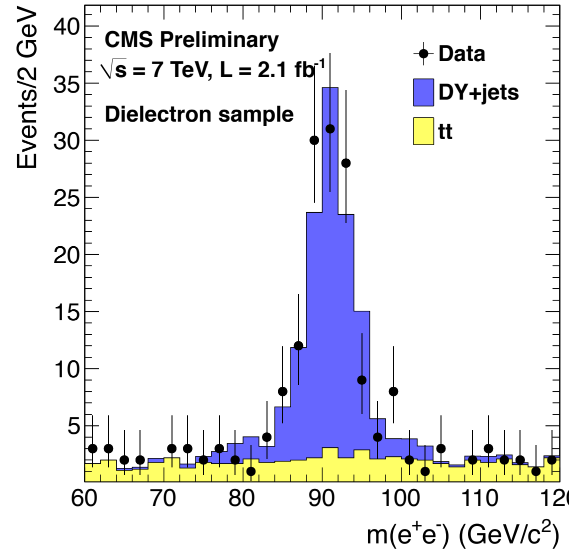



JHEP 06 (2012) 141

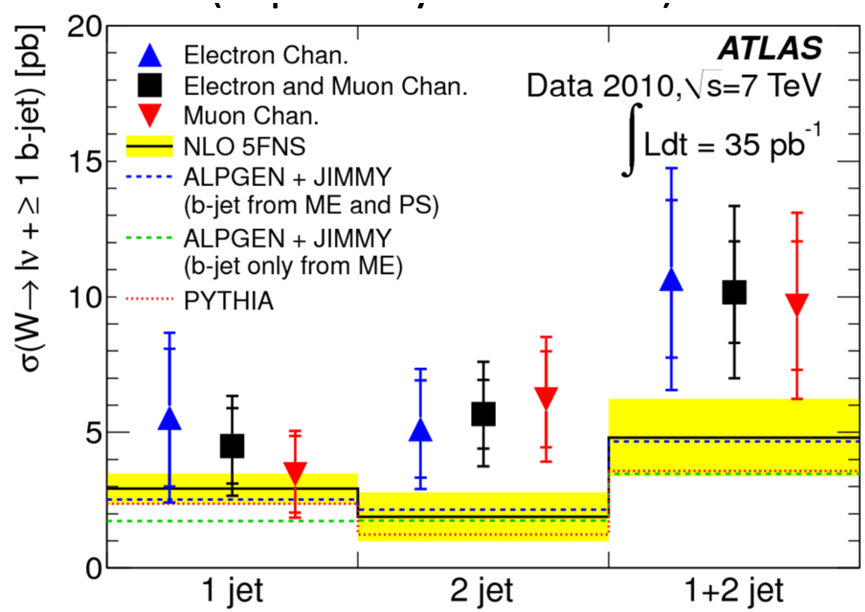
# HF in association with vector bosons




ATLAS Phys. Lett B 706 (2012) 295

| | |
|---|---|
| Experiment | $3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb |
| MCFM | $3.88 \pm 0.58$ pb |
| ALPGEN | $2.23 \pm 0.01$ (stat only) pb |
| SHERPA | $3.29 \pm 0.04$ (stat only) pb |




CMS-PAS-SMP-12-003 arXiv:1204.1643

| Multiplicity bin | ee | $\mu\mu$ |
|---|---|---|
| $\sigma_{hadron}(Z+1b, Z\to \ell\ell)$(pb) | $3.25 \pm 0.08 \pm 0.29 \pm 0.06$ | $3.47 \pm 0.06 \pm 0.27 \pm 0.11$ |
| $\sigma_{hadron}(Z+2b, Z\to \ell\ell)$(pb) | $0.39 \pm 0.04 \pm 0.07 \pm 0.02$ | $0.36 \pm 0.03 \pm 0.07 \pm 0.03$ |
| $\sigma_{hadron}(Z+b, Z\to \ell\ell)$(pb) | $3.64 \pm 0.09 \pm 0.35 \pm 0.08$ | $3.83 \pm 0.07 \pm 0.31 \pm 0.14$ |