Quarkonium Production @ LHCb

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on behalf of the LHCb Collaboration

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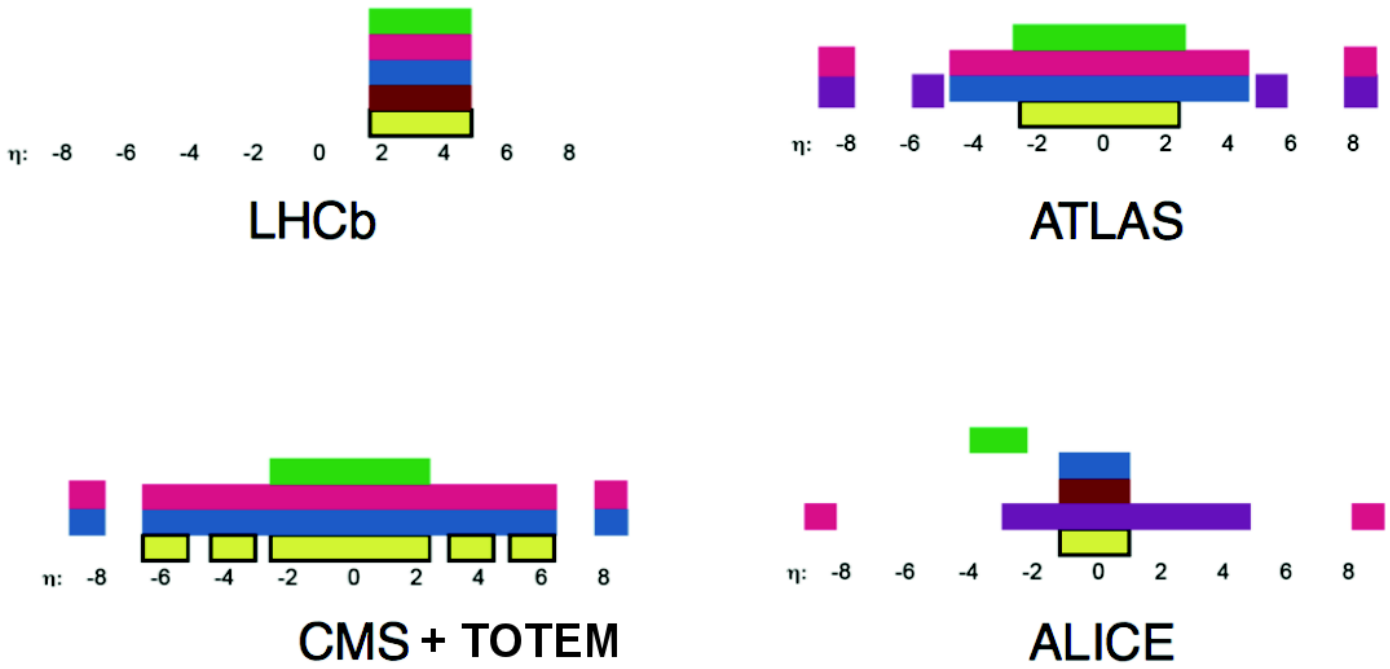
The LHCb Experiment

conceived for CP violation and rare decays in the heavy flavour sector

- single–armed forward spectrometer covering the rapidity range where most $b\bar{b}$ pairs are produced

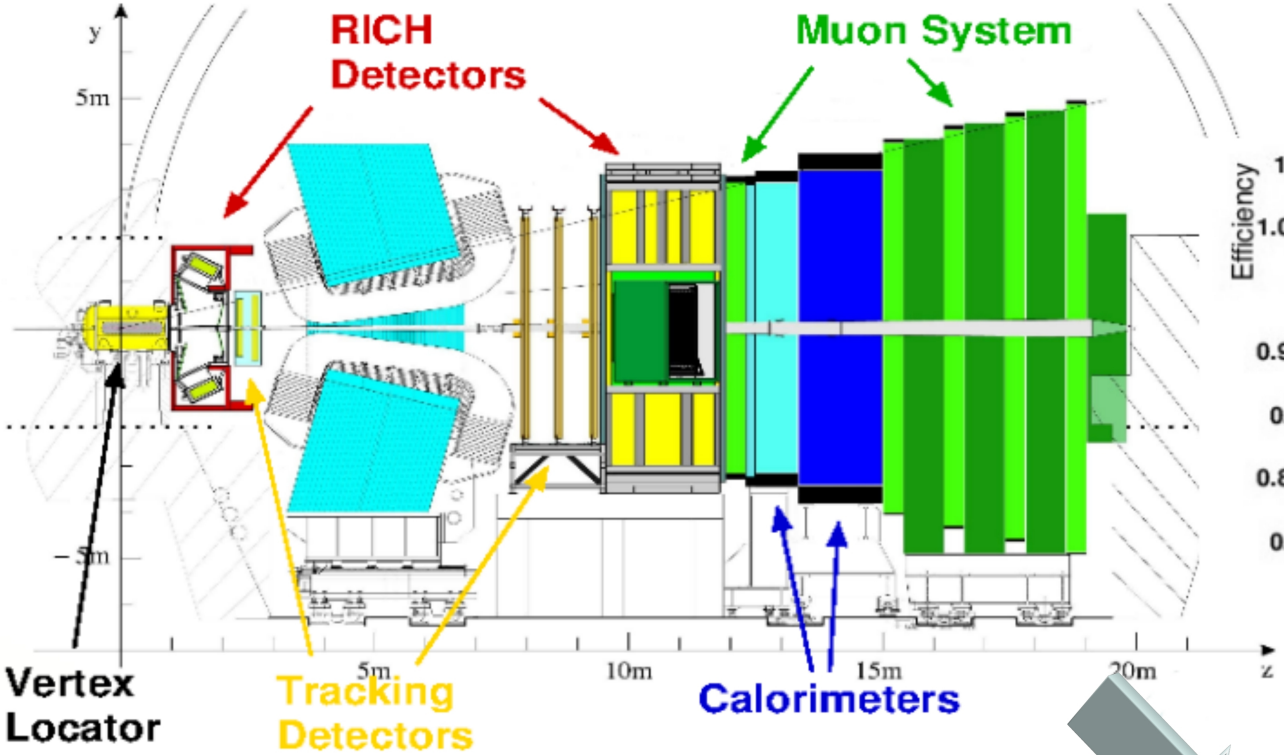


tracking, ECAL, HCAL, counters lumi, muon, hadron PID

Can study quarkonia production in unique rapidity range at the LHC energy frontier

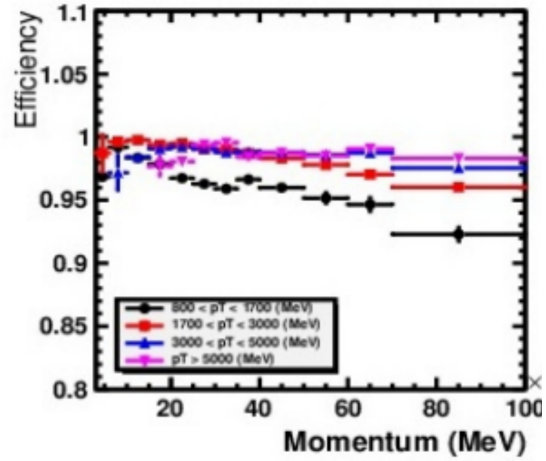
The LHCb Detector

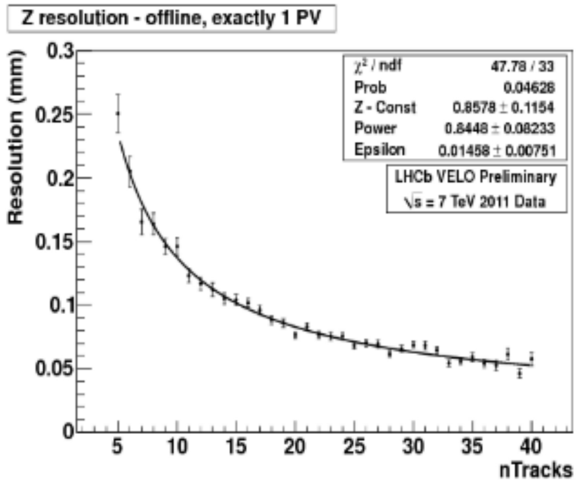
optimized for B meson decays: emphasis on vertexing, p resolution, PID, trigger



Muon ID eff: ~ 97 %

Mis-ID ($\pi \rightarrow \mu$) 1-3 %





Momentum resolution:

$\sigma(p)/p \sim 0.4\%$ (5 GeV/c)

0.6% (100 GeV/c)

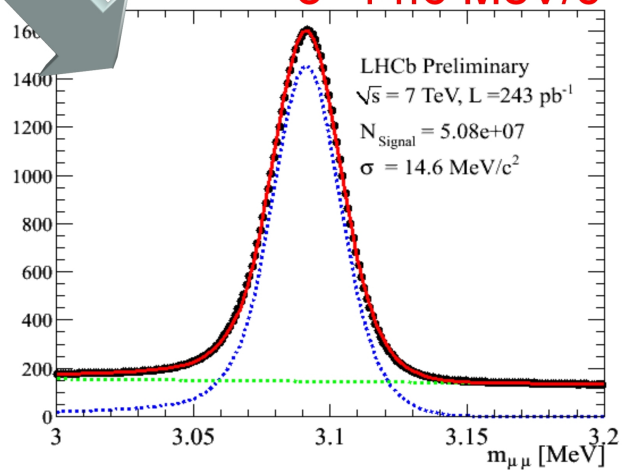
Vertex resolution for average mult. (25 tracks):

$\sigma_{X,Y} \sim 15\ \mu m$

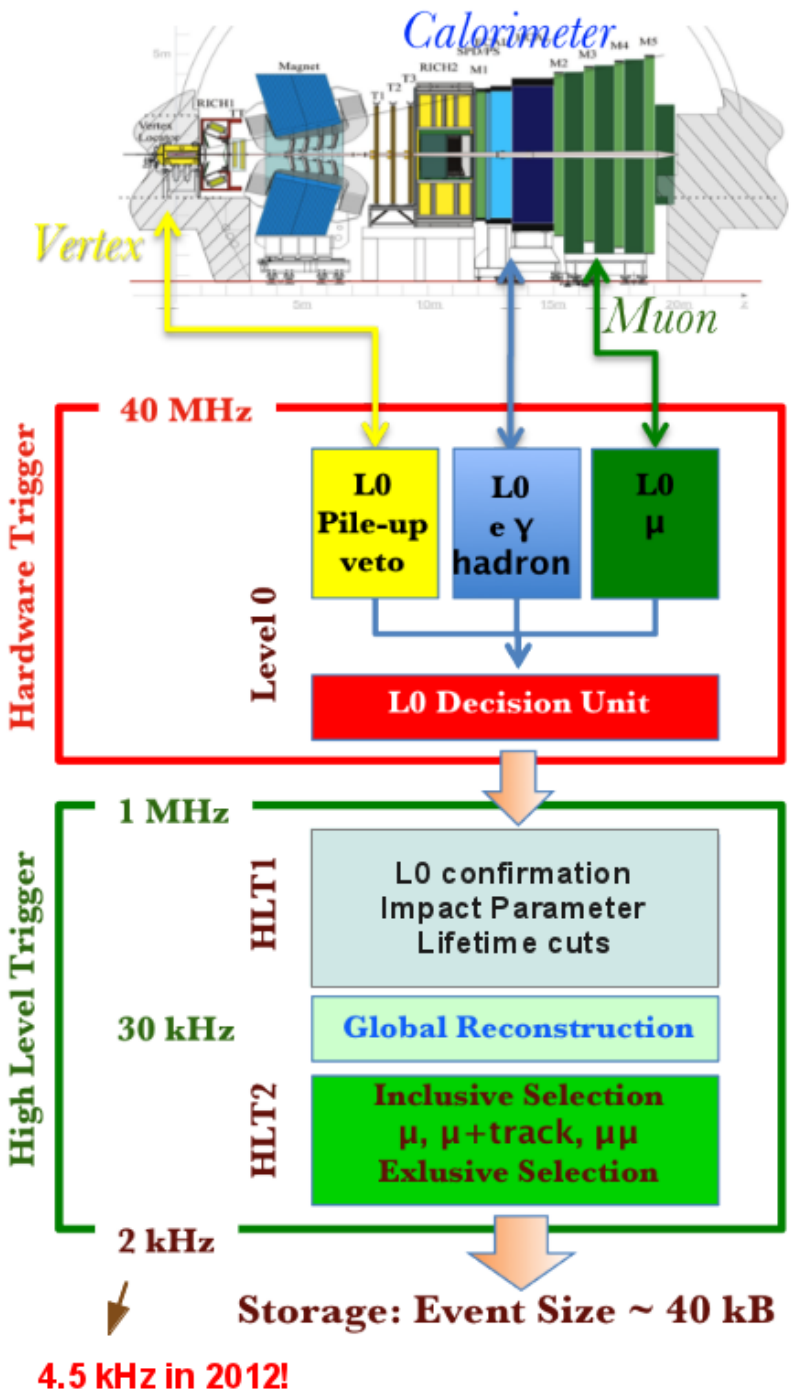
$\sigma_Z \sim 70\ \mu m$

J/Ψ Mass

$\sigma = 14.6\ MeV/c^2$



The Trigger

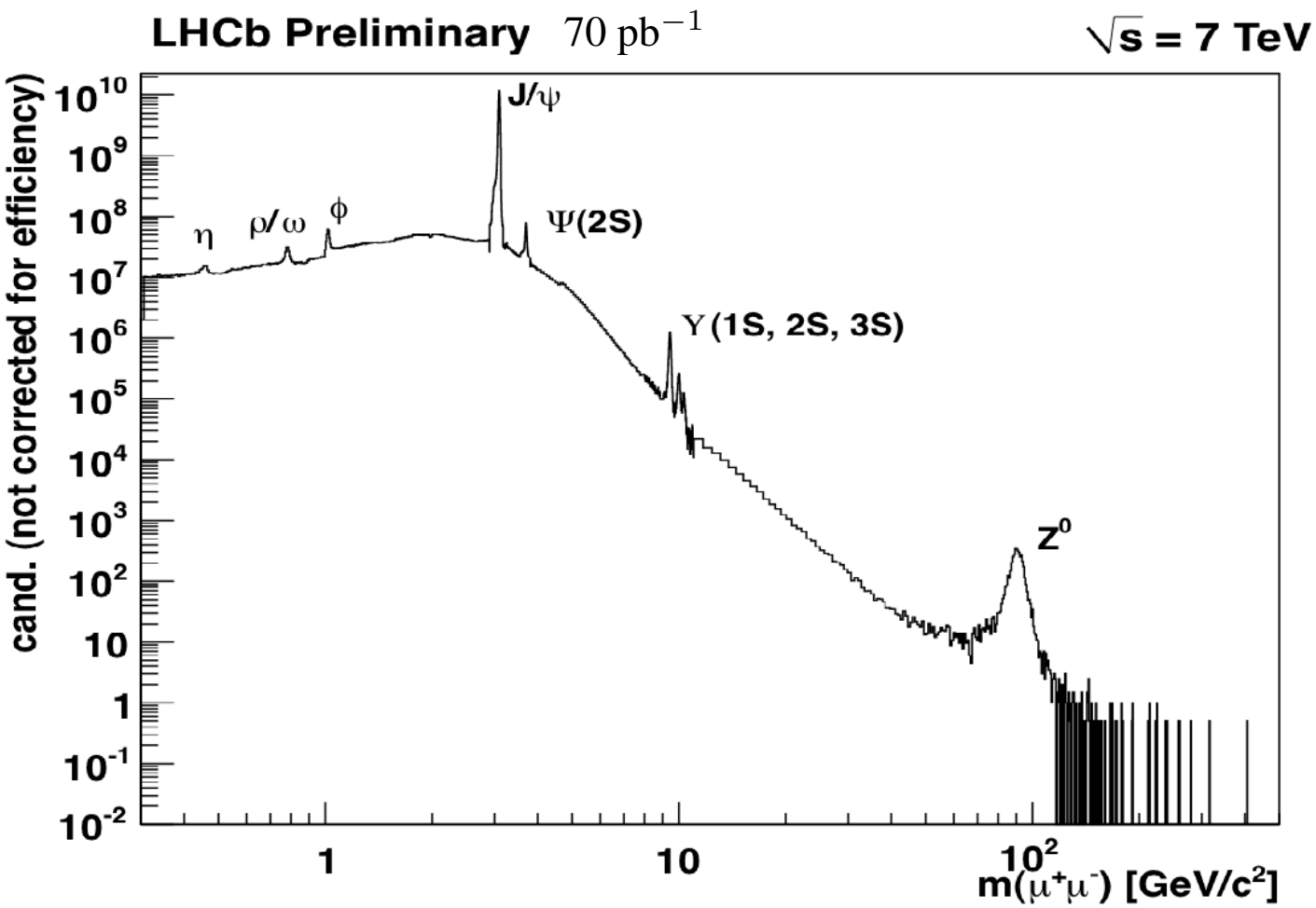


	Muon Lines
L0	Single- μ: p_T> 1.4 GeV/c μμ: p_{T1}>0.48 GeV/c p_{T2}>0.56 GeV/c
HLT1	single-μ: p_T>1.8 GeV/c, di-μ: $M_{\mu\mu}$>2.5 GeV/c^2
HLT2	Several dimuon lines with p_T or $M_{\mu\mu}$ cuts

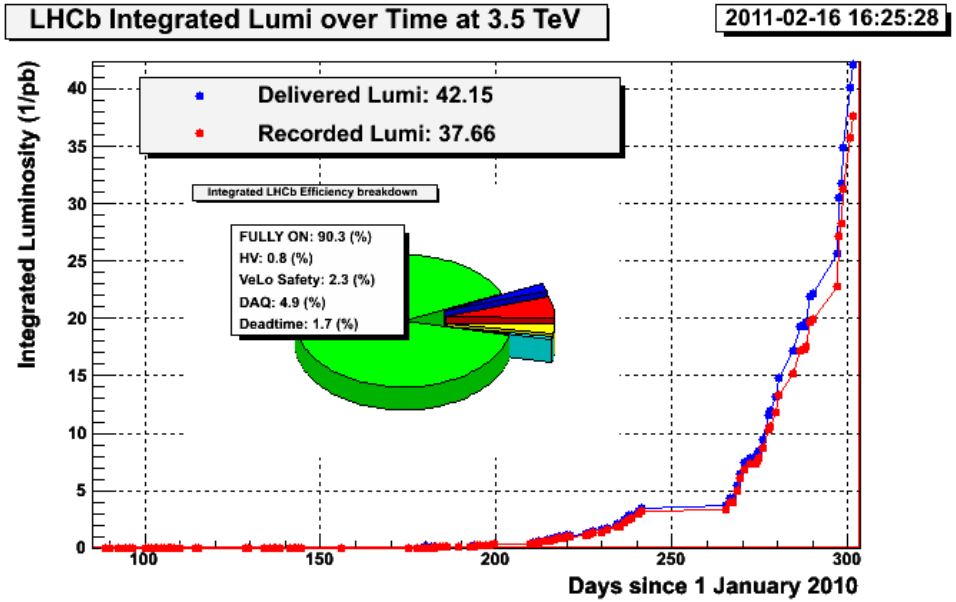
- robust and flexible design
- **very low p_T cuts!**
- **Half of bandwith for (di)muon lines!**
- bandwith increase in 2012 thanks to farm upgrade and deferred trigger

A Quarkonium Mine

Dimuon mass spectrum after 48 hours
of data taking at the current luminosity
$\mathcal{L} = 4 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



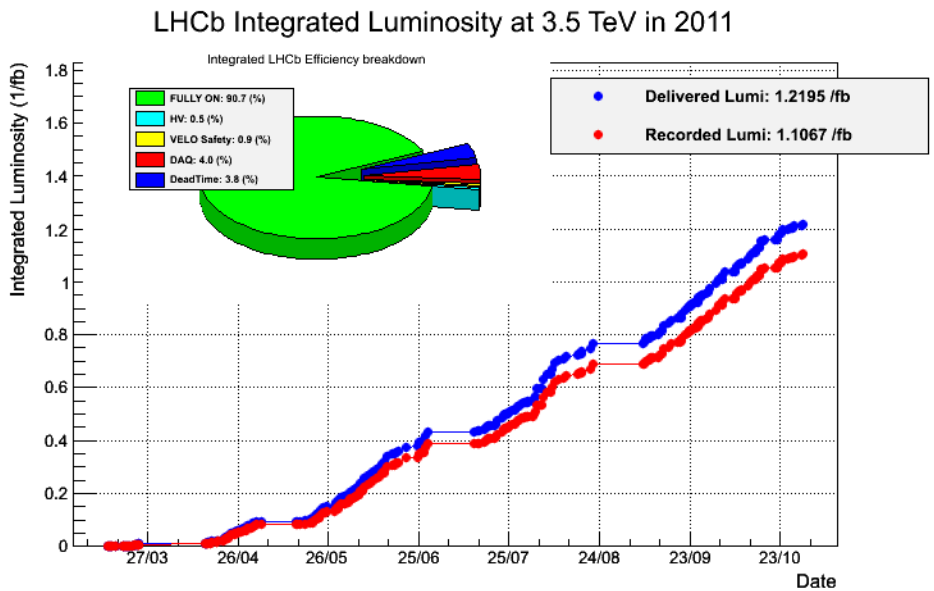
LHCb data samples

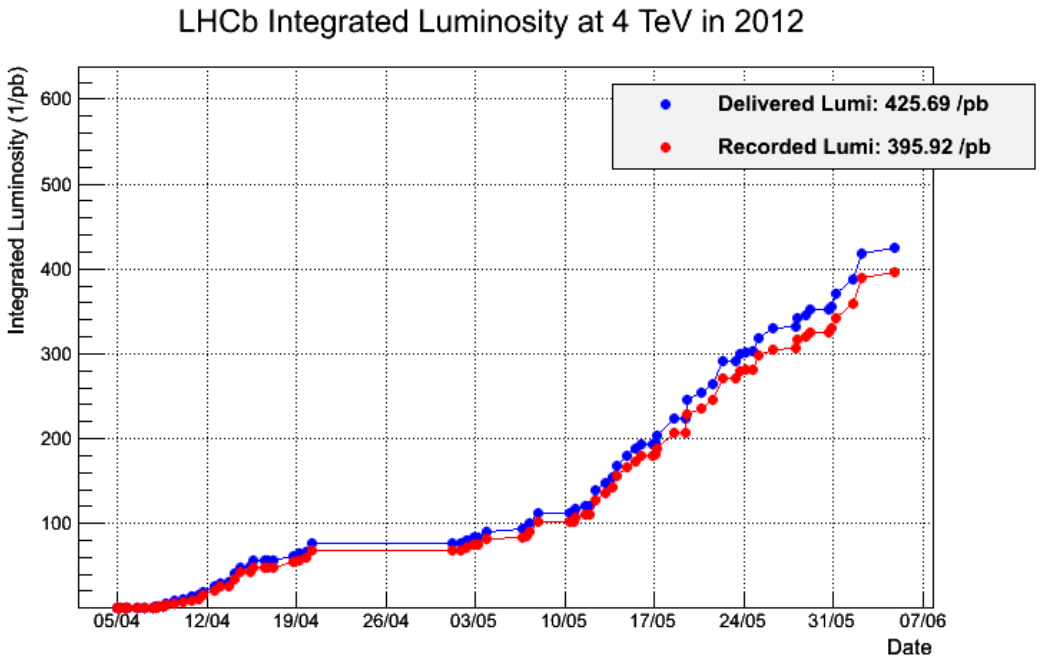


2010: 37 pb^{-1}, low luminosity, Minimum Bias triggers

2011: 1100 pb^{-1}

2012: $\sqrt{s}$= 8 TeV
currently 400 pb^{-1}, aim at 1500





Overview

- Measuring production (and soon polarization) of $c\bar{c}$ and $b\bar{b}$ states
  ➡ tests QCD production models:
  Color Singlet (CS) model vs Color Octet (CO) contributions
  - J/ψ , $\psi(2S)$
  - $\chi_c/J/\psi$
  - $\Upsilon(nS)$

- the B_c meson
  ➡ test QCD in unique meson made from 2 pairs of heavy quarks

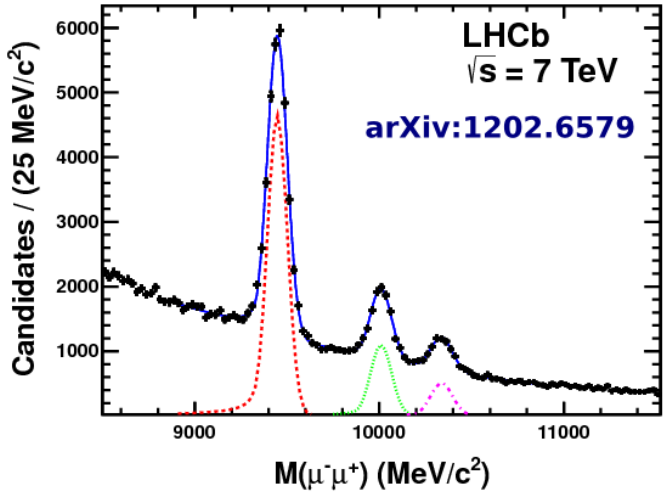
- double J/ψ and double charm production
  ➡ probe of double parton scattering, possible contributions from tetraquarks,...

- unpredicted X states: X(3872) and the mysterious X(4140)

Charmonium/Bottomonium to $\mu^+\mu^-$

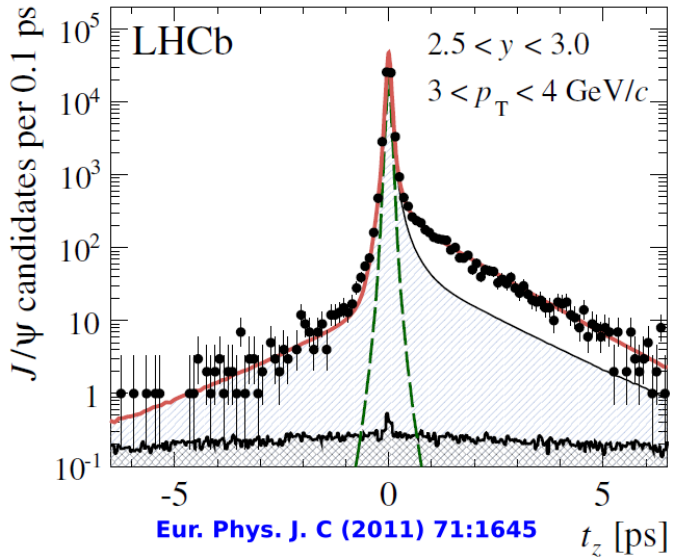
- production rates of J/ψ, $\psi(2S)$, $\Upsilon(nS)$ (n=1,2,3) measured from the 2010 data

- high efficiency of dimuon channels:
  $\epsilon_{tot} > 40\ \%$ (including acceptance, trigger, reconstruction and selection)
  for high $p_{\rm T}$ (> 10 GeV/c)
  and $2 < \eta < 4.5$
- mass resolution: ~ 15 MeV/c^2 for J/ψ,
  ~ 50 MeV/c^2 for $\Upsilon(1S)$



- for charmonium, prompt production separated from b decays using pseudo proper time

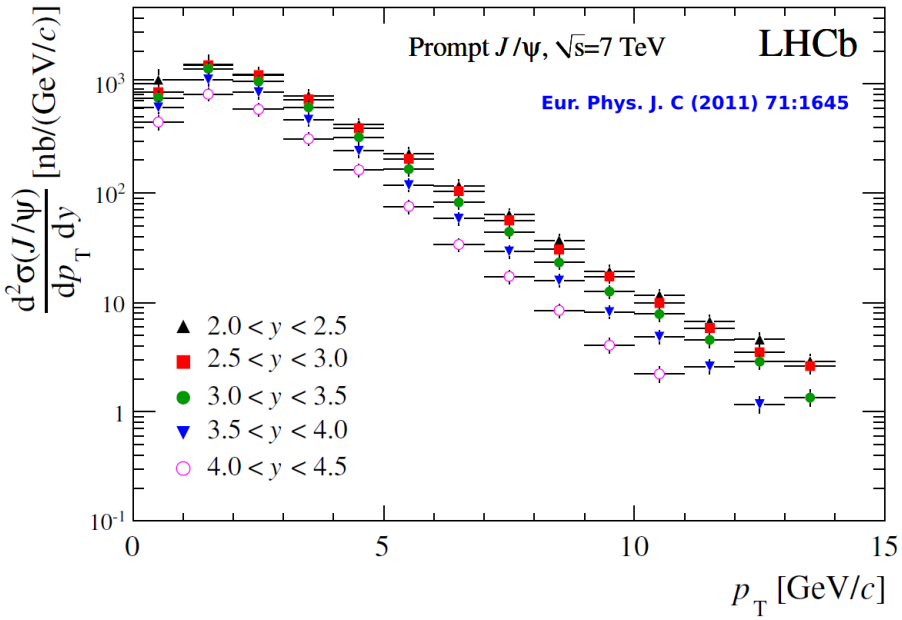
$$t_z = \frac{(z_{J/\psi} - z_{PV})m_{J/\psi}}{p_z}$$



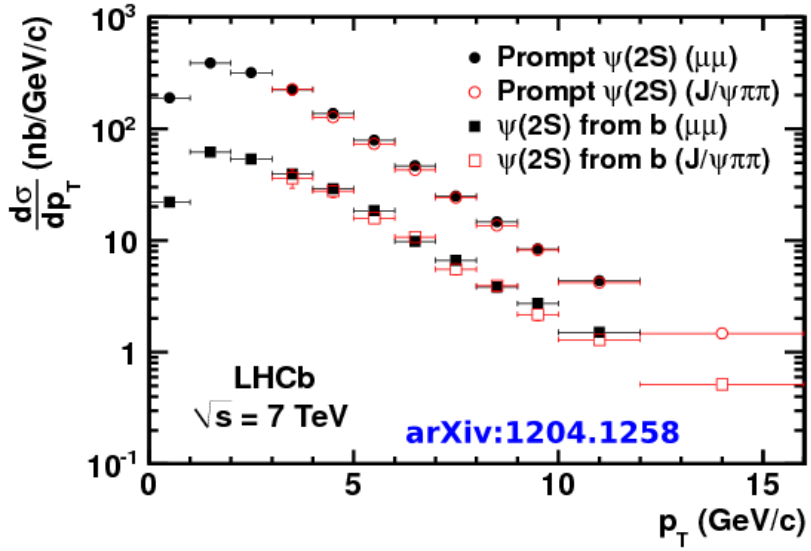
- limited by systematics: largest error from the unknown polarizations (10 – 20 %)

Production cross sections assuming unpolarized states

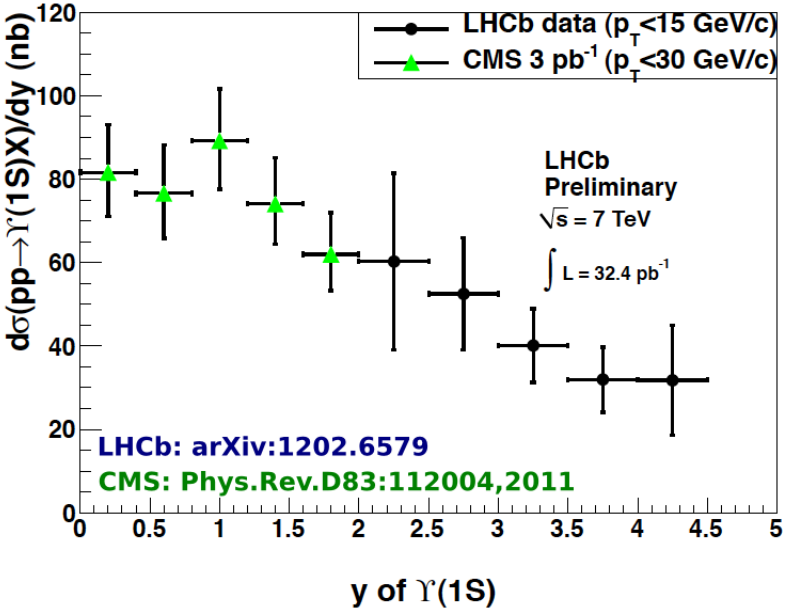
J/ψ



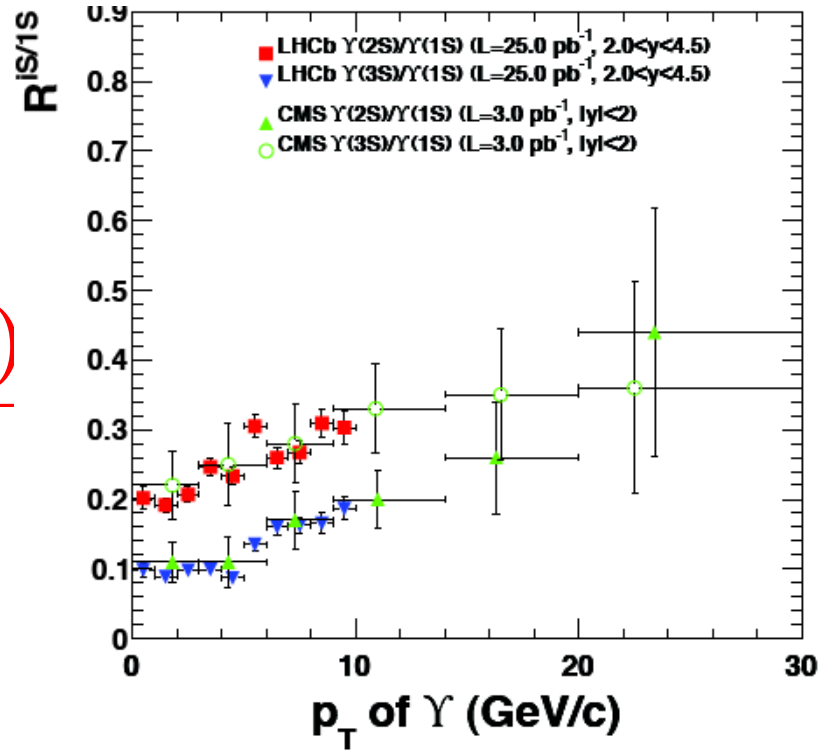
$\psi(2S)$



$\Upsilon(1S)$



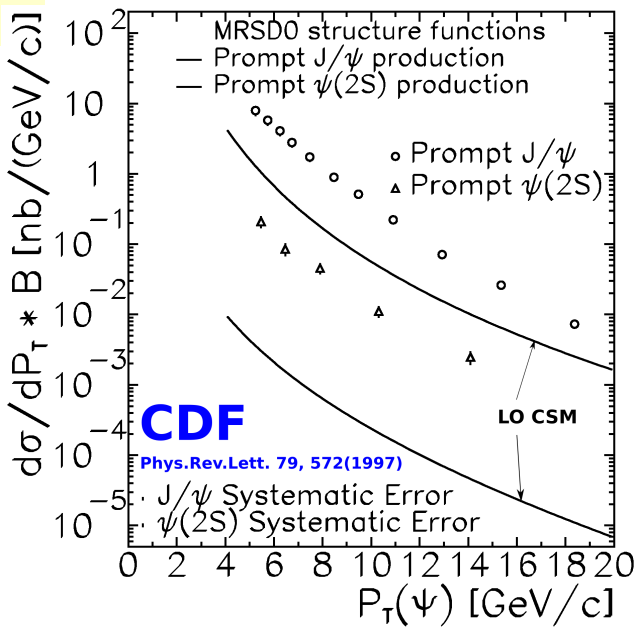
$$\frac{\Upsilon(2,3S)}{\Upsilon(1S)}$$

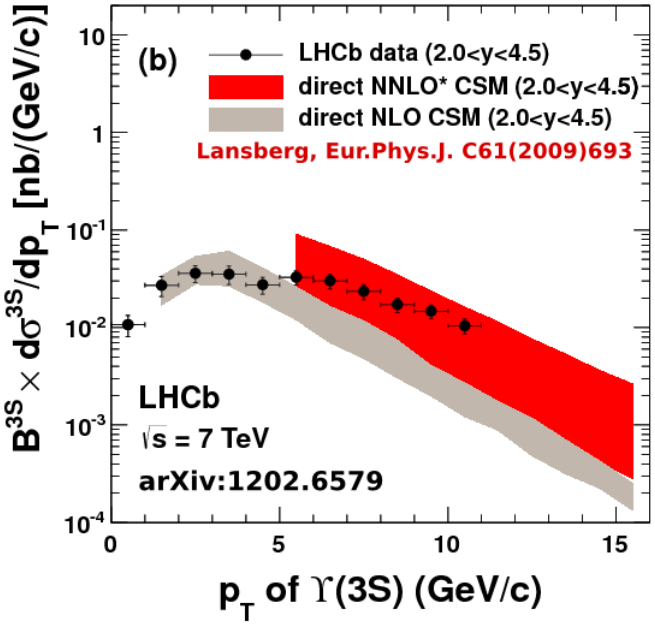


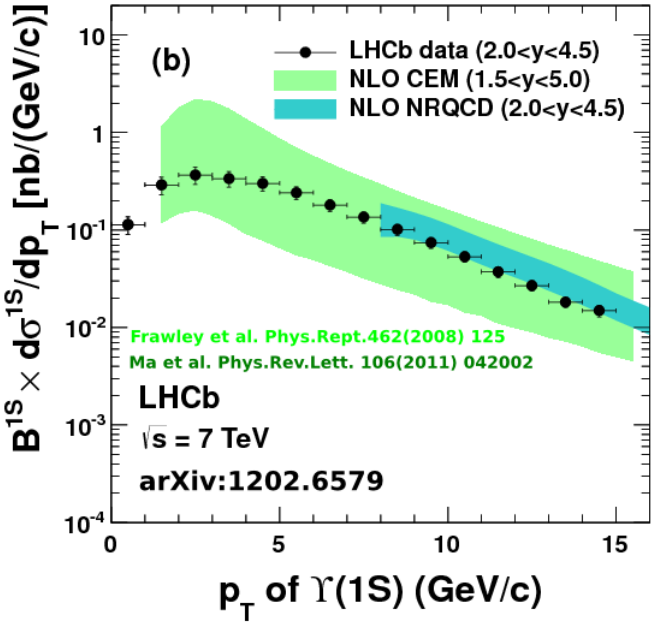
Comparison with theory

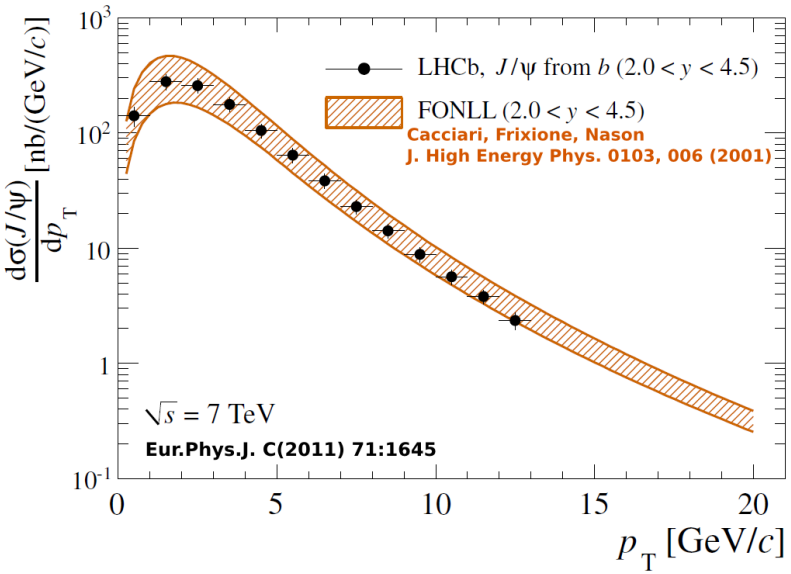
- as already seen by Tevatron, production is larger by 2 orders of magnitude than LO CSM predictions

- better agreement with N(N)LO CSM calculations
- remarkable agreements with NRQDC calculations including CO, and FONLL formalism for $b \to Q$



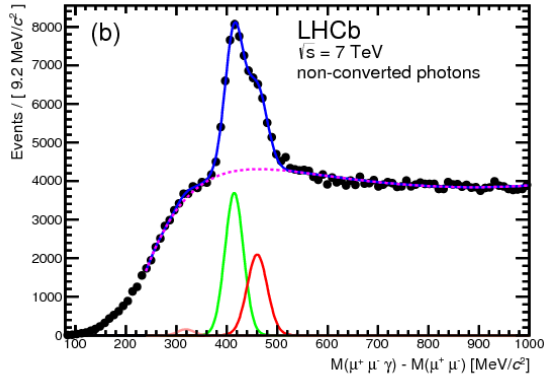


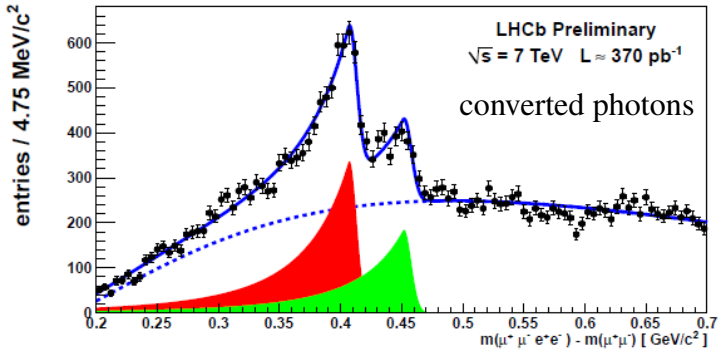


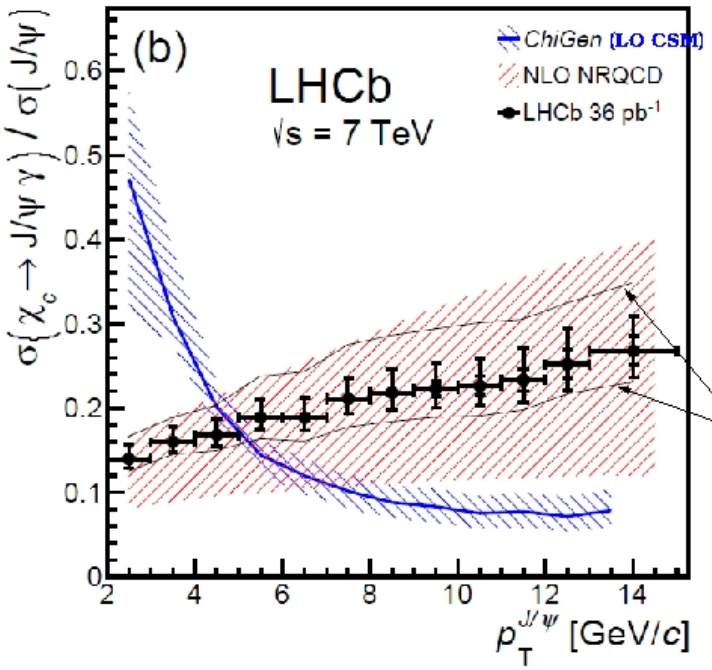


χ_c Production

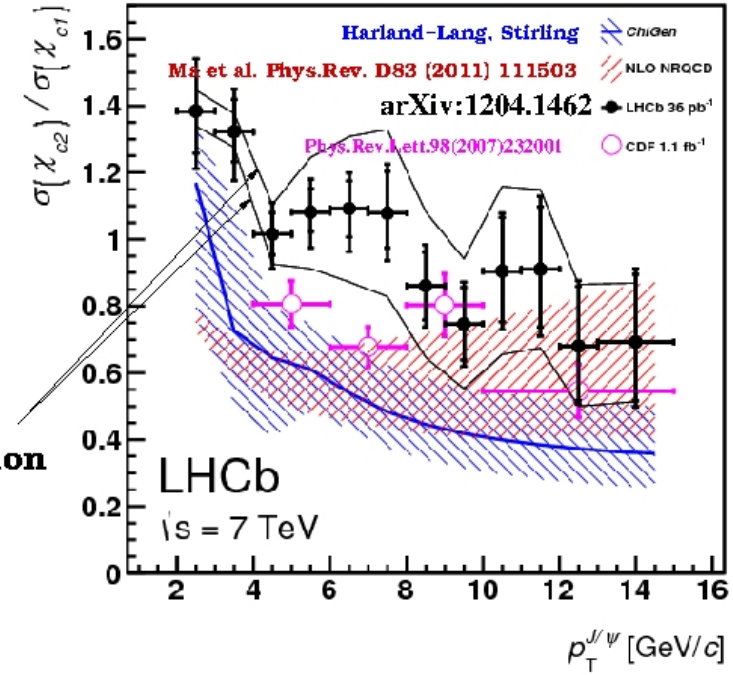
- radiative decays with low–p_T γ: challenging!
- measure $\sigma(\chi_c \rightarrow J/\psi\gamma)/\sigma(J/\psi)$, mostly due to $\chi_{c1,2}$, using calorimeter system for γ identification and energy reconstruction
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ seems larger than any prediction
- result confirmed using photons converted in tracker (lower statistics, better mass resolution)



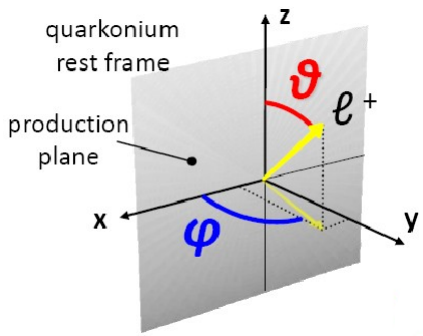




Max effect of polarization



Polarization

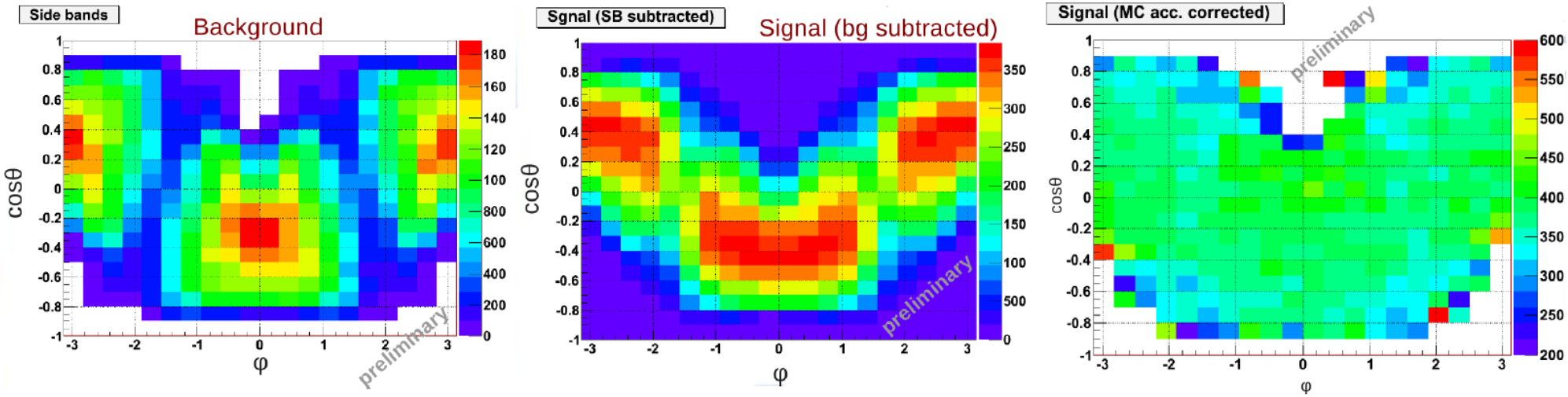


- polarization in helicity frame

$$\frac{dN}{dcos\theta d\phi} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin^2\theta \cos\phi$$

- improve accuracy on cross sections, but also
  critical test for production models: sizeable J/ψ polarization predicted by COM not observed by CDF!

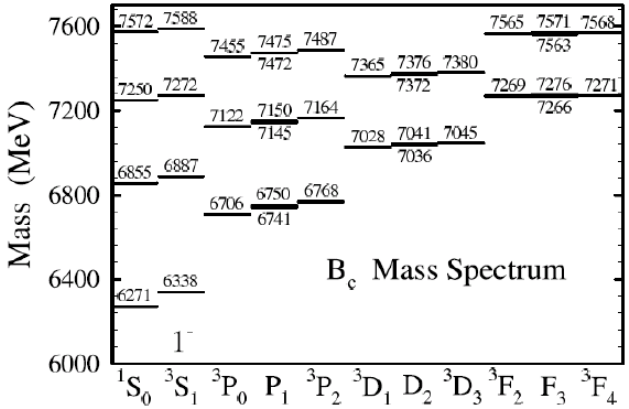
- strategy: extract $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ from unbinned ML fit in bins of η, p_T



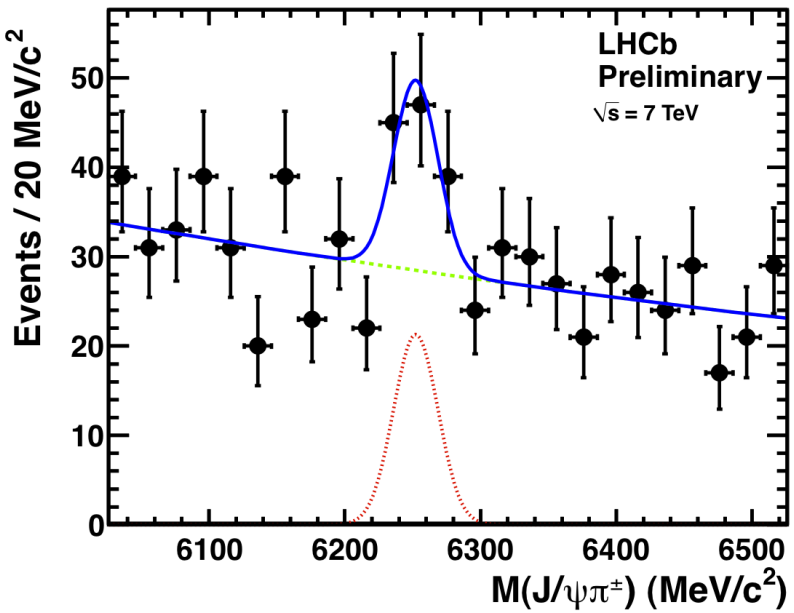
- J/ψ result expected soon

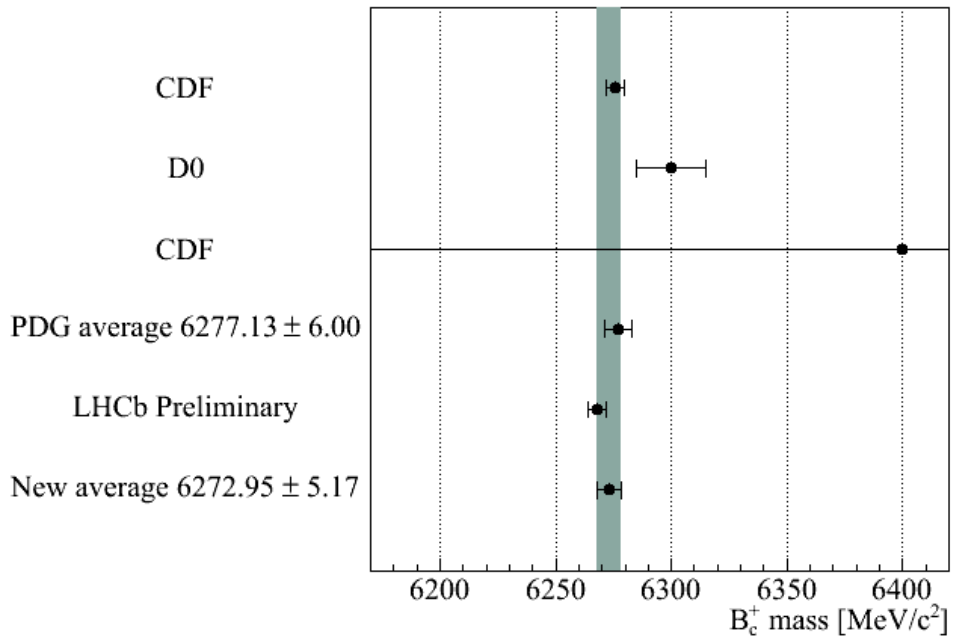
The B_c *meson*

- quarkonium–like state made of $b\bar{c}$ (or c.c.)
- only ground state observed so far,
  a rich spectroscopy to be started
- LHCb already provided the world best mass measurement from 2010 data in $B_c^+ \to J/\psi\,\pi^+$



S. Godfrey, PRD 70, 054017 (2004)





B_c *production*

- $J/\psi\ \pi^+$ channel: preliminary result from 2010 data **(CERN-LHCb-CONF-2011-017)**

$$\frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \to J/\psi\,\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \to J/\psi\,K^+)} = (2.2 \pm 0.8_{\text{stat}} \pm 0.2_{\text{syst}})\% \qquad (p_T > 4\ \text{GeV/c},\ 2.5 < \eta < 4.5)$$

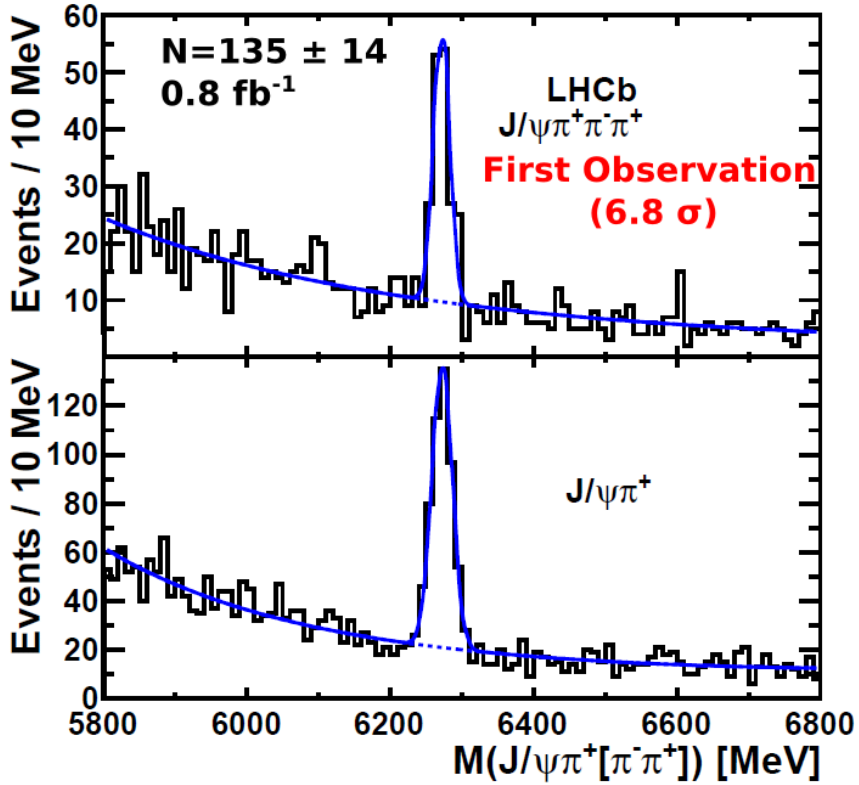
to be improved using 2011 data and more precise lifetime measurement (largest systematic)

- First Observation of $B_c^+ \to J/\psi\ \pi^+\pi^-\ \pi^+$ using 2011 data **(arXiv:1204.0079)**

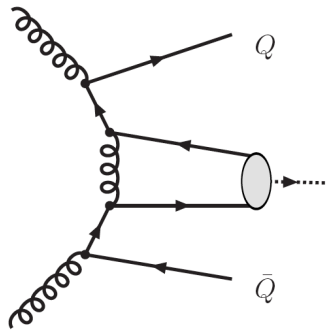
$$\frac{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)} = 2.41 \pm 0.30_{\text{stat}} \pm 0.33_{\text{syst}}$$

Systematics dominated by uncertainty on decay model

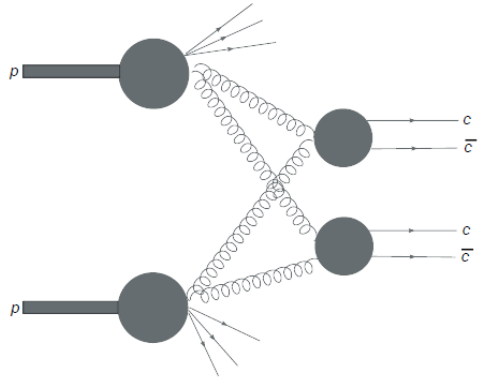
Predictions were ranging from 1.5 to 2.3



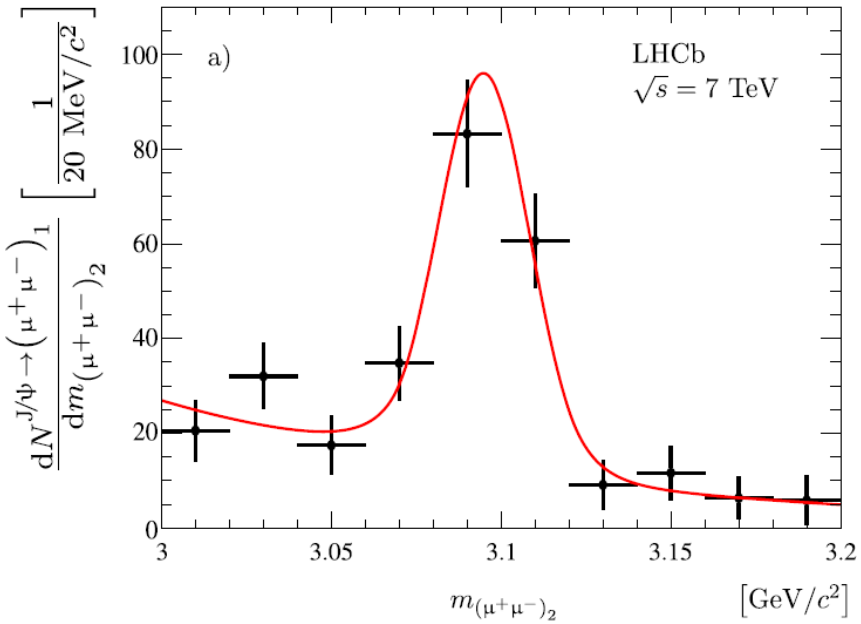
Double J/ψ production



- Production of double $c\bar{c}$ pair is expected from high order gluon-gluon diagrams, with strong sensitivity to possible CO contributions



- Could be enhanced by double parton scattering (DPS)
  and charm content of the proton (IC)



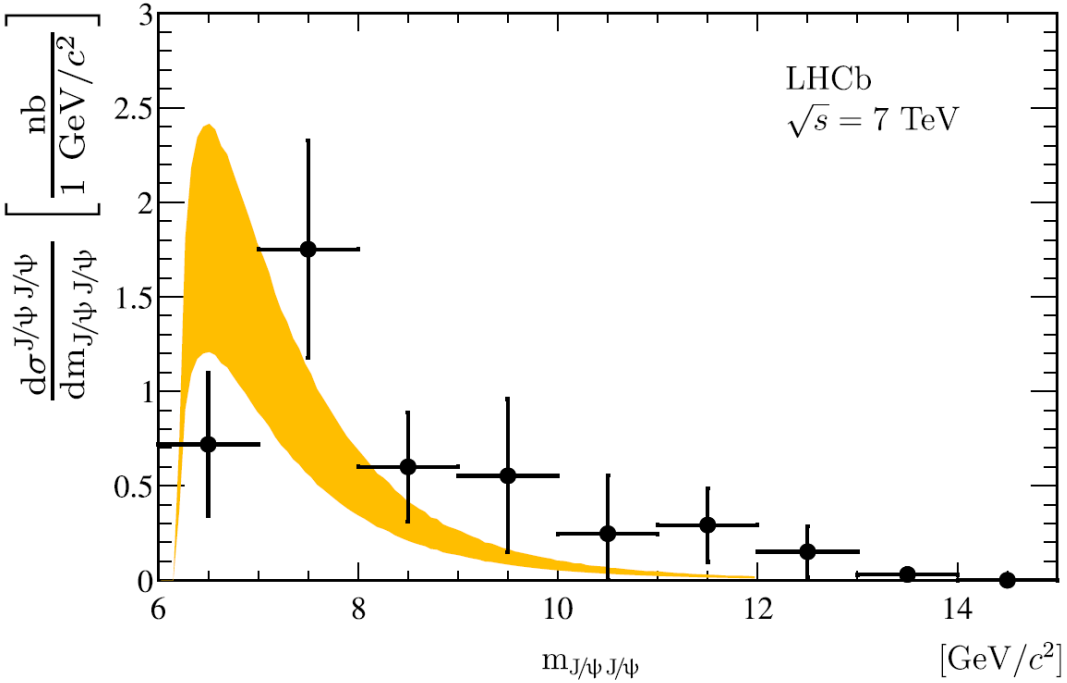
- $\sigma(J/\psi\, J/\psi)$ measured from 2010 data ($37.5\ \mathrm{pb}^{-1}$) requiring 2 J/ψ from common vertex
- 141 ± 19 events observed,
  with average efficiency of 21 %

- cross–section result for $p_T < 10$ GeV/c, $2 < \eta < 4.5$

$$\sigma(J/\psi\, J/\psi) = 5.1 \pm 1.0_{\text{stat}} \pm 1.1_{\text{syst}} \text{ nb}$$

Phys. Lett. B 707 (2012) 52-59

- Theoretical predictions:
  4.1 ± 1.2 nb from LO CSM **(Berezhnoy et al., Phys.Rev.D84 (2011))**
  (including feed–down from $\psi(2S)$)
  2 ± 1 nb from double parton scattering **(Novoselov, arXiv:1106.2184)**

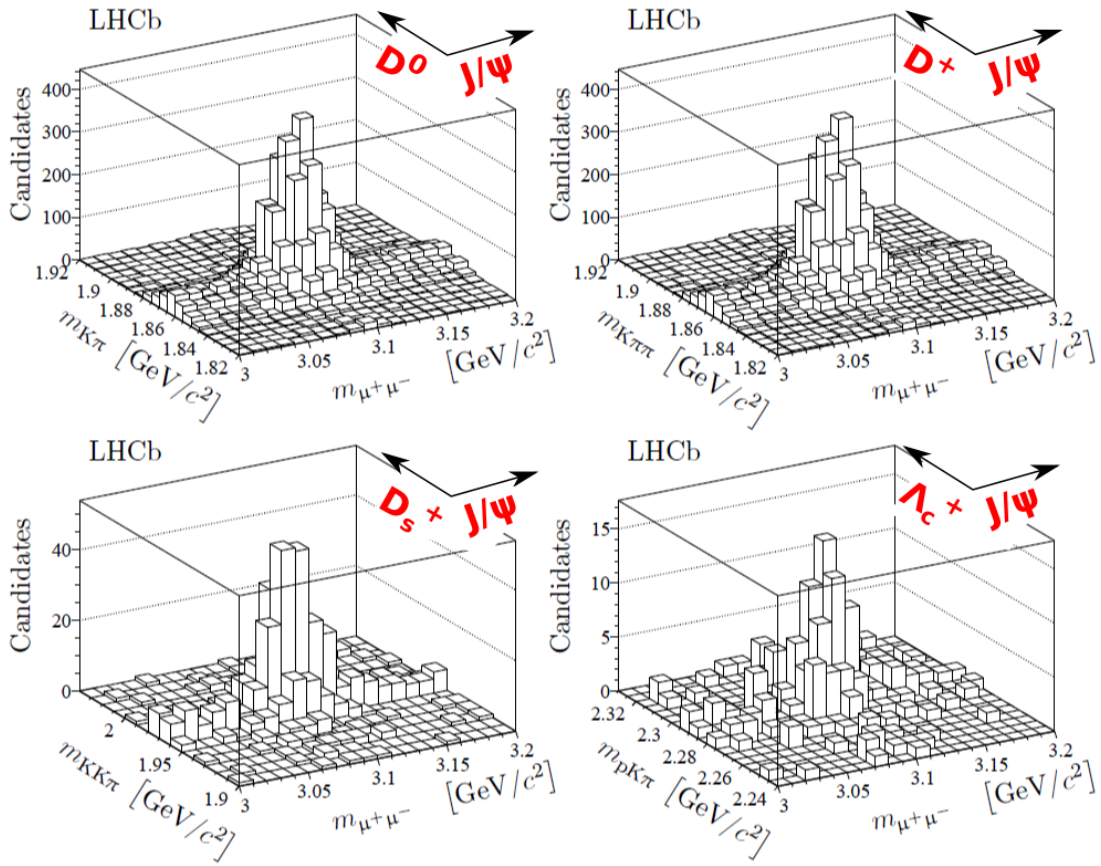


- look at invariant mass to test production model and possible feed–down from charm tetraquark (low mass) or χ_b
- result to be updated with full statistics

J/ψ + *open charm*

arXiv:1205.0975

- Double charm production was also looked at in channels
  J/ψ C (or J/ψ $\overline{C}$) and CC ($\overline{CC}$)
  where $C = \mathrm{D}^0(\to \mathrm{K}^-\pi^+), \mathrm{D}^+(\to \mathrm{K}^-\pi^+\pi^+), \mathrm{D}_s^+(\to \phi\pi^+), \Lambda_c^+(\to p\mathrm{K}^-\pi^+)$,
  measuring also $C\overline{C}$ states as a reference
- predictions from DPS and IC larger by one order of magnitude than LO CSM calculations



- if DPS dominates, one would expect

$$\frac{\sigma_{C_1}\sigma_{C_2}}{\sigma_{C_1C_2}} = \sigma_{eff}^{DPS} \sim 15 \text{ mb}$$

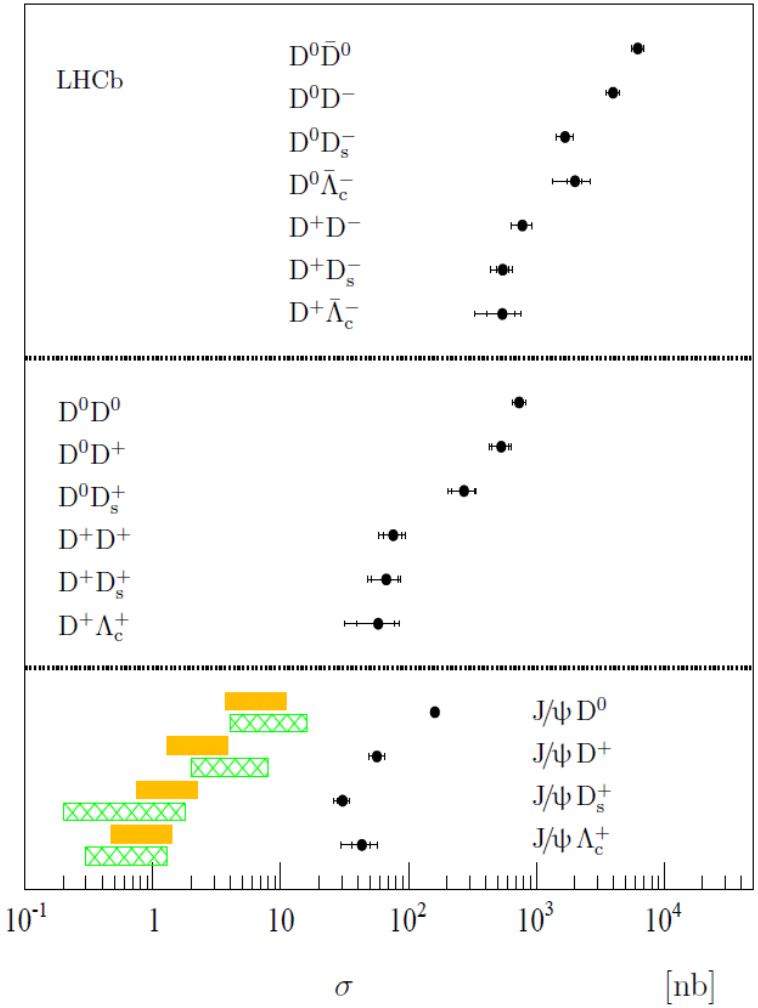
(from Tevatron multi–jet events)

- very clean and large samples obtained from 0.36 fb^{-1}

Mode	S
J/ψ D^0	4875 ± 86
J/ψ D^+	3323 ± 71
J/ψ D_s^+	328 ± 22
J/ψ Λ_c^+	116 ± 14

and 6 CC modes with $> 3\sigma$ SIG.

Cross–section results:



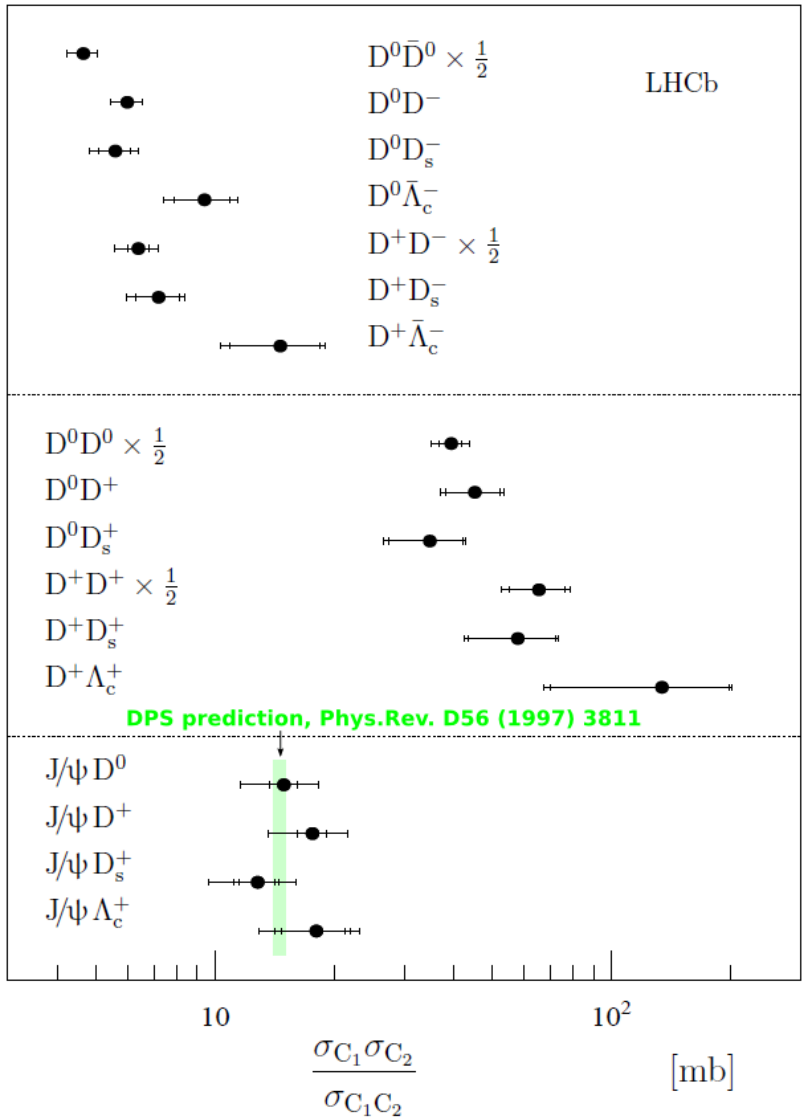
Much larger than LO predictions:

Berezhnoy et al., Phys.Rev. D57 (1998) 4385

Lansberg, Eur. Phys. J C61 (2009) 693

DPS prediction works well for $J/\psi\, C$ modes!

while CC modes are lower by factor 2 to 3



Looking for X,Y,Z states

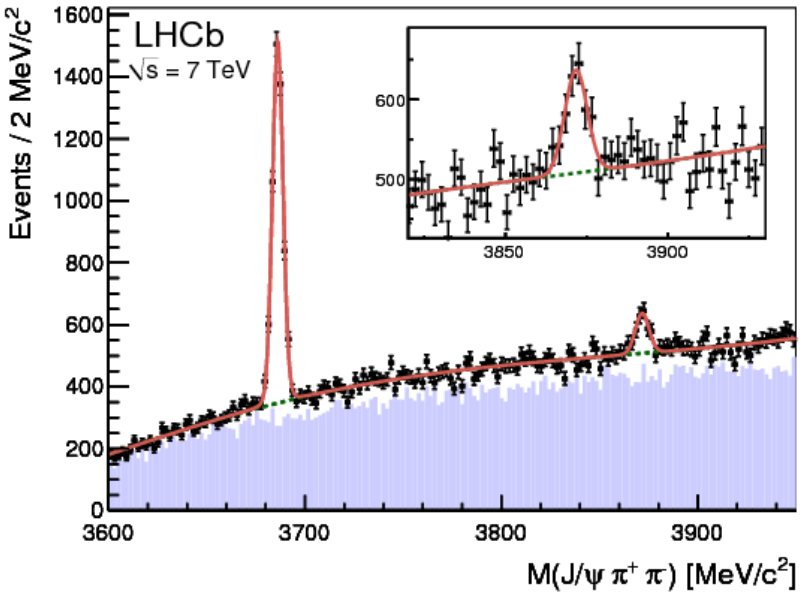
- X(3872) production from 2010 data (35 pb^{-1}):

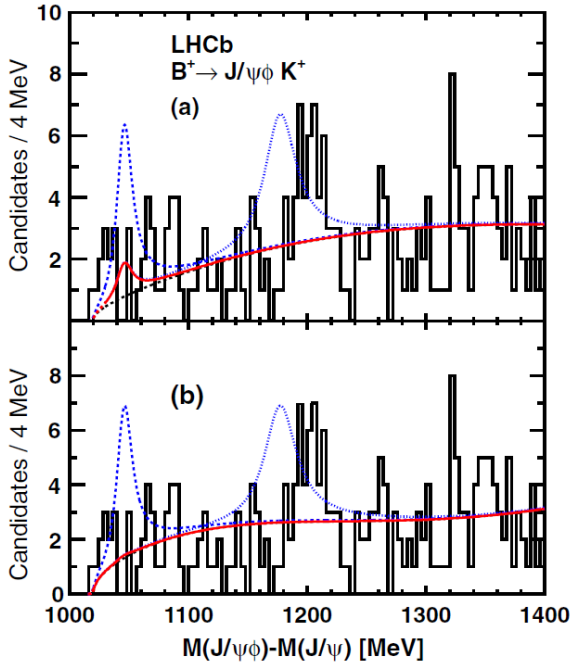
$$\sigma\left(X(3872)\right) \times \mathcal{B}(X(3872) \to J/\psi\,\pi^+\pi^-) = 5.4 \pm 1.3_{\text{stat}} \pm 0.8_{\text{syst}}\ \text{nb}$$

for $5 < p_T < 20$ GeV/c, $2.5 < \eta < 4.5$

Eur.Phys.J.C(2012) 72:1972

- $m_{X(3872)} = 3871.95 \pm 0.48_{\text{stat}} \pm 0.12_{\text{syst}}$ MeV/c^2
still unclear if above DD^* threshold or not
(m(D^0)+m(D^{*0}) = 3871.79 $\pm$ 0.29 MeV/c^2)





- search for the X(4140) and X(4274) states claimed by CDF (arXiv:1101.6058) with significance $> 5\sigma$ and 3.1σ
- no evidence for such states is found from 0.37 fb^{-1}
disagreement with CDF is estimated at the 2.4σ level

Phys. Rev. D 85, 091103 (2012)

Conclusions and Prospects

	Achieved	**much more to come**
Quarkonia	Accurate production measurements of main quarkonia states @7 TeV: plenty of inputs for theorists!	Polarization for J/ψ and others, studies @8 TeV, χ_b studies
B_c	production in J/ψ π channel and first observation of J/ψ π π π, best mass measurement	updated results, search in new decay modes
Double $c\bar{c}$	Observation of double J/ψ, 4 J/ψ + C and 6 CC modes with high ($> 3\sigma$) significance, strong hint for DPS!	updated J/ψ J/ψ result, search for double heavy baryons
New/exotic states	X(3872) production and mass, search for X(4140)	X(3872) from B, search for claimed Z states and for tetra/pentaquarks