

# Charmonium studies with hadron final state

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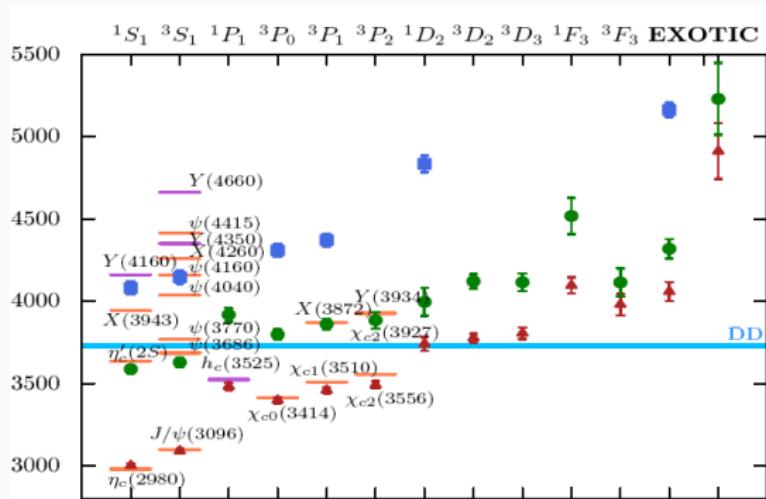
Laboratoire de l'Accélérateur Linéaire, Orsay

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Journées de Rencontre des Jeunes Chercheurs 2013

# Introduction

- Quarkonium — heavy ( $b, c$ ) quark-antiquark bound state
- ( $c\bar{c}$ ), charmonium
  - ▶ light enough to be easily produced ( $m_c = 1.29$  GeV)
  - ▶ heavy enough to test QCD models



"Old physics" searches in frame of Standart Model

# Hadron decay channels

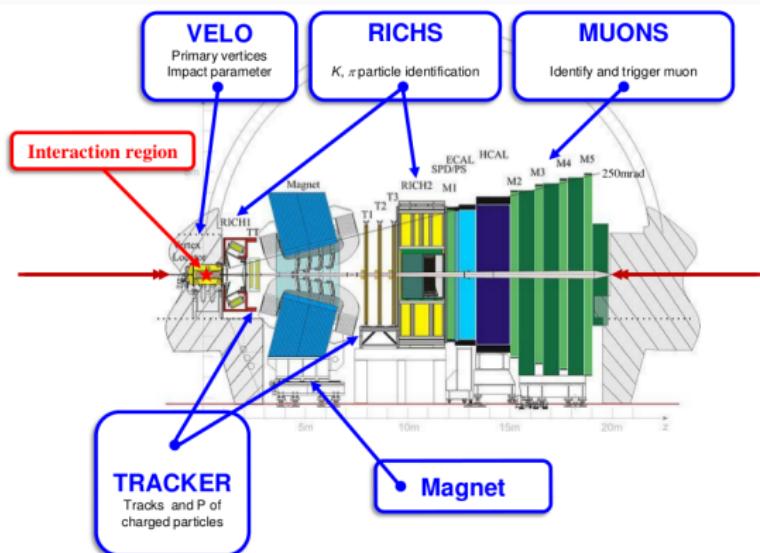
$c\bar{c} \rightarrow \ell\bar{\ell}$  ( $\mu^+\mu^-$ ) channel is forbidden for several charmonium states because it requires quantum numbers  $1^{--}$ .

We use hadron decays:

- $c\bar{c} \rightarrow p\bar{p}$ 
  - ▶ simultaneous measurement (relative to the  $J/\psi$ )
  - ▶ topologically identical channels allow partially cancel systematics
- $c\bar{c} \rightarrow \phi\phi$ 
  - ▶ topologically identical channels allow partially cancelled systematics
  - ▶ many  $c\bar{c}$  states decay into the  $\phi\phi$  pair
  - ▶  $2(K^+K^-)$  final state, relatively clean
  - ▶ two narrow  $\phi$  peaks

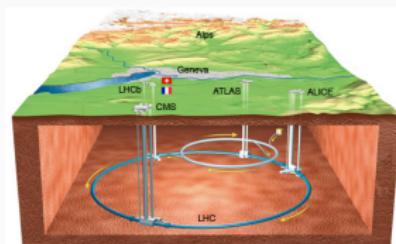
# LHCb detector

One of the four big experiments @ LHC



- good to study pure hadron states
- much higher cross-sections than @ B-factories
  - ▶ but large background due to dense hadron medium

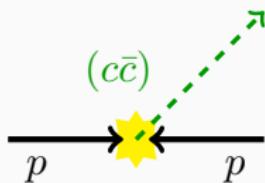
- excellent muon ID:
  - ▶  $(\mu \rightarrow \mu) = 97\%$
  - ▶  $(\pi \rightarrow \mu) = 2\%$
- Vertexing: proper time resolution 30-50 fs
- charged tracks
- $\Delta p/p \lesssim 0.5\%$
- $3.2 \text{ fb}^{-1}$  of data collected



# $c\bar{c}$ production

Charmonium is produced in two ways:

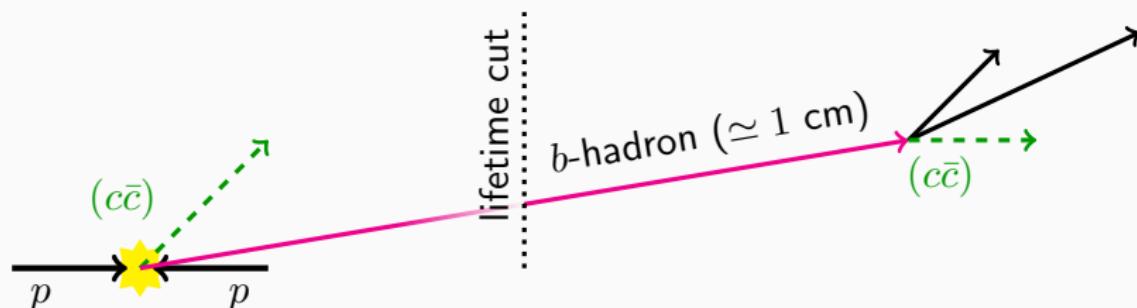
- prompt ← precious for theorists, first  $\eta_c$  yield measurement
  - ▶ direct parton interactions (hadroproduction)
  - ▶ decays of higher  $c\bar{c}$  states



# $c\bar{c}$ production

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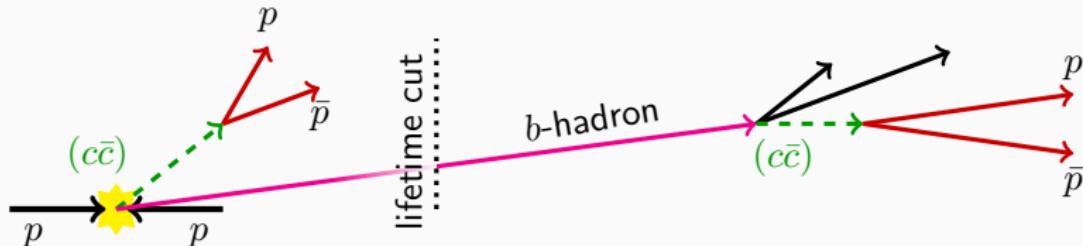
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  - ▶ direct parton interactions (hadroproduction)
  - ▶ decays of higher  $c\bar{c}$  states
- $b$ -decays ← new measurements
  - ▶  $b$ -hadron decays
  - ▶  $b$ -hadron decays via higher  $c\bar{c}$  states



# Masses and branching ratios

$$c\bar{c} \rightarrow p\bar{p}$$

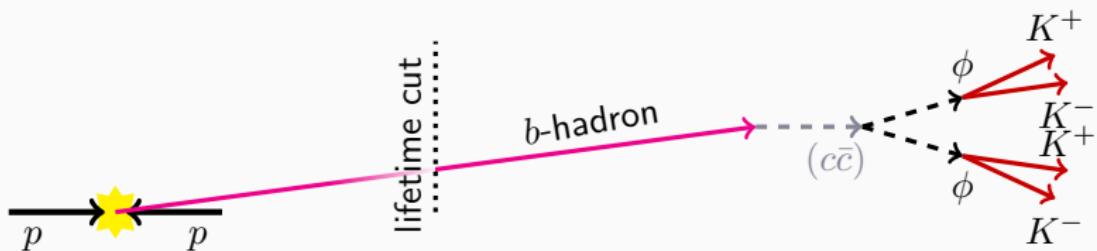
	mass, MeV	$\Gamma$ , MeV	$\mathcal{B}_{c\bar{c} \rightarrow p\bar{p}} \times 10^{-3}$	$\mathcal{B}_{c\bar{c} \rightarrow \phi\phi} \times 10^{-3}$
$\eta_c(1S)$	$2980.5 \pm 1.47$	$29.7 \pm 1.0$	$1.51 \pm 0.16$	$1.94 \pm 0.30$
$J/\psi(1S)$	$3096.916 \pm 0.011$	negligible	$2.120 \pm 0.029$	forbidden
$\chi_{c0}(1S)$	$3414.75 \pm 0.31$	$10.4 \pm 0.6$	$0.213 \pm 0.012$	$0.82 \pm 0.08$
$\chi_{c1}(1P)$	$3510.66 \pm 0.07$	$0.86 \pm 0.5$	$0.073 \pm 0.004$	$0.44 \pm 0.06$
$h_c(1P)$	$3525.67 \pm 0.32$	$< 1$	not seen	not seen
$\chi_{c2}(1P)$	$3556.20 \pm 0.09$	$1.98 \pm 0.11$	$0.071 \pm 0.004$	$1.14 \pm 0.12$
$\eta_c(2S)$	$3638.9 \pm 1.3$	$10 \pm 4$	$< 0.29 @ 90\%$	not seen
$\psi(2S)$	$3686.09 \pm 0.04$	negligible	$0.275 \pm 0.012$	forbidden
$\psi(3770)$	$3773.15 \pm 0.33$	$27.2 \pm 1.0$	not seen	not seen
$X(3872)$	$3871.68 \pm 0.17$	$< 1.2 @ 90\%$	not seen	not seen
$X(3915)$	$3917.5 \pm 2.7$	$27 \pm 10$	not seen	not seen



# Masses and branching ratios

$$c\bar{c} \rightarrow \phi\phi$$

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# $c\bar{c} \rightarrow p\bar{p}$ channel

$\eta_c(1S)$  state - a pseudo scalar  $0^{-+}$

- poorly studied
- many theories require its production cross-section

$J/\psi(1S)$  state - a vector  $1^{--}$

- well studied by  $J/\psi \rightarrow \mu^+ \mu^-$
- agree with models

Presently (PDG13):

$\mathcal{B}_{b \rightarrow J/\psi X} = (11.6 \pm 1.0) \times 10^{-3}$ ,  
from  $B^\pm/B^0/B_s/b-$  baryon admixture  
 $\mathcal{B}_{b \rightarrow \eta_c X}$  is unknown

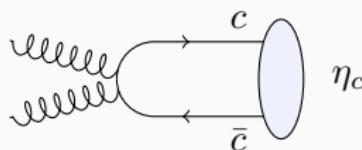
# Production mechanism

Prompt production:  
(factorisation approach, CS model)

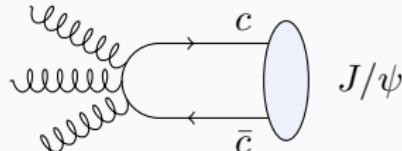


— single gluon is not “white”.

For spin  $\neq 1$  states:



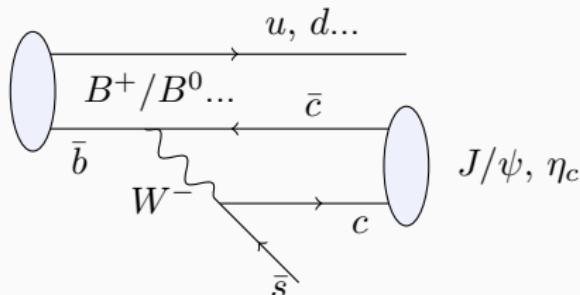
and any  $c\bar{c}$  can be produced as:



If pQCD works well, one should expect

$$\sigma_{\eta_c} > \sigma_{J/\psi}$$

Inclusive  $b$ -decay production:



$\approx 3$  times more  $J/\psi$   $\mathcal{BR}$  due to spin factor

# Cross-talk estimate

Measured quantities  $n^P$  and  $n^S$  are linked with yields  $N^P$  and  $N^S$

$$\begin{cases} n^P = \varepsilon_{P \rightarrow P} N^P + \varepsilon_{S \rightarrow P} N^S \\ n^S = \varepsilon_{S \rightarrow S} N^S + \varepsilon_{P \rightarrow S} N^P \end{cases}$$

Reconstruction efficiency,  $\times 10^{-3}$ :

	$\eta_c$ production:		$J/\psi$ production:	
reconstruction:	prompt	secondary	prompt	secondary
prompt	6.0	0.45	6.2	0.45
secondary	0.04	7.7	0.04	7.7

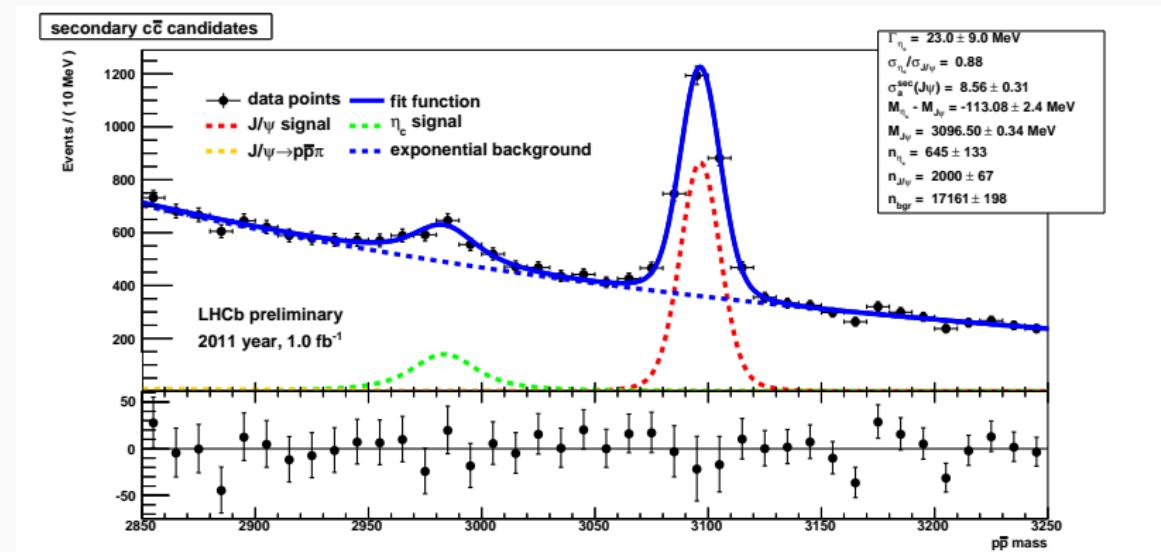
$$\frac{N_{\eta_c}^P}{N_{J/\psi}^P} = \eta \times \frac{\varepsilon_{S \rightarrow S} n_{\eta_c}^P - \varepsilon_{S \rightarrow P} n_{\eta_c}^S}{\varepsilon_{S \rightarrow S} n_{J/\psi}^P - \varepsilon_{S \rightarrow P} n_{J/\psi}^S},$$

flip the indices  $S \leftrightarrow P$  for  $N_{\eta_c}^S / N_{J/\psi}^S$ ,  $\eta = 1$ .

$J/\psi$  polarisation affects efficiency as  $\eta = \varepsilon_{pol}^{P \rightarrow P, S} / \varepsilon^{P \rightarrow P, S} = 1.02 \pm 0.2$

# b-decay $c\bar{c}$ candidates

2011 year



$$n_{J/\psi}^{snd} = 2000 \pm 67$$

$$M_{J/\psi} = 3096.50 \pm 0.34 \text{ MeV}/c^2$$

$$n_{\eta_c}^{snd} = 645 \pm 133$$

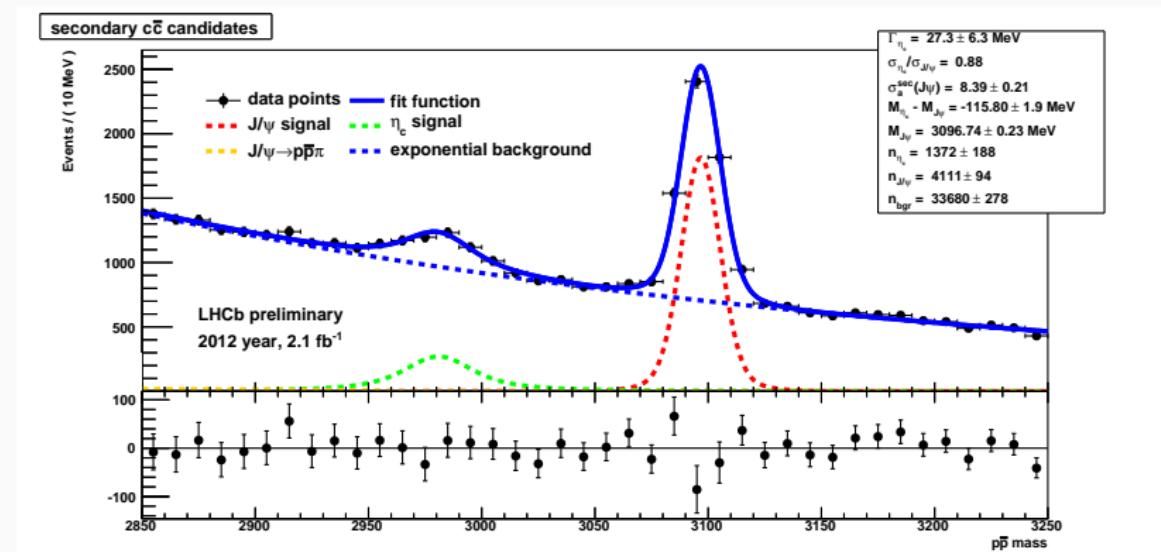
$$M_{J/\psi} - M_{\eta_c} = \mathbf{113.1 \pm 2.4 \text{ MeV}/c^2}$$

$$n_{\eta_c}/n_{J/\psi} = \mathbf{0.323 \pm 0.068}$$

$$\Gamma_{\eta_c} = \mathbf{23.0 \pm 9.0 \text{ MeV}}$$

# b-decay $c\bar{c}$ candidates

2012 year



$$n_{J/\psi}^{snd} = 4110 \pm 94 \quad M_{J/\psi} = 3096.74 \pm 0.34 \text{ MeV}/c^2$$

$$n_{\eta_c}^{snd} = 1372 \pm 188 \quad M_{J/\psi} - M_{\eta_c} = \mathbf{115.8 \pm 1.9} \text{ MeV}/c^2$$

$$n_{\eta_c}/n_{J/\psi} = \mathbf{0.334 \pm 0.047} \quad \Gamma_{\eta_c} = 27.3 \pm 6.3 \text{ MeV}$$

# Inclusive b-decay $c\bar{c}$ yields

2011 year data set:

$$N_{\eta_c}^S/N_{J/\psi}^S = 0.289 \pm 0.069 \pm 0.015$$

2012 year data set:

$$N_{\eta_c}^S/N_{J/\psi}^S = 0.308 \pm 0.048 \pm 0.014$$

## Average

$$\frac{N_{\eta_c}^S}{N_{J/\psi}^S} = \frac{\mathcal{B}_{b \rightarrow \eta_c X} \times \mathcal{B}_{\eta_c \rightarrow p\bar{p}}}{\mathcal{B}_{b \rightarrow J/\psi X} \times \mathcal{B}_{J/\psi \rightarrow p\bar{p}}} = \mathbf{0.302 \pm 0.039 \pm 0.010}$$

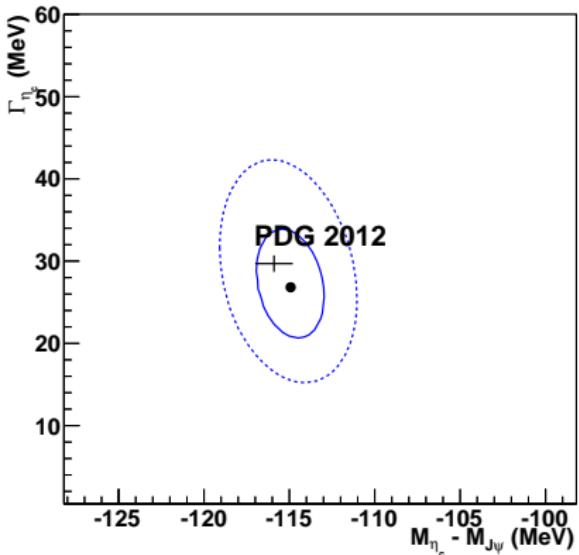
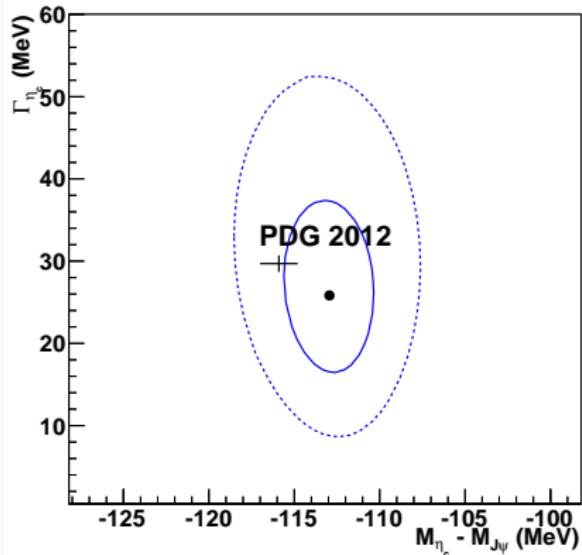
$$\mathcal{B}_{b \rightarrow \eta_c X} / \mathcal{B}_{b \rightarrow J/\psi X} = \mathbf{0.424 \pm 0.055_{stat} \pm 0.014_{syst} \pm 0.045_{BR}}$$

— almost factor 1/3 ( $\approx$  within error)

$$\mathcal{B}_{b \rightarrow \eta_c X} = (4.91 \pm 0.64_{stat} \pm 0.17_{syst} \pm 0.53_{BR}) \times 10^{-3}$$

— the first measurement (only the limit before)

$M_{\eta_c}$  and  $\Gamma_{\eta_c}$   
average



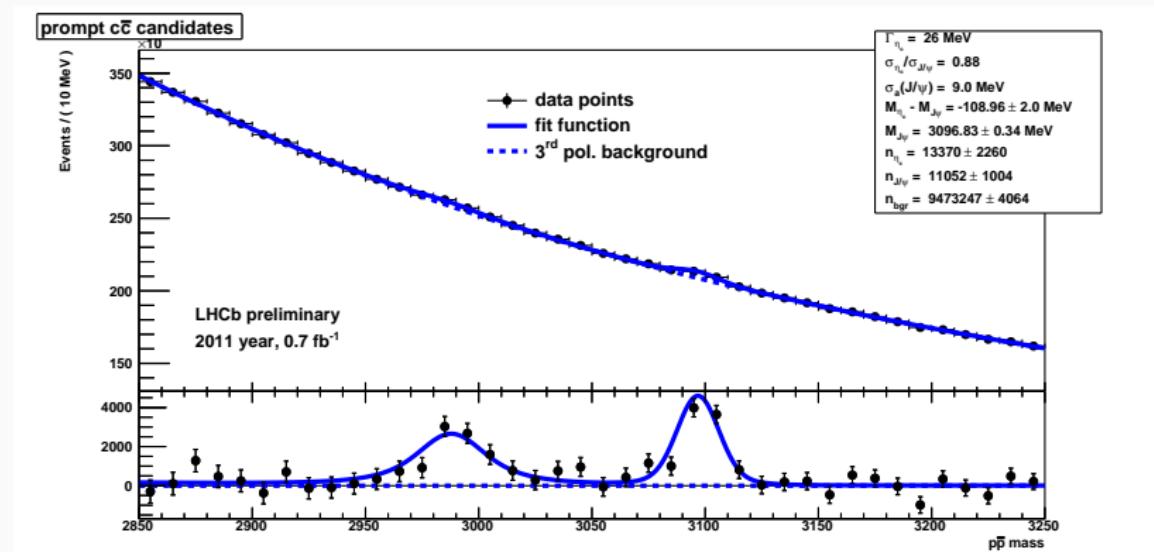
2011-2012 average:

$$\Delta M_{\eta_c} = \mathbf{114.7 \pm 1.5 \pm 0.1} \text{ MeV}/c^2$$

$$\Gamma_{\eta_c} = \mathbf{25.8 \pm 5.2 \pm 1.9} \text{ MeV}$$

# Prompt $c\bar{c}$ candidates

2011 year



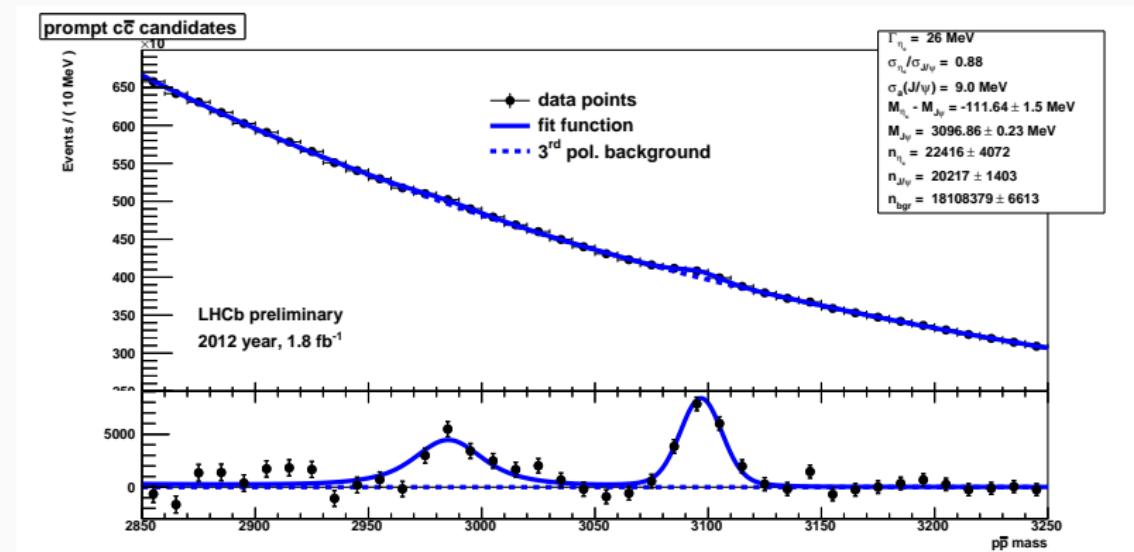
$$n_{J/\psi}^{snd} = 11052 \pm 1004 \quad M_{J/\psi} = 3096.8 \pm 0.3 \text{ MeV}/c^2$$

$$n_{\eta_c}^{snd} = 13370 \pm 2260 \quad M_{J/\psi} - M_{\eta_c} = 109.0 \pm 2.0 \text{ MeV}/c^2$$

$$n_{\eta_c}/n_{J/\psi} = \mathbf{1.21 \pm 0.22}$$

# Prompt $c\bar{c}$ candidates

2012 year



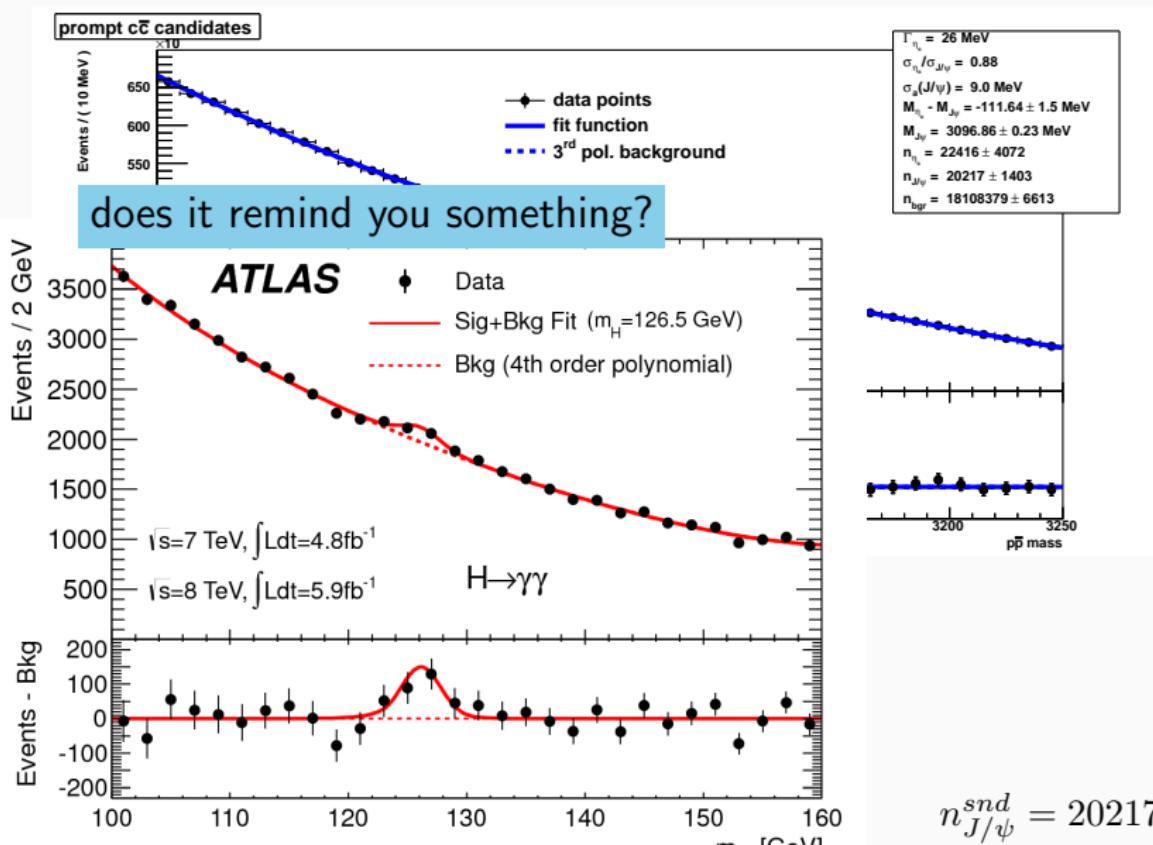
$$n_{J/\psi}^{snd} = 20217 \pm 1403 \quad M_{J/\psi} = 3096.9 \pm 0.2 \text{ MeV}/c^2$$

$$n_{\eta_c}^{snd} = 22416 \pm 4072 \quad M_{J/\psi} - M_{\eta_c} = 111.6 \pm 1.5 \text{ MeV}/c^2$$

$$n_{\eta_c}/n_{J/\psi} = \mathbf{1.11 \pm 0.20}$$

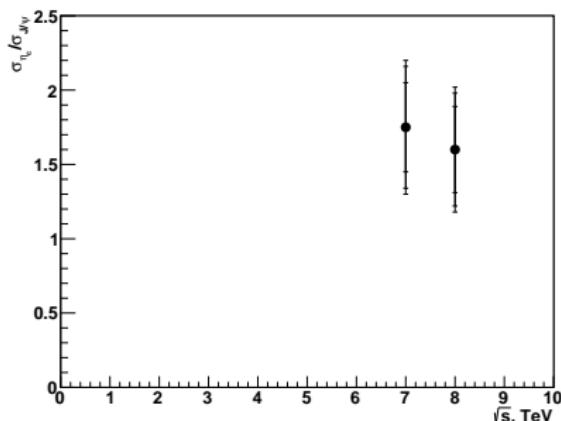
# Prompt $c\bar{c}$ candidates

2012 year



# Relative cross-section

Taking  $\mathcal{B}_{J/\psi} \rightarrow p\bar{p}$  and  $\mathcal{B}_{\eta_c} \rightarrow p\bar{p}$  from PDG13 (BES IIIs), we extract the  $\eta_c$  to  $J/\psi$  cross-section ratios



prompt  $p\bar{p}$ ,  $\sqrt{s} = 7$  TeV:

$$N_{\eta_c}/N_{J/\psi} = 1.24 \pm 0.21 \pm 0.17$$

prompt  $p\bar{p}$ ,  $\sqrt{s} = 8$  TeV:

$$N_{\eta_c}/N_{J/\psi} = 1.14 \pm 0.21 \pm 0.16$$

2011,  $\sqrt{s} = 7$  TeV:  $\sigma_{\eta_c}/\sigma_{J/\psi} = 1.75 \pm 0.30_{stat} \pm 0.24_{syst} \pm 0.19_{\mathcal{BR}}$

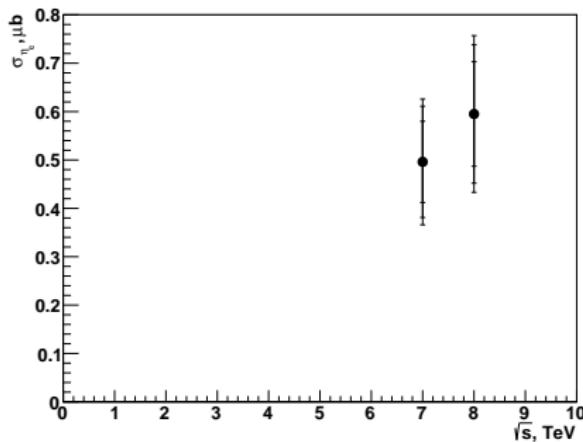
2012,  $\sqrt{s} = 8$  TeV:  $\sigma_{\eta_c}/\sigma_{J/\psi} = 1.60 \pm 0.29_{stat} \pm 0.22_{syst} \pm 0.17_{\mathcal{BR}}$

- results will improve with higher statistics,  $\mathcal{BR}$  error is significant
- 14 TeV point can be interesting

# Prompt $\eta_c$ cross-section

Using known  $\sigma_{J/\psi}$

extract the prompt  $\eta_c$  cross-sections



- $p_T > 6500 \text{ MeV/c}$
- $2.0 < y < 4.5$

So does factorisation works  
at least in the forward high- $p_T$   
region?

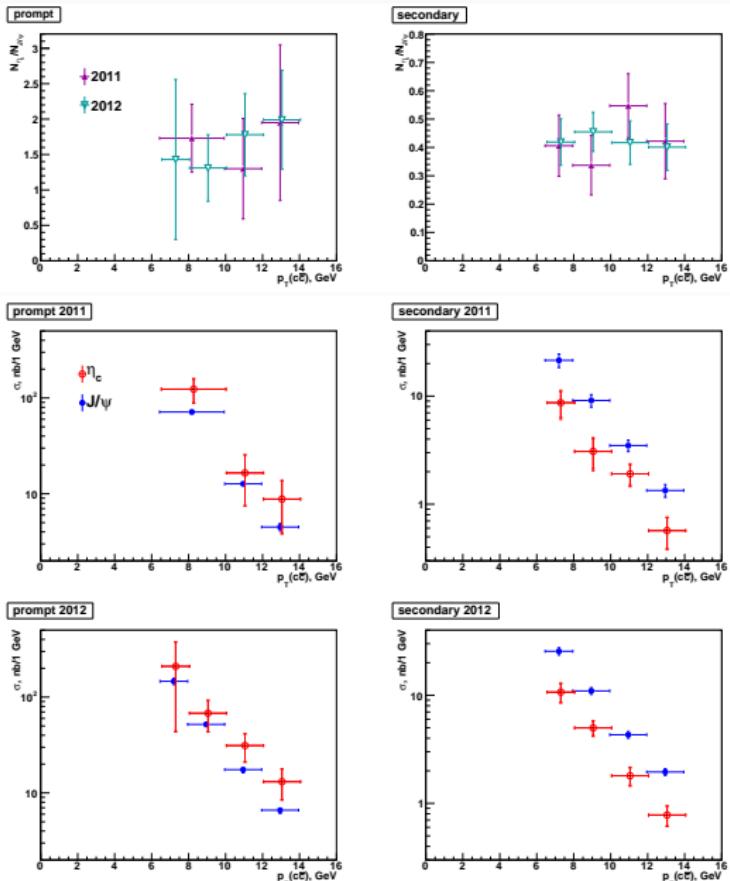
Still waiting for theorists

2011,  $\sqrt{s} = 7 \text{ TeV}$ :  $\sigma_{\eta_c} = 0.50 \pm 0.08_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.06_{\mathcal{BR}}, \sigma_{J/\psi} \mu\text{b}$

2012,  $\sqrt{s} = 8 \text{ TeV}$ :  $\sigma_{\eta_c} = 0.59 \pm 0.11_{\text{stat}} \pm 0.09_{\text{syst}} \pm 0.08_{\mathcal{BR}}, \sigma_{J/\psi} \mu\text{b}$

- the first measurement
- 14 TeV point can be interesting

# $N_{\eta_c}/N_{J/\psi}$ in $p_T$ bins

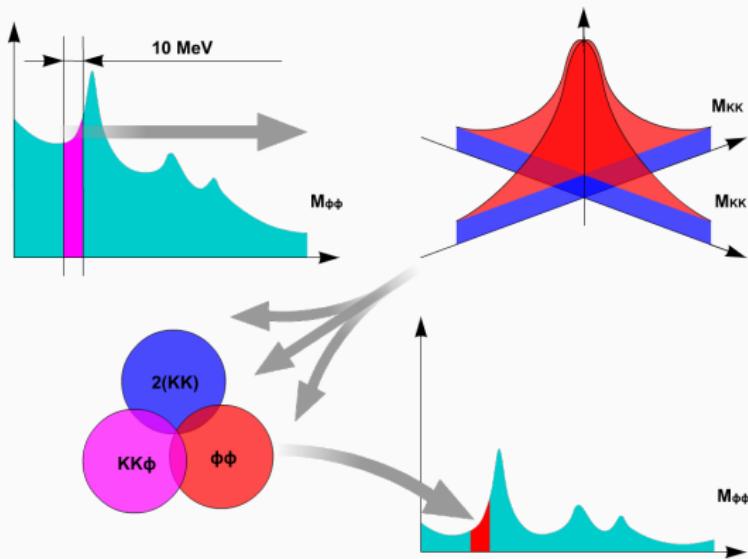


The yield ratio in bins of transverse momentum

- potentially interesting for theorists
- ratio is rather "flat"
- errors are **large**  
**huge** in case of prompt)

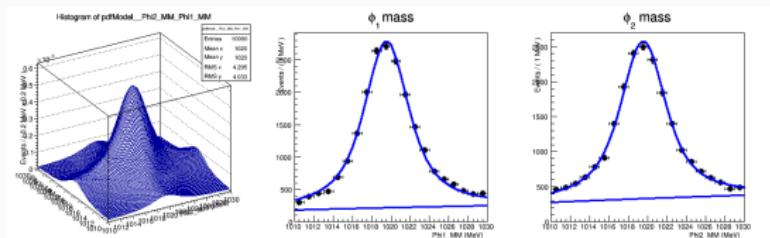
# $\phi\phi$ mass spectrum

## component extraction scheme



Bin-by-bin fitting technique

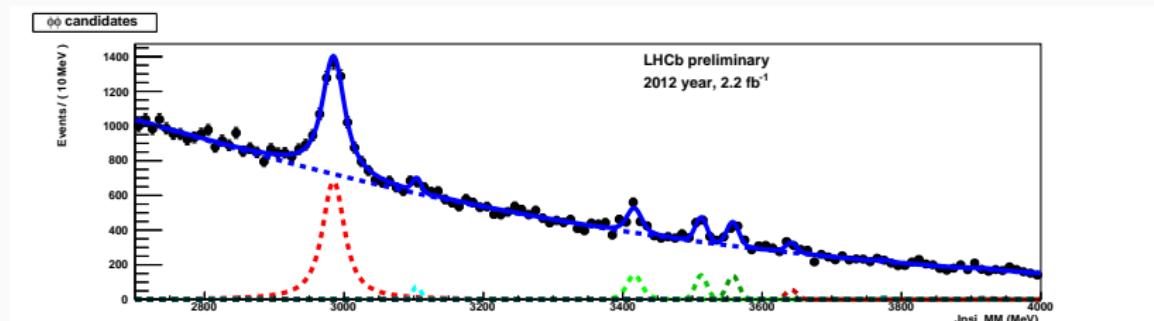
- 1 take all events from the mass bin
- 2 make 2D fit of  $\phi$  mass
- 3 extract pure  $\phi$  component
- 4 fill  $\phi\phi$  mass histogram



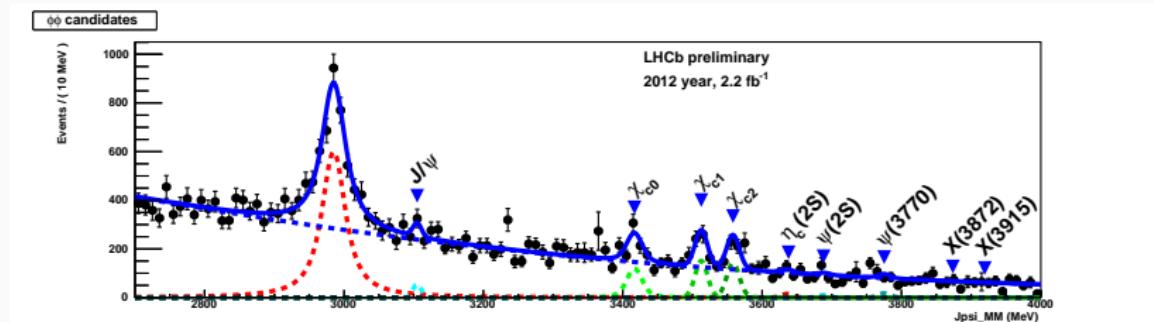
# $\phi\phi$ mass spectrum

2012 data

"Raw" data:



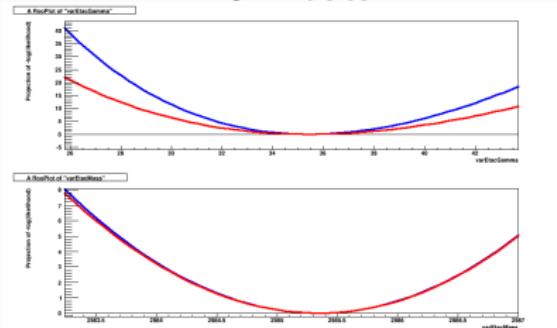
after bin-by-bin fitting:



# $\eta_c(1S)$ : mass and natural width

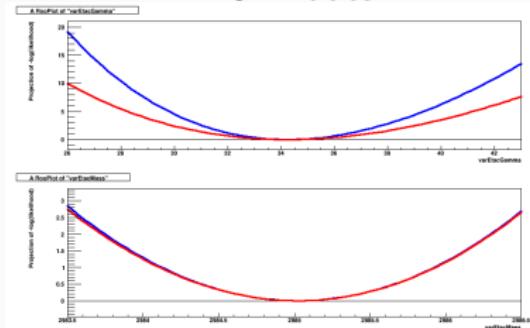
2011 and 2012 data

2011 data



$$\begin{aligned}\Gamma_{\eta_c} &= 30.6 + 2.6 - 2.2 \text{ MeV} \\ M_{\eta_c} &= 2986.0 \pm 0.7 \text{ MeV}\end{aligned}$$

2012 data



$$\begin{aligned}\Gamma_{\eta_c} &= 34.3 + 2.2 - 1.8 \text{ MeV} \\ M_{\eta_c} &= 2985.0 \pm 0.6 \text{ MeV}\end{aligned}$$

## Profile likelihood analysis: 2011 and 2012 average

$$\begin{aligned}\Gamma_{\eta_c} &= 32.6 \pm 2.0 \text{ MeV} \\ M_{\eta_c} &= 2985.5 \pm 0.5 \text{ MeV}\end{aligned}$$

- Statistical errors only

$$\begin{aligned}\Gamma_{\eta_c}^{PDG} &= 29.7 \pm 1.0 \text{ MeV} \\ M_{\eta_c}^{PDG} &= 2981.0 \pm 1.1 \text{ MeV}\end{aligned}$$

# Conclusions

- $c\bar{c} \rightarrow p\bar{p}$ 
  - ▶ first measurement of prompt  $\eta_c$  production
  - ▶ first measurement of  $\eta_c$  inclusive yield from b-decays
- $c\bar{c} \rightarrow \phi\phi$ 
  - ▶ charmonium inclusive yield from b-decays studied using  $\phi\phi$  final state
  - ▶ many results ongoing!
  - ▶ look at mass & width of  $\eta_c(1S)$