



Charm and Charmonia production at LHCb



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On behalf of LHCb Collaboration

“LHC on the March”

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Outline

- *Physics motivation*
- *The LHCb detector*
- *Production of J/ψ*
- *Production of $\psi(2S)$*
- *Production of χ_c and measurements of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ & $\sigma(\chi_c)/\sigma(J/\psi)$*
- *Double charm(onia) production ($J/\psi J/\psi$, $J/\psi C$, CC and $\overline{C}\overline{C}$)*

Physics motivation

- *The study of properties of bound states of heavy quarks plays a central role in our understanding of perturbative QCD.*
- *J/ ψ and $\psi(2S)$ surplus problem (found by CDF 20 years ago). Color-Singlet model failed to explain the data.*
- *Color-Octet Model was introduced to solve the problem. But COM failed to explain the quarkonia polarization. Renaissance of CSM. So (CSM vs COM), or (CSM + COM), or something else.*
- *Prompt χ_c give substantial feed-down to J/ ψ production: crucial for polarization studies of J/ ψ .*

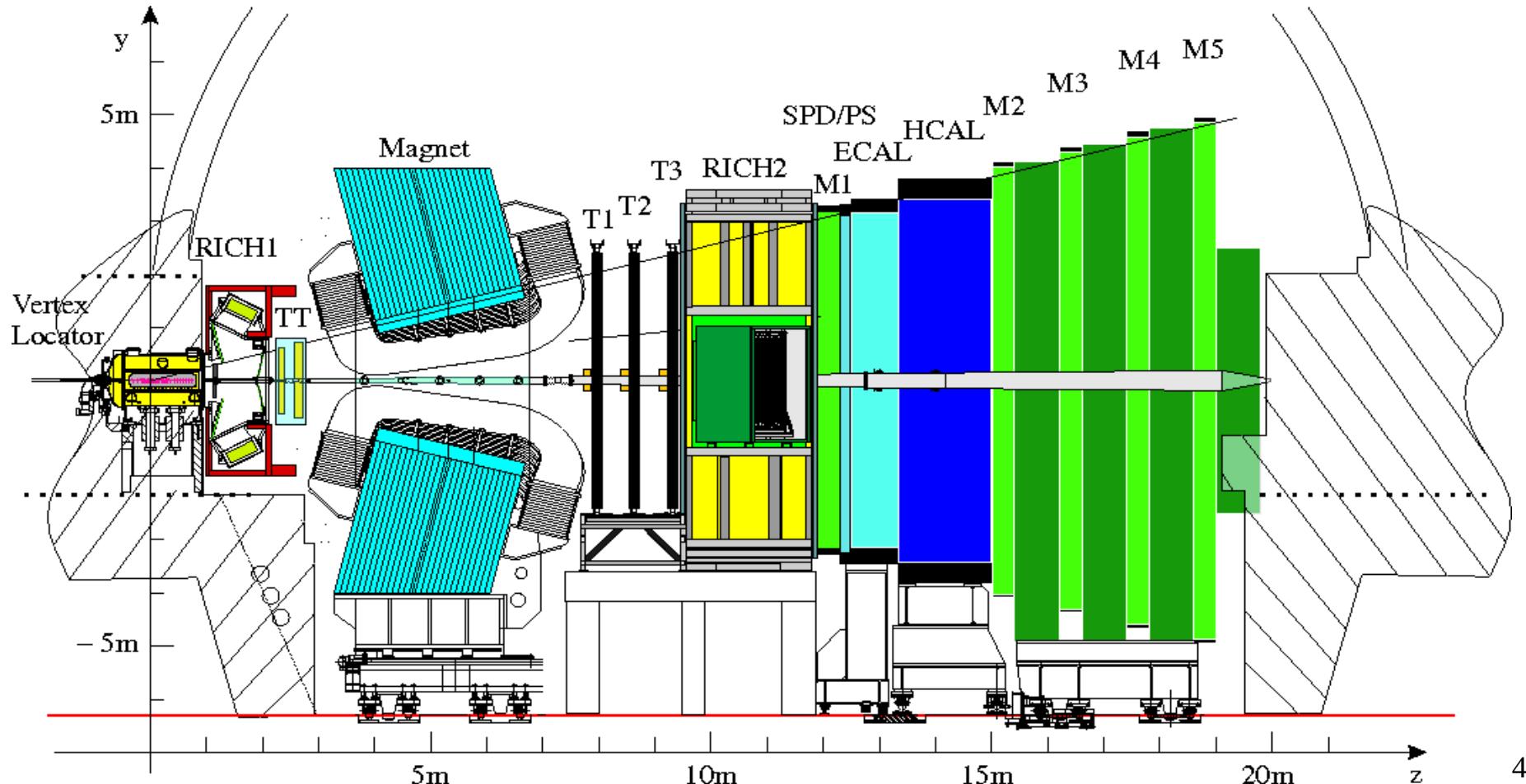
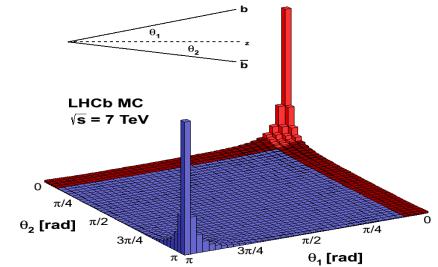
$2 < \eta < 5$

4% of solid angle

40% of heavy quarks

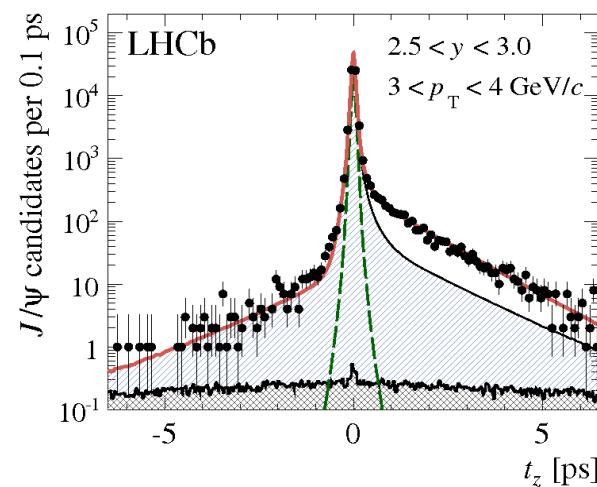
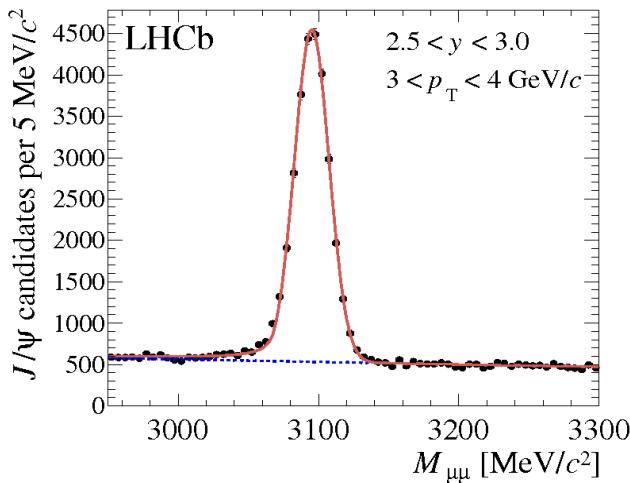
The LHCb detector

is a forward spectrometer designed for precision studies
of CP violation and rare decays of b- and c-hadrons



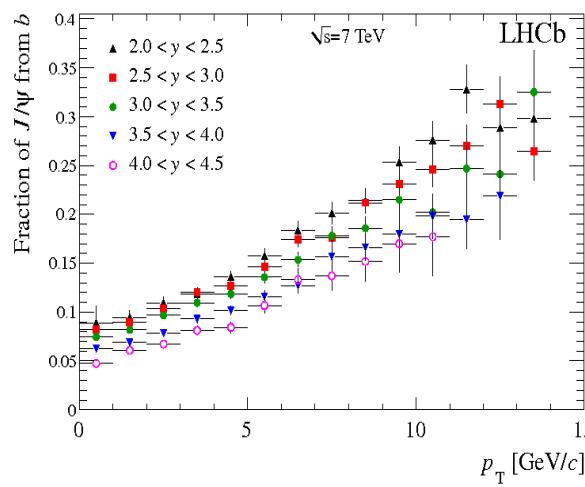
J/ψ production (selection)

Eur. Phys. J. C71 (2011) 1645



LHC on the March 2012

- *J/ψ production at LHCb: $\sqrt{s} = 7 \text{ TeV}$, $p_T < 14 \text{ GeV}/c$, $2.0 < y < 4.5$*
- *About 565'000 of J/ψ in $\mu^+\mu^-$ decay mode per $\mathcal{L} = (5.2 \pm 0.5) \text{ pb}^{-1}$*
- *Mass resolution $\sigma_M = (12.3 \pm 0.1) \text{ MeV}/c^2$ for $(3 < p_T < 4) \text{ GeV}/c$ & $(2.5 < y < 3.0)$*
- *J/ψ pseudo-proper time is defined as* $t_z = \frac{(z_{J/\psi} - z_{\text{PV}}) \times M_{J/\psi}}{p_z}$
- *RMS of t_z resolution function is 53 fs*



A.V.Artamonov

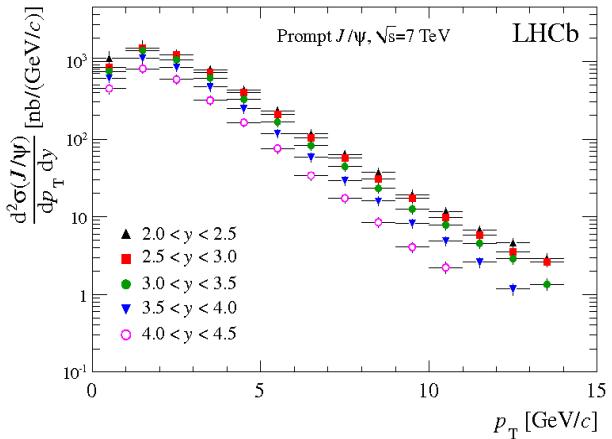
The 3 sources of J/ψ production:

- *direct production (prompt)*
- *feed-down from excited states (prompt)*
- *from b -hadron decays (delayed)*

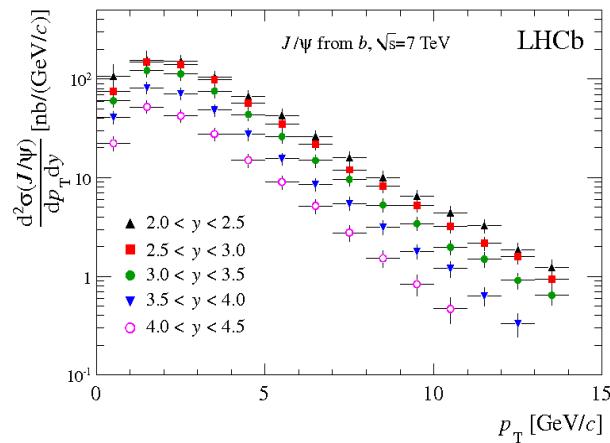
J/ψ production (cross-sections)

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Cross-section results for J/ψ production at LHCb: $\sqrt{s} = 7 \text{ TeV}$, $p_T < 14 \text{ GeV}/c$, $2.0 < y < 4.5$



$$\sigma(\text{prompt } J/\psi, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5) = 10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20} \mu\text{b},$$

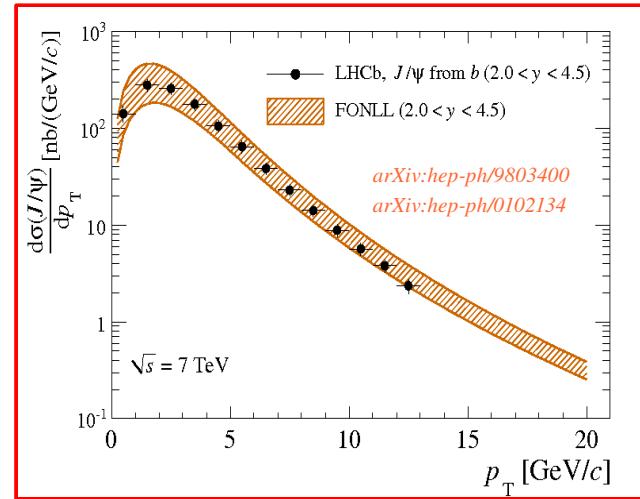
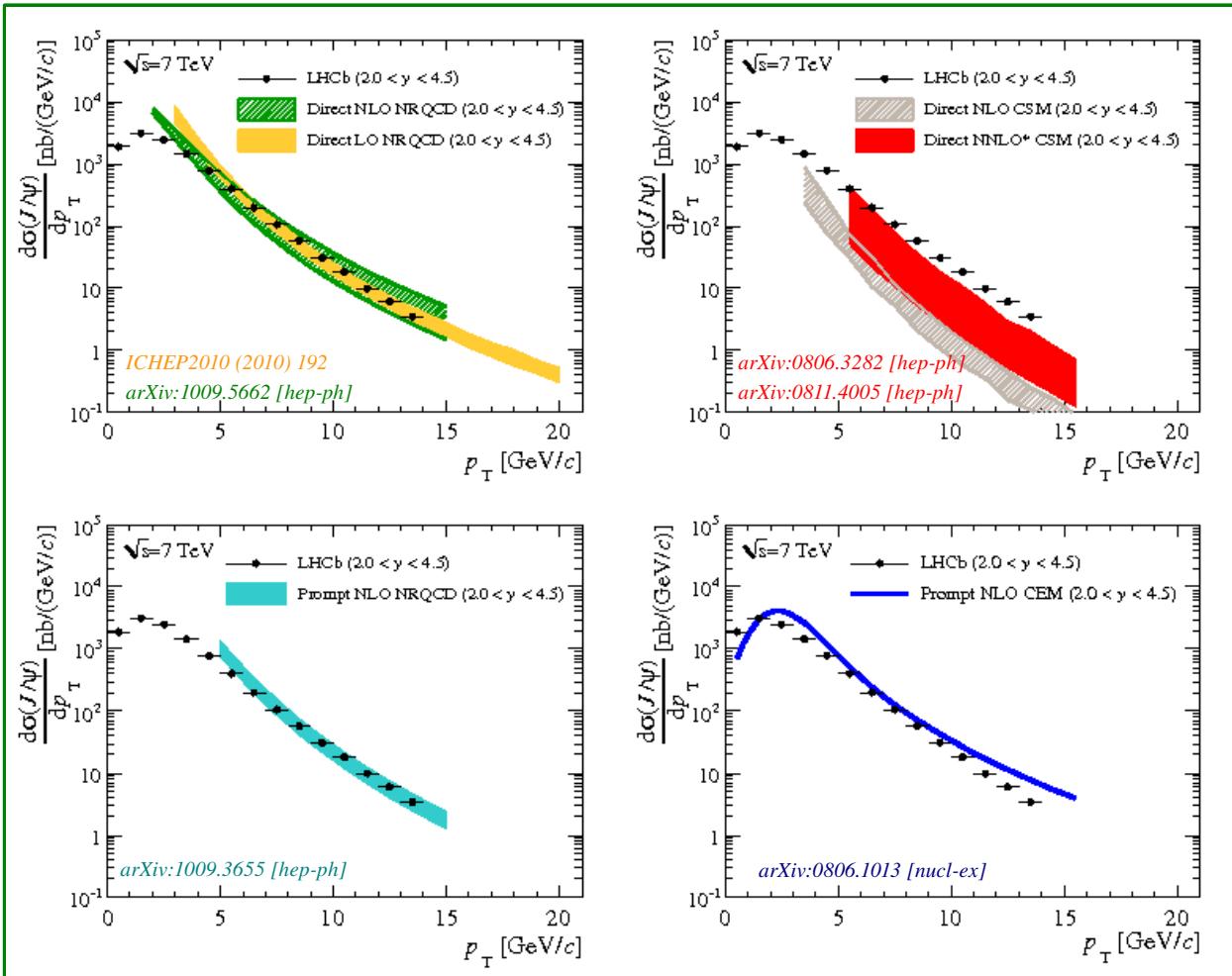


$$\frac{d^2\sigma}{dy dp_T} = \frac{N(J/\psi \rightarrow \mu^+ \mu^-)}{\mathcal{L} \times \mathcal{E}_{\text{tot}} \times \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) \times \Delta y \times \Delta p_T},$$

$$\sigma(J/\psi \text{ from } b, p_T < 14 \text{ GeV}/c, 2.0 < y < 4.5) = 1.14 \pm 0.01 \pm 0.16 \mu\text{b},$$

J/ψ production (results and theory predictions)

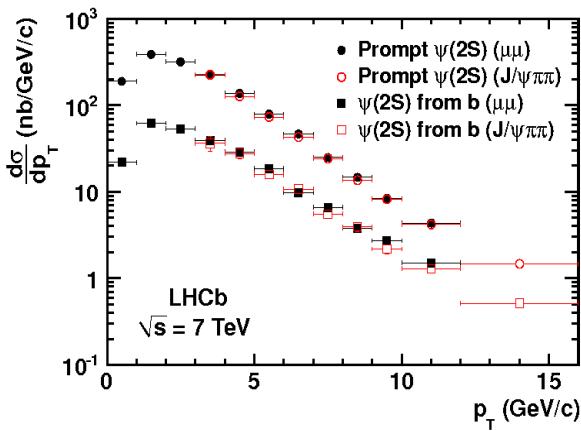
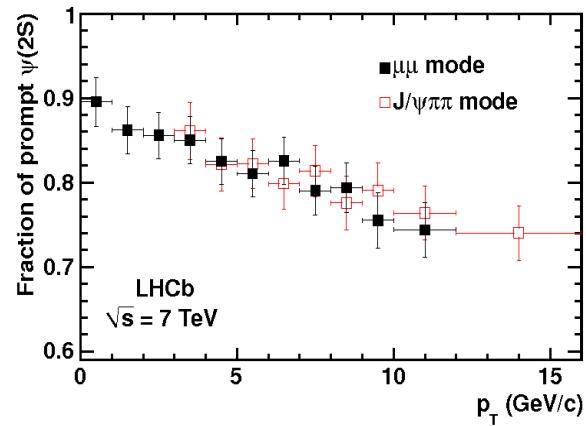
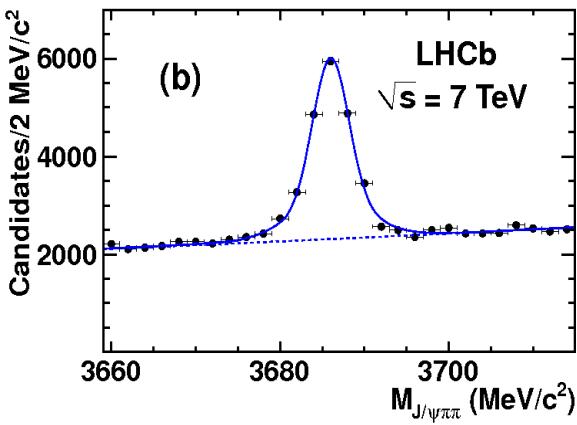
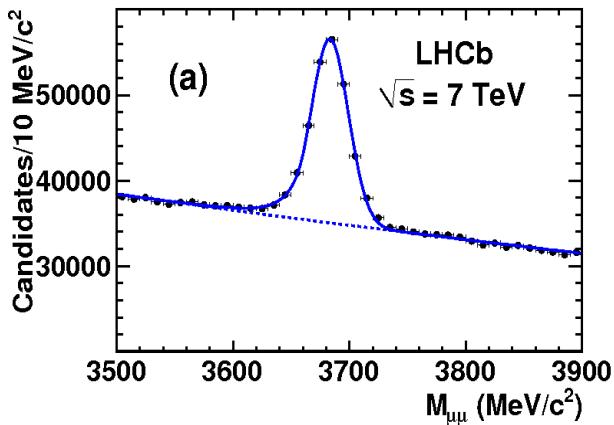
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prompt J/ψ production
 J/ψ from b production

$\psi(2S)$ production (1)

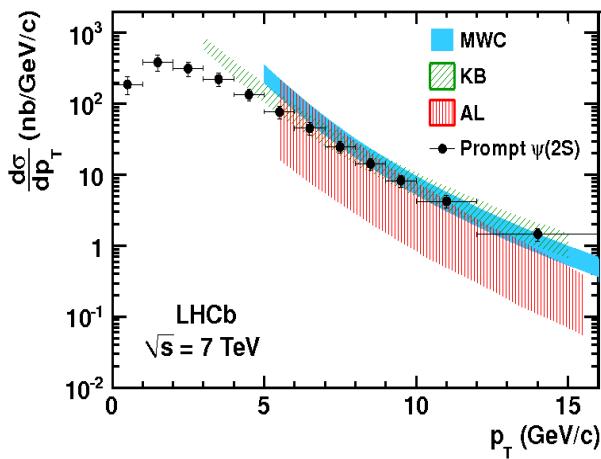
Eur. Phys. J. C72 (2012) 2100



- $\psi(2S)$ production at LHCb: $\sqrt{s} = 7 \text{ TeV}$, $p_T \leq 16 \text{ GeV}/c$, $2.0 < y < 4.5$
- Reconstructed in two decay modes:
 $\psi(2S) \rightarrow \mu^+\mu^-$ & $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$
- $(90'600 \pm 690)$ events for $\mu^+\mu^-$ decay mode
& $(12'300 \pm 200)$ events for $J/\psi \pi^+\pi^-$ decay mode per $\mathcal{L} = (35.9 \pm 1.3) \text{ pb}^{-1}$
- Mass resolutions: $\sigma_M = (16.01 \pm 0.12) \text{ MeV}/c^2$ for $\mu^+\mu^-$ mode & $\sigma_M = (2.10 \pm 0.07) \text{ MeV}/c^2$ for $J/\psi \pi^+\pi^-$ mode (constraint on $\mu^+\mu^-$)
- pseudo-proper time is used to separate prompt and delayed $\psi(2S)$ mesons
- good consistency between different decay modes of $\psi(2S)$

$\psi(2S)$ production (2)

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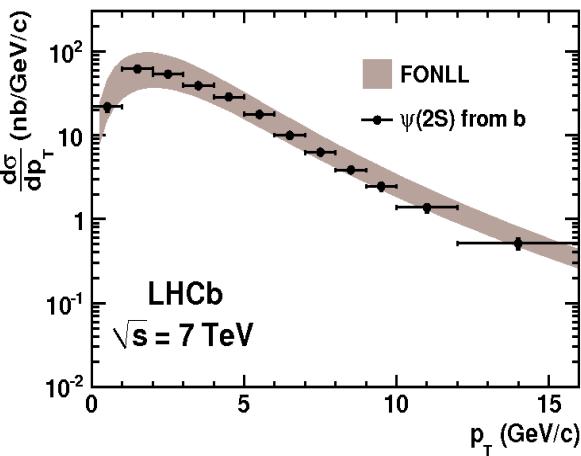
Cross-section results for $\psi(2S)$ production at LHCb: $\sqrt{s} = 7 \text{ TeV}$, $p_T \leq 16 \text{ GeV}/c$, $2.0 < y < 4.5$ (measured as weighted average of the $\mu^+\mu^-$ and $J/\psi\pi^+\pi^-$ channels)

$$\sigma_{\text{prompt}}(\psi(2S)) = 1.44 \pm 0.01 \text{ (stat)} \pm 0.12 \text{ (syst)} {}^{+0.20}_{-0.40} \text{ (pol)} \text{ } \mu\text{b},$$

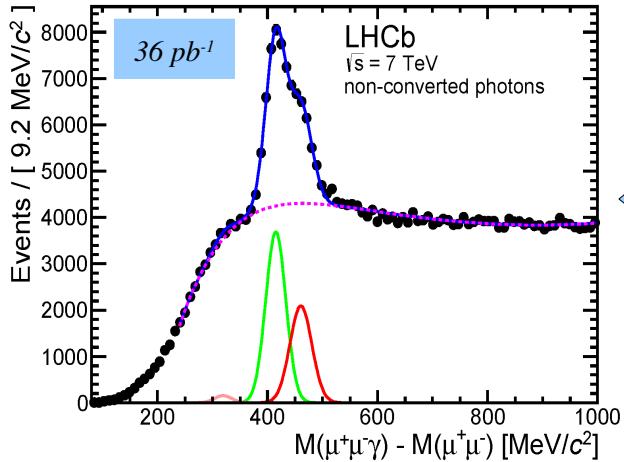
- MWC and KB are NLO calculations including CS and CO contributions ([arXiv:hep-ph/1012.1030](https://arxiv.org/abs/hep-ph/1012.1030), PRL 106 (2011) 022003). Good agreement with these calculations at large p_T
- AL is CSM including NNLO terms (PRL 101 (2008) 152001, Eur. Phys. J. C61 (2009) 693)
- FONLL is QCD prediction based on the Fixed-Order-Next-to-Leading-Log approximation (JHEP 9805 (1998) 007, JHEP 0407 (2004) 033). The calculations are found to be in good agreement with the measurements.

$$\sigma_b(\psi(2S)) = 0.25 \pm 0.01 \text{ (stat)} \pm 0.02 \text{ (syst)} \text{ } \mu\text{b},$$

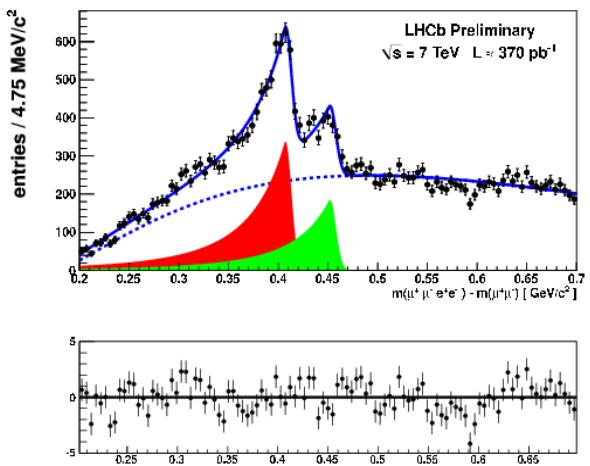
$$\mathcal{B}(b \rightarrow \psi(2S)X) = (2.73 \pm 0.06 \text{ (stat)} \pm 0.16 \text{ (syst)} \pm 0.24 \text{ (BF)}) \times 10^{-3},$$



χ_c production

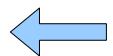
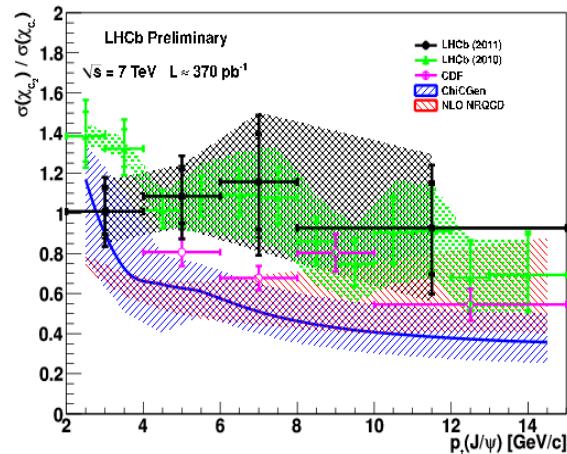


- χ_c production at LHCb: $\sqrt{s} = 7 \text{ TeV}$, $2 < p_T(J/\psi) < 15 \text{ GeV}/c$, $2.0 < y(J/\psi) < 4.5$, $\mathcal{L} = 36 \text{ pb}^{-1}$ (*Phys. Lett. B* 714 (2012) 215 & *arXiv:1204.1462*)
- Reconstructed in decay mode: $\chi_c \rightarrow J/\psi \gamma$, where $J/\psi \rightarrow \mu^+ \mu^-$
- Photon identified in ECAL: $p_T(\gamma) > 650 \text{ MeV}/c$, $p(\gamma) > 5 \text{ GeV}/c$
- Observed yields of χ_{c0} , χ_{c1} and χ_{c2} are (820 ± 650) , (38630 ± 550) and (26110 ± 620) events per $\mathcal{L} = 36 \text{ pb}^{-1}$



- χ_c production at LHCb: $\sqrt{s} = 7 \text{ TeV}$, $2 < p_T(J/\psi) < 15 \text{ GeV}/c$, $2.0 < y(J/\psi) < 4.5$, $\mathcal{L} = 370 \text{ pb}^{-1}$ (*LHCb-CONF-2011-062*)
- Reconstructed in decay mode: $\chi_c \rightarrow J/\psi \gamma$, where $J/\psi \rightarrow \mu^+ \mu^-$, $\gamma \rightarrow e^+ e^-$
- Photon converted before the magnet

Measurements of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ and $\sigma(\chi_c)/\sigma(J/\psi)$



- Results for $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ are found to be larger than any prediction and CDF measurement

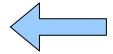
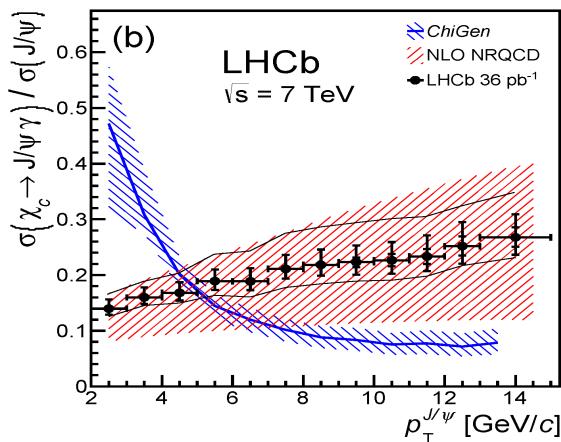
LHCb (2010) - *Phys. Lett. B714 (2012) 215*

LHCb (2011) - *LHCb-CONF-2011-062*

CDF - *PRL 98 (2007) 232001*

ChiCGen - *http://project.hepforge.org/superchic/chigen.html* (uses LO CSM)

NLO NRQCD - *PR D83 (2011) 111503*



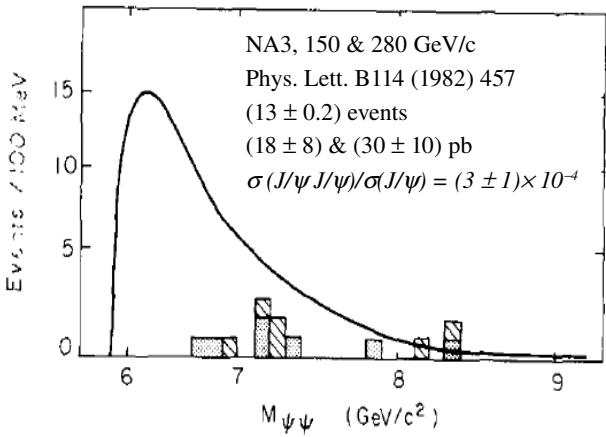
- Results for $\sigma(\chi_c)/\sigma(J/\psi)$ (*arXiv:1204.1462*) is in excellent agreement with NLO NRQCD over the full range of $p^T(J/\psi)$. Significant discrepancy compared to ChiCGen.

Double charm(onia) production

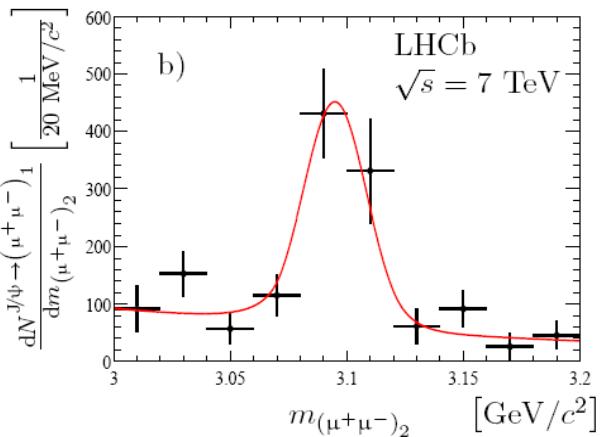
- *The total cross-section, $\sigma(pp \rightarrow c\bar{c}X) = (6.10 \pm 0.93) \text{ mb}$, measured by LHCb at $\sqrt{s} = 7 \text{ TeV}$ is found to be large and in agreement with QCD predictions ([LHCb-CONF-2010-013](#))*
 - a) *about 1/10 of inelastic cross-section*
 - b) *about 20 times the bb cross-section ([PL B694 \(2010\) 209](#))*
- *Prompt production of J/ψ is also large: $\sigma(pp \rightarrow J/\psi X) = (10.5 \pm 2.5) \mu\text{b}$ for $(2 < y < 4.5)$ & $p_T < 14 \text{ GeV}/c$ ([Eur. Phys. J. C71 \(2011\) 1645](#))*
- *The question of multiple production of charm states naturally arises*
- *To shed more light on charm and charmonium production mechanism(s), LHCb studied*
 - a) $J/\psi + J/\psi$
 - b) $J/\psi + \text{open charm}$
 - c) $\text{open charm} + \text{open charm}$
where (open charm) = D^0 , D^+ , D_s^+ and Λ_c^+

Double charmonia production ($J/\psi J/\psi$)

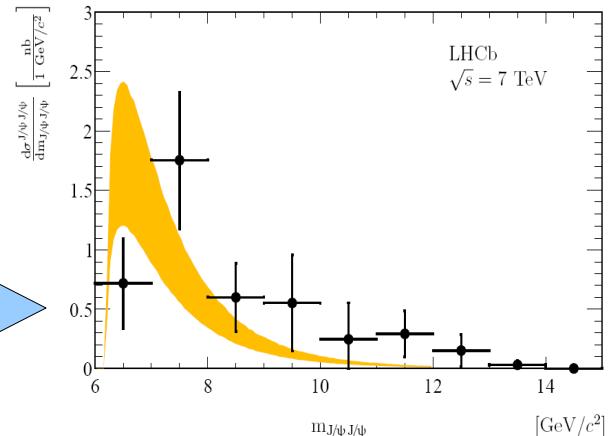
Phys. Lett. B707 (2012) 52-59



- *The first observation of ($J/\psi J/\psi$) 30 years ago!*
- *Recent observation of ($J/\psi J/\psi$) in pp collisions $\sqrt{s} = 7$ TeV at LHCb ($2 < y < 4.5$) & ($p_T < 10$ GeV/c)*



Good prediction



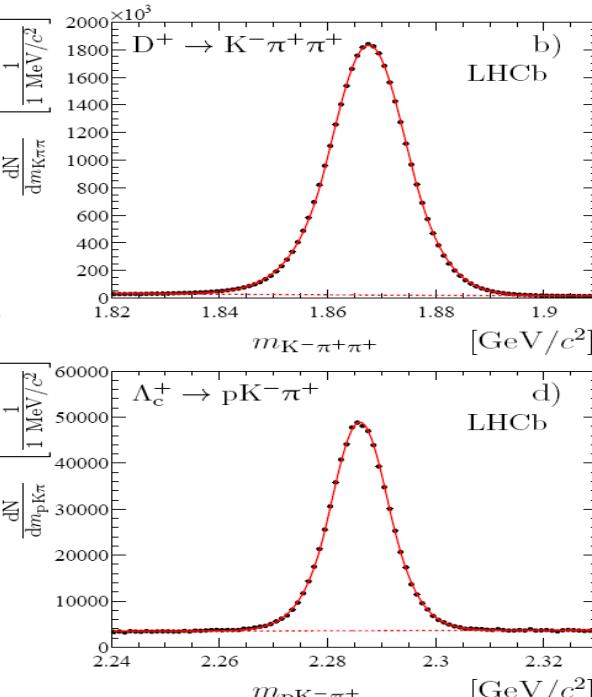
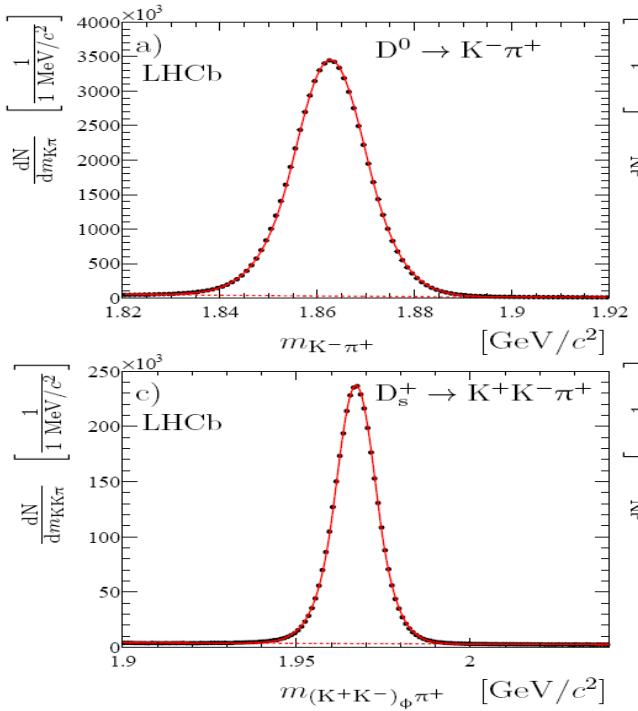
$\sqrt{s} = 7$ TeV, $\mathcal{L} = (37.5 \pm 1.3) \text{ pb}^{-1}$
 $N^{\text{raw}} = (116 \pm 16) \text{ events}$
 $N^{\text{corr}} = (672 \pm 129) \text{ events}$
 $\sigma(J/\psi J/\psi) = (5.1 \pm 1.0 \pm 1.1) \text{ nb}$

$$\sigma^{J/\psi J/\psi}/\sigma^{J/\psi} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4}$$

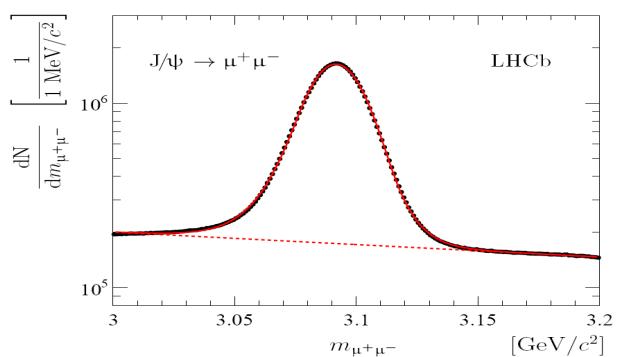
$\sigma(J/\psi J/\psi) = (4.1 \pm 1.2) \text{ nb}$ for $gg \rightarrow 2 \times J/\psi$
Phys. Rev. D57 (1998) 4385
Phys. Rev. D84 (2011) 094023

Double charm production (charm hadrons)

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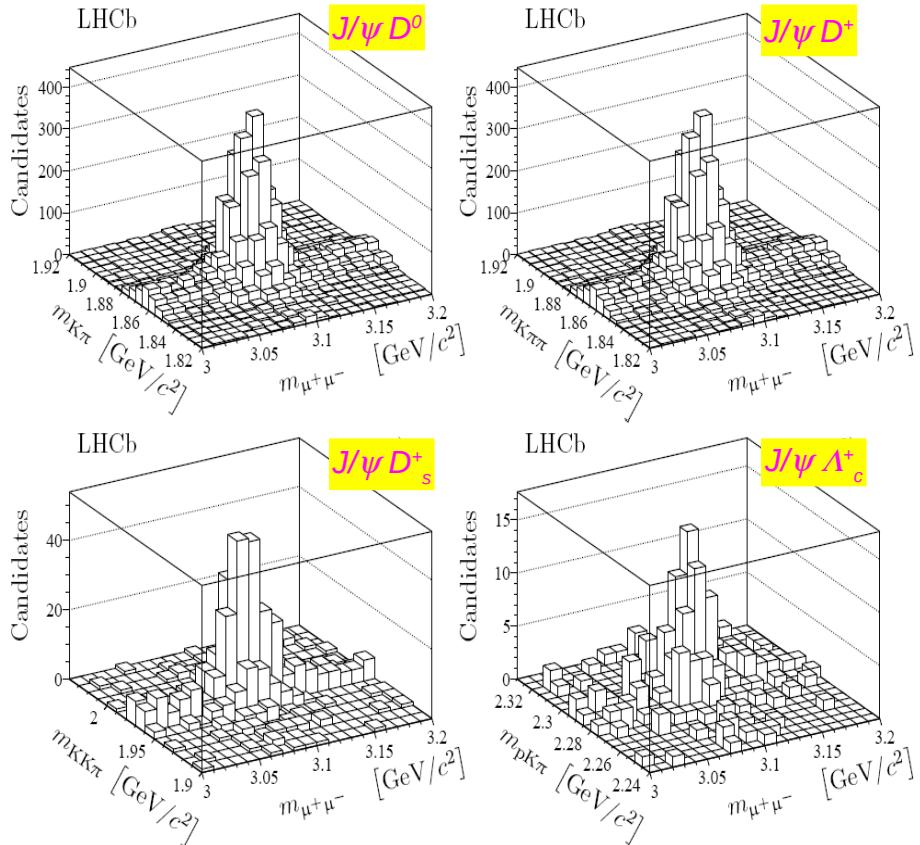
- Double charm production at LHCb:
 $\sqrt{s} = 7 \text{ TeV}$, $\mathcal{L} = (355 \pm 13) \text{ pb}^{-1}$
- LHCb fiducial volume: $(2 < y < 4)$,
 $(3 < p_T^c < 12) \text{ GeV}/c$ & $(p_T^{\psi} < 12 \text{ GeV}/c)$



	J/ψ $\mu^+\mu^-$	D^0 $K^-\pi^+$	D^+ $K^-\pi^+\pi^+$	D_s^+ $(K^+K^-)_\phi\pi^+$	Λ_c^+ $pK^-\pi^+$
Raw yields	S	49.57	65.77	33.25	3.59
Contamination from b	f_b^{MC} [%]	1.6	1.7	1.3	4.5

$(J/\psi C + J/\psi \bar{C})$ 2D mass spectra @ $\sqrt{s} = 7\text{ TeV}$, $\mathcal{L} = (355 \pm 13) \text{ pb}^{-1}$

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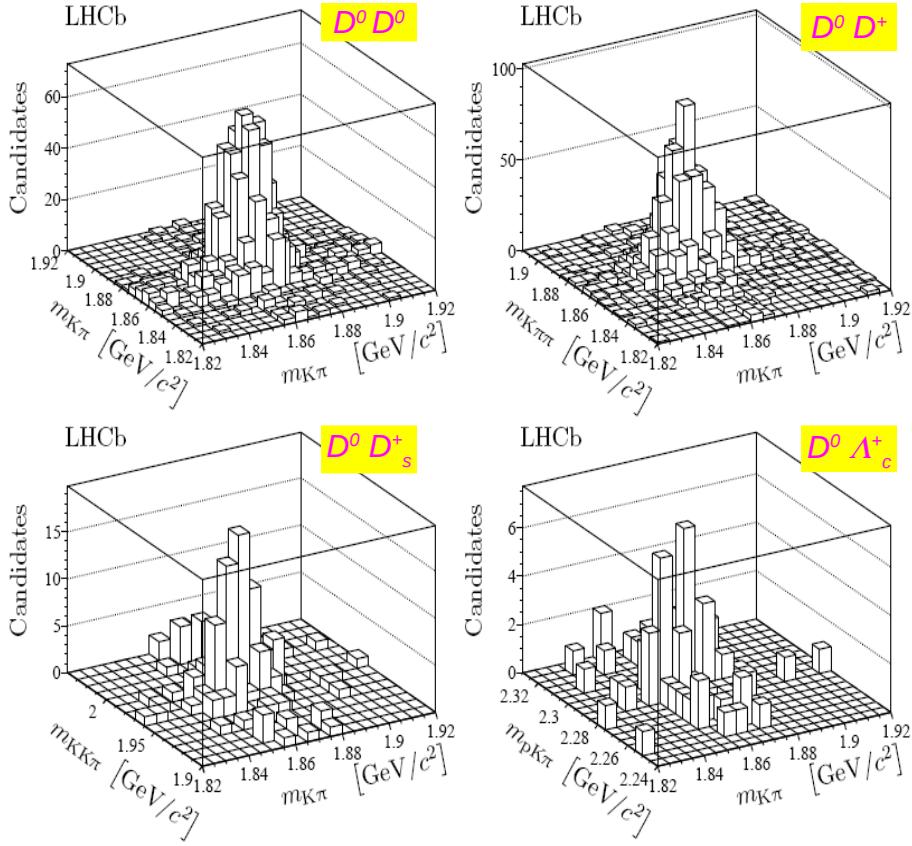


- Paired charm hadrons with vertex requirement to remove contamination from pile-up and B hadron decays
- Charge conjugate modes included in the plots
- Raw signal yields from 2D mass fit
- When no significance is quoted, it is in excess of 8σ

Mode	S	S_σ	P [%]
$J/\psi D^0$	4875 ± 86		59
$J/\psi D^+$	3323 ± 71		26
$J/\psi D_s^+$	328 ± 22		65
$J/\psi \Lambda_c^+$	116 ± 14	7.3σ	98

$D^0 C + \bar{D}^0 \bar{C}$ 2D mass spectra @ $\sqrt{s} = 7$ TeV, $\mathcal{L} = (355 \pm 13) \text{ pb}^{-1}$

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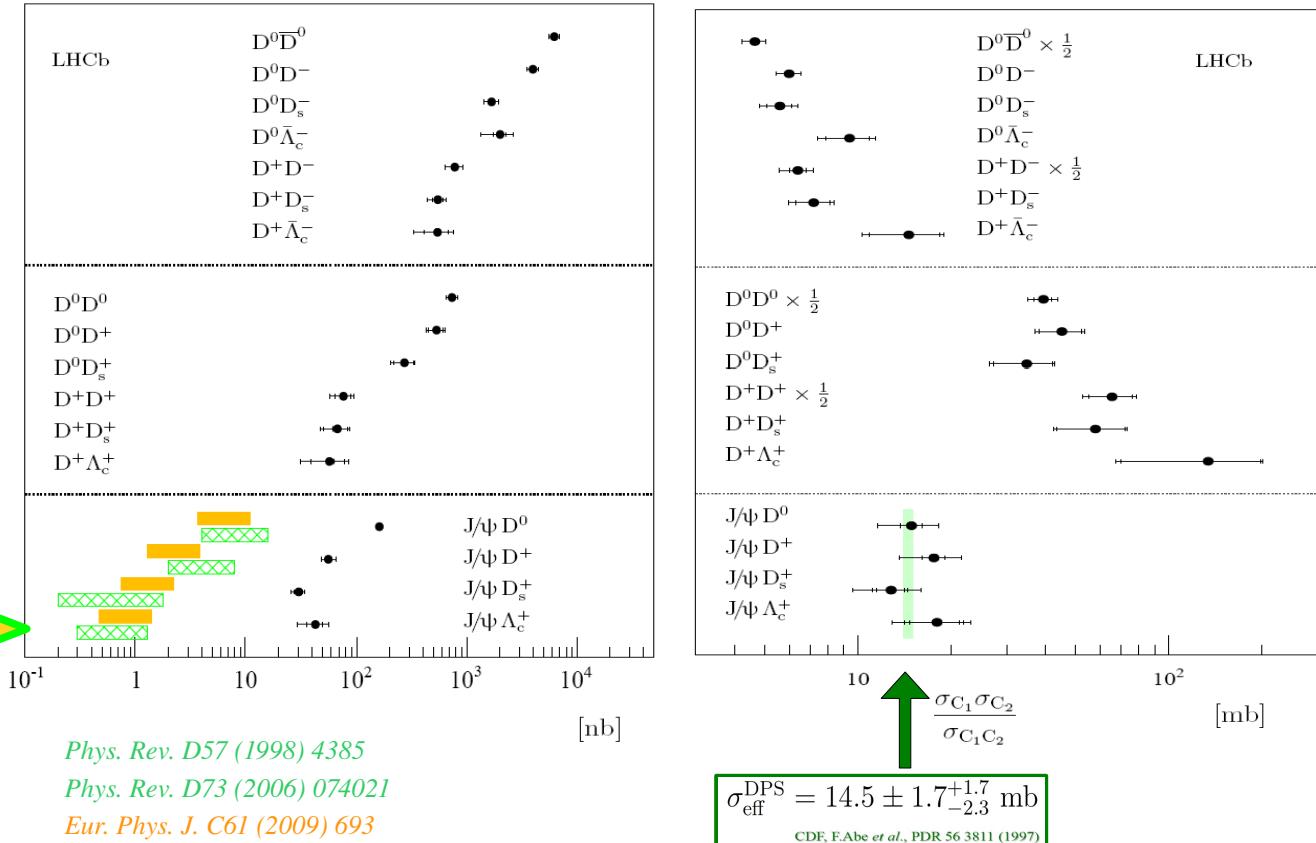
- Charge conjugate modes included in the plots
- Raw signal yields from 2D mass fit
- When no significance is quoted, it is in excess of 8σ

Mode	S	S_σ	P [%]
$D^0 D^0$	1087 ± 37		4.5
$D^0 \bar{D}^0$	10080 ± 105		33
$D^0 D^+$	1177 ± 39		24
$D^0 D^-$	11224 ± 112		36
$D^0 D_s^+$	111 ± 12	8σ	10
$D^0 D_s^-$	859 ± 31		13
$D^0 \Lambda_c^+$	41 ± 8	5σ	9
$D^0 \bar{\Lambda}_c^-$	308 ± 19		35
$D^+ D^+$	249 ± 19		15
$D^+ D^-$	3236 ± 61		67
$D^+ D_s^+$	52 ± 9	5σ	54
$D^+ D_s^-$	419 ± 22		59
$D^+ \Lambda_c^+$	21 ± 5	2.5σ	36
$D^+ \bar{\Lambda}_c^-$	137 ± 14	8σ	7

Cross-sections and ratios @ $\sqrt{s} = 7 \text{ TeV}$, $\mathcal{L} = (355 \pm 13) \text{ pb}^{-1}$

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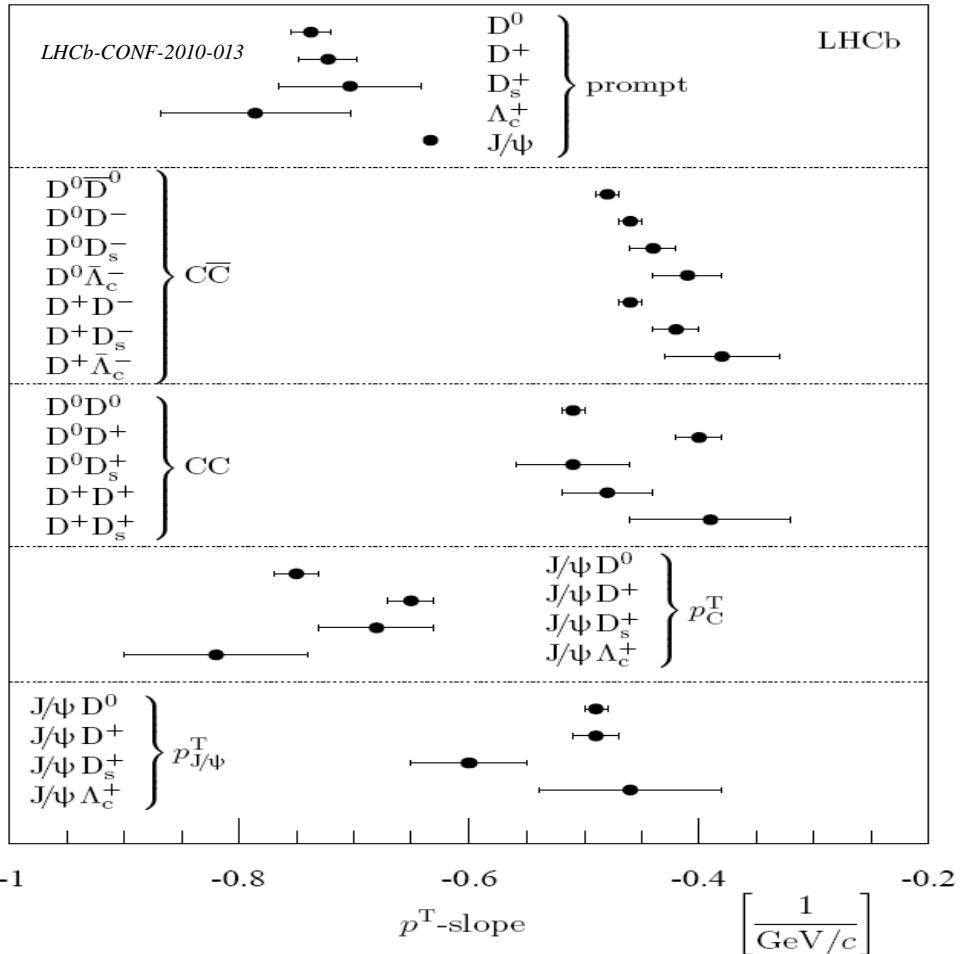
- Model independent cross-sections measured by per-event efficiency corrections (estimated from data directly when possible)
- First observation of ($J/\psi C$ & $J/\psi \bar{C}$) events and (CC & $\bar{C}\bar{C}$) events in hadronic collisions
- gg fusion predictions ($gg \rightarrow J/\psi cc$) significantly underestimate the cross-sections
- Good consistency between DPS prediction and the measurements for ($J/\psi C$) events. In case DPS dominates, $\sigma_{c_1} \sigma_{c_2} / \sigma_{c_1 c_2} \sim 15 \text{ mb}$



Slope parameters of p^T spectra

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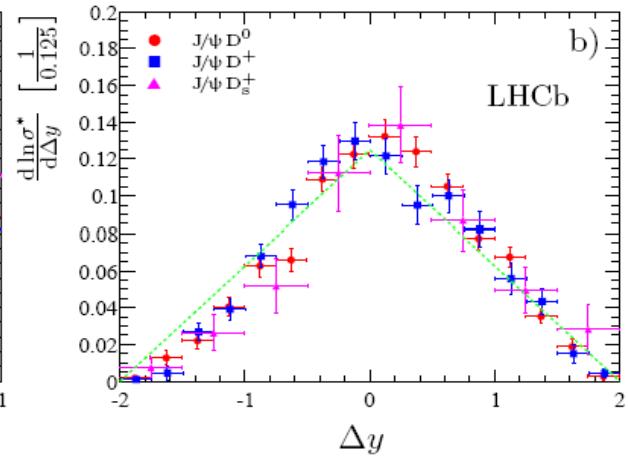
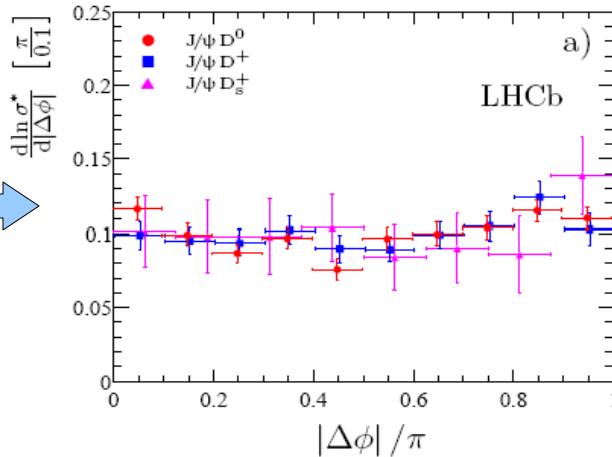
- $p^T(J/\psi)$ spectra in $(J/\psi C)$ events harder than p^T spectrum of prompt J/ψ (in inclusive). But $p^T(C)$ spectra in $(J/\psi C)$ events have almost the same form as in inclusive.
- $p^T(C)$ spectra in CC and $\bar{C}\bar{C}$ events are similar but different from those found in single prompt charm events and in $(J/\psi C)$ events.



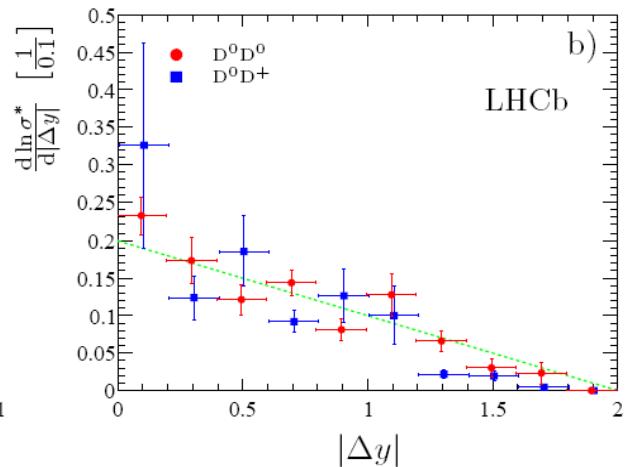
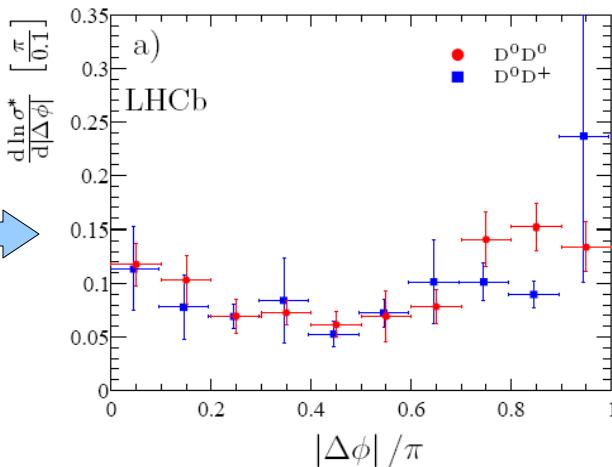
Search for rapidity and azimuthal correlations (1)

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- No evidence for $|\Delta\phi|$ and Δy correlations in ($J/\psi C$) events
- Another plus for DPS model?



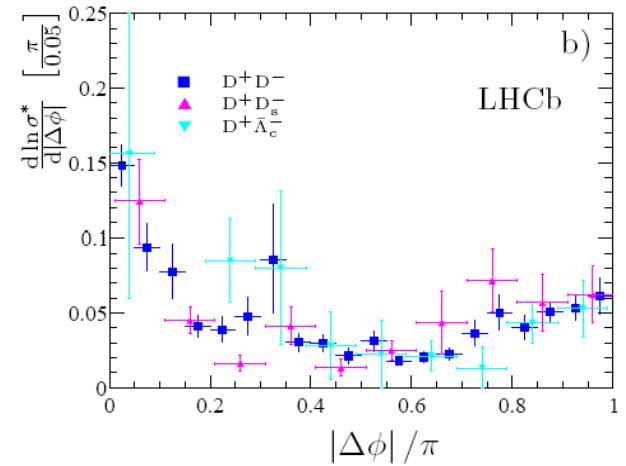
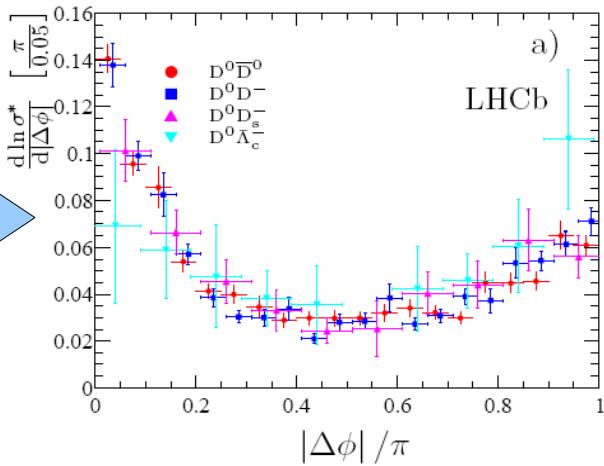
- No evidence for $|\Delta\phi|$ and $|\Delta y|$ correlations in (CC) events given the present statistics



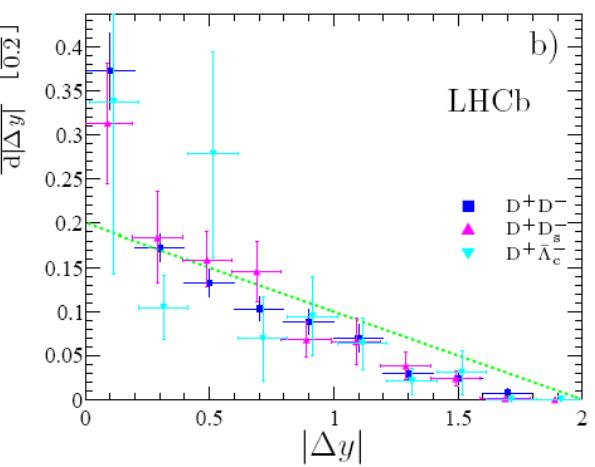
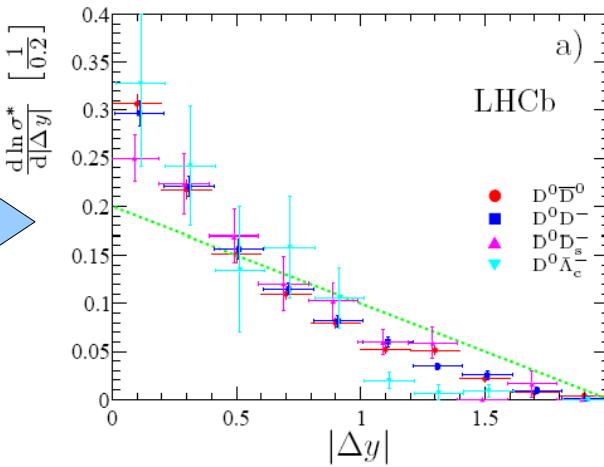
Search for rapidity and azimuthal correlations (2)

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- *Clear enhancement at small $|\Delta\phi|$ in (CC) events*
- *Consistent with cc production via the gluon splitting mechanism*



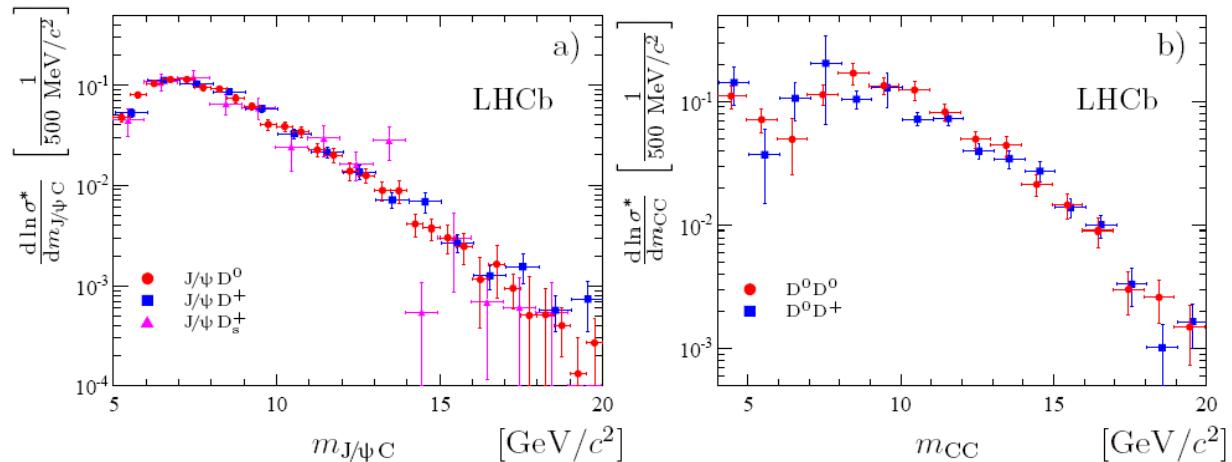
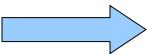
- *Some enhancement at small $|\Delta y|$ in (CC) events*



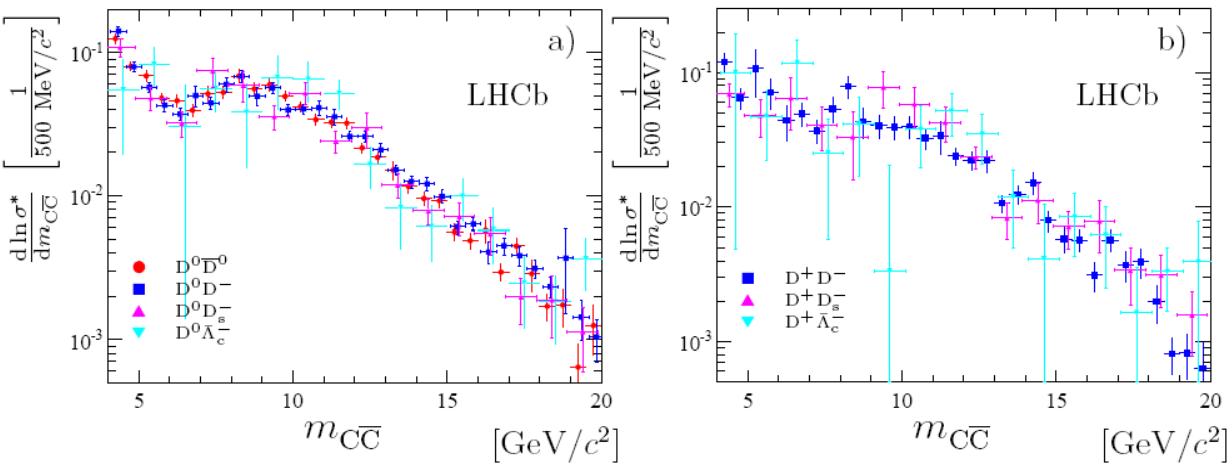
Mass spectra for some double charm events

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- mass spectra for ($J/\psi C$) and (CC) events appear to be independent of charm type



- mass spectra for (CC) events are similar and independent of charm type. Enhancement at small mass (due to the gluon splitting process?)



Conclusion

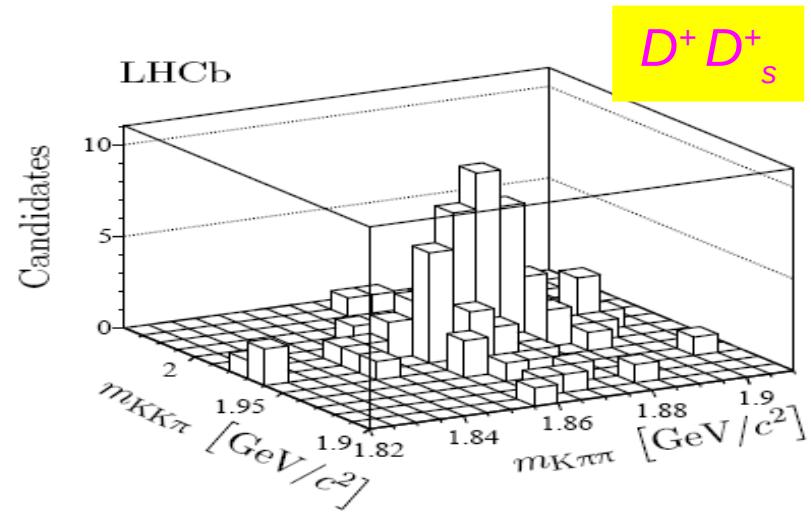
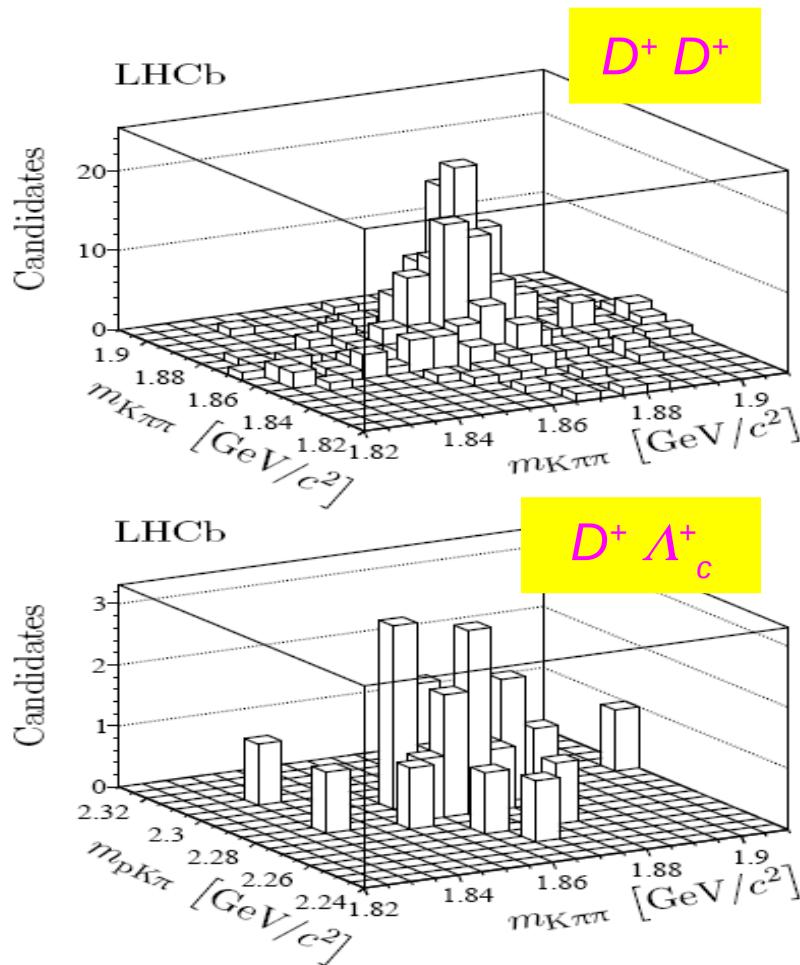
- Differential cross-sections for J/ψ and $\psi(2S)$ were measured as functions of p^T and y , ($2 < y < 4.5$). Recent QCD calculations are found to be in good agreement with these measurements.
- Ratios of prompt production cross-sections $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ and $\sigma(\chi_c \rightarrow J/\psi \gamma)/\sigma(J/\psi)$ have been determined as functions of $p^T(J/\psi)$. Results for $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ are found to be larger than any prediction and CDF measurement. Results for $\sigma(\chi_c)/\sigma(J/\psi)$ are in excellent agreement with NLO NRQCD over the full range of p^T .
- $(J/\psi J/\psi)$ events has been observed with $S > 6\sigma$. The production cross-section of the events is $(5.1 \pm 1.0 \pm 1.1)$ nb, consistent with predictions of gg-fusion. Higher statistics will allow to study the kinematic properties and to probe different production models, and to study a possibility of charm tetraquarks (low mass) or decay of $\chi_b \rightarrow J/\psi J/\psi$ (~ 9 GeV/c 2).
- The first observation of $(J/\psi C)$ and (CC) in hadronic collisions. The cross-sections and properties of these events have been studied. Higher statistics will allow to elaborate different production models.
- In this year, LHC is delivering pp collisions at $\sqrt{s} = 8$ TeV. The production measurements to be repeated at this higher energy.

Thank You

Back Up

$D^+ C$ production: 2D mass spectra

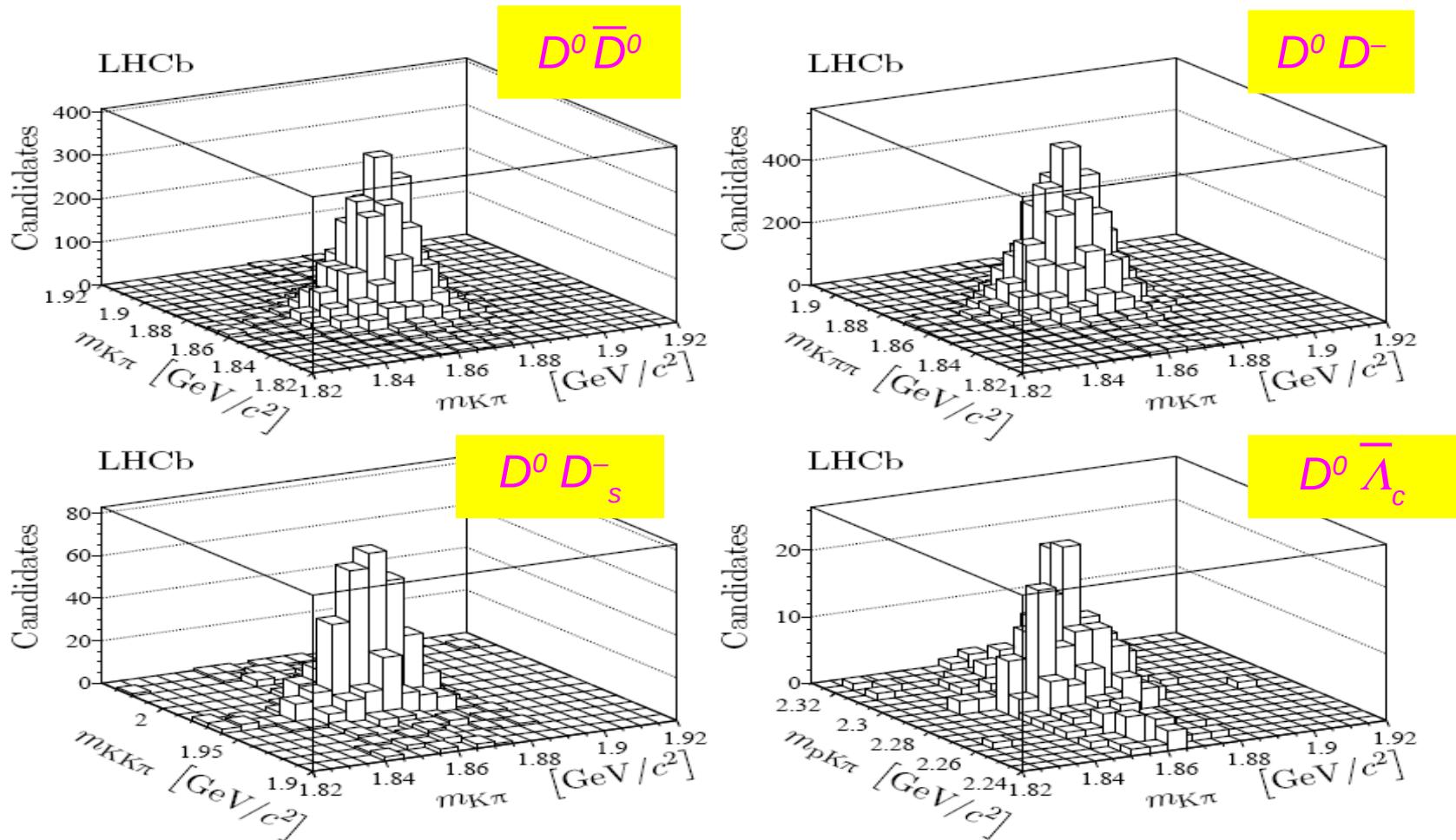
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Not (yet) enough statistics for
 $D_s D_s$, $D_s \Lambda_c$ & $\Lambda_c \Lambda_c$

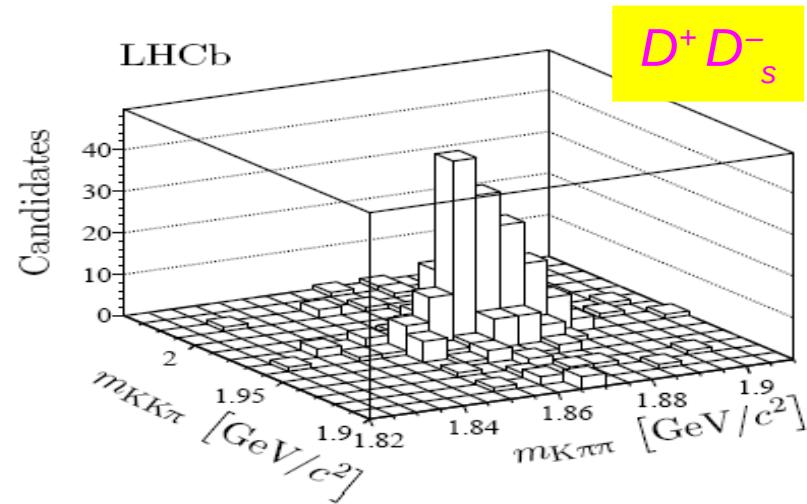
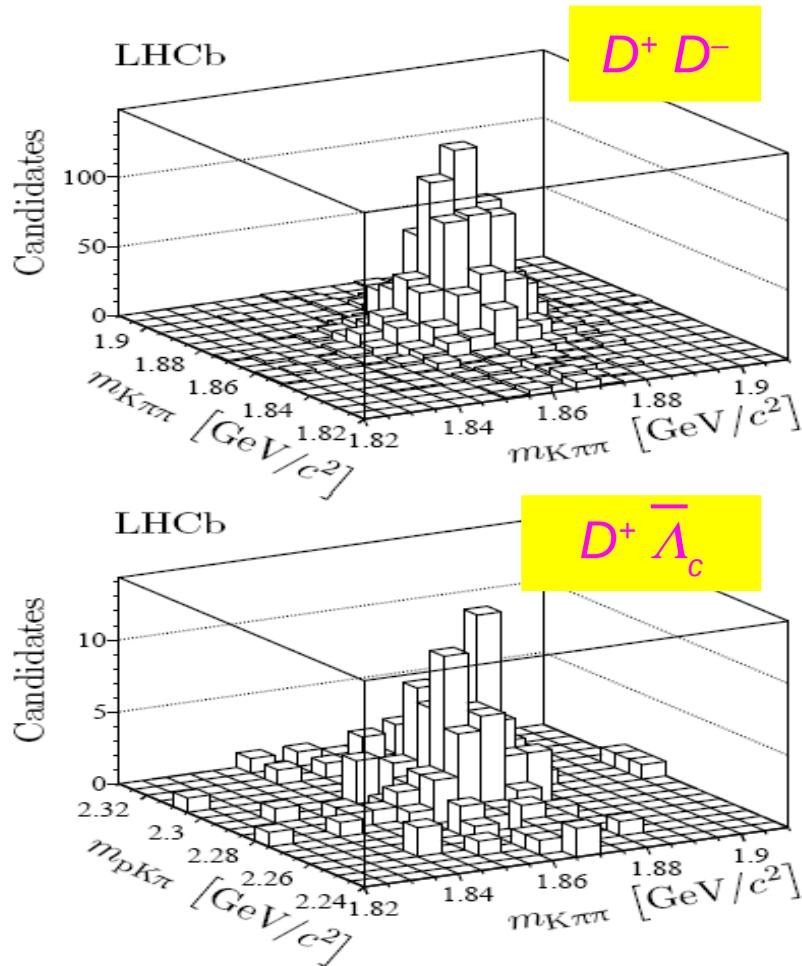
$D^0 \bar{C}$ production: 2D mass spectra

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$D^+ \bar{C}$ production: 2D mass spectra

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Not (yet) enough statistics for
 $D_s \bar{D}_s$, $D_s \Lambda_c$ & $\Lambda_c \bar{\Lambda}_c$

J/ψ C cross-sections and ratios

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Mode	σ [nb]
$J/\psi D^0$	$161.0 \pm 3.7 \pm 12.2$
$J/\psi D^+$	$56.6 \pm 1.7 \pm 5.9$
$J/\psi D_s^+$	$30.5 \pm 2.6 \pm 3.4$
$J/\psi \Lambda_c^+$	$43.2 \pm 7.0 \pm 12.0$

Mode	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ [10^{-3}]	$\sigma_{J/\psi C}/\sigma_C$ [10^{-4}]	$\sigma_{J/\psi} \sigma_C / \sigma_{J/\psi C}$ [mb]
$J/\psi D^0$	$16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}$	$6.7 \pm 0.2 \pm 0.5$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
$J/\psi D^+$	$5.7 \pm 0.2 \pm 0.6^{+1.2}_{-0.9}$	$5.7 \pm 0.2 \pm 0.4$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$
$J/\psi D_s^+$	$3.1 \pm 0.3 \pm 0.4^{+0.6}_{-0.5}$	$7.8 \pm 0.8 \pm 0.6$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$
$J/\psi \Lambda_c^+$	$4.3 \pm 0.7 \pm 1.2^{+0.9}_{-0.7}$	$5.5 \pm 1.0 \pm 0.6$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$

Cross-sections and ratios for CC and $\bar{C}\bar{C}$

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Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\bar{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
$D^0 D^0$	$690 \pm 40 \pm 70$	10.9 ± 0.8	$2 \times (42 \pm 3 \pm 4)$
$D^0 \bar{D}^0$	$6230 \pm 120 \pm 630$		$2 \times (4.7 \pm 0.1 \pm 0.4)$
$D^0 D^+$	$520 \pm 80 \pm 70$		$47 \pm 7 \pm 4$
$D^0 D^-$	$3990 \pm 90 \pm 500$	12.8 ± 2.1	$6.0 \pm 0.2 \pm 0.5$
$D^0 D_s^+$	$270 \pm 50 \pm 40$		$36 \pm 8 \pm 4$
$D^0 D_s^-$	$1680 \pm 110 \pm 240$	15.7 ± 3.4	$5.6 \pm 0.5 \pm 0.6$
$D^0 \bar{\Lambda}_c^-$	$2010 \pm 280 \pm 600$	—	$9 \pm 2 \pm 1$
$D^+ D^+$	$80 \pm 10 \pm 10$		$2 \times (66 \pm 11 \pm 7)$
$D^+ D^-$	$780 \pm 40 \pm 130$	9.6 ± 1.6	$2 \times (6.4 \pm 0.4 \pm 0.7)$
$D^+ D_s^+$	$70 \pm 15 \pm 10$		$59 \pm 15 \pm 6$
$D^+ D_s^-$	$550 \pm 60 \pm 90$	12.1 ± 3.3	$7 \pm 1 \pm 1$
$D^+ \Lambda_c^+$	$60 \pm 30 \pm 20$		$140 \pm 70 \pm 20$
$D^+ \bar{\Lambda}_c^-$	$530 \pm 130 \pm 170$	10.7 ± 5.9	$15 \pm 4 \pm 2$

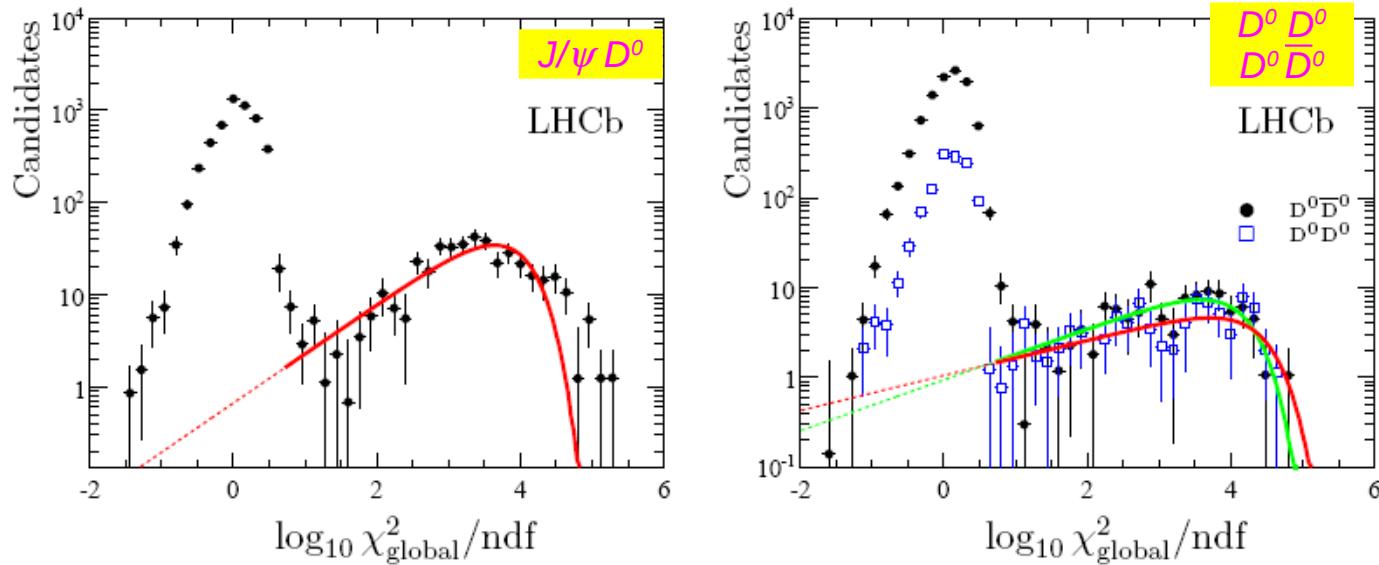
Slope parameters of p^T spectra

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Mode	p^T -slope $\left[\frac{1}{\text{GeV}/c} \right]$		Mode	p^T -slope $\left[\frac{1}{\text{GeV}/c} \right]$
	J/ ψ	C		
J/ ψ D ⁰	-0.49 ± 0.01	-0.75 ± 0.02	D ⁰ D ⁰	-0.51 ± 0.02
J/ ψ D ⁺	-0.49 ± 0.02	-0.65 ± 0.02	D ⁰ \bar{D}^0	-0.48 ± 0.01
J/ ψ D _s ⁺	-0.60 ± 0.05	-0.68 ± 0.05	D ⁰ D ⁺	-0.40 ± 0.02
J/ ψ Λ_c^+	-0.46 ± 0.08	-0.82 ± 0.08	D ⁰ D ⁻	-0.46 ± 0.01
J/ ψ	-0.633 ± 0.003		D ⁰ D _s ⁺	-0.51 ± 0.05
D ⁰		-0.77 ± 0.03	D ⁰ D _s ⁻	-0.44 ± 0.02
D ⁺		-0.70 ± 0.03	D ⁰ $\bar{\Lambda}_c^-$	-0.41 ± 0.03
D _s ⁺		-0.57 ± 0.13	D ⁺ D ⁺	-0.48 ± 0.04
Λ_c^+		-0.79 ± 0.08	D ⁺ D ⁻	-0.46 ± 0.01
			D ⁺ D _s ⁺	-0.39 ± 0.07
			D ⁺ D _s ⁻	-0.42 ± 0.02
			D ⁺ $\bar{\Lambda}_c^-$	-0.38 ± 0.05

Pile-up from data

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Pile-up is totally negligible