Double heavy flavour production

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On behalf of the LHCb collaboration

01 March 2016, Quarkonium2016 @ Trento

Content

Double heavy flavour production **in pp collisions** at LHCb

- J/ψ + open charm, open charm pair *JHEP 06 (2012) 141*

- Υ + open charm *arXiv:1510.05949*

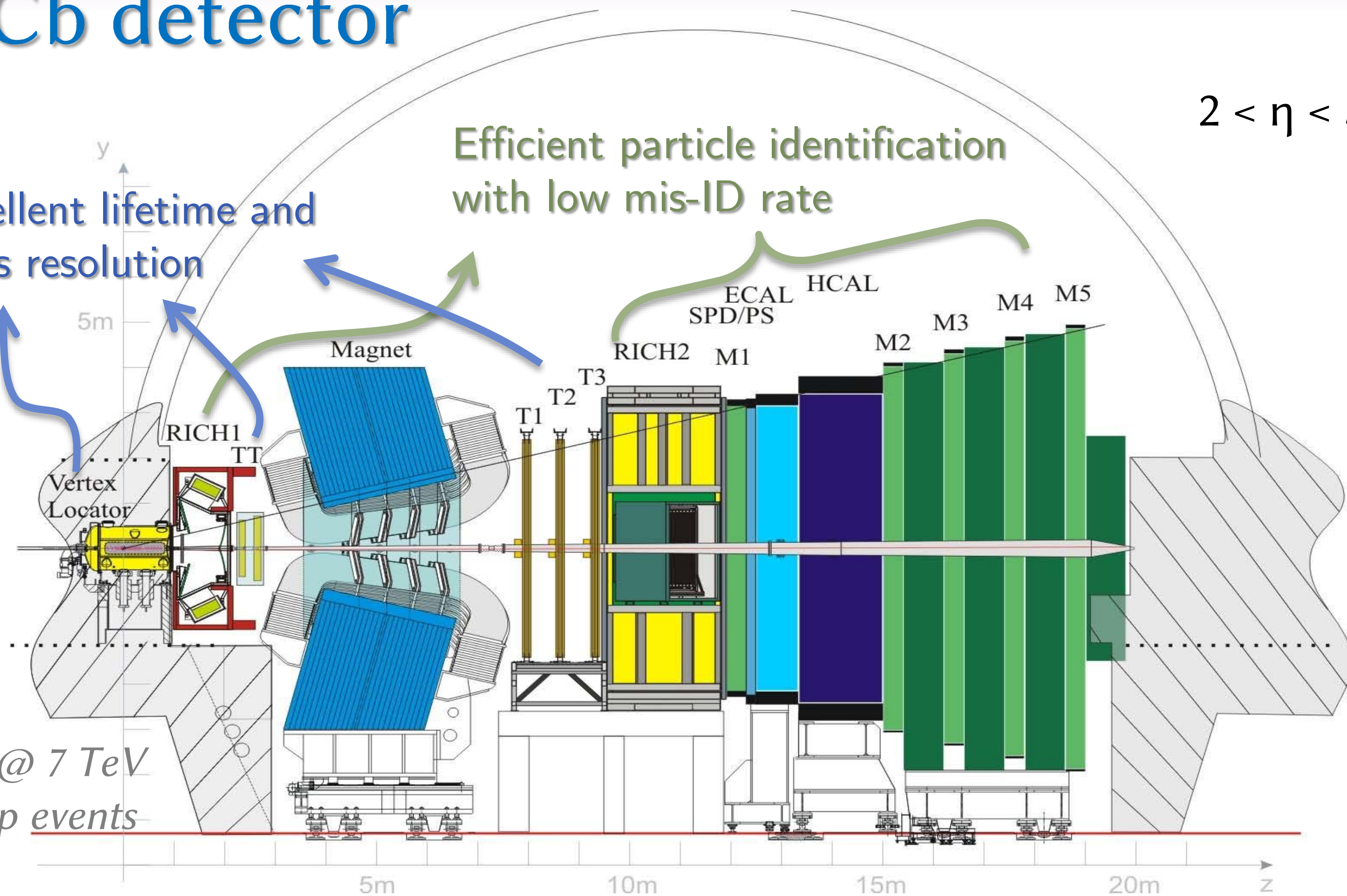
- NB: Associated J/ψ pair production *PLB 707 (2012) 52*
  covered by Daniel Souza Covacich : *"Exclusive production of J/ψ and double J/ψ"*

LHCb detector

$2 < \eta < 5$

Excellent lifetime and mass resolution

Efficient particle identification with low mis-ID rate



μ = 1.79 @ 7 TeV
⇒ Pile-up events

JINST 3 (2008) S08005

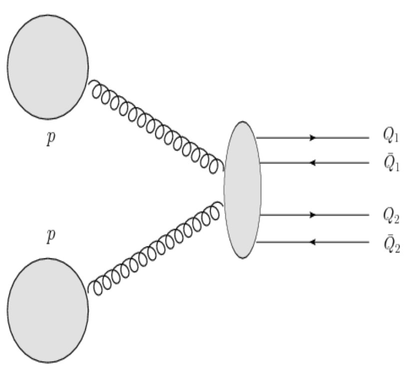
$\mathcal{L}$ (*pp* collision) :
Run I : 1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV
Run II: 320 pb^{-1}@ 13 TeV

J/ψ + OPEN CHARM, DOUBLE OPEN CHARM

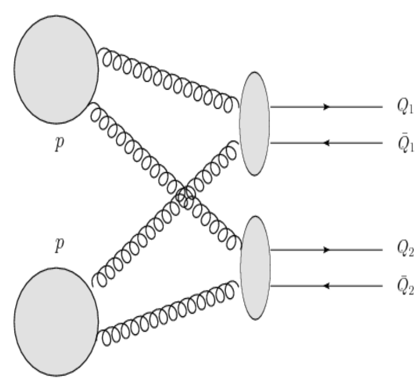
$J/\psi + C$ and CC – why interesting?

- $J/\psi + C$: J/ψ associated with open charm (C=D^0, D^+, D_s^+, Λ_c^+)
- CC : double open charm production

- Probes of quarkonium production
- In *pp* collisions several contributions could come to play
  - $gg \to J/\psi c\bar{c}, c\bar{c}c\bar{c}$
  - Double parton scattering (DPS)
  - Intrinsic charm content of proton, ...



Single-parton scattering (SPS)



Double-parton scattering (DPS)

$J/\psi + C$ and CC at LHCb

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- Search using 355 (± 13) pb^{-1} @ 7 TeV
- $C\bar{C}$ events as normalisation channel

- Final states for $J/\psi C$, CC and $C\bar{C}$ candidates:
  - $J/\psi \to \mu^+\mu^-$
  - $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$,
    $D_s^+ \to K^-K^+\pi^+$, $\Lambda_c^+ \to pK^-\pi^+$

- Main fiducial cuts:
  - $2 < y_{J/\psi,C} < 4$
  - $p_T^{J/\psi} < 12$ GeV, $3 < p_T^C < 12$ GeV

Selection

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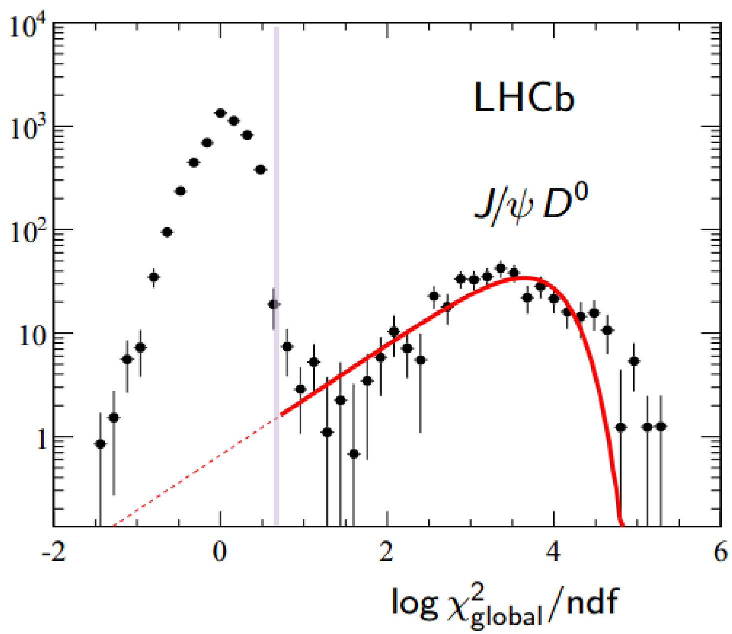
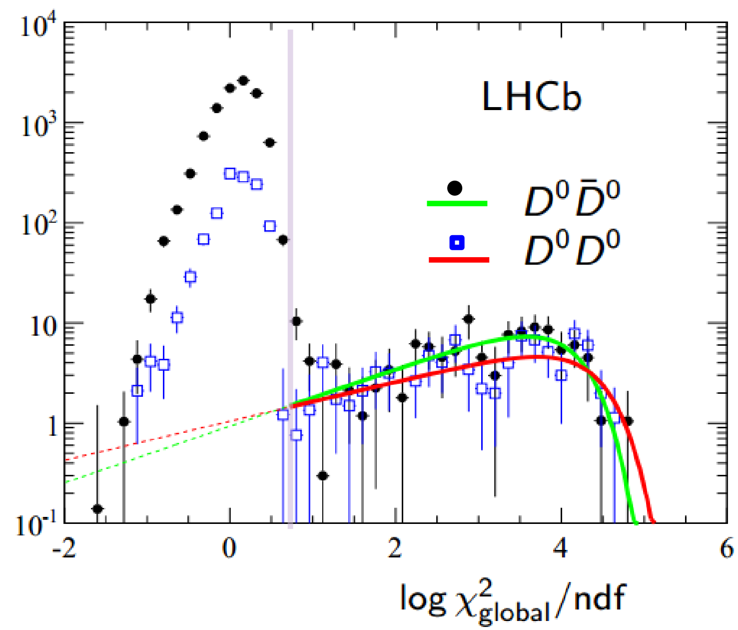
- Track quality, vertex quarlity, particle ID, C lifetime …
- Pile-up effect: each meson from a different PV
  - Negligible by requiring both mesons from the same PV ($\chi^2_{\text{global}}/\text{ndf} < 5$)





$J/\psi + C$

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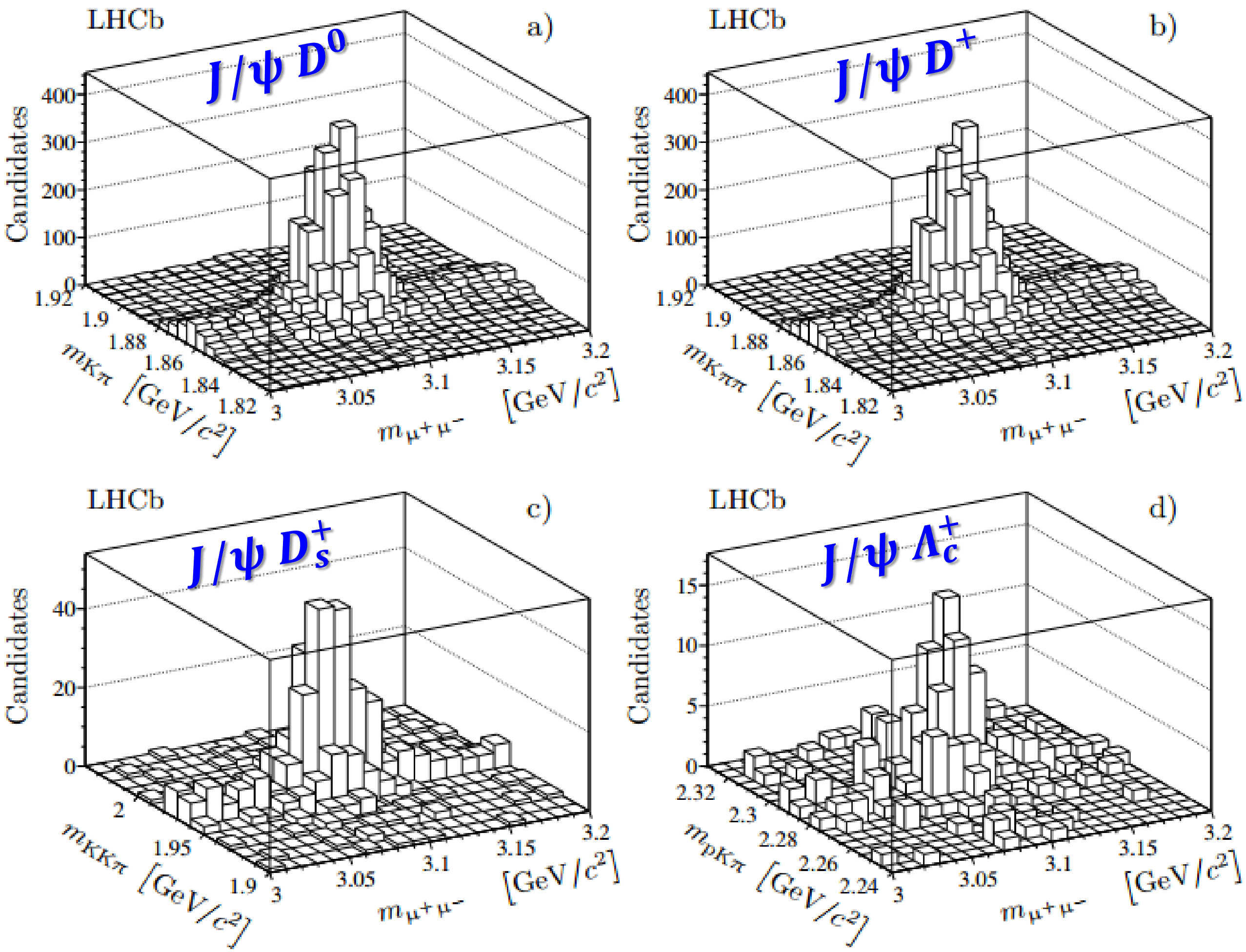

Yields obtained from the fits to 2-D invariant mass distributions

Mode	Yields	S_σ
$J/\psi\, D^0$	4875 ± 86	$> 8\,\sigma$
$J/\psi\, D^+$	3323 ± 71	$> 8\,\sigma$
$J/\psi\, D_s^+$	328 ± 22	$> 8\,\sigma$
$J/\psi\, \Lambda_c^+$	116 ± 14	$7.3\,\sigma$

$D^0 + C$

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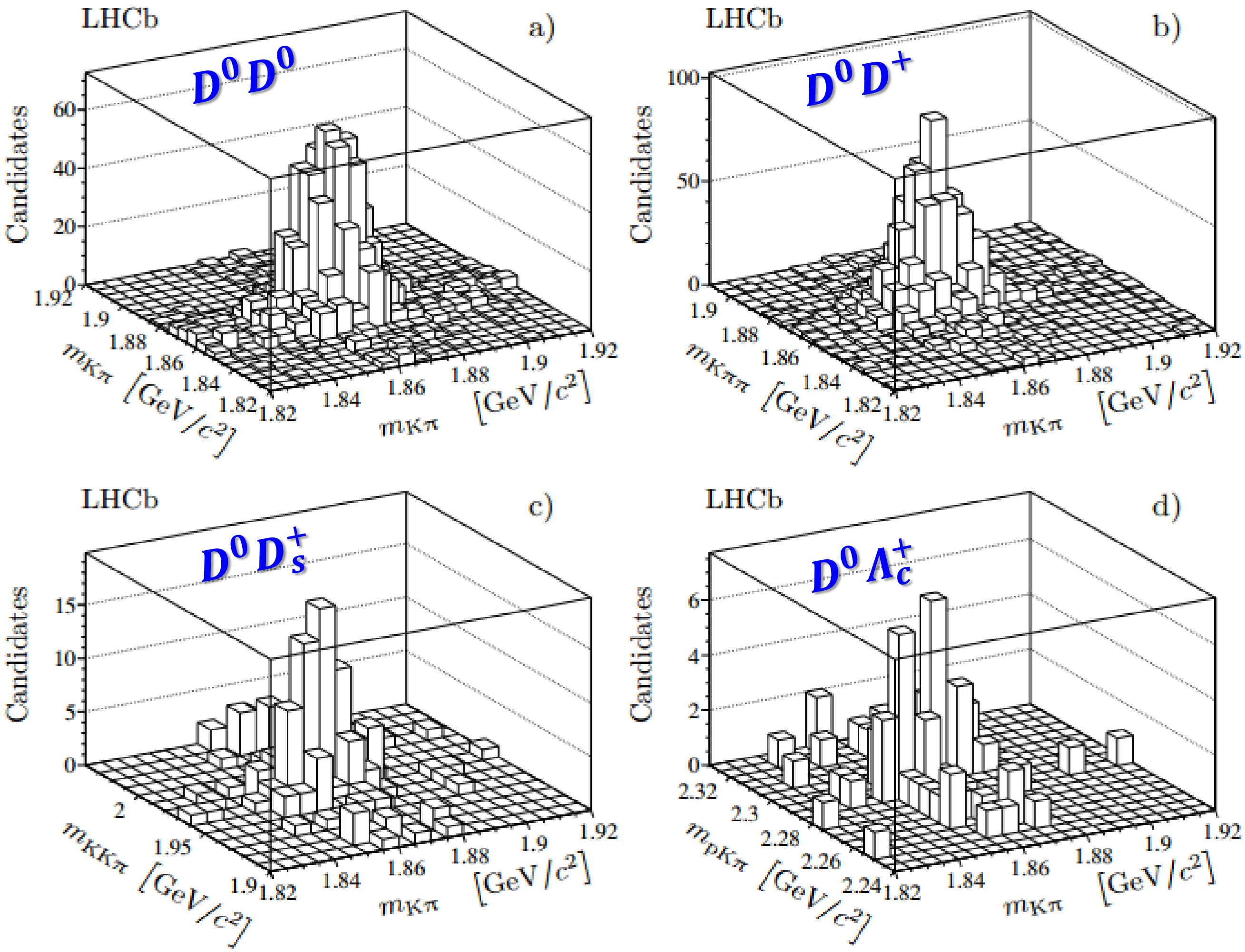

Mode	Yields	S_σ
$D^0 D^0$	1087 ± 37	$> 8\,\sigma$
$D^0 D^+$	1177 ± 39	$> 8\,\sigma$
$D^0 D_s^+$	111 ± 12	$8\,\sigma$
$D^0 \Lambda_c^+$	41 ± 8	$5\,\sigma$

$D^0 \bar{C}$ yields larger by $\sim\mathcal{O}(10)$

$D^+ + C$

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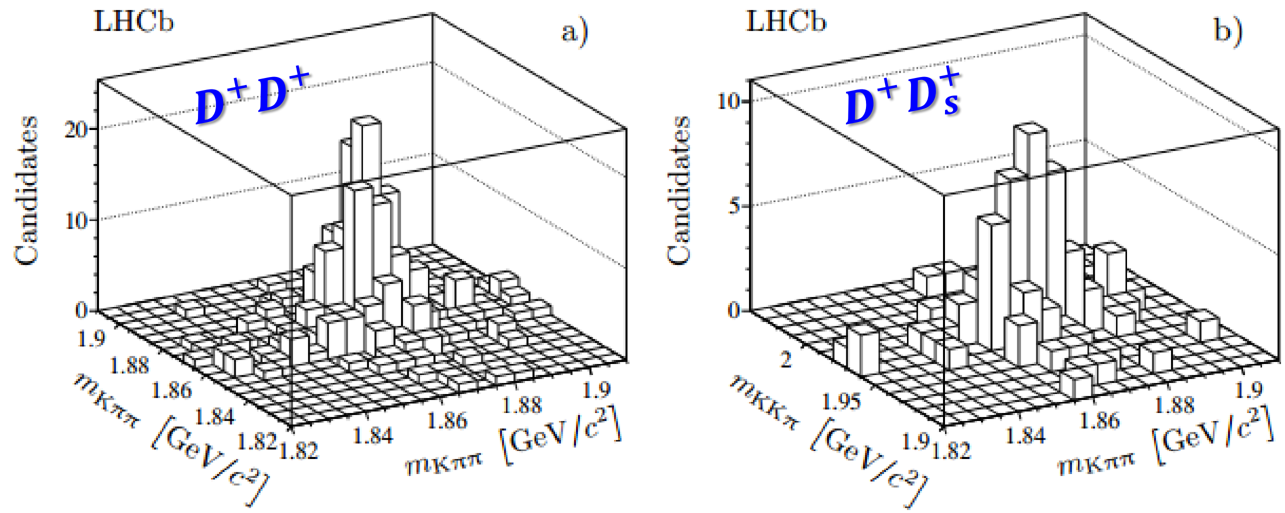

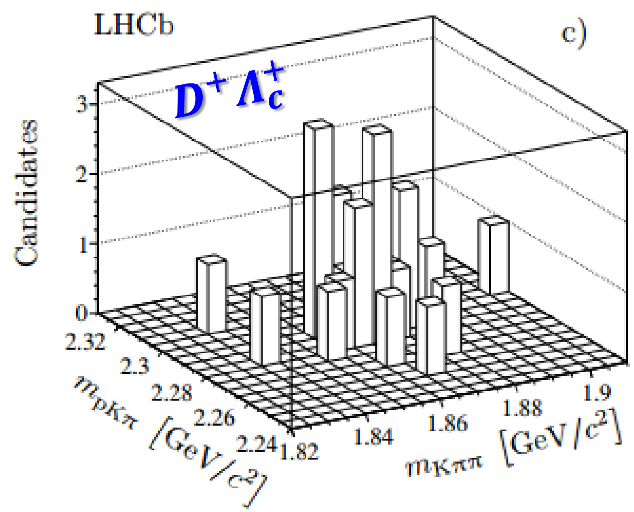

Mode	Yields	S_σ
D^+D^0	249 ± 19	$> 8\,\sigma$
$D^+D_s^+$	52 ± 9	$5\,\sigma$
$D^+\Lambda_c^+$	21 ± 5	$2.5\,\sigma$

$D^+\bar{C}$ yields larger by $\sim\mathcal{O}(10)$

Cross-section measurement

- $$\sigma = \frac{N^{\mathrm{corr}}}{\mathcal{L}\times\mathcal{B}_1\times\mathcal{B}_2}$$
- N^{corr} is efficiency corrected signal yields
  - Efficiency corrections using data-driven methods as much as possible : tracking, hadron ID…
  - Efficiency correction using MC considering imperfect simulation on y, p^T and J/ψ polarization
  - D^0C : corrected for double Cabibbo suppressed $D^0 \to K^+\pi^-$
  - $\mathcal{B}_{1,2}$: $\mathcal{B}$ of $C_{1,2}$ decay to final states
- The major systematics from track reconstruction efficiency

Cross-sections

Lansberg, EPJC 61(2009) 693

Berezhnoy et. al.,PRD 57(1998) 4385; Baranov, PRD 73(2006) 074021

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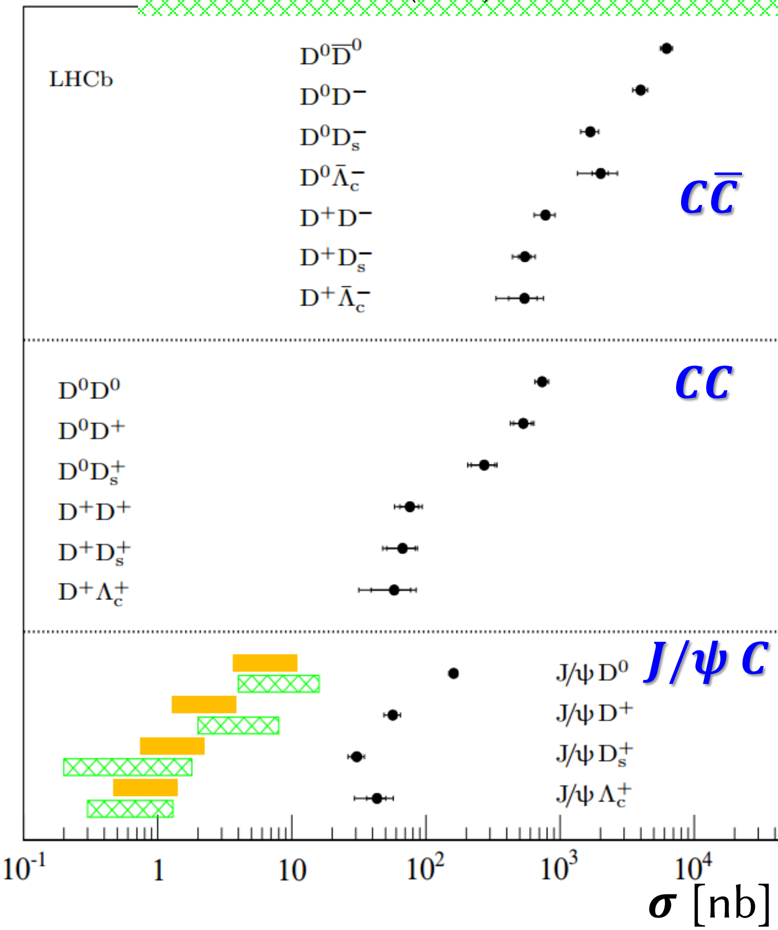
Mode	σ [nb]	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi C}/\sigma_{C}$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_{C}/\sigma_{J/\psi C}$ [mb]
$J/\psi D^0$	$161.0 \pm 3.7 \pm 12.2$	$16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}$	$6.7 \pm 0.2 \pm 0.5$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
$J/\psi D^+$	$56.6 \pm 1.7 \pm 5.9$	$5.7 \pm 0.2 \pm 0.6^{+1.2}_{-0.9}$	$5.7 \pm 0.2 \pm 0.4$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$
$J/\psi D_s^+$	$30.5 \pm 2.6 \pm 3.4$	$3.1 \pm 0.3 \pm 0.4^{+0.6}_{-0.5}$	$7.8 \pm 0.8 \pm 0.6$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$
$J/\psi \Lambda_c^+$	$43.2 \pm 7.0 \pm 12.0$	$4.3 \pm 0.7 \pm 1.2^{+0.9}_{-0.7}$	$5.5 \pm 1.0 \pm 0.6$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$

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



- Expectation from gluon-gluon fusion below measured $\sigma_{J/\psi C}$

Effective σ in DPS

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Neglecting partonic correlations in proton, DPS contribution estimated naively as:

$$\sigma_{C_1C_2} = \left(\frac{1}{2}\times\right)\frac{\sigma_{C_1}\times\sigma_{C_2}}{\sigma_{\rm eff}^{\rm DPS}}. \quad (\text{if } C_1 = C_2)$$

Pocket formula

Mode	σ [nb]	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi C}/\sigma_{C}$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_{C}/\sigma_{J/\psi C}$ [mb]
$J/\psi D^0$	$161.0 \pm 3.7 \pm 12.2$	$16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}$	$6.7 \pm 0.2 \pm 0.5$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
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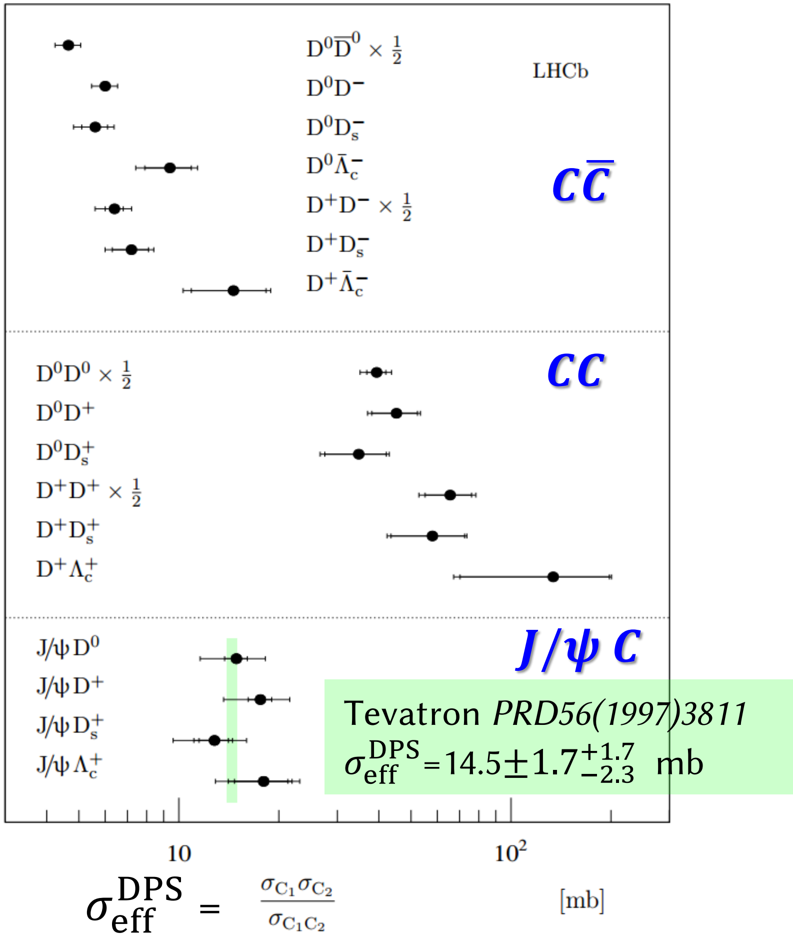

- Good agreement with Tevatron $\sigma_{\rm eff}^{\rm DPS}$ for $J/\psi C$
- Yet $\sigma_{\rm eff}^{\rm DPS}$ from CC is 2~3 factor larger

Properties : p_T

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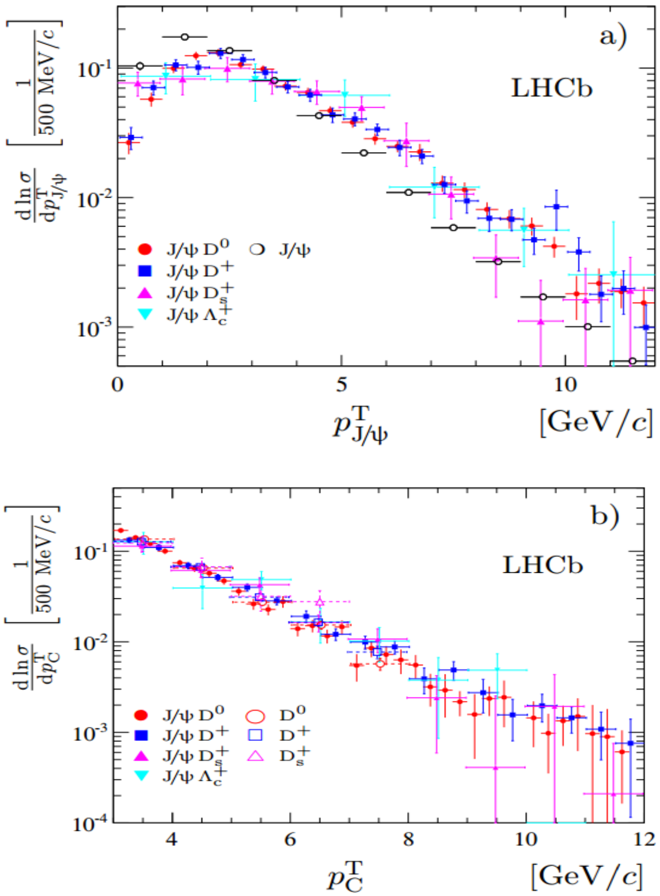
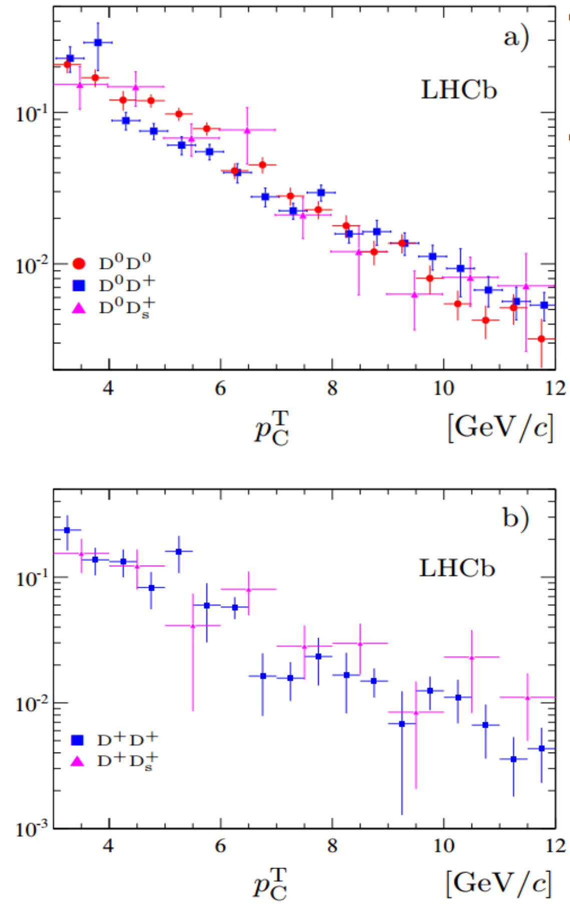
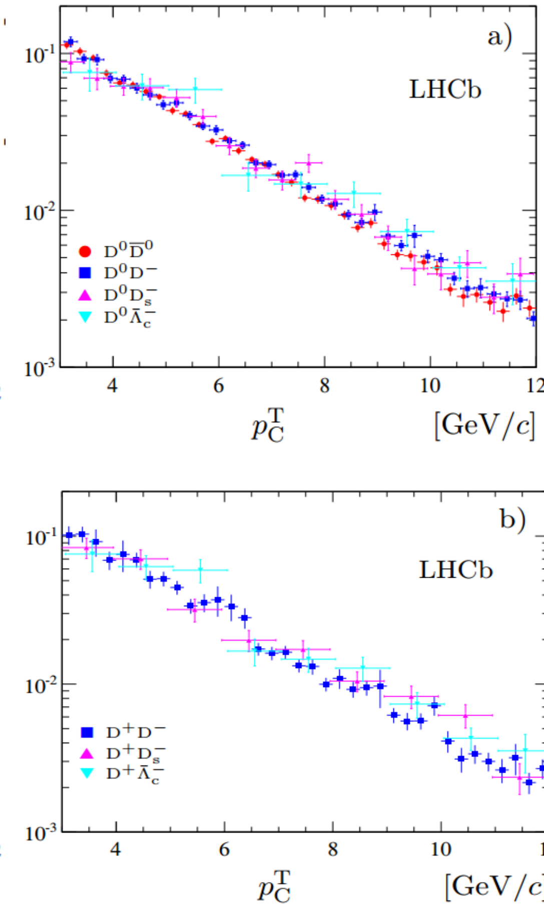
$J/\psi\, C$



CC



$C\bar{C}$



- $p_T^{J/\psi}$ harder than prompt J/ψ;
- p_T^{C} compatible with prompt C

- p_T^{C} all similar for $CC, C\bar{C}$, significantly different from (harder than) prompt C

Azimuthal angle and rapidity

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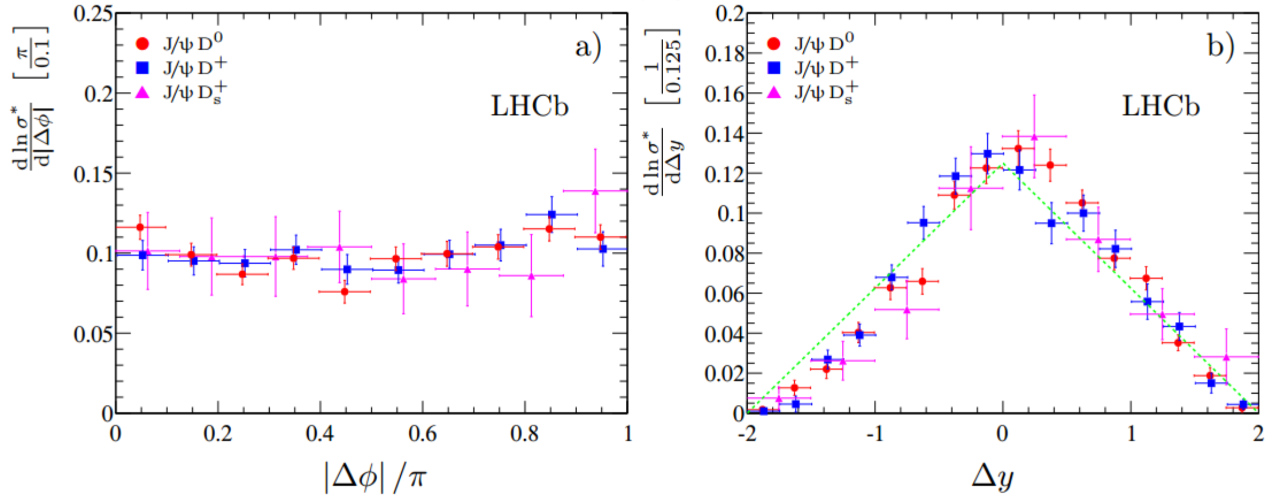
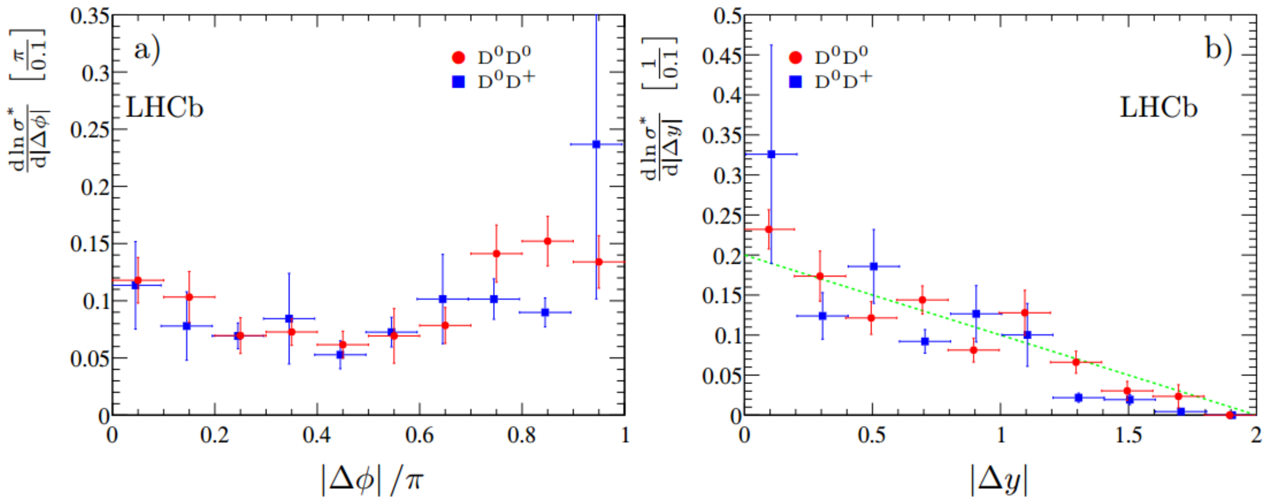
J/ψ c



cc



- $|\Delta\phi|/\pi$ shows no significant correlation
- $|\Delta y| \Rightarrow$ triangular shape as expected from two uncorrelated flat y distributions

Azimuthal angle and rapidity (cont.)

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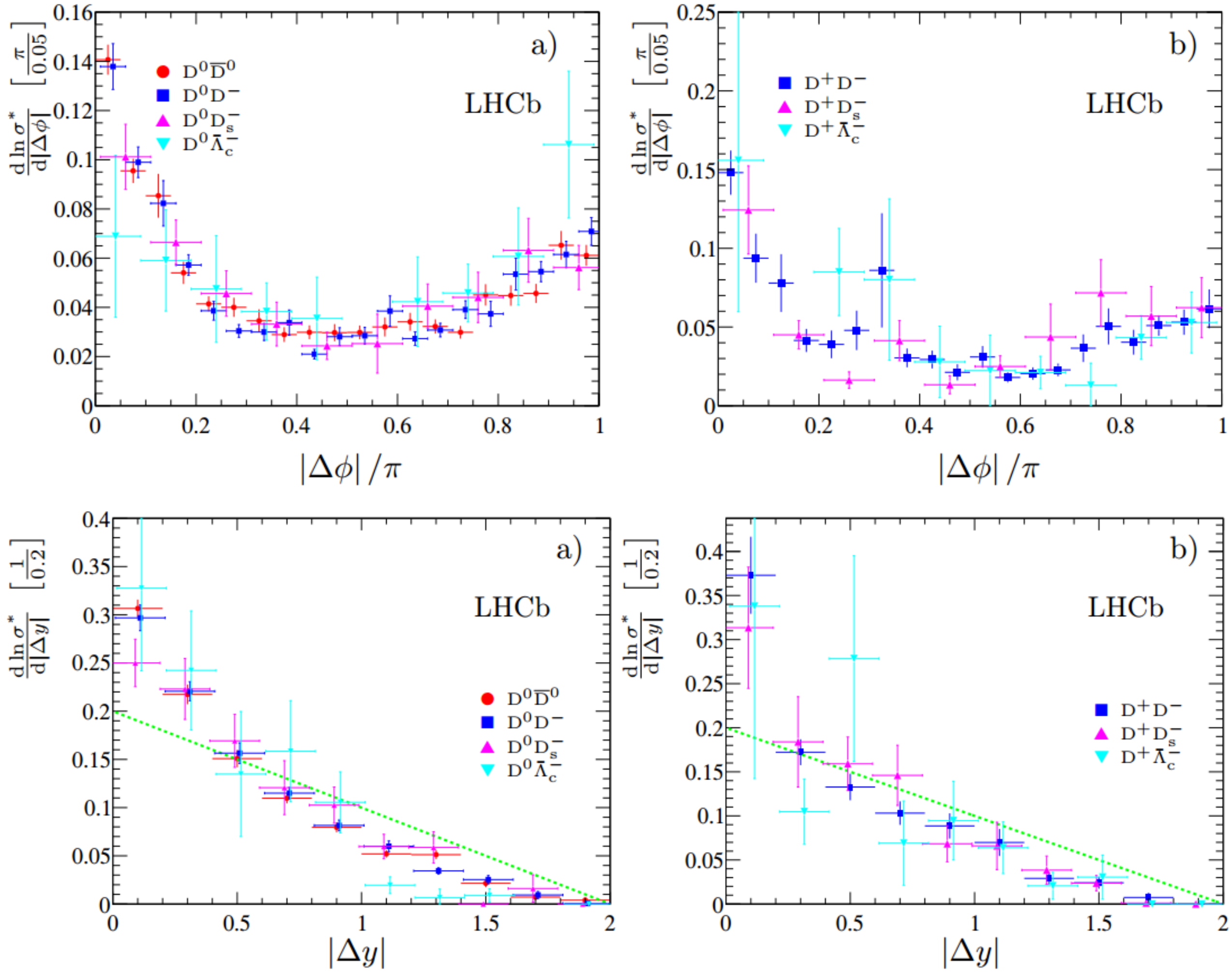
$c\bar{c}$

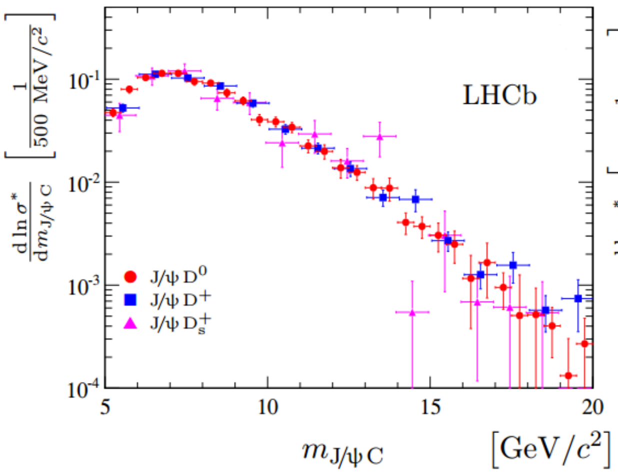


- $|\Delta\phi|/\pi$: enhancement at small $|\Delta\phi|$
- $|\Delta y|$: enhancement at small $|\Delta y|$
- Consistent with $c\bar{c}$ production via gluon splitting mechanism

Invariant mass of charm pairs

[JHEP06 (2012) 141]

$J/\psi\, C$



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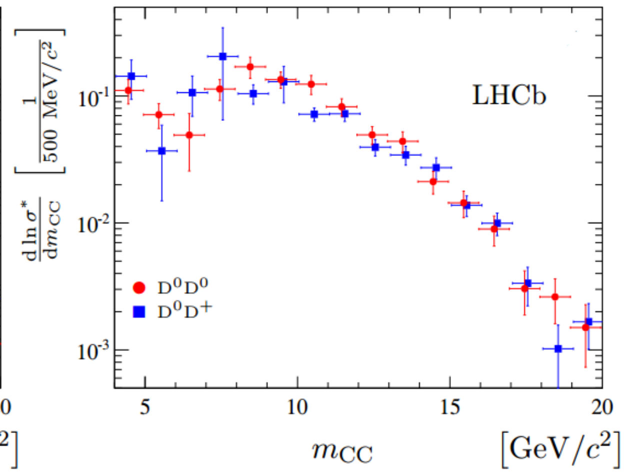
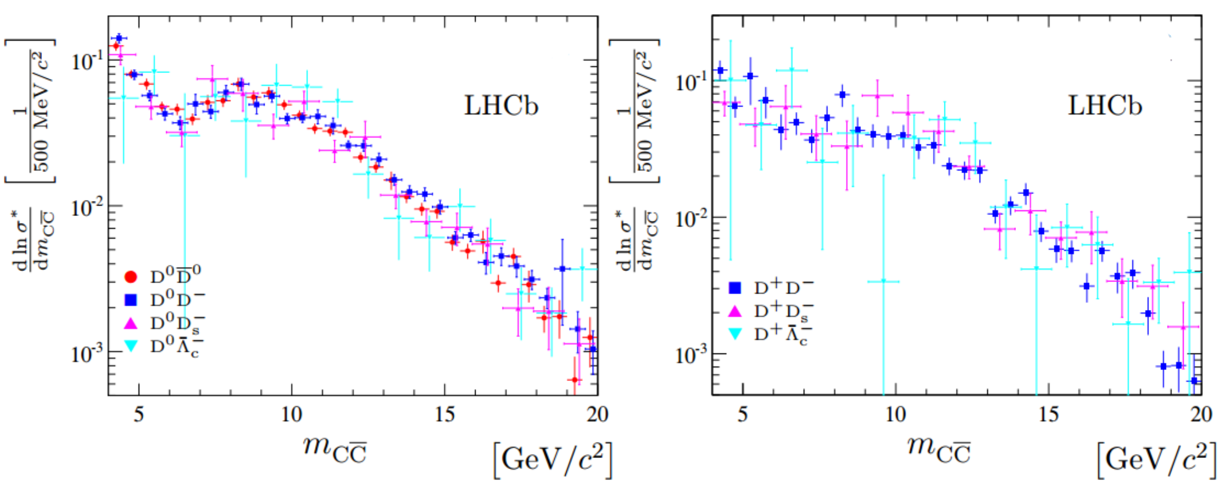


$C\bar{C}$



- Similar for all types of charm hadrons
- Enhancement at small m in $C\bar{C}$ also likely due to gluon splitting

Υ + OPEN CHARM

Υ + open charm

- Production of $b\bar{b}c\bar{c}$ has been studied mainly using B_c^+
  - NRQCD calculation (SPS) in good agreement with LHCb result

- Measurement of $\sigma(\Upsilon C)$ also provides probe in the production mechanism
  - SPS predicts $R_{\text{SPS}} = \frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}}$ to be small (0.2~2.0)%

    Belezhnoy and Likhoded, Int.J.Mod.Phys.A30(2015) 1550125

  - Naive DPS estimation gives $R_{DPS} \sim 10\%$, assuming $\sigma^{\Upsilon c\bar{c}} = \frac{\sigma^{\Upsilon} \times \sigma^{c\bar{c}}}{\sigma^{\text{eff}}}$

ΥC at LHCb

arXiv:1510.05949

- Search using 1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV

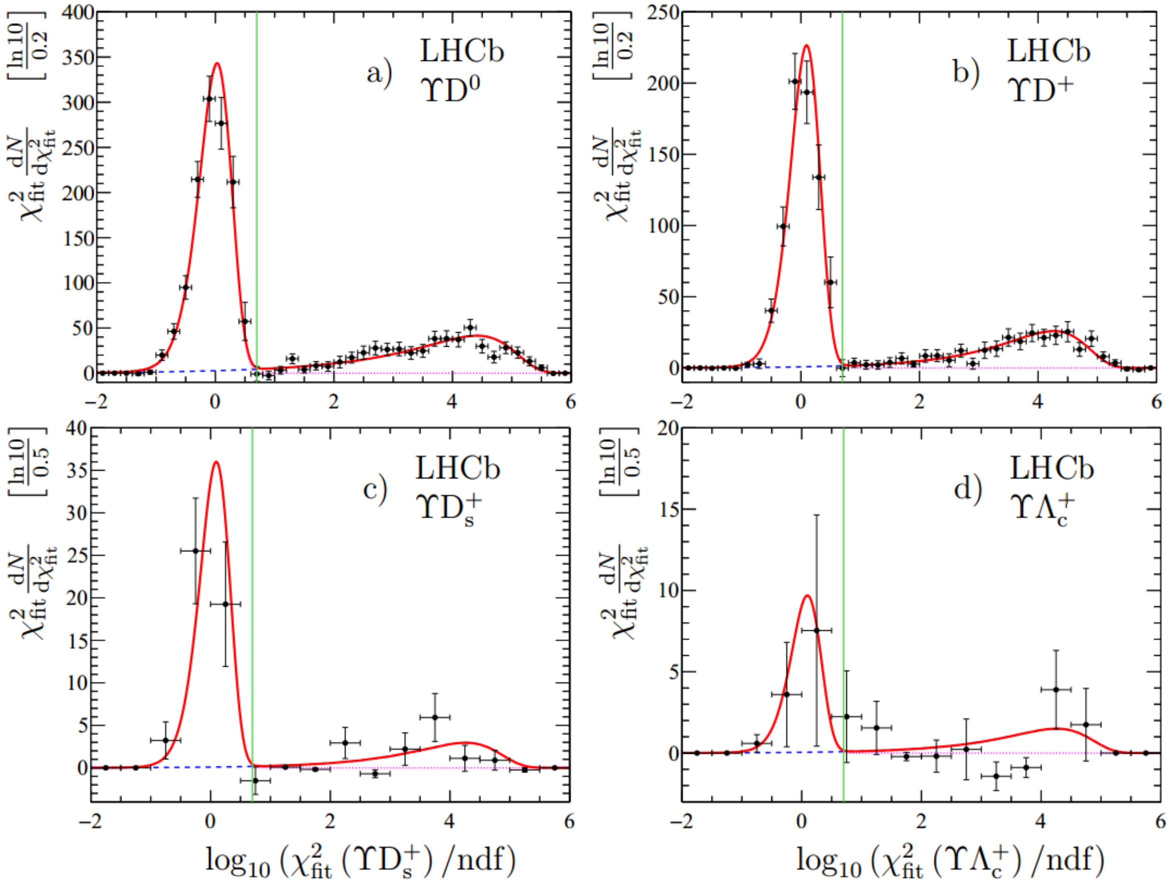
- Final states for ΥC candidates:
  - $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \rightarrow \mu^+\mu^-$
  - $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$, $D_s^+ \rightarrow K^-K^+\pi^+$, $\Lambda_c^+ \rightarrow pK^-\pi^+$

- Main fiducial cuts:
  - $2.0 < y_{\Upsilon,C} < 4.5$
  - $p_T^{\Upsilon} < 15$ GeV, $1 < p_T^C < 20$ GeV

Selection

arXiv:1510.05949

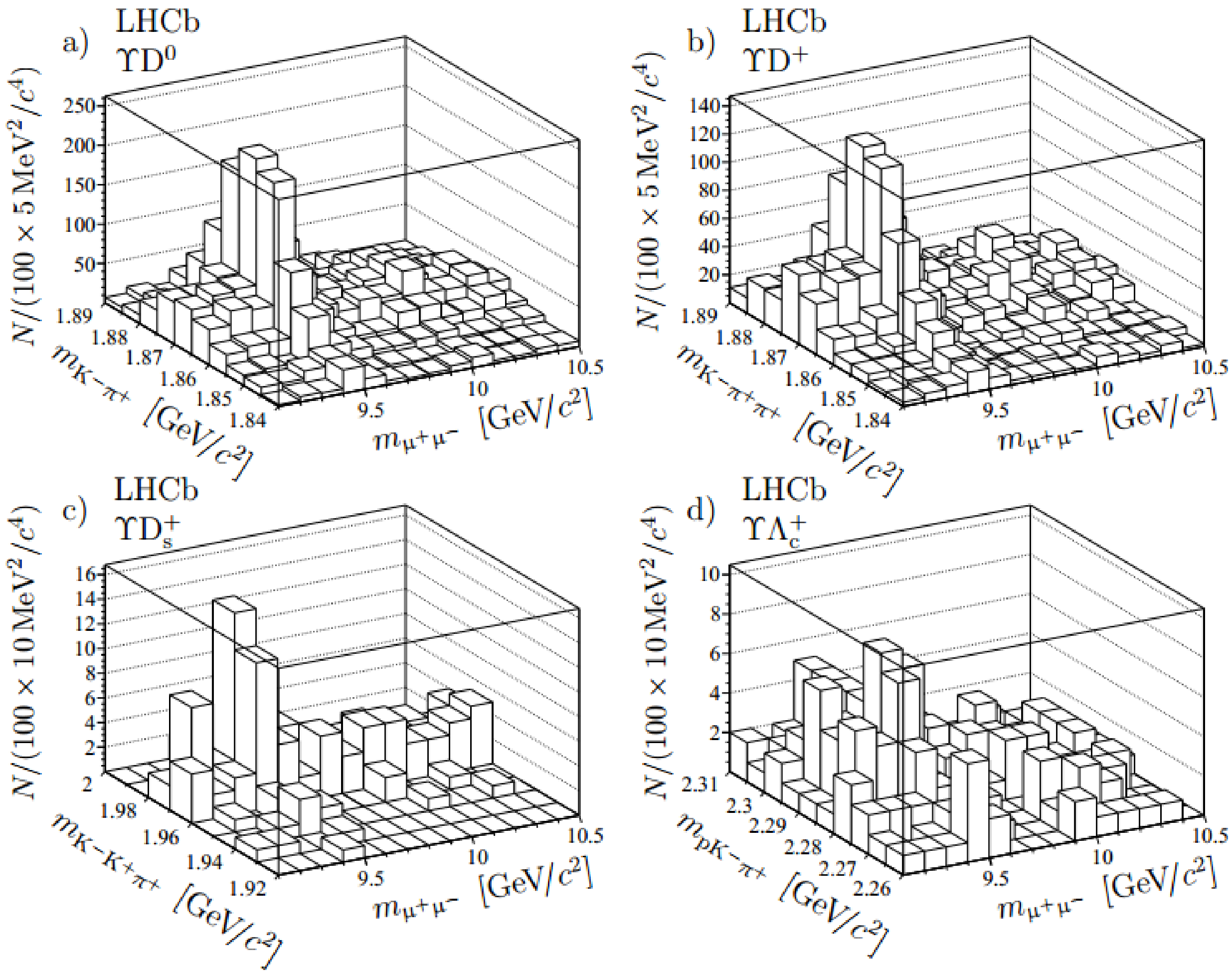
- Similar selections as for $J/\psi C$
  - $c\tau_C > 100\ \mu\text{m}/c$, good track & vertex quality, Υ from PV
- Pile-up negligible by requiring $\chi^2_{\text{global}}/\text{ndf} < 5$



Signals

arXiv:1510.05949

$$f = \Sigma_{i=1}^{3} N_i^{\Upsilon C}\, S_\Upsilon \times S_C + \Sigma_1^3\, N^{\Upsilon B} S_\Upsilon \times S_{B_C} + N^{BC} S_{B_\Upsilon} \times S_C + N^{BB} S_{B_C} \times S_{B_\Upsilon}$$



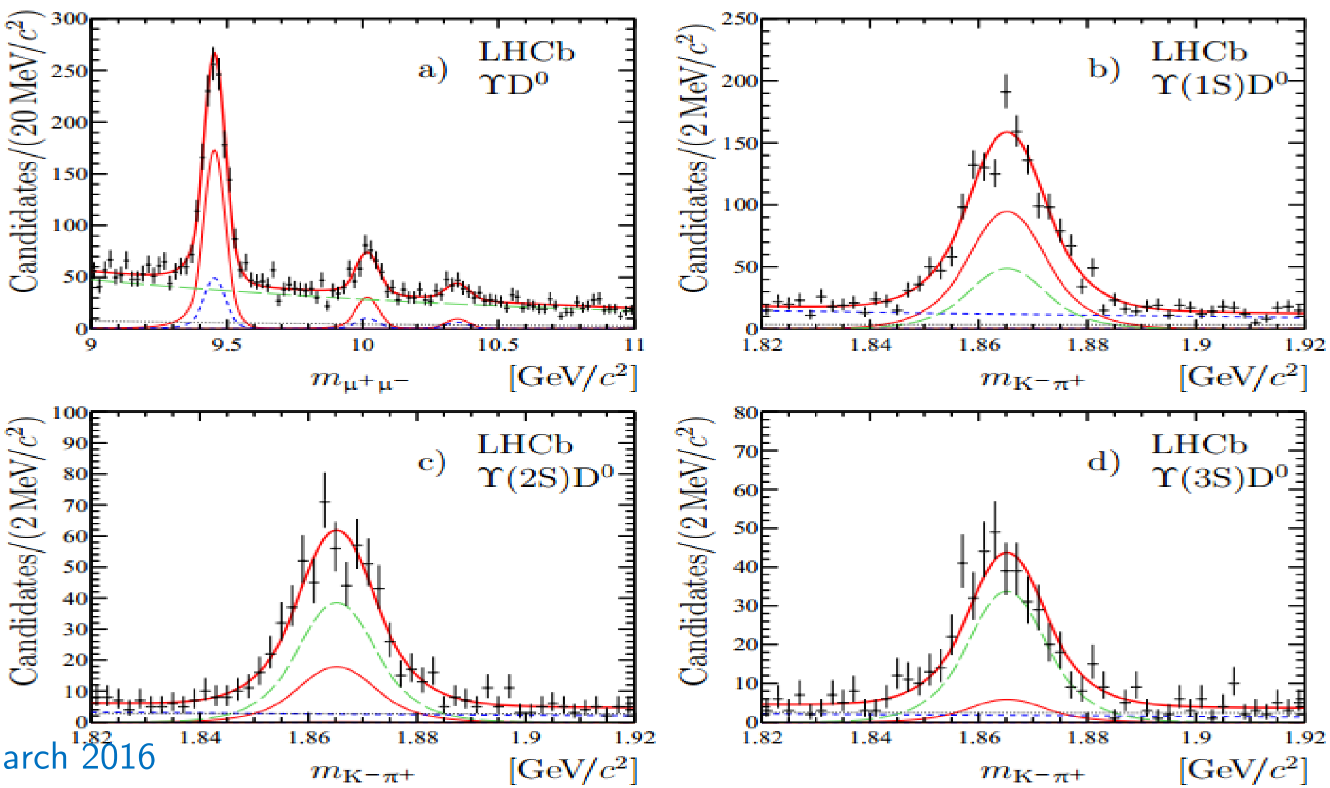
Fitted yields

arXiv:1510.05949

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
D^0	980 ± 50	84 ± 27	60 ± 22
D^+	556 ± 35	116 ± 20	55 ± 17
D_s^+	31 ± 7	9 ± 5	6 ± 4
Λ_c^+	11 ± 6	1 ± 4	1 ± 3

> 5σ, First observation

No significant signal for $\Upsilon + \Lambda_c^+$



ΥD^0 projection from the 2D fit:

- $S_\Upsilon \times S_{D^0}$
- $S_\Upsilon \times S_{B_{D^0}}$
- $S_{B_\Upsilon} \times S_{D^0}$

Cross-section

arXiv:1510.05949

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}$	155 ± 21 (stat) ± 7 (syst) pb	250 ± 28 (stat) ± 11 (syst) pb
$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}$	82 ± 19 (stat) ± 5 (syst) pb	80 ± 16 (stat) ± 5 (syst) pb
$R^{D^0/D^+} = \frac{\sigma^{\Upsilon(1S)D^0}}{\sigma^{\Upsilon(1S)D^+}}$	1.9 ± 0.5 (stat) ± 0.1 (syst)	3.1 ± 0.7 (stat) ± 0.1 (syst)
$R^{\Upsilon(1S)c\bar{c}} = \frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}$	$(5.5 \pm 1.7)\%$	$(6.2 \pm 0.7)\%$
$R^{\Upsilon(1S)\Upsilon(2S)}_{D^0} = \mathcal{B}_{2S/1S} \times \frac{\sigma^{\Upsilon(2S)D^0}}{\sigma^{\Upsilon(1S)D^0}}$	$(13 \pm 5)\%$	$(20 \pm 4)\%$
$R^{\Upsilon(1S)\Upsilon(2S)}_{D^+} = \mathcal{B}_{2S/1S} \times \frac{\sigma^{\Upsilon(2S)D^+}}{\sigma^{\Upsilon(1S)D^+}}$	$(22 \pm 7)\%$	$(22 \pm 6)\%$

Agrees with DPS estimation:

$$R^{D^0/D^+} = \frac{\sigma^{D^0}}{\sigma^{D^+}} = 2.41 \pm 0.18$$

$$R_C^{\Upsilon(2S)/\Upsilon(1S)} = \mathcal{B}_{2S/1S} \times \frac{\sigma^{\Upsilon(2S)}}{\sigma^{\Upsilon(1S)}} = 0.249 \pm 0.033$$

Larger than SPS prediction: (0.2~2.0)%
Belezhnoy and Likhoded, Int.J.Mod.Phys.A30(2015) 1550125

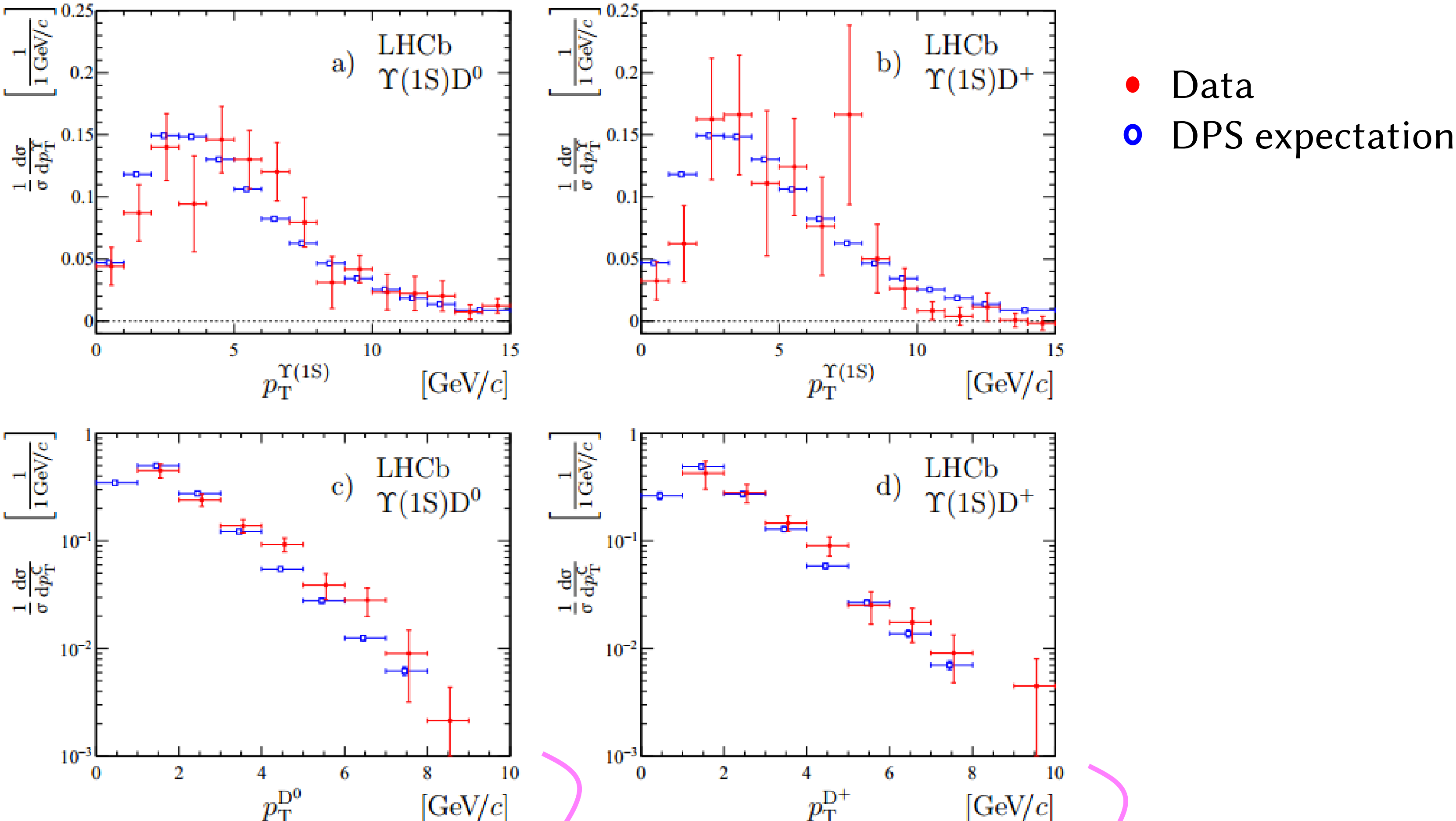
- Effective DPS cross-section (averaging $\Upsilon(1S)D^{0,+}$, 7 & 8 TeV):

$$\boldsymbol{\sigma_{\text{eff}} = \frac{\sigma^{\Upsilon} \times \sigma^{C}}{\sigma^{\Upsilon C}} = 18.0 \pm 1.3\ (\text{stat}) \pm 1.2\ (\text{syst}) = 18.0 \pm 1.8\ \text{mb}}$$

- The large $\sigma^{\Upsilon C} \Rightarrow$ potential for *b*-flavour tagging

Kinematic properties : p_T

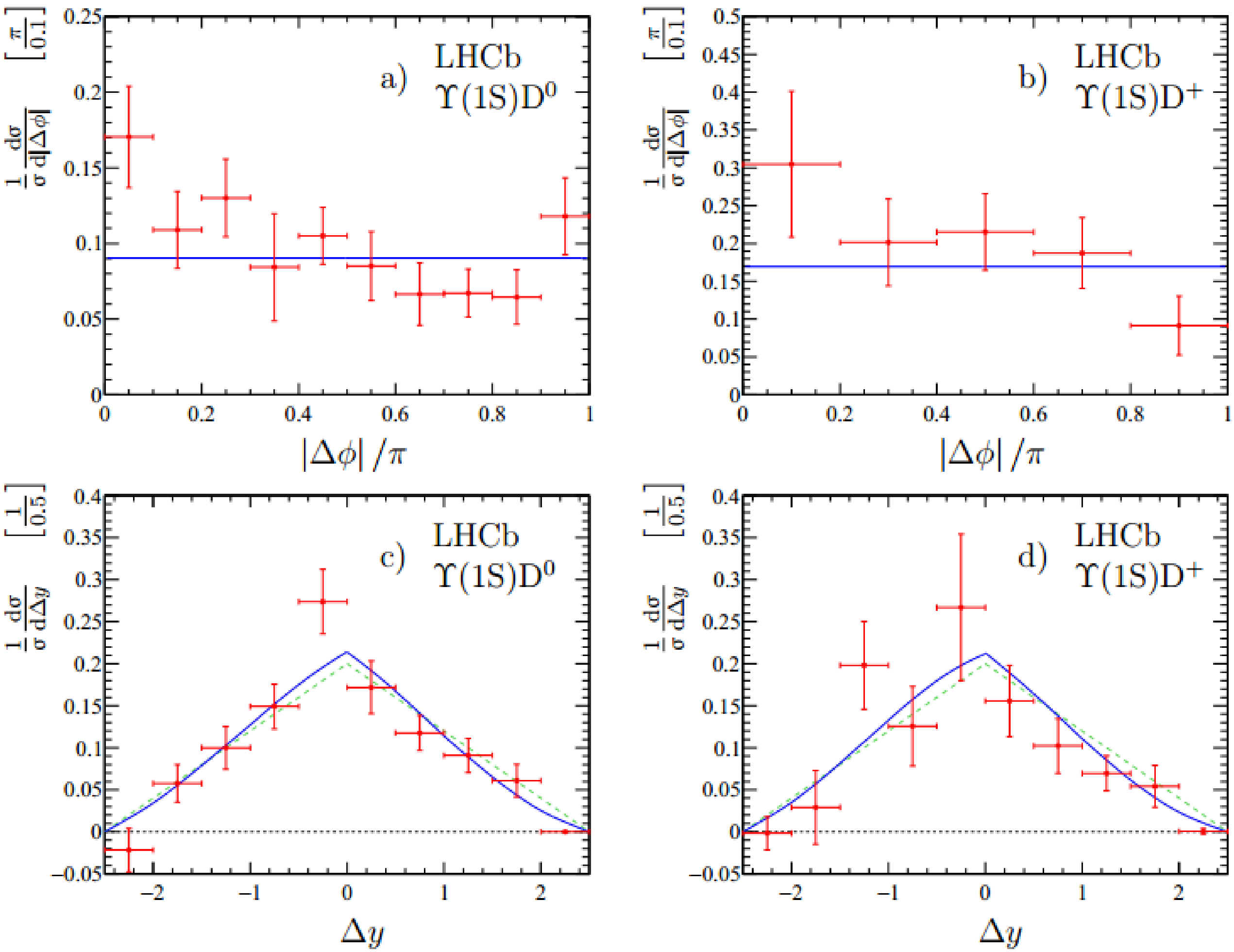
arXiv:1510.05949



A large contribution from intrinsic charm in the nucleon pdf would expect C with high $p_T > 10$ GeV

Azimuthal angle and rapidity

arXiv:1510.05949



$|\Delta\phi|$:

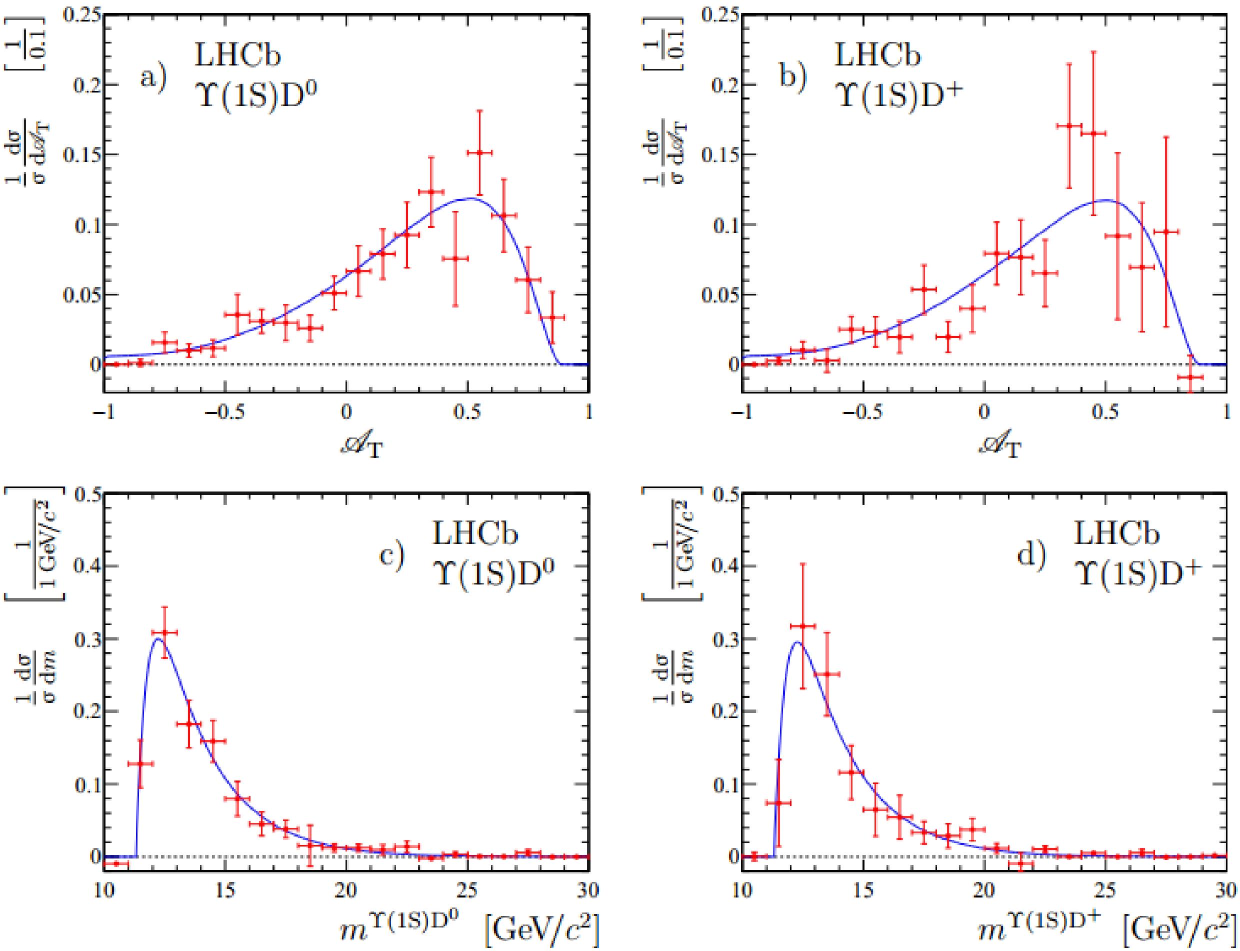
SPS: enhancement $\sim \pi$

DPS: flat

- Data
- DPS expectation
- Assuming uncorrelated production of Υ and D

p_T asymmetry and invariant mass

arXiv:1510.05949



$$\mathcal{A}_T = \frac{p_T^{\Upsilon(1S)} - p_T^C}{p_T^{\Upsilon(1S)} + p_T^C}$$

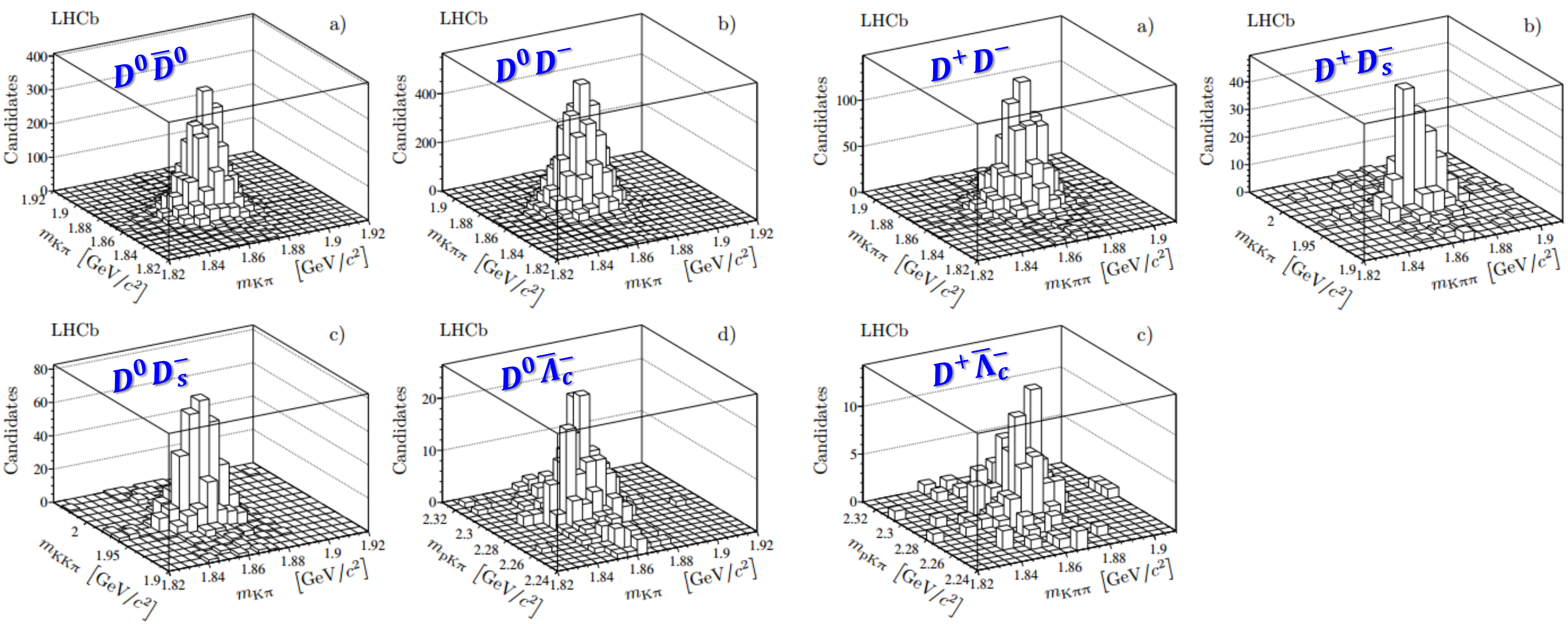
- Data
- DPS expectation

Summary and prospects

- Several double heavy flavor hadron pairs observed at LHCb
  - $cc\bar{c}\bar{c}$: $J/\psi + D^0/D^+/D_s^+/\Lambda_c^+$,
    $D^0 + D^0/D^+/D_s^+/\Lambda_c^+, D^+D^+, D^+D_s^+$,
    $D^0\overline{D}^0, D^0/D^+ + D^-/D_s^-/\bar{\Lambda}_c^-$
  - $b\bar{b}c\bar{c}$: $\Upsilon(1S)D^0, \Upsilon(2S)D^0, \Upsilon(1S)D^+, \Upsilon(2S)D^+, \Upsilon(1S)D_s^+$
- The cross-sections measured, and kinematic properties studied, shedding light on the heavy quarkonium production mechanism
- So far only with LHC Run I data (at 7/8 TeV), and limited by statistics. More to expect with more ongoing Run I search, as well as 13 TeV results!

BACKUP

$c\bar{c}$



LHCb
a)
$D^0\bar{D}^0$
Candidates
$m_{K\pi}$ [GeV/c^2]
$m_{K\pi}$ [GeV/c^2]
LHCb
b)
D^0D^-
Candidates
$m_{K\pi\pi}$ [GeV/c^2]
$m_{K\pi}$ [GeV/c^2]
LHCb
a)
D^+D^-
Candidates
$m_{K\pi\pi}$ [GeV/c^2]
$m_{K\pi\pi}$ [GeV/c^2]
LHCb
b)
$D^+D_s^-$
Candidates
$m_{KK\pi}$ [GeV/c^2]
$m_{K\pi\pi}$ [GeV/c^2]
LHCb
c)
$D^0D_s^-$
Candidates
$m_{KK\pi}$ [GeV/c^2]
$m_{K\pi}$ [GeV/c^2]
LHCb
d)
$D^0\bar{\Lambda}_c^-$
Candidates
$m_{pK\pi}$ [GeV/c^2]
$m_{K\pi}$ [GeV/c^2]
LHCb
c)
$D^+\bar{\Lambda}_c^-$
Candidates
$m_{pK\pi}$ [GeV/c^2]
$m_{K\pi\pi}$ [GeV/c^2]

$J/\psi C$, CC fit model

- Di-charm signal. This is modelled by a product PDF of the individual signal components for the first and the second particle.
- Combinatorial background. This is modelled by a product PDF of the individual background components i and j denoted by $B_i(m_i)$ and $B_j(m_j)$.
- Single production of component i together with combinatorial background for component j. This is modelled by a product PDF of the signal component i denoted $S_i(m_i)$ and the background component j denoted $B_j(m_j)$.
- Single production of component j together with combinatorial background for component i. This is modelled by a product PDF of the signal component j denoted $S_j(m_j)$ and the background component i denoted $B_i(m_i)$.

The total PDF is then

$$F(m_i, m_j) \propto N^{S_i \times S_j} \times S_i(m_i)S_j(m_j) + N^{S_i \times B_j} \times S_i(m_i)B_j(m_j) \\ + N^{B_i \times S_j} \times B_i(m_i)S_j(m_j) + N^{B_i \times B_j} \times B_i(m_i)B_j(m_j), \quad (4.1)$$

More prediction on σ_{cc}

- R.Maciuła and A.Szczurek, *PRD87 (2013) no.7, 074039*
- A.van Hameren, R.Maciuła and A.Szczurek, *Phys.Lett. B748 (2015) 167*
- ....

Systematic uncertainty of $\sigma_{J/\psi C}$ (%)

Source		$J/\psi D^0$	$J/\psi D^+$	$J/\psi D_s^+$	$J/\psi \Lambda_c^+$
J/ψ reconstruction	ε_1^{reco}	1.3	1.3	1.3	1.3
C reconstruction	ε_2^{reco}	0.7	0.8	1.7	3.3
Muon ID	$\varepsilon_{J/\psi}^{ID}$	1.1	1.1	1.1	1.1
Hadron ID	ε_{had}^{ID}	1.1	1.9	1.1	1.5
Tracking	ξ^{trk}	4.9	7.0	7.0	7.0
Trigger	$\varepsilon_{J/\psi C}^{trg}$	3.0	3.0	3.0	3.0
J/ψ polarization	$\varepsilon_{J/\psi}^{reco}$	3.0	3.0	3.0	3.0
Global event cuts	ε^{GEC}	0.7	0.7	0.7	0.7
Luminosity	$\mathcal{L}$	3.7	3.7	3.7	3.7
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	$\mathcal{B}_1$	1.0	1.0	1.0	1.0
C branching fractions	$\mathcal{B}_2$	1.3	4.3	6.0	26
Total		8	10	11	28

Systematic uncertainty of CC and $C\bar{C}$ (%)

Source		D^0D^0	D^0D^+	$D^0D_s^+$	$D^0\Lambda_c^+$
D^0C reconstruction	$\varepsilon_1^{reco} \times \varepsilon_2^{reco}$	1.4	1.4	2.3	3.6
Hadron ID	ε_{had}^{ID}	1.2	1.8	1.6	2.4
Tracking	ξ^{trk}	8.5	10.7	10.6	10.6
Trigger	$\varepsilon_{CC,C\overline{C}}^{trg}$	1.8	2.5	3.9	5.2
Global event cuts	ε^{GEC}	1.0	1.0	1.0	1.0
Luminosity	$\mathcal{L}$	3.7	3.7	3.7	3.7
$\mathcal{B}(D^0 \to K^-\pi^+)$	$\mathcal{B}_1$	1.3	1.3	1.3	1.3
C branching fractions	$\mathcal{B}_2$	1.3	4.3	6.0	26
Total		10	12	14	30

Source		D^+D^+	$D^+D_s^+$	$D^+\Lambda_c^+$
D^+C reconstruction	$\varepsilon_1^{reco} \times \varepsilon_2^{reco}$	1.4	2.2	4.0
Hadron ID	ε_{had}^{ID}	2.3	2.4	3.0
Tracking	ξ^{trk}	12.8	12.8	12.8
Trigger	$\varepsilon_{CC,C\overline{C}}^{trg}$	3.7	5.8	5.0
Global event cuts	ε^{GEC}	1.0	1.0	1.0
Luminosity	$\mathcal{L}$	3.7	3.7	3.7
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	$\mathcal{B}_1$	4.3	4.3	4.3
C branching fractions	$\mathcal{B}_2$	4.3	6.0	26
Total		17	17	31

Modified Novosbirsk function

- Or "Bukin" function. Used in ΥC analysis to model C shape

The so called empirically modified Novosibirsk function divides the fitting region into a peaking region, a low tail region and a high tail region. For a variable x, the modified Novosibirsk function $f(x) = A_p \times \exp(g(x))$, where $g(x)$ is defined, in the peak region $x_1 < x < x_2$, as

$$-\ln 2 \times \left(\frac{\ln\left(1 + 2\tau\sqrt{\tau^2+1}\frac{x-x_p}{\sigma_p\sqrt{2\ln 2}}\right)}{\ln(1 + 2\tau^2 - 2\tau\sqrt{\tau^2+1})} \right)^2 ,$$

in the low tail region $x < x_1$, as

$$\frac{\tau\sqrt{\tau^2+1}(x-x_1)\sqrt{2\ln 2}}{\sigma_p(\sqrt{\tau^2+1}-\tau)^2\ln(\sqrt{\tau^2+1}+\tau)} + \rho_1\left(\frac{x-x_1}{x_p-x_1}\right)^2 - \ln 2,$$

and in the high tail region $x > x_2$, as

$$-\frac{\tau\sqrt{\tau^2+1}(x-x_2)\sqrt{2\ln 2}}{\sigma_p(\sqrt{\tau^2+1}+\tau)^2\ln(\sqrt{\tau^2+1}+\tau)} + \rho_2\left(\frac{x-x_2}{x_p-x_2}\right)^2 - \ln 2.$$

The parameters are:

- A_p is the value at the maximum of the function,
- x_p is the peak position,
- σ_p is the width of the peak defined as the width at half-height divided by $2\sqrt{2\ln 2} \simeq 2.35$,
- τ is an asymmetry parameter.
- $\rho_{1/2}$ described the width of the respective tails.

The positions $x_{1,2}$ are $x_p + \sigma_p\sqrt{2\ln 2}\left(\frac{\xi}{\sqrt{\xi^2+1}} \mp 1\right)$. Left and right tails are attached to the peak with the conditions of continuity and first derivative.

Feed-down in ΥD

- From $\Upsilon b\bar{b}$: estimated assuming DPS production
  - $\sigma(\Upsilon)$, $\sigma(b\bar{b})$ using LHCb results

- From $\chi_b c\bar{c}$:
  - Included in the selected signal
  - $\leq$ a few percent in theory

A.K. Likhoded, A.V. Luchinsky, S.V. Poslavsky, *Phys.Let.B 2016.01.051*

Systematic uncertainty of $\sigma^{\Upsilon C}$ (%)

Source	$\sigma^{\Upsilon D^0}$	$\sigma^{\Upsilon D^+}$
Signal ΥC extraction		
Υ and C signal shapes	$0.1 \oplus 0.3$	$0.1 \oplus 0.5$
2D fit model	0.4	0.7
Υ radiative tail	1.0	1.0
Efficiency corrections	0.1	1.3
Efficiency calculation		
muon identification	0.2	0.2
hadron identification	0.5	0.8
simulated samples size	0.2	0.2
tracking	$0.4 \oplus 4 \times 0.4$	$0.5 \oplus 5 \times 0.4$
hadronic interactions	2×1.4	3×1.4
trigger	2.0	2.0
data-simulation agreement	1.0	1.0
$\mathcal{B}_C$	1.3	2.1
Total	4.3	5.9