Double-parton scattering measurements and prospects at LHCb

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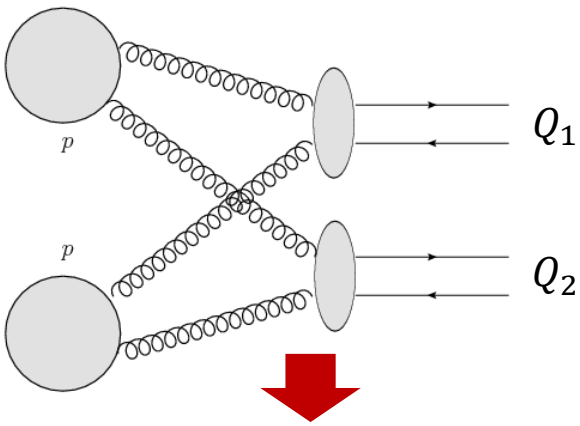
Outline

- Introduction
- The LHCb detector
- LHCb measurements
  - ✓ $2 \times J/\psi$ [PLB 707 (2012) 52-59]
  - ✓ $J/\psi + \text{open charm} \ \& \ 2 \times \text{open charm}$ [JHEP 06 (2012) 141] [JHEP 1403 (2014) 108]
  - ✓ $Z + \text{open charm}$ [JHEP (2014) 091]
  - ✓ $\Upsilon + \text{open charm}$ [arXiv:1510.05949]
- Summary and prospects

Introduction

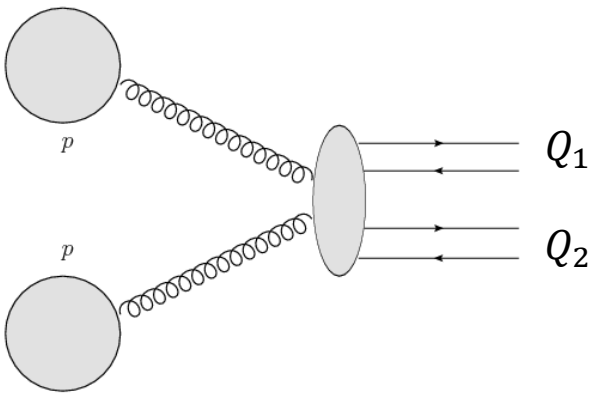
Double-parton scattering (DPS)

- ✓ Two independent processes



Single-parton scattering (SPS)

- ✓ Products highly correlated

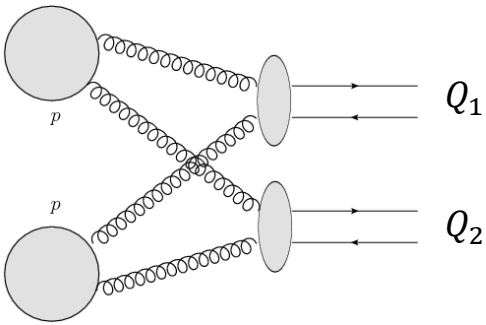


- ✓ Provide information on parton transverse profile & correlations in proton
- ✓ Help better understand background in searches for new physics ($Z + b\bar{b}$, W^+W^+ etc.)

- ➢ Studies in various experiments
  - ✓ pp: W+2-jets, J/ψ+W, J/ψ+Z, $2 \times J/\psi$, $2 \times \Upsilon$ etc.
  - ✓ $p\bar{p}$: 4-jets, γ+3-jets, $J/\psi + \Upsilon$ etc.
  - ✓ $p - Pb$: W^+W^+, W^-W^- (proposed)
  - ✓ $Pb - Pb$: $2 \times J/\psi$ (proposed)

- ➢ LHCb: pp collisions, smaller x

DPS in $pp/p\bar{p}$ collisions



$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2' d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}$$
$$\times \boxed{\Gamma_{ij}(x_1, x_2, \mathbf{b}_1, \mathbf{b}_2)} \boxed{\hat{\sigma}^{Q_1}_{ik}(x_1, x_1')\, \hat{\sigma}^{Q_2}_{jl}(x_2, x_2')} \boxed{\Gamma_{kl}(x_1', x_2', \mathbf{b}_1 - \mathbf{b}, \mathbf{b}_2 - \mathbf{b})},$$

Generalized double parton PDF

SPS parton-level cross-section

- Assumption 1: factorization of transverse & longitudinal components

$$\Gamma_{ij}(x_1, x_2, \boldsymbol{b}_1, \boldsymbol{b}_2) = D_{ij}(x_1, x_2) T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2)$$

- Assumption 2: no correlation

$$D_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2), \qquad T_{ij}(\boldsymbol{b}_1, \boldsymbol{b}_2) = T_i(\boldsymbol{b}_1) T_j(\boldsymbol{b}_2)$$

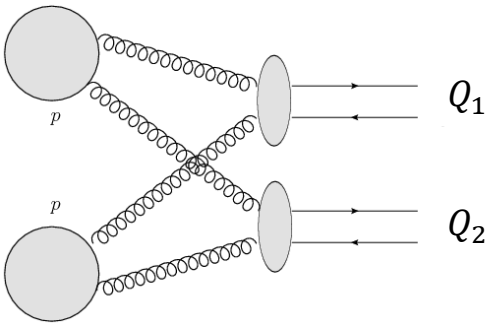
$\Rightarrow$ Pocket formula

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}}$$

✓ Also valid for differential cross-sections

DPS in $pp/p\bar{p}$ collisions (cont.)

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}}$$



- $\sigma_{\text{eff}} = \left[\int d^2\boldsymbol{b} F(\boldsymbol{b})^2\right], F(\boldsymbol{b}) = \int T(\boldsymbol{b}_i) T(\boldsymbol{b}_i - \boldsymbol{b}) d^2\boldsymbol{b}_i$
  - ✓ A property of proton
  - ✓ Thought to be universal, i.e. independent of process and energy
  - ✓ Experimental result indicates a smaller "proton radius" $0.3 - 0.7$ fm

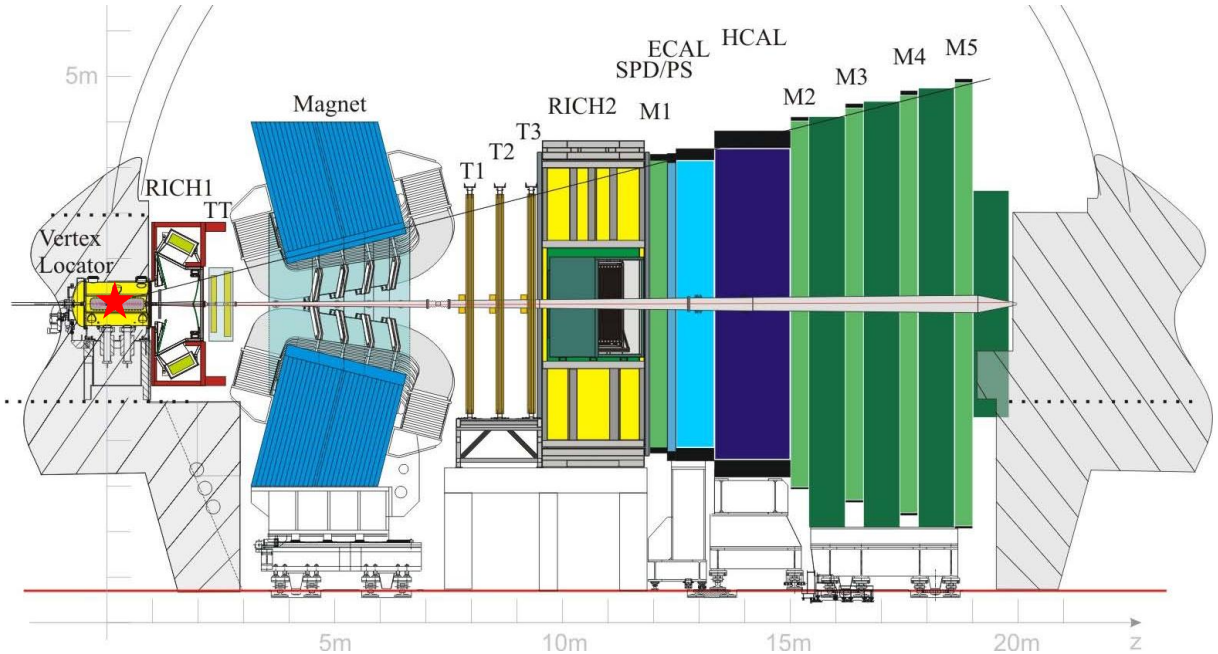
- General purpose of DPS measurements
  - ✓ Measure σ_{eff} :

    validate its universality or probe the dependence on process and energy
  - ✓ Test the pocket formula for differential cross-sections

The LHCb detector

- A single-arm forward region spectrometer covering $2 < \eta < 5$
- Excellent vertexing, tracking, PID
- RunI: $\mathcal{L}_{\text{int}} = 1\ \text{fb}^{-1}$ @ 7 TeV & $2\ \text{fb}^{-1}$ @ 8 TeV

pp interaction point



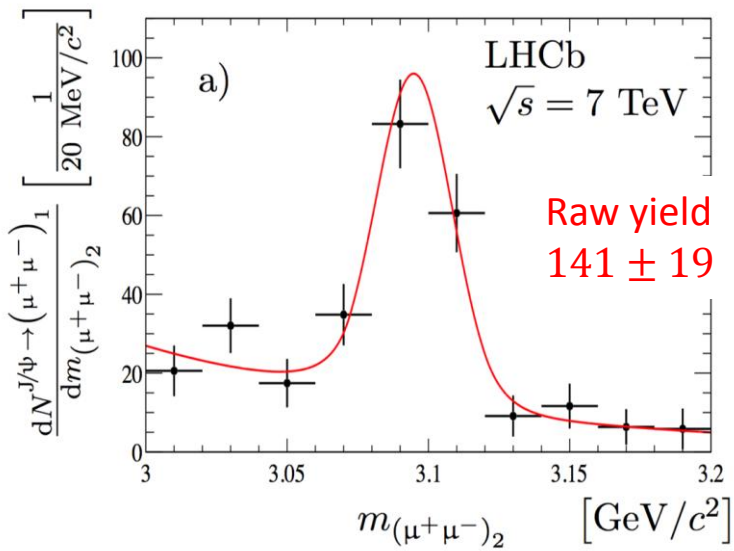
[JINST 3 (2008) S08005]

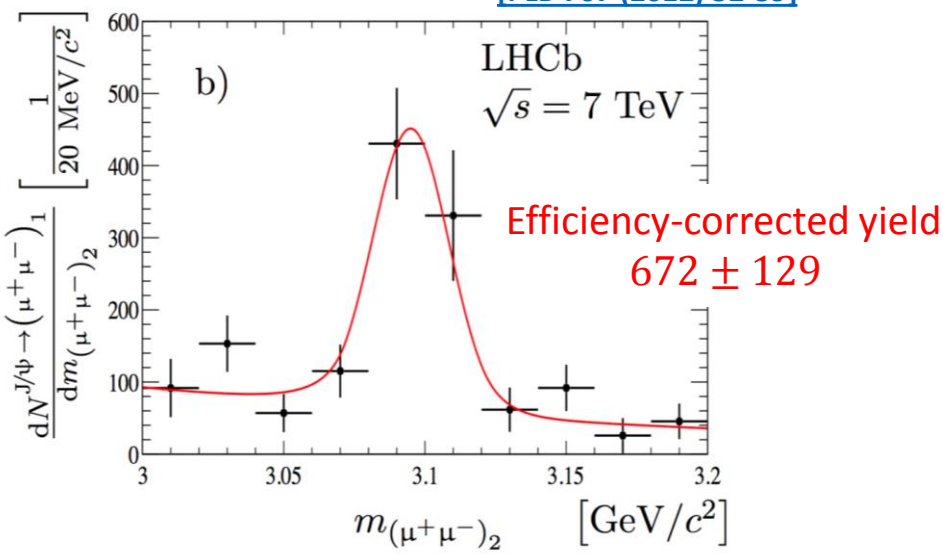
- ✓ **Vertex Locator:** $\sigma_{\text{PV},x/y} \sim 10\ \mu\text{m}$, $\sigma_{\text{PV},z} \sim 60\ \mu\text{m}$
- ✓ **Tracking (TT, T1-T3):** $\Delta p/p = 0.5 - 0.6\%$ for $5 < p < 100\ \text{GeV}/c$
- ✓ **RICHs:** $\varepsilon(K \to K) \sim 95\%$ @ misID rate $(\pi \to K) \sim 5\%$
- ✓ **Muon system (M1-M5):** $\varepsilon(\mu \to \mu) \sim 97\%$ @ misID rate $(\pi \to \mu) \sim 1 - 3\%$
- ✓ **ECAL:** $\sigma_E/E \sim 10\% / \sqrt{E} \otimes 1\%$ (E in GeV)
- ✓ **HCAL:** $\sigma_E/E \sim 70\% / \sqrt{E} \otimes 10\%$ (E in GeV)

$2 \times J/\psi$

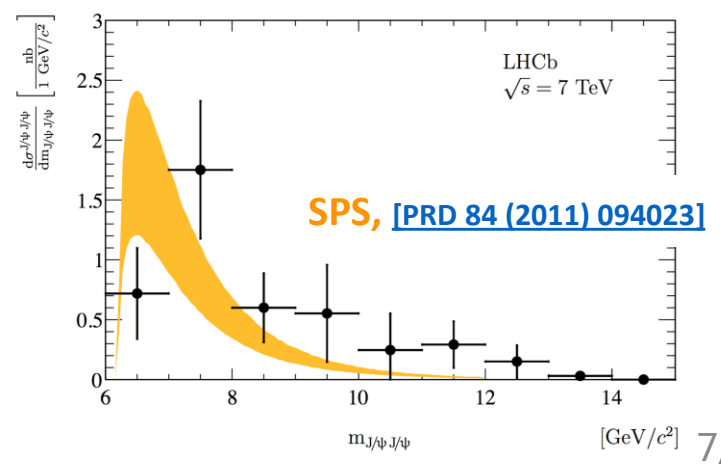
- Using 37.5 pb^{-1} data at $\sqrt{s} = 7$ TeV
- Fiducial region: $2 < y^{J/\psi} < 4.5$, $p_{\mathrm{T}}^{J/\psi} < 10$ GeV/c
- Observed with significance $> 6\sigma$

[PLB 707 (2012) 52-59]



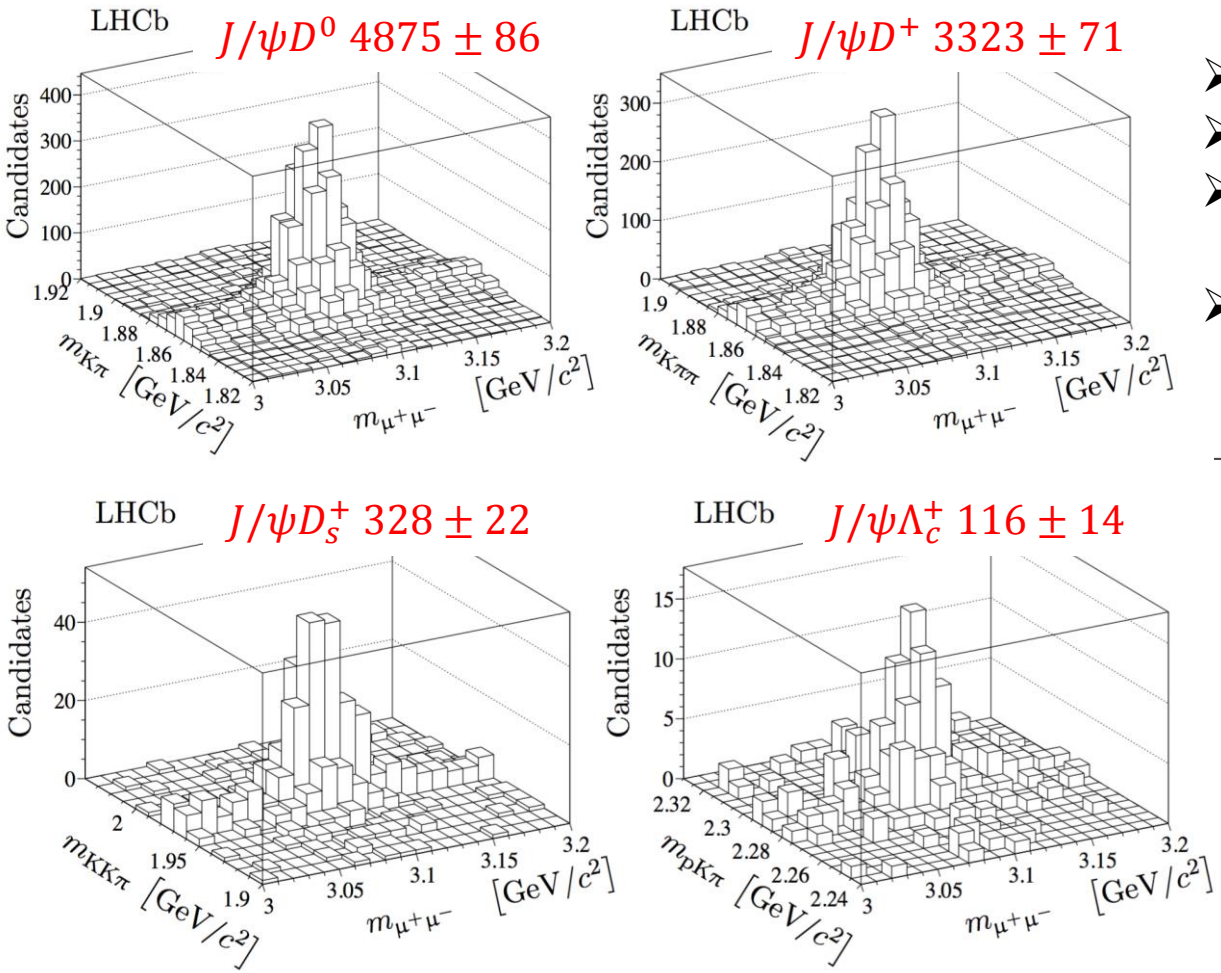


- $\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1$ nb
  - ✓ $\sigma_{\mathrm{SPS}} = 4.1 \pm 1.2$ nb
  - ✓ $\sigma_{\mathrm{DPS}} \approx 2.5$ nb
- Not enough events to disentangle SPS and DPS contributions;
- Update with $\times$ 80 statistics in progress



J/ψ + open charm

- Using 350 pb^{-1} data at $\sqrt{s} = 7$ TeV
- Fiducial region: $J/\psi \in 2 < y < 4,\ p_{\mathrm{T}} < 12\ \mathrm{GeV}/c$
  open charm $\in 2 < y < 4,\ 3 < p_{\mathrm{T}} < 12\ \mathrm{GeV}/c$



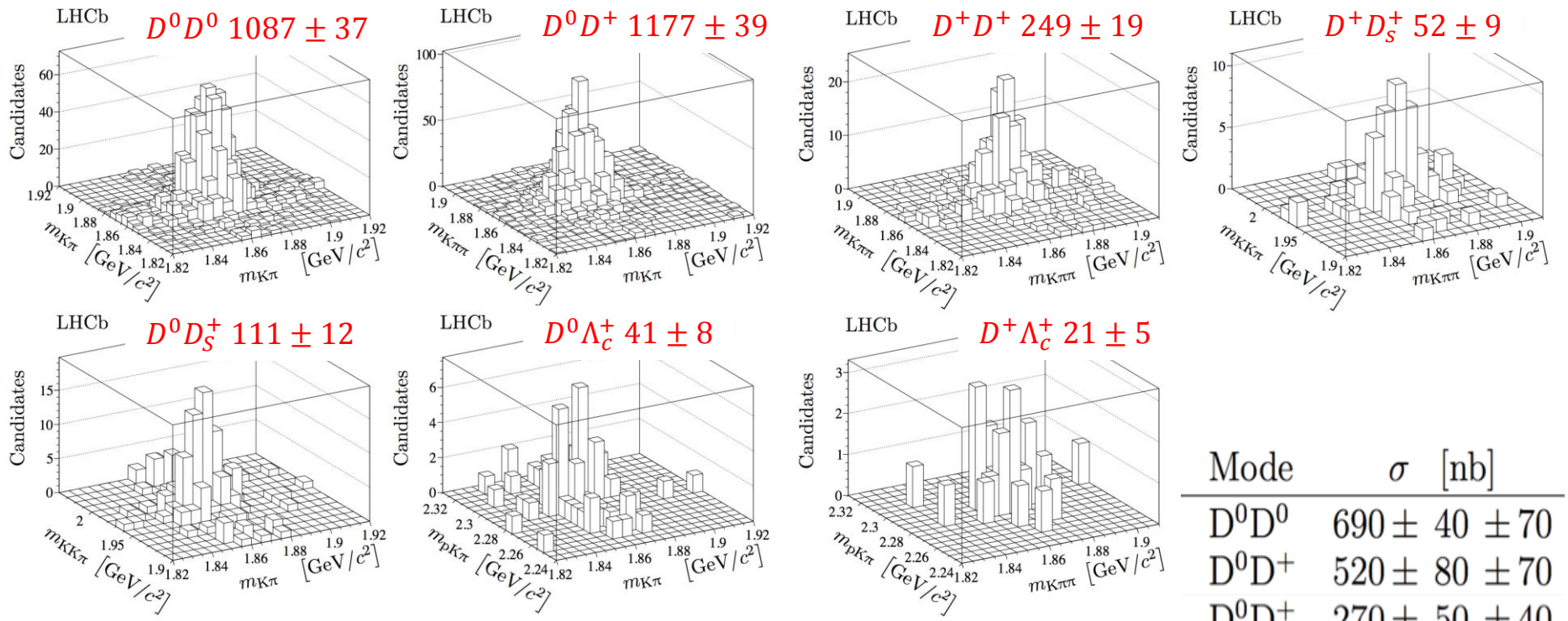
- Cut-based selection
- Signal significance $> 7\sigma$
- Efficiency estimated using simulation & data
- Cross-sections

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

[JHEP 06 (2012) 141]

2 × open charm

- Using 350 pb^{-1} data at $\sqrt{s} = 7$ TeV
- Fiducial region: open charm $\in 2 < y < 4,\ 3 < p_{\mathrm{T}} < 12\ \mathrm{GeV}/c$



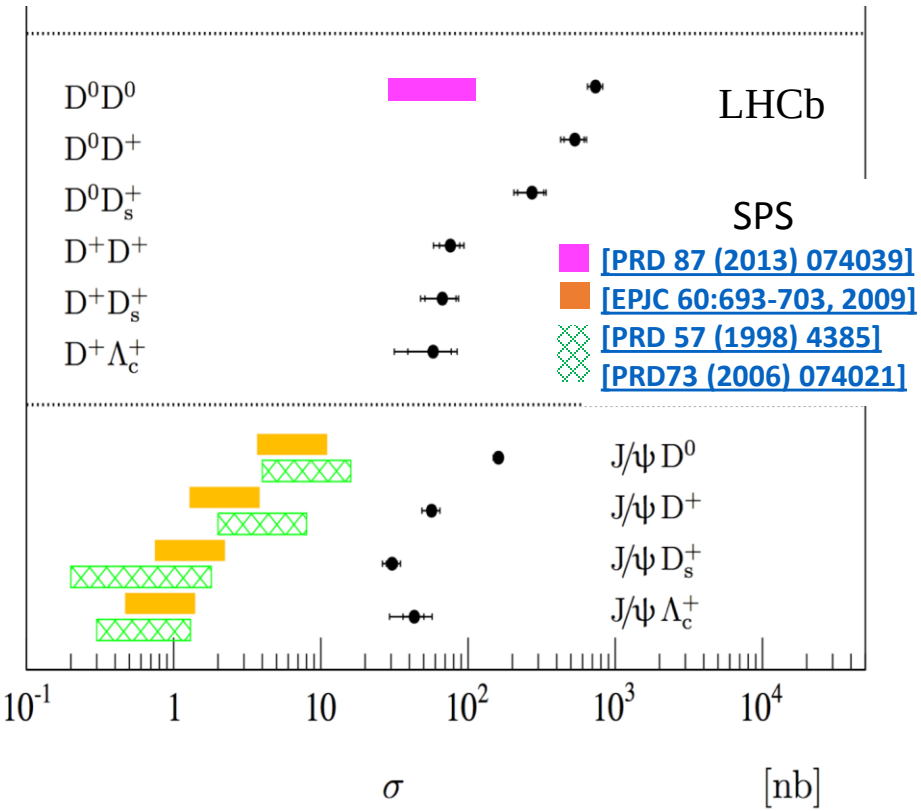
[JHEP 06 (2012) 141]

Mode	σ [nb]
D^0D^0	$690 \pm 40 \pm 70$
D^0D^+	$520 \pm 80 \pm 70$
$D^0D_s^+$	$270 \pm 50 \pm 40$
D^+D^+	$80 \pm 10 \pm 10$
$D^+D_s^+$	$70 \pm 15 \pm 10$
$D^+\Lambda_c^+$	$60 \pm 30 \pm 20$

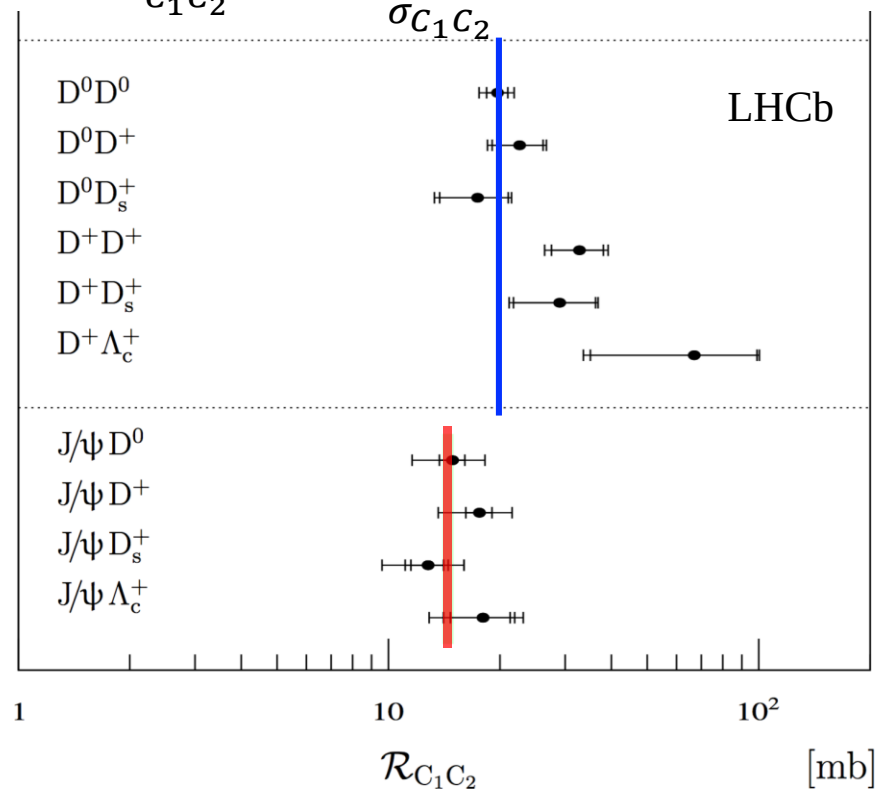
- Signal significance $\geq 5\sigma$ except for $D^+\Lambda_c^+$ (2.5σ)

J/ψ + open charm & 2 × open charm

- Production cross-sections



- $\mathcal{R}_{C_1C_2} \equiv \alpha' \frac{\sigma_{C_1} \times \sigma_{C_2}}{\sigma_{C_1C_2}}$ [JHEP 06 (2012) 141]



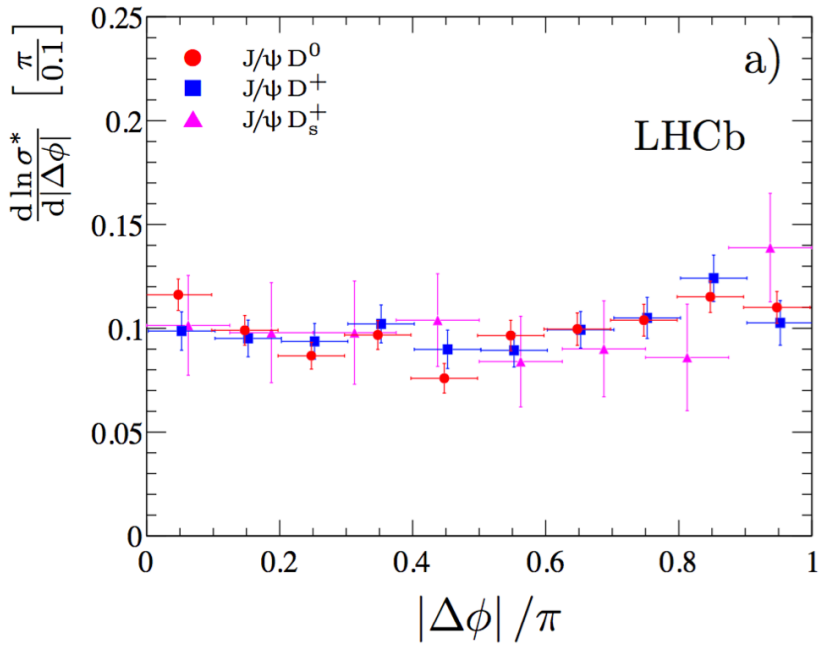
- ✓ Significantly larger than SPS predictions
- ✓ SPS fraction $1-5\%$
- ✓ Clean DPS!!!

- ✓ Interpreted as σ_{eff} in DPS [PRD 56 (1997) 3811]
- ✓ J/ψ + open charm: in good agreement with Tevatron measurement in multi-jet production $\sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb
- ✓ 2 × open charm: closer to 20 mb

- Differential distributions studied!

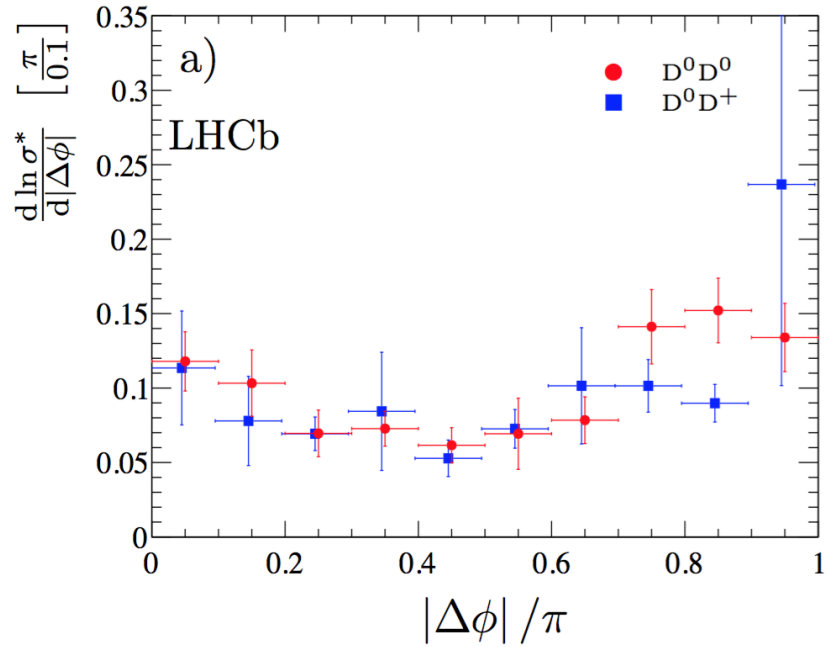
$\Delta\phi$ distributions

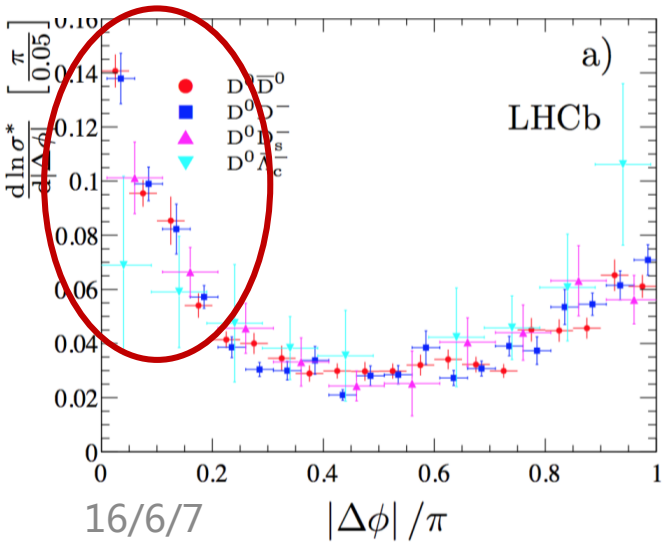
- J/ψ + open charm:



- 2 × open charm:

[JHEP 06 (2012) 141]





- $D\bar{D}$ as comparison:

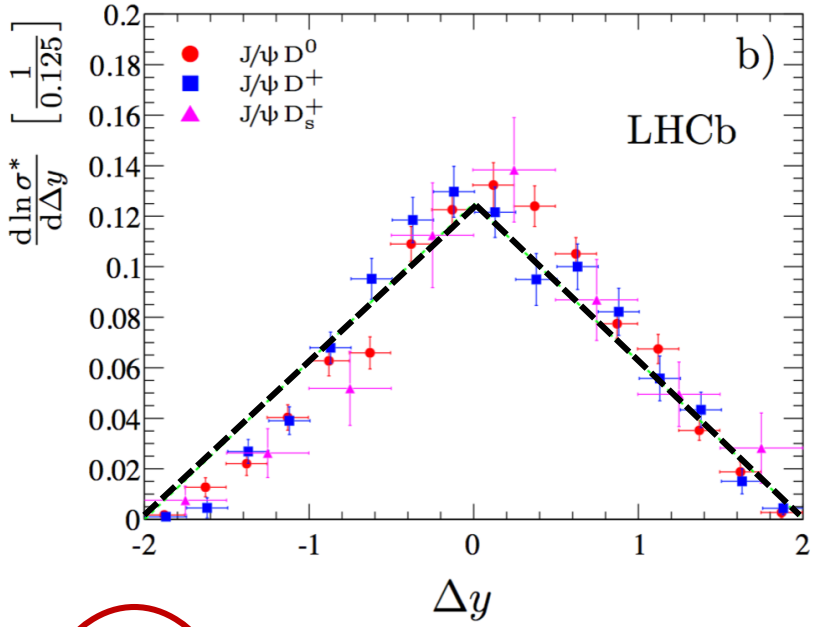
Enhancement at small $\Delta\phi$

- J/ψ + open charm &2 × open charm:

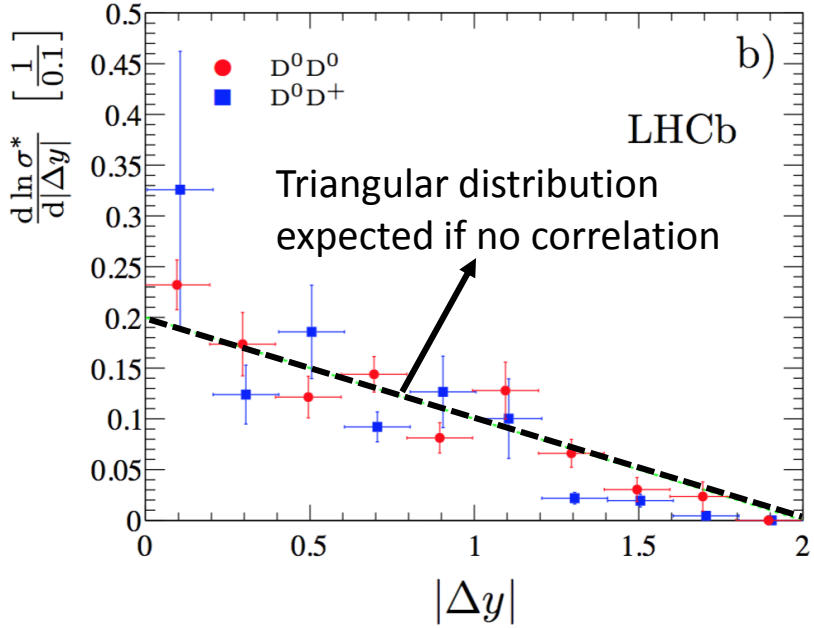
Reasonably consistent with a flat distribution

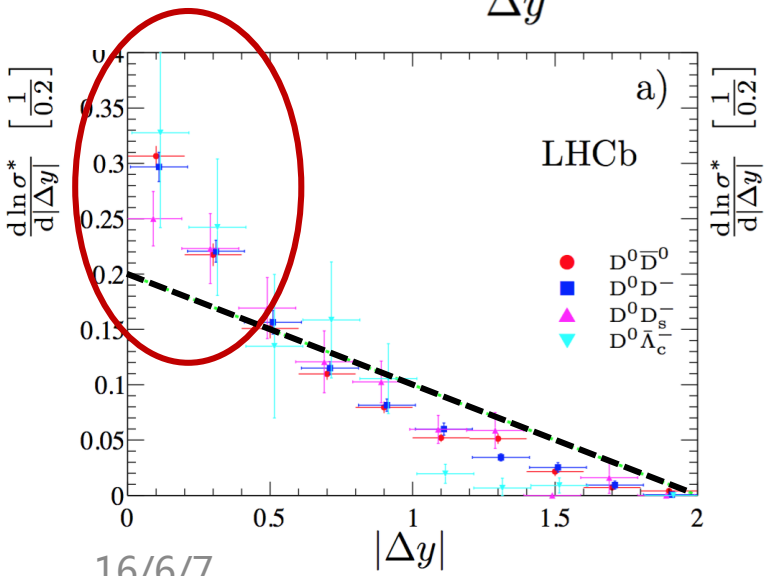
Δy distributions

- J/ψ + open charm:



- 2 × open charm: [JHEP 06 (2012) 141]





- $D\bar{D}$ as comparison:

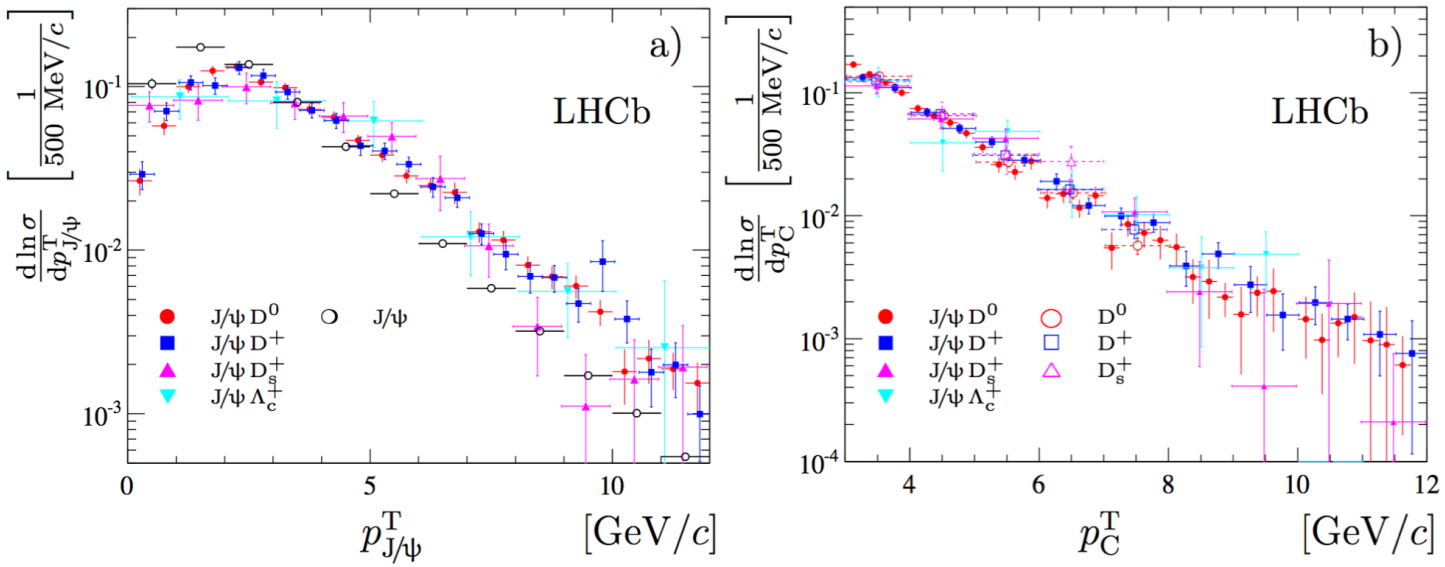
Enhancement at small Δy

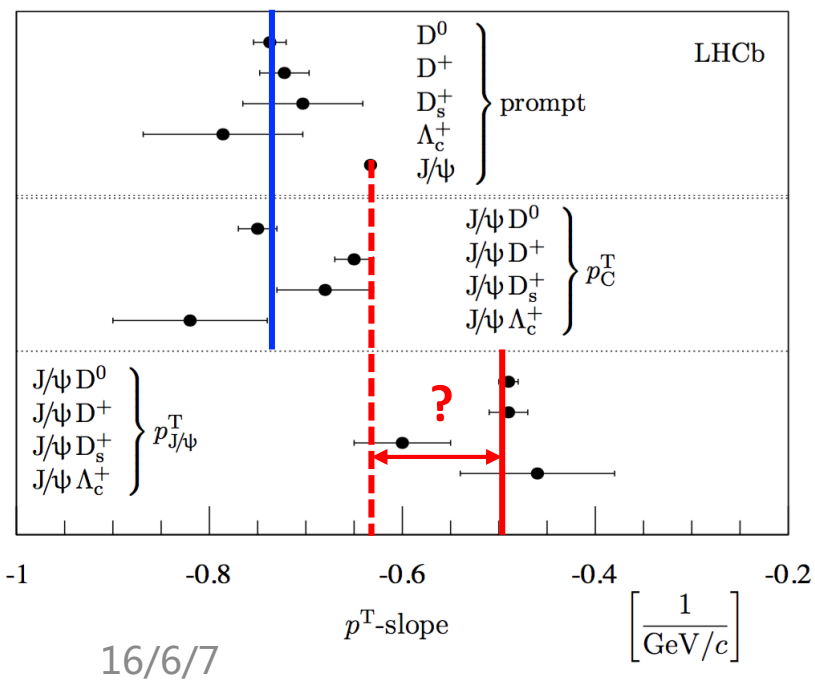
- J/ψ + open charm &2 × open charm:

Reasonably consistent with the triangular distribution

p_T spectra - J/ψ + open charm

[JHEP 06 (2012) 141]

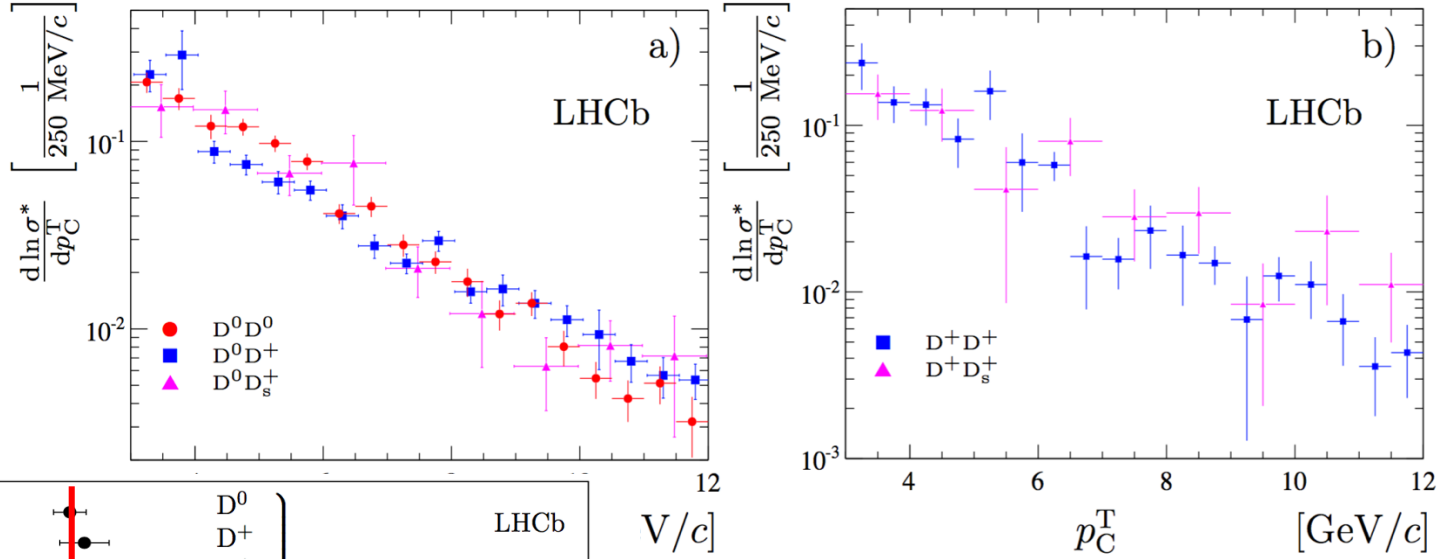


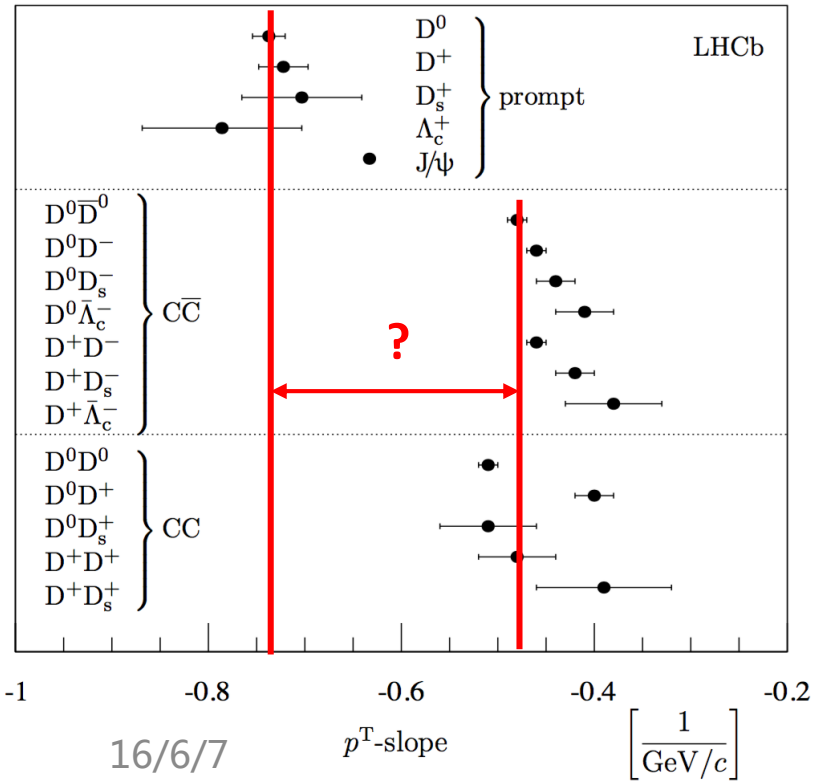


- Fit with exponential for $3 < p_T < 12$ GeV/c
- Open charm compatible with prompt charm
- J/ψ + open charm harder than prompt J/ψ?

p_T spectra – 2 × open charm

[JHEP 06 (2012) 141]

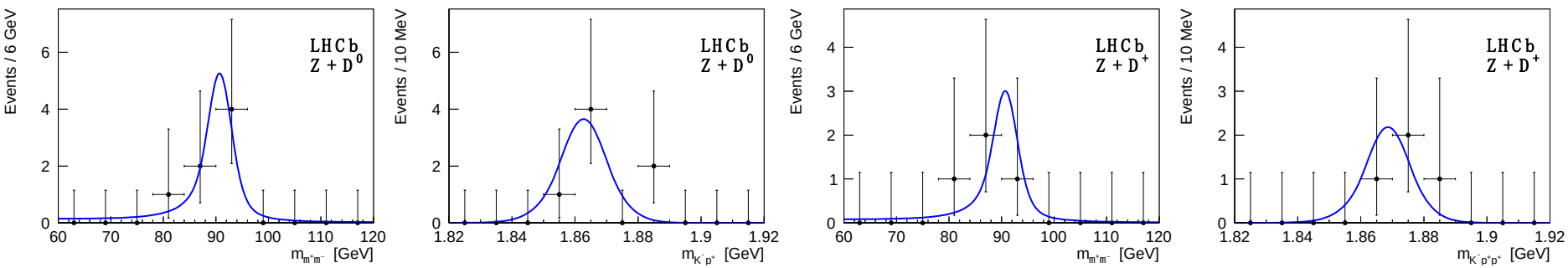




- Fit with exponential for $3 < p_T < 12\ \mathrm{GeV}/c$
- Similar to $D\bar{D}$ but significantly larger than prompt charm?

Z + open charm

- Using 1.0 fb^{-1} data at $\sqrt{s} = 7$ TeV
- Reconstructed with $Z \to \mu^+\mu^-$, $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$
- Fiducial region: $60 < m_{\mu^+\mu^-} < 120\ \mathrm{GeV}/c^2$, $p_\mathrm{T}(\mu^\pm) > 20\ \mathrm{GeV}/c$, $2 < \eta(\mu^\pm) < 4.5$, open charm $\in 2 < y < 4$, $2 < p_\mathrm{T} < 12\ \mathrm{GeV}/c$
- **7** $Z + D^0$ & **4** $Z + D^+$ candidates with combined significance of 5.1σ



[JHEP (2014) 091]

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	measured	SPS	DPS
$\mathrm{Z} + \mathrm{D}^0$	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12}_{-0.07}{}^{+0.11}_{-0.17} \pm 0.05$	$3.28^{+0.68}_{-0.58}$
$\mathrm{Z} + \mathrm{D}^+$	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05}_{-0.03}{}^{+0.05}_{-0.07} \pm 0.03$	$1.29^{+0.27}_{-0.23}$

In pb

$\sigma_\mathrm{eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb

[PRD 56 (1997) 3811]

- ✓ $Z + D^0$ prefers to have a DPS contribution
- ✓ $Z + D^+$ inconclusive due to large uncertainty
- ✓ More data needed!

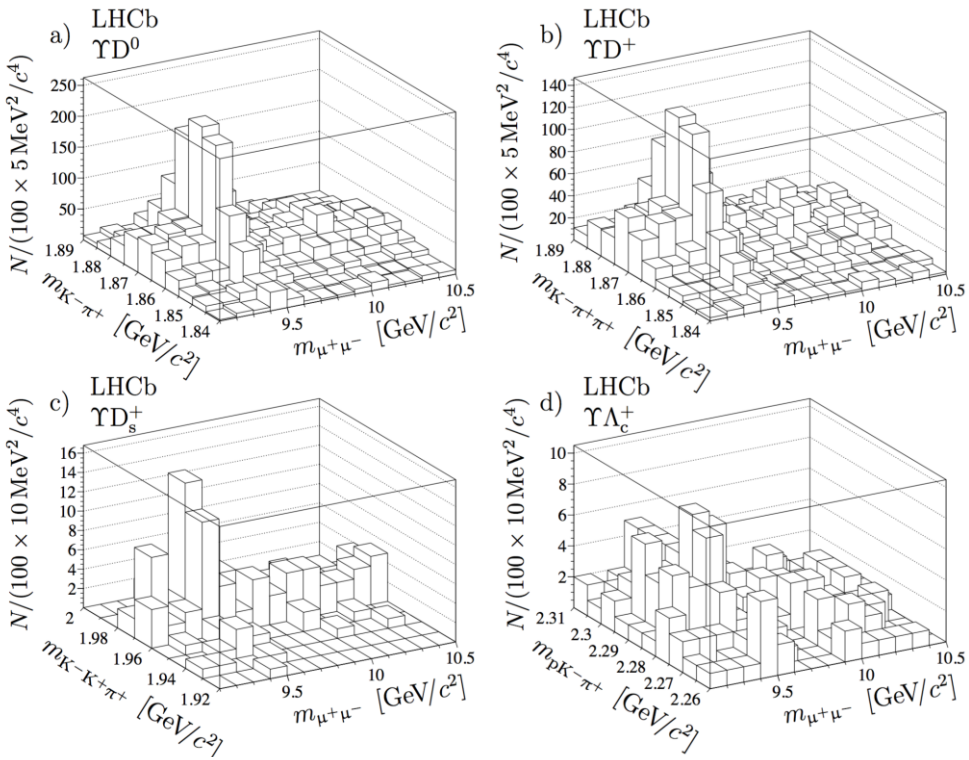
Υ + open charm

New

- Using 3 fb^{-1} data at $\sqrt{s} = 7\ \mathrm{TeV}$ & $8\ \mathrm{TeV}$
- Fiducial region: $\Upsilon \in 2.0 < y < 4.5,\ p_{\mathrm{T}} < 15\ \mathrm{GeV}/c$

  open charm $\in 2.0 < y < 4.5,\ 1 < p_{\mathrm{T}} < 20\ \mathrm{GeV}/c$

[arXiv:1510.05949]



	$\Upsilon(1S)$		$\Upsilon(2S)$	$\Upsilon(3S)$
D^0	980 ± 50	$> 5\sigma$	184 ± 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

- Results:

$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}} = 155 \pm 21\,(\mathrm{stat}) \pm 7\,(\mathrm{syst})\,\mathrm{pb},$$
$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}} = 82 \pm 19\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\,\mathrm{pb},$$
$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}} = 250 \pm 28\,(\mathrm{stat}) \pm 11\,(\mathrm{syst})\,\mathrm{pb},$$
$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}} = 80 \pm 16\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\,\mathrm{pb},$$

- DPS predictions:
  - ✓ With $\sigma_{\mathrm{eff}} = 14.5$ mb

$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}\Big|_{\mathrm{DPS}} = 206 \pm 17\,\mathrm{pb},$$
$$\mathscr{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}\Big|_{\mathrm{DPS}} = 86 \pm 10\,\mathrm{pb},$$

- Consistent!

More comparisons

$$R^{D^0/D^+}_{\sqrt{s}=7\,\mathrm{TeV}} = \frac{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}} = 1.9 \pm 0.5\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst})\,,$$

$$R^{D^0/D^+}_{\sqrt{s}=8\,\mathrm{TeV}} = \frac{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}}} = 3.1 \pm 0.7\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst})\,,$$

- ✓ Consistent with DPS prediction 2.41 ± 0.18

$$R^{\Upsilon(1S)c\bar{c}}_{\sqrt{s}=7\,\mathrm{TeV}} = \left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\mathrm{TeV}} = (7.7 \pm 1.0)\,\%\,,$$

$$R^{\Upsilon(1S)c\bar{c}}_{\sqrt{s}=8\,\mathrm{TeV}} = \left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\mathrm{TeV}} = (8.0 \pm 0.9)\,\%\,,$$

- ✓ Consistent with DPS prediction $\sim 10\%$
- ✓ Exceeds SPS expectation $(0.1 - 0.6)\%$

$$R^{\Upsilon(2S)/\Upsilon(1S)}_{D^0} = \mathscr{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}} = (13 \pm 5)\%\,,$$

$$R^{\Upsilon(2S)/\Upsilon(1S)}_{D^0} = \mathscr{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}}} = (20 \pm 4)\%\,,$$

$$R^{\Upsilon(2S)/\Upsilon(1S)}_{D^+} = \mathscr{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}} = (22 \pm 7)\%\,,$$

$$R^{\Upsilon(2S)/\Upsilon(1S)}_{D^+} = \mathscr{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}}} = (22 \pm 6)\%\,,$$

- ✓ Compatible with DPS prediction 0.249 ± 0.033

- ✓ Kinematic distributions of Υ + open charm also show good agreement with DPS

Neglecting SPS contribution:

$\sigma_{\mathrm{eff}} = 18.0 \pm 1.3(\mathrm{stat}) \pm 1.2(\mathrm{syst})$ mb

- ✓ Consistent with previous measurements

[arXiv:1510.05949]

Summary & prospects

- DPS is explored at LHCb through several processes
- Relevant DPS contribution is observed in
  - ✓ $J/\psi + \text{open charm}$ & $2 \times \text{open charm}$
  - ✓ $\Upsilon + \text{open charm}$

- Prospects
  - ✓ Still a lot to be analyzed with RunI data
    - Update existing measurements with more data
    - New channels to look into: $\Upsilon + J/\psi$, $2 \times \Upsilon$ etc.
  - ✓ RunII is in progress
    - New energy scale: $\sqrt{s} = 13\ \text{TeV}$
    - More statistics expected: $\mathcal{L}_{\text{int}} = 5\ \text{fb}^{-1}$
    - Trigger improved
    - Possibility for triple-parton scattering?

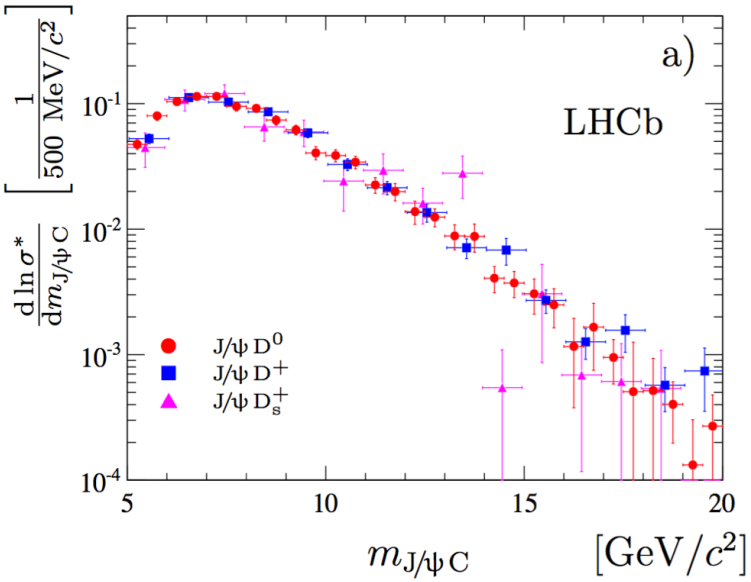
Thank you!

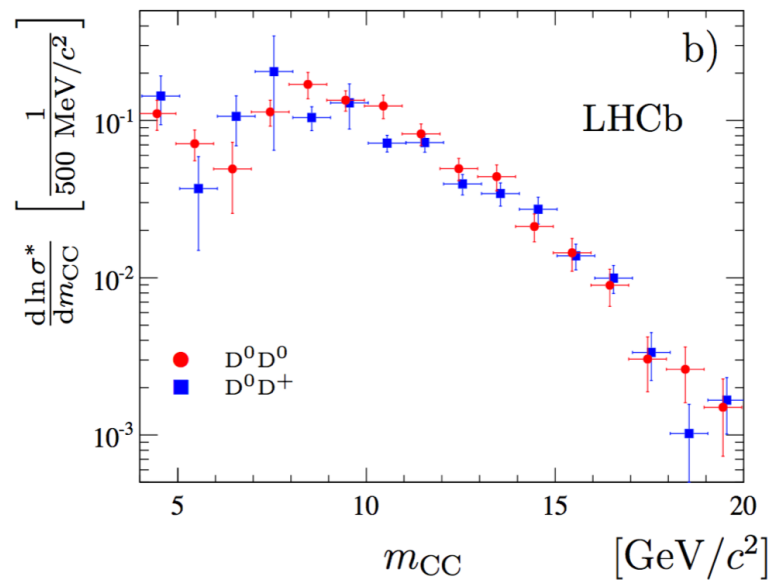
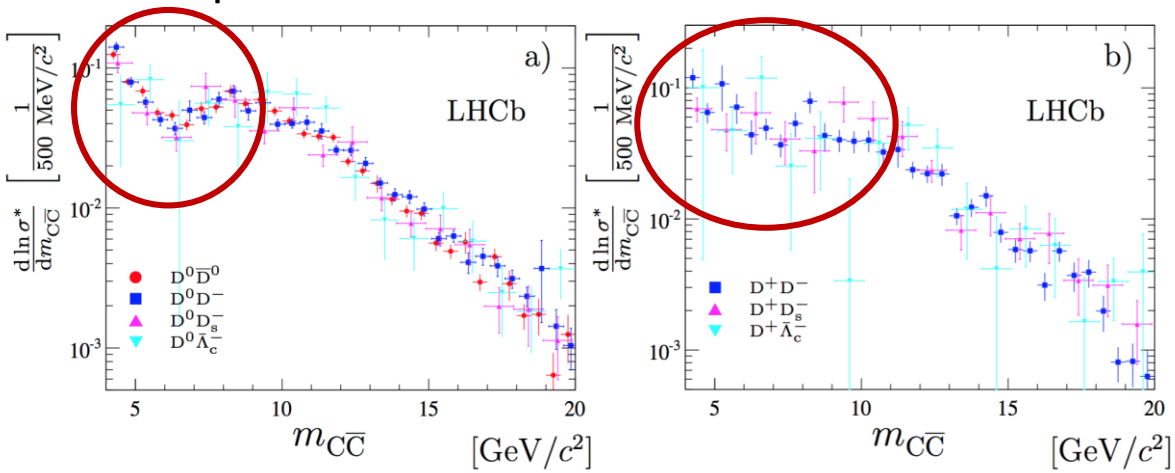
Back up

Mass spectra

- J/ψ + open charm:
- $2 \times$ open charm:

[JHEP 06 (2012) 141]





- $D\bar{D}$ as comparison: