Workshop on Multiple Partonic Interactions at the LHC
(Prague, Czech Republic, 18-22 of November 2019)

Double parton scattering at LHCb

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on behalf of the LHCb collaboration

Outline

- Double parton scattering
- LHCb experiment
- DPS measurements
  - Involving open charm: DD, J/ψ+D, Υ+D
  - Double J/ψ production
  - Associated production of Z-boson with charm

Double parton scattering

Factorization approach:

$$\sigma_{\mathrm{DPS}} = \frac{1}{\boxed{S}} \frac{\boxed{\sigma_A \sigma_B}}{\boxed{\sigma_{\mathrm{eff}}}}$$

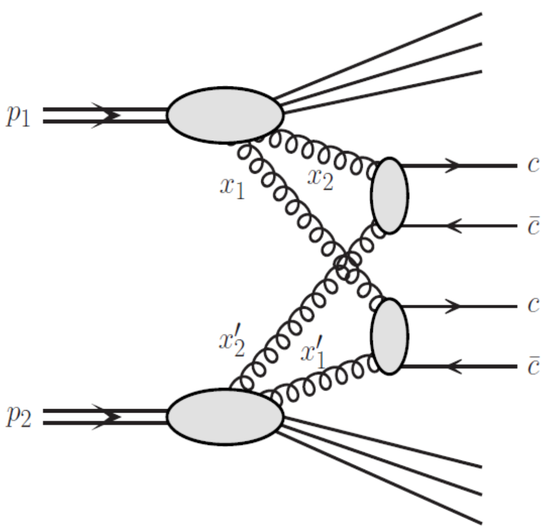
Individual cross-sections

Symmetry factor

Effective cross-section

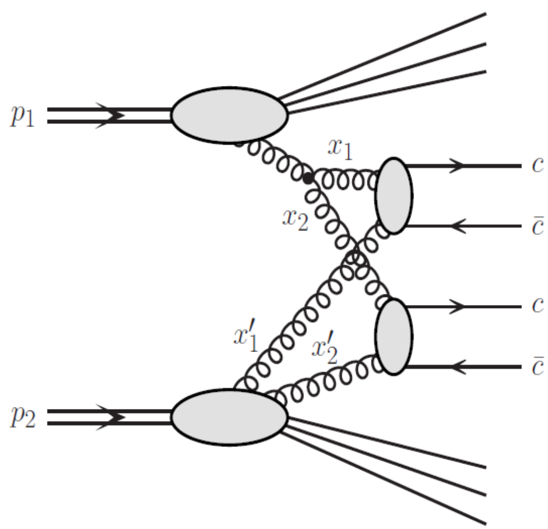
- Process- and energy- independent
- Expected to be of the order of inelastic scattering
- Can't be calculated from the first principles
- Can vary for some kinematical regions

Independent scattering of two pairs of partons



$2\otimes2$

Parton splits at hard scales to create two independent SPS



$1\otimes2$

[Phys. Rev. D90 (2014), no. 5 054017]

Test the effective cross-section (in)dependence

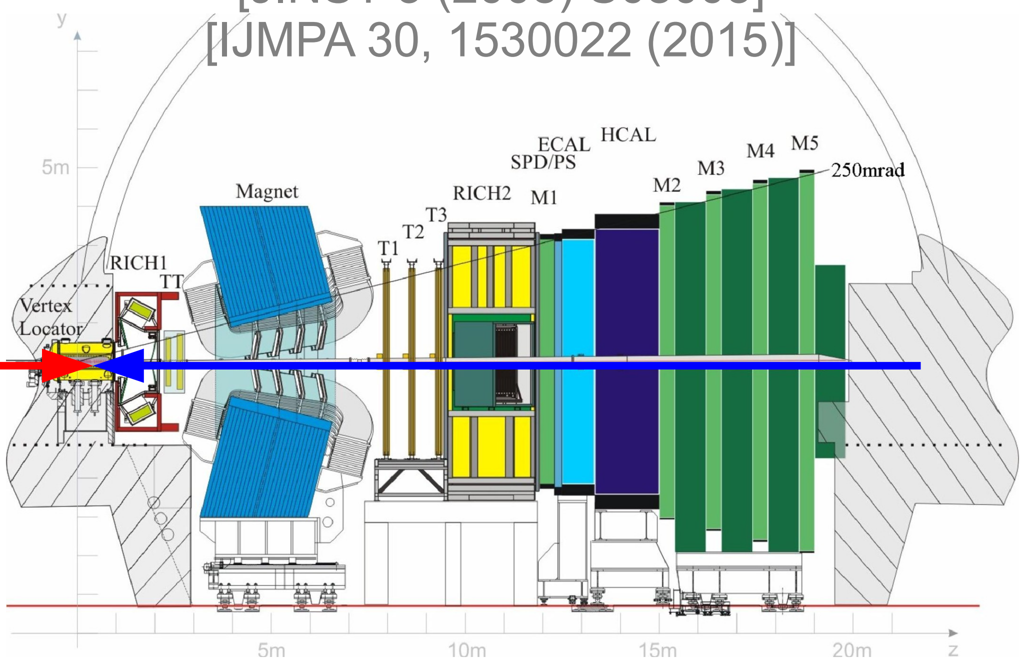
Probing parton-parton correlation

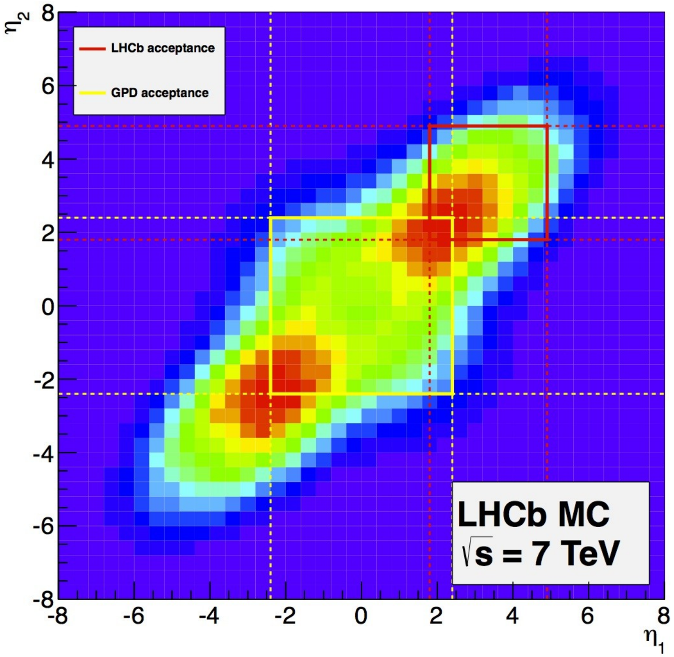
Test $1\otimes2$ contribution

Important background for NP search

The LHCb experiment

[JINST 3 (2008) S08005]
[IJMPA 30, 1530022 (2015)]





Fully instrumented rapidity range 2 < η < 5: ~40% of heavy quarks produced hit the detector acceptance

VELO: Decay time resolution ~45fs
Impact parameter resolution: (15 +29/pT[GeV]) μm

Relative track momentum resolution: 0.5% at low momentum 1.0% at 200 GeV/c

Particle identification:
Kaon ID ~95 % for ~ 5 % π→K mis-id probability
Muon ID ~97 % for 1-3 % π→μ mis-id probability

Muon system: ~90% trigger efficiency for dimuon channels

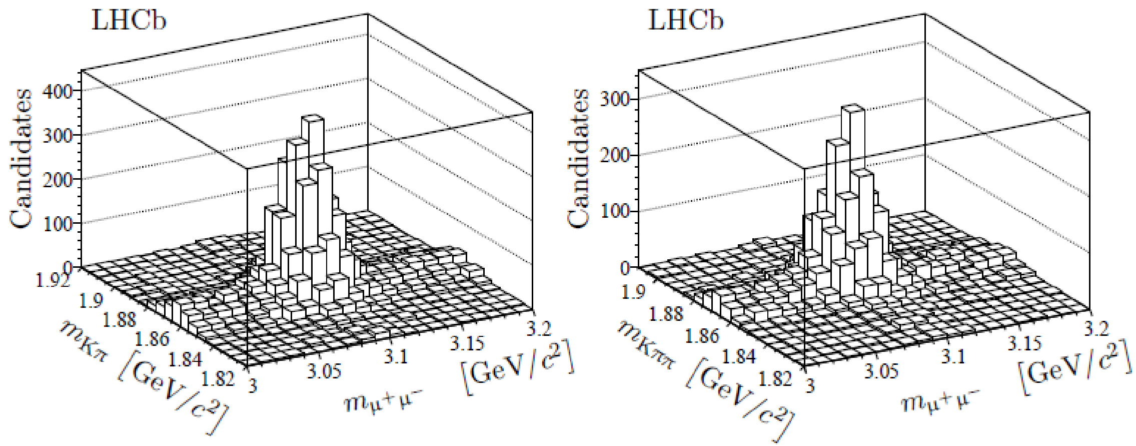
Studies with D/Λ_c and J/ψ

[JHEP06 (2012) 141] [JHEP03 (2014) 108]

0.355 fb^{-1} @7TeV

Reconstructed in the modes:

- $J/\psi \to \mu^+\mu^-$
- $D^0 \to K^-\pi^+$
- $D^+ \to K^-\pi^+\pi^+$
- $D^+_s \to K^-K^+\pi^+$
- $\Lambda^+_c \to pK^-\pi^+$

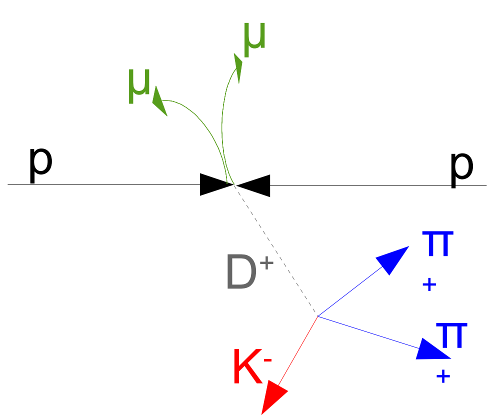


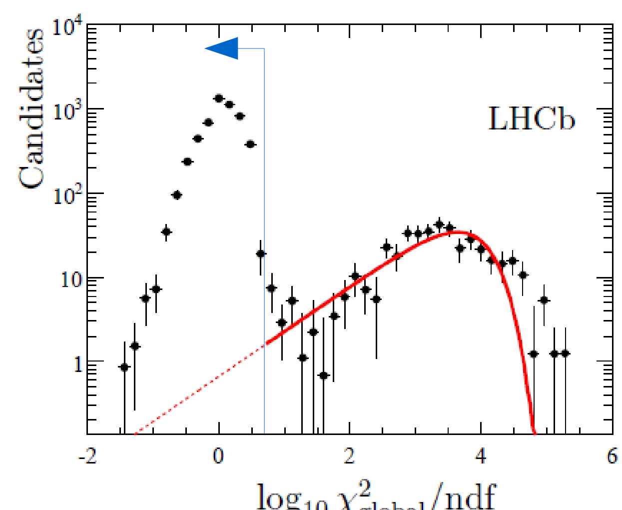
Event yields determined from 2D fits to the data

Only few percent contamination from the feed-down backgrounds

Mode	Yield
$J/\psi D^0$	4875 ± 86
$J/\psi D^+$	3323 ± 71
$J/\psi D^+_s$	328 ± 22
$J/\psi \Lambda^+_c$	116 ± 14
D^0D^0	1087 ± 37
D^0D^+	1177 ± 39
$D^0D^+_s$	111 ± 12
$D^0\Lambda^+_c$	41 ± 8
D^+D^+	249 ± 19
$D^+D^+_s$	52 ± 9
$D^+\Lambda^+_c$	21 ± 5

Kinematical fit to the whole decay chain to remove pile-up





Studies with D/Λ_c and J/ψ

[JHEP06 (2012) 141] [JHEP03 (2014) 108]

Efficiency-corrected event yield

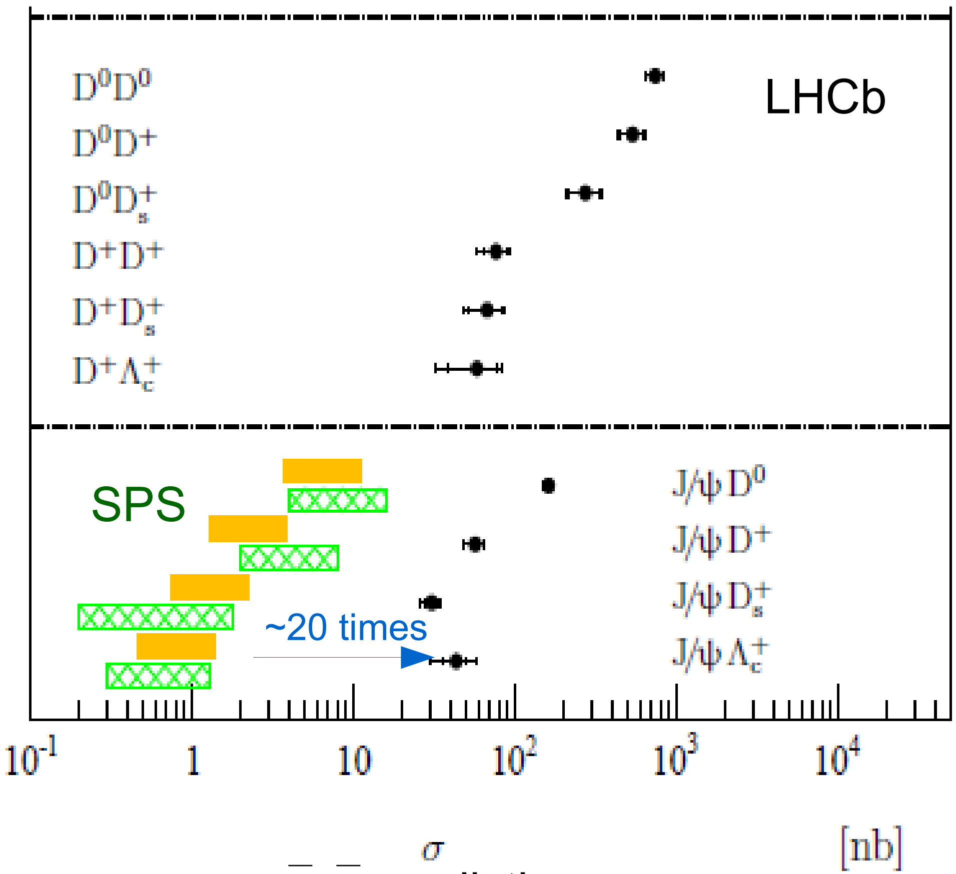
$$\sigma = \frac{\boxed{N^{\mathrm{corr}}}}{\boxed{\mathcal{L}} \times \boxed{\mathcal{B}_1 \times \mathcal{B}_2} \times \varepsilon^{\mathrm{GEC}}}$$

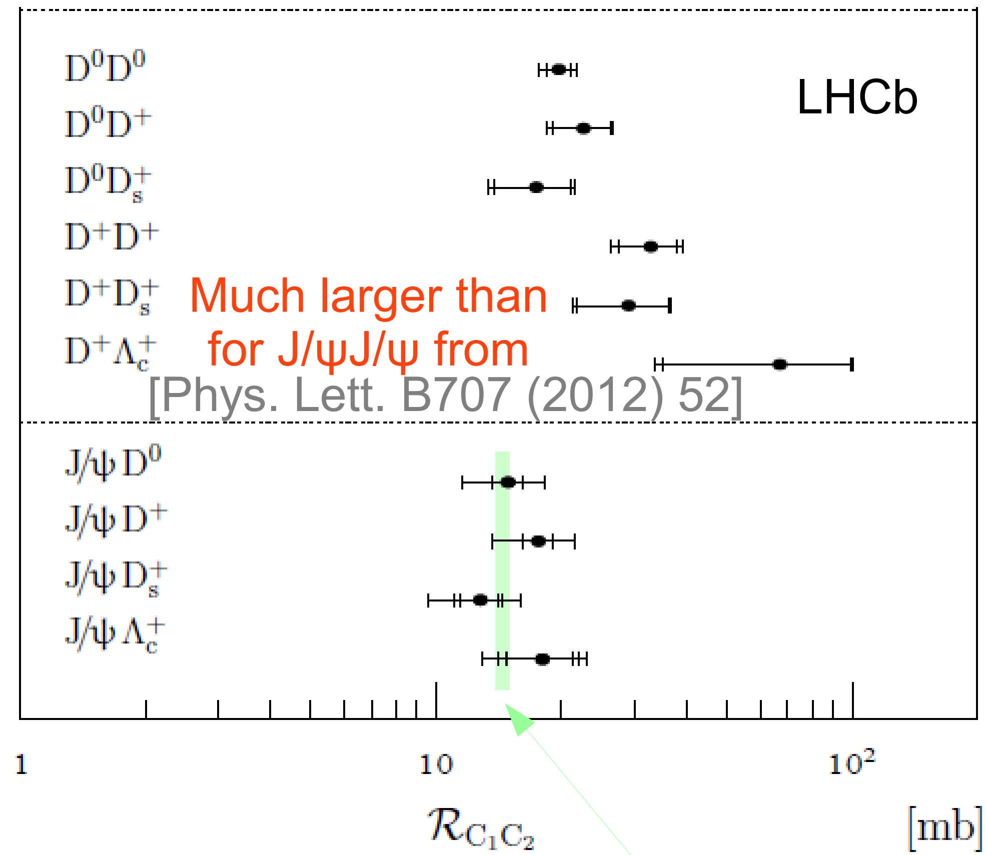
Integrated lumi

Branching fractions

$$\mathcal{R}_{C_1C_2} \equiv \alpha' \frac{\sigma_{C_1} \times \sigma_{C_2}}{\sigma_{C_1C_2}}$$

~ σ_{eff} assuming DPS-only





gg → $c\bar{c}c\bar{c}$ predictions

[Phys. Rev. D57 (1998) 4385]
[Phys. Rev. D73 (2006) 074021]
[Eur. Phys. J. C61 (2009) 693]

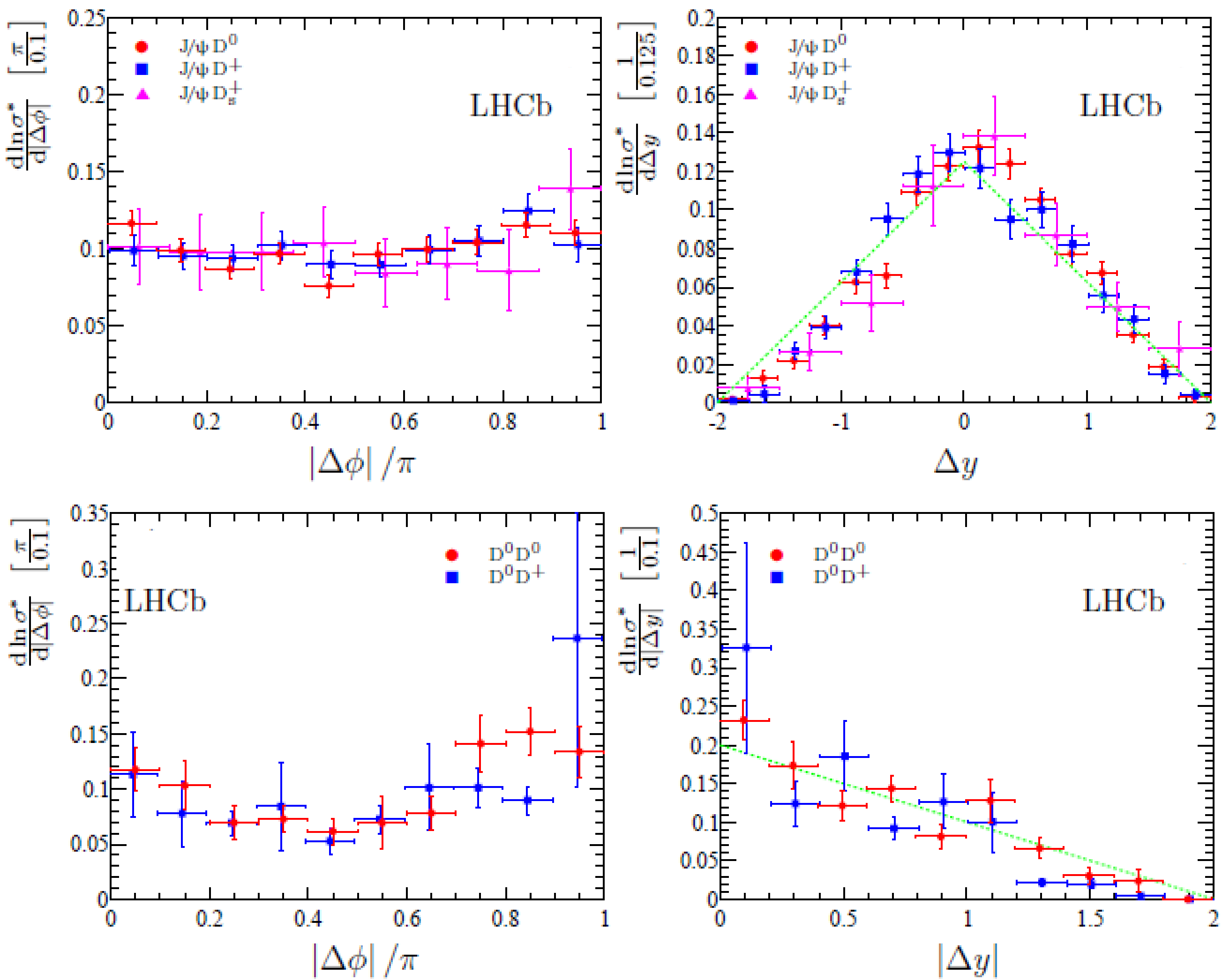
DPS expectations using σ_{eff} from Tevatron

Studies with D/Λ_c and J/ψ

[JHEP06 (2012) 141] [JHEP03 (2014) 108]

Testing $|\Delta\varphi|$ - azimuthal angle
$|\Delta y|$ - rapidity difference
m_{CC} — invariant mass of the pair

Consistent with flat distribution



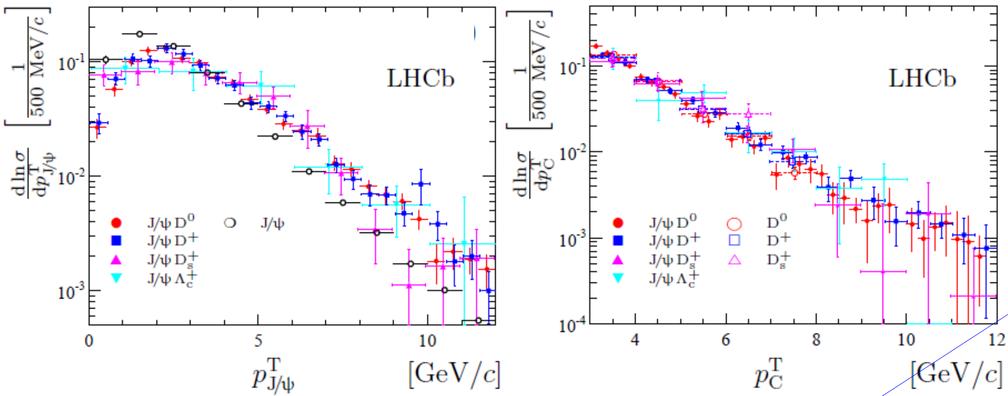
Consistent with uncorrelated production

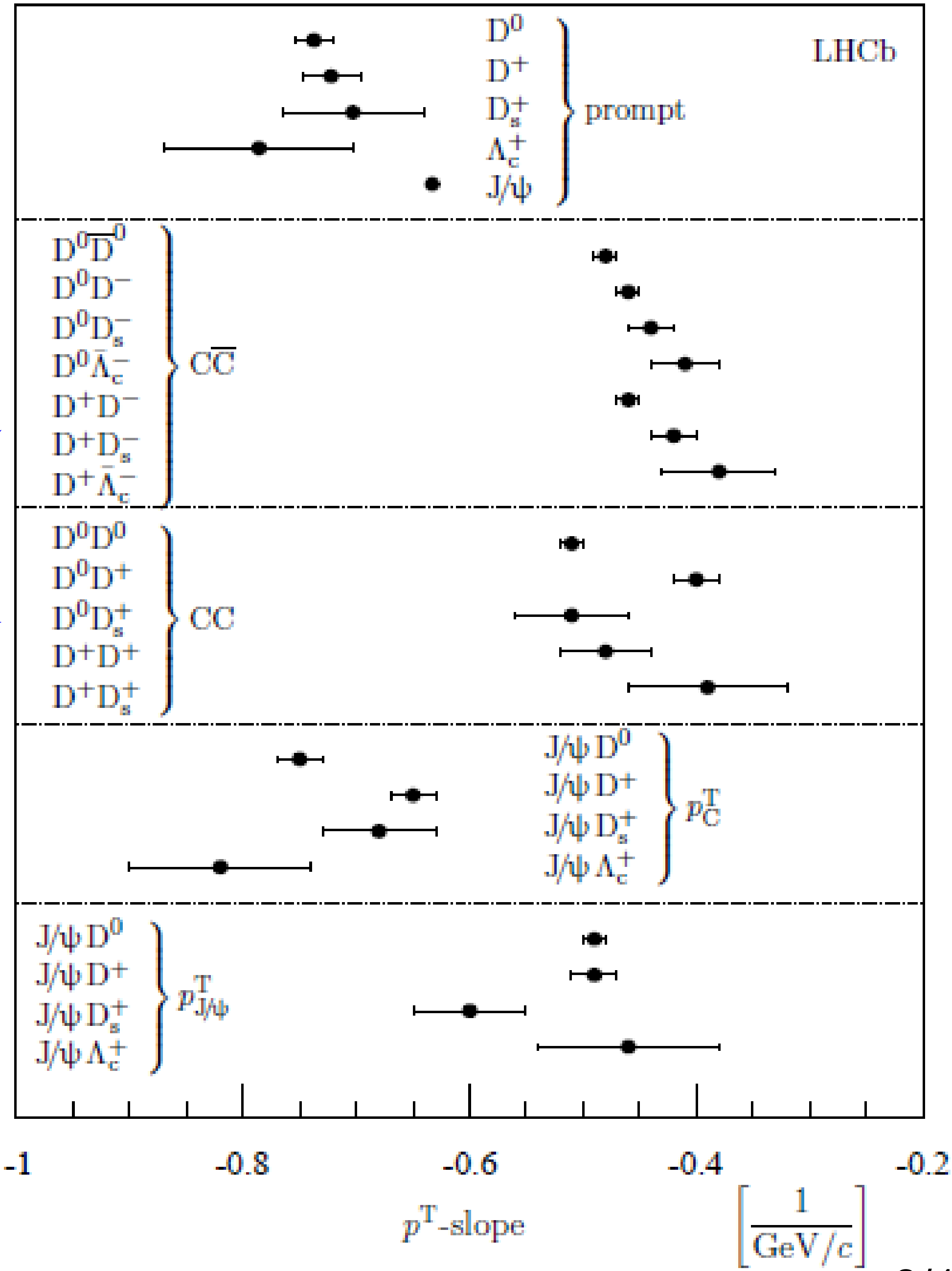
Studies with D/Λ_c and J/ψ

[JHEP06 (2012) 141] [JHEP03 (2014) 108]

Kinematical properties

Transverse momenta fit with an exponential function





Harder than for prompt production

Could indicate the gluon-splitting contribution

Comparable to the prompt production

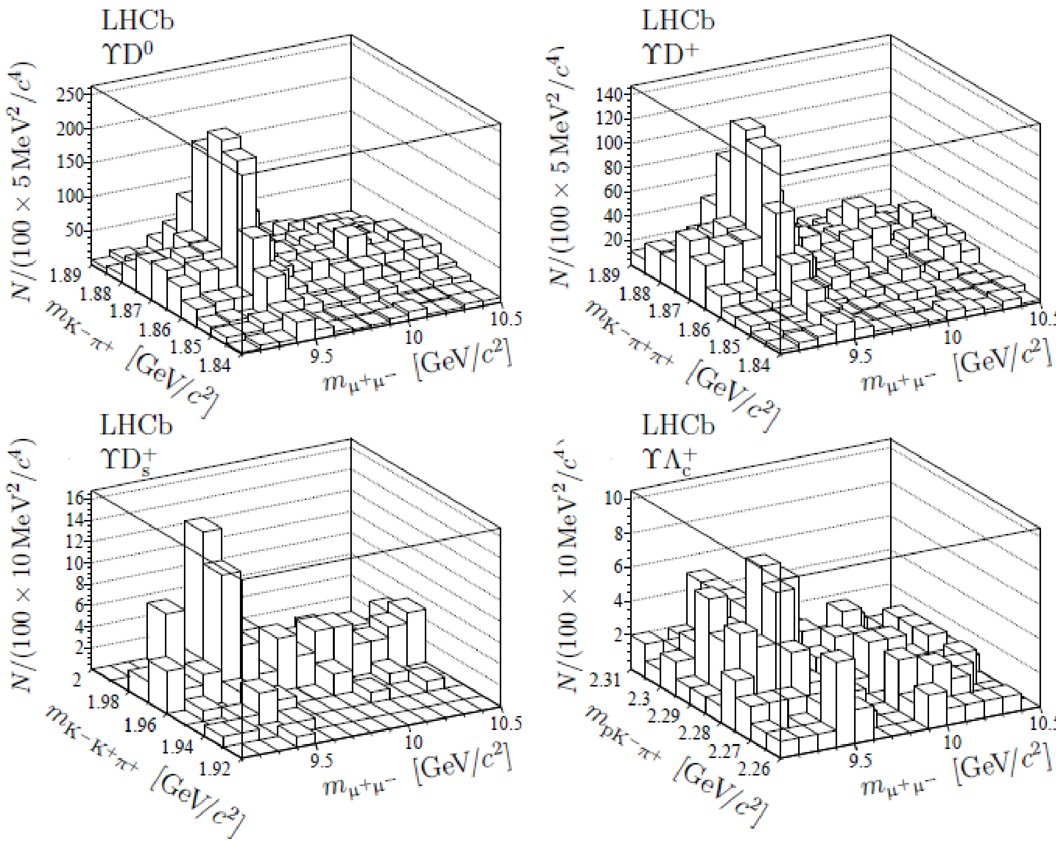
Harder than for prompt production

Open charm with Υ

[JHEP 07 (2016) 052]

Reconstructed in the modes:

$\Upsilon(nS) \to \mu^+\mu^-$
$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+$
$D^+_s \to K^-K^+\pi^+$
$\Lambda^+_c \to pK^-\pi^+$



3 fb^{-1}
@7 and 8TeV

$p_T^{\Upsilon} < 15$ GeV/c
$1 < p_T^{C} < 20$ GeV/c
$2 < y^{\Upsilon} < 4.5$
$2 < y^{C} < 4.5$

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
D^0	980 ± 50	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

5 modes with significance above 5σ
With pile-up contribution below 1.5%

Open charm with Υ

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon C} = \frac{1}{\mathcal{L} \times \mathcal{B}_C} N^{\Upsilon C}_{\text{corr}},$$ [JHEP 07 (2016) 052]

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

Exceed the SPS predictions
In good agreement with the DPS

$B_{\mu\mu} \times \sigma^{Y(1S)D0}|_{\sqrt{s}\,=\,7\text{TeV}} = 206 \pm 17\text{pb}$

$B_{\mu\mu} \times \sigma^{Y(1S)D+}|_{\sqrt{s}\,=\,7\text{TeV}} = 86 \pm 10\text{pb}$

In good agreement with the DPS expectation 2.41 ± 0.18
[Nucl. Phys. B871(2013)1]
[JHEP 11 (2015) 103]

$$\begin{aligned}
R^{D^0/D^+}_{\sqrt{s}=7\,\text{TeV}} &= \frac{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\text{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\text{TeV}}} = 1.9 \pm 0.5\,(\text{stat}) \pm 0.1\,(\text{syst}) \\
R^{D^0/D^+}_{\sqrt{s}=8\,\text{TeV}} &= \frac{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\text{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\text{TeV}}} = 3.1 \pm 0.7\,(\text{stat}) \pm 0.1\,(\text{syst})
\end{aligned}$$

$$\begin{aligned}
R^{\Upsilon(1S)c\bar{c}}_{\sqrt{s}=7\,\text{TeV}} &= \left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\text{TeV}} = (7.7 \pm 1.0)\,\% \\
R^{\Upsilon(1S)c\bar{c}}_{\sqrt{s}=8\,\text{TeV}} &= \left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\text{TeV}} = (8.0 \pm 0.9)\,\%
\end{aligned}$$

Far beyond the SPS predictions
(0.2-0.6)% for NRQCD [IJMP A30 (2015) 1550125]
(0.1-0.3)% for k_T-factorization [Phys. Rev. D73 (2006) 074021]

~ 10% for DPS expectation with $\sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}\,\text{mb}$

Consistent with the DPS expectation of ~25%

$$\begin{aligned}
R^{\Upsilon(2S)/\Upsilon(1S)}_{D^+} &= \mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=7\,\text{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\text{TeV}}} = (22 \pm 7)\% \\
R^{\Upsilon(2S)/\Upsilon(1S)}_{D^+} &= \mathcal{B}_{2/1} \times \frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=8\,\text{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\text{TeV}}} = (22 \pm 6)\%
\end{aligned}$$

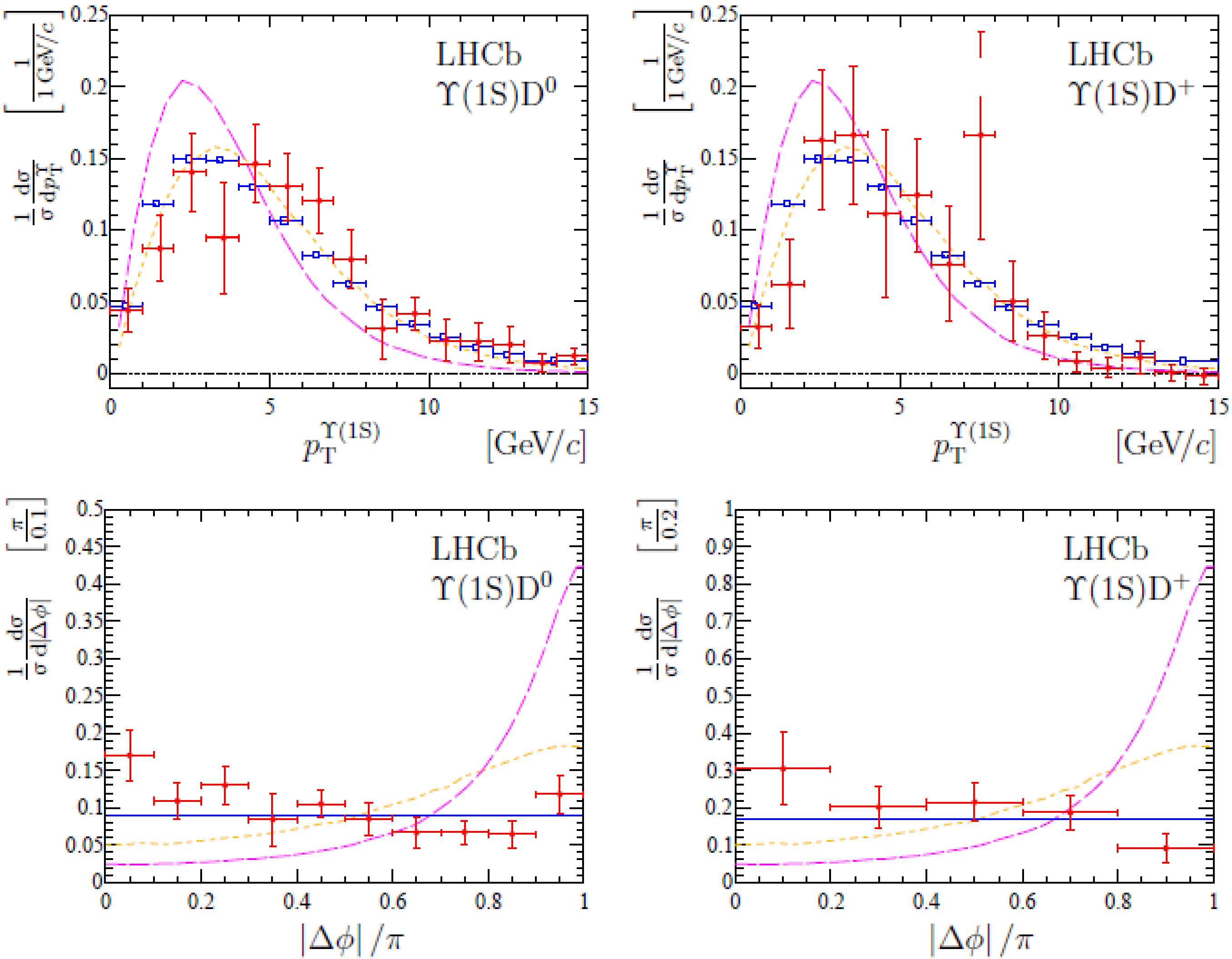
$$\boxed{\sigma_{\text{eff}}|_{\Upsilon(1S)D^{0,+}} = 18.0 \pm 1.3\,(\text{stat}) \pm 1.2\,(\text{syst}) = 18.0 \pm 1.8\,\text{mb}\,.}$$

Open charm with Υ

Testing kinematic properties:

[JHEP 07 (2016) 052]

- transverse momenta of Υ, D and ΥD system
- rapidities of Υ, D and the ΥD system
- |Δy| — rapidity difference between Υ- and D-meson
- |Δφ| — difference in the azimuthal angle
- $m_{\Upsilon D}$ — invariant mass of the pair



Data

DPS
[Nucl. Phys. B871(2013)1]
[JHEP 11 (2015) 103]

k_T-factorization

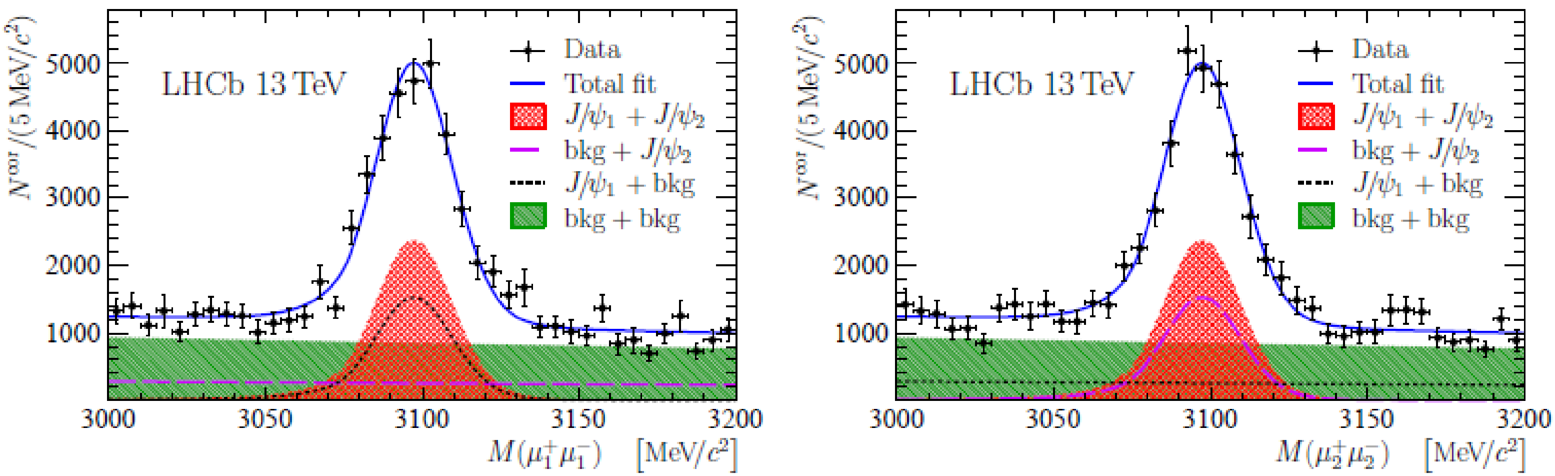
Collinear approximation

Kinematic distributons are very well described under the DPS assumption

Double J/ψ

[JHEP 06 (2017) 047]

Reconstructed as $J/\psi \to \mu^+\mu^-$



0.279 fb^{-1} @13TeV

$p_T^{J/\psi} < 10$ GeV/c
$2 < y^{J/\psi} < 4.5$

Efficiency-corrected signal yield determined from the 2D fit $(15.8 \pm 1.1) \times 10^3$ candidates.

Feed-down contribution 4.5% (determined from simulation)

	$\sigma(J/\psi\, J/\psi)$ [nb]		
	no p_T cut	$p_T > 1\,\mathrm{GeV}/c$	$p_T > 3\,\mathrm{GeV}/c$
LO CS [92]	$1.3 \pm 0.1^{+3.2}_{-0.1}$	—	—
LO CO [95, 96]	$0.45 \pm 0.09^{+1.42+0.25}_{-0.36-0.34}$	—	—
LO k_T [102]	$6.3^{+3.8+3.8}_{-1.6-2.6}$	$5.7^{+3.4+3.2}_{-1.5-2.1}$	$2.7^{+1.6+1.6}_{-0.7-1.0}$
NLO* CS′ [92]	—	$4.3 \pm 0.1^{+9.9}_{-0.9}$	$1.6 \pm 0.1^{+3.3}_{-0.3}$
NLO* CS″ [70, 93–96]	$15.4 \pm 2.2^{+51}_{-12}$	$14.8 \pm 1.7^{+53}_{-12}$	$6.8 \pm 0.6^{+22}_{-5}$
NLO CS [39]	$11.9^{+4.6}_{-3.2}$	—	—
DPS [44, 85, 91]	$8.1 \pm 0.9^{+1.6}_{-1.3}$	$7.5 \pm 0.8^{+1.5}_{-1.2}$	$4.9 \pm 0.5^{+1.0}_{-0.8}$
Data	$15.2 \pm 1.0 \pm 0.9$	$13.5 \pm 0.9 \pm 0.9$	$8.3 \pm 0.6 \pm 0.5$

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

$$\sigma_{\rm eff} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma(J/\psi\, J/\psi)} = 7.3 \pm 0.5\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst})\ \mathrm{mb}$$

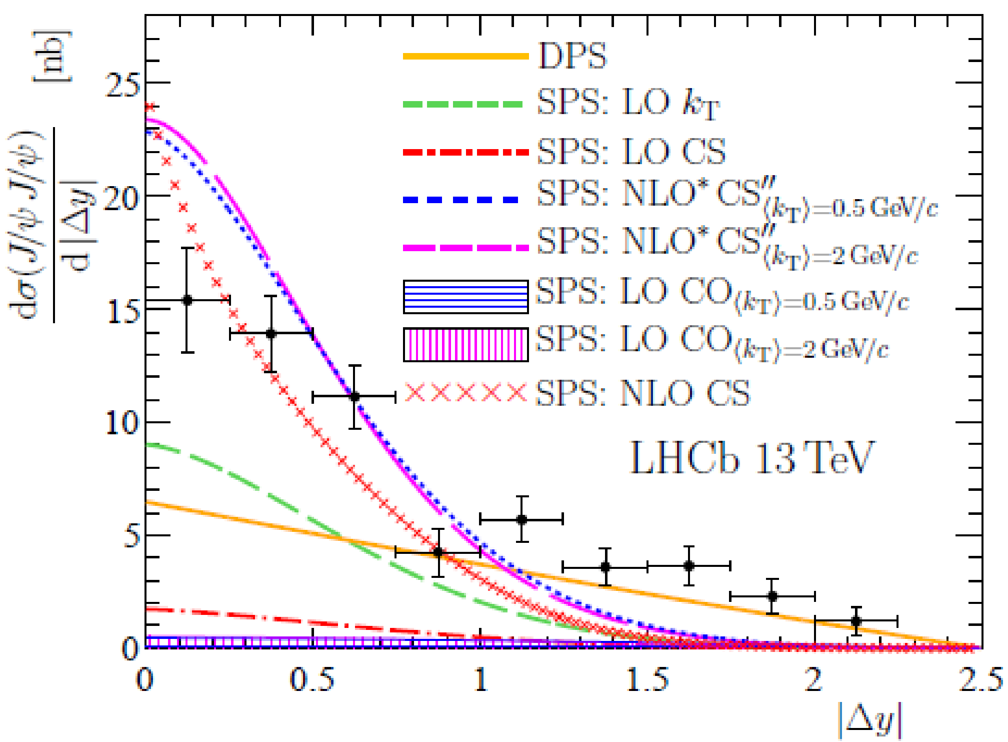
Double J/ψ

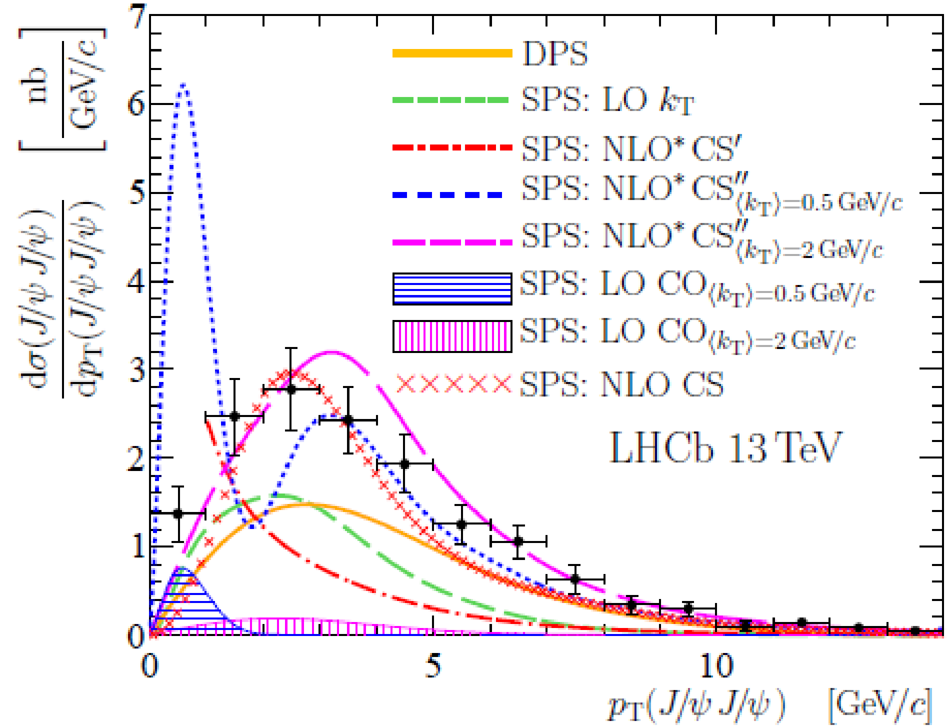
Testing kinematic properties:

[JHEP 06 (2017) 047]

- transverse momentum of a J/ψ-meson and (J/ψJ/ψ) pair
- rapidities of J/ψ and (J/ψJ/ψ) pair
- |Δy| — rapidity difference between two J/ψ-mesons
- |Δφ| — difference in the azimuthal angle
- $m_{J/\psi}$ — invariant mass of the pair

Neither DPS or SPS alone can describe the data distributions





Fit to the data was performed as a sum of DPS and SPS contributons

$$\frac{d\sigma}{dv} = \sigma_{DPS} F_{DPS}(v) + \sigma_{SPS} F_{SPS}(v); \longrightarrow \sigma_{eff} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{DPS}}$$

Double J/ψ

[JHEP 06 (2017) 047]

Resulting effective cross-sections

Variable	LO k_T	NLO* CS″ $\langle k_T\rangle = 2\,\mathrm{GeV}/c$	NLO* CS″ $\langle k_T\rangle = 0.5\,\mathrm{GeV}/c$	NLO CS
$p_T(J/\psi\, J/\psi)$	9.7 ± 0.5	8.8 ± 5.6	9.3 ± 1.0	—
$y(J/\psi\, J/\psi)$	—	11.9 ± 7.5	10.0 ± 5.0	—
$m(J/\psi\, J/\psi)$	10.6 ± 1.1	10.2 ± 1.0		10.4 ± 1.0
$\lvert\Delta y\rvert$	12.5 ± 4.1	12.2 ± 3.7	12.4 ± 3.9	11.2 ± 2.9

Previous measurements:

Central production at LHC:

σ_{eff} = 8.2 ± 2.2 mb — double J/ψ [Phys. Lett. B751 (2015) 479]

σ_{eff} = 6.3 ± 1.9 mb — double J/ψ [Eur. Phys. J. C77 (2017) 76]

D0 measurements:

σ_{eff} = 4.8 ± 2.5 mb — double J/ψ [Phys. Rev. D90 (2014) 111101]

σ_{eff} = 2.2 ± 1.1 mb — Υ+J/ψ [PRL 116 (2016) 082002]

LHCb measurements:

σ_{eff} ~ 15 mb — J/ψ+$c\bar{c}$ [JHEP 06 (2012) 141]

σ_{eff} = 18.0 ± 1.8 mb — Υ+D [JHEP 07 (2016) 052]

Z+open charm

[JHEP(2014)091]

1 fb^{-1}
@7TeV

Reconstructed modes:

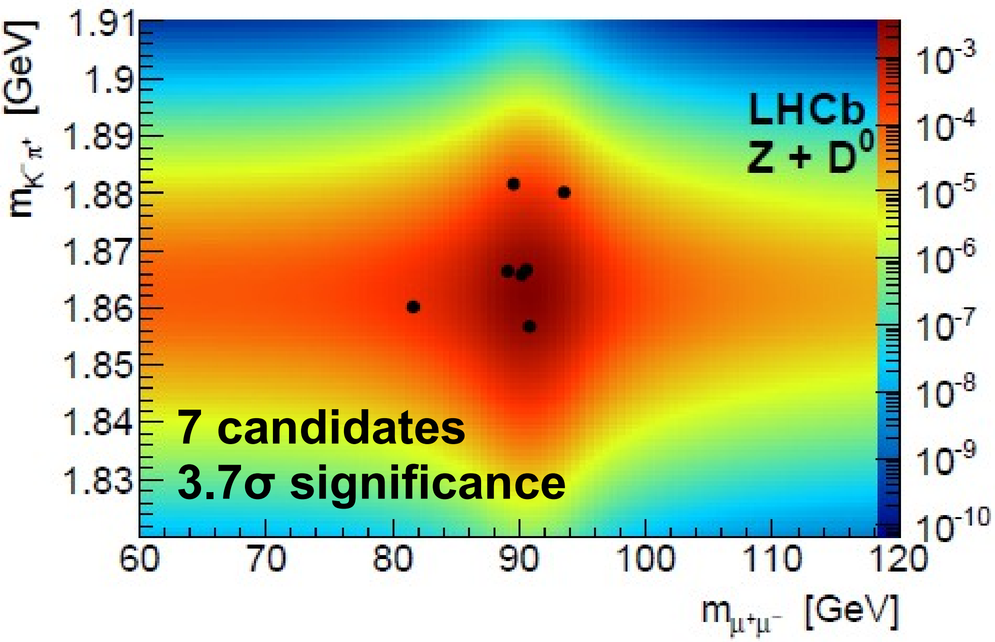
$Z \rightarrow \mu^+\mu^-$
$D^0 \rightarrow K^-\pi^+$
$D^+ \rightarrow K^-\pi^+\pi^+$

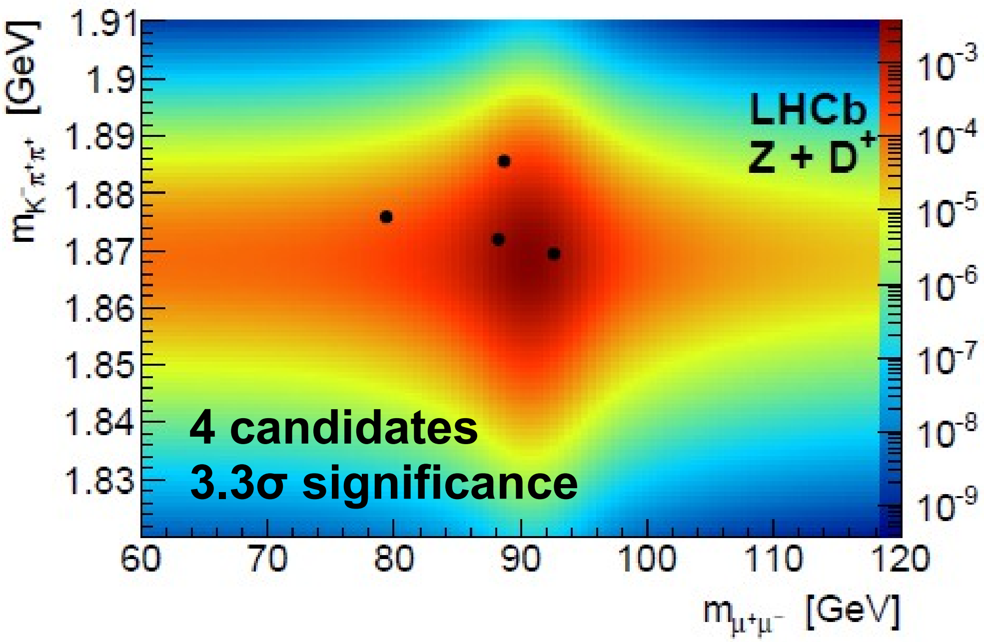
With $c\tau(D^{0,+}) > 100$ μm and Z+D pair consistent with originating from the same vertex

20 GeV/c < p_T^μ
2 < p_T^D < 12 GeV/c
2 < η^μ < 4.5
2 < y^D < 4

Background contamination:

Feed-down from b → c decays (estimated from simulation)
Pile-up (estimated from the data)
Combinatorial background (included in the fit)





In total 11 ZD candidates observed with 5.1σ significance

Z+open charm

[JHEP(2014)091]

$$\sigma_{Z\to\mu^+\mu^-,D} = \frac{\boxed{\rho}}{\boxed{\mathcal{L}}\,\boxed{\mathcal{B}_D}} \sum_{\text{candidates}} \boxed{\varepsilon^{-1}}$$

Signal purity

Integrated luminosity

Charmed hadron branching fractions

Total reconstruction, selection and trigger efficiency for candidate

[Nucl. Phys. Proc. Suppl. 205-206 (2010) 10]

	measured [pb]	MCFM massless [pb]	MCFM massive [pb]	DPS [pb]
$Z+D^0$	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12}_{-0.07}\,{}^{+0.11}_{-0.17} \pm 0.05$	$0.64^{+0.01}_{-0.01}\,{}^{+0.08}_{-0.13} \pm 0.04$	$3.28^{+0.68}_{-0.58}$
$Z+D^+$	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05}_{-0.03}\,{}^{+0.05}_{-0.07} \pm 0.03$	$0.28^{+0.01}_{-0.01}\,{}^{+0.04}_{-0.06} \pm 0.02$	$1.29^{+0.27}_{-0.23}$

Factorization approach with $\sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}\,\text{mb}$

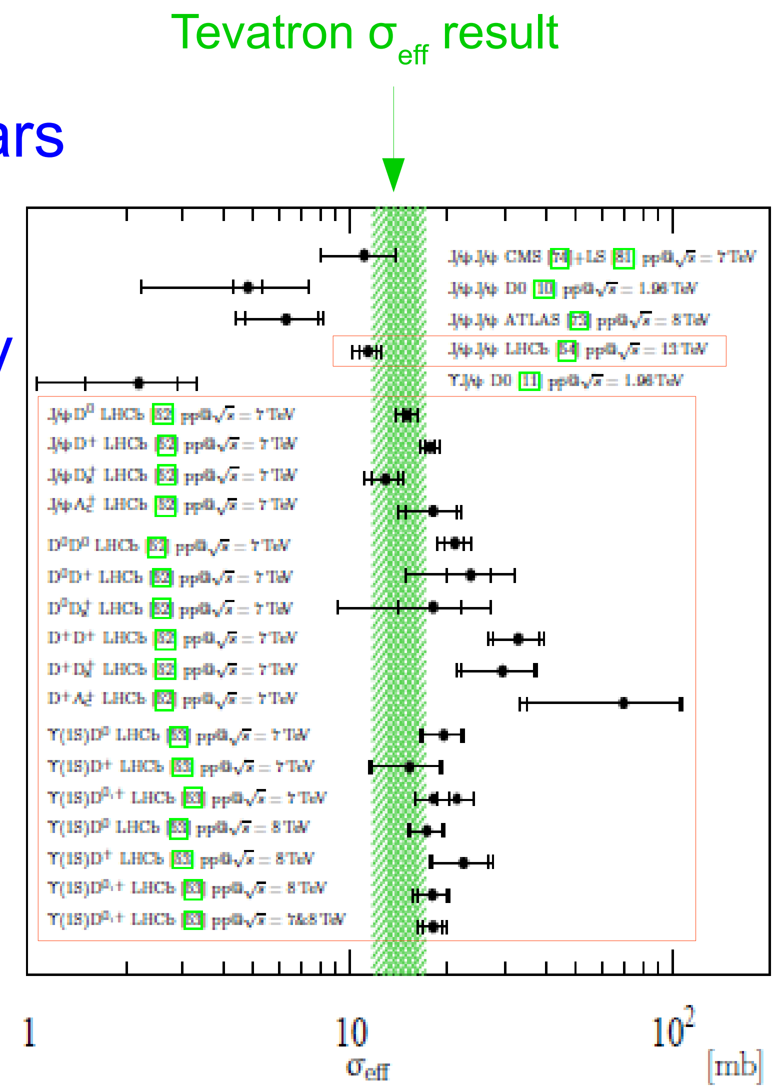
$Z+D^0$ consistent with production as a sum of SPS and DPS mechanisms

$Z+D^+$ below the expectation

More data needed for more conclusive statement

Conclusions

- Large interest and number of studies of the DPS in the last few years



- Mainly with heavy flavours but not only
- Larger samples are collected by now
  - Higher precision
  - Open beauty?
  - Triple parton scattering?