Recent results of double parton scattering studies at LHCb

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Outline

- ➢Introduction
- ➢The LHCb detector
- ➢LHCb measurements
  - ✓J/ψ + open charm & 2×open charm @ 7 TeV [JHEP 06 (2012) 141] [JHEP 1403 (2014) 108]
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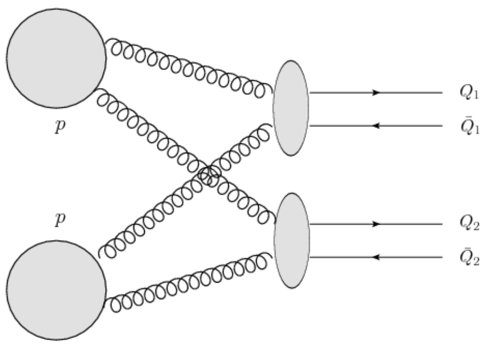
- ➢Summary and prospects

Introduction



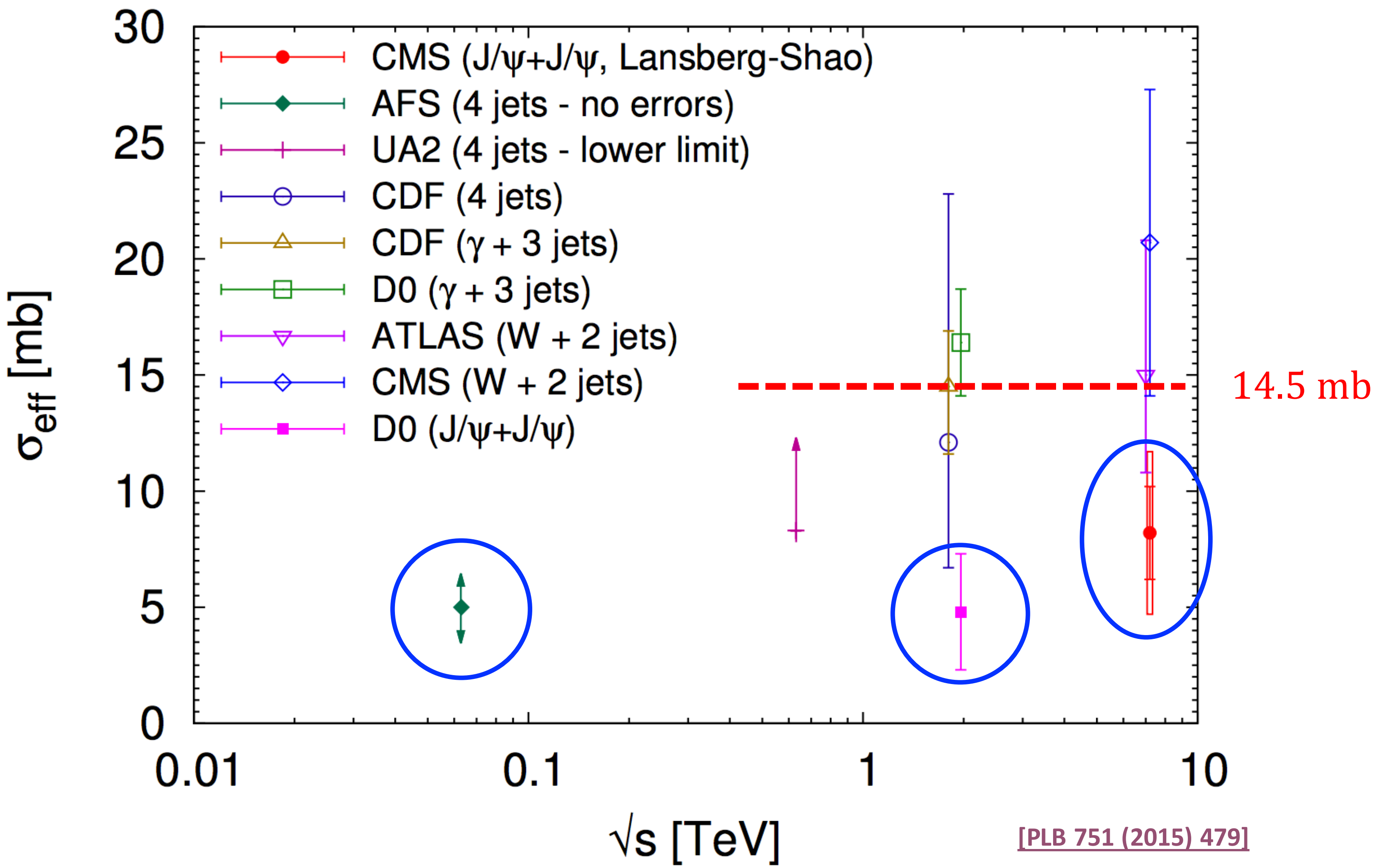
- DPS studies in various experiments
  - ✓ pp: W+2-jets, J/ψ+W, J/ψ+Z, $2\times J/\psi$, $2\times\Upsilon$ etc.
  - ✓ $p\bar{p}$: 4-jets, γ+3-jets, $J/\psi+\Upsilon$ etc.
  - ✓ $p-Pb$: $W^{\pm}W^{\pm}$ (proposed)
  - ✓ $Pb-Pb$: $2\times J/\psi$ (proposed)
- LHCb: pp collisions, smaller x
- Pocket formula

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

  - ✓ σ_{eff} thought to be universal, i.e. independent of process and energy
- 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

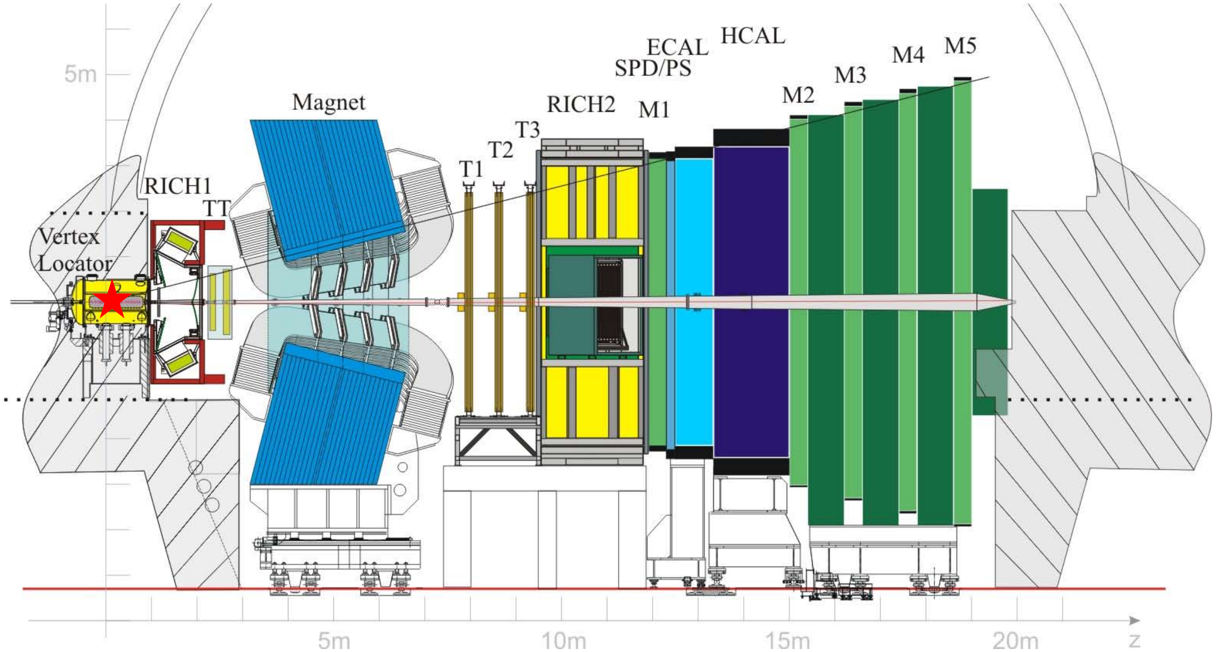
Effective cross-section



[PLB 751 (2015) 479]

The LHCb detector

- A single-arm forward region spectrometer covering $2 < \eta < 5$
- RunI (2011-2012): $\mathcal{L}_{\text{int}} = 3\ \text{fb}^{-1}$ @ 7 & 8 TeV ; $\sigma(b\bar{b}) \approx 250\ \mu\text{b}^{-1}$ @ 7 TeV [EPJC 71 (2011) 1645]
- RunII (2015-2018): $\mathcal{L}_{\text{int}} = 5\ \text{fb}^{-1}$ @ 13 & 14 TeV ; $\sigma(b\bar{b}) \approx 500\ \mu\text{b}^{-1}$ @ 13 TeV [JHEP 10 (2015) 172]

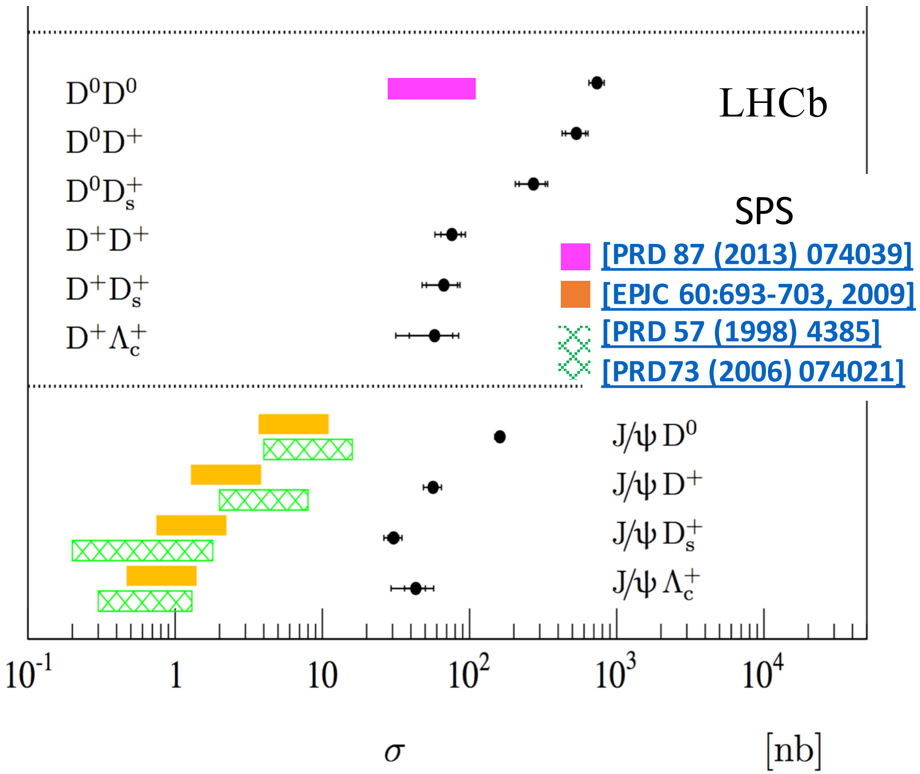


[JINST 3 (2008) S08005]

- ✓ **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)

J/ψ + open charm & 2×open charm

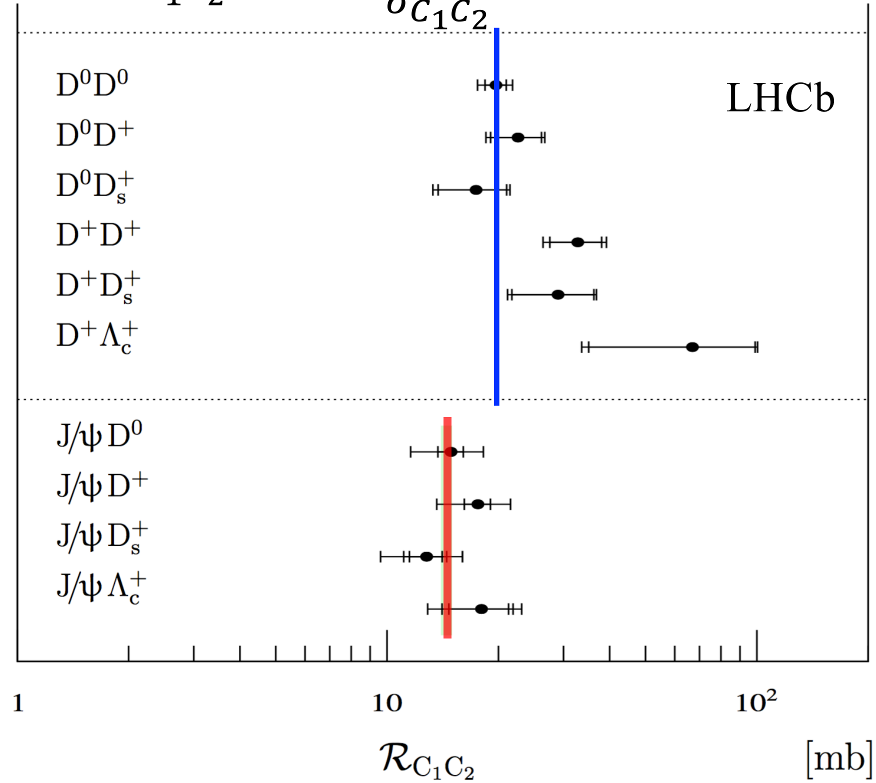
- Using 350 pb^{-1} data at $\sqrt{s} = 7$ TeV
- Production cross-sections



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

[JHEP 06 (2012) 141]

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

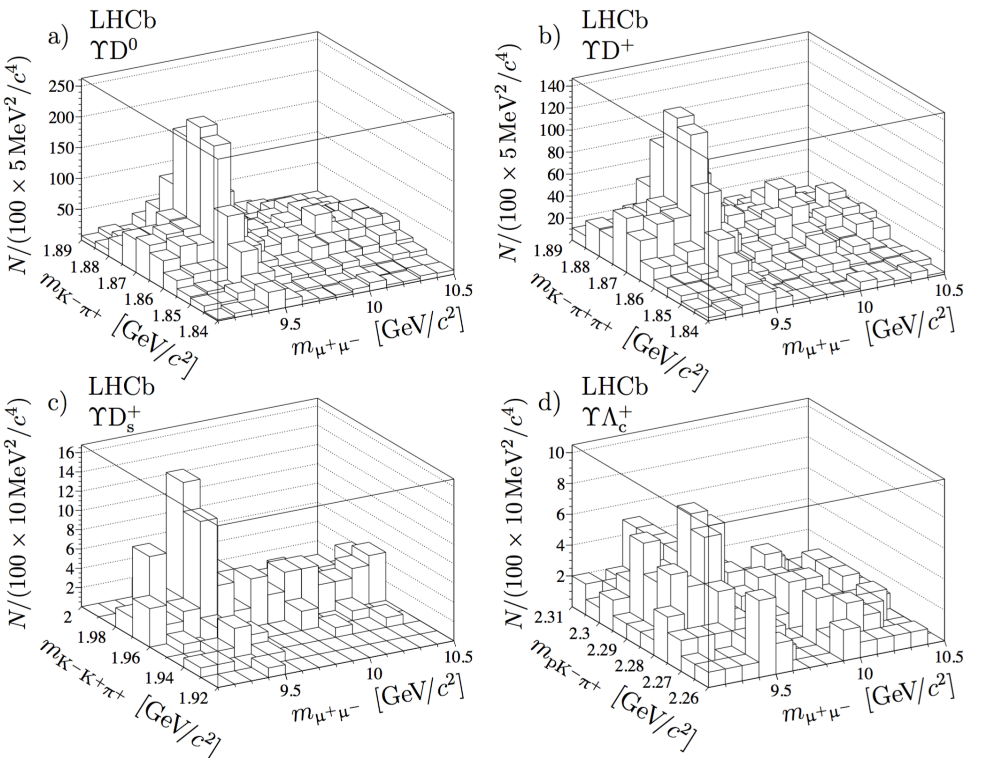


- ✓ Interpreted as σ_{eff} in DPS [PRD 56 (1997) 3811]
- ✓ J/ψ + open charm: in good agreement with CDF measurement in multi-jet production $\sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb
- ✓ 2×open charm: closer to 20 mb

Υ + open charm

- Using 3 fb^{-1} data at $\sqrt{s} = 7$ TeV & 8 TeV
- Fiducial region: $\Upsilon \in 2.0 < y < 4.5,\ p_T < 15\ \text{GeV}/c$
  open charm $\in 2.0 < y < 4.5,\ 1 < p_T < 20\ \text{GeV}/c$

[JHEP 07 (2016) 052]



	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
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

$> 5\sigma$

- Results:

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

- DPS predictions: [PRD 56 (1997) 3811]
  - ✓ With $\sigma_{\text{eff}} = 14.5$ mb

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

- 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:

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

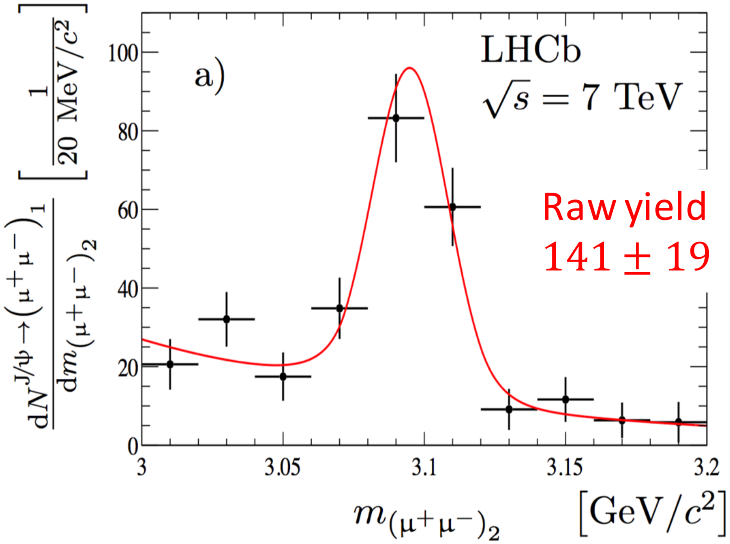
- ✓ Consistent with previous measurements

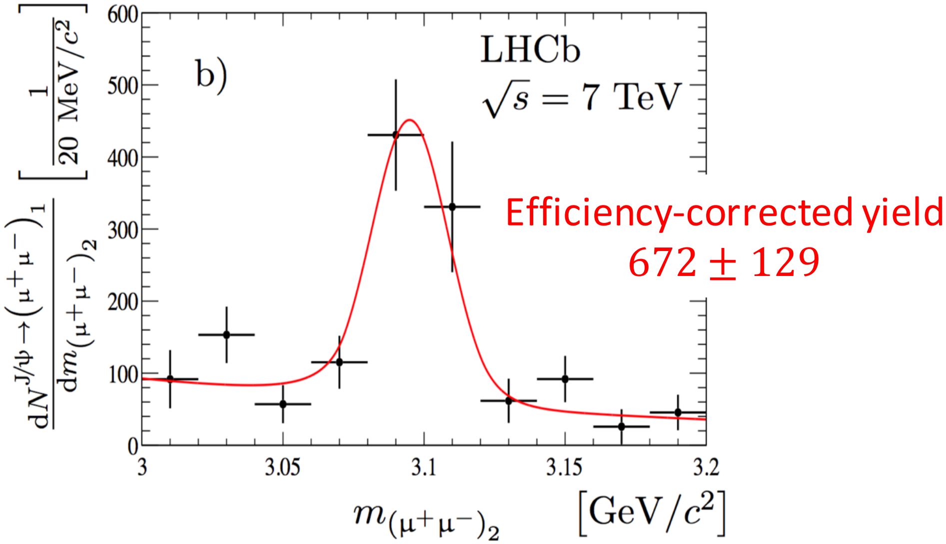
[JHEP 07 (2016) 052]

$2\times J/\psi$ @ 7 TeV

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

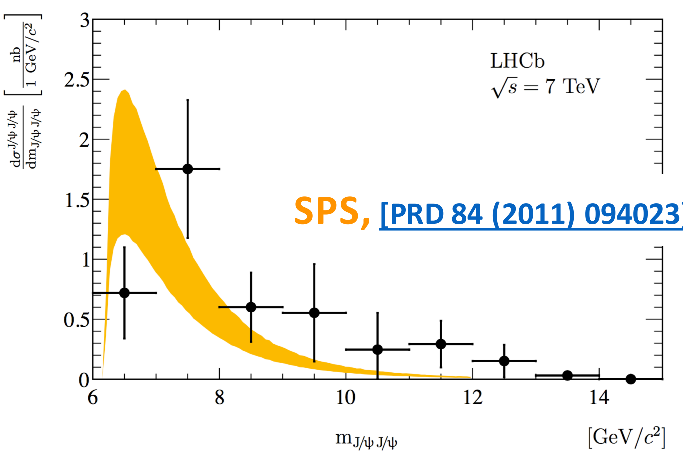
[PLB 707 (2012) 52-59]





- $\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1$ nb
  - ✓ $\sigma_{SPS} = 4.0 \pm 1.2$ nb; LO NRQCD CS
  - ✓ $\sigma_{DPS} \approx 3.8 \pm 1.3$ nb; $\sigma_{eff} = 14.5$ mb

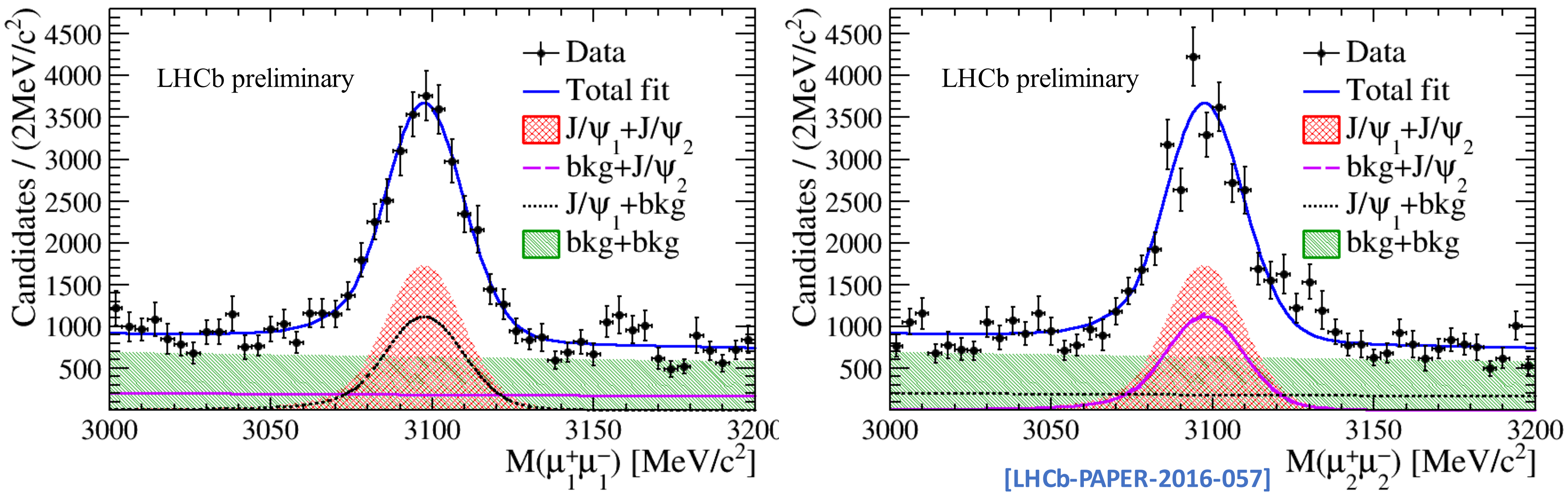
[PRD 56 (1997) 3811]



- Not enough events to disentangle SPS and DPS contributions

$2\times J/\psi$ @ 13 TeV **New!**

- Using $\sim 279\ \text{pb}^{-1}$ data at $\sqrt{s} = 13$ TeV
- Fiducial region: $2 < y^{J/\psi} < 4.5$, $p_{\text{T}}^{J/\psi} < 10\ \text{GeV}/c$
- Cut-based selection
- Efficiency estimated using simulation & data
- Signal yield obtained from simultaneous fit to the efficiency-corrected 2D $\left(M(\mu_1^+\mu_1^-), M(\mu_2^+\mu_2^-)\right)$ distribution



[LHCb-PAPER-2016-057]

- $\sigma(J/\psi J/\psi) = 13.5 \pm 0.9(\text{stat}) \pm 0.8(\text{syst})$ nb

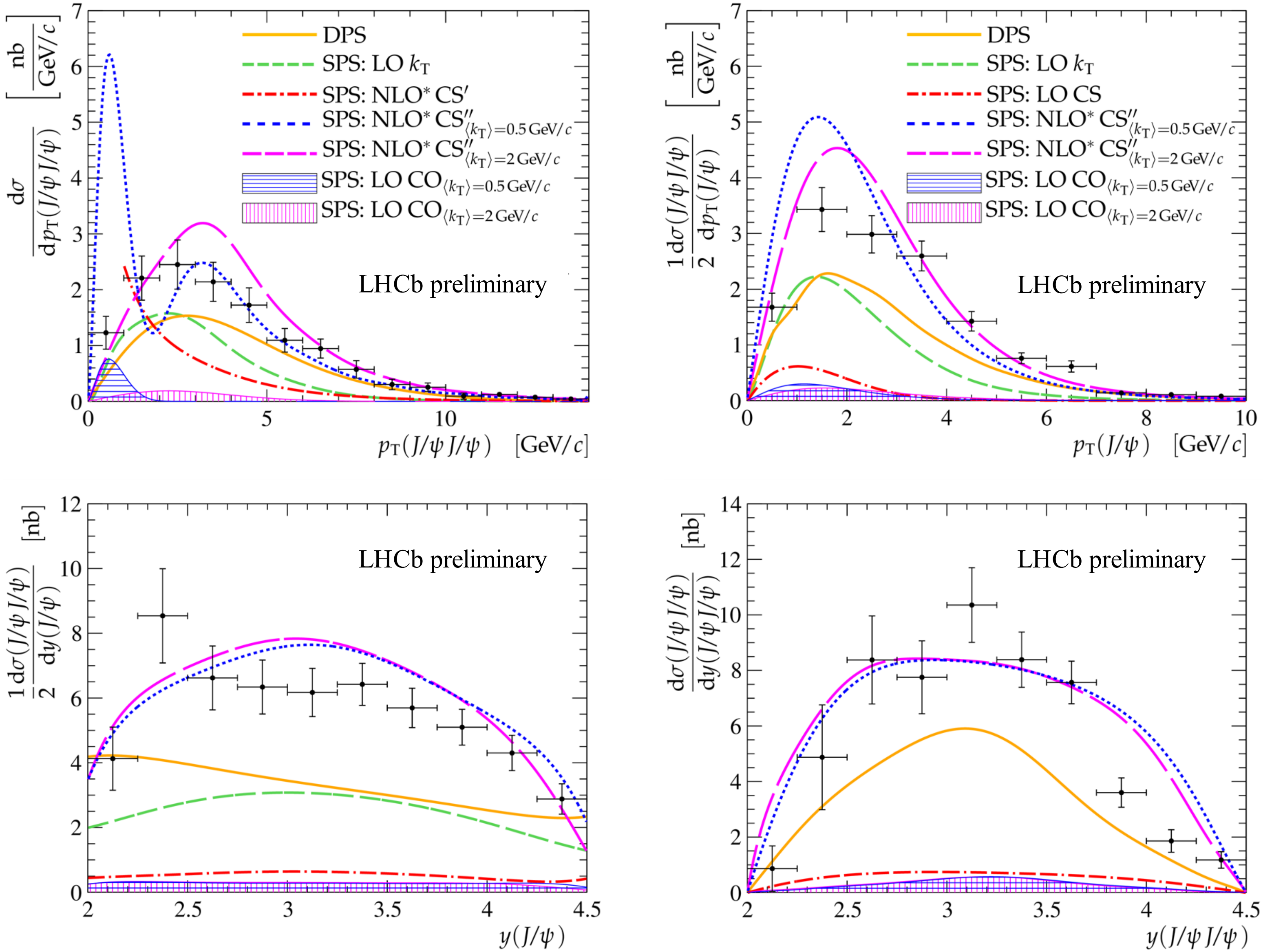
Comparison to theory

Approach	$\sigma(J/\psi\, J/\psi)$ [nb] no p_{T}-cut	$p_{\mathrm{T}}^{J/\psi\, J/\psi} > 1\,\mathrm{GeV}/c$	$p_{\mathrm{T}}^{J/\psi\, J/\psi} > 3\,\mathrm{GeV}/c$	
SPS: LO CS	$1.3 \pm 0.1^{+3.2}_{-0.1}$	—	—	[PRD 94 (2016) 054017]
SPS: LO CO	$0.45 \pm 0.09^{+1.42+0.25}_{-0.36-0.34}$	—	—	[CPC 198 (2016) 238]
SPS: LO k_{T}	$6.3^{+3.8+3.8}_{-1.6-2.6}$	$5.7^{+3.4+3.2}_{-1.5-2.1}$	$2.7^{+1.6+1.6}_{-0.7-1.0}$	[PRD 84 (2011) 054012]
SPS: NLO* CS′	—	$4.3 \pm 0.1^{+9.9}_{-0.9}$	$1.6 \pm 0.1^{+3.3}_{-0.3}$	[PRD 94 (2016) 054017]
SPS: NLO* CS″	$15.4 \pm 2.2^{+51}_{-12}$	$14.8 \pm 1.7^{+53}_{-12}$	$6.8 \pm 0.6^{+22}_{-5}$	[CPC 198 (2016) 238]
DPS	$8.1 \pm 0.9^{+1.6}_{-1.3}$	$7.5 \pm 0.8^{+1.5}_{-1.2}$	$4.9 \pm 0.5^{+1.0}_{-0.8}$	
DATA	$13.5 \pm 0.9 \pm 0.8$	$12.0 \pm 0.8 \pm 0.8$	$7.4 \pm 0.6 \pm 0.5$	

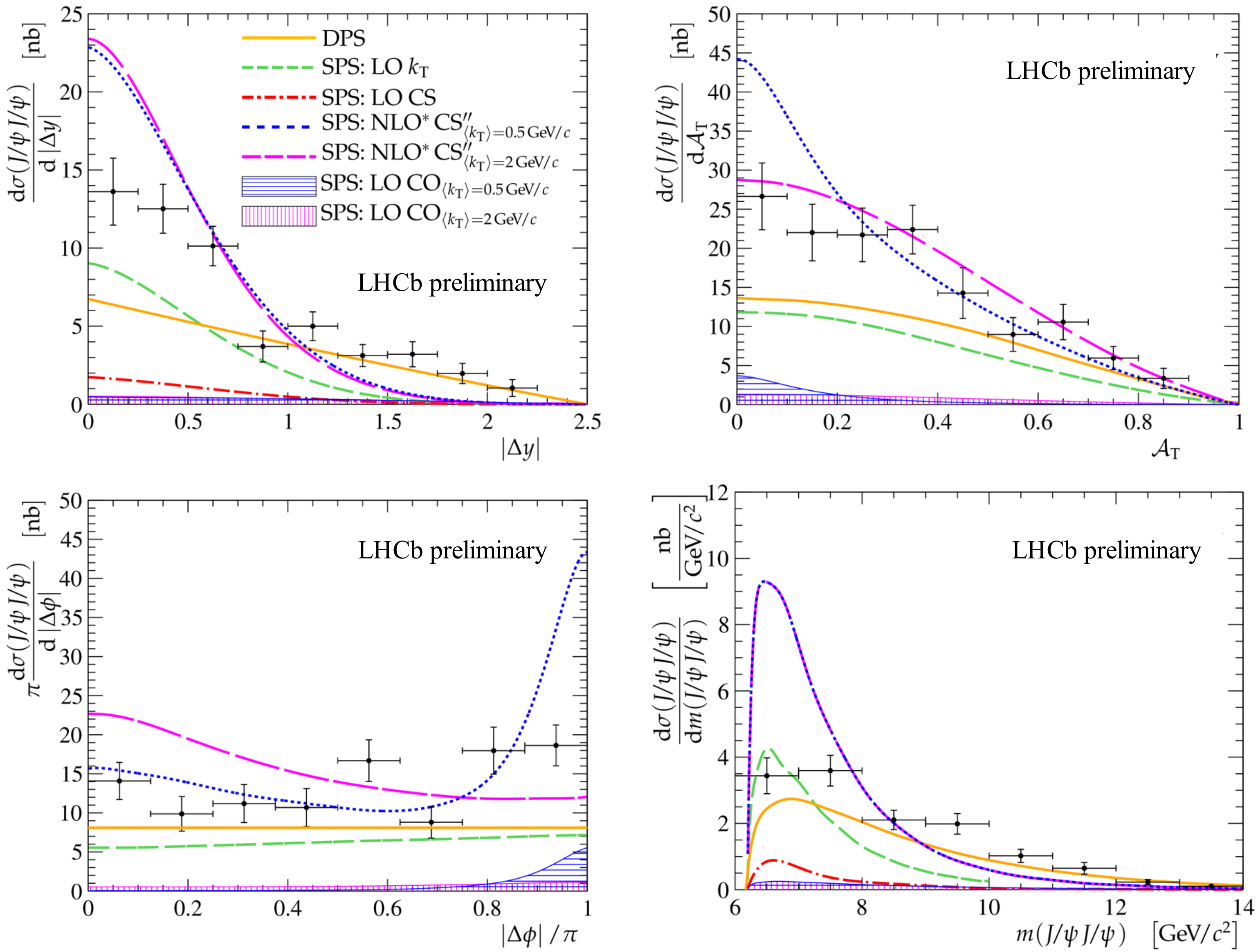
DPS: assuming $\sigma_{\mathrm{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb [PRD 56 (1997) 3811]

- LO CO : contribution very small
- LO CS/ NLO* CS’ : need DPS contribution
- LO k_{T} and NLO* CS’’ : uncertainty quite large; consistent with measurement within uncertainty

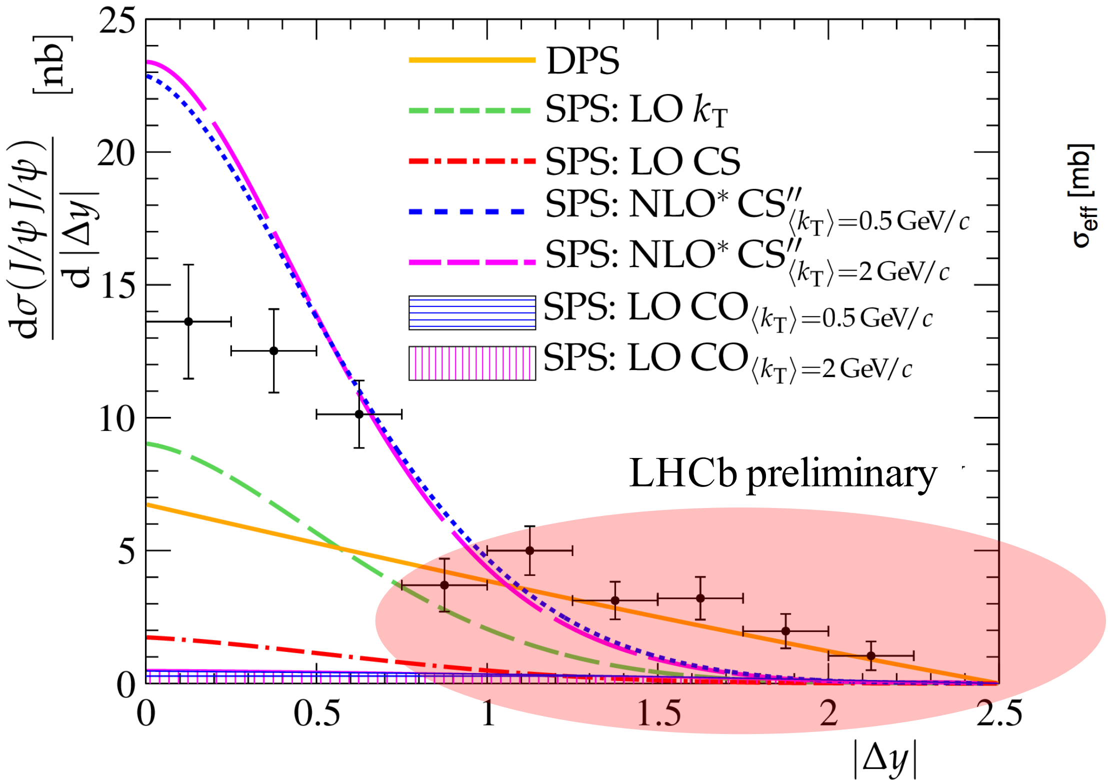
Differential cross-sections

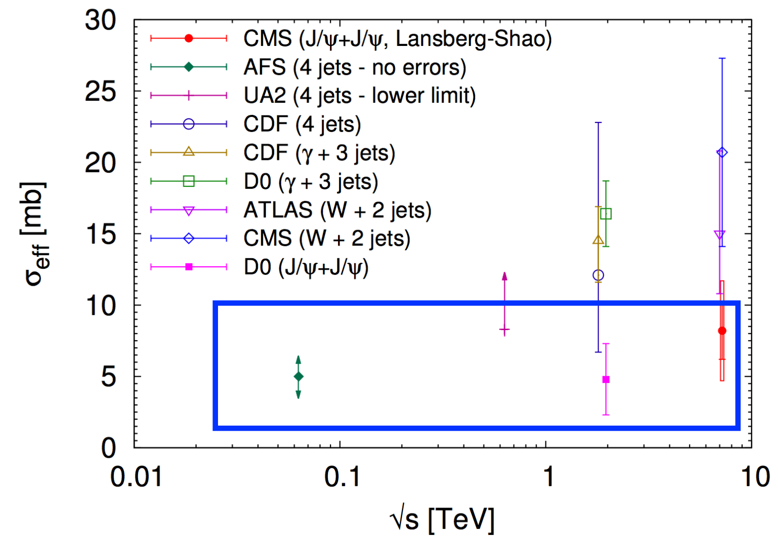


Differential cross-sections (cont.)



DPS contribution





- DPS contribution essential for the region $|\Delta y| > 1.5$
- Compatible with expectations for $\sigma_{\mathrm{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb
- Much smaller σ_{eff} values are disfavoured

- Comparisons with $p_{\mathrm{T}}(J/\psi J/\psi) > 1$ GeV/c or 3 GeV/c give same conclusions

Summary & prospects

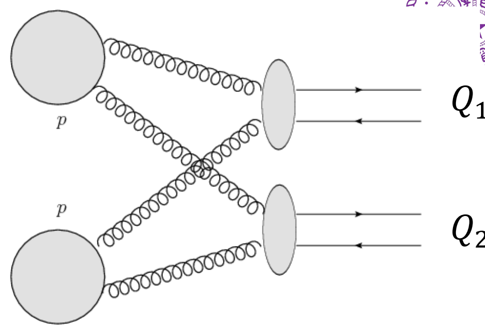
- DPS is explored at LHCb through several processes
- Relevant DPS contribution is observed in
  - ✓ J/ψ + open charm & 2×open charm
  - ✓ Υ + open charm
- Indication for DPS contribution in $2\times J/\psi$ @ 13 TeV

- 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: $\sqrt{s} = 13$ TeV
    - More statistics expected: $\mathcal{L}_{\text{int}} = 5\ \text{fb}^{-1}$
    - Possibility for triple-parton scattering?

Thank you!

Back up

DPS formula



$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \sum_{i,j,k,l} \int dx_1 dx_2 dx_1' dx_2' d^2\mathbf{b}_1 d^2\mathbf{b}_2 d^2\mathbf{b}$$

$$\times \Gamma_{ij}(x_1, x_2, \mathbf{b}_1, \mathbf{b}_2)\, \hat{\sigma}_{ik}^{Q_1}(x_1, x_1')\, \hat{\sigma}_{jl}^{Q_2}(x_2, x_2')\, \Gamma_{kl}(x_1', x_2', \mathbf{b}_1 - \mathbf{b}, \mathbf{b}_2 - \mathbf{b}),$$

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