DPS studies with open charm hadrons at LHCb

Vanya BELYAEV (CERN/Geneva & ITEP/Moscow)
on behalf of LHCb collaboration

13.12.2k+17

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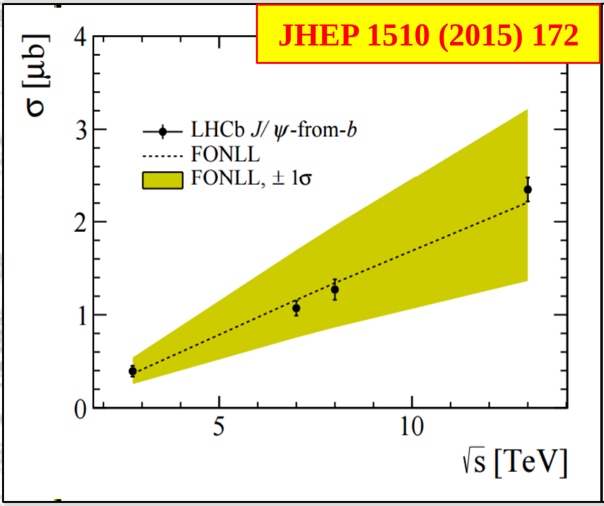
High energy ~~hadron~~ gluon collision

- Heavy flavour production at LHC is dominated by gg-fusion process
- Quarkonia: reasonably (rapidly improving) agreement with NR QCD
  - J/ψ, ψ', η_c, $\chi_{c1,2}$, $\chi_{b1,2}(nP)$, ….
- Open flavour: FONLL does good job



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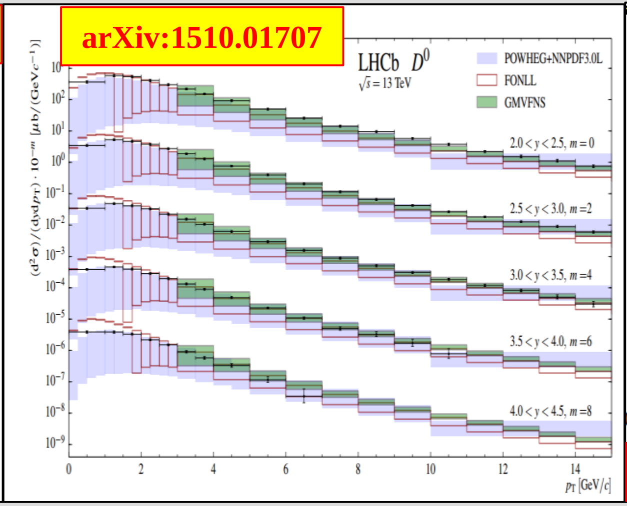
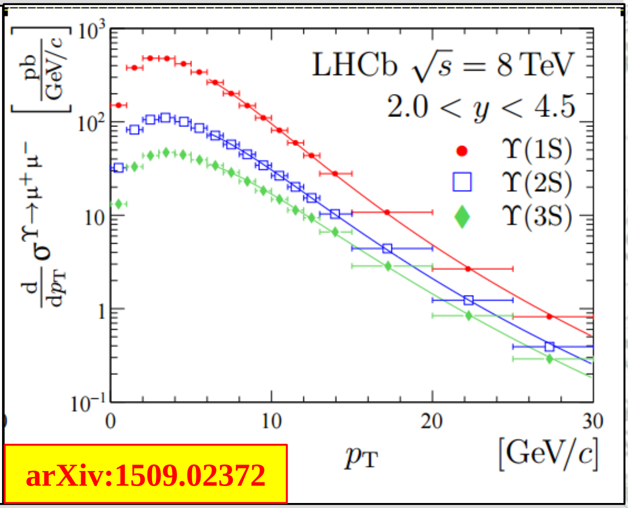


arXiv:1510.01707



arXiv:1509.02372

- Heavy flavour production cross-section in forward region is large

$$\sigma(c\bar{c})_{p_T<8\,\mathrm{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\,\mu\mathrm{b},$$

vs

$$\sigma^{\mathrm{acc}}_{\mathrm{inel}}(p_T > 0.2\,\mathrm{GeV}/c,\ 2.0 < \eta < 4.5) = 55.0 \pm 2.4\,\mathrm{mb}\,,$$

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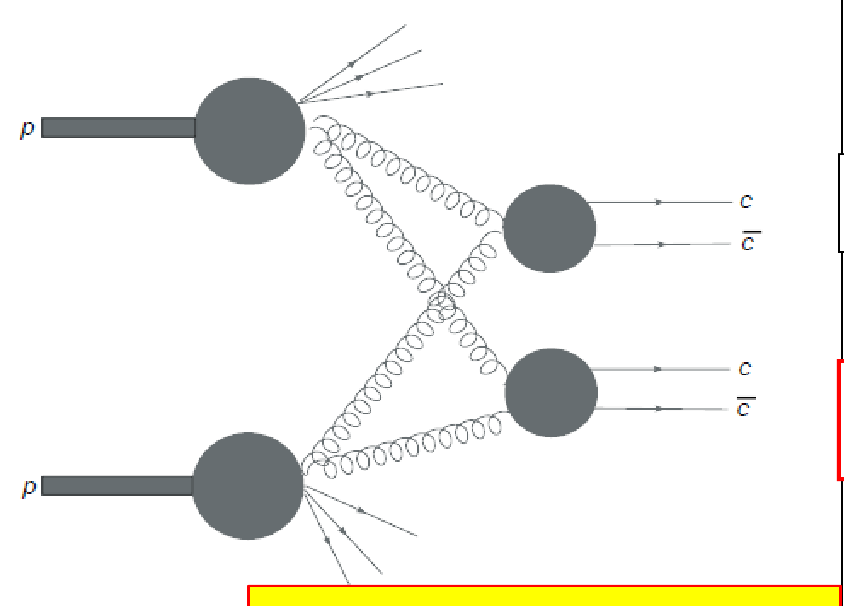
DPS: simple paradigm



Two independent hard scattering processes

Relations through (unknown) *double* PDF

$$\Gamma_{ij}(x_1, x_2; \mathrm{b}_1, \mathrm{b}_2; Q_1^2, Q_2^2) = D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) f(\mathrm{b}_1) f(\mathrm{b}_2),$$

Assume factorization of *double* PDFs

$$D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) = D_h^i(x_1; Q_1^2) D_h^j(x_2; Q_2^2).$$

(Can't be true for all x, Q^2)

Easy to make predictions!

And the predictions are easy to test

Pocket formula

$$\sigma_{\mathrm{DPS}}^{AB} = \frac{m}{2} \frac{\sigma_{\mathrm{SPS}}^{A} \sigma_{\mathrm{SPS}}^{B}}{\sigma_{\mathrm{eff}}}.$$

m=1,2

Universal (energy and process independent) factor)

$$1/\sigma_{eff} = \int d^2 b F^2(b)$$

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

CDF, F.Abe *et al.*, PDR 56 3811 (1997)

DPS

- Simple pattern, a lot of powerful consequences and interesting predictions
- *Pocket formula* is also ***valid for differential cross-sections***

$$\sigma^{\mathrm{DPS}}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{\mathrm{eff}}}\sigma^{\mathrm{SPS}}(pp \to c\bar{c}X_1) \cdot \sigma^{\mathrm{SPS}}(pp \to c\bar{c}X_2).$$

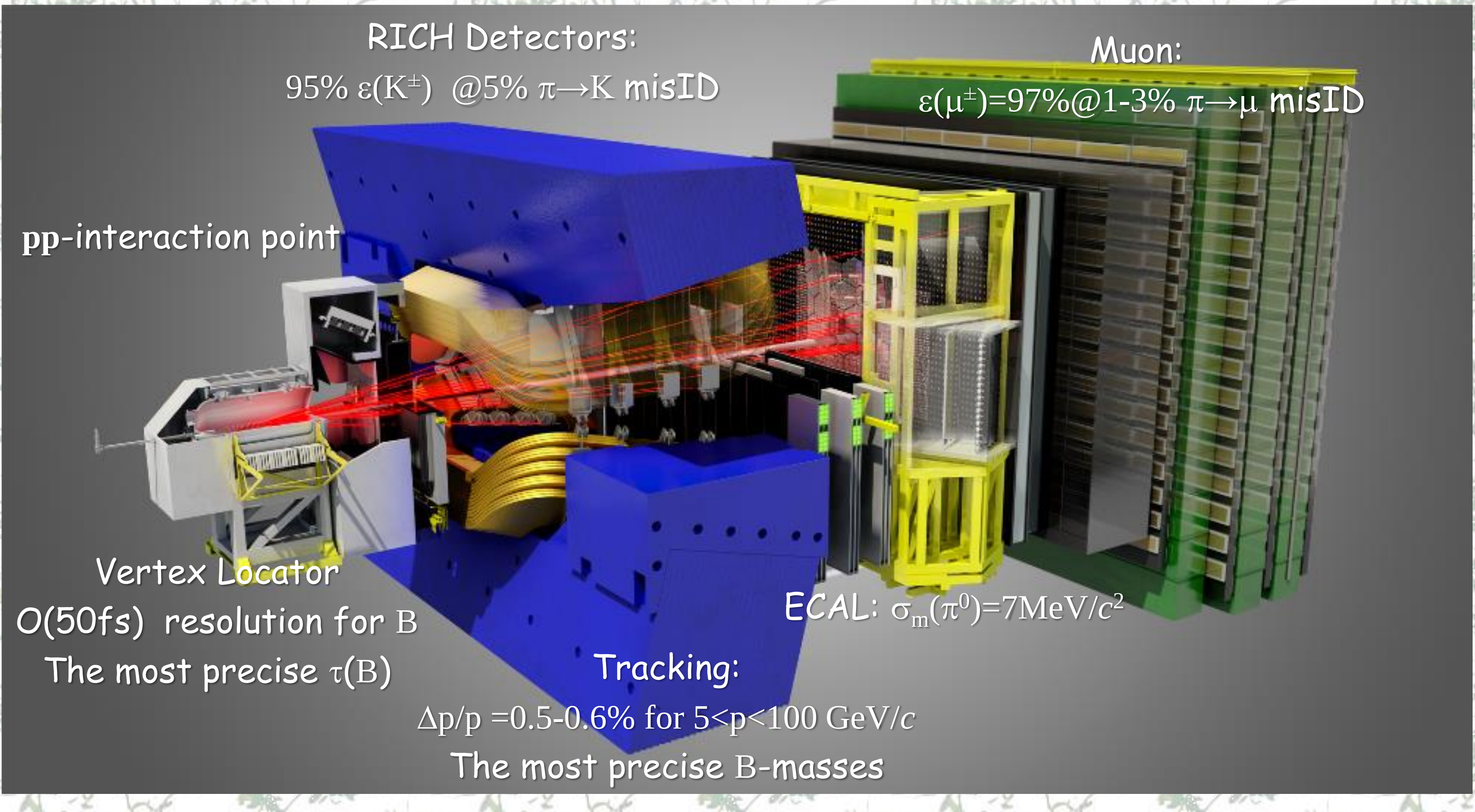
$$\frac{d\sigma^{\mathrm{DPS}}(pp \to c\bar{c}c\bar{c}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t} dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}} = \frac{1}{2\sigma_{\mathrm{eff}}} \cdot \frac{d\sigma^{\mathrm{SPS}}(pp \to c\bar{c}X_1)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} \cdot \frac{d\sigma^{\mathrm{SPS}}(pp \to c\bar{c}X_2)}{dy_3 dy_4 d^2p_{3,t} d^2p_{4,t}}.$$

- The effective cross-section is a property of proton (integral over transverse degrees of freedom)
  - Smaller than "*proton size*": $\pi R^2 \approx 50\mathrm{mb}$
  - It is universal: ***energy and process independent***
    - easy to compare Tevatron, GPD and LHCb

$\sigma_{\mathrm{eff}} \sim \frac{1}{4}\,\sigma_{\mathrm{in}}$ production of cross-section for A+B is enhanced with ***factor of four*** with respect to naïve model

- ***LHCb: 10% of all "hard" events (irrespectively from the process) have additional charm pair***

~40% of heavy quarks in <4% of 4π



RICH Detectors:

95% $\varepsilon(K^{\pm})$ @5% $\pi\rightarrow K$ misID

Muon:

$\varepsilon(\mu^{\pm})$=97%@1-3% $\pi\rightarrow\mu$ misID

pp-interaction point

Vertex Locator

O(50fs) resolution for B

The most precise $\tau(B)$

ECAL: $\sigma_m(\pi^0)=7\,\mathrm{MeV}/c^2$

Tracking:

$\Delta p/p$ =0.5-0.6% for $5<p<100$ GeV/c

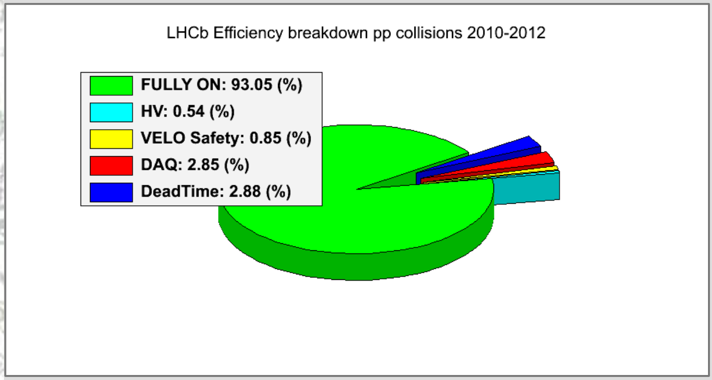
The most precise B-masses

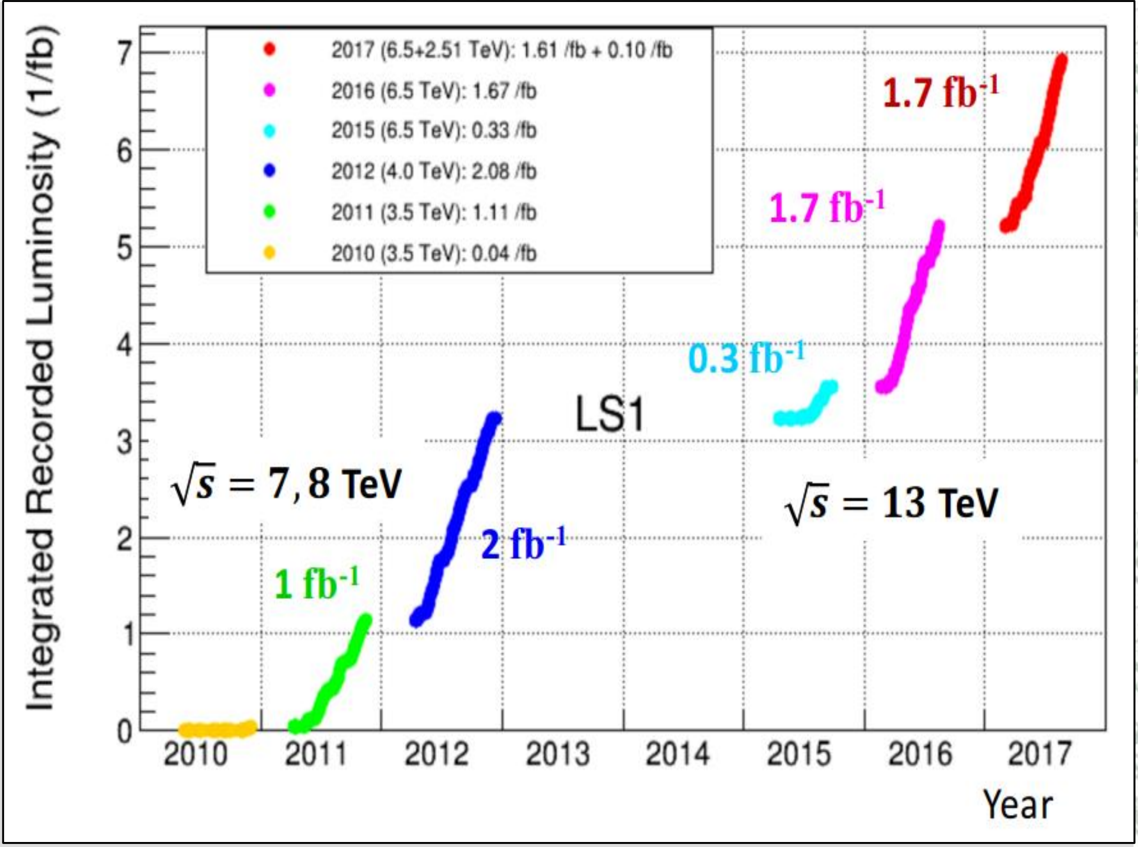
Run I+II

$1\,\mathrm{fb}^{-1}$@7TeV

$2\,\mathrm{fb}^{-1}$@8TeV

$3.5\,\mathrm{fb}^{-1}$ @13TeV





Thanks to LHC accelerator team for the excellent performance of machine

$J/\psi + c\bar{c}$ and $2\times c\bar{c}$

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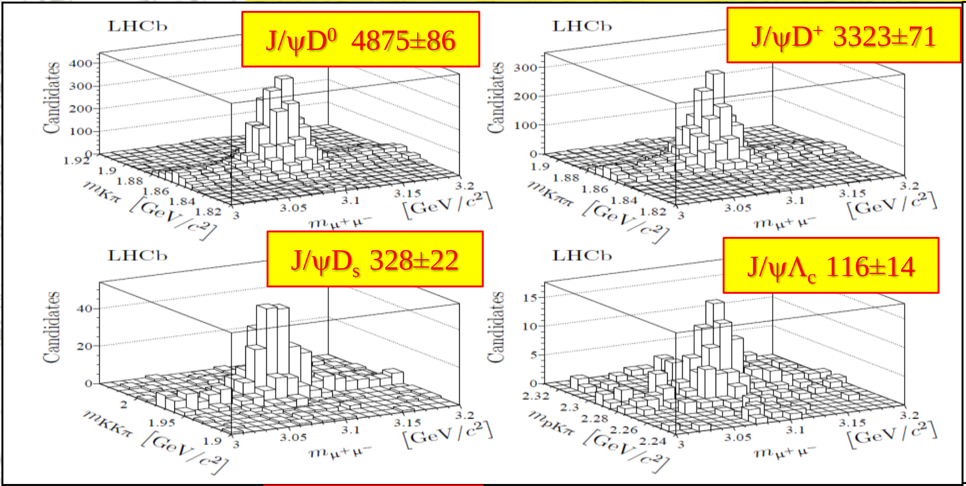
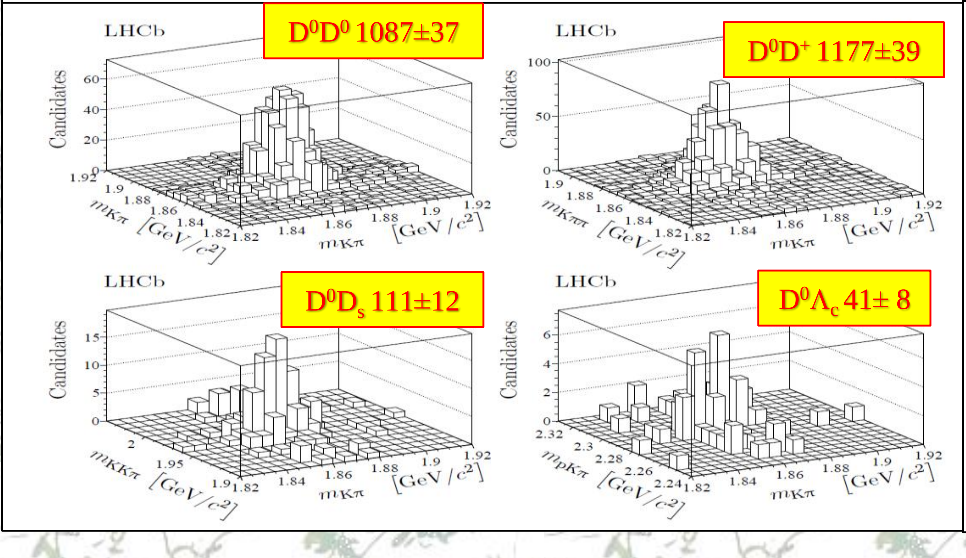
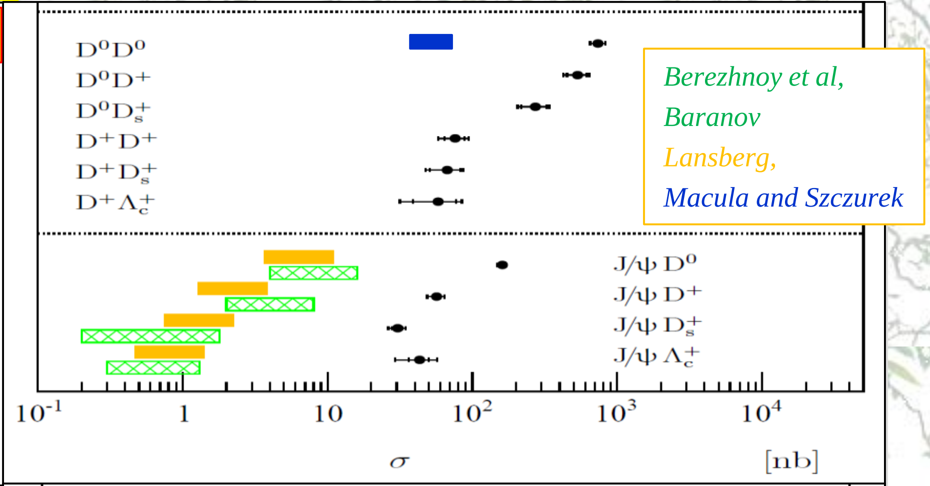
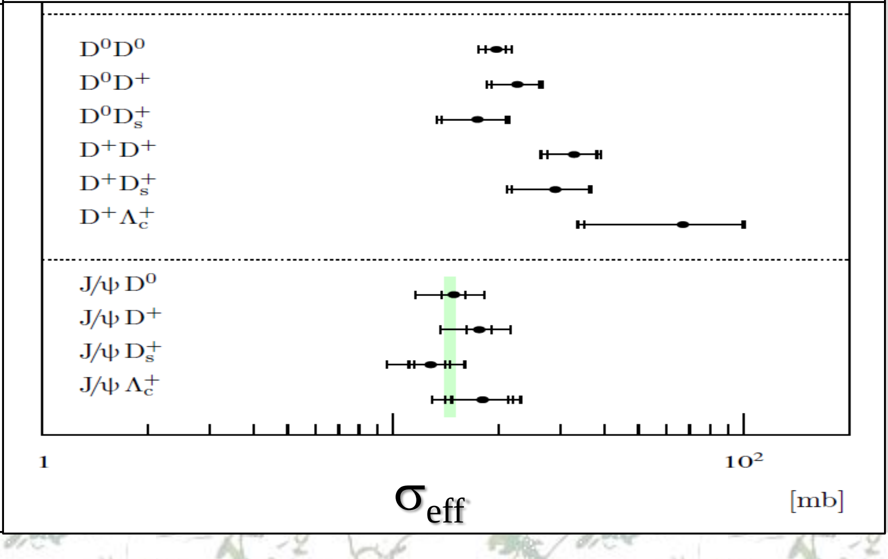
$\sqrt{s}$=7TeV, 355pb^{-1}









$\Upsilon + c\bar{c}$?

- NRQCD SPS (*Berezhnoy, Likhoded*)

$$\frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = (0.2 - 0.6)\,\%$$

- Gluon splitting: (0.4-2.0)%
- DPS:

$$\frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = \frac{\sigma^{c\bar{c}}}{\sigma_{\mathrm{eff}}}.$$

$\mathcal{O}(10\%)$

- Predictions are very different
- Expected to be dominated by DPS
- Different kinematic range from $J/\psi + c\bar{c}$

$\Upsilon + c\bar{c}$

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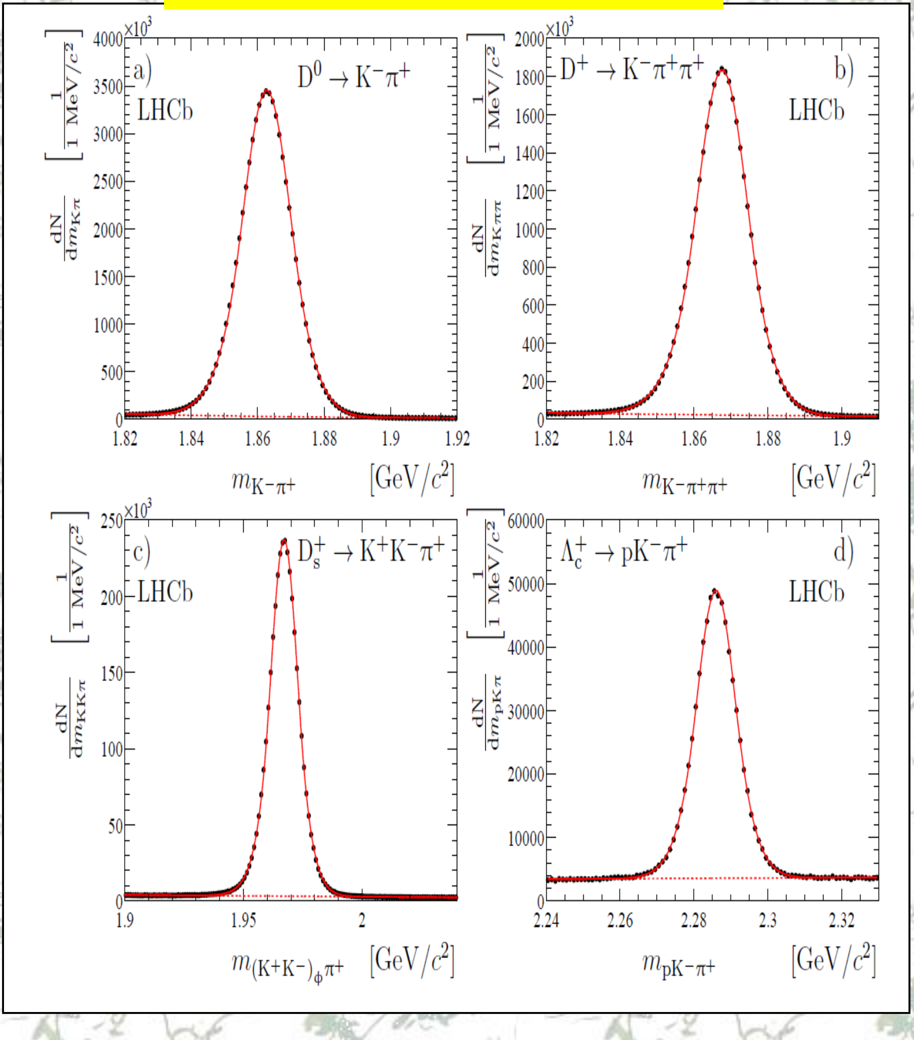

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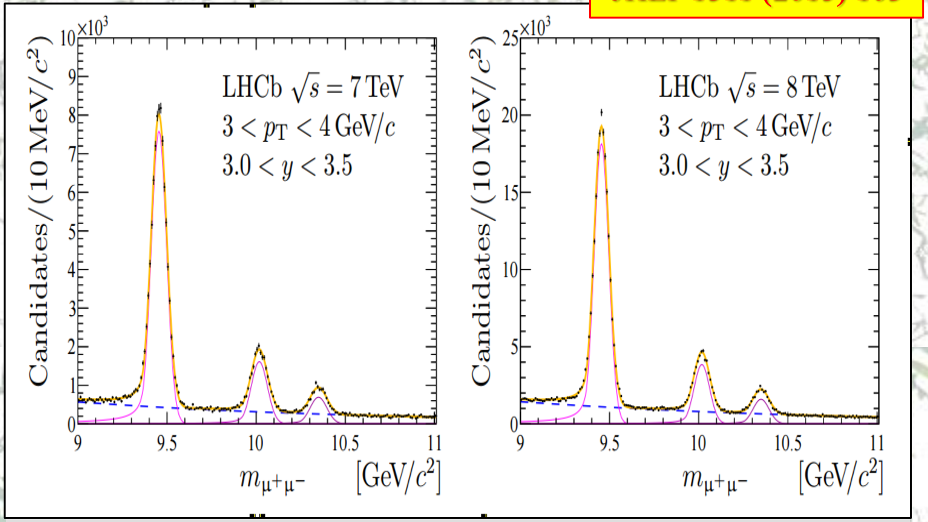

- Whole Run-I dataset: 1+2fb^{-1}

D^0	O(200M/fb^{-1})
D^+	O(100M/fb^{-1})
D_s	O(10M/fb^{-1})
Λ_c	O(20M/fb^{-1})
Υ(1,2,3S):	O(3,0.7,0.3M/fb^{-1})

$\Upsilon + c\bar{c}$

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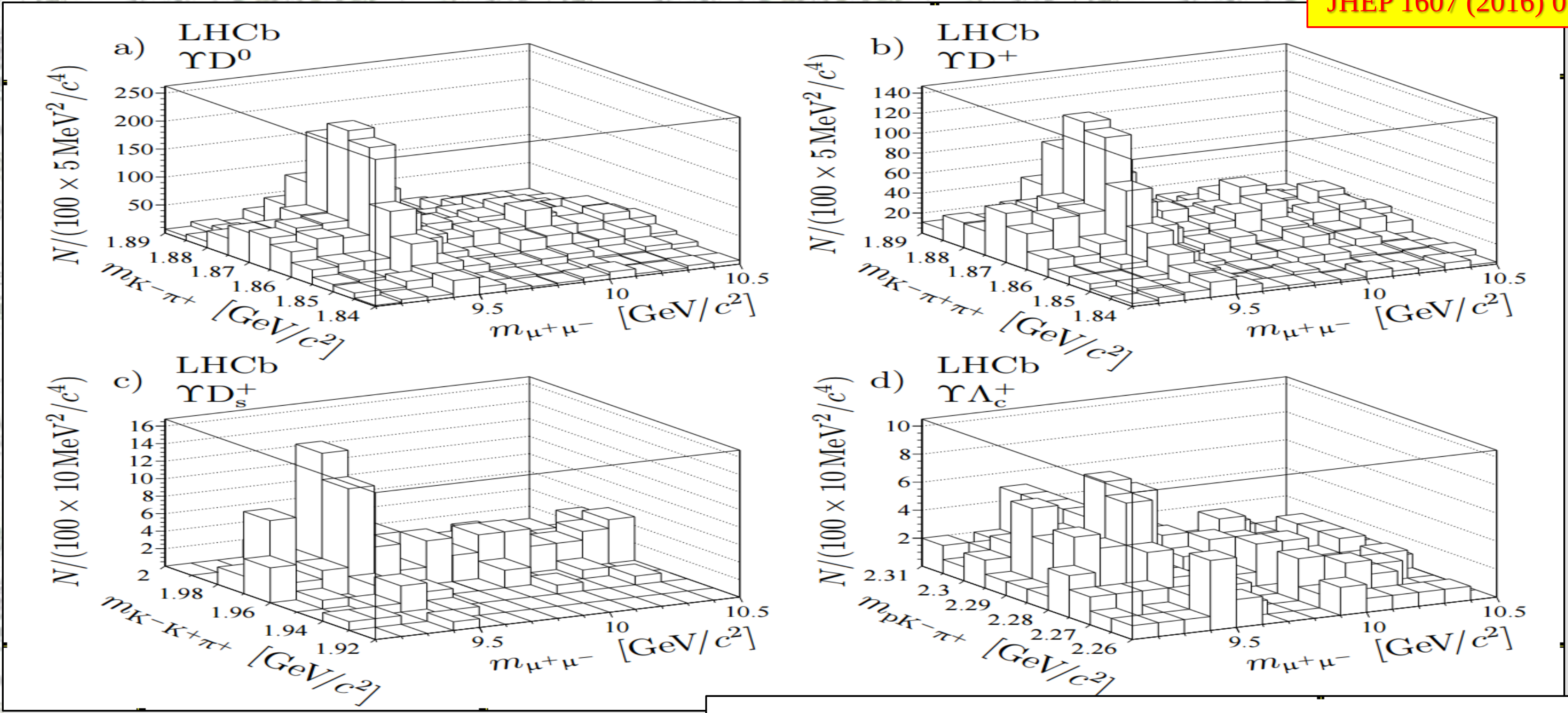

Five modes with >5σ!

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

Pileup?

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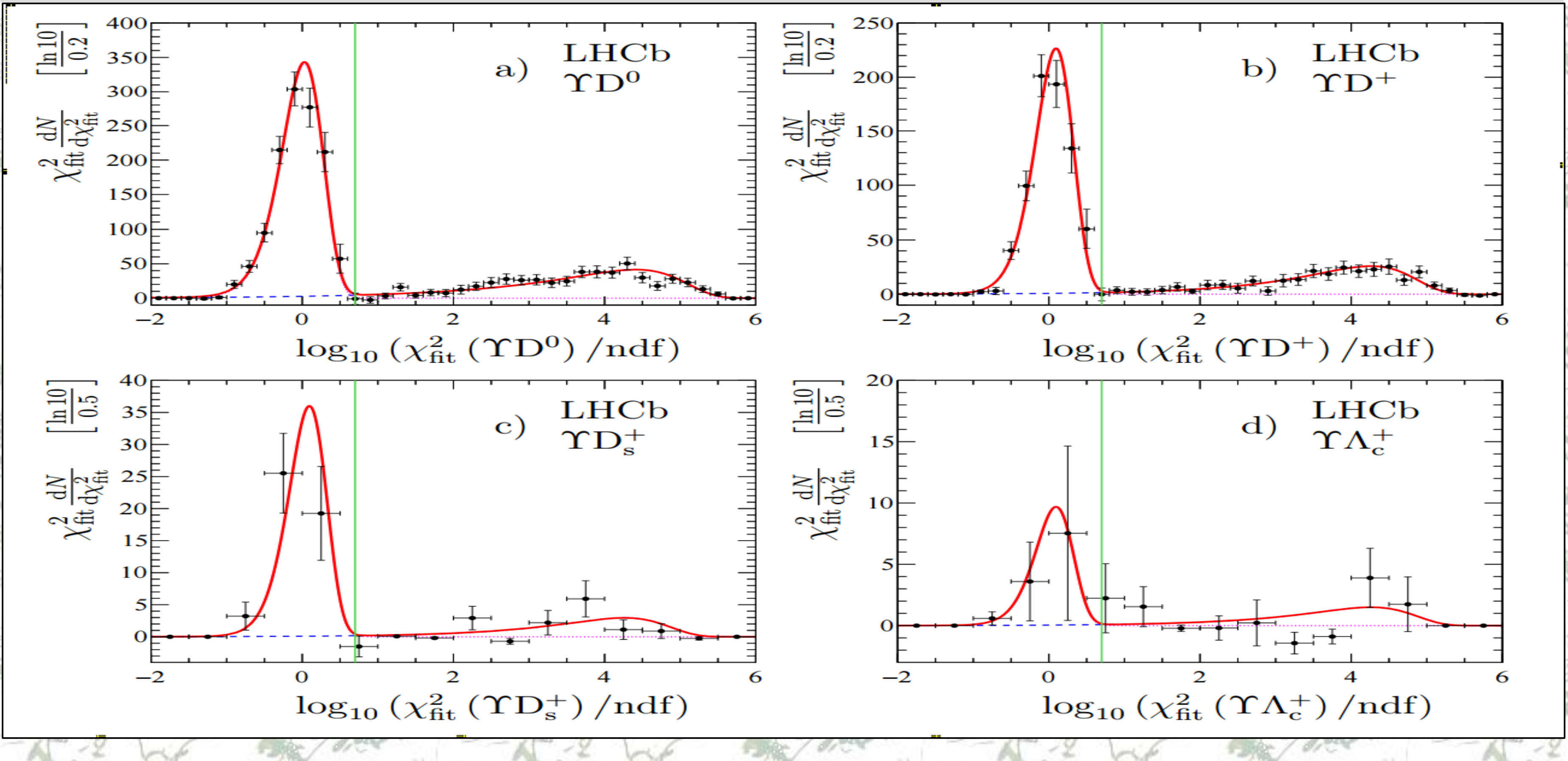
- Discriminating variable:

← signal   pileup →



Cross-sections

Model-independent

- Per-event efficiencies
  - mainly using data-driven techniques
- Major systematic contributions:
  - hadron interactions in the detector (3-4%) and trigger (2%)

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}} = 155 \pm 21\,(\mathrm{stat}) \pm 7\,(\mathrm{syst})\,\mathrm{pb}\,,$$

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}} = 82 \pm 19\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\,\mathrm{pb}\,,$$

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}} = 250 \pm 28\,(\mathrm{stat}) \pm 11\,(\mathrm{syst})\,\mathrm{pb}\,,$$

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}} = 80 \pm 16\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\,\mathrm{pb}\,,$$

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- Agrees with DPS using σ_{eff}(CDF)
- Significantly exceeds SPS

Cross-section ratios – I

Reduced uncertainties

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

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

$$\left.\frac{\sigma^{\Upsilon(1S)D^0}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\mathrm{TeV}} = (6.3 \pm 0.8\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}))\,\%\,,$$

$$\left.\frac{\sigma^{\Upsilon(1S)D^+}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\mathrm{TeV}} = (3.4 \pm 0.8\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}))\,\%\,,$$

$$\left.\frac{\sigma^{\Upsilon(1S)D^0}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\mathrm{TeV}} = (7.8 \pm 0.9\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst}))\,\%\,,$$

$$\left.\frac{\sigma^{\Upsilon(1S)D^+}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\mathrm{TeV}} = (2.5 \pm 0.5\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}))\,\%\,.$$

$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\mathrm{TeV}} = (5.5 \pm 1.7)\,\%\,,$$

$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\mathrm{TeV}} = (6.2 \pm 0.7)\,\%\,,$$

DPS

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

DPS

$$\frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = \frac{\sigma^{c\bar{c}}}{\sigma_{\mathrm{eff}}}\,.$$

SPS

$$\frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = (0.2 - 0.6)\,\%$$

Cross-section ratios – II

Reduced uncertainties

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$$\mathscr{B}_{2/1}\times\frac{\sigma^{\Upsilon(2S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}} = (13\pm5)\%\,,$$

$$\mathscr{B}_{2/1}\times\frac{\sigma^{\Upsilon(2S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}}} = (20\pm4)\%\,,$$

$$\mathscr{B}_{2/1}\times\frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}} = (22\pm7)\%\,,$$

$$\mathscr{B}_{2/1}\times\frac{\sigma^{\Upsilon(2S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}}}{\sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}}} = (22\pm6)\%\,,$$

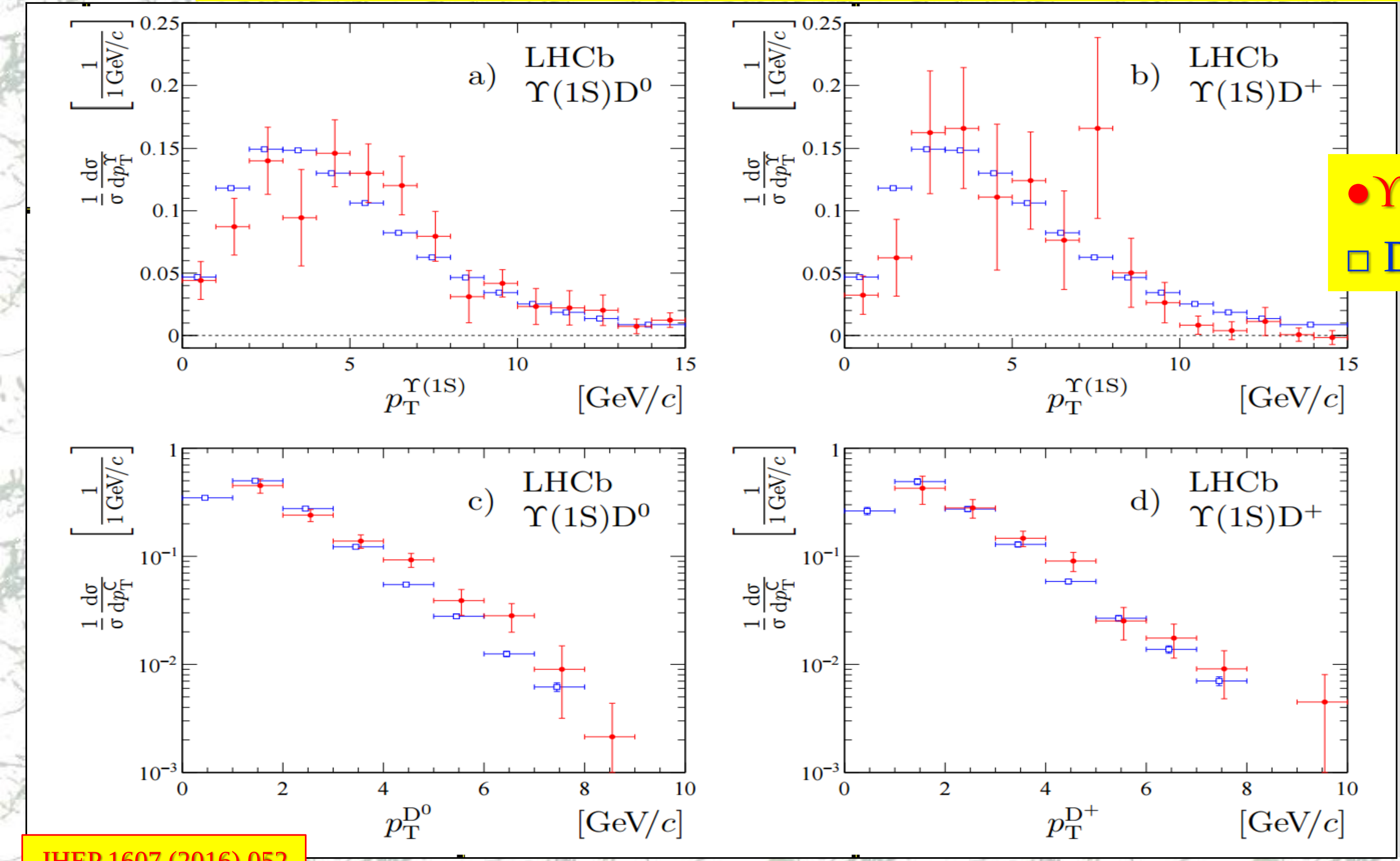
$$\Updownarrow \qquad\qquad \Updownarrow$$

DPS

$$\mathscr{B}_{2/1}\frac{\sigma^{\Upsilon(2S)D^0}}{\sigma^{\Upsilon(1S)D^0}} = \mathscr{B}_{2/1}\frac{\sigma^{\Upsilon(2S)D^+}}{\sigma^{\Upsilon(1S)D^+}} = \mathscr{B}_{2/1}\frac{\sigma^{\Upsilon(2S)}}{\sigma^{\Upsilon(1S)}} = 0.249\pm0.033\,,$$

p_T spectra

DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and Υ-production JHEP 1511 (2015) 103



● $\Upsilon + c\bar{c}$ (data)

□ DPS

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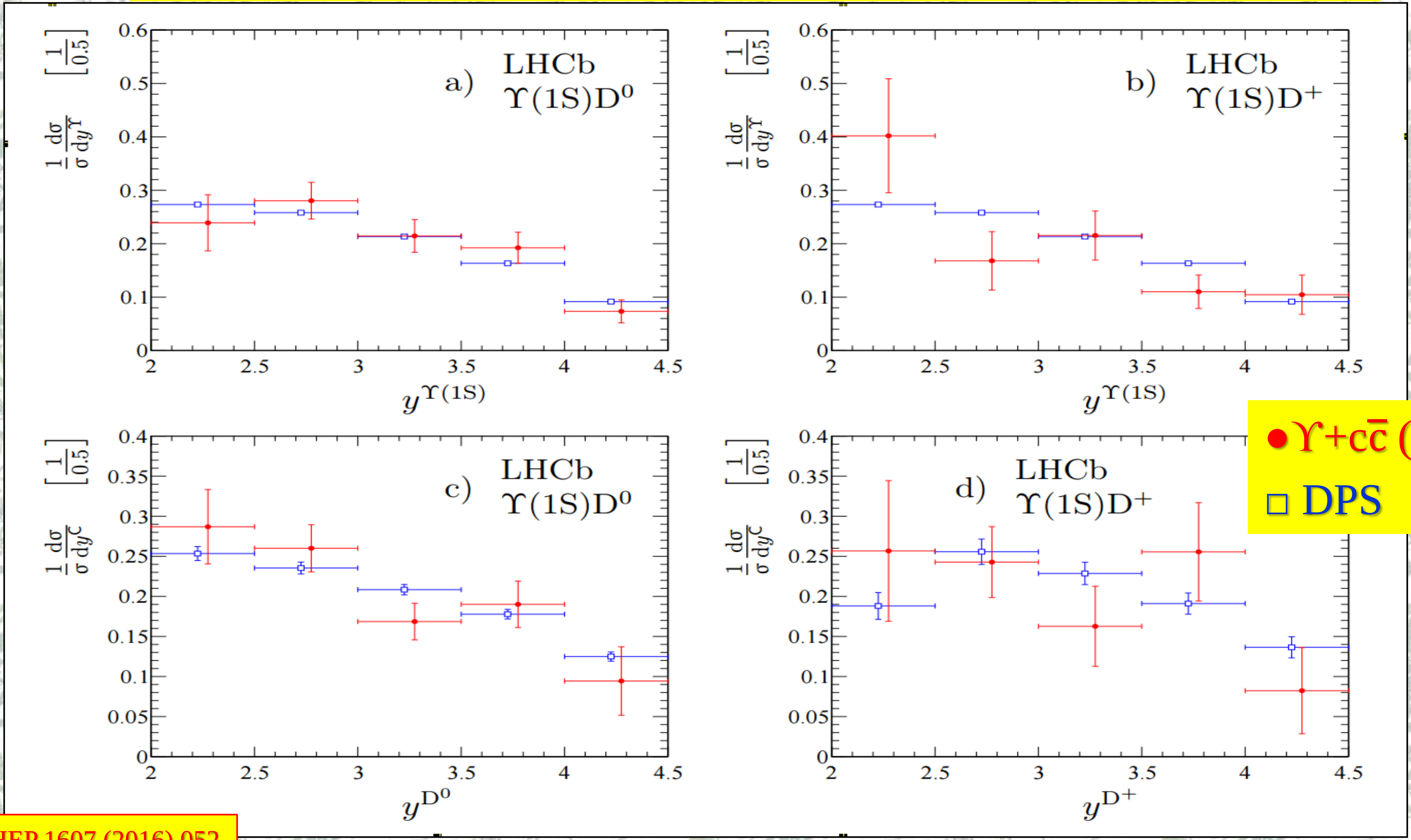
Rapidity

DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and ϒ-production JHEP 1511 (2015) 103



● $\Upsilon + c\bar{c}$ (data)

□ DPS

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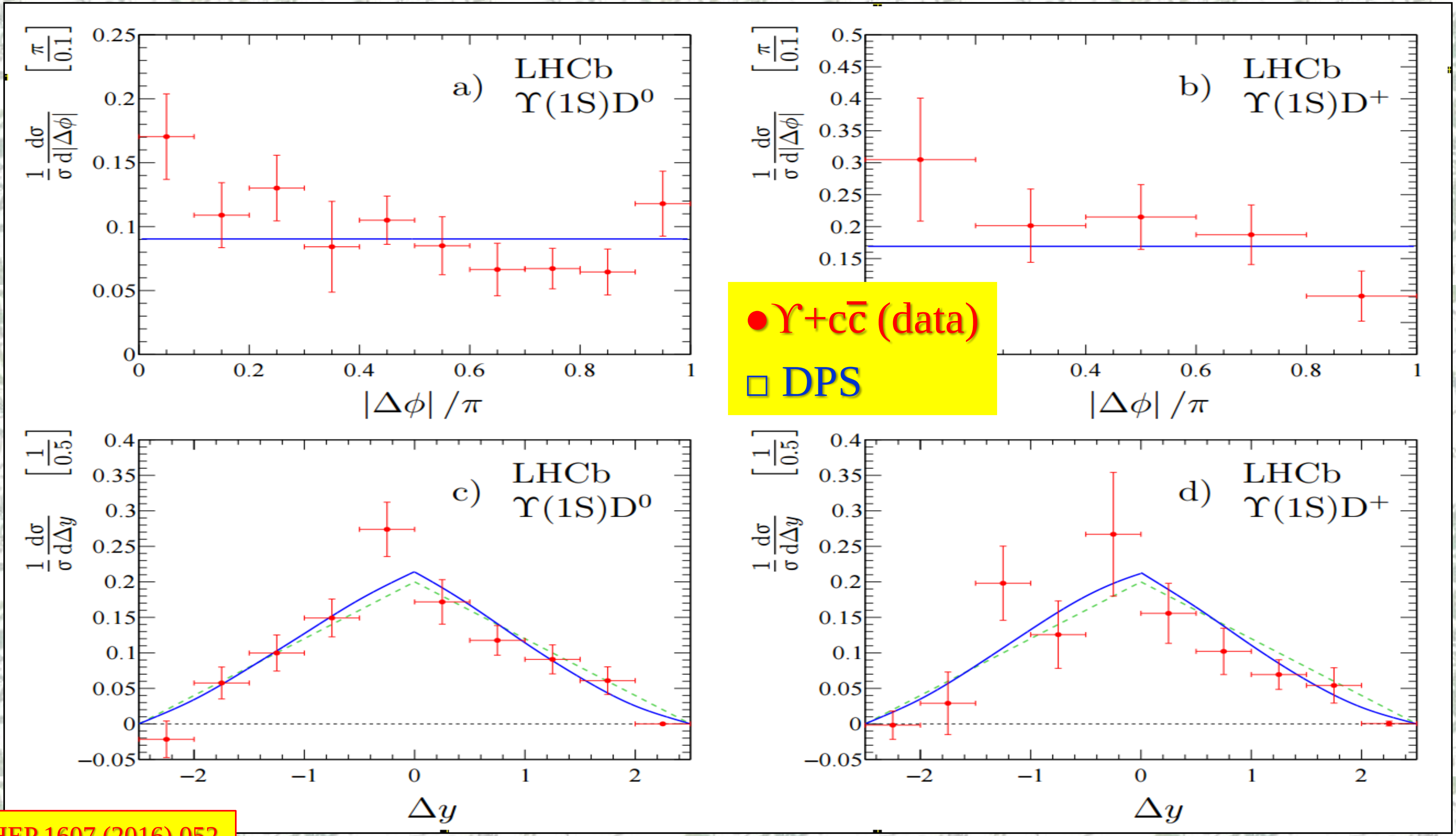
Δϕ and Δy

DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and ϒ-production JHEP 1511 (2015) 103



● ϒ+$c\bar{c}$ (data)

□ DPS

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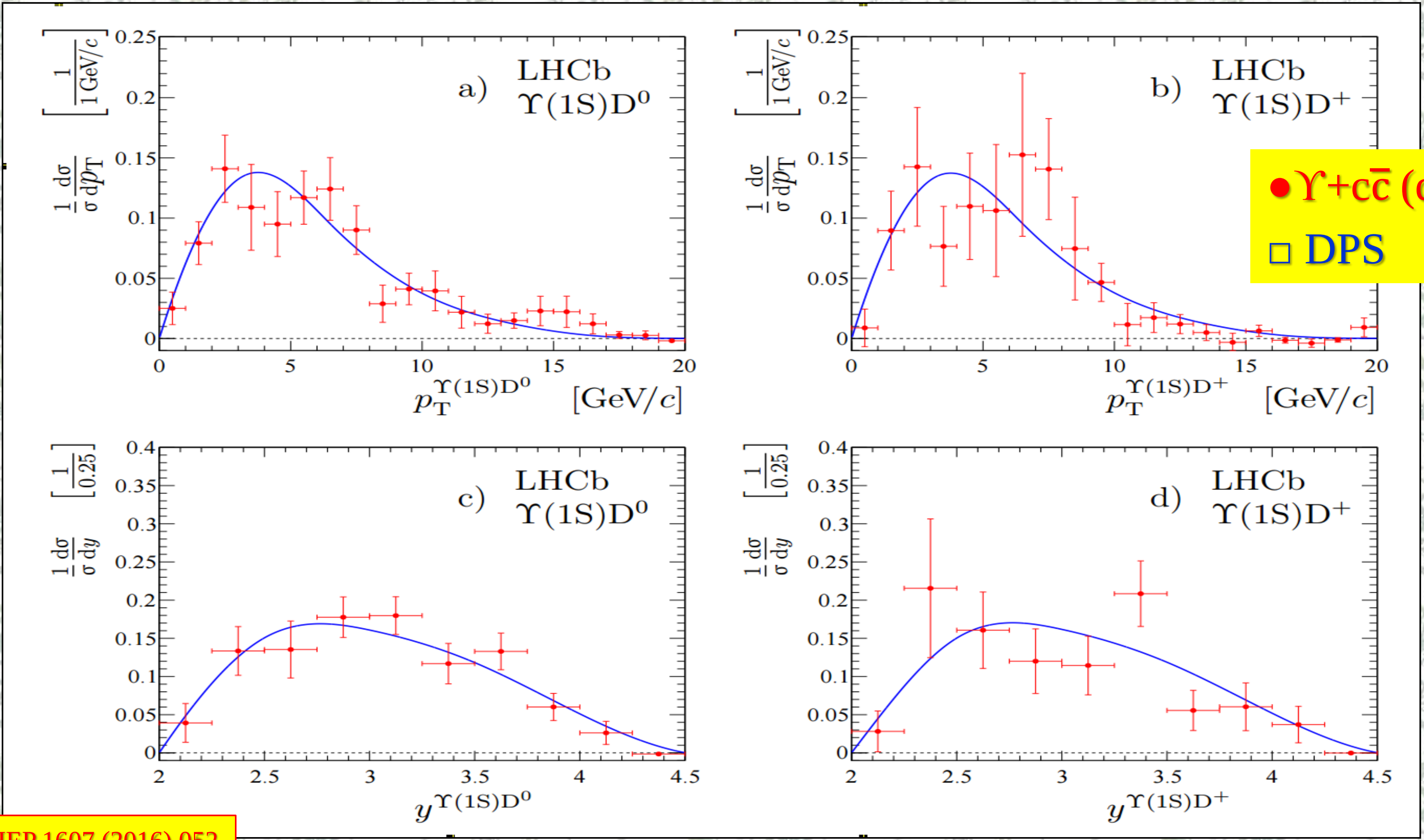
p_T and rapidity

DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and Υ-production JHEP 1511 (2015) 103



● $\Upsilon + c\bar{c}$ (data)

□ DPS

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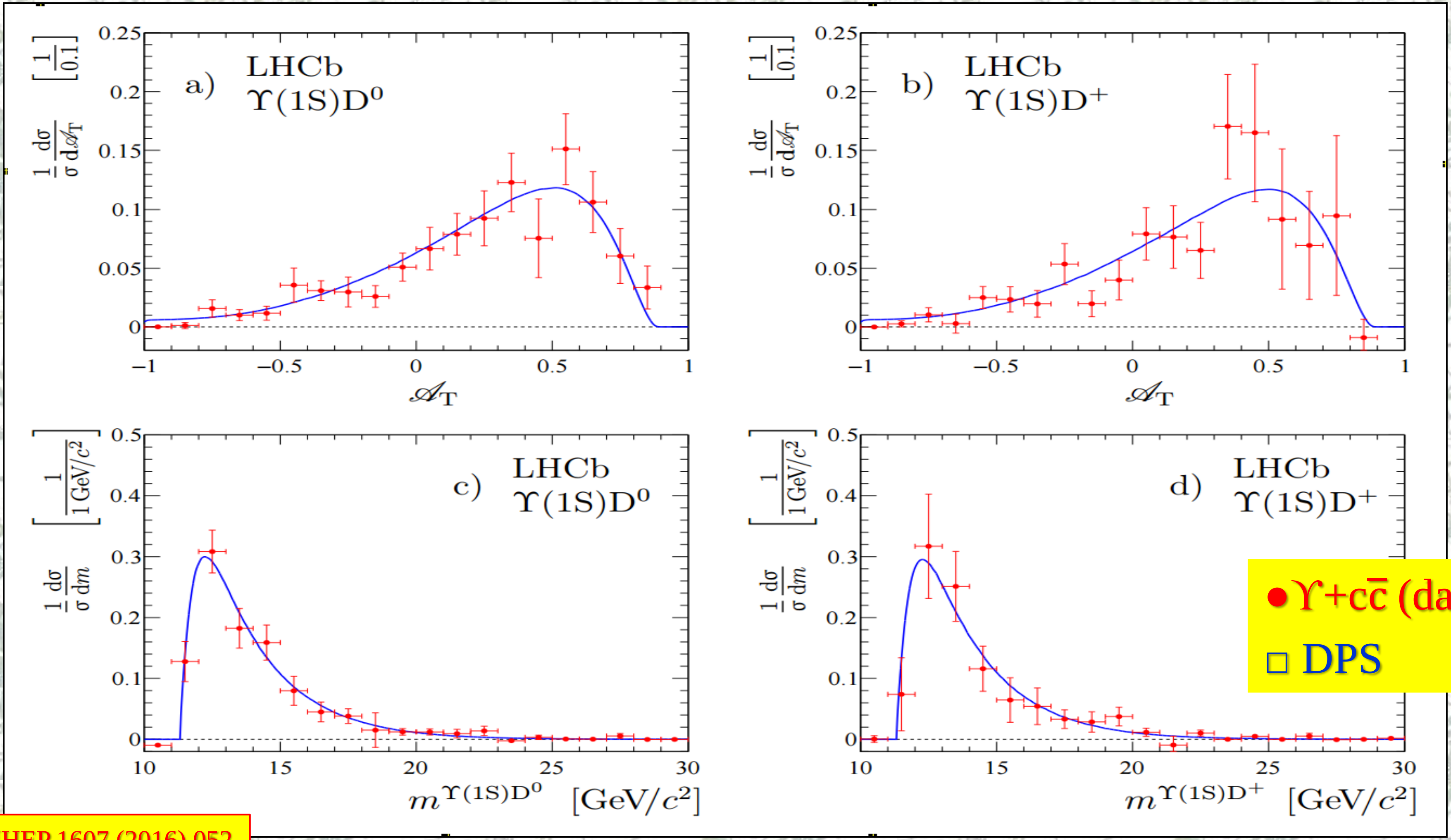
p_T asymmetry and mass

DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and Υ-production JHEP 1511 (2015) 103



● $\Upsilon+c\bar{c}$ (data)

☐ DPS

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DPS? DPS!

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- Measured cross-section significantly exceeds SPS expectations, agrees with DPS with σ_{eff}(CDF)
- All cross-section ratios agree with DPS
- Differential distributions agree with DPS
- Measure σ_{eff}

7TeV

$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^0} = 19.4 \pm 2.6\,(\mathrm{stat}) \pm 1.3\,(\mathrm{syst})\,\mathrm{mb}\,,$$
$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^+} = 15.2 \pm 3.6\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})\,\mathrm{mb}\,.$$

8TeV

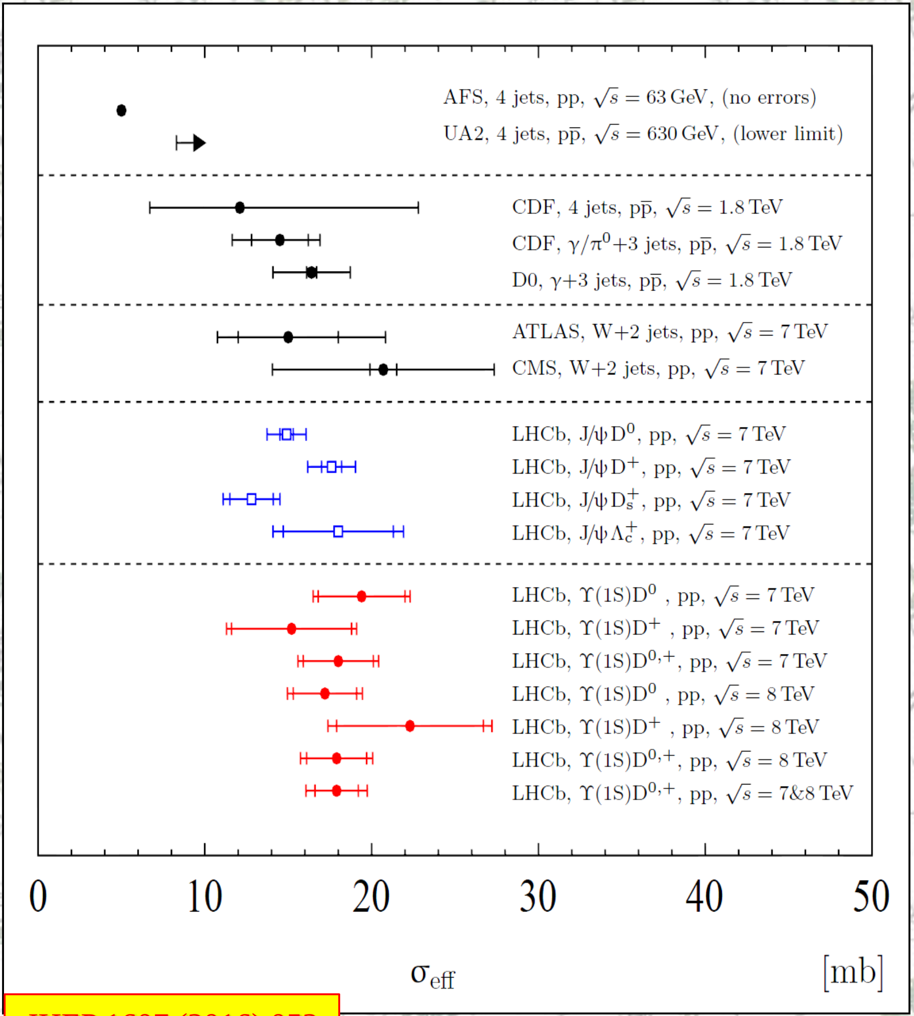
$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^0} = 17.2 \pm 1.9\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst})\,\mathrm{mb}\,,$$
$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^+} = 22.3 \pm 4.4\,(\mathrm{stat}) \pm 2.2\,(\mathrm{syst})\,\mathrm{mb}\,,$$

$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^{0,+},\sqrt{s}=7\,\mathrm{TeV}} = 18.0 \pm 2.1\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst}) = 18.0 \pm 2.4\,\mathrm{mb}\,.$$

$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^{0,+},\sqrt{s}=8\,\mathrm{TeV}} = 17.9 \pm 1.8\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst}) = 17.9 \pm 2.1\,\mathrm{mb}\,,$$

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

σ_{eff}



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- Excellent agreement with J/ψ+c$\bar{\text{c}}$
- Agrees well with γ+3*jets*
- Agrees well with W+2*jets*

A kind of tension with

2×J/ψ 8.2±2.0±2.9mb

(CMS+Lansberg,Shao)

2×J/ψ 4.8±0.5±2.5mb D0

J/ψ+Υ 2.2±0.7±0.9mb D0

Summary

- Associative production of $\Upsilon+c\bar{c}$ is observed
- For five modes with $>5\sigma$ significance
- Cross-sections are measured for $\Upsilon(1,2S)D^{0,+}$
- Cross-sections and their rations agree with DPS
- Cross-sections significantly exceed SPS
- Differential distributions supports DPS
- *Precise measurement of* σ_{eff}
    - In an excellent agreement with $J/\psi+c\bar{c}$ results
- Other interesting measurements with Run-I data:
    - $Z+c\bar{c}$, $2\times J/\psi$, ….

13TeV data : importance of DPS is increasing

Who waits ***Triple Parton Scattering***?

Thank you!

Refs

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- A.V. Berezhnoy, V.V. Kiselev, A.K. Likhoded and A.I. Onishchenko, "*Double charmed baryon production in hadronic experiments*", Phys.Rev. D57(1998), 4385, arXiv:hep-ph/9710339
- S.P.Baranov, "*Topics in associated $J/\psi+c+\bar{c}$ production at modern colliders*", Phys.Rev. D73 (2006) 074021
- J.P.Lansberg, "*On mechanisms of heavy-quarkonium hadroproduction*", Eur.Phys.J. C61 (2009) 693, arXiv:0811.4005
- R.Maciula and A.Szczurek, "*Single and double charmed meson production at the LHC*", EPJ Web Conf. 81 (2014) 01007

Too simple?

- Validity of factorization anzatz:

$$D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) \ = \ D_h^i(x_1; Q_1^2) D_h^j(x_2; Q_2^2).$$

- This anzatz allow $x_1+x_2>1$:
  - energy non-conservation. Need to suppress such configurations: at least $\theta(1-x_1-x_2)$ factor is needed
  - Makes integration impossible
- Numerical studies within Lund dipole cascade model shows violation of factorization at large Q_1^2 and/or Q_2^2
  - up to 20% deviation from factorization in γ+*jets* cross-sections in Tevatron case
  - Up to 30-50% for certain kinematical ranges
- For processes with (very) small x only factorization is fine

$$\Gamma_{gg}(b, x_1, x_2; \mu_1^2, \mu_2^2) \\ = F_g(x_1, \mu_1^2) F_g(x_2, \mu_2^2) F(b; x_1, x_2, \mu_1^2, \mu_2^2),$$

$$\sigma_{\text{eff}}(x_1, x_2, x_1', x_2', \mu_1^2, \mu_2^2) \\ = \left(\int d^2 b F(b; x_1, x_2, \mu_1^2, \mu_2^2) F(b; x_1', x_2', \mu_1^2, \mu_2^2) \right)^{-1}.$$

Differential distributions

- Powerful tool to judge on the production mechanism
- **DPS:** all kinematic distributions can be calculated from ***measured*** inclusive Υ and D spectra
  - Make ***toy-MC*:**
    - Sample 4-momenta of Υ and D from the measured published differential cross-sections (+ assume uniform uncorrelated ϕ-distributions)
- **SPS:** there are no differential predictions
  - But some non-trivial correlations are expected