DPS studies at LHCb

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On behalf of LHCb collaboration

The Abdus Salam
International Centre
for Theoretical Physics
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The Abdus Salam International Centre for Theoretical Physics (ICTP), in collaboration with the Italian Institute for Nuclear Physics (INFN), will hold the

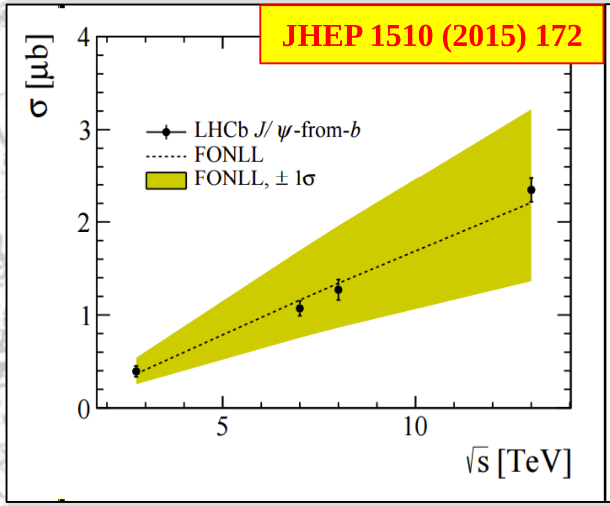
7th International Workshop on
Multiple Partonic Interactions
at the LHC

23 - 27 November 2015

Miramare, Trieste, Italy

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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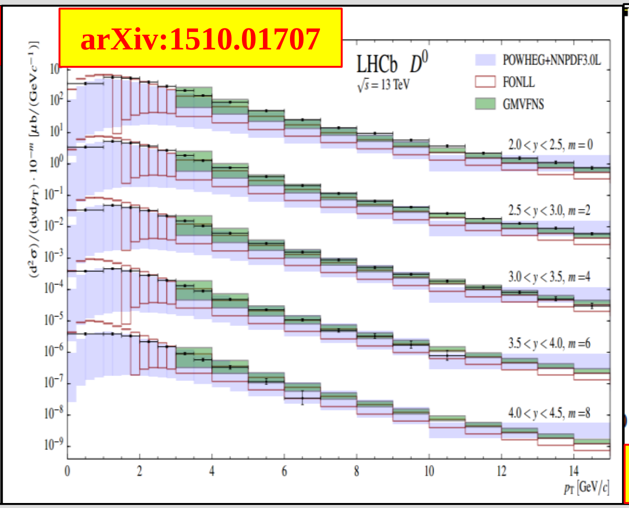
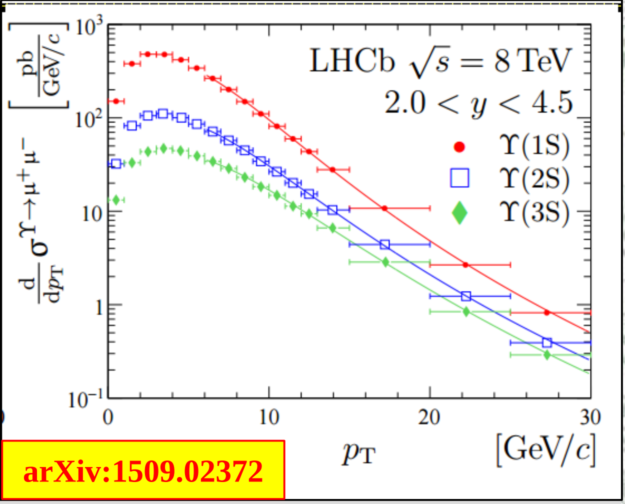


arXiv:1510.07707



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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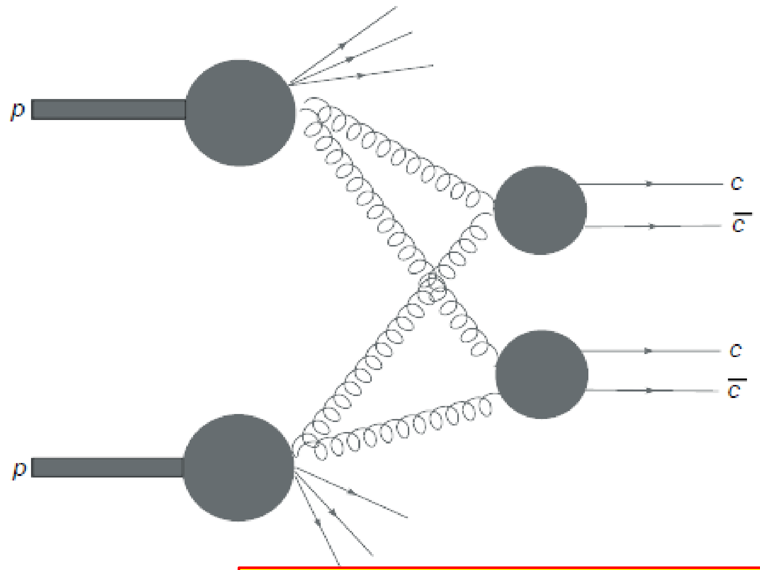
DPS: simple paradigm



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***

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

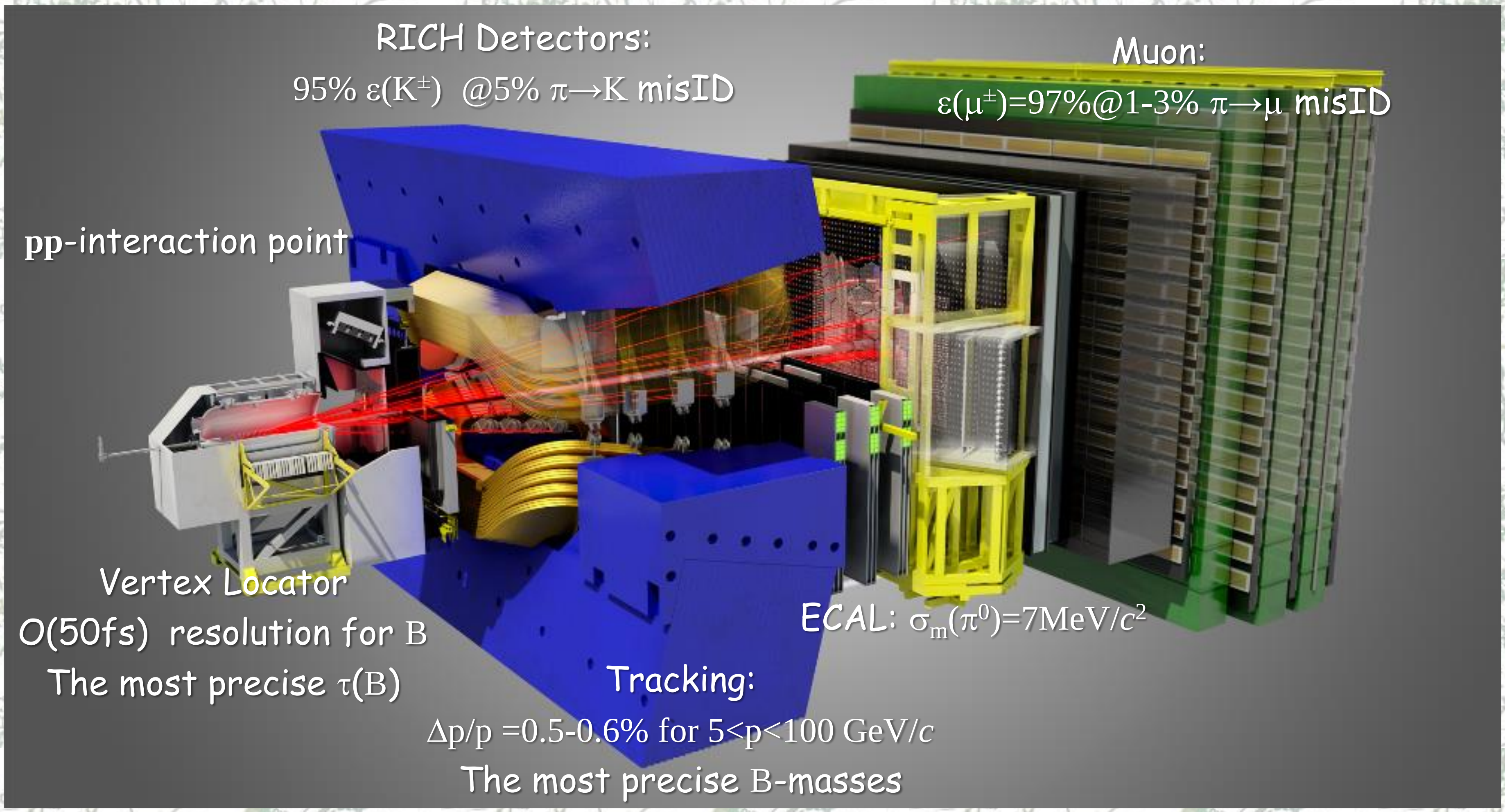
$$\frac{d\sigma^{\rm DPS}(pp \to c\bar{c}c\bar{c}X)}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t} dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}} = \frac{1}{2\sigma_{\rm eff}} \cdot \frac{d\sigma^{\rm SPS}(pp \to c\bar{c}X_1)}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} \cdot \frac{d\sigma^{\rm SPS}(pp \to c\bar{c}X_2)}{dy_3 dy_4 d^2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

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

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

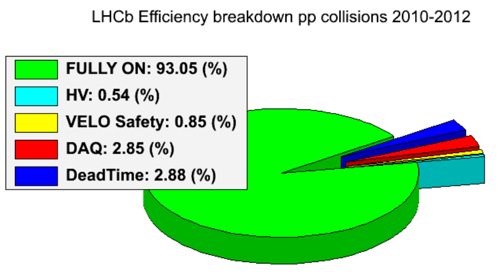
- ***LHCb: 10% of all "hard" events (irrespectively from the process) have additional charm pair***

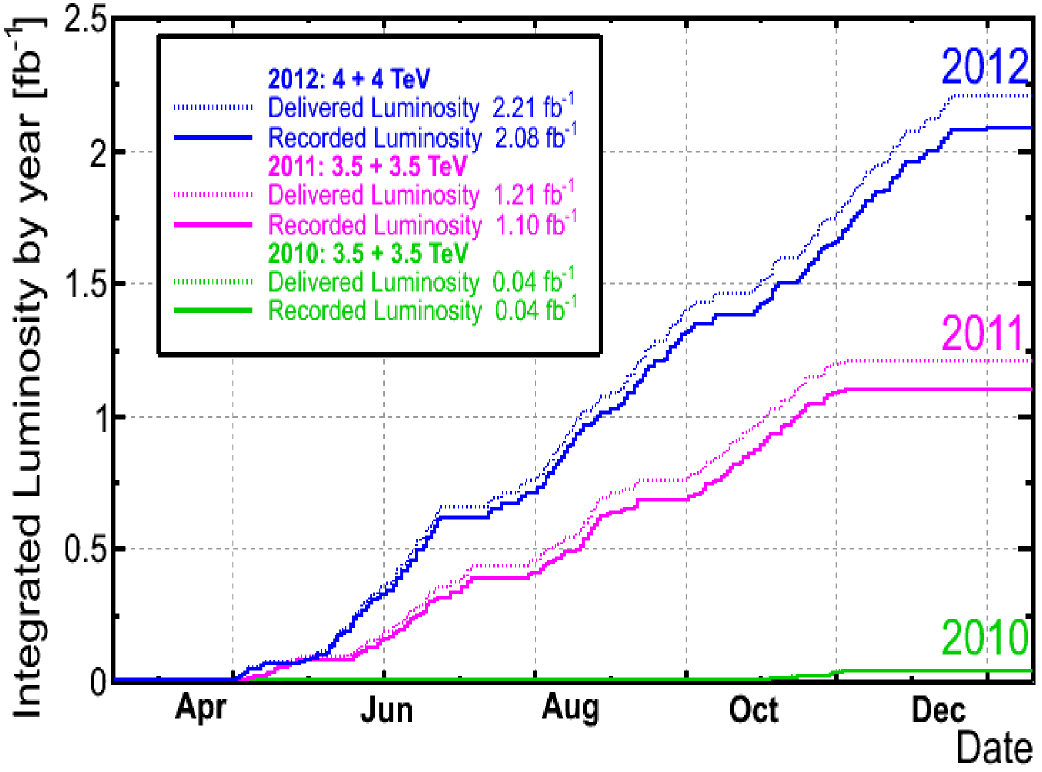
~40% of heavy quarks in <4% of 4π



Run I

- $1fb^{-1}$@7TeV
- $2fb^{-1}$@8TeV
- $3.3pb^{-1}$ @2.76TeV
- $1.6\ nb^{-1}$ pA & Ap





Thanks to LHC accelerator team for the excellent performance of machine

Run-II: $>300pb^{-1}$ @ $\sqrt{s}$=13TeV

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

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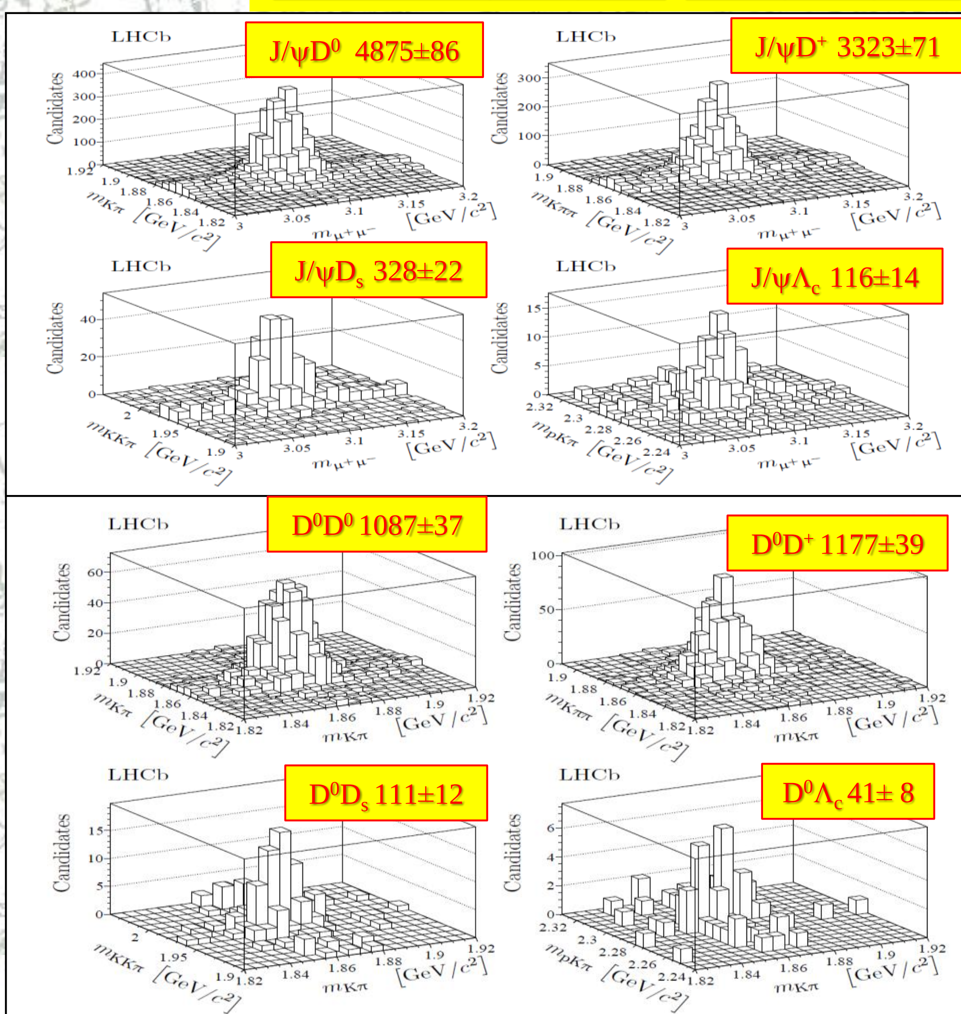
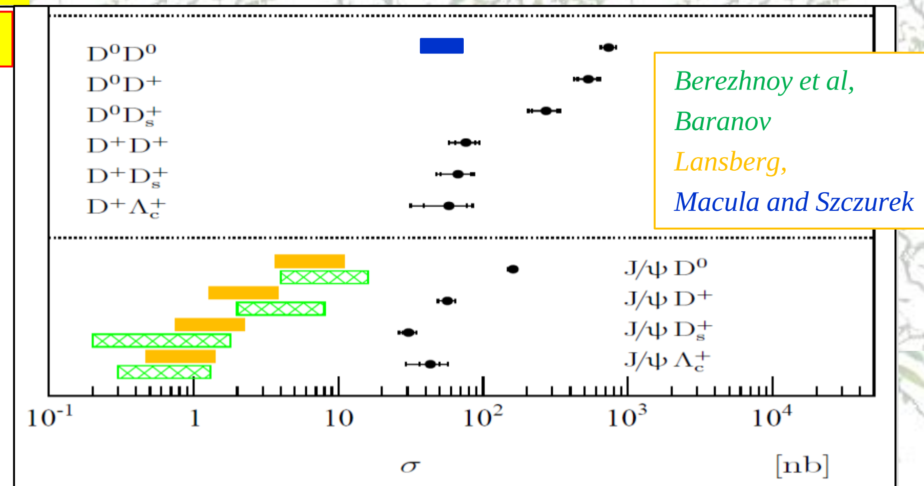
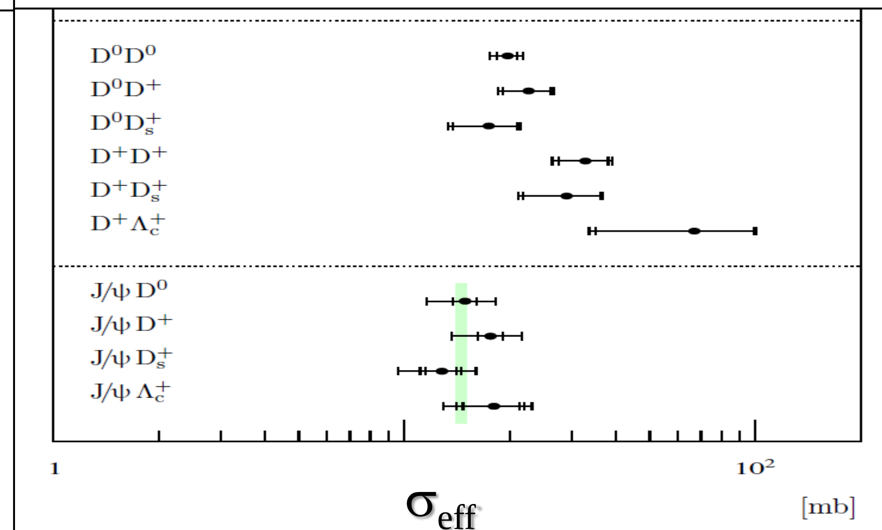
$\sqrt{s}$=7TeV, 355pb^{-1}







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

- 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 $J/\psi + c\bar{c}$

Υ + $c\bar{c}$

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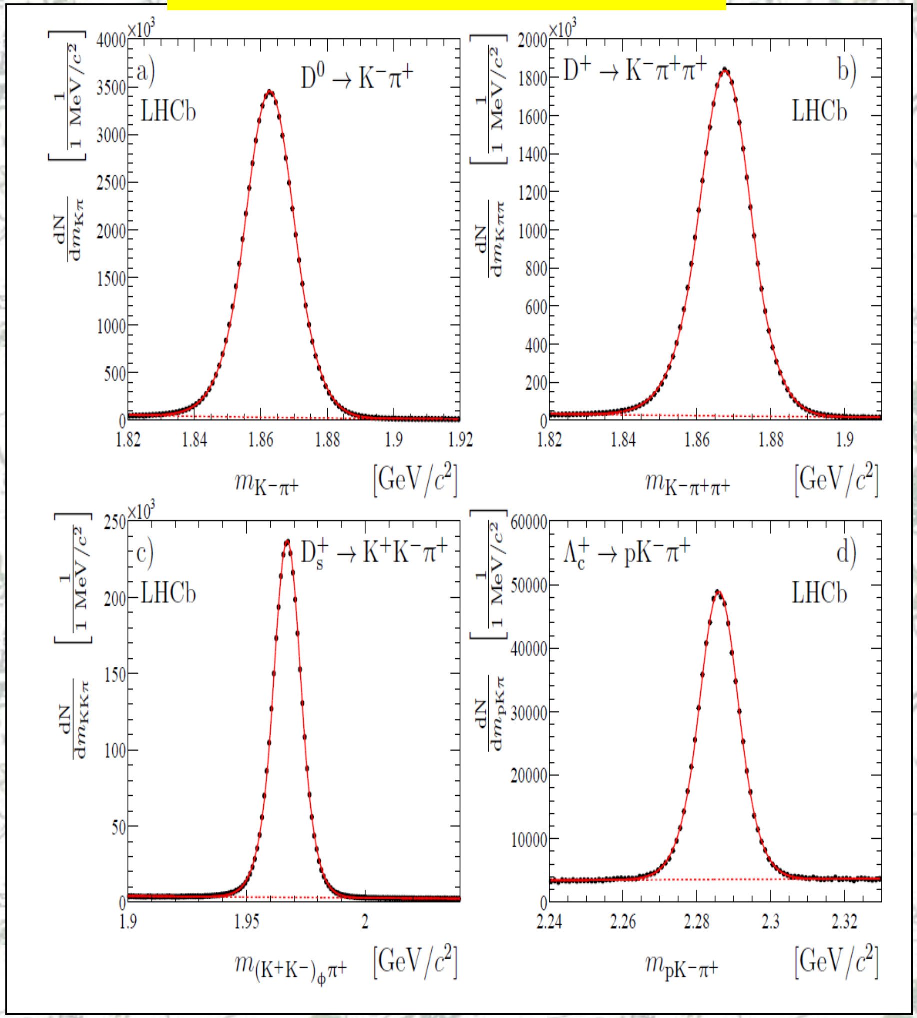
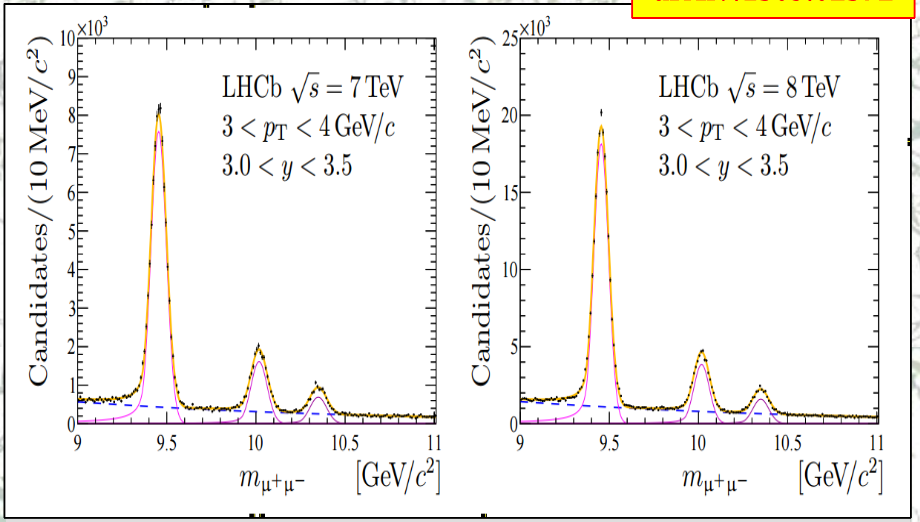
arXiv:1509.02372





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

  D^0 $O(200M/fb^{-1})$

  D^+ $O(100M/fb^{-1})$

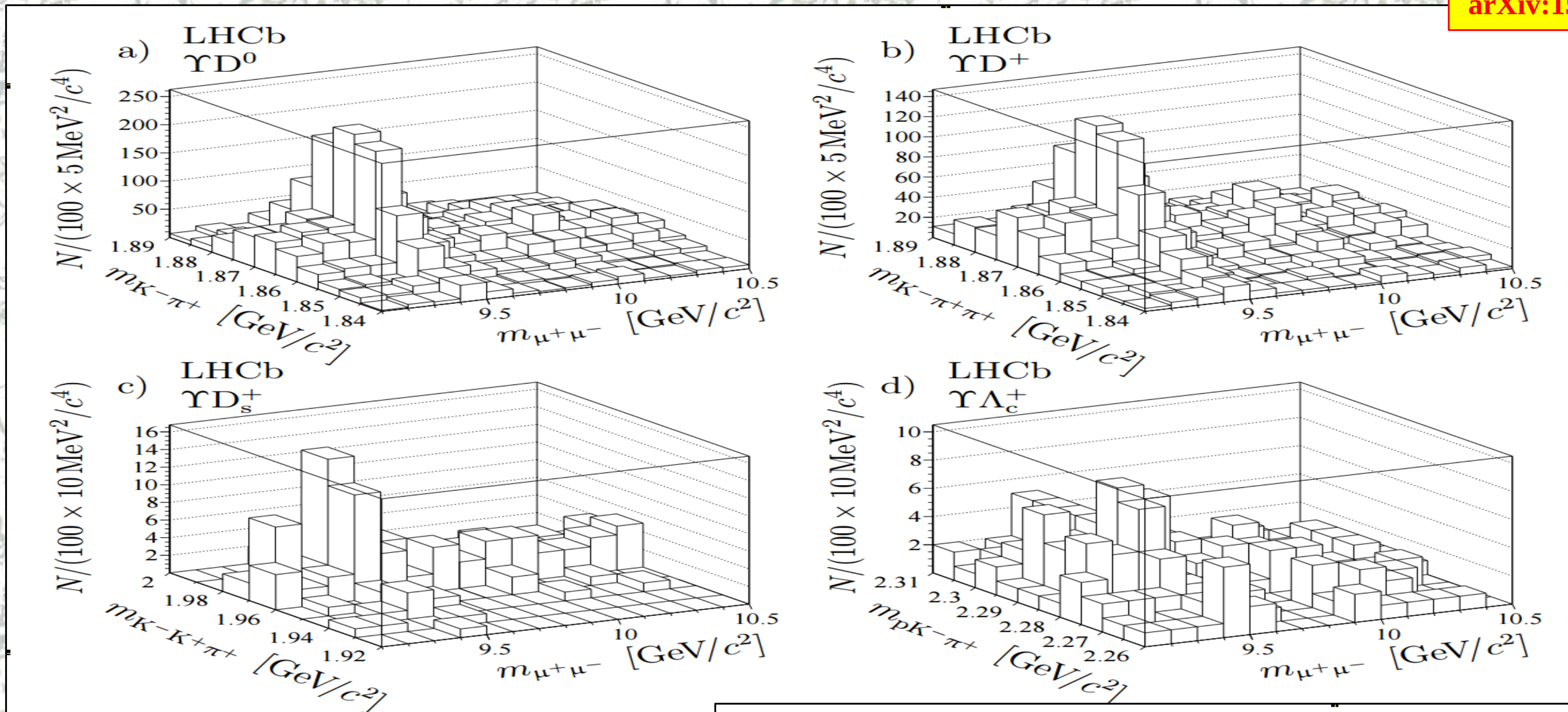
  D_s $O(10M/fb^{-1})$

  Λ_c $O(20M/fb^{-1})$

  $\Upsilon(1,2,3S)$: $O(3, 0.7, 0.3M/fb^{-1})$

$\Upsilon + c\bar{c}$

arXiv:1509.05949



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

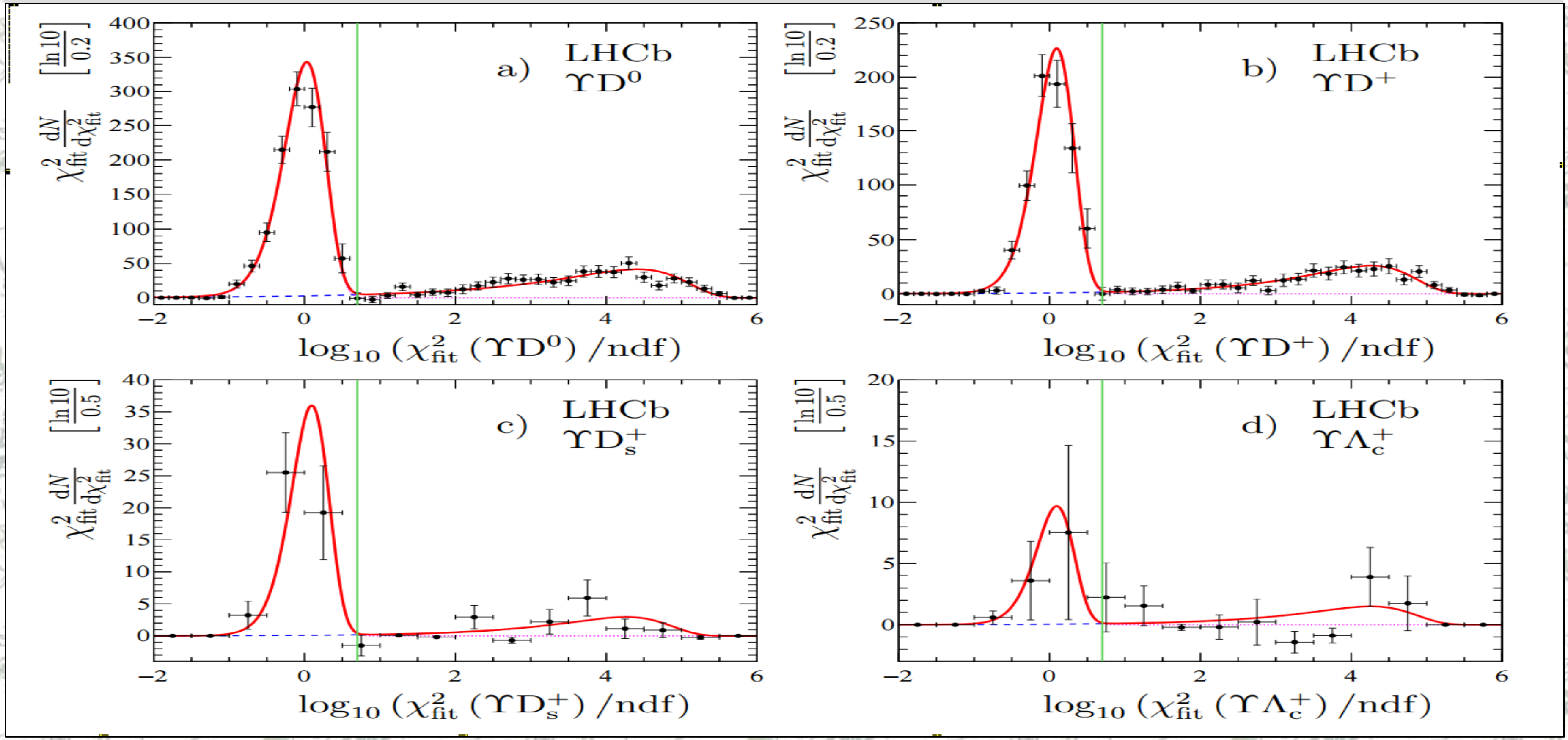
Five modes with >5σ!

Pileup?

arXiv:1509.05949

- 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%)

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

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

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

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

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

arXiv:1509.05949

Cross-section ratios – I

Reduced uncertainties

arXiv:1509.05949

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

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

DPS

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

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

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

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

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

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

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

DPS

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

SPS

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

arXiv:1510.05949

Cross-section ratios – II

Reduced uncertainties

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

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

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

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

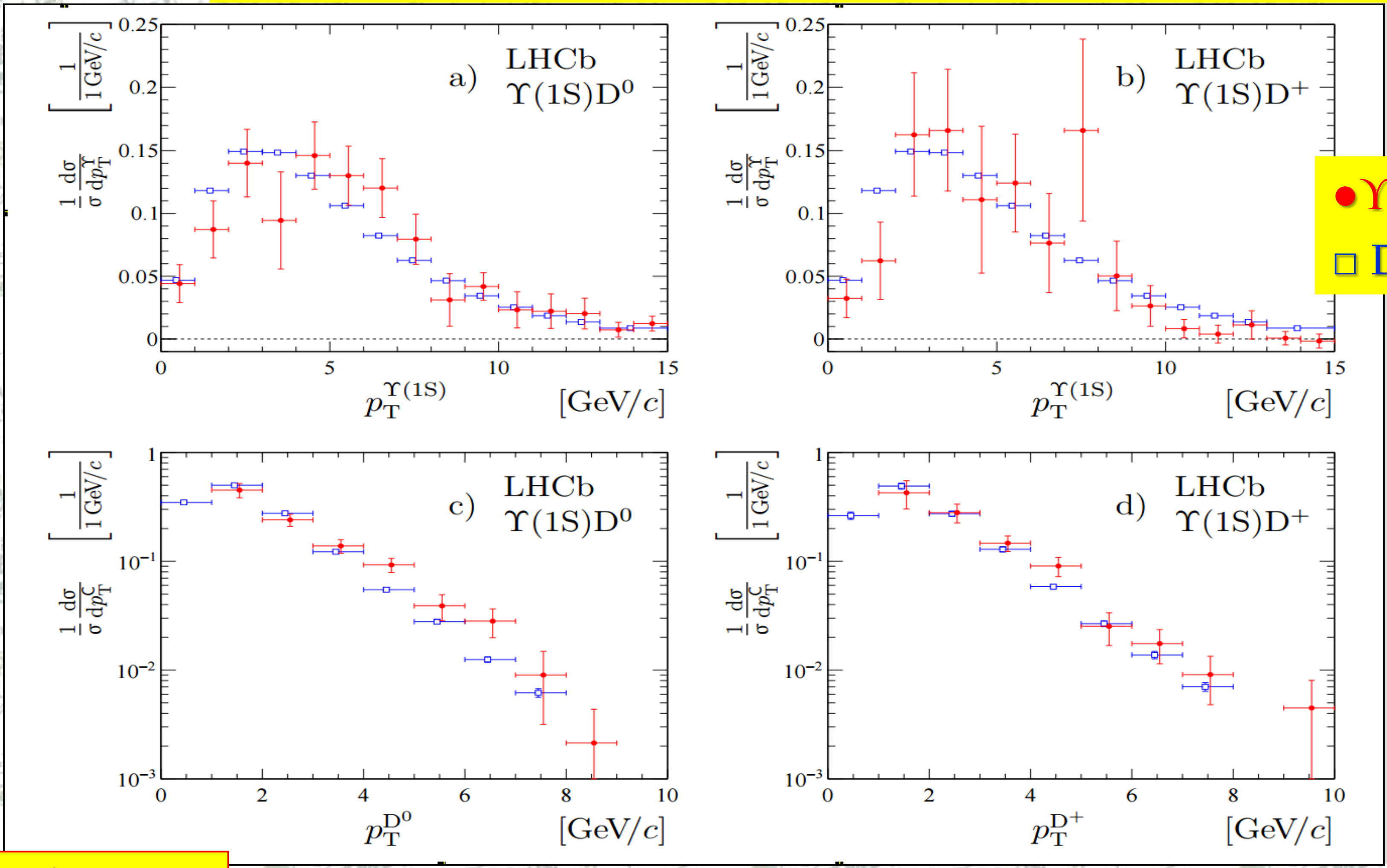
DPS

$$\mathscr{B}_{2/1} \frac{\sigma^{\Upsilon(2S)D^0}}{\sigma^{\Upsilon(1S)D^0}} = \mathscr{B}_{2/1} \frac{\sigma^{\Upsilon(2S)D^+}}{\sigma^{\Upsilon(1S)D^+}} = \mathscr{B}_{2/1} \frac{\sigma^{\Upsilon(2S)}}{\sigma^{\Upsilon(1S)}} = 0.249 \pm 0.033\,,$$

arXiv:1510.05949

p_T spectra

DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and Υ-production arXiv:1509.02372



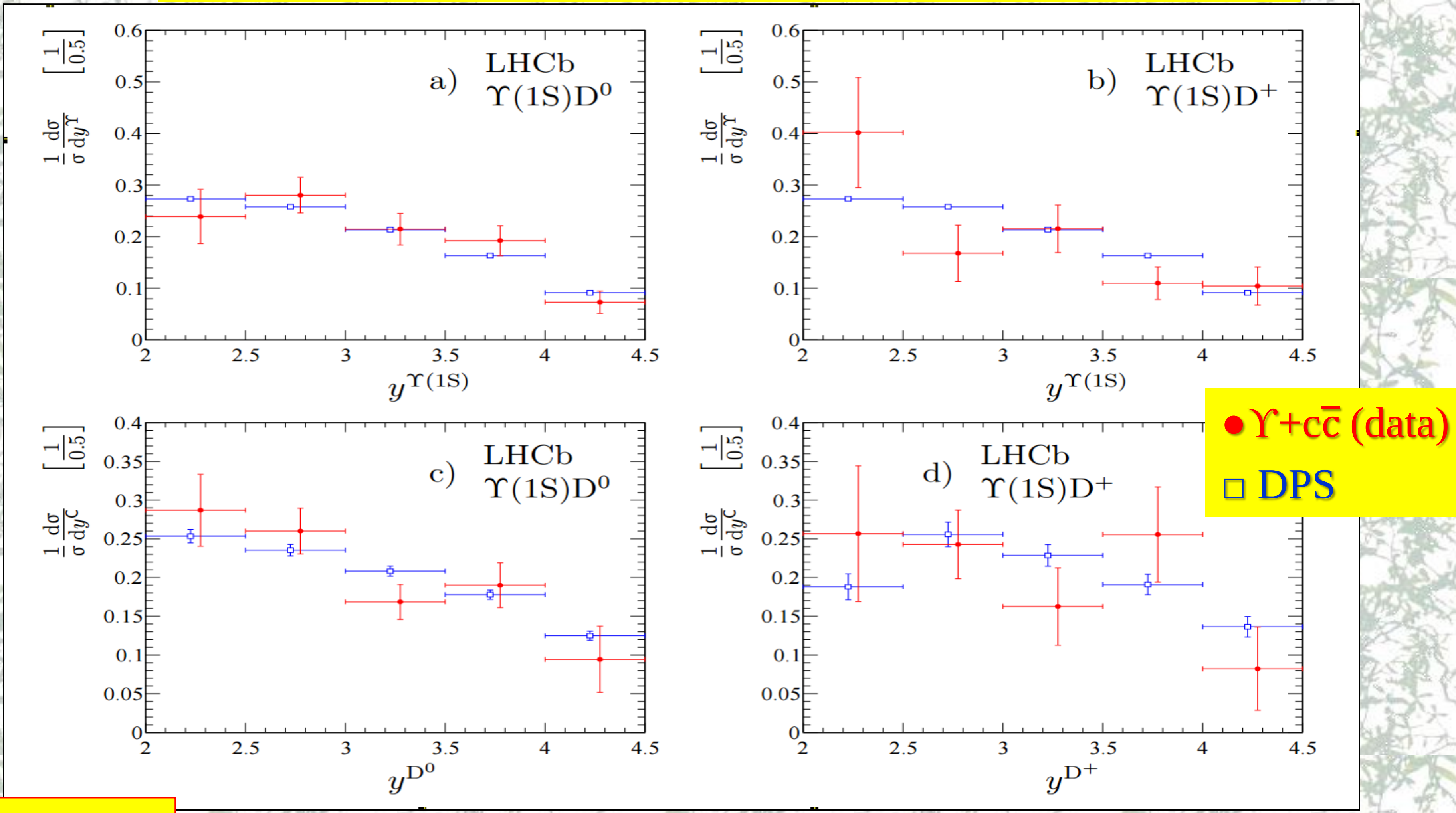
● $\Upsilon + c\bar{c}$ (data)

□ DPS

arXiv:1510.05949

Rapidity

DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and Υ-production arXiv:1509.02372



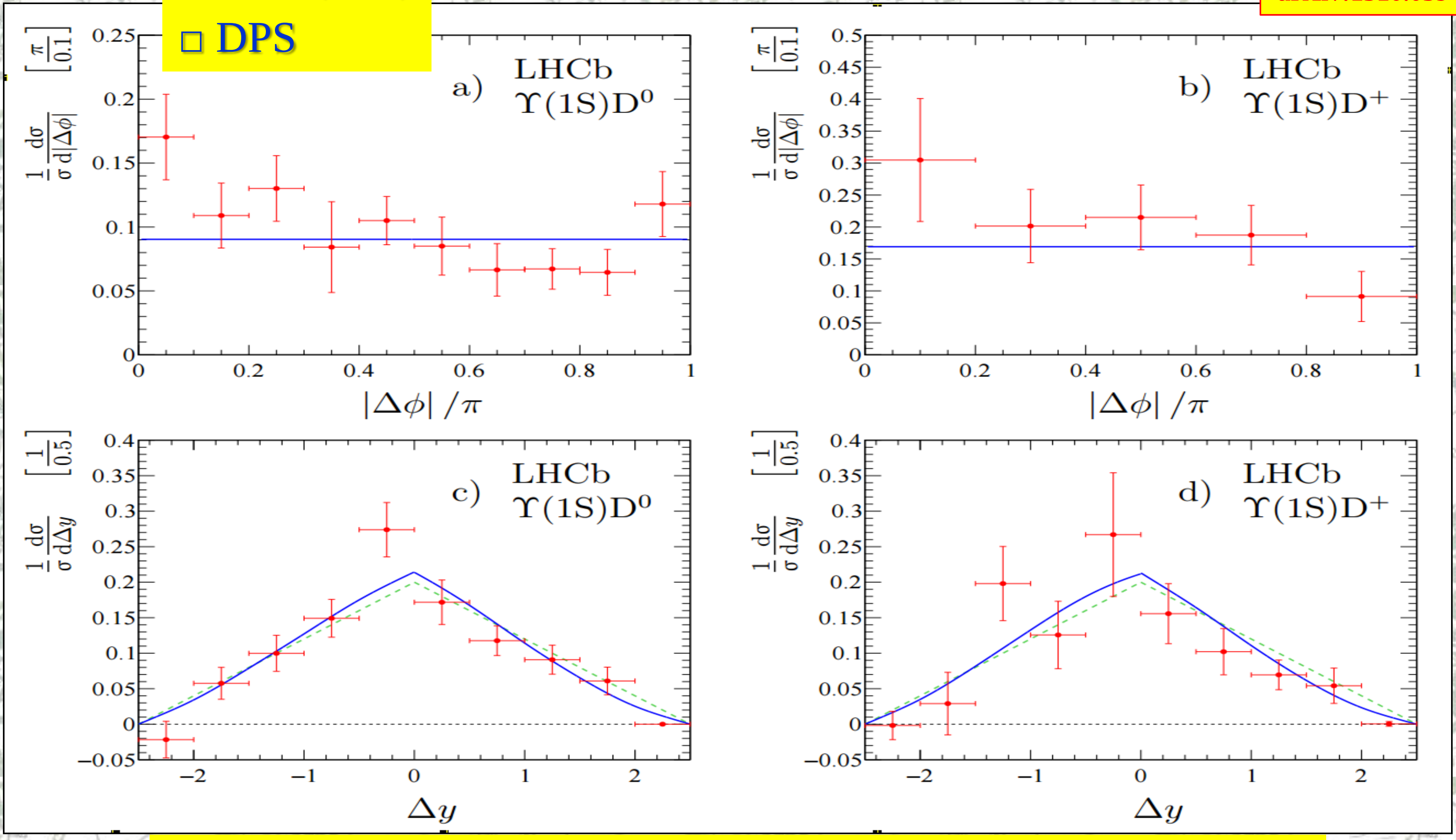
arXiv:1510.05949

Δϕ and Δy

●ϒ+c$\bar{c}$ (data)

□ DPS

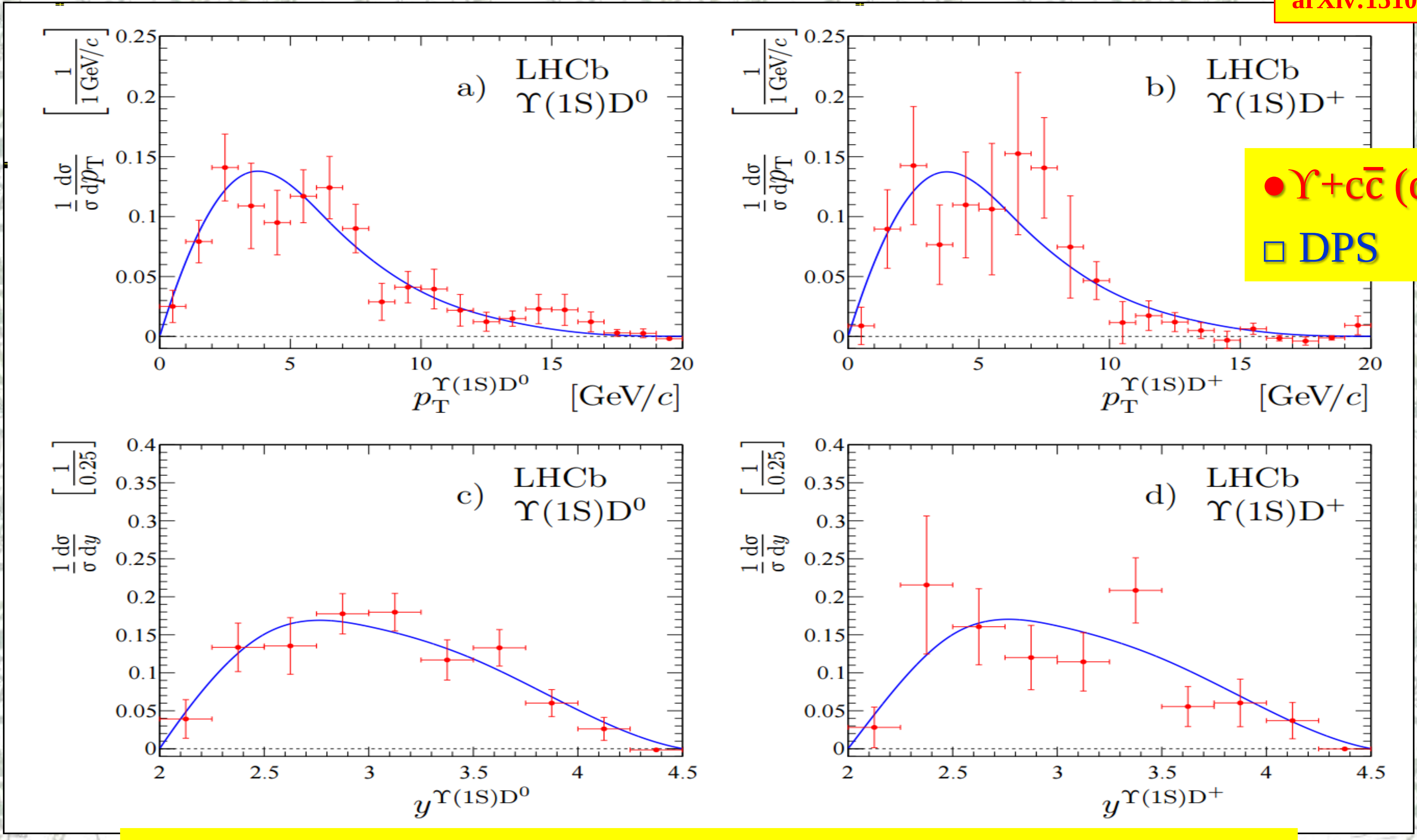
arXiv:1510.05949



DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and ϒ-production arXiv:1509.02372

p_T and rapidity

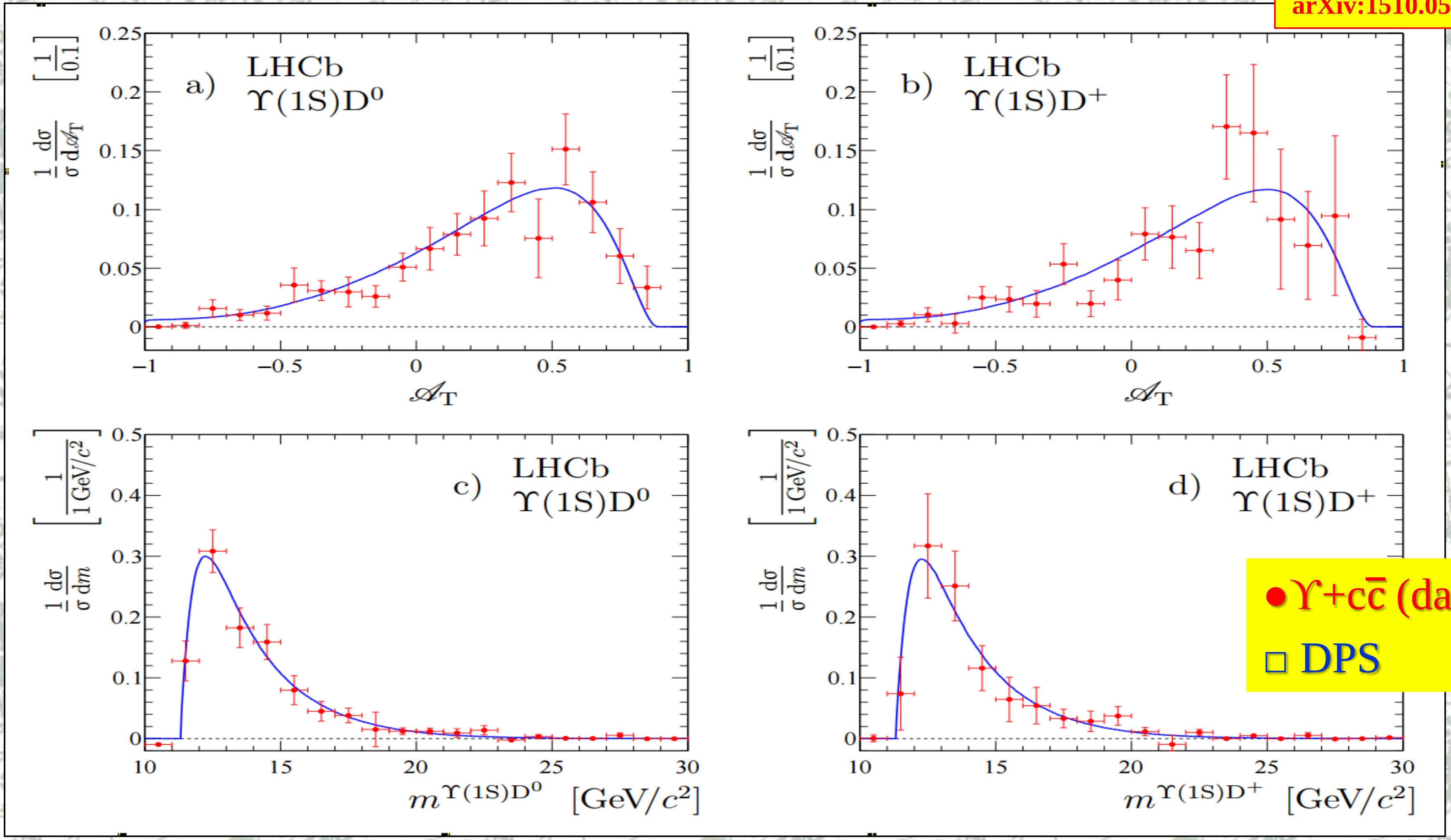
arXiv:1510.05949



DPS: LHCb data for open charm (Nucl.Phys. B871 (2013) 1) and Υ-production arXiv:1509.02372

p_T asymmetry and mass

arXiv:1510.05949



DPS? DPS!

arXiv:1510.05949

- 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

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

8TeV

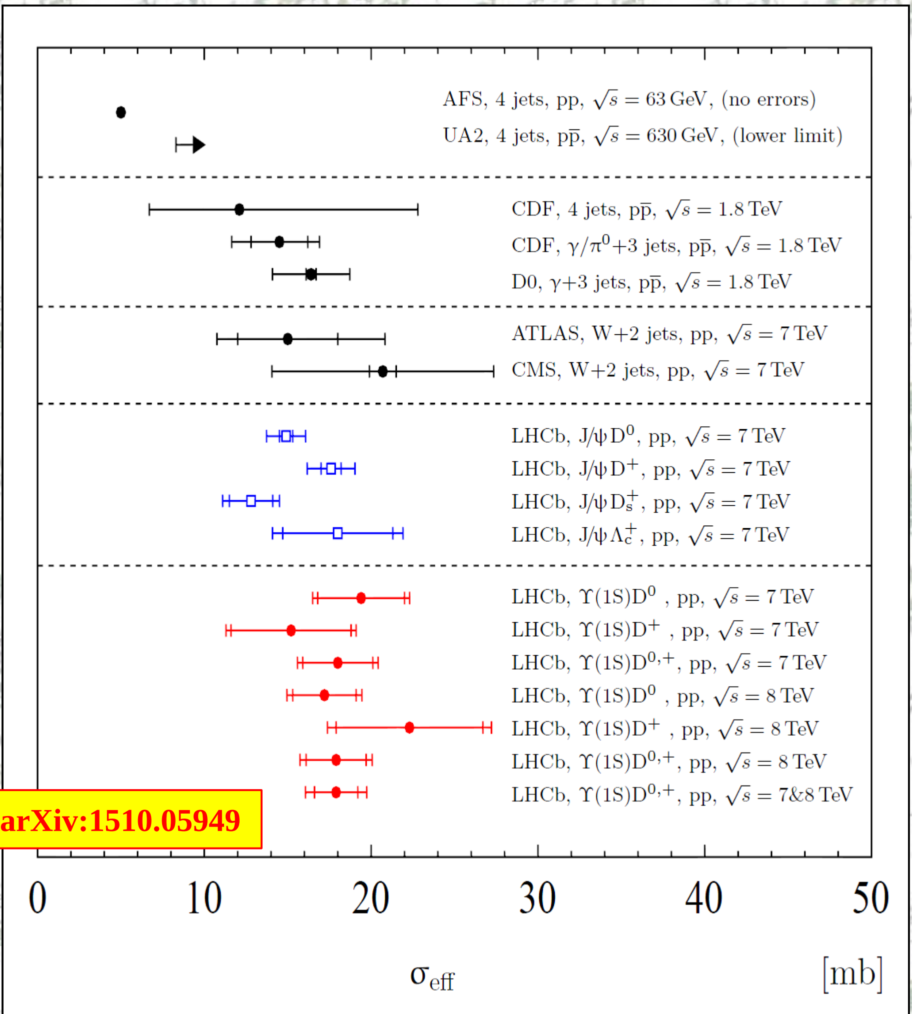
$$\sigma_{eff}|_{\Upsilon(1S)D^0} = 17.2 \pm 1.9\,(stat) \pm 1.2\,(syst)\,mb\,,$$
$$\sigma_{eff}|_{\Upsilon(1S)D^+} = 22.3 \pm 4.4\,(stat) \pm 2.2\,(syst)\,mb\,,$$

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

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

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

σ_{eff}



- Excellent agreement with $J/\psi + c\bar{c}$
- Agrees well with $\gamma+3jets$
- Agrees well with $W+2jets$

A kind of tension with

$2\times J/\psi$ 8.2±2.0±2.9mb (CMS+Lansberg,Shao)

$2\times J/\psi$ 4.8±0.5±2.5mb D0

$J/\psi+\Upsilon$ 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

- A.V. Berezhnoy, A.K.Likhoded, *"Associated production of Υ and open charm at LHC"*, Int.J.Mod.Phys,A30 (2015) 1550125, arXiv:1503.04445
- 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

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

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

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