LHCb results on associated production of heavy quarks

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On behalf of LHCb collaboration

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

See talk by M.Needham and R. Silva Coutinho

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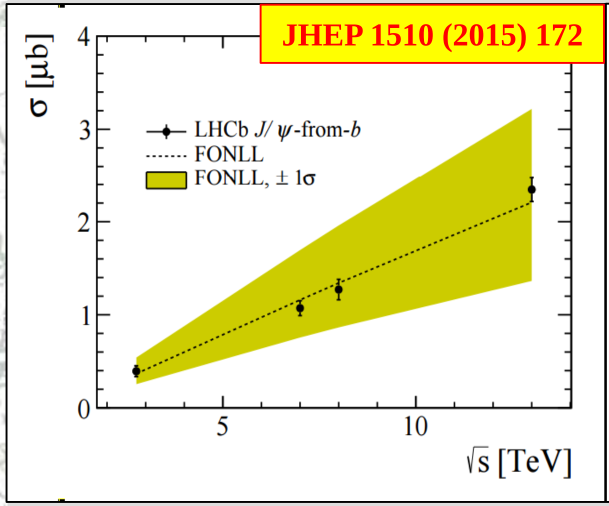

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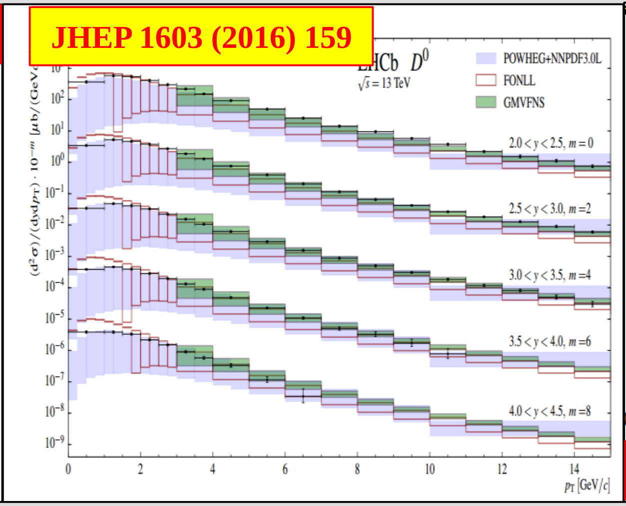

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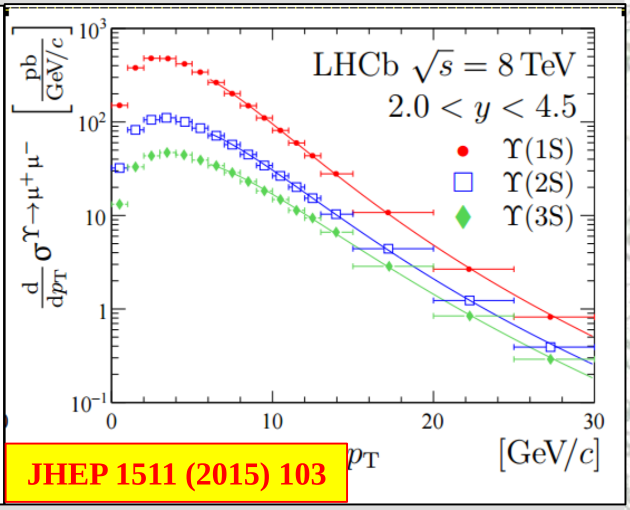

- Heavy flavour production cross-section in forward region is large

$\sigma(c\bar{c})_{p_T<8\,\mathrm{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\ \mu\mathrm{b},$ vs $\sigma^{\mathrm{acc}}_{\mathrm{inel}}(p_T > 0.2\ \mathrm{GeV}/c,\ 2.0 < \eta < 4.5) = 55.0 \pm 2.4\ \mathrm{mb}\,,$

Nucl.Phys. B871 (2013) 1

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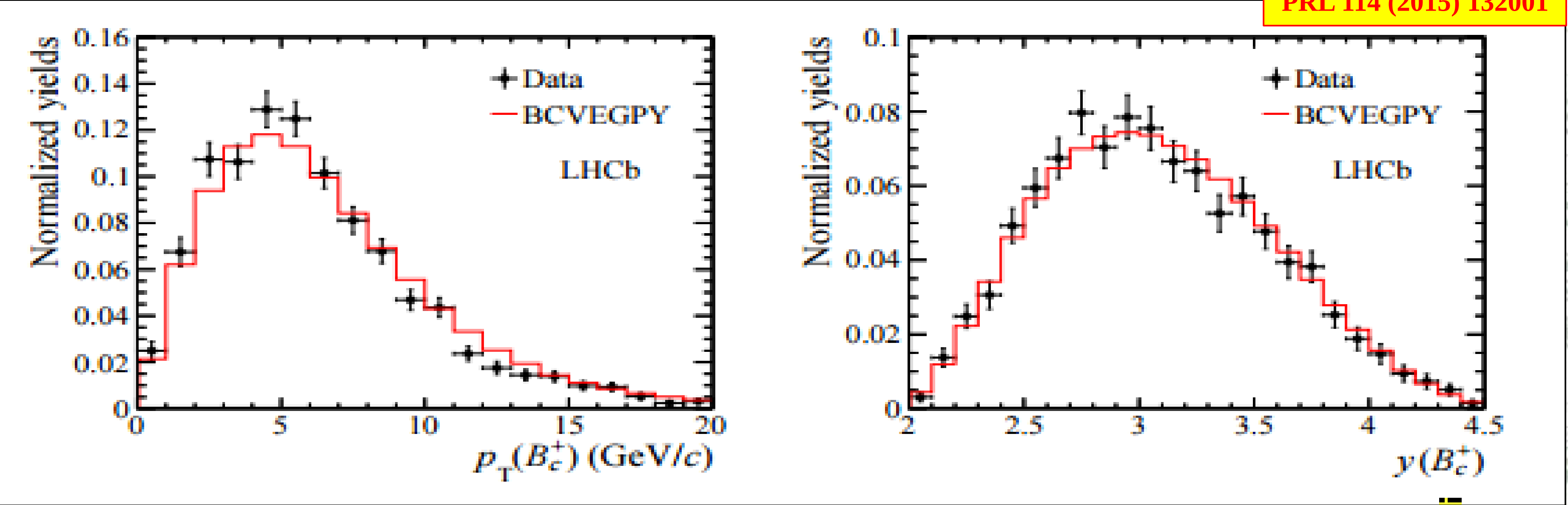
Multiple heavy quark production

- Simplest case: B_c charm and beauty
  - Largest sample of B_c, the most precise mass and lifetime measurements
  - Excellent agreement in p_T,y-spectra with NR QCD

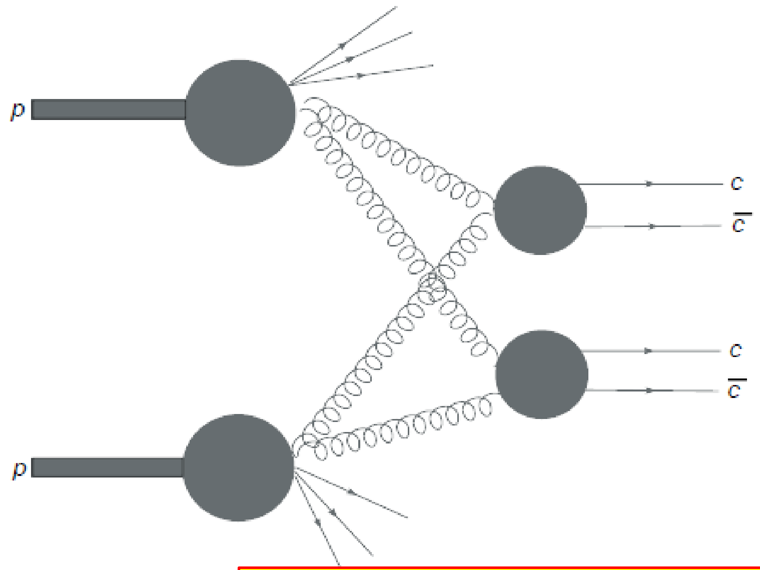
PRL 114 (2015) 132001



Multiple heavy quark production

- (Unique?) probe for high order α_s processes
- Excellent probe for Double Parton Scattering
  - NRQCD works well
- Important background for many searches of New Physics (multi-jets, multi-leptons with high-p_T and significant detachment)

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)

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

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

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***

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

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

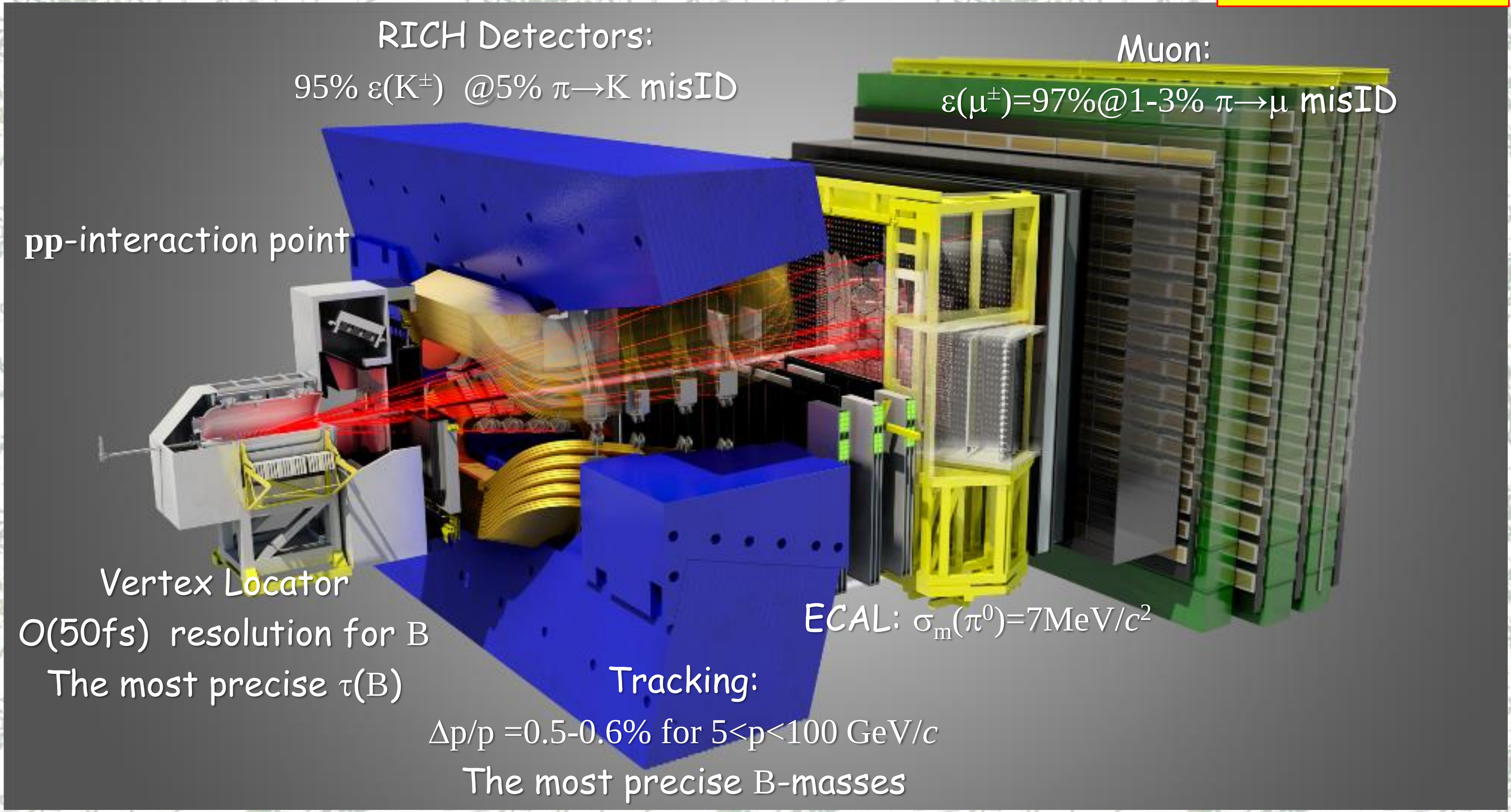
- The effective cross-section is a property of proton (integral over transverse degrees of freedom)
  - Smaller than "*proton size*": $\pi R^2 \approx 50\mathrm{mb}$
  - It is universal: ***energy and process independent***
    - easy to compare Tevatron, GPD and LHCb

$\sigma_{\mathrm{eff}} \sim \frac{1}{4}\sigma_{\mathrm{in}}$ 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

JINST 3 (2008) S08005



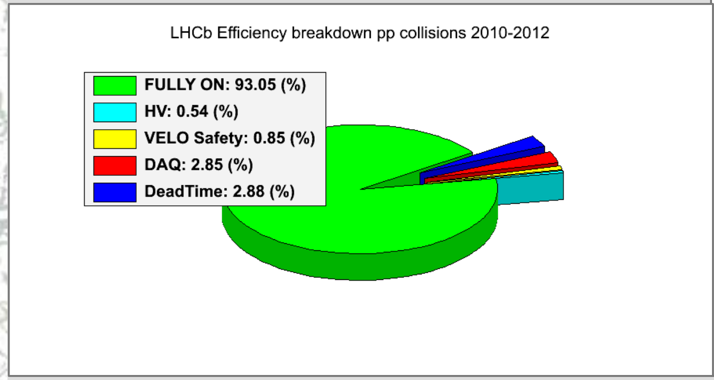
Run I

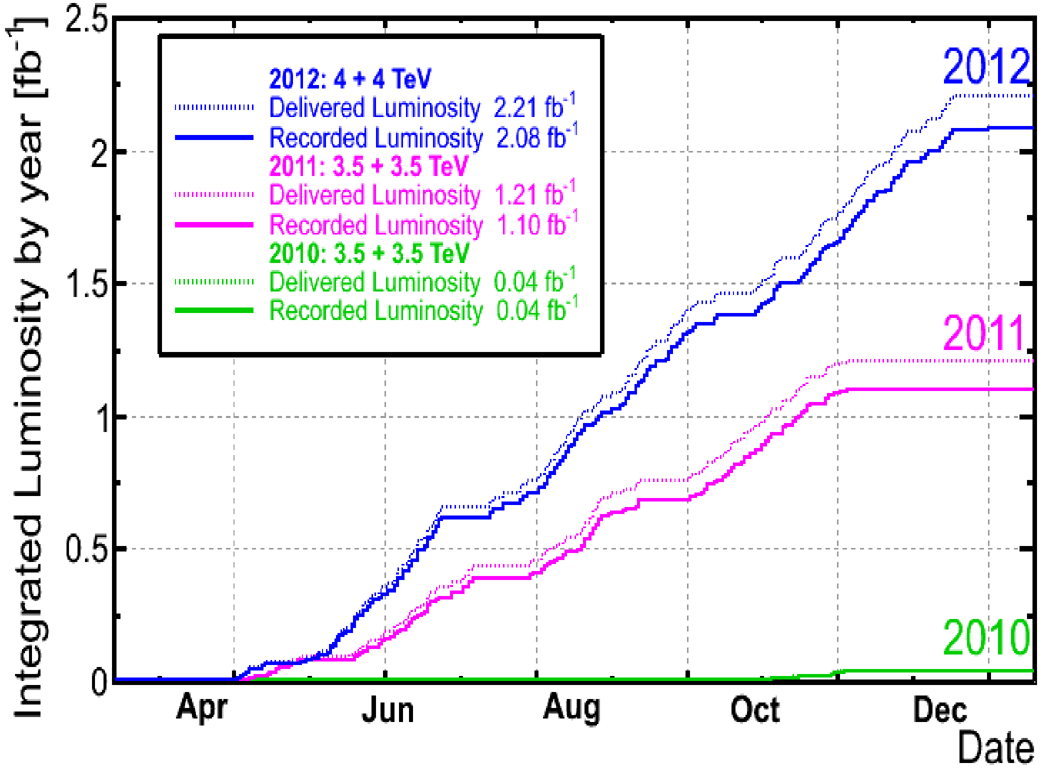
1fb^{-1}@7TeV

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} (2015) & >1fb^{-1} (2016) @ $\sqrt{s}$=13TeV (2015)

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

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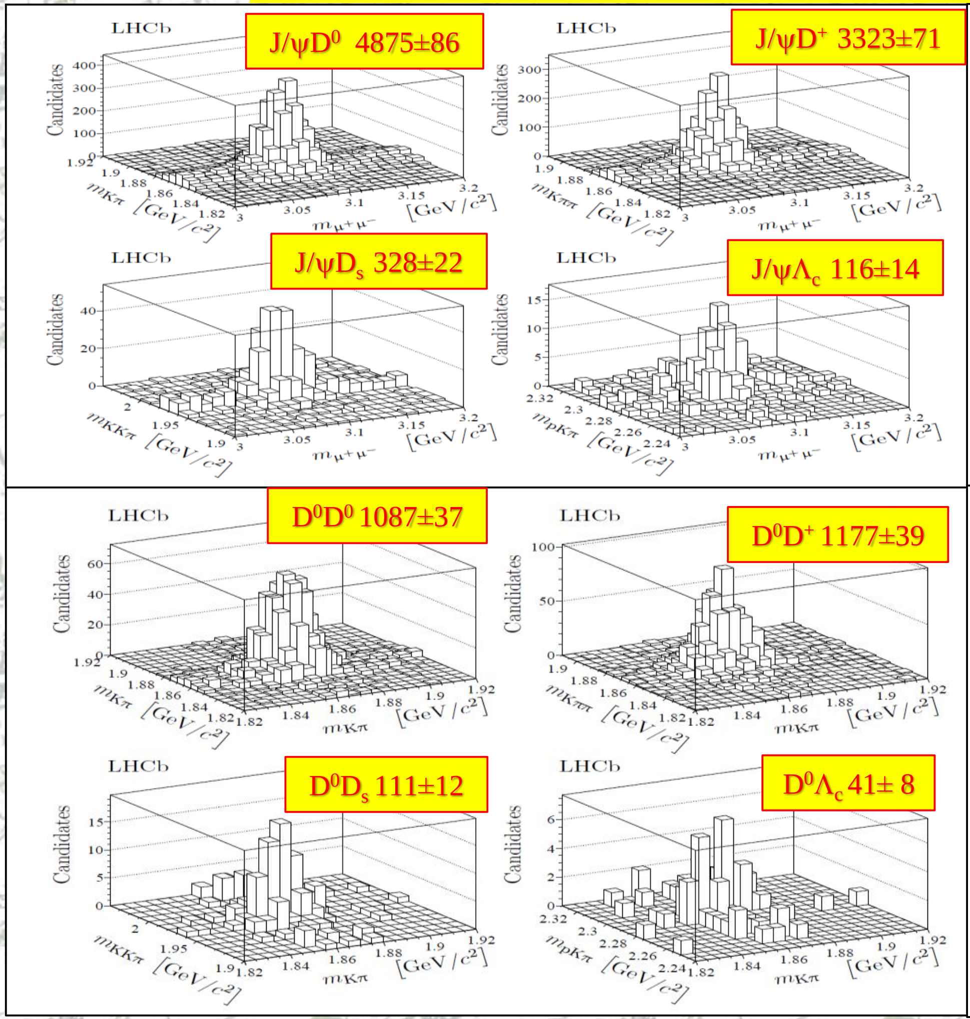
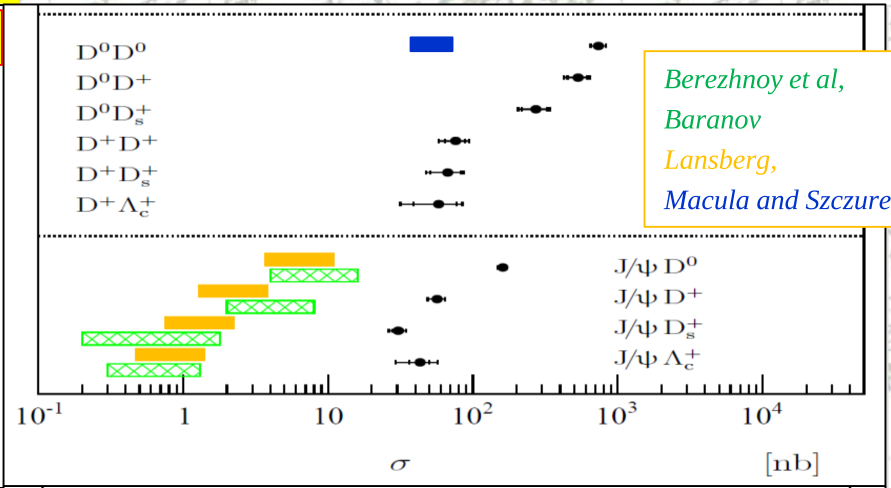
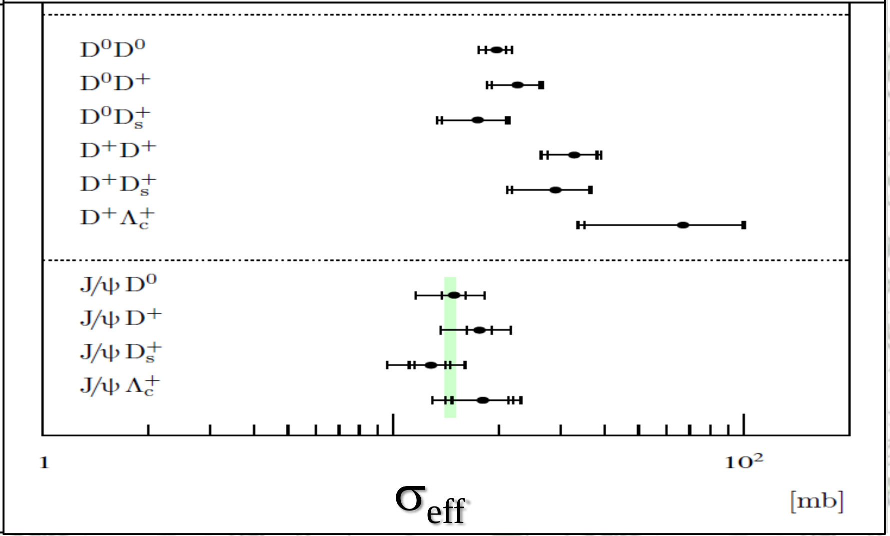
$\sqrt{s}$=7TeV, 355pb^{-1}







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

- NRQCD SPS (*Berezhnoy, Likhoded*)
- k_T-factorization, (*Baranov*)

$$\frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = (0.2 - 0.6)\,\%\,.$$
$$\frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = (0.1 - 0.3)\,\%\,.$$

- Gluon splitting: (0.4-2.0)%
- DPS: $\frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = \frac{\sigma^{c\bar{c}}}{\sigma_{\mathrm{eff}}}.$ $O(10\%)$

- SPS and DPS 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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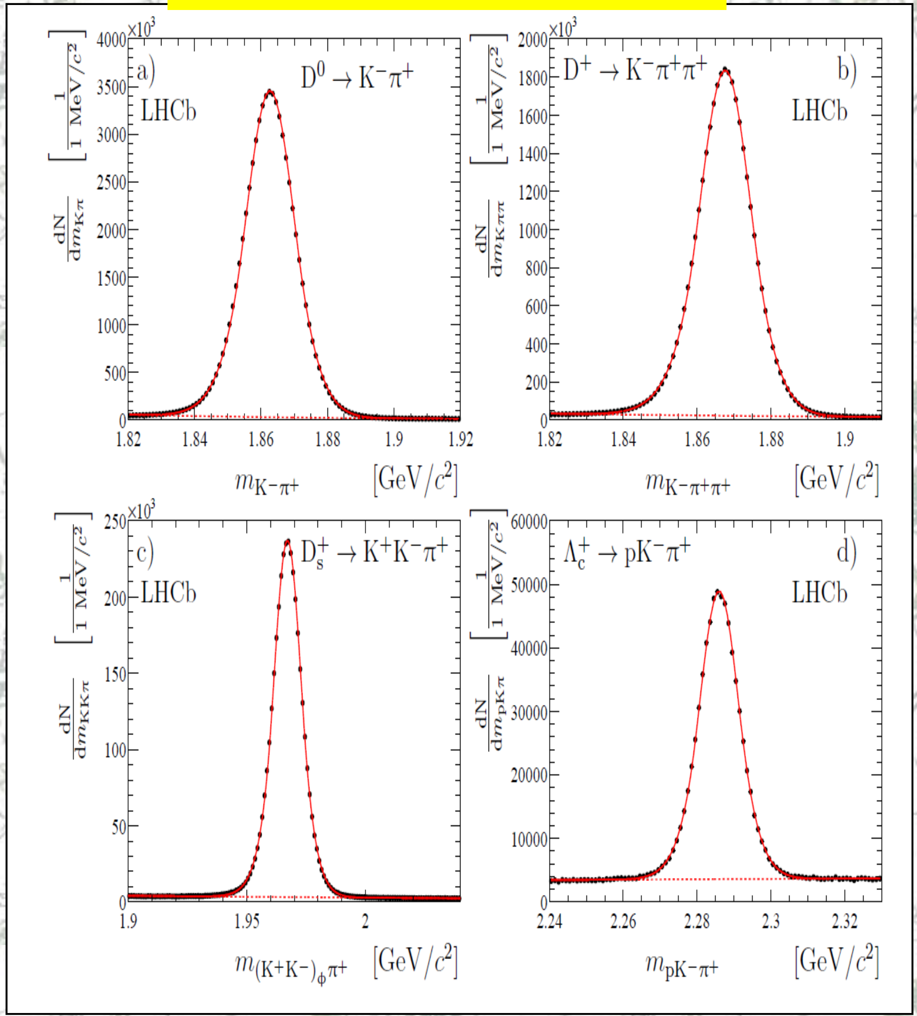

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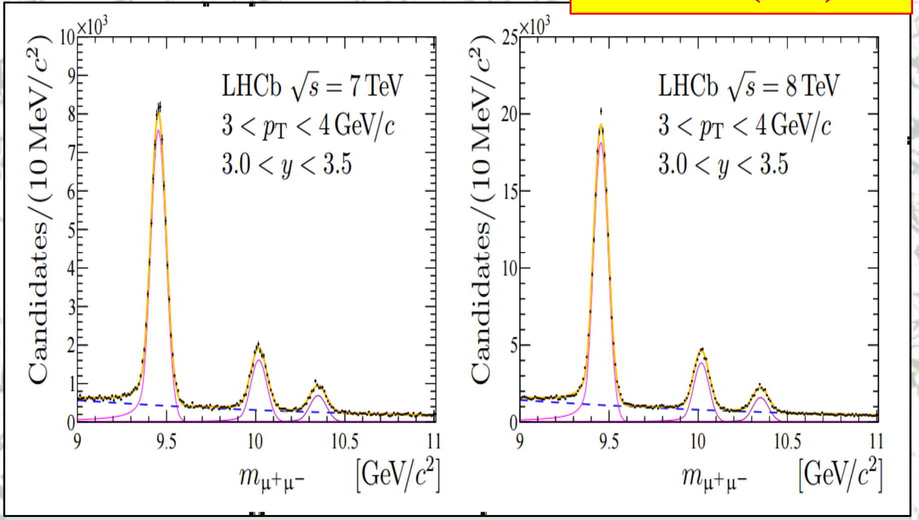

- **Whole Run-I dataset:** $1+2\,\mathrm{fb}^{-1}$
  - D^0 $O(200\mathrm{M/fb^{-1}})$
  - D^+ $O(100\mathrm{M/fb^{-1}})$
  - D_s $O(10\mathrm{M/fb^{-1}})$
  - Λ_c $O(20\mathrm{M/fb^{-1}})$
  - Υ(1,2,3S): $O(3,0.7,0.3\mathrm{M/fb^{-1}})$

$\Upsilon + c\bar{c}$

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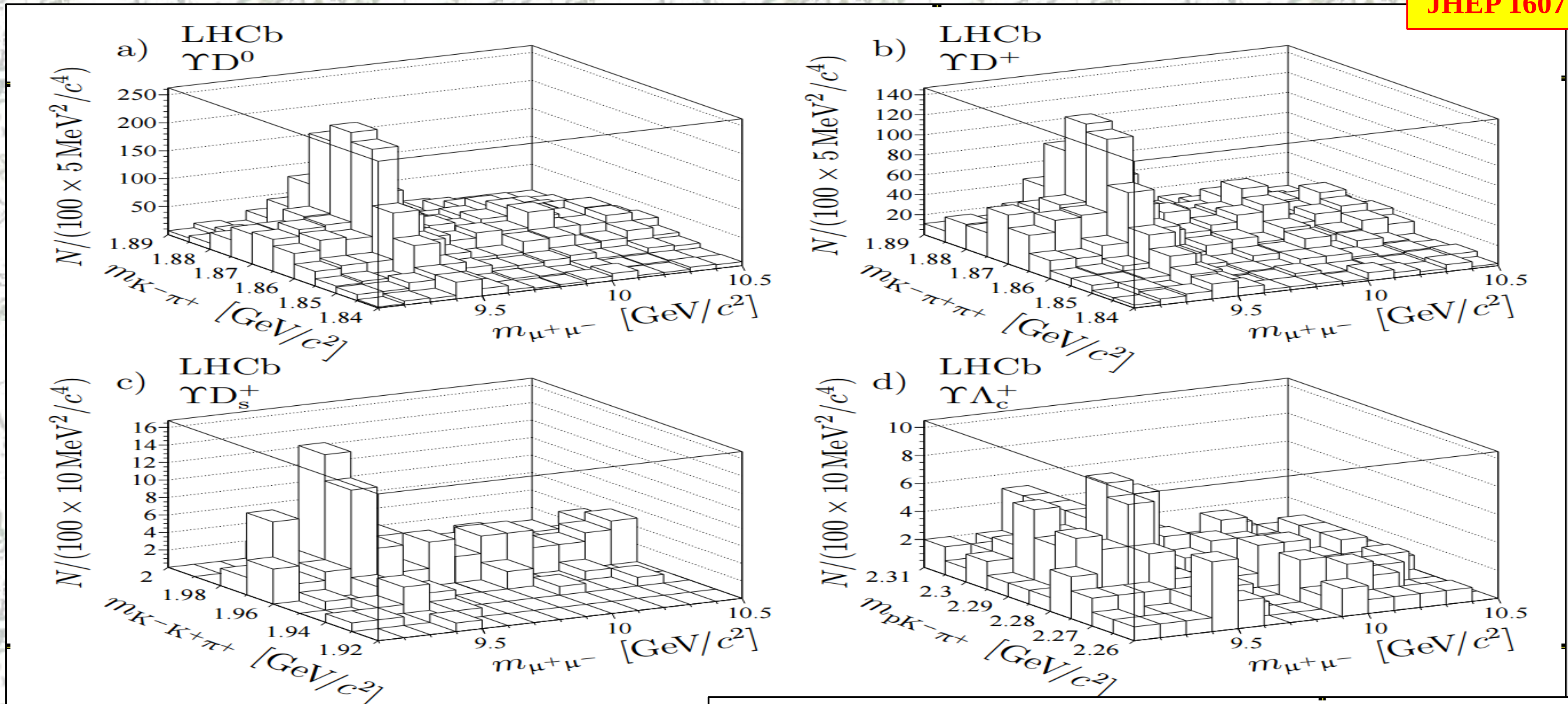

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
D^0	980 ± 50	184 ± 27	60 ± 22
D^+	556 ± 35	116 ± 20	55 ± 17
D_s^+	31 ± 7	9 ± 5	6 ± 4
Λ_c^+	11 ± 6	1 ± 4	1 ± 3

Five modes with >5σ!

Pileup?

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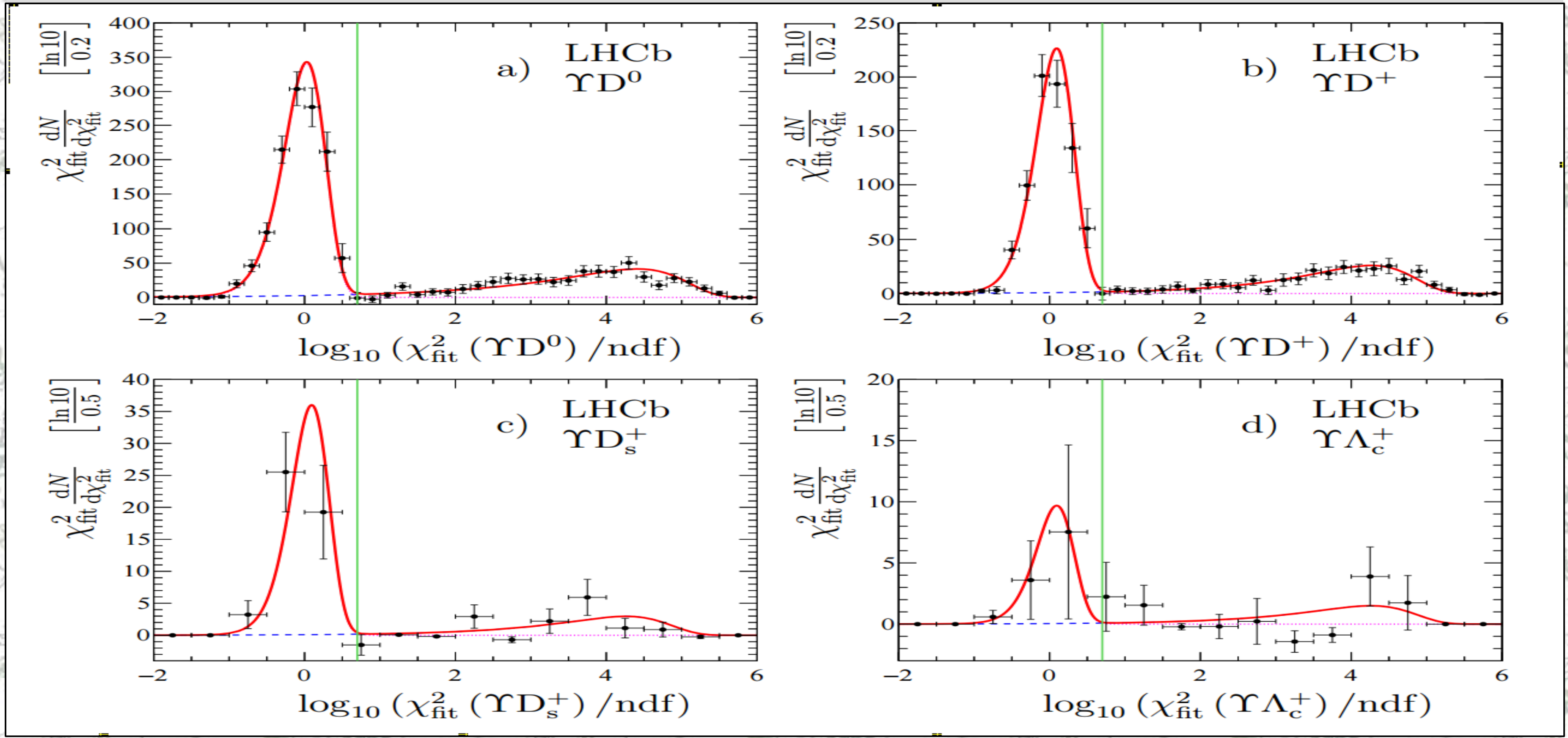
- Discriminating variable:

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%)

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

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

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

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

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

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Cross-section ratios – I

Reduced uncertainties

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

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

DPS

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

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

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

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

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

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

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

DPS

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

SPS

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

$$\frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = (0.1 - 0.3)\,\%\,.$$

Cross-section ratios – II

Reduced uncertainties

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

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

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

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

DPS

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

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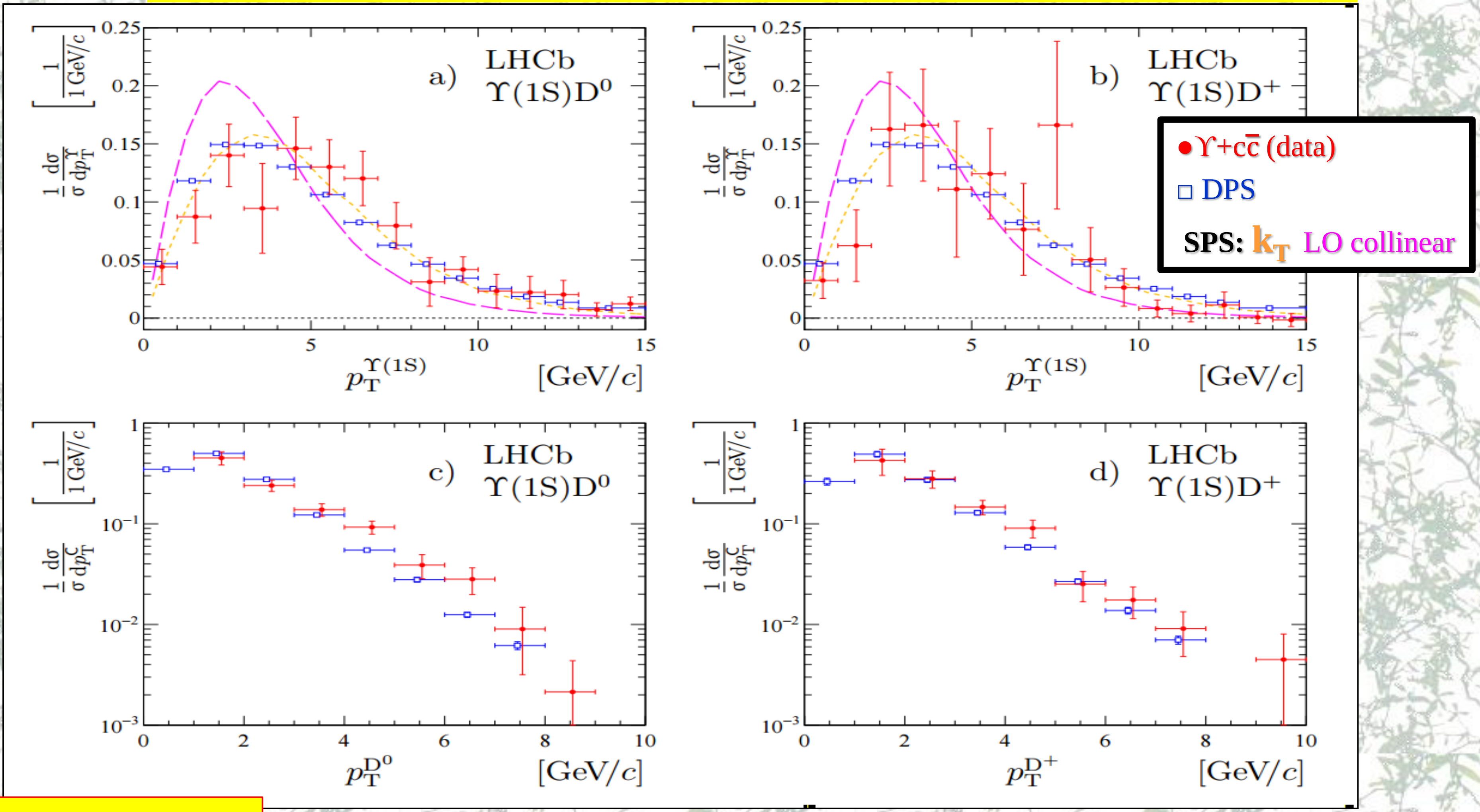
p_T spectra

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



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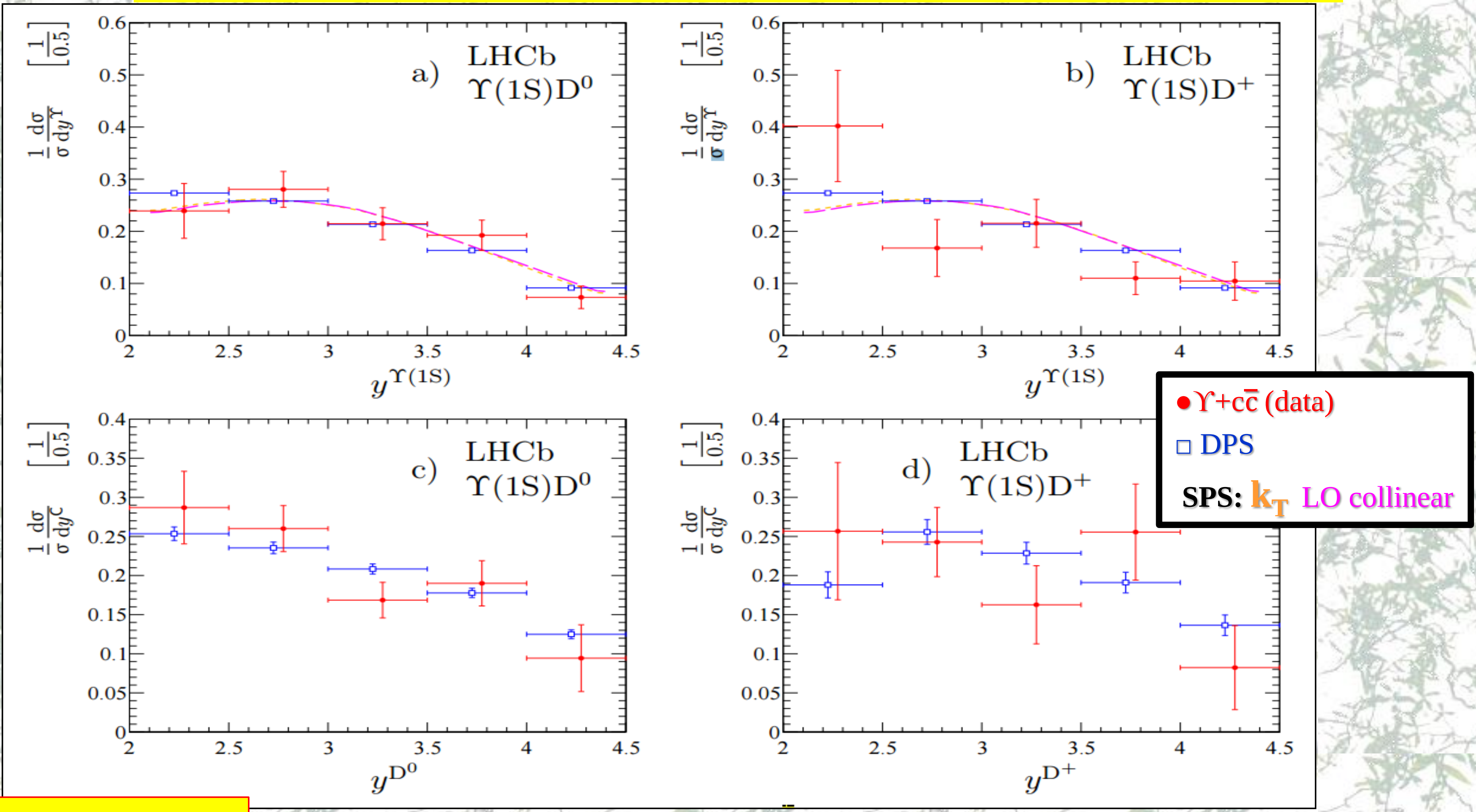
Rapidity

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



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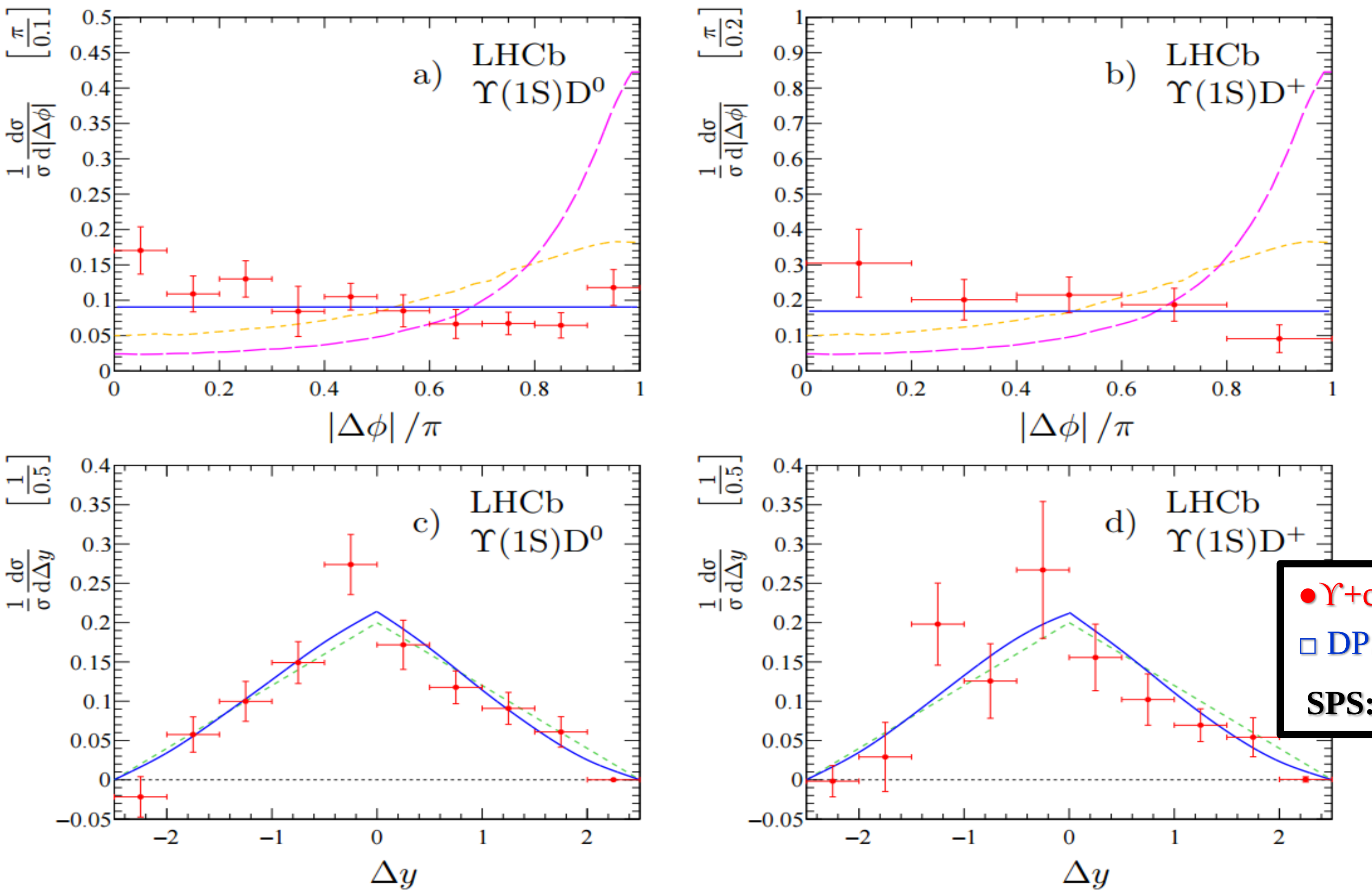
Δϕ and Δy

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



● ϒ+$c\bar{c}$ (data)

□ DPS

SPS: k_T LO collinear

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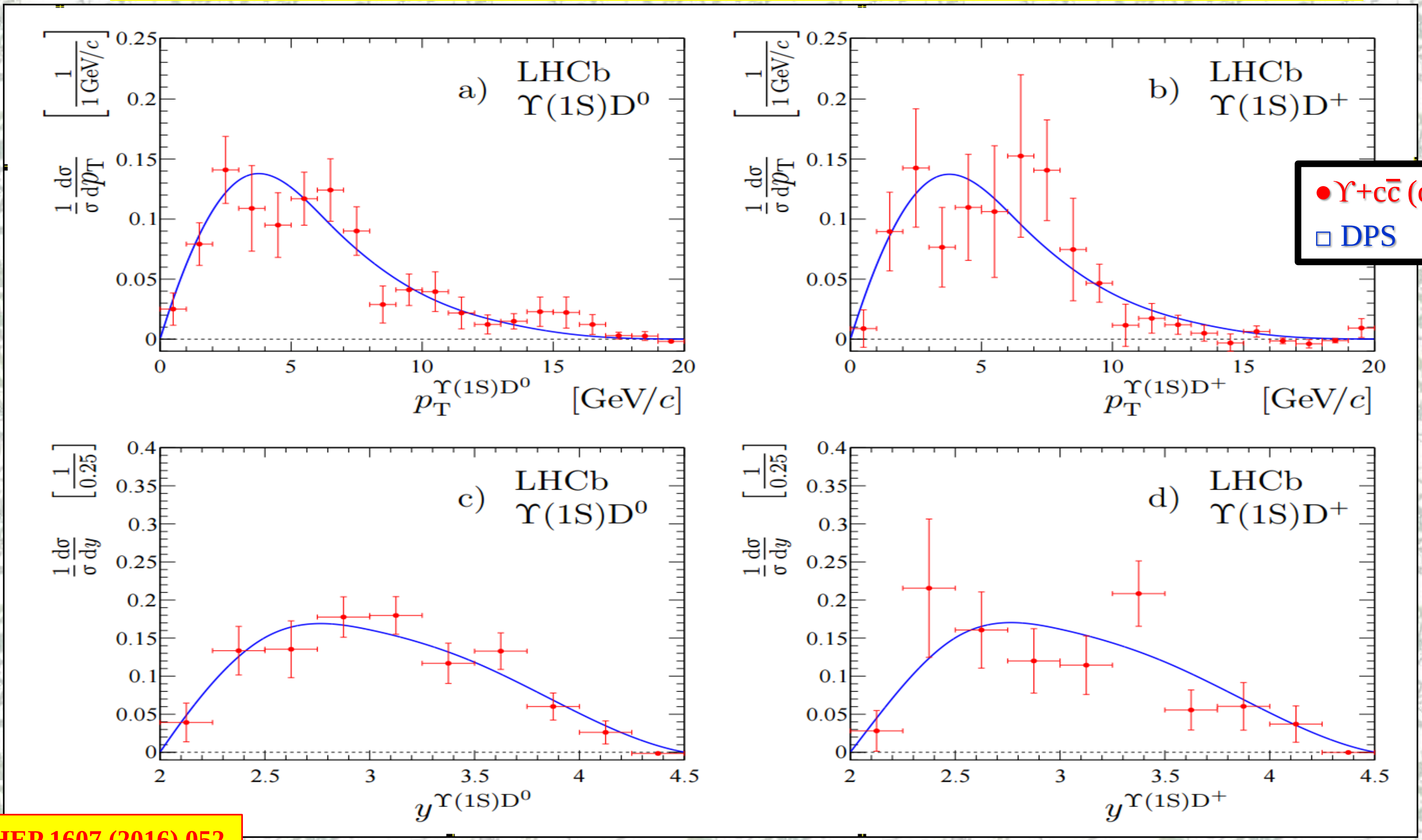
p_T and rapidity

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



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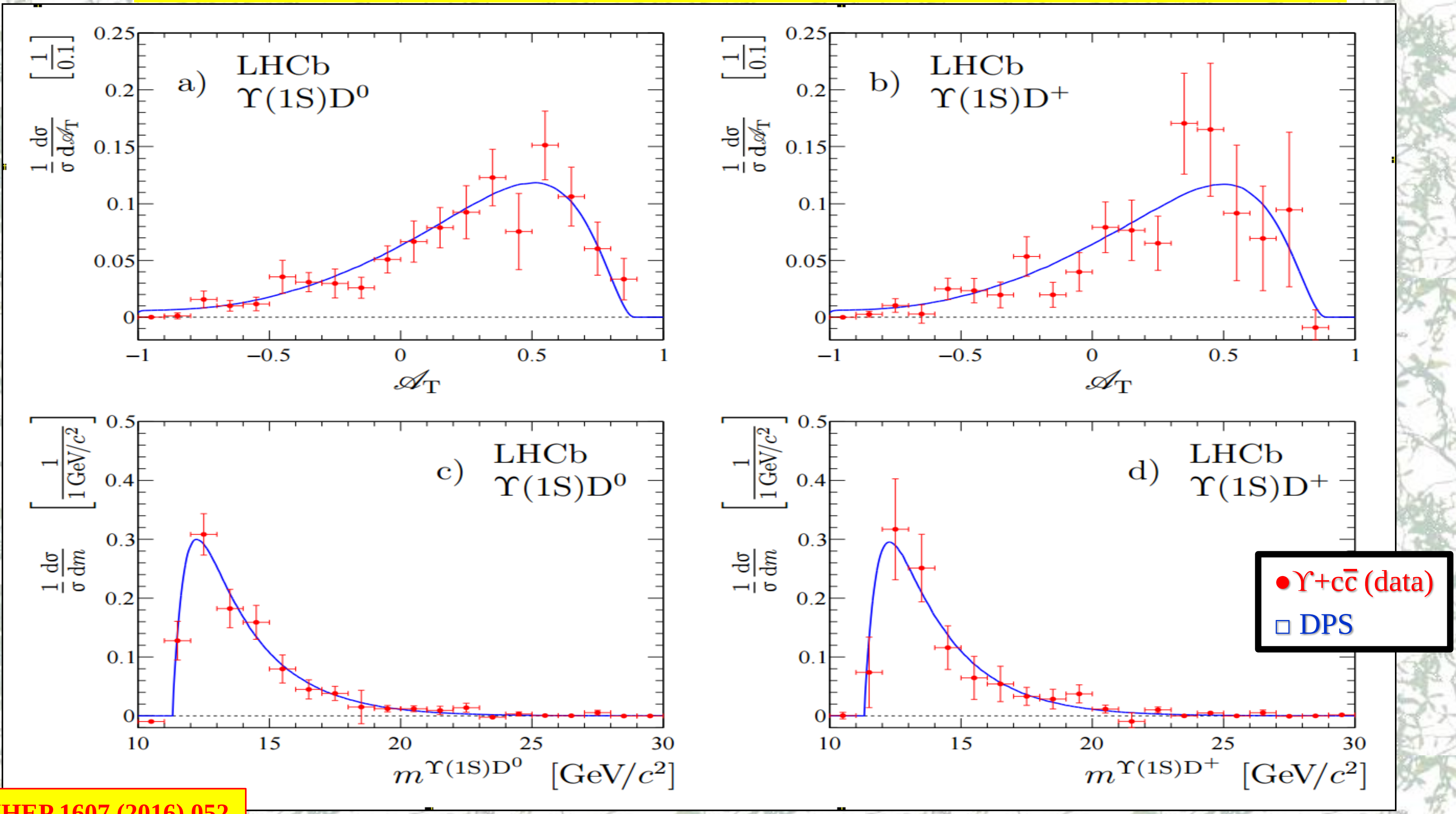
p_T asymmetry and mass

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



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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

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

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

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

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

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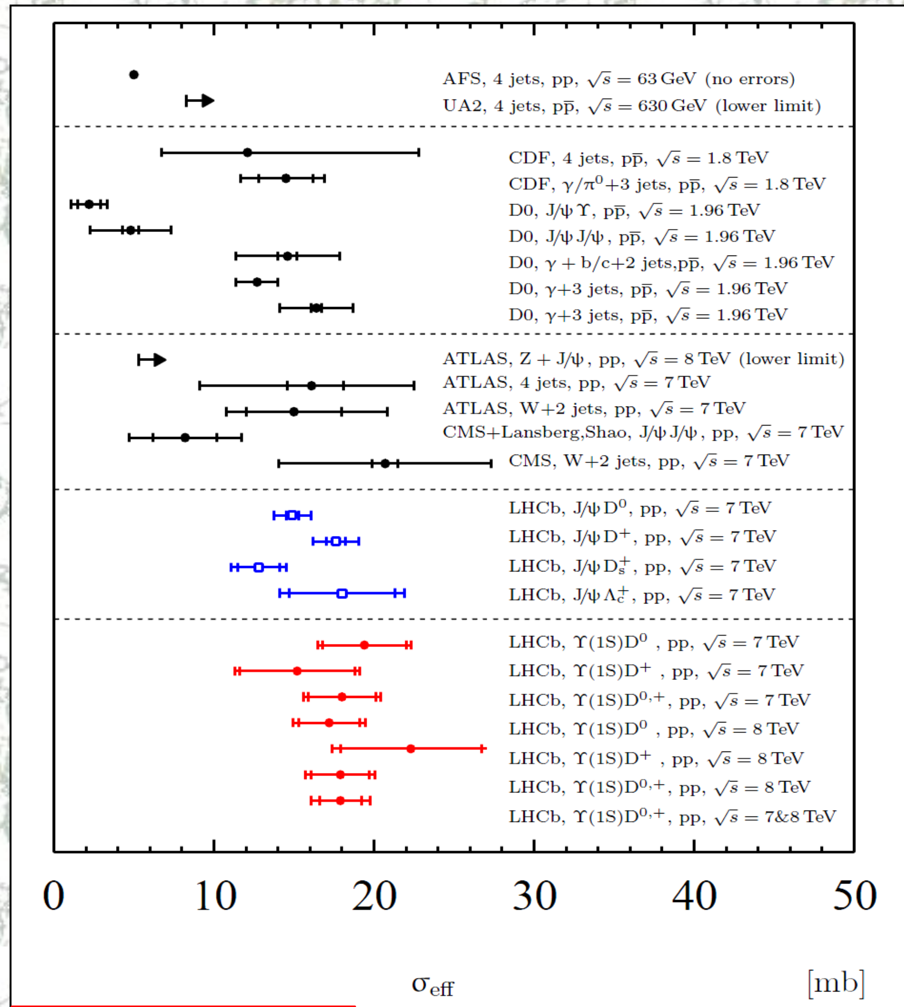
σ_{eff}



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- Excellent agreement with J/ψ+c$\bar{c}$
- Agrees well with γ+3*jets*
- Agrees well with W+2*jets*
- Agrees well with 4*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

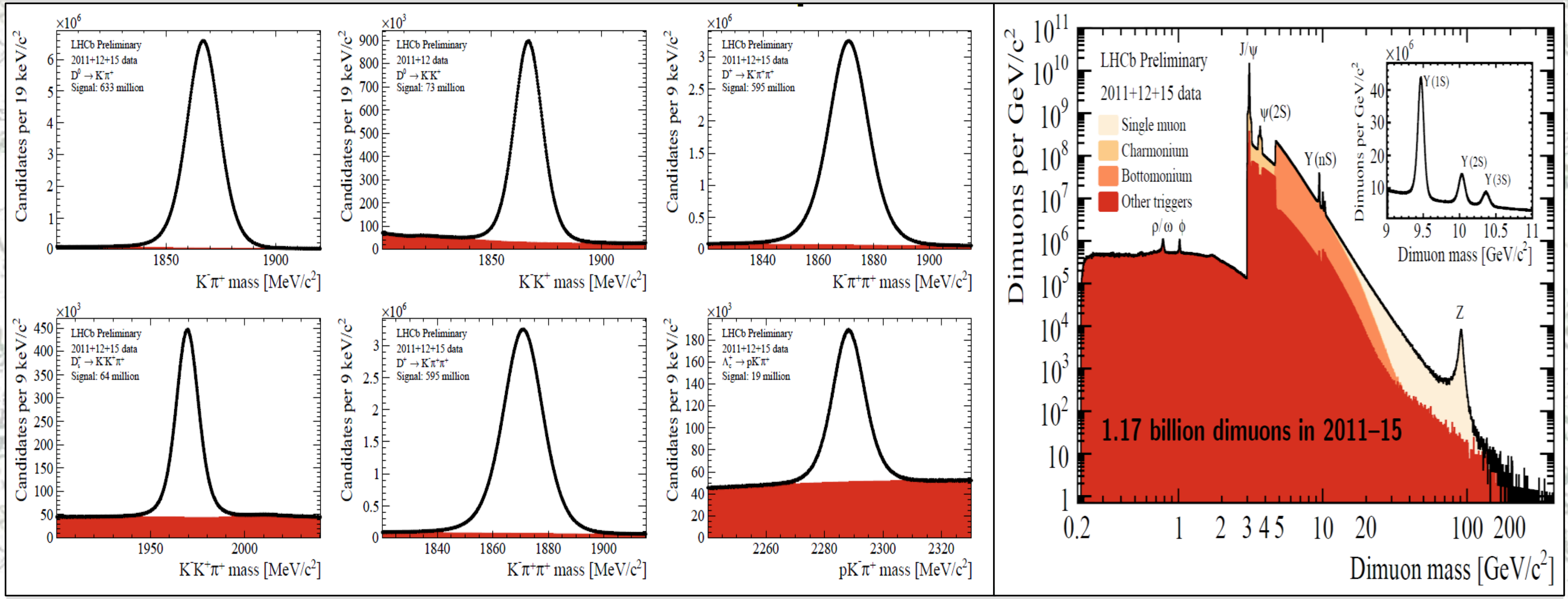
Summary

- 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

Run-II

- Importance of DPS is increasing
- Larger sample of charmed hadrons: great improvements in trigger!



LHCb-CONF-2016-005

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

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

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

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