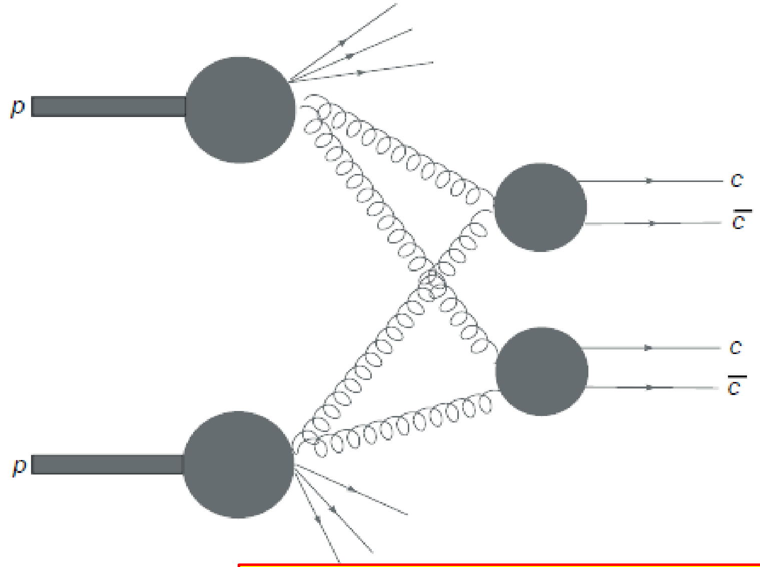
Double Parton Scattering @ LHCb

Vanya Belyaev (ITEP/Moscow)

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***

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

$$\frac{d\sigma^{\rm DPS}(pp \to c\bar{c}c\bar{c}X)}{dy_1dy_2d^2p_{1,t}d^2p_{2,t}dy_3dy_4d^2p_{3,t}d^2p_{4,t}} = \frac{1}{2\sigma_{\rm eff}}\cdot\frac{d\sigma^{\rm SPS}(pp \to c\bar{c}X_1)}{dy_1dy_2d^2p_{1,t}d^2p_{2,t}}\cdot\frac{d\sigma^{\rm SPS}(pp \to c\bar{c}X_2)}{dy_3dy_4d^2p_{3,t}d^2p_{4,t}}.$$

- The cross-section is ***larger*** than in naïve model

$\sigma_{\rm eff}$ = 15mb vs $\sigma_{\rm in}$ = 55mb

- 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 and process independent***
    - easy to compare Tevatron, GPD and LHCb
- Easy to extend to pA and AA collisions with interesting predictions
  - Large enhancement for certain processes

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

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

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

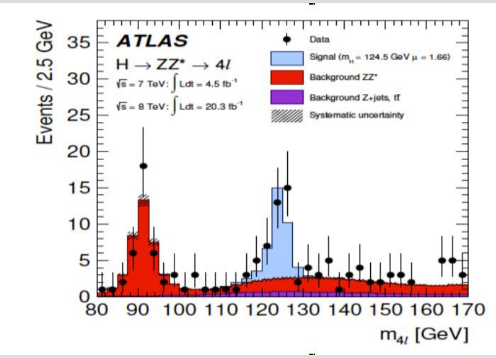
DPS

- Need to measure σ_{eff}
  - validate independence on energy and process
  - … or measure the dependence
- Validate/probe the pocket formula for differential cross-sections
  - Due to $\theta(1-x_1-x_2)$ insert the differential formula dies the first
  - "A" and "B" have larger rapidity separation with respect to uncorrelated case…

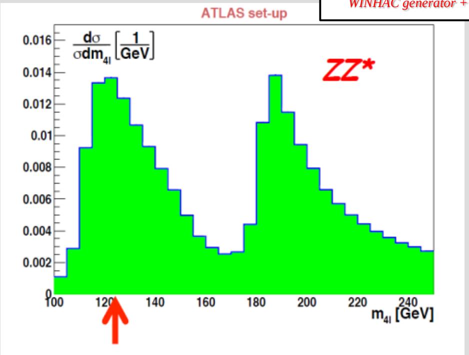
$$D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) = D_h^i(x_1; Q_1^2) D_h^j(x_2; Q_2^2).$$

DPS importance

- Can easily mimic crucial signals



M.Krasny
WINHAC generator + cuts

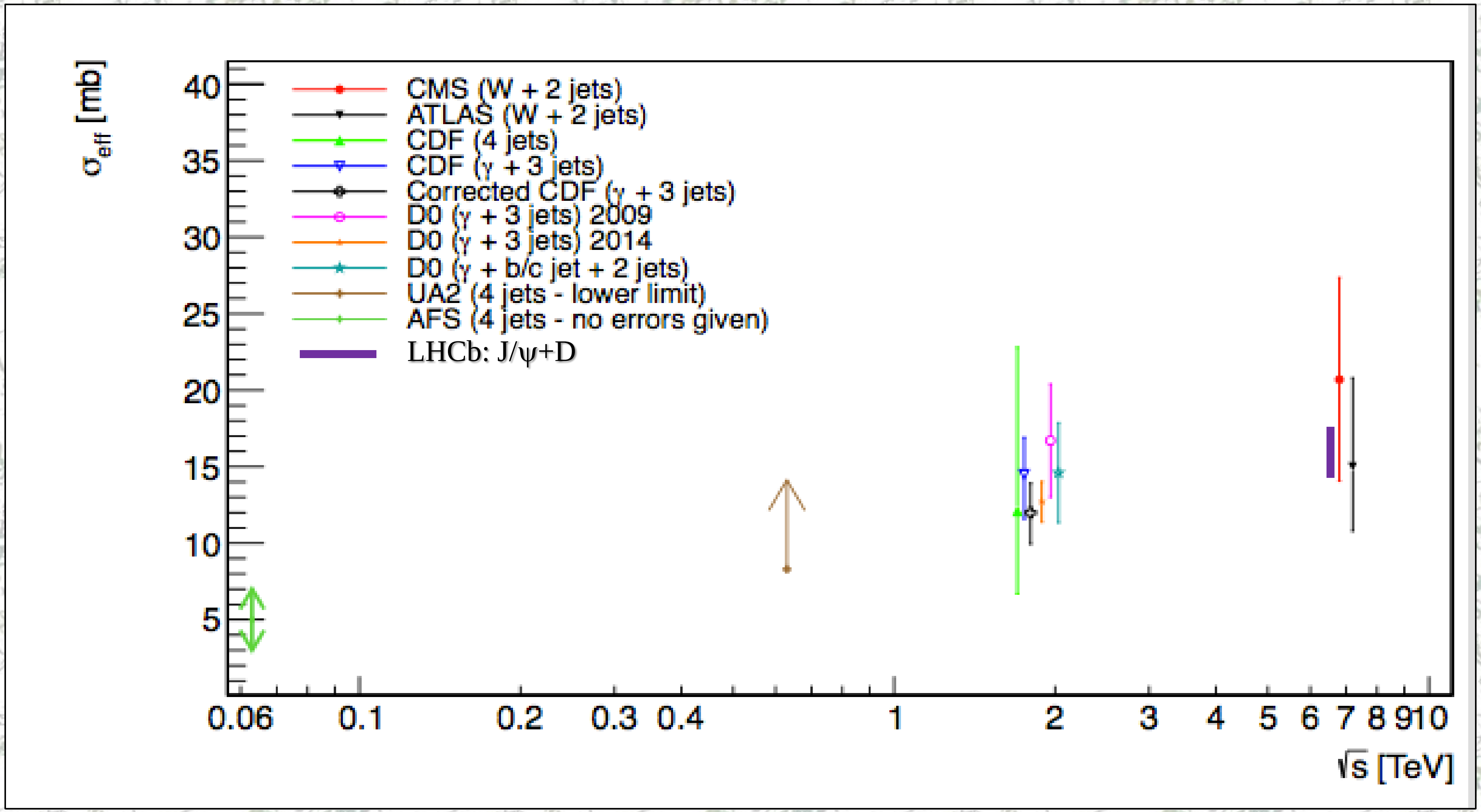


- DPS importance grows with energy/gluon density (smaller x)
- Interparton correlations
- First observed long time ago:
  - 4-jets AFS@ISR
  - 3-jets+γ CDF, D0, …
- @ LHC
  - ATLAS, CMS: 4-jets, W+jets, 2×J/ψ, W+J/ψ, Z+J/ψ, …
  - **LHCb: 2×J/ψ, Z+D, *double charm*, ….**

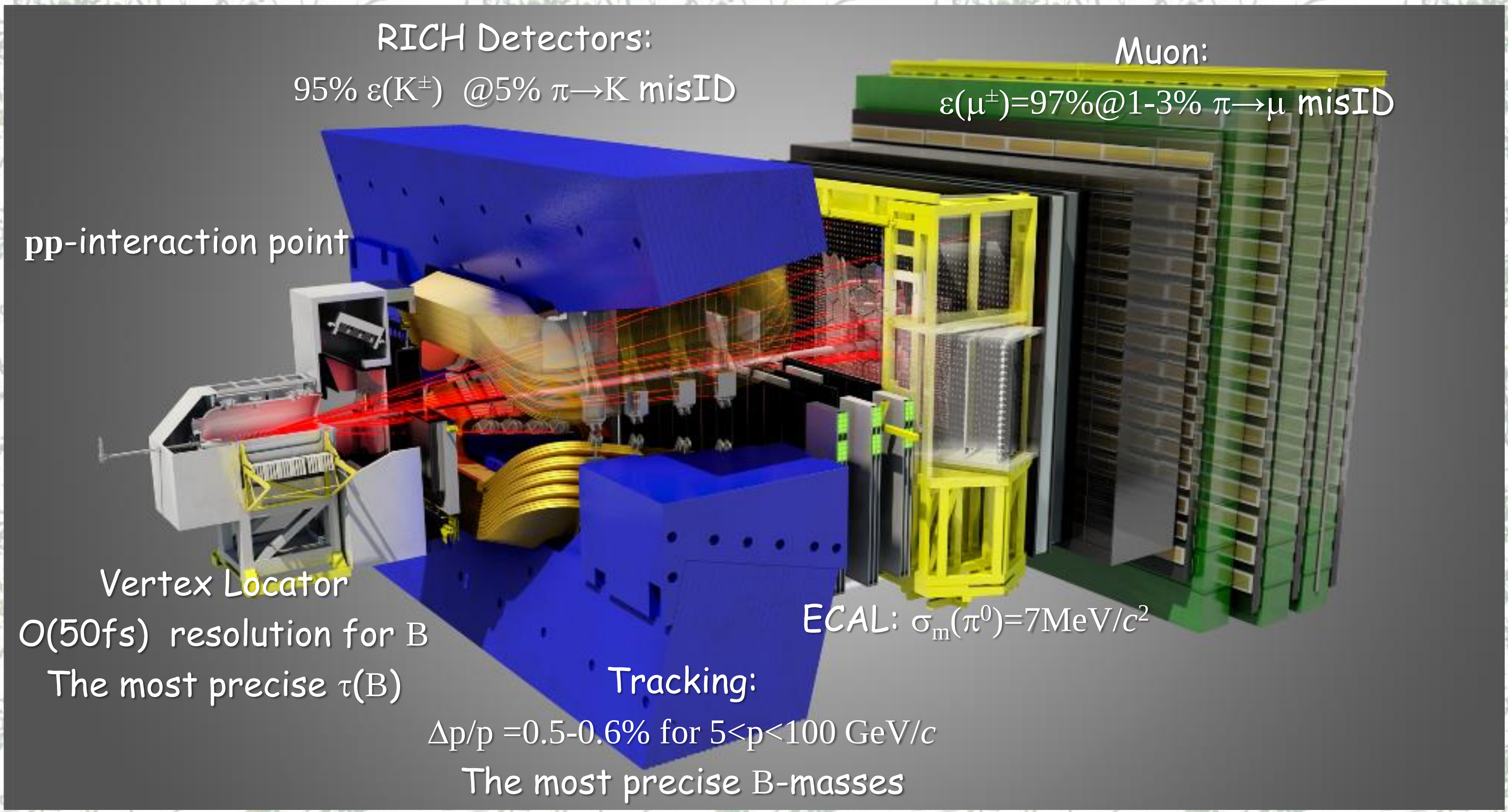
σ_{eff} is important QCD parameter:
Energy independent (?)
Process independent (?)

TEST IT!

Energy/process independent?



~40% of heavy quarks in <4% of 4π



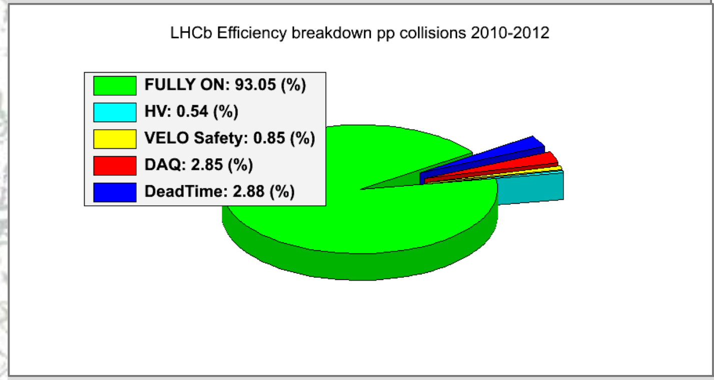
Run I

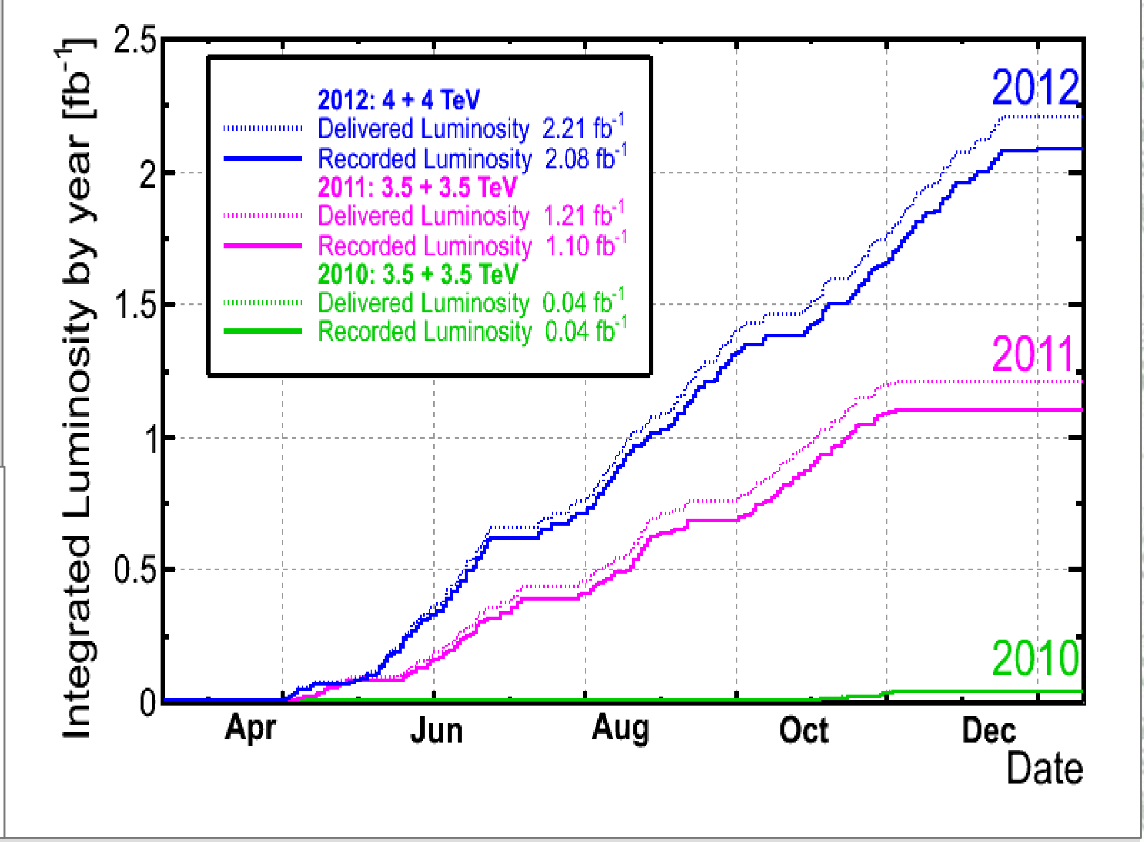
1fb^{-1}@7TeV

2fb^{-1}@8TeV

3.3pb^{-1} @2.76TeV

1.6 nb^{-1} pA & Ap

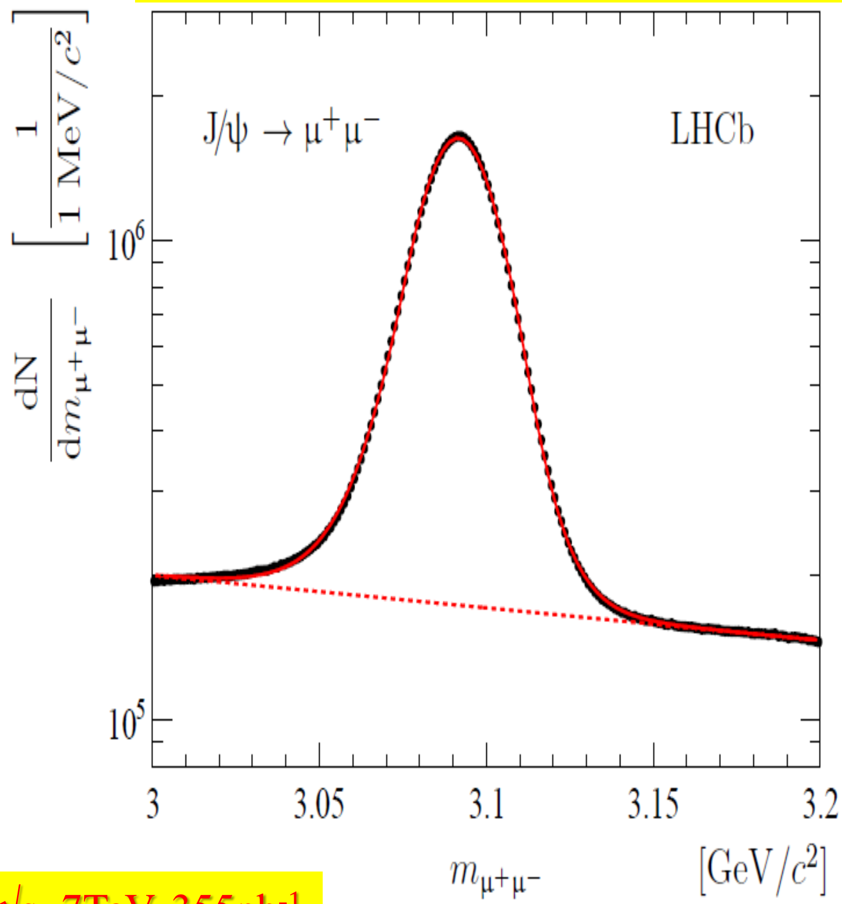




Thanks to LHC accelerator team for the excellent performance of machine

$J/\psi \to \mu^+\mu^-$ @ LHCb

JHEP 1206(2012) 141, 1403(2014) 108



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

- High trigger efficiency
  - Dimuon trigger
  - No $p_T(J/\psi)$ cut
- Excellent μID
- Very low background
- Resolution ~13MeV/c^2
- High yield: ~150M/fb^{-1}
- Cross-section is measured at $\sqrt{s}$=7,8 &2.76TeV

EPJC71 (2011) 1645

JHEP 06(2013) 064

JHEP 02(2013) 041

Prompt open charm at LHCb

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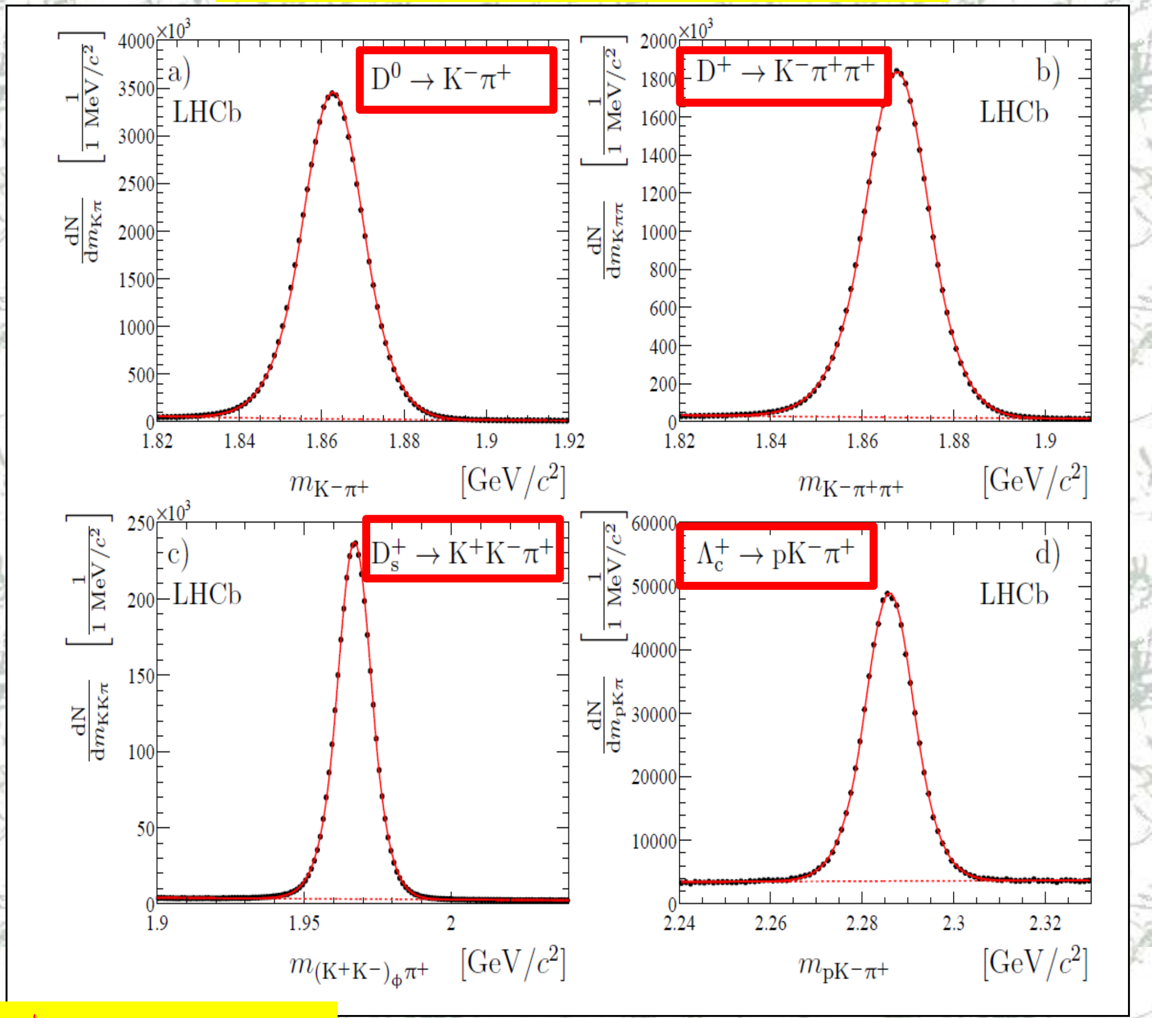


$\sqrt{s}$=7TeV, 355pb^{-1}

- Dedicated charm triggers
  - further improvement for 2012, and even further for Run II
- Excellent hadron ID
  - RICH detectors
- Excellent mass-resolution O(5MeV/c^2)
- "*background-free*" signals p_T>3GeV/c^2

  $D^0 \to K^-\pi^+$ 200M/fb^{-1}

  $D^+ \to K^-\pi^+\pi^+$ 100M/fb^{-1}

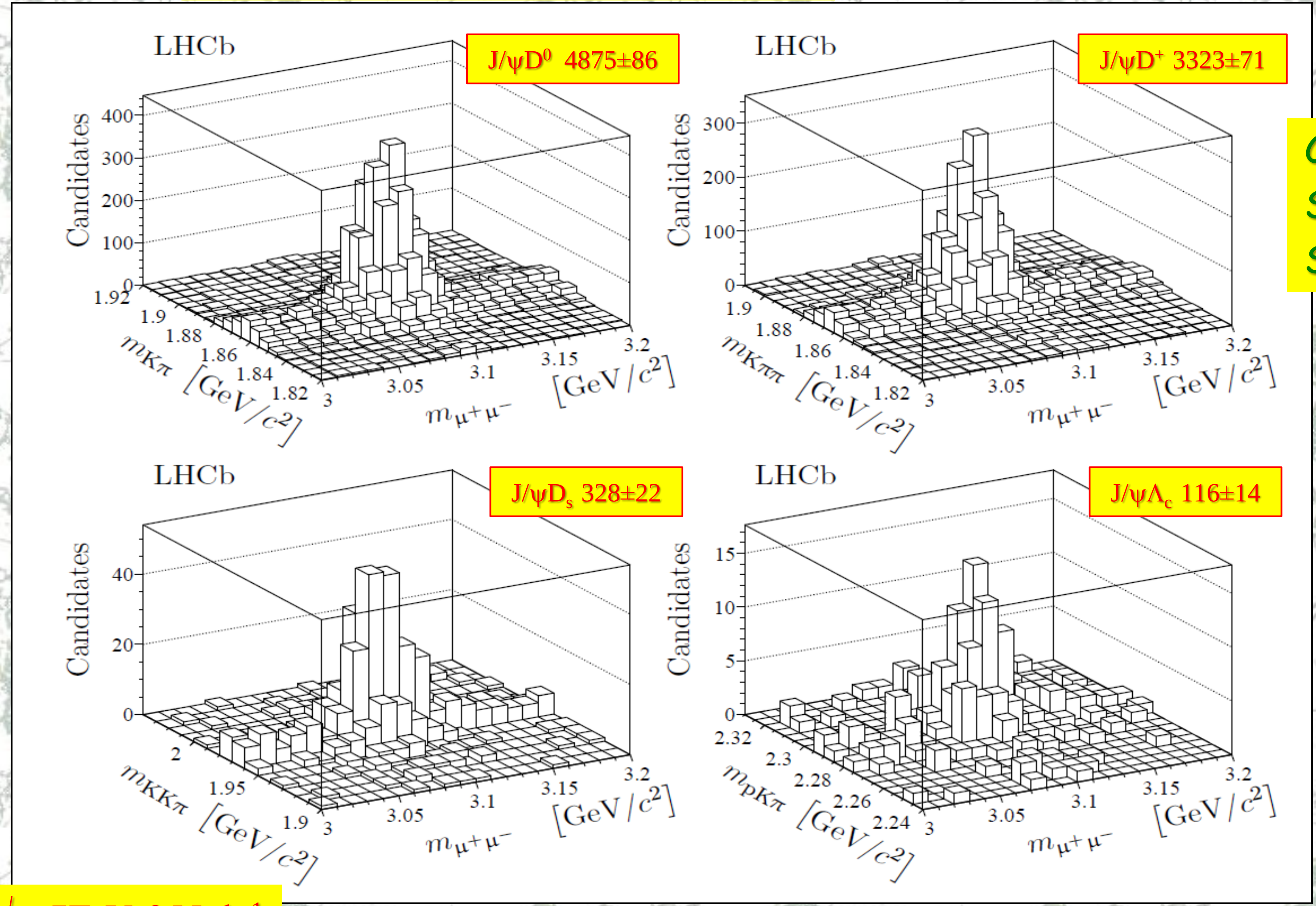
  $D_s \to \phi\pi^+$ 10M/fb^{-1}

  $\Lambda_c \to pK^-\pi^+$ 2M/fb^{-1}
- Measured cross-section at $\sqrt{s}$=7TeV

NPB871(2013)1

J/ψ + open charm signals

[JHEP 1206(2012) 141](), [1403(2014) 108]()



- Clear signals
- Small background
- Significances >7σ

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

2× open charm signals

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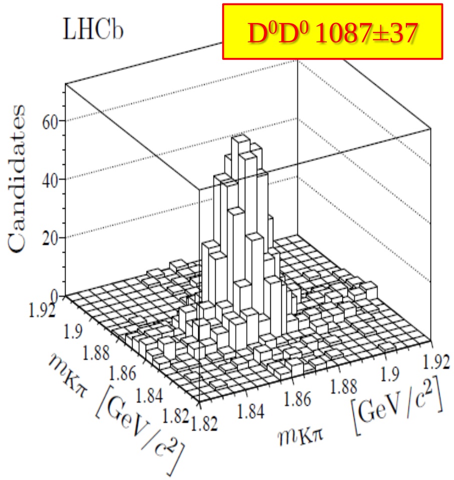

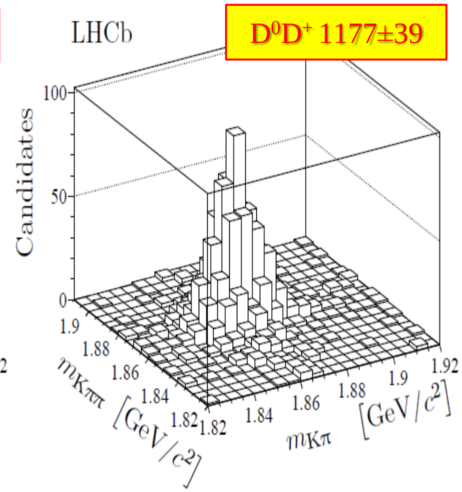

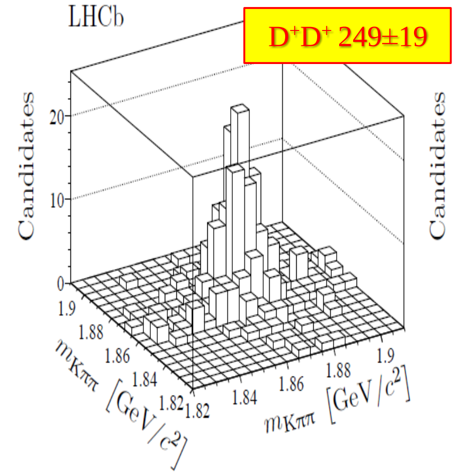

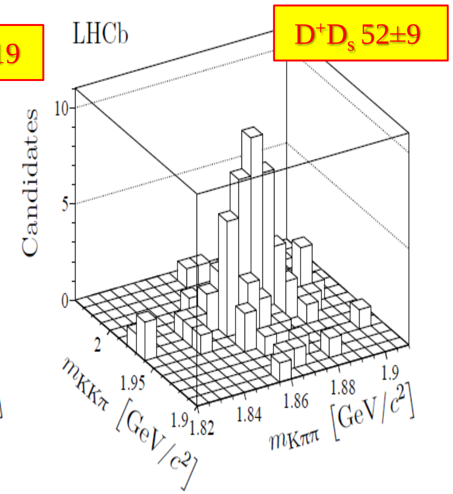

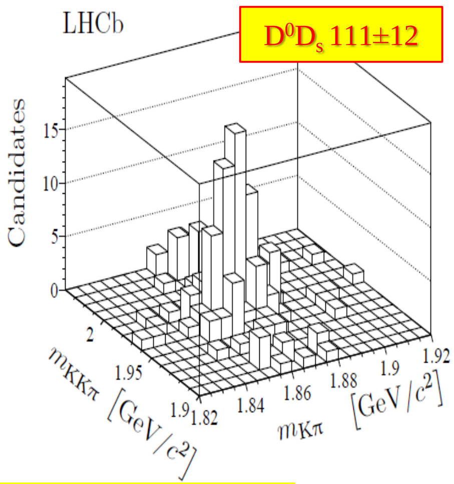

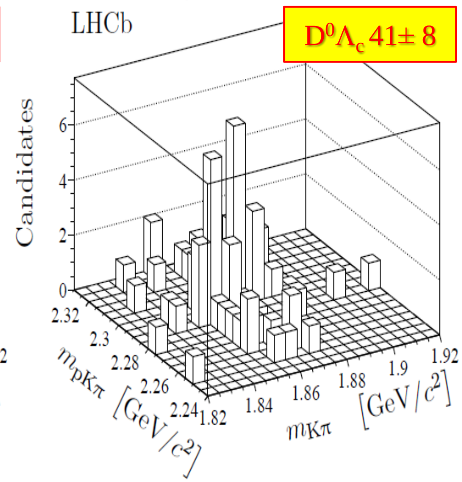

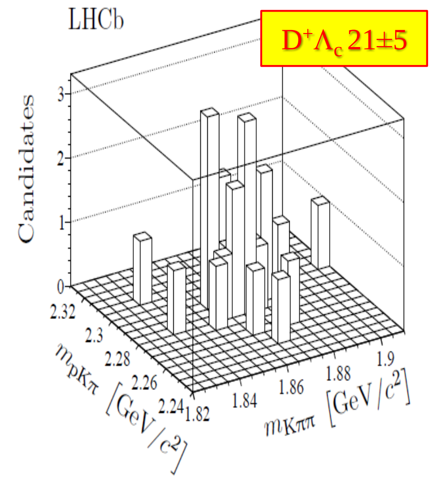

Small background
Significances for
6 modes exceed 5σ

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

Production cross-sections

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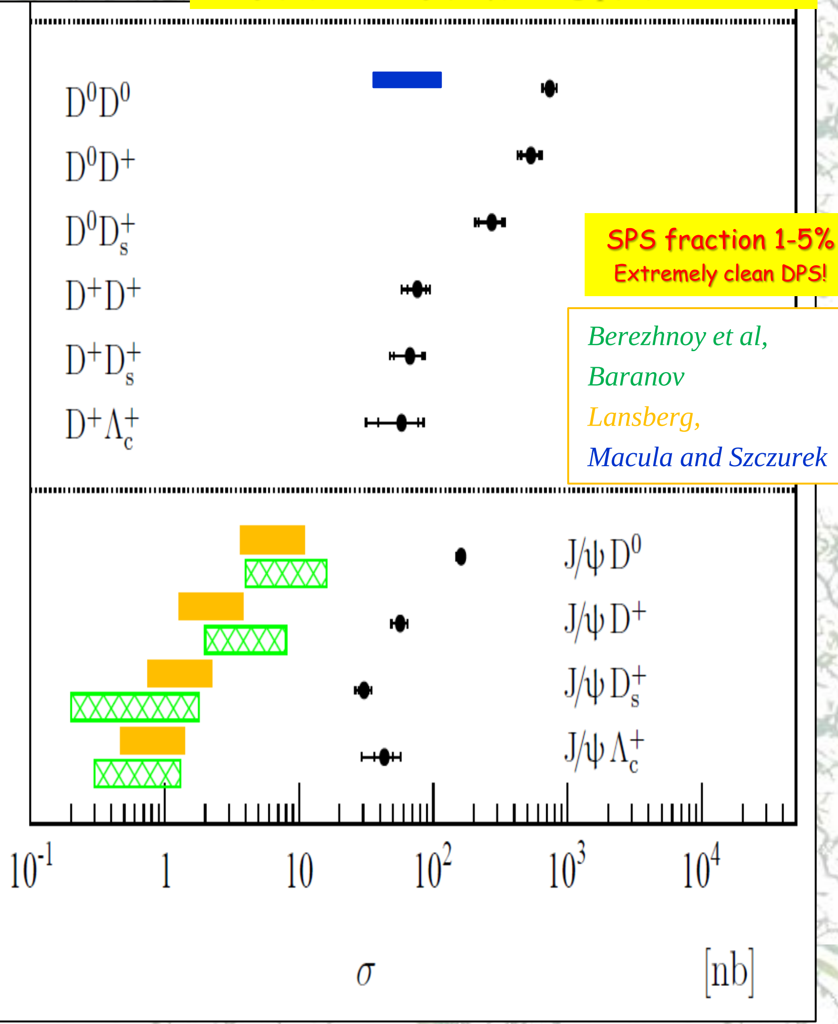
$2<y(D)<4$, $2<y(J/\psi)<4$, $p_T(D)>3$GeV/c

Mode	$\sigma_{J/\psi C}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi C}/\sigma_{C}$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_{C}/\sigma_{J/\psi C}$ [mb]
$J/\psi D^0$	$16.2\pm0.4\pm1.3^{+3.4}_{-2.5}$	$6.7\pm0.2\pm0.5$	$14.9\pm0.4\pm1.1^{+2.3}_{-3.1}$
$J/\psi D^+$	$5.7\pm0.2\pm0.6^{+1.2}_{-0.9}$	$5.7\pm0.2\pm0.4$	$17.6\pm0.6\pm1.3^{+2.8}_{-3.7}$
$J/\psi D_s^+$	$3.1\pm0.3\pm0.4^{+0.6}_{-0.5}$	$7.8\pm0.8\pm0.6$	$12.8\pm1.3\pm1.1^{+2.0}_{-2.7}$
$J/\psi \Lambda_c^+$	$4.3\pm0.7\pm1.2^{+0.9}_{-0.7}$	$5.5\pm1.0\pm0.6$	$18.0\pm3.3\pm2.1^{+2.8}_{-3.8}$

Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\overline{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
D^0D^0	$690\pm40\pm70$	10.9 ± 0.8	$2\times(42\pm3\pm4)$
$D^0\overline{D}^0$	$6230\pm120\pm630$		$2\times(4.7\pm0.1\pm0.4)$
D^0D^+	$520\pm80\pm70$	12.8 ± 2.1	$47\pm7\pm4$
D^0D^-	$3990\pm90\pm500$		$6.0\pm0.2\pm0.5$
$D^0D_s^+$	$270\pm50\pm40$	15.7 ± 3.4	$36\pm8\pm4$
$D^0D_s^-$	$1680\pm110\pm240$		$5.6\pm0.5\pm0.6$
$D^0\bar{\Lambda}_c^-$	$2010\pm280\pm600$	—	$9\pm2\pm1$
D^+D^+	$80\pm10\pm10$	9.6 ± 1.6	$2\times(66\pm11\pm7)$
D^+D^-	$780\pm40\pm130$		$2\times(6.4\pm0.4\pm0.7)$
$D^+D_s^+$	$70\pm15\pm10$	12.1 ± 3.3	$59\pm15\pm6$
$D^+D_s^-$	$550\pm60\pm90$		$7\pm1\pm1$
$D^+\Lambda_c^+$	$60\pm30\pm20$	10.7 ± 5.9	$140\pm70\pm20$
$D^+\bar{\Lambda}_c^-$	$530\pm130\pm170$		$15\pm4\pm2$



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

Pure DPS?

- Measured cross-sections significantly (×30-100) larger than theory predictions for SPS
- DPS process with purity in excess of 97% ???
  - Really unique

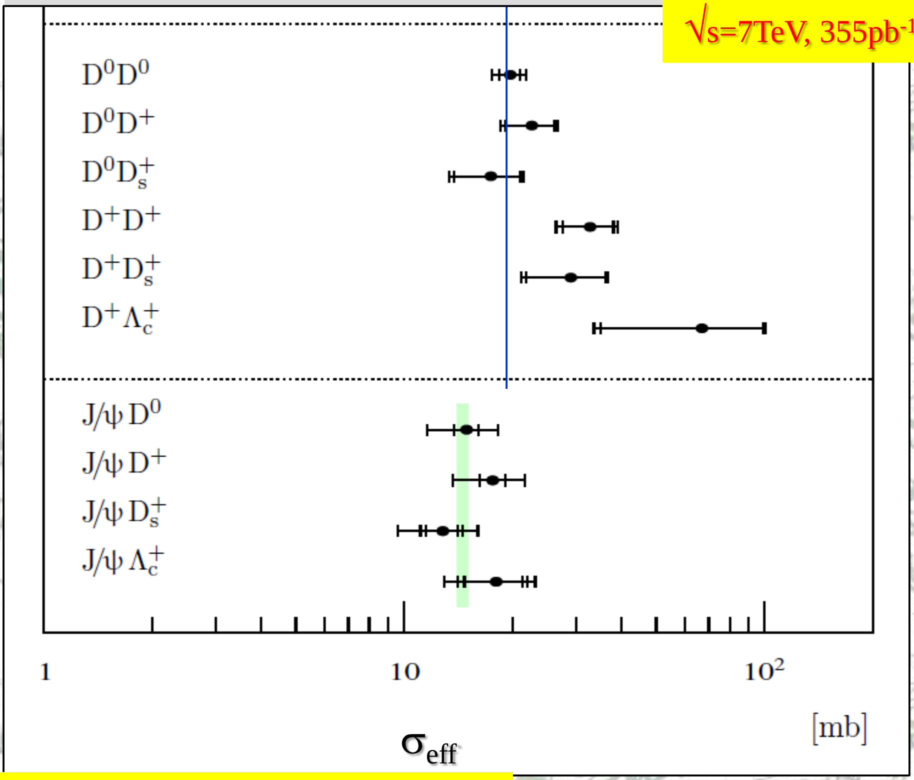
Test differential distributions

Most precise σ_{eff}

$J/\psi C$ agrees perfectly with CDF

DD closer to ≈20mb

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



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Correlations: $\Delta\phi$, Δy, m

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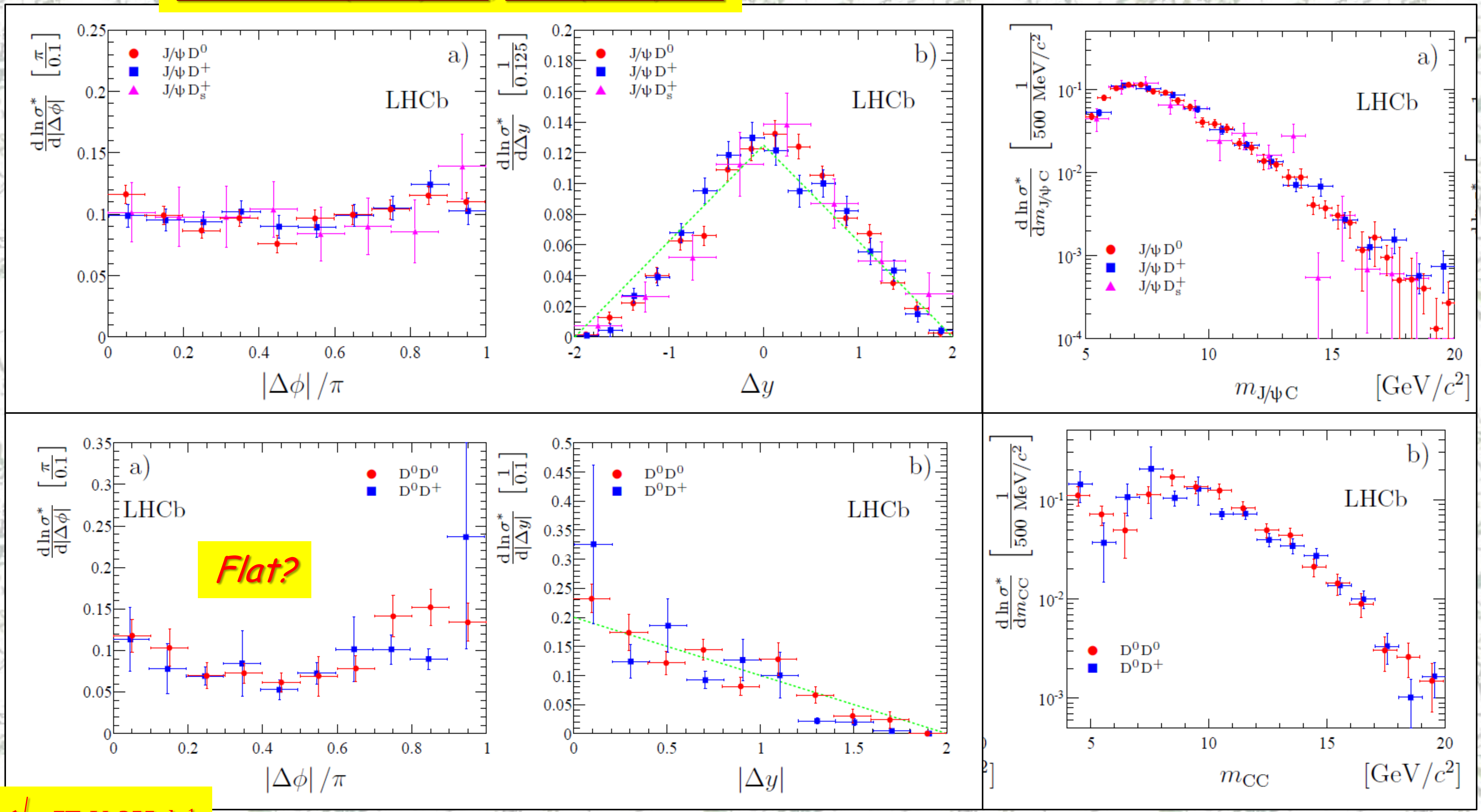

$\sqrt{s}$=7TeV, 355pb^{-1}

Just for comparison: $D\bar{D}$

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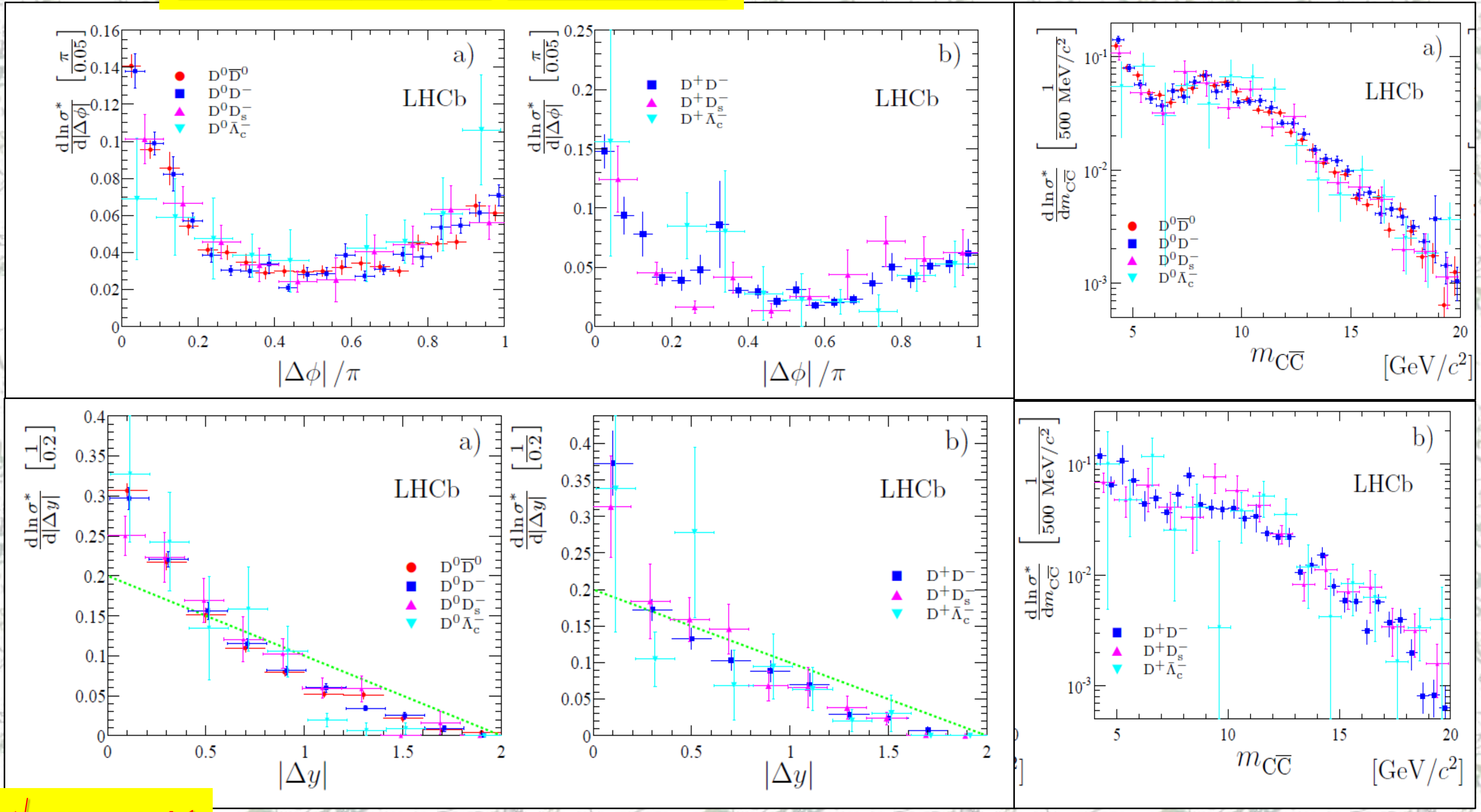

$\sqrt{s}$=7TeV, 355pb^{-1}

p_T-spectra: puzzle?

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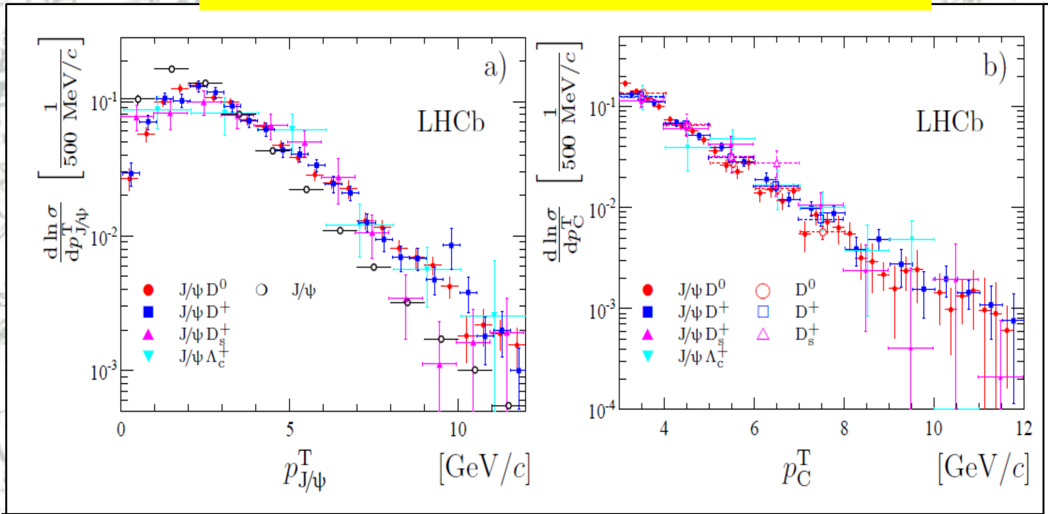
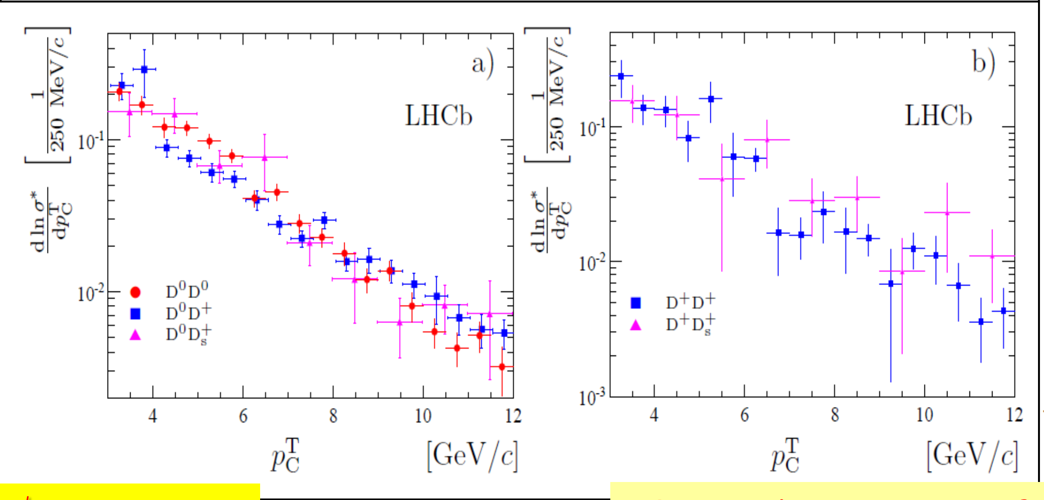
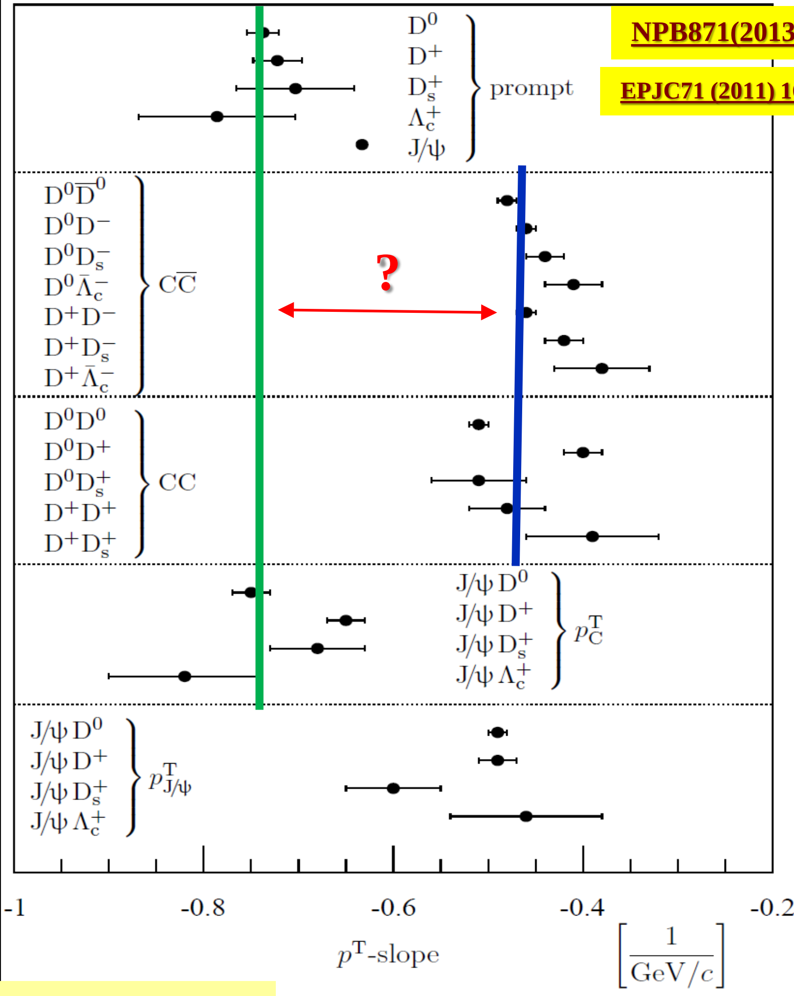




NPB871(2013)1

EPJC71 (2011) 1645

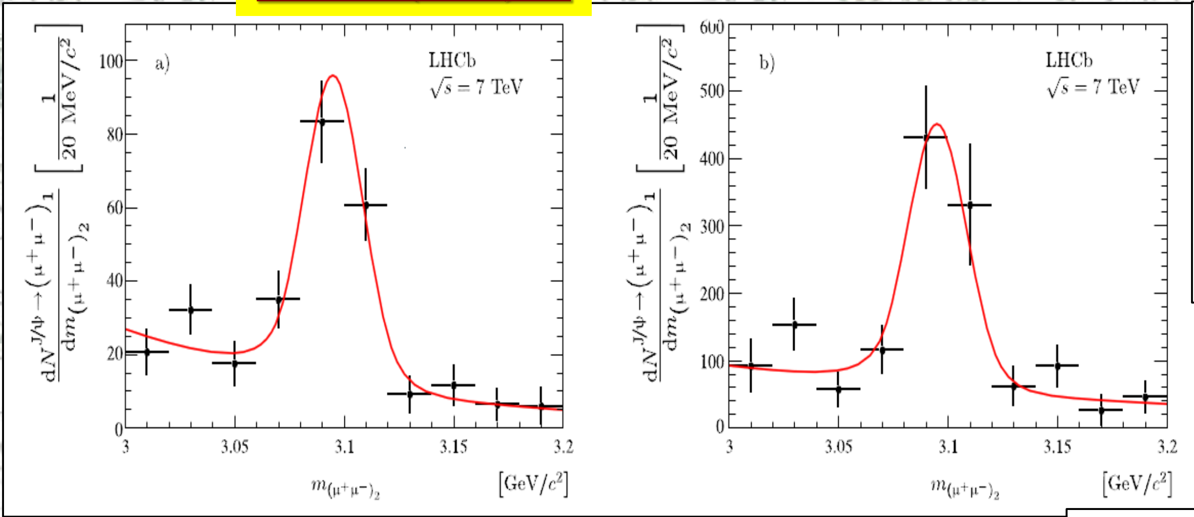


√s=7TeV, 355pb⁻¹

Fit with exponent for p_T>3GeV/c

Other processes? $2\times J/\psi$

PLB707(2012) 52



Luminosity:

37.5pb^{-1} (2010 data)

significance >6σ

- 139 18 events
- 672 129 eff-corrected

$$\sigma^{J/\psi\, J/\psi} = 5.1 \pm 1.0 \pm 1.1\ \mathrm{nb},$$

$$\sigma^{J/\psi\, J/\psi}/\sigma^{J/\psi} = (5.1 \pm 1.0 \pm 0.6\,^{+1.2}_{-1.0}) \times 10^{-4},$$

Theory

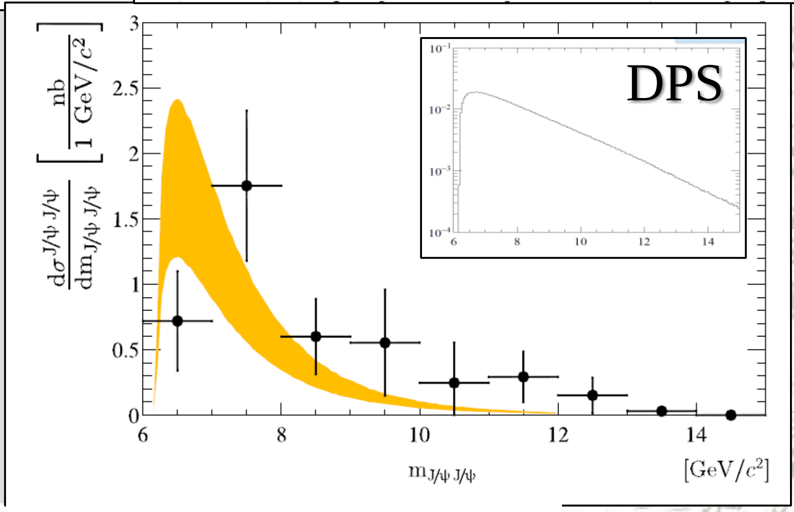
DPS σ=2.3nb

SPS (LO CS) σ=4nb (30%)

χ_c feedown, CO, …

Not too conclusive.

Update for full statistic (x80) is in process

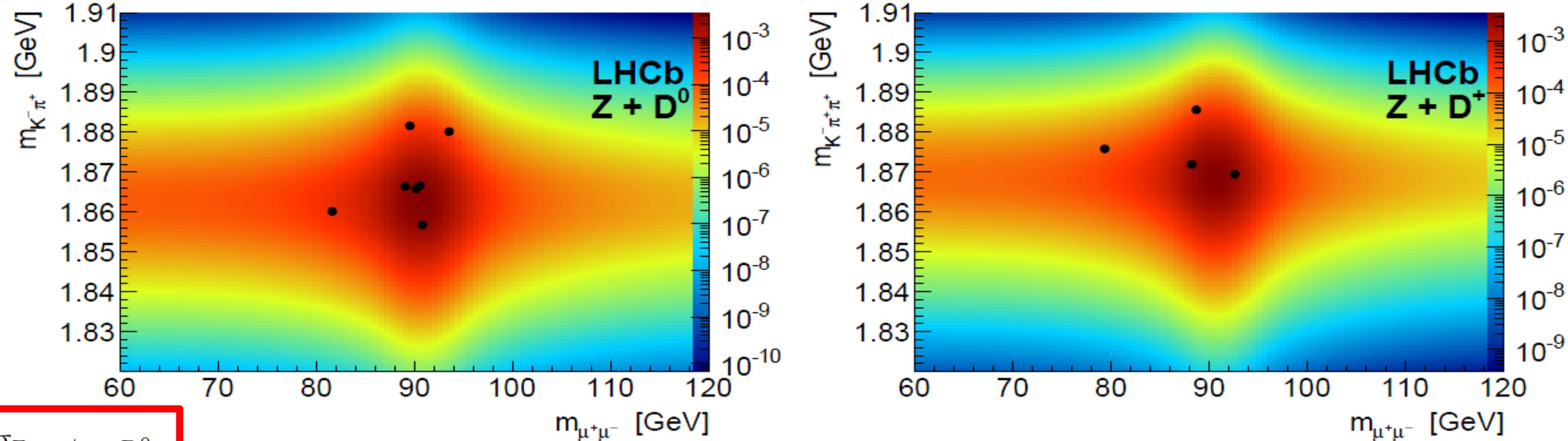


Berezhnoy et al, PRD84 (2011) 094023

Try harder scale: $Z+c\bar{c}$

7+4 *background free* ZD^0 and ZD^+ events

JHEP 1404(2014) 091



$\frac{\sigma_{Z\to\mu^+\mu^-,D^0}}{\sigma_{Z\to\mu^+\mu^-,D^+}}$	measured	MCFM massless	MCFM massive	DPS
$Z+D^0$	$2.50\pm1.12\pm0.22$	$0.85^{+0.12}_{-0.07}\,^{+0.11}_{-0.17}\pm0.05$	$0.64^{+0.01}_{-0.01}\,^{+0.08}_{-0.13}\pm0.04$	$3.28^{+0.68}_{-0.58}$
$Z+D^+$	$0.44\pm0.23\pm0.03$	$0.37^{+0.05}_{-0.03}\,^{+0.05}_{-0.07}\pm0.03$	$0.28^{+0.01}_{-0.01}\,^{+0.04}_{-0.06}\pm0.02$	$1.29^{+0.27}_{-0.23}$

More data is needed.

Very interesting region: 30-90% violation of factorization formula is expected

Next steps?

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

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- *Something* + $c\bar{c}$ at LHCb

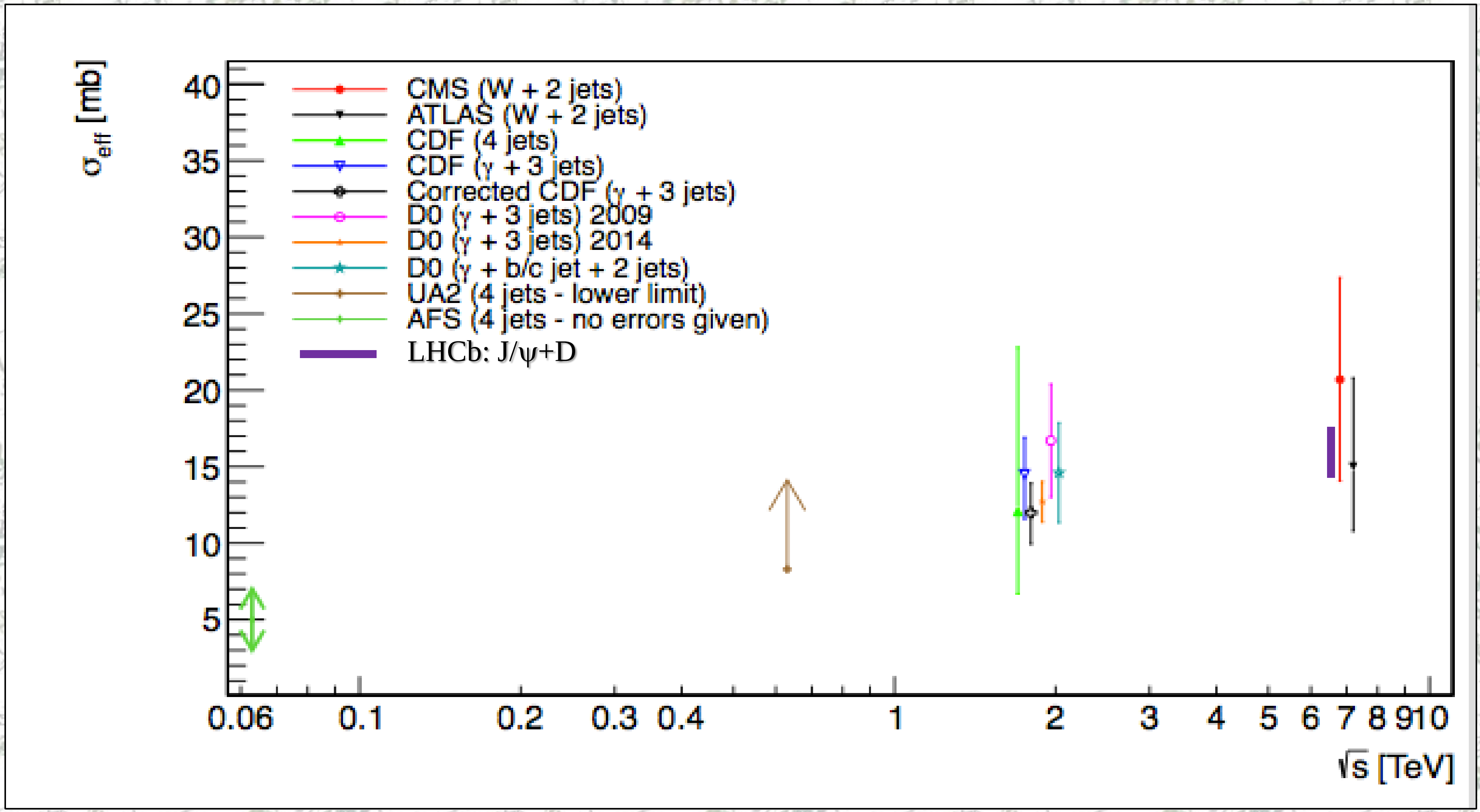
$$\sigma(X+c\bar{c})_{DPS} = \sigma(X)\times\sigma(c\bar{c})/\sigma_{eff} \approx 10\%\ \sigma(X)$$

  - 10% of "hard" events has additional charm!
- Choice of "X" defines the process scale, vary from soft $c\bar{c}$ to hard Z/W, …
  - Intermediate scales?
- Large statistic allows precise differentia measurements
- Probe pocket formula and search for factorization violations

Summary ("*Towards TPS*")

- DPS is actively explored at LHC by ATLAS, CMS and LHCb
  - Great degree of complementarity:
    - large variety of processes
    - different kinematics range
    - different DPS purity
- Testing the basic principles of DPS paradigm
  - … and search for factorization violation
- Charm and multiple charm production is very good DPS probe
- DPS processes have different energy dependence from SPS
  - data at $\sqrt{s}$=13TeV will be very useful for better DPS understanding
  - for $\sqrt{s}$=13TeV for some processes, e.g. $c\bar{c}$, one probably can speculate also about ***Triple Parton Scattering***

Energy/process independent?



Compare with CDF'2k+6

http://www-cdf.fnal.gov/physics/new/bottom/060921.blessed-double-charm-corr/

- CDF: azimuthal correlations for $D^{(0,+)} D^{*-}$
- Large gluon splitting contribution

Very different kinematical region