Double Parton Scattering @ LHC

(ATLAS, CMS & LHCb)

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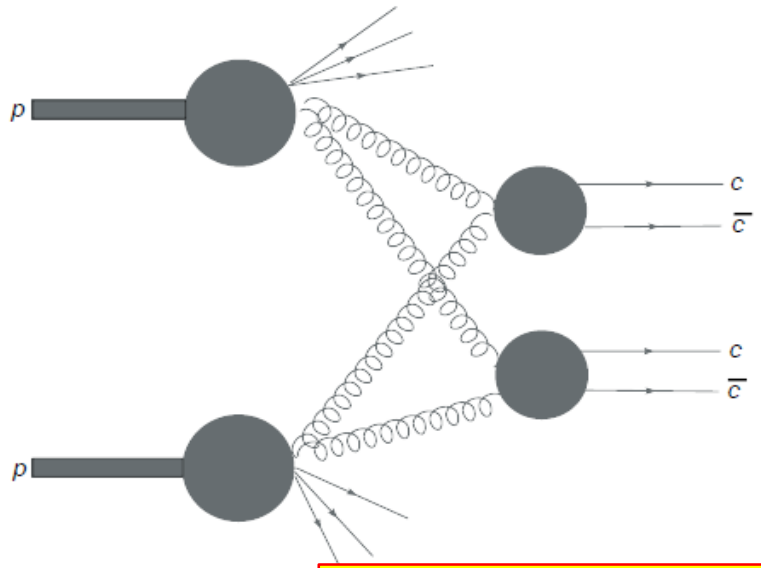
DPS: simple paradigm



Two independent hard scattering processes
Relations through (unknown) *double* PDF

$$\Gamma_{ij}(x_1, x_2; \mathbf{b_1}, \mathbf{b_2}; Q_1^2, Q_2^2) = D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) f(\mathbf{b_1}) f(\mathbf{b_2}),$$

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

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

m=1,2

Universal (energy and process independent) factor)

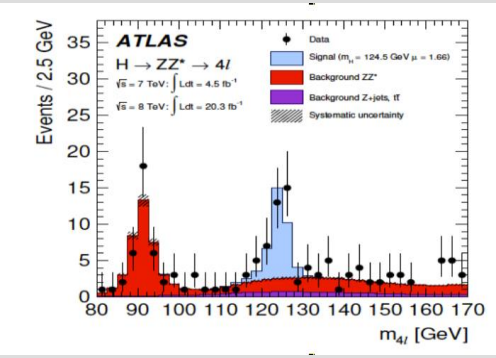
$$1/\sigma_{eff} = \int d^2b F^2(b)$$

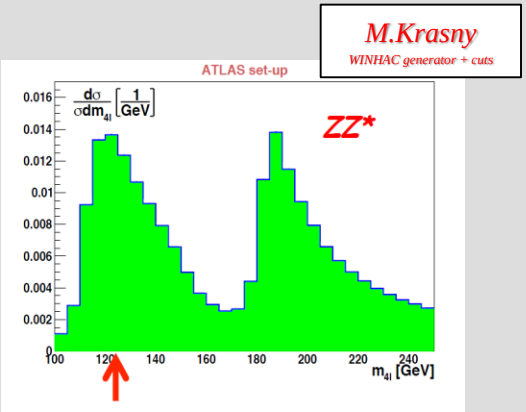
$$\sigma_{\rm eff}^{\rm DPS} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb}$$

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

DPS importance

- Can easily mimic crucial signals



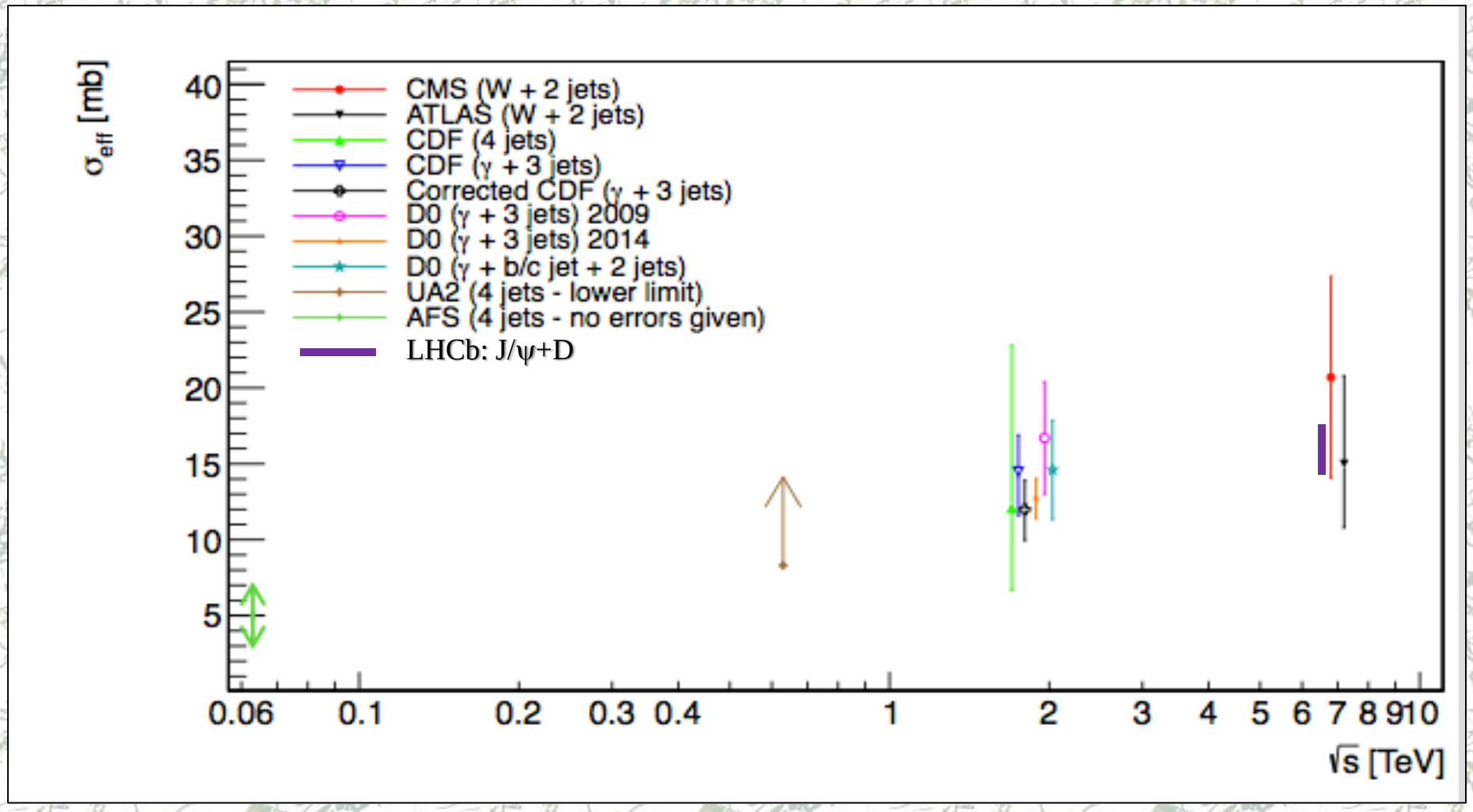


- DPS importance grows with energy/gluon density (smaller x)
- Interparton correlations
- First observed long time ago:
  - 4-jets AFS@ISR
  - 3-jets+γ CDF, D0, …
- @ LHC
  - ATLAS, CMS: 4-jets, W+jets, 2×J/ψ, W+J/ψ, Z+J/ψ, …
  - LHCb: 2×J/ψ, Z+D, *double charm*, ….

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

TEST IT!

Energy/process independent?



How to access DPS: 3 approaches

- ATLAS & CMS: separation via correlations
- DPS: *no correlations* vs SPS: *strong correlations*

- Study correlations, e.g. fit $\Delta\phi$
  - Separate small (DPS) component
- Tune DPS fraction in corresponding generator
  - Model dependence of SPS shapes
  - E.g. initial gluon p_T

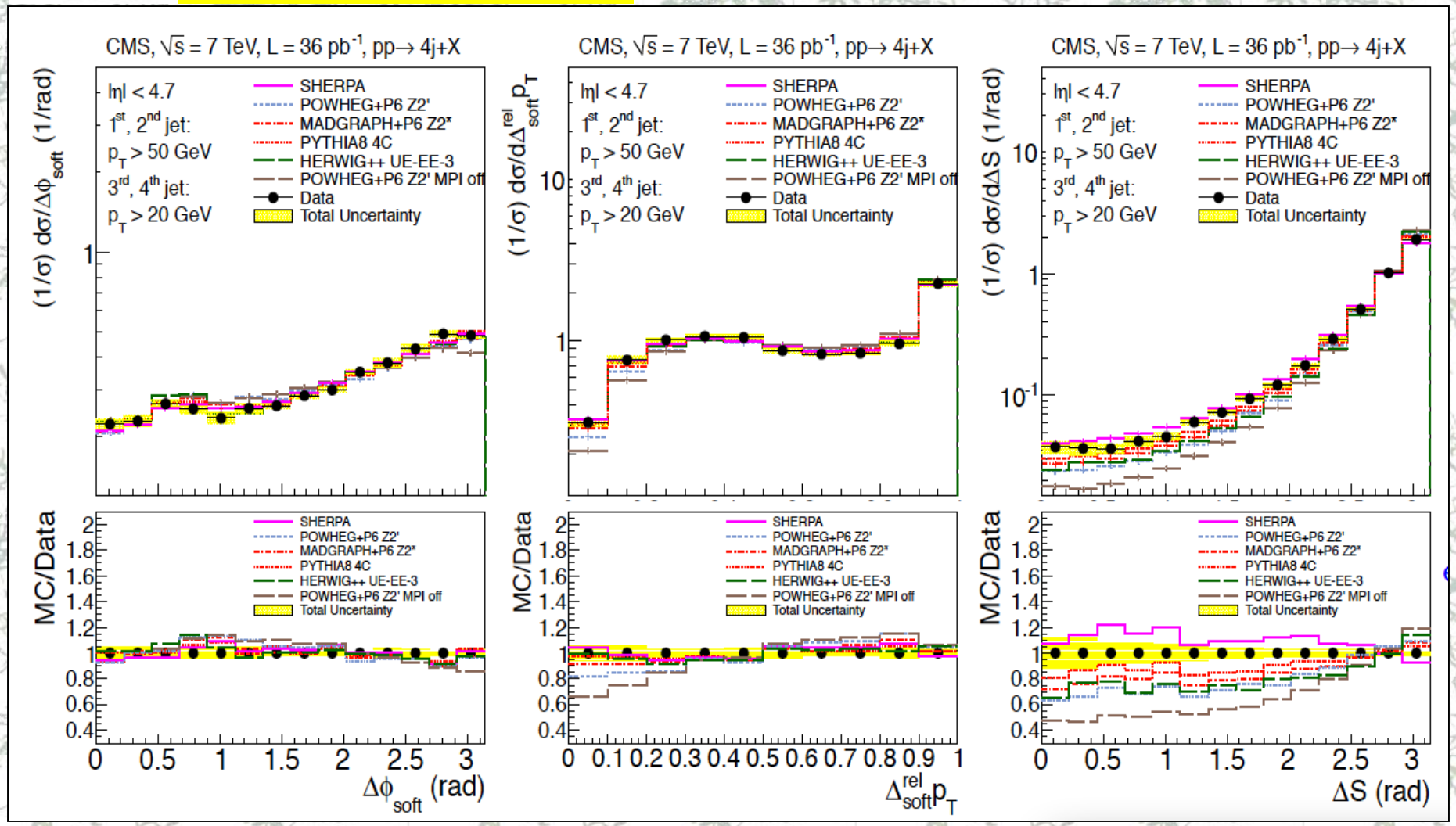
CMS: 4-jets

CMS, PRD 89 (2014) 092010

$$\Delta\phi(j_i, j_k) = \phi_i - \phi_k$$

$$\Delta^{rel}_{soft} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$$

$$\Delta S = \arccos\left(\frac{\vec{p}_T(j^i, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(j^i, j^k)| \cdot |\vec{p}_T(j^l, j^m)|}\right)$$



CMS: σ_{eff} from 4-jets

- Extracted σ_{eff} is tune-dependent: 19-30mb

CDPSTP8S1	$21.3^{+1.2}_{-1.6}$
CDPSTP8S1	$19.0^{+4.7}_{-3.0}$
CUETP8S1-CTEQ6L1	$27.8^{+1.2}_{-1.3}$
CUETP8S1-HERAPDF	$29.1^{+2.3}_{-2.0}$

Pythia-8 tunes

Choice of PDF

- Depends on interplay between soft and hard MPI
- DPS contribution is rather small *O(%)*
  - DPS templates from data

Other processes?

W+2jets

ATLAS, NJP 15(2013) 033038

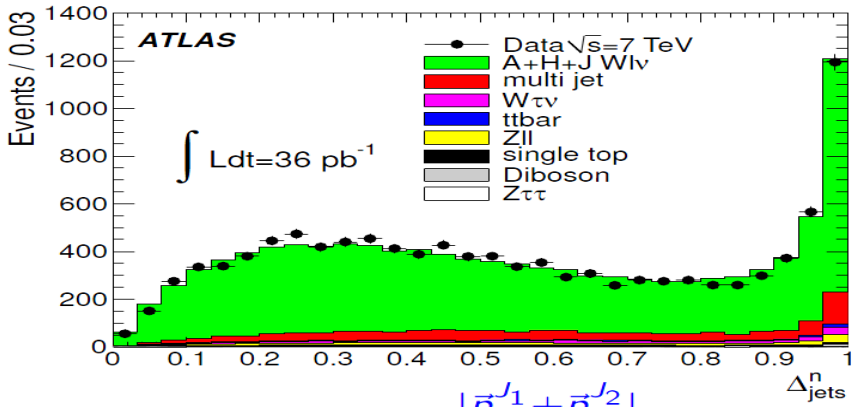
$$\frac{\hat{\sigma}_Y(s)\cdot\hat{\sigma}_Z(s)}{f_{\rm DP}^{(D|)}\cdot\hat{\sigma}^{(tot)}_{Y+Z}(s)}\cdot \qquad \sigma_{\rm eff} = \frac{1}{f_{\rm DP}^{(D)}}\cdot\frac{N_{W_{0j}}N_{2j}}{N_{W+2j}}\cdot\frac{\mathcal{L}_{W_{0j}+2j_{\rm DPI}}}{\mathcal{L}_{W_{0j}}\mathcal{L}_{2j}}\cdot\frac{\mathcal{A}_{W_{0j}+2j_{\rm DPI}}}{\mathcal{A}_{W_{0j}}\mathcal{A}_{2j}}\cdot\frac{C_{W_{0j}+2j_{\rm DPI}}}{C_{W_{0j}}C_{2j}}\cdot\frac{\varepsilon_{W_{0j}+2j_{\rm DPI}}}{\varepsilon_{W_{0j}}\varepsilon_{2j}}.$$

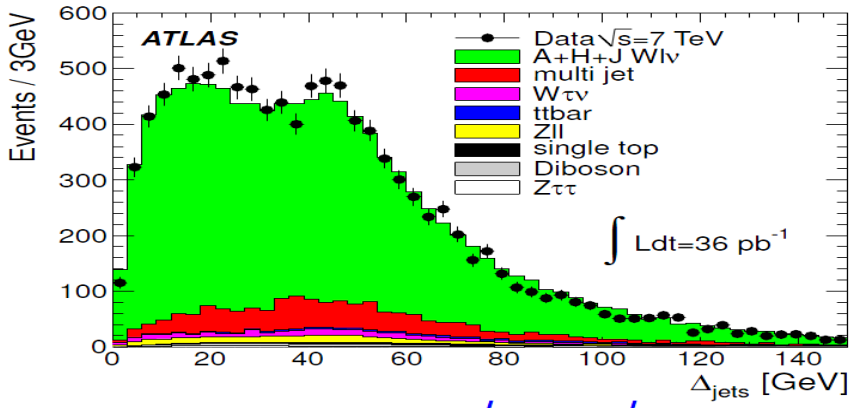
$$\sigma_{\rm eff} = \frac{1}{f_{\rm DP}^{(D)}}\cdot\frac{N_{W_{0j}}}{N_{W+2j}}\cdot\frac{N_{2j}}{\mathcal{L}_{2j}}$$

- 3 selections: W+0j, W+2j – selected in similar way
  - *anti*-k_T, $p_T(j)$>20 GeV
  - $p_T(l)$>20 GeV – trigger
  - $E_T$miss>25 GeV
  - M_T>40 GeV
- *dijets*- use minimum bias trigger (fully efficient)

Fraction of DPS

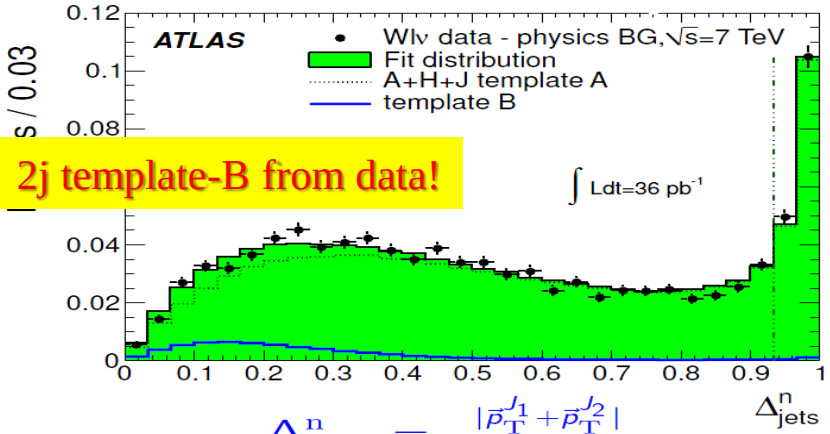
ATLAS, NJP 15(2013) 033038





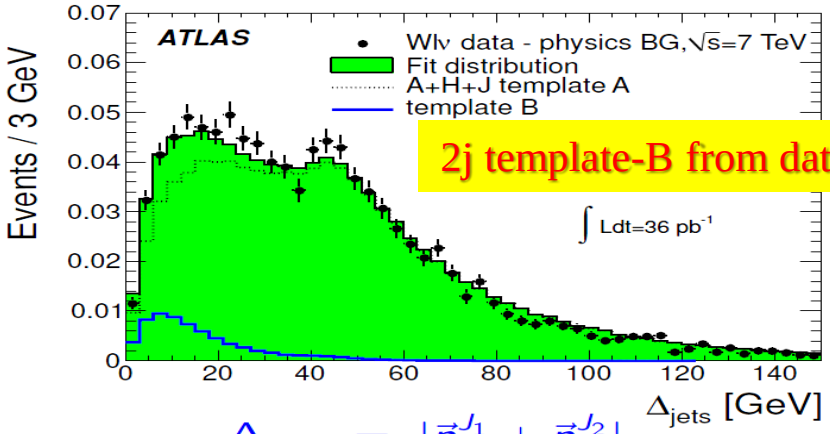
back-to-back ← $\Delta^n_{jets} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$ → collinear

$\Delta_{jets} = |\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|$



2j template-B from data!

$\Delta^n_{jets} = \frac{|\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|}{|\vec{p}_T^{J_1}| + |\vec{p}_T^{J_2}|}$



2j template-B from data!

$\Delta_{jets} = |\vec{p}_T^{J_1} + \vec{p}_T^{J_2}|$

σ_{eff} from W+2j

ATLAS, NJP 15(2013) 033038

f_{DP}

Systematic source	Unc [%]
Theory	10
Pile-up	13
Jet energy scale	12
Jet energy resolution	8
Background & lepton	11
Total systematic	24
Total statistical	17

σ_{eff}

Systematic source	Unc. [%]
$f_{DP}^{(D)}$	24
Background & lepton response	3
Luminosity	3
Total systematic	$^{+33}_{-20}$
Total statistical	17

$$f_{DP} = 0.08 \pm 0.01(stat) \pm 0.02(syst)$$

$$\sigma^{eff} = 15 \pm 3(stat) + 5/-3(syst)\ mb$$

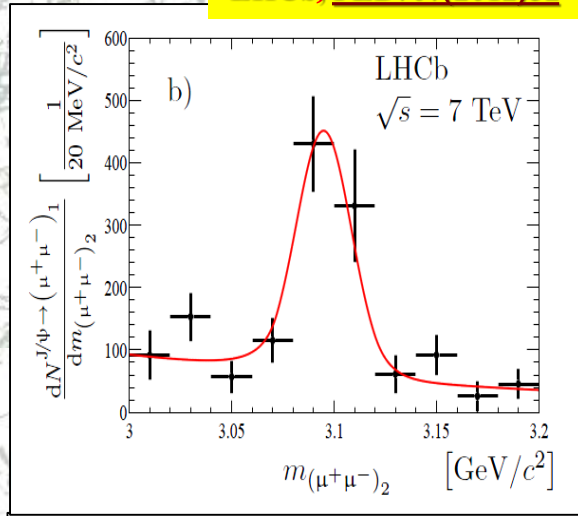
$\sigma_{eff} = 20.7 \pm 0.8(stat) \pm 6.6(syst)$ mb

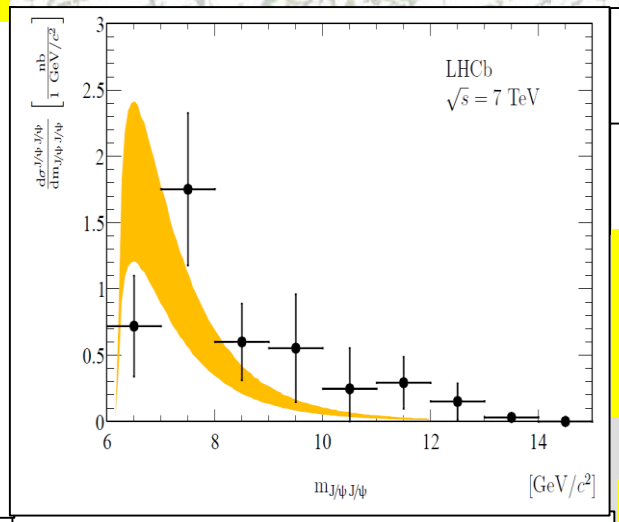
CMS, JHEP03(2014) 032

DPS purity is still small..

Other processes? 2×J/ψ

LHCb, PLB707(2012)52





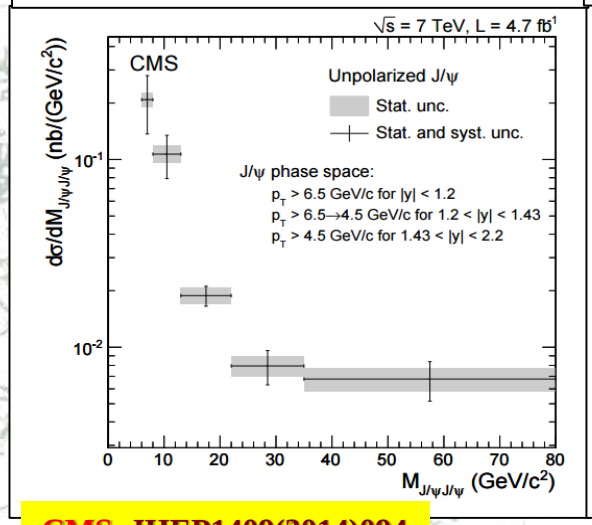
$$\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb},$$

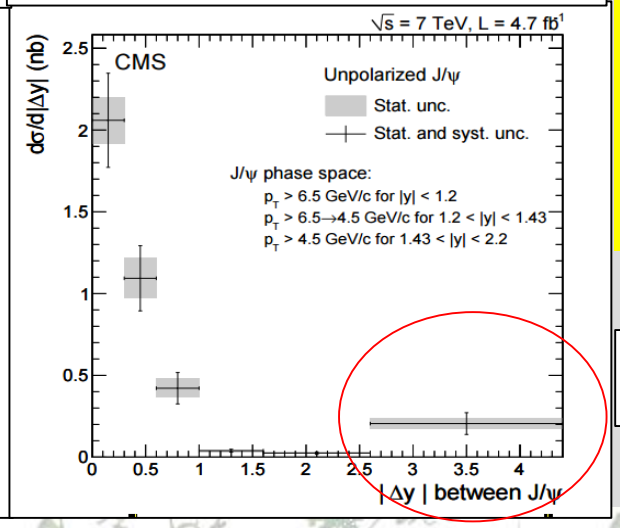
$$\sigma^{J/\psi J/\psi}/\sigma^{J/\psi} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4},$$

SPS CS 4nb (~30%)

DPS 2.3nb

Not too conclusive (116 events)





CMS: 446±32 events

Study differential distributions

Positive signal in region where SPS is suppressed:

very strong argument for DPS

$$\sigma(pp \to J/\psi J/\psi + X) = 1.49 \pm 0.07 \pm 0.13 \text{ nb},$$

CMS, JHEP1409(2014)094

Other processes? J/ψ+cc̄

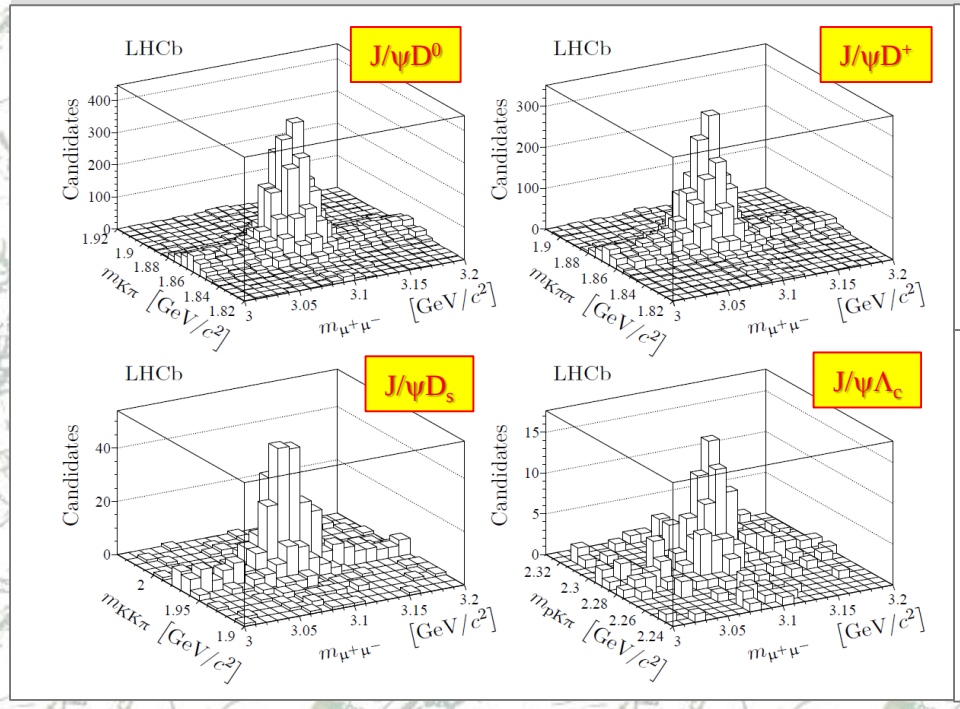
LHCb, JHEP1206(2012)141, JHEP 1403(2014)108

- *Something* + cc̄ at LHCb

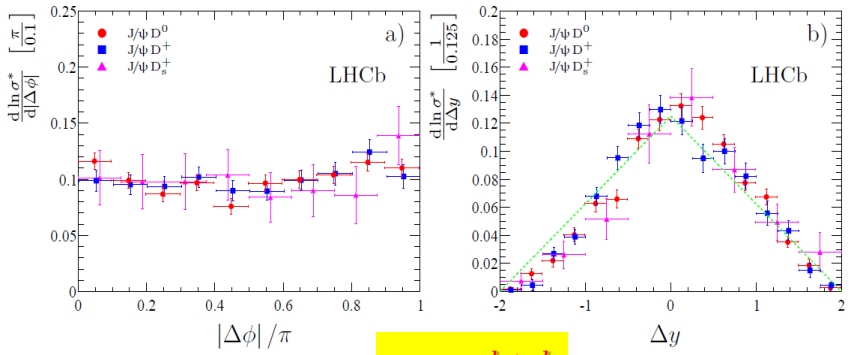
$$\sigma(c\bar{c})_{p_T<8\,\mathrm{GeV}/c,\,2.0<y<4.5} = 1419 \pm 12\,(\mathrm{stat}) \pm 116\,(\mathrm{syst}) \pm 65\,(\mathrm{frag})\ \mu\mathrm{b},$$

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

- 10% of "hard" events has additional charm!



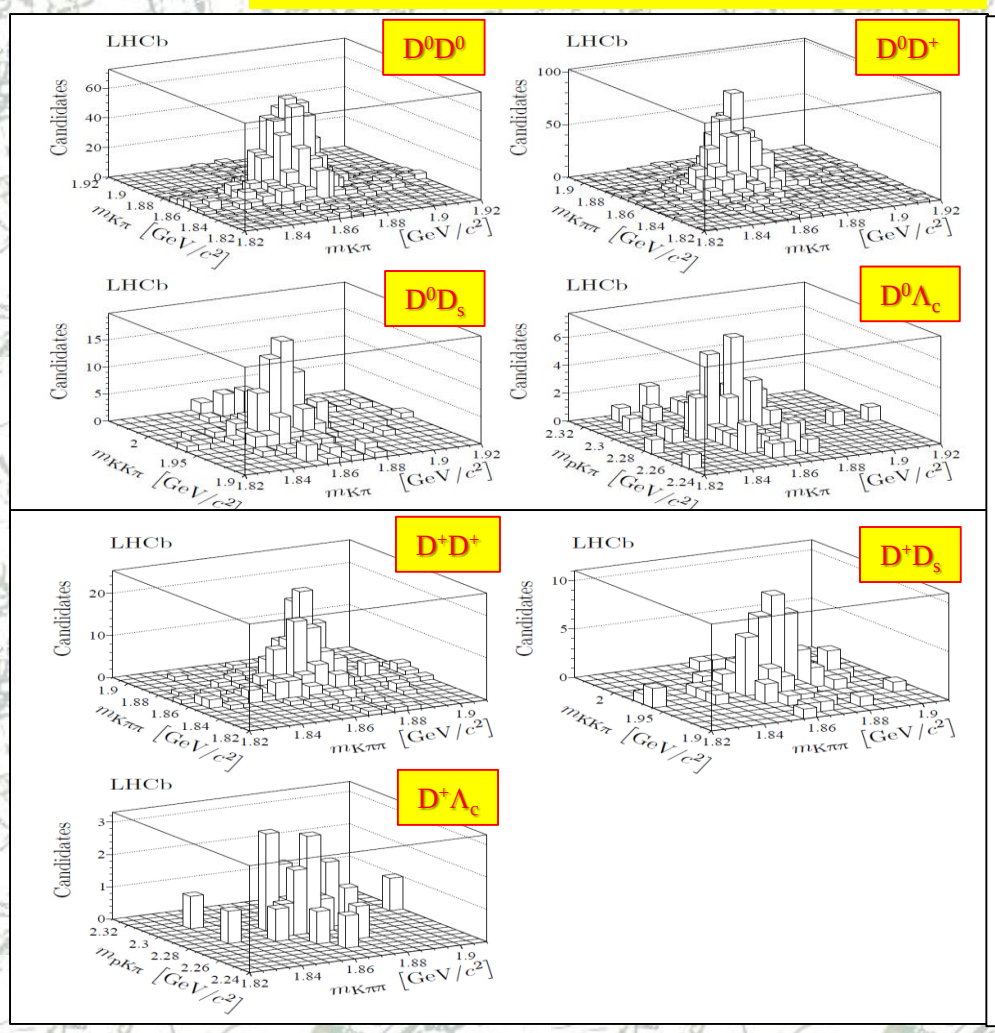
Mode	$\sigma_{J/\psi c}/\sigma_{J/\psi}$ $[10^{-3}]$	$\sigma_{J/\psi c}/\sigma_{c}$ $[10^{-4}]$	$\sigma_{J/\psi}\sigma_{c}/\sigma_{J/\psi c}$ [mb]
$J/\psi D^0$	$16.2 \pm 0.4 \pm 1.3^{+3.4}_{-2.5}$	$6.7 \pm 0.2 \pm 0.5$	$14.9 \pm 0.4 \pm 1.1^{+2.3}_{-3.1}$
$J/\psi D^+$	$5.7 \pm 0.2 \pm 0.6^{+1.2}_{-0.9}$	$5.7 \pm 0.2 \pm 0.4$	$17.6 \pm 0.6 \pm 1.3^{+2.8}_{-3.7}$
$J/\psi D_s^+$	$3.1 \pm 0.3 \pm 0.4^{+0.6}_{-0.5}$	$7.8 \pm 0.8 \pm 0.6$	$12.8 \pm 1.3 \pm 1.1^{+2.0}_{-2.7}$
$J/\psi \Lambda_c^+$	$4.3 \pm 0.7 \pm 1.2^{+0.9}_{-0.7}$	$5.5 \pm 1.0 \pm 0.6$	$18.0 \pm 3.3 \pm 2.1^{+2.8}_{-3.8}$

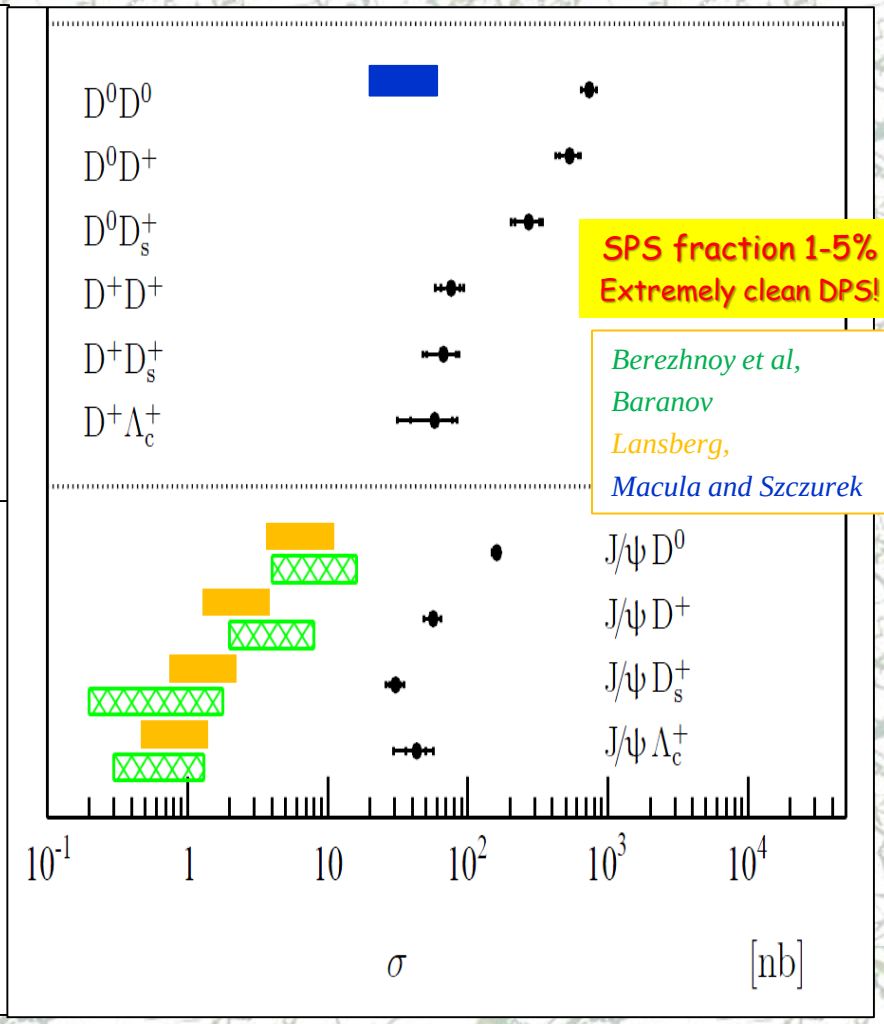


uncorrelated

Other processes? $2\times(c\bar{c})$

LHCb, JHEP1206(2012)141, JHEP 1403(2014)108



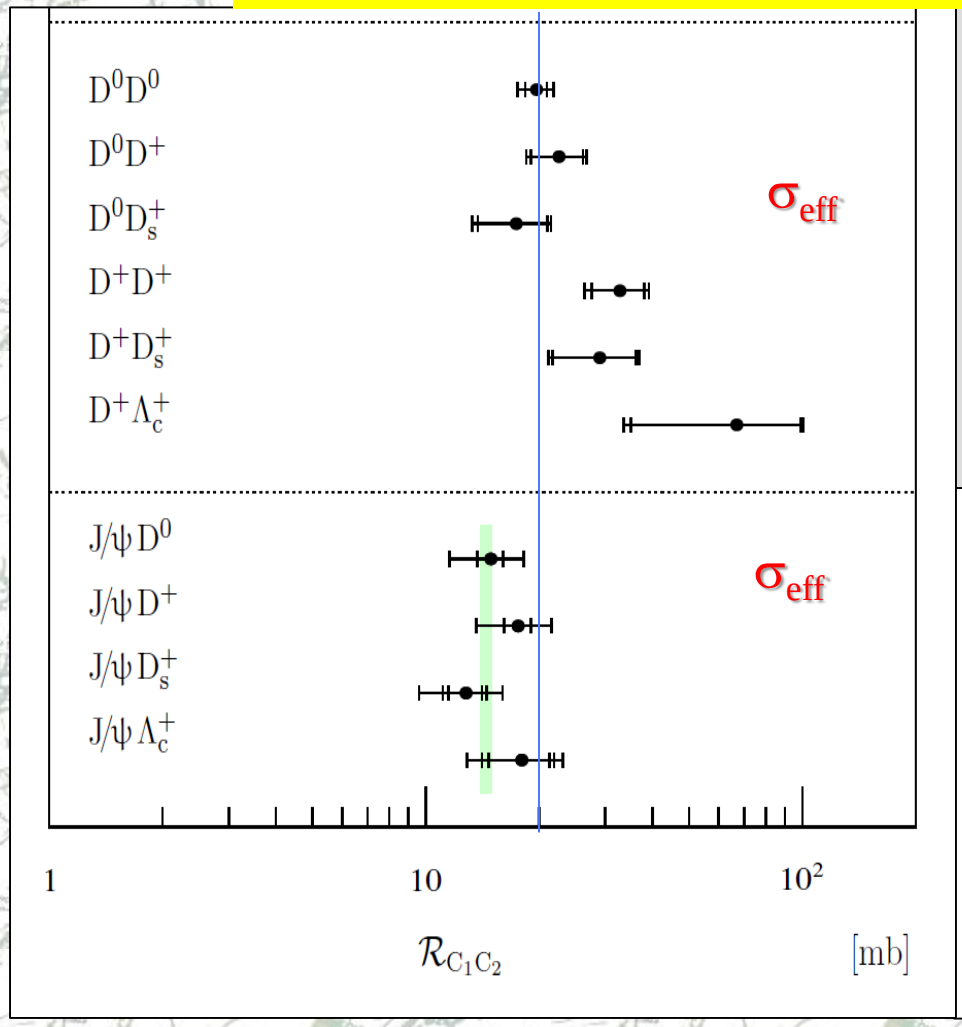


SPS fraction 1-5%
Extremely clean DPS!

Berezhnoy et al,
Baranov
Lansberg,
Macula and Szczurek

σ_{eff} from $J/\psi+c\bar{c}$ and $2\times(c\bar{c})$

LHCb, JHEP1206(2012)141, JHEP 1403(2014)108

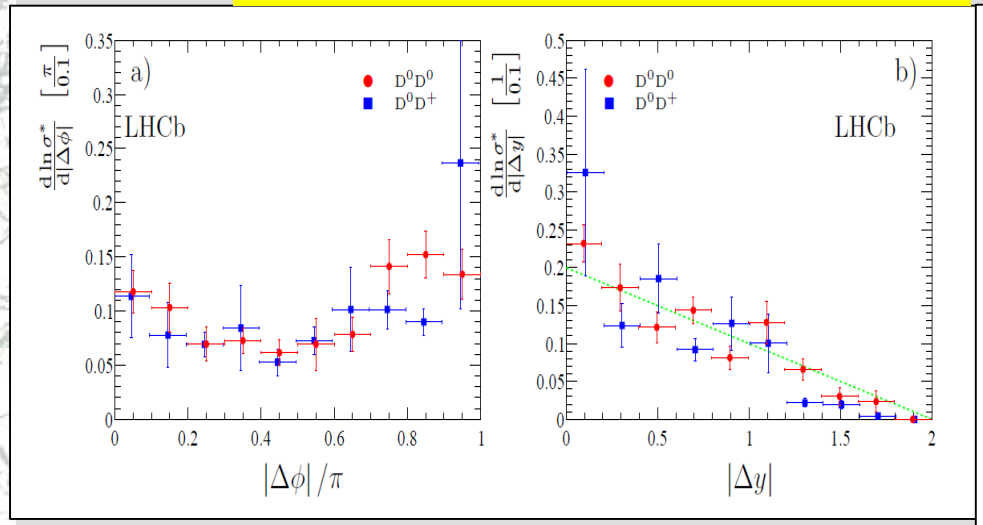


- DPS with charm is not rare
- DPS dominates over SPS
- Extra clean environment and large signals
  - "DPS factory"
  - e.g. look for factorisation violation

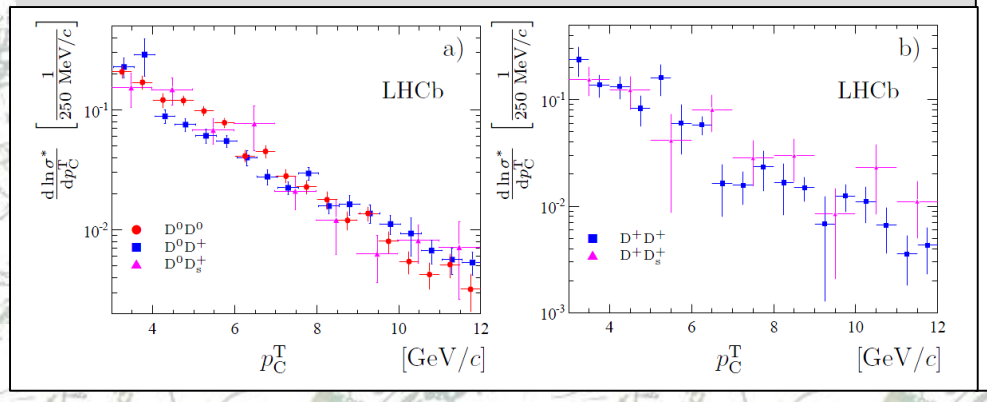
Mode	σ [nb]	$\sigma_{CC}/\sigma_{C\bar{C}}$ [%]	$\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ [mb]
D^0D^0	$690 \pm 40 \pm 70$	10.9 ± 0.8	$2 \times (42 \pm 3 \pm 4)$
$D^0\overline{D}^0$	$6230 \pm 120 \pm 630$		$2 \times (4.7 \pm 0.1 \pm 0.4)$
D^0D^+	$520 \pm 80 \pm 70$	12.8 ± 2.1	$47 \pm 7 \pm 4$
D^0D^-	$3990 \pm 90 \pm 500$		$6.0 \pm 0.2 \pm 0.5$
$D^0D_s^+$	$270 \pm 50 \pm 40$	15.7 ± 3.4	$36 \pm 8 \pm 4$
$D^0D_s^-$	$1680 \pm 110 \pm 240$		$5.6 \pm 0.5 \pm 0.6$
$D^0\bar{\Lambda}_c^-$	$2010 \pm 280 \pm 600$	—	$9 \pm 2 \pm 1$
D^+D^+	$80 \pm 10 \pm 10$	9.6 ± 1.6	$2 \times (66 \pm 11 \pm 7)$
D^+D^-	$780 \pm 40 \pm 130$		$2 \times (6.4 \pm 0.4 \pm 0.7)$
$D^+D_s^+$	$70 \pm 15 \pm 10$	12.1 ± 3.3	$59 \pm 15 \pm 6$
$D^+D_s^-$	$550 \pm 60 \pm 90$		$7 \pm 1 \pm 1$
$D^+\Lambda_c^+$	$60 \pm 30 \pm 20$	10.7 ± 5.9	$140 \pm 70 \pm 20$
$D^+\bar{\Lambda}_c^-$	$530 \pm 130 \pm 170$		$15 \pm 4 \pm 2$

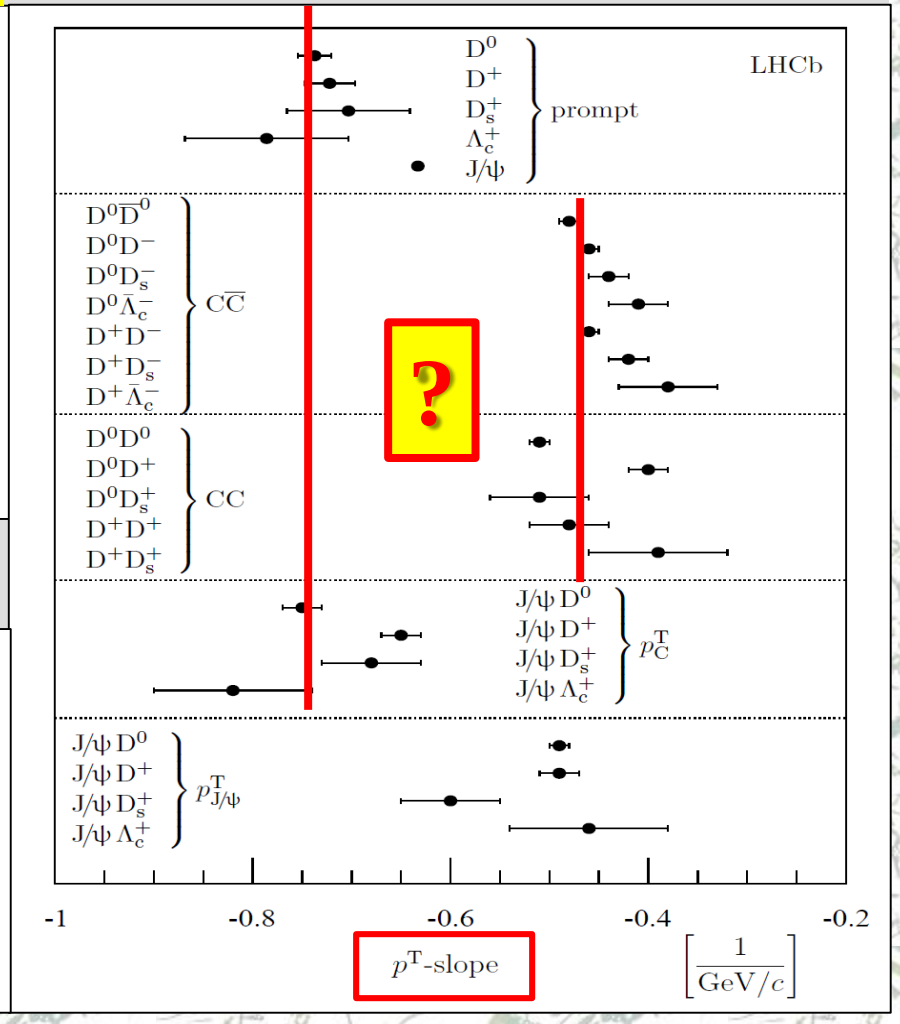
DPS: is everything fine?

LHCb, JHEP1206(2012)141, JHEP 1403(2014)108



Compare p_T-spectra and fit with *exp*

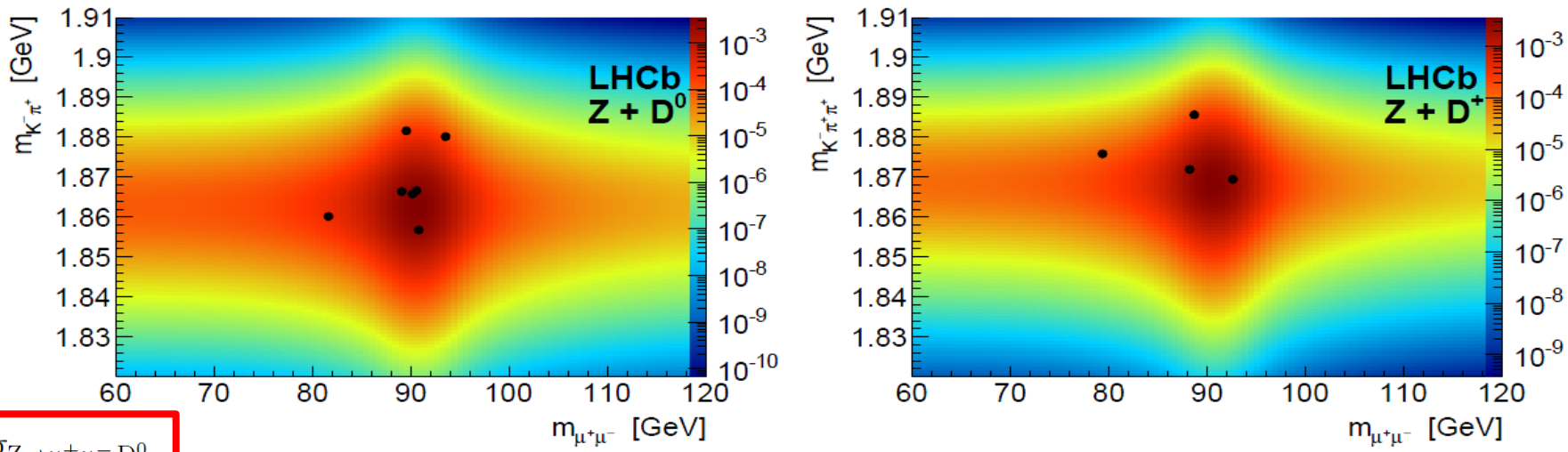




Try harder scale: $Z+c\bar{c}$

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

LHCb, JHEP 1404(2014) 091



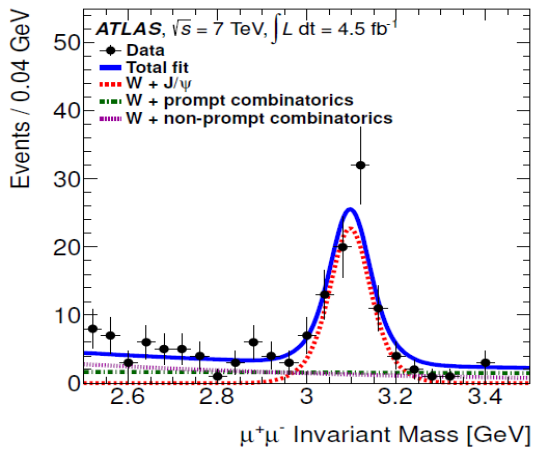
$\sigma_{Z\to\mu^+\mu^-,D^0}$ $\sigma_{Z\to\mu^+\mu^-,D^+}$	measured	MCFM massless	MCFM massive	DPS
$Z+D^0$	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12}_{-0.07}{}^{+0.11}_{-0.17} \pm 0.05$	$0.64^{+0.01}_{-0.01}{}^{+0.08}_{-0.13} \pm 0.04$	$3.28^{+0.68}_{-0.58}$
$Z+D^+$	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05}_{-0.03}{}^{+0.05}_{-0.07} \pm 0.03$	$0.28^{+0.01}_{-0.01}{}^{+0.04}_{-0.06} \pm 0.02$	$1.29^{+0.27}_{-0.23}$

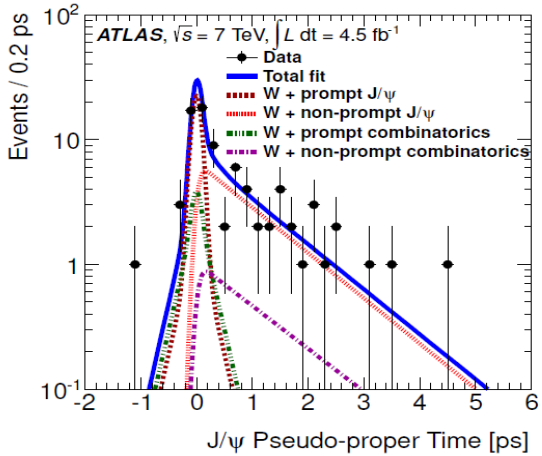
More data is needed.

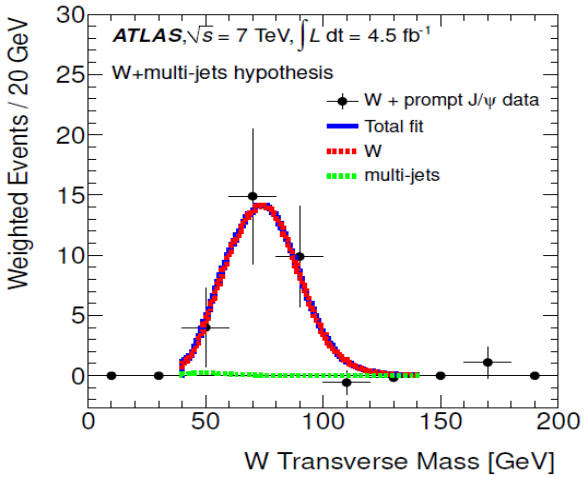
Very interesting region: 30-90% violation of factorization formula is expected

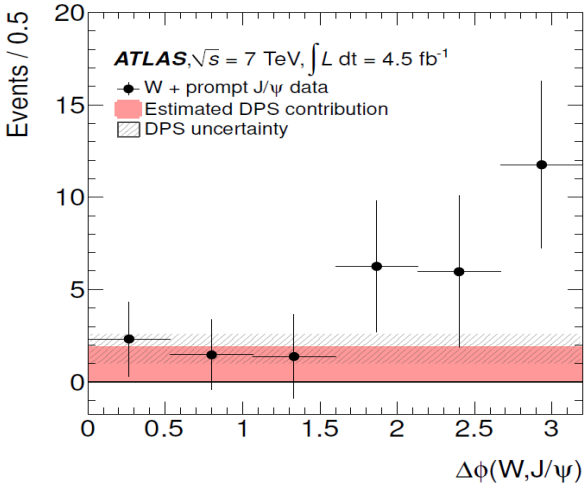
One more process: W+J/ψ

JHEP04(2014)172









Small statistics ~30 events

Very interesting region for DPS. DPS is large but not dominant

$$R^{\rm incl}_{J/\psi} = \frac{\mathrm{BR}(J/\psi \to \mu^+\mu^-)}{\sigma_{\rm fid}(pp \to W^\pm)} \cdot \frac{\mathrm{d}\sigma(pp \to W^\pm + J/\psi)}{\mathrm{d}y}$$

$$R^{\rm incl}_{J/\psi} = (126 \pm 32 \pm 9^{+41}_{-25}) \times 10^{-8}$$

$$R^{\rm DPS\ sub}_{J/\psi} = (78 \pm 32 \pm 22^{+41}_{-25}) \times 10^{-8},$$

Summary

- 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
- Qualitative and quantative testing the basic principles of DPS paradigm
  - … and search for factorization violation
- 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?