

# LHCb QCD Results

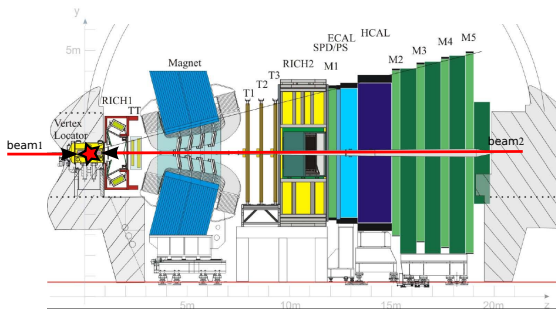
Victor Coco, on behalf of the LHCb Collaboration

CERN

September 4, 2015



# Introduction



- ▶ LHCb is fully instrumented for  $2 < \eta < 4.5$ .
- ▶ Low  $p_T$ , low mass triggers.
- ▶ Interesting domain of phase space for **MPI studies**.
- ▶ Low pile-up environment → allow studies of **central exclusive production** .
- ▶ In this region models have been extrapolated in energy but also in rapidity  
→ Forward region provides an interesting **test for MC models**.  
Not discussed in this talk.

# Double parton scattering

- ▶ The "simple" paradigm:

- ▶ Independent hard scattering processes.

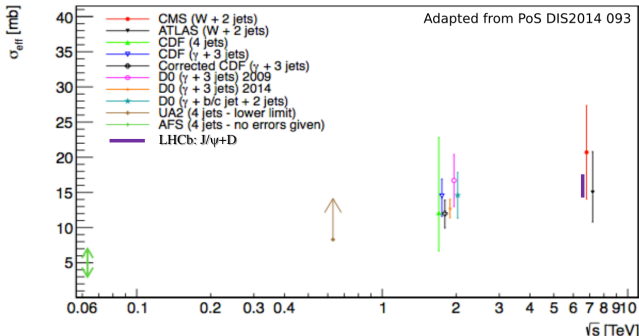
- ▶ Assuming factorisation of the double PDF:  $\sigma_{DPS}^{AB} = \frac{\delta_{A,B}}{2} \frac{\sigma_{SPS}^A \sigma_{SPS}^B}{\sigma_{eff}}$ .

- ▶  $\sigma_{eff}$  assumed to be a energy and process independent factor.

- ▶ Experimental tests:

- ▶ Is  $\sigma_{eff}$  really universal?

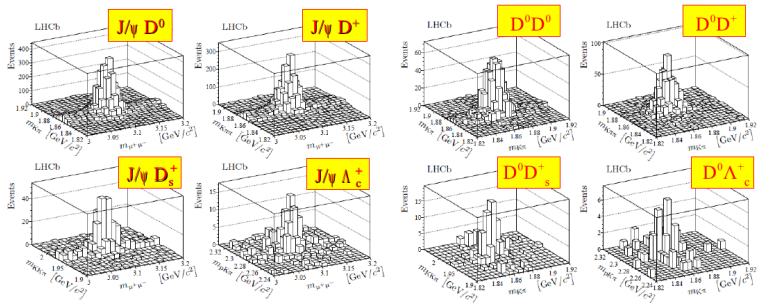
- ▶ Is the "pocket formula" for  $\sigma_{DPS}^{AB}$  always valid?



# DPS studies @ LHCb

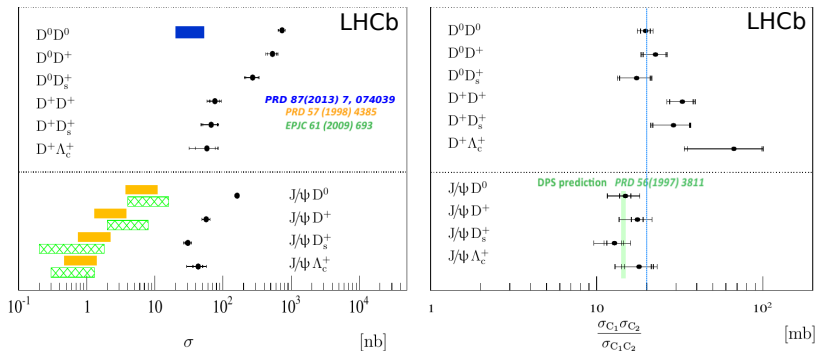
Double Charm cross sections @  $\sqrt{s} = 7$  TeV, JHEP 06 (2012) 141, JHEP 03(2014)108

- ▶ Production of multiple heavy flavour: pQCD, double parton scattering (DPS), intrinsic charm content of the proton (IC).
- ▶ Measurement of  $J/\psi C$  and  $CC$  production cross section and differential distributions with:
  - ▶  $J/\psi \rightarrow \mu\mu$
  - ▶  $C = D_0(K^- \pi^+), D^+(K^- \pi^+ \pi^+), D_s^+(K^- K^+ \pi^+), \Lambda_c^+(pK^- \pi^+)$
- ▶ 17 channels measured,  $J/\psi C$  with  $> 7\sigma$ ,  $CC$  with  $> 5\sigma$  for 6 modes.



# DPS studies @ LHCb

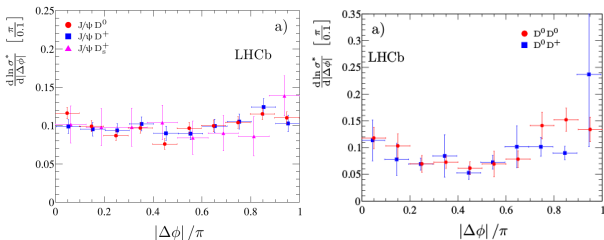
Double Charm cross sections @  $\sqrt{s} = 7 \text{ TeV}$ , JHEP 06 (2012) 141, JHEP 03(2014)108



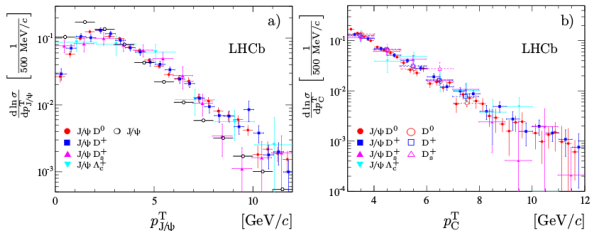
- ▶ DPS is dominant, 1-5% SPS contribution.
- ▶  $\sigma_{eff}$  from  $J/\psi + C$  in good agreement with other measurements.
- ▶ For CC if DPS indeed dominates would mean a 2-3 higher  $\sigma_{eff}$ .

# DPS studies @ LHCb

Double Charm cross sections @  $\sqrt{s} = 7 \text{ TeV}$ , J. High Energy Phys. 06 (2012) 141



- Uncorrelated production in  $J/\psi C$  and  $CC$  dominant, support DPS hypothesis.

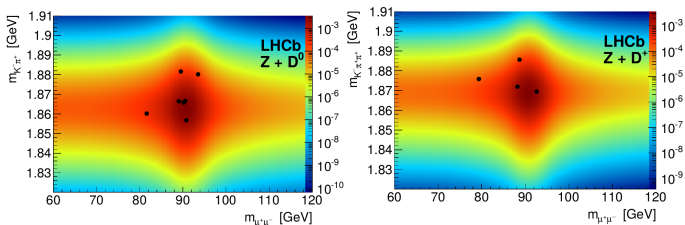


- $p_T(J/\psi)$  in  $J/\psi C$  harder than in inclusive  $J/\psi$ , but  $p_T(C)$  similar.
- $p_T(C)$  in  $CC$  similar to  $p_T(C)$  in inclusive open-charm ( not in  $CC$ ).

# MPI studies @ LHCb

Z+D @  $\sqrt{s} = 7 \text{ TeV}$ , JHEP 1404(2014)91

- Selected  $Z \rightarrow \mu\mu + D^0 \rightarrow K^- \pi^+$  and  $Z \rightarrow \mu\mu + D^+ \rightarrow K^- \pi^+ \pi^+$ .
- Observed 11 events at  $\sqrt{s} = 7 \text{ TeV}$  with  $1.0 \text{ fb}^{-1} \rightarrow 5.1\sigma$  observation.

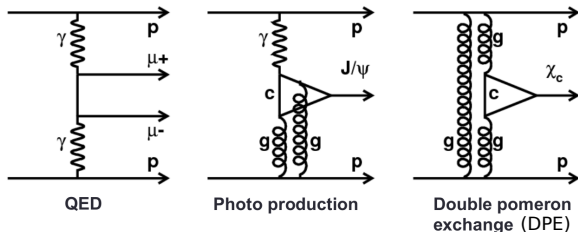


	measured	MCFM massless [1]	MCFM massive [17]	DPS ( : pocket formula )
Z + D <sup>0</sup>	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12}_{-0.07} {}^{+0.11}_{-0.17} \pm 0.05$	$0.64^{+0.01}_{-0.01} {}^{+0.08}_{-0.13} \pm 0.04$	$3.28^{+0.68}_{-0.58}$
Z + D <sup>+</sup>	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05}_{-0.03} {}^{+0.05}_{-0.07} \pm 0.03$	$0.28^{+0.01}_{-0.01} {}^{+0.04}_{-0.06} \pm 0.02$	$1.29^{+0.27}_{-0.23}$

- Not enough data to disentangle SPS from DPS but interesting region where 30 to 90% violation of the factorisation is expected
- An update with full Run I dataset, and lower  $p_T(D)$  threshold would allow to look at differential distributions.

# Central exclusive production @ LHCb

- ▶  $p + p \rightarrow p + X + p$  with exchange of a colourless objects ( $\gamma$  or Pomeron).



- ▶ Data taking with luminosity levelling

→ for Run I stable average pile-up  $\sim 2$ ,  $\sim 20\%$  single pp interaction.

- ▶ X detected in the LHCb detector, and requires a rapidity gap

→ No other activity in LHCb. Backward coverage from VELO  $-3.5 < \eta < -1.5$ .

- ▶ Several measurement performed during Run I:

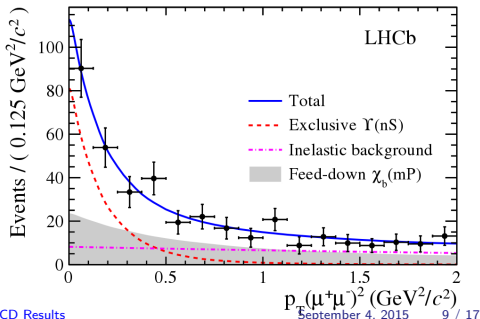
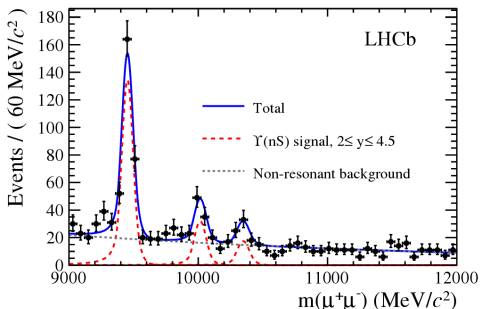
- ▶  $J/\psi$  and  $\psi(2S)$  production through  $\gamma P$  exchange JPG41 (2013) 055002.
- ▶  $\chi_c(0, 1, 2)$  production through  $PP$  exchange LHCb-CONF-2011-022.
- ▶ Non-resonant di- $\mu$  production through  $PP$  exchange LHCb-CONF-2011-022.



# Central exclusive production @ LHCb

Upsilon CEP LHCb-PAPER-2015-011

- ▶ Two well reconstructed  $\mu$ .
- ▶ Rapidity gap: No other tracks backward or forward.
- ▶ Fit of the  $p_T^2$  of the di- $\mu$  candidate after subtraction of the non-resonant contribution.
  - ▶ Exclusive  $Y(nS)$  and feed-down  $\chi_b(mP)$  shapes from SuperChIC EPJC 69(2010)179.
  - ▶ Inelastic background assumed exponential.
- ▶ CEP represent  $54 \pm 11\%$  of the  $Y(nS)$  production.
- ▶ Dominant uncertainty from  $\chi_b(mP)$   $p_T^2$  description and description of exclusive signal.



# Central exclusive production @ LHCb

Upsilon CEP LHCb-PAPER-2015-011

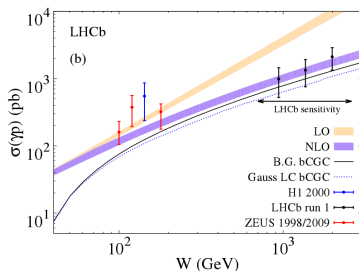
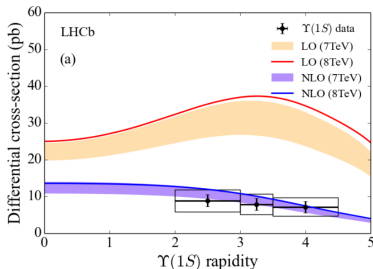
- ▶ Cross section average for 7 and 8 TeV:

$$\sigma(pp \rightarrow p\Upsilon(1S)p) = 9.0 \pm 2.1 \pm 1.7 \text{ pb},$$

$$\sigma(pp \rightarrow p\Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3 \text{ pb}, \text{ and}$$

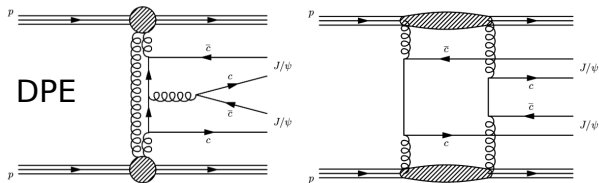
$$\sigma(pp \rightarrow p\Upsilon(3S)p) < 3.4 \text{ pb at the 95\% confidence level}$$

- ▶ Sensitive to a region of  $W$  ( $\gamma p$  c.m.e) where the LO  $\neq$  NLO predictions diverge.
- ▶ NLO predictions agree with data well.
- ▶ Reasonable agreement with models varying the  $\Upsilon$  wave function and t-channel exchange.

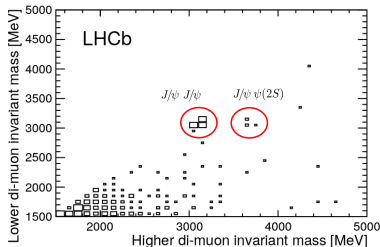


# Central exclusive production @ LHCb

Double Charmonium in CEP JPG 41(2014)115002



- ▶ Measurement uses  $1 \text{ fb}^{-1}$  @ 7 TeV and  $2 \text{ fb}^{-1}$  @ 8 TeV.
- ▶ Selection of 4 tracks events, 3 identified as  $\mu$ , compatible with  $J/\psi$  and  $\psi(2S)$  masses.
- ▶  $\chi_c$  candidate from an extra  $\gamma$ .
- ▶ Rapidity gap from no  $\gamma$  and no other tracks in VELO.
- ▶ No background expected from inclusive production.
- ▶ Observed 37  $J/\psi J/\psi$ , 5  $J/\psi \psi(2S)$ , 0  $\psi(2S) \psi(2S)$ , 1/0/0  $\chi_c(0/1/2)$



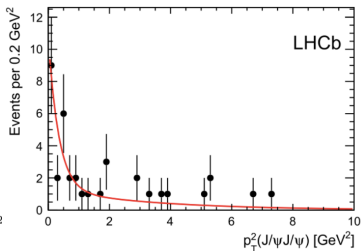
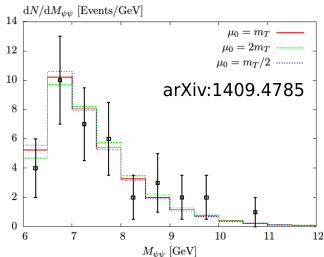
# Central exclusive production @ LHCb

## Double Charmonium in CEP reference

- ▶ Cross-section for double charmonium with  $\eta \in (2.0, 4.5)$  and no extra activity in pseudorapidity range  $(-3.5, -1.5)$  and  $(1.5, 5.0)$ :

$$\begin{aligned}\sigma^{J/\psi J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst}) \text{ pb}, & \sigma^{\chi_{c0}\chi_{c0}} &< 69 \text{ nb}, \\ \sigma^{J/\psi\psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst}) \text{ pb}, & \sigma^{\chi_{c1}\chi_{c1}} &< 45 \text{ pb}, \\ \sigma^{\psi(2S)\psi(2S)} &< 237 \text{ pb}, & \sigma^{\chi_{c2}\chi_{c2}} &< 141 \text{ pb}\end{aligned}$$

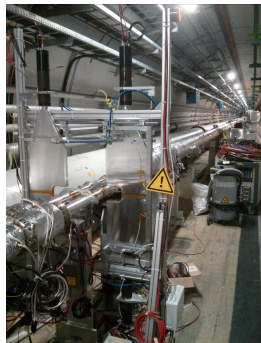
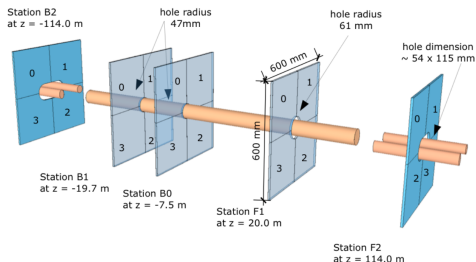
- ▶ Good agreement of the mass distribution with theory  $\rightarrow$  compatible with DPE production alone.
- ▶ Pure CEP contribution estimated from a fit of  $p_T^2(J/\psi J/\psi)$ :  $f_{CEP} = 0.42 \pm 0.13$ , very dependent to the background model.
- ▶  $\sigma_{CEP}(J/\psi J/\psi) = 24 \pm 9 \text{ pb}$  with theory expectation between 8 and 36 pb



# Central exclusive production @ LHCb

Herschel

- ▶ Limitation from inelastic background with activity outside of LHCb:
  - Need to increase the rapidity gap coverage
- ▶ High Rapidity Shower Counter for LHCb (HeRSChel) installed during TS1.
- ▶ Increases the tagging of rapidity gap by 6 units of rapidity ( $5 < |\eta| < 8$ ).
- ▶ Five stations located along the beamline, 2 in the forward (F) LHCb region and 3 in the backward (B).

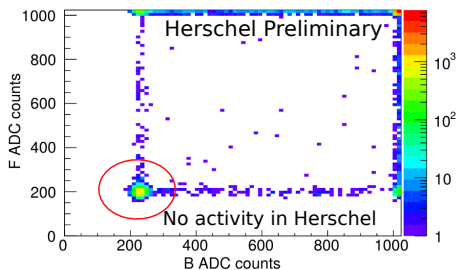


# Central exclusive production @ LHCb

Herschel

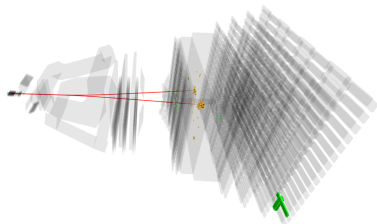
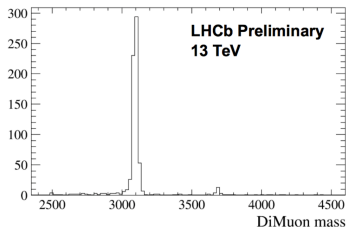
- ▶ All stations installed and readout system included in the LHCb DAQ system.
- ▶ Tested during 50ns and 25ns intensity ramp-up.
- ▶ Still some calibration work to do to optimise the inelastic event veto.
- ▶ Working on including Herschel activity veto in the L0 trigger.

- ▶ Maximum ADC counts seen in quadrants of F side VS B side.
- ▶ Herschel run from 50ns data taking.



# Outlook

- ▶ Several measurement sensitive to DPS performed on Run I dataset.
- ▶ New measurements to be expected soon to test factorisation of DPS.
- ▶ Will be interesting to compare with 13 TeV data to test universality of  $\sigma_{eff}$ .
- ▶ Several CEP measurement on Run I dataset.
- ▶ Forward shower counters ready for Run II, will allow better control on the inelastic background.
- ▶ A glimpse at 13 TeV data:  $m_{\mu\mu}$  distribution and a di- $\pi$  candidate in events with rapidity gap:



# BACKUP



## Run I measurements

Several measurements related to particle production, MPI, diffraction:

- ▶  $K_S^0$  cross section @  $\sqrt{s} = 0.9 \text{ TeV}$ , PLB 693 (2010) 69-80.
- ▶  $V_0$  ratios @  $\sqrt{s} = 0.9 \text{ TeV}$  and  $\sqrt{s} = 7 \text{ TeV}$ , JHEP 1108 (2011) 034.
- ▶  $\phi$  cross section @  $\sqrt{s} = 7 \text{ TeV}$ , PLB 703 (2011) 267-273.
- ▶ Charged particle multiplicities @  $\sqrt{s} = 7 \text{ TeV}$ , EPJC 72 (2012).
- ▶ Observation of  $J/\psi$  pair production @  $\sqrt{s} = 7 \text{ TeV}$  PLB 707 (2012) 52-59
- ▶ Central exclusive dimuon production @  $\sqrt{s} = 7 \text{ TeV}$  LHCb-CONF-2011-022
- ▶ Prompt hadron production ratio @  $\sqrt{s} = 0.9 \text{ TeV}$  and  $\sqrt{s} = 7 \text{ TeV}$ , EPJC 72 (2012) 2168.
- ▶ Observation of double charm production @  $\sqrt{s} = 7 \text{ TeV}$ , JHEP 06 (2012) 141
- ▶ Measurement of the forward energy flow in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$ , EPJC 73 (2013) 2421
- ▶ Exclusive  $J/\psi$  and  $\psi(2S)$  at  $\sqrt{s} = 7 \text{ TeV}$ , JPG 40 (2013) 045001
- ▶ Measurement of charged particle multiplicities and densities in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$  in the forward region EPJC 74 (2014) 2888
- ▶ Updated measurements of exclusive  $J/\psi$  and  $\psi(2S)$  production cross-sections in pp collisions at  $\sqrt{s} = 7 \text{ TeV}$ , JPG 41 (2013) 055002

$\sigma_{pp}$  relation to  $\sigma_{\gamma p}$

Absorption factors

The  $pp$  cross-section is given by

$$\frac{d\sigma^{\text{th}}(pp)}{dy} = S^2(W_+) \left( k_+ \frac{dn}{dk_+} \right) \sigma_+^{\text{th}}(\gamma p) + S^2(W_-) \left( k_- \frac{dn}{dk_-} \right) \sigma_-^{\text{th}}(\gamma p),$$

Photon flux