LHCb as a forward general purpose detector

Results and Prospect

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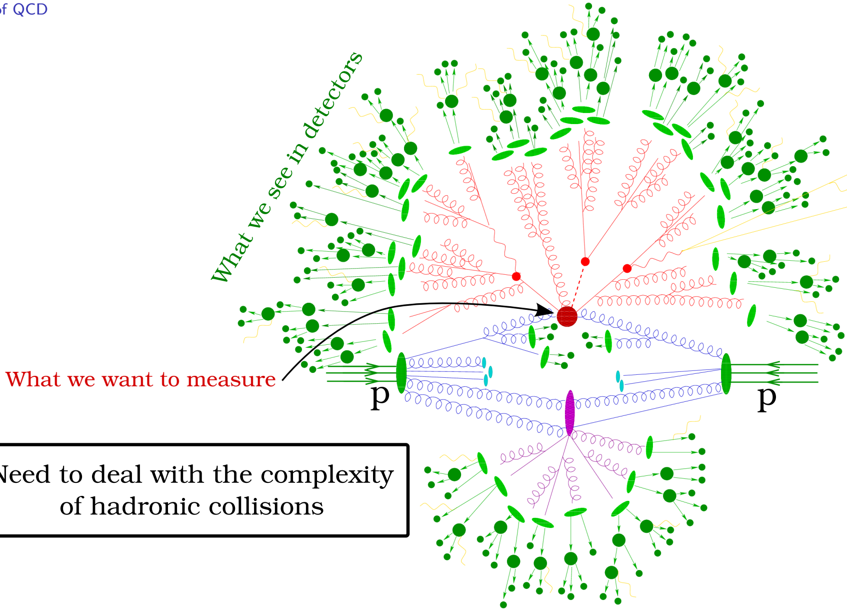
Introduction

- Rich harvest of measurements with the Run I of the LHC.
  - Higgs discovery, coupling measurements.
  - Precision measurements of top production.
  - ...
- Many direct and indirect searches for physics beyond the standard model.
  - No discovery yet
  - Few interesting hints and cracks ($\gamma\gamma$@750 GeV, FCNC, Lepton universality)
- Goes along with precise measurement of many processes to validate the theoretical framework.

Interactions in hadronic machine

The reign of QCD



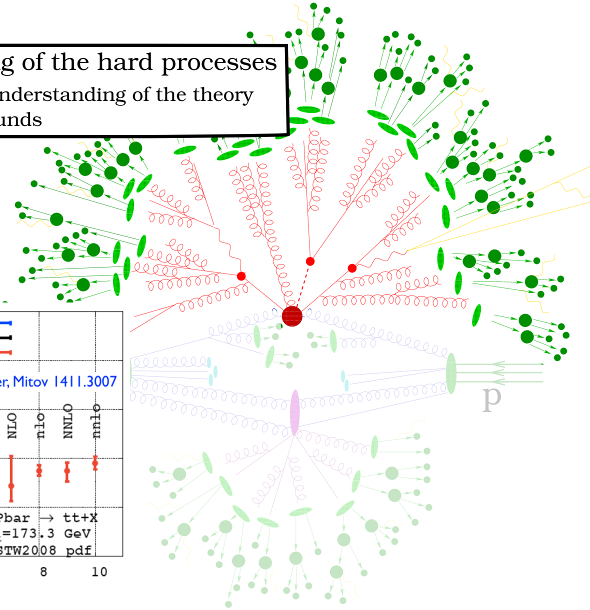
Need to deal with the complexity of hadronic collisions

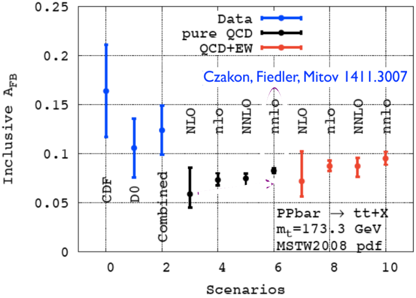
Interactions in hadronic machine

The reign of QCD

Accurate understanding of the hard processes

To test our level of understanding of the theory
To evaluate backgrounds

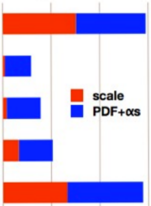




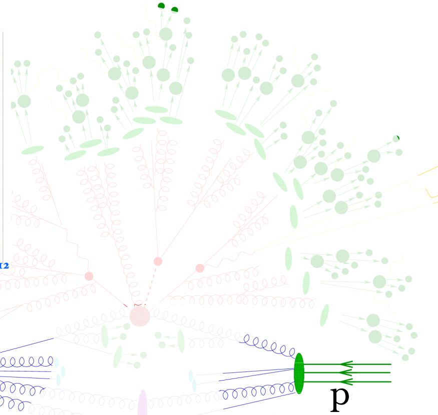
Interactions in hadronic machine

The reign of QCD

	σ (8 TeV)	uncertainty
gg→H	19.5 pb	14.7%
VBF	1.56 pb	2.9%
WH	0.70 pb	3.9%
ZH	0.39 pb	5.1%
ttH	0.13 pb	14.4%



J. Campbell, ICHEP 2012



The proton is a composite particle

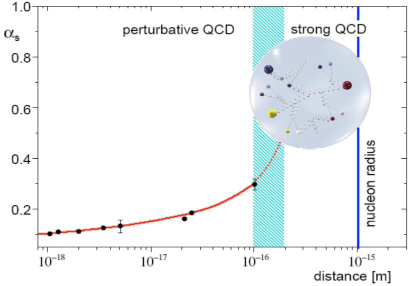
- Need accurate knowledge of the kinematic of the parton involved in the hard process
- Parton distribution functions (PDF)

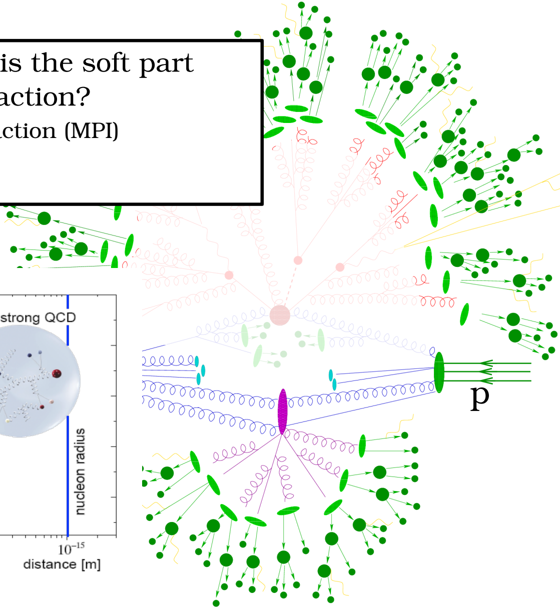
Interactions in hadronic machine

The reign of QCD

How well modelled is the soft part of the interaction?

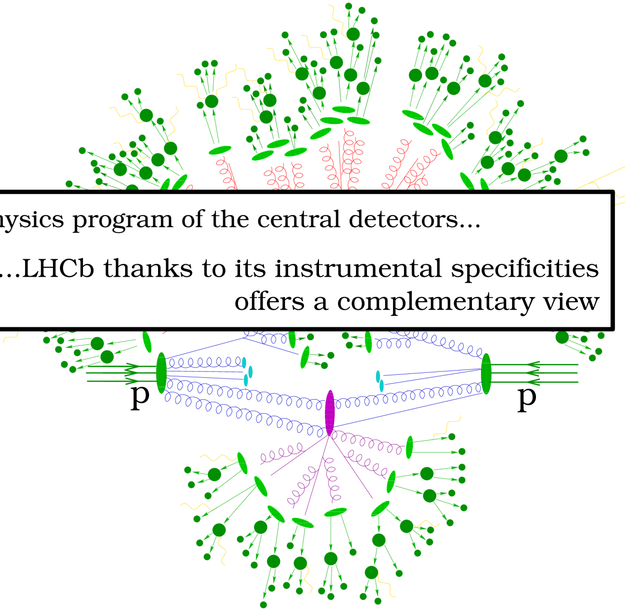
Multiple parton interaction (MPI)
Underlying event
Hadronisation





Interactions in hadronic machine

The reign of QCD

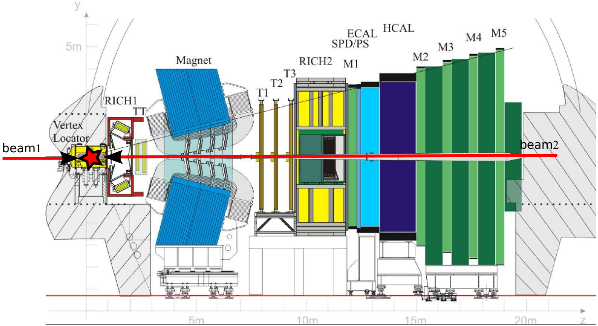


Large part of the physics program of the central detectors...

...LHCb thanks to its instrumental specificities
offers a complementary view

LHCb detector

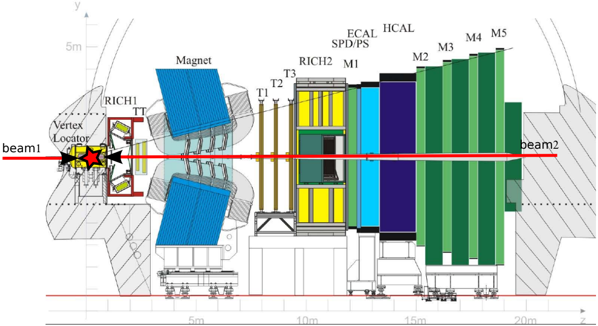
2008 JINST 3 S08005



- Designed for CP violation studies in b and c hadrons decays and their rare decays.
- Single arm spectrometer, $\sim 30\%$ of $b\bar{b}$ pairs produced in the acceptance.
- Fully instrumented forward $2 < \eta < 4.5$
- Excellent tracking and vertexing performances
- Particle identification through RICH, Calorimeter and Muon chambers

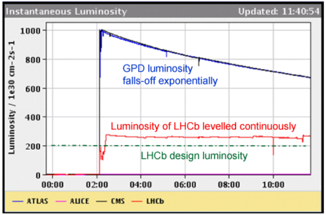
LHCb detector

2008 JINST 3 S08005



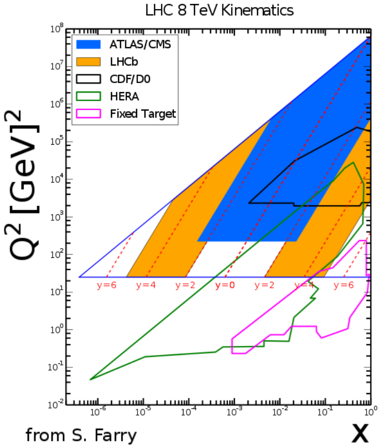
- During Run I, pp collisions:
  - $1\ \text{fb}^{-1}$ @ $\sqrt{s} = 7$ TeV,
  - $2\ \text{fb}^{-1}$ @ $\sqrt{s} = 8$ TeV.
- RunII: Expect $\sim 5\ \text{fb}^{-1}$ @ $\sqrt{s} = 13$ TeV.
  - $320\ \text{pb}^{-1}$ recorded in 2015.
- Data taking with luminosity levelling

$\rightarrow$ stable average pile-up ~ 2



LHCb and the forward region

- Complementary to central detectors:
  - high/low-x partons involved.
  - Different production mechanism. (e.g. more q initiated $t\bar{t}$ production).
- Low p_T, low mass triggers
  - Interesting domain of phase space for MPI studies
- Low pile-up environment
  - allow studies of **central exclusive production**
- Tracking in the forward region
  - b,c jet tagging @ $2 < \eta < 5$



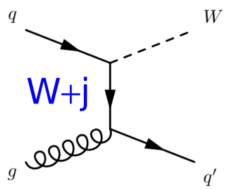
from S. Farry

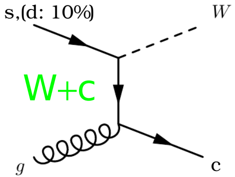
$$Q^2(x) = e^{\pm 2y} x^2 s$$

- Outline
  - W+(b,c) production ratios at $\sqrt{s} = 7, 8\ TeV$
  - Forward Top production
  - $J/\psi C$ and ΥC double parton scattering
  - Central exclusive production and HeRSCheL

W+(b,c)-jet production ratio @ $\sqrt{s} = 7, 8\, TeV$

Motivations



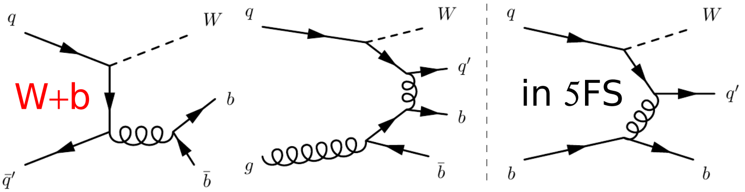


W+c

- LO production involve s-quark PDFs
- $Q \sim 100\ GeV$ and x down to 10^{-5}
- Existing constraints based on DIS with $Q \sim 1\ GeV$ and $x \sim \mathcal{O}(0.1)$.
- At higher Q, measurement in the central region at TeVatron and LHC.

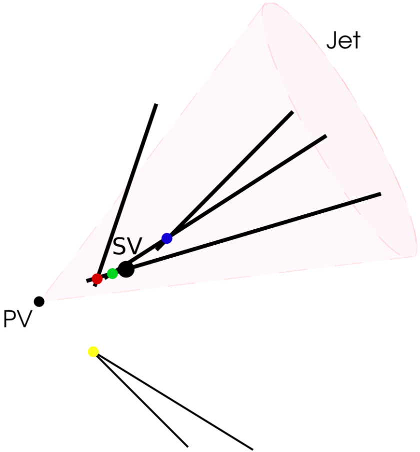
W+b

- Main production process sensitive to probability of gluon splitting in $b\bar{b}$.
- LO production in 5FS from intrinsic b quark content of the proton.



b and c jet tagging @ LHCb
[JINST 10 P06013]

- Particle Flow jets, anti-k_T with R=0.5
- Tracks consistent with B,D decays.
- Inclusive 2-body vertexing.
- Merge into n-body.
- Quality requirements at every steps.

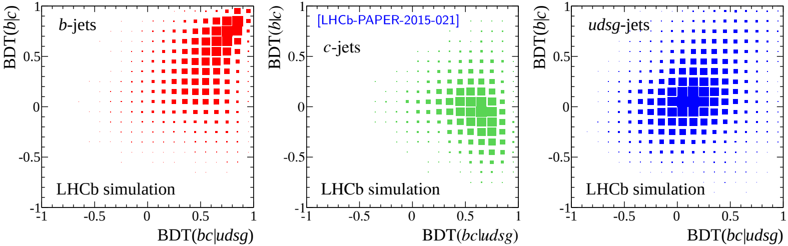


- **light jet mistag rate well below 1%**

for b tag efficiency $\sim$ 65%, c tag efficiency $\sim$ 25%.

b and c jet tagging @ LHCb
[JINST 10 P06013]

- SV properties (displacement, kinematics, mulitplicity,...) and jet properties combined in two BDTs.
  - $BDT_{bc|udsg}$ optimised for heavy flavour versus light discrimination.
  - $BDT_{b|c}$ optimised for b versus c discrimination.



- Either enrich in *b* or *c*-jets with cuts on the BDT distributions.
  - down to the 0.1% mis-tag rate for $10-15\%$ efficiency loss.
- Or get the flavour content from 2D fit of the BDT distributions.
- Relative uncertainty of 10% of (b,c)-jet tagging efficiencies and $\sim 30\%$ on mis-tag rate.

Measurement of $W + (b, c)$-jet ratios and asymmetries.

Strategy

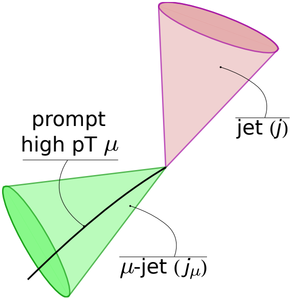
- $W \to \mu\nu$ final state.
- Jets tagged with the SV-tagger,

Fiducial volume

$$p_T(\mu) > 20\ GeV,\ 2.0 < \eta_\mu < 4.5$$
$$p_T(j) > 20\ GeV,\ 2.2 < \eta_j < 4.2$$
$$\Delta R(\mu, j) > 0.5$$
$$p_T(\mu + j) > 20\ GeV$$

Selection:

- Prompt μ selection as in [JHEP12(2014)079].
- Events with 2 μ vetoed or classified as Z+jet.
- "j" is the highest-p_T jet.
- μ candidate used in the jet reconstruction.
- ν missed $\to$ p_T-unbalance.
- $p_T(j_\mu + j) > 20$ GeV .
- **Isolation defined as $\mathbf{p_T(\mu)/p_T(j_\mu)}$.**
- **Selection $\equiv$ fiducial volume**[a]

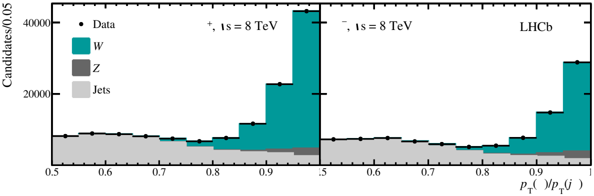


[a] For W+jet, $p_T(j_\mu + j) > 20\ GeV \equiv p_T(\mu + j) > 20 GeV$ to $\sim 1\%$

Measurement of $W + (b, c)$-jet ratios and asymmetries.

[PRD92 (2015) 052001]

- μ_W+jet yields obtained from fit of the μ isolation

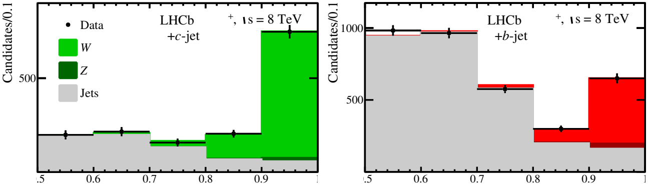


Shape from MC, cor. with Z data

Yields from $Z[\mu\mu]$+jet

Shape from data

- Yields of μ_W+(b,c)jet from 2D BDT fit of SV-tagged sample and isolation fit

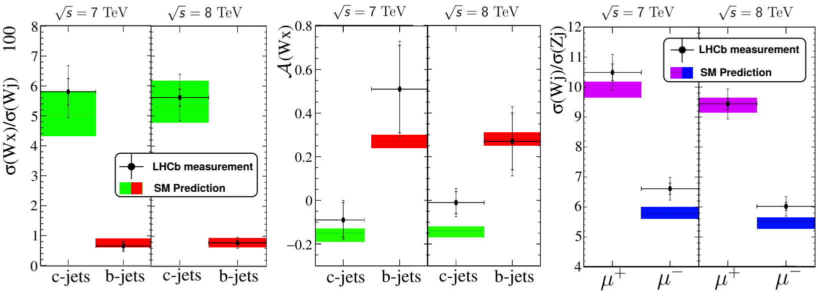


- μ+(b,c)tag corrected for SV tagging efficiencies.
- W+jet and W+(b,c)jet yields corrected for backgrounds from $Z \to \tau\tau$ and top.

Measurement of $W + (b, c)$-jet ratios and asymmetries

Results [PRD92 (2015) 052001]

- $\mathcal{A}(Wq) = \frac{\sigma(W^+q)-\sigma(W^-q)}{\sigma(W^+q)+\sigma(W^-q)}$.
- Main uncertainties from heavy flavour fraction determination (5-10%), tagging efficiency (10%), isolation fit (4-10%), and for $W + b$ the Top background (13%)
- Predictions @NLO: MCFM[PRD62(00)114012] and CT10 PDF set,[PRD82(10)074024].

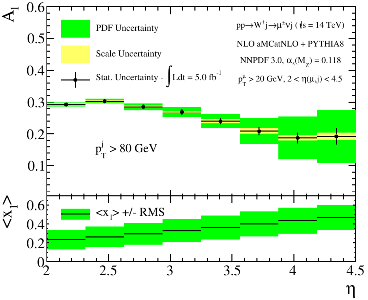


- Overall good agreement with NLO predictions.
- $|\mathcal{A}(Wc)|$ is 2σ lower than predictions using CT10 PDFs.
- Could point to asymmetric $(s,\bar{s})$ PDFs.

Vector Boson (+ jets) prospects

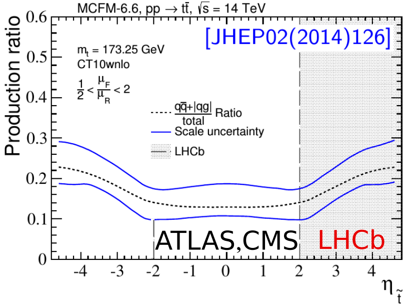
- Z+jet [JHEP 01(2014)33], Z+b-jet [JHEP 01(2015)064], Z+D [JHEP 04(2014)91] performed at 7 *TeV* → **to be updated.**
- At $\sqrt{s} = 13$ *TeV*, W+(b,c,ℓ)jet **cross sections increases** by a factor $\sim 2 - 2.5$.
- **Differential measurements** becomes accessible.

- [arXiv:1505.01399] shows the impact of W+jet differential measurements on large-x d-quark PDF.
- Up to $\sim 35\%$ improvement of the d-quark PDF uncert. at $x = 0.7$ with RunII dataset.



Top production
in the forward region @$\sqrt{s} = 7, 8\,TeV$

Top quark production in pp collisions

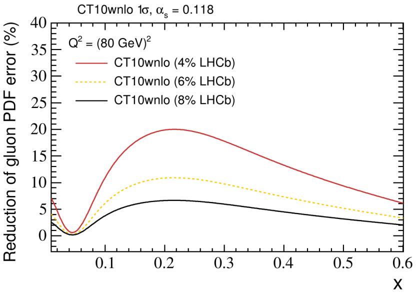


Motivation for studies in the forward region:

- test for the differential predictions.
- reduced g-initiated production.
- enhanced $t\bar{t}$ charge asymmetry

Large uncertainty on the high-x gluon PDFs:

- ATLAS/CMS $t\bar{t}$ measurements constraint the high-x gluon PDF [JHEP07(2013)167]
- $t\bar{t}$ production in the forward region involve higher-x / lower-x gluon, [JHEP02(2014)126].

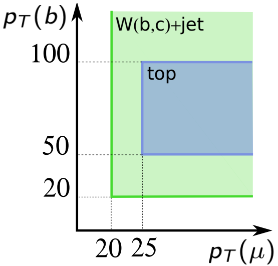


Top production in the forward region

PRL 115 (2015) 112001

- Combined measurement of the single-t and $t\bar{t}$ production.
- $t\bar{t}$ accounts for 3/4 of the top production.
- Consider $t \to W(\mu\nu)b$ ie same final state than previous analysis.

- Tightened fiducial region to enhance top contribution.
  - $p_T(\mu) > 25$ GeV.
  - $50 < p_T(b) < 100$ GeV
- Reduces the uncertainty associated to QCD jets.
- Same isolation fit + SV tag to get $\mu + b$ contribution



- $p_T(\mu + b)$ provides discrimination between top and $W + b$-jets.
- $\mathcal{A}(Wb) \sim 1/3$ while $\mathcal{A}(top) \sim 0.1$, mainly from single-$t$.

- Look for an excess of $\mu + b$ events and deviation of $\mathcal{A}$ as function of $p_T(\mu + b)$.
- **Needs good control on W + b-jets predictions.**

Top production in the forward region

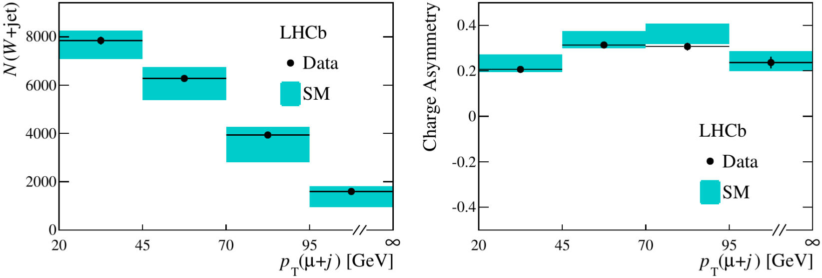
In situ constraint from W+jet

PRL 115 (2015) 112001

- NLO prediction from MCFM[JPG(2015)42] with 4FS and CT10 PDF set.
- In the most significant bin of $p_T(\mu + b)$:

$$\text{rel. error}[\sigma(Wb)/\sigma(Wj)] \sim \frac{1}{3}\ \text{rel. error}[\sigma(Wb)]$$

- **Measure W+jets yields to fix the scale of W + b-jets from data**



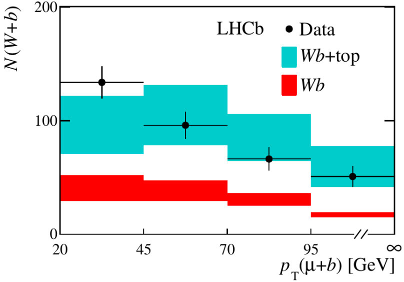
- **Low uncertainty allows to fix the scale of $\mathbf{W(c, b)}$ from $\mathbf{W(c, b)/Wj}$ predictions.**

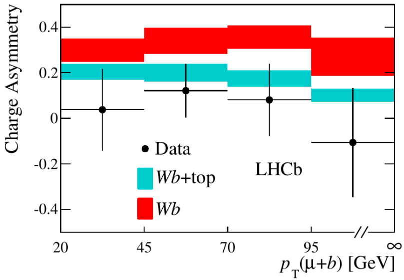
$\rightarrow$ Validated on **Wc** sample, yields in agreements with the NLO predictions.

Top production in the forward region

$W + b$-tag yields and asymmetry

PRL 115 (2015) 112001





- Discrepancy between data and *Wb* predictions.
- Good agreement with $Wb + top$ predictions.

- Binned likelihood fit of $N(top)$ and $\mathcal{A}(top)$.
- Systematic uncertainties treated as Gaussian constraints.
- $N(top)$ and $\mathcal{A}(top)$ shapes are fixed. The total yields is allowed to vary.
- Profile likelihood to compare $Wb + top$ and Wb hypotheses

5.4σ observation of top production in the forward region.

Top production in the forward region

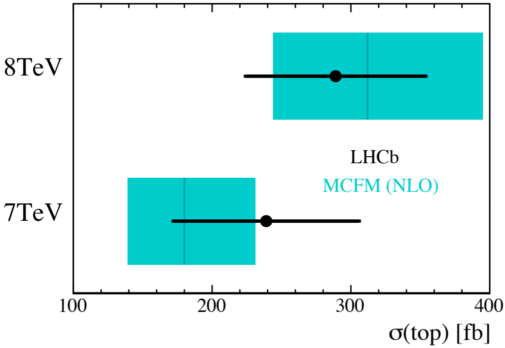
Cross section measurements

PRL 115 (2015) 112001

- The observed excess above Wb prediction is used to measure $\sigma(t\bar{t} + t + \bar{t})$.

$$\sigma(top)[7\ \ TeV] = 239 \pm 53(\text{stat}) \pm 33(\text{syst}) \pm 24(\text{theory})\ \text{fb}$$
$$\sigma(top)[8\ \ TeV] = 289 \pm 43(\text{stat}) \pm 40(\text{syst}) \pm 29(\text{theory})\ \text{fb}$$

- b-tagging, jet energy scale and isolation fit related uncertainties dominates the systematics uncertainties.



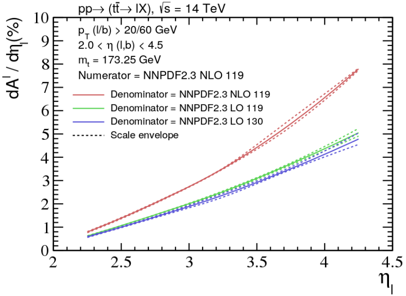
Cross sections at $\sqrt{s} = 7, 8$ TeVare consistent with NLO SM predictions.

Top production prospects

- Cross-sections and acceptance at RunII: $\sim 20\times$RunI yields.
- $\sim 5\%$ stat. uncertainty at RunII on (μb) final state.
- Separation between $t\bar{t}$ and single-t using the various final states.
- Differential cross-section.
- b-jet properties in top decay.

[LHCb-PUB-2013-009]

$d\sigma$(fb)	8 TeV			14 TeV		
lb	504	$\pm$	94	4366	$\pm$	663
lbj	198	$\pm$	35	2335	$\pm$	323
lbb	65	$\pm$	12	870	$\pm$	116
$lbbj$	26	$\pm$	4	487	$\pm$	76
l^+l^-	79	$\pm$	15	635	$\pm$	109
l^+l^-b	39	$\pm$	8	417	$\pm$	79

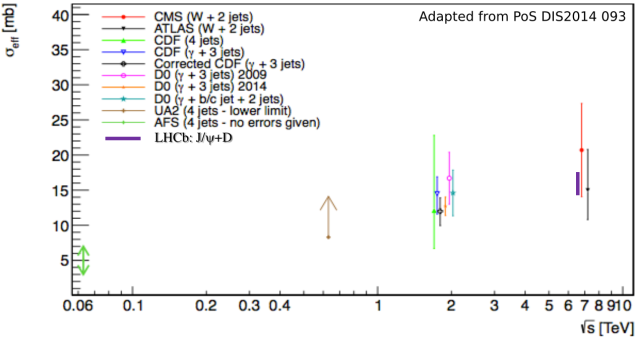


- Investigated in [PRL(2011)107],[PRD91(2015)054029]
- $A_\ell = \frac{N(\mu^+ b) - N(\mu^- b)}{N(\mu^+ b) + N(\mu^- b)}$.
- Small dilution in the forward region.
- With upgrade statistics (50 fb^{-1}) with $A^l_{SM} = (1.4 - 2.0)$ expect 0.3% statistical error.

Multiple Parton Interaction @ LHCb

Double parton scattering

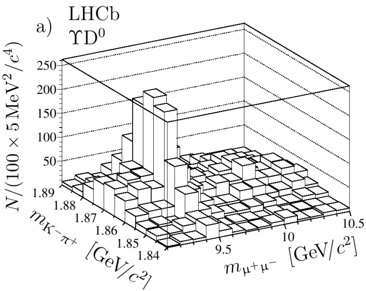
- The "simple" paradigm:
  - Independent hard scattering processes.
  - Assuming factorisation of the double PDF: $\sigma^{AB}_{DPS} = \frac{\delta_{A,B}}{2} \frac{\sigma^{A}_{SPS}\sigma^{B}_{SPS}}{\sigma\, eff}$.
  - σ_{eff} assumed to be a energy and process independent factor.
- Experimental tests:
  - Is σ_{eff} really universal?
  - Is the "pocket formula" for σ^{AB}_{DPS} always valid?

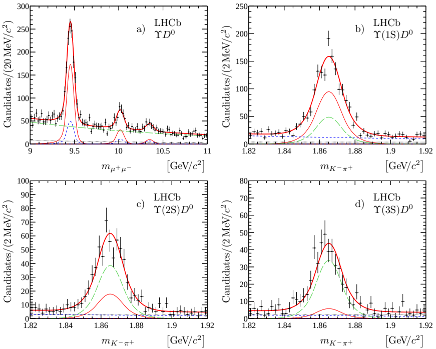


DPS studies @ LHCb

$J/\psi C$, CC [JHEP 06 (2012) 141, JHEP 03(2014)108] and ΥC LHCb-PAPER-2015-046

- Production of multiple heavy flavour: pQCD (SPS), double parton scatt. (DPS)
- Measurement of $J/\psi C$, CC, ΥC production with:
  - $J/\psi \to \mu\mu$, $\Upsilon \to \mu\mu$
  - $C = D_0(K^-\pi^+), D^+(K^-\pi^+\pi^+), D_s^+(K^-K^+\pi^+), \Lambda_c^+(pK^-\pi^+)$
- Expect $1-6\%$ contribution from SPS.





ΥC production @ $\sqrt{s} = 7, 8$ TeV

Cross section and ratios LHCb-PAPER-2015-046

- Cross section in good agreement with DPS expectations.

measurement

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

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

prediction

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}}\Big|_{\mathrm{DPS}} = 206 \pm 17\,\mathrm{pb},$$

$$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}}\Big|_{\mathrm{DPS}} = 86 \pm 10\,\mathrm{pb},$$

- Ratios show clear excess with respect to SPS contribution.

measurement

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

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

SPS prediction

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

Fragmentation fraction

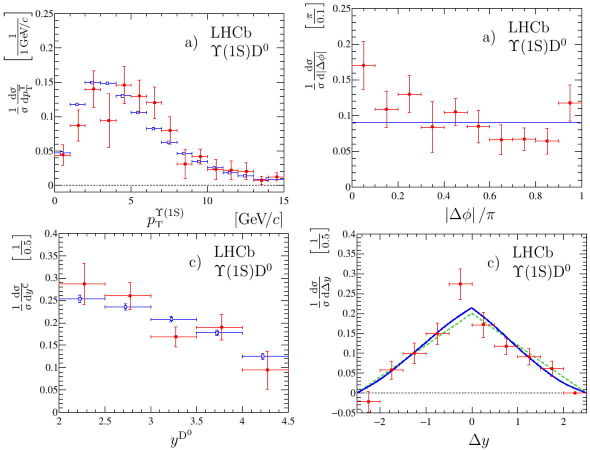
$$\left.\frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\mathrm{TeV}} = (5.5 \pm 1.7)\,\%$$

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

- Other ratios lead to the same conclusion $\frac{\sigma_{\Upsilon(1S)D^0}}{\sigma_{\Upsilon(1S)D^+}} \sim \frac{\sigma_{D^0}}{\sigma_{D^+}}$ or $\frac{\sigma_{\Upsilon(2S)D^+}}{\sigma_{\Upsilon(1S)D^+}} \sim \frac{\sigma_{\Upsilon(2S)}}{\sigma_{\Upsilon(1S)}}$

ΥC production @ $\sqrt{s} = 7, 8$ TeV

Differential cross sections LHCb-PAPER-2015-046

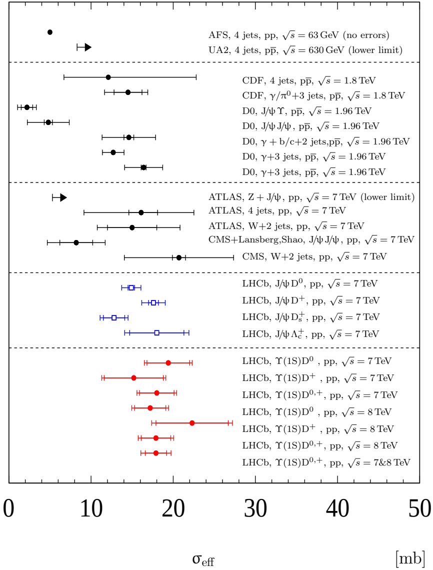


- Predictions assumes uncorrelated production of $\Upsilon(1S)$ and D^0.
- Deduced from open charm production measurement and Υ measurement
- Good agreement with DPS expectation.

σ_{eff} and the DPS pocket formula

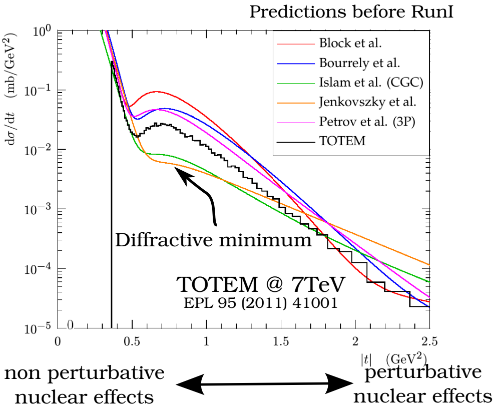
- Excellent agreement between $J/\psi C$ and ΥC
- Agreement with $\gamma + 3j$ and $W + 2j$
- Slight tension with $J/\psi J/\psi$ and $J/\psi\Upsilon$ at 1.96 TeV.
- **Will be interesting to compare with RunII results at 13 TeV.**

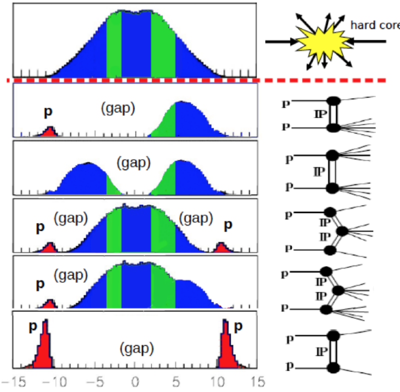
- $(W, Z) + C$ allow to probe a different kinematic range
- Z+C @ $\sqrt{s} = 7$ TeV was observed at LHCb, [JHEP 1404(2014)91]
- Not enough data to disentangle SPS from DPS at RunI



Central Exclusive Production @ LHCb and the HeRSCheL detector

A word on elastic cross section





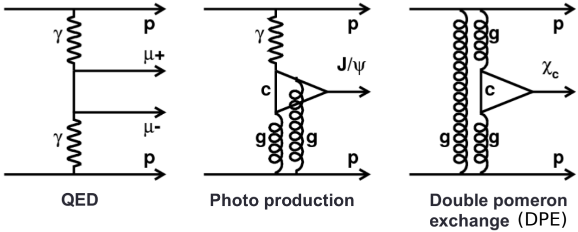
$|t|$: square of elastic scatter 4-momentum transfer, inversely related to the impact parameter.

- Difficult to model the transition region.

Central exclusive production

Motivation

- $p + p \to p + X + p$ with exchange of a colourless objects (γ or Pomeron).



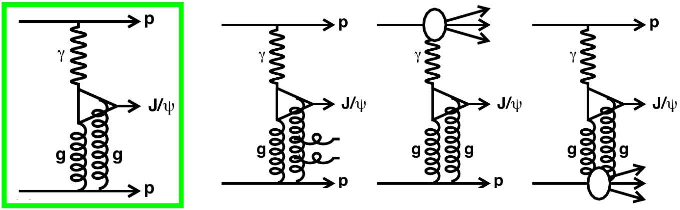
- Laboratory at the interface between soft (non-perturbative) and hard (perturbative) QCD.
- Sensitive to very low-x gluon PDF (down to $x \sim 10^{-5}$) where saturation effects occurs.
- Very clean experimental environment which can allow spectroscopy studies (exotic quarkonia, glueball,...)

Central exclusive production @ LHCb

Experimental challenge

- Data taking with luminosity levelling

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



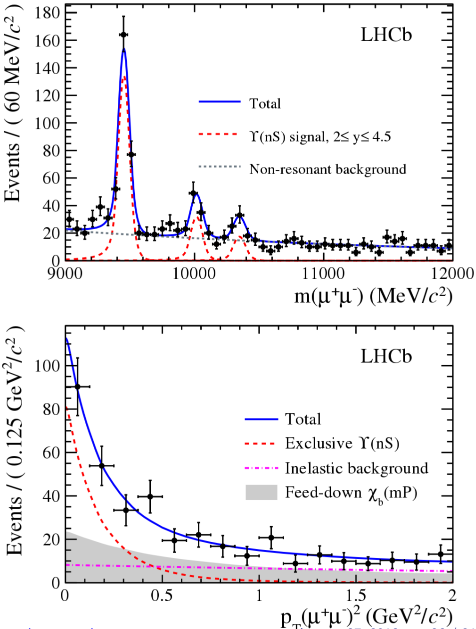
- X detected in the LHCb detector, and requires a rapidity gap

  $\rightarrow$ No other activity in LHCb. Backward coverage from VELO $-3.5 < \eta < -1.5$.
- Several measurement performed during Run I:
  - J/ψ and $\psi(2S)$ production through γP exchange JPG41 (2013) 055002.
  - $\chi_c(0, 1, 2)$ production through PP exchange LHCb-CONF-2011-022.
  - Non-resonant di-μ production through $\gamma\gamma$ exchange LHCb-CONF-2011-022.
  - Double Charmonium in CEP JPG 41(2014)115002

Central exclusive production @ LHCb

Upsilon CEP JHEP 09 (2015) 084

- Two well reconstructed μ.
- Rapidity gap: No other tracks backward or forward.
- Fit of the p_T^2 of the di-μ 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 $\Upsilon(nS)$ production.
- Dominant uncertainty from $\chi_b(mP)$ p_T^2 description and description of exclusive signal.



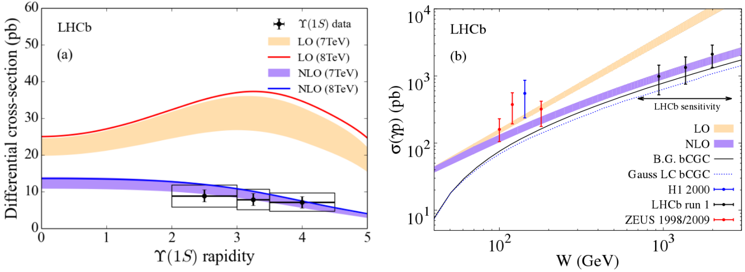
Central exclusive production @ LHCb

Upsilon CEP JHEP 09 (2015) 084

- Cross section average for 7 and 8 TeV:

$$\begin{aligned}
\sigma(pp \to p\Upsilon(1S)p) &= 9.0 \pm 2.1 \pm 1.7 \text{ pb}, \\
\sigma(pp \to p\Upsilon(2S)p) &= 1.3 \pm 0.8 \pm 0.3 \text{ pb}, \text{ and} \\
\sigma(pp \to p\Upsilon(3S)p) &< 3.4 \text{ pb at the 95\% confidence level}
\end{aligned}$$

- Sensitive to a region of W (γp c.m.e) where the LO $\neq$ NLO predictions diverge.
- NLO predictions agree with data well [JHEP 1311 (2013) 085]
- Reasonable agreement with models varying the Υ wave function and t-channel exchange.

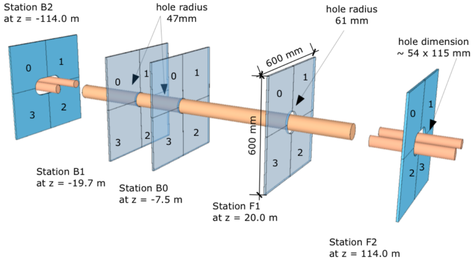


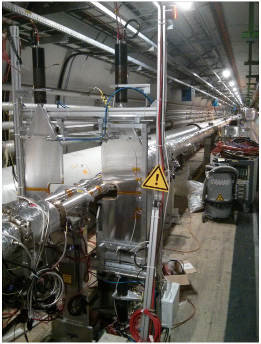
Central exclusive production @ LHCb

Herschel

- Limitation from inelastic background with activity outside of LHCb:

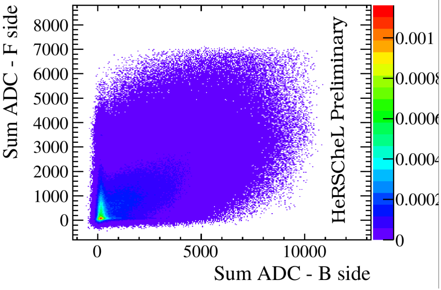
  $\rightarrow$ Need to increase the rapidity gap coverage
- High Rapidity Shower Counter for LHCb (HeRSCheL) installed during TS1.
- Increases the tagging of rapidity gap by 6 units of rapidity ($5 < |\eta| < 8$).
- Five stations located along the beamline, 2 in the forward (F) LHCb region and 3 in the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

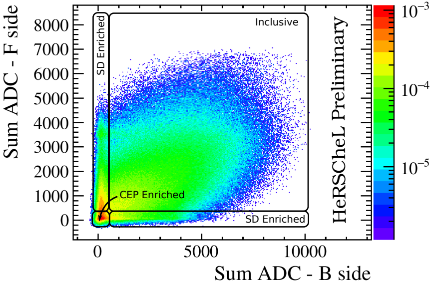




- All stations installed and readout system included in the LHCb DAQ system.
- Tested during 50ns and 25ns intensity ramp-up.
- Took $> 90\%$ of the RunII pp collisions with LHCb, as well as the AA run.

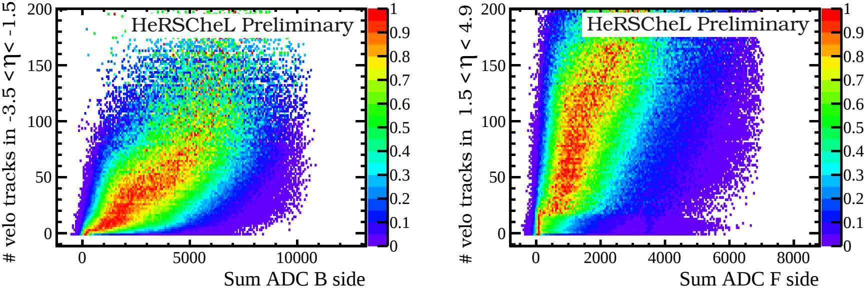
Mix of triggered events ($\sim 7\ pb^{-1}$). Inclusive, single diffractive and double diffractive enriched contributions are visible.





A glimpse through RAW data

Herschel versus VeLo

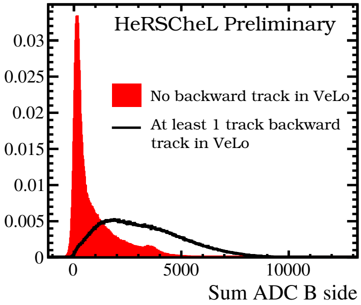


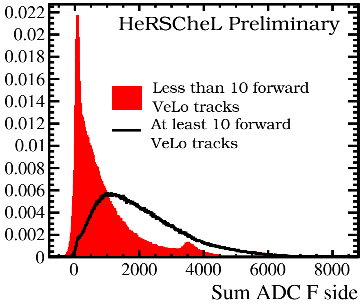
- Visible correlation between VeLo activity and Herschel activity.

A glimpse through RAW data

Herschel versus VeLo

- Still large Herschel activity in events with "signal-like" topology in LHCb (low activity).



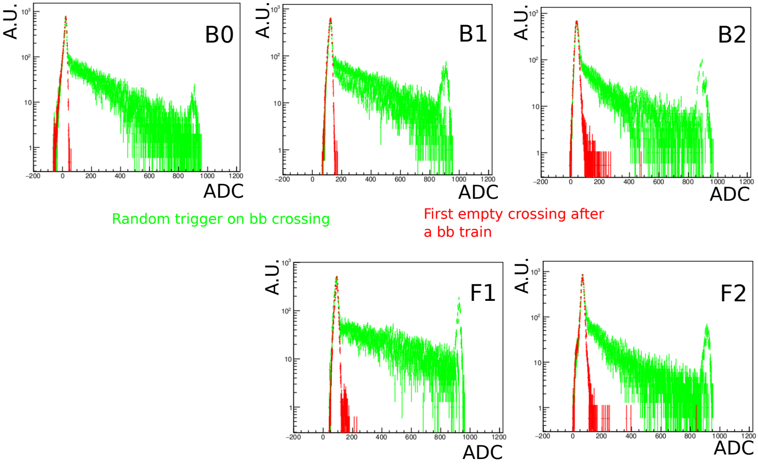


A glimpse through RAW data

Response to "signal"-like events

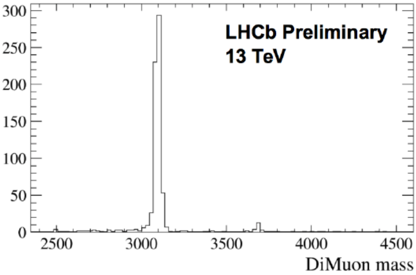
- Optimised settings to minimize the spillover effect.
- First "empty-empty" bunch after a "beam-beam" train:

$\rightarrow$ shape of the signal (event with no activity).

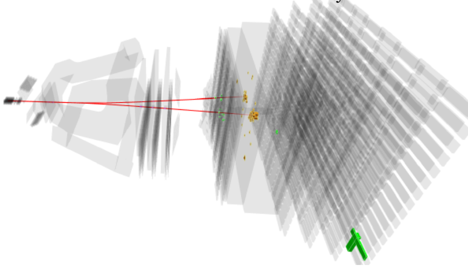


Ongoing work

- Calibration work on-going to do to optimise the inelastic event veto.
- First physics results with HeRSCheL should appear in the coming months.
- Working on including Herschel activity veto in the L0 trigger.
  - allow to reduce the central multiplicity veto.
  - allow to reduce the kinematic requirements.
- Large range of potential measurements for RunII (di-hadron spectra, more quarkonia, exotic charmonium, χ_c,...)



Di-Pion event with no extra activity



Outlook

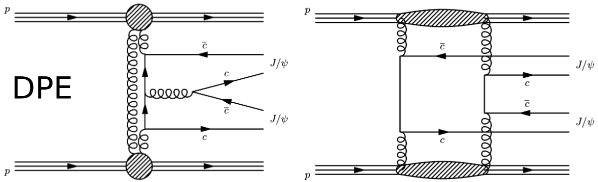
- I have shown various LHCb measurements relevant for understanding the structure of the proton, multiple parton interaction and diffractive physics.
- There are several other measurements out of the "core" LHCb physics program:
  - EW bosons production measurement in the forward region.

    Including the most precise determination of $sin^2(\theta_W)$ at the LHC
  - Various soft QCD measurement relevant for hadronisation modelling.
  - Direct searches for exotic long-lived particles.
  - pA and AA measurements.
- Full list here LHCb QCD, Electroweak and Exotica results
- With higher partonic cross-section and new tools this part of the physics program will develop further during RunII at $\sqrt{s} = 13\ TeV$

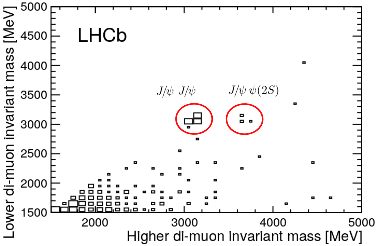
BACKUP

Central exclusive production @ LHCb

Double Charmonium in CEP JPG 41(2014)115002



- Measurement uses 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV.
- Selection of 4 tracks events, 3 identified as μ, compatible with J/ψ and $\psi(2S)$ masses.
- χ_c candidate from an extra γ.
- Rapidity gap from no γ 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 $\chi_c(0/1/2)$

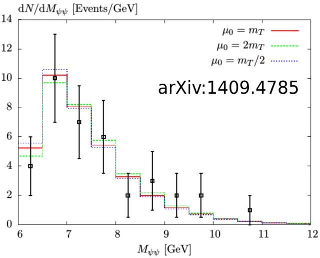
Central exclusive production @ LHCb

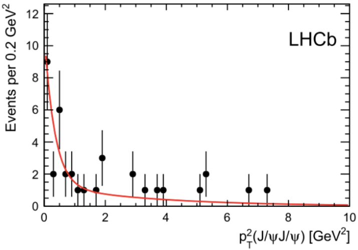
Double Charmonium in CEP JPG 41(2014)115002

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

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

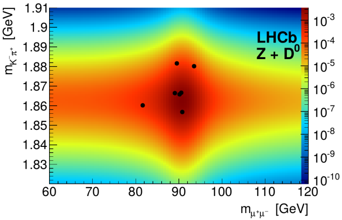
- Good agreement of the mass distribution with theory $\rightarrow$ compatible with DPE production alone.
- Pure CEP contribution estimated from a fit of $p_T^2(J/\psi J/\psi)$: $f_{CEP} = 0.42 \pm 0.13$, very dependent to the background model.
- $\sigma_{CEP}(J/\psi J/\psi) = 24 \pm 9$ *pb* with theory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

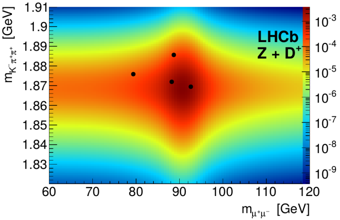




Z+D @ $\sqrt{s} = 7$ TeV, JHEP 1404(2014)91

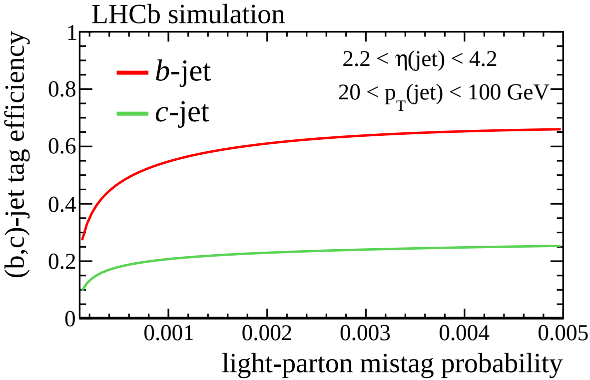
- Selected $Z \to \mu\mu + D^0 \to K^-\pi^+$ and $Z \to \mu\mu + D^+ \to K^-\pi^+\pi^+$.
- Observed 11 events at $\sqrt{s} = 7$ TeV with 1.0 $fb^{-1} \to 5.1\sigma$ observation.





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

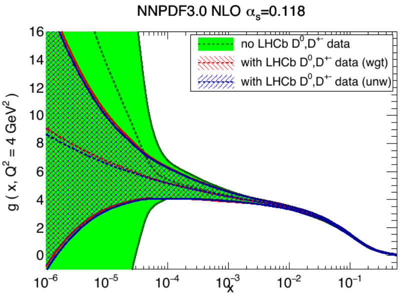
- Not enough data to disantangle SPS from DPS but intersting region where 30 to 90% violation of the factorisation is expected
- An update with full Run I dataset, and lower $p_T(D)$ threshold would allow to look at differential distributions.

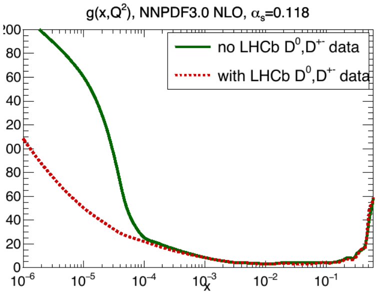


- Relative uncertainty of 10% of (b,c)-jet tagging efficiencies.
- Uncertainties on the mis-tag rate $\sim$ 30%.

Production measurements @ LHCb and impact on PDFs

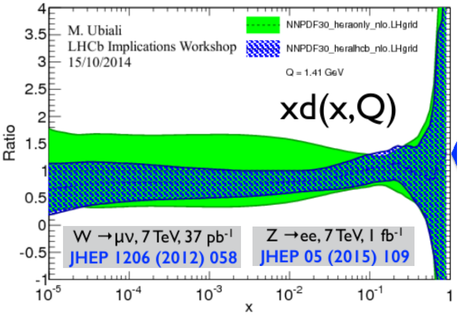
- Open charm production at $\sqrt{s} = 7\ TeV$, Nucl.Phys. B871 (2013)
- Impact low x-gluon PDF.

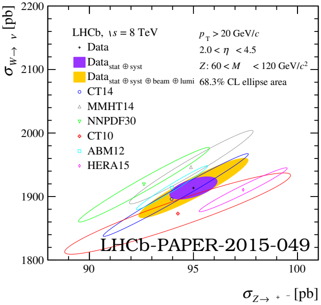




Production measurements @ LHCb and impact on PDFs

- W,Z cross section and asymmetries at $\sqrt{s} = 7, 8\ TeV$ ref
- Impact on u/d PDFs, see [M. Ubiali, LHCb Impliciation workshop]
- More recent measurement to be included





- With jet reconstruction and heavy flavour jet tagging we have access to new observables

SM predictions for Top

- NLO predictions from MCFM [JPG42(2015)1,015005] in the 4FS and CT10 PDF set [PRD82(2010)074024].
- NLO PowhegBox [JHEP01(2012)137] showered with Pythia8 [CPC178(2008)852-867] (for consistency check)

- Prediction uncertainties from PDFs, α_s and scale.
- Integration uncertainties and from $m_{c,b,t}$ negligible.
- α_s and PDF uncertainties are found to be close to 100% correlated between bins.

- Detector response folded to the prediction:
  - Main contribution from μ efficiencies, b-jet p_T migration, (b,c)-tagging efficiencies.

- $\sigma(Wb)/\sigma(Wj)$ theory uncertainties partially cancel in the ratio.
- In the most significant bin of $p_T(\mu + b)$:

$$\text{rel. error}[\sigma(Wb)/\sigma(Wj)] \sim \frac{1}{3}\ \text{rel. error}[\sigma(Wb)]$$

Measure W+jets yields to fix the scale of W + b-jets from data

Sytematic uncertainties

For significance evaluation and cross section measurement

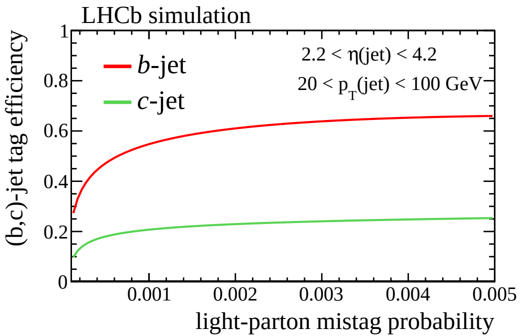
PRL 115 (2015) 112001

source	uncertainty
GEC	2%
$p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$ templates	5%
jet reconstruction	2%
SV-tag BDT templates	5%
b-tag efficiency	10%
trigger & μ selection	2%†
jet energy	5%†
$W \to \tau \to \mu$	1%†
luminosity	1–2%†
Total	14%
Theory	10%

- $5 - 10\%$ difference in yields from purly data based templates for $p_T(\mu)/p_T(jet)$
- 5% difference in yields using the alternative fit using $M_{cor}(SV)$,$N(trk)$.
- (b,c)-tagging uncertainty of 10%.
- 5% difference in yields when including non-gaussian effects in the data-driven jet energy smearing factors.

Performances in simulation

further discrimination with $BDT_{bc\ vs\ udsg}$ cut

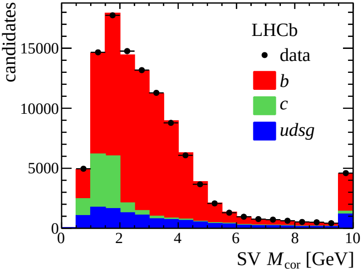


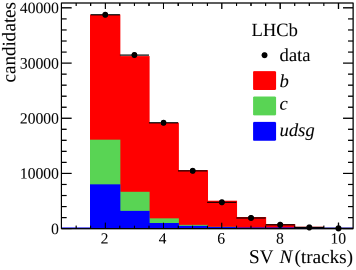
- Flavour content can be obtained by fitting the 2D BDT distributions but when needed they can be used to cut.

Alternative Tagged yields

Systematics for BDT shapes modeling

- Alternative fit using SV based only variables
  - N_{trk} for b-jet discrimination.
  - $M_{cor}(SV)$ for c-jet discrimination.
- 2D fit in each (p_T, η) bins, for each sample.
- Difference with 2D BDT fits used as BDT shapes modeling uncertainties.
- $1-2\%$ uncertainty on the flavour fraction.

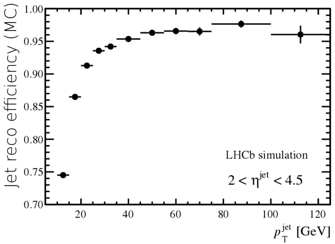


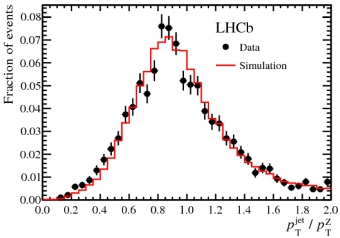


Jets @ LHCb

- ParticleFlow approach:
  - Charge particles from tracking.
  - Neutrals from calorimetry.
- Anti-k_T with $R = 0.5$.
- Jet Energy Scale:
  - corrections from MC (factor 0.9 to 1.1)
  - Validated on data, JES data vs. MC difference $< 5\%$
- Jet Energy Resolution:
  - $\sim 15 - 20\%$ for $p_T \in [10, 100\ \mathrm{GeV}]$
  - Same ball-park than GPD for low-p_T.
  - Studied in $Z + jet$ and b-enriched dataset.

Z+jet @ 7TeV [JHEP01 (2014) 033]





Systematic uncertainties

[PRD92 (2015) 052001]

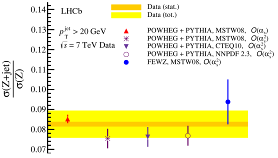
- μ+(b,c)tag corrected for SV tagging efficiencies.
- W+jet and W+(b,c)jet yields corrected for backgrounds from $Z \to \tau\tau$ and top.
- **Charge asymmetry**: $\mathcal{A}(Wq) = \frac{\sigma(W^+q)-\sigma(W^-q)}{\sigma(W^+q)+\sigma(W^-q)}$.
  - Obtained from $\mu + (b,c)$ yields in $p_T(\mu)/p_T(j_\mu) > 0.9$.
  - Most backgrounds are charge symmetric (only introduce dilution)$\rightarrow \mathcal{A} \sim \frac{\mathcal{A}_{raw}}{purity}$

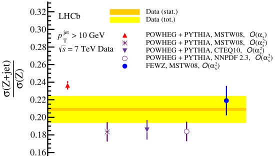
Source	$\frac{\sigma(Wb)}{\sigma(Wj)}$	$\frac{\sigma(Wc)}{\sigma(Wj)}$	$\frac{\sigma(Wj)}{\sigma(Zj)}$	$\mathcal{A}(Wb)$	$\mathcal{A}(Wc)$
Muon trigger and selection	–	–	2%	–	–
GEC	1%	1%	1%	–	–
Jet reconstruction	2%	2%	–	–	–
Jet energy	2%	2%	1%	0.02	0.02
(b,c)-tag efficiency	10%	10%		–	–
SV-tag BDT templates	5%	5%		0.02	0.02
$p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$ templates	10%	5%	4%	0.08	0.03
Top quark	13%	–	–	0.02	
$Z \to \tau\tau$	–	3%	–	–	–
Other electroweak	–	–	–	–	–
$W \to \tau \to \mu$	–	–	1%	–	–
Total	20%	13%	5%	0.09	0.04

Z+jet production in pp at $\sqrt{s} = 7$ TeV

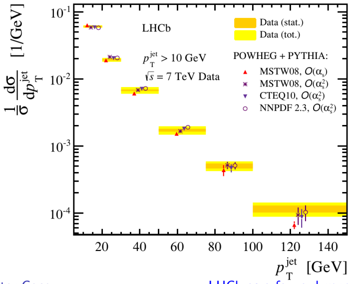
Result

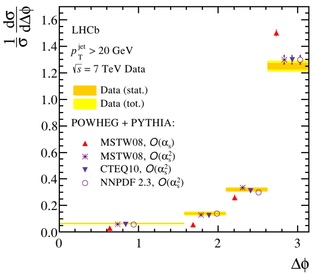
- Predictions from POWHEG+PYTHIA at $O(\alpha_s)$ and $O(\alpha_s^2)$ with different PDF sets.
- Predictions from FEWZ at $O(\alpha_s^2)$ not corrected for hadronisation and underlying event.





- Not corrected for FSR
- Shapes in good agreement with NLO





Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Motivation

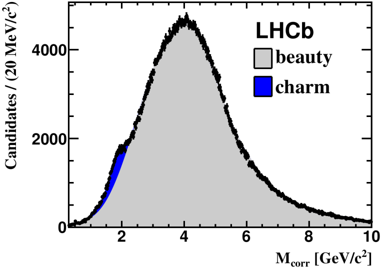
- Depending on new physics flavour structure, asymmetry could shows up in the bottom sector.

[arXiv:1108.3301,Kahawala et al.]

- At LHC access to the forward central asymmetry.
- Expected to be $O(1\%)$ from QCD with an extra $O(1\%)$ in the Z mass region.

PRL 113 (2014) 082003

- Analysis performed with 1 fb^{-1}
- Pairs of b-jets with $\Delta\phi(bb) > 2.6$ *rad*.
- One of the b-jets charge is tagged with a muon.
- Purity of the charge tagging $70.3 \pm 0.3\%$



Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Result with 1 fb^{-1}

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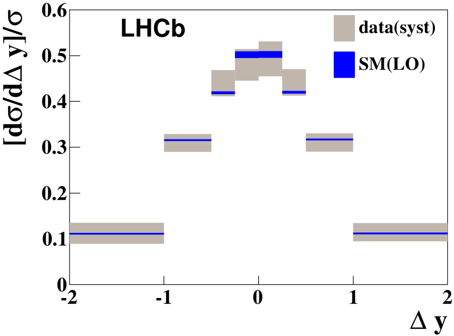

$A_{FC}^{b\bar{b}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$,
$\Delta y = |y_b| - |y_{\bar{b}}|$
In different m_{bb} bins:

- $A_{FC}^{b\bar{b}}(40,75) =$
  $0.4 \pm 0.4 \pm 0.3$ %
- $A_{FC}^{b\bar{b}}(75,105) =$
  $2.0 \pm 0.9 \pm 0.6$ %
- $A_{FC}^{b\bar{b}}(>105) =$
  $1.6 \pm 1.7 \pm 0.6$ %

- No deviation from expectation with available statistics.
- Still 2 fb^{-1} of the Run I data to be analysed.
- More efficient b-tagging available now.

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Next-to-leading order QCD predictions for $W + 1$ jet and $W + 2$ jet production with at least one b jet at the 7 TeV LHC

TABLE V. Inclusive event cross sections (in pb) for different PDF sets including PDF + α_s uncertainties at 68% C.L., determined according to the PDF4LHC NLO prescription [22] (with $\mu_R = \mu_F = \mu_0$).

	W^+b incl.		$W^+(bb)$ incl.	W^-b incl.		$W^-(bb)$ incl.
	4FNS	5FNS	4FNS	4FNS	5FNS	4FNS
NNPDF2.1 [19]	44.1	59.2 ± 1.7	11.4 ± 0.3	27.6	36.2 ± 1.0	7.1 ± 0.2
CTEQ6.6 [18,20]	42.6	56.7 ± 2.1	10.9 ± 0.3	26.3	34.8 ± 1.3	6.8 ± 0.2
MSTW2008 [21]	44.2	59.8 ± 1.7	11.5 ± 0.3	28.6	37.9 ± 1.0	7.4 ± 0.2