Probes of soft and hard QCD at LHCb

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Les Rencontres de Physique de la Vallee d'Aoste

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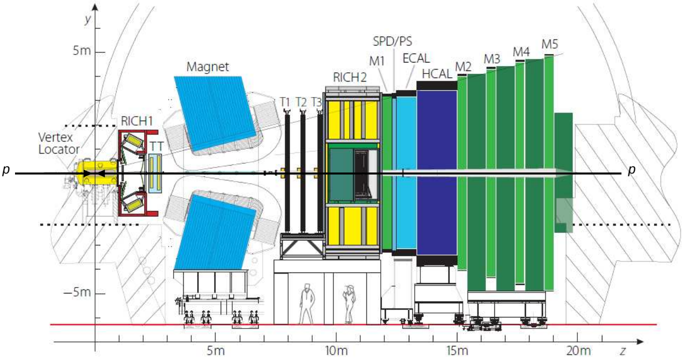
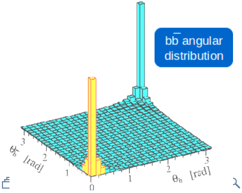
Outline

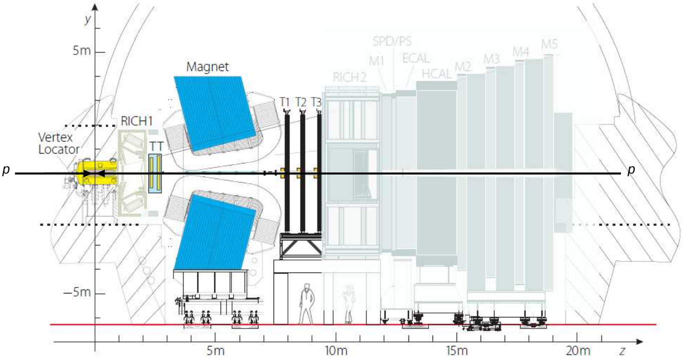
The LHCb detector



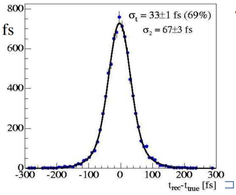
- Designed for CP violation and rare decays of haevy mesons.
- Single arm spectrometer, 40% of $b\bar{b}$ pairs produced in the acceptance. Unique kinematic region: high rapidity ($2.0 < y < 4.5$) and low p_T
- Huge amount of $b\bar{b}$ produced ($\sigma \sim 300\ \mu$b), all particle species (B^0, $B^{\pm}$, B_S, B_c, Λ_b ...)

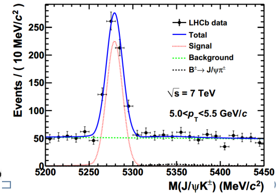


Tracking

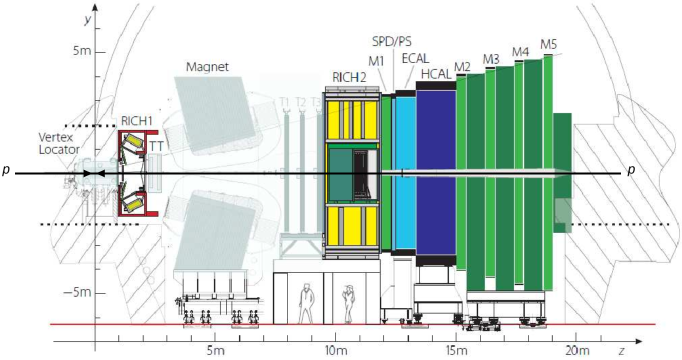


- Tracking efficiency $\sim$ 95%
- $\delta p/p \sim 0.5\%$
- Proper time resolution: 30 $\div$ 50 fs
- Mass resolution: 10 $\div$ 20 MeV/c^2

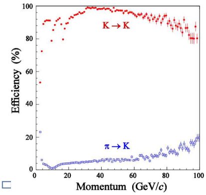




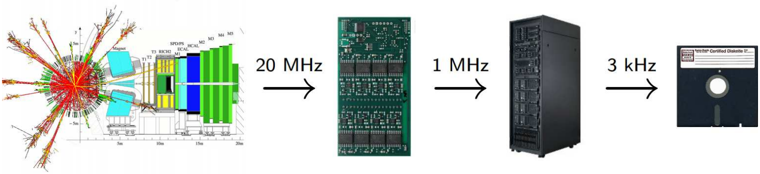
Particle identification



- Muon ID $\epsilon(\mu \rightarrow \mu) \simeq 94\%$
- Mis-ID $\epsilon(\pi \rightarrow \mu) \simeq 2\%$
- RICH ID: $\epsilon(K \rightarrow K) \simeq 95\%$
- Mis-ID $\epsilon(\pi \rightarrow K) \simeq 10\%$



Trigger



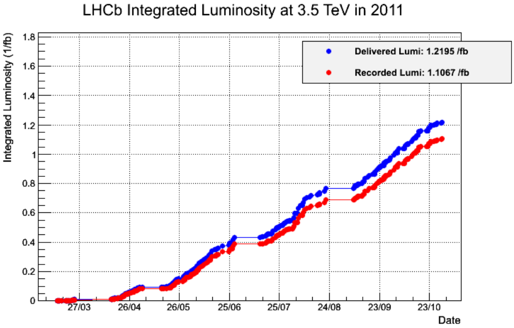
The online farm can read data at 1 MHz $\rightarrow$ hardware trigger needed

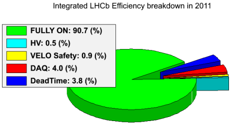
- L0 (hardware) requires large E_T in calorimeters or large p_T in muon stations. It also cuts on high multiplicity.
  $\epsilon(B \rightarrow \mu X) \sim 90\%$, $\epsilon(B \rightarrow \text{hadrons} \sim 30\%)$;
- HLT (software) runs 26k PROCs (giving it just 20 ms/event) to reduce the rate by another factor of 300.

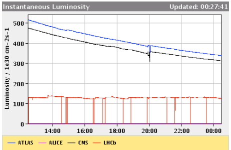
HLT1 Confirm L0 candidate with more complete info, add impact parameter and lifetime cuts: 1 MHz$\rightarrow$30 kHz.

HLT2 global event reconstruction + selections: 30 kHz$\rightarrow$3 kHz (1 kHz is dedicated to charm).

2011 Running





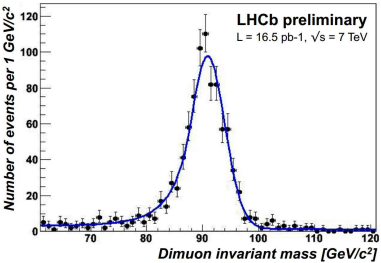


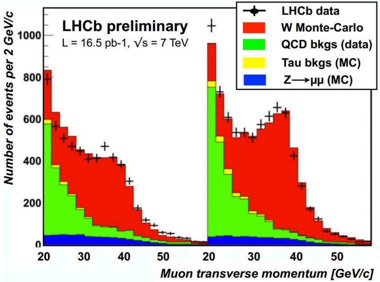
- LHCb collected **1.1 fb**$^{-1}$ in 2011 ($\sim$ 91% of L delivered by the LHC).
- The luminosity leveling system to keep L constant throughout each fill worked very well.

$$\sigma = \frac{N_{cand} - N_{bkg}}{A \times \epsilon_{trigger} \times \epsilon_{tracking} \times \epsilon_{\mu ID} \times \epsilon_{selection} \times \int L}$$

- Decay channels: $Z \to \mu\mu$ and $W \to \mu\nu$
- All efficiency evaluated on data
- Selection on μ with:
  - $p_T > 20$ GeV/c and $2 < \eta < 4.5$ for Z
  - 81 GeV/c^2 $< M_\mu <$ 101 GeV/c^2 and μ isolation
- Backgound for Z: QCD, b and c semi-leptonic decays, $Z \to \tau\tau$
- Background for W: QCD, $Z \to \mu\mu$, $W \to \tau\nu$, $Z \to \tau\tau$

eff	$Z \to \mu\mu$	$W \to \mu\nu$
trigger	$86 \pm 1\%$	$73 \pm 1\%$
tracking	$83 \pm 1\%$	$73(78) \pm 3\%$
μID	$96.5 \pm 0.7\%$	$98.2 \pm 0.5\%$
selection	100%	$55 \pm 1\%$





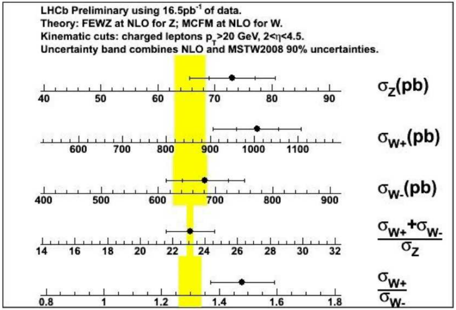
Events Yields		
channel	N_{sig}	N_{bkg}
$Z \to \mu\mu$	883	1.2 ± 1.2
$W^+ \to \mu^+\nu$	7624	2194 ± 150
$W^- \to \mu^-\nu$	5732	1654 ± 150

Systematic effects (%)			
	Z	W^+	W^-
background	0.1	3	5
trigger	1	1	1
μID	0.7	0.5	0.5
tracking	4	4	4
selection	n/a	2	2
luminosity	10	10	10
Stat. error	4	1	1

Results in our kinematic region (LHCb Preliminary)

$$\sigma_Z = 73 \pm 4(stat) \pm 7.3(sist)\ \text{pb}$$
$$\sigma_{W+} = 1007 \pm 48(stat) \pm 101(sist)\ \text{pb}$$
$$\sigma_{W-} = 680 \pm 40(stat) \pm 68(sist)\ \text{pb}$$

- Measurements are compatible with NLO prediction (MSTW2008NLO).
- For these rapidity, uncertainty of the prediction due to PDF is between 4 and 7%.

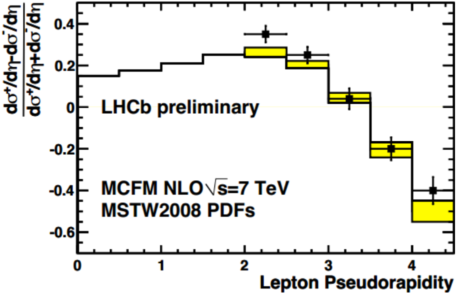


LHCb-CONF-2011-012

W charge asymmetry

$A_W = \frac{\sigma(W^+)-\sigma(W^-)}{\sigma(W^+)+\sigma(W^-)}$

- Asymmetry changes sign in the forward region.
- In this region, PDF uncertainty on A_W is of the order of 2 - 8% (MSTW2008NLO, 68%C.L.)
- LHCb measurements already constrain PDFs with present analysis (analysis of the 2011 data ongoing).



LHCb-Preliminary

η_μ	A_W
2.0 - 2.5	0.35 ± 0.04
2.5 - 3.0	0.25 ± 0.04
3.0 - 3.5	0.04 ± 0.05
3.5 - 4.0	-0.20 ± 0.055
4.0 - 4.5	-0.40 ± 0.065

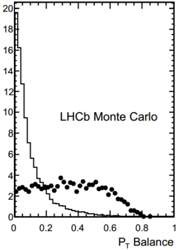
Z cross section with $Z \to \tau\tau$

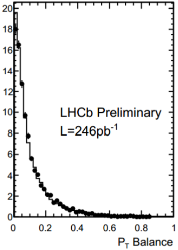
Event selection and background rejection

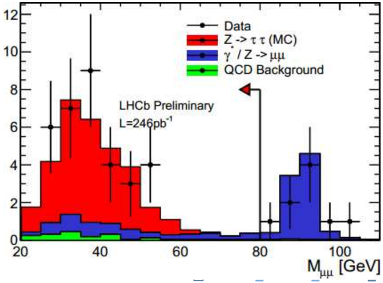
- Two final states considered $Z \to \tau\tau \to (\mu\nu\nu)(\mu\nu\nu)$ and $Z \to \tau\tau \to (\mu\nu\nu)(e\nu\nu)$
- For the $\mu\,\mu$ final state we require one μ with $p_T > 20$ GeV/c, $2.0 < \eta < 4.5$ and $E_{tot}/p < 0.2$. Second muon with $p_T > 5$ GeV/c
- For the $\mu\,e$ final state we require one μ with $p_T > 20$ GeV/c, $2.0 < \eta < 4.5$ and $E_{tot}/p < 0.2$. Electron with $p_T > 5$ GeV/c and E/p cut on calorimeters

Background:

- Drell-Yan
  - removal of Z-peack: $M_{\mu\mu} < 80$ MeV/c^2
  - cut on $p_T^{balance} = (p_T^{(1)} - p_T^{(2)})/(p_T^{(1)} + p_T^{(2)})$, cut on IP_{sum}
- QCD background: cut on Energy isolation
- WW, WZ and ZZ: cut on $\Delta\phi > 2.7$ rad (signal is back to back)







Z cross section with $Z \to \tau\tau$

LHCb-CONF-2011-041

How we measure the cross section

$$\sigma = \frac{N_{cand} - N_{bkg}}{2 \times A \times \epsilon \times BR(\tau \to e\nu\nu) \times BR(\tau \to \mu\nu\nu) \times \int L} \qquad \sigma = \frac{N_{cand} - N_{bkg}}{A \times \epsilon \times BR(\tau \to \mu\nu\nu)^2 \times \int L}$$

Results (LHCb-Preliminary)

$\sigma(Z \to \tau\tau \to \mu\mu) = 79 \pm 9(stat.) \pm 8(syst.) \pm 4(lum.)$ pb

$\sigma(Z \to \tau\tau \to \mu e) = 89 \pm 15(stat.) \pm 10(syst.) \pm 5(lum.)$ pb

- Combining the two channel results we have:

$$\sigma(Z \to \tau\tau) = 82 \pm 8(stat) \pm 7(syst) \pm 4(lum)\ pb$$

$$p_T > 20\,\mathrm{GeV/c}; \quad 2 < \eta < 4.5; \quad 60\,\mathrm{GeV/c^2} < M_Z < 120\,\mathrm{GeV/c^2}$$

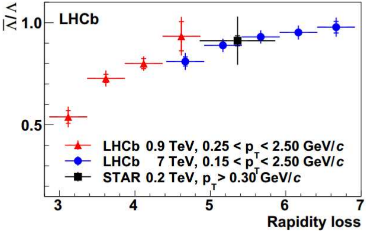
- We can then compare this measurement with $\sigma(Z \to \mu\mu)$

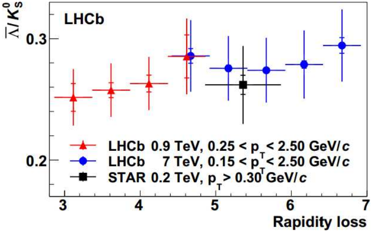
$$\frac{\sigma(Z \to \tau\tau)}{\sigma(Z \to \mu\mu)} = 1.09 \pm 0.17$$

consistent with lepton universality

Production ratio: $\bar{\Lambda}/\Lambda$, $\bar{\Lambda}/K^0_S$

- $\bar{\Lambda}/\Lambda = \frac{\sigma(pp\to\bar{\Lambda}X)}{\sigma(pp\to\Lambda X)}$ probes the baryon number transport.
- $\bar{\Lambda}/K^0_S = \frac{\sigma(pp\to\bar{\Lambda}X)}{\sigma(pp\to K^0_S X)}$ probes the strange baryon suppression.
- Several models exist to describe this transport, but it is not clear which mechanisms are most important in driving the phenomenon.
- Measurements performed at $\sqrt{s} = 900$ GeV (0.3 nb^{-1}) and $\sqrt{s} = 7$ TeV (1.8 nb^{-1}).
  - Very loose trigger: one track seen in the VELO or downstream. A primary vertex is required.
  - Prompt K^0_S and $\Lambda(\bar{\Lambda})$ decaying to $\pi^+\pi^-$ and $p\,\pi^-$ $(p\,\pi^+)$.
  - Measurements are done in 6 bins of p_T (250 MeV/c$< p_T <$2500 MeV/c) and 4 bins of rapidity ($2 < y < 4$).
    Rapidity loss = $y_{beam} - y$



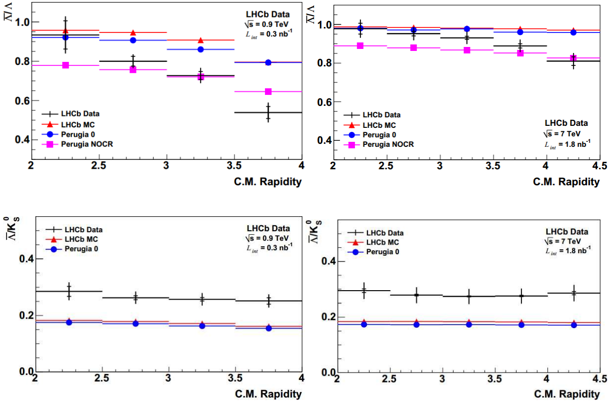


- Consistency between the two measurements ($\sqrt{s} = 900$ GeV and 7 TeV) and the previous results.

JHEP 08 (2011) 034

Production ratio: $\bar{\Lambda}/\Lambda$, $\bar{\Lambda}/K^0_S$

Comparison with Monte Carlo

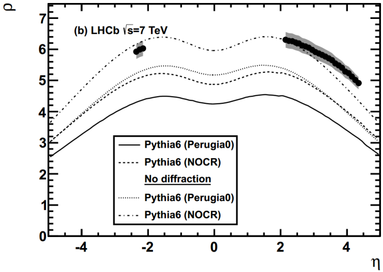


- $\bar{\Lambda}/\Lambda$: good agreement with Perugia0 at low rapidity while at high rapidity Perugia NOCR looks to be favoured.
- $\bar{\Lambda}/K^0_S$ measured ratio is significantly larger than predicted by the generators, i.e. more baryons are produced in strange hadronization than expected.

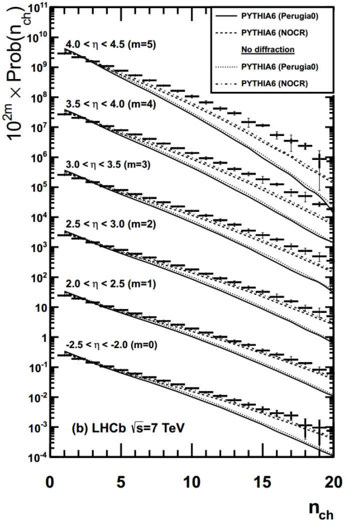
Charged track multiplicity

- Important for good simulation of environment aside from hard scatter
- Particles counted by reconstructing tracks in the VELO outside magnetic field, no momentum measurement
- Correction for non-prompt contamination (5-10%) and for efficiency drop at loe p_T (residual field)

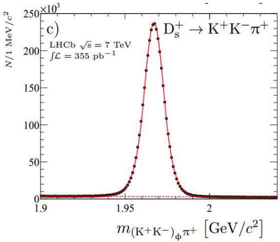
- All models fail to describe the mean charged particle multiplicity per unit of pseudorapidity, (mainly at high η).
- The Perugia (NOCR) tune gives the best description of the data in the backward direction but fails to reproduce the size of the asymmetry.

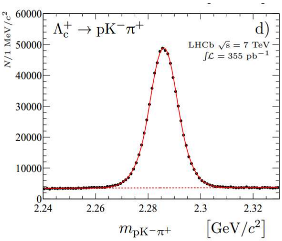


LHCB-PAPER-2011-011

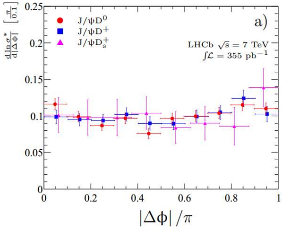


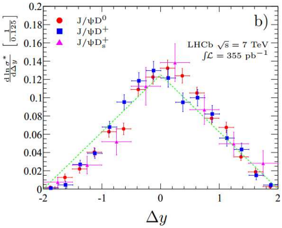
- Intrinsic Charm Model: we are testing/constraining (badly known) charm PDFs, typical uncertainties $\times 2$
- Double Parton Scattering
- We want to measure $c\bar{c}\,c\bar{c}$, $J/\Psi\,c$ and $c\,c$ (dominated by the regular $gg \to cc$)
- In total 25 possible modes: (1 $J/\Psi\,J/\Psi$) + (4 $J/\Psi\,c$) + (10 cc) + (10 $c\bar{c}$)
- Reconstruct prompt charm hadrons:
  $J/\Psi \to \mu^+\mu^-$, $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_S \to (K^+K^-)_\phi\pi^+$, $\Lambda_c \to pK^-\pi^+$
- Charm hadron selection:
  - Cut on tracks χ^2 and particle PID
  - Vertex quality cuts: PV and decay consistency
  - Cut on $c\tau$ for open charm hadrons
  - Require both hadrons consistent with the same PV



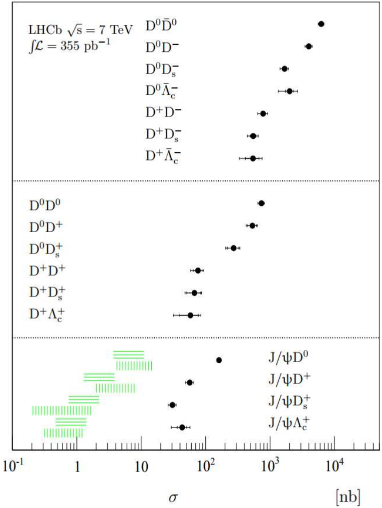


- Invariant mass distributions for selected D mesons and Λ_c^+
- Fit with double Crystal Ball for $J/\Psi \to \mu^+\mu^-$, Bukin function for D mesons.





- Azimuthal (a) and rapidity (b) correlations for three $J/\Psi\ D$, decays.
  No correlation in the angle.
  Slight correlation in rapidity
- Exstensive study of spectra in transverse momenta and global invariant mass



$J/\Psi\, c$ production has been measured ($> 7\sigma$) for the first time at hadron machines.
$J/\Psi D^0$, $J/\Psi\, D^+$, $J/\Psi\, D_s$, $J/\Psi\, \Lambda_c$.

cc production has been observed for the first time for six modes with $> 5\sigma$ significance.
D^0D^0, D^0D^+, D^0D_s, $D^0\Lambda_c$, D^+D^+, D^+D_s

$c\bar{c}$ production have been measured for seven modes cross-sections and ratios have been obtained

p_T, $\Delta\phi$, Δy and $M(c_1, c_2)$ have been studied

LHCb-PAPER-2012-003

$\Psi(2S)$ production cross section

- The $\Psi(2S)$ does not suffer from the problem of the feed-down mechanism: prompt $\Psi(2S) \equiv$ direct $\Psi(2S)$
- Measeured through the decay channels $\Psi(2S) \to \mu^+\mu^-$ and $\Psi(2S) \to J/\Psi\pi^+\pi^-$ averaged, with 37 pb^{-1}.

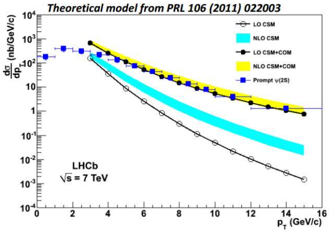
$$\sigma(pp \to \Psi(2S)X) = 1.44 \pm 0.01(stat) \pm 0.12(syst)^{+0.20}_{-0.40}(pol.)\ \mu\mathrm{b}$$

- Inclusive $b \to J/\Psi$ and $b \to \Psi(2S)$ can be used to extract $B(b \to \Psi(2S)X)$ known at 50% level: $4.8 \pm 2.4 \pm 10^{-3}$ [PDG].

$$BR(b \to \Psi(2S)X) = 2.73 \pm 0.06 \pm 0.16 \pm 0.24$$

- The prompt $\Psi(2S)$ results are in good agreement with the NLO CSM+COM model
- Good agreement with the CMS results:

LHCB: $BR(b \to \Psi(2S)X) = 2.73 \pm 0.17(stat + syst) \pm 0.24(BR)$
CMS: $BR(b \to \Psi(2S)X) = 3.08 \pm 0.18(stat + syst) \pm 0.42(BR)$



LHCb: LHCB-PAPER-2011-045
CMS: CMS-BPH-10-014

Quarkonia: $\Upsilon(nS)$

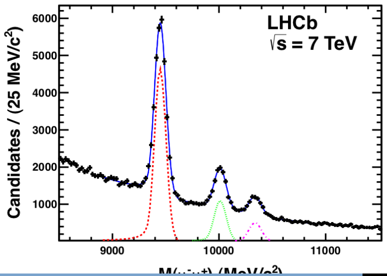
- Test of the bottomonium production mechanism
- Direct production or feed-down from higher Υ states or χ_b states.
- Measured through the decay channels $\Upsilon \to \mu^+\mu^-$ with 25 pb^{-1} of 2010 data
- Signal fitted by Crystal Ball functions.

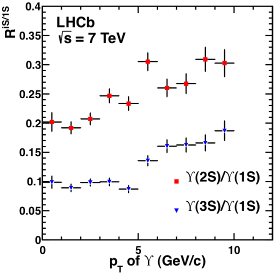
$$\sigma(pp \to \Upsilon(1S)\,X)\cdot BR(\mu^+\mu^-) = 2.29 \pm 0.02(stat) \pm 0.10(syst)^{0.19}_{-0.37}(pol)\ \text{nb}$$

$$\sigma(pp \to \Upsilon(2S)\,X)\cdot BR(\mu^+\mu^-) = 0.56 \pm 0.01(stat) \pm 0.02(syst)^{0.05}_{-0.09}(pol)\ \text{nb}$$

$$\sigma(pp \to \Upsilon(3S)\,X)\cdot BR(\mu^+\mu^-) = 0.28 \pm 0.01(stat) \pm 0.01(syst)^{0.03}_{-0.05}(pol)\ \text{nb}$$

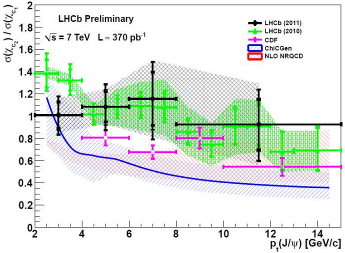
LHCb-PAPER-2011-036

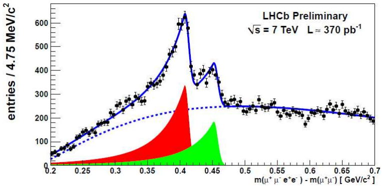




Quarkonia: χ_c

- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ measurement to test the production mechanism (sensitive to CS and CO models)
- Substantial feed-down contributions to the prompt J/Ψ production through $\chi_c \to J/\Psi\gamma$
- States identified through their radiative decay $\chi_c \to J/\Psi\,\gamma$ with $J/\Psi \to \mu^+\mu^-$ and $\gamma \to e^+e^-$. 370 pb^{-1} analysed.
- 2011 analysis with converted photons in the tracking system (better resolution).
- In agreement with NLO NRQCD model (CS+CO) above 8 GeV/c

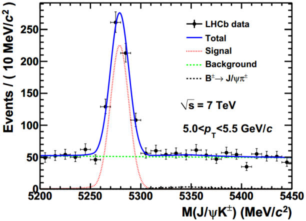




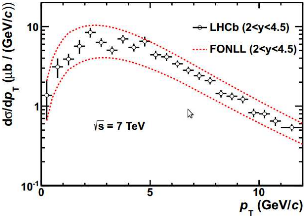
LHCB-PAPER-2011-019

B^+ cross section

- Powerful probe of pQCD calculations.
- Recently measured by CDF ($p_T > 6$ GeV/c and $|y| < 1$) and by CMS ($p_T > 5$ GeV/c and $|y| < 2.4$).
- In LHCb, reconstructed via $J/\Psi(\mu^+\mu^-)K^+$ mode. with $\tau(B) > 0.3$ ps to reject prompt background.
  35 pb^{-1}, $2 < y < 4.5$, $0 < p_t < 40$ GeV/c
- Results in good agreement with FONLL predictions (overall scale fixed to $f_{b\to B} = 40.1 \pm 1.3\%$)



$$\sigma(pp \to B^+ X) = 41.4 \pm 1.5(stat) \pm 3.1(syst)\ \mu\text{b}$$



LHCB-PAPER-2011-043

CDF: ($p_T > 6GeV/c$, $|y| < 1$) $= 2.78 \pm 0.24\ \mu$b - PR D75 (2007) 012010

CMS: ($p_T > 5GeV/c$, $|y| < 2.4$) $= 28.1 \pm 2.4 \pm 2.0 \pm 3.1\ \mu$b - PRL 106 (2011) 112001

Conclusions

- LHCb probed high rapidity region at LHC.
- Presented analysis based on small part of 2011 data. With all the statistics, sensitivity to constraint PDF from W and Z measurements.
- Important results for improving MC models:
  - Baryon number transport is lower than expected at 900 GeV but disagreement depends on the generator model. Better agreement at 7 TeV.
  - More strange mesons produced than expected.
  - Charged track multiplicity above any generators prediction.
- A lot of measurements in quarkonia sector: production cross sections and mass. Important inputs for theorists
- Big expectations from 2012 running (1.5 fb^{-1})

Spare slides

Z cross section with $Z \to \tau\tau$

Yields and efficiency

How we measure the cross section

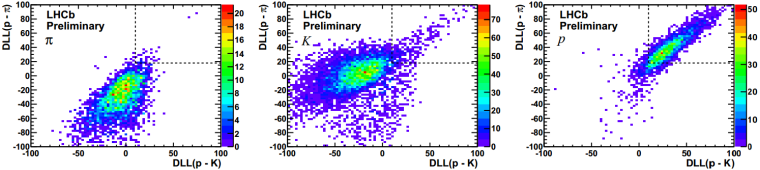
$$\sigma = \frac{N_{cand} - N_{bkg}}{2 \times A \times \epsilon \times BR(\tau \to e\nu\nu) \times BR(\tau \to \mu\nu\nu) \times \int L} \qquad \sigma = \frac{N_{cand} - N_{bkg}}{A \times \epsilon \times BR(\tau \to \mu\nu\nu)^2 \times \int L}$$

Yields and efficiency

	$e\mu$		$\mu\mu$	
	2010 data	2011 data	2010 data	2011 data
Events	10	71	4	29
Background	1.9 ± 0.5	10.6 ± 2.7	1.1 ± 0.3	6.1 ± 2.0
$\epsilon_{trigger}$	0.73 ± 0.01	0.78 ± 0.01	0.81 ± 0.01	0.86 ± 0.01
ϵ^{μ}_{track}	0.84 ± 0.02			
ϵ^{e}_{track}	0.80 ± 0.03		-	
ϵ^{μ}_{ID}	0.991 ± 0.002			
ϵ^{e}_{ID}	0.962 ± 0.010		-	
ϵ^{e}_{sel}	0.46 ± 0.03		0.172 ± 0.014	
ϵ	0.215 ± 0.017	0.230 ± 0.019	0.097 ± 0.009	0.103 ± 0.010
Acceptance	0.249 ± 0.012		0.386 ± 0.009	
Luminosity (pb^{-1})	37.5 ± 1.3	210.4 ± 12.6	37.5 ± 1.3	208.9 ± 12.5
Branching ratio	0.062		0.030	
FSR Correction (pb^{-1})	0.7 ± 0.1			
Cross section (pb)	$79 \pm 9(stat.) \pm 8(syst.) \pm 4(lum.)$		$89 \pm 15(stat.) \pm 10(syst.) \pm 5(lum.)$	

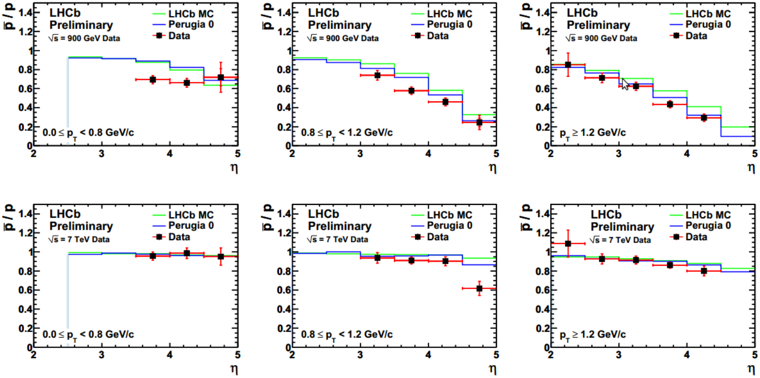
$\bar{p}/p$ ratio

- $\bar{p}/p = \frac{\sigma(pp \to \bar{p}X)}{\sigma(pp \to pX)}$ probes the **baryon number transport**.
- Several models exist to describe this transport, but it is not clear which mechanisms are most important in driving the phenomenon.
- Prompt protons with $p > 5$ GeV/c are selected with PID requirements ($\sim$ 95% purity on MC, with efficiency $\sim$ 85%).

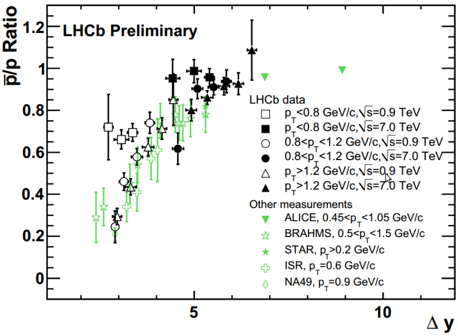


- Efficiency and purity of the PID evaluated on data using tag and probe method on calibration samples: $\phi \to K^+K^-$, $K_S \to \pi^+\pi^-$ and $\Lambda \to \pi$
- Measurements are done in 3 bins of p_T (0.8 GeV/c; 1.2 GeV/c) and 5 bins of rapidity $2.0 < y < 4.5$.
- Measurements performed at $\sqrt{s} = 900$ GeV (0.3 nb^{-1}) and $\sqrt{s} = 7$ TeV (1.8 nb^{-1}).

$\bar{p}/p$ ratio: results



- At 900 GeV, in the low and middle p_T bins data values are below both generators (LHCb PYTHIA and Perugia0). In the high p_T bin better agreement with Perugia0.
- At 7 TeV energy, the measurements are compatible with the expectation of both the generators



- Reasonable consistency with other experiments.
- Indication of some p_T dependence. Slight disagreement for 900 GeV p_T data

Quarkonia: $X(3872)$

- Discovered by Belle in 2003 and confirmed by Babar, CDF and D0.
- Quantum numbers not yet established ($J^{PC} = 2^{-+}$ or 1^{++}). Nature still uncertain:
  - conventional charmonium (e.g. η_{c2})
  - bound $D^{*0}\bar{D}^0$ molecule
  - tetraquark state
- Mass is a critical input to theories
- In LHCb detected through the $J/\Psi(\mu^+\mu^-)\pi^+\pi^-$ decay channel

$$M_{X(3872)} = 3871.96 \pm 0.46 \pm 0.10 \text{ MeV/c}^2$$

$$\sigma(pp \to X(3872)...) \cdot BR(J/\Psi\pi^+\pi^-) = 4.74 \pm 1.10(stat) \pm 1.01(syst) \text{ nb}$$