EW and quarkonia production studies in the forward acceptance

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QCD@LHC 2015

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Overview

- RUN-I electroweak and quarkonia production in the forward region, $2 < \eta < 4.5$.

Topic	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [pb^{-1}]	**Ref.**
$W \rightarrow \mu\nu / Z \rightarrow \mu\mu$	7	1000	JHEP 08 (2015) 039
$Z \rightarrow ee$	8	2000	JHEP 05 (2015) 109
$J/\Psi \rightarrow \mu\mu$	8	18	JHEP 06 (2013) 064
$\Upsilon \rightarrow \mu\mu$	7/8	3000	Preliminary

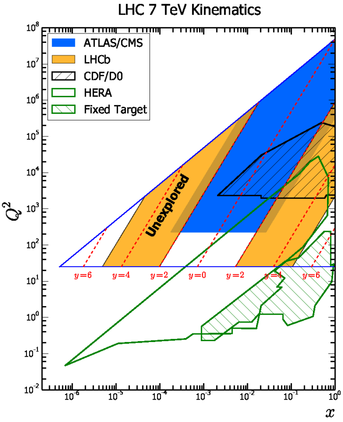
- Focus on *pp* collisions.
- A selection of analyses not discussed here are listed in the back-up.
- See slides by Matt Needham for details on J/Ψ at $\sqrt{s} = 13$ TeV.

EW motivations: Parton density functions

$$\sigma_{pp\to V} = \sum_{a,b} \int dx_1 dx_2 \underbrace{f_a\left(x_1, Q^2\right) f_b\left(x_2, Q^2\right)}_{PDFs} \hat{\sigma}_{ab}(x_1, x_2, Q^2)$$

CERN-LHCb-PROC-2014-057

- PDFs parameterised as functions of x and Q^2.
- x constrained by kinematics: $x_{\pm} = \frac{M}{\sqrt{s}} e^{\pm y}$.
- Two distinct regions (orange) low- and high-x due to forward acceptance $2 < \eta < 4.5$.
- High-x well known HERA, Tevatron. Lox-x unexplored LHCb.
- W/Z: $Q^2 \sim 10^4$ and $x \sim 10^{-4}$ or $x \sim 10^{-1}$.



EW motivations: Testing the SM

$$\sigma_{pp\to V} = \sum_{a,b} \int dx_1 dx_2 \underbrace{f_a\left(x_1, Q^2\right) f_b\left(x_2, Q^2\right)}_{PDFs} \hat{\sigma}_{ab}(x_1, x_2, Q^2)$$

Measure ratios of cross-sections: $R_{W/Z} = \frac{\sigma_W}{\sigma_Z}$, $R_W = \frac{\sigma_{W+}}{\sigma_{W-}}$

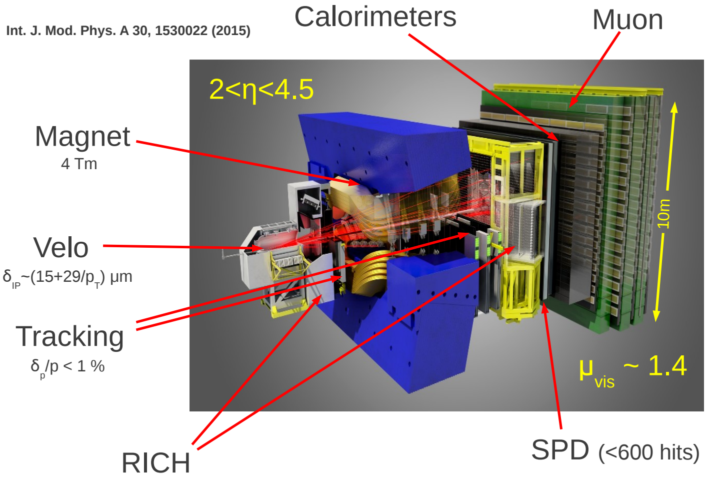
- Experimental precision
  - Luminosity cancels in the ratio. Largest uncertainty on cross-sections removed.
  - Correlated systematic uncertainties means relative uncertainty much reduced.
- Theoretical precision
  - Largest uncertainty on predicted cross-section is due to PDFs.
  - Since these are correlated the relative uncertainty on the ratio is reduced.
  - Scale and α_s uncertainties almost fully correlated. These also reduced.

Inclusive quarkonia (motivations)

Phys. Lett. B167 (1986) 437; Phys. Rev. D51 (1995) 1125

- Colour singlet mechanism (CSM) underestimates the observed J/Ψ cross-section at high-p_T at Tevatron by an order of magnitude **Phys. Rev. Lett. 69 (1992) 3704**.
- Non-relativisitc QCD (NRQCD) introduced. Contains CS and colour octet (CO) matrix elements. CO matrix elements determined from fit to HERA, Tevatron and LHC data.
- Higher order corrections (NLO, NNLO*) to leading order CSM also give better description.
- Additional measurements help shed light on these descriptions.

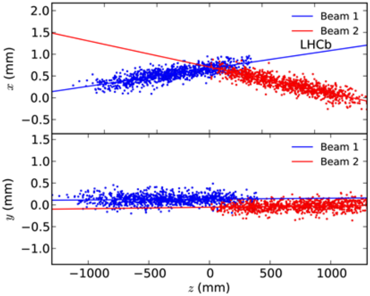
LHCb detector



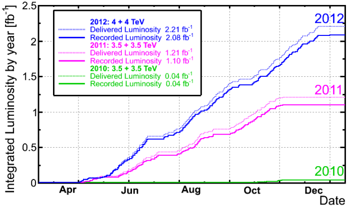
Int. J. Mod. Phys. A 30, 1530022 (2015)

Precision luminosity

2014 JINST 9 P12005



- Luminosity levelling (< 2 pp interactions per bunch crossing).
- Luminosity measured at LHCb using Van der Meer scans (VDM) and Beam-Gas Imaging (BGI).
- Inject Ne gas to increase rate for BGI.
- $\frac{\sigma_{\mathcal{L}}}{\mathcal{L}}$: 1.7%(1.1%) in 2011(2012).

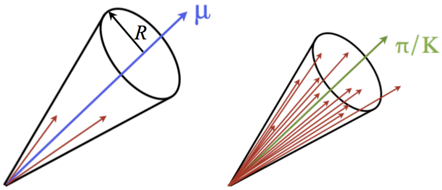


- "This represents the most precise luminosity measurement achieved so far at a bunched-beam hadron collider".

Electroweak

Selecting electroweak bosons

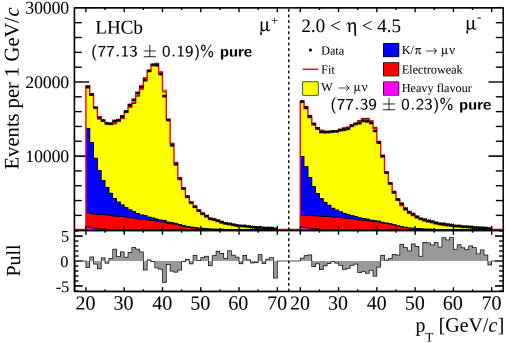
JHEP 12 (2014) 079; JHEP 08 (2015) 039



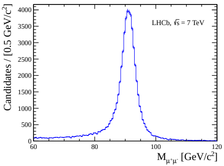
- Common to W and Z:
  - High p_T (> 20 GeV/c).
  - $2 < \eta < 4.5$.
  - Good track-fit quality.
  - Isolated muons consistent with primary interaction point.
  - Candidate event triggered by muon trigger.
  - Residual backgrounds include: π/K decay-in-flight, decays of heavy flavour hadrons, other QCD and electroweak.
- W: 1 muon
- Z: 2 muons. $60 < M_{\mu\mu} < 120$ GeV/c^2

Purity estimation

JHEP 12 (2014) 079; JHEP 08 (2015) 039; Comput. Phys. Comm. 178 (2008) 852



Z sample $\sim$ 99% **pure**



- $\sim 800,000$ W candidates.
- Fit muon p_T distribution.

- **Signal**: RESBOS shape, normalisation free in η and charge.
- **Electroweak**: ($Z \rightarrow \mu\mu$, $W \rightarrow \tau\nu$, $Z \rightarrow \tau\tau$): RESBOS/PYTHIA shapes and normalisation $(9.82 \pm 0.16)\%$ from data.
- **Decay-in-flight**: Data shape. Normalisation free in η and charge.
- **Heavy flavour**: Data shape ($IP > 100\mu m$) and normalisation $(0.48 \pm 0.03)\%$.

Phys. Rev. D50 (1994) 4239; Phys. Rev. D56 (1997) 5558; Phys. Rev. D67 (2003) 073016

Fiducial cross-sections

Nucl.Instrum.Meth. A602 (2009) 432-437
CERN-ATS-2013-040

- Cross-sections defined in fiducial region: muons with $2 < \eta < 4.5$, $p_T > 20\ GeV/c$ and in the case of the Z boson an invariant mass $60 < M_Z < 120\ GeV/c^2$.

$$\sigma_{VB} = \frac{\rho N}{\mathcal{A}\varepsilon\mathcal{L}}$$

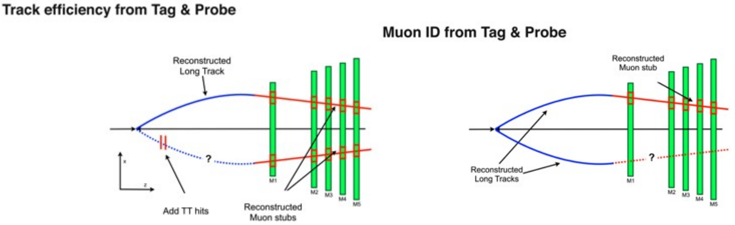
- The cross-section measured in bin i of y_Z, $p_{T,Z}$ and ϕ^*_Z or W muon η^μ.

$$\phi^*_Z = \frac{\tan\left(\phi_{\pi - |\Delta\phi|}/2\right)}{\cosh\left(\Delta\eta/2\right)}.$$

- Total cross-sections obtained by summing the differential cross-sections.
- Dominant uncertainties are the luminosity, W purity ρ and efficiency due to 600 SPD hit threshold.
- $\sim 1\%$ uncertainty for beam energy since results quoted at specific $\sqrt{s}$.

Efficiencies

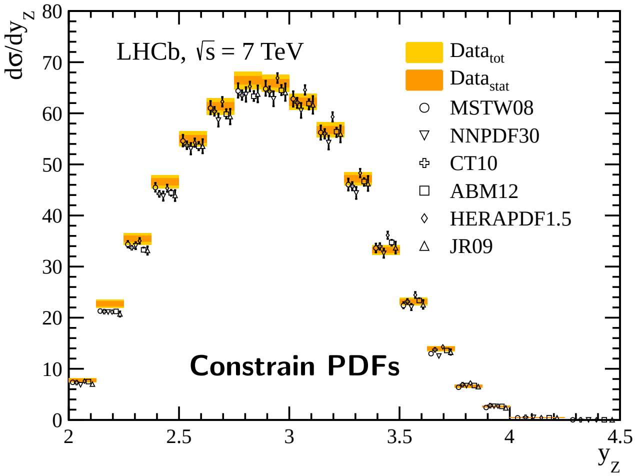
- Muon reconstruction efficiencies: tag-and-probe with the Z resonance.
- Efficiencies studied as function of muon kinematics and detector occupancy.



- Must also correct for threshold at 600 SPD sub-detector hits in muon trigger.
- Evaluated in previous W boson analysis JHEP 12 (2014) 079 to be $(95.9 \pm 1.1)\%$.
- New method $(94.0 \pm 0.2)\%$. Update W cross-sections to profit from increased precision.
- Systematic uncertainty accounting for differences between $W^{\pm}$ and Z $\sim 0.3\%$.

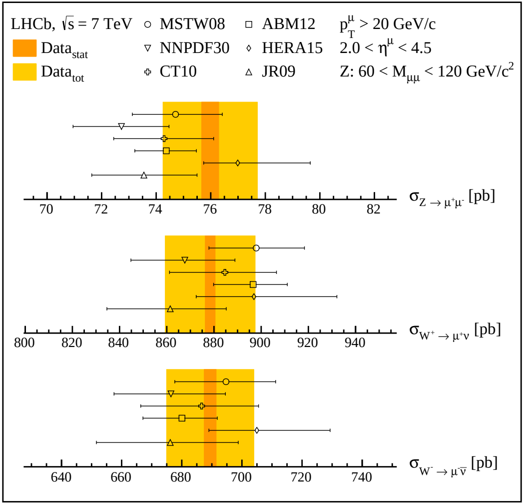
Differential cross-sections: y_Z

Phys. Rev. D86 (2012) 094034; JHEP 08 (2015) 039



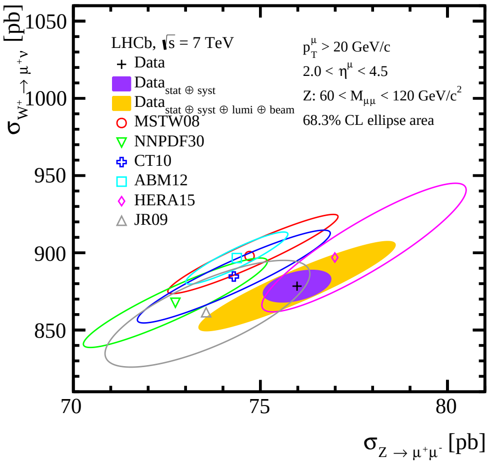
Results: cross-sections

JHEP 08 (2015) 039



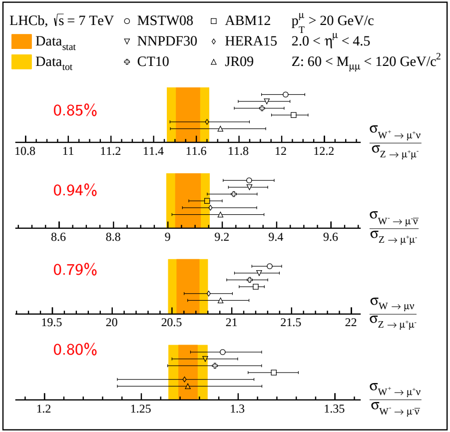
Results: confidence ellipse

JHEP 08 (2015) 039



Results: cross-section ratios

JHEP 08 (2015) 039



$\frac{\sigma_{W+}}{\sigma_Z}$

$\frac{\sigma_{W-}}{\sigma_Z}$

$\frac{\sigma_W}{\sigma_Z}$

$\frac{\sigma_{W+}}{\sigma_{W-}}$

- Luminosity uncertainty cancels. Sub 1% precision (exact values in red above).
- Sensitivity to choice of PDF.
- Overall agreement with SM.

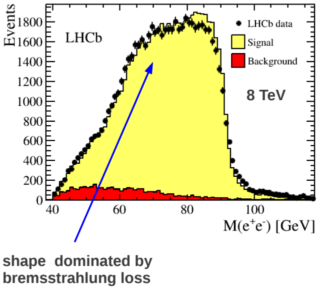
$Z \to ee$ at $\sqrt{s} = 8$ TeV

JHEP 05 (2015) 109

- Aim: Measure 'fiducial' cross-section with $p_T^e > 20$ GeV/c, $2 < \eta^e < 4.5$ and $60 < M_{ee} < 120$ GeV/c^2.

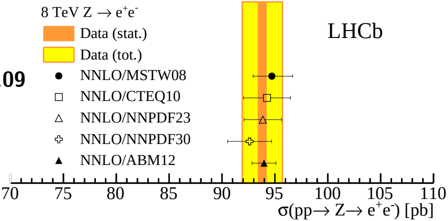
- Dominant systematics different to muon analyses (bremsstrahlung)
- Use ϕ^* variable (directions known better than momenta).

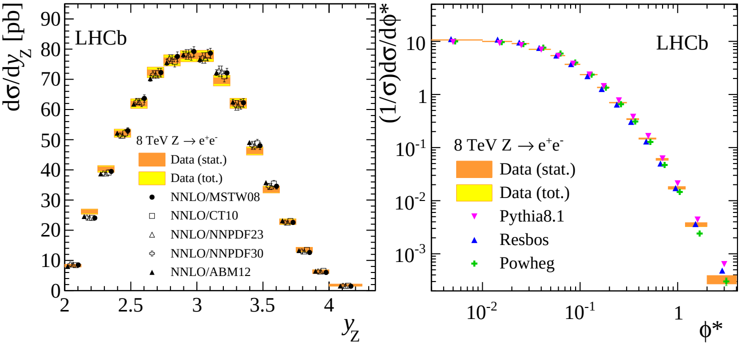
$$\phi_Z^* = \frac{\tan\left((\pi - |\Delta\phi|)/2\right)}{\cosh\left(\Delta\eta/2\right)}$$



$Z \to ee$ at $\sqrt{s} = 8$ TeV: Results

JHEP 05 (2015) 109





Inclusive quarkonia

Inclusive J/Ψ at $\sqrt{s} = 8$ TeV

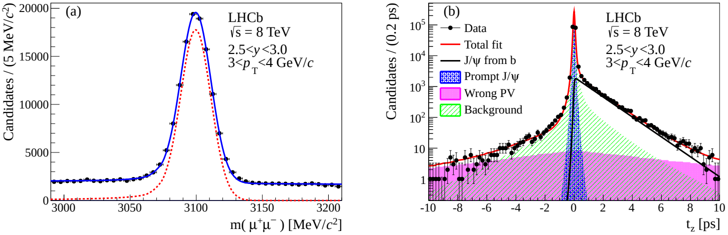
- Measure: J/Ψ in $2 < \eta < 4.5$ and $p_T^{J/\Psi} < 14$ GeV/c.
- Luminosity: 18 pb^{-1}.
- Hardware trigger: Dimuon product of transverse momenta > 1.68 $(\text{GeV/c})^2$.
- Software trigger: Muon $p_T > 500$ MeV/c, $p > 6$ GeV/c, $|m_{\mu^+\mu^+} - M_{J/\Psi}| < 120$ MeV/c^2.

$$\frac{d^2\sigma}{dy\ dp_T}(pp \to V\ X) = \frac{N\ (V \to \mu^+\mu^-)}{\mathcal{L}\ x\ \varepsilon_{tot}\ x\ \mathcal{B}\ (V \to \mu^+\mu^-)\ x\ \Delta y\ x\ \Delta p_T}$$

- N from fit to candidates. $\sim$2.6 million.
- ε_{tot} determined using simulation. Validated with data-driven techniques.

Inclusive J/Ψ at $\sqrt{s} = 8$ TeV

JHEP 06 (2013) 064

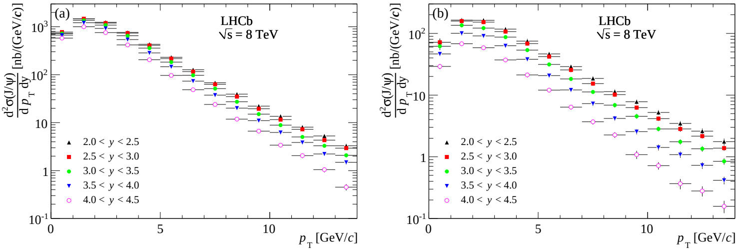


- Yields determined from 2D fit to J/Ψ mass and pseudo proper time t_z in each y and p_T bin.
- t_z distinguishes prompt J/Ψ (smeared delta function) and J/Ψ from B (smeared decaying exponential).
- Shape of incorrect assignment of PV studied using J/Ψ from event n and PV from event $n+1$.
- Background from J/Ψ mass sidebands.

$$t_z = \frac{(z_{J/\Psi} - z_{PV})xM_{J/\Psi}}{p_z}$$

Inclusive J/Ψ at $\sqrt{s} = 8$ TeV

JHEP 06 (2013) 064



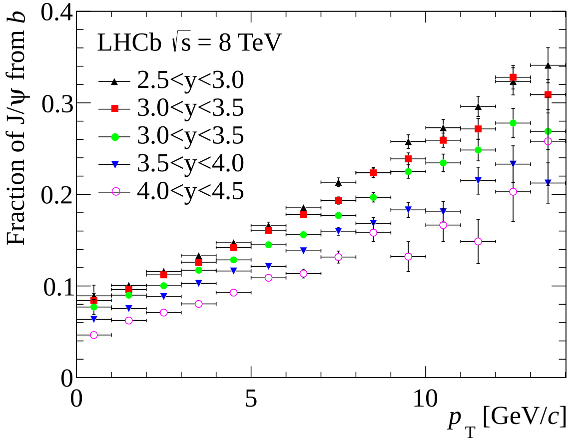
- (Left) Differential prompt J/Ψ. (Right) Differential J/Ψ from B ($\sim$10% of total).
- Largest systematics due to luminosity (5%), trigger efficiency (4%), t_z fit (1.0-12.0% uncorrelated between bins).

$$\sigma(\text{prompt } J/\Psi) = (10.94 \pm 0.02 \text{ (stat.)} \pm 0.79 \text{ (sys.)})\ \mu b$$

$$\sigma(J/\Psi \text{ from } B) = (1.28 \pm 0.01 \text{ (stat.)} \pm 0.11 \text{ (sys.)})\ \mu b$$

Fraction of J/Ψ from B

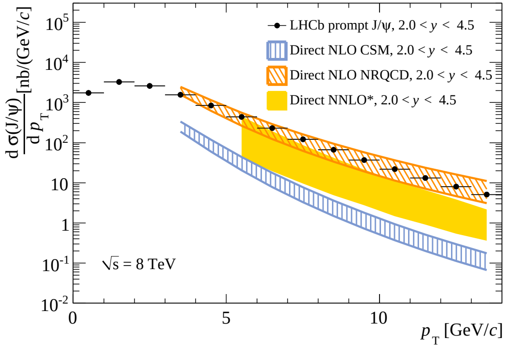
JHEP 06 (2013) 064



– In all rapidity ranges the fractions of J/Ψ from B increases with p_T.

Prompt J/Ψ

JHEP 06 (2013) 064. NLO CSM: Phys. Rev. Lett. 98 (2007) 252002. NNLO* CSM: Eur. Phy. J. C61 (2008) 693

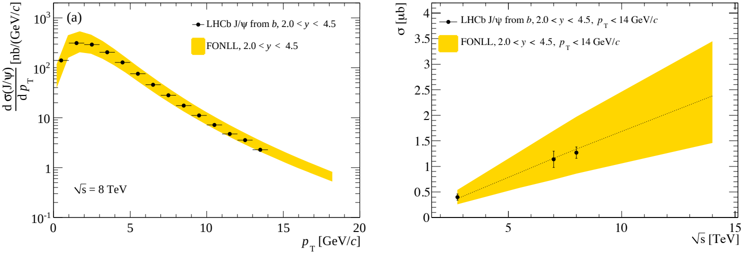


- NNLO* CSM and NLO NRQCD provide reasonable descriptions of the data.
- NLO CSM underestimates data by an order of magnitude.
- Note: Data include feedown of J/Ψ from higher charmonium states whereas predictions do not.
- Similar picture at $\sqrt{s} = 7$ TeV.

NLO NRQCD: Phys. Rev. D84 (2011) 051501; Phys. Rev. Lett. 106 (2011) 022003

J/Ψ from B

JHEP 06 (2013) 064; **JHEP 10 (2012) 137**; **JHEP 05 (1998) 007**



- FONLL formalism predicts b-quark productions with subsequent fragmentation to b-hadrons and their decays to J/Ψ.
- Good agreement with differential measurements in p_T (also in y).
- Previous measurements at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV. Measured evolution with $\sqrt{s}$ in agreement with FONLL.
- Confidence in predictions for Run-II energies.

Inclusive Υ at at $\sqrt{s} = 7/8$ TeV

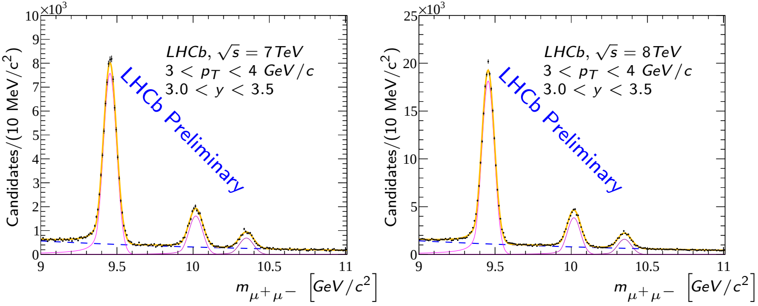
- Measure: Υ in $2 < \eta < 4.5$ and $p_T^{\Upsilon} < 30$ GeV/c.
- Luminosity: 1 fb^{-1} (7 TeV) and 2 fb^{-1} (8 TeV).
- Hardware trigger: Dimuon product of transverse momenta $> 1.7(2.6)$ $(\text{GeV/c})^2$ at $\sqrt{s} = 7(8)$ TeV.
- Software trigger: Muon $p_T > 500$ MeV/c, $p > 6$ GeV/c, $m_{\mu^+\mu^-} > 4.7$ GeV/c^2.

$$\mathcal{B}_{\Upsilon \to \mu^+\mu^-} \; x \; \frac{d^2\sigma}{dy \; dp_T}(pp \to \Upsilon \; X) = \frac{1}{\Delta y \; x \; \Delta p_T} \; \frac{N_{\Upsilon \to \mu^+\mu^-}}{\mathcal{L}}$$

- N is efficiency corrected number of $\Upsilon \to \mu^+\mu^-$ decays.
- Efficiencies determined with simulation and validated with data-driven techniques.

Inclusive Υ at at $\sqrt{s} = 7/8$ TeV

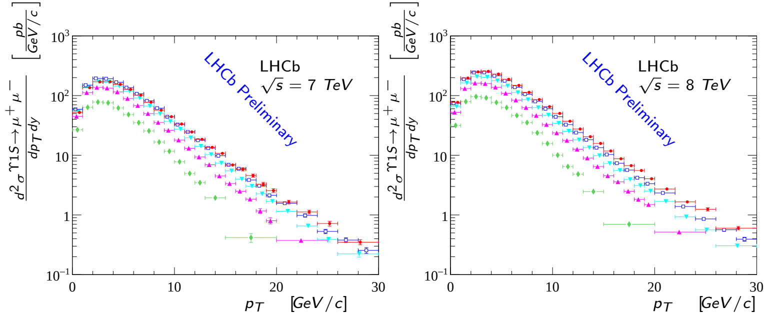
LHCb-PAPER-2015-045



- Fits performed in each (p_T, y) bin in range $8.5 < m_{\mu^+\mu^-} < 12.5$.
- Signal: 3 crystal ball functions.
- Background: Convolution of exponential and 2$^{\text{nd}}$ order polynomial.
- Mean value and width of $\Upsilon(1S)$ peak free. Position of other peaks fixed with known differences between masses. Widths fixed to $\Upsilon(1S)$ width, scaled by ratio of masses.
- Fit parameters consistent on 7 and 8 TeV data sets.

Inclusive Υ at at $\sqrt{s} = 7/8$ TeV

LHCb-PAPER-2015-045



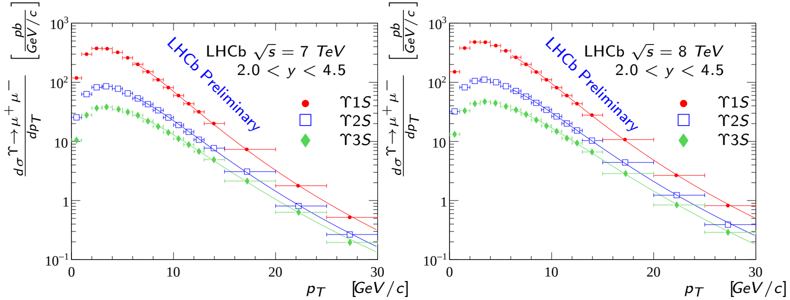
- Differential Υ cross-sections at $\sqrt{s} = 7$ TeV (left) and $\sqrt{s} = 8$ TeV (right) in different y ranges.
- Largest systematics due to luminosity ($< 2\%$), trigger efficiency (2%), fit model (0.1-4.8%).

$$\sigma(\Upsilon(1S) \text{ at } \sqrt{s} = 7 \text{ TeV}) = (2510 \pm 3 \text{ (stat.)} \pm 80 \text{ (sys.)})\ pb$$

$$\sigma(\Upsilon(1S) \text{ at } \sqrt{s} = 8 \text{ TeV}) = (3280 \pm 3 \text{ (stat.)} \pm 100 \text{ (sys.)})\ pb$$

Inclusive Υ at at $\sqrt{s} = 7/8$ TeV

LHCb-PAPER-2015-045; J. Statist. Phys. 52 (1988) 479

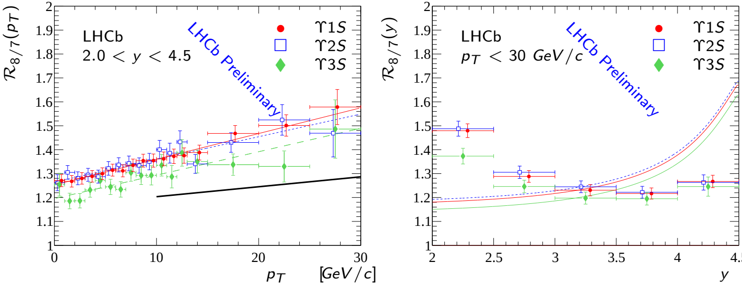


$$\frac{d\sigma}{p_T\, dp_T} \propto \left(1 + \frac{E_T^{kin}}{nT}\right)^{-n}$$

- Transverse momentum spectra fit with Tsallis function **J. Statist. Phys. 52 (1988) 479**.
- $E_T^{kin} \equiv \sqrt{m_\Upsilon^2 + p_T^2} - m_\Upsilon$. n and T are free parameters.
- Good agreement in the region of applicability at high p_T.

Inclusive Υ at at $\sqrt{s} = 7/8$ TeV

LHCb-PAPER-2015-045; arXiv:0811.4005; Mod. Phys. Lett. A29 (2014) 1450082



- Ratios between Υ(nS) cross-sections on different data set performed. Many correlated systematics cancel. Luminosity uncertainty 1.4%.
- (Left) Results as functions of p_T fit with linear function and compared to prediction of NRQCD (thick black line from **arXiv:0811.4005**).
- (Right) Results as functions of rapidity compared to NRQCD predictions (Refs. below). Predicted increase of ratio with y not supported by data.
- Ratios between Υ(nS) cross-sections on same data set performed. Many correlated systematics cancel.

Colour octet: Phys. Rev. D84 (2011) 114020 (erratum D86 (2012) 039902); Mod. Phys Lett. A28

Conclusions

- LHCb measurements of electroweak boson and quarkonia inclusive cross-sections have been presented.
- All W and Z measurements are in agreement with the SM.
- Quarkonium results provide important input to QCD models for bound states.
  - At large p_T prompt J/Ψ production seems in agreement with NRQCD.
  - Υ less well described especially in the y distribution.
- Full Run-I data set being exploited with comparisons between measurements at different centre-of-mass energies.

Acknowledgements

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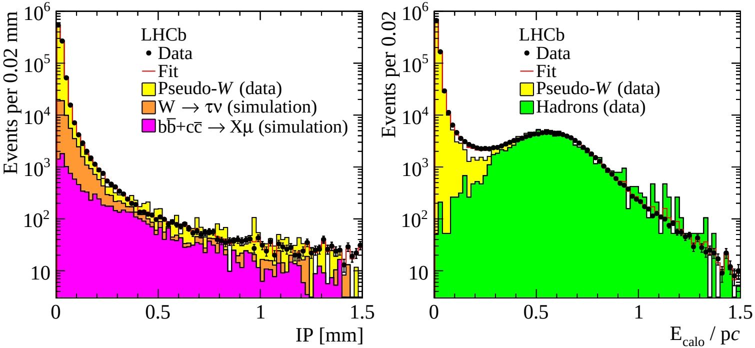
BACKUP

Other analyses of interest

Topic	$\sqrt{s}$ [TeV]	$\mathcal{L}$ [pb^{-1}]	Ref.
$Z + b$-*jet*	7	1000	JHEP 01 (2015) 064
Inclusive J/Ψ	7	5.2	Eur.Phys.J.C71 (2011) 1645
Inclusive Υ	2.76	3.3	Eur. Phys. J. C74 (2014) 2835
Inclusive χ_c	7	1000	JHEP10(2013)115
Inclusive χ_b	7/8	3000	Eur.Phys.J. C74 (2014) 3092
Inclusive χ_b	7/8	3000	JHEP 10(2014)088
Exclusive J/Ψ and $\Psi(2s)$	7	930	J. Phys. G 41 (2014) 055002
Exclusive J/Ψ and $\Psi(2s)$ pairs	7/8	3000	J. Phys. G 41 (2014) 115002
Exclusive Υ	7/8	2900	arXiv:1505.08139
pPb J/Ψ	5	0.0016	JHEP 02 (2014) 072
pPb Υ	5	0.0016	JHEP 07 (2014) 094
pPb Z	5	0.0016	JHEP 09 (2014) 030

Reducing *W* backgrounds

JHEP 12 (2014) 079



EW normalisation

$$N^{1\mu}_{Z\to\mu\mu} = N^{2\mu}_{Z\to\mu\mu} \cdot \mathcal{A}^{Z}_{m_{\mu\mu}} \cdot \mathcal{F}^{1\mu/2\mu}_{Z\to\mu\mu} \cdot \frac{\varepsilon^{W}_{RECO}}{\varepsilon^{Z}_{RECO}} \cdot \varepsilon^{W}_{SEL}$$

- $N^{2\mu}_{Z\to\mu\mu}$ from Pseudo-W.
- $\mathcal{A}^{Z}_{m_{\mu\mu}}$ mass window acceptance correction.
- $\mathcal{F}^{1\mu/2\mu}_{Z\to\mu\mu}$ fraction of events with one muon inside to two muons (~ 2).
- $\frac{\varepsilon^{W}_{RECO}}{\varepsilon^{Z}_{RECO}} = \frac{1}{(2-\varepsilon_{TRG})\cdot\varepsilon_{TRK}\cdot\varepsilon_{ID}}$

Z cross-section systematics

Source	Uncertainty (%)
Statistical	0.39
Trigger efficiency	0.07
Identification efficiency	0.23
Tracking efficiency	0.53
FSR	0.11
Purity	0.22
GEC efficiency	0.26
Systematic	0.68
Beam energy	1.25
Luminosity	1.72
Total	2.27

Cross-section ratios systematics

Source	Uncertainty (%)			
	R_{WZ}	R_{W^+Z}	R_{W^-Z}	R_W
Statistical	0.45	0.48	0.50	0.38
Trigger efficiency	0.15	0.16	0.13	0.07
Identification efficiency	0.12	0.12	0.12	0.03
Tracking efficiency	0.24	0.23	0.26	0.08
FSR	0.16	0.21	0.17	0.21
Purity	0.41	0.49	0.55	0.62
GEC efficiency	0.27	0.28	0.29	0.18
Systematic	0.60	0.67	0.72	0.69
Beam energy	0.26	0.19	0.34	0.15
Total	0.79	0.85	0.94	0.80