

# Charmonium studies at LHC energies using the ALICE Muon Spectrometer

by

Biswarup Paul

PHYS05201004010

Saha Institute of Nuclear Physics  
Kolkata, India

*A thesis submitted to the  
Board of Studies in Physical Science Discipline  
In partial fulfillment of requirements  
For the Degree of  
DOCTOR OF PHILOSOPHY  
of  
HOMI BHABHA NATIONAL INSTITUTE*



May, 2015

# Contents

Synopsis	xxi
List of Figures	xxxii
List of Tables	xliii
<b>1 Physics Motivation</b>	<b>1</b>
1.1 The Standard Model of Particle Physics . . . . .	1
1.2 QCD and Asymptotic Freedom . . . . .	3
1.3 QCD Phase Diagram . . . . .	5
1.4 Time evolution of QGP matter in Heavy-Ion Collisions . . . . .	8
1.5 The quarkonium and QGP . . . . .	10
1.6 Cold Nuclear Matter (CNM) Effects . . . . .	13
1.6.1 Initial-state effects . . . . .	13
1.6.2 Final-state effects . . . . .	18
1.7 Hot Matter Effects or QGP-Induced Effects . . . . .	20
1.7.1 Color screening . . . . .	20
1.7.2 Regeneration . . . . .	22
1.8 Kinematic variables . . . . .	23
<b>2 ALICE at the LHC</b>	<b>33</b>
2.1 The Large Hadron Collider (LHC) at CERN . . . . .	33
2.2 A Large Ion Collider Experiment (ALICE) . . . . .	36
2.3 Central Barrel Detectors . . . . .	38
2.3.1 Silicon Pixel Detector (SPD) of ITS . . . . .	40
2.4 Forward Detectors . . . . .	41
2.4.1 V0 Detector . . . . .	42
2.4.2 Zero Degree Calorimeter (ZDC) . . . . .	43
2.5 The Forward Muon Spectrometer . . . . .	45
2.5.1 Front Absorber . . . . .	46
2.5.2 Dipole Magnet . . . . .	48
2.5.3 Tracking Stations . . . . .	49
2.5.4 Muon Filter . . . . .	51
2.5.5 Trigger Stations . . . . .	52
2.5.6 Beam Shield . . . . .	54

2.6	Detector Readout . . . . .	54
2.7	Online Control System . . . . .	56
2.7.1	Detector Control System (DCS) . . . . .	56
2.7.2	Central Trigger Processor (CTP) . . . . .	57
2.7.3	Data Acquisition System (DAQ) . . . . .	57
2.7.4	High Level Trigger (HLT) . . . . .	58
2.7.5	Data Quality Monitoring (DQM) . . . . .	58
2.7.6	Detector Algorithms (DA) . . . . .	59
2.8	Offline Framework . . . . .	59
2.8.1	AliRoot . . . . .	60
2.8.2	The GRID . . . . .	62
2.9	Future ALICE Upgrade Program . . . . .	62
<b>3</b>	<b>Experiment and data analysis</b>	<b>71</b>
3.1	Data types . . . . .	71
3.2	Alignment . . . . .	71
3.3	Track reconstruction . . . . .	73
3.3.1	Method of the tracking efficiency calculation . . . . .	75
3.4	Data Processing . . . . .	79
3.4.1	Pass1 . . . . .	79
3.4.2	Pass2 . . . . .	80
3.4.3	Pass2 with refit . . . . .	80
3.5	Trigger definition . . . . .	81
3.5.1	Minimum Bias (MB) trigger . . . . .	81
3.5.2	$p_T$ trigger threshold . . . . .	81
3.5.3	Dimuon trigger . . . . .	81
3.6	pp collisions at $\sqrt{s} = 7$ TeV . . . . .	82
3.6.1	Data sample . . . . .	82
3.6.2	Event and trigger selection . . . . .	82
3.7	p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV . . . . .	83
3.7.1	Data samples . . . . .	83
3.7.2	Data selection . . . . .	84
3.7.3	Event and trigger selection . . . . .	84
3.7.4	Integrated luminosity . . . . .	85
3.8	Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV . . . . .	87
3.8.1	Data sample . . . . .	87
3.8.2	Event and trigger selection . . . . .	87
3.9	Track selections . . . . .	89
<b>4</b>	<b>J/<math>\psi</math> and <math>\psi(2S)</math> production in pp collisions</b>	<b>93</b>
4.1	Data Processing . . . . .	93
4.2	Signal extraction . . . . .	94
4.2.1	Fit procedure . . . . .	94
4.2.2	Fit results . . . . .	97
4.2.3	Systematic uncertainties in signal extraction . . . . .	100

4.3	Acceptance and efficiency corrections . . . . .	108
4.3.1	$A \times \epsilon$ as a function of $p_T$ . . . . .	108
4.3.2	$A \times \epsilon$ as a function of $y$ . . . . .	109
4.3.3	Systematics on the MC input . . . . .	110
4.4	Tracking and Trigger efficiency . . . . .	111
4.4.1	Tracking efficiency and systematics . . . . .	111
4.4.2	Trigger efficiency and systematics . . . . .	113
4.5	Matching efficiency . . . . .	116
4.6	Summary of systematic uncertainties . . . . .	116
4.7	Results . . . . .	116
4.7.1	$J/\psi$ resonance . . . . .	117
4.7.2	$\psi(2S)$ resonance . . . . .	120
4.7.3	$\psi(2S)$ to $J/\psi$ cross-section ratio . . . . .	123
4.8	Model Comparison . . . . .	126
4.8.1	Differential production cross-section as a function of $p_T$ . . . . .	126
4.8.2	Differential production cross-section as a function of rapidity .	130
4.8.3	Theoretical work . . . . .	131
<b>5</b>	<b><math>\psi(2S)</math> production in p-Pb collisions</b>	<b>135</b>
5.1	Data Processing . . . . .	135
5.2	Signal extraction . . . . .	136
5.2.1	Fitting technique . . . . .	136
5.2.2	“Electron-like” technique . . . . .	138
5.2.3	Systematic uncertainties in signal extraction . . . . .	139
5.3	Acceptance and efficiency corrections . . . . .	141
5.3.1	Systematics on the MC input . . . . .	142
5.4	Tracking and Trigger efficiency . . . . .	142
5.4.1	Tracking efficiency and systematics . . . . .	143
5.4.2	Trigger efficiency and systematics . . . . .	143
5.5	Matching efficiency . . . . .	145
5.6	Normalization CINT7 - CMUL7 . . . . .	146
5.7	Others . . . . .	146
5.8	Summary of systematic uncertainties . . . . .	146
5.9	Results . . . . .	147
5.9.1	$\psi(2S)$ cross-section . . . . .	147
5.9.2	$\psi(2S)$ to $J/\psi$ cross-section ratio . . . . .	149
5.9.3	The double ratio $[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pPb}/[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pp}$ . . . . .	151
5.9.4	Nuclear Modification Factor of $\psi(2S)$ . . . . .	154
5.10	Summary . . . . .	159
<b>6</b>	<b>Fractional double differential cross-section of <math>J/\psi</math> in pp and Pb-Pb collisions</b>	<b>165</b>
6.1	Motivation . . . . .	166
6.2	Signal extraction . . . . .	168
6.2.1	Fit results . . . . .	169

6.2.2	Systematic uncertainty . . . . .	171
6.3	Acceptance and efficiency corrections . . . . .	175
6.4	Tracking and Trigger efficiency . . . . .	177
6.5	Other systematic uncertainties . . . . .	177
6.6	Results . . . . .	177
6.6.1	The rapidity dependence of FDDC . . . . .	178
6.6.2	Comparison with the published results . . . . .	178
6.6.3	Discussion . . . . .	179
<b>7</b>	<b>Quarkonia production cross-section calculation within the framework of NRQCD</b>	<b>183</b>
7.1	Introduction . . . . .	183
7.2	Theoretical formalism . . . . .	187
7.3	Results of charmonium calculations . . . . .	192
7.4	Results of bottomonium calculations . . . . .	199
7.5	Summary and outlook . . . . .	204
<b>8</b>	<b>Summary and Outlook</b>	<b>209</b>
8.1	$J/\psi$ and $\psi(2S)$ production in pp collisions . . . . .	209
8.2	$\psi(2S)$ production in p-Pb collisions . . . . .	210
8.3	Fractional double differential cross-section of $J/\psi$ in pp and Pb-Pb collisions . . . . .	211
8.4	Quarkonium production cross-section calculation within the framework of NRQCD . . . . .	212
8.5	Outlook . . . . .	213
<b>A</b>	<b>Effect of Front Absorber on Mass resolution</b>	<b>219</b>
A.1	Motivation . . . . .	219
A.2	Mass spectrum and $p_T$ distribution of the dimuon decaying from $J/\psi$ and $\Upsilon$ . . . . .	219
A.3	$p_T$ and $\eta$ resolution of Muon Spectrometer . . . . .	221
A.4	Can $\Upsilon$ mass resolution be better ? . . . . .	222
A.5	Further studies . . . . .	227
<b>B</b>	<b>Fitting functions</b>	<b>233</b>
B.1	Crystal Ball function . . . . .	233
B.2	Extended Crystal Ball function or Double Crystal Ball function . . . . .	234
B.3	NA60 function . . . . .	235
B.4	Variable Width Gaussian . . . . .	235
B.5	Exponential times 4th order polynomial function . . . . .	236