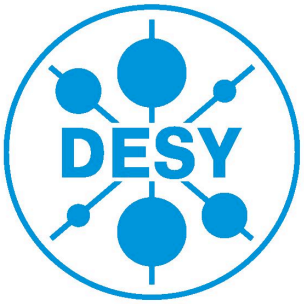

High-Mass Double Quarkonia Production

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Contents

1 Introduction/Motivation

Lots of quarkonia were produced in LHC. Because quarkonia has high signal-to-background ratio, it is not hard to investigate its properties (Figure 1).

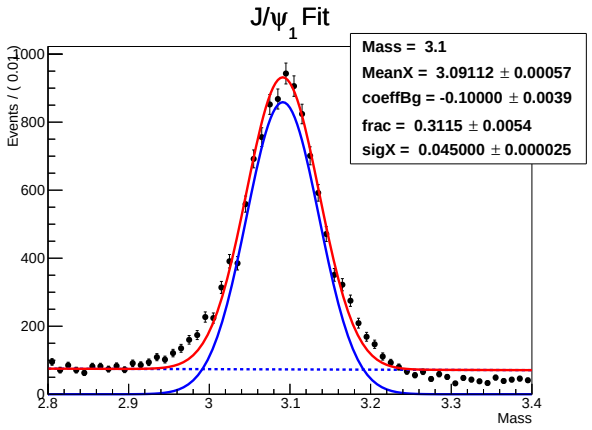

Figure 1: J/ψ Resonance at LHC measured by the ATLAS detector.

Standard Model predicts different models of multiple quarkonia production. For double J/ψ we have "Single Parton Scattering" and "Double Parton Scattering" as illustrated in Figure 2, as well as Non-Prompt production described in section 1.1.

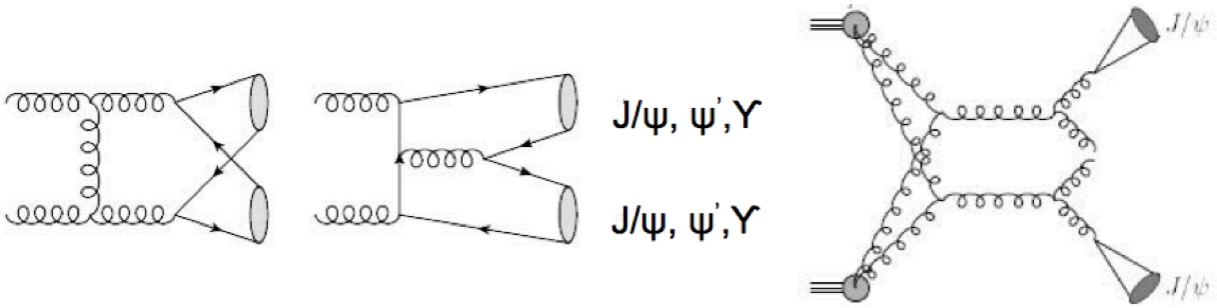

Figure 2: Single and Double Parton Scattering Production Modes for double J/ψ.

1.1 Non-Prompt Production

Non-Prompt double quarkonia production comes from B-hadrons. For instance, double J/ψ's are decay products of 2 B mesons and can be used as a proxy for 2b jet events. For this kind of events, there is a discrepancy between different MC generators where angular distributions can be studied from data using double J/ψ.

Non-Prompt Double J/ψ production is also important for analyses with $b\bar{b}$ final states (i.e. Higgs$\rightarrow b\bar{b}$, VH, ttH).

2 Data Set and Selection

For our analysis, ATLAS 2012 DataSet was used. In this dataset, we primarily focused on two streams: Muon Stream Period A-L and BPhysics Delayed Stream Period B-L.

2.1 Muon Pre-Selection

In muon stream, we required at least two muons as well as $P_t \geq 0.5$ GeV for these muons. In addition, we require a muon to not be a cosmic muon.

2.2 Electron Pre-Selection

We required electrons in the muon stream with $P_t \geq 1$GeV.

2.3 Onia Selection (J/ψ)

We have a general code for finding lepton resonances. What the code does is :

1. Makes opposite charged μ pairs. μ's are ordered by highest to lowest pT.
2. Pair combinations are selected according to their χ^2's and stored into a new ntuple.

The code also works for other resonances like ρ,ω,ϕ,ψ(2S),Υ(1S,2S,3S).

3 Double Quarkonia (All-Muon Channel) Events

3.1 2D Plots

J/ψ candidates are selected in the mass window 2.8 - 3.4 GeV. For the case of Υ candidates, they are selected in the mass window 7.5 - 11.5 GeV. Finaly, ψ(2S) candidates are selected in the mass window 3.4 - 4 GeV. In general, this is called "loose selection".

For the case of J/ψ, tight selection of 3.0 - 3.2 GeV was introduced. For Υ, it is 9.0 - 10.0 GeV; for ψ(2S), it is 3.6 - 3.8 GeV.

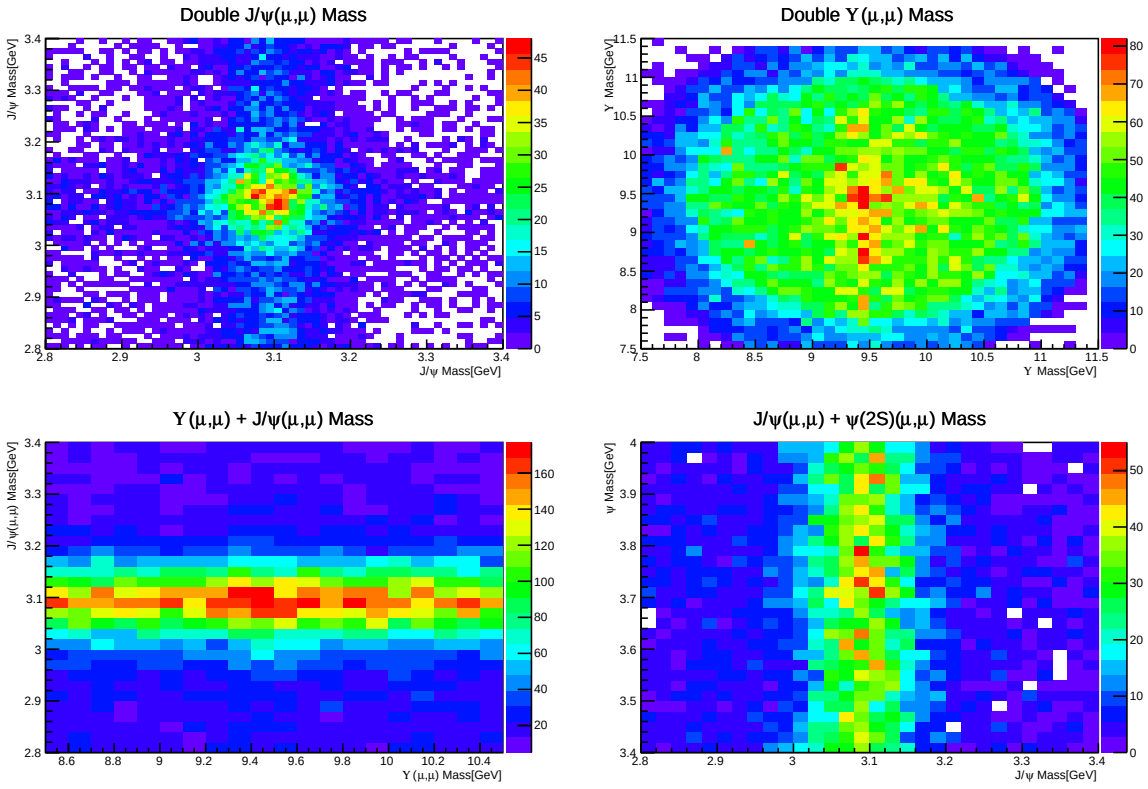

Figure 3: 2D plots of Double Quarkonia Events

3.2 Double Quarkonia Invariant Mass

After introducing tight selection, invariant mass plots of double quarkonia are shown in Figure 4.

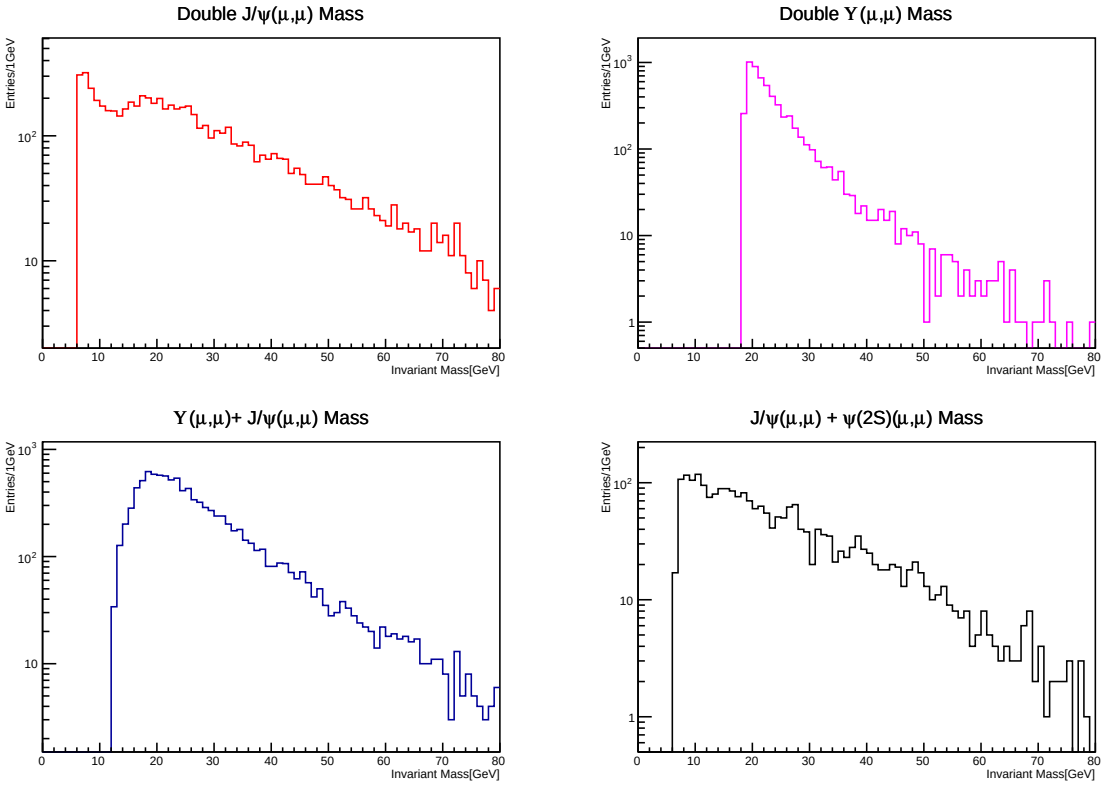

Figure 4: Invariant mass plots of Double Quarkonia

4 Triple Quarkonia (All-Muon Channel) Events

We also observed triple quarkonia events.

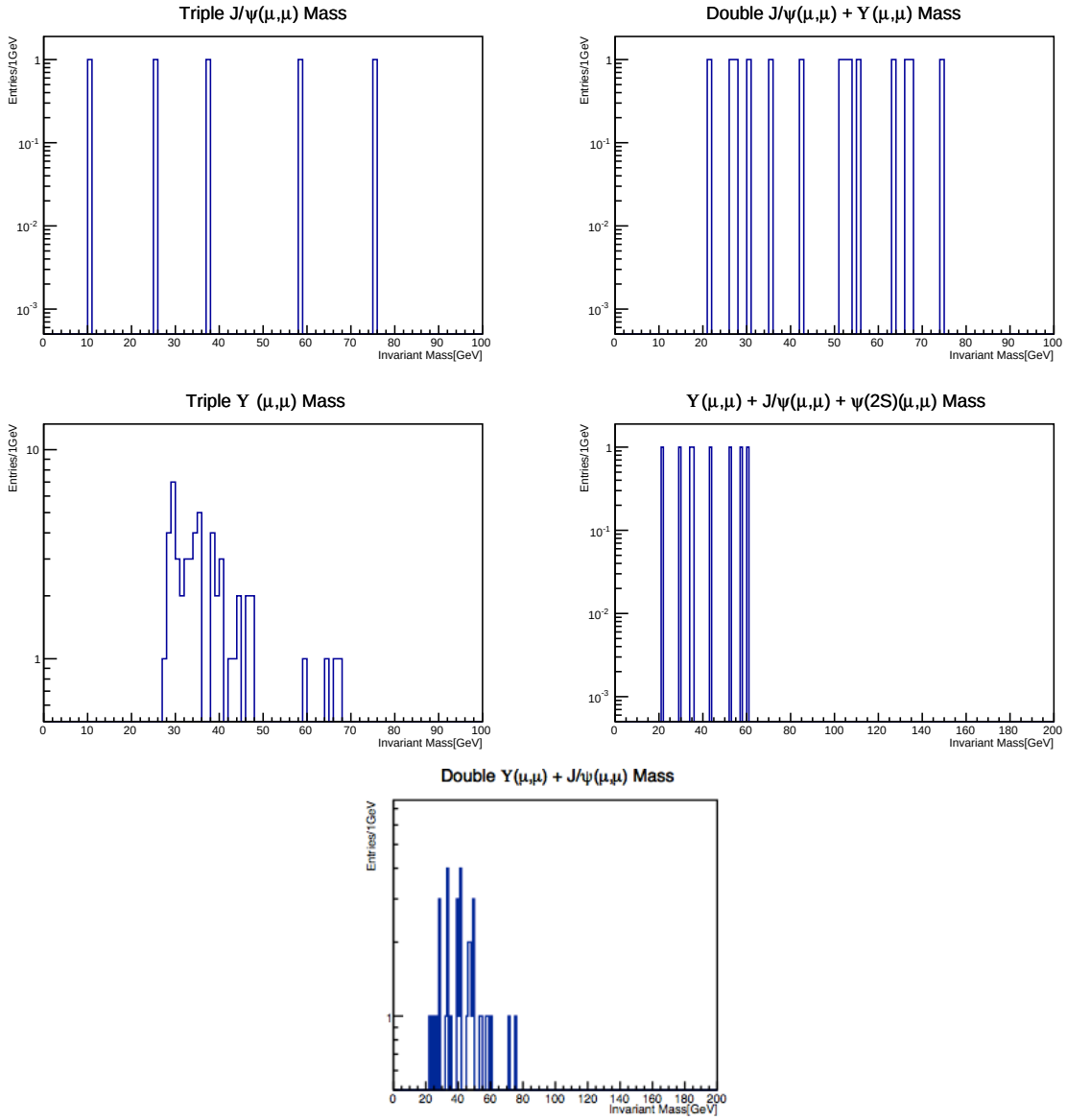

Figure 5: Invariant mass distributions of Triple Quarkonia Events

5 Double J/ψ Production (All Muon-Channel)

The Delayed B-Physics stream is used for Double J/ψ Production analysis. To obtain reliable results, we put cuts on both muon number and muon transverse momentum: # of muons ≥ 2 and $P_t > 1.5$GeV. In addition, we also required that at least one muon should be a combined muon. We also required that at least one oppositely charged pair should be in mass range 2.6 GeV - 4.2 GeV. For the Double J/ψ selection, we required $n_\mu \geq 4$ and 2 J/ψ per event.

After selection, individual J/ψ resonances in double J/ψ events are shown in Figure 6.

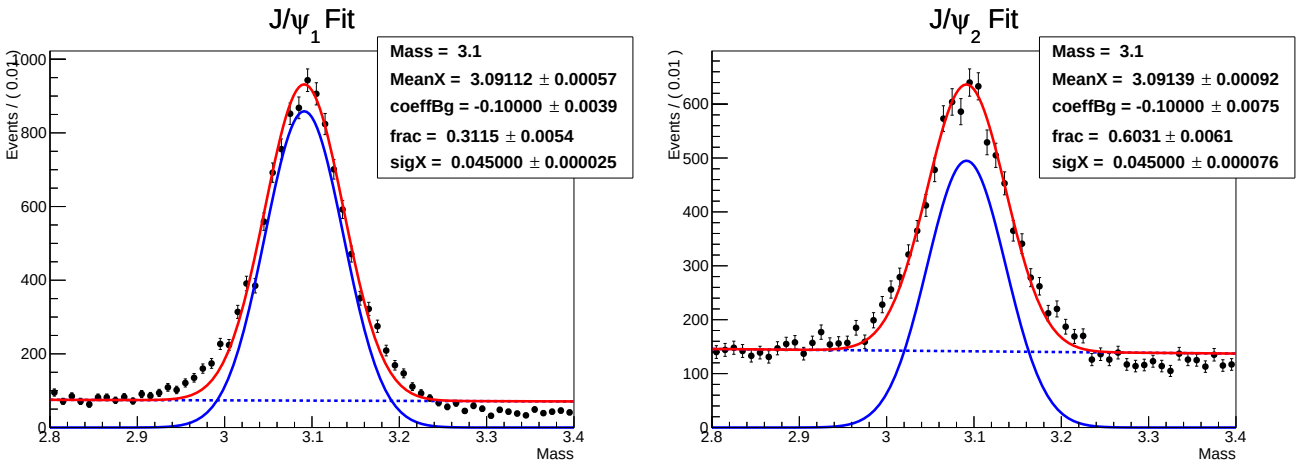

Figure 6: Double J/ψ Resonances

J/ψ_1 is on the left, J/ψ_2 is on the right. Blue line is simple gaussian (signal) and blue dashed line is background. Signal + background is seen as red line.

5.1 LHCb Results in 2011

In 2011, LHCb collaboration published a conference note about Double J/ψ Production[1]. Since LHCb detector is a forward detector[1], it is limited by detector geometry

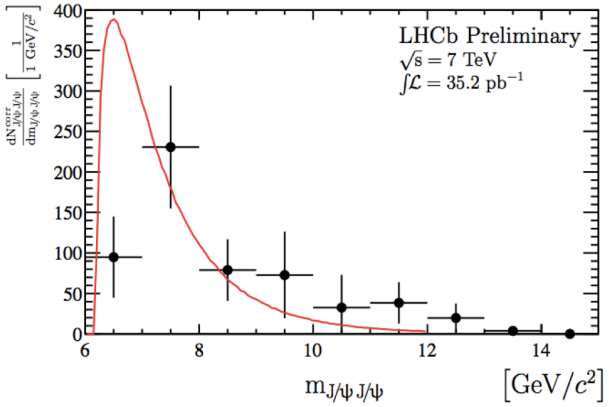

Figure 7: LHCb Result for Double J/ψ Production

to low-mass region. However, we can study high-mass double J/ψ.

5.2 Double J/ψ Invariant Mass

Invariant Mass of Double J/ψ and MC comparison for different production modes are shown in Figure 8.

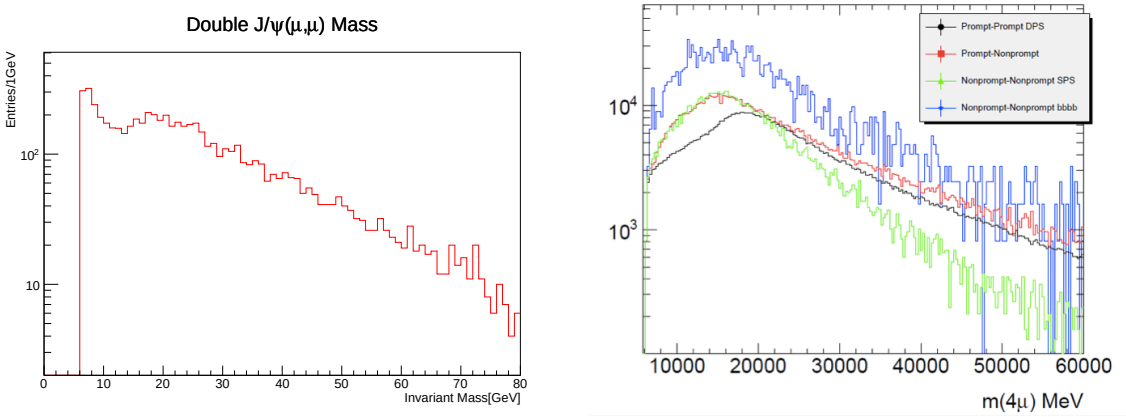

Figure 8: Double J/$\psi \to \mu\mu$ and MC Comparison of Double J/$\psi(\mu,\mu)$ Mass For Different Production Modes

[1]https://lhcb-public.web.cern.ch/lhcb-public/en/Detector/Detector-en.html

5.3 Distribution of $\Delta\eta$ and $\Delta\phi$ of Double J/ψ Events

As stated in the motivation, the angular difference between two J/ψs is crucial for investigating MC discrepancy in 2-b jet events.
Applying an additional cut on lifetime $c_\tau > 1.5$ for both J/ψs allows us to select double non-prompt events. The angular difference between two J/ψs in η and ϕ is shown in Figure 9 for loose and tight selections.

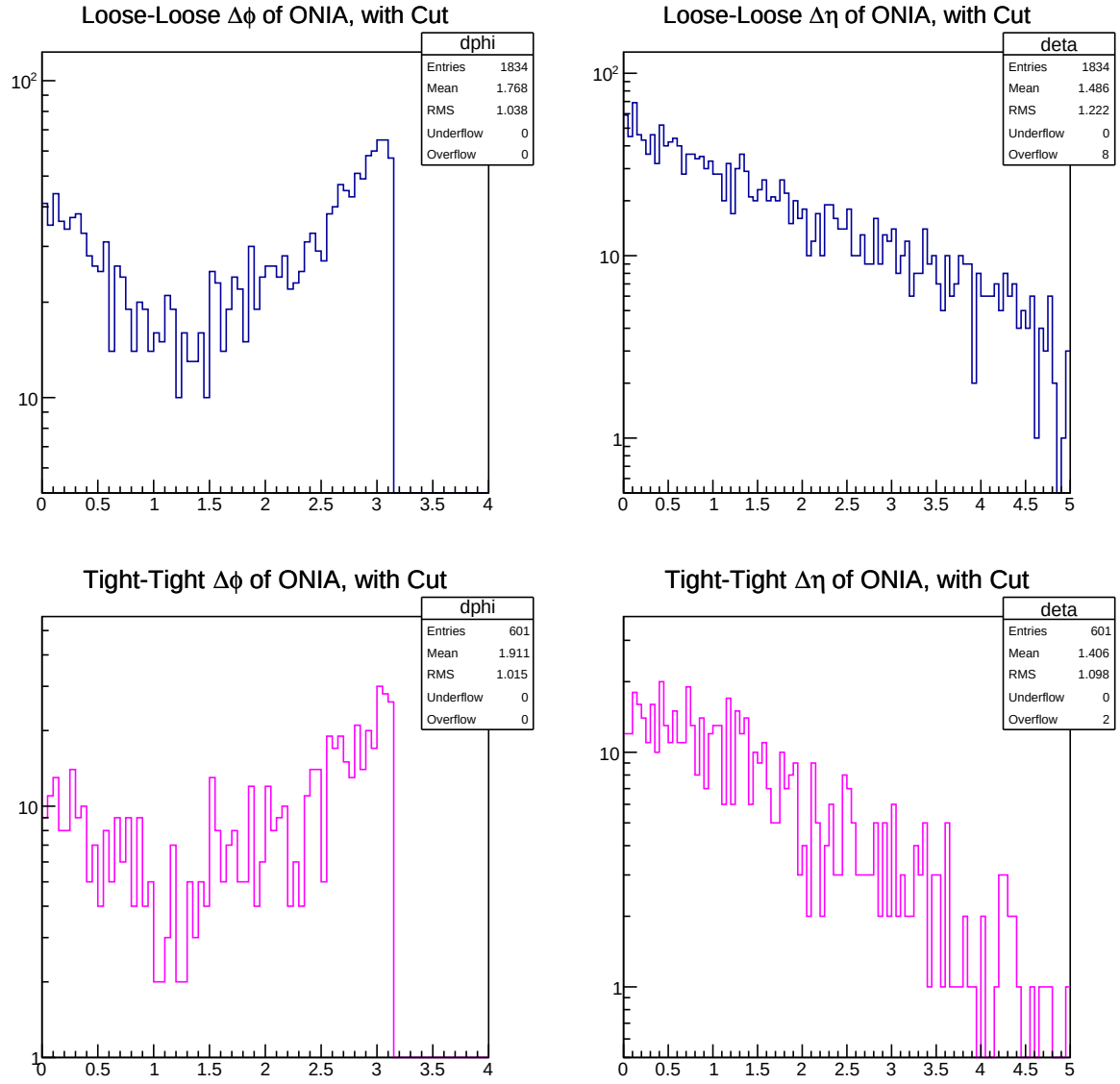

Figure 9: η and ϕ difference between two J/ψ's.

Comparing this with the angular distributions obtained from Monte-Carlo simulations show in Figure 10, we see that indeed we have selected non-prompt J/ψ coming from

the B decays.

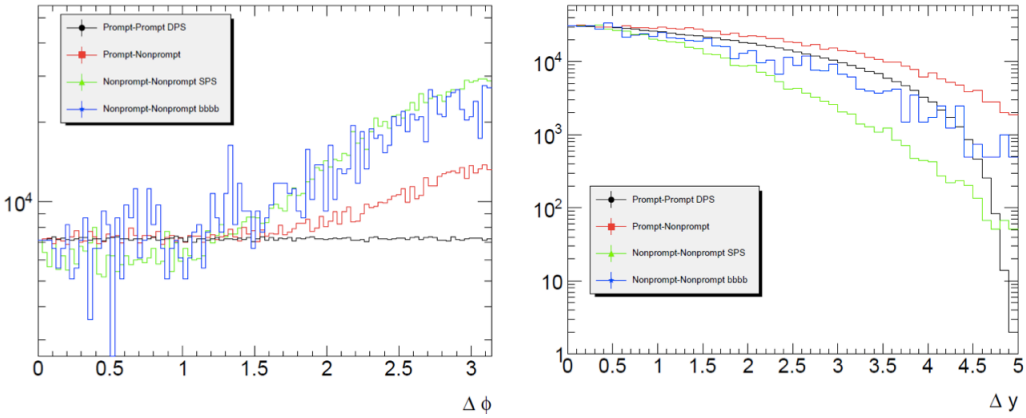

Figure 10: MC comparison for η and ϕ difference between two J/ψ's.

6 Conclusion

Double and Triple Quarkonia are observed on multiple channels (all-muon, mixed muon-electron channel [See Appendix for mixed muon-electron channel]).

Table 1: What is observed?

Double Quarkonia	Triple Quarkonia	High Mass Double Quarkonia
J/ψ - J/ψ	J/ψ + J/ψ + J/ψ	J/ψ - J/ψ
ψ(2S) - ψ(2S)	J/ψ + J/ψ + Υ	Υ - Υ
Υ - ψ(2S)	Υ + Υ + Υ	
J/ψ - ψ(2S)	Υ + J/ψ + ψ(2S)	
J/ψ - Υ	Υ + Υ + J/ψ	
Υ - Υ		

Ongoing double J/ψ studies are interesting for H$\rightarrow b\bar{b}$ (VH, ttH) analyses and can additionally help solve the MC Generator Discrepancy for double b-jet events. As demonstrated in Section 5.3, $\Delta\eta$ and $\Delta\phi$ of b-jets can be studied using double J/ψs.

References

[1] Conference Note: Observation of double J/ψ production in proton-proton collisions at a centre-of-mass energy of $\sqrt{s}$ =7 TeV *LHCb Collaboration*

[2] 2 J/ψ - An analysis of data to extract relative fractions of prompt and non-prompt pair combinations using four dimensional fitting in tau1 tau2 mass1 and mass2 for the J/Psi pair. *Rob Henderson: 07/08/2013*

7 Appendix

7.1 Extra Information about Quarkonia in Mixed Electron-Muon Channel

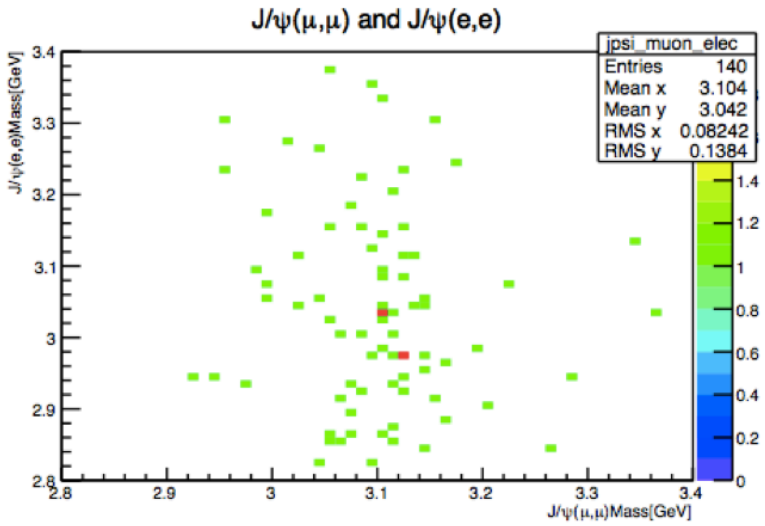

Figure 11: Double J/ψ from Mixed Muon-Electron Channel

It is also possible to detect double quarkonia events in mixed channels. For instance, electrons in muon stream can give one J/ψ in double J/ψ events. However, contribution is much small compared to the all-muon channel due to much lower electron reconstruction efficiency of electrons.