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PROPERTIES OF HEAVY FLAVOR HADRONS IN ATLAS

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Abstract

The LHC will offer an opportunity for study of QCD at unprecedented energy scales. ATLAS, which will cover central proton-proton collisions, plans to study heavy flavor hadrons including quarkonium states. The expected statistics will permit high precision measurements of production polarization of the Λ_b and J/ψ. We also present new studies of production mechanisms, lifetime, and branching ratios for decays in the B_c and Υ systems and a program of studies of χ_b decays to resonant and non-resonant states.

1 Introduction

The Large Hadron Collider (LHC), which will provide 7 TeV-on-7 TeV proton-proton collisions, will offer unprecedented energy scales for QCD studies. ATLAS, one of the four LHC detectors, will cover collisions to pseudorapidity

$|\eta| \leq 2.4$ for high precision measurements. The LHC has a 27 km circumference and 40 kHz crossing rate. The total $b\bar{b}$ production cross section there will be 500μb: one $b\bar{b}$ pair in every 100 collisions. The goal is to take 10 fb^{-1} per year (at luminosity 10^{33}cm^{-2}sec^{-1}) in Years 1–3 and 100 fb^{-1} per year subsequently.

The features of the ATLAS detector have been described elsewhere. [1] ATLAS is well instrumented for B Physics, having been designed with precision vertexing and tracking, good muon identification, high resolution calorimetry, and a flexible dedicated B trigger. A rich B Physics program is planned, including CP violation studies (especially for the Λ_b and B_s systems, which are not accessible to the B factories), rare decays sensitive to new physics (including $b \to sl^+l^-$ and $b \to dl^+l^-$), and baryons and heavy flavor mesons which are the subject of this paper.

The ATLAS Collaboration's planned high statistics studies of heavy flavor hadrons, including quarkonia, will throw light on the properties of bound states, the spin dependence of quark confinement, the nature of the strong potential, factorization in Heavy Quark Effective Theory, the source of CP Violation, and perhaps the resolution of some puzzles in existing data on hyperon polarization and cross sections.

ATLAS triggers have been described elsewhere. [2] Muons will provide a reliable flavor tag. The studies described in this paper will make use of three threshold-dependent Level 1 triggers. Those trigger types are referred to as the "Dimuon" (which requires muon transverse momentum $p_T > 6$ GeV/c in the barrel or > 3 GeV/c in the endcaps), the "Muon + EM" (which requires one muon with $p_T > 6$ GeV/c in the barrel and an electromagnetic cluster with transverse energy $E_T > 5$ GeV, and the "Muon + Jet" (which requires one muon with $p_T > 6$ GeV/c in the barrel and an electromagnetic cluster with $E_T > 10$ GeV. Level 1, which uses only the calorimeter and muon trigger chambers, identifies Regions of Interest and outputs at 75 kHz. Level 2 uses the Regions of Interest and dedicated online algorithms, reconfirms the muon and calorimeter information, refits tracks in the Inner Detector, and outputs at 1 kHz. The final stage is the Event Filter, which uses full event buffers and processor subfarms and applies offline algorithms with alignment and calibration. The Event Filter reconstructs decay vertices and selects exclusive final states via mass and decay length requirements. It outputs at 200 Hz.

2 Λ_b Production, Lifetime, and Polarization

Existing data [3] on the polarization of Λ particles produced inclusively in proton-proton and proton-Beryllium collisions shows the unexpected feature that the polarization rises with p_T to large negative values and, beginning at a p_T around 1 GeV/c, reaches a plateau whose amplitude depends upon x and which does not diminish even at the highest p_T values recorded. The shape is unexpected; small polarization is expected for Λ's produced inclusively. Most models predict negligible polarization at high p_T and high energy. These data raise questions about the production mechanisms for different flavors and the relationship between polarization and quark mass. A measurement of the Λ_b polarization may cast light upon this issue.

There is, additionally, a longstanding puzzle in the B-baryon lifetime data. The ratio of lifetimes of the Λ_b and B^0 are not consistent with theoretical predictions made by models which nonetheless succeed in predicting the ratio of lifetimes of B^0 and $B^{\pm}$. Probing this puzzle in a new energy regime, with improved precision and models, may clarify the issue. Thirdly, a measurement of the Λ_b polarization will probe CP violation in a new way, since if CP is not conserved, the asymmetry parameters of the b and $\bar{b}$ quarks should differ. This study takes as its goals the world's first measurement of the asymmetry parameter α_b and polarization P_b for Λ_b, to precision 2%, and a measurement of the Λ_b lifetime, to 0.3%.

The selection process uses the channel $\Lambda_b \to \Lambda \mathrm{J}/\psi$, where $\Lambda \to \pi^- p$ and $\mathrm{J}/\psi \to \mu^+\mu^-$. The number of Λ_b events anticipated in 30 fb^{-1} is predicted to be 18000 by combining the acceptance for Λ_b detection, estimated with the generator PYTHIA [4] at 0.157%; the production cross section for Λ_b, 0.00828113 mb; the branching ratio for $\Lambda_b \to \mathrm{J}/\psi$, 4.7×10^{-4}; the branching ratio for $\Lambda \to \pi^- p$, 0.64, the branching ratio for $\mathrm{J}/\psi \to \mu^+\mu^-$, 0.06, and the combined efficiency for trigger and selection cuts, 0.004. An equal number of $\overline{\Lambda}_b$ is expected as well. The selection strategy begins with the requirement of two muons with p_T values greater than 4 GeV/c and 2.5 GeV/c, respectively; combination of a pion and a proton with p_T values greater than 0.5 GeV/c each; and a restriction of $|\eta| < 2.7$ for all tracks. The expected number of background $pp \to \mathrm{J}/\psi \Lambda X$ events is 3.2×10^6.

The polarization measurement, which has been described elsewhere [5], assumes a general decay amplitude of the form

$$M = \overline{\Lambda}_b(p_{\Lambda_b})\epsilon^*_\mu(p_{J/\psi})\left[A_1\gamma^\mu\gamma^5 + A_2\frac{p^\mu_{\Lambda_b}}{m_{\Lambda_b}}\gamma^5 + B_1\gamma^\mu + B_2\frac{p^\mu_{\Lambda_b}}{m_{\Lambda_b}}\right]\Lambda_b(p_{\Lambda_b}), \quad (1)$$

where A_1, A_2, B_1, and B_2 depend on the choice of perturbative QCD model. If one defines

$$a_+ = |a_+|e^{i\alpha_+} \equiv M_{+1/2,0} \quad (2)$$

$$a_- = |a_-|e^{i\alpha_-} \equiv M_{-1/2,0} \quad (3)$$

$$b_+ = |b_+|e^{i\beta_+} \equiv M_{-1/2,-1} \quad (4)$$

$$b_- = |b_-|e^{i\beta_-} \equiv M_{+1/2,+1} \quad (5)$$

where M_{λ_1,λ_2} is the amplitude for decay into Λ with helicity λ_1 and J/ψ with helicity λ_2, then for normalized amplitudes,

$$\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2. \quad (6)$$

The angular distribution for $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda(p\pi^-)$ is

$$w(\vec{A},\vec{\alpha},\vec{\theta}) = \sum_{k=0}^{19} f_{1k}(\vec{A})f_{2k}(\vec{\alpha})F_k(\vec{\theta}) \quad (7)$$

where parameters f_{1i}, f_{2i}, and F_i are defined in [5]. The angular distribution depends on nine unknown parameters: P_b and the four amplitudes and four phases of the a_+, a_-, b_+, and b_-. After normalization of the amplitudes and application of the global phase constraint, the number of independent unknowns is seven. These are extracted from the measured decay angles by a fit of the likelihood function,

$$L = -2\sum_{j=1}^{N} log(w_{obs}(\vec{\theta}',\vec{A},P_b)) \quad (8)$$

where N = number of events,

$$w_{obs}(\vec{\theta}',\vec{A},P_b) = \frac{\int w(\vec{\theta},\vec{A},P_b)T(\vec{\theta},\vec{\theta}')d\vec{\theta}}{\int\int w(\vec{\theta},\vec{A},P_b)T(\vec{\theta},\vec{\theta}')d\vec{\theta}d\vec{\theta}'} \quad (9)$$

and

$$T(\vec{\theta},\vec{\theta}') = \epsilon(\vec{\theta})R(\vec{\theta},\vec{\theta}') \quad (10)$$

for acceptance $\epsilon =$ and resolution $R =$. The resolutions on the angles measured is anticipated to be about 10 mrad. Detector acceptance corrections come from a Monte Carlo data sample with $P = 0$.

3 Quarkonium Production and Decay

One of the goals of this and the following section is a comparison of ATLAS data to predictions by the quarkonium production models, especially the Color Singlet Model [6] (which assumes that each quarkonium state can be produced only by a $q\overline{q}$ pair in the same color and angular momentum J state as the quarkonium) and non-relativistic (NR) QCD with the Color Octet Mechanism [7] (which treats quarkonium as a non-relativistic system so that $q\overline{q}$ pairs produced with one set of quantum numbers can evolve into a quarkonium state with different quantum numbers by emitting low energy gluons). NR QCD with the Color Octet Mechanism agrees with CDF data [8] on the J/ψ p_T cross section with free normalization up to accessible (Tevatron) energies; however, data at higher p_T, and for quarkonia farther from the QCD scale, are needed. The goal of this ATLAS study is measurements of the distributions in p_T, η, and polarization for the J/ψ, measurements of the ratio of Υ and J/ψ production cross sections, and an assessment of hadronic activity associated with quarkonium production.

The LHC will produce heavy quarkonia with high p_T at a high rate. In 10^6 seconds at luminosity $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, for muon pairs selected with the requirement that one have $p_T > 6$ GeV/c and the other, $p_T > 4$ GeV/c, 175000 $J/\psi \to \mu\mu$ and 36000 $\Upsilon \to \mu\mu$ events may be available.

Several strategies are being applied to maximize the ratio of signal to background. One is an examination of the option to lower the dimuon trigger threshold from 6 GeV/c + 4 GeV/c to 4 GeV/c + 4 GeV/c. This captures a subtantially larger fraction of the signal, especially for the Υ. It also is expected to increase the contribution of color singlet production, which dominates for $p_T < 10$ GeV/c. A second strategy is the application of a cut on pseudo-proper time to separate direct from indirect J/ψ's. As expected, the resolution worsens with increasing p_T and η. The third strategy involves measuring the quarkonium spin. For the angle θ between the positive muon in the quarkonium reference frame and the quarkonium direction in the lab frame,

$$\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha\cos^2\theta, \tag{11}$$

where

$$\alpha \equiv \frac{\sigma_T + 2\sigma_L}{\sigma_T - 2\sigma_L}. \tag{12}$$

The parameter α takes the values 0, +1, and -1 for unpolarized, transversely polarized, and longitudinally polarized mesons, respectively. Octet production predicts transverse polarization at large p_T.

From a study of the reconstructed and "truth" $\cos\theta$ distributions of simulated J/ψ events in the ranges $9 < p_T < 12$ GeV/c and $p_T > 21$ GeV/c, ATLAS observes that the acceptance in $\cos\theta$ is limited by the p_T of the second muon and concludes that a single muon trigger would be useful to this analysis if the rate could be reduced by some other means. Present NR QCD formalisms model Tevatron data well up to $p_T = 20$ GeV/c. High acceptance is predicted for $J/\psi \rightarrow \mu_{(6\mathrm{GeV/c})}\mu_{(4\mathrm{GeV/c})}$ and $\Upsilon \rightarrow \mu_{(6\mathrm{GeV/c})}\mu_{(4\mathrm{GeV/c})}$ such that this agreement can be tested with precision to $p_T \approx 50$ GeV/c at least. A fourth strategy involves analysis of the level of hadronic activity associated with the quarkonium production. The Color Singlet and Color Octet models may predict different levels. ATLAS is preparing to study this with isolation cones about the quarkonium direction. As a first step, we study the application of the cone to the muon direction. Challenges to this technique include the procedure for subtracting the muon contribution to the energy captured in the quarkonium cone; modelling the energetic photon associated with the χ_c decay which produces 29% of the J/ψ's; and accommodating the fact that the photon and muon are almost collinear for the J/ψ.

4 χ_b Resonant and Non-resonant Decay

A single measurement of the branching ratio for $\chi_{c0} \rightarrow \phi\phi$ exists and is substantially larger than its prediction. [9] This motivates the question as to whether the enhancement reflects internal motion of the quarks in the hard part of the amplitude. A study of the analogous channel $\chi_{bJ} \rightarrow \psi\psi X$ could provide an answer. A second motivation for the study of χ_b comes from the known inconsistency between Tevatron data and the predictions of the Color Singlet Model for ψ production via $gg \rightarrow \psi g$.

Preparations are underway to search for the process $\chi_{b0,2} \rightarrow \psi\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$. At luminosity $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the production cross section for $pp \rightarrow \chi_{bi}X$ is enhanced at the LHC relative to the Tevatron by ratios of 1.5μb : 250nb (for $i = 0$) and 2.0μb : 320nb (for $i = 2$). Combining these LHC cross sections with the branching ratio for $\chi_{bi} \rightarrow \psi\psi$, $2.2 \times 10^{-4} (i = 0)$ or $5 \times 10^{-4} (i = 2)$, the branching ratio for $J/\psi \rightarrow \mu^+\mu^-$, 5.93%, and selecting events with muon $p_T^{\mathrm{Level1}} > 6$ GeV/c, muon $p_T^{\mathrm{Level2}} > 4$ GeV/c, and muon $\eta > 2.5$ for Levels 1 and 2, estimating the detection efficiency at 1.63% predicts 200 (generator-level) χ_{b0} events per year. This signal, though small, is likely to be backgroundless, as the combinatorics of four muons forming two J/ψ masses is vanishingly small.

5 B_c Production and Decay

A precision reconstruction of B_c ground and excited states can be used to constrain models of the strong potential. The combination of the doubly-heavy quark system with the restriction that the decays must go weakly predicts that the states will be narrow and in a regime sensitive to non-perturbative as well as perturbative effects.

We select hadronic B_c decays connecting states with the largest possible mass difference to maximize efficiency for observing the final state tracks. Several channels, including

$$B_c^*(2^1S_0) \to B_c(1^1S_0)\pi^+\pi^- \tag{13}$$

and

$$B_c^*(2^1S_1) \to B_c^*(1^1S_1)\pi^+\pi^- \tag{14}$$

are predicted to have mass differences in the realm of 600 MeV. Efficient tracking at very low p_T will be essential, as will be generation and simulation of realistic decays of the excited states in the PYTHIA framework. Figure 1 predicts the p_T distributions of all B_c's (white histogram) and those whose muons pass the 6 GeV/c and 4 GeV/c requirements (shaded histogram). The predicted number of B_c events in 20 fb^{-1} integrated luminosity at ATLAS is 10000.

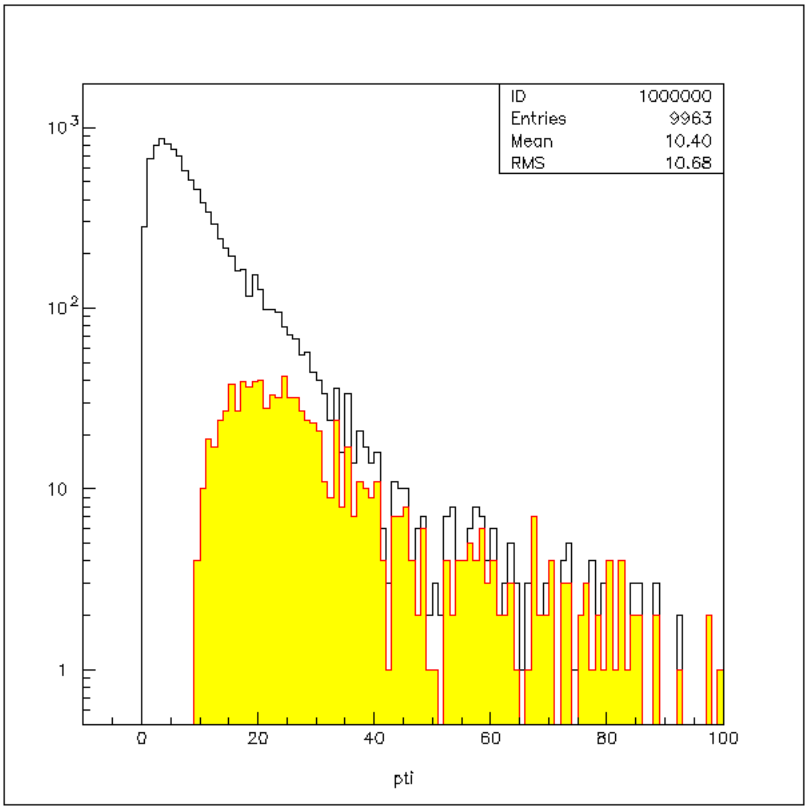

Figure 1: *The transverse momentum of B_c particles (white) and of those whose muons pass the 6 GeV/c + 4 GeV/c p_T requirement (shaded), for events generated with the program BCVEGPY2.1.* [10]

6 Conclusions

With 1 fb^{-1} integrated luminosity, Λ_b studies will yield the Λ_b lifetime, known better than the present world average, and first results on Λ_b polarization. The large predicted quarkonia cross sections at the LHC will permit definitive studies of quarkonium spin alignment as a test of the Color Octet Mechanism, for which 100 pb^{-1} of integrated luminosity are needed for a competitive polarization measurement. The large cross sections may also permit a comparison of jet activity associated with quarkonium decay to levels predicted by the Color Singlet and Color Octet mechanisms. With 10 pb^{-1}, ATLAS will measure ratios of quarkonia cross sections to constrain NR QCD octet matrix elements. Subsequent statistical power will fix the matrix elements. The LHC will be the first opportunity for significant statistics on excited states in the B_c family. These measurements can constrain models of the strong potential and cast light on interaction between the electroweak and strong forces. Finally, χ_b decays may point the way to solving longstanding puzzles in the $gg \to \psi g$ and $e^+e^- \to \psi\eta_c$ cross sections.

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