Properties of Heavy Flavor Hadrons in ATLAS

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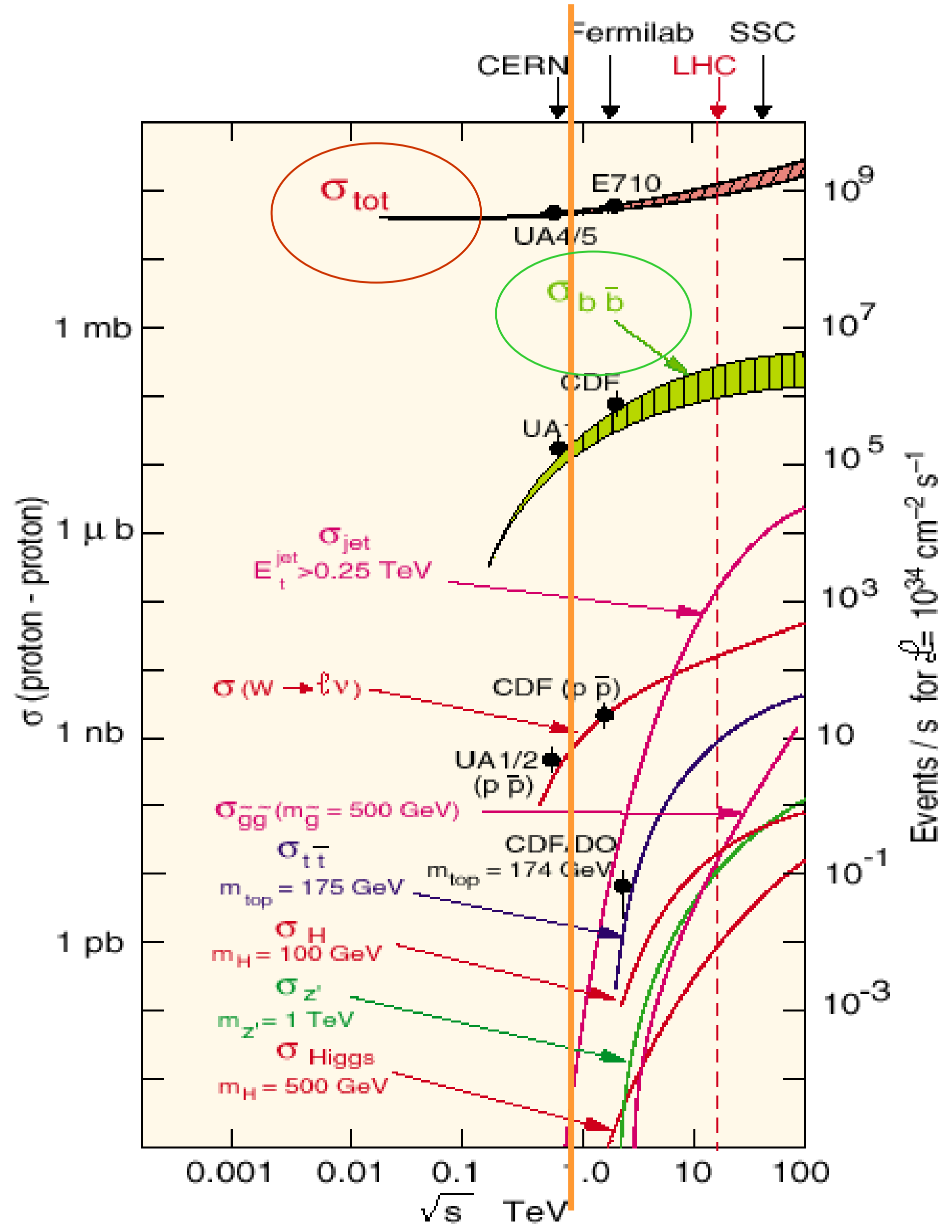
The Large Hadron Collider (7 TeV - on - 7 TeV proton-proton collisions) will provide unprecedented energy scales for QCD study.

LHC AERIAL VIEW

ATLAS, one of 4 LHC detectors, will cover collisions to pseudorapidity $|\eta| \leq 2.4$ for high precision measurements.

ATLAS, the LHC, and B Physics

- LHC has a 27 km circumference, 40 kHz crossing rate
- The total $b\bar{b}$ production cross section is 500 μb: 1 $b\bar{b}$ pair in every 100 collisions.
- Luminosity expectation: 10 fb^{-1} per year (@ L=$10^{33}/cm^2/s$) in Years 1-3, 100 fb^{-1} per year subsequently.



The ATLAS Detector

Tracking ($|\eta| < 2.5$, B = 2T) :

Silicon pixels and strips

Transition Radiation Detector (tracking and e/π separation)

Calorimetry ($|\eta| < 5$) :

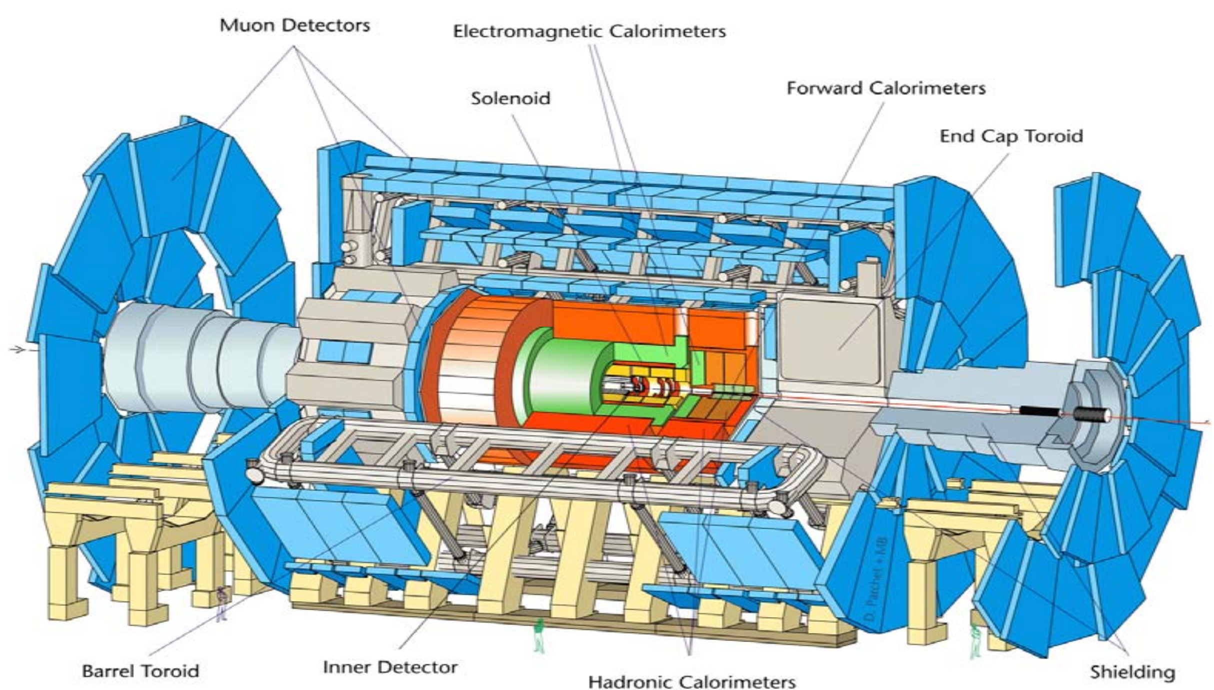
EM : Pb-LAr

HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

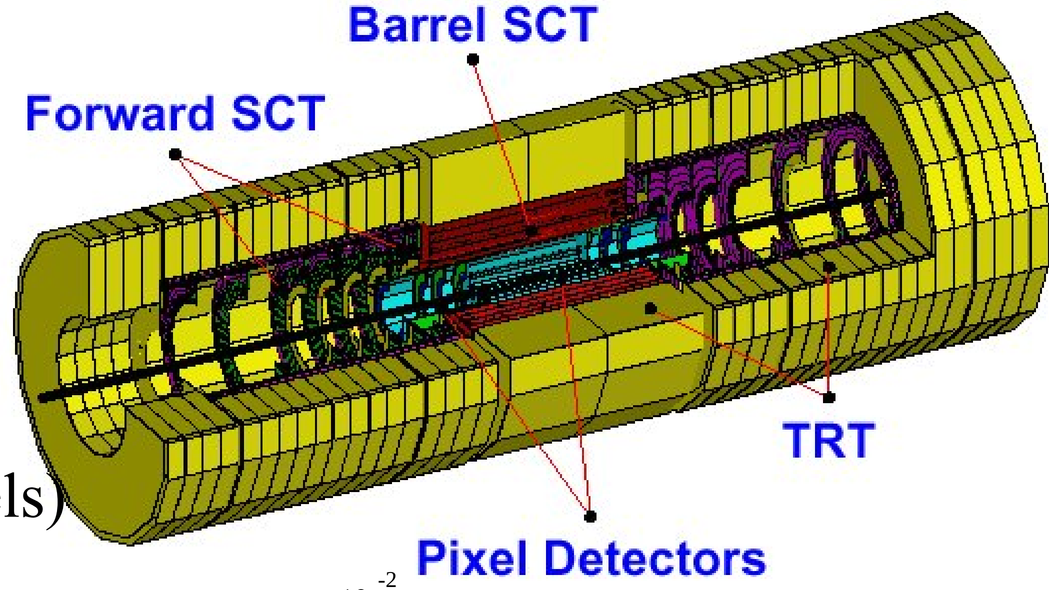
Muon Spectrometer ($|\eta| < 2.7$) :

Air-core toroids with muon chambers

- 46 m long
- 22 m diameter
- 7000 t total weight
- 2T solenoid and 0.5 T toroid
- 10^8 electronics channels
- 3000 km of cables.



Inner Detector



Pixels:

•$(0.8\times10^8$ channels)

•σ_φ=12 μm, σ_z=66 μm

Silicon Tracker (SCT):

•5cm<radii<50cm (6×10^6 channels)

•σ_φ=16 μm, σ_z=580 μm

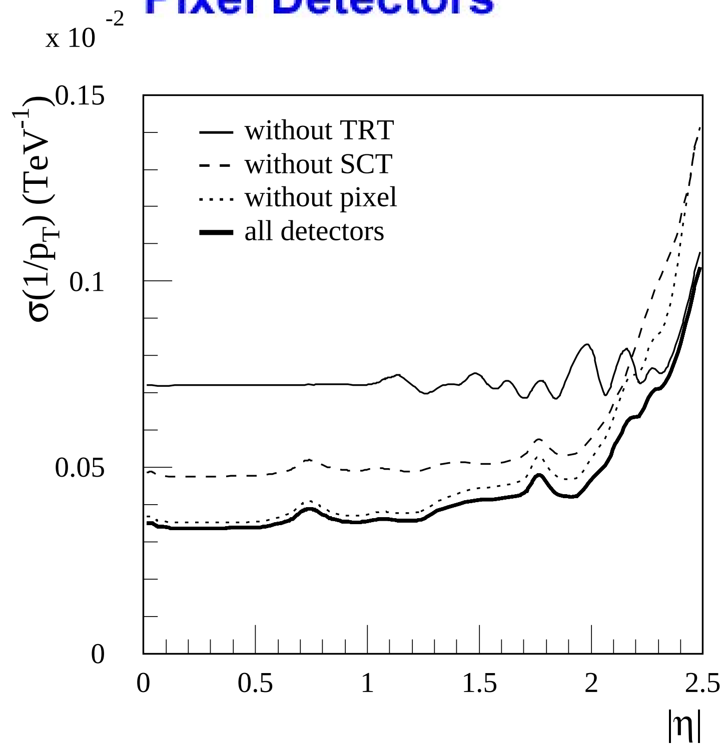
Transition Radiation Tracker (TRT)

•50<radii<100 cm (4×10^5 channels)

•σ=150 μm per straw

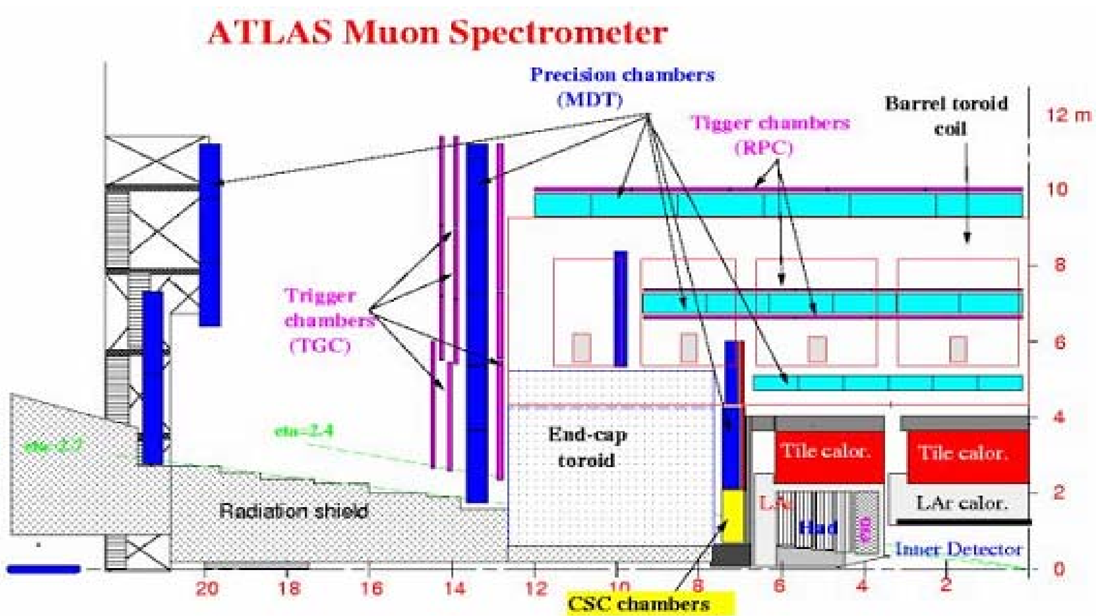
The silicon detectors provide ~ 10 azimuthal position measurements for 10 - 20μm resolution.

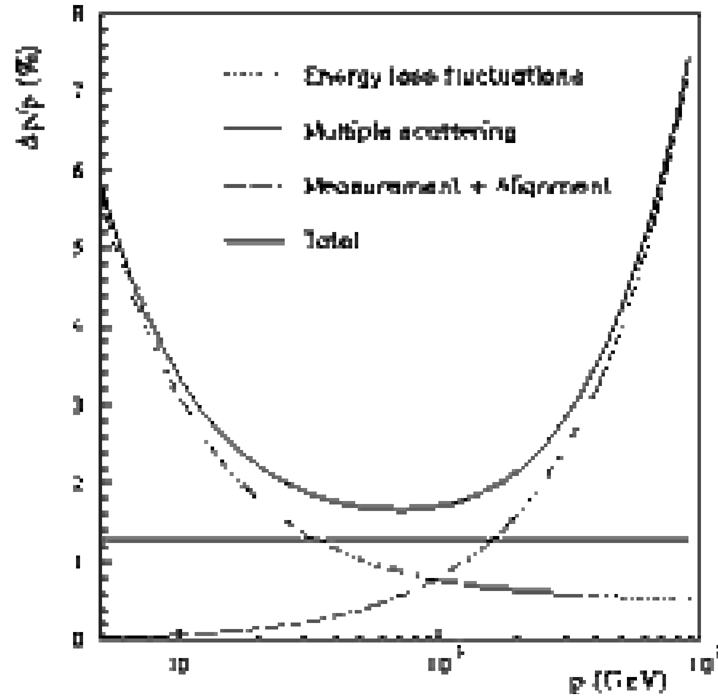
The TRT provides ~ 36 azimuthal position measurements for 150 microns.



Muon Spectrometer

The momentum of the muons is determined from the curvatures of their tracks in a toroidal magnetic field.





Muon tracks are identified and measured after their passage through ~2m of material.

Track measurement is made with $\sigma = 60$ μm intrinsic resolution in three precision measurement (Monitored Drift Tube) stations.

ATLAS is well instrumented for *B* Physics: precision vertexing and tracking, good muon id, high resolution calorimetry, and a flexible dedicated *B* trigger.

A rich *B* Physics program is planned, including CP violation (especially in the Λ_b and B_s systems not accessible to the *B* factories), rare decays sensitive to new physics (including $b \rightarrow s\, l^+ l^-$ and $b \rightarrow d\, l^+ l^-$), and baryons and heavy flavor mesons.

- ATLAS high statistics studies of heavy flavor hadrons, including quarkonia, throw light on:
- bound states
- the spin dependence of quark confinement
- the nature of the strong potential
- Heavy Quark Effective Theory factorization
- CP violation
- puzzles in present measurements of hyperon polarization and cross sections.

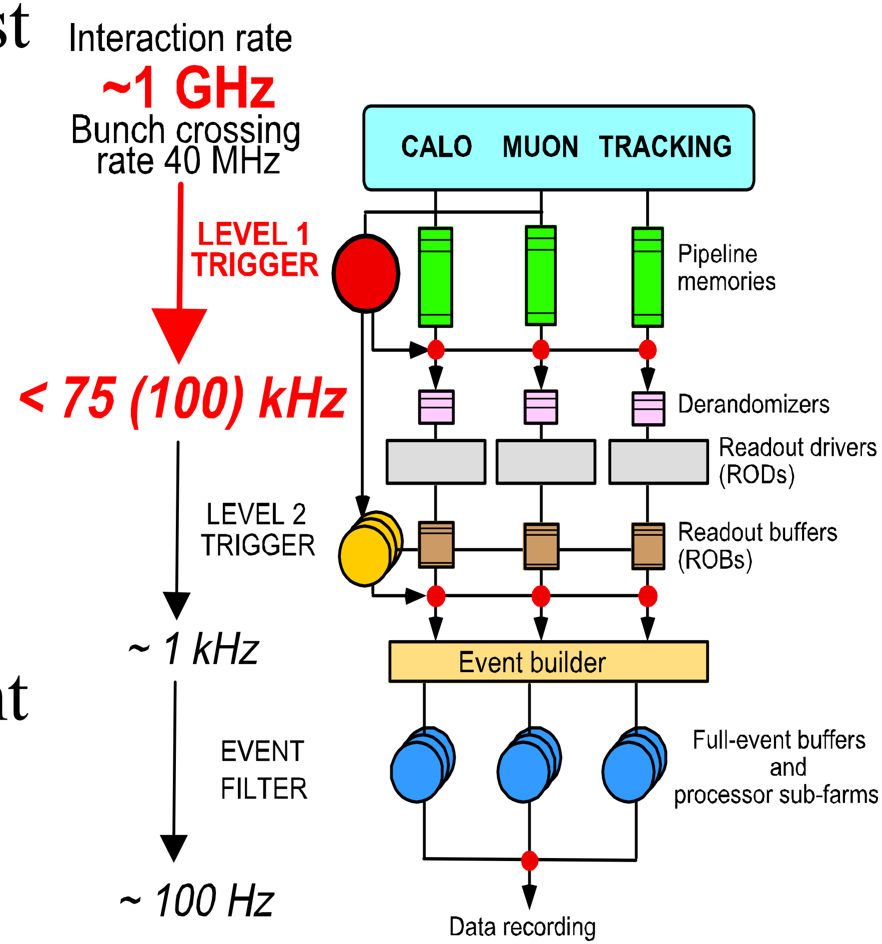
Triggering and the B Physics program…

- Muons provide efficient identification and a reliable flavor tag.
- Level 1: Uses calorimeter + muon trigger chambers, identifies Regions of Interest; outputs 75 kHz. Thresholds are luminosity-dependent. Paths:
  - dimuon ($p_T > 6$ GeV [barrel] or > 3 GeV [endcaps])
    - Ex. $B_d \rightarrow J/\psi K_s^0,\ B_s \rightarrow J/\psi\phi,\ B \rightarrow \mu\mu,\ \Lambda_b \rightarrow \Lambda^0 J/\psi$
  - MU ($p_T > 6$ GeV) + EM (cluster $E_T > 5$ GeV)
    - Ex. $B_d \rightarrow J/\psi(ee)K_s^0 + b \rightarrow \mu X,\ B_d \rightarrow \mathrm{K}^{0*}\gamma,\ B_s \rightarrow \phi\gamma + b \rightarrow \mu X$
  - MU ($p_T > 6$ GeV) + JET (cluster $E_T > 10$ GeV)
    - Ex. $B_s \rightarrow D_s\phi(KK),\ B_s \rightarrow D_s(\phi(KK))a_1(\rho^0\pi^+),$
      $B^+ \rightarrow K^+K^+\pi^-,\ B_d \rightarrow \pi^+\pi^-(+b \rightarrow \mu X)$

Trigger, continued

- Level 2: uses Regions of Interest and dedicated online algorithms; confirms muons and calorimeter info, refits tracks in Inner Detector; outputs 1 kHz

- Event Filter: uses full event buffers + processor subfarms; offline algorithms with alignment and calibration; reconstructs decay vertices; selects exclusive final states via mass and decay length; outputs 200 Hz



Heavy flavor hadron studies underway:

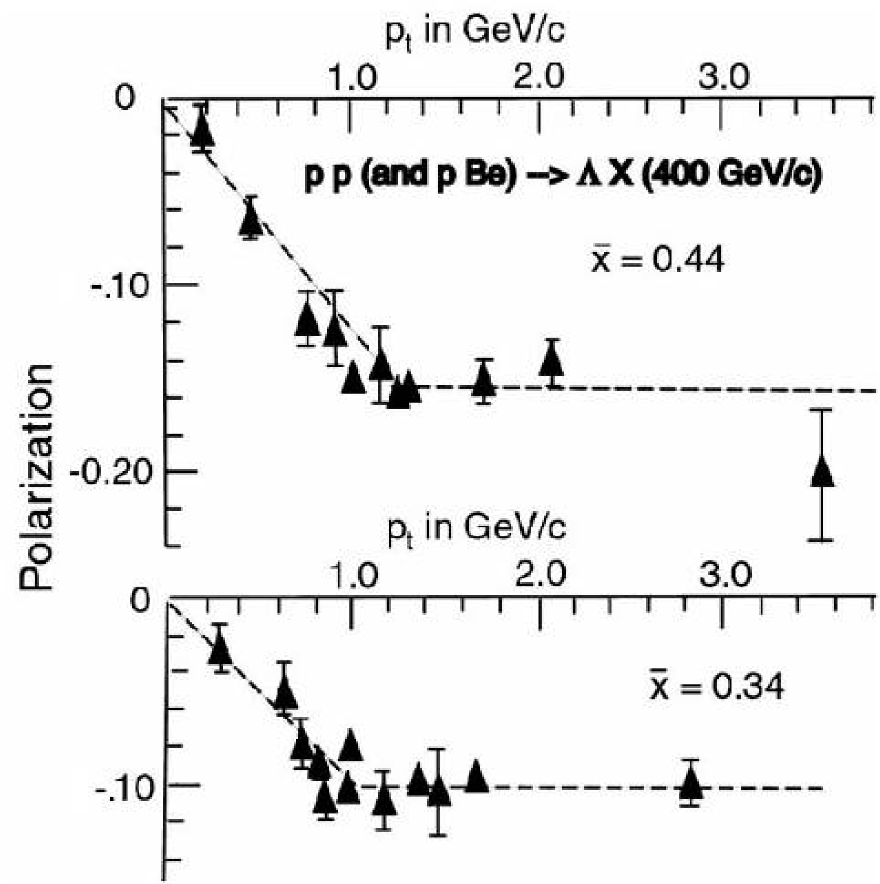
- Production characteristics, lifetime, and polarization properties of the Λ_b
- Production mechanisms, lifetime, and branching ratios for decays in the J/ψ and Υ systems.
- Resonant and non-resonant decays of χ_b
- Masses and lifetimes of excited states of the B_c

Λ_b Production, Lifetime, and Polarization

Motivations:

- What is the role of spin in heavy quark production leading to polarization? What determines the Λ polarization magnitude, p_T spectrum, and *x* dependence? How does polarization depend on quark mass? Are the polarization patterns of Λ and Λ_b the same? Are the *s* and *b* production mechanisms similar?

- What produced this unusual shape? Expect *small* polarization because the Λ's are produced inclusively; and most theories predict negligible polarization at high p_T, high energy.



K. Heller, Proc. 9th Int. Symp. on High Energy Spin Physics, Bonn, p. 97, Springer-Verlag

Λ_b Production, Lifetime, and Polarization

Motivations, continued:

- Longstanding B-baryon lifetime puzzle: $\tau_{\Lambda_b} / \tau_{B^0}$ data are not consistent with predictions by theory that succeeds for $\tau_{B^0} / \tau_{B^\pm}$. Probe this in a new regime with better precision and improved theory.

- Tests perturbative QCD, Heavy Quark Effective Theory, the non-relativistic quark model.

- Probes CP violation in a regime not previously explored: if CP is not conserved, asymmetry parameters $\alpha_b \neq \alpha_{\bar{b}}$.

Goals: World's first measurements of the asymmetry parameter α_b and polarization P_b for Λ_b, to 2%, and the lifetime, to 0.3%.

Process:

- $\Lambda_b \rightarrow \Lambda\ J/\psi;\ \Lambda \rightarrow \pi p,\ J/\psi \rightarrow \mu\mu$

Predicting the number of events:

- Acceptance for Λ_b, from Pythia: 0.157%
- $\sigma(pp \rightarrow \ldots \rightarrow \Lambda_b)$: 0.00828113 mb
- $BR(\Lambda_b \rightarrow \Lambda\ J/\psi) \sim 4.7 \times 10^{-4}$
- $BR(\Lambda \rightarrow \pi p) \sim 0.64$
- $BR(J/\psi \rightarrow \mu^+\mu^-) \sim 0.06$
- Generator-level selection cut efficiency ~ 0.05
- Trigger and reconstruction efficiency ~ 0.08

Anticipated number of Λ_b events in 30 fb^{-1}: 18000

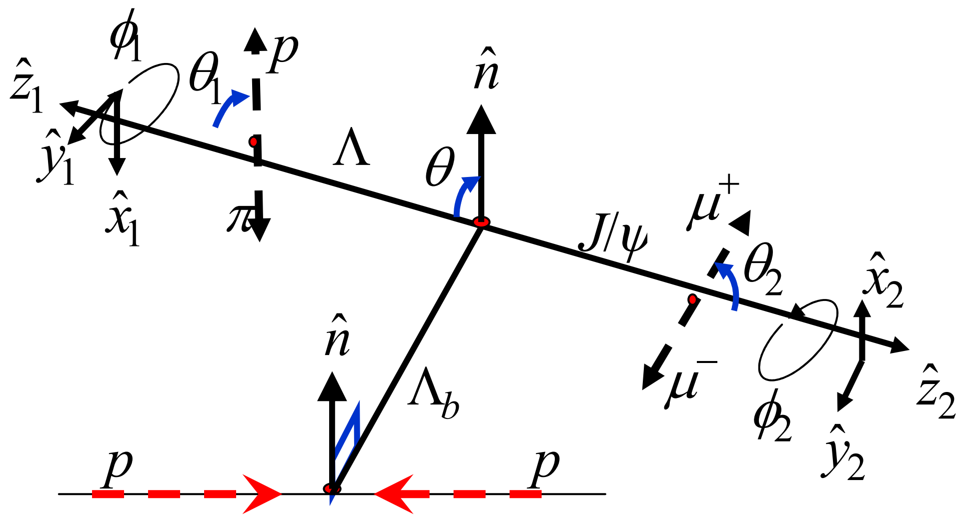
Selection Strategy:

- $p_T > 2.5$ GeV and > 4 GeV for two muons
- $p_T > 0.5$ GeV for π and p
- $\eta < 2.7$ for all tracks

Expected number of background $pp \rightarrow J/\psi \Lambda X$: 3.2×10^6

A lifetime cut will beused to remove the $pp \rightarrow J/\psi X$ background.

The polarization measurement analyzes the angular distribution of the decay $\Lambda_b \rightarrow J/\psi(\mu\mu)\Lambda(p\pi)$



The general decay amplitude is given by

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

where A_1, A_2, B_1, and B_2 are model-dependent parameters.

Define: $a_+ = |a_+| e^{i\alpha_+} \equiv M_{+1/2,0}$ $\qquad a_- = |a_-| e^{i\alpha_-} \equiv M_{-1/2,0}$

$b_+ = |b_+| e^{i\beta_+} \equiv M_{-1/2,-1}$ $\qquad b_- = |b_-| e^{i\beta_-} \equiv M_{+1/2,+1}$

where $M_{\lambda 1,\lambda 2}$ is the amplitude for decay into Λ with helicity λ_1 and J/ψ with helicity λ_2.

Then for normalized amplitudes, $\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$

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

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

where…

Parameters f_{1i}, f_{2i}, and F_i are:

i	f_{1i}	f_{2i}	F_i
0	$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$	1	1
1	$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$	P_b	$\cos\theta$
2	$a_+a_+^* - a_-a_-^* - b_+b_+^* + b_-b_-^*$	α_Λ	$\cos\theta_1$
3	$a_+a_+^* + a_-a_-^* - b_+b_+^* - b_-b_-^*$	$P_b\alpha_\Lambda$	$\cos\theta\cos\theta_1$
4	$-a_+a_+^* - a_-a_-^* + \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	1	$d_{00}^2(\theta_2)$
5	$-a_+a_+^* + a_-a_-^* + \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	P_b	$d_{00}^2(\theta_2)\cos\theta$
6	$-a_+a_+^* + a_-a_-^* - \frac{1}{2}b_+b_+^* + \frac{1}{2}b_-b_-^*$	α_Λ	$d_{00}^2(\theta_2)\cos\theta_1$
7	$-a_+a_+^* - a_-a_-^* - \frac{1}{2}b_+b_+^* - \frac{1}{2}b_-b_-^*$	$P_b\alpha_\Lambda$	$d_{00}^2(\theta_2)\cos\theta\cos\theta_1$
8	$-3Re(a_+a_-^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\cos\phi_1$
9	$3Im(a_+a_-^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2\sin\phi_1$
10	$-\frac{3}{2}Re(b_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2 cos(\phi_1+2\phi_2)$
11	$\frac{3}{2}Im(b_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\sin\theta_1\sin^2\theta_2 sin(\phi_1+2\phi_2)$
12	$-\frac{3}{\sqrt{2}}Re(b_-a_+^* + a_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\cos\phi_2$
13	$\frac{3}{\sqrt{2}}Im(b_-a_+^* + a_-b_+^*)$	$P_b\alpha_\Lambda$	$\sin\theta\cos\theta_1\sin\theta_2\cos\theta_2\sin\phi_2$
14	$-\frac{3}{\sqrt{2}}Re(b_-a_-^* + a_+b_+^*)$	$P_b\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1+\phi_2)$
15	$\frac{3}{\sqrt{2}}Im(b_-a_-^* + a_+b_+^*)$	$P_b\alpha_\Lambda$	$\cos\theta\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1+\phi_2)$
16	$\frac{3}{\sqrt{2}}Re(a_-b_+^* - b_-a_+^*)$	P_b	$\sin\theta\sin\theta_2\cos\theta_2\cos\phi_2$
17	$-\frac{3}{\sqrt{2}}Im(a_-b_+^* - b_-a_+^*)$	P_b	$\sin\theta\sin\theta_2\cos\theta_2\sin\phi_2$
18	$\frac{3}{\sqrt{2}}Re(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\cos(\phi_1+\phi_2)$
19	$-\frac{3}{\sqrt{2}}Im(b_-a_-^* - a_+b_+^*)$	α_Λ	$\sin\theta_1\sin\theta_2\cos\theta_2\sin(\phi_1+\phi_2)$

The angular distribution depends on 9 unknown parameters: P_b and 4 amplitudes and 4 phases of the a_+, a_-, b_+, and b_-.

After normalization $|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2 = 1$ and global phase constraint, number of independent unknowns=7.

Extract these from the measured decay angles by a five-dimensional likelihood fit:

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

where N = number of events,

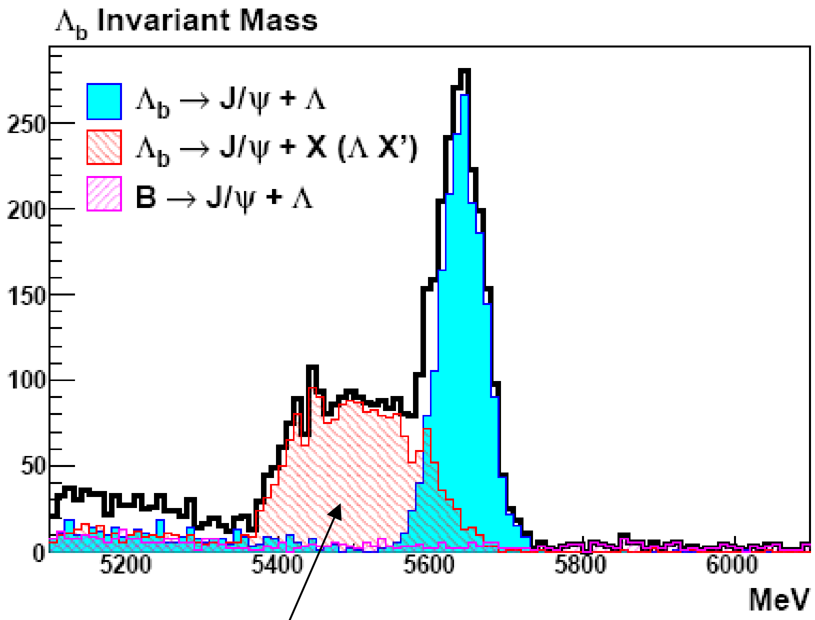
$$w_{obs}(\vec{\theta}', \vec{A}, P_b) = \frac{\int w(\vec{\theta}, \vec{A}, P_b) T(\vec{\theta}, \vec{\theta}') d\vec{\theta}}{\iint w(\vec{\theta}, \vec{A}, P_b) T(\vec{\theta}, \vec{\theta}') d\vec{\theta} d\vec{\theta}'}$$

$$T(\vec{\theta}, \vec{\theta}') = \varepsilon(\vec{\theta}) R(\vec{\theta}, \vec{\theta}')$$

for ε = acceptance and R = resolution.

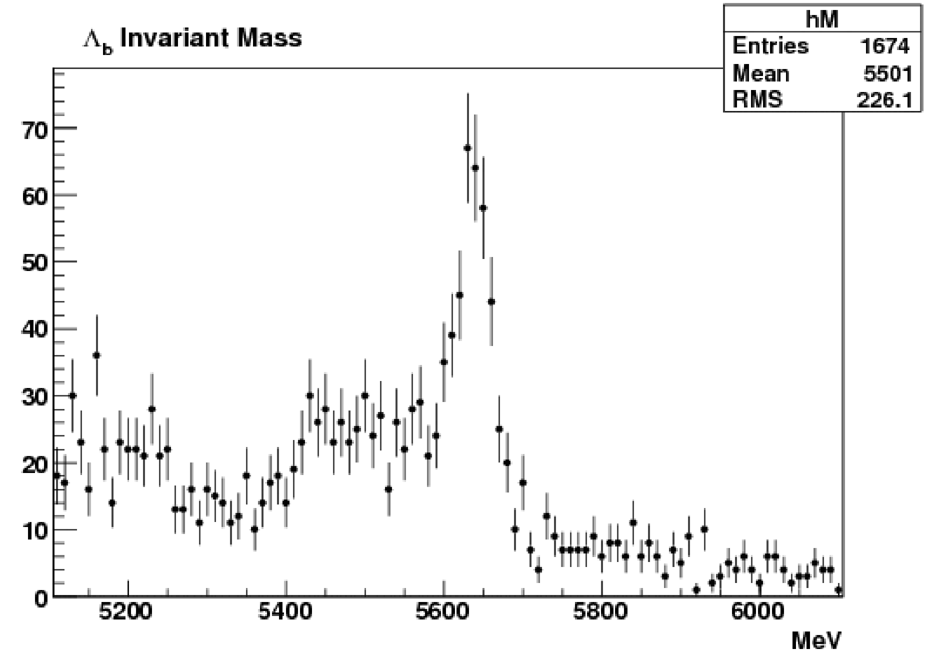
The resolution on the angles measured is ~10 mrad. Detector acceptance corrections come from a phase space Λ_b monte carlo sample.

Expected signal and background shapes, using Pythia with EVTGEN:



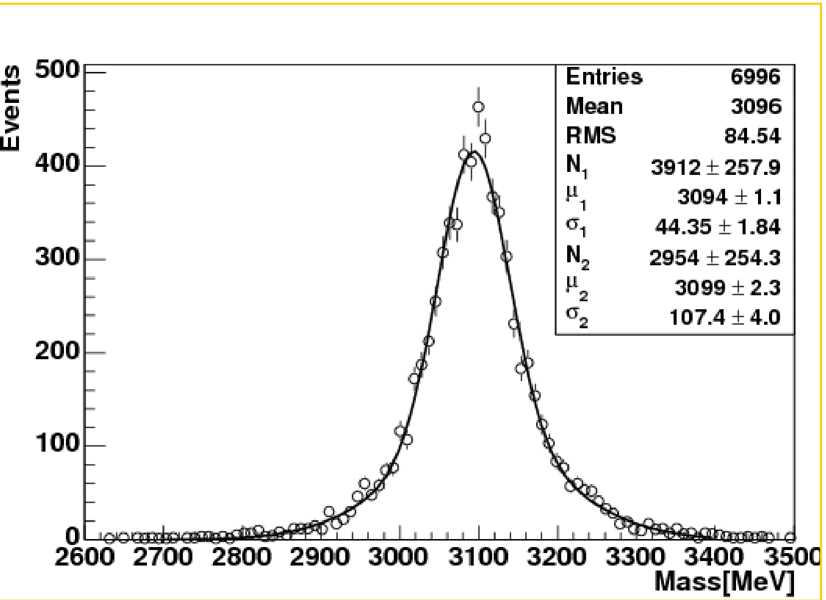
Generated and smeared

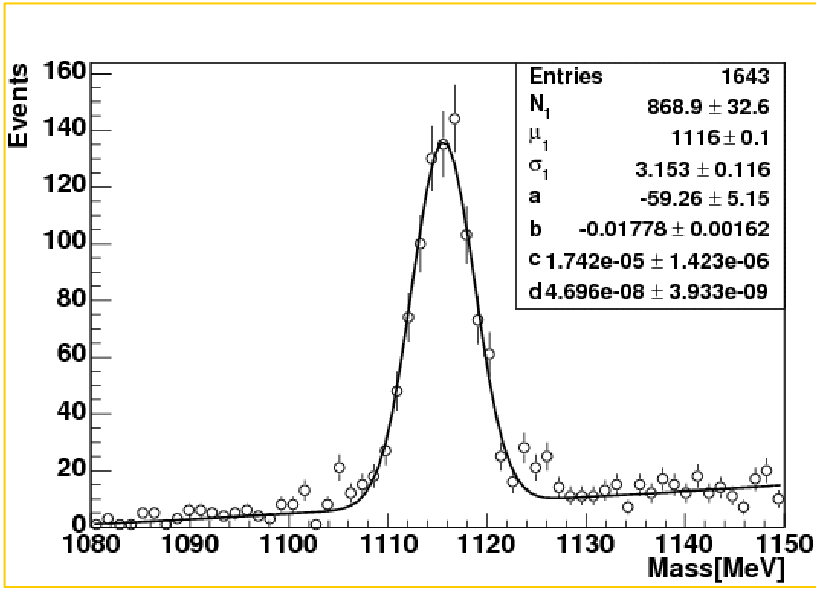
Note this enhancement reflects all $\Lambda_b \to J/\psi X$ BR's set to same BR as $\Lambda_b \to J/\psi\Lambda$---unlikely situation in the real data.



Reconstructed, excluding trigger effects

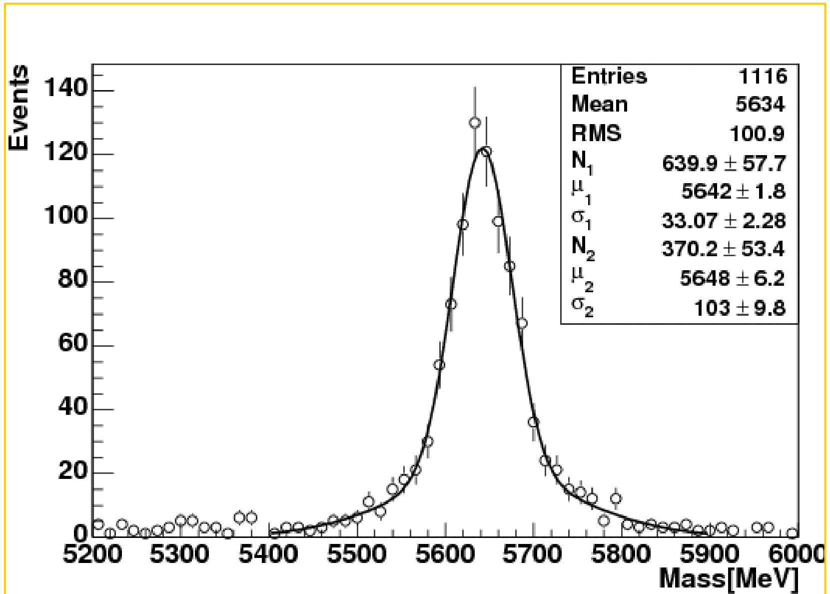
Mass distributions





$J/\psi \to \mu\mu$, with $\mu\mu$ vertexing

$\Lambda \to \pi p$, after $J/\psi\Lambda$ vertex required



$\Lambda_b \to J/\psi\Lambda$, with vertexing and J/ψ and ψ mass constraints

A word about heavy quarkonium production models…

One of the goals of the next two studies is a comparison of ATLAS data to predictions by the quarkonium production models---esp. the Color Singlet Model (*assumes each quarkonium state can be produced only by a $q\bar{q}$ pair in the same color and J state as the quarkonium)* and Non-Relativistic QCD with the Color Octet Mechanism (*treats quarkonium as a non-relativistic system; thus $q\bar{q}$ pairs produced with one set of quantum numbers can evolve into a quarkonium state with different quantum numbers by emitting low energy gluons.)*

Heavy quarkonia production and decay

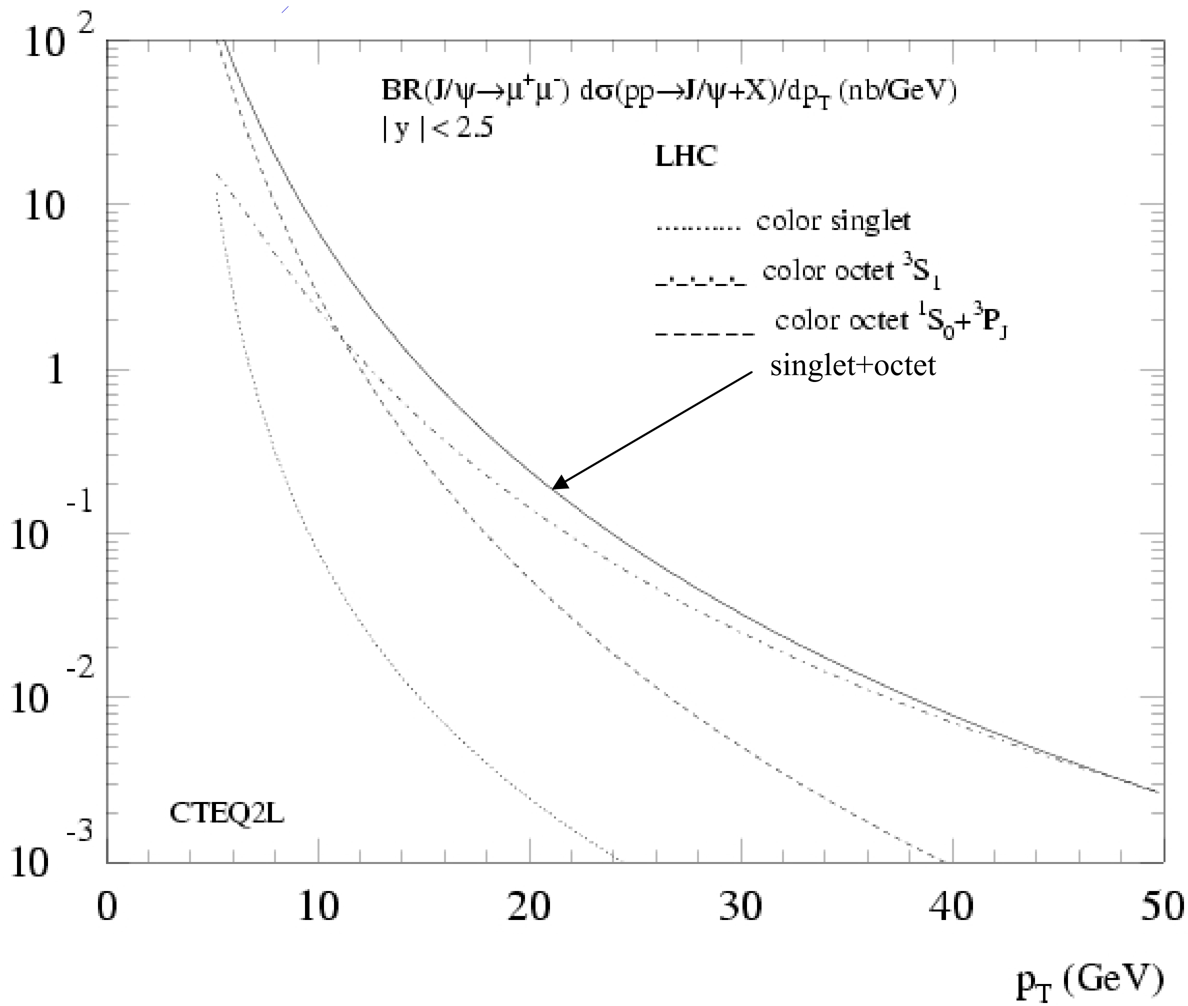
Motivation:

- The production mechanism of quarkonia is not fully understood. Several models have been proposed. NRQCD with the Color Octet Mechanism, with free normalization, agrees with CDF data on J/ψ p_T cross section up to accessible Tevatron energies. Its polarization vs. p_T predictions have not been confirmed. Additional data, especially at higher p_T and for other onia farther from the QCD scale, are needed.

Goals:

- Distributions in p_T, η, and polarization for J/ψ; measurement of the ratio of Υ and J/ψ production cross sections; assessment of hadronic activity associated with quarkonium production.

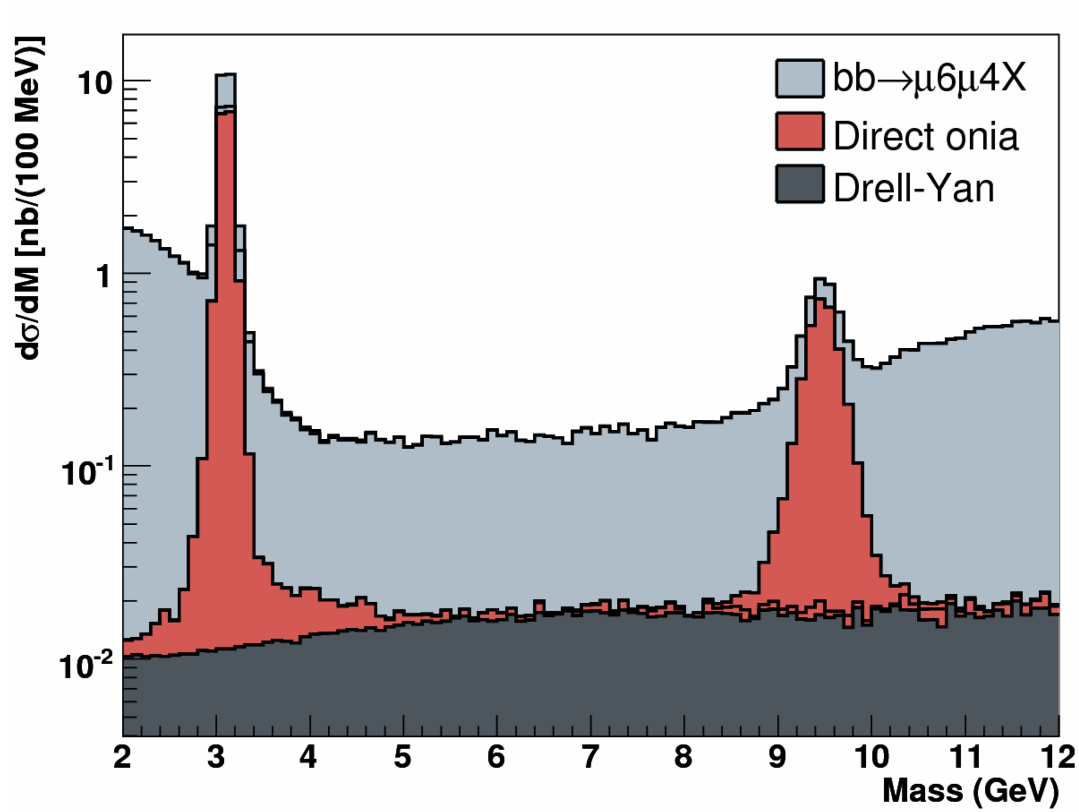
The LHC will produce heavy quarkonia with high p_T at high rate:



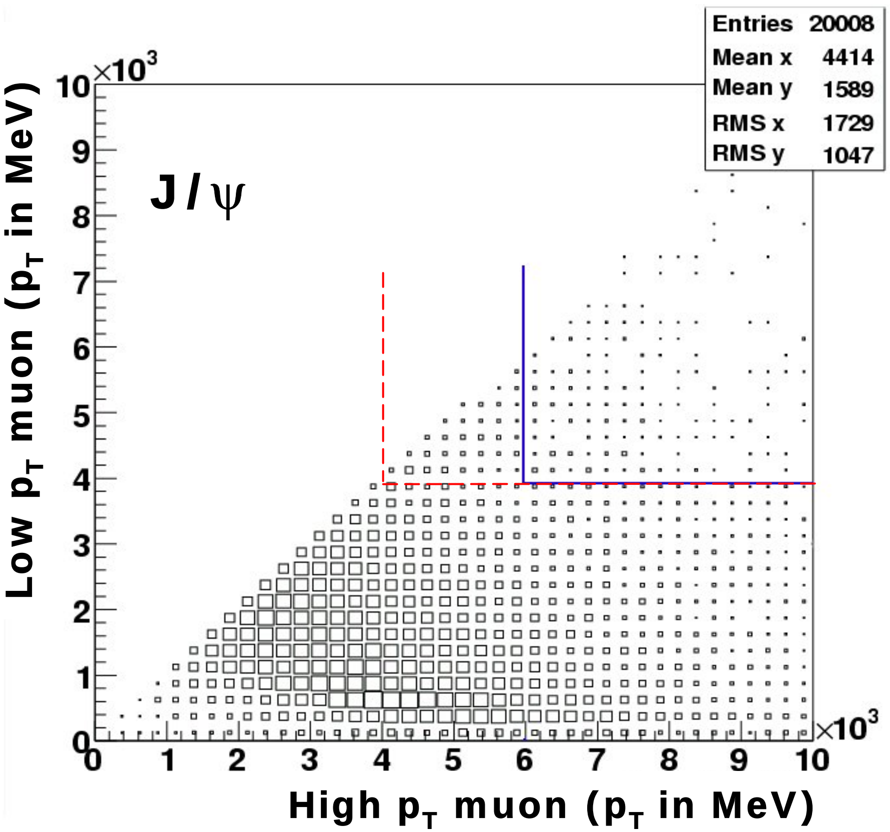
Processes and #events expected in 10^6 seconds @ $L=10^{31}/cm^2s$:

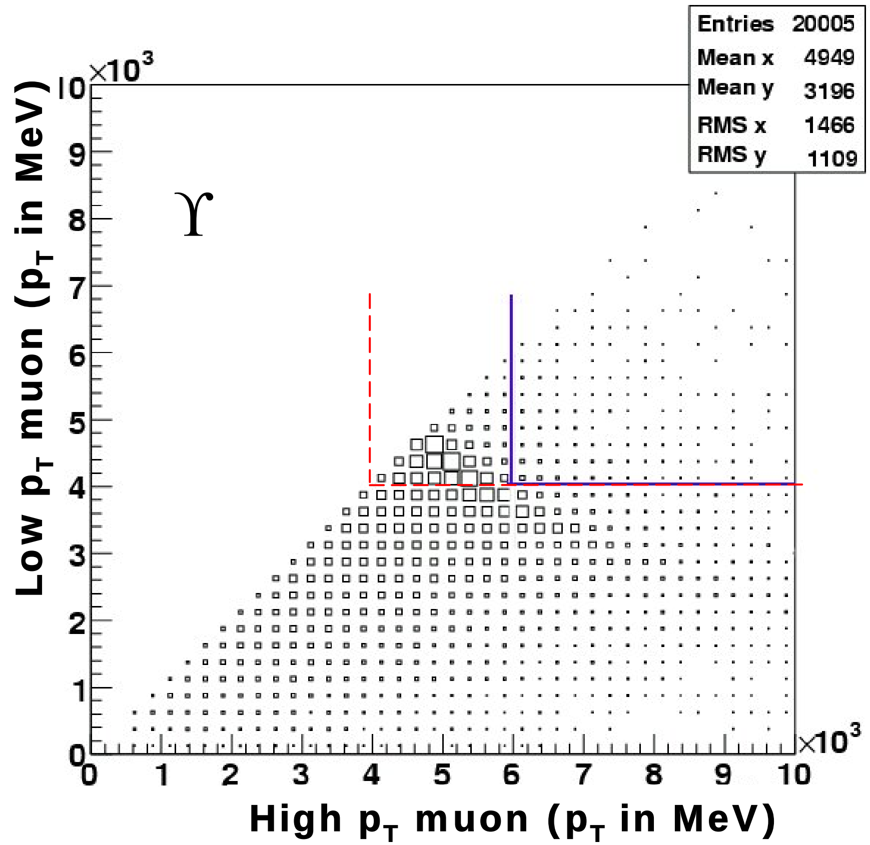
- $J/\psi \to \mu(p_T \geq 6$ GeV$)\ \mu(p_T \geq 4$ GeV$)$: 175k events
- $Y \to \mu(p_T \geq 6$ GeV$)\ \mu(p_T \geq 4$ GeV$)$: 36k events

Generator-level study of the backgrounds from bb $\to \mu\mu X$ and Drell-Yan production, including trigger and detection efficiency:



Analysis strategy #1: Examine the option to lower dimuon p_T trigger threshold from 6 GeV+4 GeV to 4 GeV+4 GeV



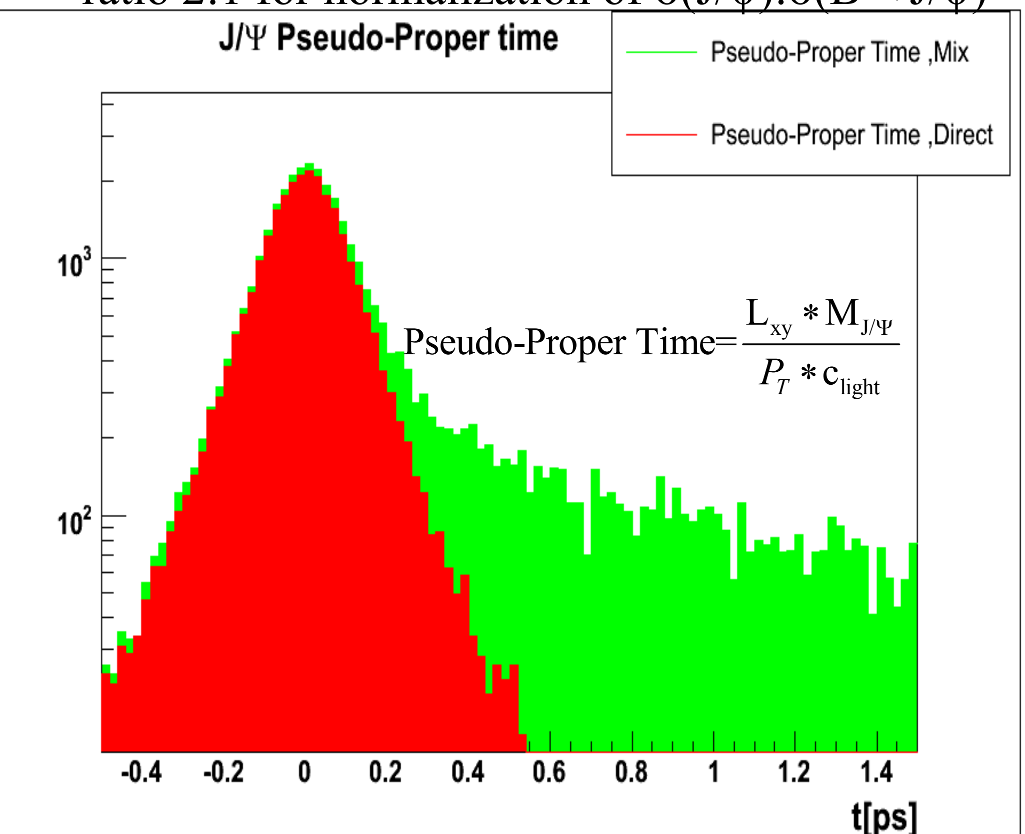


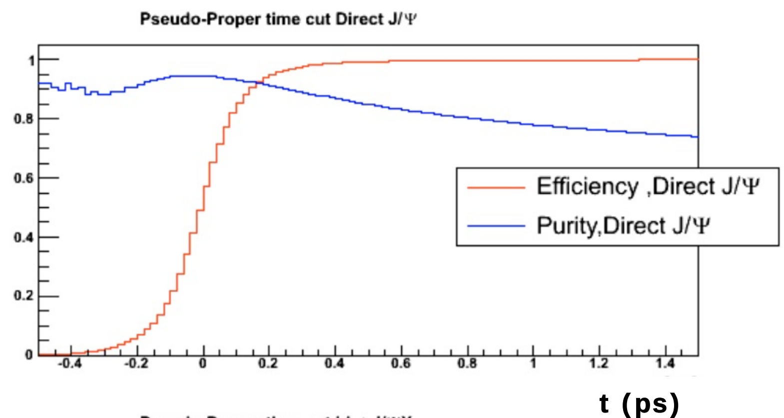
This also increases the contribution of color singlet production, which dominates for p_T<10 GeV.

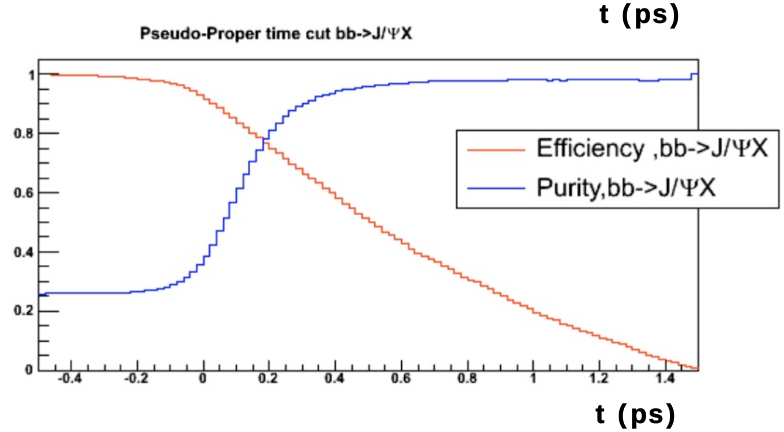
Analysis strategy #2:

Cut on pseudo-proper time to separate direct from indirect J/ψ's. As expected, the resolution worsens with increasing p_T and η.

"Mix" sample is direct + indirect J/ψ combined, with ratio 2:1 for normalization of σ(J/ψ):σ(B→J/ψ)



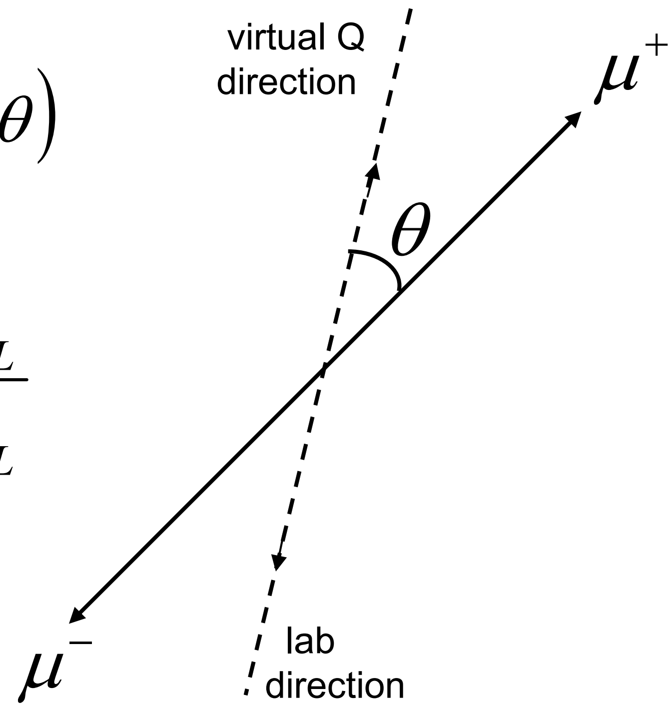




Analysis strategy #3: Measure the quarkonium spin

For the angle θ between the positive muon in the quarkonium reference frame and the quarkonium direction in the lab frame,

$$\frac{d\Gamma}{d\cos\theta} \propto \left(1+\alpha\cos^2\theta\right)$$



where $$\alpha \equiv \frac{\sigma_T + 2\sigma_L}{\sigma_T - 2\sigma_L}$$

α = 0: unpolarized meson

α = +1: tranverse polarization

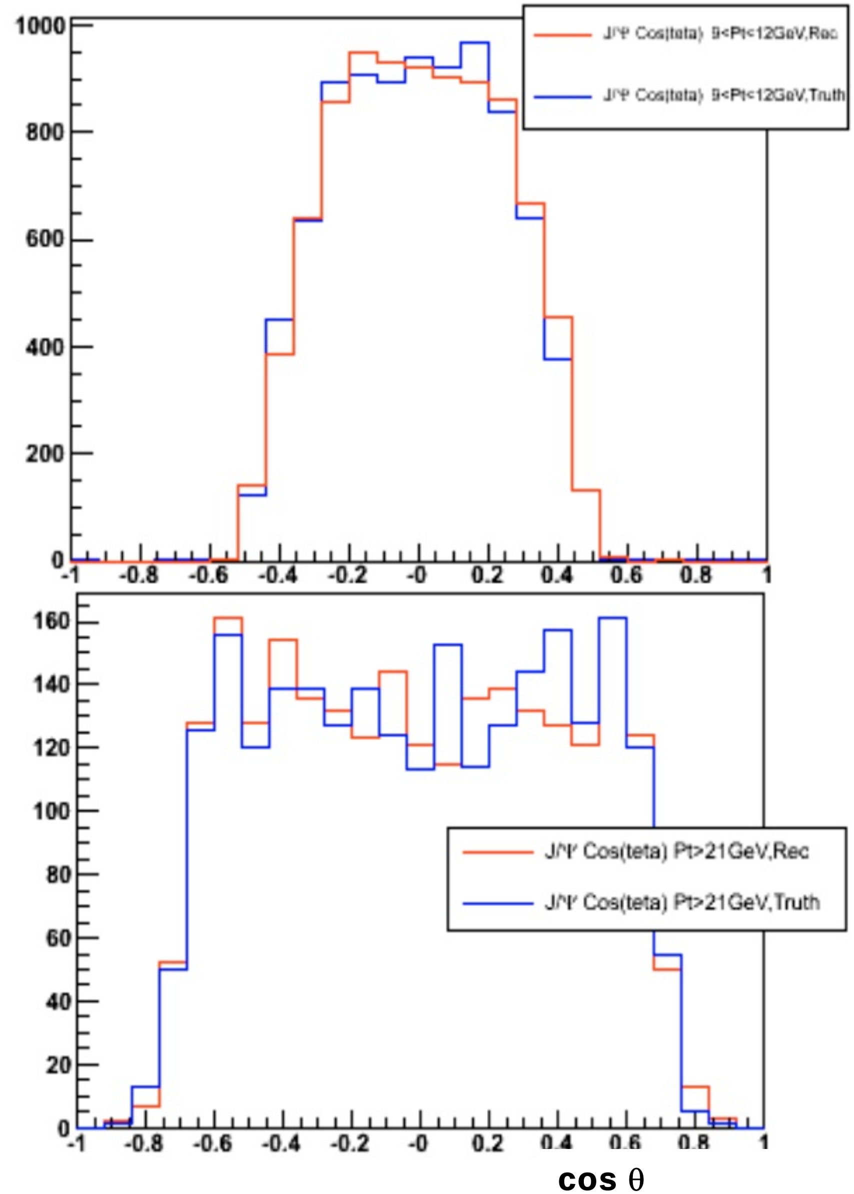
α = -1: longitudinal polarization

Octet production predicts transverse polarization at large p_T.

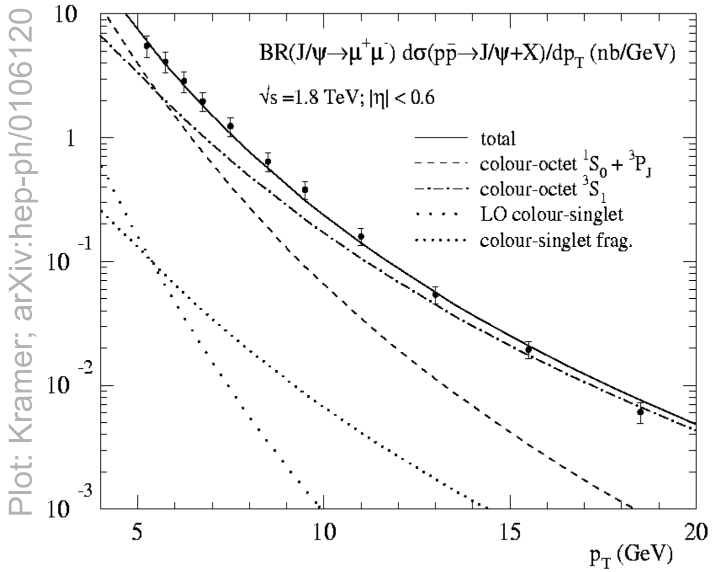
Preparation for this polarization study…

Reconstructed versus truth distributions for simulated J/ψ events:

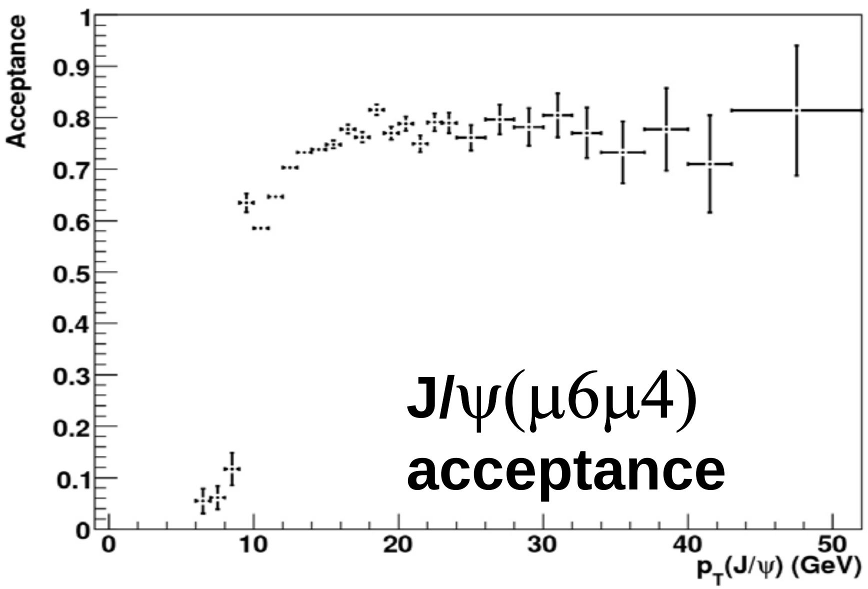
- Acceptance in cos θ is limited by the p_T of the second muon.
- A single muon trigger would be useful if the rate could be reduced by other means.

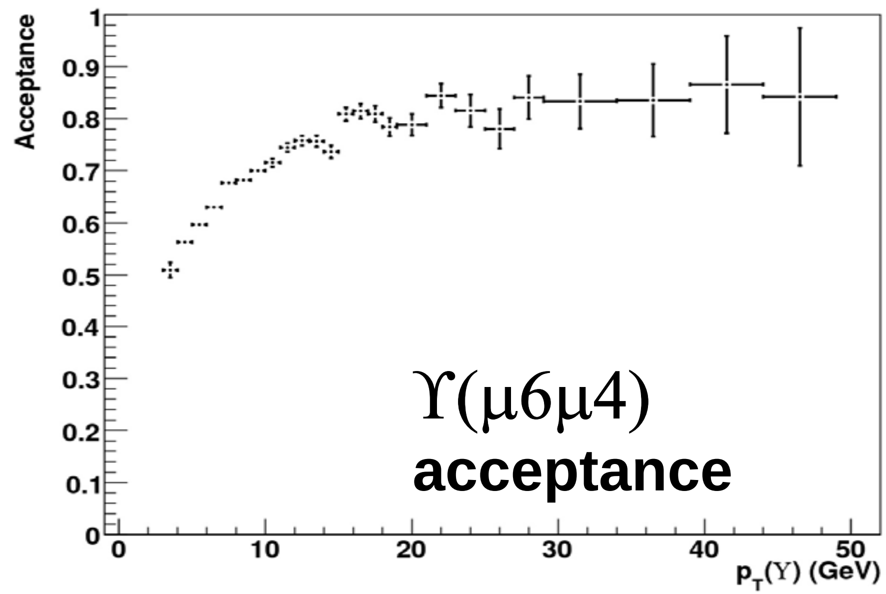


The present NRQCD formalism models Tevatron data up to p_T=20 GeV well →



Will this success continue at higher p_T? Exploit the high LHC acceptance for onia p_T up to 50 GeV ↓

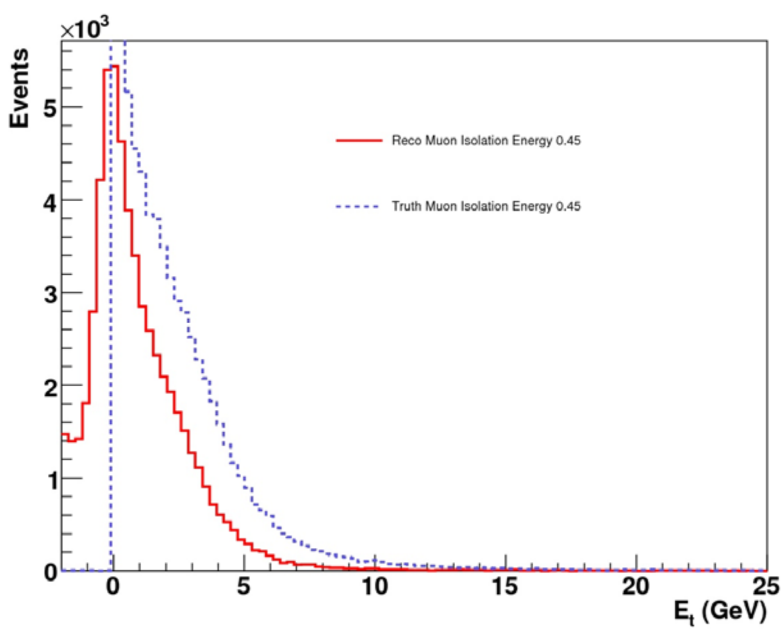




Analysis strategy #4: the jet analysis

The Color Singlet and Color Octet Models may predict different levels of hadronic activity associated with onium production. Prepare to study this with isolation cones about the onium direction.

First step: study using the isolation cone about the muon direction:



Muons from onium must be subtracted.

But 29% of the J/ψ cross section comes from χ_c decays, which have an associated energetic γ. These photons must be modelled.

For J/ψ the photon and muon directions are almost collinear.

χ_b Resonant and Non-resonant Decay

Motivations:

- A single measurement of $Br(\chi_{c0} \to \varphi\varphi)$ exists and is substantially larger than prediction. Is this due to internal motion of the quarks in the hard part of the amplitude? Probe this hypothesis for analogous channel $\chi_{bJ} \to \psi\psi X$ at LHC.

- The color singlet model for ψ production via $gg \to \psi + g$ is inconsistent with Tevatron data. Color Octet Model parameters can take input from LHC data.

Search for process:

- $\chi_{b0,2} \to \psi\psi \to \mu^+\mu^-\mu^+\mu^-$

Predicting the statistics at the LHC, and the expected enhancement relative to the Tevatron:

For $L=10^{33}/\text{cm}^2\text{s}$:

$$\sigma(pp \to \chi_{bi} + X) = \begin{cases} \left.\begin{array}{l} 250 \text{ nb at Tevatron} \\ 1.5\ \mu\text{b at LHC} \end{array}\right\} & \text{for } i=0 \\ \left.\begin{array}{l} 320 \text{ nb at Tevatron} \\ 2.0\ \mu\text{b at LHC} \end{array}\right\} & \text{for } i=2 \end{cases}$$

$$BR(\chi_{bi} \to \psi\psi) = \begin{cases} 2.2\times10^{-4} & \text{for } i=0 \\ 5\times10^{-4} & \text{for } i=2 \end{cases}$$

$$BR(J/\psi \to \mu^+\mu^-) = 5.93\%$$

Selection strategy:

- for muon $p_T^{Level\ 1} > 6$ GeV,
- muon $p_T^{Level\ 2} > 4$ GeV,
- muon $\eta^{Level\ 1\ and\ 2} > 2.5$
- for Pythia subprocesses for χ_b production:
    - $gg \to bb{\sim}[3P0(1)]+g$
    - $gg \to bb{\sim}[3P0(1)]+q$,

Efficiency = 1.63%.

Number of expected χ_{b0} events per year: 200.

Background (4 μ's forming 2 J/ψ's): almost 0.

B_c Production and Decay

Motivation:

Precision reconstruction of B_c ground and excited states can be used to constrain strong potential models.

Analysis strategy:

•Select hadronic B_c decays. The expected mass difference between 2S and 1S is ~600 MeV. Possible channels:

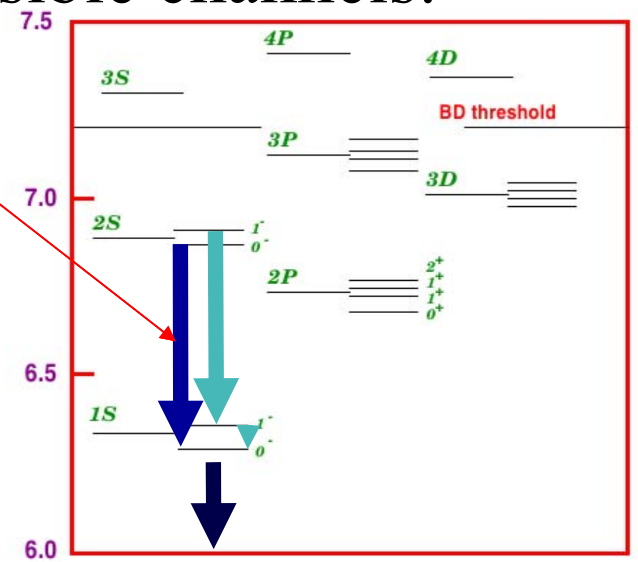
$B^*_c(2^1S_0) \rightarrow B_c(1^1S_0)\,\pi^+\pi^-$

$B_c(1^1S_0) \rightarrow J/\psi\pi^+$

$B^*_c(2^1S_1) \rightarrow B^*_c(1^1S_1)\pi^+\pi^-$

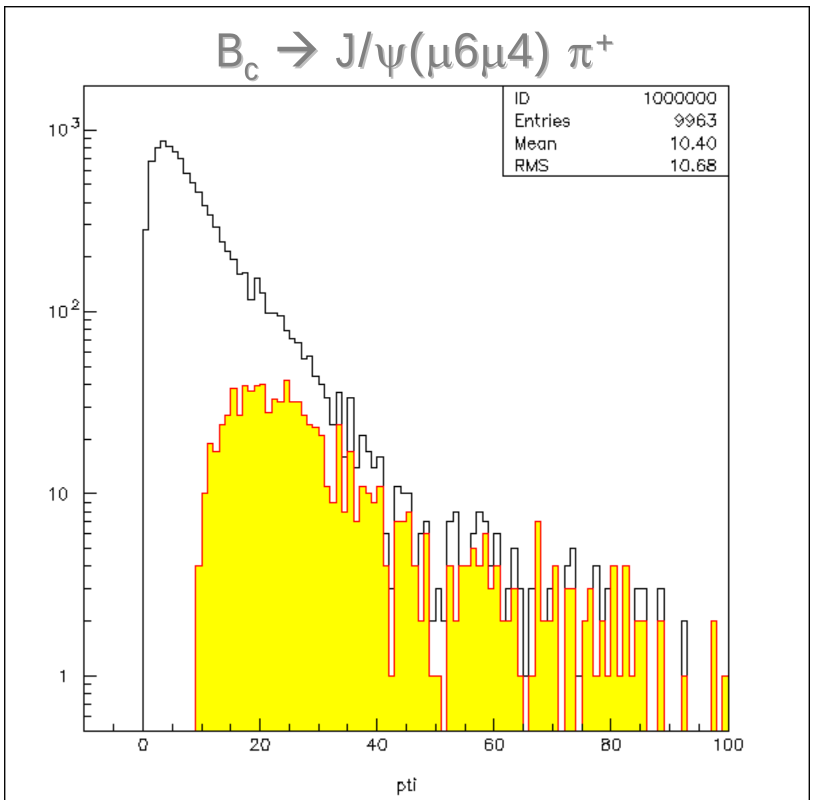
$B^*_c(1^1S_1) \rightarrow B_c(1^1S_0) + \gamma$

$B_c(1^1S_0) \rightarrow J/\psi\pi^+$



The p_T of B_c using standalone generator BCVEGPY2.1 (white)

and p_T of B_c whose muons pass the 6 GeV + 4 GeV requirement (yellow):



Needed:

- Efficient tracking at very low p_T
- Excited state generation and decay in Pythia

Expected number of B_c events in 20 fb^{-1}:

$\# b\bar{b}$ pairs $\times$ $P(b \to B_c) \times BR(B_c \to J/\psi\pi) \times BR(J/\psi \to \mu\mu) \times \varepsilon(\mu\mu\text{-trig}) \times \varepsilon(\text{cuts})$:

$1.4 \times 10^{11} \times 0.0015 \times 0.002 \times 0.0593 \times 0.61 \times 0.64 =$

10000 events.

Conclusions

- With 1 fb^{-1}, the Λ_b studies will yield:
  - the Λ_b lifetime, known better than the present world average
  - first results on the Λ_b polarization.
- The large predicted onia cross sections at the LHC will permit definitive studies of:
  - quarkonium spin alignment as a test of the Color Octet Mechanism. 100 pb^{-1} are needed for a competitive polarization measurement.
  - jet activity associated with onium decay: the Color Singlet and Color Octet Mechanisms predict different associated jet activity levels.

Conclusions, *continued*

- with 10 pb^{-1}, ATLAS will measure ratios of onia cross sections to constrain NRQCD octet matrix elements. Subsequent statistics 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 EW and strong forces.

- χ_b decays may point the way to solving longstanding puzzles in the $gg \rightarrow \psi + g$ and $e^+e^- \rightarrow \psi\eta_c$ cross sections.