Quarkonia Production at CDF in Run II

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2nd Quarkonium Workshop
September 20-22, 2003
Fermilab, IL, USA

CDF Detector in Run II

Inherited from Run I:

Central Calorimeter (|h|<1)

Solenoid (1.4T)

Partially New:

Muon system (extended to |η|~1.5)

Completely New:

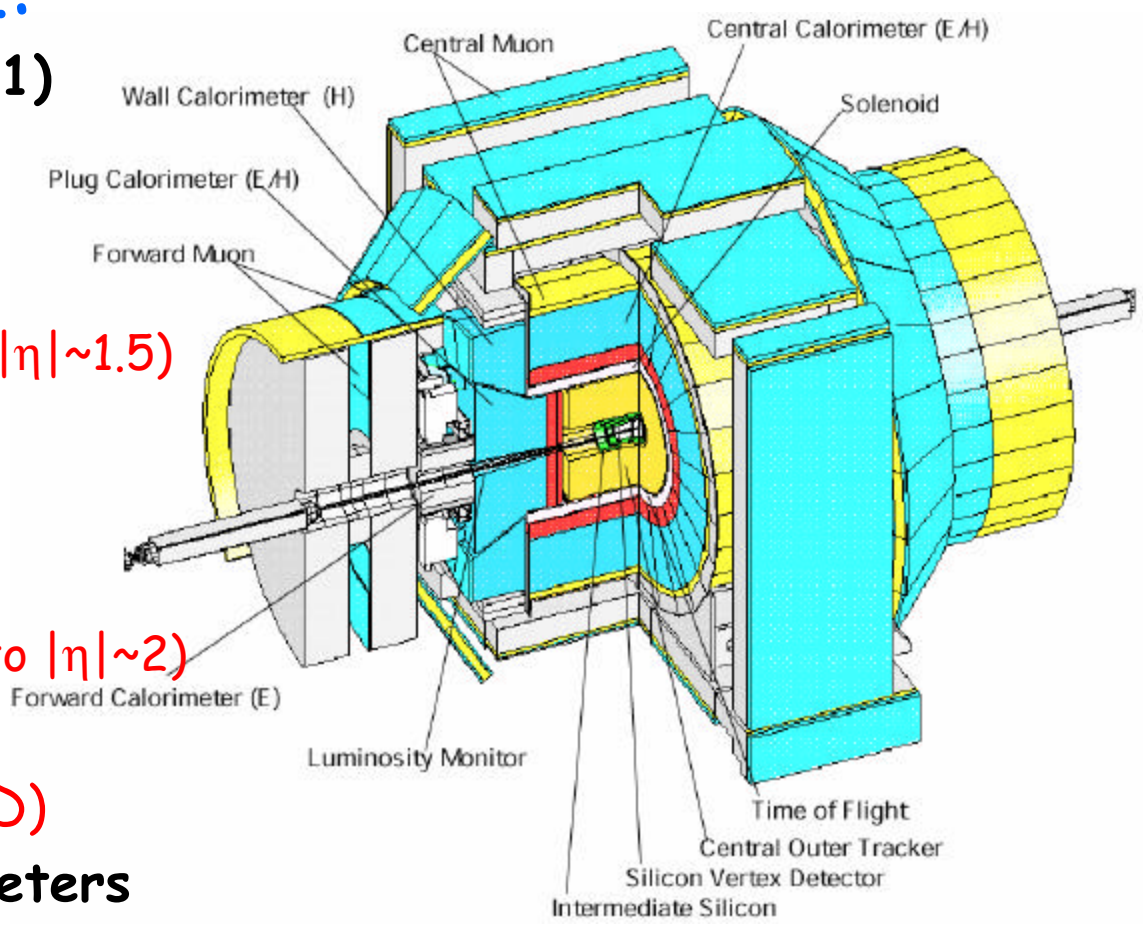
Tracking System

- 3D Silicon Tracker (up to |η|~2)
- Faster Drift Chamber

Time-of-Flight (particle ID)

Plug and Forward Calorimeters

DAQ & Trigger system (Online Silicon Vertex Tracker: trigger on displaced vertices, first time at hadron collider)



B physics with Run II CDF

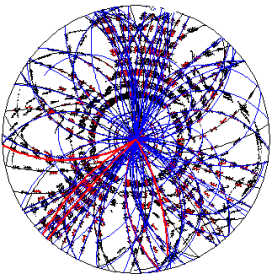
Open wide spectrum of B hadrons
$B^{\pm}$, B^0, B_s, B_c, Λ_b, Ξ_b ... (unuque)

$b\bar{b}$ cross section is 50-100 mb
~$O(10^5)$ larger than e^+e^-@ $\Upsilon(4S)/Z^0$
~$O(10^3)$ B's per second at design luminosity
(~10 B's per second at $\Upsilon(4S)$ factories)
BUT:
- B hadrons are hidden in a 10^3 larger background ($\sigma_{inelastic}(pp)$ » 50 mb
- Events more complicated than at $\Upsilon(4S)$

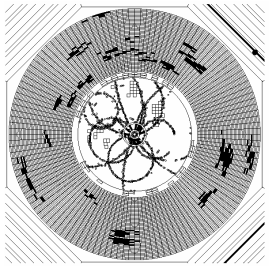
BRs for interesting processes: ~$O(10^{-6})$
- S/B @ production (Tevatron): ~10^{-9}
- S/B @ production (B factory): ~10^{-6}

Mean multiplicity of tracks/event: ~4 $\Upsilon(4S)$
- Combinatoric background

Events pile-up within the same beam x-ing
- Combinatoric background
- Typical S/B @ analysis level: ~$O(0.5 \div 5)$



CDF



CLEO

Solution:
Vertex detector
+ trigger
+ Particle ID

B physics signatures:

- QCD physics
  - Quarkonium cross section and B fraction down to 0 GeV, polarization
  - B cross section; fragmentation
- CKM studies: CP violation and mixing
  - B_s mixing, $B_s \to D_s\pi$, $l\nu D_s$
  - $|V_{td}|$: $B^0 \to J/\psi K^{*0}$, $l\nu D$, $|V_{ts}|$: $B_s \to J/\psi \phi$
  - $\Delta\Gamma_s$: $B_s \to J/\psi \phi$, $J/\psi\eta$, $l\nu D_s$, D_sD_s
  - CP asymmetry: $B^0(B_s) \to hh$
  - γ: $B_s \to D_sK^+$, $B \to DK$
  - γ: B^0, $B_s \to K\pi,\pi\pi,KK$
  - β: $B^0 \to J/\psi K^0_s$
  - α: $B^0 \to \pi\pi$
- Properties of B_s, B_c, Λ_b, etc
  - Production, mass, lifetime
- Rare decays
  - $B \to \mu\mu K^{(*)}$
  - Physics beyond the standard model: B^0, $B_s \to \mu\mu$ and $B_s \to e\mu$

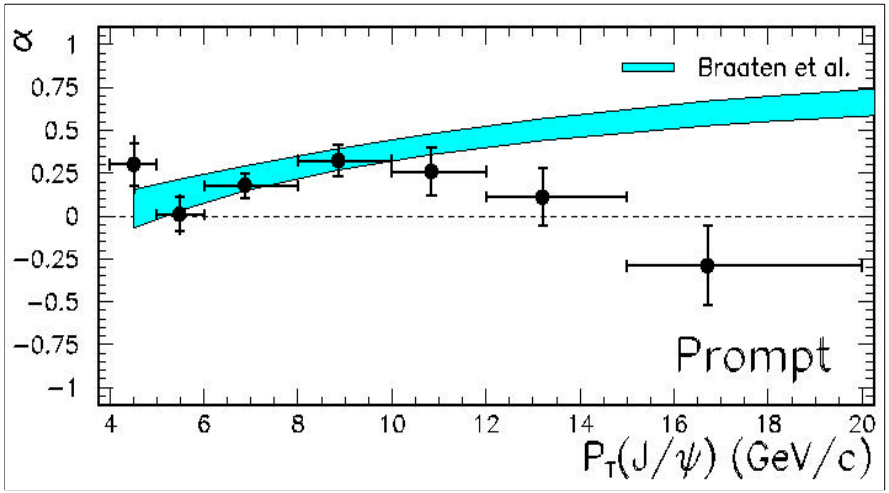
J/y production cross section

Theory: Non-Relativistic QCD (NRQCD)

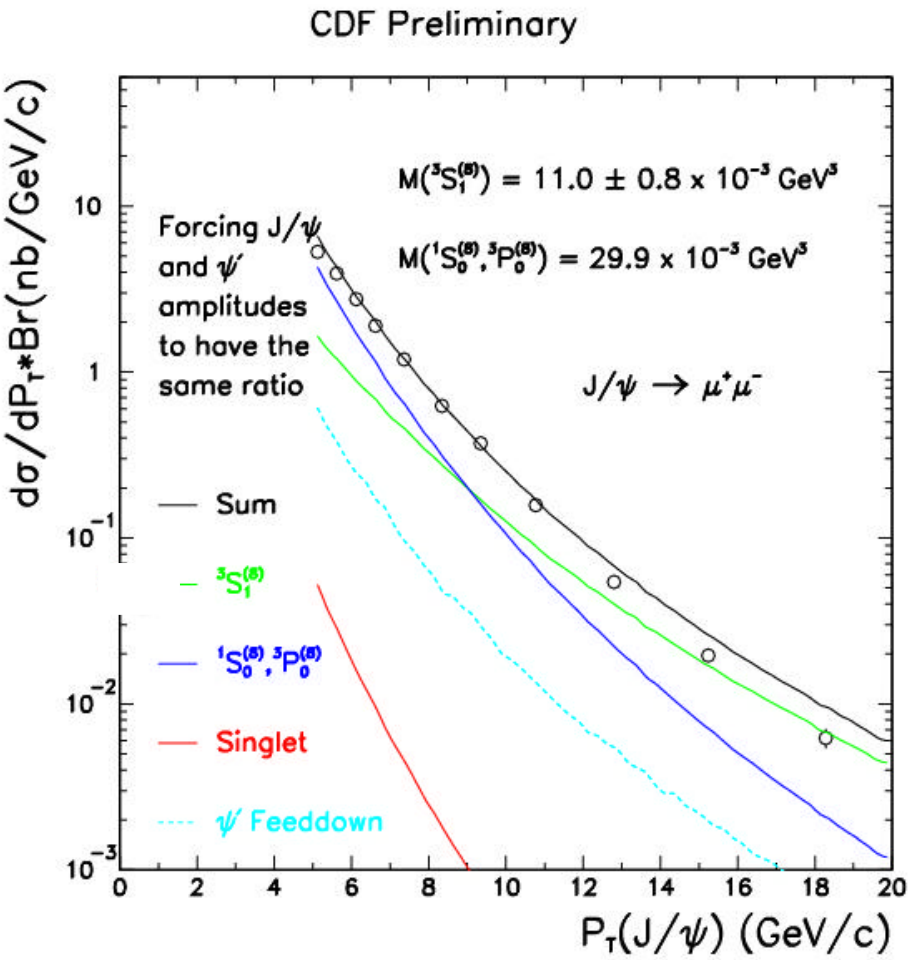
- color octet and color singlet mechanism
- J/y production is dominated by the color octet mechanism
- reasonable agreement of the shape with Run I data
- normalized by fitting the data
- no prediction at low p_T(J/y)
- J/y is polarized at high p_T

(2s discrepancy with Run I)

Run II: 1.8 TeV ⇨ 1.96 TeV



CDF Run I J/y production 1.8 TeV



Lepton B triggers

$\sigma(b\bar{b}) / \sigma(p\bar{p}) \approx 10^{-3}$ ⇒ Need specialized triggers

CDF Run I, lepton-based triggers:

- Di-leptons ($\mu\mu$, $P_T \geq 2$ GeV/c): $B \rightarrow J/\psi\, X$, $J/\psi \rightarrow \mu\mu$
- Single high P_T lepton (≥ 8 GeV/c): $B \rightarrow l\, \nu\, D\, X$

Suffer of low BR and not fully reconstructed final state

Nevertheless, many important measurements by CDF I:
B^0_d mixing, sin(2β), B lifetimes, B_c observation, …

Now enhanced, thanks to XFT (precise tracking at L1) :

- Reduced (2→1.5 GeV/c) and more effective P_T thresholds
- Increased muon and electron coverage
- Also $J/\psi \rightarrow ee$

J/y ®mm sample

Di-m trigger (J/y)

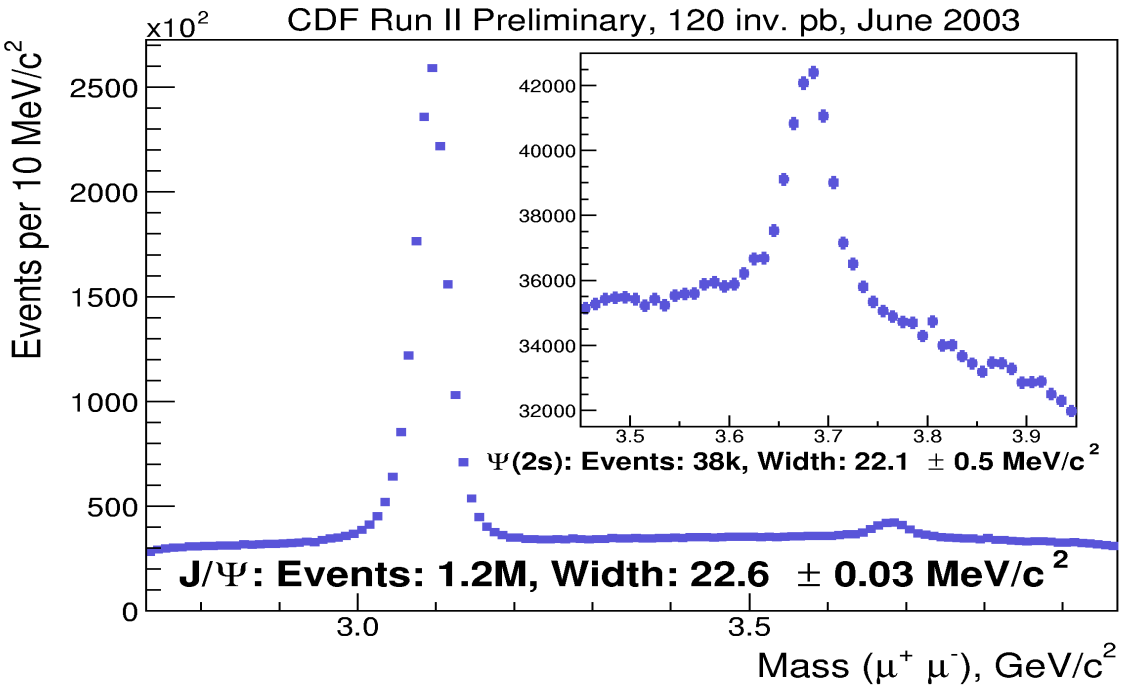
2 central muons

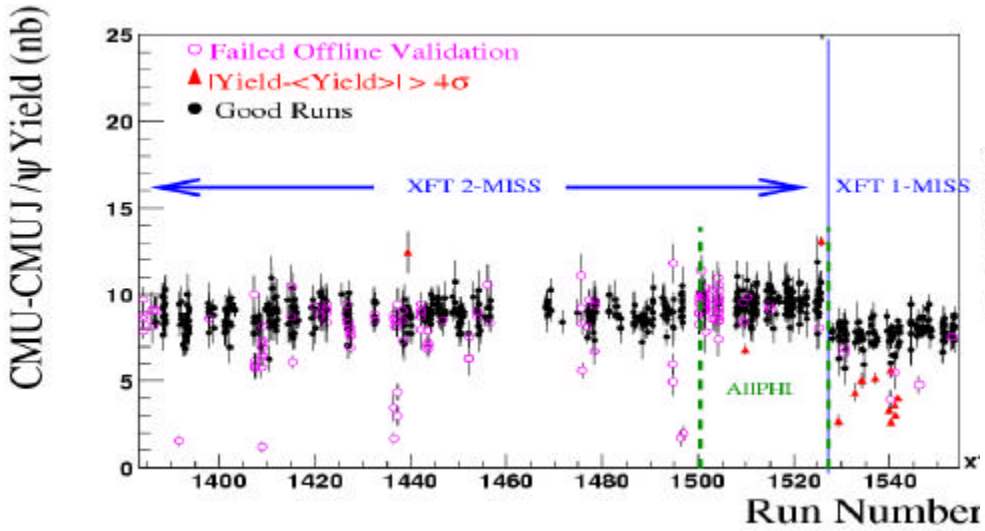
$P_T(m)$ ³ 1.5 GeV, $P_T(J/y)$ ³ 0

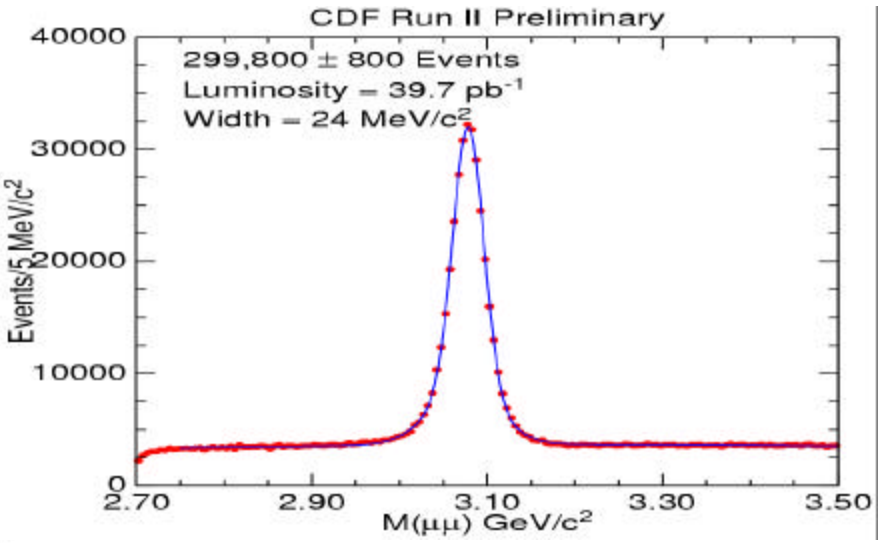
Run I: $P_T(m)$ > 2 GeV, 18 pb^{-1}

Trigger on J/y ®mm
Collected ~ 240 pb^{-1}
~ 2.4M J/y ®mm signal

J/y modes down to low $P_T(J/\psi)$ (~ 0 GeV)



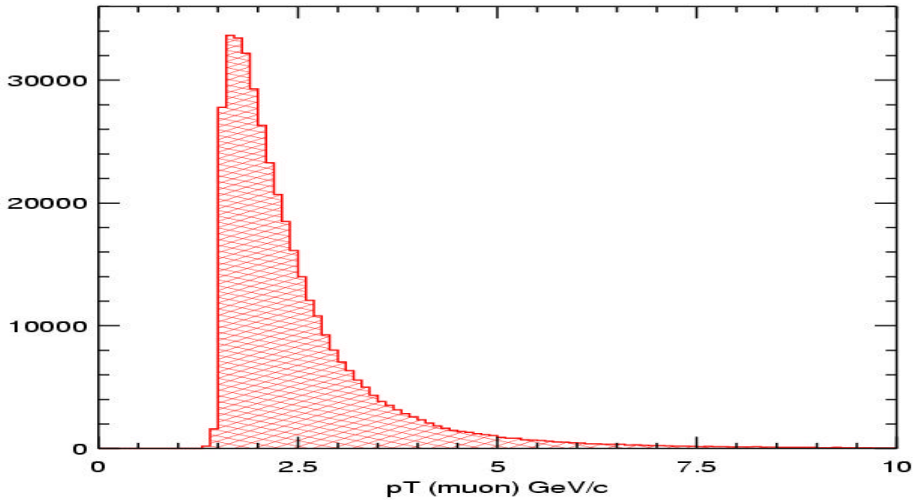


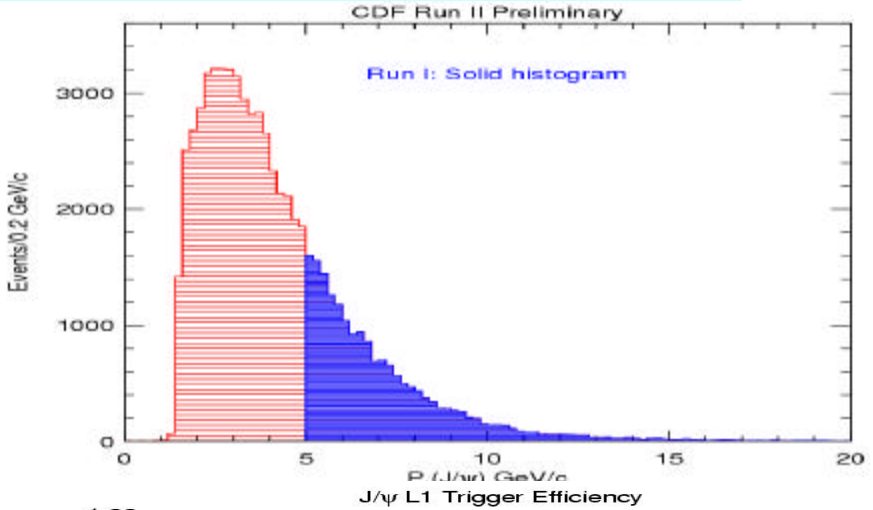


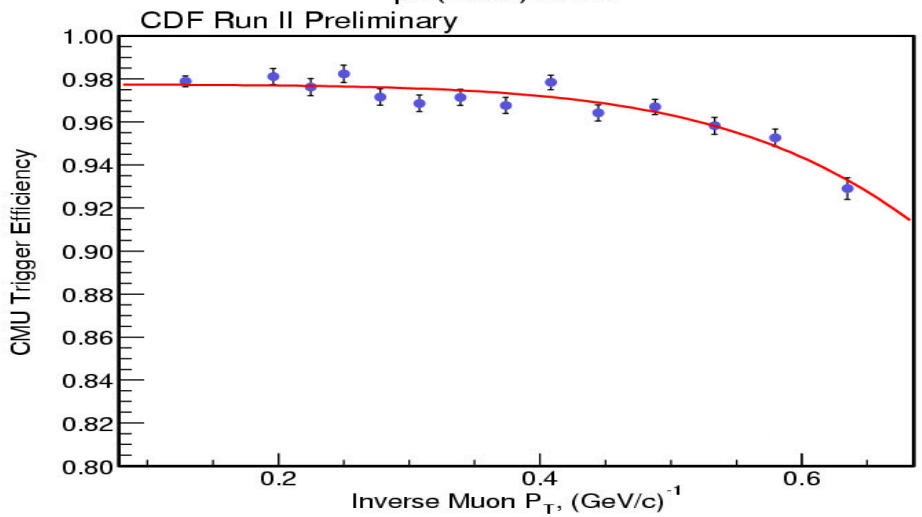
J/y ® μμ

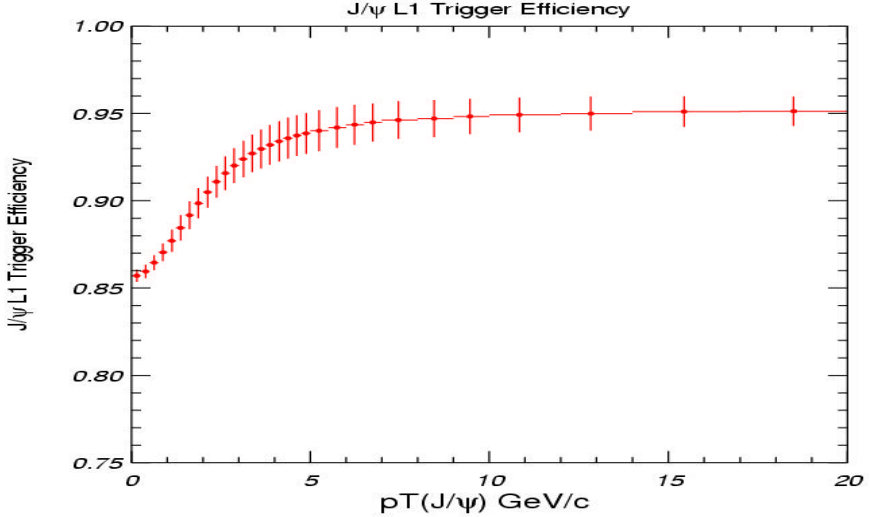
Run II dimuon sample: yield 10 nb, $p_T(\mu)>1.5$ GeV/c

Run I measurement: yield 3 nb, $p_T(J/y)>5.0$ GeV/c, $p_T(\mu)>2.0$ GeV/c



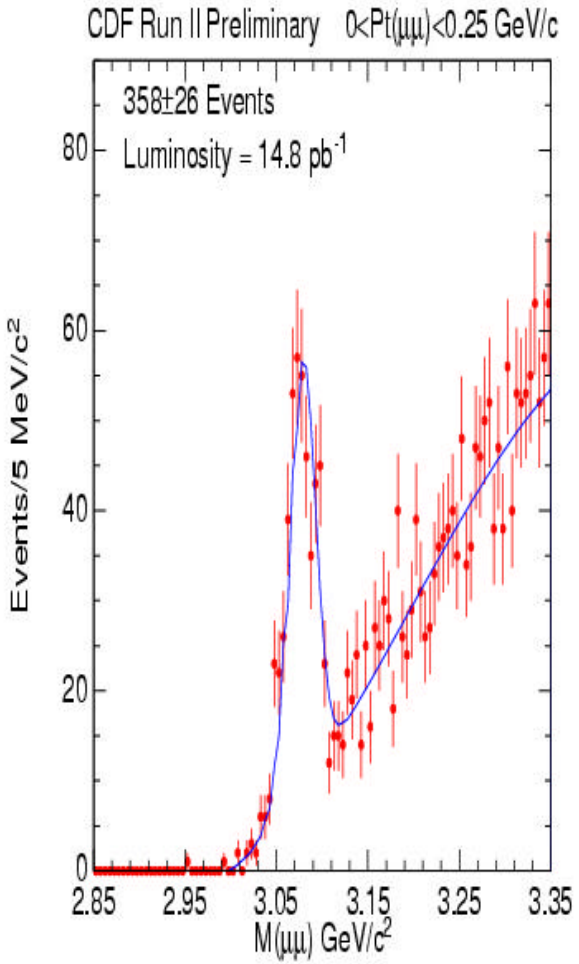




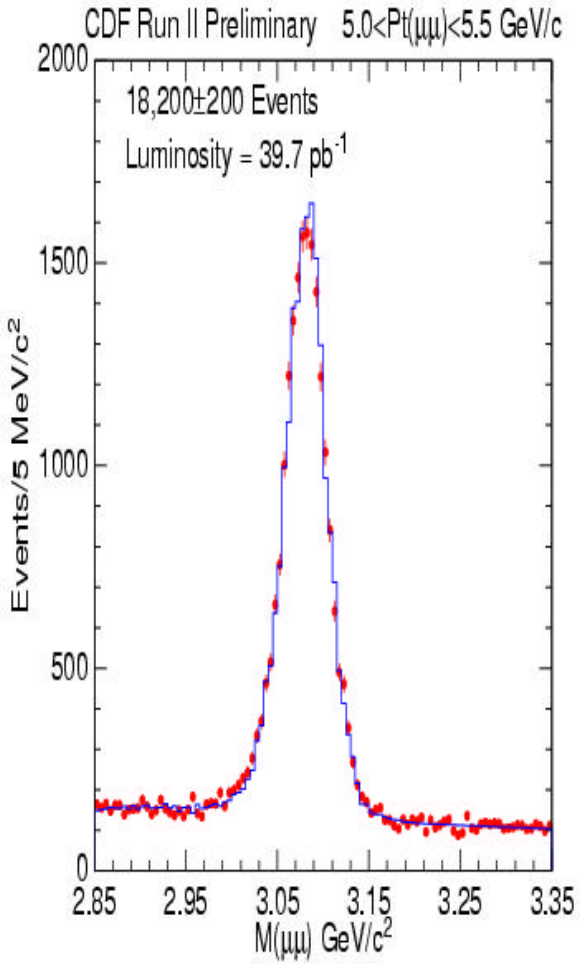


J/ψ Yield from Invariant Mass Fits

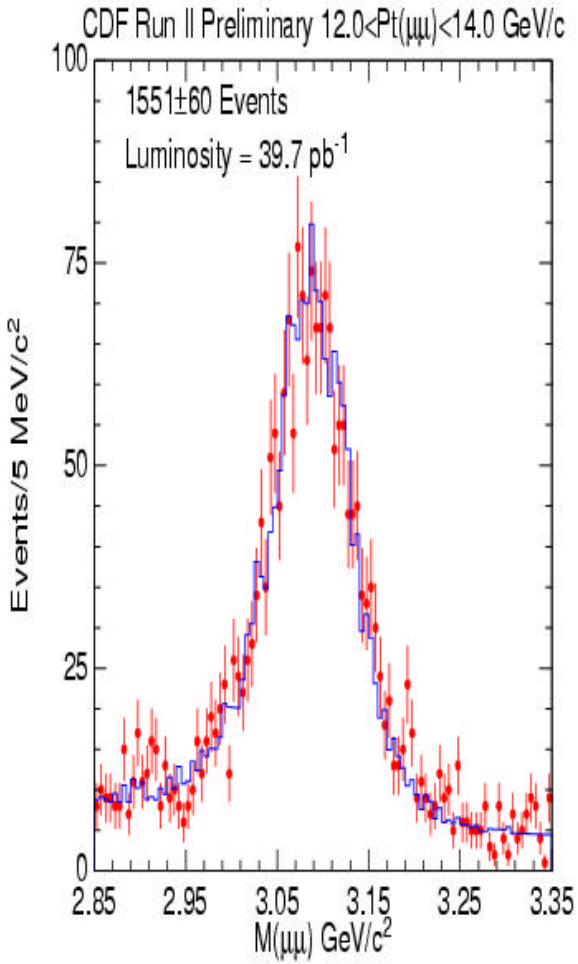
Fitted using signal MC mass template shapes + Chebyshev polynomial for background



$0 < p_T(J/\psi) < 0.25 GeV/c$



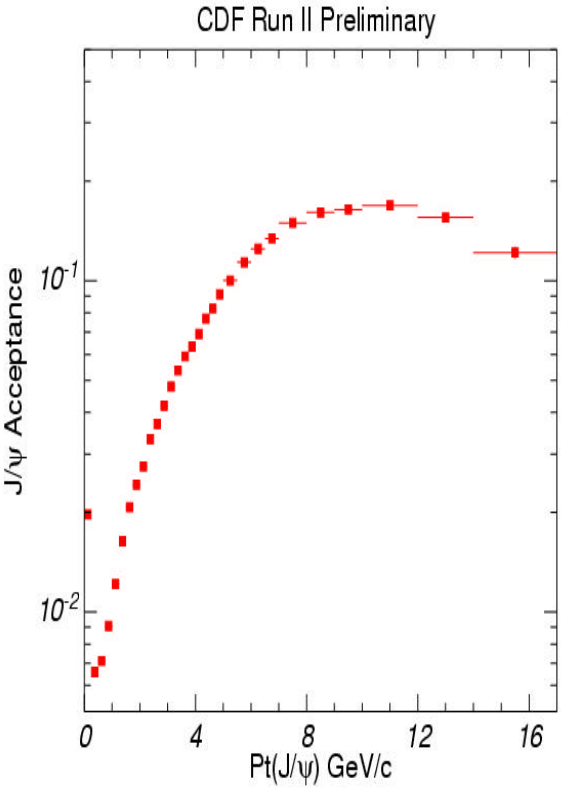
$5.0 < p_T(J/\psi) < 5.5 GeV/c$

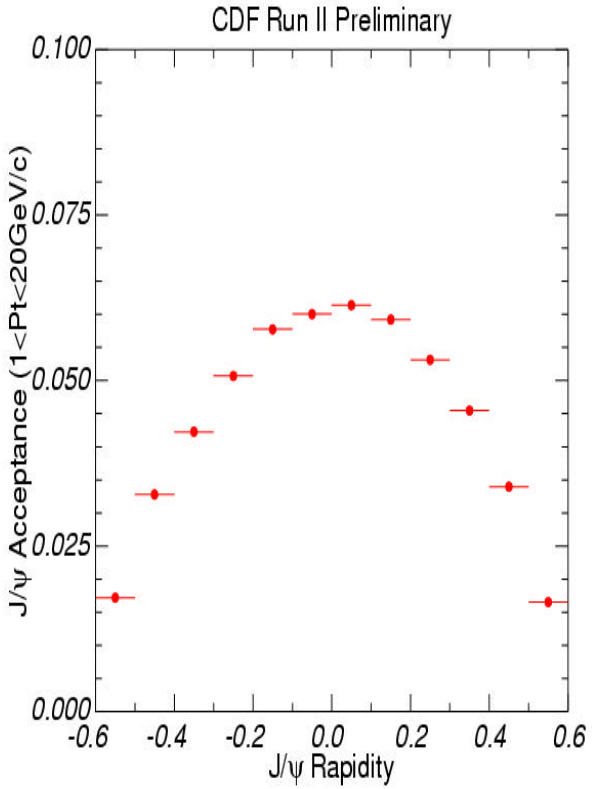


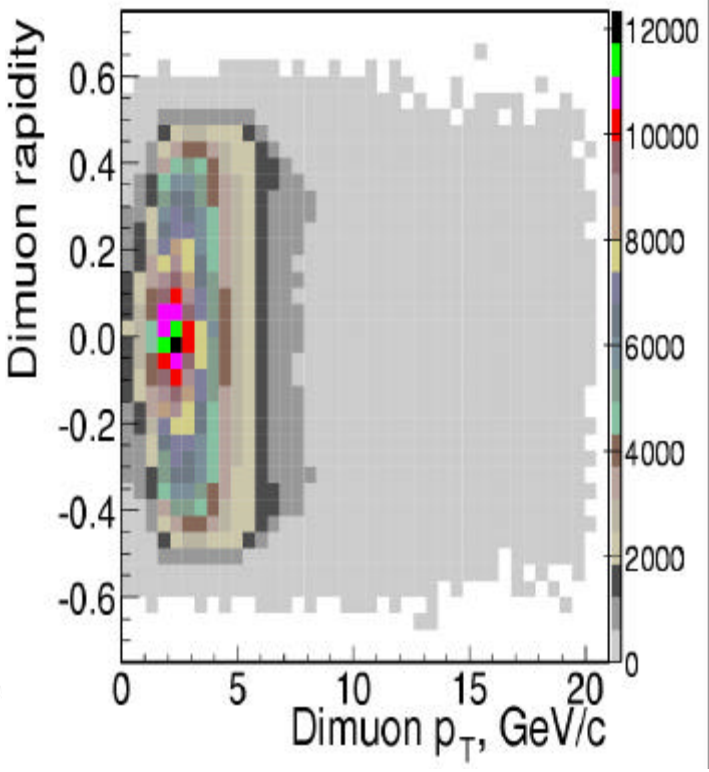
$10.0 < p_T(J/\psi) < 12.0 GeV/c$

Acceptance A (p_T(J/y), |y|<0.6)

Full GEANT simulation of the CDF detector, kinematics match well
Parametric simulation also used to study effects of different detector components



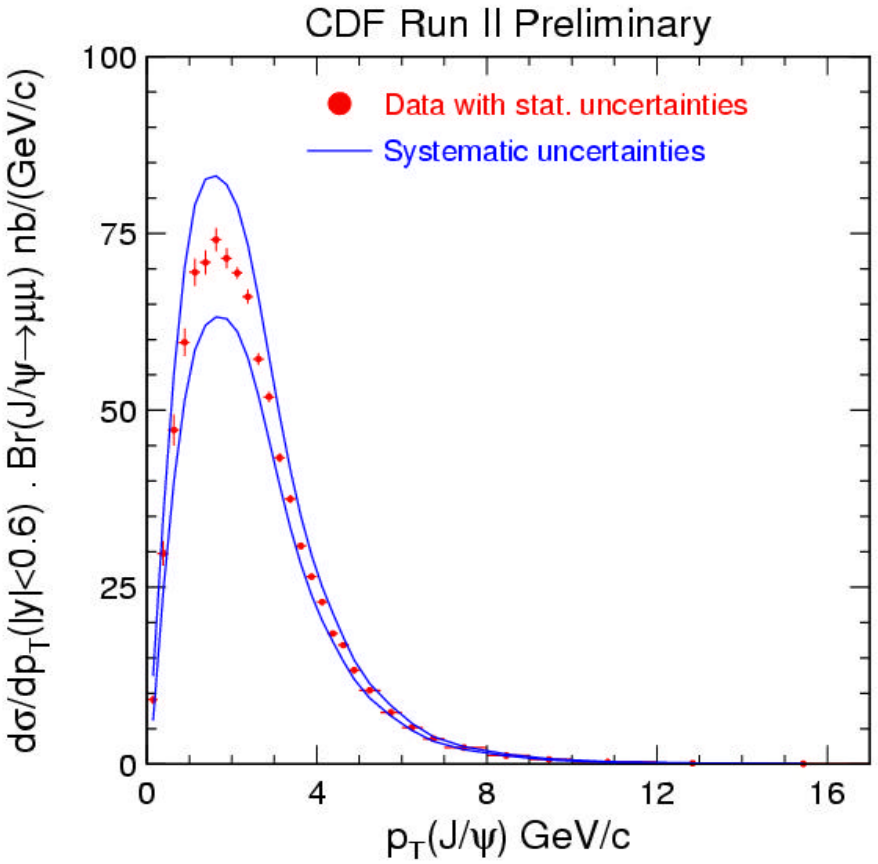


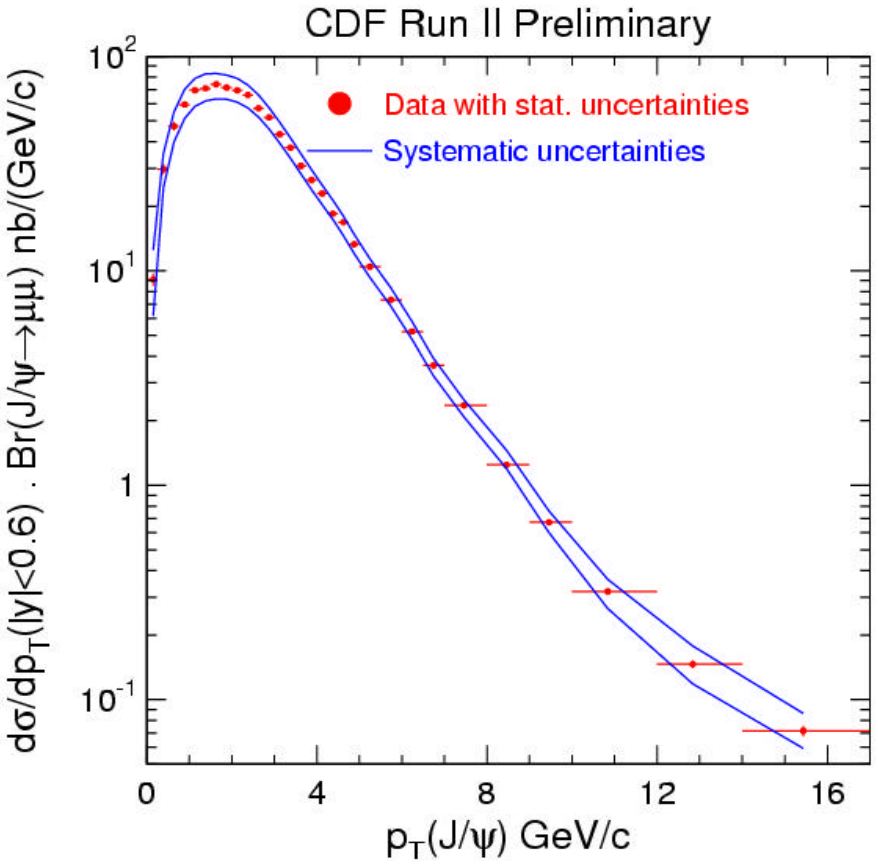


MC

data

Differential Cross Section





Total Integrated Inclusive J/y Cross-Section:

$$\sigma(p\bar{p}\to J/\psi X, |\, y(J/\psi)\,| < 0.6, \cdot Br(J/\psi\to\mu\mu) = 240 \pm 1(stat)^{+35}_{-28}(syst)\ \text{nb}$$

$$\sigma(p\bar{p}\to J/\psi X, |\,\eta(J/\psi)\,| < 0.6,\ p_T(J/\psi) > 5.0\,\text{GeV/c})\cdot Br(J/\psi\to\mu\mu) = 17.4 \pm 0.1(stat)^{+2.6}_{-2.8}(syst)\ \text{nb}$$

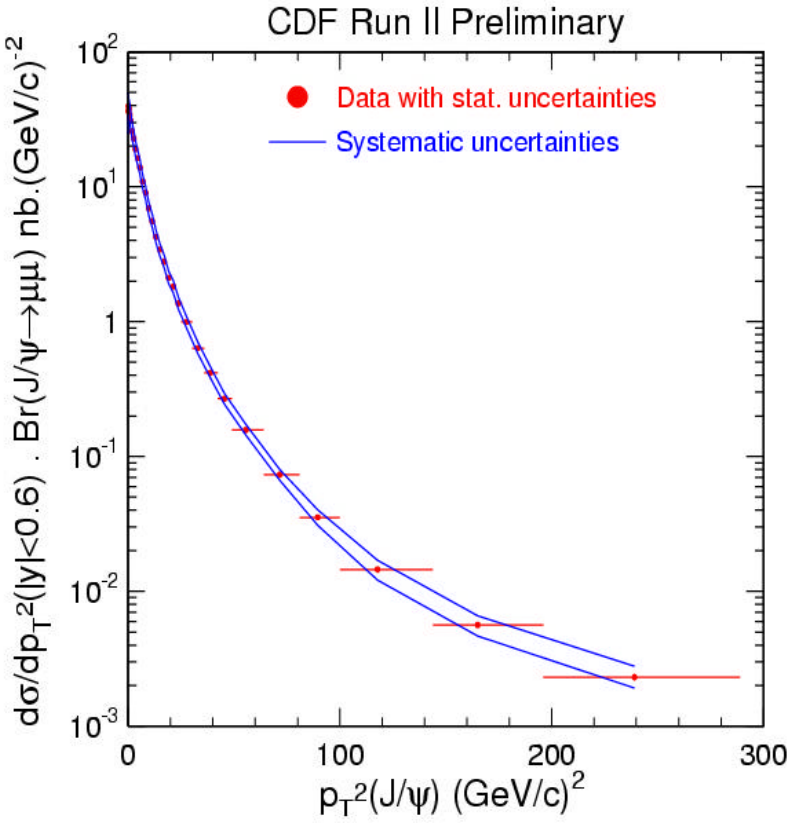
Run I measurement

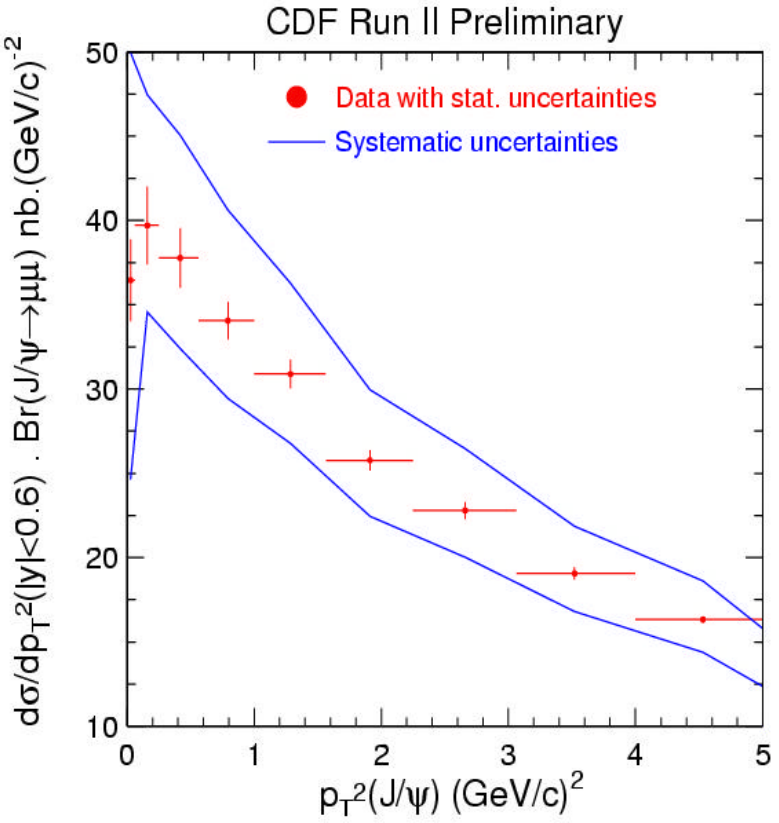
Systematic uncertainties

Source	Systematic uncertainty
J/ψ Polarization	$\pm 4 - 10\%$ (p_T dependent)
J/ψ Spectrum	$\pm 3 - 30\%$ (p_T dependent)
SVXII material	-3% *to* $+6\%$ (p_T dependent)
L1 trigger efficiency	-7.0% *to* $+13\%$ (p_T dependent)
Mass fits	-0.7% *to* $+13\%$ (p_T dependent)
Momentum scale	-0.08% *to* $+0.7\%$ (p_T dependent)
Luminosity	$\pm 5.9\%$
CMU Simulation	$\pm 1.4\%$
Data quality	$\pm 1.0\%$
Reconstruction eff.	$+2.1 - 2.7\%$
L1 trigger efficiency	$\pm 0.2\%$
Total	$\pm 6.7\% \oplus \epsilon(p_T^{J/\psi})$

Cross Section: $d\sigma/dp_T^2$

$d\sigma/dp_T^2$ is Lorentz invariant phase space element proportional to the matrix elements





Measurement of the J/ψ Meson and b Quark Production Cross Sections in $\bar{p}p$ Collisions at $\sqrt{s} = 1960$ GeV

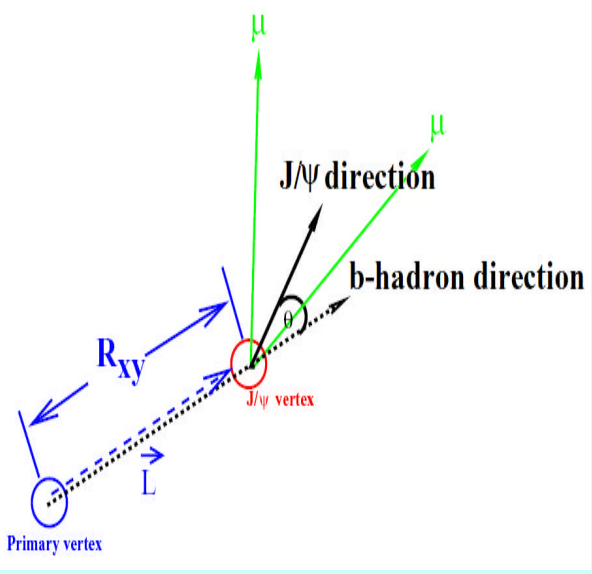
M.Bishai et al.

b-fractions

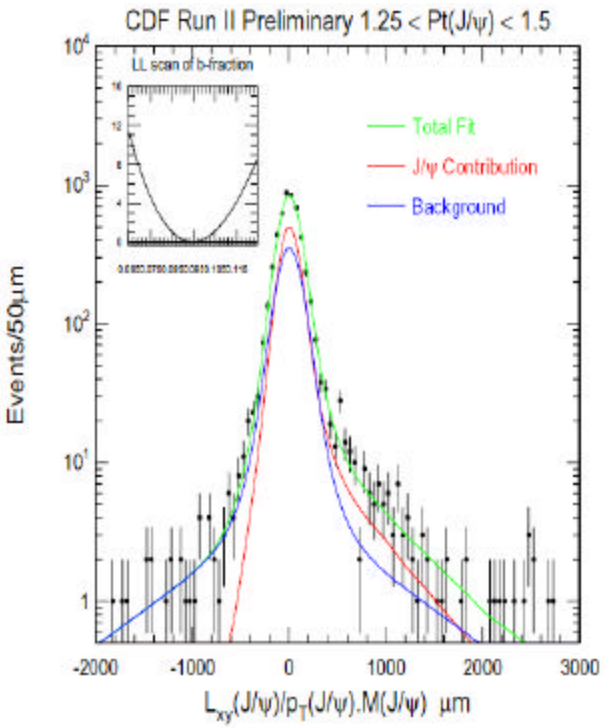
Simultaneous fit was used to J/y proper decay length, $X = L_{xy}(J/y)/p_T(J/y)\, M(J/y)$ and invariant mass $M(mm)$ to extract the fraction of events from b-hadron decays

- B-hadron signal shape: MC templates of X distributions are convoluted with resolution function measured in data
- Prompt signal shape: A double Gaussian with width of the dominant Gaussian = scale factor X decay length uncertainty. 2nd Gaussian relative width and area fixed. This is also the resolution function shape.
- Background decay length shape: A prompt double Gaussian with different scale factor + symmetric exponential + long lived positive exponential
- Invariant mass signal shape: Double Gaussian with all parameters floating
- Invariant mass background shape: 1st order polynomial

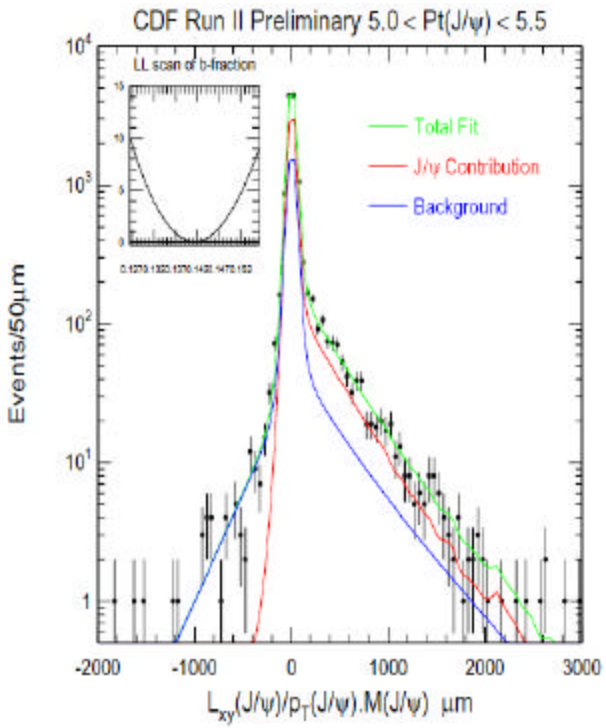
MC templates used for B®J/y signal with decay table tuned using CLEO results
Lxy/p_T convoluted with resolution function
Reliable separation for J/y from B and prompt at $p_T(J/y)>1.25$ GeV
J/y has different shapes for B and prompt components
Fitter tested on MC sample
MC templates of the J/y proper decay length, X are used to fit the b-hadron contribution to the inclusive J/y distribution.
A parametric simulation is used to model the detector geometric and kinematic acceptance



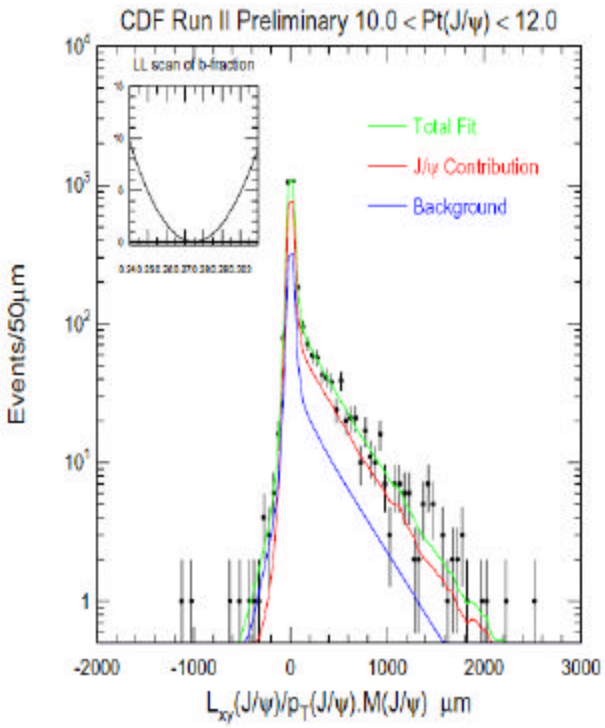
b-fractions



$$f_b = 0.097 \pm 0.010^{+0.012}_{-0.010}$$

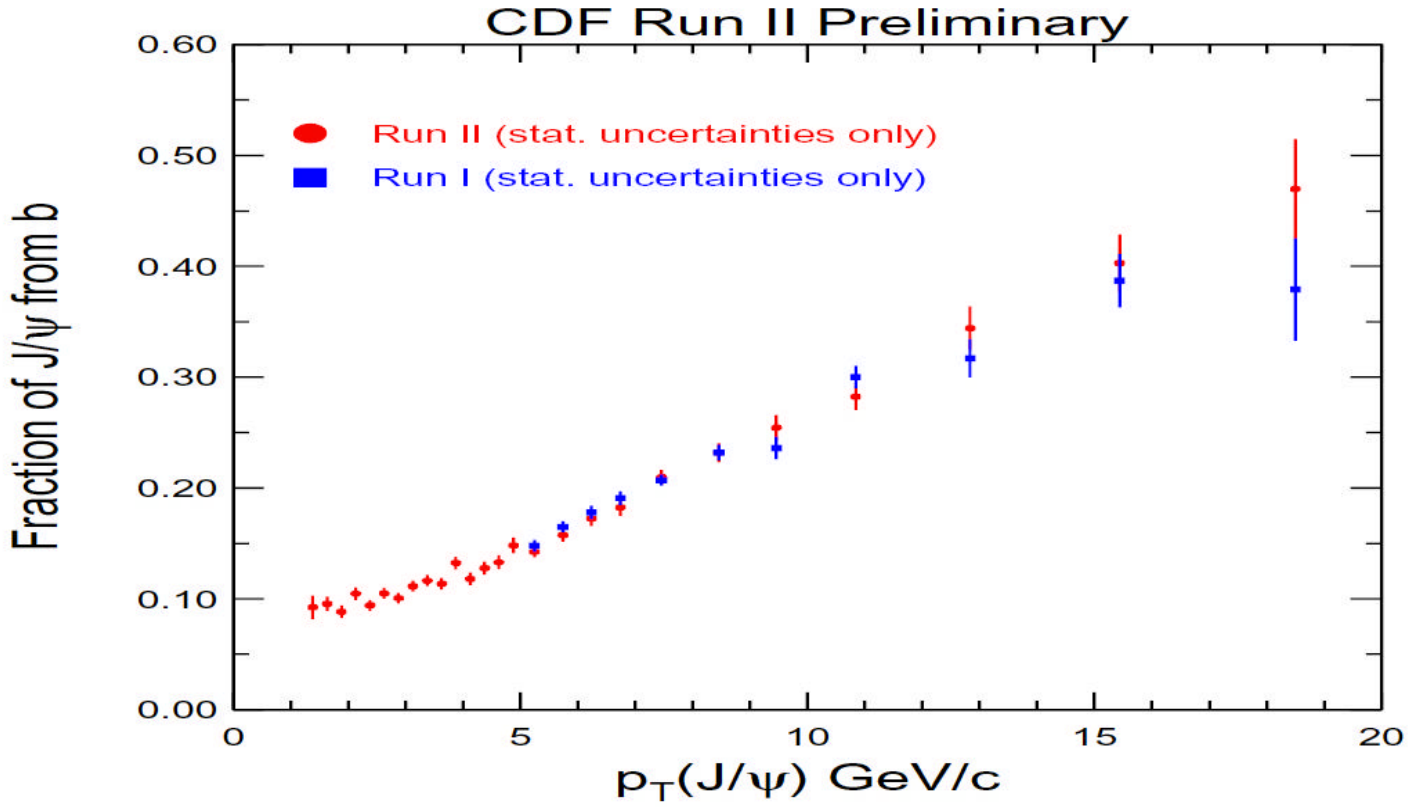


$$f_b = 0.143 \pm 0.005^{+0.006}_{-0.006}$$



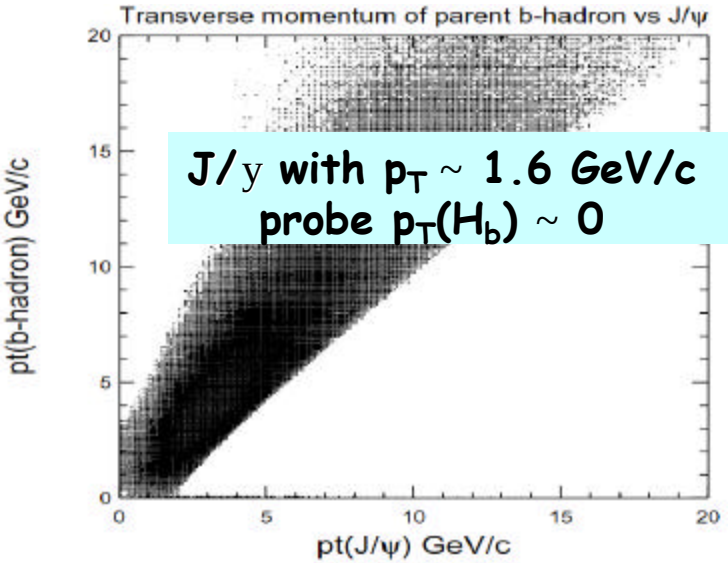
$$f_b = 0.279 \pm 0.012^{+0.008}_{-0.007}$$

b-fractions

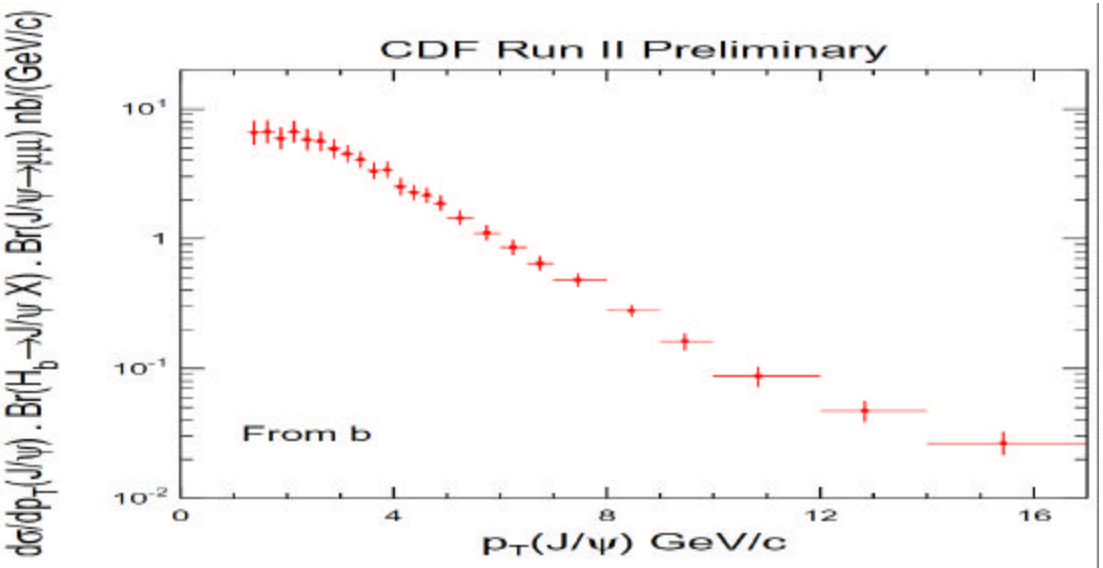


Source of uncertainty	Value
Uncertainties on b-fraction	
Resolution function shape (including tails)	$1-8\%$ (p_T dependent)
MC production spectrum	$2-7\%$ (p_T dependent)
MC decay spectrum	$0.5-4\%$ (p_T dependent)
MC b-hadron lifetime	$1-4\%$ (p_T dependent)
Background fit model	$< 3\%$ (p_T dependent)

b Cross Section

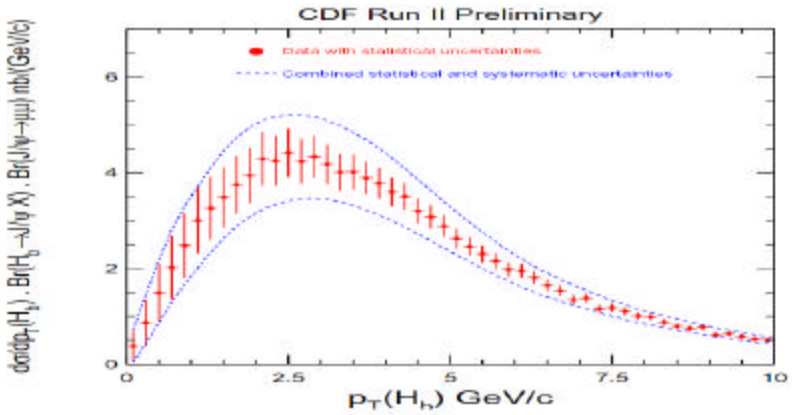


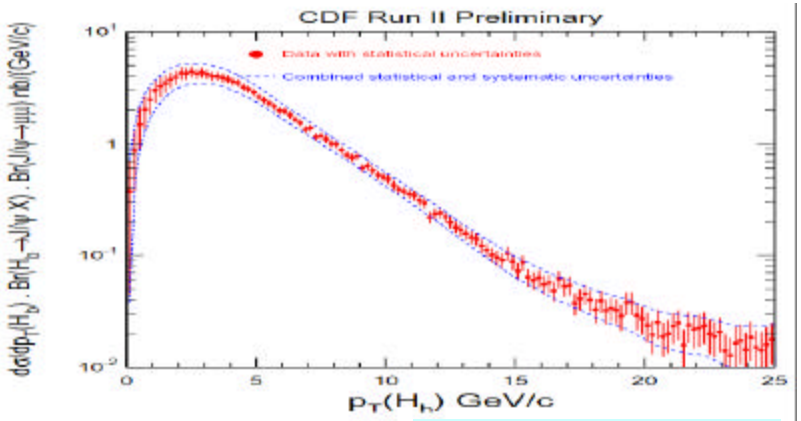
J/ψ with $p_T \sim 1.6$ GeV/c probe $p_T(H_b) \sim 0$



Integrated J/ψ →

$$\sigma(p\bar{p} \to bX, p_T(J/\psi) > 1.25 \text{ GeV/c}, |y(J/\psi)| < 0.6|) \cdot Br(H_b \to J/\psi X) \cdot Br(J/\psi \to \mu\mu) = 19.9 \pm 0.3(stat) \pm 3.8(syst) \text{ nb}$$





$$\sigma(p\bar{p} \to H_b X, |y| < 0.6).Br(H_b \to J/\psi X).Br(J/\psi \to \mu\mu) = 24.5 \pm 0.5(stat) \pm 4.7(syst) \text{ nb}$$

Total b hadron

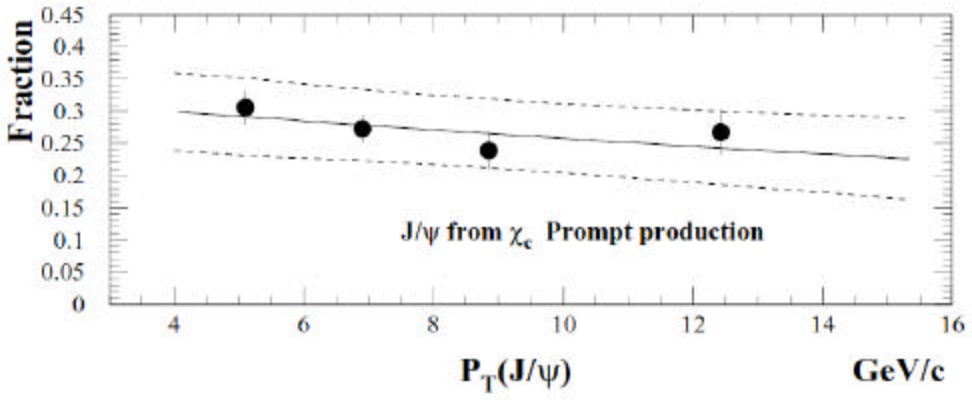
$$\sigma(p\bar{p} \to \bar{b}X, |y| < 1.0) = 29.4 \pm 0.6(stat) \pm 6.2(syst)\mu\text{b}$$

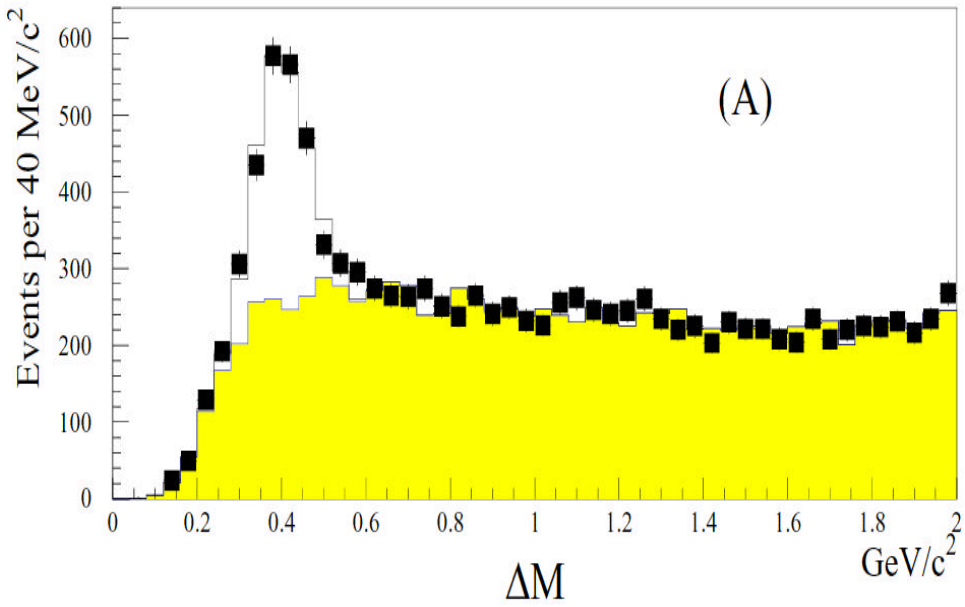
Total b quark

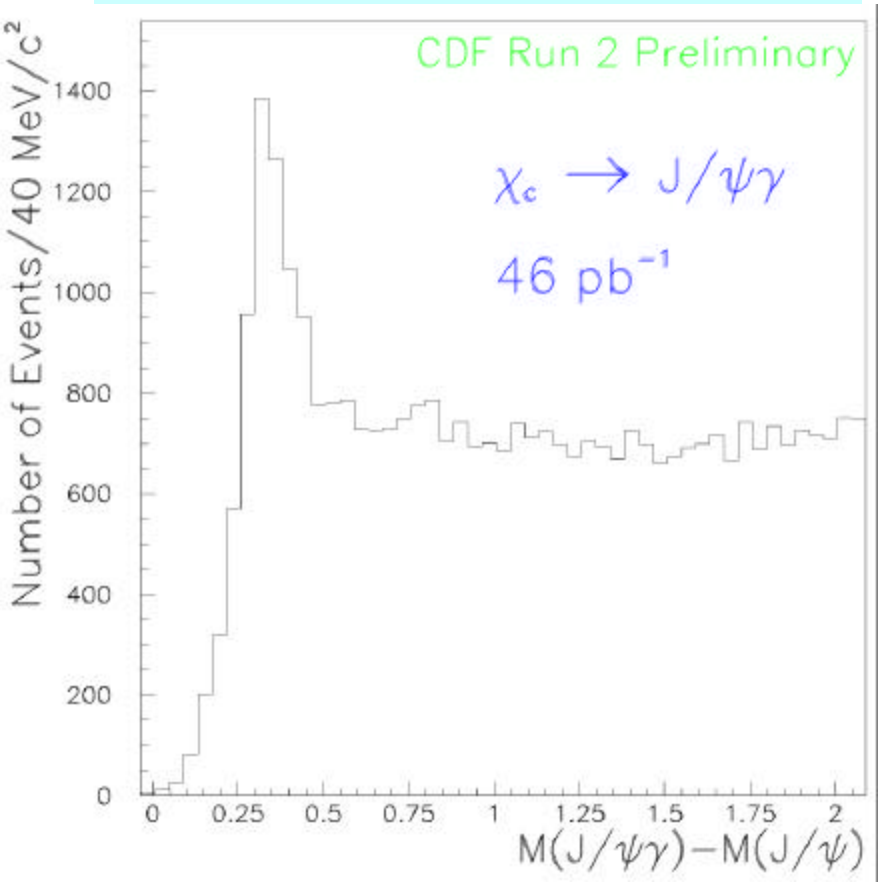
c_c contribution

PRL 79, 578 (1997)

65% of prompt J/y are direct
35% - from c_c and y(2S)
$p^+p^- \rightarrow c_c X$; $c_c \rightarrow J/y\ g$
Run I: 1230±72 events in 18 pb^{-1}

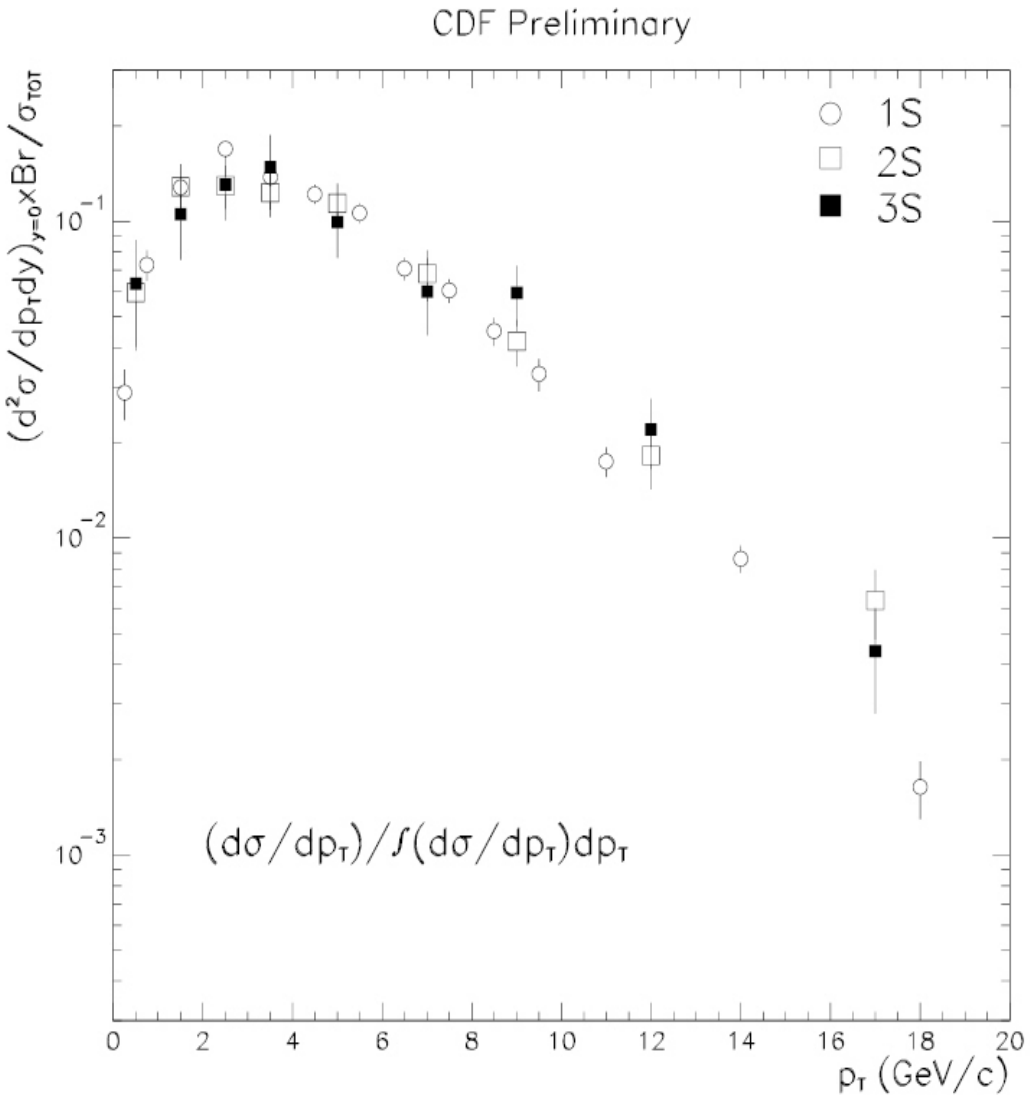


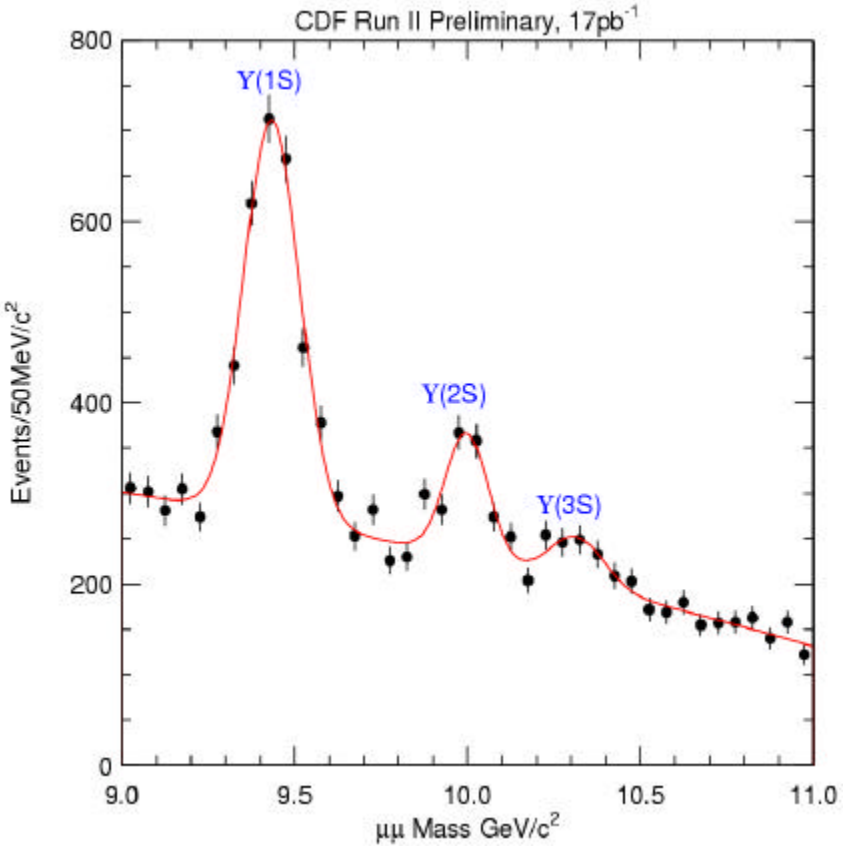




DM=M(J/yg) - M(J/y)

52% of prompt ¡(1S) are direct ¡(1S) unpolarized at 2-20 GeV/c
Run I: 77pb^{-1}. 4430±95 ¡(1S), 1114±65 ¡(2S), 584±53 ¡(3S)
|y(¡)|<0.4 p$_T$(¡) = 0-20 GeV/c



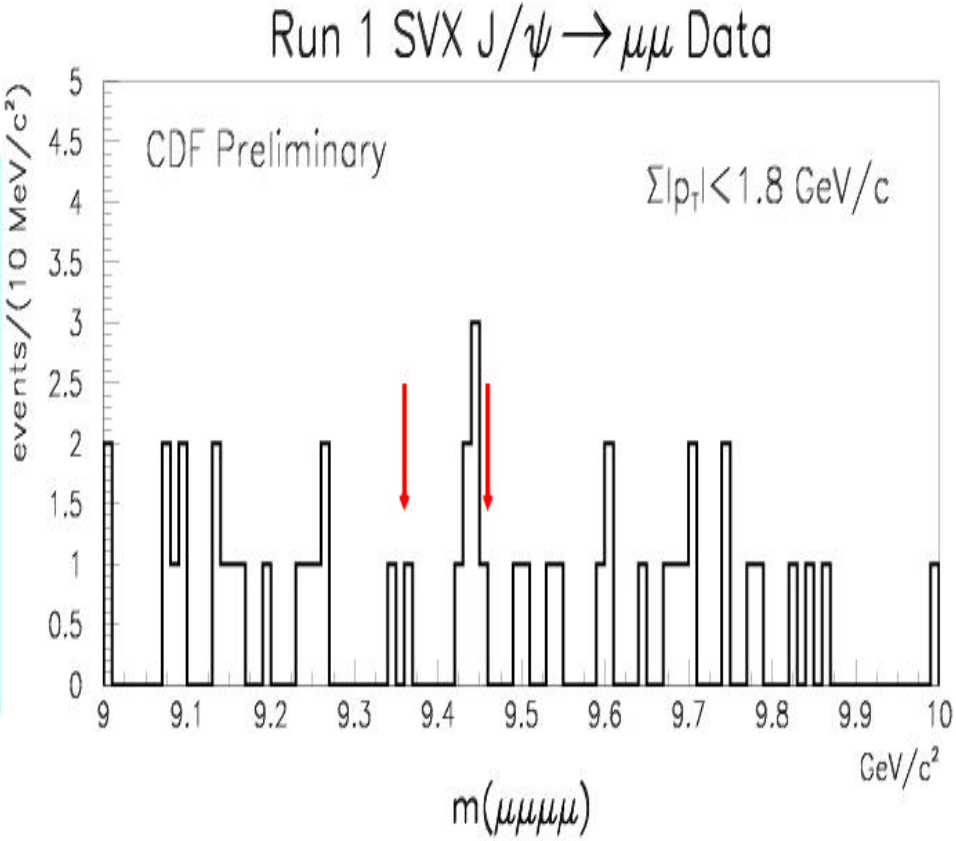


h_b

Search for h_b in Run I data (80 pb^{-1}):

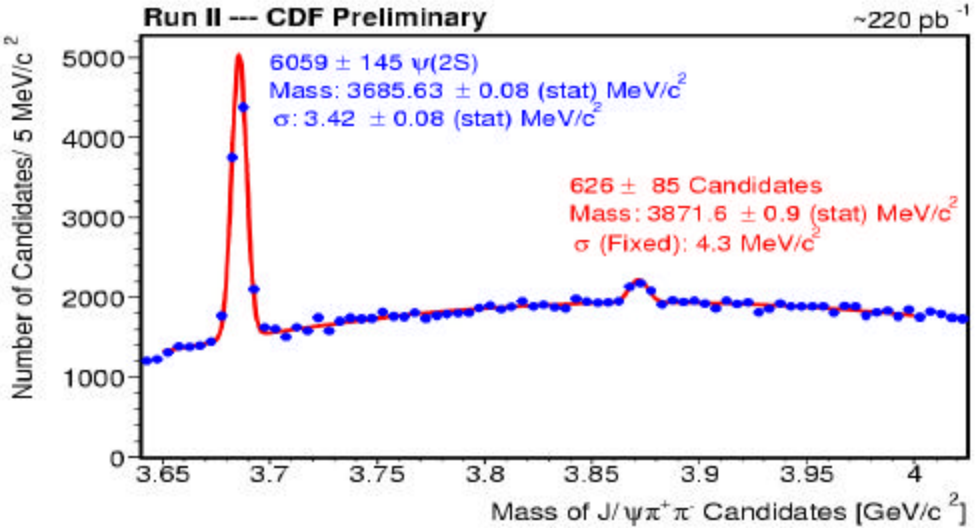
Decay h_b ® J/y J/y
Expected mass: 9.36 – 9.46 GeV
7 events in window (background: 1.8 events)
1.5% probability (2.2s)
Mass of potential signal 9446 ± 6(stat) MeV

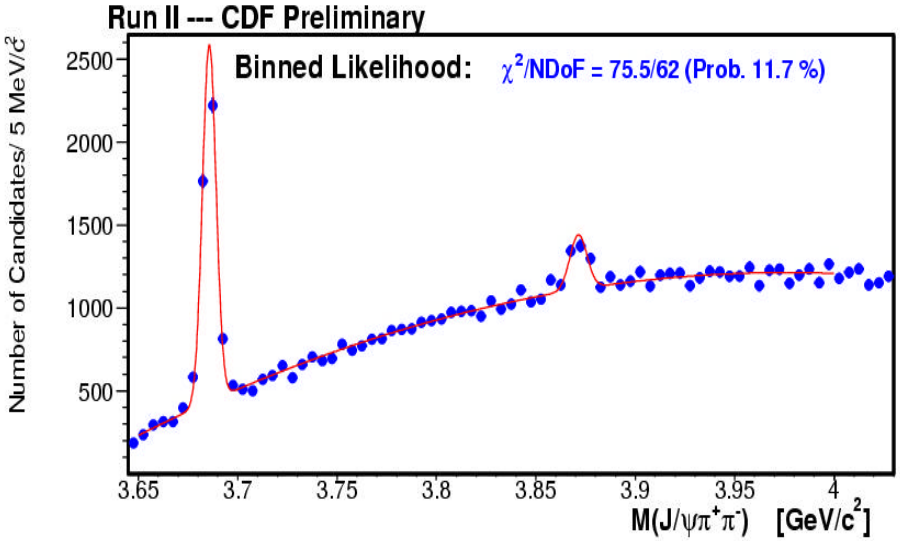
Soon sufficient data for further h_b study

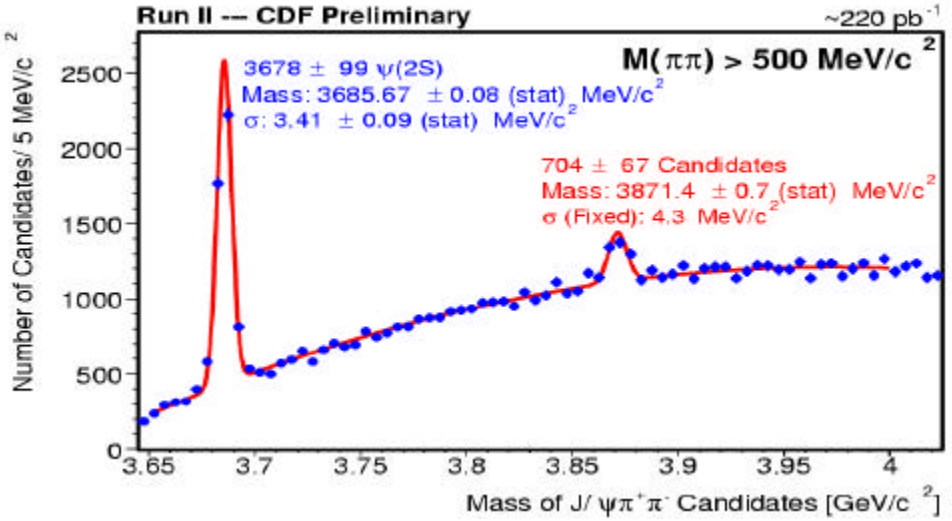


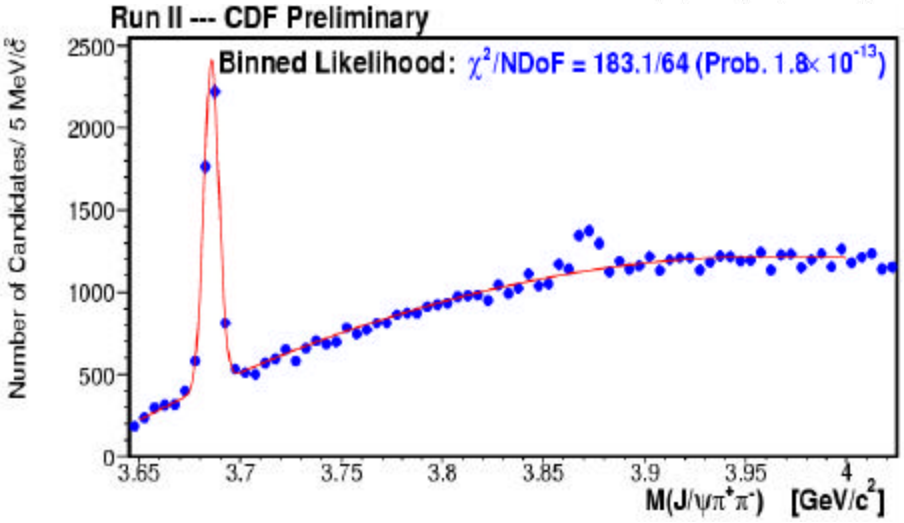
Observation of a narrow state decaying to J/ψ $\pi^+\pi^-$

See talk G. Bauer "Quarkonium production: new results from CDF"









Summary

- Run II CDF collected ~234 pb^{-1} (in FY 2003) of data for heavy flavor physics (Run I total: 110 pb^{-1})
- Detector is well calibrated, mass scales and vertexing resolution are understood, Run I physics signals are re-established
- First measurement of inclusive J/ψ Cross Section down to $p_T(J/\psi) = 0$
- Observation of X(3870)
- CDF as Charm/B factory
- Great heavy flavor physics potential, we have results on:

  Masses, lifetimes, production Cross Sections competitive with or superseeding Run I
- **Near future: exellent quarkonia prospects. Measurement of polarization for J/y, $y(2S)$ and U, production Cross Sections for B_c and h_b**

Lots of heavy flavors at CDF, stay tuned for new exiting results