Heavy Quarkonium Production and Polarization and the Bc Meson at CDF

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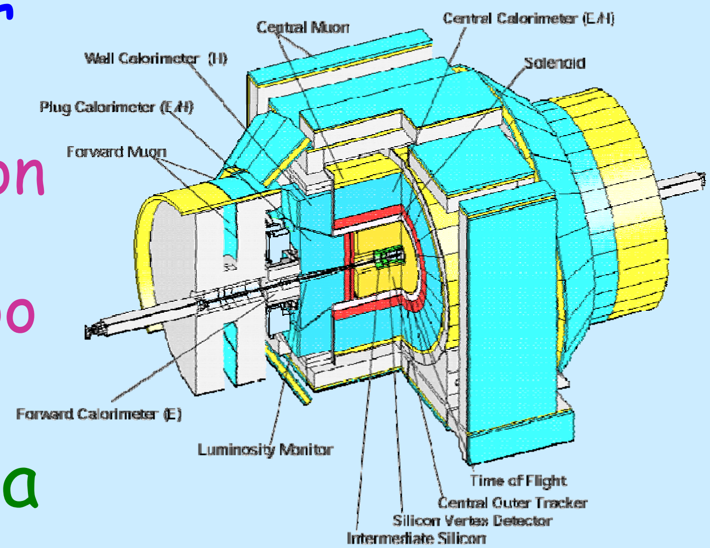
CDF Detector

- CDF was originally designed for high-Pt physics
  - Tracking was meant for calibration of the calorimeter
  - Muon system was too “leaky” … too much punch through.
- These “flaws” have resulted in a low-Pt dimuon trigger that has provided quarkonium samples for study and a window into B physics.
- Note that CDF is intrinsically a central detector with tracking coverage in pseudorapidity to ~1.

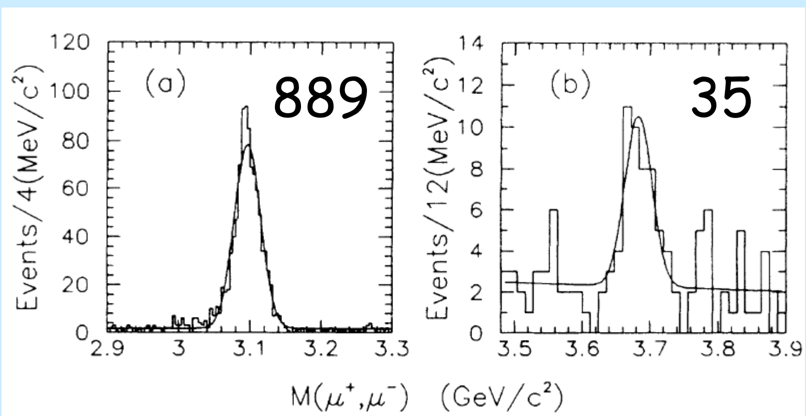


Upgrades have enhanced the tracking both with the central outer tracker and the silicon systems

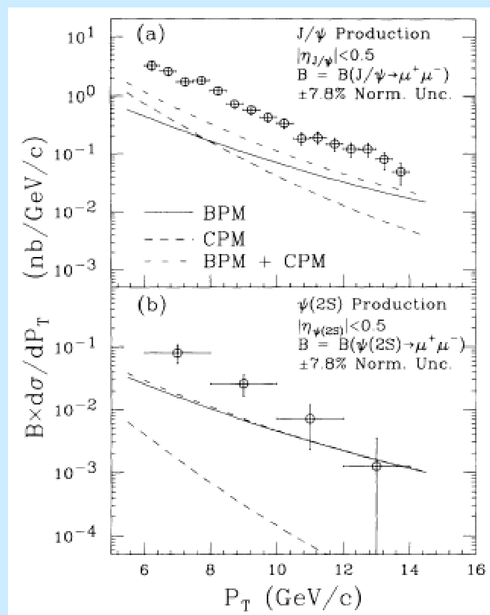
Very early CDF

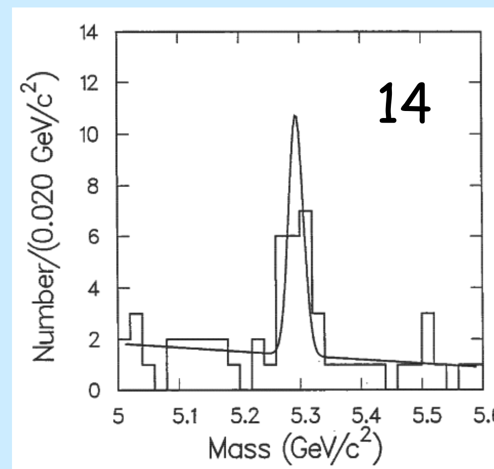
- Run 0 ('88-'89) saw the first sizable $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ at CDF
  - Measured cross-sections compared with theory
  - Also interest because J/ψ's lead to B Physics

Run 0 (88-89)
No SVX 2.6pb^{-1}



J/ψ and $\psi(2S)$
PRL 69, 3704 (1992)





CDF $B_u \to J/\psi K$
PRL 68, 3403 (1992)

Early CDF

- Run I ('92-'96) studied quarkonium and observed exclusive Bs->$J/\psi\phi$ and Λ_b->$J/\psi\Lambda$ and a first hint of Bc in semileptonic decays
  - Expand quarkonium studies to include χ's and Υ's
  - Dis-entangle *direct* quarkonium production from feed down and from b decay
  - B Physics at a hadron collider is for real

Early CDF

Quarkonium Measurements

Inclusive Chi_c and b-Quark Production in pp= Collisions at sqrt{s} = 1.8 TeV
Phys.Rev.Lett. 71, 2537 (1993) .

Upsilon Production in ppbar Collisions at sqrt{s} = 1.8 TeV
Phys.Rev.Lett. 75, 4358 (1995)

J/psi and psi(2S) Production in pp= Collisions at sqrt(s) = 1.8 TeV
Phys.Rev.Lett. 79, 572 (1997)

Production of J/psi from chi$_c$ Decays in pp= Collisions
Phys.Rev.Lett. 79, 578 (1997) .

Production of Upsilon(1S) from chi$_b$ decays in pp= Collisions
Phys. Rev. Lett. 84, 2094 (2000)

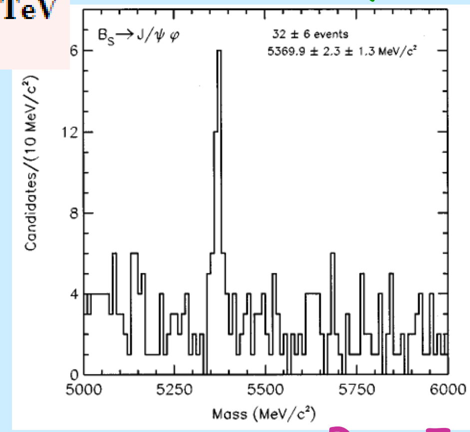
Measurement of J/psi and psi(2S) Polarization in p pbar Collisions at sqrt(s) = 1.8 TeV
Phys. Rev. Lett. 85, 2886 (2000)

Producction of chi_c1 and chi_c2 in pp= Collisions at sqrt(s) = 1.8 TeV
Phys. Rev. Lett. 86, 3963 (2001)

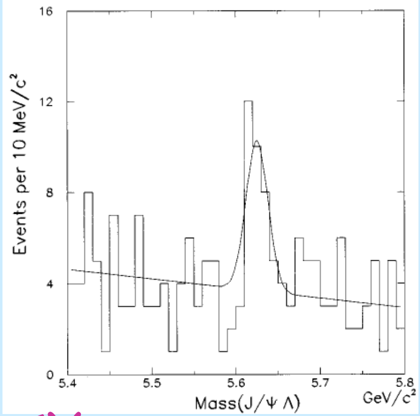
Upsilon Production and Polarization in pp= Collisions at sqrt(s) = 1.8 TeV
Phys. Rev. Lett. 88, 161802 (2002) .

Cross-section for Forward J/psi Production in p p= Collisions at sqrt{s} = 1.8 TeV
Phys. Rev. D 66, 092001 (2002) .

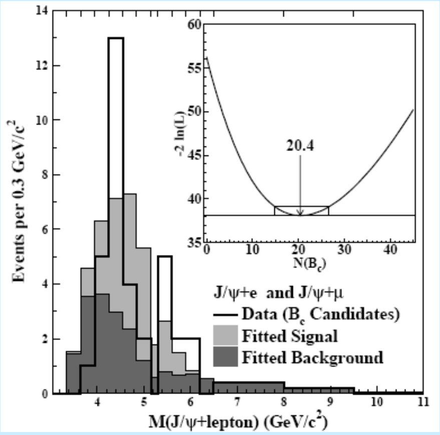
$B_s \to J/\psi\phi$
PRD 53, 3496 (1996)



$\Lambda_b \to J/\psi\Lambda$
PRD 55, 1142 (1997)



$B_c \to J/\psi \ell X$
PRL 81, 2432 (1998) PRD 58, 112004 (1998)

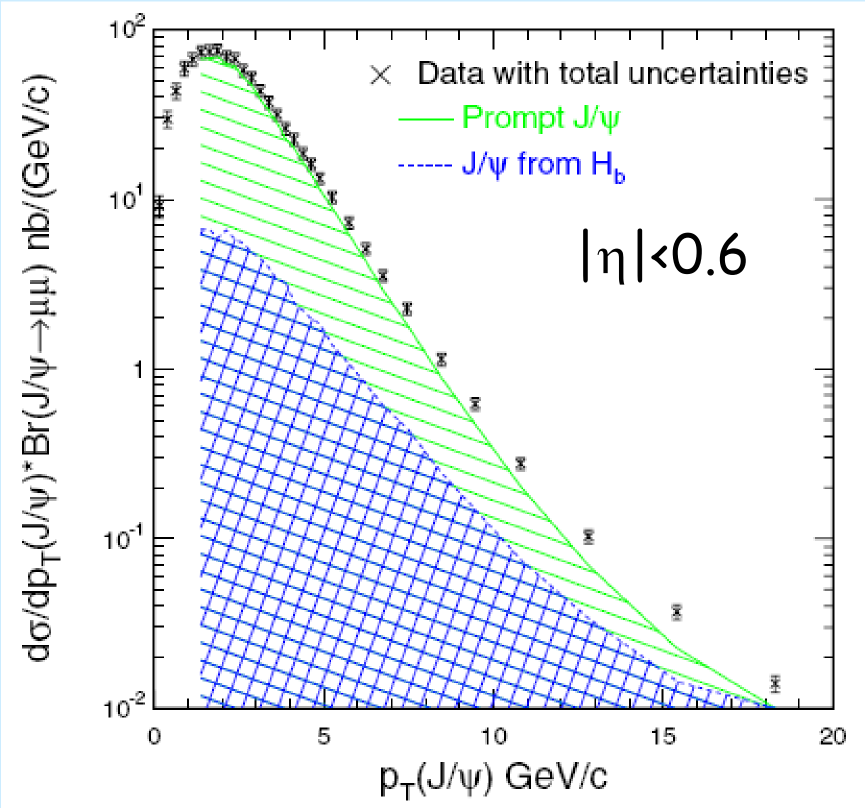


Quarkonium puzzle

- How are the quarkonium being produced?
  - Use silicon to isolate quarkonium from B decay
  - Prompt fraction includes
    - Feed down from higher spin states
    - Directly produced quarkonium
- Measurements have shown a large discrepancy between the simplest production models (color singlet). Other mechanisms (color octet) might contribute but would suggest transverse polarization at high-Pt where the CDF statistics and sensitivity were reduced.

Run II Quarkonium results

- J/ψ cross section early in Run II (systematics limited) and with an emphasis on extracting the b-hadron cross section. ($40pb^{-1}$, 300K J/ψ's) PRD 71, 032001, 2005

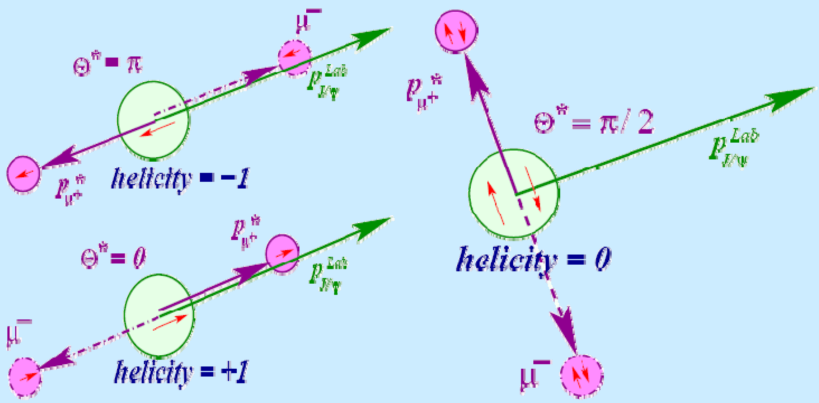


Compare b-hadron cross section for sqrt(s)=1.8 TeV with sqrt(s)=1.96 TeV

$\psi(2S)$ cross section measurement is current work in progress

Polarization of J/ψ and ψ(2S)

- 800pb^{-1} sample presented at QWG 2006 and just published. PRL 99, 132001, 2007



θ^*: angle between μ^+ in the J/ψ rest frame & J/ψ in the lab frame.

Transverse $(\alpha = 1)$ Longitudinal: $(\alpha = -1)$

Zero polarization $(\alpha = 0)$ means that all 3 helicity states are equally populated.

Angular distribution depends on the polarization parameter α:

$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha\cos^2\theta^* \quad (-1 \le \alpha \le 1)$$

Polarization of J/ψ and ψ(2S)

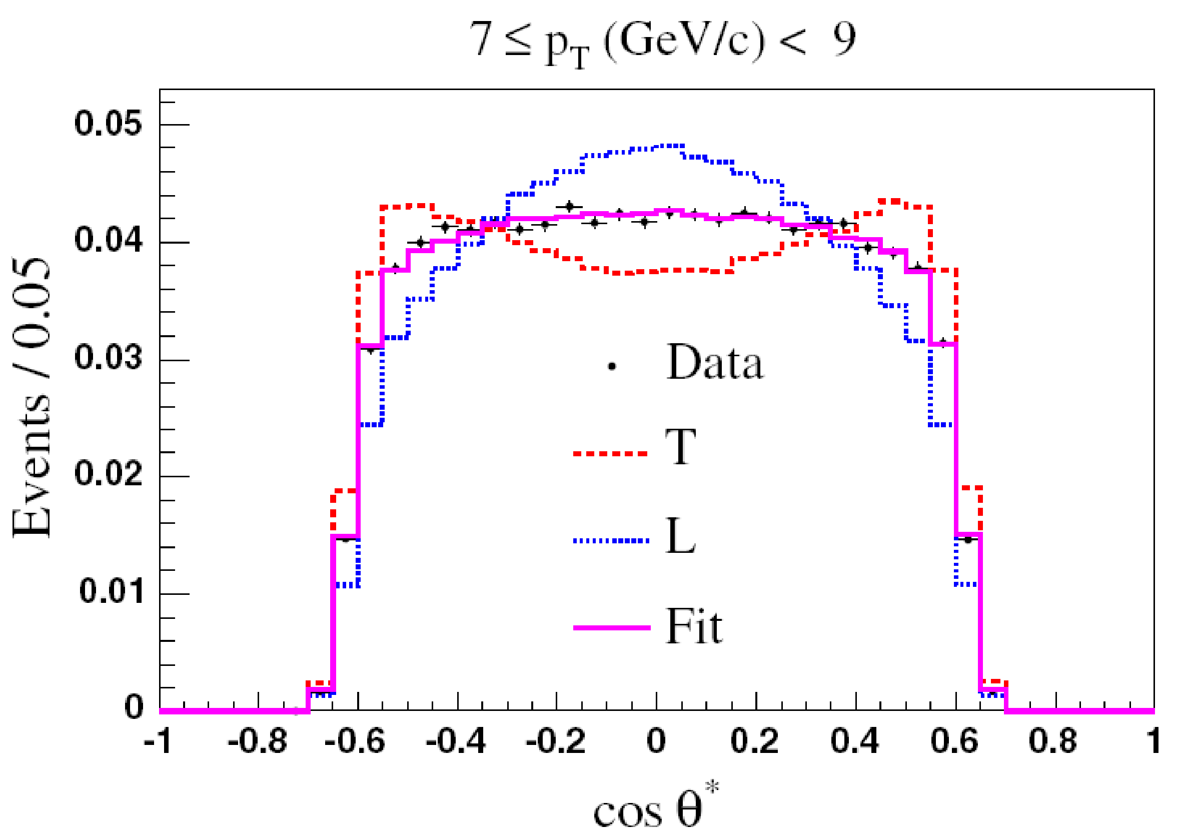
- Select J/ψ and ψ(2S):

5<Pt<30 GeV,|y|<0.6

- Min(μ_{Pt})>1.75 GeV/c

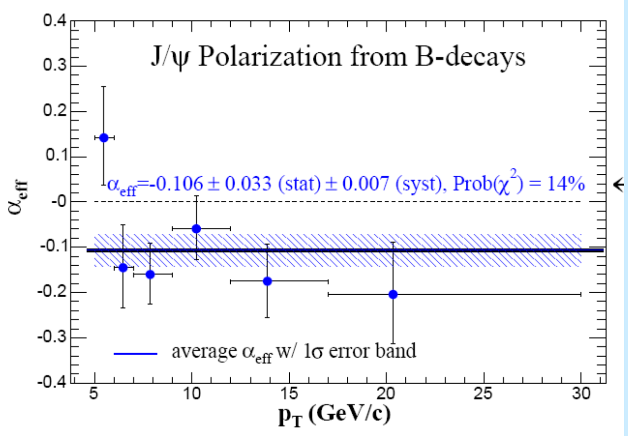
- Separate out prompt/displaced

- Use MC templates for acceptance and efficiency

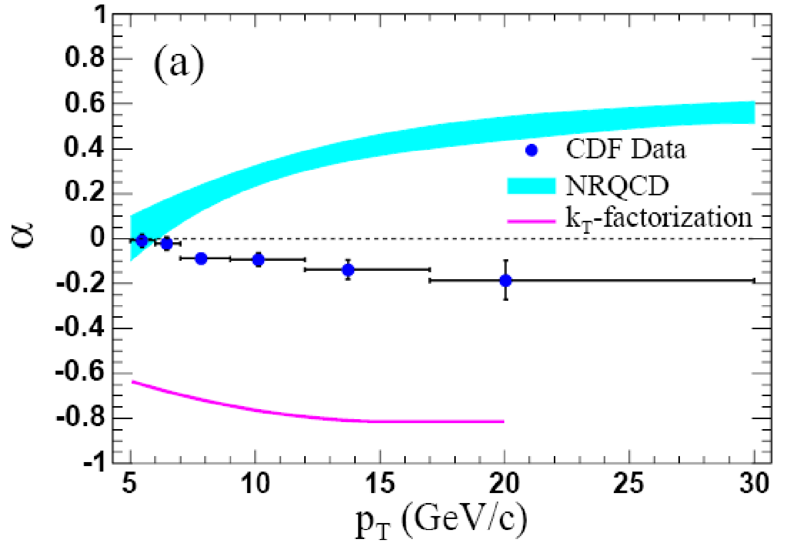


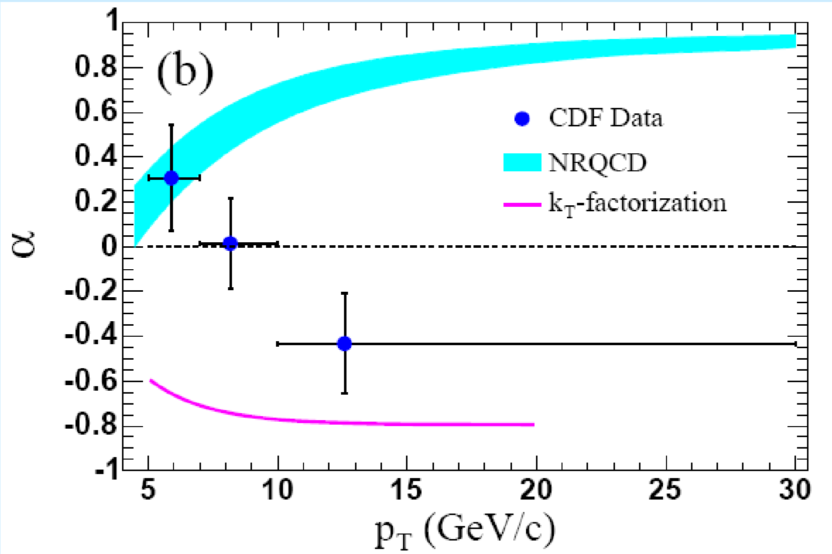
Polarization of J/ψ and ψ(2S)

- Polarization from B-decays agrees with B factories despite some differences



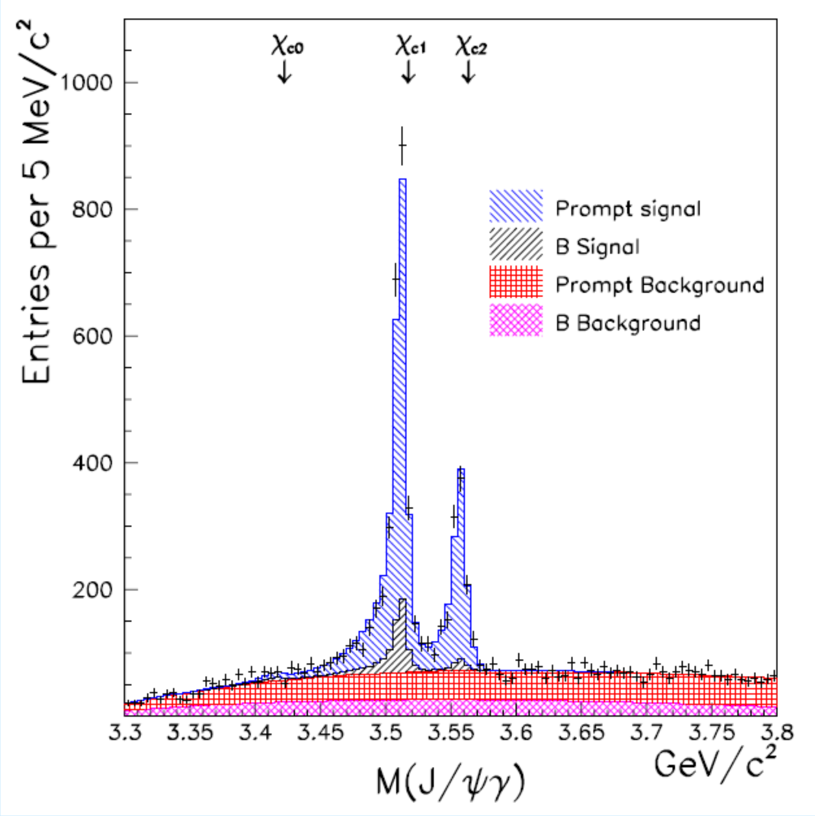
- Prompt polarization does not show the trend towards transverse polarization





Ratio of $\sigma(\chi_{c2}) / \sigma(\chi_{c1})$

- $1.1 fb^{-1}$ sample presented at QWG 2006 and just published.
  PRL 98, 232001, 2007
- Uses γ->conversion electrons which gives great resolution.



- R_p and R_B are the measured ratio's of cross section x BF for prompt/B

TABLE I. The acceptance ratio and ratios of cross section times branching fractions of the χ_{cJ} states for the prompt events and B decay events. Uncertainties listed are statistical only.

$p_T(J/\psi)$ (GeV/c)	$\epsilon_{\chi_{c2}}/\epsilon_{\chi_{c1}}$	R_p	R_B
4–6	1.27 ± 0.01	0.457 ± 0.039	0.150 ± 0.087
6–8	1.17 ± 0.01	0.384 ± 0.034	0.080 ± 0.094
8–10	1.14 ± 0.01	0.455 ± 0.053	0.116 ± 0.070
>10	1.10 ± 0.01	0.309 ± 0.045	0.197 ± 0.082
>4	1.23 ± 0.01	0.395 ± 0.016	0.143 ± 0.042

- Using BF's: $\sigma(\chi_{c2})/\sigma(\chi_{c1})=0.75+/-0.06$
- Spin counting would predict ~5/3

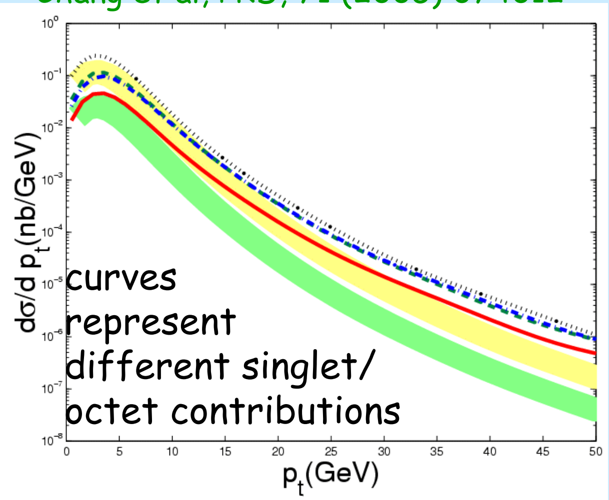
Much still to do

- Upsilon measurements in Run II
  - Work in progress
- Study of feed down from χ's
  - Low-Pt photons in the EM calorimeter are difficult
  - Direct component of prompt is interesting
- Quarkonium outside of central region
  - Forward production interesting in own right
  - Asymmetric two track trigger/other selection could allow for better polarization separation

Bc at CDF

- Bc is a heavy-heavy system [quarkonium like!]
  - Production: Factorization with two scales $M_b + M_c$ and contributions of color singlet / octet
    - Soft P_T distribution?
  - Decay: both b and c quarks can participate
    - Shorter *c-like* lifetime?
    - Large number of final state *BR's*.
  - Mass: new system for potential models and new lattice QCD calculations
- All aspects of the theoretical work require experimental measurement

Chang et al, PRD, 71 (2005) 074012



Bc -> J/ψ e ℓ X

- Background

63.6±4.9(stat)±13.6(syst)

- Observed

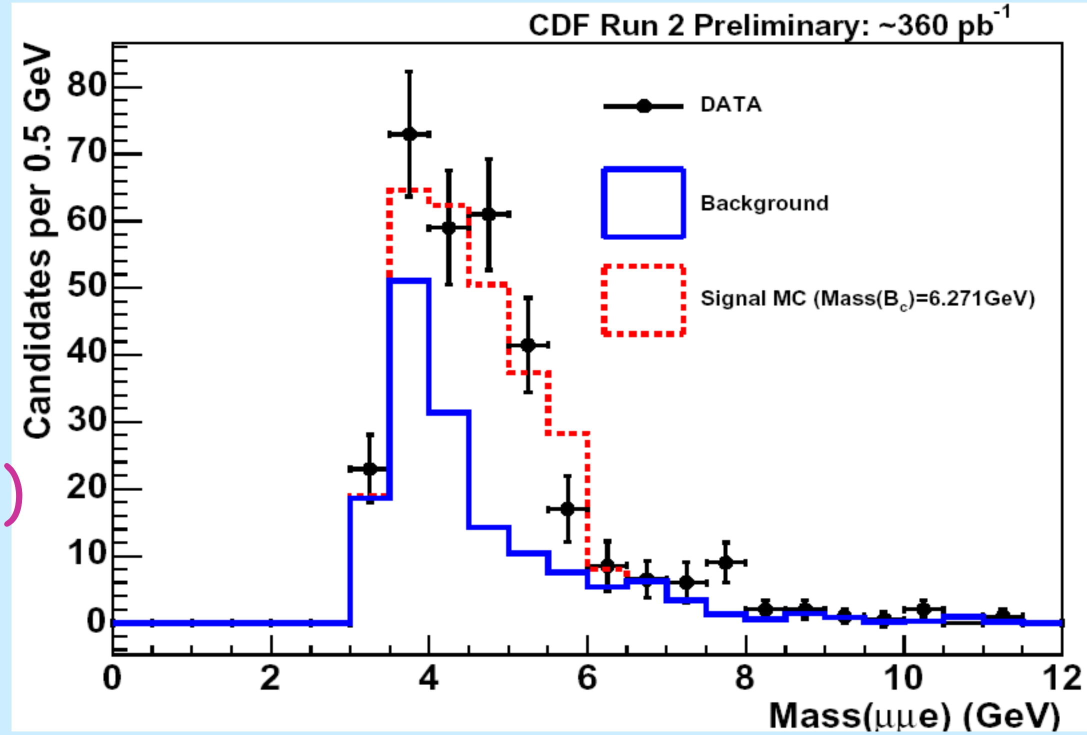
178.5±14.7(stat)±

- Excess

114.9±15.5(stat)±13.6(syst)

- Significance

5.9σ



$$\frac{\sigma(B_c)\times B(B_c\text{->}J/\psi \ell \nu)}{\sigma(B_u)\times B(B_u\text{->}J/\psi K)} =$$

Relative production

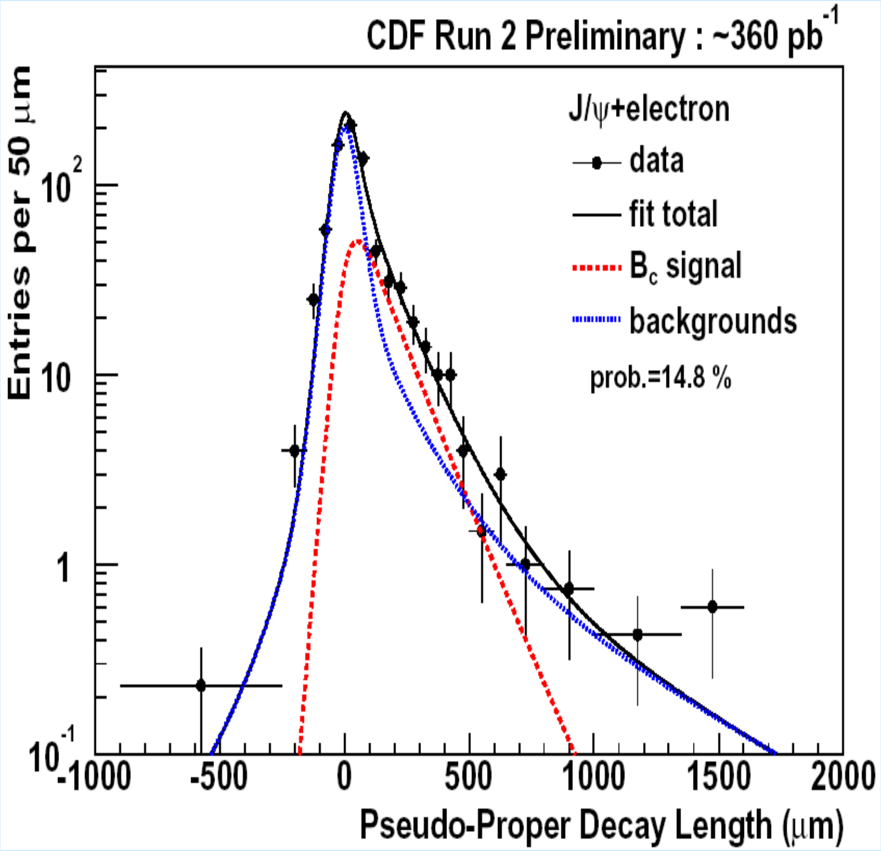
$P_T(B)$>4 and $|y|$ < 1

PRL 97, 012002, 2006

0.282±0.038(stat.)±0.035(yield)±0.065(acceptance)

Bc lifetime

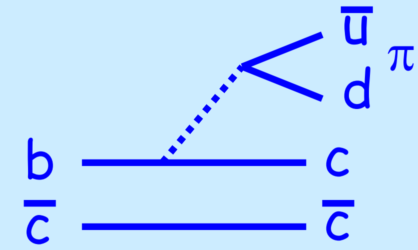
- Relax cτ requirement of the electron selection



PRL 97, 012002, 2006

$\tau(B_c)$ =0.463 +0.073/-0.065(stat) ±0.036(syst) ps

Bc -> J/ψ π



- Full reconstruction allows for a precise mass measurement
- Early 360pb^{-1} "observation" (~3σ) published
- Newer analysis
  - Tune selection on the data:
    Bu -> J/ψ K reference decay
  - After the analysis was finalized, "open box".
  - Wait for events to become a significant excess
  - Watch the signal grow and measure properties of the Bc

Analysis overview: tune on Bu -> J/ψK

Optimization A / Standard

Initial selection

- $P_T(\pi/K) > 1.7$ GeV/c
- $P_T(B) > 5$ GeV/c
- $c\tau > 80\ \mu m$
- $\delta(c\tau) < 30\ \mu m$
- Prob(χ^2) > 0.1%
- Pointing angle, $\beta < 0.4$
- $|ip(B)_{signif}|$ wrt pv < 2.5σ
- $|ip(\pi/K)|$ wrt $\mu\mu$ < 100 μm
- $|ip(\pi/K)_{signif}|$ wrt pv > 2.5σ

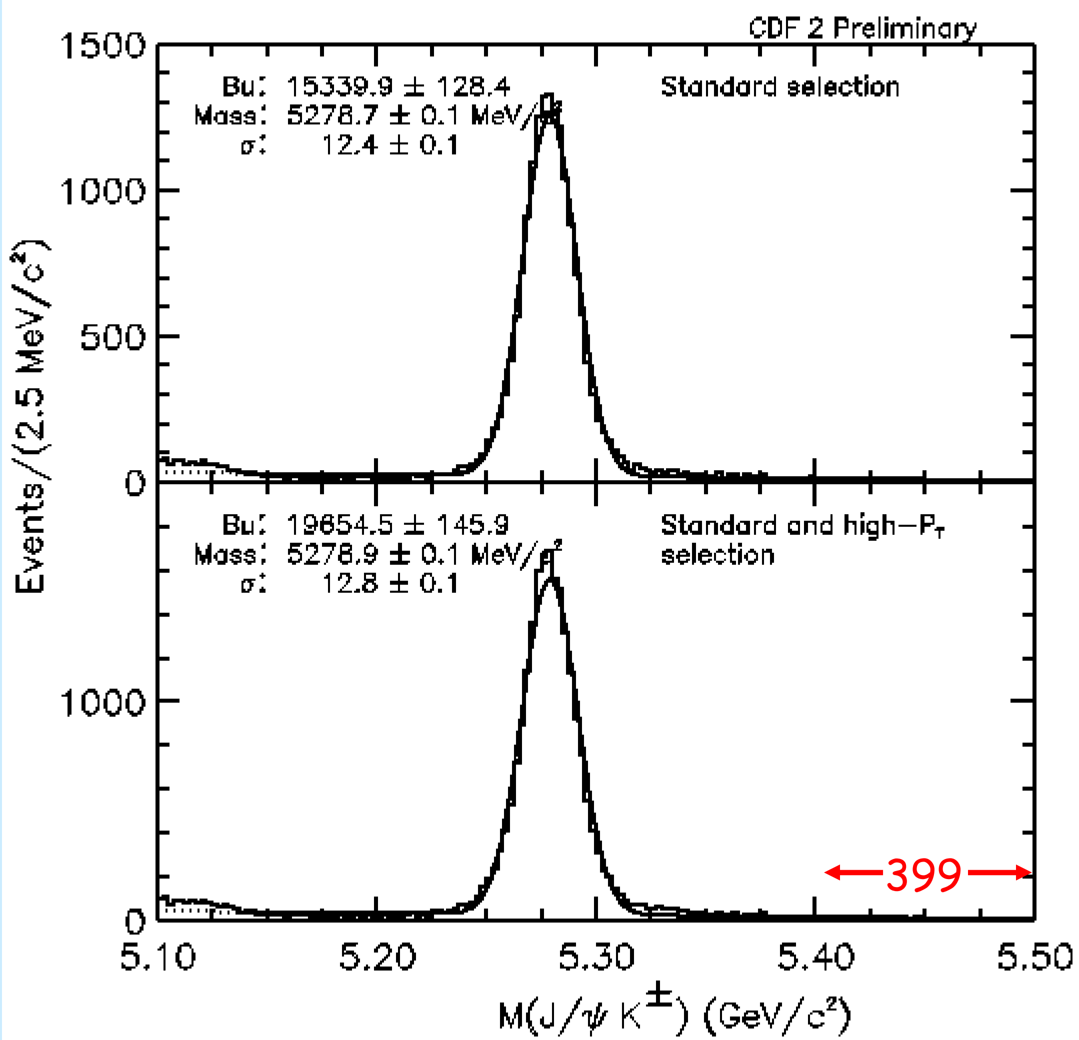
Optimization B / high-P_T

Allow events that fail one Opt A cut, pass all but one Opt B (*except* P_T)

- $P_T(\pi/K) > 2.5$ GeV/c
- $P_T(B) > 6$ GeV/c
- $c\tau > 100\ \mu m$
- $\delta(c\tau) < 25\ \mu m$
- Prob(χ^2) > 1%
- Angle, $\beta < 0.3$
- $|ip(B)_{signif}|$ wrt pv < 2σ
- $|ip(\pi/K)|$ wrt $\mu\mu$ < 80 μm
- $|ip(\pi/K)_{signif}|$ wrt pv > 3σ

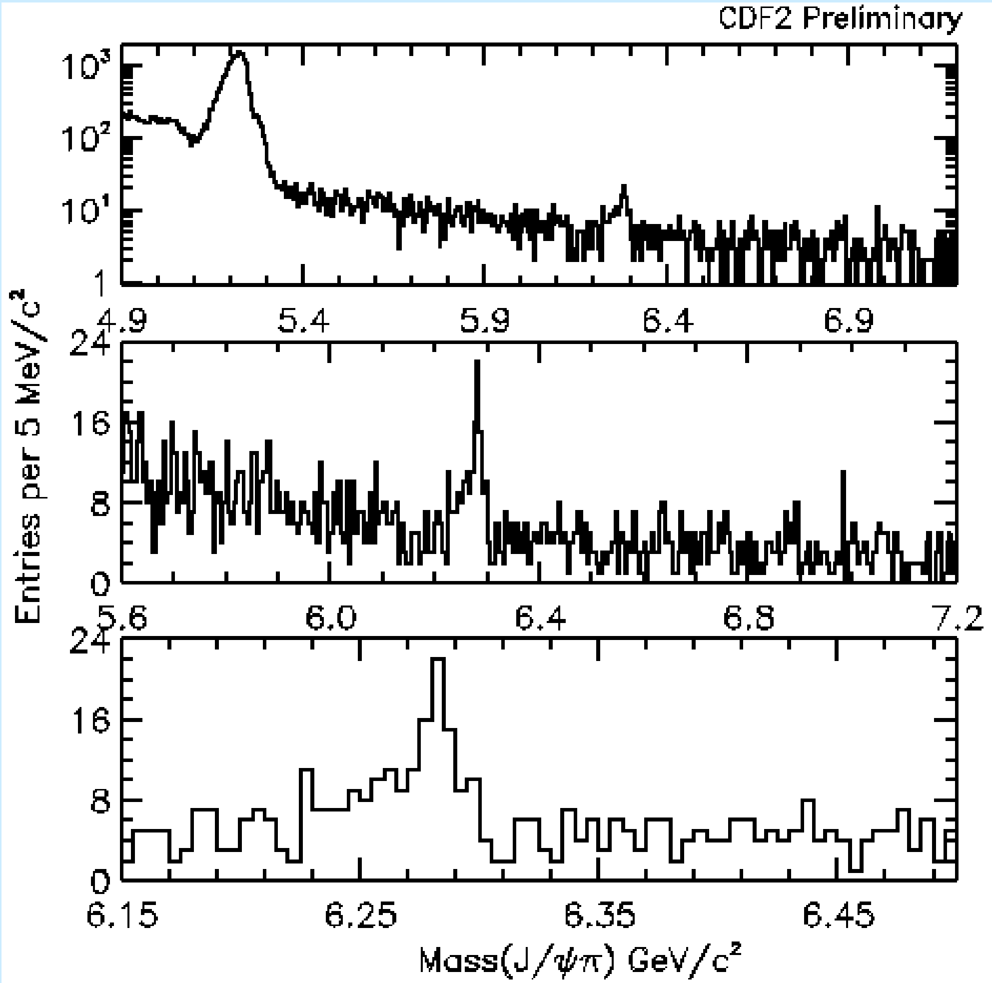
Bu -> J/ψ K

- 2.2fb^{-1} results
- 2nd pass of the selection results in a gain of 28% (15.3K->19.7K).
- 399 background between 5.4 and 5.5 GeV/c^2.
- Search for Bc -> J/ψ π by changing only the K for a π.



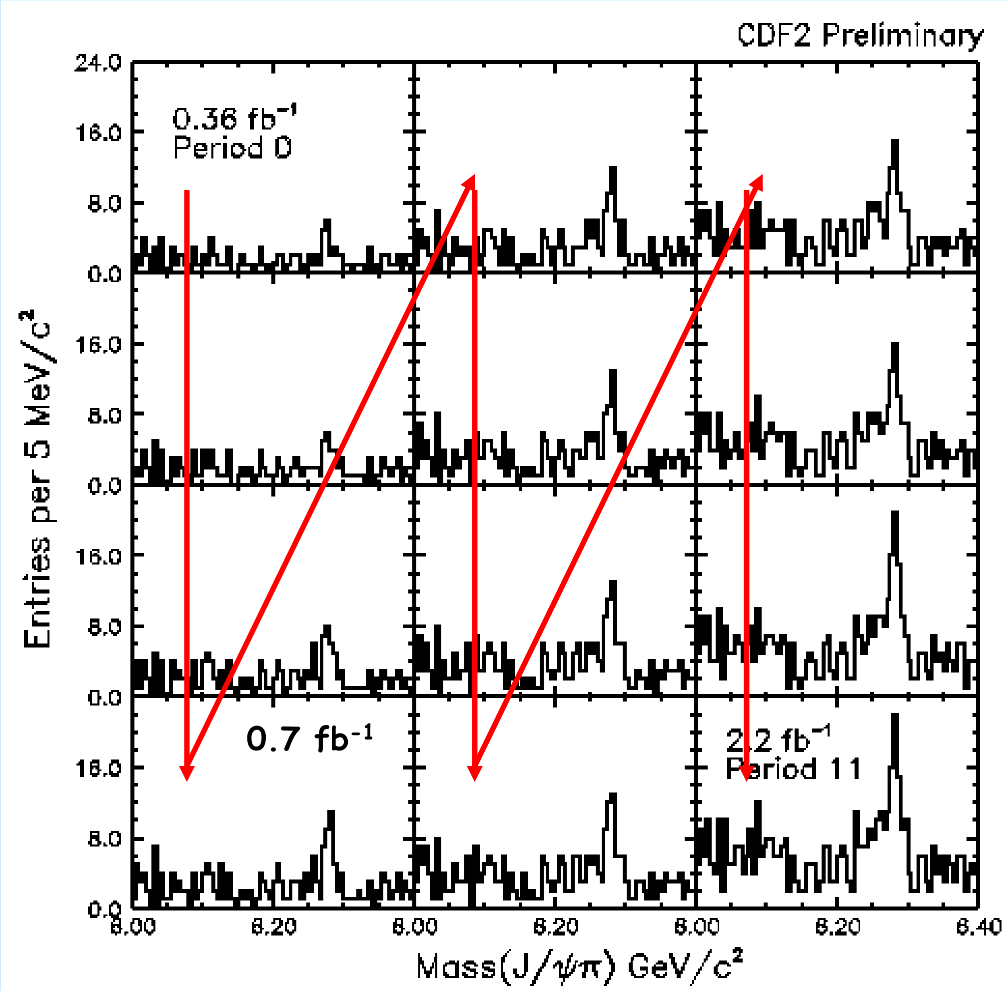
Bc -> J/ψ π

- Note the Bu -> J/ψ K peak when assigning π mass to the K
- Note the hump for the Cabibbo suppressed Bu -> J/ψ π decay
- Finally, note the Bc peak above background (fine binning is used)



Bc -> J/ψ π
watch it grow

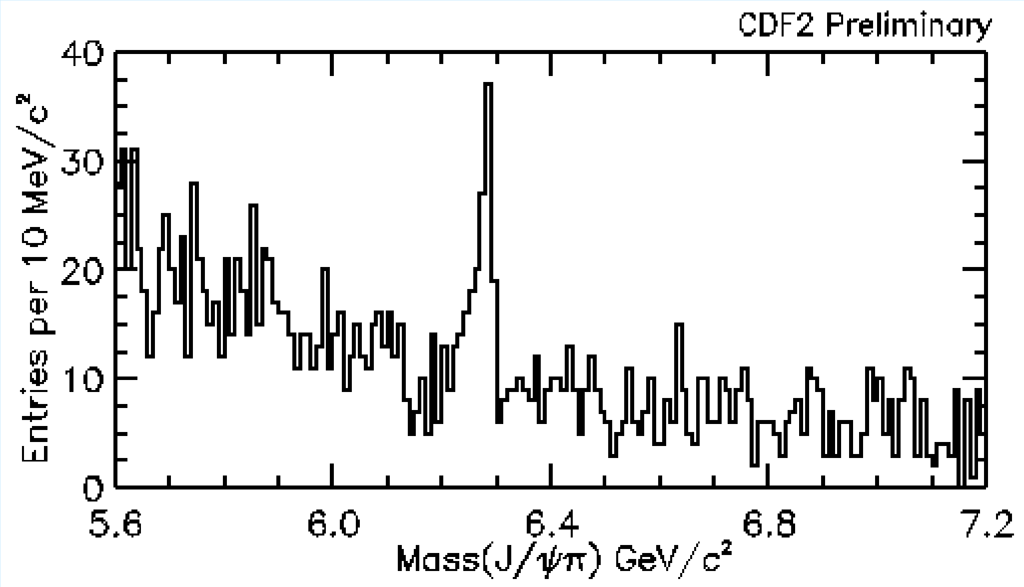
- Data accumulates
- Initial hint at 360pb^{-1}
- 5σ at 700pb^{-1}
- Current significance estimated >8σ



Mass measurement

- Central Value
  - Unbinned log likelihood fit to Gaussian plus linear background to the event-by-event masses and scaled mass uncertainties (x1.59 as found for $J/\psi K$) with signal fraction, background slope, and mass returned.
- Statistical uncertainty - from the fit

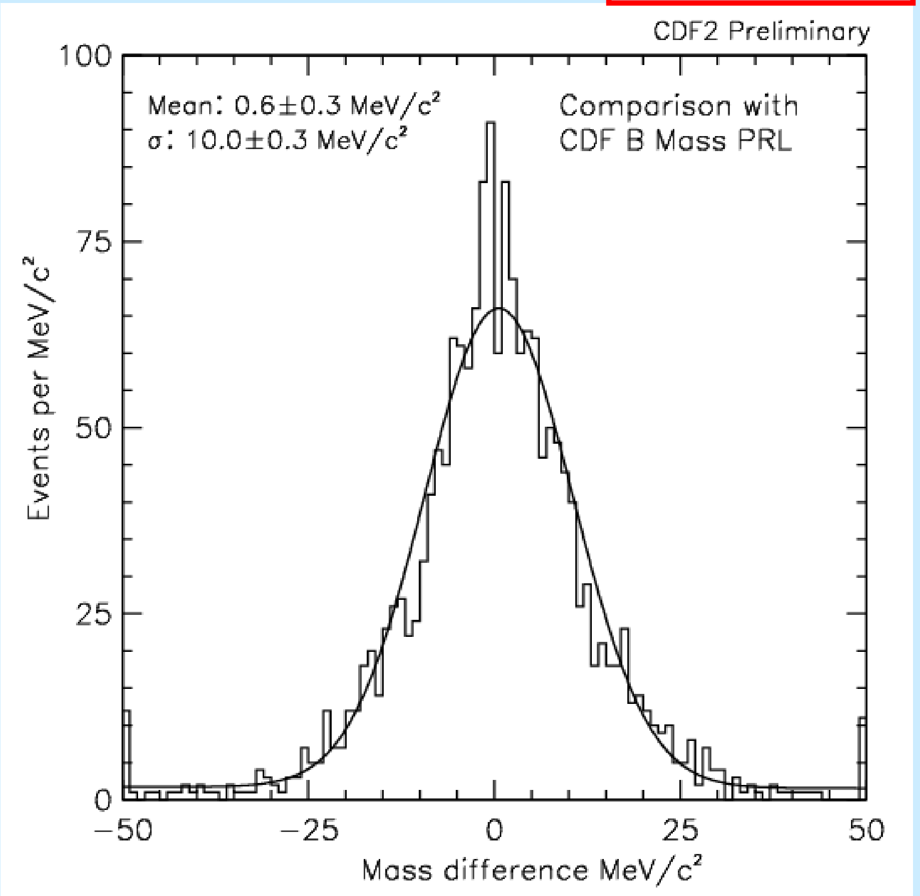
- 87.1 +/- 12.8 Bc signal events
  Mass = 6274.1 +/- 3.2 MeV/c^2
  Bkgd (60 MeV bin): 57.1 evts

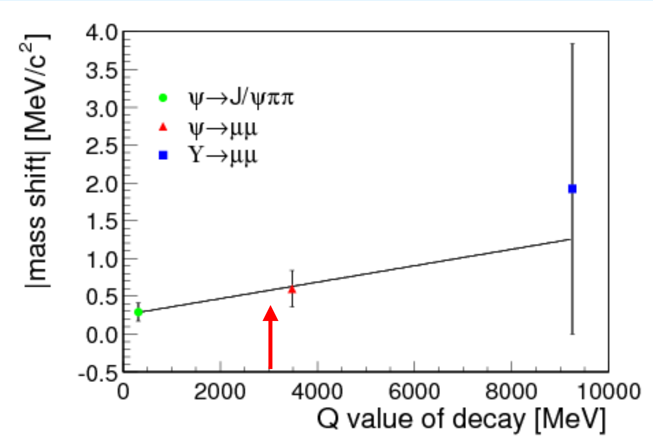


Systematic uncertainties

Compare with B mass PRL analysis PRL 96, 202001, 2006

Calibration systematic ~ 0.6 MeV/c^2





- Momentum scale
  - Q-value(Bc) -> 0.6 MeV/c^2
- Track type study
  - Add 0.2 MeV/c^2
- Radiative π/K differences
  - Add 0.2 MeV/c^2

Tracking systematic: 0.7 MeV/c^2

Fit procedure systematic

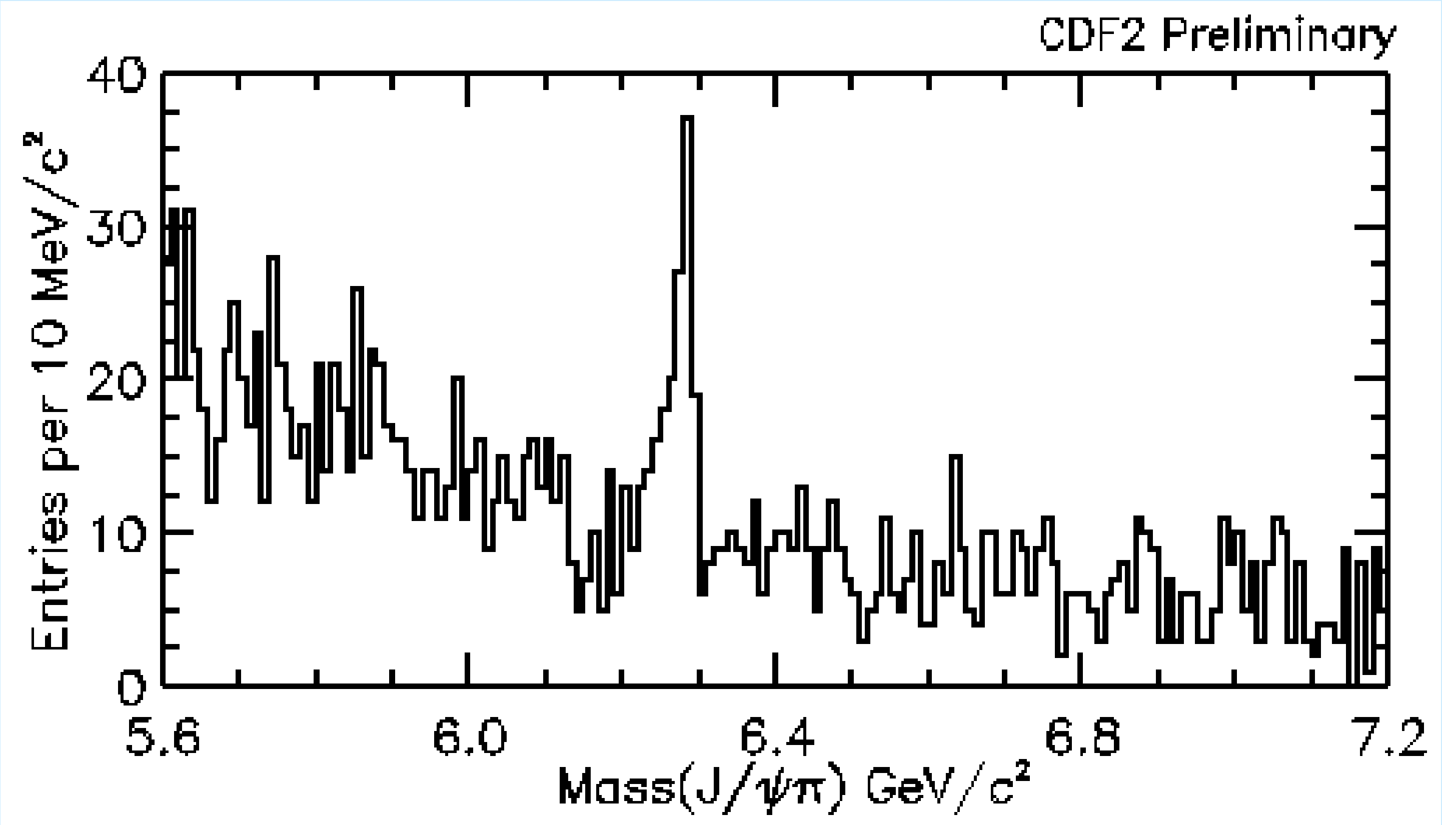
The result of the mass fit depends somewhat more than one would like on the scale factor on the mass uncertainty.

scale factor	Events	Mass (MeV/c^2)
1.59 fixed	87.1 +/- 12.8	6274.1 +/- 3.2
2.00 fixed	93.8 +/- 13.8	6272.0 +/- 3.7
1.25 fixed	78.7 +/- 11.8	6276.8 +/- 2.7

}4.8 MeV

Fitting procedure systematic: 2.4 MeV

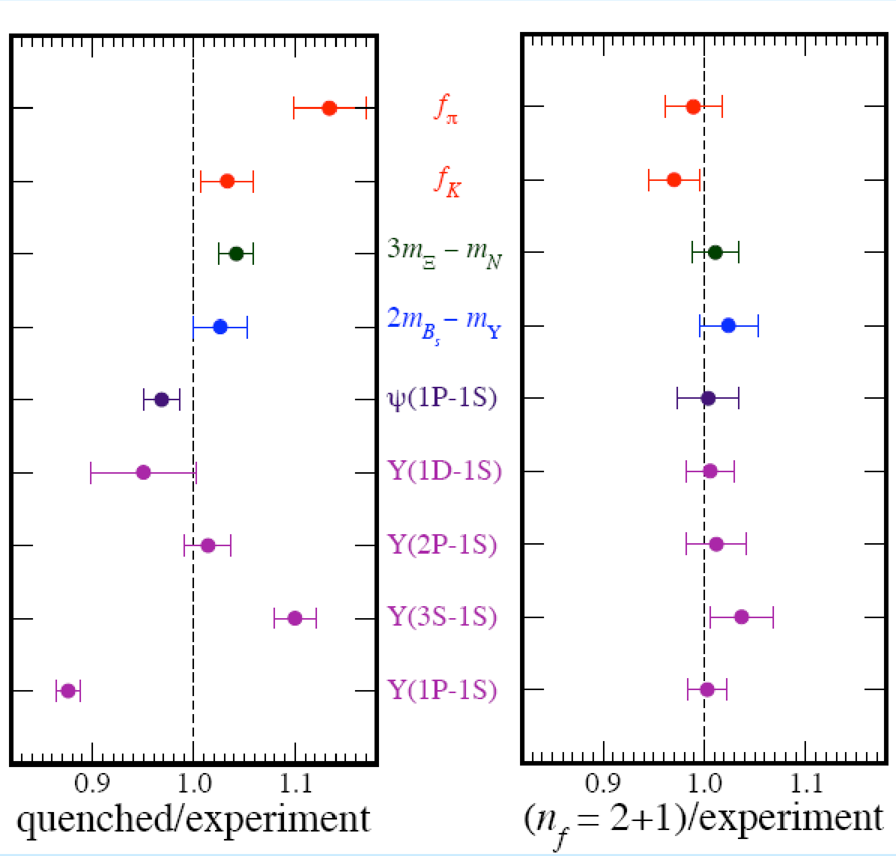
Mass plot

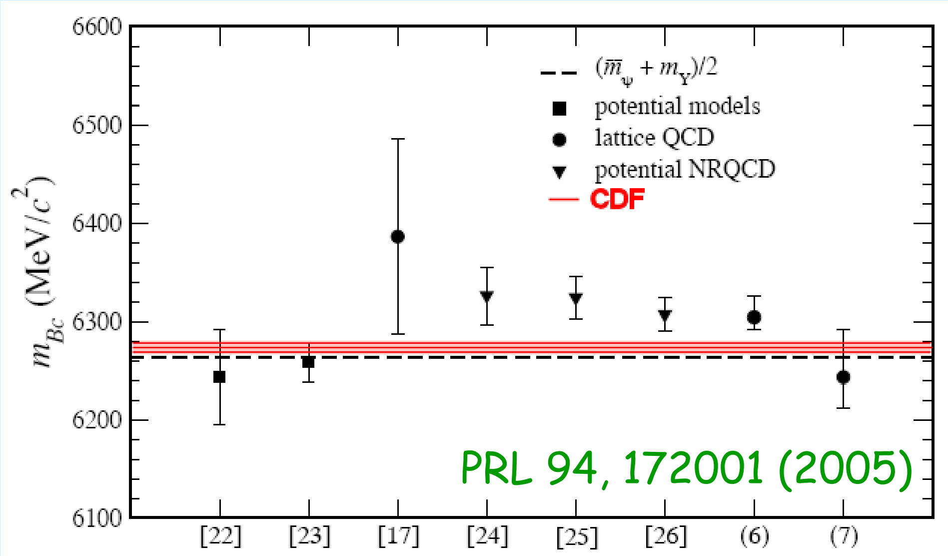


- 87.1 events and the significance is now > 8σ
- M(Bc) = 6274.1 +/- 3.2 +/- 2.6 MeV/c^2

Relatively Recent Lattice Calculations

- Lattice calculations that show good agreement with experiment were used to *predict* the mass of the Bc





$M(Bc)_{CDF}$ = 6274.1 +/- 3.2 +/- 2.6 MeV/c^2

$M(Bc)_{LAT}$ = 6304 +/- 12 $^{+18}_{-0}$ MeV/c^2

Difference ~30 MeV

Much still to do

- Semi-leptonic decays use 360pb^{-1}
  - New electron detector subsystem requires additional study
  - Muons not done
- Exclusive Bc signal: next extract lifetime, search for excited states
  - Need modified selection that doesn't rely on lifetime correlated quantities
- Revisit Bc production issues
  - What can it reveal?

Summary and conclusions

- Quarkonium measurements have been made since the early days of CDF
- Strong indications are that the NRQCD predictions of transverse polarization at high-Pt are falsified for J/ψ and $\psi(2S)$
- Bc's are another system wide open to contribute to quarkonium understanding
- There is still much to do