HADRON05

Hadron Physics at the Tevatron

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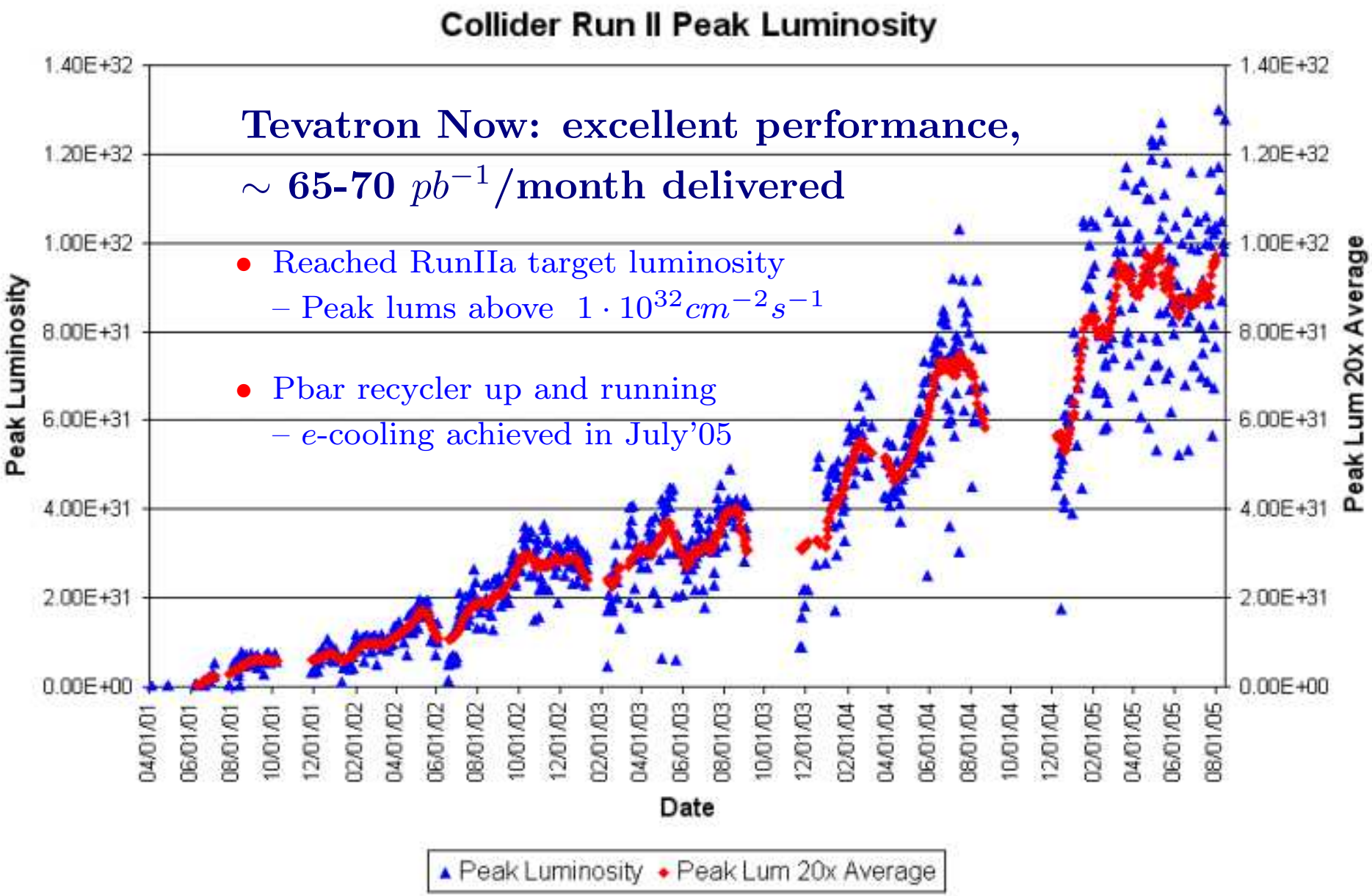
- Tevatron
- Detectors
- B_c Mesons
- D^{**} States
- B^{**} States
- X(3872)

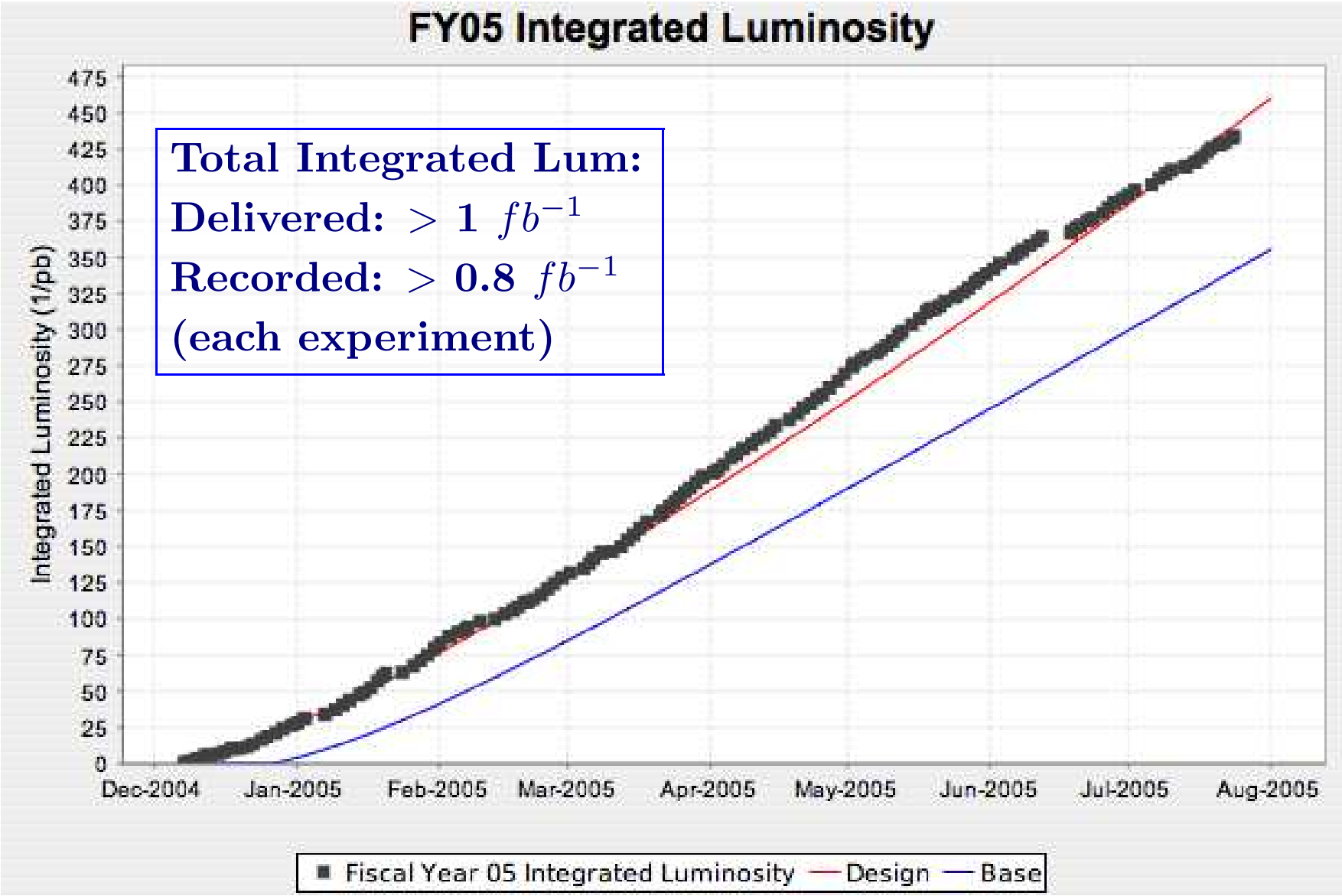


Tevatron Now: excellent performance,

$\sim$ 65-70 pb^{-1}/month delivered

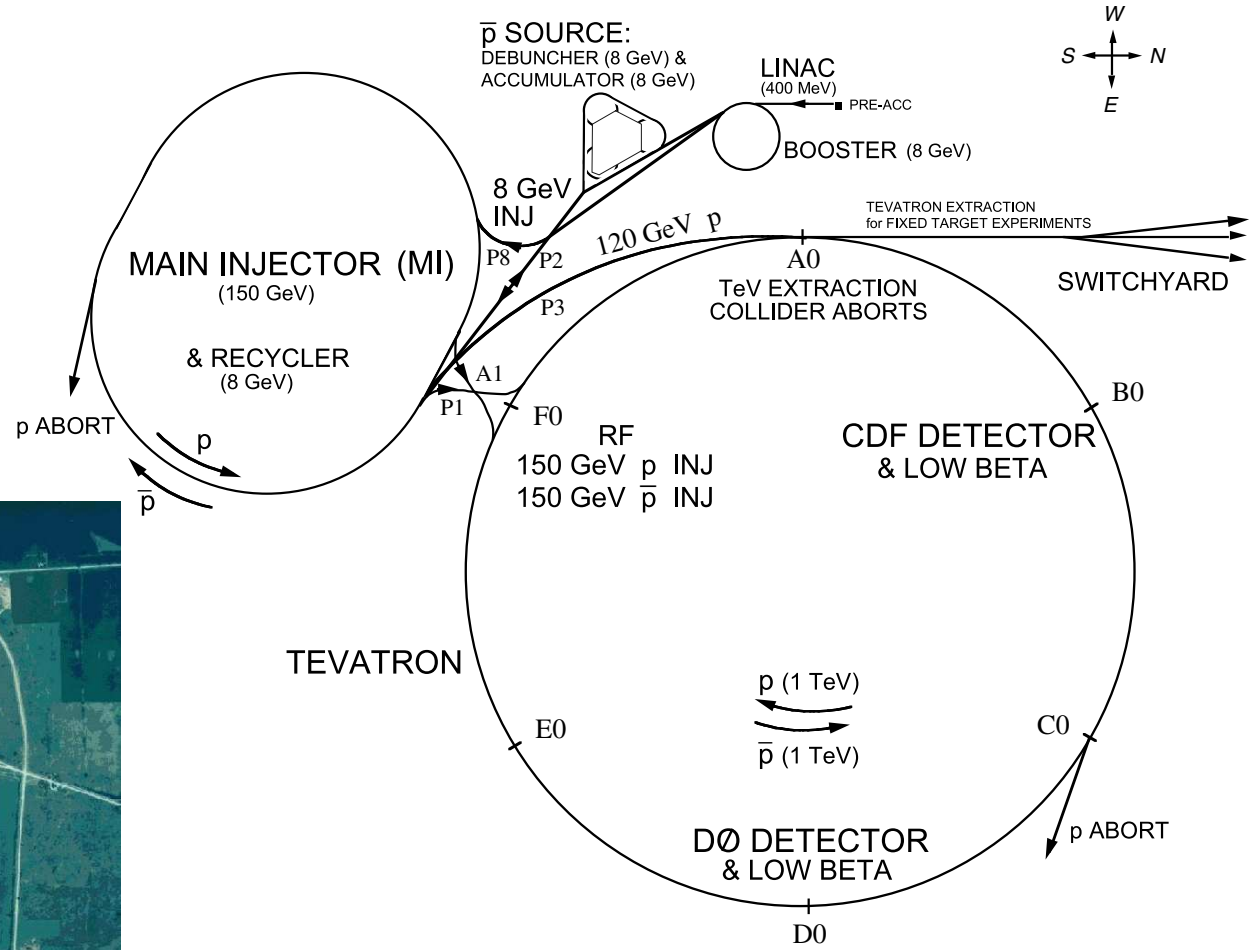
- Reached RunIIa target luminosity
  - Peak lums above $1 \cdot 10^{32} cm^{-2} s^{-1}$
- Pbar recycler up and running
  - e-cooling achieved in July'05

Tevatron Performance in 2005



Total Integrated Lum:
Delivered: $> 1\ fb^{-1}$
Recorded: $> 0.8\ fb^{-1}$
(each experiment)

~3 months' shutdown coming up in October

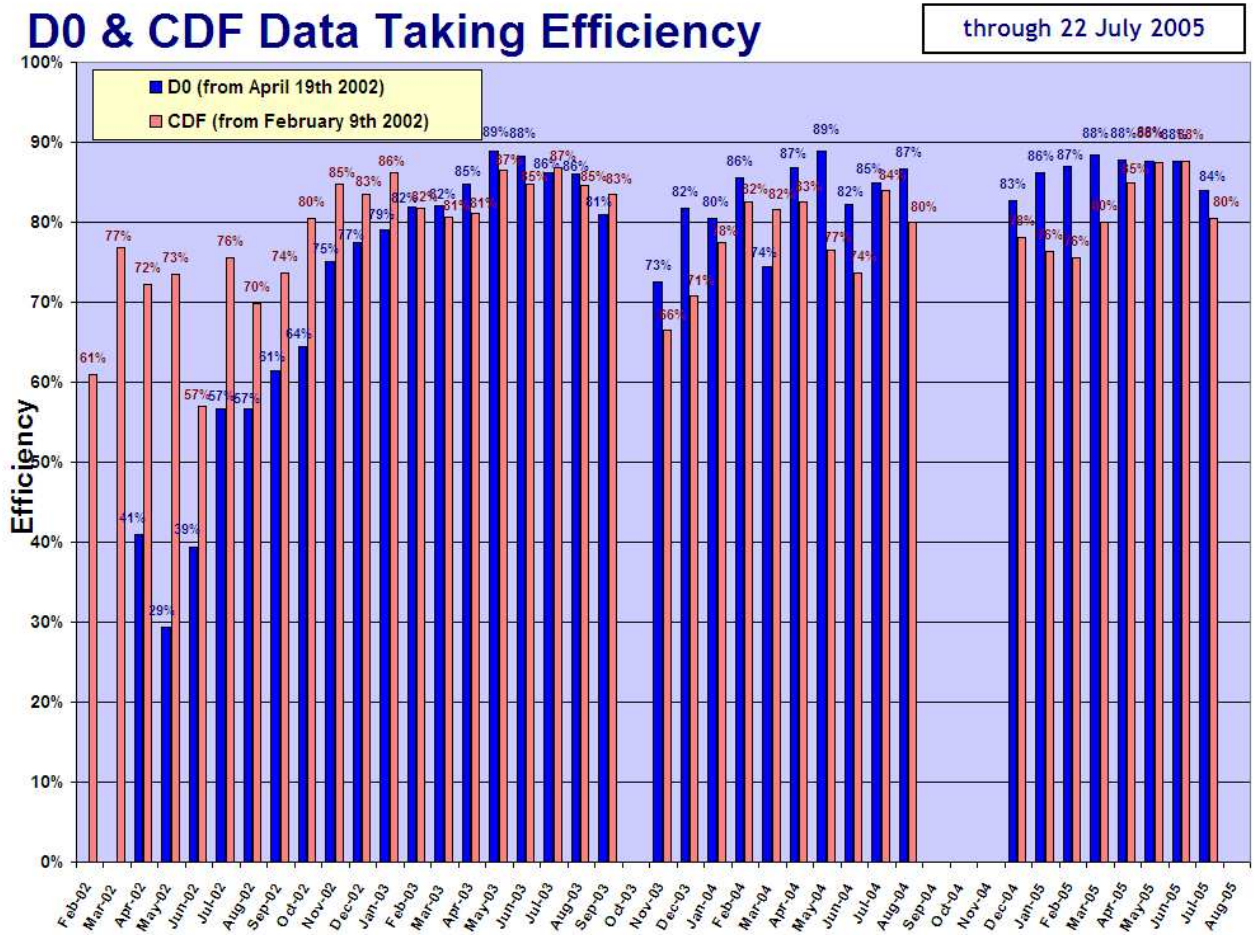


Tevatron RunIIb

- **starts ~Jan. 2006**
- **expecting $> 1\ fb^{-1}$/yr.**

CDF & DØ RunII

- Data taking efficiency in 2005 is $\sim 85\%$
  - **currently translates to 55-60 pb^{-1}/month**

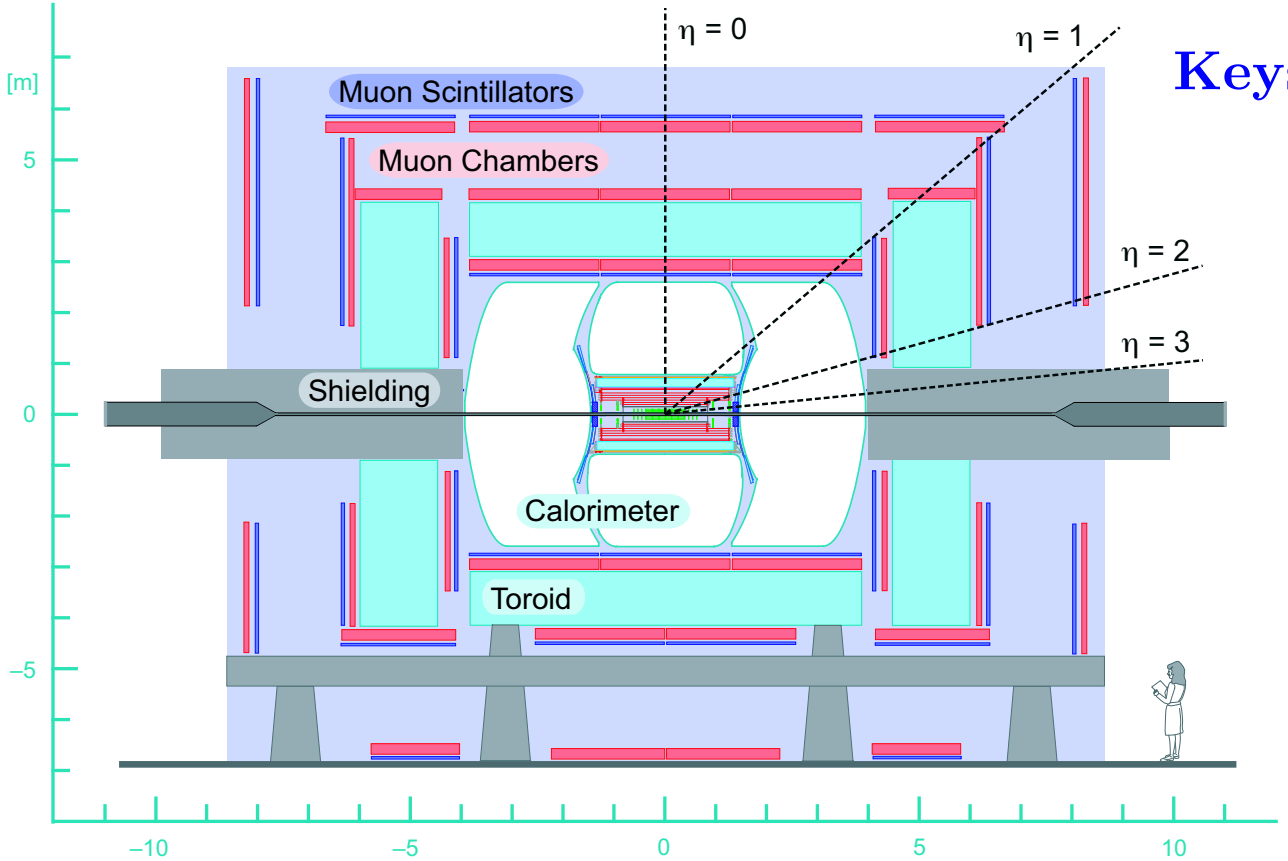


- (Unique!) All B species produced
  - B_u, B_d, B_s, B_c
  - $\Lambda_b, \Xi_b \cdots$

- Tev B-program success largely dependent on trigger strategies

- $\sigma(p\bar{p} \to b\bar{b}) \approx 100\mu$b at 2 TeV
- $\sigma(e^+e^- \to b\bar{b}) \approx 7$ nb at $M(Z)$
- $\sigma(e^+e^- \to b\bar{b}) \approx 1$ nb at Υ_{4s}
- but... $\sigma(b\bar{b})/\sigma^{inel} \approx 10^{-3}$

The DØ RunII Detector



Keys to the B-program:

Central magnetic tracking volume:

- Is a RunII addition
- Compact ($r < 52cm$)
- Modest p resolution $\Gamma_{\mu\mu} = 60$ MeV at J/ψ

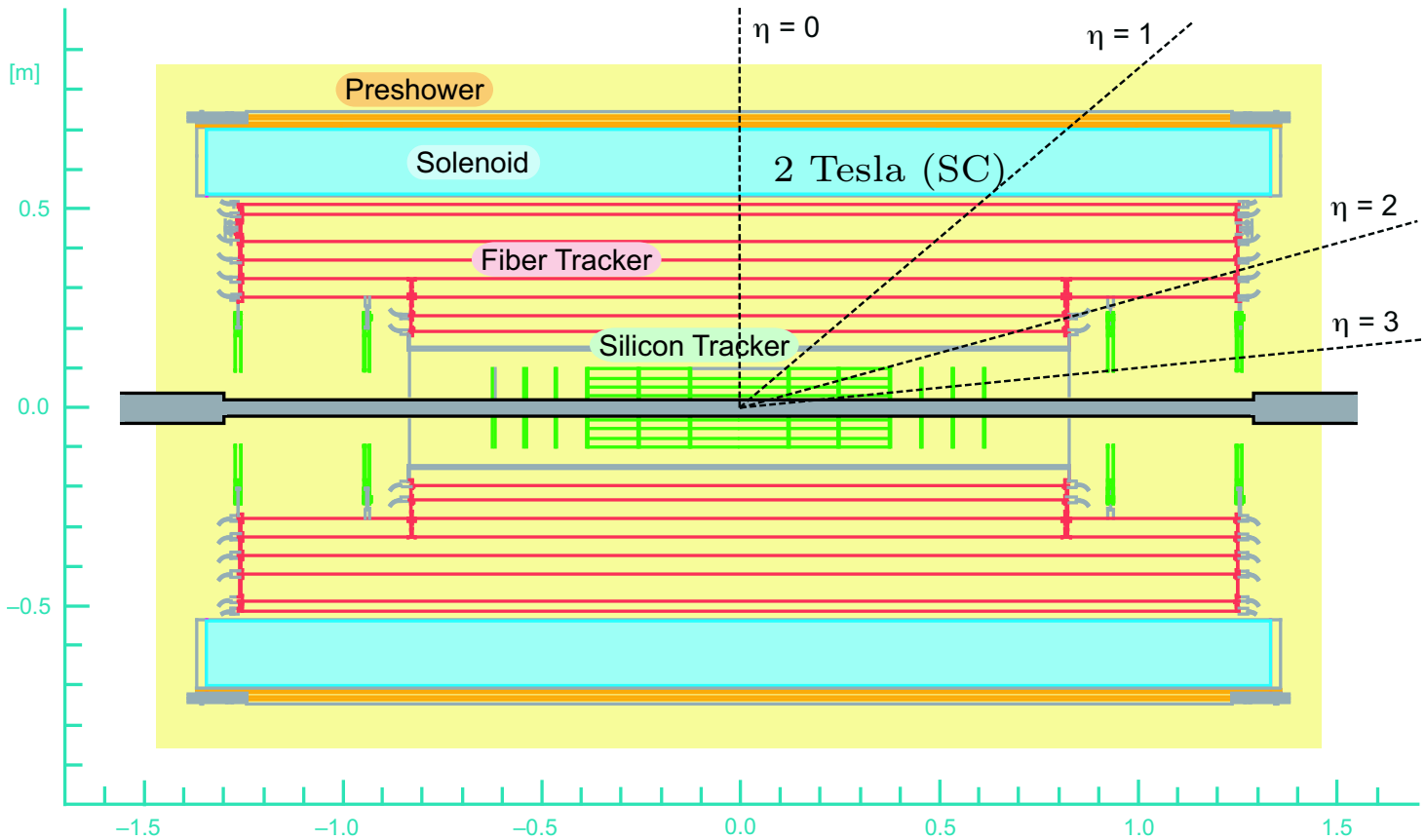
Wide angle coverage:

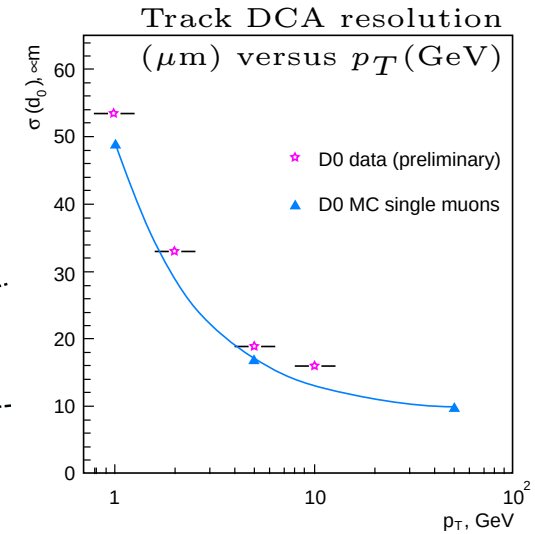
- Muon chambers; $|\eta| < 2.0$
- Tracking volume; $|\eta| < 3.0$

Clean muon-ID:

- Efficient muon triggers
- single-μ 60% pure at L1

The DØ Tracking Volume

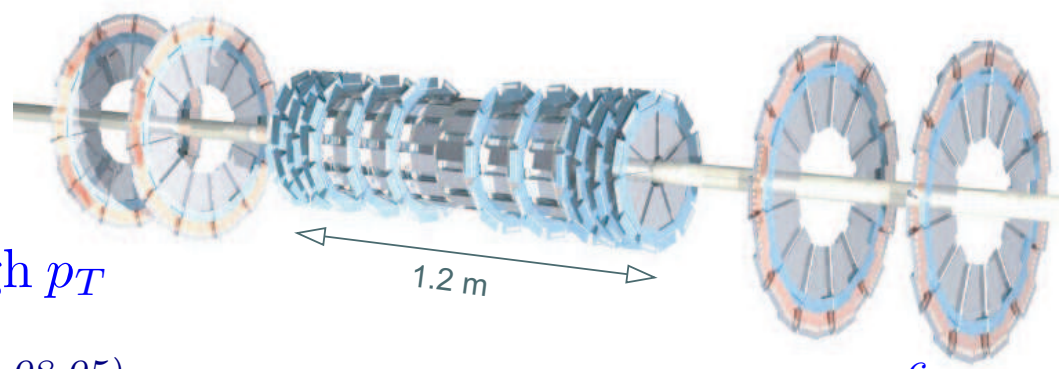




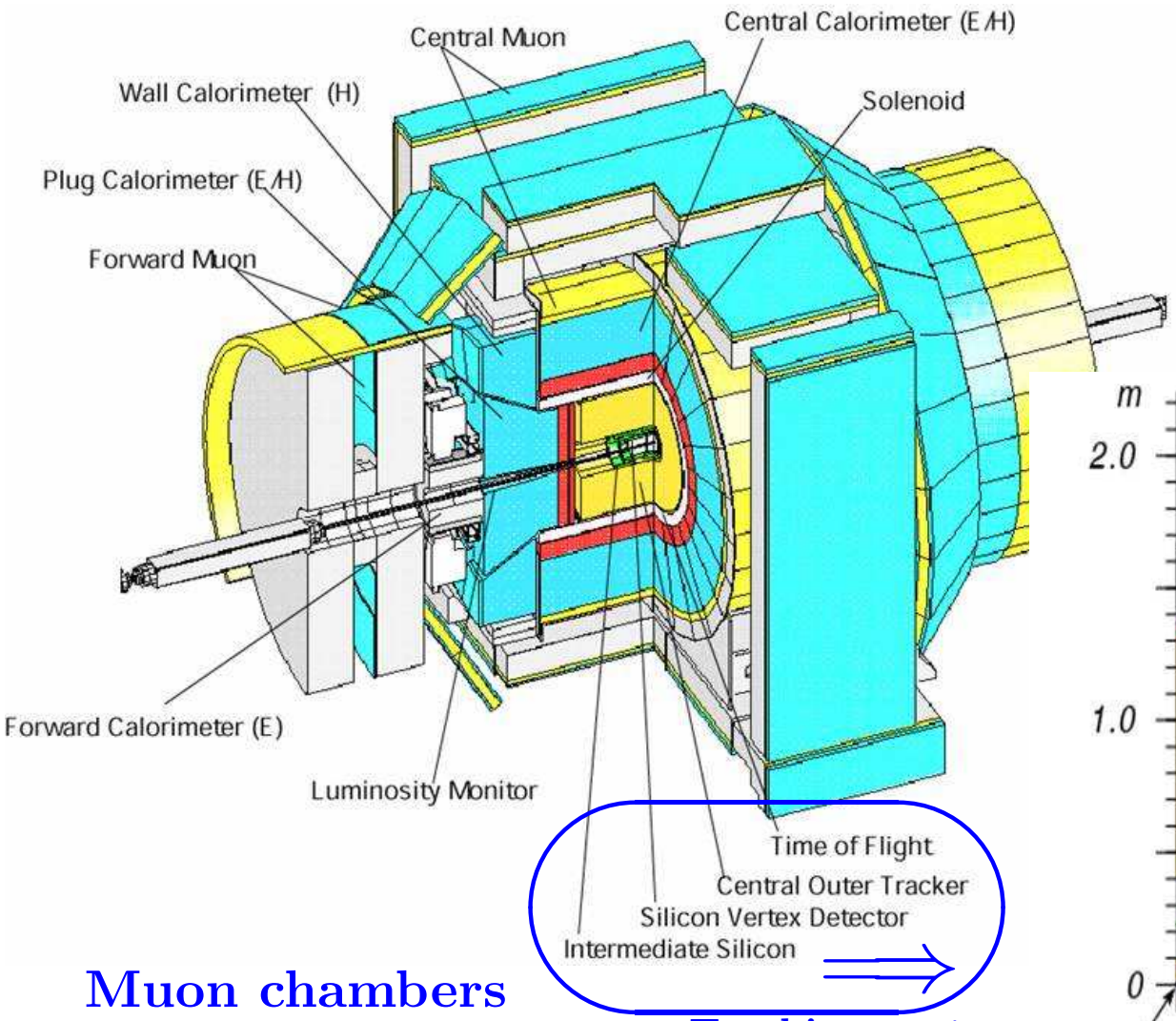
SMT 2nd^{ry} vtx resol^{n}:

- 40μm (r, ϕ)
- 80μm (r, z)

- Impact parameter resolution
  - of $\sim 50\mu$m at p_T of 1 GeV
  - improving to $\sim 10\mu$m at high p_T



The CDF-II Detector

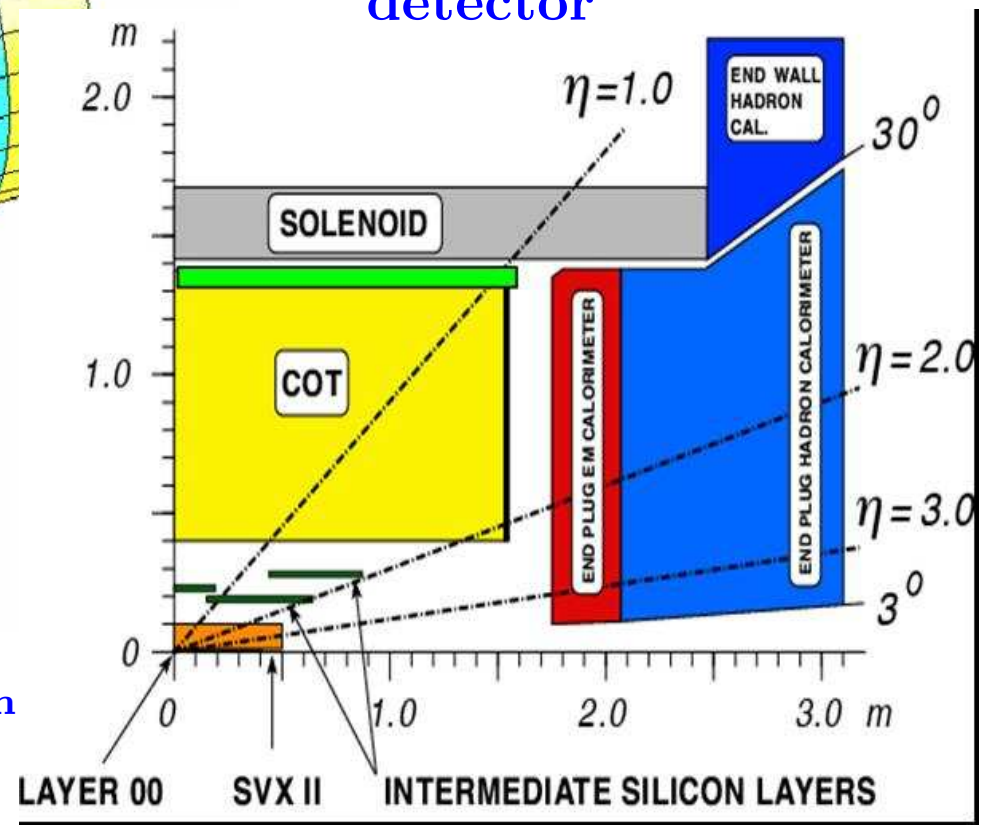


Tracking system

Muon chambers out to $\eta < 1.1$

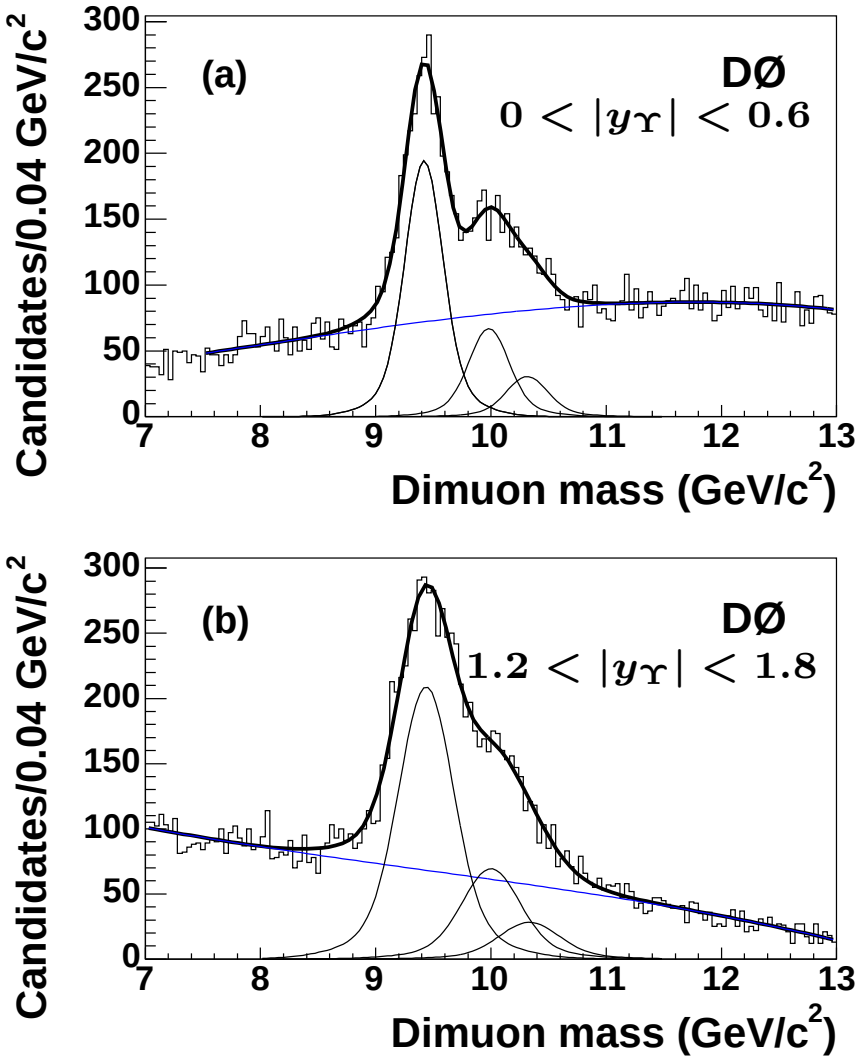
Particle ID:

- dE/dx **in COT**
- **Time of Flight detector**

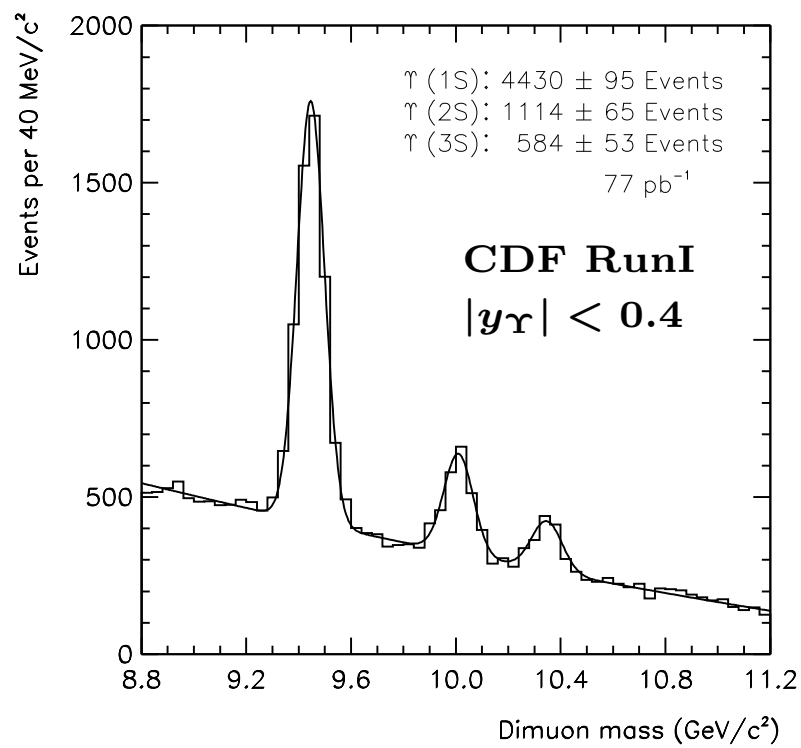


Two rather different detectors...

$\Upsilon(1S)$ Production (DØRunII)

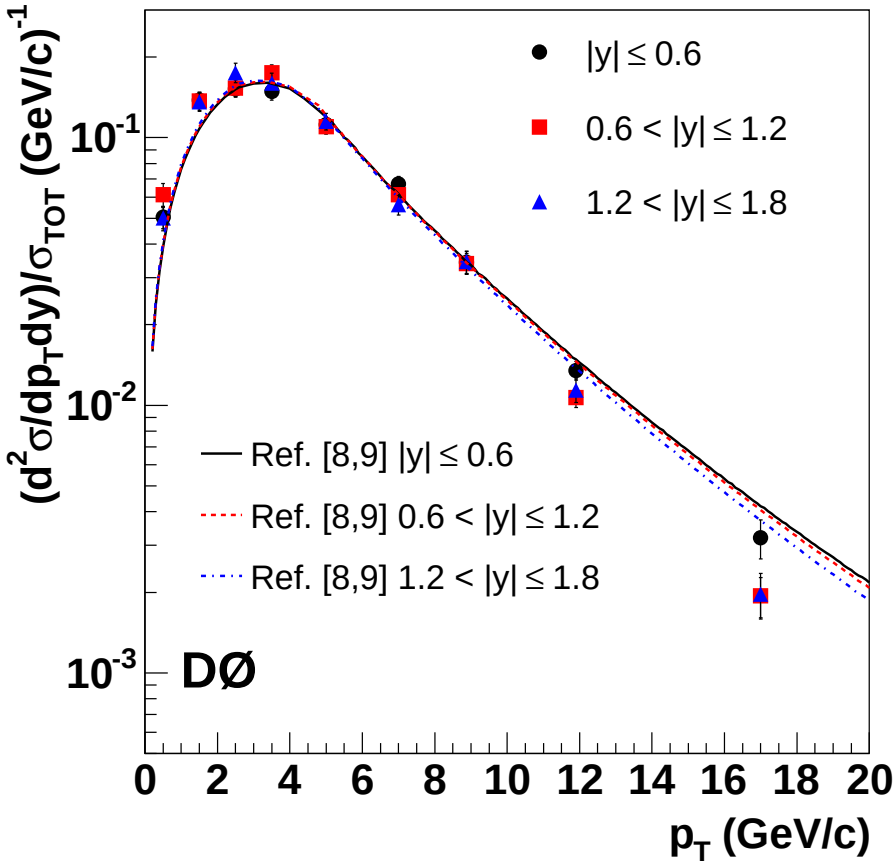


- Phys.Rev.Lett. 94, 232001('05)
- Signal ($\mu^+\mu^-$) yields ~40,000 $\Upsilon(1S)$ in $160pb^{-1}$ $(250/pb^{-1})$
- Extends CDF RunI measurement from $y_\Upsilon < 0.4$ to $y_\Upsilon < 1.8$

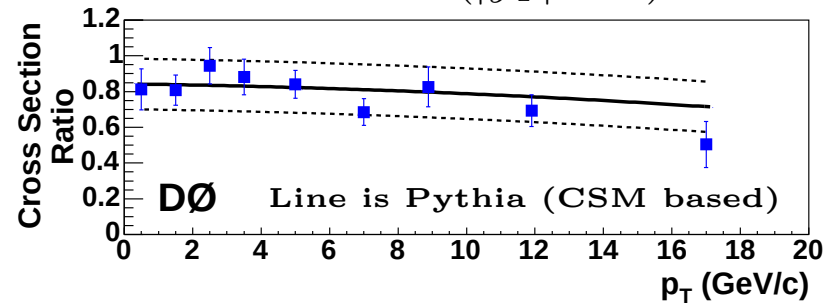


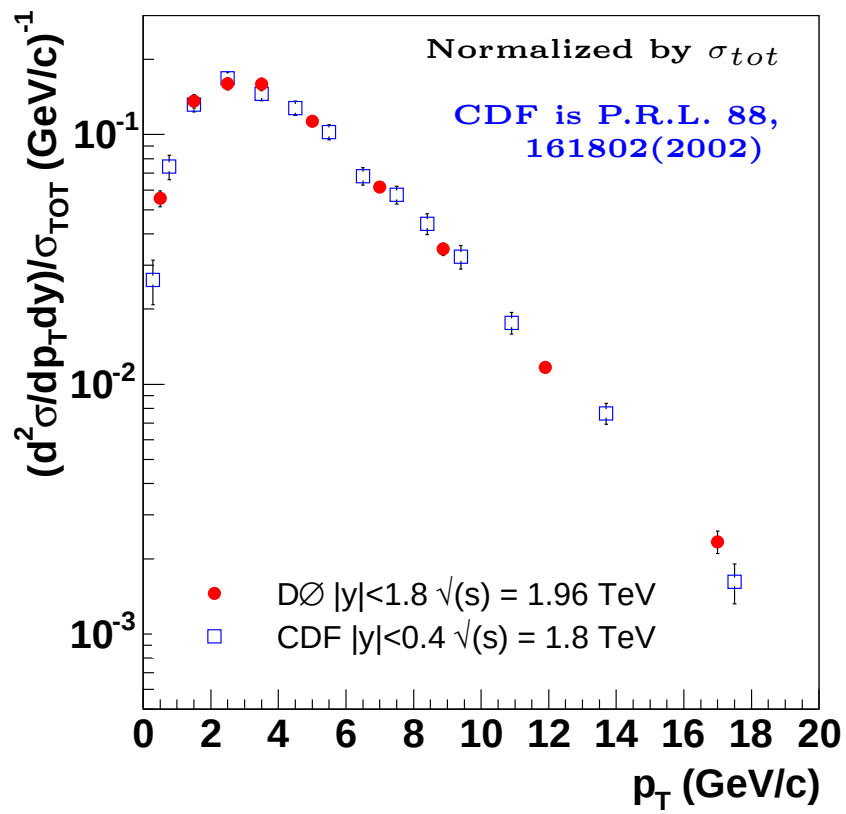
$\Upsilon(1S)$ Production Results

$\Upsilon(1S)$ *Differential Cross Section*



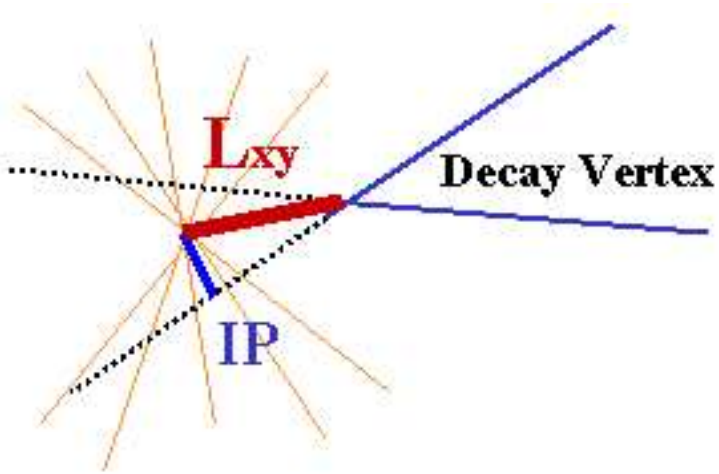
Fraction $\frac{\sigma(1.2<|y_\Upsilon|<1.8)}{\sigma(|y_\Upsilon|<0.6)}$





- Theory calculations (Ref.[8,9]) are by Berger, Qiu and Wang (P.R.D 71, 034007 (2005))

...with rather different trigger strategies



CDF: non-leptonic trigger

- CDF's Secondary Vertex Trigger; online L2 selection of displaced (IP) tracks based on Si-detector hits.

- Example: **L1:** two tracks, $\Delta\phi < 135^0$
  p_{T1} , $p_{T2} > 2GeV/c$
  L2: $IP > 100\mu$m (both)
  $L_{xy} > 200\mu$m

Approximate accept rates (Hz)

output rates	DØ		CDF	
	Run IIa	Run IIb	Run IIa	Run IIb
Level-1	1500	2500	25000	25000
Level-2	850	1000	300	750
Level-3	50	50+50	50	85

B_c Mesons

B_c at the Tevatron

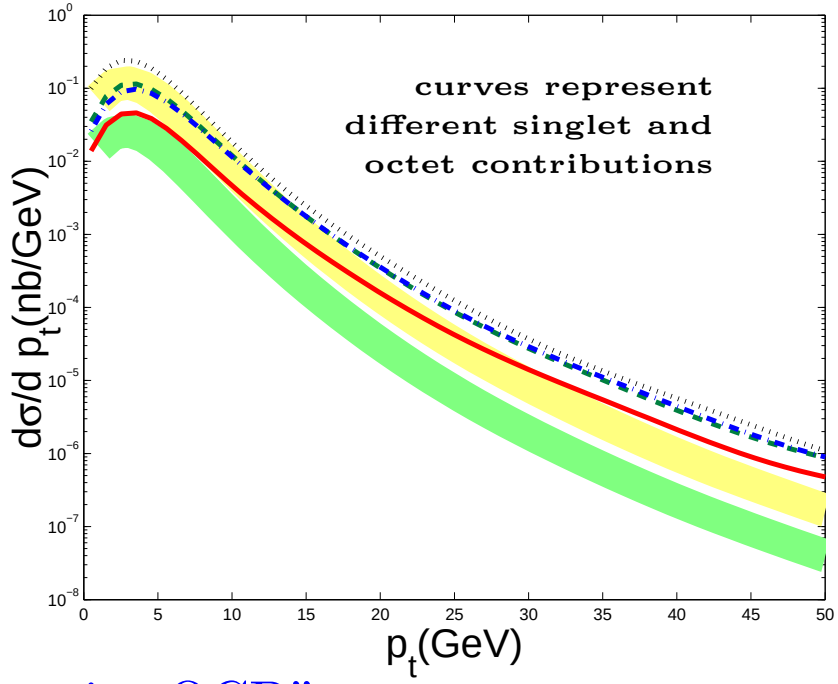
The B_c is a unique (heavy-heavy, $\neq q$'s) system

- probes the heavy quark potential in a region between the J/ψ and the Υ — expected rich spectroscopy of excited states

- production: contributions from color singlet/octet
  - factorization+fragmentation with only heavy q's involved

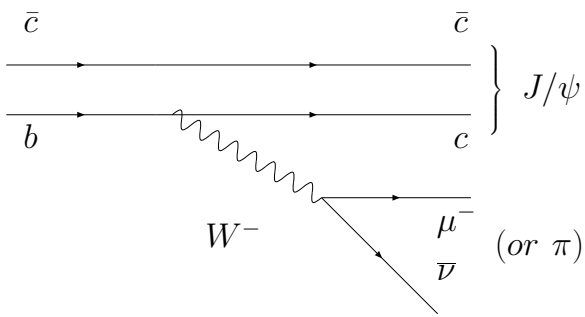
- both b and c can decay weakly, with comparable probabilities
  - shorter c- like lifetimes ?
  - various final states (BR's)

C-H Chang et.al. PRD 71, 074012,2005

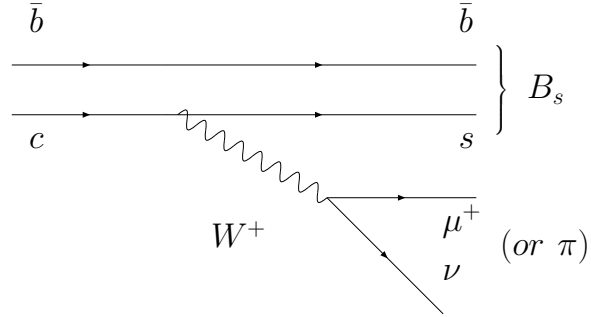


- "Mass of the B_c Meson in 3-Flavor Lattice QCD"
  - HPQCD + FNAL-Lattice + UKQCD + (MILC ensembles), PRL 94, 172001,2005.

Decays of the B_c



c as spectator (this talk)



b as spectator (not seen)
...but important for B_s-mixing program!!

- A J/ψ in the final state is a *huge* advantage for hadron collider experiments (ease of triggering and reconstruction)
- Observation and studies of the B_c at the Tevatron:

RunI	CDF	$B_c \to J/\psi + (\mu, e)\nu$	PRL 81, 2432 (1998) PRD 58, 112004 (1998)
RunII	CDF and DØ	$B_c \to J/\psi + \mu\nu$	(conference notes)
RunII	CDF sees evidence of $B_c \to J/\psi + \pi$		(hep-ex/0505076)

RunII B_c - semileptonic decays

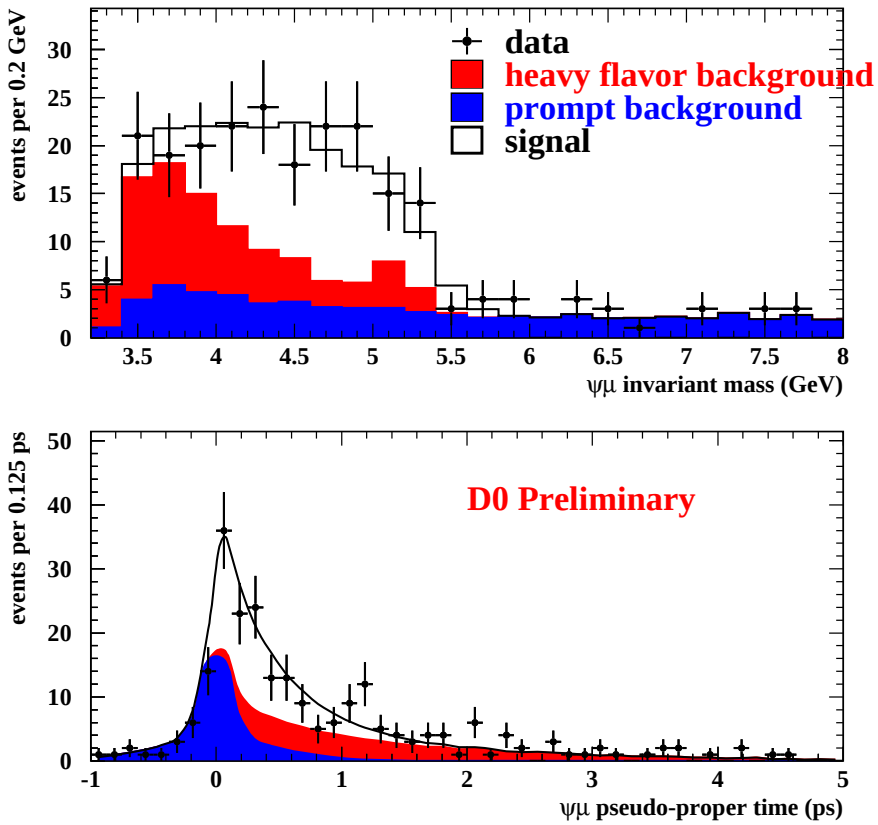
- Not fully reconstructed (missing neutrino)
  - mass is extracted with relatively large uncertainty
- Strategy: look for B_c excess above expected background
  - key item is the understanding of backgrounds
    - fake leptons, $b\bar{b}$ evts + 1-semileptonic, etc.
  - help from: $B^{\pm} \to J/\psi\ K^{\pm}$ and J/ψ + non-lepton-track
- Summary of (preliminary) results

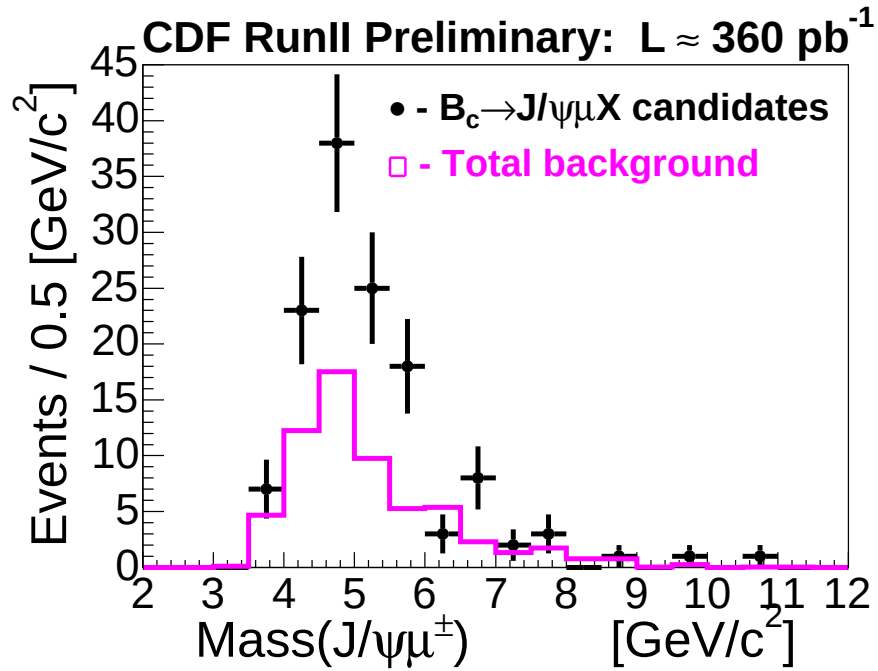
	int.lum.	n.cand	signal	mass(GeV/c^2)	lifetime(ps)
DØ	210 pb^{-1}	231	95.5±11.8	$5.95\ ^{+0.14}_{-0.13} \pm 0.34$	$0.45\ ^{+0.12}_{-0.10} \pm 0.12$
CDF	360 pb^{-1}	106	60.0±12.6	(*)	(*)

(*) in preparation. CDF-RunI results are; $6.40 \pm 0.39 \pm 0.13$ $0.46\ ^{+0.18}_{-0.16} \pm 0.03$

110 pb^{-1} $20.4\ ^{+6.2}_{-5.5}$ ($e + \mu$, published)

RunII B_c - semileptonic signals





- DØ combined likelihood fit for $M(J/\psi\ \mu)$ and pseudo-proper lifetime.

- CDF also extracts;

$$\frac{\sigma(B_c) \times B(B_c \to J/\psi \ell \nu)}{\sigma(B_u) \times B(B^{\pm} \to J/\psi K^{\pm})} =$$

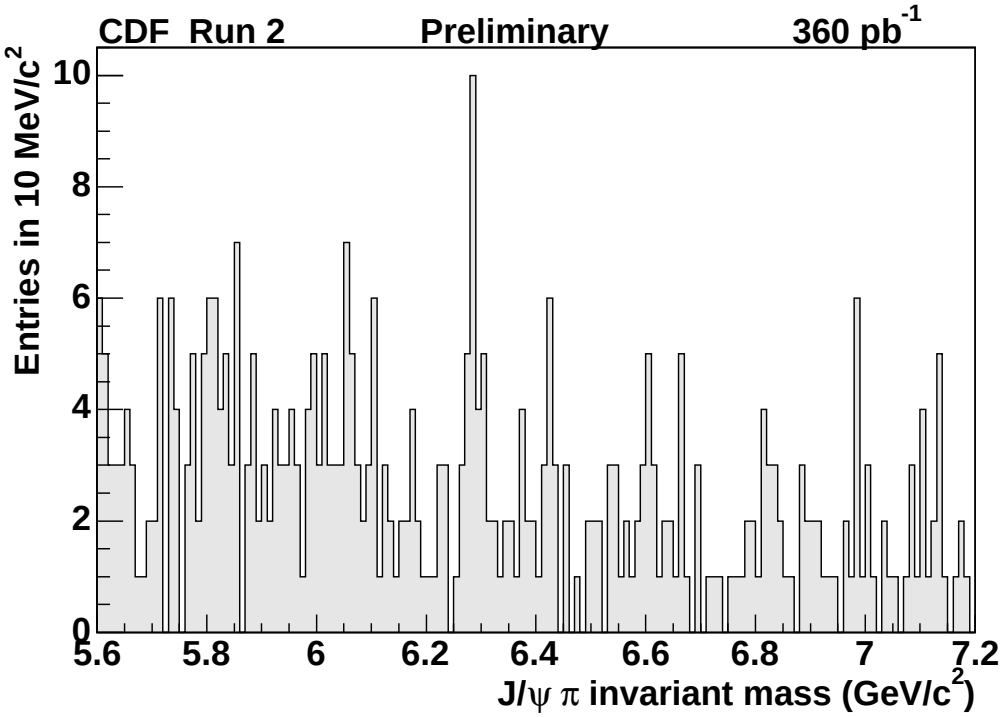
$$0.245 \quad \pm 0.045 \quad \pm 0.066 \quad {}^{+0.080}_{-0.032}$$

$$stat. \qquad syst. \qquad life.$$

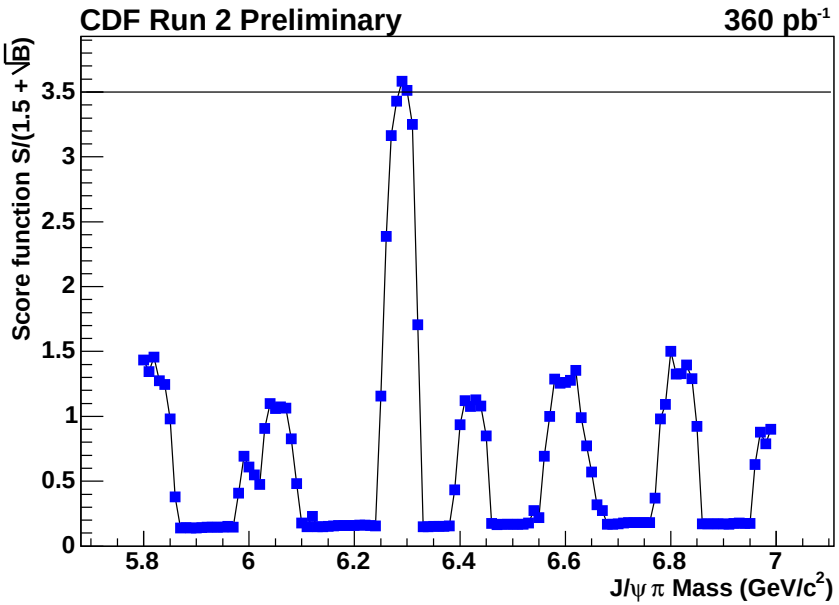
B_c — Full Reconstruction

- CDF(Dec.2004) – evidence of $B_c \to J/\psi(\mu^+\mu^-) + \pi$ (in 360 pb^{-1})
- Search range: $5.6 < M(B_c) < 7.2\ GeV/c^2$ (RunI mass value $\pm 2\sigma$)
- Optimize selection (MC signal) using a sensitivity figure of merit
- Perform a "blind" analysis until selection is established

- Search range is scanned with a sliding fit window.
- Use predetermined (MC) threshold on "score function" for a positive result.

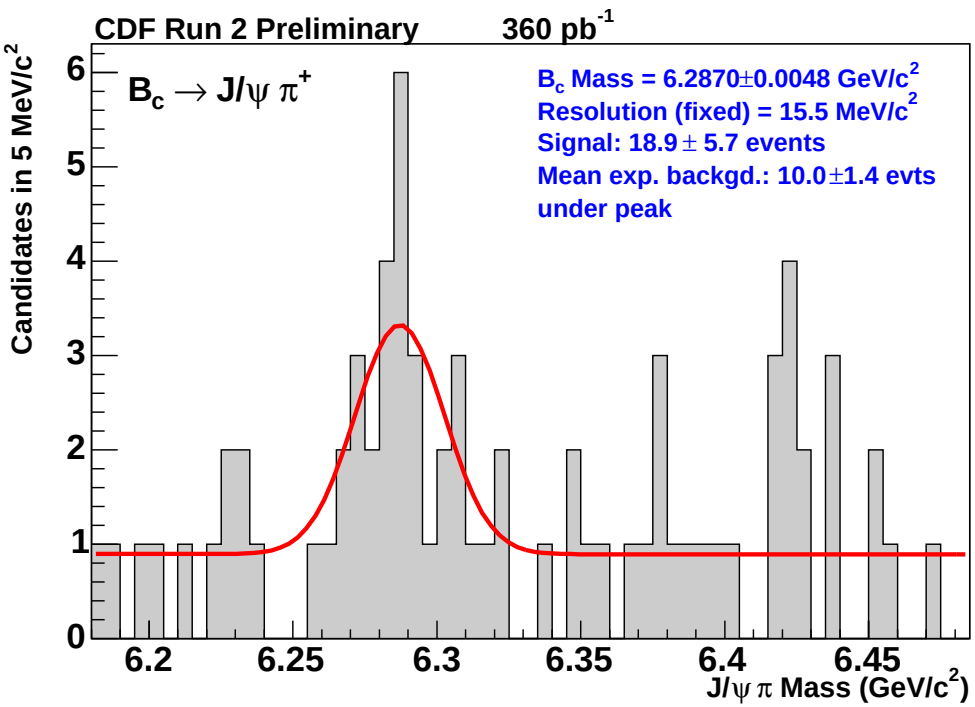


B_c — Full Reconstruction

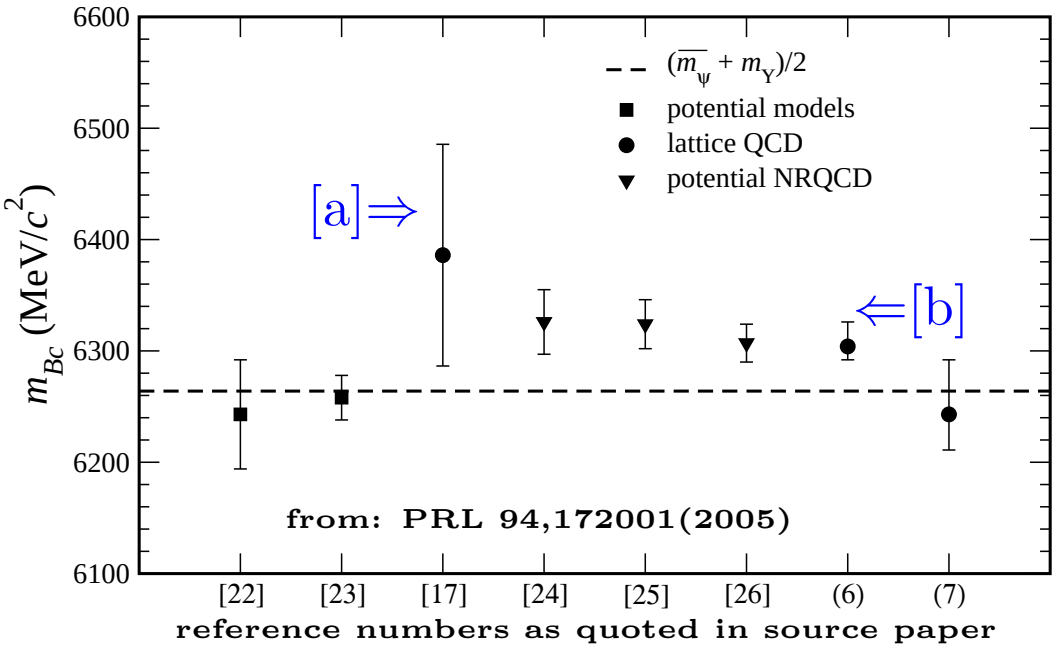


- Sliding fit window
  - 300 MeV wide
  - in steps of 10 MeV
  - Gaussian + Linear(bkgd)
  - MC-fixed (variable) width

- Predetermined threshold is clipped at 6.3 GeV/c^2
- Prob that bkgd fluctuates to this signal is 0.3%
- $M = 6287.0 \pm 4.8 \pm 1.1$ MeV/c^2

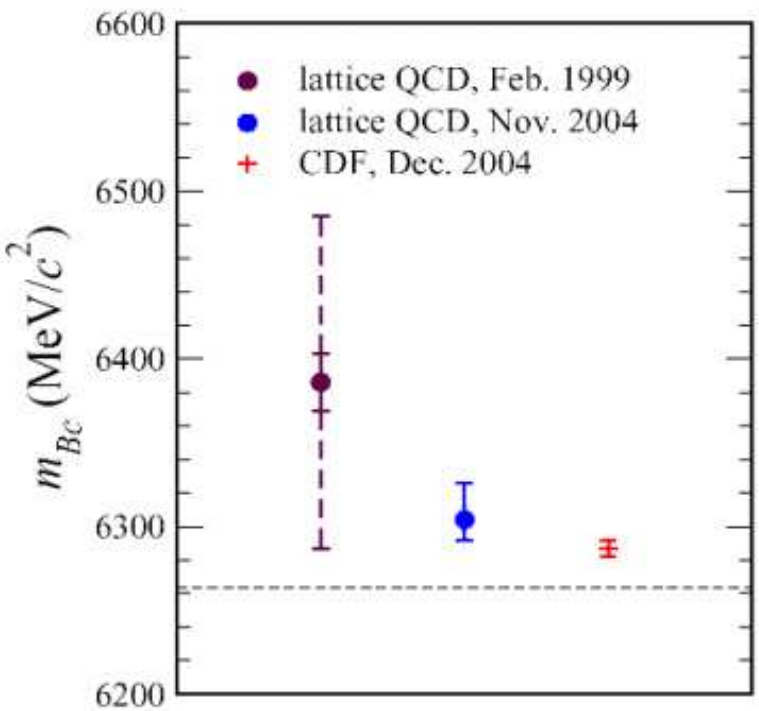


B_c Mass Predictions



Lattice QCD:

- [a] Omitting sea quarks, (quenched approx.)
- [b] Add 2+1 sea flavors, u, d as light as possible, and strangeness mass



- [a] PLB 453, 289 (1999)
  $6386 \pm 9 \pm 15 \pm 98 \ MeV/c^2$
- [b] PRL 94,172001(2005)
  $6304 \pm 4 \pm 11 \ ^{+18}_{-0} \ MeV/c^2$
- [CDF] hep-ex/0505076
  $6287.0 \pm 4.8 \pm 1.1 \ MeV/c^2$

D^{**} Mesons

D^{**} at the Tevatron

- **Four orbitally excited D-meson states, collectively known as D^{**}**

- Both CDF and DØ have studies on the narrow ($j_q = 3/2$) resonances:

CDF; masses and widths

DØ; semileptonic branching fractions ($B \to D^{**}$)

- Theoretical interest (HQET)
  - hyperfine splittings between states with different j_q
  - B.F. ratios are among least model-dependent predictions

- Previous studies by various experiments, most recently by Belle ($\mathcal{R}_\pi$)

In the heavy charm limit ($\vec{j_q} = \vec{L} + \vec{s_q}$)

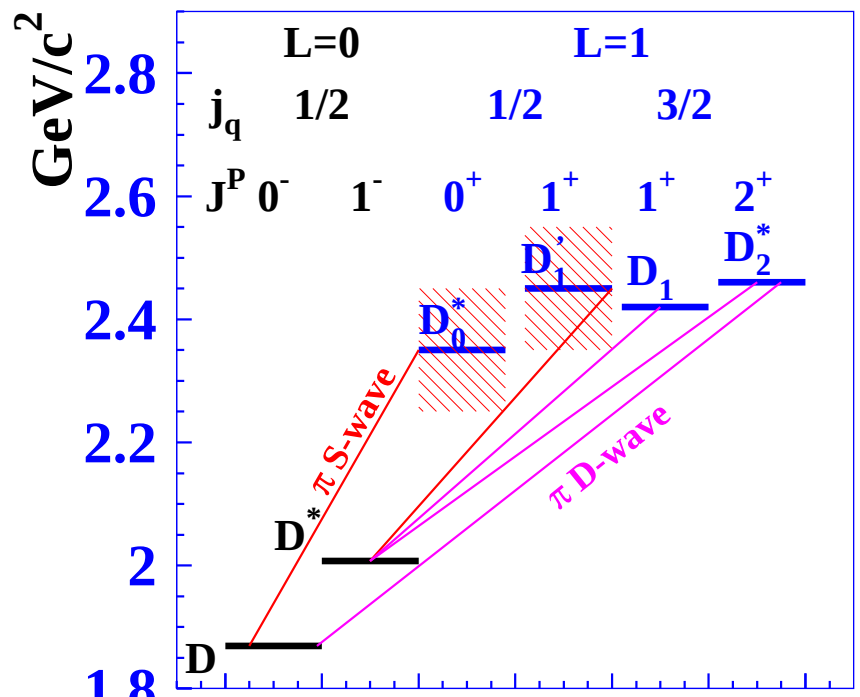
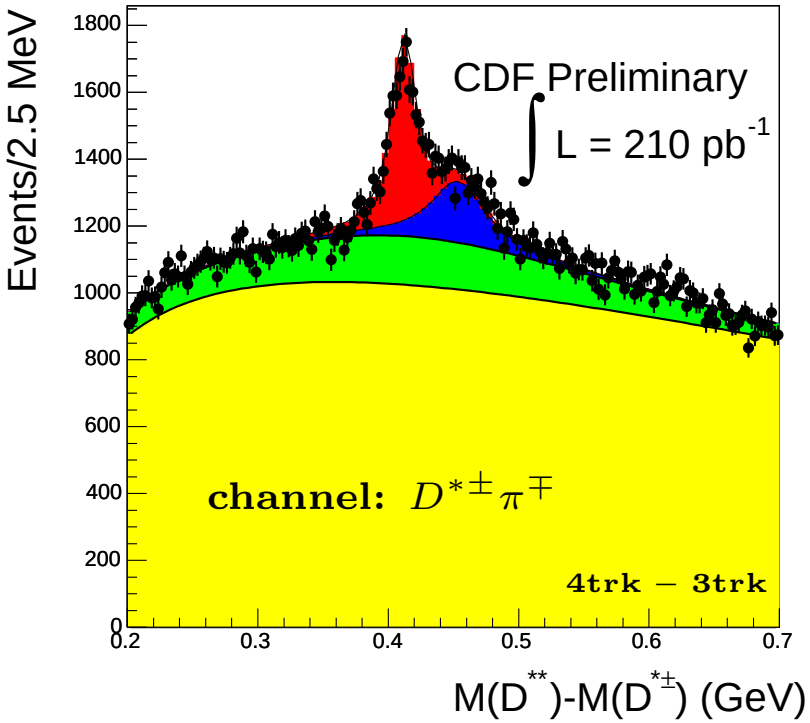


Fig. from hep-ex/0307021 (Belle) or, PRD 69, 112002 (2004)

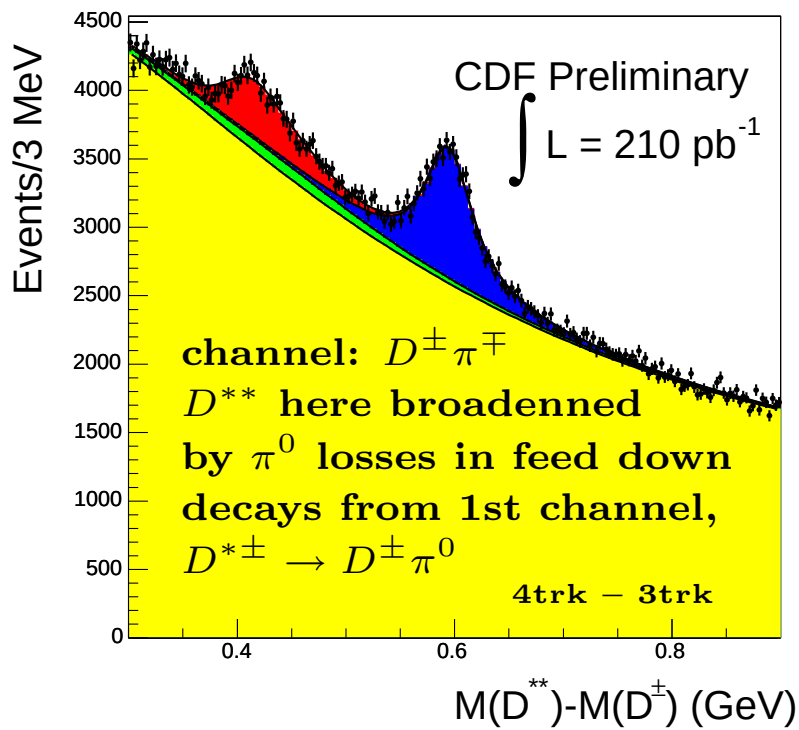
Four ($L = 1$) resonant states decaying thru

- S-waves; expected wide ($\Gamma \sim \mathcal{O}(100)$MeV) ($j_q = 1/2$) – not observed directly (Belle?)
- D-waves; narrow ($\Gamma \sim \mathcal{O}(20)$MeV) ($j_q = 3/2$) – seen by various experiments

D^{**} at CDF



- Two hadronic channels studied
- SVT trigger:
  2-Track(O.S.), $p_T > 2\ GeV/c$
  $IP > 100\mu$m per track



- Fits indicate that excess background (in green) can be attributted to broad D_1' and D_0^* components respectively

D^{**} - CDF Results

- Simultaneous fits to the two measurements (channels)
- Independent background and broad state description
- Resolution modelling, full simulation of feed downs
- tests for selection biases w/ (2*Data)-larger MC sample

$M(D_1^0) - M(D^{*\pm}) = 411.7 \pm 0.7 \pm 0.4$ $\quad$ $M(D_2^{*0}) - M(D^{\pm}) = 594.0 \pm 0.6 \pm 0.5$

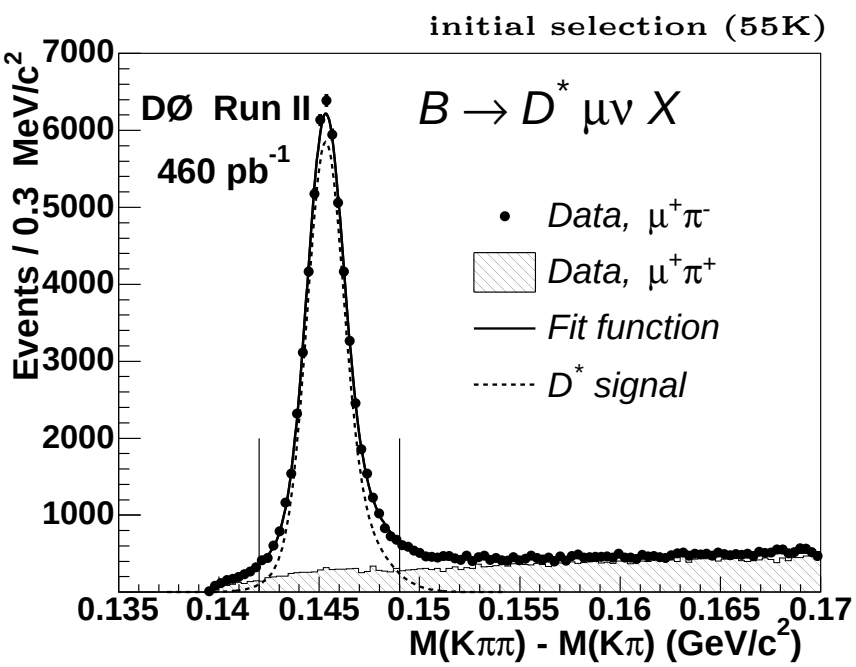
(GeV/c^2)	$Mass$	$Width$
D_1	$2421.7 \pm 0.7 \pm 0.6$	$20.0 \pm 1.7 \pm 1.3$
D_2	$2463.3 \pm 0.6 \pm 0.8$	$49.2 \pm 2.3 \pm 1.3$

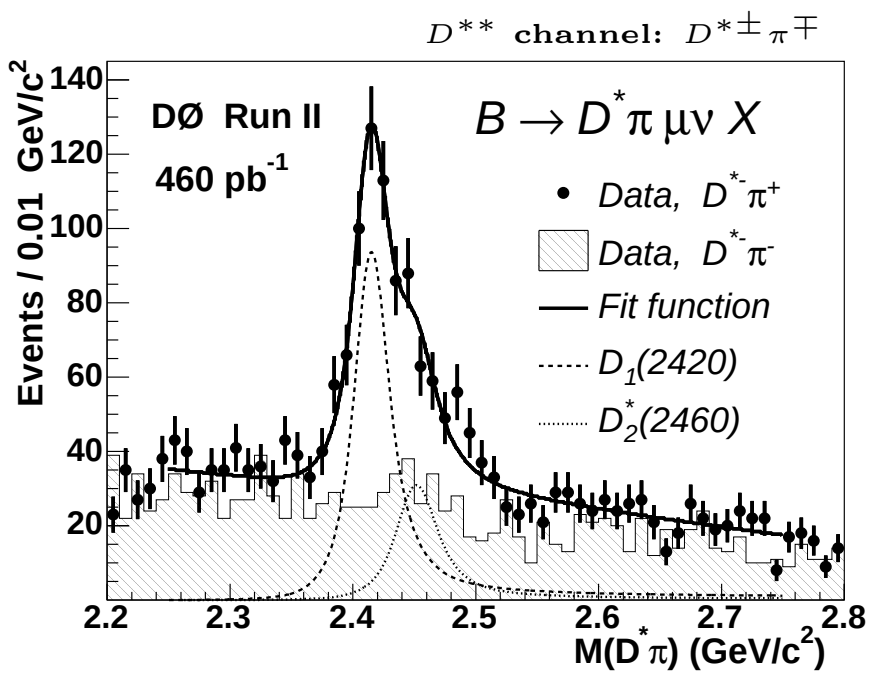
– CDF note 7191 (2004)

D^{**} at DØ

- Data (460 pb^{-1}) from suite of single-muon triggers
- Measure: $\mathcal{B}(B \to (narrow)D^{**}_{1,2} + \mu\nu X)$ and their ratio
- D^{**} Fit: two relativistic B-W fns $\oplus$ 2nd order polynom(bkgnd)
  Fixed[PDG] $M(D_2^*) - M(D_1)$ and widths.

PRL submitted, and hep-ex/0507046





D^{**} - DØ Results

Semileptonic ($B \to D^{**}$) branching fractions and their ratio

$$\mathcal{B}(\bar{b} \to B) \cdot \mathcal{B}(B \to (\bar{D}_1^0, \bar{D}_2^{*0})\mu^+\nu_\mu X) \cdot \mathcal{B}((\bar{D}_1^0, \bar{D}_2^{*0}) \to D^{*-}\pi^+) = (0.122 \pm 0.007\ (\mathrm{st}) \pm 0.015\ (\mathrm{sy}))\%$$

$$\mathcal{B}(\bar{b} \to B) \cdot \mathcal{B}(B \to \bar{D}_1^0\mu^+\nu_\mu X) \cdot \mathcal{B}(\bar{D}_1^0 \to D^{*-}\pi^+) = (0.087 \pm 0.007\ (\mathrm{st}) \pm 0.014\ (\mathrm{sy}))\%$$

$$\mathcal{B}(\bar{b} \to B) \cdot \mathcal{B}(B \to \bar{D}_2^{*0}\mu^+\nu_\mu X) \cdot \mathcal{B}(\bar{D}_2^{*0} \to D^{*-}\pi^+) = (0.035 \pm 0.007\ (\mathrm{st}) \pm 0.008\ (\mathrm{sy}))\%$$

$$\frac{\mathcal{B}(B \to \bar{D}_2^{*0}\mu^+\nu_\mu X) \cdot \mathcal{B}(\bar{D}_2^{*0} \to D^{*-}\pi^+)}{\mathcal{B}(B \to \bar{D}_1^0\mu^+\nu_\mu X) \cdot \mathcal{B}(\bar{D}_1^0 \to D^{*-}\pi^+)} = 0.39 \pm 0.09\ (\mathrm{st}) \pm 0.12\ (\mathrm{sy})$$

Stats $> 10\times$ that of previous experiments...

- **input (PDG):** $\mathcal{B}(\bar{b} \to B) = (39.7 \pm 1.0)\%$
- **assuming that the D_1 meson decays only into $D^*\pi$**
- **assuming that D_2^* decays into $D^*\pi$ in $(30 \pm 6)\%$ of the cases (PDG)**
- **Ratio (first direct measurement)**
  HQET $= 1.6\rfloor_{m_c=\infty} - \mathcal{O}(1/m_c)$

$$\mathcal{B}(B \to \bar{D}_1^0\ell^+\nu X) = (0.33 \pm 0.06)\%$$

different from PDG value $(0.74 \pm 0.16)\%$ by $2.5\ \sigma$

$$\mathcal{B}(B \to \bar{D}_2^{*0}\ell^+\nu X) = (0.44 \pm 0.16)\%$$

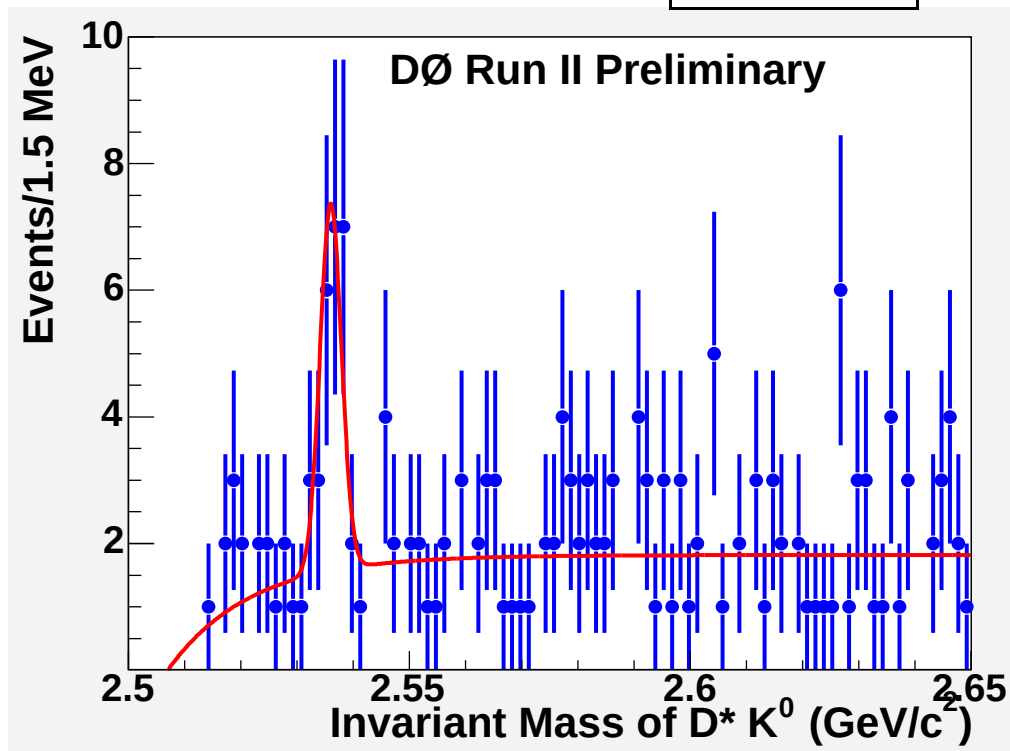
in agreement with (PDG) 95% CL upper limit 0.65%

$$\mathcal{R} = 1.31 \pm 0.29\ (\mathrm{stat}) \pm 0.47\ (\mathrm{syst})$$

DØ: $B_s \to D_{s1}^{\pm}(2536)\mu\nu X$

$485\ pb^{-1}$

very recent: evidence of $D_{s1}^{\pm}(2536)$ an orbitally excited (c, s) pair in a $J^P = 1^+$ state



- Reconstruction
  - 18 ± 5 events
  - significance $> 3\sigma$
- Decay chain is

$$D_{s1}^{\pm}(2536) \to D^{*\pm}\ K_s^0$$
$$D^{*+} \to D^0\pi^+$$
$$D^0 \to K^-\pi^+$$

- **Muon plus 5-Track final state**
- Towards investigation of D_s^{**} properties

  — there are no experimental measurements of $\mathcal{B}(B_s \to D_s^{**})$

B^{**} Mesons

B^{**} at the Tevatron

- B^{**} ($L = 1$) states follow the same pattern (J^P, allowed decays) as D^{**} — see diagram on page 20
- Not yet well established experimentally; unknown masses and widths, and not PDG(2004) listed
- Previous B^{**} observations were only of single wide structure in inclusive or semi-inclusive decays (LEP + CDF-I)
- In contrast, mass, width and BF predictions exist with good precision in various theory models
- Narrow states observed for the first time as two separate objects Tevatron RunII: DØ (Aug'04) , CDF (Mar'05)
- Observed decays are $B^{**} \to B^{(*)}\pi$, with exclusive reconstruction of B mesons. $B^*(\to B\gamma)$ decays have an undetected γ

B^{**} at the Tevatron

- DØ and CDF use similar methods;
  - collect $B^{\pm}$ and B^0 from $\begin{cases} \boldsymbol{B^{\pm} \to J/\psi K^{\pm}} \\ \boldsymbol{B^0 \to J/\psi K^{*0}} \\ \boldsymbol{B^0 \to J/\psi K_s} \end{cases}$
  - add track (π hypothesis), plot mass difference

$$\Delta M = M(B\pi) - M(B)$$

- Expected structure consists of three peaks

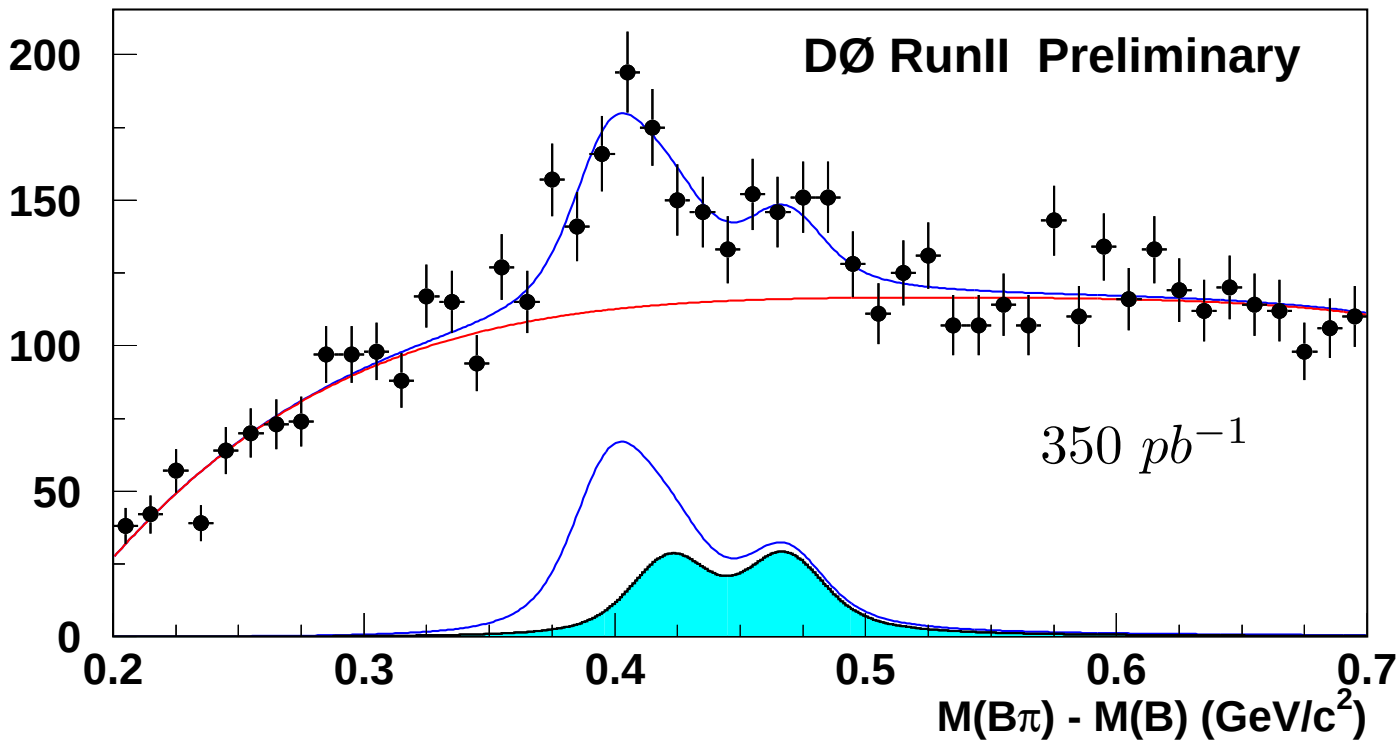
(1) $B_1 \to B^*\pi$, $B^* \to B\gamma$ (shifted by δM)

relative rates 1:1 $\begin{cases} (2)\ B_2 \to B^*\pi\ ,\ B^* \to B\gamma & \text{(shifted by } \delta M) \\ (3)\ B_2 \to B\pi & \text{(true position)} \end{cases}$

where $\delta M = M(B^*) - M(B) \approx 46$ MeV is from the undetected γ

- Peaks (1) and (2) merge. All have same width.

B^{**} - DØ Results

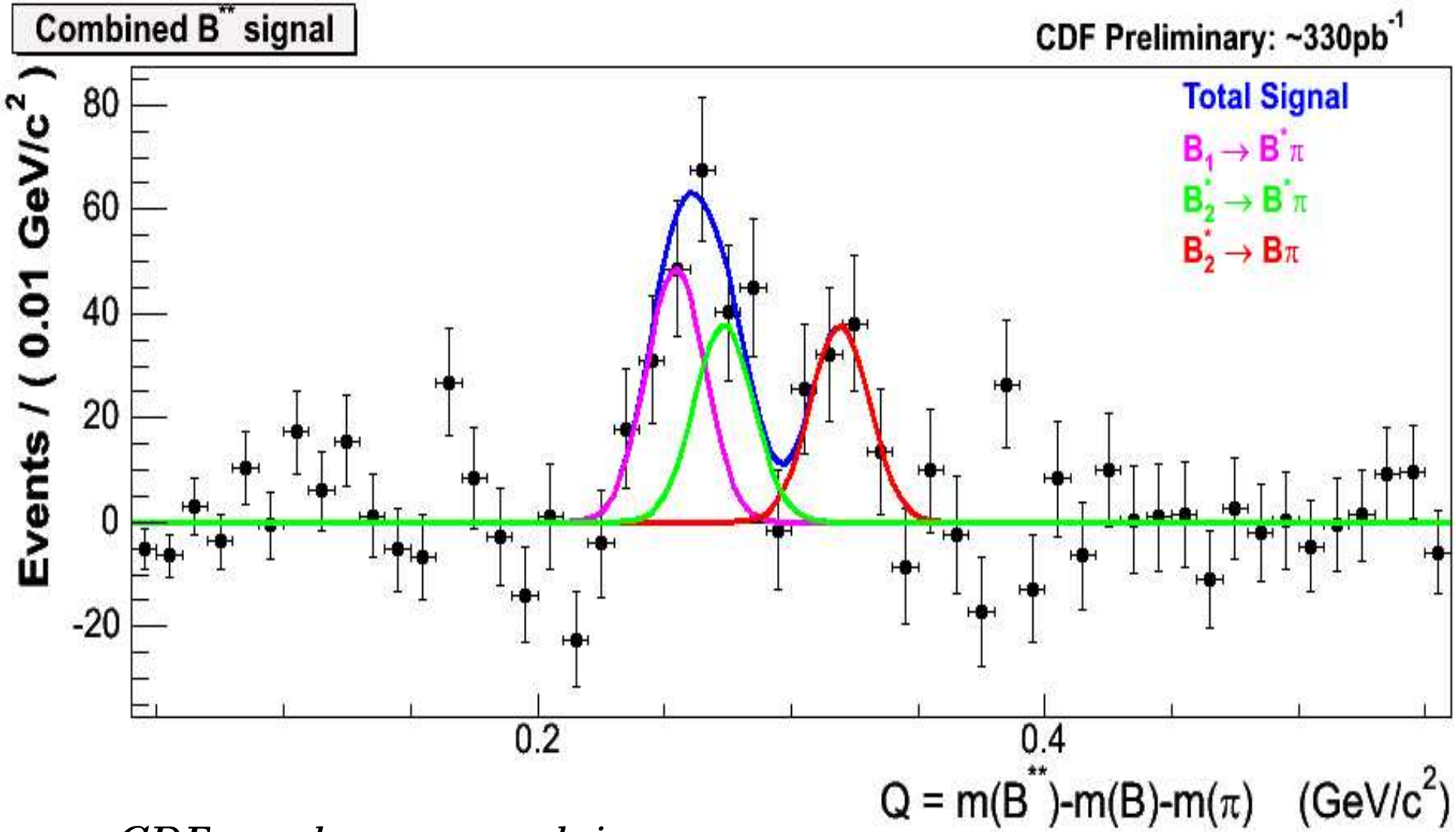


$$M(B_1) = 5724 \pm 4(stat) \pm 7(syst)\ MeV/c^2$$

$$M(B_2^*) - M(B_1) = 23.6 \pm 7.7(stat) \pm 3.9(syst)\ MeV/c^2$$

$$\Gamma_1 = \Gamma_2 = 23 \pm 12(stat) \pm 9(syst)\ MeV/c^2$$

B^{**} - CDF Results



CDF numbers are work in progress

The $X(3872)$

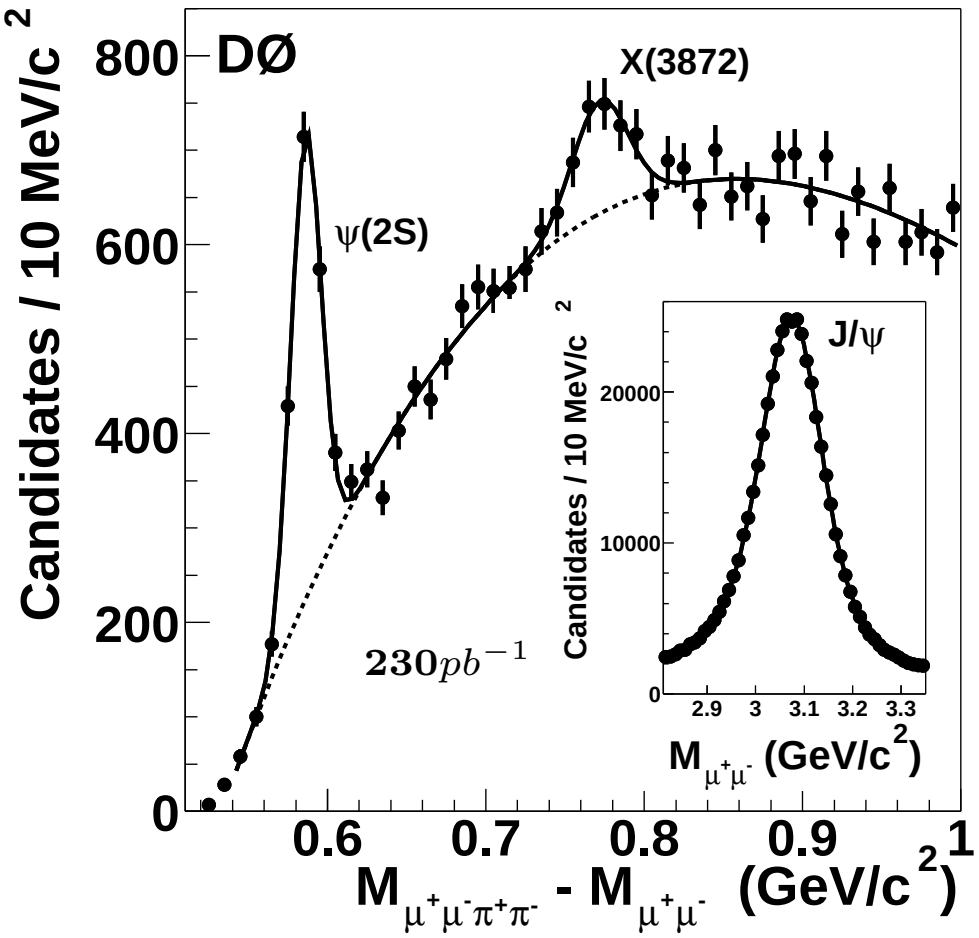
Belle; PRL 91, 262001 (2003)

$$B^{\pm} \rightarrow X\ K^{\pm}$$
$$X \rightarrow J/\psi\ \pi^{+}\pi^{-}$$

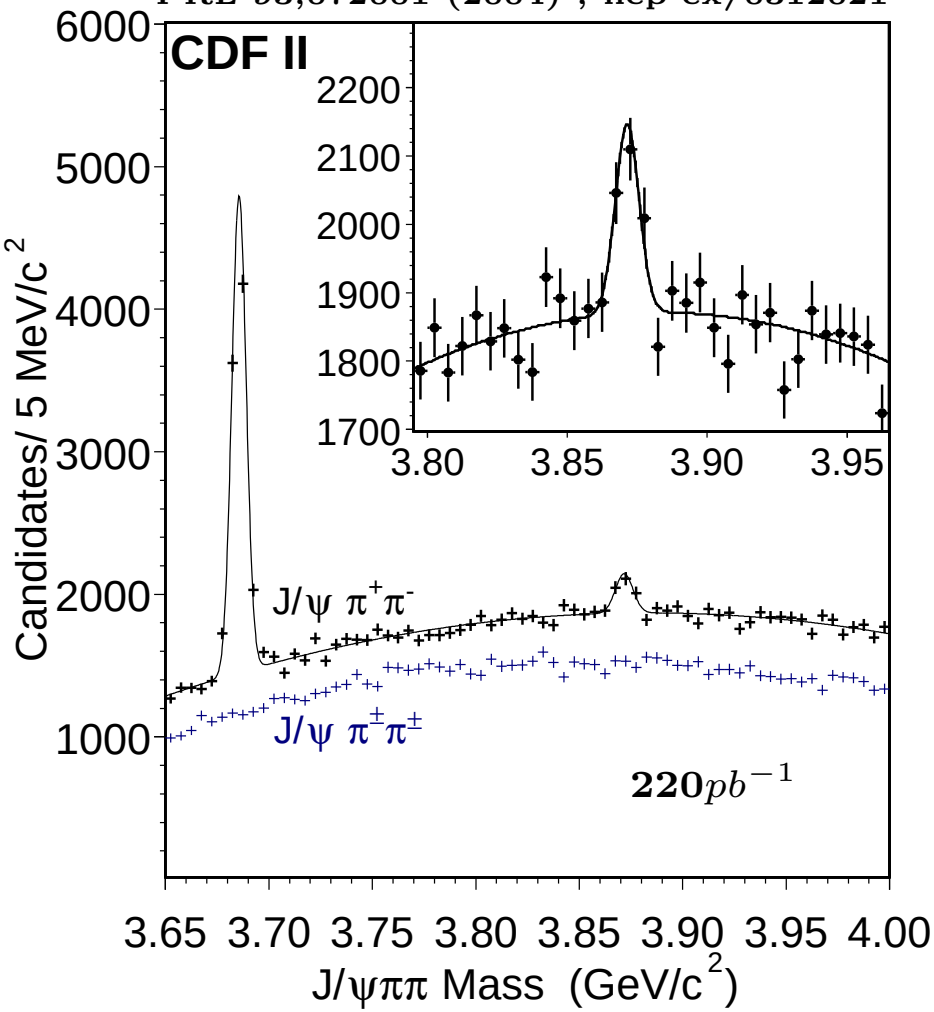
...difficulty in finding a conventional $\bar{c}c$ candidate...

Observation of X(3872) $(J/\psi\ \pi^+\ \pi^-)$

PRL 93,162002 (2004) , hep-ex/0405004



PRL 93,072001 (2004) , hep-ex/0312021

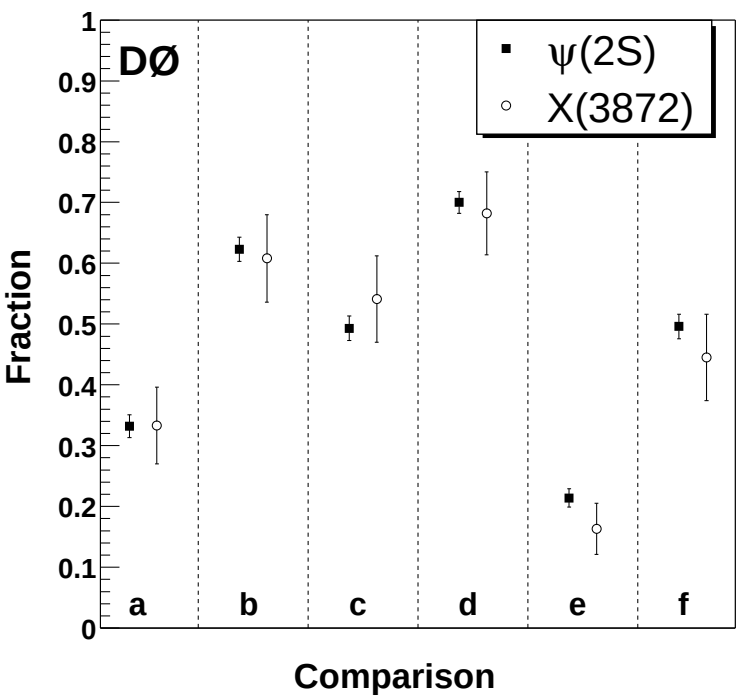


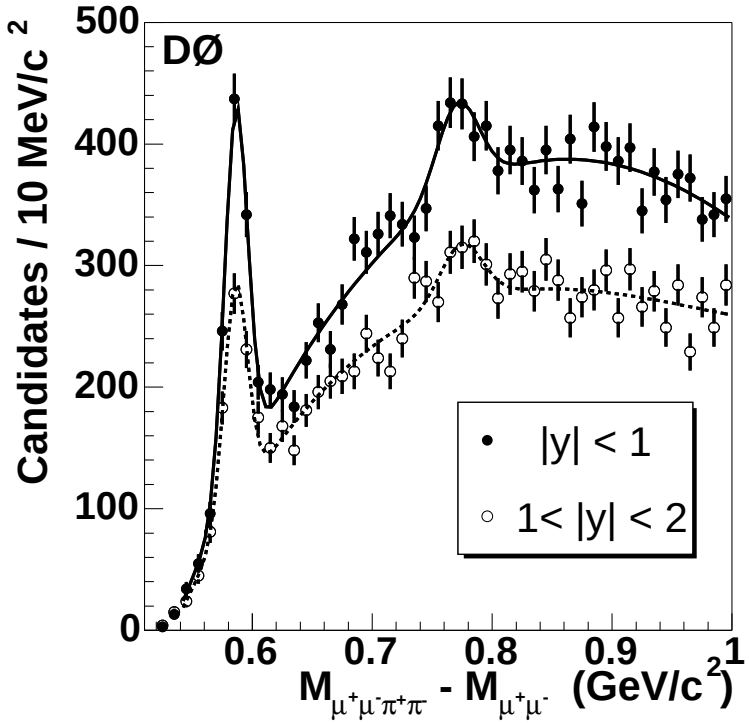
- $\psi(2S)$ **has same decay mode (good benchmark)**

X(3872) - DØ Studies

- Comparative study of production and decay properties; $X(3872)$ *vs* $\psi(2S)$
- **No visible discrimination**

$\Downarrow$





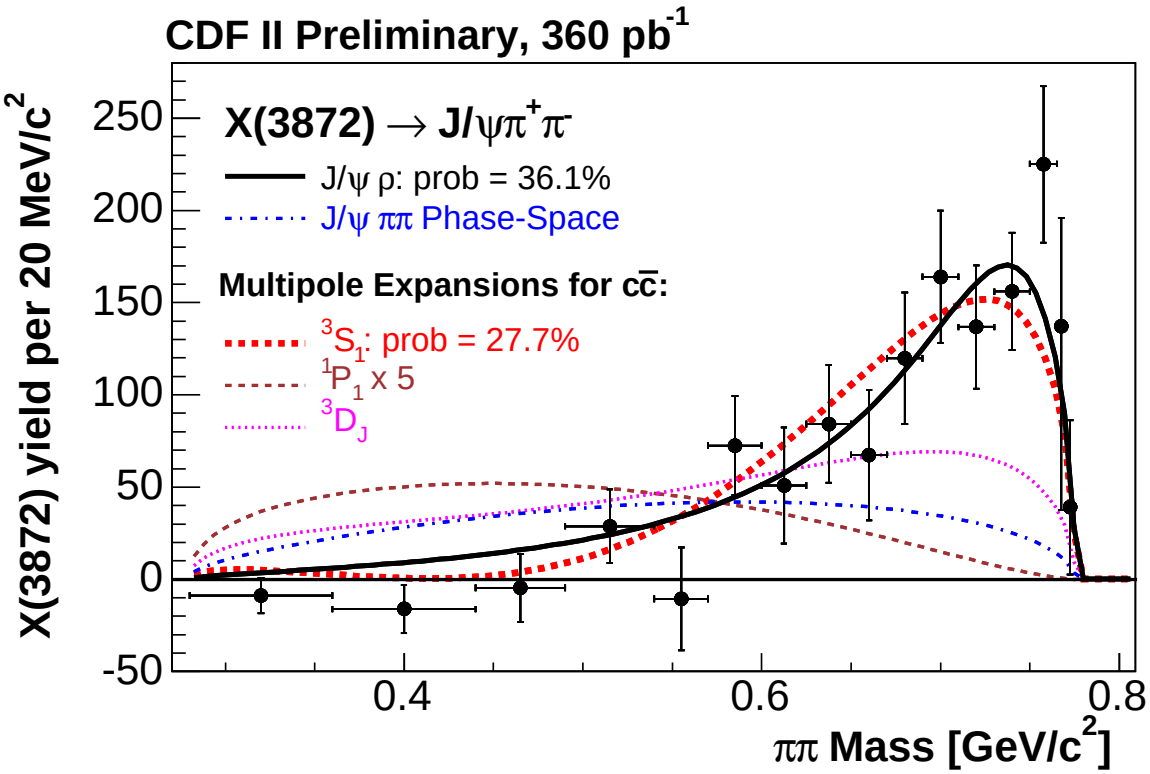
- Fractional yields in separate regions of
  - (a) **transv. momentum**
  - (b) **rapidity (fig. above)**
  - (c) **decay length**
  - (d) **dipion ang.dist.**
  - (e) **isolation (0.5 cone)**
  - (f) **dimuon ang.dist.**

X(3872) - CDF Studies

- Lifetime properties, production fraction from B ($\sim$15%)
  $\Rightarrow$ X and $\psi(2S)$: similar behavior within uncertainties
- **Most recently:** X(3872) Dipion Mass Spectrum
- Motivation: distribution of $M(\pi\pi)$ constrains J^{PC}
  - (π, π) subsystem in S, P, D wave?
  - intermediate sub-resonances (ρ)?
- $M(\pi\pi)$ peaks near upper kinem limit (Belle)
  - as expected for $\rho \to \pi\pi$
- Belle (Beauty'05), 4σ evidence of $X \to J/\psi\ \gamma$ established $\boxed{C = +1}$
  - allows decay to $J/\psi\ \rho$ and $J/\psi\ \omega$
    - $J/\psi\ \rho$ is isospin suppressed for charmonium,
    - which in turn supports molecule hypothesis

$M(\pi\pi)$ - CDF Results

- CDF compares $M(\pi\pi)$ to QCD multipole expansion predictions for charmonium states where the $(\pi\pi)$ system
  - has (lowest L) $J^{PC} = 0^{++}$; $^3S_1$, $^1P_1$ and ^3D_J
- To hypothesis $X \to J/\psi\ \rho$; $(\pi\pi)$ forms a 1^{--} resonance *(B-W)*



Summary:

- **$^1P_1$ and ^3D_J excluded by data**
- **best fit is for resonant $J/\psi\ \rho$**
- **$^3S_1$ just as good, but not viable (no available slots)**
- **caution: reliability of multipole expansions not well established...**

And we have not talked about...

- Baryons
- Rare decays
- Lifetimes
- B_s mixing, $\Delta\Gamma_s/\Gamma_s \cdots$
  - the main thrust of the Tevatron B-program

- Examples of largely complementary talks that overview most recent CDF and DØ analyses not covered here can be found *e.g.* in the Beauty(2005) conference pages, (first session – Monday morning)

http://www.pg.infn.it/beauty2005/

Conclusion

- The Tevatron is producing a wealth of heavy flavor results.
- A competitive program, with
  - many unique measurements
  - decisive impact on world's averages and limits

- Key RunII measurements are on track, with uncertainties dominated by statistics, not systematics.
- HF program to be further enhanced by RunIIb upgrades (not covered here).