The CDF Run II Experiment

High Statistics Top and Bottom Quark Studies

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1. Physics, Detector Upgrades and Schedule (PKS)
2. Proposed Contributions by IPP (WT)
   - Kinematic Mounts for SVX-II and ISL
   - Dynamic Mounts for Silicon Trackers
   - Position Monitoring System
3. IPP Role in Run II (PKS)

TRIUMF
January 1997

The CDF Run II Experiment

CDF is completing successful Run I programme

- Collected 110 pb^{-1} of 1.8 TeV $\bar{p}p$ collisions
- Discovered the top quark
- High precision W^{+} mass and production measurements
- Making high statistics B physics measurements
- Sensitive to very high energy parton-parton collisions (eg $q\bar{q} \rightarrow WW$)

A significant extension of this programme is underway

- $\times$20 increase in integrated luminosity
- Increased $\sqrt{s}$ to 2.0 TeV
- Extensive detector upgrade project
- Data-taking to take place 1999-2002

We are proposing IPP involvement in CDF for Run II

- Excellent physics opportunity
- Well-matched to experience and size of group
- Important step toward ATLAS physics

IPP Physics Research using CDF

IPP group has focused on mainly heavy quark physics

- Top quark discovery and study
- Bottom hadron studies

Best seen by looking at research activities

- $B \to J/\psi X$ exclusive decays (G. Sganos)
- $B \to \gamma K^*$ decays (K. Kordas)
- $B \to \psi(2S)X$ exclusive decays (A. Warburton)
- $B \to e^{\pm} D/D^* X$ decays (W. Taylor)
- Top quark mass and branching ratio measurements (PKS)
- Rare B decays (K. Strahl and KR)
- B semileptonic cascade decays (S. Gadomski)
- B mixing studies (WT)
- W' searches (H. Kim)
- QCD multijet studies (B. Hinrichsen)

SM Top Quark Phenomenology

Top quarks decay via the weak force

- Predict $\sim$ 100% $t \to W^+ b$
- Lifetime depends on mass
- For heavy top ($M_{top} \gtrsim 100 - 120$ GeV/c^2), decays before it hadronises

Can be viewed as a "pure" charged current

$$\Gamma_{\rm top} = \frac{G_F M_t^3}{8\sqrt{2}\pi}\left(1 - \frac{M_W^2}{M_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{M_t^2}\right)$$

$$\sim 175 \text{ MeV} \left(\frac{M_t}{M_W}\right)^3 \sim 2 \text{ GeV}$$

- Toponium doesn't have time to form
- T mesons $\sim$ degenerate (if there was time...)

Decay dominated by "longitudinal W^+"

- Means the W^+ prefers helicity 0
- Result of large top and W^+ mass

What Do Top Decays Tell Us?

SM predicts "pure" $V - A$ decay

- clear test of polarisation at decay vertex

$$\frac{W_{\text{long}}}{W_{\text{T}}} \sim \frac{1}{2}\left(\frac{M_t}{M_W}\right)^2 \sim 2.2$$

- V_{ts} CKM matrix elements
- Constraints on other SM parameters (eg. A_{LR})
- Effectively another consistency check of SM

Sensitive to some classes of "new physics"

- Higgs couples strongly to top
- Could decay into a SUSY H^+

$$t \rightarrow H^+ b, \quad H^+ \rightarrow \tau^+ \nu_\tau$$

- Top quark might be "special" in unexpected way
  - New physics that couples to $t\bar{t}$ system

$\boxed{\text{SM Bottom Quark Decays}}$

SM predicts similar charged-current decays

- Dominated by weak matrix element
- However, b is imbedded in "brown muck"
  - Strong interaction effects are important
  - higher-order diagrams also play a role

Have resorted to an effective Hamiltonian approach

- Use a basis convenient for a $Q\bar{q}$ system
  - $\Rightarrow$ Heavy Quark Effective Theory
- Assume that decay amplitude "factors" (BSW)
- Determine parameters empirically

Hadronic Bottom Decays

Start with

$$H = \frac{G_F}{\sqrt{2}} V_{cb} \left\{ \left[(\bar{d}u) + (\bar{s}c) \right] (\bar{c}b) \right\}$$

- Renormalise H to take into account QCD corrections

$$\begin{aligned} H_{\text{eff}} &= \frac{G_F}{\sqrt{2}} V_{cb} \Big\{ c_1(\mu) \left[(\bar{d}u) + (\bar{s}c) \right] (\bar{c}b) + \\ &\qquad c_2(\mu) \left[(\bar{c}u)(\bar{d}b) + (\bar{c}c)(\bar{c}b) \right] \Big\} \end{aligned}$$

- For $B \to J/\psi$ decays, employ BSW factorisation:

$$\begin{aligned} d\Gamma(B^+ \to J/\psi X) &\propto a_2(m_b)^2 |V_{cb} V_{cs}^*|^2 \\ &\qquad |\langle J/\psi|(\bar{c}c)|0\rangle|^2 \, |\langle X|(\bar{s}b)|B\rangle|^2 \end{aligned}$$

- Have to put in b quark form factors by hand

Model is fundamental enough to warrant detailed study

- CLEO/ARGUS have looked at many decays systematically
- But earlier studies have had limitations
  - low statistics
  - only produce B° & B^+ (no B_s° or baryons)

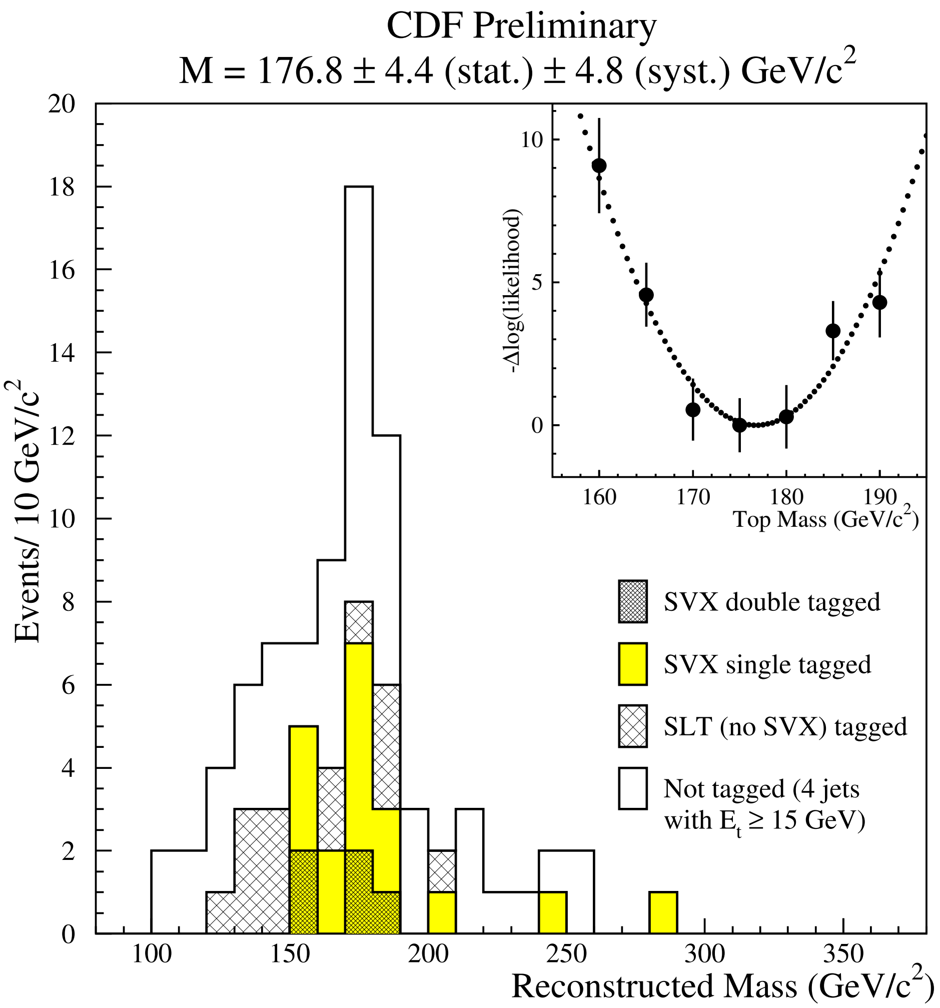
Hadron collider experiment overcomes some limitations

- Tevatron has produced $\sim 3 \times 10^9$ $b\bar{b}$ events

Top Mass Results

Estimate mass based on 34 $W+ \geq 4$ jet sample

- Use known fake tag rates and $Wb\bar{b}$
- Background shape in M_{top} comes from MC calculation
- Estimate background to be $6.4^{+2.1}_{-1.4}$ events
  - Primarily QCD W+jet



$\boxed{\textbf{Exclusive B} \rightarrow \textbf{J}/\psi\textbf{X Decays}}$

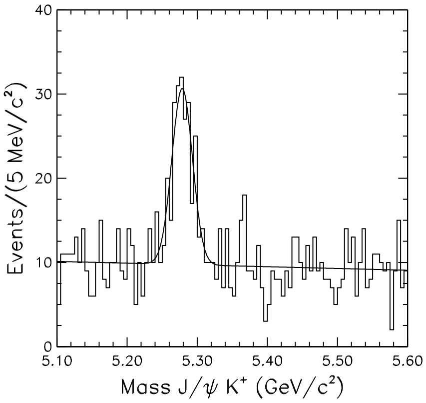
Search for exclusive decays

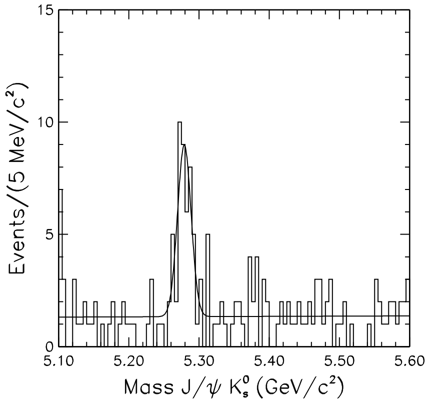
$$\begin{aligned} B^+ &\rightarrow J/\psi K^+, \\ B^\circ &\rightarrow J/\psi K^\circ, \\ B^+ &\rightarrow J/\psi K^*(892)^+, \\ B^\circ &\rightarrow J/\psi K^*(892)^0, \\ B_s^\circ &\rightarrow J/\psi \phi(1020) \end{aligned}$$

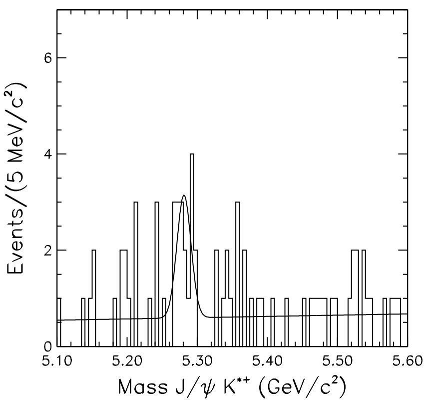
Select decays by requiring

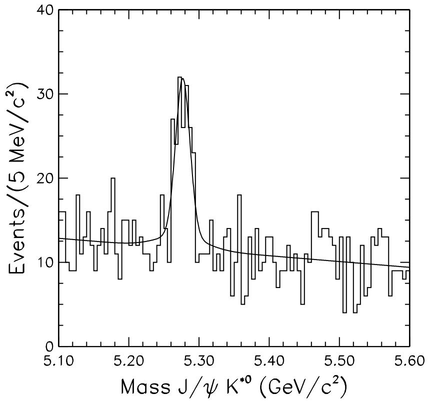
- Two muon candidates with $P_T \gtrsim 3$ GeV/c
- Require muons to come from common vertex
- Search combinatorially for daughter mesons
- Require B candidate $P_T > 6$ or 8 GeV/c
- Require meson daughter $P_T > 1.5$ or 2.0 GeV/c
- Require decay length of B candidate to be > 0

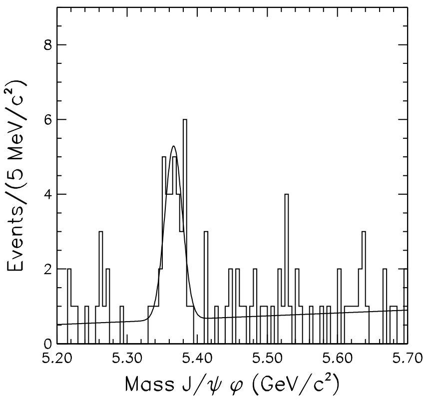
Run IA Results











Ratios of Branching Fractions

$$R^{K^\circ}_{K^+} = \frac{f_d}{f_u}\,\frac{\mathcal{B}(B^\circ \to J/\psi K^\circ)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 1.15 \pm 0.27 \pm 0.09,$$

$$R^{K^{*+}}_{K^+} = \frac{\mathcal{B}(B^+ \to J/\psi K^{*+})}{\mathcal{B}(B^+ \to J/\psi K^+)} = 1.92 \pm 0.60 \pm 0.17,$$

$$R^{K^{*\circ}}_{K^+} = \frac{f_d}{f_u}\,\frac{\mathcal{B}(B^\circ \to J/\psi K^{*\circ})}{\mathcal{B}(B^+ \to J/\psi K^+)} = 1.59 \pm 0.33 \pm 0.12,$$

$$R^{K^\phi}_{K^+} = \frac{f_s}{f_u}\,\frac{\mathcal{B}(B_s^\circ \to J/\psi \phi)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 0.41 \pm 0.12 \pm 0.04,$$

$$R^{K^{*+}}_{K^\circ} = \frac{f_u}{f_d}\,\frac{\mathcal{B}(B^+ \to J/\psi K^{*+})}{\mathcal{B}(B^\circ \to J/\psi K^\circ)} = 1.68 \pm 0.58 \pm 0.11,$$

$$R^{K^{*\circ}}_{K^\circ} = \frac{\mathcal{B}(B^\circ \to J/\psi K^{*\circ})}{\mathcal{B}(B^\circ \to J/\psi K^\circ)} = 1.39 \pm 0.36 \pm 0.10,$$

$$R^{K^\phi}_{K^\circ} = \frac{f_s}{f_d}\,\frac{\mathcal{B}(B_s^\circ \to J/\psi \phi)}{\mathcal{B}(B^\circ \to J/\psi K^\circ)} = 0.35 \pm 0.12 \pm 0.03,$$

$$R^{K^{*\circ}}_{K^{*+}} = \frac{f_d}{f_u}\,\frac{\mathcal{B}(B^\circ \to J/\psi K^{*\circ})}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = 0.83 \pm 0.27 \pm 0.07,$$

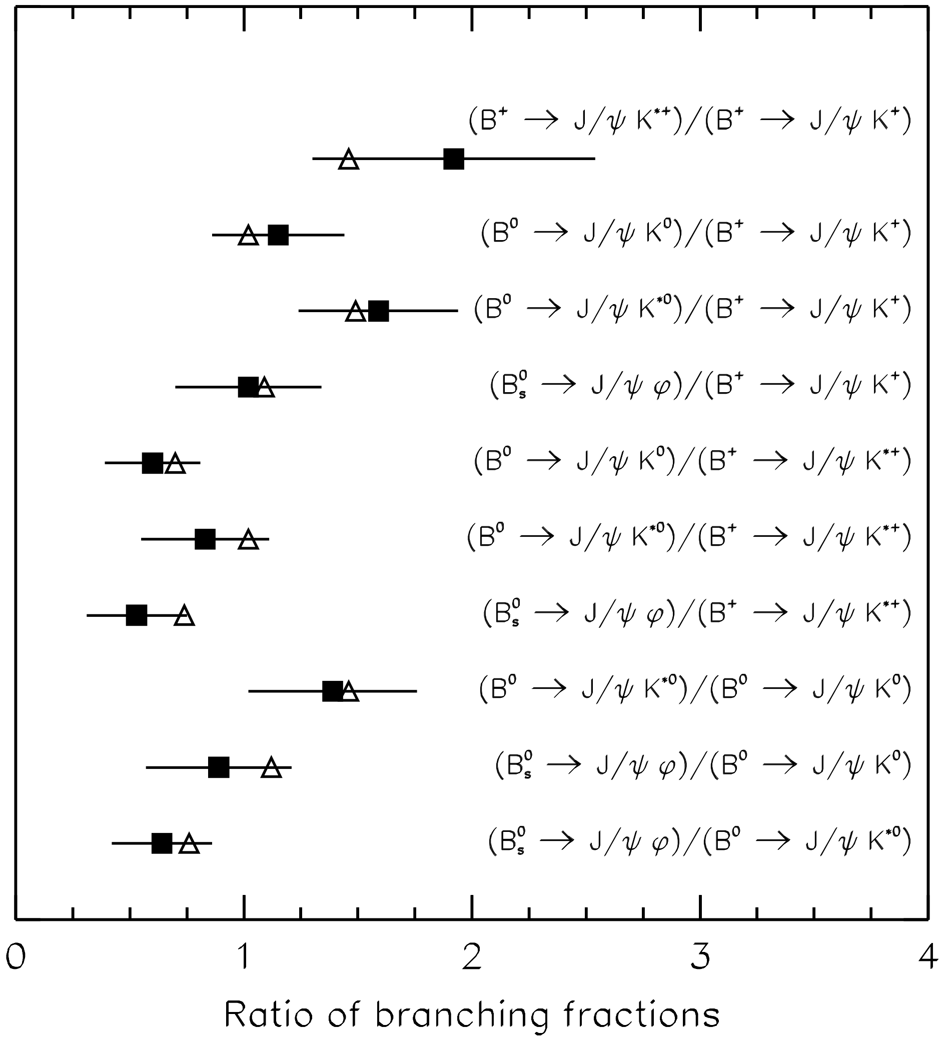
$$R^{K^\phi}_{K^{*+}} = \frac{f_s}{f_u}\,\frac{\mathcal{B}(B_s^\circ \to J/\psi \phi)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = 0.21 \pm 0.08 \pm 0.02,$$

$$R^{K^\phi}_{K^{*\circ}} = \frac{f_s}{f_d}\,\frac{\mathcal{B}(B_s^\circ \to J/\psi \phi)}{\mathcal{B}(B^\circ \to J/\psi K^{*\circ})} = 0.26 \pm 0.08 \pm 0.02.$$

Comparison with HQET and BSW

Have compared results with several model predictions

- A. Deandrea, N. Di Bartolomeo, R. Gatto and G. Nardulli, Phys. Lett. B **318**, 549 (1993).
- Other calculations give similar results



$\psi(2S)$ Branching Fractions

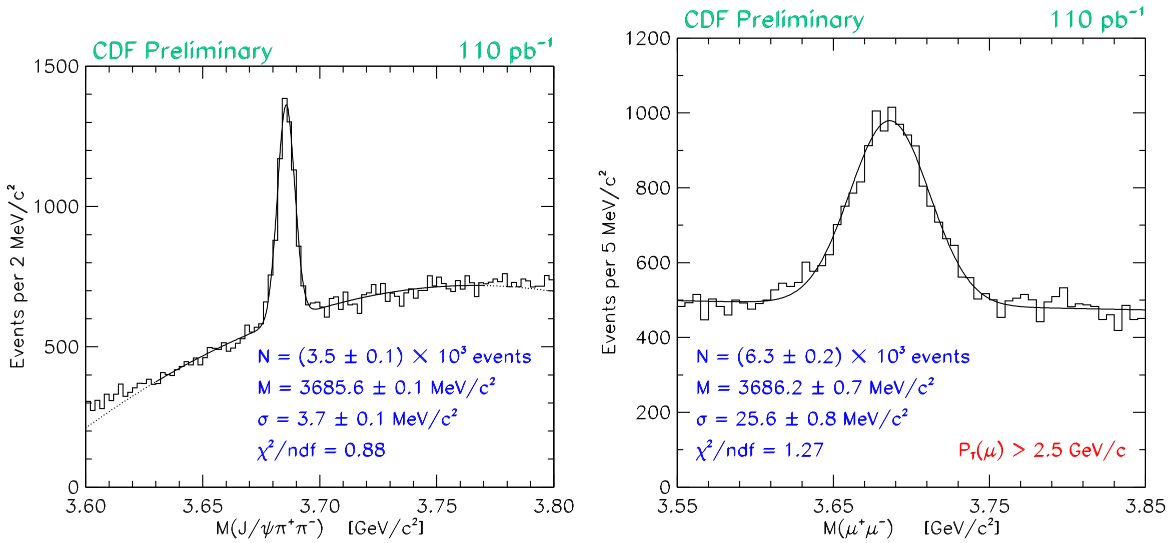
Currently working on measuring ratios

$$\frac{\mathcal{B}(B^+ \to \psi(2S)K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)}$$

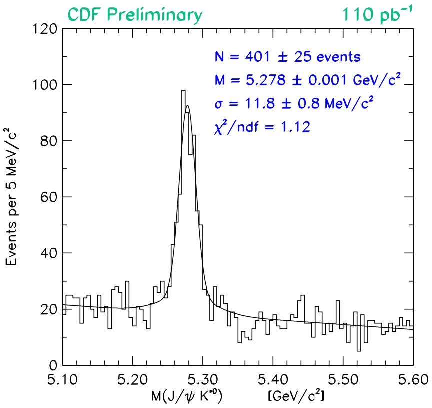
$$\frac{\mathcal{B}(B^0 \to \psi(2S)K^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})}$$

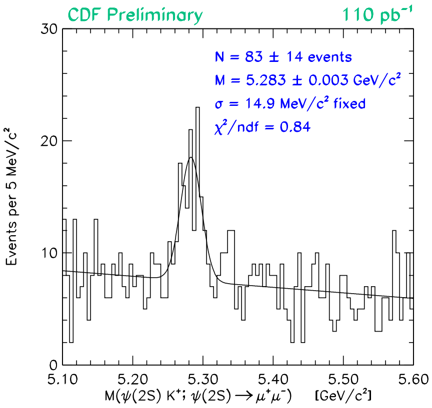
- Using full Run I data sample
- See clean inclusive $\psi(2S)$ signal

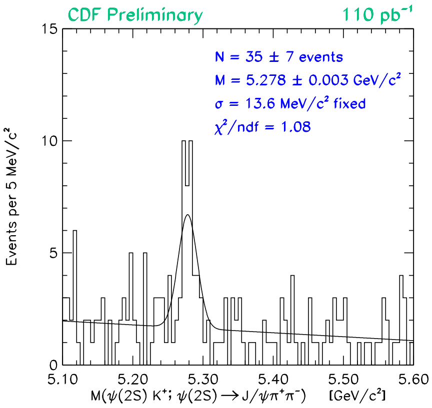
$\psi(2S) \to J/\psi\pi^+\pi^-$ and $\psi(2S) \to \mu^+\mu^-$

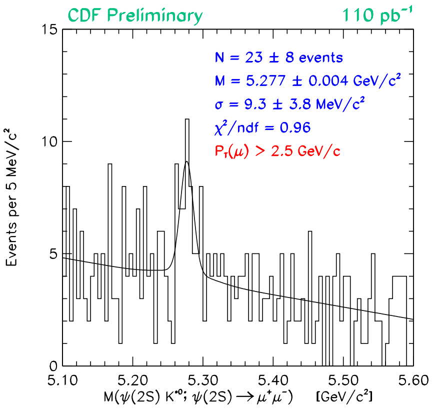


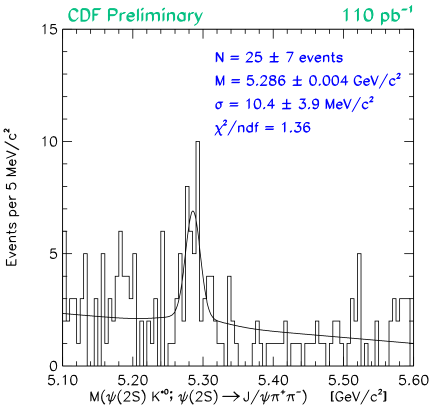
Run IB $B \rightarrow \psi(2S)X$ Signals











Preliminary Results

The ratios of branching fractions are

$$\frac{\mathcal{B}(B^+ \to \psi(2S)K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 0.666 \pm 0.093 \pm 0.101$$
$$\frac{\mathcal{B}(B^0 \to \psi(2S)K^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} = 0.569 \pm 0.131 \pm 0.074$$

Can turn these into absolute branching fractions using

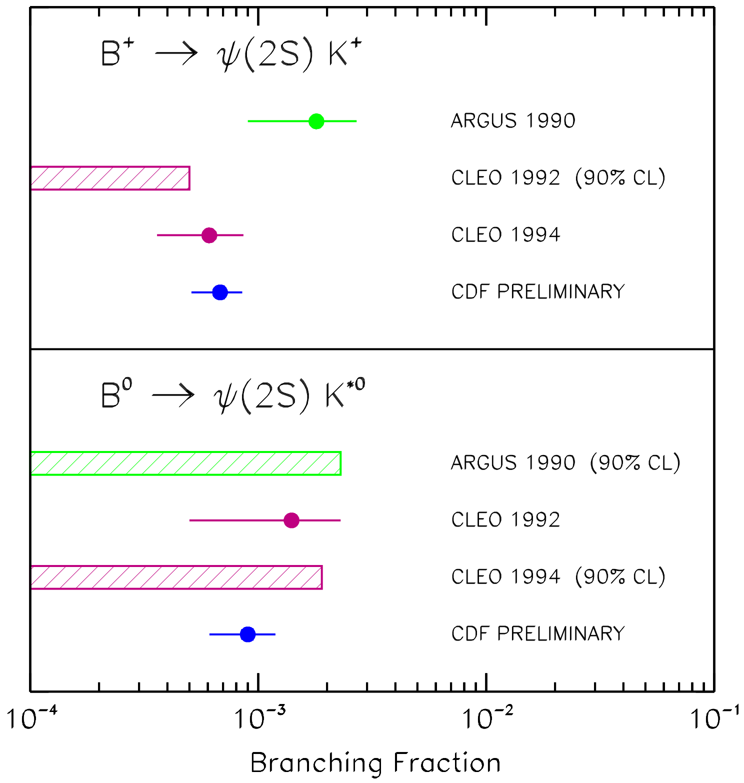
$$\mathcal{B}(B^+ \to J/\psi K^+) = (1.02 \pm 0.14) \times 10^{-3}$$
$$\mathcal{B}(B^0 \to J/\psi K^{*0}) = (1.58 \pm 0.28) \times 10^{-3}$$

This gives us the branching fractions

$$\mathcal{B}(B^+ \to \psi(2S)K^+) = (6.8 \pm 1.0 \pm 1.4) \times 10^{-4}$$
$$\mathcal{B}(B^0 \to \psi(2S)K^{*0}) = (9.0 \pm 2.1 \pm 2.0) \times 10^{-4}$$

Comparison with Other Measurements

These results can be compared with CLEO results



Now the world's best measurement

Physics Outlook for Run II

So far, top decays just like the SM predicts

- Constraints on $V_{tb} > 0.38$ at 95% C.L.
- Polarisation studies underway
- Nothing anomolous found

Bottom decay studies really only starting

- Expect to have the most precise $B \to J/\psi$ and $B \to \psi(2S)$ measurements in next year
- Polarisation studies of entire Run I sample underway
- Will allow tests of HQET and BSW factorisation

Run II expected to start in 1999

- Integrated luminosity of ~ 2 fb^{-1}
- Upgraded tracking, calorimetry and DAQ
- Will increase top and bottom samples by $\times 50$

Heavy Quark Yields for Run II

Top quark yields will increase by a factor of ~ 50

- factor of 20 from integrated luminosity
- factor of 1.3 from increased $\sqrt{s}$
- factor of 1.8 from SVX II B-tagging

$\Rightarrow \sigma M_{top} \sim 1 - 2$ GeV/c^2

B yields will also increase by factor of ~ 40

- Can measure $\sin 2\beta$ to accuracy of ~ 0.14
  - From $B^\circ \rightarrow J/\psi K^\circ$ channel
  - Estimate that $\epsilon D^2 \sim 0.10$
- Can measure $\sin 2\alpha$ to accuracy of ~ 0.10
  - From $B^\circ \rightarrow \pi^+\pi^-$ channel
  - New SVT will provide 5 events per pb^{-1}

$\Rightarrow$ an effective assault on CP violation

$\boxed{\text{Run II Upgrades to CDF}}$

Major Detector Upgrade Programme

1. New calorimetry for $|\eta| > 1.1$
   - scintillating tile technology
   - Improve triggering and uniformity of calorimetry

2. Upgraded muon system coverage for $|\eta| > 0.7$

3. Improved DAQ and trigger system
   - Distributed Level 1 trigger
   - Deadtimeless readout at rates > 100 Hz
   - Impact parameter trigger (SVT) at Level 2

4. New Online and Offline Systems
   - Object-oriented model for software implementation
   - Completely UNIX-based

Run II Upgrades to CDF (Cont)

5. New Central Open-cell Tracker (COT)
   - Small-cell drift chamber for $r > 40$ cm

6. New Silicon Tracker - SVX II
   - Five-layer silicon-strip tracker 65 cm long
   - Double-sided readout for $r - \phi - z$ tracking
   - Intrinsic precision of $\sim 10\ \mu$

7. Silicon Strip Intermediate Tracker - ISL
   - 4 “barrels” of Si strips to cover $1.0 \lesssim |\eta| \lesssim 2.0$
   - An additional central “barrel” at $r = 30$ cm
   - Momentum measurement up to $|\eta| < 2.0$

Canadian effort has focused on silicon tracking systems

- Mounting and alignment
- Dynamic position during data collection
- Monitoring to maintain precision better than 10 μ

Schedule for Run II

Run II requires upgrades to both Collider and CDF

- Main Injector will replace Main Ring as injector
  - Excellent progress of construction
  - Will start to commission MI in late 1998 and early 1999
  - Schedule sensitive to levels of out-year funding
- CDF Upgrade is well underway
  - Some systems essentially complete or well underway
    - Plug Calorimeter
    - Muon Upgrades
  - Other systems in reasonable shape
    - SVX II readout chip critical path item
    - Depends on "good" engineering of prototype
  - Current schedule calls for commissioning to start spring 1999
- Physics running to begin in fall 1999

Schedule is mainly funding limited

IPP Contributions and Funding

The IPP group has grown substantially in last year

- New faculty member and second RA (S. Gadomski)
- Three new graduate students (total of seven)

Has been interest by other IPP researchers

- Discussions are continuing, although no commitments yet
- Part of this is the "chicken-and-egg" issue of funding
- This is directly related to Fenton Report recommendation
  - IPP had recommended deferring Run II decision till now
  - In our view, Fenton panel did not consider significant intellectual IPP investment in CDF programme
    - Very exciting physics opportunity
    - Team of experienced and effective researchers
    - Intellectual investment towards ATLAS
- We believe that Run II provides cost-effective vehicle to both do exciting physics and prepare for ATLAS effort

Implications of NSERC Equipment Support

NSERC support of Run II upgrade effort is essential for continued IPP role

- Upgrade effort is roughly \$ 50M US, shared among $\sim$ 450 Ph.D.'s
- IPP represents about 3% of collaboration
- Sets scale of contribution at about \$1.5M
- Commensurate with Japanese and Italian contributions

These provide rough guide, but real scale set by specific responsibilities and proposals

- IPP proposal reflects the responsibilities that we have agreed to take on
- Proposed equipment funding is what we estimate will be required

We cannot proceed without NSERC equipment funding

Projected Operating Support

CDF project has received \$218K of operating support

- Original base level set in 1994 was inadequate
- Has not reflected increase in personnel effort
- Additional support provided by
  - University start-up funds
  - IPP discretionary funding
  - Departmental and FCAR support

Estimate operating support at $\sim$ 294K

1. Student support (6) - 78K
2. RA salaries (2) - 105K
3. Travel support - 80K
4. Materials, supplies and CPU support - 31K

- Assumes no increased personnel effort
- All infrastructure support from other sources

Reductions in Scope?

The proposal has three components

A. Static kinematic mounts (39K)

B. Dynamic kinematic mounts (50K)

C. FSI position monitoring system (360K)

D. Travel for consultation and installation (27K)

Most likely possibility for COST reduction is FSI

- Dominated by high-power, high-stability laser (207K)
- R & D in next 8 months will work toward reducing power requirement
  - Goal is to replace it with laser in 30K-40K range
  - Fall-back is to implement a smaller scale monitoring system
- Strategy would be:
  - Go ahead with items A, B and D
  - Continued to develop C for next eight months
  - Make decision on final system for C in fall 1997

Training and Education

CDF project has been an effective vehicle for HQET

- Have granted 9 M.Sc's (4 in progress)
- Have granted 1 Ph.D.'s (7 in progress)
- Will graduate another 5 Ph.D.'s in next year
- One RA now working in silicon design in Germany
- One RA now staff scientist at FNAL
- Two RA's currently in group

Already have assembled a strong team for Run II

- Two RA's involved in Run II work
- Five M.Sc. students and 1 Ph.D. student

CDF will be an excellent training ground for ATLAS

Timescale and Interaction with ATLAS

Work on Si tracking has strong ATLAS overlap

- Have agreed to collaborate with UK group on SCT position monitoring
- The CDF monitoring system will be a small scale version of ATLAS system
- Continuing interest in radiation-hard detectors

Time scales work in our favour

- Two senior people already committed to ATLAS R & D
- Expect the IPP group interested in this to grow...
- Work in next two years will be combination:
  - Development of CDF system
  - Prototyping of ATLAS components for SCT
- Expect that emphasis will steadily shift toward ATLAS
- Physics will continue to flow from CDF through 2002