B physics at the Tevatron

S. Donati
University and INFN Pisa

April 2003 Meeting of the American Physical Society

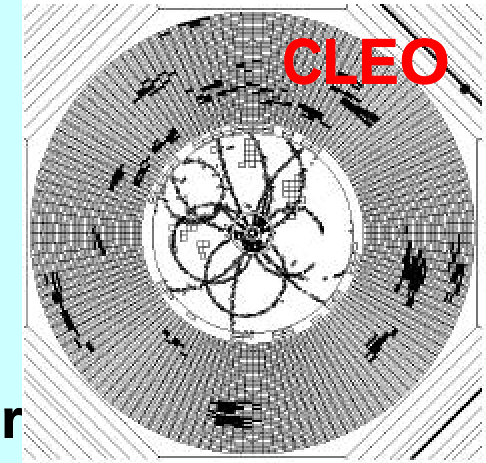
Why B physics at $p\bar{p}$ collider

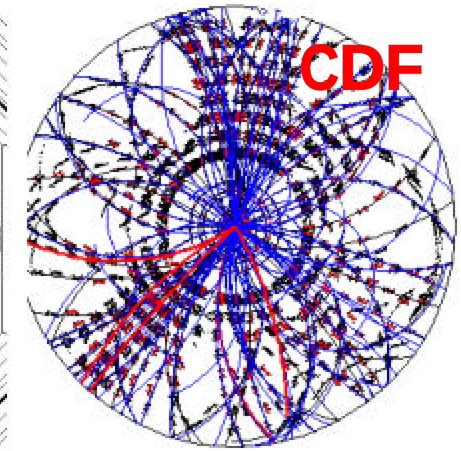
Open wide spectrum of B hadrons
$B^{\pm}$, B^0, B_s, B_c, L_b, X_b

$b\bar{b}$ cross section is 50-100 mb
~O(10^5) larger than @¡(4S)/Z^0

BUT:
B hadrons are hidden in a 10^3 larger background ($s_{inelastic}$(pp) » 50 mb)

Events more complicated than at ¡(4S)





Crucial detector components:
- Tracking system
  Excellent pt resolution/Vertexing
- Trigger
  Large bandwidth
  Strong background reduction
- Particle identification

Tevatron $p\bar{p}$ collider

Main Injector (new injection stage for Tevatron)

- **Ability to accelerate and deliver higher intensity of protons**
- **More efficient anti-proton production**

Collision rate: 396 ns crossing time

(36x36 bunches) → ~ 2M collisions/sec

Center of Mass energy: 1.96 TeV

Today: luminosity ~4.0 x 10^{31} $cm^{-2}s^{-1}$

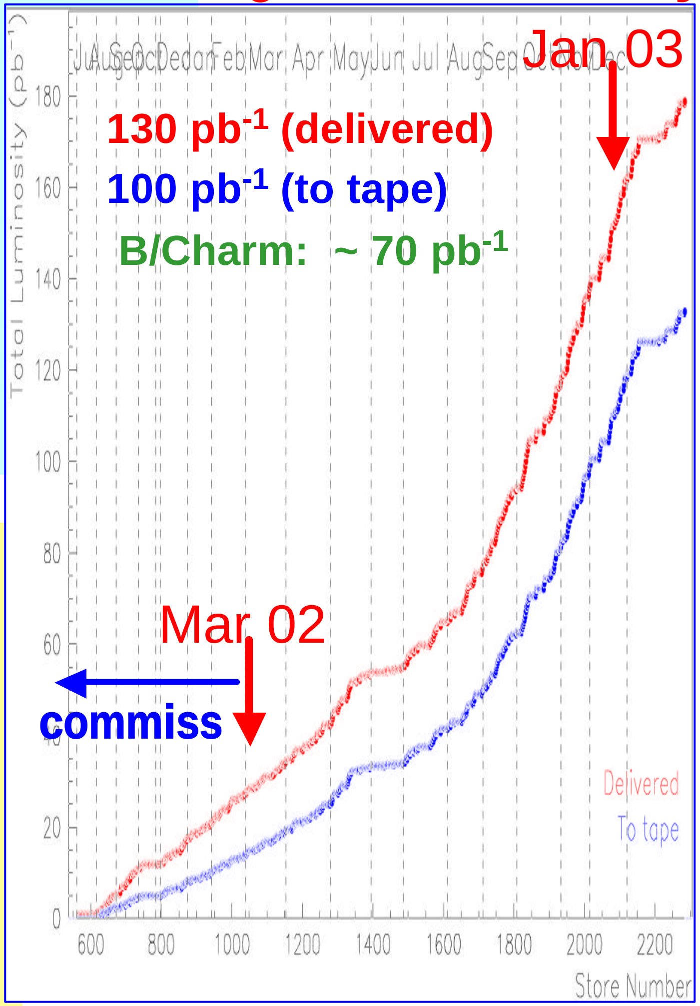
4 to 7 pb^{-1}/week delivered

Goal: luminosity: ~10^{32} $cm^{-2}s^{-1}$

16 pb^{-1}/week delivered

In this talk: results with 70 pb^{-1} for CDF and 40 pb^{-1} for D0

CDF Integrated Luminosity



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:

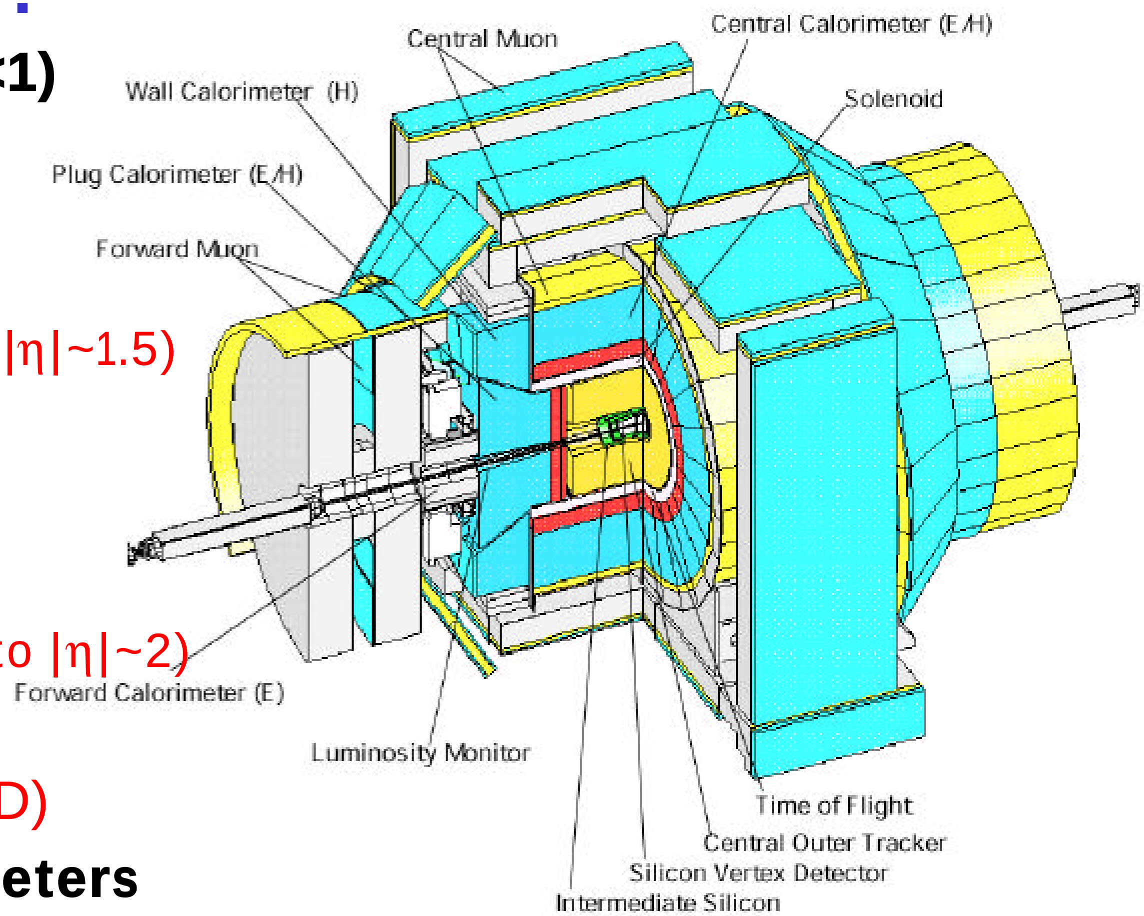
Tracking System

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

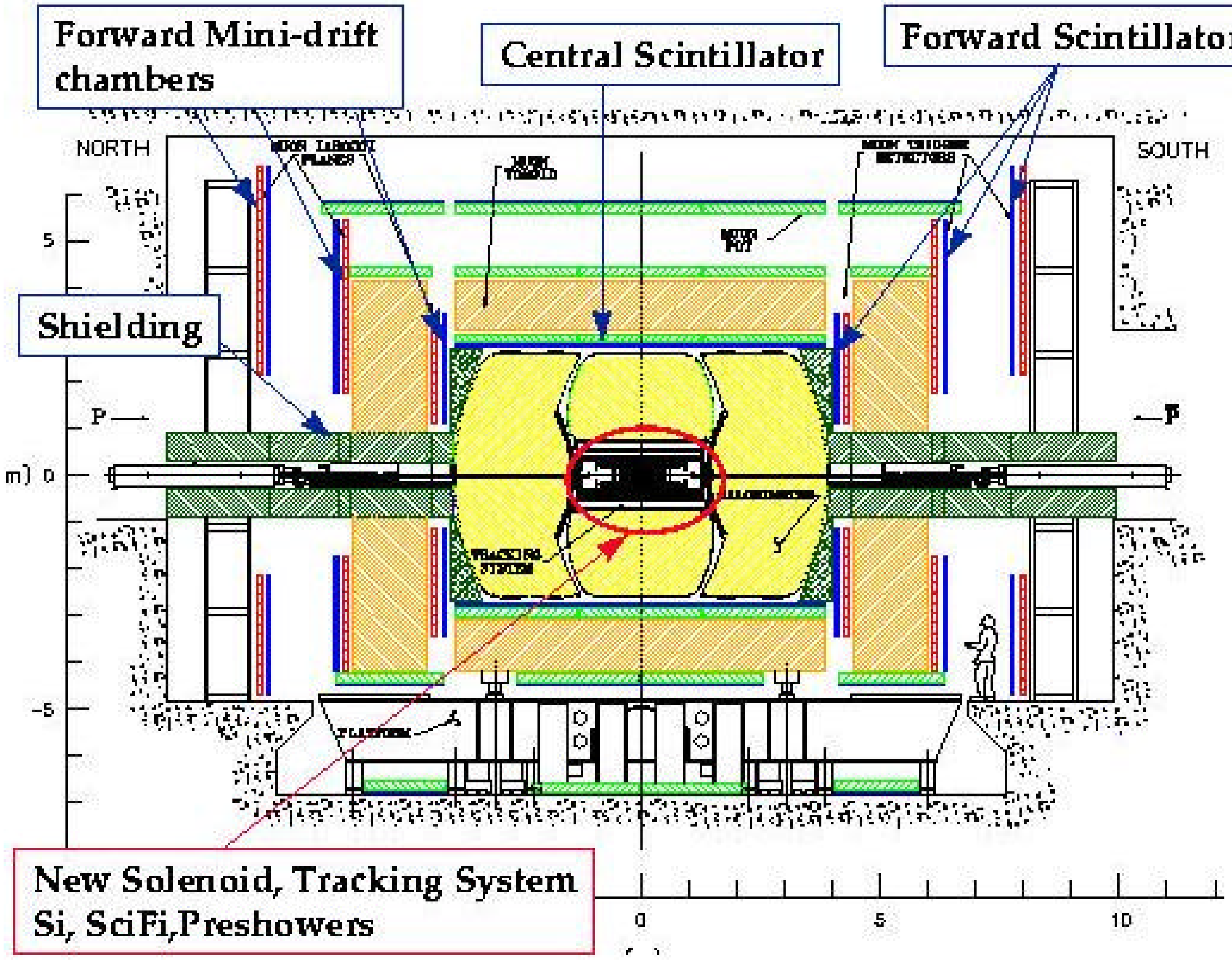
Time-of-Flight (particle ID)

Plug and Forward Calorimeters

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



D0 detector in Run II



B Triggers and data samples

(Conventional)

Di-Muon (J/ψ)

$P_t(\mu) > 1.5$ GeV (CDF)

J/ψ modes down to low Pt(J/ψ) (~ 0 GeV)

- **CP violation**
- **Masses, lifetimes**
- **Quarkonia, rare decays**

(New in CDF/Short term upgrade in D0)

Displaced trk + lepton (e, μ)

IP(trk) > 120μm

Pt(lepton) > 4 GeV

Semileptonic modes

- **High statistics lifetime**
- **Sample for tagging studies, mixing**

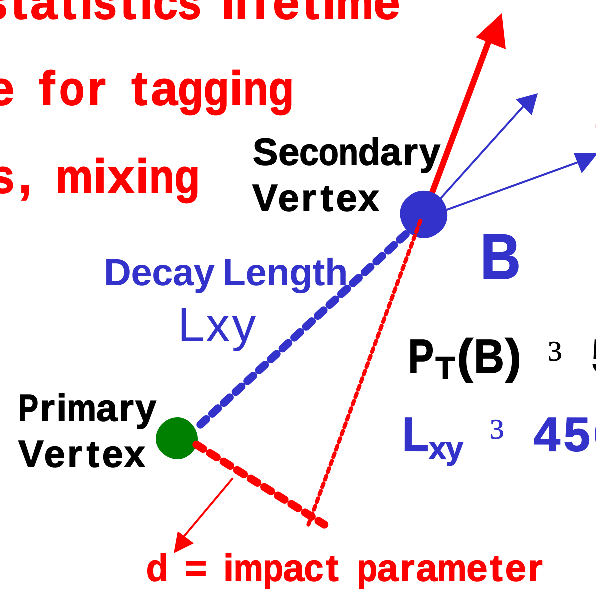
2-Track Trig.

Pt(trk) > 2 GeV

IP(trk) > 100 μm

Fully hadronic modes

- **B_s mixing**
- **CP asymmetry in 2-body charmless decays**



$P_T(B) \geq 5$ GeV

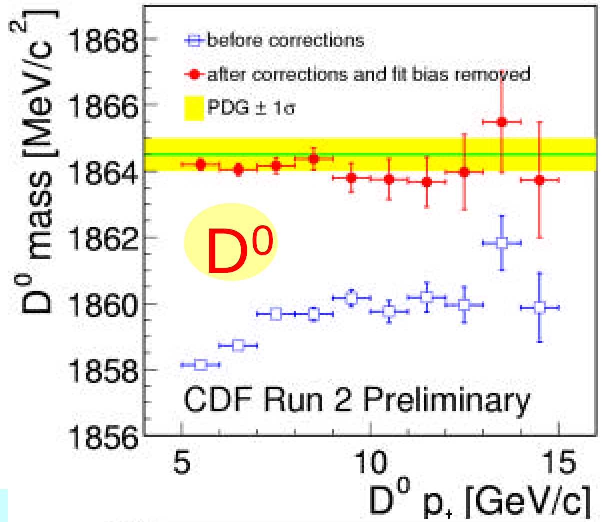
$L_{xy} \geq 450\mu m$

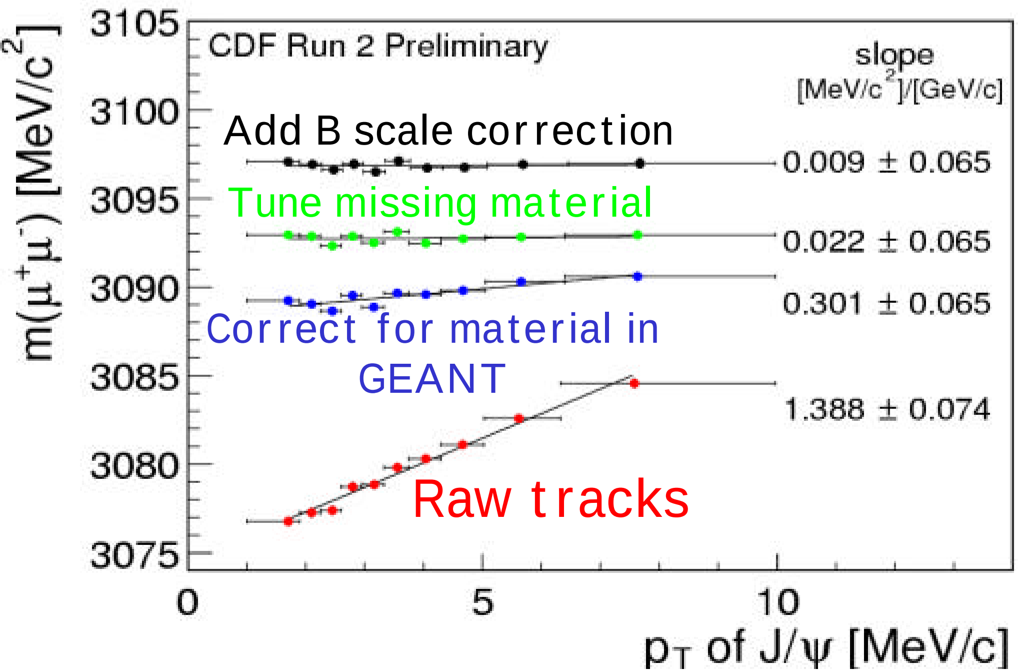
Detector calibration: p scale & B-field correction

MASS SCALE: **$M_{CDF} = M_{PDG} - $ DM(Pt)**

Use J/y to correct for B field and energy loss:

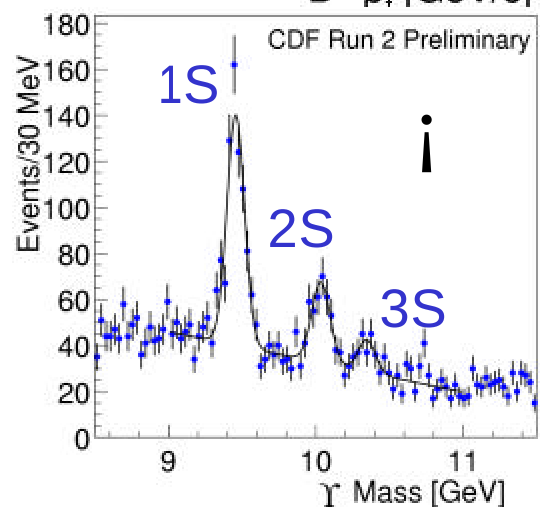
s(scale)/scale ~ 0.02%





Sanity check with known signals:

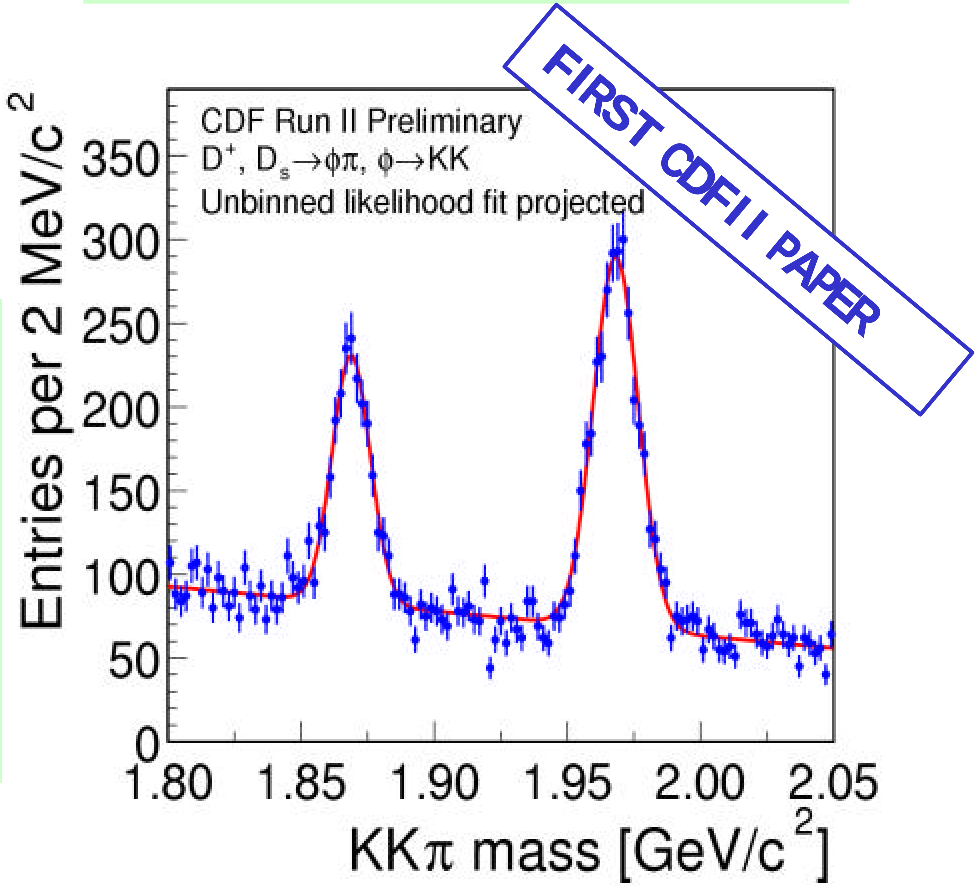
D0 and ¡



Mass measurements

	CDF mass (only~20 pb^{-1})	? $_{PDG}$ / s $_{CDF}$
B^+	5280.6 ± 1.7 ± 1.1	0.8
B_d	5279.81 ± 1.9 ± 1.4	0.2
B_s	$5360.3 \pm 3.8 \pm ^{2.1}_{2.9}$	-2.1
ψ(2S)	3686.43 ± 0.54	0.9

M(B_s) is already the second best in the world (after CDF RunI)



$D_s^\pm$ - $D^\pm$ mass difference

Both D →f p (f→KK)

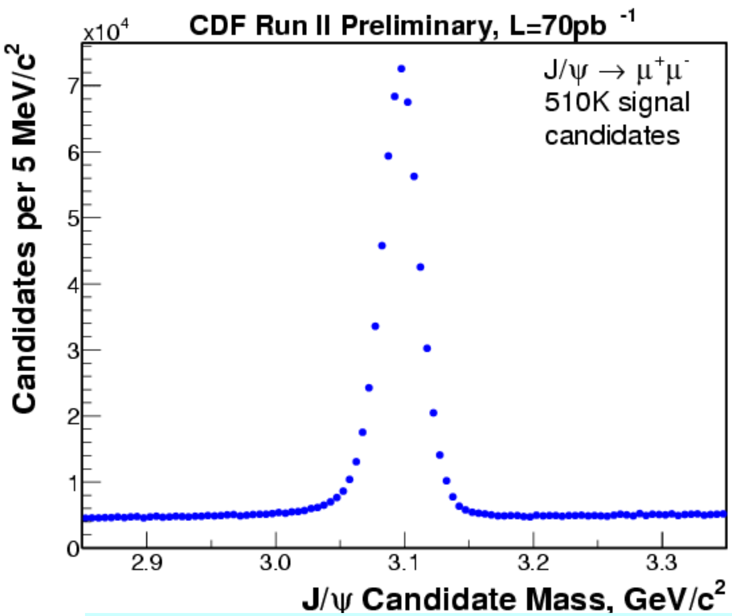
Dm = 99.28 ± 0.43 ± 0.27MeV

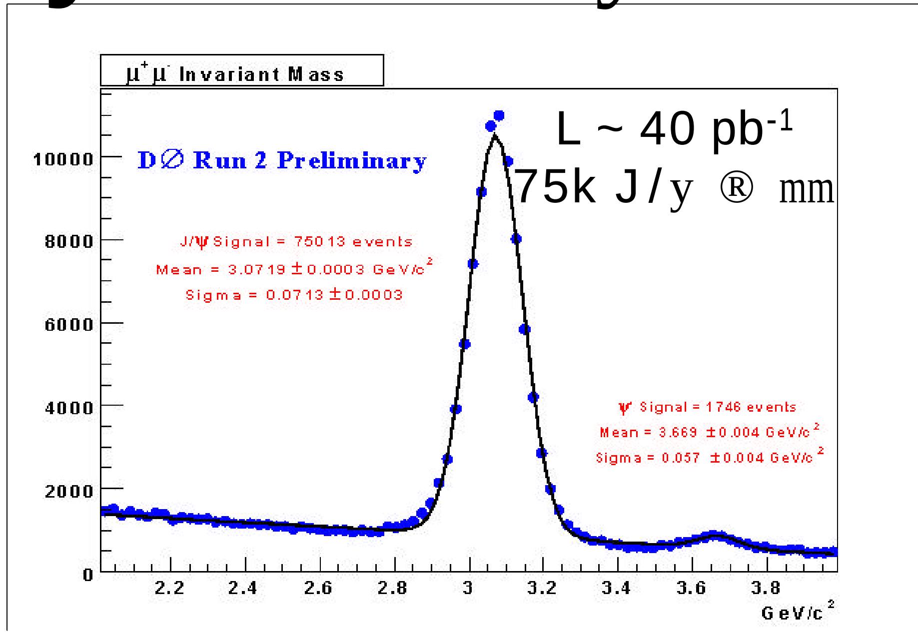
PDG: 99.2 ± 0.5 MeV (CLEO2, E691)

Systematics dominated by background modeling

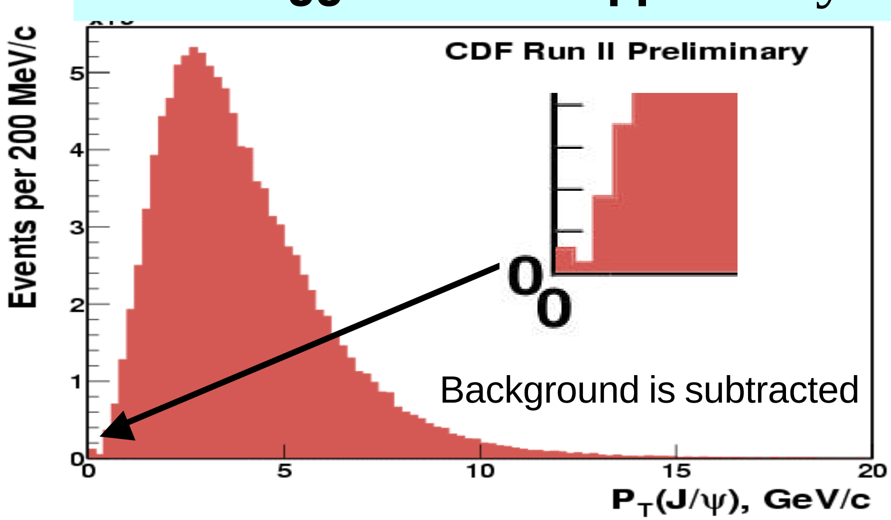
See A. Korn's talk

Conventional way to B: J/y ®mm





CDF triggers on stopped J/y ® mm: pt(m) ³ 1.5 GeV/c, pt(J/y) ³ 0



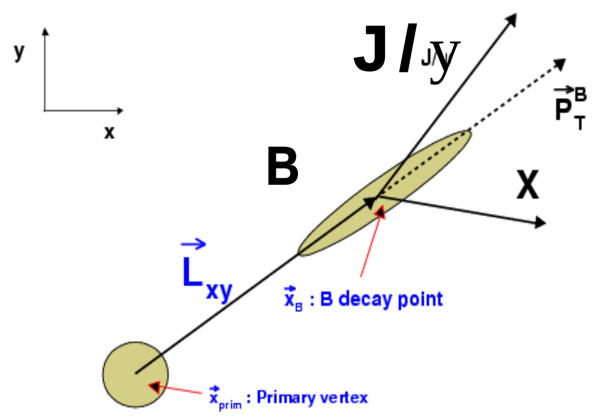
CDF can measure cross section down to p_T = 0 (first at hadron collider)

s(pp→J/y; p_T>0; |h|<0.6) =

240 ± 1 (stat) ±35/28(syst) nb

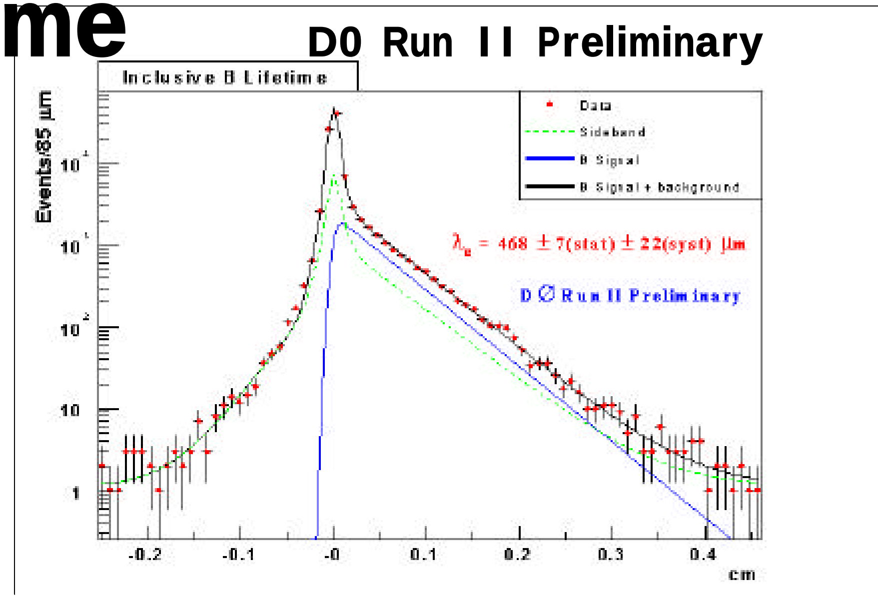
See Y. Gotra's Talk

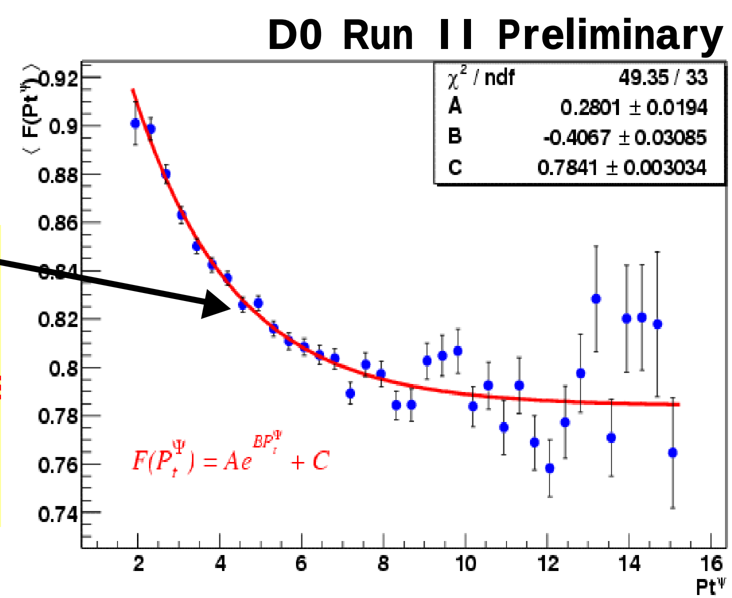
First step: Inclusive B ® J/y X Lifetime



Estimate l_B through l_y

$$l_B = L_{xy} \frac{M^{\Psi}}{P_T^{\Psi} \langle F(P_T^{\Psi}) \rangle}$$





CDF July 2002 (18 pb^{-1}): τ=1.526±0.034±0.035 ps

D0 March 2003 (40 pb^{-1}): τ=1.561±0.024±0.074 ps

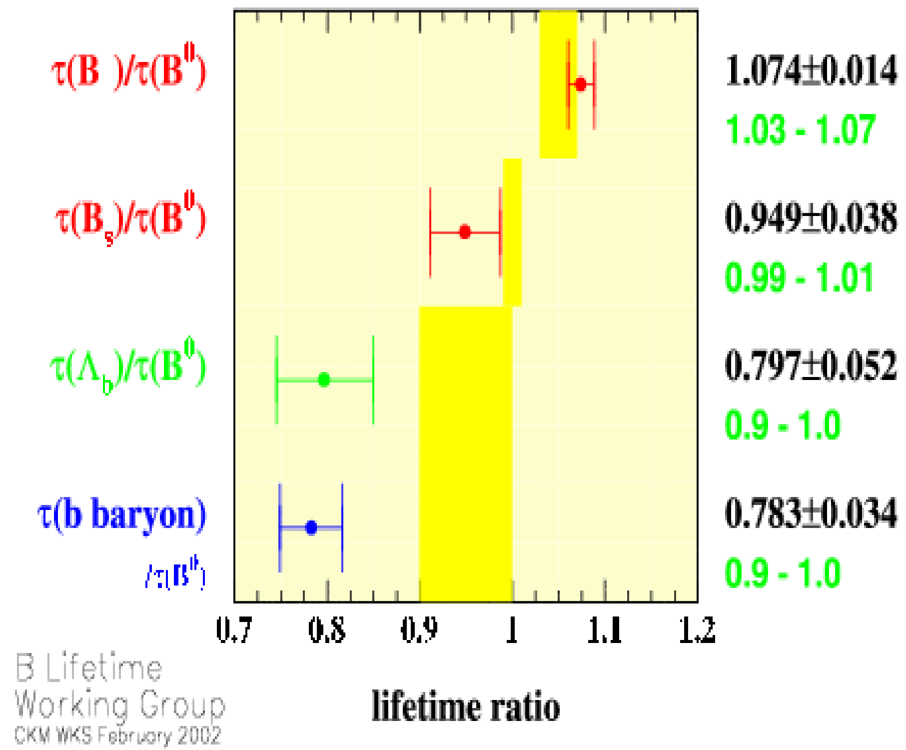
PDG 2002: τ = 1.674 ± 0.018

B Lifetimes

Heavy Quark Expansion predicts the lifetimes for different B hadron species

$t(B_c) << t(X_b{}^0) \sim t(L_b)$
$< t(B^0) \sim t(B_s) < t(B^-)$
$< t(X_b{}^-) < t(W_b)$

- $t(B^+)/t(B^0)$ = **1.03-1.07**
- $t(B_s)/t(B^0)$ = **1.00 ± 0.01**
- $t(L_b)/t(B^0)$ = **0.9-1.0**

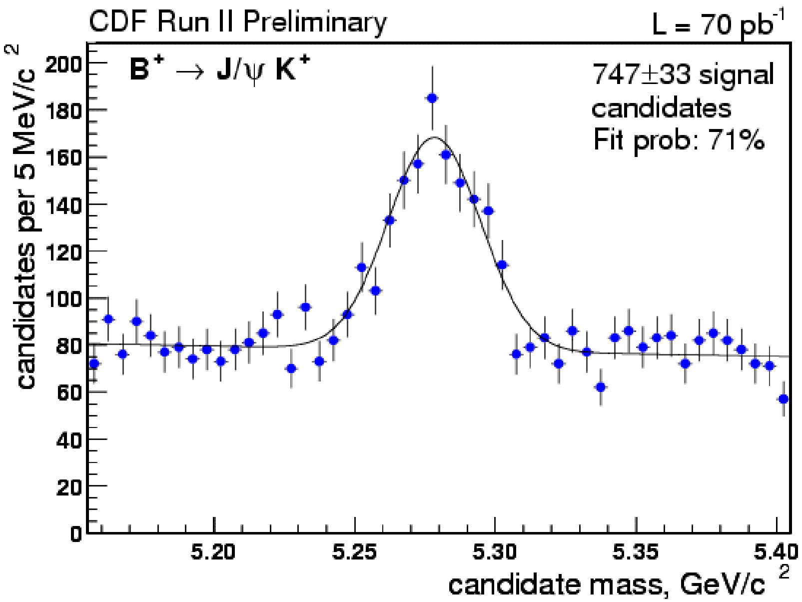


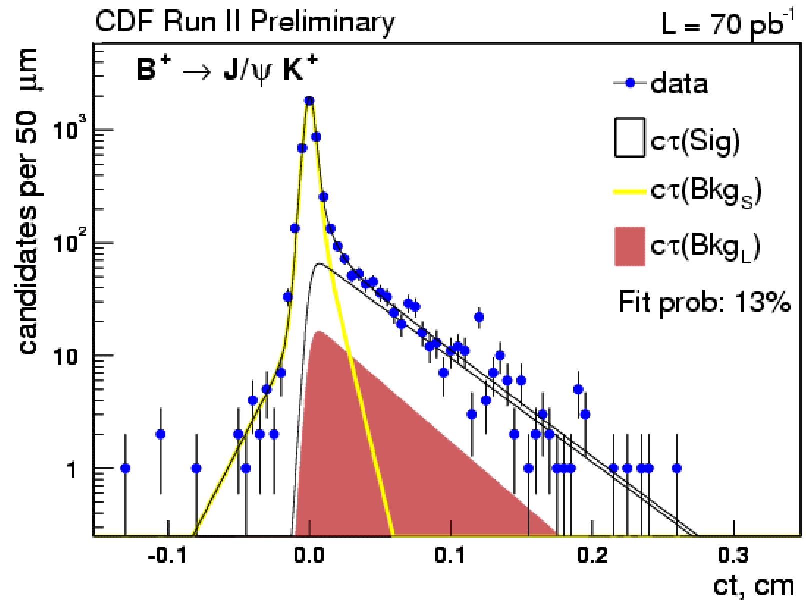
B^+/B^0 and B_s/B^0 measurements agree with prediction

Small discrepancy for L_b lifetimes

- **LEP + CDF Run I**

Exclusive B ® J/yK Lifetime (1)





Use exclusively reconstructed B

B^+ →J/y K^+

B^0 →J/y K^{0*} (K^{0*} → Kp)

B_s → J/y f (f →KK)

L_b→J/y L (L→pp)

Simultaneous fitting of

M_B: Extract signal fraction

ct: Extract the lifetime

CDF March 2003 (70 pb^{-1}): t(B^+)=1.57±0.07±0.02 ps

D0 March 2003 (40 pb^{-1}): t(B^+)=1.76 ± 0.24 ps

Exclusive B ® J/yK lifetime (2)
(B_s Unique to Tevatron)

Important for simultaneous measurement } $\frac{t(B_s)}{t(B_d)}$

Use control channels: B_u → J/y K^+ and B_d → J/y K^{0*}

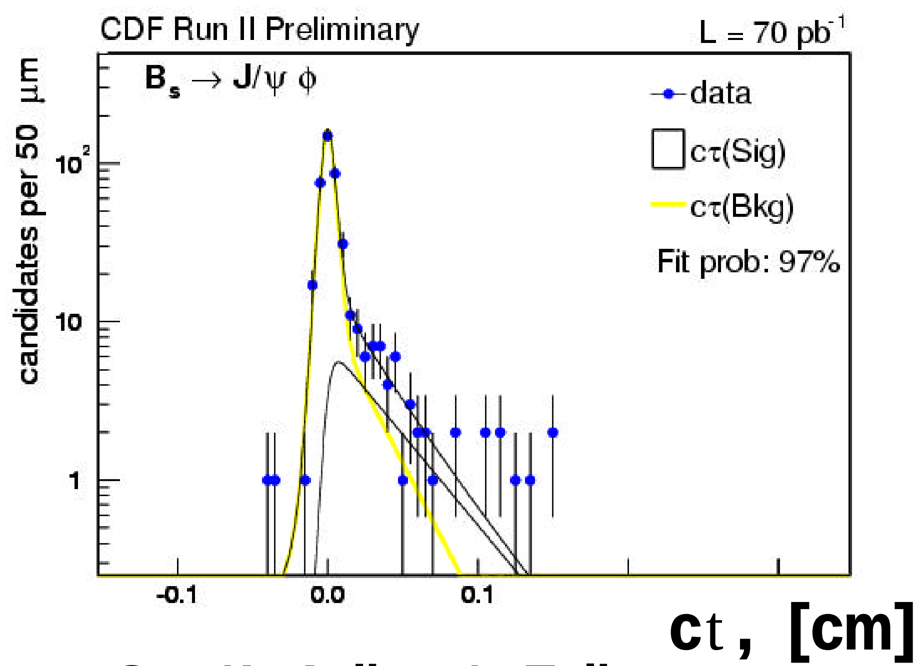
Measurement limited only by statistics

	CDF Preliminary
B^+	1.57 ± 0.07 ± 0.02 (ps)
B_d	1.42 ± 0.09 ± 0.02 (ps)
B_s	1.26 ± 0.2 ± 0.02 (ps)

Systemat. & statist. errors already @ Run I level

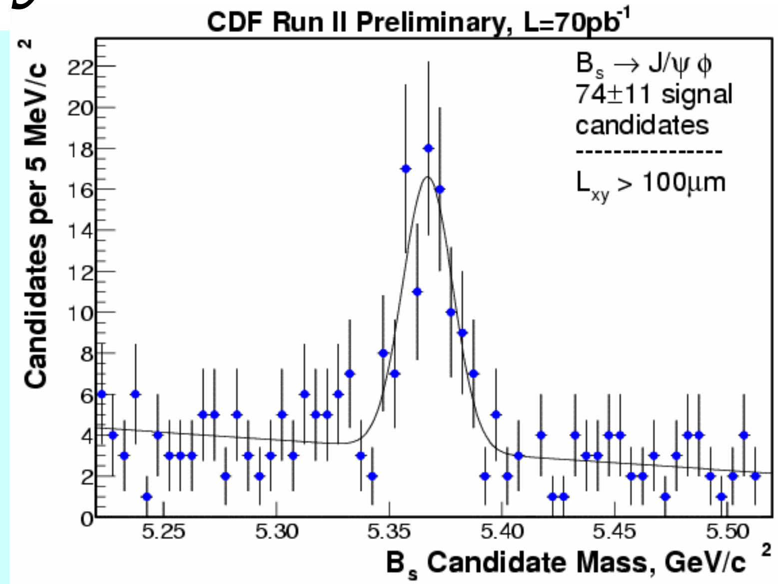
$$\frac{t(B_s)}{t(B_d)} = 0.89 \pm 0.15$$

$$\frac{t(B^+)}{t(B_d)} = 1.11 \pm 0.09$$



See K. Anikeev's Talk

Physics with B^0_s ® J/ y f



CDF: largest fully reconstructed sample in the world: 74 ±11 evts

Yield/Lumi = 2 x RunI

CP asymmetry measures the weak phase of V_{ts} (angle $f_s = 2b_s$)

Expected to be very small: sin($2b_s$) » O(l^2) » 0.03

Complicated analysis: requires x_s and angular analysis to disentangle CP even/odd final states

<u>CDF reach</u> : s(sin($2b_s$)) »**0.1 with 2fb^{-1} (»0.03-0.06 with 10fb^{-1})**

If asymmetry observed with 2fb^{-1} ® signal for NEW Physics

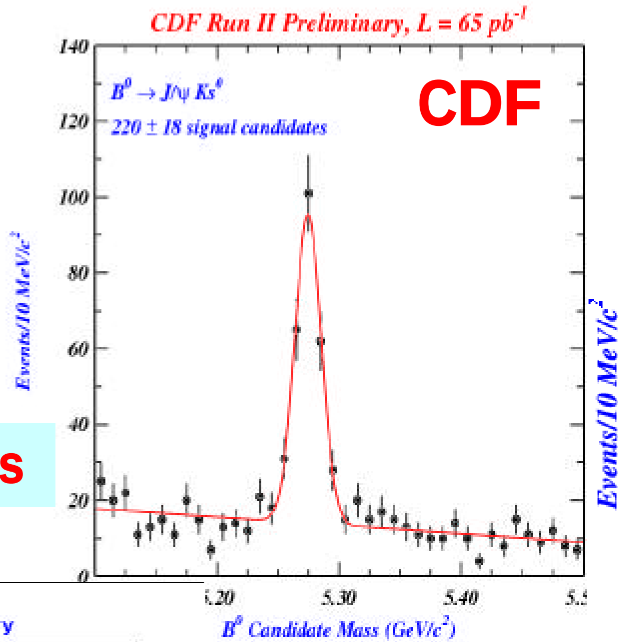
We also want to measure of lifetime difference: $DG_s = B_s^H - B_s^L$

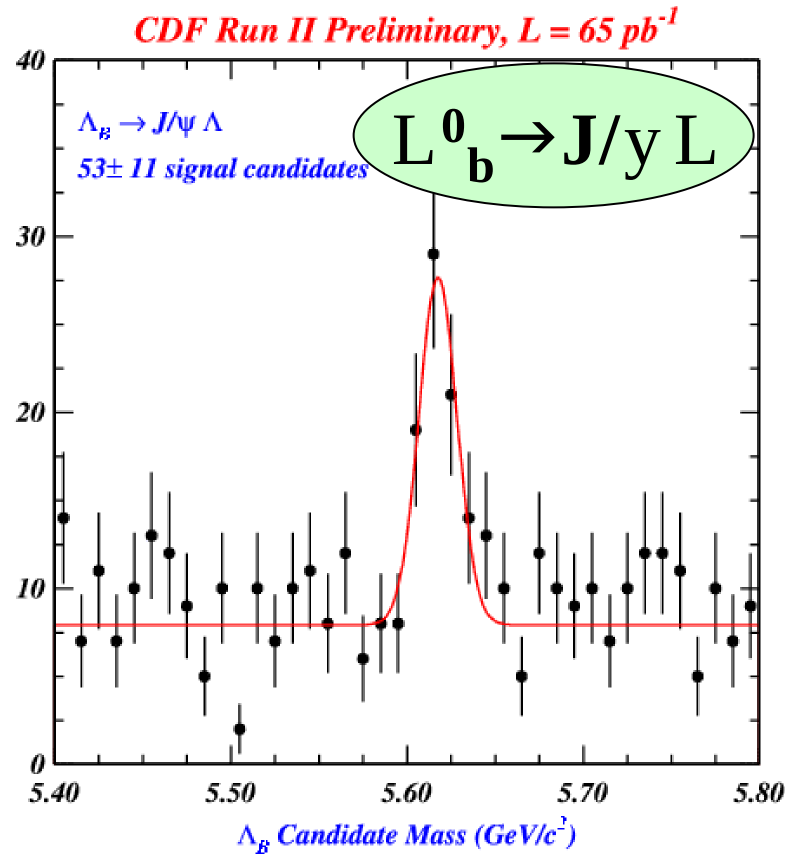
Current limit (LEP): DG_s / G_s **<0.31 (S.M.:** DG/G **= 0.05 - 0.20)**

More about B→J/y signals

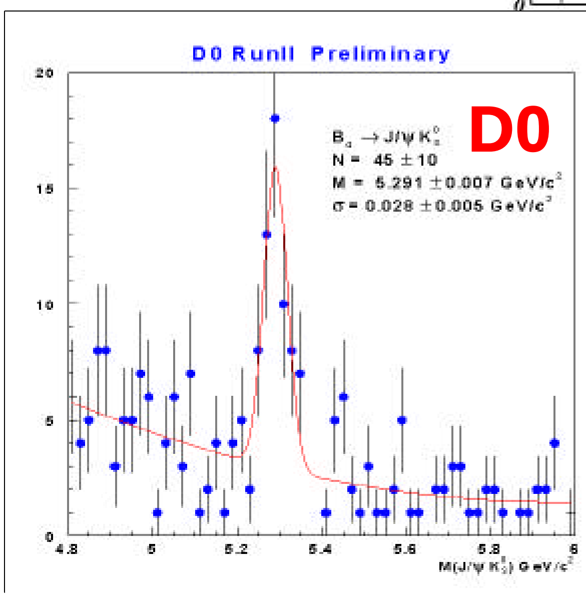
$B^0 \to J/y\, K^0_s$

CDF~220 events





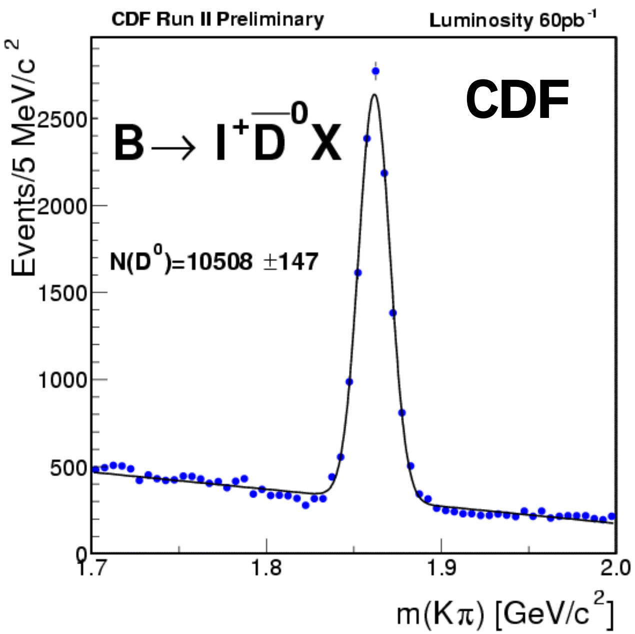
$L^0_b \to J/y\, L$

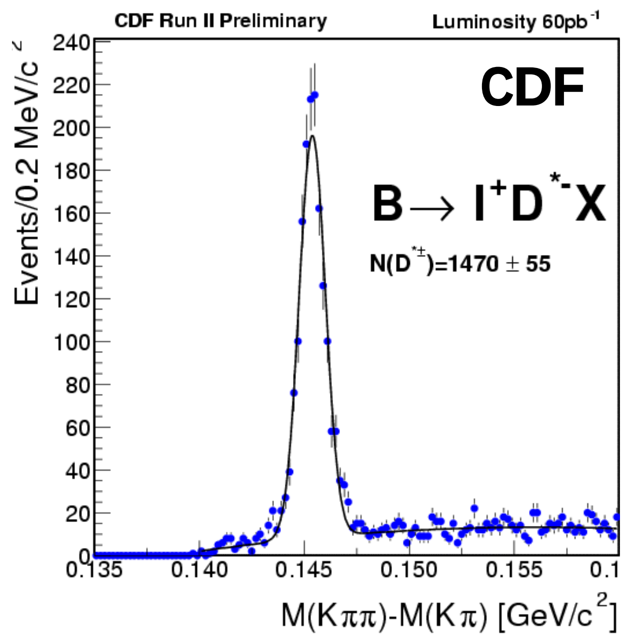


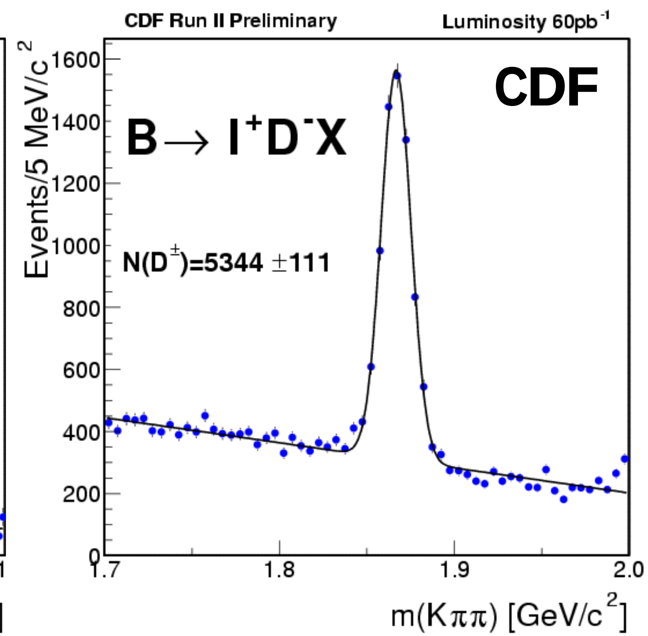
First steps towards sin(2b) Measurement

$L^0_b \to J/y\, L$ Br.Ratio and Lifetime meas. in progress (see T. Yamashita, R. Madrak's Talk)

B^+/B^0 from lepton+displaced track







CDF: high statistics semileptonic B samples

Excellent calibration samples for B^+/B^0 lifetime, tagging and B^0 mixing

$B \rightarrow lD^0X$ ($D^0 \rightarrow K\pi$): ~10,000 events

$B \rightarrow lD^{*+}X$ ($D^{*+} \rightarrow D^0\pi$): ~1,500 events

$B \rightarrow lD^+X$ ($D^+ \rightarrow K\pi\pi$): ~5,000 events

Run II yields significantly larger, lower lepton pt threshold possible thanks to i.p trigger

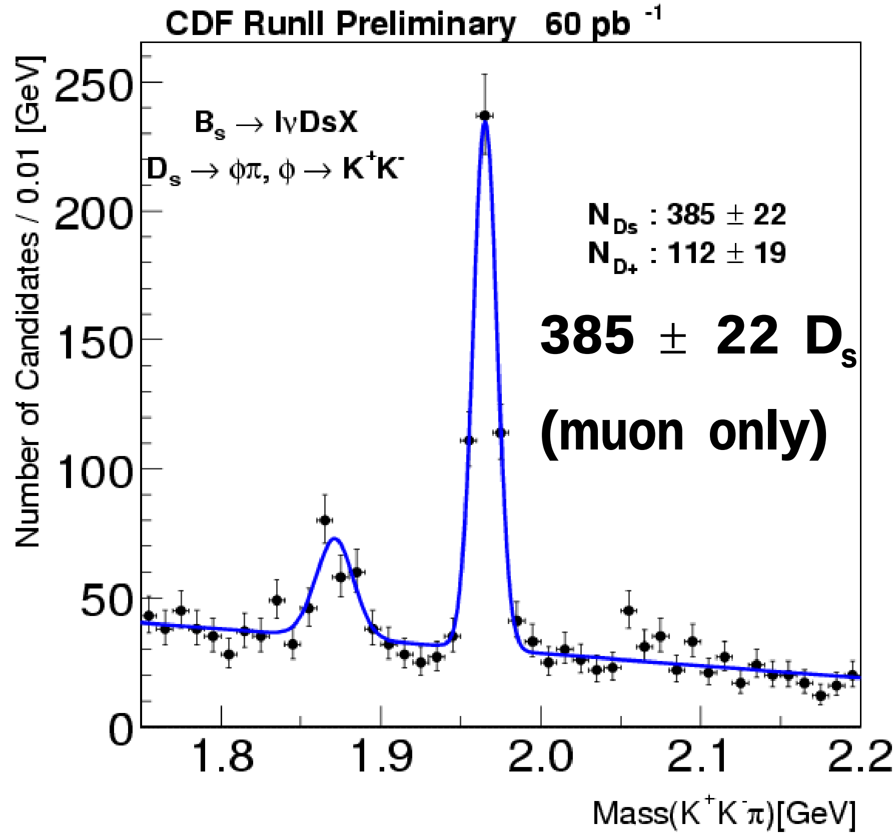
B_S from lepton + displaced track

$B_s \rightarrow D_s$ln → [fp] ln → [[KK] p]ln ONLY @ Tevatron

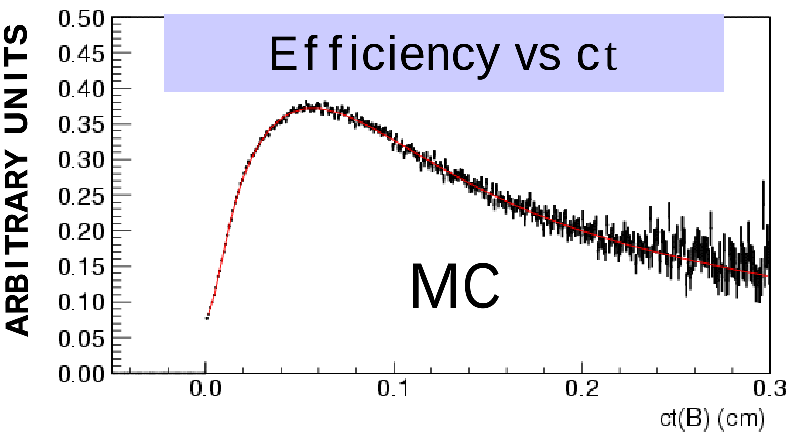
HIGH STATISTICS SAMPLE:

- Inclusive lifetime: → $\frac{t(B_s)}{t(B_d)}$
- Mixing (moderate x_S):

  good S/N, limited time resolution: back-up sample



Systematics of trigger bias



Yield/Lumi ~ Run I x 3
S/N ~ Run I x 2

Λ_b from lepton+displaced track

$\Lambda_b \to \Lambda_c l\nu \to [pK\pi]\, l\nu$

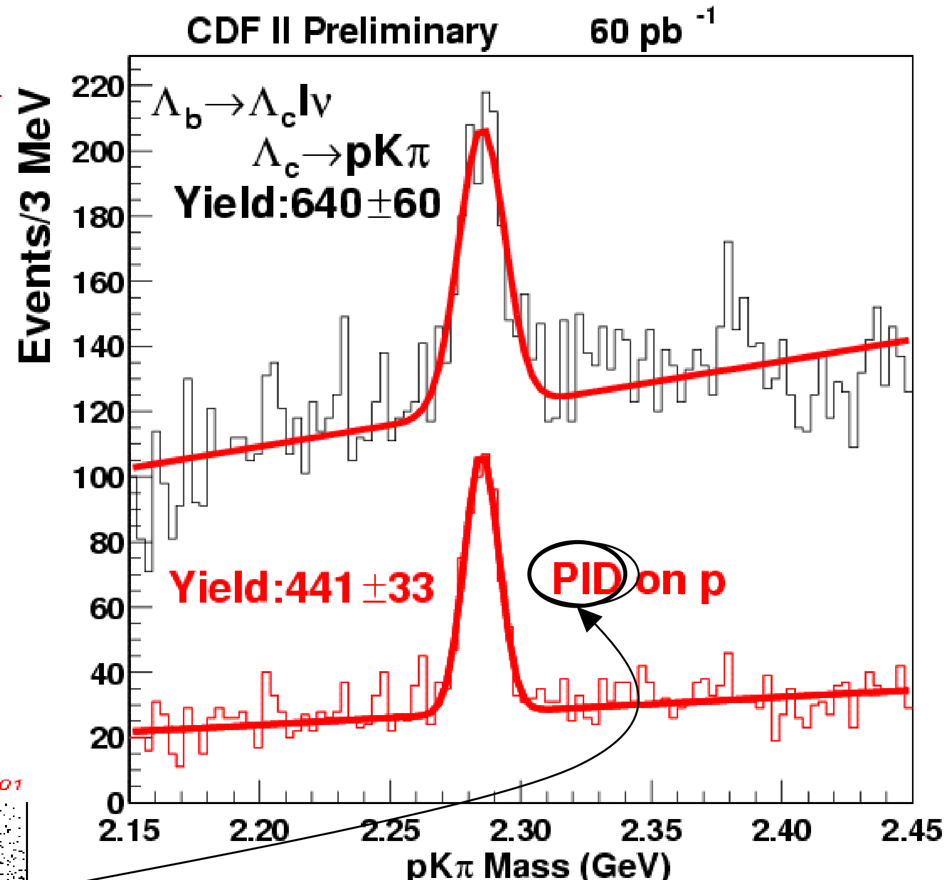
- Branching Ratio
- Measure $\to \frac{1}{\Gamma}\frac{d\Gamma}{dQ^2}$

  $Q^2 = m(l\nu)$

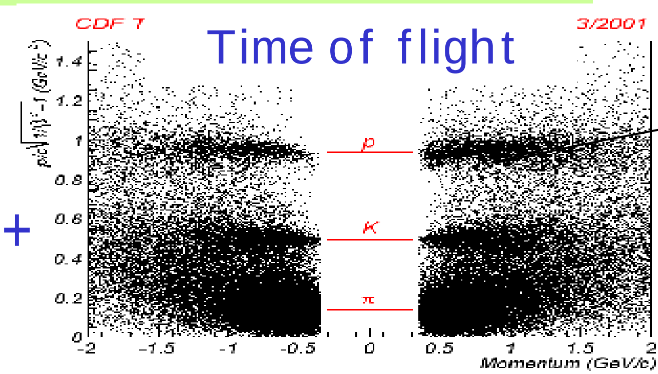
  important for theory

Experimental challenge:

disentangle from decays through excited baryons



dE/dx +

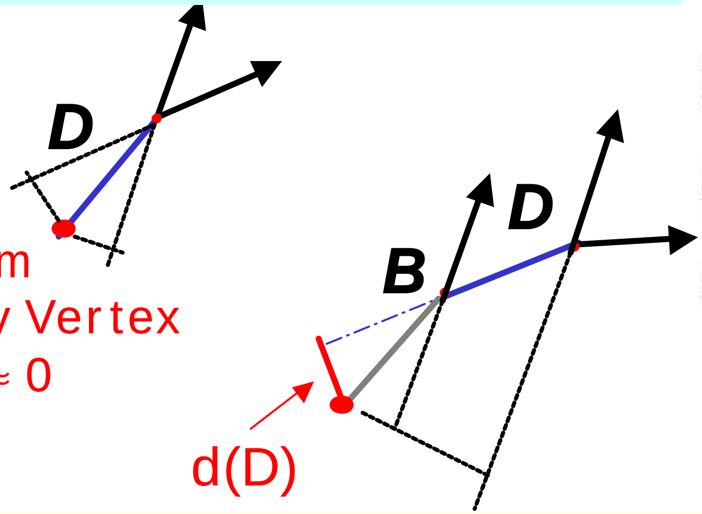


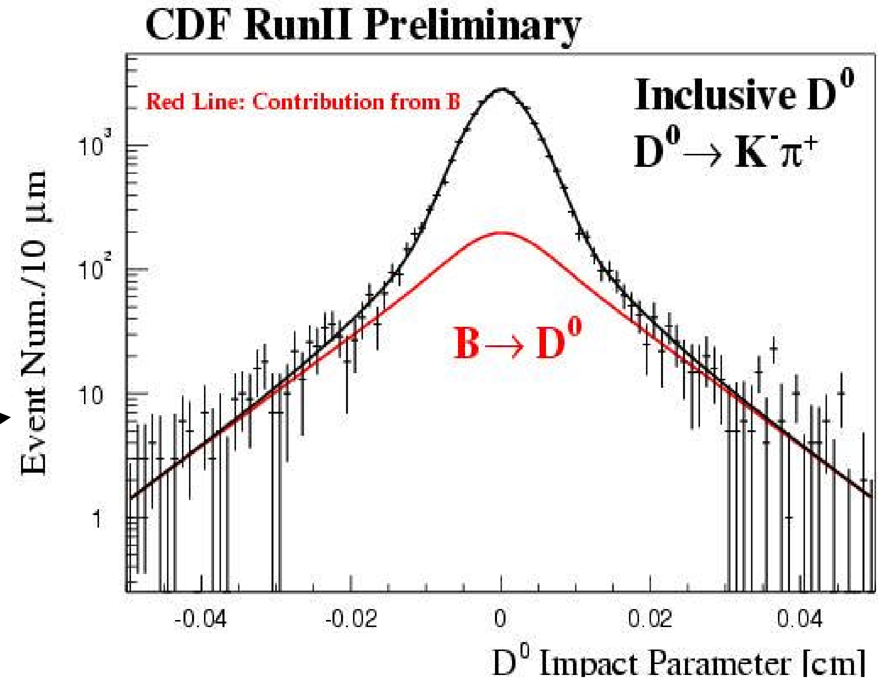
Yield/Lumi = 4 x Run I

S/N ~ 2 x Run I

Physics with the hadronic trigger

CDF: open access to fully hadronic D and B signals





D mesons I.P. (d) distribution

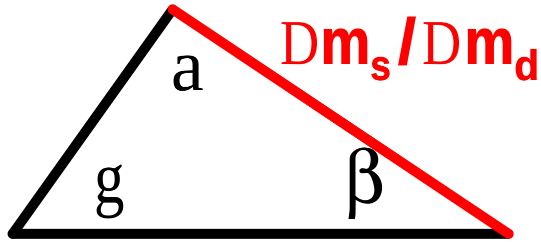
Reconstructed large (0.5M) D mesons:
$D^\pm \to K\pi\pi$, $D^0 \to K\pi$, $D^* \to \pi D^0$, $D_s \to \phi\pi$
$D^0 \to KK$, $D^0 \to \pi\pi$
See K. Stenson's (Charm Physics review),
C. Chen (D x-section),
S. Vallecorsa (D Cabibbo supp. decays),
M. Campanelli (D orb. excited states)
talks for CDF Charm results

	Direct Charm
$D^0 \to Kp$	86.5 ± 0.4 % (stat)
$D^* \to pD^0$	87.6 ± 1.1 % (stat)
$D^\pm \to Kpp$	89.1 ± 0.4 % (stat)
$D_s \to jp$	72.4 ± 3.4 % (stat)

B fraction » 10 - 20 %

Ingredients for $B^0{}_s$ mixing

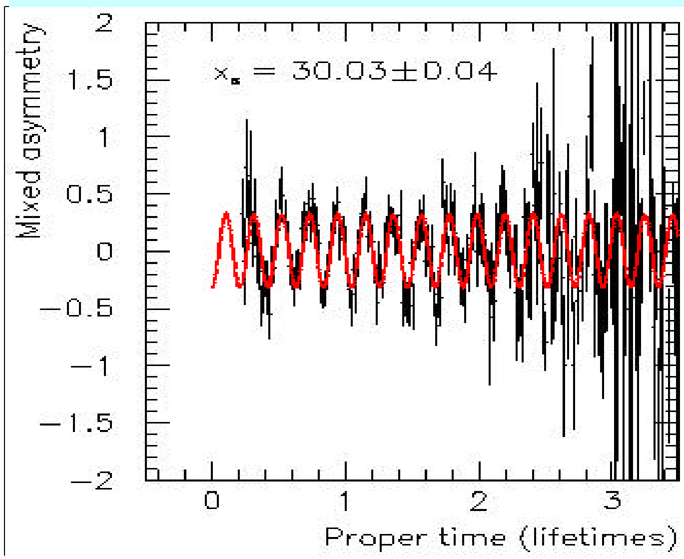
$$A_{mix}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = D\cdot\cos(Dm_s t)$$



1. **Reconstruct the final state** (use fully rec. $B^0{}_s$? $D^-{}_s p^+(3p)$) **with good S/B** (thanks to precise tracking, vertexing, PID)

2. **Measure proper decay time:**

$$c\tau = \frac{L_{xy}}{\gamma\beta} \; ; \quad \gamma\beta = P_T(B) / M(B)$$



Current limit:
$\Delta m_s \geq 14.4$ ps^{-1}

$$\sigma_{c\tau} = \left(\frac{\sigma_L}{\gamma\beta}\right) \oplus \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta}\right) \cdot c\tau$$

60 fs (SVX II detector)
45 fs (also Layer 00 is used)

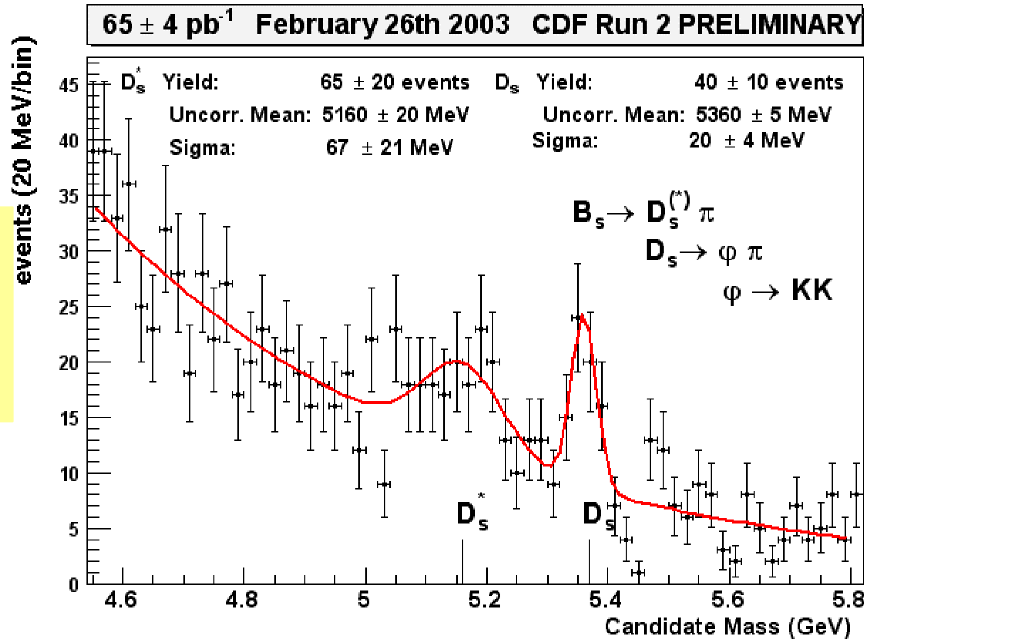
Error on B momentum, ~ 15% (semileptonic)
negligible (~ 0.5%) for fully reconstructed final states

3. **Identify the flavor of B_s at production:** **B-flavor tagging algorithms**

First steps towards B^0_s mixing in CDF

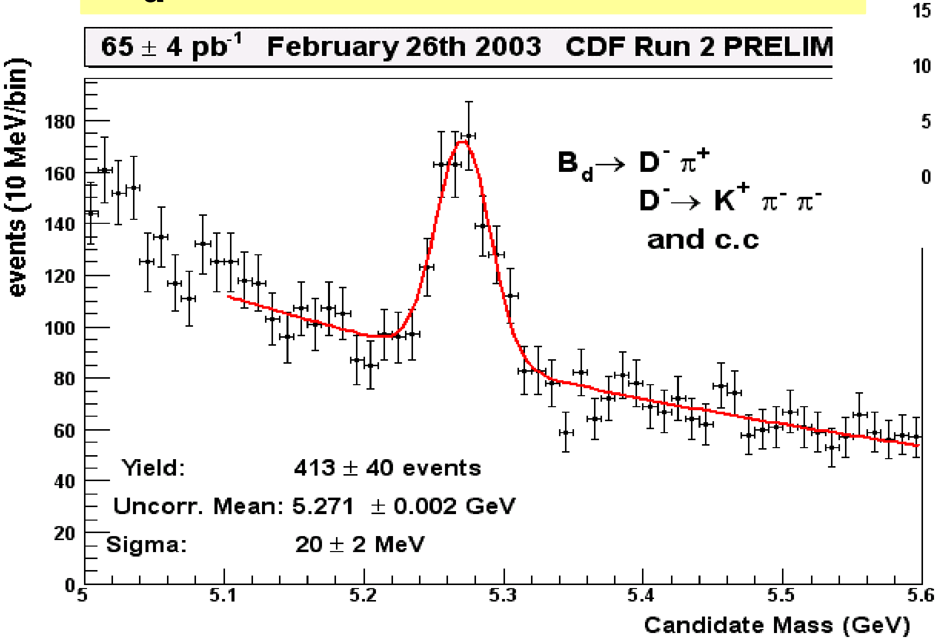
B_s → $D_s^{(*)}$p → [fp] p → [[KK] p] p

Fully reconstructed



B_s is consistent with

B_d→ Dp control sample

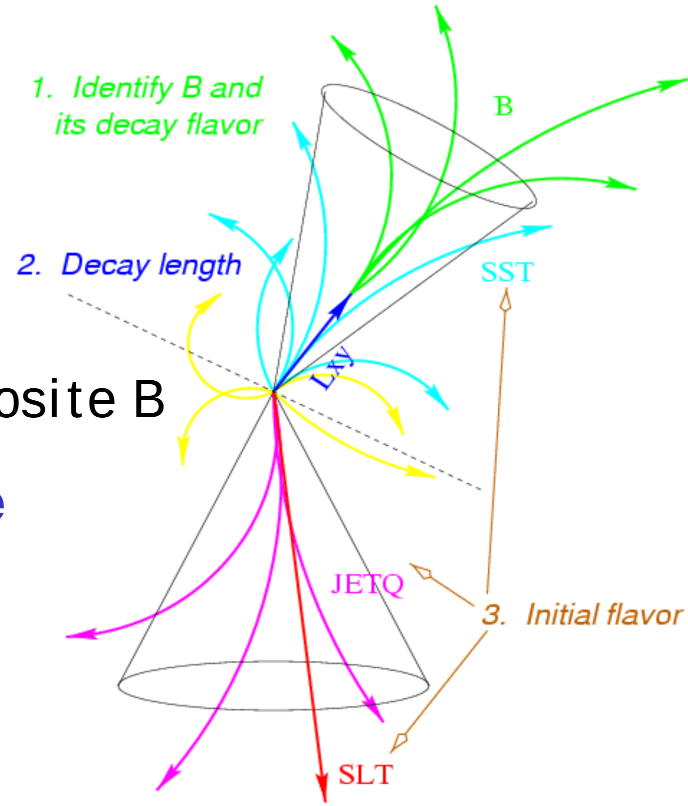


Collect more data and understand tagging

See S. DaRonco's Talk

B Flavor Tagging

"Identify the flavor of B at production"



OST (opposite side tagging):

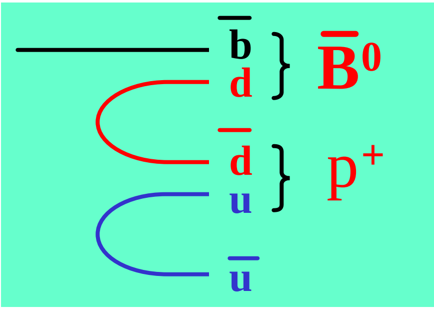
B's produced in pairs → measure flavor of opposite B

JETQ: **sign of the weighted average charge of opposite B-Jet**

SLT: **identify the soft lepton from semileptonic decay of opposite B**

SST (same side tagging):

$\overline{B}^0$ (B^0) is likely to be accompanied close by a p+ (p-)



Search for the track with minimum P_T^{REL}

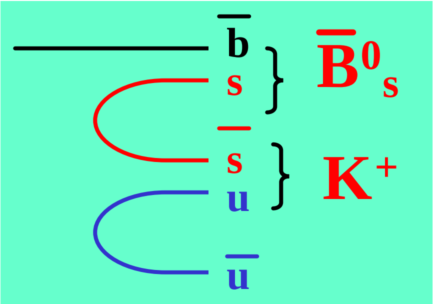
Figure of merit: eD^2 "tagging effectiveness" » **2%**

$$e = \text{efficiency} \; ; \; \mathbf{D} = \text{"Dilution"} = 1 - 2P_{mistag}$$

Effective size of sample is reduced by eD^2

NEW in CDF: “Kaon b-taggers”

- Exploit K/p separation of new TOF
- Well suited for strange B mesons



Same Side K: a $\overline{B}^0_s$ (B^0_s) is likely to be accompanied close by a K^+ (K^-) from fragmentation

Opposite Side K: due to b®c®s it is more likely that a B meson contains in final state a K^- than a K^+

Þ to identify a $\overline{B}^0_s$ look for a K^- from the decay of the opposite B

D0 Run II	Preliminary
Jet charge tag	Muon tag
e=63.0±3.6 %	ε= 8.3 ±1.9%
D=15.8±8.3 %	D=44.4±21.1 %
2.4 ±1.7%	3.3 ±1.8 %

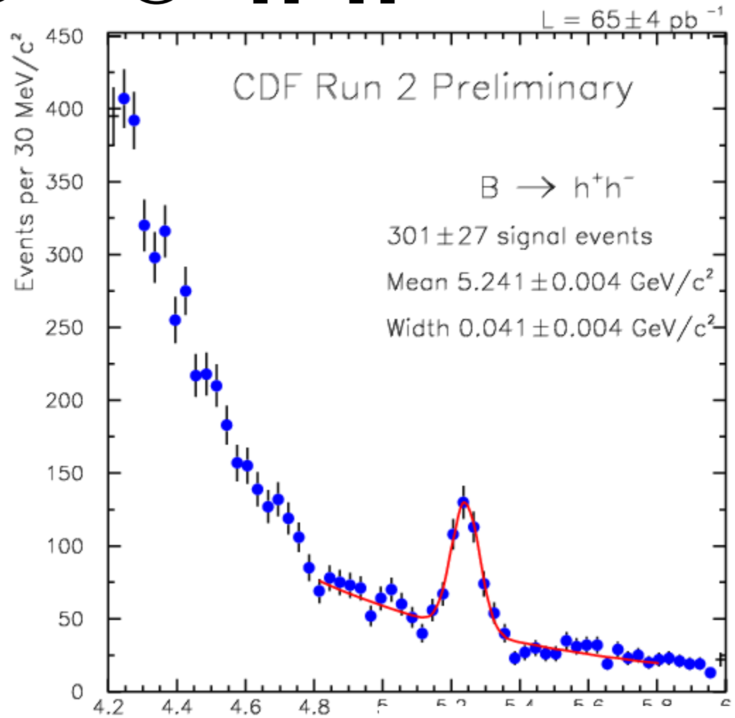
For CDF studies see A. Ratikin and T. Moulik’s Talks

Physics with B^0 ® h^+h^-

300 events in 65 pb^{-1} of CDF Hadron Trigger data with very good S/B

B^0 ® h^+h^- is a mixture of

B_d→pp; B_d→Kp; B_s→Kp; B_s→KK



(pp inv.mass)

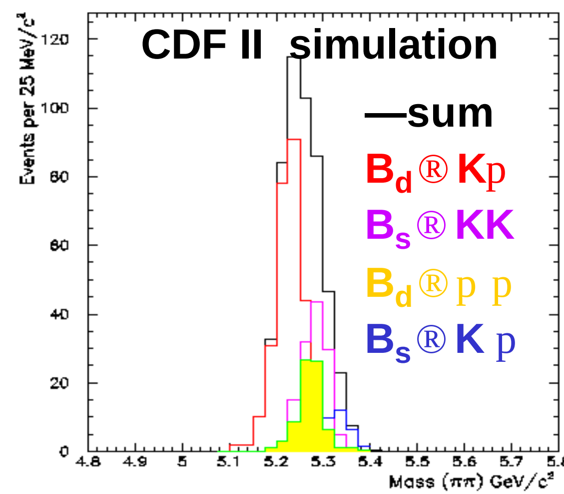
Strategy for disentangling channels:

- Invariant mass shape (s_M ~25 MeV)
- Kinematical variables
- Particle Identification
- Oscillation of CP asymmetry

Can soon perform interesting measurements:

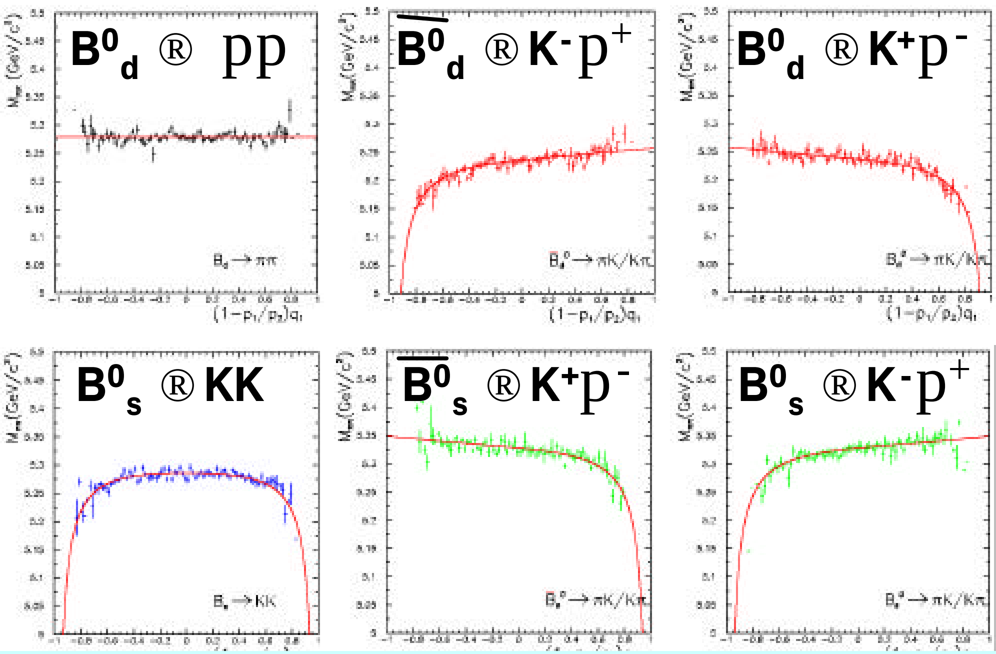
- Relative B. Ratios: B_d→ pp/Kp ; B_s→ KK/Kp
- Direct CP asymmetries in B_d →Kp (self tagging)
- CP asymmetries in B_d →pp (with b-tagging)

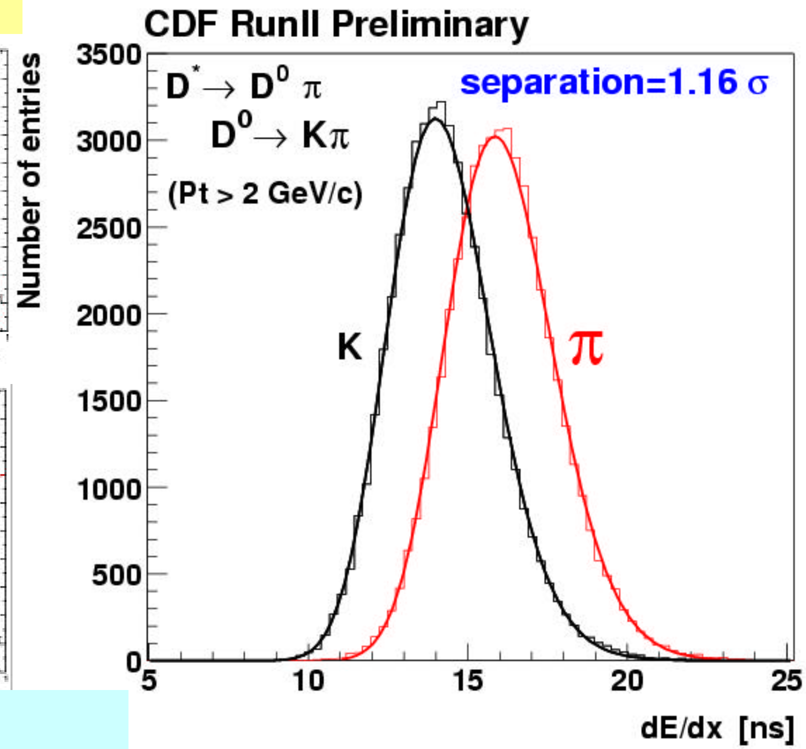
Later on: CKM angle g



Disentangling the B^0 ® h^+h^- contributions

Use Mππ vs $(1-p_1/p_2)\cdot q_1$





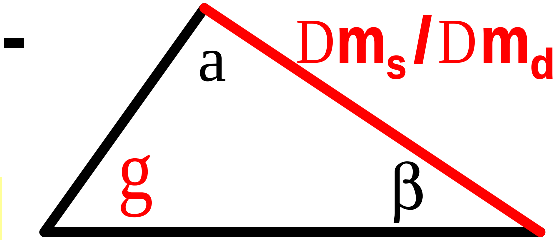
Expected fraction res. (MC »65 pb^{-1})

- B^0_d ® Kp(0.6): ± 0.062 (stat)
- B^0_d ® pp(0.15): ± 0.056 (stat)
- B^0_s ® KK(0.2): ± 0.045 (stat)
- B^0_s ® Kp(0.05): ± 0.036 (stat)
- ACP(B^0_d ® Kp): ± 0.14 (PDG-2002: ±0.06)

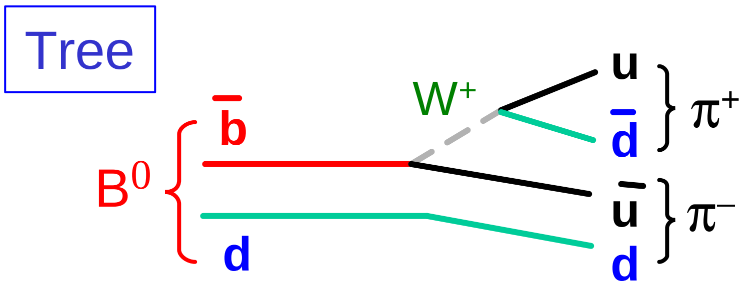
Use K/p separation dE/dx 1.16s

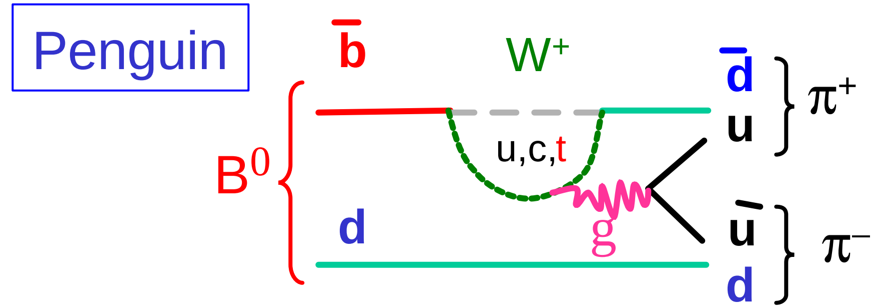
See M. Morello's talk

Angle g from B^0 ® h^+h^-



B^0 ® p^+p^- has two (comparable) decay amplitudes:





direct ~~CP~~ **~~CP~~ from mixing alone**

$$A_{CP}(t) = A_{CP}^{dir} \cos(\Delta m_d t) + A_{CP}^{mix} \sin(\Delta m_d t)$$

A_{CP}^{dir}, A_{CP}^{mix} functions of γ, β, d, q ($d\, e^{iq} \approx$ P / T decay amplitude)

<u>R. Fleischer</u> ***(PLB 459 (1999) 306):***

Assume U-spin symmetry (d ↔ s)

Similar relation holds for $B_s \rightarrow K^+K^-$ (Δm_d replaced by Δm_s)

The 4 asymmetries can be expressed as function of γ, β and P/T amplitude ratio

Parameters can be extracted from fit of meas. of $A_{CP}(t)$ for $B_d \rightarrow \pi\pi$ and $B_s \rightarrow KK$

Expected ($2fb^{-1}$) accuracy: σ(g) = ±10°(stat) ±3°(syst) **(SU(3) breaking effects)**

Hadronic $L_b \rightarrow L_c\ p$ signal

$L_b \rightarrow L_c\ p \rightarrow [pKp]\ p$

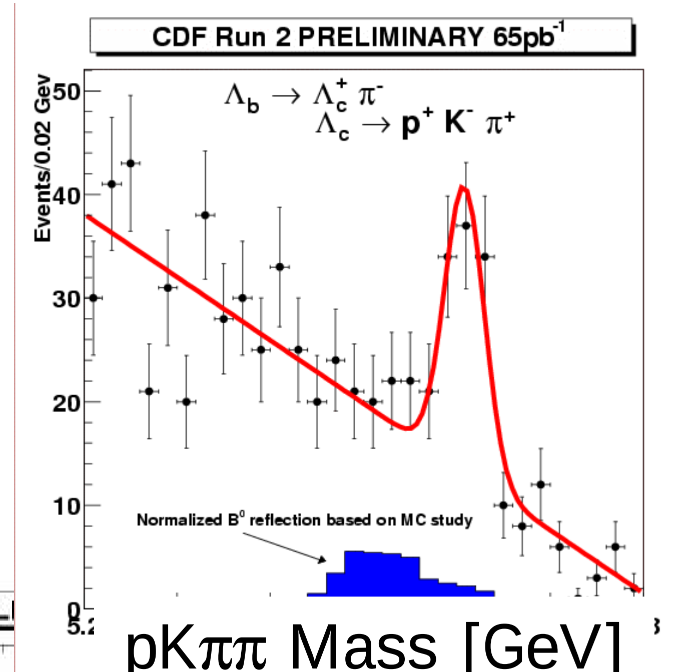
Largest fully rec. hadronic channel

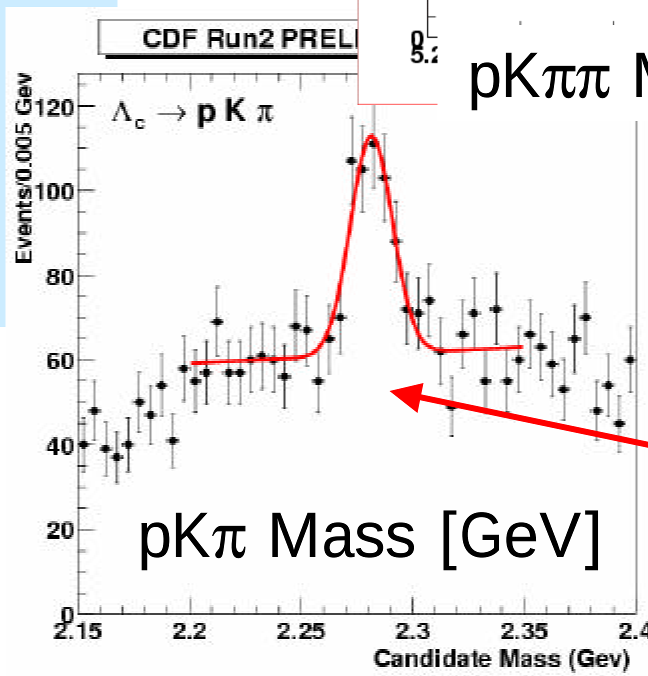
- **Measure mass, lifetime, polarization**
- **Precise Lifetime** $\rightarrow \frac{t(?_b)}{t(B^0)}$

Discrepancy with theory:

Is it valid for baryons ?

See Y. Li's Talk





NO PID YET

Conclusions

The upgraded CDF/D0 detectors are taking new data

Great B physics potential, we have results on:

- Masses, lifetimes in the B® *J*/*y* K exclusive channels and production cross sections
- New impact parameter trigger (CDF-only): huge/clean semileptonic/all hadronic B signals (and also Charm):
  - Large and clean B→lDX reconstructed in CDF (excellent for lifetime, tagging and Dm_d meas.)
  - B^0_s ? $D^-_s p^+$: first ingredient towards Dm_s
  - B^0® h^+h^-: important results awaiting on our way to g (B^0_s®KK, CP in B^0_d®Kp)

Lots of Beauty (and Charm) at the Tevatron