Heavy flavor results from CDF Run II

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Outline

- Introduction

- **Bottom Physics**
  - Triggers and data samples
  - Detector calibration
  - B masses
  - Lifetime: B^0, B^+, $B_s \rightarrow J/\psi X$
  - Dimuon B decays
  - Semileptonic B decays
  - Two body $B \rightarrow hh$ decays

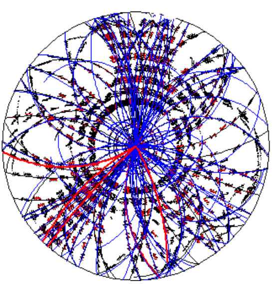
- **Top Physics**
  - top production
  - $t\bar{t}$ cross-section
    - dilepton channel
    - lepton + jets channel
  - top mass

- Summary

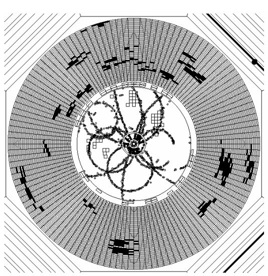
B physics with Run II CDF

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

$b\bar{b}$ cross section is 50-100 mb
~O(10^5) larger than e^+e^-@ ¡(4S)/Z^0
~O(10^3) B's per second at design luminosity
(~10 B's per second at ¡(4S) factories)
BUT:
- B hadrons are hidden in a 10^3 larger background (s $_{inelastic}$($p\bar{p}$) » 50 mb
- Events more complicated than at ¡(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 ¡(4S)
- Combinatoric background
- Events pile-up within the same beam crossing: problem for the trigger
- Typical S/B @ analysis level: ~O(0.5÷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®D_sp, lnD_s
  - $|V_{td}|$: B^0®lnD
  - DG_s: B_s®J/y f, J/y h, lnD_s, $D_s D_s$
  - CP asymmetry: B^0(B_s)®hh
  - g: B_s®$D_s K^+$, B®DK
  - g: B^0, B_s®Kp, pp, KK
  - b: B^0®J/y$K^0{}_s$
- Properties of B_s, B_c, L_b, etc
  - Production, mass, lifetime
- Rare decays
  - B®mm$K^{(*)}$, B^0, B_s®mm
  - Physics beyond the standard model: B_s®em

B Triggers and data samples

Conventional | **New at CDF**

DiMuon (J/y)

2 central muons
P_T(m) > 1.5 GeV
Run I: > 2 GeV Trigger on J/y®mm
Collected ~ 70 pb^{-1}
~ 0.5M J/y®mm signal

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

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

Displaced track + lepton (e, m)

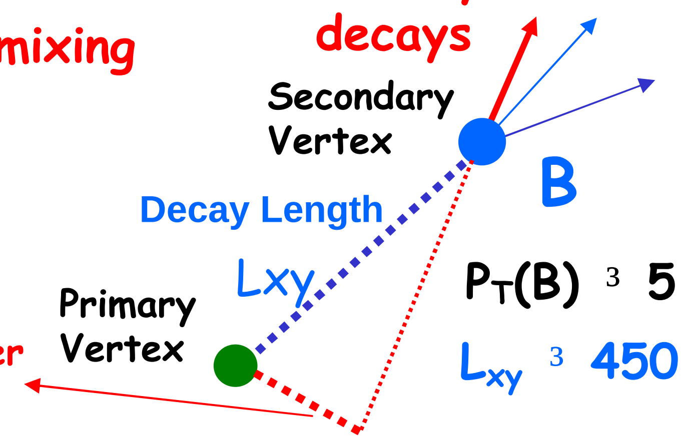
1 muon/electron p_T> 4 GeV
1 other track p_T > 2 GeV
SVT IP>120 mm
M(l-Track) < 5 GeV
Collected ~70 pb^{-1}
~ 0.5M B®lX signal
Semileptonic modes

- High statistics lifetime
- tagging studies, mixing

2-Track Trig.

2 Tracks with p_T > 2 GeV
SVT IP > 120 mm
$p_{T1}+p_{T2}$ > 5.5 GeV
Collected ~70 pb^{-1}
~ 0.5M D^0®Kp signal
Fully hadronic modes

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



P_T(B) 3 5 GeV
L_{xy} 3 450 mm

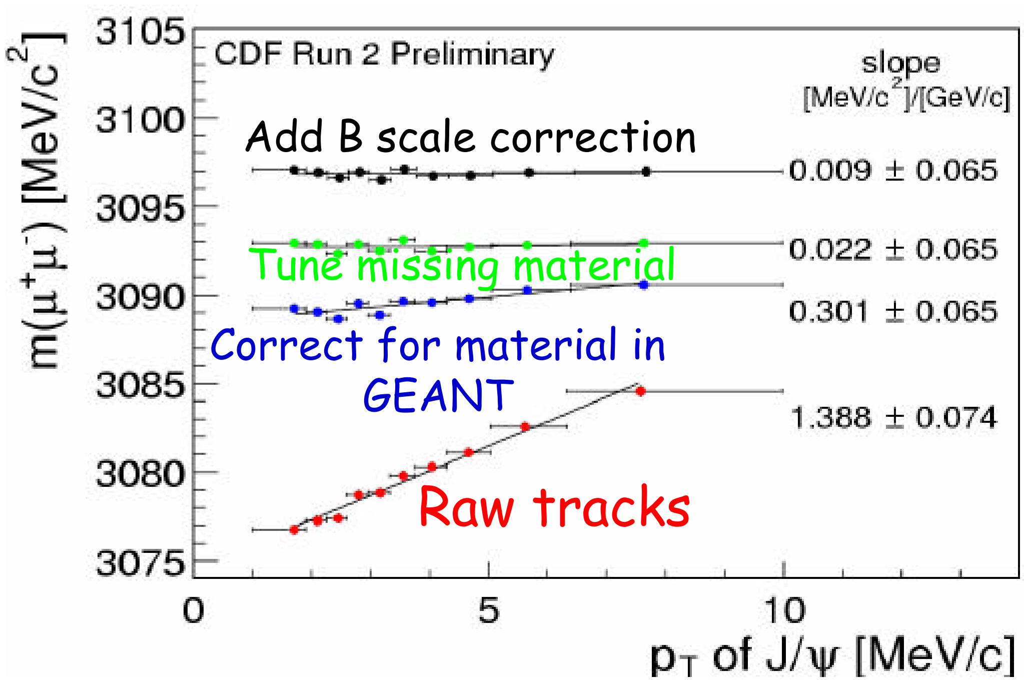
Detector calibration: p scale & B-field correction

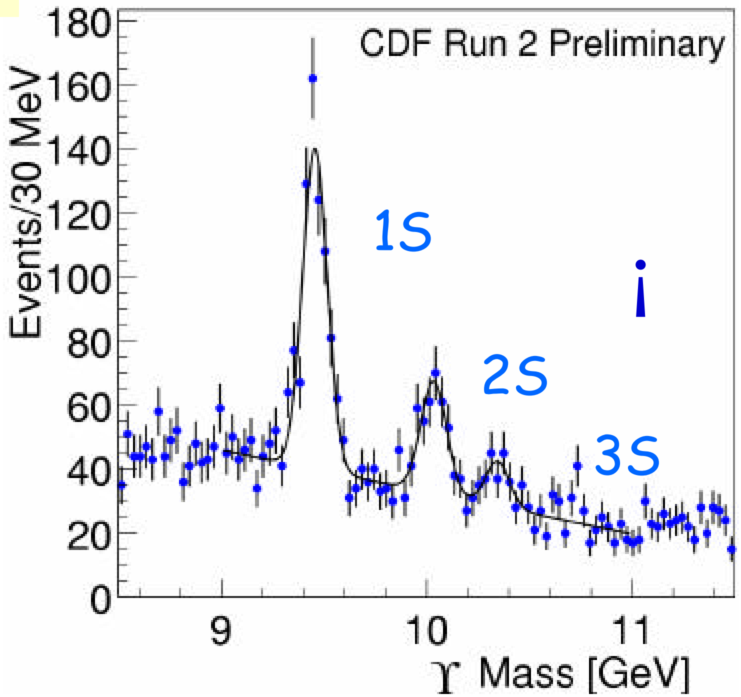
MASS SCALE: M_{CDF} = M_{PDG}-DM(P_T)

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

s(scale)/scale ~ 0.02%

Sanity check with known signals:





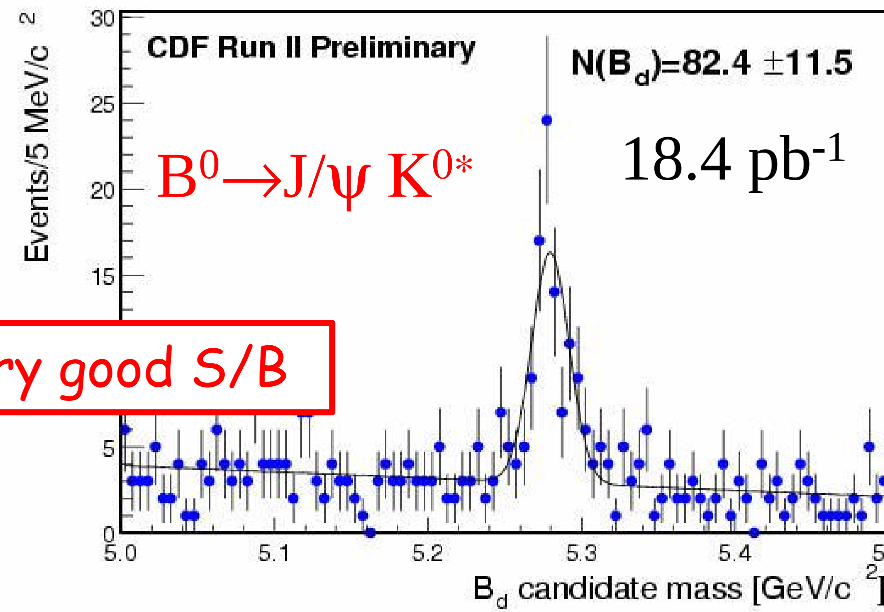
B masses in exclusive J/ψ channels

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

Prerequisite: momentum scale was precisely set (@0.02%) using J/ψ sample (~200K events)

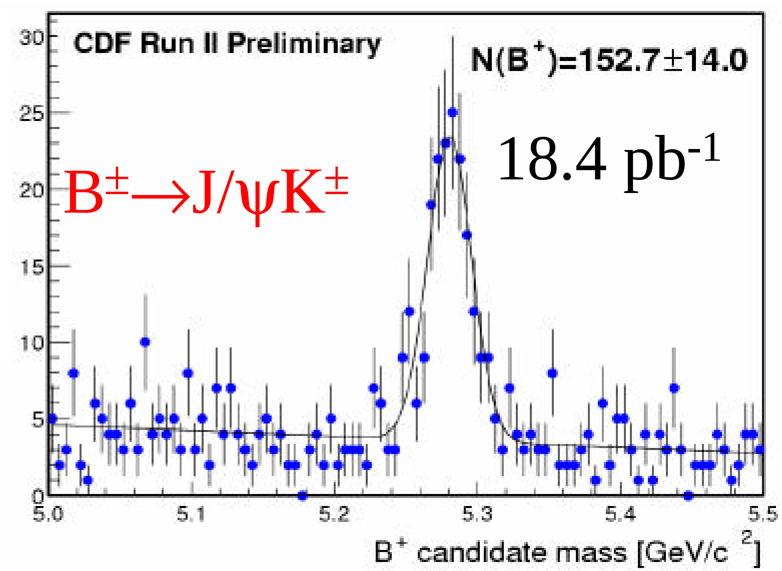
- $B_u \rightarrow J/\psi\ K^+$
- $B_d \rightarrow J/\psi\ K^{0*}$ ($K^{0*} \rightarrow K^+\pi^-$)
- $B_s \rightarrow J/\psi\ \phi$ ($\phi \rightarrow K^+K^-$)

Very good S/B

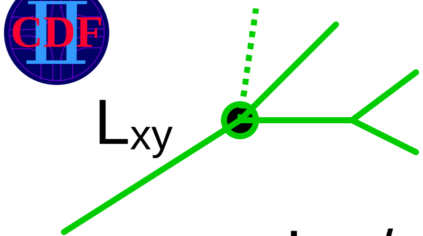


	CDF2 (MeV/c²)	ΔM/σ CDF	σ CDF/σ PDG
Bu	5280.6 ±1.7 ±1.1	+0.8	4.0
Bd	5279.8 ±1.9 ±1.4	+0.2	4.8
Bs	5360.3 ±3.8 $\pm^{2.1}_{2.9}$	–2.1	1.9

- *Statistics limited, but compare well w/PDG*
- *Systematics already under control.*
- *Precise measurements, soon!*



B lifetimes (1)

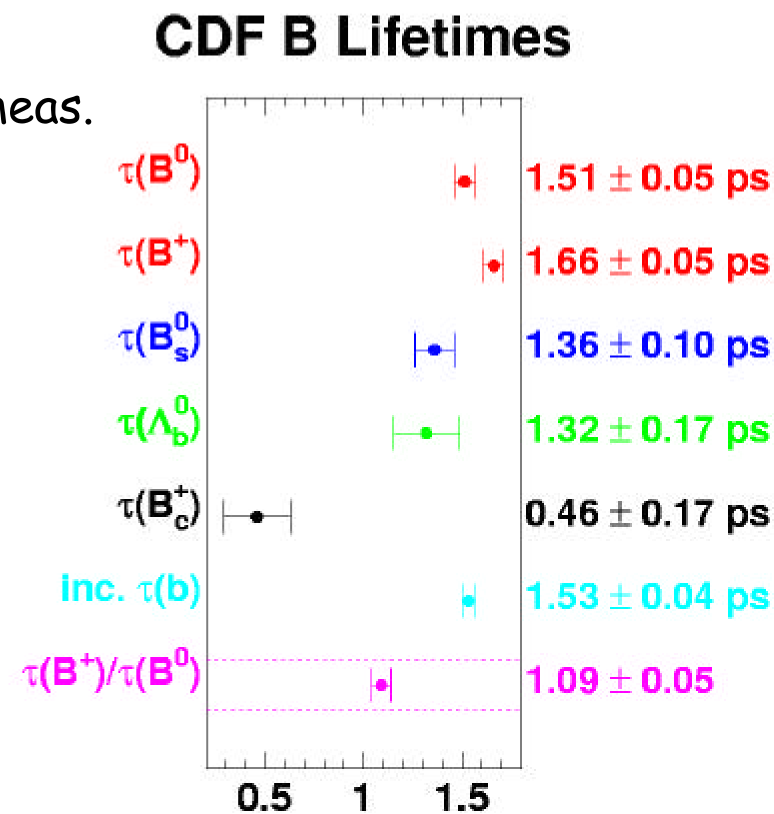


PV

$$c\tau = L_{xy} / \gamma\beta$$

$$\gamma\beta = P_T(B) / M(B)$$

__Crucial__: precise Secondary Vertexing
Silicon VerteX detector (SVX)



CDF Run I: full set of precise B-lifetime meas.
Competitive with LEP

- __Inclusive__: $B \to l\nu DX$, $B \to J/\psi\ X$
  Large statistics, but…
  Final state not fully reconstructed
  $P_T(B)$ has to be corrected from MC

- __Exclusive__: $B_s \to J/\psi\ \phi$, $\Lambda_b \to J/\psi\ \Lambda$
  Small systematics
  Limited statistics

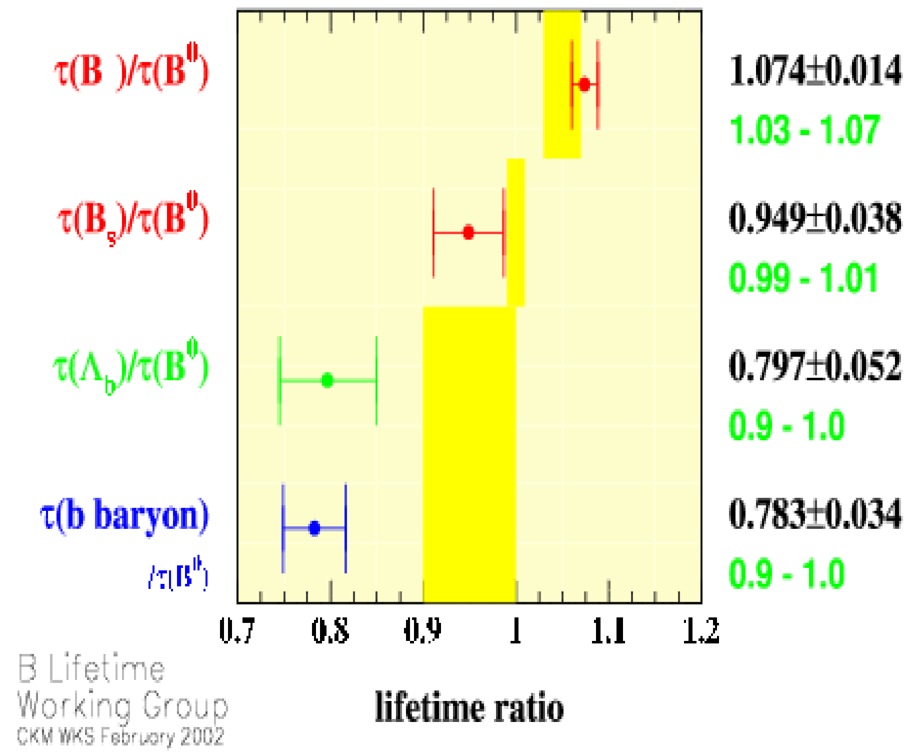
Run II: x50 statistics ($2fb^{-1}$, wider silicon & lepton coverage, hadronic triggers)
Improve measurements. Especially B_c, B_s, Λ_b down to ~0.01 ps

B lifetimes (2)

Heavy Quark Expansion predicts 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

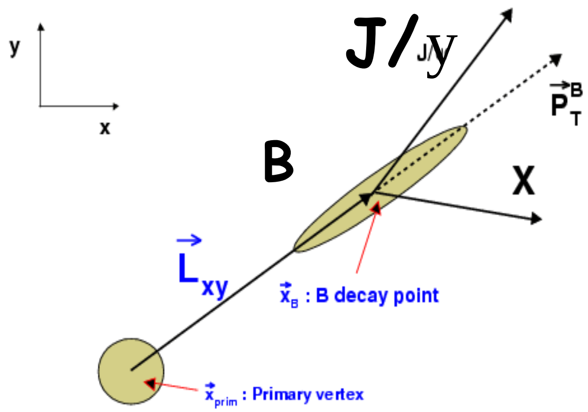


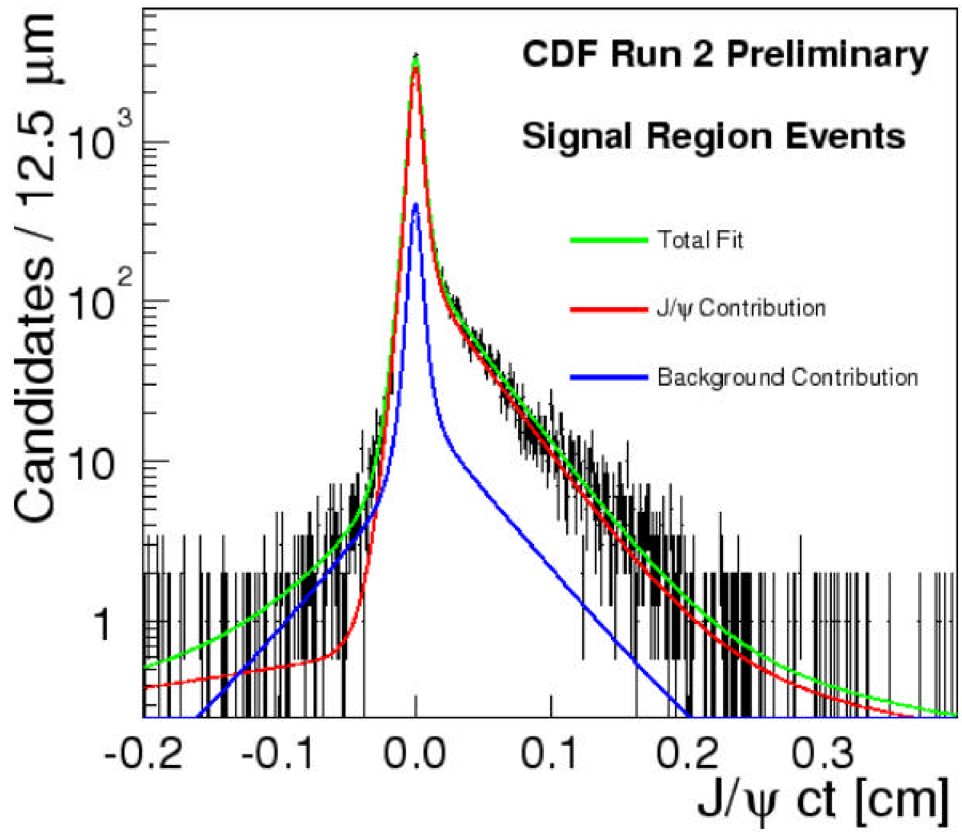
B^+/B^0 and B_s/B^0 measurements agree with prediction

Small discrepancy for L_b lifetimes

- LEP + CDF Run I

Inclusive B ® J/y X Lifetime





CDF July 2002 (18 pb^{-1}):
t=1.526±0.034±0.035 ps
PDG 2002: t=1.674±0.018 ps

Inclusive B lifetime with J/y's

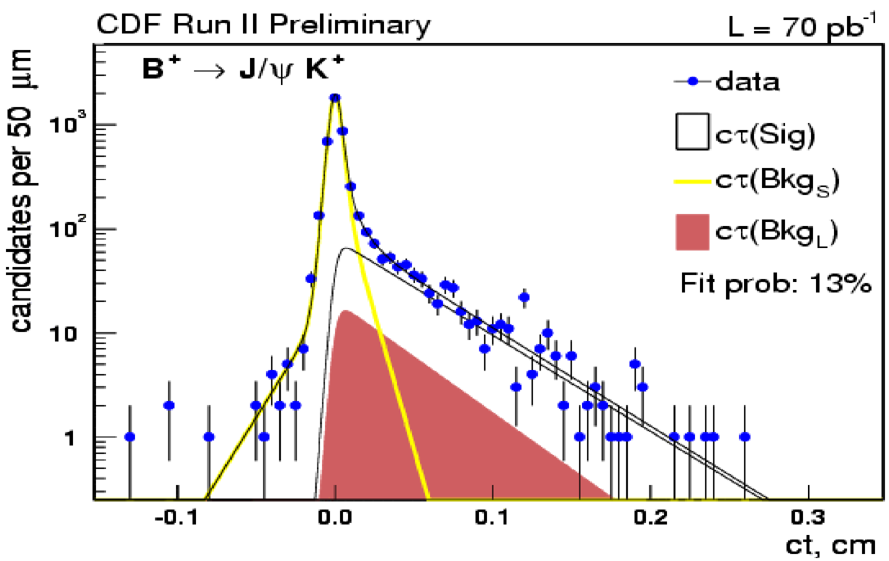
B®J/yX from ~ 28.000 J/y®mm events

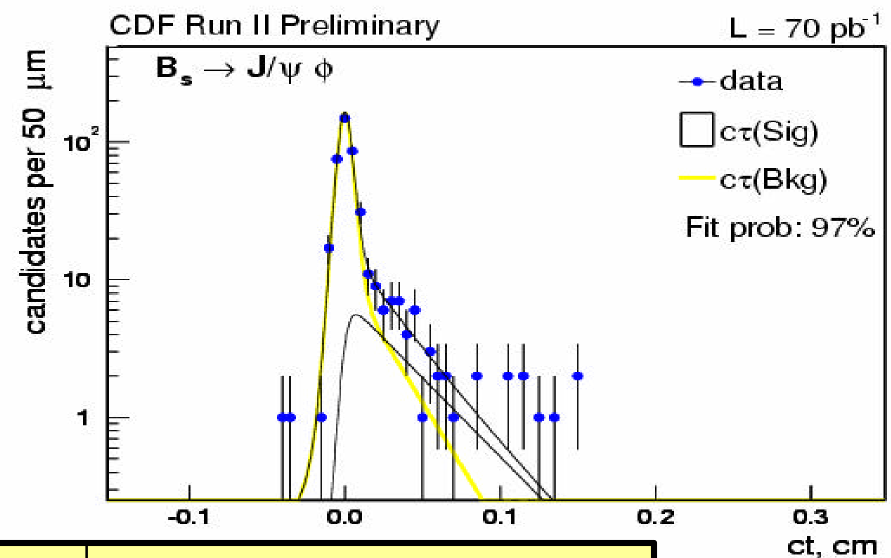
ct = J/y (prompt + non-prompt) + non-J/y

ct(B) = 458 ± 10(stat) ± 11(syst) mm

PDG: 469 ± 4 μm

Exclusive B Lifetimes





$B^+ \rightarrow J/y\ K^+$

$B^0 \rightarrow J/y\ K^{0*}$ ($K^{0*} \rightarrow K^+p^-$)

$B_s \rightarrow J/y\ f$ ($f \rightarrow K^+K^-$)

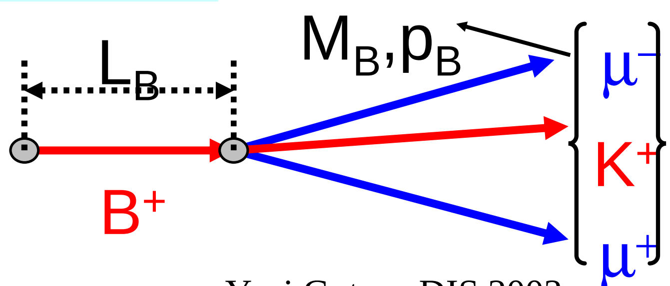
uncertainties @ Run I level

	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)

Unique to Tevatron

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

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



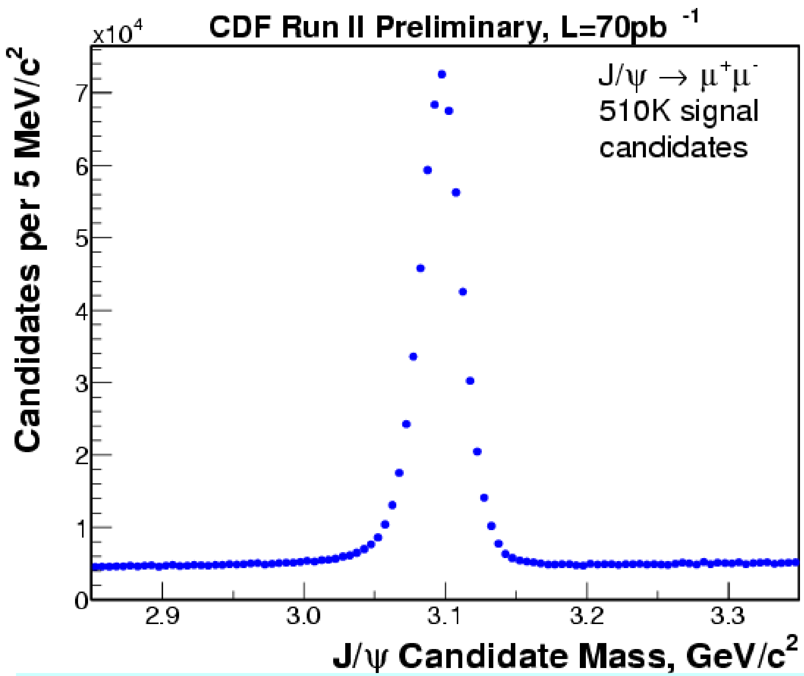
Simultaneous fitting of

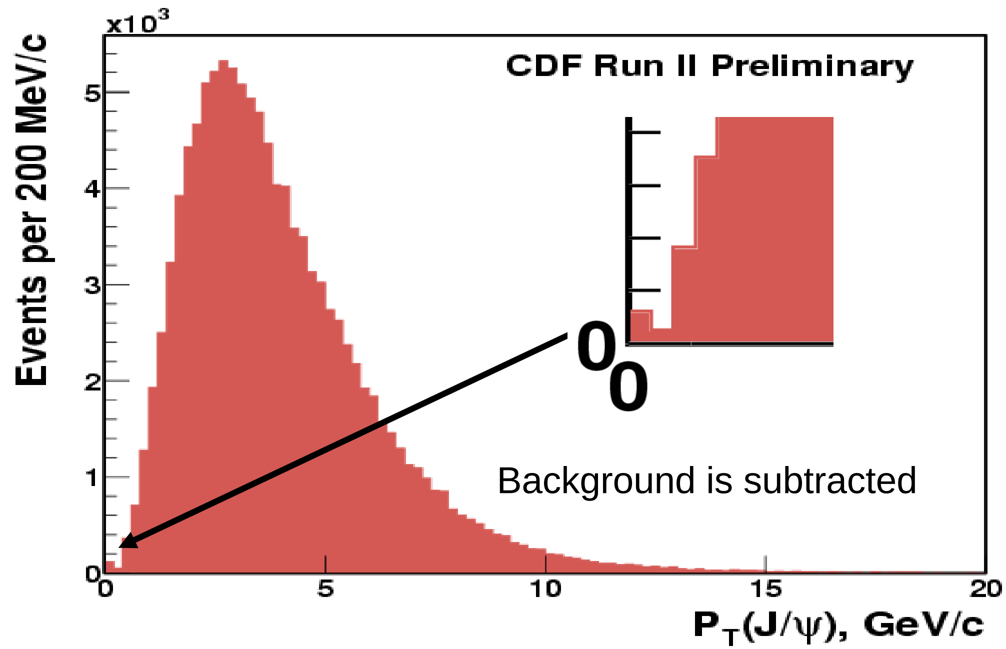
M_B: Extract signal fraction

ct: Extract the lifetime

•$ct = L_B / p_B \times M_B^{PDG}$

Conventional way to B: J/y ®mm





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

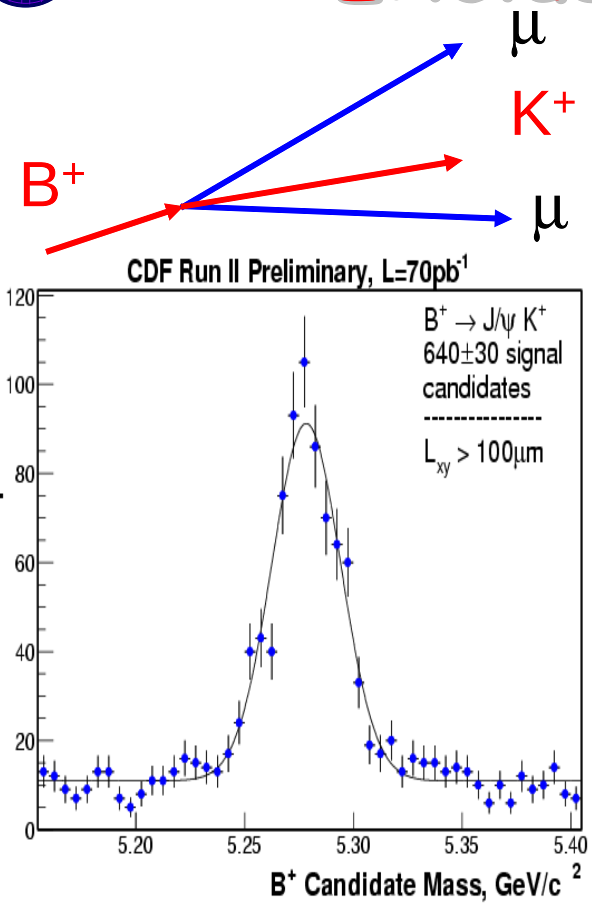
CDF can measure cross section down to p_T = 0

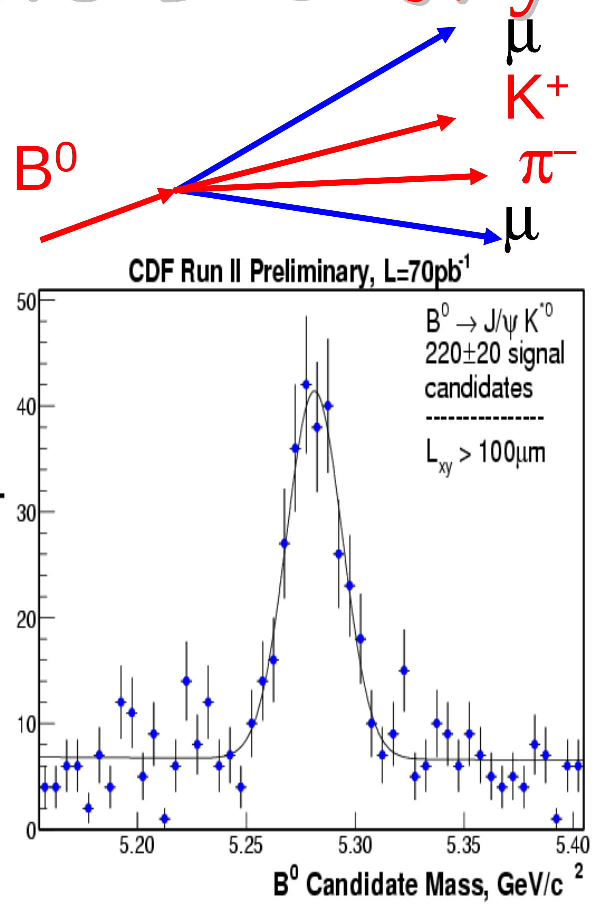
(first at hadron collider)

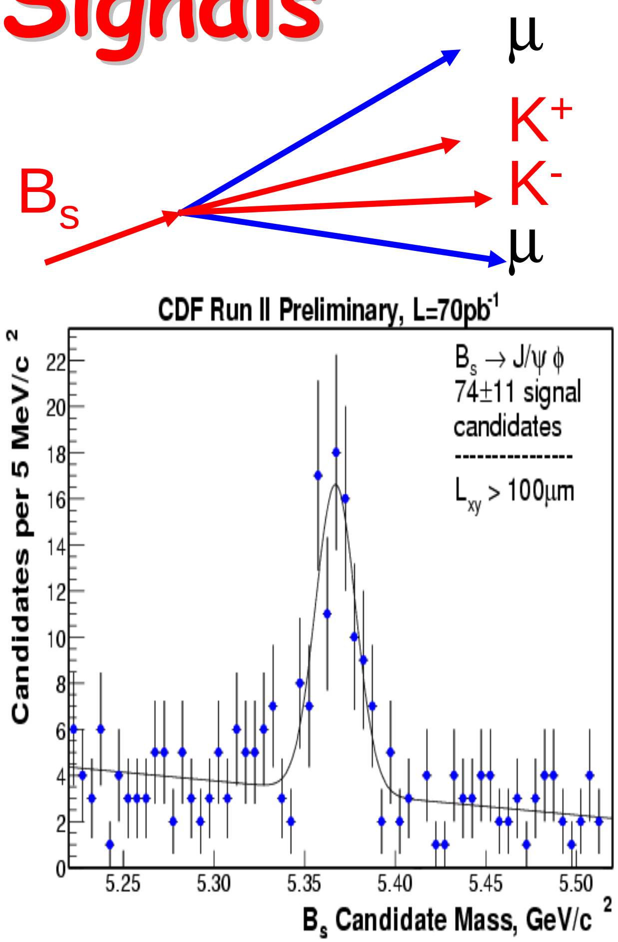
s($p\bar{p}$→J/y; p_T>0; |y|<0.6) = 240 ± 1 (stat) ± 35/28 (syst) nb

s(b®J/yX): in progress

Exclusive B ® J/y Signals







B+→J/y K+
~ 640 signal events

(>1000 events with loose selection)

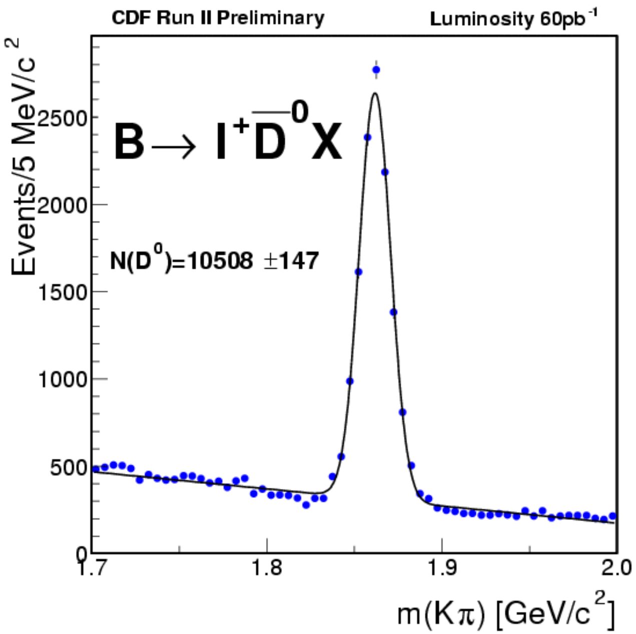
B0→J/y K*0 (→Kp)
~ 220 signal events

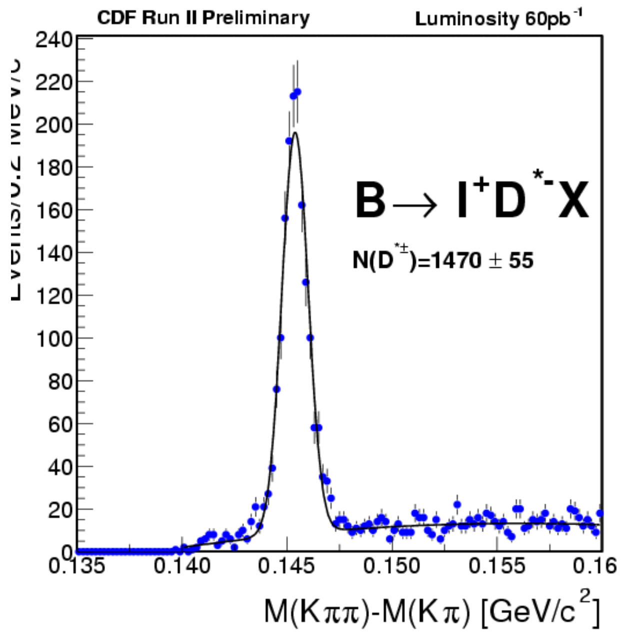
Normalization mode for sin2β analysis

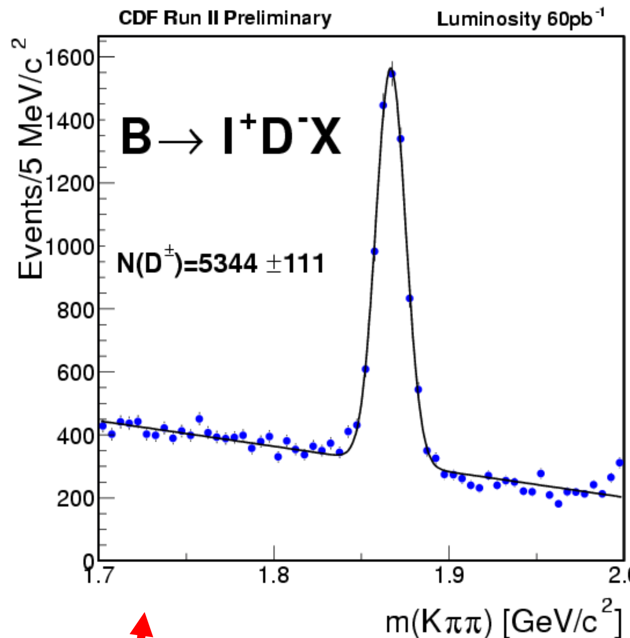
Bs→J/y f (→KK)
~75 signal events

Golden mode for $\Delta\Gamma_s$ measurement

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







high statistics semileptonic B samples

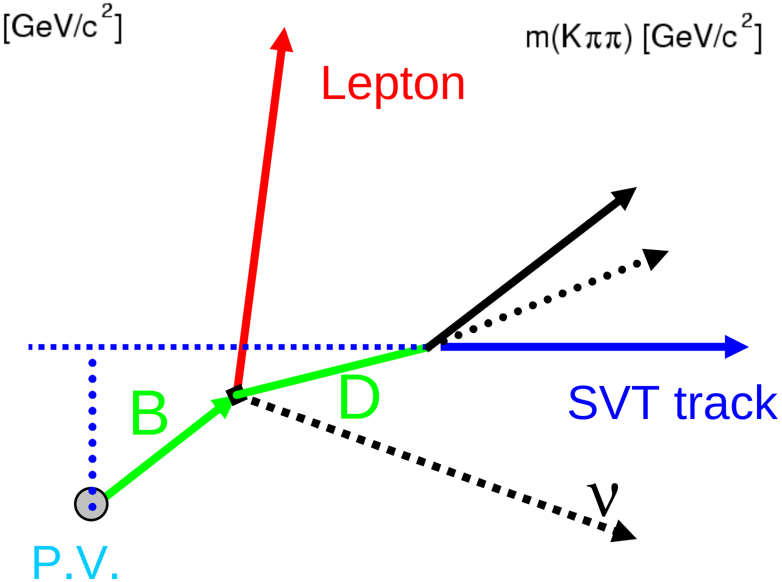
Excellent calibration samples for

B^+/B^0 lifetime, tagging and B^0 mixing

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

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

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



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

B_s from lepton + displaced track

B_s ® $D_s$ln ® [fp] ln ® [[KK] p]ln ONLY @ Tevatron

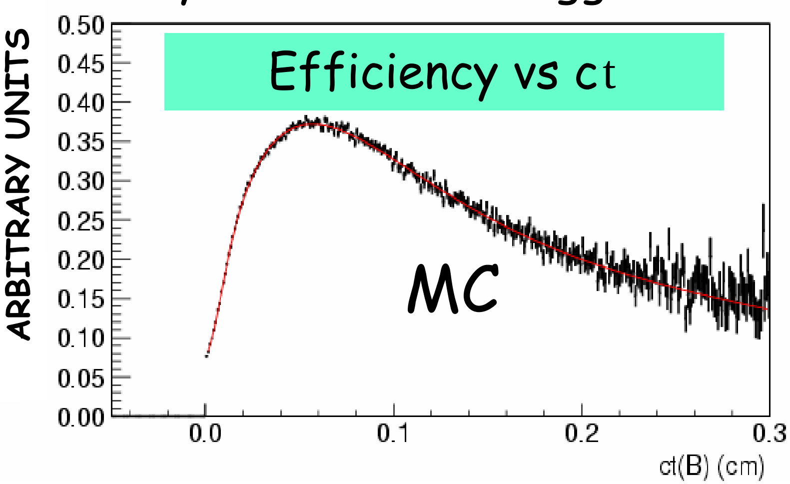
Yield/Lumi ~ Run I x 3, S/N ~ Run I x 2

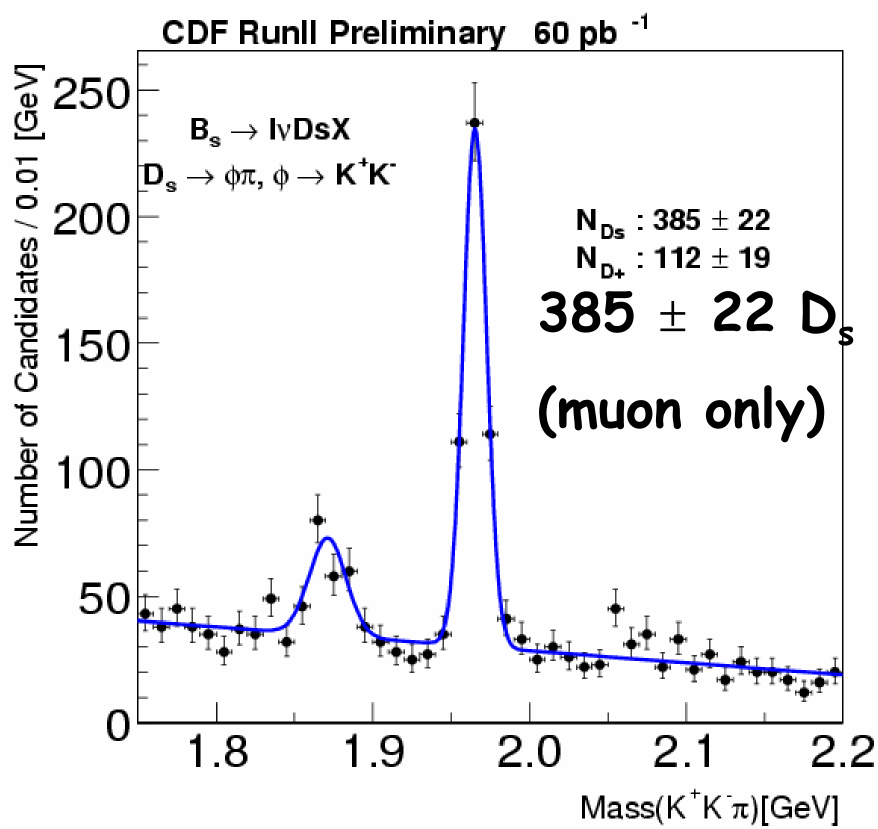
HIGH STATISTICS SAMPLE:

- **Inclusive lifetime:** ⇨ $\frac{\tau(B_s)}{\tau(B_d)}$
- **Mixing (moderate x_s):**

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

Systematics of trigger bias





Lifetime: stat. ~ 0.07 ps (PDG:0.057 ps)
Future: B_s mixing (low Δm_s case)

L_b from lepton+displaced track

Yield/Lumi = 4 x Run I, S/N ~ 2 x Run I

L_b ® $L_c$ln ® [pKp]ln

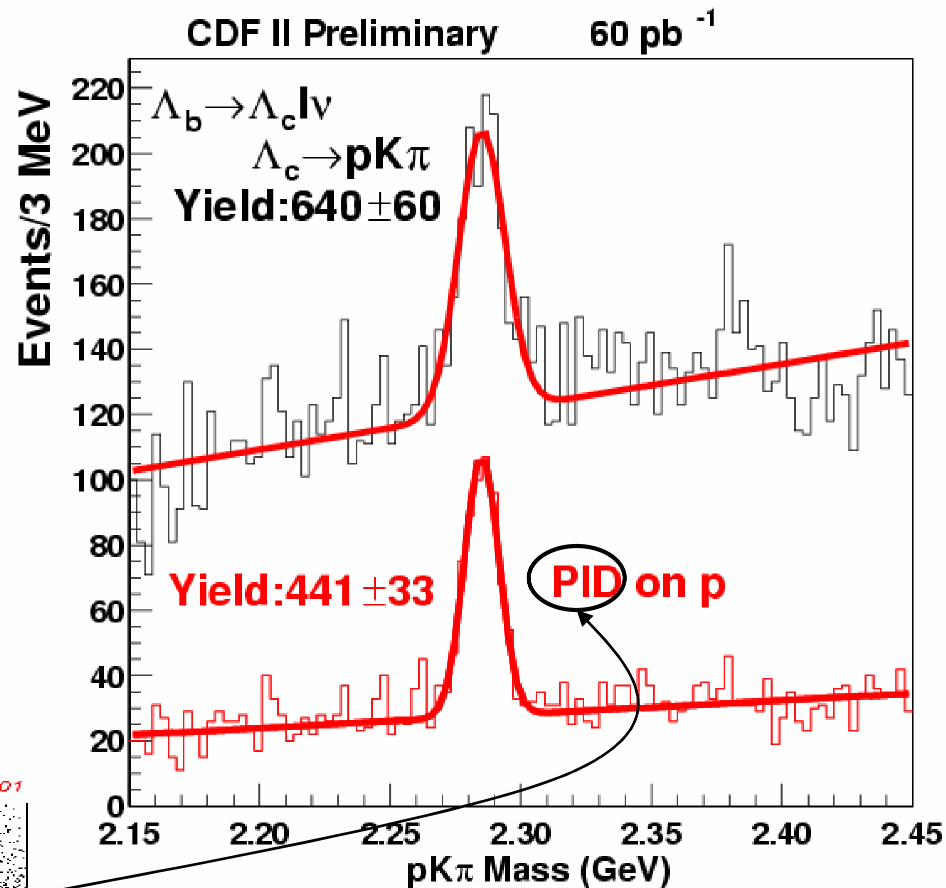
- Branching Ratio
- Measure $\rightarrow \frac{1}{G}\frac{dG}{dQ^2}$

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

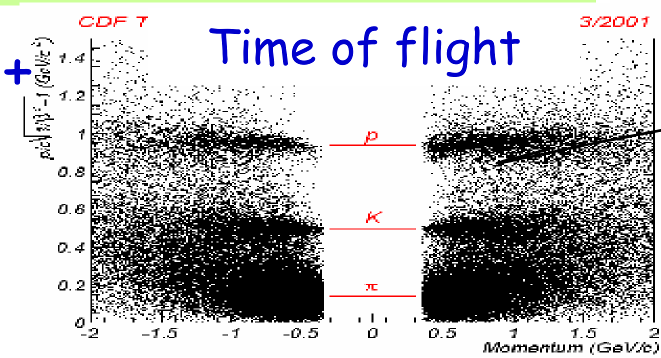
important for theory

Experimental challenge:

disentangle from decays through excited baryons



dE/dx + Time of flight



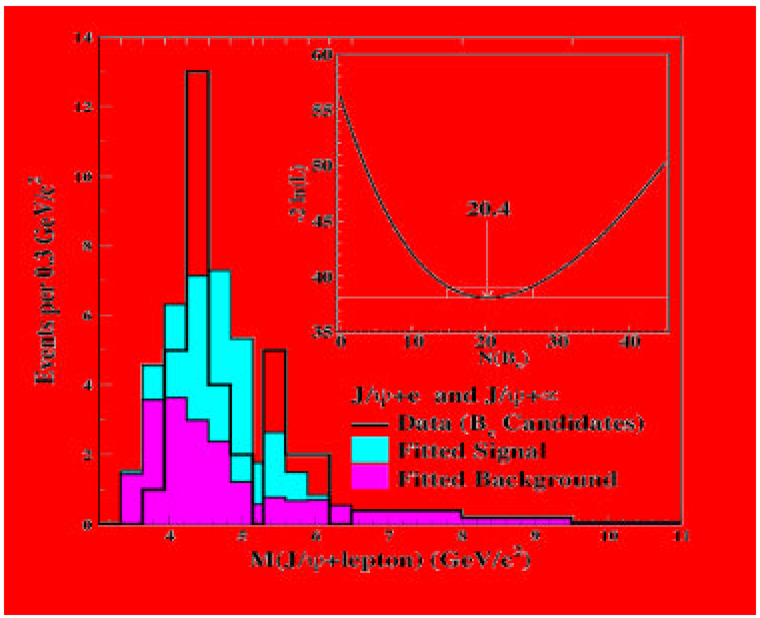
Lifetime: stat. ~ 0.12 ps (PDG:0.08)
Future: semileptonic form factor

B_c and Λ_b

Run I: ~20 events $B_c \to J/\psi\ e/\mu\ \nu$

$M(B_c) = 6.40 \pm 0.39 \pm 0.13$ GeV/c^2

$\tau(B_c) = 0.46\ ^{+0.18}_{-0.16} \pm 0.03$ ps



Run II: better Mass, Lifetime, BR

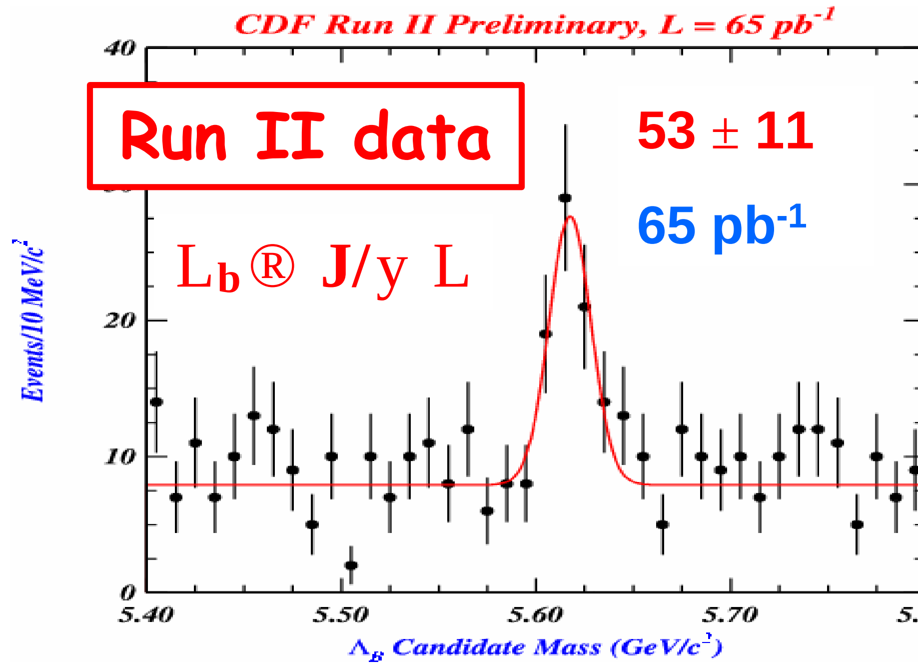
Also exclusive channels: $B_c \to J/\psi\ \pi$

and fully hadronic: $B_c \to B_s\ \pi$

Run I: $\Lambda_b \to \Lambda^+_c\, l^-\, \nu$

$\Lambda_b \to J/\psi\ \Lambda\ (\Lambda \to p\pi)$

$\tau(\Lambda_b) = 1.32 \pm 0.15 \pm 0.07$ ps



Also hadronic modes:

$\Lambda_b \to \Lambda_c\ \pi\ \ (\Lambda_c \to pK\pi)$

$\Lambda_b \to pD^0\pi^-\ (D^0 \to K\pi)$

$\Lambda_b \to pK\ /\ p\pi$

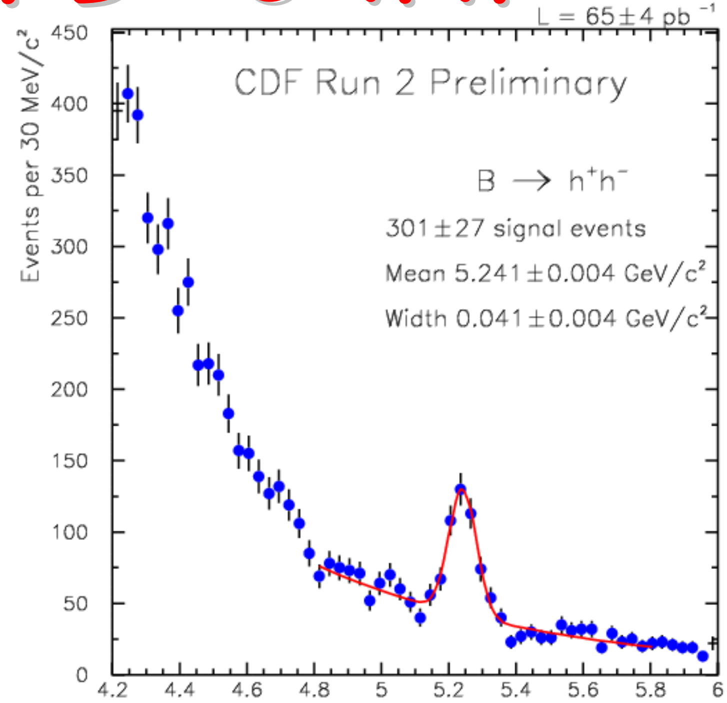
Physics with B^0 ® h^+h^-

300 events in 65 pb^{-1}: **first charmless B's at hadronic collider**

B^0 ® h^+h^- is a mixture (1:4:2:0.5) of

B_d®pp; B_d®Kp; B_s®Kp; B_s®KK;

tree, BR~5×10^{-6} penguin, BR~1.5×10^{-5}

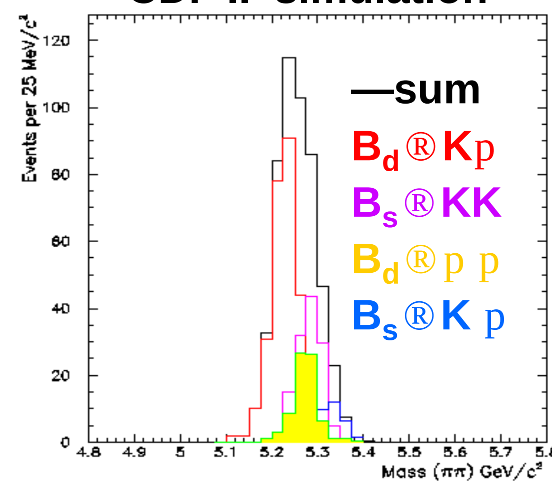


(pp inv.mass)

Strategy for disentangling channels:

- Invariant mass shape (s_M ~25 MeV/c^2)
- Kinematical variables
- Particle Identification
- COT dE/dx
- Oscillation of CP asymmetry

CDF II simulation



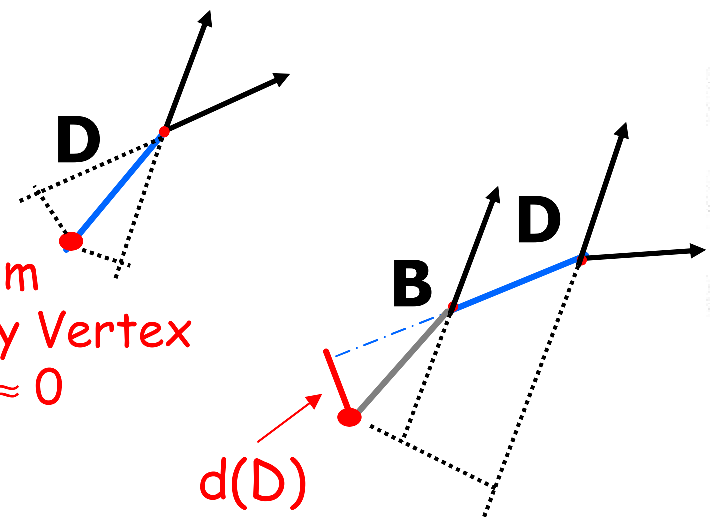
Can soon perform interesting measurements:

- 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)

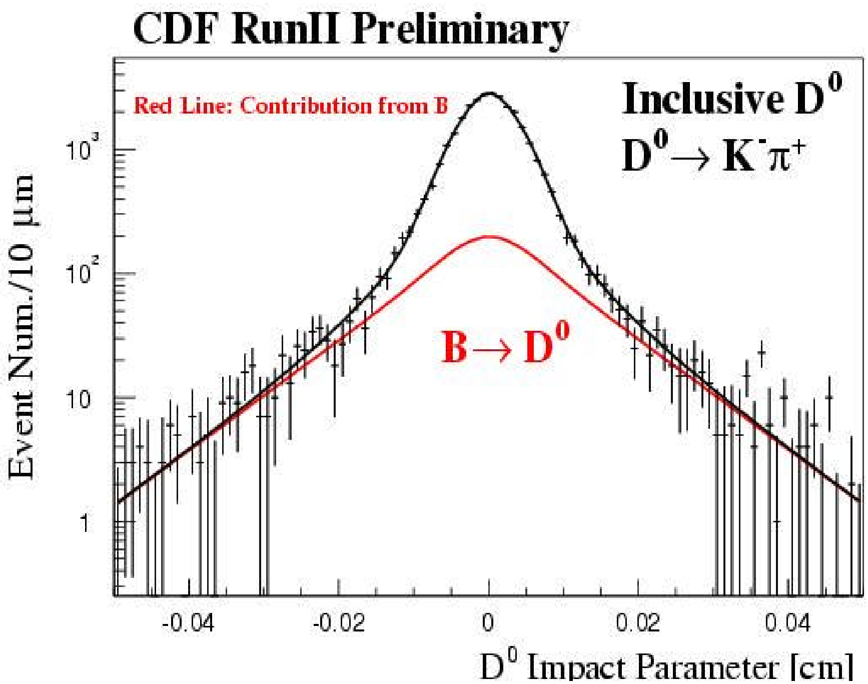
Later on: CKM angle g

Physics with the hadronic trigger

open access to fully hadronic D and B signals



D-mesons Impact Parameter (d) used to discriminate the two components



D mesons I.P. (d) distribution

Reconstructed large (0.5M) D mesons:
$D^\pm \to K\pi\pi$, $D^0 \to K\pi$, $D^* \to \pi D^0$, $D_s \to \varphi\pi$
$D^0 \to KK$, $D^0 \to \pi\pi$

Measured prompt D vs. D from B

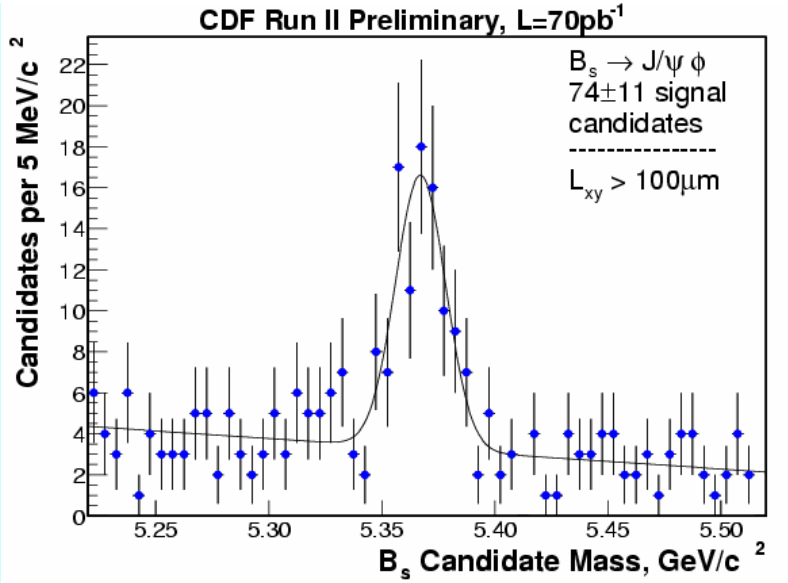
	B fraction
$D^0 \to K\pi$	16.4 ± 0.7 %
$D^* \to \pi D^0$	11.4 ± 1.4 %
$D^\pm \to K\pi\pi$	11.3 ± 0.5 %
$D_s \to \varphi\pi$	34.8 ± 2.8 %

Physics with B^0_s ® J/y f

largest fully reconstructed sample in the world: **74±11 events**

Yield/Lumi = 2 x RunI

Expected in 2 fb^{-1}: ~ 4000 events



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

Expected to be very small in SM:

f_s » 2° ⇒ sin($2b_s$) » O(1^2) » 0.03

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

CDF II reach : s(sin($2\,b_s$)) » 0.1 with 2 fb^{-1} (»0.03÷0.06 with 10 fb^{-1})

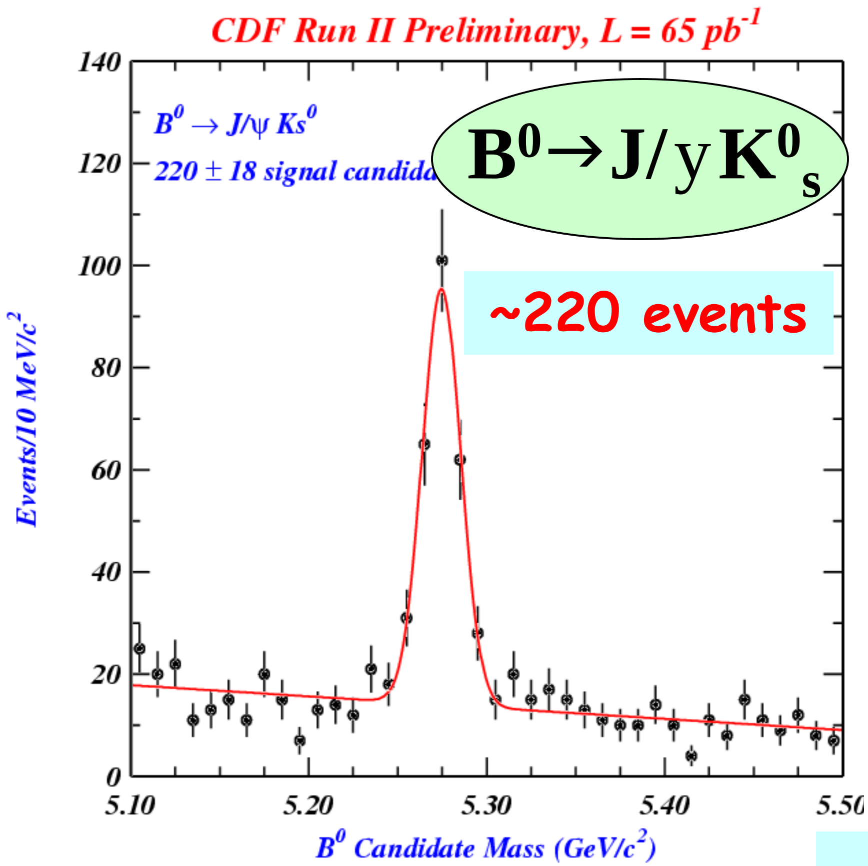
If asymmetry observed with 2fb^{-1} ® signal for NEW Physics

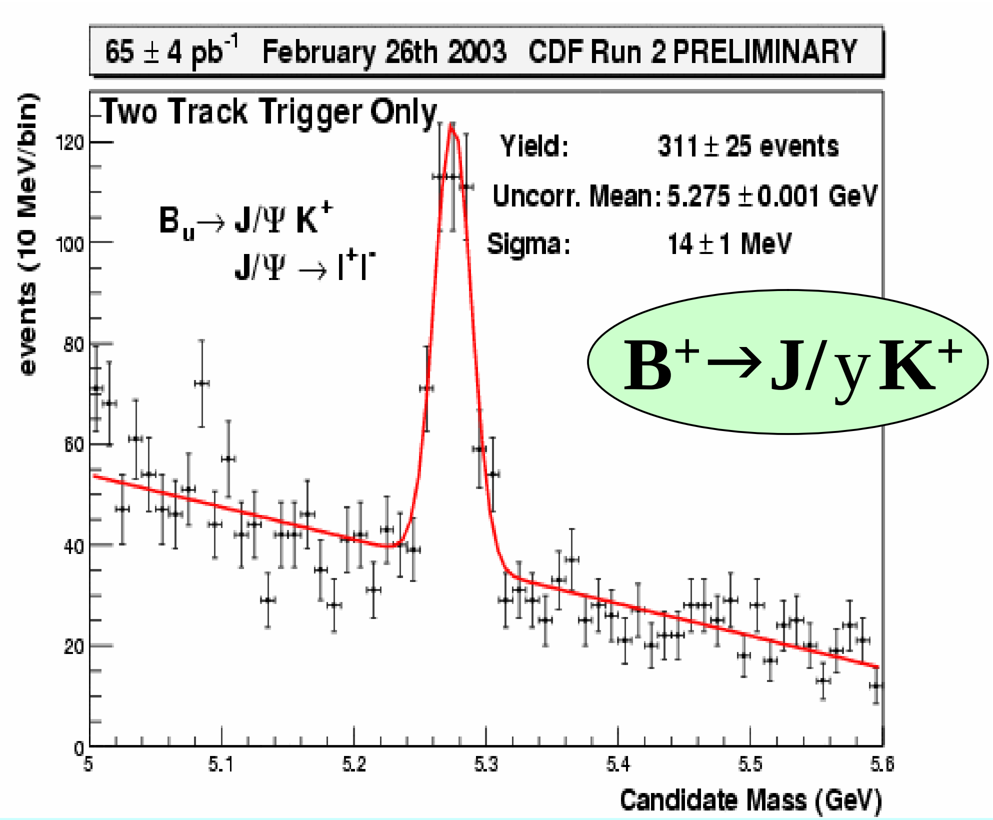
➢We also want to measure the lifetime difference between two B_s mass eigen states: $DG_s = \mathbf{B_s^H - B_s^L}$

Current limit (LEP): $DG_s/G_s < \mathbf{0.31}$ (S.M.: $DG/G = \mathbf{0.05 \div 0.20}$)

Expected uncertainty: s (DG_s / G_s) = **0.05**

More B→J/y signals





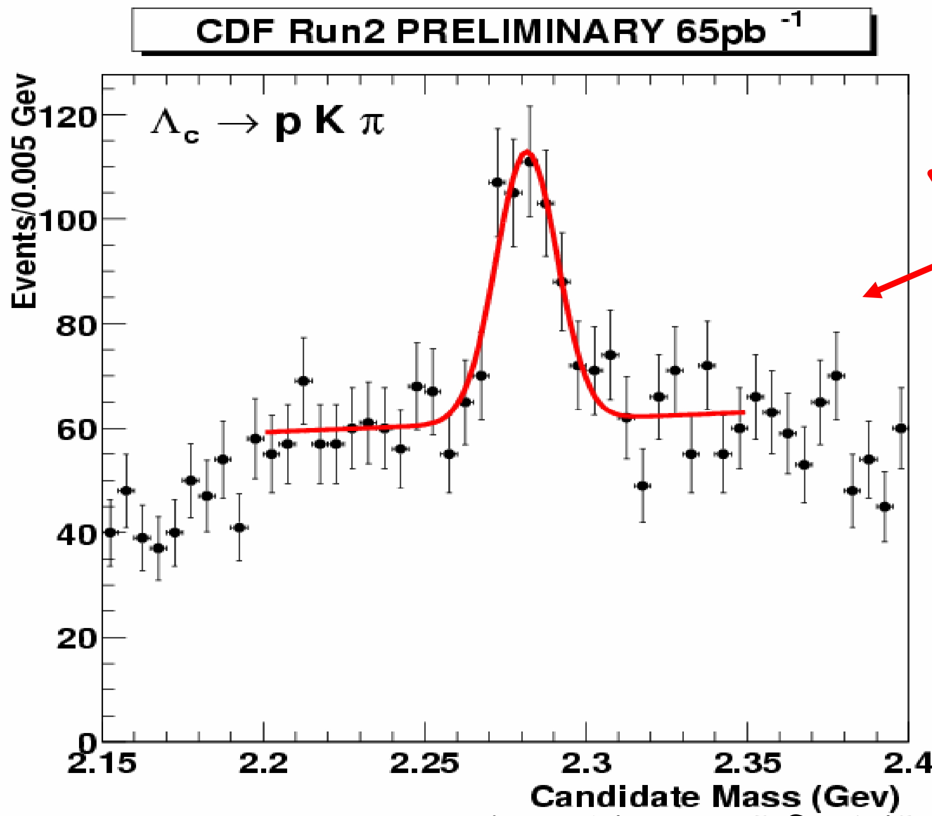
First steps towards sin(2b) measurement

- Two track trigger data (65 pb^{-1})
- Reconstruct hadronic B decays
  - $B^+ \to J/\psi K^+ (J/\psi \to l^+ l^-)$: 311±25 normalization mode

Hadronic L_b ® L_c p signal

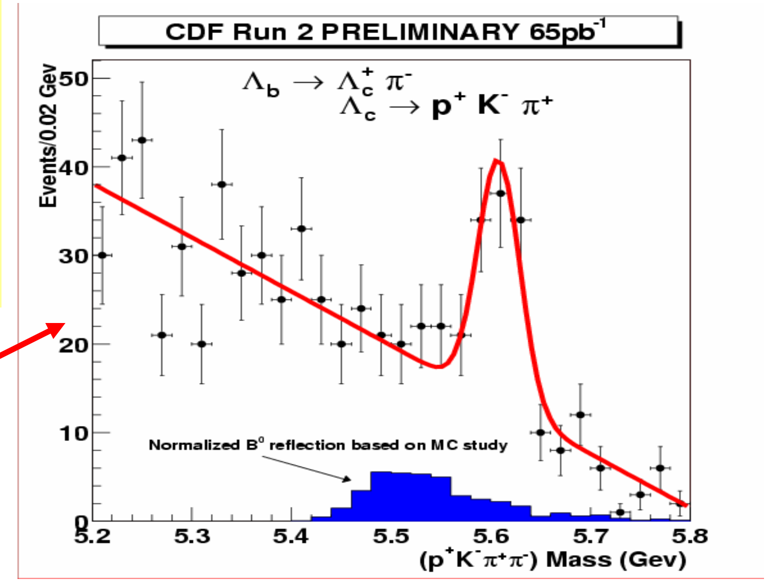
L_b ® $L_c p$ ® [pKp]p

40 events in 65 pb^{-1}, largest fully reconstructed hadronic channel



pKπ Mass [GeV]

NO PID YET

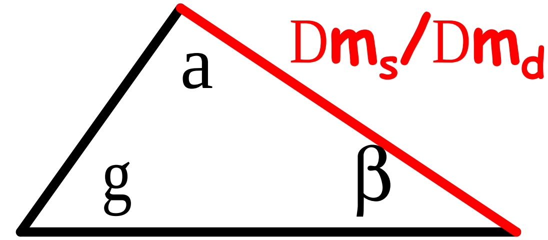


pKππ Mass [GeV]

- **Measure mass, lifetime, polarization, $\tau(L_b)/\tau(B^0)$**
- **More channels to be added**
  - $\Lambda_b \to \Lambda_c\pi\pi\pi$, $pD^0\pi$
  - $\Lambda_c \to \Lambda\pi\pi\pi$

Ingredients for B^0_s mixing

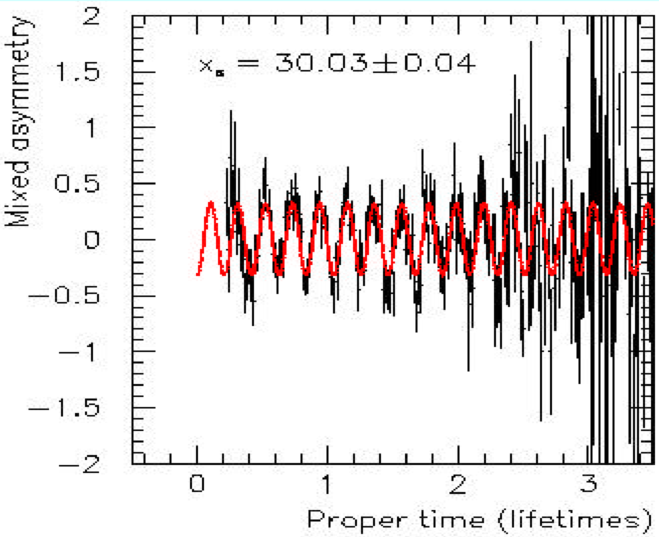
$$A_{mix}(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = D \times \cos(Dm_s t)$$



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:**

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



<u>Current limit</u>:
$\Delta m_s \geq 14.4\ ps^{-1}$

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

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

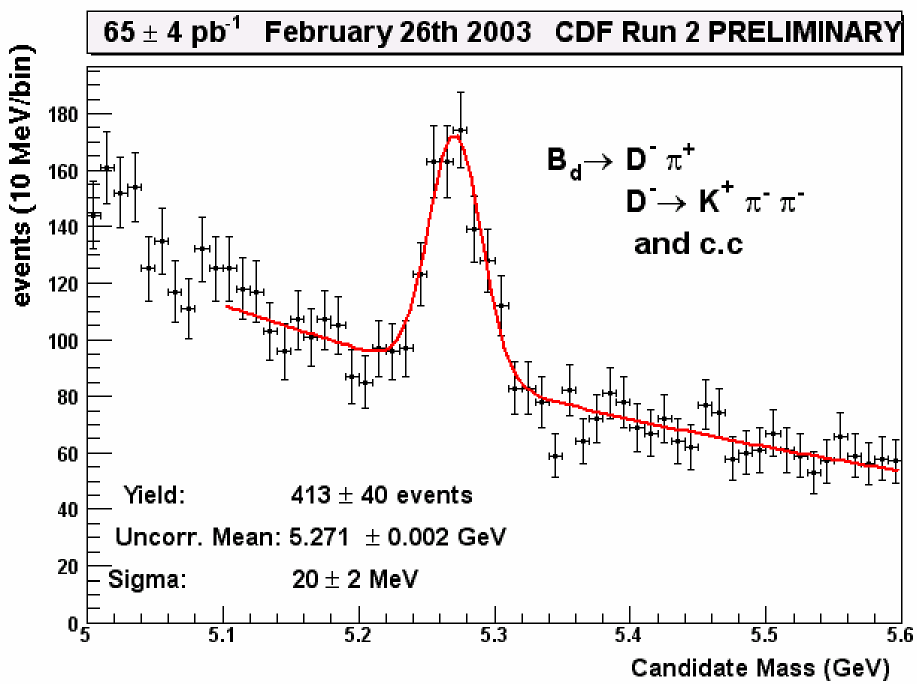
3. **Identify the flavor of B_s at production:** **B-flavor tagging algorithms**

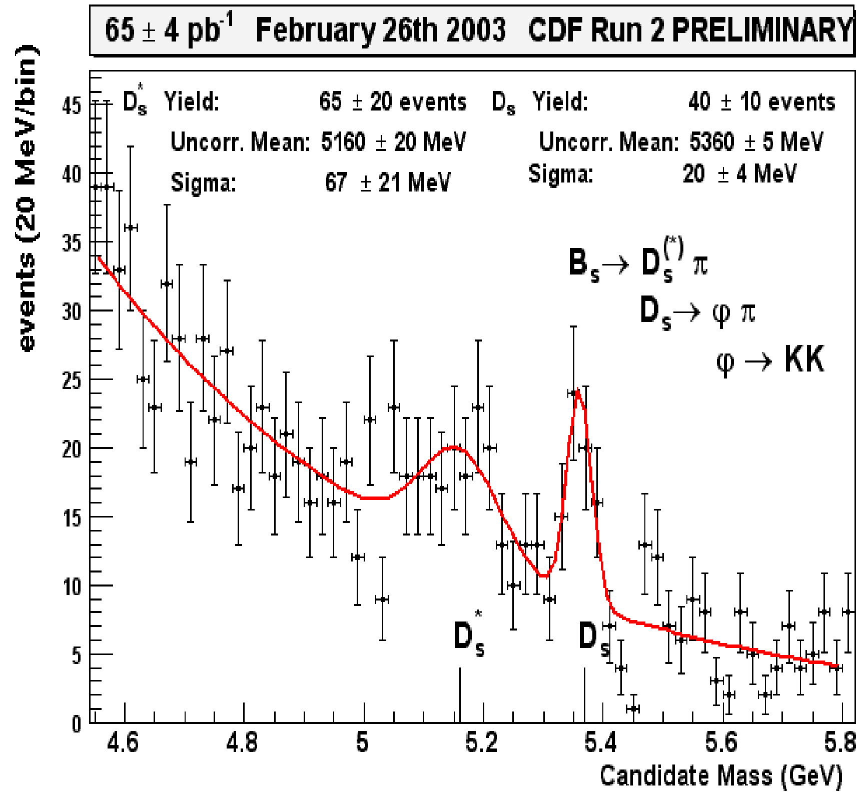
First steps towards B^0_s mixing

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

Fully reconstructed

Collect more data
and understand tagging

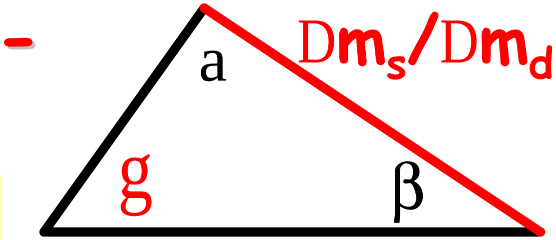




B_s is consistent with
$B_d \to D^- p^+$ control sample

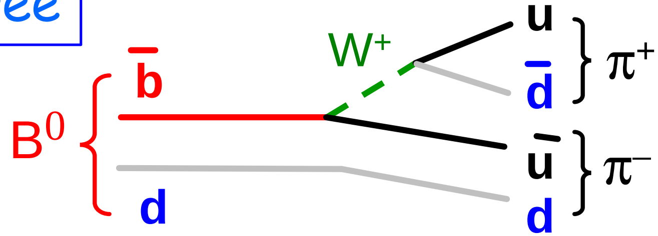
More channels to be added
$B_s \to D_s$ppp, $D_s \to K^*K$, K^0_sK, ppp

Angle g from B^0 ® h^+h^-

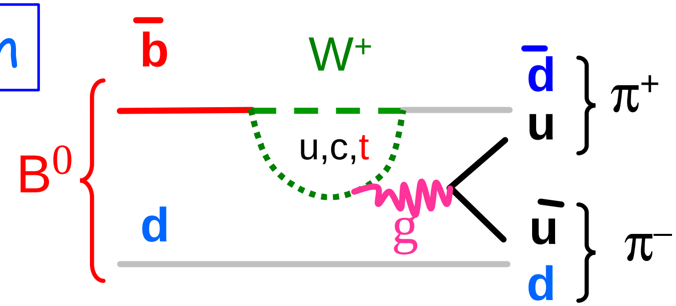


B^0 ® p^+p^- has two (comparable) decay amplitudes:

Tree



Penguin



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

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

$B^0 \to \pi^+\pi^-$

$B_s \to K^+K^-$

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

R. Fleischer (PLB 459 (1999) 306): Assume U-spin symmetry ($d \leftrightarrow s$)

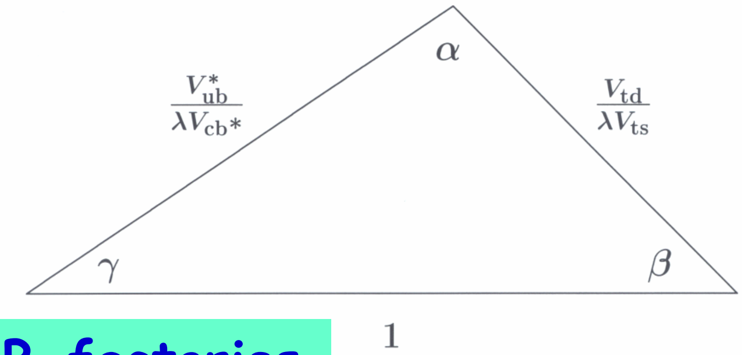
Similar relation holds for $B_s \to K^+K^-$ (Δm_d replaced by Δm_s)

The 4 asymmetries: function of γ, β and P/T amplitude ratio

Parameters: from fit of meas. of $A_{CP}(t)$ for $B_d \to \pi\pi$ and $B_s \to KK$

Expected (2fb^{-1}) accuracy: $\sigma(g) = \pm 10°$(stat) $\pm 3°$(syst)   (SU(3) breaking effects)

B physics prospects (with 2fb-1)



Both competitive and complementary to B-factories

The B physics potential is great and we expect:

- B_s mixing: B_s®D_sp(D_s3p) (x_s up to 60, with x_d meas. one side of U.T.), direct and mixing asymmetries in two body decays
- Angle b: B^0®J/yK$_s$ (refine Run I measurement up to s(sin2b) » 0.05)
- CP violation, angle g: B^0®pp(pK), B_s®KK(Kp), g at ~10° possible
- Angle b$_s$ and DG$_s$/G$_s$: B_s®J/y f (probe for New Physics)
- Precise Lifetimes, Masses, BR for all B-hadrons: B_s, B_c, L$_b$ …
  (CDF observed: B_c®J/y e(m)n.
  Now hadronic channels B_c®B_sX can be explored)
- HF cross sections (beauty and charm)

By the end of Run IIb (~2008): ´5 the statistics of Run IIa !

- **Stringent tests of SM … or evidence for new physics !**

Why do we care about Top?

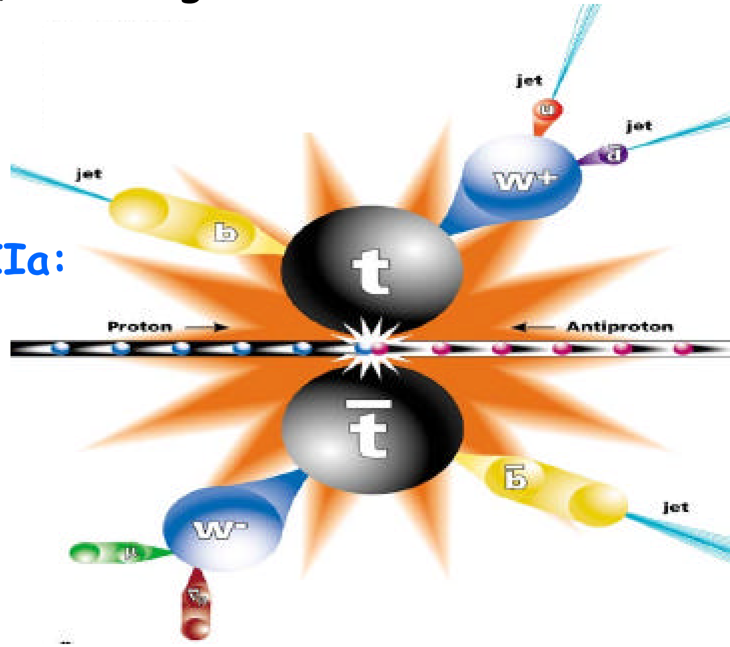
The Discovery of the top quark in 1995 was no big surprise. What was surprising is that its mass is almost 40 times that of the b quark, and tantalizingly close to the scale of EWSB.

The Fermilab Tevatron has been the only place, and will be until the LHC turns on in ~2008, to study the top quark.

Everything we know about top is based on ~100 events from the Tevatron Run I.
$s_{t\bar{t}}$ measurement: (Precision test of QCD, Probe for physics beyond SM)
Top mass:
•Fundamental parameter of Standard Model (SM)
•Affects predictions of SM via radiative corrections (BB mixing, W and Z mass, measurements of M_W, m_t constrains M_H)
•Large mass of top quark (Yukawa coupling » 1, may provide clues about electroweak symmetry breaking)

With 30 times more top events, as expected in Run IIa:

- Why is top so heavy ?
- Is it or the third generation special ?
- Is top involved with EWSB ?
- Is it connected to new physics ?



Production and Decay of Top Quark

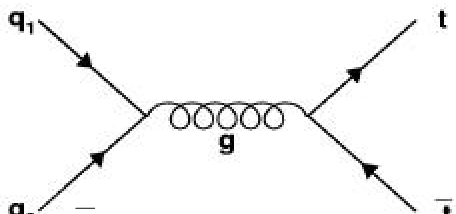
At the Tevatron, top quarks are primarily produced in pairs via strong interaction. Single production via weak interaction not yet observed

$\tau_{top} \sim 4 \times 10^{-25}$ s

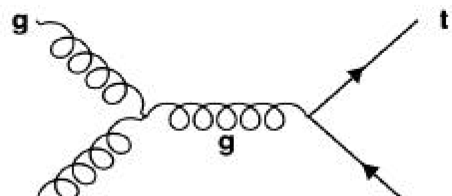
$\Lambda^{-1} \sim (100\ \mathrm{MeV})^{-1} \sim 10^{-23}$ s

Top decays as free quark!

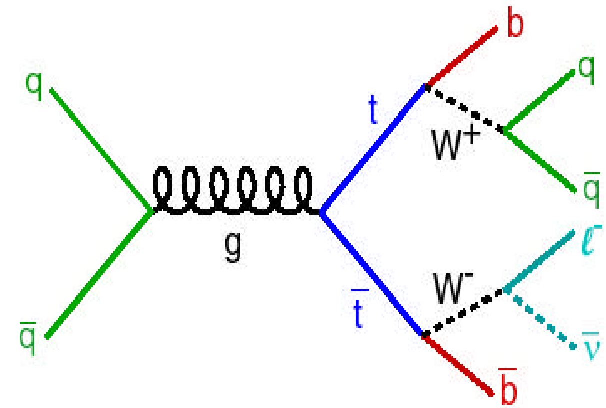
BR($t \to Wb$) @100%



$q\bar{q}$ annihilation (90%)

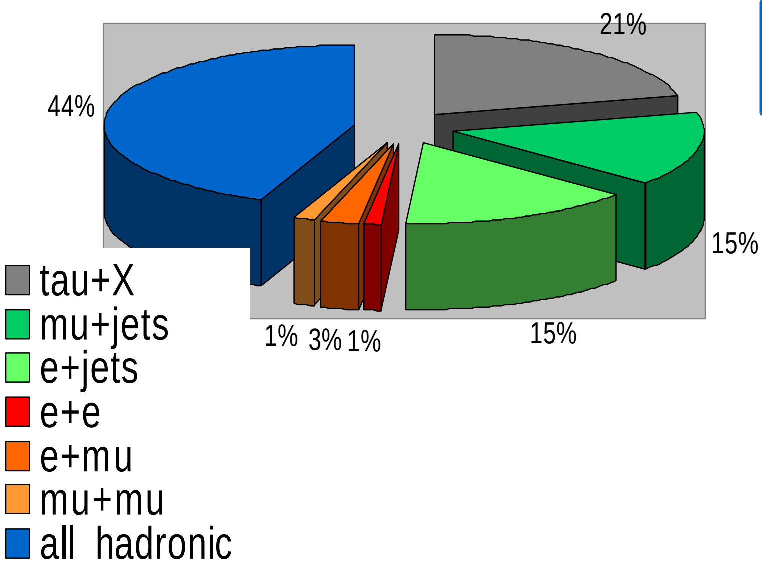


gg fusion (10%)



CDF Run I: $\int L dt \approx 109\ \mathrm{pb}^{-1}$
(~300 top candidates)

$$\sigma_{t\bar{t}}(\sqrt{s}=1.96\,\mathrm{TeV}) \approx 1.30\times\sigma_{t\bar{t}}(\sqrt{s}=1.8\,\mathrm{TeV})$$



Main "usable" top event topologies:

Dilepton: $t\bar{t} \to l\nu l\nu bb$ 2 high-P_T leptons, 2 bjets, large Missing E_T (BR 5% e+μ)

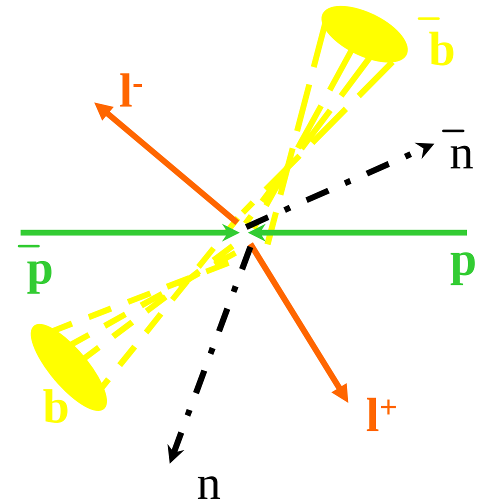
Lepton + Jets: $t\bar{t} \to l\nu qqbb$ 1 high-P_T lepton, 4 jets (2 b's), large missing E_T (BR 30% e+μ)

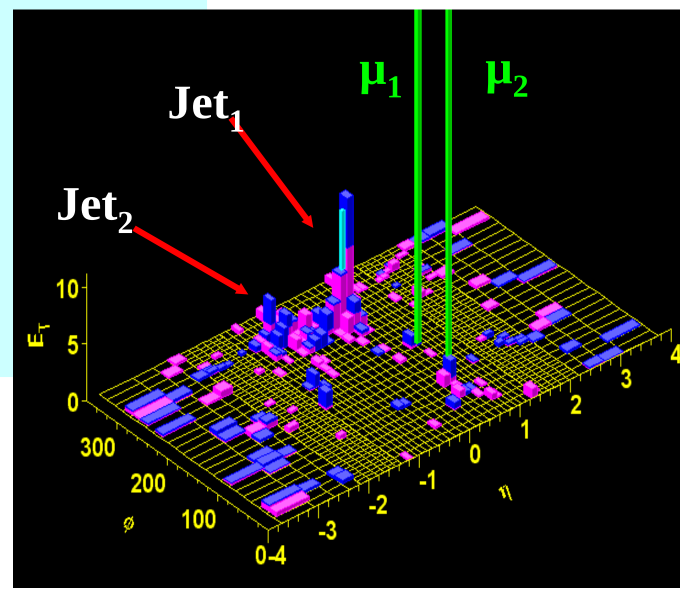
All-hadronic: $t\bar{t} \to qqqqbb$ 6 jets (BR 44%)

$s_{t\bar{t}}$: dilepton cross section

- Event selection
  - 2 High P_T (P_T>20 GeV) oppositely charged leptons (e,m).
  - Both isolated: I_{CAL}< 0.1
  - Veto Z's, cosmics, and conversions
  - Neutrinos: large missing E_T > 25 GeV
  - at least 2 jets with $\not{E}_T$ > 10 GeV
  - Total transverse energy of the event > 200 GeV
- BR~5%, detection efficiency ~ 11%
- 5 candidate events in 72 pb^{-1}

  (Run I: 9 events) $s_{t\bar{t}}$ = 8.2 ± 4 pb
- Backgrounds: Drell-Yan, Z^0->tt, WW : 0.30±0.12
- Disadvantages low yield, difficult to measure M_{top} accurately
- Advantages high S/B ~8





$$s_{t\bar{t}} = 13.2 \pm 5.9_{stat} \pm 1.5_{sys} \pm 0.8_{lum}\ \mathrm{pb}$$

NLO @ Ös=1.96 TeV for

$$M_{top} = 175\ \mathrm{GeV}: 6.70^{+0.71}_{-0.88}\ \mathrm{pb}$$

$$s\ (t\bar{t}) = \frac{N_{obs} - N_{bkg}}{A \cdot \int L}$$

$\sigma_{t\bar{t}}$: lepton + jets cross section

Event selection

- One high momentum, central, isolated lepton, P_T > 20 GeV/c, e or m.
- Veto Z's, cosmics, and conversions.
- Neutrinos: large missing E_T > 20 GeV
- 3 or more jets with E_T > 15 GeV
- At least 1 jet with secondary vertex tag

15 observed events in 57.5 pb^{-1}

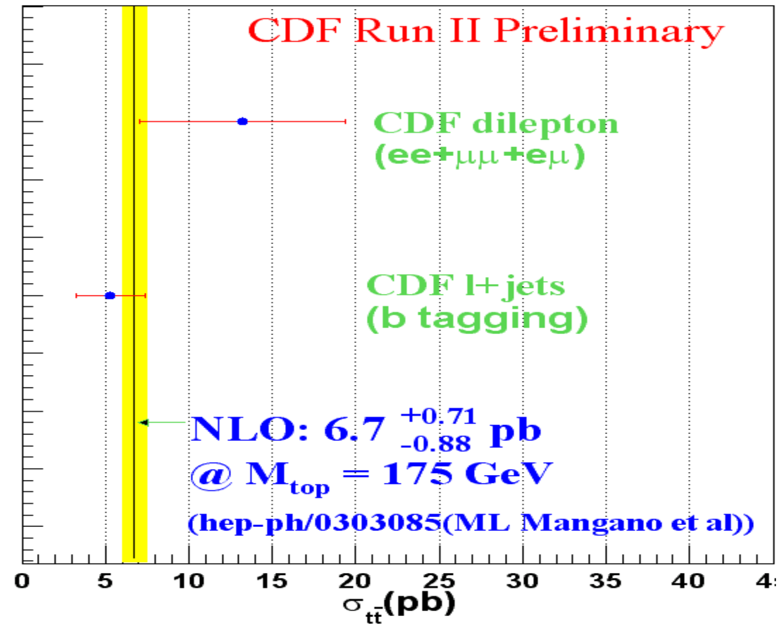
Backgrounds from Wbb, Wcc, mistags, Wc, non-W (fake lepton): 3.8 ± 0.5

✓ Lower S/B»1:6 for W+³ 3 jets

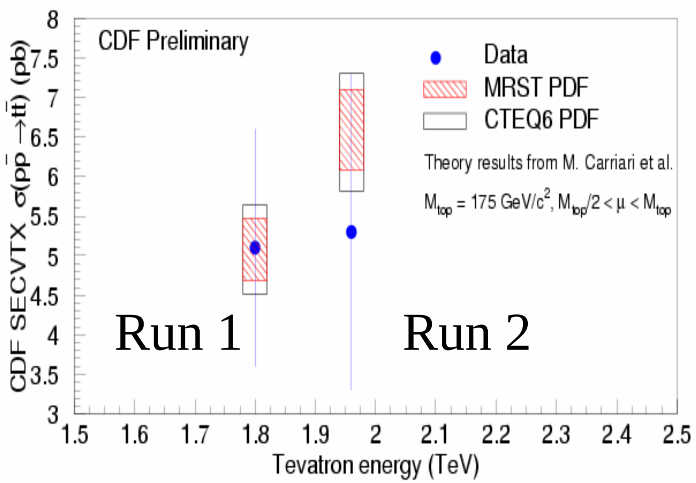
✓ b-tagging improves S/B»3:

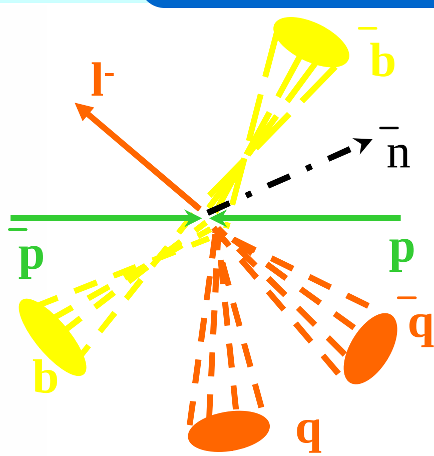
✓ Higher statistics

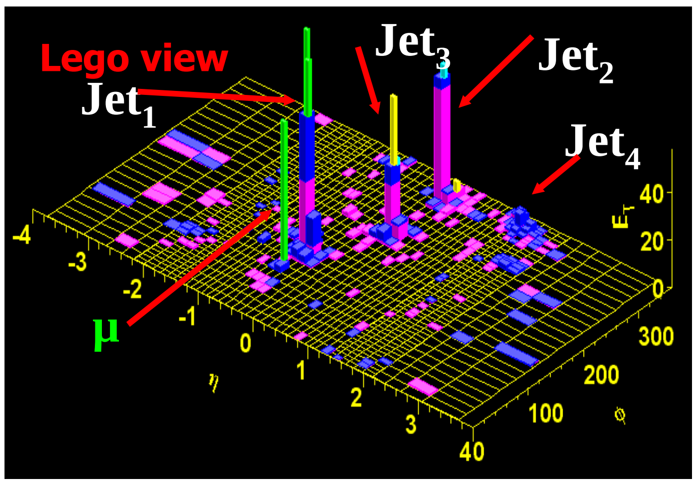
✓ Essential for M_{top} (2 b-tags jets)



$$\sigma_{t\bar{t}} = 5.3 \pm 1.9_{stat} \pm 0.8_{sys} \pm 0.3_{lum}\ \text{pb}$$







Top mass: lepton + 4 jets

METHOD

Use 2C constrained fitting technique with constraints

- $m(l\nu) = m(qq) = m_W$
  - $m(l\nu b) = m(qqb)$
  - PDG: M_W, G_W, G_t

24 combinations:

- 12 correspond to the jet-parton match
- every combination has 2 solutions for neutrino P_Z

Choose combination with lowest c².

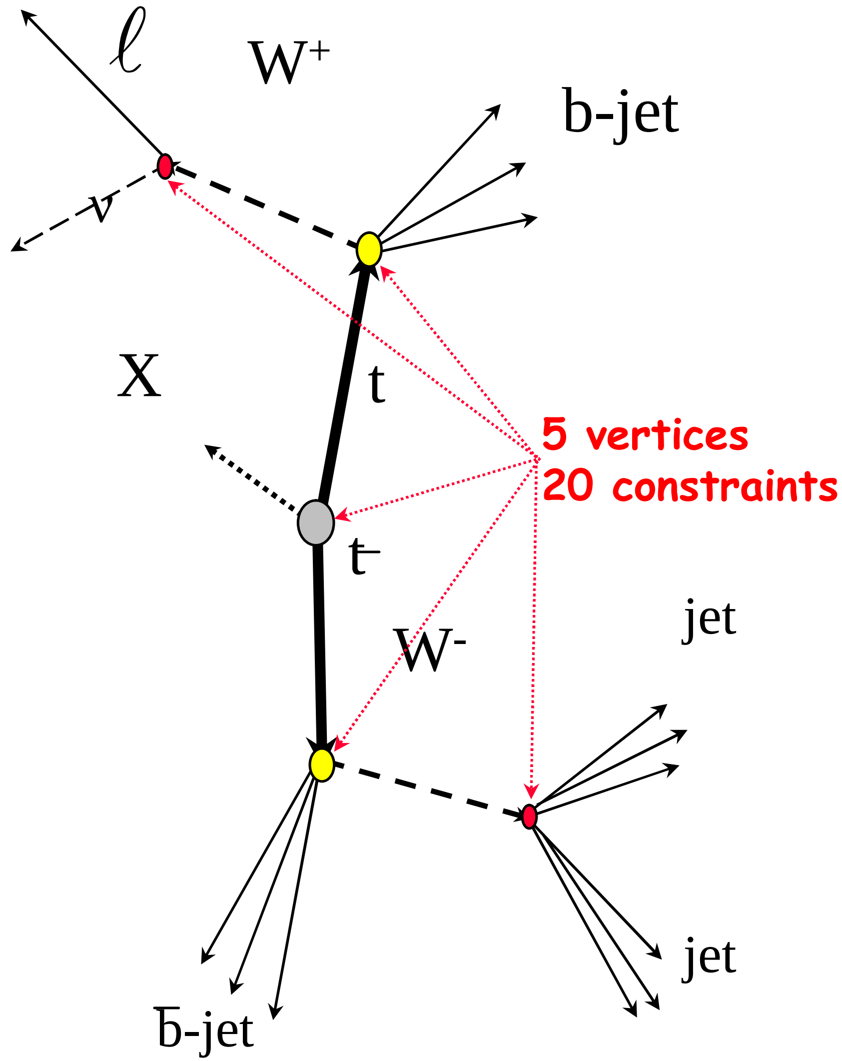
Improvements to DM_{top}:

Statistics:

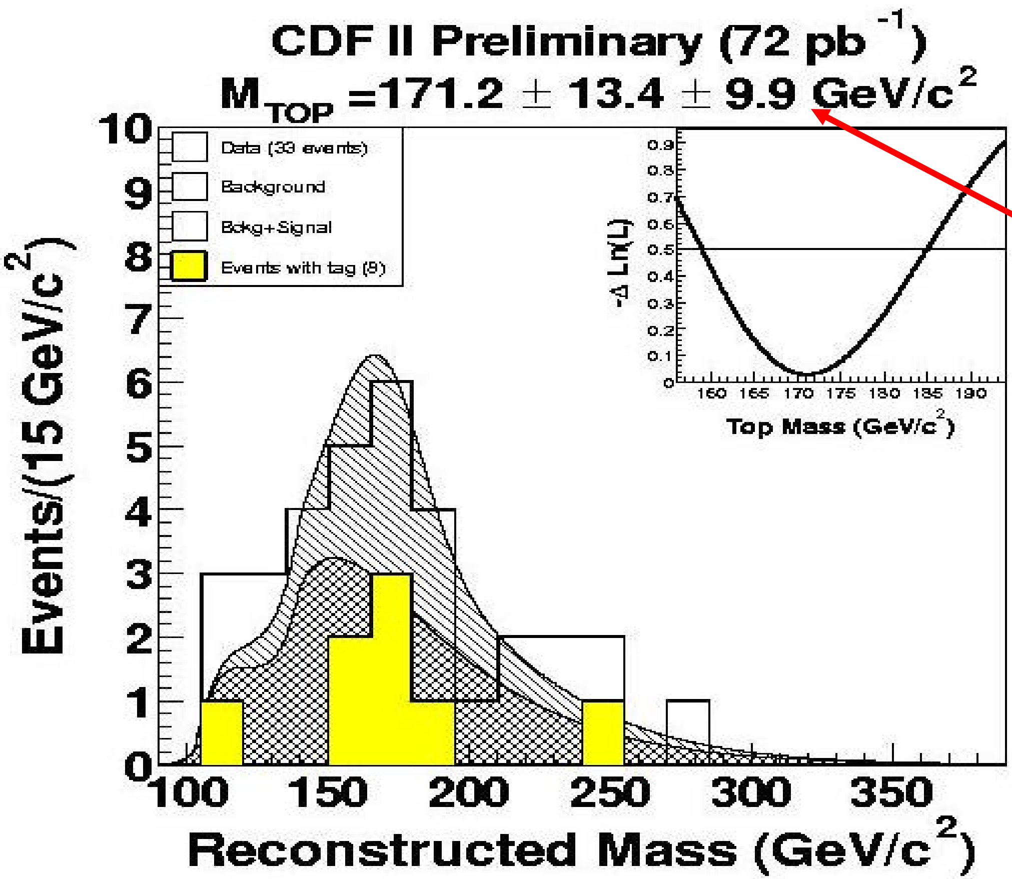
✓ Increased b-tag acceptance
events with b-tag reduce combinatorics
✓ Choose best measured events

Jet Energy Scale:

✓ Use control samples (Z®b$\bar{b}$, W®q$\bar{q}$) to reduce systematics
✓ Jet energy flow techniques



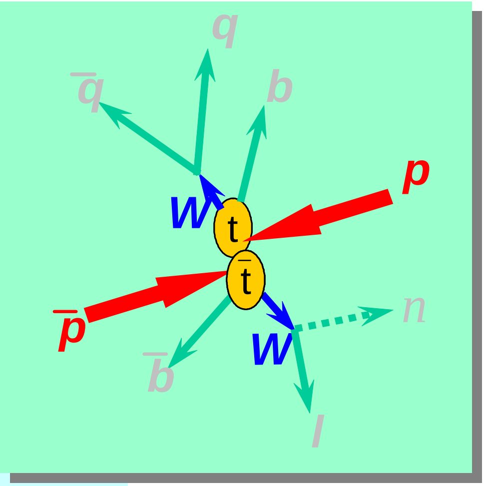
Top mass



Run I CDF+D0 combined:
m_t=174.3± 5.1 GeV/c^2

dominated by jet energy measurement

Run 2a expectations:
DM_{top} = ±2-3 GeV



Use a continuous likelihood method to extract top mass and statistical uncertainty

M_{top} is the minimum of the log-likelihood distribution

s$_{top}$ corresponds to a change of 0.5 units in the log-likelihood

Physics with large top samples

- top quark mass measurements (within 2-3 GeV/c^2)
- $t\bar{t}$ pair production cross section (within 8%)
- single top production cross section
- $t\bar{t}$ spin correlations, studies of top polarization
- rapidity of $t\bar{t}$ system
- mass of $t\bar{t}$ system
- soft gluon radiation in $t\bar{t}$ events
- W helicity in top decays
- single top production ⇨ $|V_{tb}|$
- any anomalies in the above studies
- rare decays…
- NEW PHYSICS ?

~800 b-tagged $t\bar{t}$ lepton+jets events in 2pb^{-1}

With larger samples (later this year) we will be able to extend our Run I searches for extensions to the SM

Summary

Run II CDF collected ~100 pb^{-1} 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. Some of the systematic uncertainties are still conservative. Will be reduced in future Impact parameter trigger: huge/clean semileptonic/all hadronic B signals
- The SVT ⇨ great success:
  - unique @ hadron collider
  - CDF as Charm/B factory
- Forward detectors ⇨ diffractive physics
- ***Great heavy flavor physics potential***, we have results on:

  – Masses, lifetimes, production cross sections competitive with Run I
- We are preparing for high luminosity:

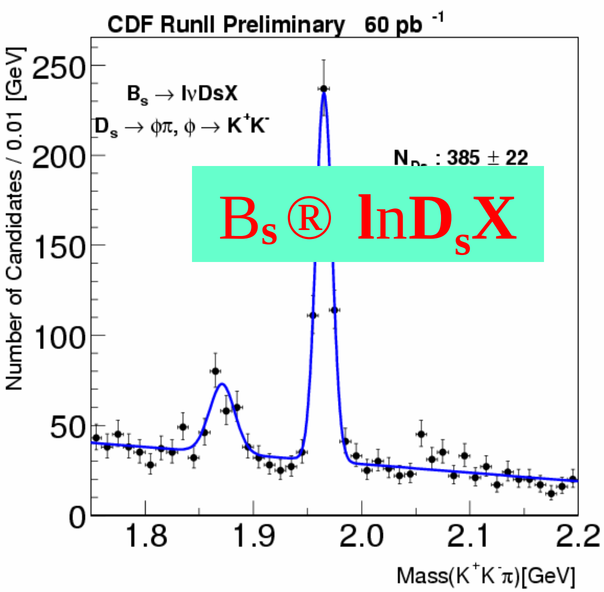
  – Promising perspectives for flagship analyses: studies of B_s, B_c, CP violation, B_s mixing, $\Delta\Gamma_s$, Λ_b, charmless B-decays and other topics unique to Tevatron are in progress.

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

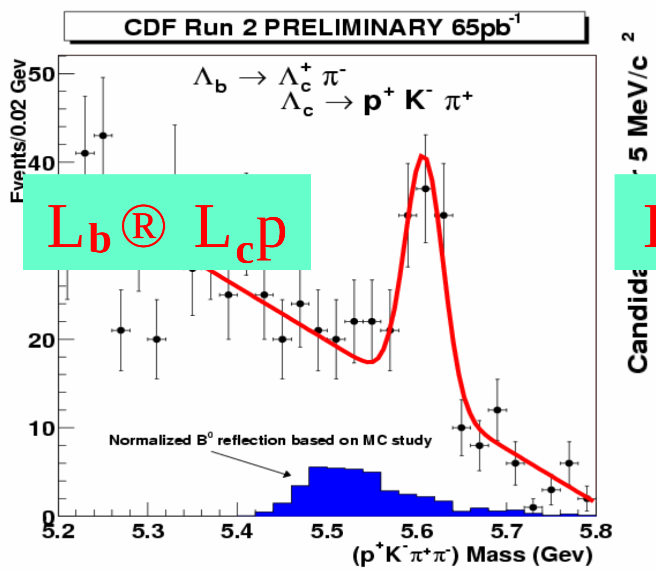
Heavy flavor results from CDF Run II: B physics

- Run II CDF collected ~100 pb^{-1} of data for heavy flavor physics
- Masses, lifetimes, production cross sections competitive with Run I
- studies of B_s, B_c, CP violation, B_s mixing, $\Delta\Gamma_s$, Λ_b etc are in progress

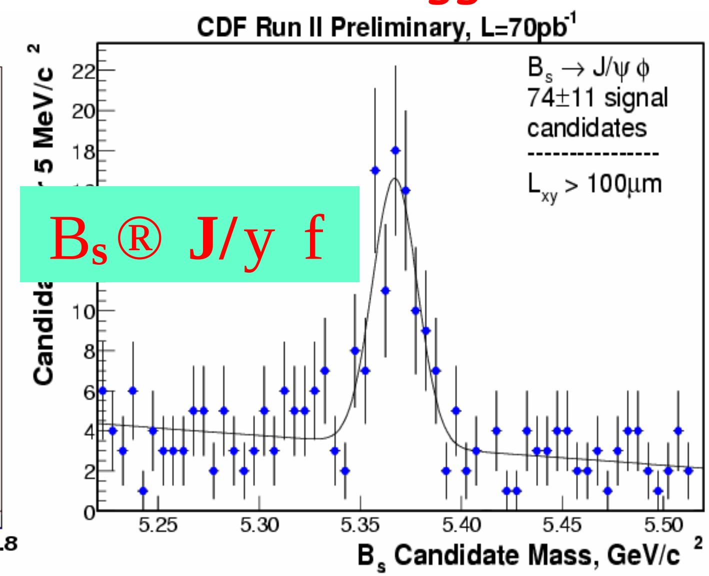
Lepton + displaced track



Two track trigger



Dimuon trigger



Mass

	CDF2 (MeV/c²)	S_{CDF}/S_{PDG}
B_u	5280.6 ±1.7 ±1.1	4.0
B_d	5279.8 ±1.9 ±1.4	4.8
B_s	5360.3 ±3.8 ±	1.9

Lifetime

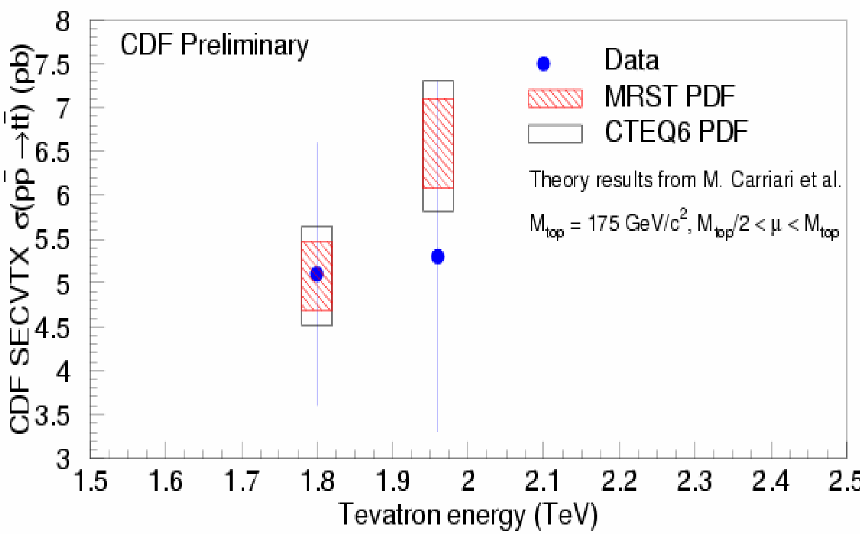
B^+	1.57 ± 0.07 ± 0.02 (ps)
B_d	1.42 ± 0.09 ± 0.02 (ps)
B_s	1.26 ± 0.2 ± 0.02 (ps)

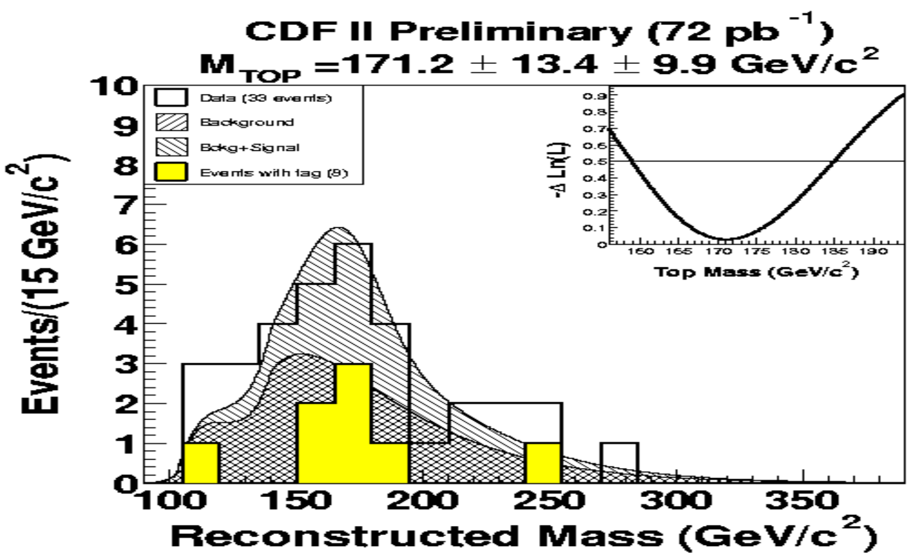
Heavy flavor results from CDF Run II: top quark

- We have reestablished the presence of the top quark in Run II
- Cross sections in **dilepton** and **lepton plus jets** channels are in agreement with the SM expectations
- The $t\bar{t}$ events show mass compatible with the run I measurement
- **The Fermilab Tevatron has been the only place, and will be until the LHC turns on in ~2008, to study the top quark**

Dileptons $\sigma_{t\bar{t}} = 13.2 \pm 5.9_{stat} \pm 1.5_{sys} \pm 0.8_{lum}$ pb

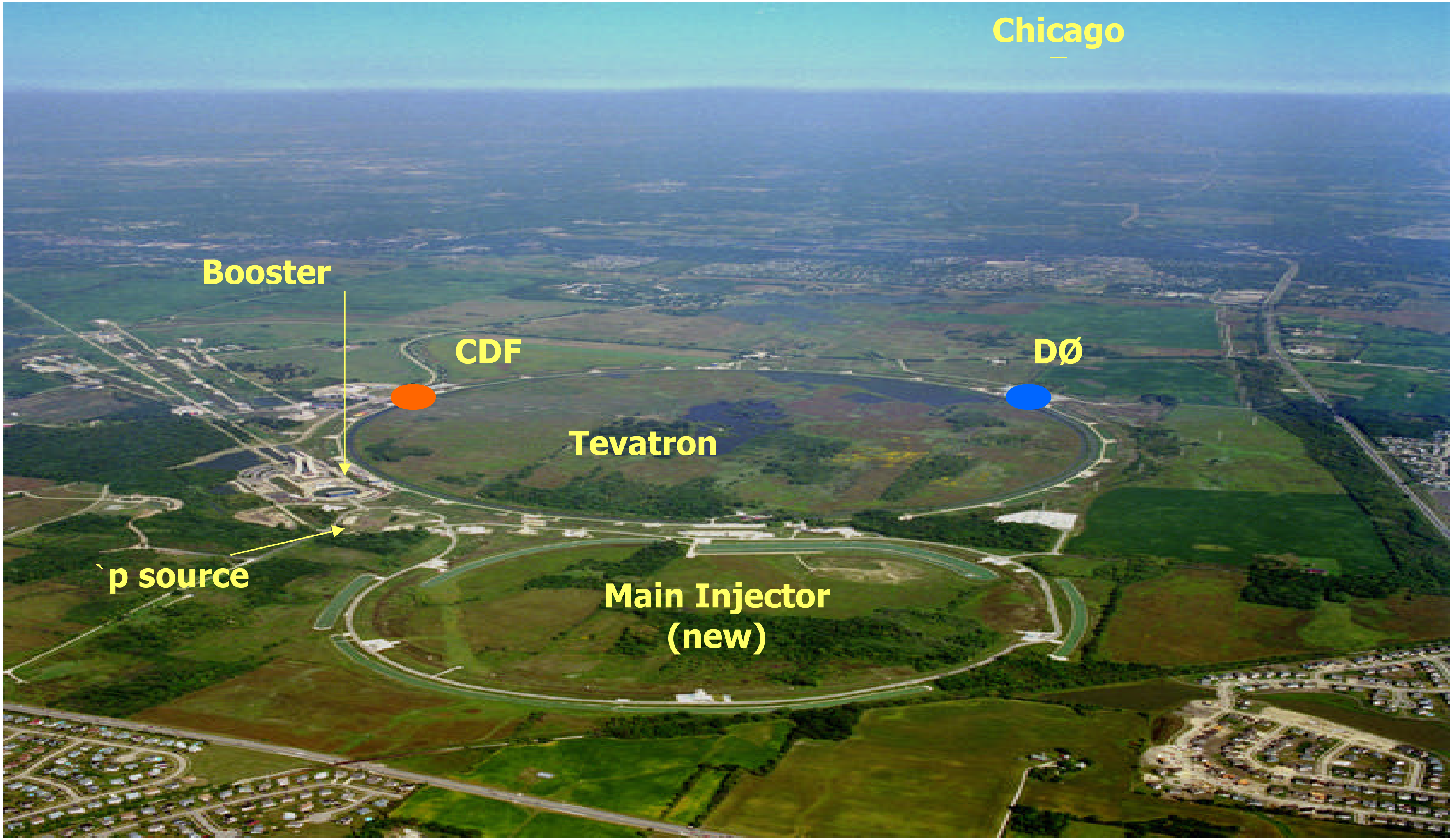
Lepton plus jets $\sigma_{t\bar{t}} = 5.3 \pm 1.9_{stat} \pm 0.8_{sys} \pm 0.3_{lum}$ pb





Backup Slides

Our machinery at Fermilab



Run II: proton-antiproton collisions at $\sqrt{s}$=1.96 TeV

Tevatron $p^{+}p^{-}$ 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} $cm^{-2}s^{-1}$

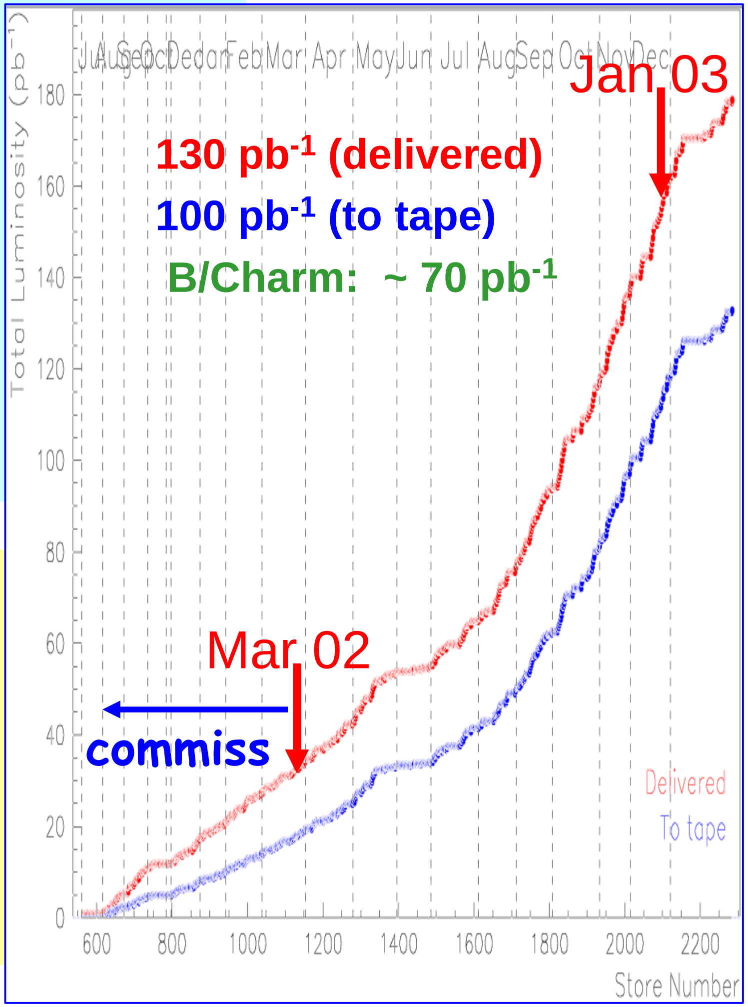
4 to 7 pb^{-1}/week delivered

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

16 pb^{-1}/week delivered

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

CDF Integrated Luminosity

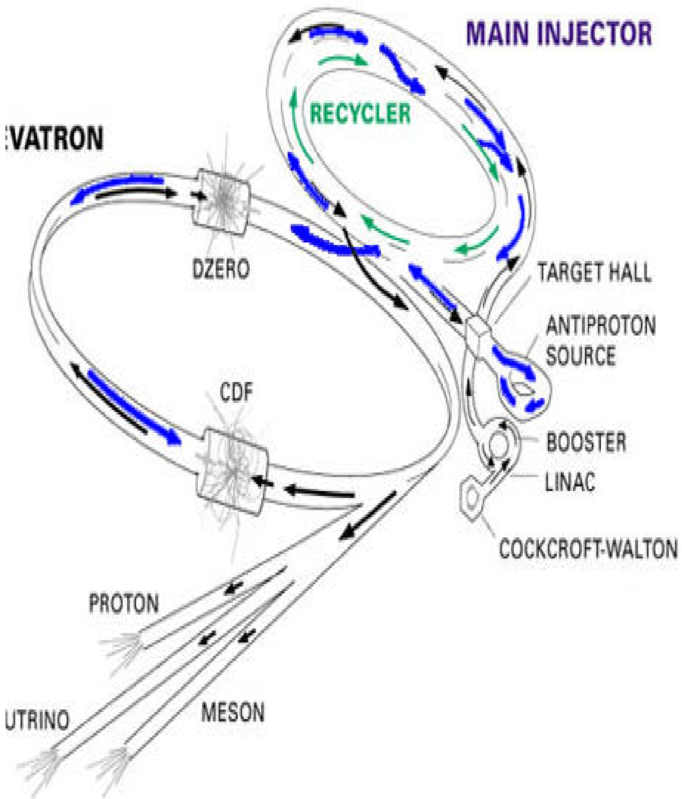


What is New at the Tevatron

- ✓ Main Injector: new injection stage, more efficient anti-p transfer to Tevatron ring
- ✓ Recycler: new storage ring for reuse anti-p (still commissioning, ready 2004)
- ✓ Higher collision rate: 396ns crossing time (36x36 bunches) (→ 132ns, 108x108)

major upgrades in detector, electronics and trigger !!!

- ✓ Slightly higher C.M. energy: 1.8 → 1.96 TeV
- ✓ Higher Inst. Luminosity: 5-10 times higher than in Run 1



Run plans: Run 2a: $L = 5\text{-}8 \times 10^{31} cm^{-2}\, s^{-1}$

($L = 10\text{-}20 \times 10^{31} cm^{-2}\, s^{-1}$, with Recycler)

Total integrated L = $2 fb^{-1}$

2005

Run 2b: Total integrated L = 6 - $10 fb^{-1}$

...2008

Tevatron status and goals

$$L = \frac{10^{-6} f_0 B N_p N_{pb} (6 b_r g_r)}{2pb^* (e_p + e_{pb})} H(s_l / b^*) (10^{31} cm^{-2} s^{-1})$$

Accelerator parameters:

	Now best	Run 2a goals	units
Protons/bunch	**211**	**270**	10^9
Pbar / bunch	**26**	**30**	10^9
Peak Pbar prod.	**130**	**200**	10^9/ hr
Pbar: AA → low β	**0.60**	**0.80**	
P emittance	**20**	**20**	π mm·mrad
Pbar emittance	**18**	**15**	π mm·mrad
P bunch lenght	**0.61**	**0.37**	m
Pbar bunch lenght	**0.54**	**0.37**	m
Max. Lum.	**3.8**	**8.0**	10^{31}
Integrated Lum.	**6.7**	**16**	pb^{-1}/ wk

Integrated Luminosity (fb^{-1})

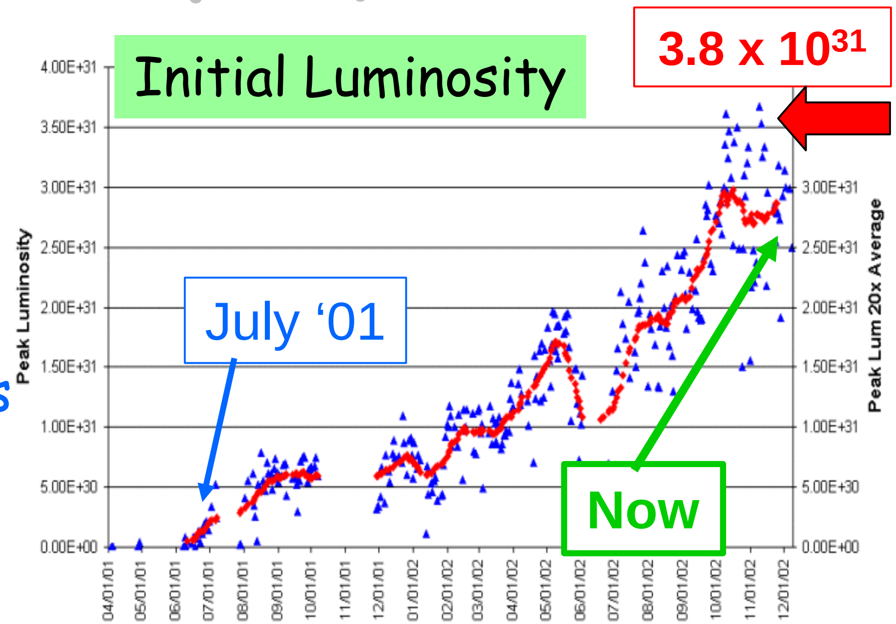
FY	Base	Stretched
2002	**0.08**	**0.08**
2003	**0.20**	**0.32**
2004	**0.40**	**0.60**
2005	**1.00**	**1.50**
2006	**1.50**	**2.50**
2007	**1.50**	**3.00**
2008	**1.80**	**3.00**
Total	**6.50**	**11.0**

Tevatron Performance

Tevatron operations

- Startup slow, but progress steady !
- **Now**: $L \sim 3.5 \times 10^{31}\ cm^{-2}s^{-1}$
  integrating ~ 6. pb^{-1}/week
- … still factor 2-3 below planned values

additional improvements (~10-20%) expected from Jan. 3weeks shutdown

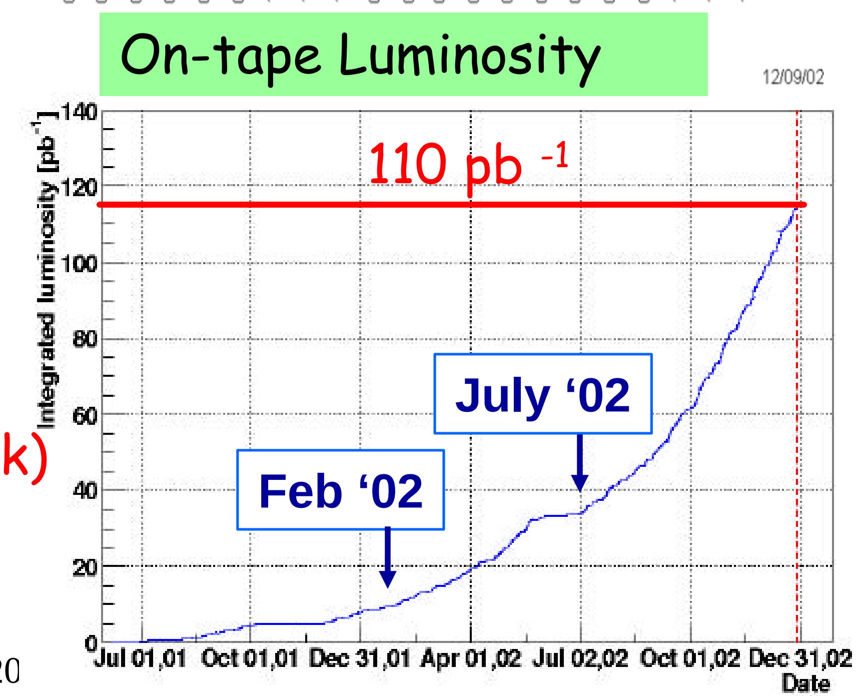


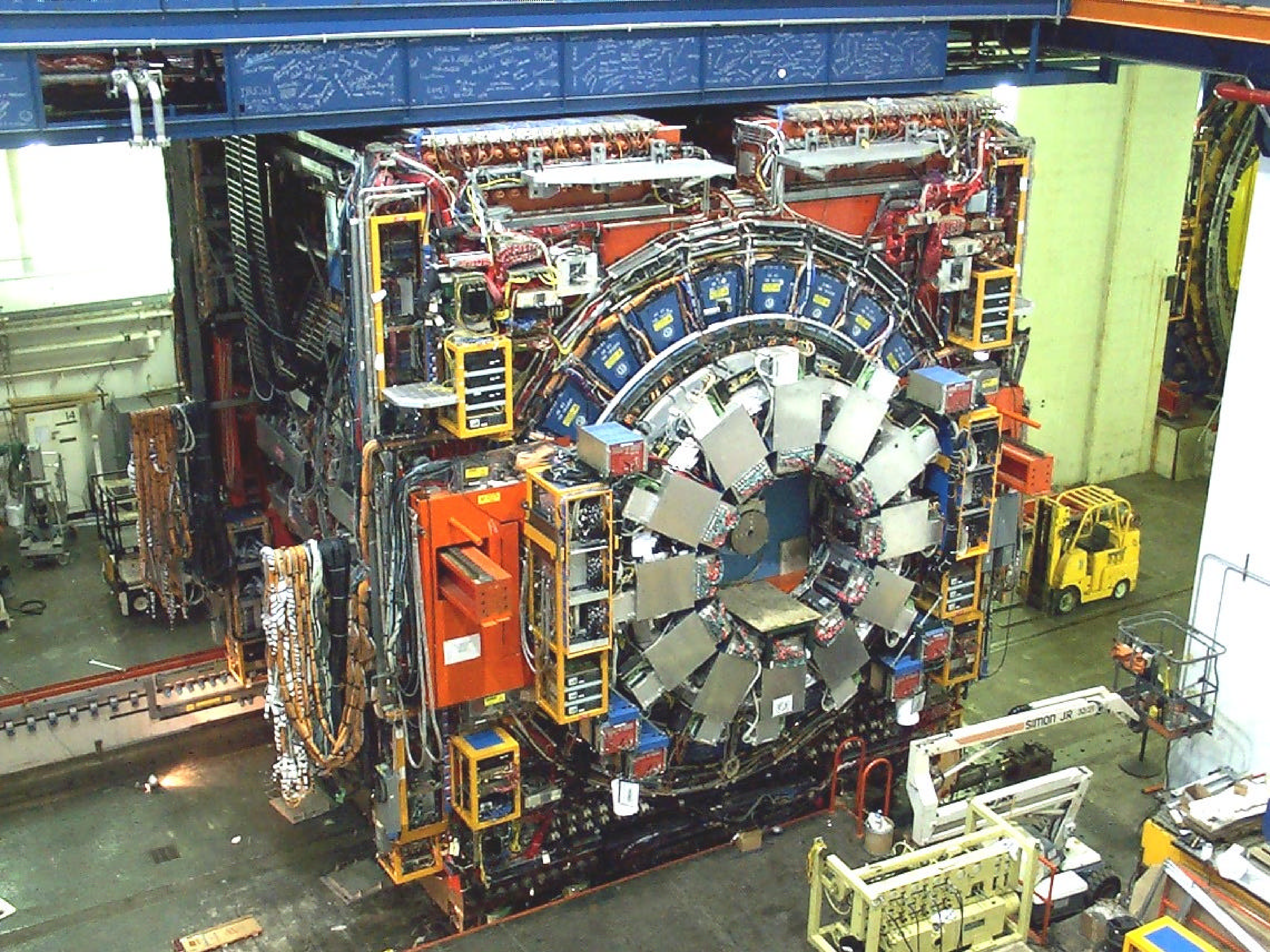
CDF operations

- Commissioning: Summer 2001
- Physics data since February 2002
- Running with >90% Silicon integrated since July 2002

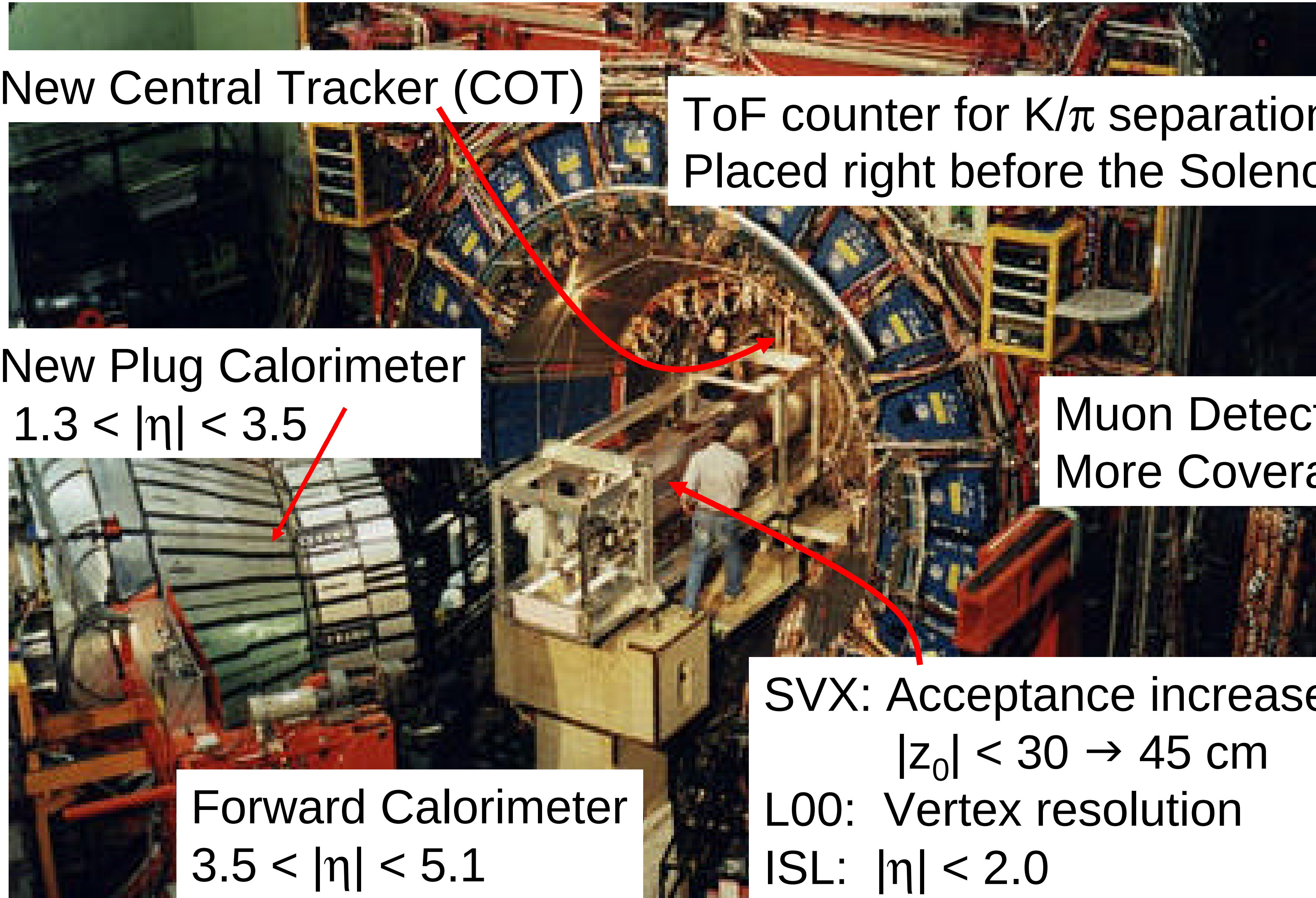
Luminosity (on-tape):

- ~20pb^{-1} until June (analyses in this talk)
- Additional 90pb^{-1} July – December
- Reach 300- 400 pb^{-1} by October 2003




SIMON JR

CDF Detector overview



CDF Detector in Run II

Inherited from Run I:

Central Calorimeter (|h|<1)

Solenoid (1.4T)

Partially New:

Muon system (extended to $|\eta|$~1.5)

Completely New:

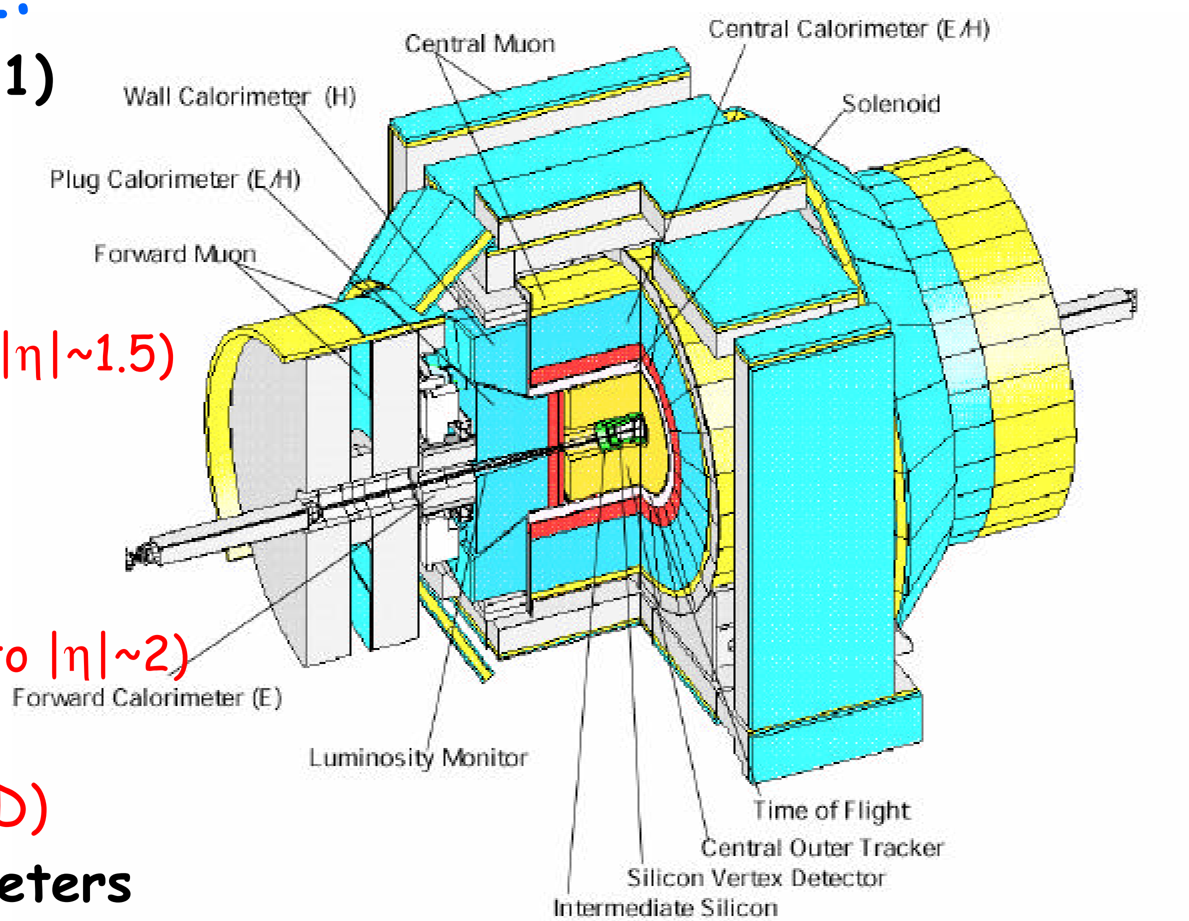
Tracking System

- 3D Silicon Tracker (up to $|\eta|$~2)
- Faster Drift Chamber

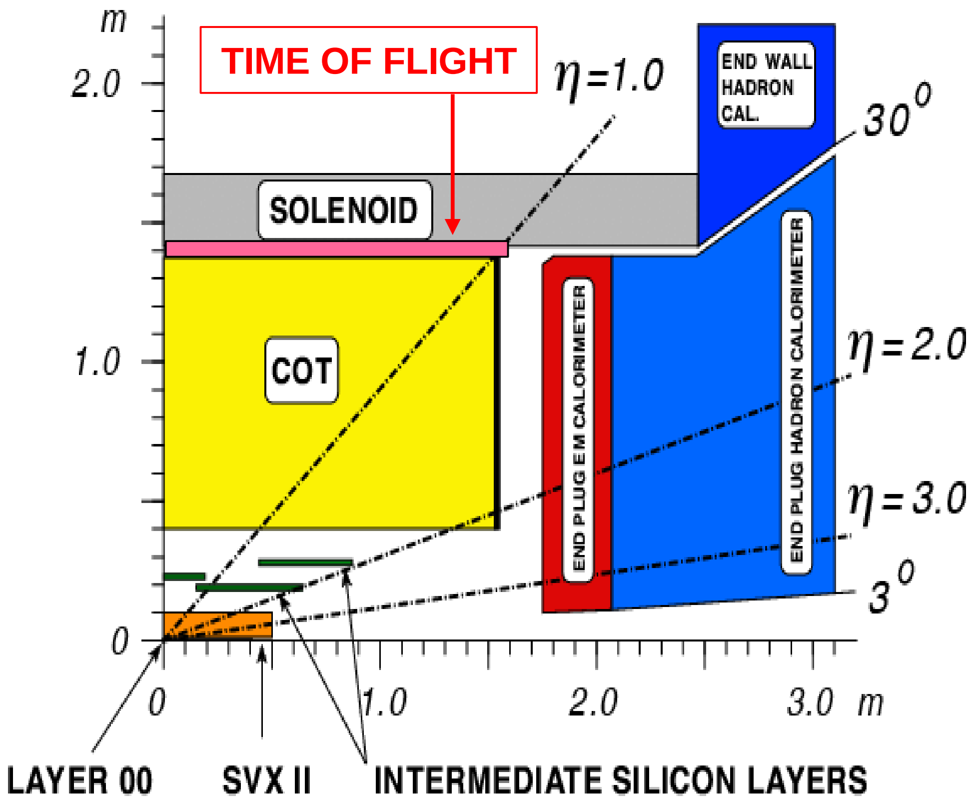
Time-of-Flight (particle ID)

Plug and Forward Calorimeters

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



Quadrant of CDF II Tracker



TOF: 100ps resolution, 2 sigma K/p separation for tracks below 1.6 GeV/c (significant improvement of B_s flavor tag effectiveness)

COT: large radius (1.4 m) Drift C.

- 96 layers, 100ns drift time
- Precise P_T above 400 MeV/c
- Precise 3D tracking in |h|<1

$\sigma(1/P_T)$ ~ 0.1%GeV^{-1}; σ(hit)~150mm

- dE/dx info provides 1 sigma K/p separation above 2 GeV

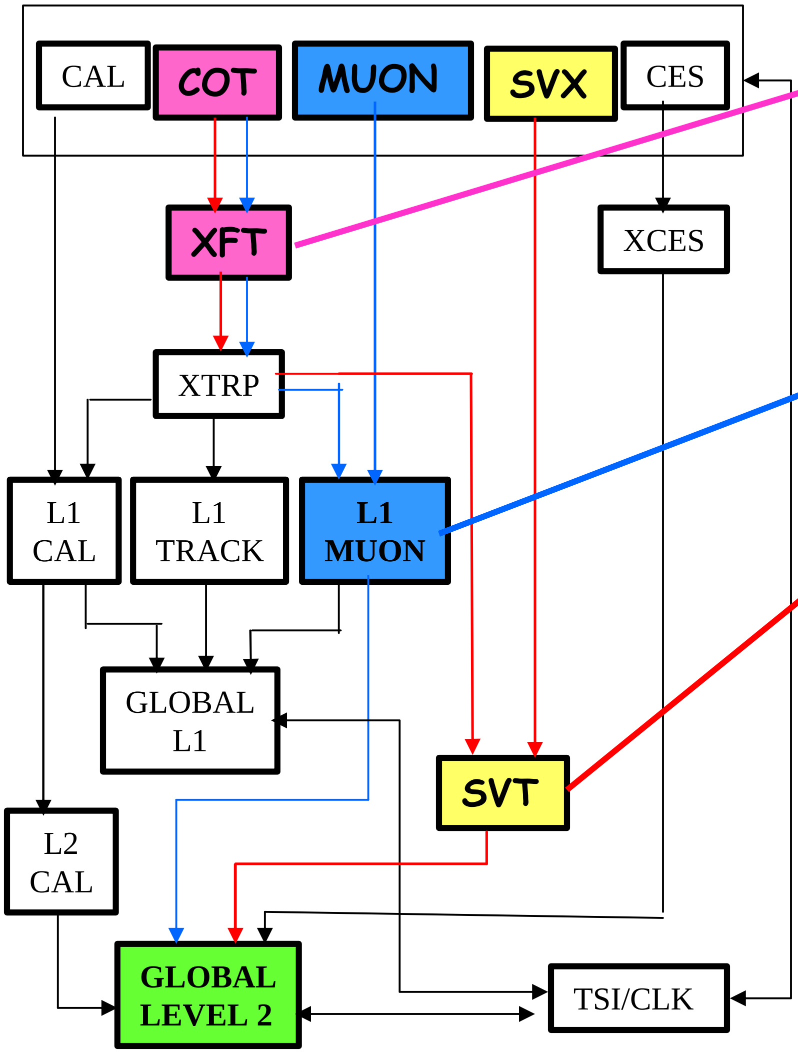
SVX-II + ISL: 6 (7) layers of double-side silicon (3cm < R < 30cm)

- Standalone 3D tracking up to |h|= 2
- Very good I.P. resolution: ~30mm (~20 mm with Layer 00)

LAYER 00: 1 layer of radiation-hard silicon at very small radius (1.5 cm) (achievable: 45 fs proper time resolution in $B_s \rightarrow D_s \pi$)

CDF II Trigger System

3 levels : 5 MHz ($p\bar{p}$ rate) $\rightarrow$ 50 Hz (disk/tape storage rate)
almost no dead time (< 10%)



XFT: "EXtremely Fast Tracker"
2D COT track reconstruction at Level 1
- P_T res. $\Delta p_T/p^2_T$ = 2% (GeV^{-1})
- azimuthal angle res. Df = 8 mrad

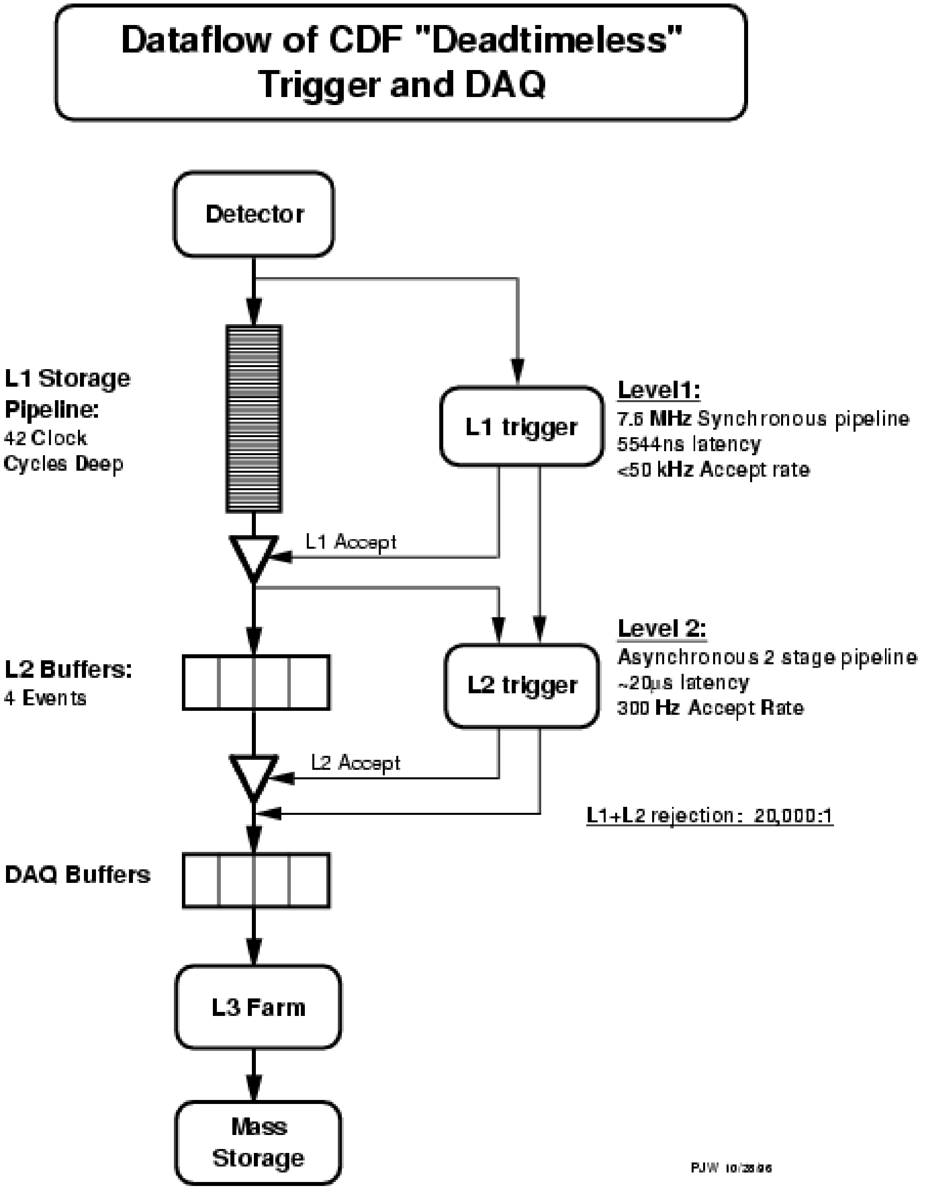
Matched to L1 ele. and muons
⇒ enhanced J/y samples

SVT: "Silicon Vertex Tracker"
precise 2D Silicon+XFT tracking at Level 2
- impact parameter res. σ_d = 35 mm
  Offline accuracy !!

CDF II can trigger on secondary vertices !!
⇒ Select large B,D samples !!

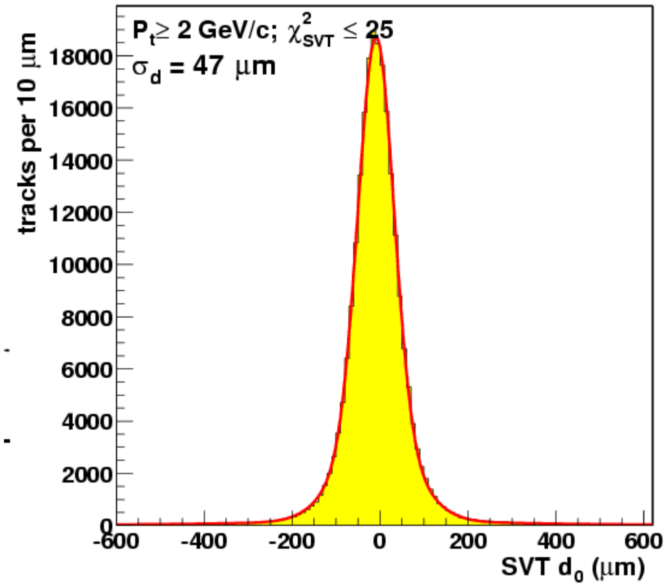
CDF Trigger System Overview

- Crossing: 396 ns: 2.5 MHz
- Level 1: hardware
  - Calorimeter, Muon, Track
  - 15kHz (reduction ~x200)
- Level 2: hardware + CPU
  - Cal cluster, Silicon track
  - 300 Hz (reduction ~x5)
- Level 3: Linux PC farm
  - ~ Offline quantities
  - 50 Hz (reduction ~ x6)

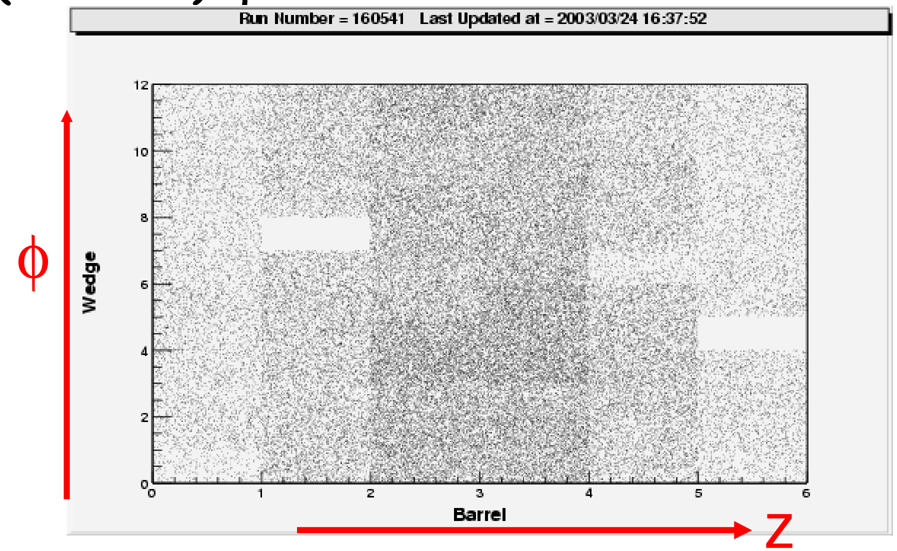


Silicon Vertex Tracker (SVT)

- Level 2: Silicon Vertex Trigger
  - Use silicon detector information
    - Good IP resolution
    - Trigger on displaced track
  - beamline reconstruction
    - update every ~ 30 seconds
  - IP resolution: ~ 50 μm
    - 35μm beam size + 35μm SVT

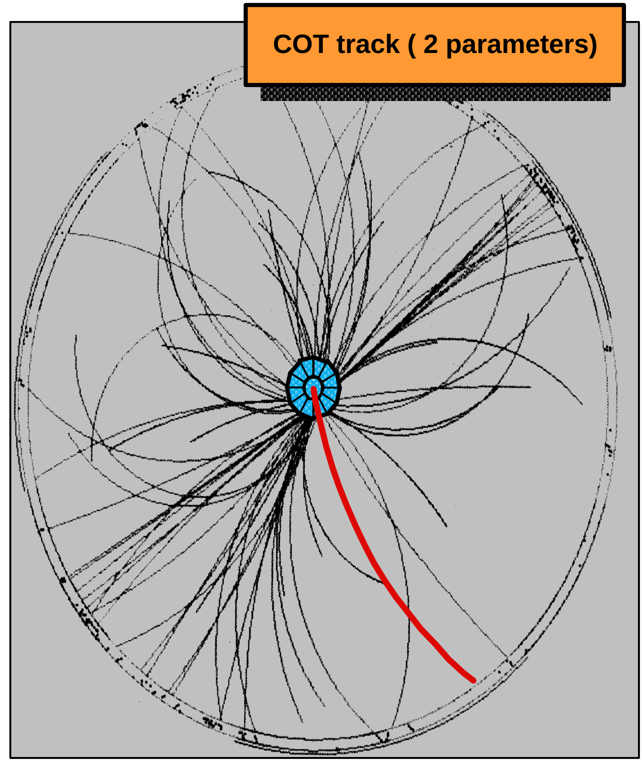


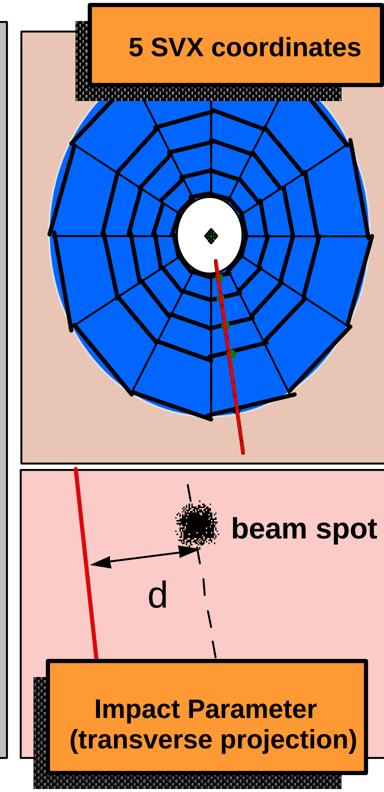
- Increase physics sensitivity of the Run II CDF
  - CDF as "Charm Factory"
    - Millions of D's per 100 pb^{-1}
  - Collect Hadronic B sample
    - No Lepton required in final state
    - B_s physics (mixing in $D_s\pi$)
  - Higgs/new particles decaying heavy (b and c) quarks



SVT: Triggering on impact parameters

~150 VME boards





- Combines COT tracks (from XFT) with Silicon Hits (via pattern matching)
- Fits track parameters in the transverse plane (d, f, P_T) with offline res.
- All this in ~15µs !
- Allows triggering on displaced impact parameters/vertices
- CDF becomes a beauty/charm factory

B triggers: conventional

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

CDF Run I, lepton-based triggers:

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

Suffer of low BR and not fully rec. final state

Nevertheless, many important measurements by CDF I:
B^0_d mixing, $\sin(2\beta)$, B lifetimes, B_c observation, ...

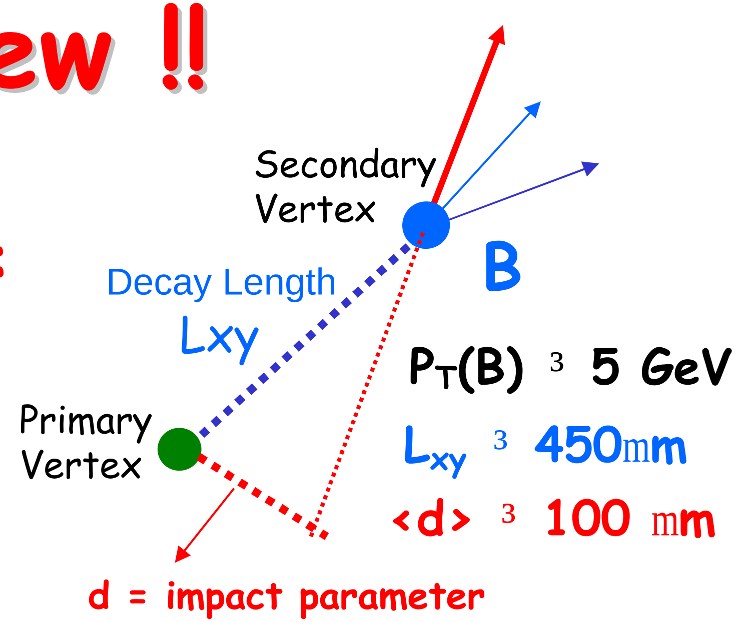
Now enhanced, thanks to XFT (precise tracking at L1) **:**

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

B triggers: New !!

CDF 2, displaced tracks triggers:

Trigger on tracks significantly displaced from primary vertex



Made possible by SVT:

precise meas. of track impact parameter at Level 2
2D Secondary Vertices reconstructed online !

- Two displaced tracks (d > 100μm, L_{xy} cut, $\Delta\varphi$ cut)
  - All hadronic B decays: $B \to \pi\pi(KK)$, $\Lambda_b \to p\pi(K)$, $B_s \to D_s\pi(3\pi)$ ...
  - Lots of prompt charm mesons !!!
- Lepton plus displaced track
  - Semileptonic decays at Lower P_T ($\geq$ 4 GeV/c)
  - Rare B decays ...

"All Hadronic B triggers"

Level 1: 2 XFT tracks
P_T > 2 GeV
$\Delta\varphi$ < 135°
$P_{T1} + P_{T2}$ > 5.5

1/100

"Two body decays"

"Multi-body decays"

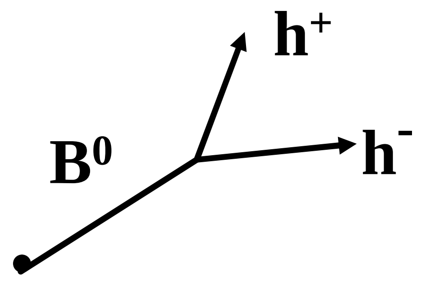
Level 2

d > 100 μm 20° < $\Delta\varphi$ < 135° $L_{xy} \geq$ 200 μm d_B < 140 μm	d > 120 μm 2° < $\Delta\varphi$ < 90° $L_{xy} \geq$ 200 μm

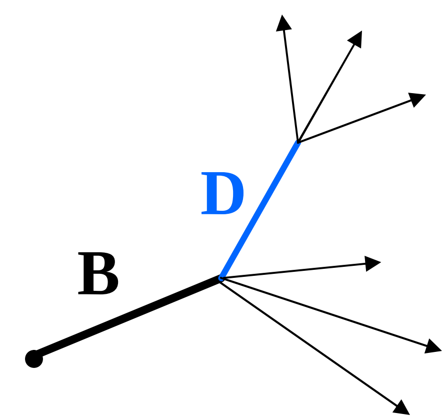
1/1000

Level 3

SAME with refined tracks
& Mass cuts

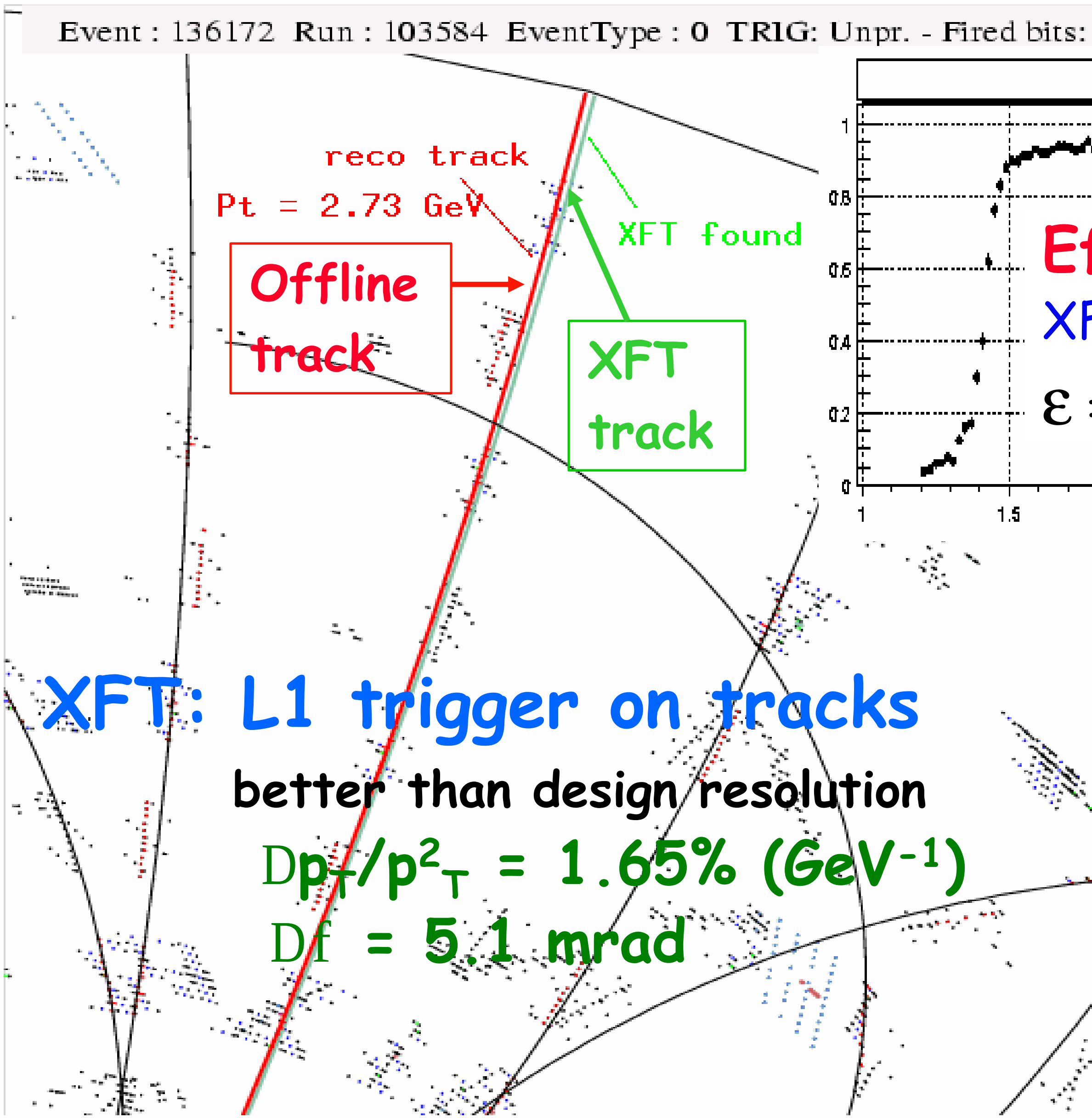


B^0 ® p p
B^0 ® K p
B_s ® K K
B_s ® p K
Λ_b ® **p** p(K)



B_s ® D_s p
B_s ® D_s p p p
B ® **D K**/π
+ Lots of
prompt charm decays

XFT performance

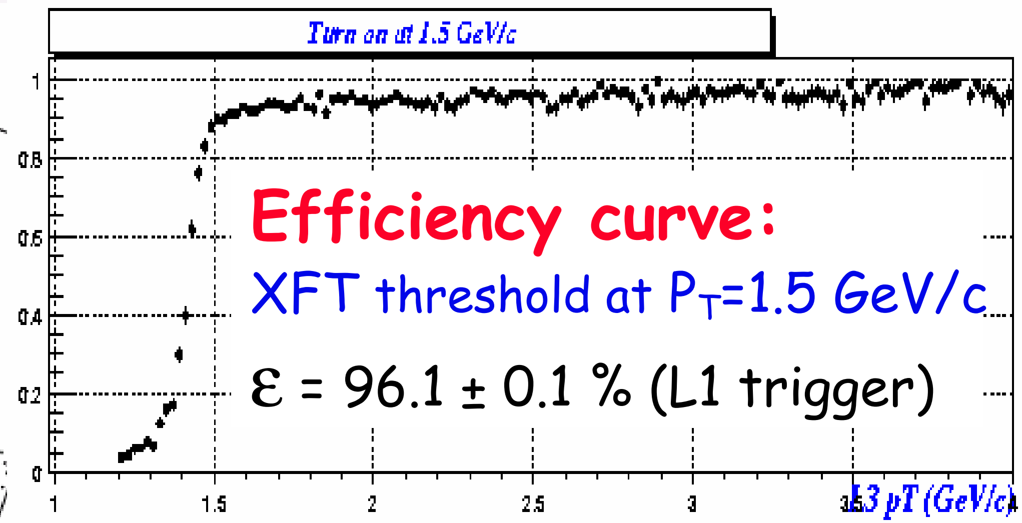


XFT: L1 trigger on tracks

better than design resolution

$\Delta p_T/p_T^2 = 1.65\%$ (GeV^{-1})

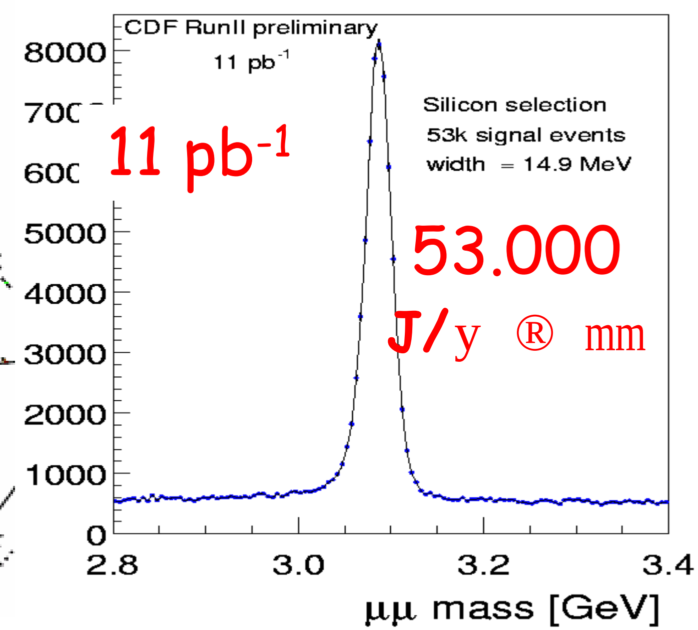
$\Delta\phi$ = 5.1 mrad



Efficiency curve:

XFT threshold at P_T=1.5 GeV/c

$\varepsilon = 96.1 \pm 0.1\ \%$ (L1 trigger)

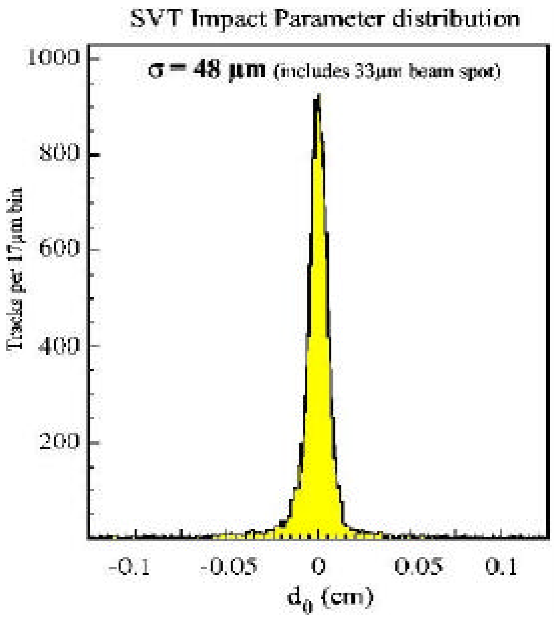


11 pb^{-1}

53.000

$J/\psi \to \mu\mu$

SVT performance



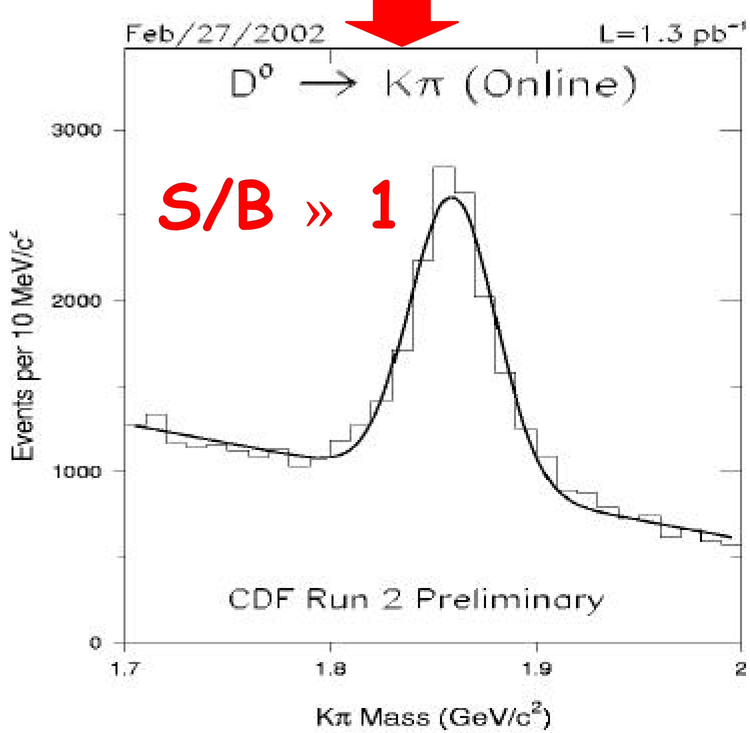
- I.P. resolution as planned

σ_d = 48 μm = 35 μm ⊕ 33 μm

intrinsic

transverse beam size

D⁰ ® Kp used as online monitor of the hadronic SVT triggers

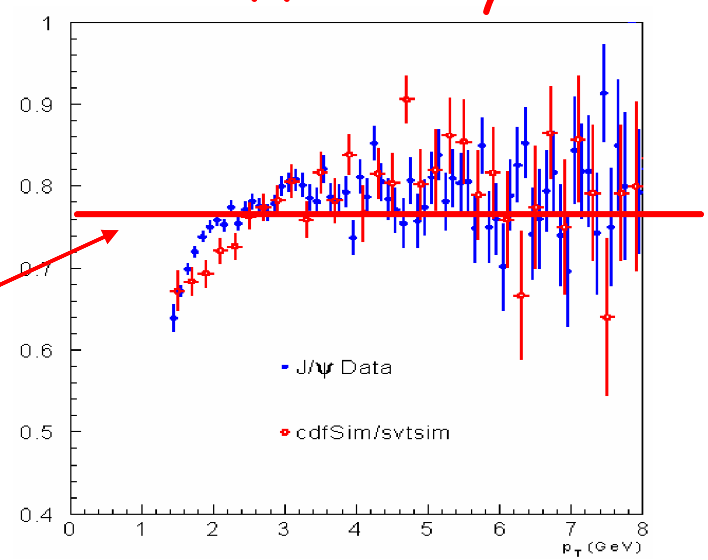


- Efficiency

90%

soon

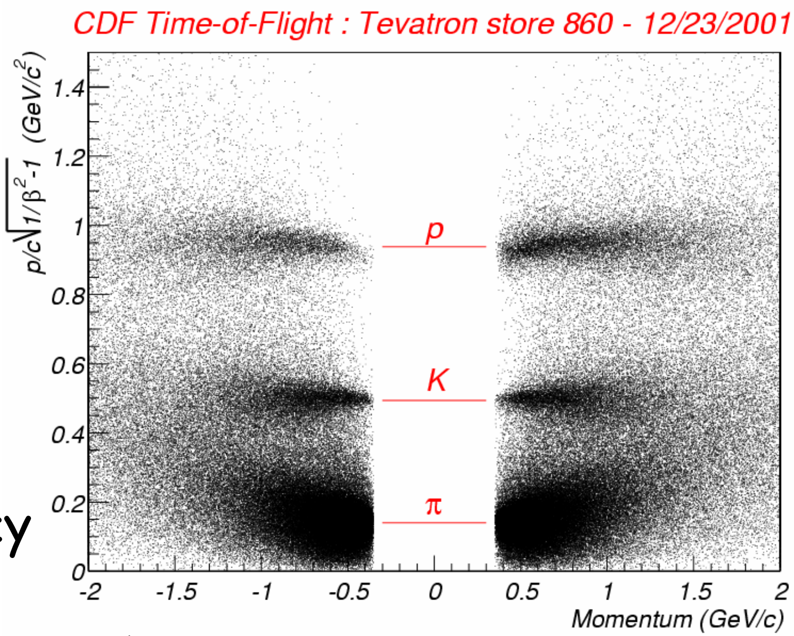
80%

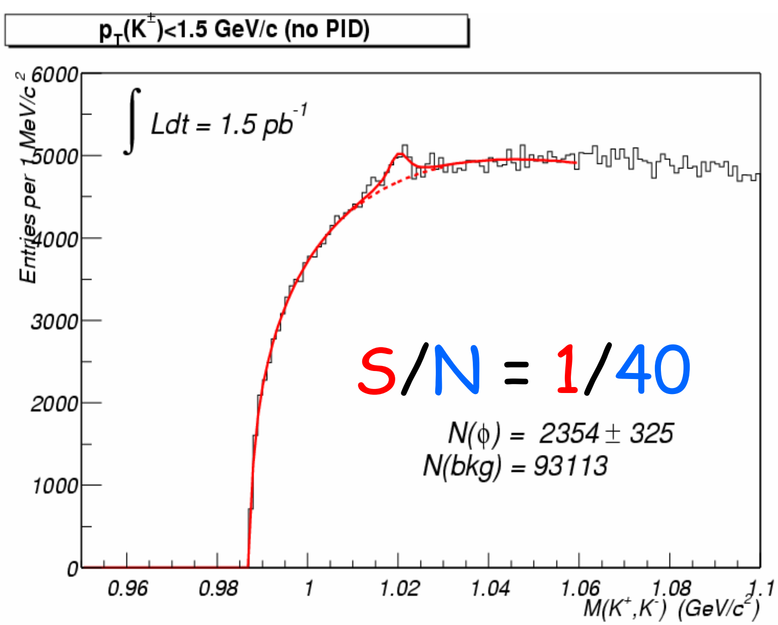


TOF performance

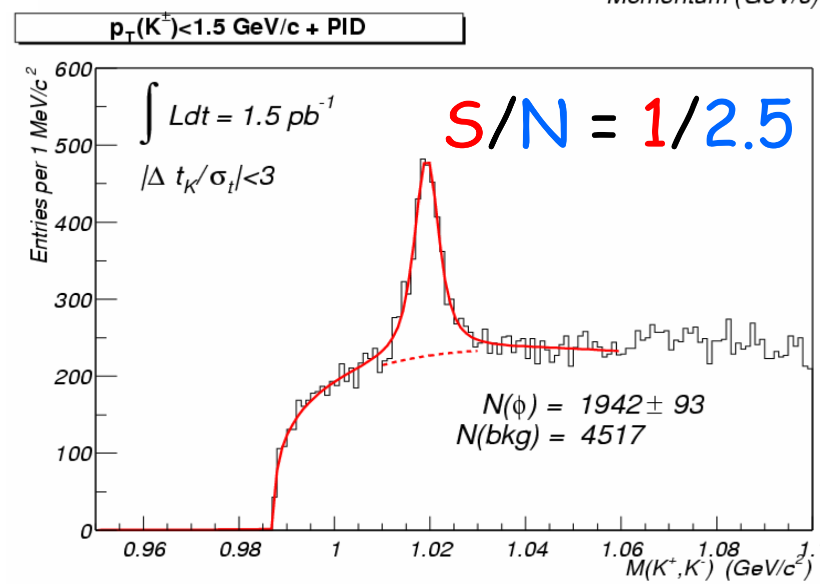
- TOF resolution (110ps) within 10% of design value

Background reduction in j ® **KK:**
Low P_T (< 1.5 GeV/c) track pairs before and after a cut on TOF kaon probability
x20 bkg reduction, 80% signal efficiency

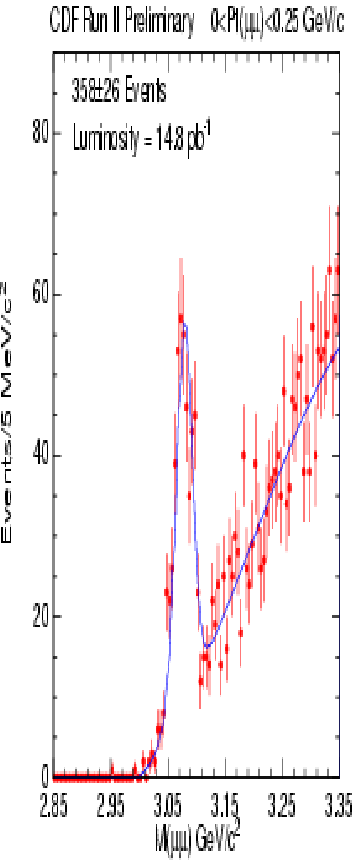




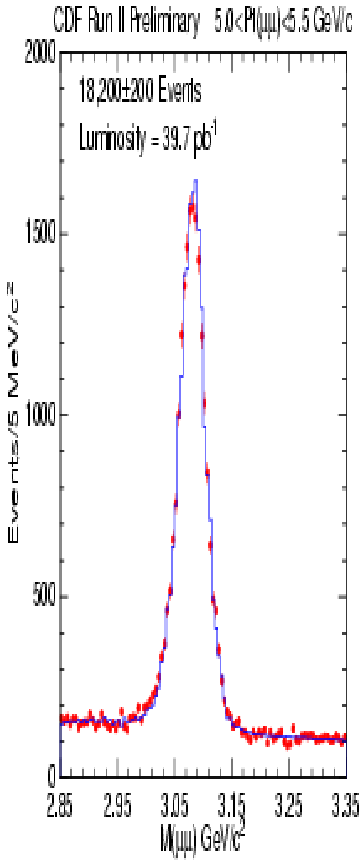
with TOF PID



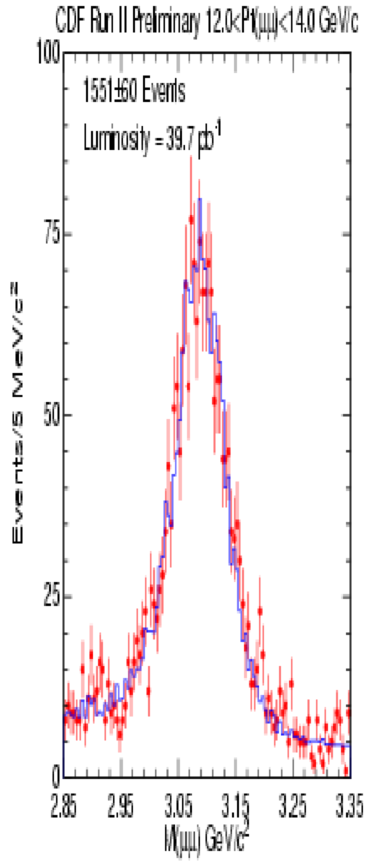
CDF J/y cross section



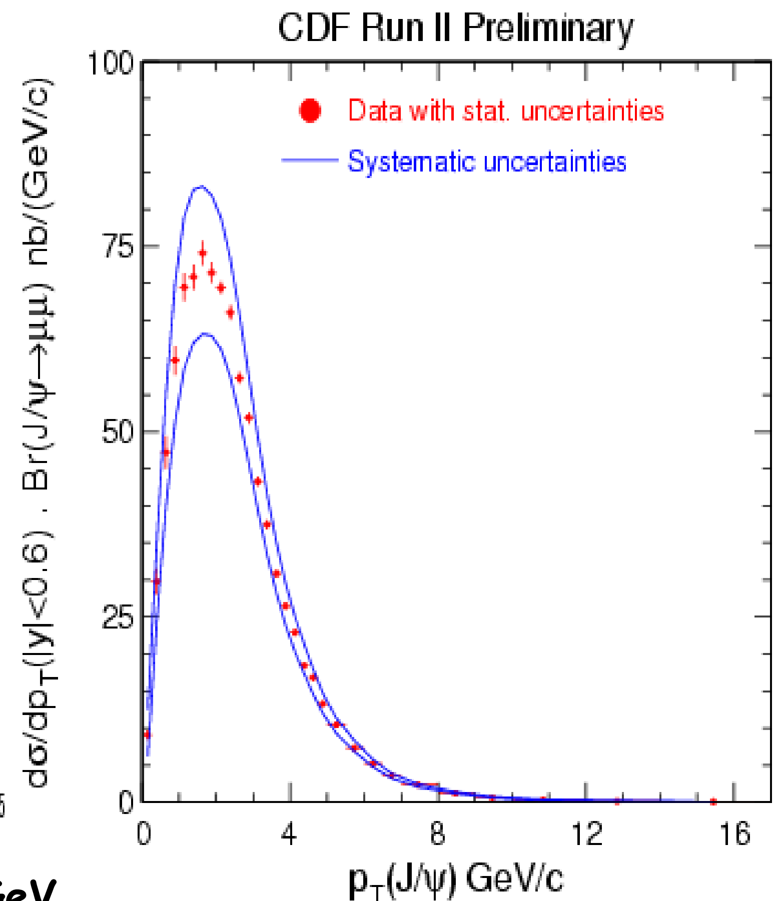
0<pt<0.25 GeV



5.0<pt<5.5 GeV



10.0<pt<12.0 GeV



s(pp→J/y; p_T>0; |y|<0.6) =240 ± 1 (stat) ±35/28(syst) nb

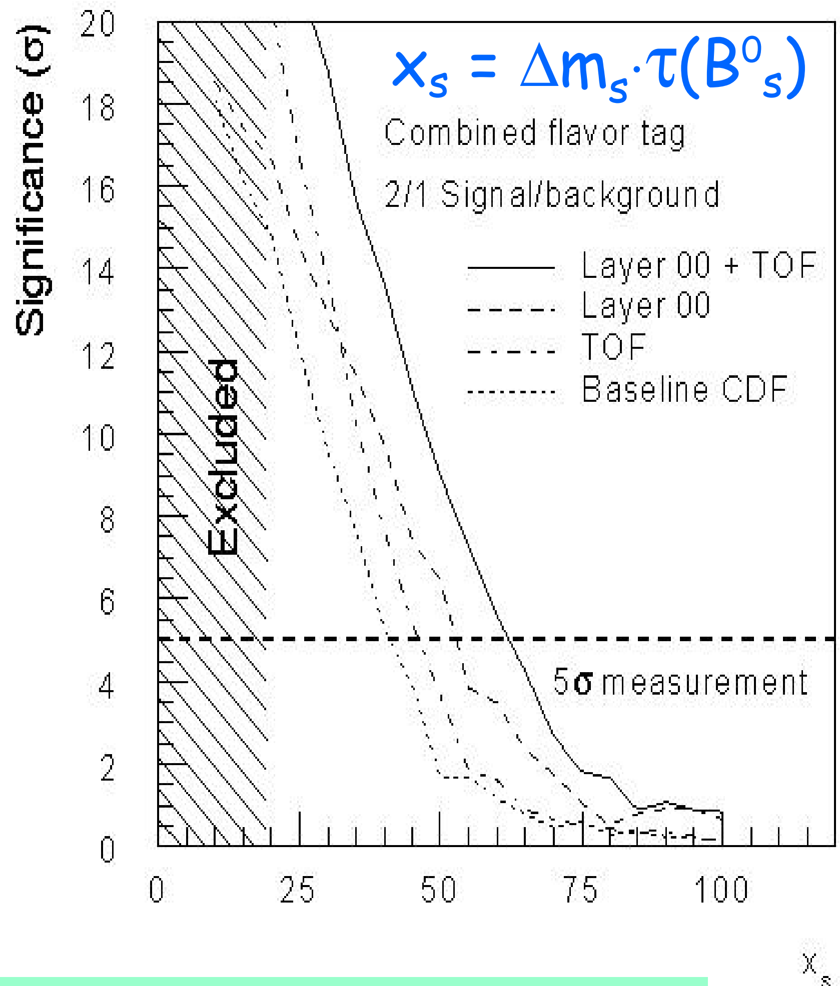
B^0_s mixing: expectations with $2fb^{-1}$

$B_s \to D_s\pi,\ D_s\,\pi\,\pi\,\pi$

$D_s \to \varphi\pi,\ K^*K,\ \pi\pi\pi$

- Signal: 20K ($\phi\pi$ only) - 75K (all) events
  - with SVT hadronic trigger
  - **BR (D_s p) = 0.3 % ; BR (D_s p p p) = 0.8 %**
- Resolution:
  - s(ct) = 45 fs (with Layer00)
  - eD^2 = 11.3% (with TOF)
- S/B: 0.5-2 (based on CDF I data)

$$(s\,x_s)^2 = \frac{1}{N}\frac{1}{eD^2}\frac{S+B}{S}e^{(\Delta m_s s_t)^2}$$



5s sensitivity up to:

X_s = 63 (S/B = 2/1)

X_s = 53 (S/B = 1/2)

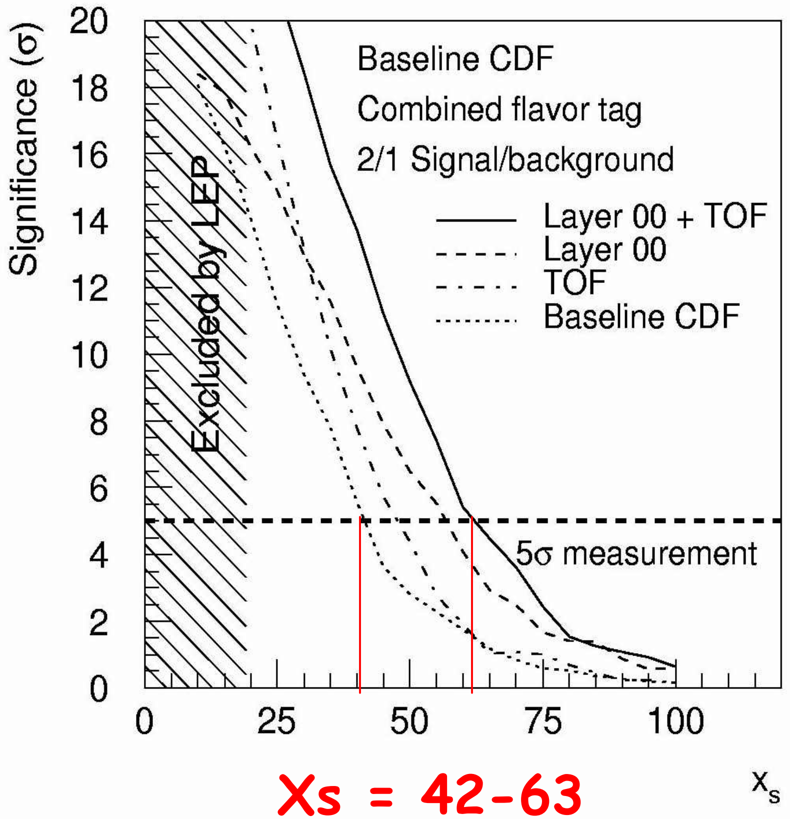
S.M. allowed range: 20. < X_s < 35.

Can do a precise measurement

… or evidence for new physics !

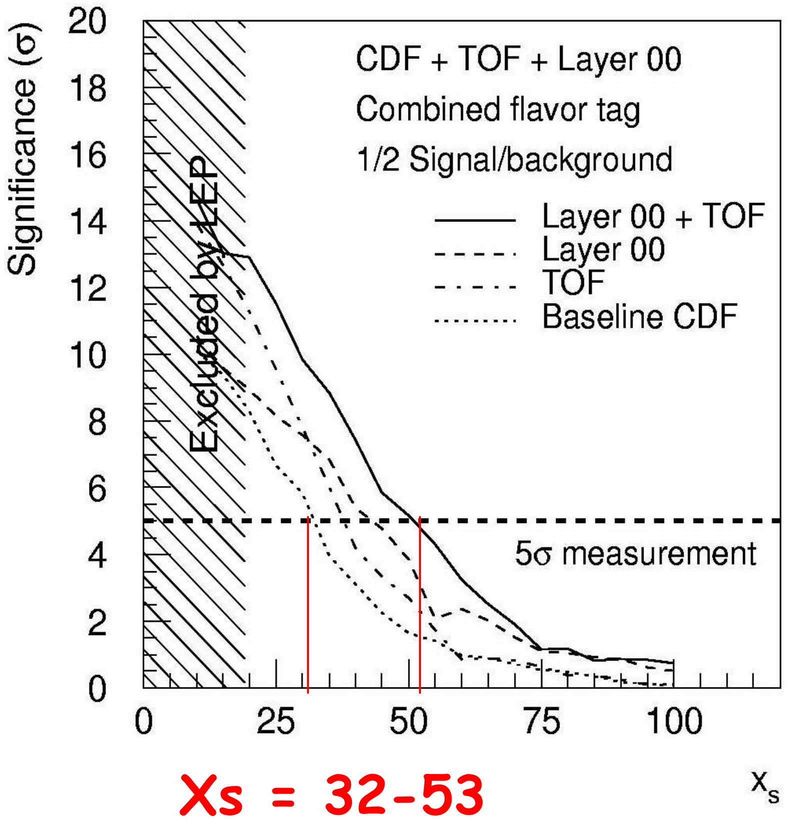
Projections for x_s reach with 2fb^{-1}

Optimistic: S/B =2/1



Xs = 42-63

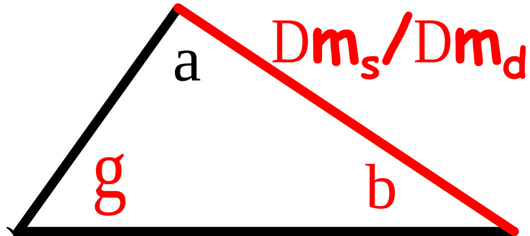
Conservative: S/B =1/2



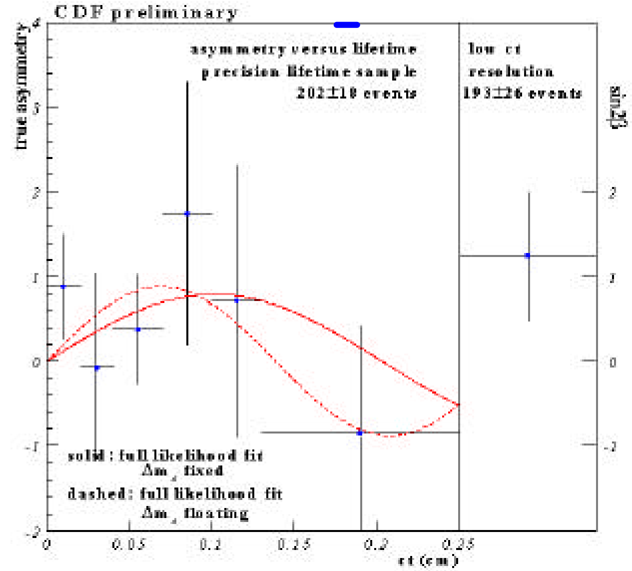
Xs = 32-53

<u>MC simulation</u>: accounts also for SVT cuts on proper time acceptance, non-Gaussian tails in proper time resolution function

Sin(2b) in B^0 ® J/y K_s



$$A_{CP}(t) = \frac{N(B^0)(t) - N(\overline{B^0})(t)}{N(B^0)(t) + N(\overline{B^0})(t)} = D \times \sin(2\beta) \times \sin(\Delta m_d\, t)$$



In Run1 measured: $B^0 \to J/\psi\ K_s$; $J/\psi \to \mu\mu$

$\sin(2\beta)=0.79\pm0.39\pm0.16$ (400 events)

$\sin(2\beta)=0.91\pm0.32\pm0.18$ (+60 $B^0 \to$ y (2S) K_s)

With $2fb^{-1}$ can refine this measurement
Although: no way to compete with B-Factories !

N(J/y K_s) from scaling Run I data:

• x 20 luminosity	8,000
• x 1.25 tracks at L1 trigger	10,000
• x 2 muon acceptance	**20,000**
• Trigger on $J/\psi \to e^+e^-$	+ 10,000

Stat. Error:

$$d(\sin(2\beta)) \approx \frac{1}{\sqrt{\varepsilon D^2 N}}\sqrt{1+\frac{B}{S}}$$

Expect: s(sin2b) » 0.05

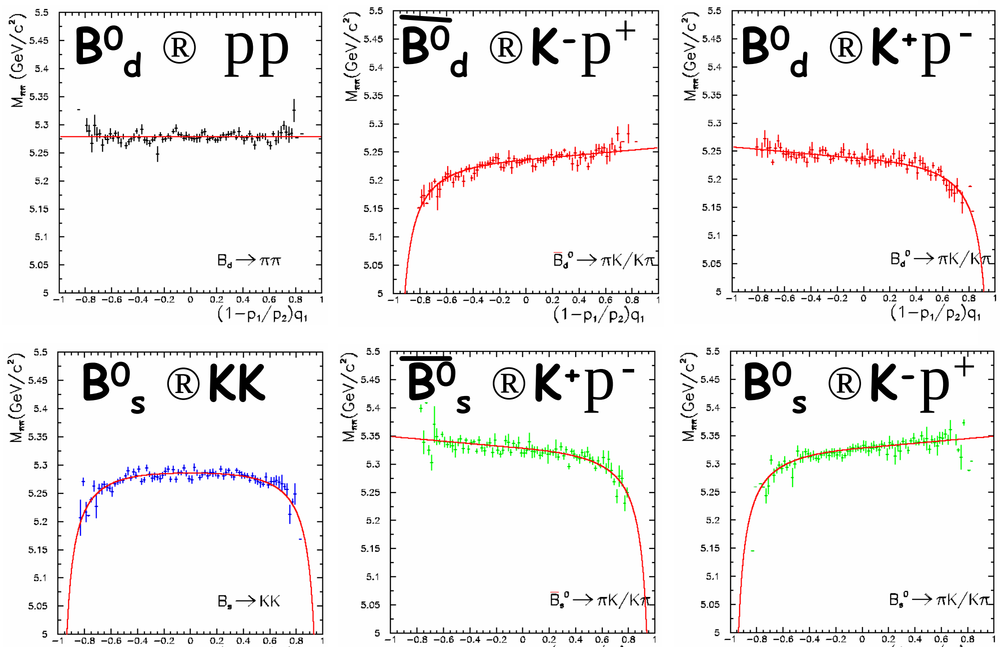
Combined εD^2: from 6.3% to 9.1% (Kaon b-tag)

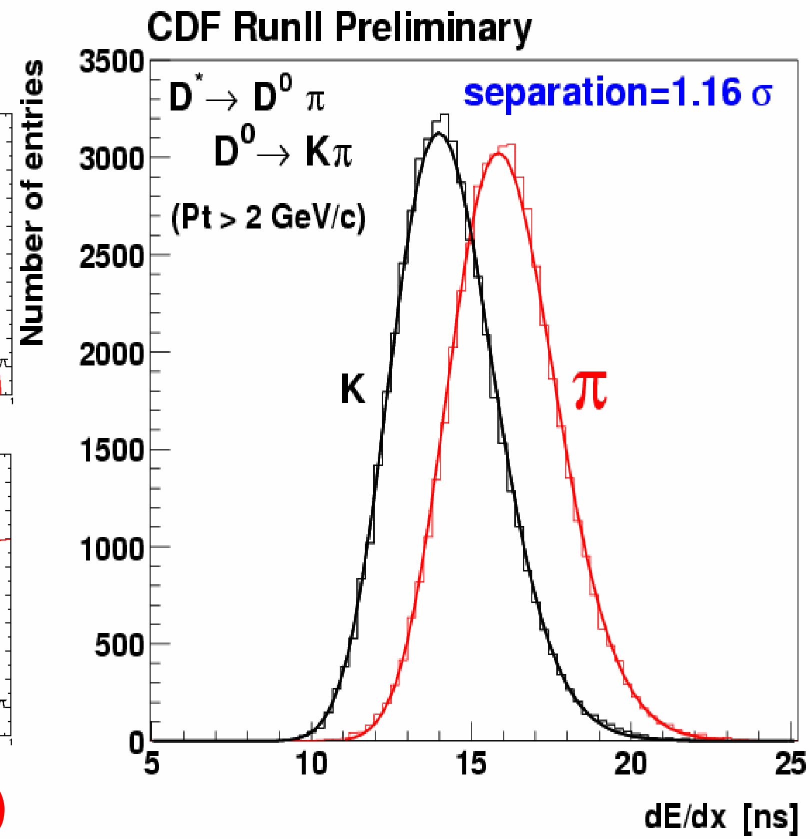
Same S/B = 1

Systematic ~ 0.5xStatistical (scales with control sample statistics)

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

Use $M_{\pi\pi}$ vs $\alpha=(1-p_1/p_2)\cdot q_1$





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)

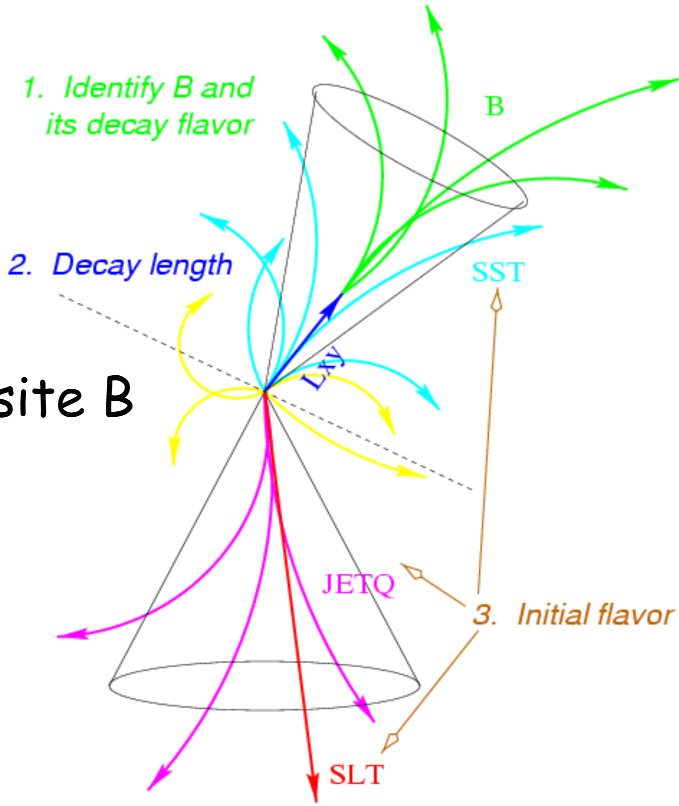
$B^0{}_s$®Kp(0.05): ± 0.036 (stat)

$A_{CP}(B^0_d$ ®Kp): ±0.14 (PDG-2002: ±0.06)

Use K/p separation
dE/dx 1.16s

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}

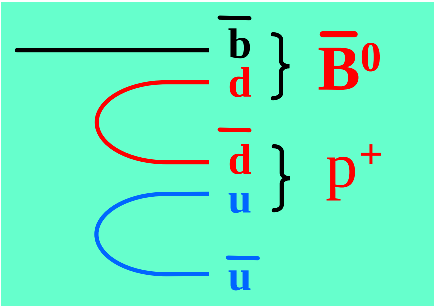


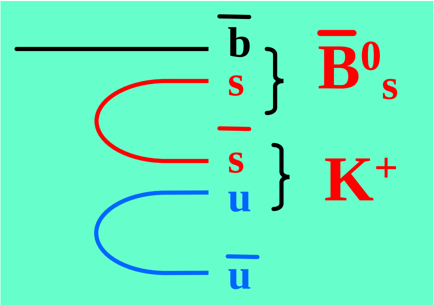
Figure of merit: eD^2 "tagging effectiveness" » **2%**

e = tagging efficiency ; **D** = "Dilution" = $1 - 2P_{mistag}$

Effective size of sample is reduced by eD^2

NEW at CDF: "Kaon b-taggers"

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



Same Side K: a $\bar{B}^0_s$ (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^+

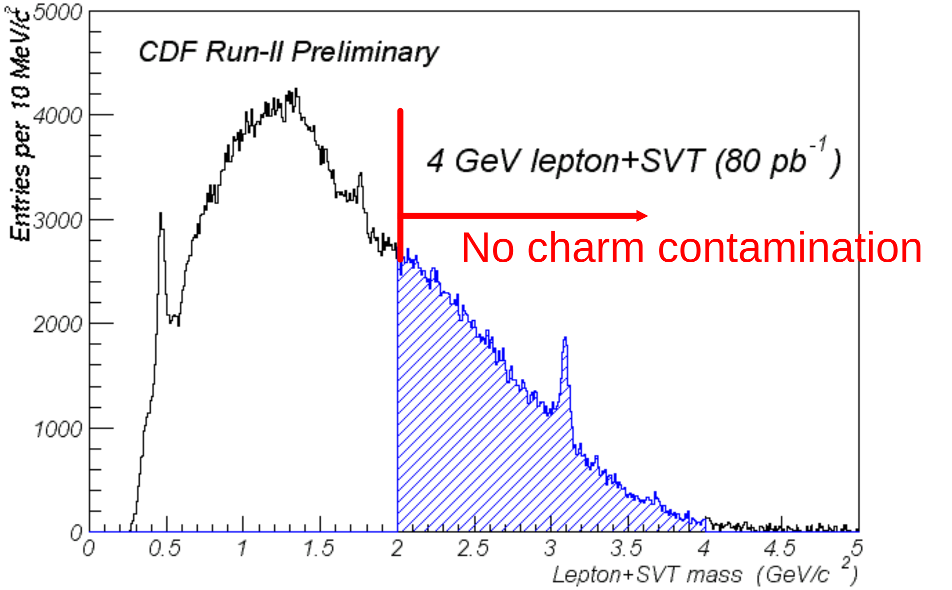
Þ to identify a $\bar{B}^0_s$ look for a K^- from the decay of the opposite B

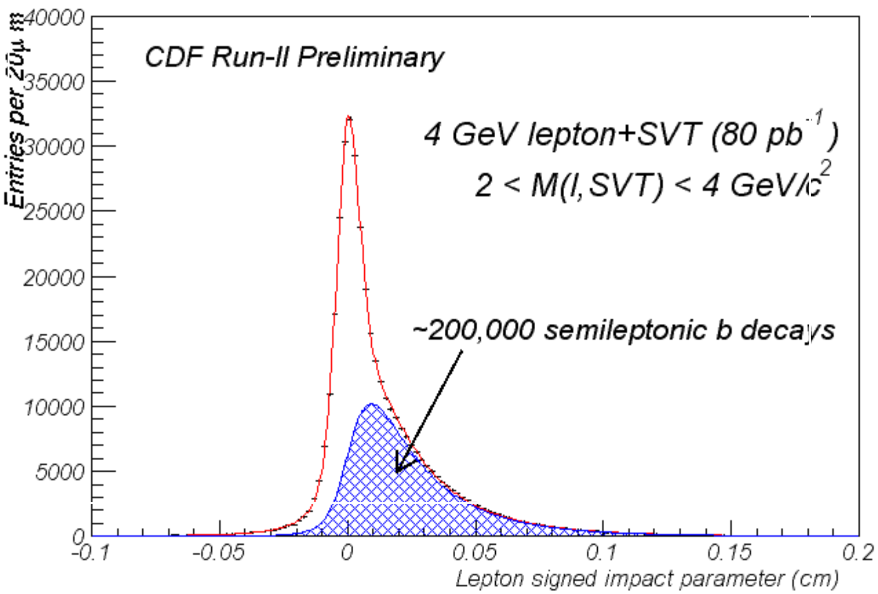
Run II Projections

	$B^0 \rightarrow J/\psi K_s$	$B_s \rightarrow D_s \pi$
SST	1.9%	4.2% (TOF)
SLT	1.7%	1.7%
JETQ	2.0%	3.0%
Kaon	2.4%	2.4%
Total	9.0%	11.3%

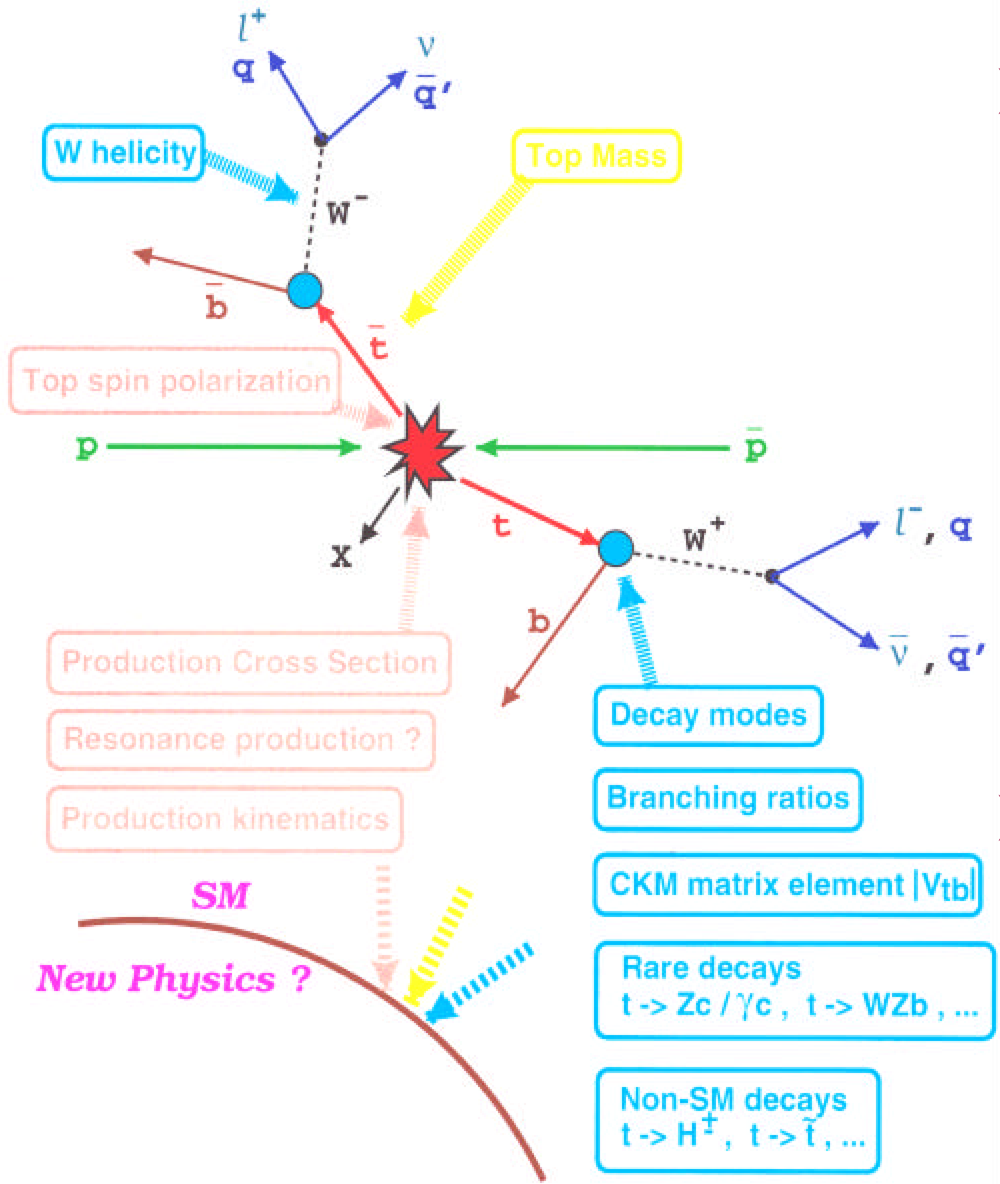
B Flavor Tagging

- Statistical uncertainty for tagging efficiency
  - A typical tagging: $\varepsilon=0.1$, $D=0.4$, $\varepsilon D^2=1.6\%$
  - 1000 events: $\varepsilon D^2=1.6\underline{+}0.7\%$ (44%)
  - 100K events: $\varepsilon D^2=1.60\underline{+}0.07\%$ (4.4%)
- We can't study/optimize the flavor tagging with ~O(1000) events of the B signal events
  - $B \to J/\psi K$: ~ 1000 events/100pb^{-1}
  - $B \to D\pi$: ~ 500 events/100pb^{-1}
- Solution: Use Semileptonic B decays in the lepton + track dataset
  - ~200K semileptonic B signal events
  - High B purity
  - Lepton Charge = Decay flavor of B





Top Properties



➢Top pairs: s(tt) ~ 8 pb

- W helicity in top events
- t-tbar spin correlations
- Top P_T
- QCD tests
- Top Drell-Yan via ds/dM of tt
- New physics in X® tt
- Anomalous couplings, new particles

➢Single top: s(tb) ~ 3 pb

- $|V_{tb}|$
- QCD tests
- New physics?

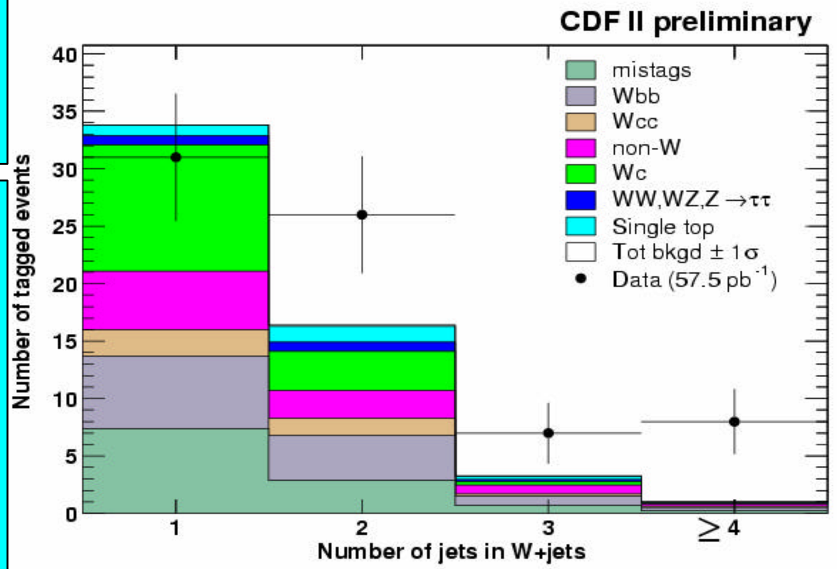
Top production numbers

	Run 1	Run 2a
CM Energy (TeV)	**1.8**	**1.96**
L(cm^{-2} s^{-1})	**$2x10^{31}$**	**$2x10^{32}$**
L(fb^{-1})	**0.11**	**2.0**
s**(tt) (pb)**	**5.0**	**7.0**
s**(single top) (pb)**	**2.5**	**3.4**
N(tt) produced	**500**	**14000**
N(single t) produced	**250**	**7000**
N(tt->dilepton)	**4**	**150**
N(tt->l+3j) (1tag)	**25**	**1400**
N(tt->l+4j) (2tags)	**5**	**600**

l+jets channel BACKGROUNDS

Mistags:
fake rate matrix(Et,η) from inclusive jet data per jet : neg-rate=#tagged jets with Lxy<0 / #taggable jets
$\rightarrow$is applied to every single taggeable jet found in W+jets sample

Wbb,Wcc Wc:
[Evt Fraction] $\times$[Efficiency]$\times$ [N W+jet]
Event Fraction: heavy flavor fraction in W+jets events from Run 1
Efficiency: b-tagging rate from Run 2 MC, Scale Factor applied
N W+jets in Run 2 data.



Non-W: from data, isolation vs Et method
WW,WZ,Z->$\tau\tau$,Single top from MC