B Physics at CDF

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Introduction : *B* Physics at Tevatron/CDF

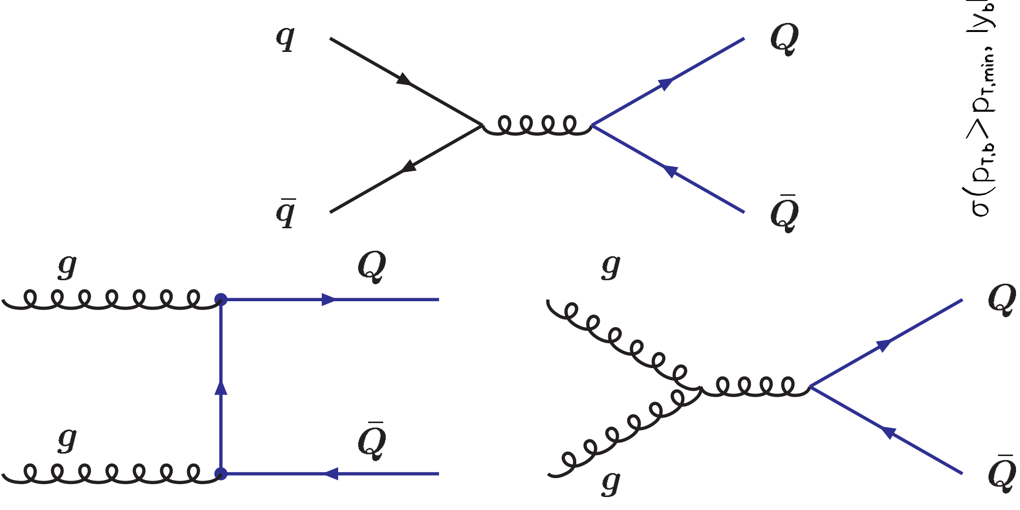
Production rates are high

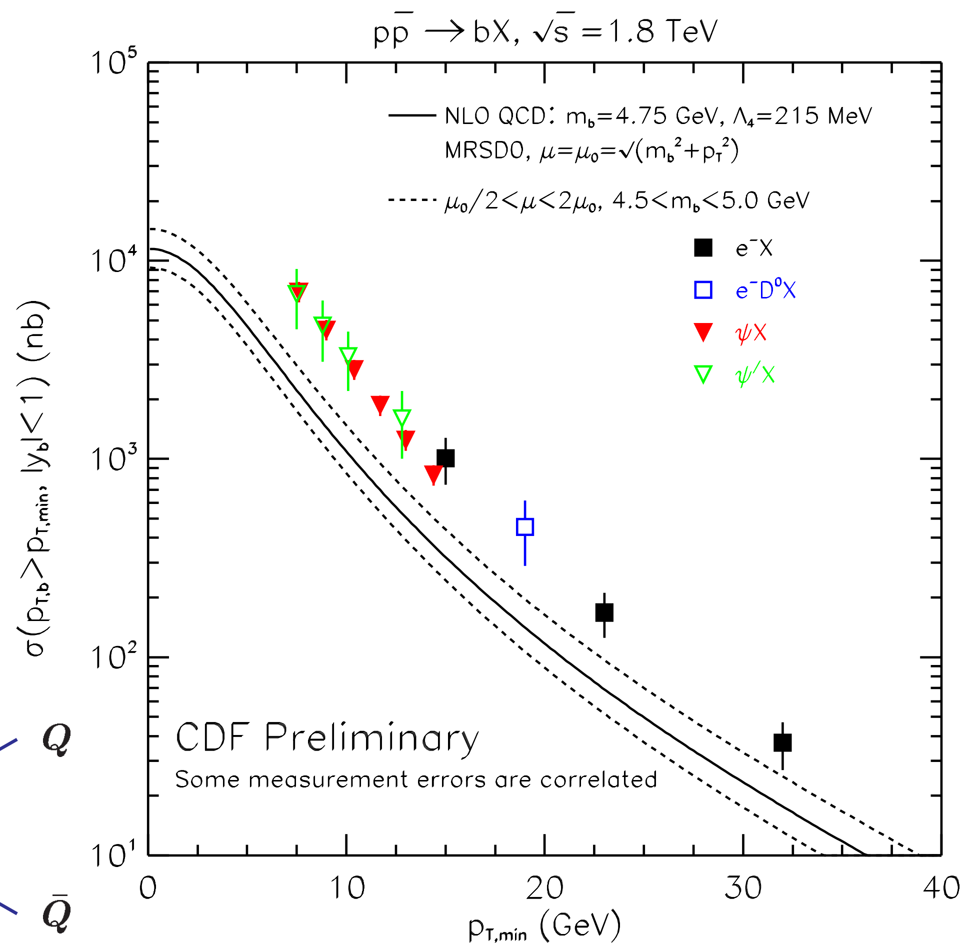
$$\sigma(e^+e^- \to b\bar{b}) \simeq 1 \text{ nb at } \Upsilon(4S), \quad 6 \text{ nb at } Z^0$$

$\bar{p}p \longrightarrow b\bar{b}X$

via strong interaction

$\sigma \sim 10\ \mu$b at 1.8 TeV





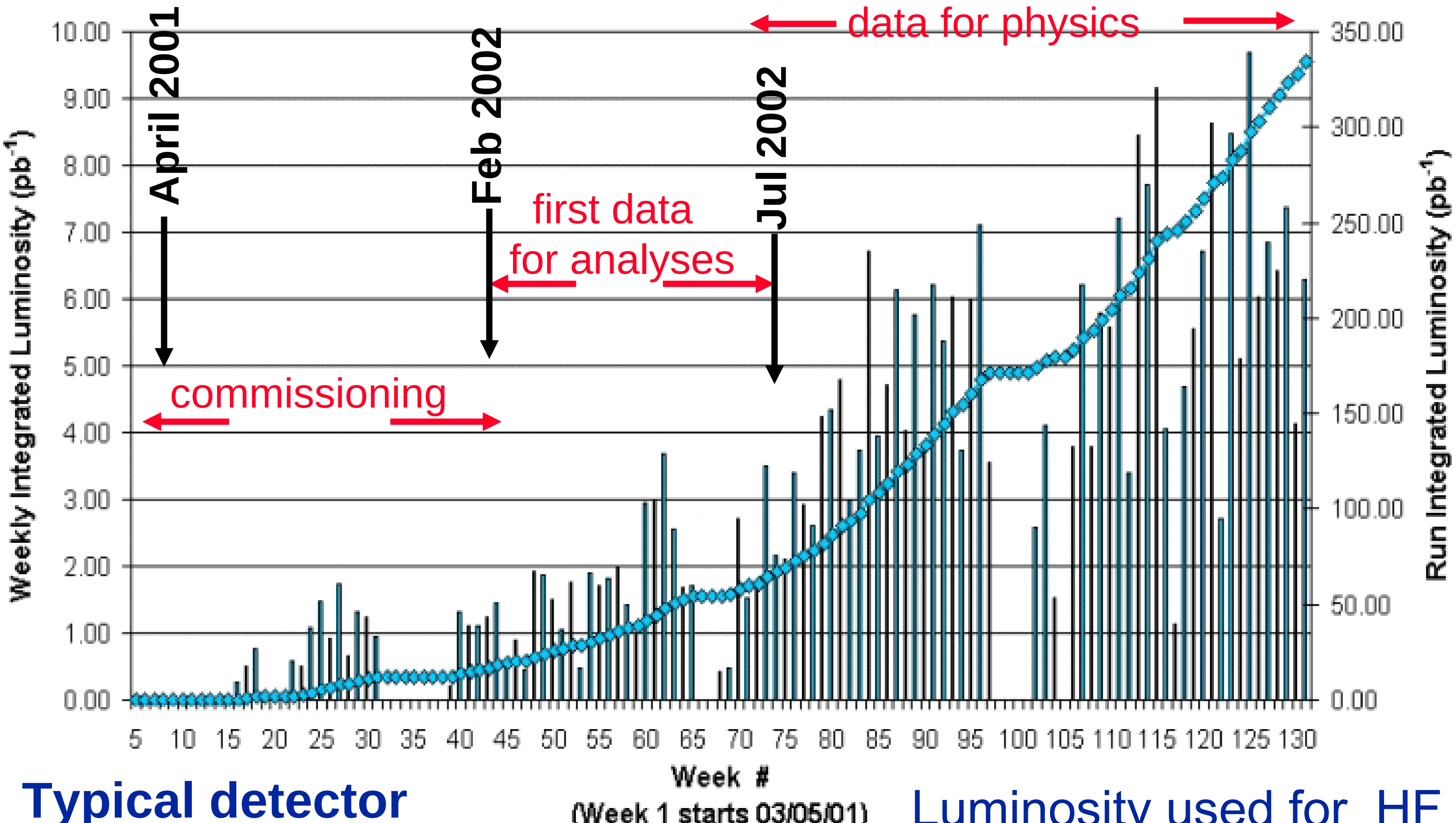
Tevatron Accelerator

- New 120/150 GeV Main Injector replaced Main Ring
  - Increased intensity of protons and antiprotons.
- Tevatron operates with 36 x 36 bunches
- Increased CM energy 1.8 TeV to 1.96 TeV

Run II started in March 2001.

Tevatron Run-II weekly and total integrated luminosity

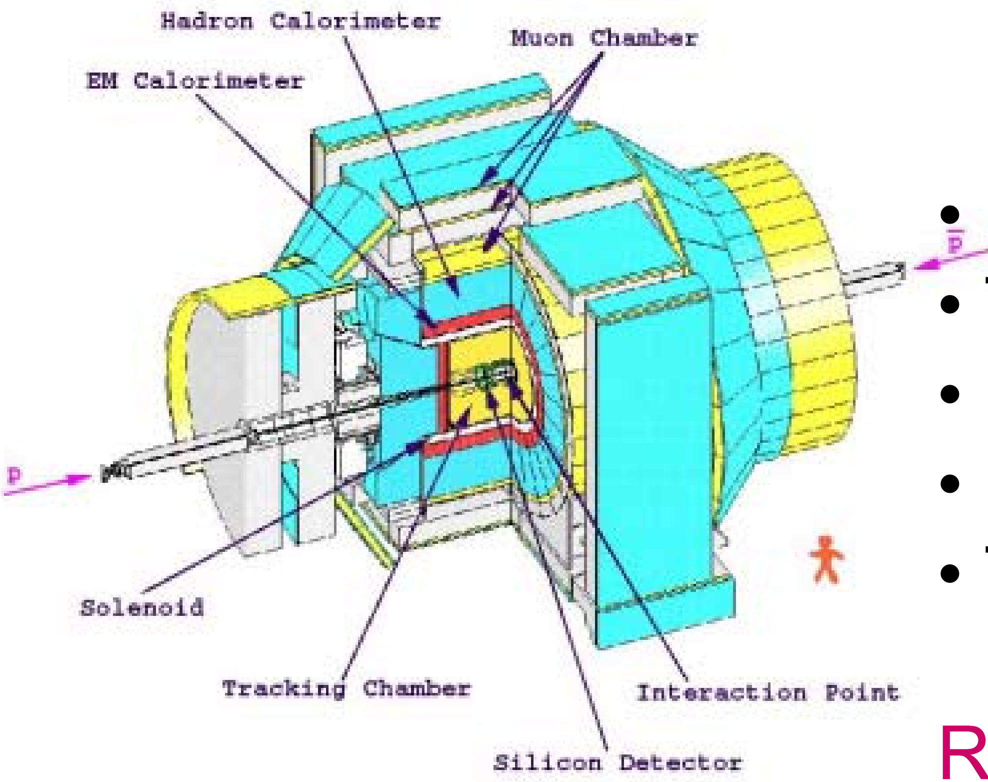
~220 pb^{-1} on tape per experiment



Typical detector efficiency ~85-90%

Luminosity used for HF analyses 6–140 pb^{-1}

CDF Run-II Detector

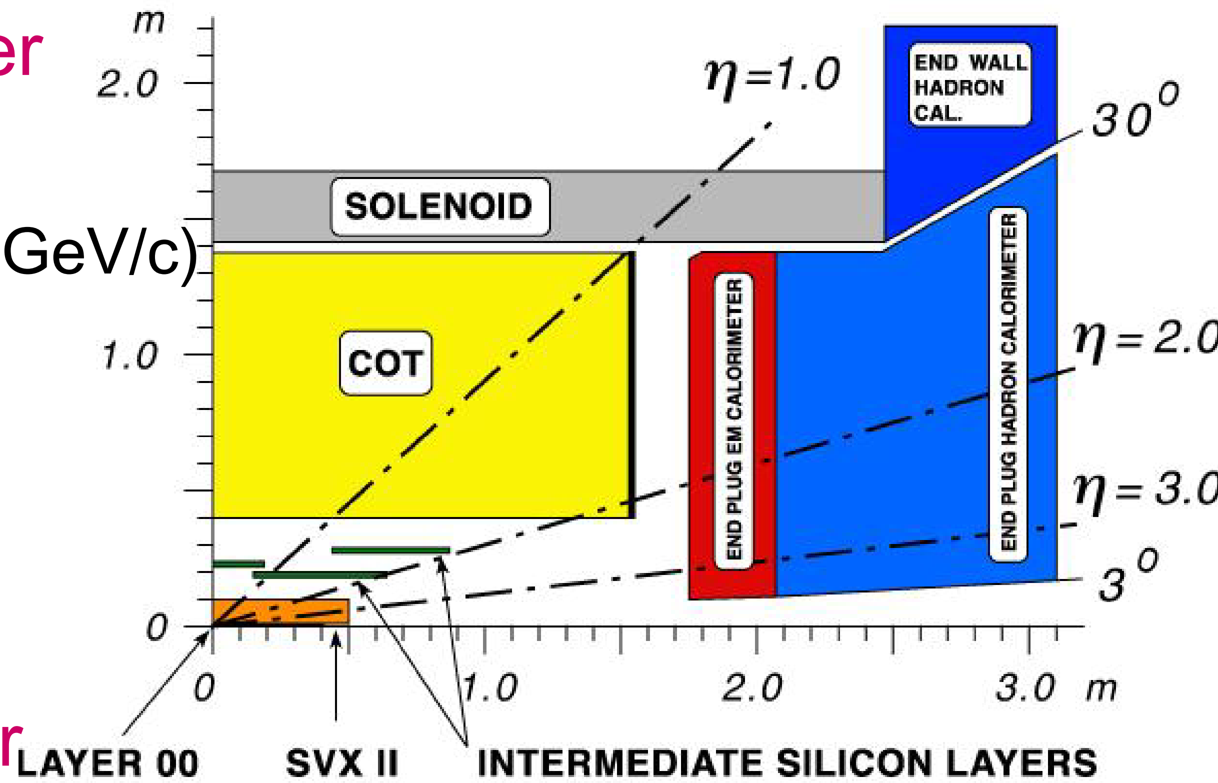


Many detector components are brand-new

- Tracking system
    - Silicon detectors
    - Main drift chamber
- FE electronics
- Trigger/DAQ
- Plug calorimeter
- Extended muon coverage
- TOF system

Retained good momentum resolution & lepton ID.

CDF Run-II Detector



Central Outer Tracker

- 30 k sense wires
- $\sigma(p_T)/p_T = 0.0008\, p_T$ (GeV/c)
- Relativistic rise dE/dx

Silicon detector

- 700 k channels,
- max 15 hits per track.

New plug calorimeter

- To $|\eta| < 3.6$, electron ID

TOF particle ID

- K/π separation to 1.5 GeV

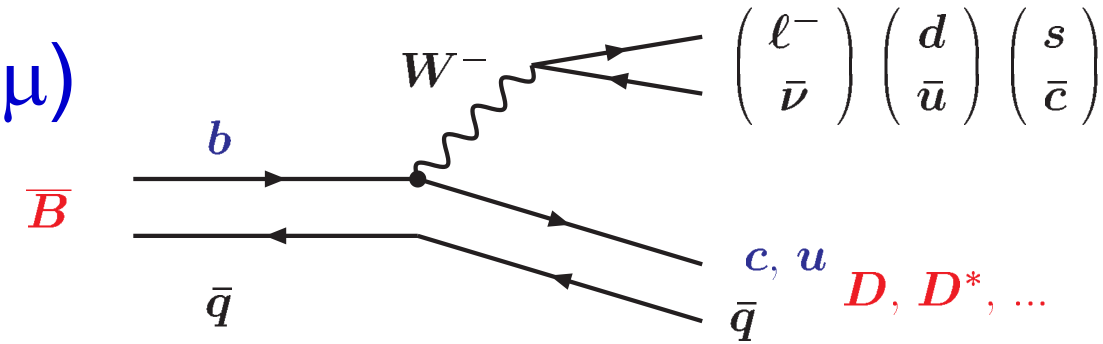
Muon coverage

To do B physics at hadron colliders, you need to trigger on B decays

Traditionally CDF relied on leptons :

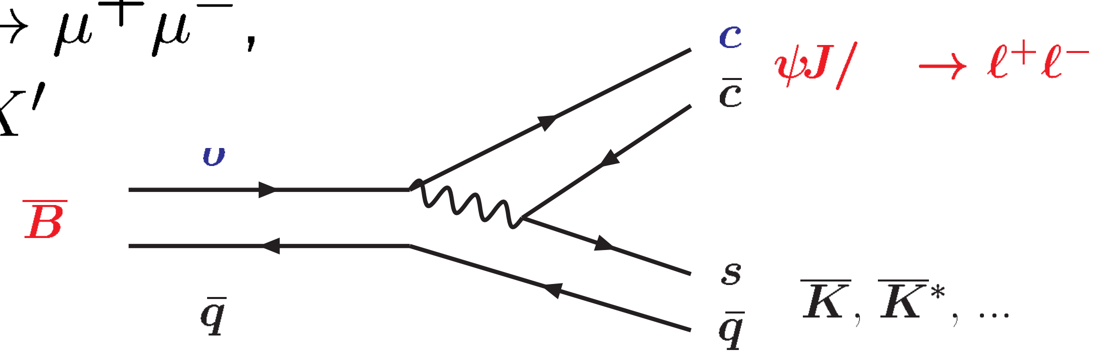
- Single leptons (e, μ)

$$\overline{B} \to \ell^- \bar{\nu} X$$



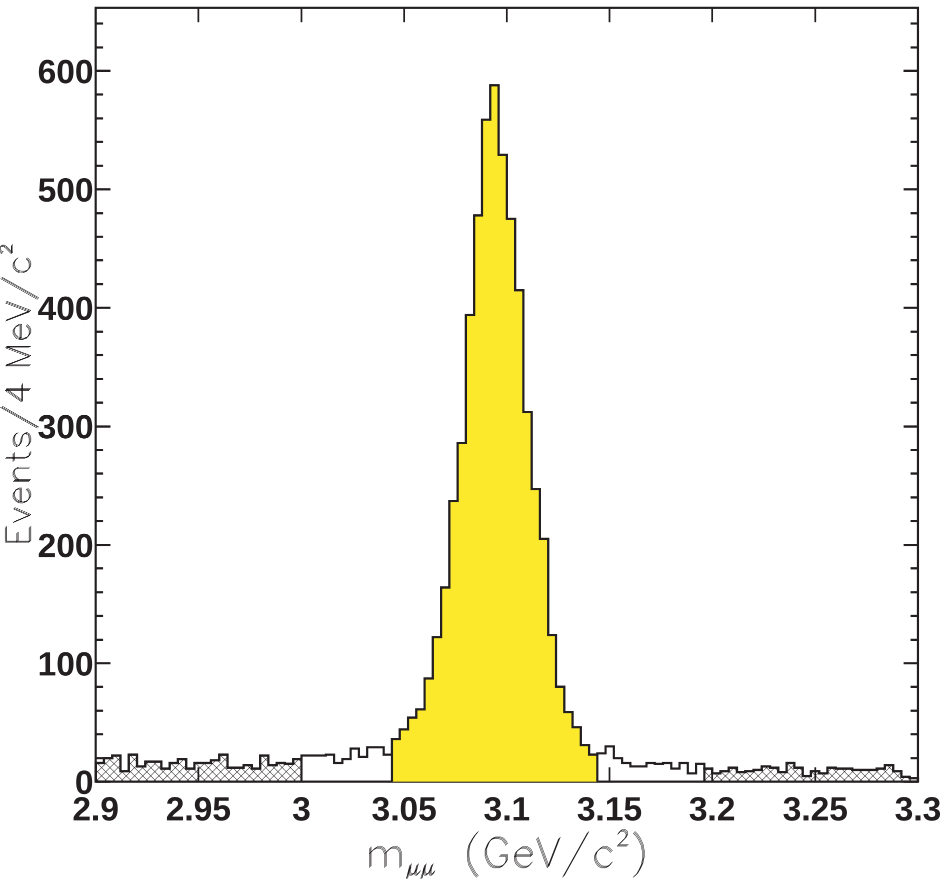
- Di-leptons (μμ, eμ)

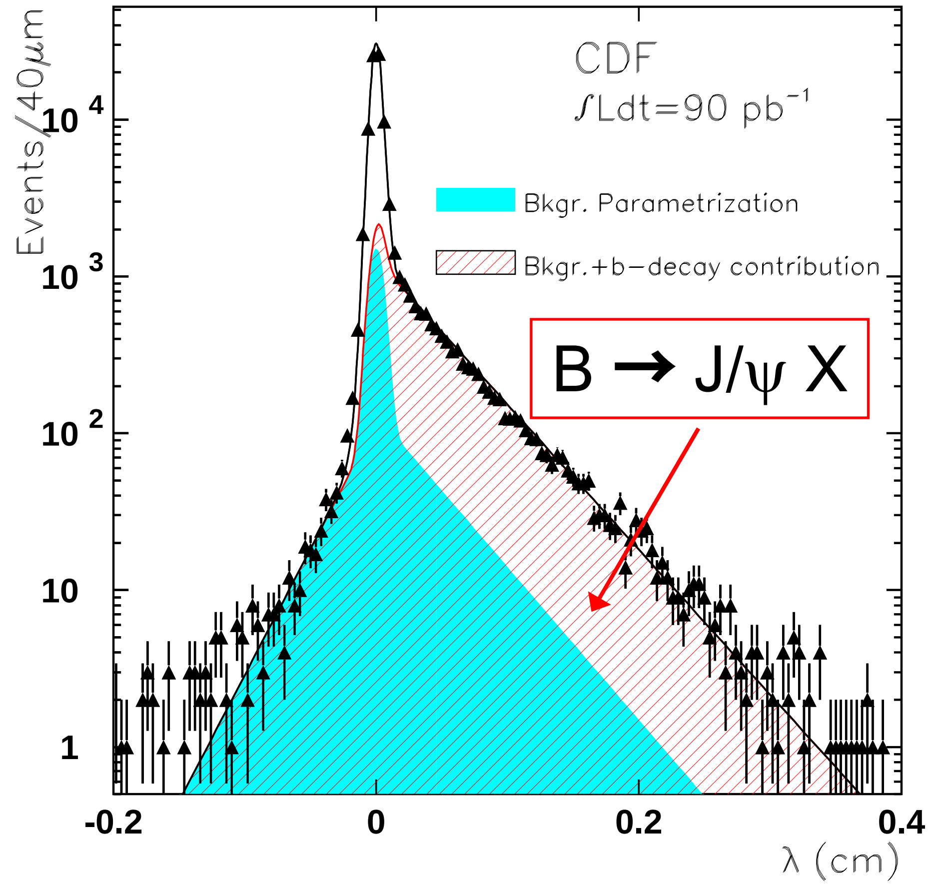
$$B \to J/\psi X,\ J/\psi \to \mu^+\mu^-,$$
$$b \to \ell^- X,\ \bar{b} \to \ell^+ X'$$



Run-I signal : $J/\psi \to \mu^+\mu^-$

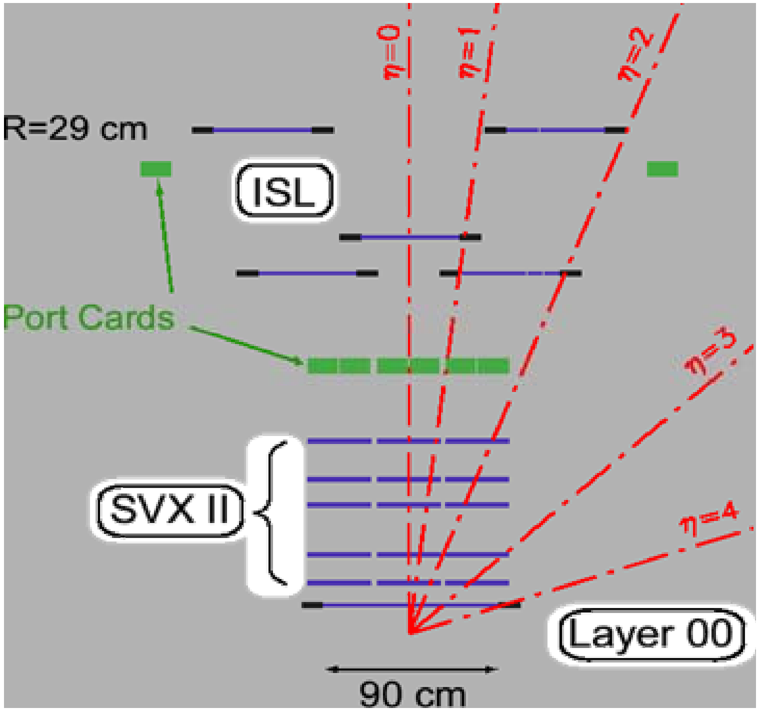
Decay length dist.

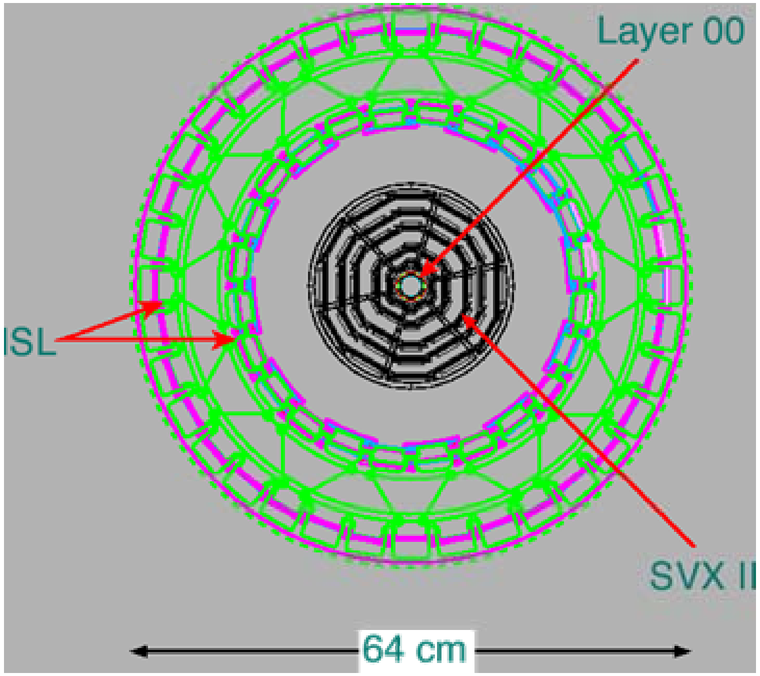




- ~240 k $J/\psi \to \mu^+\mu^-$.
- Mass resolution ~16 MeV/c^2.
- ~20% from *B* decays, others direct / $\chi_c \to J/\psi\ \gamma$.

CDF-II silicon detectors





SVX II

- Radii 2.5 cm to 11 cm
- 5 layers
- Double-sided, 90^{o} and 1.2^{o} stereo
- Main vertex detector

Intermediate silicon layers (ISL)

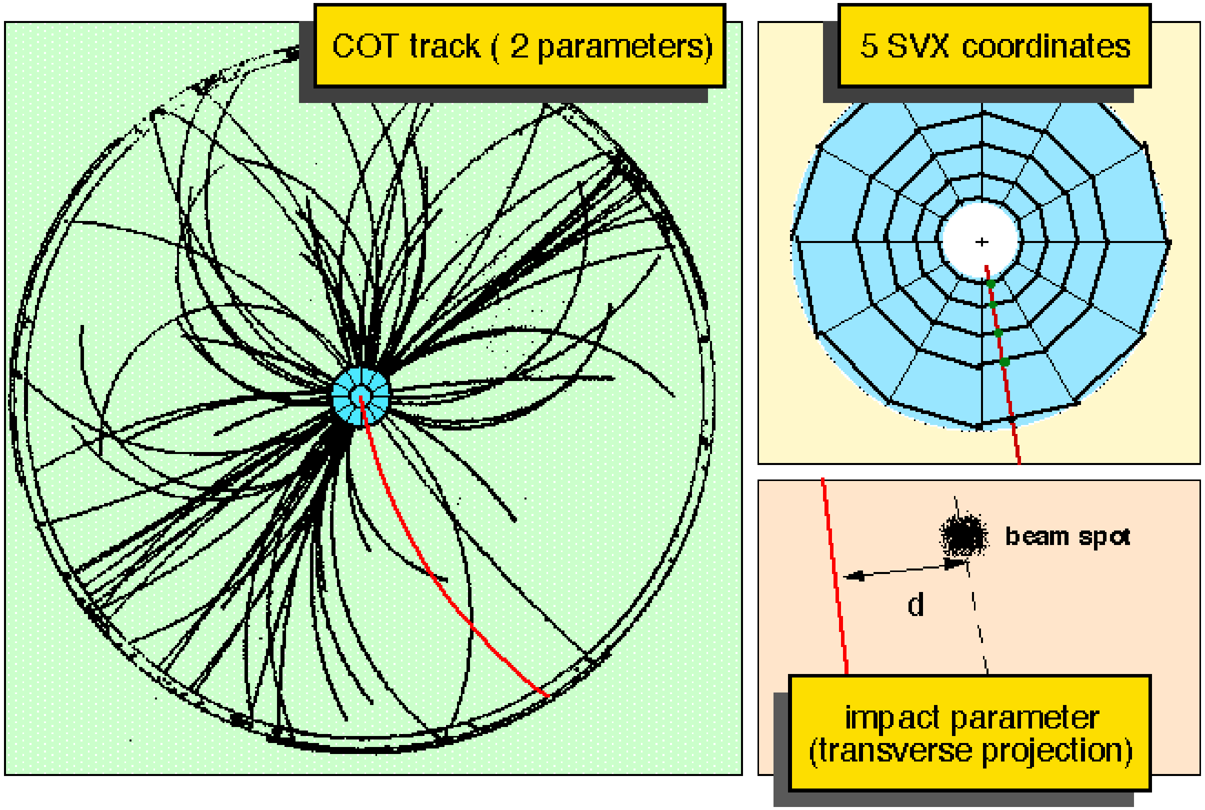
- 3 more layers at R = 20 - 29 cm
- Construction similar to SVX II
- Precision tracking to higher eta.
- Aid linking from COT to SVX.

Layer 00

- At radius ~1.6 cm, on beam pipe.
- Minimize multiple scattering effects.
- Single-sided.

Run-II Silicon Vertex Trigger : SVT

Use silicon information at the 2nd level of trigger

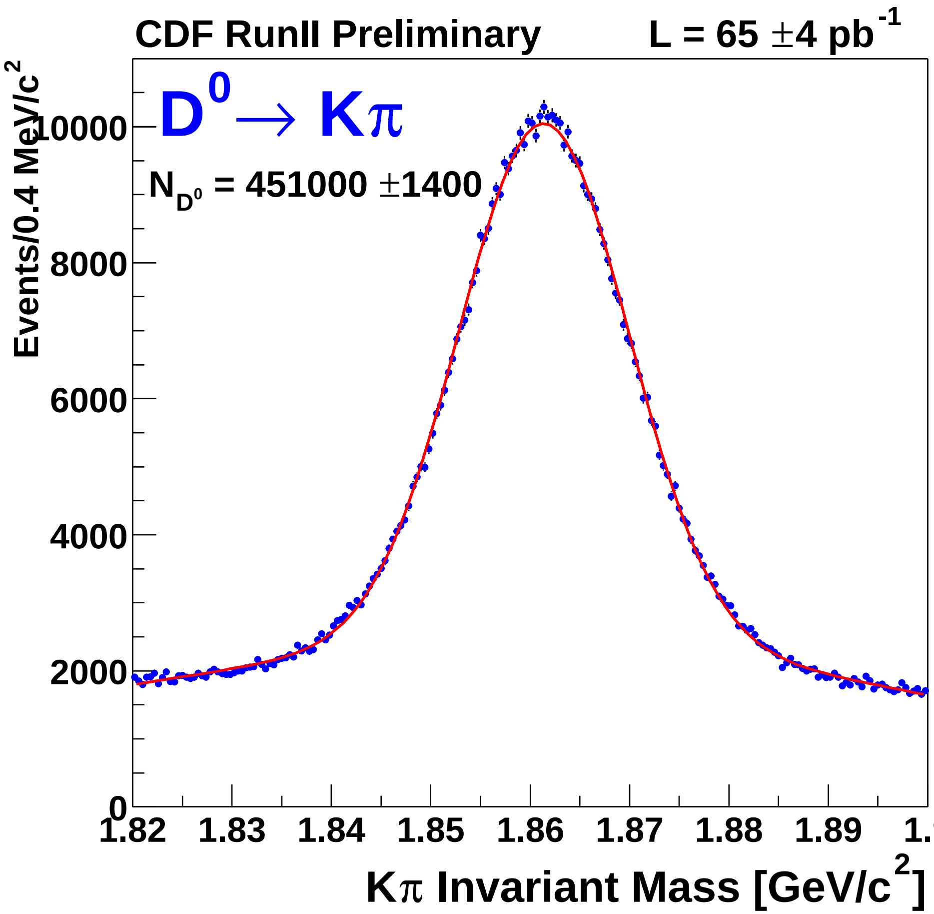


- Find a track in the main tracker COT.
- Extrapolate toward the SVX.
- Find SVX hits along the road.
- Calculate impact parameter wrt the primary vertex (beam spot).
- Resolution ~50 μm for > 2 GeV/c.

Typical trigger :
two tracks above 2 GeV/c,
| d | > 120 μm,
L_{xy} > 500 μm.

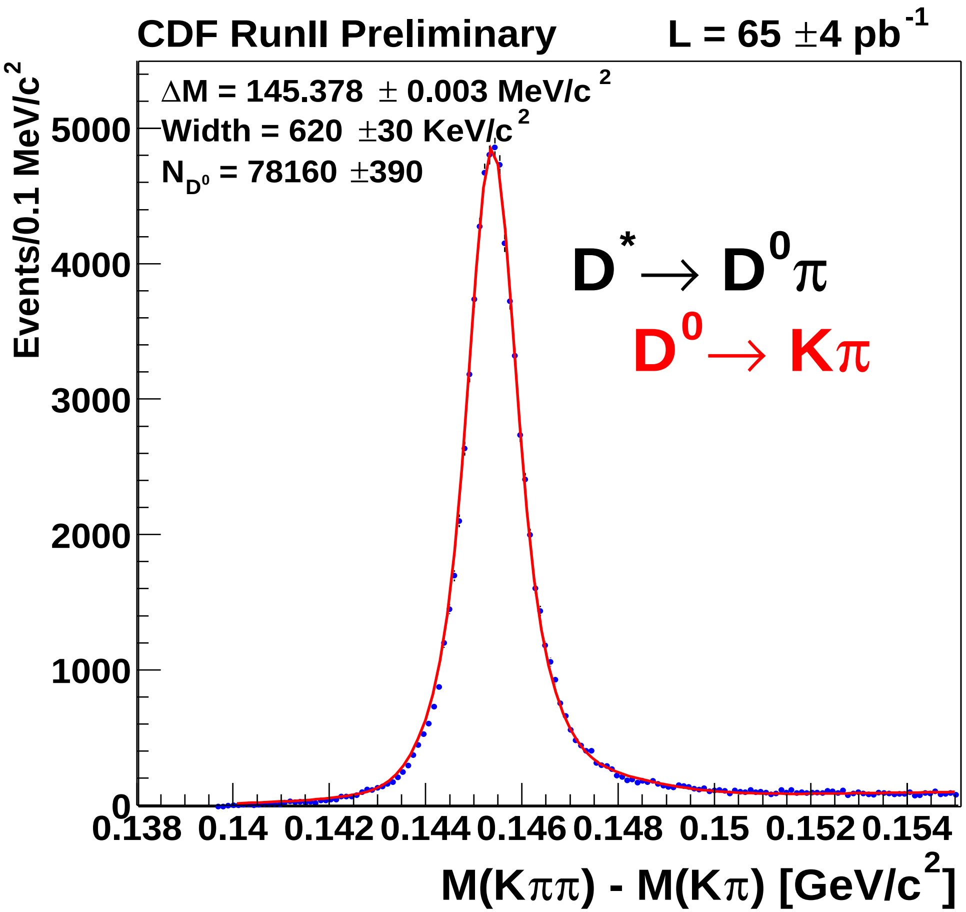
Huge charm signals observed

$D^0 \to K^- \pi^+$



$450 \text{ k ev. } / \ 65 \text{ pb}^{-1}$

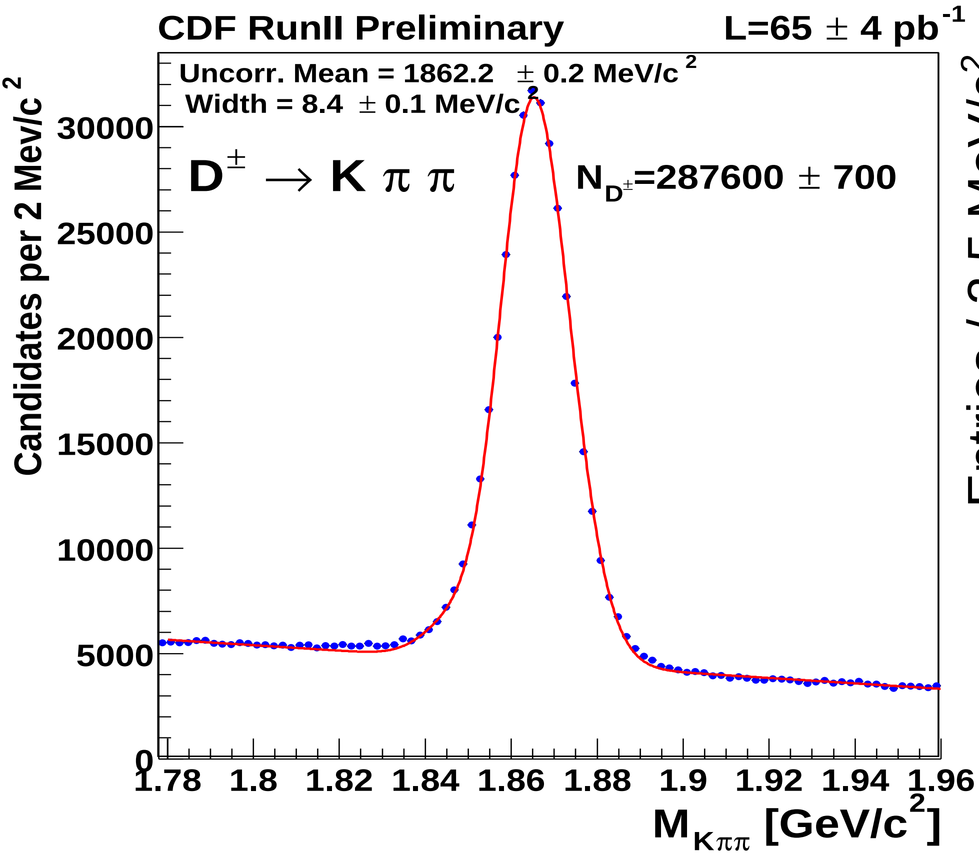
$D^{*+} \to D^0 \pi^+ \to (K^- \pi^+) \pi^+$

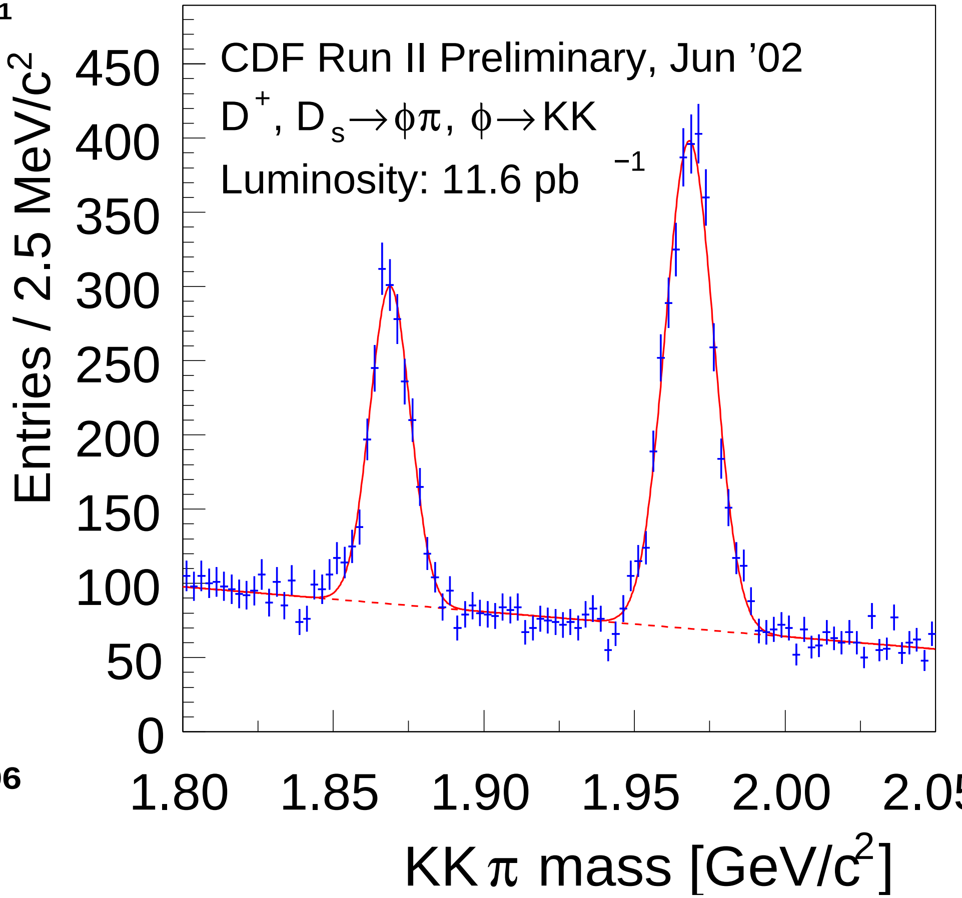


More charm

$D^+ \to K^- \pi^+ \pi^+$

$D_s^+ \to \phi \pi^+, \ \phi \to K^+ K^-$

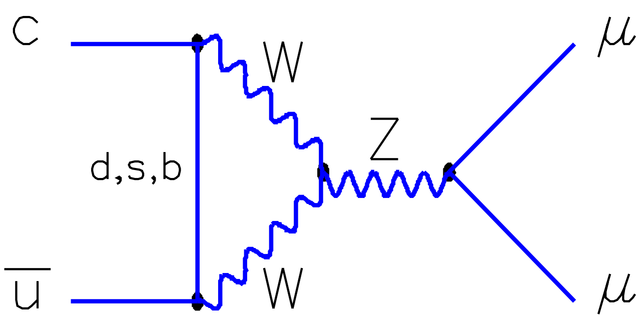


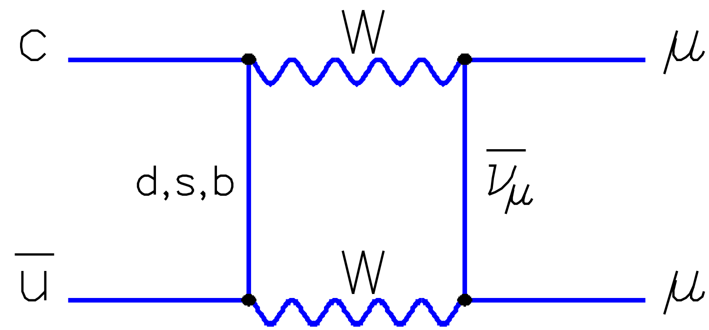


D meson production cross-sections measured.
Sub. to PRL (hep-ex/0307080)

Search for $D^0 \rightarrow \mu^+\mu^-$

FCNC decay. Proceed via loop and box diagrams in SM.



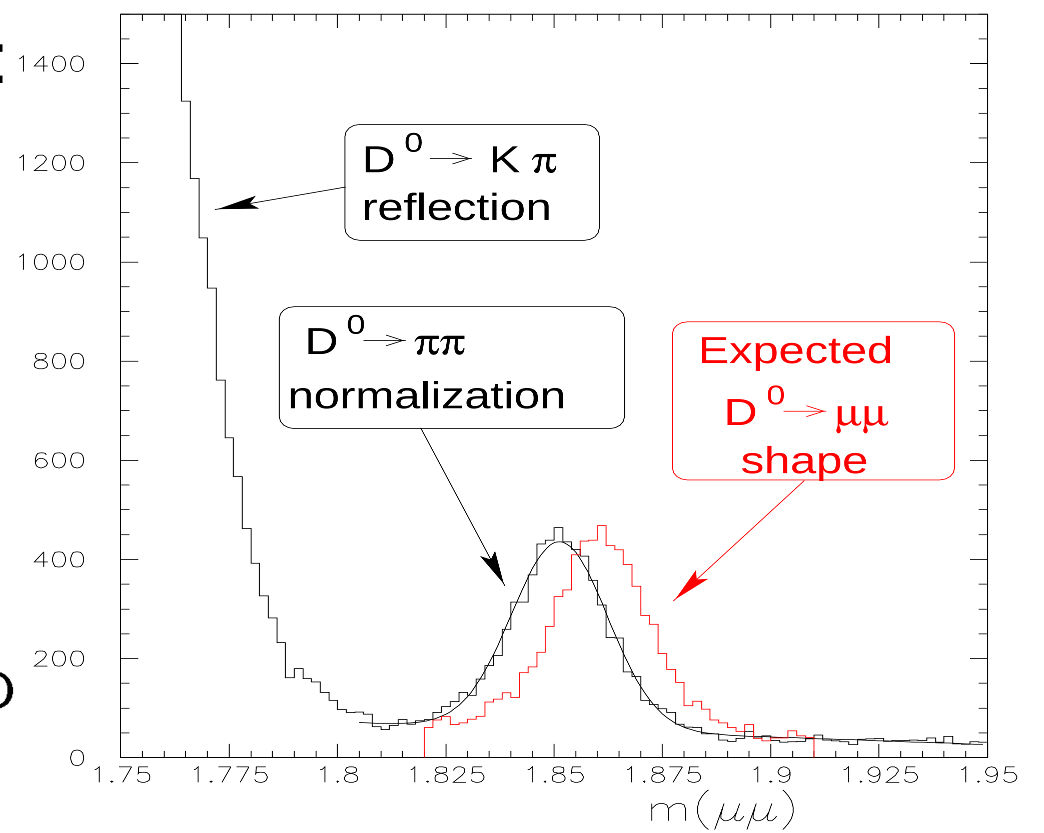


Also helicity suppressed :

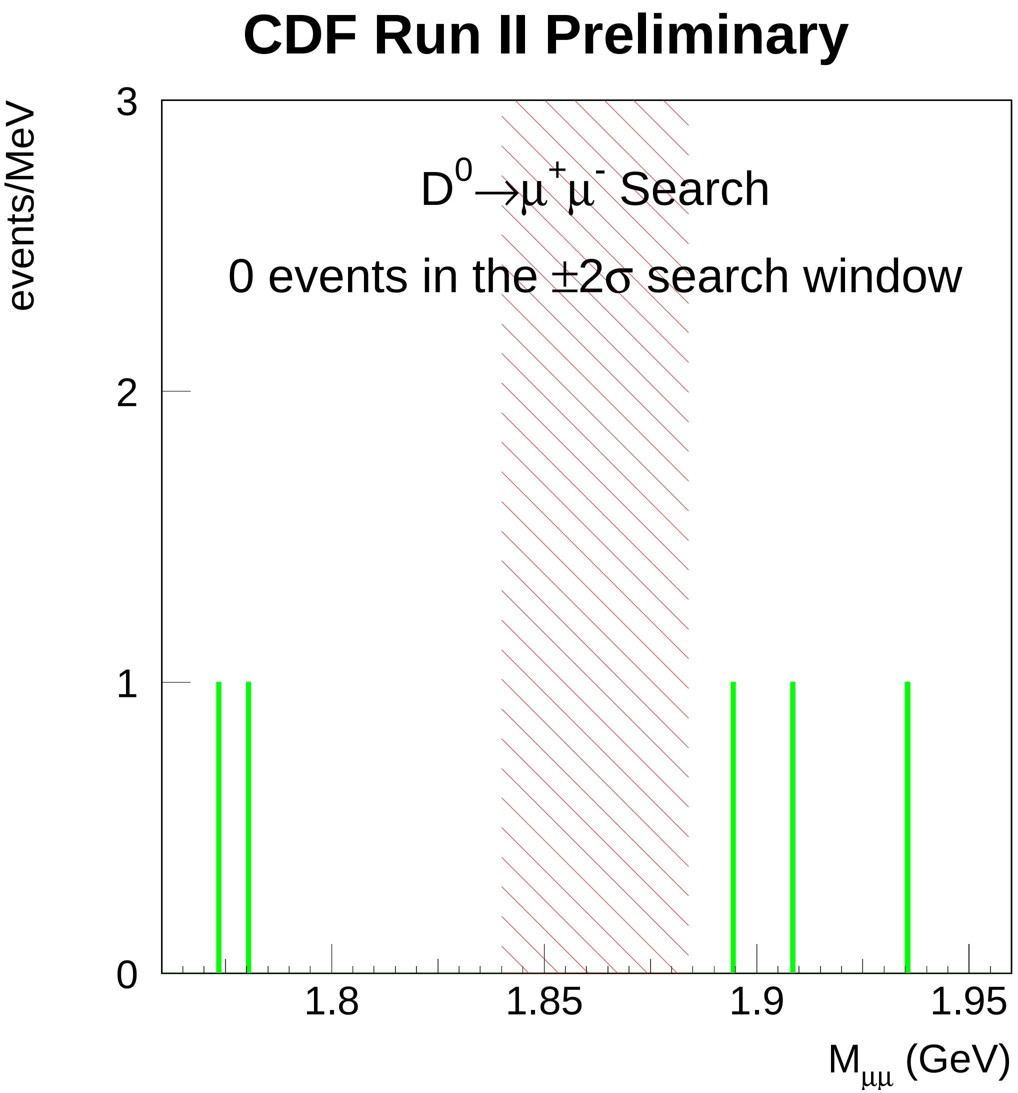
B.F. ~ 10^{-13}.

Good place to look for new physics effects.

Use $D^0 \rightarrow \pi^+\pi^-$ as normalization. Can also feed into signal region.



$D^0 \to \mu^+\mu^-$ search result



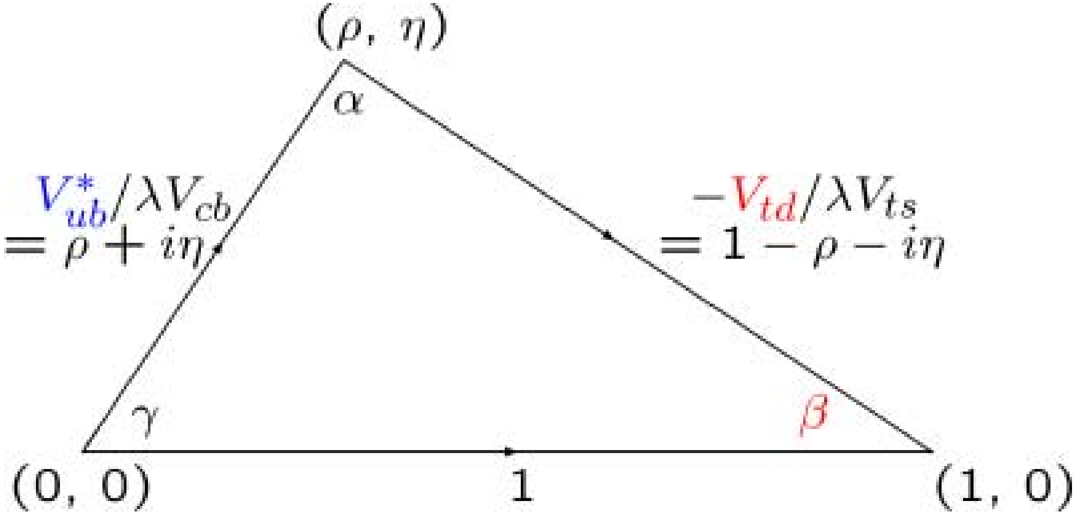
0 candidate observed,
1.7 BG expected.

$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.4 \times 10^{-6}$
(90% C.L.)

PDG 2002 :
$\mathcal{B}(D^0 \to \mu^+\mu^-) < 4.1 \times 10^{-6}$

Sub. to PRD,
hep-ex/0308059

B physics : does the unitarity triangle close?



- $|V_{cb}|$ from $b \to c\ell\nu$, $|V_{ub}|$ from $b \to u\ell\nu$.
- $|V_{td}|$ from Δm_d, but large QCD uncertainties.
- Use ratio to partially cancel the uncertainties

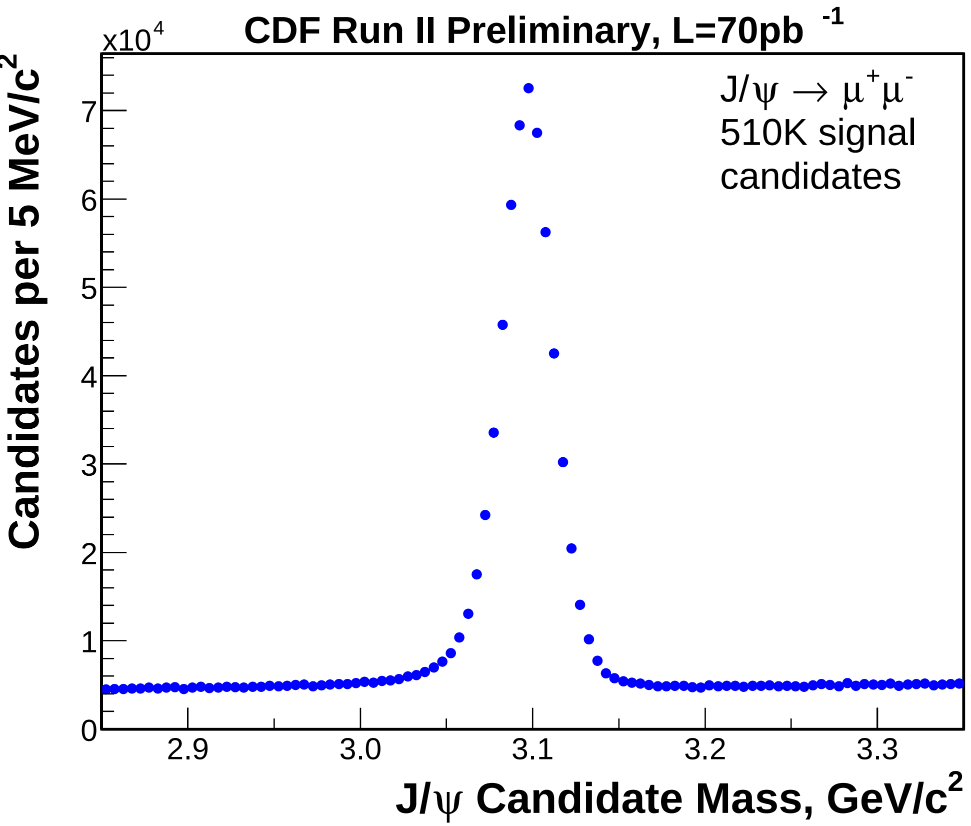
$$\frac{\Delta m_s}{\Delta m_d} = \left|\frac{V_{ts}}{V_{td}}\right|^2 \frac{M_{B_s}}{M_{B_d}} \xi^2 \quad (\xi = 1.14 \pm 0.03\,{}^{+0.13}_{-0.02})$$

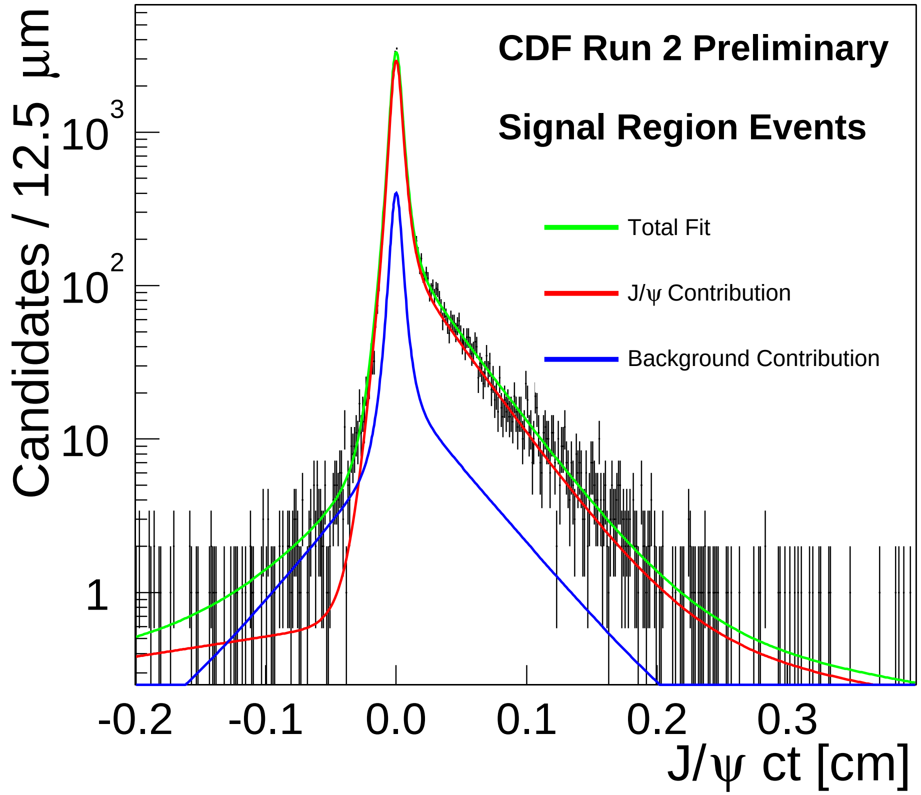
hep-ph/0307039
S. Aoki et al.

- Present limit on Δm_s (95% C.L.)

$$\frac{\Delta m_s}{\Delta m_d} > \frac{13.1}{0.489} \Rightarrow \left|\frac{V_{td}}{\lambda V_{ts}}\right| < 1.1$$

Run-II Di-muon data





p_T threshold lowered :
from 2 GeV/c to 1.5 GeV/c

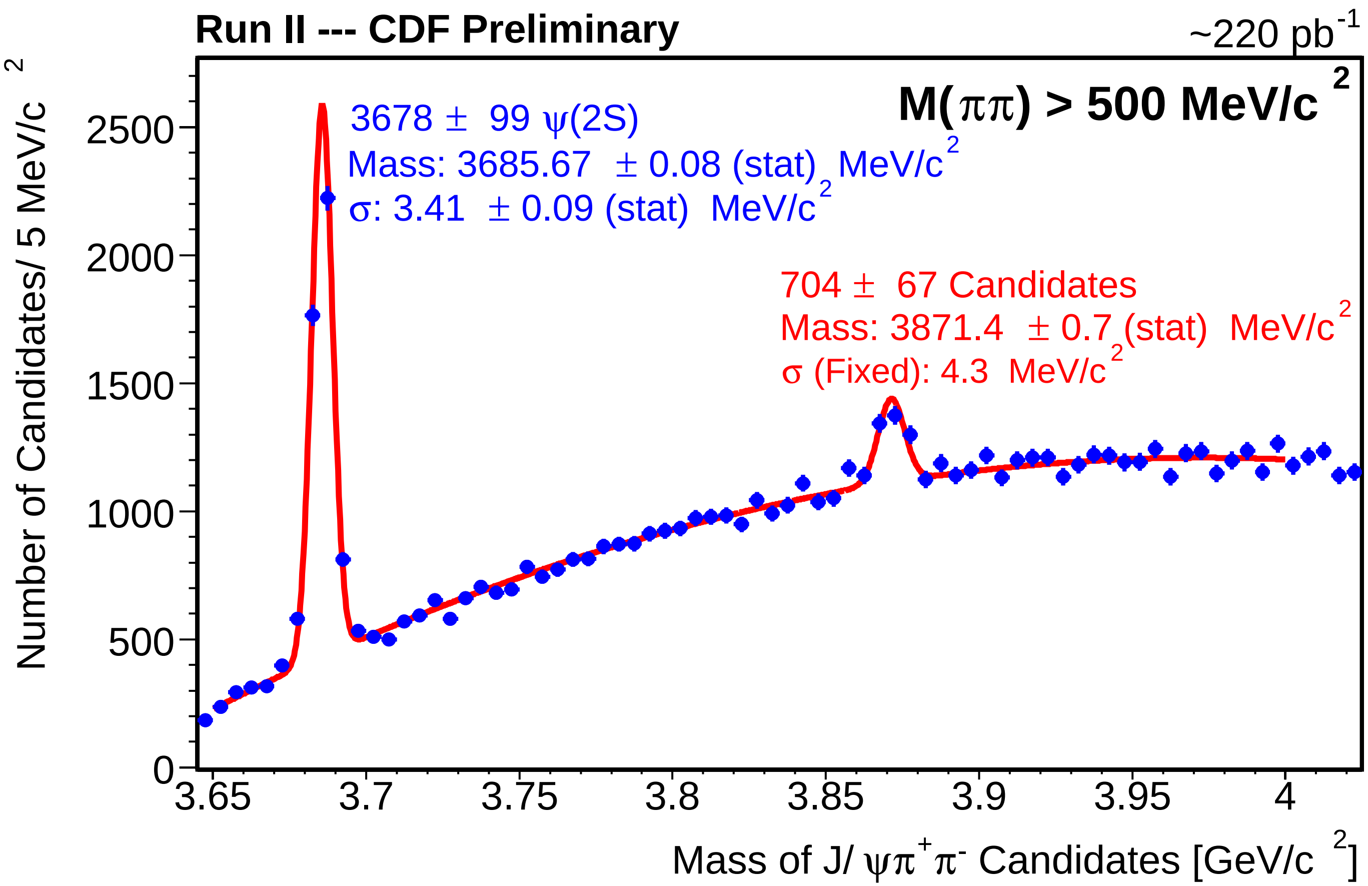
B fraction ~ 15%

$$\tau(B) = 1.526 \pm 0.034 \pm 0.035 \text{ ps}$$

Yield ~ 2 x Run I

State $X(3780) \to J/\psi\,\pi^+\pi^-$

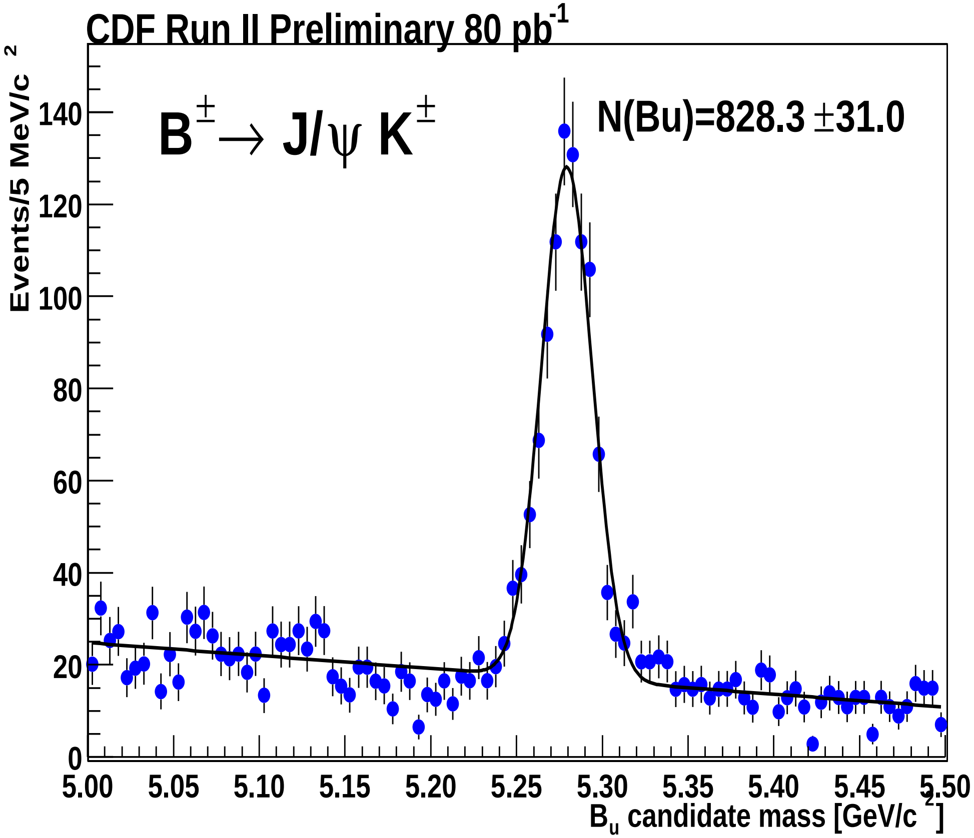
CDF confirms Belle discovery

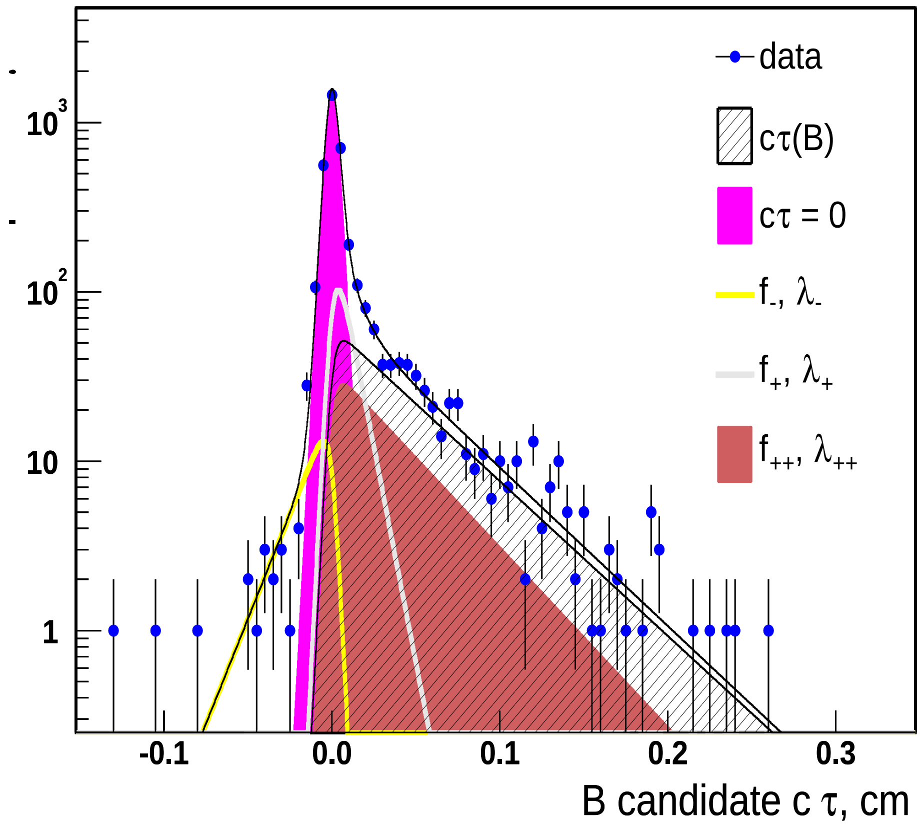


$$\text{Mass} : \ 3871.4 \pm 0.7 \pm 0.4 \ \text{MeV}/c^2$$

Width : narrow, consistent with resolution.

$$B^+ \to J/\psi\, K^+$$

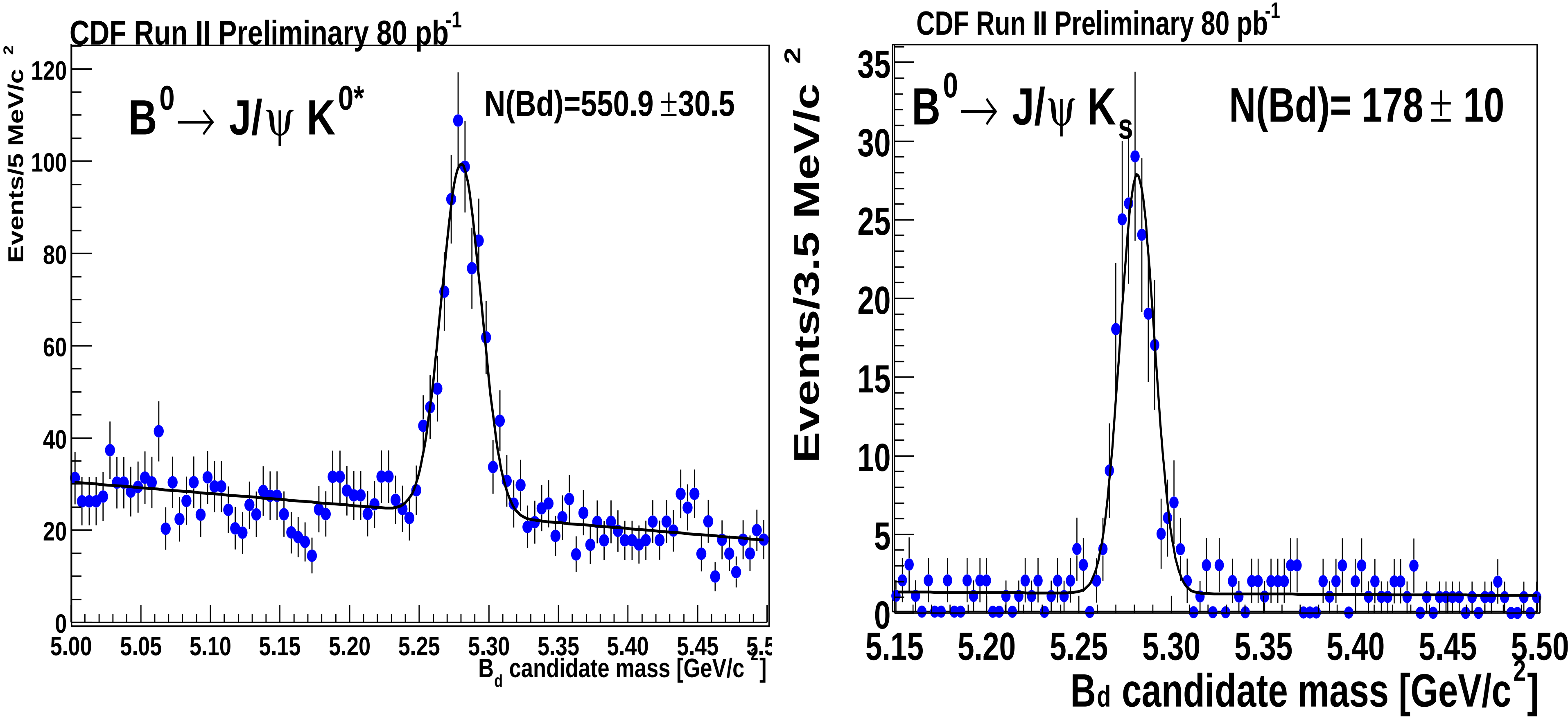




$$m(B^+) = 5279.32 \pm 0.68 \pm 0.94\ \text{MeV}/c^2$$
$$\tau(B^+) = 1.57 \pm 0.07 \pm 0.02\ \text{ps}$$

$B^0 \to J/\psi\, K^{*0} \to \mu^+\mu^-\, K^+\pi^-$

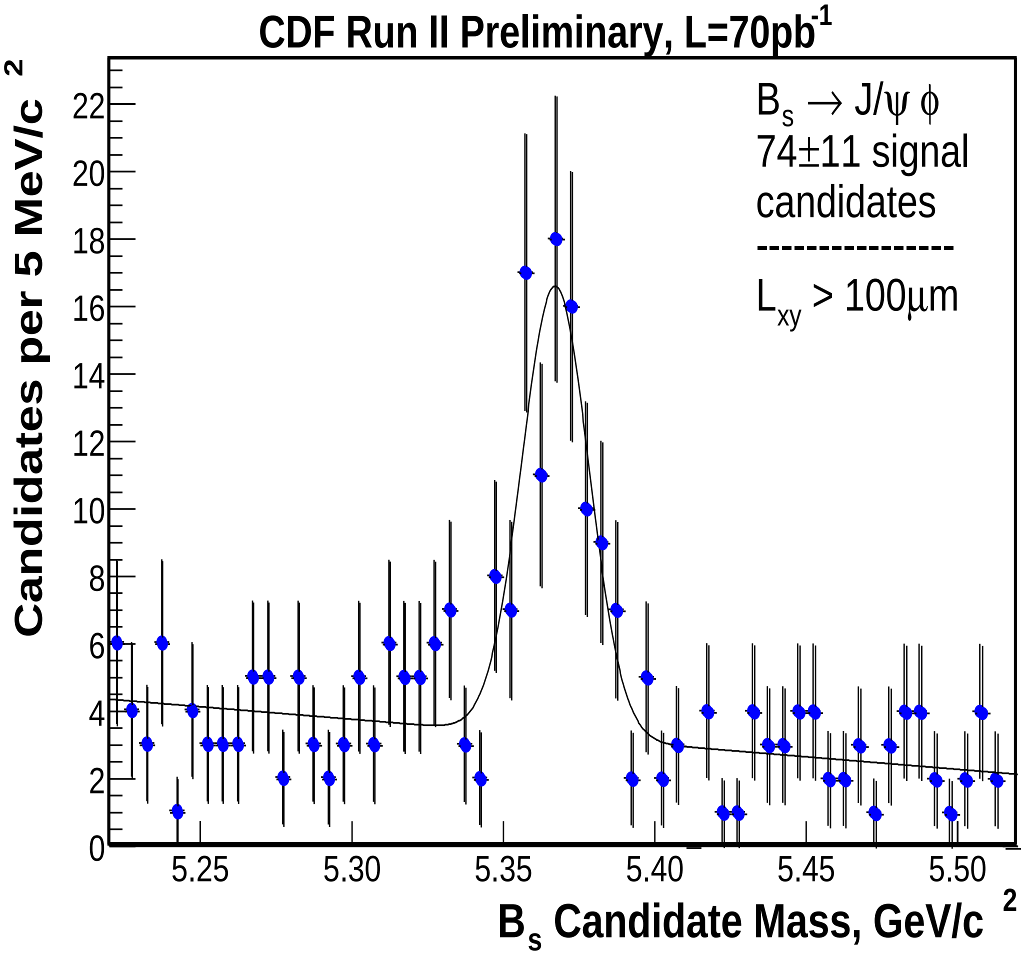
$B^0 \to J/\psi\, K_S^0 \to \mu^+\mu^-\, \pi^+\pi^-$



$m(B^0) = 5280.30 \pm 0.92 \pm 0.96\ \text{MeV}/c^2$

Mode for $\sin 2\beta$.

$B_s^0 \to J/\psi\,\phi \to \mu^+\mu^-K^+K^-$



Predict $\tau(B_s^0)/\tau(B^0) = 1.0 \pm \mathcal{O}(1\%)$

But expect $\Delta\Gamma_s/\Gamma_s \sim 0.1$.

This mode is dominated by CP-even eigenstate.
Can exhibit different τ from flavor eigenstates, e.g. $\ell^-\bar{\nu}D_s^+$ and $D_s^+\pi^-$.

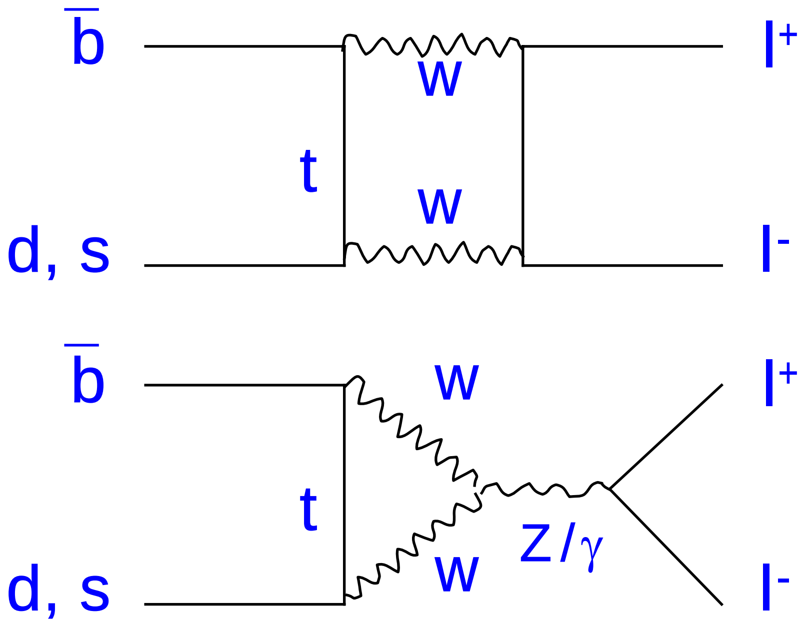
$m(B_s^0) = 5365.50 \pm 1.29 \pm 0.94$ MeV$/c^2$

$\tau(B_s^0) = 1.33 \pm 0.14 \pm 0.02$ ps

Future : look for CP-violation ~ zero expected in SM, arg(V_{ts}).

Rare decays $B^0/B_s^0 \to \mu^+\mu^-$

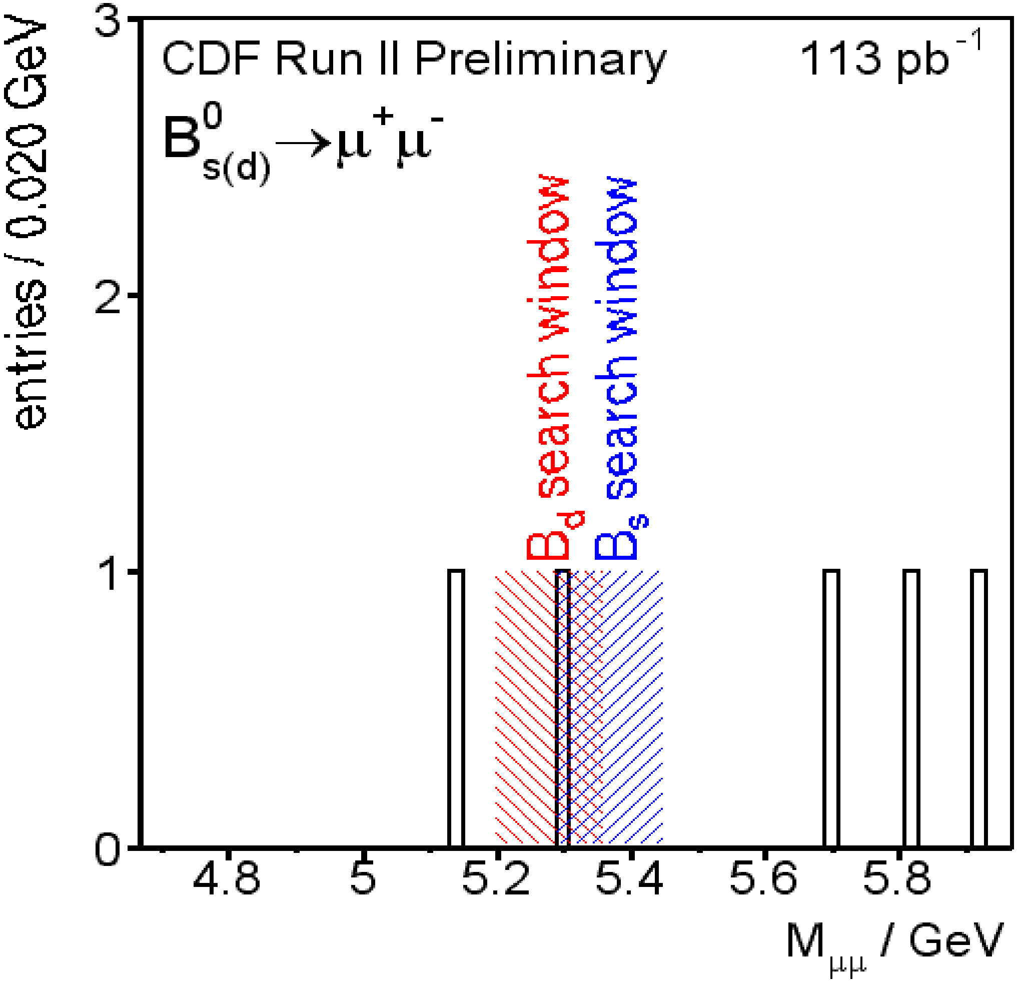
- V_{td} for B^0, V_{ts} for B^0_s
- Helicity suppressed.
- B.F. very small.



SM predictions for B.F.

- $B^0 \to \mu^+\mu^-$ $(1.5 \pm 1.4) \times 10^{-10}$
- $B_s^0 \to \mu^+\mu^-$ $(3.5 \pm 1.0) \times 10^{-9}$
- $B^0 \to e^+e^-$ $(3.4 \pm 3.1) \times 10^{-15}$
- $B_s^0 \to e^+e^-$ $(8.0 \pm 3.5) \times 10^{-14}$

Search for $B^0/B^0_s \rightarrow \mu^+\mu^-$



One candidate in the overlap region of B^0 and B^0_s mass windows.

B.R. < 3.1×10^{-7} for B^0

B.R. < 1.2×10^{-6} for B^0_s

@ 95% C.L.

Previous CDF limits :

B.R. < 8.6×10^{-7} for B^0

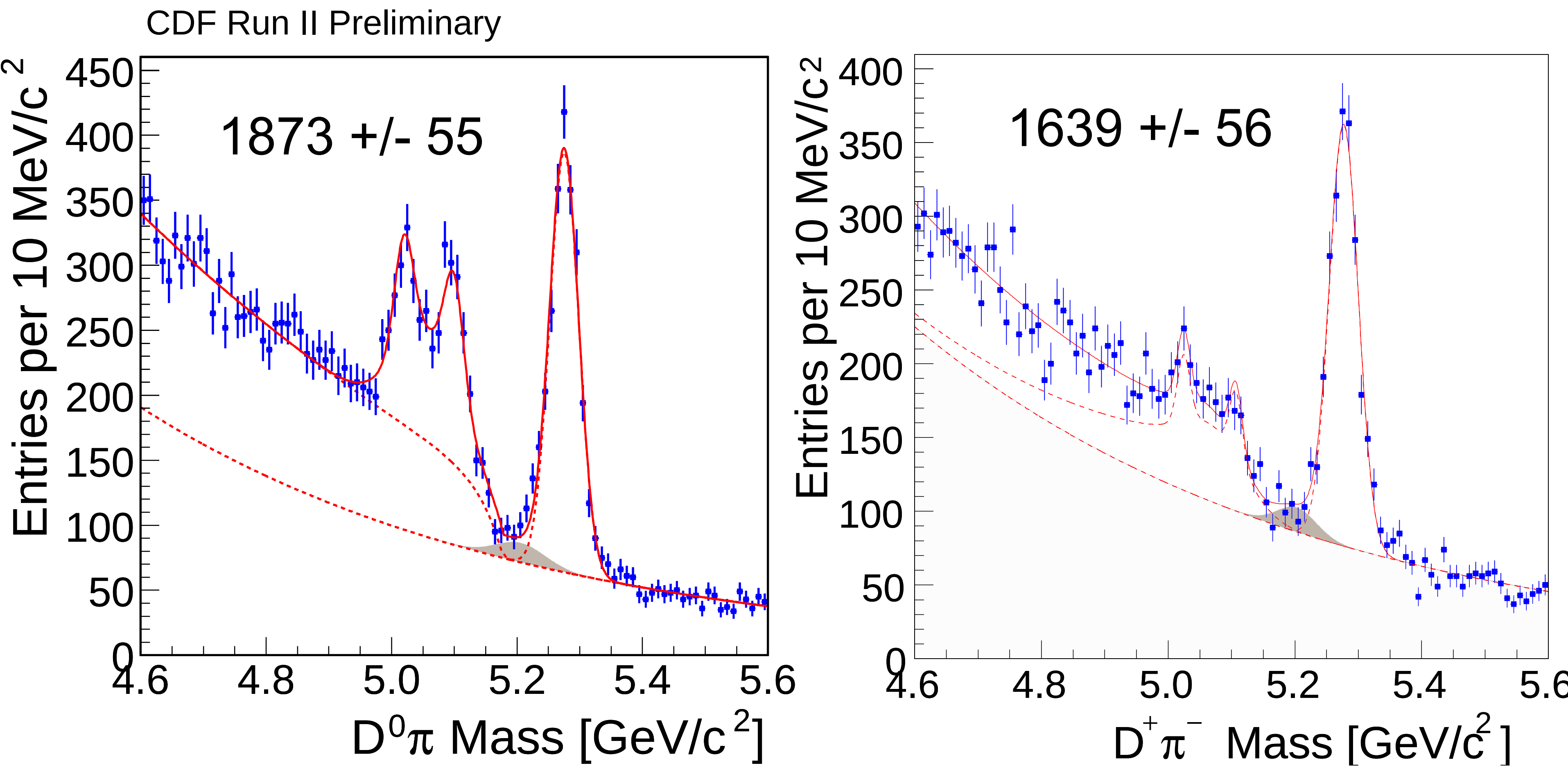
B.R. < 2.6×10^{-6} for B^0_s

PRD 57, 3811 (1998)

Some new physics models constrained.

B signals from SVT triggers : full reconstruction

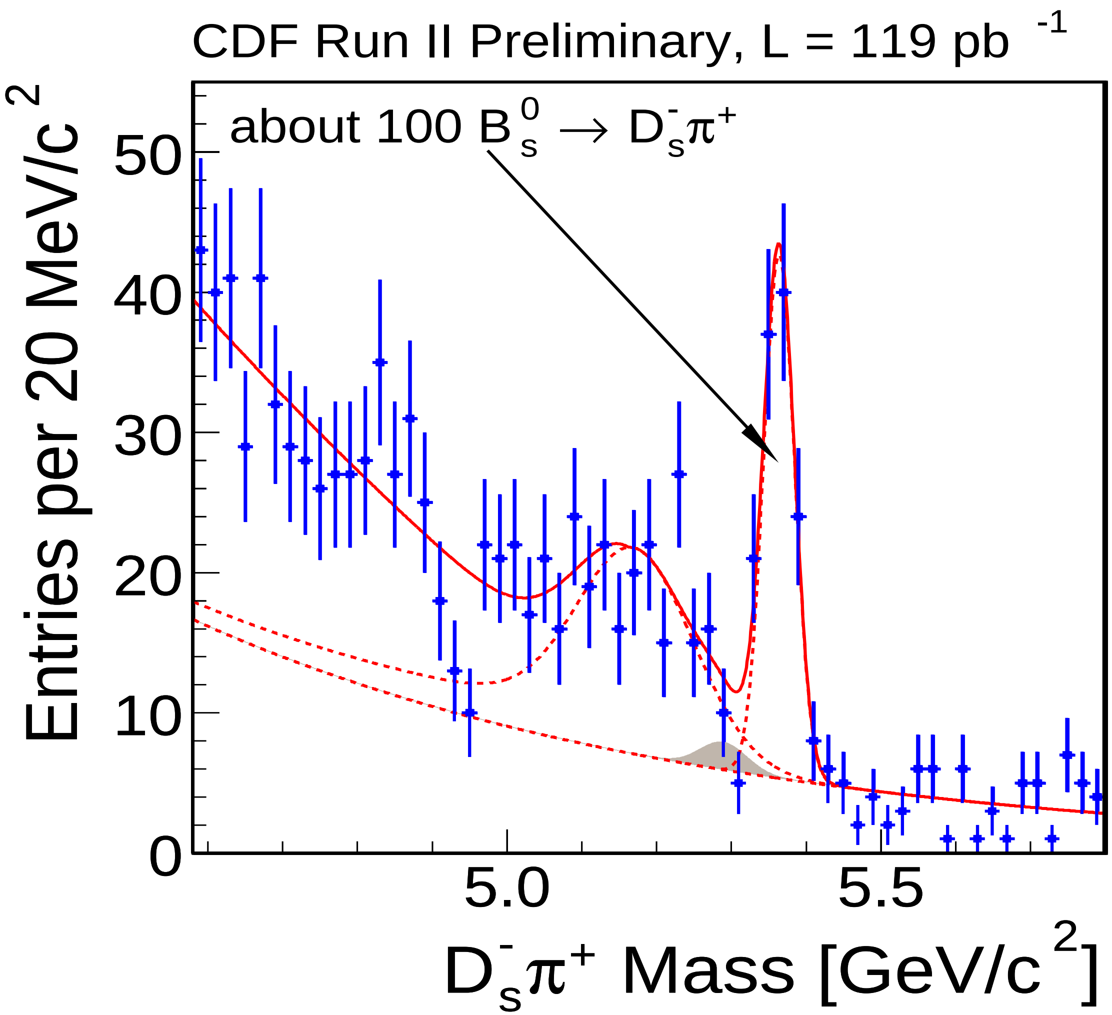
$B^- \to D^0\pi^- \to (K^-\pi^+)\,\pi^-$ $\qquad$ $\bar{B}^0 \to D^+\pi^- \to (K^-\pi^+\pi^+)\,\pi^-$



Calibration modes for B_s^0-$\bar{B}_s^0$ oscillations.

Understand proper time resolution and flavor tagging

What we wanted : $\bar{B}_s^0 \to D_s^+ \pi^- \to (\phi\pi^+)\pi^-$

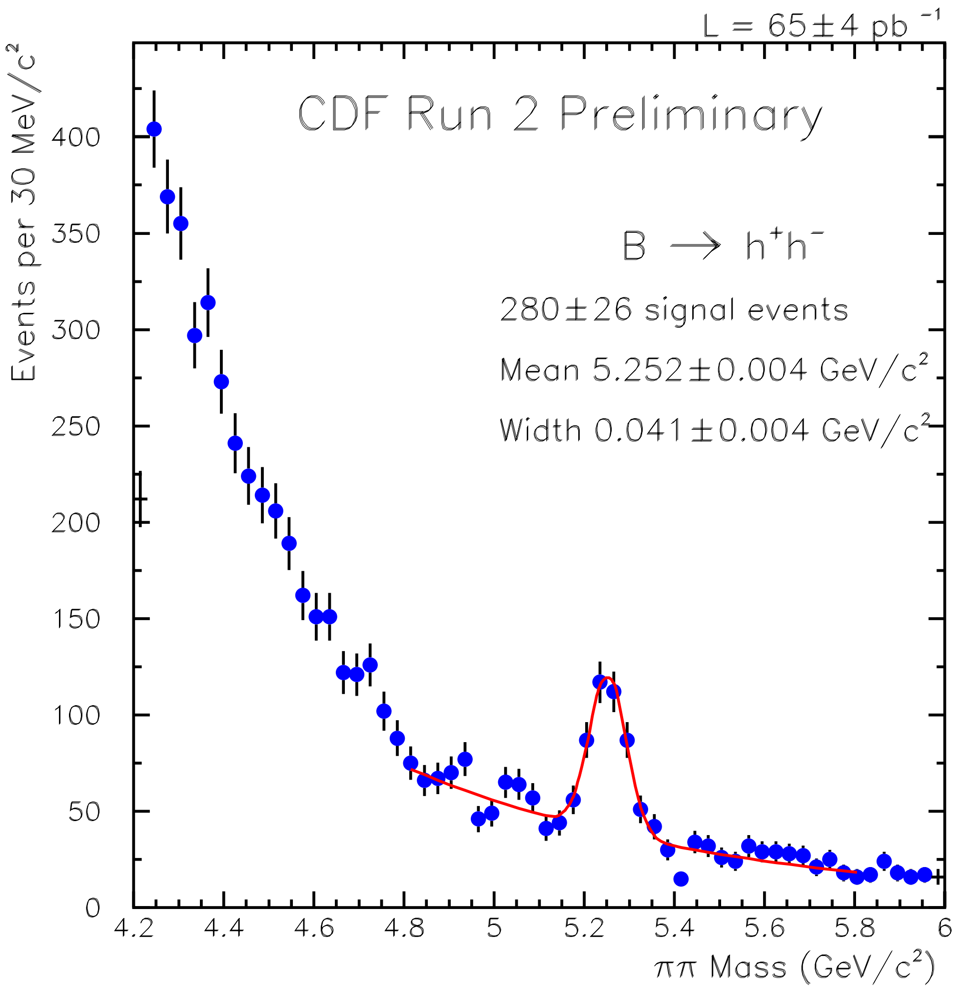


Next step :
Accumulate stats,
look for oscillations.

$\Delta m_s \Rightarrow$
Crucial for $|V_{td}/V_{ts}|$

Theory :
To what extent does the f_B uncertainty cancel in the ratio ξ ?
Does not seem as simple as we once thought…

What we wanted II : $B^0/B_s^0 \to h^+h'^-$

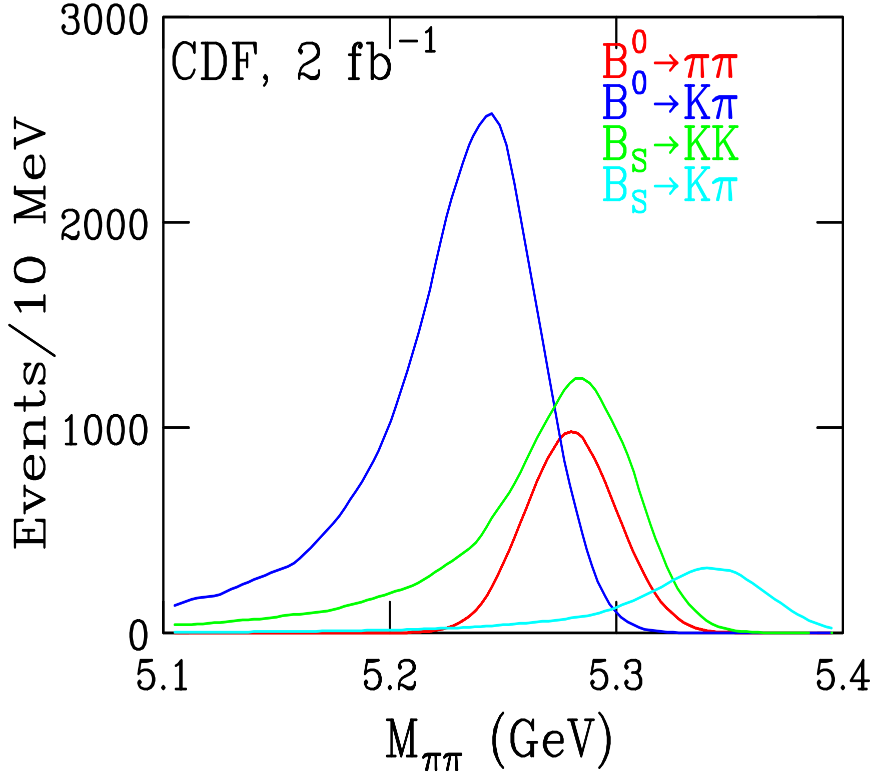


Pion mass assigned to $h^+ h^-$

Peak is mixture of

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

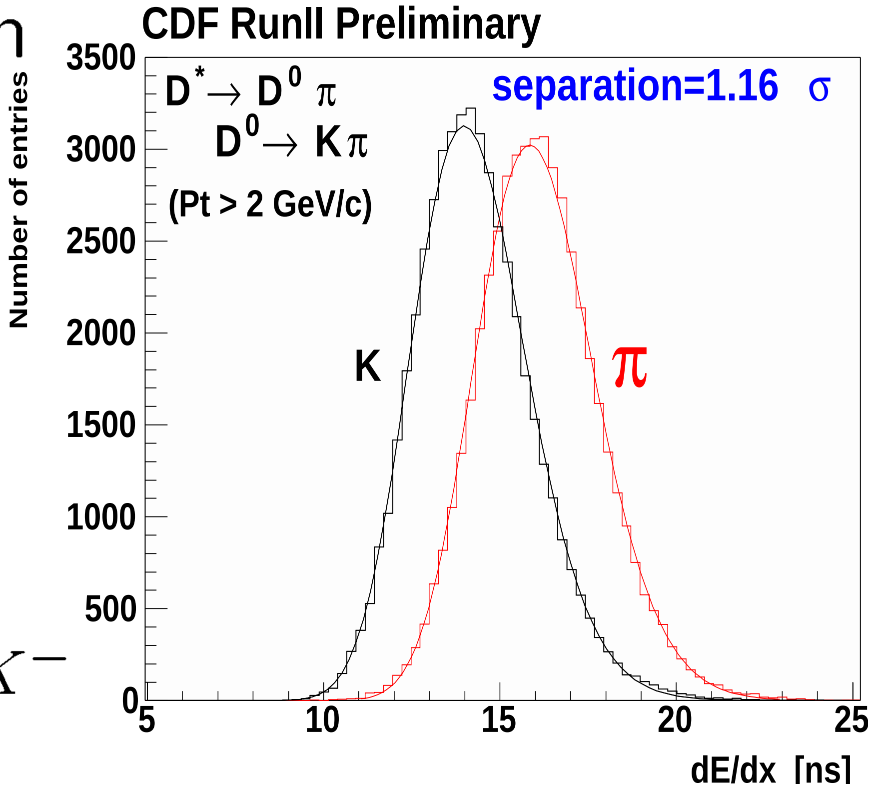
$B_s^0 \to K^+K^-,\ K^-\pi^+$



Use dE/dx and mass distributions to determine composition

$B^0/B_s^0 \to h^+h'^-$ composition

Mode	Yield (65 pb^{-1})
$B^0 \to K^+\pi^-$	$148 \pm 17 \pm 17$
$B^0 \to \pi^+\pi^-$	$39 \pm 14 \pm 17$
$B_s^0 \to K^+K^-$	$90 \pm 17 \pm 17$
$B_s^0 \to K^+\pi^-$	$3 \pm 11 \pm 17$



First observation of $B_s^0 \to K^+K^-$

$$\frac{f(b \to B_s^0) \cdot \mathcal{B}(B_s^0 \to K^+K^-)}{f(b \to B_d^0) \cdot \mathcal{B}(B_d^0 \to K^+\pi^-)} = 0.74 \pm 0.20 \pm 0.22$$

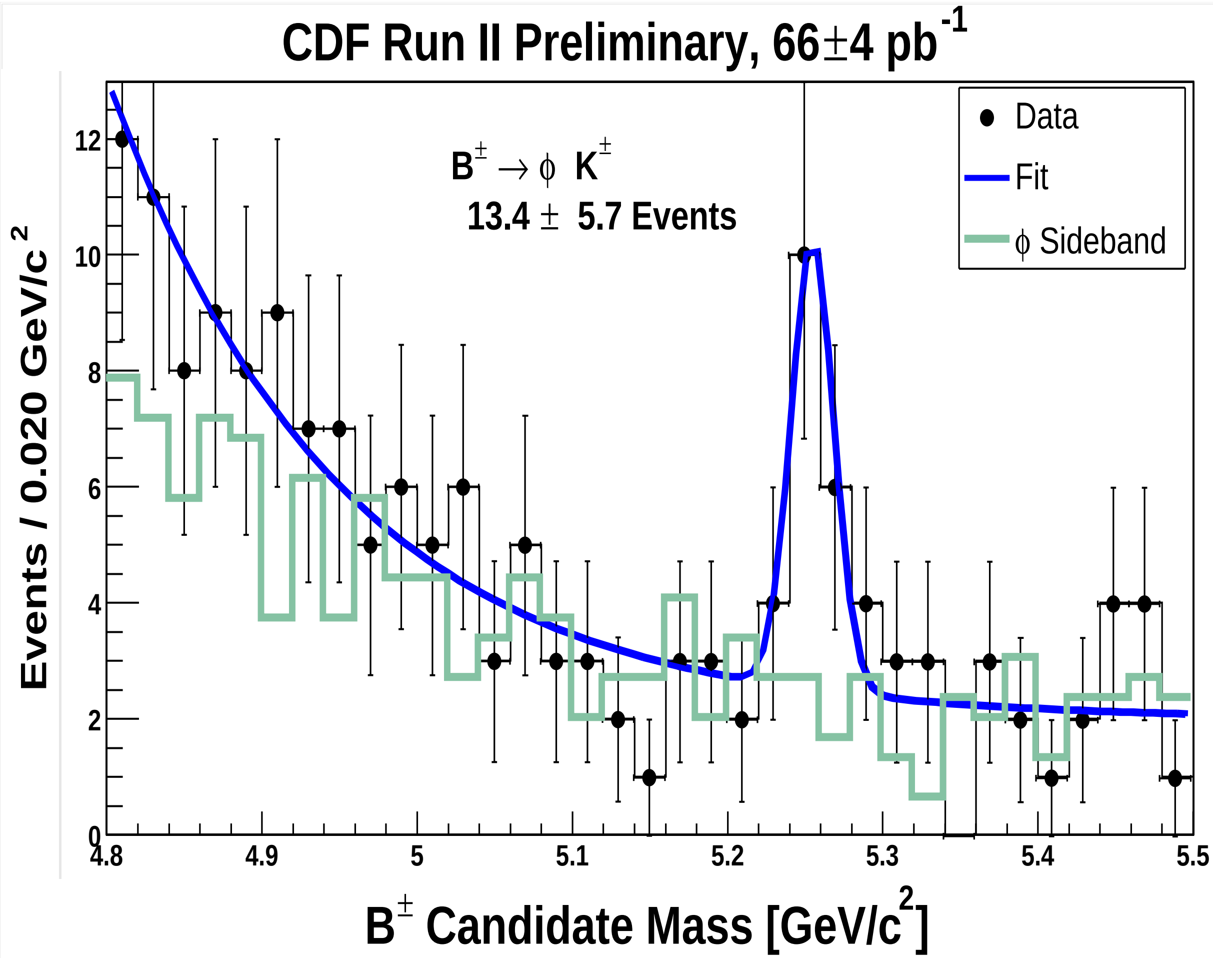
Also :

$$\mathcal{B}(B_d^0 \to \pi^+\pi^-)/\mathcal{B}(B_d^0 \to K^+\pi^-) = 0.26 \pm 0.11 \pm 0.06$$

$$\mathcal{A}_{\mathrm{CP}}(B^0 \to K^+\pi^-) = 0.02 \pm 0.15 \pm 0.02$$

Hope to extract angle γ in a longer term (after Δm_s)

Even $B^+ \to \phi K^+$ is seen



$$\frac{\mathcal{B}(B^+ \to \phi K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = (0.68 \pm 0.21 \pm 0.07) \times 10^{-2}$$

Summary

CDF Run-II in progress since 2001 :

- Finally we are back in business.
- So far recorded 250 pb^{-1}, analyzed up to ~100 pb^{-1}
  - surpassed Run-I total. More to come.
- Enhanced B physics capabilities :
  - has added silicon-based trigger, enabling to collect all-hadronic final states such as $B \rightarrow D\ \pi$.
  - lepton triggers remain valuable.
- Hope to collect ~2 fb^{-1} in the coming few years, and to make significant measurements of B decays. Some are quite complementary to Belle/BaBar.

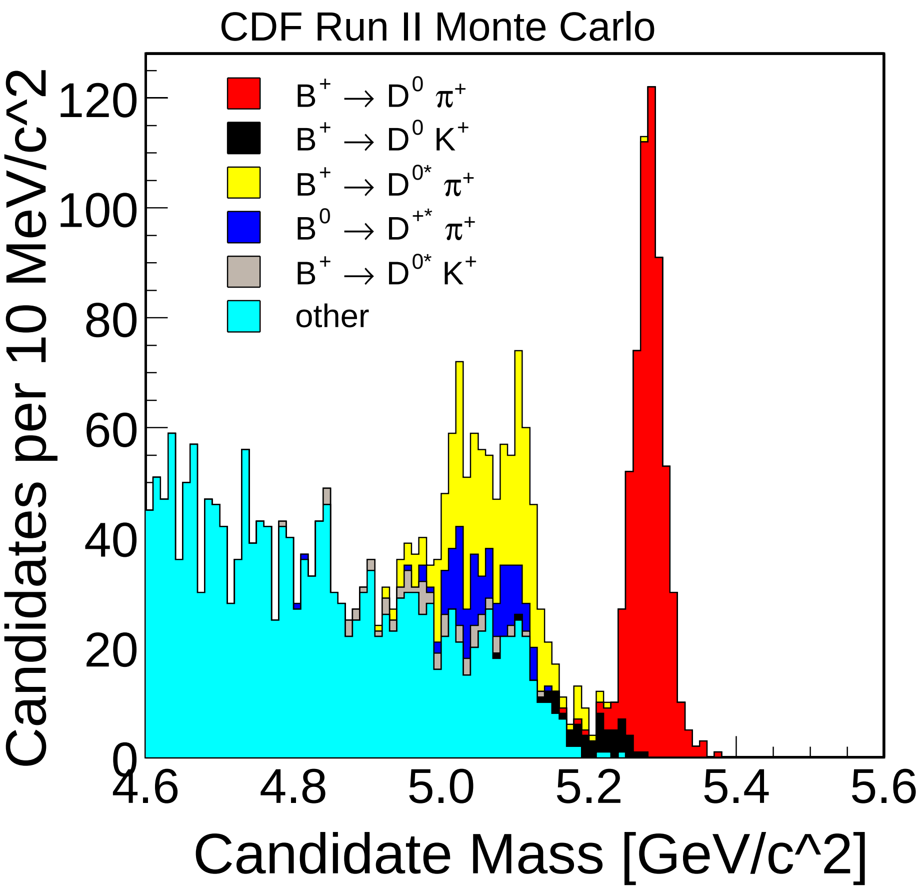
Plans

- Open and onium charm/bottom production.
- B^-, $\bar{B}^0$, $\bar{B}^0_s$, Λ^0_b, B^-_c masses/lifetimes.
  Also $\Delta\Gamma_s$.
- Re-establish B^0-$\bar{B}^0$ oscillations, calibrate flavor tagging.
- Measure $\sin 2\beta$.
- Rare decays, $B \to K^{(*)}\ell^+\ell^-$, $B^0_s/D^0 \to \mu^+\mu^-$.
- Measure Δm_s with $\bar{B}^0_s \to D^+_s\pi^-$.
- Measure CP violation in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$.
  Angle γ to 10° ?
- Look for CP violation in $B^0_s \to J/\psi\,\phi$,
  new phase in B^0_s oscillations ??
- Angle γ from $\bar{B}^0_s \to D^\pm_s K^\mp$???

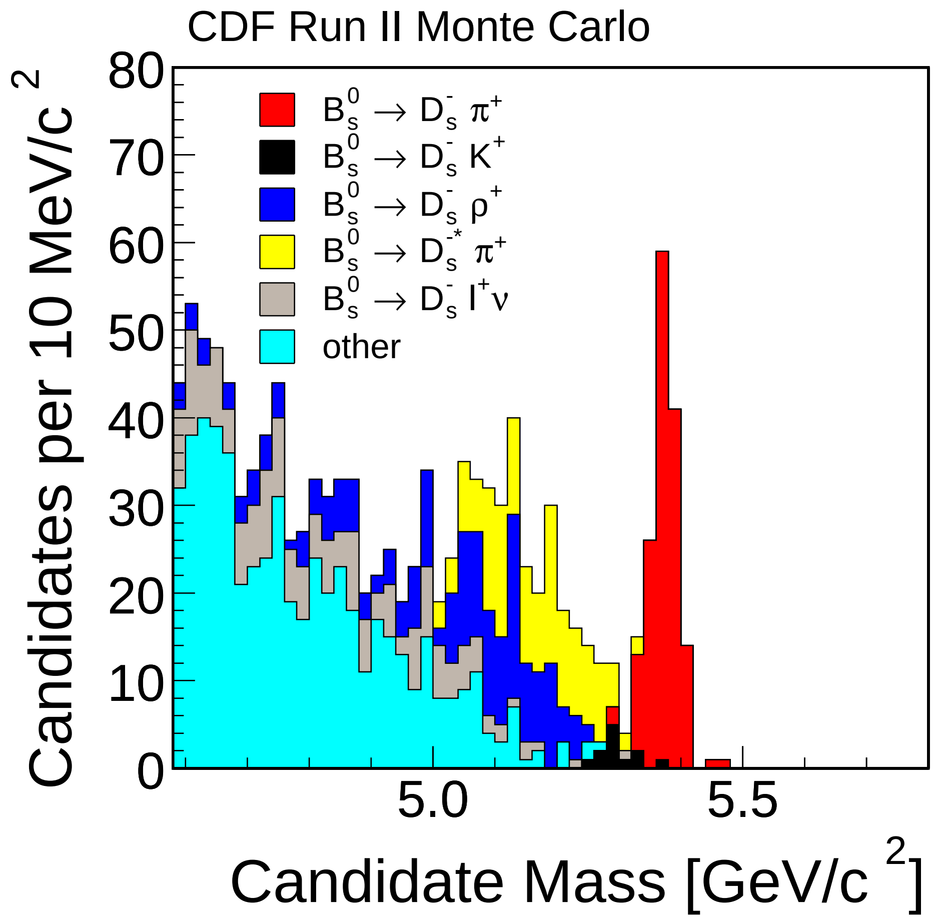
Backup Slides follow

$\bar{B} \to D\pi^-$ mass distribution from Monte Carlo

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



$\bar{B}_s^0 \to D_s^+\pi^-$



Structure below B mass understood from missing neutrals.

Probing angle γ (phase of V_{ub})

- $B^0 \rightarrow \pi^+ \pi^-$ once thought to be the mode for $\sin 2(\pi-\gamma-\beta)$.

  (assuming $b \rightarrow u$ tree dominance over penguin)
- CLEO finds much larger $K^- \pi^+$ and tiny $\pi^+ \pi^-$.
- Not just small rates, but also means penguin pollution.

  $\rightarrow$ Relation to $\sin(2\alpha)$ less clear.
- Strategies proposed, but are challenging experimentally...

New approach : R. Fleischer, Phys. Lett. B 459, 306 (1999).
Throw in $B^0_s \rightarrow K^+K^-$, measure asymmetries in both B^0 and B^0_s.

In general, for a decay $B^0 \rightarrow f$ (f = CP eigenstate) :

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

A^{dir} : "direct" CP violation, A^{mix} : CP violation thru mixing.

Experimentally, measure 4 A's from $B^0 \rightarrow \pi^+ \pi^-$ and $B^0_s \rightarrow K^+K^-$.

Then extract β, γ and penguin and tree decay amplitudes.

Angle γ (phase of V_{ub}) continued

Four CP asymmetries to measure. ($\lambda = \sin\theta_c$)

- $A^{dir}(B^0 \to \pi^+\pi^-) = -2d \sin\theta \sin\gamma \,/\, (1 - 2d\cos\theta\cos\gamma + d^2)$
- $A^{mix}(B^0 \to \pi^+\pi^-) = [\sin 2(\beta+\gamma) - 2d\cos\theta \sin(2\beta+\gamma) + d^2 \sin 2\beta] \,/\, [1 - 2d\cos\theta\cos\gamma + d^2]$
- $A^{dir}(B^0_s \to K^+K^-) \sim 2(\lambda^2/d) \sin\theta \sin\gamma$
- $A^{mix}(B^0_s \to K^+K^-) \sim 2(\lambda^2/d) \cos\theta \sin\gamma$

If no penguin,
$A^{dir} = 0 \quad (B^0, B^0_s)$
$A^{mix} = \sin 2(\beta+\gamma) \quad (B^0)$
$A^{mix} = \sin(2\gamma) \quad (B^0_s)$

Four unknowns to extract :

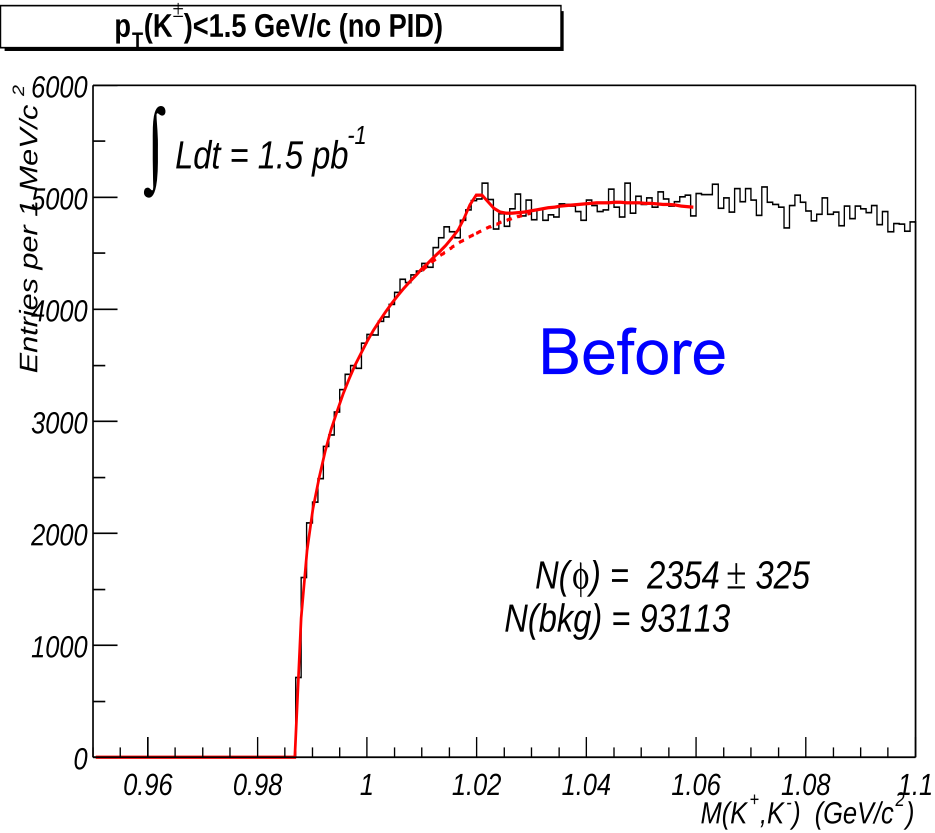
- β, γ = angles of the unitarity triangle.
- d = ratio of penguin *(P)* to tree *(T)* decay amplitudes,
  θ = phase of "*P/T*"
  $d\,e^{i\theta} \equiv \lambda |V_{cb}/V_{ub}| \,/\, (1-\lambda^2/2)\, [\, P \,/\, (T+P)\,]$

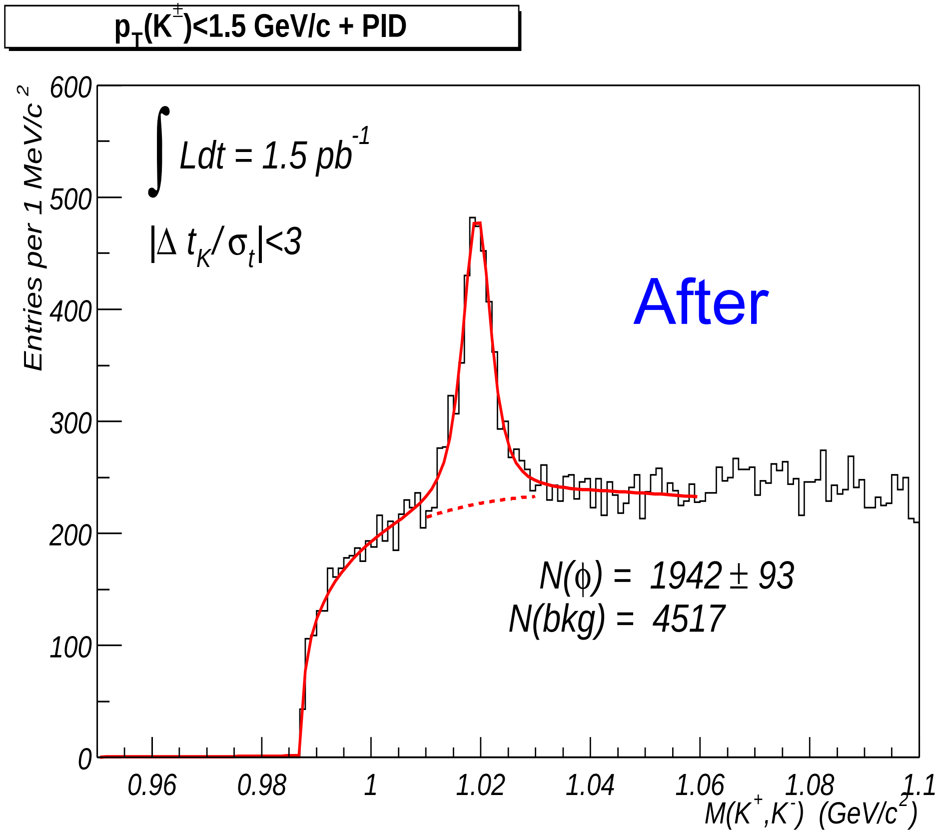
Expect ~5 k $B^0 \to \pi^+\pi^-$, ~10 k $B^0_s \to K^+K^-$
$\to$ angle γ to ~10°.

TOF kaon identification

$\phi \to K^+K^-$

$(p_T < 1.5 \text{ GeV}/c)$





S/N improves by a factor of 20, while keeping 82% of signal.

CDF B_s Sensitivity Estimate

hadronic mode only

- Current performance :
  - S=1600 events / fb^{-1}
  - S/B = 2/1
  - $\varepsilon D^2 = 4\%$
  - $\sigma_t = 67$ fs

  2σ sensitivity for $\Delta m_s=15ps^{-1}$ with ~0.5 fb^{-1} of data

    - surpass the current world average
- With "modest" improvements
  - S=2000 / fb (improve trigger, reconstruct more modes)
  - S/B = 2/1 (unchanged)
  - $\varepsilon D^2 = 5\%$ (kaon tagging)
  - $\sigma_t = 50$ fs (event-by-event vertex + L00)

  5σ sensitivity for $\Delta m_s=18ps^{-1}$ with ~1.7fb^{-1} of data

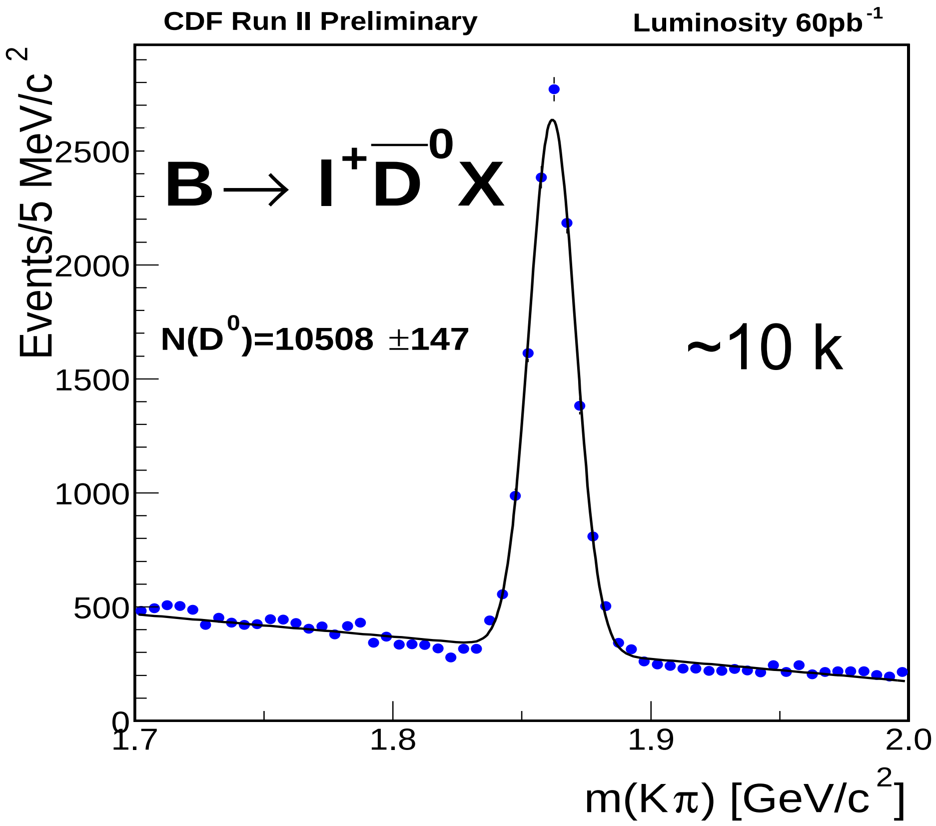
  5σ sensitivity for $\Delta m_s=24ps^{-1}$ with ~3.2fb^{-1} of data

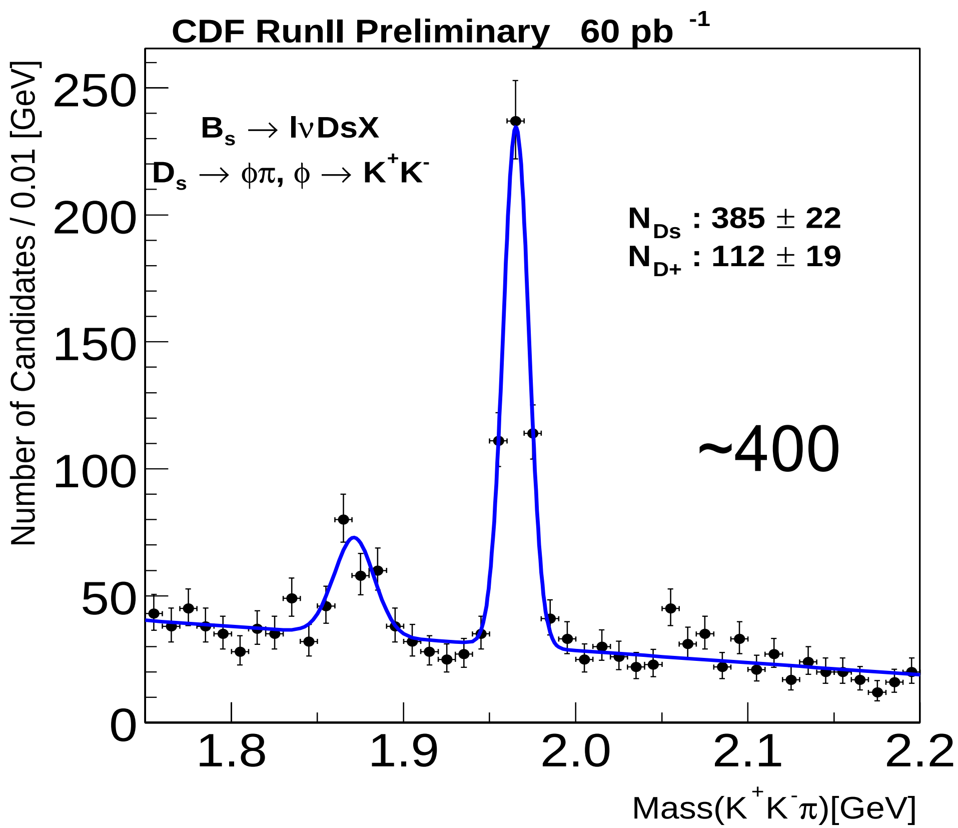
    - ✓ $\Delta m_s=24ps^{-1}$ "covers" the expected region based upon indirect fits.
- *This is a difficult measurement.*
- *There are ways to further improve this sensitivity…*

Semileptonic B decay signals

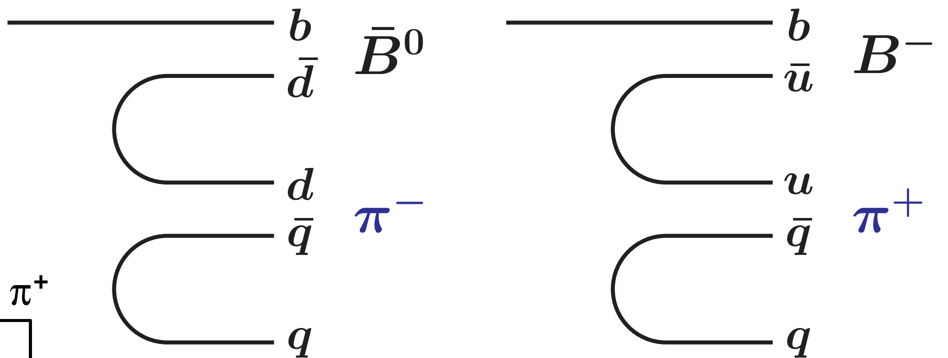
$\bar{B} \rightarrow \ell^- \bar{\nu} D^0 X$

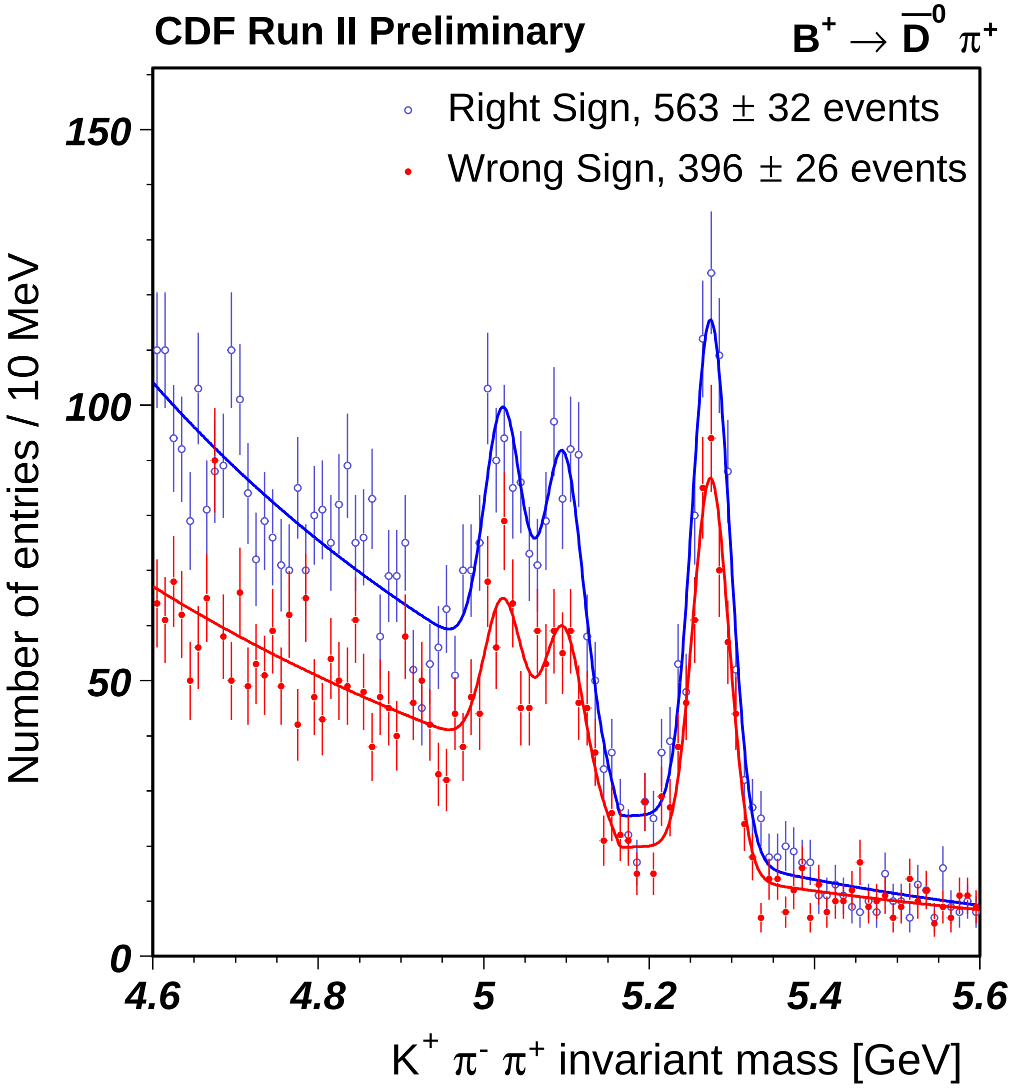
$\bar{B}^0_s \rightarrow \ell^- \bar{\nu} D_s^+ X$





Flavor tagging example : same-side pion tag





Look at near $B^- \to D^0 \pi^-$

Blue : right-sign tags

Red : wrong-sign tags

$\varepsilon D^2 = (2.1 \pm 0.7)\%$ for B^+

Also, muon tagging

$\varepsilon D^2 = (0.7 \pm 0.1)\%$

D** mesons :

$$L = 0 : J = S = 0, 1 \Rightarrow D, D^*$$

$$L = 1 \text{ and } S = 0, 1 : J^P = 1^+, 0^+, 1^+, 2^+$$

Spectroscopy of D mesons