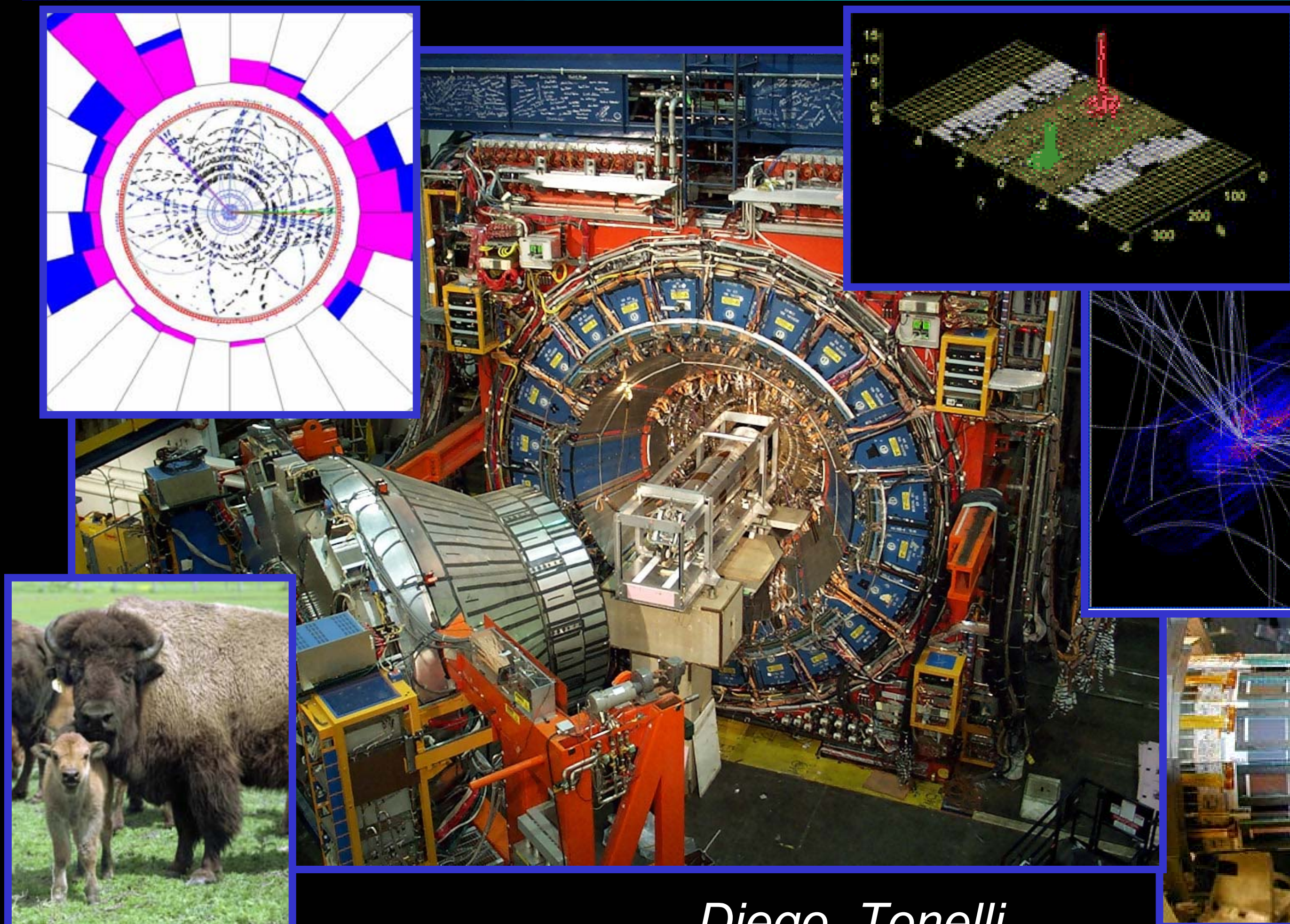
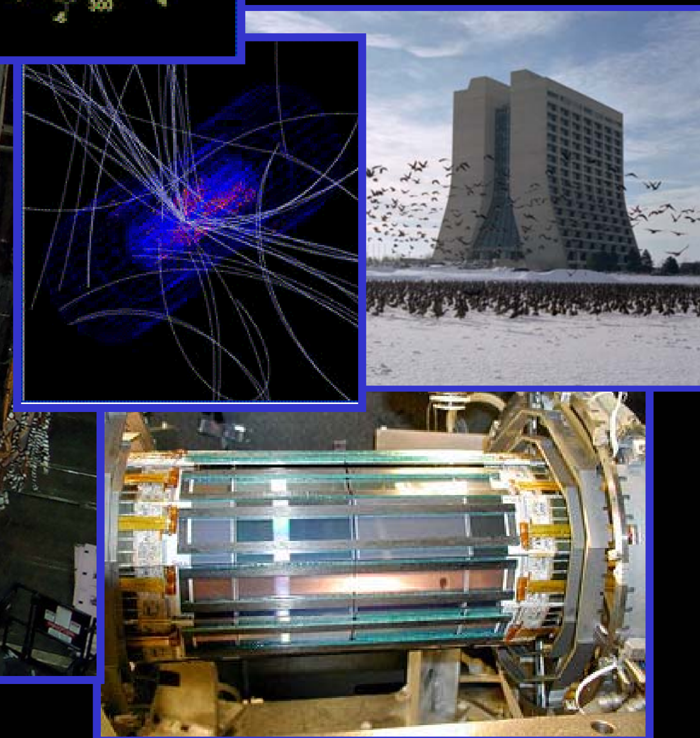
# CDF Hot Topics



FPCP 2006
Vancouver, BC
April 9th – 12th 2006



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# Outline

Focus on charm-less *B* decays in two charged particles.

Analysis of such modes provides CDF with a physics program competitive with ($B^0$ modes), and complementary ($B^0_s$ modes) to *B*-factories. Well suited to illustrate the methods used in flavor physics analyses at CDF.

- ✓ CDF at the Tevatron: HF physics at hadron colliders;
- ✓ Triggering on displaced tracks;
- ✓ CP asymmetry in $B^0 \longrightarrow K^+\pi^-$ decays;
- ✓ $\Delta\Gamma_s/\Gamma_s$ in $B^0_s \longrightarrow K^+K^-$ decays;
- ✓ search for FCNC $B^0_{(s)} \longrightarrow \mu^+\mu^-$ decays.

# The Tevatron $\bar{p}p$ collider

Superconducting proton-synchrotron…………: 36 (*proton*) $\times$ 36 (antiproton) bunches

a crossing every 396 ns at $\sqrt{s}$ = 1.96 TeV

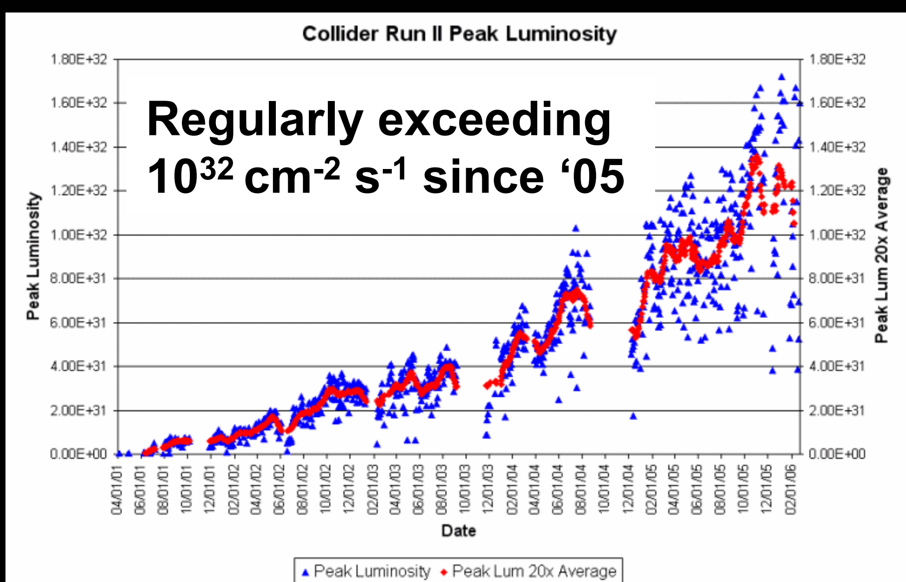
# of interactions per bunch-crossing……………………: $\langle N \rangle_{poisson} = 2$ (at $10^{32}\,cm^{-2}s^{-1}$)

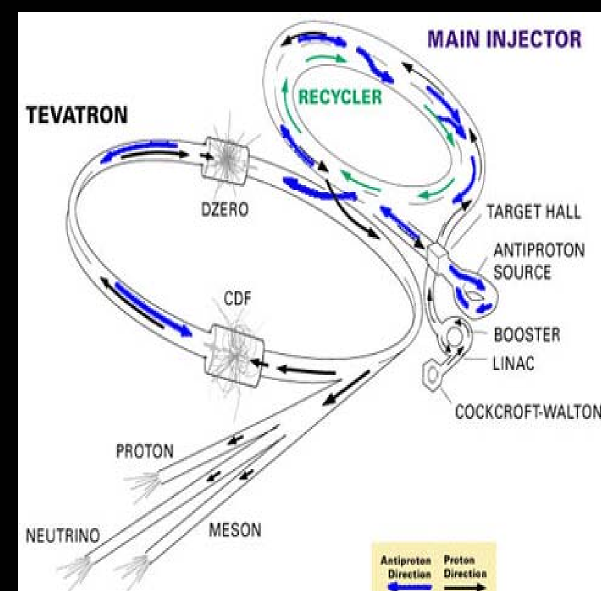
Luminous region size……………………: 30 cm (beam axis) $\times$ 30 $\mu$m (transverse)

**need long Si-vertex** **small wrt c$\tau$(*B*) ~ 450 $\mu$m**

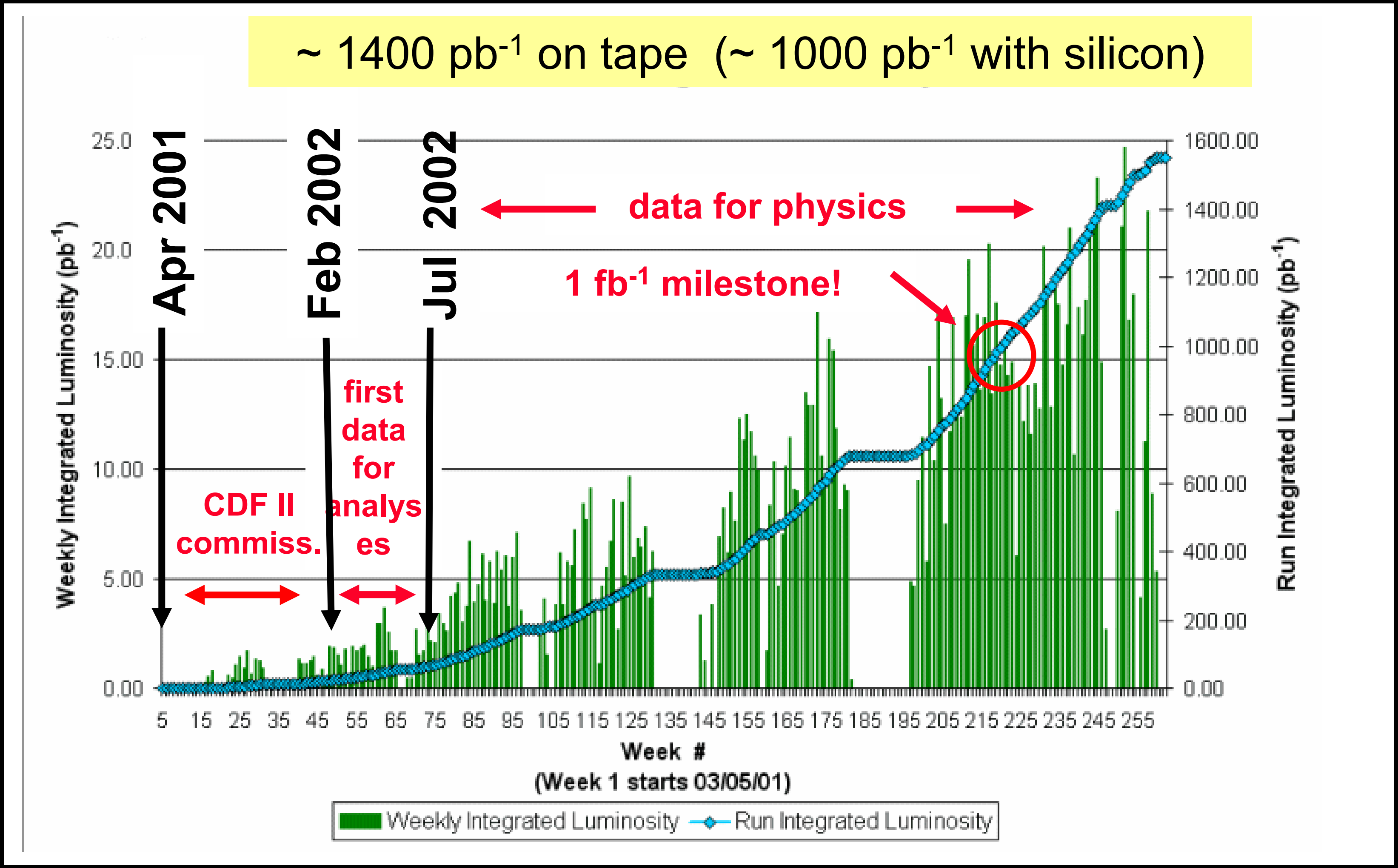
Luminosity…………………………………………: record peak is $1.82 \times 10^{32}\,cm^{-2}\,s^{-1}$

typically 18 $pb^{-1}$ / week on tape



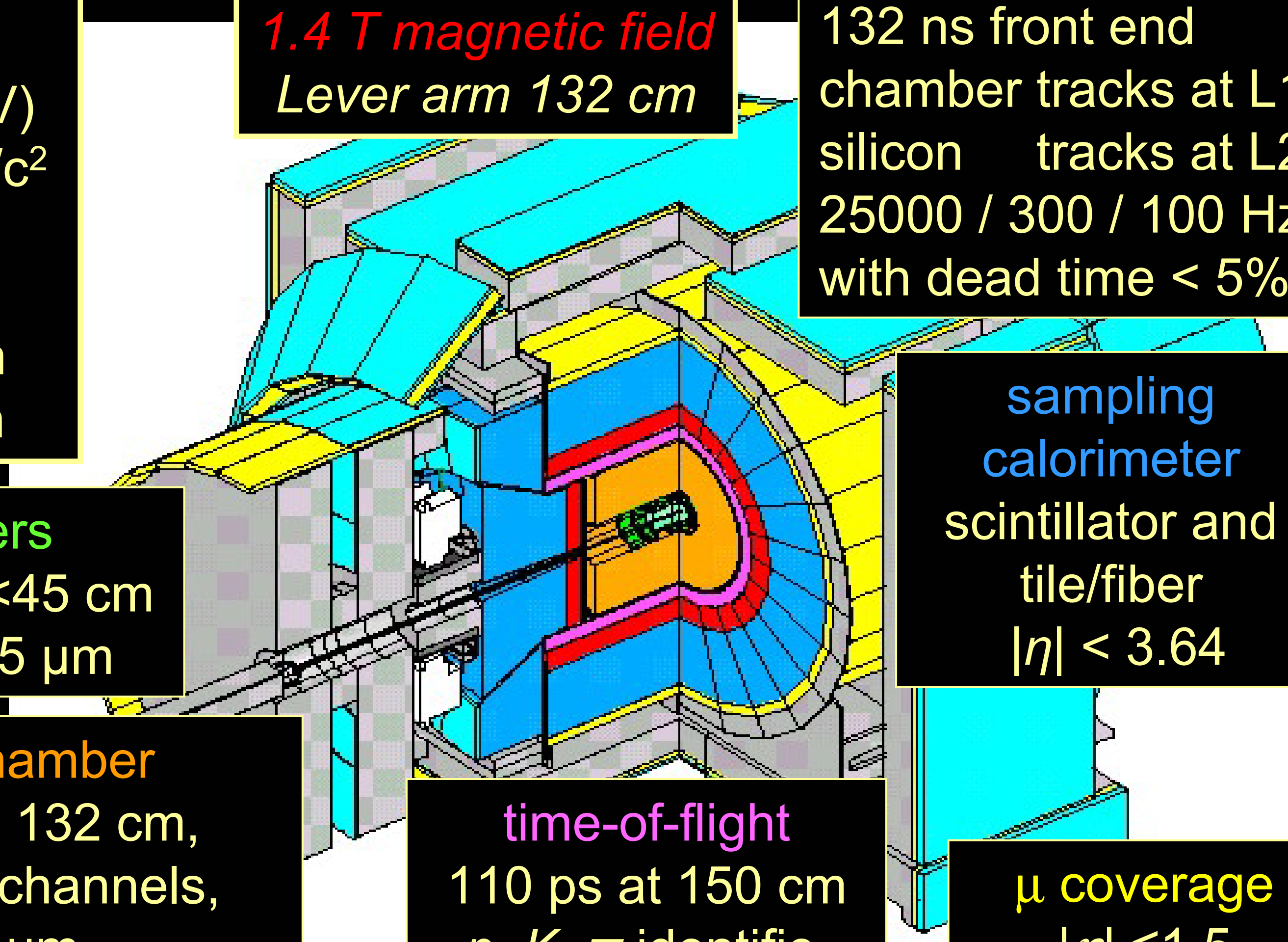



# Integrated luminosity




Stable data taking efficiency: > 85%. Results here use 360 - 780 pb$^{-1}$

# The CDF II detector



some resolutions
$p_T$~0.15% $p_T$ (c/GeV)
*J/Ψ* mass ~14 MeV/c$^2$
EM E ~ 16%/√E
Had E ~ 80%/√E
vertex *r-φ* ~ 30 μm
vertex *r-z* ~ 80 μm

*1.4 T magnetic field*
*Lever arm 132 cm*

132 ns front end
chamber tracks at L1
silicon tracks at L2
25000 / 300 / 100 Hz
with dead time < 5%

7 - 8 silicon layers
1.6 < *r* < 28 cm, |z|<45 cm
|*η*| ≤ 2.0 σ(hit) ~ 15 μm

sampling
calorimeter
scintillator and
tile/fiber
|*η*| < 3.64

96 layer drift chamber
|*η*| ≤ 1.0 44 < *r* < 132 cm,
|z|<155 cm 30k channels,
σ(hit) ~ 140 μm
dE/dx for *p, K, π,* e identification

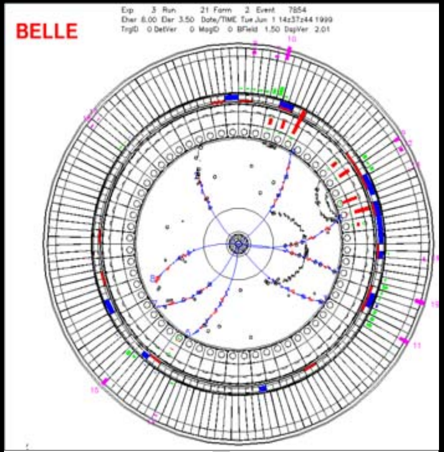
time-of-flight
110 ps at 150 cm
*p, K, π* identific.
2σ at *p* <1.6 GeV/c

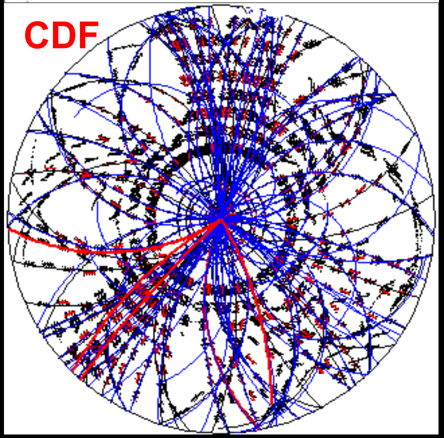
μ coverage
|*η*| ≤1.5
84% in *φ*

# Heavy Flavor physics at the Tevatron

## The Good

Reconstructable $p\bar{p} \to b\bar{b}$ x-section is $O(10^3)$ larger than $e^+e^- \to b\bar{b}$ at $\Upsilon(4S)$ or $Z^0$. Copious samples of all *b*-hadrons, $B^+$, $B^0$, $B^0_s$, $B_c$, $\Lambda_b$, $\Xi_b$ produced by strong interaction.




## The Bad

Total inelastic x-section $\times 10^3$ larger than $\sigma(b\bar{b})$ and $p_T(B) \sim 5$ GeV/c: need high background rejection. Incoherent production and low (~10%) acceptance for "other *B*": hard flavor-tagging.

## …and The Ugly

multiple interactions/event and debris from interacting $\bar{p}$ and *p*: messy environments with large combinatorics. Challenging reduction from 1.7 MHz collision-rate, to ~100 Hz tape-writing.

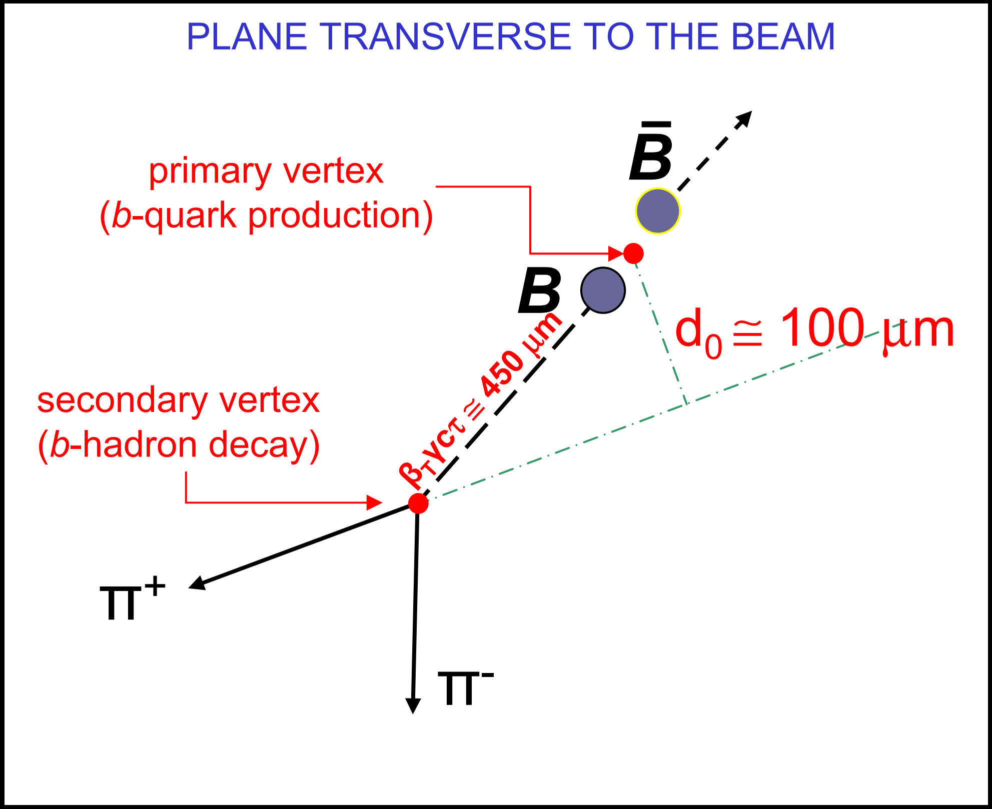
**Need highly selective trigger**

# Heavy flavor trigger signature

"Long" (~1.5 ps) lifetime of *b*-hadrons: a powerful signature against light-quark background.

Before decaying, sufficiently boosted *b*-hadrons fly a distance resolvable with vertex detectors.

CDF exploits it at trigger level.




An experimental challenge:

(1) high resolution vertex detector (silicon)

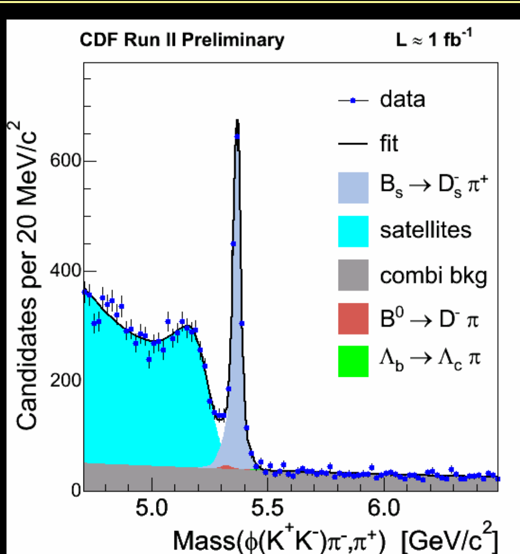
(2) online read out of silicon;

(3) do pattern recognition and track fitting in silicon.

} within 25 μs,

# Displaced track trigger: pros and cons

Very high-purity samples of hadronic *B* (and *D*) decays.

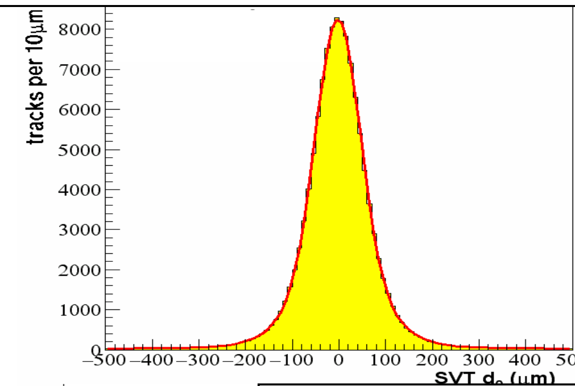


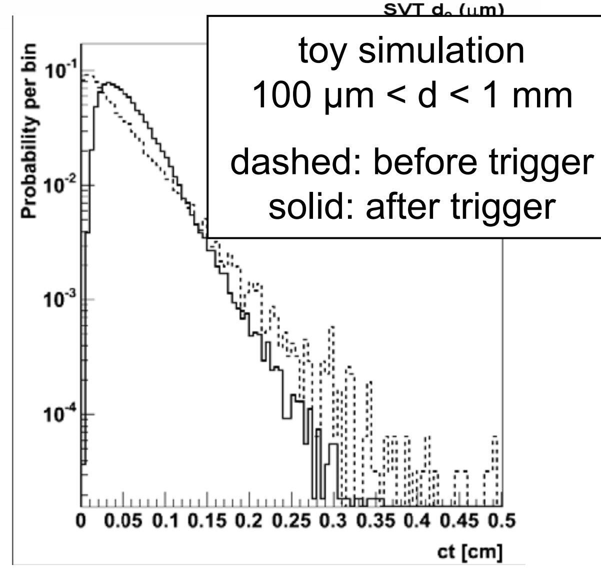

"golden" modes for $B^0_s$ mixing

price to pay: trigger-bias distorts proper-time distributions. Introduce complexity in lifetime-based analyses, ....more later...

impact parameter resolution

48 μm = 35 [SVT] ⊕ 33 [beam-spot size]



# Triggering heavy flavors

Traditional *B*-trigger at hadron collider: look for one ($B \to l\nu X$) or two leptons ($B \to J/\psi X$) exploiting clear signature and ~20% of total width.

For the first time, trigger HF without leptons: rare hadronic *B* decays.

| **conventional** | ***partially new approach*** | ***new approach*** |
|---|---|---|
| di-muon | electron or $\mu$ and displaced track | two displaced tracks |
| $B \longrightarrow$ charmonium<br>$B \longrightarrow \mu\mu$ | $B \to l\nu X$ | $B \to hh$ |
| two muons with: | electron (or $\mu$) with: | two tracks with: |
| $p_T > 1.5$ GeV $\lvert\eta\rvert < 1$ | $p_T > 4$ (or 1.5) GeV $\lvert\eta\rvert < 1$ | $p_T > 2.0$ GeV |
| | and one track with: | $\Sigma p_T > 5.5$ GeV |
| | $p_T > 2.0$ GeV $d_0 > 120\ \mu m$ | $d_0 > 100\ \mu m$ |

# CP Asymmetry in $B^0 \to K^+\pi^-$ decays and $B^0_s \to K^+K^-$ lifetime

# Motivation

Interpretation of *B* results often plagued by uncertainties from non-perturbative QCD. Opportune use of symmetries allows partial cancellation of the unknowns.

Joint study of $B^0$ and $B^0_s$ 2-body decays into charged kaons and pions ($KK$, $\pi\pi$ and $K\pi$) plays a key role: related by subgroups of SU(3) symmetry.

Until the beginning of the planned *Y(5S)* run at Belle, only CDF has simultaneous access to both $B^0/B^0_s \longrightarrow h^+h'^-$ decays thus exploiting an original physics program complementary to *B-factories.*

# Motivation (cont'd)

In $B^0 \longrightarrow K^+\pi^-$ decays, direct CP asymmetry was observed for the first time in $B$ sector ($B$-factories).

Large (~10%) effect established, but still many things to understand, e.g. asymmetry in $B^0$ not compatible with $B^+$ as expected.
(Gronau and Rosner, Phys.Rev.D71:074019, 2005).

Additional experimental input is helpful: copious yields at Tevatron make CDF a major player in the direct-CPV game.

Compare rates and asymmetries of $B^0 \longrightarrow K^+\pi^-$ and $B^0_s \longrightarrow K^-\pi^+$ - unique to CDF - to probe NP with no need for assumptions, just basing on SM.
(Lipkin, Phys.Lett.B621:126, 2005)

From lifetime of $B^0_s \longrightarrow K^+K^-$ (unique to CDF), information on the relative width-difference $\Delta\Gamma_s/\Gamma_s$. Compare with $B^0_s$ mixing results to search for new, CP-violating physics.

Many more: BR and time-dependent asymmetries of $B^0_s \longrightarrow K^+K^-$ …

# Trigger confirmation

TRIGGER REQUIREMENTS

Two oppositely-charged tracks (i.e. *B* candidate) from a long-lived decay:

✓ track's impact parameter >100 μm;

✓ *B* transverse decay length > 200 μm;

*B* candidate pointing back to primary vertex:

✓ impact parameter of the *B* < 140 μm;

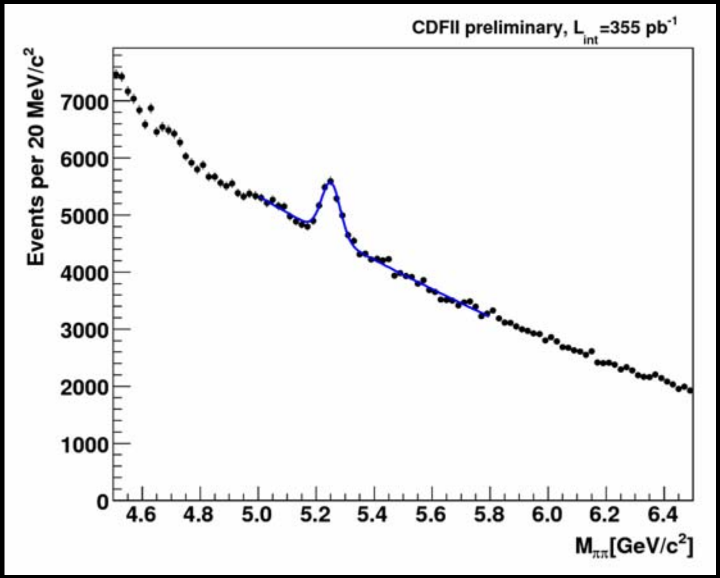
reject light-quark background from jets:

✓ transverse opening angle [20°, 135°];

✓ $p_{T1}$ and $p_{T2}$ > 2 GeV;

✓ $p_{T1} + p_{T2}$ > 5.5 GeV.

BR~$10^{-5}$ visible with just trigger confirmation !



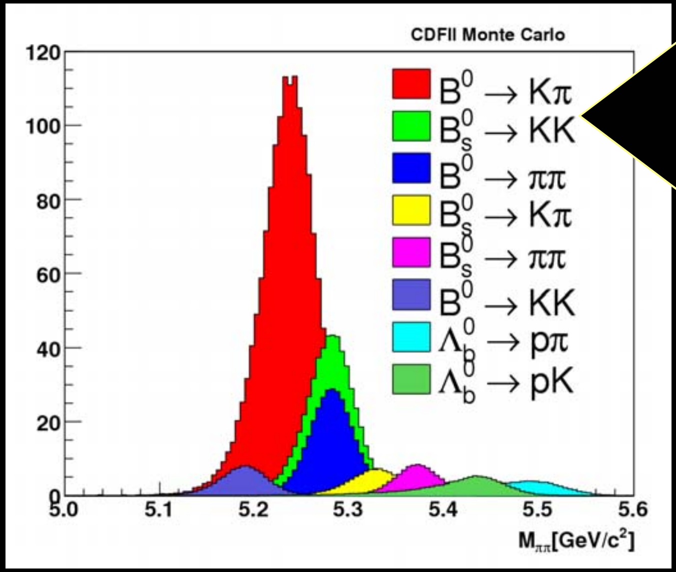

a bump of ~3850 events with S/B ≈ 0.2 (at peak) in $\pi\pi$-invariant mass

# "Optimized" cut optimization

Optimize cuts by minimizing the expected statistical resolution on $A_{CP}$. Its expression in terms of S and B is determined from actual resolutions observed in full analyses of toy-MC samples

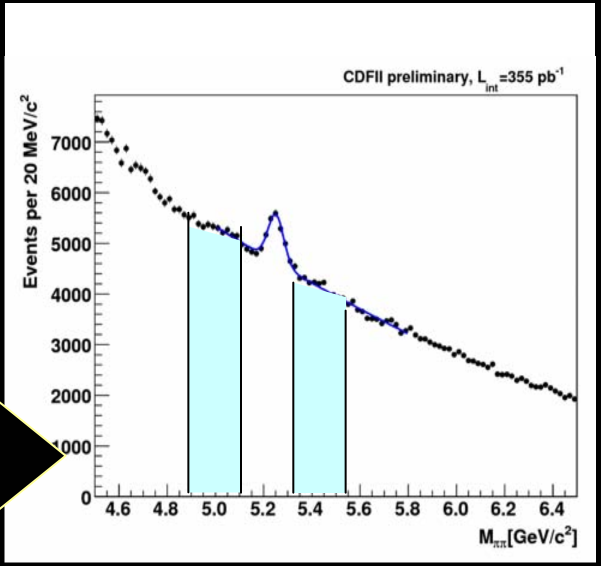
Gain ~10% improvement in resolution *versus* standard $S/\sqrt{(S+B)}$

Unbiased cut optimization: for any combination of cuts, evaluate the above score function; optimal cuts are found when the function reach its maximum.




signal yield S is derived from MC simulation

background B from data (mass sidebands)



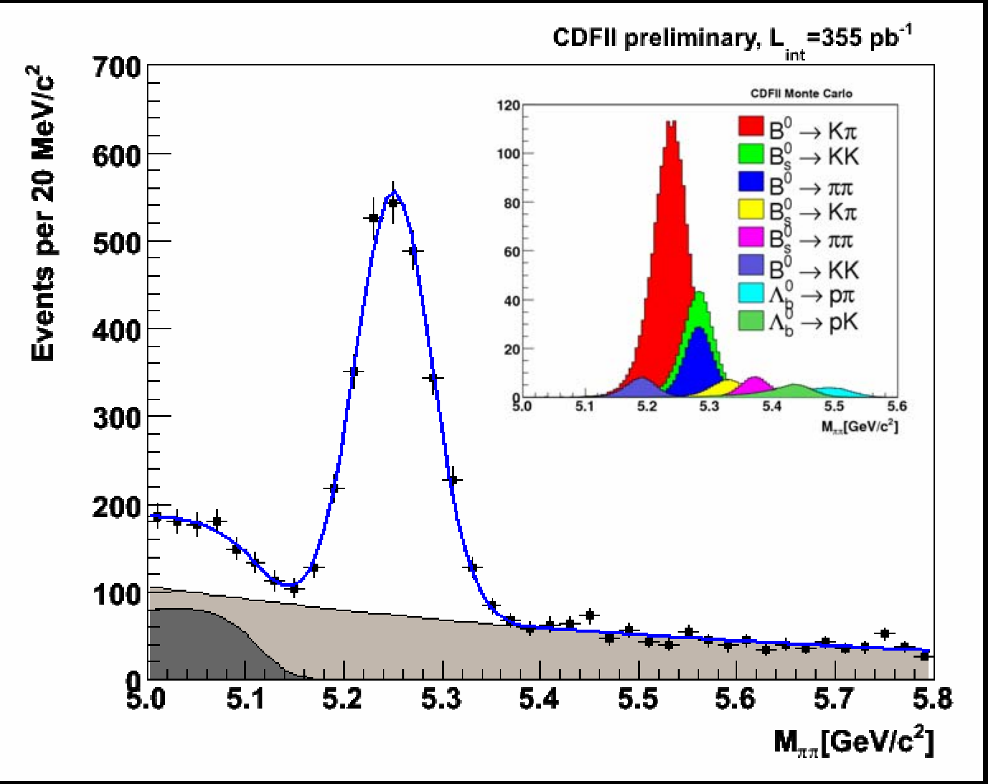
# Signal extraction

Signal yield: ~2300 events
S/B ≈ 6.5 (peak value)

~1.7× reduction in signal yield
~50× reduction in background

Crucial requirements:

- ✓ isolation of the *B* candidate to reject light quark background
- ✓ 3D-tracks to reject combinatorics from HF




Despite excellent mass resolution, modes overlap into an unresolved mass peak, and PID resolution is insufficient for event-by-event separation. Hence, fit signal composition with a Likelihood that combines information from kinematics (masses and momenta) *and* particle ID (dE/dx).

# Peak composition handle 1: kinematics

Exploit the (small) kinematic differences among different modes:

4 values of the invariant mass of the track pair, resulting from all possible mass assignments (*Kπ, πK, KK, ππ* ): complicated joint distribution.

Use instead approximate relation between any 2 invariant masses obtained with 2 arbitrary mass assignment to the tracks (if $m \ll p$):

2-body invariant mass with $\overline{m}_1$ and $\overline{m}_2$ mass assignments

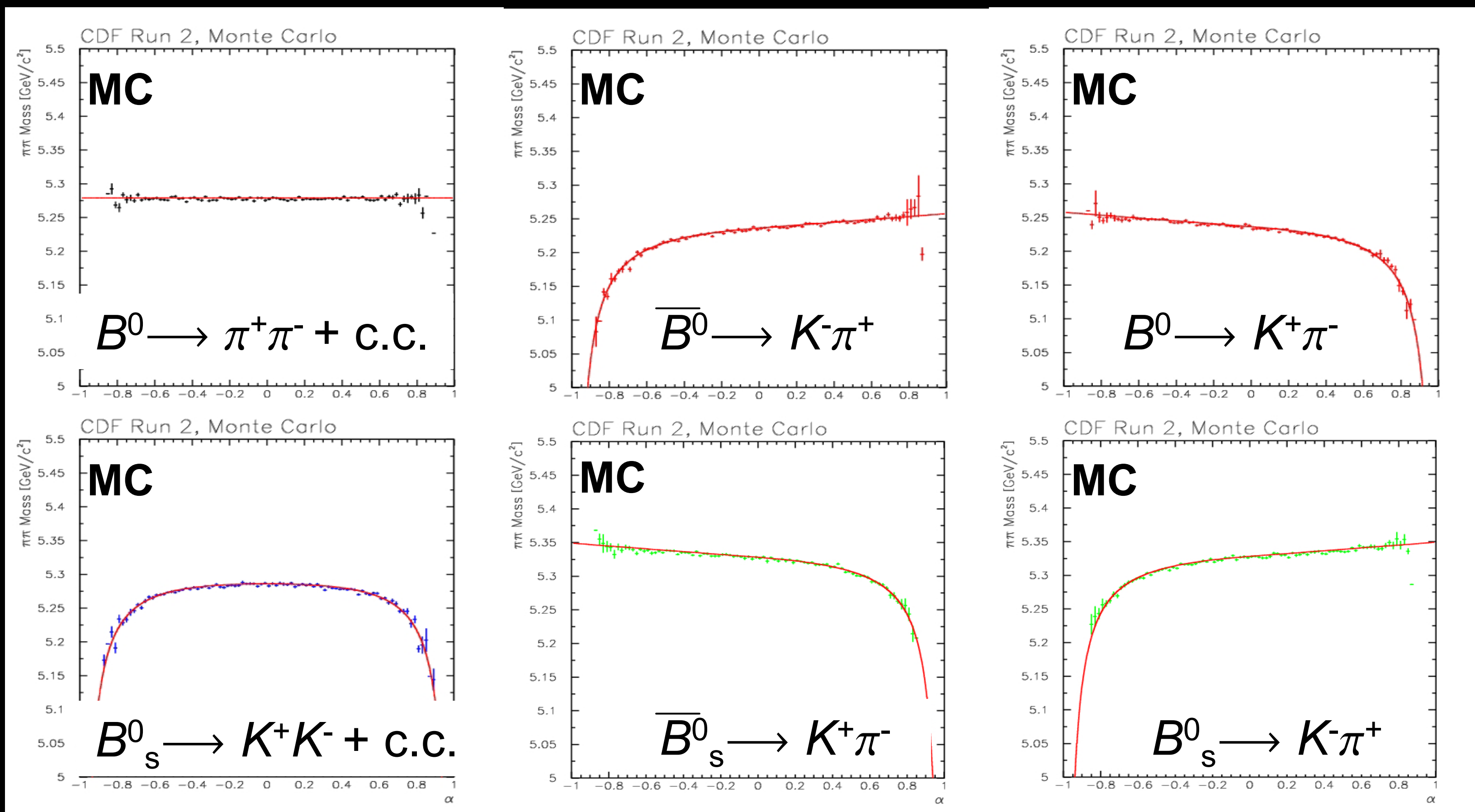
$$M^2_{m_1,m_2} \approx M^2_{\overline{m}_1,\overline{m}_2} + \left(1+\frac{p_1}{p_2}\right)\left(m_2^2-\overline{m}_2^2\right) + \left(1+\frac{p_2}{p_1}\right)\left(m_1^2-\overline{m}_1^2\right)$$

2-body invariant mass with $m_1$ and $m_2$ mass assignments

Information condensed in just 2 observables: a single candidate invariant mass and ratio of momenta: looser correlation and easier to handle

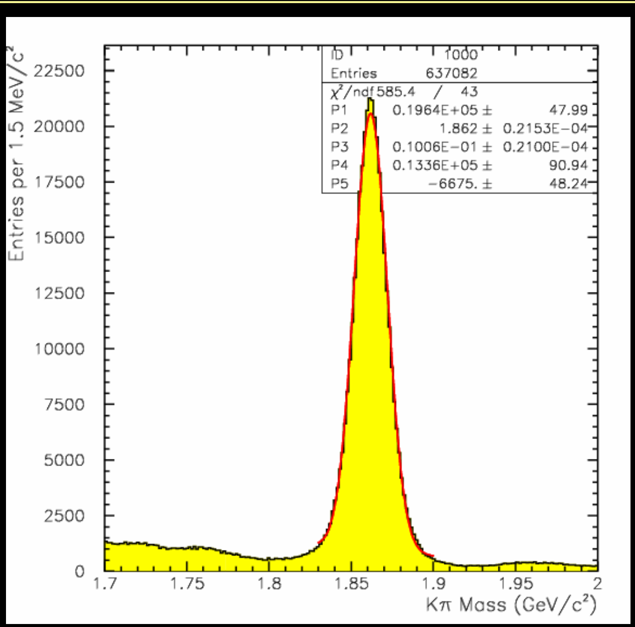
# Peak composition handle 1: kinematics

$\pi\pi$-mass *vs* signed momentum imbalance: $(1 - p_{min}/p_{max})q_{min}$




discriminates among modes (and among flavors in $K\pi$ modes).

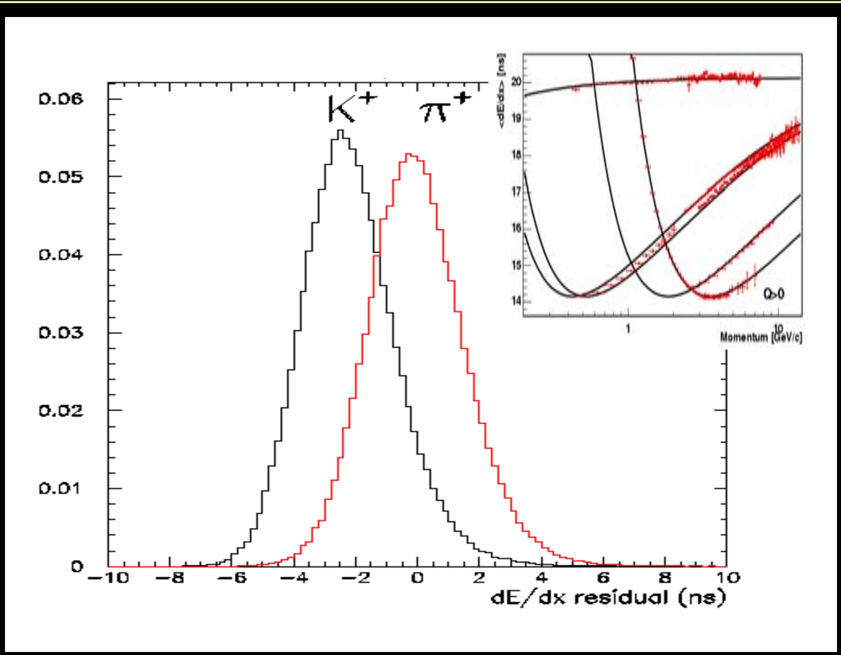
# Peak composition handle 2: dE/dx




~95% pure *K* and $\pi$ samples from ~300,000 decays:

$D^{*+} \longrightarrow D^0\, \pi^+ \longrightarrow [K^- \pi^+]\, \pi^+$

Strong $D^{*+}$ decay tags the $D^0$ flavor. dE/dx accurately calibrated over tracking volume and time.




1.4$\sigma$ $K/\pi$ separation at $p$ > 2 GeV

(≡ 60% of “perfect” separation)

~11% residual correlation from gain/baseline common fluctuations included in the fit of composition

# Fit of composition

Un-binned ML fit that uses kinematic and PID information from 5 observables

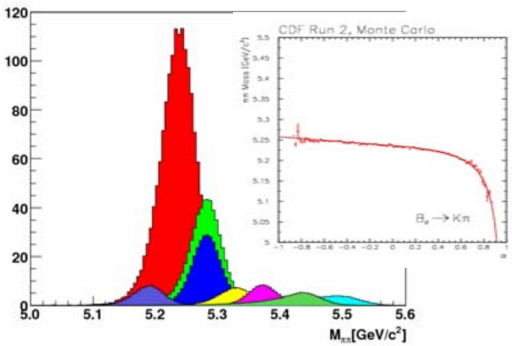
$$\mathscr{L}(\vec{\theta}) = \prod_{i=1}^{N} \mathscr{L}_i(\vec{\theta})$$

$$\mathscr{L}_i(\vec{\theta}) = (1-b)\sum f_j \mathscr{L}_j^{\mathrm{sign}} + b\mathscr{L}^{\mathrm{bckg}}$$

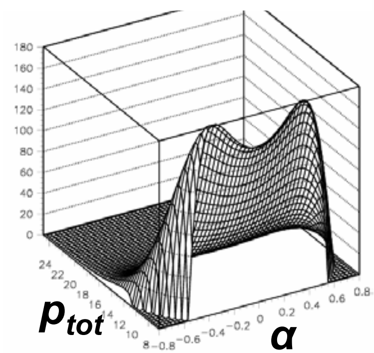
fraction of j[th] mode, to be determined by the fit

$$\mathscr{L} \sim \wp^m(m_{\pi\pi}|\alpha) \times \wp^p(\alpha, p_{\mathrm{tot}}) \times \wp^{\mathrm{PID}}(dE/dx_1, dE/dx_2|\alpha, p_{\mathrm{tot}})$$

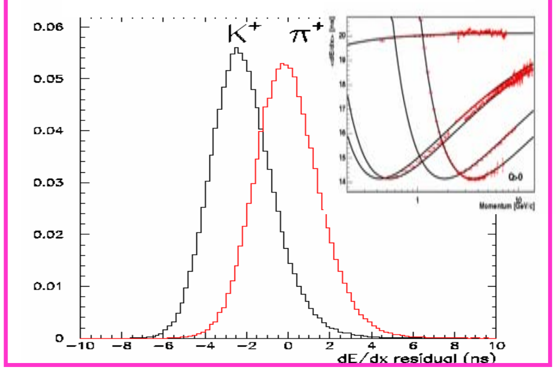
mass term




momentum term



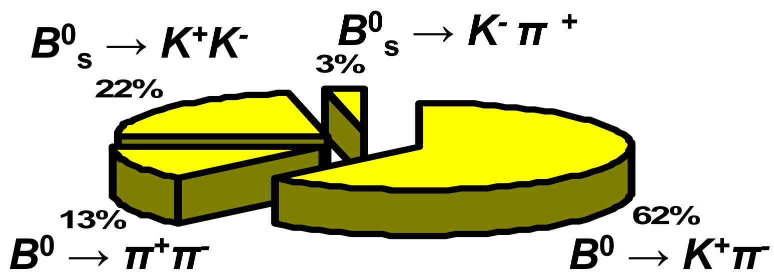

PID term



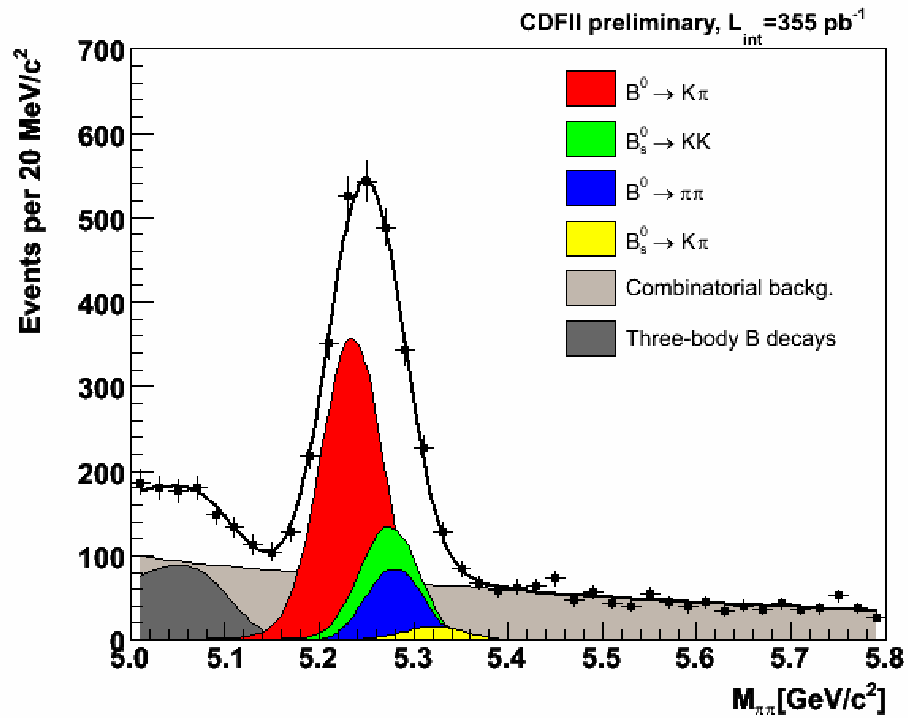

Signal shapes: from MC and analytic formula
Background shapes: from data sidebands

sign and bckg shapes from $D^0 \longrightarrow K^-\pi^+$

# Uncorrected fit results




| mode | fraction [%] | yield |
|---|---|---|
| $B^0 \to \pi^+\pi^- + \overline{B}^0 \to \pi^+\pi^-$ | $13.2 \pm 1.4$ | $313 \pm 34$ |
| $B^0_s \to K^-\pi^+ + \overline{B}^0_s \to K^+\pi^-$ | $2.7 \pm 1.3$ | $64 \pm 30$ |
| $B^0_s \to K^+K^- + \overline{B}^0_s \to K^+K^-$ | $22.0 \pm 1.6$ | $523 \pm 41$ |
| $B^0 \to K^+\pi^- + \overline{B}^0 \to K^-\pi^+$ | $62.1 \pm 1.7$ | $1475 \pm 60$ |
| $B^0 \to K^+\pi^-$ | – | $787 \pm 42$ |
| $\overline{B}^0 \to K^-\pi^+$ | – | $689 \pm 41$ |



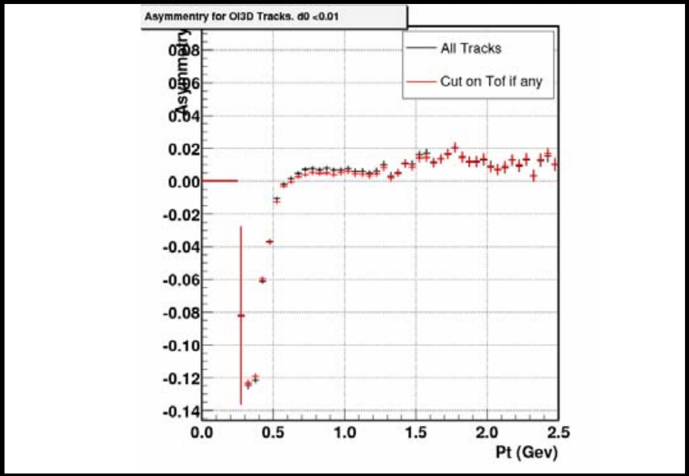

$$A_{CP}\Big|_{RAW} = \frac{N_{raw}(\overline{B}^0 \to K^-\pi^+) - N_{raw}(B^0 \to K^+\pi^-)}{N_{raw}(\overline{B}^0 \to K^-\pi^+) + N_{raw}(B^0 \to K^+\pi^-)} = -0.066 \pm 0.039$$

Small (~1%) correction of fit result for trigger, acceptance, and selection efficiency to convert it into a measurement

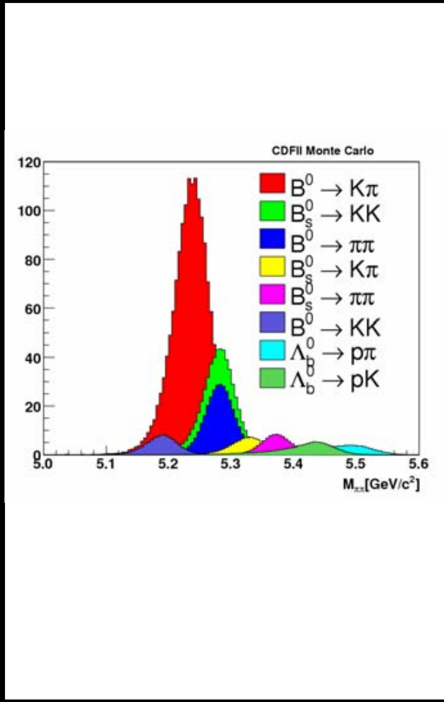
# Extraction of asymmetry

$$A_{CP} = \frac{N(\overline{B}^0 \to K^-\pi^+)\Big|_{raw} \cdot \frac{\epsilon_{kin}(B^0\to K^+\pi^-)}{\epsilon_{kin}(\overline{B}^0\to K^-\pi^+)} - N(B^0 \to K^+\pi^-)\Big|_{raw}}{N(\overline{B}^0 \to K^-\pi^+)\Big|_{raw} \cdot \frac{\epsilon_{kin}(B^0\to K^+\pi^-)}{\epsilon_{kin}(\overline{B}^0\to K^-\pi^+)} + N(B^0 \to K^+\pi^-)\Big|_{raw}}$$

A < 2% charge asymmetry affects the CDF II detector and tracking code.

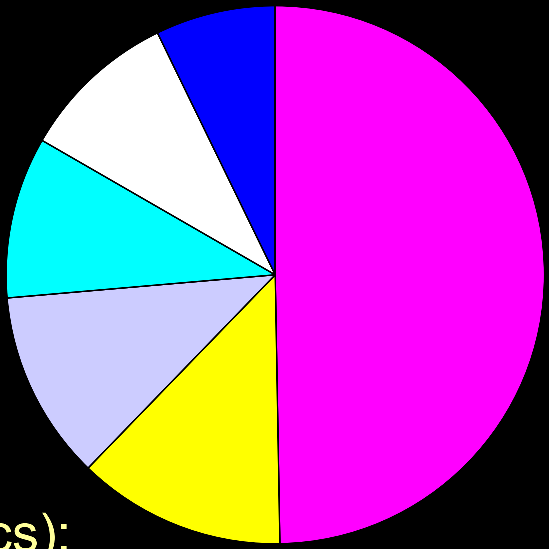



Only the different $K^+/K^-$ interaction rate with material matters.
Effect under control down to 0.5% in CDF $A_{CP}(D^0 \longrightarrow h^+h')$ measurement
(Phys.Rev.Lett.94:122001, 2005).
Used unbiased kaons to extract the ~ 1% correction



# Dominant systematic uncertainties

Total systematic uncertainty is 0.7% , much smaller than the 3.9% statistical uncertainty.



- dE/dx model (partially reduces with statistics);
- nominal *B*-meson masses input to the fit (reduces with statistics);
- mass-resolution model;
- global scale of masses;
- charge-asymmetries in background;
- combinatorial background model.

# Asymmetry Result (360 pb$^{-1}$)

$$A_{\mathrm{CP}}^{\mathrm{CDF}}(B^0 \to K^+\pi^-) = -0.058 \pm 0.039\ (stat.) \pm 0.007\ (syst.)$$

Result is ~1.5σ different from 0, and compatible with *B*-factories results:

$$A_{\mathrm{CP}}^{\mathrm{Belle}}(B^0 \to K^+\pi^-) = -0.113 \pm 0.022\ (stat.) \pm 0.008\ (syst.)$$

$$A_{\mathrm{CP}}^{\mathrm{Babar}}(B^0 \to K^+\pi^-) = -0.133 \pm 0.030\ (stat.) \pm 0.009\ (syst.)$$

Systematic uncertainties from CDF and *B*-factories are comparable.

With data already available on disk, we expect ~2.5% statistical uncertainty: CDF will be soon (summer) very competitive.

In same data, is likely first observation of $B^0_s \longrightarrow K^-\pi^+$ decay: will measure its BR and CP asymmetry that is expected large. Model-independent NP-probe proposed by Lipkin (Lipkin, Phys.Lett.B621:126, 2005).

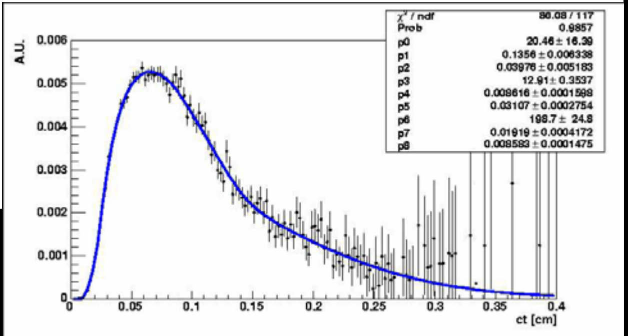
# $B^0_s \rightarrow K^+K^-$ lifetime analysis

Add lifetime information to the fit of composition:

$$\mathcal{L} \sim \wp^m(m_{\pi\pi}|\alpha)\wp^p(\alpha, p_{\text{tot}})\wp^{\text{PID}}(dE/dx_1, dE/dx_2|\alpha, p_{\text{tot}})\wp^{\text{life}}(ct).$$

$$\wp^{\text{life}}(ct) = \exp(\text{ct}) \times \text{Gauss}(\text{ct}) \times \varepsilon(\text{ct})$$

decay — detector smearing — trigger bias




Trigger bias for signal is extracted from detailed simulation.

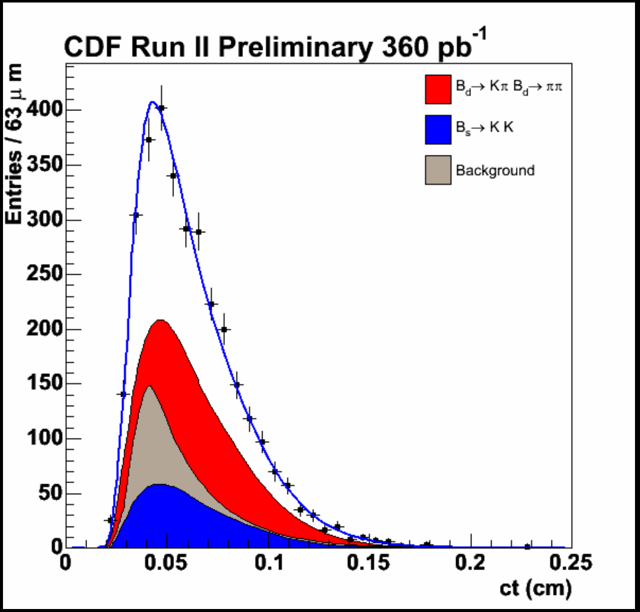
Procedure validated in unbiased $B \rightarrow J/\psi X$ decays from dimuon trigger.

Check that lifetime fits of samples with/without applying track-trigger cuts yield consistent results.

Lifetime p.d.f for background is extracted from higher mass data sideband.

# $B^0_s \to K^+K^-$ lifetime results (360 $pb^{-1}$)

| | $c\tau(B^0)$ [$\mu$m] | $c\tau(B^0_s \to K^+K^-)$ [$\mu$m] |
|---|---|---|
| both free | $452 \pm 24$ | $463 \pm 56$ |
| $c\tau(B^0)$ constrained to PDG | – | $458 \pm 53$ |



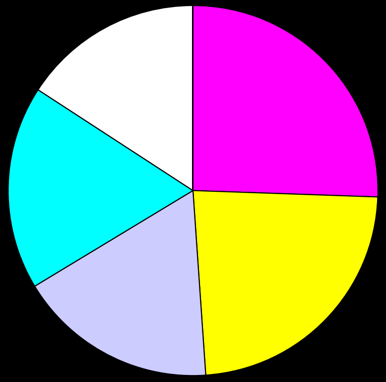

$B^0_s \to K^+K^-$ predicted ~95% CP-even: has the lifetime of "light $B^0_s$" :

$$\tau_L = 1.53 \pm 0.18\ (stat.) \pm 0.02\ (syst.)\mathrm{ps}$$

Combine with HFAG average $(\tau_L^2 + \tau_H^2)/(\tau_L + \tau_H)$:

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s^{CP}} = -0.08 \pm 0.23\ (stat.) \pm 0.03\ (syst.)$$

Dominant systematics :



- detector alignment;
- input $p_T(B)$ in simulation;
- lifetime model of background;
- dE/dx model;
- trigger-bias.



Diego Tonelli, CDF

# Search for FCNC decays

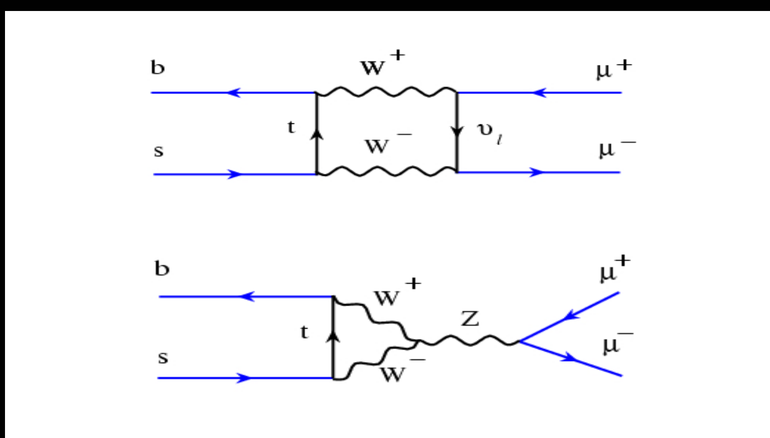
# $B^0 / B^0_s \rightarrow \mu^+\mu^-$

# Search for $B^0/ B^0_s \to \mu^+\mu^-$ decays

## STANDARD MODEL

FCNC strongly suppressed. expected BR($B^0_s \to \mu^+\mu^-$) ~ $10^{-9}$ : much lower than CDF reach.

$B^0 \to \mu^+\mu^-$ further suppressed by factor $|V_{td}/V_{ts}|^2$

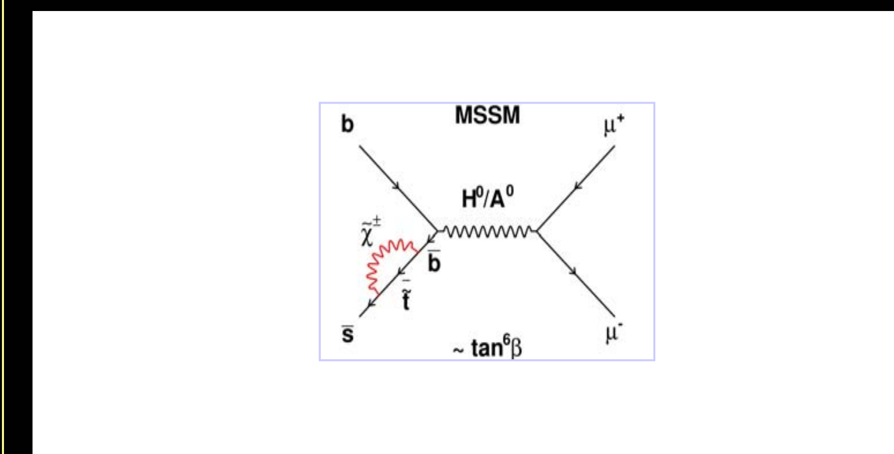



## SUSY

NP contributions may enhance BR , allowing possible observation at the Tevatron.

MSSM: BR~$(\tan\beta)^6$: up to ×100 larger

RPV: tree diagram allowed




Only CDF can observe both $B^0_s$ and $B^0$ and distinguish between them

# $B^0/B^0_s \to \mu^+\mu^-$ results (780 $pb^{-1}$)

Search in sample from "rare" di-muon trigger:

Use a Likelihood-Ratio discriminant to distinguish signal from background

LR uses: (a) decay-length, (b) isolation of the *B*, (c) 3D-pointing of the *B* to the $\bar{p}p$ vertex

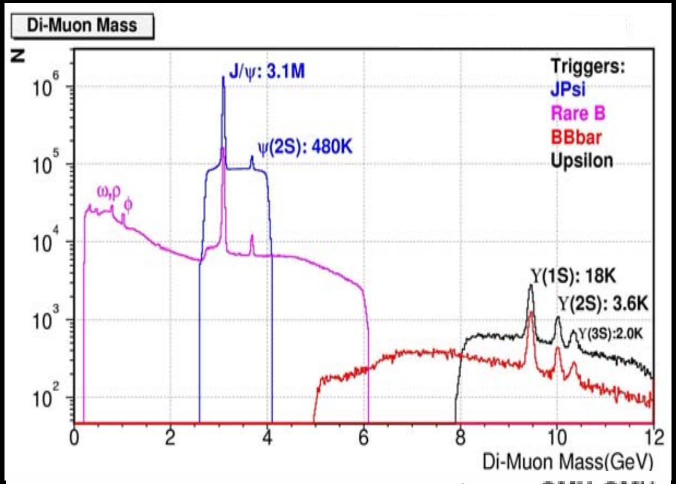
Understand backgrounds: sequential and double semileptonic decays, fakes.

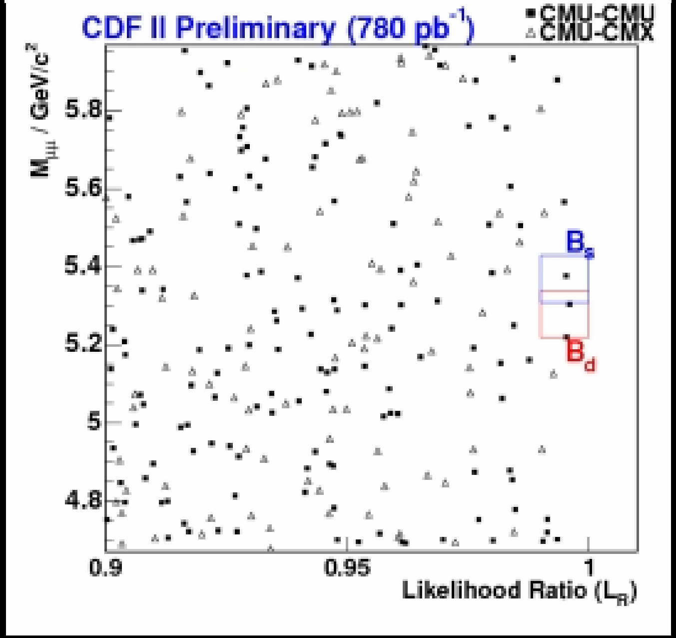
Measure BR (or set limit) with respect to normalization $B^+ \to J/\psi K^+$ mode.

No signal found, world best upper limits set:

$$BR(B^0_s \to \mu^+\mu^-) < 8 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$

$$BR(B^0 \to \mu^+\mu^-) < 2.3 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$



# Summary

As data keep flowing, CDF impact on FP becomes more and more crucial: Charm-less two-body *B* decays, a case-study to show how CDF is competitive with ($B^0$) and complementary to ($B^0_s$) *B*-factories.

- direct CPV in $B^0 \longrightarrow K^+\pi^-$ , small systematics, and as yet available statistics places CDF among the best by this summer;

- Unique opportunity to combine with $B^0_s \longrightarrow K^-\pi^+$ decays;

- Unique extraction of $\Delta\Gamma_s/\Gamma_{s\ i}$ in $B^0_s \longrightarrow K^-K^+$ (already one of world best results)

- Unique simultaneous sensitivity to $B^0$ /$B^0_s \rightarrow \mu^+\mu^-$ (already world best results);

Latest results on $B^0_s$ mixing;
Jónatan Piedra, today at 17.00

Quantum numbers of *X(3872)*;
Ilya Kravchenko, tomorrow at 11.00

*b*-hadron production fractions;
Ilya Kravchenko, tomorrow at 11.00

World best $B^+_c$ lifetime;
Ilya Kravchenko, tomorrow at 11.00

World best $B^+_c$ mass;
Ilya Kravchenko, tomorrow at 11.00

First $B^0_s \rightarrow D_sD_s$ observation;
Rick Van Kooten, tuesday at 16.30