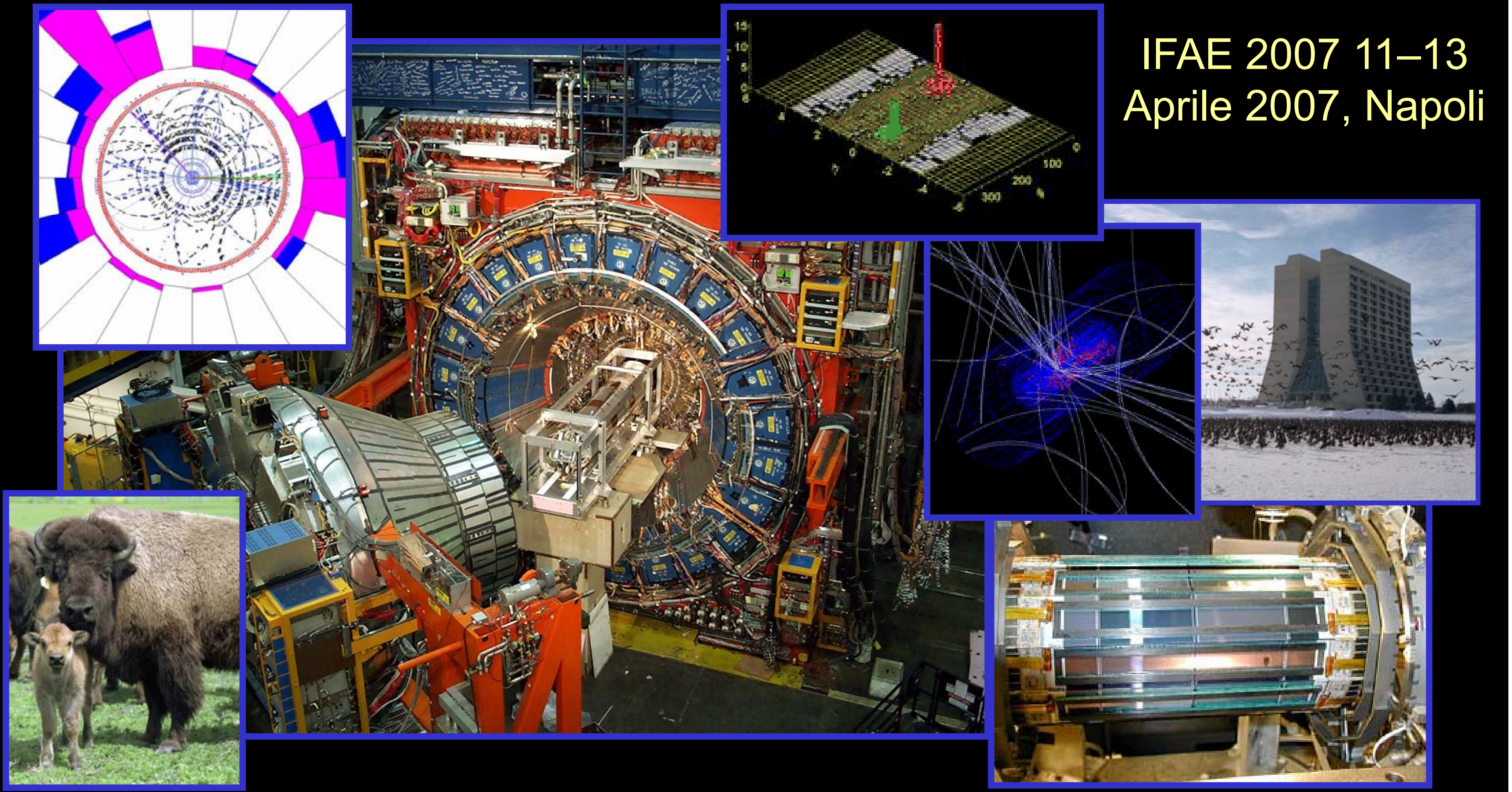
# Decadimenti charmless e rari di adroni *B* a CDF



IFAE 2007 11–13
Aprile 2007, Napoli

*Diego Tonelli*
*CDF Pisa*

# Outline

Decadimenti di adroni $B$ in coppie di particelle cariche charmless: un programma di fisica competitivo ($B^0$), e complementare ($B^0_s$) a quello delle $B$-factories.

✓ Branching ratio di decadimenti $B^0_{(s)} \longrightarrow h^+h'^-$

✓ ricerca di decadimenti FCNC del tipo $B^0_{(s)} \longrightarrow \mu^+\mu^-$.

✓ ricerca di decadimenti mediati da transizioni $b \longrightarrow sl^+l^-$.

Risultati estratti da campioni di luminosita' 780 –1000 $pb^{-1}$ . Per generalita' su macchina, detector ecc riferitevi alle trasparenze di Giovanni Punzi (Mercoledi' 11, ore 14.45)

# Branching Fractions di decadimenti $B^0_{(s)} \rightarrow h^+h^-$

Vedi anche hep-ex/0612018 che contiene l'aggiornamento su 1 $\text{fb}^{-1}$ dell'analisi pubblicata in PRL 97:211802,2006

# Introduzione

Decadimenti charmless dei *B* molto popolari nelle misure di fisica del flavor. *B*-factories: ricca messe di misure su $B^0$ *e* $B^+$. Incertezze adroniche complicano l'estrazione parametri CKM.

Possibile chiave: completare il quadro con misure di $B^0_s$ e barioni. Per esempio alcuni ritengono che la combinazione di $B^0_s$ e $B^0$ attraverso simmetrie di sapore sia l'unica strada per un'estrazione "pulita" di γ dai *B* charmless in due corpi.

Nel $B^0 \longrightarrow K^+\pi^-$ si e' misurata per la prima volta la asimmetria di CP diretta nei *B* (~10%) . Confronto di rates e asimmetrie di $B^0 \longrightarrow K^+\pi^-$ and $B^0_s \longrightarrow K^-\pi^+$ (accessibile solo a CDF) proposto come test non ambiguo di esistenza di NP senza necessita' di assunzioni. (Lipkin, PLB 621:126, 2005)

Molte misure ancora: asimmetrie vs tempo di $B^0_s \longrightarrow K^+K^-$, asimmetrie di rate di decadimento della $\Lambda^0_b$ ecc..

# Estrazione del segnale (trigger)

Due tracce di carica opposta provenienti da decadimento ‘long-lived’

✓ grossi valori di parametri d’impatto e lunghezza trasversa di decadimento

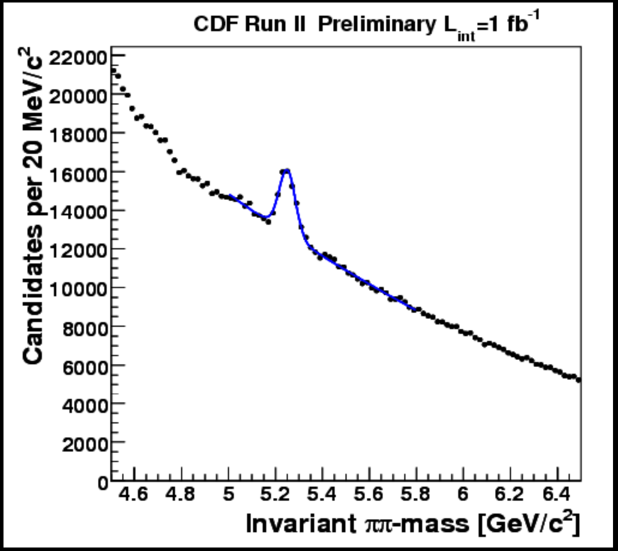
Il candidato *B* deve provenire dal vertice primario

✓parametro impatto compatibile con 0

Riduco fondo di QCD generico

✓ impulsi trasversi di qualche GeV e tagli in apertura angolare in azimuth.

BR~$10^{-5}$ visibile con solo conferma di trigger



Bump di 14,500 eventi con S/B ≈ 0.2 (al picco)

Ottimizzazione unbiased della selezione minimizzando l’ incertezza statistica aspettata sulle quantita’ che si vanno a misurare

# Estrazione ottimizzata del segnale (offline)

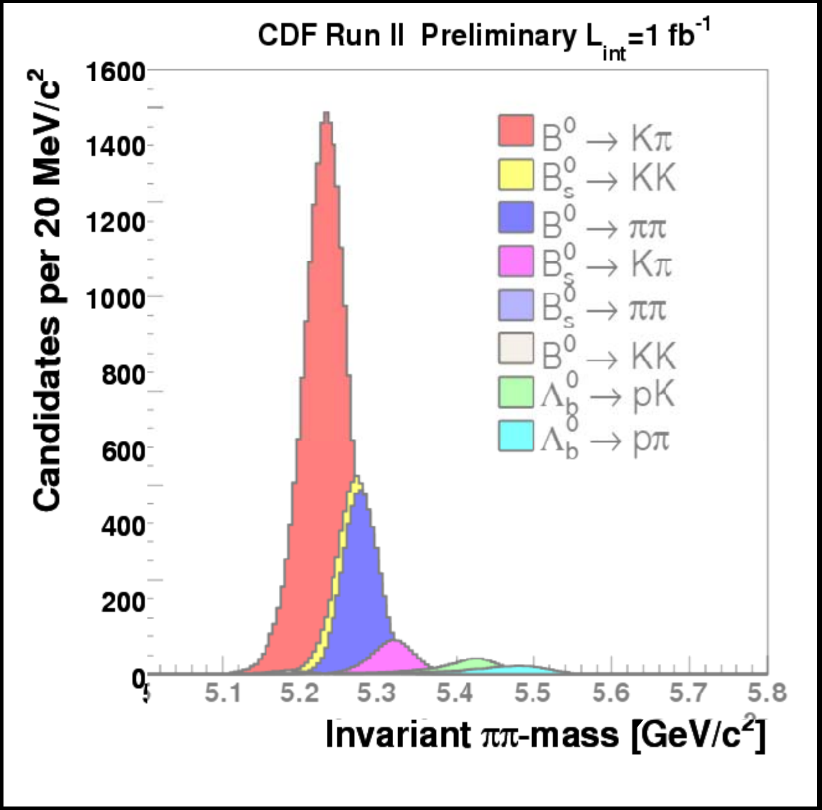
Segnale: ~7000 decadimenti
S/B ≈ 6.5 (valore di picco)

Riduco fattore ~2× segnale
Riduco fattore ~40× fondo

Ingredienti cruciali:

✓ isolamento del candidato *B:* riduce fondo di quark leggeri

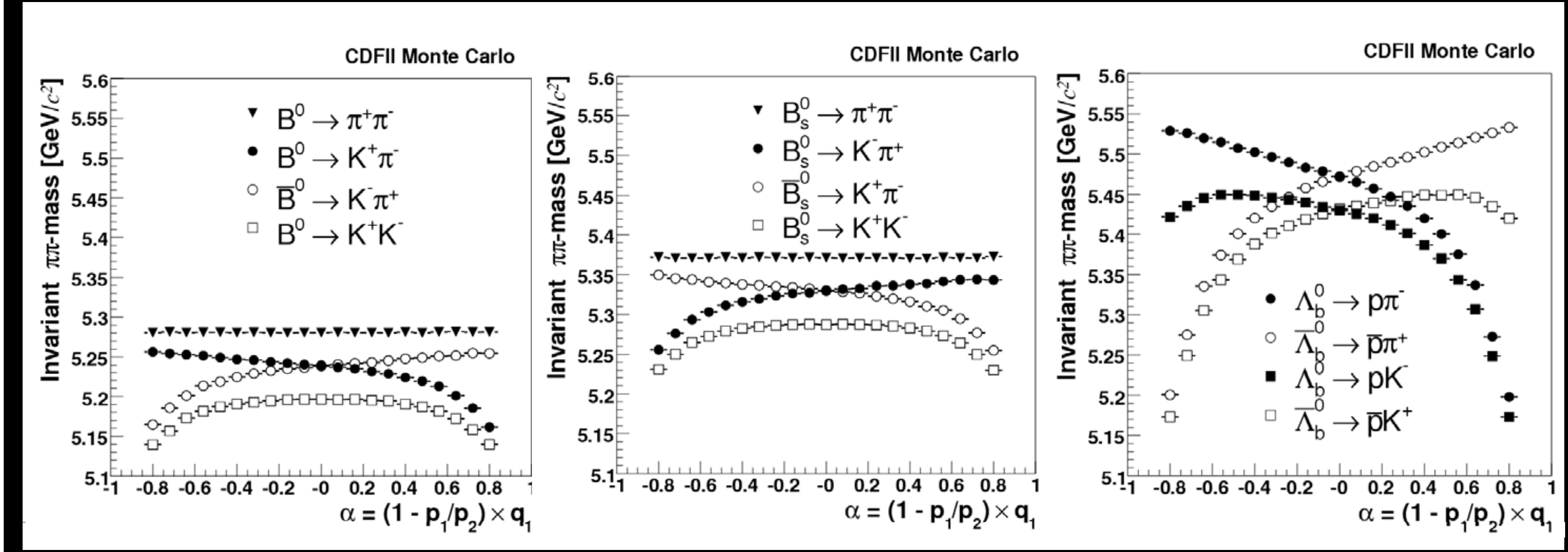
✓ tracce 3D riducono combinatorio di quark pesanti



Nonostante l'ottima risoluzione in massa, I canali si sovrappongono in un unico picco. Risoluzione in PID e' insufficiente per separazione evento per evento. Pertanto, fit della composizione del segnale combinando cinematica (masse e impulsi) *col* dE/dx.

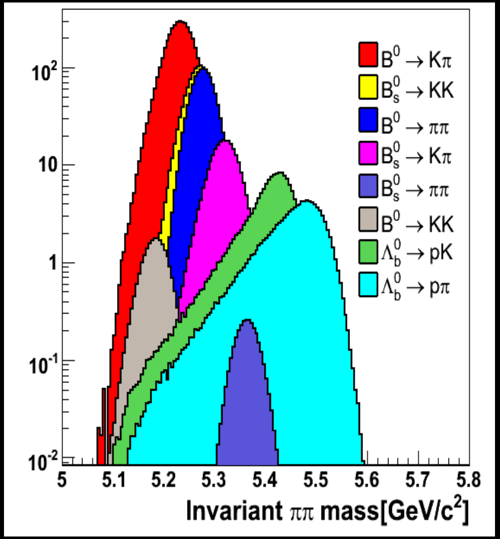
# primo ingrediente: cinematica

Massa $\pi\pi$ *vs* rapporto tra moduli degli impulsi: $(1- p_{min}/p_{max})q_{min}$

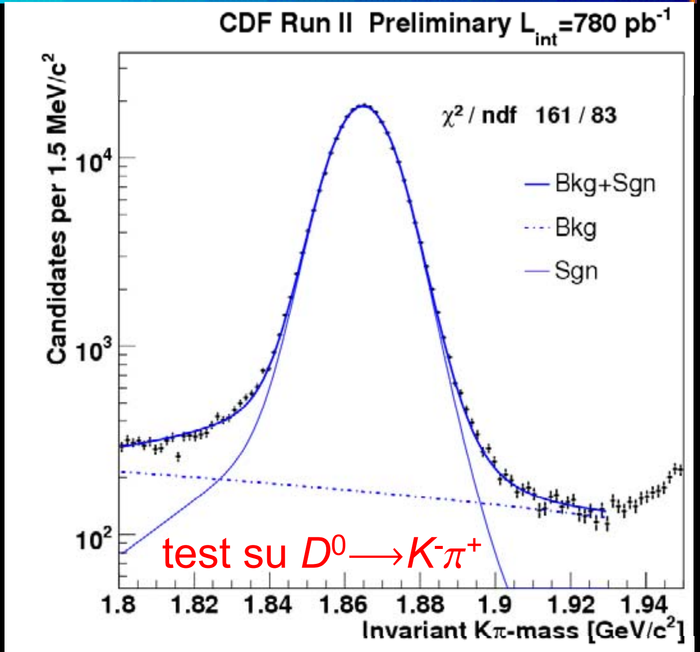


Distingue tra canali diversi (e tra sapori nei canali $K\pi$).

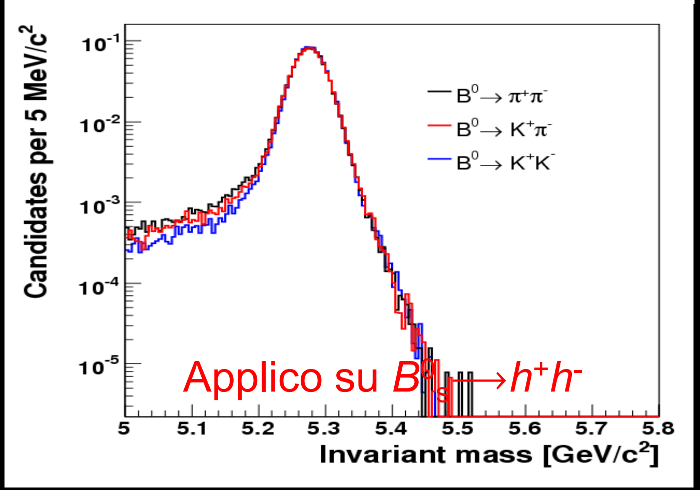
# Line-shape in massa e radiazione di fotoni soffici



Dettagli della distribuzione in massa cruciali per osservazione canali rari (mimetizzati sotto code canali abbondanti)



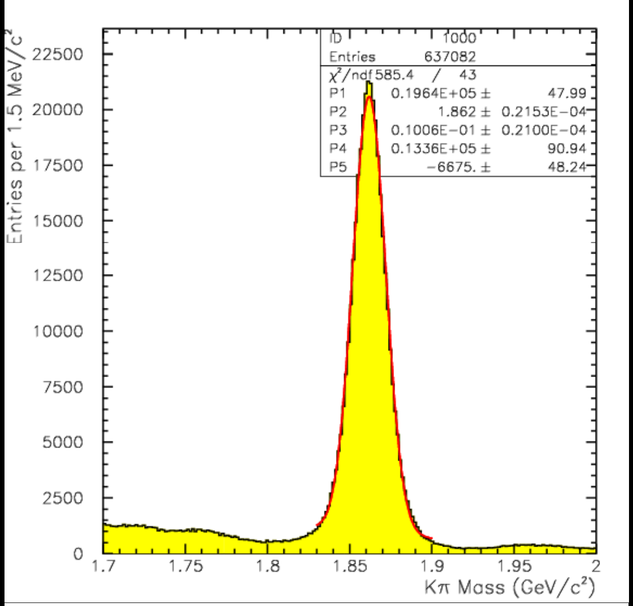
test su $D^0 \longrightarrow K^- \pi^+$



Applico su $B^0_s \longrightarrow h^+ h^-$

Controllo di effetti non-Gaussiani di risoluzione e radiazioni di fotoni soffici negli stati finali estratti dai dati ($D^0$) e dai calcoli QED. [Baracchini,Isidori PLB633: 309,2006]

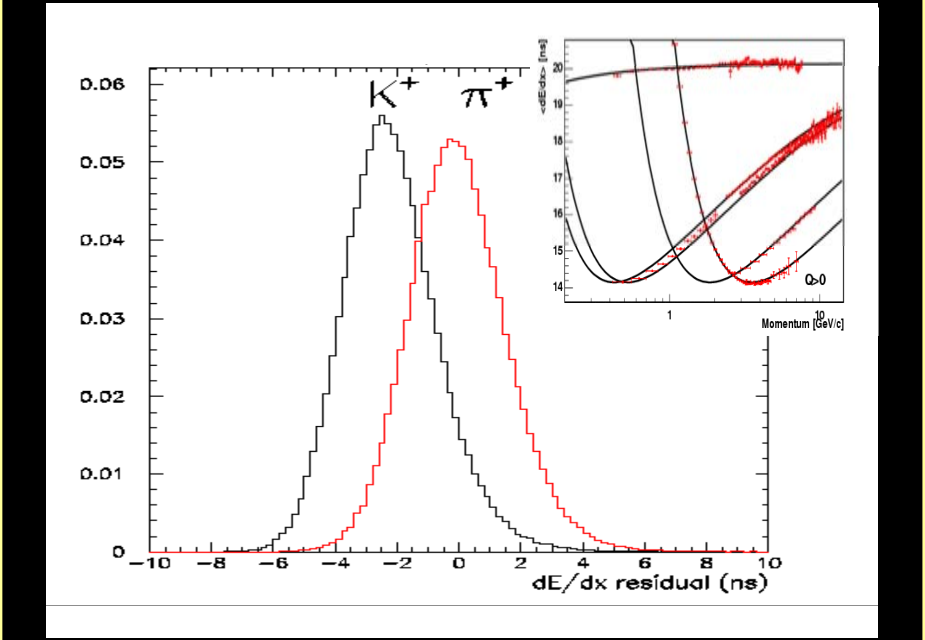
# ..secondo ingrediente: dE/dx



Campioni di *K* e $\pi$ puri al 95% da ~1.5M decadimenti:

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

Decadimento forte del $D^{*+}$ fissa il sapore del $D^0$. dE/dx calibrato sul volume di tracking e nel tempo.



1.4$\sigma$ di separazione $K/\pi$ a $p$ > 2 GeV

(≡ 60% della performance "ideale")

11% di correlazione residua da fluttuazioni comuni e' inclusa nella likelihood (controllo sistematiche)

# Fit di composizione del campione

Un-binned ML fit che usa informazione da cinematica e PID (5 osservabili)

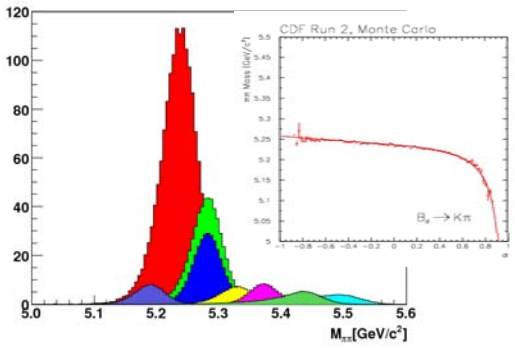
$$\mathscr{L}(\vec{\theta}) = \prod_{i=1}^{N} \mathscr{L}_i(\vec{\theta})$$

frazione del j^th modo, determinata dal fit

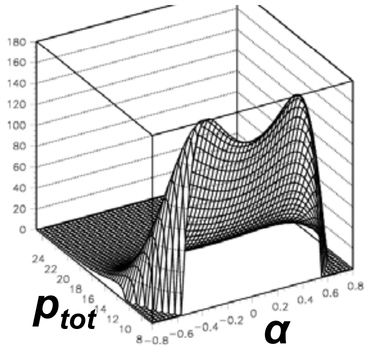
$$\mathscr{L}_i(\vec{\theta}) = (1-b)\sum f_j \mathscr{L}_j^{\text{sign}} + b\mathscr{L}^{\text{bckg}}$$

$$\mathscr{L} \sim \wp^{m}(m_{\pi\pi}|\alpha) \times \wp^{p}(\alpha, p_{\text{tot}}) \times \wp^{\text{PID}}(dE/dx_{1}, dE/dx_{2}|\alpha, p_{\text{tot}})$$

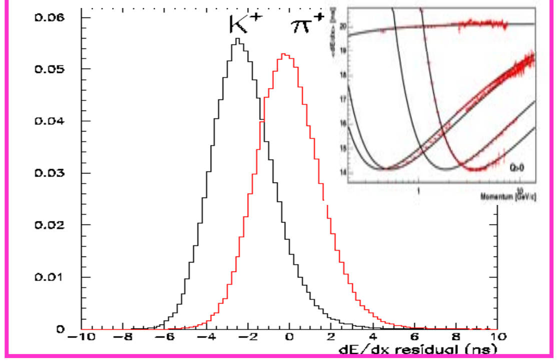
massa



impulso



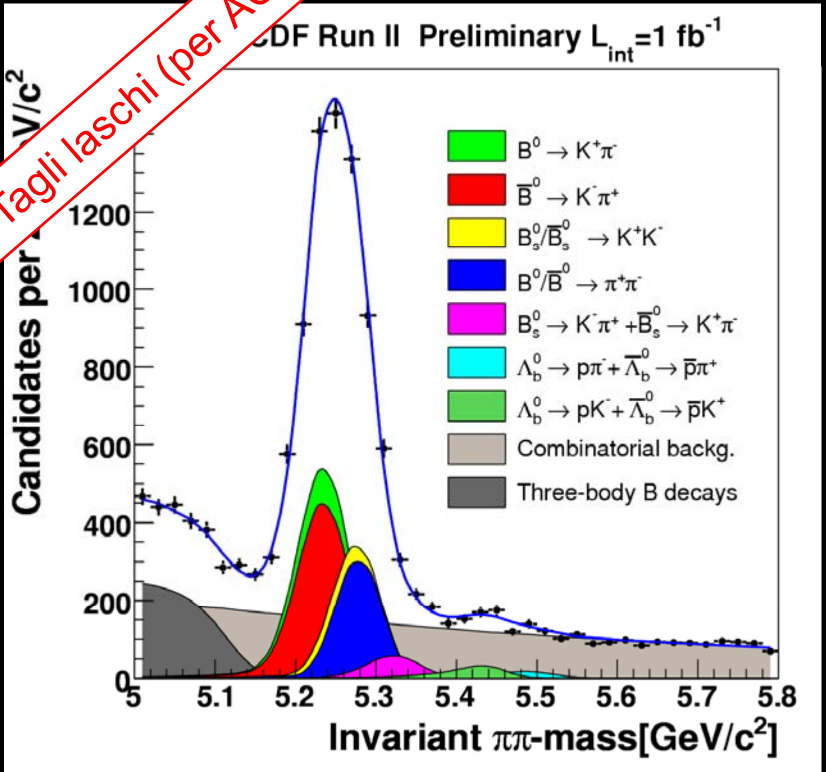
PID



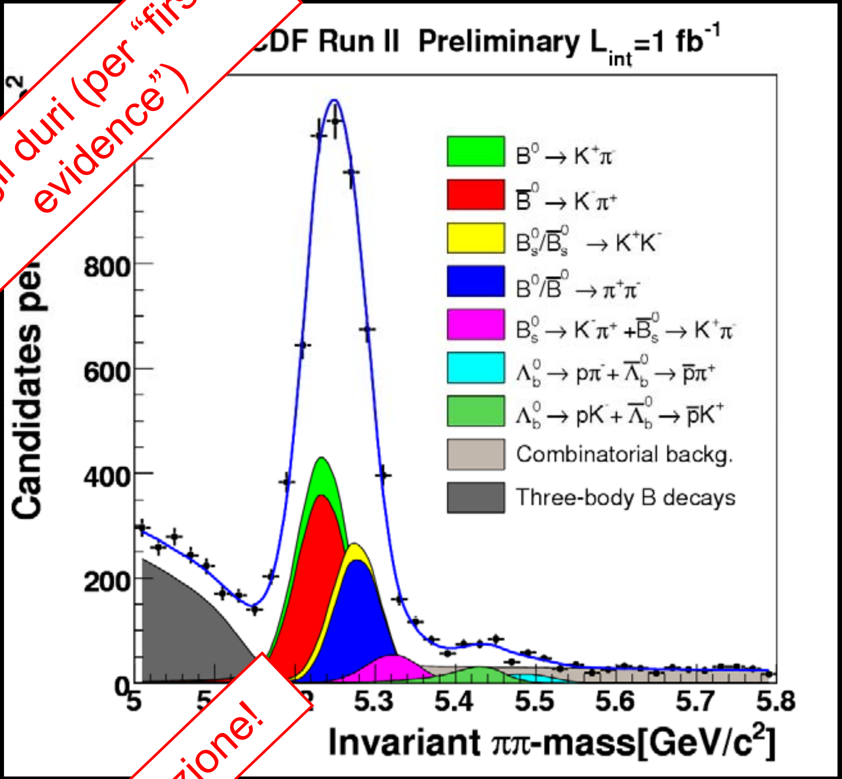
Segnale: da MC e formule analitiche
Fondo: sidebands dei dati

segnale e fondo da
$D^0 \longrightarrow K^-\pi^+$

# Risultati del fit



Tagli laschi (per ACP)



Tagli duri (per "first evidence")

| parameter | fraction | yield |
|---|---|---|
| $B^0 \to \pi^+\pi^-$ + c.c. | ( 0.160 ± 0.009) | 1121 ± 63 |
| $B^0 \to K^+\pi^-$ + c.c. | ( 0.577 ± 0.010) | 4045 ± 84 |
| $B_s^0 \to K^+K^-$ + c.c. | ( 0.186 ± 0.009) | 1307 ± 64 |

prima osservazione!

| ameter | fraction | yield |
|---|---|---|
| $B_s^0 \to K^-\pi^+$ + c.c. | ( 0.040 ± 0.006) | 230 ± 34 |
| $\Lambda_b^0 \to p\pi^-$ + c.c. | ( 0.019 ± 0.003) | 110 ± 18 |
| $\Lambda_b^0 \to pK^-$ + c.c. | ( 0.027 ± 0.003) | 156 ± 20 |

# Asimmetria in $B^0 \longrightarrow K^+\pi^-$

$$A_{\mathrm{CP}} = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} \quad = \quad -0.086 \pm 0.023\ (stat.) \pm 0.009\ (syst.)$$

Circa 3.5σ differente da zero e compatibile con risultati delle *B*-factories

$$A_{\mathrm{CP}}^{\mathrm{Babar}} = -0.107 \pm 0.018(\mathrm{stat.})^{+0.007}_{-0.004}(\mathrm{syst})$$

$$A_{\mathrm{CP}}^{\mathrm{Belle}} = -0.093 \pm 0.018(\mathrm{stat.}) \pm 0.008(\mathrm{syst})$$

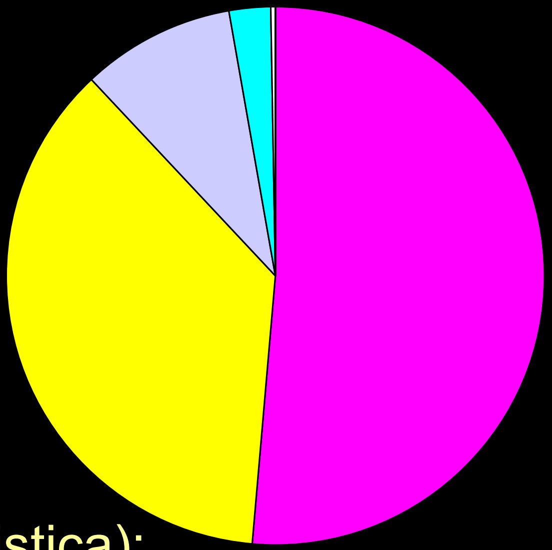
Incertezze sistematiche di CDF al livello di quelle delle *B*-factories.

Questa misura usa solo 1 $\mathrm{fb}^{-1}$ . Con statistiche previste nei prossimi due anni ci aspettiamo migliore misura al mondo (<1%)

CDF ha opportunita' di confrontarla con l'asimmetria nel $B^0_s \longrightarrow K^-\pi^+$ seguendo un test model-independent della presenza di NP proposto da Lipkin (Lipkin, Phys.Lett.B621:126, 2005).

# Incertezze sistematiche dominanti

Incertezza sistematica totale e’ 0.9% , da confrontare con 2.3% statistica
Grazie a 15M $D^0 \longrightarrow K^-\pi^+$ prompt usati per investigare asimmetrie spurie e correzioni efficienza.
C’e’ ancora margine di miglioramento.



- 🟪 modello dE/dx (si riduce  parzialmente con statistica);
- 🟨 valori nominali delle masse dei *B* in input al fit (si riduce con  statistica);
- ☐ modello del fondo combinatorio;
- ☐ asimmetrie di carica nel fondo;

# $B^0_s \longrightarrow K^-\pi^+$: prima osservazione

$$BR(B^0_s \to K^-\pi^+) \;=\; (5.0 \pm 0.75\ (stat.) \pm 1.0\ (syst.)) \times 10^{-6}$$

Prima osservazione (~8σ). Limite precedente $5.4\times10^{-6}$ (CDF). Incertezza non sufficiente per discriminare tra differenti predizioni (pQCD, SCET, QCDF), anch' esse affette da incertezze 20-50%.

Gronau e Rosner, e poi Lipkin: verifica sperimentale della relazione, robusta teoricamente, tra $A_{CP}(B^0_s \longrightarrow K^-\pi^+)$ e $A_{CP}(B^0 \longrightarrow K^+\pi^-)$. Test di presenza di NP

$$\Gamma(\overline{B}^0 \to K^-\pi^+) - \Gamma(B^0 \to K^+\pi^-) \;=\; \Gamma(B^0_s \to K^-\pi^+) - \Gamma(\overline{B}^0_s \to K^+\pi^-)$$

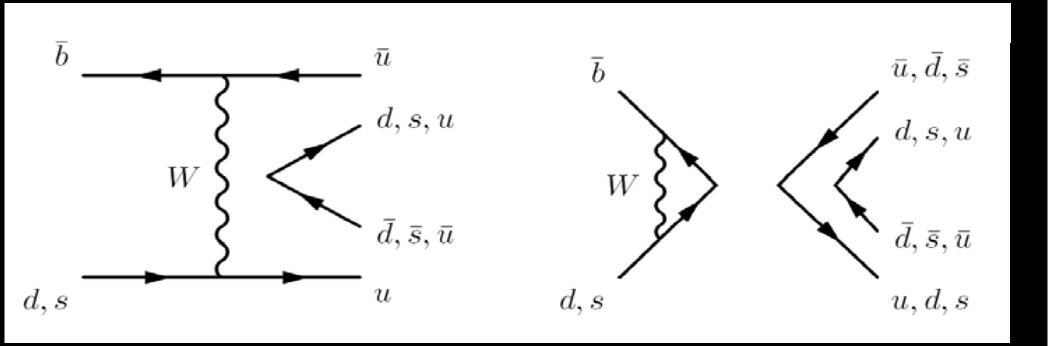
Sembrerebbe favorita una grande (~40%) asimmetria nel $B^0_s \longrightarrow K^-\pi^+$. Misura preliminare.

$$A_{CP} \;=\; 0.39 \pm 0.15\ (stat.) \pm 0.08\ (syst.)$$

Promettente in vista di campioni multi-fb$^{-1}$.

# $B^0_s \longrightarrow \pi^+\pi^-$ e $B^0 \longrightarrow K^+K^-$

Ampiezze di annichilazione e W-exchange, molto difficili da calcolare in QCDF. Il loro contributo induce incertezza in molti altri processi.
La sensibilita' di CDF incomincia a lambire valori di rates aspettati



$$BR(B^0_s \to \pi^+\pi^-) = (0.53 \pm 0.31\ (stat.) \pm 0.40\ (syst.)) \times 10^{-6}$$

Accessibile solo a CDF, combinato con $B^0 \longrightarrow K^+K^-$ permette estrazione di ampiezze di annichilazione.

$$BR(B^0 \to K^+K^-) = (0.39 \pm 0.16\ (stat.) \pm 0.12\ (syst.)) \times 10^{-6}$$

**0.05 ± 0.15 (stat) ±0.08 (syst) [Babar]**

**0.09 +0.18-0.14 (stat) ±0.1 (syst) [Belle]**

# $\Lambda^0_b \longrightarrow p\pi^-/pK^-$: prima osservazione

$$\begin{aligned} N_{\rm raw}(\Lambda^0_b \to pK^-) &= 156 \pm 20\ (stat.) \pm 11\ (syst.) \\ N_{\rm raw}(\Lambda^0_b \to p\pi^-) &= 110 \pm 18\ (stat.) \pm 16\ (syst.) \end{aligned}$$

Prima osservazione (6σ e 11σ ) di decadimenti barionici charmless.

$$\frac{BR(\Lambda^0_b \to p\pi^-)}{BR(\Lambda^0_b \to pK^-)} = 0.66 \pm 0.14\ (stat.) \pm 0.08\ (syst.)$$

Consistente con predizioni (0.60—0.62, Mohanta PRD63:074001,2001).

Misure di BR e asimmetria diretta (aspettata grande!) *in fieri.*

# Ricerca dei decadimenti FCNC $B^0_{(s)} \rightarrow \mu^+\mu^-$

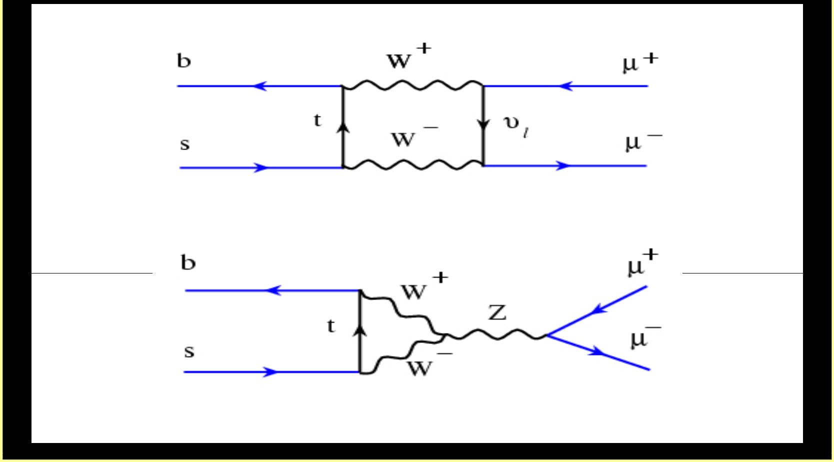
Vedi anche CDF public note 8176. Aggiornamento su 780 pb$^{-1}$ di analisi pubblicata in PRL93:032001,2004 e PRL95: 221805, 2005

# Ricerca dei decadimenti $B^0_{(s)}\rightarrow\mu^+\mu^-$

MODELLO STANDARD

Decadimenti FCNC soppressi. BR($B^0_s\rightarrow\mu^+\mu^-$) previsto ~ $10^{-9}$ : inaccessibile al Tevatron

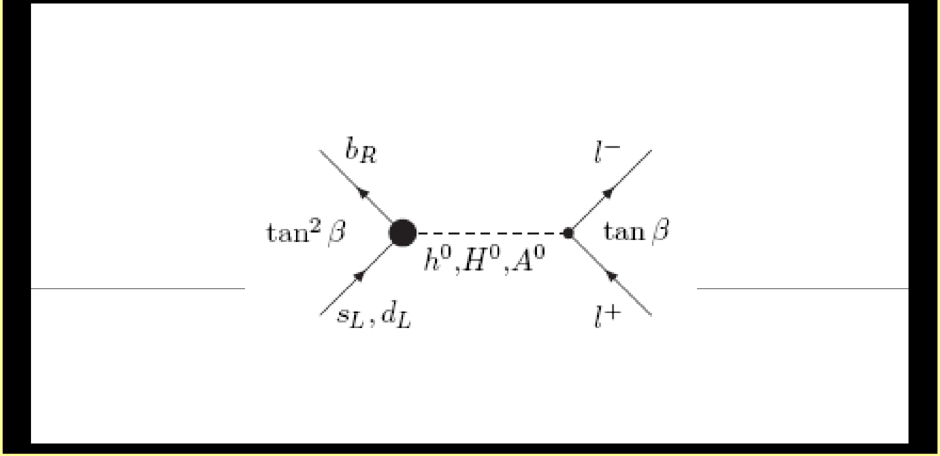
$B^0\rightarrow\mu^+\mu^-$ ulteriormente soppresso di fattore $|V_{td}/V_{ts}|^2$



SUSY

Contributi NP possono aumentare I rates, rendendo possibile osservazione al Tevatron.

MSSM: BR~$(\tan\beta)^6$: fino a 100 volte + grande RPV: diagramma "albero"



Solo CDF puo' distinguere $B^0_s$ da $B^0$ in massa ($\sigma_{M\mu\mu}$ = 24 MeV/$c^2$ )

# $B^0_{(s)}\rightarrow\mu^+\mu^-$ :risultati (780 $pb^{-1}$)

Trigger di dimuoni ($p_T$>1.5 GeV/c, |η|<1).

Likelihood-Ratio distingue segnale (Pythia MC) dal fondo (sidebands dati) usando: (a) lunghezza di decadimento, (b) isolamento del *B*, (c) proiezione 3D della direzione del *B* verso il vertice $p\bar{p}$.

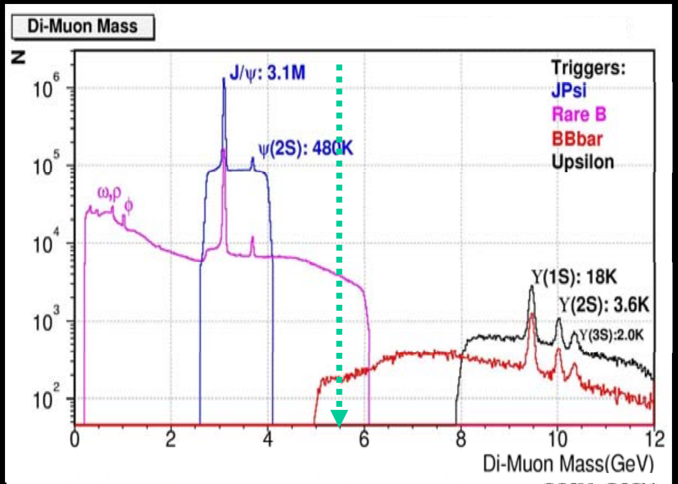
Capire i fondi: sequenziali e doppio semileptonico, fakes.

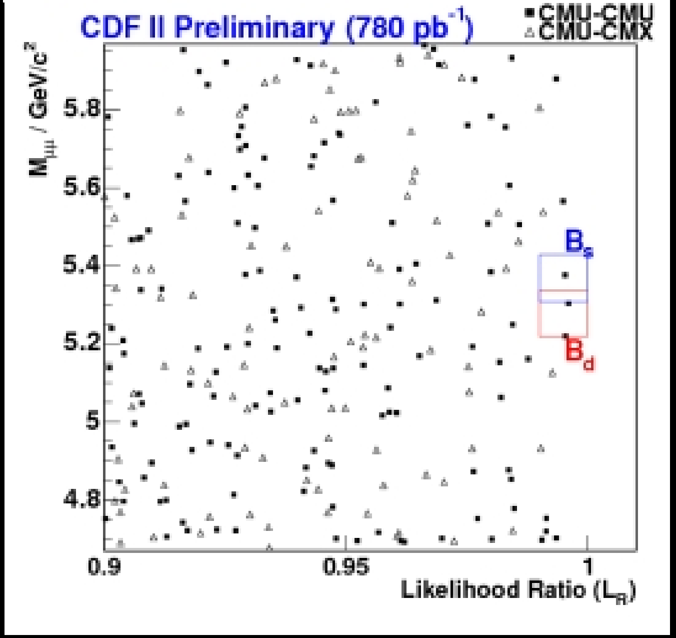
Misura di BR (o limite) rispetto al canale $B^+ \rightarrow J/\psi K^+$ usato per normalizzare.

Nessuna evidenza di segnale:

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

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





# Ricerca dei decadimenti (mediati da) $b \rightarrow s l^+ l^-$

Vedi anche CDF public note 8543.

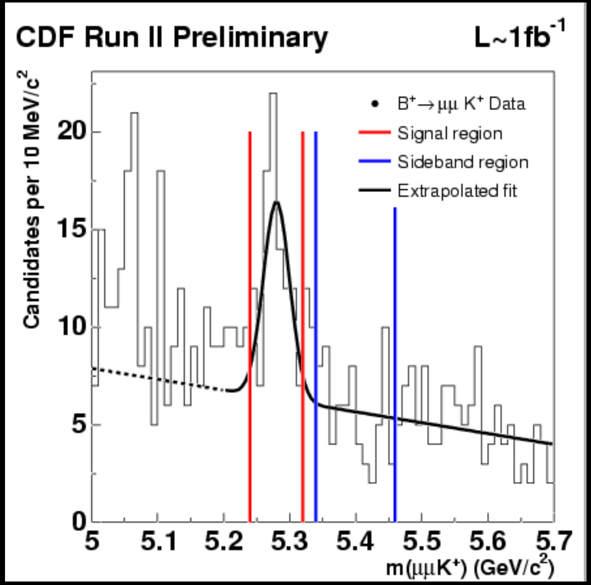
# Obiettivi e strategia

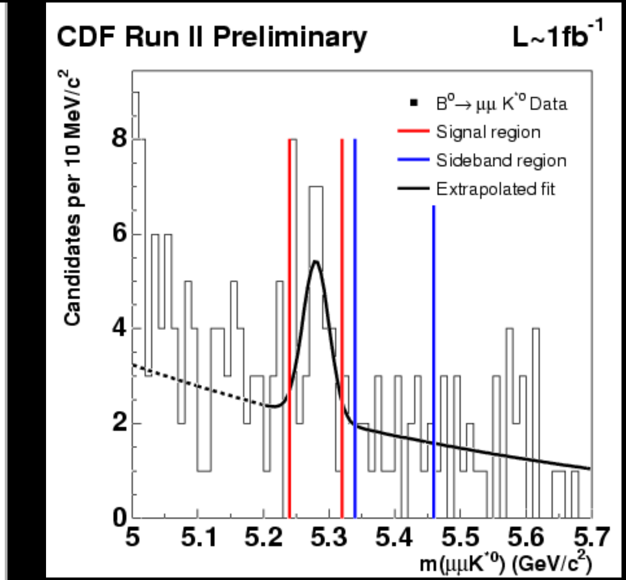
Decadimenti sensibili a NP (rate e asimmetrie)

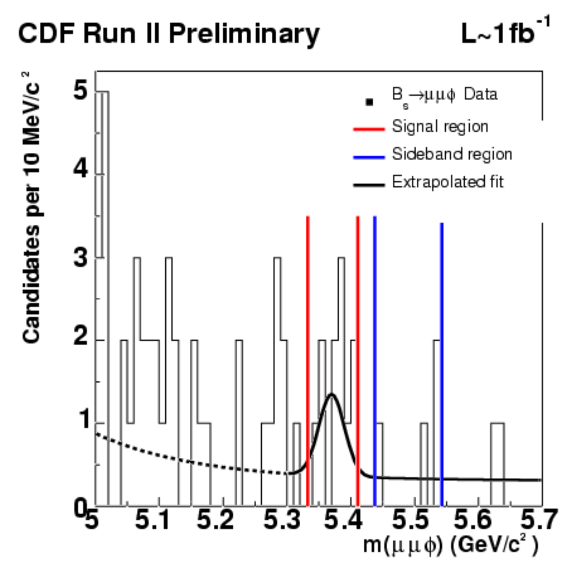
$B^+$ e $B^0$ osservati alle B-factories. Conferma al Tevatron e esplorazione di $B^0_s$

Strategia simile a $B^0_{(s)} \rightarrow \mu^+\mu^-$ : ottimizzazione usando MC (segnale) e dati (fondo), normalizzazione a $B \rightarrow J/\psi h^-$ . $J/\psi$ e $\psi'$ escluse da spettro $\mu^+\mu^-$

Contare gli eventi in una finestra di 2σ intorno alla massa del *B* e estrapolo fondo da finestra di 3--9σ nella zona del segnale.





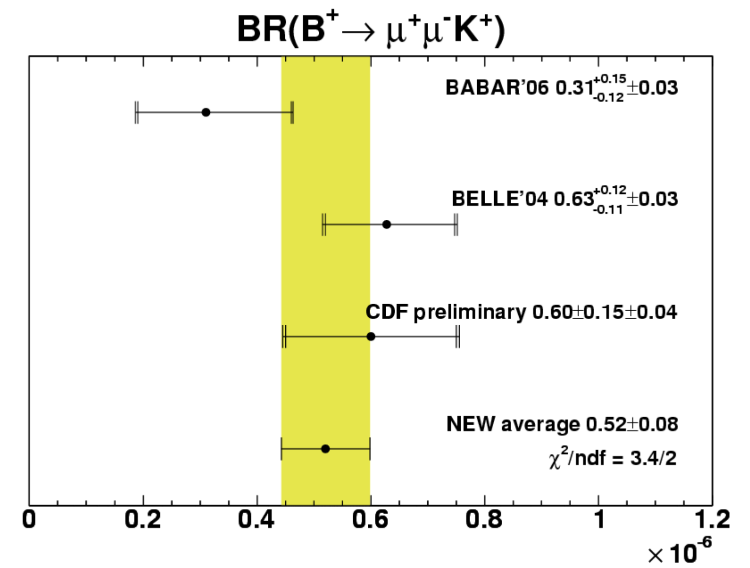


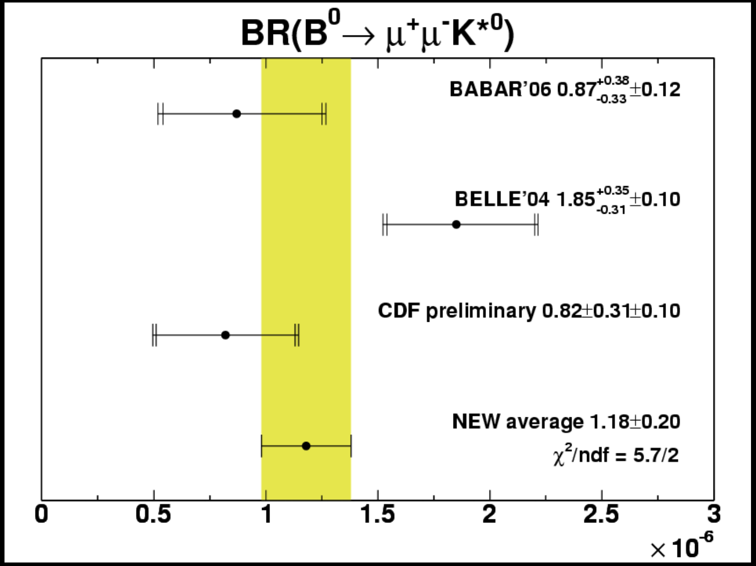
# Risultati (920 $pb^{-1}$)

- BR($B^0_s \rightarrow \mu\mu\varphi$))<2.4 x$10^{-6}$ (90% CL) = [1.16 ± 0.56(stat.) ± 0.42(sys.)]x$10^{-6}$
Miglior limite oggi.

- BR($B^+ \rightarrow \mu\mu K^+$) = [0.72 ± 0.15(stat.) ± 0.05(sys.)]x$10^{-6}$ (45 ev.)
- BR($B^0 \rightarrow \mu\mu K^*$) = [0.82 ± 0.31(stat.) ± 0.10(sys.)]x$10^{-6}$ (20 ev.)

Incertezze confrontabili con B-factories.





# Conclusioni

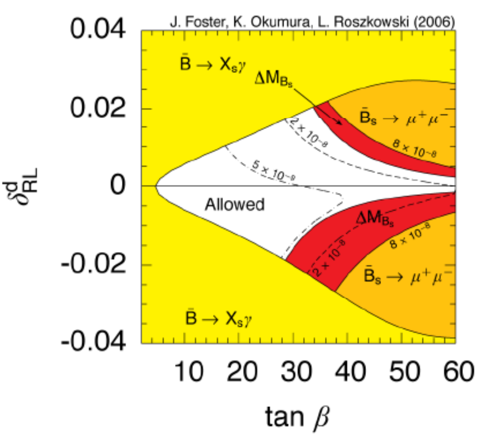
CDF integra ~30 $pb^{-1}$/settimana, corrispondenti a ~200 $B^0_{(s)} \rightarrow h^+h'^-$: raccogliamo decadimenti di $B^0$ ad un tasso doppio rispetto a Belle/*BaBar*. Incertezza statistica e' solo il 22% peggiore, fissato lo yield di segnale.

Impatto nel flavor sempre piu' incisivo. Misure integrate nel tempo di decadimenti charm-less competitive ($B^0$) e complementari ($B^0_s$) a quelle delle *B*-factories. Accesso esclusivo a $B^0_s$ e $\Lambda^0_b$. Potrebbero essere essenziali per completare il quadro delineato da $B^0$ e $B^+$.

Ci sono tutti gli ingredienti per misure dipendenti dal tempo. Con 5 $fb^{-1}$ aspettiamo risoluzioni su $A_{CP}(t)$ competitive con quelle delle *B*-factories nel $B^0$, e del 20%-30% sul $B^0_s$.

Continua la ricerca di nuova fisica "virtuale". Vincoli attuali da $\Delta m_s$ e $B^0_s \rightarrow \mu\mu$ si complementano nell'esplorazione di spazio dei parametri di NP.

Sensibilita' attesa a BR~pochi $10^{-8}$



# Materiale di riserva

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

Superconducting proton-synchrotron…………: 36 (*proton*) × 36 (antiproton) bunches

a crossing every 396 ns at √s = 1.96 TeV

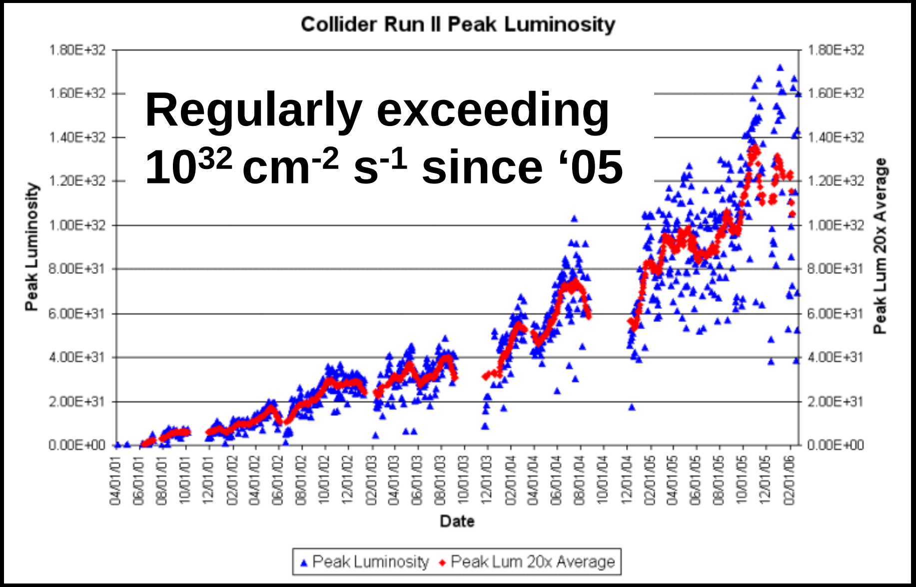
# of interactions per bunch-crossing……………………: $< N >_{\text{poisson}} = 2$ (at $10^{32}$ cm$^{-2}$s$^{-1}$)

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

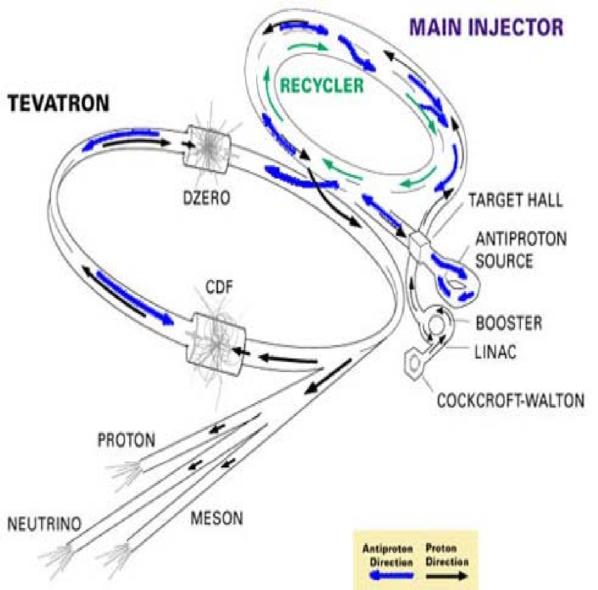
**need long Si-vertex** **small wrt $c\tau(B)$ ~ 450 $\mu$m**

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

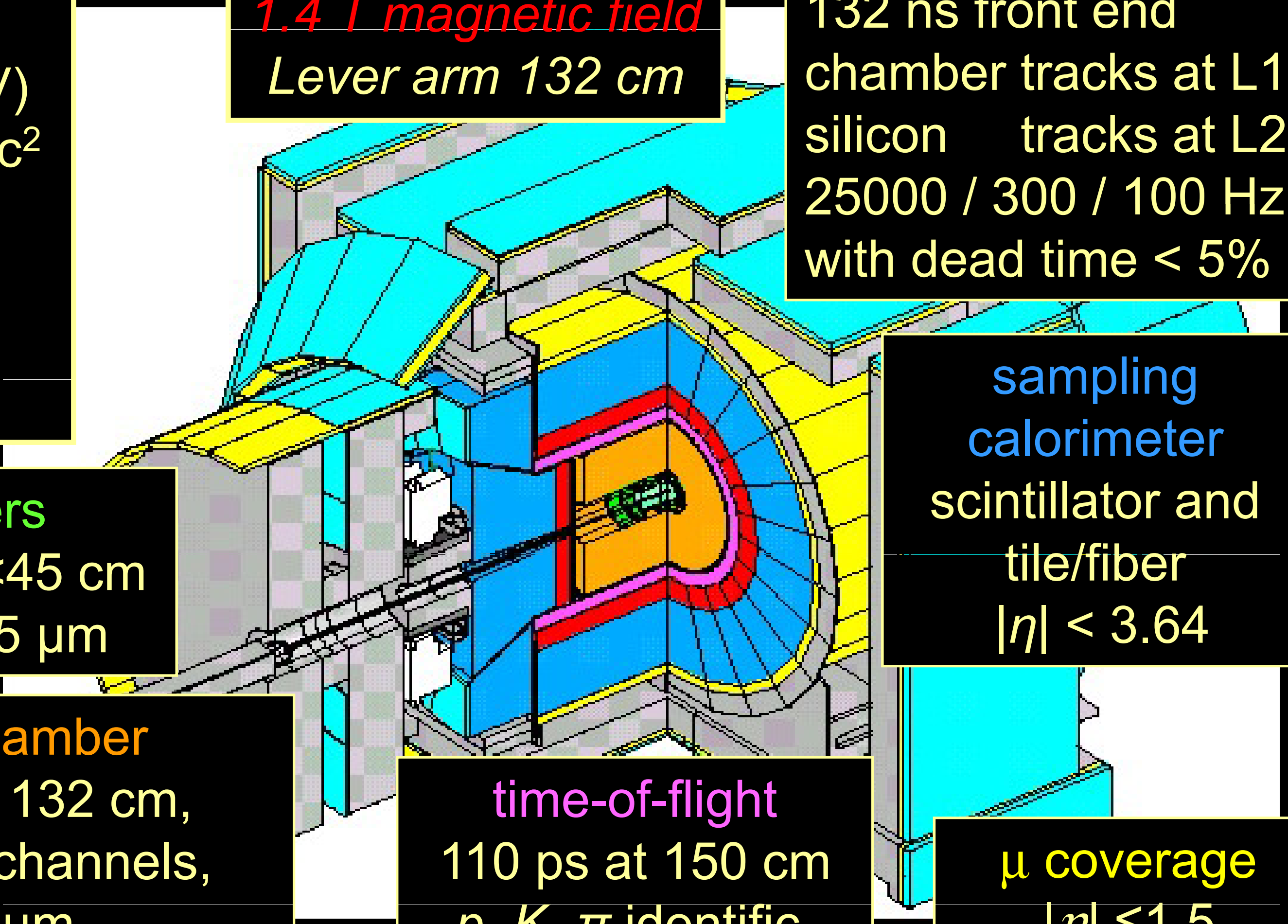
typically 18 pb$^{-1}$ / week on tape



**Regularly exceeding $10^{32}$ cm$^{-2}$ s$^{-1}$ since '05**



# 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

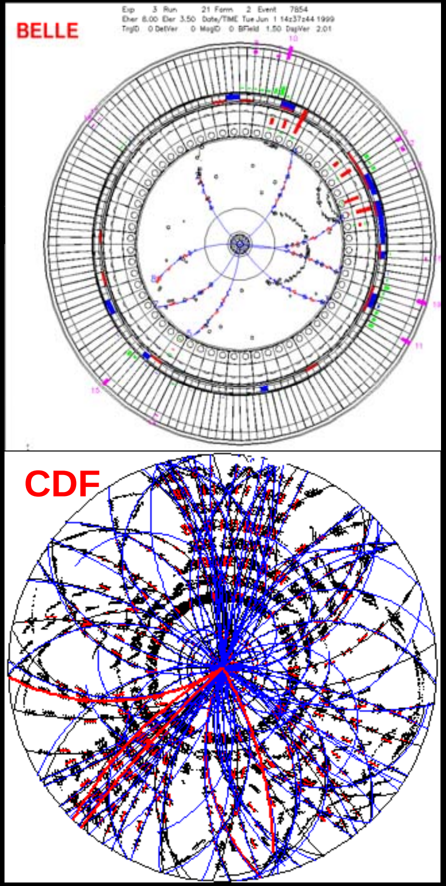
time-of-flight
110 ps at 150 cm
*p, K, π* identific.
2σ at *p* <1.6 GeV/c

μ coverage
|*η*| ≤1.5
84% in *ϕ*

# Heavy Flavor physics at the Tevatron

## The Good

Reconstructable $p\bar{p} \rightarrow b\bar{b}$ x-section is O($10^3$) larger than $e^+e^- \rightarrow b\bar{b}$ 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 ×$10^3$ 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

# Triggering heavy flavors

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

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

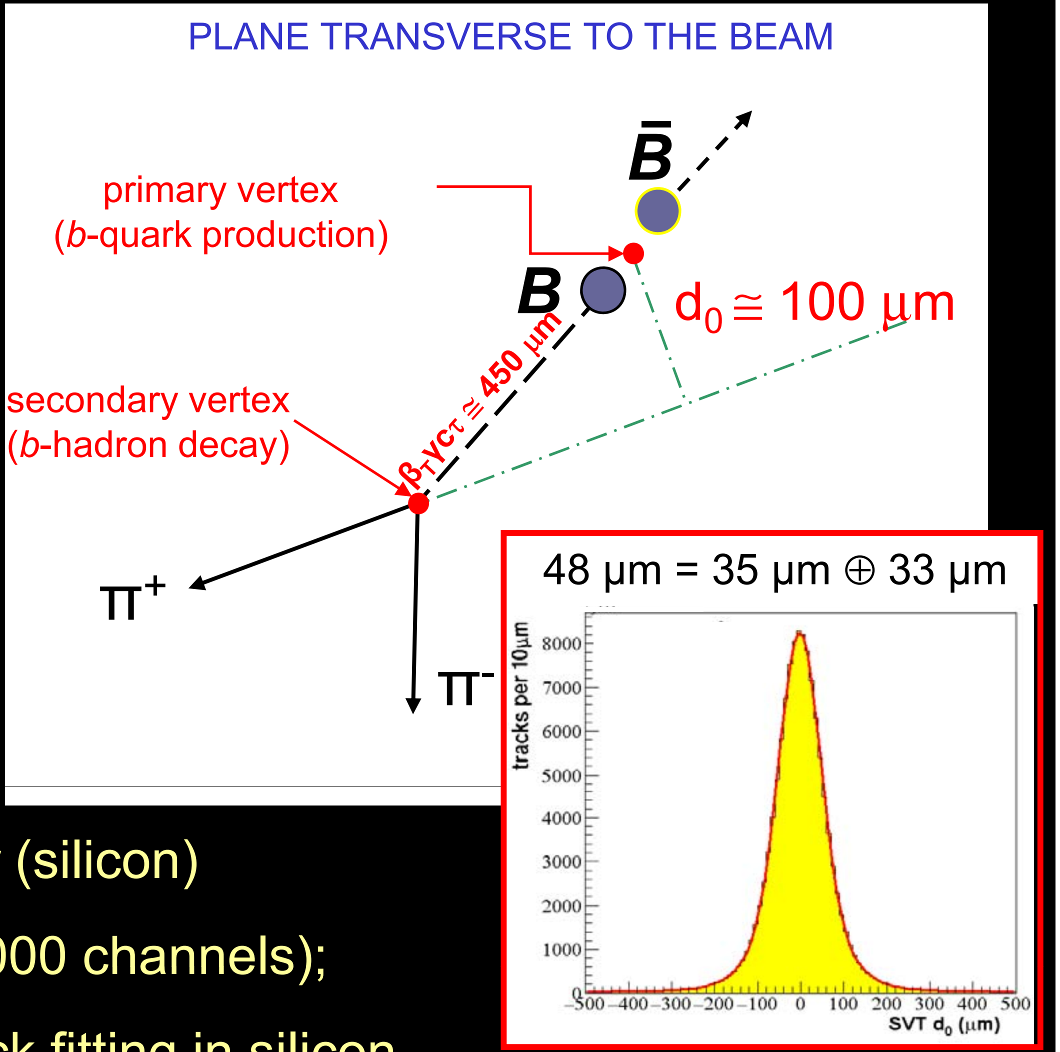
| **conventional** | ***partially new approach*** | ***new approach*** |
|---|---|---|
| di-muon | electron or $\mu$ and displaced track | two displaced tracks |
| $B \longrightarrow$ charmonium<br>$B \longrightarrow \mu\mu$ | $B \rightarrow l\nu X$ | $B \rightarrow hh$ |
| two muons with: | electron (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 |

# Heavy flavor signature

“Long” (~1.5 ps) lifetime of *b*-hadrons: a discriminating signature against light-quark background. Before decaying, sufficiently boosted *b*-hadrons fly a distance resolvable with vertex detectors.

Traditionally exploited offline. CDF exploits it at trigger level.

An experimental challenge that requires:



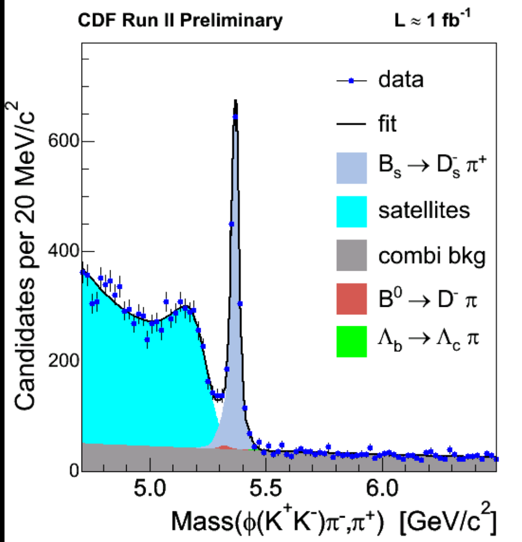
(1) high resolution vertex detector (silicon)

(2) read out silicon r-φ side (212,000 channels);

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

# Displaced track trigger: pros and cons

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

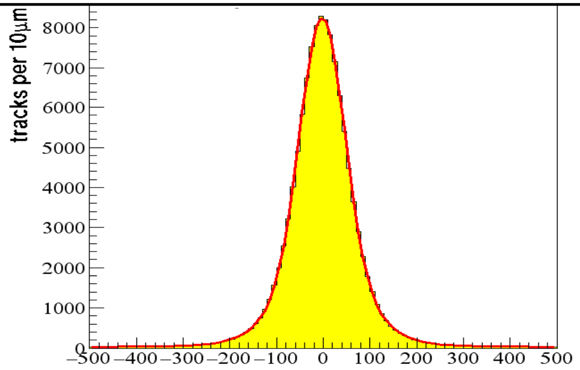


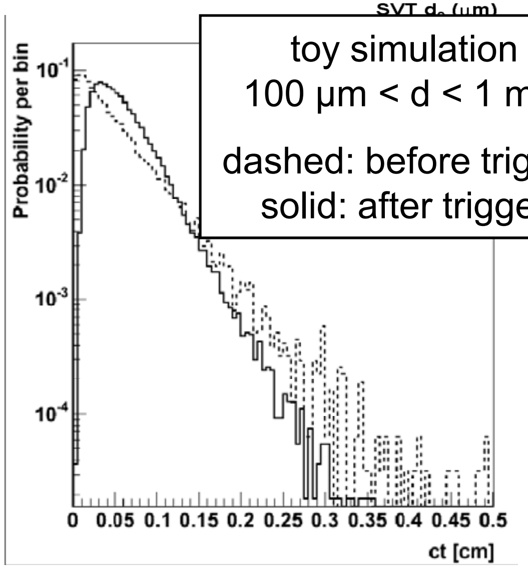
“golden” modes for $B^0_s$ mixing

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**]





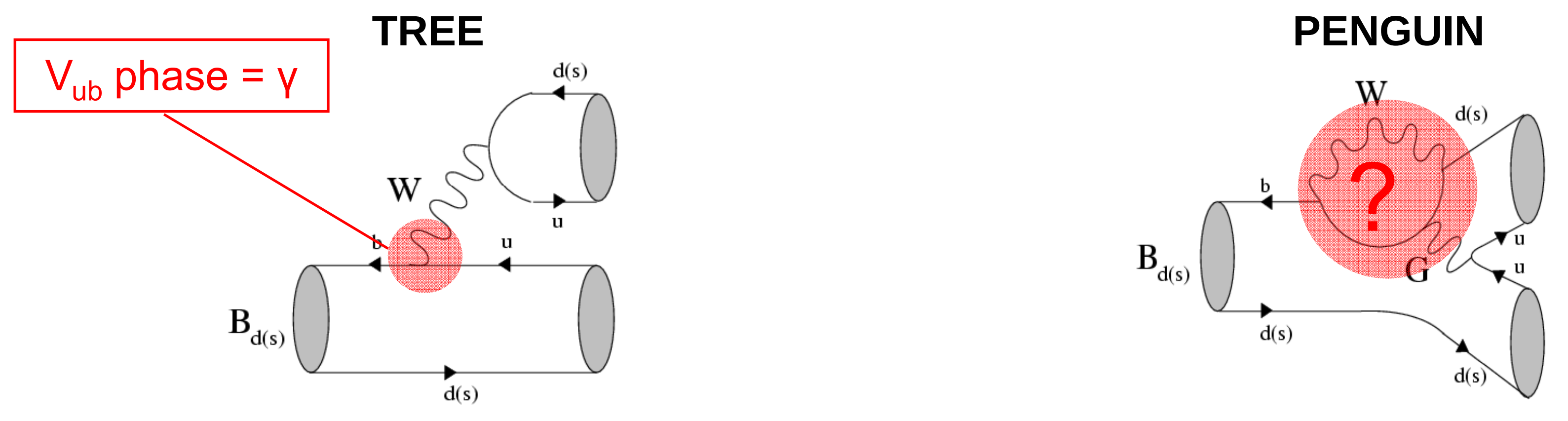
toy simulation
100 μm < d < 1 mm

dashed: before trigger
solid: after trigger

# Introduction

Two-body charmless *B* decays: the most popular probe of flavor physics in the *B* sector. Only two (light) bodies, many open channels provide multiple, experimentally similar, ways to measure the same set of quantities: decay rates, dependent (or not) on time.

Initial interest: measurement of angle α, assuming negligible contributions of second-order hadronic loop diagrams (“penguins”). BR($B^0 \to K^+\pi^-$) > BR($B^0 \to \pi^+\pi^-$) by CLEO invalidated the assumption.

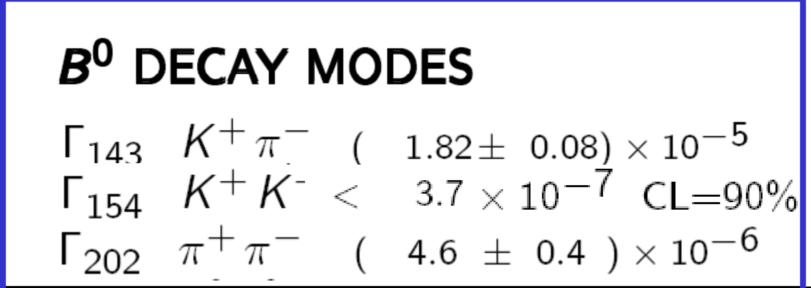


# Experimental status

Interplay of interfering amplitudes: an opportunity rather than a limitation.

Methods to constrain hadronic uncertainties required.

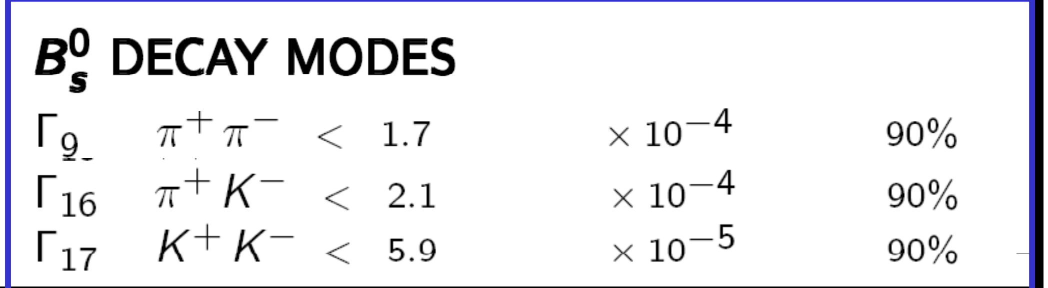
Theory still immature, experimental information needed to discriminate or refine models.



**$B^0$ DECAY MODES**

| | | | |
|---|---|---|---|
| $\Gamma_{143}$ | $K^+\pi^-$ | $(1.82\pm 0.08)\times 10^{-5}$ | |
| $\Gamma_{154}$ | $K^+K^-$ | $< 3.7\times 10^{-7}$ | CL=90% |
| $\Gamma_{202}$ | $\pi^+\pi^-$ | $(4.6\pm 0.4)\times 10^{-6}$ | |

Belle and *BaBar* cover $B^0$ decays with impressive precision.



**$B^0_s$ DECAY MODES**

| | | | | |
|---|---|---|---|---|
| $\Gamma_9$ | $\pi^+\pi^-$ | $< 1.7$ | $\times 10^{-4}$ | 90% |
| $\Gamma_{16}$ | $\pi^+K^-$ | $< 2.1$ | $\times 10^{-4}$ | 90% |
| $\Gamma_{17}$ | $K^+K^-$ | $< 5.9$ | $\times 10^{-5}$ | 90% |

Only information are upper limits from ALEPH (LEP1)

$B^0$ and $B^+$ data controversial …$B^0\to K\pi$ puzzle, Belle/*BaBar* disagreement in direct asymmetry of $B^0\to\pi^+\pi^-$ .
Opportunity for CDF to supplement crucial experimental information

# Role of $B^0_s \rightarrow K^+K^-$

$V_{ub}$ phase of the CKM matrix (angle γ) is the least known and most difficult to measure. Dunietz (1993) and Fleischer (1999) proposed a method to determine it from amplitudes of $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$

Modes related by U-spin: sub-group of SU(3) that exchanges *d* and *s* quarks. Not (exactly) conserved in the SM but may cancel hadronic uncertainties

Compare to other extractions of γ (e.g. from tree $B \rightarrow DK$) to search for inconsistencies in CKM mechanism or insight into hadronic low-energy interactions in *B* decays.

STEP 1.

Untagged BR. Derive allowed regions in space of $B^0_s \rightarrow K^+K^-$, $B^0 \rightarrow \pi^+\pi^-$ , and $B^0 \rightarrow K^+\pi^-$ observables to constrain γ and U-spin

$$R_d^s \equiv \frac{\mathcal{B}(B_s^0 \rightarrow K^+K^-)}{\mathcal{B}(B^0 \rightarrow \pi^+\pi^-)} = \frac{1}{\epsilon}\left|\frac{\mathcal{C}'}{\mathcal{C}}\right| \frac{\epsilon^2 + 2\epsilon d' \cos(\theta')\cos(\gamma) + d'^2}{1 - 2d\cos(\theta)\cos(\gamma) + d^2} \times \frac{m_{B^0}}{m_{B_s^0}} \times \frac{\tau_{B^0}}{\tau_{B_s^0}} \times \frac{\sqrt{1 - \left(\frac{m_K}{m_{B_s^0}}\right)^2}}{\sqrt{1 - \left(\frac{m_\pi}{m_{B^0}}\right)^2}}$$

# Role of $B^0_s \to K^+K^-$ (cont'd)

## STEP 2.

Needs flavor-tagged samples and time-dependent analysis. Direct extraction of tight gamma bounds from systems of equations.

$$A_{\mathsf{CP}}^{\mathrm{dir}}(B^0 \to \pi^+\pi^-) = -\frac{2d\sin(\theta)\sin(\gamma)}{1-2d\cos(\theta)\cos(\gamma)+d^2}$$

$$A_{\mathsf{CP}}^{\mathrm{dir}}(B^0_s \to K^+K^-) = \frac{2(d'/\epsilon)\sin(\theta')\sin(\gamma)}{1-2(d'/\epsilon)\cos(\theta')\cos(\gamma)+(d'/\epsilon)^2}$$

$$A_{\mathsf{CP}}^{\mathrm{mix}}(B^0 \to \pi^+\pi^-) = \frac{\sin(\phi_d+2\gamma)-2d\cos(\theta)\sin(\phi_d+\gamma)+d^2\sin(\phi_d)}{1-2d\cos(\theta)\cos(\gamma)+d^2}$$

$$A_{\mathsf{CP}}^{\mathrm{mix}}(B^0_s \to K^+K^-) = \frac{\sin(\phi_s+2\gamma)-2(d'/\epsilon)\cos(\theta')\sin(\phi_s+\gamma)+(d'/\epsilon)^2\sin(\phi_s)}{1-2(d'/\epsilon)\cos(\theta')\cos(\gamma)+(d'/\epsilon)^2},$$

$\Phi_d$ from *B*-Factories, $\Phi_s \approx 0$, ε known. U-spin limit: d=d', θ = θ'. Four equations and three unkowns. Corrections for U-spin violation from other modes.

Challenging. Theoretically because U-spin is violated and independent measurements of violation-magnitude are needed. Experimentally because large samples of tagged $B^0_s \to K^+K^-$ decays are needed.

Accessible only at CDF (at least until Fall 2008, at LHCb start-up)

This analysis is the first step toward the completion of this measurement.

# Not only *gamma*

✓ Time-evolution of $B^0_s \to K^+K^-$ valuable information on lifetime-difference $\Delta\Gamma_s/\Gamma_s$ . Abnormally small value indicate non-SM CP-violating phases.

✓ Measure direct CP-violating asymmetry in $B^0 \to K^+\pi^-$ decays (10% effect)

✓ First observation and direct CP-violating asymmetry in $B^0_s \to K^-\pi^+$

✓ Sample of (still unobserved) $B^0_s \to K^-\pi^+$ provides model-independent test for non-SM physics in $B \to K\pi$ decays – shed light on "$B \to K\pi$ puzzle"

✓ Observation (or tighter bounds) on pure-annihilation modes, $B^0_s \to \pi^+\pi^-$ and $B^0 \to K^+K^-$ . Information on their amplitudes crucial to reduce uncertainties in many other modes.

✓ Observation (or tighter bounds) on two-body charmless $\Lambda^0_b$ decays and measurement of direct CP-violating asymmetries (expected large ~ 30%)

# Analysis strategy

Data-driven approach

Simulators do not reproduce *b*-hadron production, QCD backgrounds and detector/trigger absolute efficiencies in hadron-hadron collisions.

Use data whenever possible, simulation only when strictly necessary and reliable (kinematic of signal decay and ratios of detector acceptances between similar modes)

Measurement of ratios of branching fractions (rather than absolute BF)

More meaningful for comparison with theoretical predictions

Reduced systematic effects

6% uncertainty

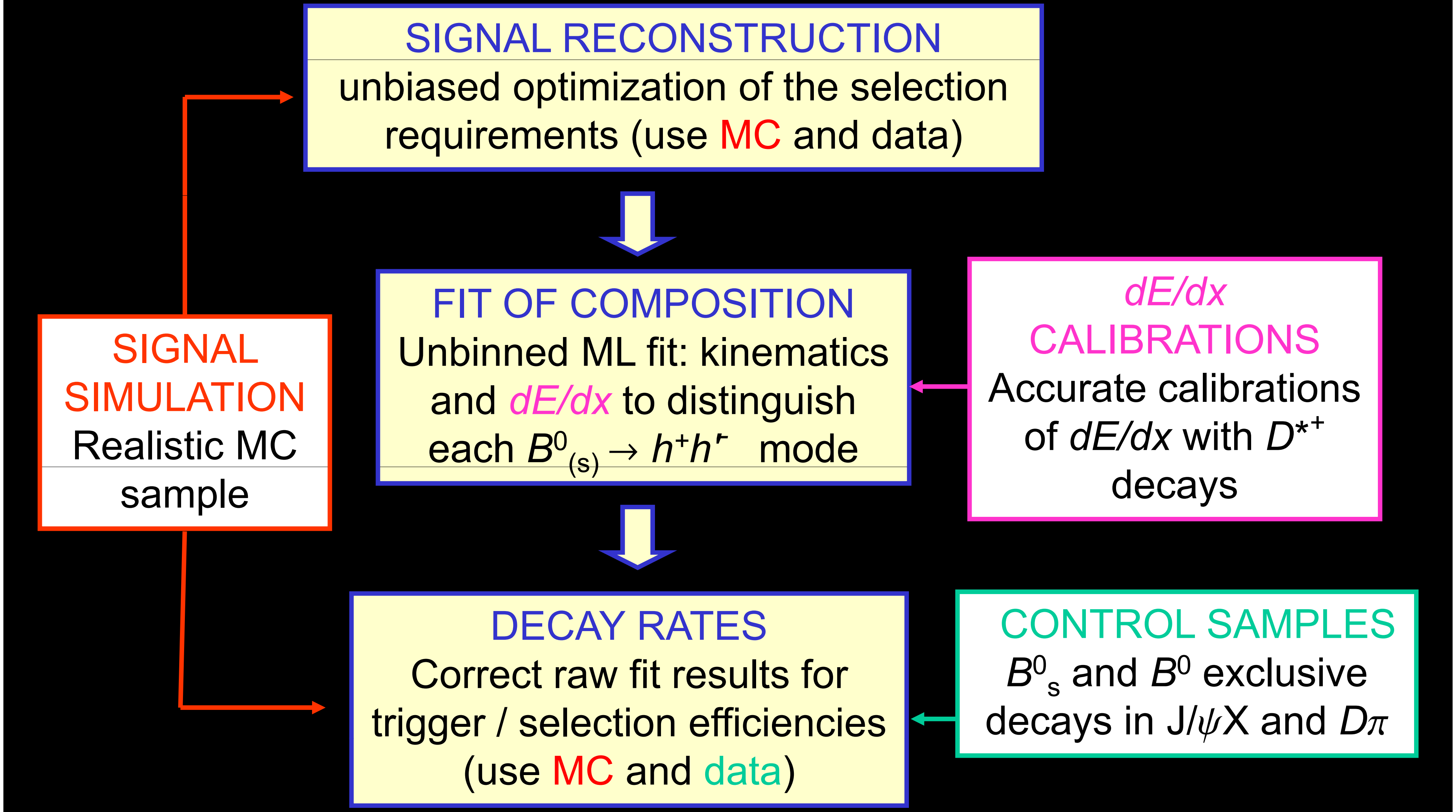
$$\mathcal{B}(B_s^0 \to K^+K^-) = \frac{N(B_s^0 \to K^+K^-)}{2\varepsilon \times \sigma(\mathrm{p\bar{p}} \to b\bar{b} + X) \times f_s \times \int \mathcal{L}dt}$$

Hard to reproduce with simulation

15% uncertainty

2.5%-10% uncertainty

# Analysis overview



SIGNAL RECONSTRUCTION
unbiased optimization of the selection requirements (use MC and data)

FIT OF COMPOSITION
Unbinned ML fit: kinematics and *dE/dx* to distinguish each $B^0_{(s)} \rightarrow h^+h'^-$ mode

DECAY RATES
Correct raw fit results for trigger / selection efficiencies (use MC and data)

SIGNAL SIMULATION
Realistic MC sample

*dE/dx* CALIBRATIONS
Accurate calibrations of *dE/dx* with $D^{*+}$ decays

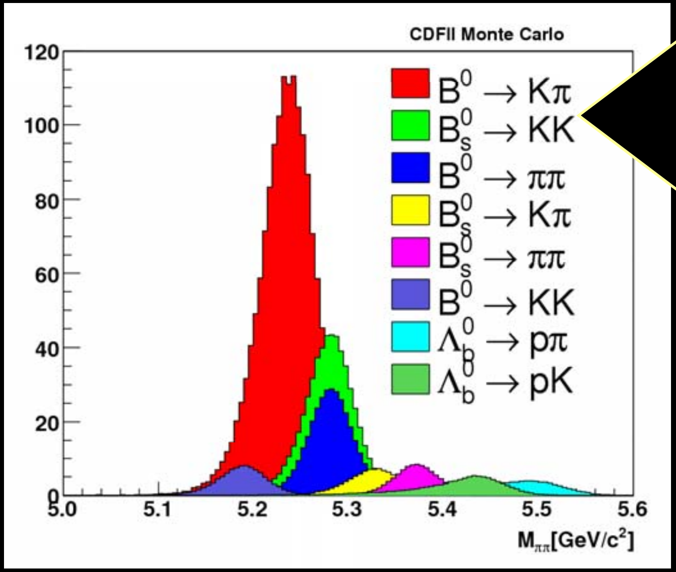
CONTROL SAMPLES
$B^0_s$ and $B^0$ exclusive decays in $J/\psi X$ and $D\pi$

# “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

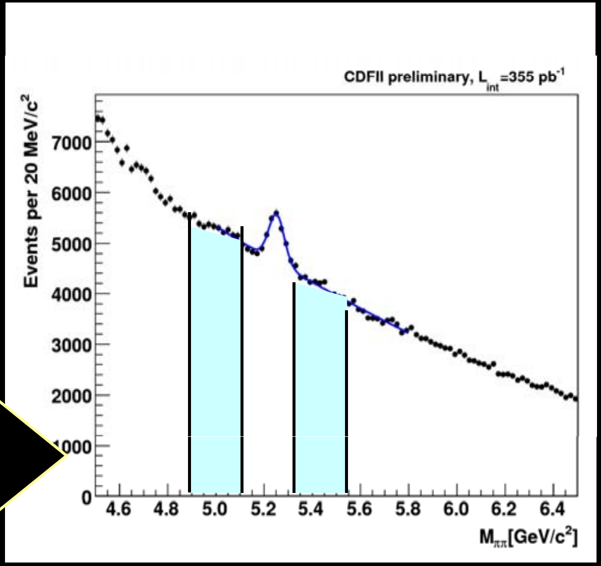
Gain ~10% improvement in resolution *versus* standard S/√(S+B)

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)



# Peak composition handle 1: kinematics

Hard to include in the fit the 4 values of the invariant mass of the track pair, resulting from all possible mass assignments (*Kπ, πK, KK, ππ* ) because of complicated joint distribution of all 4 possible masses.

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

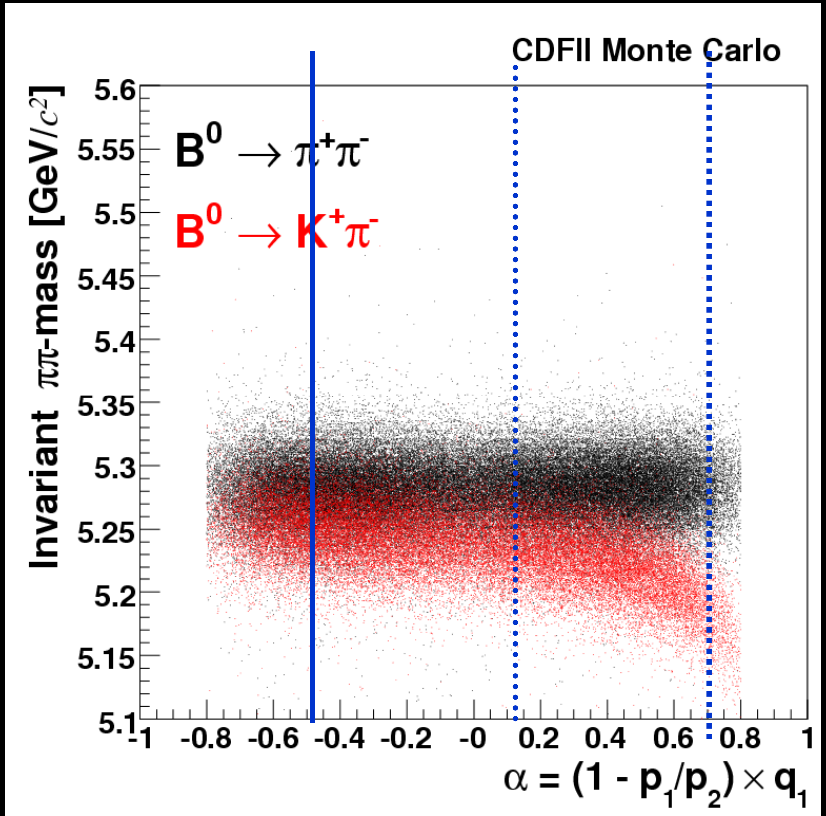
2-body invariant mass with $\overline{m}_1$ and $\overline{m}_2$ mass assignments

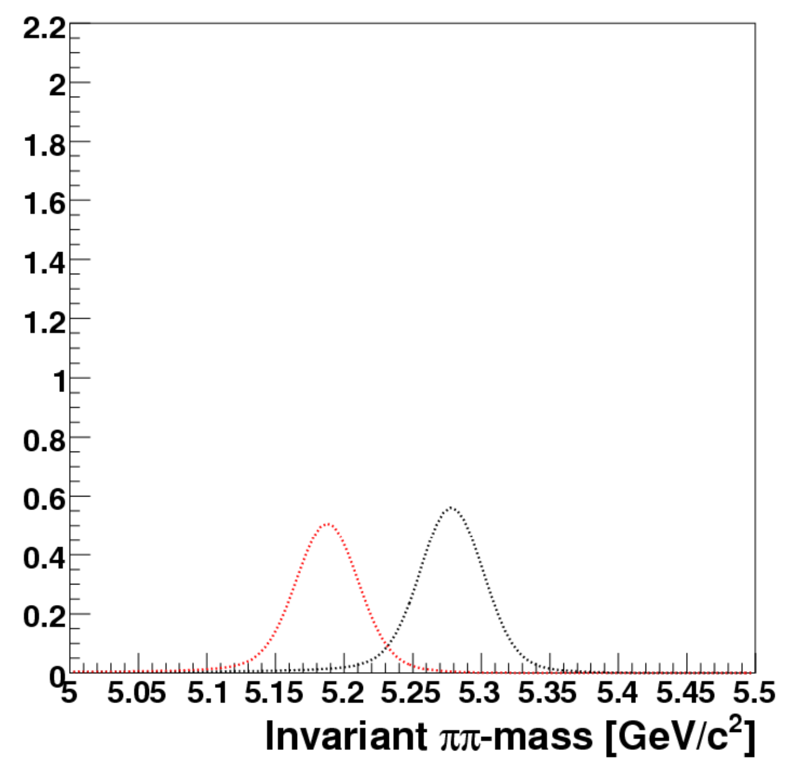
$$M^2_{m_1,m_2} \approx M^2_{\overline{m}_1,\overline{m}_2} + \left(1+\frac{p_1}{p_2}\right)\left(m_2^2 - \overline{m}_2^2\right) + \left(1+\frac{p_2}{p_1}\right)\left(m_1^2 - \overline{m}_1^2\right)$$

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

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

# Kinematics at work





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

Add lifetime information to the fit of composition:

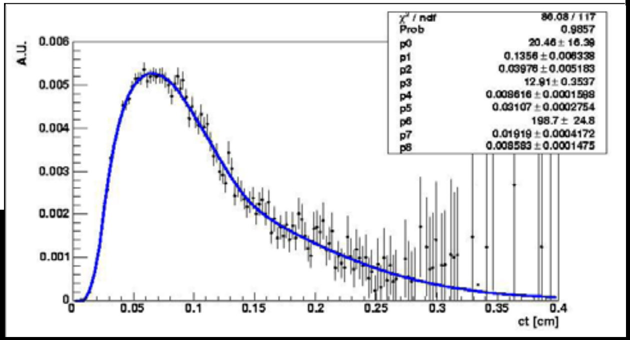
$$\mathscr{L} \sim \wp^m(m_{\pi\pi}|\alpha)\wp^p(\alpha, p_{\rm tot})\wp^{\rm PID}(dE/dx_{\,1}, dE/dx_{\,2}|\alpha, p_{\rm tot})\wp^{\rm life}(ct).$$

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

decay

detector smearing

trigger bias



Trigger bias for signal is extracted from detailed simulation.

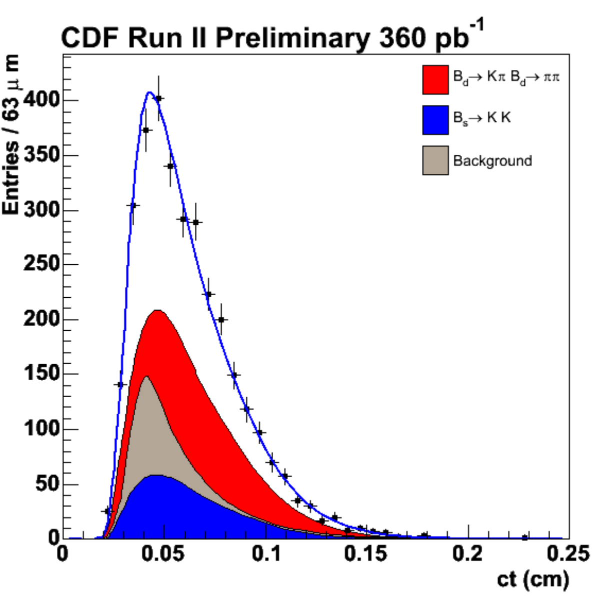
Procedure validated in unbiased $B \to J/\psi X$ decays from dimuon trigger.

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 | – | $458 \pm 53$ |



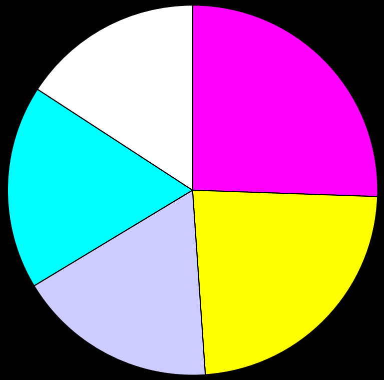
$B^0_s \to K^+K^-$ predicted ~95% CP-even: has the lifetime of "light $B^0_s$" :

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

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

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

Dominant systematics :



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

# Efficiency/acceptance corrections

Correct for relative acceptance, trigger and selection effic.: 5 -10%

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

$$\frac{BR(B^0 \to \pi^+\pi^-)}{BR(B^0 \to K^+\pi^-)} = \frac{N(B^0 \to \pi^+\pi^-)}{N(B^0 \to K^+\pi^-)}\Big|_{\mathrm{raw}} \cdot \frac{\epsilon_{kin}(B^0 \to K^+\pi^-)}{\epsilon_{kin}(B^0 \to \pi^+\pi^-)} \cdot \frac{c_{XFT}(B^0 \to K^+\pi^-)}{c_{XFT}(B^0 \to \pi^+\pi^-)}$$

$$\frac{f_s \cdot BR(B^0_s \to K^+K^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = \frac{N(B^0_s \to K^+K^-)}{N(B^0 \to K^+\pi^-)}\Big|_{\mathrm{raw}} \cdot \frac{\epsilon_{kin}(B^0 \to K^+\pi^-)}{\epsilon_{kin}(B^0_s \to K^+K^-)} \cdot \frac{c_{XFT}(B^0 \to K^+\pi^-)}{c_{XFT}(B^0_s \to K^+K^-)} \cdot \frac{\epsilon_{iso}(B^0)}{\epsilon_{iso}(B^0_s)}$$

$$\frac{f_d \cdot BR(B^0 \to \pi^+\pi^-)}{f_s \cdot BR(B^0_s \to K^+K^-)} = \frac{N(B^0 \to \pi^+\pi^-)}{N(B^0_s \to K^+K^-)}\Big|_{\mathrm{raw}} \cdot \frac{\epsilon_{kin}(B^0_s \to K^+K^-)}{\epsilon_{kin}(B^0 \to \pi^+\pi^-)} \cdot \frac{c_{XFT}(B^0_s \to K^+K^-)}{c_{XFT}(B^0 \to \pi^+\pi^-)} \cdot \frac{\epsilon_{iso}(B^0_s)}{\epsilon_{iso}(B^0)}$$

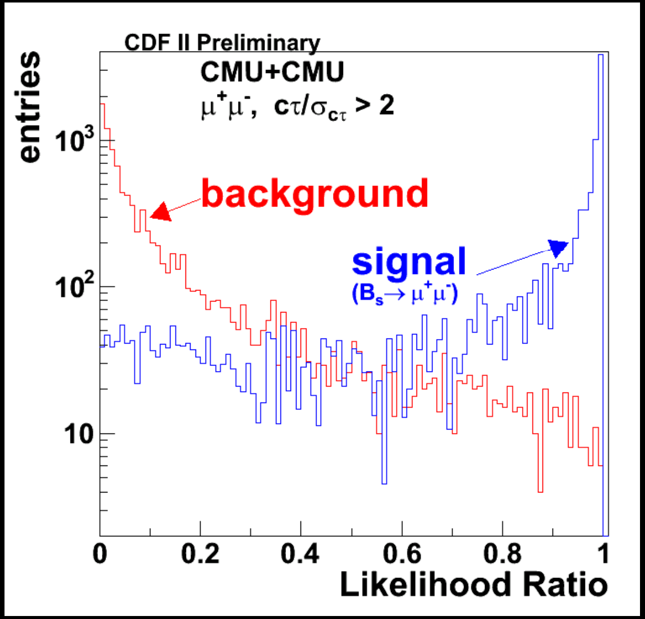
Kinematics and nuclear interaction efficiencies (Monte Carlo and data)

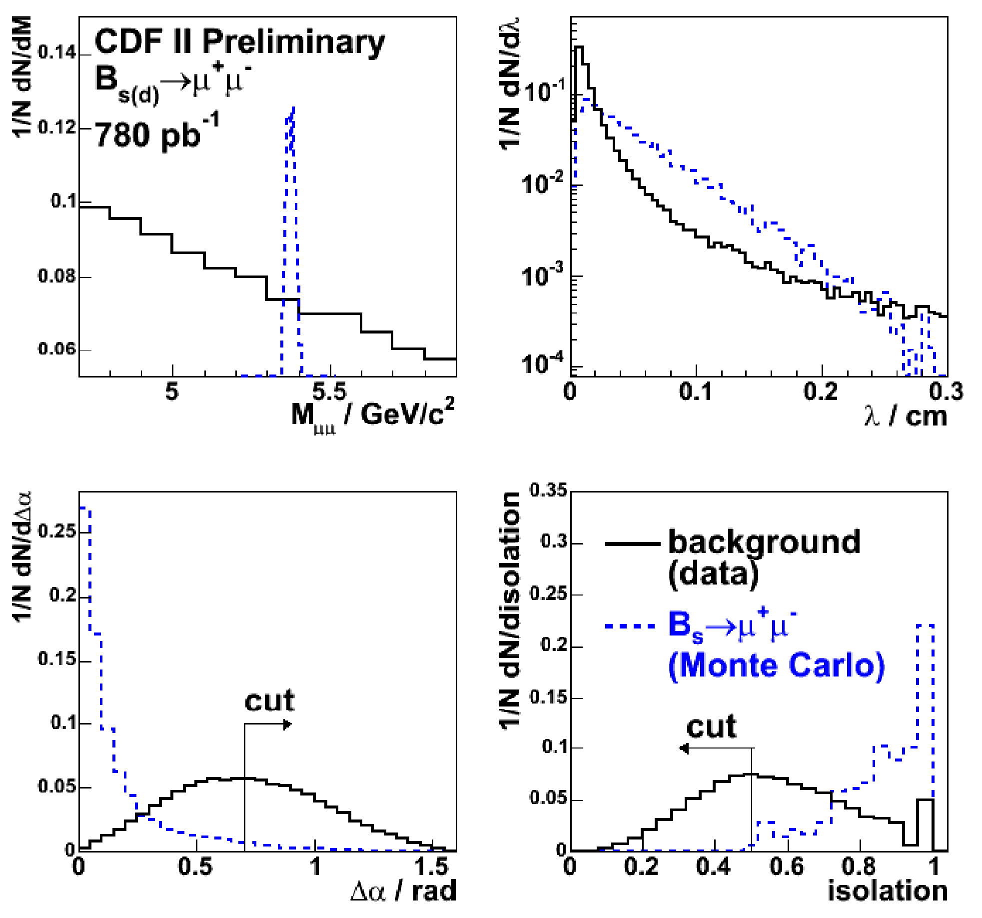
Trigger-bias: correct for dE/dx-dependent trigger efficiency ($D^+$ data)

Isolation efficiency, measured from exclusive decays ($B^0$ and $B^0_s$ data)

# selezione

$$L = \frac{\prod_i P_{sig}(x_i)}{\prod_i P_{sig}(x_i) + \prod_i P_{bkg}(x_i)}$$





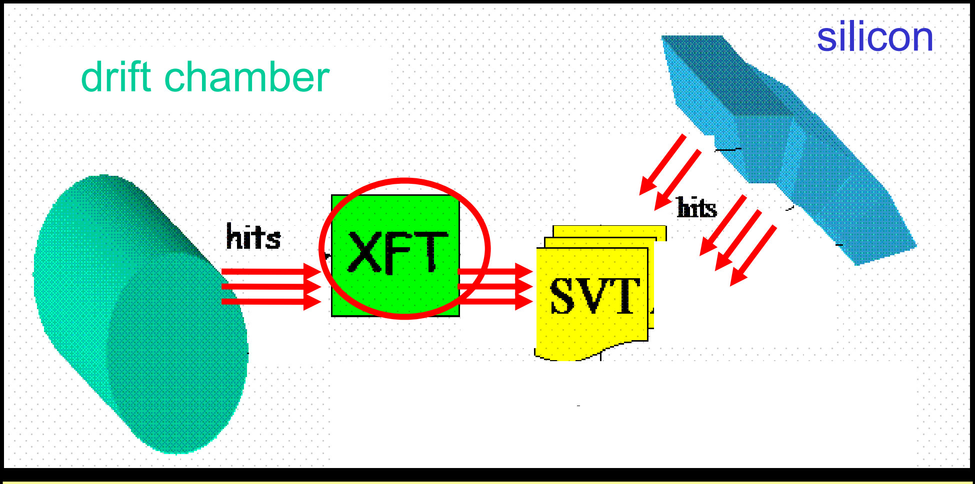
# SVT at work

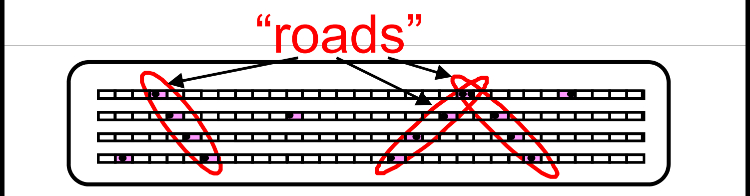
1. axial hits from chamber are input in XFT

2. XFT reconstructs axial tracks

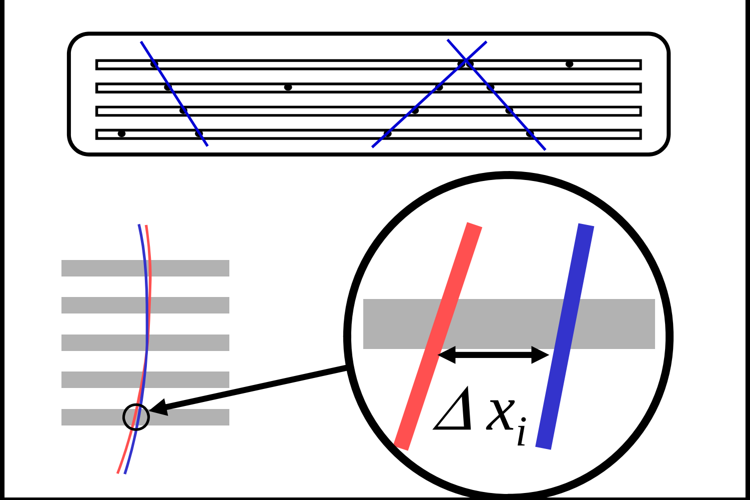
3. $p_T$, $\Phi$ from XFT and axial Si hits input to SVT

4. SVT finds low-resolution track candidates (pattern matching with pre-stored database)

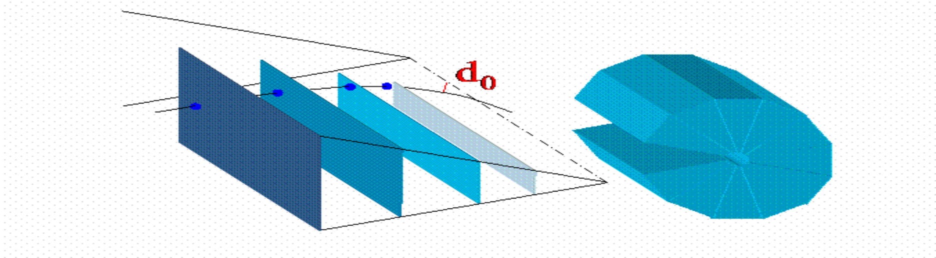




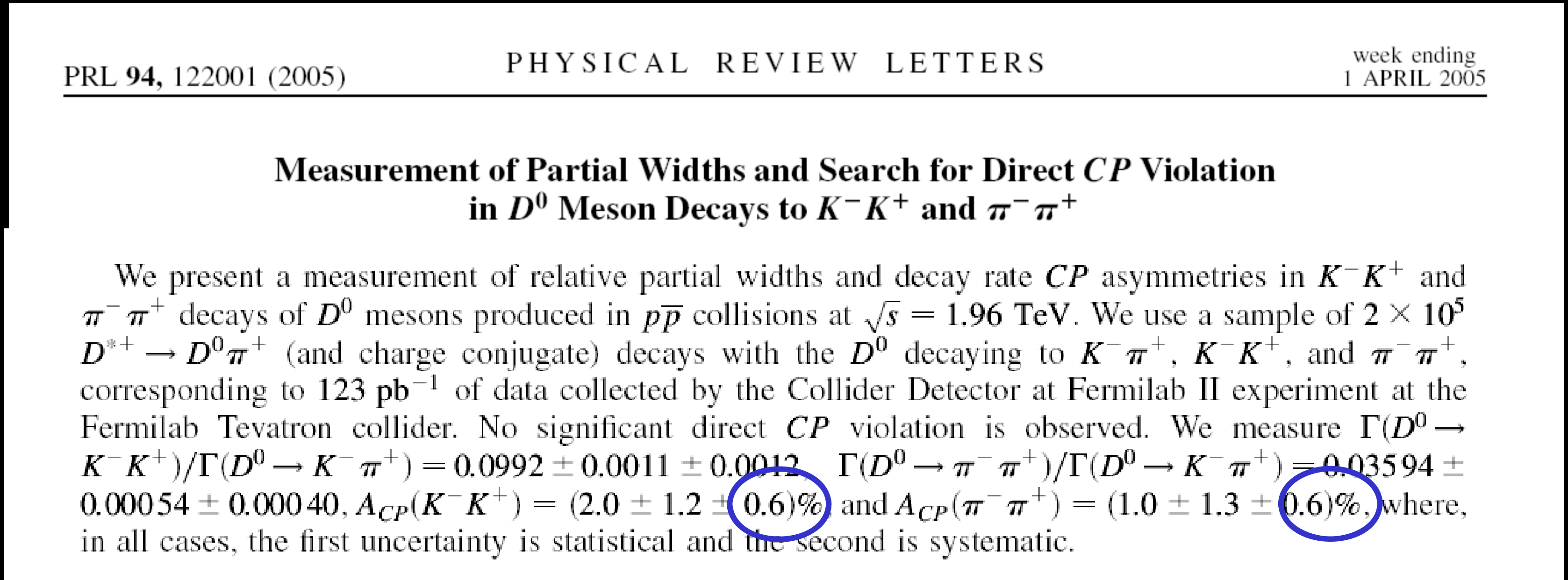
5. fit tracks at full resolution inside roads. 1st order expansion of non-linear constraint for a circle



6. End up with offline-like $p_T$, $\Phi$ and impact parameter in 25 μs



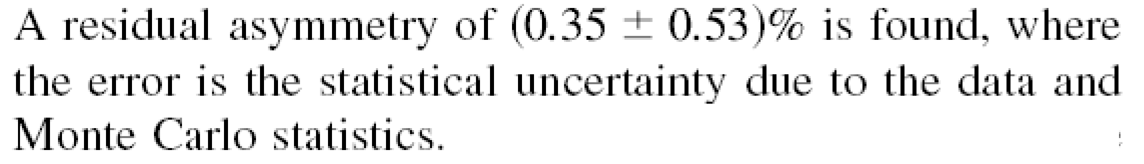
# Detector asymmetries



PRL **94,** 122001 (2005) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2005

**Measurement of Partial Widths and Search for Direct $CP$ Violation in $D^0$ Meson Decays to $K^-K^+$ and $\pi^-\pi^+$**

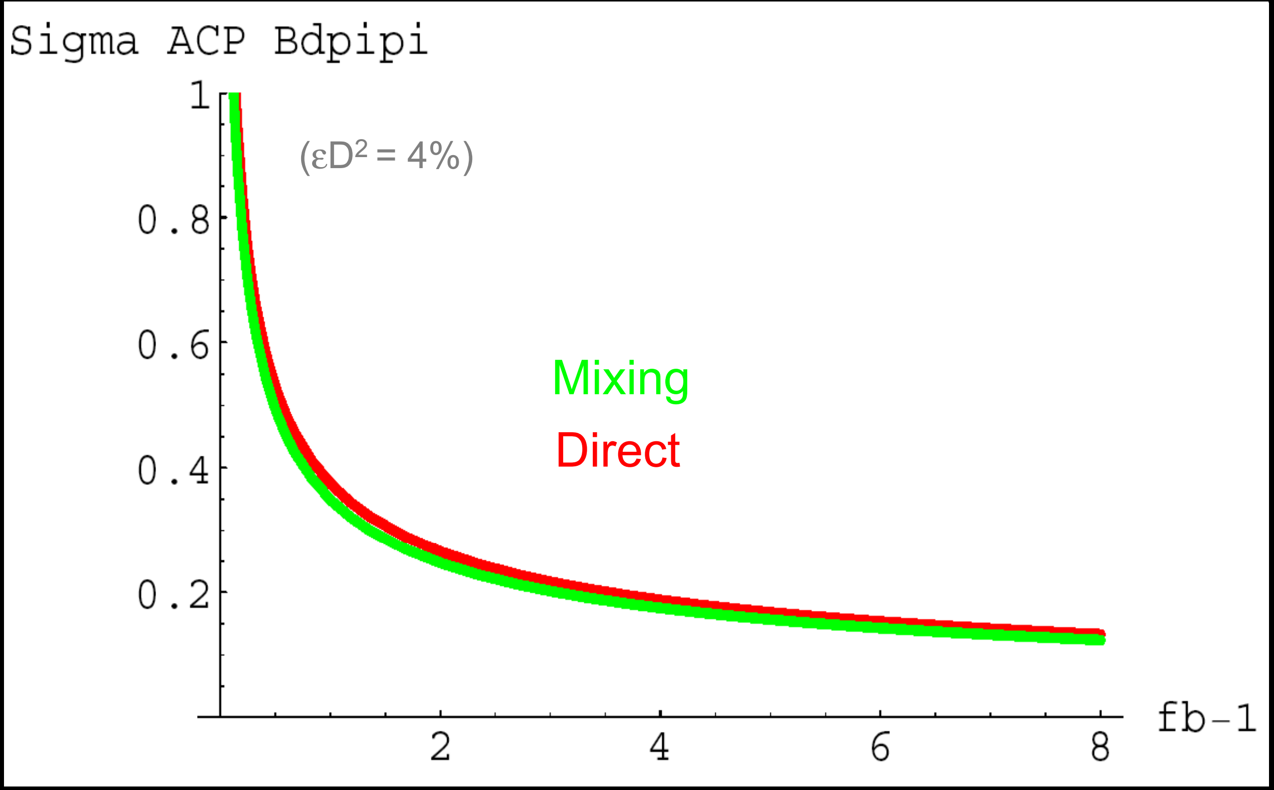
We present a measurement of relative partial widths and decay rate $CP$ asymmetries in $K^-K^+$ and $\pi^-\pi^+$ decays of $D^0$ mesons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We use a sample of $2 \times 10^5$ $D^{*+} \rightarrow D^0\pi^+$ (and charge conjugate) decays with the $D^0$ decaying to $K^-\pi^+$, $K^-K^+$, and $\pi^-\pi^+$, corresponding to 123 pb$^{-1}$ of data collected by the Collider Detector at Fermilab II experiment at the Fermilab Tevatron collider. No significant direct $CP$ violation is observed. We measure $\Gamma(D^0 \rightarrow K^-K^+)/\Gamma(D^0 \rightarrow K^-\pi^+) = 0.0992 \pm 0.0011 \pm 0.0012$, $\Gamma(D^0 \rightarrow \pi^-\pi^+)/\Gamma(D^0 \rightarrow K^-\pi^+) = 0.03594 \pm 0.00054 \pm 0.00040$, $A_{CP}(K^-K^+) = (2.0 \pm 1.2 \pm 0.6)\%$, and $A_{CP}(\pi^-\pi^+) = (1.0 \pm 1.3 \pm 0.6)\%$, where, in all cases, the first uncertainty is statistical and the second is systematic.



A residual asymmetry of $(0.35 \pm 0.53)\%$ is found, where the error is the statistical uncertainty due to the data and Monte Carlo statistics.

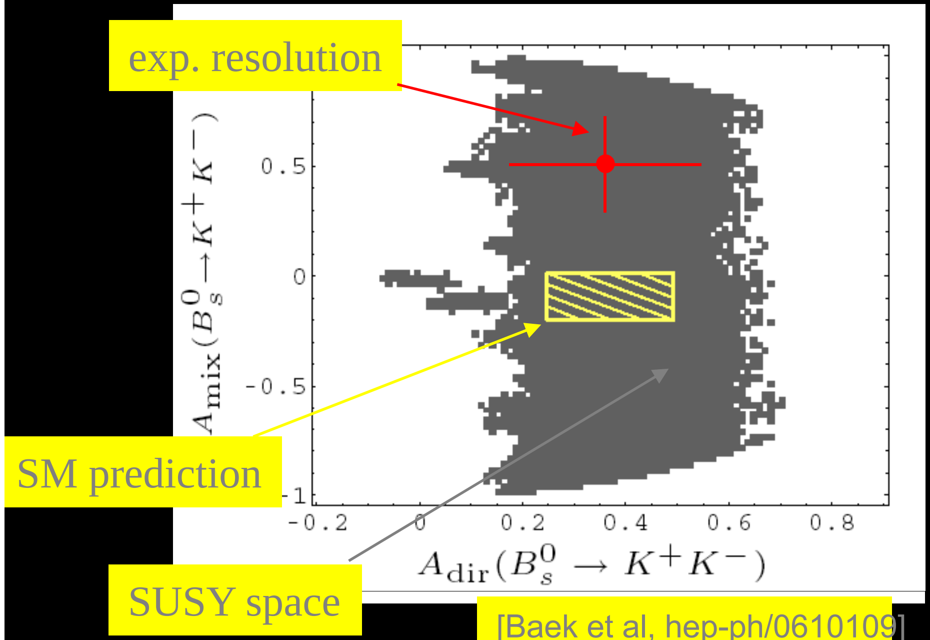
# Altri risultati

$$\frac{BR(B^0 \to \pi^+\pi^-)}{BR(B^0 \to K^+\pi^-)} = 0.259 \pm 0.017\ (stat.) \pm 0.016\ (syst.)$$

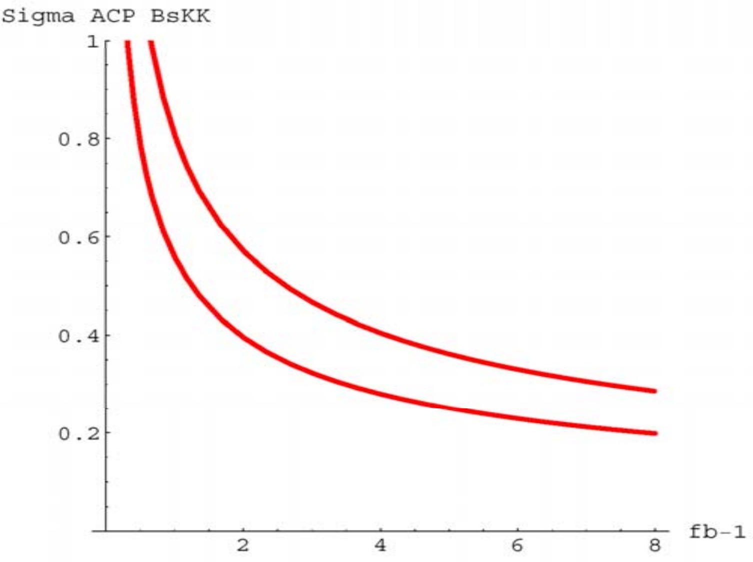


# Altri risultati

$$BR(B_s^0 \to K^+K^-) \quad = \quad (24.4 \pm 1.4\ (stat.) \pm 4.6\ (syst.)) \times 10^{-6}$$



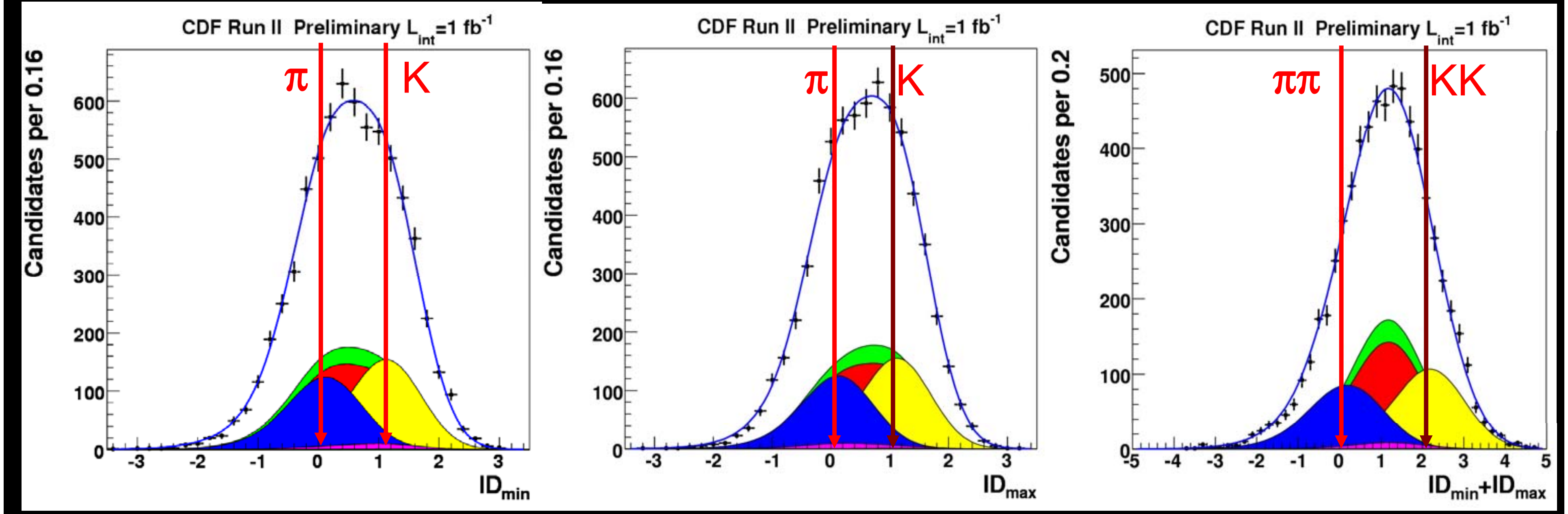
[Baek et al, hep-ph/0610109]



# Altri risultati

PID separation $\pi/K \cong 1.4\sigma$

PID separation $\pi\pi/KK \cong 2\sigma$



# Altri risultati