The 7th International Conference on Hyperons, Charm And Beauty Hadrons,

BEACH 2006, 2-8 July, Lancaster

CP Violation Studies @ TeVatron

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For the CDF and DØ Collaborations

Outline

- B physics at a hadron collider
- TeVatron detectors

- An overview of a few recent TeVatron measurements of CP violation (CPV) in mixing, direct CPV and branching ratios in the B sector:
  - Precise measurement of CP violation parameter ε_B of B_d meson from DØ
  - New CP asymmetry measurement in $B^0 \to K^+\pi^-$ from CDF
  - Branching ratio of the Cabibbo suppressed $B^\pm \to D^0K^\pm$ from CDF

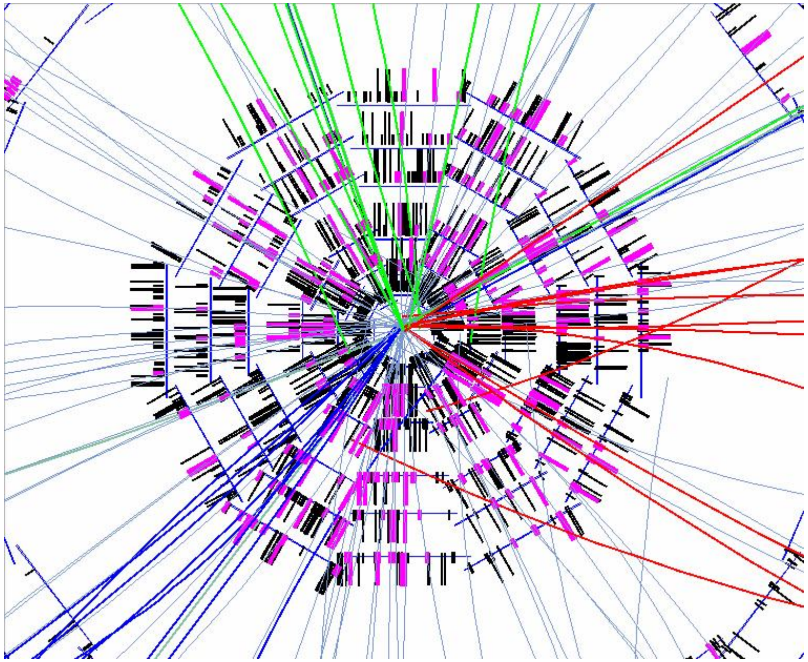
- Summary and conclusions

B Physics at a Hadron Collider

- The TeVatron is the Fermilab $p\bar{p}$ collider at $\sqrt{s}$ = 1.96 TeV.
- Features of $b\bar{b}$ production at a hadron collider:
  - $\sigma(p\bar{p} \to b\bar{b})$ ~100 μb, O(10^5) larger than e^+e^- at $\Upsilon(4S)/Z^0$
  - incoherent strong production of all *b*-flavored hadrons:

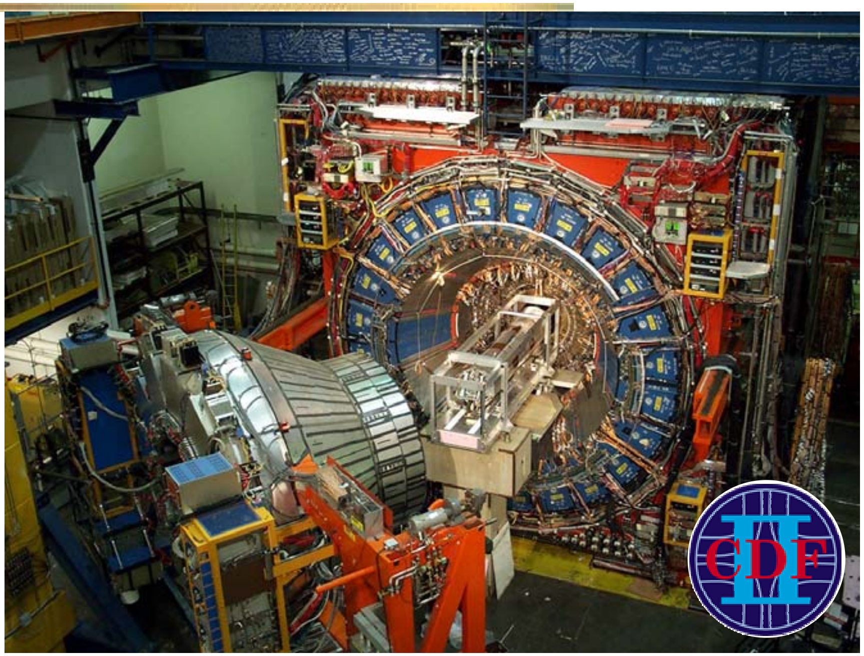
    $B^{\pm}$, B^0, B_s, B_c, Λ_b, Ξ_b, …
- Total inelastic x-section is ~10^3 × $\sigma(b\bar{b})$.
- *BR*'s for interesting processes are often O(10^{-6})-O(10^{-5}).
- Messy environments with large combinatorics

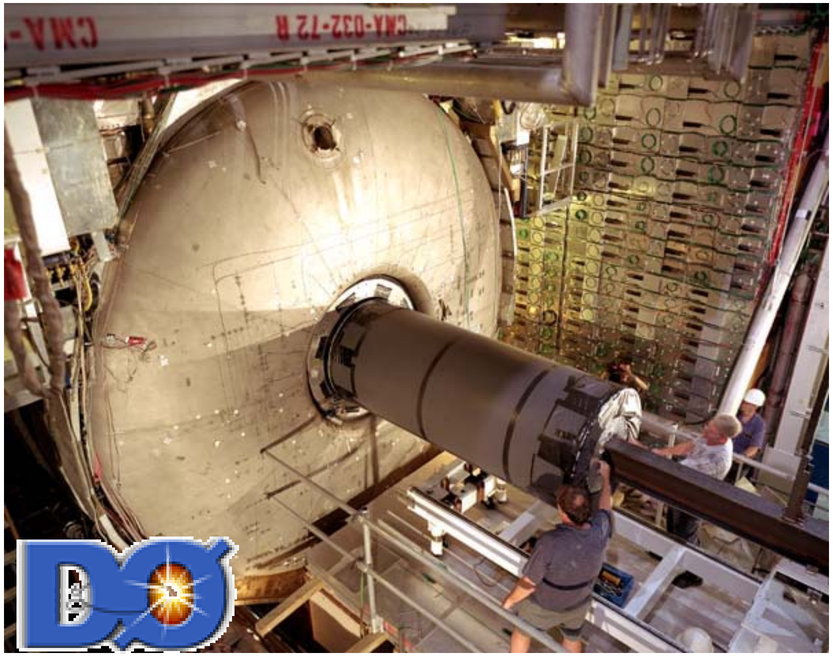
  ⇒ need for highly selective trigger.



Tevatron Detectors

- Both detectors:
  - silicon microvertex detectors
  - central tracking in solenoid
  - high rate trigger/DAQ system
  - EM and Had calorimeters
  - muon systems





- DØ:
  - excellent electron and muon ID
  - excellent tracking acceptance
  - ability to change magnet polarity
- CDF:
  - particle ID (ToF and dE/dx)
  - excellent mass resolution
  - displaced track trigger at L2

CP Violation in Mixing:

Measurement of ε_B from Dimuon Charge Asymmetry

with 1 fb^{-1}

ε_B from Dimuon Charge Asymmetry

- CP violation in mixing has not yet been observed for B mesons
- Very small in SM (M. Ciuchini *et al.* hep-ph/0308029):

$$\frac{4\,\mathrm{Re}(\varepsilon_b)}{1+|\varepsilon_b|^2} \cong \frac{1-|q/p|^4}{1+|q/p|^4} = A_{SL} = (-5.0 \pm 1.1)\cdot 10^{-4}$$

→ Sensitive to contributions from new physics

- CPV in Mixing can be obtained by measuring the asymmetry of the same sign lepton pairs coming from direct B decays:

$$A_{SL} = \frac{N(b\bar{b} \to l^+l^+X) - N(b\bar{b} \to l^-l^-X)}{N(b\bar{b} \to l^+l^+X) + N(b\bar{b} \to l^-l^-X)}$$

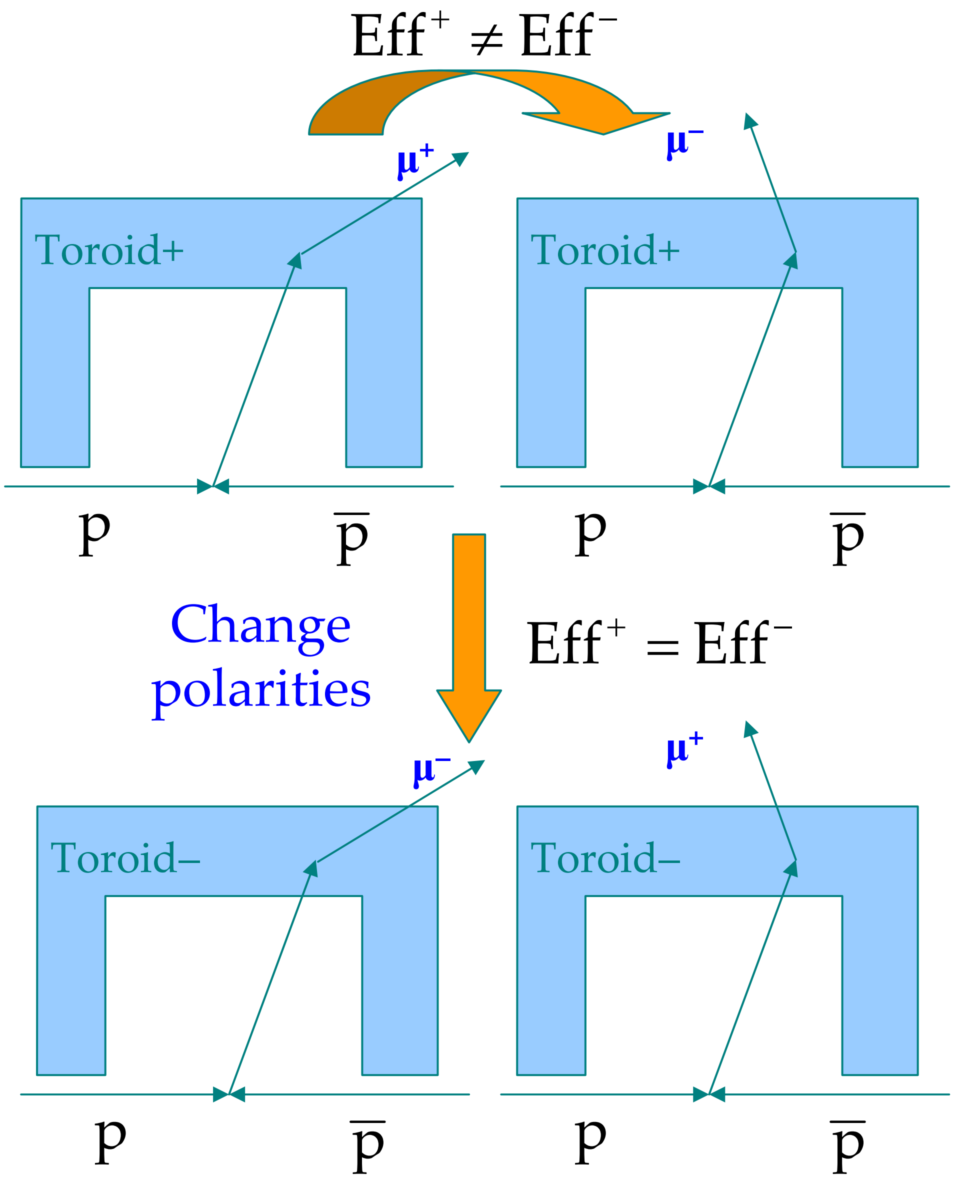
- Difficulty: separating the asymmetry from detector effects
- Analysis strategy:
  - Select di-muon events;
  - Extract the physics charged asymmetry A separating it from the detector effects:

$$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

  - Find contribution of different processes in A
  - Obtain CP violation asymmetry A^d_{SL};

ε_B from Dimuon Charge Asymmetry

- Changing Magnet Polarities:
  - Efficiency of reconstruction of positive and negative tracks may be different due to different trajectories in detector
  - Polarities of toroid and solenoid are reversed regularly
  - This cancels the first order detector effects and reduces significantly systematics in the present analysis

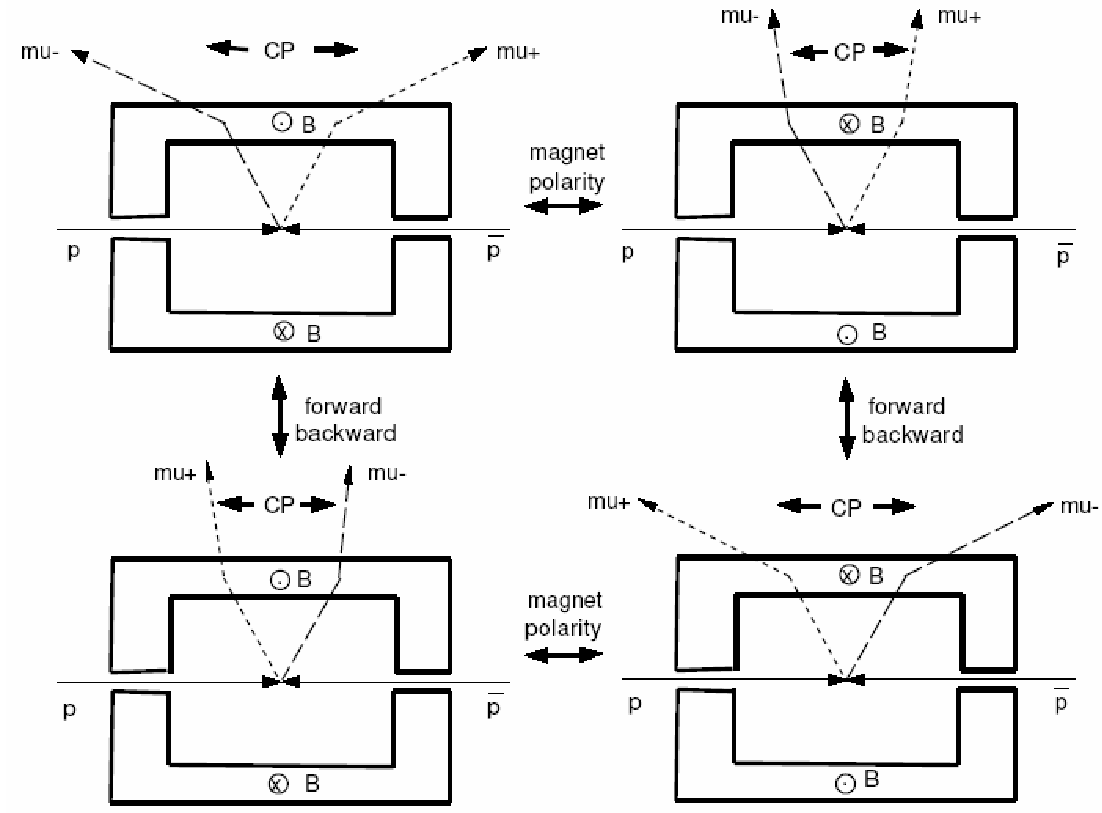


ε_B from Dimuon Charge Asymmetry

- Divide all selected muons into 8 groups according to their charge, direction and polarity of toroid
- Number of muons per group:

$$n_q^{\beta\gamma}$$

- β ← toroid polarity
- γ ← muon direction
- q ← muon charge



selected muons with toroid polarity β → $\{N\,\varepsilon^{\beta}\}$

Forward-backward → A_{fb}

polarity → $A_{q\beta}$

Detector → A_{det}, A_{ro}, $A_{\beta\gamma}$

$$n_q^{\beta\gamma} = \frac{1}{4}\{N\,\varepsilon^{\beta}\}(1+q\,A)(1+q\,\gamma\,A_{fb})(1+q\,\beta\,A_{q\beta})(1+\gamma\,A_{det})(1+q\,\beta\,\gamma\,A_{ro})(1+\beta\gamma A_{\beta\gamma})$$

ε_B from Dimuon Charge Asymmetry

$$n_q^{\beta\gamma} = \frac{1}{4} N\, \varepsilon^{\beta} (1 + q\, A)(1 + q\, \gamma\, A_{fb})(1 + q\, \beta\, A_{q\beta})(1 + \gamma\, A_{det})(1 + q\, \beta\, \gamma\, A_{ro})(1 + \beta\gamma A_{\beta\gamma})$$

- 8 measurements of n with 8 unknowns.
- Result for A:

$$A = 0.0015 \pm 0.0012(stat) \pm 0.0008(syst)$$

- To relate it to A_{SL} for B^0, all processes contributing to A have to be identified. The result takes into account the weight of each process. This gives:
  - The dimuon charge asymmetry:

$$A_{SL} = -0.0044 \pm 0.0040(\mathrm{stat}) \pm 0.0028(\mathrm{syst})$$

  - And the CP violation parameter:

$$\frac{\mathrm{Re}(\varepsilon_{B^0})}{1 + |\varepsilon_{B^0}|^2} = -0.0011 \pm 0.0010(stat) \pm 0.0007(syst)$$

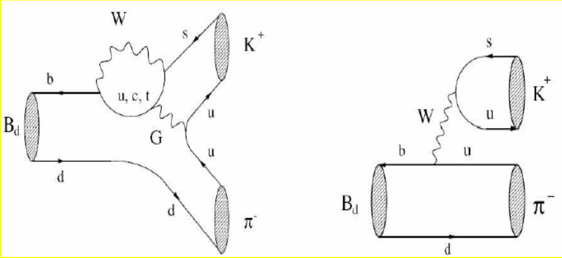
Direct CP Violation:

CP Asymmetry in $B^0 \to K^+\pi^-$

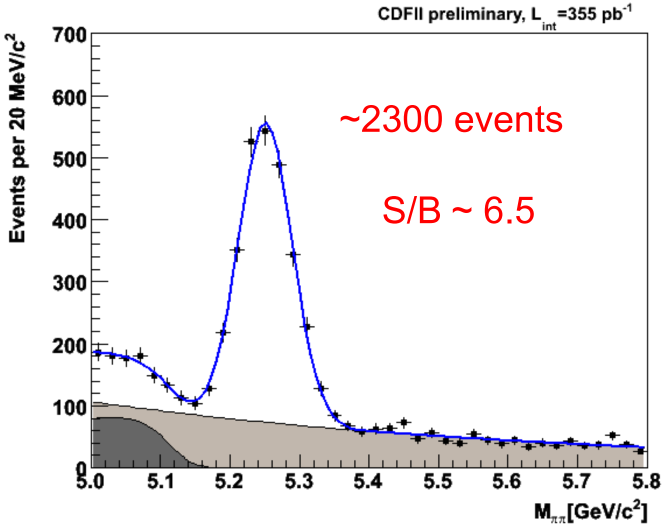
with 355 pb^{-1}

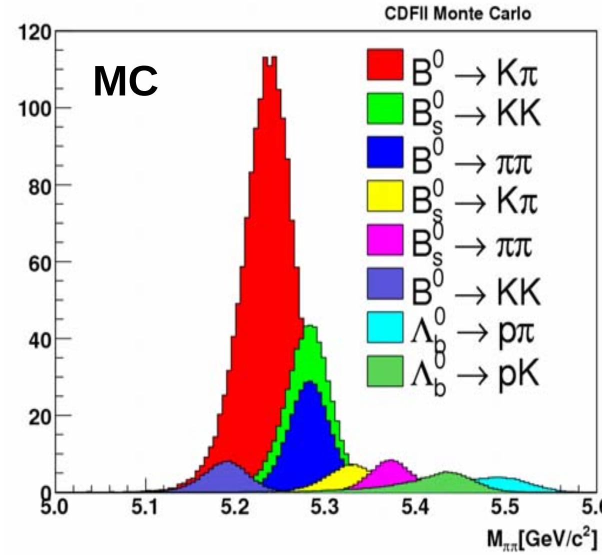
A_{CP} for $B^0 \to K^+\pi^-$

- Induced by interference between Tree and Penguin diagrams:



- Study of B^0 and B^0_s 2-body decays into charged *Kaons* and pions (*KK*, $\pi\pi$ and *K*π) plays a key role: related by subgroups of SU(3) symmetry.
- Potential sensitivity to Physics beyond the Standard Model.
  - Lipkin, Phys.Lett.B621:126, 2005
  - BFRS, Phys.Rev.Lett.92:101804,2004



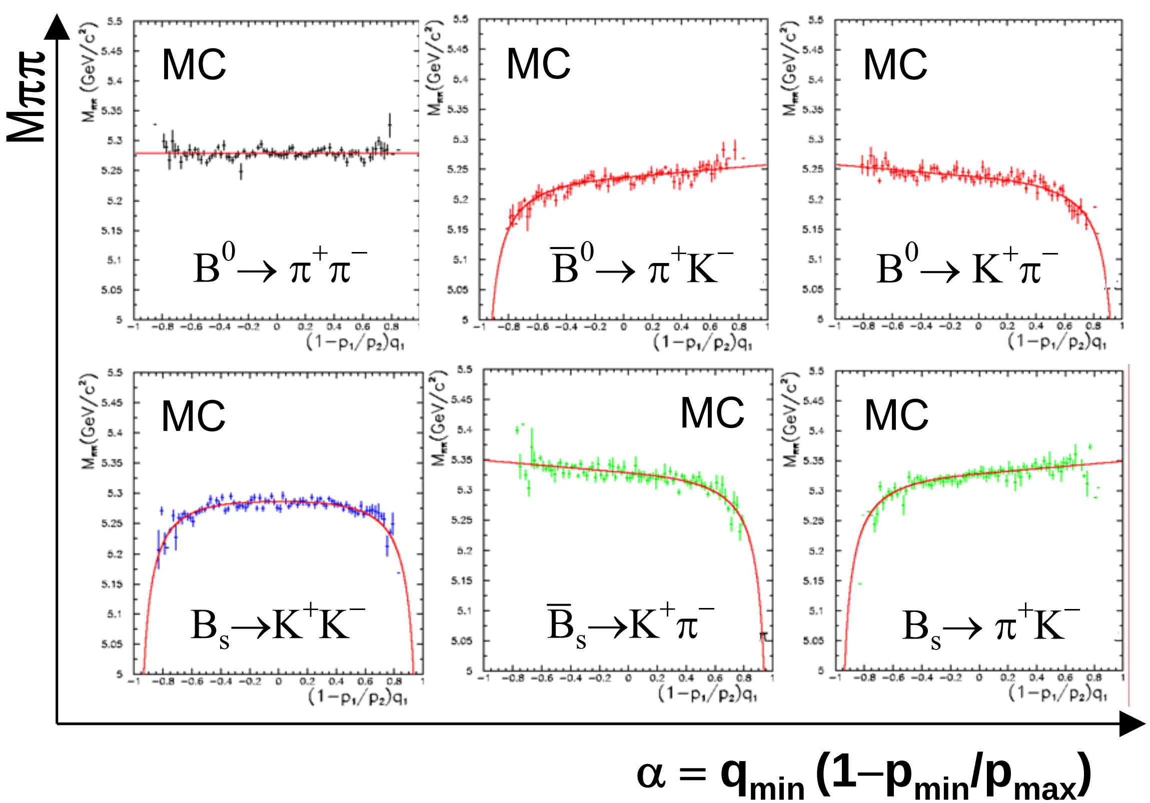


- Two-prong vertices are reconstructed with π mass assignment to tracks.
- Selected signal is the superposition of four major modes:
  - $B^0 \to K^+\pi^-$
  - $B_s \to K^+K^-$
  - $B^0 \to \pi^+\pi^-$
  - $B_s \to K^-\pi^+$

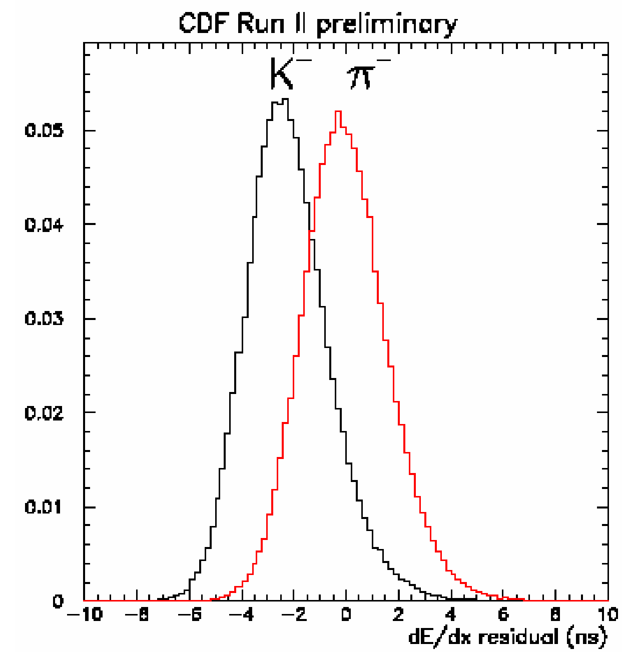
A_{CP} for $B^0 \to K^+\pi^-$

- Unbinned multidimensional likelihood fit to disentangle signal components and background: $M_{\pi\pi}$, α (momentum imbalance) , p_{tot}, dE/dx. The fit exploits:

❶ Kinematics



❷ dE/dx



Calibrated on $D^{*+} \to D^0\pi^+ \to [K^-\pi^+]\,\pi^+$ (K/π separation 1.4σ, p_T >2 GeV/c)

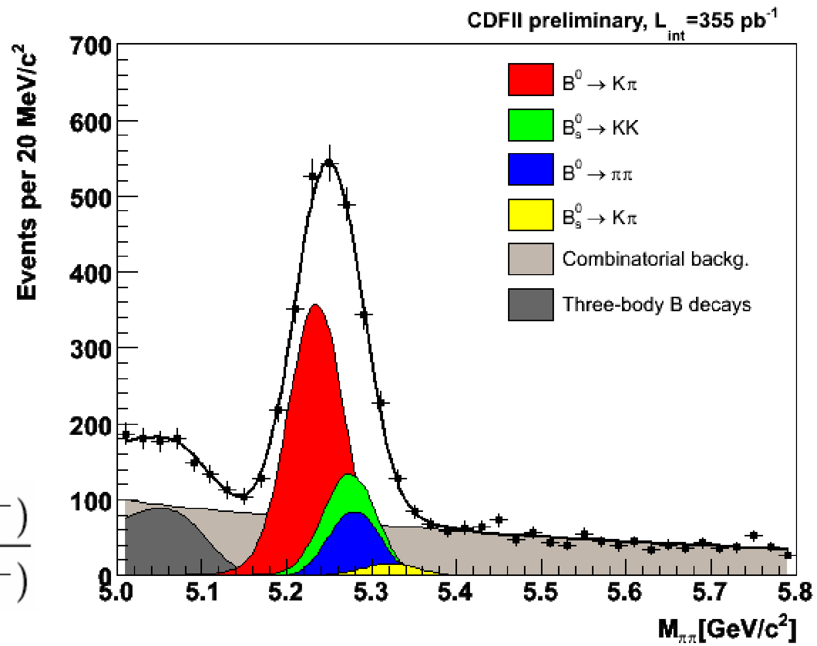
- Discriminates between modes, and flavors in $K\pi$ modes

A_{CP} for $B^0 \to K^+\pi^-$

- Fit result:

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

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



- Small (~1%) correction of fit results to account for different trigger, acceptance, and selection efficiencies.

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

- ~1.5σ different from zero, and compatible with B-factories results:

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

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

A Step towards CKM Angle γ

$$\frac{BR(B^+ \rightarrow \bar{D}^0 K^+)}{BR(B^+ \rightarrow \bar{D}^0 \pi^+)}$$

with 355 pb^{-1}

$BR(B^+ \to \bar{D}^0 K^+) / BR(B^+ \to \bar{D}^0 \pi^+)$

- First step toward the determination of the CKM angle γ by using the <u>Gronau-London-Wyler method</u>.
- Measure the observables:

$$R = \frac{BR(B^+ \to \bar{D}^0_{flav} K^+)}{BR(B^+ \to \bar{D}^0_{flav} \pi^+)}$$

$$R_\pm = \frac{BR(B^- \to D^0_{CP\pm} K^-) + BR(B^+ \to D^0_{CP\pm} K^+)}{BR(B^- \to D^0_{CP\pm} \pi^-) + BR(B^+ \to D^0_{CP\pm} \pi^+)}$$

$$A_{CP\pm} = \frac{BR(B^- \to D^0_{CP\pm} K^-) - BR(B^+ \to D^0_{CP\pm} K^+)}{BR(B^- \to D^0_{CP\pm} K^-) + BR(B^+ \to D^0_{CP\pm} K^+)}$$

- Use:

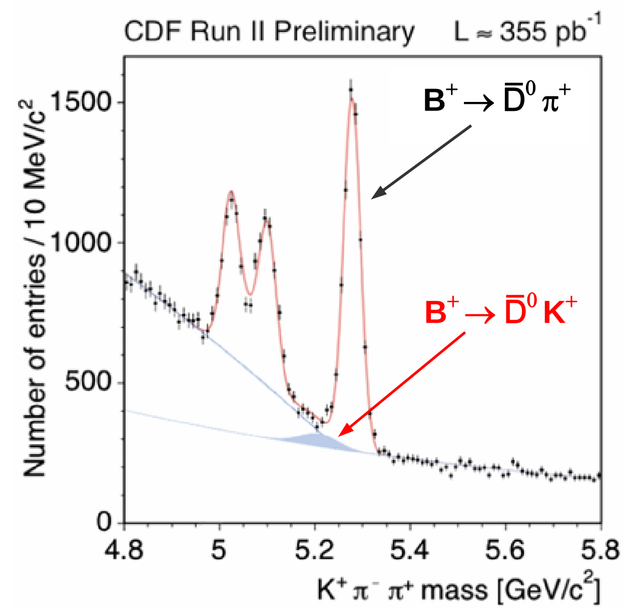
$$R_{CP\pm} = 1 + r^2 \pm 2r \cos\delta \cos\gamma$$

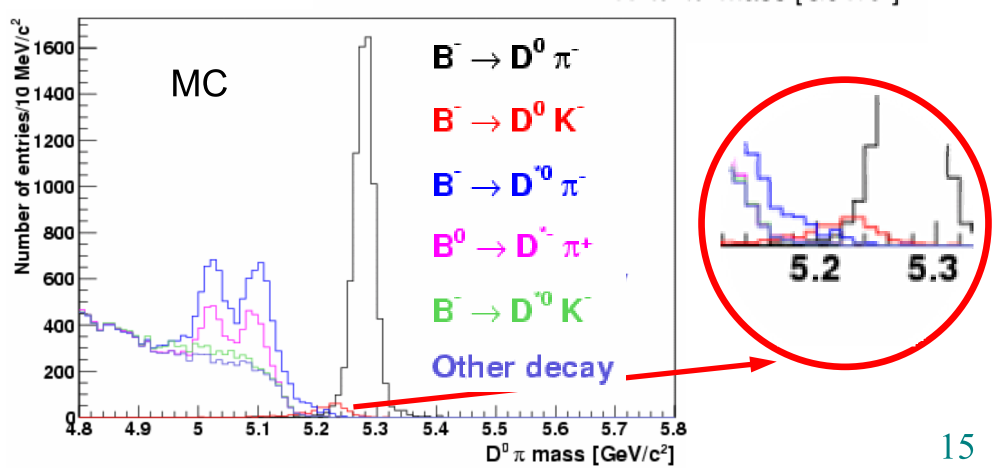
$$A_{CP\pm} = \pm 2r \sin\delta \sin\gamma / R_{CP\pm}$$

where $R_{CP\pm} = R_\pm / R$

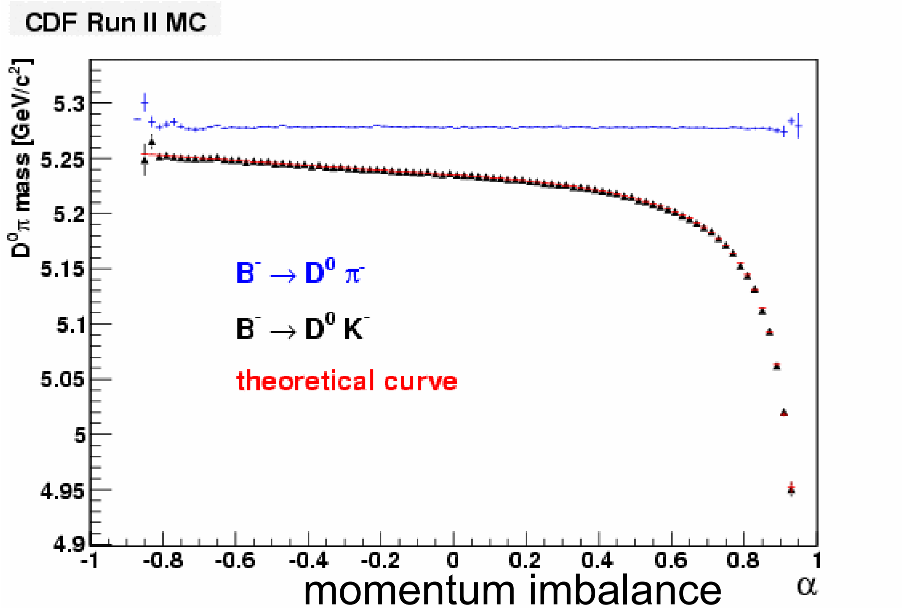
$$r = \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \sim 0.1\text{–}0.2$$

- Reconstruction:
  - $D^0 \to K^+ \pi^-$
  - π mass hypothesis to B daughter track.





$BR(B^+\to\bar{D}^0K^+)/BR(B^+\to\bar{D}^0\pi^+)$

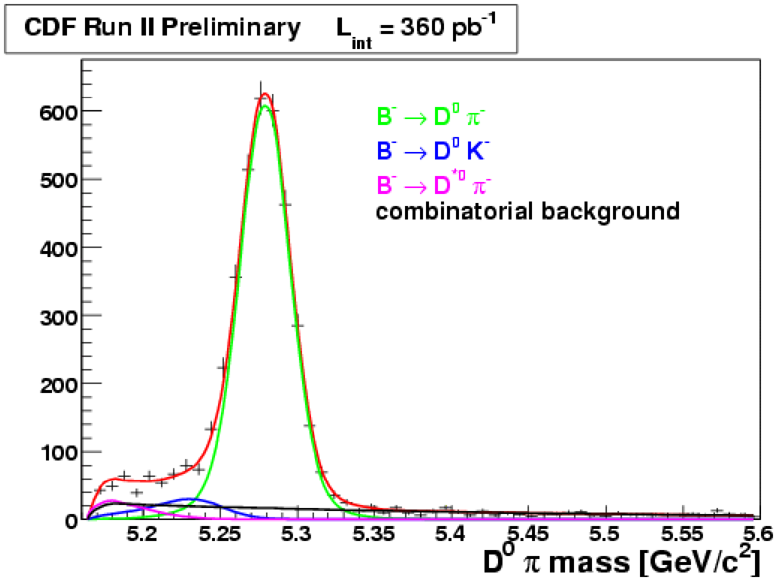


- Unbinned multidimensional likelihood fit, which combines kinematics and dE/dx information:

$$M_{D\pi},\ p_{tot},\ \mathrm{PID},\ \ \alpha = \begin{cases} 1 - p_{tr}/p_D & p_{tr} < p_D \\ -(1 - p_D/p_{tr}) & p_{tr} \geq p_D \end{cases}$$

- To reject most physical backgrounds, use a narrow fit window: [5.17, 5.6].
- Fit result:

$$N_{DK} = 224 \pm 22 \qquad N_{D\pi} = 3265 \pm 38$$



- Raw result corrected w/ MC efficiencies.

$$\frac{BR(B^+\to\bar{D}^0K^+)}{BR(B^+\to\bar{D}^0\pi^+)} = 0.065 \pm 0.007(stat.) \pm 0.004(syst.)$$

- World average:

$$R = 0.083 \pm 0.0035$$

Summary and Conclusions

- A rich harvest of results from interesting CP violation studies has been produced and already published by CDF and DØ Collaborations.

- This talk gave just a taste:
  - currently many analyses are underway on 1 fb^{-1} dataset and will be released soon, and data continue to be collected…
  - many more challenging results are expected in the future as more data become available, and more precise measurements become possible

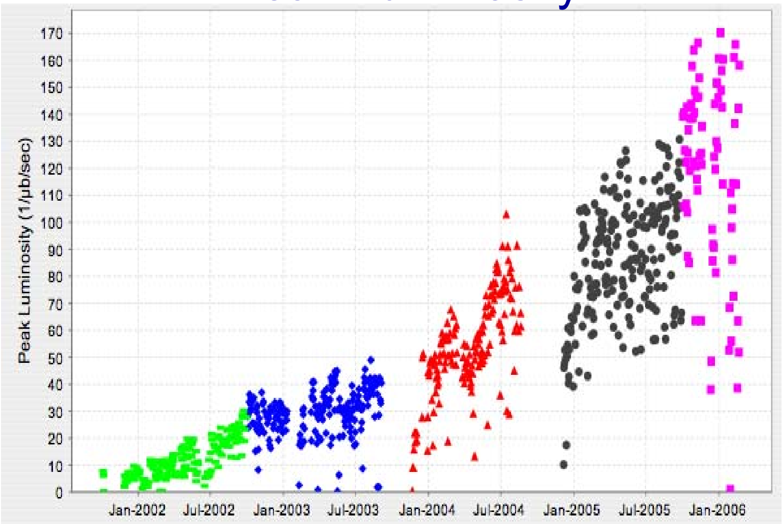
- Copious samples of all b-hadrons, as well as unique properties of the CDF and DØ detectors, provide the TeVatron with a physics program that is competitive with (B_0 modes) and complementary to (B_s modes) B-factories

Backup

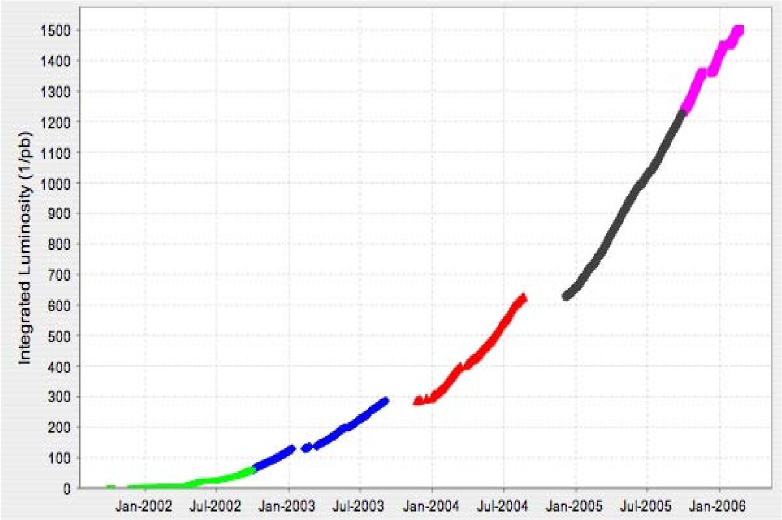
TeVatron Luminosity

- Peak luminosity record:
  1.8×10^{32} cm^{-2} s^{-1}
- Integrated luminosity:
  - weekly record:
    27 pb^{-1} / week / expt
  - total delivered:
    1.5 fb^{-1} / expt,
    total recorded:
    1.3 fb^{-1} / expt
- Doubling time: 1 year
- Future: ~2 fb-1 by 2006,
  ~4 fb-1 by 2007, ~8 fb-1 by 2009.

Peak Luminosity



Int. Lum. (delivered) / Experiment



ε_B from Dimuon Charge Asymmetry

- Muon Selection:
  - Hits in all 3 layers of muon chambers
  - Associated central track
  - Good quality of track
  - $P_T > 4.2$ GeV or $|P_Z|>6.4$ GeV
  - $3.0 < P_T < 15$ GeV
  - Impact parameter to primary interaction: < 0.3 cm
  - at least one scintillator hit with $|\Delta t|<5$ ns
- **Cuts on di-muons**
  - $\Delta P > 0.2$ GeV
  - $10° < \text{Opening angle} < 170°$
  - $\Delta z < 2$ cm
  - Distance between hits in muon chamber $\Delta r > 5$ cm

ε_B from Dimuon Charge Asymmetry

- Selected Events:

Tor*Sol polarity	-1	+1
N++	177,950	156,183
N--	176,939	156,148
N+-	1,175,547	1,029,604

ε_B from Dimuon Charge Asymmetry

- Extracted Parameters:

Tor*Sol polarity	+1	-1	All
$\varepsilon^+/\varepsilon^-$	1.032	0.9163	-
A_{det}	-0.0178±0.0006	-0.0164±0.0006	-0.0171±0.0004
A_{ro}	-0.0285±0.0006	-0.0302±0.0006	-0.0294±0.0004
$A_{q\beta}$	-0.0068±0.0006	-0.0075±0.0006	-0.0072±0.0004
$A_{\beta\gamma}$	-0.0001±0.0006	-0.0019±0.0006	-0.0010±0.0004
A	0.0028±0.0017	0.0001±0.0018	0.0015±0.0012
A_{fb}	0.0006±0.0006	0.0003±0.0006	0.0005±0.0004

- Detector asymmetries are large, but under control
- Physics asymmetries are compatible with zero

ε_B from Dimuon Charge Asymmetry

- Contribution of physics processes into A:

Process		Weight	$N^{++}-N^{--}$
$b\to\mu$, bbar $\to\mu$	P_1	≡1	
$b\to c\to\mu$, bbar $\to\mu$	P_2	0.116±0.055	0
$b\to c\to\mu$, bbar $\to c\to\mu$	P_3	0.003±0.003	
dimuon cosmic rays	P_7	0.003±0.003	0
μ and $K^{\pm}$ decay	P_8	0.098±0.014	
μ and cosmics	P_9	0.0001±0.0001	
μ and punch-through	P_{10}	0.001±0.001	
μ and combinatoric	P_{11}	0.0002±0.0002	
other(B and τ, B and J/ψ ...)	P_{12}	0.163±0.066	
dimuon with wrong sign	P_{13}	0.0005±0.0005	0

The main process (includes mixing)

Its contribution into number of dimuons (χ_d - probability to mix for B_d meson)

$$N^{++}\sim\chi(1-\bar\chi)\quad N^{--}\sim\bar\chi(1-\chi)\quad N^{+-}\sim\chi+\bar\chi-2\chi\bar\chi$$

$$\chi=f_d\chi_d+f_s\chi_s$$

$$\chi_d\neq\bar\chi_d \text{ means CP violation}: A_{SL}=\frac{\chi_d-\bar\chi_d}{\chi_d+\bar\chi_d-2\chi_d\bar\chi_d}$$

The most important background contribution is from “muon and K± decay”

ε_B from Dimuon Charge Asymmetry

- Kaon decay:
  - Kaon decay $K^{\pm} \rightarrow \mu\nu$ produces an asymmetry in number of μ^+ and μ^-.
  - Inelastic interaction length of K^+ in calorimeter is larger than of K^-, $\sigma(K^- d)$ = 36 mb, $\sigma(K^+ d)$ = 28 mb for p_K=10 GeV
    - Reaction $K^- N \rightarrow Y\pi$ ($Y=\Lambda,\Sigma...$) has no $K^+ N$ analog.
  - K^+ has more time to decay than K^-
  - Charge asymmetry due to a kaon decay is $a=0.026 \pm 0.005$

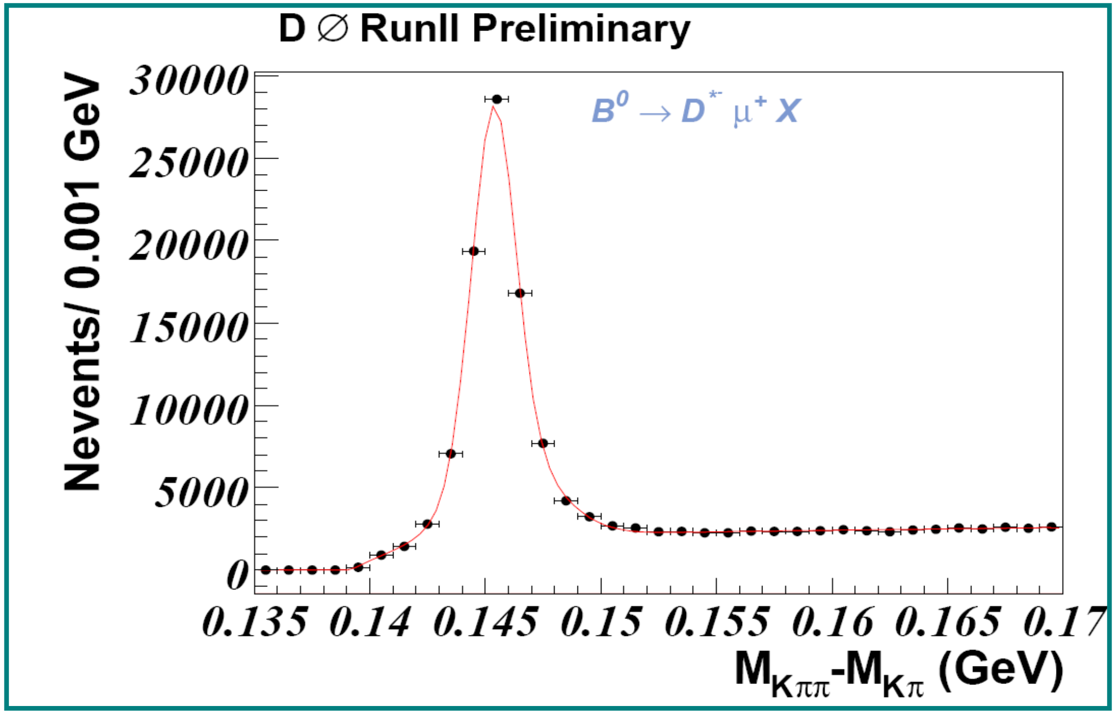
    (determined by the distance to calorimeter, and inelastic cross sections $K^- d$, $K^+ d$)

Because of a big impact of this process on the result, the fraction of kaon decays in dimuon sample (P_8) was measured experimentally

ε_B from Dimuon Charge Asymmetry

- Measuring P_8
  - DØ has very pure $K^\pm$ ID:
  - ~80000 events reconstructed;
  - Kaon track is clearly identified;

$$B \to \mu^+ \nu D^{*-}; \quad D^{*-} \to \overline{D}^0 \pi^-; \quad \overline{D}^0 \to K^+ \pi^-$$



ε_B from Dimuon Charge Asymmetry

- Measuring P_8
  - Apply the same dimuon selections to the $B \to \mu\nu D^{*-}$ sample.
  - From the number of events passing dimuon cuts and the number of events with a second muon associated to a kaon, we get the fraction of "muon and $K^{\pm}$ decay" in dimuon sample:

$$P_8 = 0.098 \pm 0.014$$

  - These events give a contribution to the measured asymmetry:

$$\delta A = -0.0028 \pm 0.0007$$

ε_B from Dimuon Charge Asymmetry

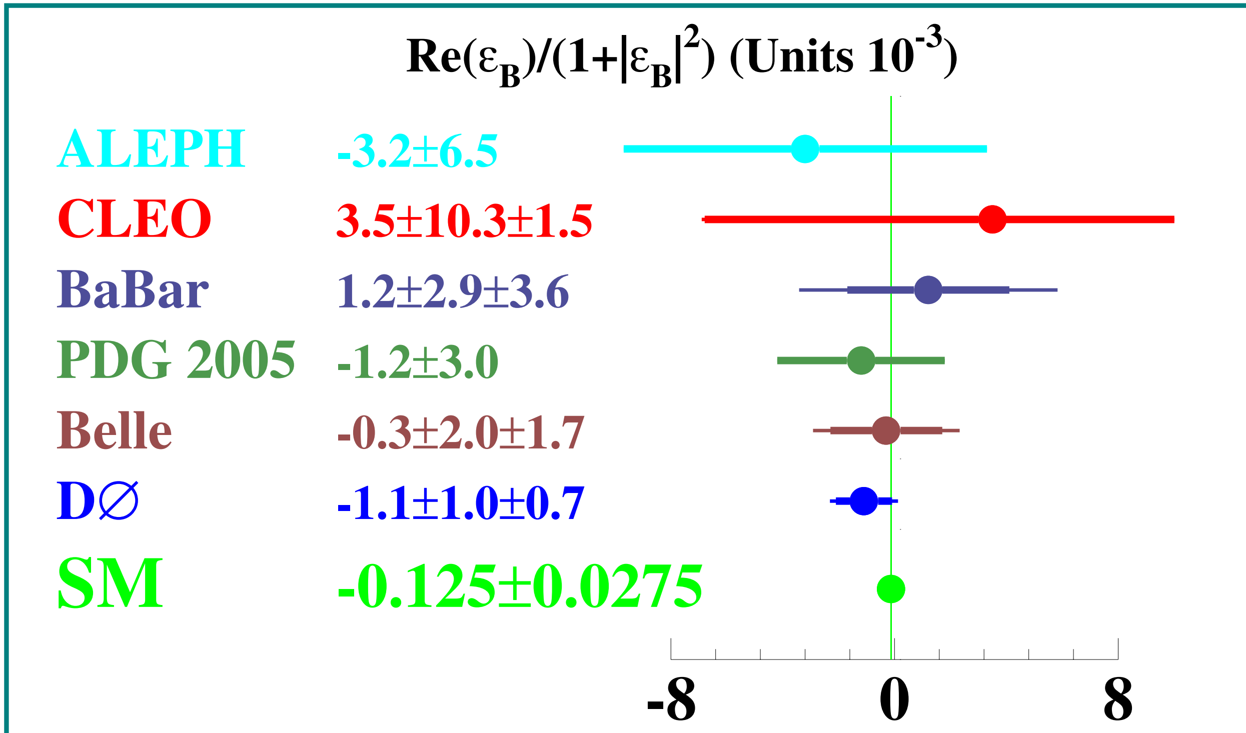
- Systematic Uncertainties:

Source of error	ΔA
detector	0.00015
$\varepsilon^+/\varepsilon^-$	0.00018
muon and $K^\pm$ decay	0.00068
dimuon cosmic rays	0.00010
prompt μ and cosmic μ	0.00001
Wrong charge sign	0.00015
punch-through	0.00001
Total	0.00074

- Uncertainty in $K^\pm$ decay dominates

ε_B from Dimuon Charge Asymmetry

- Comparison with other measurements:



- This result is the most precise measurement of ε_B
- Even more precise than the world average!
- Consistent with SM and other measurements

A_{CP} for $B^0 \to K^+\pi^-$

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;

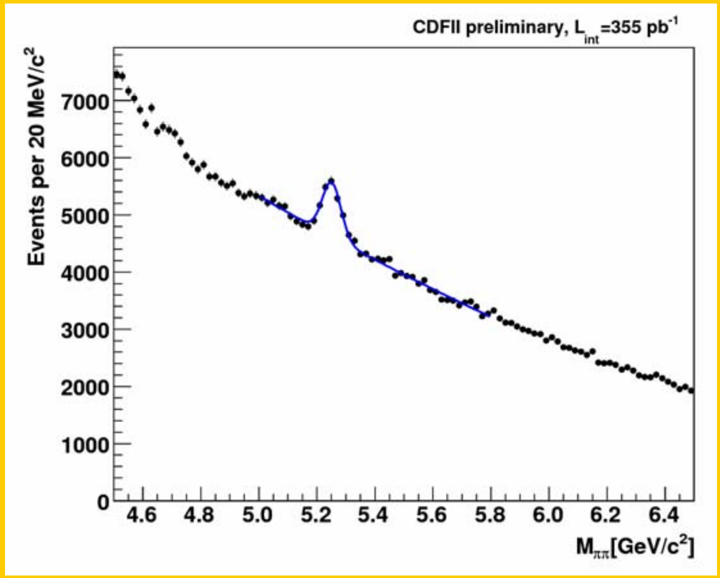
reject light-quark background from jets:

✓ 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 !



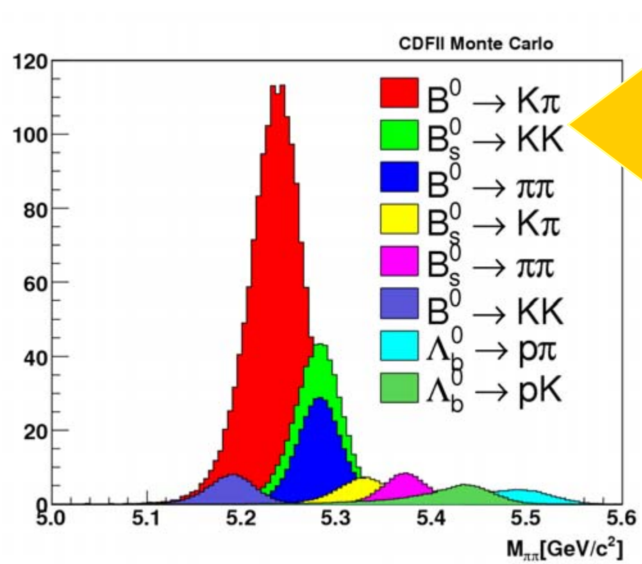
a bump of ~3850 events with S/B ≈ 0.2 (at peak) in $\pi\pi$-invariant mass

A_{CP} for $B^0 \to K^+\pi^-$

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

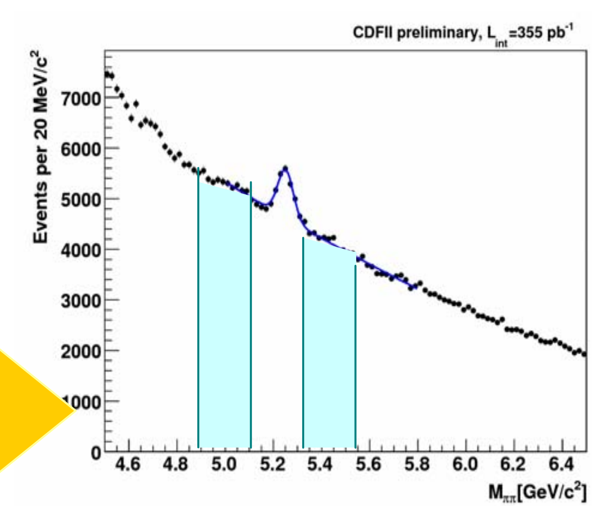
Gain ~10% improvement in resolution *versus* standard $S/\sqrt{(S+B)}$

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



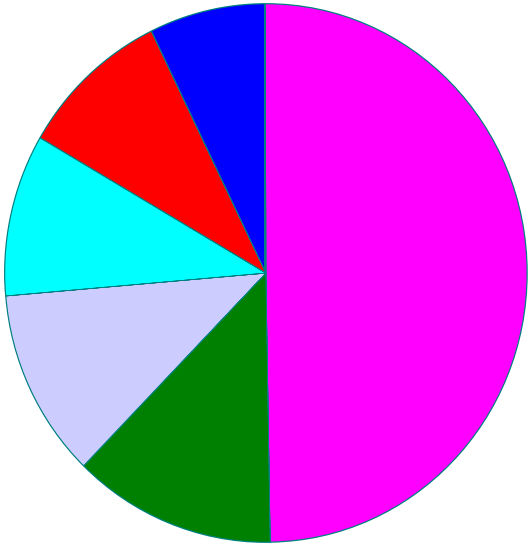
signal yield S is derived from MC simulation

background B from data (mass sidebands)



A_{CP} for $B^0 \to K^+\pi^-$

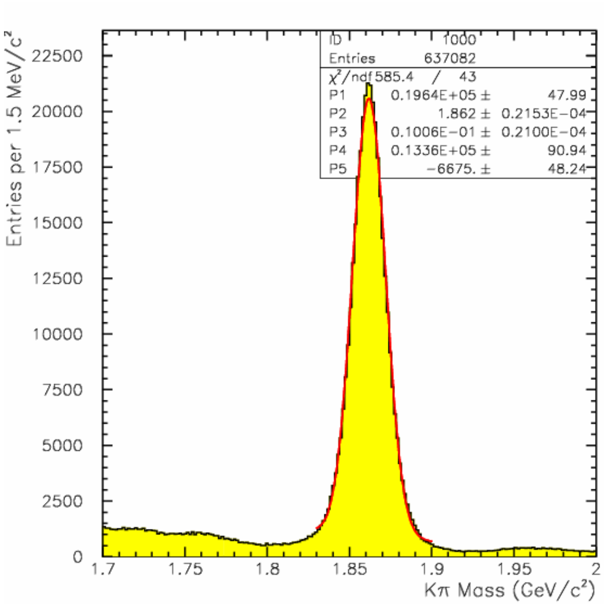
- Systematic uncertainties:
  - Total systematic uncertainty is 0.7%
  - Much smaller than the 3.9% statistical uncertainty.

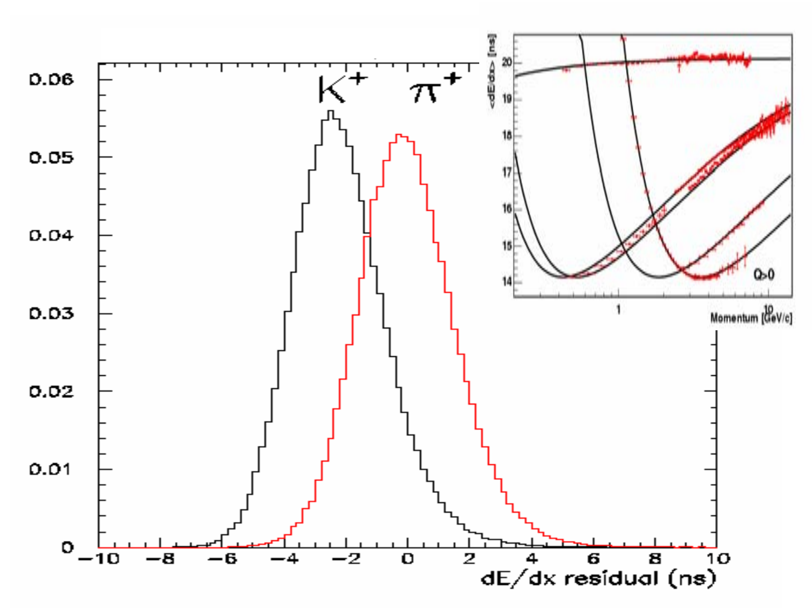


- dE/dx model (partially reduces with statistics)
- nominal *B*-meson masses input to the fit (reduces with statistics)
- mass-resolution model
- global scale of masses
- charge-asymmetries in background
- combinatorial background model

A_{CP} for $B^0 \rightarrow K^+\pi^-$

Peak composition handle: dE/dx





~95% pure *K* and π samples from ~300,000 decays:

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

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

1.4♦ *K*/π separation at *p* > 2 GeV

(= 60% of "perfect" separation)

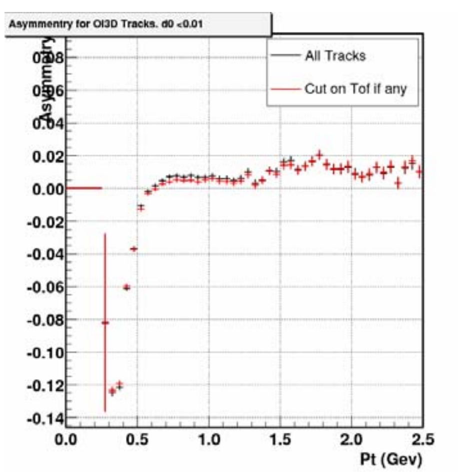
~11% residual correlation from gain/baseline common fluctuations included in the fit of composition

A_{CP} for $B^0 \to K^+\pi^-$

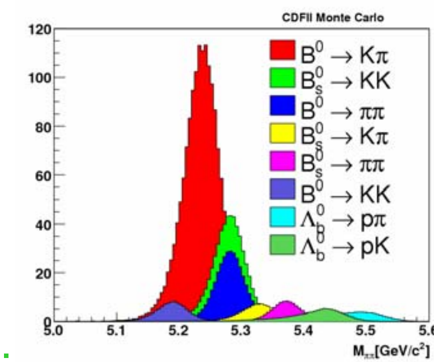
Extraction of asymmetry

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

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 $A_{CP}(D^0 \to h^+h^-)$ measurement
(Phys.Rev.Lett.94:122001, 2005).
Used unbiased kaons to extract the ~ 1% correction



$BR(B^+ \to \bar{D}^0 K^+)/BR(B^+ \to \bar{D}^0 \pi^+)$

- Systematics:

Source	Shift wrt central fit
Mass resolution tails	0.0006
Input mass	0.001
dE/dx	0.0015
combinatorial background model	0.001
$D^{*0}\pi$ left free in the fit	0.003
changing $D^{*0}\pi$ mass model	0.001
MC statistics/XFT eff	0.002
Total(sum in quadrature)	0.004

$BR(B^+ \to \bar{D}^0 K^+) / BR(B^+ \to \bar{D}^0 \pi^+)$

- D_{CP} modes: