Direct CP violation and branching ratio results from the Tevatron

Massimo Casarsa

INFN – Trieste, Italy

for the CDF and DØ Collaborations

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Outline

- A rich harvest of interesting B Physics results has been produced and already published by CDF and DØ Collaborations.

- This talk will give an overview of the most recent measurements on direct CP violation and branching ratios in the B sector:
  - ✓ new CP asymmetry measurement for $B^0 \to K\pi$;
  - ✓ branching ratio of the Cabibbo suppressed $B^{\pm} \to D^0 K^{\pm}$;
  - ✓ branching ratio of the double charmed decay $B_s \to D_s^{(*)} D_s^{(*)}$;
  - ✓ first observation of the exclusive $B_s \to D_s^- D_s^+$ decay mode.

B Physics at a hadron collider

- The Tevatron is the Fermilab $p\bar{p}$ collider at $\sqrt{s}$ = 1.96 TeV.

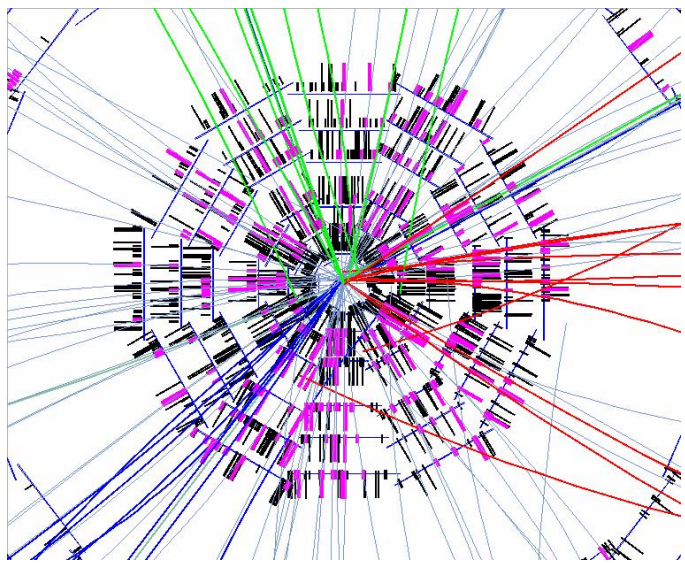
- Features of $b\bar{b}$ production at an hadron collider:
  - $\sigma(p\bar{p} \to b\bar{b}) \sim 100\ \mu b$, $O(10^5)$ larger than e^+e^- at $\Upsilon(4S)/Z^0$;
  - incoherent strong production of all *b*-flavored hadrons: $B^{\pm}$, B^0, B_s, B_c, Λ_b, Ξ_b, …

- Total inelastic x-section is $\sim 10^3 \times \sigma(b\bar{b})$.

- *BR*'s for interesting processes are often $O(10^{-6})$-$O(10^{-5})$.

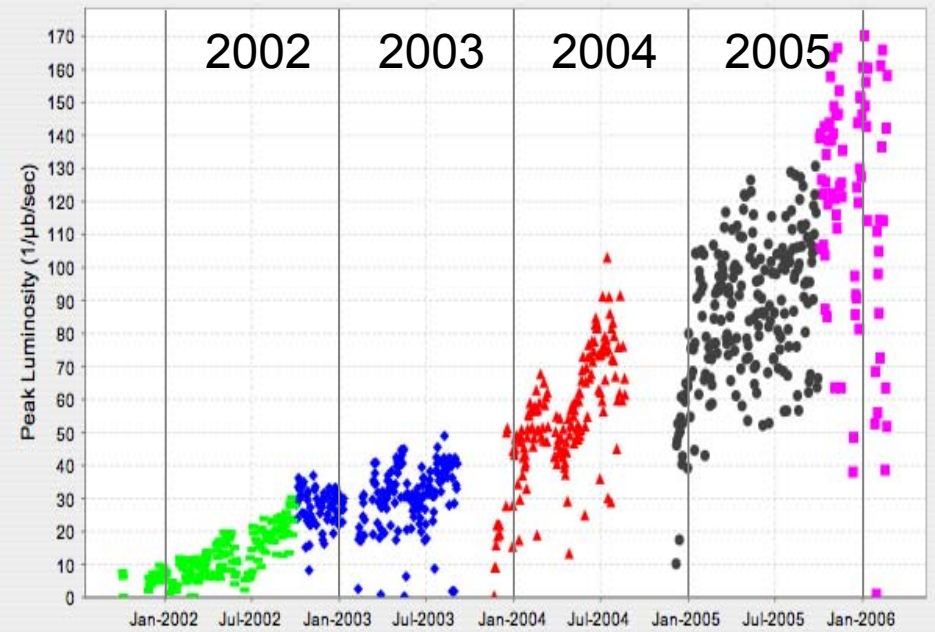
- Messy environments with large combinatorics

  $\Rightarrow$ need for <u>highly selective trigger</u>.

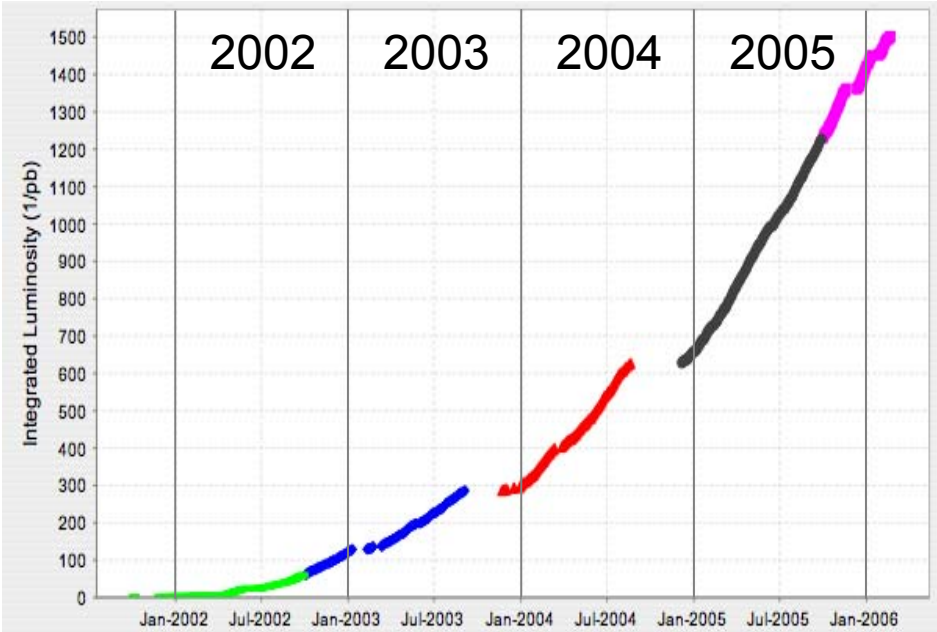


Tevatron Luminosity

Peak Luminosity



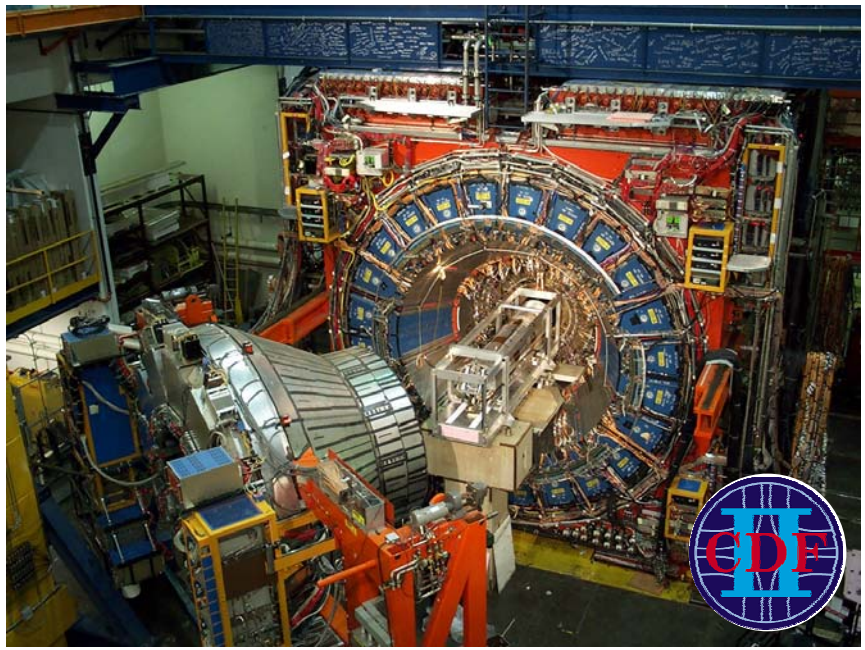
Int. Lum. (delivered) / Experiment

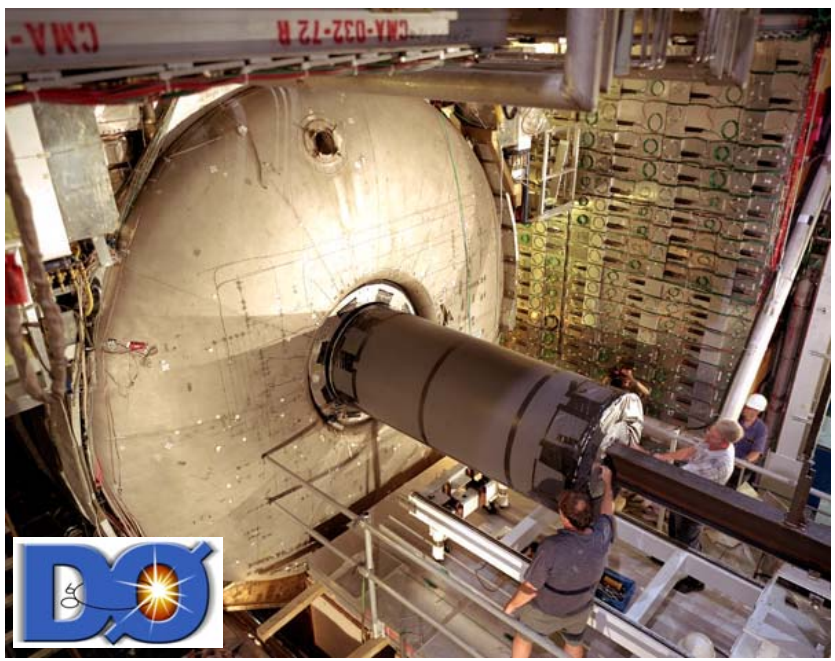


- Peak luminosity record: 1.8×10^{32} cm^{-2} s^{-1};
- Integrated luminosity:
  - weekly record: 27 pb^{-1} / week / expt;
  - total delivered: 1.5 fb^{-1} / expt, total recorded: 1.3 fb^{-1} / expt;
- Doubling time: 1 year;
- Future: ~2 fb^{-1} by 2006, ~4 fb^{-1} by 2007, ~8 fb^{-1} by 2009.

Tevatron detectors

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



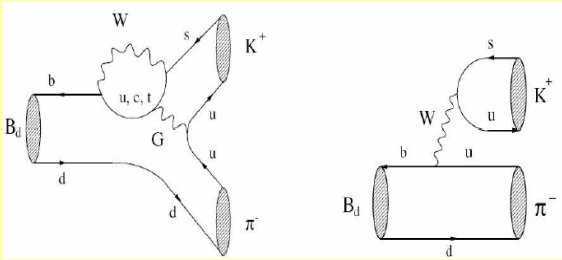


- DØ:
  - excellent electron and muon ID;
  - excellent tracking acceptance.
- CDF:
  - particle ID (ToF and dE/dx);
  - excellent mass resolution;
  - displaced track trigger at L2.

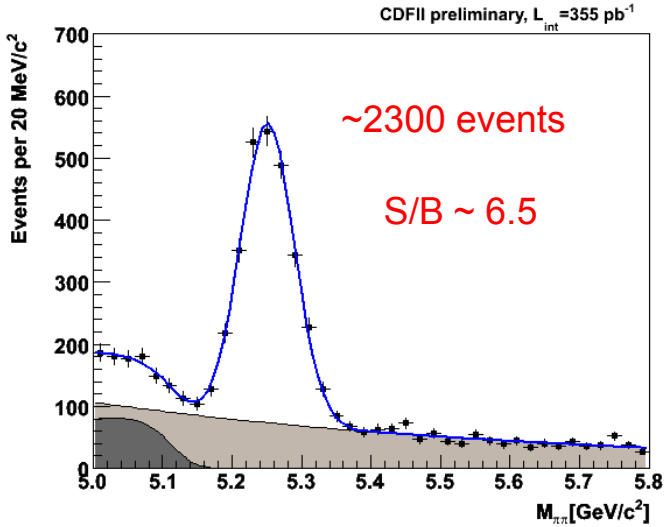
CP asymmetry in $B^0 \to K^+\pi^-$

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

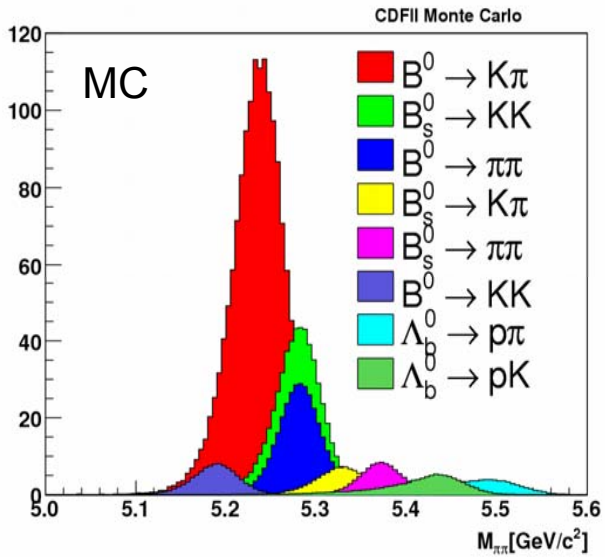
- Induced by interference between Tree and Penguin diagrams:



- Could be sensitive to Physics beyond the Standard Model.



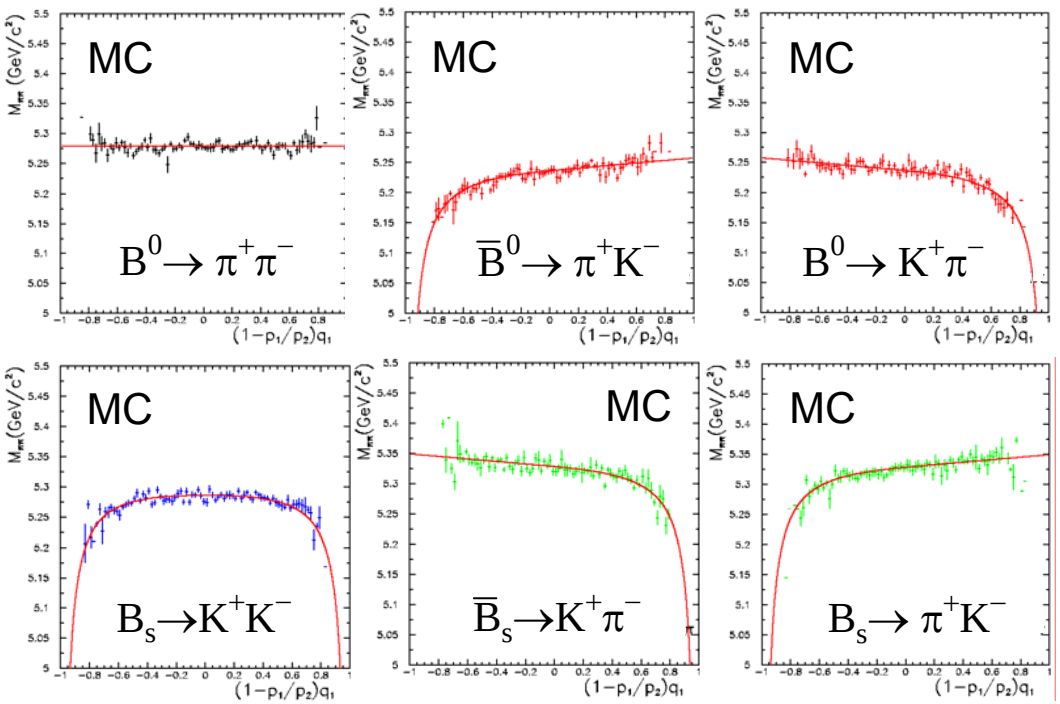
- Two-prong vertices are reconstructed with π mass assignment to tracks.
- Selected signal is the superposition of four major modes:
  - $B^0 \to K^+\pi^-$;
  - $B_s \to K^+K^-$;
  - $B^0 \to \pi^+\pi^-$;
  - $B_s \to K^-\pi^+$.



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

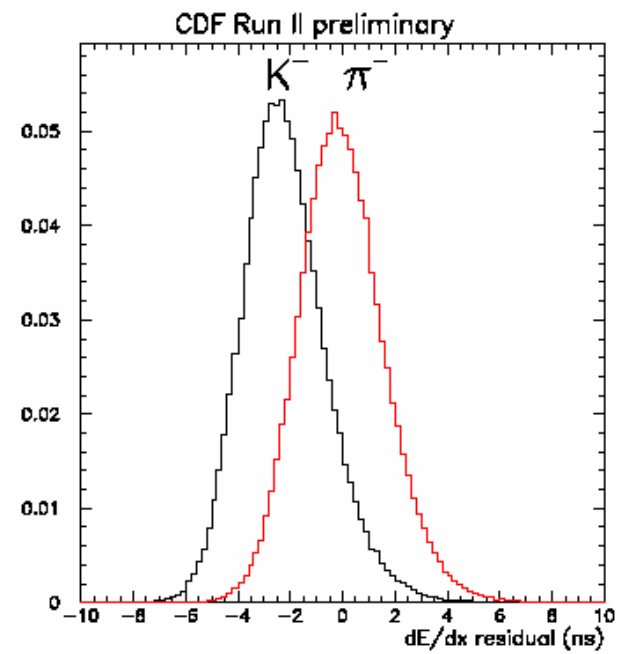
- Unbinned multidimensional likelihood fit to disentangle signal components and bkg: $M_{\pi\pi}$, α, p_{tot}, dE/dx. The fit exploits:

❶ Kinematics



$M_{\pi\pi}$ vs. $\alpha = q_{min}\,(1-p_{min}/p_{max})$

❷ dE/dx



Calibrated on

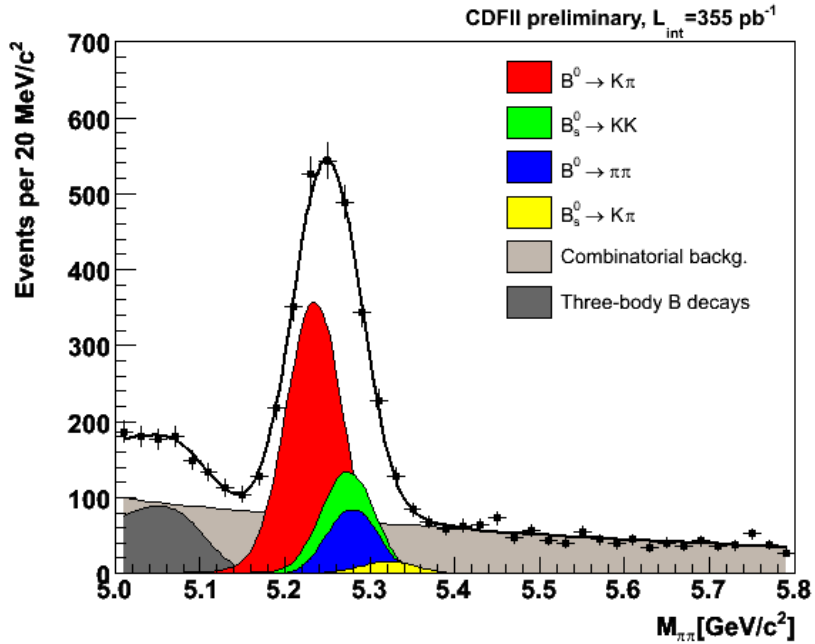
$D^{*+} \to D^0\pi^+ \to [K^-\pi^+]\,\pi^+$

(K/π separation 1.4σ, p_T >2 GeV/c)

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
$B_s^0 \to K^-\pi^+ + \overline{B}_s^0 \to K^+\pi^-$	2.7 ± 1.3	64 ± 30
$B_s^0 \to K^+K^- + \overline{B}_s^0 \to K^+K^-$	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



- 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:

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

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

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

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

- First step toward the determination of the CKM angle γ by using the Gronau-London-Wyler method.
- 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:

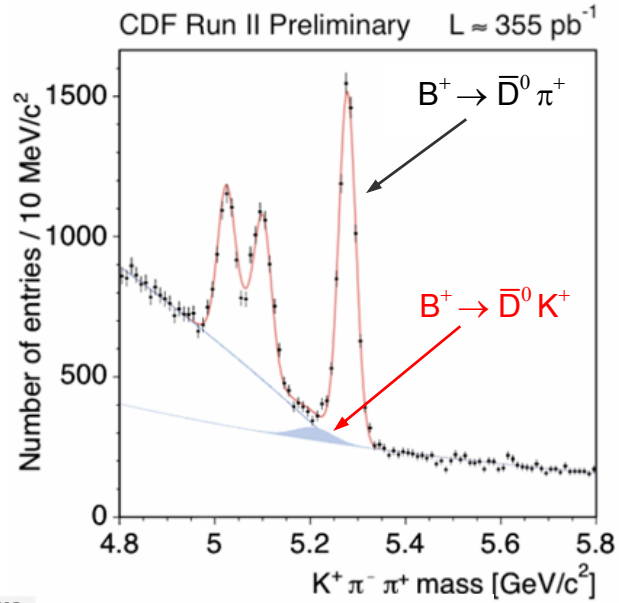
$$R_{CP\pm} = 1 + r^2 \pm 2r \cos\delta \cos\gamma$$

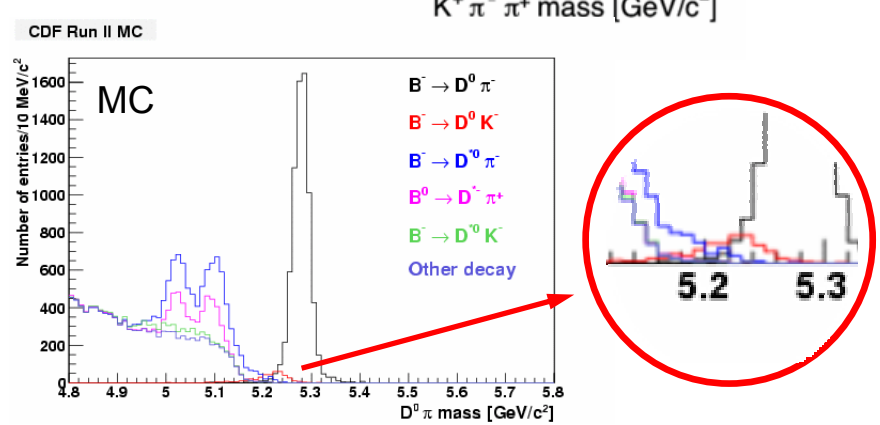
$$A_{CP\pm} = \pm 2r \sin\delta \sin\gamma / R_{CP\pm}$$

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

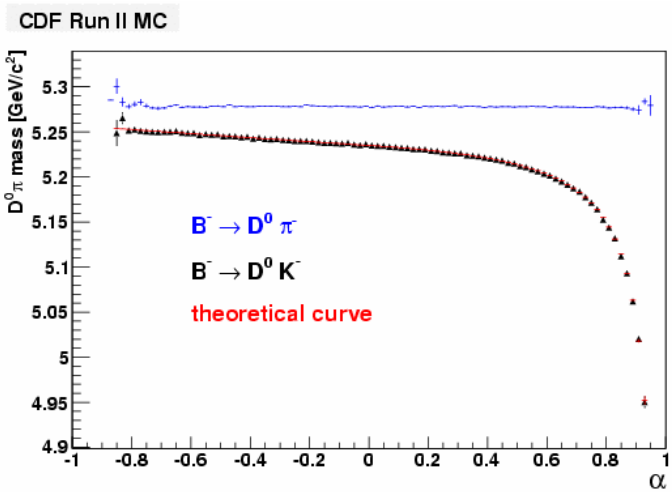
$$r = \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \sim 0.1\text{–}0.2$$

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





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



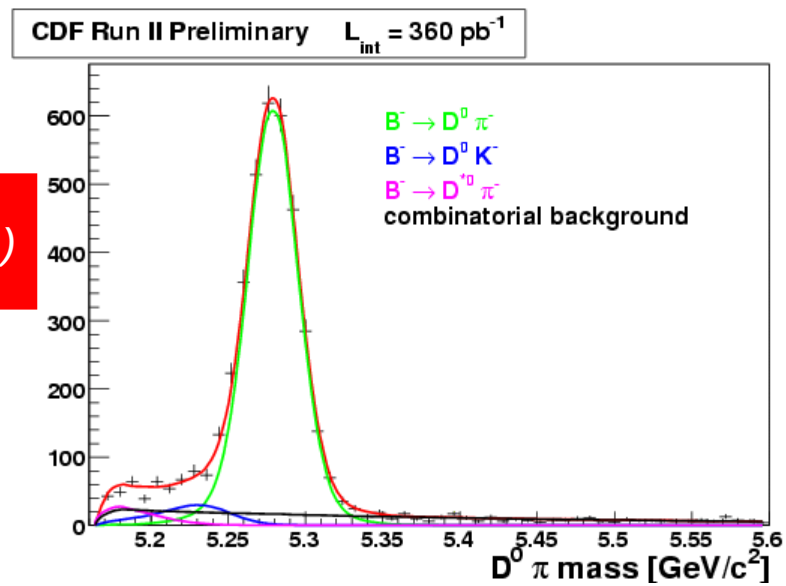
- Unbinned multidimensional likelihood fit, which combines kinematics and dE/dx information:

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

- To reject most of physical backgrounds, 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.



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

- World average:

$$R = 0.083 \pm 0.035$$

$BR(B_s \rightarrow D_s^{(*)} D_s^{(*)})$

$BR(B_s \to D_s^{(*)-} D_s^{(*)+})$

- $BR(B_s \to D_s^{(*)} D_s^{(*)})$ allows to determine $\Delta\Gamma_s/\Gamma_s$ w/o time dep. analysis or tagging.
- $B_s \to D_s^{(*)} D_s^{(*)}$ is predominantly CP-even and gives the largest contribution to $\Delta\Gamma_s$:

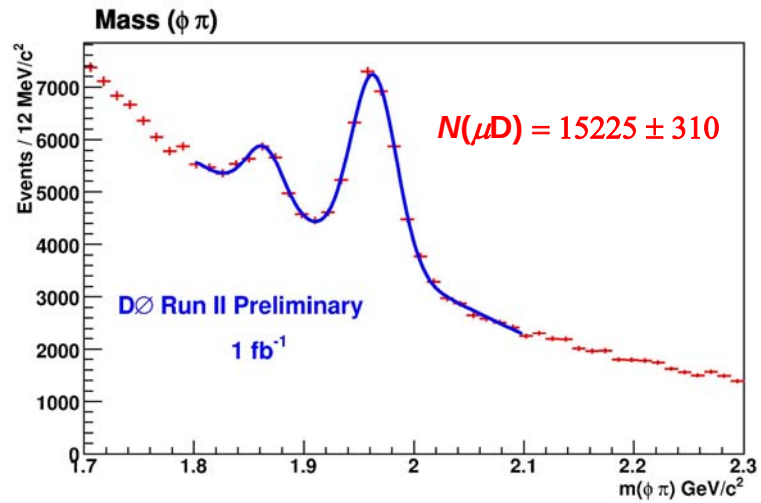
$$2\, BR(B_s \to D_s^{(*)} D_s^{(*)}) \cong \Delta\Gamma_{CP}/\Gamma \qquad (*)$$

where $\Delta\Gamma_{CP} = \Delta\Gamma_s/\cos\phi$.

I.Dunietz, R.Fleischer, U.Nierste, hep-ph/0012219

- Strategy :
  - reconstruct final state:
    - $D_s \to \phi\pi^-, \quad \phi \to K^-K^+$
    - $D_s \to \mu\phi\nu, \quad \phi \to K^-K^+$
  - normalize to $B_s \to \mu\nu D_s^{(*)}$ to reduce detector related systematics;
  - consider two samples:
    - μD_s
    - $\mu\phi D_s$

- $B_s \to \mu\nu D_s^{(*)}$ searched for in (μD_s) sample:
  - number of events from binned fit to $(KK\pi)$ mass



  - physical backgrounds composition from MC:
    - $B \to D_s D^{(*)} X$;
    - $B_s \to D_s^{(*)} D_s^{(*)}$;
    - $B_s \to D_s D X$;
    - $c\bar{c} \to \mu\nu D_s X$;
    - $b\bar{b} \to \mu\nu D_s X$.

$$\left.\right\} \; f_{bkg} = 21\%$$

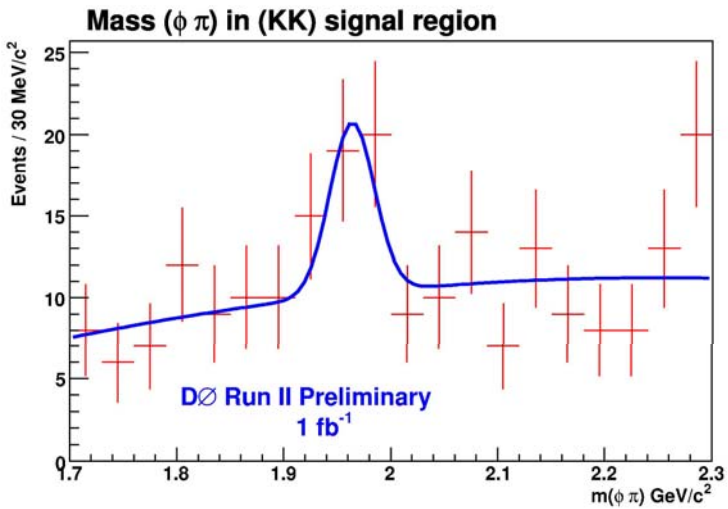
$BR(B_s \to D_s^{(*)-} D_s^{(*)+})$

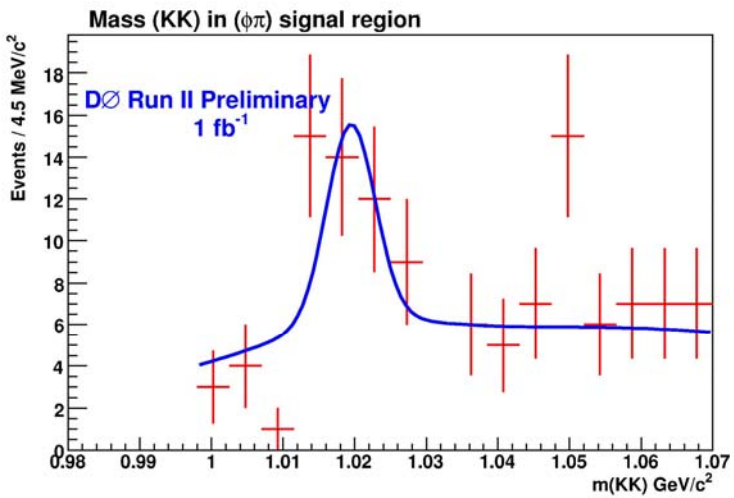
- $B_s \to D_s^{(*)} D_s^{(*)}$ searched for in $(\mu\phi D_s)$ sample:
  - number of events from an unbinned maximum likelihood fit to:
    - $\phi\pi$ invariant mass,
    - KK invariant mass from $\mu\phi$ system;

$$N(\mu\phi D) = 19.34 \pm 7.85$$

  - physical backgrounds composition:
    - $B \to D_s^{(*)} D_s^{(*)} KX$;
    - $B_s \to D_s^{(*)} D_s^{(*)} X$;
    - $B_s \to \mu\nu D_s^{(*)} \phi$;
    - $c\bar{c} \to \mu\phi D_s^{(*)}$;
    - $B_s \to \mu\nu D_s^{(*)}$ + ϕ from fragm.

$$N_{bkg}(\mu\phi D) = 1.7 \pm 1.2$$





- Relative reconstruction efficiency from full MC simulation and *BR* from PDG.

$BR(B_s \to D_s^{(*)-} D_s^{(*)+})$

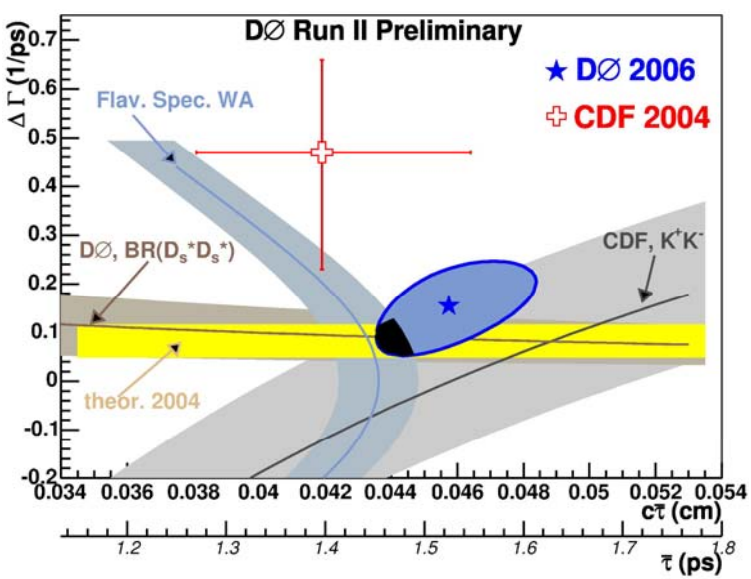
- Final result:

$$BR(B_s \to D_s^{(*)} D_s^{(*)}) = 0.071 \pm 0.035(stat.)\,^{+0.029}_{-0.025}\,(syst.)$$

  - in agreement with ALEPH measurement: $BR(B_s \to D_s^{(*)} D_s^{(*)}) = 0.23 \pm 0.10\,^{+0.19}_{-0.09}$

- Assuming that theoretical relation (∗) is true:

$$\frac{\Delta\Gamma_{CP}}{\Gamma} = 0.142 \pm 0.064(stat.)\,^{+0.058}_{-0.050}\,(syst.)$$



- SM prediction:

  $\Delta\Gamma/\Gamma = 0.12 \pm 0.06$;

- DØ direct measurement in $B_s \to J/\psi\ \phi$:

  $\Delta\Gamma = 0.15 \pm 0.10\,^{+0.03}_{-0.04}$ ps^{-1},

  $1/\bar{\Gamma} = 1.53 \pm 0.08\,^{+0.01}_{-0.04}$ ps;

- CDF direct measurement in $B_s \to J/\psi\ \phi$:

  $\Delta\Gamma/\Gamma = 0.65\,^{+0.25}_{-0.33} \pm 0.01$;

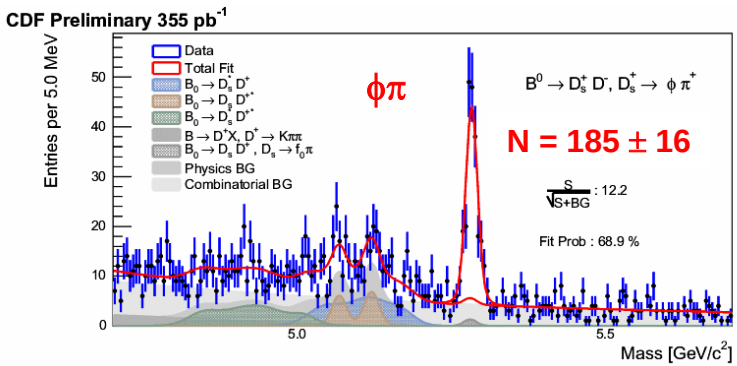
- CDF direct measurement in $B_s \to KK$:

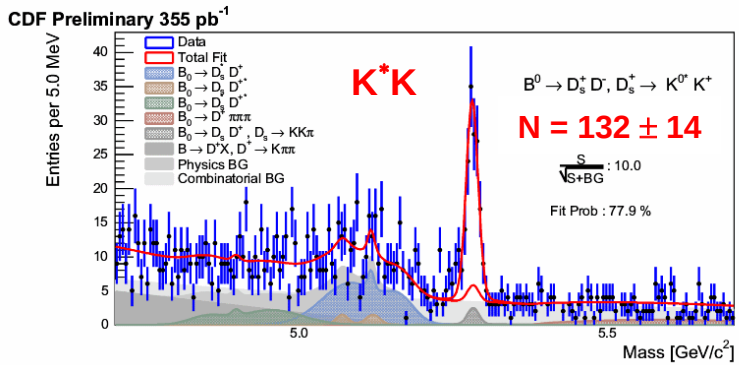
  $\Delta\Gamma/\Gamma = -0.08 \pm 0.23 \pm 0.03$.

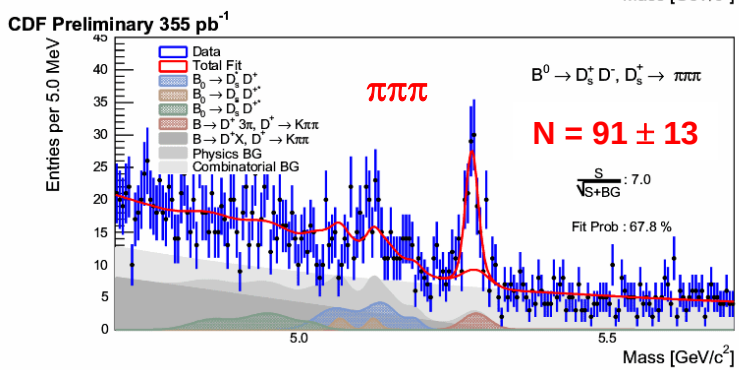
$$\frac{BR(B_s \to D_s^- D_s^+)}{BR(B^0 \to D_s^- D^+)}$$

$BR(B_s \to D_s^- D_s^+)/BR(B^0 \to D_s^- D^+)$

- Strategy: measure *BR* normalized to a more abundant channel with the same topology as the signal.
- Normalization channel: $B^0 \to D_s^- D^+$.
  - ► multiple final states reconstructed:
    - $D^+ \to K^- \pi^+ \pi^+$,
    - $D_s^- \to \phi\pi^-$, $K^{*0}K^-$, $\pi^+\pi^-\pi^-$;
      - $\phi \to K^-K^+$, $K^{*0} \to K^+\pi^-$
  - ► yield determination:
    - physical bkg templates from MC,
    - fit invariant mass distribution,
    - float fractions with fixed shapes;
  - ► estimate from MC relative reconstruction efficiencies and use PDG values to calculate the branching fraction ratio.







$BR(B_s \to D_s^- D_s^+)/BR(B^0 \to D_s^- D^+)$

- $B^0 \to D_s^+ D^-$ mode:

$$\frac{BR(B^0 \to D_s^+ D^-)}{BR(B^0 \to D^- 3\pi)} = 1.99 \pm 0.13(stat.) \pm 0.46(syst.)$$

[PDG 2005: 1.0 ± 0.5]

- $B^0 \to D_s^{(*)} D^{(*)}$ modes:

$$\frac{BR(B^0 \to D_s^{*-} D^+)}{BR(B^0 \to D_s^+ D^-)} = 0.9 \pm 0.2(stat.) \pm 0.1(syst.)$$

[PDG 2005: 1.3 ± 0.6]

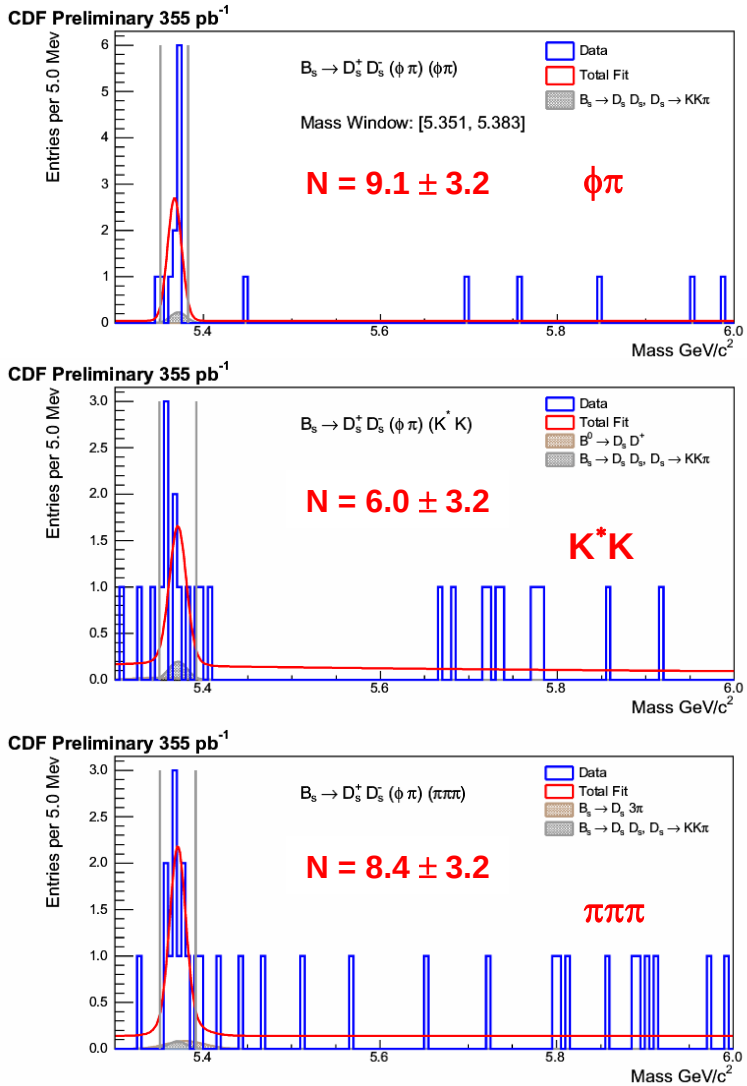
$$\frac{BR(B^0 \to D_s^- D^{*+})}{BR(B^0 \to D_s^+ D^-)} = 1.5 \pm 0.5(stat.) \pm 0.1(syst.)$$

[PDG 2005: 1.3 ± 0.6]

$$\frac{BR(B^0 \to D_s^{*-} D^{*+})}{BR(B^0 \to D_s^+ D^-)} = 2.6 \pm 0.5(stat.) \pm 0.2(syst.)$$

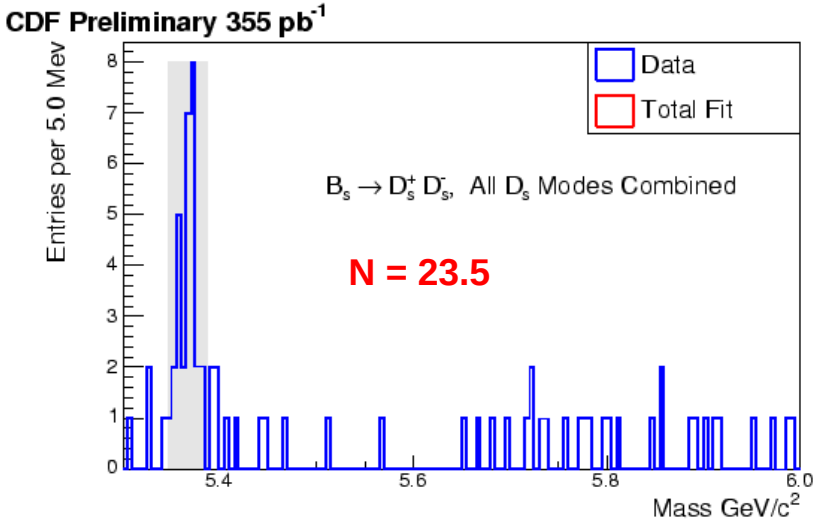
[PDG 2005: 2.4 ± 1.1]

- Signal:
  - reconstruct:
    - first D_s^- into $\phi\pi^-$ with $\phi \to K^- K^+$,
    - other D_s^- into $\phi\pi^-$, $K^{*0}K^-$, $\pi^+\pi^-\pi^-$;
  - apply same procedure as norm. mode.



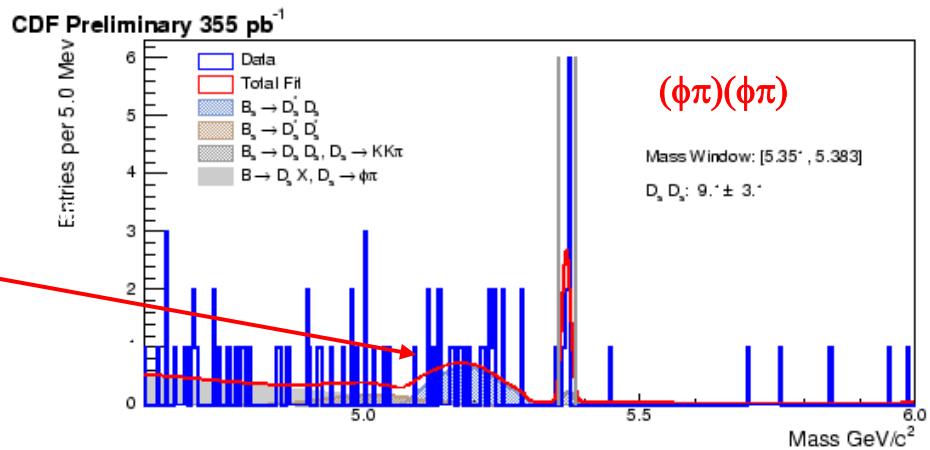
$BR(B_s \to D_s^- D_s^+)/BR(B^0 \to D_s^- D^+)$

- Combined result:



$$\frac{BR(B_s \to D_s^+ D_s^-)}{BR(B^0 \to D_s^+ D^-)} = 1.67 \pm 0.41(stat.) \pm 0.12(syst.) \pm 0.38(BR) \pm 0.24(f_s/f_d)$$

$B_s \to D_s^{(*)} D_s^{(*)}$ modes



Conclusions

- An overview of recent B Physics results from the Tevatron has been presented :
  - ✓ new CP asymmetry measurement for $B^0 \to K\pi$;
  - ✓ branching ratio of the Cabibbo suppressed $B^{\pm} \to D^0 K^{\pm}$, first step towards CKM angle γ;
  - ✓ branching ratio of the double charmed decay $B_s \to D_s^{(*)} D_s^{(*)}$ and $\Delta\Gamma/\Gamma$;
  - ✓ first observation of the exclusive $B_s \to D_s^- D_s^+$ decay mode.

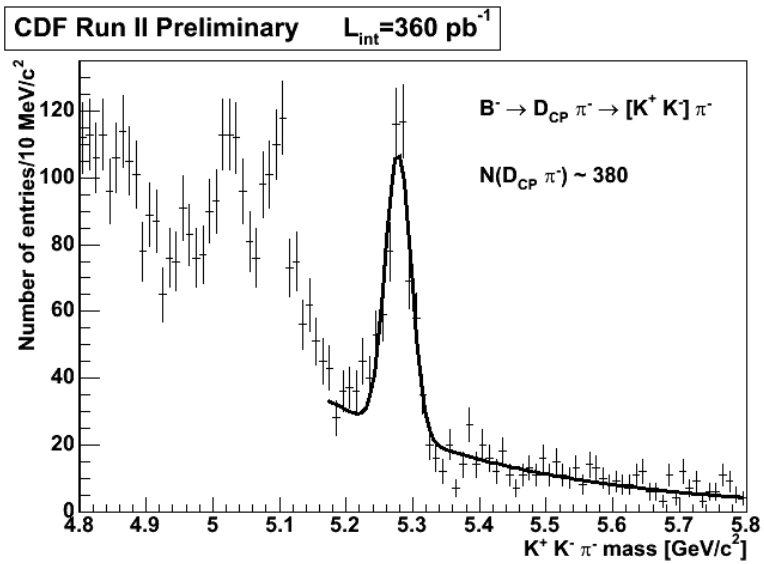
- This represents just a taste:
  - ✓ currently many analyses are under way on 1 fb^{-1} dataset and will be soon released;
  - ✓ many more challenging results are expected in the future; as more data are available, more precise measurements become possible and new rare modes become accessible.

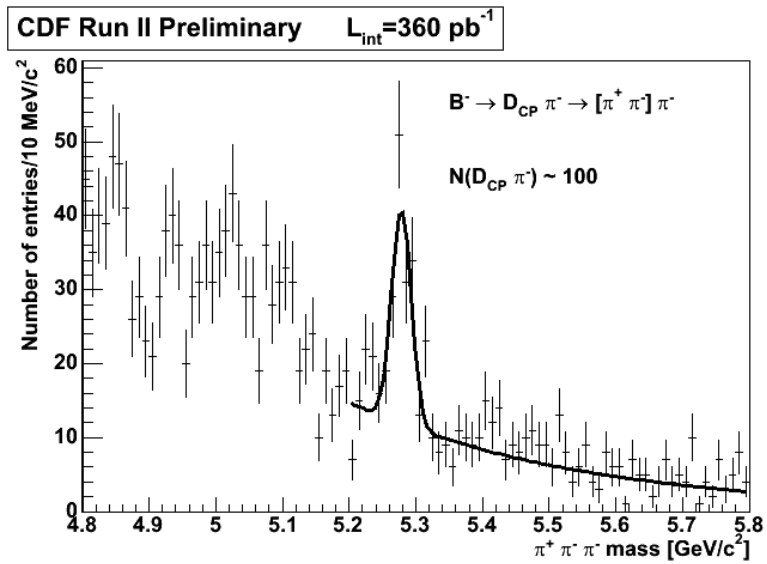
Backup slides

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

source	shift wrt central fit
mass scale	0.0022
mass resolution	0.0024
asymmetric momentum-p.d.f	0.0003
dE/dx	0.0050
input masses	0.0025
combinatorial background model	0.0019
p **spectra of background**	0.0005
MC statistics	0.0010
charge asymmetry	0.0022
$m_{\pi\pi} - p_{tot}$ **non-factorizability**	0.0018
TOTAL (sum in quadrature)	**0.0074**

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





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

$BR(B_s \to D_s^{(*)-} D_s^{(*)+})$: systematics

Source	Uncertainty in $\mathrm{Br}(B_s^0 \to D_s^{(*)} D_s^{(*)})$
$\mathrm{Br}(D_s \to \phi\pi) = 0.0440 \pm 0.0520$	$^{+0.020}_{-0.014}$
$\mathrm{Br}(B_s^0 \to \mu\nu D_s^{(*)})\ \mathrm{Br}(D_s \to \phi\pi)$	0.012
$\mathrm{Br}(D_s \to \phi\mu\nu)/\mathrm{Br}(D_s \to \phi\pi)$	0.005
$f(B_s^0 \to \mu\nu D_s^{(*)}) = 0.79 \pm 0.05$	0.005
Background contribution in $N(\mu\phi D_s)$	0.007
Ratio of efficiencies	0.010
Reweighting of MC	0.011

$BR(B_s \to D_s^- D_s^+)/BR(B^0 \to D_s^- D^+)$: systematics

Effect	Syst. Uncertainty [%]
B-meson spectrum	$\pm 3.0\%$
B_s lifetime	$\pm 2.0\%$
$D_s \to \pi\pi\pi$ composition	$\pm 3.0\%$
$B^0 \to D_s D^+(\phi\pi)$ Fit	$\pm 2.3\%$
$B^0 \to D_s D^+(K^* K)$ Fit	$\pm 4.2\%$
$B^0 \to D_s D^+(\pi\pi\pi)$ Fit	$\pm 8.4\%$
$B_s \to D_s^- D_s^+(\phi\pi)$ Fit	$\pm 6.3\%$
$B_s \to D_s^- D_s^+(K^* K)$ Fit	$\pm 8.5\%$
$B_s \to D_s^- D_s^+(\pi\pi\pi)$ Fit	$\pm 4.1\%$
$B^0 \to D_s^- D^+(\phi\pi)$ Cuts	$\pm 5.0\%$
$B_s \to D_s^- D_s^+(\phi\pi)$ Cuts	$\pm 5.0\%$
Common	$\pm 6.9\%$