# Precision Measurement of CP Violation in $D^0 \to \pi^+\pi^-$ at CDF

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On behalf of the CDF collaboration

**X International Conference on Heavy Quarks and Leptons**

11-15 Oct 2010, INFN - Laboratori Nazionali di Frascati (Italy)

# Today

25th anniversary of the first collisions in the Tevatron

# CP violation in the Charm sector

- Precision measurements of CP violation probe the possible existence of New Physics beyond what is currently accessible through direct searches.
- CP violation observed so far is explained within the Standard Model and is far from sufficient to explain the matter-antimatter asymmetry of the Universe, so there must be something else...
- Until recently most CP violation measurements have been done in the area of down-quarks ($s$, $b$), so what about up-quarks? Why not look where we did not look before?
- Charm is a unique window to New Physics because it probes up-quark sector (unaccessible through $t$ or $u$ quarks).
- Observed $D^0$ mixing rate is large, consistent only with most stretched Standard Model predictions. Could this be a first hint of New Physics?

# CP asymmetry in $D^0 \to \pi^+\pi^-$ decays

What do we measure?

$$A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) = \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^-\pi^+)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^-\pi^+)}$$

- CP symmetric initial state ($p\bar{p}$) ensures charge symmetric production.
- Tag flavor at production time through $D^\star \to D^0\pi_s$ decay.
- With $\sim 215$K candidates the expected statistical resolution is $\sim 0.2\%$.
- Small $Q$-value in $D^\star$ decay causes $\pi_s$ to be low momentum:
  - typically in the range where detector efficiency for tracks of opposite charge is asymmetric to the level of a few percents.
- Need to suppress detector charge asymmetry by more than one order of magnitude to control systematics at $\sim 0.1\%$.
- Turns out this can be done with a very high degree of confidence using only data, no need to rely on Monte Carlo.

# How are we doing it?

Combine the "raw" asymmetries of three different event samples to minimize systematic errors caused by the detector induced asymmetries:

✓ $D^\star \to D^0\pi_s \to [\pi\ \pi]\ \pi_s$ $\qquad A^{\text{raw}}_{\text{CP}}(\pi\pi^\star) = A_{\text{CP}}(\pi\pi) + \delta(\pi_s)$

cancel asymmetry due to $\pi_s^+/\pi_s^-$
different reconstruction efficiencies

✓ $D^\star \to D^0\pi_s \to [K\pi]\ \pi_s$ $\qquad A^{\text{raw}}_{\text{CP}}(K\pi^\star) = A_{\text{CP}}(K\pi) + \delta(\pi_s) + \delta(K\pi)$

cancel asymmetry due to $K^+/K^-$
different interaction with matter
$+$ possible CPV in $D^0 \to K\pi$

✓ $D^0 \to [K\pi]$ $\qquad A^{\text{raw}}_{\text{CP}}(K\pi) = A_{\text{CP}}(K\pi) + \delta(K\pi)$

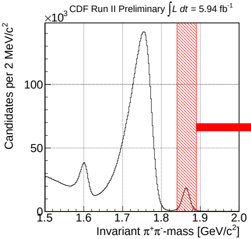
The physical $A_{\text{CP}}$ could be extracted through the combination:

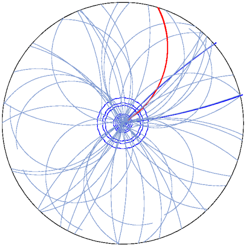
$$A_{\text{CP}}(\pi\pi) = A^{\text{raw}}_{\text{CP}}(\pi\pi^\star) - A^{\text{raw}}_{\text{CP}}(K\pi^\star) + A^{\text{raw}}_{\text{CP}}(K\pi)$$

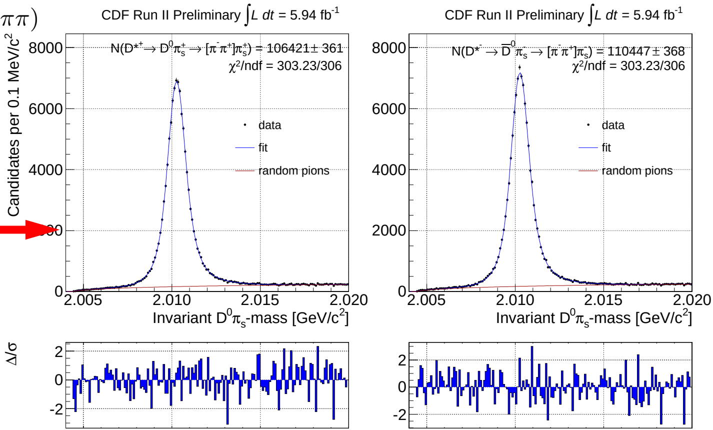
# Counting $D^\star$-tagged $D^0 \to \pi^+\pi^-$

Select signal with $M(\pi\pi)$

then fit $M(D^0\pi_s)$





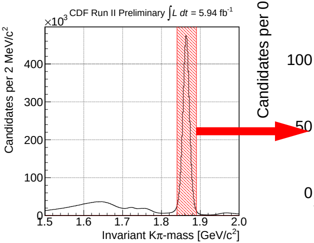

$\sim 215'000$ $D^\star$-tagged $D^0 \to \pi\pi$

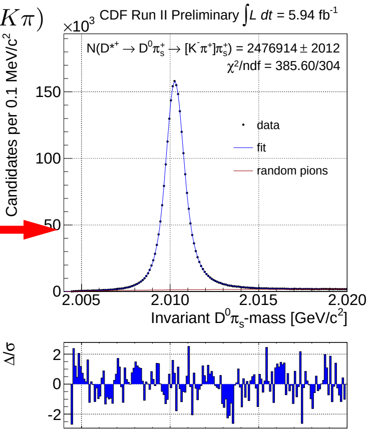
$$A_{\mathrm{CP}}^{\mathrm{raw}}(\pi\pi^\star) = (-1.86 \pm 0.23)\%$$

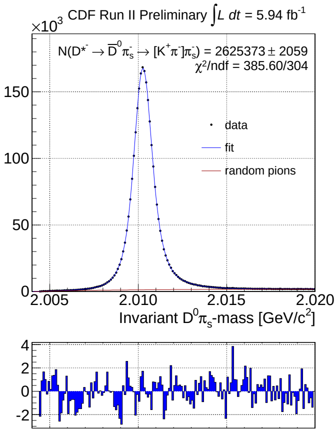
# Counting $D^\star$-tagged $D^0 \to K^-\pi^+$

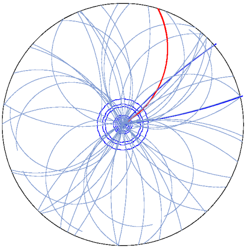
Select signal with $M(K\pi)$

then fit $M(D^0\pi_s)$



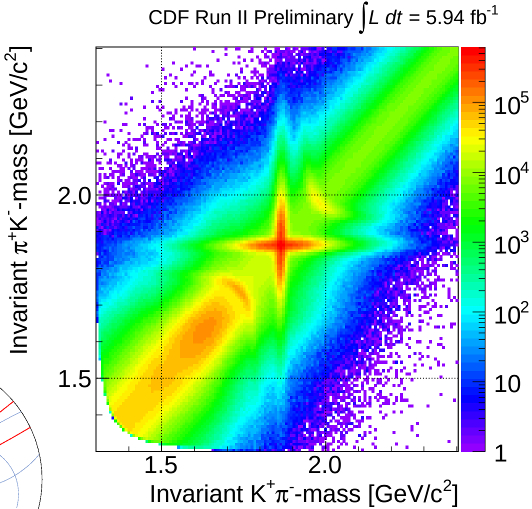



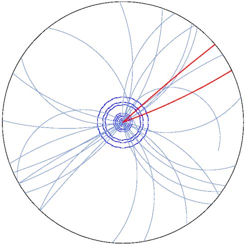



$\sim 5'000'000$ $D^\star$-tagged $D^0 \to K\pi$

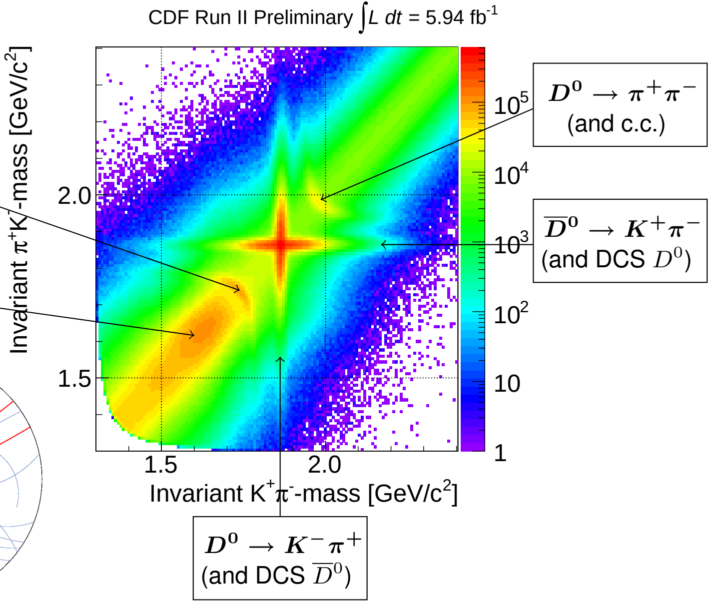
$$A_{\text{CP}}^{\text{raw}}(K\pi^\star) = (-2.91 \pm 0.05)\%$$

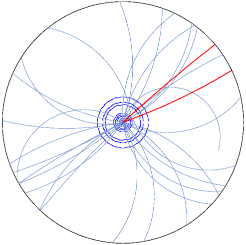
# Counting untagged $D^0 \to K^-\pi^+$ (1)



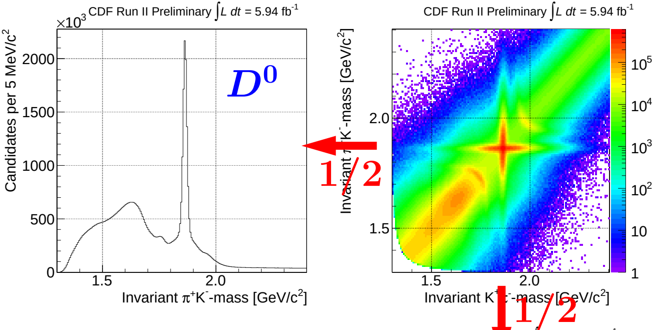



# Counting untagged $D^0 \to K^-\pi^+$ (1)

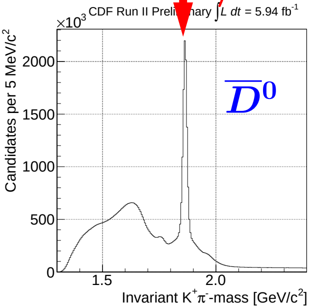


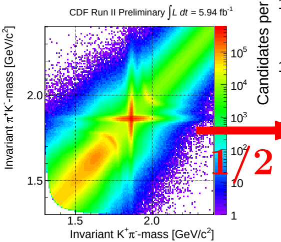
# Counting untagged $D^0 \to K^-\pi^+$ (1)

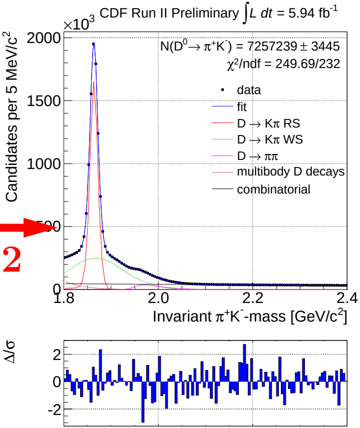


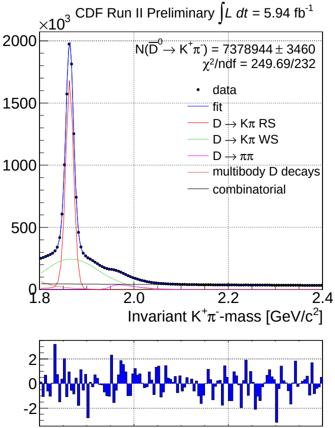

- ✓ two statistically independent samples with half the events each
- ✓ can easily afford to loose a factor of two in statistics here
- ✓ signal is in narrow peak (ignore DCS contribution)

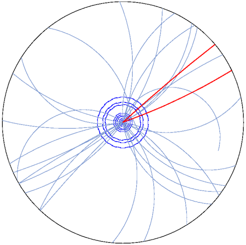


# Counting untagged $D^0 \to K^-\pi^+$ (2)



$\sim 2 \times 15'000'000$ untagged $D^0 \to K\pi$

$$A_{CP}^{\text{raw}}(K\pi) = (-0.83 \pm 0.03)\%$$

# Systematics

Summary of all sources of systematic error:

| Source of systematic uncertainty | Variation on $A_{\text{CP}}(\pi\pi)$ |
|---|---|
| Approximations in the method | $0.009\%$ |
| Beam drag effects | $0.004\%$ |
| Contamination of non-prompt $D^0$s | $0.034\%$ |
| Templates used in fits | $0.010\%$ |
| Templates charge differences | $0.098\%$ |
| Asymmetries from non-subtracted backgrounds | $0.018\%$ |
| Imperfect sample reweighing | $0.0005\%$ |
| Sum in quadrature | $0.105\%$ |

# Final result

- In 5.94 $\mathrm{fb}^{-1}$ of CDF data we measure

$$A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) = [+0.22 \pm 0.24\ (stat.) \pm 0.11\ (syst.)]\%$$

Public documentation: http://www-cdf.fnal.gov/physics/new/bottom/100916.blessed-Dpipi6.0/

- World's best measurement so far

  BaBar on 386/fb $[-0.24 \pm 0.52\ (stat.) \pm 0.22\ (syst.)]\%$

  *Phys. Rev. Lett.* **100** (2008) 061803

  Belle on 540/fb $[+0.43 \pm 0.52\ (stat.) \pm 0.12\ (syst.)]\%$

  *Phys. Lett.* **B 670** (2008) 190

- To correctly compare with B-factories we need to better understand what we measured.

# Direct and indirect CPV in $D^0 \to \pi^+\pi^-$

- Time-integrated CP asymmetry

$$A_{\text{CP}}(\pi^+\pi^-) = \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^-\pi^+)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^-\pi^+)},$$

receives contribution from different amplitudes in $D^0$ and $\overline{D}^0$ decays (direct CP violation) but also from mixing induced effects (indirect CP violation).

- The latter source produces a time-dependent asymmetry that persists when integrated over time.
- Since flavour mixing parameters are small in the charm sector, at first order, the measured integrated asymmetry is the linear combination of the two contributions

$$A_{\text{CP}}(\pi^+\pi^-) \approx a_{\text{CP}}^{\text{dir}} + \frac{\langle t \rangle}{\tau} a_{\text{CP}}^{\text{ind}}$$

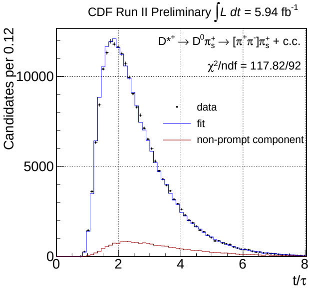
where $t/\tau$ is the proper decay time in unit of $D^0$ lifetime.

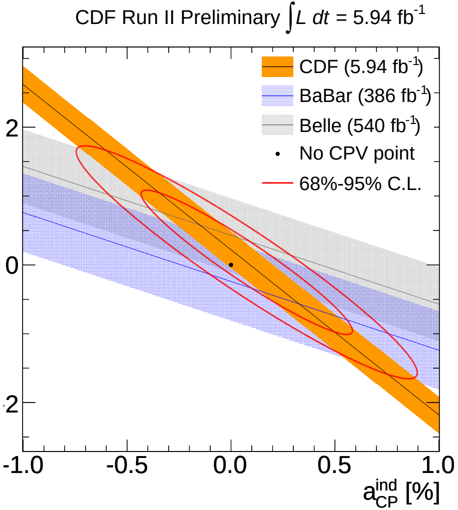
- The measurement describes a straight band in the plane $(a_{\text{CP}}^{\text{ind}}, a_{\text{CP}}^{\text{dir}})$ with slope given by the average proper time of the $D^0 \to \pi^+\pi^-$ sample.

# Comparing with B-factories (1)

CDF trigger bias proper time distribution towards higher values

$\langle t \rangle \approx 2.40\,\tau$



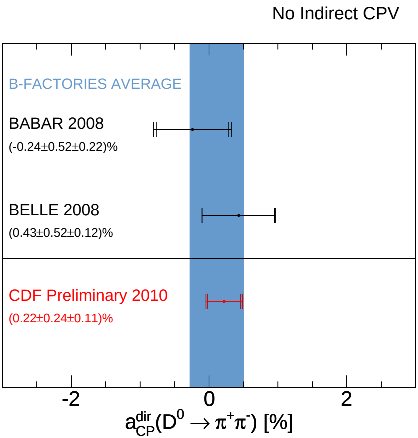



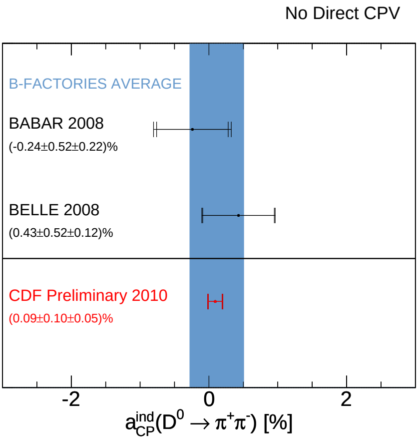

at B-factories

$\langle t \rangle \approx \tau$

combination assuming gaussian errors

# Comparing with B-factories (2)



# Conclusions

- Most precise $A_{\text{CP}}$ measurement ever in the Charm sector
- We have now enough precision to probe the Charm sector for new physics in a significant way
- High precision measurements competitive or even superior to the B-factories are possible at the Tevatron
- Still limited by statistics and will improve with integrated luminosity ($5.9 \rightarrow 10 \rightarrow 20$ fb$^{-1}$?)
- Short term prospect: $D^0 \rightarrow K^+K^-$