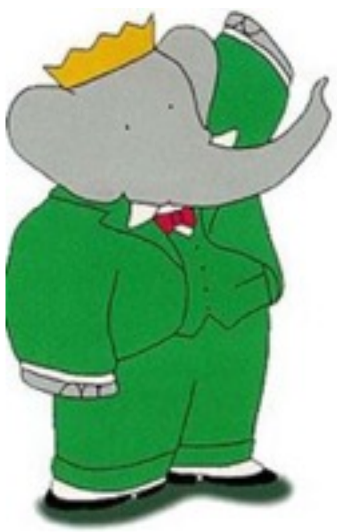
New D^0–$\bar{D}^0$ Mixing from the *BABAR* Experiment



Giulia Casarosa - INFN Pisa

on behalf of the *BABAR* Collaboration

Outline

- Charm Mixing & CP Violation
- The *BaBar* Experiment
- Mixing with a Time-Dependent Amplitude Analysis of the Decay $D^0 \rightarrow \pi^+ \pi^- \pi^0$

Neutral Meson Mixing

➡ Mixing occurs when the mass eigenstates differ from the flavour eigenstates:

$$\boxed{|D_{1,2}\rangle} = p \boxed{|D^0\rangle} \pm q \boxed{|\overline{D}^0\rangle}$$

with $|p|^2 + |q|^2 = 1$
and assuming CPT conservation

➡ The mass eigenstates and their time evolution are obtained diagonalizing the Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = (\mathbf{M} - \frac{i}{2}\mathbf{\Gamma})\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

$\mathcal{H}_{\text{eff}} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$ effective Hamiltonian, M and Γ Hermitian Matrices

➡ The mass eigenstates propagate as free particles with different masses $m_{1,2}$ and widths $\Gamma_{1,2}$:

$$|D_{1,2}(t)\rangle = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}|D_{1,2}(0)\rangle$$

note:

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}$$

D^0 Mixing Parameters

➡ Mixing is described by the mixing parameters:

$$\boxed{x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}} \qquad \text{with} \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

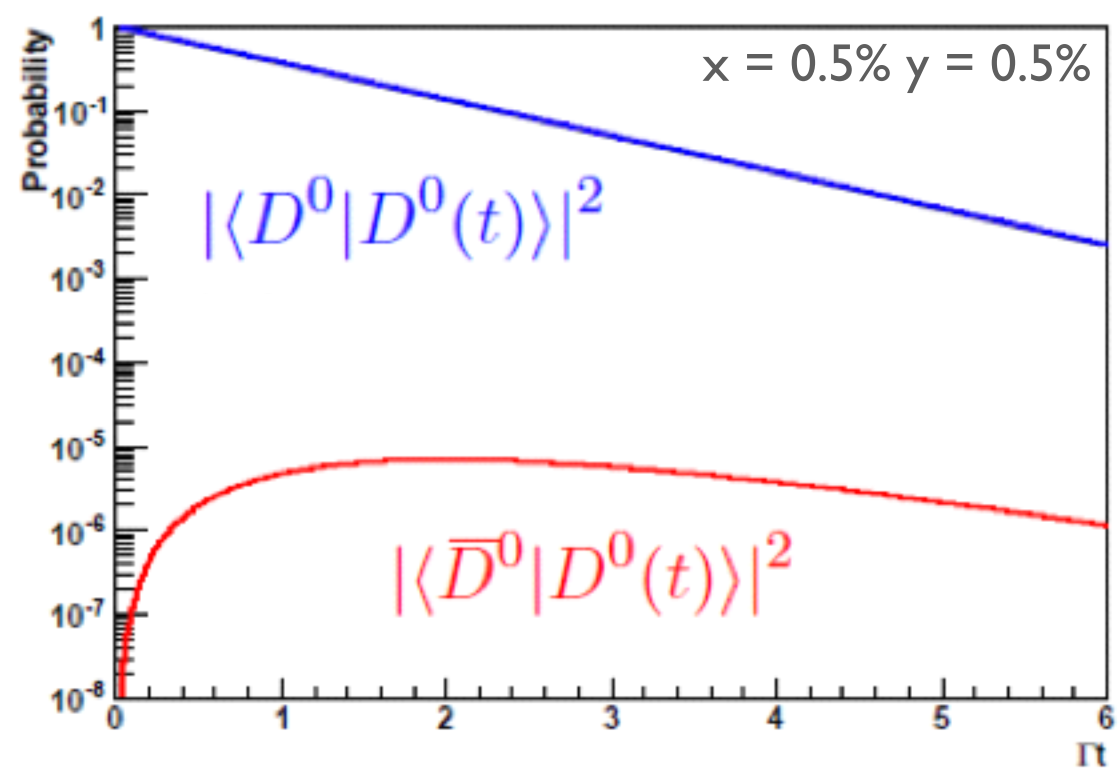
➡ Let's consider the state of a neutral charmed meson that was a D^0 at t = 0:

- The probability that the flavour is unchanged at time t is:

$$|\langle D^0|D^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

- The probability that the flavour is changed at time t is:

$$|\langle \overline{D}^0|D^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$



CP Violation Observables

direct CPV (final state dep.) + indirect CPV (for D^0 only)

➡ CP Violation in the decay if $\boxed{|A_f| \neq |\bar{A}_{\bar{f}}|}$

- need at least 2 amplitudes with different strong and weak phases, the observables are in form of asymmetries:

$$A_{CP}(f) = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

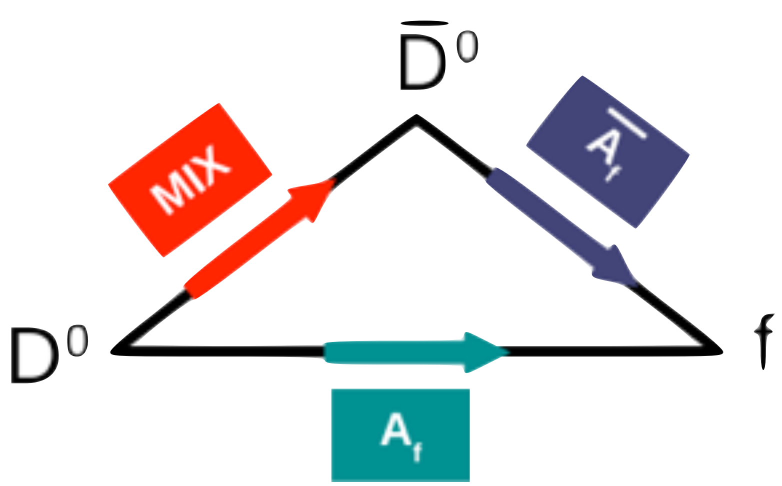
indirect CPV

➡ CP Violation in the mixing if $\boxed{R_M = \left|\frac{q}{p}\right| \neq 1}$

- probability of $D^0 \to \bar{D}^0$ is different than the CP-conjugate $\bar{D}^0 \to D^0$

direct CPV + indirect CPV

➡ CP Violation in the interference between decays with and without mixing

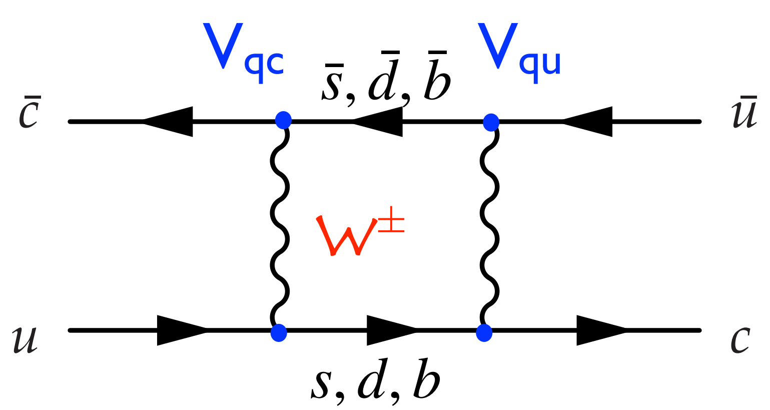


if $\boxed{\phi_f \neq 0}$ where $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left|\frac{q}{p}\frac{\bar{A}_f}{A_f}\right| \exp\left[i(\delta_f + \phi_f)\right]$

strong + weak phase

Standard Model Predictions

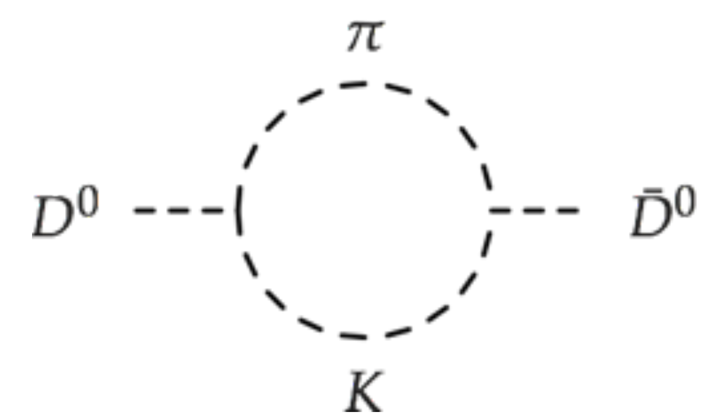
short-distance contributions



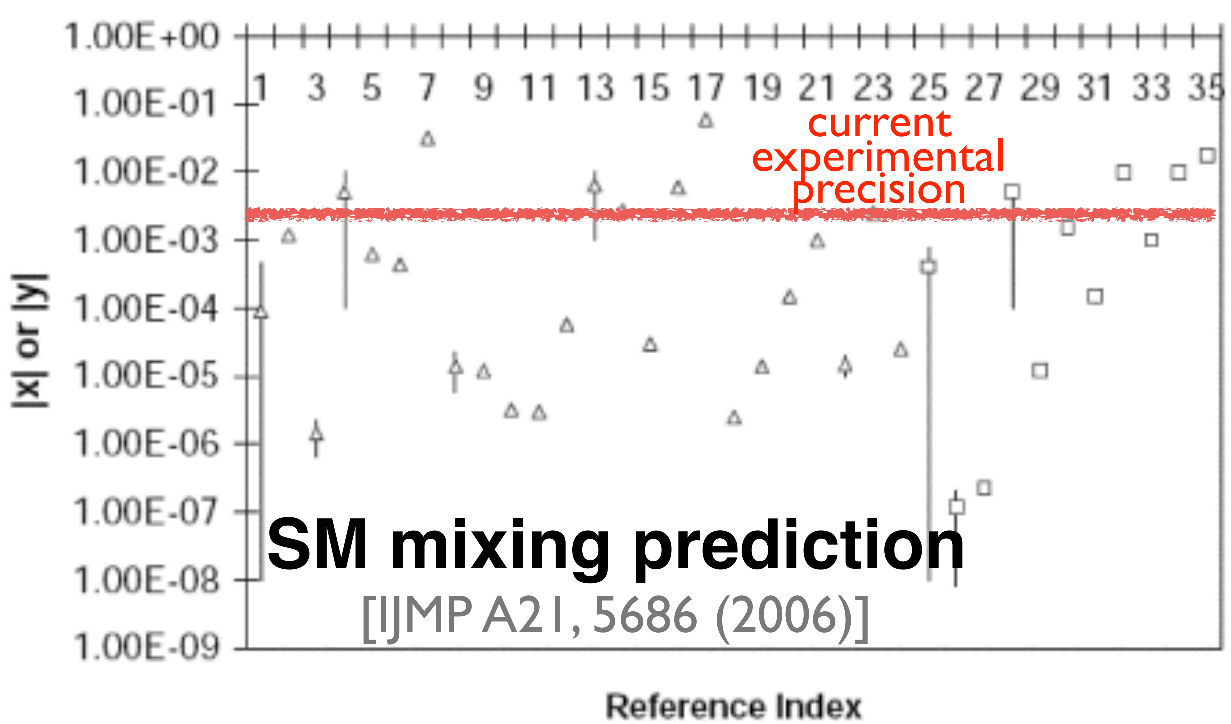
- virtual particles in the loop
- CKM & GIM suppressed

+

long-distance contributions



- real intermediate state
- *dominant* contribution

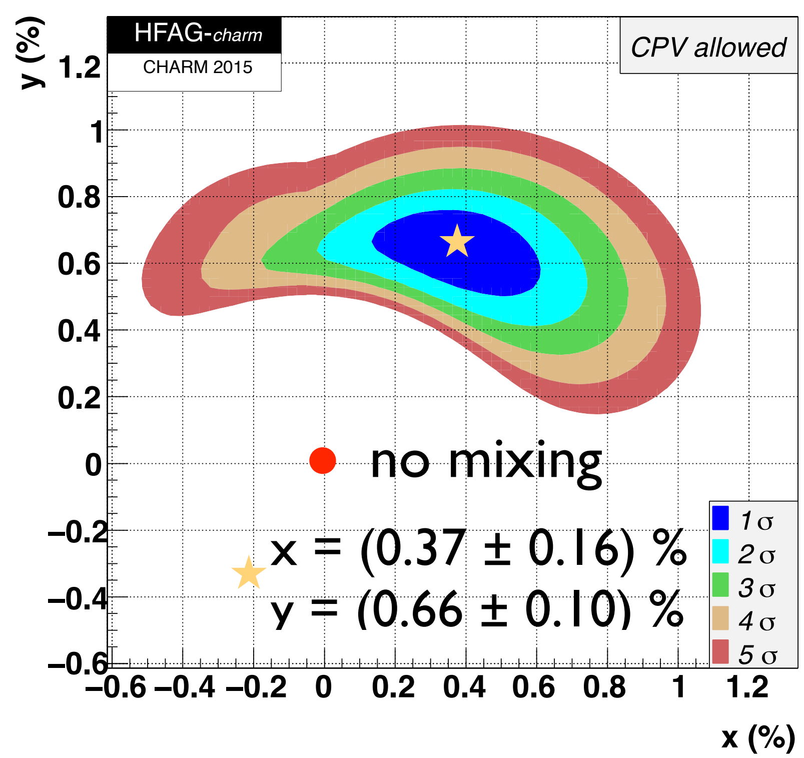


SM mixing prediction
[IJMP A21, 5686 (2006)]

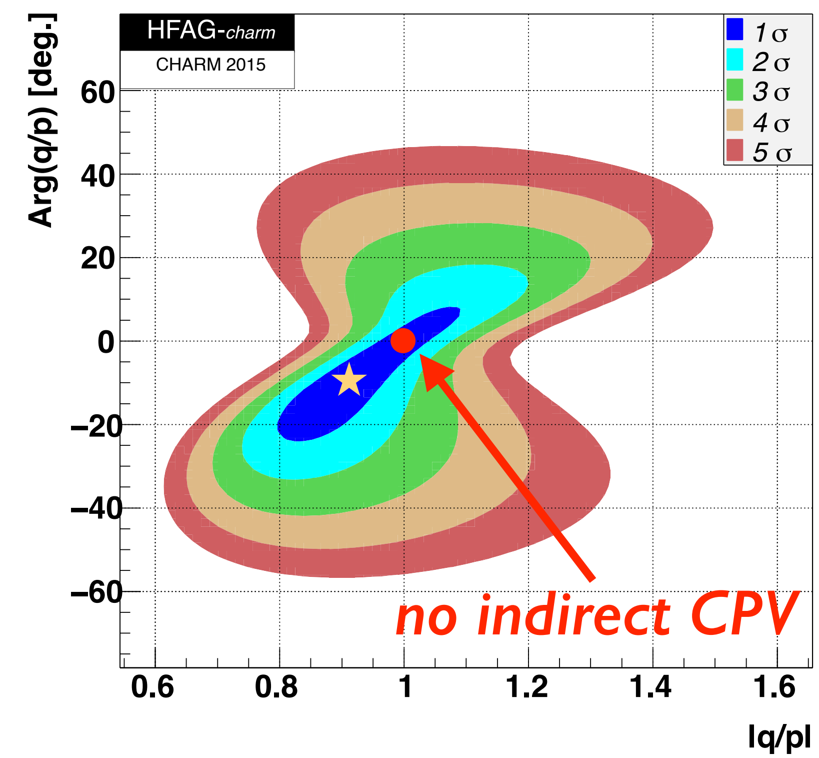
The Standard Model predictions on mixing and CP Violation parameters are affected by large uncertainties due to the difficulties in the computation of the dominant long-distance contributions

Experimental World-Averages

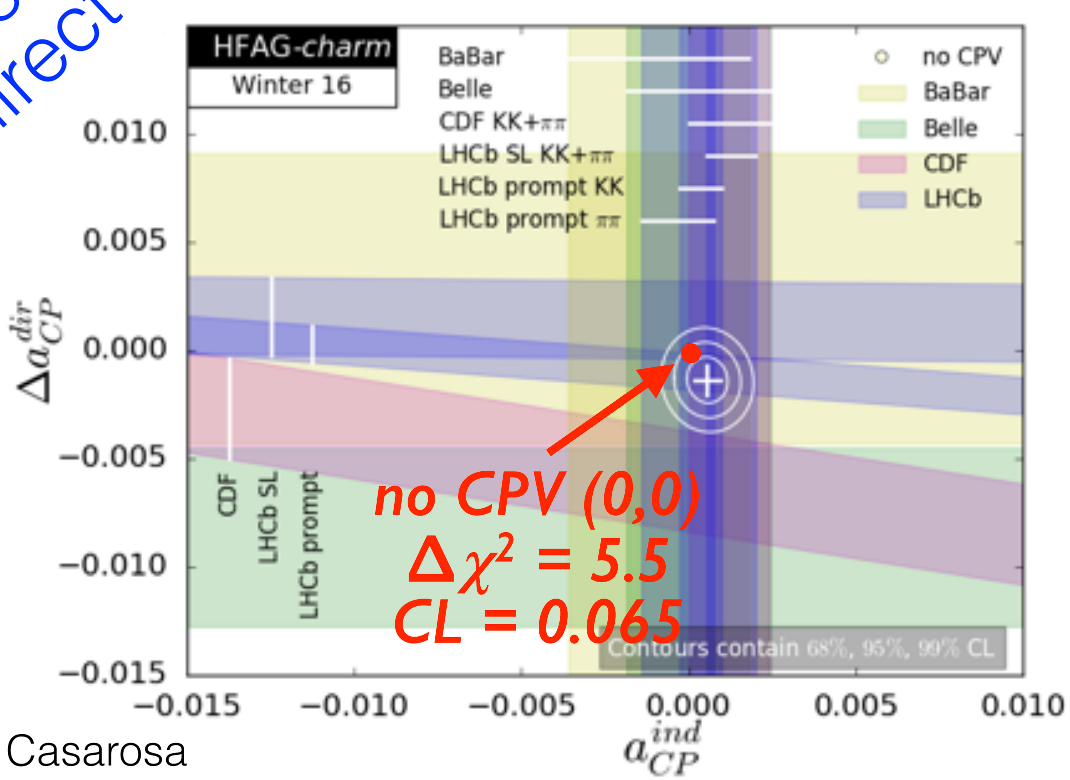
mixing



indirect CPV



direct vs indirect CPV



- $D^0 - \bar{D}^0$ mixing has been experimentally established
- No hints of indirect CPV
- No clear evidence of direct CPV

BaBar Contributions

mixing

- $D^0 \to \pi^+\pi^-, K^+K^-$ y_{CP}
- $D^0 \to K^+\pi^-$ x'^2, y'
- $D^0 \to K_S\pi^+\pi^-, K_SK^+K^-$ x, y
- $D^0 \to K^+\pi^-\pi^0$ y'', x''^2
- $\boxed{D^0 \to \pi^+\pi^-\pi^0 \quad x, y}$

NEW
PRELIMINARY RESULT

direct CPV

- $D^0 \to \pi^+\pi^-, K^+K^-$ $A_{CP}, \Delta A_{CP}$
- $D^0 \to K^+K^-\pi^0$
- $D^0 \to \pi^+\pi^-\pi^0$
- $D_s^+ \to K_S\pi^+$
- $D_s^+ \to K_SK^+$
- $D^+ \to K_S\pi^+$
- $D^+ \to K^+K^-\pi^+$
- ☆ $D^+ \to \pi^+\pi^0$ *ALMOST READY…*

$$A_{CP} = \frac{(\Gamma_D - \Gamma_{\bar{D}})}{(\Gamma_D + \Gamma_{\bar{D}})}$$

direct vs indirect CPV

$A_{CP}, \Delta Y$ (aka A_Γ)

- $D^0 \to \pi^+\pi^-, K^+K^-$

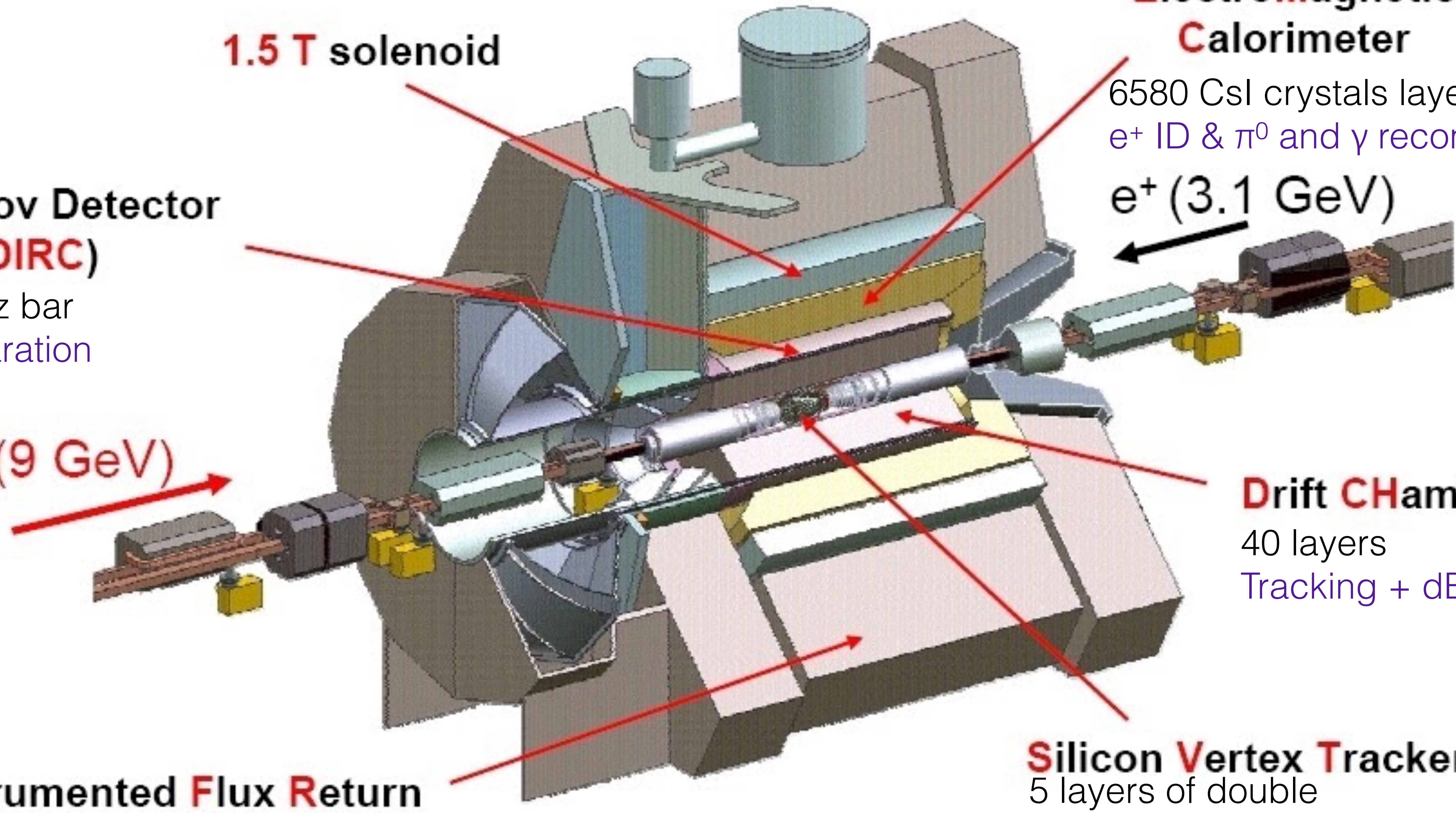
CP violation with triple-product asymmetries

$$C_T = (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3$$

- $D^0 \to K^+K^-\pi^+\pi^-$
- $D^+ \to K_SK^+\pi^+\pi^-$
- $D_s^+ \to K_SK^+\pi^+\pi^-$

The *BaBar* Detector

$e^+e^- \rightarrow \Upsilon(4S)$, $\beta\gamma = 0.56$



1.5 T solenoid

ElectroMagnetic Calorimeter
6580 CsI crystals layers
e^+ ID & π^0 and γ reconstruction

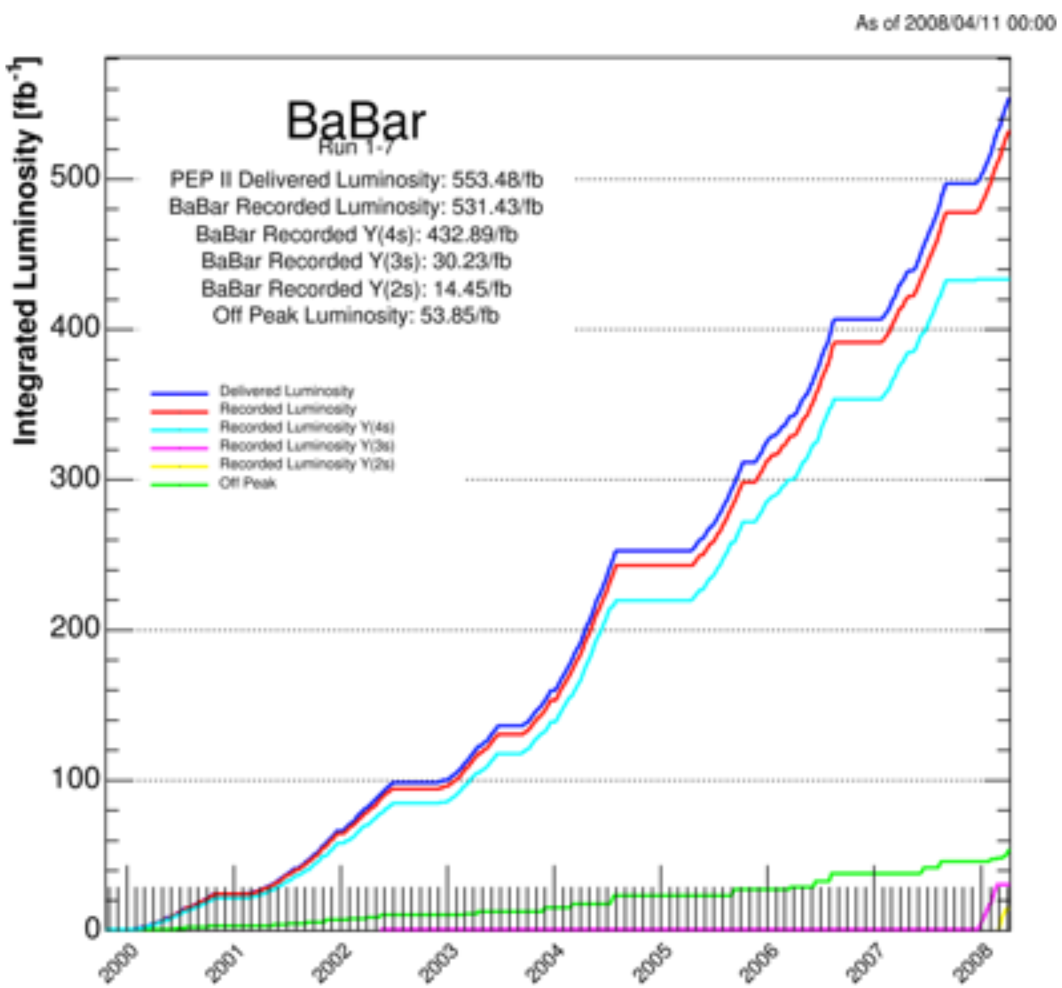
Čerenkov Detector (DIRC)
144 quarz bar
K, π separation

Drift CHamber
40 layers
Tracking + dE/dx

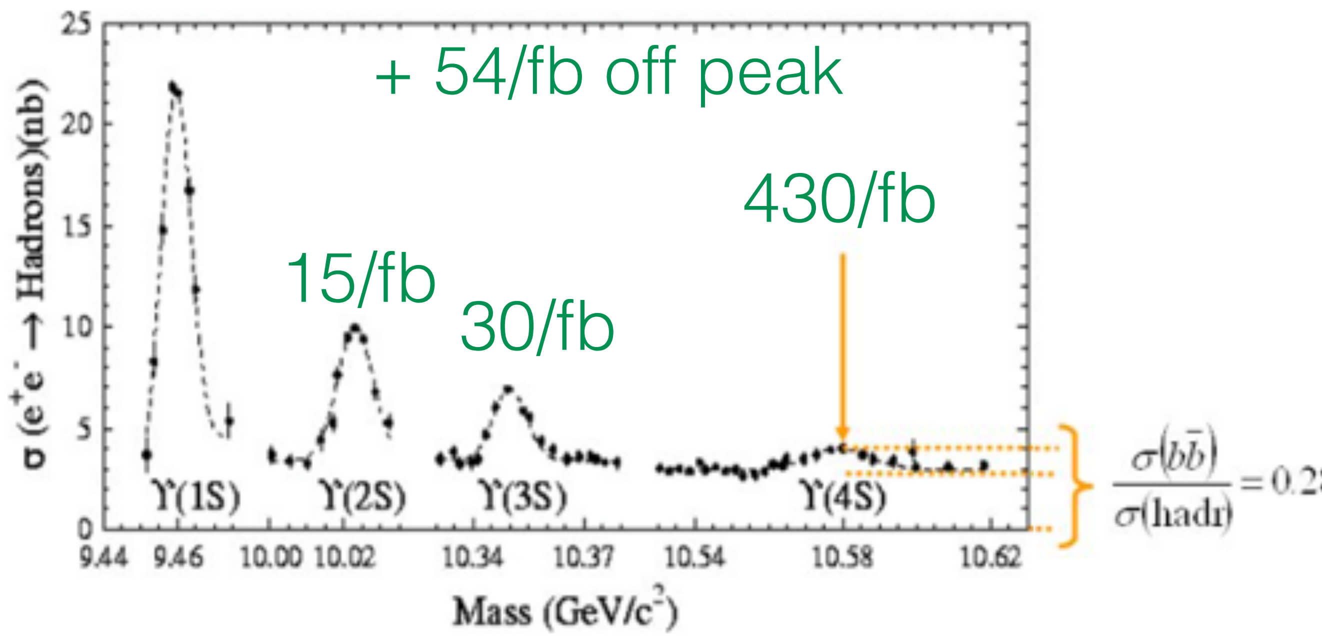
Instrumented Flux Return
19 layers of RPCs (LSTs)
μ & K_L ID

Silicon Vertex Tracker
5 layers of double sided Si strips
Tracking + Vertexing

The BABAR Dataset



Total Integrated Luminosity = 531/fb in 8 years operation



~700M of $c\bar{c}$ events

Process	Cross-section (nb)
$e^+e^- \to b\bar{b}$	1.099
$e^+e^- \to c\bar{c}$	1.30
$e^+e^- \to s\bar{s}$	0.35
$e^+e^- \to u\bar{u}$	1.39
$e^+e^- \to d\bar{d}$	0.35
$e^+e^- \to e^+e^-$	~53
$e^+e^- \to \mu^+\mu^-$	1.16
$e^+e^- \to \tau^+\tau^-$	0.94

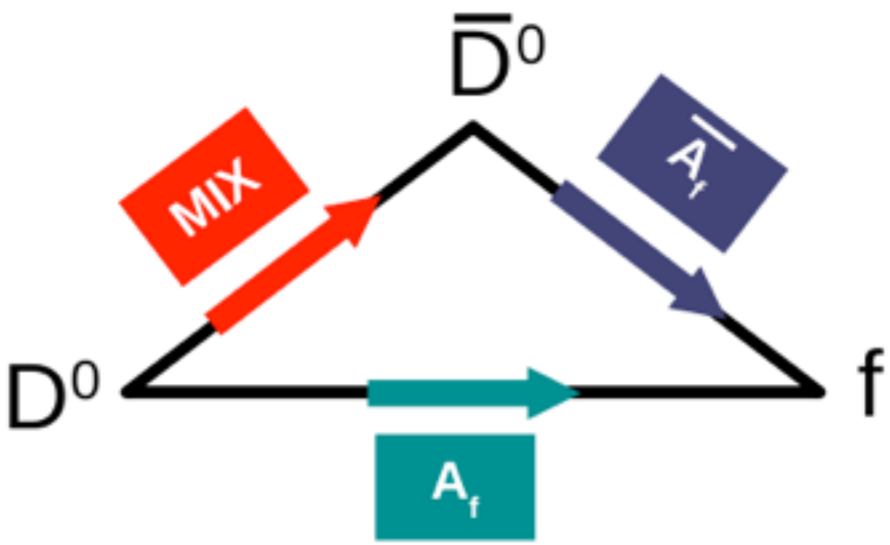
Time-Dependent Amplitude Analysis of the Decay $D^0 \to \pi^+\pi^-\pi^0$

- allows to *directly* extract the mixing parameters
- first measurement with a time-dependent amplitude analysis of the SCS decay $D^0 \to \pi^+\pi^-\pi^0$
- e-Print: arXive:1604.00857
- submitted to PRD

Direct Measurement of the Mixing Parameters

- The golden channel to *directly* access the mixing parameters is $D^0 \rightarrow K_S\pi^+\pi^-$
- The $D^0\rightarrow\pi^+\pi^-\pi^0$ has a lower BR (~1/3) and it is less clean from the experimental point of view, but it has the same properties that allows to directly access to x and y:

the relative strong phase between A_f and $\overline{A}_f$ is not accessible and would redefine x and y by a rotation



$f = D^0\rightarrow\pi^+\pi^-\pi^0$

- neglecting CPV, $|f\rangle$ and the CP-Conjugate $|\overline{f}\rangle$ are the same state, provided the momentum of the π^+ is exchanged with the momentum of the π^-, and changes direction :

$$\mathbf{CP}|\pi^+(\vec{p}_1)\,\pi^-(\vec{p}_2)\pi^0(\vec{p}_3)\rangle = |\pi^-(-\vec{p}_1)\,\pi^+(-\vec{p}_2)\pi^0(-\vec{p}_3)\rangle$$

- consequently both D^0 and $\overline{D}^0$ decays belong to the same Dalitz Plot and can be described by the same amplitude:

$$\overline{A}_f(s_-, s_+) = A_f(s_+, s_-) \qquad \text{where } s_\pm = m^2(\pi^\pm,\pi^0)$$

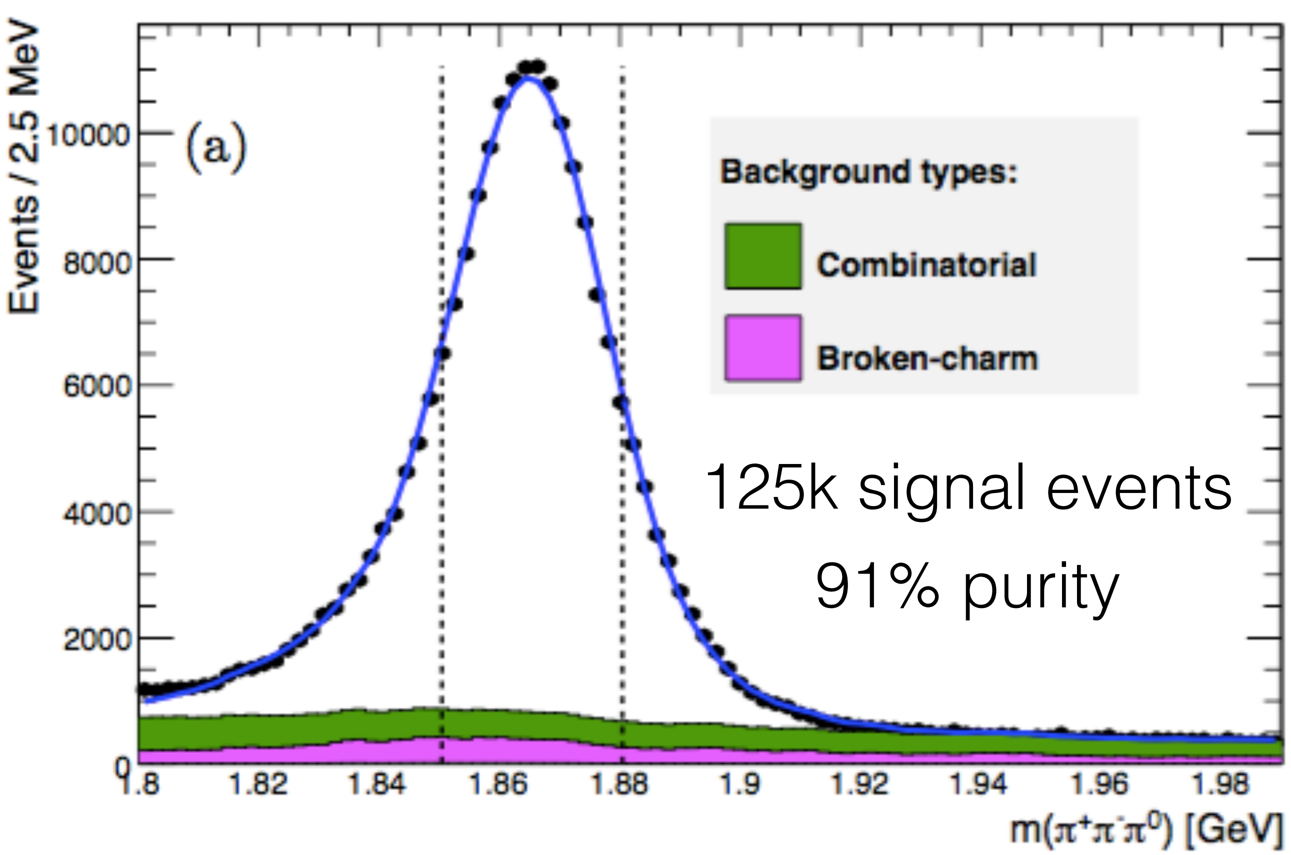
- the knowledge of the relative strong phase between A_f and $\overline{A}_f$ is not needed anymore

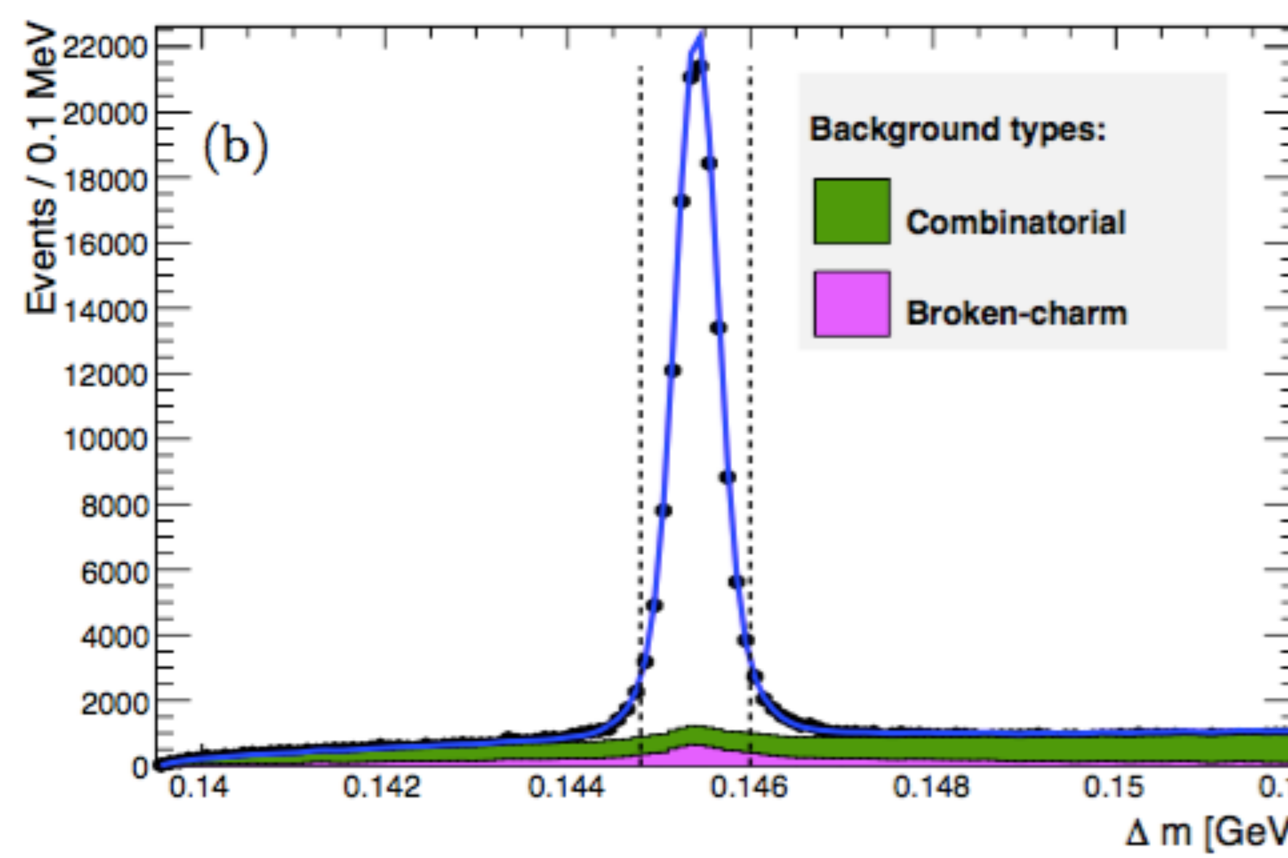
Yields Extraction

$D^0 \to \pi^+\pi^-\pi^0$

- dataset: 474/fb on+off Y(4S) resonance
- assumes CP is conserved
- D^0 are selected from $D^{*+} \to D^0\pi_s^+$ decays
- yields are extracted from a 2-D fit in the (m_D, Δm) plane

$m_D = m(\pi^+\pi^-\pi^0)$
$\Delta m = m(\pi_s^+\pi^+\pi^-\pi^0) - m(\pi^+\pi^-\pi^0)$





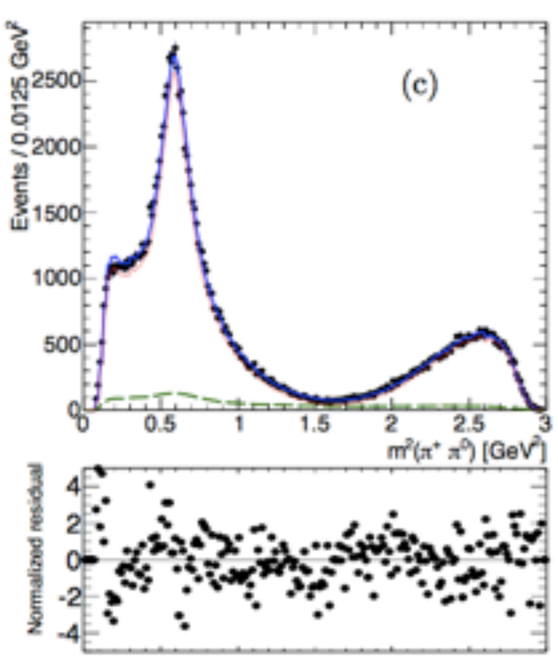
Dalitz Plot Amplitudes

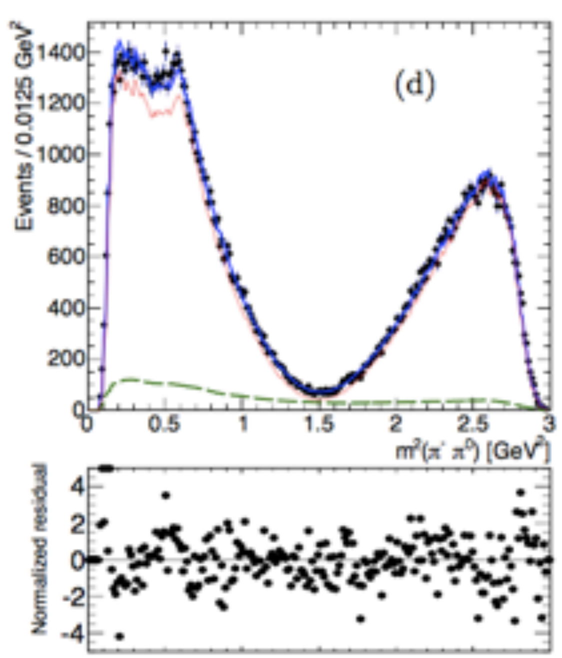
- D^0 and $\bar{D}^0$ decays can be described with one single Dalitz Plot
- the total amplitude can be described as a function of DP position as a coherent sum of partial waves W_k

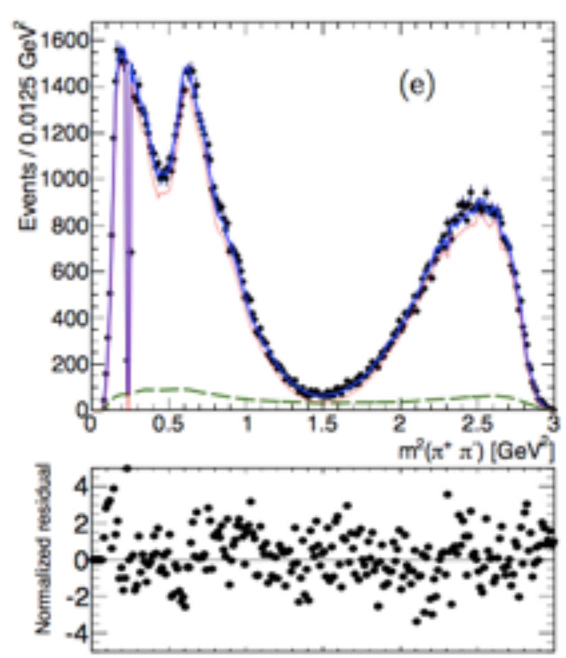
$$\overline{A}_f(s_-, s_+) = A_f(s_+, s_-) = \sum_k c_k \mathcal{W}_k(s_+, s_-)$$

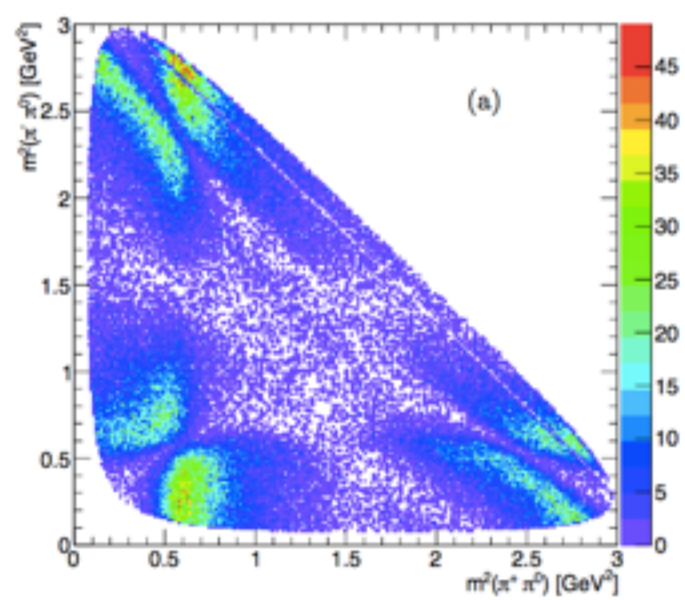
- magnitude, phase and fraction of each resonance are extracted from the time-dependent fit
    - the values of x and y are *blinded* at this stage

	Fit to data results		
State	Magnitude	Phase (°)	Fraction f_r (%)
$\rho(770)^+$	1	0	66.4±0.5
$\rho(770)^0$	0.55±0.00	16.1±0.4	23.9±0.3
$\rho(770)^-$	0.73±0.01	−1.6±0.5	35.6±0.4
$\rho(1450)^+$	0.55±0.07	−7.7±8.2	1.1±0.3
$\rho(1450)^0$	0.19±0.07	−70.4±15.9	0.1±0.1
$\rho(1450)^-$	0.53±0.06	8.2±6.7	1.0±0.2
$\rho(1700)^+$	0.91±0.15	−23.3±10.3	1.5±0.5
$\rho(1700)^0$	0.60±0.13	−56.3±16.0	0.7±0.3
$\rho(1700)^-$	0.98±0.17	78.9±8.5	1.7±0.6
$f_0(980)$	0.06±0.00	−58.8±2.9	0.3±0.0
$f_0(1370)$	0.20±0.03	−19.6±9.5	0.3±0.1
$f_0(1500)$	0.18±0.02	7.4±7.4	0.3±0.1
$f_0(1710)$	0.40±0.08	42.9±8.8	0.3±0.1
$f_2(1270)$	0.25±0.01	8.8±2.6	0.9±0.0
$f_0(500)$	0.26±0.01	−4.1±3.7	0.9±0.1
NR	0.43±0.07	−22.1±11.7	0.4±0.1









Mixing Fit & Results

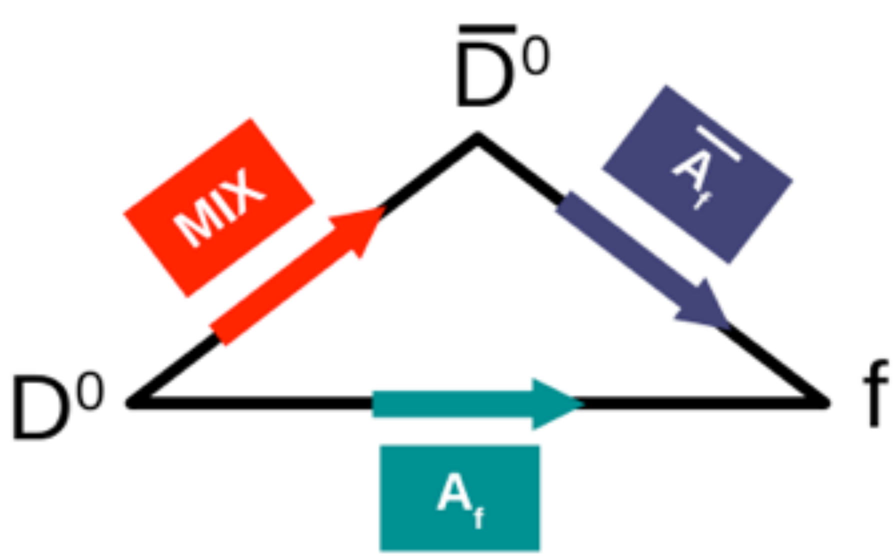
- Mixing modifies the pure exponential time-dependence to:

$$
\begin{aligned}
|\mathcal{M}(D^0)|^2 \propto \frac{1}{2}e^{-\Gamma_D t}\Big\{ & |A_f|^2 \left[\cosh(y\Gamma_D t) + \cos(x\Gamma_D t)\right] \\
& + \left|\frac{q}{p}\overline{A}_f\right|^2 \left[\cosh(y\Gamma_D t) - \cos(x\Gamma_D t)\right] \\
& - 2\Big[\mathrm{Re}\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sinh(y\Gamma_D t) \\
& - \mathrm{Im}\left(\frac{q}{p}A_f^*\overline{A}_f\right)\sin(x\Gamma_D t)\Big]\Big\}
\end{aligned}
$$

DIRECT DECAY

MIXING AND DECAY

INTERFERENCE



- a time dependent fit of the DP distribution allows to extract:

$x = (1.5 \pm 1.2 \pm 0.6)\%$

$y = (0.2 \pm 0.9 \pm 0.5)\%$

$\tau_D = (410.2 \pm 3.8)$ fs

Conclusions

- ***BaBar*** continues to produce charm mixing and CPV measurement
  - stay tuned for the $D^+ \to \pi^+\pi^0$ CP asymmetry
- The *first* measurement of D^0 mixing parameters from a time dependent analysis of $D^0 \to \pi^+\pi^-\pi^0$ was presented
  - GooFit: a (public) GPU friendly fitting framework

R. Andreassen et al., IEEE Access 2, 160 (2014)
http://github.com/GooFit/GooFit

- Next generation experiments will improve this measurement currently limited by the statistical error

backup slides

Systematics

Source	x [%]	y [%]
"Lucky" false slow pion fraction	0.01	0.01
Time resolution dependence on reconstructed D^0 mass	0.03	0.02
Amplitude-model variations	0.31	0.12
Resonance radius	0.02	0.10
DP efficiency parametrization	0.03	0.03
DP normalization granularity	0.03	0.04
Background DP distribution	0.21	0.11
Decay time window	0.18	0.19
σ_t cutoff	0.01	0.01
Number of σ_t ranges	0.11	0.26
σ_t parametrization	0.05	0.03
Background-model MC time distribution parameters	0.06	0.11
Fit bias correction	0.29	0.02
SVT misalignment	0.20	0.23
Total	0.56	0.46

Heavy Flavour Averaging Group Summary Tables

Parameter	No CPV	No direct CPV in DCS decays	CPV-allowed	95% CL Interval
x (%)	$0.49\,^{+0.14}_{-0.15}$	$0.44\,^{+0.14}_{-0.15}$	0.37 ± 0.16	[0.06, 0.67]
y (%)	0.61 ± 0.08	0.60 ± 0.07	$0.66\,^{+0.07}_{-0.10}$	[0.46, 0.79]
$\delta_{K\pi}$ (°)	$6.9\,^{+9.7}_{-11.2}$	$3.6\,^{+10.4}_{-12.1}$	$11.8\,^{+9.5}_{-14.7}$	[−21.1, 29.3]
R_D (%)	0.349 ± 0.004	0.348 ± 0.004	0.349 ± 0.004	[0.342, 0.357]
A_D (%)	–	–	$-0.39\,^{+1.01}_{-1.05}$	[−2.4, 1.5]
$\lvert q/p \rvert$	–	1.002 ± 0.014	$0.91\,^{+0.12}_{-0.08}$	[0.77, 1.14]
ϕ (°)	–	-0.07 ± 0.6	$-9.4\,^{+11.9}_{-9.8}$	[−28.3, 12.9]
$\delta_{K\pi\pi}$ (°)	$18.1\,^{+23.3}_{-23.8}$	$20.3\,^{+24.0}_{-24.3}$	$27.3\,^{+24.4}_{-25.4}$	[−23.3, 74.8]
A_π	–	0.10 ± 0.14	0.10 ± 0.15	[−0.19, 0.38]
A_K	–	-0.14 ± 0.13	-0.15 ± 0.14	[−0.42, 0.12]
x_{12} (%)	–	$0.44\,^{+0.14}_{-0.15}$		[0.13, 0.69]
y_{12} (%)	–	0.60 ± 0.07		[0.45, 0.74]
ϕ_{12}(°)	–	0.2 ± 1.7		[−4.1, 4.6]