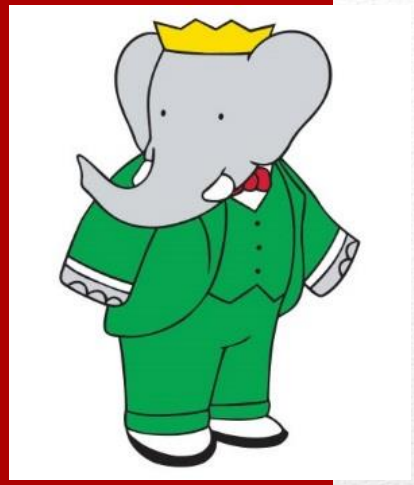
Recent *BABAR* results on mixing in the charm sector



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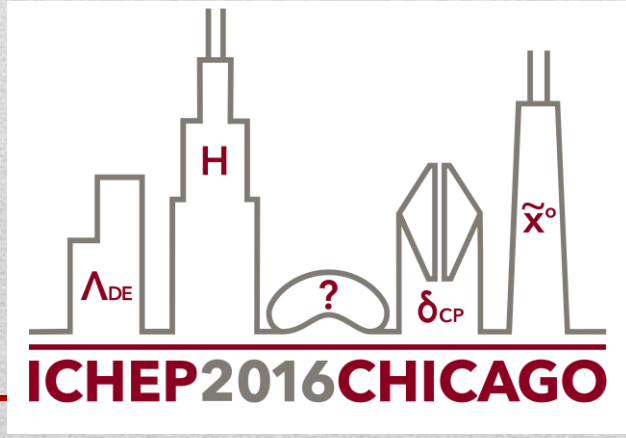
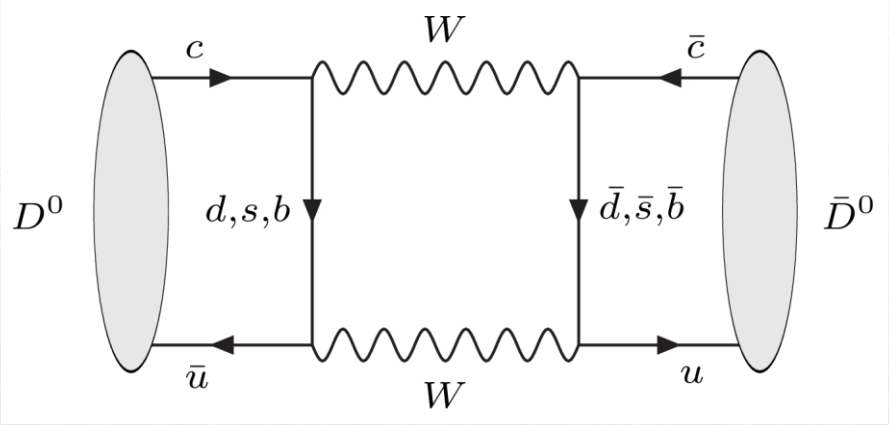
on behalf of the BABAR Collaboration

Jefferson Lab

ICHEP 2016
Chicago – August 4th, 2014



Mixing in the charm sector



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

$$x = \frac{m_1 - m_2}{\Gamma_D}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}$$

Mixing and CPV parameters for charm are small in the SM

$x, y \sim \lambda_C^2 \times SU(3)$ breaking $\sim O(10^{-3})$

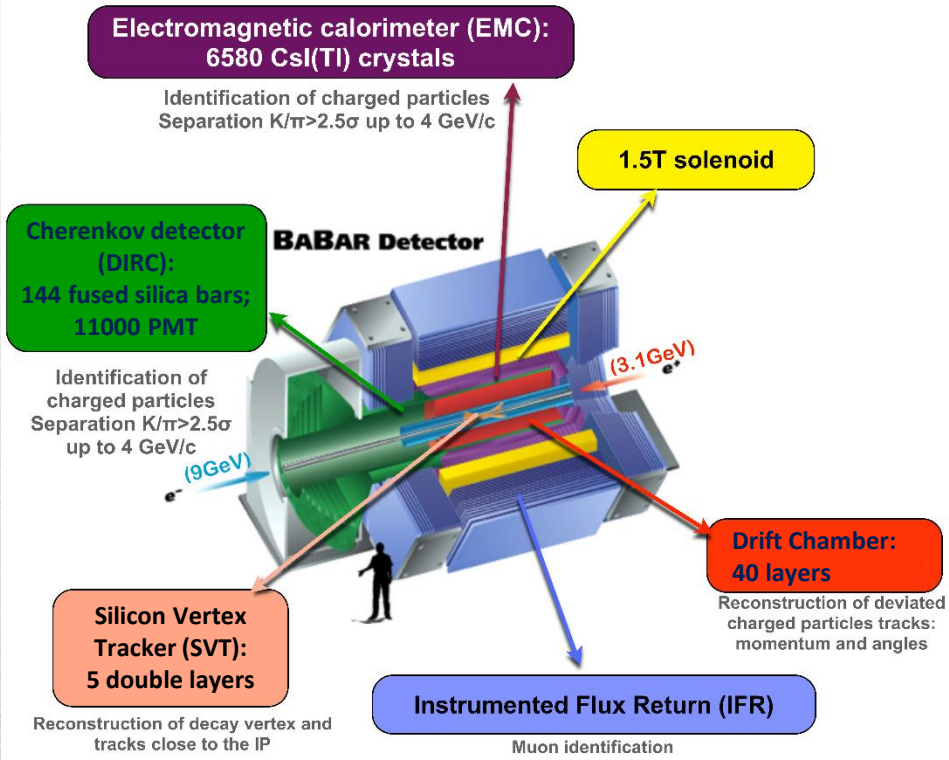
We present the first measurement of mixing parameters in the singly Cabibbo-suppressed channel $D^0 \to \pi^+\pi^-\pi^0$ (no CPV), PRD 93, 112014 (2016)

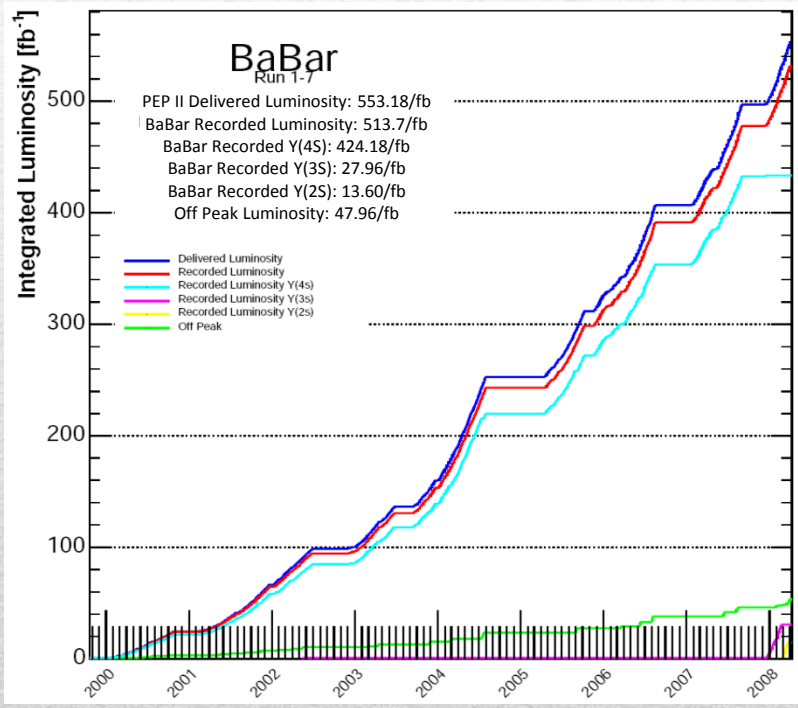
$$|\mathcal{M}(D^0)|^2 \propto \frac{1}{2}e^{-\Gamma_D t}\left\{ |A_f|^2 \left[\cosh(y\Gamma_D t) + \cos(x\Gamma_D t)\right] + \left|\frac{q}{p}\bar{A}_f\right|^2 \left[\cosh(y\Gamma_D t) - \cos(x\Gamma_D t)\right] \right.$$
$$\left. - 2\left[\mathrm{Re}\left(\frac{q}{p}A_f^*\bar{A}_f\right)\sinh(y\Gamma_D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

The *BABAR* experiment

The *BABAR* detector was located at the interaction point of PEP II at SLAC

Asymmetric e^+e^- collider, mostly at $\sqrt{s} \sim 10.58$ GeV



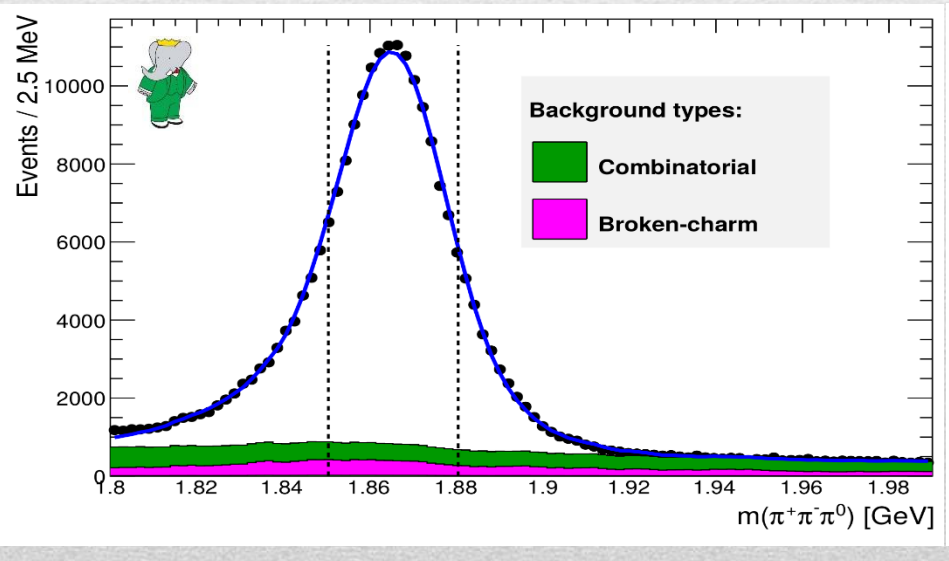


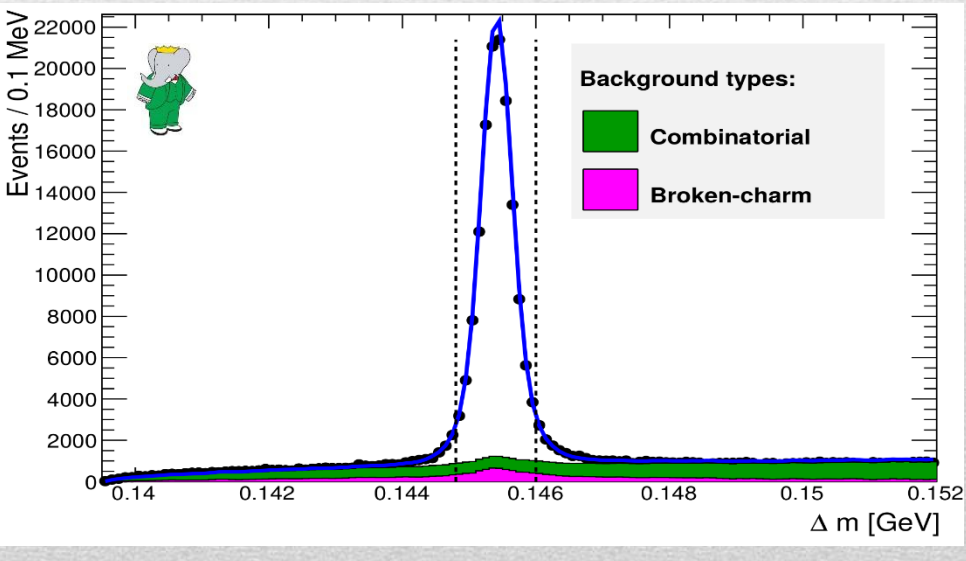
$\int L\,dt \sim 514\ \text{fb}^{-1}$ close to the $\Upsilon(4S), \Upsilon(2S), \Upsilon(3S)$ peaks, $670 \times 10^6\ c\bar{c}$ pairs

Event selection

- Reconstructed $D^{*+} \to \pi_s^+ D^0$ to select flavor (π_s^+ = soft pion)
- Vetoes on $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K_S\,\pi^+\pi^0$, $D^0 \to K_S\,\pi^0$
- $E_{\rm lab}(\pi^0) > 350$ MeV
- $p_{\rm cms}(D^0) > 2.8$ GeV to remove $B \to D$ events
- $-2 < t(D^0) < 3$ ps, $\sigma_t < 0.8$ ps
- $P(\chi^2) > 0.1\%$ for the D^* candidates
- $|m(D^0) - m_{\rm PDG}| < 15$ MeV, $|\Delta m - \Delta m_{\rm PDG}| < 600$ keV

138k events, 91% purity



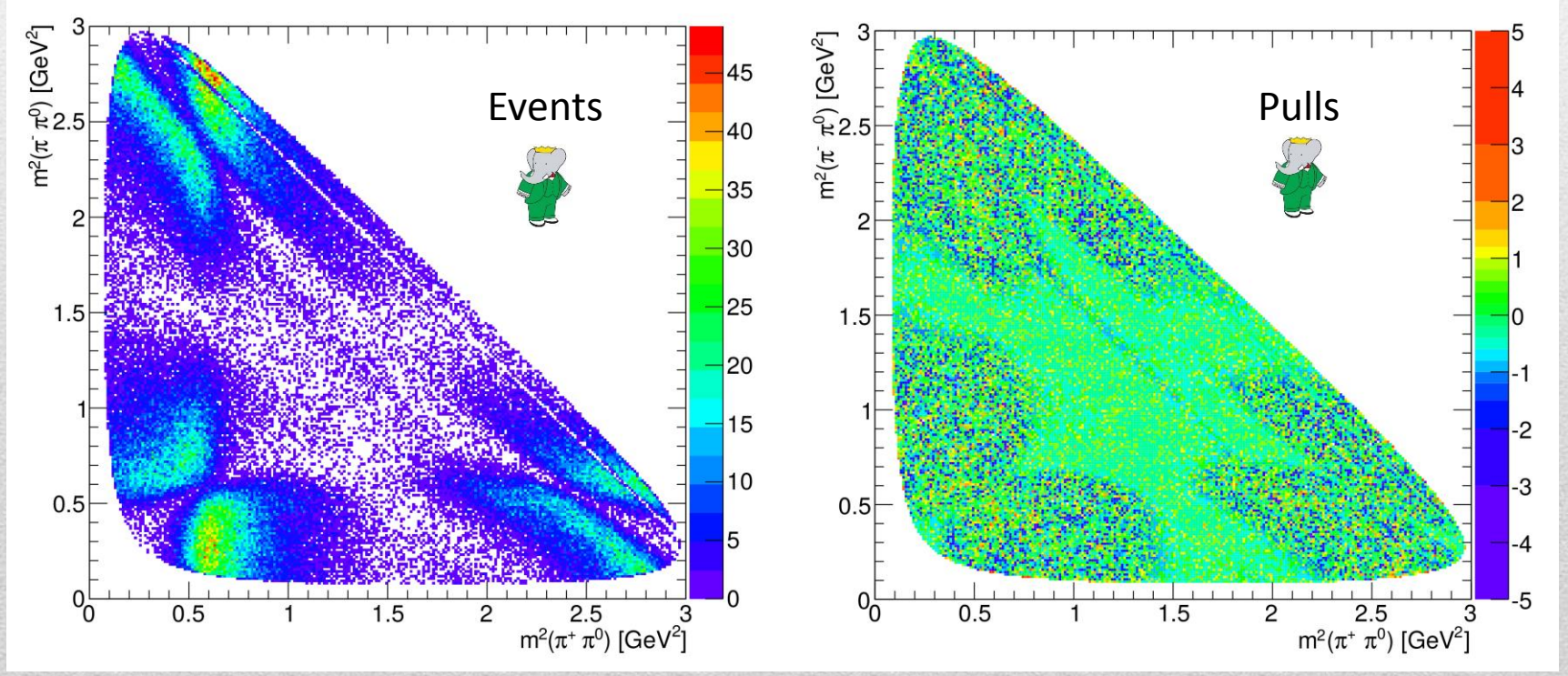


Time-Integrated Dalitz plot/1

An unbinned maximum-likelihood fit is performed to extract the parameters using **`GooFit`**

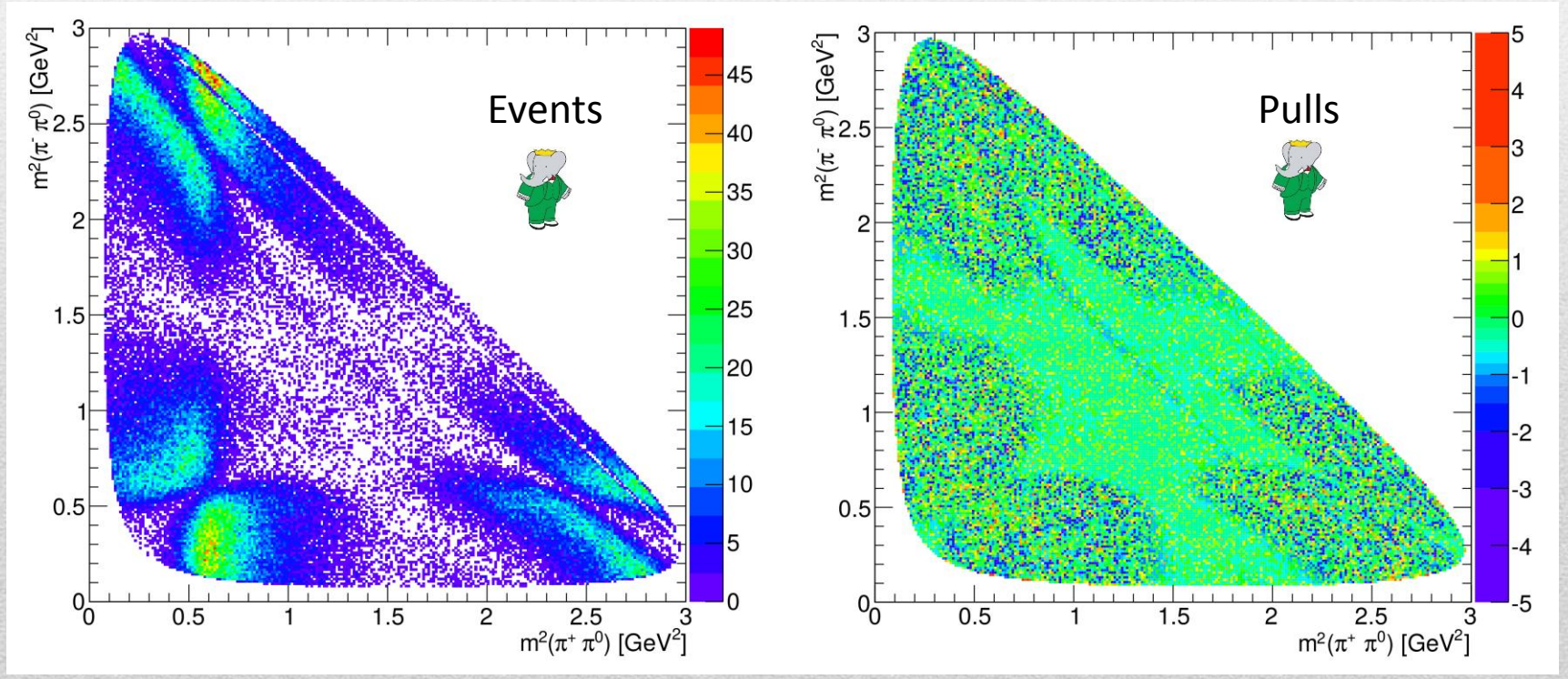
R. Andreassen *et al.*, IEEE Access 2, 160 (2014)

- **Signal:** Dalitz Plot (DP) distribution given by isobar model (coherent sum of Breit-Wigners); decay time distribution given by an exponential convolved with resolution (3 gaussians $\propto \sigma_t$). σ_t modeled separately in 6 regions of the Dalitz plot.



Time-Integrated Dalitz plot/2

- **Wrong π_s^+ bkg:** ($< 1\%$) same DP and decay time distributions as the signal, $\sim 50\%$ gives right flavor assignment (lucky pion)
- **Broken charm bkg:** misreconstructed D^0 (but peaks in Δm). DP distribution from MC, decay time distributions given by two exponentials convolved with gaussians.
- **Combinatorial bkg:** DP distribution from sidebands, decay time distributions given by two exponentials convolved with gaussians. σ_t modeled separately in 6 regions of decay time.



Time-Integrated Dalitz plot/3

$$A(s_+, s_-) = \sum_i c_i \frac{T(s)}{M_r - s - i\, M_r\, \Gamma(s)} F(s)$$

T is a tensor structure depending on spin

$$\Gamma(s) = \Gamma \left(\frac{q(s)}{q(M_r)}\right)^{2l+1} \left(\frac{M_r}{\sqrt{s}}\right) F^2$$

F is the Blatt-Weisskopf barrier factor

$$F_0 = 1, F_1 = \sqrt{\frac{1+R^2 q^2(M_r)}{1+R^2 q^2(s)}}, F_2 = \cdots$$

Masses and widths fixed to the PDG value

State	J^{PC}	Resonance parameters Mass (MeV)	Width (MeV)	Fit to data results Magnitude	Phase (°)	Fraction f_r (%)
$\rho(770)^+$	1^{--}	775.8	150.3	1	0	66.4±0.5
$\rho(770)^0$	1^{--}	775.8	150.3	0.55±0.01	16.1±0.4	23.9±0.3
$\rho(770)^-$	1^{--}	775.8	150.3	0.73±0.01	−1.6±0.5	35.6±0.4
$\rho(1450)^+$	1^{--}	1465	400	0.55±0.07	−7.7±8.2	1.1±0.3
$\rho(1450)^0$	1^{--}	1465	400	0.19±0.07	−70.4±15.9	0.1±0.1
$\rho(1450)^-$	1^{--}	1465	400	0.53±0.06	8.2±6.7	1.0±0.2
$\rho(1700)^+$	1^{--}	1720	250	0.91±0.15	−23.3±10.3	1.5±0.5
$\rho(1700)^0$	1^{--}	1720	250	0.60±0.13	−56.3±16.0	0.7±0.3
$\rho(1700)^-$	1^{--}	1720	250	0.98±0.17	78.9±8.5	1.7±0.6
$f_0(980)$	0^{++}	980	44	0.06±0.01	−58.8±2.9	0.3±0.1
$f_0(1370)$	0^{++}	1434	173	0.20±0.03	−19.6±9.5	0.3±0.1
$f_0(1500)$	0^{++}	1507	109	0.18±0.02	7.4±7.4	0.3±0.1
$f_0(1710)$	0^{++}	1714	140	0.40±0.08	42.9±8.8	0.3±0.1
$f_2(1270)$	2^{++}	1275.4	185.1	0.25±0.01	8.8±2.6	0.9±0.1
$f_0(500)$	0^{++}	500	400	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

To estimate systematics:

- We vary the radii R from 1.5 to 5 GeV^{-1}
- We remove a resonance from the fit, and if $\Delta\chi^2 < 100$, we estimate the variation in x, y
- We also allow the mass and width of $f_0(500)$ to float

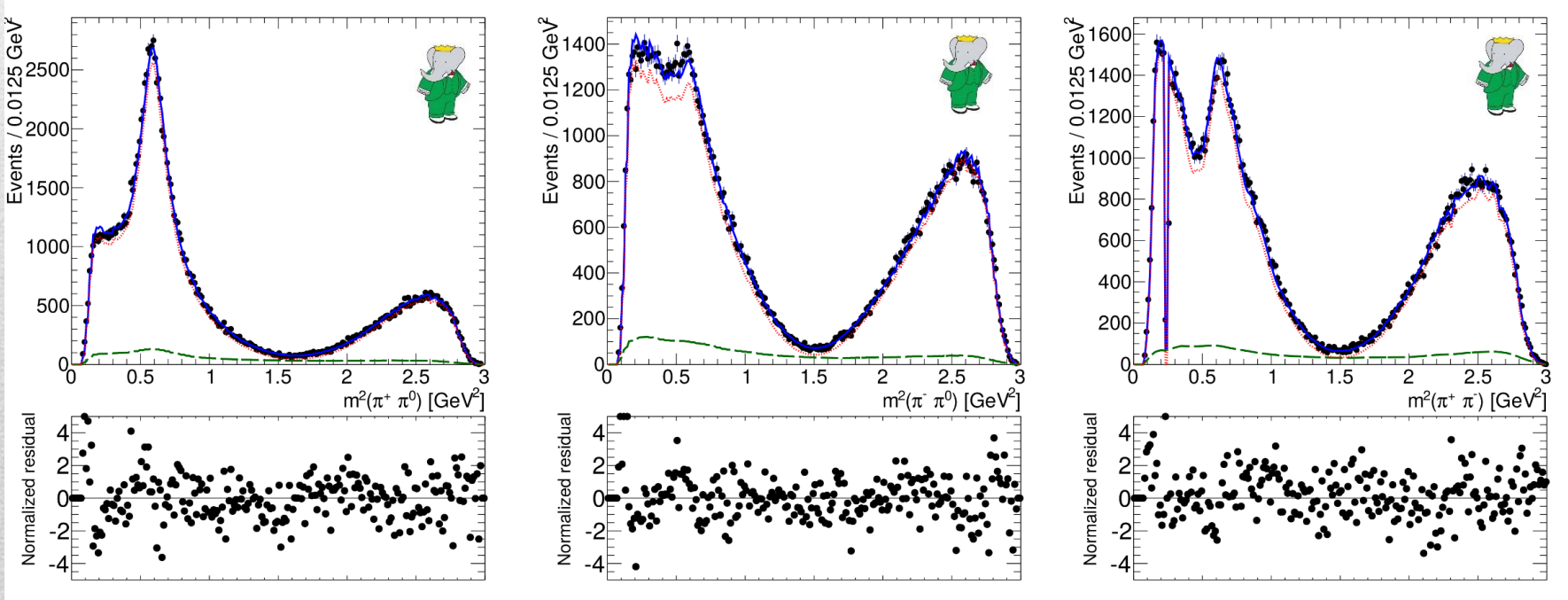
Time-Dependent fit results

Large pull values near low and high values of m^2 in all projections, similar effect in MC
Likely due to migration from the edge, due to misreconstruction + constrained fit

$$\tau_D = (410.2 \pm 3.8)\ \text{fs}$$
$$x_{\text{raw}} = (2.08 \pm 1.17)\%$$
$$y_{\text{raw}} = (0.14 \pm 0.89)\%$$

To estimate any possible bias, the same fit is performed to MC samples with given $x = \pm 1\%, y = \pm 1\%$

The mean bias is
$\Delta x = 0.58\%, \Delta y = -0.05\%$



Systematic uncertainties

Dominant sources of systematics are:

- Amplitude-model variations, estimated removing the least relevant resonances
- Combinatorial DP distribution, when the MC is used instead of data
- Different decay time windows, and number of σ_t ranges
- Fit bias correction, taken as half of the bias measured from MC
- Effect of SVT misalignment, estimated creating MC signal samples with deliberately-wrong alignment files

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

Summary

We present the first measurement of charm mixing in the singly Cabibbo-suppressed $D^0 \to \pi^+\pi^-\pi^0$ channel

PRD 93, 112014 (2016)

$$x = (1.5 \pm 1.2 \pm 0.6)\%$$
$$y = (0.2 \pm 0.9 \pm 0.5)\%$$

to compare with the HFAG average
(from $D^0 \to K^0_S\pi^+\pi^-$ and indirectly from other channels):

$$x = \left(0.49^{+0.14}_{-0.15}\right)\%$$
$$y = (0.61 \pm 0.08)\%$$

Thank you!

BACKUP

Definition of mixing and CPV parameters

$$R_M = \frac{1}{2}(x^2 + y^2)$$

$$2\,y_{CP} = \big(|q/p| + |p/q|\big)y\cos\phi - \big(|q/p| - |p/q|\big)x\sin\phi$$
$$2\,A_\Gamma = \big(|q/p| - |p/q|\big)y\cos\phi - \big(|q/p| + |p/q|\big)x\sin\phi$$

$$x_{K^0\pi\pi} = x$$
$$y_{K^0\pi\pi} = y$$
$$|q/p|_{K^0\pi\pi} = |q/p|$$
$$\mathrm{Arg}\,(q/p)_{K^0\pi\pi} = \phi$$

$$\begin{pmatrix} x'' \\ y'' \end{pmatrix}_{K^+\pi^-\pi^0} = \begin{pmatrix} \cos\delta_{K\pi\pi} & \sin\delta_{K\pi\pi} \\ -\sin\delta_{K\pi\pi} & \cos\delta_{K\pi\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x'\cos\phi \pm y'\sin\phi)$$

$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y'\cos\phi \mp x'\sin\phi)$$

$$\frac{\Gamma(D^0 \to K^+\pi^-) + \Gamma(\overline{D}{}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+) + \Gamma(\overline{D}{}^0 \to K^+\pi^-)} = R_D$$

$$\frac{\Gamma(D^0 \to K^+\pi^-) - \Gamma(\overline{D}{}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+) + \Gamma(\overline{D}{}^0 \to K^+\pi^-)} = A_D$$

$$\frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\overline{D}{}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\overline{D}{}^0 \to K^+K^-)} = A_K + \frac{\langle t \rangle}{\tau_D}\mathcal{A}_{CP}^{\mathrm{indirect}}$$

$$\frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}{}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}{}^0 \to \pi^+\pi^-)} = A_\pi + \frac{\langle t \rangle}{\tau_D}\mathcal{A}_{CP}^{\mathrm{indirect}}$$

$$2\mathcal{A}_{CP}^{\mathrm{indirect}} = \big(|q/p| + |p/q|\big)x\sin\phi - \big(|q/p| - |p/q|\big)y\cos\phi$$

If no CPV is allowed,

$y_{CP} = y, \phi = A_* = 0, |q/p| = 1$

Measurements of x and y

The combination $R_M = \frac{1}{2}(x^2 + y^2)$ can be measured in semileptonic decays

BaBar, PRD 76, 14018
Belle, PRD77, 112003

If no CPV is allowed, y can be meaured in $D^0 \to K^+K^-, \pi^+\pi^-, K^+K^-K_S^0$ decays

BaBar, PRD 87, 120004
Belle, arXiv:1212.3478
LHCb, JHEP 1204, 129

x and y can be independenlty measured:

- In coherent production, $\psi(3770) \to D^0\overline{D^0}$, CLEO-c, PRD 86, 112001
- In self-conjugate final states, $D^0 \to K_S^0\pi^+\pi^-$, Belle, PRD 89, 91103; BaBar, PRL 105, 81803

The Cabibbo-favored mode has more statistics and give much more precise measurements wrt the singly-Cabibbo suppressed $D^0 \to \pi^+\pi^-\pi^0$
Nevertheless, the latter can get larger contributions from New Physics, and deserve an independent measurement