Experimental Study of 3-body Cabibbo-suppressed D^0 Decays & Extraction of CP Violation Parameters

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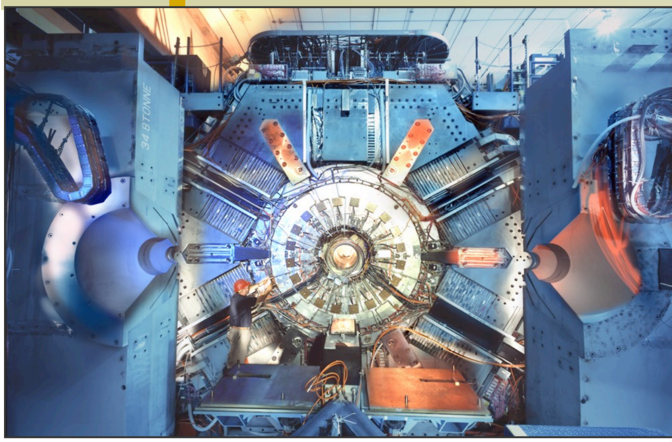
BaBar Collaboration

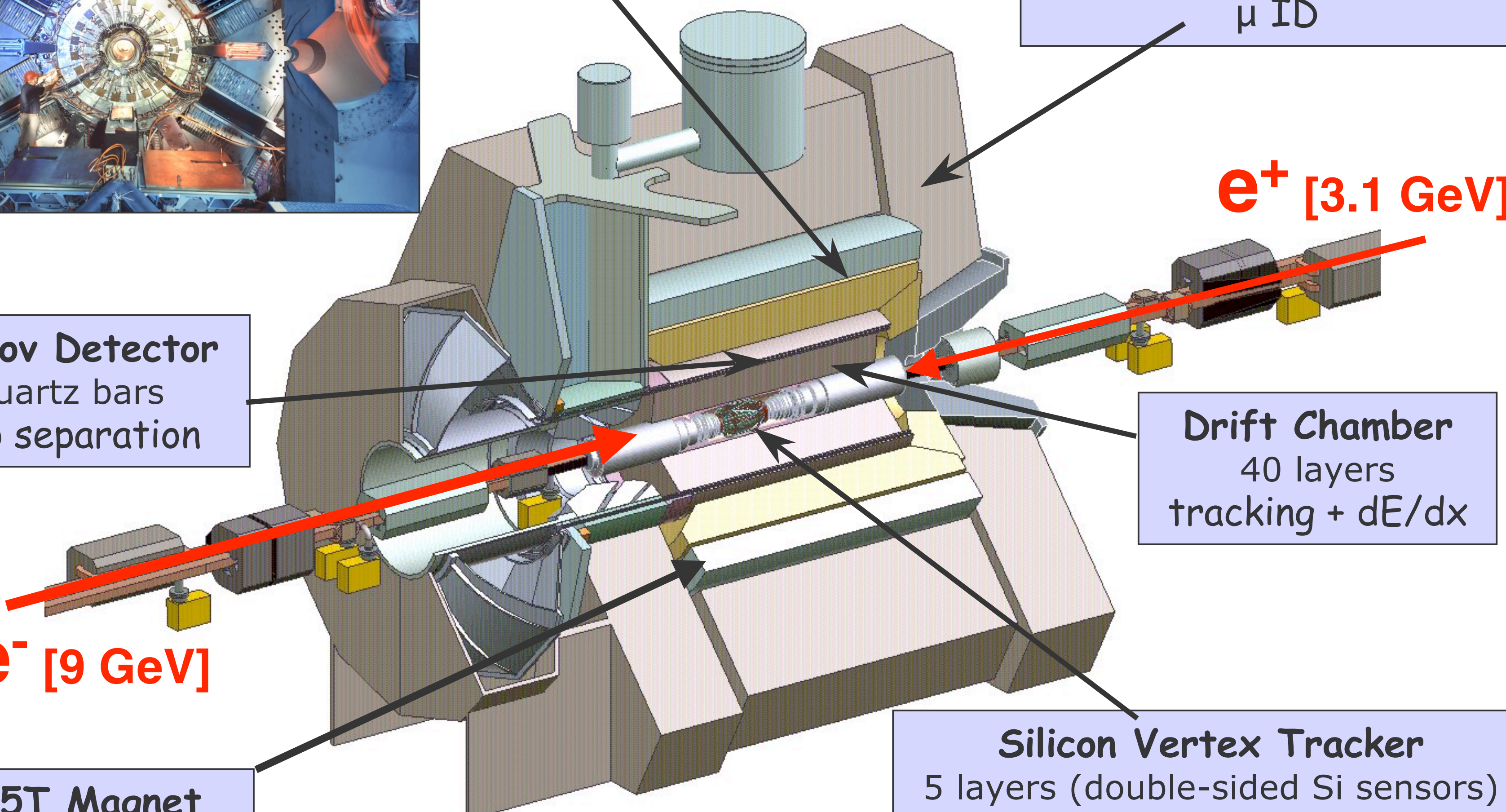
- Branching Ratios: $D^0 \rightarrow \pi^-\pi^+\pi^0$, $K^-K^+\pi^0$ — **Phys. Rev. D 74, 091102 (R) (2006)**
- Dalitz plot analysis: $D^0 \rightarrow K^-K^+\pi^0$ — **Phys. Rev. D 76, 011102 (R) (2007)**
- DP of $D^0 \rightarrow \pi^-\pi^+\pi^0$ & measurement of γ using the decay $B^\pm \rightarrow D_{\pi^-\pi^+\pi^0} K^\pm$ — **Phys. Rev. Lett. 99, 251801 (2007)**
- Search for CP violation at the 1% level in $D^0 \rightarrow \pi^-\pi^+\pi^0$, $K^-K^+\pi^0$ — **Preliminary**

Also, for angular moments analysis of the above Dalitz plots:

arXiv:0711.1544 (2007) (HADRON-07 proceedings)

BaBar: B and charm Factory

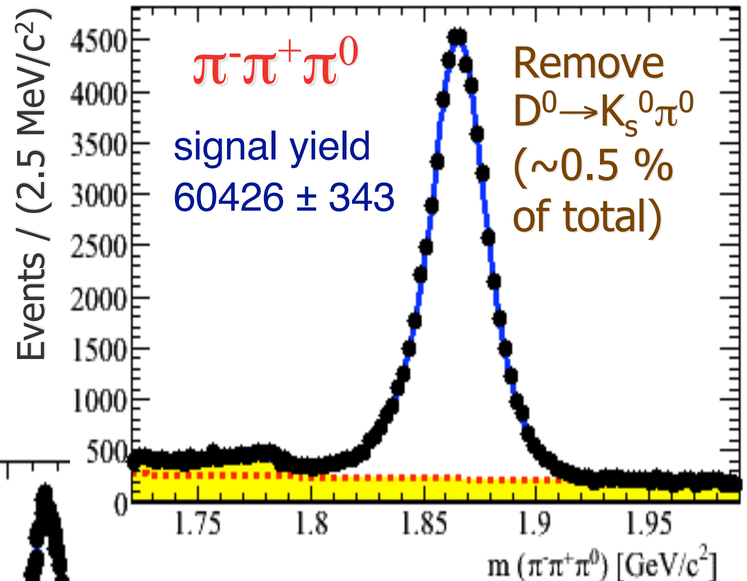


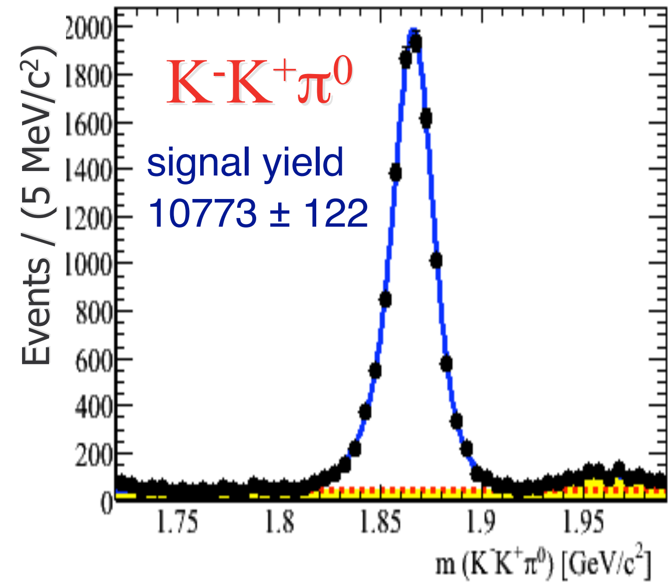


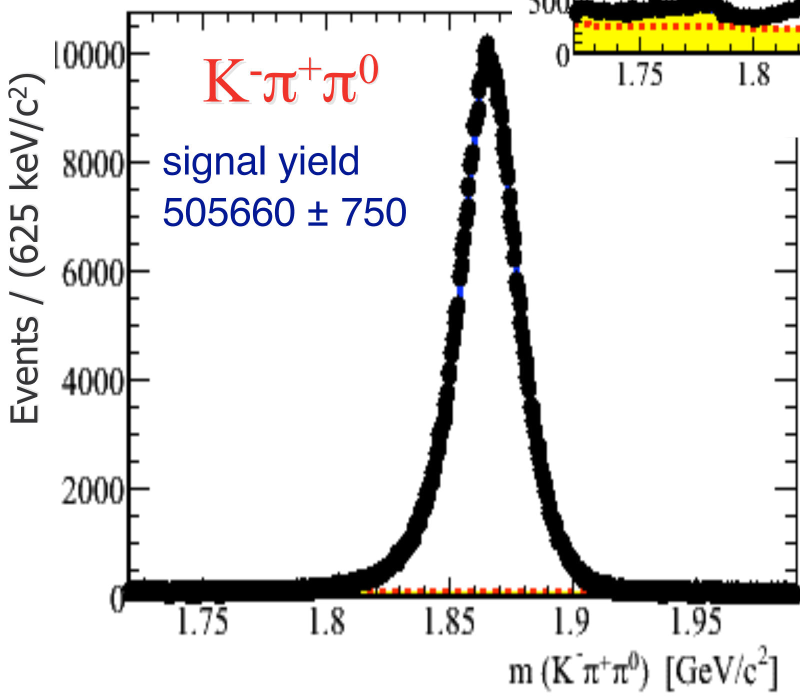
Precise BR Measurement of $D^0 \to \pi^-\pi^+\pi^0$, $K^-K^+\pi^0$

Data = 232 fb^{-1}

Use the CF decay $D^0 \to K^-\pi^+\pi^0$ as reference.



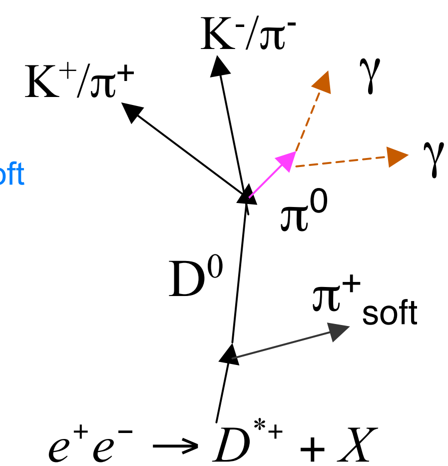




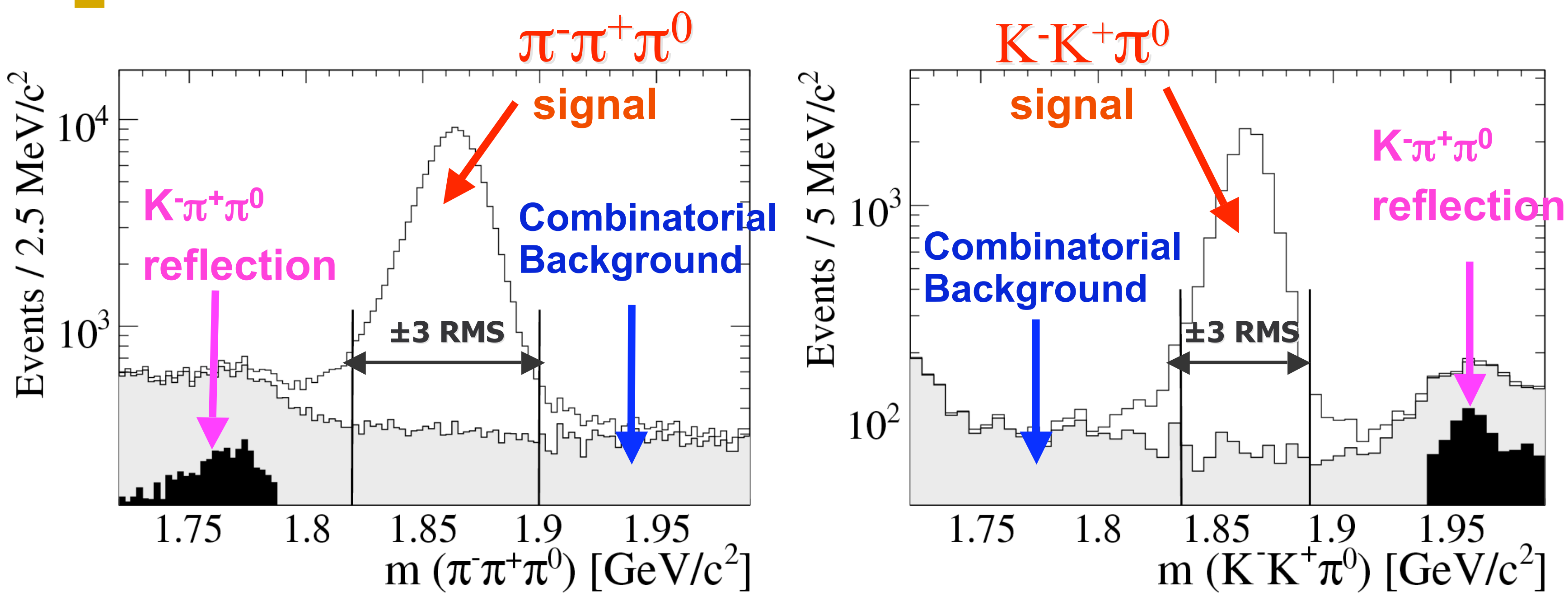
D^0 decay reconstruction

The charge of the π_{soft} determines D^0 or $\overline{D}^0$.

- P_{CM} (D^0) > 2.77 GeV/c
- $|m_{D*} - m_{D0} - 145.5| <$ 0.6 MeV/c^2



Background Events in Simulation



Note Log y-scale.

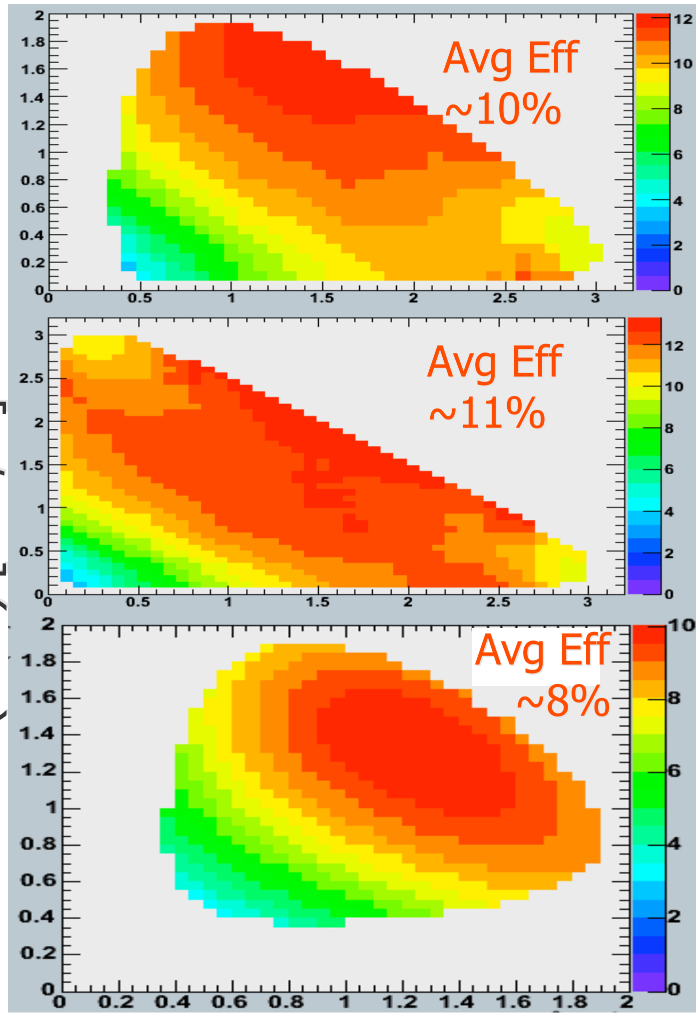
- $K^- \pi^+\pi^0$ reflection events peak in the sidebands of $\pi^-\pi^+\pi^0$, $K^-K^+\pi^0$.
- We take the shape of the reflection events from simulation and their numbers from data.

Phys. Rev. D 74, 091102 (R) (2006)

Signal Reconstruction Efficiency

Reco. Efficiency (%) from simulation

Dalitz plot of events in data



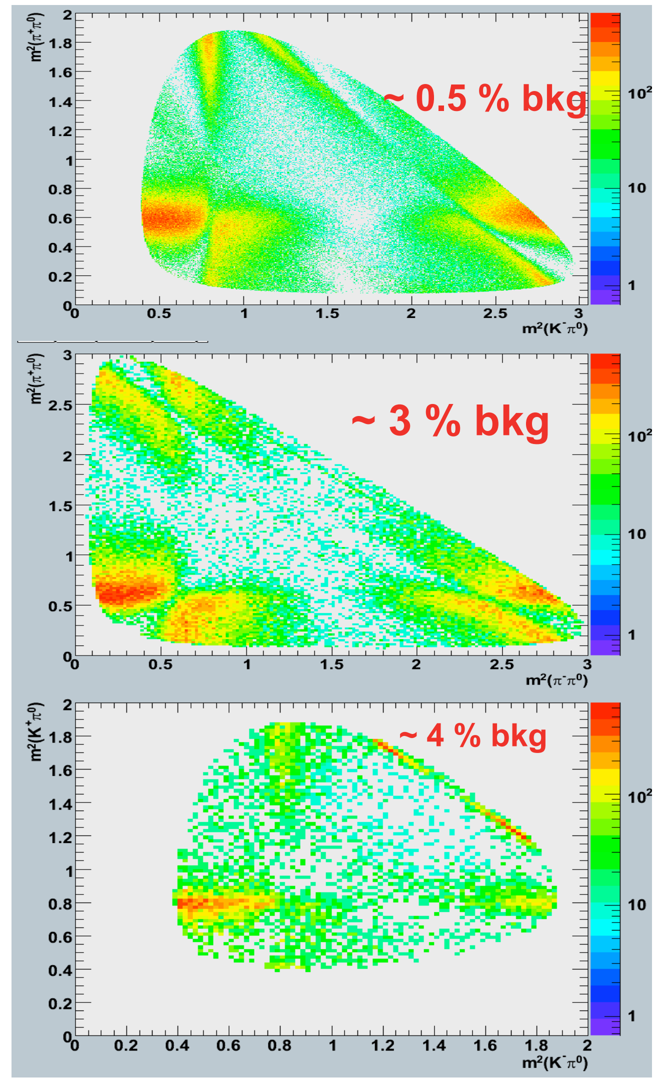
$K^-\pi^+\pi^0$

$\pi^-\pi^+\pi^0$

$K^-K^+\pi^0$

$m^2\ (h^+\pi^0)\ [GeV/c^2]^2$

$m^2(h^-\pi^0)\ \ [GeV/c^2]^2$



Results on B.R.

> 5σ difference with PDG-06. Excellent PID has greatly improved our sensitivity.

D^0 decay mode	Our Results(%)	PDG-2006 (%)
$B(\pi^-\pi^+\pi^0)/B(K^-\pi^+\pi^0)$	$10.59 \pm 0.06 \pm 0.13$	8.40 ± 3.11
$B(K^-K^+\pi^0)/B(K^-\pi^+\pi^0)$	$2.37 \pm 0.03 \pm 0.04$	0.95 ± 0.26

Decay rate $\Gamma = \langle |M|^2 \rangle . \Phi$

M = decay matrix element, Φ = phase space

= For 3-body decays: area of the Dalitz plot
For 2-body decays: momentum of either daughter in D^0 rest frame.

Using 2-body B.R. values from PDG:

$|M|^2(\pi^-\pi^+) / |M|^2(K^-\pi^+) = 0.034 \pm 0.001$
$|M|^2(K^-K^+) / |M|^2(K^-\pi^+) = 0.111 \pm 0.002$

$|M|^2(K^-K^+) / |M|^2(\pi^-\pi^+) = 3.53 \pm 0.12$

Very different from naïve expectations.

Using branching ratio values from above table:

$|M|^2(\pi^-\pi^+\pi^0) / |M|^2(K^-\pi^+\pi^0) = 0.0668 \pm 0.0004 \pm 0.0008$
$|M|^2(K^-K^+\pi^0) / |M|^2(K^-\pi^+\pi^0) = 0.0453 \pm 0.0006 \pm 0.0008$

Roughly consistent with naïve expectations, i.e., $\sin^2\theta_c = 0.05$

$|M|^2(K^-K^+\pi^0) / |M|^2(\pi^-\pi^+\pi^0) = 0.678 \pm 0.014 \pm 0.021$ (Naïve expectation = 1.0)

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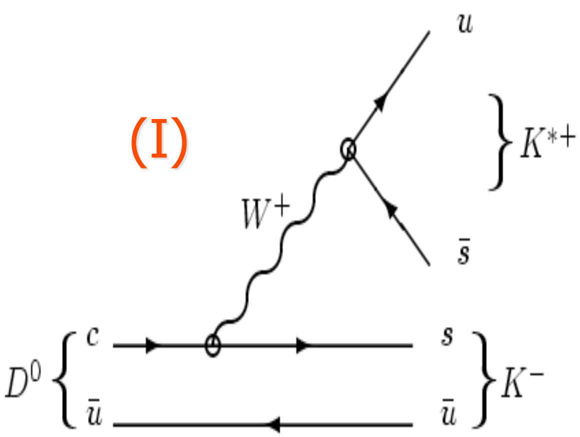
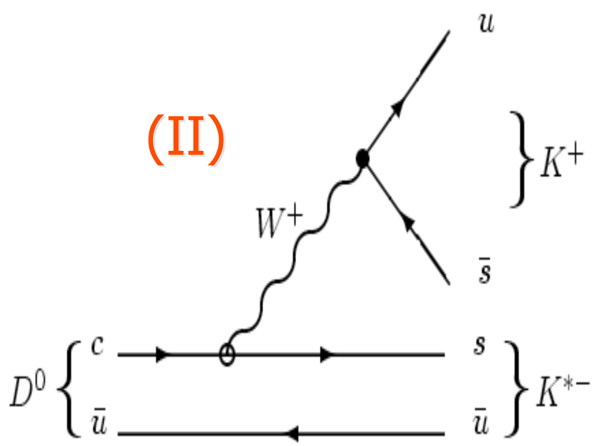
$D^0 \to K^- K^+ \pi^0$ Dalitz Plot Analysis

Interference among three types of singly Cabibbo-suppressed amplitudes

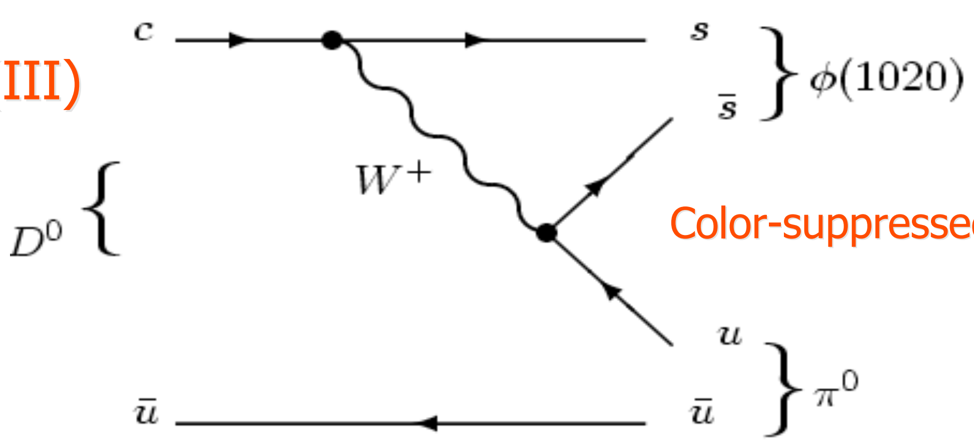
(I)



(II)



(III)

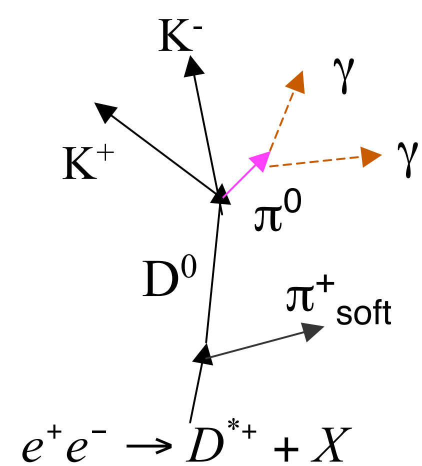


Color-suppressed

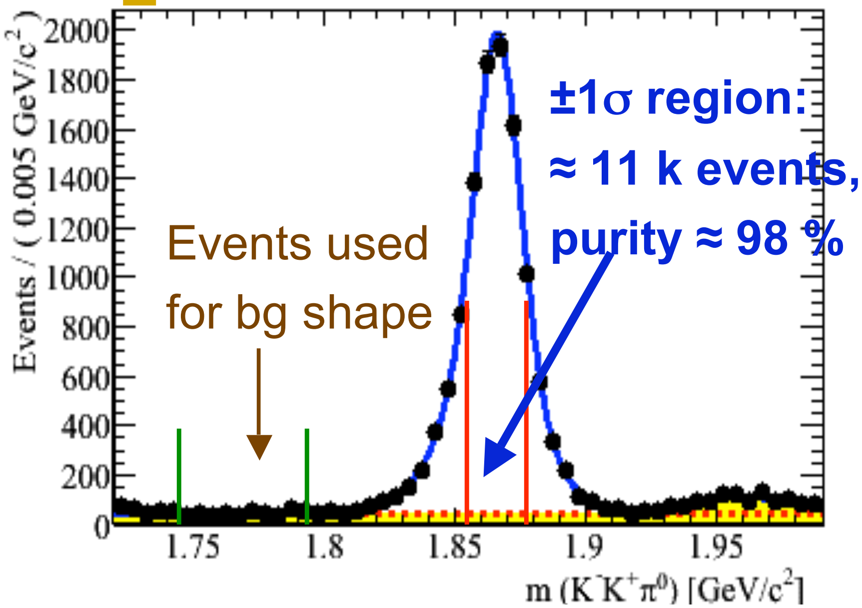
Motivation

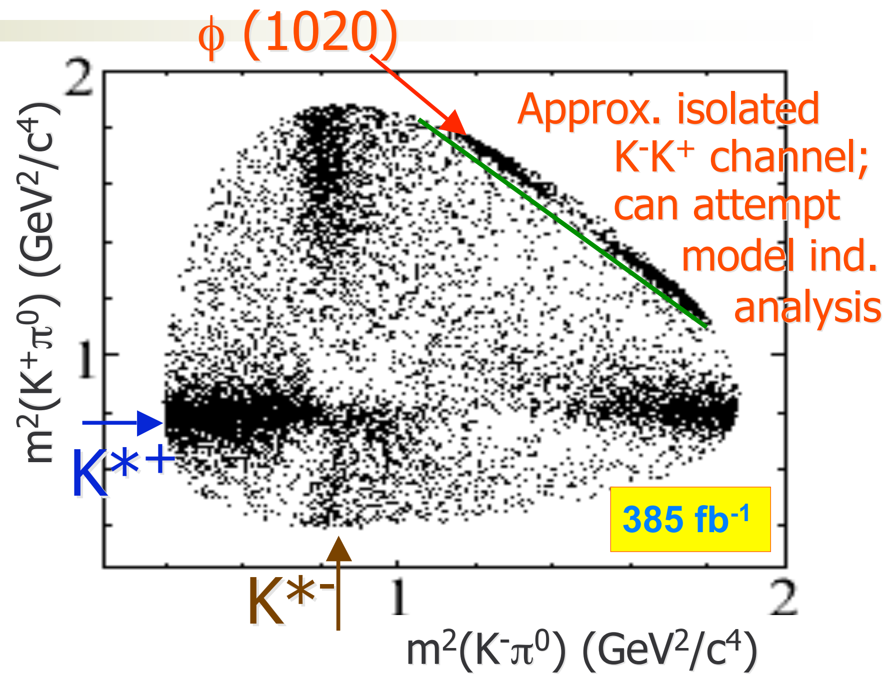
- Nature of $K\pi$ S-wave below 1.4 GeV.
- Is there a charged κ state?
- Nature of f_0/a_0 (980): $K\bar{K}$ S-wave.

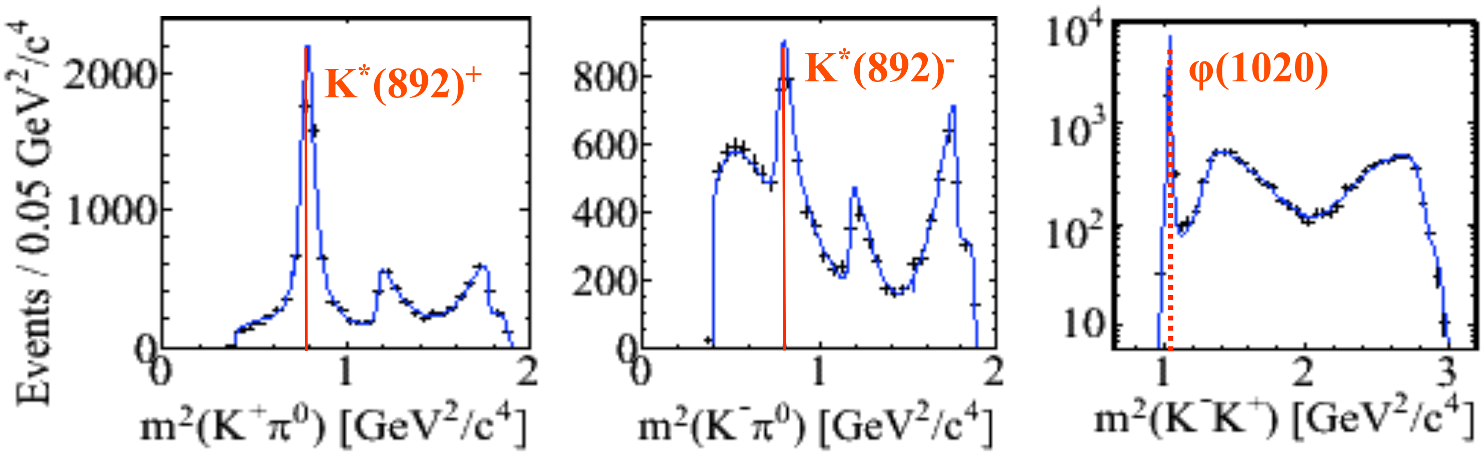
D^0 decay reconstruction



Dalitz Plot for $D^0 \to K^- K^+ \pi^0$







Use isobar model to fit the Dalitz plot

Fit Results for $D^0 \to K^- K^+ \pi^0$ Dalitz Plot

Strong-phase Difference & Amplitude Ratio

$$r_D e^{i\delta_D} = \frac{a_{D^0 \to K^{*-}K^+}}{a_{D^0 \to K^{*+}K^-}} e^{i(\delta_{K^{*-}K^+} - \delta_{K^{*+}K^-})}$$

K^{*+} : 45 %
K^{*-} : 16 %
ϕ : 19 %
f_0/a_0: 7-10%

BaBar	CLEO
r_D = 0.599 ± 0.013 (stat) ± 0.011 (syst)	0.52 ± 0.05 (stat) ± 0.04 (syst)
δ_D = -35.5° (stat) ± 1.9° ± 2.2° (syst)	-28° ± 8° (stat) ± 11°(syst)

Ambiguity between a large $K^+\pi^0$ S-wave & $K^*(1410)$, $f_2'(1525)$.

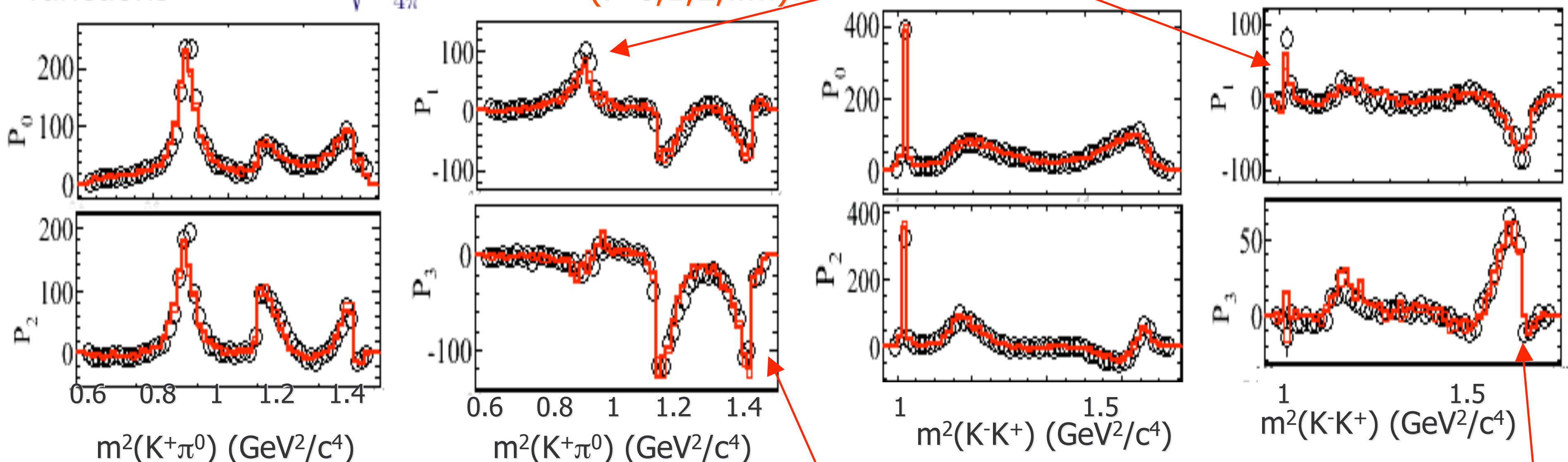
	Model-I (χ^2 Prob = 62 %)			Model-II (χ^2 Prob = 48 %)		
State	Amplitude, a_r	Phase, ϕ_r (°)	Fraction, f_r (%)	Amplitude, a_r	Phase, ϕ_r (°)	Fraction, f_r (%)
$K^*(892)^+$	1.0 (fixed)	0.0 (fixed)	45.2±0.8±0.6	1.0 (fixed)	0.0 (fixed)	44.4±0.8±0.6
$K^*(1410)^+$	2.29±0.37±0.20	86.7±12.0±9.6	3.7±1.1±1.1			
$K^+\pi^0(S)$	1.76±0.36±0.18	-179.8±21.3±12.3	16.3±3.4±2.1	3.66±0.11±0.09	-148.0±2.0±2.8	71.1±3.7±1.9
$\phi(1020)$	0.69±0.01±0.02	-20.7±13.6±9.3	19.3±0.6±0.4	0.70±0.01±0.02	18.0±3.7±3.6	19.4±0.6±0.5
$f_0(980)$	0.51±0.07±0.04	-177.5±13.7±8.6	6.7±1.4±1.2	0.64±0.04±0.03	-60.8±2.5±3.0	10.5±1.1±1.2
[$a_0(980)^0$]	[0.48±0.08±0.04]	[-154.0±14.1±8.6]	[6.0±1.8±1.2]	[0.68±0.06±0.03]	[-38.5±4.3±3.0]	[11.0±1.5±1.2]
$f_2'(1525)$	1.11±0.38±0.28	-18.7±19.3±13.6	0.08±0.04±0.05			
$K^*(892)^-$	0.601±0.011±0.011	-37.0±1.9±2.2	16.0±0.8±0.6	0.597±0.013±0.009	-34.1±1.9±2.2	15.9±0.7±0.6
$K^*(1410)^-$	2.63±0.51±0.47	-172.0±6.6±6.2	4.8±1.8±1.2			
$K^-\pi^0(S)$	0.70±0.27±0.24	133.2±22.5±25.2	2.7±1.4±0.8	0.85±0.09±0.11	108.4±7.8±8.9	3.9±0.9±1.0

Analysis of Angular Moments

Each event is weighted by the spherical harmonic functions $Y_l^0(\cos\theta_H) = \sqrt{\frac{2l+1}{4\pi}} P_l(\cos\theta_H)$ (l=0,1,2,…..).

Excellent agreement between data & models.

Large interference between S and P waves.



Higher moments above 1.1 GeV are coming from cross channels.

$$\begin{cases} \sqrt{4\pi}\left\langle Y_0^0 \right\rangle = S^2 + P^2 \\ \sqrt{4\pi}\left\langle Y_1^0 \right\rangle = 2|S||P|\cos\phi_{SP} \\ \sqrt{4\pi}\left\langle Y_2^0 \right\rangle = \frac{2}{\sqrt{5}} P^2 \end{cases}$$

For S- and P- waves only, in the absence of cross-feeds from other channels, the amplitudes and the relative phase are given by:

We solve these equations for the K^-K^+ system in a limited mass range (where the above conditions are satisfied) to extract |S|, |P|, and cos ϕ_{SP}.

Partial Wave Analysis in K^-K^+ channel

Look into the distributions of the spherical harmonic

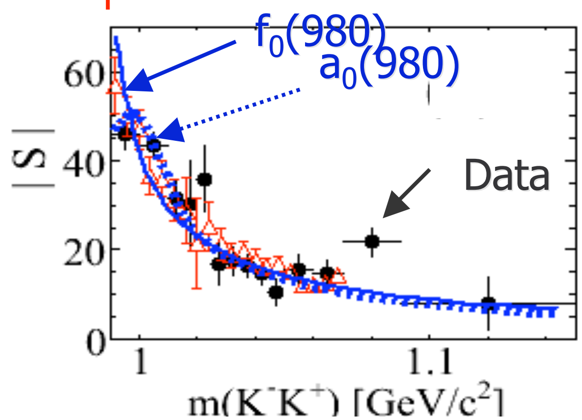
functions $Y_l^0(\cos\theta_H) = \sqrt{\frac{2l+1}{4\pi}}\, P_l(\cos\theta_H)$ (l=0,1,2,…..).

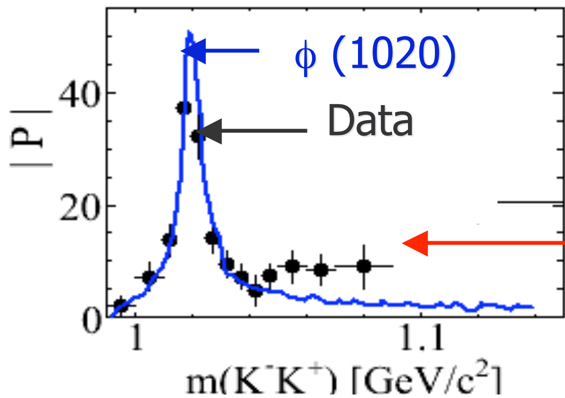
[in the region where the Kπ cross-channels have little effect]

$$\begin{cases} \sqrt{4\pi}\left\langle Y_0^0 \right\rangle = S^2 + P^2 \\ \sqrt{4\pi}\left\langle Y_1^0 \right\rangle = 2|S||P|\cos\phi_{SP} \\ \sqrt{4\pi}\left\langle Y_2^0 \right\rangle = \frac{2}{\sqrt{5}} P^2 \end{cases}$$

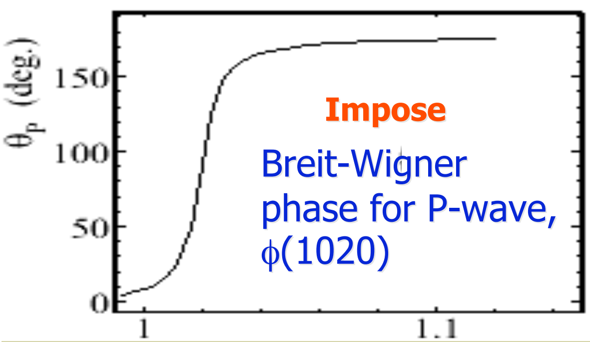
Solve these equations to extract |S|, |P|, and cos θ_{SP}.

Δ S-wave as in $D^0 \to K^-K^+\overline{K^0}$.

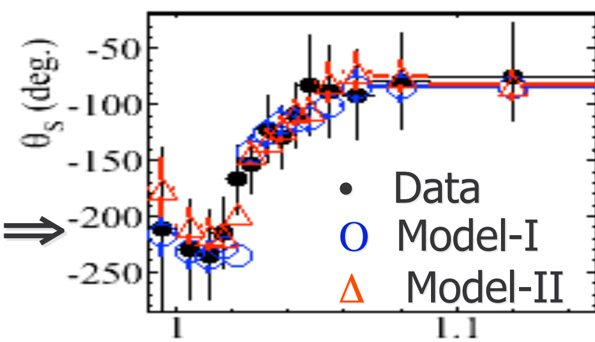




Because of the interference from the crossing Kπ channels, the model independent partial-wave analysis performed here seems valid only up to about 1.02 -1.03 GeV/c².

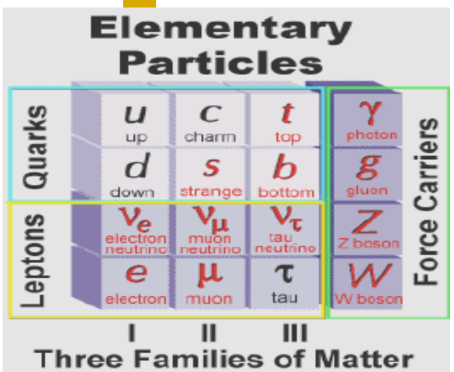


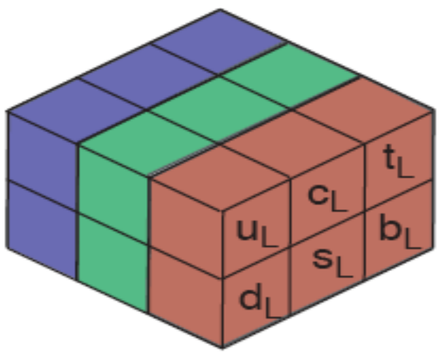
⇒

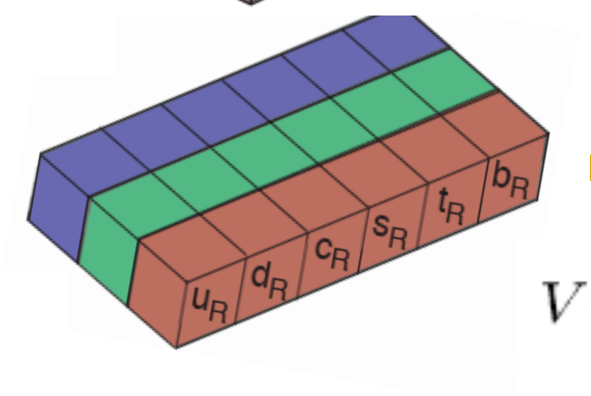


Choose the solution with increasing S-wave phase (Wigner causality)

Weak interaction of quarks in SM





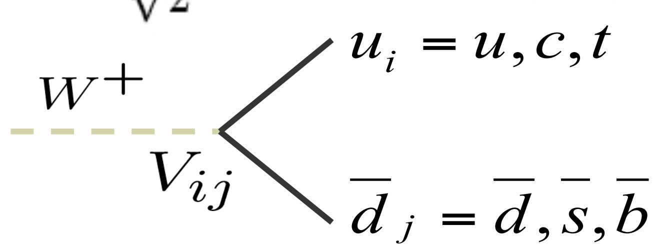


Left handed quarks in doublets $q^i_L = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix}$

Right handed quarks in singlets ⇒ do not couple to W

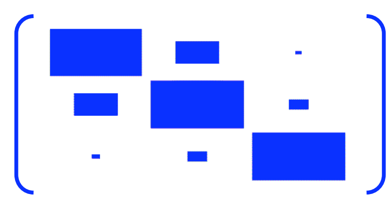
- The electroweak coupling strength of W to left-handed quarks is described by Cabibbo-Kobayashi-Maskawa matrix

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}}\, \overline{u_{Li}}\, \gamma^\mu\, (V_{\rm CKM})_{ij}\, d_{Lj}\, W^+_\mu + \text{h.c.}$$



- 3x3 unitary matrix ==> 4 parameters

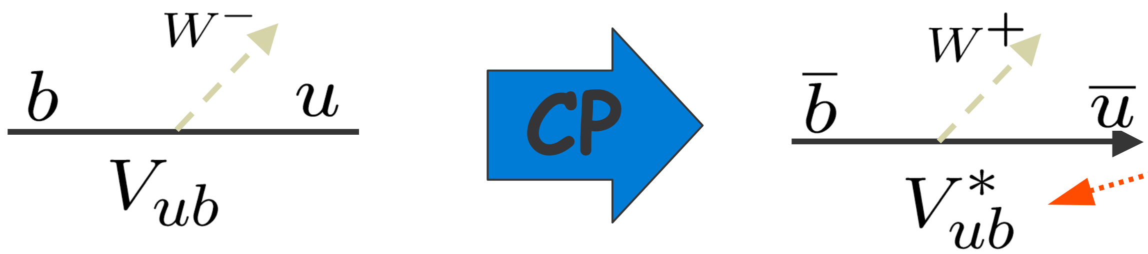
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$



relative magnitude of the elements

The CKM Matrix

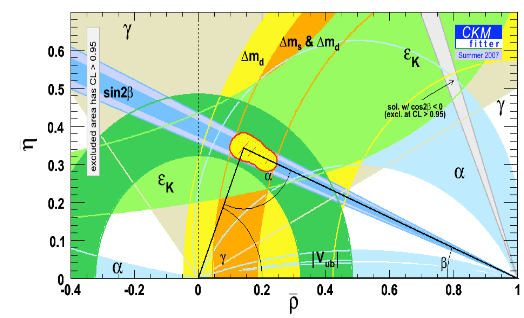
- An irremovable complex phase in V_{CKM} is the origin of CP violation in the SM



the phase changes sign in the CP-conjugated process

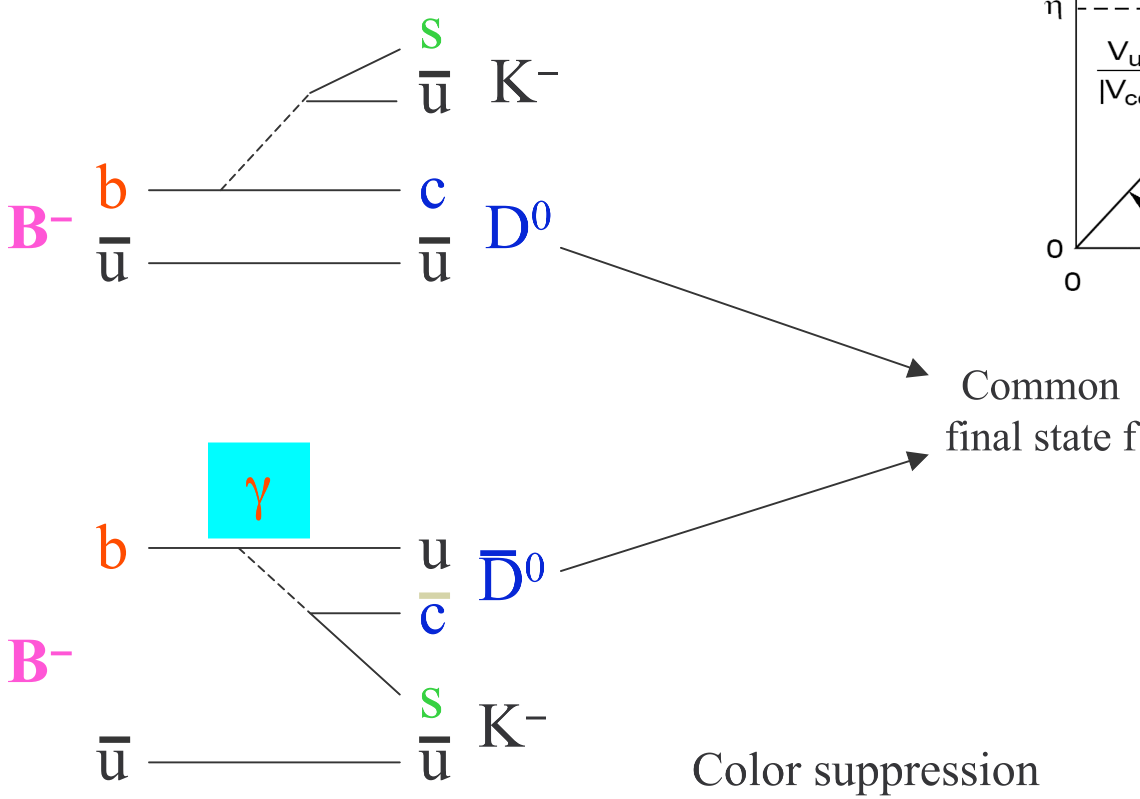
- In the Wolfenstein parameterization:

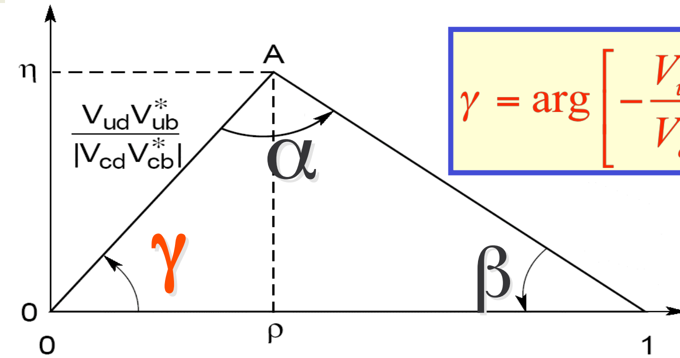
$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



- ➢ *Expect* γ to be ~ (60±10)°, *if the Standard Model is consistent*.
- ➢ But need to *measure* it directly, need redundant measurements ….
- ➢ Several ways to measure γ, no single one of them is "silver bullet" !

Extraction of γ with B→D⁰K





$$\gamma = \arg\left[-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right]$$

Secret to Success: interference between color-allowed D^0K and color-suppressed D^0K amplitudes.
Decay time-independent!

Color suppression

$$\text{Magnitude ratio} \equiv r_B \approx \left|\frac{V_{ub}}{V_{cb}} \cdot \frac{V_{cs}}{V_{us}}\right| \cdot \frac{1}{N_{colors}} \approx \frac{\rho - i\eta}{N_{colors}} \approx \frac{0.4}{3} \approx 0.1$$

The bigger the better!
Larger r_B ⇒ larger interference term ⇒ better constraints on γ.

A Simple Interference Algebra

Amplitude 1 = $A\,e^{i\gamma}$

Amplitude 2 = $B\,e^{i\delta}$

Total amplitude = $Ae^{i\gamma} + Be^{i\delta}$

Decay Rate = $A^2 + B^2 + 2AB\cos(\delta-\gamma)$

Decay Rate of CP-conjugate decay

= $A^2 + B^2 + 2AB\cos(\delta+\gamma)$

If 2 parameters are known (A/B and δ), use the 2 equations to solve for B and γ.

B→DK, through a more complicated analysis, allows to measure γ when δ is not known.

Discrete Ambiguities

Observables $\cos(\delta+\gamma)$ and $\cos(\delta-\gamma)$ are invariant under

- ✓ S_{ex} : $\delta \leftrightarrow \gamma$
- ✓ $S_{\pm}$: $\delta \to -\delta$, $\gamma \to -\gamma$
- ✓ S_{π} : $\delta \to \delta + \pi$, $\gamma \to \gamma + \pi$

If δ_f and $\delta_{f'}$ are different, S_{ex} is resolved, since you can't simultaneously satisfy both $\delta_f \leftrightarrow \gamma$ and $\delta_f{'} \leftrightarrow \gamma$

Analysis Steps for $B^{\pm} \to D_{\pi^-\pi^+\pi^0} K^{\pm}$

Step 1: Obtain $D^0 \to \pi^+\pi^-\pi^0$ Dalitz Plot parameterization using $D^{*+} \to D^0\pi^+$ (and c.c) sample

Step 2: Fit $B^- \to D_{\pi\pi\pi^0} K^-$ (and c.c) sample to obtain signal yield and branching-ratio asymmetry

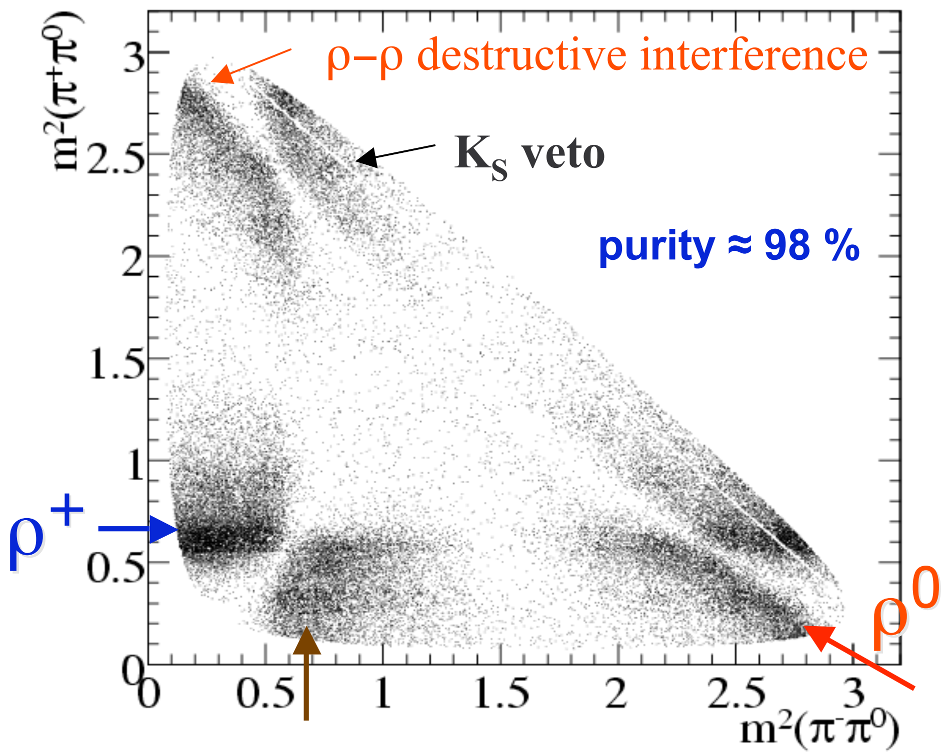
Step 3: Fit for CP parameters using results of Steps 1 and 2 for $B^- \to D_{\pi\pi\pi^0} K^-$ sample

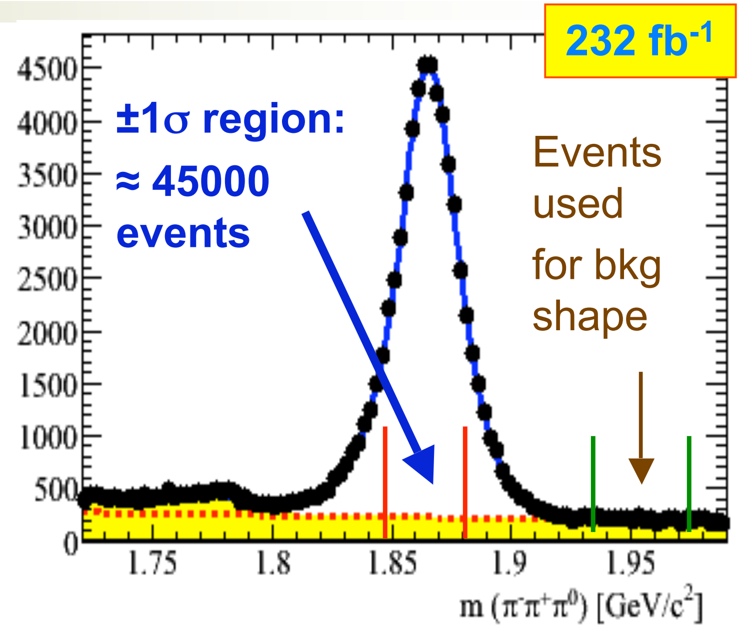
Step 1

Dalitz Plot Analysis of $D^0 \rightarrow \pi^-\pi^+\pi^0$

Motivation: **CKM angle γ using $B^\pm \rightarrow D[\rightarrow \pi^-\pi^+\pi^0] K^\pm$**

- Three $I=1$ particles in the final state
- Gives rise to a rich interference structure
- The three ρ regions are clearly enhanced in the DP, and ρ-ρ destructive interference is evident





The 3 destructively interfering ρπ amplitudes suggest an $I = 0$, $\Delta I = 1/2$ dominated final state.

C. Zemach, Phys. Rev. 133, B1201 (1964).

Phys. Rev. Lett. 99, 251801 (2007)

Step 1

Fit Results

ρ^+ : 68 %
ρ^- : 35 %
ρ^0 : 26 %

Small contributions from higher ρ, f_0, f_2 and σ states

Phys. Rev. Lett. 99, 251801 (2007)

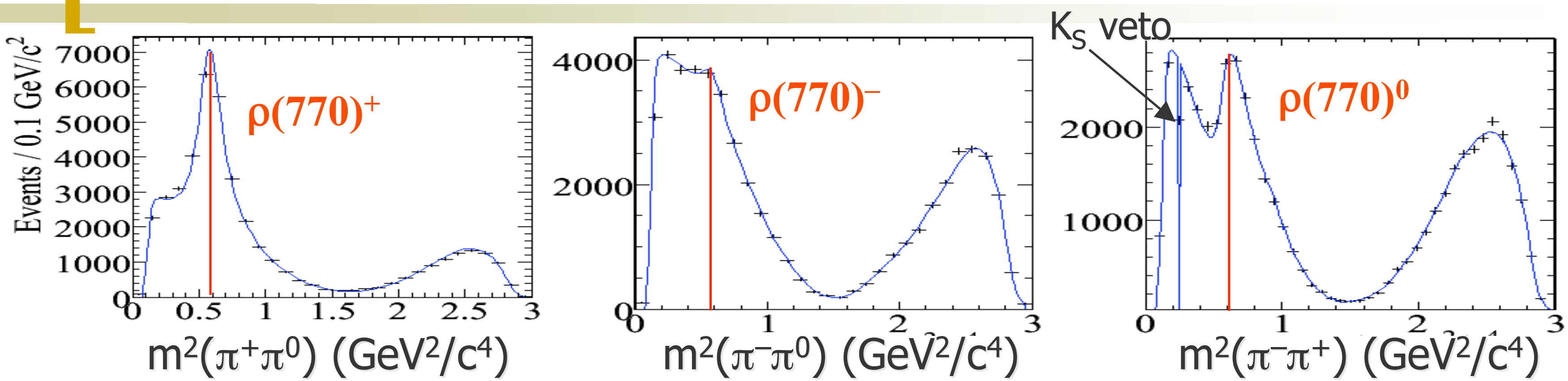
State	Amplitude a_r	Phase ϕ_r	Fraction $f_r(\%)$
$\rho^+(770)$	1	0	67.8±0.0±0.2
$\rho^0(770)$	0.588±0.006±0.001	16.2±0.6±0.3	26.2±0.5±0.4
$\rho^-(770)$	0.714±0.008±0.003	-2.0±0.6±0.5	34.6±0.8±0.1
$\rho^+(1450)$	0.21±0.06±0.10	-146±18±8	0.11±0.07±0.06
$\rho^0(1450)$	0.33±0.06±0.04	10±8±6	0.30±0.11±0.07
$\rho^-(1450)$	0.82±0.05±0.04	16±3±3	1.79±0.22±0.12
$\rho^+(1700)$	2.25±0.18±0.14	-17±2±2	4.1±0.7±0.7
$\rho^0(1700)$	2.51±0.15±0.13	-17±2±2	5.0±0.6±0.9
$\rho^-(1700)$	2.00±0.11±0.07	-50±3±3	3.2±0.4±0.6
$f_0(980)$	0.052±0.004±0.006	-59±5±3	0.25±0.04±0.04
$f_0(1370)$	0.22±0.03±0.03	156±9±6	0.37±0.11±0.09
$f_0(1500)$	0.20±0.02±0.02	12±9±4	0.39±0.08±0.07
$f_0(1710)$	0.39±0.05±0.06	51±8±7	0.31±0.07±0.08
$f_2(1270)$	0.30±0.01±0.06	-171±3±2	1.32±0.08±0.08
σ (400, 600)	0.24±0.02±0.04	8±4±3	0.82±0.10±0.10
Non-Res	0.57±0.07±0.08	-11±4±2	0.84±0.21±0.12

Systematic errors:
- σ and $\rho(1700)$ parameters
- reconstruction & PID eff
- Form factor variation
- Flavor mistags

The distribution is marked by 3 destructively interfering $\rho\pi$ amplitudes, suggesting an $I = 0$, $\Delta I = 1/2$ dominated final state.
C. Zemach, Phys. Rev. 133, B1201 (1964).

Step 1

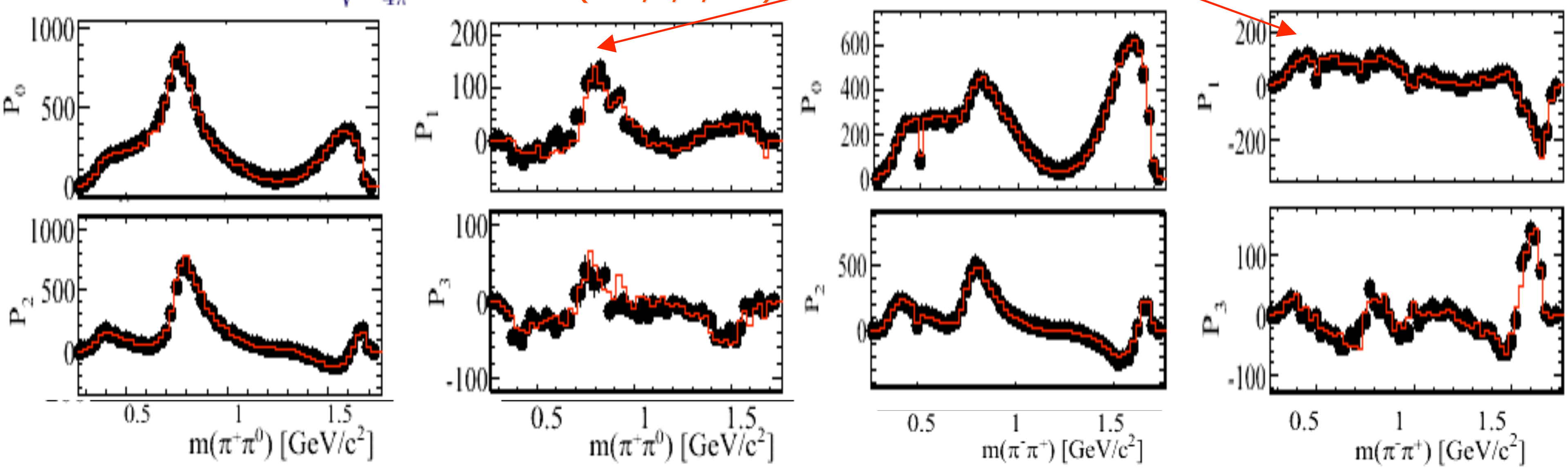
Mass-projections & Angular Moments



Excellent agreement between data & fit.

Each event is weighted by the spherical harmonic functions $Y_l^0(\cos\theta_H) = \sqrt{\frac{2l+1}{4\pi}}\, P_l(\cos\theta_H)$ (l=0,1,2,…..).

Large interference between S and P waves.



Step 2

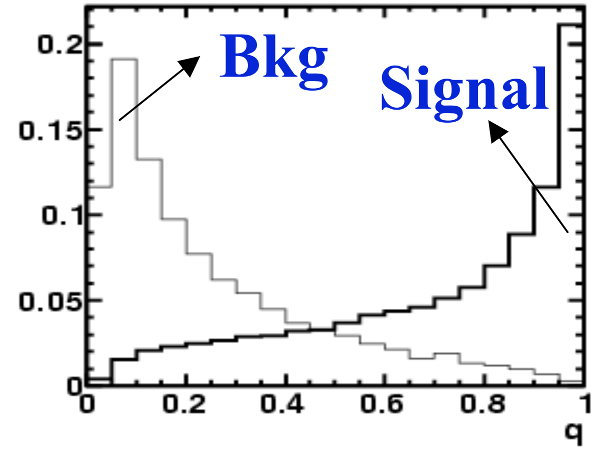
BR & Asymmetry for $B^{\pm} \to D_{\pi^- \pi^+ \pi^0} K^{\pm}$

Fit $B^- \to D_{\pi\pi\pi^0} K^-$ sample with ΔE, q, d

Obtain signal yield & asymmetry

Nsig	170 ± 29
Asym	-0.02 ± 0.15

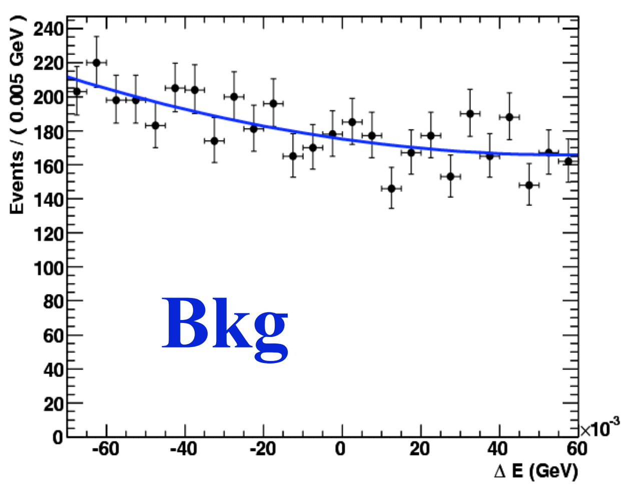
Phys. Rev. D72, 071102 (2005)

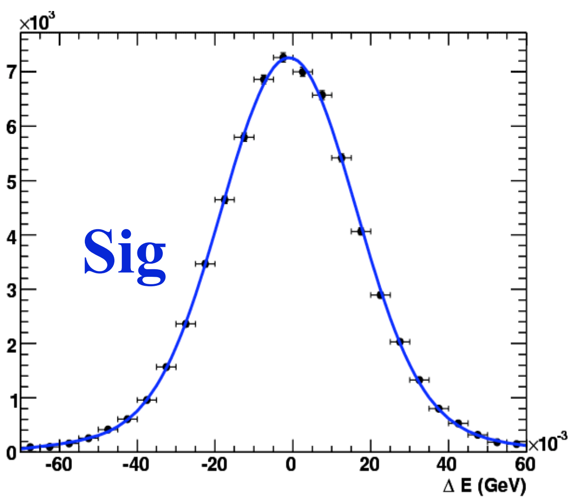


q = continuum NN

d = fake D^0 NN

ΔE PDFs are Gaussian and 2nd-order polynomial:





$BR(B^- \to D_{\pi\pi\pi 0} K^-) =$
$(4.6 \pm 0.8 \pm 0.7) \times 10^{-6}$

$A(B^- \to D_{\pi\pi\pi 0} K^-) =$
$-0.02 \pm 0.15 \pm 0.03$

Step 3

Result with 344 M $e^+e^- \to B\bar{B}$ Events

$$r_B e^{i(\delta\pm\gamma)} = x_\pm + y_\pm$$

$$\rho_\pm \equiv \sqrt{\left(x_\pm - x^0\right)^2 + y_\pm^2}$$

$$x^0 = 0.85$$

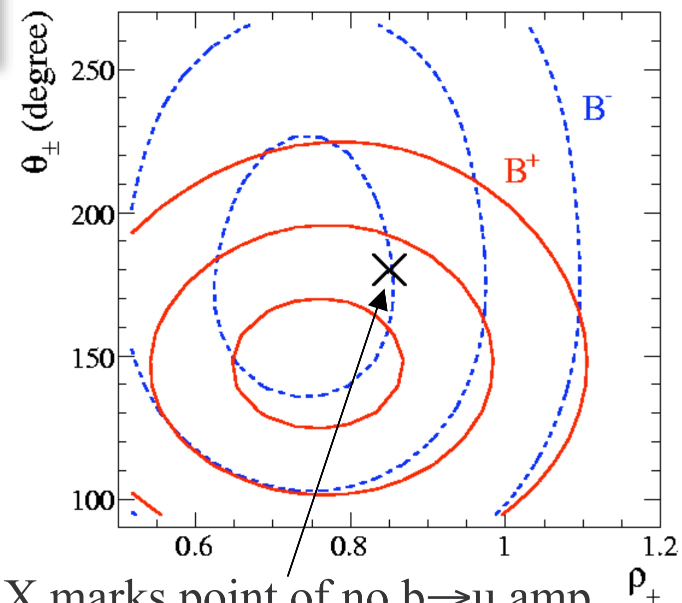
$$\theta_\pm \equiv \tan^{-1}\left(\frac{y_\pm}{x_\pm - x^0}\right)$$

$\rho^- = 0.72 \pm 0.11 \pm 0.06$;
$\theta^- = (173 \pm 42 \pm 16)°$

$\rho^+ = 0.75 \pm 0.11 \pm 0.06$;
$\theta^+ = (147 \pm 23 \pm 11)°$

However, not trivial to directly determine γ

- First measurement of CP-violating quantities in $B \to D_{\pi\pi\pi^0} K$
- First combined use of DP distribution and absolute BR to extract CP parameters.
- σ_θ is too large for a meaningful extraction of γ from this analysis alone
- σ_ρ is small enough to contribute to overall CKMFitter/UTFit fits of γ



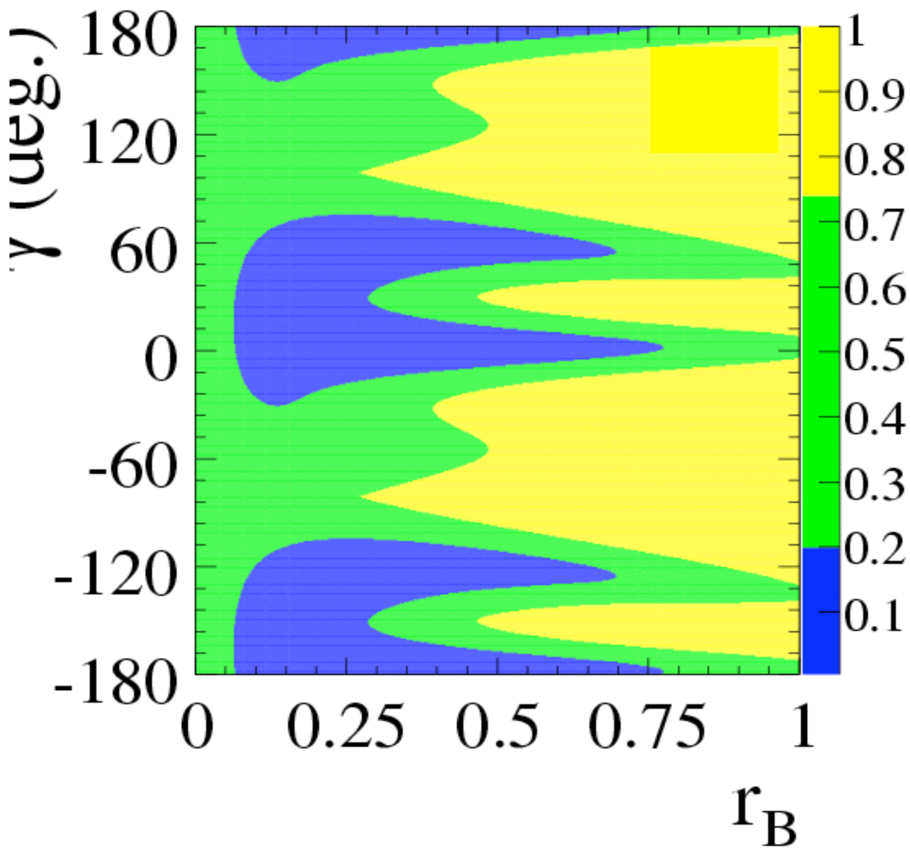
X marks point of no $b \to u$ amp
$\rho = 0.85$, $\theta = 180°$

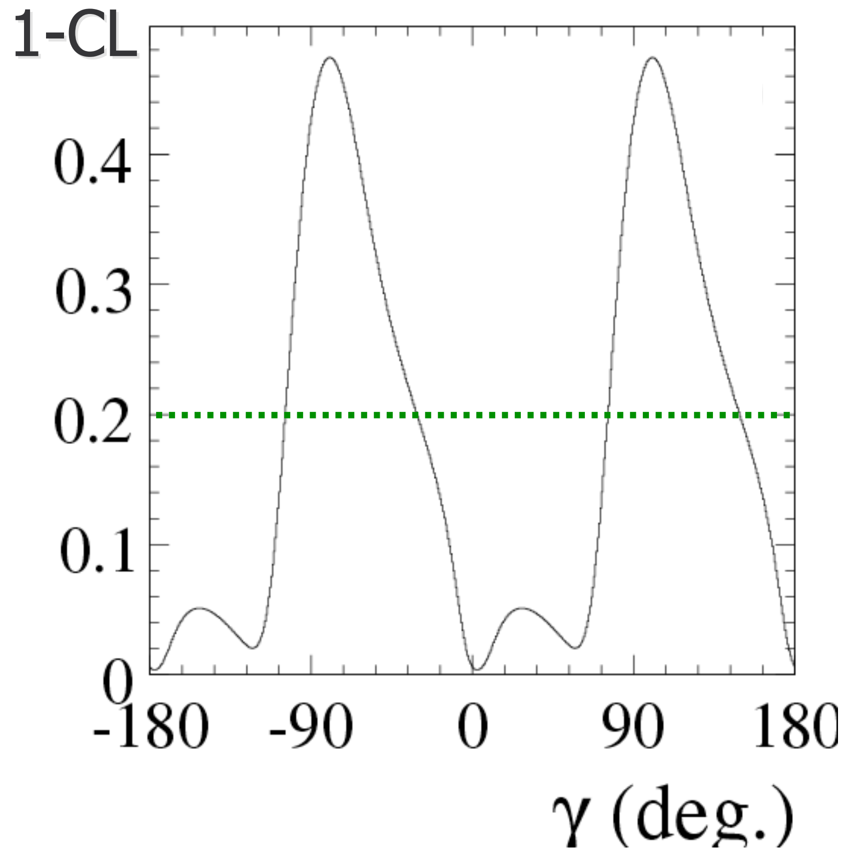
Step 3

From ($\rho_\pm$, $\theta_\pm$) to (r_B, δ, γ)

Use frequentist method to extract γ, r_B, δ from ($\rho_\pm$,$\theta_\pm$)

(3dim confidence intervals projections)





1σ, 2σ, and 3σ regions are defined as containing the three-dimensional significance, 1-CL, smaller than 19.9 %, 73.9 %, and 97.1 %, respectively.

Step 3

Constraints on (r_B, δ, γ)

1σ bounds on the physical parameters, including both stat. and syst. errors

First direct lower bound on r_B

$$0.06 < r_B < 0.78$$
$$-30^o < \gamma < 76^o$$
$$-27^o < \delta < 78^o$$

Phys. Rev. Lett. 99, 251801 (2007)

These bounds come from the results of this analysis alone.
Sensitivity to r_B, γ, and δ comes from the Dalitz plot and BR asymmetry.

$B^{\pm} \to D[\to K_S^0 \pi^+ \pi^-] K^{\pm}$:

$r_B < 0.142$ ($r_B < 0.198$)
1σ (2σ)

$\gamma = (92 \pm 41 \pm 10 \pm 13)^o$
(stat) (syst) (Dalitz)

Hopefully, a more powerful bound will be obtained after combining the results of this analysis with with those from $B^{\pm} \to D[\to K_S^0 \pi^+ \pi^-] K^{\pm}$ analysis.

Time-integrated CP̸ in SCS D^0 Decays

- SM predictions $O(0.1\%)$. ← **CPV in charm decays highly suppressed.**
- New Physics must be playing a role if an asymmetry is observed with present experimental sensitivity [$O(1\%)$].
- 3-body decays permit the measurement of phase differences which are required to create CP violation in the interference between SM and non-SM processes.
- Access to both CP eigen states ($\rho^0\pi^0$, $f_0\pi^0$, $\phi\pi^0$) and flavor states ($\rho^{\pm}\pi^{-+}$, $K^{*\pm}K^{-+}$). Therefore, can probe diverse possibilities of CPV.

With the present data sample, we are sensitive to asymmetry of $O(1\%)$ in amplitude and $O(2^o)$ in phase in the main decay channels. Sensitivity is higher in $D\rightarrow\pi^-\pi^+\pi^0$ decay compared to $D\rightarrow K^-K^+\pi^0$.

For details:

Y. Grossman, A.L. Kagan, and Y. Nir, Phys. Rev. D75, 036008 (2007).
I.I. Bigi, hep-ph/0104008 (2001).

Methodology to Measure CP Asymmetry

Perform a blind analysis to search for CPV

- Use 4 independent methods to measure CP asymmetry:

- directly compare Dalitz plot distributions for $D^0/\overline{D}^0$ events. (Model independent, calculate χ^2/ν and compare with null hypothesis).

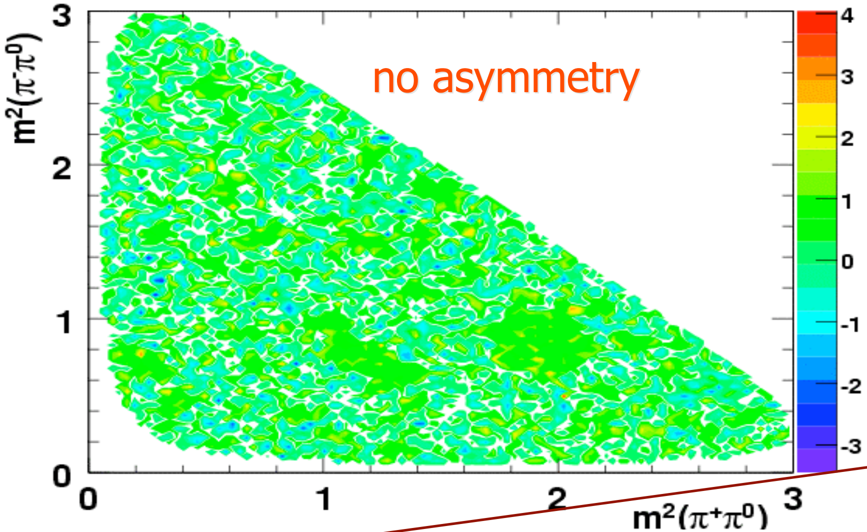
- compare angular moments of the cosine of helicity angle (Model independent, calculate χ^2/ν and compare with null hypothesis).

- fit the D^0 and $\overline{D}^0$ Dalitz plots separately and extract asymmetry in amplitudes and phases. (Model dependent).

- asymmetry in the total number of signal events. (Model independent).

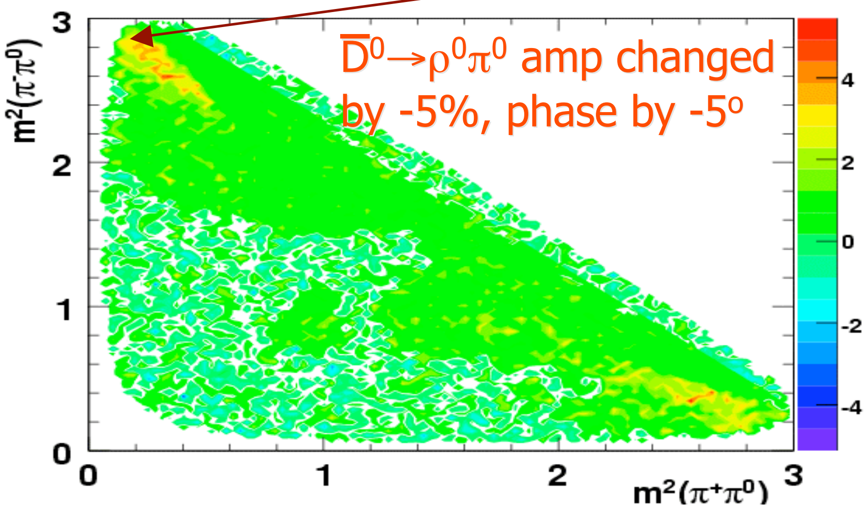
The model independent methods would help establish asymmetry, the model fit can help interpret measured asymmetry in data.

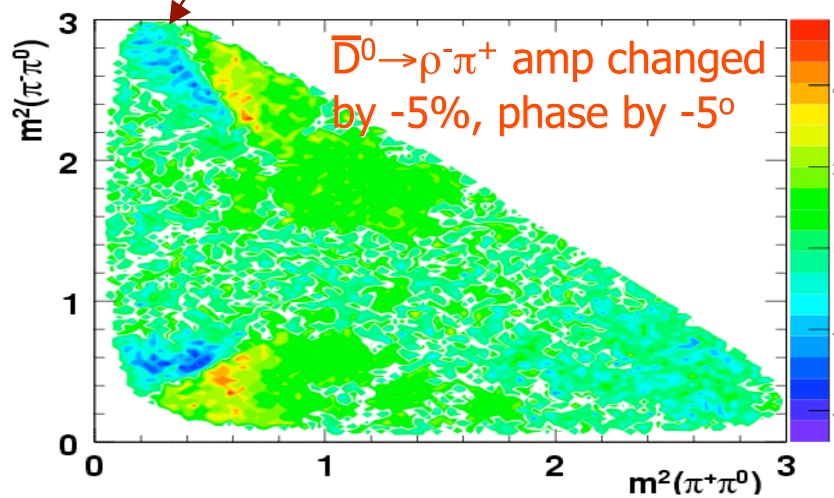
Sensitivity to CPV: Simulation Studies



Plot the difference in the Dalitz plot distributions of $\bar{D}^0$ and D^0 events (in number of standard deviations).

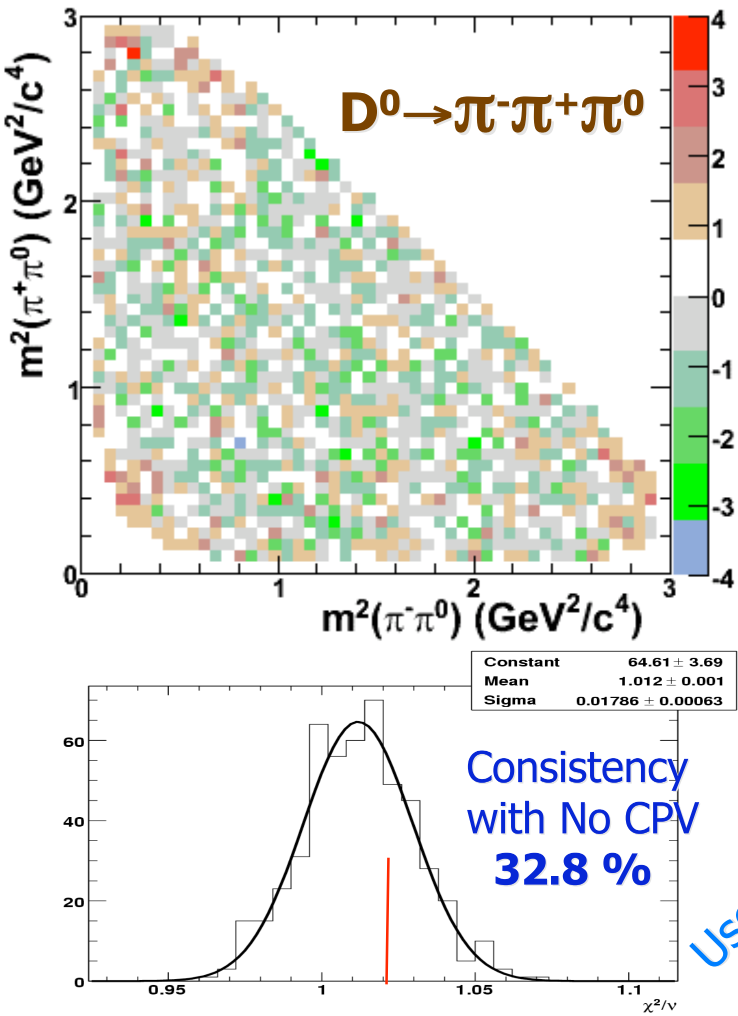
Clear signal of asymmetry in expected places.

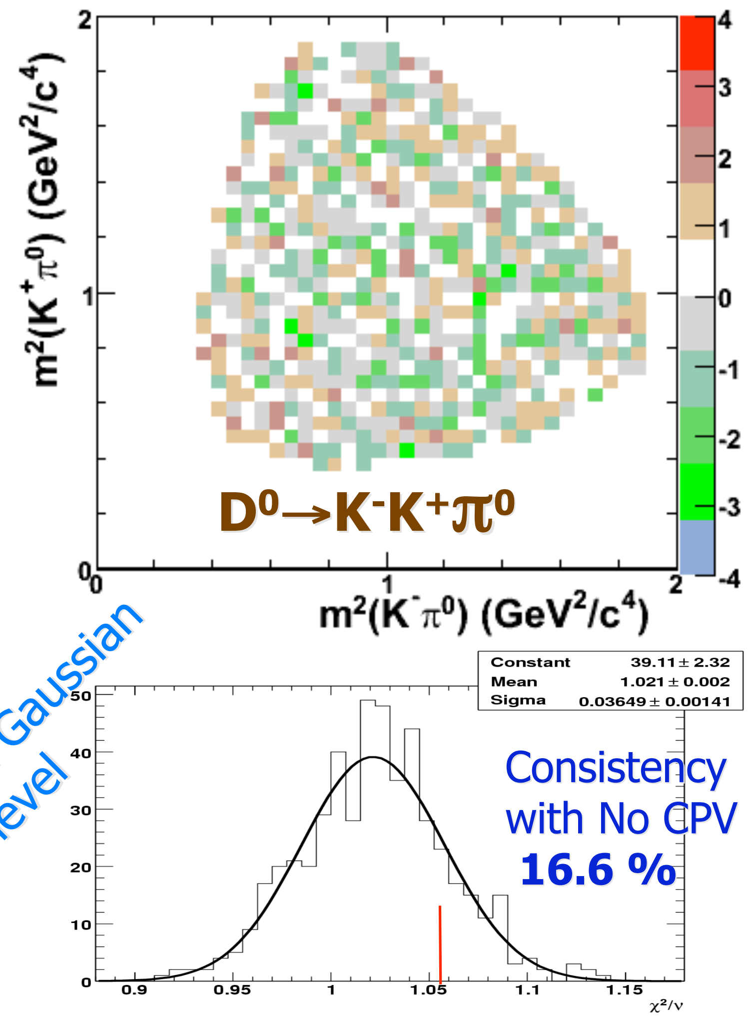




$D^0 \to \pi^-\pi^+\pi^0$, 25 times larger statistics

Asymmetry in Data: Dalitz Plot

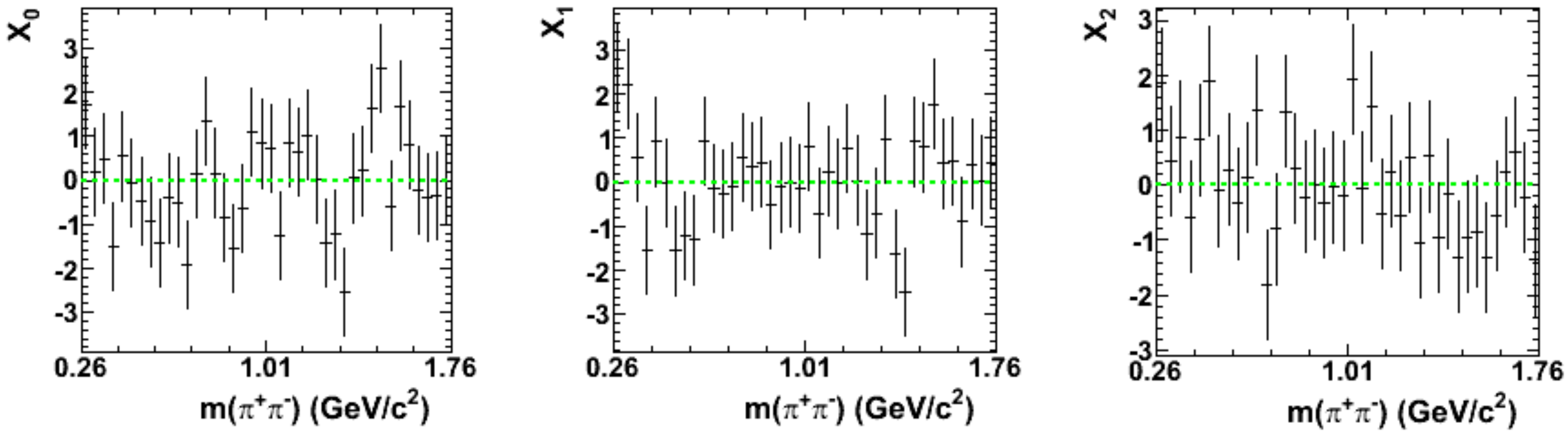




Use one sided Gaussian confidence level

Conclusion: no hint of CP violation in direct comparison of DPs.

Asymmetry in Data: Angular Moments

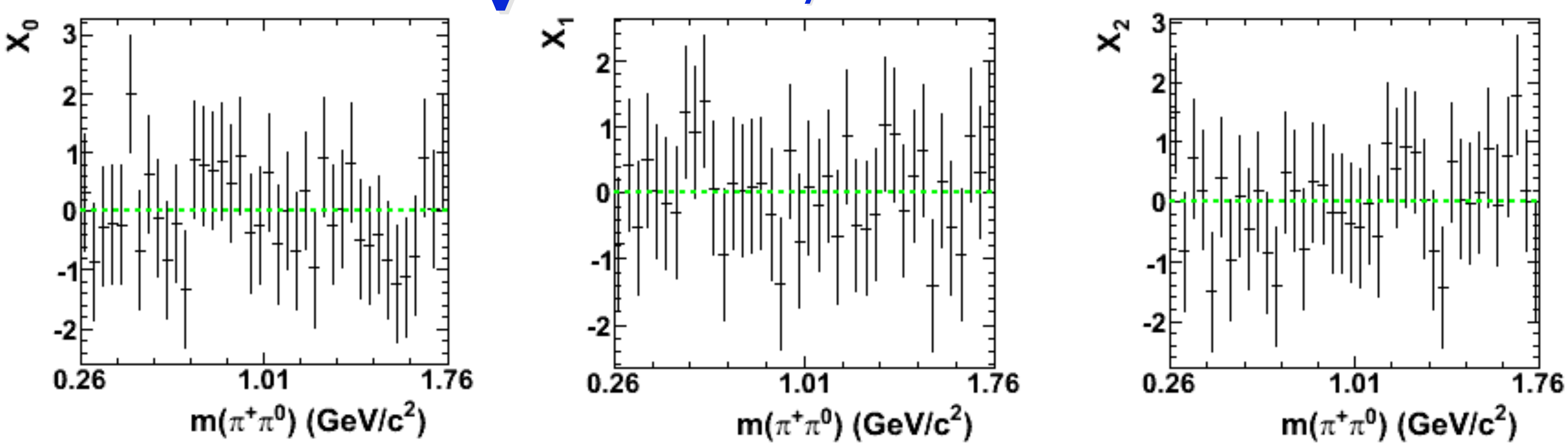


$\pi^+\pi^-$ channel moments

↑ Consistency with No CPV: **28.2 %**

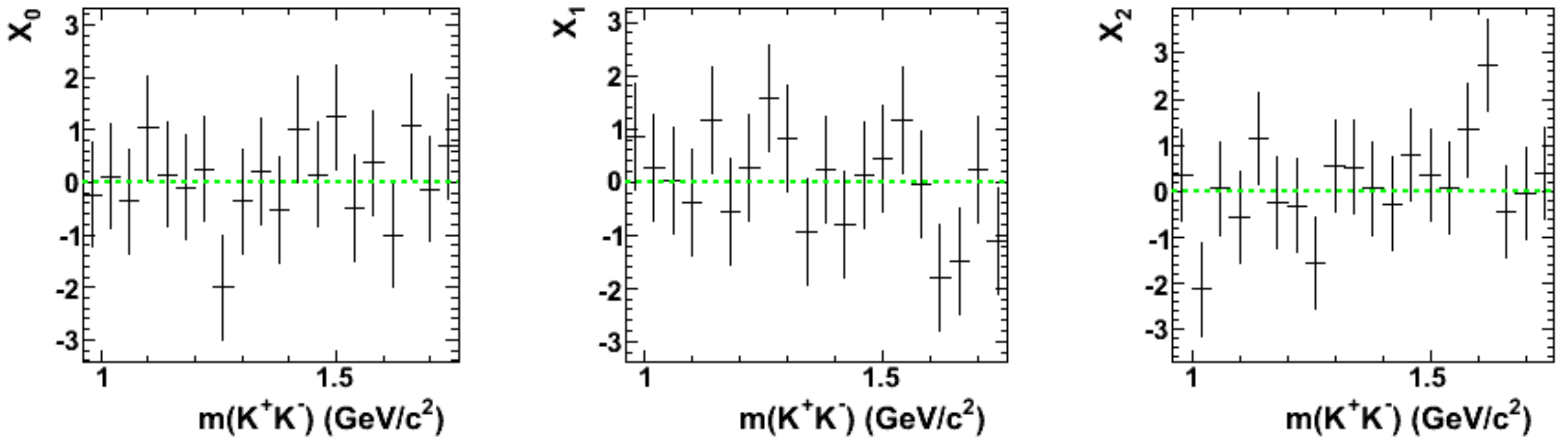
Only 3 moments shown here, but χ^2/ν comes from first 8 moments

↓ Consistency with No CPV: **28.4 %**



$\pi^+\pi^0$ channel moments

Asymmetry in Data: Angular Moments

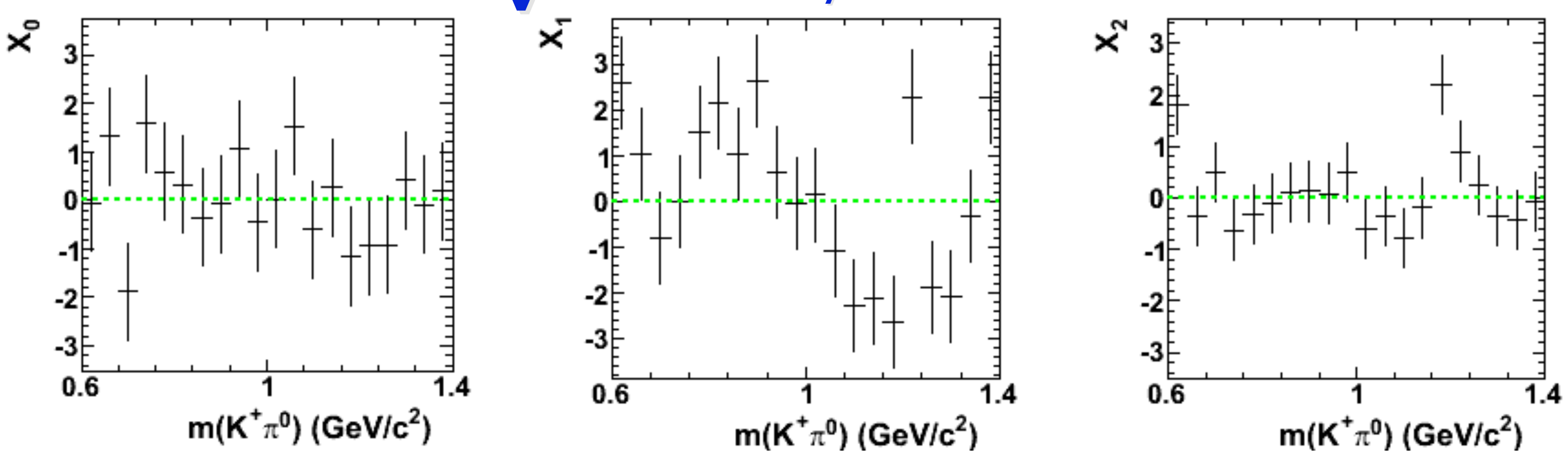


K^+K^- channel moments

↑ Consistency with No CPV: **63.1 %**

Only 3 moments shown here, but χ^2/ν comes from first 8 moments

↓ Consistency with No CPV: **23.8 %**



$K^+\pi^0$ channel moments

Asymmetry in Data: Model Fit

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

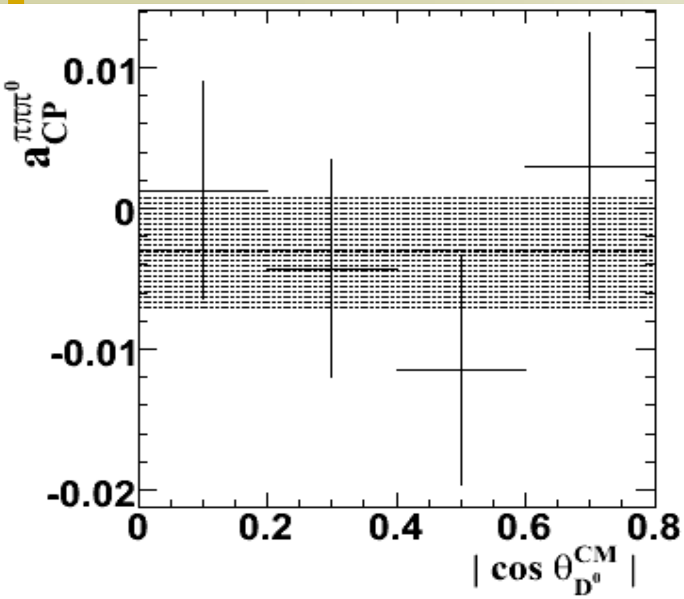
State	Δa_r (%)	$\Delta\phi_r$ (°)	Δf_r (%)
$\rho^+(770)$	-3.2±1.7±0.8	-0.8±1.0±1.0	-1.6±1.1±0.4
$\rho^0(770)$	2.1±0.9±0.5	0.8±1.0±0.4	1.6±1.4±0.6
$\rho^-(770)$	2.0±1.1±0.8	-0.6±0.9±0.4	0.7±1.1±0.5
$\rho^+(1450)$	2±11±8	-30±25±9	0.0±0.1±0.1
$\rho^0(1450)$	13±8±6	-1±14±3	0.1±0.2±0.1
$\rho^-(1450)$	-3±6±5	8±7±3	-0.2±0.3±0.1
$\rho^+(1700)$	19±27±9	9±7±3	0.4±1.0±0.4
$\rho^0(1700)$	-31±20±12	-7±6±2	-1.3±0.8±0.3
$\rho^-(1700)$	-3±14±11	-3±8±3	-0.5±0.6±0.3
$f_0(980)$	0.0±0.1±0.2	-3±7±4	0.0±0.1±0.1
$f_0(1370)$	-0.3±1.3±1.2	7±14±5	-0.2±0.1±0.1
$f_0(1500)$	0.4±1.1±0.7	-1±12±1	0.0±0.1±0.1
$f_0(1710)$	-3±3±2	-25±13±11	0.0±0.1±0.1
$f_2(1270)$	8±4±5	2±5±2	0.1±0.1±0.1
$\sigma(400)$	-0.3±0.7±2.0	-4±7±3	-0.1±0.1±0.1
Non-Res	12±7±8	11±9±4	0.2±0.3±0.2

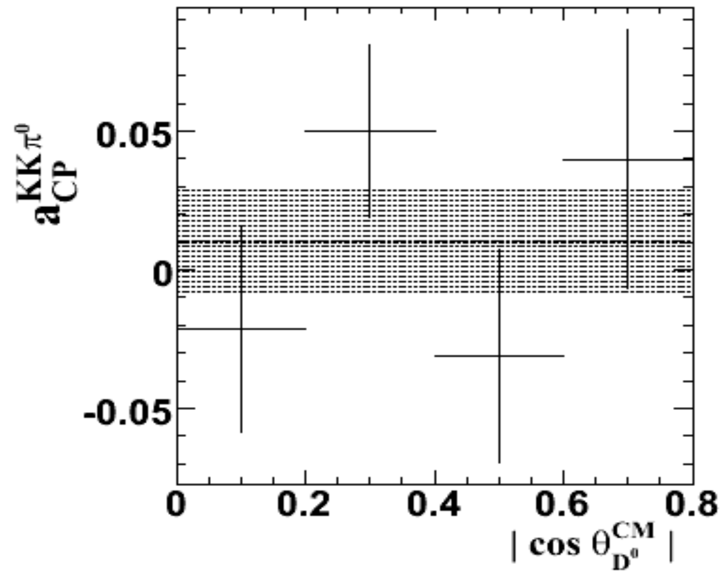
$D \to K^- K^+ \pi^0$

State	Δa_r	$\Delta\phi_r$ (°)	Δf_r (%)
$K^*(892)^+$	0.02±0.03±0.02	10±12±3	0.8±1.1±0.4
$K^*(1410)^+$	1.0±0.7±0.4	1±21±6	1.7±1.8±0.6
$K^+\pi^0(S)$	-1.3±0.6±0.5	-9±10±6	-2.3±4.7±1.0
$\phi(1020)$	-0.01±0.02±0.01	-10±20±5	-0.4±0.8±0.2
$f_0(980)$	0.1±0.2±0.06	-12±25±8	0.4±2.6±0.2
$[a_0(980)^0]$	[0.2±0.2±0.06]	[-7±16±8]	[0.6±1.9±0.2]
$f_2'(1525)$	-0.4±0.7±0.1	6±36±12	0.0±0.1±0.3
$K^*(892)^-$	0.01±0.03±0.01	-7±4±2	1.7±1.3±0.4
$K^*(1410)^-$	1.3±0.9±0.7	-23±13±9	1.7±2.8±0.7
$K^-\pi^0(S)$	0.1±0.7±0.4	32±39±14	0.4±2.4±0.5

Conclusion: No evidence for CPV in any CP eigen or flavor state in either decay mode.

Phase-space-integrated Asymmetry





$\pi^-\pi^+\pi^0$: a_{CP} = [-0.31 ± 0.41 (stat) ± 0.17 (syst)] %

$K^-K^+\pi^0$: a_{CP} = [1.00 ± 1.67 (stat) ± 0.25 (syst)] %

$\pi^-\pi^+\pi^0$: a_{CP} = [-0.28 ± 0.34 (stat) ± 0.19 (syst)] %

$K^-K^+\pi^0$: a_{CP} = [0.62 ± 1.24 (stat) ± 0.28 (syst)] %

Consistency check, ± 2.5σ region for reco. D mass peak

Conclusion: consistent with no integrated asymmetry.

Summary

- Performed branching ratio measurements of the SCS decays $D^0 \rightarrow \pi^-\pi^+\pi^0$, $K^-K^+\pi^0$ relative to the CF decay $D^0 \rightarrow K^-\pi^+\pi^0$

- Dalitz plot analysis of the decay $D^0 \rightarrow K^-K^+\pi^0$

- Dalitz plot analysis of the decay $D^0 \rightarrow \pi^-\pi^+\pi^0$

- Measurement of γ using the decay $B^\pm \rightarrow D_{\pi^-\pi^+\pi^0} K^\pm$

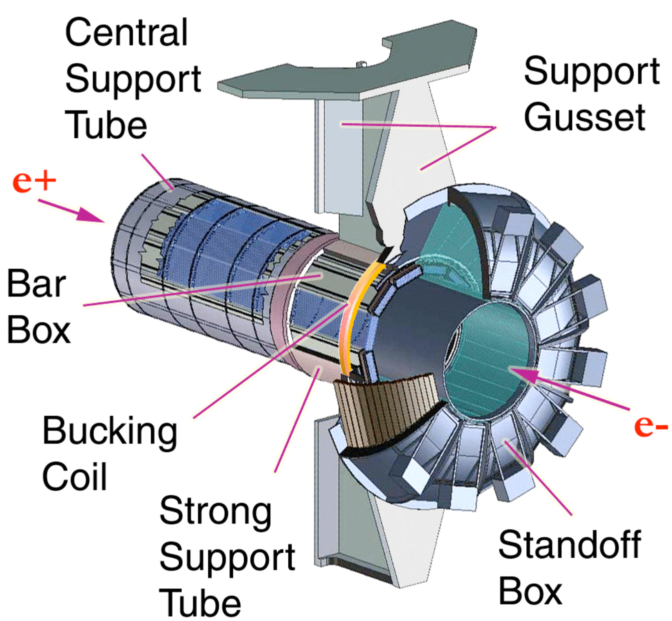
- Search for CP violation at the 1% level in the decays $D^0 \rightarrow \pi^-\pi^+\pi^0$, $K^-K^+\pi^0$

End of Talk ! Thank You !

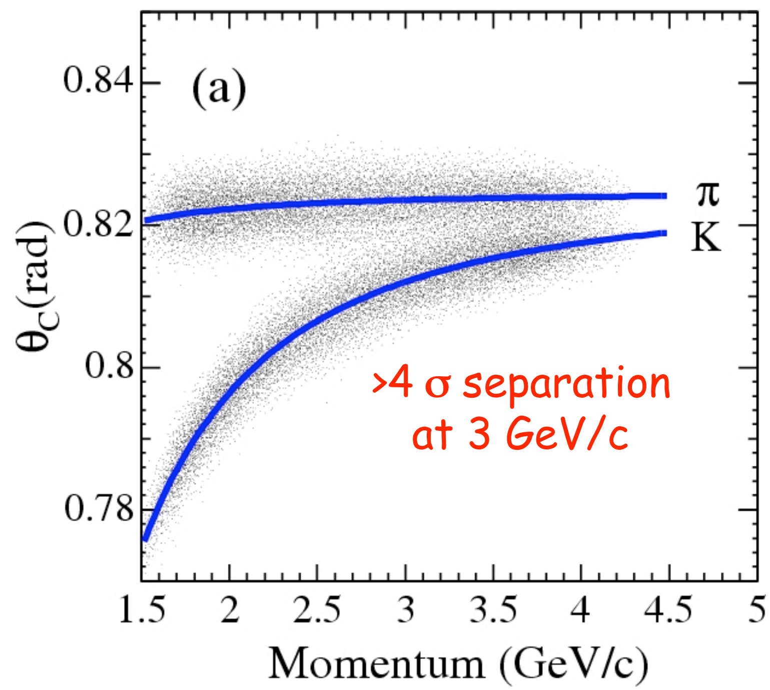
Back up slides

Kaon/Pion Discrimination: DIRC

LAYOUT



Cherenkov angle vs. momentum for pions and kaons



B.R. of the Decays $D^0 \to \pi^-\pi^+\pi^0$, $K^-K^+\pi^0$

Use the the Cabibbo-favored decay $D^0 \to K^-\pi^+\pi^0$ as reference for normalization.
Reconstruct the decay chain: [$D^{*+} \to D^0\pi_s^+$, $D^0 \to h^-h^+\pi^0$, $\pi^0 \to \gamma\gamma$] and c.c.

Motivation

1. Precision measurement of the branching ratios of 3-body Cabibbo-suppressed decays of D^0.
2. To investigate the anomaly in the BR of 2- & 3-body CS decays of D^0.

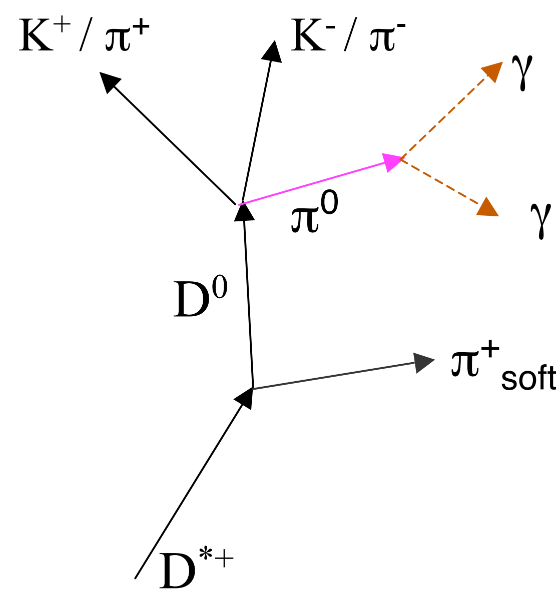
The charge of the π_{soft} determines the charm content of the D^0 meson (i.e., whether it is D^0 or $\overline{D^0}$).

Background Sources

- Combinatorial
- $K\pi\pi^0$ reflection in $\pi\pi\pi^0$ and $KK\pi^0$ modes

Event Reconstruction

- P_{CM} (D^0) > 2.77 GeV/c
- $|m_{D*} - m_{D0} - 145.5| < 0.6$ MeV/c^2



Data Sample = 232 fb^{-1}

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

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

- h^- and h^+ tracks are fit to a vertex
- Mass of π^0 candidate is constrained to m_{π^0} at $h^- h^+$ vertex
- P_{CM} (D^0) > 2.77 GeV/c

Background Sources

- Charged track combinatoric
- Mis-reconstructed π^0
- Real D^0, fake π_s
- $K\pi\pi^0$ reflection in $\pi\pi\pi^0$ and $KK\pi^0$ modes

D* Reconstruction

- D^{*+} candidate is made by fitting the D^0 and the π_s^+ to a vertex constrained in x and y to the measured beam-spot for the run.
- $|m_{D^*} - m_{D^0} - 145.5| < 0.6$ MeV/c^2
- Vertex χ^2 probability > 0.01
- Choose a single best candidate with smallest χ^2 for the whole decay chain (multiplicity = 1.03).

$K^-K^+\pi^0$ branching ratio: CLEO result

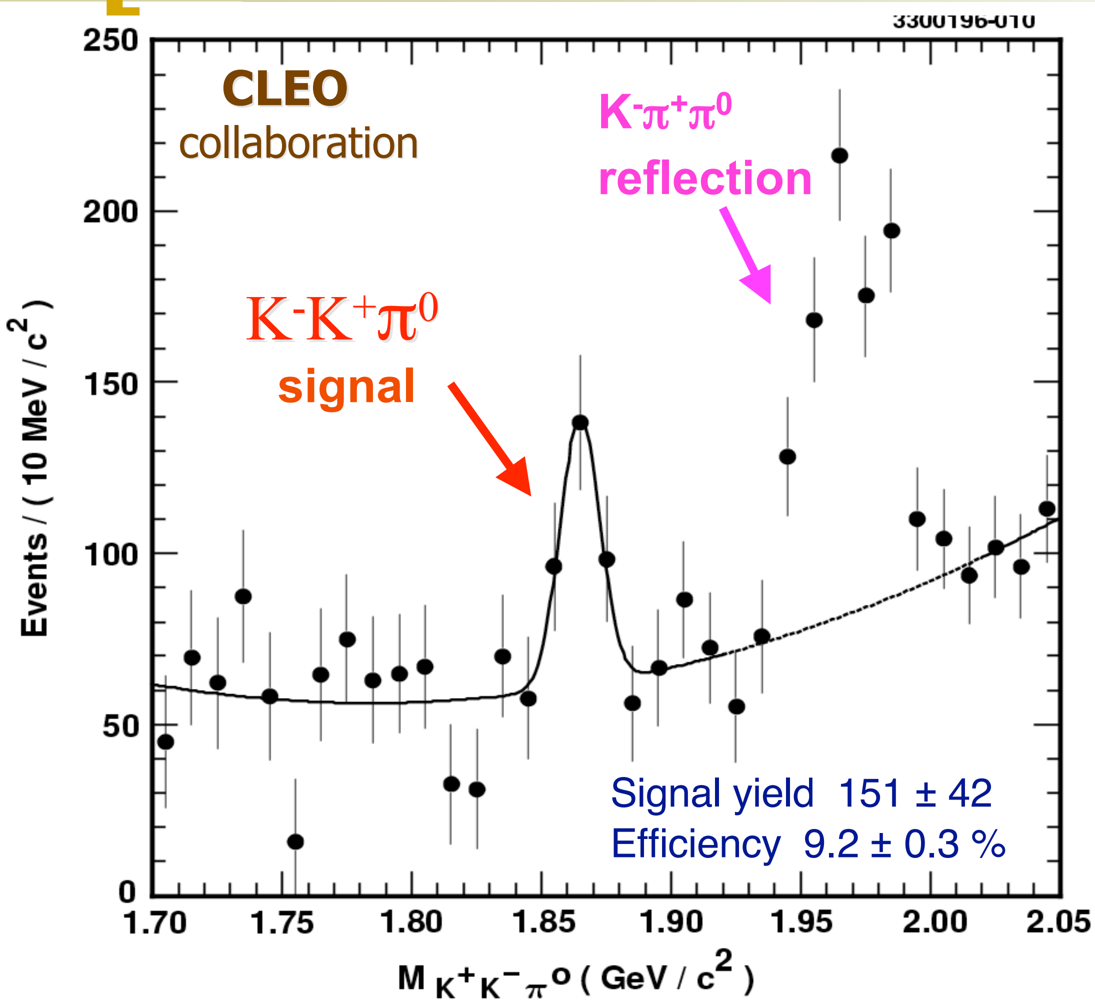


FIG. 10. The invariant mass distribution of $K^+K^-\pi^0$ after doing the normalized mass difference sideband subtraction. In fitting, we exclude the region between 1.92 and 2.02 GeV/c^2 due to an excess of misidentified $D^0 \to K^-\pi^+\pi^0$ events which survive the veto.

Phys. Rev. D54, 4211 (1996)
$B(D^0 \to KK\pi^0)/ B(D^0 \to KK\pi^0)$ =
0.95 ± 0.26 %

- High pion-to-kaon misidentification rate ⇒ contamination from $D^0 \to K^-\pi^+\pi^0$ events very high.
- Had to apply various vetoes and the corresponding efficiency corrections.
- Combinatorial background not fully understood.

A new cross-check done by the CLEO collaboration shows $B(D^0 \to KK\pi^0)/ B(D^0 \to K\pi\pi^0)$ = 2.21 ± 0.14 (stat) %, which is consistent with our measurement.

Phys. Rev. D74, 031108 (2006)

3-Particle Phase Space

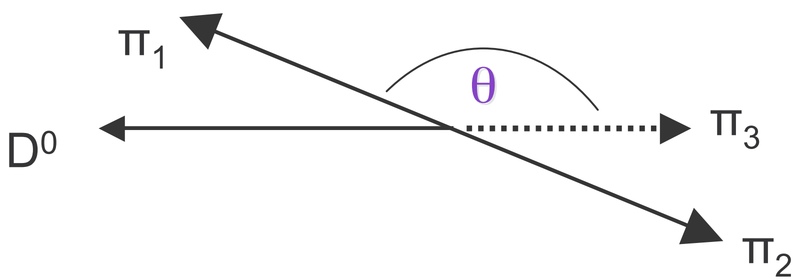
- **2 Observables**

From four vectors	12
Conservation laws	-4
Final state particle masses	-3
Free rotation in decay plane	-3
Σ	2

- **Usual choice**

  Invariant mass squared m^2_{12}

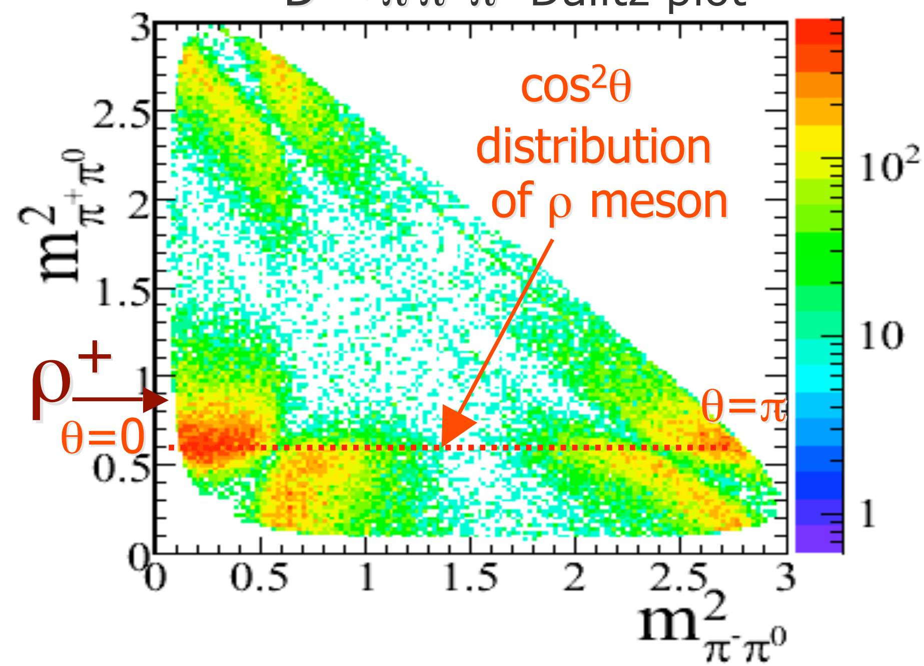
  Invariant mass squared m^2_{13}



$\{ \pi_1 , \pi_2, \pi_3 \} = \{ \pi^+, \pi^0, \pi^- \}$

- Dalitz plot provides info on angular distr.
- Also about dynamical amplitudes involved.
- Flat if no dynamics involved.

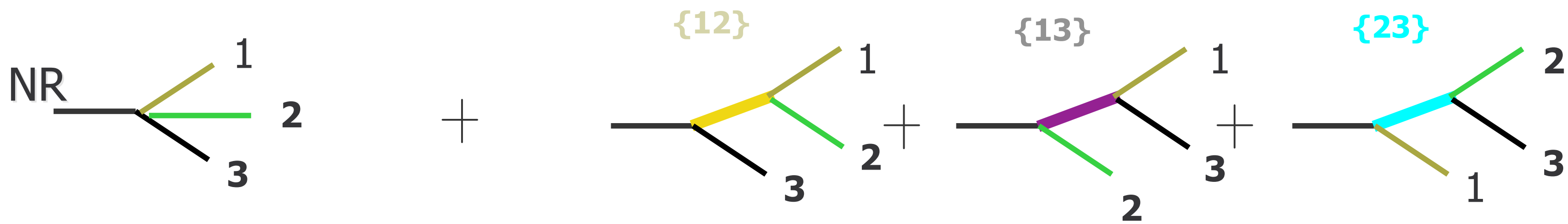
$D^0 \rightarrow \pi^- \pi^+ \pi^0$ Dalitz plot



- Dalitz applied this method first to K_L-decays
  - To resolve τ/θ puzzle with only few events
  - goal was to determine spin and parity
- And he never called them Dalitz plots !

Isobar Model Formalism

three-body decay D→ABC decaying through an r=[AB] resonance



D decay three-body amplitude $\mathcal{A}_D(s_{12}, s_{13}) = a_0 e^{i\delta_0} + \sum_r a_r e^{i\delta_r} \mathcal{A}_r(s_{12}, s_{13})$

NR term(direct 3 body decay)

a_0, δ_0, a_r, δ_r : Free parameters of fit

$$\mathcal{A}_r(s_{12}, s_{13}) = F_D^J F_r^J \times M_r^J \times BW_r^J$$

Relativistic Breit-Wigner

$$BW_r^J(s) = \begin{cases} \dfrac{1}{M_r^2 - s - iM_r\Gamma_r(\sqrt{s})} \\ \dfrac{1}{M_r^2 - s - i\ (\ \rho_1 g_1^2 + \rho_2 g_2^2)} \end{cases}$$

$f_0(980)$
$a_0(980)$

Angular distribution

D and *r* Blatt-Weisskopf form factors

Introducing Angular Distributions

Schrödinger's Equation

$$-\frac{\hbar}{2\mu}\nabla^2\Psi(\vec{r}) + V(\vec{r})\Psi(\vec{r}) = E\Psi(\vec{r})$$

$$\begin{cases} V(\vec{r}) = 0 \\ \vec{k} = \frac{\vec{p}}{\hbar} = \mu\frac{\vec{v}}{\hbar} \quad \mu = \frac{m_1 m_2}{m_1 + m_2} \end{cases}$$

$$|i\rangle = \Psi_i = \sum_{l=0}^{\infty} U_l(r) P_l(\cos\vartheta)$$

Angular Amplitude

$$\Psi_S = \Psi_f - \Psi_i = \frac{1}{k}\sum_{l=0}^{\infty}(2l+1)\frac{\eta_l e^{2\imath\delta_l} - 1}{2\imath} P_l(\cos\vartheta)\frac{e^{\imath kr}}{r}$$

Dynamic Amplitude (BW, Flatte, S-wave)

In case only l = 0 (S-wave) and 1 (P-wave) amplitudes are present :

$$\begin{cases} \sqrt{4\pi}\left\langle Y_0^0 \right\rangle = S^2 + P^2 \\ \sqrt{4\pi}\left\langle Y_1^0 \right\rangle = 2|S||P|\cos\phi_{SP} \\ \sqrt{4\pi}\left\langle Y_2^0 \right\rangle = \frac{2}{\sqrt{5}} P^2 \end{cases}$$

For S- and P- waves only, in the absence of cross-feeds from other channels, the amplitudes and the relative phase are given by these relations.

Kπ and K^+K^- *S*-wave Amplitudes

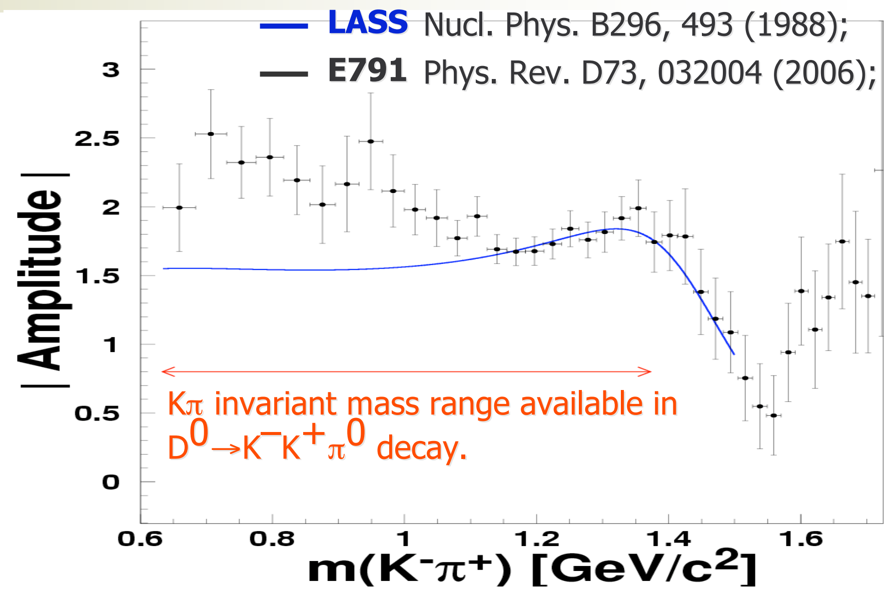
For Kπ S-wave

- The LASS amplitude gives the best fit.
- E-791 fit worse at low mass.

- κ model yields

mass 870 ± 30 MeV/c²
width 150 ± 20 MeV/c²

significantly different from the values reported for κ^0.
- κ with E-791 parameters does not give a satisfactory fit.



Use LASS amplitude for nominal fit and E-791 amplitude for syst. uncertainty.

For K^-K^+ S-wave

- $f_0(980)$ and $a_0(980)$ virtually indistinguishable from each other.
- Both $f_0(980)$ and $a_0(980)$ give satisfactory fits.

Since they are so similar, we try each as a description of the $K\bar{K}$ S-wave amplitude.

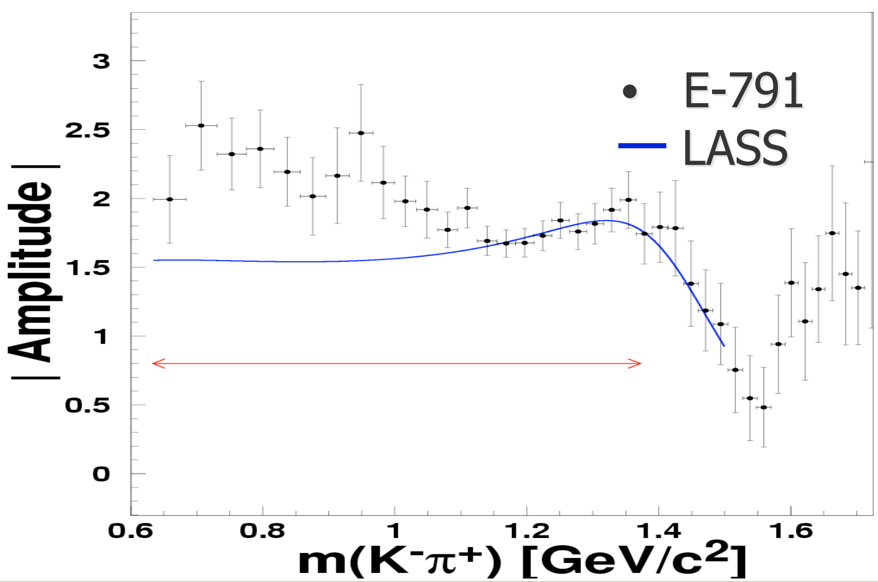
$KK\pi^0$: $K\pi$ S-wave Parametrization

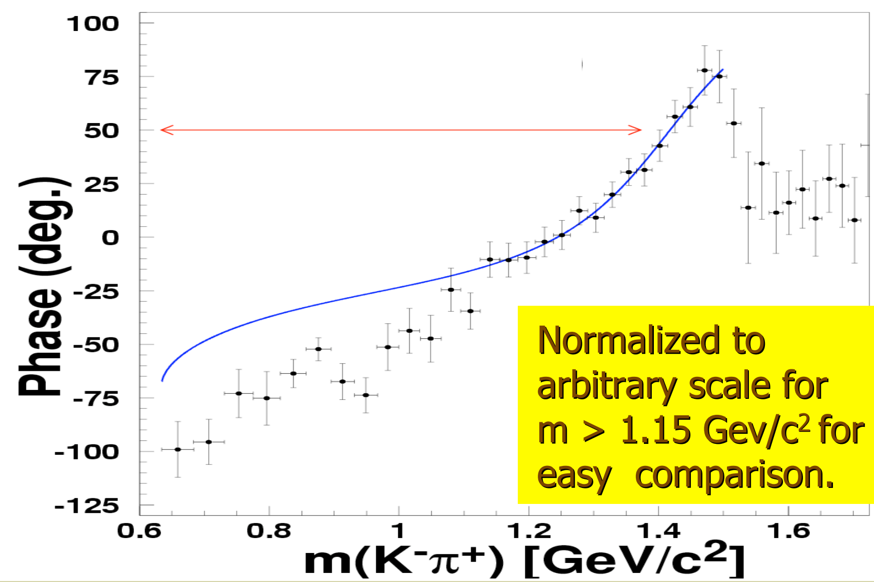
- $K\pi$ S-wave in mass range 0.6–1.4 GeV/c^2 is not well-understood.
- A possible κ state ~ 800 MeV/c^2 has been conjectured, but has only been reported in the neutral state.
- For the $K^+\pi^0$ and $K^-\pi^0$ S-wave amplitudes, we try three models:

- Amplitude from LASS $K^-\pi^+ \to K^-\pi^+$ scattering. Nucl. Phys. B296, 493 (1988);

- $K^-\pi^+$ amplitude from a model-independent analysis of $D^+ \to K^-\pi^+\pi^+$ data by the E791 collaboration. Phys. Rev. D73, 032004 (2006);

- [coherent sum of $\kappa(800)$ + uniform NR + $K^*_0(1430)$]. {No evidence in $K\pi$ elastic scattering.}





LASS Kπ S-wave Parameterization

Kπ S-wave amplitude is described by the coherent sum of an effective range term and the $K^*_0(1430)$ resonance:

$$S(s) = (\sqrt{s}/p) . \sin\Delta . e^{i\Delta}$$

Phase space factor

$$\Delta = \cot^{-1}[1/ap + rp/2] + \cot^{-1}[(m^2_R - s)/(m_R \Gamma_R)]$$

Effective Range (NR) term **$K^*_0(1430)$ resonance term**

a = scat. length, r = eff. range, m_R = mass of $K^*_0(1430)$, Γ_R= width
p = momentum of either daughter in the Kπ rest frame.

For Kπ scattering, S-wave is elastic up to Kη' threshold (1.45 GeV).

Kπ S-wave from $D^0 \to K^-\pi^+\pi^+$ DP

[E791 Collaboration, slide from Brian Meadow's Moriond 2005 talk]

- Divide $m^2(K^-\pi^+)$ into slices
- Find s–wave amplitude in each slice (two parameters)
  - Use remainder of Dalitz plot as an interferometer

$$\frac{d^2\Gamma}{ds_{12}ds_{13}} \propto |\mathcal{S} + (\mathcal{P}+\mathcal{D})|^2$$

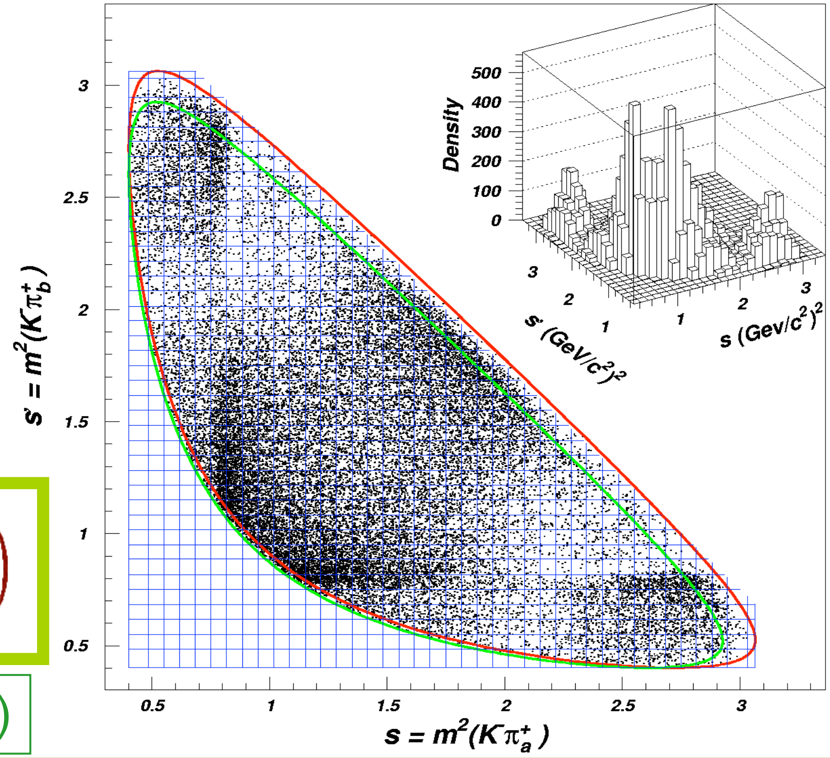
- For s-wave:

- Interpolate between (c_k,γ_k).

- Model P and D waves.

$$\mathcal{S} = \mathrm{Interp}\left(c_k e^{i\gamma_k}\right) \times F_0^D(q,r_D)F_0^R(p,r_R)$$

S ("partial wave")

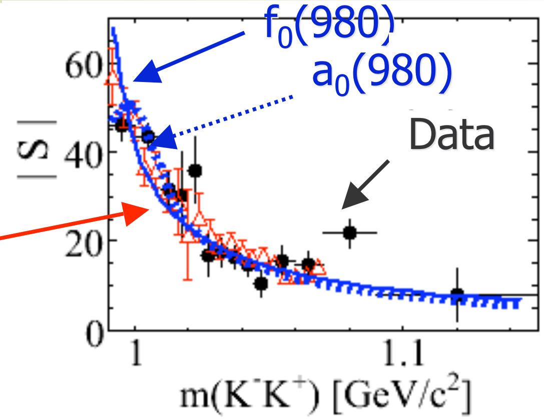


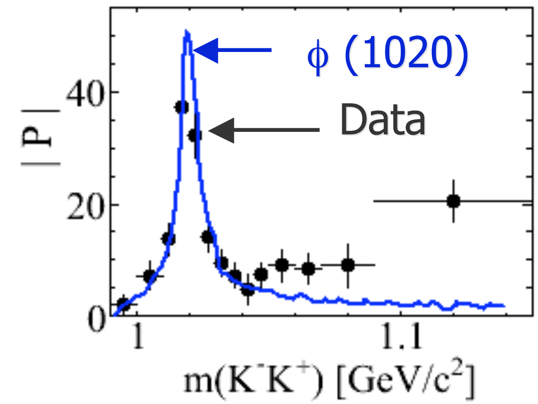
Partial Wave Analysis in K^-K^+ channel

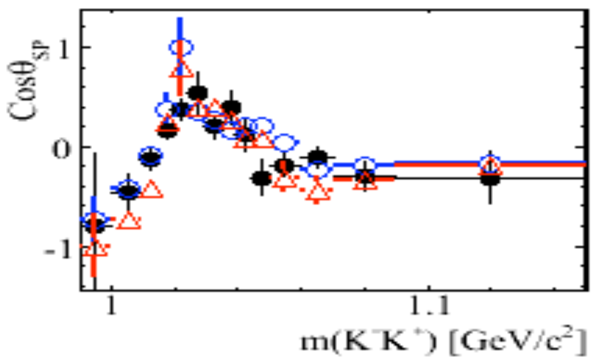
Solve the equations on the previous slide to extract |S|, |P|, and cos θ_{SP}.

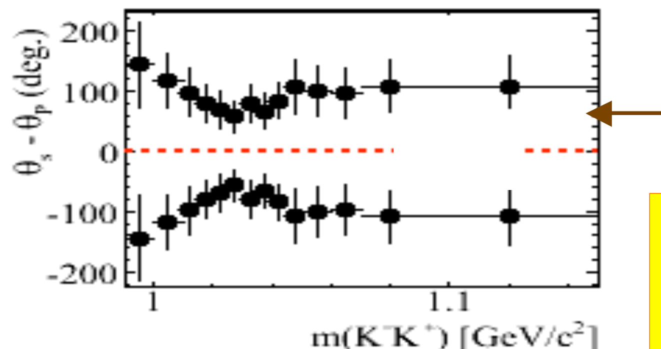
KK S-wave amplitude, extracted in a model independent analysis of the decay $D^0 \rightarrow K^-K^+\overline{K}^0$.

Phys. Rev. D 72, 052008 (2005)



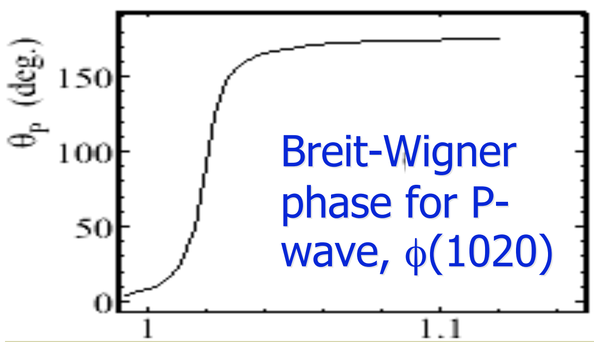


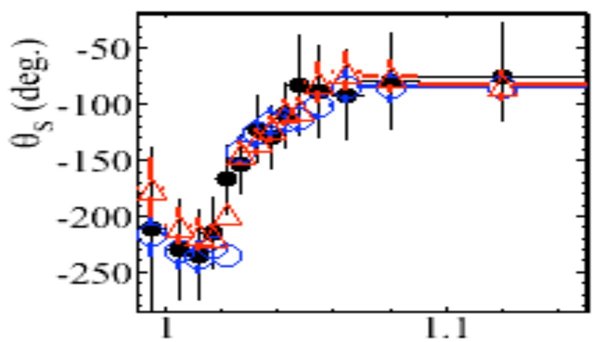




Two solutions for $\theta_{SP} \Rightarrow$ upper one is the physical

Because of the interference from the crossing $K\pi$ channels, the model independent partial-wave analysis performed here is valid only up to about 1.02 -1.03 GeV/c^2



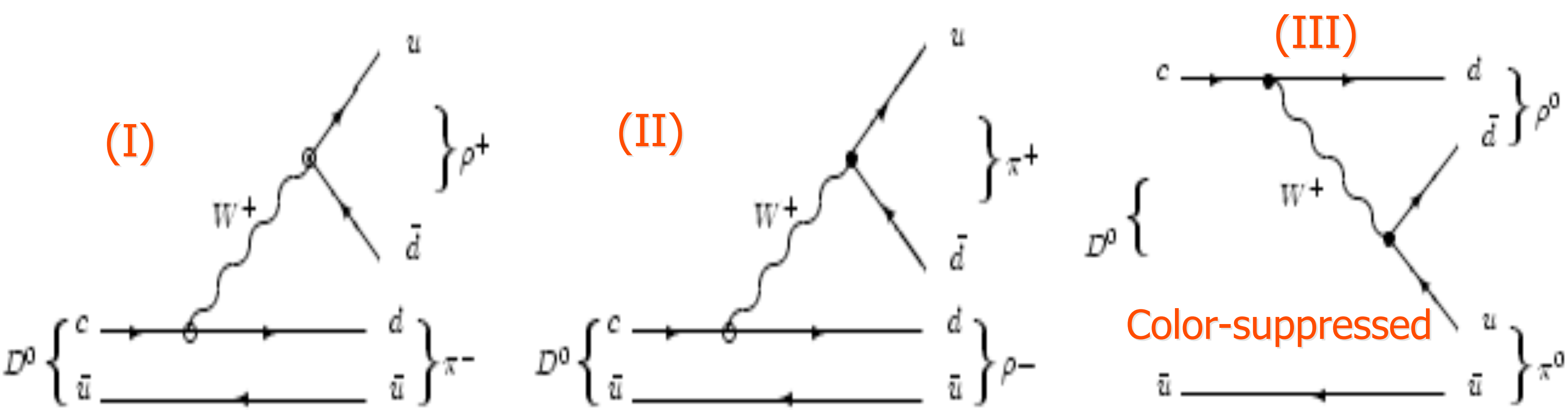


- • Data
- O Model-I
- Δ Model-II

Step 1

$D^0 \to \pi^- \pi^+ \pi^0$ Dalitz Plot Amplitudes

Interference between three types of singly Cabibbo-suppressed amplitudes



$$\mathcal{A}[D^0 \to \pi^- \pi^+ \pi^0] \equiv f_{D^0}(m^2_{\pi^+\pi^0}, m^2_{\pi^-\pi^0})$$
$$\bar{\mathcal{A}}[\bar{D}^0 \to \pi^+ \pi^- \pi^0] \equiv f_{D^0}(m^2_{\pi^-\pi^0}, m^2_{\pi^+\pi^0})$$

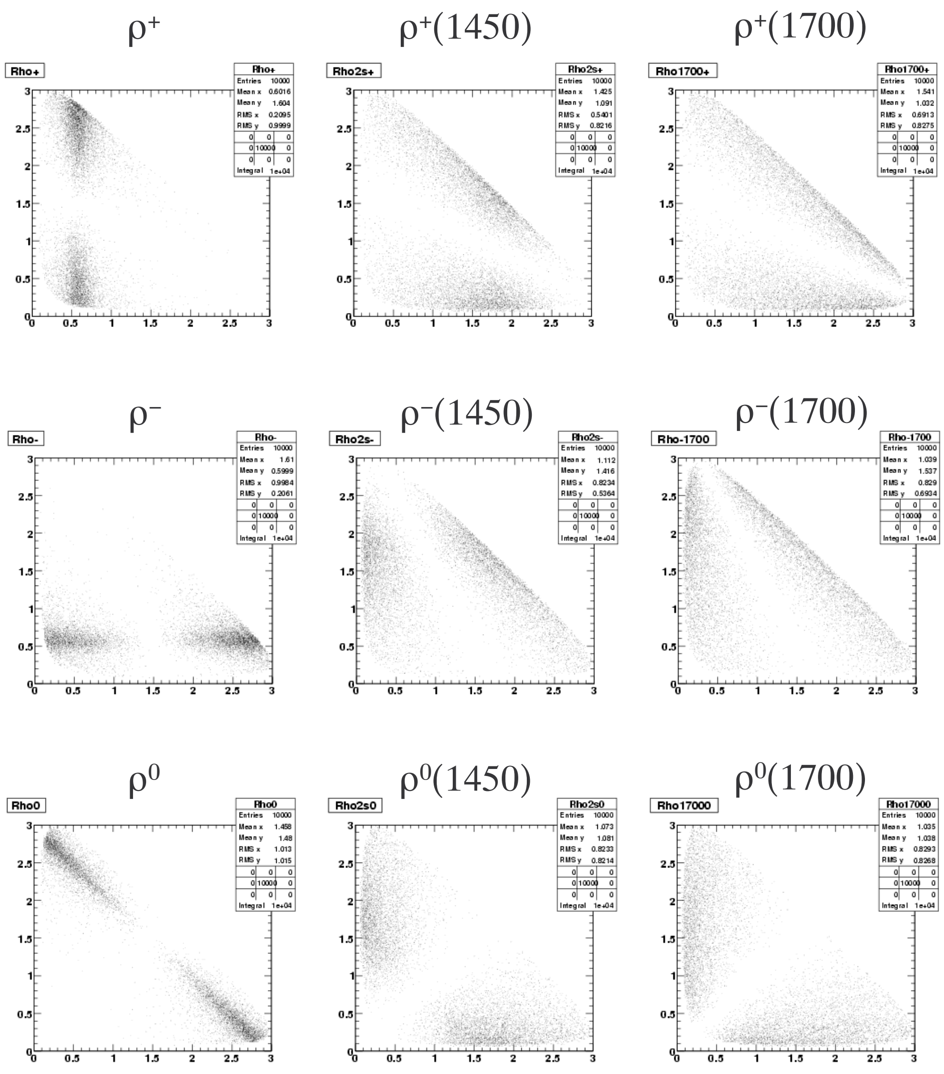
$m^2_{\pi^+\pi^0} + m^2_{\pi^-\pi^0} + m^2_{\pi^+\pi^-} =$
$m^2_{\pi^+} + m^2_{\pi^-} + m^2_{\pi^0} + m^2_{D^0}$

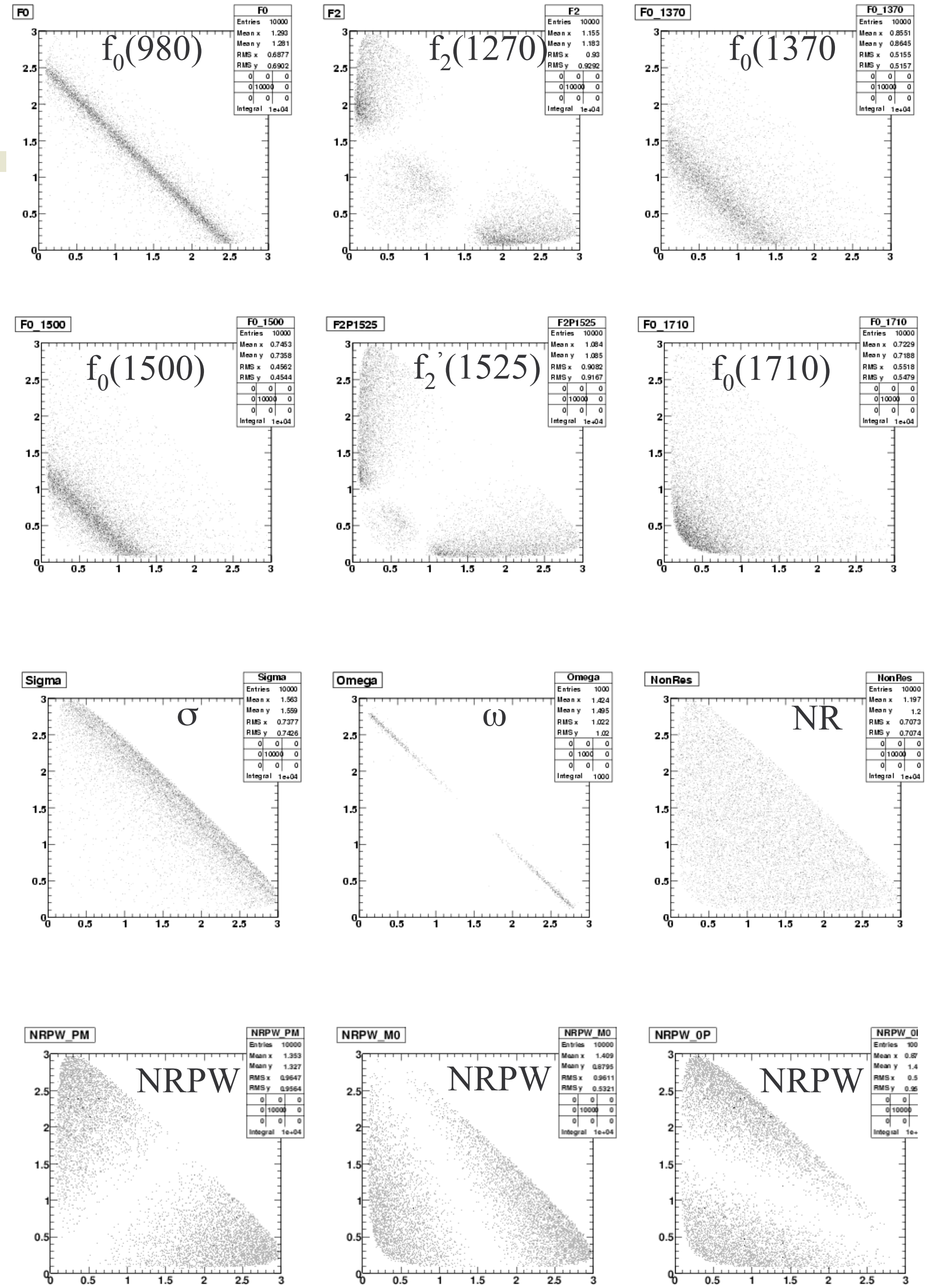
PDF for signal events = $|f|^2$

Assumes no D-mixing, no CP violation in D decays!

Step 1

Signal Dalitz PDFs





Step 1

Strong-phase Diff. & Amplitude Ratio

- The strong phase difference δ_D and relative amplitude r_D between the decays of D^0 and $\bar{D}^0$ to $\rho(770)^+\pi^-$ state are defined, neglecting direct CP violation in D decays, by the equation:

$$r_D e^{i\delta_D} = \frac{a_{D^0\to\rho^-\pi^+}}{a_{D^0\to\rho^+\pi^-}} e^{i(\delta_{\rho^-\pi^+} - \delta_{\rho^+\pi^-})}$$

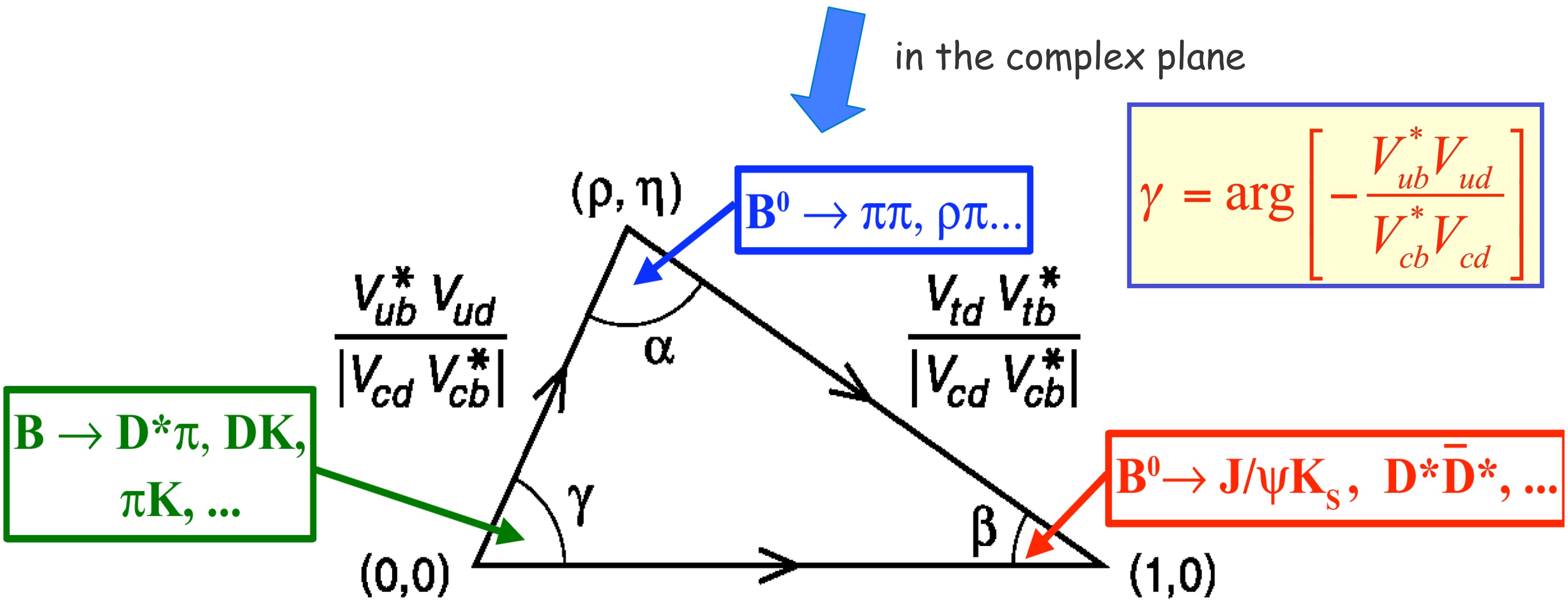
- We find

BaBar	Cleo
$r_D = 0.714 \pm 0.008$ (stat) ± 0.003 (syst) $\delta_D = -2.0°$ (stat) $\pm 0.6° \pm 0.6°$ (syst)	$r_D = 0.65 \pm 0.03$ (stat) ± 0.04 (syst) $\delta_D = -4° \pm 3°$ (stat) $\pm 4°$(syst)
Hep-ex / 0703037 (2007)	Hep-ex / 0306048 (2003)

These measurements are consistent with each other.

The Unitarity Triangle

- V is unitary: $VV^{+}=1$ $= V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



- *Expect* γ to be ~ (60±10)°, *if the Standard Model is consistent*.
- But need to *measure* it directly, need redundant measurements ….
- Several ways to measure γ, no single one of them is "silver bullet" !

Evolution of Methods on γ

- **Gronau, Landon, and Wyler (GLW) Phys. Lett. B 265, 172 (1991)**
  - This was the original $B \to DK$ paper. Reconstruct D in a CP eigenstate.
  - Additional measurements are needed to determine them all: r_B, δ, γ.

Main Drawback:

$BF(B \to DK) \sim \mathbf{10^{-4}}$, $BF(D \to \mathbf{f_{CP}}) \sim \mathbf{10^{-2}}$

Small… $\Rightarrow$ strongly statistics limited

- **Atwood, Dunietz, and Soni (ADS), Phys. Rev. Lett. 78, 3257 (1997)**
  - Noted the sizable interference between the DCS and CF decays of D, and proposed to use them, to realize the interference.
  - Method can't be used standalone either, since there is only one 2-body DCS mode, $D^0 \to K^+\pi^-$, while at least 2 modes are needed. Need additional input of strong phase difference in D decays.

No significant signal with current data

- **Giri, Grossman, Soffer, Zupan (GGSZ) Phys. Rev. D68, 054018 (2003)**
  - Outlines the method for using multi-body D decays with model-dependent and –independent analysis

Will elaborate on this later

- **BaBar, hep-ex/0507101 and Belle, hep-ex/0504013 (2005)**
  - The experimental measurements of γ using $B \to DK$, $D \to K_S\pi^+\pi^-$
- **Bondar, A. Poluektov, ph/0510246 (2005)**
  - MC study of the model-independent (binned Dalitz plot) measurement of γ

Discrete Ambiguities

- The observables are $\cos(\delta + \gamma)$ and $\cos(\delta - \gamma)$, which are invariant under
  - ✓ S_{ex} : $\delta \leftrightarrow \gamma$
  - ✓ $S_{\pm}$: $\delta \rightarrow -\delta, \quad \gamma \rightarrow -\gamma$
  - ✓ S_{π} : $\delta \rightarrow \delta + \pi, \quad \gamma \rightarrow \gamma + \pi$

- If δ_f and $\delta_{f'}$ are different enough, S_{ex} is resolved, since you can't simultaneously satisfy both $\delta_f \leftrightarrow \gamma$ and $\delta_{f'} \leftrightarrow \gamma$

While measuring γ, one encounters two devils: statistics and ambiguity, and they often feed each other.

2-body vs Multi-body D^0 Final States

Advantages of multi-body final states:

- Effectively, provide many final states, due to the variation of r_f and δ_f. This helps to resolve ambiguities down to an irreducible 2-fold ambiguity :)
- Add statistics – access to modes for which the 2-body final-state technique for measuring γ is not applicable :)

Disadvantages:

- More complicated analysis :(
- New systematic errors (how well do we understand the D final-state phase-space distribution?) unless using model-independent analysis approach :(

Overall:

- A-priori, both kinds of states are approximately equally useful in measuring γ. Measurement is statistically limited, need all the modes we can get. In practice, some modes will turn out to be more useful than others.

Dalitz Plot Method

- We saw that at least 2 D final states are needed in order to solve for all the unknowns.
- This 2-state requirement can be satisfied by a single multi-body D final states, in which each point in the final state phase space (Dalitz plot for a 3-body decay) serves effectively as a different final state.
- In terms of the γ analysis, what differentiates 2 final states is their values of r_f and/or δ_f. In this sense, different points in phase space can function as different D final states when they have different values of r_f or δ_f.
- Broad resonances are the most obvious cause for variation of r_f and δ_f in different points of final-state phase space.

Step 2

Event Types in $B^{\pm} \to D_{\pi^-\pi^+\pi^0} K^{\pm}$

1. DK_D: Correctly reconstructed signal ("signal")
2. DK_{bgd}: Mis-reconstructed signal events
3. $D\pi_D$: Correctly-reconstructed $D\pi$ with π misidentified as K
4. $D\pi_{badD}$: $D\pi$ events with a fake D candidate. K candidate is usually a true kaon picked at random from the event
5. DKX: $B \to DK$ with $D \to$ non-$\pi\pi\pi^0$. The K is good
6. $D\pi X$: $B \to D\pi/\rho$ with $D \to$ non-$\pi\pi\pi^0$. K candidate is usually a true kaon picked at random from the event
7. BBC_D: Combinatoric BB events with a good D candidate
8. BBC_{badD}: Combinatoric BB events with a fake D candidate
9. qq_D: Continuum with a good D candidate
10. qq_{badD}: continuum with a fake D candidate

Step 2

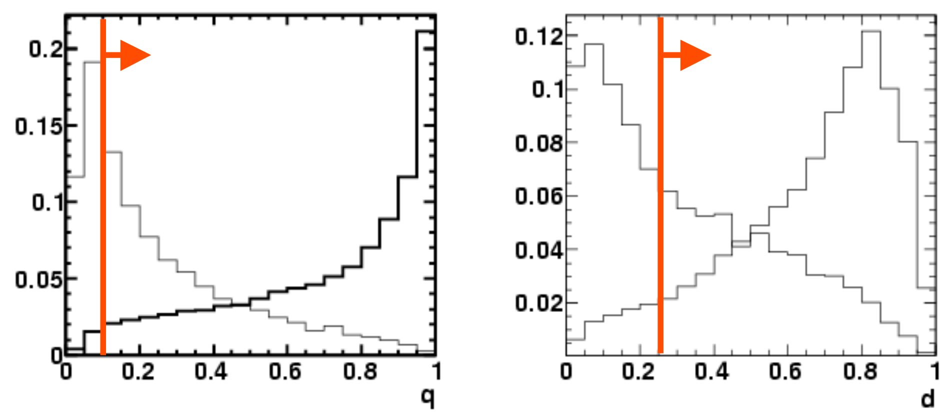
Event Selection for $B^{\pm} \to D_{\pi^-\pi^+\pi^0} K^{\pm}$

Based on BR and asymmetry analysis

Phys. Rev. D72, 071102 (2005)

- $5.272 < m_{ES} < 5.3$ GeV (Avoids DP-m_{ES} correlations in bkg)
- $1.83 < m_D < 1.895$ GeV (Avoids DP-m_D correlations in bkg)
- Kaon, pion identification
- $K_S \to \pi\pi$ veto ($D^0 \to K_S\pi^0$ is a CF decay unrelated to GGSZ method)
- $q > 0.1$ (continuum NN)
- $d > 0.25$ (fake D^0 NN)
- $\varepsilon = 11.4\%$

(only for γ fit)

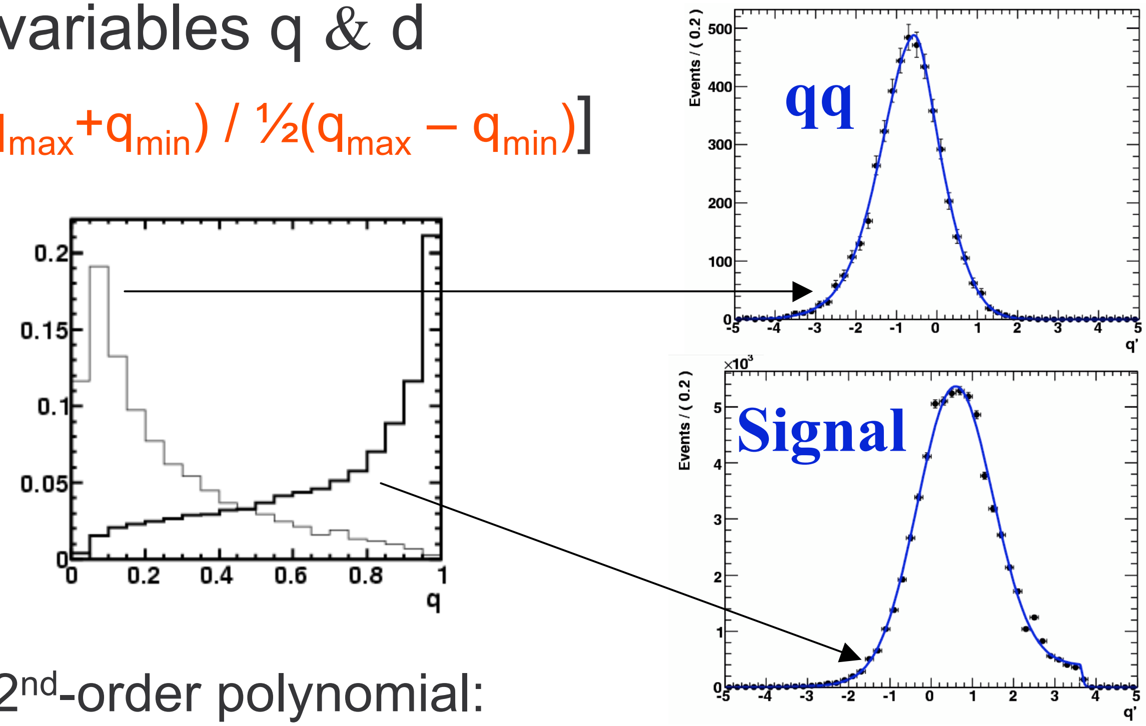


Step 2

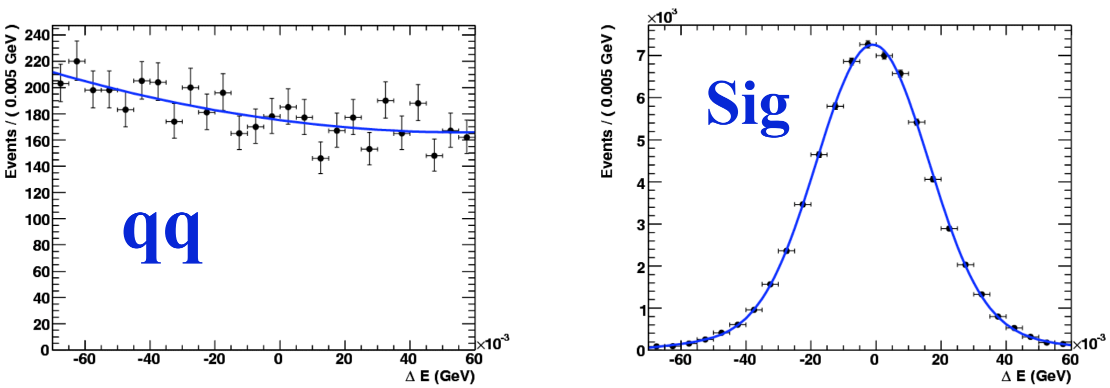
BR of $B^{\pm} \to D_{\pi^-\pi^+\pi^0} K^{\pm}$: PDF Shapes

"Normalize" neural net variables q & d

$q \to q' = \tanh^{-1}[(q - ½ (q_{max}+q_{min}) / ½(q_{max} - q_{min})]$



ΔE PDFs are Gaussians and 2nd-order polynomial:



Fit $B^- \to D_{\pi\pi\pi^0} K^-$ sample with ΔE, q, d

Obtain signal yield and asymmetry.

Step 2

BR & Asymmetry for $B^{\pm} \to D_{\pi^-\pi^+\pi^0} K^{\pm}$

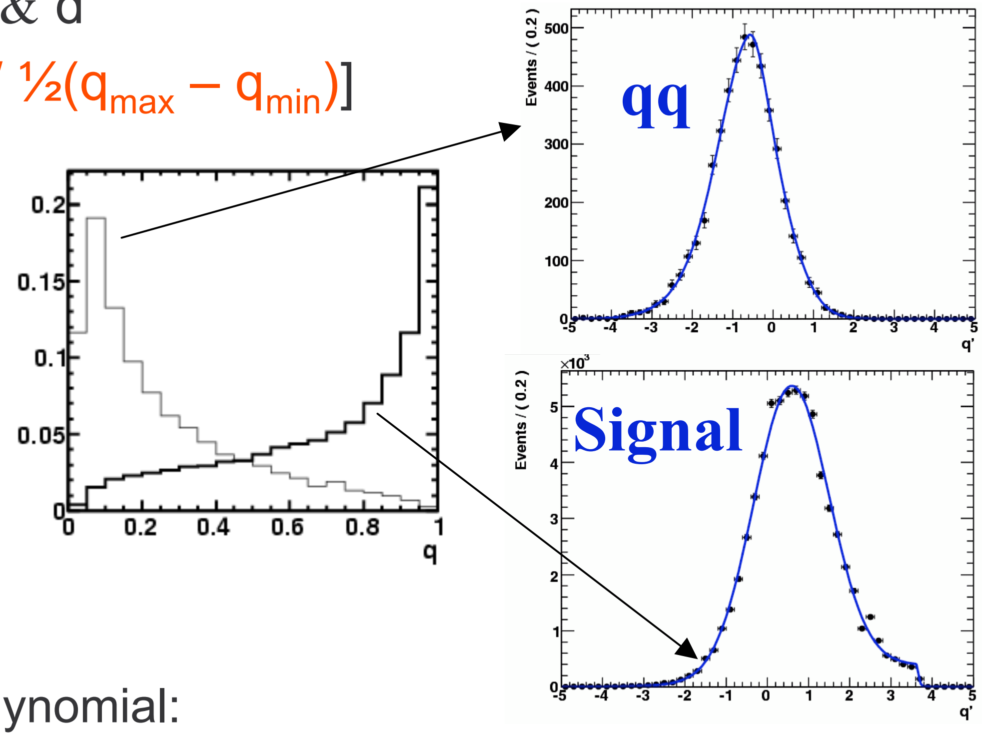
"Normalize" neural net variables q & d

$q \to q' = \tanh^{-1}[(q - \frac{1}{2}(q_{max}+q_{min}) / \frac{1}{2}(q_{max} - q_{min})]$

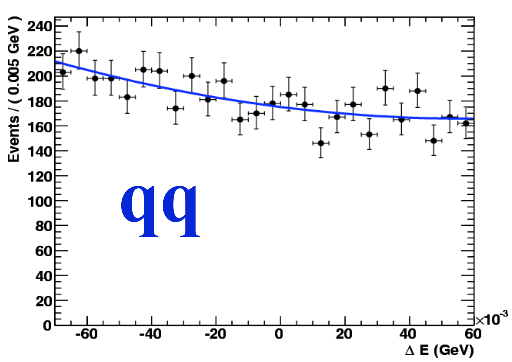
Fit $B^- \to D_{\pi\pi\pi^0} K^-$ sample with ΔE, q, d

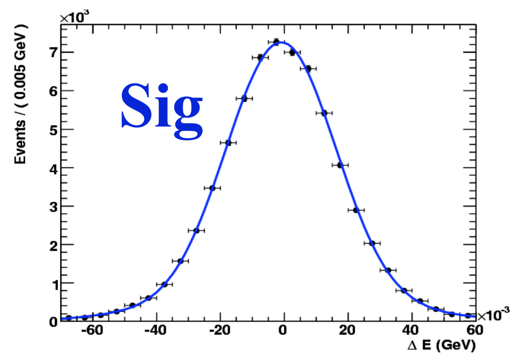
Obtain signal yield & asymmetry

Nsig	170 ± 29
Asym	-0.02 ± 0.15



ΔE PDFs are Gaussian and 2nd-order polynomial:





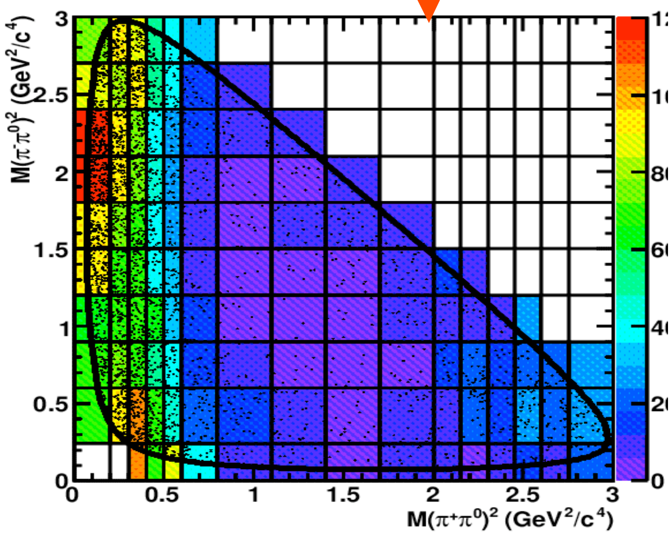
$BR(B^- \to D_{\pi\pi\pi 0} K^-) =$
$(4.6 \pm 0.8 \pm 0.7) \times 10^{-6}$

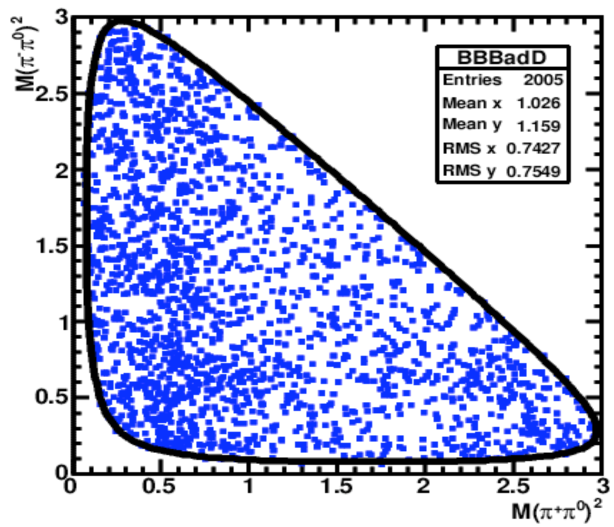
$A(B^- \to D_{\pi\pi\pi 0} K^-) =$
$-0.02 \pm 0.15 \pm 0.03$

Step 3

$B^{\pm} \rightarrow D_{\pi^- \pi^+ \pi^0} K^{\pm}$: Bkg Dalitz Shapes

- Fake-D background Dalitz shapes are NR + 3 incoherent, unpolarized ρ's:
- Shape for 2 event types can't be fit to this way.
  We use an empirical shape from simulation:





For CP Fit

- Fit $D^0 \rightarrow \pi^+\pi^-\pi^0$ Dalitz plot from $B^- \rightarrow D_{\pi\pi\pi^0} K^-$ sample with ΔE, q, s^+, s^-
- NN variable d not used – highly correlated with s^+, s^-
- m_{ES} and M_D not used – correlated with other variables for the background

Step 3

Systematics details

- Dalitz Model:

Dalitz model	ρ_-	θ_-	ρ_+	θ_+
$\text{NR}_S,\ \rho(770)$	0.0633	17.70	0.0359	-7.30
$+\ f_0(980)$	0.0583	22.86	0.0260	4.63
$+\ \rho(1450)$	0.0010	7.20	-0.0138	-8.50
$+\ \rho(1700)$	0.0248	4.12	0.0043	-10.46
$+\ f_0(1370, 1500, 1710),\ f_2(1270)$	-0.0249	-11.89	-0.0287	-1.67
$+\ \sigma$	0	0	0	0
$+\ \text{NR}_P$	0.0106	-0.23	0.0086	-1.46
$+\ \omega,\ f'_2(1525)$	0.0091	2.66	0.0077	-2.07
$R = 0$	0.0017	-8.56	0.0005	-0.09

- BR:

Source	BF error (%)	Section
PID efficiency	3.1	13.12
π^0 efficiency	3.0	13.16
Tracking efficiency	1.5	13.17
B counting	1.1	13.18
Total	4.70	

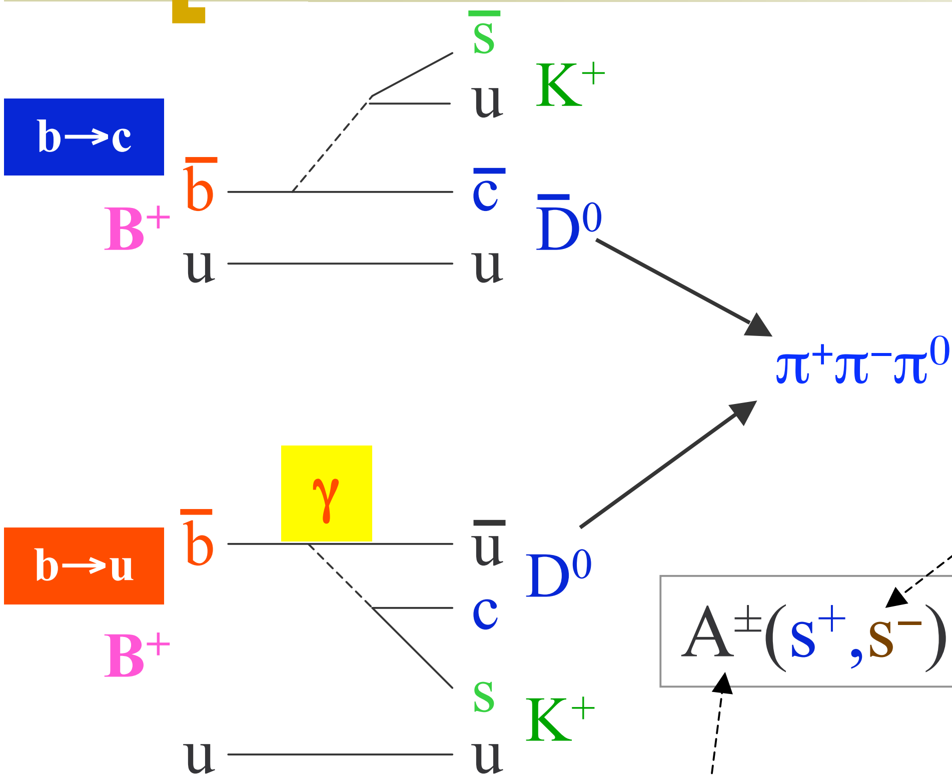
- CP systematics

Source	ρ_-	θ_-	ρ_+	θ_+	Section
$\mathcal{B}(B^- \to D^0 K^-)$	0.0288	1.56	0.0277	1.05	13.19
$\mathcal{B}(D^0 \to K^- \pi^+ \pi^0)$	0.0174	0.88	0.0167	0.66	13.19
$\frac{\mathcal{B}(D^0 \to \pi^+\pi^-\pi^0)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^0)}$	0.0058	0.01	0.0056	0.01	13.19
Signal efficiency	0.0148	0.02	0.0141	0.03	13.19
$N_{B\overline{B}}$	0.0049	0.01	0.0046	0.01	13.19
Total	0.0375	1.79	0.0360	1.24	

Step 3

Extraction of γ : Basic Idea

Atwood et al., PRL78, 3257 (1997)
Giri et al., PRD68,054018 (2003)



- δ_B is strong phase diff. of $A(B^- \to D^0K^-)$ and $A(B^- \to \overline{D}^0K^-)$
- Unknowns: r_B, δ_B and γ

Dalitz plot variables

$$A^{\pm}(s^+,s^-) = f_D(s^+,s^-) + r_B e^{i(\delta\pm\gamma)} f_D(s^-,s^+)$$

$B^{\pm}\to D_{\pi\pi\pi^0}K^{\pm}$ amplitude — $\overline{D}^0\to\pi\pi\pi^0$ amplitude — $D^0\to\pi\pi\pi^0$ amplitude

- Based on GGSZ method of **PRD68, 054018**, so far used only with $D\to K_S\pi^+\pi^-$
- Goal: add modes for maximum γ precision

Step 3

Add more Information to the Likelihood

- The Dalitz plot shape $|A^{\pm}(s^{+},s^{-})|^2$ depends on the CP parameters $r_B e^{i(\delta\pm\gamma)}$
  - Previous Dalitz analyses, with $K_S\pi^+\pi^-$, used only this signature

$= x_{\pm} + y_{\pm}$

- But the branching fractions = $\int|A^{\pm}(s^{+},s^{-})|^2$ are also sensitive to the CP parameters
  - Using both the shape and the absolute rates gives higher sensitivity

- It turns out that in this mode, the BRs give a higher sensitivity
  - Don't know how it is in $K_S\pi^+\pi^-$ – need to check. If the same is true there, expect significant improvement in $K_S\pi^+\pi^-$ sensitivity to γ

Step 3

CP Parameters: Max Likelihood Fit

- To make use of both the shape and the absolute decay rates, we minimize the function

$$L = L_{DP} + L_{BA}$$

$$L_{DP} = -\log \prod P_{DP}$$

$$L_{BA} = \tfrac{1}{2}\, Y_i\, V_{ij}^{-1}\, Y_j$$

$$Y = \begin{pmatrix} N_{meas} - N_{expected} \\ Asym_{meas} - Asym_{expected} \end{pmatrix}$$

V = error matrix from N and Asym fit

$$N^{\pm}_{expected} = \eta \int |A^{\pm}(s^+,s^-)|^2\, \varepsilon(s^+,s^-) \,/\, \int |f_D(s^+,s^-)|^2\, \varepsilon(s^+, s^-)$$

where η = $1/2\, N_{BB}\, \varepsilon\, BR(D^0 \to \pi\pi\pi^0)\, BR(B^- \to D^0 K^-)$

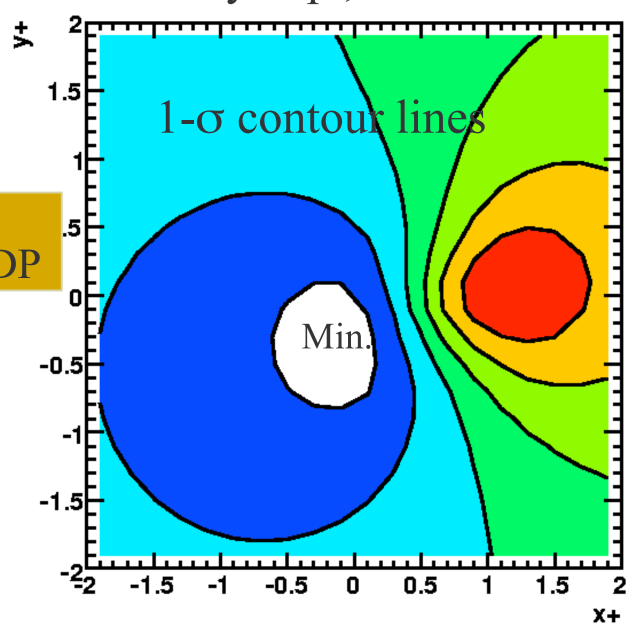
Step 3

Behavior of L_{DP} & L_{BA} for $x_{true} = y_{true} = 0$

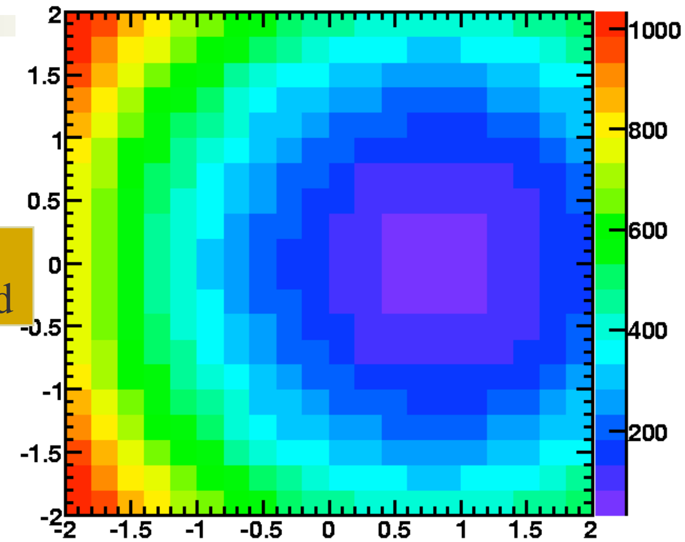
$$r_B e^{i(\delta \pm \gamma)} = x_{\pm} + y_{\pm}$$

Toy exp., S+B

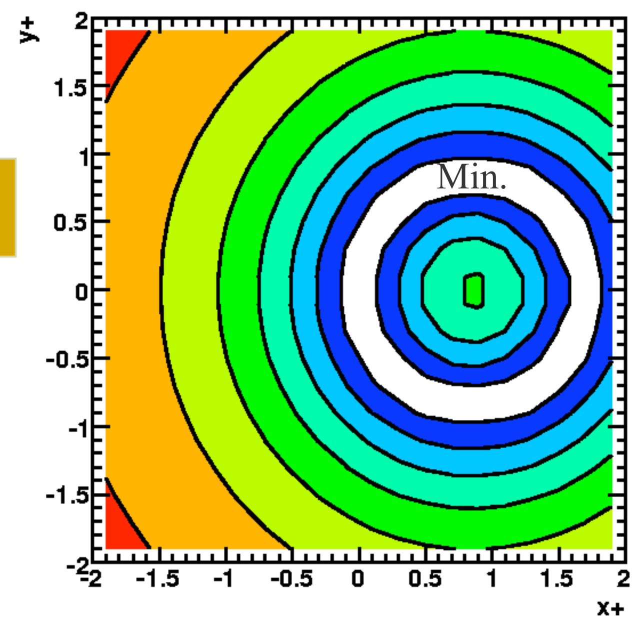
L_{DP}



$N^{+}_{expected}$



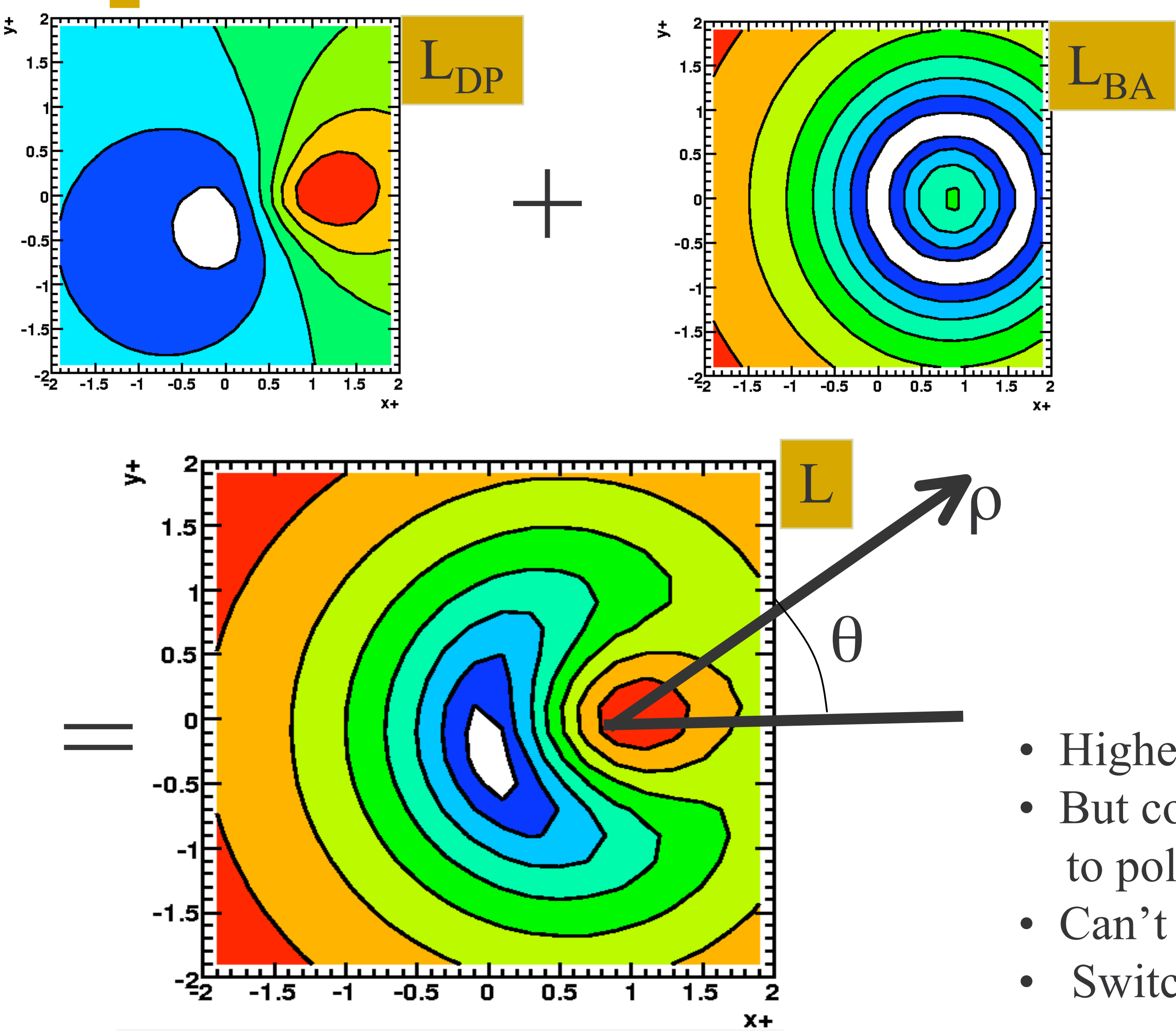
L_{BA}



- L_{DP} (L_{BA}) has Cartesian (polar) symmetry
- L_{BA} is more sensitive (denser contour lines) in radial direction (ρ), not sensitive at all in θ

Step 3

Combined behavior $L = L_{DP} + L_{BA}$



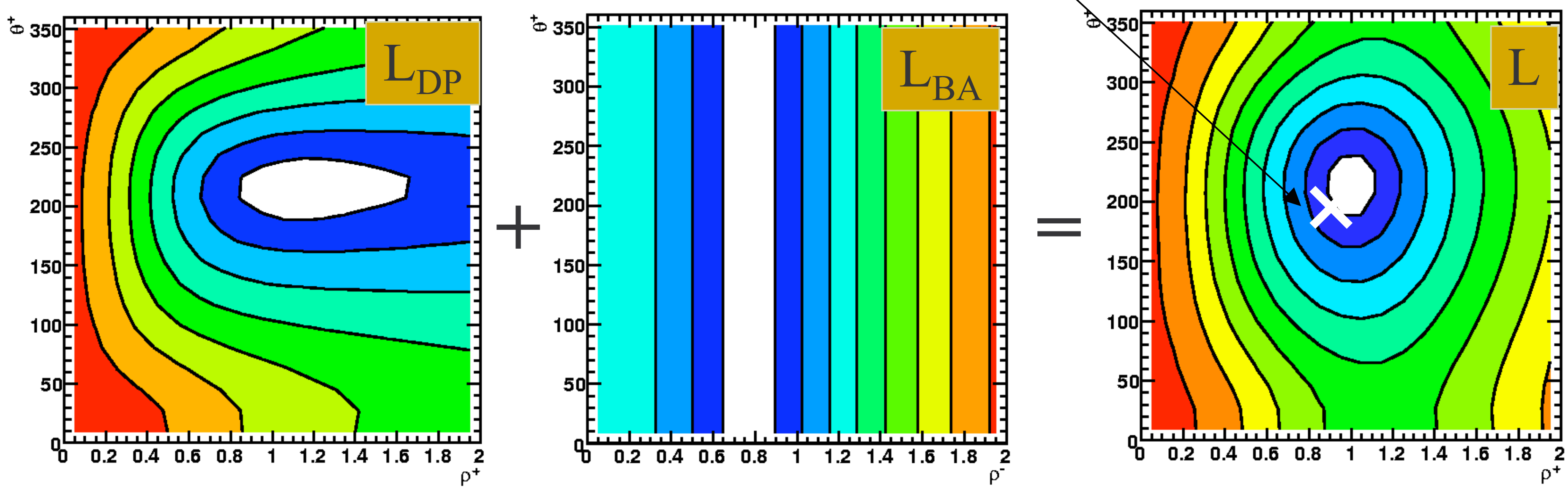
- Highest sensitivity
- But correlated contours due to polar symmetry of L_{BA}
- Can't quote sensible errors
- Switch to polar coordinates

Polar coordinates

$$\rho_{\pm} \equiv \sqrt{(x_{\pm} - x^0)^2 + y_{\pm}^2} \qquad \theta_{\pm} \equiv \tan^{-1}\left(\frac{y_{\pm}}{x_{\pm} - x^0}\right)$$

$$x^0 = \int f_D(s^+, s^-)^* \, f_D(s^-, s^+) \, ds^- ds^+ = 0.85$$

$\rho_{\pm} = x^0$ and $\theta = 180°$ for $r_B = 0$ (no CP violation)



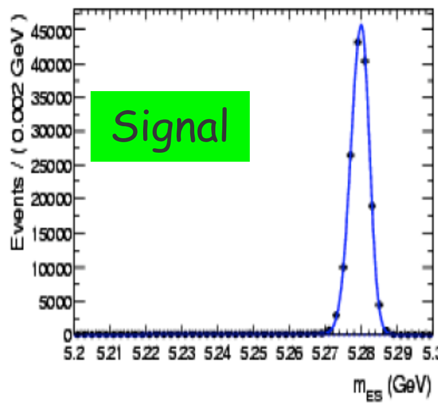
Summary on γ

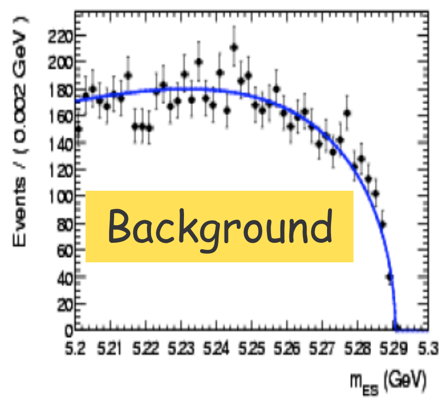
- Direct measurement of γ is crucial to constrain new physics contributions in quark sector of the Standard Model.
- Many different approaches to measure γ. Information from GLW, ADS, GGSZ, and other methods are all useful.
- The GGSZ/Dalitz method has emerged as the most powerful technique.
- Precise parameterizations of the amplitudes and phases and the inclusion of information on branching ratio and decay-rate asymmetry improve sensitivity in γ. A lot of progress made in the analysis and technique development.
- Statistics are the only thing holding us back ! Adding additional D decay modes to $B \rightarrow DK$ and combining results from them will definitely help in the future analysis.

γ: Key Analysis Technique

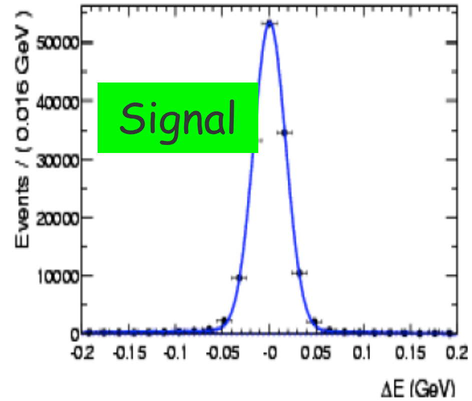
Exploit kinematics of $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ for signal selection

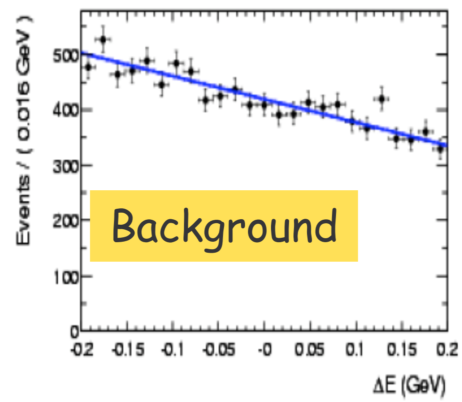
$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$



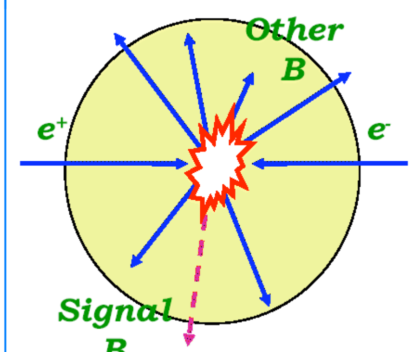


$$\Delta E = E_B^* - E_{beam}^*$$

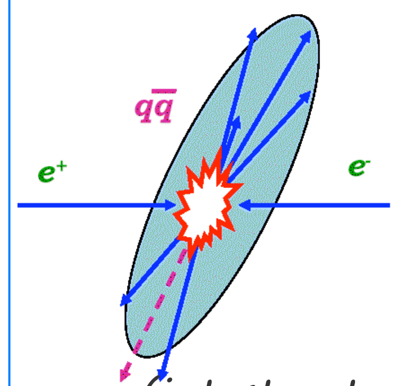




Event topology



(spherical)

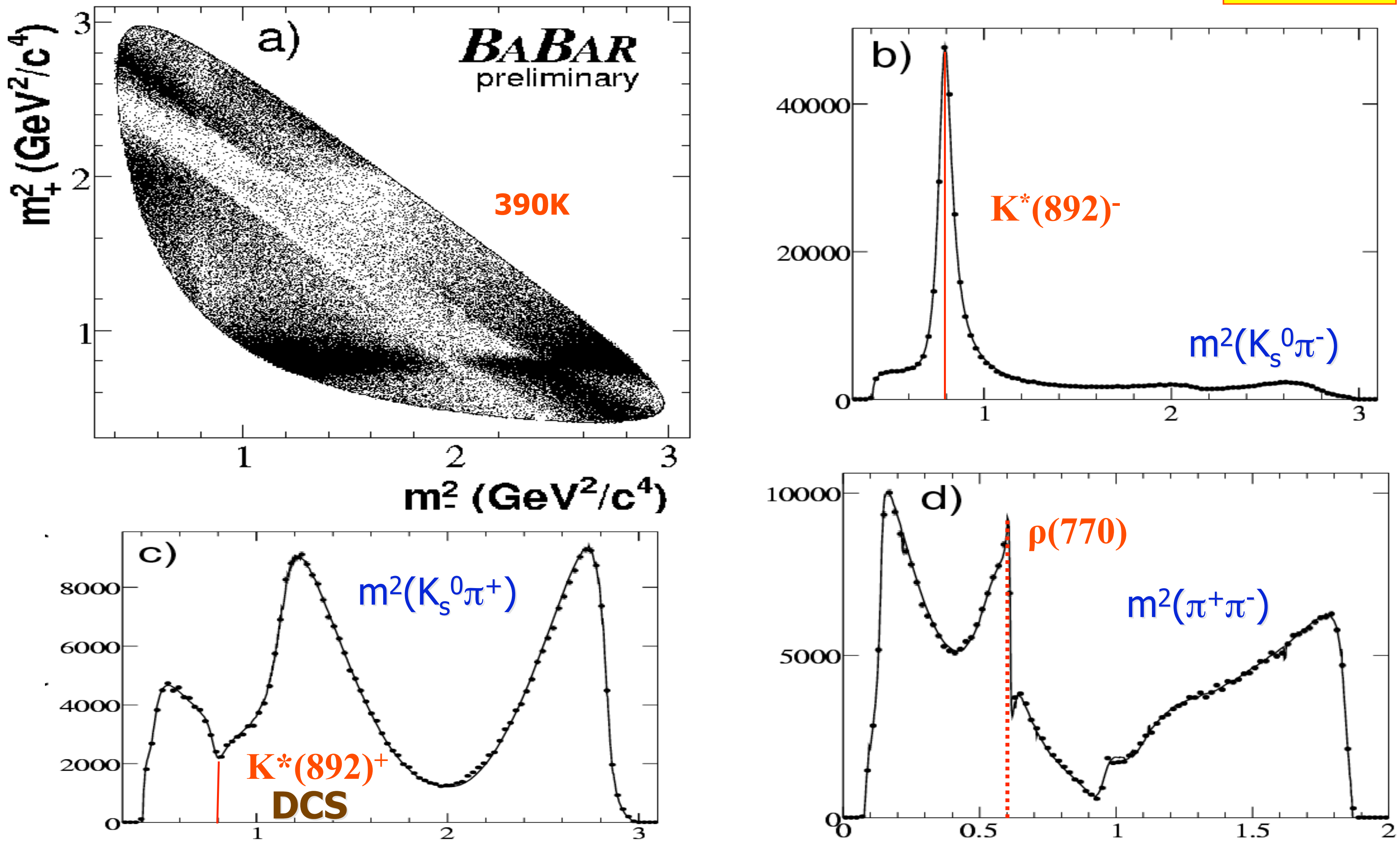


(jet-structure)

$D^0 \rightarrow K_S^0\pi^+\pi^-$ Dalitz Plot analysis

Motivation: **CKM angle γ using $B \rightarrow D[K_S^0\pi^+\pi^-]K^-$ decay**

270 fb^{-1}



$D^0 \to K_s^0 \pi^+ \pi^-$ (Isobar Model)

BABAR™

Component	$Re\{a_r e^{i\phi_r}\}$	$Im\{a_r e^{i\phi_r}\}$	Fit fraction (%)
$K^*(892)^-$	-1.223 ± 0.011	1.3461 ± 0.0096	58.1
$K_0^*(1430)^-$	-1.698 ± 0.022	-0.576 ± 0.024	6.7
$K_2^*(1430)^-$	-0.834 ± 0.021	0.931 ± 0.022	3.6
$K^*(1410)^-$	-0.248 ± 0.038	-0.108 ± 0.031	0.1
$K^*(1680)^-$	-1.285 ± 0.014	0.205 ± 0.013	0.6
$K^*(892)^+$ DCS	0.0997 ± 0.0036	-0.1271 ± 0.0034	0.5
$K_0^*(1430)^+$ DCS	-0.027 ± 0.016	-0.076 ± 0.017	0.0
$K_2^*(1430)^+$ DCS	0.019 ± 0.017	0.177 ± 0.018	0.1
$\rho(770)$	1	0	21.6
$\omega(782)$	-0.02194 ± 0.00099	0.03942 ± 0.00066	0.7
$f_2(1270)$	-0.699 ± 0.018	0.387 ± 0.018	2.1
$\rho(1450)$	0.253 ± 0.038	0.036 ± 0.055	0.1
Non-resonant	-0.99 ± 0.19	3.82 ± 0.13	8.5
$f_0(980)$	0.4465 ± 0.0057	0.2572 ± 0.0081	6.4
$f_0(1370)$	0.95 ± 0.11	-1.619 ± 0.011	2.0
σ (490, 406)	1.28 ± 0.02	0.273 ± 0.024	7.6
σ'(1024, 89)	0.290 ± 0.010	-0.0655 ± 0.0098	0.9

$K^*(892)^-$: 58 %
$\rho(770)^0$: 22 %
Non-Res.: 8 %
σ (500): 8 %
$K^*(1430)^-$: 7 %
$f_0(980)$: 6 %

Important for γ and D-mixing measurements

hep-ex/0607104

The 'Cartesian coordinates'

- Goal: Fit the Dalitz plot distributions of $D^0 \rightarrow K_S\pi\pi$ from B^- and B^+ decays to extract r_B, δ_B and γ
- Complication: The Maximum Likelihood fit overestimates r_B and underestimates the error of γ
- Solution: Write the Likelihood as a function of the cartesian coordinates $x_\pm$, $y_\pm$:

$$x_\mp = r_B \cos(\delta_B \mp \gamma)$$
$$y_\mp = r_B \sin(\delta_B \mp \gamma)$$

$$\Gamma(B^+) \propto \left|f_+\right|^2 + (x_+^2 + y_+^2)\left|f_-\right|^2 + 2x_+ \,\mathrm{Re}\left(f_+ f_-^*\right) + 2y_+ \,\mathrm{Im}\left(f_+ f_-^*\right)$$
$$\Gamma(B^-) \propto \left|f_-\right|^2 + (x_-^2 + y_-^2)\left|f_+\right|^2 + 2x_- \,\mathrm{Re}\left(f_- f_+^*\right) + 2y_- \,\mathrm{Im}\left(f_- f_+^*\right)$$

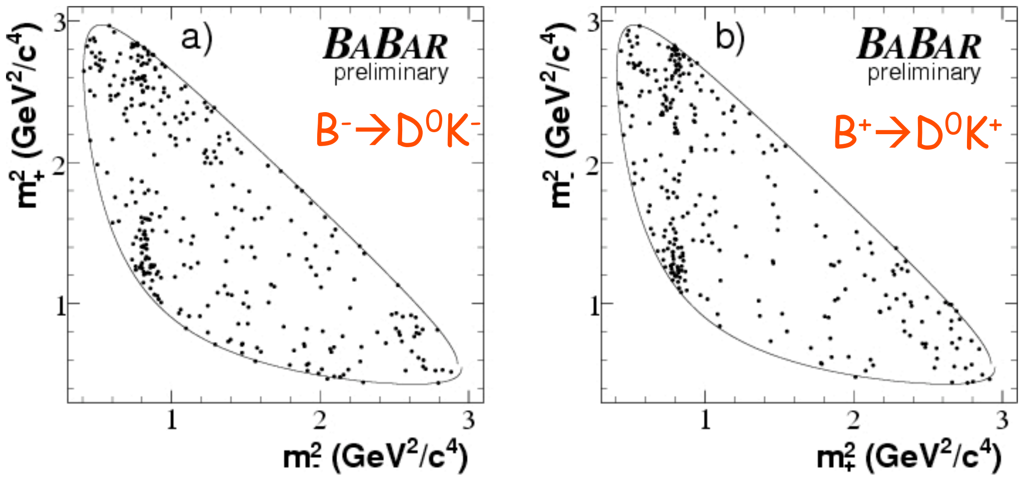
$$f_\mp \equiv A_D(m_\mp^2, m_\pm^2)$$

Likelihood is Gaussian and unbiased in $x_\pm$, $y_\pm$

- Strategy: Extract $x_\pm$, $y_\pm$ from ML fit to the $D^0 \rightarrow K_S\pi\pi$ Dalitz plot and derive r_B, δ_B and γ from $x_\pm$, $y_\pm$ with stat. procedure

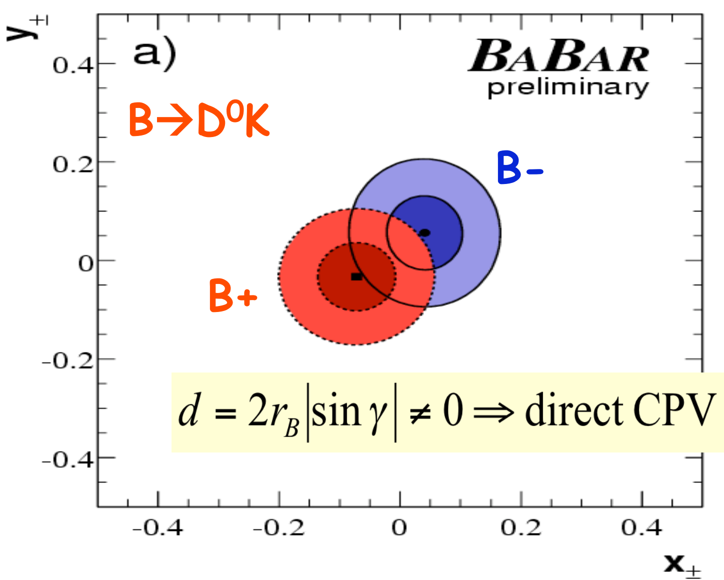
From x,y to γ

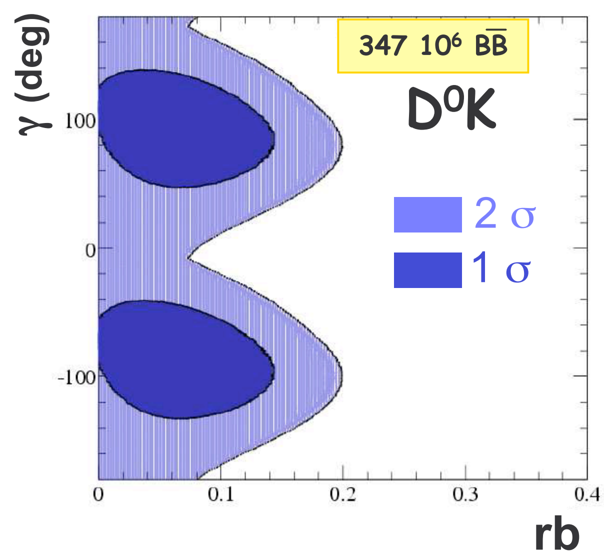
$D \rightarrow K_S \pi\pi$ Dalitz plot distribution in signal region



Used frequentist method to extract γ, r_B, δ_B from $(x_\pm, y_\pm)$

$(x_\pm, y_\pm)$ are extracted from the $D^0 \rightarrow K_S\pi\pi$ Dalitz plot





$r_B < 0.142$ ($r_B < 0.198$)
1σ (2σ)

$\gamma = (92 \pm 41 \pm 10 \pm 13)^o$
(stat) (syst) (Dalitz)

(5dim confidence intervals projections)

hep-ex/0607104
hep-ex/0507101

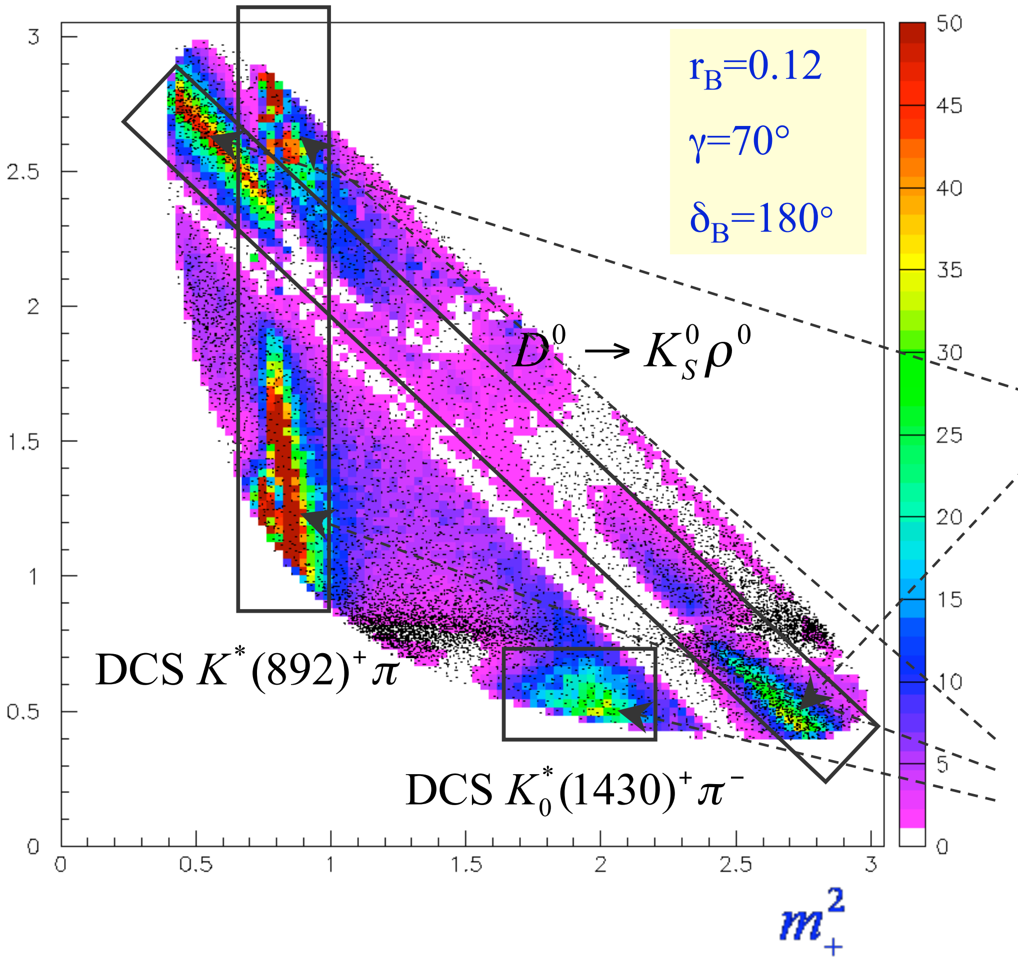
Sensitivity to γ over Dalitz plot

- Sensitivity varies strongly over Dalitz plane
- 2nd derivative of the log(L) event-by-event weighs the event

$$\sigma^2(\gamma) \sim \frac{1}{\frac{d^2\ln(L)}{d\gamma^2}}$$

$$\text{weight} = \frac{d^2\ln(L)}{d\gamma^2}$$

events: points (weight = 1)



Interference of $B^- \to D^0[\to K_S^0\rho^0]K^-$ with $B^- \to \overline{D}^0[\to K_S^0\rho^0]K^-$

≡ GLW like

Interference of $B^- \to D^0[\to K^{*+}\pi^-]K^-$ (suppressed) with $B^- \to \overline{D}^0[\to K^{*+}\pi^-]K^-$

≡ ADS like

CP Violation in Charm Decays

- SM predictions $O(0.01\%)$. ← **CPV in charm decays highly suppressed.**
- New Physics must be playing a role if an asymmetry is observed with present experimental sensitivity $[O(1\%)]$.
- The CP violation can be of any of the three types:
  - in decay ← **direct CPV.**
  - in mixing between D^0 and $\bar{D}^0$
  - in interference of decay with mixing ← **indirect CPV.**
- Indirect CPV is universal.
- Direct CPV is localized => different parts of phase-space might have different asymmetries (and may even cancel each other out when integrated over the whole phase-space).

For details:

Y. Grossman, A.L. Kagan, and Y. Nir, Phys. Rev. D75, 036008 (2007).
I.I. Bigi, hep-ph/0104008 (2001).

Why 3-body SCS D^0 Decays ?

- 3-body decays permit the measurement of phase differences which are required to create CP violation in the interference between SM and non-SM processes.
- Access to both CP eigen states ($\rho^0\pi^0$, $f_0\pi^0$, $\phi\pi^0$) and flavor states ($\rho^{\pm}\pi^{-+}$, $K^{*\pm}K^{-+}$). Therefore, can probe diverse possibilities of CPV.
- Also, these are relatively high statistics modes (84000 $D^0/\bar{D}^0 \to \pi\pi\pi^0$ and 15000 $KK\pi^0$ events).

–

Find that, with the present data sample, we are sensitive to asymmetry of the order *O*(1%) in amplitude and *O*(1°) in phase in the main decay channels. Sensitivity is higher in $D \to \pi^-\pi^+\pi^0$ decay compared to $D \to K^-K^+\pi^0$.

What is Known ?

- CLEO measures A_{CP} in $D^0 \to \pi^- \pi^+ \pi^0$ decays

$$A_{CP} = \mathbf{0.01}^{+0.07}_{-0.05} \pm 0.05$$

Asymmetry in the Dalitz-Plot-integrated coherent sum of all amplitudes in the Dalitz Plot for D^0 and $\bar{D}^0$ events.

- No $\boldsymbol{A_{CP}}$ measurements available for $D^0 \to K^- K^+ \pi^0$

PDG 2006 ⇒

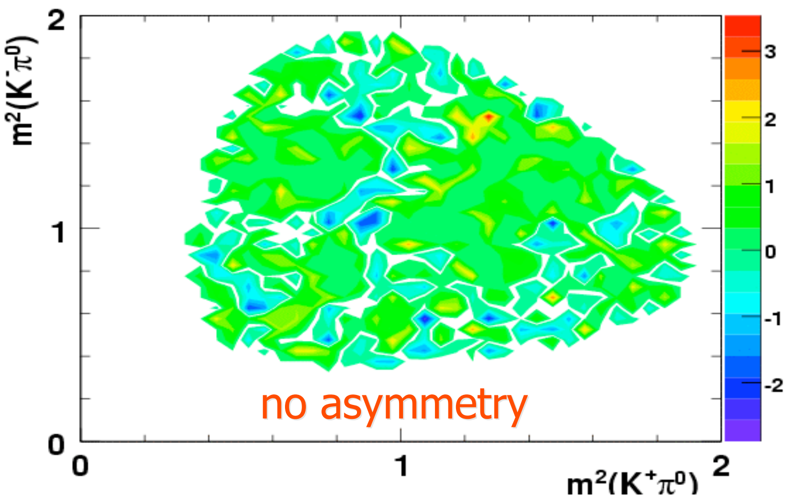
- $A_{CP}(K^+K^-) = 0.014 \pm 0.010$
- $A_{CP}(\pi^+\pi^-) = 0.013 \pm 0.012$
- $A_{CP}(\pi^0\pi^0) = 0.00 \pm 0.05$
- $A_{CP}(K^+K^-\pi^+\pi^-) = -0.08 \pm 0.07$

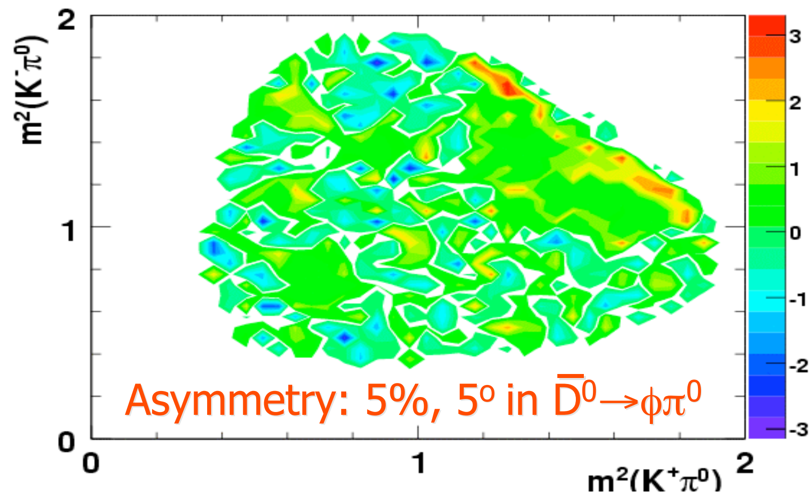
BaBar 2007 ⇒

- $A_{CP}(K^+K^-) = (0.00 \pm 0.34 \pm 0.13)\%$
- $A_{CP}(\pi^+\pi^-) = (-0.24 \pm 0.52 \pm 0.22)\%$

Sensitivity to CPV: MC Studies continued …

$D^0 \to K^- K^+ \pi^0$, 25 times larger statistics





Generate asymmetry in amplitude, phase of either $\bar{D}^0 \to \rho^0\pi^0$ [$\bar{D}^0 \to \phi\pi^0$] or $\bar{D}^0 \to \rho^-\pi^+$ [$\bar{D}^0 \to K^{*-}K^+$]. Then fit the resulting Dalitz plot to see with what sensitivity we get the original parameters back.

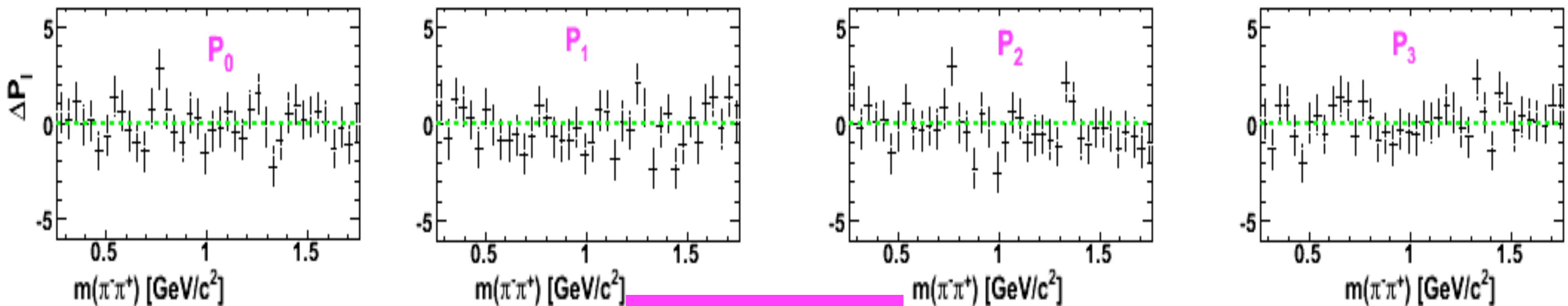
Find that, with the present data sample, we are sensitive to asymmetry of the order *O*(1%) in amplitude and *O*(1°) in phase in the main decay channels. Sensitivity is higher in $D^0 \to \pi^-\pi^+\pi^0$ decay compared to $D^0 \to K^-K^+\pi^0$.

Sensitivity to CPV in Simulation

Plot the difference of moments between D^0 and $\bar{D}^0$ events

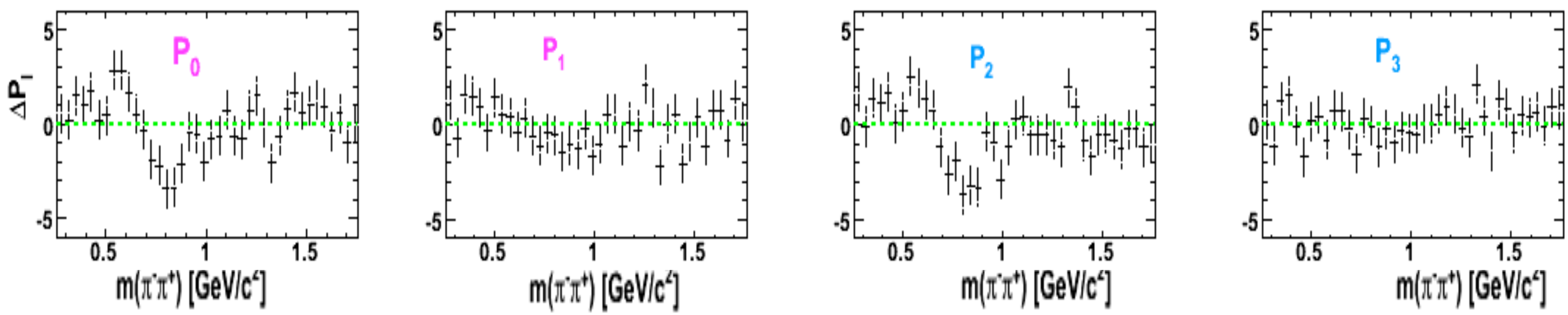
Only 4 moments shown here, but χ^2/ν comes from first 8 moments. Also take correlation among the moments into account in each bin.

(i) When there is no asymmetry (i.e., "noise level")



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

(ii) When $\bar{D}^0 \to \rho^0\pi^0$ amplitude is changed by -5% and its phase changed by -5°



Definition of χ^2 for Model Indep. Methods

Dalitz Plot Comparison: Calculate normalized residual in each bin

$$\Delta = \frac{\left(n_{\bar{D}^0} - R \cdot n_{D^0}\right)}{\sqrt{\sigma^2_{n_{\bar{D}^0}} + R^2 \cdot \sigma^2_{n_{D^0}}}}$$

Then $\chi^2 = \sum_{\text{bins}} \Delta^2$

$R = N_D / N_{Dbar}$

Angular Moments Comparison: Calculate normalized residual in each bin for first eight moments (l = 0 - 7)

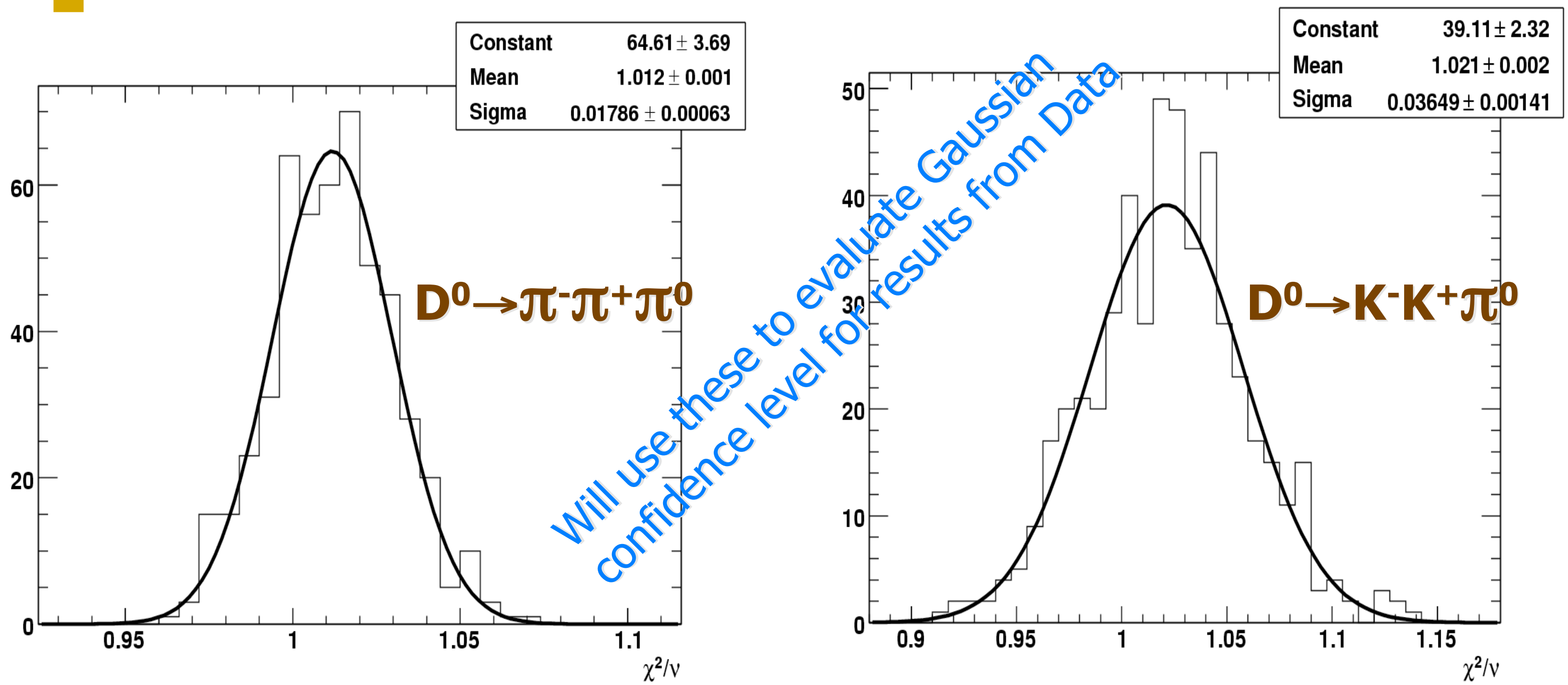
$$X_l = \frac{\bar{P}_l - R.P_l}{\sqrt{\sigma^2_{\bar{P}_l} + R^2.\sigma^2_{P_l}}}$$

Then $\chi^2 = \sum_{\text{bins}} \sum_i \sum_j X_i \rho_{ij} X_j$

where ρ_{ij} is the correlation between moments of order i and j in a bin

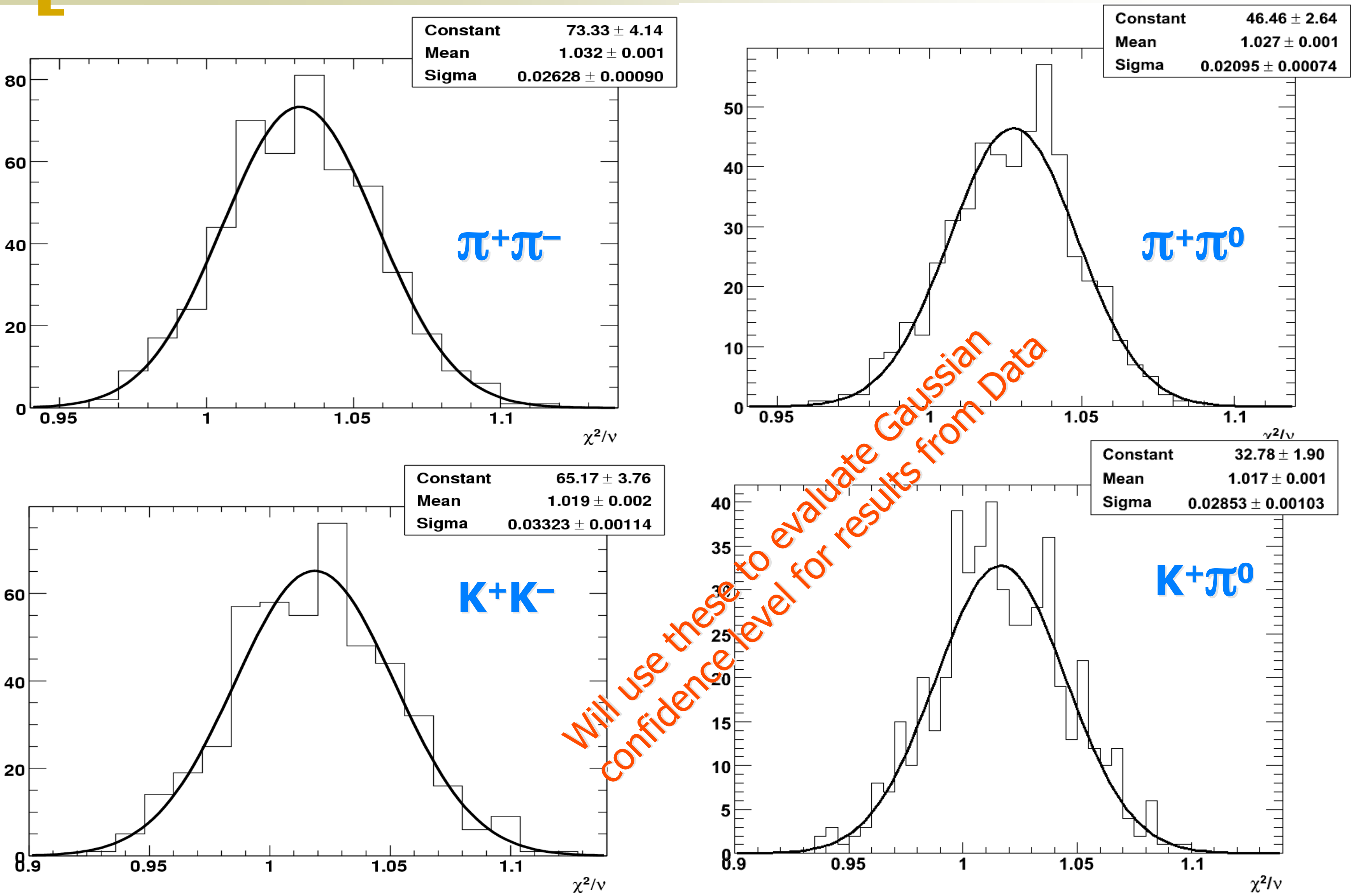
$$\rho_{ij} = \frac{\langle X_i X_j \rangle - \langle X_i \rangle \langle X_j \rangle}{\sqrt{\langle X_i^2 \rangle - \langle X_i \rangle^2} \cdot \sqrt{\langle X_j^2 \rangle - \langle X_j \rangle^2}}$$

χ^2/ν from Dalitz Plot for No CPV



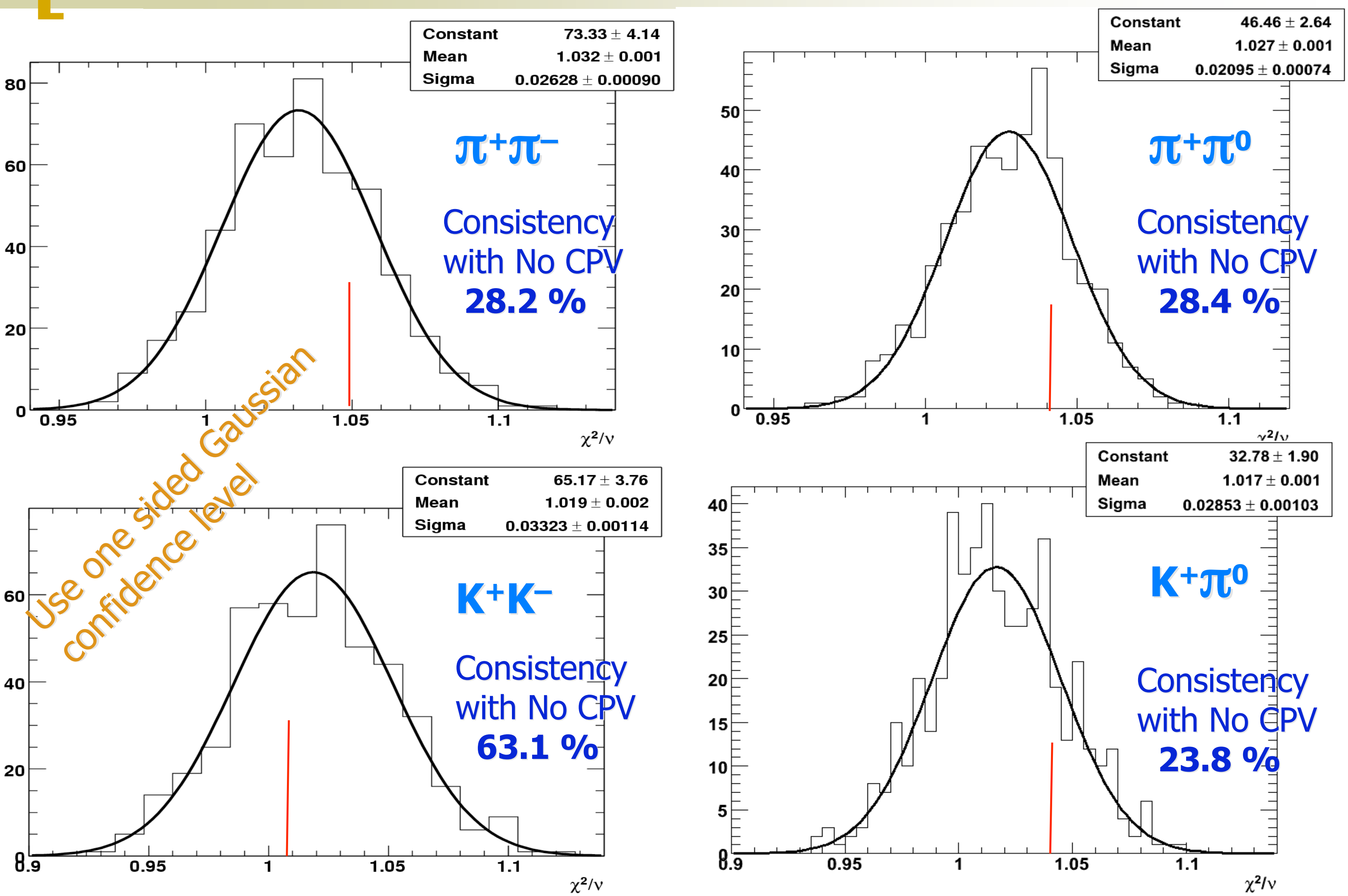
- Ploted the χ^2/ν distribution for Dalitz plot distribution from CP symmetric 500 toy MC samples (ν = number of bins in the Dalitz plot)
- Use the same number of events in each experimental sample as the number of events in our real Data sample.
- These plots give an estimate of the scale and spread in χ^2/ν values.

χ^2/ν from Ang. Moments for No CPV



Will use these to evaluate Gaussian confidence level for results from Data

Angular Moments: Consistency with No CPV



Decouple Localized vs DP-integrated A_{CP}

CP asymmetry can be:

- either localized in some specific part of the Dalitz plot (as predicted by most new physics models)

- or integrated over the whole phase-space (a la 2-body decay)

Best way is to decouple the two:

- For obtaining asymmetry in the Dalitz plot distribution, normalize D^0 and $\overline{D}^0$ events to the same number:

$\chi^2/\nu = n_D - R.\, n_{Dbar}$ / Poisson error $\qquad R = N_D / N_{Dbar}$

- obtain the phase-space integrated asymmetry after applying the soft pion efficiency corrections as done in the 2-body $D^0 \to KK, \pi\pi$ decays.

Validation Studies

Validation studies on toy Monte Carlo treated as data

- Analysis on CP-symmetric $D \rightarrow \pi^- \pi^+ \pi^0$, $K^- K^+ \pi^0$ samples
- Analysis on asymmetric samples

Validation studies on signal Monte Carlo treated as data

- Repeat the above steps

Validation studies on data

- We are still ‘blind’.
- Divide the data sample randomly into two disjoint samples of equal size (without looking into the flavor of the D meson)
- Perform the whole analysis
- Repeat the procedure several times

Summary: We find consistent results and get the input parameters back.

Study of Systematic Uncertainties

Experimental:

- efficiency parametrization
- PID corrections
- MC statistics
- background shape
- ….

→ D^0 and $\overline{D}^0$ may have slightly different coefficients

Similar to the ones in the original DP analysis

Model dependent:

- form factors
- inclusion / exclusion of some resonant states
- uncertainty in the shape of component amplitudes
- …..

D^0 / $\overline{D}^0$ cross-feed: Tabulate the systematic uncertainty for different levels of cross-feed

Plus: Take into account the correlations among Legendre polynomial moments of different orders in each bin

Also: There are some discrete ambiguities in the asymmetry measurement. Fortunately, this can be resolved in a straightforward way in most cases.

Summary on CPV in Charm Decays

- CPV with present sensitivity would signal new physics.
- $D^0 \to \pi^- \pi^+ \pi^0$, $K^- K^+ \pi^0$ sensitive to asymmetry in amplitude and phase for CP eigenstates and flavor states.
- Model independent methods show no evidence of CPV in either decay modes.
- Model dependent measurements of asymmetry in the amplitudes and phases show no CPV either.
- Phase-space-integrated asymmetry consistent with 0.
- These results do not contradict SM.
- Can provide constraints on some theories beyond SM.