Interference Effects in D Meson Decays

D. Cinabro
Wayne State University
FPCP 2006, 12 April

Why Interference Effects?

- Provide unique information
- Phases and amplitudes are otherwise inaccessible
- Need these to extract fundamental parameters (CKM elements for example) from other measurements
- Challenge and input for QCD

Outline

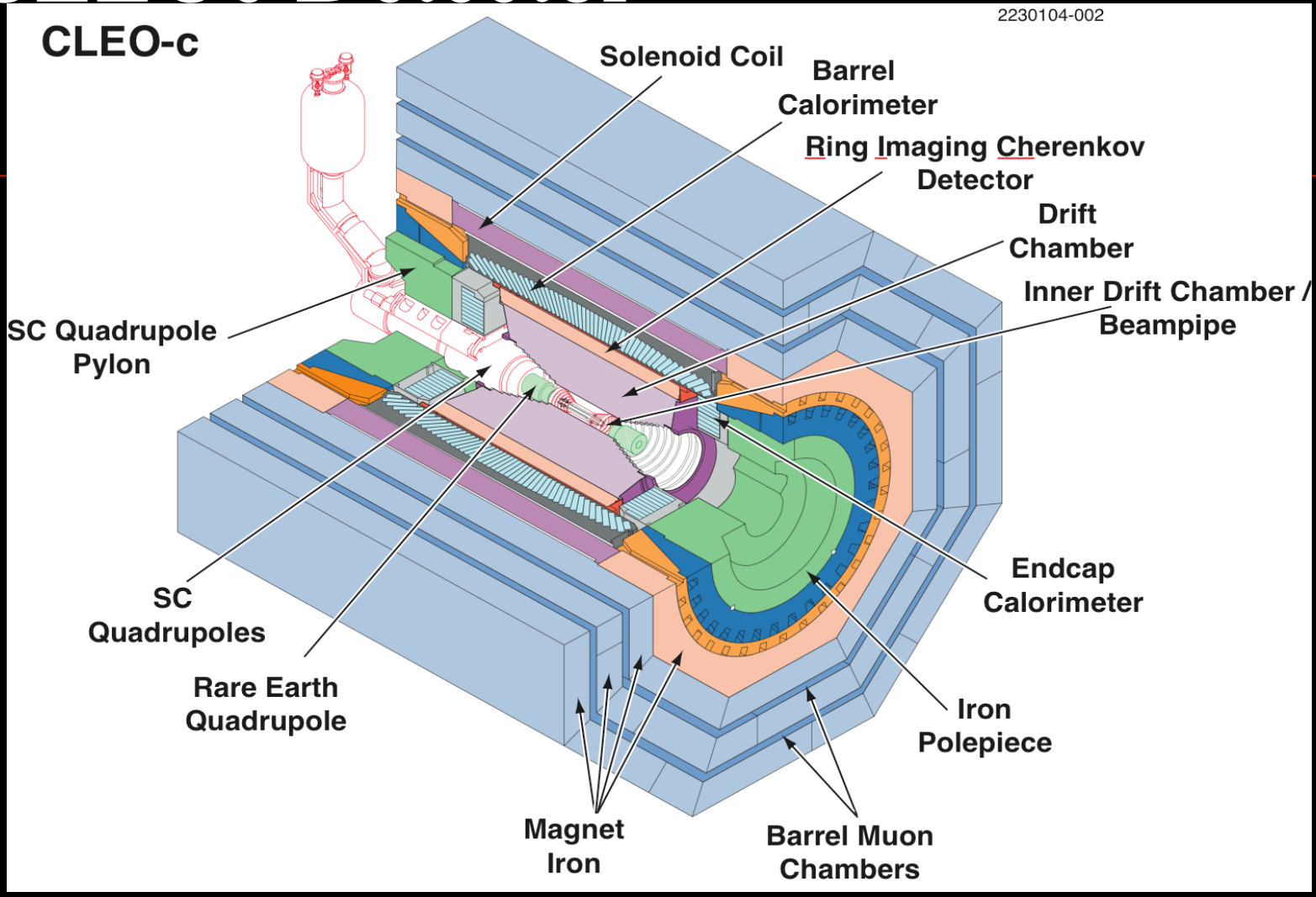
New results (since summer 2005) are thin

- $D \to KK\pi^0$ Dalitz analysis for $D \to KK^*$ strong phase from CLEO-III
- $D \to 3\pi$ Dalitz analysis from CLEO-c
- Quantum Correlations in $D^0\bar{D}^0$ decays from the ψ'' for phases and mixing parameters from CLEO-c

CLEO Data Sets

- CLEO-III data on $\Upsilon(4S)$, 9/fb with charm produced in continuum or from B decay
- CLEO-c data on the ψ'', 281/pb, which corresponds to 1.4M D pairs.

CLEOc Detector

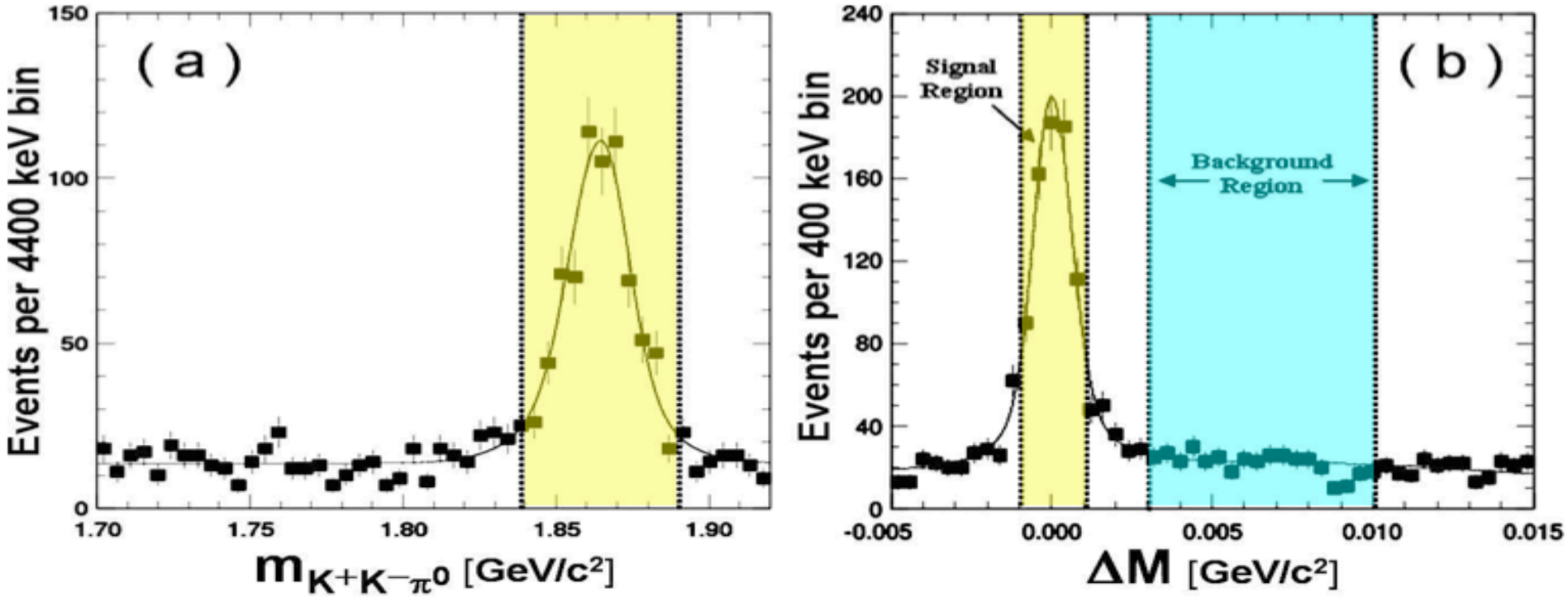


Venerable CsI Calorimeter 2.2% resolution on 1 GeV photon, 5% on 100 MeV, $\delta p/p = 0.6\%$ at 1 GeV, RICH particle ID

CLEO-III: $D \rightarrow KK\pi^0$

- Motivation is to extract strong phase difference in $D \rightarrow K^*K$
- See Grossman, Ligeti, and Soffer (PRD 67(2003)07130) and Rosner and Suprun (PRD68(2003)054010) for how this helps measure CKM γ (ϕ_3) in charged B decay

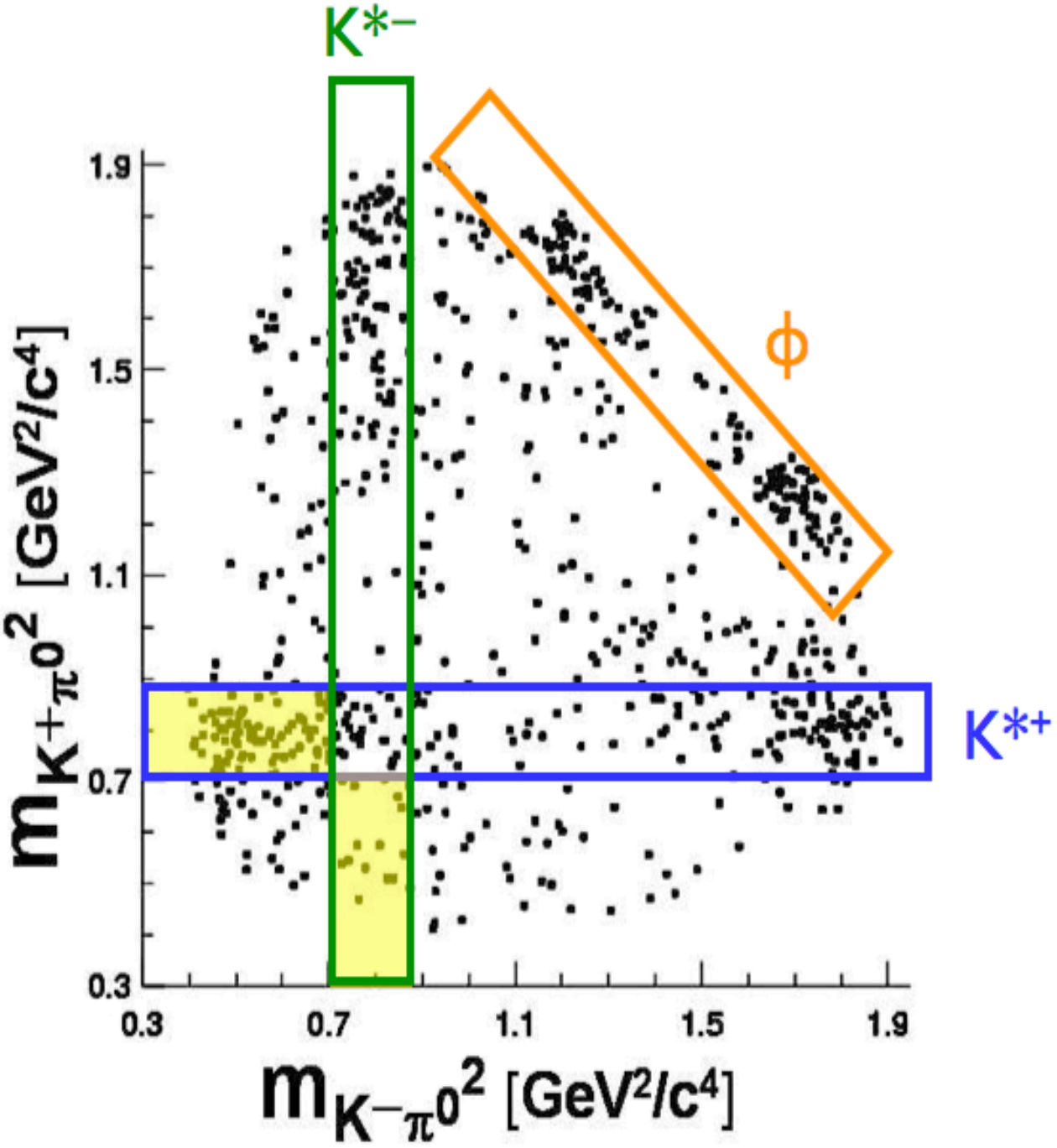
$D \rightarrow KK\pi^0$: Charged D* Tag



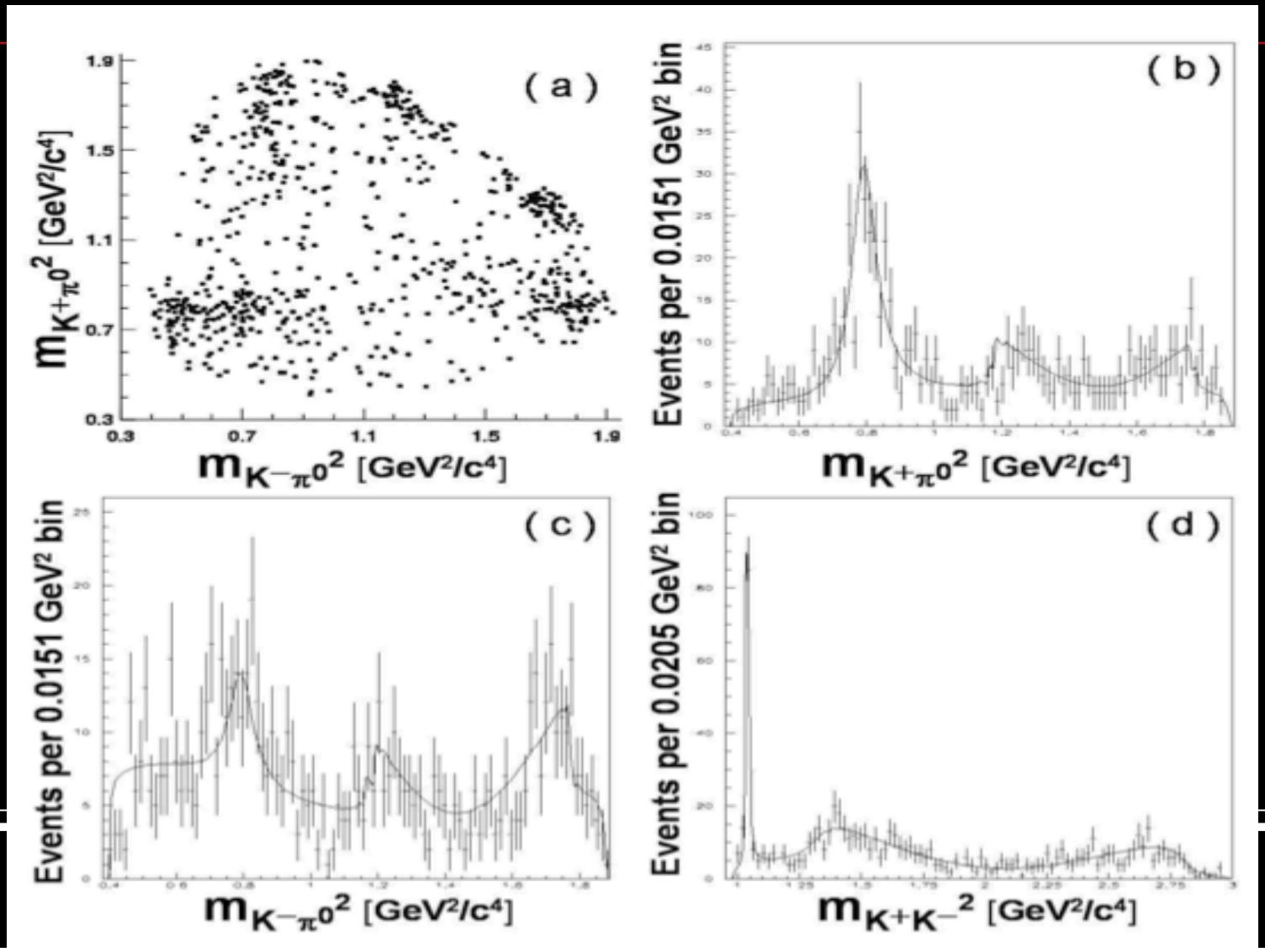
- 600 Signal S:B=4:1, Soft π tag gives D^0 flavor

$D \to KK\pi^0$

- Both charges of K* and ϕ contributions clearly visible
- Interference between K*'s is also clear



$D \to KK\pi^0$


(a)
$m_{K^+\pi^0}{}^2$ [GeV²/c⁴]
$m_{K^-\pi^0}{}^2$ [GeV²/c⁴]
(b)
Events per 0.0151 GeV² bin
$m_{K^+\pi^0}{}^2$ [GeV²/c⁴]
(c)
Events per 0.0151 GeV² bin
$m_{K^-\pi^0}{}^2$ [GeV²/c⁴]
(d)
Events per 0.0205 GeV² bin
$m_{K^+K^-}{}^2$ [GeV²/c⁴]

	Amplitude	Phase	Fit Fraction
FIT A $S.L. = 18.6\%$	*This fit is used for the result quoted.*		
K^{*+}	1.0 (fixed)	0.0° (fixed)	$(46.1 \pm 3.1)\%$
K^{*-}	$0.52 \pm 0.05 \pm 0.04$	$332° \pm 8° \pm 11°$	$(12.3 \pm 2.2)\%$
ϕ	0.64 ± 0.04	$326° \pm 9°$	$(14.9 \pm 1.6)\%$
NR	5.62 ± 0.45	$220° \pm 5°$	$(36.0 \pm 3.7)\%$
FIT B $S.L. = 17.2\%$	*This fit tests sensitivity to the Kπ S-wave shap*		
K^{*+}	1.0 (fixed)	0.0° (fixed)	$(48.1 \pm 4.5)\%$
K^{*-}	0.52 ± 0.05	$313° \pm 9°$	$(12.9 \pm 2.6)\%$
ϕ	0.65 ± 0.05	$334° \pm 12°$	$(16.1 \pm 1.9)\%$
κ^+	1.78 ± 0.43	$109° \pm 17°$	$(12.6 \pm 5.8)\%$
κ^-	1.60 ± 0.29	$128° \pm 17°$	$(11.1 \pm 4.7)\%$

#	Systematic Check	Uncertainty in δ_D	Uncertainty in r_D
1	Adding other reasonable resonances	$\pm 11^\circ$	± 0.04
2	Changing the fitting region on the DP	$\pm 2^\circ$	± 0.02
3	Fitting ($m^2_{K^-\pi^0}$, $m^2_{K^+\pi^0}$) rather than ($m^2_{K^+\pi^0}$, $m^2_{K^+K^-}$)	$\pm 1^\circ$ (<)	± 0.03
4a / 4b	Variation in π^0 cuts (Pull mass acceptance, Energy cuts)	$\pm 4^\circ$ / $\pm 3^\circ$	± 0.02 / ± 0.01 (<)
5	Variation in D* fractional momentum ("X") cut	$\pm 5^\circ$	± 0.01
6	RICH cuts*	$\pm 5^\circ$	± 0.03
7	$m_{KK\pi}$ acceptance	$\pm 2^\circ$	± 0.01
8	ΔM acceptance	$\pm 2^\circ$	± 0.01 (<)
9	Vary size of the ΔM vs. $m_{KK\pi}$ window	$\pm 2^\circ$	± 0.02
10	Vary dE/dx Parameters**	$\pm 1^\circ$	± 0.01
11	Vary the Original Signal Fraction	$\pm 5^\circ$	± 0.01
12	Vary the Original Signal Fraction via Penalty Term	$\pm 1^\circ$	± 0.01 (<)
13	Vary the background parameters	$\pm 8^\circ$	± 0.01
14	Vary the efficiency parameters	$\pm 4^\circ$	± 0.05
15	Vary the width of the ϕ by allowing it to float	$\pm 1^\circ$ (<)	± 0.01
	Total Systematic Error (Added as in reference [14]):	$\pm 11^\circ$	± 0.04

CLEO-III: $D \to KK\pi^0$

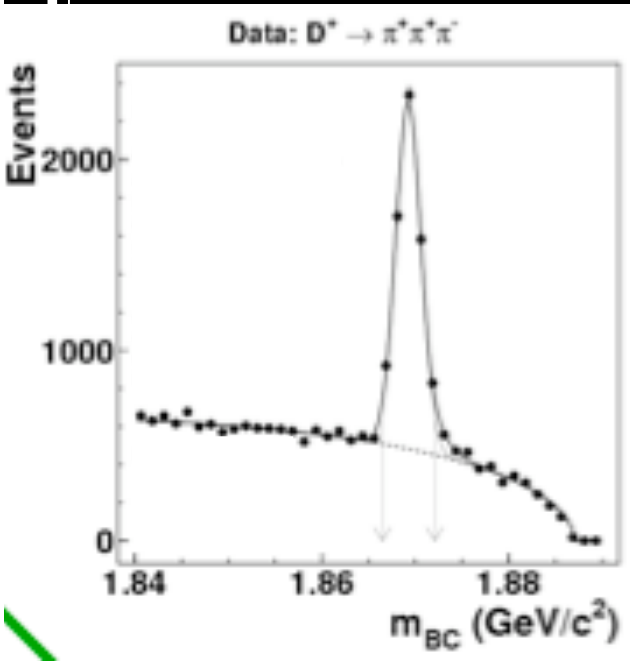
- Preliminary
- $\delta_{D \to K^*K} = 332^o \pm 8^o \pm 11^o$, large interference
- $|A(D \to K^{*-}K^+)| / |A(D \to K^{*+}K^-)| = 0.52 \pm 0.05 \pm 0.04$
- Precision limited by non-K* contributions to the decays
- Observed branching fractions consistent with previous measurements

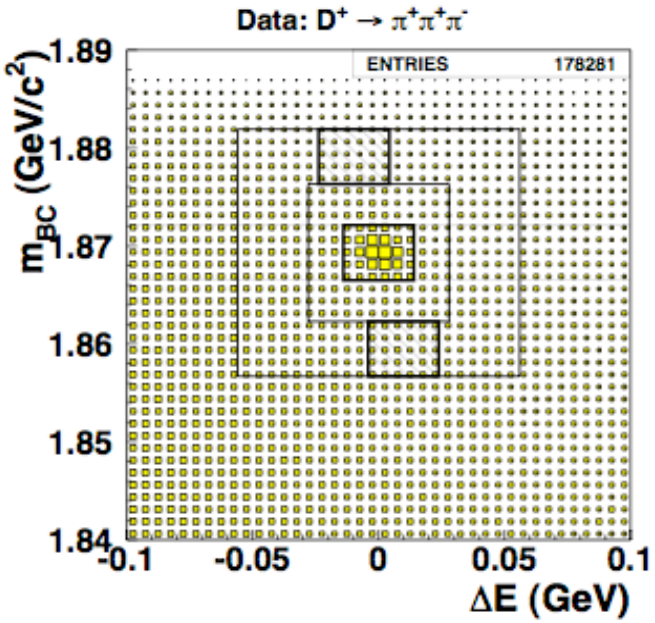
CLEO-c: D→3π Dalitz

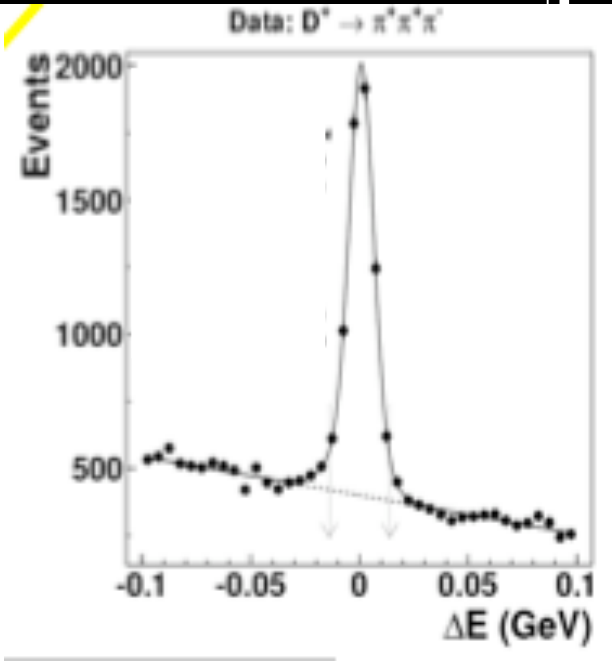
First time doing a Dalitz analysis that has been done by E791 and FOCUS (previously concentrated on modes with π^0)

2600 signal on S:B of 2:1 (E791 1200, FOCUS 1500)

$M_{bc} = \sqrt{E_{beam}^2 + p_{3\pi}^2}$, $\Delta E = E_{beam} - E_{3\pi}$

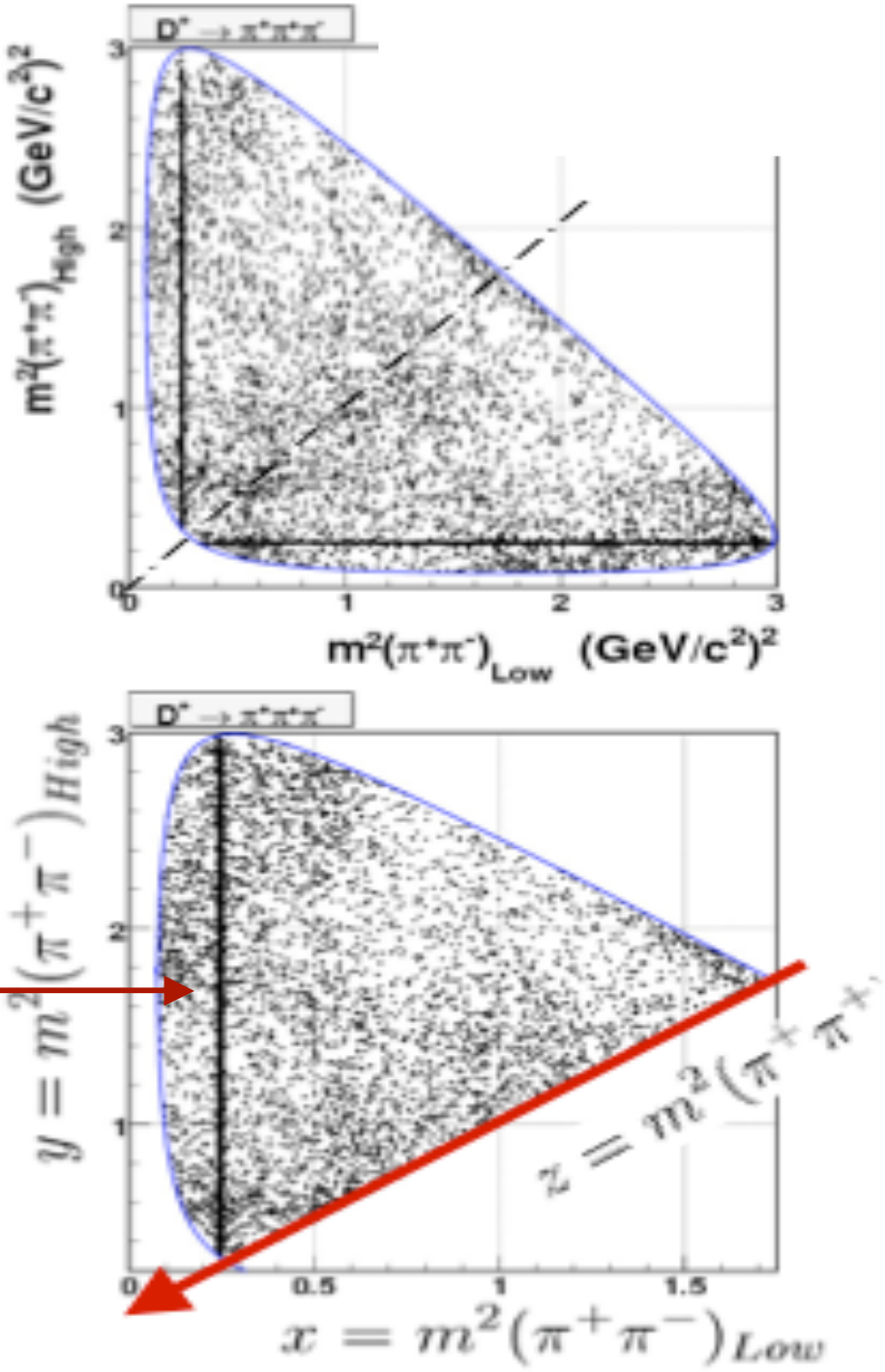






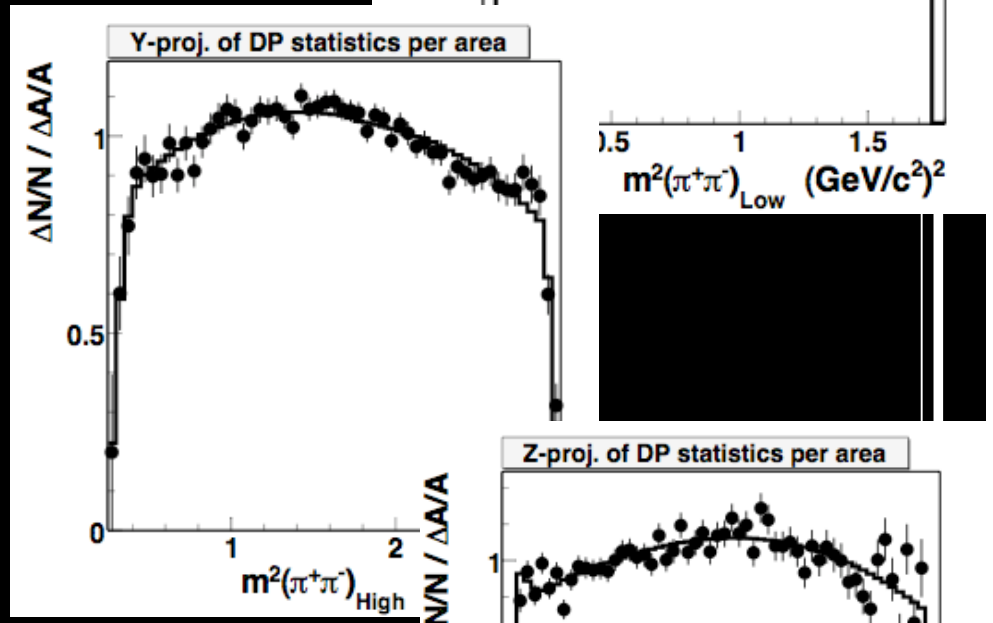
D→3π Dalitz

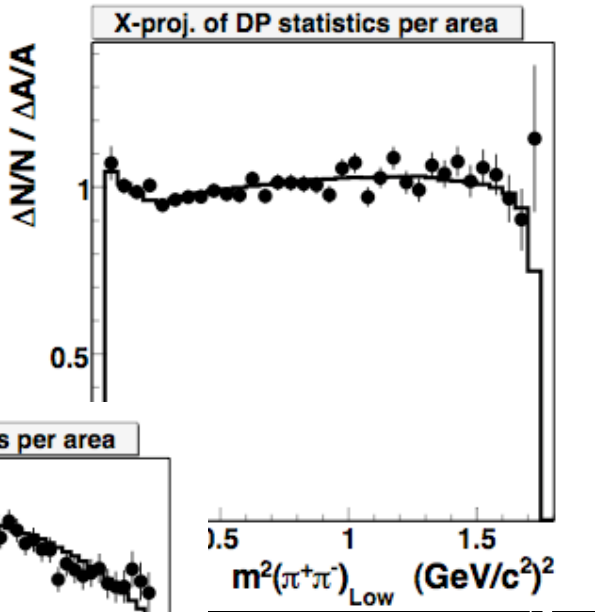
- Symmetry under interchange of like-sign pions
- Dalitz analysis on high mass versus low mass unlike-sign pion combinations
- Big vertical stripe is $K_s\pi$

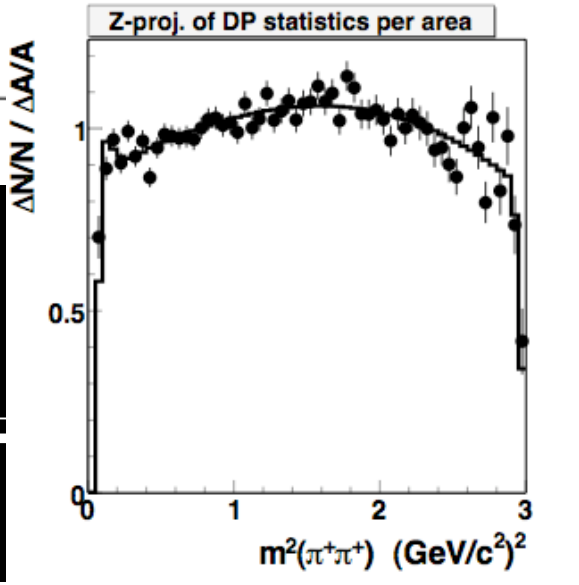


D→3π Dalitz

- Worry that efficiency will be difficult in corners of the Dalitz plot since D^+ starts nearly at rest.
- Looks good, changes are smooth.
- Model with both MC bin-by-bin and polynomial fit.

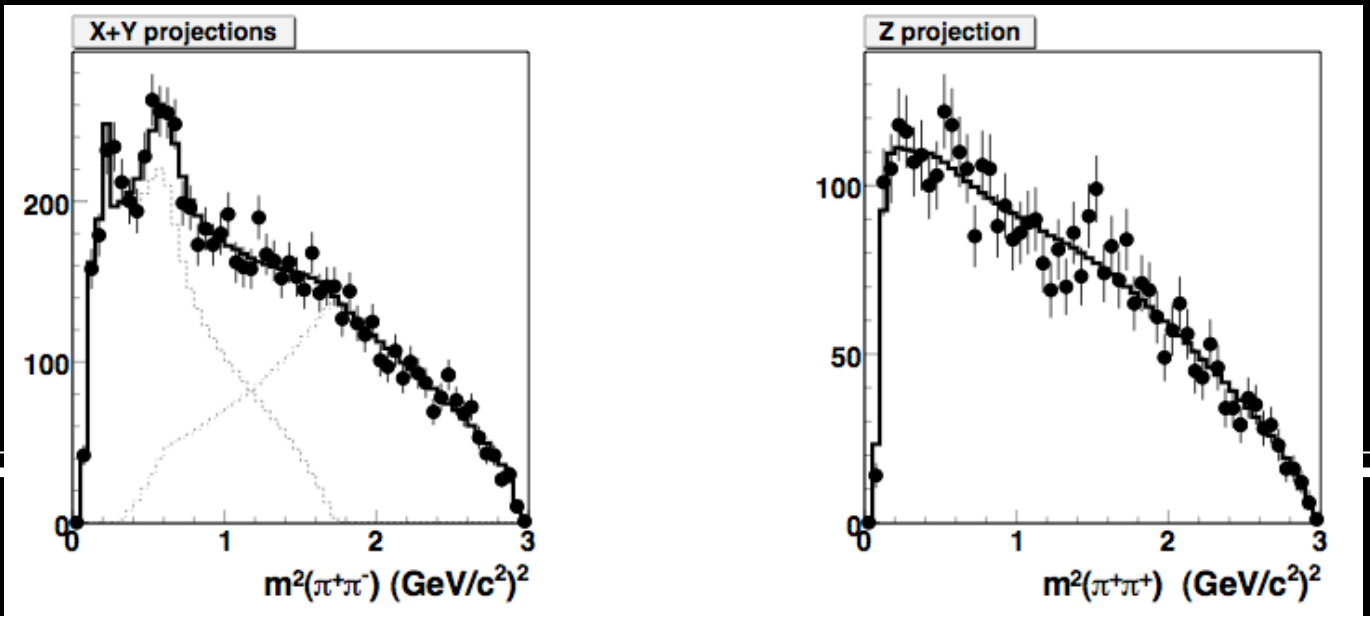






$D \rightarrow 3\pi$ Dalitz

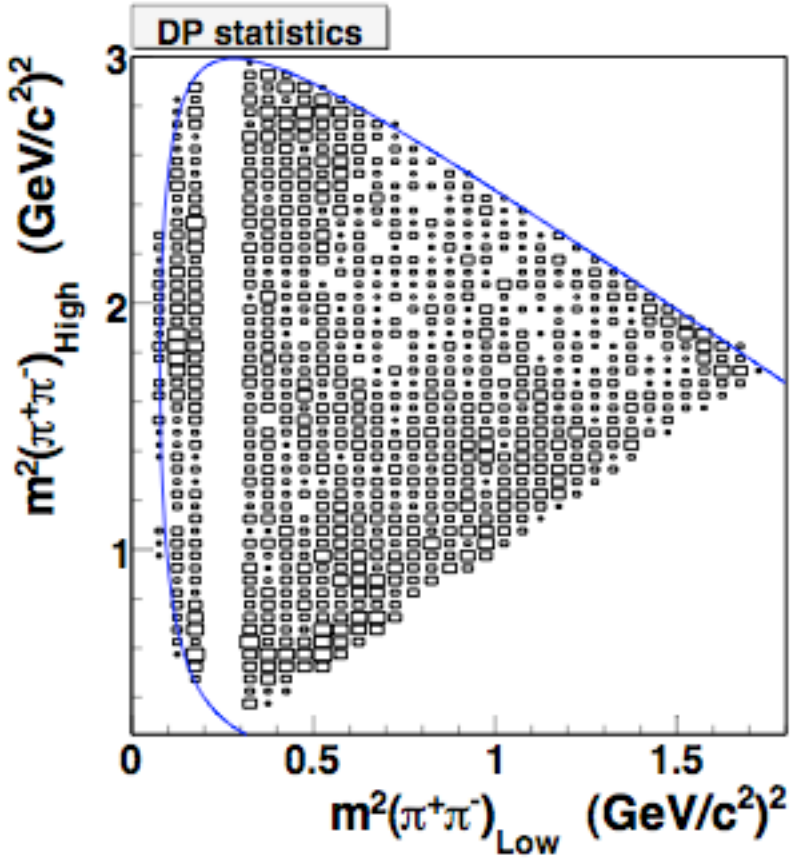
- Backgrounds from sidebands (offset in ΔE to insure that it remains on the Dalitz plot)
- Add in K_s, ρ, $f^0(1370)$ to represent possible resonance contributions

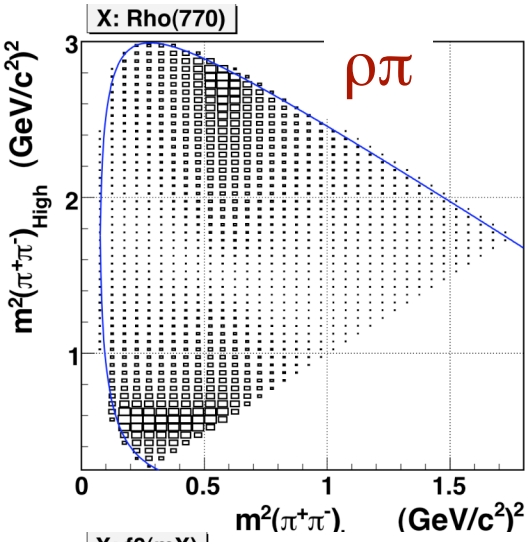


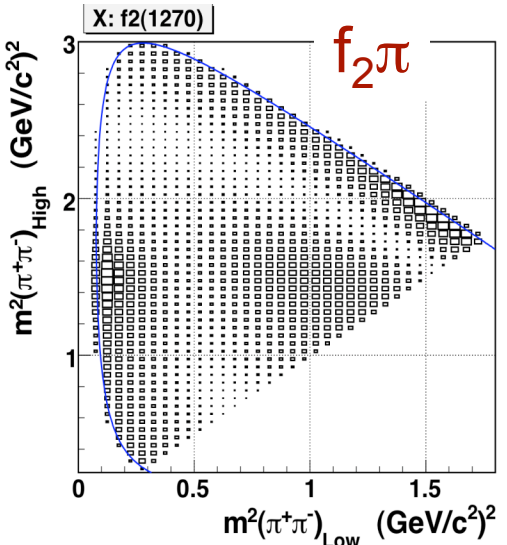
D→3π Dalitz: Many potential contributions

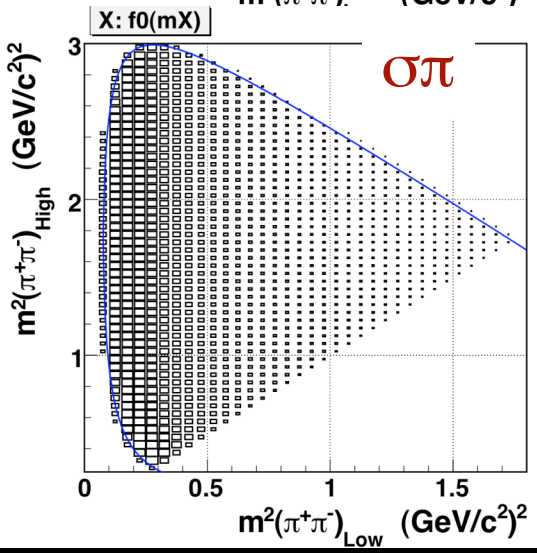
Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	$\mathcal{B}(R \to \pi\pi)$ (%)
$\rho(770)$	775.8±0.5	150.3±1.6	~100
$f_2(1270)$	1275.4±1.2	185.1±3.5	84.8±2.5
$f_0(1370)$	1200 to 1500	200 to 500	seen
	1350±50	265±40	with $f_0(1500)$
	1410±50	-.-	w/o $f_0(1500)$
	1434±18±9	173±32±6	
$\rho(1450)$	1465±25	400±60	seen
$f_0(1500)$	1507±5	109±7	34.9±2.3
$f_0(1710)$	1714±5	140±10	seen, $K\bar{K}$-domin.
$f_0(1790)$	1790^{+40}_{-30}	270^{+60}_{-30}	seen
σ	$478^{+24}_{-23}\pm17$	$324^{+42}_{-40}\pm21$	seen?
$f_2'(1525)$	1525±5	73±6	0.82±0.15
$\rho_3(1690)$	1688.8±2.1	161±10	23.6±1.3
$\rho(1700)$	1720±20	250±100	seen
$f_2(1950)$	1945±13	475±19	seen
$f_4(2050)$	2034±11	222±19	17.0±1.5

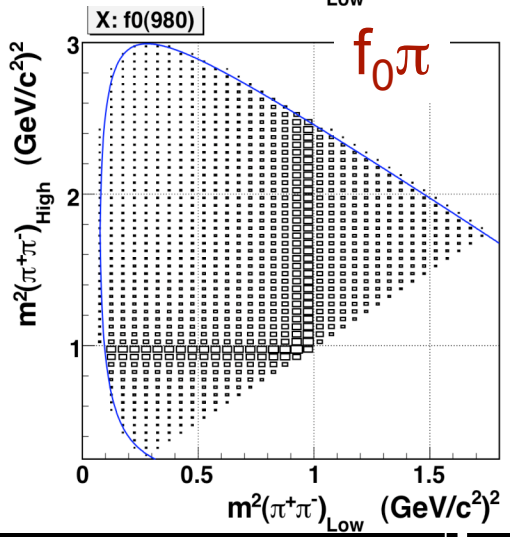
D→3π Dalitz


DP statistics
$m^2(\pi^+\pi^-)_{High}$ (GeV/c^2)^2
$m^2(\pi^+\pi^-)_{Low}$ (GeV/c^2)^2


X: Rho(770)
ρπ
$m^2(\pi^+\pi^-)_{High}$ (GeV/c^2)^2
$m^2(\pi^+\pi^-)_{Low}$ (GeV/c^2)^2

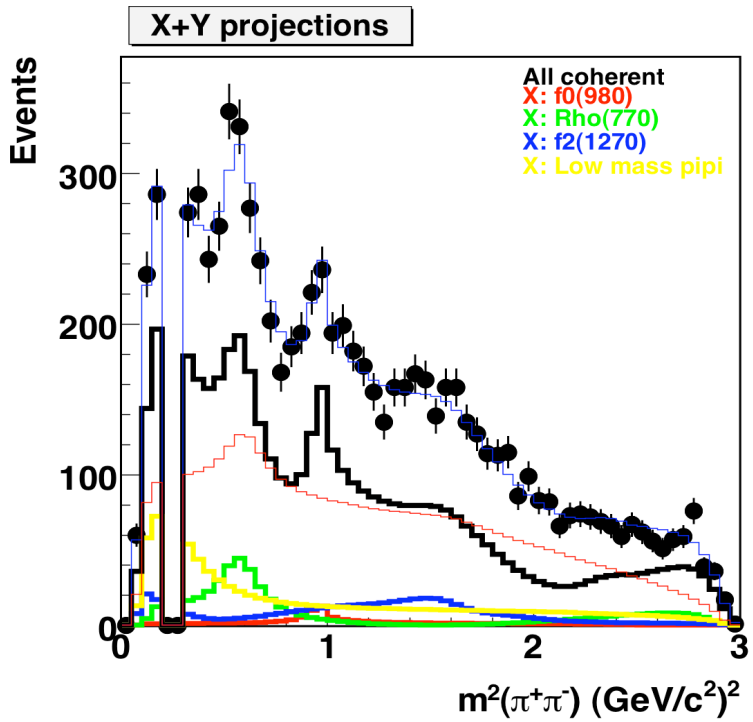

X: f2(1270)
$f_2\pi$
$m^2(\pi^+\pi^-)_{High}$ (GeV/c^2)^2
$m^2(\pi^+\pi^-)_{Low}$ (GeV/c^2)^2

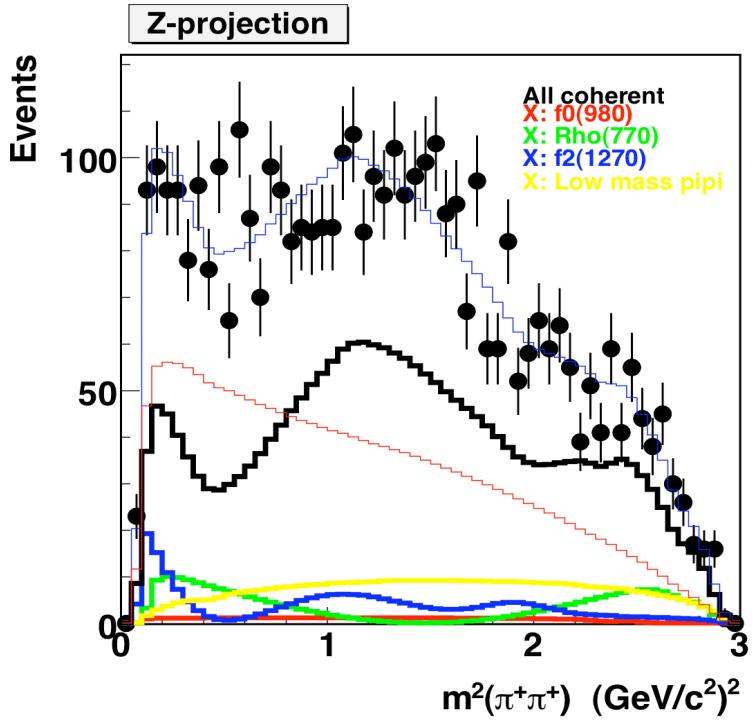

X: f0(mX)
σπ
$m^2(\pi^+\pi^-)_{High}$ (GeV/c^2)^2
$m^2(\pi^+\pi^-)_{Low}$ (GeV/c^2)^2


X: f0(980)
$f_0\pi$
$m^2(\pi^+\pi^-)_{High}$ (GeV/c^2)^2
$m^2(\pi^+\pi^-)_{Low}$ (GeV/c^2)^2

$D \to 3\pi$ Dalitz

FF in %	E791	CLEOc
$\rho\pi$	33.6±3.9	20.0±2.5
$\sigma\pi$	46.3±9.2	41.8±2.9
$f_2\pi$	19.4±2.5	18.2±2.7
$f_0(980)\pi$	6.2±1.4	4.1±0.9
$f_0(1500)\pi$	----------	3.4±1.3
Non-res	7.8±6.6	<3.5
$\rho(1450)\pi$	0.7±0.8	<2.4
Prob(χ^2)	96.3	27.8





CLEO-c: $D \rightarrow 3\pi$ Dalitz

- Still preliminary
- Need to consider other models of $\pi\pi$ S-wave (for example replace σ and f_0 contributions by generalized $\pi\pi$ interaction) to compare with FOCUS which used the K-matrix
- Broad agreement with E791 (σ contribution, first observation for CLEO)

CLEO-c: TQCA

- The Quantum Correlation Analysis
- $ee \rightarrow \gamma^* \rightarrow D^0\bar{D}^0$ is C -1
- $K^-\pi^+$ vs $K^+\pi^-$ interfere and thus sensitive to DCSD and strong phase
- Time integrated rate depends on both $\cos\delta_{D\rightarrow K\pi}$ and mixing parameter $y = \Delta\Gamma/2\Gamma$
- $K^-\pi^+$ vs $K^-\pi^+$ forbidden unless there is mixing.
- $K^-\pi^+$ vs semileptonic measures isolated decay rate and tags flavor of decaying D
- Different sensitivity to mixing vs DCSD
- D decays to CP eigenstates also interfere and opposite semileptonics to get isolated rate, flavor tags for yet another dependence on y and strong phase
- CP eigenstate vs CP eigenstate shows maximal correlations

TQCA

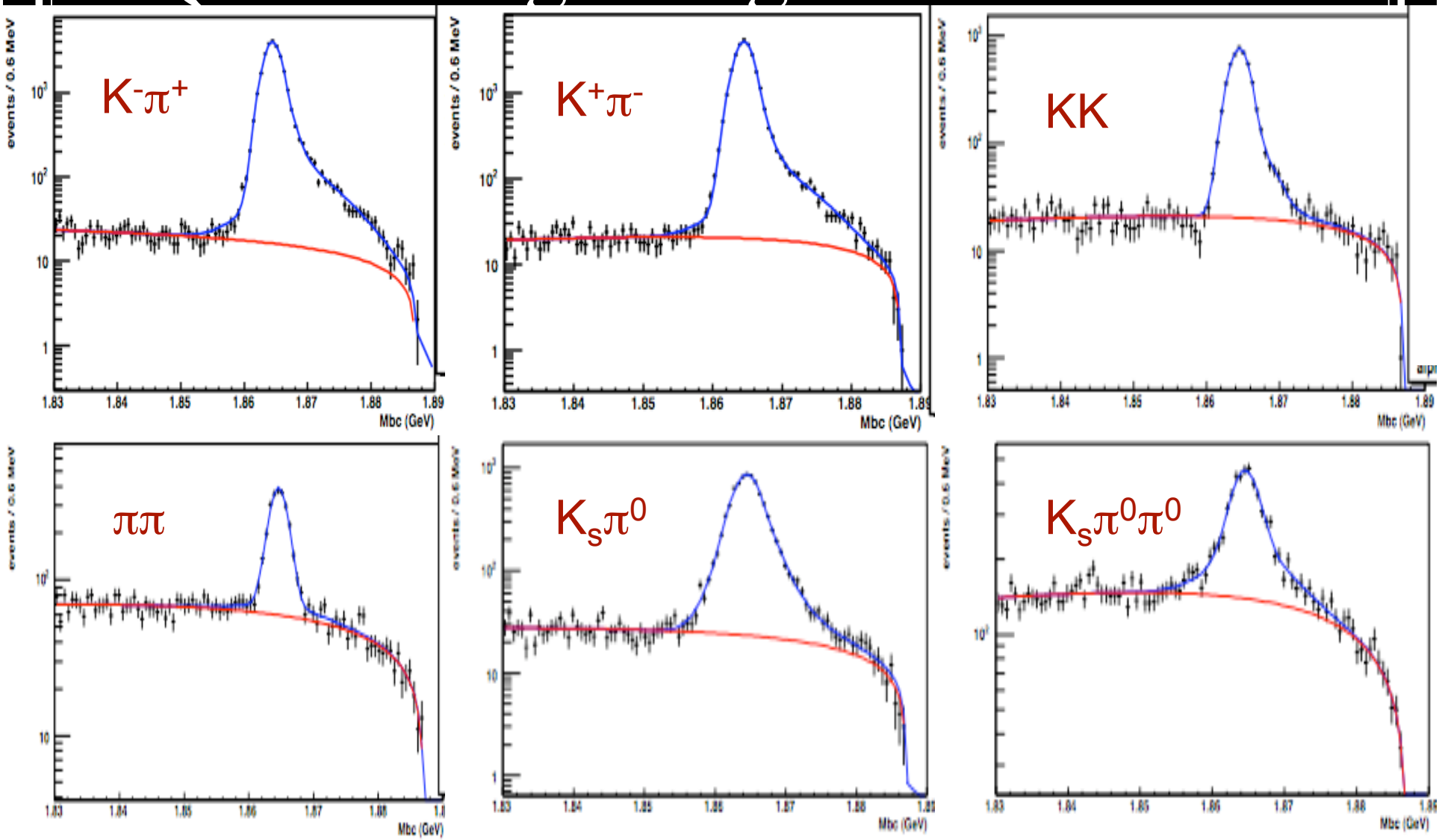
See PRD **73** 034024 (2006) [**hep-ph/0507238**]
by Asner and Sun

$R_M = (x^2+y^2)/2$
r = Amp DCS/Amp CF

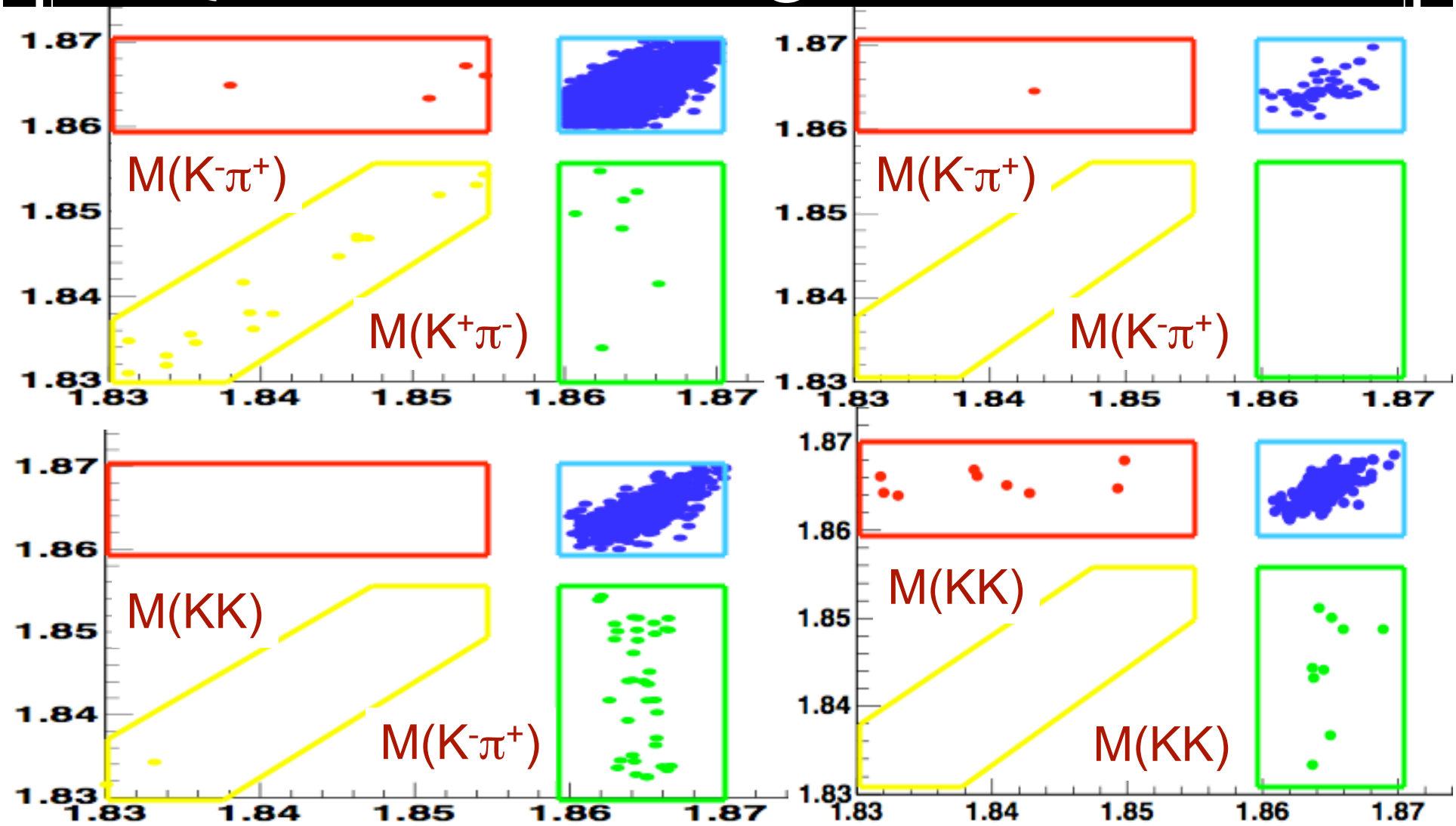
	f	*l*+	*CP*+	*CP*-
f	R_M/r^2			
$\bar{f}$	$1+r^2(2-(2\cos\delta)^2)$			
l-	1	1		
CP+	$1+r\,(2\cos\delta)$	1	0	
CP-	$1-r\,(2\cos\delta)$	1	2	0
X	$1+ry\,(2\cos\delta)$	1	$1-y$	$1+y$

And measure branching fractions simultaneously

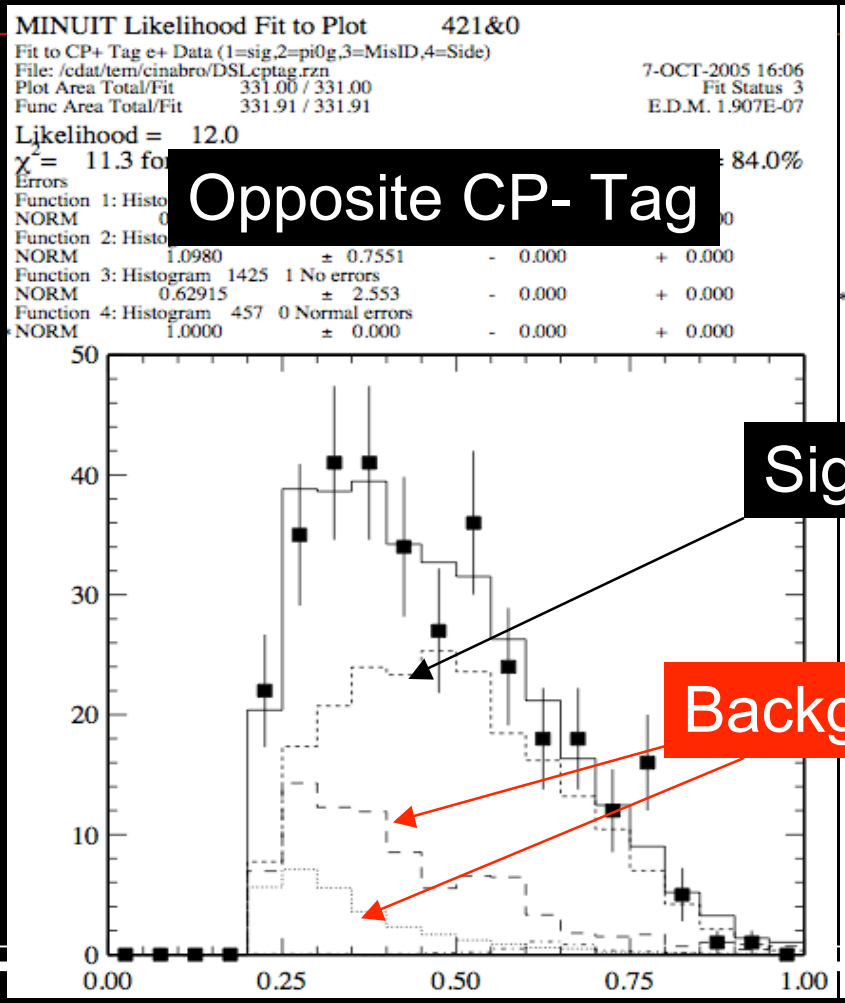
TQCA: Single Tags in Data

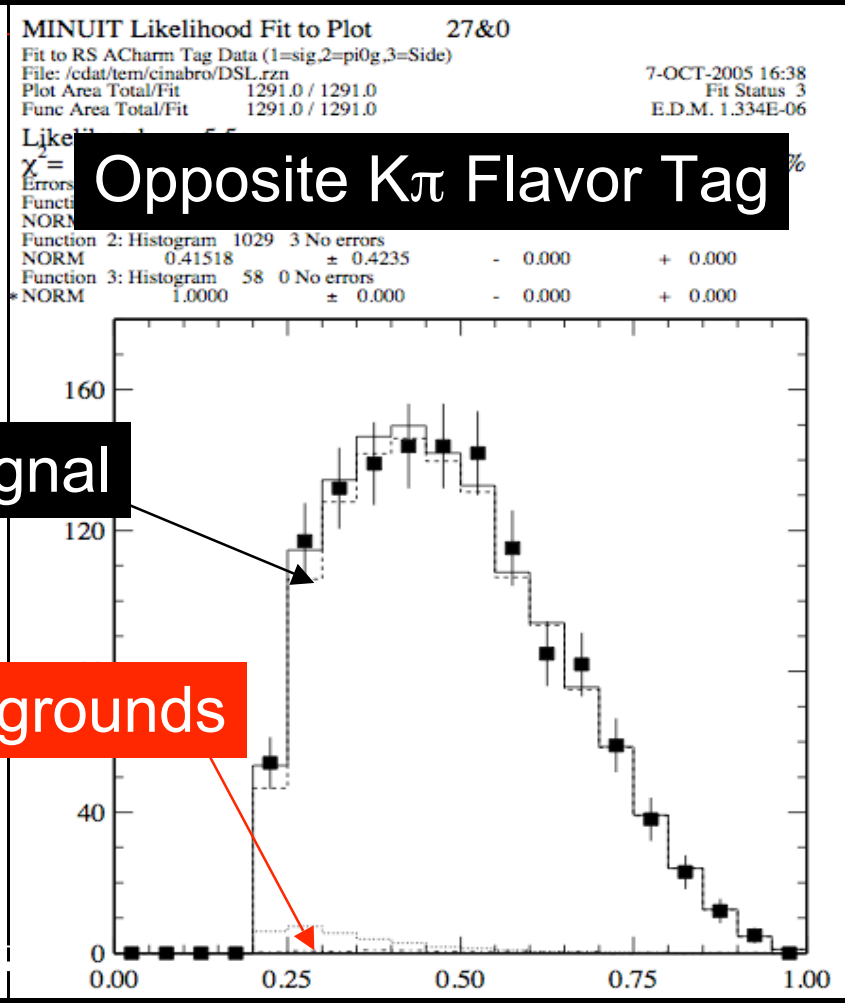


TQCA: Double Tags in Simulation



TQCA:Semileptonics





CP tags vs CP tags clearly shows Quantum Correlation

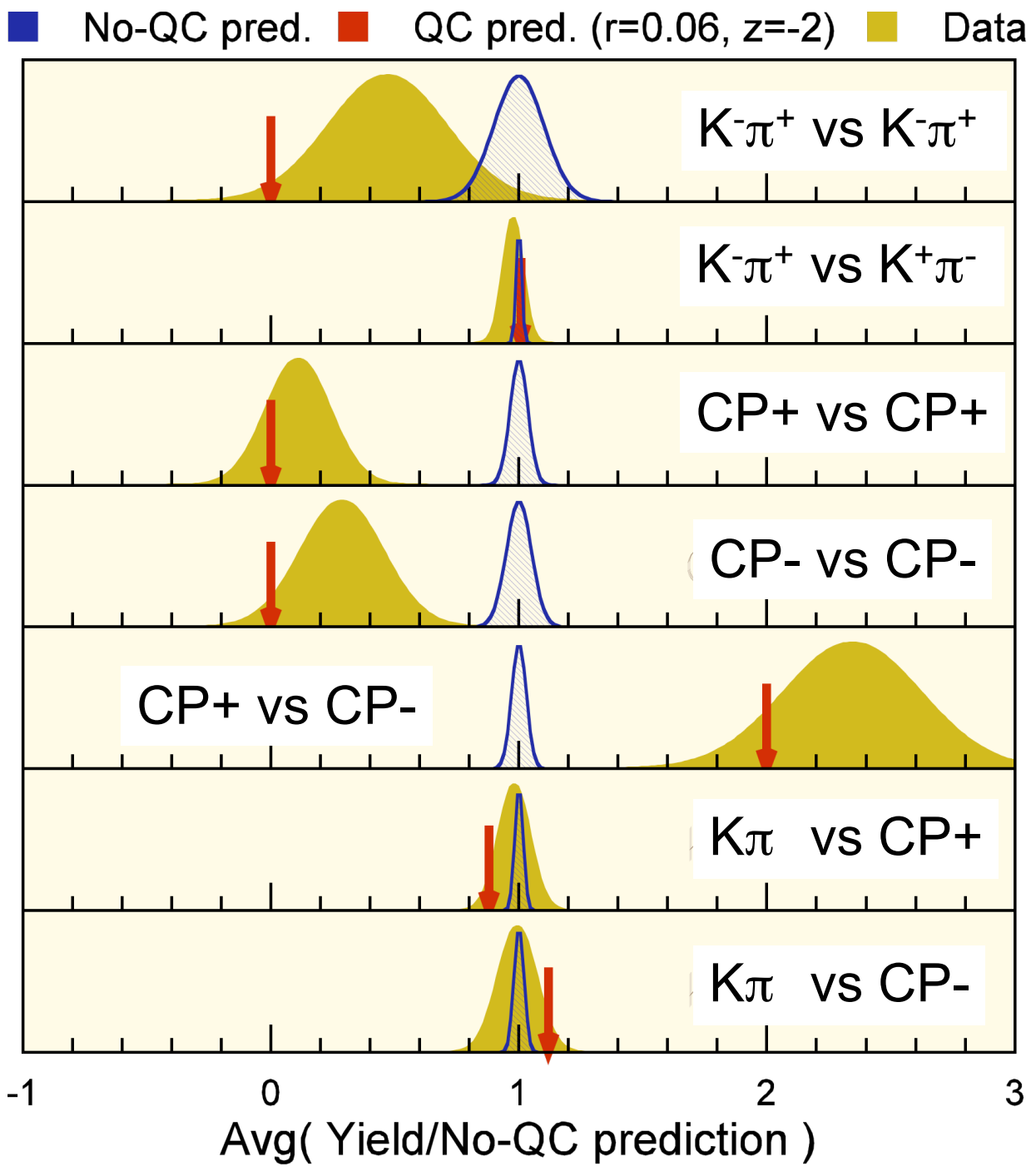
TQCA

No QC Data	K-K+	π-π+	$K_s\pi^0\pi^0$	$K_s\pi^0$
		CP+		CP-
K-K+	5.2±0.4 -2.2±1.9	4.5±0.3 0.1±0.9	5.7±0.4 1.6±1.3	16.0±0.6 39.6±6.3
π-π+		1.1±0.2 0.2±1.4	2.2±0.2 1.6±1.3	5.8±0.4 14.0±3.7
$K_s\pi^0\pi^0$			1.2±0.2 1.0±1.0	7.3±0.4 19.0±4.4
$K_s\pi^0$				9.7±0.5 3.0±1.7

CP+

TQCA

Data clearly favors QC interpretation showing constructive and destructive interference and no effect as predicted



Parameter	CLEO TQCA	PDG or CLEOc
y	$-0.057 \pm 0.066 \pm ?$	0.008 ± 0.005
r^2	$-0.028 \pm 0.069 \pm ?$	$(3.74 \pm 0.18) \times 10^{-3}$
$r\,(2\cos\delta_{D\to K\pi})$	$0.130 \pm 0.082 \pm ?$	
R_M	$(1.74 \pm 1.47 \pm ?) \times 10^{-3}$	$< \sim 1 \times 10^{-3}$
$B(D\to K\pi)$	$(3.80 \pm 0.029 \pm ?)\%$	$(3.91 \pm 0.12)\%$
$B(D\to KK)$	$(0.357 \pm 0.029 \pm ?)\%$	$(0.389 \pm 0.012)\%$
$B(D\to \pi\pi)$	$(0.125 \pm 0.011 \pm ?)\%$	$(0.138 \pm 0.005)\%$
$B(D\to K_s\pi^0\pi^0)$	$(0.932 \pm 0.087 \pm ?)\%$	$(0.89 \pm 0.41)\%$
$B(D\to K_s\pi^0)$	$(1.27 \pm 0.09 \pm ?)\%$	$(1.55 \pm 0.12)\%$
$B(D^0\to Xe\nu)$	$(6.21 \pm 0.42 \pm ?)\%$	$(6.46 \pm 0.21)\%$

CLEO-c: TQCA

- Obviously still preliminary, but very promising
- Systematics look tractable (< stats)
- Number of CP tags is limit so working on adding more
- C+ fraction < 0.06±0.05±? on ψ''
- Ultimate sensitivity with projected CLEO-c data set y ±0.012, x^2 ±0.0006, $\cos\delta_{D\to K\pi}$ ±0.13, $x(\sin\delta_{D\to K\pi})$ ±0.024 (needs C+1 initial state from running above the ψ'')

Conclusions

- Unique information from interference effects in D decays
- All since summer 2005 from CLEO
- $\delta_{D\to K^*K} = 332^o \pm 8^o \pm 11^o$ and $|A(D\to K^{*-}K^+)|/|A(D\to K^{*+}K^-)| = 0.52\pm0.05\pm0.04$ in $D\to KK\pi^0$ Dalitz
- $D\to 3\pi$ Dalitz agrees with E791 on need for low mass $\pi\pi$ S-Wave contribution
- CLEO TQCA sensitive to D mixing parameters and $\delta_{D\to K\pi}$