Evidence for Direct *CP* Violation from a Dalitz-plot Analysis of $B^{+} \rightarrow K^{+}\pi^{+}\pi^{-}$ at the BaBar Experiment

24th April 2008

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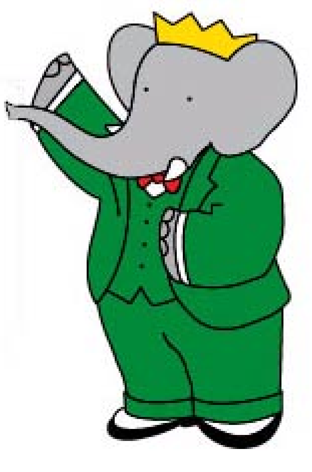
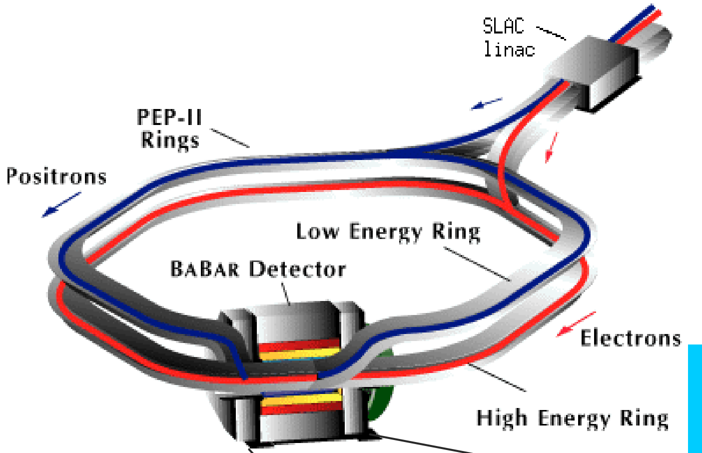


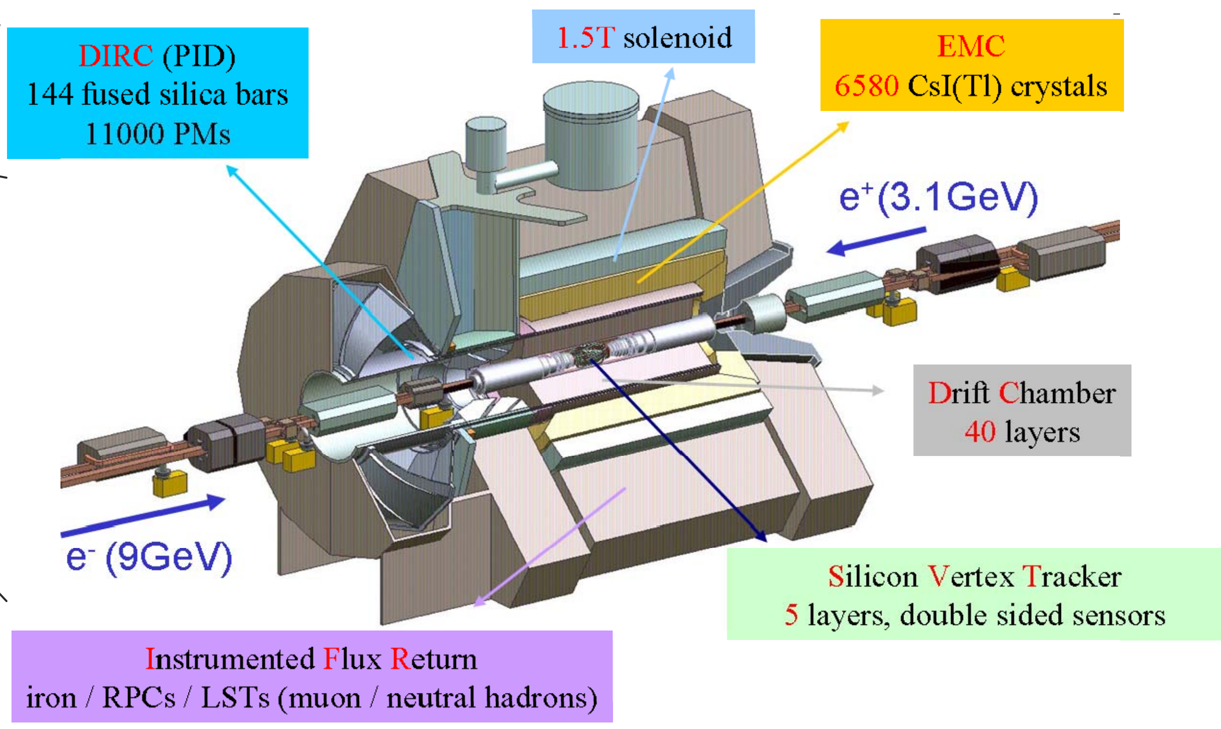
Overview

- Introduction
- Motivation
- Analysis
- Results
- Conclusion

PEP II and BaBar

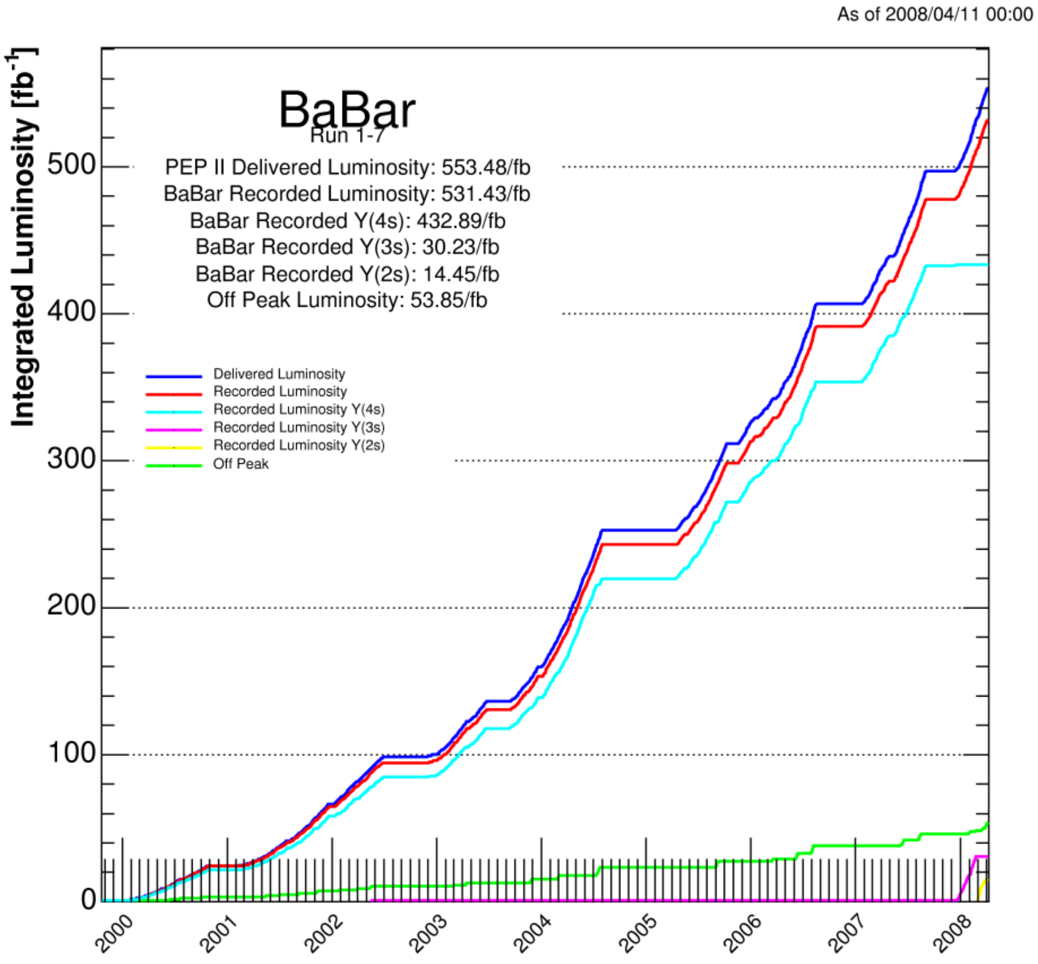


- PEP II/BaBar *B*-Factory located at Stanford Linear Accelerator Center
- Collides beams of electrons and positrons with asymmetric energies



Dataset

- BaBar data-taking ended on 7th April
- Total of ~531 fb^{-1} recorded, ~432 fb^{-1} at the Y(4S)
- Luminosity used in this analysis 347fb^{-1} = 383 million B pairs



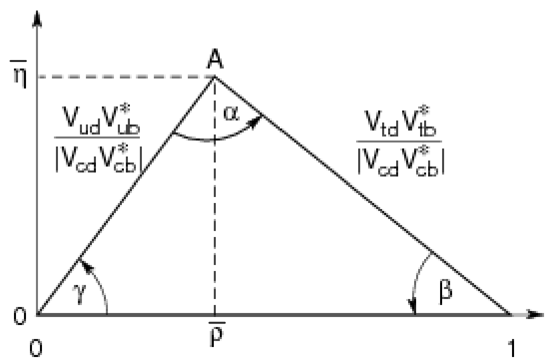
The CKM Mechanism

- CP violation in the standard model arises from phase in the quark-mixing (CKM) matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

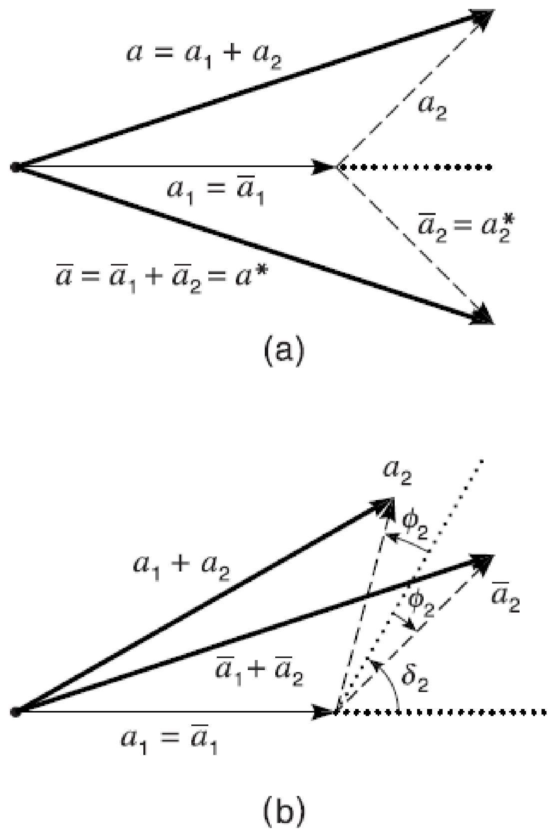
- Unitarity conditions of matrix can be expressed as triangles in complex plane



$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

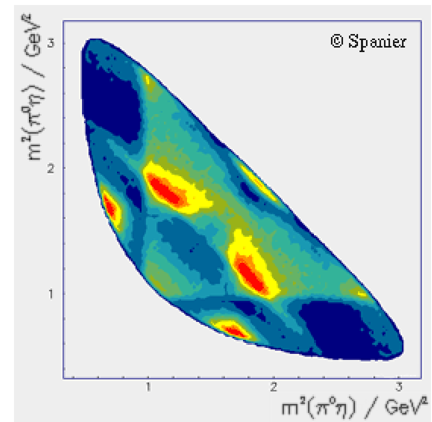
Direct *CP* Violation

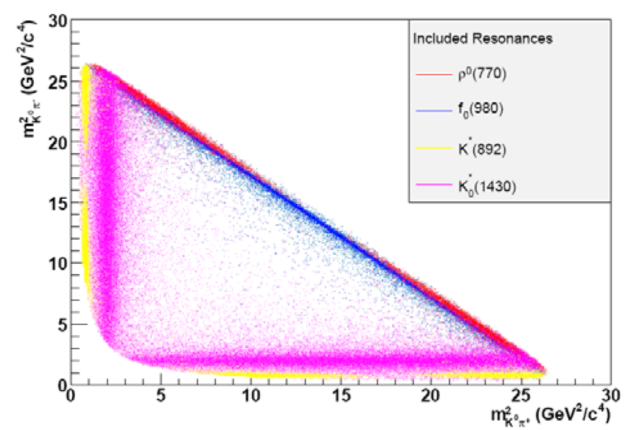
- *CP* violation in decay
- Rate asymmetry requires two amplitudes with different weak and strong phases to contribute
- Observed in decays of neutral K and B mesons



What are Dalitz plots?

- Representation of the pseudoscalar to three pseudoscalar phase space
- Formed from the squares of the invariant masses of two pairings of particles
- Examples shown on right
- Structure reveals information on mass, width and spin of intermediate particles
- Interference between different intermediate states allows measurement of magnitudes and phases





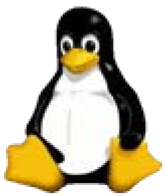
CP Violation in Dalitz plots

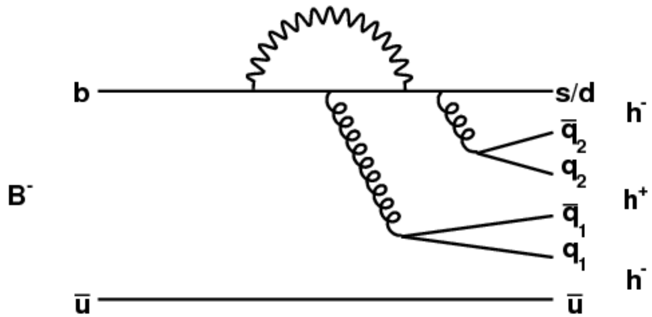
- Measurement of relative phases of intermediate states gives greater sensitivity to CP violation effects
- e.g. direct CP violation with only a relative weak phase
- Comes at the cost of model dependence

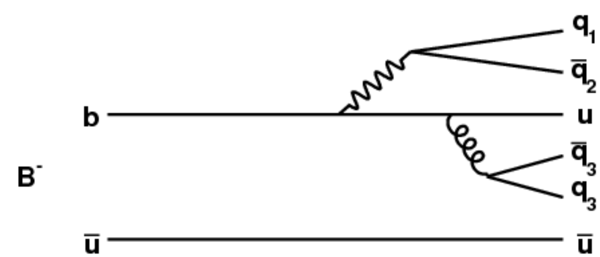
Isobar Model

- Model each contribution to the Dalitz plot as a separate amplitude with a complex coefficient
- Total amplitude is simply the sum of all the contributions
- Intensity therefore includes both diagonal and interference terms
- Complex coefficients tell you the relative magnitudes and phases of the contributions
- Several ways to parameterise these coefficients:
  - magnitude and phase
  - real and imaginary parts
  - etc.

Why charmless 3-body decays?







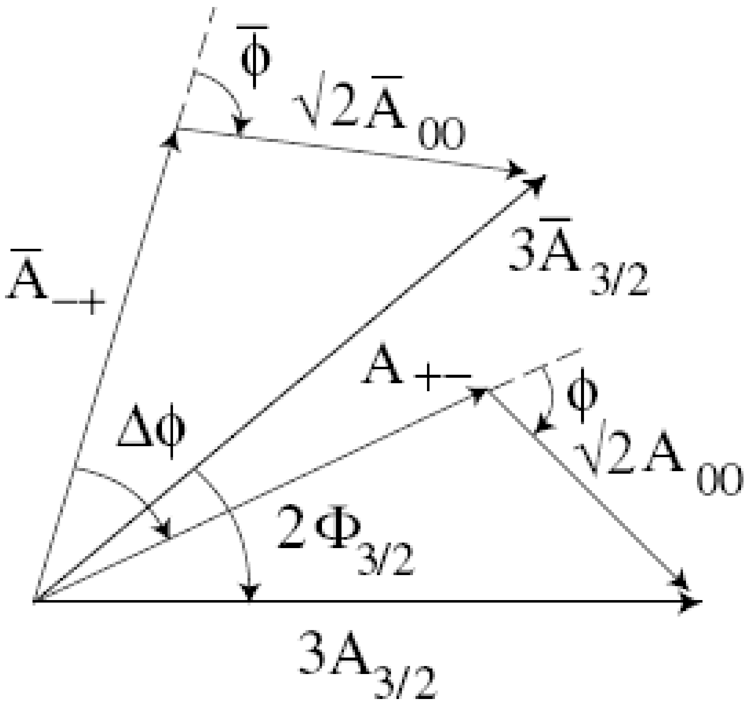
- Contributions from both tree and penguin diagrams can give rise to direct CP violation
- Interferences between different intermediate states can allow measurement of CKM angles alpha and gamma
- Time-dependent measurements of neutral B decays can allow measurement of the angle beta
- Can help improve understanding of nature of some intermediate resonances, e.g. $f_0(980)$

Why $K\pi\pi$?

- There are six different $K\pi\pi$ Dalitz plots
- Each allows determination of different pieces of information
  - e.g. time-dependent analysis of $K_s\pi^+\pi^-$ or $K_s\pi^0\pi^0$ allows measurement of CKM angle beta
- Combining information from several modes can allow a constraint on the rho-eta plane similar to the angle gamma:
  - Ciuchini, Pierini & Silvistrini, Phys. Rev. D74 051301 (2006)
  - Gronau, Pirjol, Soni & Zupan, Phys. Rev. D75 014002 (2007)
- Vast wealth of intermediate states can contribute
- Reasonably high branching fractions, $O(10^{-5})$
- Predictions for direct *CP* asymmetries from QCD factorisation etc. O(10%) for some modes

Constraint on rho-eta plane

- Relative weak phase between tree and penguin diagrams in $K\pi\pi$ is gamma
- Use B → $K^*\pi$ modes to form isospin triangles
- $A_{ij} = A(B^0 \to K^{*i}\pi^j)$
- $\Phi_{3/2}$ = gamma up to a correction due to electroweak penguins
- The three other angles can be measured from Dalitz-plot analyses of $K^+\pi^-\pi^0$ and $K_s\pi^+\pi^-$

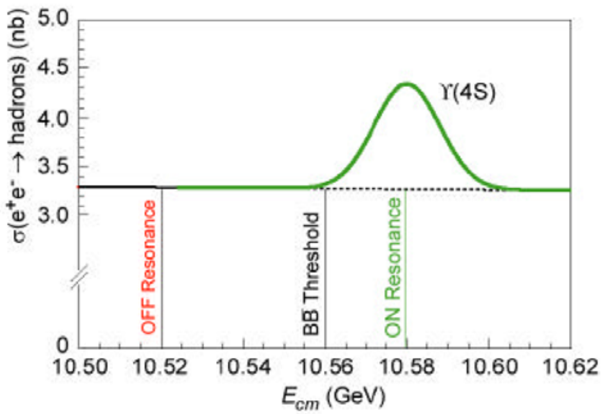


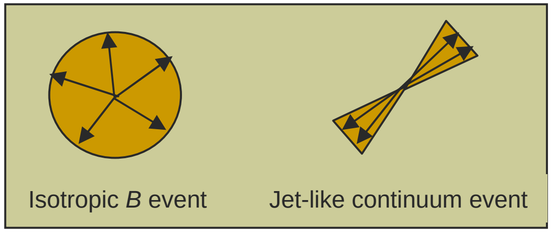
Why $K^+\pi^+\pi^-$?

- Predictions for possible large A_{CP} in the intermediate state $B^+ \to \rho^0 K^+$
  - Previous analyses have seen evidence of this ~30%
- Highest branching fraction of 6 modes
- Simplest final state to reconstruct
- Good place to determine Dalitz-plot model to feed into other $K\pi\pi$ modes

Analysis Variables – Topological

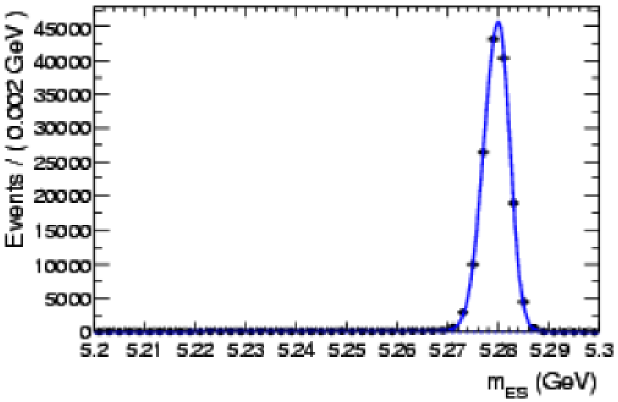
- Light quark continuum cross section ~3x $b\bar{b}$
- B mesons produced almost at rest since just above threshold
- Use event topology to discriminate
- Combine variables in an MVA, e.g. Fisher, Neural Network or Decision Tree

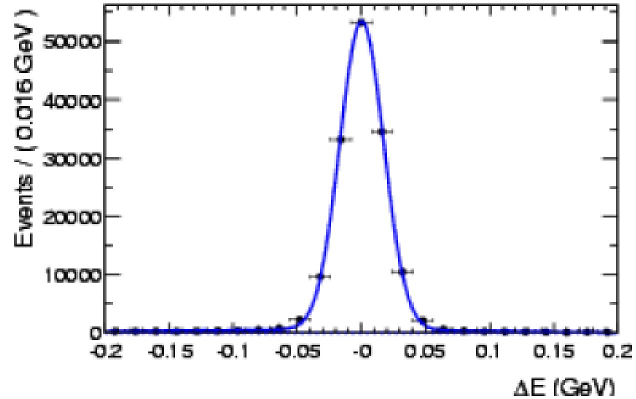




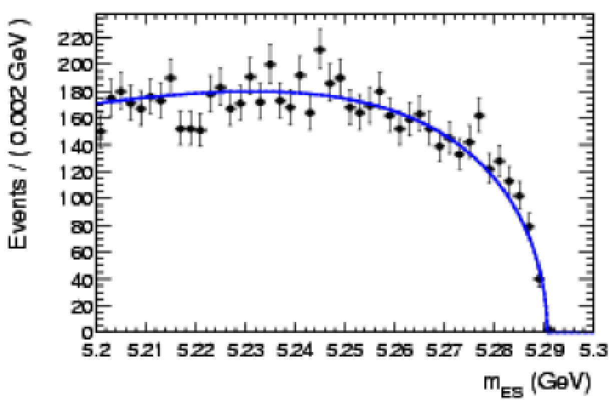
Analysis Variables – Kinematic

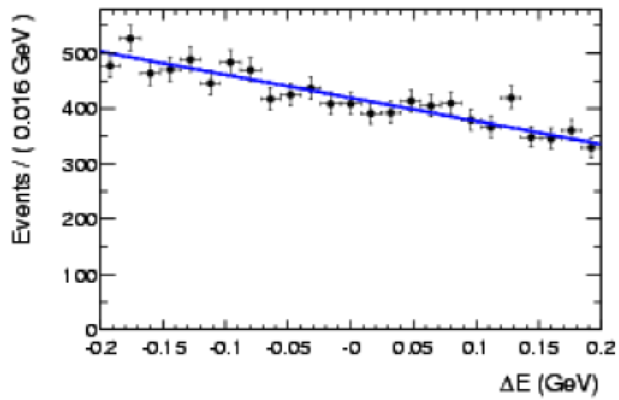
Make use of precision kinematic information from the beams.





Characteristic Signal Distributions





Characteristic Continuum Distributions

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

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

Analysis Strategy

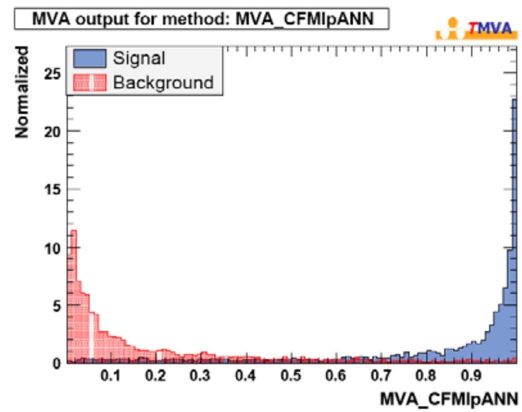
- Reconstruct B candidates from three charged tracks
- Apply reasonably tight cuts on particle ID, kinematic variables and MVA
- Fit to Dalitz plot and kinematic variables to obtain event yields and isobar coefficients in a single fit
- Simultaneous fit to B^+ and B^- candidates to extract *CP*-violating parameters

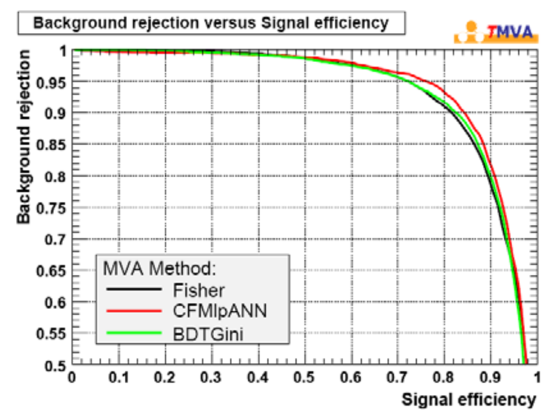
Building the MVA

- Input variables:
  - Ratio of L2 and L0:

$$L_0 = \sum_i^{\mathrm{ROE}} p_i \qquad L_2 = \sum_i^{\mathrm{ROE}} p_i \times \frac{1}{2}(3\cos^2(\theta_i) - 1)$$

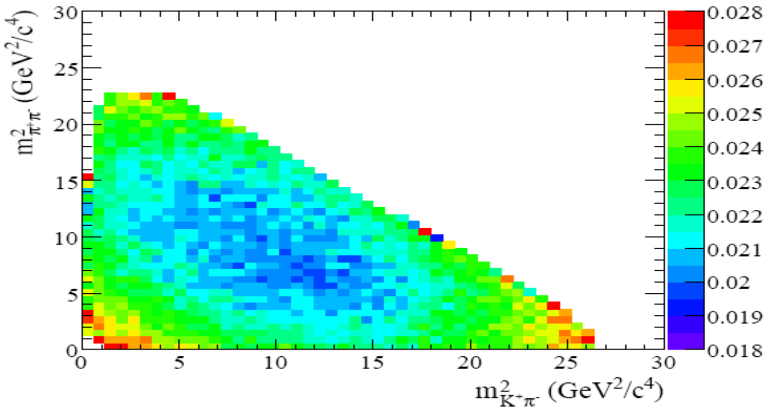
  - Cosine of angle between B momentum and beam axis
  - Cosine of angle between B thrust axis and beam axis
  - Significance of proper time difference between B vertices
  - Charge of B candidate multiplied by output of flavour tagger
- Neural Network found to give best discrimination

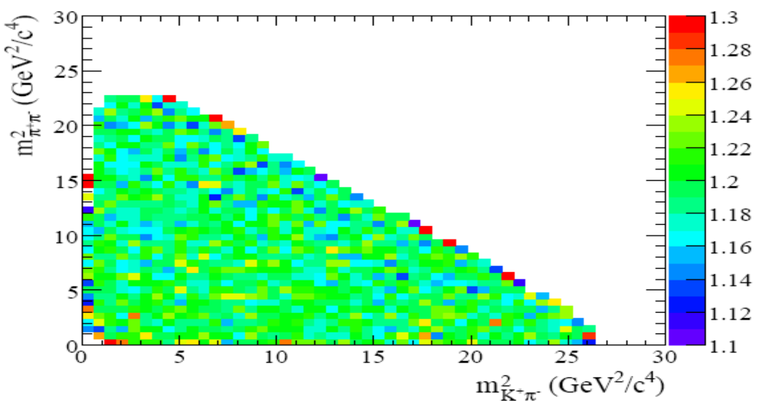




Correlations between fit variables

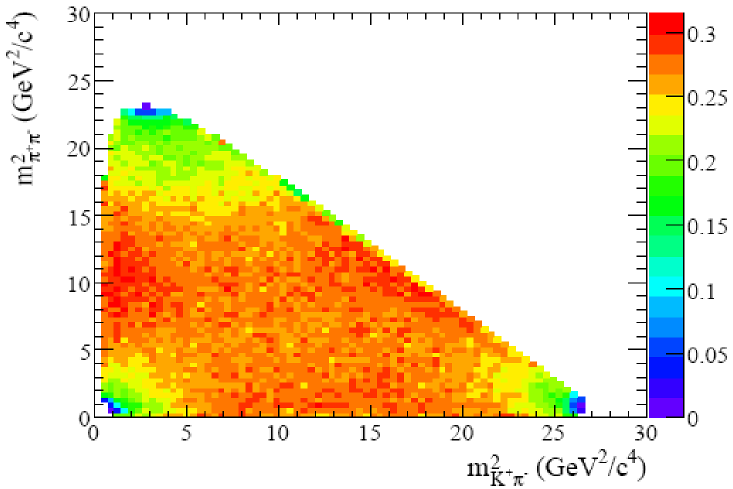
- MVA exhibits strong correlation with DP position in background events – not used in fit
- Width of signal ΔE distribution shows some correlation (top)
- Use instead $\Delta E/\sigma(\Delta E)$, which shows no such correlation (bottom)

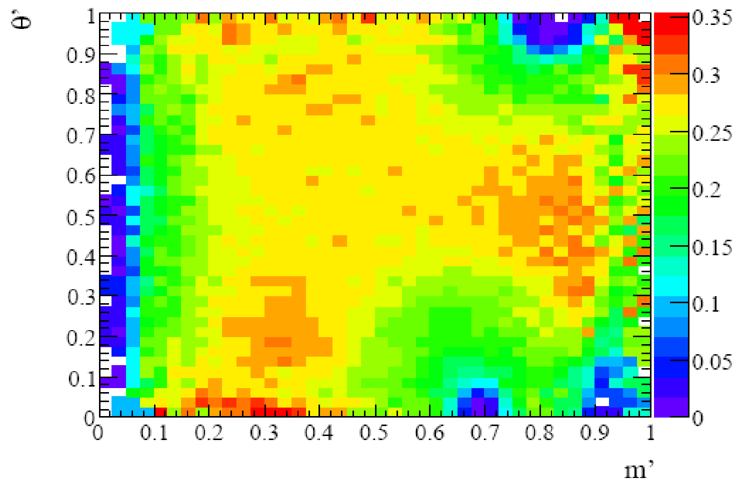




Signal efficiency

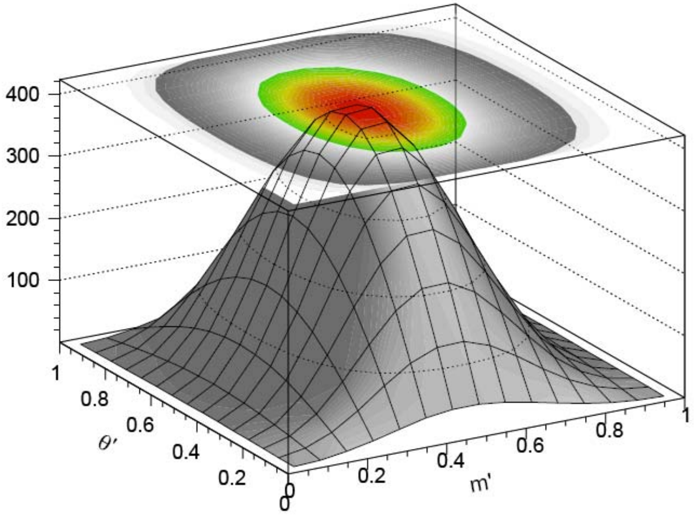
- Average signal efficiency for phase-space distributed events is 21.2%
- However, efficiency varies over the DP
- Need to model this in the likelihood fit
- Use 2D histogram in “square DP” coordinates





The Square Dalitz Plot

$$m' \equiv \frac{1}{\pi}\arccos\left(2\frac{m_{K^+\pi^+} - m^{\min}_{K^+\pi^+}}{m^{\max}_{K^+\pi^+} - m^{\min}_{K^+\pi^+}} - 1\right),$$
$$\theta' \equiv \frac{1}{\pi}\theta_{K^+\pi^+},$$

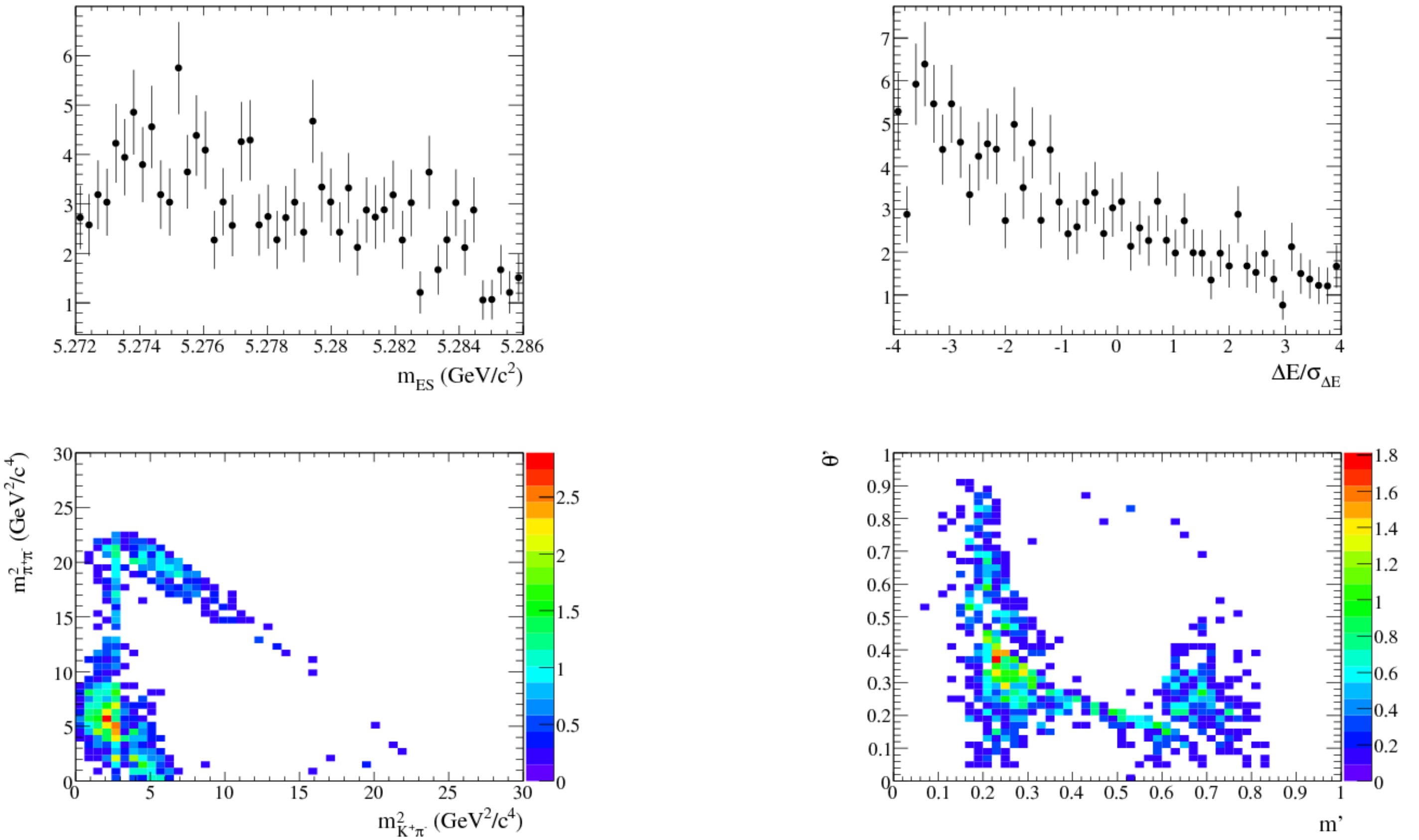


- Transformation of coordinates
- “Zooms” into the areas around the boundary of the conventional Dalitz plot
- Increases resolution in those areas of interest
- Used for all DP histograms in this analysis

Background from B decays

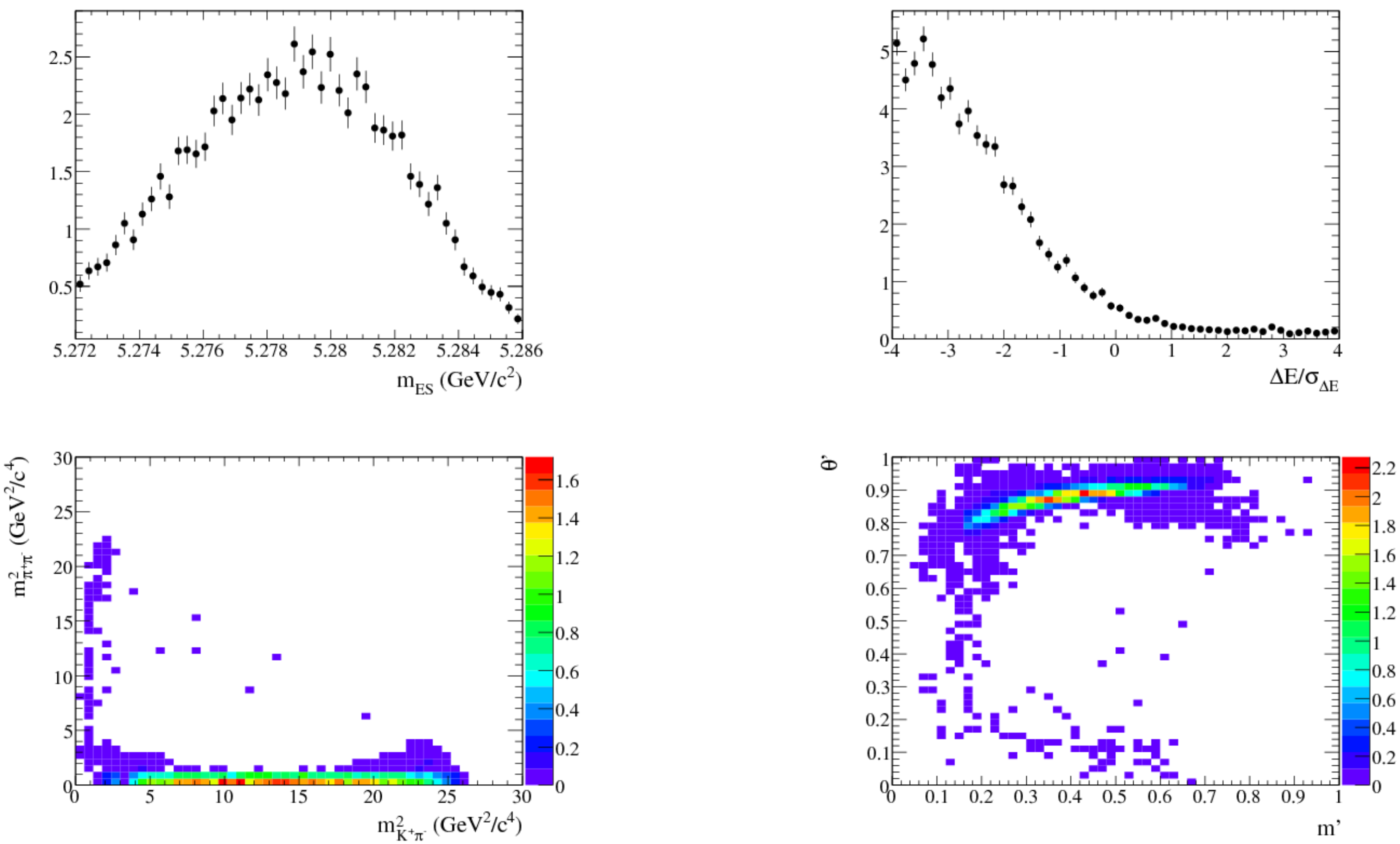
- The decay mode $B^+ \to \overline{D}^0\pi^+;\ \overline{D}^0 \to K^+\pi^-$ has the same final state as our signal
- Its branching fraction is ~3x larger
- Similarly there are decays of J/ψ and ψ(2S) that are very large contributors
- We employ vetoes on the Dalitz plot to remove almost all of these events
  - Rejected Dπ events used to calibrate signal PDFs
- The modes that are left are modelled using samples of Monte Carlo events

B-Background Example 1



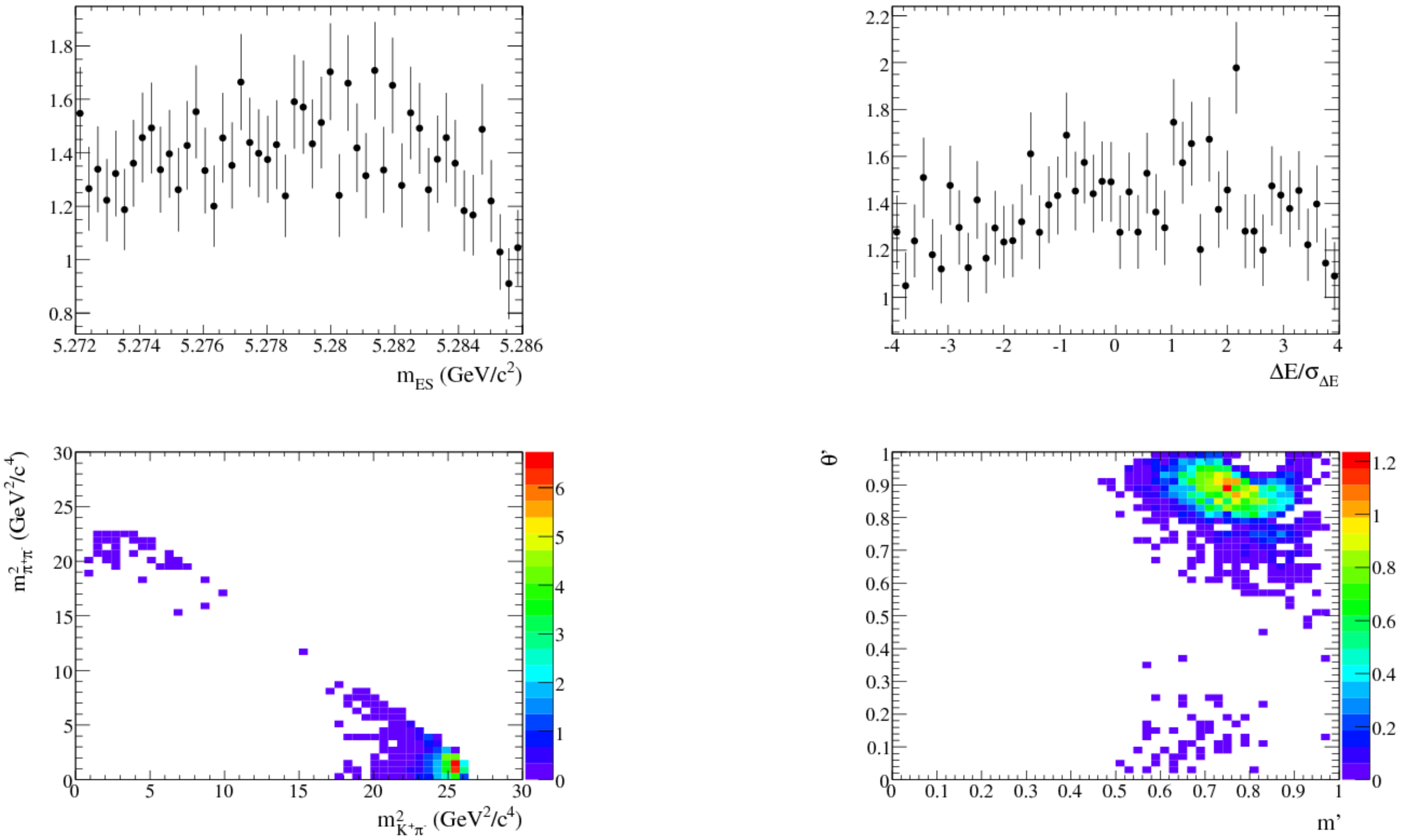
$$B^+ \rightarrow \overline{D}^0\pi^+;\ \overline{D}^0 \rightarrow K^+\pi^-\pi^0$$

B-Background Example 2



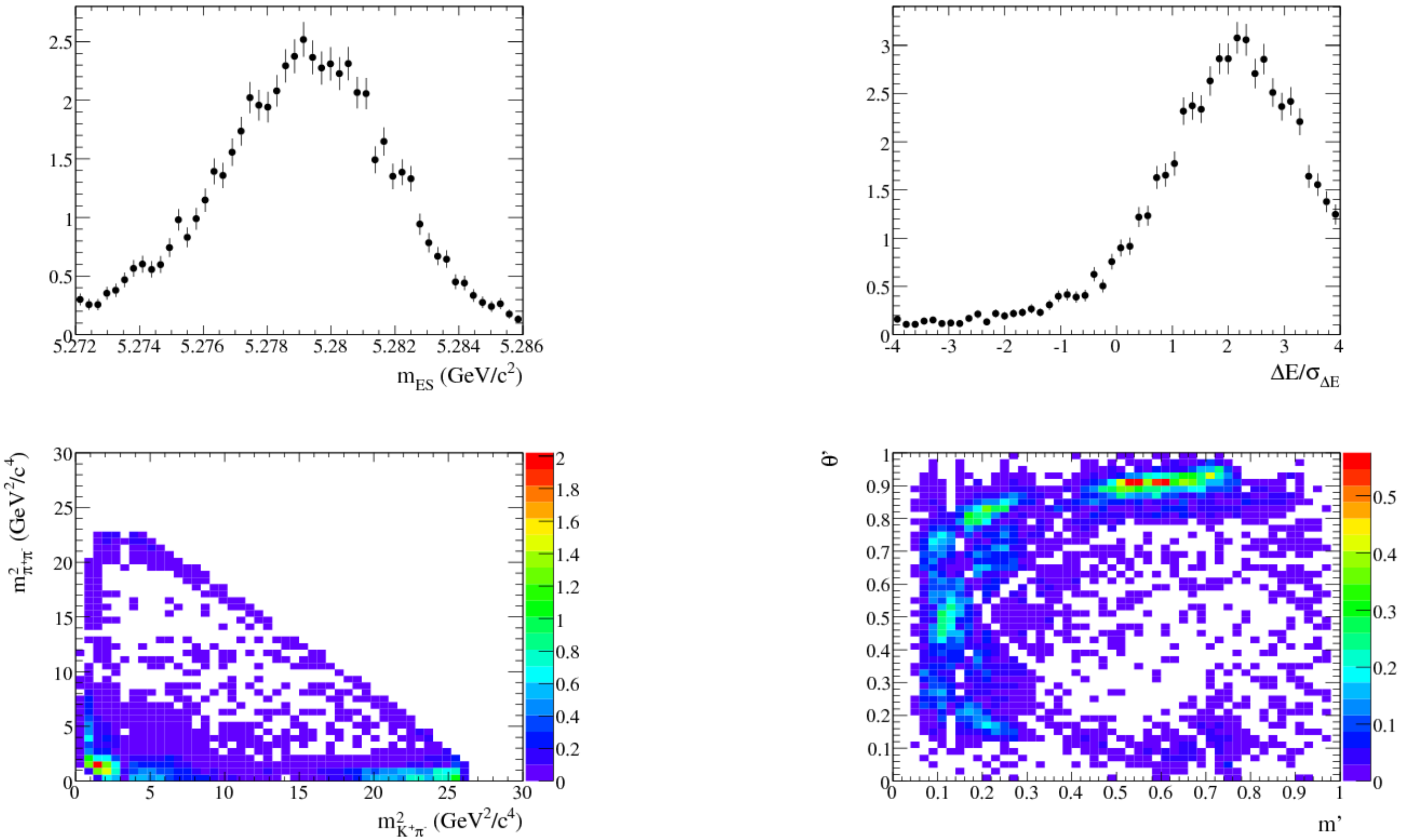
$$B^+ \to \eta' K^+; \, \eta' \to \pi^+\pi^-\gamma$$

B-Background Example 3



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

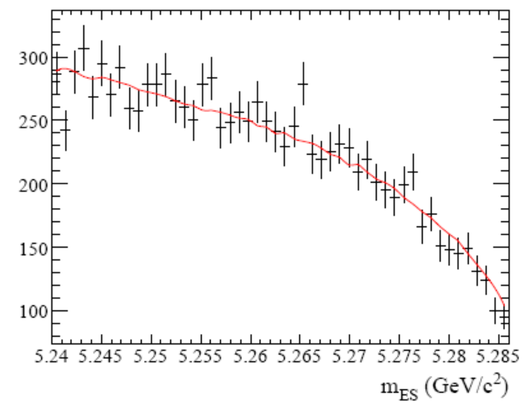
B-Background Example 4

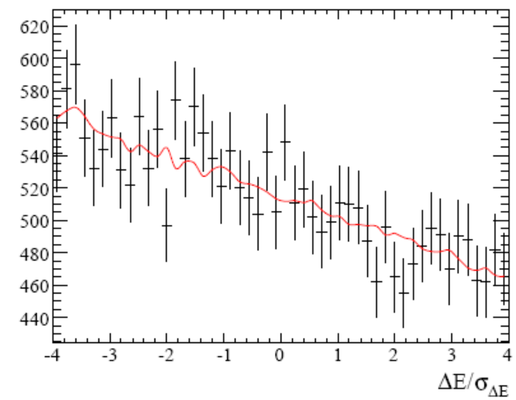


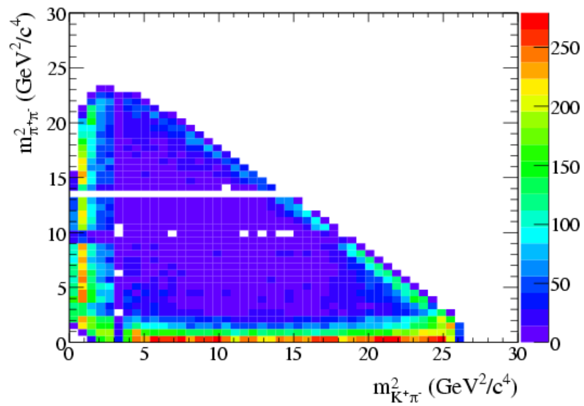
$$B^+ \rightarrow \pi^+\pi^-\pi^+$$

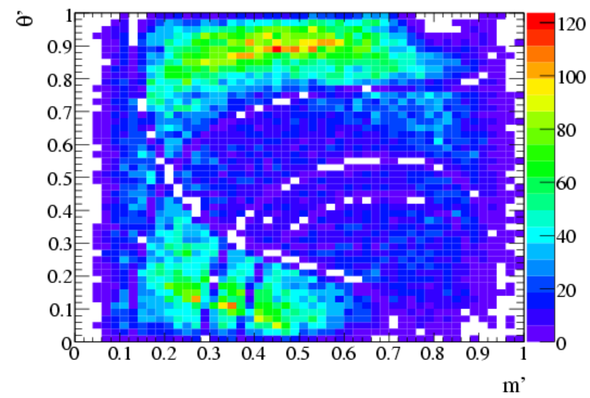
Continuum background

- Shown here are the m_{ES}, $\Delta E'$ and Dalitz-plot distributions for the continuum background
- All analysis cuts have been applied

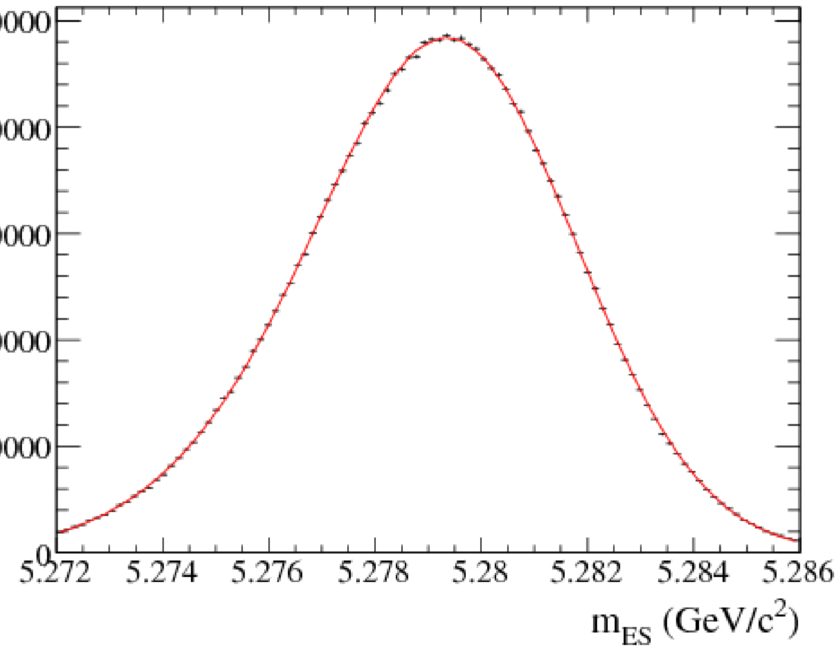


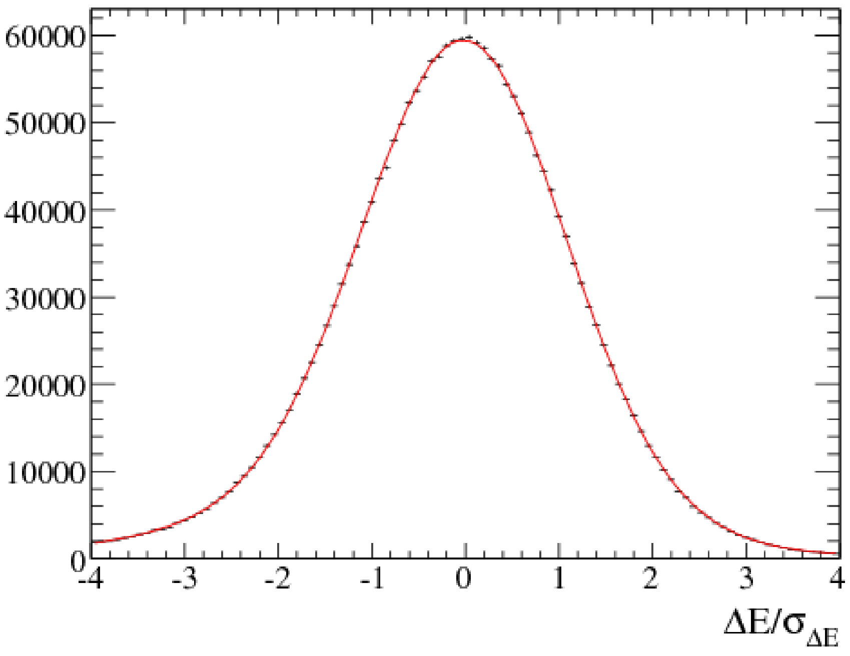






Signal PDFs





- Dalitz-plot PDF formed from isobar model

Signal Dalitz-plot model

Component	Lineshape
$K^{*0}(892)\ \pi^+$	Relativistic Breit–Wigner (RBW)
$(K\pi)_0^{*0}\ \pi^+$	LASS
$K_2^{*0}(1430)\ \pi^+$	RBW
$\rho^0(770)K^+$	RBW
$\omega(782)\ K^+$	RBW
$f_0(980)\ K^+$	Flatté
$f_2(1270)\ K^+$	RBW
$f_x(1300)\ K^+$	RBW
$\chi_{c0}\ K^+$	RBW
Nonresonant $K^+\pi^+\pi^-$	Phase space

LASS Lineshape

- The LASS parameterisation of the Kπ S-wave consists of the $K_0^{*0}(1430)$ resonance together with an effective-range nonresonant component:

$$\mathcal{M} = \frac{m_{K\pi}}{q\cot\delta_B - iq} + e^{2i\delta_B}\frac{m_0\Gamma_0\frac{m_0}{q_0}}{(m_0^2 - m_{K\pi}^2) - im_0\Gamma_0\frac{q}{m_{K\pi}}\frac{m_0}{q_0}},$$

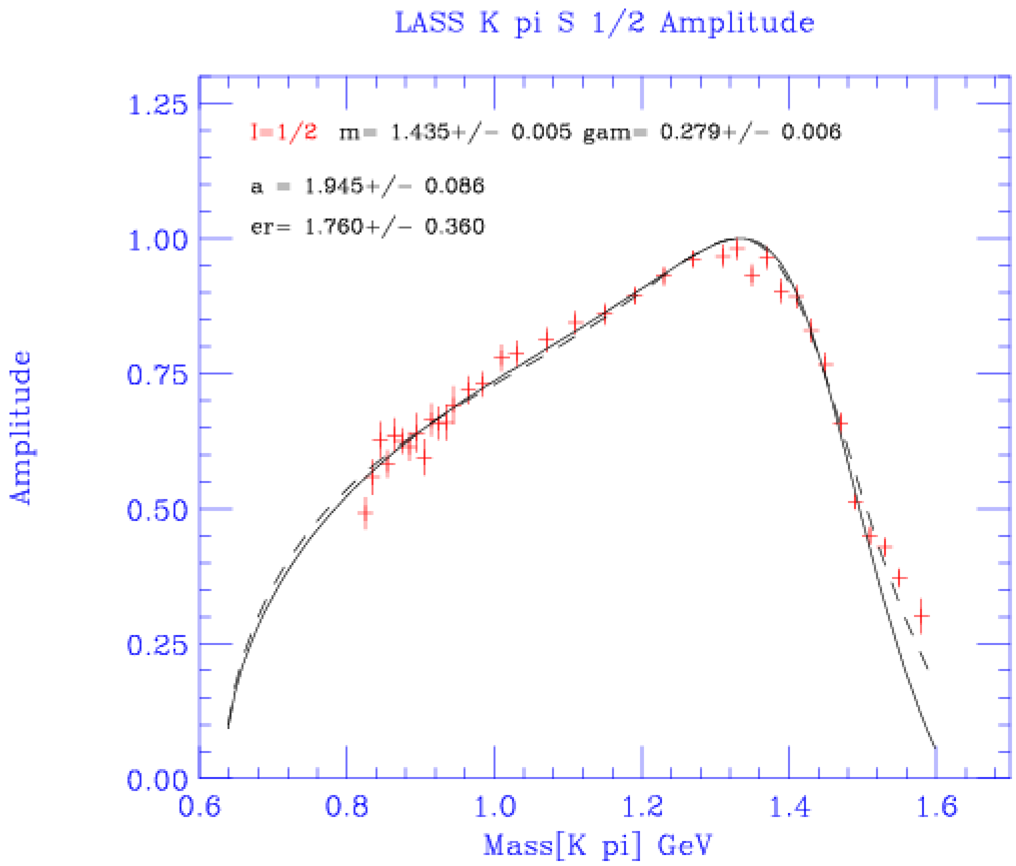
$$\cot\delta_B = \frac{1}{aq} + \frac{1}{2}rq\,.$$

- We have used the following values for the scattering length and effective range parameters:

$$a = (2.07 \pm 0.10)\,(\mathrm{GeV}/c)^{-1}\,,$$

$$r = (3.32 \pm 0.34)\,(\mathrm{GeV}/c)^{-1}\,.$$

LASS Lineshape – plot



Flatté Lineshape

- Also known as a coupled-channel Breit–Wigner

$$R_j(m) = \frac{1}{(m_0^2 - m^2) - i m_0 (\Gamma_{\pi\pi}(m) + \Gamma_{KK}(m))}$$

- The decay widths in the $\pi\pi$ and KK systems are given by:

$$\begin{aligned}
\Gamma_{\pi\pi}(m) &= g_\pi \left(\frac{1}{3}\sqrt{1 - 4m_{\pi^0}^2/m^2} + \frac{2}{3}\sqrt{1 - 4m_{\pi^\pm}^2/m^2} \right) , \\
\Gamma_{KK}(m) &= g_K \left(\frac{1}{2}\sqrt{1 - 4m_{K^\pm}^2/m^2} + \frac{1}{2}\sqrt{1 - 4m_{K^0}^2/m^2} \right) .
\end{aligned}$$

- The fractional coefficients come from isospin conservation and g_π and g_K are coupling constants for which we assume the values obtained by the BES experiment:

$$\begin{aligned}
g_\pi &= (0.165 \pm 0.010 \pm 0.015)\ \mathrm{GeV}/c^2 , \\
g_K &= (4.21 \pm 0.25 \pm 0.21) \times g_\pi .
\end{aligned}$$

Isobar Coefficients

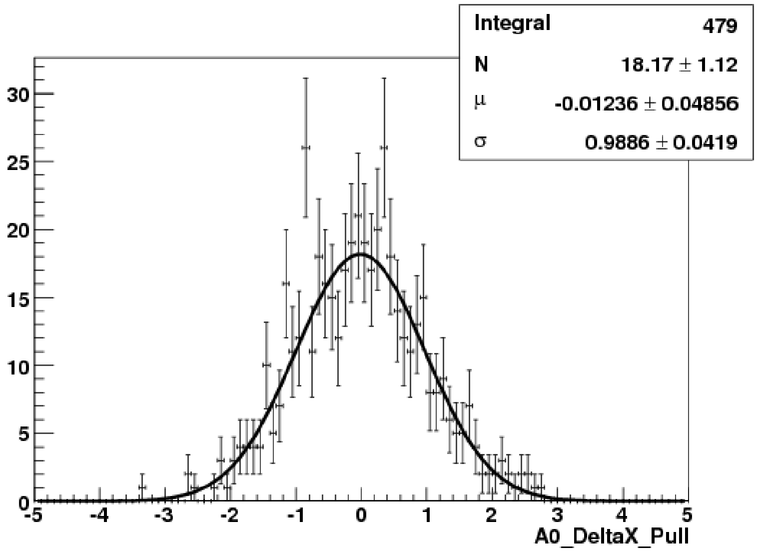
- Several possible ways of parametrising the isobar coefficients
- We have chosen to use a Cartesian form since these are statistically better behaved in the fit
- Have chosen them such that determination of the significance of direct CP violation is simple to calculate

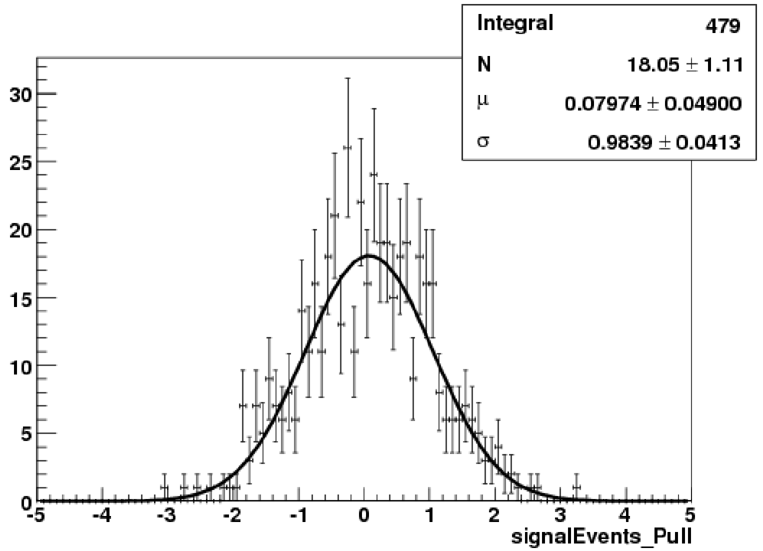
$$c_j = (x_j + \Delta x_j) + i\,(y_j + \Delta y_j)$$

$$\bar{c}_j = (x_j - \Delta x_j) + i\,(y_j - \Delta y_j)$$

Fit Validation 1 – Toy MC

- The first test that the fit is working correctly is to generate several samples of toy MC from the PDFs and fit them
- We then construct pull distributions for each fitted parameter
- The results from this test were very good, see examples plots below:





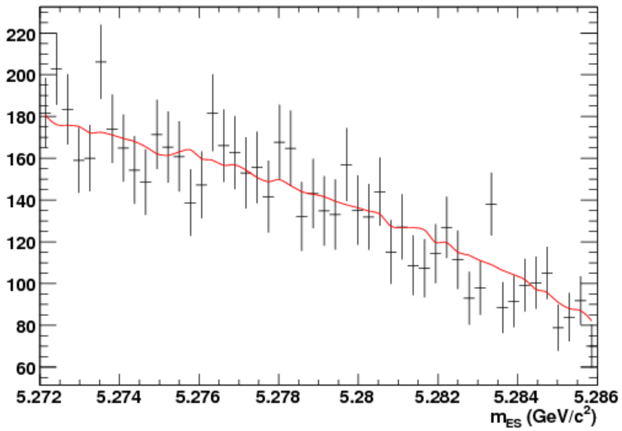
Fit Validation 2 – Full MC

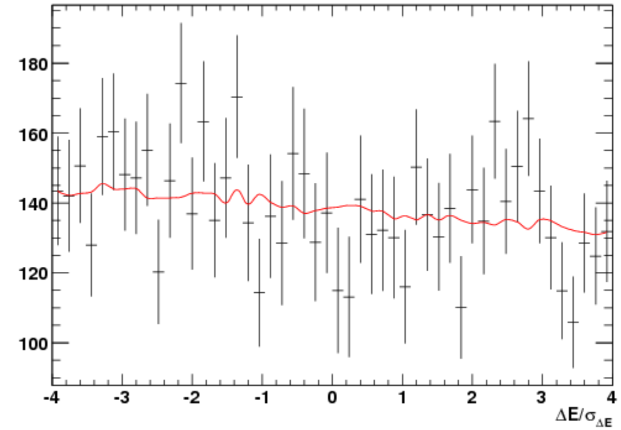
- In the second test the toy MC for the signal and B-background components is replaced by fully simulated events
- The signal is generated using a known set of isobar amplitudes
- The pull distributions again look very good
- Except for a 2% pull on the signal yield, which is accounted for in the systematics

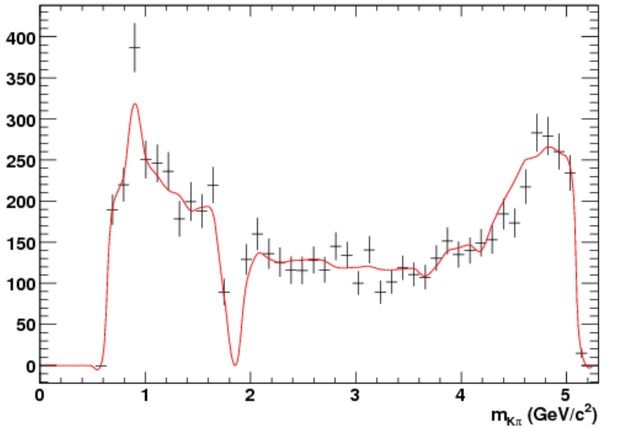
Blind fits to the data

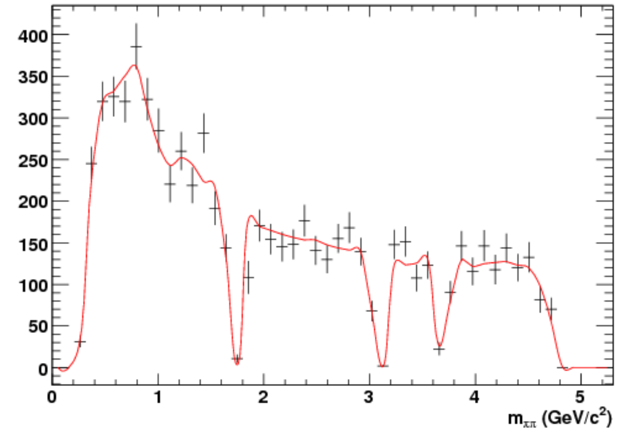
- We next performed fits to the data where we were blinded to signal parameters
- Likelihood ratio plots were constructed from toy generated from the fitted parameters and compared with the data (with large values blinded)
- sPlots of the continuum distributions were also constructed and checked against the model

Continuum sPlots



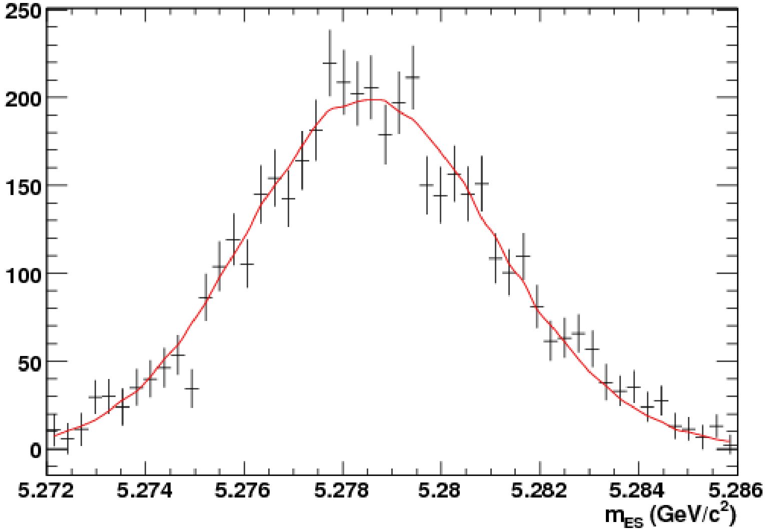


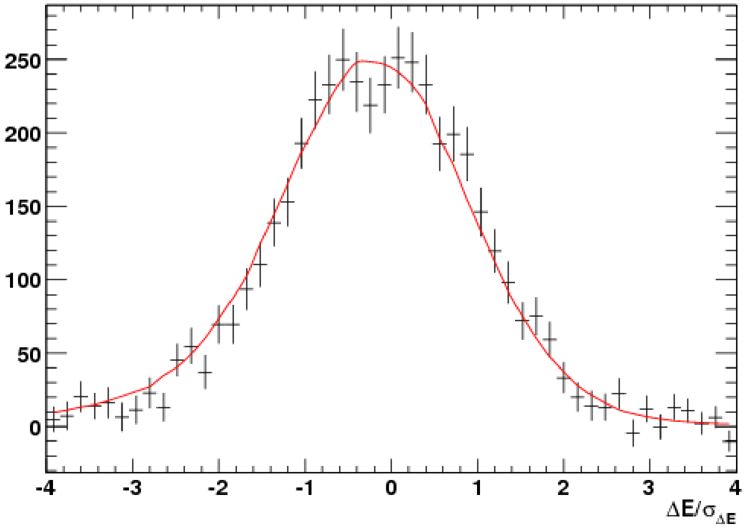




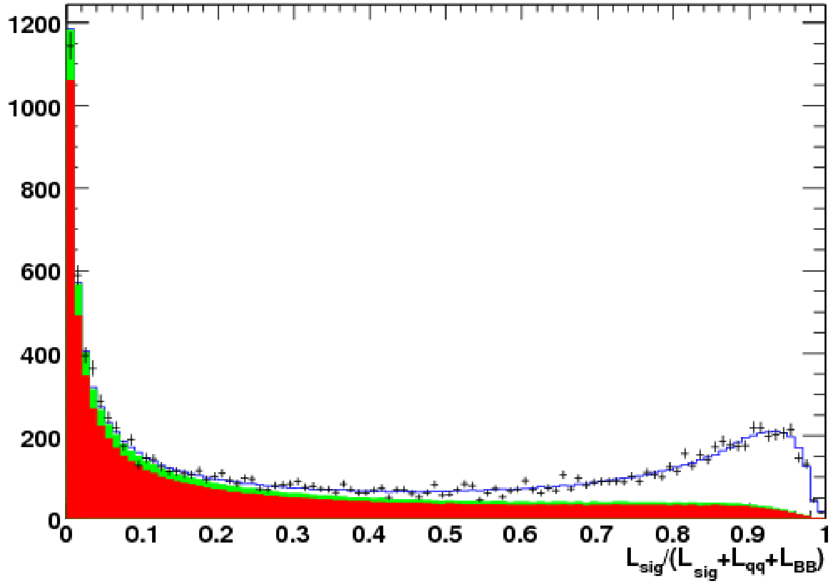
Unblind non-DP parameters

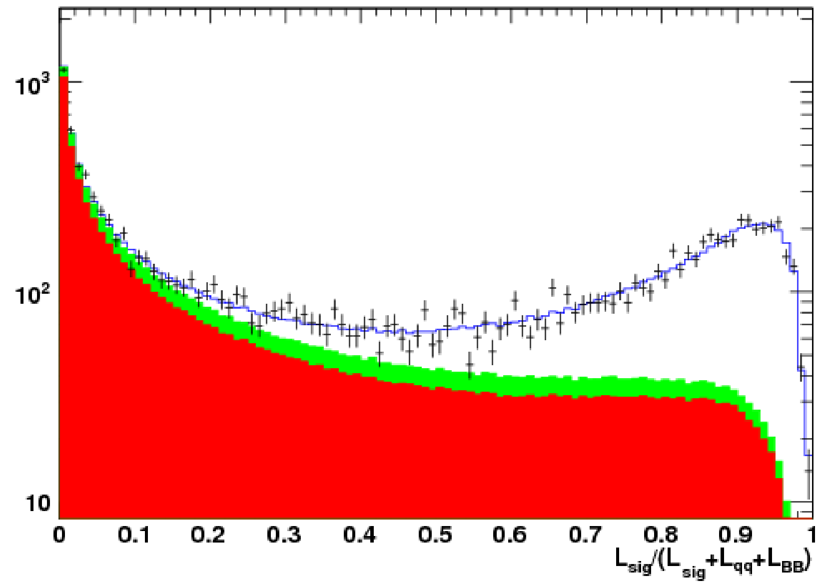
- The next stage was to unblind the non Dalitz plot parameters and distributions
- Signal yield = 4585 ± 90 (stat. error only)





Likelihood ratio plots

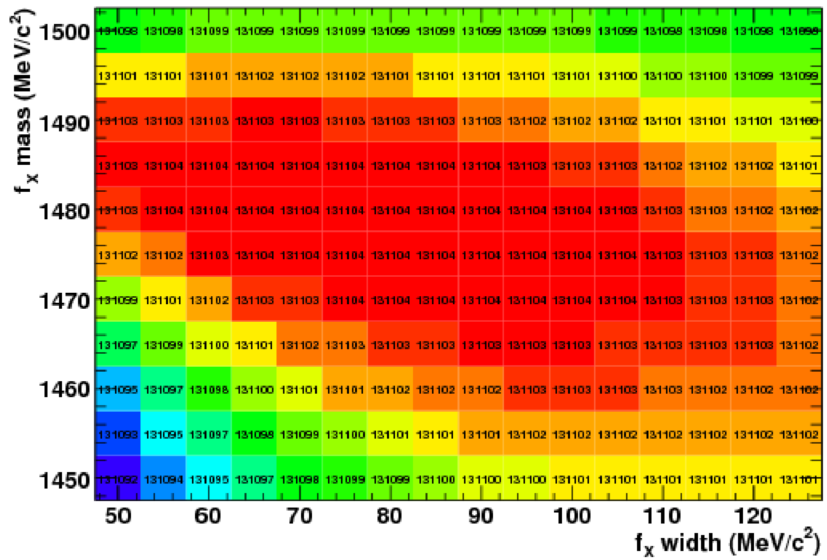




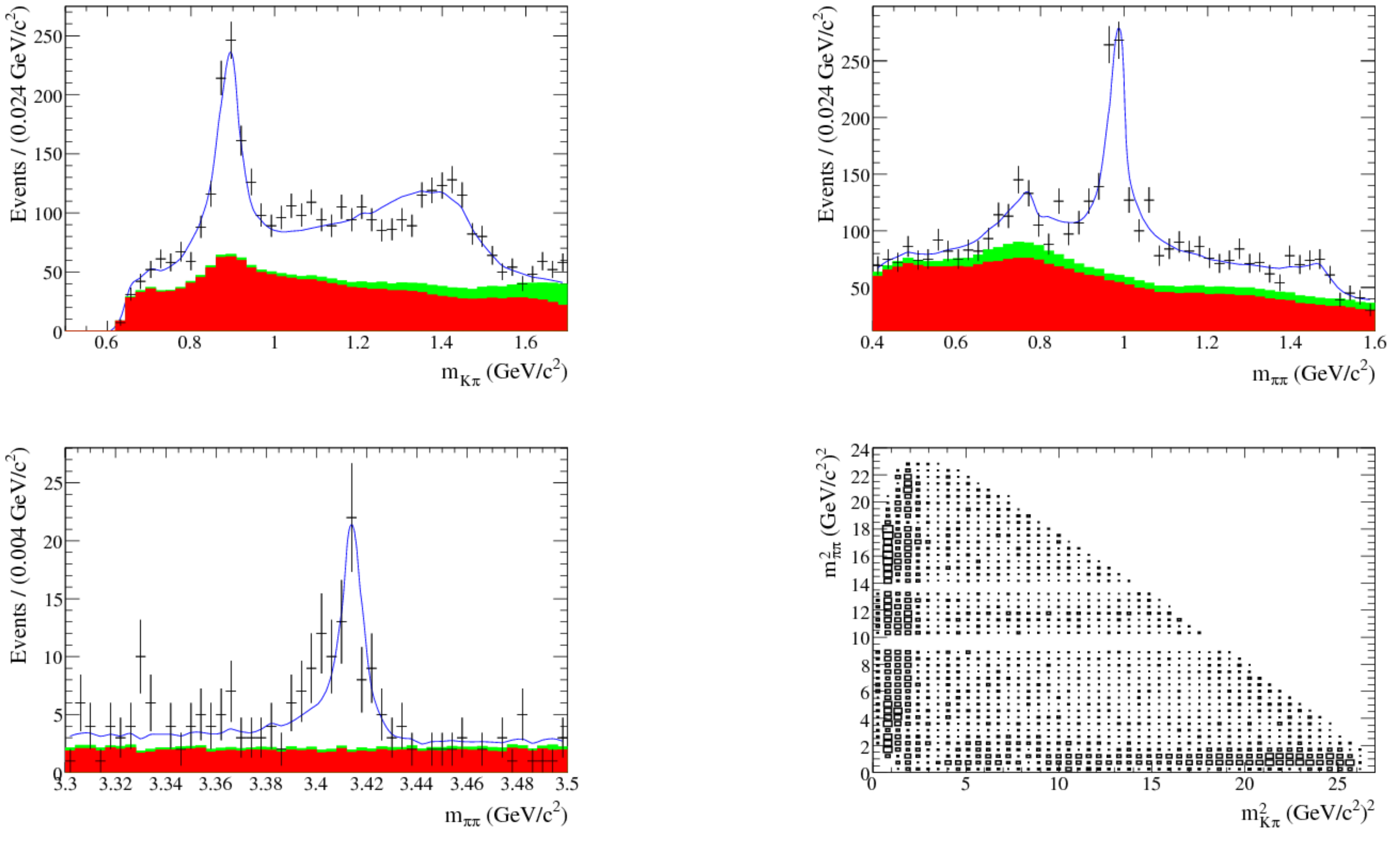
Black points are the data,
Red histogram is continuum background,
Green histogram is total background,
Blue line is total

Scan for f_x(1300) parameters

- We performed a likelihood scan for the mass and width of the f_x(1300) resonance
- We treat this component as a scalar
- Found parameters to be:
  - m = 1479 MeV/c^2
  - Γ = 80 MeV/c^2
- Consistent with the PDG values of the f_0(1500)



Dalitz plot and projections



Significance of Direct CPV

- Refit data fixing the Δx and Δy parameters for the given component to zero
- Note the change in the fit likelihood, $\Delta \ln \mathcal{L}$
- Evaluate a p-value for 2 degrees of freedom according to:

$$p = \int_{2\Delta \ln \mathcal{L}}^{\infty} f(z; n_d)\, dz$$

- Where f is the χ^2 PDF and $n_d = 2$
- Determine the equivalent 1D significance
- Double checked using toy MC

Systematic Errors

- Fixed B-background yields and asymmetries
- B-background m_{ES} and ΔE histograms
- Fixed signal m_{ES} and ΔE PDF parameters
- B-background DP histogram
- Continuum background DP histogram
- Efficiency histogram
- Fit bias

Model-dependent errors

- Float $\omega(782)$ CP parameters
- Alternative lineshape for $\rho^0(770)$
- Alternative form for NR component
- Remove smaller components from model
- Add extra components to model
- Vary BW, LASS and Flatté parameters
- Vary masses and widths of resonances

Results

Mode	Fit Fraction (%)	$\mathcal{B}(B^+ \to \text{Mode})(10^{-6})$	A_{CP} (%)	DCPV Sig.
$K^+\pi^-\pi^+$ Total		$54.4 \pm 1.1 \pm 4.5 \pm 0.7$	$2.8 \pm 2.0 \pm 2.0 \pm 1.2$	
$K^{*0}(892)\pi^+$; $K^{*0}(892) \to K^+\pi^-$	$13.3 \pm 0.7 \pm 0.7\,^{+0.4}_{-0.9}$	$7.2 \pm 0.4 \pm 0.7\,^{+0.3}_{-0.5}$	$+3.2 \pm 5.2 \pm 1.1\,^{+1.2}_{-0.7}$	0.9σ
$(K\pi)^{*0}_0\pi^+$; $(K\pi)^{*0}_0 \to K^+\pi^-$	$45.0 \pm 1.4 \pm 1.2\,^{+12.9}_{-0.2}$	$24.5 \pm 0.9 \pm 2.1\,^{+7.0}_{-1.1}$	$+3.2 \pm 3.5 \pm 2.0\,^{+2.7}_{-1.9}$	1.2σ
$\rho^0(770)K^+$; $\rho^0(770) \to \pi^+\pi^-$	$6.54 \pm 0.81 \pm 0.58\,^{+0.69}_{-0.26}$	$3.56 \pm 0.45 \pm 0.43\,^{+0.38}_{-0.15}$	$+44 \pm 10 \pm 4\,^{+5}_{-13}$	3.7σ
$f_0(980)K^+$; $f_0(980) \to \pi^+\pi^-$	$18.9 \pm 0.9 \pm 1.7\,^{+2.8}_{-0.6}$	$10.3 \pm 0.5 \pm 1.3\,^{+1.5}_{-0.4}$	$-10.6 \pm 5.0 \pm 1.1\,^{+3.4}_{-1.0}$	1.8σ
$\chi_{c0}K^+$; $\chi_{c0} \to \pi^+\pi^-$	$1.29 \pm 0.19 \pm 0.15\,^{+0.12}_{-0.03}$	$0.70 \pm 0.10 \pm 0.10\,^{+0.06}_{-0.02}$	$-14 \pm 15 \pm 3\,^{+1}_{-5}$	0.5σ
$K^+\pi^-\pi^+$ nonresonant	$4.5 \pm 0.9 \pm 2.4\,^{+0.6}_{-1.5}$	$2.4 \pm 0.5 \pm 1.3\,^{+0.3}_{-0.8}$	—	—
$K^{*0}_2(1430)\pi^+$; $K^{*0}_2(1430) \to K^+\pi^-$	$3.40 \pm 0.75 \pm 0.42\,^{+0.99}_{-0.13}$	$1.85 \pm 0.41 \pm 0.28\,^{+0.54}_{-0.08}$	$+5 \pm 23 \pm 4\,^{+18}_{-7}$	0.2σ
$\omega(782)K^+$; $\omega(782) \to \pi^+\pi^-$	$0.17 \pm 0.24 \pm 0.03\,^{+0.05}_{-0.08}$	$0.09 \pm 0.13 \pm 0.02\,^{+0.03}_{-0.04}$	—	—
$f_2(1270)K^+$; $f_2(1270) \to \pi^+\pi^-$	$0.91 \pm 0.27 \pm 0.11\,^{+0.24}_{-0.17}$	$0.50 \pm 0.15 \pm 0.07\,^{+0.13}_{-0.09}$	$-85 \pm 22 \pm 13\,^{+22}_{-2}$	3.5σ
$f_X(1300)K^+$; $f_X(1300) \to \pi^+\pi^-$	$1.33 \pm 0.38 \pm 0.86\,^{+0.04}_{-0.14}$	$0.73 \pm 0.21 \pm 0.47\,^{+0.02}_{-0.08}$	$+28 \pm 26 \pm 13\,^{+7}_{-5}$	0.6σ

First error is statistical, second systematic and third model-dependent. Significance of DCPV is statistical only.

Total NR branching fraction = $(9.3 \pm 1.0 \pm 1.2\,^{+6.7}_{-0.4} \pm 1.2) \times 10^{-6}$

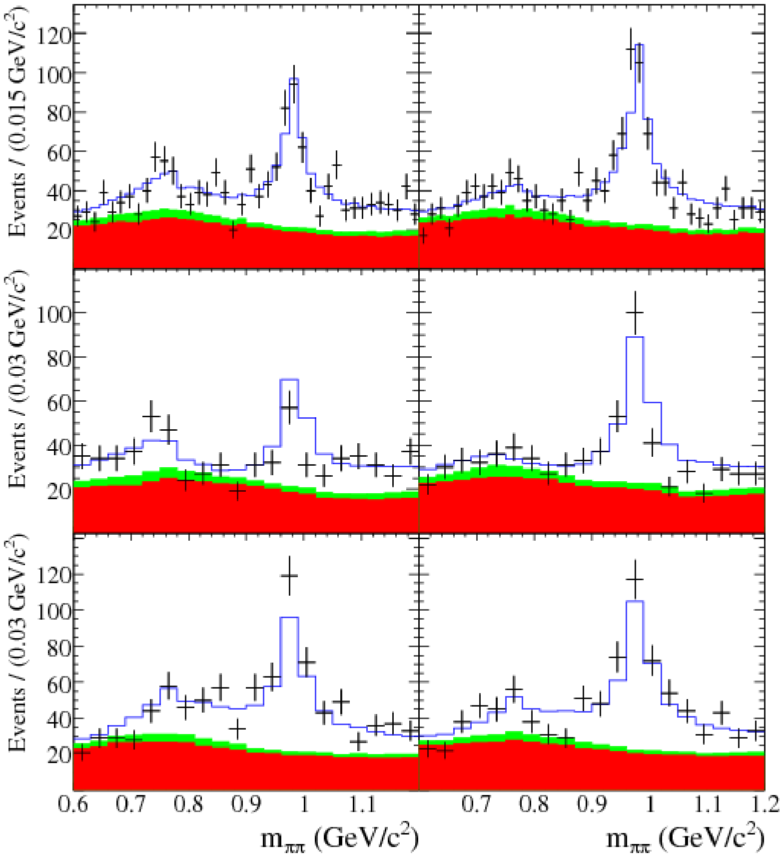
Evidence of DCPV in $\rho^0(770)K^+$

B^- B^+

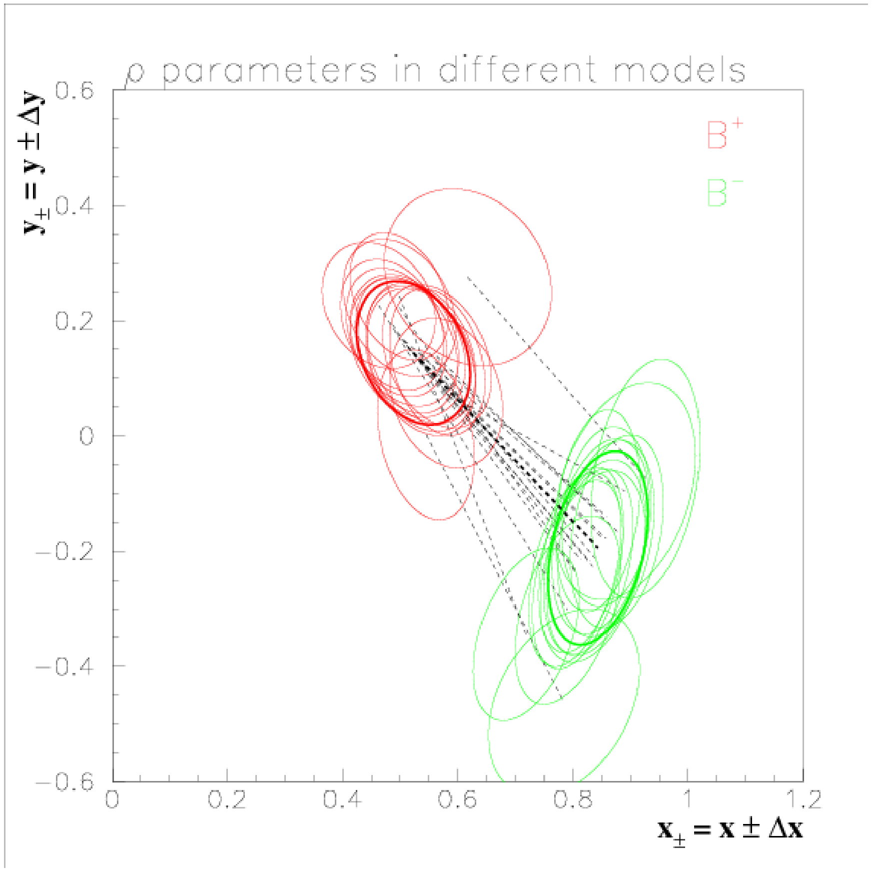
All

Positive helicity

Negative helicity



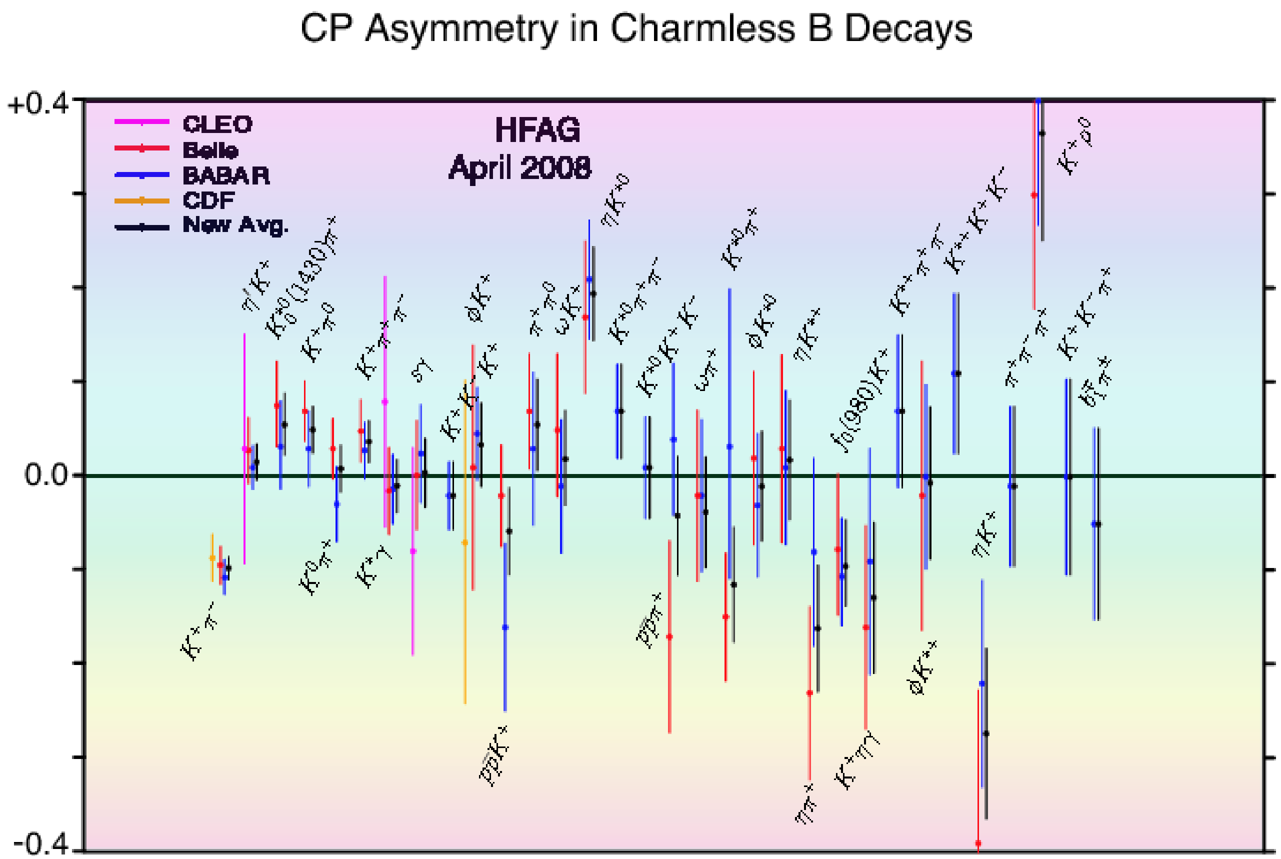
Systematic/Model dependence of DCPV in $\rho^0(770)K^+$



Summary

- Completed Dalitz-plot analysis of $B^+ \rightarrow K^+\pi^+\pi^-$ using 383 million B pairs
- Measure branching fractions and CP asymmetries for inclusive mode plus nonresonant and nine intermediate resonances
- Found evidence for direct CP violation in the decay $B+ \rightarrow \rho^0(770)K^+$
- Results consistent with previous analysis and with those from Belle
- Results presented at Moriond QCD 2008
- Journal paper submitted to Phys. Rev. D
  - arXiv:0803.4451 [hep-ex]

Summary – pretty plot



Backup Material

sPlots [Nucl. Instrum. Meth. A 555 (2005) 356-369]

- The sPlots technique is a statistical tool that allows the distribution of a variable for a particular species, e.g. signal, to be reconstructed from the PDFs of other variables
- An sWeight is assigned to each event according to:

$$ {}_sW_n(y_e) = \frac{\sum_{j=1}^{N_S} \mathbf{V}_{nj} f_j(y_e)}{\sum_{k=1}^{N_S} N_k f_k(y_e)} $$

- Where NS is the number of species, V is the covariance matrix from the fit, f are the PDFs of the variables y, the subscript n refers to the species of interest and the subscript e refers to the event under consideration
- These sWeights have the property that:

$$ \sum_e {}_sW_n(y_e) = N_n $$

- A histogram in a variable (not in the set y) can then be filled with each event weighted by its sWeight
- This histogram will reproduce the e.g. signal distribution of that variable
- sWeights can also be used e.g. in order to correctly deal with signal reconstruction efficiency (ε) variation on an event-by-event basis
- In this case a branching fraction can be correctly determined from:

$$ BF = \sum_n \frac{{}_sW_n(y_e)}{\varepsilon_n N_{B\bar{B}}} $$

Results on $\rho-\eta$ constraint

$B \to K\pi\pi$ Dalitz analyses

Dalitz analysis	measurements
$B^0 \to K^+\pi^-\pi^0$	$\lvert A(K^{*+}\pi^-)\rvert,\ \lvert A(K^{*0}\pi^0)\rvert,\quad c.c.$
$c.c.$	$\phi \equiv \arg[A(K^{*0}\pi^0)/A(K^{*+}\pi^-)],\ \bar{\phi}$
$B^0(t) \to K_S\pi^+\pi^-$	$\Delta\phi \equiv \arg[A(K^{*+}\pi^-)/\bar{A}(K^{*-}\pi^+)]$

Mode	Branching ratio	A_{CP}	quantities
$K^{*+}\pi^-$	10.4 ± 0.9	-0.14 ± 0.12	$\lvert A(K^{*+}\pi^-)\rvert,\ c.c.$
$K^{*0}\pi^0$	3.6 ± 0.9	-0.09 ± 0.24	$\lvert A(K^{*0}\pi^0)\rvert,\ c.c.$

$\Delta\phi = (-164 \pm 30.7)^\circ$ χ^2 for $\phi, \bar{\phi}$ has shallow minima (next)

Babar, arXiv:07082097, arXiv:0711.4417 $\sim$ 200fb^{-1} on $\Upsilon(4S)$

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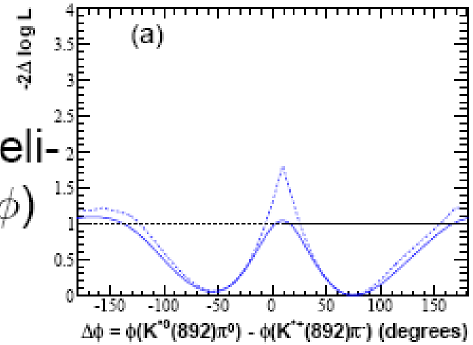
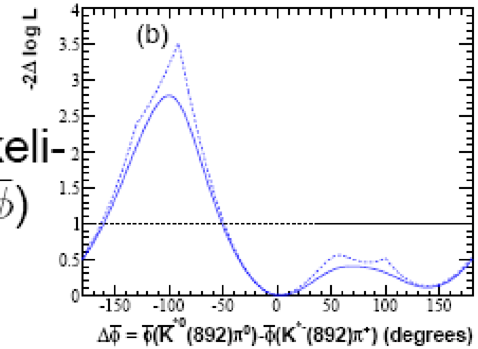
Allowed range for $\Phi_{3/2}$

-Loglikelihood (ϕ)



- Loglikelihood($\bar{\phi}$)

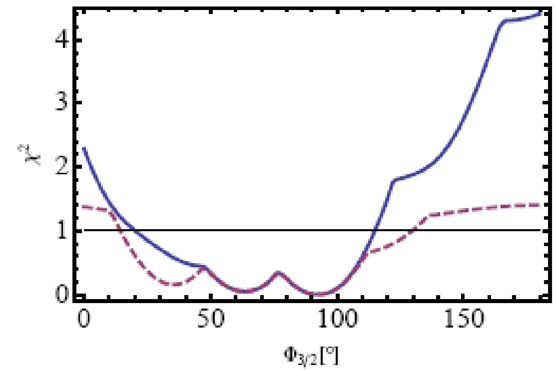


No direct overlap of K^{*+} & K^{*0}; both interfere with ρ

Translate into $\chi^2(\Phi_{3/2})$

$0.8 < |R_{3/2}| < 1.2$

1σ: $\boxed{20^\circ < \Phi_{3/2} < 115^\circ}$



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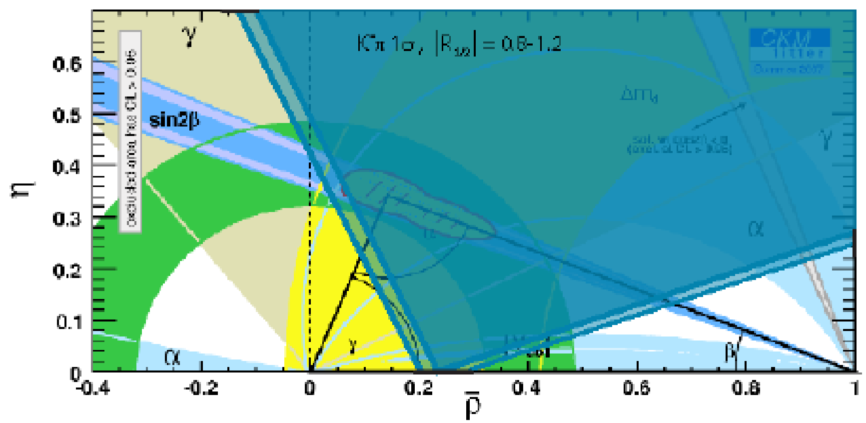
Compare with other CKM constraints



$$\bar{\eta} = \tan \Phi_{3/2} \, [\bar{\rho} - 0.24 \pm 0.03]$$

- New constraint is consistent with all others
- However, large experimental error in $\Phi_{3/2}$

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