Charmless B Decays

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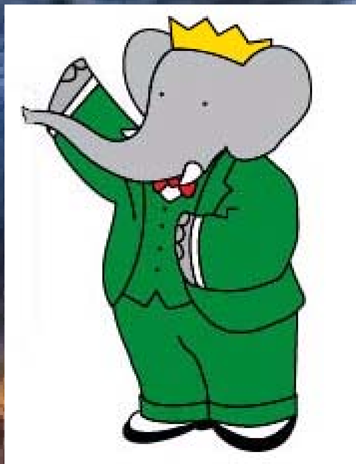
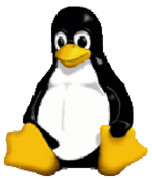
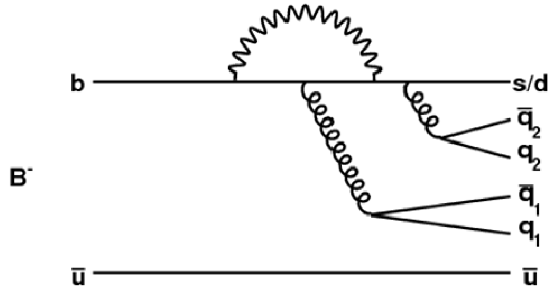
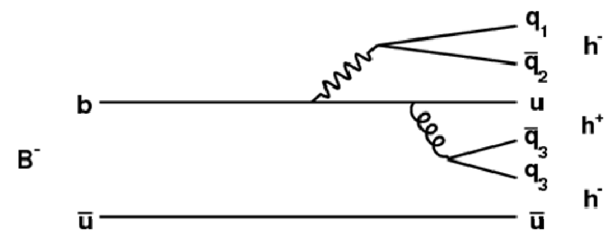


Not so charmless…

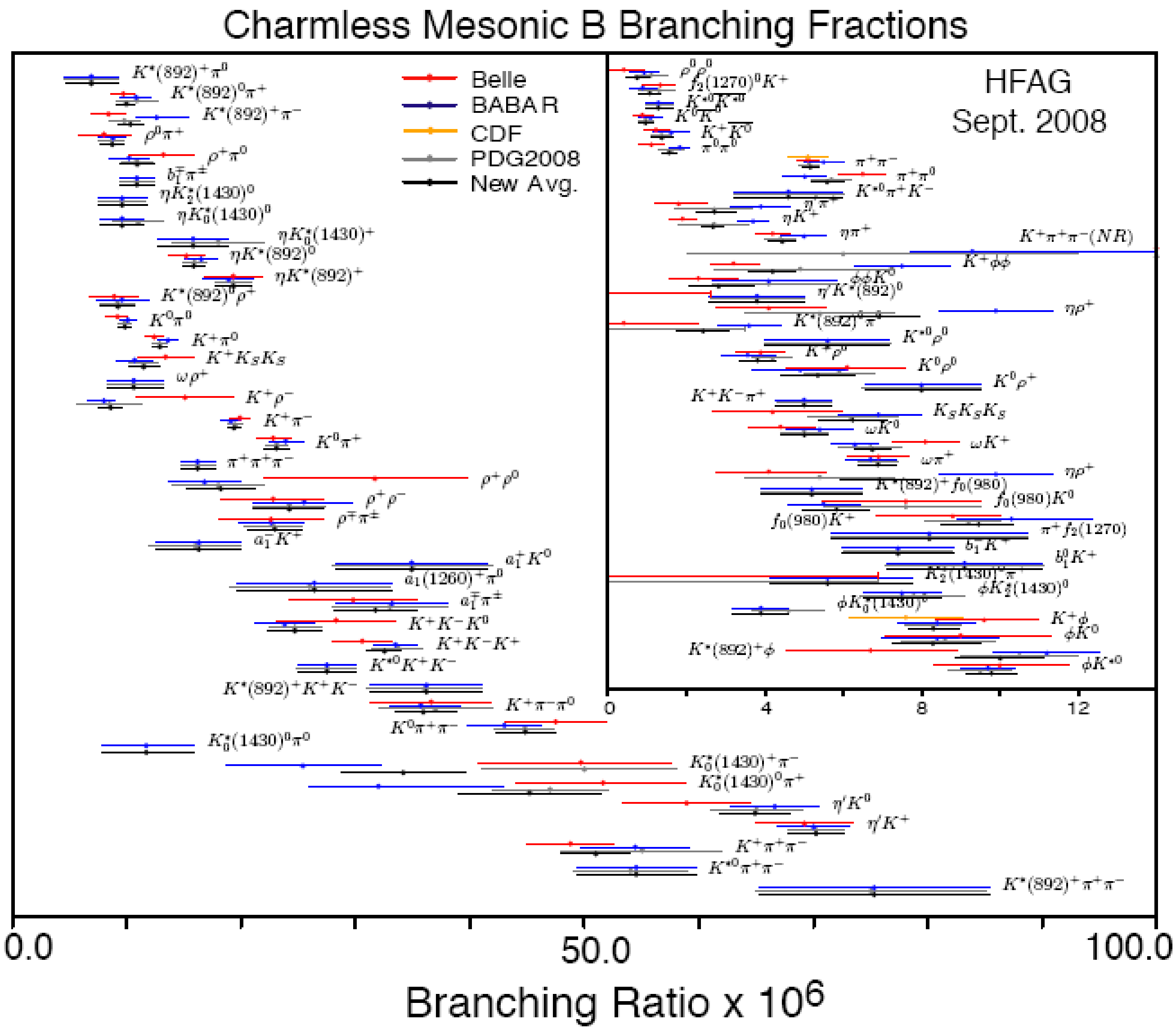






- Charmless B decays have many great features
- Several contributing (and interfering) diagrams
- Potential to measure all 3 UT angles
- Potential for direct CP violation
- Rich spectrum of resonant states
- Scalars, vectors, tensors, pseudo-scalars, axial-vectors etc.

A wealth of decay modes!

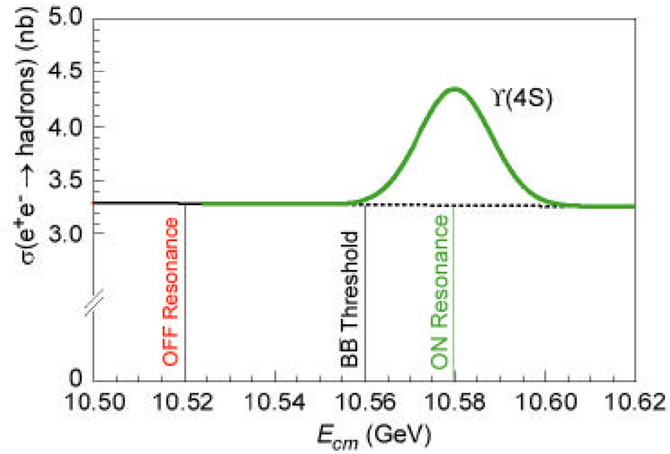


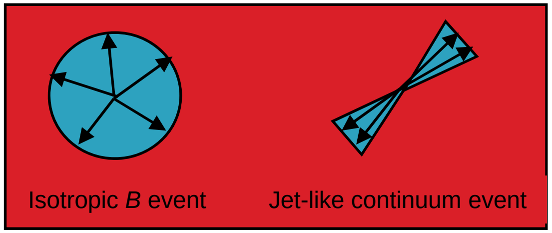
What to pick?

- UK has had a high level of involvement in all 3 charmless AWGs over the years, including providing several of the conveners
- Very difficult to select from > 100 published analyses (large % of BaBar total!)
- I shall concentrate on 2 main topics:
  - Development of analysis techniques
  - Surprises and puzzles
- Apologies if your analysis isn't mentioned

Continuum background fighting

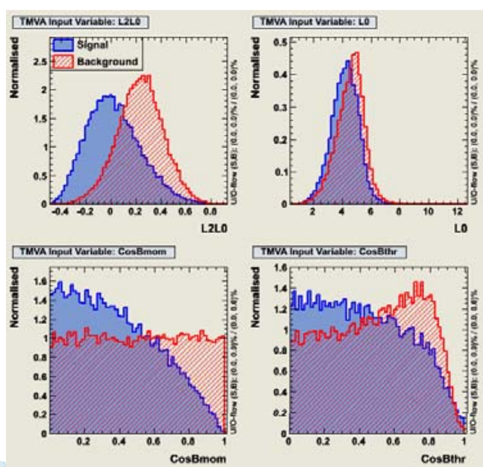
- Big problem for charmless decays
- Light quark continuum cross section ~3x$b\bar{b}$
- *B* mesons produced almost at rest since just above threshold
- Use the topology of the event to discriminate

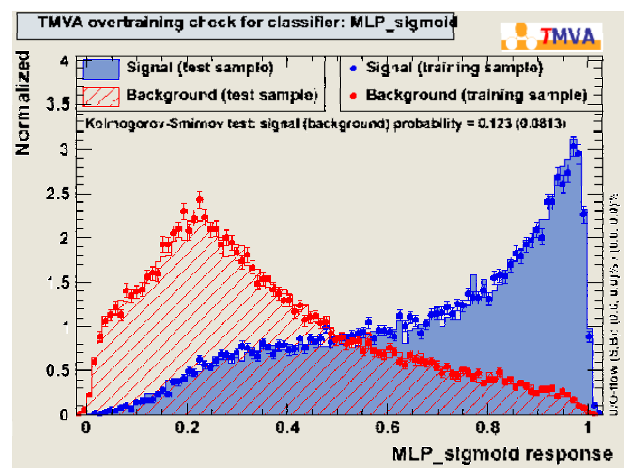




Multivariate Analysers

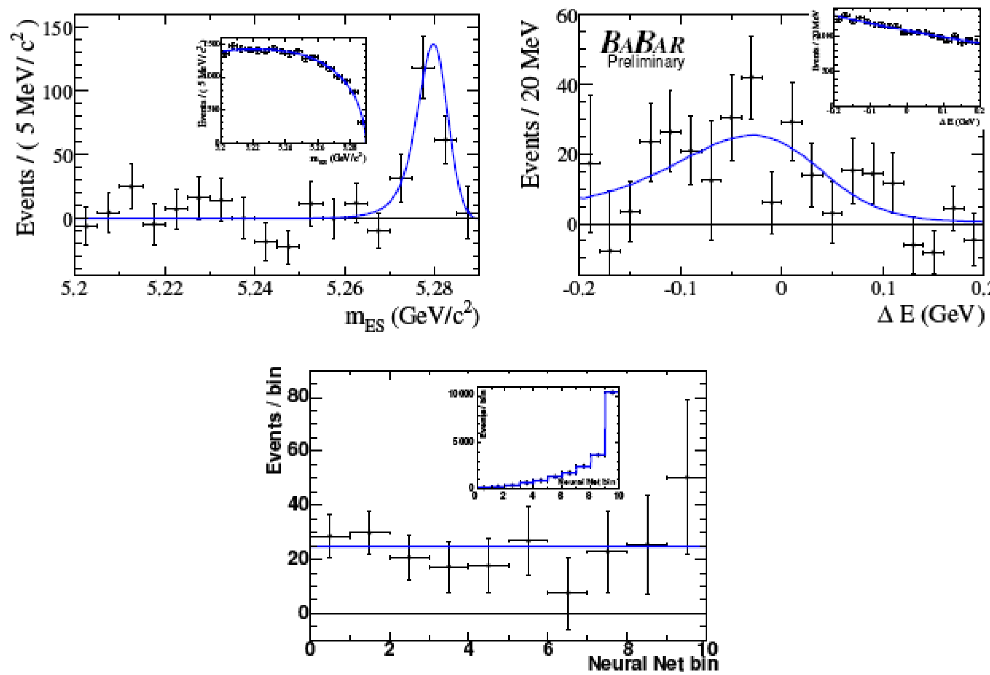
- Usually combine topological variables in an MVA
- Development of dedicated packages such as TMVA and StatPatternRecognition
- Over the years have seen a great improvement in discriminating power
  - Improved range and performance of classifiers
  - Improved knowledge and selection of input variables





Multi-dimensional likelihood fits

- Multi-dimensional extended maximum likelihood fits are the norm in all BaBar analyses of charmless hadronic decays
- Have maximised our sensitivity to the data
- Allowed observations of decays like $\pi^0\pi^0$, $K_S K^+$ and $K_S K_S$ and evidence for $\rho^0\rho^0$



sPlots of $\pi^0\pi^0$ signal
arXiv:0807.4226 [hep-ex]

Dalitz-plot analysis

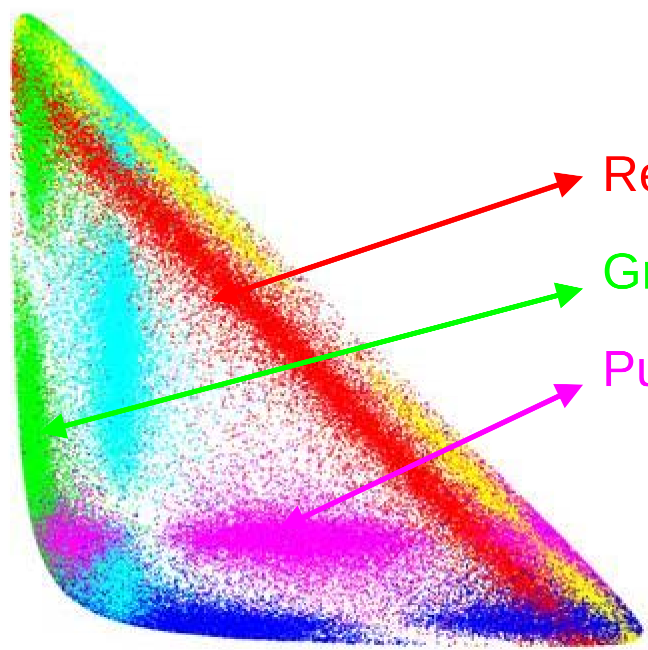
- Dalitz plot (DP) is a 2D visualisation of the complete phase space for decays of a spin-0 particle into 3 spin-0 particles (i,j,k)
  - e.g. decays of a *B* meson into combinations of $\pi^{\pm}$, π^0, $K^{\pm}$, K^0, η, η' etc.
- Any point in the DP must satisfy

$$m_B^2 + m_i^2 + m_j^2 + m_k^2 = m_{ij}^2 + m_{ik}^2 + m_{jk}^2$$

- Traditionally plotted as m^2_{ik} vs. m^2_{jk}
- Purely phase-space decays would uniformly populate the DP

The power of the Dalitz plot

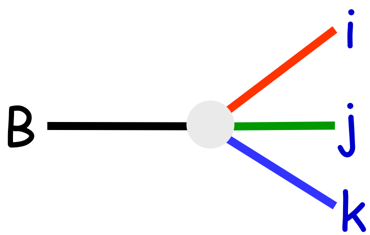
- Resonances appear as bands of events in the Dalitz plot
- Position and size of band related to mass and width
- Resonance spin governs distribution of events along the band
- Exact pattern of events in Dalitz plot determined by interference between the various contributing states

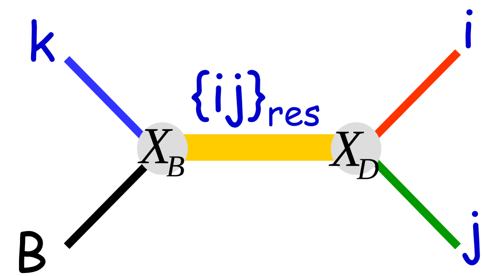


Isobar Model

- Model the complete 3-body decay as a sum of contributing amplitudes

$$A = c_{\mathrm{NR}} e^{i\theta_{\mathrm{NR}}} + \sum_{\mathrm{res}} c_{\mathrm{res}} e^{i\theta_{\mathrm{res}}} F_{\mathrm{res}}$$





- Both nonresonant and resonant amplitudes
- F = resonance dynamics
- c and θ are relative magnitudes and phases

Resonance Dynamics

$$F_j = R_j \times X_J(p^\star) \times X_J(q) \times T_j$$

$$R_j(m) = \frac{1}{(m_0^2 - m^2) - i m_0 \Gamma(m)}$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2J+1} \left(\frac{m_0}{m}\right) \frac{X_J^2(q)}{X_J^2(q_0)}$$

$$\Gamma(m) = \Gamma_{\pi\pi}(m) + \Gamma_{KK}(m)$$

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

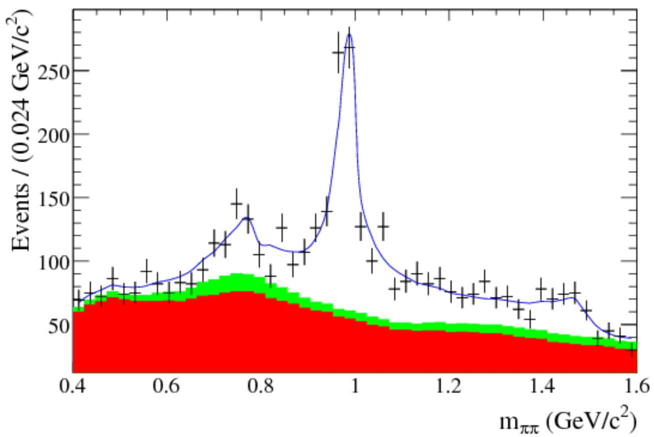
$$\begin{aligned}
T_j^{J=0} &= 1 \\
T_j^{J=1} &= -2\,\vec{p}\cdot\vec{q} \\
T_j^{J=2} &= \frac{4}{3}\left[3(\vec{p}\cdot\vec{q})^2 - (|\vec{p}||\vec{q}|)^2\right]
\end{aligned}$$

$$\begin{aligned}
X_{J=0}(z) &= 1, \\
X_{J=1}(z) &= \sqrt{1/(1 + (z\,r_{\rm BW})^2)}, \\
X_{J=2}(z) &= \sqrt{1/((z\,r_{\rm BW})^4 + 3(z\,r_{\rm BW})^2 + 9)}
\end{aligned}$$

$$\begin{aligned}
R_j(m) &= \frac{m_{K\pi}}{q\cot\delta_B - iq} \\
&+ e^{2i\delta_B} \frac{m_0\Gamma_0 \frac{m_0}{q_0}}{(m_0^2 - m_{K\pi}^2) - i m_0 \Gamma_0 \frac{q}{m_{K\pi}} \frac{m_0}{q_0}}
\end{aligned}$$

$$\cot\delta_B = \frac{1}{aq} + \frac{1}{2} r q$$

Results from $K^+\pi^+\pi^-$ DP Fit

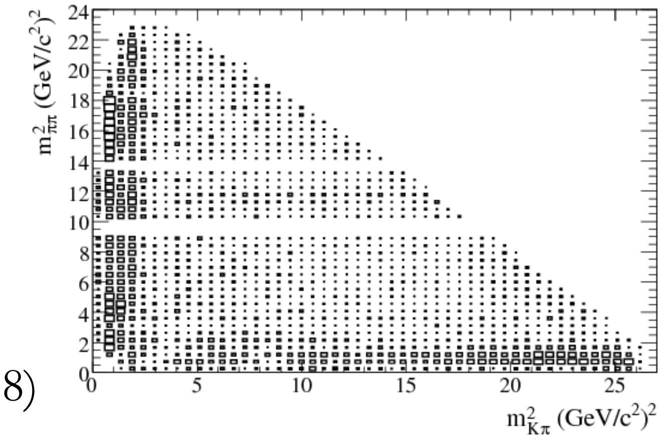


Total Fit Result

Continuum background

BB background

Phys. Rev. D78, 012004 (2008)

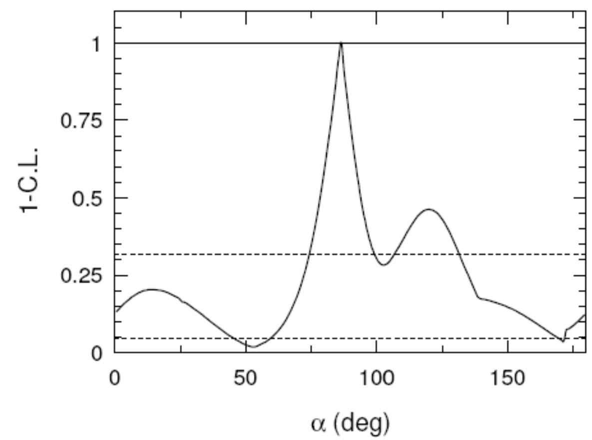


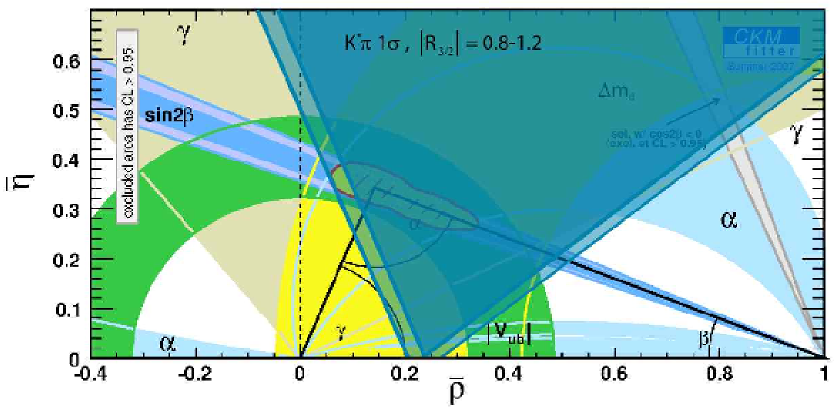
Mode	Fit Fraction (%)	$\mathcal{B}(B^+ \to \text{Mode})(10^{-6})$	A_{CP} (%)	DCPV Sig.
$K^+\pi^-\pi^+$ Total		$54.4 \pm 1.1 \pm 4.5 \pm 0.7$	$2.8 \pm 2.0 \pm 2.0 \pm 1.2$	
$K^{*0}(892)\pi^+;\ K^{*0}(892) \to K^+\pi^-$	$13.3 \pm 0.7 \pm 0.7\,^{+0.4}_{-0.9}$	$7.2 \pm 0.4 \pm 0.7\,^{+0.3}_{-0.5}$	$+3.2 \pm 5.2 \pm 1.1\,^{+1.2}_{-0.7}$	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	$4.5 \pm 0.9 \pm 2.4\,^{+0.6}_{-1.5}$	$2.4 \pm 0.5 \pm 1.3\,^{+0.3}_{-0.8}$	—	—
$K_2^{*0}(1430)\pi^+;\ K_2^{*0}(1430) \to K^+\pi^-$	$3.40 \pm 0.75 \pm 0.42\,^{+0.99}_{-0.13}$	$1.85 \pm 0.41 \pm 0.28\,^{+0.54}_{-0.08}$	$+5 \pm 23 \pm 4\,^{+18}_{-7}$	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

Time-dependent DP analysis!

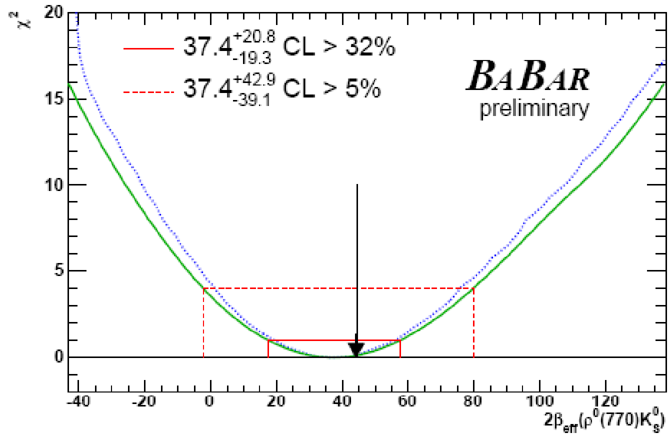
- Combining the two techniques has led to determinations of:
- α from $\pi\pi\pi^0$
- β from $K_S\pi\pi$ and K_SKK
- NB β itself, not $\sin(2\beta)$!
- Combining measurements from $K\pi\pi$ modes → γ

Phys. Rev. D76, 012004 (2007)



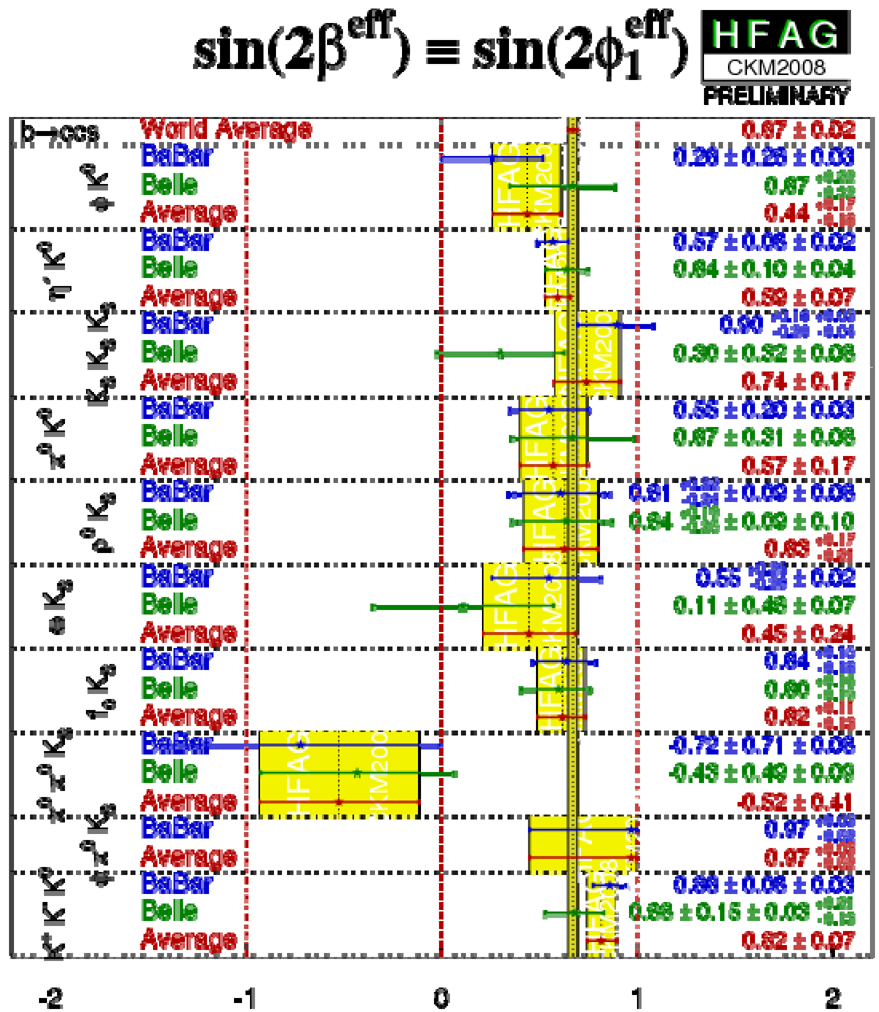


Phys. Rev. D78, 017505 (2008)



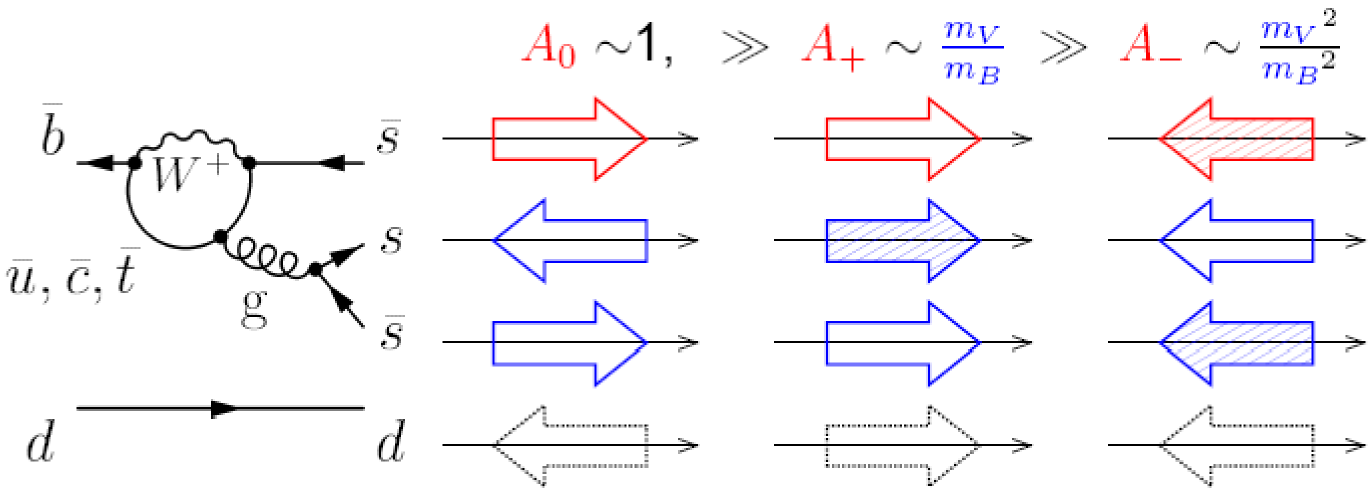
arXiv:0708.2097 [hep-ex]

b → s Penguin HFAG Averages



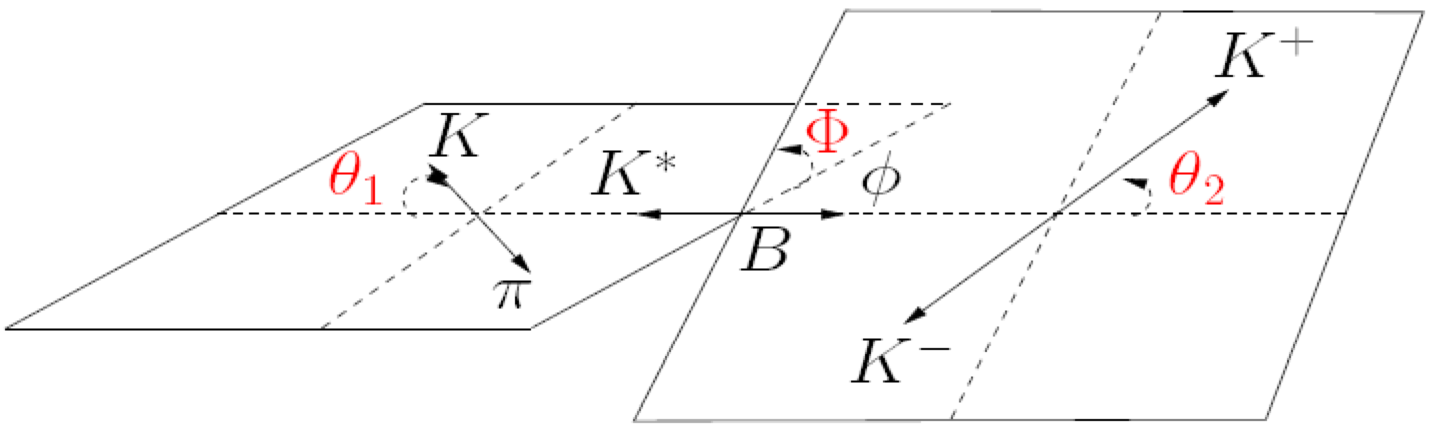
Results from time-dependent Dalitz-plot analyses

B → VV decays



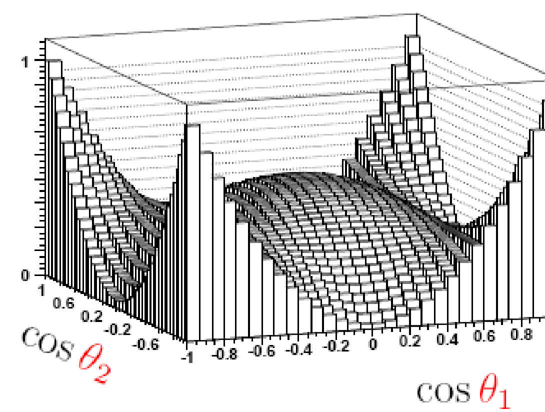
- Three helicity states in Vector–Vector decays
- Requires very sophisticated angular analysis to untangle different helicity contributions
- SM expectation is for ~ longitudinal polarisation

B → VV Angular Analysis



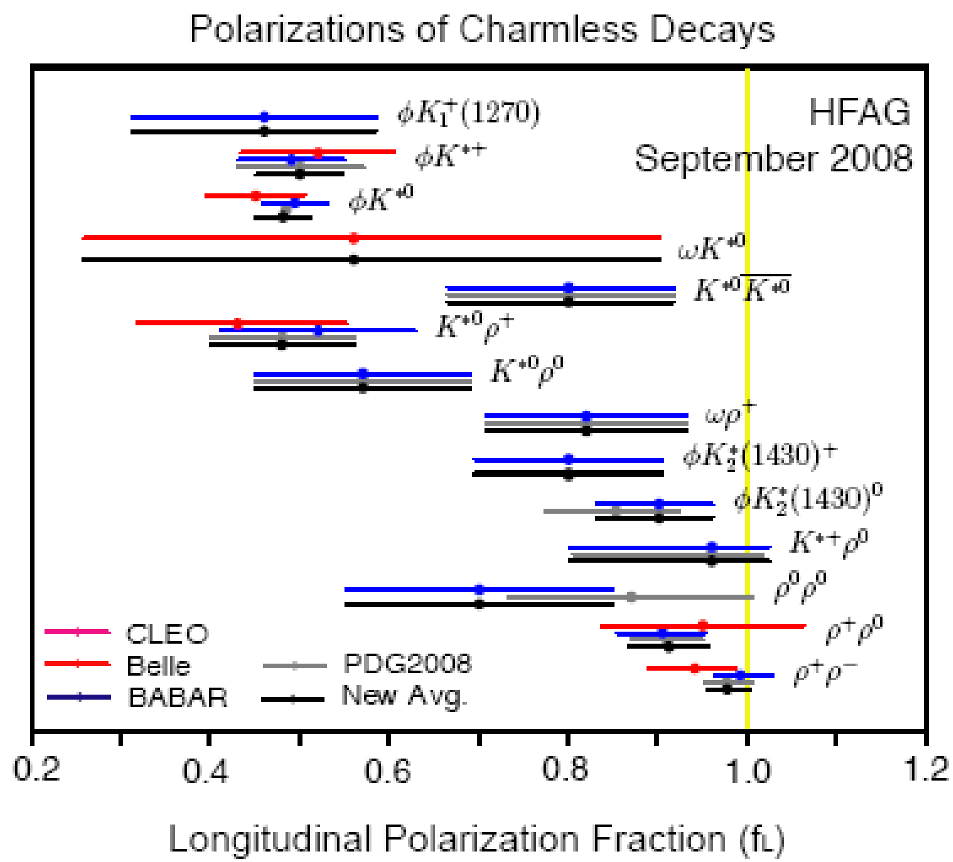
- Similar to DP analysis in its complexity
- Need to model the 3 angular distributions

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto \left\{ \underbrace{\boxed{\frac{1}{4}\sin^2\theta_1\sin^2\theta_2\left(|A_+|^2+|A_-|^2\right)}}_{\text{transverse}} + \underbrace{\boxed{\cos^2\theta_1\cos^2\theta_2|A_0|^2}}_{\text{longitudinal}} \right.$$
$$+\frac{1}{2}\sin^2\theta_1\sin^2\theta_2\left[\cos 2\Phi\,\mathrm{Re}(A_+A_-^*) - \sin 2\Phi\,\mathrm{Im}(A_+A_-^*)\right]$$
$$\left. +\frac{1}{4}\sin 2\theta_1\sin 2\theta_2\left[\cos\Phi\,\mathrm{Re}\left(A_+A_0^* + A_-A_0^*\right) - \sin\Phi\,\mathrm{Im}\left(A_+A_0^* - A_-A_0^*\right)\right]\right\}$$



The "Polarisation Puzzle"

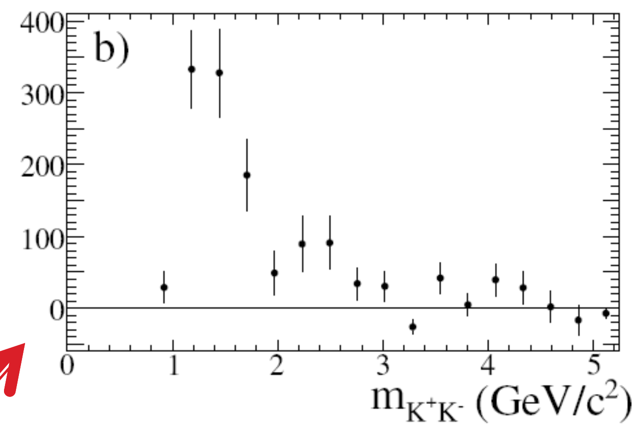
- Experimental results show a range of f_L values
- Apparent trend:
  - Tree dominated, $f_L \sim 1$
  - Penguin dominated, $f_L \sim 0.5$
- However, Vector-Tensor seem not to show the same trend
- But Vector-Axial Vector look like they might be the same
- Need more data!

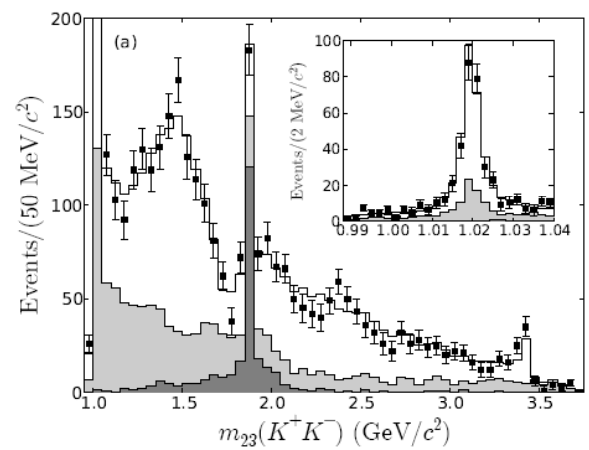


Another surprise: $B^- \to K^+K^-\pi^-$

- Possible contributions to this DP (e.g. $K^{*0}K^-$ or $\phi\pi^-$) predicted to be small
- Experimental searches confirmed this – only upper limits in range 10^{-7} – 10^{-6} found
- But inclusive search found BF of 5×10^{-6}!!
- Large enhancement in K^+K^- spectrum seen around 1500 MeV
- Similar structure seen in DP analyses of 3K decays
- What is it?

Phys. Rev. Lett. 99, 221801 (2007)





Phys. Rev. D74, 032003 (2006)

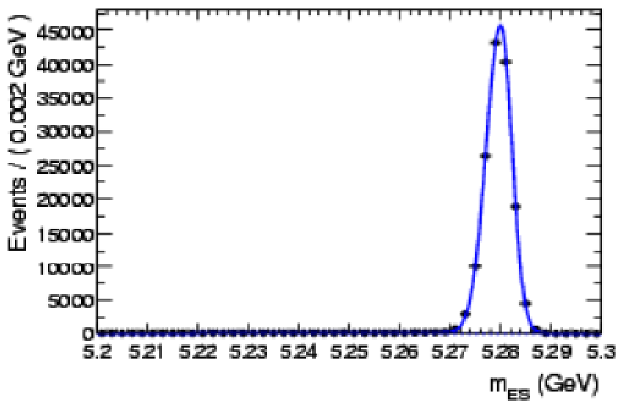
Conclusion

- Studies of charmless decays of *B* mesons provide:
  - Measurements of all 3 Unitarity Triangle angles
  - Comparison with predictions of BFs, CP asymmetries, polarisation fractions from factorisation, SU(3), SCET, etc.
  - Insights into light meson spectroscopy
- Furthermore these analyses have led to the development of some extremely sophisticated techniques
- More precise measurements vital to really test the Standard Model
- Future experiments, such as LHCb and a possible Super Flavour Factory, will be able to improve the precision of these results
- And you never know what surprises you might find!

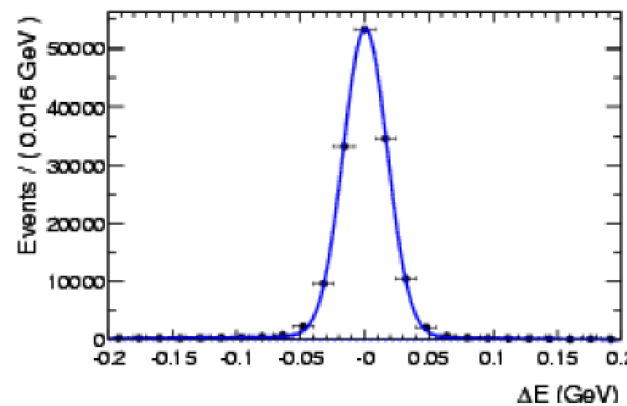
Backup Material

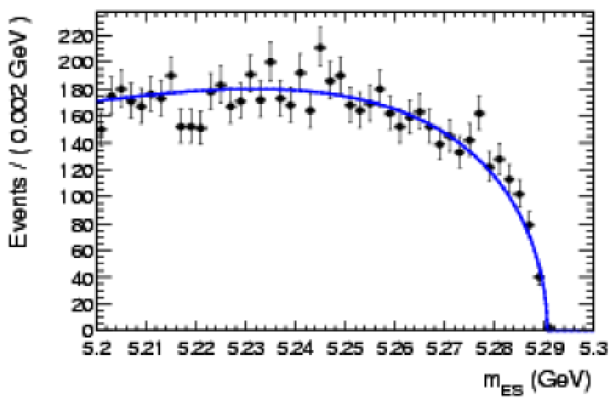
Analysis Variables – Kinematic

Make use of precision kinematic information from the beams.

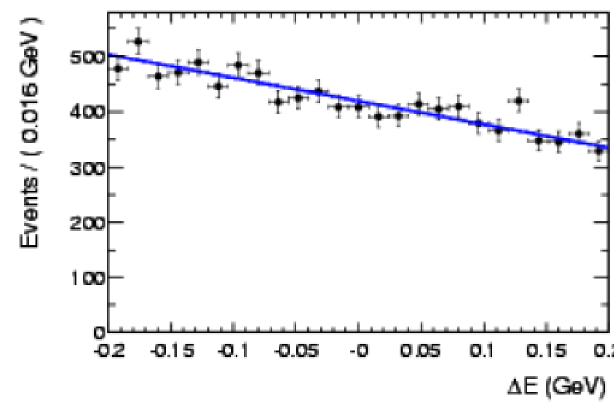


Characteristic Signal Distributions





Characteristic Continuum Distributions

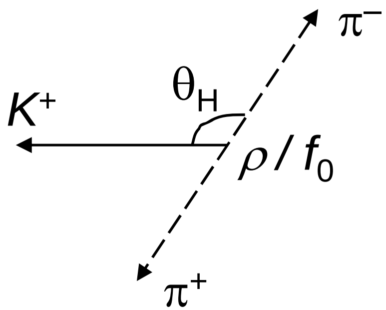


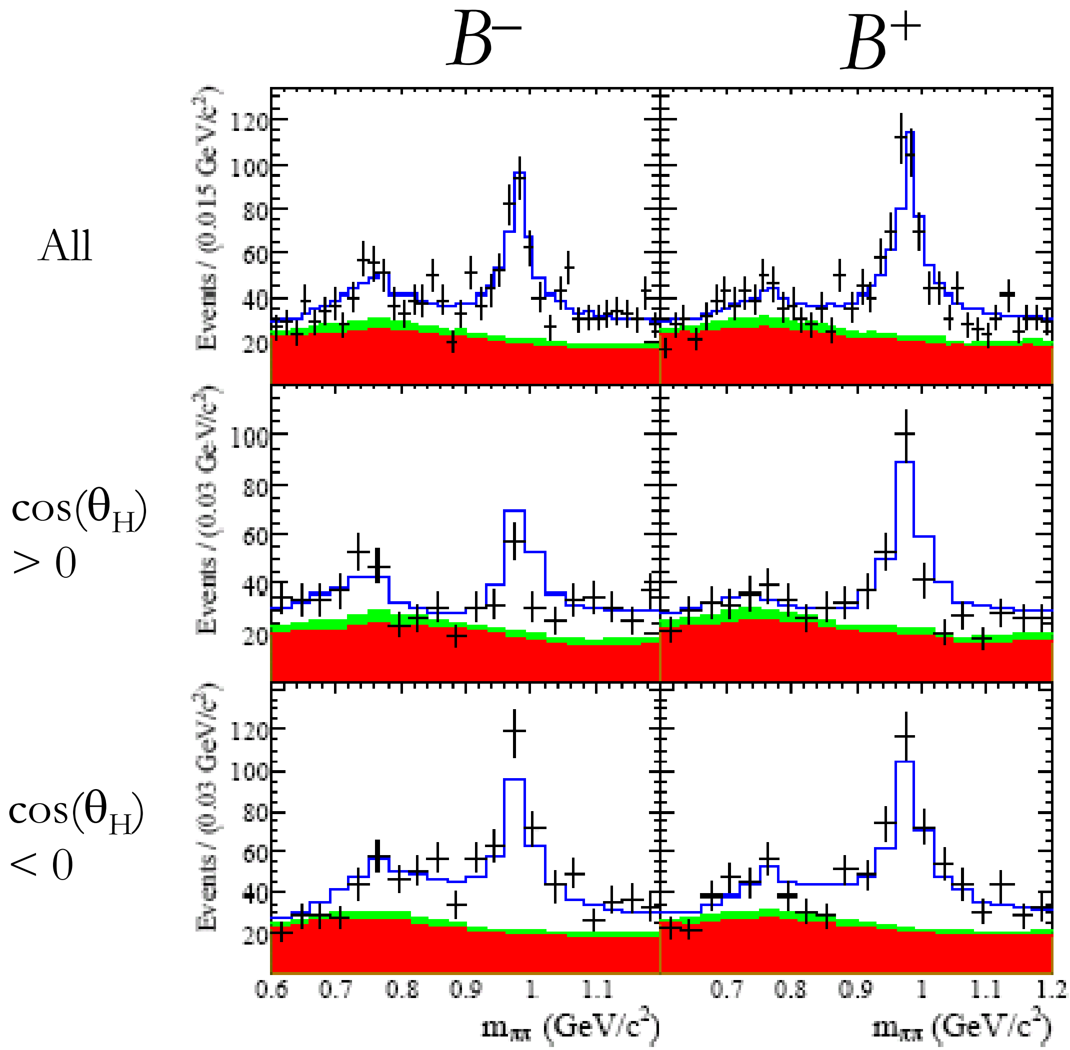
$$m_{ES} = \sqrt{E_{beam}^{*2} - p_B^{*2}}$$

Plots show MC data

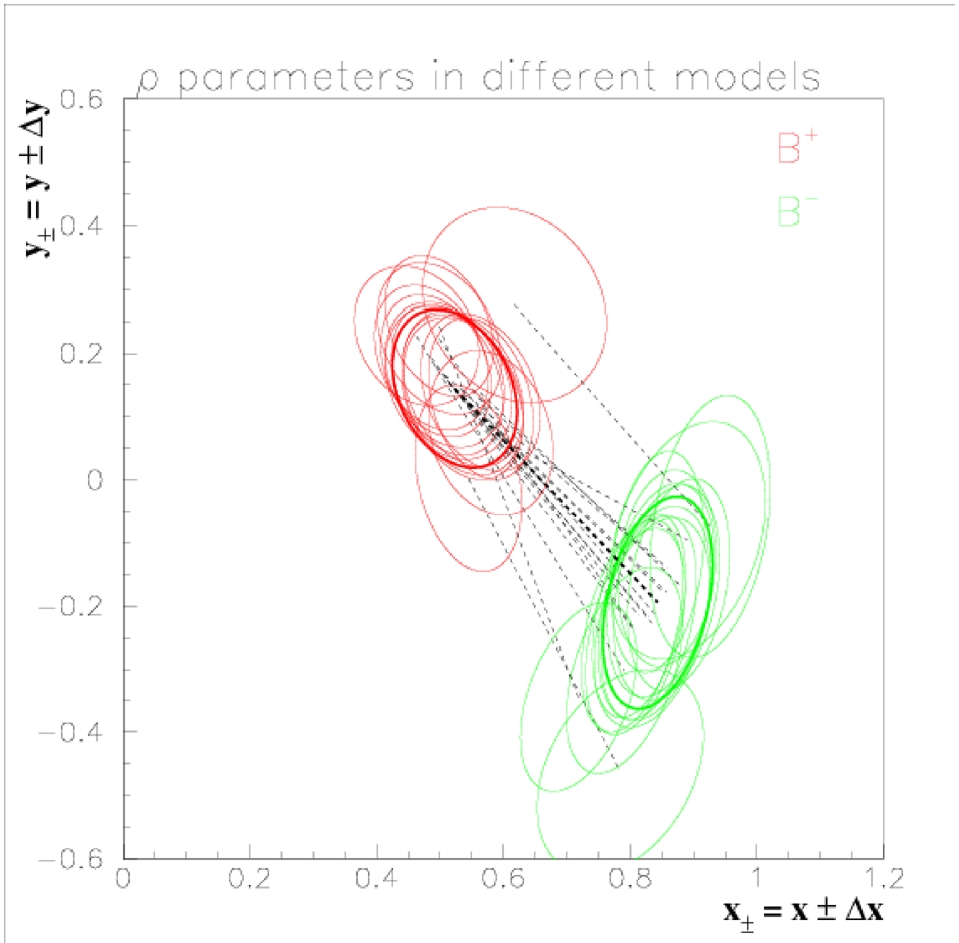
$$\Delta E = E_B^{*} - E_{beam}^{*}$$

$B^+ \to \rho^0 K^+$ Direct *CP* Asymmetry

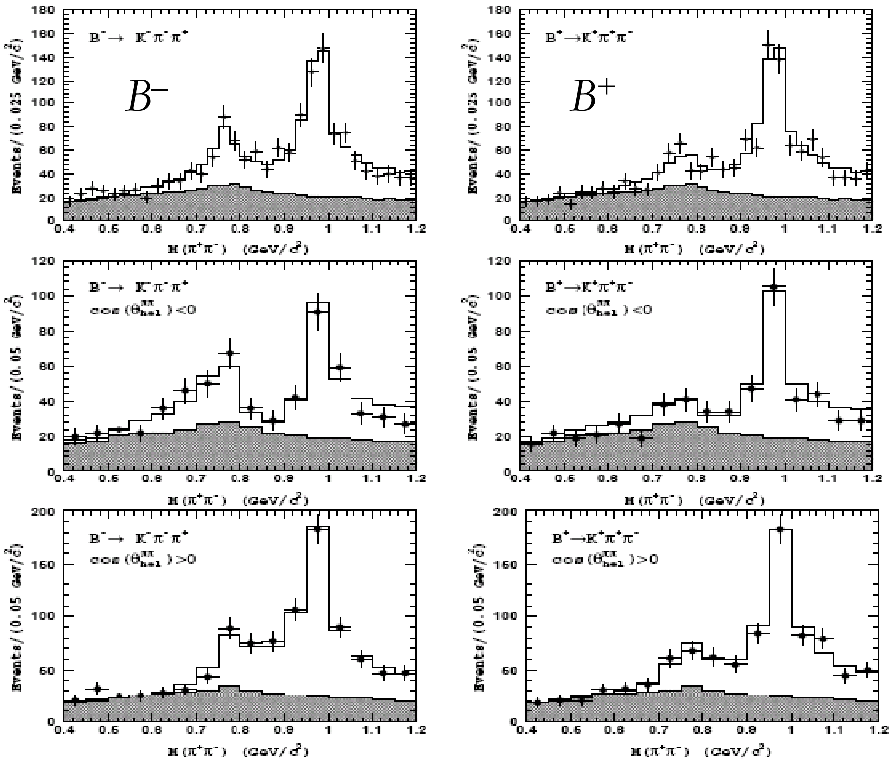




Systematic/Model dependence of DCPV in $\rho^0 K^+$



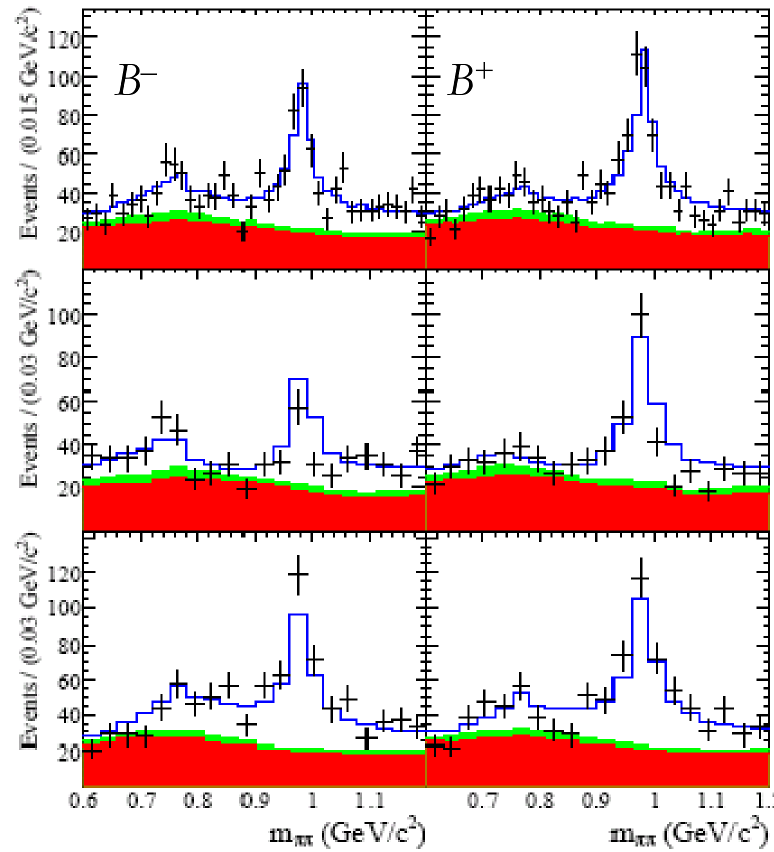
Comparison with Belle – $B^+ \to K^+\pi^+\pi^-$



All

$\cos(\theta_H) > 0$

$\cos(\theta_H) < 0$



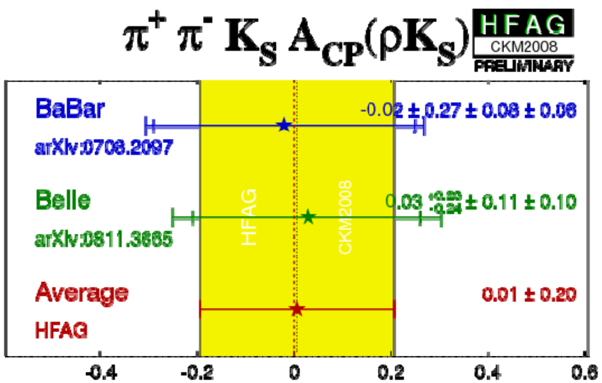
BELLE-CONF-0827 – 657 million BB

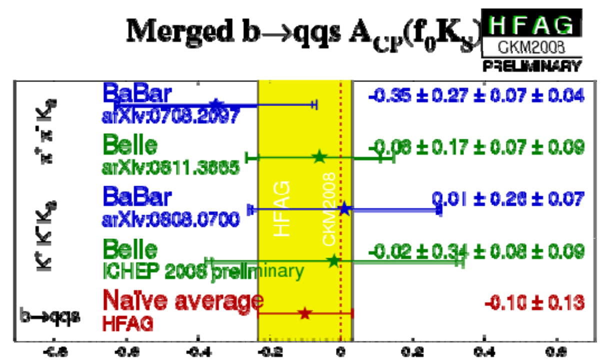
PRD 78, 012004 (2008) – 383 million BB

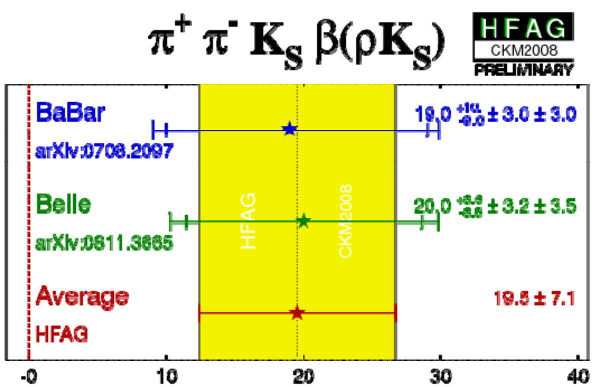
$A_{CP}(\rho^0 K^+) = (+41 \pm 10 \pm 3 \pm {}^{3}_{7})\%$

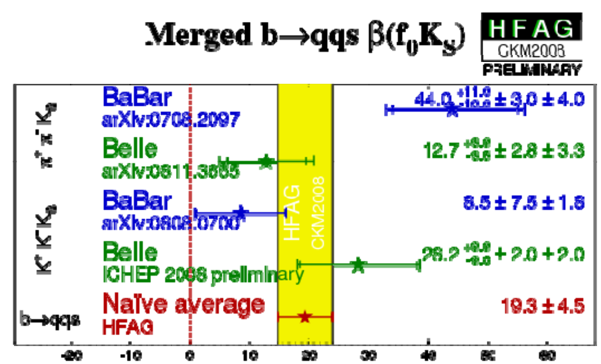
$A_{CP}(\rho^0 K^+) = (+44 \pm 10 \pm 4 \pm {}^{5}_{13})\%$

$B \to K_S h^+ h^-$ HFAG Averages





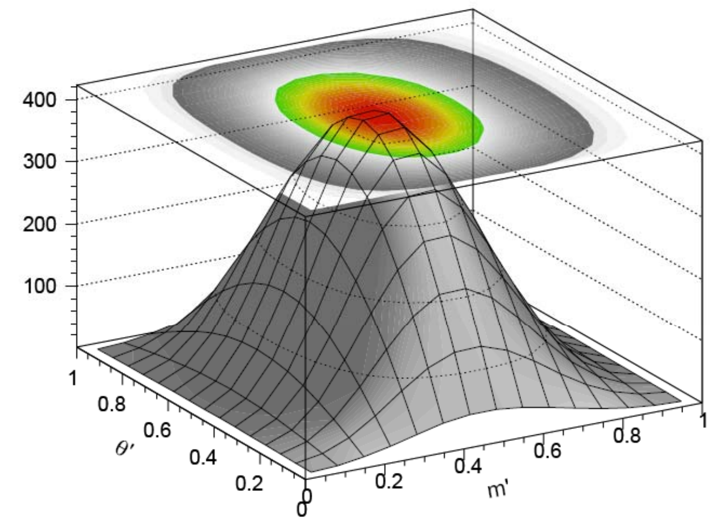




The Square Dalitz Plot

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

$$\theta' \equiv \frac{1}{\pi}\theta_{K^+\pi^+},$$



- Transformation of coordinates
- "Zooms" into the areas around the boundary of the conventional Dalitz plot
- Increases resolution in those areas of interest
- Used for DP histograms in most analyses

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:

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