# A model independent study of CP violation in decays of charmed mesons to three-body final states


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# Outline

- CKM matrix formalism.
- CP violation in the quark sector.
- Dalitz Plot analysis and Isobar model.
- Model independent methods.
- Miranda procedure and its application to decays of charm mesons.

# CKM matrix formalism

Electroweak eigenstates and mass eigenstates are not the same in the SM (Spontaneous Symmetry Breaking).

Flavour Changing Neutral Currents (FCNC) are not allowed at tree-level in the SM.

Family mixing is given by the Cabibbo-Kobayashi-Maskawa (CKM) matrix

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

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$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

**Particle Data Group 2018, DOI: 10.1103/PhysRevD.98.030001**

# CKM matrix formalism

$$VV^\dagger = V^\dagger V = 1$$

Unitarity of the CKM matrix implies there are 3 mixing angles and a complex CP violating phase.

Wolfenstein parametrization is an approximate representation that shows more explicitly the CP violating effects.

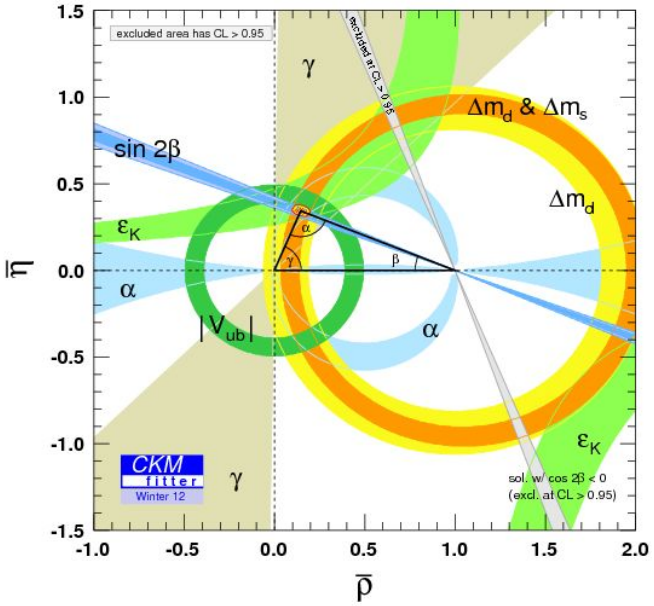
$$V_{CKM} = \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta + i\eta\lambda^2/2) \\ -\lambda & 1-\lambda^2/2 - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

# CP violation in the quark sector

While violation of the CP symmetry has been well established experimentally for Kaons [1964] and B mesons [2001].

Several measurements have allowed to constraint the mixing and CP violating parameters in the SM. But not many results from the charm sector.

In 2007 Belle and BaBar published measures of $D^0 - \bar{D}^0$ mixing. Since then the effect has been confirmed by CDF and LHCb.



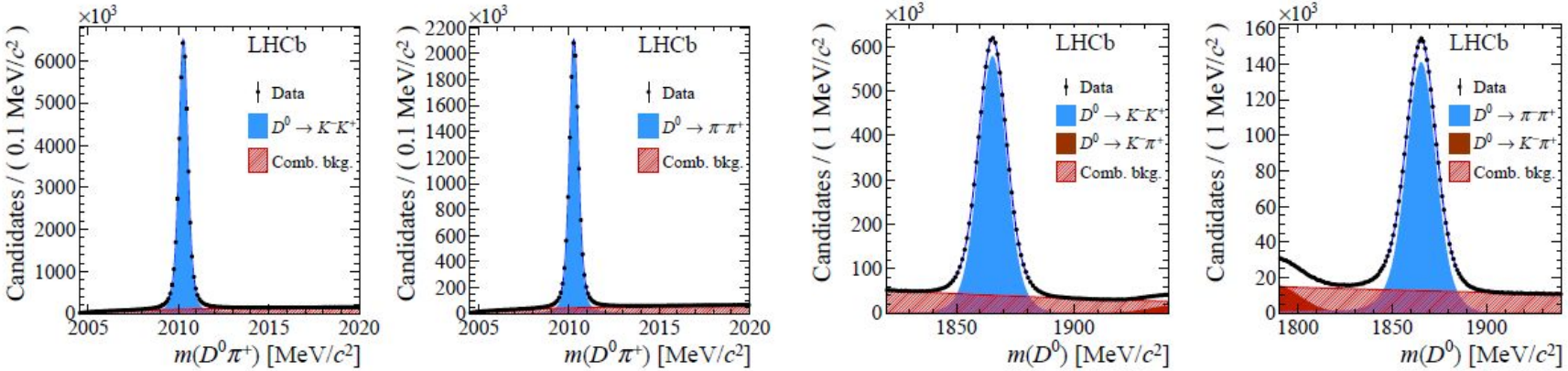

Physical Review D 91.7 (2015)

# Observation of CP violation in charm

Earlier this year the LHCb collaboration reported a measurement of CP violation in the decays $D^0 \to K^-K^+, \quad D^0 \to \pi^-\pi^+$

Finding a CP asymmetry of $A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

This is the first measurement of CPV in decays of charm hadrons.




Physical Review Letters 122.21 (2019)

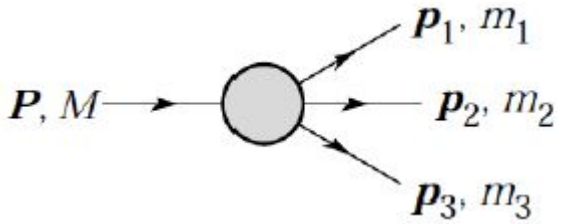
# Dalitz Plot Analysis

A representation of the phase-space of a three-body decay for spin-0 particles in a two-dimensional plot.

In a three-body decay there are only 2 independent degrees of freedom.

| Constraints | Degree of freedom |
|---|---|
| 3 four-vectors | 12 |
| 4-momentum conservation | -4 |
| 3 masses | -3 |
| 3 Euler angles | -3 |
| TOT | 2 |

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}|\mathcal{M}|^2 dm_{12}^2 dm_{23}^2$$



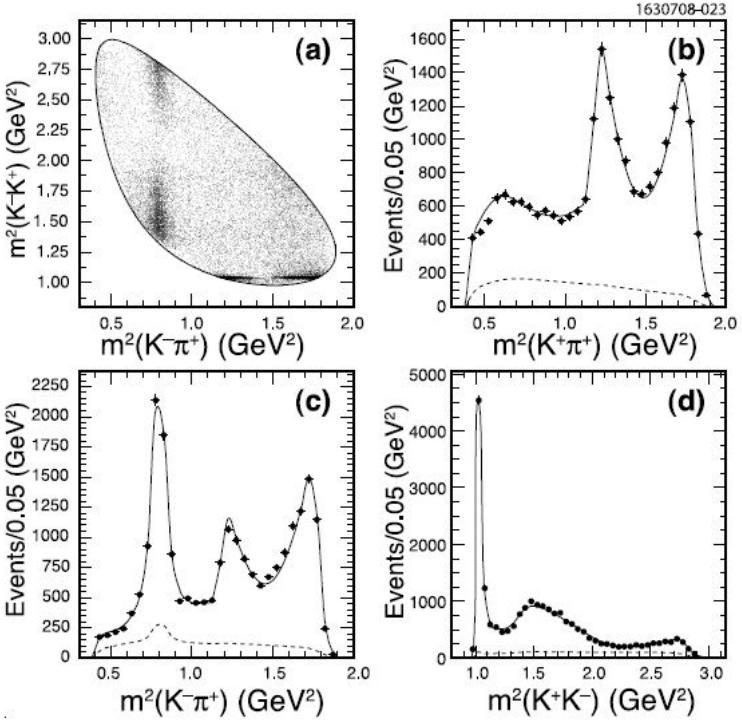
# Dalitz Plot Analysis

Density of points in the Dalitz Plot depends on the structure in the invariant amplitude.

Here the intermediate states are shown as bands on the Dalitz Plot.

If there is CPV for a process

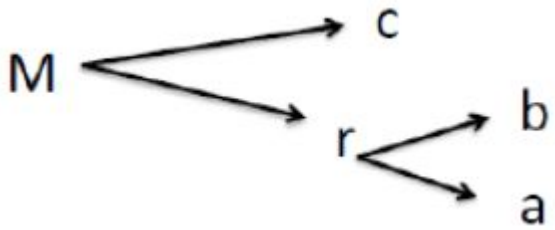
$$|A/\bar{A}| \neq 1$$




Cleo Phys.Rev.D78:072003,2008

$D^+ \rightarrow K^- K^+ \pi^+$

# Isobar Model

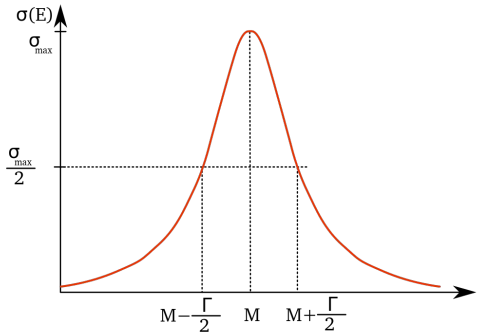



The total decay amplitude is expressed as a coherent sum of processes where one daughter is spectator.

$$\mathcal{A}(s_{12}, s_{13}) = a_0 e^{i\delta} + \sum_r a_r e^{i\delta_r} \mathcal{A}_r(s_{12}, s_{13})$$

Intermediate states are modeled using a relativistic Breit-Wigner distribution. This approximation doesn't preserves unitarity.

$$\frac{1}{m_R^2 - m_{AB}^2 - i m_R \Gamma_{AB}(q)}$$

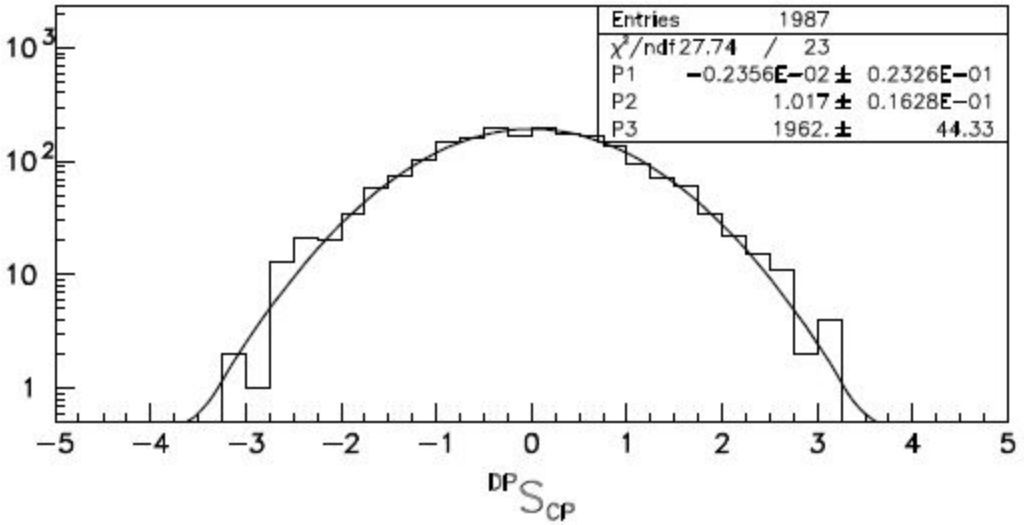


# Model Independent Methods

Miranda Procedure

$$\mathcal{S}^i_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}\ , \qquad \alpha = \frac{N_{\rm tot}(D^+)}{N_{\rm tot}(D^-)}$$

In the absence of asymmetries in the Dalitz Plot the $\mathcal{S}^i_{CP}$ distributes as a Gaussian with zero mean and unit width.



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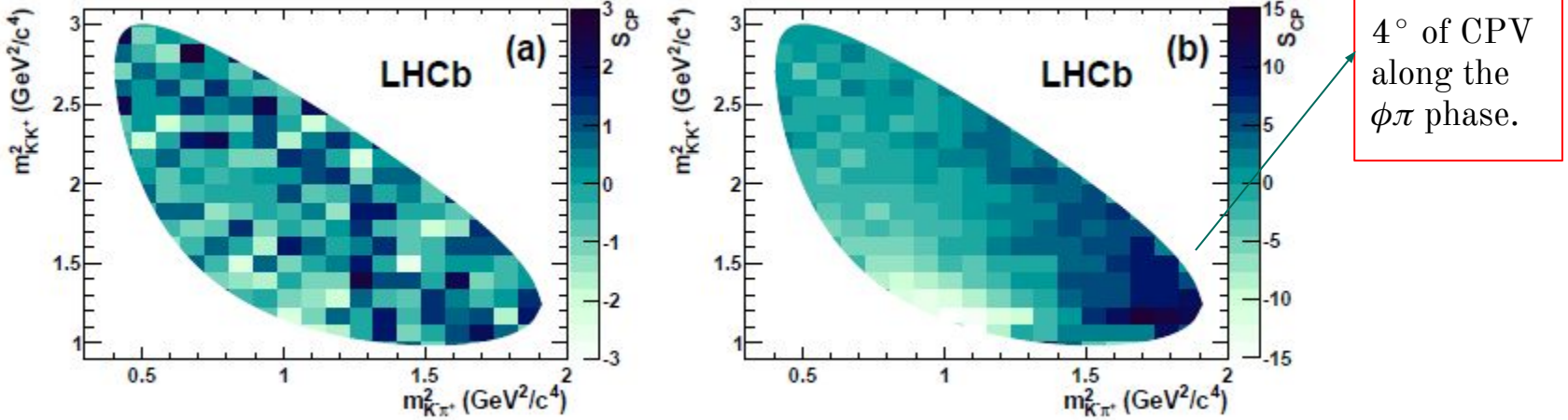
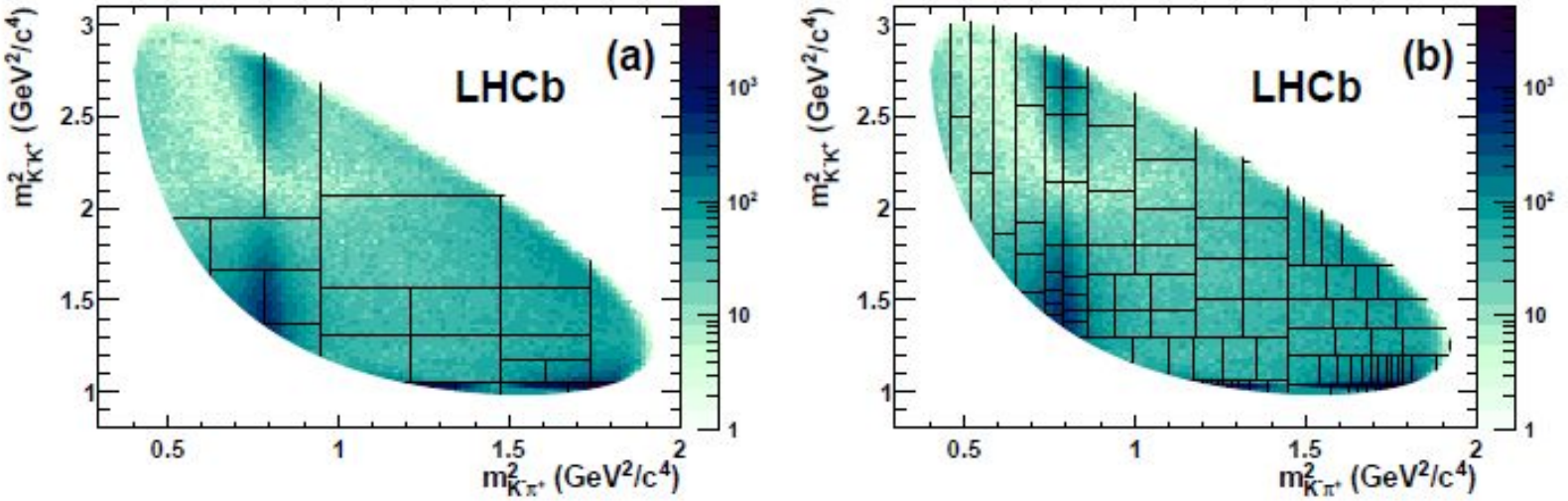



LHCb, Phys. Rev. D 84, 112008 (2011)

# Adaptive binning

Sensitivity to the manifestation of CP violation is changed depending on the binning choice.




LHCb, Phys. Rev. D 84, 112008 (2011)

# A study of the decay $D^+ \to K^- K^+ \pi^+$

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A binned Dalitz Plot analysis using the Miranda Procedure is proposed.

CLEO-c model is used to generate a toy MC sample for the particular process.

| Resonance | Amplitude | Relative phase | Fit fraction |
|---|---|---|---|
| $\overline{K}^*(892)^0$ | 1 (fixed) | 0 (fixed) | $25.7 \pm 0.5^{+0.4+0.1}_{-0.3-1.2}$ |
| $\overline{K}_0^*(1430)^0$ | $4.56 \pm 0.13^{+0.10+0.42}_{-0.01-0.39}$ | $70 \pm 6^{+1+16}_{-6-23}$ | $18.8 \pm 1.2^{+0.6+3.2}_{-0.1-3.4}$ |
| $\kappa(800)$ | $2.30 \pm 0.13^{+0.01+0.52}_{-0.11-0.29}$ | $-87 \pm 6^{+2+15}_{-3-10}$ | $7.0 \pm 0.8^{+0.0+3.5}_{-0.6-1.9}$ |
| $\overline{K}_2^*(1430)^0$ | $7.6 \pm 0.8^{+0.5+2.4}_{-0.6-4.8}$ | $171 \pm 4^{+0+24}_{-2-11}$ | $1.7 \pm 0.4^{+0.3+1.2}_{-0.2-0.7}$ |
| $\phi(1020)$ | $1.166 \pm 0.015^{+0.001+0.025}_{-0.009-0.009}$ | $-163 \pm 3^{+1+14}_{-1-5}$ | $27.8 \pm 0.4^{+0.1+0.2}_{-0.3-0.4}$ |
| $a_0(1450)^0$ | $1.50 \pm 0.10^{+0.09+0.92}_{-0.06-0.33}$ | $116 \pm 2^{+1+7}_{-1-14}$ | $4.6 \pm 0.6^{+0.5+7.2}_{-0.3-1.8}$ |
| $\phi(1680)$ | $1.86 \pm 0.20^{+0.02+0.62}_{-0.08-0.77}$ | $-112 \pm 6^{+3+19}_{-4-12}$ | $0.51 \pm 0.11^{+0.01+0.37}_{-0.04-0.15}$ |

Cleo Phys.Rev.D78:072003,2008

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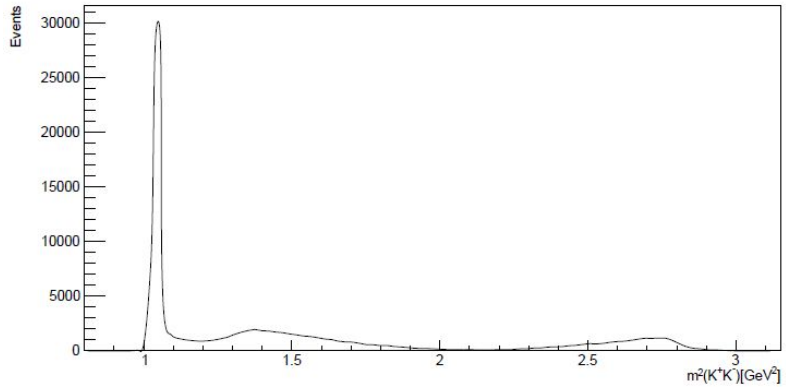


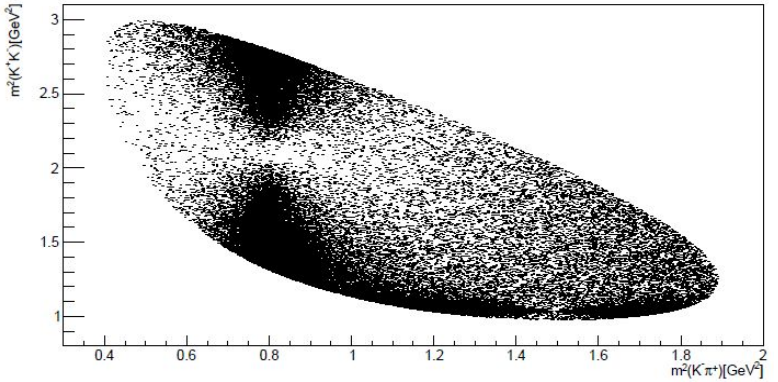


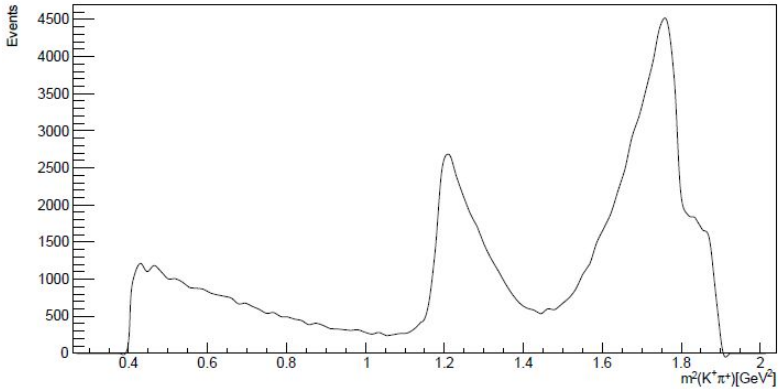


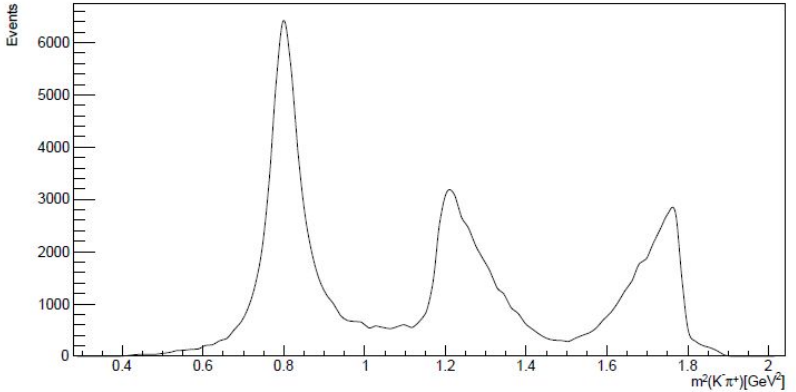

# Summary

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CP violation studies in heavy flavoured mesons are an important way to constraint and test the SM.

In the charm sector this effect is not as well measured as in Kaon and B meson systems. Greater statistic is needed.

Model independent methods like Miranda can increase the sensitivity to CP detection for these kind of processes. In this method, an optimum binning method must be used.

# Bibliography


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