TRR110 Workshop

$B \to 3h$ Amplitude Analysis in LHCb

Jeremy Dalseno

on behalf of the LHCb collaboration

J.Dalseno [at] bristol.ac.uk

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Outline

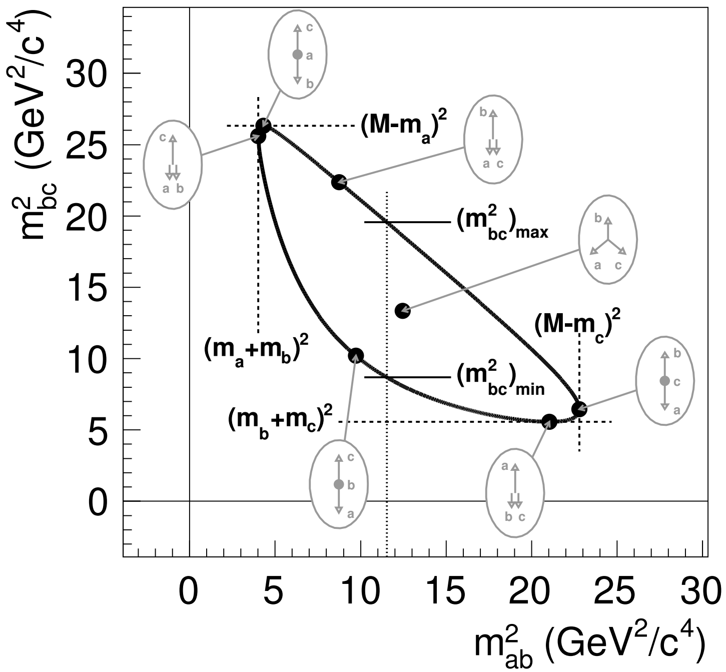
1. Manifestation of Direct CP Violation in the Dalitz Plot

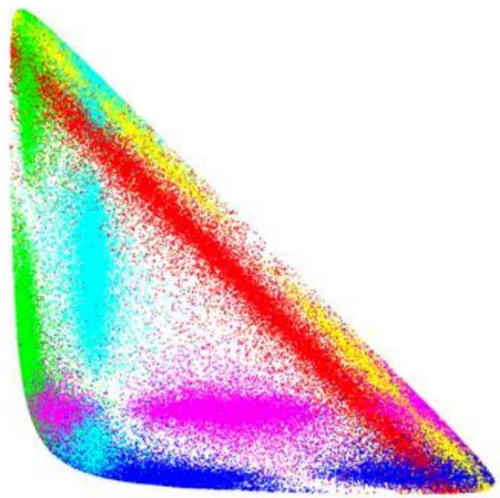
   -Short/long-distance effects, rescattering

2. Recent Developments in Charmless Amplitude Analyses

   -Rescattering, K-matrix, quasi-model-independent approaches to the S-wave

Dalitz Plot





Toy MC Dalitz plot (DP)

Dalitz plot contains all kinematic and dynamic information of decay

Amplitude analysis one of the most powerful techniques

Extract amplitude-level information rather than amplitude-squared information

Interference between intermediate states allows measurement of relative magnitudes and phases

Resolve trigonometric ambiguities in phases that plague 2-body measurements

Conditions for Direct CP Violation

In charged B decays, presence of multiple amplitudes may lead to direct CP violation

$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$

$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |A_i| e^{i(\delta_i - \phi_i)}$

Strong phase (δ) invariant under CP, while weak phase (ϕ) changes sign under CP

$$\mathcal{A}_{CP}(B \to f) \equiv \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} \propto \sum_{i,j} |A_i||A_j| \sin(\delta_i - \delta_j) \sin(\phi_i - \phi_j)$$

3 conditions required for direct CP violation

- At least 2 amplitudes
- Non-zero strong phase difference, $\delta_i - \delta_j \neq 0$
- Non-zero weak phase difference, $\phi_i - \phi_j \neq 0$

Source of weak phase differences comes from different CKM phases of each amplitude

Short-Distance Contributions

Direct CP violation more complicated in $B \to 3h$ decay channels compared to 2-body decays

- There are at least 4 possible sources of strong phase

1. Short-distance contributions (quark level)

   - BSS mechanism, PRL **43** 242 (1979)

   - Tree contribution (a)

   - Penguin diagram (b) contains 3 quark generations in loop

   - S-matrix unitarity, CPT require absorptive amplitude

   - If gluon in penguin is timelike (on-shell)

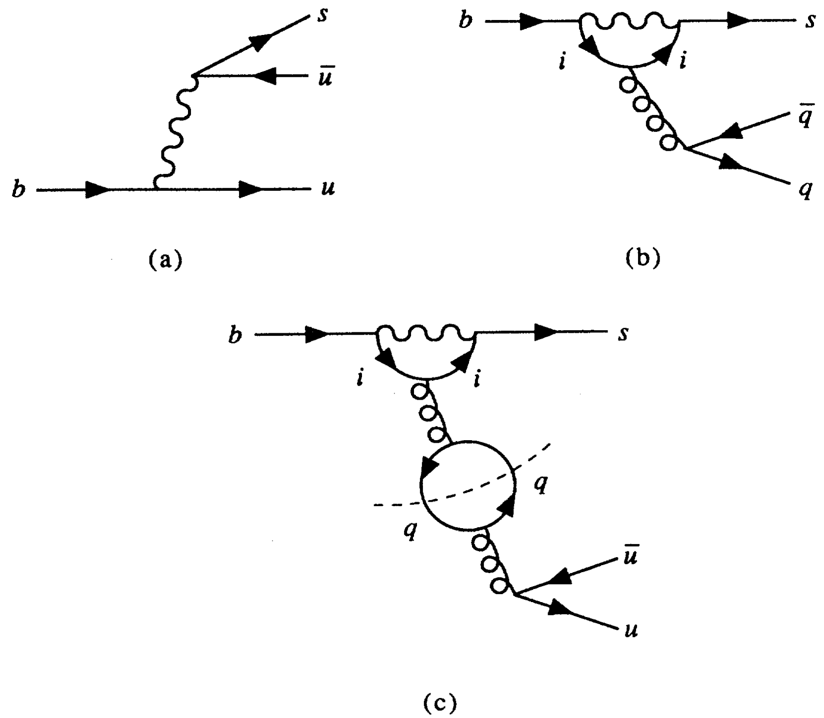
     - Momentum transfer $q^2 > 4m_i^2$ where $i = u, c$

     - Imaginary part depends on quark masses

     - Particle rescattering (c) generates a phase difference

   - CP violation in 2-body processes caused by this effect

     - eg. $B^0 \to K^+\pi^-$



(a) (b) (c)

Long-Distance Contributions

Remaining sources unique to multibody decays

Long-distance contributions ($q\bar{q}$ level)

2. Breit-Wigner phase

Propagator represents intermediate resonance states

$$F_R^{\mathrm{BW}}(s) = \frac{1}{m_R^2 - s - i m_R \Gamma_R(s)}$$

Phase varies across the Dalitz plot

3. Relative CP-even phase in the isobar model

$$A(B \to f) = \sum_i |A_i| e^{i(\delta_i + \phi_i)}$$
$$\bar{A}(\bar{B} \to \bar{f}) = \sum_i |\bar{A}_i| e^{i(\delta_i - \phi_i)}$$

Related to final state interactions between different resonances

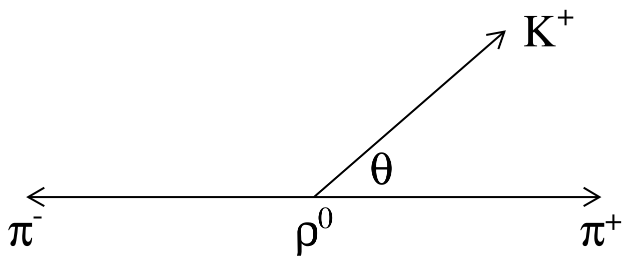
Manifestation of CP Violation

Each source of strong phase leaves a unique signature in the Dalitz plot

Illustrate with series of examples

Consider $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ with only 2 isobars

$B^{\pm} \to \rho^{0}K^{\pm}$ and flat non-resonant (NR) component



ρ^0 lineshape a Breit-Wigner, F_{ρ}^{BW}

ρ^0 is a vector resonance, so angular distribution follows $\cos\theta$

$$A_{+} = |a_{+}^{\rho}|e^{i\delta_{+}^{\rho}}F_{\rho}^{\mathrm{BW}}\cos\theta + |a_{+}^{\mathrm{NR}}|e^{i\delta_{+}^{\mathrm{NR}}}$$

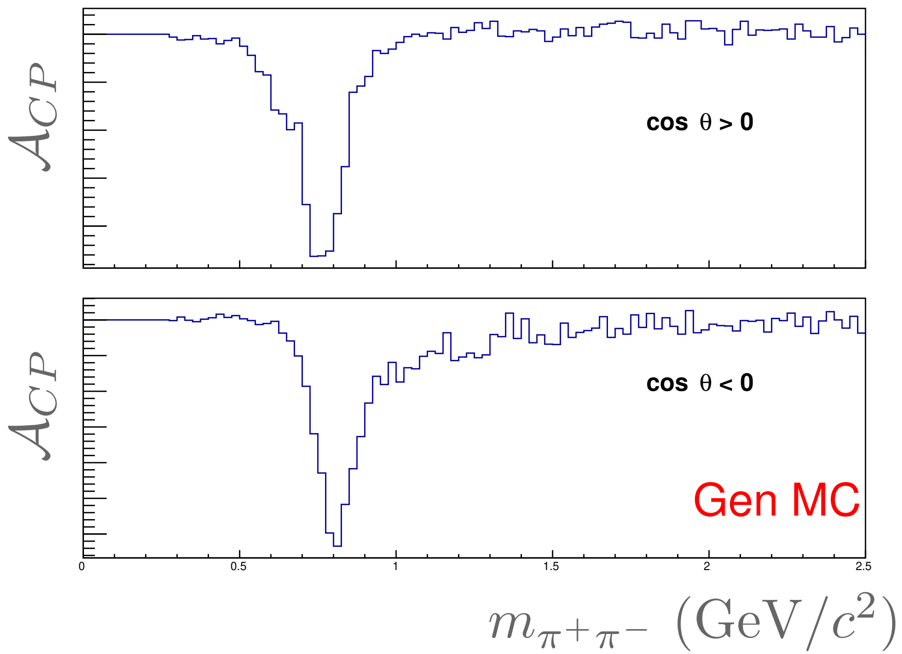
$$A_{-} = |a_{-}^{\rho}|e^{i\delta_{-}^{\rho}}F_{\rho}^{\mathrm{BW}}\cos\theta + |a_{-}^{\mathrm{NR}}|e^{i\delta_{-}^{\mathrm{NR}}}$$

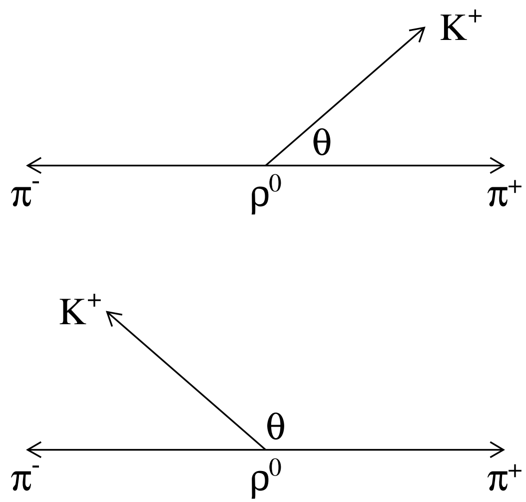
$$\begin{aligned}\mathcal{A}_{CP} &\propto |A_{-}|^2 - |A_{+}|^2 \\ &\propto (|a_{-}^{\rho}|^2 - |a_{+}^{\rho}|^2)|F_{\rho}^{\mathrm{BW}}|^2\cos^2\theta\ldots \\ &\quad -2(m_{\rho}^2 - s)|F_{\rho}^{\mathrm{BW}}|^2\cos\theta\ldots \\ &\quad +2m_{\rho}\Gamma_{\rho}|F_{\rho}^{\mathrm{BW}}|^2\cos\theta\ldots\end{aligned}$$

Short-Distance Effects

$$\mathcal{A}_{CP} \quad \propto \quad (|a^{\rho}_{-}|^2 - |a^{\rho}_{+}|^2)|F^{\mathrm{BW}}_{\rho}|^2 \cos^2\theta \ldots$$
$$-2(m^2_{\rho} - s)|F^{\mathrm{BW}}_{\rho}|^2 \cos\theta \ldots$$
$$+2m_{\rho}\Gamma_{\rho}|F^{\mathrm{BW}}_{\rho}|^2 \cos\theta \ldots$$

Only depends on ρ resonance, maximum difference at ρ pole, quadratic in helicity



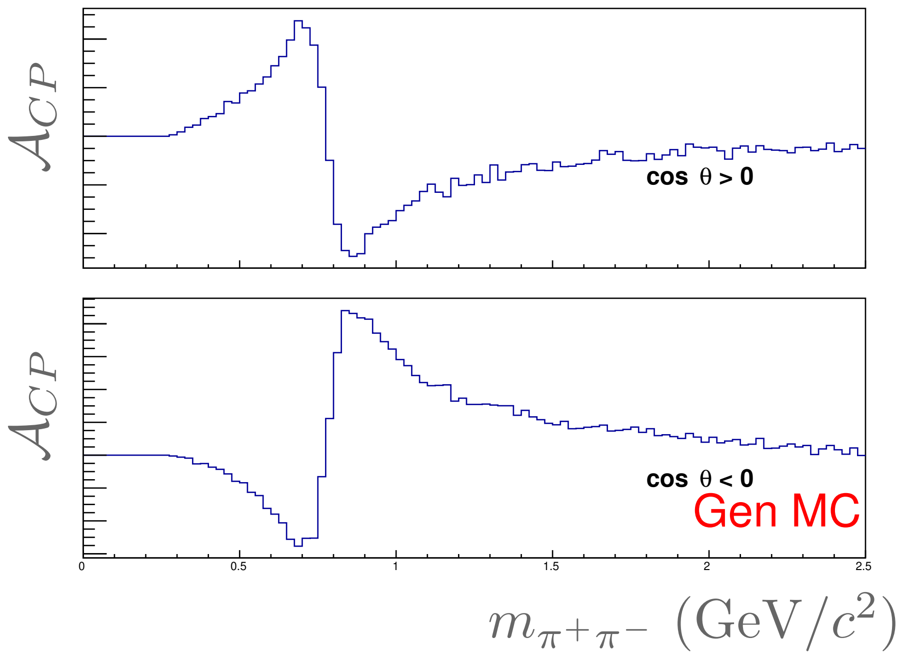


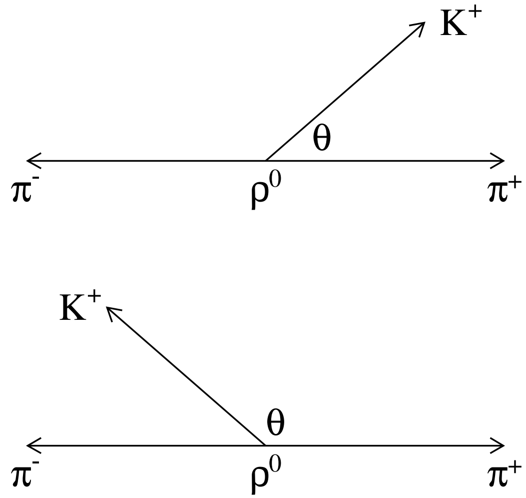
Only short-distance effects can create $|a^{\rho}_{+}| \neq |a^{\rho}_{-}|$

Long-Distance Effects

$$
\begin{aligned}
\mathcal{A}_{CP} \quad \propto \quad & (|a_{-}^{\rho}|^2 - |a_{+}^{\rho}|^2)|F_{\rho}^{\mathrm{BW}}|^2 \cos^2\theta ... \\
& -2(m_{\rho}^2 - s)|F_{\rho}^{\mathrm{BW}}|^2 \cos\theta ... \\
& +2m_{\rho}\Gamma_{\rho}|F_{\rho}^{\mathrm{BW}}|^2 \cos\theta ...
\end{aligned}
$$

Interference term from real part of Breit-Wigner, zero at ρ pole, linear in helicity



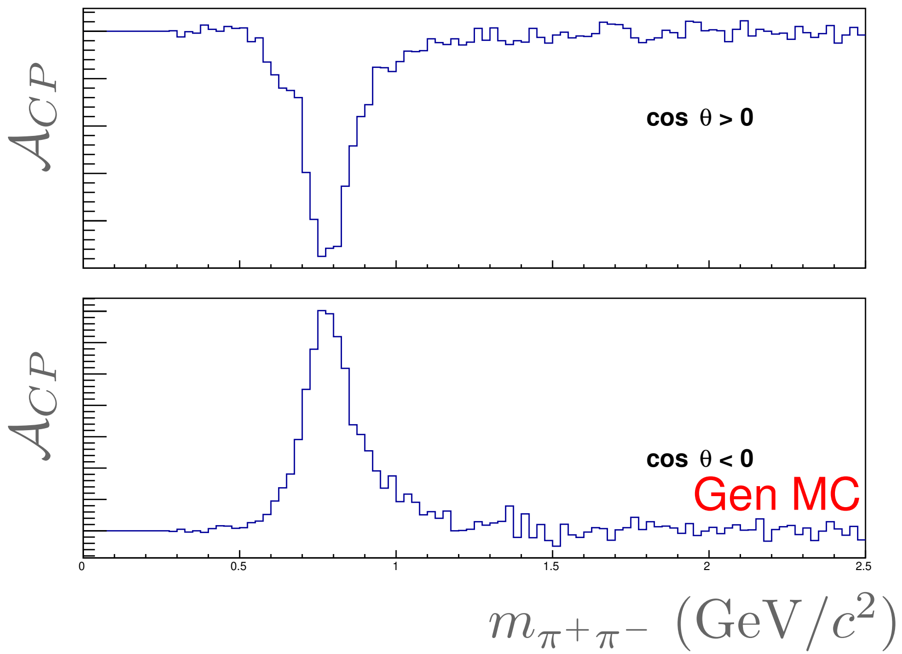


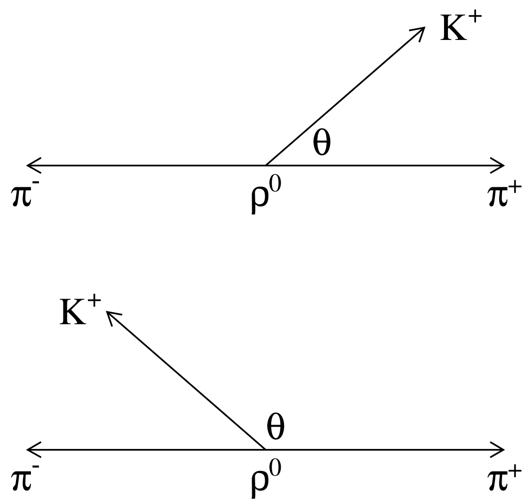
Caused by long-distance effects from final state interactions

Long-Distance Effects

$$\mathcal{A}_{CP} \propto (|a^\rho_-|^2 - |a^\rho_+|^2)|F^{\rm BW}_\rho|^2 \cos^2\theta...$$
$$-2(m^2_\rho - s)|F^{\rm BW}_\rho|^2 \cos\theta...$$
$$+2m_\rho\Gamma_\rho|F^{\rm BW}_\rho|^2 \cos\theta...$$

Interference term from imaginary part of Breit-Wigner, maximum at ρ pole, linear in helicity





Caused by long distance effects from Breit-Wigner phase and final state interactions

Rescattering Contributions

Last source of strong phase

4. Final state $KK \leftrightarrow \pi\pi$ rescattering

Can occur between decay channels with the same flavour quantum numbers

eg. $B^{\pm} \to K^{\pm}K^{+}K^{-}$ and $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$

CPT conservation constrains hadron rescattering

For given quantum numbers, sum of partial widths equal for charge-conjugate decays

$KK \leftrightarrow \pi\pi$ rescattering generates a strong phase

Look into rescattering region

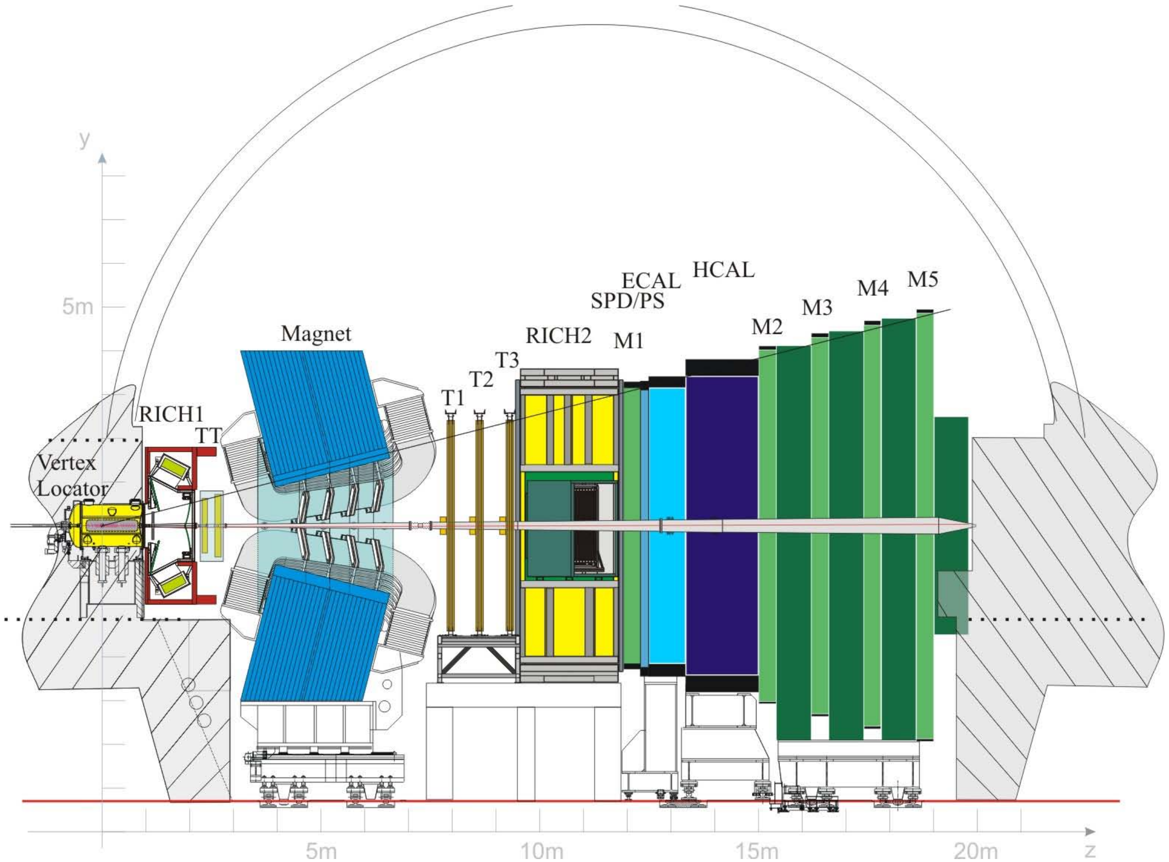
If rescattering phase in one decay channel generates direct CP violation in this region

Rescattering phase should generate opposite sign direct CP violation in partner decay channel

LHCb Detector

pp collisions

b quark tends to foward/backward direction



Data set: 1 fb^{-1} @ 7 TeV and 2 fb^{-1} @ 8 TeV

Forward spectrometer

Vertex Locater (VeLo)
- Precision tracking
- $20\ \mu\mathrm{m}$ IP resolution

Tracking Stations (TT & T)
- $\Delta p/p = 0.4\% - 0.6\%$
- for $5 - 100\ \mathrm{GeV}$ tracks

Ring Imaging Cherenkov (RICH)
- K, π ID

Electromagnetic Calorimeter (ECAL)
- e, γ ID

Hadronic Calorimeter (HCL)
- Hadron ID

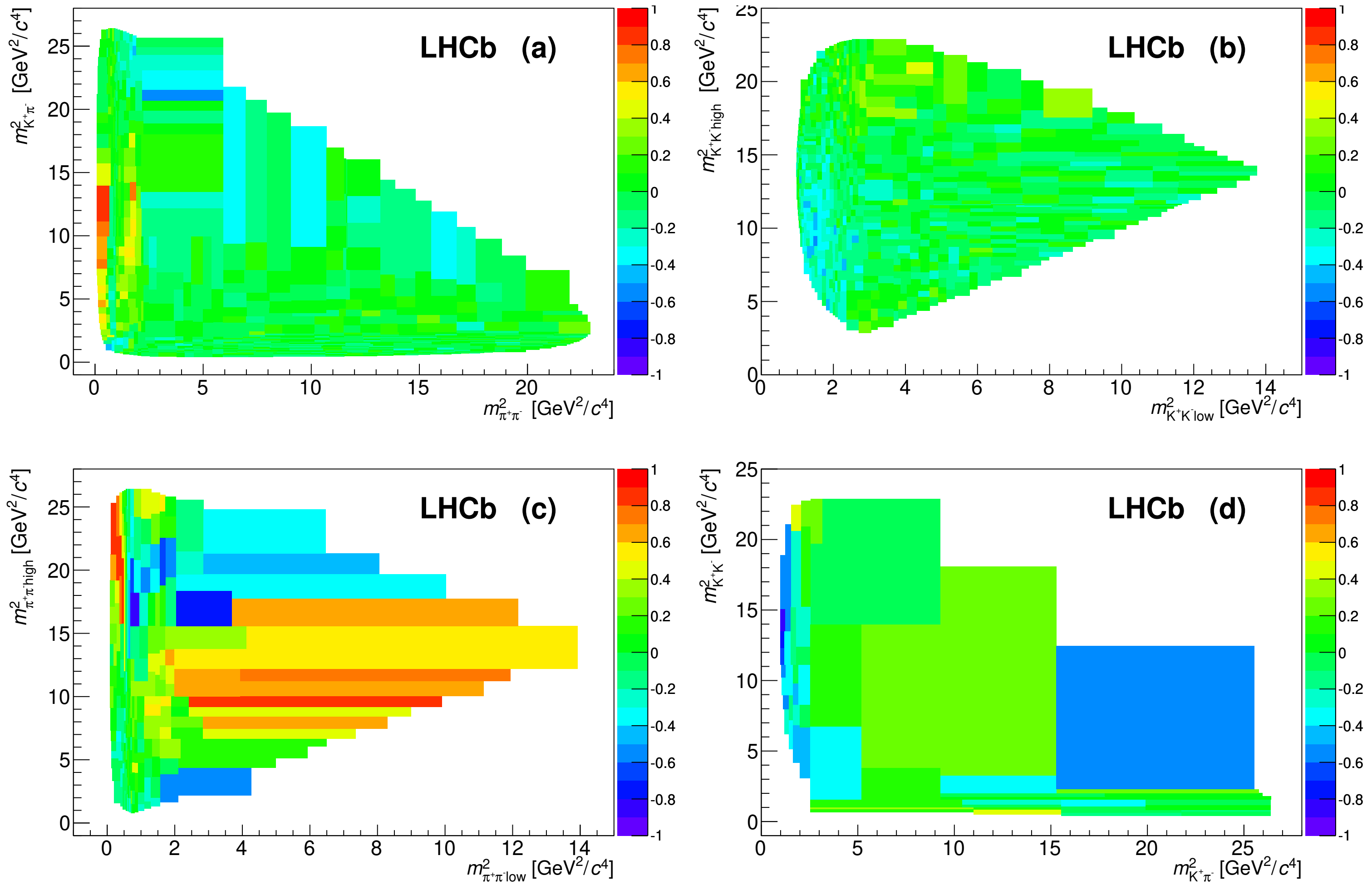
Muon Stations

Dipole magnet polarity reversal

$B^{\pm} \to K^{\pm}h^{+}h^{-}, \pi^{\pm}h^{+}h^{-}$

Observed large CP violating effects in the phase space, Phys. Rev. D **90**, 112004 (2014)

$B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ $B^{\pm} \to K^{\pm}K^{+}K^{-}$



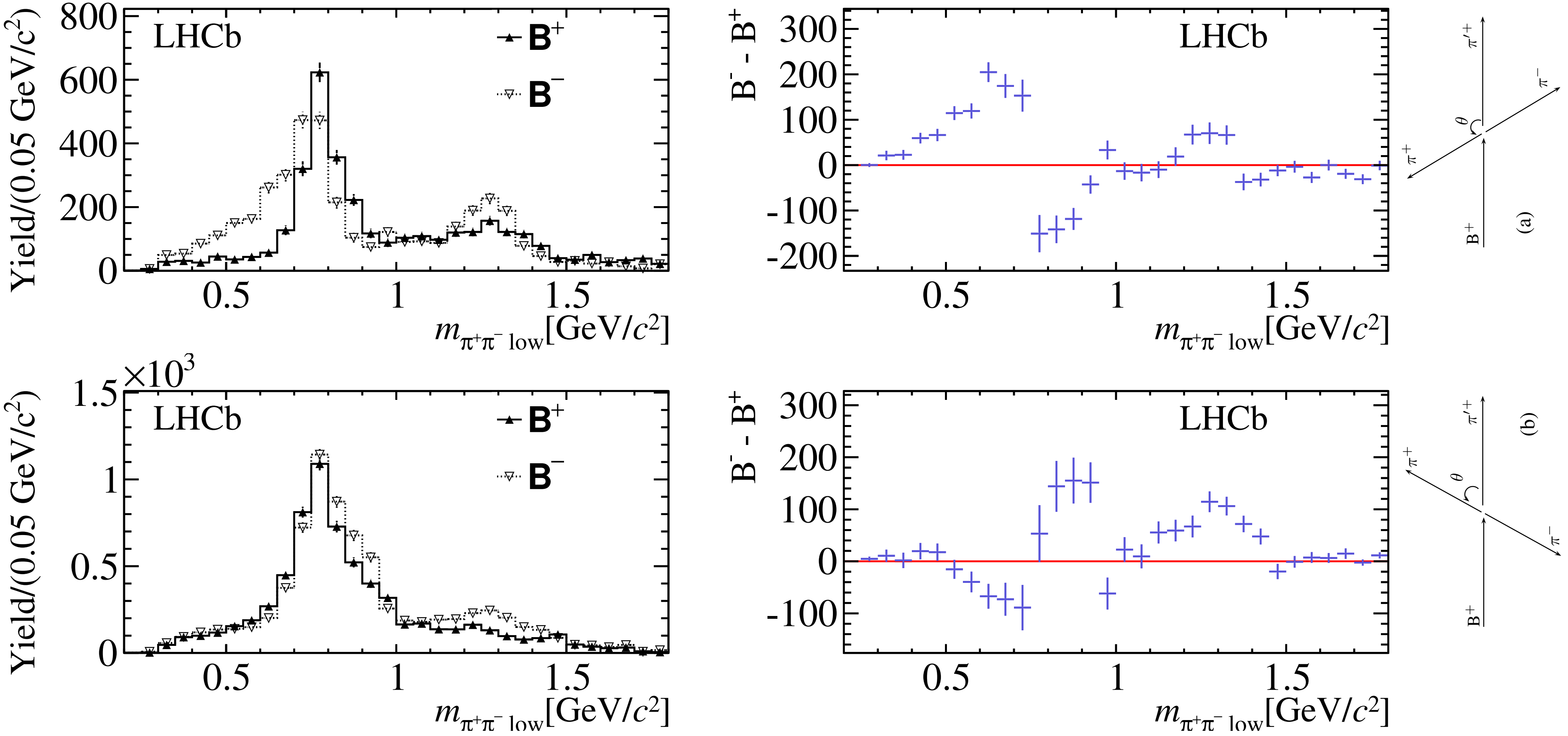
Penguin

Tree

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$

CP Asymmetry by Interference

Project onto $m_{\pi\pi}$ of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, Phys. Rev. D **90**, 112004 (2014)

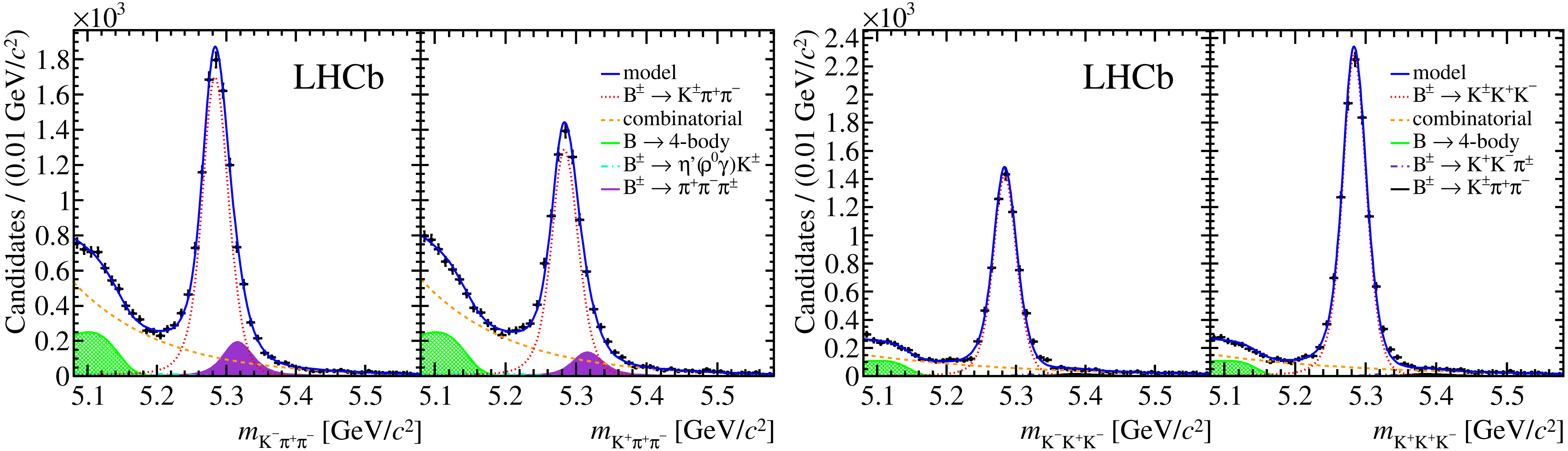


Sign-flip and zero around ρ^0 pole, CP asymmetry may be dominated by real part of Breit-Wigner

CP Asymmetry by Rescattering

$\pi\pi \leftrightarrow KK$ rescattering region: $1.0 - 1.5\ \text{GeV}/c^2$

$B^- \to K^-\pi^+\pi^-$ $B^+ \to K^+\pi^+\pi^-$ $B^- \to K^-K^+K^-$ $B^+ \to K^+K^+K^-$



Clear opposite sign CP asymmetry in $KK/\pi\pi$ - related channels

$KK \leftrightarrow \pi\pi$ rescattering would require this by CPT conservation

Phys. Rev. D **90**, 112004 (2014)

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Rescattering Lineshape

Inspired by $\pi\pi \leftrightarrow KK$ scattering in 2-body interactions

In the context of 3-body decays, production of one pair of mesons can affect the coupled channel

Attempt to account for this with phenomenological form factor

$$A(s) = \frac{\hat{T}}{1 + \frac{s}{\Delta^2_{PP}}}$$

Phys. Rev. D **92**, 054010 (2015)

Intended to describe the partonic interaction that produces $\pi\pi$ and KK in 3-body final state

$\hat{T}$ is the observable amplitude related to the unitary S-matrix as, $\hat{S} = 1 + 2i\hat{T}$

$$\hat{S}(s) = \begin{pmatrix} \eta(s)e^{2i\delta_{\pi\pi}(s)} & i\sqrt{1-\eta^2(s)}e^{i(\delta_{\pi\pi}(s)+\delta_{KK}(s))} \\ i\sqrt{1-\eta^2(s)}e^{i(\delta_{\pi\pi}(s)+\delta_{KK}(s))} & \eta(s)e^{2i\delta_{KK}(s)} \end{pmatrix}$$

Rescattering Lineshape

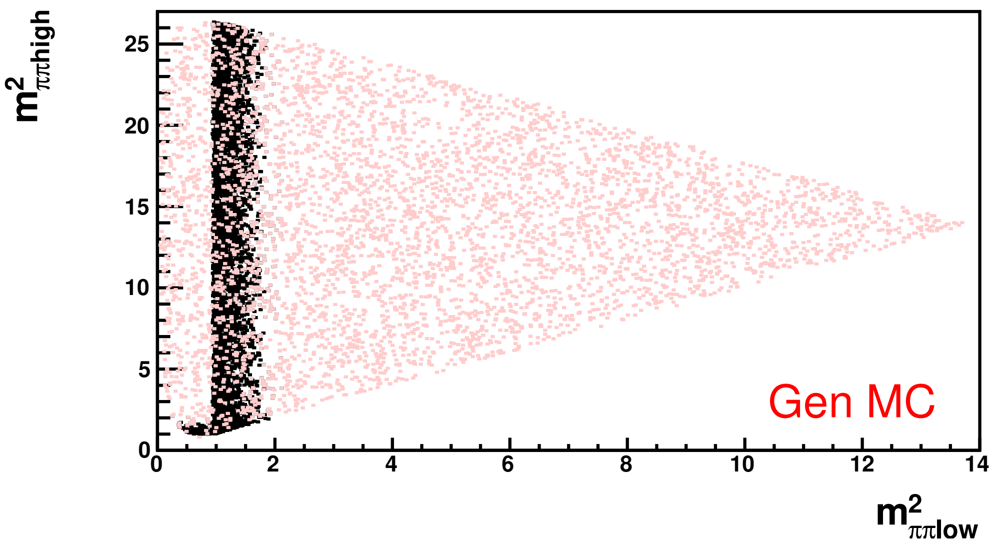
Only off-diagonal elements are relevant for amplitude anlaysis

Use models for the phase shifts $\delta_{\pi\pi}(s)$, $\delta_{KK}(s)$ and inelasticity $\eta(s)$

Phys. Rev. D **71**, 074016 (2005);

Phys. Rev. D **83**, 094011 (2011)

Rescattering vs phase space



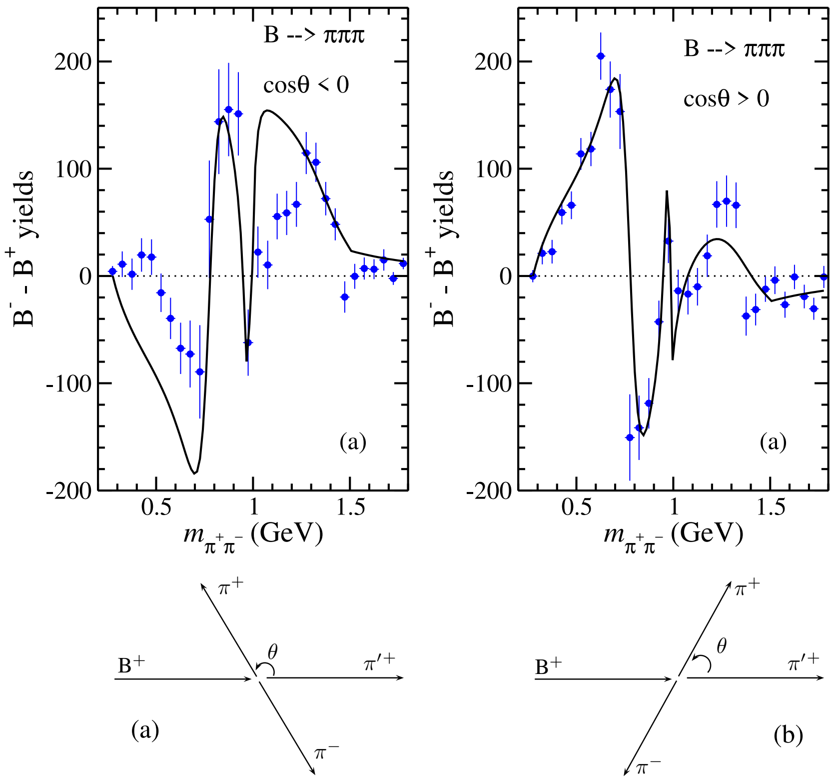
Also tested on LHCb asymmetry

ρ, $f_0(980)$ considered in addition

Reproduces the main features

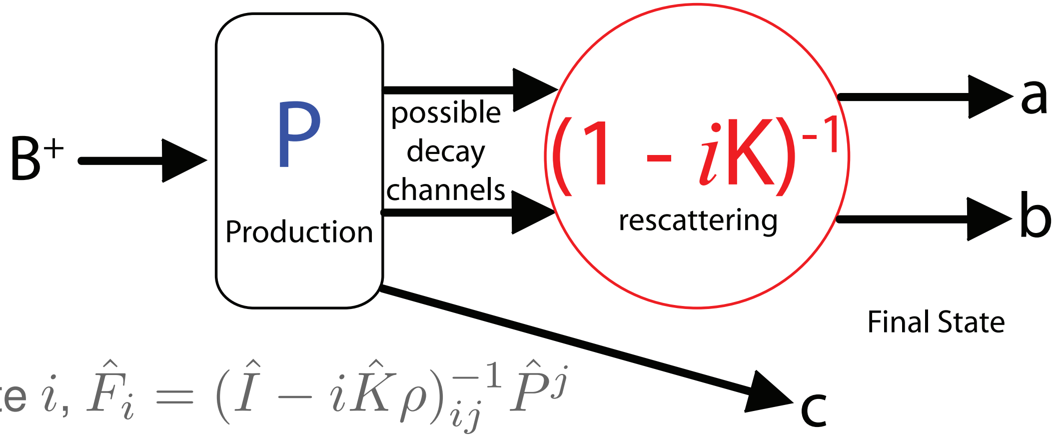
Exp: Phys. Rev. D **90**, 112004 (2014)

Th: Phys. Rev. D **92**, 054010 (2015)



K-Matrix

From unitarity of the S-matrix, physical transition amplitude given by $\hat{T} = (\hat{I} - i\hat{K}\rho)^{-1}\hat{K}$



For observed final state i, $\hat{F}_i = (\hat{I} - i\hat{K}\rho)^{-1}_{ij}\hat{P}^j$

$\hat{K}$ parametrised by summation of base mass poles and a slowly varying part for non-resonant

$$(\rho\hat{K})_{ij}(s) \equiv \sqrt{\rho_i\rho_j}\left(\sum_R \frac{g_i^R g_j^R}{m_R^2 - s} + f_{ij}^{\text{scat}}\frac{c - s_0^{\text{scat}}}{s - s_0^{\text{scat}}}\right) f_{A0}(s)$$

Parameters taken from scattering data

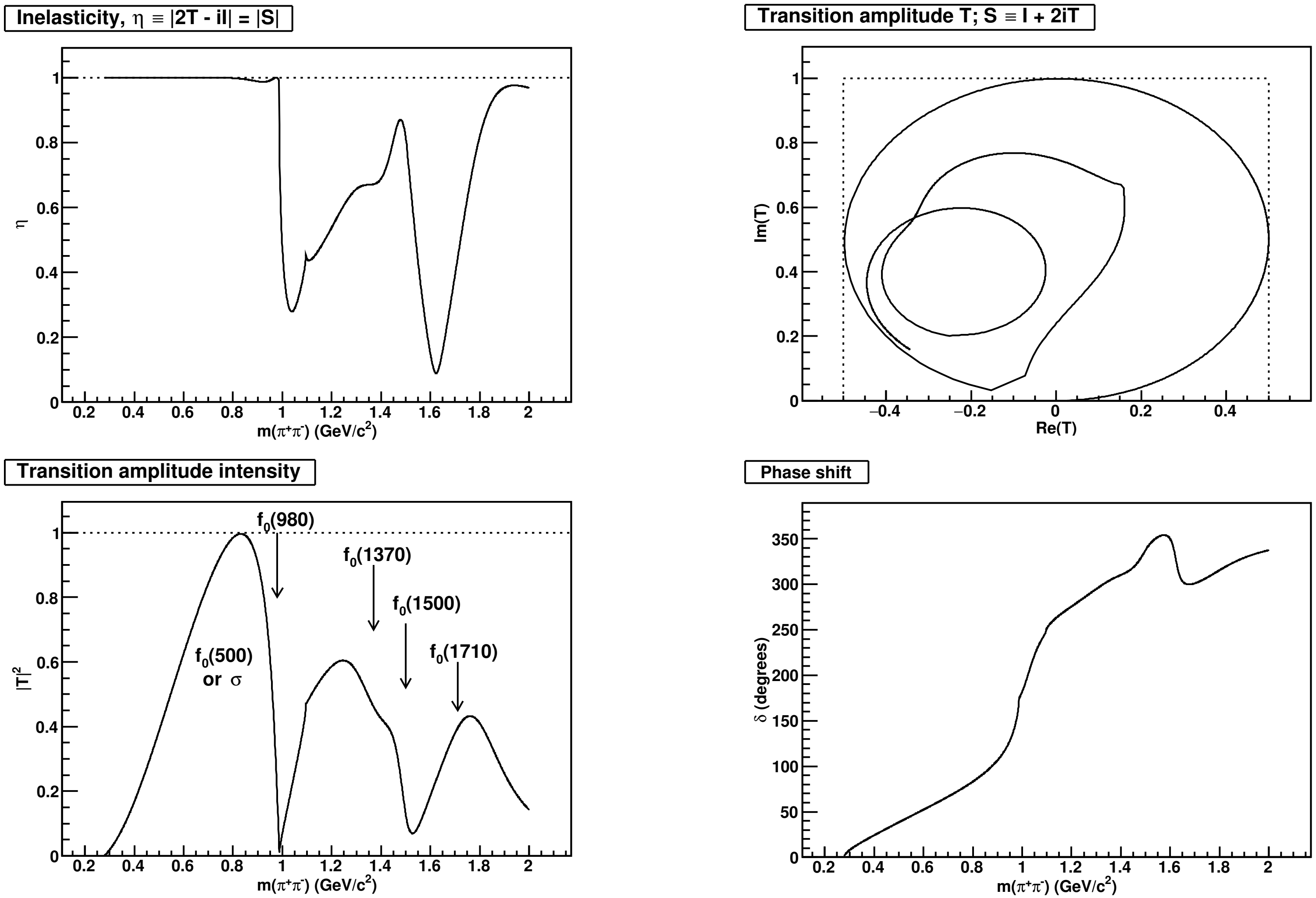
The production vector $\hat{P}$ takes on an analogous form to $\hat{K}$

$$\hat{P}_j(s) \equiv \sum_R \frac{\beta_R^{\text{prod}} g_j^R}{m_R^2 - s} + f_j^{\text{prod}}\frac{c - s_0^{\text{prod}}}{s - s_0^{\text{prod}}}$$

j: $\pi\pi$, KK, 4π, $\eta\eta$, $\eta\eta'$; β_R^{prod} and f_j^{prod} are the complex free parameters of the model

K-Matrix

Elastic scattering on the physical boundary, inelastic scattering inside



Resonances don't necessarily manifest as Breit-Wigner structure

Quasi-Model-Independent Approach

Construct spin-1 and spin-2 resonances with the isobar model as usual

Model $\pi\pi$ S-waves with adaptive binning method

Equal number of events in each bin

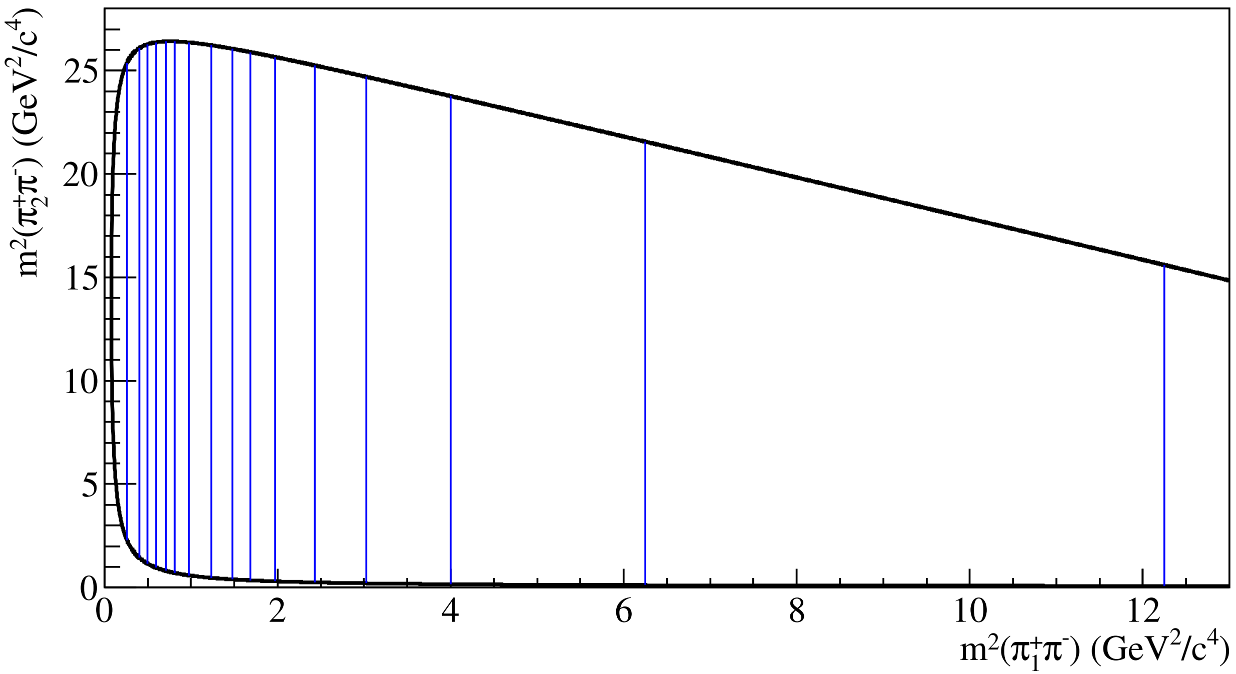
1D bins in $m^2(\pi^+\pi^-)$, 15 bins below charm veto, 2 bins above

In each bin,

- float an amplitude and phase

81 free parameters in total

Bose-symmetric amplitude implied



Quasi-Model-Independent Approach

Quasi-model-independent method

- Reminiscent of partial wave analysis

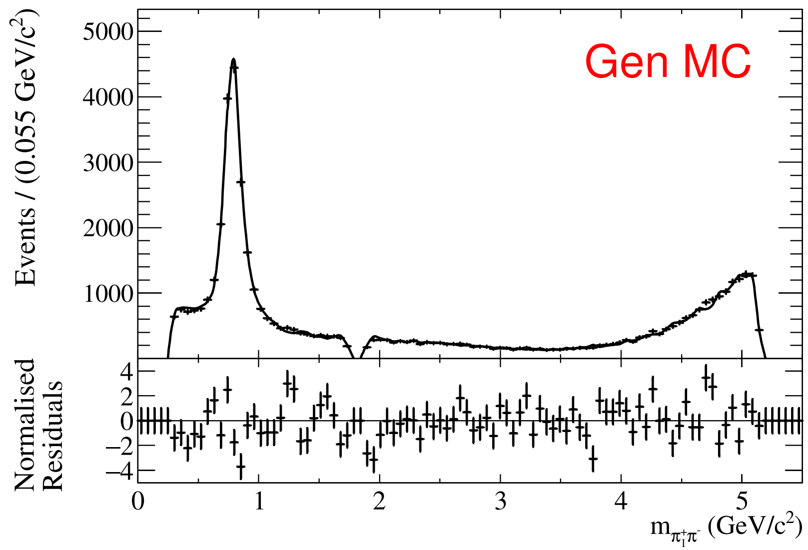
Divide the data into bins

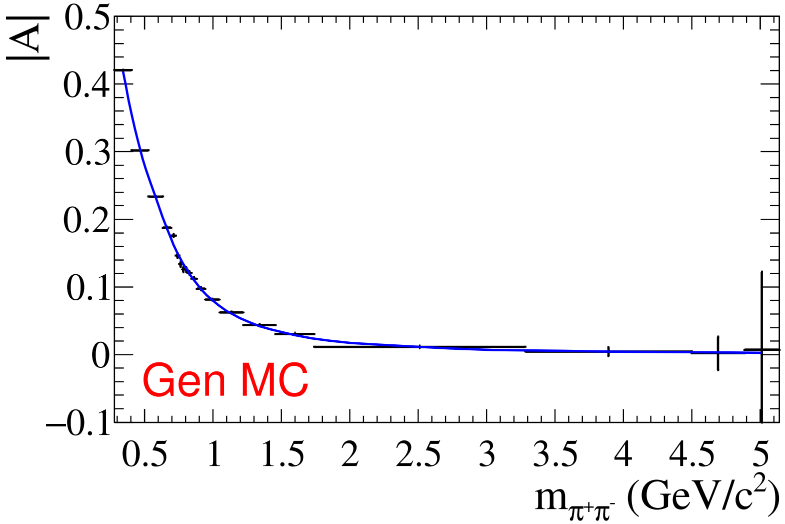
Free magnitude and phase in each bin

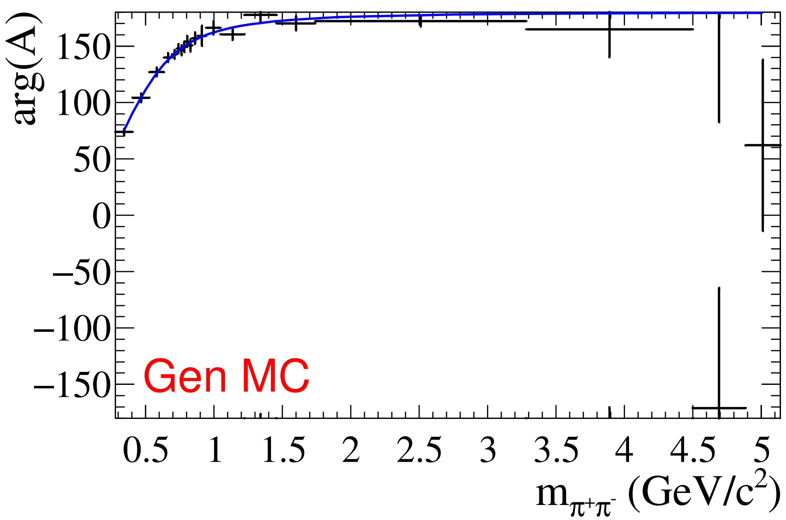
Data points: Fit results

Blue Curve: Generated $f_0(500)$ Breit-Wigner

MC sample generated with ρ, $f_0(500)$







Summary

Large CP violating effects observed in the phase space

Arise from a variety of potential sources that need to be studied

Invoking CPT constraints to model rescattering effects between $\pi\pi$ and KK

Promising method to interface with the wealth of results from scattering experiments

Quasi-model-independent measurement of S-wave obtained directly from the data

Allows direct comparison with the two physics-motivated analytic S-wave analyses