Measuring the CKM angle γ

J. Blouw

Physikalisches Institut, Universitaet Heidelberg

Tagungsstaette, Neckarzimmern, March 28-30, 2007

Introduction

- The CKM Triangle
- Why γ?
- Possible ways to measure γ
- Rare decays

Particle Decays

Corollary

CKM matrix describes quark-flavour changing

Example

1. decays described by quark-flavour transformations
2. 3 up-type quarks, 3 down-type quarks
3. Unitarity requirement imposes constraints on elements

Particle Decays

Corollary

CKM matrix describes quark-flavour changing

Example

1. decays described by quark-flavour transformations
2. 3 up-type quarks, 3 down-type quarks
3. Unitarity requirement imposes constraints on elements

Particle Decays

Corollary

CKM matrix describes quark-flavour changing

Example

1. decays described by quark-flavour transformations
2. 3 up-type quarks, 3 down-type quarks
3. Unitarity requirement imposes constraints on elements

Particle Decays

Corollary

CKM matrix describes quark-flavour changing

Example

1. decays described by quark-flavour transformations
2. 3 up-type quarks, 3 down-type quarks
3. Unitarity requirement imposes constraints on elements

Particle Decays

Corollary

CKM matrix describes quark-flavour changing

Example

1. decays described by quark-flavour transformations
2. 3 up-type quarks, 3 down-type quarks
3. Unitarity requirement imposes constraints on elements

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

Particle Decays

Corollary

CKM matrix describes quark-flavour changing

Example

1. decays described by quark-flavour transformations
2. 3 up-type quarks, 3 down-type quarks
3. Unitarity requirement imposes constraints on elements

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix}$$

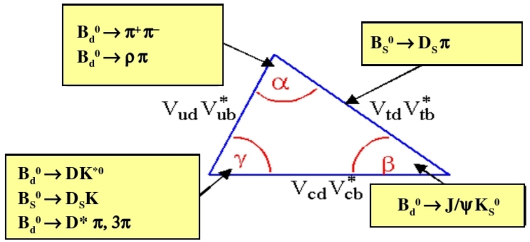
Unitarity yields ($V_{\mathrm{CKM}} \cdot V^{*}_{\mathrm{CKM}} = \mathbb{1}$)

Unitarity of the CKM matrix

Conclusion

The CKM Triangle:

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

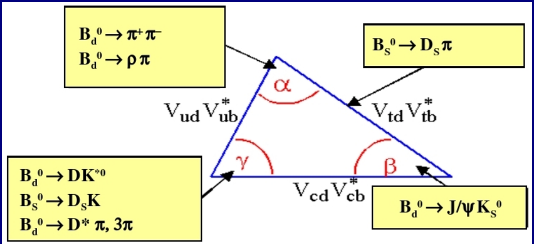


Unitarity of the CKM matrix

Conclusion

The CKM Triangle:

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



More triangle exist, *e.g.* for $\mathrm{B_s}$ physics:

$$V_{\rm ud} V_{\rm us}^* + V_{\rm cd} V_{\rm cs}^* + V_{\rm td} V_{\rm ts}^* = 0$$

Angles of the Triangle(s)

The 3 Angles

1. $\alpha = \mathrm{Arg}\left[-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*}\right]$
2. $\beta = \mathrm{Arg}\left[-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right]$
3. $\beta = \mathrm{Arg}\left[-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right]$

More Angles

1. $\beta_s = \mathrm{Arg}\left[-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*}\right]$
2. $\beta_K = \mathrm{Arg}\left[-\frac{V_{cs} V_{cd}^*}{V_{us} V_{ud}^*}\right]$

Angles of the Triangle(s)

The 3 Angles

1. $\alpha = \text{Arg}\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$
2. $\beta = \text{Arg}\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$
3. $\beta = \text{Arg}\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$

More Angles

1. $\beta_s = \text{Arg}\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$
2. $\beta_K = \text{Arg}\left[-\frac{V_{cs}V_{cd}^*}{V_{us}V_{ud}^*}\right]$

Angles of the Triangle(s)

The 3 Angles

1. $\alpha = \mathrm{Arg}\left[-\frac{V_{\mathrm{td}}V^*_{\mathrm{tb}}}{V_{\mathrm{ud}}V^*_{\mathrm{ub}}}\right]$
2. $\beta = \mathrm{Arg}\left[-\frac{V_{\mathrm{cd}}V^*_{\mathrm{cb}}}{V_{\mathrm{td}}V^*_{\mathrm{tb}}}\right]$
3. $\beta = \mathrm{Arg}\left[-\frac{V_{\mathrm{ud}}V^*_{\mathrm{ub}}}{V_{\mathrm{cd}}V^*_{\mathrm{cb}}}\right]$

More Angles

1. $\beta_s = \mathrm{Arg}\left[-\frac{V_{\mathrm{ts}}V^*_{\mathrm{tb}}}{V_{\mathrm{cs}}V^*_{\mathrm{cb}}}\right]$
2. $\beta_K = \mathrm{Arg}\left[-\frac{V_{\mathrm{cs}}V^*_{\mathrm{cd}}}{V_{\mathrm{us}}V^*_{\mathrm{ud}}}\right]$

Angles of the Triangle(s)

The 3 Angles

1. $\alpha = \text{Arg}\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$
2. $\beta = \text{Arg}\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$
3. $\beta = \text{Arg}\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$

More Angles

1. $\beta_s = \text{Arg}\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$
2. $\beta_K = \text{Arg}\left[-\frac{V_{cs}V_{cd}^*}{V_{us}V_{ud}^*}\right]$

Angles of the Triangle(s)

The 3 Angles

1. $\alpha = \mathrm{Arg}\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$
2. $\beta = \mathrm{Arg}\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$
3. $\beta = \mathrm{Arg}\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$

More Angles

1. $\beta_s = \mathrm{Arg}\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$
2. $\beta_K = \mathrm{Arg}\left[-\frac{V_{cs}V_{cd}^*}{V_{us}V_{ud}^*}\right]$

Direct Measurement of γ

$$B_u^{\pm} \rightarrow \pi^{\pm}(\pi^{\pm} + \pi^{\mp})$$

1. Small branching fraction
2. Measure γ through mixing of resonances w/o CP phase
3. Direct CP-violating asymmetries

- $\mathcal{B} = (16.2 \pm 1.2 \pm 0.9) \cdot 10^{-6}$
- $(\pi^{+} + \pi^{-})-$ resonance: $\rho^{0}, f_0, \chi_{c0} \cdots$
- access to cp-violation in interference

Direct Measurement of γ

$$B_u^{\pm} \rightarrow \pi^{\pm}(\pi^{\pm} + \pi^{\mp})$$

1. Small branching fraction
2. Measure γ through mixing of resonances w/o CP phase
3. Direct CP-violating asymmetries

- $\mathcal{B} = (16.2 \pm 1.2 \pm 0.9) \cdot 10^{-6}$
- $(\pi^{+} + \pi^{-})-$ resonance: $\rho^{0}, f_0, \chi_{c0} \cdots$
- access to cp-violation in interference

Direct Measurement of γ

$$B_u^\pm \to \pi^\pm(\pi^\pm + \pi^\mp)$$

1. Small branching fraction
2. Measure γ through mixing of resonances w/o CP phase
3. Direct CP-violating asymmetries

- $\mathcal{B} = (16.2 \pm 1.2 \pm 0.9) \cdot 10^{-6}$
- $(\pi^+ + \pi^-)-$ resonance: $\rho^0, f_0, \chi_{c0} \ldots$
- access to cp-violation in interference

Direct Measurement of γ

$$B_u^{\pm} \to \pi^{\pm}(\pi^{\pm} + \pi^{\mp})$$

1. Small branching fraction
2. Measure γ through mixing of resonances w/o CP phase
3. Direct CP-violating asymmetries

- $\mathcal{B} = (16.2 \pm 1.2 \pm 0.9) \cdot 10^{-6}$
- $(\pi^{+} + \pi^{-})-$ resonance: $\rho^0, f_0, \chi_{c0} \dots$
- access to cp-violation in interference

Direct Measurement of γ

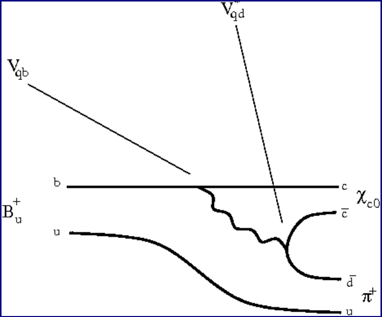
$$B_u^\pm \to \pi^\pm(\pi^\pm + \pi^\mp)$$

1. Small branching fraction
2. Measure γ through mixing of resonances w/o CP phase
3. Direct CP-violating asymmetries

- $\mathcal{B} = (16.2 \pm 1.2 \pm 0.9) \cdot 10^{-6}$
- $(\pi^+ + \pi^-)-$ resonance: $\rho^0, f_0, \chi_{c0} \ldots$
- access to cp-violation in interference

$\longrightarrow$ interference between (ρ^0, f_0) and (χ_{c0}) : sensitivity to CP.

Feynmann Diagram



- $M(\chi_{c0}) = 3414.76 \pm 0.35\ \mathrm{GeV}$
- χ_{c0} is a $\mathrm{c\bar{c}}$-state

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(...)
3. F_i: amplitudes from resonances included in fit

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(...)
3. F_i: amplitudes from resonances included in fit

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

$$\begin{aligned}\mathcal{F}_{B^+\to\pi^+\pi^-\pi^+}(s_1, s_2) &= \left|\sum_i a_i e^{i\theta_i} F_i(s_1, s_2)\right| \\ s_{12} &= (p_1^\mu + p_2^\mu)\cdot(p_1^\mu + p_2^\mu) \\ s_{23} &= (p_2^\mu + p_3^\mu)\cdot(p_2^\mu + p_3^\mu)\end{aligned}$$

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(…)
3. F_i: amplitudes from resonances included in fit

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

$$\begin{aligned}\mathcal{F}_{B^+\to\pi^+\pi^-\pi^+}(s_1,s_2) &= \left|\sum_i a_i e^{i\theta_i} F_i(s_1,s_2)\right| \\ s_{12} &= (p_1^\mu + p_2^\mu)\cdot(p_1^\mu + p_2^\mu) \\ s_{23} &= (p_2^\mu + p_3^\mu)\cdot(p_2^\mu + p_3^\mu)\end{aligned}$$

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(...)
3. F_i: amplitudes from resonances included in fit

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

$$\begin{aligned}\mathcal{F}_{B^+\to\pi^+\pi^-\pi^+}(s_1,s_2) &= \left|\sum_i a_i e^{i\theta_i} F_i(s_1,s_2)\right| \\ s_{12} &= (p_1^\mu + p_2^\mu)\cdot(p_1^\mu + p_2^\mu) \\ s_{23} &= (p_2^\mu + p_3^\mu)\cdot(p_2^\mu + p_3^\mu)\end{aligned}$$

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(...)
3. F_i: amplitudes from resonances included in fit

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

$$\begin{aligned}\mathcal{F}_{B^+\to\pi^+\pi^-\pi^+}(s_1,s_2) &= \left|\sum_i a_i e^{i\theta_i} F_i(s_1,s_2)\right| \\ s_{12} &= (p_1^\mu + p_2^\mu)\cdot(p_1^\mu + p_2^\mu) \\ s_{23} &= (p_2^\mu + p_3^\mu)\cdot(p_2^\mu + p_3^\mu)\end{aligned}$$

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(...)
3. F_i: amplitudes from resonances included in fit

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

$$\begin{aligned}\mathcal{F}_{B^+\to\pi^+\pi^-\pi^+}(s_1,s_2) &= \left|\sum_i a_i e^{i\theta_i} F_i(s_1,s_2)\right| \\ s_{12} &= (p_1^\mu + p_2^\mu)\cdot(p_1^\mu + p_2^\mu) \\ s_{23} &= (p_2^\mu + p_3^\mu)\cdot(p_2^\mu + p_3^\mu)\end{aligned}$$

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(...)
3. F_i: amplitudes from resonances included in fit

Split phase in cp-conserving & cp-violating part:

$$\theta_i = \delta_i + \phi_i$$

$\rightarrow$ need another decay to disentangle sum of phases

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

$$\begin{aligned}\mathcal{F}_{B^+\to\pi^+\pi^-\pi^+}(s_1,s_2) &= \left|\sum_i a_i e^{i\theta_i} F_i(s_1,s_2)\right| \\ s_{12} &= (p_1^\mu + p_2^\mu)\cdot(p_1^\mu + p_2^\mu) \\ s_{23} &= (p_2^\mu + p_3^\mu)\cdot(p_2^\mu + p_3^\mu)\end{aligned}$$

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(...)
3. F_i: amplitudes from resonances included in fit

Split phase in cp-conserving & cp-violating part:

$$\theta_i = \delta_i + \phi_i$$

$\rightarrow$ need another decay to disentangle sum of phases

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

A Little Complication

- Apply common known Dalitz-plot analysis technique.
- need fit function for each type of resonance:

$$\begin{aligned} \mathcal{F}_{B^+\to\pi^+\pi^-\pi^+}(s_1,s_2) &= \left|\sum_i a_i e^{i\theta_i} F_i(s_1,s_2)\right| \\ s_{12} &= (p_1^\mu + p_2^\mu)\cdot(p_1^\mu + p_2^\mu) \\ s_{23} &= (p_2^\mu + p_3^\mu)\cdot(p_2^\mu + p_3^\mu) \end{aligned}$$

1. a_i: unkown (!!) parameter, amplitude fraction
2. θ_i: unkown parameter, phase(...)
3. F_i: amplitudes from resonances included in fit

Split phase in cp-conserving & cp-violating part:

$$\theta_i = \delta_i + \phi_i$$

$\rightarrow$ need another decay to disentangle sum of phases

1. B^+ yields $\theta_i = \delta_i + \phi_i$
2. B^- yields $\bar{\theta}_i = \delta_i - \phi_i$

$b\bar{b}$ production at BaBar

PEP-II at SLAC in Kalifornia

Electron-Positron-Collisions:

e^- : 9.0 GeV e^+ : 3.1 Gev

→ two storage rings

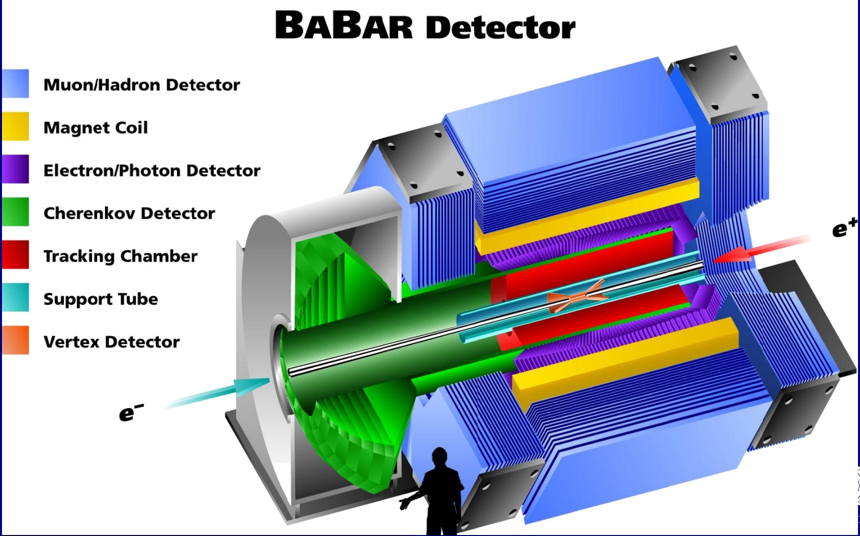
→ Boost

→ center of mass energy: 10.58 G

- corresponds to $\Upsilon(4S)$ resonance

B-Factory	$e^+e^- \rightarrow B\bar{B}$:	$\sigma = 1.05\,nb$
... but also Tau-Factory	$e^+e^- \rightarrow \tau\tau$:	$\sigma = 0.89\,nb$

$b\bar{b}$ production at BaBar



How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^{*}_{\mathrm{B}} - \sqrt{s}/2,$
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2/E_i^2 - p_{\mathrm{B}}^2}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^*_{\mathrm{B}} - \sqrt{s}/2,$
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2 / E_i^2 - p^2_{\mathrm{B}}}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi's$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^*_{\mathrm{B}} - \sqrt{s}/2,$
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2/E_i^2 - p_{\mathrm{B}}^2}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^*_{\mathrm{B}} - \sqrt{s}/2,$
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2/E_i^2 - p_{\mathrm{B}}^2}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

(Babar: Amplitude Analysis of the Decay $\mathrm{B}^{\pm} \rightarrow \pi^{\pm}\pi^{\pm}\pi^{\mp}$, hep-ex/0507025)

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^{*}_{\mathrm{B}} - \sqrt{s}/2$,
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2/E_i^2 - p_{\mathrm{B}}^2}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^*_{\mathrm{B}} - \sqrt{s}/2$,
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2 / E_i^2 - p_{\mathrm{B}}^2}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^*_{\mathrm{B}} - \sqrt{s}/2,$
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2 / E_i^2 - p^2_{\mathrm{B}}}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E_{\mathrm{B}}^{*} - \sqrt{s}/2$,
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2 / E_i^2 - p_{\mathrm{B}}^2}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^*_{\mathrm{B}} - \sqrt{s}/2,$
4. $m_{\mathrm{ES}} = \sqrt{(s/2 + p_i \cdot p_B)^2 / E_i^2 - p_{\mathrm{B}}^2}$
5. 2 independent variables

How to Analyse?

- reconstruct $B^{\pm}$
- which π belongs to which?
- through which resonance did the $\pi' s$ go?
- Example 1: BaBar analysis:

1. 3 identical particles in final state
2. use Dalitz-plot analysis
3. $\Delta E = E^*_{\rm B} - \sqrt{s}/2,$
4. $m_{\rm ES} = \sqrt{(s/2 + p_i \cdot p_B)^2 / E_i^2 - p_{\rm B}^2}$
5. 2 independent variables

Analysis Techniques

$$e^+ + e^- \rightarrow \Upsilon(4\mathrm{S}) \rightarrow (b\bar{b}) : \mathrm{at}\sqrt{(s)} = 10.5\ \mathrm{GeV}$$

1. Use kinematics of $(b\bar{b})$ production at resonance
2. (Compare with LHCb: $E(b\bar{b})$ and $p(b\bar{b})$ not *a priori* known!)
3. kinematic constraints from $b\bar{b}$ production help to suppress background
4. construct "invariant" masses of 2 combinations of π's:

Analysis Techniques

$$e^+ + e^- \to \Upsilon(4S) \to (b\bar{b}) : \text{at} \sqrt{(s)} = 10.5 \text{ GeV}$$

1. Use kinematics of $(b\bar{b})$ production at resonance
2. (Compare with LHCb: $E(b\bar{b})$ and $p(b\bar{b})$ not *a priori* known!)
3. kinematic constraints from $b\bar{b}$ production help to suppress background
4. construct “invariant” masses of 2 combinations of π’s:

Analysis Techniques

$$e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow (b\bar{b}) : \text{at} \sqrt{(s)} = 10.5 \text{ GeV}$$

1. Use kinematics of $(b\bar{b})$ production at resonance
2. (Compare with LHCb: $E(b\bar{b})$ and $p(b\bar{b})$ not *a priori* known!)
3. kinematic constraints from $b\bar{b}$ production help to suppress background
4. construct "invariant" masses of 2 combinations of π's:

Analysis Techniques

$$e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow (b\bar{b}) : \mathrm{at} \sqrt(s) = 10.5\ \mathrm{GeV}$$

1. Use kinematics of $(b\bar{b})$ production at resonance
2. (Compare with LHCb: $E(b\bar{b})$ and $p(b\bar{b})$ not *a priori* known!)
3. kinematic constraints from $b\bar{b}$ production help to suppress background
4. construct “invariant” masses of 2 combinations of π’s:

Analysis Techniques

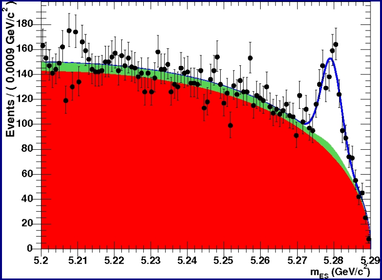
$$e^+ + e^- \rightarrow \Upsilon(4\mathrm{S}) \rightarrow (b\bar{b}) : \mathrm{at}\sqrt(s) = 10.5\ \mathrm{GeV}$$

1. Use kinematics of $(b\bar{b})$ production at resonance
2. (Compare with LHCb: $E(b\bar{b})$ and $p(b\bar{b})$ not *a priori* known!)
3. kinematic constraints from $b\bar{b}$ production help to suppress background
4. construct “invariant” masses of 2 combinations of π’s:

Analysis Techniques

$$e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow (b\bar{b}) : \text{at}\sqrt{(s)} = 10.5\ \text{GeV}$$

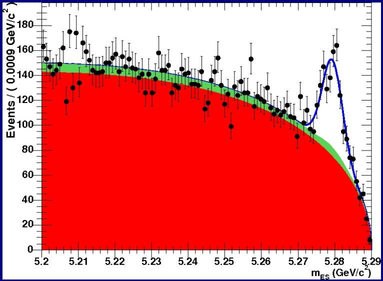
1. Use kinematics of $(b\bar{b})$ production at resonance
2. (Compare with LHCb: $E(b\bar{b})$ and $p(b\bar{b})$ not *a priori* known!)
3. kinematic constraints from $b\bar{b}$ production help to suppress background
4. construct “invariant” masses of 2 combinations of π’s:



Analysis Techniques

$$e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow (b\bar{b}) : \text{at} \sqrt{(s)} = 10.5\ \text{GeV}$$

1. Use kinematics of $(b\bar{b})$ production at resonance
2. (Compare with LHCb: $E(b\bar{b})$ and $p(b\bar{b})$ not *a priori* known!)
3. kinematic constraints from $b\bar{b}$ production help to suppress background
4. construct "invariant" masses of 2 combinations of π's:

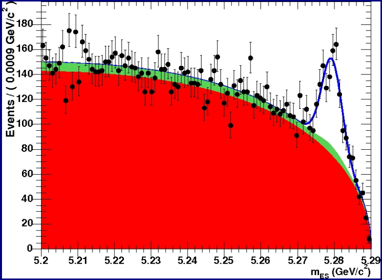


e.g. $B^+ \rightarrow \pi_1^+(\pi_2^- \pi_3^+)$

Analysis Techniques

$$e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow (b\bar{b}) : \text{at} \sqrt{(s)} = 10.5\ \text{GeV}$$

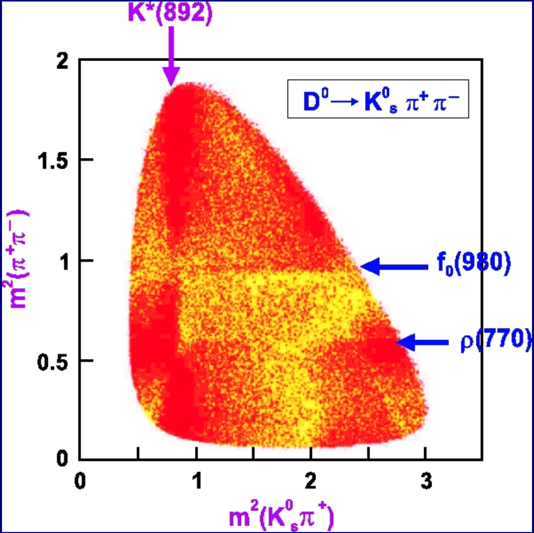
1. Use kinematics of $(b\bar{b})$ production at resonance
2. (Compare with LHCb: $E(b\bar{b})$ and $p(b\bar{b})$ not *a priori* known!)
3. kinematic constraints from $b\bar{b}$ production help to suppress background
4. construct “invariant” masses of 2 combinations of π’s:



e.g. $B^+ \rightarrow \pi_1^+(\pi_2^- \pi_3^+)$

$$s_{13} = m^2_{\pi_1^+\pi_2^-}$$
$$s_{23} = m^2_{\pi_2^+\pi_3^-}$$

Dalitz Plot Analysis



Example: $D^0 \to K_s^0 \pi^+ \pi^-$

Dalitz Plot Analysis

Example: $D^0 \to K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

   1. R_k: mass distribution
   2. T_k: angular-dependent amplitude
   3. R_k usual a Breit-Wigner
   4. $T_k^{(0)} = 1$, $T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
   5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$

Dalitz Plot Analysis

Example: $D^0 \rightarrow K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?
   1. R_k: mass distribution
   2. T_k: angular-dependent amplitude
   3. R_k usual a Breit-Wigner
   4. $T_k^{(0)} = 1$, $T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
   5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$

Dalitz Plot Analysis

Example: $D^0 \to K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?
   1. R_k: mass distribution
   2. T_k: angular-dependent amplitude
   3. R_k usual a Breit-Wigner
   4. $T_k^{(0)} = 1$, $T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
   5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$

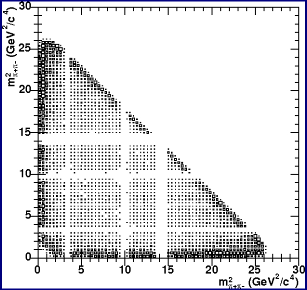
Dalitz Plot Analysis

Example: $D^0 \rightarrow K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

Resonances...

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$



1. R_k: mass distribution
2. T_k: angular-dependent amplitude
3. R_k usual a Breit-Wigner
4. $T_k^{(0)} = 1$, $T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

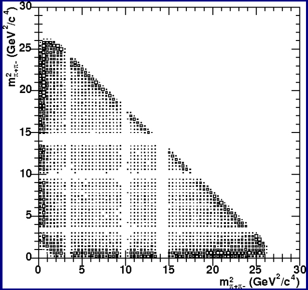
Dalitz Plot Analysis

Example: $D^0 \rightarrow K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

Resonances...

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$



1. R_k: mass distribution
2. T_k: angular-dependent amplitude
3. R_k usual a Breit-Wigner
4. $T_k^{(0)} = 1$, $T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

Dalitz Plot Analysis

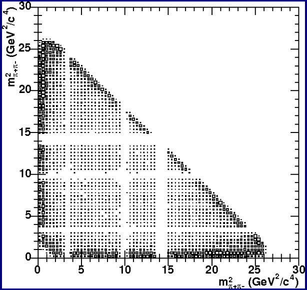
Example: $D^0 \to K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

1. R_k: mass distribution
2. T_k: angular-dependent amplitude
3. R_k usual a Breit-Wigner
4. $T_k^{(0)} = 1$, $T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

Resonances…

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$



Dalitz Plot Analysis

Example: $D^0 \rightarrow K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

Decay rate:

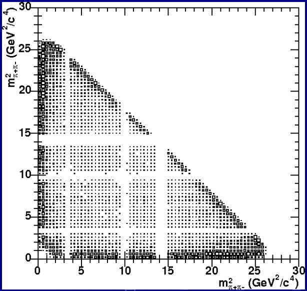
$$\frac{d\Gamma}{ds_{13}ds_{23}} = |\mathcal{M}|^2 \propto \left| \sum_k c_k e^{i\theta_k} \mathcal{D}_k(s_{12}, s_{23}) \right|^2$$

$\mathcal{D}_k = R_k \times T_k$

1. R_k: mass distribution
2. T_k: angular-dependent amplitude
3. R_k usual a Breit-Wigner
4. $T_k^{(0)} = 1,\ T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

Resonances. . .

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$



Dalitz Plot Analysis

Example: $D^0 \to K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

Decay rate:

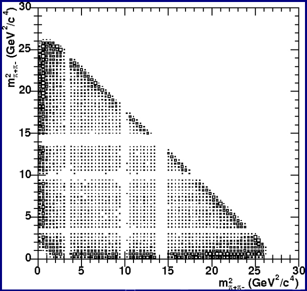
$$\frac{d\Gamma}{ds_{13} ds_{23}} = |\mathcal{M}|^2 \propto \left| \sum_k c_k e^{i\theta_k} \mathcal{D}_k(s_{12}, s_{23}) \right|^2$$

$\mathcal{D}_k = R_k \times T_k$

1. R_k: mass distribution
2. T_k: angular-dependent amplitude
3. R_k usual a Breit-Wigner
4. $T_k^{(0)} = 1$, $T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

Resonances...

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$



Dalitz Plot Analysis

Example: $D^0 \to K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

Decay rate:

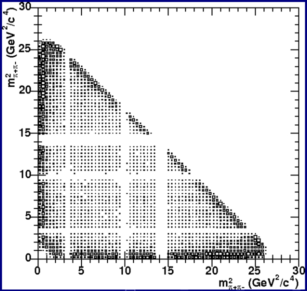
$$\frac{d\Gamma}{ds_{13}ds_{23}} = |\mathcal{M}|^2 \propto \left| \sum_k c_k e^{i\theta_k} \mathcal{D}_k(s_{12}, s_{23}) \right|^2$$

$\mathcal{D}_k = R_k \times T_k$

1. R_k: mass distribution
2. T_k: angular-dependent amplitude
3. R_k usual a Breit-Wigner
4. $T_k^{(0)} = 1$, $T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

Resonances...

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$



Dalitz Plot Analysis

Example: $D^0 \to K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

Decay rate:

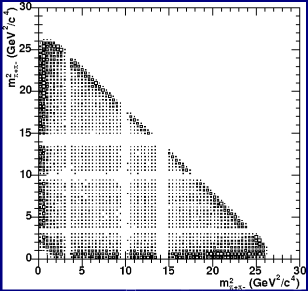
$$\frac{d\Gamma}{ds_{13}ds_{23}} = |\mathcal{M}|^2 \propto \left| \sum_k c_k e^{i\theta_k} \mathcal{D}_k(s_{12}, s_{23}) \right|^2$$

$$\mathcal{D}_k = R_k \times T_k$$

1. R_k: mass distribution
2. T_k: angular-dependent amplitude
3. R_k usual a Breit-Wigner
4. $T_k^{(0)} = 1,\ T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

Resonances...

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$



Dalitz Plot Analysis

Example: $D^0 \rightarrow K_s^0 \pi^+ \pi^-$

1. Plot invariant masses
2. Why observe structure in Dalitz plot?
3. What did we expect?

Decay rate:

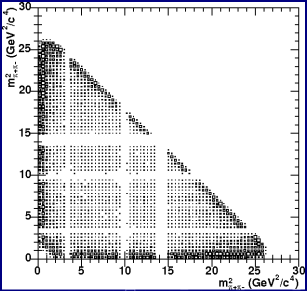
$$\frac{d\Gamma}{ds_{13}ds_{23}} = |\mathcal{M}|^2 \propto \left| \sum_k c_k e^{i\theta_k} \mathcal{D}_k(s_{12}, s_{23}) \right|^2$$

$$\mathcal{D}_k = R_k \times T_k$$

1. R_k: mass distribution
2. T_k: angular-dependent amplitude
3. R_k usual a Breit-Wigner
4. $T_k^{(0)} = 1,\ T_k^{(1)} = -2\vec{p} \cdot \vec{q}$
5. $T_k^{(2)} = \frac{4}{3}[3(\vec{p} \cdot \vec{q})^2 - (|\vec{p}|\,|\vec{q}|)^2$

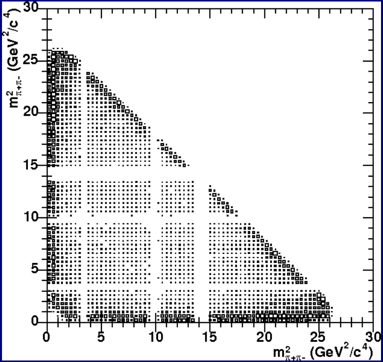
Resonances...

1. Resonances from $(\pi^- + \pi^+ = \rho^0, f_0(989))$
2. Resonances from $(\pi^+ + K_s^0 = K^{*+}(892))$



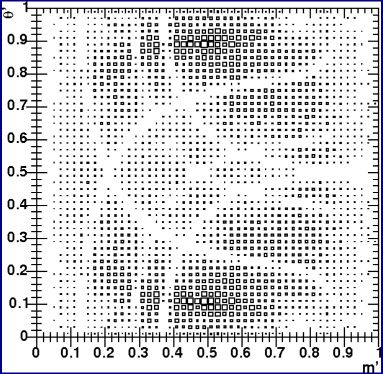
Dalitz: $B^{\pm} \rightarrow \pi^{\mp}\pi^{\pm}\pi^{\pm}$

Usual Dalitz plot



Note: resonances occur at bounderies…

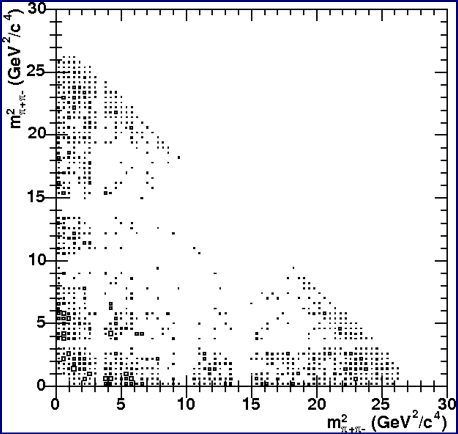
Rescale co-ordinates:



Empty space from charm vetoes

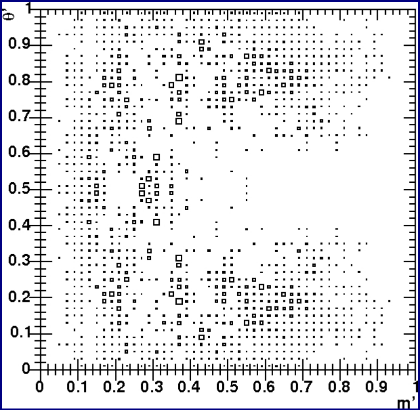
Dalitz from $B\bar{B}$ background

$B\bar{B}$ background: usual co-ordinates



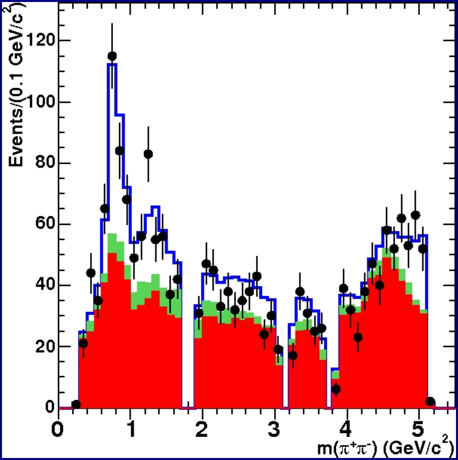
Holes are from charm vetoes

re-scaled co-ordinates:

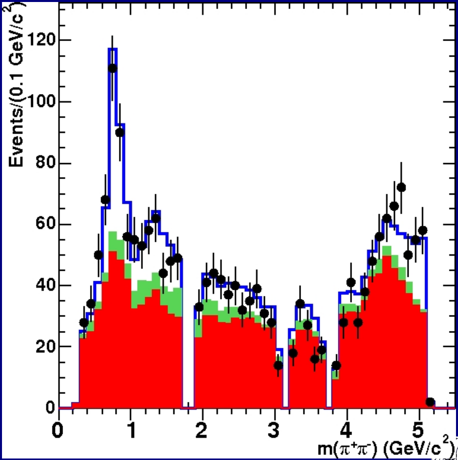


Results
Mass projections

Projection from B^+ onto $m(\pi^+\pi^-)$

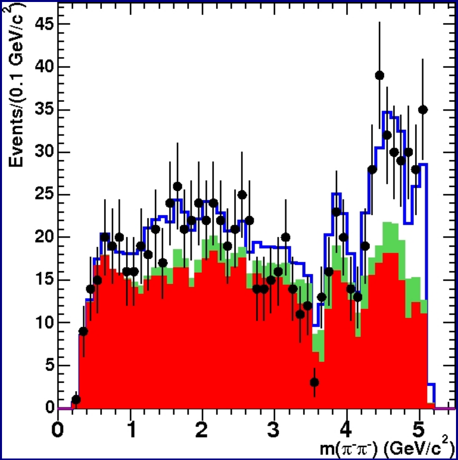


Projection from B^- onto $m(\pi^-\pi^-)$

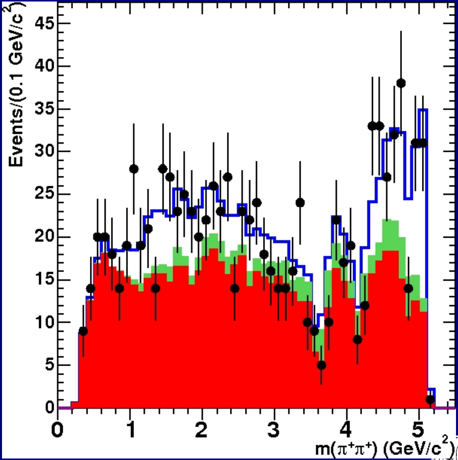


Results
Mass projections

Project from B^- onto $m(\pi^-\pi^-)$



Projection from B^+ onto $m(\pi^+\pi^+)$



Results & Conclusions

1. $B^+ \to \pi^\pm \pi^\pm \pi^\mp$: $(16.2 \pm 1.2 \pm 0.9) \times 10^{-6}$
2. $\rho^0(770)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(8.8 \pm 1.0 \pm 0.6) \times 10^{-6}$
3. $\rho^0(1450)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(1.0 \pm 0.6 \pm 0.4) \times 10^{-6}$
4. $f_0(980)\pi^\pm(f_0 \to \pi^+\pi^-)$: $(1.2 \pm 0.6 \pm 0.5) \times 10^{-6}$
5. $\chi_{c0}\pi^\pm(\chi_{c0} \to \pi^+\pi^-)$: < 0.3 at 90% CL

Results & Conclusions

1. $B^+ \to \pi^\pm\pi^\pm\pi^\mp$: $(16.2 \pm 1.2 \pm 0.9) \times 10^{-6}$
2. $\rho^0(770)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(8.8 \pm 1.0 \pm 0.6) \times 10^{-6}$
3. $\rho^0(1450)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(1.0 \pm 0.6 \pm 0.4) \times 10^{-6}$
4. $f_0(980)\pi^\pm(f_0 \to \pi^+\pi^-)$: $(1.2 \pm 0.6 \pm 0.5) \times 10^{-6}$
5. $\chi_{c0}\pi^\pm(\chi_{c0} \to \pi^+\pi^-)$: < 0.3 at 90% CL

Results & Conclusions

1. $B^+ \rightarrow \pi^\pm\pi^\pm\pi^\mp$: $(16.2 \pm 1.2 \pm 0.9) \times 10^{-6}$
2. $\rho^0(770)\pi^\pm(\rho^0 \rightarrow \pi^+\pi^-)$: $(8.8 \pm 1.0 \pm 0.6) \times 10^{-6}$
3. $\rho^0(1450)\pi^\pm(\rho^0 \rightarrow \pi^+\pi^-)$: $(1.0 \pm 0.6 \pm 0.4) \times 10^{-6}$
4. $f_0(980)\pi^\pm(f_0 \rightarrow \pi^+\pi^-)$: $(1.2 \pm 0.6 \pm 0.5) \times 10^{-6}$
5. $\chi_{c0}\pi^\pm(\chi_{c0} \rightarrow \pi^+\pi^-)$: < 0.3 at 90% CL

Results & Conclusions

1. $\mathrm{B}^+ \to \pi^\pm\pi^\pm\pi^\mp$: $(16.2 \pm 1.2 \pm 0.9) \times 10^{-6}$
2. $\rho^0(770)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(8.8 \pm 1.0 \pm 0.6) \times 10^{-6}$
3. $\rho^0(1450)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(1.0 \pm 0.6 \pm 0.4) \times 10^{-6}$
4. $f_0(980)\pi^\pm(f_0 \to \pi^+\pi^-)$: $(1.2 \pm 0.6 \pm 0.5) \times 10^{-6}$
5. $\chi_{c0}\pi^\pm(\chi_{c0} \to \pi^+\pi^-)$: < 0.3 at 90% CL

Results & Conclusions

1. $B^+ \to \pi^\pm \pi^\pm \pi^\mp$: $(16.2 \pm 1.2 \pm 0.9) \times 10^{-6}$
2. $\rho^0(770)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(8.8 \pm 1.0 \pm 0.6) \times 10^{-6}$
3. $\rho^0(1450)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(1.0 \pm 0.6 \pm 0.4) \times 10^{-6}$
4. $f_0(980)\pi^\pm(f_0 \to \pi^+\pi^-)$: $(1.2 \pm 0.6 \pm 0.5) \times 10^{-6}$
5. $\chi_{c0}\pi^\pm(\chi_{c0} \to \pi^+\pi^-)$: < 0.3 at 90% CL

Results & Conclusions

1. $\mathrm{B}^+ \to \pi^\pm\pi^\pm\pi^\mp$: $(16.2 \pm 1.2 \pm 0.9) \times 10^{-6}$
2. $\rho^0(770)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(8.8 \pm 1.0 \pm 0.6) \times 10^{-6}$
3. $\rho^0(1450)\pi^\pm(\rho^0 \to \pi^+\pi^-)$: $(1.0 \pm 0.6 \pm 0.4) \times 10^{-6}$
4. $f_0(980)\pi^\pm(f_0 \to \pi^+\pi^-)$: $(1.2 \pm 0.6 \pm 0.5) \times 10^{-6}$
5. $\chi_{c0}\pi^\pm(\chi_{c0} \to \pi^+\pi^-)$: < 0.3 at 90% CL

Conclusion

No χ_{c0} signal(!)

Results & Conclusions

1. $\mathrm{B}^+ \rightarrow \pi^\pm\pi^\pm\pi^\mp$: $(16.2 \pm 1.2 \pm 0.9) \times 10^{-6}$
2. $\rho^0(770)\pi^\pm(\rho^0 \rightarrow \pi^+\pi^-)$: $(8.8 \pm 1.0 \pm 0.6) \times 10^{-6}$
3. $\rho^0(1450)\pi^\pm(\rho^0 \rightarrow \pi^+\pi^-)$: $(1.0 \pm 0.6 \pm 0.4) \times 10^{-6}$
4. $f_0(980)\pi^\pm(f_0 \rightarrow \pi^+\pi^-)$: $(1.2 \pm 0.6 \pm 0.5) \times 10^{-6}$
5. $\chi_{c0}\pi^\pm(\chi_{c0} \rightarrow \pi^+\pi^-)$: < 0.3 at 90% CL

Conclusion

No χ_{c0} signal(!) $\Rightarrow$ CP-violation measurement not possible!!!