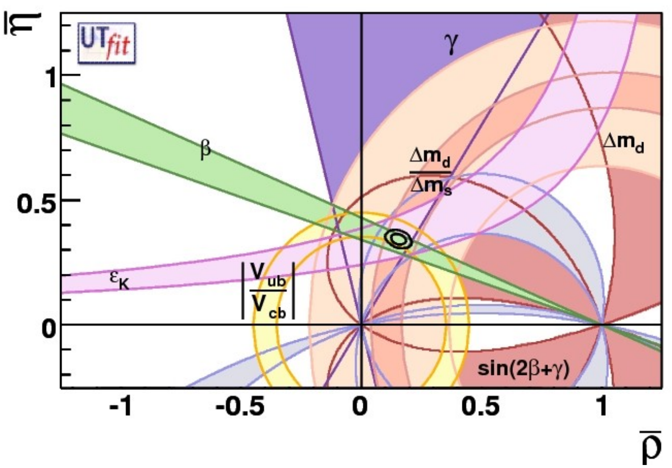
Flavour Physics and CP Violation



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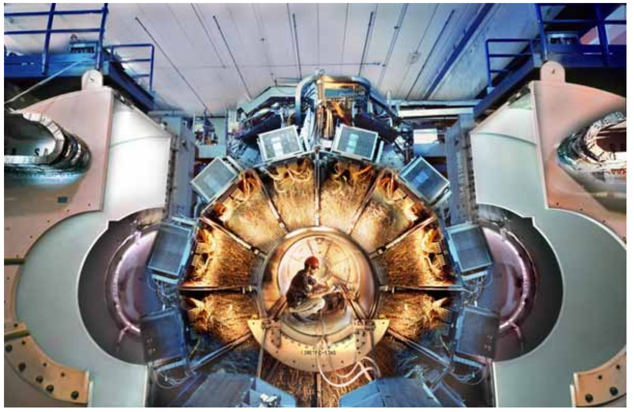


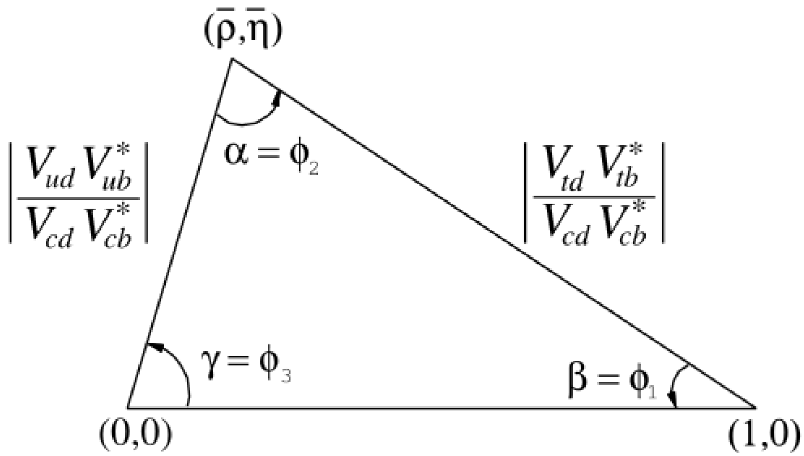
Post-FPCP 2018 Summer School

IIT Hyderabad, India

Lecture 3

Outline

- Short recap
- Angles of the unitarity triangle



The Unitarity Triangle [recap]

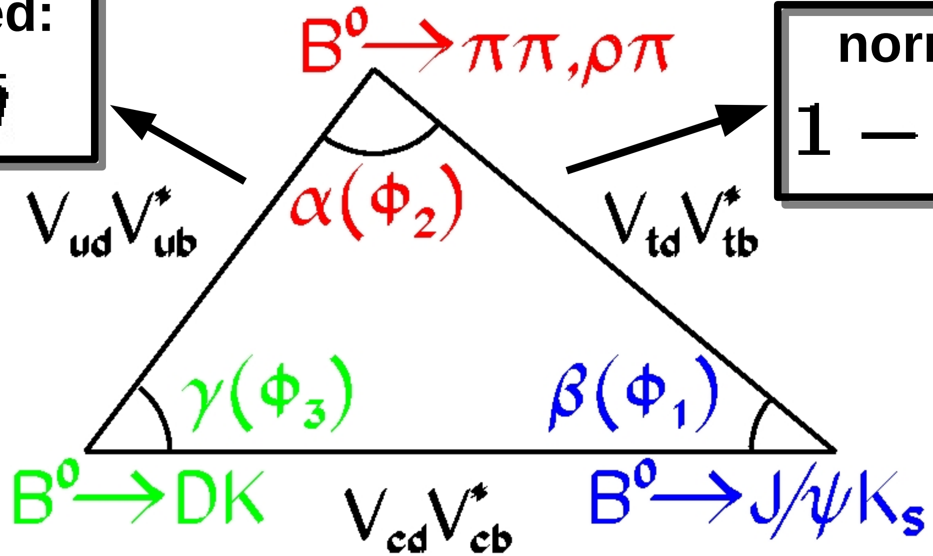
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

many observables
functions of $\bar{\rho}$ and $\bar{\eta}$:
overconstraining

$$\alpha = \pi - \beta - \gamma$$

normalized:
$$\bar{\rho} + i\bar{\eta}$$

normalized:
$$1 - \bar{\rho} - i\bar{\eta}$$



$$\gamma = atan\left(\frac{\bar{\eta}}{\bar{\rho}}\right)$$

$$\beta = atan\left(\frac{\bar{\eta}}{(1-\bar{\rho})}\right)$$

CPV Types for the B Meson System [recap]

◎ Define the quantity λ: $\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$

1. Indirect CP violation, or CPV in the mixing:

   $| q/p | \neq 1$

2. Direct CP violation, or CPV in the decays:

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

3. CP violation in interference between mixing and decay: $\mathrm{Im}\lambda \neq 0$

both neutral and charged B

neutral B

Time evolution and CP violation [recap]

◎ If we consider that both B^0 and $\overline{B}^0$ can decay to the same final state and considering here a final state that is a CP eigenstate, then the time evolution of the physical system becomes:

$$f(B^0_{phys} \to f_{CP}, \Delta t) = \frac{\Gamma}{4} e^{-\Gamma|\Delta t|} [1 - S_{f_{CP}} \sin(\Delta m_d \Delta t) + C_{f_{CP}} \cos(\Delta m_d \Delta t)]$$

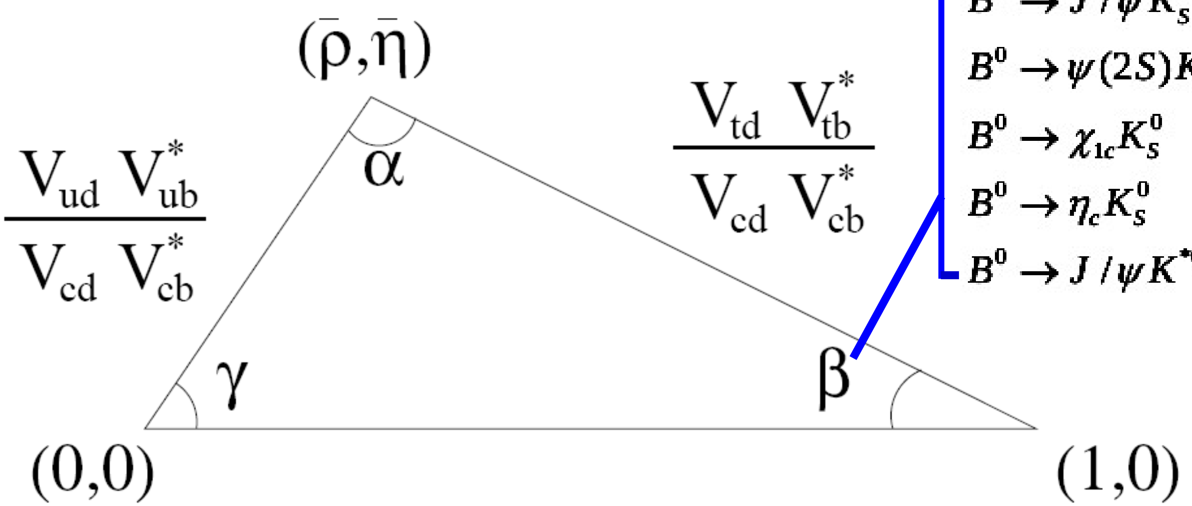
$$f(\bar{B}^0_{phys} \to f_{CP}, \Delta t) = \frac{\Gamma}{4} e^{-\Gamma|\Delta t|} [1 + S_{f_{CP}} \sin(\Delta m_d \Delta t) - C_{f_{CP}} \cos(\Delta m_d \Delta t)]$$

- ◉ direct CP violation $C \neq 0$ $$C_f (= -A_f) = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}$$
- ◉ CP violation in interference $S \neq 0$ $$S_f = \frac{2 Im \lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

β/ϕ_1 angle

Theoretically cleaner (SM uncertainties ~10^{-2} to 10^{-3})
→ tree dominated decays to Charmonium + K^0 final states.

$$\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$$



$b \to c\bar{c}s$

$B^0 \to J/\psi K_L^0$

$B^0 \to J/\psi K_S^0$

$B^0 \to \psi(2S) K_S^0$

$B^0 \to \chi_{1c} K_S^0$

$B^0 \to \eta_c K_S^0$

$B^0 \to J/\psi K^{*0}$

$B \to J/\psi \pi^0$

$B \to D^{(*)+} D^{(*)-}$

$B \to \eta' K^0$

$B \to \rho K^0$

$B \to \omega K^0$

$B \to \pi^0 K^0$

$B \to \phi K^{(*)0}$

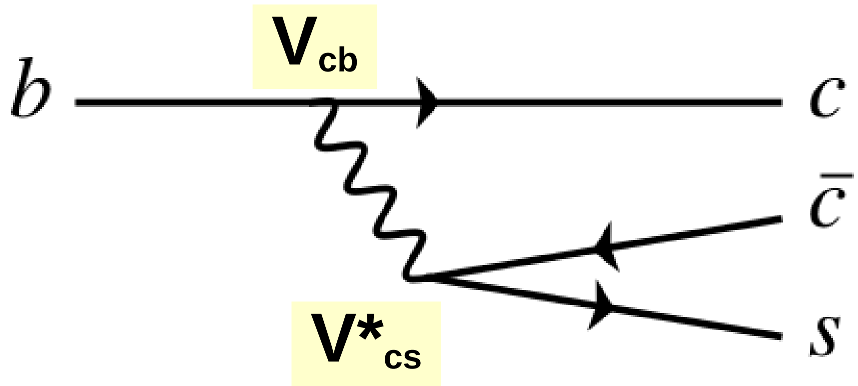
$B \to KKK^0$

$B \to f^0(980) K^0$

$\beta \equiv \arg\left[-V_{cd}V^*_{cb}/V_{td}V^*_{tb}\right]$

$\sin 2\beta$ in golden $b \to c\bar{c}s$ modes

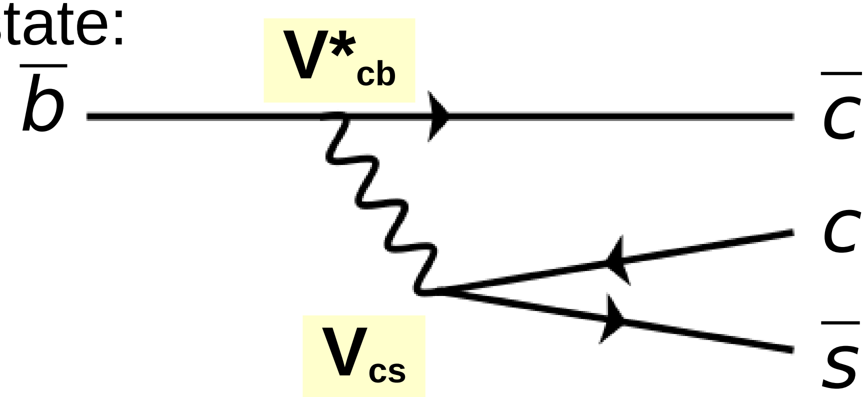
leading-order tree decays to $c\bar{c}s$ final states



$+\bar{d}$ $\bar{K}^0 \to K_{S,L}$

$\boxed{\bar{B}^0 \to J/\psi K_{S,L}}$

here the CKM elements contributing are $V_{cb}V^*_{cs}$ that in our Wolfenstein CKM parameterisation have no phase.
The CP conjugated case is also leading to (about) the same final state:



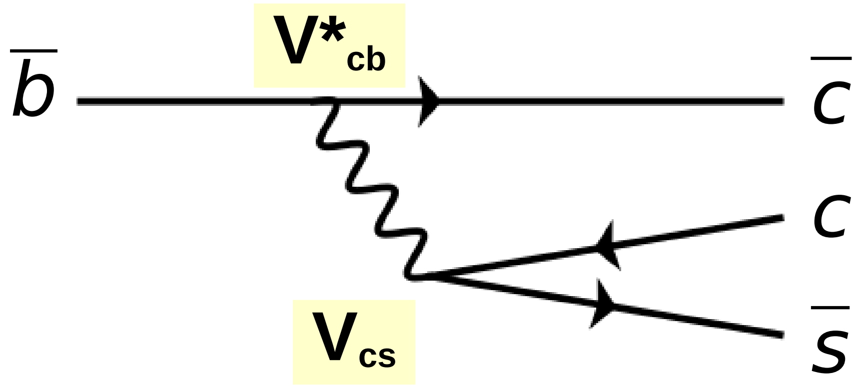
$+d$ $K^0 \to K_{S,L}$

$\boxed{B^0 \to J/\psi K_{S,L}}$

sin2β in golden $b \to \bar{c}cs$ modes

leading-order tree decays to $c\bar{c}s$ final states

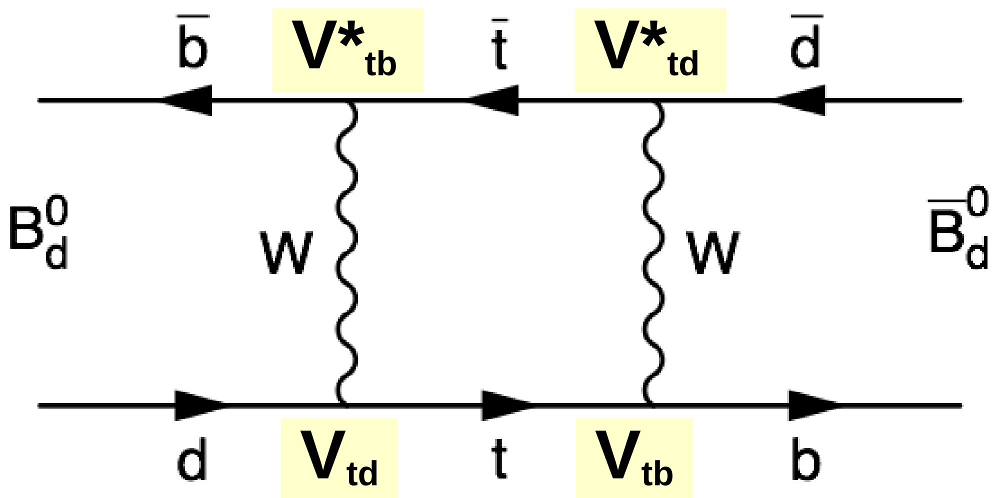
$B^0 \to J/\psi K_{S,L}$



$+d \quad K^0 \to K_{S,L}$

$$\frac{\bar{A}}{A} = \overbrace{\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}}^{\text{tree diagram}} \; \underbrace{\frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}}}_{\text{K mixing}}$$

because both B and $\bar{B}$ can decay in this common final state, this can interfere with the oscillation diagram:



$$\lambda = \frac{q}{p}\frac{A(\bar{B} \to f)}{A(B \to f)} = \frac{V^*_{td}V_{tb}}{V_{td}V^*_{tb}}\frac{\bar{A}}{A} \sim e^{-i2\beta}\frac{\bar{A}}{A}$$

$\beta \equiv \arg\left[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}\right]$

sin2β in golden b → $c\bar{c}s$ modes

$$\boxed{B^0 \rightarrow J/\psi K_{S,L}}$$

no possibility to generate this way direct or indirect CPV

$$\boxed{\lambda_{CP} = \eta_{CP}\frac{q}{p}\frac{\bar{A}}{A} = \eta_{CP}\underbrace{\frac{V_{td}V^{*}_{tb}}{V^{*}_{td}V_{tb}}}_{e^{-i2\beta}}\frac{V_{cb}V^{*}_{cd}}{V^{*}_{cb}V_{cd}}}$$

$|\lambda_{CP}| = 1$

↳ $C_{f_{CP}} = 0$

$\mathrm{Im}\,\lambda_{CP} = -\eta_{CP}\sin 2\beta$

↳ $S_{f_{CP}} = -\eta_{CP}\sin 2\beta$

$$\left\{\begin{array}{l} J/\psi\ (c\bar{c}) \rightarrow J^{PC} = 1^{--} \\ K_S \sim K_1 \rightarrow \eta_{CP} = +1 \\ L=1 \rightarrow P = (-1)^L \end{array}\right.$$

$$\boxed{\eta_{CP}(J/\psi K_S) = -1}$$

$$\boxed{\eta_{CP}(J/\psi K_L) = +1}$$

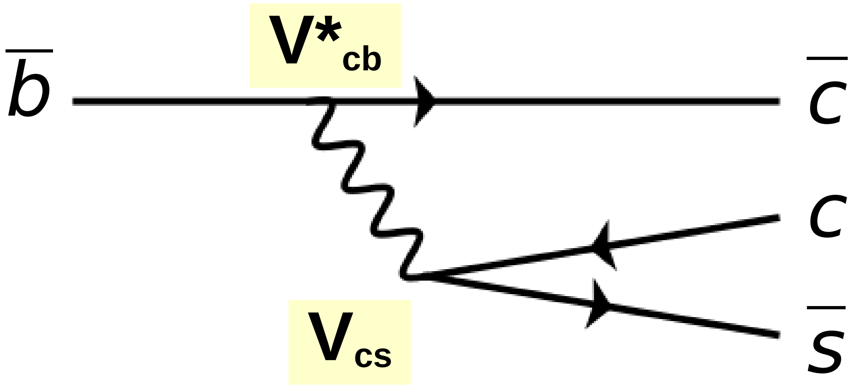
CPV in interference between mixing and decay

$\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$

Why $J/\psi K_{S,L}$ mode is golden

$B^0 \to J/\psi K_{S,L}$

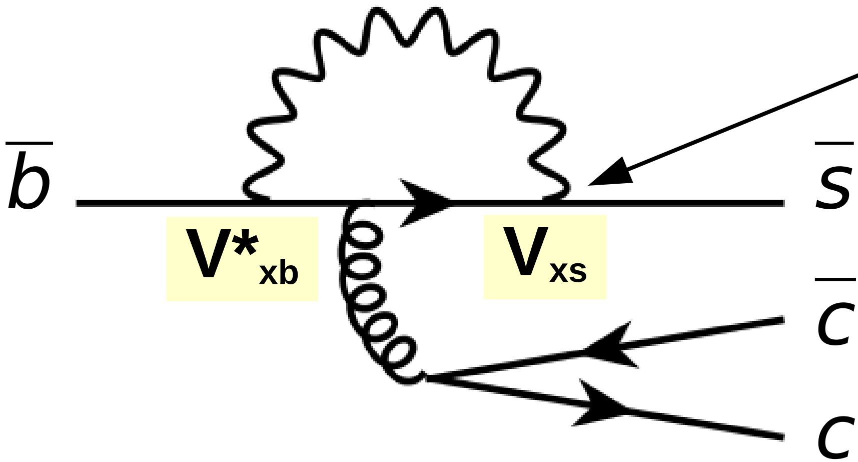
leading-order tree decays to $c\bar{c}s$ final states



+d $K^0 \to K_{S,L}$

$$\frac{\bar{A}}{A} = \overbrace{\frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}}}^{\text{tree diagram}} \underbrace{\frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}}}_{\text{K mixing}}$$

possible penguin contributions:

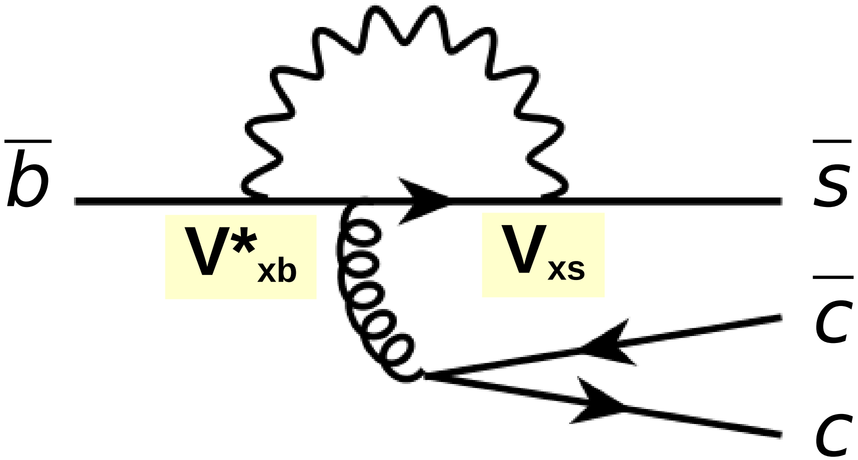


where x can be any up-type quark hence this counts for three penguin diagrams

can this be a problem?

$\beta \equiv \arg\left[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}\right]$

Why J/ψ$K_{S,L}$ mode is golden



$$\begin{cases} x=u \rightarrow P^u \sim V_{ub}V^*_{us} \\ x=c \rightarrow P^c \sim V_{cb}V^*_{cs} \\ x=t \rightarrow P^t \sim V_{tb}V^*_{ts} \end{cases}$$

using this unitary condition ($2^{nd} \rightleftarrows 3^{rd}$ family), we eliminate $V_{tb}V^*_{ts}$

$$V_{ub}V^*_{us} + V_{cb}V^*_{cs} + V_{tb}V^*_{ts} = 0 \quad \rightarrow \quad V_{tb}V^*_{ts} = -V_{ub}V^*_{us} - V_{cb}V^*_{cs}$$

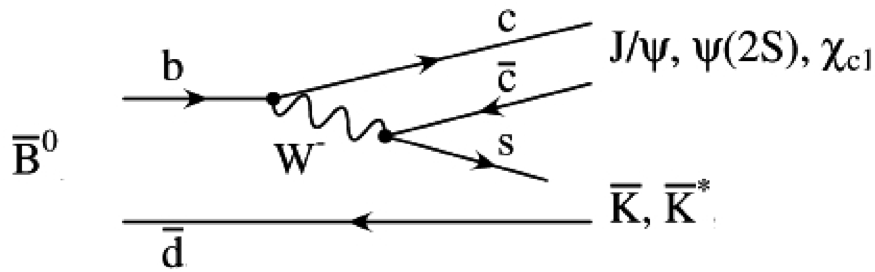
thus the amplitude is:

$$A_{ccs} \sim \underbrace{V_{cb}V^*_{cs}}_{\mathcal{O}(\lambda^2)} (T + P^c - P^t) + \underbrace{V_{ub}V^*_{us}}_{\mathcal{O}(\lambda^4)} (P^u - P^t)$$

CKM-suppressed pollution by penguins

$\beta \equiv \arg\left[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}\right]$

$\sin 2\beta$ in golden $b \to c\bar{c}s$ modes



◎ branching fraction: $O\,(10^{-3})$

the colour-suppressed tree dominates

and the penguin pollution has

the same weak phase of the tree or is CKM suppressed

◉ $$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

S ~ sin2β

C ~ 0

◎ theoretical uncertainty:

- ◉ model-independent data-driven estimation from $J/\psi\pi^0$ data:

$$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta = -0.01 \pm 0.01$$

M.Ciuchini et al. arXiv:1102.0392 [hep-ph].

- ◉ model-dependent estimates of the u- and c- penguin biases

$$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta \sim O\,(10^{-3})$$

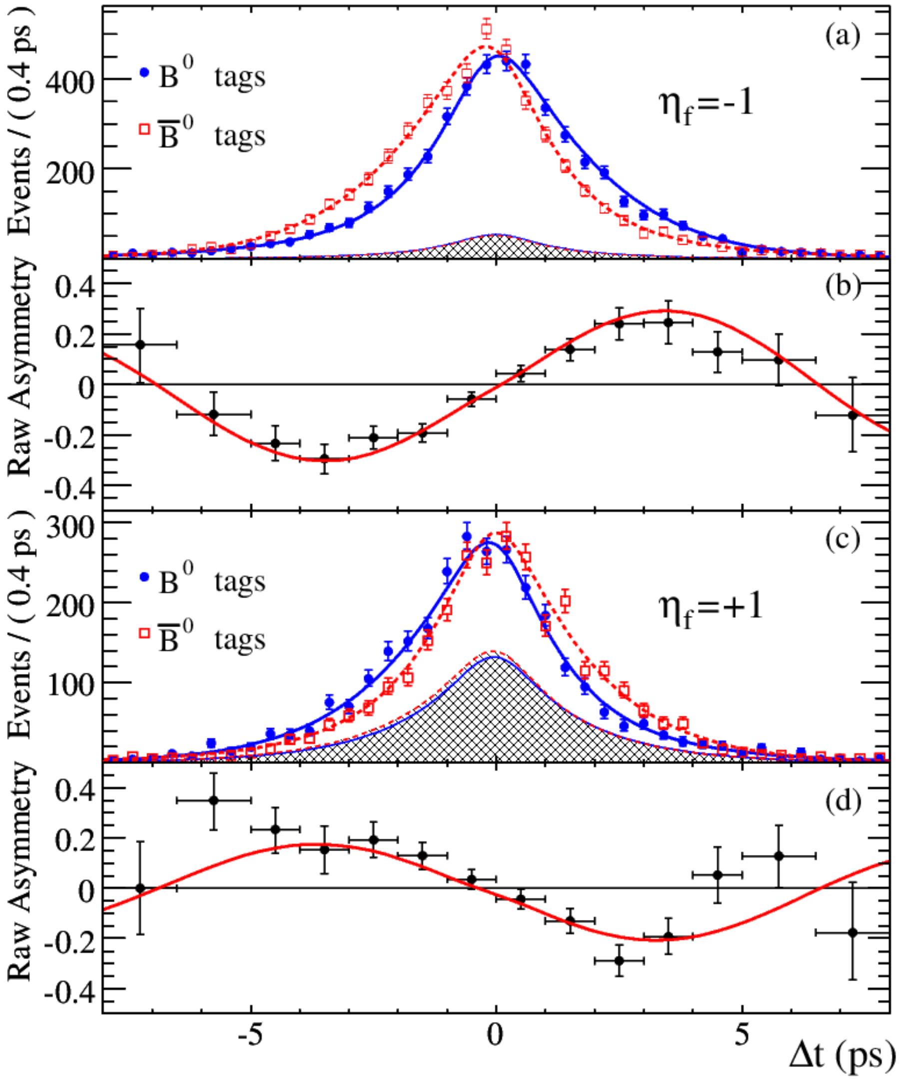
$$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta \sim O\,(10^{-4})$$

H.Li, S.Mishima JHEP 0703:009 (2007)

H.Boos et al. Phys. Rev. D73, 036006 (2006)

$\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$

sin2β in golden $b \to c\bar{c}s$ modes



$$A_{CP}(t) = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)$$

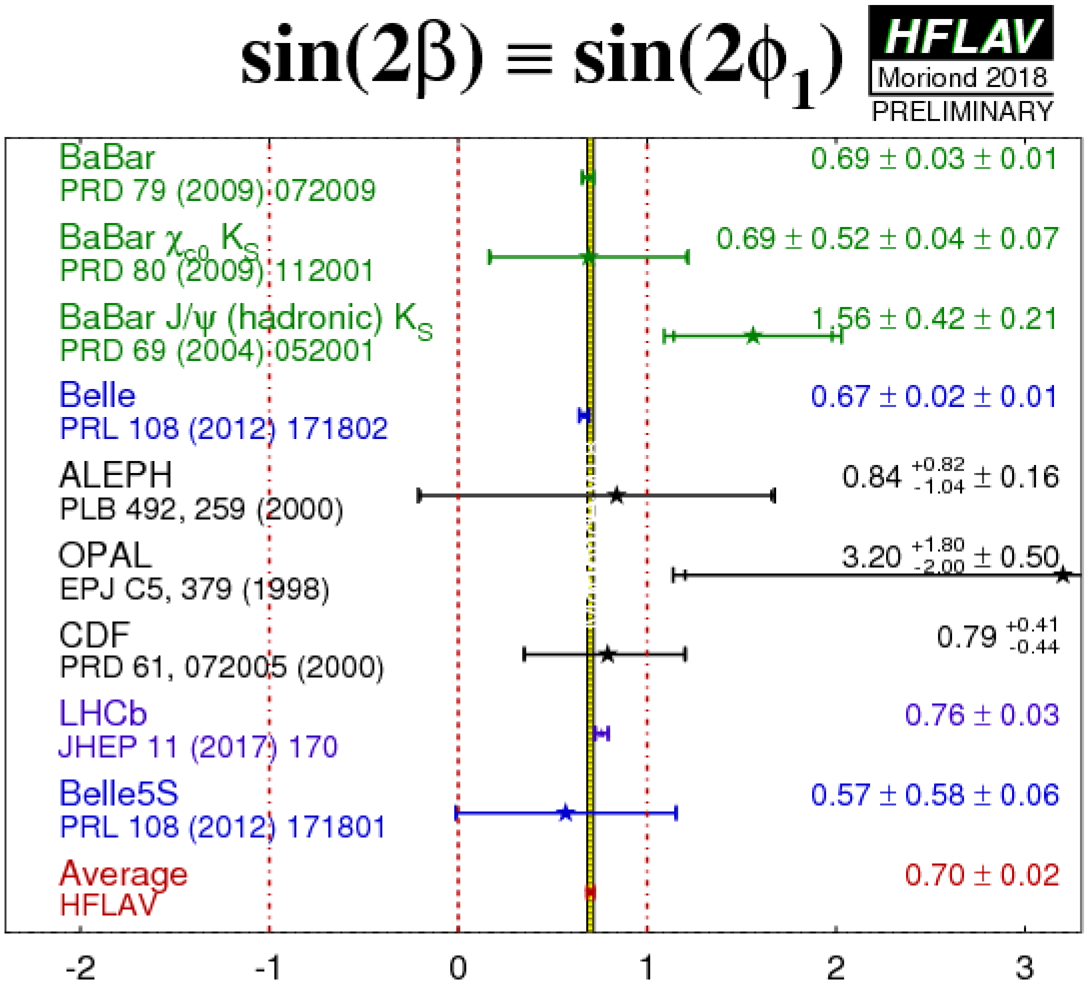
Sine term has a non-zero coefficient and this tells us that there is CP violation in the interference between mixing and decay amplitudes in $c\bar{c}s$ decays.

Heavy FLavour AVeraging (HFLAV) group for $J/\psi K_{S,L}$

$S = \sin 2\beta = 0.690 \pm 0.018$

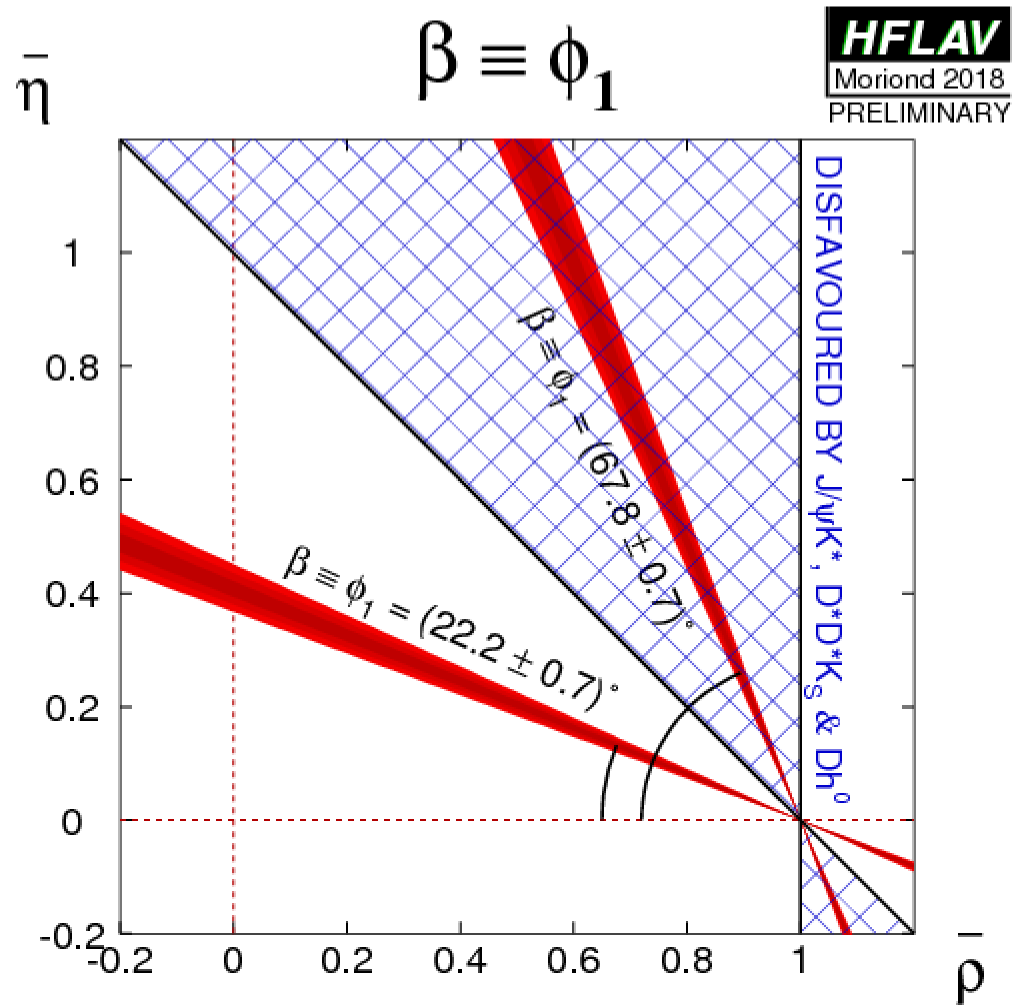
$\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$

sin2β in b → $c\bar{c}s$ modes



$\beta \equiv \arg\left[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}\right]$

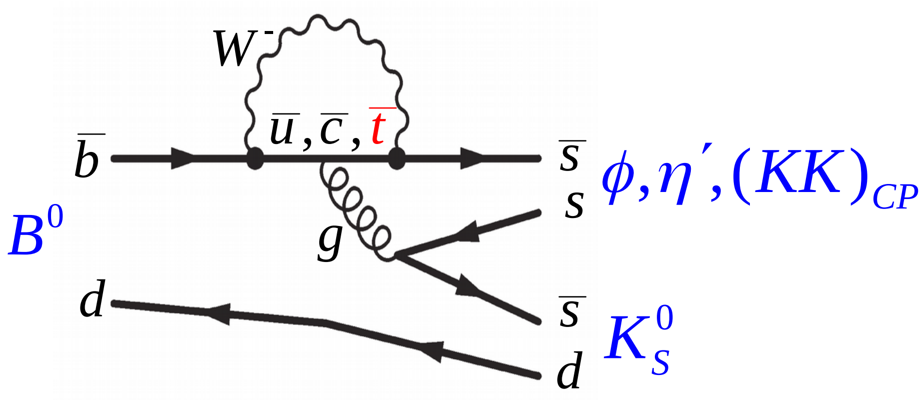
angle β in b → $c\bar{c}s$ modes



Searching for new physics via other b → $c\bar{c}s$ modes

- sin2β has been measured to O(1°) accuracy in b → $c\bar{c}s$ decays.
- Can use this to search for signs of New Physics (NP) if:
  - Identify a rare decay sensitive to sin2β (loop dominated process).
  - Measure S precisely in that mode (S_{eff}).
  - Control the theoretical uncertainty on the Standard Model 'pollution' (ΔS_{SM}).
  - Compute $\Delta S_{\rm NP} = S_{eff} - S_{c\bar{c}s} - \Delta S_{\rm SM}$

- In the presence of NP: $\Delta S_{NP} \neq 0$



► New heavy particles can introduce new amplitudes affecting physical observables of loop dominated processes.

► Observables affected include branching fractions, CP asymmetries, forward backward asymmetries.. etc..

► The Standard Model contributions need to be understood

α/ϕ_2 angle

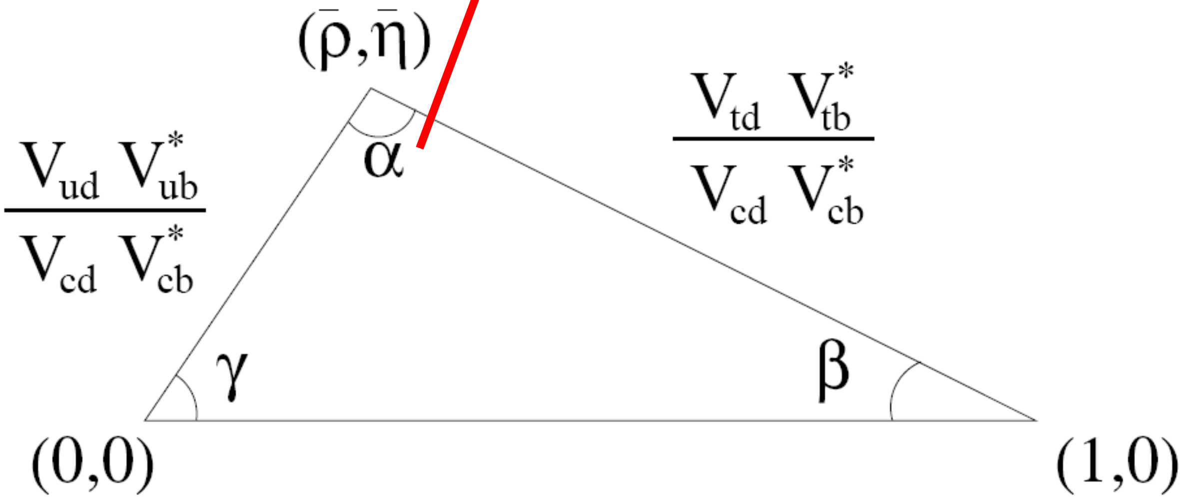
$$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$$

b → $u\bar{u}d$ transitions with possible loop contributions. Extract α using

- SU(2) Isospin relations.
- SU(3) flavour related processes.

$b \to u\bar{u}d$
$B \to \pi\pi$
$B \to \rho\pi$
$B \to \rho\rho$

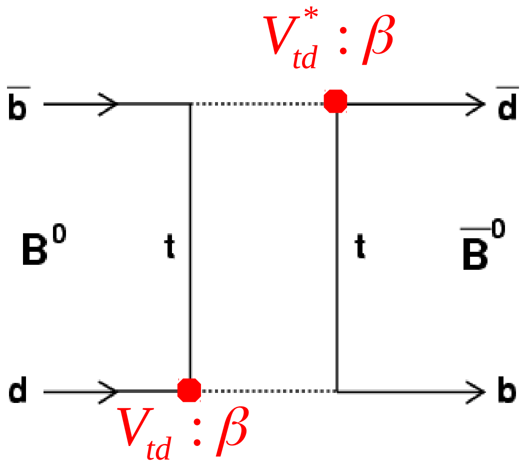
$B \to a_1\pi$
$B \to a_1\rho$
$B \to b_1\pi$
$B \to b_1\rho$
$B \to a_1 a_1$

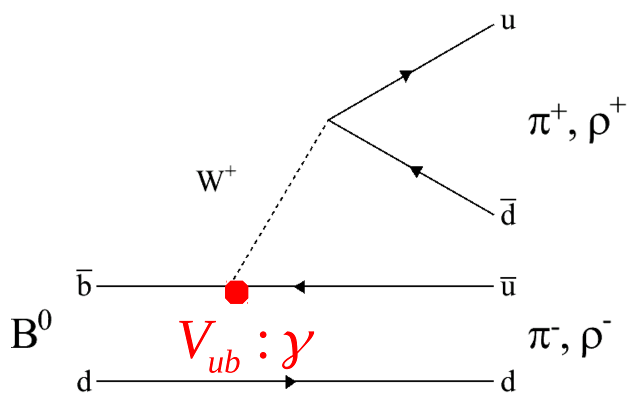


$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$

CP violation: α

- Interference between box and tree results in an asymmetry that is sensitive to α in B → hh decays: h = π, ρ, …





$$C_{hh} = 0$$

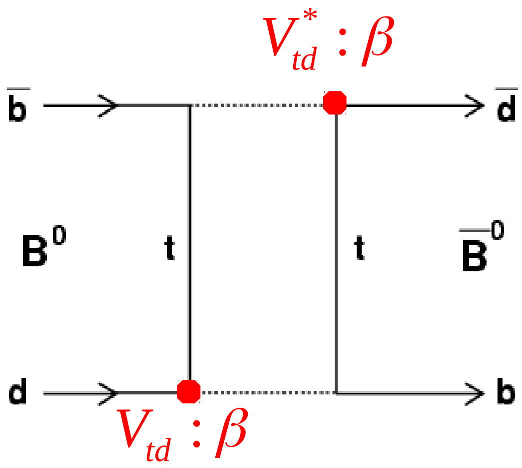
$$S_{hh} = \sin(2\alpha)$$

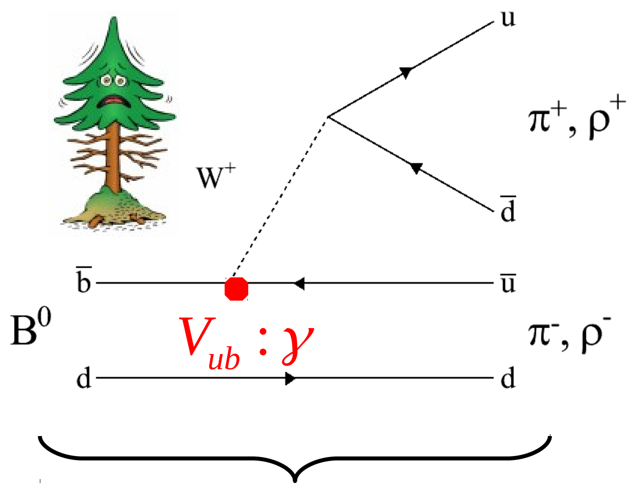
This is again a case of interference between mixing and decay.
This scenario is equivalent to the measurement of sin2β in Charmonium decays … but in this case it is more complicated..

$\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$

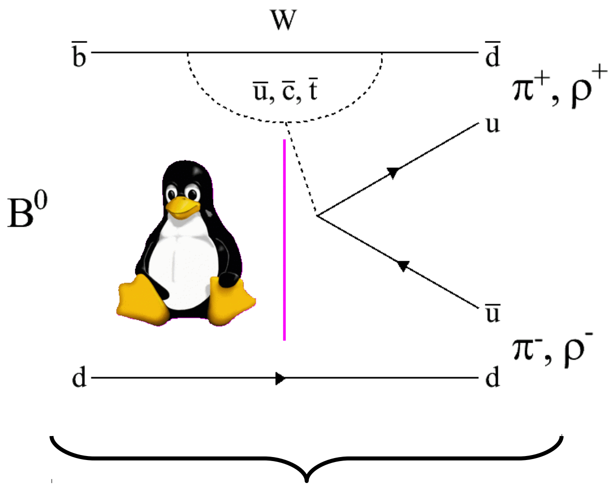
CP violation: α

◎ Interference between box and tree results in an asymmetry that is sensitive to α in B → hh decays: h = π, ρ, …





$\mathcal{O}(\lambda^3)$



$\mathcal{O}(\lambda^3)$

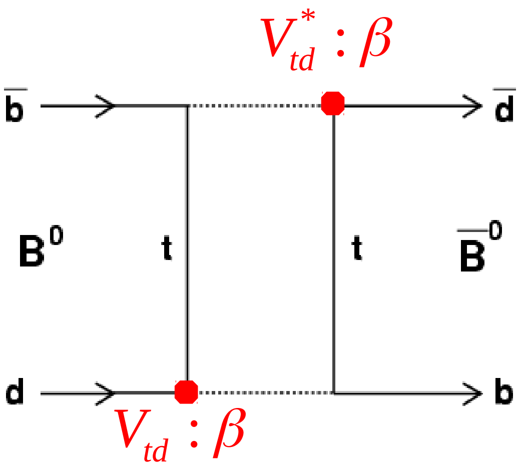
In this case the penguin diagram is not CKM suppressed so it spoils the clean measurement of the CP violation effect

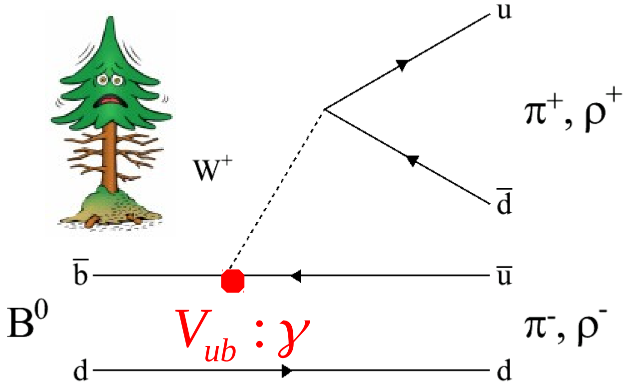
$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$

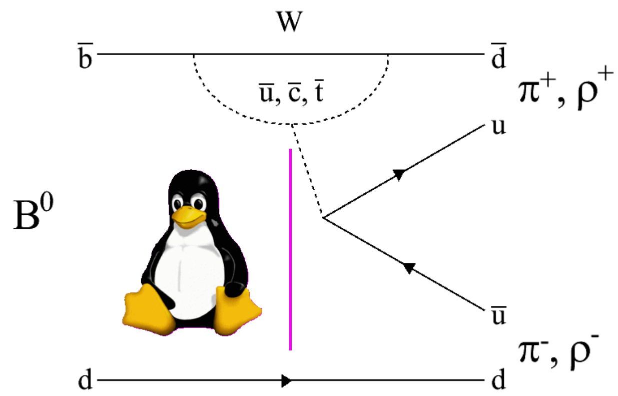
CP violation: α

- Interference between box and tree results in an asymmetry that is sensitive to α in $B \to hh$ decays: $h = \pi, \rho, \ldots$

+ Loops (penguins)







$$\underbrace{\hspace{3cm}}$$

$$C_{hh} = 0$$

$$S_{hh} = \sin(2\alpha)$$

$$C_{hh} \propto \sin(\delta)$$

$$S_{hh} = \sqrt{1 - C_{hh}^{2}}\,\sin(2\alpha_{\mathrm{eff}})$$

$$\delta = \delta_P - \delta_T$$

- Measure $S \propto \alpha_{\mathrm{eff}}$
- Need to determine $\delta_\alpha = \alpha_{\mathrm{eff}} - \alpha$ [P/T is different for each final state]

Bounding penguins

- Several recipes describe how to bound penguins and measure α.
  - These are based on SU(2) [or SU(3)] symmetry.

SU(2)
(Isospin analysis)

$\pi^+\pi^-$ and $\rho^+\rho^-$
Gronau-London
Isospin Triangles

$\pi^\pm\rho^\pm$
Lipkin (et al.)
Isospin Pentagons

$\pi^\pm\pi^\pm\pi^0$
Snyder-Quinn (et al.)
Fit Dalitz plot and extract parameters related to α

- Use charged and neutral B decays to the hh final state to constrain the penguin contribution and measure α.

M. Gronau and D. London, **65**, 3381 (1990)

- Use charged and neutral B decays to the $\rho\pi$ final state to constrain the penguin contribution and measure α. Remove any overlapping regions in

H. Lipkin *et al.*, Phys. Rev. Lett. D **44**, 1454 (1991)

- Regions of the Dalitz plot with intersecting ρ bands are included in this analysis; this helps resolve ambiguities.

A. Snyder and H. Quinn, Phys. Rev. Lett. D **48**, 2139 (1993); H. Quinn and J Silva, Phys. Rev. Lett. D **62**, 054002 (2000).

Isospin analysis

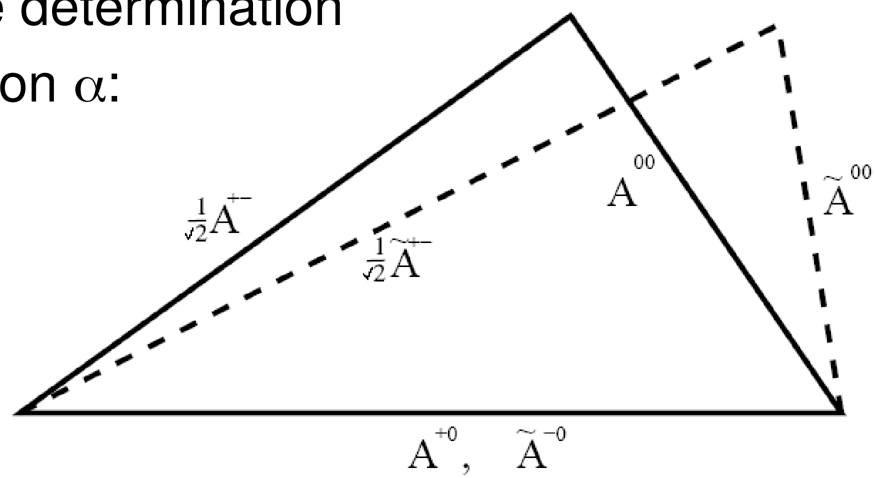
α: collecting the ingredients

from $\alpha_{eff} \rightarrow$ to α: isospin analysis

Channel	Decay Amplitudes
$\pi\pi$	$A(B^+ \to \pi^+\pi^0) = \frac{\sqrt{3}}{2} A_{3/2,2}$ $\frac{1}{\sqrt{2}} A(B^0 \to \pi^+\pi^-) = \frac{1}{\sqrt{12}} A_{3/2,2} - \sqrt{\frac{1}{6}} A_{1/2,0}$ $A(B^0 \to \pi^0\pi^0) = \frac{1}{\sqrt{3}} A_{3/2,2} + \sqrt{\frac{1}{6}} A_{1/2,0}$

- $B \rightarrow \pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$ decays are connected from isospin relations
- $\pi\pi$ states can have I = 2 or I = 0
  - ⇨ the gluonic penguins contribute only to the I = 0 state (ΔI=1/2)
  - ⇨ $\pi^+\pi^0$ is a pure I = 2 state (ΔI = 3/2) and it gets contribution only from the tree diagram
  - ⇨ triangular relations allow for the determination of the phase difference induced on α:

Both BR(B^0) and BR($\overline{B}^0$) have to be measured in all the $\pi\pi$ channels



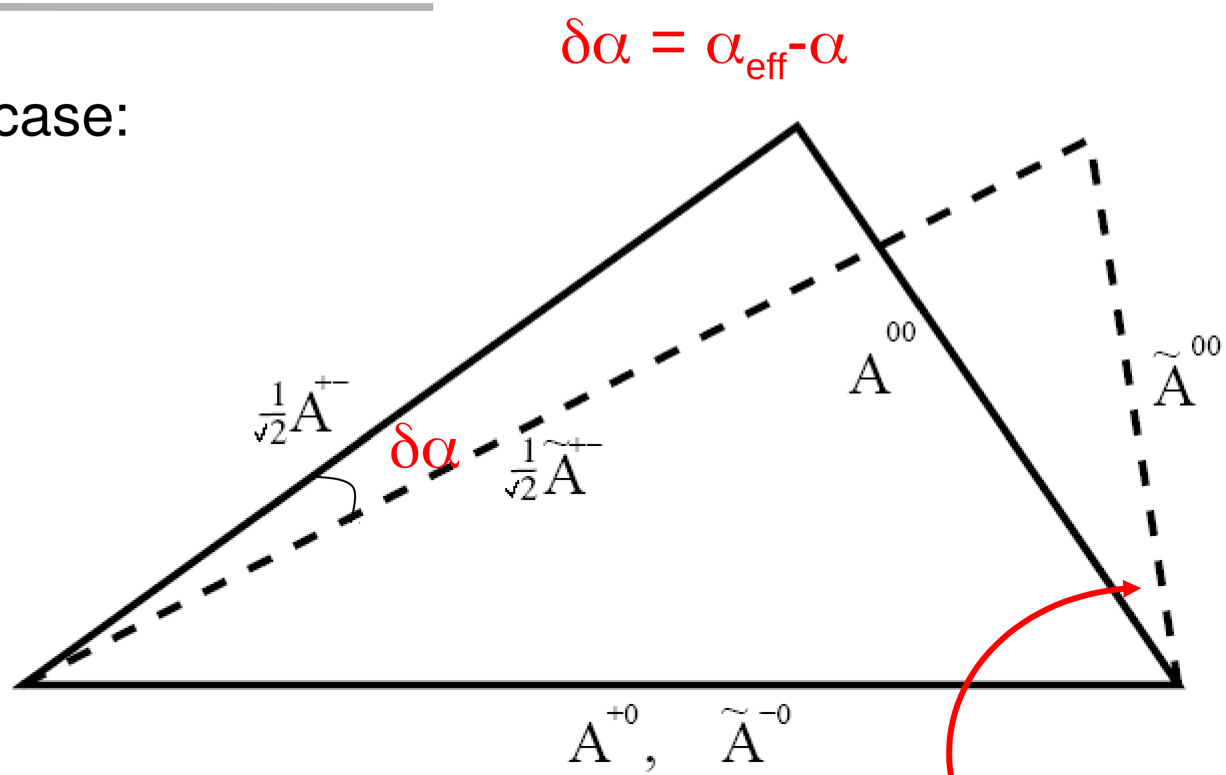
Isospin analysis

- Consider the simplest case:

  B → ππ / ρρ decays.

$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$$

$$\frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{+0}$$

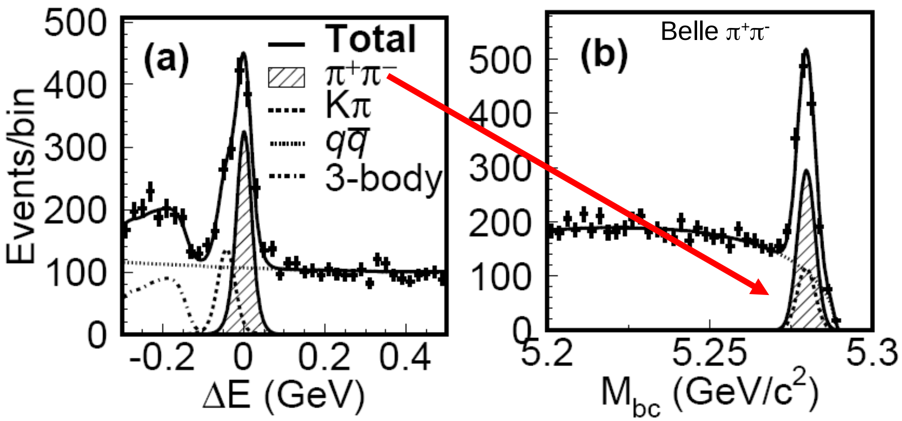


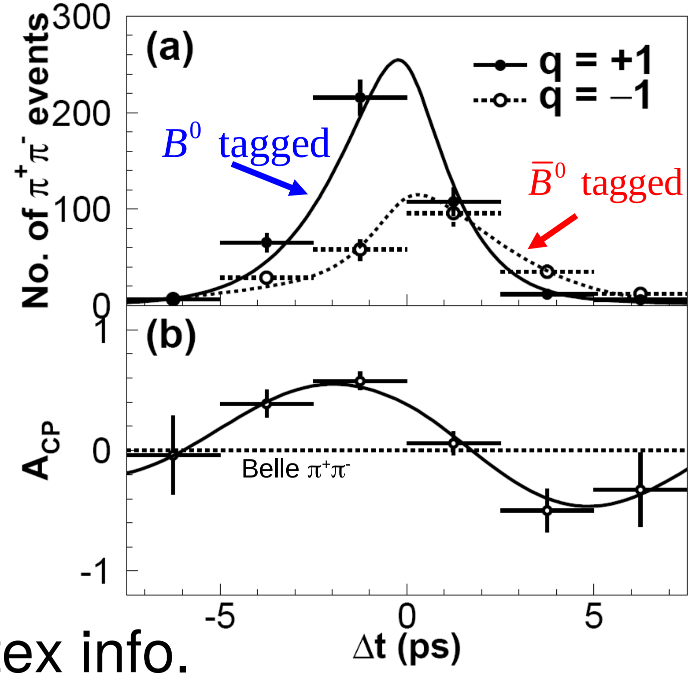
Measuring S in h^0h^0 provides an additional constraint on this angle.

- There are SU(2) violating corrections to consider, for example electroweak penguins (~5%), but these are much smaller than current experimental accuracy and eventually they can be incorporated into the Isospin analysis.

$B \to \pi\pi$

- Easy to isolate signal for $\pi^+\pi^-$ and $\pi^+\pi^0$ as these modes are relatively clean and have relatively large B ~ O(5 $\times 10^{-6}$).

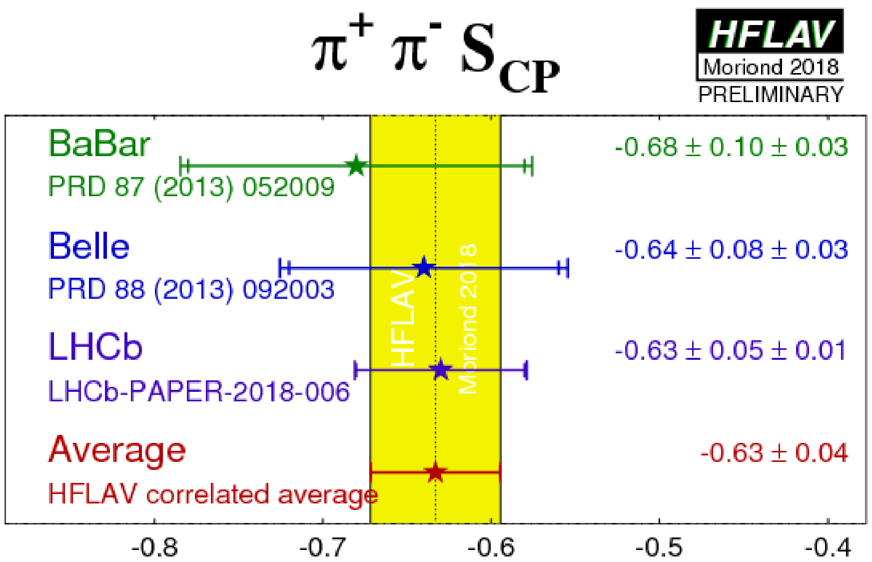


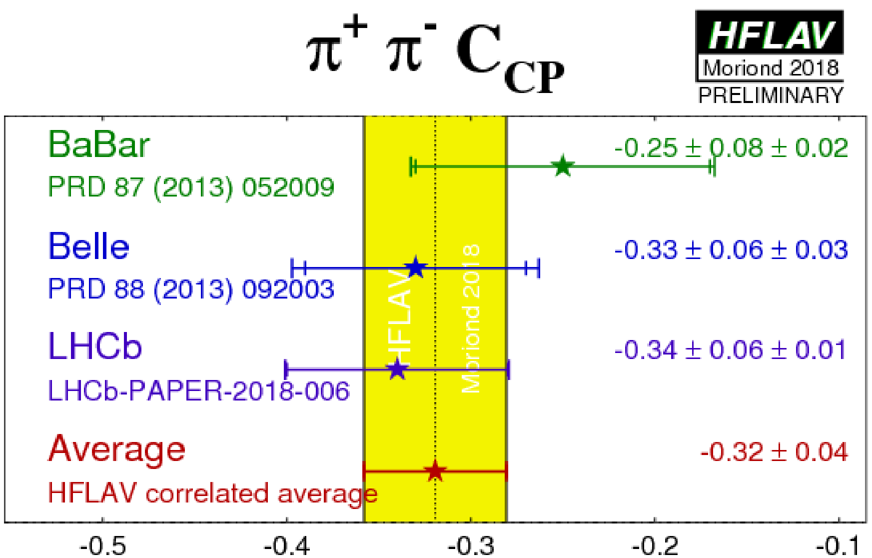


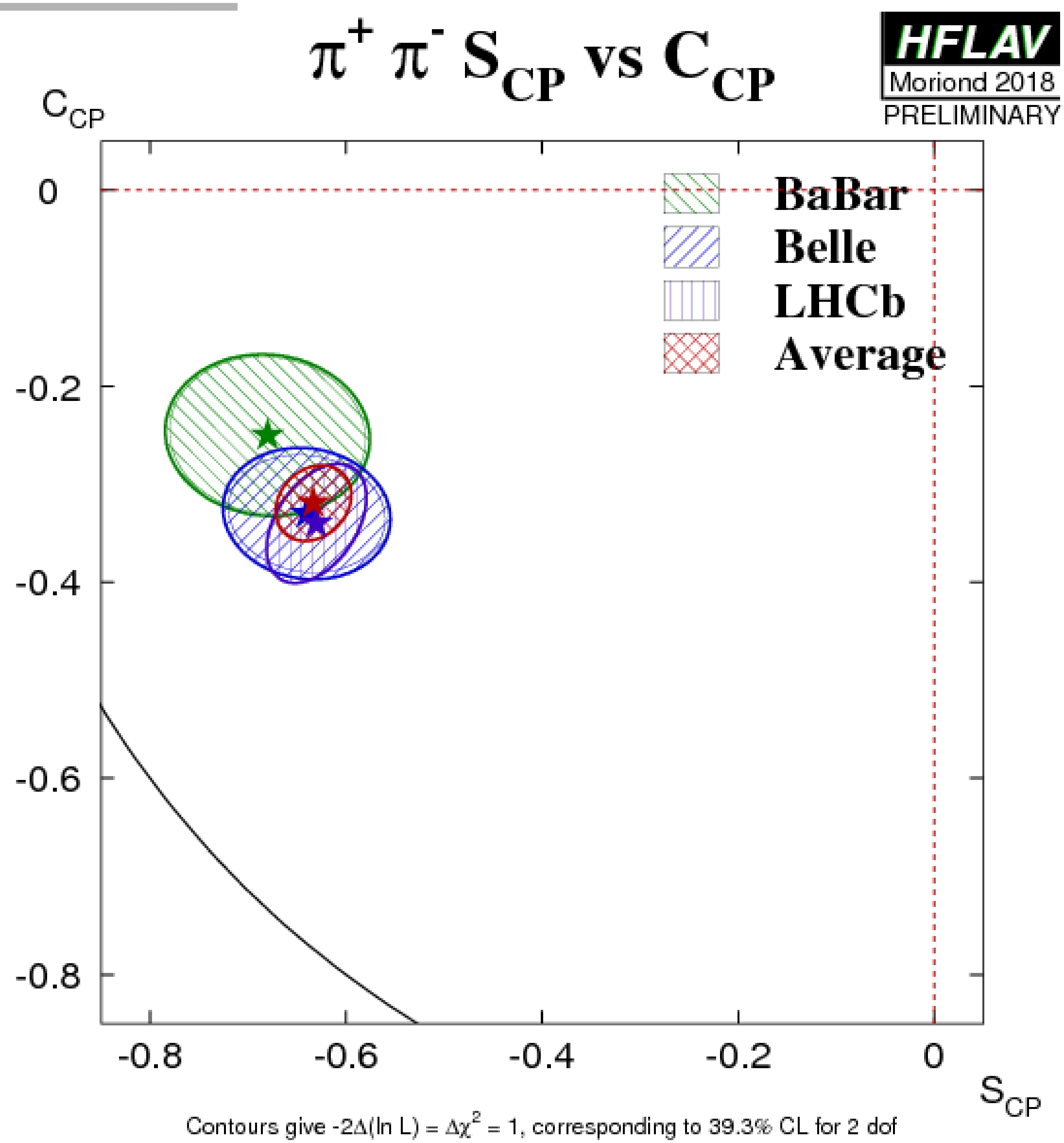
- Much harder to isolate $\pi^0\pi^0$: B ~ 1.5×10^{-6}
  - No tracks in the final state to provide vertex info.
  - $B^0 \to \pi^0\pi^0 \to \gamma\gamma\gamma\gamma$ has a large ΔE resolution.
    - Possible to separate flavour tags to measure C^{00}. This information completes the set of information required for an Isospin analysis.

$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$

$B \to \pi\pi$

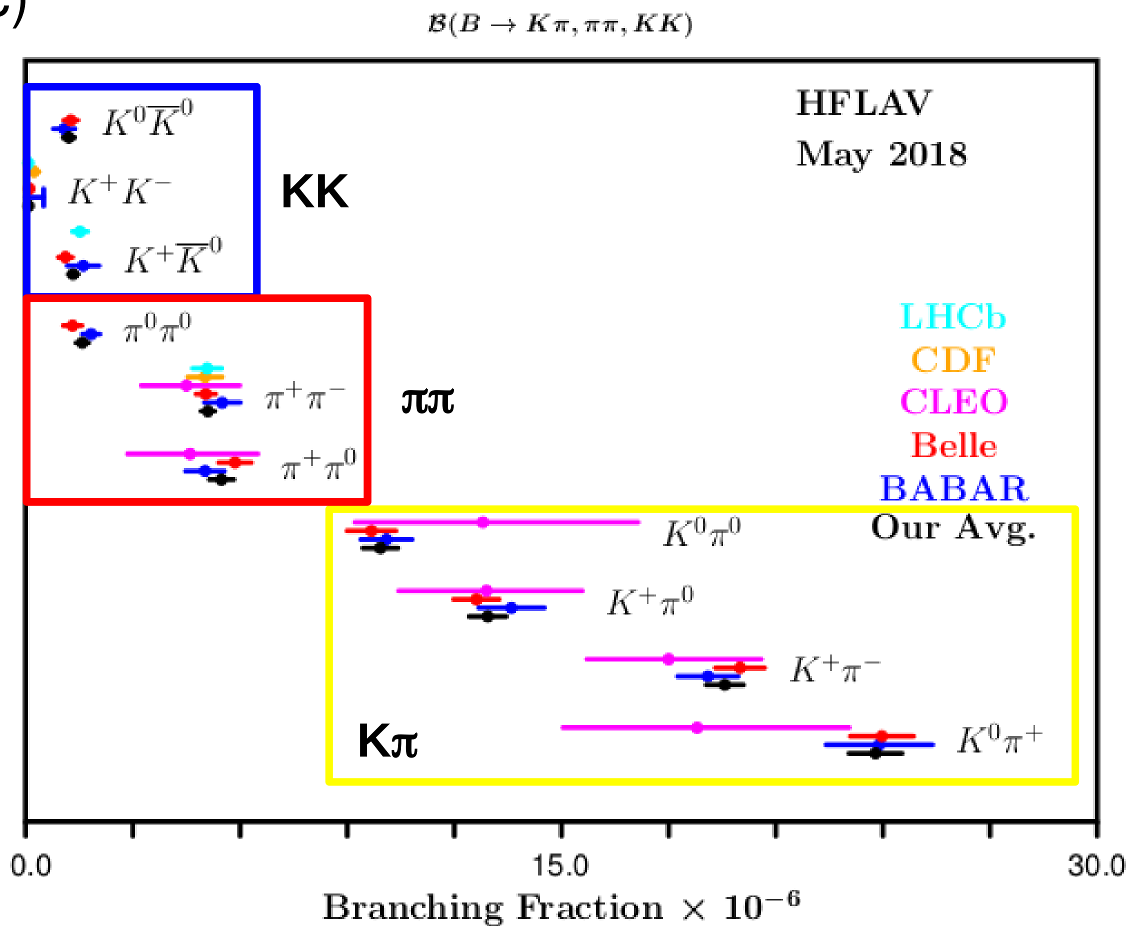






Isospin-related ππ decays

- simultaneous ML fit to all hh modes with h being π or K:
  - $B^+ \to \pi^+\pi^-$, $K^+\pi^-$, K^+K^- (and cc)
  - $B^+ \to \pi^+\pi^0$, $K^+\pi^0$ (and cc)



$\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$

B → ππ

- Inputs from: $B^0 \to \pi^+\pi^-$

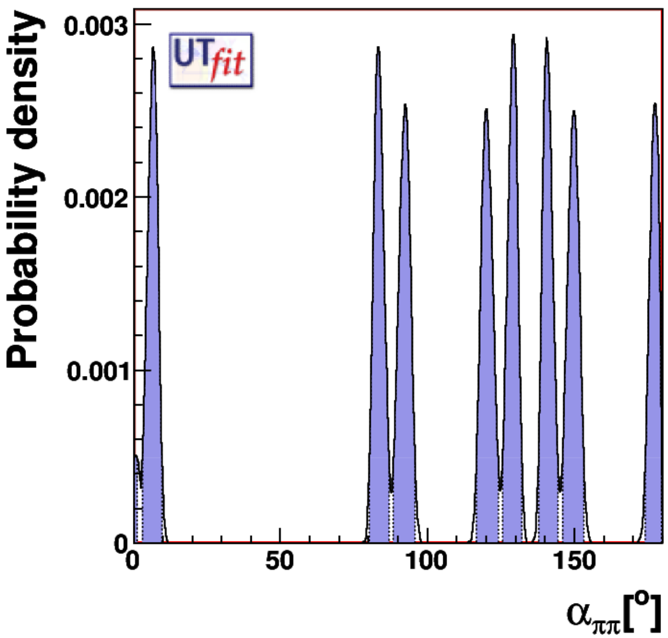
  $B^+ \to \pi^+\pi^0$

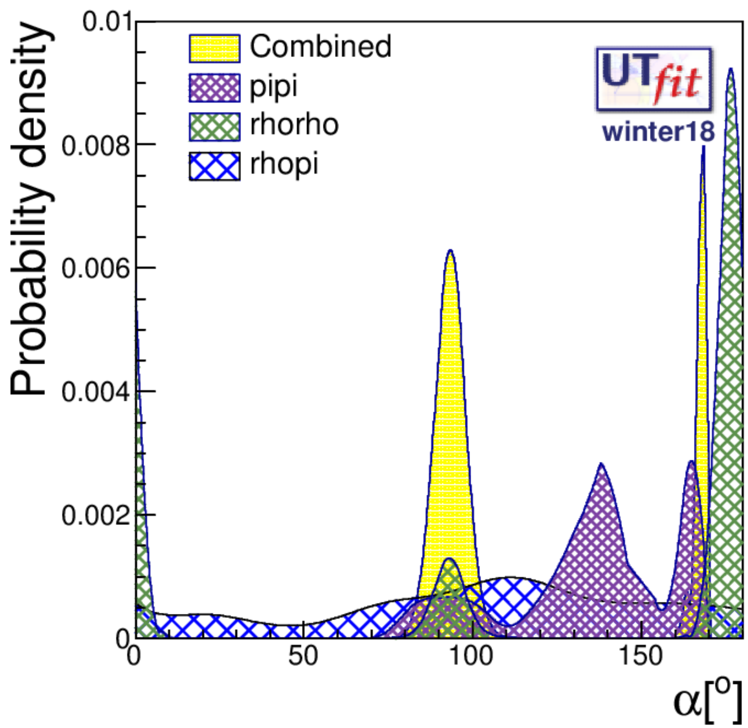
  $B^0 \to \pi^0\pi^0$

additional information can be used: to reduce the degeneracy of the solutions and also to keep the amplitudes to go to infinity (unphysical)

for example Bs to KK (assuming SU(3) and a big uncertainty on that) can put an upper limit on the penguin amplitude

eight solutions to the isospin system: shown here a case with uncertainties reduced of a factor 10





from ππ, ρρ, πρ

combined SM:

α=(93.3 ± 5.6)°

UTfit prediction:

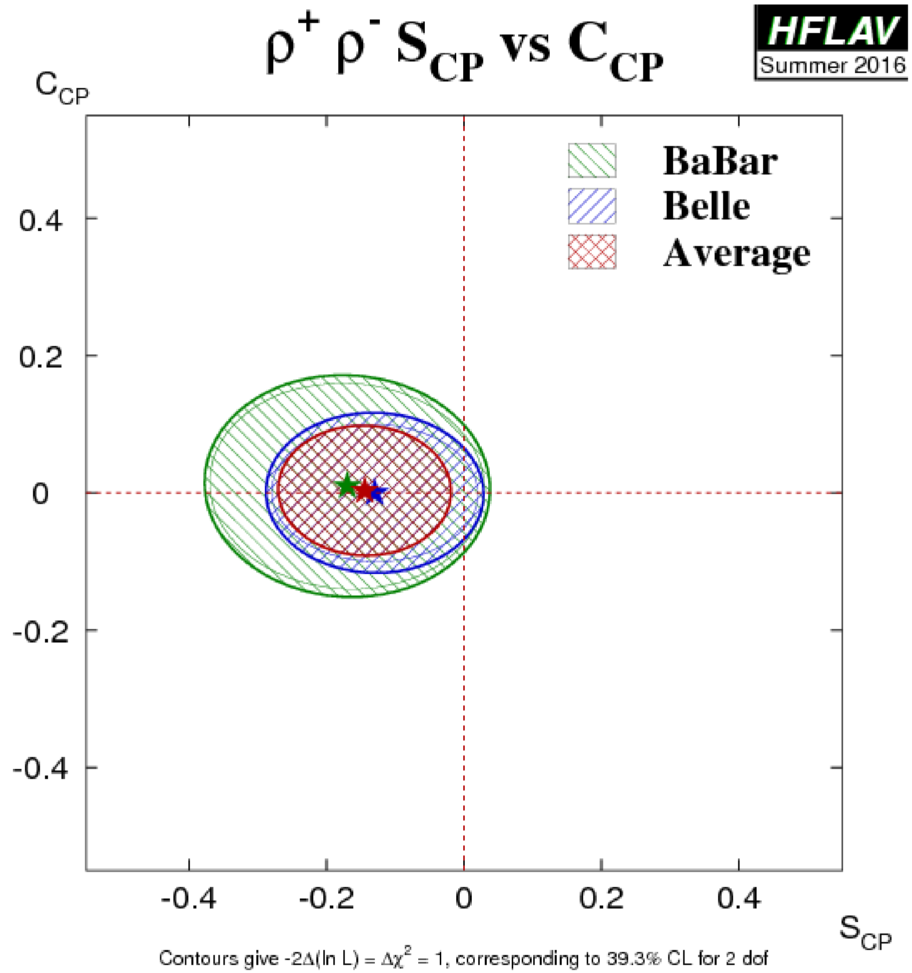
α=(90.1 ± 2.2)°

$B \to \rho\rho$

- Vector-Vector modes: angular analysis required to determine the CP content. L=0,1,2 partial waves:
  - longitudinal: CP-even state
  - transverse: mixed CP states
- +-: two π^0 in the final state
- wide ρ resonance

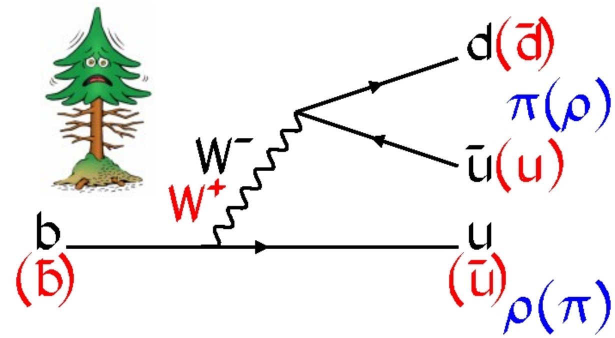
but

- BR 5 times larger with respect to $\pi\pi$
- penguin pollution smaller than in $\pi\pi$
- ρ are almost 100% polarized:
  - almost a pure CP-even state

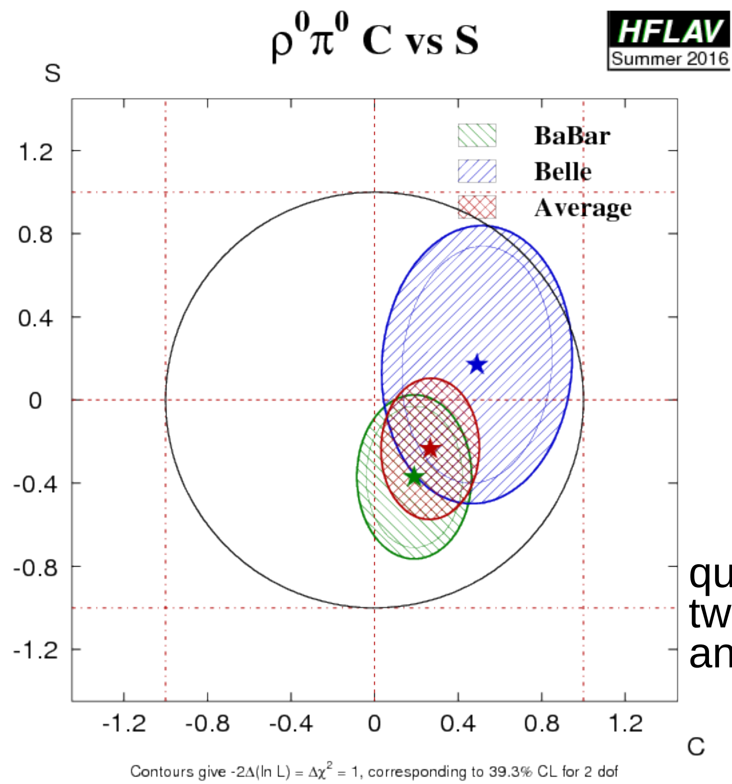


$B \to \rho\pi$ ($\pi^+\pi^-\pi^0$ Dalitz Plot)

- dominant decay $\rho\pi$ is not a CP eigenstate



- 5 amplitudes need to be considered:
  - $B^0 \to \rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ and $B^+ \to \rho^+\pi^0$, $\rho^0\pi^+$
  - Isospin pentagon
- or time-dependent dalitz analysis: α extraction together with the strong phases exploiting the amplitude interference:
  - interference at equal masses-squared give information on the strong phases between resonances



quasi-two-body analysis

$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$$

Extract γ using $B \to D^{(*)}K^{(*)}$ final states using:

- GLW: Use CP eigenstates of D^0.
- ADS: Interference between doubly suppressed decays.
- GGSZ: Use the Dalitz structure of $D \to K_s h^+ h^-$ decays.

Measurements using neutral D mesons ignore D mixing.

$b \to c$ interfering with $b \to u$

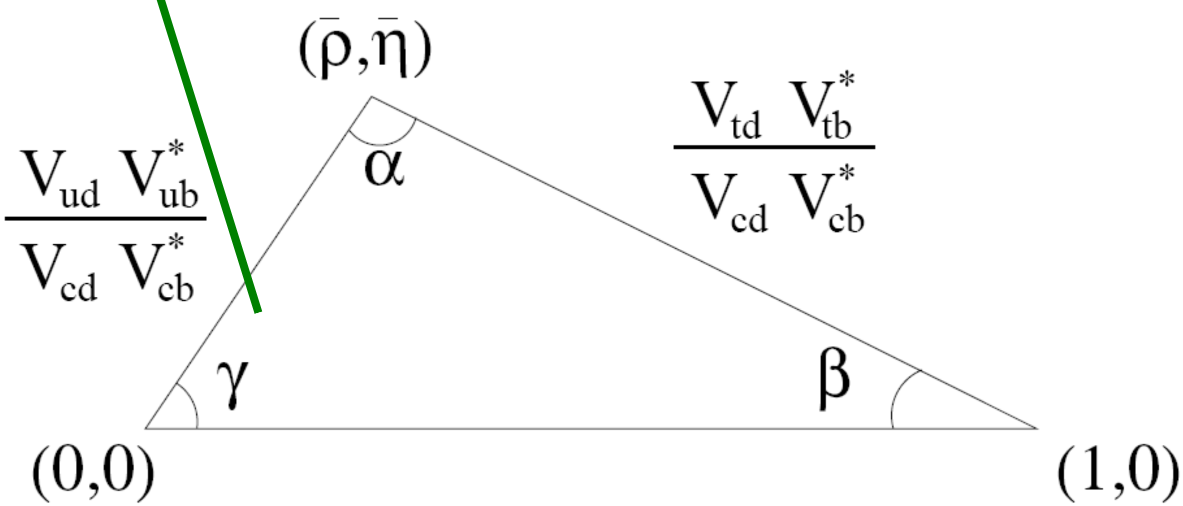
$B \to D^{(*)}K^{(*)}$

$B^0 \to D^- K^0 \pi^+$

$B^0 \to D^{(*)}\pi$

$B^0 \to D^{(*)}\rho$

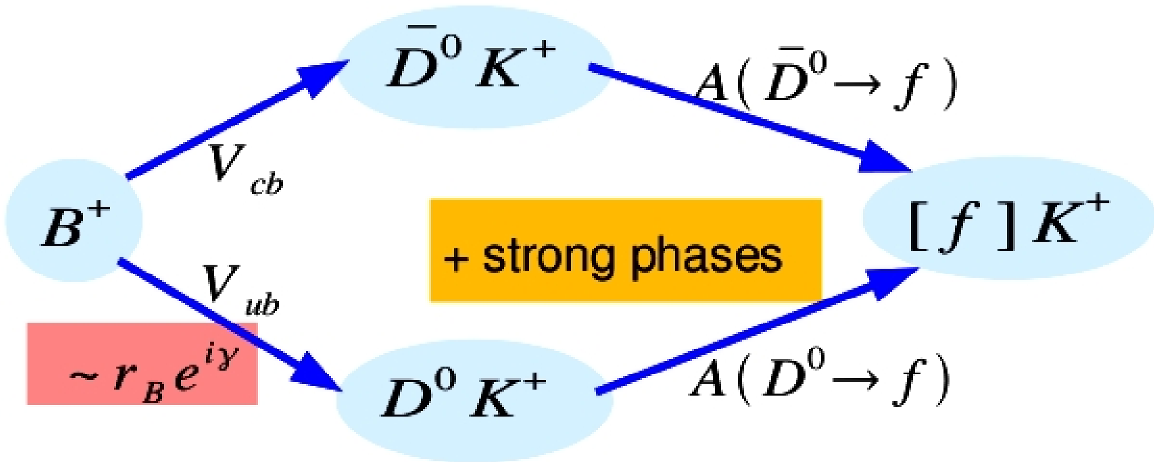
$+$ *charmless*

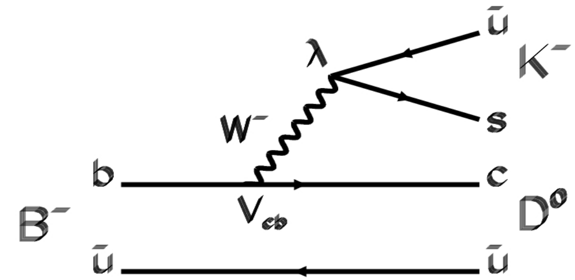


$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$

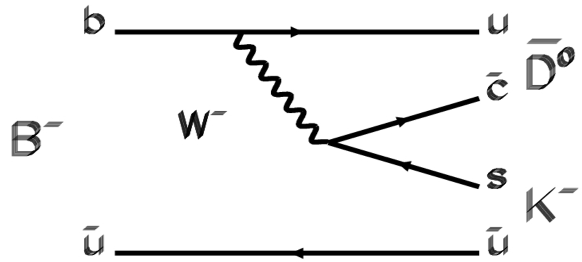
γ and DK trees

- $D^{(*)}K^{(*)}$ decays: from BRs and BR ratios, no time-dependent analysis, just rates
- the phase γ is measured exploiting interferences: two amplitudes leading to the same final states
- some rates can be really small: ~ 10^{-7}





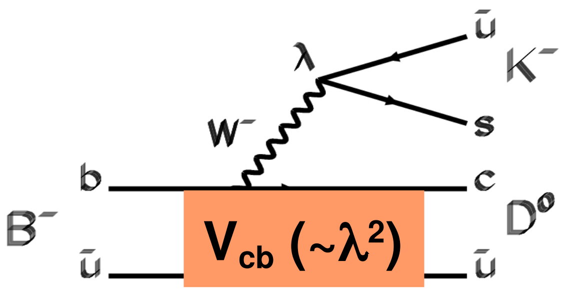
V_{cb} $(\sim\lambda^2)$



$V_{ub}=|V_{ub}|e^{-i\gamma}$ $(\sim\lambda^3)$

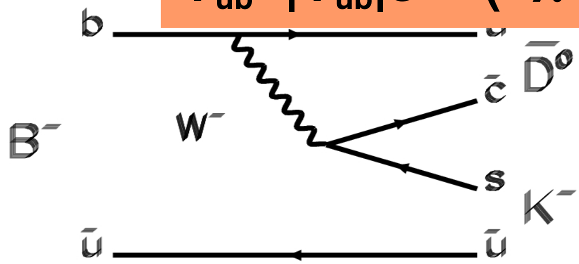
Theoretically clean (no penguins *neglecting the D^0 mixing*)

Sensitivity to γ: the ratio r_B



V_{cb} ($\sim\lambda^2$)

$V_{ub}=|V_{ub}|e^{-i\gamma}$ ($\sim\lambda^3$)



δ_B = strong phase diff.

$$A(B^- \to D^0K^-) = A_B \qquad A(B^- \to \bar{D}^0K^-) = A_B r_B e^{i(\delta_B-\gamma)}$$

$$A(B^+ \to \bar{D}^0K^+) = A_B \qquad A(B^+ \to D^0K^+) = A_B r_B e^{i(\delta_B+\gamma)}$$

r_B = amplitude ratio

$$r_B = \left|\frac{B^- \to \bar{D}^0K^-}{B^- \to D^0K^-}\right| = \sqrt{\bar{\eta}^2+\bar{\rho}^2} \times F_{CS}$$

~0.36

hadronic contribution channel-dependent

- in $B^+ \to D^{(*)0}K^+$: r_B is ~0.1
- to be measured: $r_B(DK)$, $r^*_B(D^*K)$ and $r^s_B(DK^*)$

Three ways to make DK interfere

GLW(*Gronau, London, Wyler*) method:

more sensitive to r_B

uses the CP eigenstates $D^{(*)0}{}_{CP}$ with final states:

K^+K^-, $\pi^+\pi^-$ (CP-even), $K_s\pi^0$ (ω,ϕ) (CP-odd)

$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B \qquad A_{CP\pm} = \frac{\pm 2r_B \sin\gamma \sin\delta_B}{1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B}$$

ADS(*Atwood, Dunietz, Soni*) method: B^0 and $\bar{B}^0$ in the same final state with $D^0 \to K^+\pi^-$ (suppr.) and $\bar{D}^0 \to K^+\pi^-$ (fav.)

$$R_{ADS} = r_B^2 + r_{DCS}^2 + 2r_B r_{DCS} \cos\gamma \cos(\delta_B + \delta_D)$$

the most sensitive way to γ

D^0 Dalitz plot with the decays $B^- \to D^{(*)0}[K_S\pi^+\pi^-]\, K^-$

three free parameters to extract: γ , r_B and δ_B

γ: GLW Method

- GLW Method: Study $B^+ \to D_{CP}^0 X^+$ and $B^+ \to \overline{D} X^+$ + cc ($\overline{D}^0 \to K^+\pi^-$)
- X^+ is a strangeness one meson e.g. a K^+ or K^{*+}.
- D_{CP}^0 is a CP eigenstate (use these to extract γ):

$$D^0_{CP=+1} = K^+K^-, \pi^-\pi^+$$

$$D^0_{CP=-1} = K^0_S\pi^0, K^0_S\omega, K^0_S\phi$$

- 4 observables
- 3 unknowns: r_B, γ and δ

$$R_{CP_\pm} = \frac{BF(B^- \to D^0_\pm K^-) + BF(B^+ \to D^0_\pm K^+)}{BF(B^- \to D^0 K^-) + BF(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos\delta \cos\gamma$$

$$A_{CP_\pm} = \frac{BF(B^- \to D^0_\pm K^-) - BF(B^+ \to D^0_\pm K^+)}{BF(B^- \to D^0_\pm K^-) + BF(B^+ \to D^0_\pm K^+)} = \pm 2 r_B \sin\delta \sin\gamma / R_{CP_\pm}$$

- The precision on γ is strongly dependent on the value of r_B.
  - r_B~0.1 as this is a ratio of Cabibbo suppressed to Cabibbo allowed decays and also includes a colour suppression factor for $B^+ \to D^{(*)}K^{(*)}$ $b \to u$ decays.
- Measurement has an 8-fold ambiguity on γ.

Gronau, London, Wyler, PLB253 p483 (1991).

$\gamma \equiv \arg\left[-V_{\rm ud}V_{\rm ub}^*/V_{\rm cd}V_{\rm cb}^*\right]$

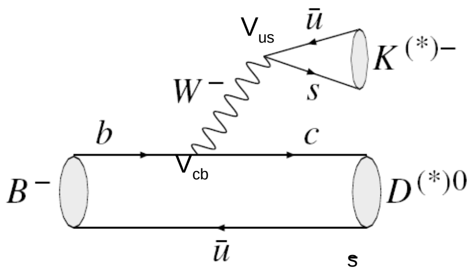
γ: ADS Method

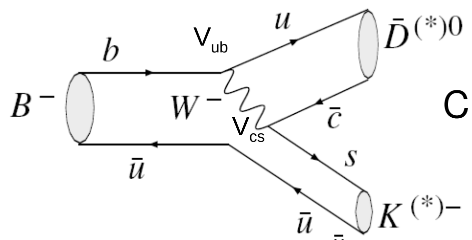
Attwood, Dunietz, Soni, PRL **78** 3257 (1997)

- ADS Method: Study $B^{\pm,0} \to D^{(*)0}\,K^{(*)\pm}$
- Reconstruct doubly suppressed decays with common final states and extract γ through interference between these amplitudes:

$B^- \to D^{(*)0}\,K^{(*)-}$

CKM Favoured



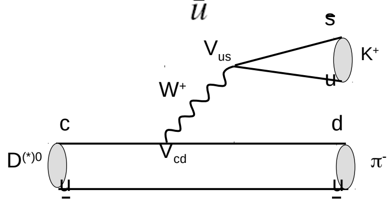


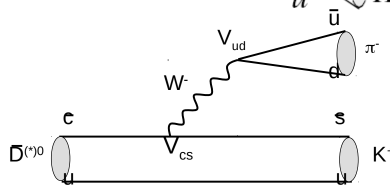
$B^- \to \overline{D}^{(*)0}\,K^{(*)-}$

CKM and Color Suppressed

$D^{(*)0} \to K^+\pi^-$

Doubly CKM Suppressed





$\overline{D}^{(*)0} \to K^+\pi^-$

CKM Favoured

- γ extracted using ratios of rates:

$$r_B^{(*)} = \left|\frac{A(B^- \to \overline{D}^{(*)0}K^-)}{A(B^- \to D^{(*)0}K^-)}\right|$$

$$r_D = \left|\frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)}\right|$$

◎ $\delta^{(*)} = \delta^{(*)}_B + \delta_D$

◎ $\delta^{(*)}$ is the sum of strong phase differences between the two B and D decay amplitudes.

◎ r_D and r_B are measured in B and charm factories.

◎ δ_D is measured by CLEO-c

γ: GGSZ Method

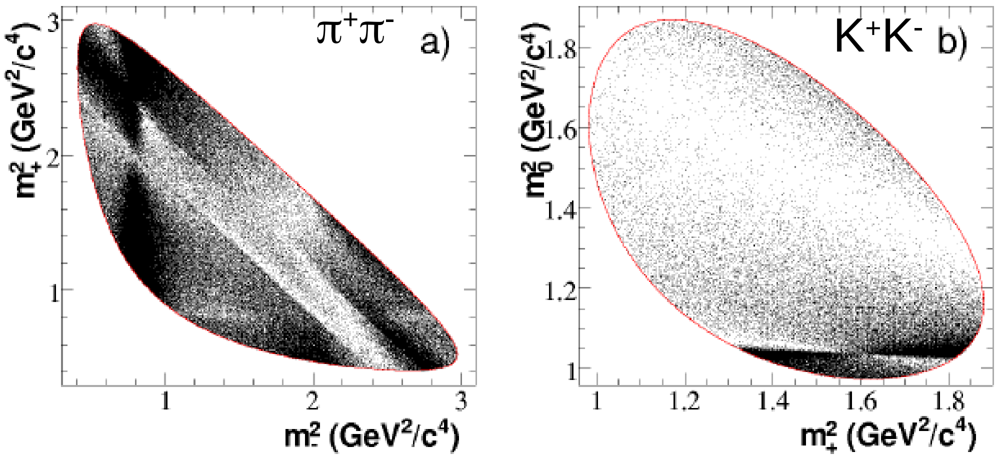
- GGSZ ("Dalitz") Method: Study $D^{(*)0}K^{(*)}$ using the $D^{(*)0} \to K_s h^+ h^-$ Dalitz structure to constrain γ. (h = π, K)
  - Self tagging: use charge for $B^\pm$ decays or $K^{(*)}$ flavour for B^0 mesons.

$$A(B^\pm \to (K_S^0 h^+ h^-)_D K^\pm) \propto f(m_+^2, m_-^2) + f(m_-^2, m_+^2) r_B e^{i(\delta_B \pm \gamma)}$$

where $m_\pm = m_{K_S^0 h^\pm}$

  - Need detailed model of the amplitudes in the D meson Dalitz plot.
    - Use a control sample (CLEO-c data or $D^{*+} \to D^0 \pi^+$) to measure the Dalitz plot.

$$D^{*+} \to D^0 \pi^-$$
$$\hookrightarrow D^0 \to K_S^0 h^+ h^-$$

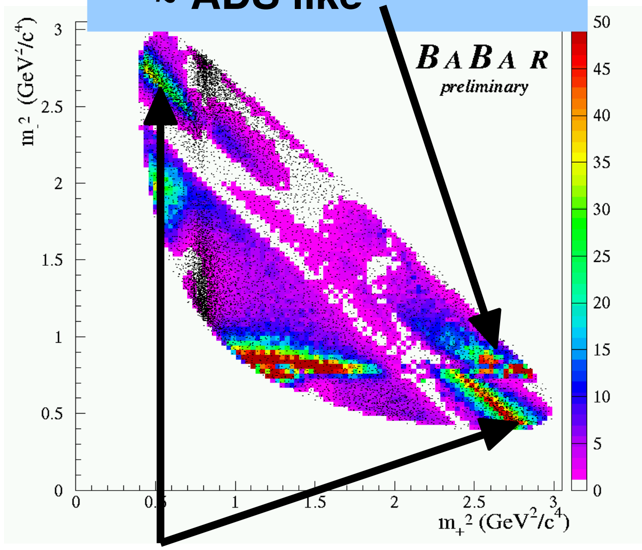


Control sample plots from BaBar GGSZ paper

γ: GGSZ Method

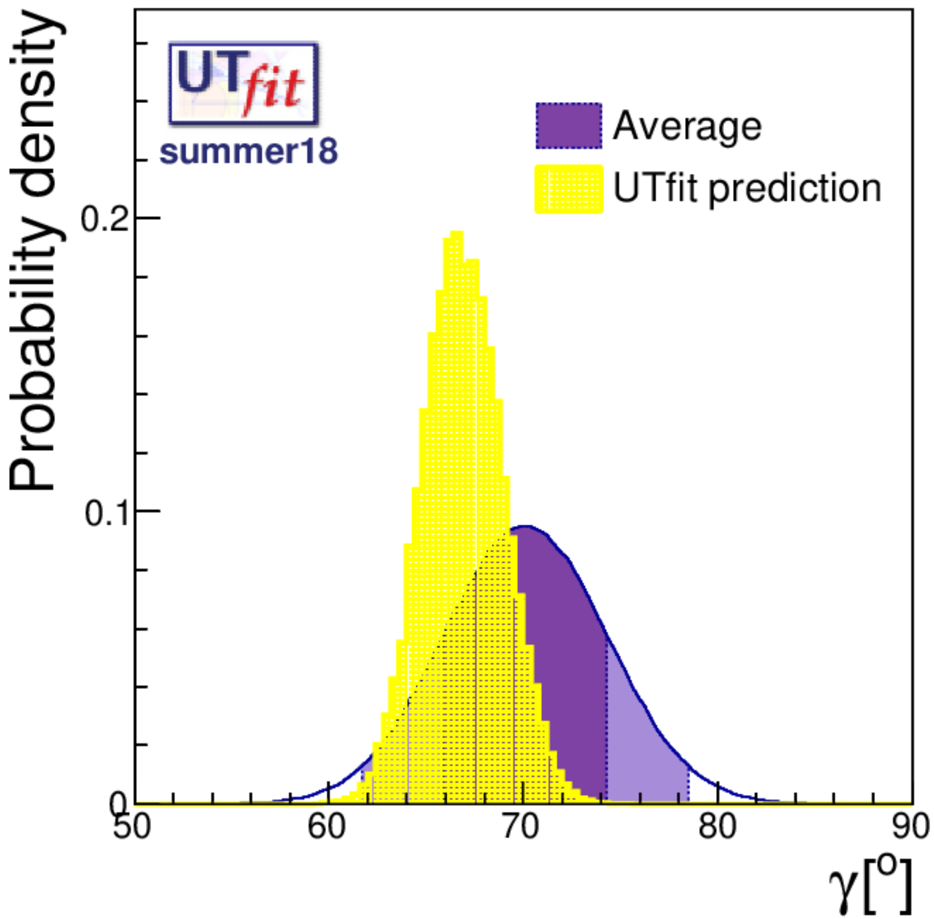
- neutral D mesons reconstructed in three-body CP-eigenstate final states (typically $D^0 \rightarrow K_S\pi^-\pi^+$)
- the complete structure (amplitude and strong phases) of the D^0 decay in the phase space is obtained on independent data sets and used as input to the analysis
- use of the cartesian coordinate:
  - $x_\pm = r_B \cos(\delta \pm \gamma)$
  - $y_\pm = r_B \sin(\delta \pm \gamma)$
- γ, r_B and δ_B are obtained from a simultaneous fit of the $K_S\pi^+\pi^-$ Dalitz plot density for B^+ and B^-
- need a model for the Dalitz amplitudes
- 2-fold ambiguity on γ

Interference of
$B^- \rightarrow D^0K^-$, $D^0 \rightarrow K^{*+}\pi^-$ (suppressed) with
$B^- \rightarrow \bar{D}^0K^-$, $\bar{D}^0 \rightarrow K^{*+}\pi^-$
~ ADS like



Interference of
$B^- \rightarrow D^0K^-$, $D^0 \rightarrow K^0_S\rho^0$ with
$B^- \rightarrow \bar{D}^0K^-$, $\bar{D}^0 \rightarrow K^0_S\rho^0$
~ GLW like

CP violation: γ



γ from B into DK decays:

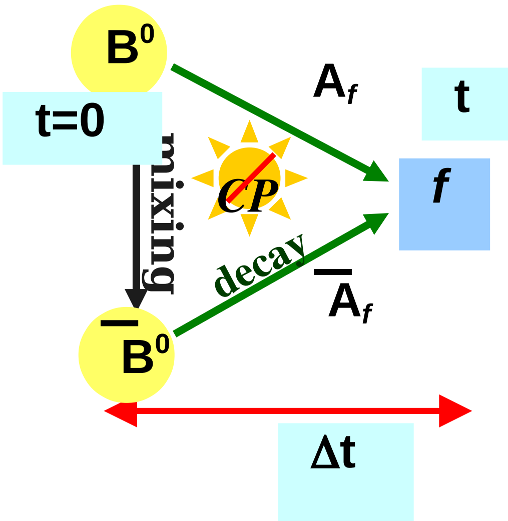
combined: $(73.4 \pm 4.4)°$

UTfit prediction: $(65.8 \pm 2.2)°$

back-up

CP violation in interference between mixing and decay:

$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$



- ◎ decays in final state *f* accessible to both a B or a $\bar{B}$ (*f* is not necessarily a CP eigenstate)
- ◎ if Im$\lambda \neq 0$ then → CP violation

$$\lambda = \frac{q}{p}\frac{A(\bar{B}\to f)}{A(B\to f)} = \frac{V_{td}^* V_{tb}}{V_{td} V_{tb}^*}\frac{\bar{A}}{A} \sim e^{-i2\beta}\frac{\bar{A}}{A}$$

β is the mixing phase

examples

	f	$\mathrm{Arg}(\frac{\bar{A}}{A})$	$\lvert\lambda\rvert$	parameter
mixing	$B^0 \to l\nu X, D^{(*)}\pi(\rho, a_1)$	0	~ 0	ΔM_{B^0}
"sin 2β"	$B^0 \to J/\psi K^0, \ldots$	0	1	$\sin 2\beta$
"sin 2α"	$B^0 \to \pi\pi, \rho\pi, \pi\pi\pi$	$\sim(-2\gamma)$	~ 1	$\sin 2\alpha$
"$\sin(2\beta+\gamma)$"	$B^0 \to D^{(*)}\pi$	$\sim(-\gamma)$	~ 0.02	$\sin(2\beta+\gamma)$

$B\bar{B}$ pair coherent production

◎ The B^0 and $\bar{B}^0$ mesons from the Υ(4S) are in a coherent L = 1 state:

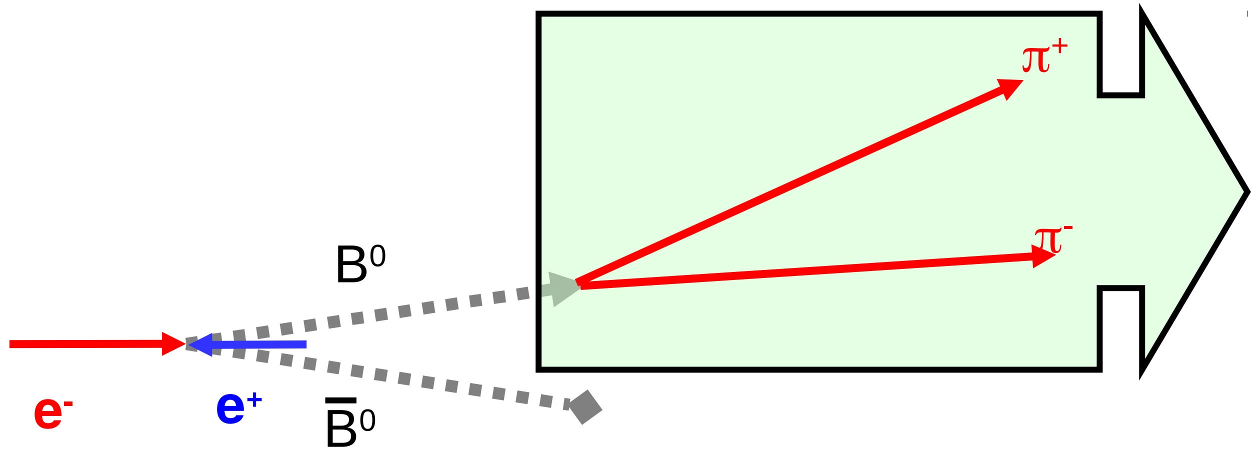
- ◉ The Υ(4S) is a $b\bar{b}$ state with **$J^{PC} = 1^{--}$**.
- ◉ B mesons are scalars (**$J^P = 0^-$**)
  - ⇨ total angular momentum conservation
  - ⇨ the $B\bar{B}$ pair has to be produced in a L = **1 state**.

◎ The Υ(4S) decays strongly so B mesons are produced in the two flavour eigenstates B^0 and $\bar{B}^0$:

- ◉ After production, each B evolves in time, but **in phase** so that at any time there is always exactly one B^0 and one $\bar{B}^0$ present, at least until one particle decays:
  - ⇨ If at a given time t one B could oscillate independently from the other, they could become a state made up of two identical mesons: but the L = 1 state is anti-symmetric, while a system of **two identical mesons (bosons!)** must be completely symmetric for the two particle exchange.

◎ Once one B decays the other continues to evolve, and so it is possible to have events with **two B or two $\bar{B}$ decays**.

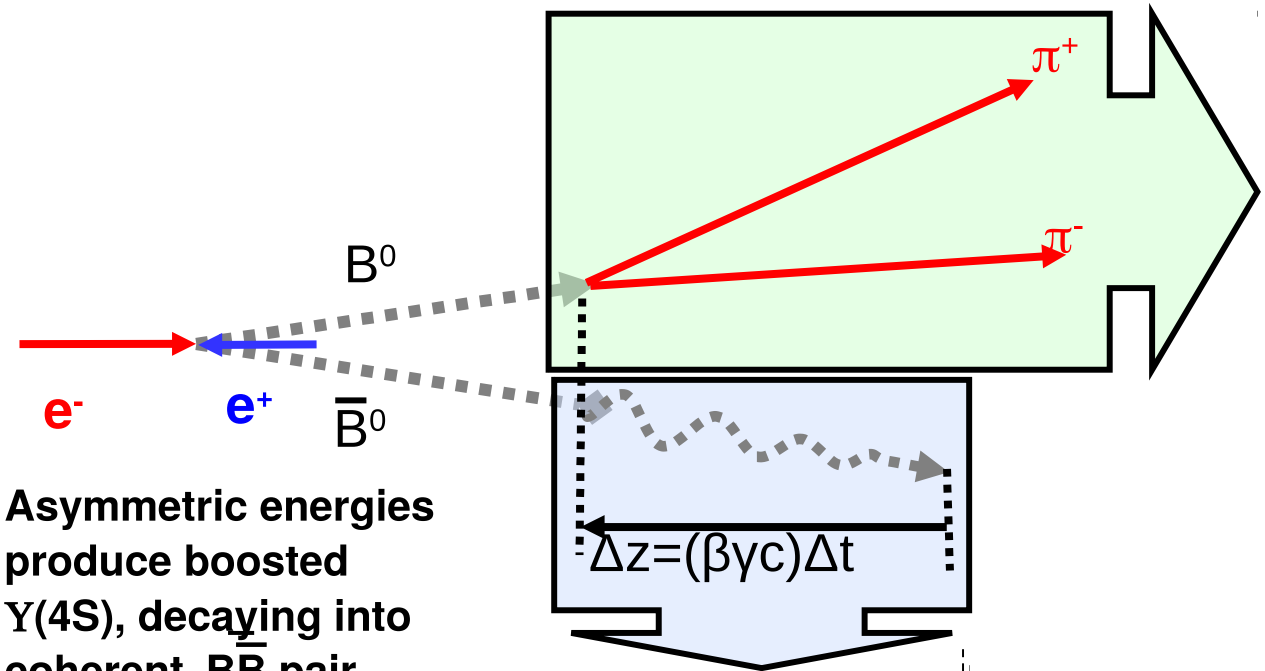
Measuring Δt



Fully reconstruct decay to state or admixture under study (B_{RECO})

Asymmetric energies produce boosted $\Upsilon(4S)$, decaying into coherent $B\bar{B}$ pair

Measuring Δt



Fully reconstruct decay to state or admixture under study (B_{RECO})

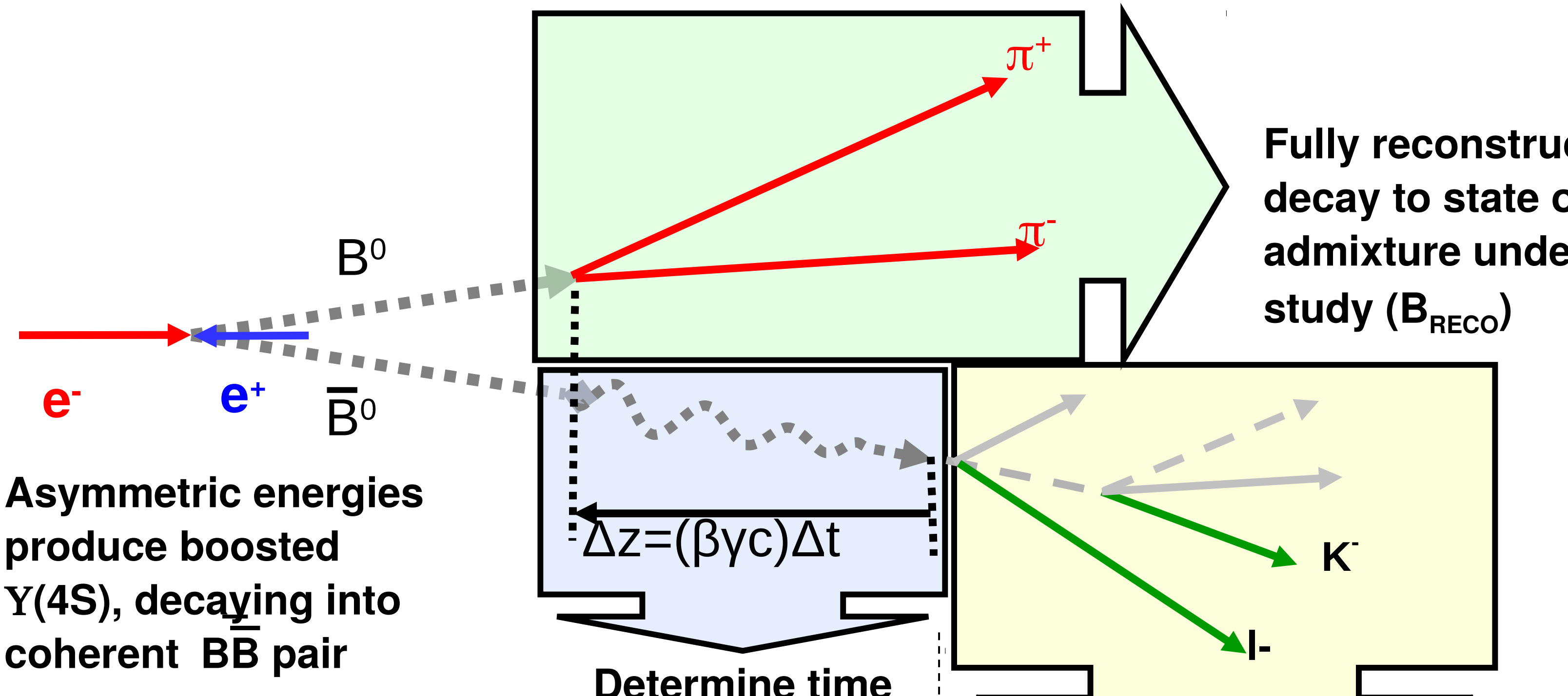
Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair

Determine time between decays from vertices

$t=t_2$ $t=t_1$

- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2-t_1= \Delta t$

Measuring Δt



Determine time between decays from vertices

Determine flavour and vertex position of other B decay (B_{TAG})

$t=t_2$ $t=t_1$

- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

⇨ Then fit the Δt distribution to obtain the amplitude of sine and cosine terms.

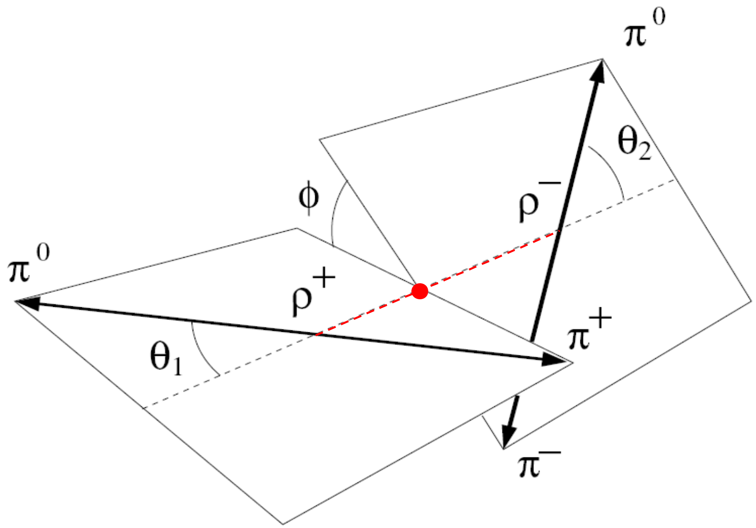
B → ρρ

- (simplified) angular analysis
- Inputs from:

$B^0 \to \rho^+\rho^-$

$B^+ \to \rho^+\rho^0$

$B^0 \to \rho^0\rho^0$



θ_i are the helicity angles: angles between the π^0 momentum and the direction opposite to that of the B^0 in the vector rest frame.

ϕ is the angle between the vector meson decay planes.

- We define the fraction of longitudinally polarised events as:

$$\frac{\Gamma_L}{\Gamma} = \frac{|H_0|^2}{|H_0|^2+|H_{+1}|^2+|H_{-1}|^2}, = f_L.$$

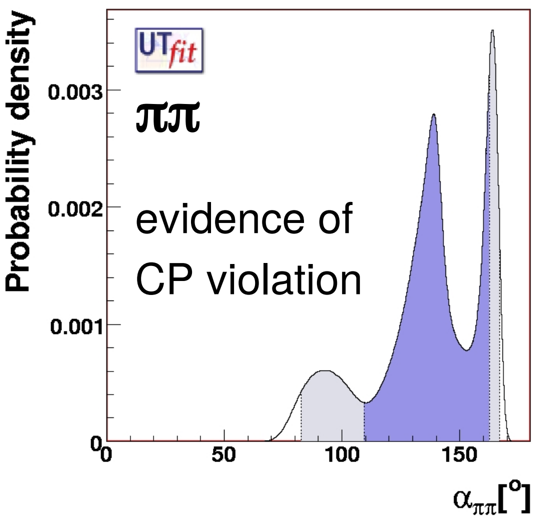
$$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left[f_L\cos^2\theta_1\cos^2\theta_2 + \frac{1}{4}(1-f_L)\sin^2\theta_1\sin^2\theta_2\right]$$

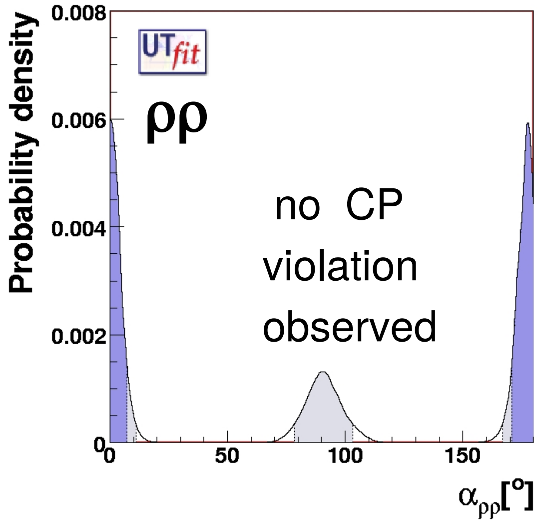
- fL ~ 1 for B → ρρ decays: this helps simplify extracting α.
- Can measure S^{00} as well as C^{00} to help resolve ambiguities.
- Finite width of the ρ is ignored in the α determination

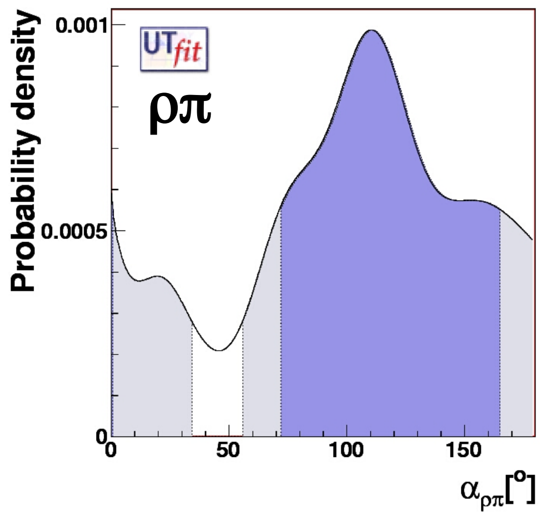
$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$

CP violation: α

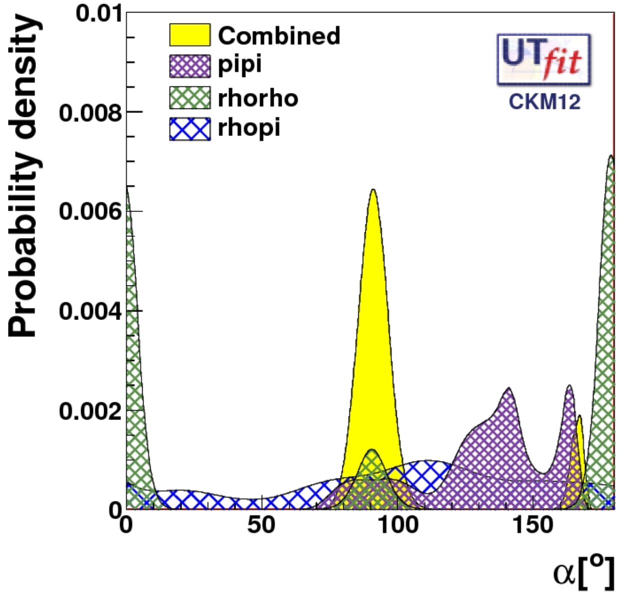
◎ Combining all the modes to maximize our knowledge of α..







bayesian analysis:
the quantity plotted is
now the Probability
Density Function (PDF)

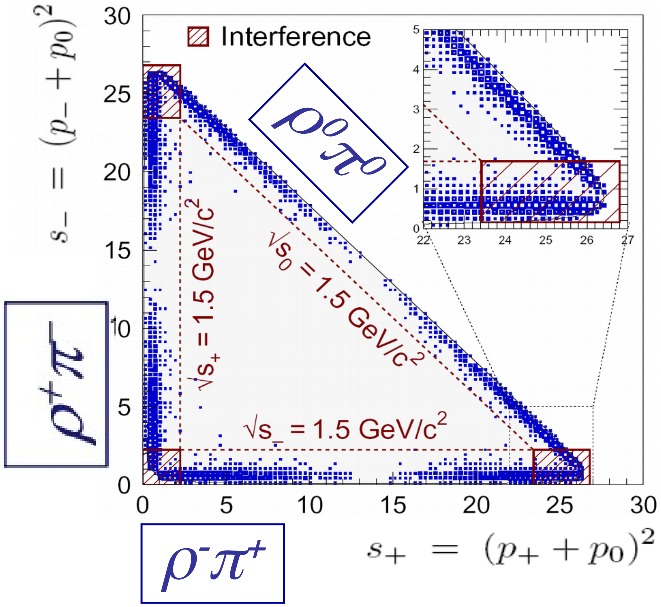


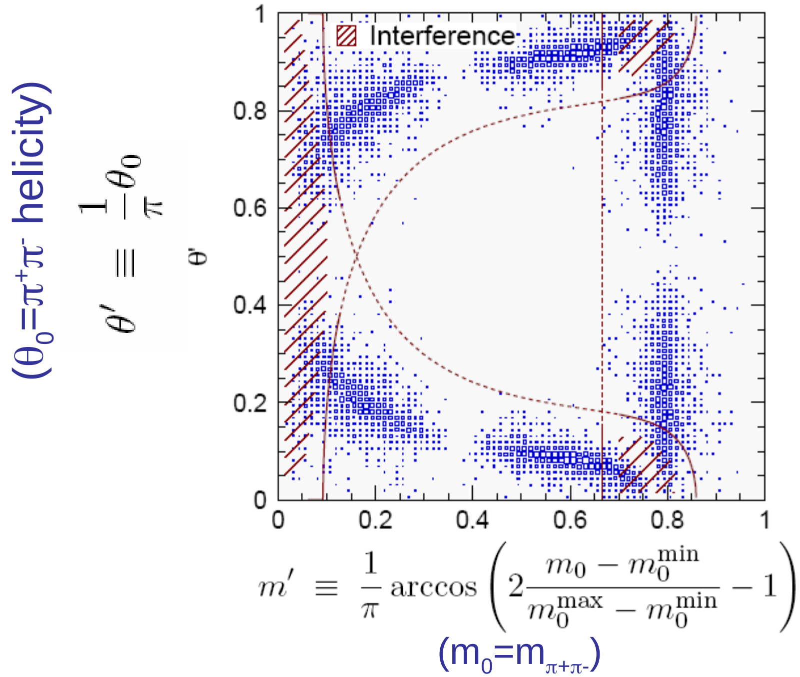
α_{SM} = (92 ± 7)°

$\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$

$B \to \rho\pi$ ($\pi^+\pi^-\pi^0$ Dalitz Plot)

- Analyse a transformed Dalitz Plot to extract parameters related to α.
- Use the Snyder-Quinn method.





- Fit the time-dependence of the amplitudes in the Dalitz plot:

$$|\mathcal{A}_{3\pi}^{\pm}(\Delta t)|^2 = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big[|\mathcal{A}_{3\pi}|^2 + |\overline{\mathcal{A}}_{3\pi}|^2 \mp \left(|\mathcal{A}_{3\pi}|^2 - |\overline{\mathcal{A}}_{3\pi}|^2\right)\cos(\Delta m_d \Delta t)$$
$$\pm 2\mathrm{Im}\left[\overline{\mathcal{A}}_{3\pi}\mathcal{A}_{3\pi}^*\right]\sin(\Delta m_d \Delta t)\Big] ,$$