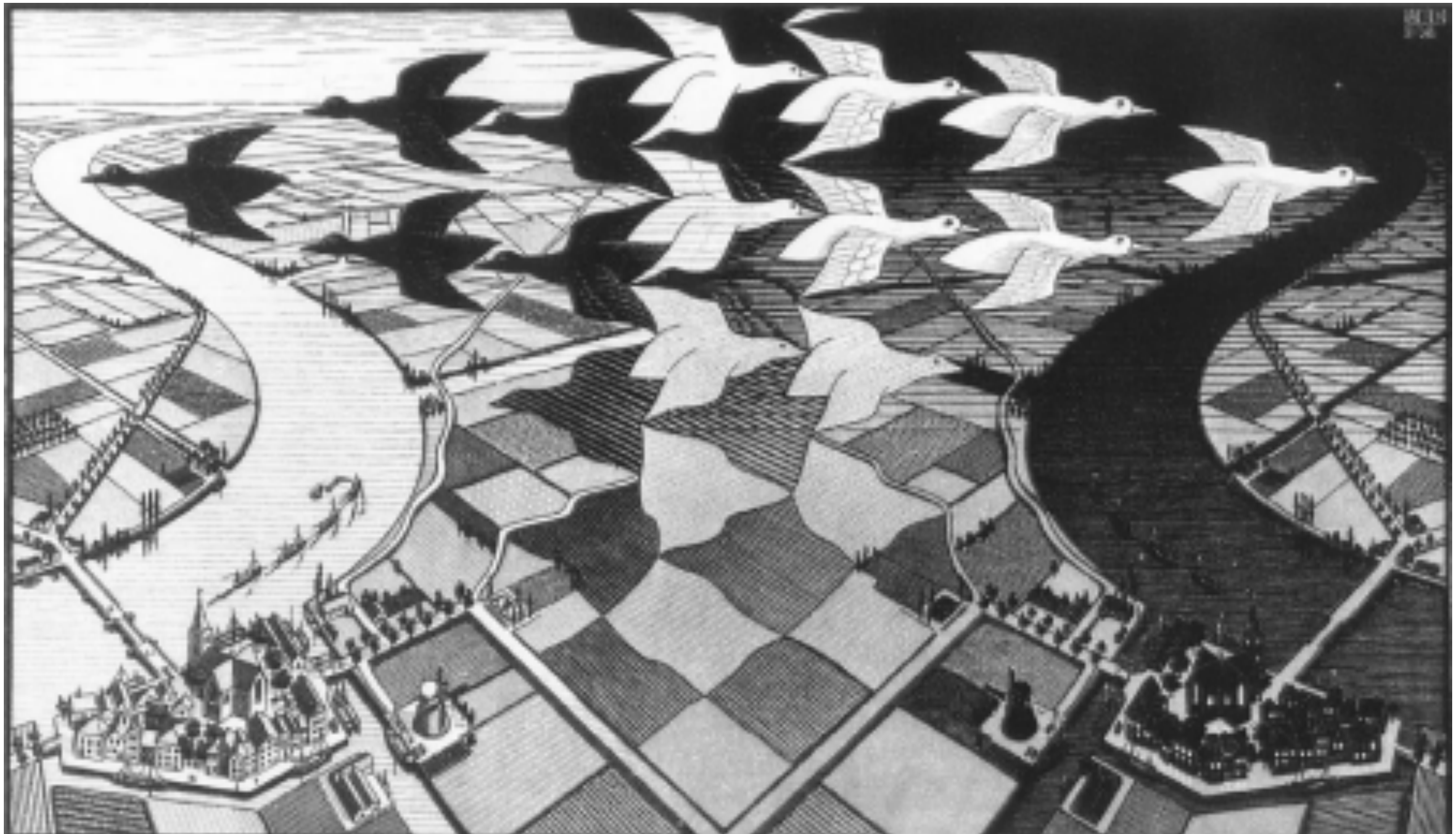
CP Violation

-- Lecture 6 --



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Summary of Lecture 5

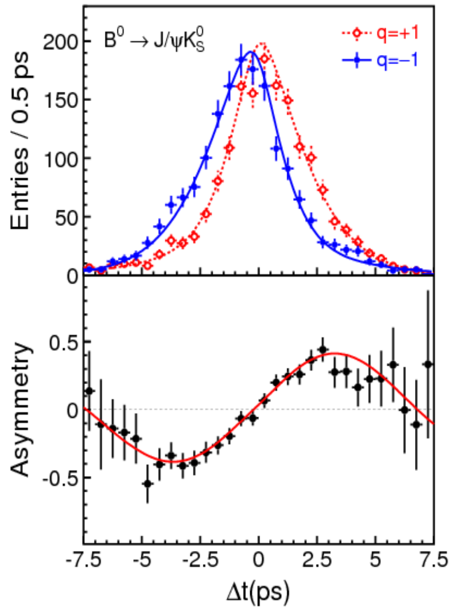
- Carter and Sanda establishes conditions on M_t, $|V_{cb}|$ and $|V_{ub}|$ for producing measureable CP violating asymmetries in B meson decays.

- Experiments at DESY, SLAC and Cornell show that the Carter-Sanda conditions are met

- Experiments at KEK (Belle) and SLAC (BaBar) were designed to test the KM predictions for large, mixing-induced CP violation asymmetries in $B^0 \rightarrow K_S J/\psi$ and $K_L J/\psi$ decays

- Both experiments found CP violating asymmetries similar to the Carter-Sanda-Bigi KM-model-based predictions

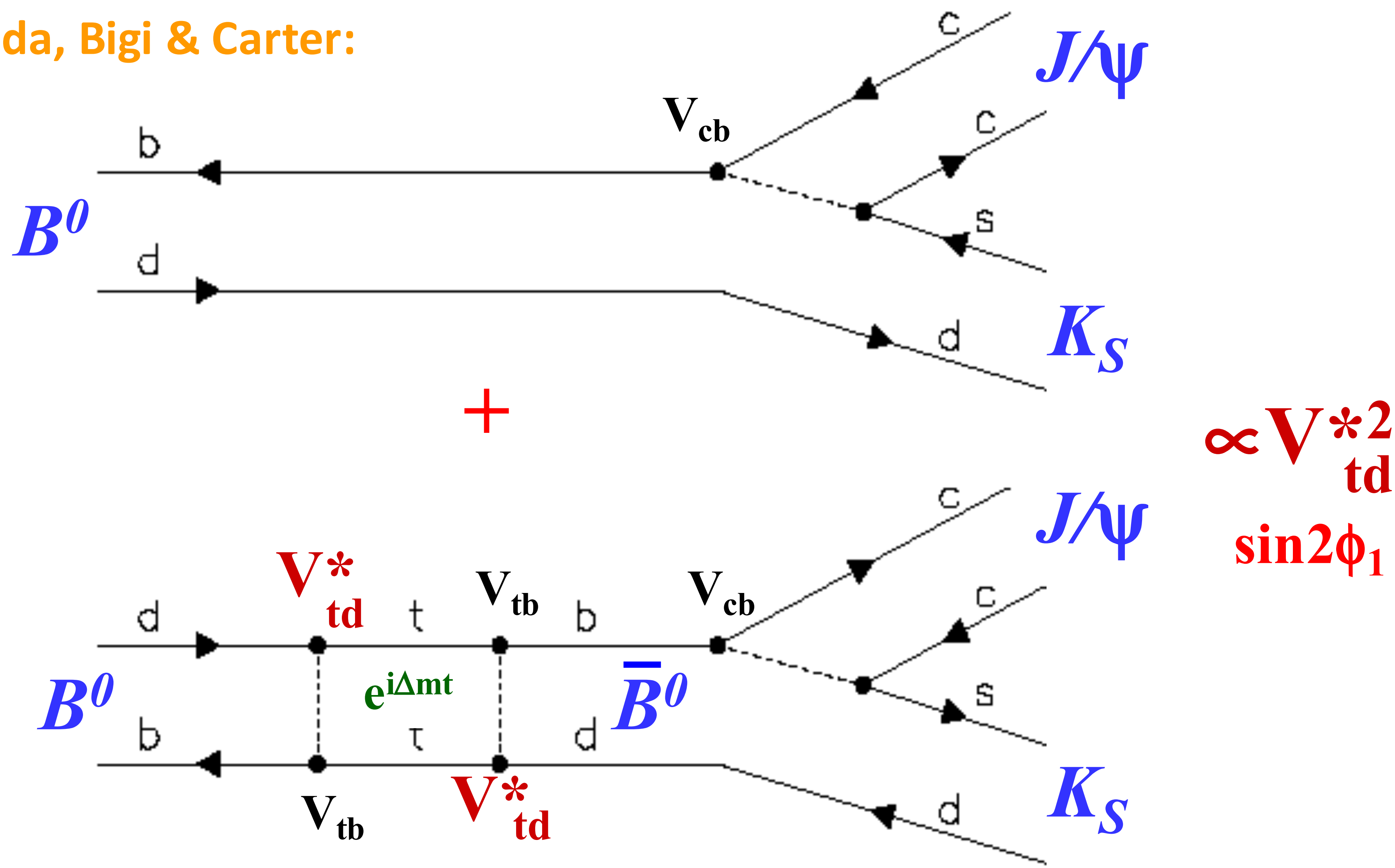
- Unlike the K meson system, where the observed CP violating effects are small, the CP violating effects in B meson decay are large, near their maximum possible values ($\sin 2\phi_1 \approx 0.68$ *vs* a maximum possible value of 1).



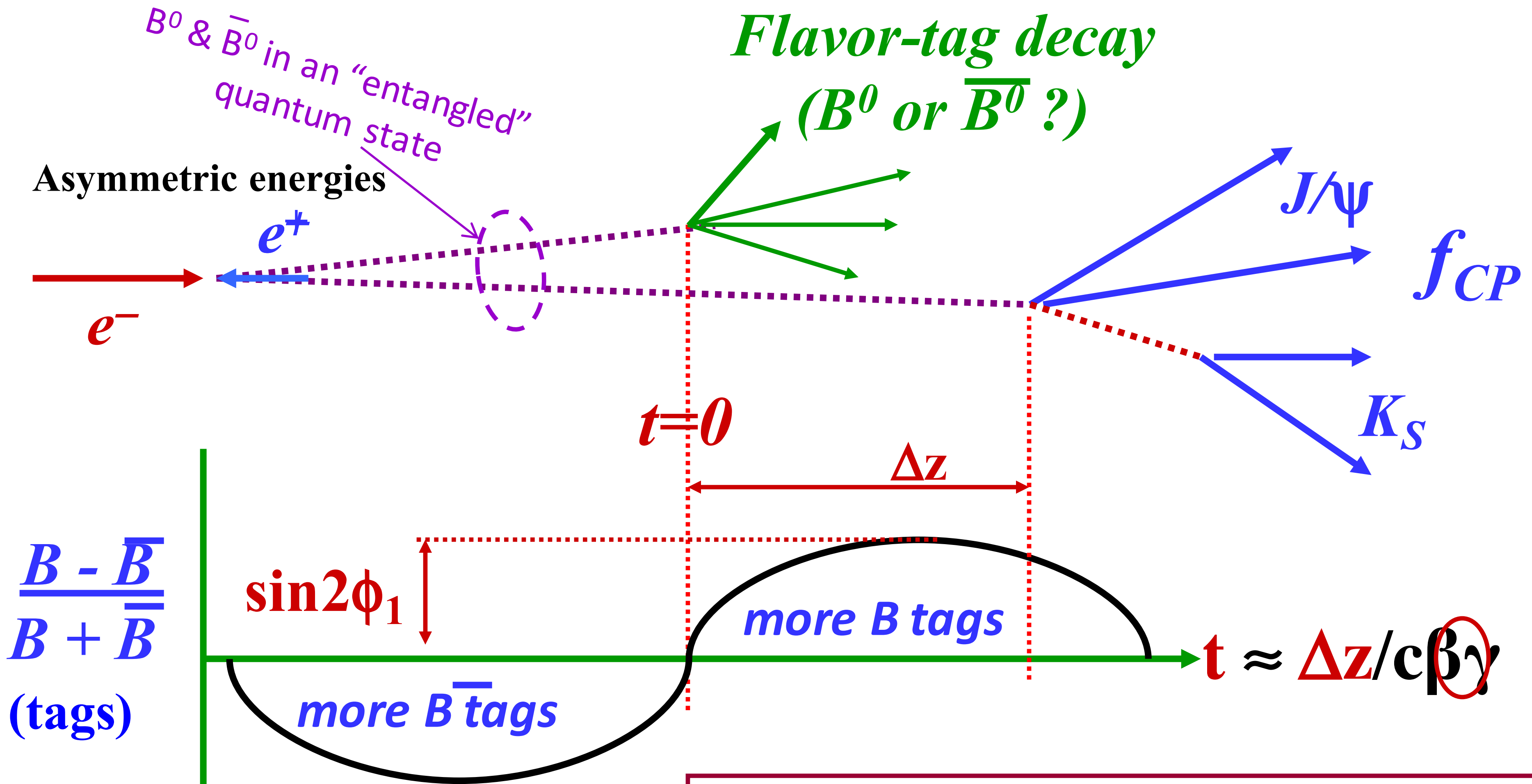
Questions about Belle/BaBar CP asymmetries

Interfere $B \rightarrow f_{CP}$ with $B \leftrightarrow \overline{B} \rightarrow f_{CP}$

Sanda, Bigi & Carter:



What do we measure?

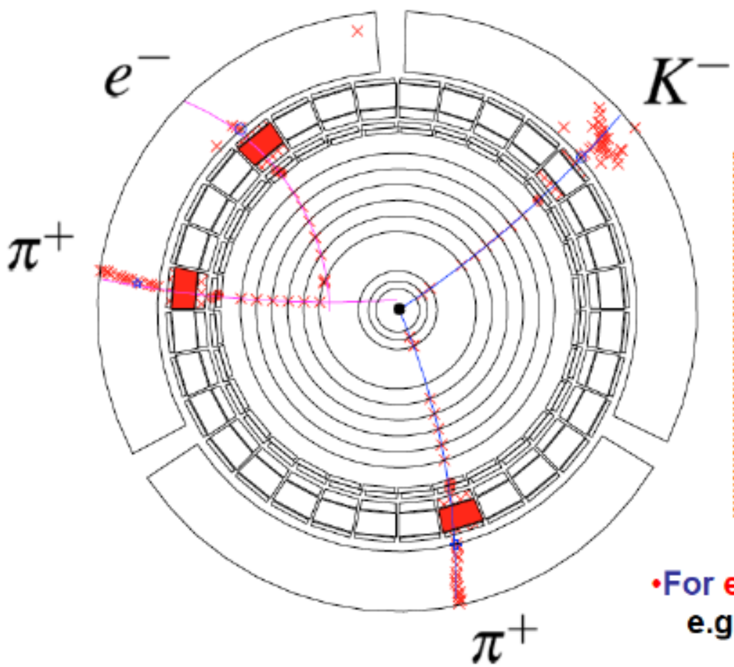


This is for CP=-1; for CP=+1, the asymmetry is opposite

We have been here before

Strangeness-tagging at CPLEAR

An example of a CPLEAR event



$K^-(s\bar{u})$
$K^0(d\bar{s})$
$\overline{K}^0(s\bar{d})$

Production:

$$\bar{p}p \rightarrow \boxed{K^-\pi^+} K^0$$

Mixing

Decay:

$$\overline{K}^0 \rightarrow \boxed{\pi^+ e^-} \overline{\nu}_e$$

- For each event know initial wave-function, e.g. here: $|\psi(t=0)\rangle = |K^0\rangle$

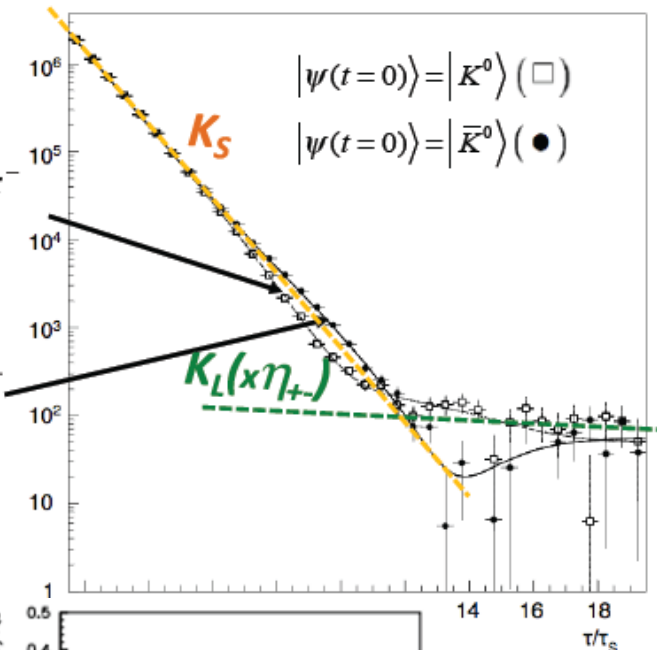
for $\bar{p}p \rightarrow \boxed{K^+\pi^-} K, \quad \left|\psi(t=0)\right\rangle = \left|\overline{K}^0\right\rangle$

$$K^0 = \frac{1}{\sqrt{1+\varepsilon^2}}\Big((1-\varepsilon)K_S + (1+\varepsilon)K_L\Big)$$

$$\bar{K}^0 = \frac{1}{\sqrt{1+\varepsilon^2}}\Big((1+\varepsilon)K_S + (1-\varepsilon)K_L\Big)$$

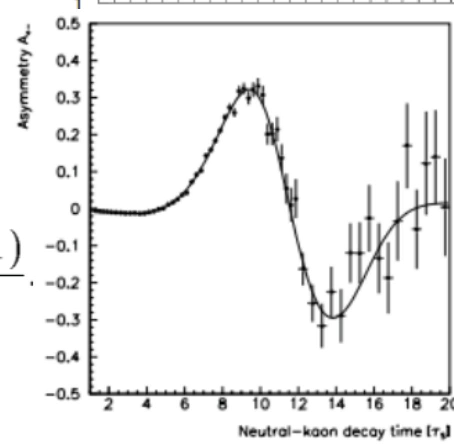
$$\left|K^0(t)\right\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}(1-\varepsilon)\left|K_S\right\rangle \\ (1+\varepsilon)\left|K_L\right\rangle\end{pmatrix}\begin{matrix} e^{-i(M_s-\frac{i}{2}\Gamma_S)t} & \to \pi^+\pi^- \\ \left|\eta_{+-}\right| e^{-i(M_L-\frac{i}{2}\Gamma_L)t+\phi_{+-}} & \to \pi^+\pi^- \end{matrix}$$

$$\left|\bar{K}^0(t)\right\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}(1+\varepsilon)\left|K_S\right\rangle \\ (\varepsilon-1)\left|K_L\right\rangle\end{pmatrix}\begin{matrix} e^{-i(M_s-\frac{i}{2}\Gamma_S)t} & \to \pi^+\pi^- \\ \left|\eta_{+-}\right| e^{-i(M_L-\frac{i}{2}\Gamma_L)t+\phi_{+-}} & \to \pi^+\pi^- \end{matrix}$$



$$A_{+-}(\tau) = \frac{\overline{N}(\tau) - \alpha N(\tau)}{\overline{N}(\tau) + \alpha N(\tau)}$$

$$= -2\frac{|\eta_{+-}|e^{\frac{1}{2}(\tau/\tau_S - \tau/\tau_L)}\cos(\Delta m\tau - \phi_{+-})}{1 + |\eta_{+-}|^2 e^{(\tau/\tau_S - \tau/\tau_L)}}.$$



$B^0(t)$ and $\overline{B}^0(t)$ time dependence

-- for B^0 mesons, no ε term --

$$B^0 = \tfrac{1}{\sqrt{2}}(B_1 + B_2) \Rightarrow B^0(t) = \tfrac{1}{\sqrt{2}}(B_1 e^{-i(M_1 - \frac{i}{2}\Gamma)t} + B_2 e^{-i(M_{21} - \frac{i}{2}\Gamma)t}) = (B_1 + B_2 e^{-i\Delta M t})\tfrac{1}{\sqrt{2}} e^{-i(M_1 - \frac{i}{2}\Gamma)t}$$

do the same for $\overline{B}^0$ & neglect the overall $\tfrac{1}{\sqrt{2}} e^{-i(M_1 - \frac{i}{2}\Gamma)t}$, which cancels in the asymmetry ratio.

mixing terms

$$B^0(t) = B^0(1 + e^{-i\Delta M t}) + \overline{B}^0(1 - e^{-i\Delta M t})$$

$e^{i2\phi_1}$

CPV phases go here

$e^{-i2\phi_1}$

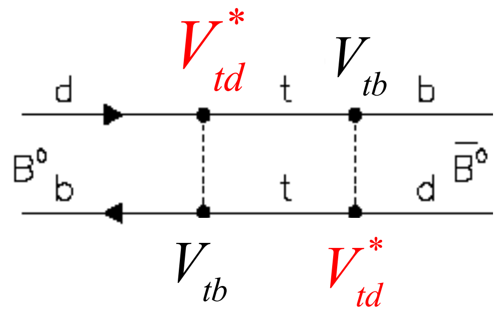
$$\overline{B}^0(t) = \overline{B}^0(1 + e^{-i\Delta M t}) + B^0(1 - e^{-i\Delta M t})$$

differences in the time evolution of B^0 and $\overline{B}^0$ mesons

-- including CPV --

time development of a B^0 at t=0: **CPV mixing phase**

$$\left|B^0(t)\right\rangle = \left(\left|B^0\right\rangle(1+e^{-i\Delta Mt}) + e^{i2\phi_1}\left|\overline{B}^0\right\rangle(1-e^{-i\Delta Mt})\right)$$



J/ψ K_S is a CP=-1 eigenstate, B_2→J/ψ K_S is allowed.
Project out the B_2 time dependence for an initial B^0

$$\left\langle B_2\middle|B^0(t)\right\rangle = \left(\left\langle B^0\right| + \left\langle \overline{B}^0\right|\right)\left|B^0(t)\right\rangle = \left\langle B^0\middle|B^0\right\rangle(1+e^{-i\Delta Mt}) + \left\langle \overline{B}^0\middle|\overline{B}^0\right\rangle e^{i2\phi_1}(1-e^{-i\Delta Mt})$$

$$\Rightarrow (1+e^{-i\Delta Mt}) + e^{i2\phi_1}(1-e^{-i(\Delta Mt)}) = (1+e^{i2\phi_1}) + e^{-i\Delta Mt}(1-e^{i2\phi_1})$$

square this:

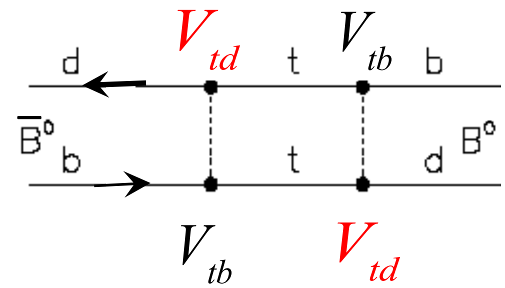
$$\left|\left\langle B_2 \mid B^0(t)\right\rangle\right|^2 = \left((1+e^{i2\phi_1}) + e^{-i\Delta Mt}(1-e^{i2\phi_1})\right)\times\left((1+e^{-i2\phi_1}) + e^{+i\Delta Mt}(1-e^{-i2\phi_1})\right)$$

and do some algebra: $\left|\left\langle B_2 \mid B^0(t)\right\rangle\right|^2 = 4 - 4\sin 2\phi_1 \sin\Delta Mt$

the CPV mixing phase for $\overline{B}^0$ has opposite sign

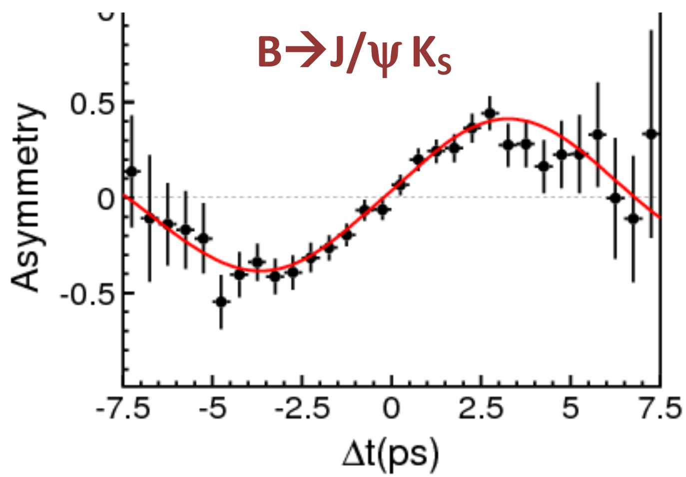
likewise: $$\left|\overline{B}^0(t)\right\rangle = \left(\left|\overline{B}^0\right\rangle(1+e^{-i\Delta Mt}) + e^{-i2\phi_1}\left|B^0\right\rangle(1-e^{-i\Delta Mt})\right)$$

and $$\left|\left\langle B_2 \,|\, \overline{B}^0(t)\right\rangle\right|^2 = 4 + 4\sin 2\phi_1 \sin \Delta Mt$$

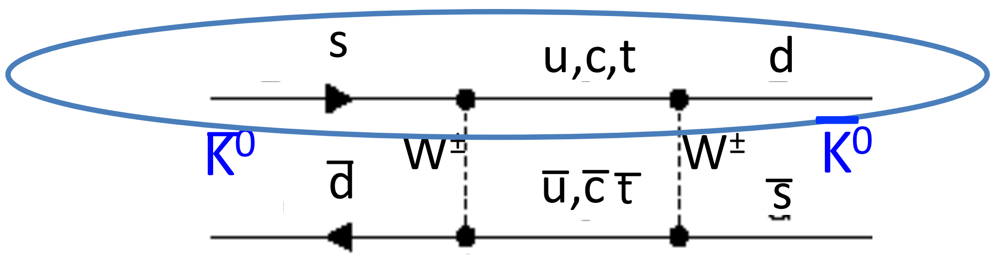


B^0 tags **$\overline{B}^0$ tags**

$$\frac{\left|\left\langle B_2 \,|\, \overline{B}^0(t)\right\rangle\right|^2 - \left|\left\langle B_2 \,|\, B^0(t)\right\rangle\right|^2}{\left|\left\langle B_2 \,|\, \overline{B}^0(t)\right\rangle\right|^2 + \left|\left\langle B_2 \,|\, B^0(t)\right\rangle\right|^2} = \frac{8\sin 2\phi_1 \sin \Delta Mt}{8} = \sin 2\phi_1 \sin \Delta Mt$$

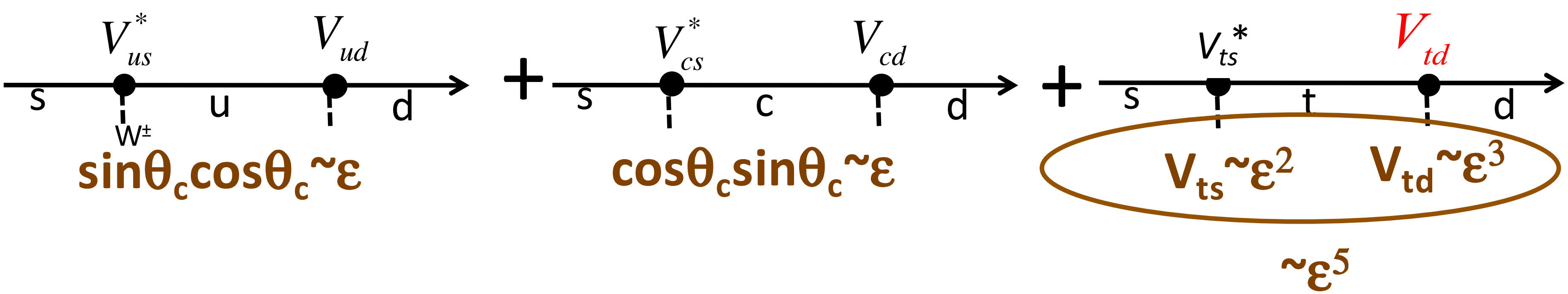


Question: if KM phases are in V_{ub} & V_{td}, why is there CPV with K^0s



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

V_{td} has a small, but non-zero influence on K^0-$\bar{K}^0$ mixing



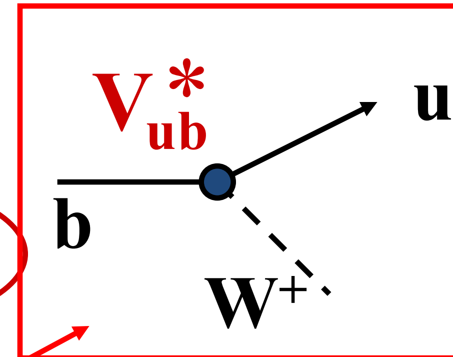
Today's topics

- How does the measured CP violating phase compare with expectations from other measurements

- Other KM-model motivated CP violation measurements

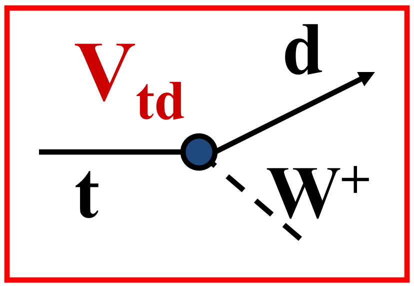
CKM matrix today

CPV phases are in the corners



$\phi_3(\gamma)$

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



$\phi_1(\beta)$

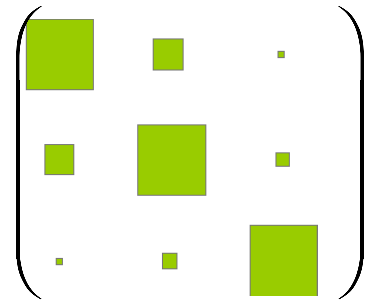
Current status of the CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

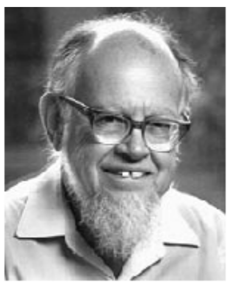
- nearly diagonal
- off-diagonal elements are small
- far-off-diagonal elements are very small

CKM matrix hierarchy

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} \varepsilon^0 & \varepsilon^1 & \varepsilon^3 \\ \varepsilon^1 & \varepsilon^0 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^0 \end{pmatrix} \rightarrow$$



$$\varepsilon \simeq 0.22$$



Lincoln Wolfenstein

Wolfenstein parameterization:

$$\lambda = \sin \theta_c \sim 0.22$$

$$V = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$

all SM CP Violations are due to this single imaginary number

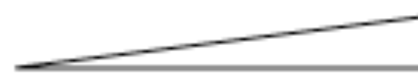
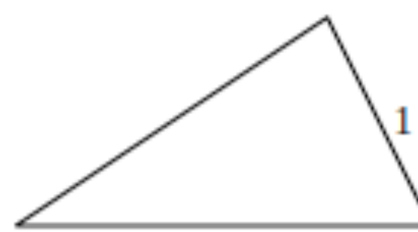
$$\lambda = 0.22453 \pm 0.00044\,, \qquad A = 0.836 \pm 0.015\,,$$

$$\bar{\rho} = 0.122^{+0.018}_{-0.017}\,, \qquad \bar{\eta} = 0.355^{+0.012}_{-0.011}\,.$$

Unitarity of the CKM triangle

$$V_{CKM}^{\dagger} V_{CKM} = \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \times \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

9 equations:

ij	$\sum V_{ik} V_{jk}^* = 0$	$\sim \epsilon^n$	shape (normalized to unit base)	
12	$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$	$\epsilon + \epsilon + \epsilon^5 = 0$		$\varepsilon^4 \simeq 0.002$
23	$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$	$\epsilon^4 + \epsilon^2 + \epsilon^2 = 0$		$\varepsilon^2 \simeq 0.05$
13	$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$	$\epsilon^3 + \epsilon^3 + \epsilon^3 = 0$		

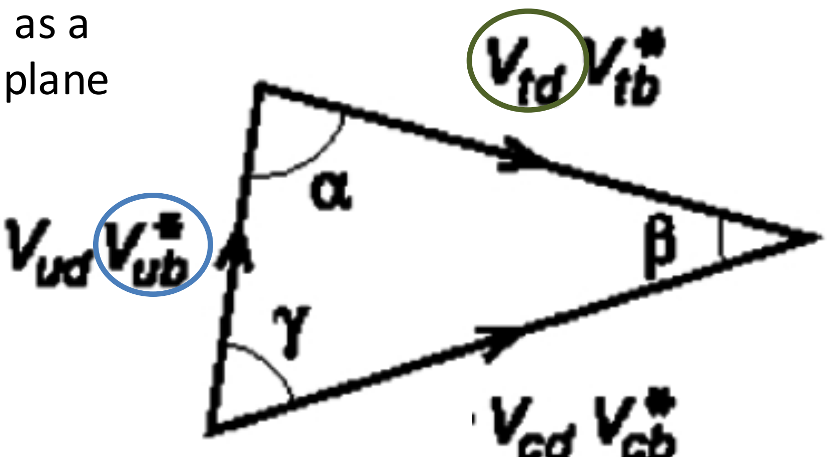
Unitarity of the CKM triangle

for CPV, the most interesting unitarity relation is

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

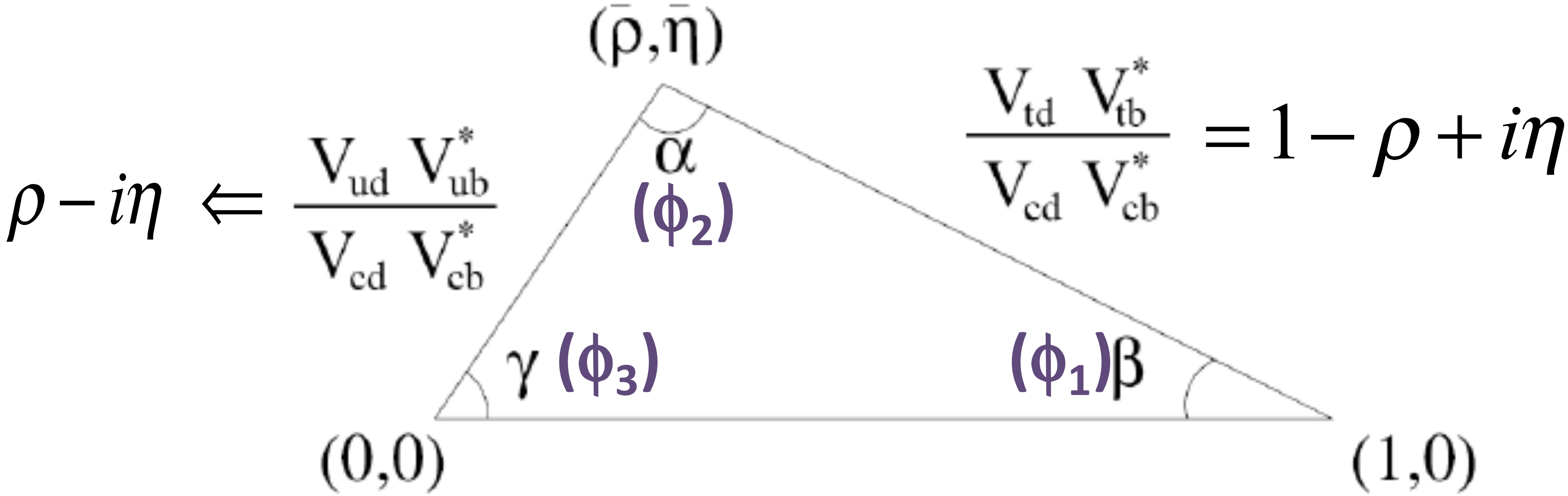
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

this can be represented as a triangle in the complex plane



V_{ub} and V_{td} are corner elements in the CKM matrix, the elements with a complex phase

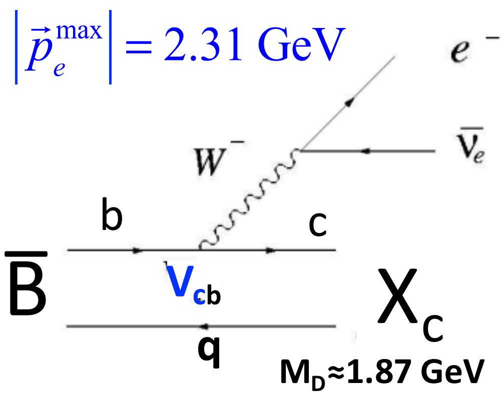
Unitary triangle normalized to $V_{cb}V_{ct}^{*}$

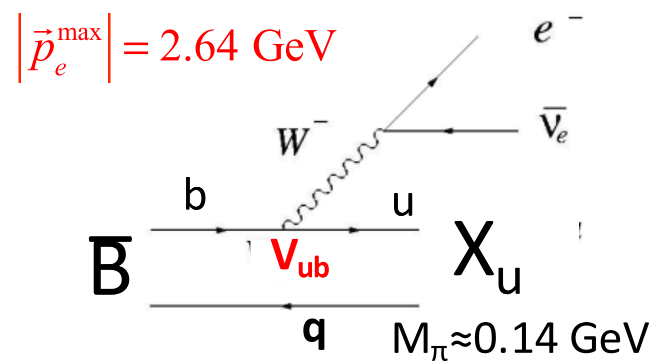


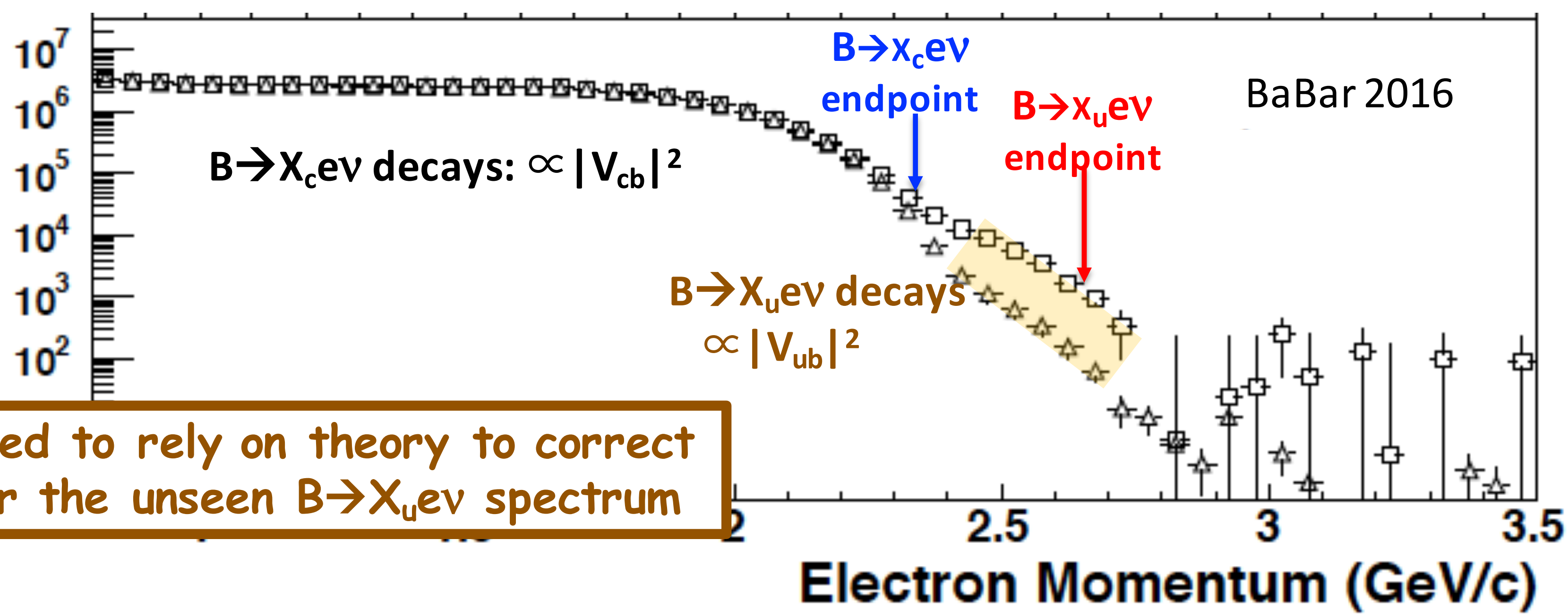
KM predictions: $\phi_1 + \phi_2 + \phi_3$ =180°
sides form a triangle

the Belle and BaBar experiments
measured $\beta/\phi_1 \simeq 22^{o}$, how about α/ϕ_2 & γ/ϕ_3?

measure $|V_{ub}|/|V_{cb}|$ from inclusive $B \to Xe^{\pm}\nu$ endpoint

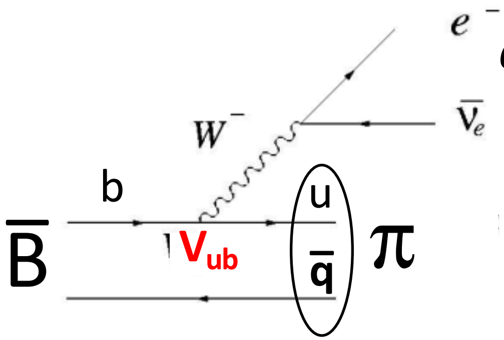






need to rely on theory to correct for the unseen $B \to X_u e\nu$ spectrum

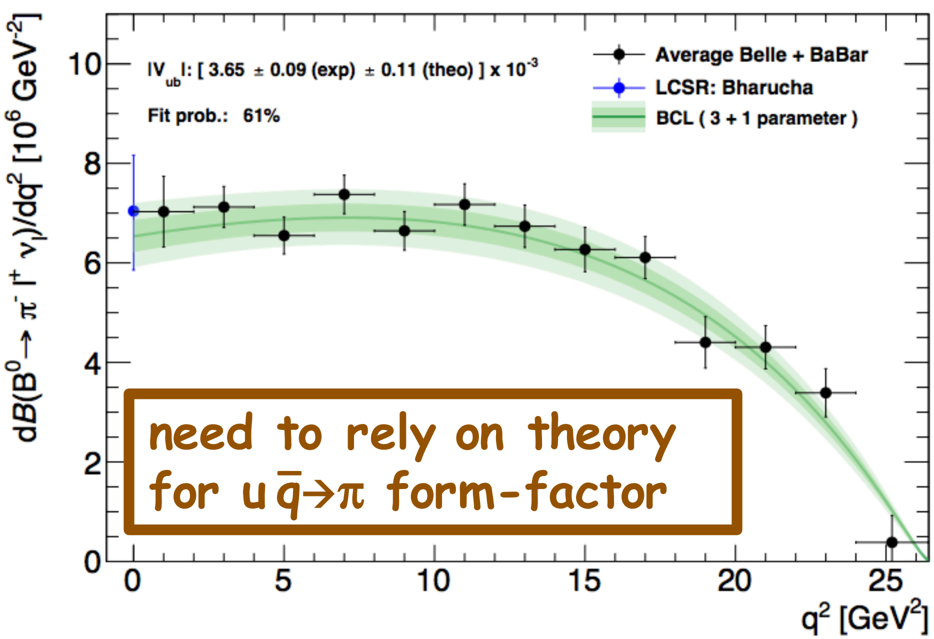
measure $|V_{ub}|$ from exclusive $B \to \pi e^{\pm}\nu$ decay rate



$q^2 = M^2(e\nu)$

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{24\pi^3} |p_\pi|^3 |f_+(q^2)|^2,$$

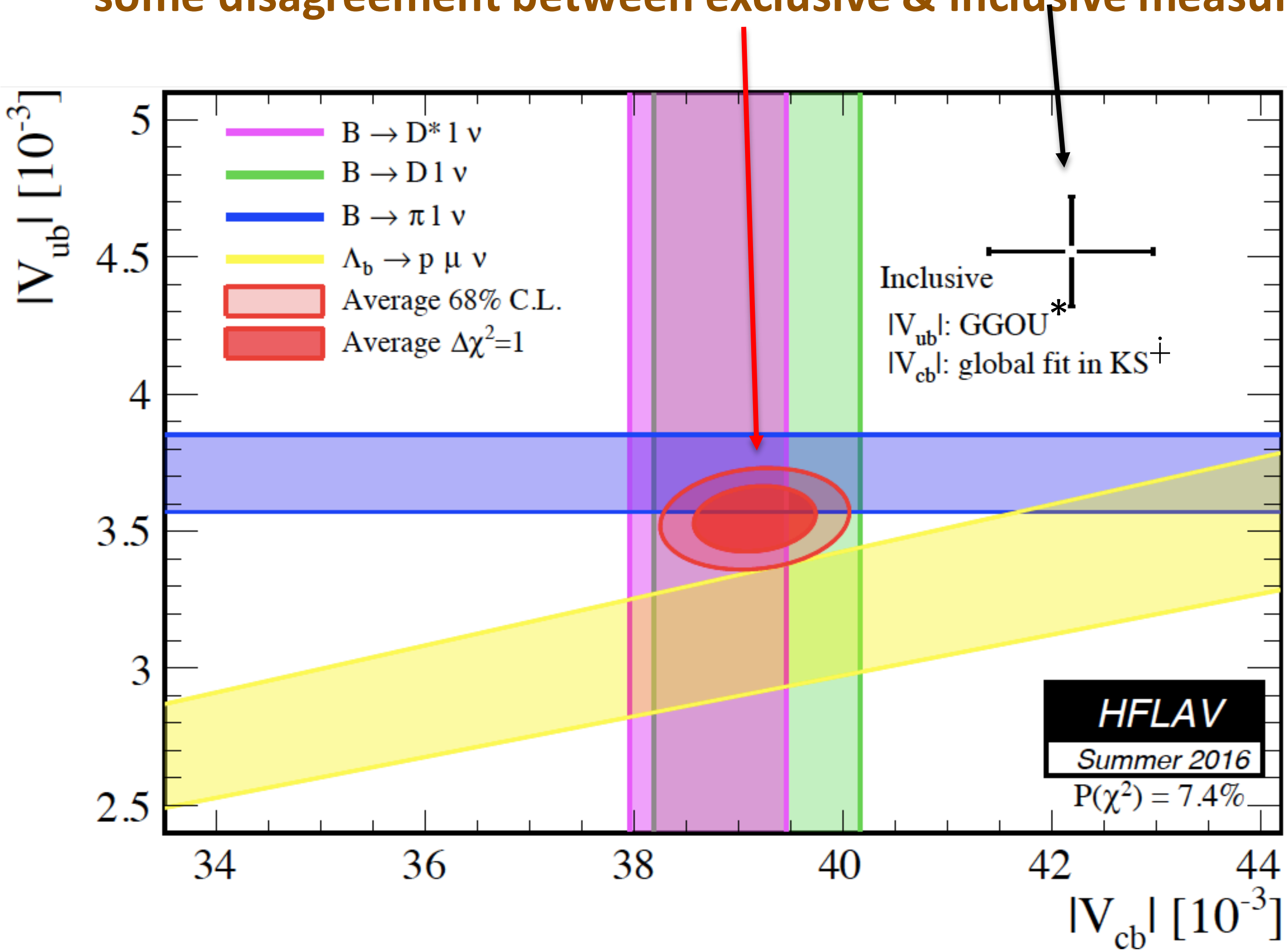
form-factor



need to rely on theory for $u\bar{q} \to \pi$ form-factor

2016 results for $|V_{ub}|$ and $|V_{cb}|$

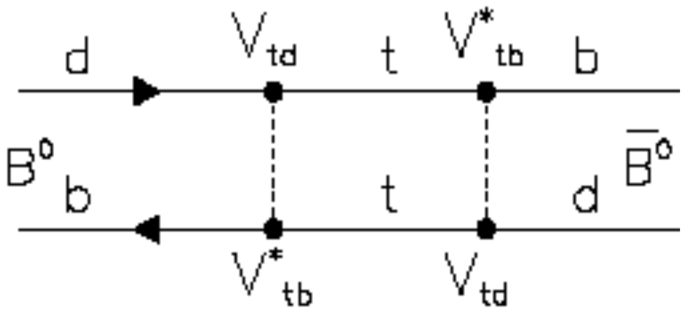
some disagreement between exclusive & inclusive measurements

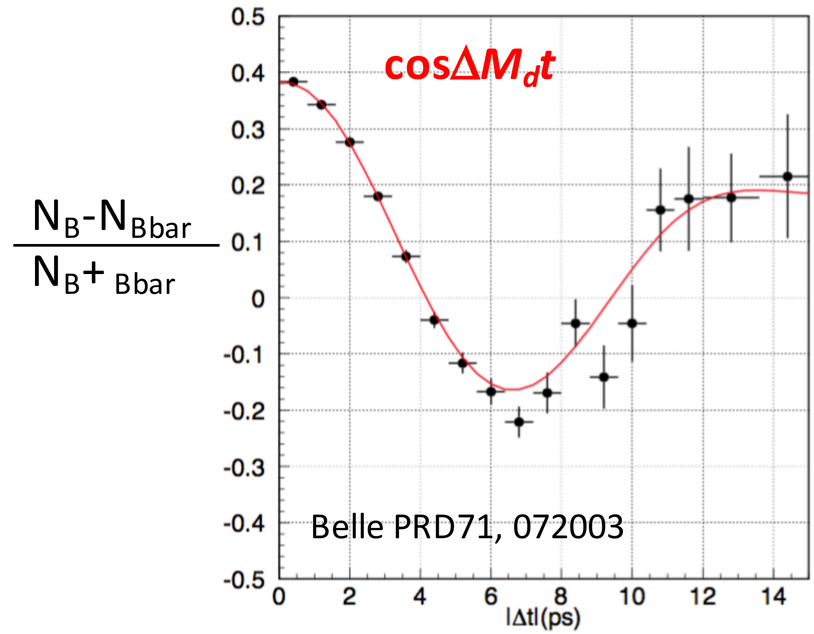


+ A. Alberti, P. Gambino, K. J. Healey, and S. Nandi (2014), 1411.6560.

* P. Gambino, P. Giordano, G. Ossola, and N. Uraltsev, *JHEP* **0710**, 058 (2007), 0707.2493.

$|V_{td}|$ from $B^0 \leftrightarrow \bar{B}^0$ mixing





PDG: ΔM_d=0.510±0.003 ps

$$\Delta M_{B^0 \leftrightarrow \bar{B}^0} = \frac{1}{12\pi^2} G_F^2 M_W^2 m_{B^0} B_B f_{B^0}^2 S_o\left(m_{top}^2 \middle/ M_W^2\right) \left| V_{td}^* V_{tb} \right|^2$$

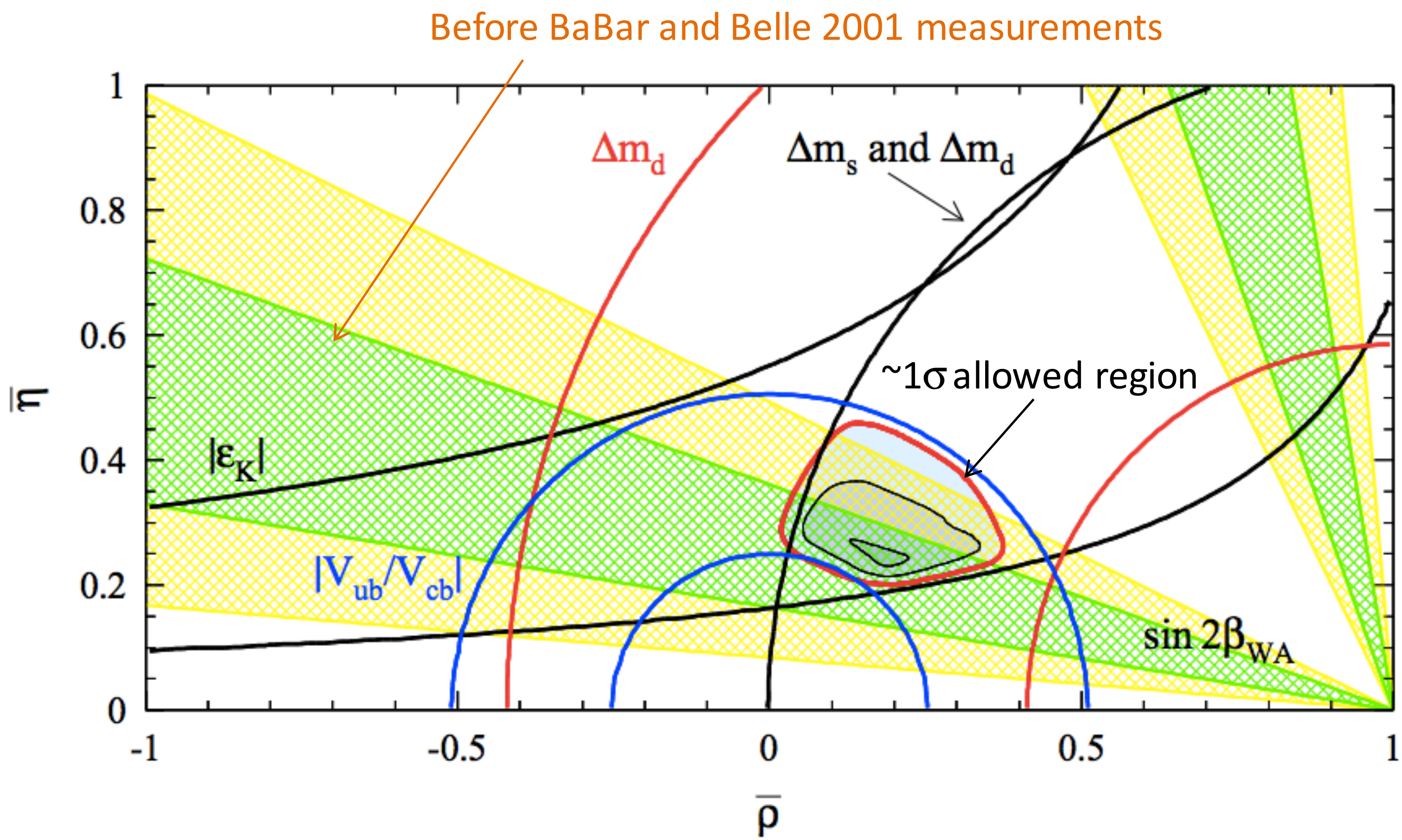
form-factor

kinematic-factor
(calculable)

$$\boxed{\text{PDG:} \quad |V_{td}| = (0.81 \pm 0.5) \times 10^{-3}}$$

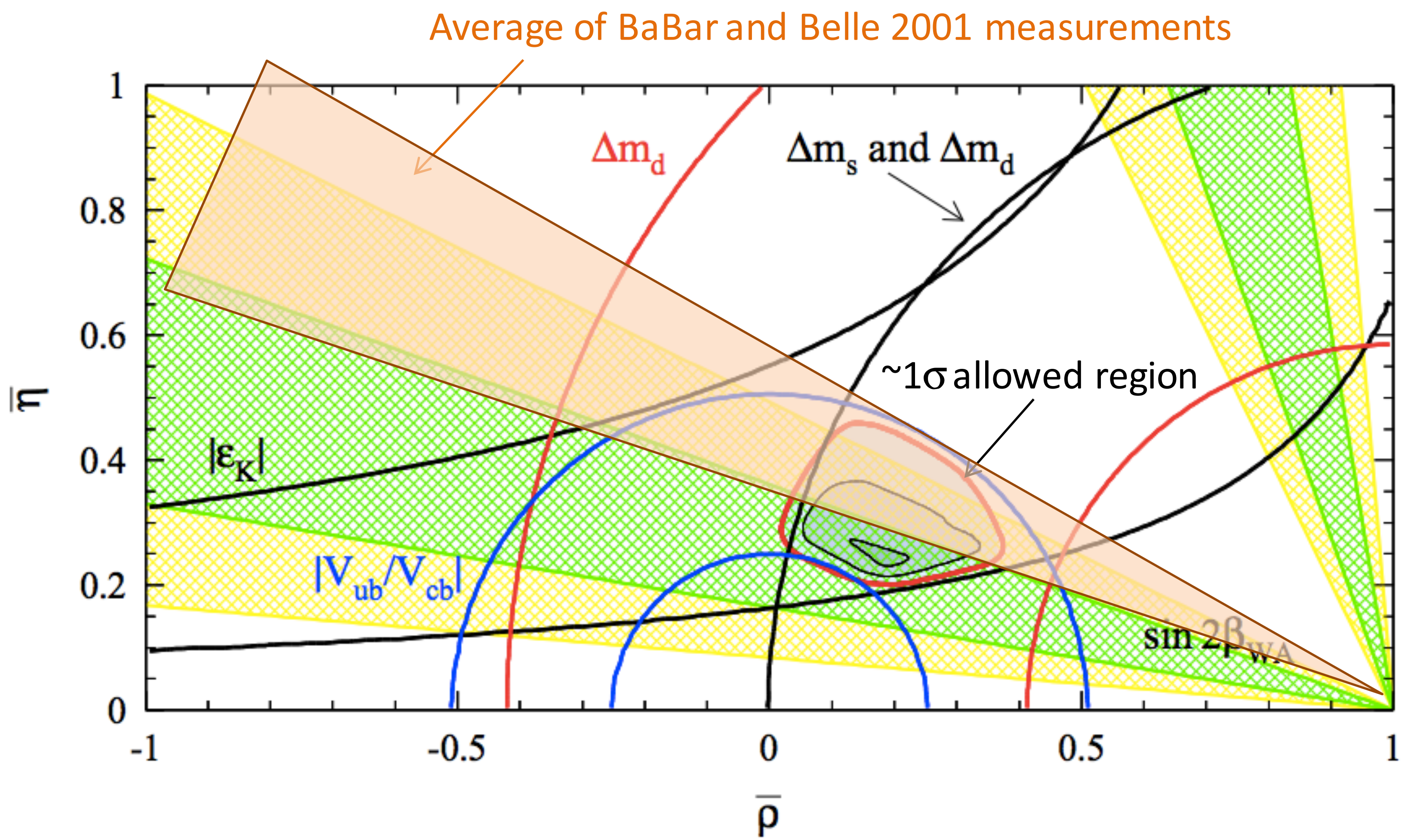
error due to theory

Constraints on the ρ–η plane in 2001



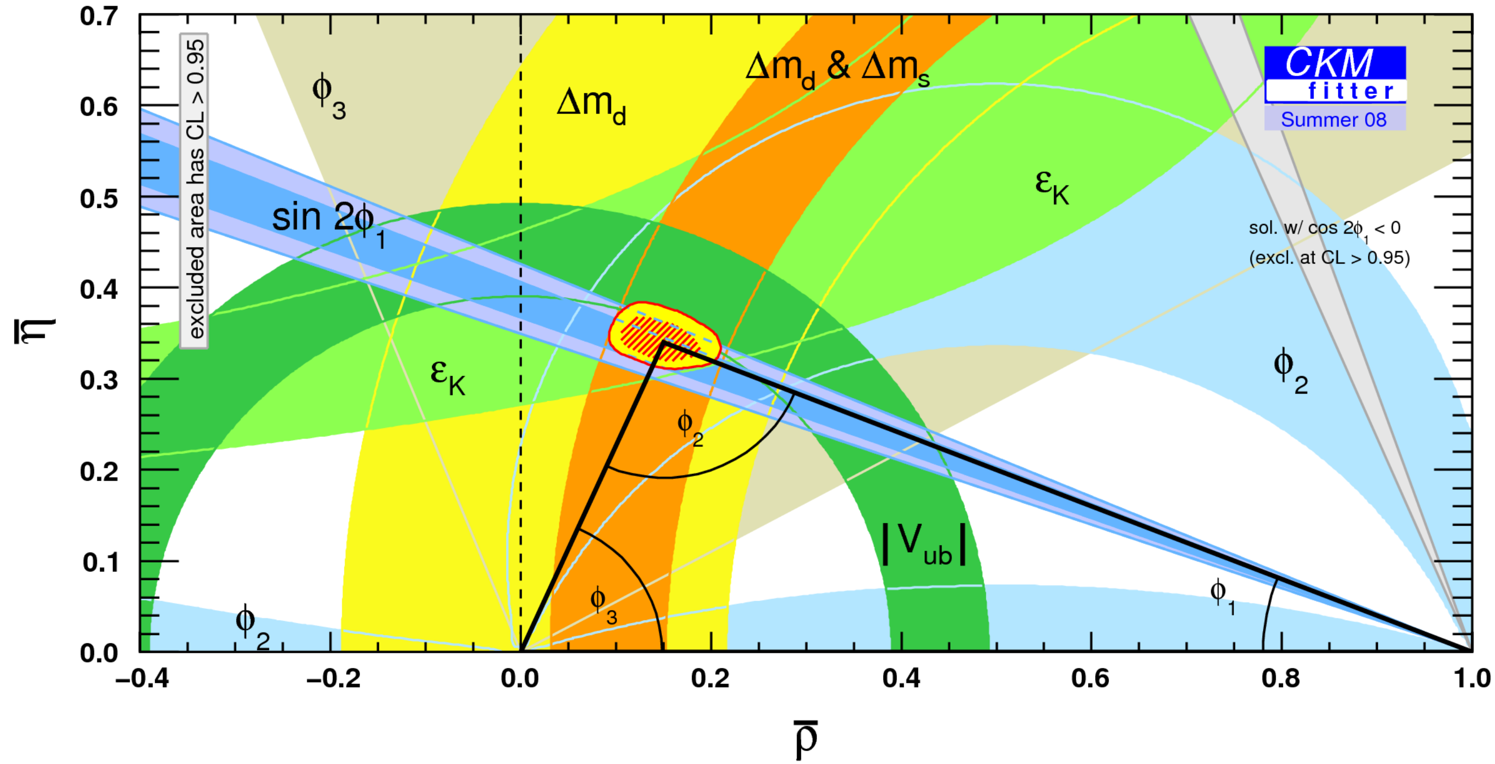
"CKM fitter" 2001: A. Hoecker et al., hep-ph/0104062v2

Constraints on Unitary Triangle in 2001



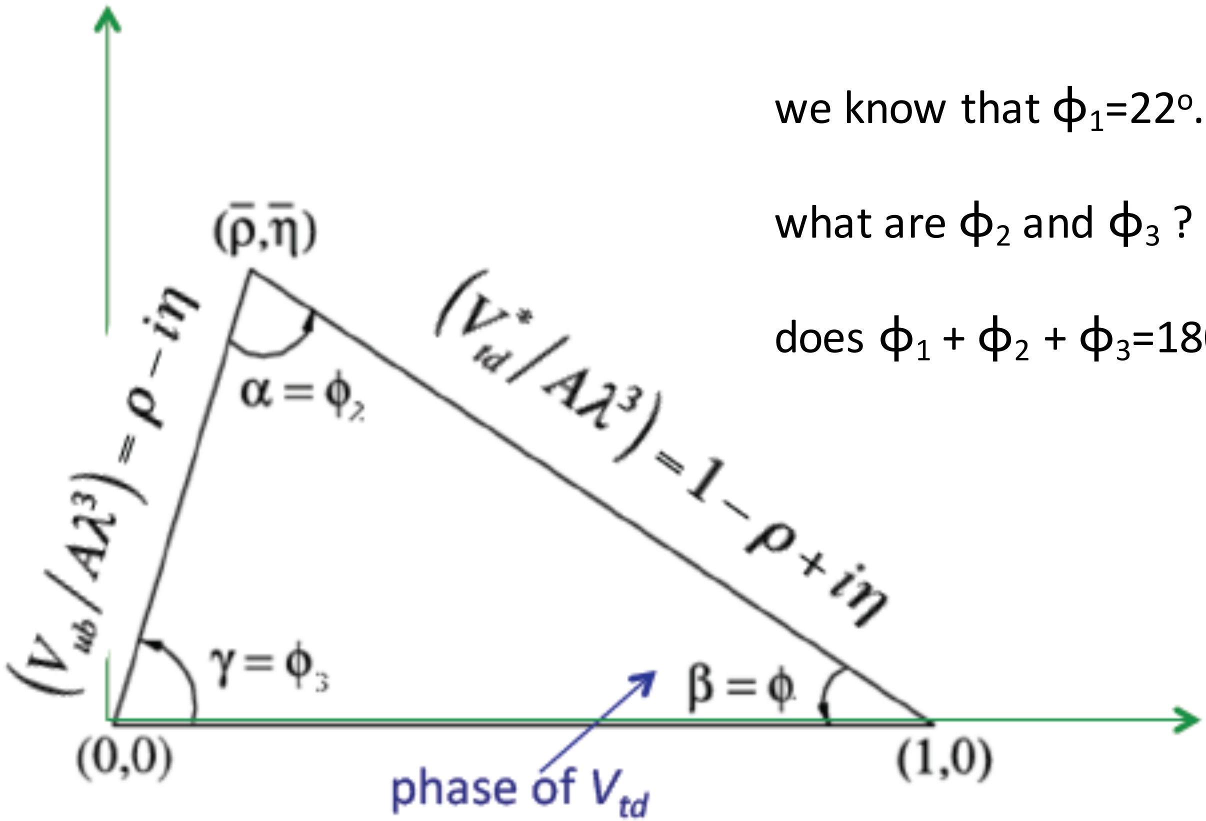
"CKM fitter" 2001: A. Hoecker et al., hep-ph/0104062v2

Unitary triangle in Summer 2008



Stockholm, December 2008

Next task; measure the other angles



we know that ϕ_1=22^o.

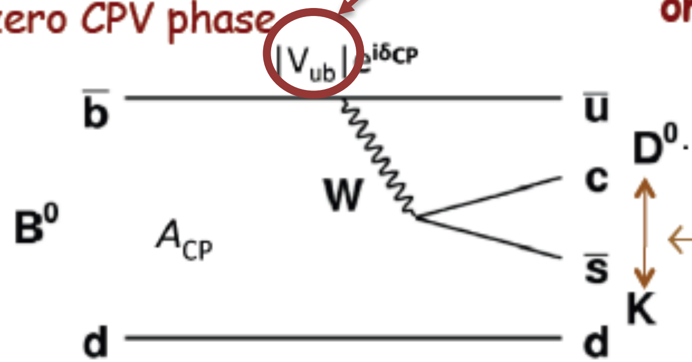
what are ϕ_2 and ϕ_3 ?

does $\phi_1 + \phi_2 + \phi_3$=180^o ?

$\gamma(\phi_1)$, the phase of V_{ub}

briefly discussed in Lecture 2: $e^{i\phi_3}$

non-zero CPV phase



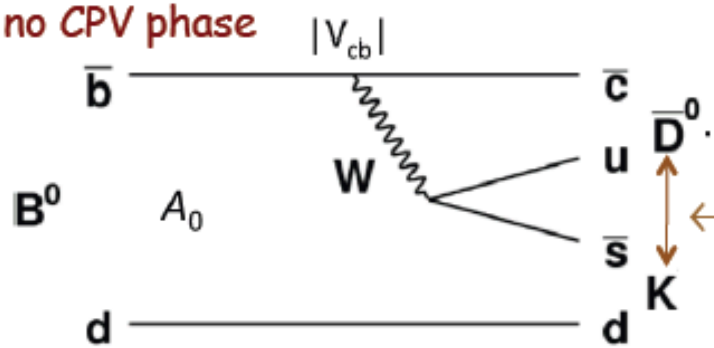
only use decay modes common to D^0 & $\bar{D}^0$

$Bf \approx 0.14\%$ $\quad 0.40\%$ $\quad 1.4\%$

$D^0 \longrightarrow \pi^+\pi^-; K^+K^-; \pi^+\pi^-\pi^0; \ldots$

$\leftarrow \delta_{DK}$ D-K strong interaction phase shift

no CPV phase

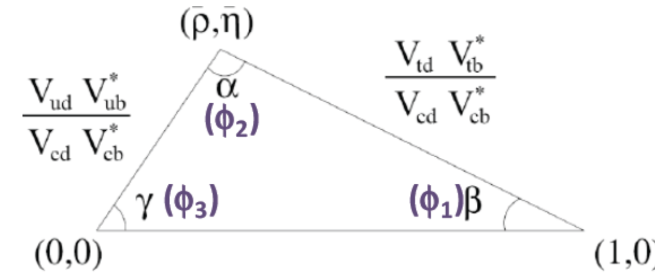


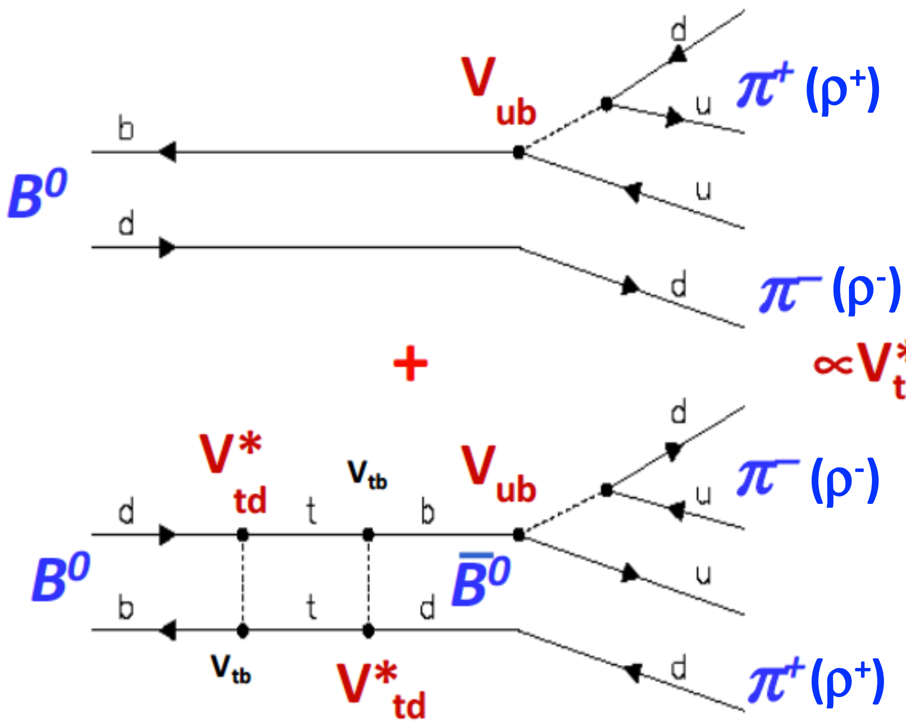
$\bar{D}^0 \longrightarrow \pi^+\pi^-; K^+K^-; \pi^+\pi^-\pi^0; \ldots$

$\leftarrow \delta_{\bar{D}K}$ $\bar{D}$-K strong interaction phase shift

$$\boxed{\delta_{com} = \delta_{\bar{D}K} - \delta_{DK} \neq 0}$$

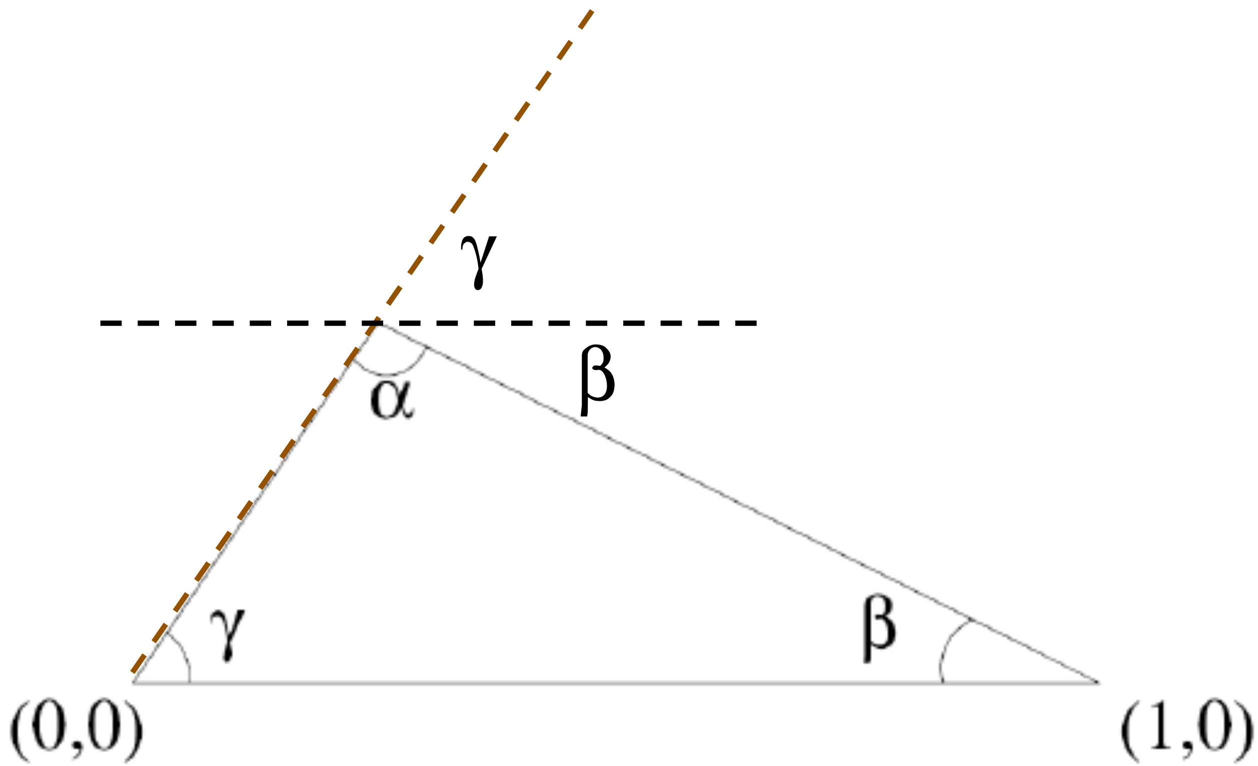
and $\alpha(\phi_1)$





$\propto V^{*2}_{td}\,V^2_{ub} \;\propto \sin 2\phi_2 (2\alpha)$

$$V_{td}^{*2}V_{ub}^{*2} \propto \sin 2\alpha?$$



$$\alpha = 180^{o} - \gamma - \beta$$

$$2\alpha = 360^{o} - 2\gamma - 2\beta = -2(\gamma + \beta)$$

first we discuss γ (ϕ_3), the phase of V_{ub}

What we need:

two interfering processes, one of them=$b \rightarrow u$

-- best if they have nearly equal strengths

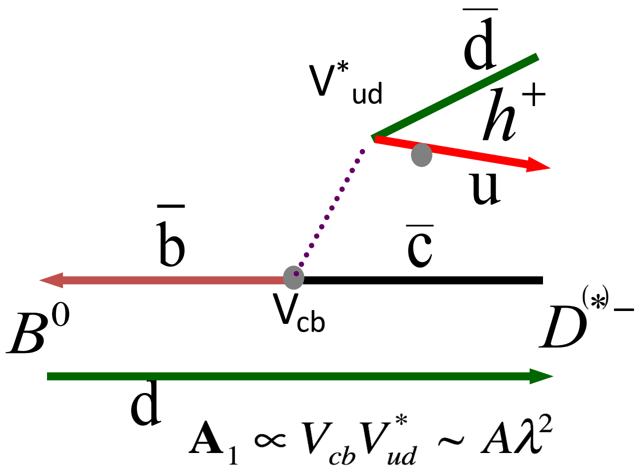
weak phase: ϕ_3

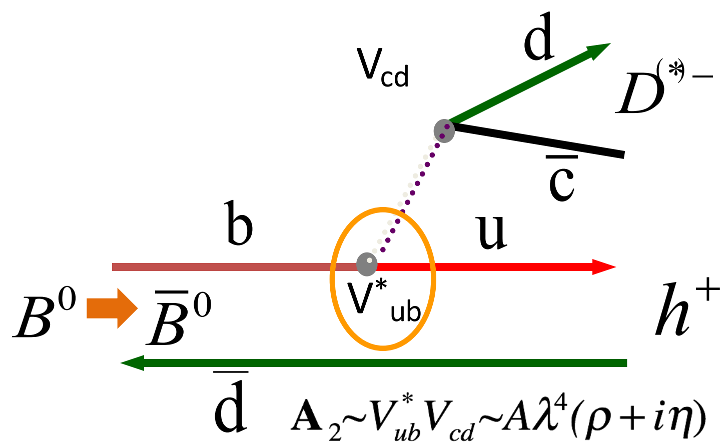
common phase

$B^0/B^0 \rightarrow h^+ D^{(*)-}$

$h = \pi, \rho, a_1$

dominant B^0 decay modes



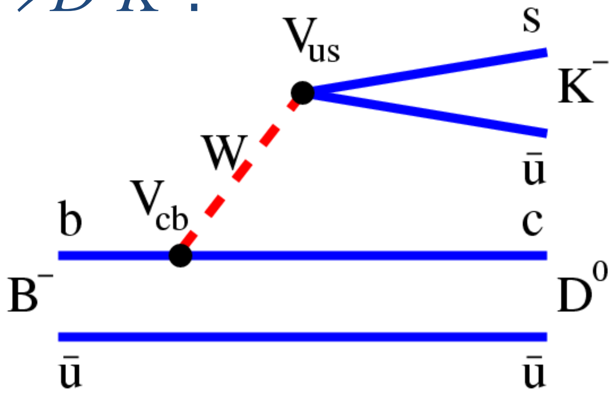


Large BR, but: $r = \dfrac{|A_2|}{|A_1|} \sim \lambda^2 \approx 0.05$ $\Rightarrow$ Interference effects are tiny

hopeless with current facilities

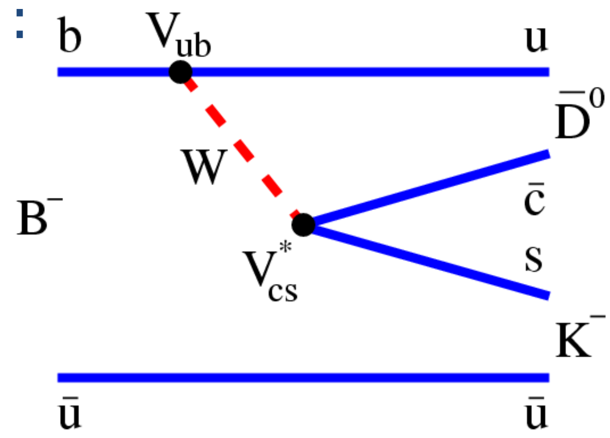
Better to use $B^- \to D^0 K^-$ decays

$B^- \to D^0 K^-$:



$$\mathbf{A}_1 \propto V_{cb} V_{us}^* \sim A\lambda^3$$

$B^- \to \bar{D}^0 K^-$:



$$\mathbf{A}_2 \sim V_{ub} V_{cs}^* \sim A\lambda^3(\rho - i\eta) \propto e^{-i\phi_3}$$

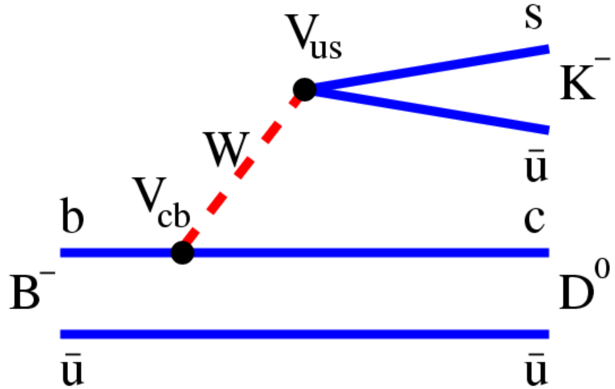
where D^0 and $\bar{D}^0$ decay to the same final state: $\left|\tilde{D}^0\right\rangle = \left|D^0\right\rangle + re^{i\theta}\left|\bar{D}^0\right\rangle$

Relative phases: $\theta = -\phi_3 + \delta_B\,(B^- \to DK^-), \theta = +\phi_3 + \delta_B\ \ (B^+ \to DK^+)$

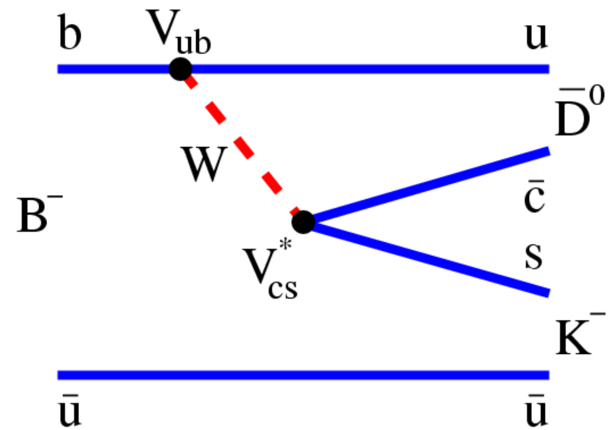
$\delta_B = \delta_{K\bar{D}} - \delta_{KD}$ is the strong phase difference between DK and $\bar{D}$K

$r_B = \left|\mathbf{A}(B^- \to \bar{D}^0 K^-)/\mathbf{A}(B^- \to D^0 K^-)\right|$ ← "color suppressed; $r_B \approx 0.1 \sim 0.2$

"color suppression"



Here the quark & antiquark colors automatically match, no matter what colors are produced by the W

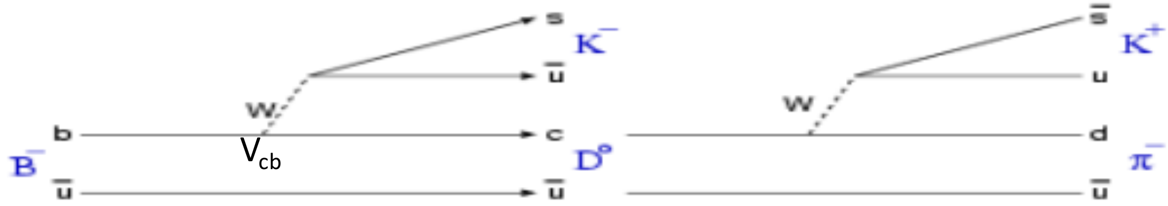


Here the colors of the quarks will match the colors of the u and ū quarks only 1/3rd of the time.

Expect a relative suppression of the amplitude by a factor of 1/3rd, but in practice it is often not so severe

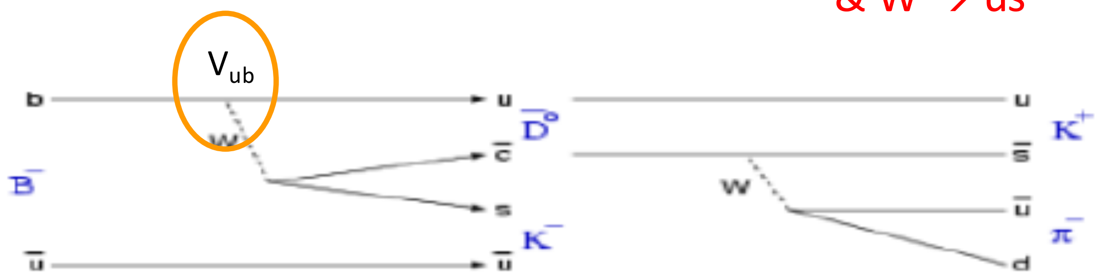
ADS method to measure ϕ_3

Atwood, Dunietz & Soni
Phys.Rev. Lett. 78, 3253



$B^- \to D^0 K^-$ *favored* $(b \to c)$ *followed by* $D^0 \to K^+ \pi^-$ *suppressed* $(c \to d)$

& $W^+ \to u\bar{s}$



$B^- \to \bar{D}^0 K^-$ *suppressed* $(b \to u)$ *followed by* $\bar{D}^0 \to K^+ \pi^-$ *favored* $(\bar{c} \to \bar{s})$

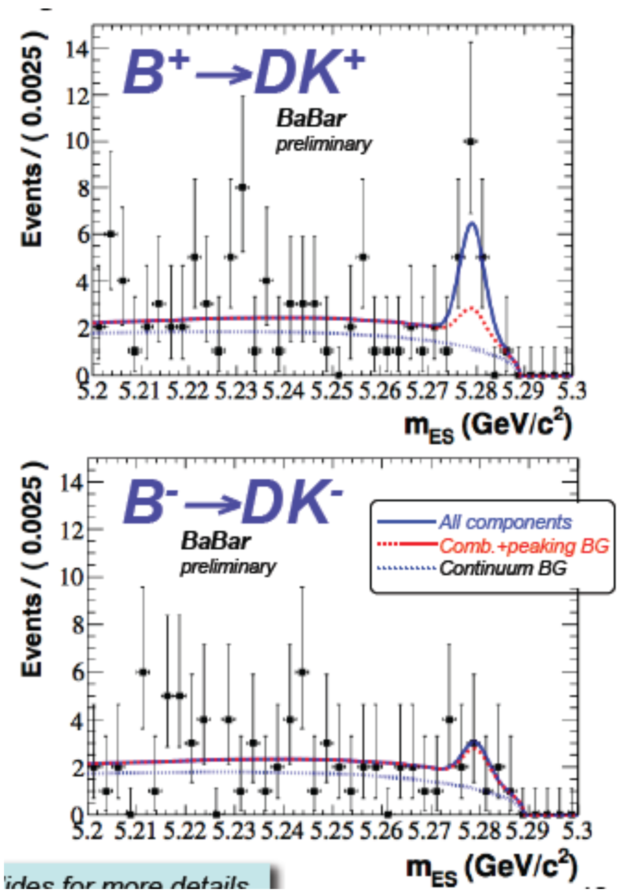
& color suppressed

expect a large B^-/B^+ asymmetry but a small event rate

-- product branching fractions are of order 10^{-7} --

BaBar results from ADS method

more B^+ events, but with only ≈2σ statistical significance

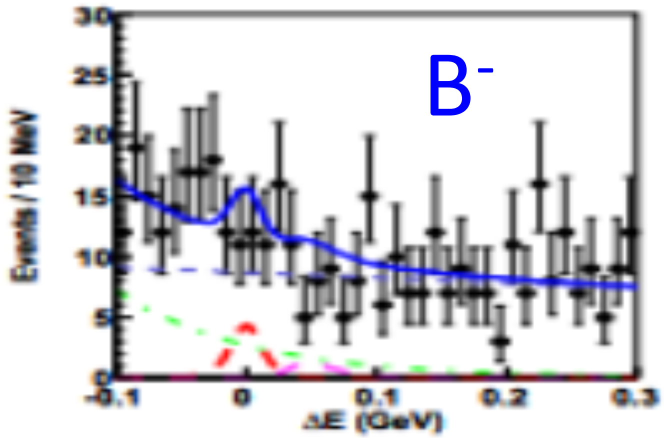


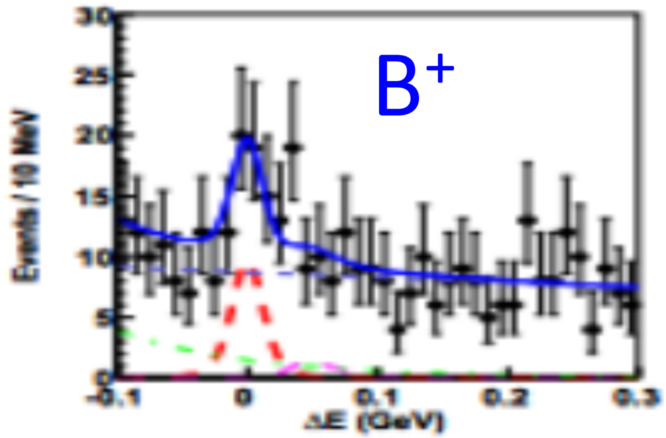
$$\mathcal{A}_{DK} \equiv \frac{\mathcal{R}_{DK}^{-} - \mathcal{R}_{DK}^{+}}{\mathcal{R}_{DK}^{-} + \mathcal{R}_{DK}^{+}} = 2\, r_B r_D \sin\gamma \sin\delta / \mathcal{R}_{DK}$$

$$\mathcal{A}_{DK} = -0.86 \pm 0.47\, {}^{+0.11}_{-0.15}$$

Belle results from ADS method

more B^+ events, but with ≈1.5σ statistical significance





$$\mathcal{R}_{DK} = [1.62 \pm 0.42(\mathrm{stat})\ ^{+0.16}_{-0.19}(\mathrm{syst})] \times 10^{-2},$$

$$\mathcal{A}_{DK} = -0.39 \pm 0.26(\mathrm{stat})\ ^{+0.06}_{-0.04}(\mathrm{syst}),$$

←same sign as BaBar

Control process (no asymmetry is expected)

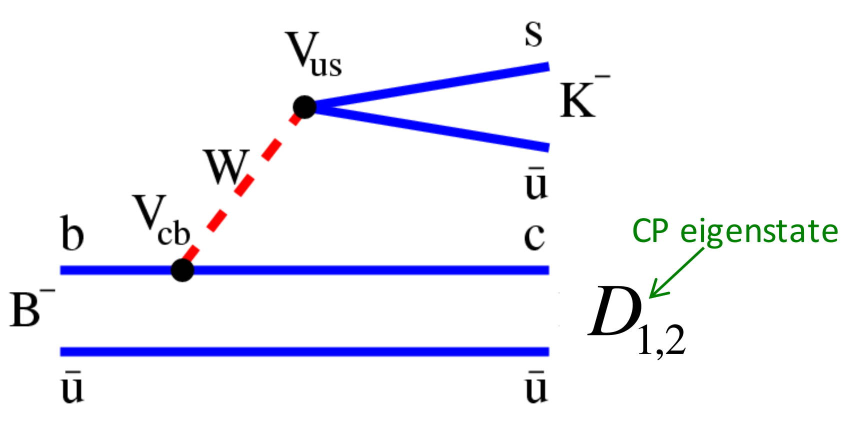
$$\mathcal{R}_{D\pi} = [3.28 \pm 0.37(\mathrm{stat})\ ^{+0.22}_{-0.23}(\mathrm{syst})] \times 10^{-3},$$

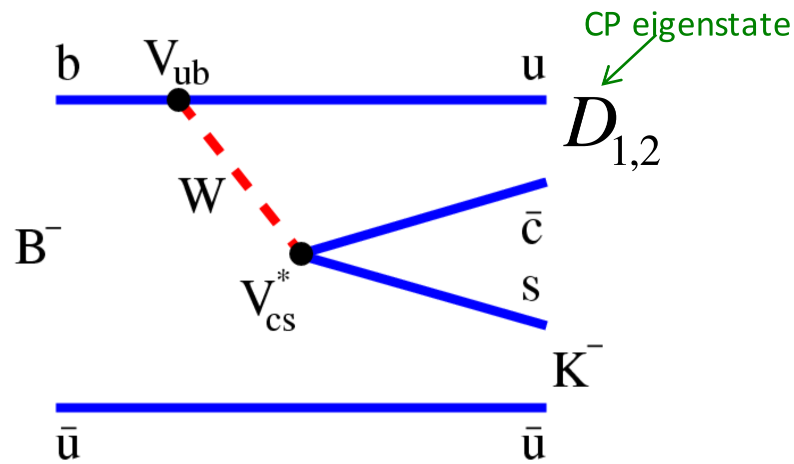
$$\mathcal{A}_{D\pi} = -0.04 \pm 0.11(\mathrm{stat})\ ^{+0.01}_{-0.02}(\mathrm{syst}),$$

this may be a useful method at BelleII

Gronau, London and Wyler
Phys. Lett. B253, 438 & B265, 172

GLW method





CP-even : $D_1 \to K^+K^-,\ \pi^+\pi^-$
CP-odd : $D_2 \to K_S\pi^0,\ K_S\omega,\ K_S\varphi,\ K_S\eta\ldots$

$$\mathcal{A}_{1,2} = \frac{Br(B^- \to D_{1,2}K^-) - Br(B^+ \to D_{1,2}K^+)}{Br(B^- \to D_{1,2}K^-) + Br(B^+ \to D_{1,2}K^+)} = \frac{2r\sin\delta'\sin\varphi_3}{1+r^2+2r\cos\delta'\cos\varphi_3}$$

$$\mathcal{R}_{1,2} = \frac{Br(B \to D_{1,2}K)/Br(B \to D_{1,2}\pi)}{Br(B \to D^0K)/Br(B \to D^0\pi)} = 1+r^2+2r\cos\delta'\cos\varphi_3$$

4 equations, 3 unknowns: (r, δ' and Φ_3)

GLW results

BaBar results (211 fb^{-1})

	$\mathcal{R}$	$\mathcal{A}$
$B \to D_{CP+}K$	0.90±0.12±0.04	0.35 ±0.13±0.04
$B \to D_{CP-}K$	0.86±0.10±0.05	-0.06±0.13±0.03
$B \to D_{CP+}K^*$	1.96±0.40±0.11	-0.08±0.19±0.08
$B \to D_{CP-}K^*$	0.65±0.26±0.08	-0.26±0.40±0.12

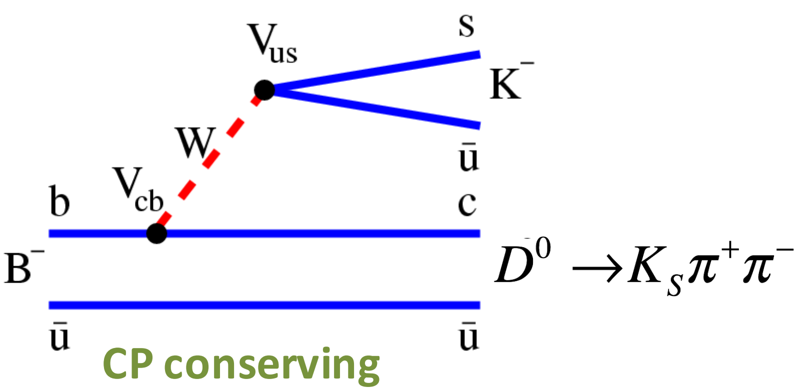
no statistically significant asymmetries

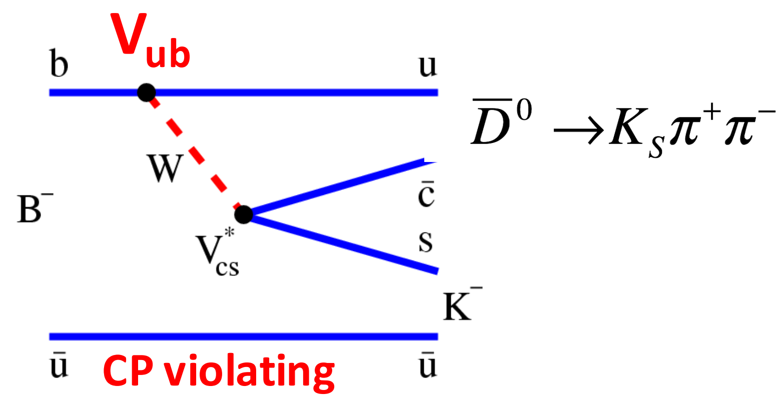
Belle results (253 fb^{-1})

	$\mathcal{R}$	$\mathcal{A}$
$B \to D_1 K$	1.13 ±0.16±0.05	0.06±0.14±0.05
$B \to D_2 K$	1.17±0.14±0.14	-0.12±0.14±0.05
$B \to D^*_1 K$	1.41±0.25±0.06	-0.20±0.22±0.04
$B \to D^*_2 K$	1.15±0.31±0.12	0.13±0.30±0.08

This method needs a lot more data

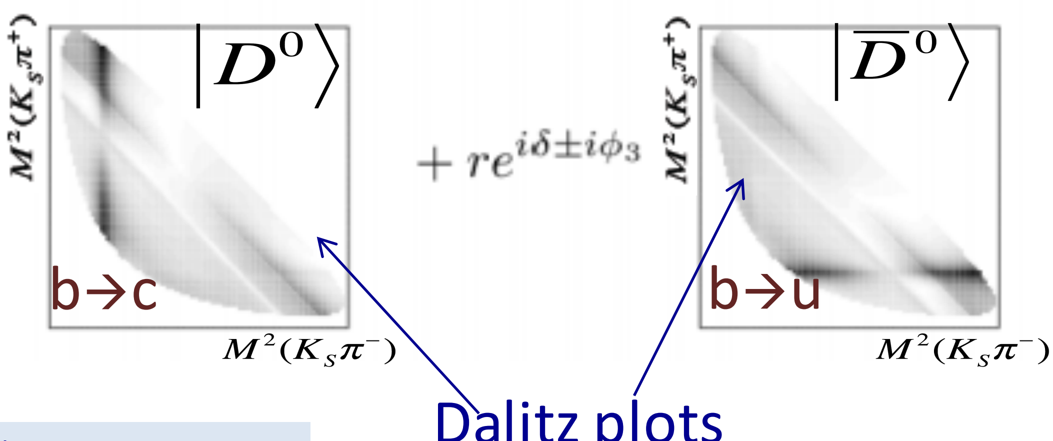
Best results: "Dalitz" analyses of $D \rightarrow K_S\pi^+\pi^-$





$$B^- \rightarrow K^-\tilde{D}^0 \rightarrow K^-K_S\pi^+\pi^-, \text{ where } \left|\tilde{D}^0\right\rangle = \left|D^0\right\rangle + re^{i(\delta+\phi_3)}\left|\overline{D}^0\right\rangle$$

$$\left|\tilde{D}^0\right\rangle = \left|D^0\right\rangle + re^{i\delta \pm i\phi_3}\left|\overline{D}^0\right\rangle$$



Giri, Grossman, Soffer and Zupan, Phys. Rev. D68, 054018
A. Bondar, unpublished

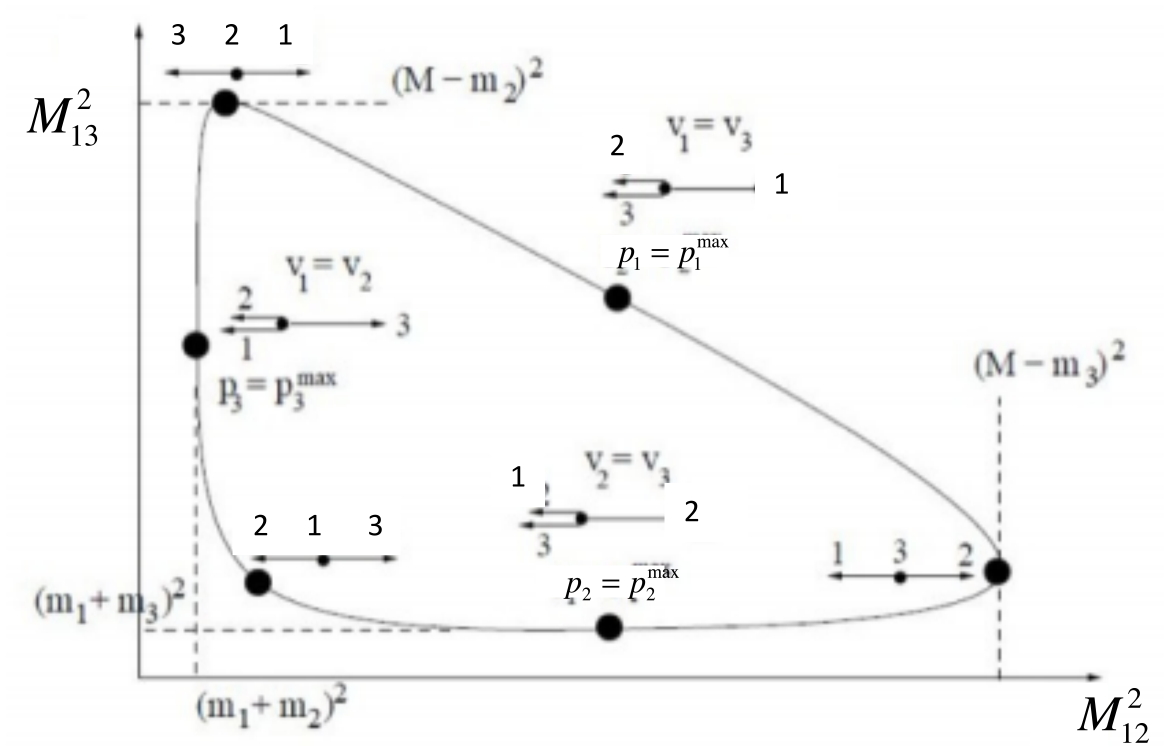
What is a Dalitz plot?

A scatter-plot that summarizes all that happens in meson decays to three spin-zero particles

$$X \rightarrow p_1 p_2 p_3$$

plot $M^2(p_1,p_2)$ versus $M^2(p_1,p_3)$

$$M^2(p_i,p_j) = M_{ij}^2 = (E_i + E_j)^2 - (\vec{p}_i + \vec{p}_j)^2$$

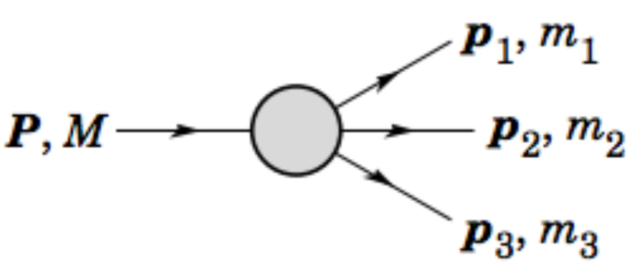


3

Why $M^2(p_i,p_j)$ and not $M(p_i,p_j)$??

If there are no dynamics in $X \rightarrow p_1 p_2 p_3$, only phase-space, the Dalitz Plot distribution is uniform,

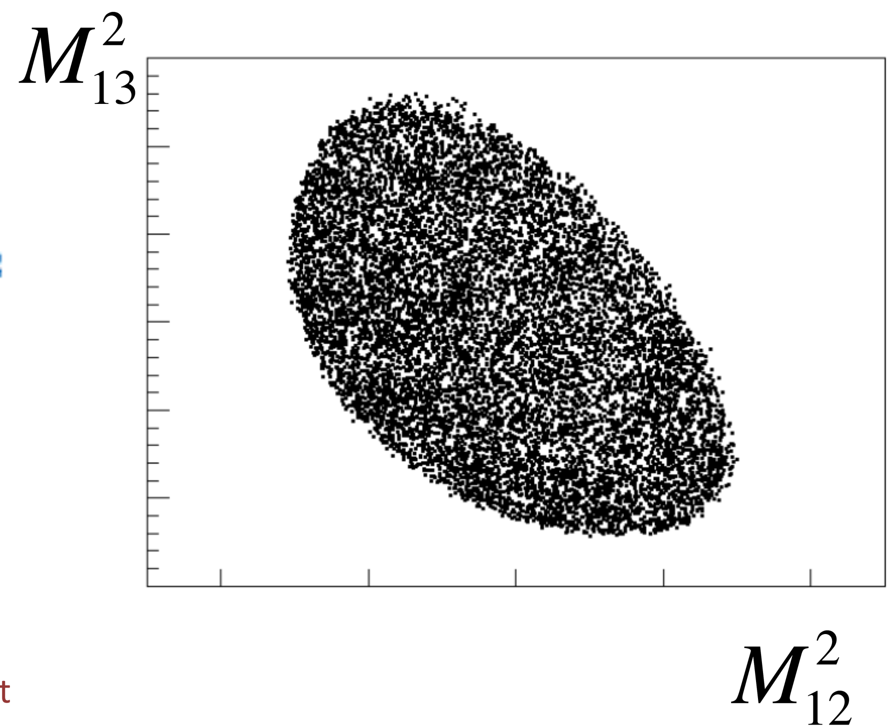
This would not be true for an $M(p_i,p_j)$ vs $M(p_i,p_k)$ plot



$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{8M} \overline{|\mathcal{M}|^2}\, dE_1\, dE_3$$

$$= \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathcal{M}|^2}\, dm_{12}^2\, dm_{13}^2$$

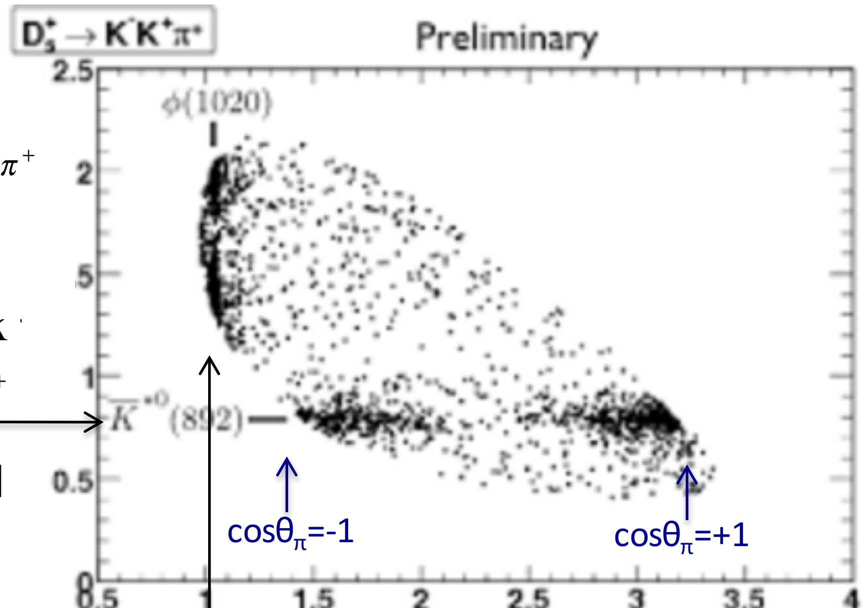
from the PDG booklet



Features of a Dalitz plot I

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

$M^2_{K^-\pi^+}$



$M^2_{K^+K^-}$

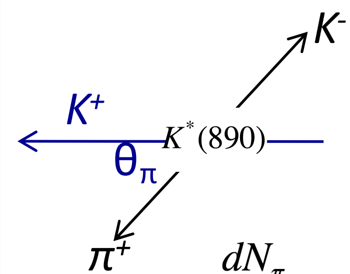
$D_S \to K^*(890)K$
$\quad \hookrightarrow K^-\pi^+$

a resonance in the p_1p_3 channel is a horizontal band

$D_S \to \phi(1020)\pi^+$
$\quad \hookrightarrow K^+K^-$

A vertical band indicates a resonance in the p_1p_2 channel

structure along a band indicates angular dependence

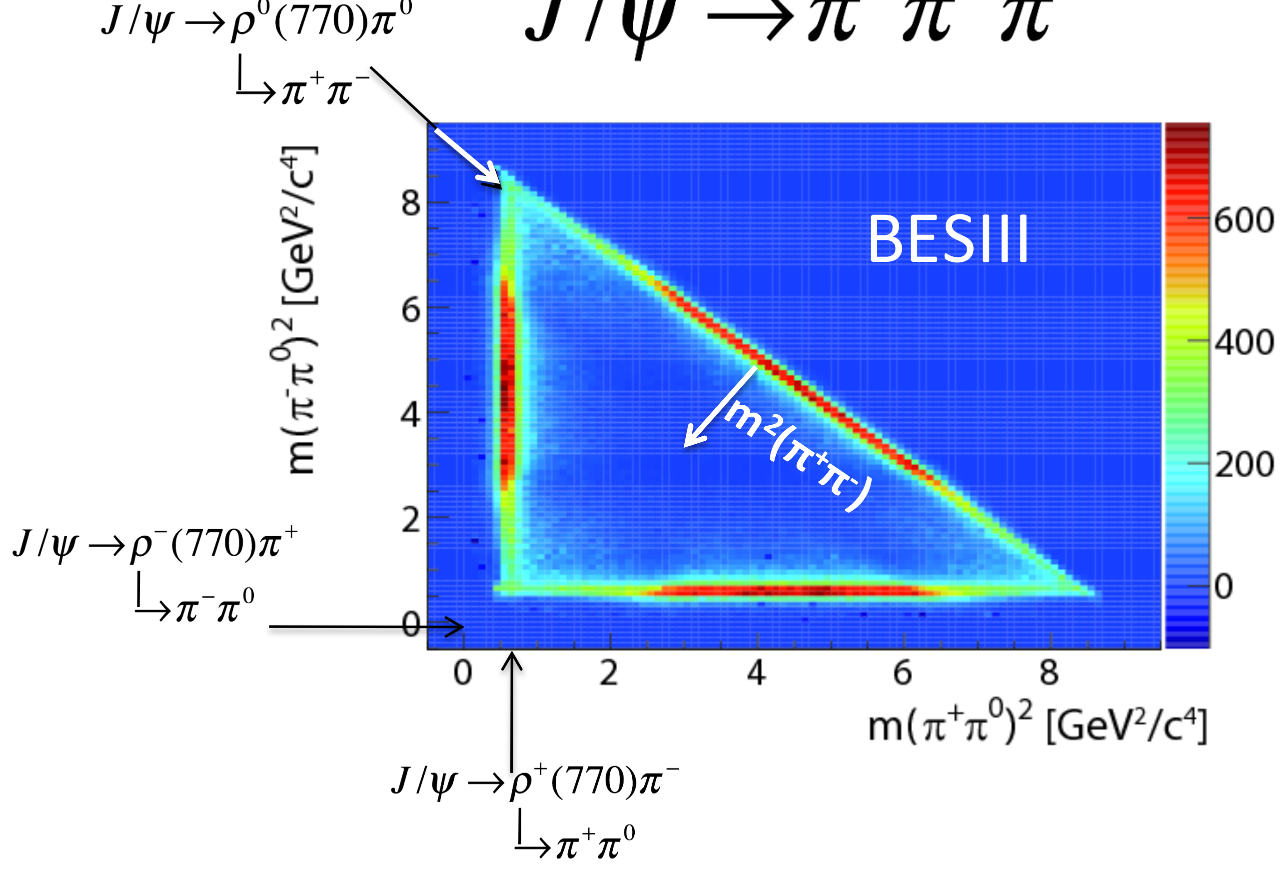


$$\frac{dN_\pi}{d\cos\theta_\pi} \propto \cos^2\theta$$

Features of a Dalitz plot II

a resonance in the p_2p_3 channel is a diagonal band

$$J/\psi \rightarrow \pi^0\pi^+\pi^-$$



Simple Breit-Wigner Resonance Amplitude

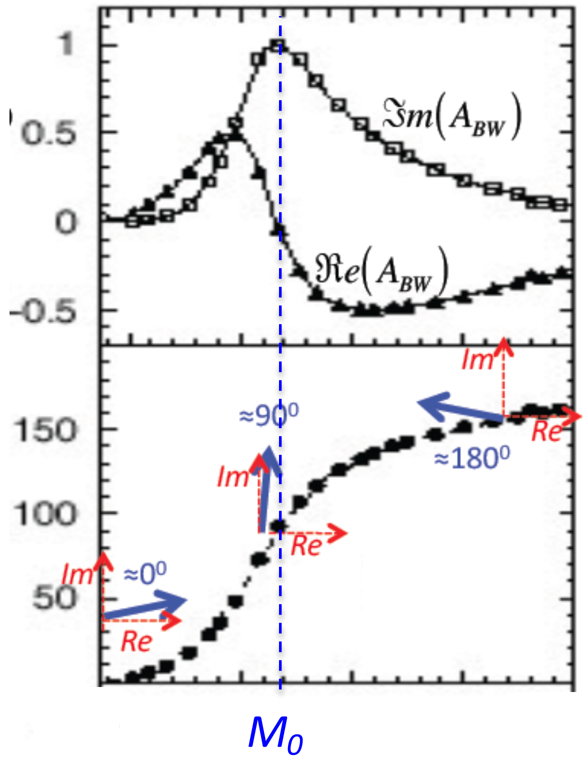
Breit Wigner Resonance Amplitude

$$A_{BW} \propto \frac{\frac{1}{2}\Gamma}{(M_0 - M_{ij}) - i\frac{\Gamma}{2}}$$

Re(A_{BW}) rapidly changes sign at $M_{ij}=M_0$

phase structure of A_{BW}

strong phase δ



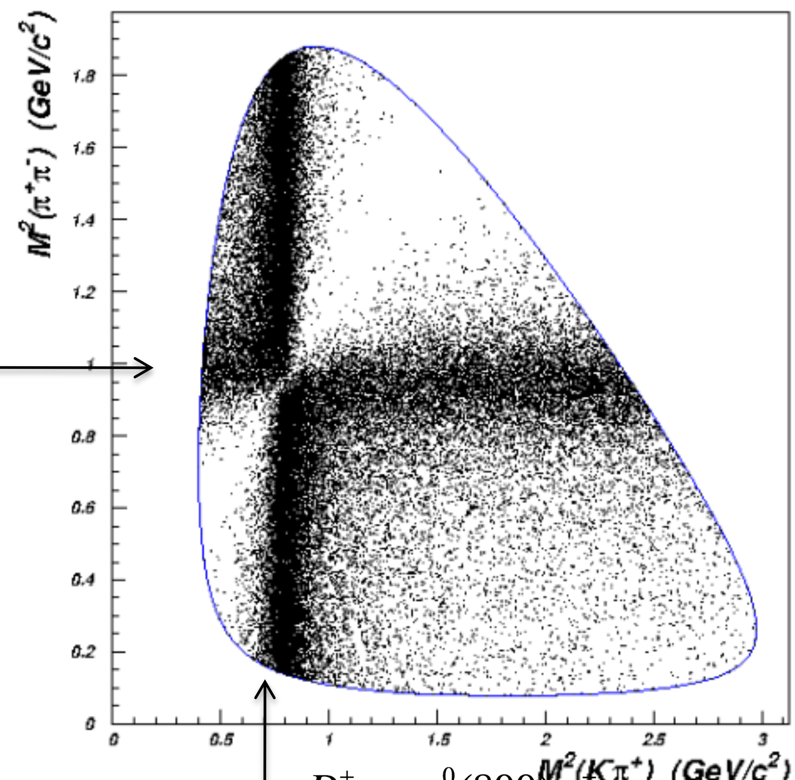
rapid phase (δ) at resonance peak

Properties of Dalitz plots III

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

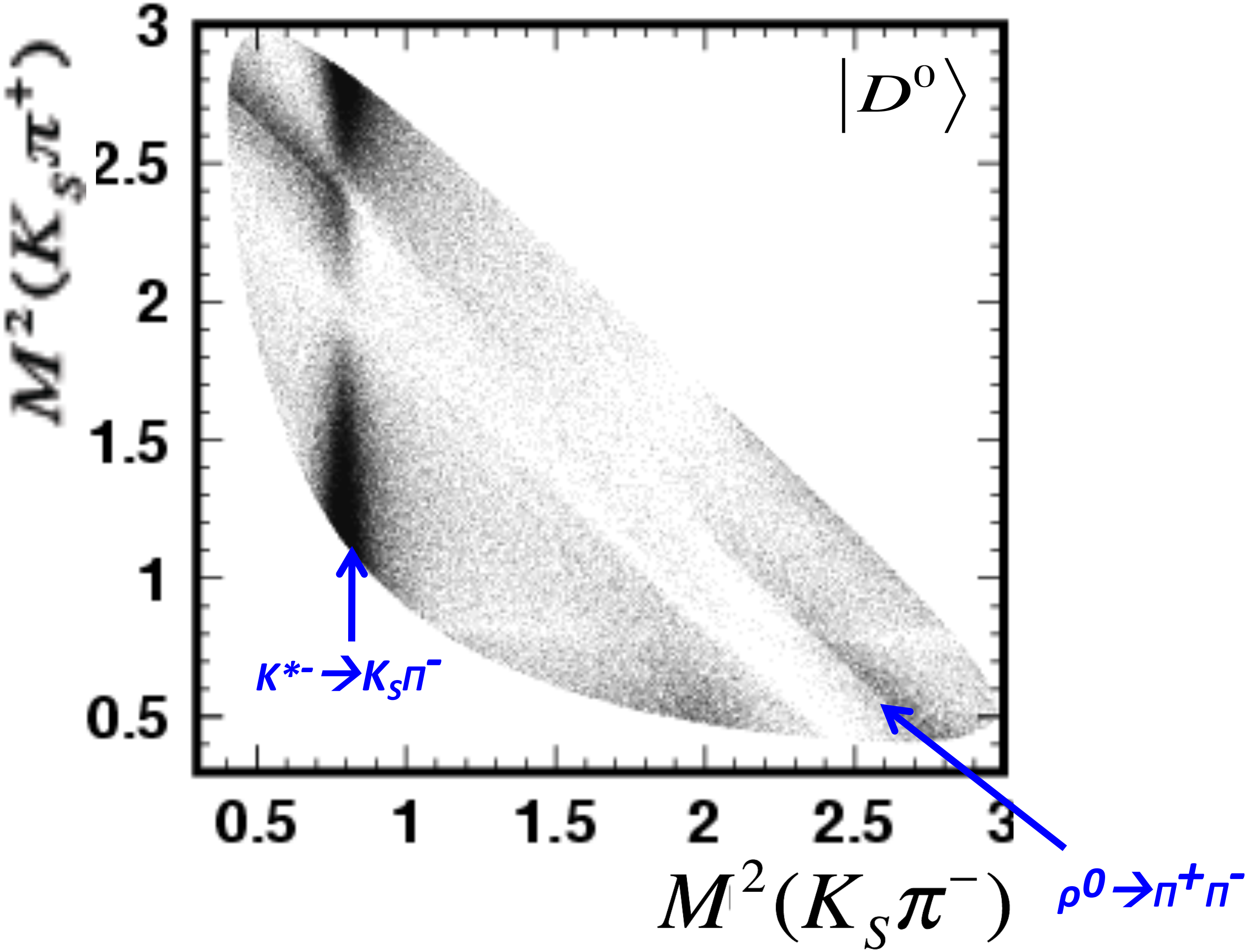
when resonance bands cross, they interfere, and the phase changes rapidly

$$D^+ \to f^0(980)K^+$$
$$\quad \hookrightarrow \pi^+\pi^-$$



$$D^+ \to \kappa^0(800)\pi^+$$
$$\quad \hookrightarrow K^-\pi^+$$

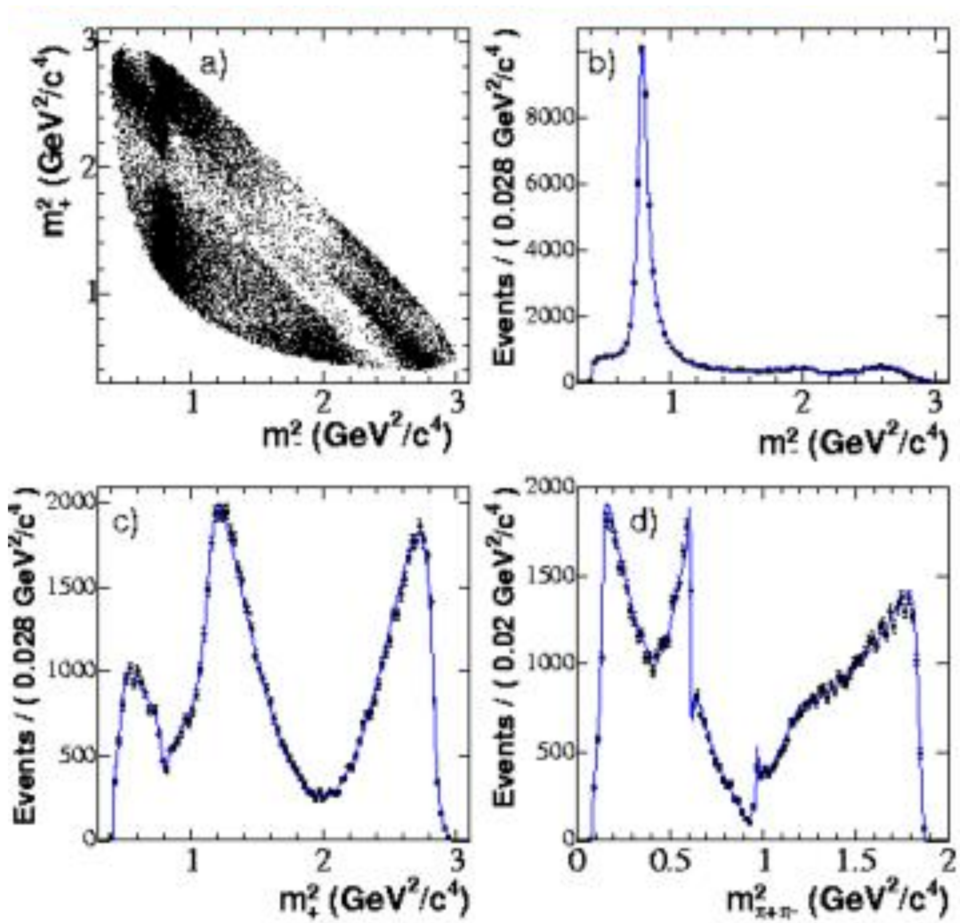
$D^0 \rightarrow K_S\pi^-\pi^+$ Dalitz plot



CLEOc model for D→$K_S\pi^+\pi^-$ DP

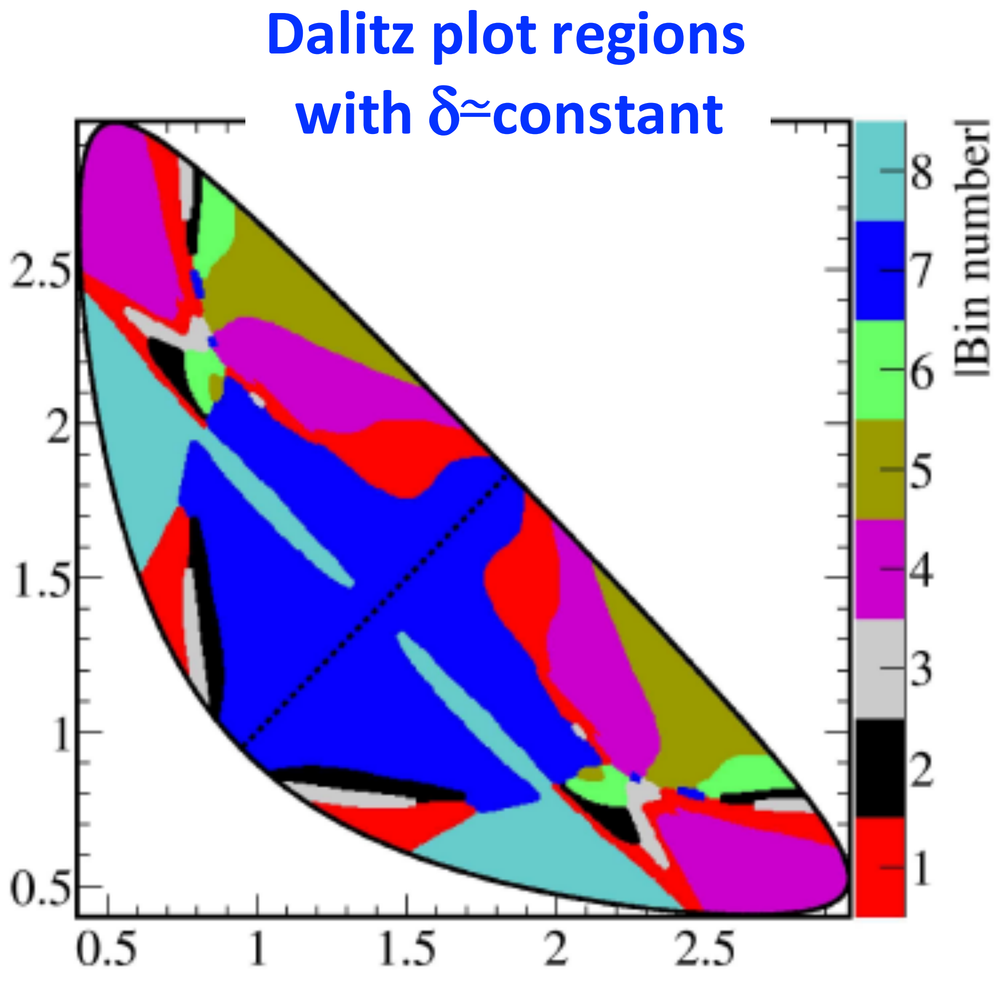
"flavor tag"

D^0? or $\bar{D}^0$? ← ψ(3770) → $K_S\pi^+\pi^-$

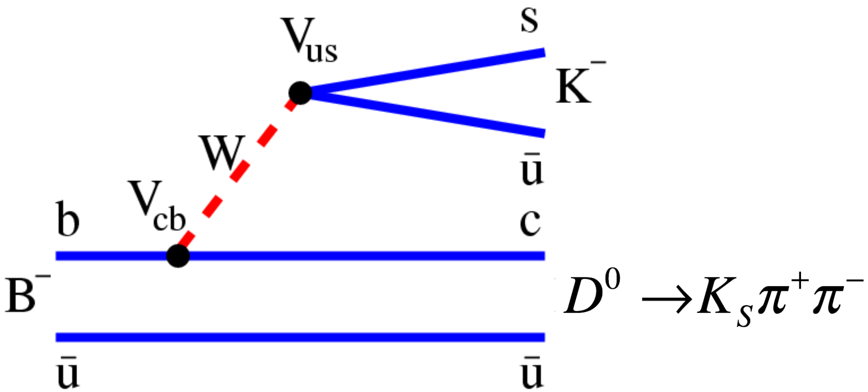


fit about 10 interfering
BW resonance amplitudes.

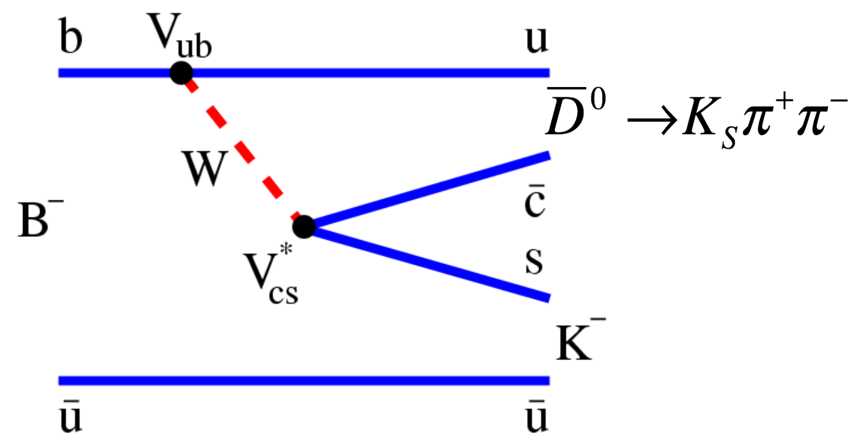
δ_{com} depends upon DP position



Back to γ (ϕ_3) in $B^{\pm} \rightarrow K^{\pm} D^0/\overline{D}^0$ decays



$\mathbf{A}_1 \propto V_{cb} V_{us}^* \sim A\lambda^3$



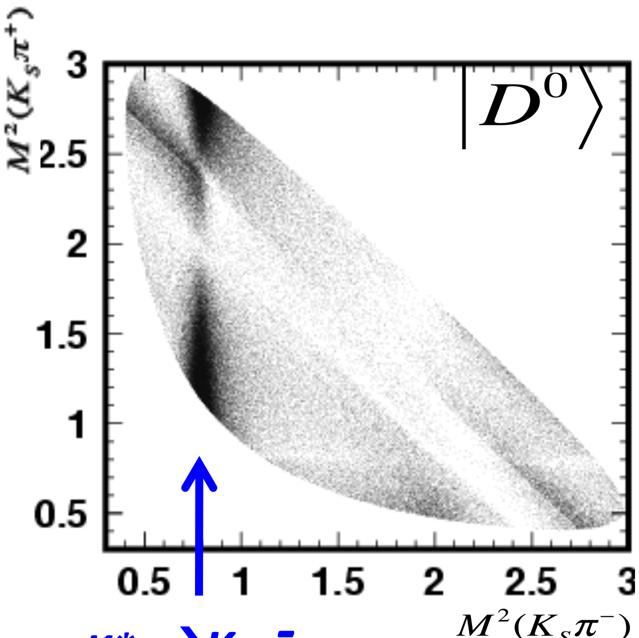
$\mathbf{A}_2 \sim V_{ub} V_{cs}^* \sim A\lambda^3(\rho - i\eta) \propto e^{-i\phi_3}$

$D^0/\bar{D}^0 \rightarrow K_S\pi^+\pi^-$ Dalitz plots

$$D^0 : \bar{u}c \longrightarrow s\bar{u} : K^{*-} \rightarrow K_S\pi^-$$

$$\bar{D}^0 : u\bar{c} \longrightarrow \bar{s}u : K^{*+} \rightarrow K_S\pi^+$$

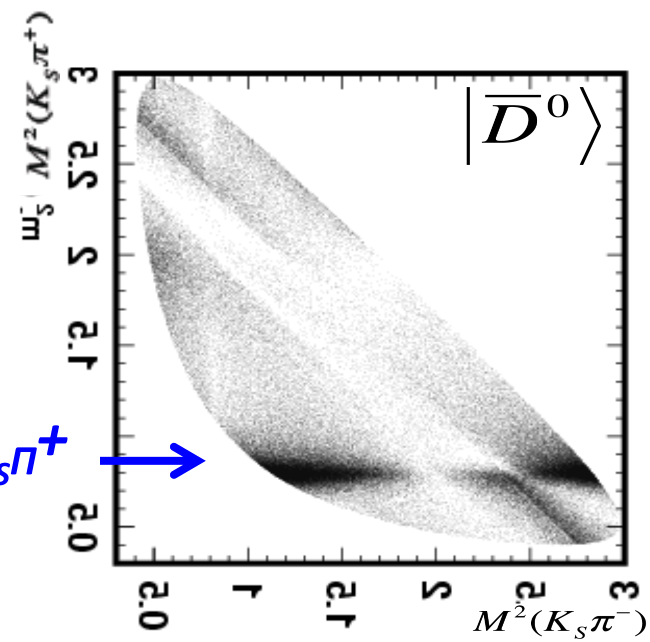
$D^0 \rightarrow K_S\pi^+\pi^-$ and $\bar{D}^0 \rightarrow K_S\pi^+\pi^-$ Dalitz plots are different



$K^{*-} \rightarrow K_S\pi^-$

$$+r_B e^{i(\delta_{com} \pm \phi_3)}$$

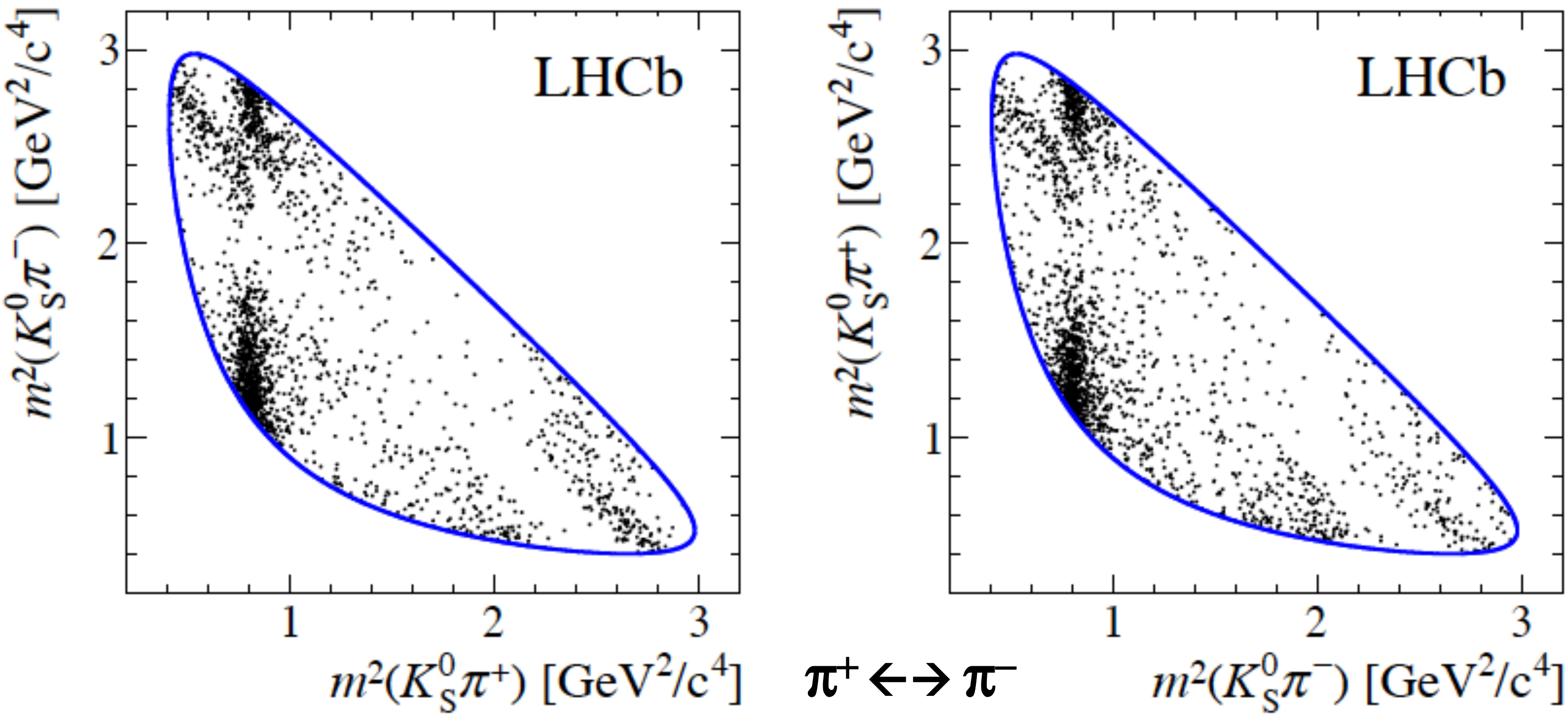
$K^{*-} \rightarrow K_S\pi^+$



LHCb Dalitz $B \to KD(K_S\pi^+\pi^-)$ samples

can you see a difference?
-- LHCb's computer can!

$B^+ \to K^+\tilde{D}$; $\tilde{D} \to K_S\pi^+\pi^-$ **$B^- \to K^-\tilde{D}$; $\tilde{D} \to K_S\pi^+\pi^-$**



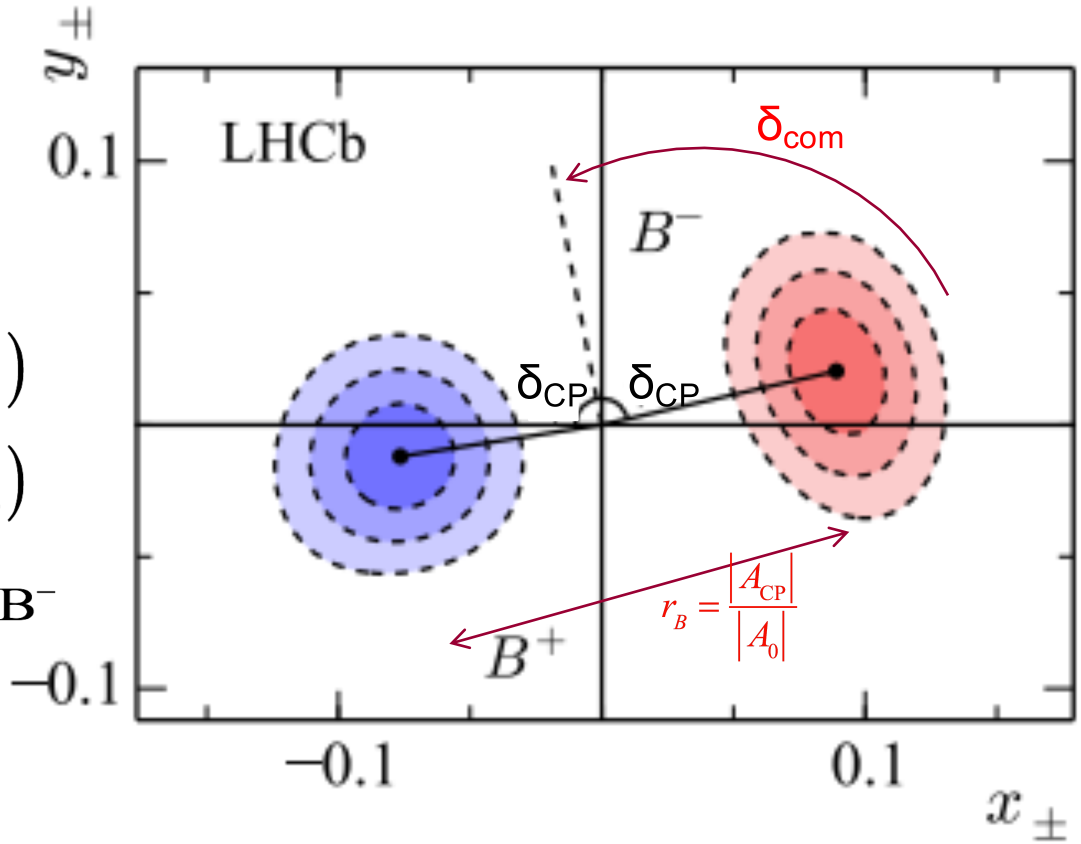
$\pi^+ \leftrightarrow \pi^-$

latest $\phi_3(\gamma)$ measurements from LHCb

$$x_\pm \equiv r_B \cos(\delta_B \pm \phi_3)$$

$$y_\pm \equiv r_B \sin(\delta_B \pm \phi_3)$$

+ for B^+ and - for B^-

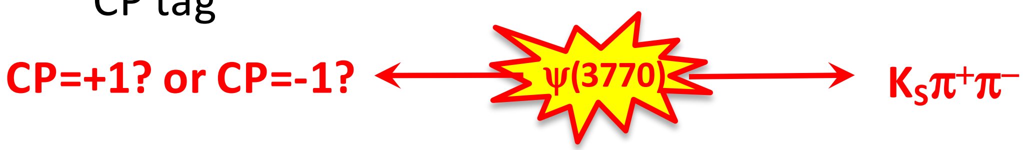


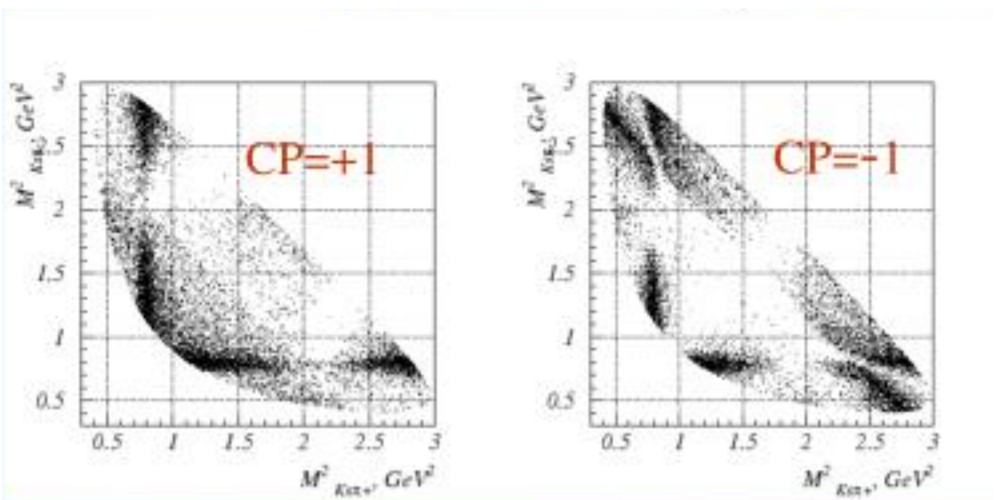
LHCb:arXiv 1806.01202

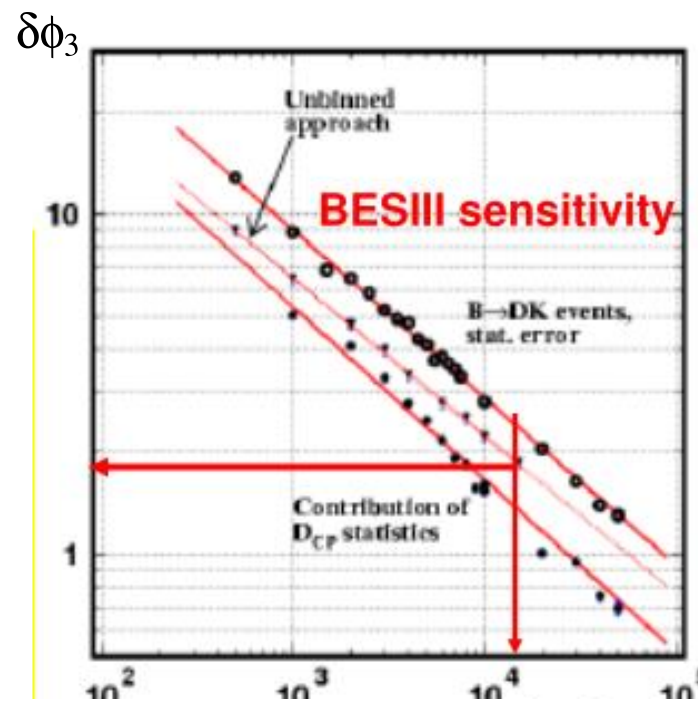
$\delta_{CP}=\gamma= 80^o \pm 10^o$
$\delta_{com}=110^o \pm 10^o$
$r_B=0.080 \pm 0.011$

Ultimate goal is CP-tagged $K_S\pi^+\pi^-$ DPs

“CP tag”







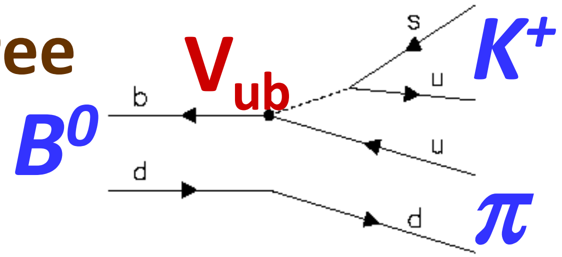
need ≈ 10 fb^{-1} of ψ(3770) data at BESIII

There is also a direct CPV in $B \rightarrow K^{\pm}\pi$ decays

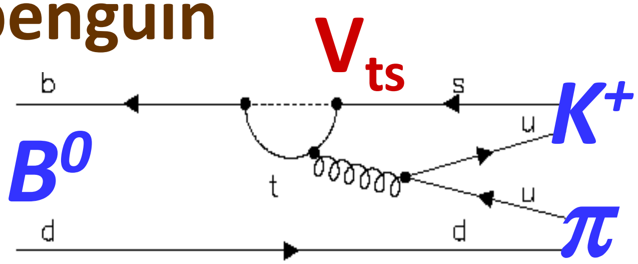
$B \rightarrow K^{\pm}\pi$

direct CPV via interference between tree and penguin

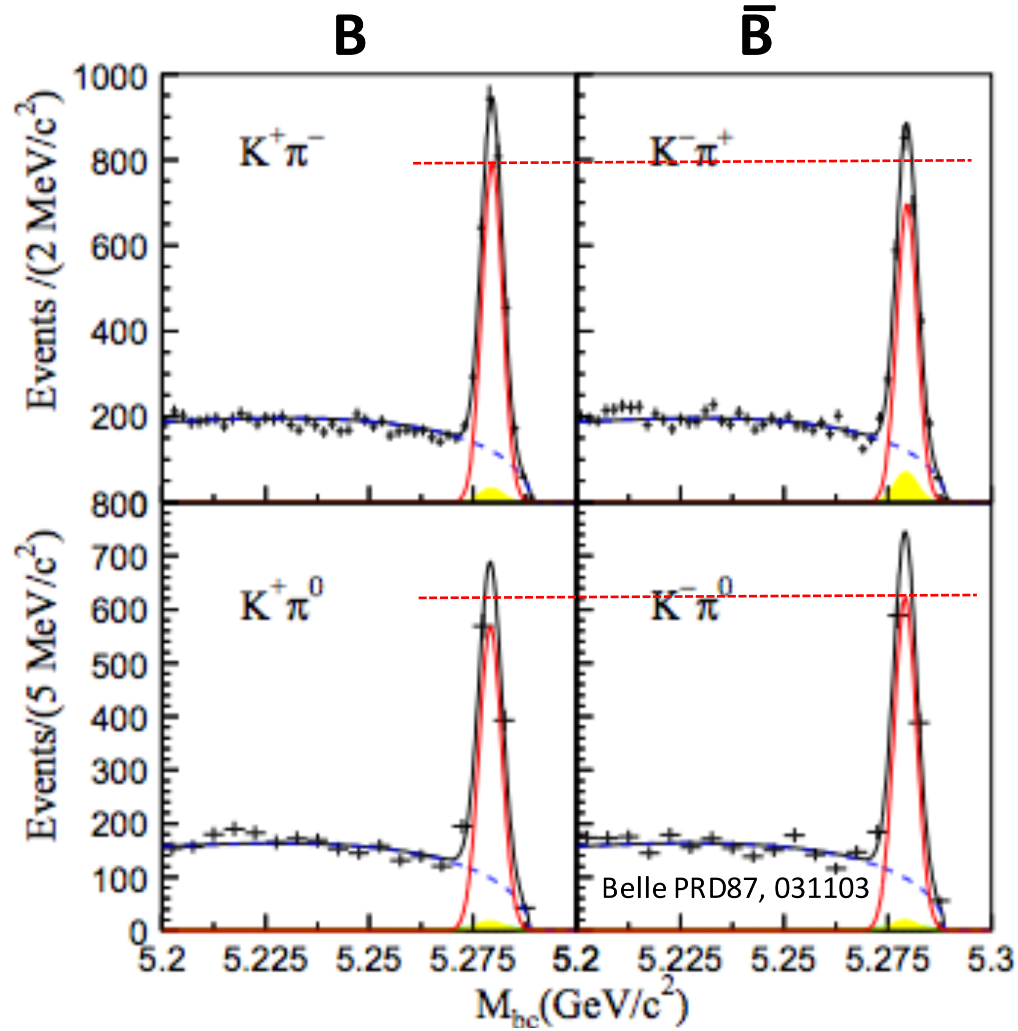
tree



penguin



difficult to interpret in terms of V_{ub}

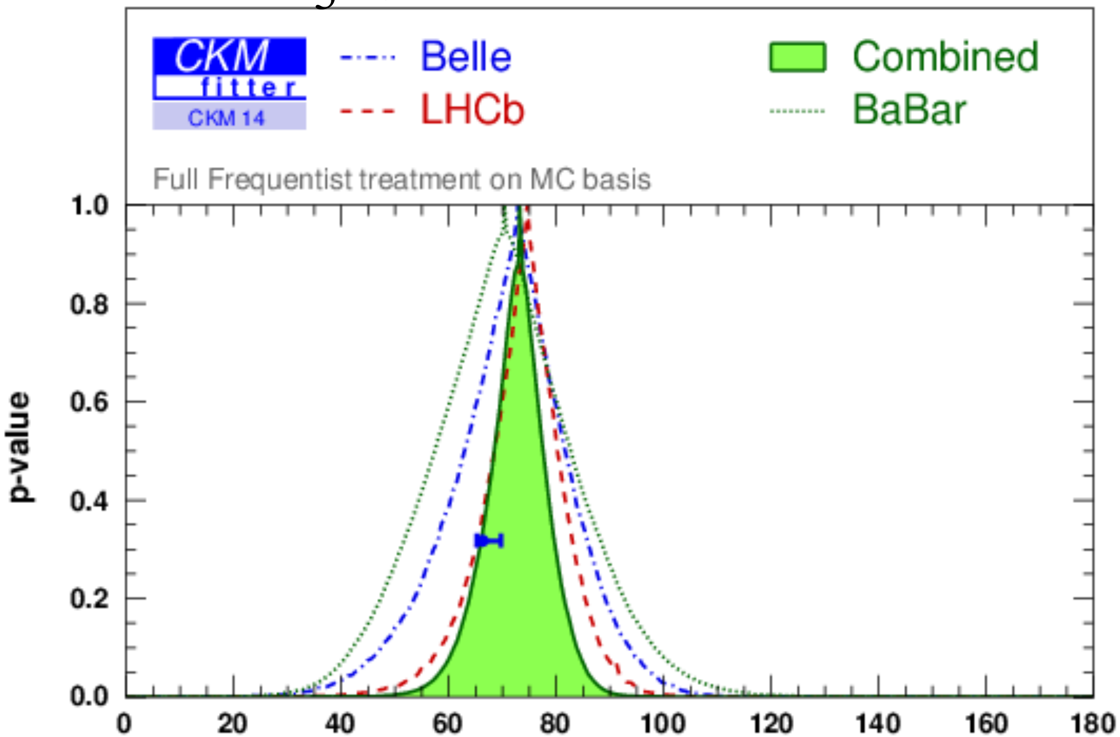


$$\mathcal{A}_{\overline{B}^0 \to K^-\pi^+} = -0.082 \pm 0.006 \;, \qquad \mathcal{A}_{B^- \to K^-\pi^0} = 0.040 \pm 0.021$$

theory prediction was that these 2 asymmetries would be equal

Summary of all measurements

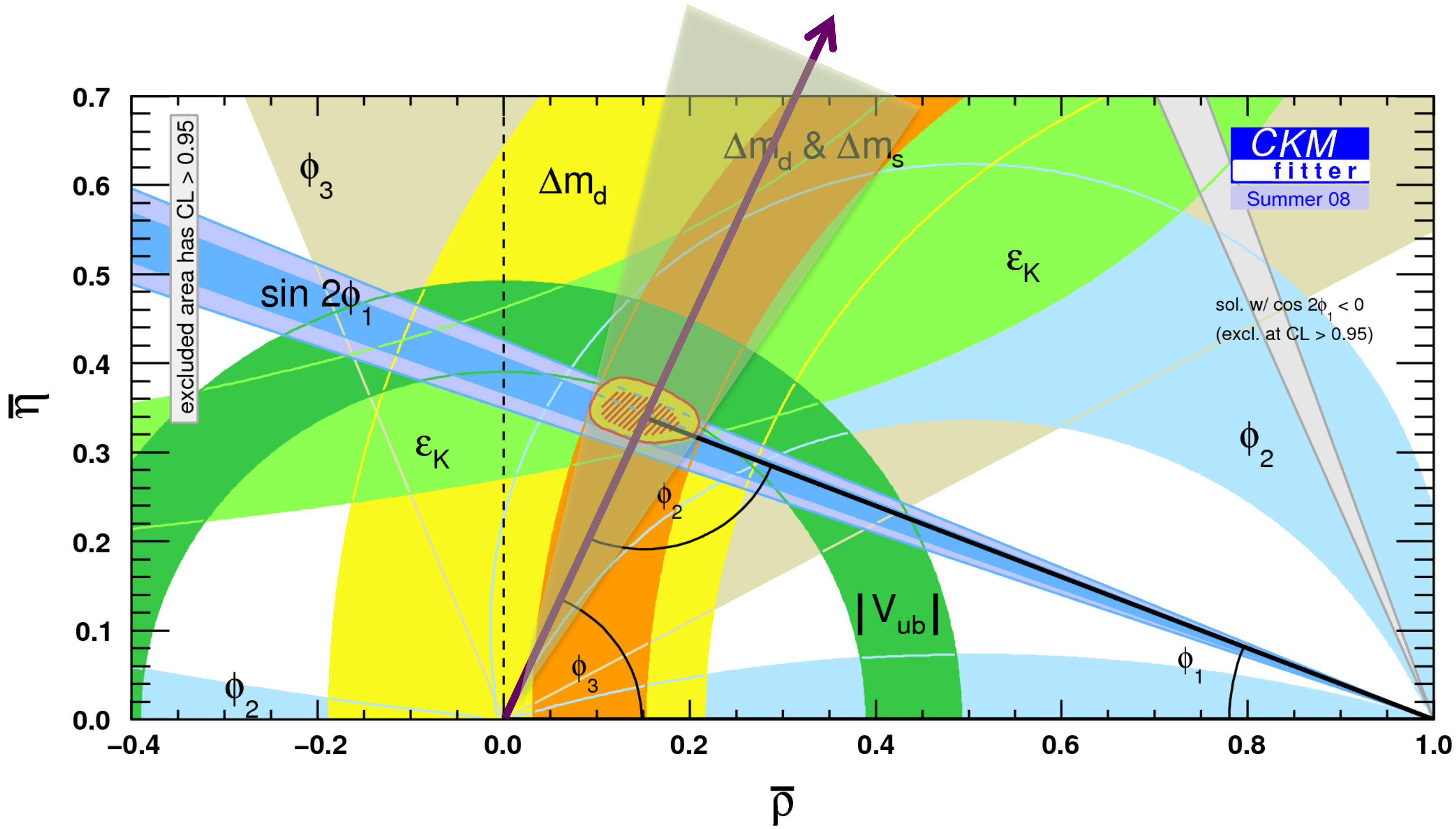
$$\phi_3(\gamma) = 76.2^{\circ} \pm 5.0^{\circ}$$



$+\phi_3$

M. Bona et al., (CKM-fitter Collab.), Eur. Phys. J C41, 113
http://CKMFITTER.IN2P3.FR

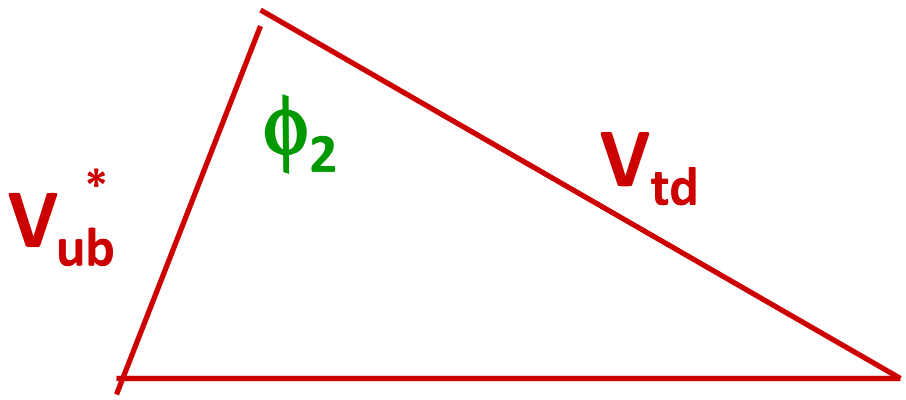
Revisit the Unitary triangle



This implies: $\phi_2 = 180^o - (21.9^o \pm 0.5^o) - (80.2^o \pm 10.0^o) = 84.2^o \pm 7.5^o$

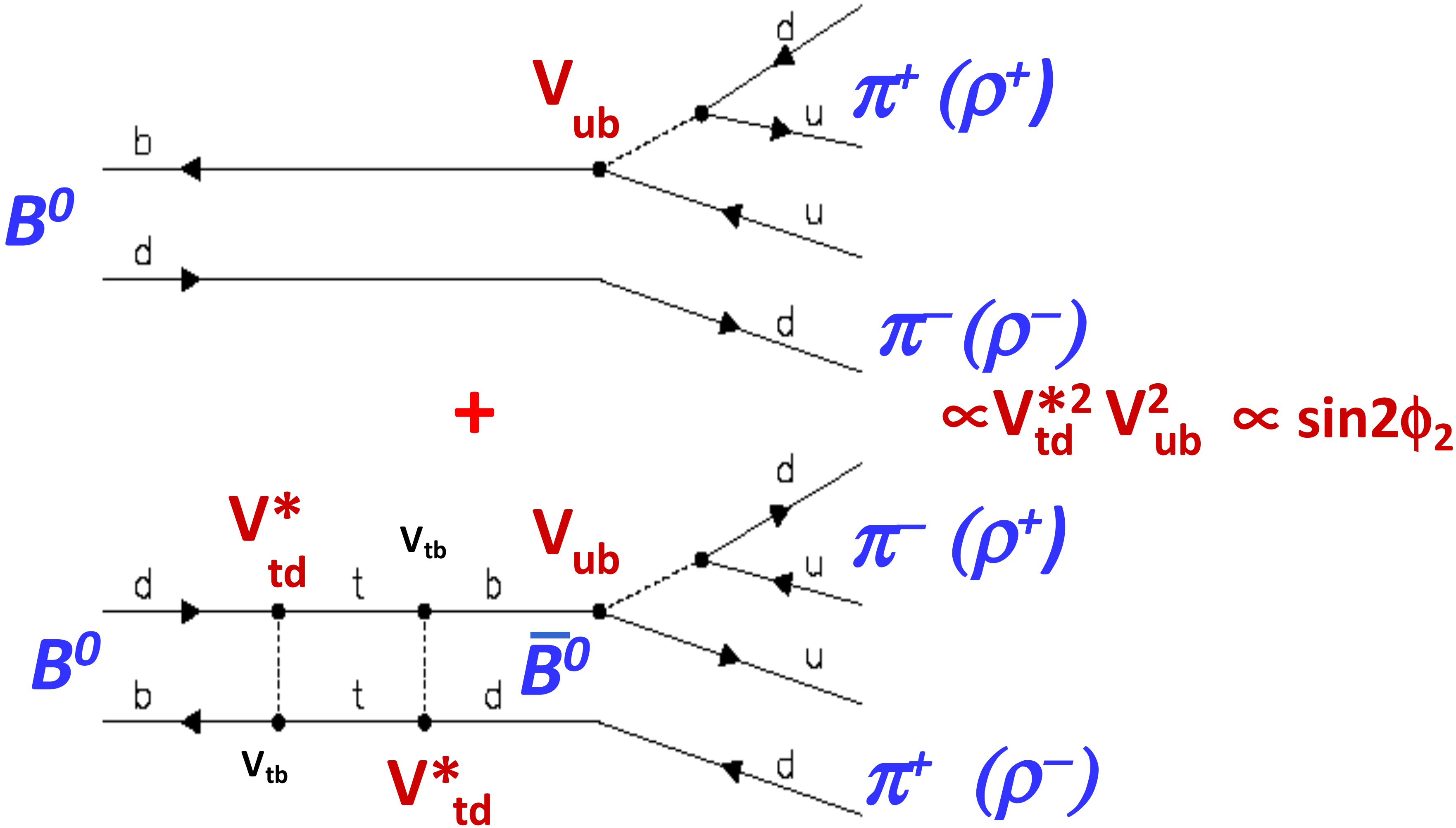
Is the Unitary triangle a right triangle??

Measuring ϕ_2 (α)



relative phase of V_{ub}^* and V_{td}

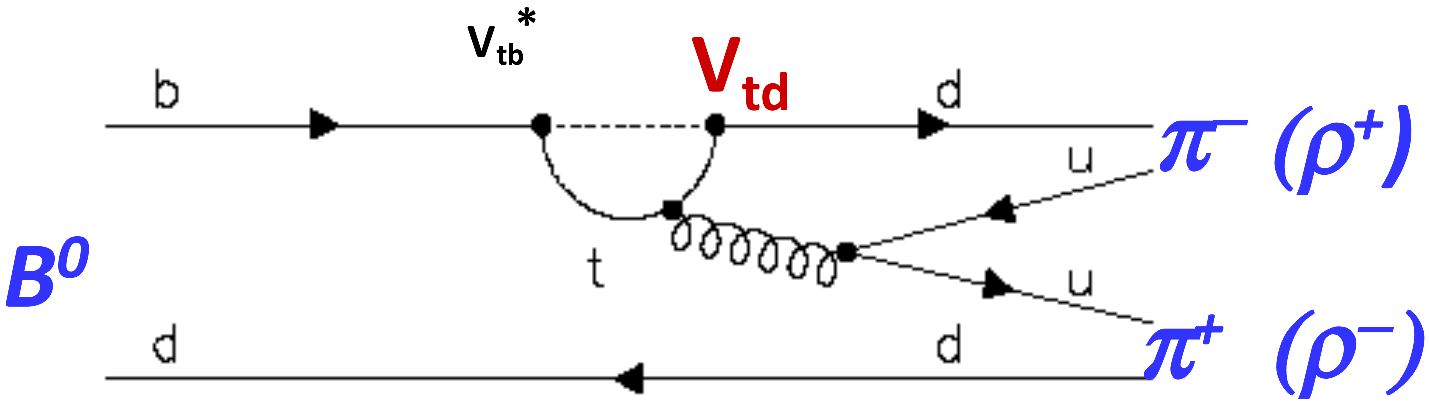
ϕ_2 (α) from $B \rightarrow \pi^+\pi^-$



Must deal with “Penguin Pollution”

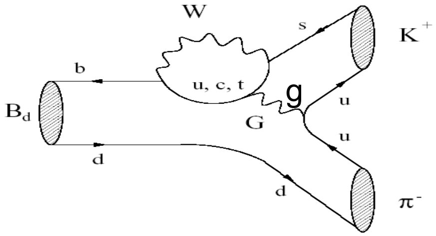
"Penguin" processes

i.e. additional, non-tree amplitudes



Penguins can be ~comparable in strength to b→u transitions

History of “Penguins”



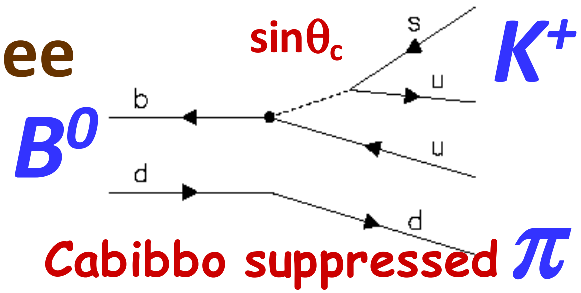
Ref: Preface to Shifman's 1999 book, ITEP Lectures on Particle Physics and Field Theory, John Ellis recalls how the gluon interference diagram came to be called a penguin diagram.

One night in spring 1977, Ellis lost a bet during a game of darts. His penalty required that he use the word "penguin" in a journal article. “For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time," Ellis wrote.

"Then, one evening I stopped on my way
back to my apartment to visit some friends living in Meyrin, where I smoked some illegal substance. *Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams looked like penguins.*
So we put the name into our paper, and the rest, as they say, is history."

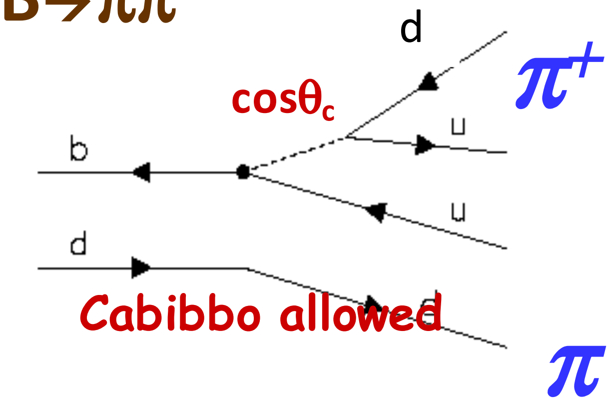
B→Kπ

tree

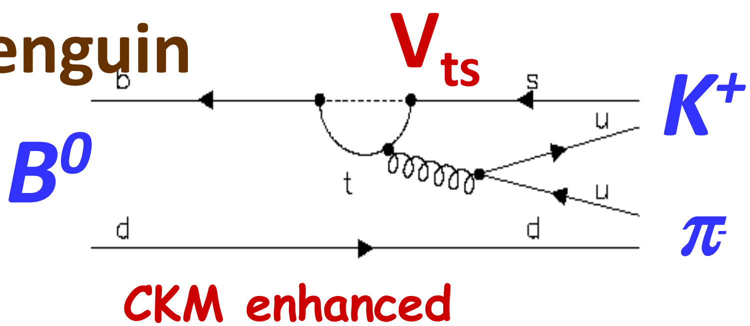


B→ππ

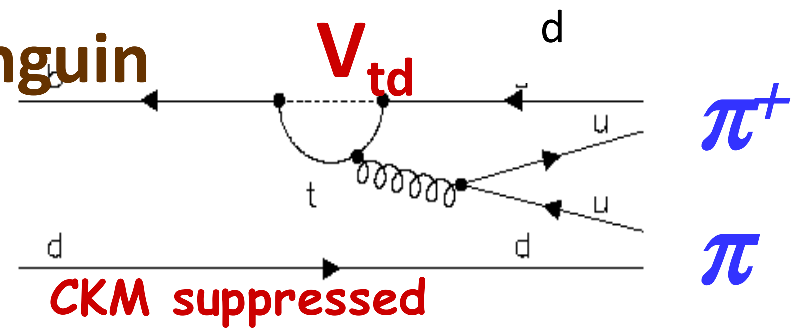
tree



penguin



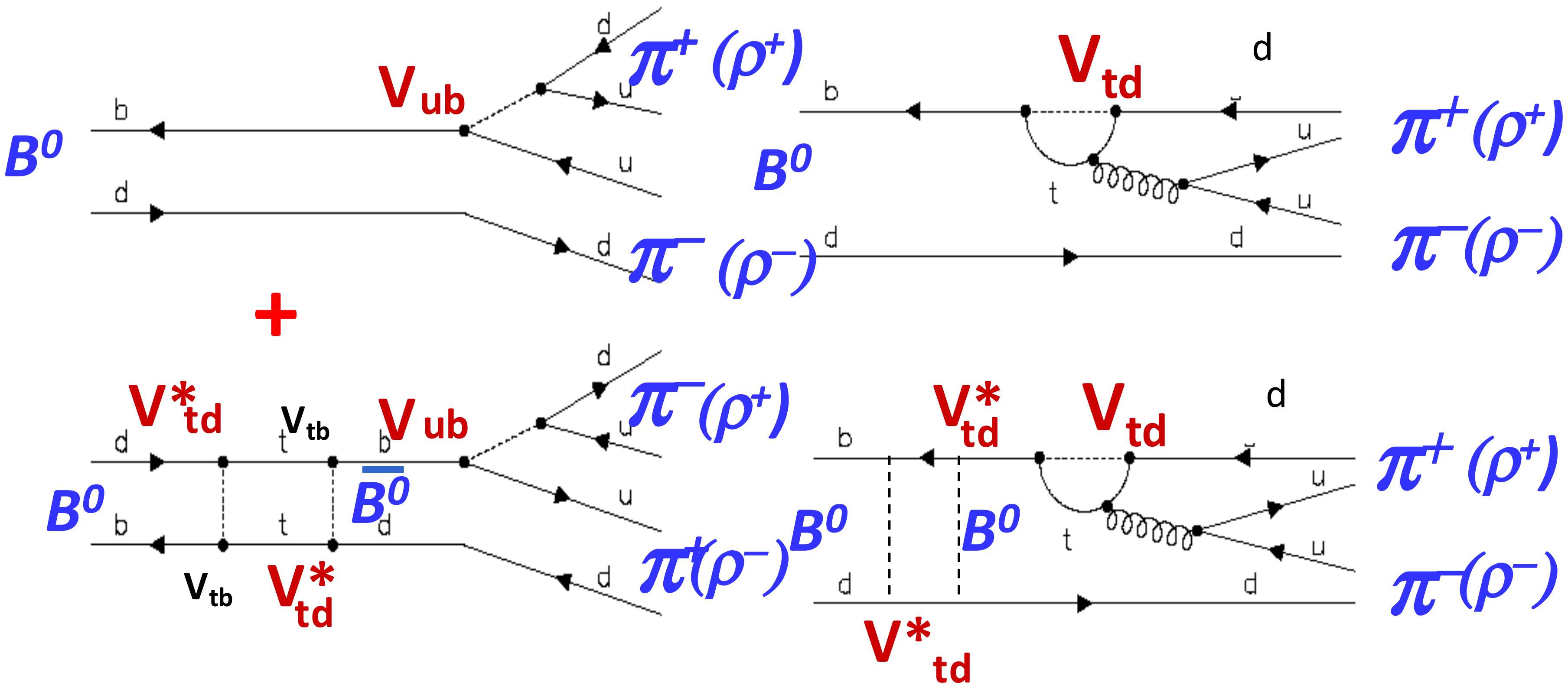
penguin



Expt: $\Gamma(K\pi) \sim 4 \times \Gamma(\pi\pi)$

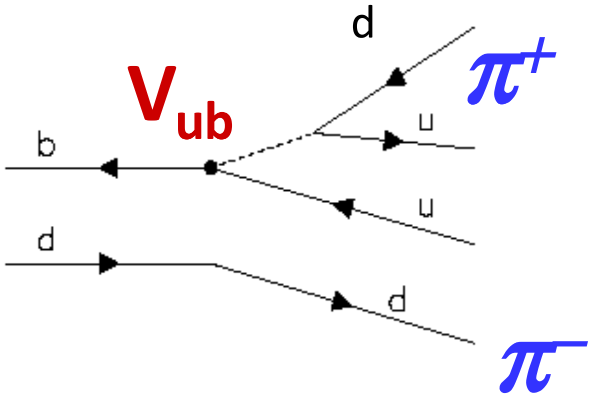
penguins ~ V_{ub} trees

Now four important diagrams

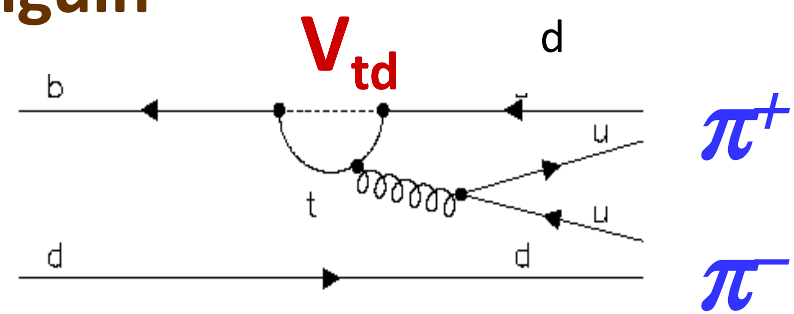


Direct CPV from penguin-tree interference??

tree



penguin



Ispin = 0 & 2 allowed

only Ispin = 0 allowed

strong phase difference (δ) is possible

$$\Gamma(B^0 \rightarrow \pi^+\pi^-) \neq \Gamma(\overline{B^0} \rightarrow \pi^+\pi^-)\ ??$$

"direct" CP violation

Δt dependence for $B \rightarrow \pi^+\pi^-$

direct CPV

mixing-induced CPV

$$R_q(\Delta t) \propto 1 + q\,(\boxed{A_{\pi\pi}}\cos(\Delta m \Delta t) + \boxed{S_{\pi\pi}}\sin(\Delta m \Delta t))$$

$q=+1 \rightarrow B^0$ tag

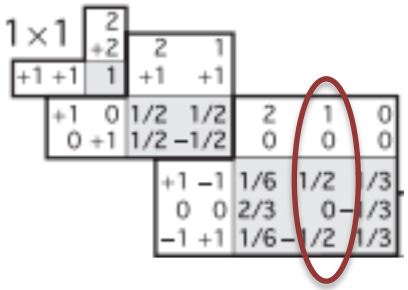
$q=-1 \rightarrow \overline{B^0}$ tag

$$S_{\pi\pi} = \sin 2\alpha_{eff} \quad \text{not} \quad \sin 2\alpha$$

$$\delta\alpha = \alpha_{eff} - \alpha \quad \Leftarrow \text{due to "Penguin pollution"}$$

Isospin analysis → triangle relation

-- pions are bosons → no *I=1* for $\pi\pi$ S-wave --



S-wave: symmetric in space exchange
I-spin=1 antisymmetric for $\pi^+ \leftarrow\rightarrow \pi^-$

$$A_{+-} = \left\langle \pi^+\pi^- \middle| H \middle| B^0 \right\rangle = -A_{\Delta I=\frac{1}{2}} + \tfrac{1}{\sqrt{2}} A_{\Delta I=\frac{3}{2}}$$

$$A_{00} = \left\langle \pi^0\pi^0 \middle| H \middle| B^0 \right\rangle = \tfrac{1}{\sqrt{2}} A_{\Delta I=\frac{1}{2}} + A_{\Delta I=\frac{3}{2}}$$

$$A_{+0} = \left\langle \pi^+\pi^0 \middle| H \middle| B^+ \right\rangle = \tfrac{3}{2} A_{\Delta I=\frac{3}{2}}$$

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

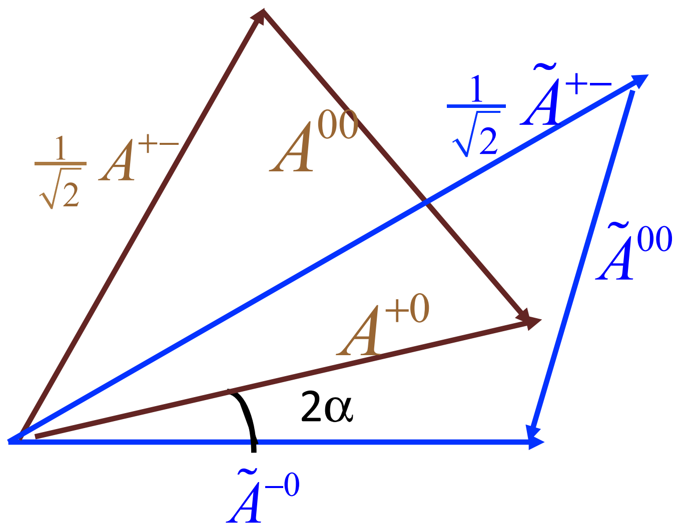
Determining $\delta\alpha = |\alpha - \alpha_{eff}|$

use triangle relations

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

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

$2\delta\alpha$



very hard to measur
errors are large

no penguin contribution to the $\pi^+\pi^0/\pi^-\pi^0$ modes: $|A^{+0}| = |\tilde{A}^{-0}|$

$$\begin{aligned}
A^{+-} &= A(B^0 \to \pi^+\pi^-) \\
\overline{A}^{+-} &= A(\overline{B}^0 \to \pi^+\pi^-) \\
A^{00} &= A(B^0 \to \pi^0\pi^0) \\
\overline{A}^{00} &= A(\overline{B}^0 \to \pi^0\pi^0) \\
A^{+0} &= A(B^+ \to \pi^+\pi^0) \\
\overline{A}^{-0} &= A(B^- \to \pi^-\pi^0)
\end{aligned}$$

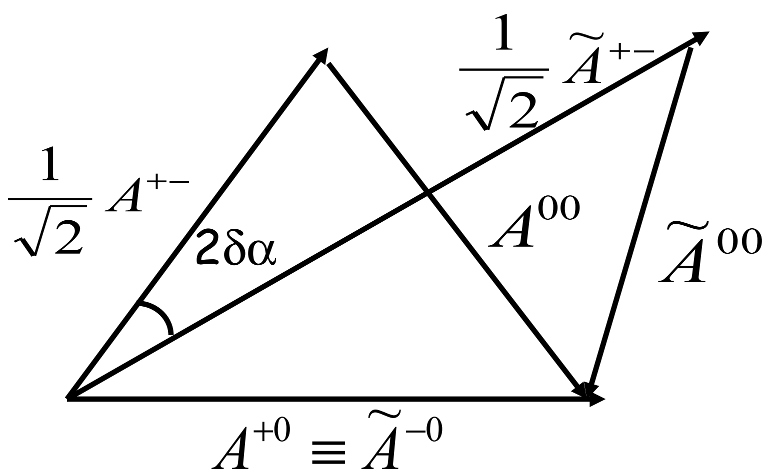
experimentally: $|A^{00}| \approx \frac{1}{\sqrt{2}} |A^{+-}|$

error on $|\overline{A}^{00}| - |A^{00}| \sim 50\%$

rotate blue triangle by 2α

i.e., allign A^{+0} & $\widetilde{A}^{-0}$

In principle, $\delta\alpha$ from the residual angle between $\frac{1}{\sqrt{2}}A^{+-}$ and $\frac{1}{\sqrt{2}}\widetilde{A}^{+-}$



need independent measurements of $B^0 \to \pi^0\pi^0$ and $\bar{B}^0 \to \pi^0\pi^0$

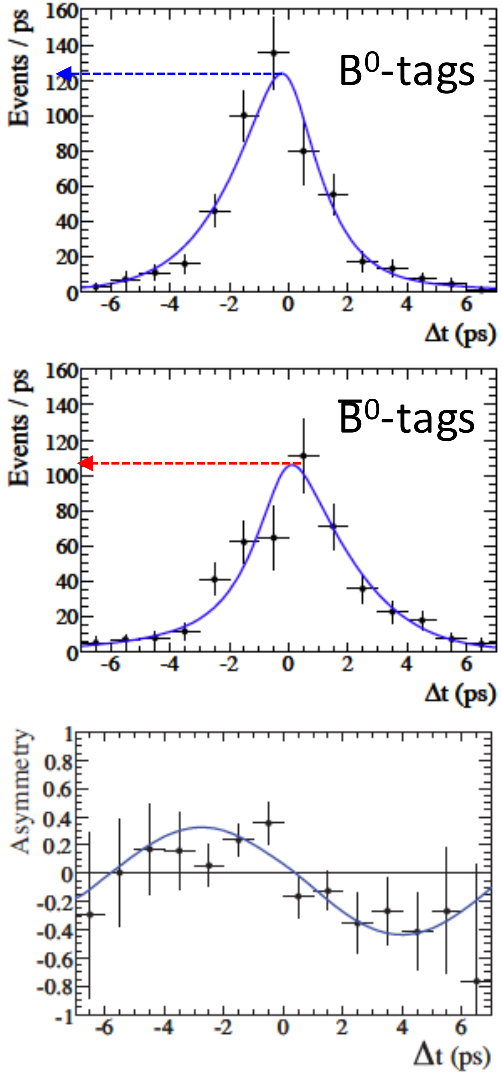
not so easy in practice:

experimentally: $\left|A^{00}\right| \approx \frac{1}{\sqrt{2}}\left|A^{+-}\right|$

error on $\left|\overline{A}^{00}\right| - \left|A^{00}\right| \sim 50\%$

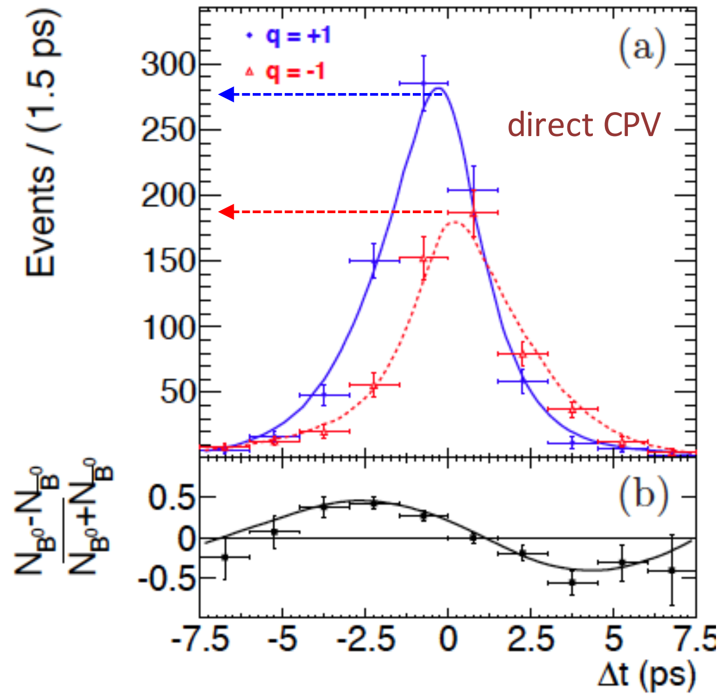
Results

BaBar



$$S_{\pi^+\pi^-} = -0.68 \pm 0.10 \pm 0.03,$$
$$C_{\pi^+\pi^-} = -0.25 \pm 0.08 \pm 0.02,$$

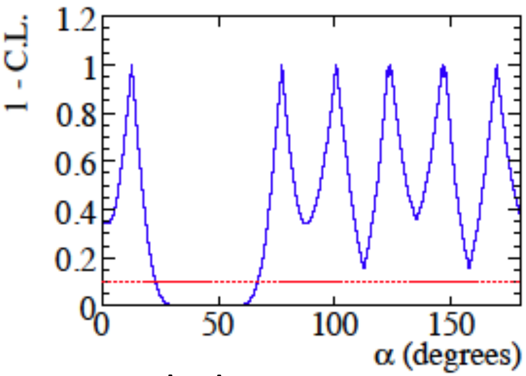
Belle



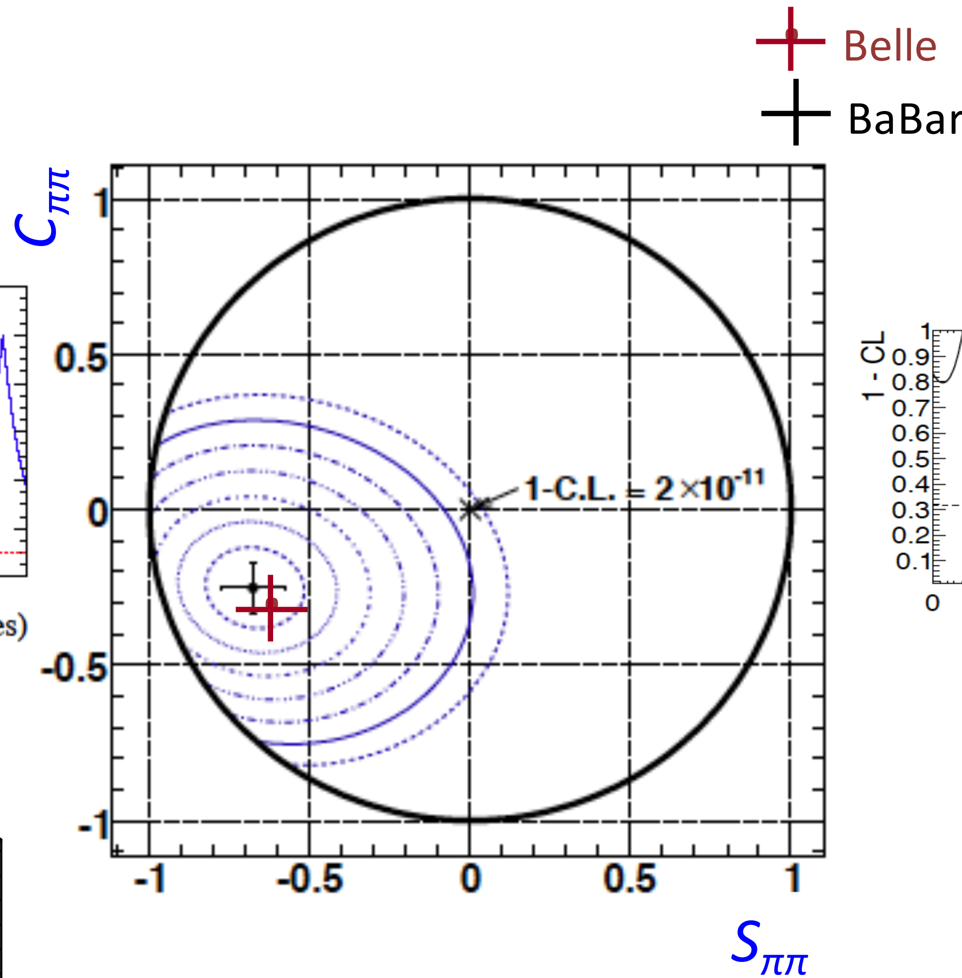
$$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06\,(\text{stat}) \pm 0.03\,(\text{syst}),$$
$$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08\,(\text{stat}) \pm 0.03\,(\text{syst}),$$

ϕ_2 Results from $B \to \pi^+\pi^-$

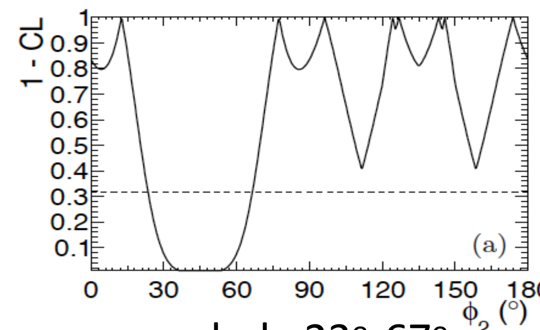
BaBar



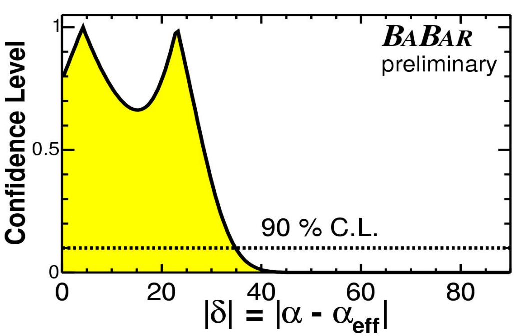
exclude 23°-67°



Belle



exclude 23°-67°



Large uncertainty due to Penguin Pollution

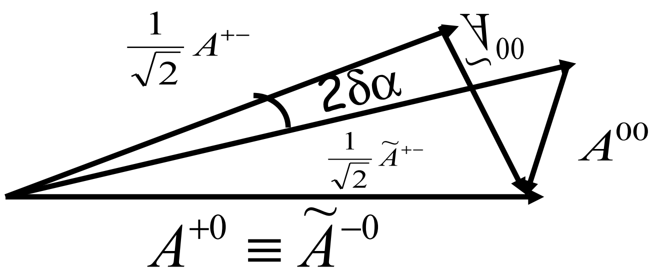
Less Penguin Pollution with B→ρρ

$$Bf(B^0 \to \rho^+\rho^-) = 24.2 \pm 3.1 \times 10^{-6}$$

$$Bf(B^0 \to \rho^0\rho^0) = 0.7 \pm 0.3 \times 10^{-6}$$

$$\begin{aligned}
A^{+-} &= A(B^0 \to \rho^+\rho^-) \\
\overline{A}^{+-} &= A(\overline{B}^0 \to \rho^+\rho^-) \\
A^{00} &= A(B^0 \to \rho^0\rho^0) \\
\overline{A}^{00} &= A(\overline{B}^0 \to \rho^0\rho^0) \\
A^{+0} &= A(B^+ \to \rho^+\rho^0) \\
\overline{A}^{-0} &= A(B^- \to \rho^-\rho^0)
\end{aligned}$$

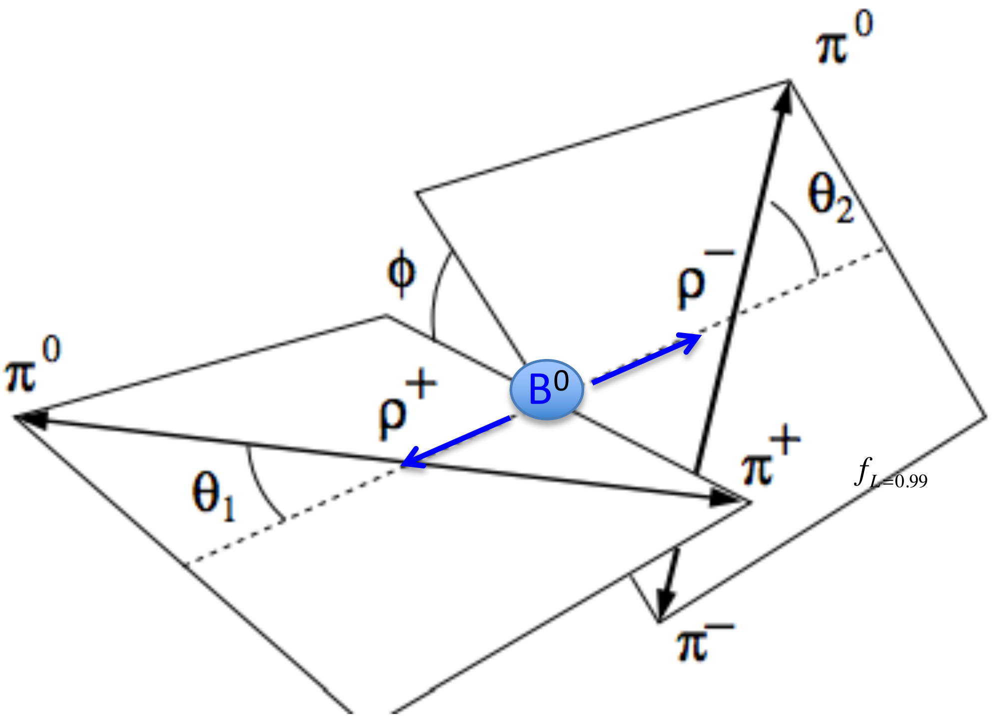
$$|A^{+-}| \approx 6 \times |A^{00}| \quad \Leftarrow \quad \text{the triangles are "squashed"}$$



No possibility for a large δα !

Also, the branching fraction for B→ρ⁺ρ⁻ is 5 times larger than B⁰->π⁺π⁻)

But: $B \rightarrow \rho^+\rho^-$ may not be a CP eigenstate

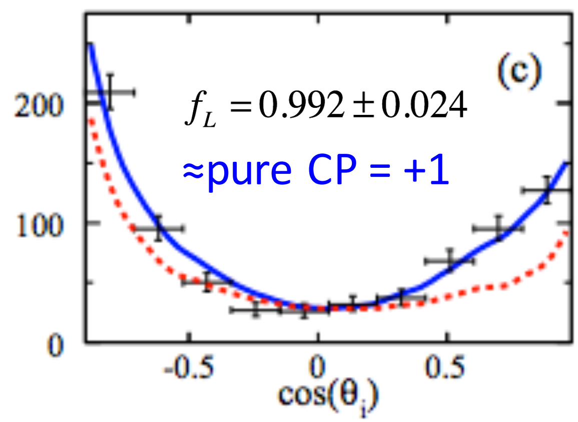


pure CP = +1

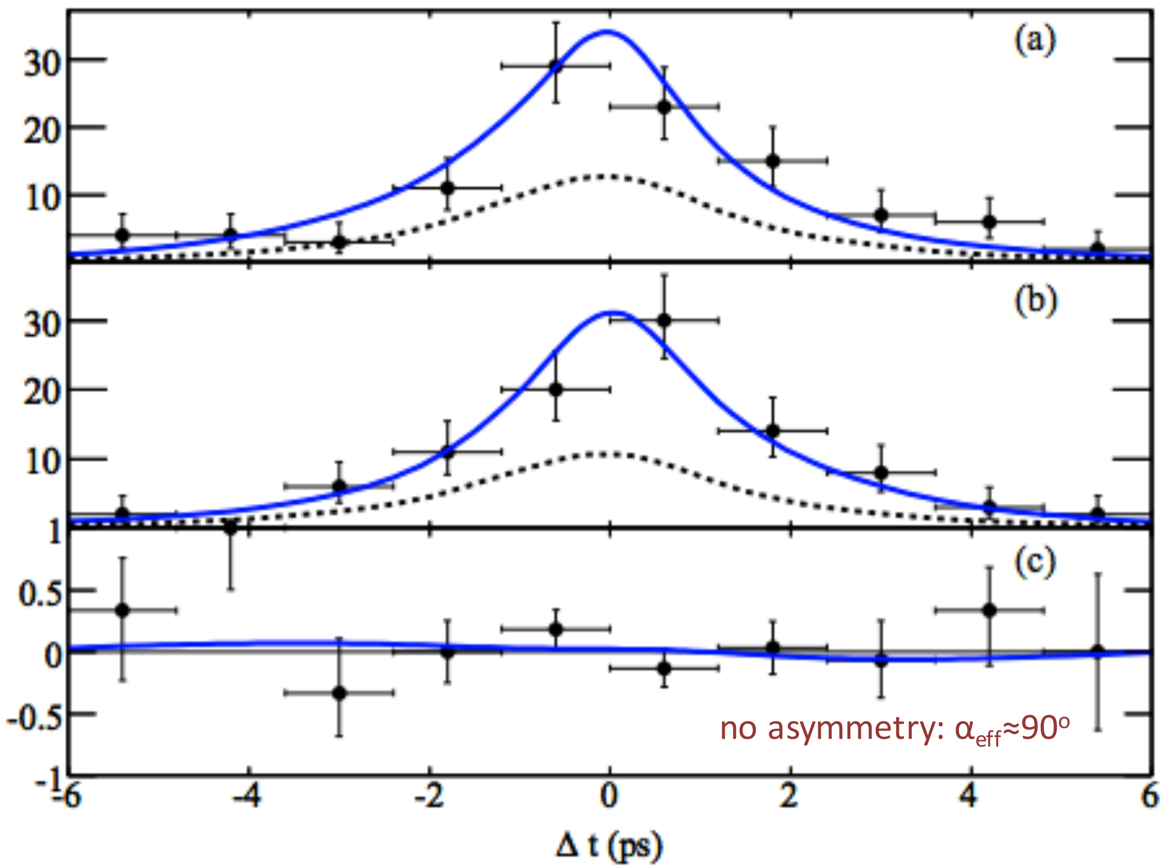
$$\frac{d^2\Gamma}{\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left[f_L \cos^2\theta_1 \cos^2\theta_2 + \frac{1}{4}(1-f_L)\sin^2\theta_1 \sin^2\theta_2 \right],$$

mixture of CP = +1 &-1

Nature is kind!



B→ρ⁺ρ⁻ results from Babar

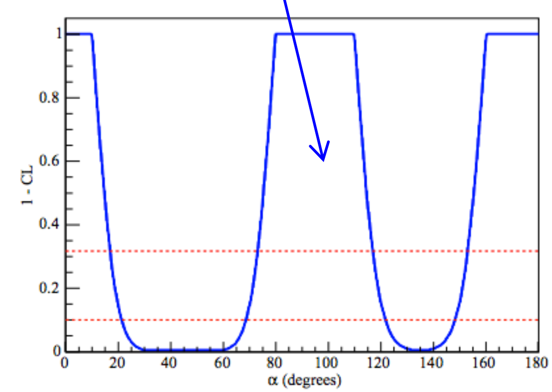


$$\sin 2\alpha_{eff} = -0.17 \pm 0.20$$

$$\Rightarrow \alpha_{eff} = 95^o \pm 11^o$$

include uncertainty in $\delta\alpha$

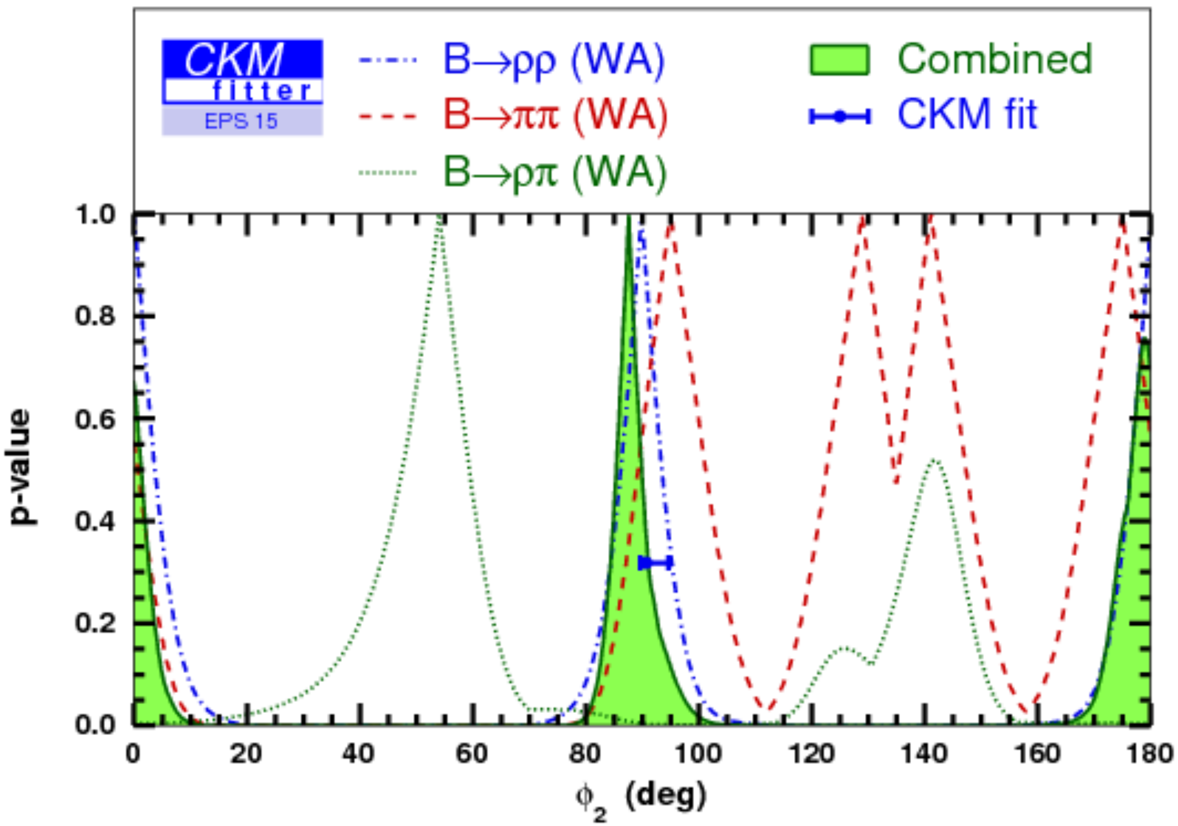
$$\Rightarrow \alpha = 95^o \pm 22^o$$



Summary of all results on ϕ_2

$\phi_2 = 87.6^o \pm 3.5^o$

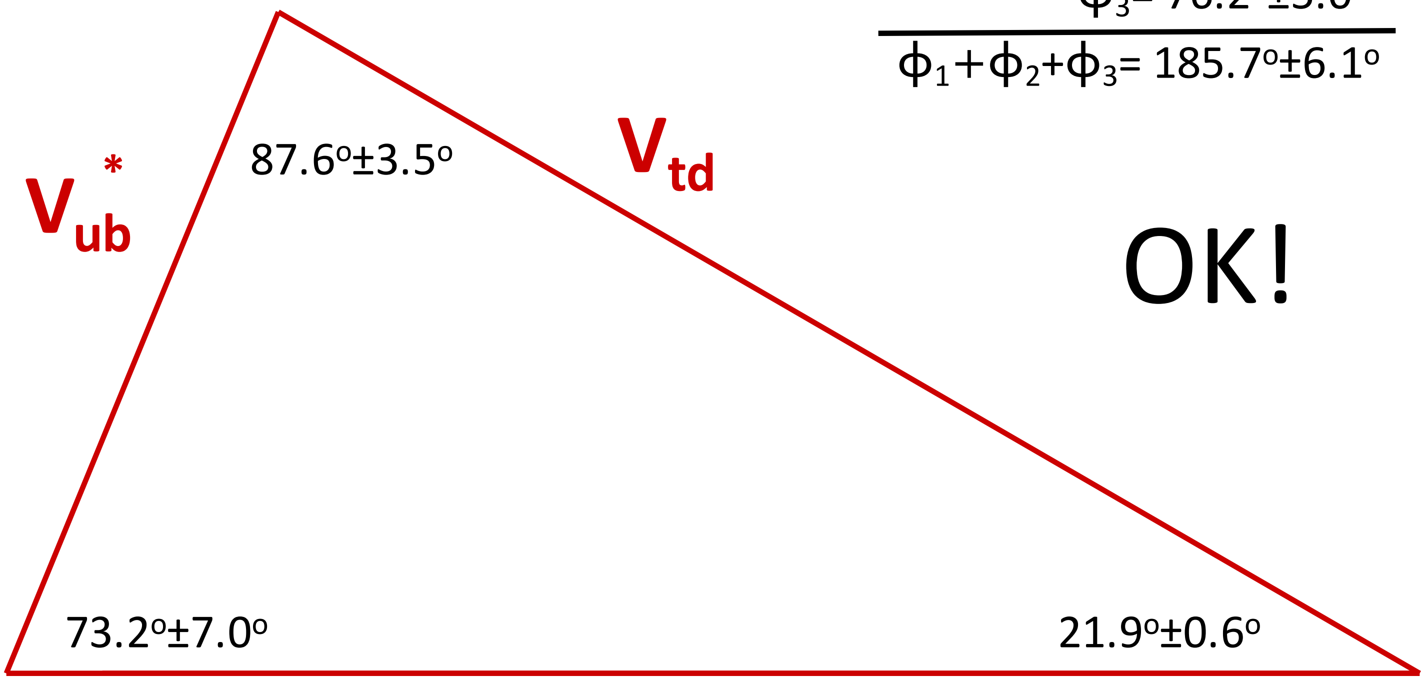
consistent with 90^o



Is the “Unitary Triangle” a triangle?

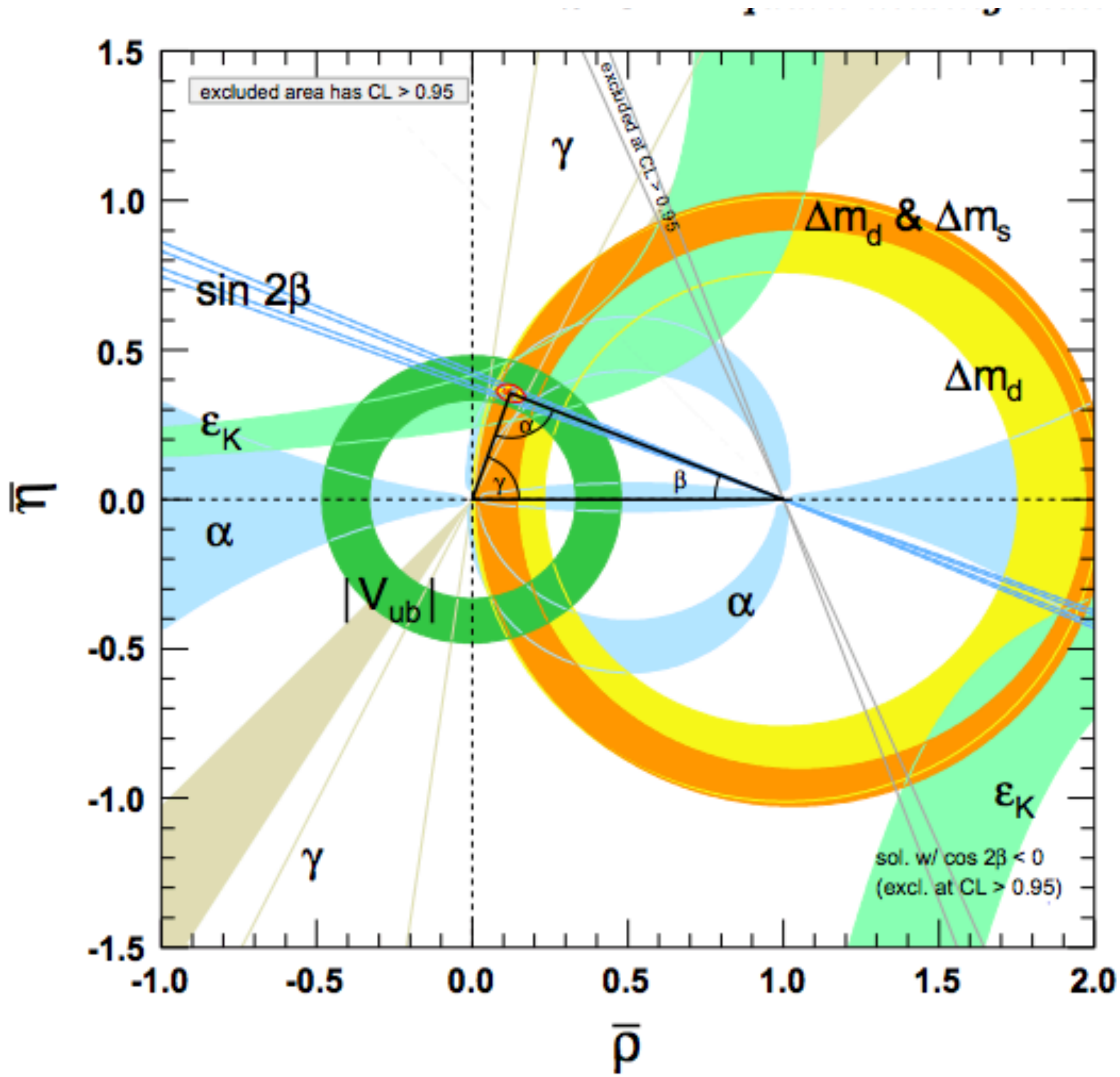
$\phi_1 = 21.9^o \pm 0.6^o$
$\phi_2 = 87.6^o \pm 3.5^o$
$\phi_3 = 76.2^o \pm 5.0^o$

$\phi_1 + \phi_2 + \phi_3 = 185.7^o \pm 6.1^o$



OK!

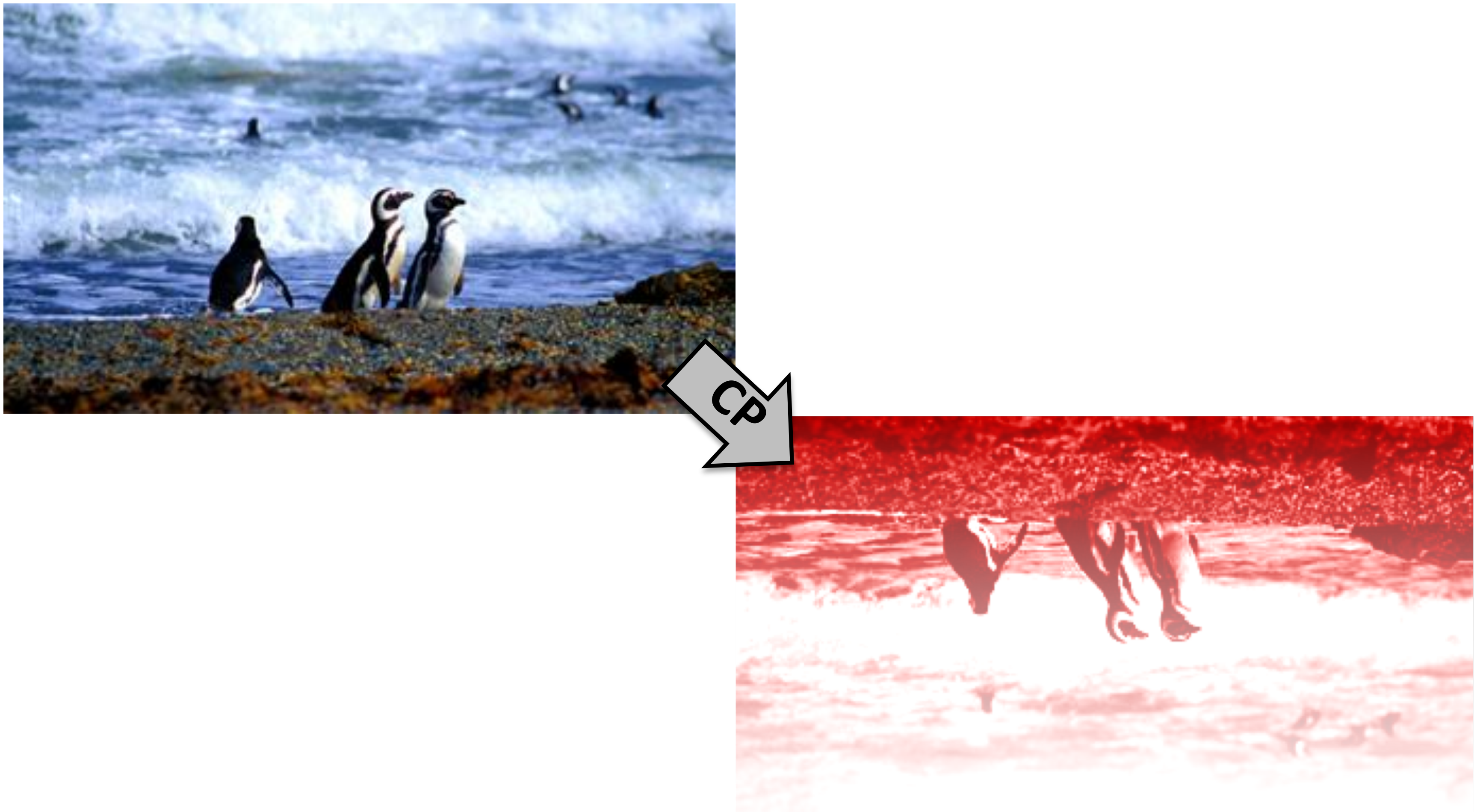
PDG 2018



excluded area has CL > 0.95
γ
excluded at CL > 0.95
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
|V_ub|
α
ε_K
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
η̄
ρ̄

What’s next?

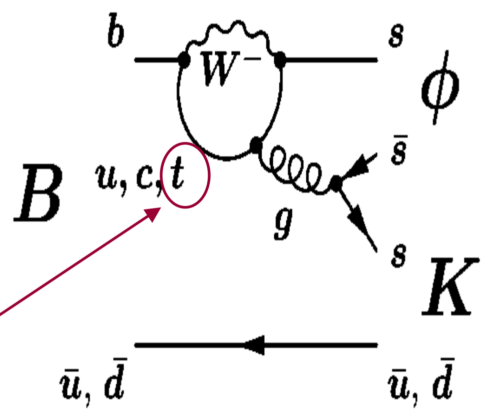
Probing CPV with Penguins



New Physics in Penguin loops

b→s FCNC decay

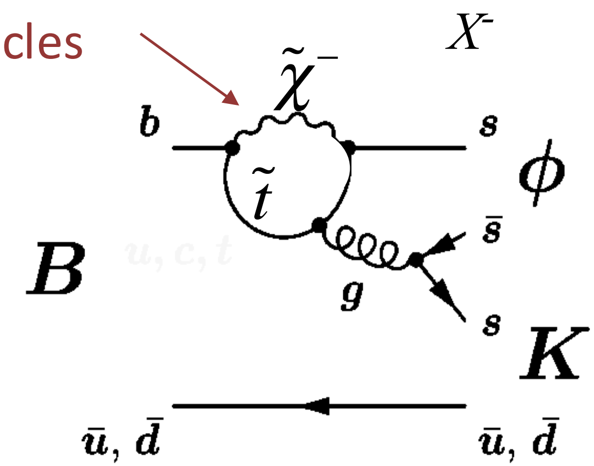
Standard Model



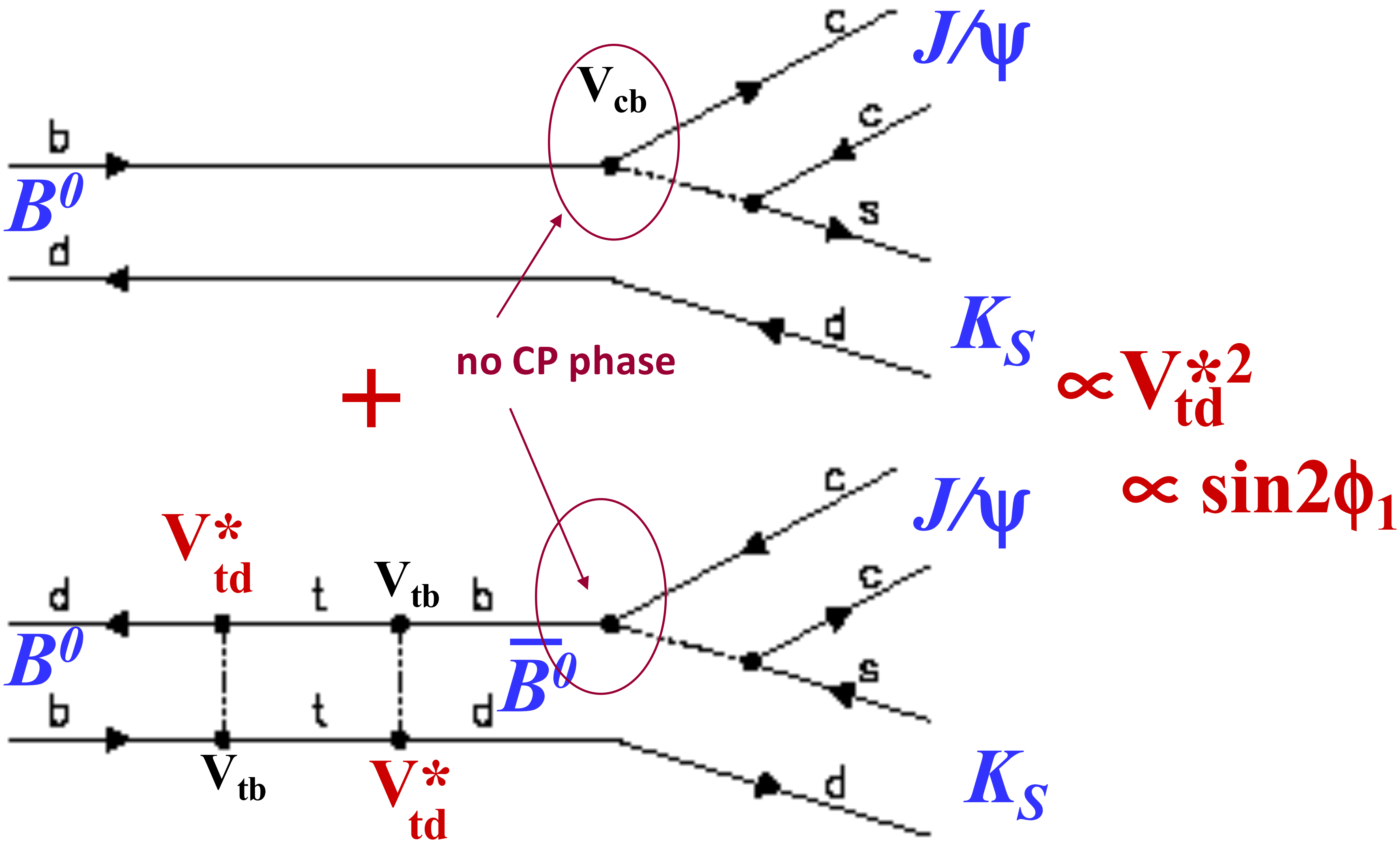
t-quark is the dominant contributor

no SM CPV phases

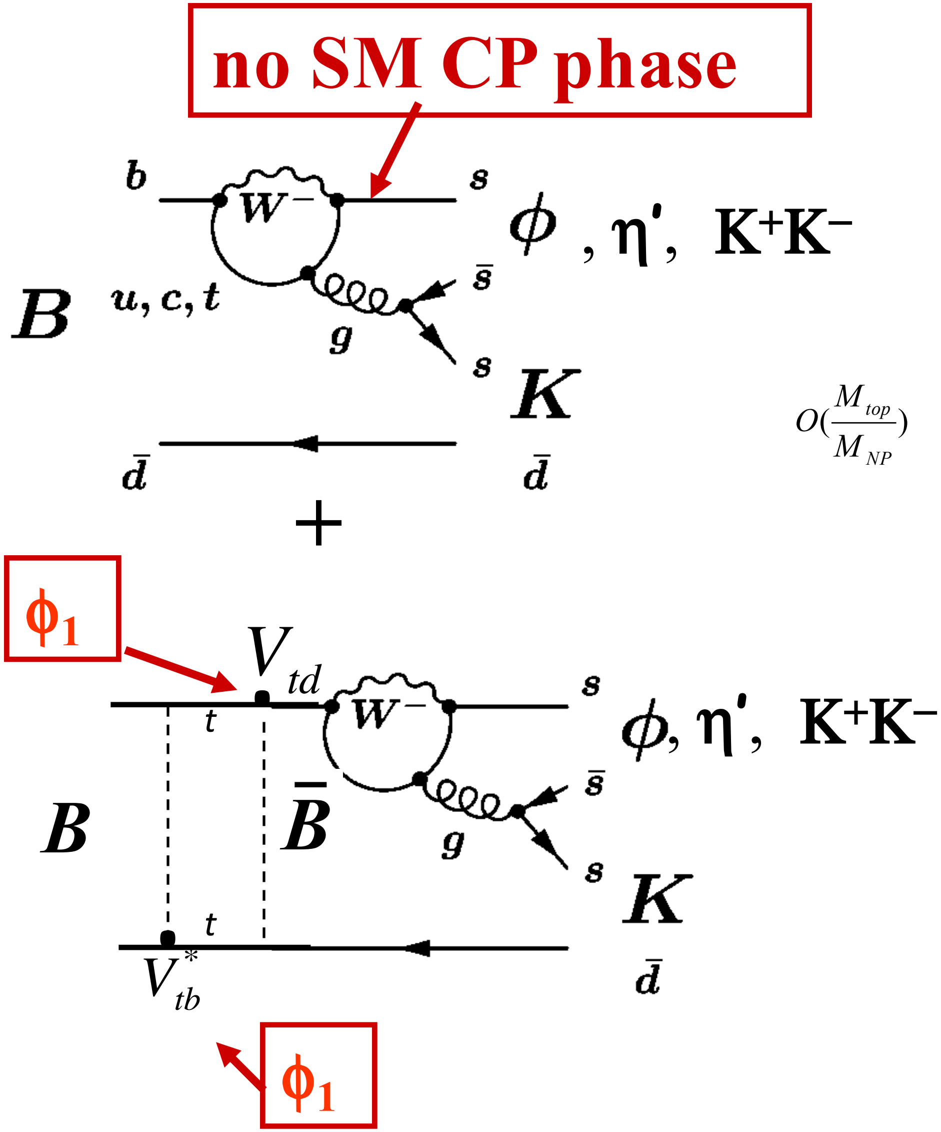
"Beyond the SM" particles



CPV in B↔B̄ mixing



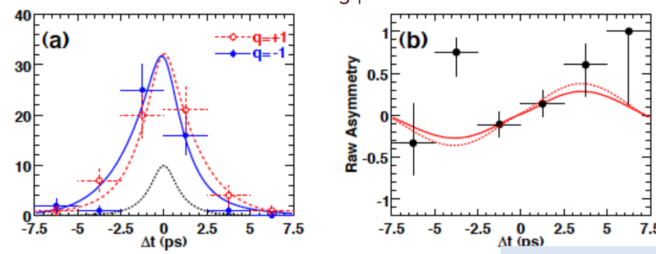
CPV with Penguins



$O(\frac{M_{top}}{M_{NP}})$

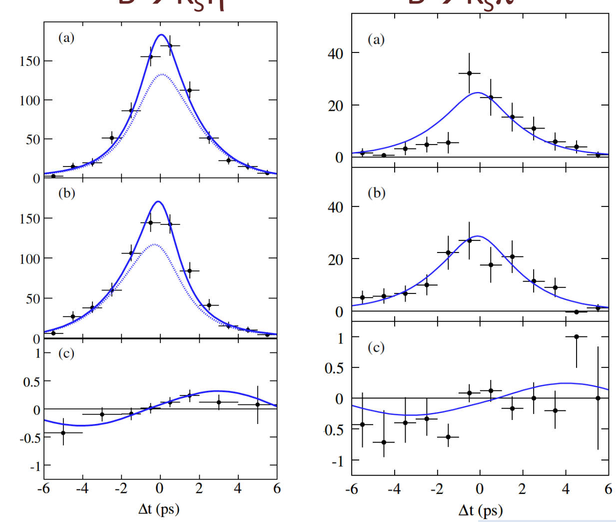
$$\text{Penguin-avg}: \ \sin 2\phi_1^{eff} = 0.64 \pm 0.03$$

B→$K_S\phi$



Belle PRD 82, 073001

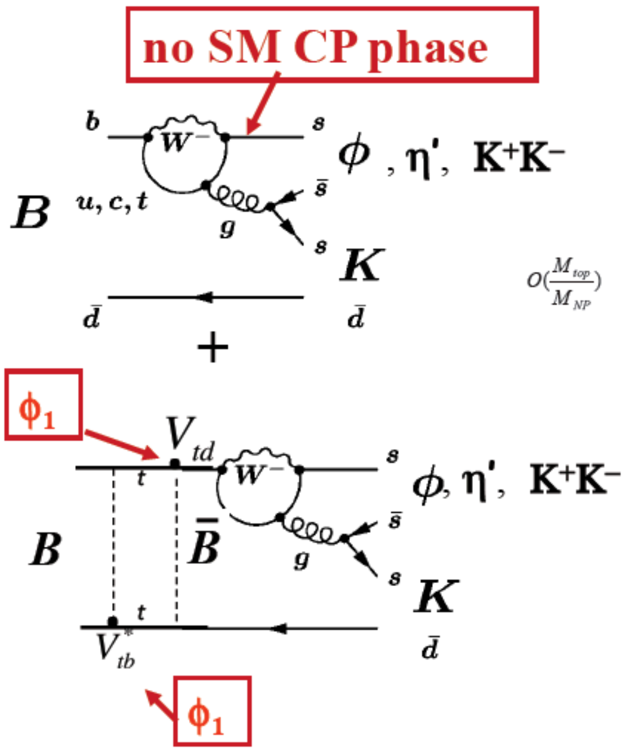
B→$K_S\eta'$ B→$K_S\pi^0$

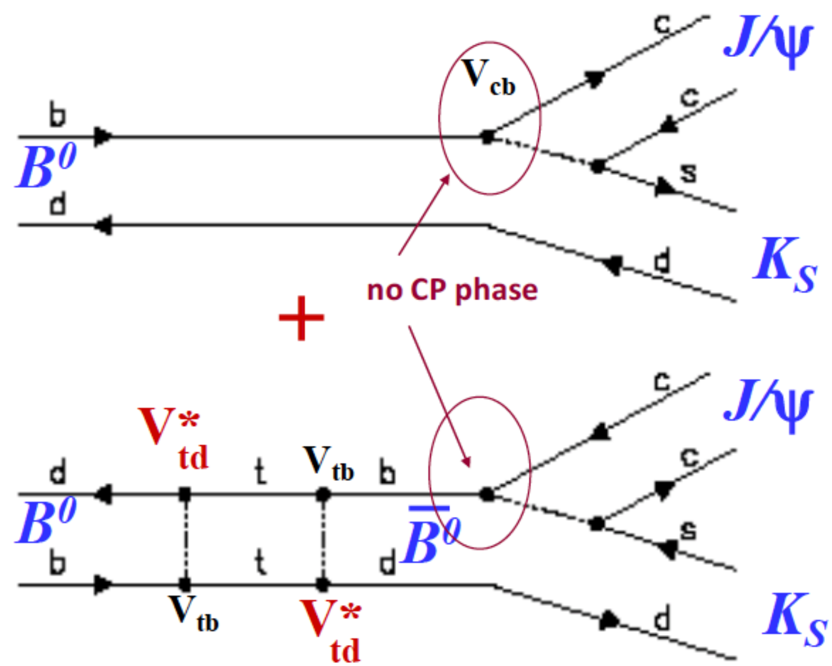


BaBar PRD 79, 052003

SM prediction

CPV violating phase here **is the same as here**





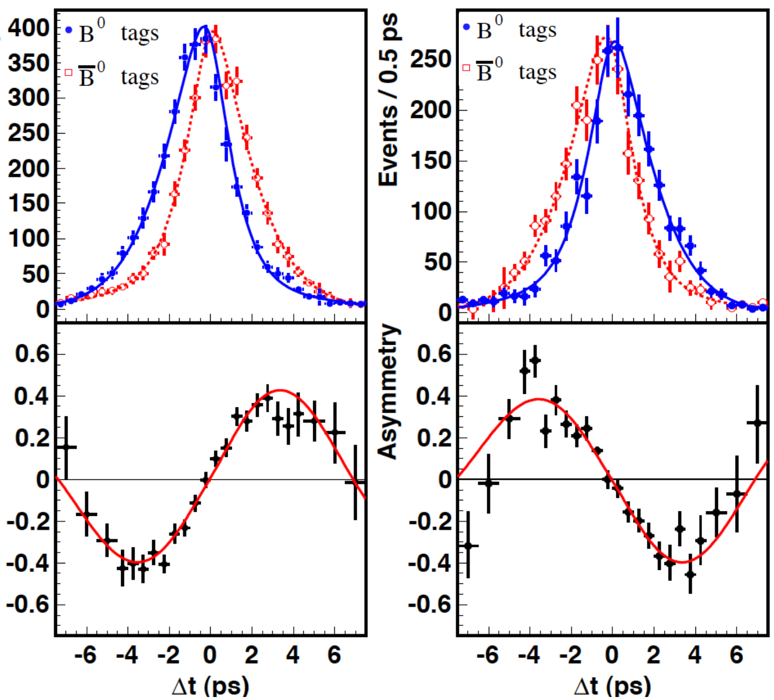
since QCD does not violate CPV, no QCD corrections are needed

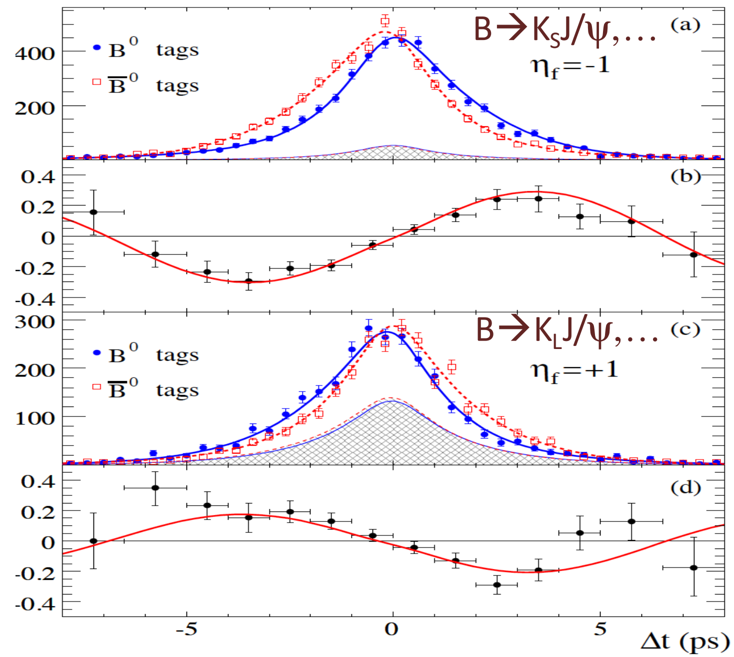
final results from Belle & BaBar

Belle PRL 198, 171802

BaBar PRD 79, 0720090

$B \rightarrow K_S J/\psi, \ldots$ $B \rightarrow K_L J/\psi, \ldots$





$$\text{Tree - avg}: \quad \sin 2\phi_1 = 0.68 \pm 0.02$$

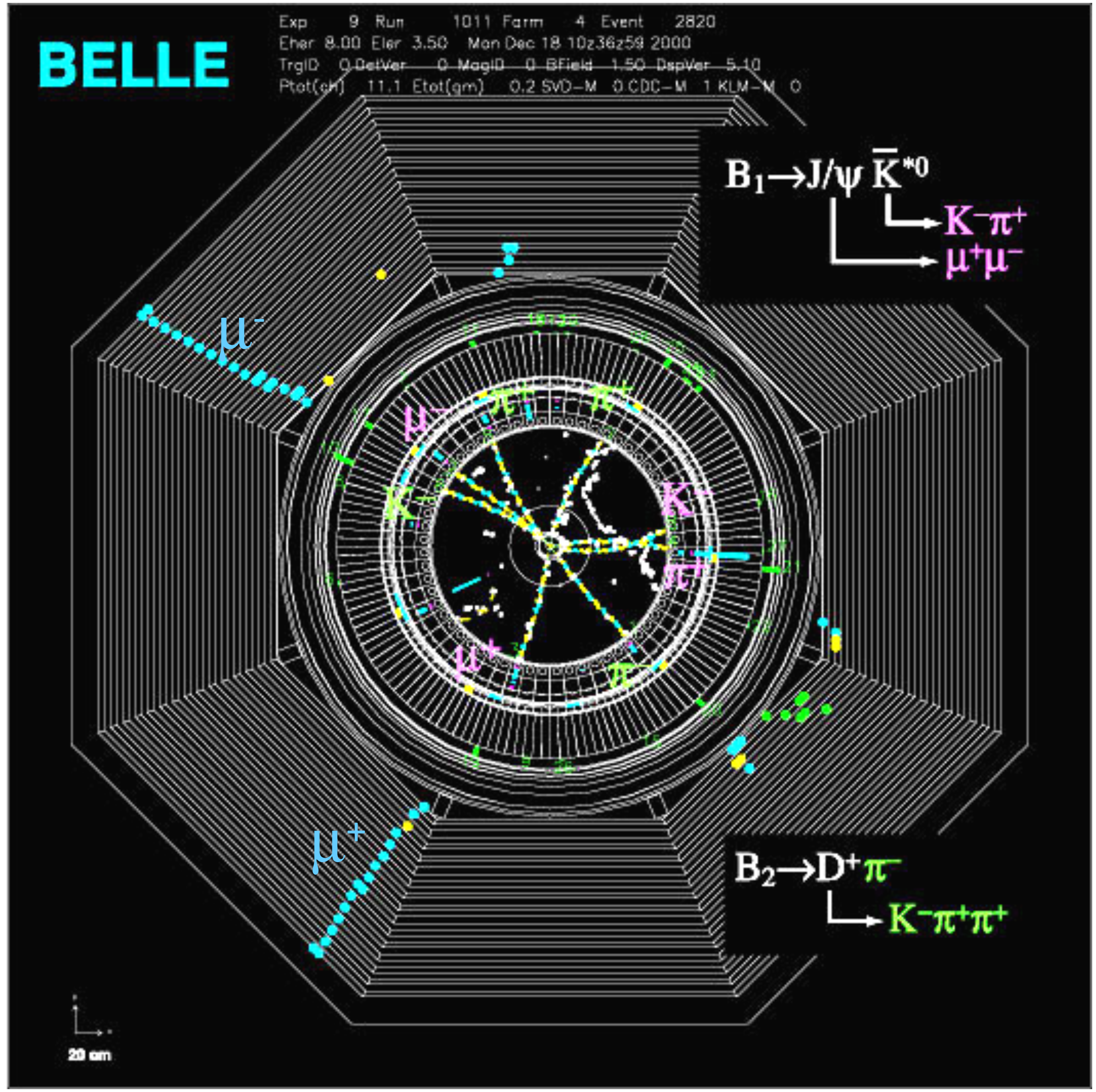
aka $\sin 2\beta$ stat error: ± 0.018

"New Physics" CPV phase with BelleII

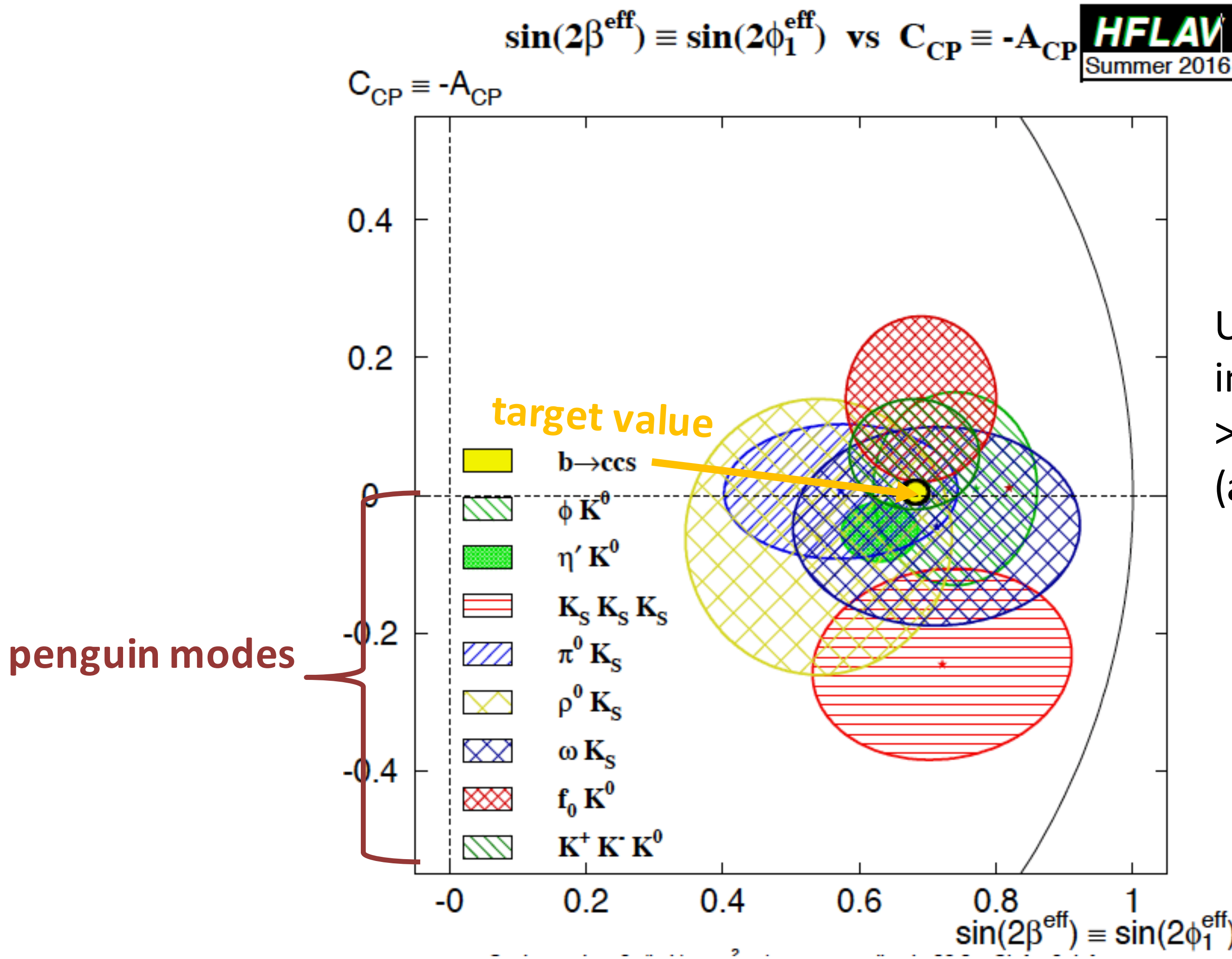
Measure ϕ_1 (β) using
$B^0 \rightarrow K^0 J/\psi$; $J/\psi \rightarrow \ell^+\ell^-$

Compare to ϕ_1^{eff} (β^{eff})
using $B^0 \rightarrow K^0\phi$; $\phi \rightarrow K^+K^-$
(& other penguin decays)

"systematic-free"
measurement:
$J/\psi \rightarrow \ell^+\ell^- / \phi \rightarrow K^+K^-$



current CPV results with Penguins



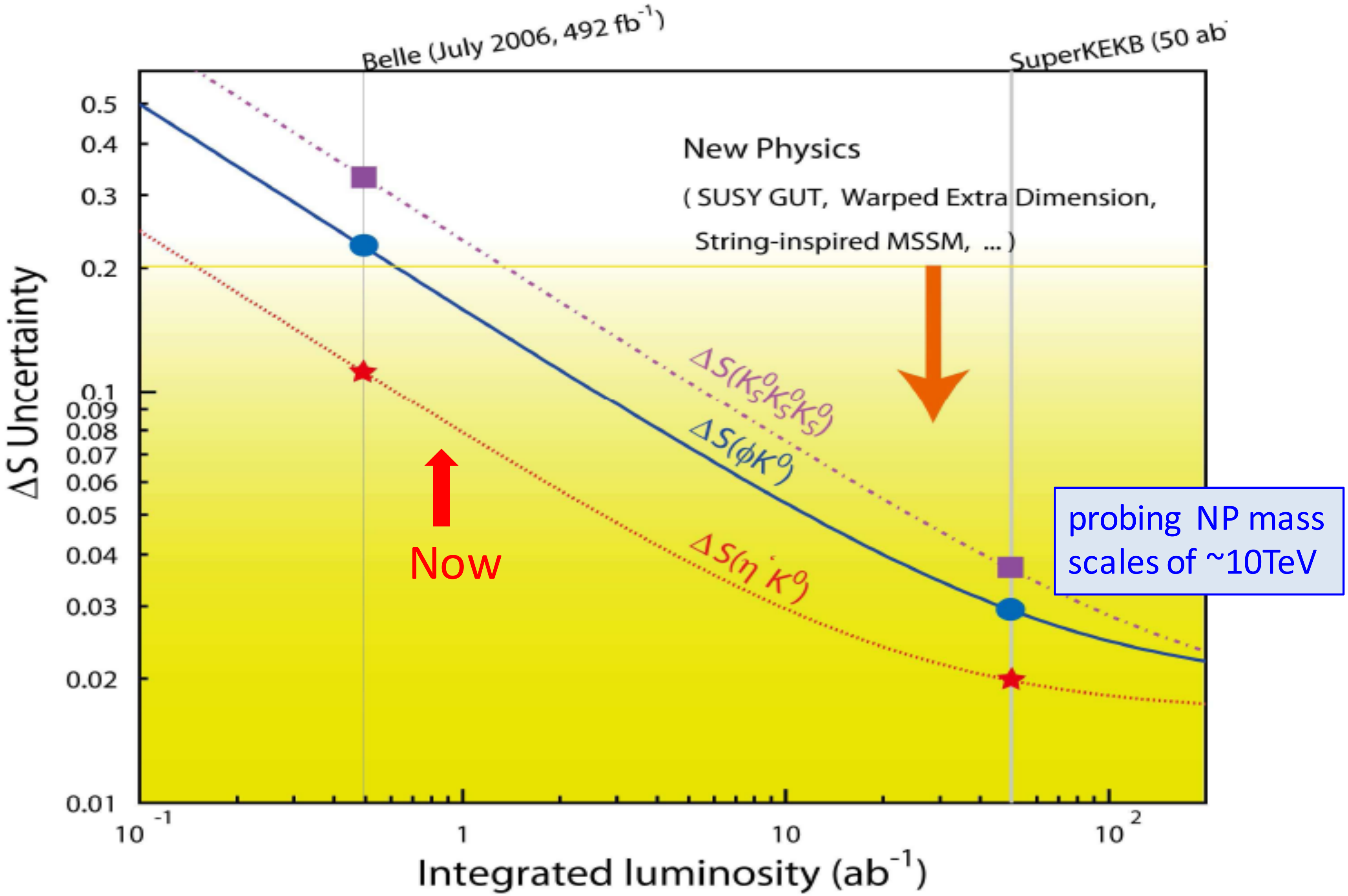
Uncertainties in individual channels >10~20% (all are statistics limited)

No signs of BSM phases at the ~10% level

$$\text{Penguin - avg}: \quad \sin 2\phi_1^{eff} = 0.64 \pm 0.03$$

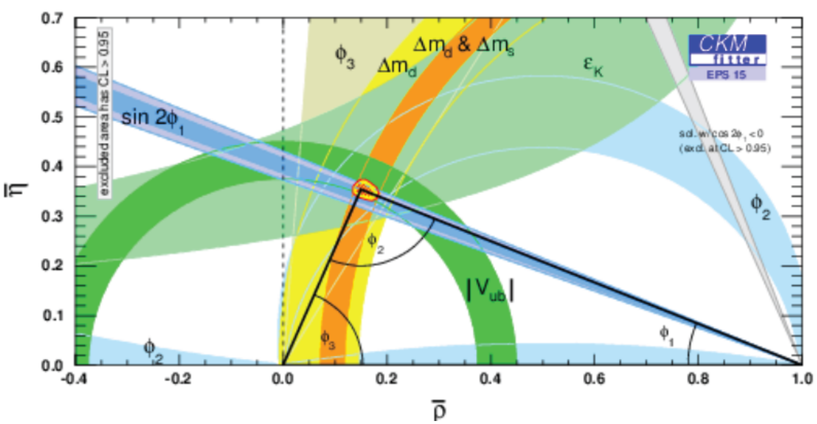
$$\text{Tree - avg}: \quad \sin 2\phi_1 = 0.679 \pm 0.020$$

Future with 50 ab^{-1} at BelleII



Summary of Lecture 6

- Measurements of ϕ_1, the phase of V_{td} agree with constraint set by measurements of $|V_{td}|$ (from B^0-$\bar{B}^0$ mixing); $|V_{ub}|$ (from $B \rightarrow \pi e^- \nu$); and ε (from CPV in K-mesons) .
- Kobayashi & Maskawa shared the 2008 Nobel prize for their 6-quark model for CPV.
- Subsequent measurements produced a precision measurement of $\phi_1 = 21.9^o \pm 0.6^o$ and first measurements of $\phi_2 = 86.7^o \pm 3.5^o$ and $\phi_3 = 76.2^o \pm 5.0^o$.
- At current precision, $\phi_1 + \phi_2 + \phi_3 = 185.9^o \pm 6.1^o$, consistent with a closed triangle.
- Large direct CP violations are observed, such as a ~30% difference between B^0 & $\bar{B}^0 \rightarrow \pi^+\pi^-$
- All observed CP violation measurements can be attributed to the KM phase in the 6-quark flavor mixing matrix. The CP violations in the 3rd generation b-quark, t-quark are near their maximum possible values (e.g, $\sin 2\phi_1 \approx 0.68$ *vs* a maximum possible value of 1).



- All measured constraints on the ρ & η Wolfenstein parameters are consistent with each other.

S-wave $\pi\pi$ and isospin

-- no $I=1$ for $\pi\pi$ S-wave --

1×1

m_1 m_2	$J=2$, $M=+2$
+1 +1	1

m_1 m_2	$J=2$, $M=+1$	$J=1$, $M=+1$
+1 0	1/2	1/2
0 +1	1/2	−1/2

m_1 m_2	$J=2$, $M=0$	$J=1$, $M=0$	$J=0$, $M=0$
+1 −1	1/6	1/2	1/3
0 0	2/3	0	−1/3
−1 +1	1/6	−1/2	1/3

$3/2\times 1/2$

m_1 m_2	$J=2$, $M=+2$
+3/2 +1/2	1

m_1 m_2	$J=2$, $M=+1$	$J=1$, $M=+1$
+3/2 −1/2	1/4	3/4
+1/2 +1/2	3/4	−1/4

m_1 m_2	$J=2$, $M=0$	$J=1$, $M=0$
+1/2 −1/2	1/2	1/2
−1/2 +1/2	1/2	−1/2

$1/2\times 1/2$

m_1 m_2	$J=1$, $M=+1$
+1/2 +1/2	1

m_1 m_2	$J=1$, $M=0$	$J=0$, $M=0$
+1/2 −1/2	1/2	1/2
−1/2 +1/2	1/2	−1/2

m_1 m_2	$J=1$, $M=-1$
−1/2 −1/2	1

$$\left\langle \pi^+\pi^0\right| = \tfrac{1}{\sqrt{2}}\left\langle 2;1\right| + \cancel{\tfrac{1}{\sqrt{2}}\left\langle 1;1\right|}$$

$$\left\langle \pi^+\pi^-\right| = \tfrac{1}{\sqrt{6}}\left\langle 2;0\right| + \cancel{\tfrac{1}{\sqrt{2}}\left\langle 1;0\right|} + \tfrac{1}{\sqrt{3}}\left\langle 0;0\right|$$

$$\left\langle \pi^0\pi^0\right| = \sqrt{\tfrac{2}{3}}\left\langle 2;0\right| - \sqrt{\tfrac{1}{3}}\left\langle 0;0\right|$$

$$\left|\tfrac{1}{2};\tfrac{1}{2}\right\rangle\left|\tfrac{3}{2};\tfrac{1}{2}\right\rangle = \sqrt{\tfrac{3}{4}}\left|2;1\right\rangle - \cancel{\tfrac{1}{2}\left|1;1\right\rangle}$$

$$\left|\tfrac{1}{2};-\tfrac{1}{2}\right\rangle\left|\tfrac{3}{2};\tfrac{1}{2}\right\rangle = \tfrac{1}{\sqrt{2}}\left|2;0\right\rangle - \tfrac{1}{\sqrt{2}}\left|1;0\right\rangle$$

$$\left\langle \pi^+\pi^0\right|T_{\frac{3}{2}}\left|B^+\right\rangle = \tfrac{1}{\sqrt{2}}\sqrt{\tfrac{3}{4}}\left\langle 2;1\right|T_{\frac{3}{2}}\left|2;1\right\rangle = \tfrac{\sqrt{3}}{2}A_{\frac{3}{2},2}$$

$$\left\langle \pi^+\pi^-\right|T_{\frac{3}{2}}\left|B^0\right\rangle = \tfrac{1}{\sqrt{6}}\tfrac{1}{\sqrt{2}}\left\langle 2;0\right|T_{\frac{3}{2}}\left|2;0\right\rangle = \tfrac{1}{\sqrt{6}}A_{\frac{3}{2},2}$$

$$\left\langle \pi^0\pi^0\right|T_{\frac{3}{2}}\left|B^0\right\rangle = \sqrt{\tfrac{2}{3}}\tfrac{1}{\sqrt{2}}\left\langle 2;0\right|T_{\frac{3}{2}}\left|2;0\right\rangle = \sqrt{\tfrac{2}{3}}A_{\frac{3}{2},2}$$

where $A_{\frac{3}{2},2} = \tfrac{1}{\sqrt{2}}\left\langle 2;0\right|T_{\frac{3}{2}}\left|2;0\right\rangle = \tfrac{1}{\sqrt{2}}\left\langle 2;1\right|T_{\frac{3}{2}}\left|2;1\right\rangle \Leftarrow$ ispin invariance

$$\left|\tfrac{1}{2};\tfrac{1}{2}\right\rangle\left|\tfrac{1}{2};-\tfrac{1}{2}\right\rangle = \cancel{\tfrac{1}{\sqrt{2}}\left|1;0\right\rangle} + \tfrac{1}{\sqrt{2}}\left|0;0\right\rangle$$

$$\left\langle \pi^+\pi^-\right|T_{\frac{1}{2},0}\left|B^0\right\rangle = \tfrac{1}{\sqrt{2}}\tfrac{1}{\sqrt{3}}\left\langle 0;0\right|T_{\frac{1}{2}}\left|0;0\right\rangle = \tfrac{1}{\sqrt{3}}A_{\frac{1}{2},0}$$

$$\left\langle \pi^0\pi^0\right|T_{\frac{1}{2},0}\left|B^0\right\rangle = -\tfrac{1}{\sqrt{2}}\tfrac{1}{\sqrt{3}} = -\tfrac{1}{\sqrt{3}}A_{\frac{1}{2},0}$$

where $A_{\frac{1}{2},0} = \tfrac{1}{\sqrt{2}}\left\langle 0;0\right|T_{\frac{1}{2}}\left|0;0\right\rangle$

$$A^{+0} = \tfrac{\sqrt{3}}{2}A_{\frac{3}{2},2}$$

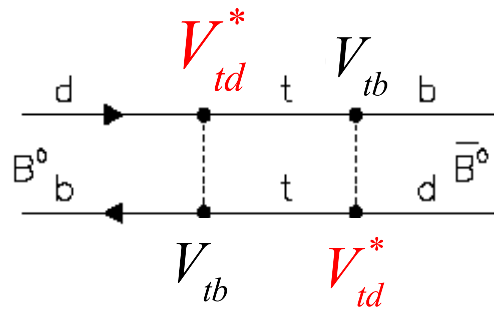
$$A^{+-} = \tfrac{1}{\sqrt{6}}A_{\frac{3}{2},2} + \tfrac{1}{\sqrt{3}}A_{\frac{1}{2},0}$$

$$A^{00} = \sqrt{\tfrac{2}{3}}A_{\frac{3}{2},2} - \tfrac{1}{\sqrt{3}}A_{\frac{1}{2},0}$$

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

differences in the time evolution of B^0 and $\bar{B}^0$ mesons

-- including CPV --



J/ψ K_S is a CP=-1 eigenstate $B_2 \rightarrow$ J/ψ K_S is allowed
project the B_2 time dependence for an initial B^0

CPV mixing phase

$$\left|B^0(t)\right\rangle = \left(\left|B^0\right\rangle(1+e^{-i\Delta Mt}) + e^{i2\phi_1}\left|\bar{B}^0\right\rangle(1-e^{-i\Delta Mt})\right)$$

$$\left\langle B_2\right|B^0(t)\rangle = \left(\left\langle B^0\right| + \left\langle \bar{B}^0\right|\right)\left|B^0(t)\right\rangle = \left\langle B^0\middle|B^0\right\rangle(1+e^{-i\Delta Mt}) + \left\langle \bar{B}^0\middle|\bar{B}^0\right\rangle e^{i2\phi_1}(1-e^{-i\Delta Mt})$$

$$\Rightarrow (1+e^{-i\Delta Mt}) + e^{i2\phi_1}(1-e^{-i(\Delta Mt)}) = (1+e^{i2\phi_1}) + e^{-i\Delta Mt}(1-e^{i2\phi_1})$$

$$\left|\left\langle B_2 \mid B^0(t)\right\rangle\right|^2 = \left((1+e^{i2\phi_1}) + e^{-i\Delta Mt}(1-e^{i2\phi_1})\right)\times\left((1+e^{-i2\phi_1}) + e^{+i\Delta Mt}(1-e^{-i2\phi_1})\right)$$

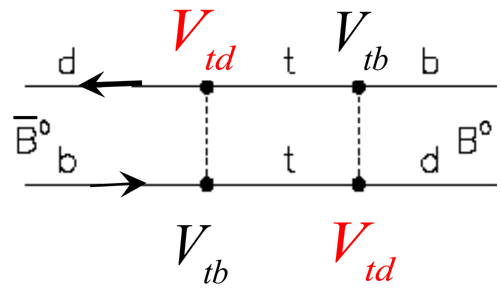
$$(1+e^{i2\phi_1})\times(1+e^{-i2\phi_1}) = 2+2\cos 2\phi_1 \;\; ; \;\; e^{-i\Delta Mt}(1-e^{i2\phi_1})\times e^{+i\Delta Mt}(1-e^{-i2\phi_1}) = 2-2\cos 2\phi_1$$

$$(1+e^{i2\phi_1})e^{+i\Delta Mt}(1-e^{-i2\phi_1}) = 2i\sin 2\phi_1 e^{+i\Delta Mt} \;\; ; \; e^{-i\Delta Mt}(1-e^{i2\phi_1})(1+e^{-i2\phi_1}) = -2i\sin 2\phi_1 e^{-i\Delta Mt}$$

$$\left|\left\langle B_2 \mid B^0(t)\right\rangle\right|^2 = 2+2\cos 2\phi_1 + 2-2\cos 2\phi_1 + \sin 2\phi_1(2i(e^{+i\Delta Mt} - e^{+i\Delta Mt}))$$

$$\left|\left\langle B_2 \mid B^0(t)\right\rangle\right|^2 = 4-4\sin 2\phi_1 \sin \Delta Mt$$

project the B_2 time dependence for an initial $\bar{B}^0$



the CPV mixing phase has opposite sign

$$\left|\bar{B}^0(t)\right\rangle = \left(\left|\bar{B}^0\right\rangle(1+e^{-i\Delta Mt}) + e^{-i2\phi_1}\left|B^0\right\rangle(1-e^{-i\Delta Mt})\right)$$

$$\left\langle B_2\middle|\bar{B}^0(t)\right\rangle = \left(\left(\left\langle B^0\right| + \left\langle \bar{B}^0\right|\right)\middle|\bar{B}^0(t)\right\rangle = \left\langle B^0\middle|\bar{B}^0\right\rangle(1+e^{-i\Delta Mt}) + \left\langle \bar{B}^0\middle|B^0\right\rangle e^{-i2\phi_1}(1-e^{-i\Delta Mt})$$

$$\Rightarrow (1+e^{-i\Delta Mt}) + e^{-i2\phi_1}(1-e^{-i(\Delta Mt)}) = (1+e^{-i2\phi_1}) + e^{-i\Delta Mt}(1-e^{-i2\phi_1})$$

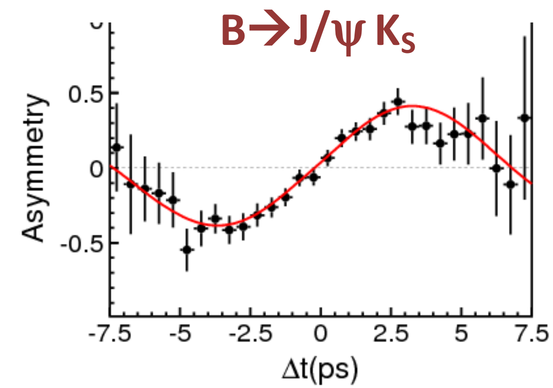
$$\left|\left\langle B_2 \mid \bar{B}^0(t)\right\rangle\right|^2 = \left((1+e^{-i2\phi_1}) + e^{-i\Delta Mt}(1-e^{-i2\phi_1})\right)\times\left((1+e^{+i2\phi_1}) + e^{+i\Delta Mt}(1-e^{+i2\phi_1})\right)$$

$$(1+e^{-i2\phi_1})\times(1+e^{i2\phi_1}) = 2+2\cos 2\phi_1 \;\;;\;\; e^{-i\Delta Mt}(1-e^{-i2\phi_1})\times e^{+i\Delta Mt}(1-e^{+i2\phi_1}) = 2-2\cos 2\phi_1$$

$$(1+e^{-i2\phi_1})e^{+i\Delta Mt}(1-e^{+i2\phi_1}) = -2i\sin 2\phi_1 e^{+i\Delta Mt} \;\;;\; e^{-i\Delta Mt}(1-e^{-i2\phi_1})(1+e^{+i2\phi_1}) = +2i\sin 2\phi_1 e^{-i\Delta Mt}$$

$$\left|\left\langle B_2 \mid \bar{B}^0(t)\right\rangle\right|^2 = 2+2\cos 2\phi_1 + 2 - 2\cos 2\phi_1 + \sin 2\phi_1(2i(e^{-i\Delta Mt} - e^{+i\Delta Mt}))$$

$$\left|\left\langle B_2 \mid \bar{B}^0(t)\right\rangle\right|^2 = 4+4\sin 2\phi_1 \sin\Delta Mt$$



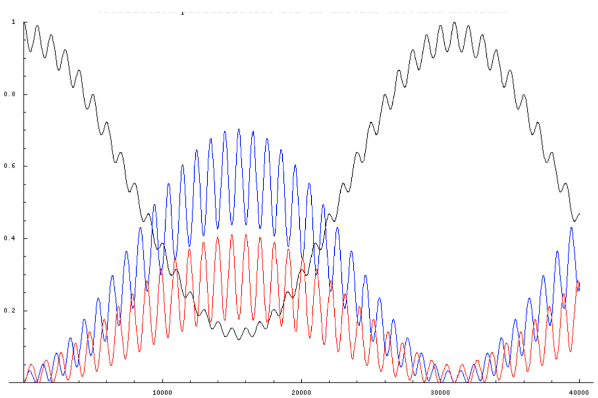
B^0 tags **$\bar{B}^0$ tags**

$$\frac{\left|\left\langle B_2 \mid \bar{B}^0(t)\right\rangle\right|^2 - \left|\left\langle B_2 \mid B^0(t)\right\rangle\right|^2}{\left|\left\langle B_2 \mid \bar{B}^0(t)\right\rangle\right|^2 + \left|\left\langle B_2 \mid B^0(t)\right\rangle\right|^2} = \frac{8\sin 2\phi_1 \sin\Delta Mt}{8} = \sin 2\phi_1 \sin\Delta Mt$$

What's next?

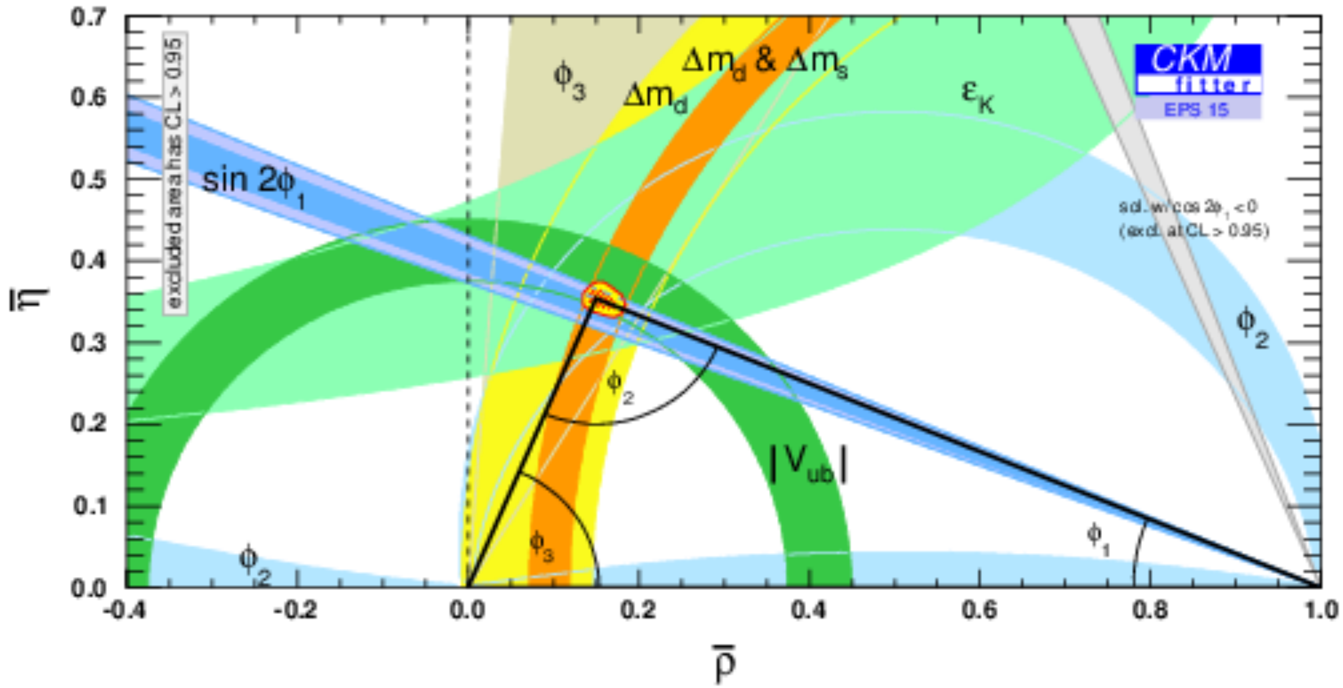
Repeat these measurements with:

NEUTRINOS



AND PENGUINS

Unitary triangle in Summer 2015



$$\phi_1 = 22.6^o \pm 0.5^0$$

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$$\sin 2\phi_1 = 0.691 \pm 0.017; \quad \phi_1 = 21.9^{\circ} \pm 0.6^{\circ}$$