Univerza v Ljubljani — THE UNIVERSITY OF TOKYO

Flavour Physics at B-factories and Hadron Colliders

Part 7: angle $\phi_2\,(\alpha)$

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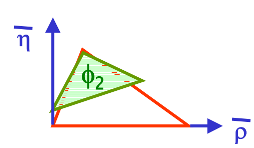


CP asymmetry

CP asymmetry:

$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP},t) - P(B^0 \to f_{CP},t)}{P(\overline{B}^0 \to f_{CP},t) + P(B^0 \to f_{CP},t)} =$$

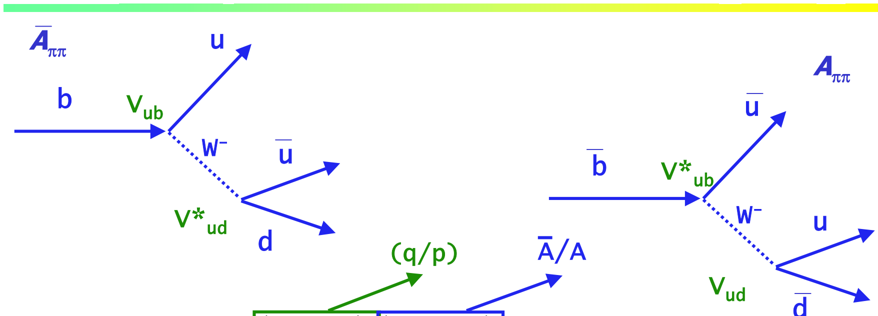
$$= \frac{(1-|\lambda_{f_{CP}}|^2)\cos(\Delta mt) - 2\,\mathrm{Im}(\lambda_{f_{CP}})\sin(\Delta mt)}{1+|\lambda_{f_{CP}}|^2}$$

$$\lambda_{f_{CP}} = \eta_{f_{CP}} \frac{q}{p} \frac{\overline{A}_{\overline{f}_{CP}}}{A_{f_{CP}}}$$

$\not{C}\not{P}$ in decay: $|\overline{A}/A| \neq 1$, $|\lambda| \neq 1$

$\not{C}\not{P}$ in interference between mixing and decay: $\mathrm{Im}(\lambda) \neq 0$

Decay asymmetry calculation for B->$\pi^+ \pi^-$ - tree diagram only

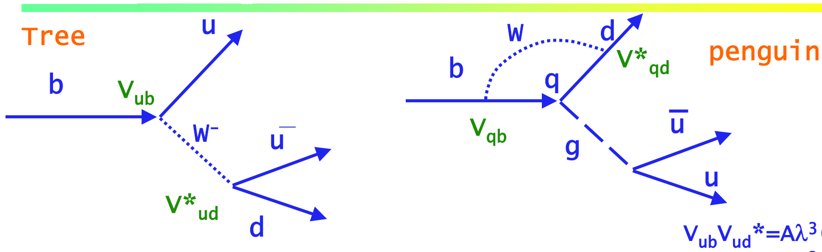


$$\lambda_{\pi\pi} = \eta_{\pi\pi} \left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\right)\left(\frac{V_{ud}^* V_{ub}}{V_{ud} V_{ub}^*}\right)$$

$$\mathrm{Im}(\lambda_{\pi\pi}) = \sin 2\phi_2 = \sin 2\alpha$$

Neglected possible penguin amplitudes ->

$\pi^+ \pi^-$ - tree vs penguin



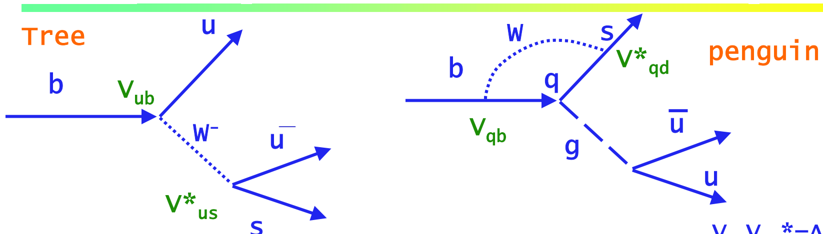
$V_{ub}V_{ud}^* = A\lambda^3(\rho - i\eta)$
$V_{tb}V_{td}^* = A\lambda^3(1 - \rho + i\eta)$

$$A(u\bar{u}d) = V_{tb}V_{td}^*(P_d^t - P_d^c) + V_{ub}V_{ud}^*(T_{u\bar{u}d} + P_d^u - P_d^t)$$

How much does the penguin contribute?

Compare $B \rightarrow K^+\pi^-$ and $B \rightarrow \pi^+\pi^-$ →

$K^- \pi^+$ - tree vs penguin



$V_{ub}V_{us}^* = A\lambda^4(\rho - i\eta)$
$V_{cb}V_{cs}^* = A\lambda^2$

$$A(u\bar{u}s) = V_{cb}V_{cs}^*(P_s^c - P_s^t) + V_{ub}V_{us}^*(T_{u\bar{u}s} + P_s^u - P_s^t)$$

Penguin amplitudes for $B \rightarrow K^+\pi^-$ and $B \rightarrow \pi^+\pi^-$ are expected to be equal. Contribution to A(uus) in $K^+\pi^-$ enhanced by λ **in comparison to** $\pi^+\pi^-$

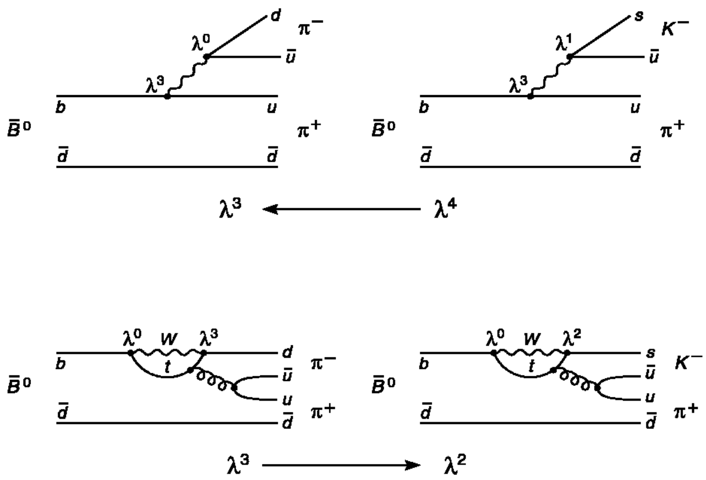
$B \rightarrow K^+\pi^-$ tree contribution suppressed by λ^2 vs $\pi^+\pi^-$.

Experiment: $Br(B \rightarrow K^+\pi^-) = 1.85\ 10^{-5}$, $Br(B \rightarrow \pi^+\pi^-) = 0.48\ 10^{-5}$

→ $Br(B \rightarrow \pi^+\pi^-) \sim 1/4\ Br(B \rightarrow K^+\pi^-)$ → penguin contribution must be sizeable

Diagrams for B→ ππ, Kπ decays

ππ



Kπ

Possibility of tree-penguin interference.

N.B. in B→ππ the two diagrams are the same order in λ

Reconstruction of rare B meson decays

$Br(B \to \pi^+\pi^-) = 0.48\ 10^{-5}$
-> Rare decay, have to fight against many background sources.

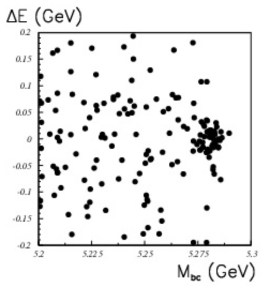
Reconstructing rare B meson decays at Y(4s): use two variables, beam constrained mass M_{bc} and energy diference ΔE

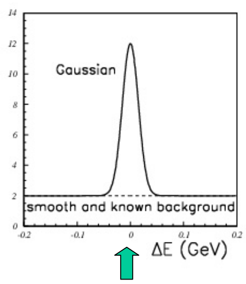
Use event topology parameters to suppress the continuum backgrounds.

Use particle identification to reduce the background from 4x more copious $B \to K^+\pi^-$ decays.

Exploit the very good momentum resolution to kinematically separate the remaining $B \to K^+\pi^-$ contribution.

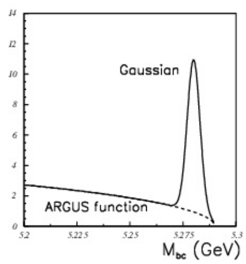
Reconstruction of rare B meson decays





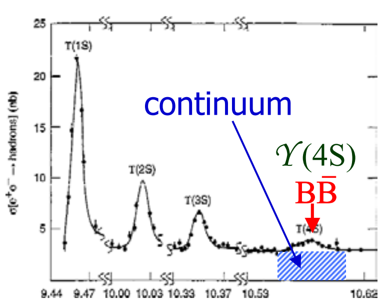
Reconstructing rare B meson decays at Υ(4s): use two variables,
beam constrained mass M_{bc}
and
energy diference ΔE

$$\Delta E \equiv \sum E_i - E_{CM}/2$$



$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

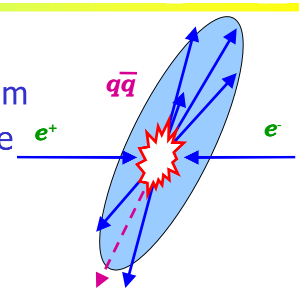
Continuum suppression



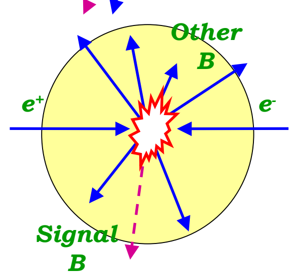
$e^+e^- \rightarrow qq$ "continuum" (~3x BB)

To suppress: use event shape variables

Continuum
Jet-like



BB
spherical



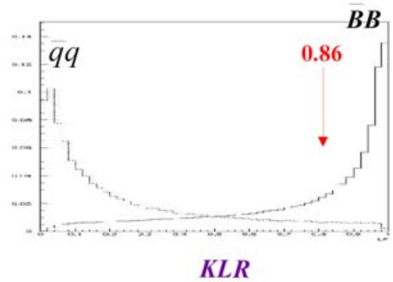
Continuum suppression

$e^+e^- \to q\bar{q}$ "continuum" (~3x BB)

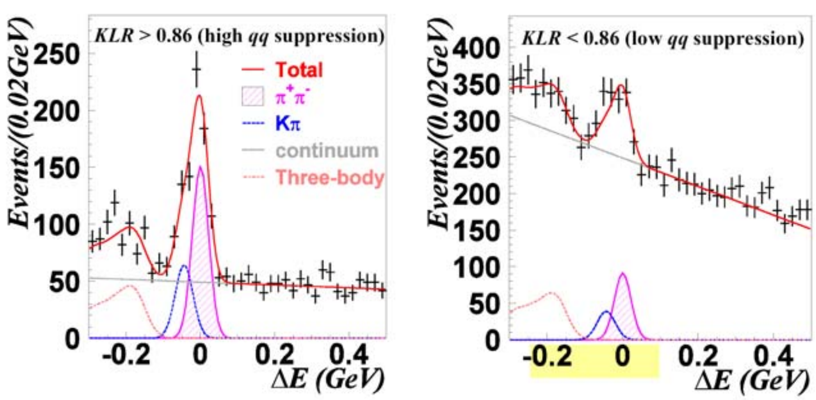
To suppress it use:
- event shape variables
- event axis direction

Combine to a likelihood ratio:

$$KLR \equiv \frac{\mathcal{L}_{B\bar{B}}}{(\mathcal{L}_{B\bar{B}} + \mathcal{L}_{q\bar{q}})}$$

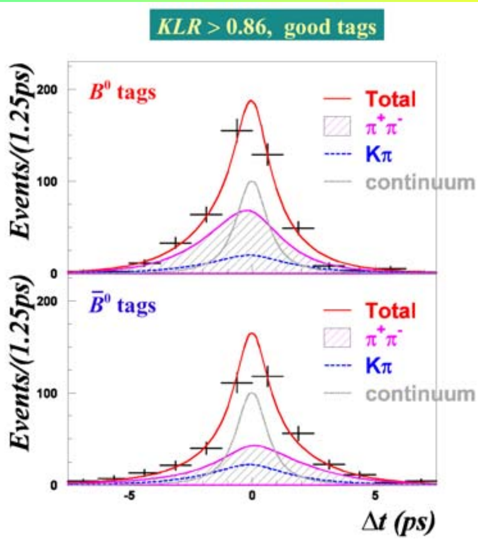


B->$\pi^+ \pi^-$ sample – 2005



$N_{\pi\pi} = 415 \pm 13$ $N_{\pi\pi} = 251 \pm 8$

B->$\pi^+ \pi^-$: 2005 sample



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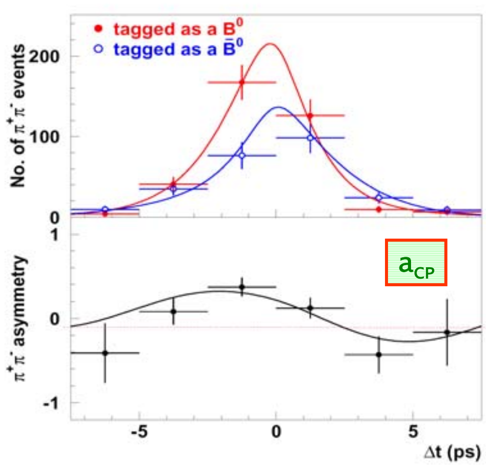
B->$\pi^+ \pi^-$: results of the fit, plotted with background subtracted



$$a_{f_{CP}} = \frac{P(\overline{B}^0 \to f_{CP},t) - P(B^0 \to f_{CP},t)}{P(\overline{B}^0 \to f_{CP},t) + P(B^0 \to f_{CP},t)} =$$

$$= S_{f_{CP}} \sin(\Delta m t) - A_{f_{CP}} \cos(\Delta m t)$$

$\mathcal{S}_{\pi\pi}$ = -0.67±0.16±0.06

$\mathcal{A}_{\pi\pi}$ = 0.56±0.12±0.06

-> direct CP violation!
Evident on this plot:
Number of anti-B events
< Number of B events

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B→$\pi^+ \pi^-$ comparison Belle-BaBar: experimental situation for in 2004

Belle 152 M $B\bar{B}$
with 372±32 $B^0 \to \pi^+\pi^-$ events

$$S_{\pi\pi} = -1.00 \pm 0.21 \pm 0.07$$
$$A_{\pi\pi} = +0.58 \pm 0.15 \pm 0.07$$

PRL 93, 021601 (2004)

5.2σ CPV,

First evidence for DCPV (3.2σ)

BABAR 227M $B\bar{B}$
with 467±33 $B^0 \to \pi^+\pi^-$ events

$$S_{\pi\pi} = -0.30 \pm 0.17 \pm 0.03$$
$$A_{\pi\pi} = +0.09 \pm 0.15 \pm 0.04$$

hep-ex/0501071, to appear in PRL

Also ~3.2s discrepancy between Belle and BaBar

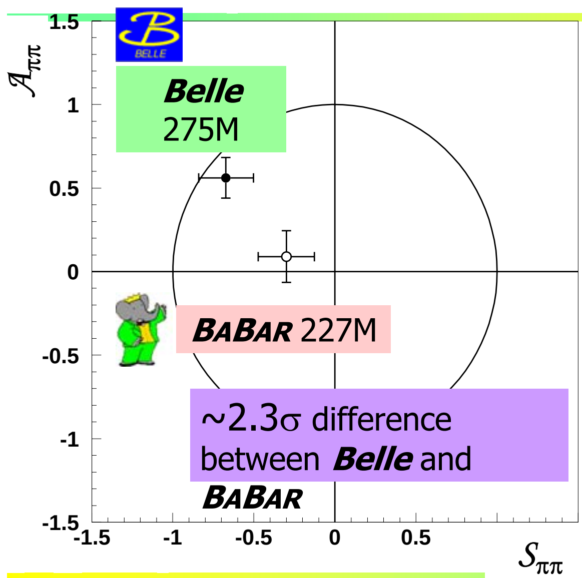
Belle $B^0 \to \pi^+ \pi^-$ 2005 results

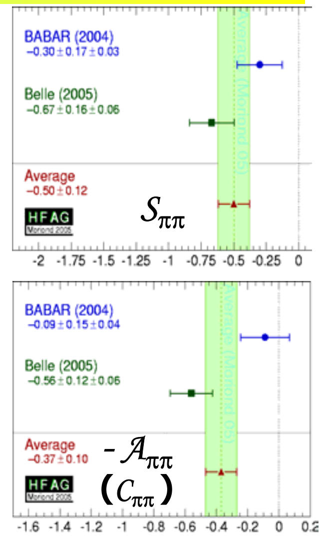
$$A_{\pi\pi} = +0.56 \pm 0.12 \pm 0.06$$
$$S_{\pi\pi} = -0.67 \pm 0.16 \pm 0.06$$

1st error statistical, 2nd systematic

- $A_{\pi\pi}$ away from 0: Compelling evidence for direct CP violation in B→$\pi^+\pi^-$ with 4.0σ significance
- Confirms previous Belle results.

2005: Status of B→$\pi^+ \pi^-$





B->$\pi^+ \pi^-$: interpretation

Interpretation:

tree level

tree + 

$$\lambda_{\pi\pi} = e^{2i\phi_2} \rightarrow \lambda_{\pi\pi} = e^{2i\phi_2} \frac{1+|P/T|e^{i\delta+i\phi_3}}{1+|P/T|e^{i\delta-i\phi_3}} \equiv |\lambda_{\pi\pi}| e^{2i\phi_{2eff}}$$

strong phase diff. P-T

weak phase (changes sign)

$$A_{\pi\pi} = 0 \rightarrow A_{\pi\pi} \propto \sin\delta$$

$$S_{\pi\pi} = \sin(2\phi_2) \rightarrow S_{\pi\pi} = \sqrt{1-A^2{}_{\pi\pi}}\ \sin(2\phi_{2eff})$$

direct CP

$$A(u\bar{u}d) = V_{cb}V_{cd}{}^*(P_d^c - P_d^t) + V_{ub}V_{ud}{}^*(T_{u\bar{u}d} + P_d^u - P_d^t) =$$
$$= V_{ub}V_{ud}{}^*T_{u\bar{u}d}\left[1 + (P_d^u - P_d^t) + (V_{cb}V_{cd}{}^*/V_{ub}V_{ud}{}^*)(P_d^c - P_d^t)\right]$$

$$\gamma \equiv \phi_3 \equiv \arg\left(\frac{V_{ud}V_{ub}{}^*}{V_{cd}V_{cb}{}^*}\right)$$

How to extract ϕ_2, δ and |P/T|?

ϕ_{2eff} depends on δ, ϕ_3, ϕ_2 and |P/T|

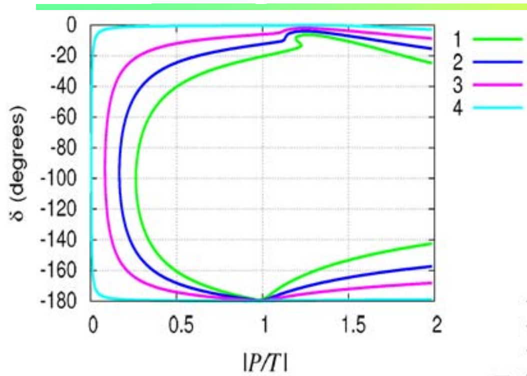
$\pi = \phi_1 + \phi_2 + \phi_3$ $\rightarrow$ ϕ_{2eff} depends on δ, ϕ_1, ϕ_2 and |P/T|

ϕ_1: well measured

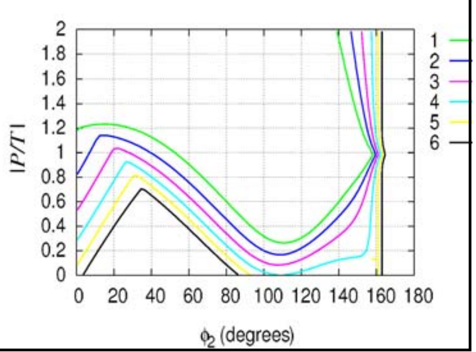
penguin amplitudes $B \rightarrow K^+\pi^-$ and $B \rightarrow \pi^+\pi^-$ are equal $\rightarrow$ limits on |P/T| (~0.3);
considering the full interval of δ values one can obtain interval of ϕ_2 values;

isospin relations can be used to constrain δ (or better to say $\phi_2 - \phi_{2eff}$);

Constraints upon ϕ_2, δ and |P/T|



For any |P/T|
$\delta < -4^\circ$ (95% CL)
For any δ
$|P/T| > 0.17$ (95% CL)

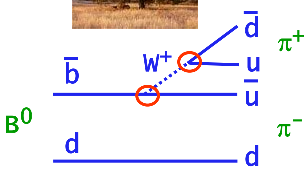


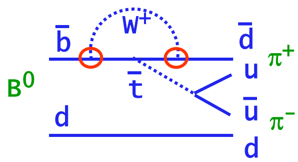
For |P/T|=0.6 (for example)
$72^\circ < \phi_2 < 146^\circ$ (95% CL)

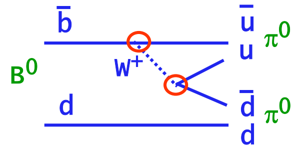
Extracting ϕ_2: isospin relations

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









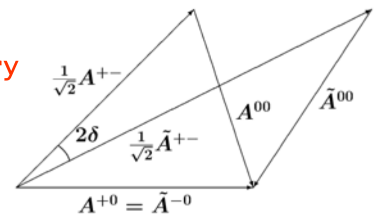
$T \sim V_{ub}^*V_{ud} \sim \lambda^3$ $P \sim V_{tb}^*V_{td} \sim \lambda^3$ $T_c \sim V_{ub}^*V_{ud}$

No pengiun!

Constraint: relation of decay amplitudes in the SU(2) symmetry

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

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



Extracting ϕ_2: isospin relations

How to derive the relation of decay amplitudes within the SU(2) symmetry?

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

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

1×1

m_1	m_2	J=2	J=1	J=0
+1	+1	1 (M=+2)		
+1	0	1/2 (M=+1)	1/2 (M=+1)	
0	+1	1/2	−1/2	
+1	−1	1/6 (M=0)	1/2 (M=0)	1/3 (M=0)
0	0	2/3	0	−1/3
−1	+1	1/6	−1/2	1/3
0	−1	1/2 (M=−1)	1/2 (M=−1)	
−1	0	1/2	−1/2	
−1	−1	1 (M=−2)		

- Symmetrize $\pi\pi$ states
- Decompose in $I_{\pi\pi}$ amplitudes (C.-G. coefficients)
- Rewrite in terms of B->$\pi\pi$ decay amplitudes

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

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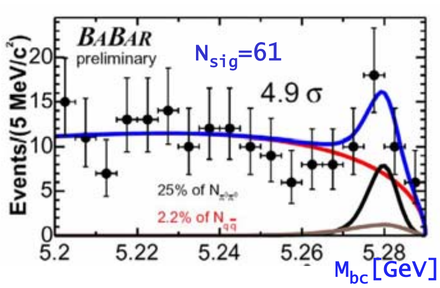
$B^0 \to \pi^0 \pi^0$

A very difficult channel - finally measured!



227M $B\bar{B}$, Belle

$Br(B^0 \to \pi^0\pi^0) =$
$(1.17 \pm 0.32 \pm 0.10) \times 10^{-6}$
$\mathcal{A}_{CP} = 0.12 \pm 0.56 \pm 0.06$

274M $B\bar{B}$, BaBar $N_{sig}=82$

$Br(B^0 \to \pi^0\pi^0) =$
$(2.32 \pm 0.45 \pm 0.20) \times 10^{-6}$
$\mathcal{A}_{CP} = 0.43 \pm 0.51 \pm 0.17$

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Extraction of ϕ_2

Use measured BRs and asymmetries in all three $B \to \pi\pi$ decays $\to$ extract ϕ_2

Similar analysis as for $B \to \pi\pi$ also for $B \to \rho\rho$
(ϕ_2^{eff} closer to ϕ_2)

... and for $B \to \rho\pi$

	BaBar/Belle	BaBar
S_{+-}	$Br(B^0 \to \pi^0\pi^0)$	Similar from $B \to \rho\rho$
A_{+-}	$Br(B^0 \to \pi^+\pi^-)$	BaBar/Belle
$\mathcal{A}_{CP}$	$Br(B^+ \to \pi^+\pi^0)$	Similar from $B \to \rho\pi$

$\phi_2 = 106^o \pm {}^{8^o}_{11^o}$