Investigations of the branching ratio and CP violation of B $\rightarrow \pi^0\pi^0$

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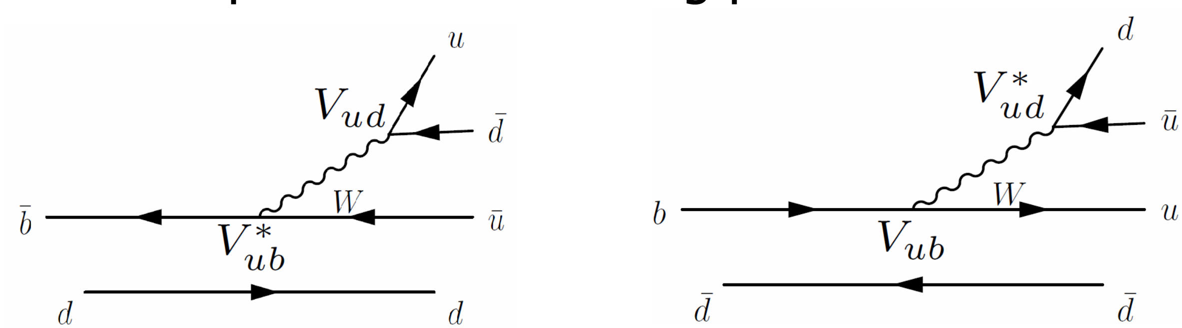
$B \to \pi^+\pi^-$

- Is a time-dependant CP violating process.



- The time dependant branching fraction for B →f is given by

$$\Gamma(B^0(t) \to f) = e^{-\Gamma|t|}[(|A_f|^2+|\bar{A}_f|^2)-(|A_f|^2-|\bar{A}_f|^2)cos(\Delta mt) + 2|A_f|^2 Im(\lambda_f) sin(\Delta mt)]$$

- λ_f is the mixing parameter (p/q) ($\bar{A}_f / A_f$) = $e^{-2i\Phi_M}$($\bar{A}_f / A_f$)

$$\lambda_{+-} = \left(\frac{V^*_{tb}V_{td}}{V_{tb}V^*_{td}}\right)\left(\frac{V^*_{ub}V_{ud}}{V_{ub}V^*_{ud}}\right)$$

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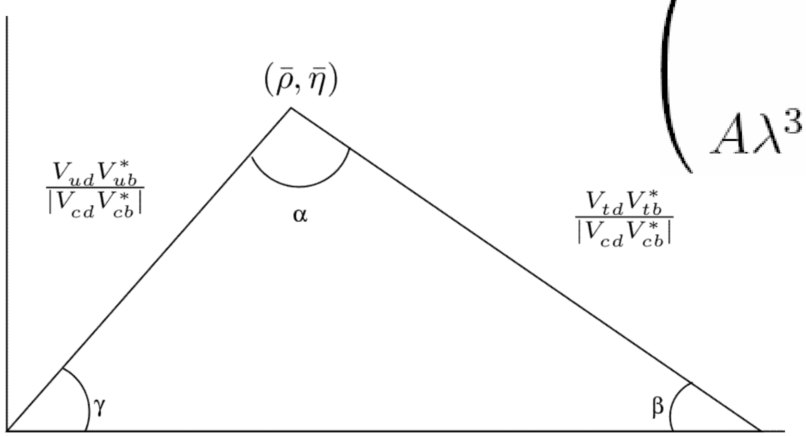
The CKM Matrix

- The mass and weak eigenstates of a quark are not the same.
- The CKM Matrix describes the mixing between each quark.
- The Wolfenstein parameterisation leads to the Unitary Triangle.

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

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



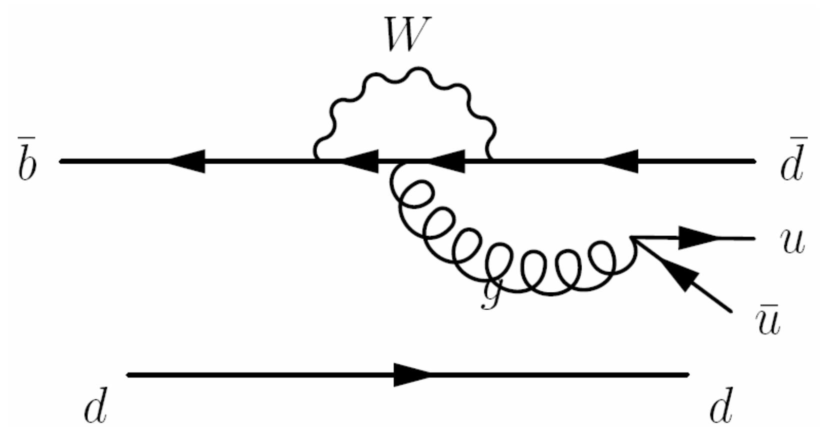
The Asymmetry

- Flavour tagging allows us to find the time dependant asymmetry in B →π+π-.

$$a_f = \frac{\Gamma[B^0(t) \to f] - \Gamma[\bar{B}^0(t) \to f]}{\Gamma[B^0(t) \to f] + \Gamma[\bar{B}^0(t) \to f]}$$

$$a_f = \frac{1}{1+|\lambda_f|^2}[(1-|\lambda_f|^2)cos(\Delta mt) - 2Im\lambda_f sin(\Delta mt)]$$

- In the absence of penguin diagrams $Im\lambda_{+-}$ is equal to $\sin(2\varphi_2)$.
- In the presence of penguin processes, the asymmetry becomes $\sin(2\varphi_2 + \kappa)$, or $\sin(2\varphi_2 eff)$



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Coupling

- Expressing $\varphi(\pi\pi)$ states in the form **$|I, I_3>$** are of the form:

$$\phi(\pi^0\pi^0) = |\,1,0\rangle\,|\,1,0\rangle = \sqrt{\frac{2}{3}}\,|\,2,0\rangle - \sqrt{\frac{1}{3}}\,|\,0,0\rangle$$

$$\phi(\pi^0\pi^+) = |\,1,0\rangle\,|\,1,+1\rangle = |\,2,+1\rangle$$

$$\phi(\pi^+\pi^-) = |\,1,-1\rangle\,|\,1,+1\rangle = \sqrt{\tfrac{1}{3}}\,|\,2,0\rangle + \sqrt{\tfrac{2}{3}}\,|\,0,0\rangle$$

- $B\rightarrow\pi\pi$ proceeds through the process $\bar{b} \rightarrow \bar{u}\,u\,\bar{d}$:

$$\phi(\bar{b} \rightarrow \bar{u}u\bar{d}) = A_{\frac{3}{2}}\,|\,\tfrac{3}{2},+\tfrac{1}{2}\rangle + A_{\frac{1}{2}}\,|\,\tfrac{1}{2},+\tfrac{1}{2}\rangle$$

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Coupling Continued

- $\phi(B^0) = |\frac{1}{2}, -\frac{1}{2}\rangle$

$$\phi(\bar{b} \to \bar{u}u\bar{d})\phi(B^0) = (A_{\frac{3}{2}} \mid \frac{3}{2}, +\frac{1}{2}\rangle + A_{\frac{1}{2}} \mid \frac{1}{2}, +\frac{1}{2}\rangle)(\mid \frac{1}{2}, -\frac{1}{2}\rangle)$$

$$= \sqrt{\frac{1}{2}} A_{\frac{3}{2}} \mid 2,0\rangle + \sqrt{\frac{1}{2}}(A_{\frac{1}{2}} + A_{\frac{3}{2}}) \mid 1,0\rangle + \sqrt{\frac{1}{2}} \mid 0,0\rangle$$

- The branching fraction of $B^0 \to \pi^0\pi^0$ is thus:

$$Br(B^0 \to \pi^0\pi^0) =$$

$$(\sqrt{\frac{2}{3}}\langle 2,0 \mid - \sqrt{\frac{1}{3}}\langle 0,0 \mid)(\sqrt{\frac{1}{2}} A_{\frac{3}{2}} \mid 2,0\rangle + \sqrt{\frac{1}{2}}(A_{\frac{1}{2}} + A_{\frac{3}{2}}) \mid 1,0\rangle + \sqrt{\frac{1}{2}} \mid 0,0\rangle)$$

$$= \sqrt{\frac{1}{3}} A_{\frac{3}{2}} + \sqrt{\frac{1}{6}} A_{\frac{1}{2}}$$

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Branching Fractions

Continuing in this fashion

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

$$Br(B^0 \to \pi^0\pi^+) = A^{0+} = \sqrt{\frac{3}{4}}A_{\frac{3}{2}}$$

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

For convenience, let's define $A_2 = \sqrt{(1/12)}\, A_{3/2}$ and $A_0 = \sqrt{(1/6)}A_{1/2}$ so that:

$$A^{00} = 2A_2 + A_0$$

$$A^{0+} = 3A_2$$

$$\sqrt{\frac{1}{2}}A^{+-} = A_2 - A_0$$

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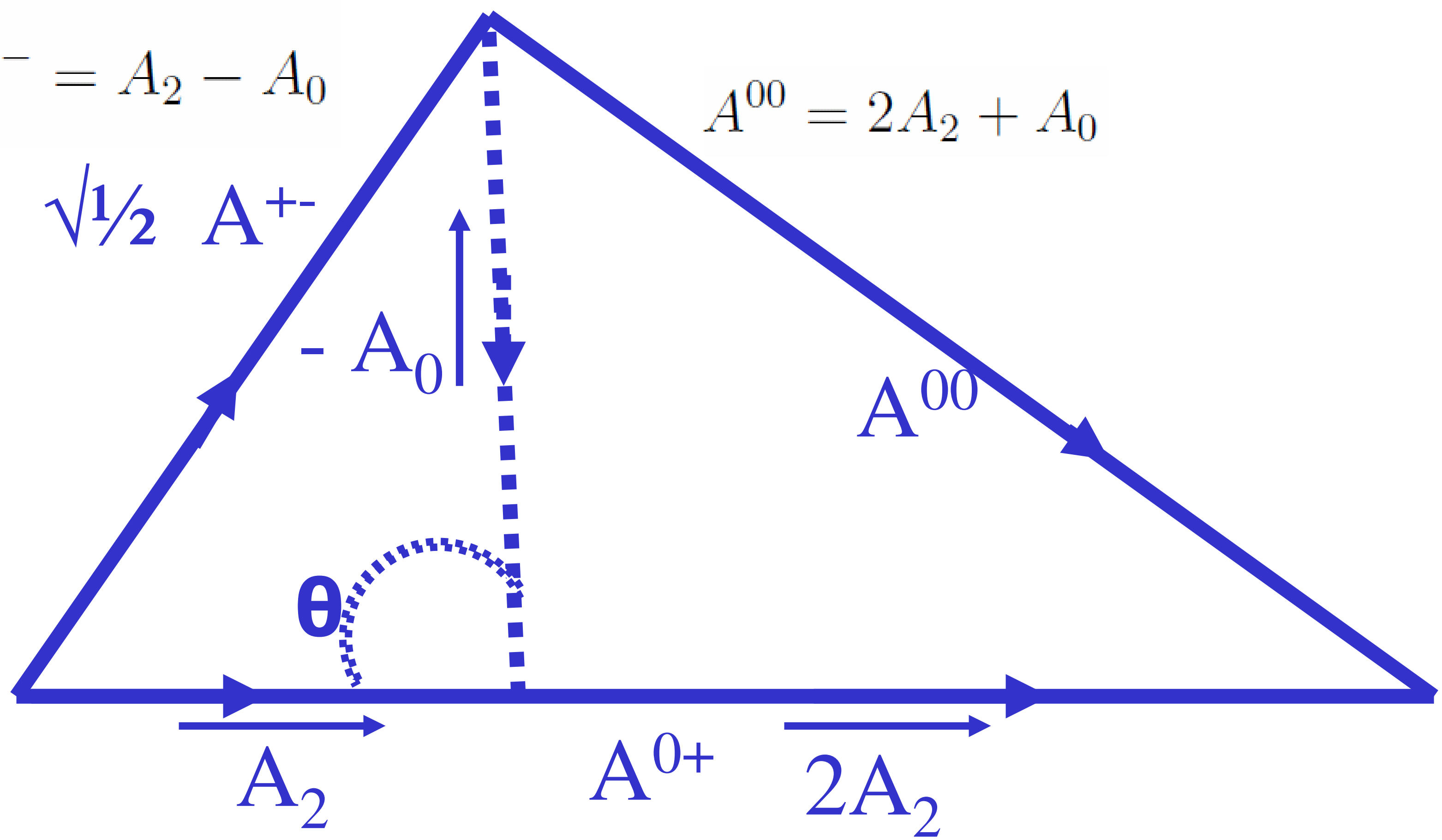
Triangle

$$\sqrt{\frac{1}{2}} A^{+-} = A_2 - A_0$$

$$A^{00} = 2A_2 + A_0$$



$$A^{0+} = 3A_2$$

Penguin in Depth

- The gluonic penguin process can contain only the A_0 modes.

- The tree process can contain both A_2 and A_0 modes.

- $$A_2 e^{-2i\phi T} = \bar{A}_2$$

  So that

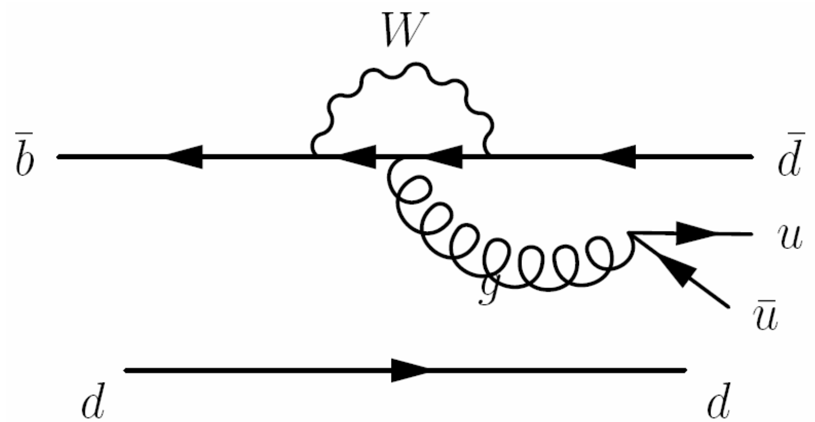
  $$|\bar{A}^{0+}| = |A^{0-}| = |A^{0+}|$$

  and

  $$\bar{A}^{00} = 2\bar{A}_2 + \bar{A}_0$$

  $$\sqrt{\frac{1}{2}}\bar{A}^{+-} = \bar{A}_2 - \bar{A}_0$$

  $$\bar{A}^{0+} = 3\bar{A}_2$$



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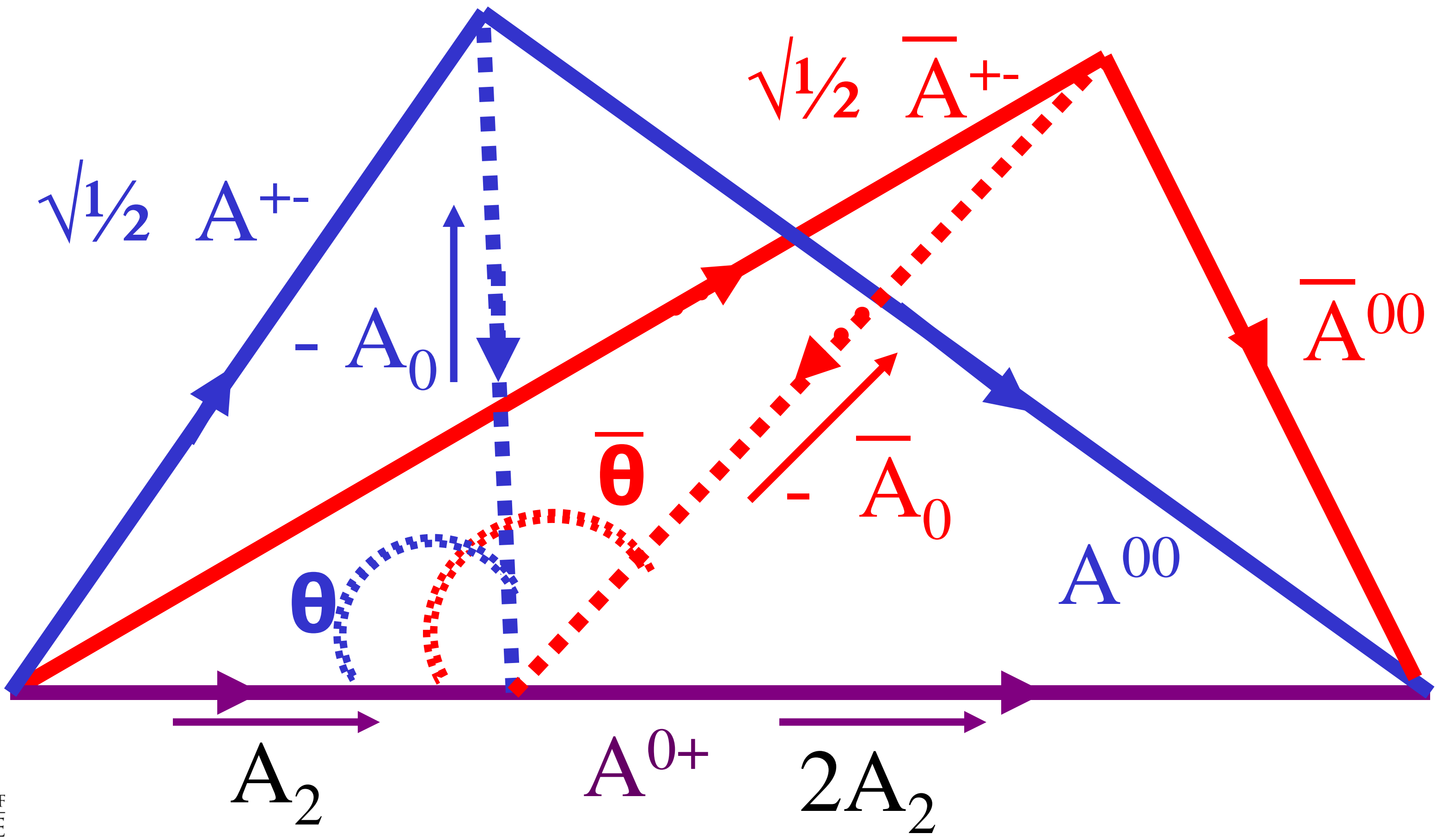
Triangles



Breaking it down

For A^{+-}

$$\lambda_{+-} = e^{-2i\phi M}\frac{\bar{A}_{+-}}{A_{+-}} = e^{-2i\phi M}\frac{\bar{A}_2 - \bar{A}_0}{A_2 - A_0}$$

let

$$z = \frac{A_2}{A_0}$$

and recall

$$A_2 e^{-2i\phi T} = \bar{A}_2$$

So that

$$e^{-2i\phi M}\frac{\bar{A}_{+-}}{A_{+-}} = e^{-2i(\phi T + \phi M)}\frac{1-\bar{z}}{1-z}$$

with $|A_2|$, $|A_0|$ and hence $\cos\theta$ determinable from geometric considerations

$$= e^{-2i(\phi_2)}\frac{1-|\bar{z}|e^{\pm i\bar{\theta}}}{1-|z|e^{\pm i\theta}}$$

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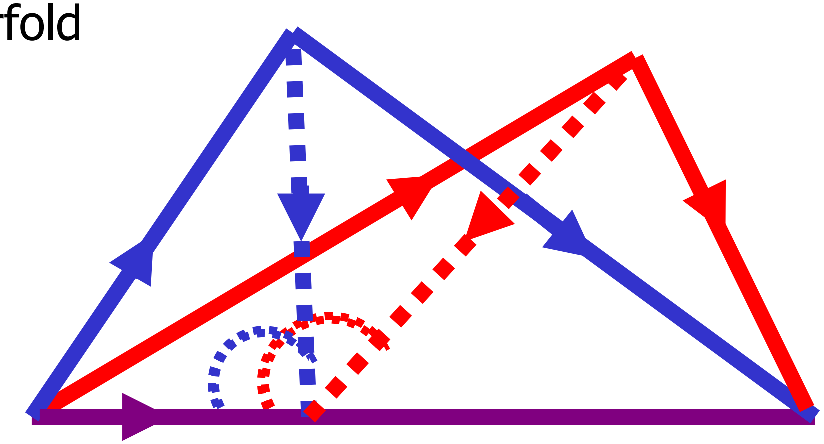
Ambiguities

- As sinθ cannot be determined from this triangle, we find that there is a fourfold ambiguity in λ_{+-}.



- $$\lambda_{00} = e^{-2i(\phi_2)} \frac{1-\frac{1}{2}|\bar{z}|e^{\pm i\bar{\theta}}}{1-\frac{1}{2}|z|e^{\pm i\theta}}$$

  contains the same ambiguity.

- There are four possible solutions for $\sin(2\varphi_2)$

$$Im(\lambda_{00}) = sin(2\phi_2)Im(\frac{1-\frac{1}{2}|\bar{z}|e^{\pm i\bar{\theta}}}{1-\frac{1}{2}|z|e^{\pm i\theta}})$$

$$sin(2\phi_2+\kappa_{00}) = Im(\lambda_{00})|\frac{1-\frac{1}{2}|z|e^{\pm i\theta}}{1-\frac{1}{2}|\bar{z}|e^{\pm i\bar{\theta}}}|$$

as κ_{00} has four different values depending upon the phase of θ.

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Eliminating Ambiguities

- $$sin(2\phi_2 + \kappa_{+-}) = Im(\lambda_{+-})|\frac{1-|z|e^{\pm i\theta}}{1-|\bar{z}|e^{\pm i\bar{\theta}}}|$$

  Also has four solutions, but (hopefully) not the same four solutions.

- Overlap between κ_{+-} and κ_{00} leaves a twofold ambiguity in $\sin(2\varphi_2)$

- These require individual measurements of A_{00}, $\bar{A}_{00}$, A_{+-}, and $\bar{A}_{+-}$.

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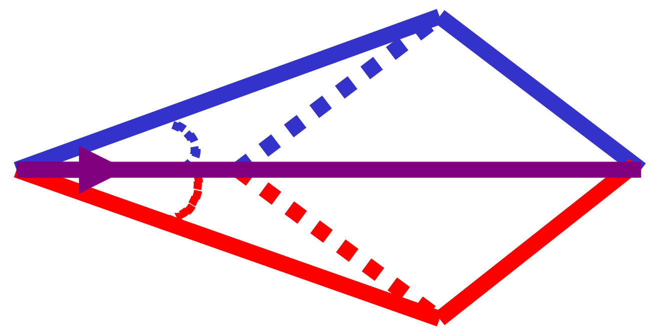
Without Flavour Tagging

- In the case that A_{00} and $\bar{A}_{00}$ can not be determined individually, an upper bound can still be placed on the penguin contributions to $\sin(2\varphi_2)$.
- By finding the amplitude $A_{00} + \bar{A}_{00}$, we can redraw the diagram so as to maximise the effects of θ and $\bar{\theta}$ by setting $A_{00} = \bar{A}_{00}$
- Using this method, it can be shown

$$sin^2(\kappa) \leq \frac{A_{00} + \bar{A}_{00}}{A_{0+} + A_{0-}}$$



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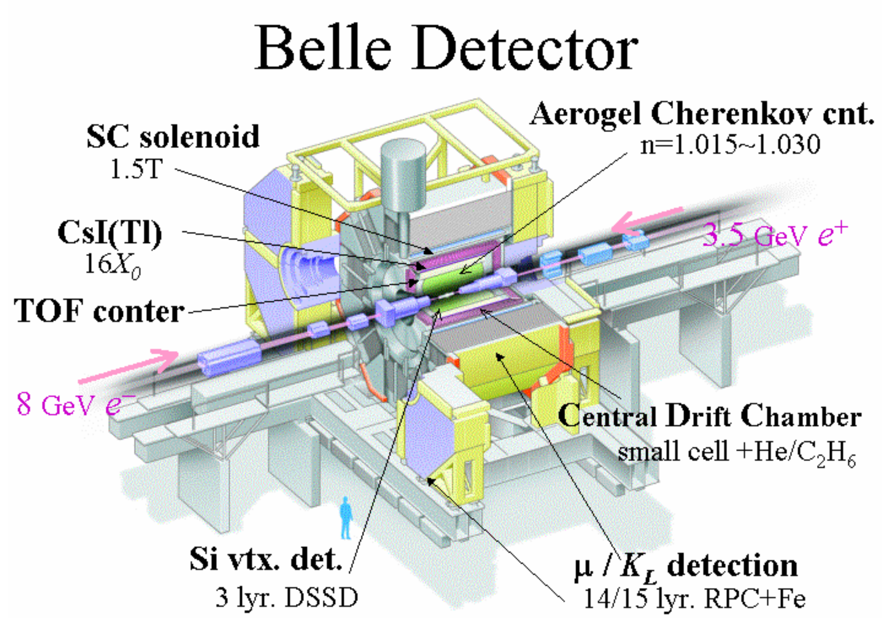
Making Mesons

- To make B-mesons we need a B factory.
- The Belle experiment is located at KEK, in Tsukuba, Japan
- It operates at the $\Upsilon(4S)$ Resonance.
- It is an asymmetrical collider.



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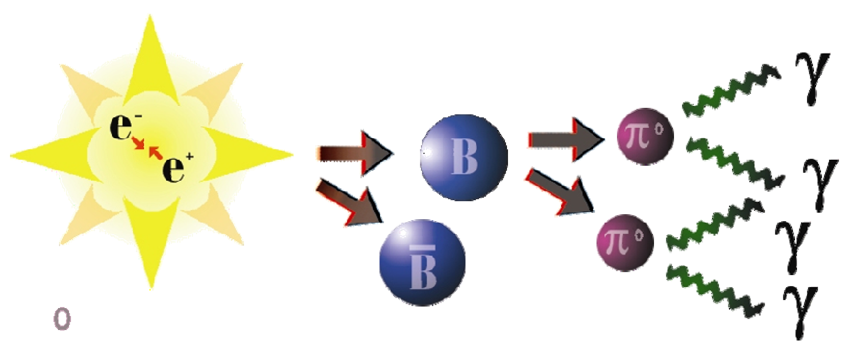
ECL Timing Data - Conceptual

- The branching fraction of is very small

  $(2.3_{-0.5\ -0.3}^{+0.4\ +0.2})\times10^{-6}$ - Y. Chao et al. (Belle Collaboration), Phys. Rev. Lett. 94, 181803 (2005).

  $(1.47 \pm 0.25 \pm 0.12) \times 10^{-6}$ - B. Aubert et al. (The BABAR Collaboration) , Phys. Rev. D 76, 091102 (2007)

- Due to the decay chain of π^0, γ identification is of the essence.



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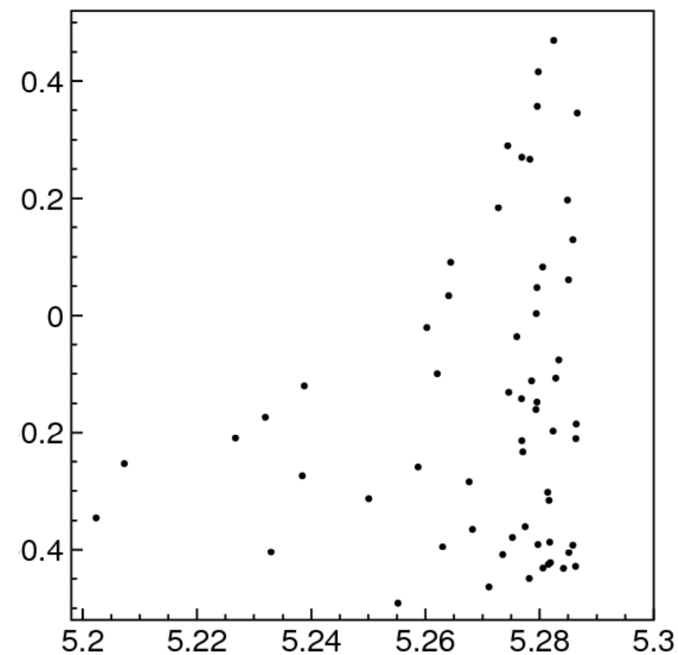
Bhabha Events and the ECL

- Bhabha events result in a highly energised particle depositing a huge amount of energy in the ECL.
- The ECL crystals have a finite decay time.
- If the crystal stays 'hot' after a subsequent beam crossing, the reading in the ECL will resemble a signal photon.



M_{BC} vs ΔE for off time events
(S.W. Lin, BN: 944)

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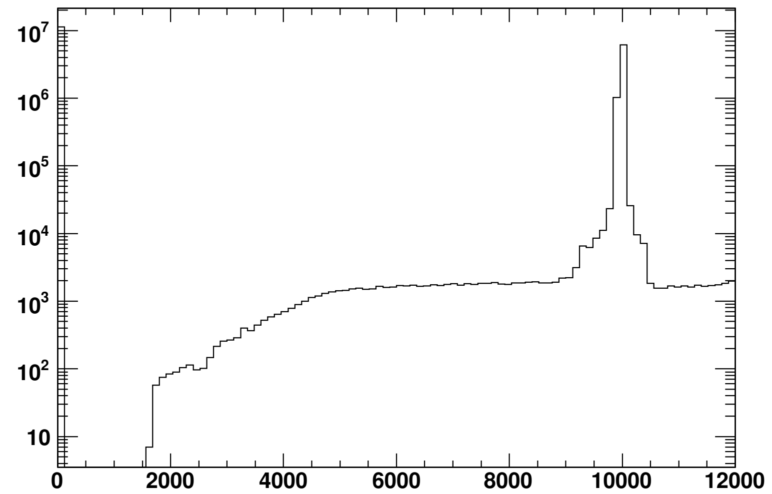
Timing Information

- To eliminate off time events, we can record the time at which events were triggered.
- A reading is ‘on-time’ if its TDC count is between 9000 and 11000.
- Outside of this range and the reading is excluded
- TDC of zero is not excluded



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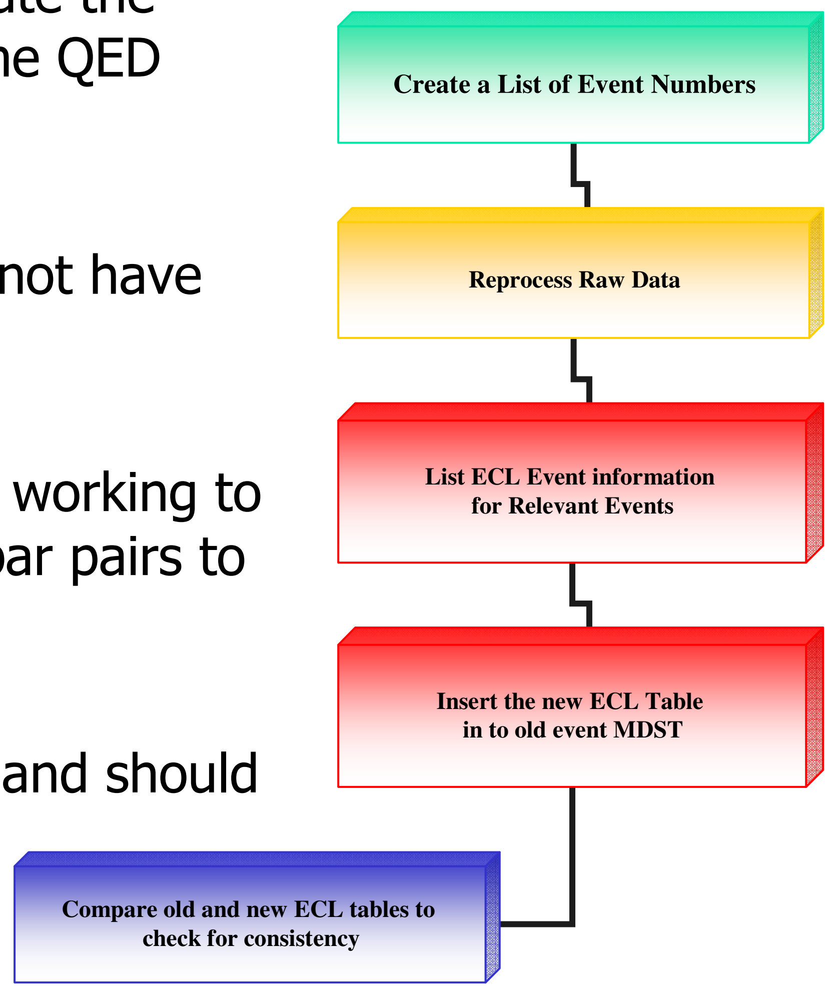
Work to Date

- It is not yet feasible to investigate the effects of the removal of off-time QED events using simulated data.
- Over a third of Belle data does not have the timing data attached.
- Over the past year I have been working to reprocess over 200 million BB-bar pairs to attach the timing data.
- This reprocessing is underway, and should be completed by July 2009



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