New method of ICPV parameter measurement at Super B factories

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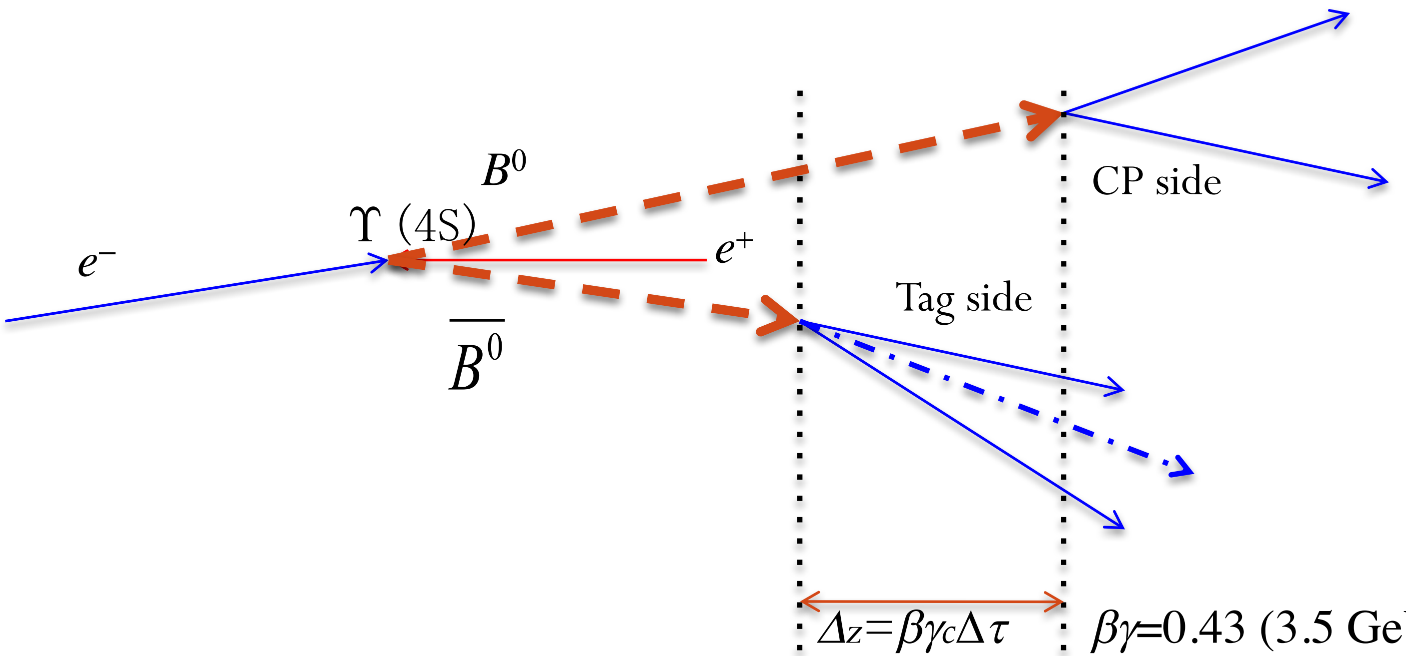
動機

- せっかくバーテックス検出器を作っているのだから、バーテックス検出器をフルに使ったデータ解析を考えたい。
- スーパーKEKBのnanoビーム衝突の特徴を生かしたい。
- B fatoryで仕事しているのだから王道のϒ(4S)からのICPVに貢献したい。

  特に弱点の $B \to \pi^0 \pi^0$ に貢献したい。

ICPV measurement in B factory

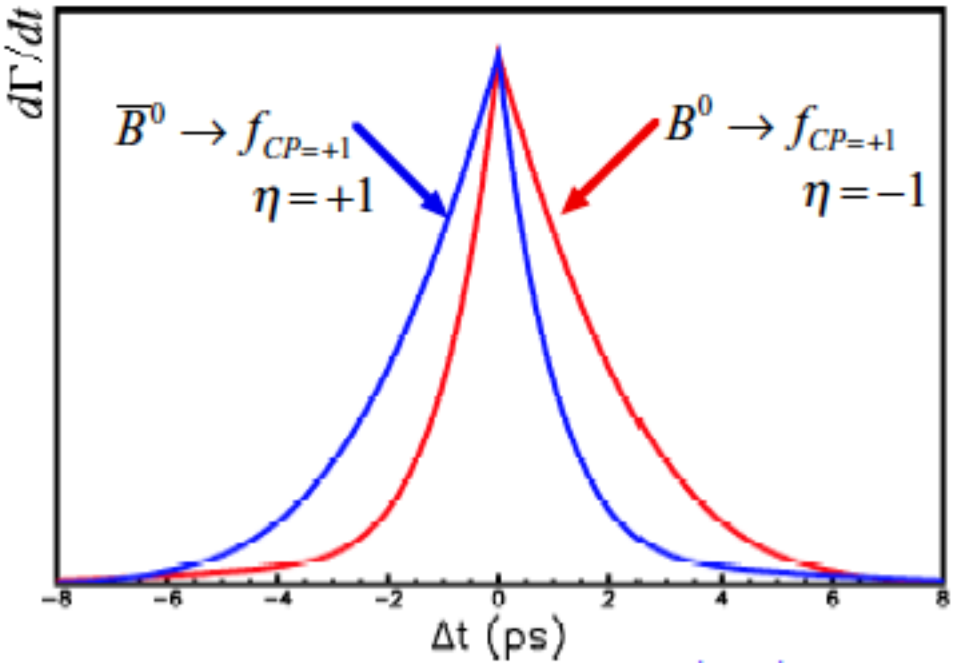
- Identify *CP* decay of one *B* meson
- Tagging flavor of the other B
- Measure $\Delta t = t_{CP} - t_{tag} = \Delta z / \beta\gamma c$



$\beta\gamma$=0.43 (3.5 GeV x 8 GeV)

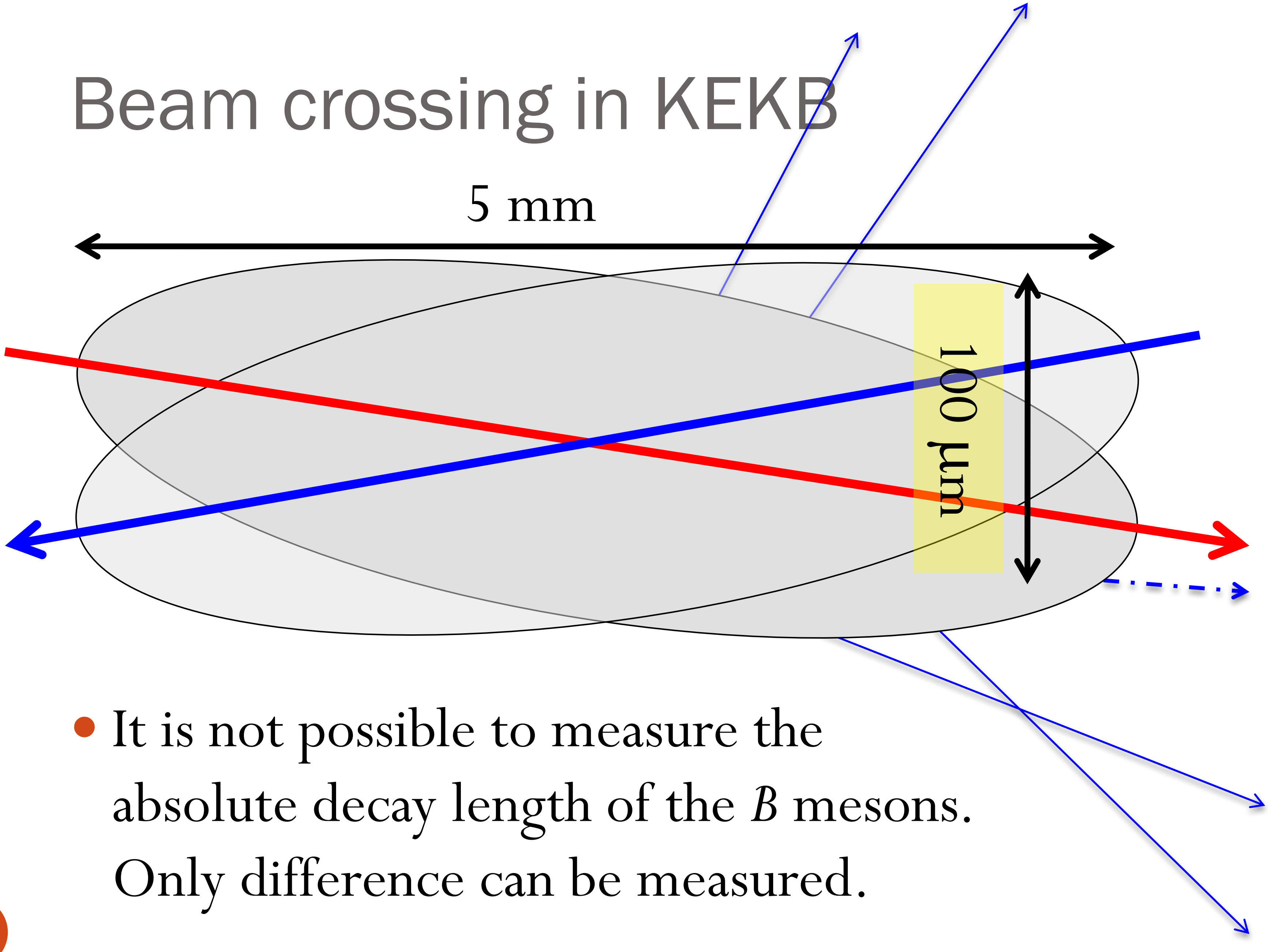
ICPV measurement in B factory

- The measurement of Δt is essential to extract the CP violation parameter S and A.
- If Δt is integrated (not measured) , the factors S and A disappear and can not be measured.
- Instead, we do not need to know where B^0 and B^0-bar are born.



$$R(q=\pm1,\Delta t)=\frac{1}{4\tau_B}e^{-\frac{|\Delta t|}{\tau_B}}(1\pm(S\sin\Delta t\Delta m+A\cos\Delta t\Delta m))$$

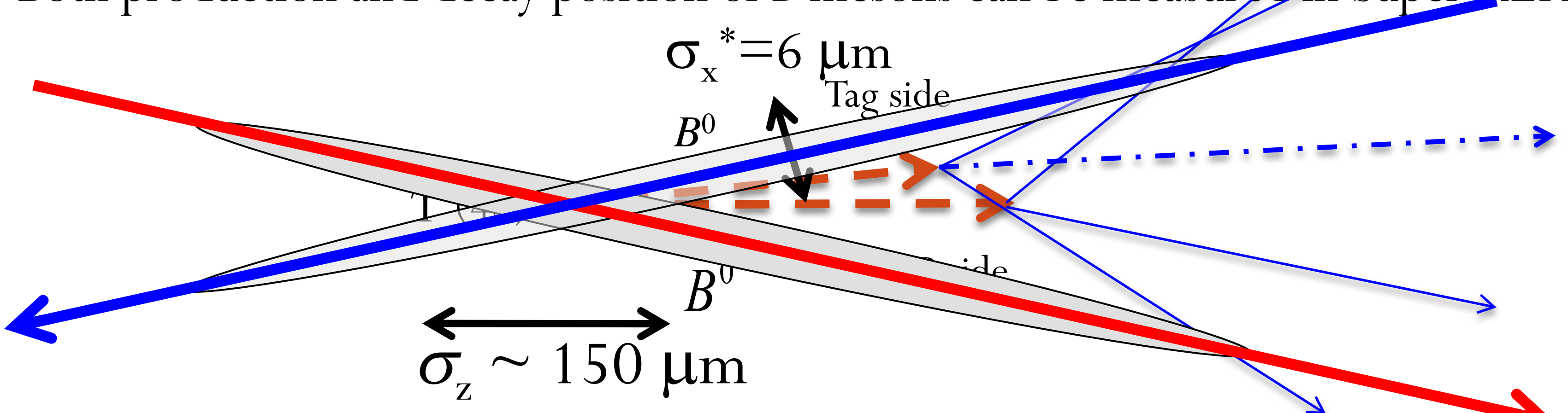
Beam crossing in KEKB



- It is not possible to measure the absolute decay length of the *B* mesons. Only difference can be measured.

Beam crossing in Super KEKB

- I have been believing the information of production position of *B* and *B*-bar must be beneficial in the ICPV analysis.
- The Beam
  - The beam size is 6 nm x 30 nm x 6 mm
  - LER and HER beam crosses at 80 mrad.
  - Length of collision point in Z direction is 6 um/sin(40mrad)=150 um
- The Physics
  - Average *B* decay life: $\tau = 1.53$ psec, $c\tau = 460\ \mu$m.
  - The Lorentz boost factor: $\beta\gamma = 0.28$ (4 GeV x7 GeV, SuperKEKB).
  - The mean decay length of B meson: $\beta\gamma c\tau = 128\ \mu$m.
- Both production and decay position of *B* mesons can be measured in Super KEKB.



$\Upsilon(4S) \rightarrow B^0\overline{B^0}$ decay

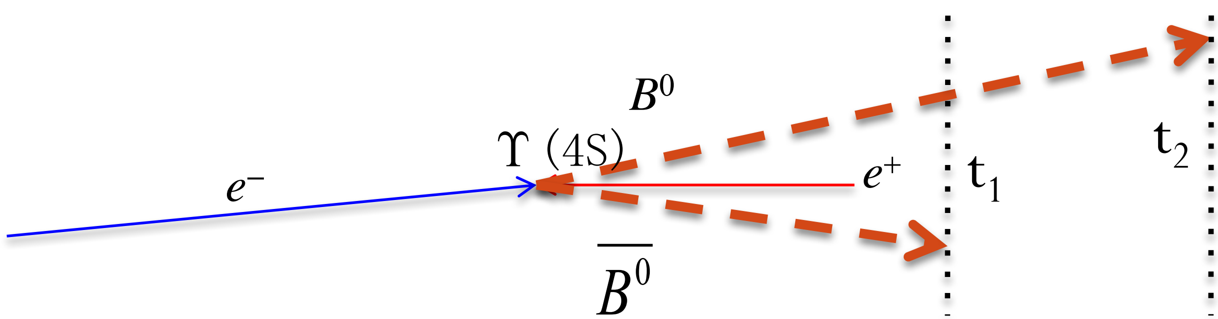
- The decay rate of $B^0\overline{B^0}$ system decaying from Υ (4S) to final state f_1 at t_1 and f_2 at t_2 is represented as

$$R(t_1,t_2) = Ce^{-\Gamma(t_1+t_2)}\{(|A_1|^2+|\overline{A_1}|^2)(|A_2|^2+|\overline{A_2}|^2) - 4\,\mathrm{Re}(\frac{q}{p}A_1^*\overline{A_1})\mathrm{Re}(\frac{q}{p}A_2^*\overline{A_2})$$

$$-\cos(\Delta m_B(t_1-t_2))[(|A_1|^2-|\overline{A_1}|^2)(|A_2|^2-|\overline{A_2}|^2) + 4\,\mathrm{Im}(\frac{q}{p}A_1^*\overline{A_1})\mathrm{Im}(\frac{q}{p}A_2^*\overline{A_2})]$$

$$+2\sin(\Delta m_B(t_1-t_2))[\mathrm{Im}(\frac{q}{p}A_1^*\overline{A_1})(|A_2|^2-|\overline{A_2}|^2) - \mathrm{Im}(\frac{q}{p}A_2^*\overline{A_2})(|A_1|^2-|\overline{A_1}|^2)]\}$$

- where $A(\overline{A})$ is the amplitude of $B^0(\overline{B^0})$ decaying into the final state, respectively.



現在のICPV解析

- 衝突点が測定できず、$t1$-$t2$だけ測定できる。
- $t1+t2$を積分して、$\Delta t=t1-t2$の項をのこした。その係数からCP破れパラメータが計算できた。

$$R(t_1,t_2)=Ce^{-\Gamma(t_1+t_2)}\{(|A_1|^2+|\overline{A_1}|^2)(|A_2|^2+|\overline{A_2}|^2)-4\,\mathrm{Re}(\frac{q}{p}A_1^*\overline{A_1})\mathrm{Re}(\frac{q}{p}A_2^*\overline{A_2})$$

$$-\cos(\Delta m_B(t_1-t_2))[(|A_1|^2-|\overline{A_1}|^2)(|A_2|^2-|\overline{A_2}|^2)+4\,\mathrm{Im}(\frac{q}{p}A_1^*\overline{A_1})\mathrm{Im}(\frac{q}{p}A_2^*\overline{A_2})]$$

$$+2\sin(\Delta m_B(t_1-t_2))[\mathrm{Im}(\frac{q}{p}A_1^*\overline{A_1})(|A_2|^2-|\overline{A_2}|^2)-\mathrm{Im}(\frac{q}{p}A_2^*\overline{A_2})(|A_1|^2-|\overline{A_1}|^2)]\}$$

$$A_{CP}(\Delta t)=\frac{R_+(\Delta t)-R_-(\Delta t)}{R_+(\Delta t)+R_-(\Delta t)}$$

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

Extraction of CP asymmetry parameters

- Assigning f_1 CP side and f_2 the B^0 tag side, $A_2 = A_{tag}, \overline{A_2} = 0,$ the decay rate becomes,

$$R_+(t_{CP},t_{tag}) = Ce^{-\Gamma(t_{CP}+t_{tag})}\left|A_{tag}\right|^2\left|A_{CP}\right|^2\{(1+\left|\overline{A_{CP}}\right|^2/\left|A_{CP}\right|^2)$$

$$-\cos(\Delta m_B(t_{CP}-t_{tag}))[(1-\left|\overline{A_{CP}}\right|^2/\left|A_{CP}\right|^2)]$$

$$+2\sin(\Delta m_B(t_{CP}-t_{tag}))[\mathrm{Im}(\frac{q}{p}A_{CP}^{*}\overline{A_{CP}})/\left|A_{CP}\right|^2]\}$$

- Let $\lambda_{CP} = \frac{q}{p}\frac{\overline{A_{CP}}}{A_{CP}}$ and $\left|\frac{q}{p}\right| = 1,$

$$R_+(t_{CP},t_{tag}) = Ce^{-\Gamma(t_{CP}+t_{tag})}\left|\overline{A_{tag}}\right|^2\left|A_{CP}\right|^2\{(1+\left|\lambda_{CP}\right|^2)$$

$$-\cos(\Delta m_B(t_{CP}-t_{tag}))[(1-\left|\lambda_{CP}\right|^2)]+2\,\mathrm{Im}(\lambda_{CP})\sin(\Delta m_B(t_{CP}-t_{tag}))\}$$

Extraction of CP asymmetry parameters

- Similarly,

$$R_-(t_{CP},t_{tag}) = Ce^{-\Gamma(t_{CP}+t_{tag})}\left|\overline{A}_{tag}\right|^2 \left|A_{CP}\right|^2 \{(1+\left|\lambda_{CP}\right|^2)$$
$$+\cos(\Delta m_B(t_{CP}-t_{tag}))[(1-\left|\lambda_{CP}\right|^2)]-2\,\mathrm{Im}(\lambda_{CP})\sin(\Delta m_B(t_{CP}-t_{tag}))\}$$

- Integrating $R_{\pm}(t_{CP}, t_{\mathrm{tag}})$ with t_{tag}, we get

$$R_{\pm}(t_{CP}) = \int_{t_{tag}=0}^{\infty} R_{\pm}(t_{CP},t_{tag})dt_{tag}$$
$$= Ce^{-\Gamma(t_{CP})}\frac{\left|\overline{A}_{tag}\right|^2 \left|A_{CP}\right|^2}{\Gamma(1+x^2)}\{(1+x^2)(1+\left|\lambda_{CP}\right|^2)$$
$$\pm(1-\left|\lambda_{CP}\right|^2)(\cos(\Delta m_B t_{CP})+x\cos(\Delta m_B t_{CP}))$$
$$\pm 2\,\mathrm{Im}(\lambda_{CP})(x\cos(\Delta m_B t_{CP})-\sin(\Delta m_B t_{CP})\}$$

  - where $x = \Delta m_B/\Gamma$.

- Note that the *CP* violation parameter, $\mathrm{Im}(\lambda_{cp})$, survives.

Extraction of *CP* asymmetry

- Let $|\lambda_{CP}|=1$, *no direct CP violation contribution*, the formula is simplified.

$$R_{\pm}(t_{CP}) = 2C\frac{\left|\overline{A}_{tag}\right|^2 \left|A_{CP}\right|^2}{\Gamma} e^{-\Gamma(t_{CP})}\{1 \pm \frac{\text{Im}(\lambda_{CP})}{\sqrt{(1+x^2)}}(\frac{x}{\sqrt{(1+x^2)}}\cos(\Delta m_B t_{CP}) - \frac{1}{\sqrt{(1+x^2)}}\sin(\Delta m_B t_{CP})\}$$

$$= 2C\frac{\left|\overline{A}_{tag}\right|^2 \left|A_{CP}\right|^2}{\Gamma} e^{-\Gamma(t_{CP})}\{1 \mp \frac{\text{Im}(\lambda_{CP})}{\sqrt{(1+x^2)}}\sin(\Delta m_B t_{CP} - \tan^{-1} x)\}$$

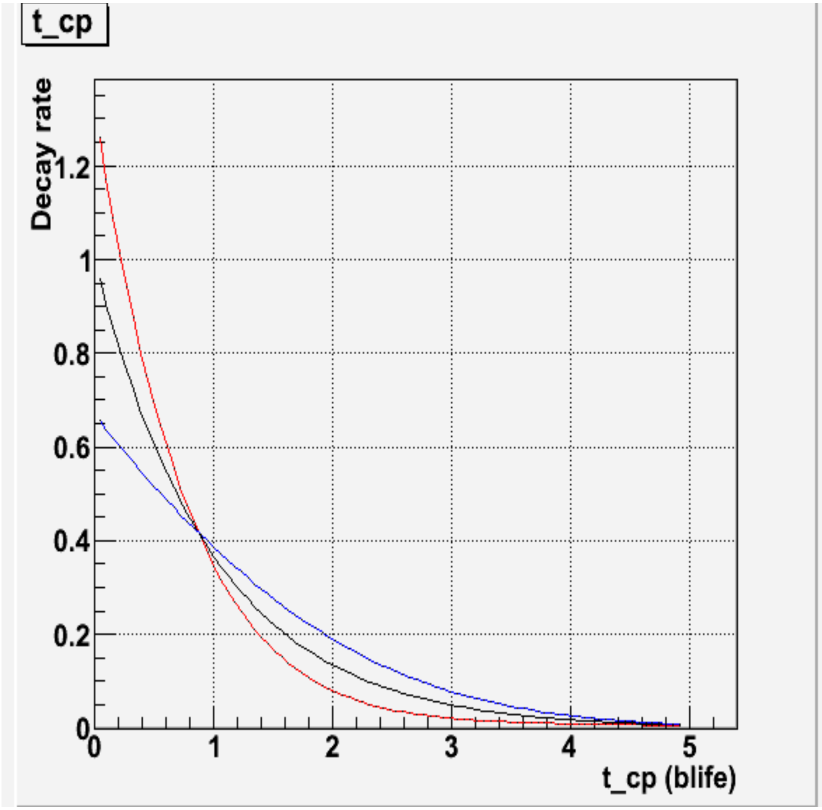
- In case of $B \rightarrow J/\psi\, K_s$, $\text{Im}(\lambda_{CP})$ corresponds to $\sin 2\phi_1$. (I do not know the sign.)
- Time dependent *CP* Asymmetry is

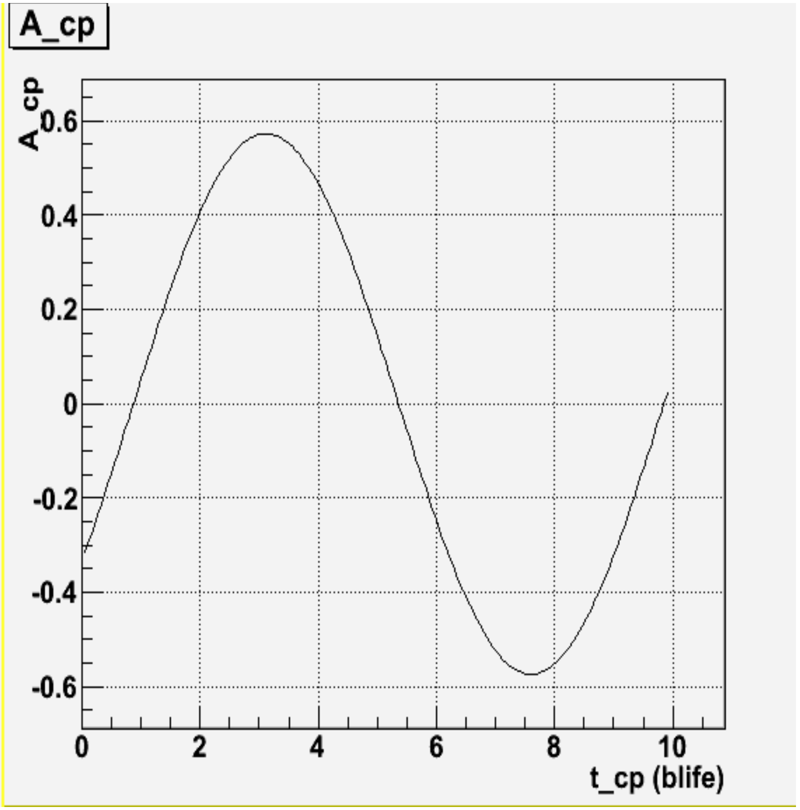
$$A_{CP}(t_{CP}) = \frac{R_+(t_{CP}) - R_-(t_{CP})}{R_+(t_{CP}) + R_-(t_{CP})} = \frac{\text{Im}(\lambda_{CP})}{\sqrt{(1+x^2)}}\sin(\Delta m_B t_{CP} - \tan^{-1} x)$$

- The penalty of this method is just factor of $1/\sqrt{1+x^2} = 0.79$ compared to the Δt method.

Results

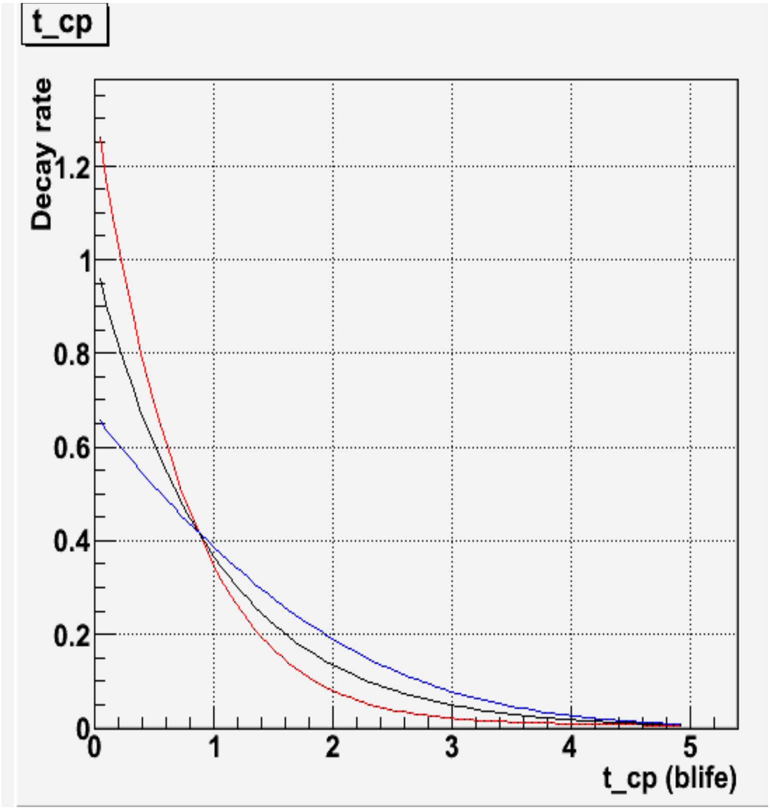
- Left figure: Decay rate for $\Upsilon(4S) \rightarrow B(\text{tag})\, B(J/\psi Ks)$ for x=0.7 and $\sin 2\phi_1$=0.7. Three curves corresponds to B^0-tag, no tag and $\overline{B^0}$ tag.
- Right figure: Asymmetry plot, the amplitude corresponds to $\mathrm{Im}(\lambda_{CP})/\sqrt{1+x^2}$.





Average decay time of CP+ and CP- state

- Clear difference in $R_{\pm}(t)$.
- The CP parameter survives if integrated: $\bar{t}_{\pm} = \int_0^{\infty} t\, R_{\pm}(t) \mathrm{d}t$
- $\Delta\bar{t} = \bar{t}_{+} - \bar{t}_{-}$ is also a good estimator of the CP violation parameter.



Impacts to physics analysis

- Analysis procedure

1. Find a *CP* mode decay of one *B* meson.
2. Determine the flavor of the other *B* meson.
3. Determine the position of decay vertex of the *CP*-side *B*.
4. The decay time distributions for B^0 and $\overline{B}^0$ tag is fit to theoretical curve including the vertex position measurement error and collision point determination errors.

- The information of Tag-side *B* vertex is not necessary.
- The analysis is free from systematic errors on the tag-side vertex determination.
- A reliable information of collision point is indispensable.

Revolutional

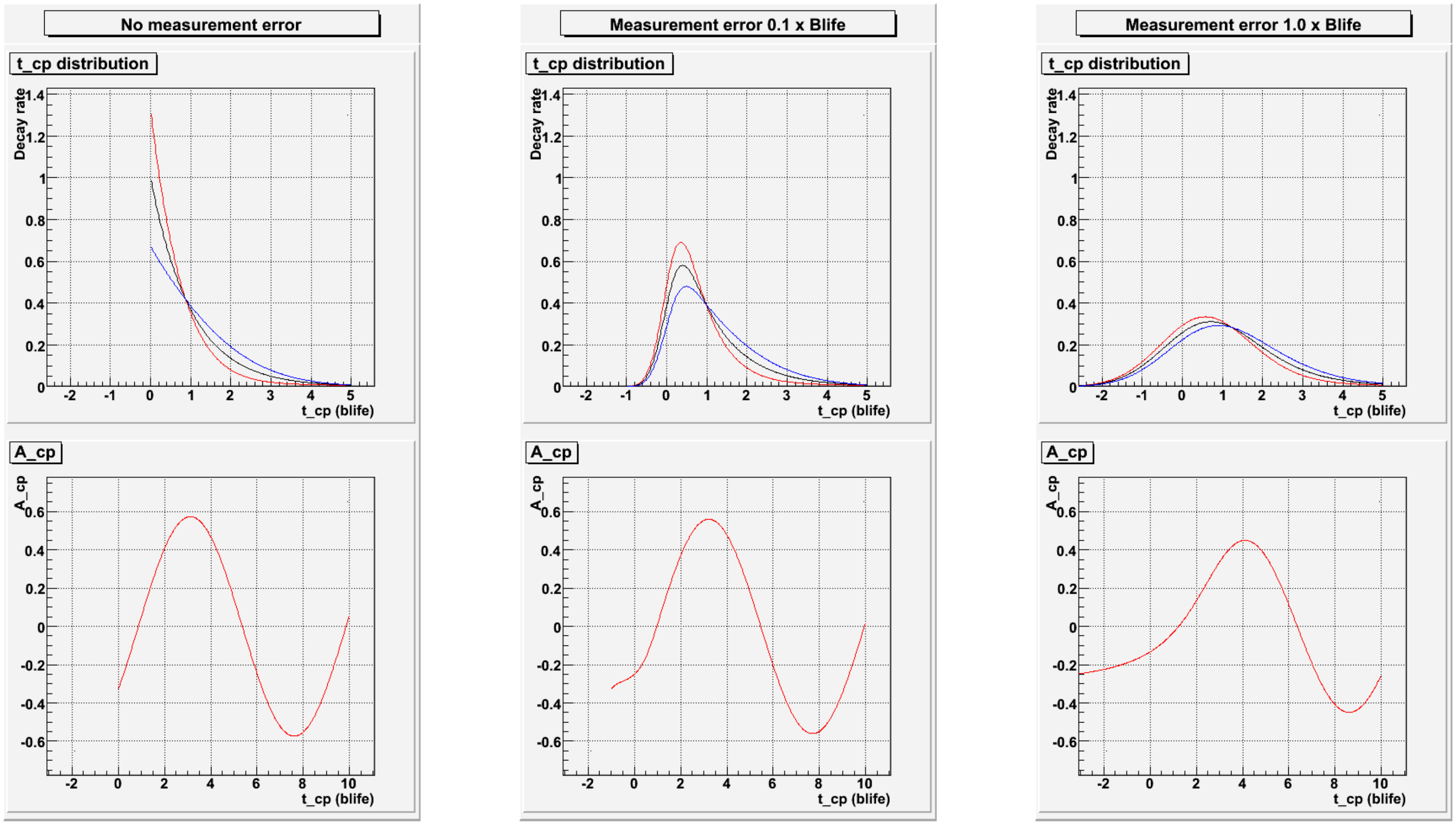
More Impacts to physics analysis

- Reversed analysis procedure

1. Find a *CP* mode decay of one *B* meson.
2. Determine the flavor of the other *B* meson.
3. Determine the position of decay vertex of the *tag-side B*.
4. The decay time distributions for B^0 and $\overline{B}^0$ tag is fit to theoretical curve including the vertex position measurement error and collision point determination errors.

- The information on *CP*-side *B* vertex is not necessary.
- *Even "all neutral" CP modes (nn, $\pi^0\pi^0$, K_SK_S, K_SK_L, K_LK_L, $\nu\nu^{(??)}$) can be analyzed in the same way as charged-mode decays.*

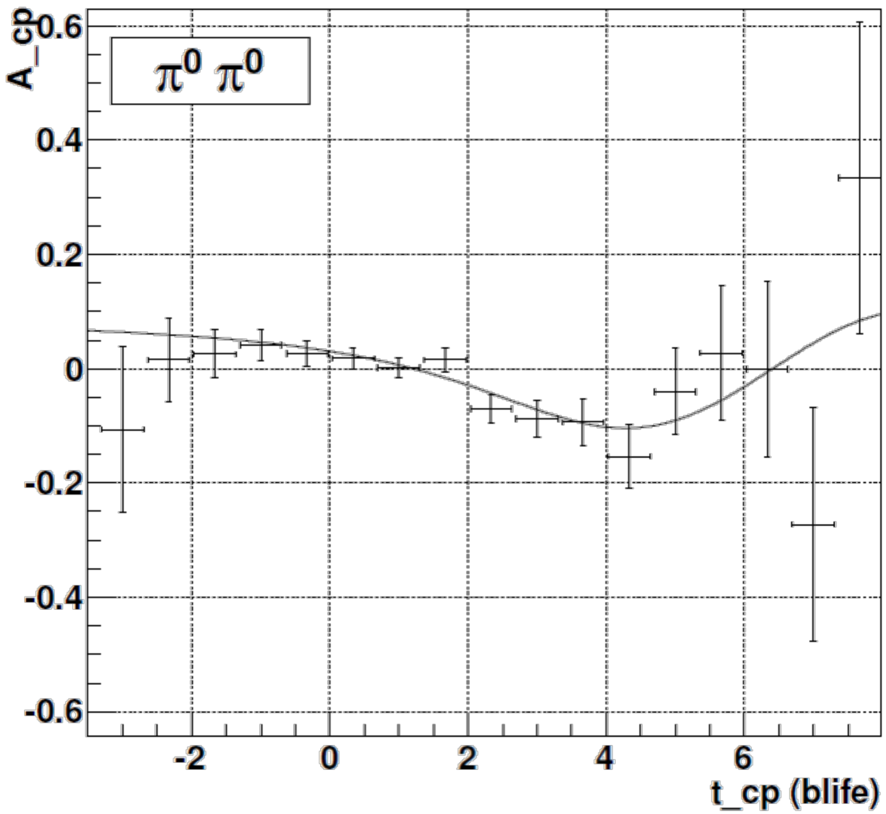
Collision point width and vertex determination errors included…



- With errors we can still observe the CP asymmetry.
- Sensitivity reduced.   More systematic shift.

A vector level simulation for B0 → $\pi^0\pi^0$

- Events corresponds to 50 ab^{-1} including
- Wrong tag
- Event reconstruction efficiency
- CP side vertex measurement error



A vector level simulation for B0 → $\pi^0\pi^0$

- Measurement stability is estimated by repeating the MC
- A_{CP} (fitting) method and $\Delta\bar{t}$ method give a comparable result.

Luminosity (ab-1)	Genenrated events	Acp (fitting) error (%)	$\Delta\bar{t}$ method error (%)
1	320	170	174
5	1600	70	72
15	4800	42	44
50	16000	23	24
100	32000	16	17

With determination errors of collision point width and vertex position.

- The length of collision point in the proposed Super KEKB (150 μm) is comparable with the average decay length (128 μm), but still acceptable.
- The stable control and monitor of the beam size and beam position may be essential.
- For the first time I require higher energy asymmetry, larger crossing angle and smaller horizontal beam size in Super KEKB. These all directly improve the sensitivity and reliability of this method.
- The systematic ambiguities in this method can be studied in detail in the benchmark modes such as $B \rightarrow J/\psi\, K_S$.

Summary

- The formula are taken from
  - Andrew D. Foland (Cornell Univ.), "Measurement of *CP* violation at the Υ(4S) without time ordering or Δt", Phys. Rev. D 60, 111301 (1999) / HEPPH9907277
  - The possibility of measurement of *CP* violation of all-neutral modes is mentioned already there.
- The paper was published before the concept of nano-beam Super B factory was proposed.
  - Clearly the method is realistic only with very small beam collision point.

追加

- LHCbではこの解析はできない。
  - この解析手法が使えるのは人類史上空前絶後SuperKEKBのみ。
- SuperKEKBの衝突点が「わかっていること」が重要。
  - 加速器安定性→衝突しないとわからない。
  - 大量の物理イベント（ee → ee/μμ/uu/dd/cc/ss)で刻々と衝突位置のモニターが可能（期待）
  - この不安定性を含めたモンテカルロ研究も必要。
  - SuperKEKBのビームバンチ構造が正しくモンテカルロに取り入れられているかの確認が必要。
- 系統誤差（再確認）：
  - 系統誤差はJψKsなどの「goldenモード」で研究できる。（tag sideだけ取り出して分布やエフィシェンシーの研究をする。CP側を使って答え合わせができる）
  - したがって、多くの不定性はキャンセルできる。

個人的な大問題

- いいわけだがSVDの開発が忙しかった。
- それでアイディアを１０年放ってある。
- どなたか一緒にMCで実現性を調べてもらえないか
- まずは $B \to \pi^0\pi^0$ モードでMCを走らせ、従来の手法とパラメータに対する感度を比較する。
- 実現性が確認できたら学位論文を考える。
- この数年の間に $B \to \pi^0\pi^0$ の研究が進んでいるが、従来の解析方法とは系統エラーが異なるので学位論文になる。
- 他の「中性の終状態」モードも試すことが可能になる。