Study of time-dependent CP violation in Ks eta gamma decays at Belle

Tohoku University

Hiroshi Nakano

20th-Feb-2014

This work is supported by JSPS KAKENHI No. 23・3221.

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1. **What is "TDCPV" ?**
2. **Why it is interesting ?**
3. **How we can detect ? (experimental setup)**
4. **The result of the study.**

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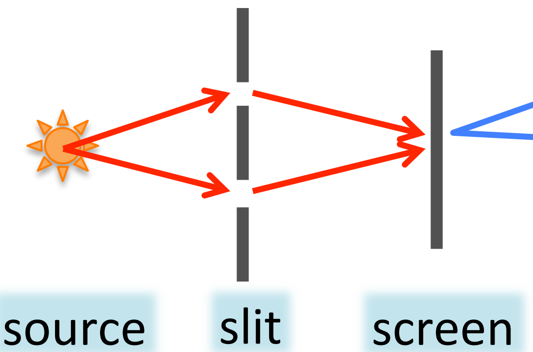
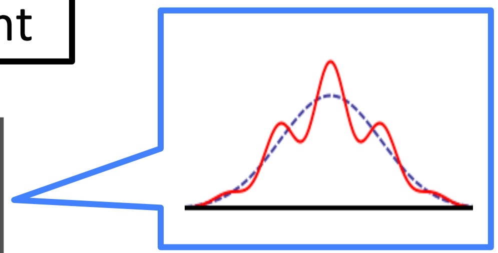
What is time dependent CP violation ?

Time dependent CPV is caused by quantum interference (like double slit experiment).

Double slit experiment



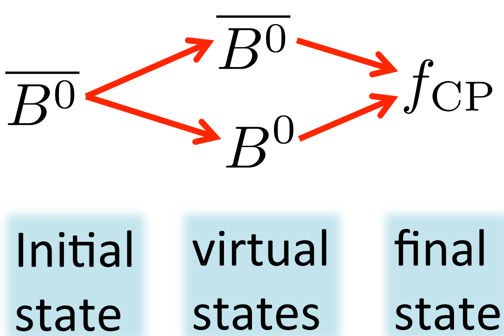


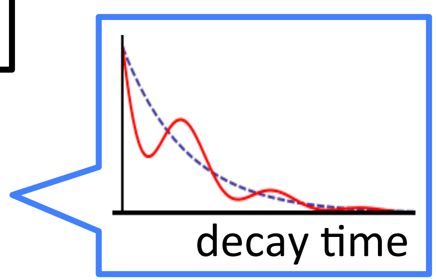
[POINT]

- Two paths can interfere both constructive and destructive.

Quantum interference on the screen.

Time dependent CPV





[POINT]

- $\overline{B^0}$ can change to B^0, and vice-versa (B-Bbar oscillation).
- Both $\overline{B^0}$ and B^0 can decay to CP eigenstate, f_{CP}.

Quantum interference on decay time distribution.

(⚠ This Illustration is drawn with an exaggeration.)

Exponential distribution is changed by interference.

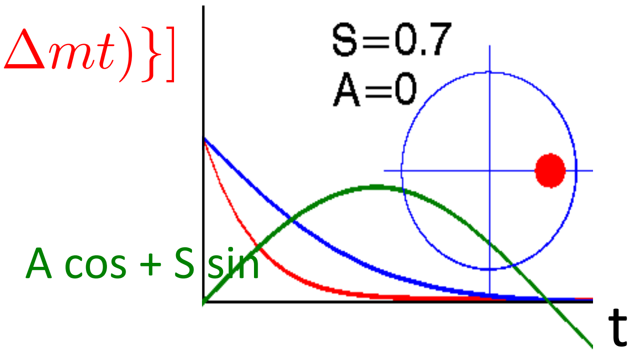
Difference btw. B0 and B0-bar →

Formula of TDCPV

Formulas of decay time distribution of $\overline{B^0}$ and B^0 are shown here.

$$\begin{cases} \Gamma_{\overline{B^0}}(t) \propto e^{-t/\tau_B}\,[1 + \{\mathcal{A}_{CP}\cos(\Delta m t) + \mathcal{S}_{CP}\sin(\Delta m t)\}] \\ \Gamma_{B^0}(t) \propto e^{-t/\tau_B}\,[1 - \{\mathcal{A}_{CP}\cos(\Delta m t) + \mathcal{S}_{CP}\sin(\Delta m t)\}] \end{cases}$$

.gif animation



Combine equations using “q”.

q = +1 : $\overline{B^0}$ at t = 0.

q = −1 : B^0 at t = 0.

$$e^{-t/\tau_B}\,[1 + q\{\mathcal{A}_{CP}\cos(\Delta m t) + \mathcal{S}_{CP}\sin(\Delta m t)\}]$$

There are two CPV parameters in the formula.

$\mathcal{A}_{CP}$

- Coefficient of cosine term.
- Caused by CP asymmetry in $B \to f_{CP}$ amplitude.

$\mathcal{S}_{CP}$

- Coefficient of sine term.
- Caused by CP phase in B-Bbar oscillation.

$\tau_B = 1.519 \pm 0.007$ [ps]
Life time of B meson.

t : Decay time.

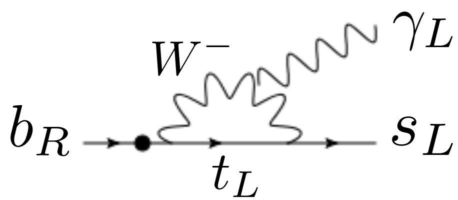
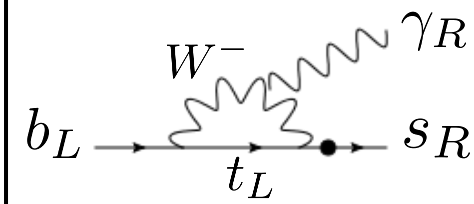
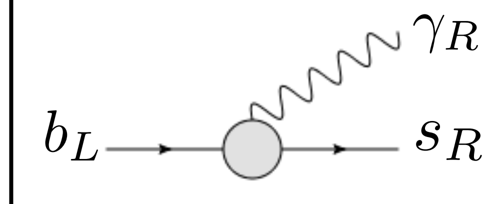
$\Delta m = 0.507 \pm 0.004$ [ps^{-1}]
Frequency of B-Bbar oscillation.

TDCPV of b to s γ →

Why TDCPV of b→sγ mode is interesting ?

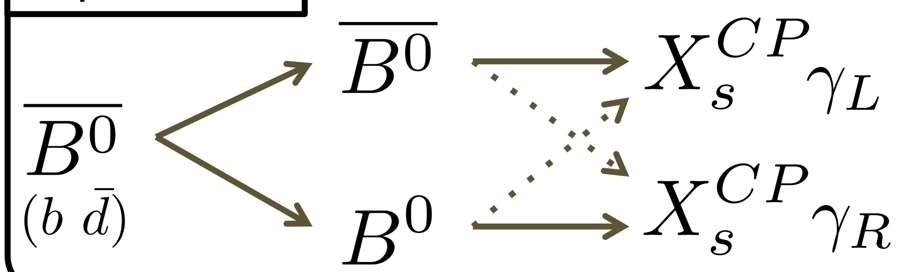
In the SM, $b \to s\ \gamma_R$ (and $\bar{b} \to \bar{s}\ \gamma_L$) process is strongly suppressed.
Because γ_L and γ_R are different, TDCPV cannot be seen.
On the other hand, some new physics permit $b \to s\ \gamma_R$ process.

Table of b→sγ process

	$b \to s\gamma_L$ **(the SM)**	$b \to s\gamma_R$ **(the SM)**	$b \to s\gamma_R$ **(new phys.)**
diagram			
amplitude	$\propto m_b G_F V_{tb} V_{ts}^*$	$\propto m_s G_F V_{tb} V_{ts}^*$	???

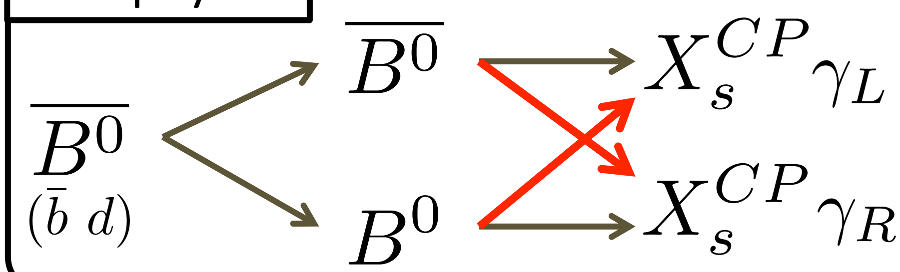
The SM expectation

Interference is suppressed.
No TDCPV is expected.



If there is new physics

Interference could be occur.
TDCPV can be seen !?



If we observe TDCPV, this is the sign of new physics !

* X_s^{CP} is CP eigenstate which contain s quark. In this study, it is Ks eta.

Why TDCPV of b→sγ mode is interesting ?

In the SM, $b \to s\ \gamma_R$ (and $\bar{b} \to \bar{s}\ \gamma_L$) process is strongly suppressed.
Because γ_L and γ_R are different, TDCPV cannot be seen.
On the other hand, some new physics permit $b \to s\ \gamma_R$ process.

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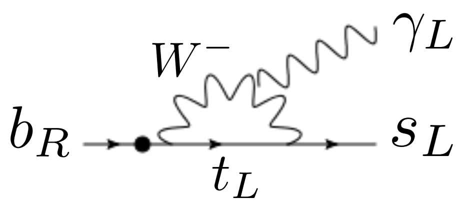
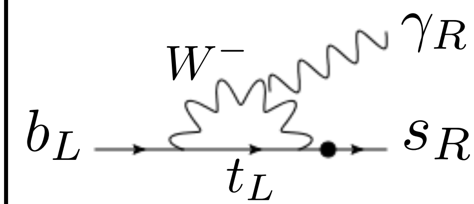
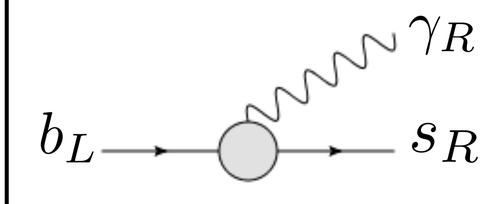
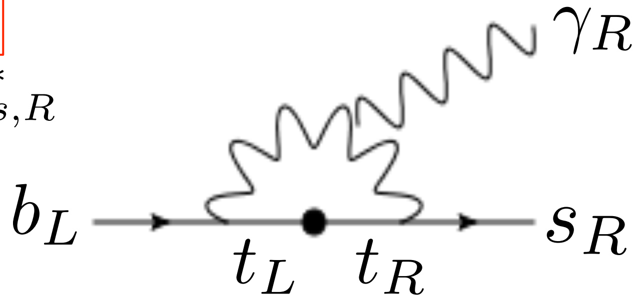
diagram			
amplitude	$\propto m_b\, G_F\, V_{tb}\, V_{ts}^*$	$\propto m_s\, G_F\, V_{tb}\, V_{ts}^*$	???

Example

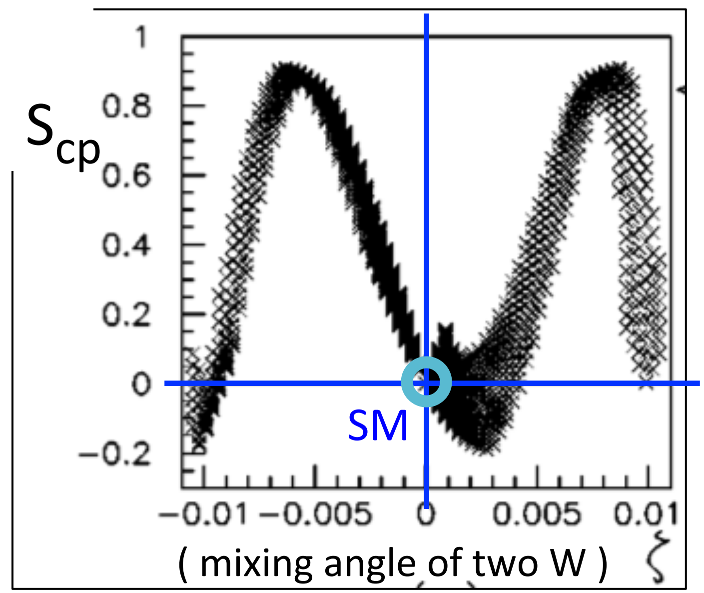
Left Right Symmetric Model predicts large S_{cp}.→
（$W^{\pm}$ can couple to ψ_R as well as ψ_L ）

Diagram of LRSM

$\propto m_t G_F V_{tb,L} V_{ts,R}^*$



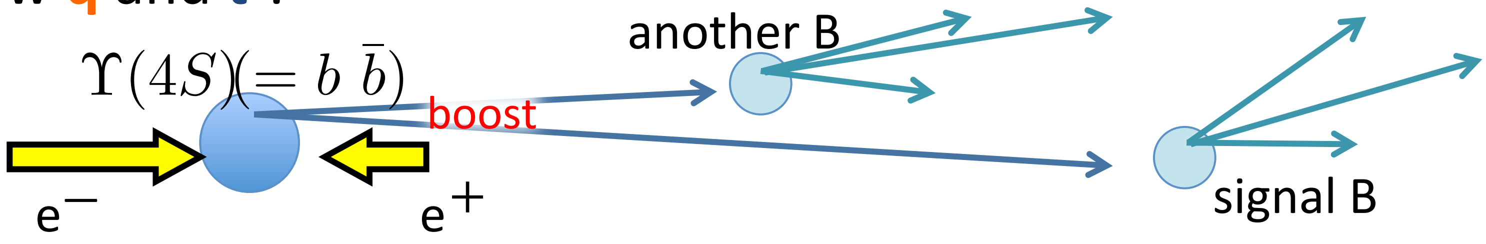
Back up P18-19



How to measure TDCPV experimentally

How can we know **q** and **t** ?

$$\Gamma(t) \propto e^{-t/\tau_B}\,[1 + q\{\mathcal{A}\cos(\Delta m t) + \mathcal{S}\sin(\Delta m t)\}]$$



Y(4S), b b-bar resonance, is produced by e+ e- collision.
B mesons are produced by decay of Y(4S).

How to measure TDCPV experimentally

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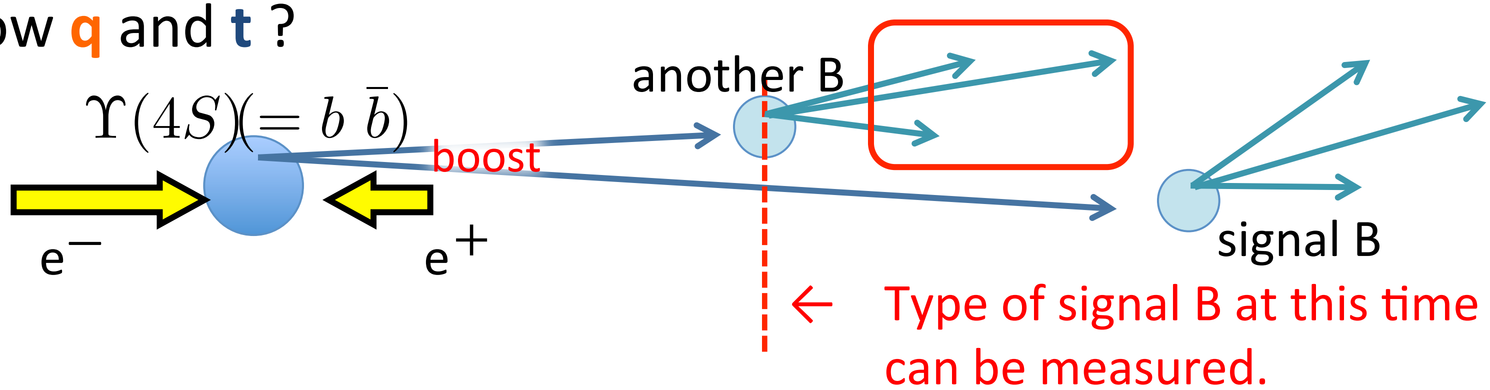
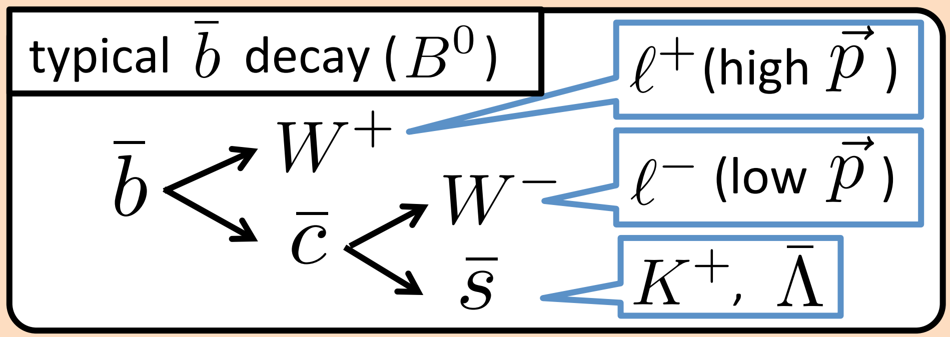


"q" (B B-bar identification) can be measured by using particle type and momentum from "another B".



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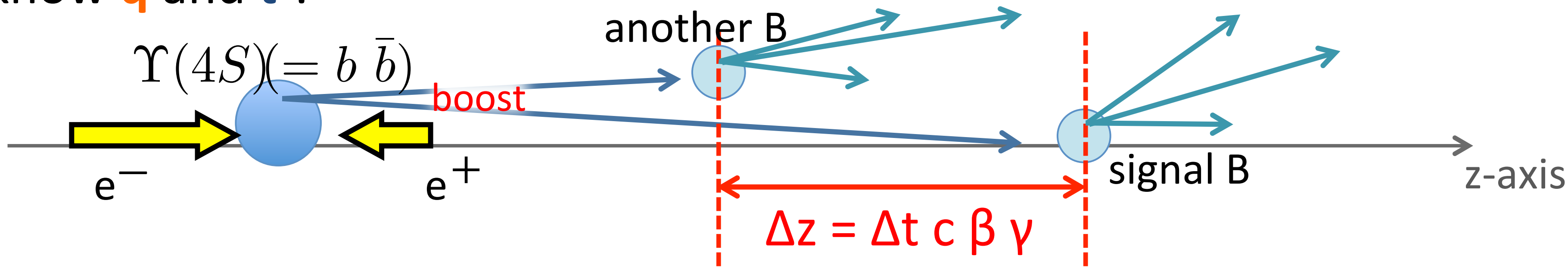

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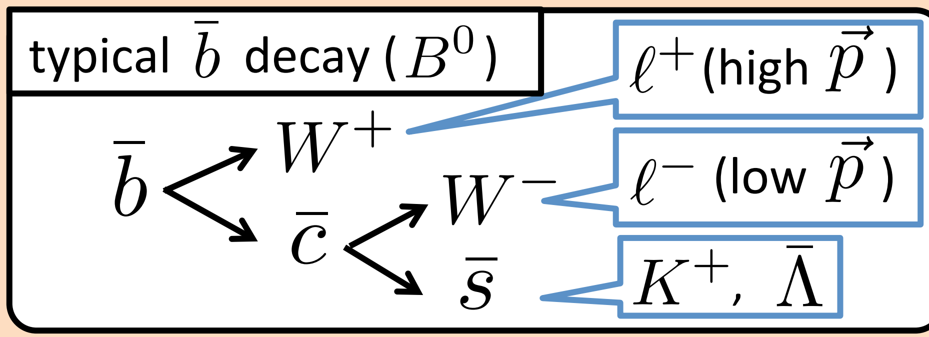


"**t**" corresponds to decay time difference Δt.

- **O(100 μm) flight length** by asymmetric energy collision and
- **Better accuracy** of vertex reconstruction than flight length

enables us to measure Δt by Δz (decay position) measurement.

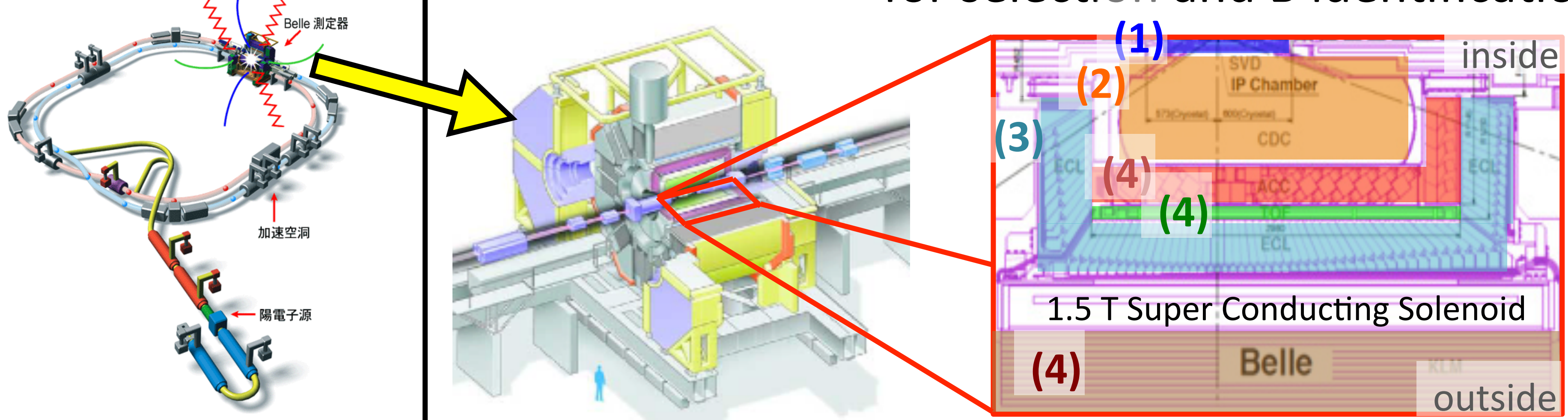
KEKB accelerator / Belle detector

KEKB accelerator

- Asymmetric energy collision (8 vs. 3.5 GeV) for large Δz. Average Δz is ~200 μm.
- 10.58 GeV center of mass energy at Υ(4S) resonance; It is suitable for BB production.
- 772 x 10^6 BB pair !

Belle detector

1) ~75 μm resolution of vertex detector for Δz measurement.
2) Drift chamber measures particle's momentum.
3) CsI (Tl) calorimeter for γ and $e^{\pm}$.
4) Other sub detectors distinguish particle's kind ($e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$,K) for selection and B identification.



Signal and backgrounds

Signal $B^0 \longrightarrow K_S \; \eta \; \gamma$

$K_S \rightarrow \pi^+\pi^-$

$\eta \rightarrow \pi^+\pi^-\pi^0$, $\eta \rightarrow \gamma\gamma$

qq BG

- Light quark jets (u, d, s, c).
- Random miss-reconstruction makes fake signal candidate.

BB BG

- Other B decay modes.
- Difficult to distinguish from signal.
- Some decay mode have known CPV.

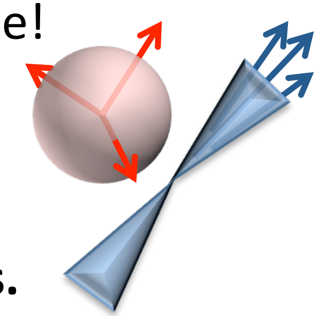
Rejection

Use decay shape difference!

Signal : spherical decay.

qq BG : 2 jet-like decay.

Neural network is used for multi variable analysis.

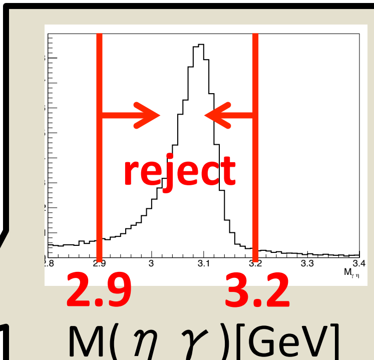


Rejection (example)

Find mass peak!

J/ψ Ks has peak at 3.1 GeV on M(γη)

$B \rightarrow J/\psi \, K_S$, $J/\psi \rightarrow \eta\gamma$



Selection and BG rejection is done to maximize significance (except for known CPV BGs rejection).

3D fit for signal yield

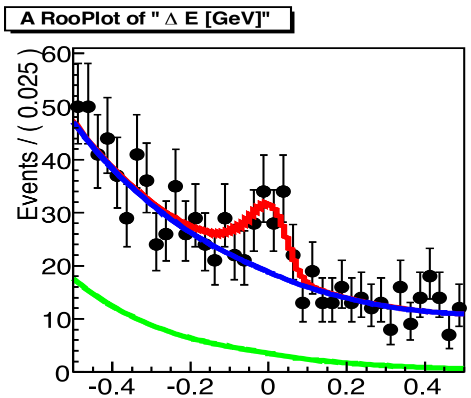
After reconstruction and BG rejection, 3 dimensional fit (ΔE, M_{bc}, NN') is done.

Fit on ΔE, M_{bc} and NN' distribution.

Free parameters are N_{sig} and N_{qq}. Function shapes and N_{BB} are fixed.

Projections on each parameter →

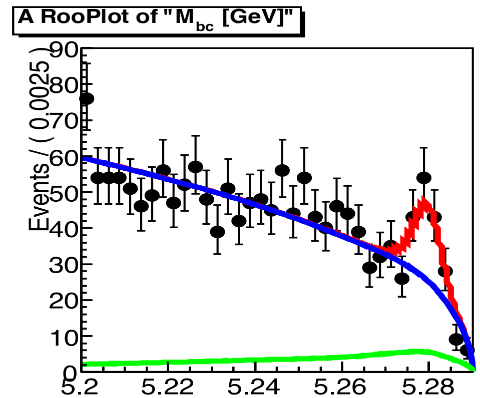
Red: signal
Blue: qq BG
Green: BB BG



ΔE [GeV]

$$\Delta E \equiv E_B - E_{\text{beam}}$$

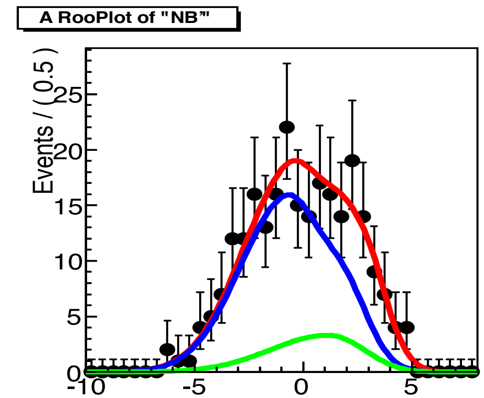
Energy difference btw. beam energy and B candidate.



M_{bc} [GeV]

$$M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2 - p_B^2}$$

Mass of B candidate from beam energy and B's momentum.



NN'

Modified distribution of Neural network output used for qq BG rejection.

Yield is $\begin{cases} N_{\eta\to2\gamma} = 70^{+13}_{-12} \\ N_{\eta\to3\pi} = 22^{+7}_{-6} \end{cases}$, they will be used for Δt distribution fit.

How to fit Δt →

The way of Δt analysis

Δt distribution is fitted by the following function.

$$P(\Delta t) = f_{\rm sig} \cdot P_{\rm sig}(\Delta t) + f_{\rm BG} \cdot P_{\rm BG}(\Delta t)$$

Event-by-event fractions of { signal/BG } function are obtained by 3D fit (last page).

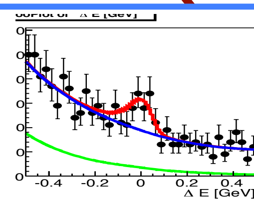
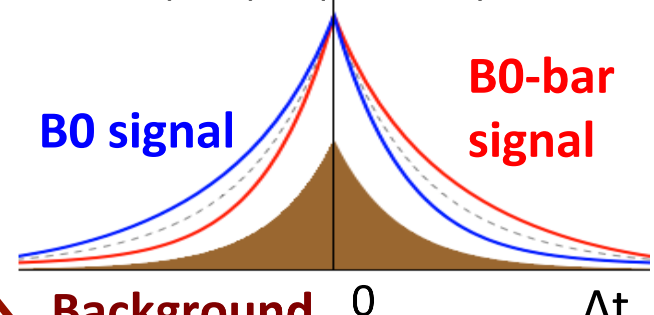


Illustration of Δt distribution when (**S**,**A**) = (+0.5, 0).

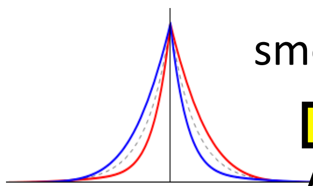


$$e^{-|\Delta t|/\tau_B}\left[1 + q\{\mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t)\}\right]$$

with

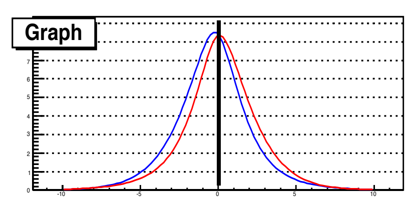
- wrong B-Bbar identification probability
- detector resolution of Δz

consideration.



smeared

Δt



BG distribution is fixed by

- BG data fit (for qq) and
- MC simulation (for BB)

Fit on Δt distribution.

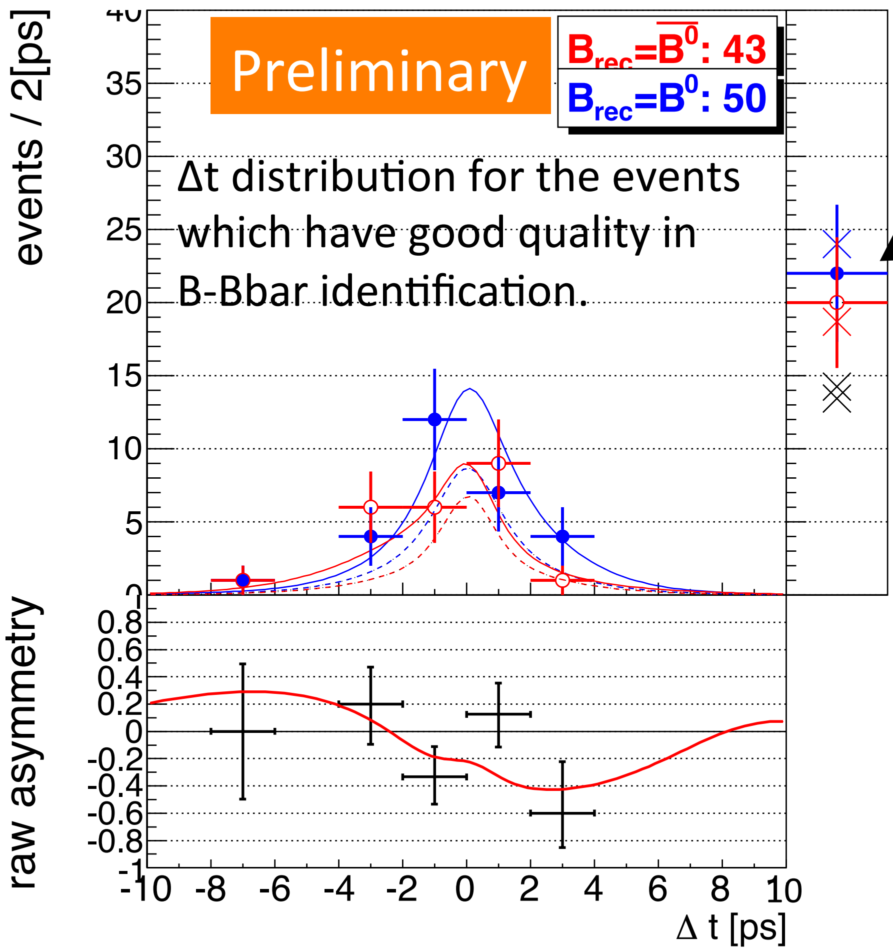
Free parameters are $\mathbf{S_{CP}}$ and $\mathbf{A_{CP}}$. Other parameters are fixed.

result →

The result of Δt analysis

$$P(\Delta t) = f_{\rm sig} \cdot P_{\rm sig}(\Delta t) + f_{\rm BG} \cdot P_{\rm BG}(\Delta t)$$

$$e^{-|\Delta t|/\tau_B} [1 + q\{\mathcal{A}_{CP} \cos(\Delta m \Delta t) + \mathcal{S}_{CP} \sin(\Delta m \Delta t)\}]$$



Events which do not have Δt information are also used.

Preliminary

$$\mathcal{S}_{CP} = -1.32 \pm 0.77(\text{stat.}) \pm 0.36(\text{syst.})$$

$$\mathcal{A}_{CP} = -0.48 \pm 0.41(\text{stat.}) \pm 0.07(\text{syst.})$$

We obtained the result.
No significant deviation from (0,0).
Statistical error is dominant.

Current status of TDCPV in b→sγ

Golden mode for this study is B → Ks pi0 gamma.
However, measurements of other decay mode are also important.
This study is **first Ks eta gamma measurement of Belle experiment data**.

HFAG 2012

http://www.slac.stanford.edu/xorg/hfag/triangle/moriond2012/index.shtml#bsgamma

Mode	Experiment	S_{CP} (b → sγ)	A_{CP} (b → sγ)
$K^*(892)\gamma$	BaBar N(BB)=467M	$-0.03 \pm 0.29 \pm 0.03$	$-0.14 \pm 0.16 \pm 0.03$
	Belle N(BB)=535M	$-0.32\ ^{+0.36}_{-0.33} \pm 0.05$	$0.20 \pm 0.24 \pm 0.05$
	Average	-0.16 ± 0.22	-0.04 ± 0.14
$K_S\pi^0\gamma$ (incl. $K^*\gamma$)	BaBar N(BB)=467M	$-0.17 \pm 0.26 \pm 0.03$	$-0.19 \pm 0.14 \pm 0.03$
	Belle N(BB)=535M	$-0.10 \pm 0.31 \pm 0.07$	$0.20 \pm 0.20 \pm 0.06$
	Average	-0.15 ± 0.20	-0.07 ± 0.12
$K_S\eta\gamma$	BaBar N(BB)=465M	$-0.18\ ^{+0.49}_{-0.46} \pm 0.12$	$-0.32\ ^{+0.40}_{-0.39} \pm 0.07$
	New	$-1.32 \pm 0.77 \pm 0.36$	$-0.48 \pm 0.41 \pm 0.07$
$K_S\rho^0\gamma$	Belle N(BB)=657M	$0.11 \pm 0.33\ ^{+0.05}_{-0.09}$	$-0.05 \pm 0.18 \pm 0.06$
$K_S\phi\gamma$	Belle N(BB)=772M	$0.74\ ^{+0.72}_{-1.05}\ ^{+0.10}_{-0.24}$	$-0.35 \pm 0.58\ ^{+0.10}_{-0.23}$

Conclusion

- Time dependent CP violation is one of probe of new physics which predict $b \to s\gamma_R$ process.
- B → Ks η γ mode is studied with using data of Belle experiment. The result obtained is

$$\mathcal{S}_{CP} = -1.32 \pm 0.77(\text{stat.}) \pm 0.36(\text{syst.})$$

Preliminary

$$\mathcal{A}_{CP} = -0.48 \pm 0.41(\text{stat.}) \pm 0.07(\text{syst.})$$

We couldn't see significant deviation from the SM expectation.

- The result can be used for constraint on new physics model.

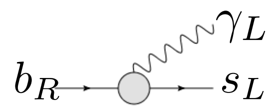
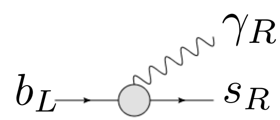
Backups Example of new physics (P18, 19)

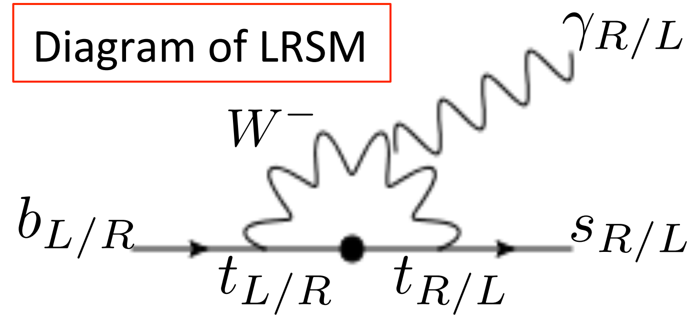
Upgrade of B factory (P20)

Back up

Related new physics model (LRSM) [1/2]

Let's consider Left Right Symmetric Model（$W^{\pm}$ can couple to ψ_R as well as ψ_L）.

amplitude of $b \to s\gamma_L$	$A_{\rm SM} + A_{\rm NP}$ ($A_{\rm NP} \propto m_t G_F V_{tb,R} V^*_{ts,L}$)	
amplitude of $b \to s\gamma_R$	~~$a_{\rm SM}$~~ (suppressed) $+ a_{\rm NP}$ ($a_{\rm NP} \propto m_t G_F V_{tb,L} V^*_{ts,R}$)	

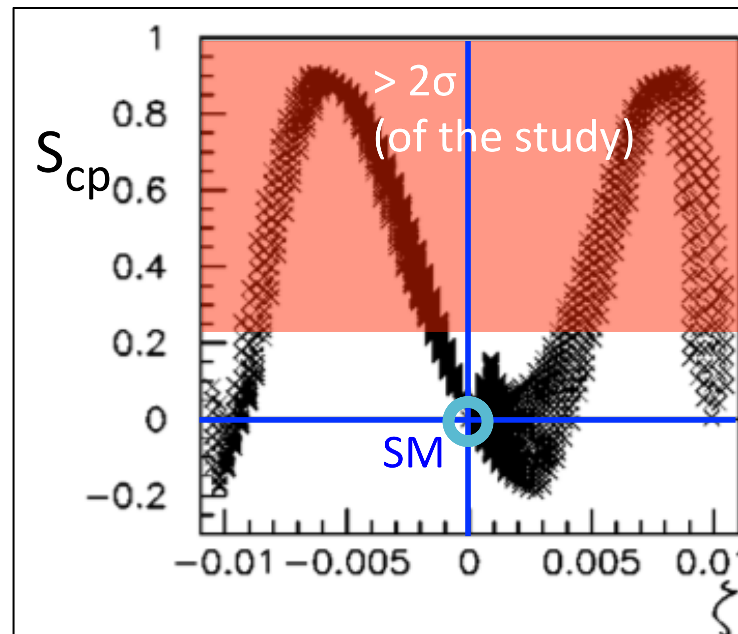


Although precise $BR(b \to s\gamma)$ measurement is consistent to the SM expectation, $A_{\rm NP}$ and $a_{\rm NP}$ can be large if they satisfy

$$|A_{\rm SM} + A_{\rm NP}|^2 + |a_{\rm NP}|^2 = \underbrace{|A_{\rm SM}|^2}_{\propto BR(b \to s\gamma)}$$

[LRSM] Phys. Rev. D 61, 054008 (2000)

There are some parameter sets which permit S_{cp} have large value.
ζ is mixing angle of W_L and W_R.



Such kind of model can be constrained by this type of study.

Related new physics model (LRSM) [2/2]

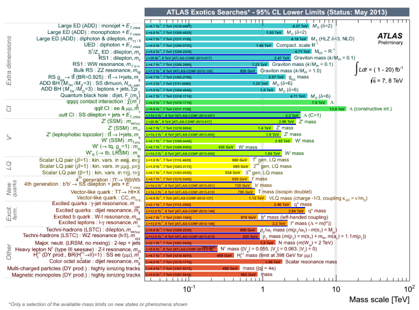
However, the model with simple parameter set are excluded by direct search.

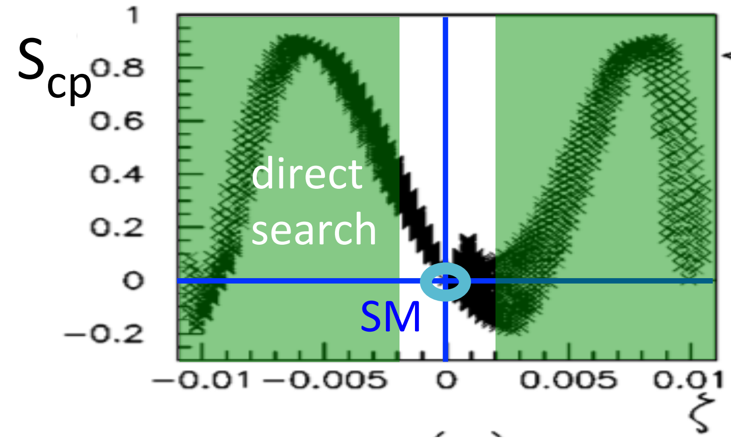
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

(mass of W_2) > 1.84 TeV (ATLAS)

$$\zeta \leq \frac{M_1^2}{M_2^2} < 1.9 \times 10^{-3}$$

(M_1 = 80 GeV, see eq.(3) of **[LRSM]**)





Right upper figure is based on an assumption

$V_{CKM, L} = V_{CKM, R}$

Assuming that $V_{ts, R} >> V_{ts, L}$ (~0.04),

S_{CP} can take large value while ζ is small.

Unexplored area is still remaining,

and the area can be searched by b→sγ TDCPV !

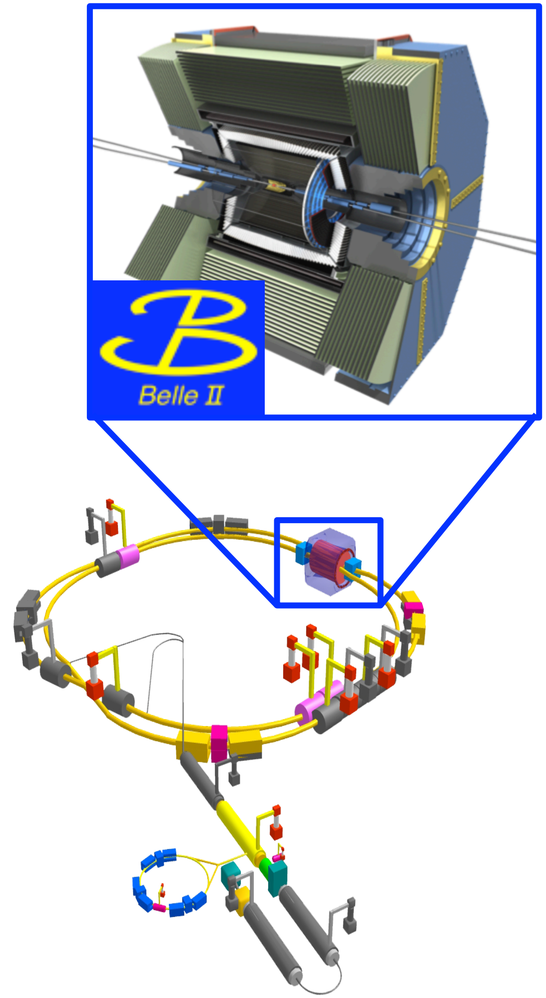
Although, simple parameter region is excluded by direct search already, TDCPV measurement of b→sγ can search unexplored area.

Future prospect

Upgrade to Belle II experiment is in progress.

- Improvement of vertexing resolution
- 50 times integrated luminosity
- Extension of silicon tracker volume (= Larger Ks acceptance).

→ **Error of S_{cp} is expected to be 1 order smaller.**



Related douments

http://arxiv.org/abs/1002.5012
"Physics at Super B Factory"
Section 3.4, 5.3.5

http://xxx.lanl.gov/abs/1011.0352
"Belle II Technical Design Report"

Wrong B B-bar identification probability

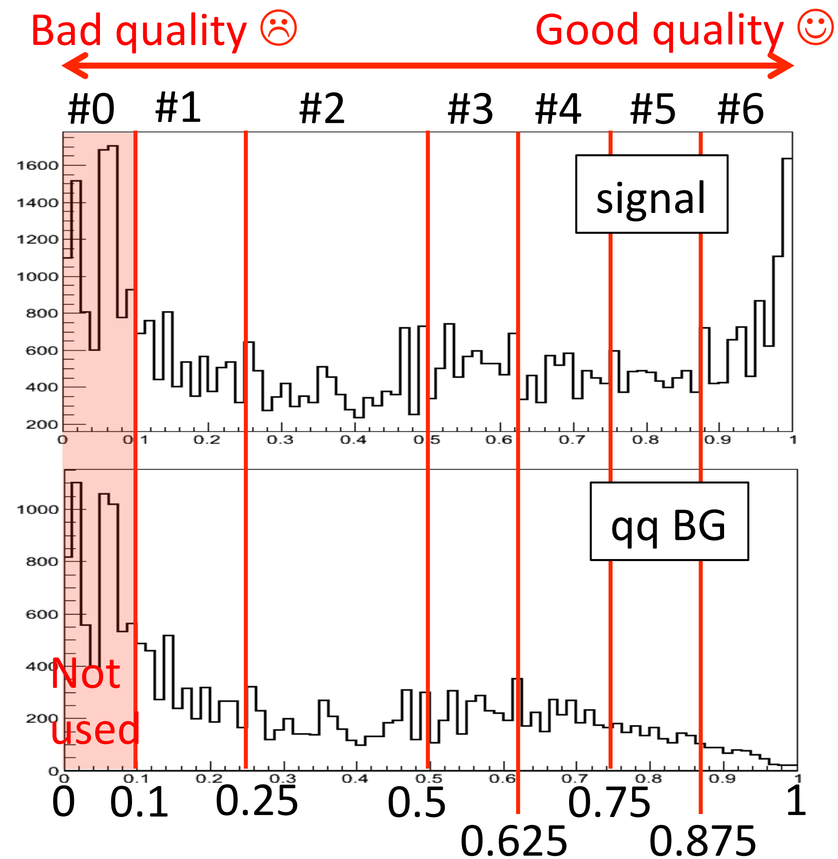
Probability of wrong identification must be considered.

$$e^{-|\Delta t|/\tau_B}\left[1+q\{\mathcal{A}\cos(\Delta m\Delta t)+\mathcal{S}\sin(\Delta m\Delta t)\}\right]$$

$$e^{-|\Delta t|/\tau_B}\left[(1-q\Delta w)+q(1-2w)\{\mathcal{A}\cos(\Delta m\Delta t)+\mathcal{S}\sin(\Delta m\Delta t)\}\right]$$

w : Probability of wrong identification.
In order to avoid bias from MC data, distribution is divided into 7 bins.

Δw : Difference of w btw. B and B-bar.
Considering efficiency of Λ, Λ-bar.
O(1%) at most.



Distribution of 1−2w

Resolution function

"Resolution fucntion", R(Δt) is convoluted to theoretical function.

$$e^{-|\Delta t|/\tau_B}\left[(1-q\Delta w)+q(1-2w)\{\mathcal{A}\cos(\Delta m\Delta t)+\mathcal{S}\sin(\Delta m\Delta t)\}\right]$$

$$\otimes$$

$$R(\Delta t) = R_{\mathrm{det(rec)}}(\Delta t)\otimes R_{\mathrm{det(tag)}}(\Delta t)\otimes R_{\mathrm{np}}(\Delta t)\otimes R_{\mathrm{k}}(\Delta t).$$

Resolution function consist from 3 parts as described below.

Detector resolution : R_{det}

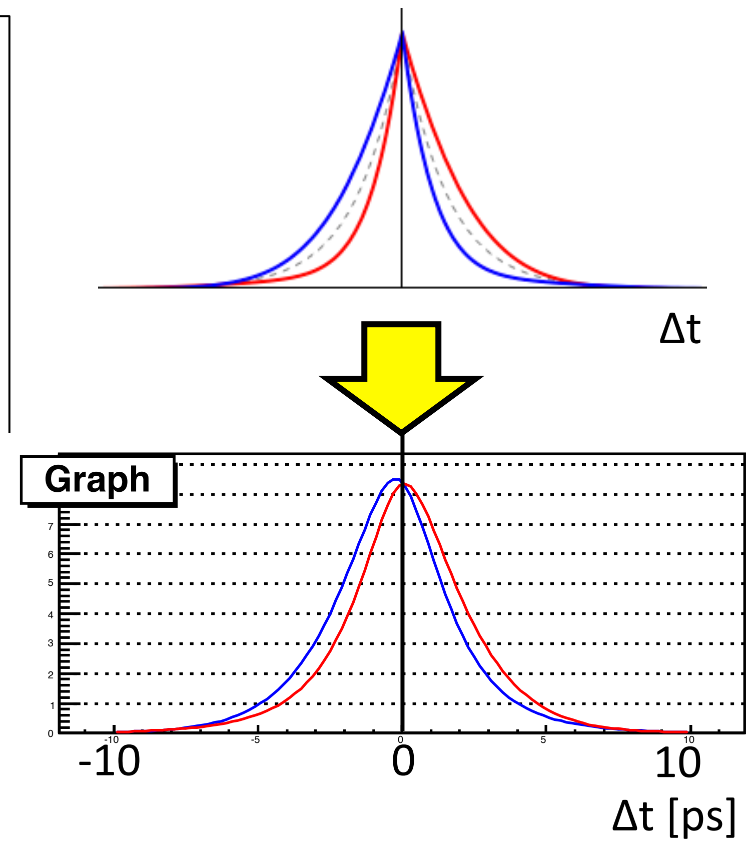
- Gaussian for vertex resolution.
- Basically, parameters are decided by real data.

Vertex shift by Non-Primary particle (like D meson) : R_{np}

- Exponential for D meson flight.
- Basically, parameters are decided by MC data.

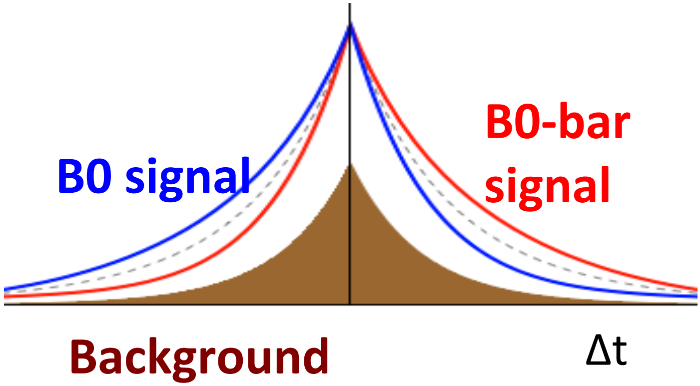
Kinematics from Y(4S) decay : R_k

- Small contribution and no systematics.



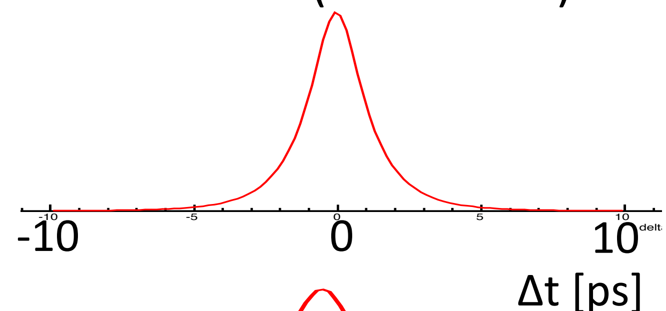
BG Δt distribution

Δt distribution data contains background.
We have to know about Δt distribution of them.



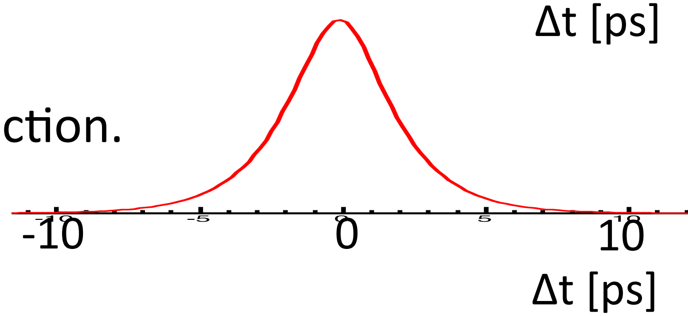
qq BG $P_{\rm qq}(\Delta t)$

- δ function (= light particle from collision) and exponential function (= D meson) are convoluted to double Gaussian.
- Function shape is fixed by real data.
  (qq BG dominant region are used for fixing.)



BB BG $P_{\rm BB}(\Delta t)$

- Exponential function is convoluted to resolution function.
- Function shape is fixed by MC data.



Outlier $P_{\rm ol}(\Delta t)$

- Describe long tail component after Resolution function consideration.
- Fraction is an order of $O(10^{-4})$, Gaussian which has ~30-40 [ps] width.