Novel approach to measure CP violation in B meson decay with application of weak measurement

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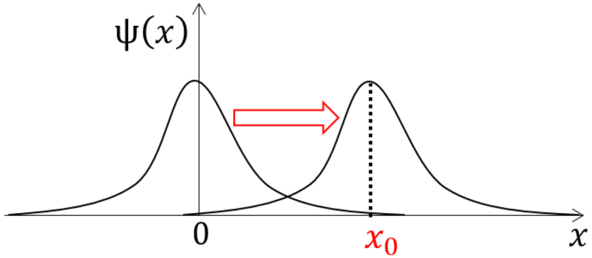
Introduction to weak measurement

Shift operator

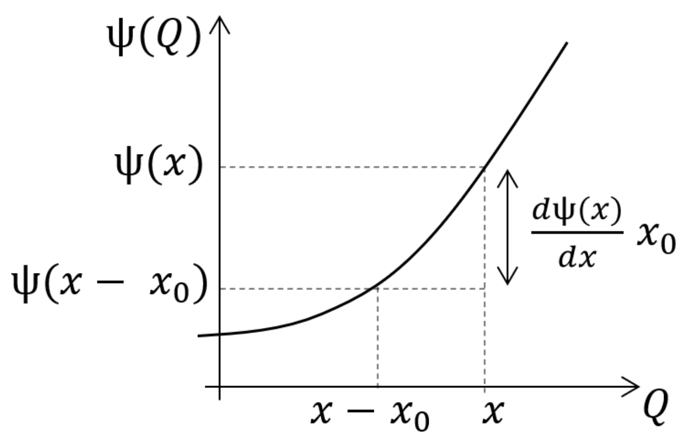
- Momentum operator is defined as $\hat{p} = -i\frac{d}{dx}$ in quantum mechanics.
- $e^{-ix_0\hat{p}}$ works as shift operator for $\psi(x)$: $e^{-ix_0\hat{p}}\psi(x) = \psi(x - x_0)$.

$$\psi(x - x_0) = \psi(x) - x_0\frac{d\psi(x)}{dx} + \left(x_0\frac{d\psi(x)}{dx}\right)^2 + \cdots$$
$$= e^{-ix_0\hat{p}}\psi(x)$$



- If $\psi(x)$ is approximated by Taylor expansion up to the first order, $(1 - ix_0\hat{p})$ also works as shift operator.

$$\psi(x - x_0) \sim \psi(x) - x_0\boxed{\frac{d\psi(x)}{dx}}\ i\hat{p}\psi(x)$$
$$= (1 - ix_0\hat{p})\psi(x)$$



Conventional measurement

The interaction between a particle (measured object) and detector is expressed with Von Neumann formula.

Particle

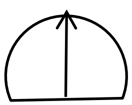
$|\varphi_i\rangle$ $\xrightarrow{\hat{A}\,|\varphi_i\rangle = A|\varphi_i\rangle}$ Final state $\hat{A}|\varphi_i\rangle$ All final eigenstates (simply, $|\varphi_i\rangle$ now)

g

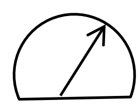
Detector

$|\psi(Q)\rangle$ $\longrightarrow$ $|\psi(Q - gA)\rangle$

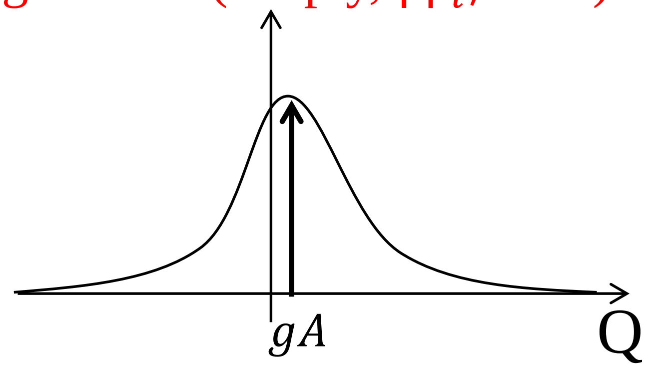
Operator : $\hat{p} = \frac{d}{dQ}$



Value : Q



Value : $Q - A$



Von Neumann interaction operator

$$|\varphi_i\rangle|\psi(Q)\rangle \Longrightarrow \langle\varphi_i|\boxed{e^{ig\hat{A}\hat{p}}}|\varphi_i\rangle|\psi(Q)\rangle$$

Shift operator on Q

$\hat{A}\,|\varphi_i\rangle = A|\varphi_i\rangle$ $$= \underbrace{\boxed{\langle\varphi_i|\varphi_i\rangle}}_{=1}\boxed{e^{igA\hat{p}}}|\psi(Q)\rangle$$

$$= |\psi(\boxed{Q - gA})\rangle$$ Meter's shift

Weak measurement (1)

Let's calculate conditional measurement with small coupling btw particle and detector (Weak Measurement: WM) with Von Neumann formula.

Particle

$|\varphi_i\rangle$

Condition-1:
$\hat{A}\,|\varphi_i\rangle \neq A|\varphi_i\rangle$

Final state

$|\varphi_f\rangle$

Condition-3:
Selection of the final state (Postselection)

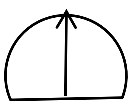
Condition-2:
g (<< 1)

Detector

$|\psi(Q)\rangle$

?

Operator: $\hat{p} = \frac{d}{dQ}$



Meter: Q

If $\hat{A}\,|\varphi_i\rangle = A|\varphi_i\rangle$, the same as conventional measurement

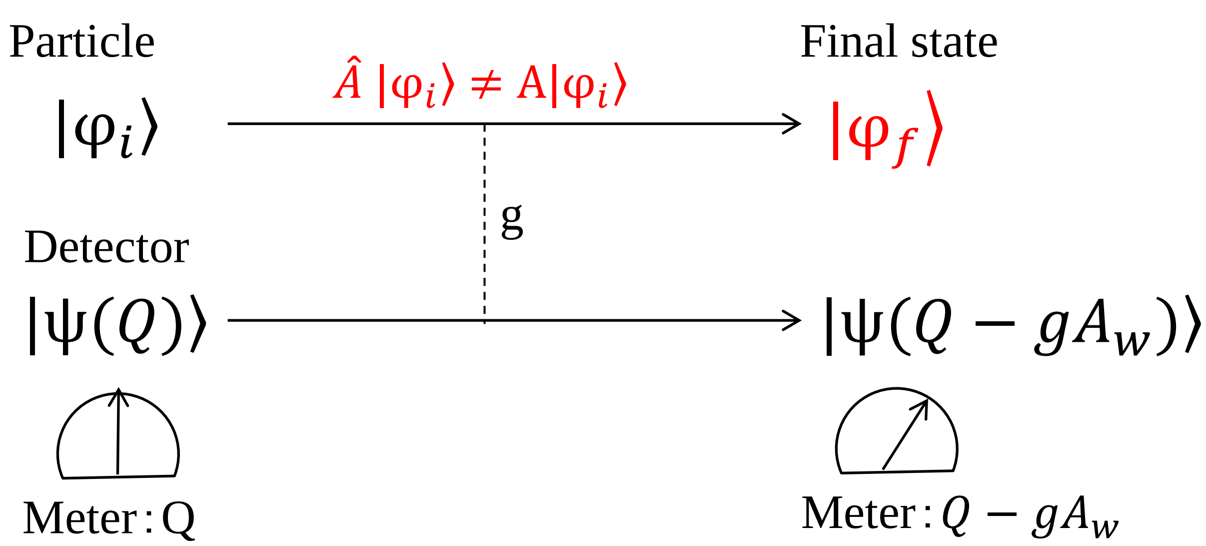
$$|\varphi_i\rangle|\psi(Q)\rangle \Rightarrow \langle\varphi_f|\boxed{e^{ig\hat{A}\hat{p}}\,|\varphi_i\rangle}|\psi(Q)\rangle$$

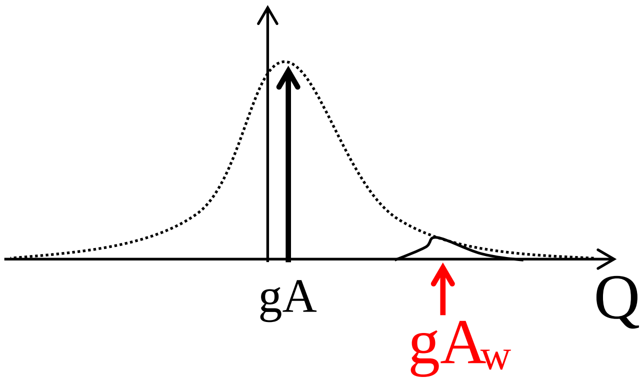
g<<1

$$\sim \langle\varphi_f|(1 - \mathrm{i}g\hat{A}\hat{p})|\varphi_i\rangle|\psi(Q)\rangle$$

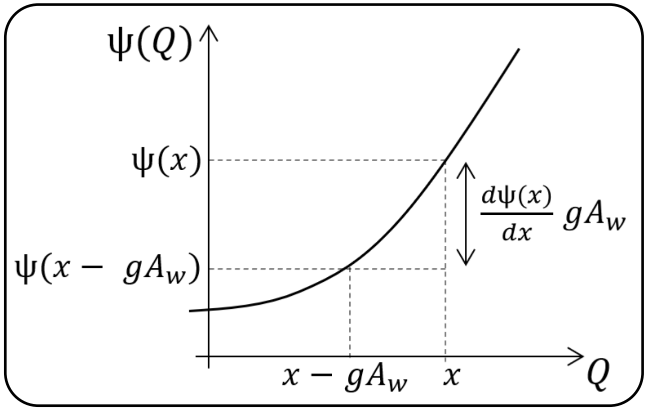
$$= \langle\varphi_f|\varphi_i\rangle\left(1 - ig\underbrace{\boxed{\frac{\langle\varphi_f|\hat{A}|\varphi_i\rangle}{\langle\varphi_f|\varphi_i\rangle}}}_{A_w}\hat{p}\right)|\psi(Q)\rangle$$

Weak measurement (2)





$$|\varphi_i\rangle|\psi(Q)\rangle \Longrightarrow \langle\varphi_f|e^{ig\hat{A}\hat{p}}\,|\varphi_i\rangle|\psi(Q)\rangle$$



Shift operator on Q for the first order of approximation

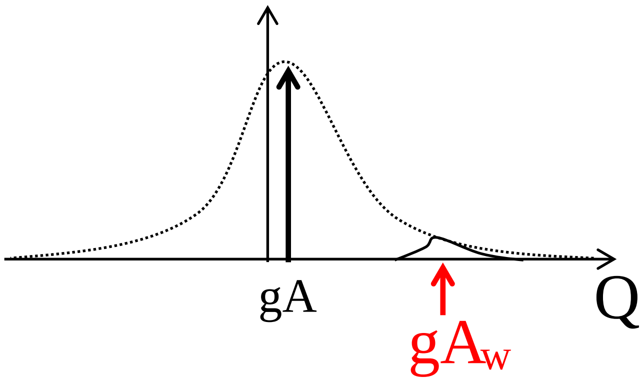
$$= \langle\varphi_f|\varphi_i\rangle\boxed{(1 - \mathrm{i}gA_w\hat{p})}|\psi(Q)\rangle$$

$$\sim \langle\varphi_f|\varphi_i\rangle|\psi(\boxed{Q - gA_w})\rangle$$

Meter's shift

Weak value amplification (1)

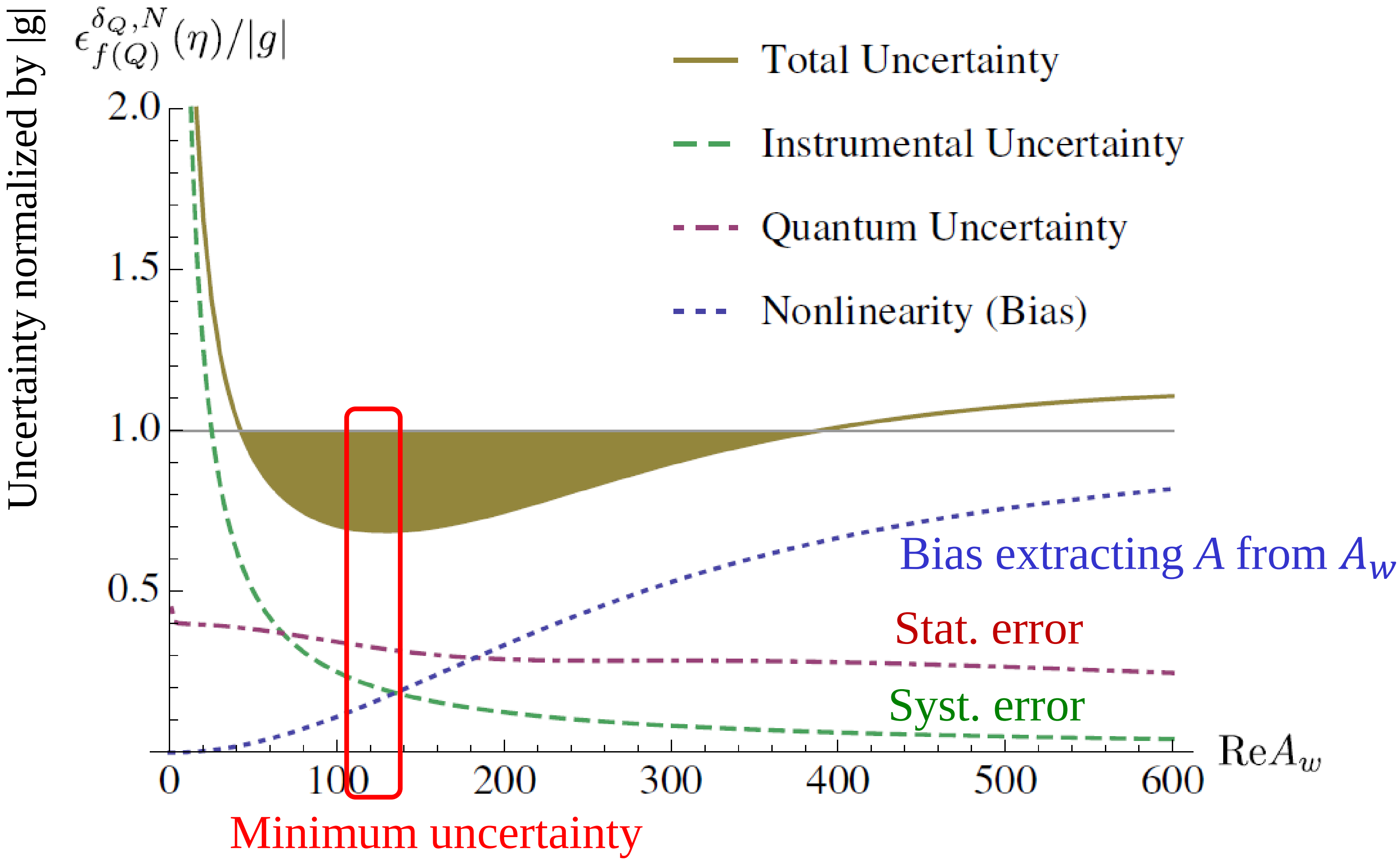
Weak value: $A_w = \dfrac{\langle \varphi_f | \hat{A} | \varphi_i \rangle}{\boxed{\langle \varphi_f | \varphi_i \rangle}}$



- Weak value can be amplified, choosing small $\mathrm{Re}\langle \varphi_f | \varphi_i \rangle$ (weak value amplification)
  - Selection of $|\varphi_i\rangle / |\varphi_f\rangle$ is called as preselection/postselection.
- The gain of the weak value amplification and loss of statistics are in the trade-off relationship.
- If systematic errors dominate to statistical error, measurement accuracy is improved significantly.
  - At the first order, $\sigma_{\mathrm{stat.}}/A_w$ does not change by postselection (because both A_w and stat. error depend on $1/\sqrt{N}$).
  - As syst. error is constant, $\sigma_{\mathrm{syst.}}/A_w$ decreases with larger A_w.

Weak value amplification (2)

Measurement uncertainty v.s. weak value amplification



Quantum Stud.: Math. Found. (2014) 1:65-78

Existing experiments with weak measurement

- Measurement of 1 Å displacement in Spin Hall effect of light: Science 319, 787 (2008)
- Light deflection measurement with 14 fm of linear travel resolution: Phys. Rev. Lett. 102, 173601 (2009)
- Light intensity measurement with timing resolution of 5×10^{-4} as: Phys. Rev. A 100, 012109 (2019)
- Application for Cheshire cat experiment with neutrons: Nat. Commun. 5, 4492 EP (2014)
- Measurement of lifetime of two-states system in atoms: Phys. Rev. Lett. 111, 023604 (2013)

Benefit of WM is already proven by existing experiments using "photon and neutron".

→ However, no proposal for experiments with other particles so far.

Weak measurement in B^0 decays

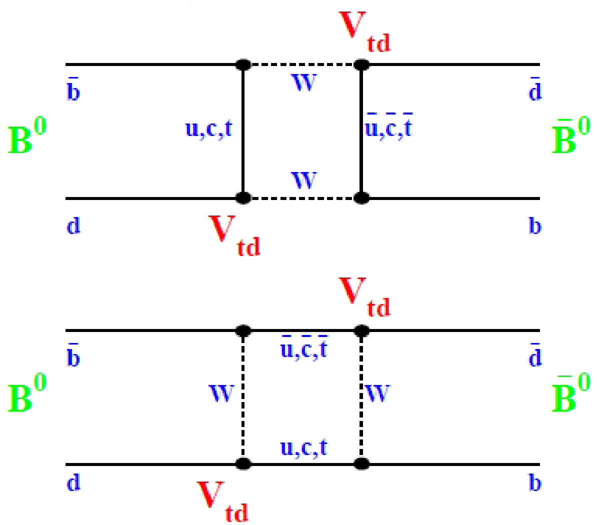
B^0-$\bar{B}^0$ mixing

The mass eigenstates of neutral B meson (B_L, B_H) are expressed by mixture of the flavor eigenstates (B^0, $\bar{B}^0$):

$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

$\Longleftrightarrow$

$$|B^0\rangle = \frac{1}{2p}\left(|B_L\rangle + |B_H\rangle\right)$$
$$|\bar{B}^0\rangle = \frac{1}{2q}\left(|B_L\rangle - |B_H\rangle\right)$$



Time evolution at t = Δt

$$|B^0(\Delta t)\rangle = e^{-i\Delta t\boxed{\hat{H}}}|B^0\rangle$$

$$\hat{H}|B_L\rangle = \left(m_L - \frac{i}{2}\Gamma_L\right)|B_L\rangle$$
$$\hat{H}|B_H\rangle = \left(m_H - \frac{i}{2}\Gamma_H\right)|B_H\rangle$$

$$= \frac{1}{2}\left(e^{-i\Delta t\left(m_L-\frac{i}{2}\Gamma_L\right)} + e^{-i\Delta t\left(m_H-\frac{i}{2}\Gamma_H\right)}\right)|B^0\rangle + \frac{q}{2p}\left(e^{-i\Delta t\left(m_L-\frac{i}{2}\Gamma_L\right)} - e^{-i\Delta t\left(m_H-\frac{i}{2}\Gamma_H\right)}\right)|\bar{B}^0\rangle$$

B^0 and $\bar{B}^0$ are mixed during time evolution (B^0- $\bar{B}^0$ mixing).

Postselection in B0 decay (1)

Postselection

The state at the timing of B^0 decay is selected as $|\mathrm{B}_{\mathrm{decay}}\rangle = \mathrm{r}|B^0\rangle + \mathrm{s}|\bar{B}^0\rangle$ $(|r|^2 + |s|^2 = 1)$.

CP phase

- $\frac{p}{q} = e^{i\varphi}$ ($|p|=|q|$ due to $1 - |q|/|p| \sim 10^{-3}$)
- $\frac{r}{s} = \frac{|r|}{\sqrt{1-|r|^2}} e^{i\theta}$ ⟵ Relative phase btw $B^0/\bar{B}^0$ in $|\mathrm{B}_{\mathrm{decay}}\rangle$
- $\Gamma_L = \Gamma_H = \Gamma$ $\left(\frac{|\Gamma_L - \Gamma_H|}{\Gamma} < 0.01\right)$

Let's calculate probability of $B^0(\Delta t)$ decaying into $\mathrm{B}_{\mathrm{decay}}$ $\left(\left|\langle \mathrm{B}_{\mathrm{decay}} | B^0(\Delta t)\rangle\right|^2\right)$, using these definitions.

Postselection in B0 decay (2)

$$\left|\langle \mathrm{B_{decay}} | B^0(\Delta t)\rangle\right|^2$$

$$= \frac{e^{-\Gamma|\Delta t|}}{2}\left\{1 + (2|r|^2 - 1)\cos(\Delta m \Delta t) - 2|r|\sqrt{1-|r|^2}\sin(\theta - \varphi)\sin(\Delta m \Delta t)\right\}$$

Here, negative Δt is taken into account with |Δt|.

Probability density function with postselection

$$P\left(\Delta t | B^0 \to B_{\mathrm{decay}}\right)$$

$$= \frac{e^{-\Gamma|\Delta t|}}{2N}\left\{1 + (2|r|^2 - 1)\cos(\Delta m \Delta t) - 2|r|\sqrt{1-|r|^2}\sin(\theta - \varphi)\sin(\Delta m \Delta t)\right\}$$

CP phase

Normalization factor

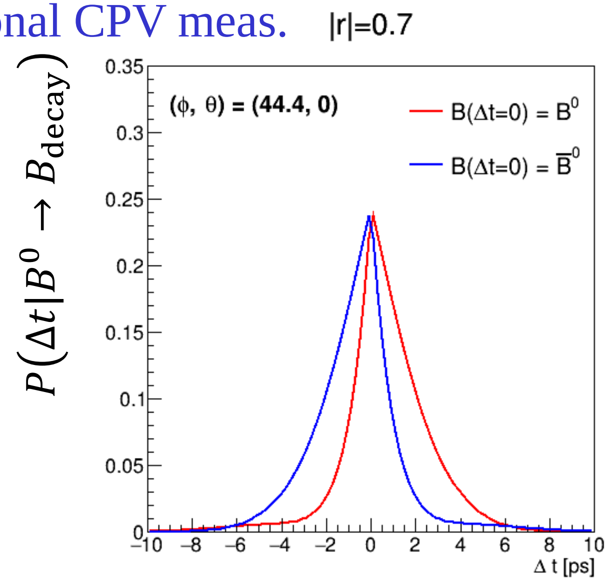
Postselection parameters

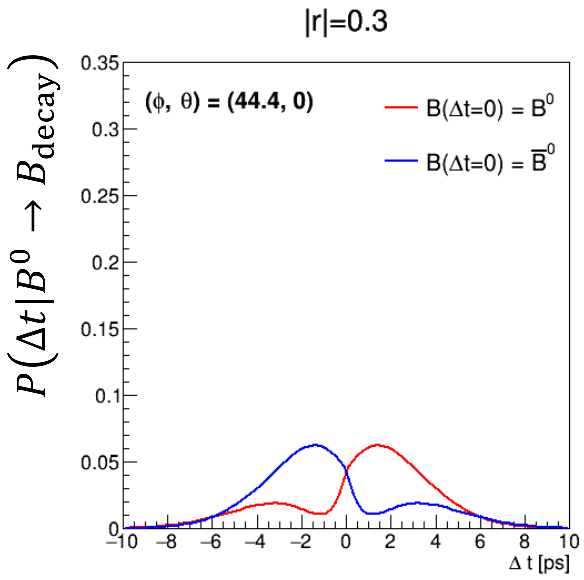
Δt distribution with postselection

- Selection of CP eigenstate ($|r| = 1/\sqrt{2} = 0.7$) corresponds to the conventional CPV measurement.
- Difference in Δt distributions between B^0 and $\bar{B}^0$ at Δt=0 is caused by CP violation with CP phase φ (called as mixing induced CPV).
- The distribution variates, choosing different $|r|$.

⇨ The sensitivity to φ may be improved by selecting optimal $|r|$.

Conventional CPV meas.



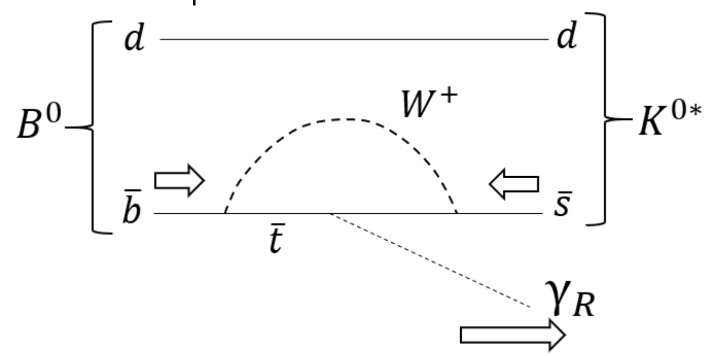


How can postselection be realized?

- For WM, a fraction of $B^0/\bar{B}^0$ in the final state ($|r|$) and their relative phase (θ) have to be identified.

- γ in $B^0 \rightarrow K^{0*}\gamma$ process seems to be possible tool for postselection:

- $|r|$ can be determined by helicity of γ associating to B^0 flavor ($B^0 \rightarrow K^{0*}\gamma_R$/ $\bar{B}^0 \rightarrow K^{0*}\gamma_L$).
  - In reality, the opposite helicity migrates in a fraction of m_s/ m_b (ignored in this study).
- θ corresponds to phase of γ.



Choosing γ-helicity/phase, $|r|$ and θ may be identified.

$K^{0*}\gamma$ in the final states have to be consistent with the state just before B^0 decay ($|B_{decay}\rangle = r|B^0\rangle + s|\bar{B}^0\rangle$).

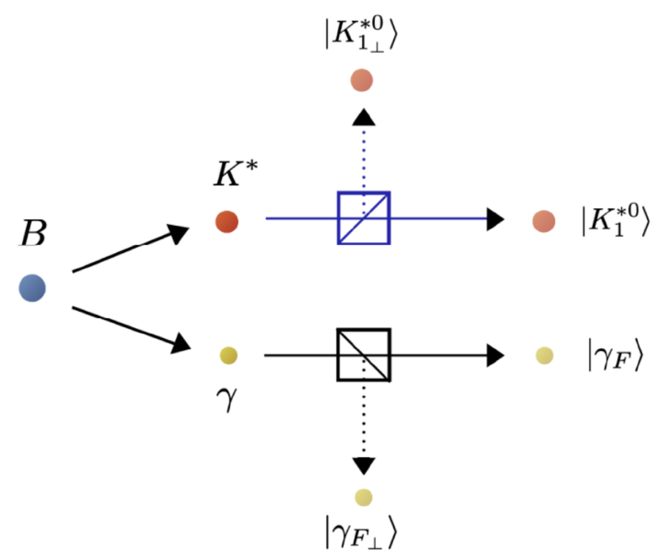
Validity of postselection with B decays (1)

To realize postselection choosing $B^0 \rightarrow K^{0*}\gamma$, the final state must satisfy consistency condition, i.e., $|K^{*0}{}_F\rangle|\gamma_F\rangle \propto \left|\mathrm{B}_{\mathrm{decay}}\right\rangle = \mathrm{r}|B^0\rangle + \mathrm{s}|\bar{B}^0\rangle$.

$\hat{U}$ is the unitary operator to connect state of B^0 and decay products:

$$\hat{U}|B^0\rangle = c|K^{0*}\rangle|\gamma_R\rangle + [\text{other decay modes}]$$

$$\hat{U}|\bar{B}^0\rangle = c|\bar{K}^{0*}\rangle|\gamma_L\rangle + [\text{other decay modes}]$$



$$\left\langle \mathrm{B}_{\mathrm{decay}} \middle| B^0(\Delta t) \right\rangle = \boxed{\langle\gamma_F|\langle K^{0*}{}_F|\hat{U}|}B^0(\Delta t)\rangle$$

$$\left|K_F^{0*}\right\rangle = \xi_1|K^{0*}\rangle + \xi_2|\bar{K}^{0*}\rangle$$
$$|\gamma_F\rangle = \eta_1|\gamma_R\rangle + \eta_2|\gamma_L\rangle$$

$$\left(\xi_1^*\eta_1^*\langle K^{*0}|\langle\gamma_R| + \xi_2^*\eta_1^*\langle\bar{K}^{*0}|\langle\gamma_R| + \xi_1^*\eta_2^*\langle K^{*0}|\langle\gamma_L| + \xi_2^*\eta_2^*\langle\bar{K}^{*0}|\langle\gamma_L|\right)\hat{U}\left(|B^0\rangle\langle B^0| + |\bar{B}^0\rangle\langle\bar{B}^0|\right)$$

$$= c\left(\xi_2^*\eta_2^*\langle B^0| + \xi_1^*\eta_1^*\langle\bar{B}^0|\right)$$

Validity of postselection with B decays (2)

$$\langle K_F^*|\langle\gamma_F|\,\hat{U} = c\left(\boxed{\xi_2^*\eta_2^*\langle B^0| + \xi_1^*\eta_1^*\langle\bar{B}^0|}\right)$$

should be $\langle \mathrm{B_{decay}}| = r\langle B^0| + s\langle\bar{B}^0|.$ $\Rightarrow$ $\frac{\xi_1\eta_1}{\xi_2\eta_2} = \frac{r}{s}$

Experimentally, it is easy to choose CP eigenstate for $|K_F^*\rangle$ by detecting $K^{*0} \to K_S^0\pi^0$:

CP eigenstate

$$\underbrace{|K_F^*(\to K_S^0\pi^0)\rangle = \xi_1|K^{*0}\rangle + \xi_2|\bar{K}^{*0}\rangle = \boxed{\frac{1}{\sqrt{2}}\left(|K^{*0}\rangle + |\bar{K}^{*0}\rangle\right)}}_{\xi_1 = \xi_2 = \frac{1}{\sqrt{2}}}$$

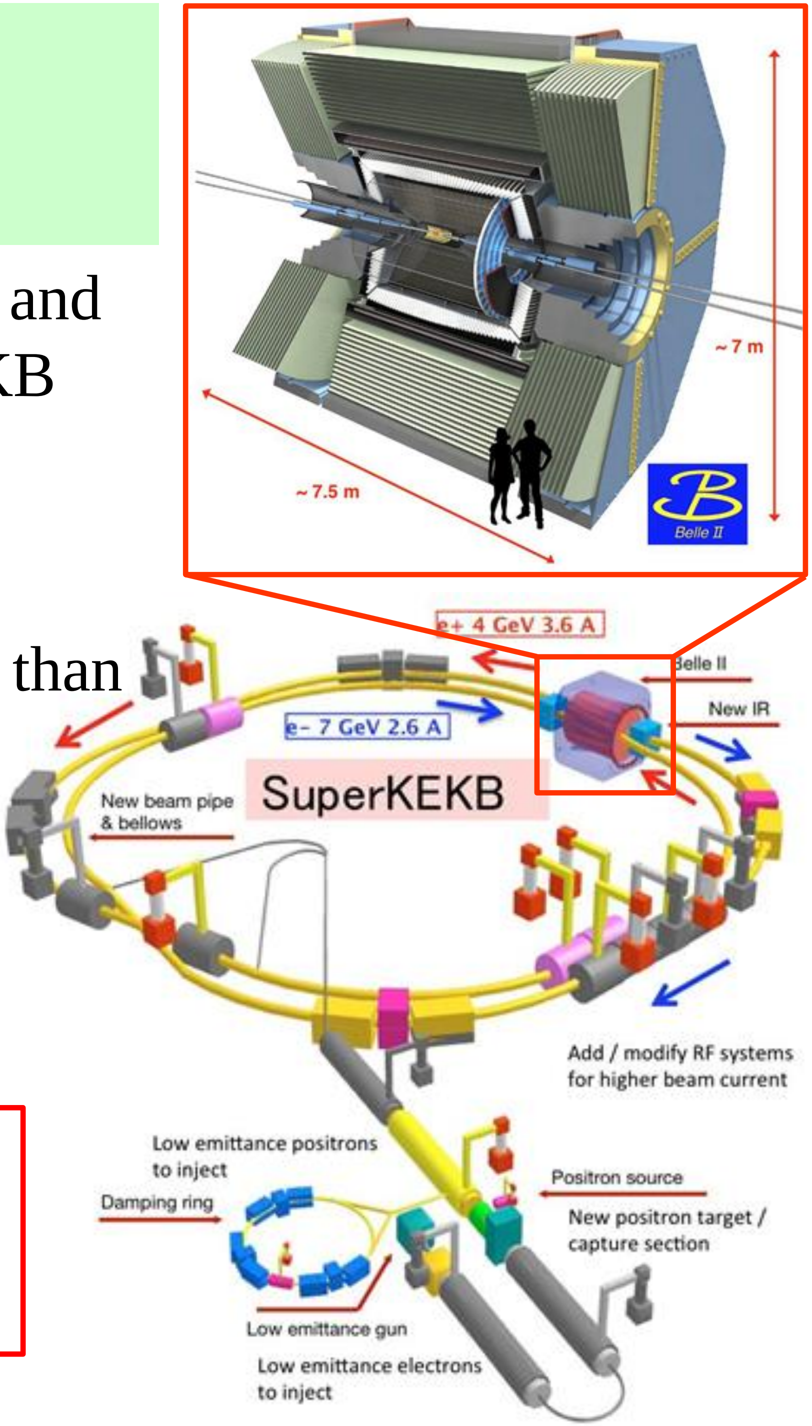
$\Rightarrow$ $\eta_1 = r$, $\eta_2 = s$ $\Rightarrow$ $|\gamma_F\rangle = \mathrm{r}|\gamma_R\rangle + \mathrm{s}|\gamma_L\rangle$

The postselection is realized by selecting γ-helicity/phase in $B^0 \to K^{0*}\gamma(K^{*0} \to K_S^0\pi^0)$.

Applicaion of WM to CPV measurement in Belle II experiment

Belle II experiment

- The experiment to measure CP violation and search for new physics, using SuperKEKB electron-positron collider.
  - Electron: 7 GeV, Positron: 4 GeV
- 40 times larger instantaneous luminosity than KEKB accelerator: $L = 8 \times 10^{35}$ cm^{-2}s^{-1}
- Aim to collect 50 ab^{-1} of data until 2031.
  - 5.5×10^{10} $B \cdot \bar{B}$ pairs



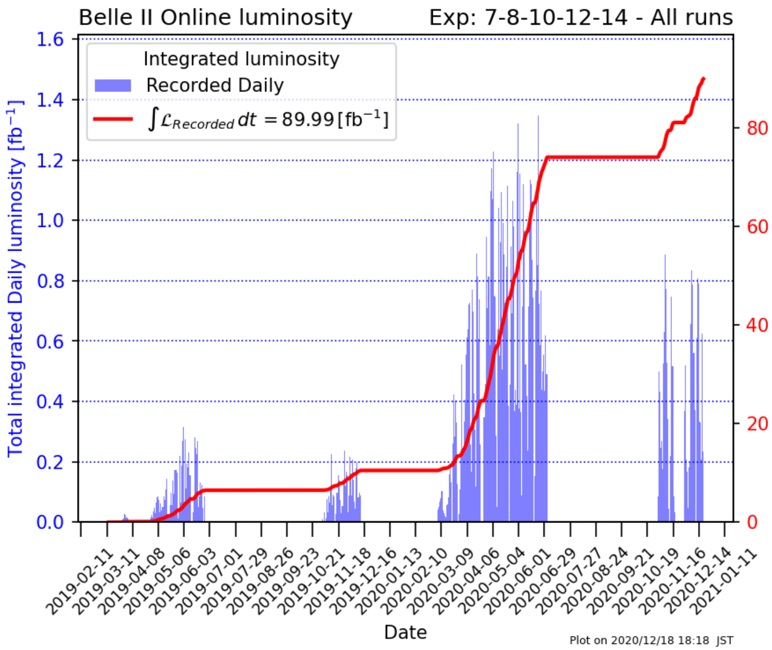
Advantage for WM

- Initial state (Υ(4S)→ $B \cdot \bar{B}$) is fixed.
- Large statistics (5.5×10^{10} $B \cdot \bar{B}$ pairs)

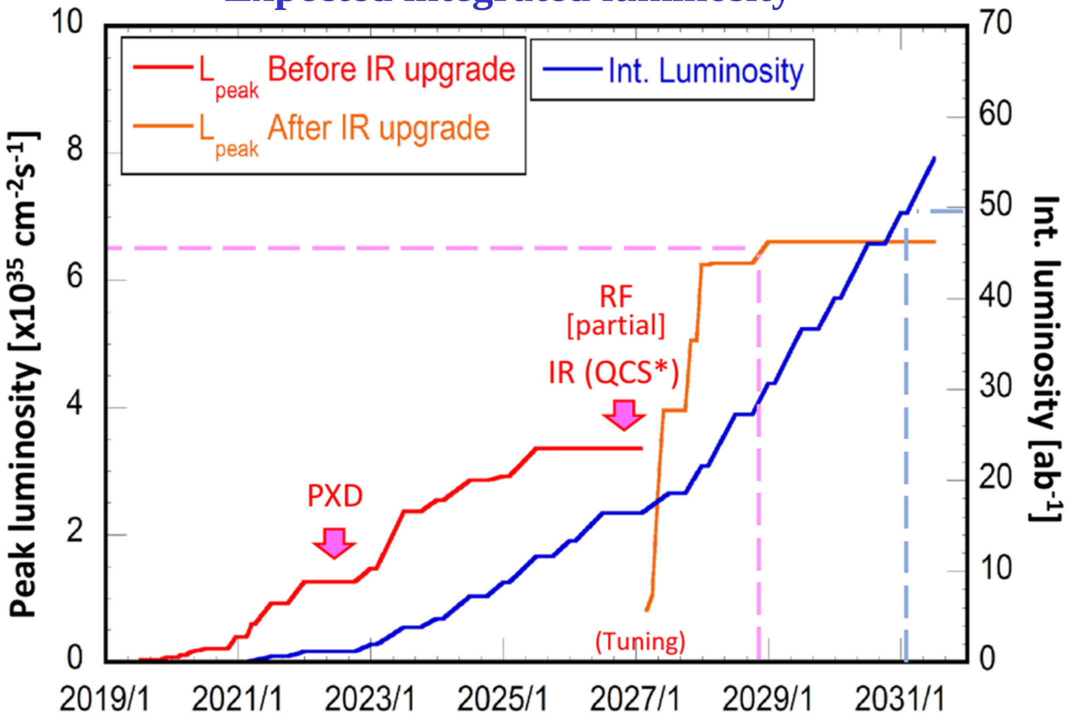
Status of Belle II experiment

- Belle II experiment started full physics data-taking on March 2019.
  - The instantaneous luminosity reached at 2.4× 10^{34} $cm^{-2}s^{-1}$.
  - ~90 fb^{-1} of integrated luminosity was accumulated.
- 50 ab^{-1} will be collected until ~2031 upgrading the accelerator.

Integrated luminosity in 2019-2021

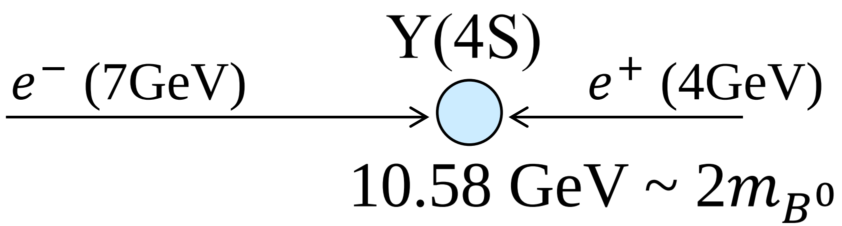


Expected integrated luminosity

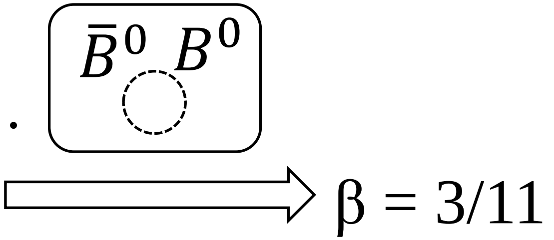


CPV measurement at Belle II (1)

1. Υ(4S) is generated at e^+e^- collision with asymmetric energy.

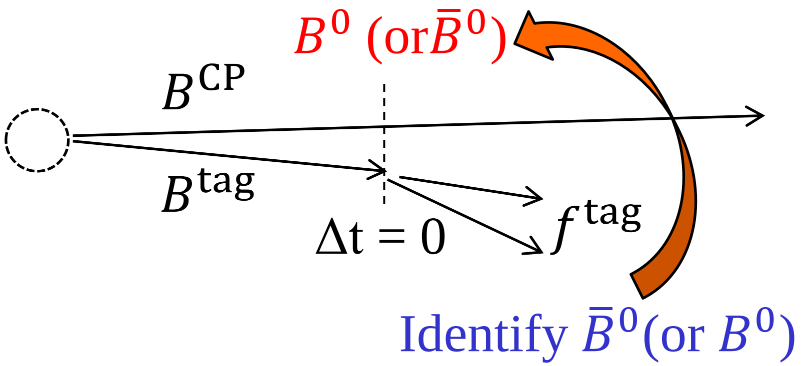


2. B^0-$\bar{B}^0$ system from decay of Υ(4S) travels with β (= p/E = 3/11).
   - $B^0/\bar{B}^0$ almost stationary at c.m system of Υ(4S) .
   - Two B^0's are defined as B^{tag} and B^{CP}.



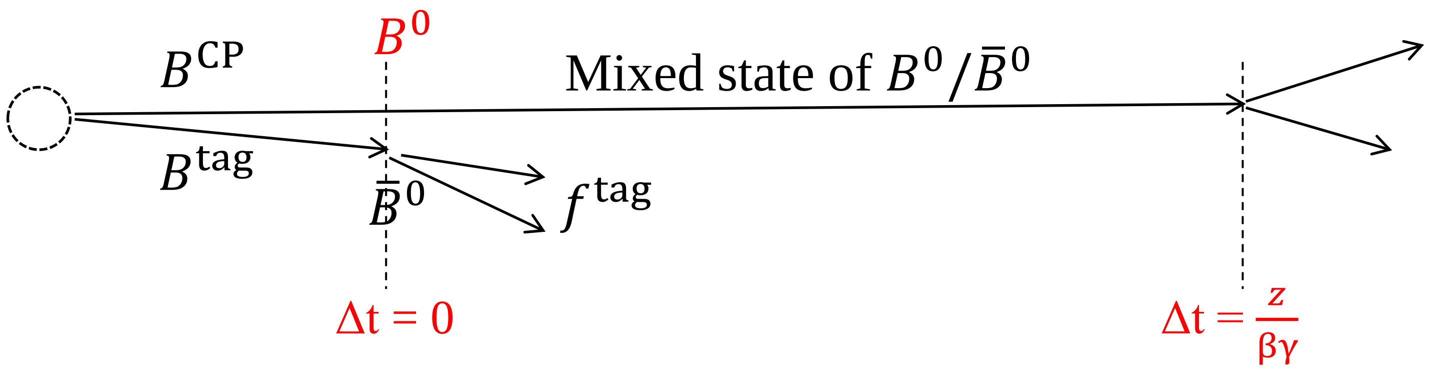
3. Flavor of B^{tag} at decay time (Δt = 0) is identified by using the decay products (f^{tag}).

→ Flavor of B^{CP} is also identified due to entanglement.

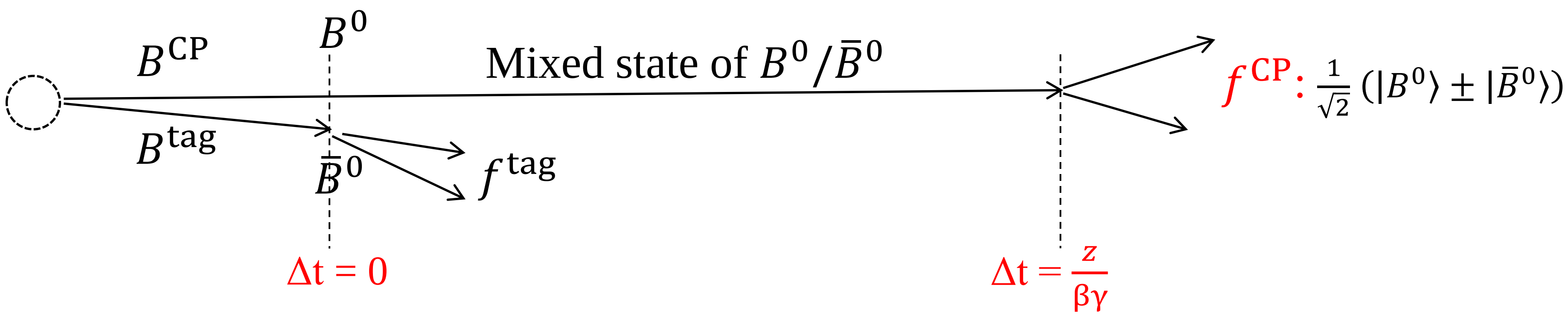


CPV measurement at Belle II (2)

4. Flavor of B^{CP} is mixed before the decay at t = Δt $(= \frac{z}{\beta\gamma})$.

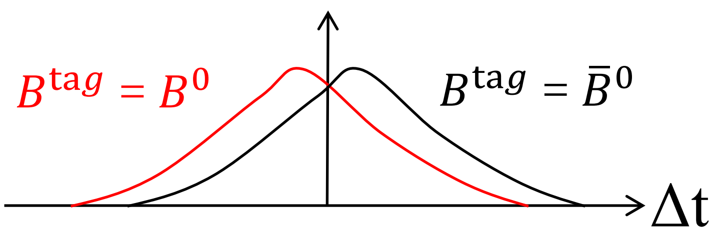


5. CP eigenstate of $B^{\mathrm{CP}}(\Delta t)$ is selected by using decay products.
Then, Δt is measured for $B^{\mathrm{tag}} = B^0$ and $\bar{B}^0$ separately.



CPV measurement at Belle II (3)

6. If difference exists in Δt distribution between $B^{tag} = B^0$ and $\bar{B}^0$, this is evidence for CPV.

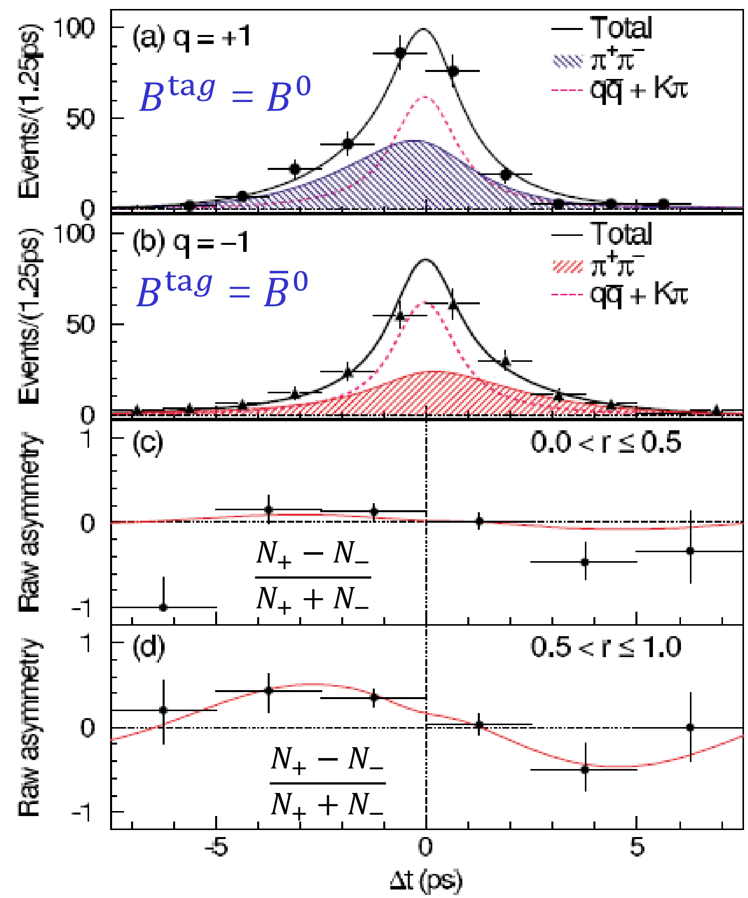


Conventional measurement corresponds to WM, selecting $(|r|, \theta) \sim (1/\sqrt{2}, 0)$.

- $|\mathrm{B}_{\mathrm{decay}}\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle \pm |\bar{B}^0\rangle)$

In this study, sensitivity to CPV is investigated, selecting $(|r|, \theta)$ dynamically.

Δt distributions for $B^{CP} \rightarrow \pi^+\pi^-$@Belle
(Phys. Rev. Lett. 93 021601 (2004))



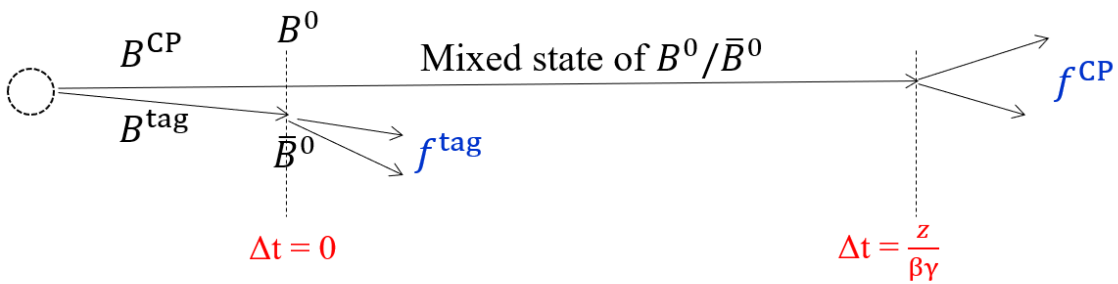
Time measurement & Flavor tag (1)

Key measurement techniques at Belle II

- Difference of decay time between B^{tag} and B^{CP} (Δt)
- Flavor tagging of B^{tag}

Decay time (Δt) measurement

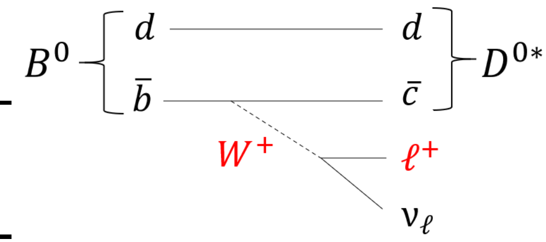
- B^0-$\bar{B}^0$ system from decay of Υ(4S) travels with β (= p/E = 3/11).
- Difference of decay time between B^{tag} and B^{CP} is determined by measuring distance of their decay position and β.
- Vertex resolution is typically 100 um. → Timing resolution ~ 1.2 ps
  - $\tau(B^0)$ = 1.5 ps



Time measurement & Flavor tag (2)

Flavor tagging

- Flavor for B^{tag} is identified by choosing the decay products sensitive to the flavor eigenstate (Nucl. Instrum. Meth. A533 (2004) 516-531).
- For example, charge of ℓ in $B^0 \rightarrow D^*\ell^+\nu$ is identical to B^0 flavor.



Likeness **f^{tag} efficiency** **Wrong tag fraction**

l	r interval	ε_l	w_l	$\varepsilon_{\mathrm{eff}}^l$
1	0.000–0.250	0.398	$0.458 \pm 0.005 \pm 0.003$	0.003 ± 0.001
2	0.250–0.500	0.146	$0.336 \pm 0.008 \pm 0.004$	0.016 ± 0.002
3	0.500–0.625	0.104	$0.228 \pm 0.009^{+0.004}_{-0.006}$	0.031 ± 0.002
4	0.625–0.750	0.122	$0.160 \pm 0.007^{+0.005}_{-0.004}$	0.056 ± 0.003
5	0.750–0.875	0.094	$0.112 \pm 0.008 \pm 0.004$	0.056 ± 0.003
6	0.875–1.000	0.136	$0.020^{+0.005}_{-0.004}{}^{+0.005}_{-0.004}$	$0.126^{+0.003}_{-0.004}$

Flavor tagging performance at Belle

Postselection with $B^0 \to K^{0*}\gamma$ process

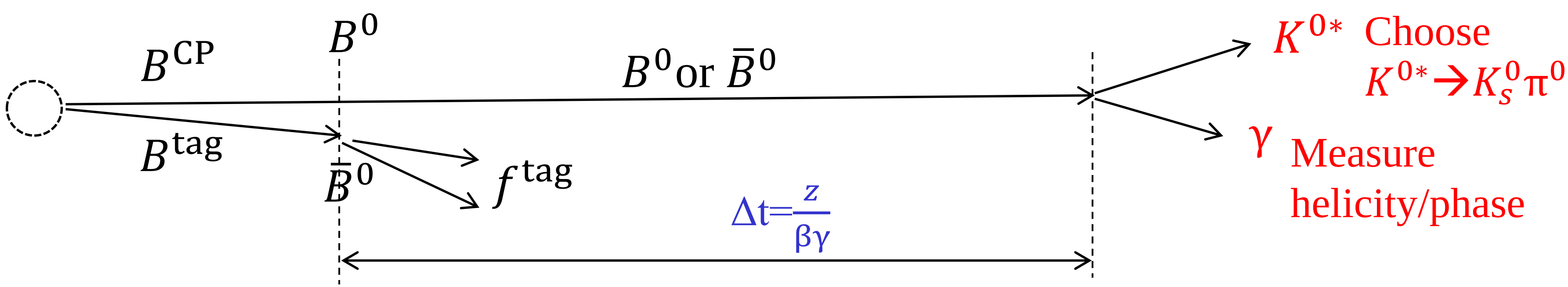
Identification of a fraction of B^0 and $\bar{B}^0$ ($|r|$) and their relative phase θ is essential for WM.

Postselection parameters

CP phase

$$P\left(\Delta t | B^0 \to B_{\mathrm{decay}}\right) = \frac{e^{-\Gamma|\Delta t|}}{2N}\left\{1 + (2|r|^2 - 1)\cos(\Delta m \Delta t) - 2|r|\sqrt{1-|r|^2}\sin(\theta - \varphi)\sin(\Delta m \Delta t)\right\}$$

- $|r|$: γ-helicity in $B^0 \to K^{0*}\gamma$ ($B^0 \to K^{0*}\gamma_R$/ $\bar{B}^0 \to K^{0*}\gamma_L$).
- θ: phase of γ
- $K^{0*} \to K_s^0 \pi^0$ has to be selected for consistency condition of states between B_{decay} and the decay product ($K^{0*}\gamma$).



Simulation study: signal yield (1)

- 5.5×10^{10} $B \cdot \bar{B}$ pairs at 50 ab^{-1}
- BR(Υ(4S) → $B^0\bar{B}^0$): 0.49
- BR(B^0→K^{0*}γ): 4.2×10^{-5}

B^0 → K^{0*}γ: 1.1×10^6

- Flavor tagging efficiency (f^{tag}): 0.136
  - Wrong tagging fraction: 0.02 (ignored in this study)
  - Nucl. Instrum. Meth. A533 (2004) 516-531
- Event reconstruction efficiency: 0.021
  - BR(K^{0*}→$K_S^0\pi^0$) is also taken into account here.
  - Phys. Rev. Lett. 119, 191802 (2017)

3.3×10^3 events remain after the event selection.

→ Looks enough statistics for postselection.

Simulation study: signal yield (2)

- For simplicity, efficiency of postselection is assumed as 0.5 for $|r|$ and 1.0 for θ.
  - In this study, efficiency of postselection with different $|r|$ and θ is not taken into account to see only effect of variation of $|r|$ and θ (inclusion of the efficiency is homework for future study).

→ 1.7×10^3 signal events after postselection

- The expected background contamination is 0.9×10^3 from the results in the Belle experiment.

Main background sources:

- $e^+e^- \rightarrow q\bar{q}$ (q = u, d, s, c)
- $e^+e^- \rightarrow B\bar{B}$: The final states of B are misidentified as signal.

Simulation study: event generation

- The pseudo-experiment was carried out with custom-made toyMC tool.
- The Δt distributions are generated, following the probability density functions of signal (P_{sig}) and background (P_{bkg}) for different $|r|$ and θ.

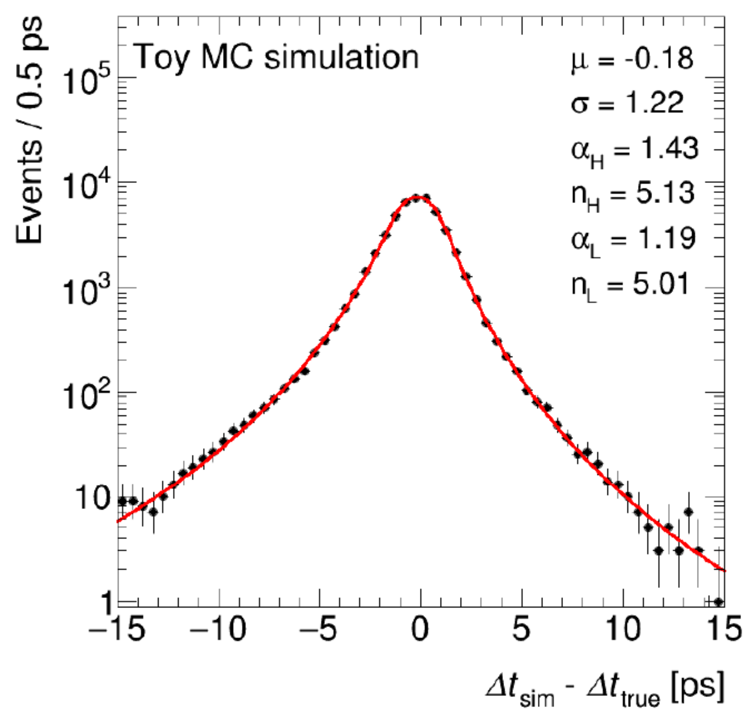
44.4 deg.

$$P_{sig}(\Delta t|B^0 \to B_{\mathrm{decay}}) = \frac{e^{-\Gamma|\Delta t|}}{2N}\left\{1 + (2|r|^2 - 1)\cos(\Delta m\Delta t) - 2|r|\sqrt{1-|r|^2}\sin(\theta - \varphi)\sin(\Delta m\Delta t)\right\}$$

  - CP phase φ (= $2\varphi_1$) is set as 44.4 degrees (the world average).

- P_{bkg} is empirically determined from the results in the Belle experiment.
- The detector response (timing scale/resolution) and background systematics are taken into account.

Detector time response ($\Delta t_{\mathrm{sim}} - \Delta t_{\mathrm{true}}$)

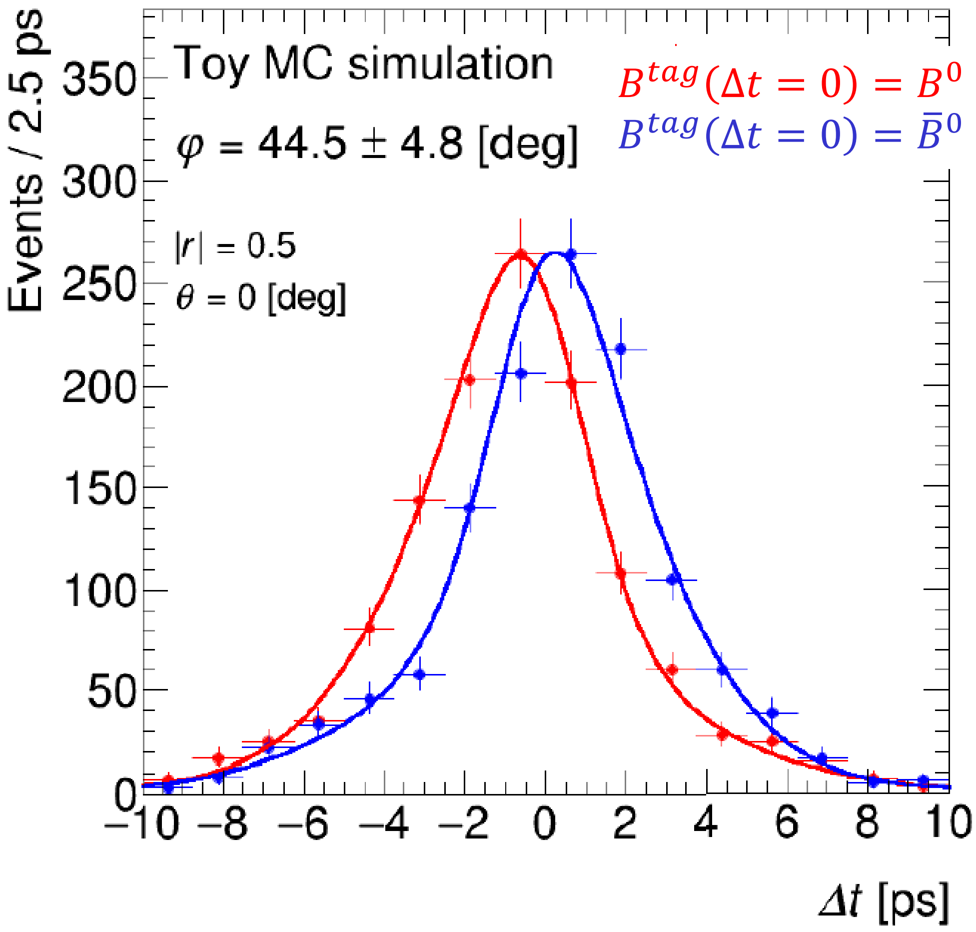


Simulation study: extraction of φ

- Δt distributions for $B^{tag}= B^0/\bar{B}^0$ were fitted by P_{sig} and P_{bkg} simultaneously to evaluate sensitivity to φ.
  - φ is fit parameter, i.e. value to be measured.
- The difference between $B^{tag}= B^0$ and $\bar{B}^0$ shows effect of φ (CP violation).

Uncertainty on φ in the fit result was investigated with different ($|r|$, θ).

Δt distribution for $B^{tag}= B^0/\bar{B}^0$ with ($|r|$, θ) = (0.5, 0)

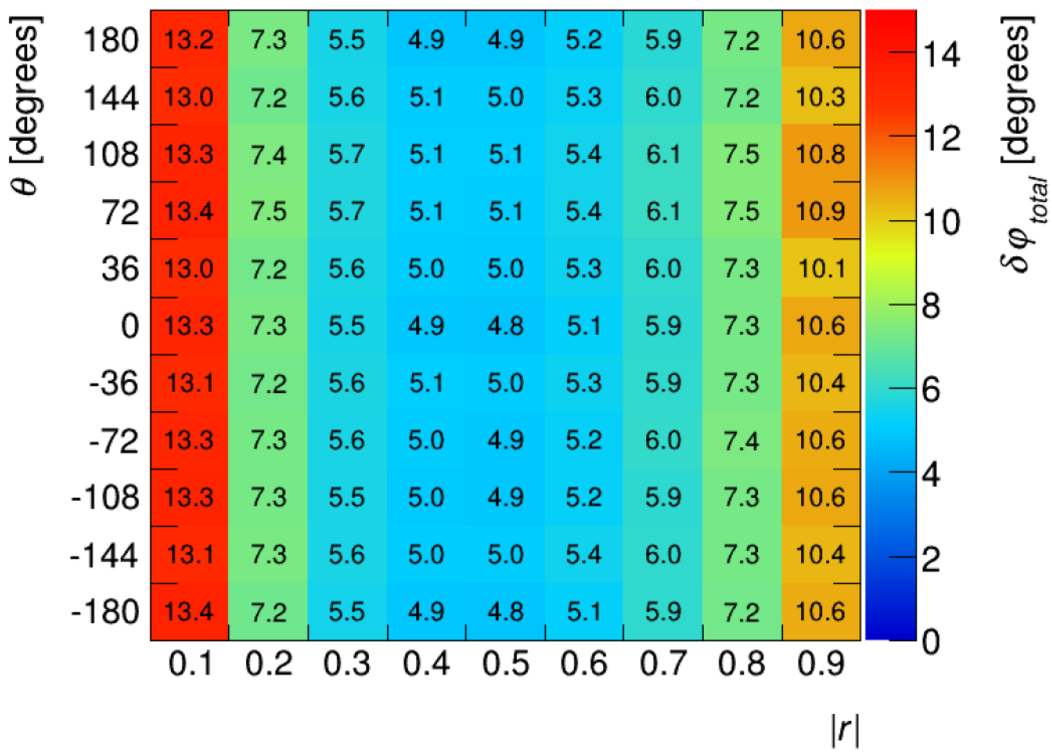


Sensitivity to CP phase

- The measurement precision on φ significantly depends on $|r|$, but not so much on θ.
- The sensitivity to φ is maximized at $|r|\sim0.5$.
- The statistical error dominates in this analysis.
  - σ_φ(syst.) = 0.22–1.1 deg.
  - σ_φ(stat.) = 4.7–13.2 deg.

WM can improve/adjust sensitivity to φ!

Measurement precision on φ with postselection

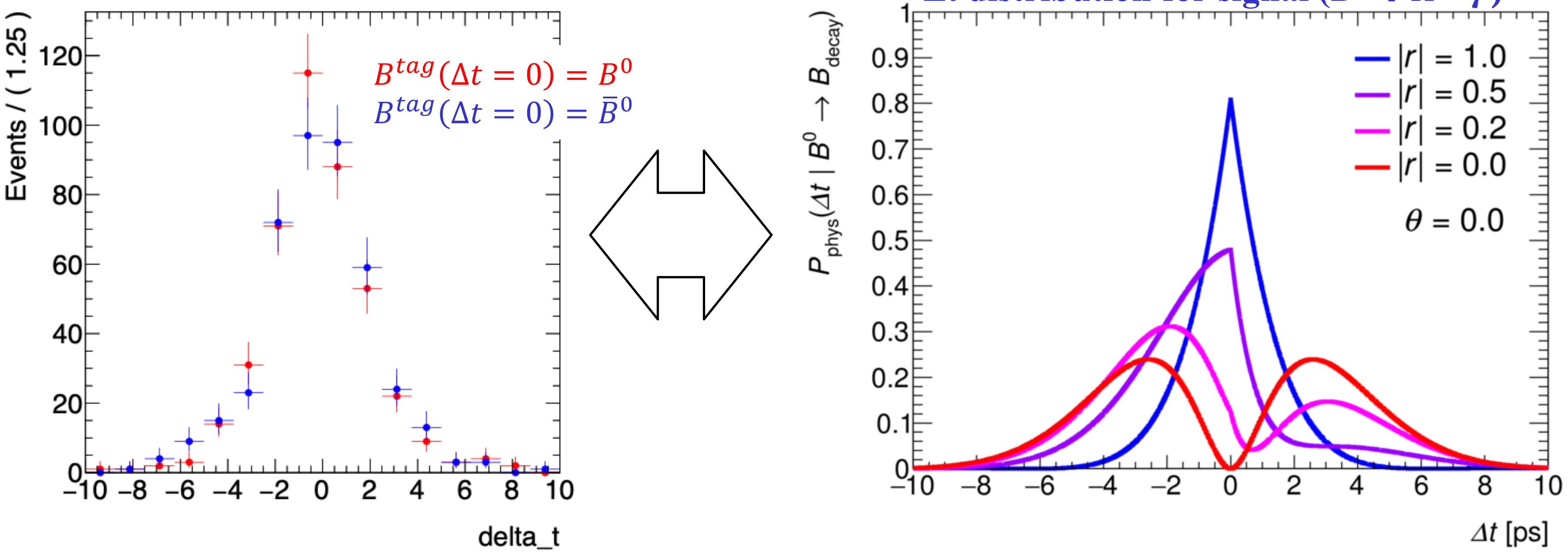


Why sensitivity is improved?

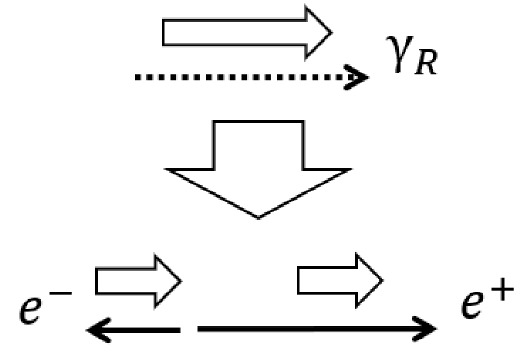
- The background distributes in the center of $\Delta t = 0$.
- The signal distribution is shifted with smaller $|r|$, escaping from $\Delta t = 0$ with large background.

  →The measurement precision on φ is improved with less background.
- With $|r| \sim 0$, the precision gets worse due to loss of statistics.

Δt distribution for BG **Δt distribution for signal ($B^0 \to K^{0*}\gamma$)**



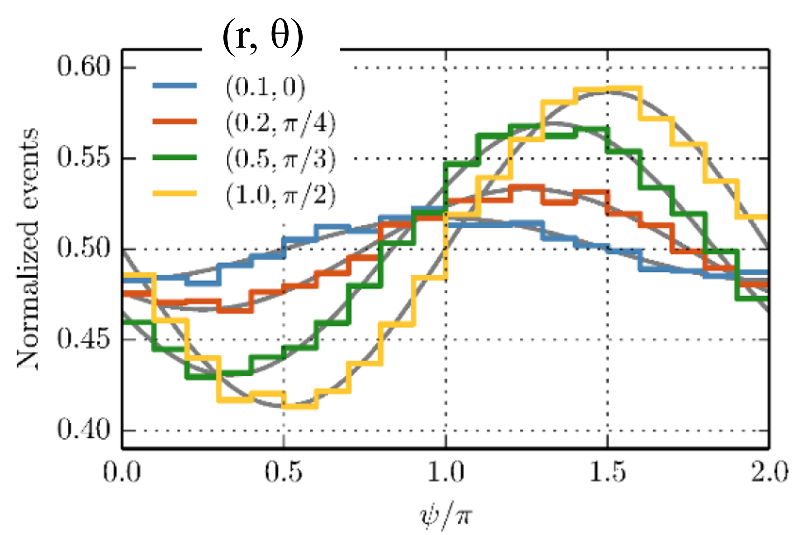
Postselection with γ



- Realization of postselection for $|r|$ and θ is the biggest technical challenge in WM.
- $|r|$ (a fraction of $B^0/\bar{B}^0$ in the final state) and θ correspond to helicity and phase of γ in $B^0 \rightarrow K^{0*}\gamma$.
- The helicity/phase of γ may be determined by measuring kinematics of e^+e^- from the conversion ([Phys. Rev. 114, 887 (1959)], [J. High Energ. Phys. 09, 013]).

Practically, including variables related with kinematics of e^+e^- as input for analysis with machine learning, effect of WM would be taken into account automatically.

Differential rate v.s. Sum of azimuthal angle of lepton pairs



Future prospect

This study is the first proposal to apply WM to high energy physics and showed possibility to improve measurement precision.

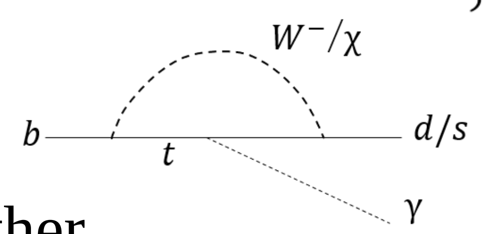
Our next target

- Study of sensitivity to direct/indirect CP violation and new physics in B meson decays with WM
  - There are three types of CP violation: Mixing induced (this study), direct and indirect CP violations.

Indirect CP

$$P(B^0(\Delta t) \to f) = N_{B^0} e^{-\Gamma|\Delta t|}\left\{1 + \frac{\boxed{|A|}^2|r|^2-(1-|r|^2)}{\boxed{|A|}^2|r|^2+(1-|r|^2)}\cos(\Delta M \Delta t) - \frac{2\boxed{|A|}|r|\sqrt{1-|r|^2}}{\boxed{|A|}^2|r|^2+(1-|r|^2)}\sin(\theta + \boxed{\delta} - \phi)\sin(\Delta M \Delta t)\right\}$$

Direct CP



- Application of the same method in this study to other two-state systems (applicable for any two-state system).
- Investigation of new method of WM for other physics processes.

Summary & Conclusions

- WM is new method of measurement in Quantum Mechanics.
  - Conditional measurement under very weak interaction.
- Effect of WM was confirmed by many existing experiments with photon and neutron, but there was no proposal with other particles.
- We developed method of WM applicable for CPV measurement with B meson decays in high energy physics.
- It was shown that WM improves sensitivity to CP phase with postselection on γ in $B^0 \rightarrow K^{0*}\gamma$ process.
- Our study is summarized in arXiv:2011.07560 (submitted to PRD).
- This is the starting point to consider application of WM for high energy physics!

  →Looking for new proposals and collaboration members!

Backup

Measurement with Von Neumann formula

In Von Neumann formula, the interaction Hamiltonian for a measured object and detector is defined as $g\delta(t-t_0)\hat{A}\hat{p}$.

- $\hat{A}$: Operator for a measured object ($\varphi(A)$).
- $\hat{p}\ \left(=-i\frac{d}{dQ}\right)$: Momentum operator for meter of the detector ($\psi(Q)$).

Time evolution of $\chi(A,Q,t)=\varphi(A,t)\psi(Q,t)$:

$$i\frac{d\chi(A,Q,t)}{dt}=g\delta(t-t_0)\hat{A}\hat{p}\chi(A,Q,t)$$

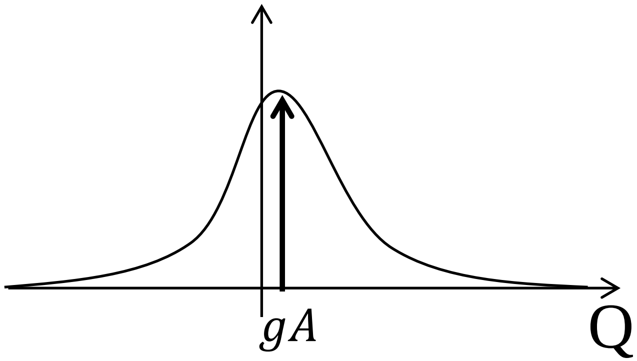
$$\Rightarrow \chi(A,Q,t)=e^{ig\hat{A}\hat{p}}\chi(A,Q,t=0)$$

Shift operator on Q

If $\hat{A}\varphi(A,t)=A\varphi(A,t)$

$$=\boxed{e^{igA\hat{p}}}\chi(A,Q,t=0)$$

$$=\chi(A,Q-gA,t=0)$$



Meter in the detector is shifted by gA.

Conventional measurement in mixed state

The interaction between a particle (measured object) and detector is expressed with Von Neumann formula.

Particle

$|\varphi_i\rangle$

$\hat{A}\,|\varphi_i\rangle = \sum_a A_a\,|a\rangle\langle a|\varphi_i\rangle$

Final state

$\hat{A}|\varphi_i\rangle$ All final eigen states

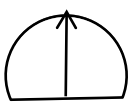
g

Detector

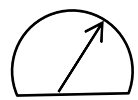
$|\psi(Q)\rangle$

Operator : $\hat{p} = \frac{d}{dQ}$

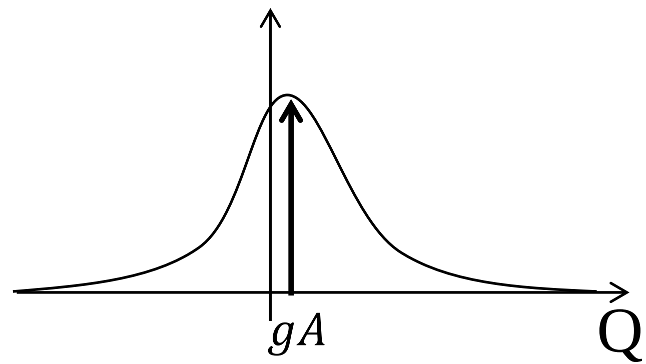
$|\psi(Q - gA)\rangle$



Value : Q



Value : $Q - A$



$$|\varphi_i\rangle|\psi(Q)\rangle \Longrightarrow \langle\varphi_i|e^{ig\hat{A}\hat{p}}\,|\varphi_i\rangle|\psi(Q)\rangle$$

Shift operator on Q

$\hat{A}\,|\varphi_i\rangle = \sum_a A_a\,|a\rangle\langle a|\varphi_i\rangle$

$$= \sum_a |\langle\varphi_i|a\rangle|^2\,\boxed{e^{igA_a\hat{p}}}\,|\psi(Q)\rangle$$

$$= \sum_a |\langle\varphi_i|a\rangle|^2\,|\psi(\boxed{Q - gA_a})\rangle$$ Meter's shift

Coupling strength for weak measurement

Let's consider how small the coupling should be for WM.

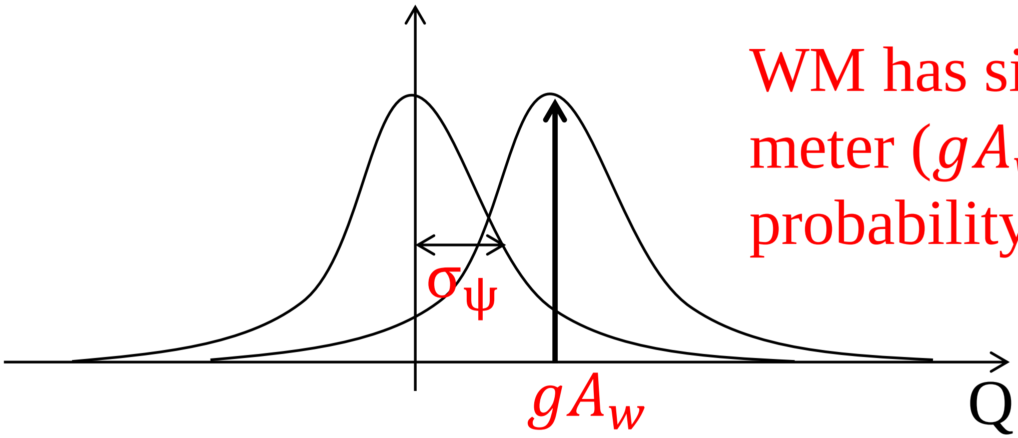
$$\langle \varphi_f | e^{ig\hat{A}\hat{p}} | \varphi_i \rangle | \psi(Q) \rangle$$

g<<1 $\sim \langle \varphi_f | (1 - \mathrm{i}g\hat{A}\hat{p}) | \varphi_i \rangle | \psi(Q) \rangle$

$$= \langle \varphi_f | \varphi_i \rangle (1 - \mathrm{i}gA_w\hat{p}) | \psi(Q) \rangle$$

$$= \langle \varphi_f | \varphi_i \rangle \left(|\psi(Q)\rangle - \boxed{gA_w} \frac{d|\psi(Q)\rangle}{dQ} \right)$$

gA_w should be $\ll \sigma_\psi$



WM has significant effect if shift in the meter (gA_w) is within width of the probability density function (σ_ψ).

Extension of effective lifetime (1)

$\hat{H}$ is Hamiltonian to give $(m_{L/H}, \Gamma_{L/H})$ for mass eigenstates (B_L, B_H).

Let's express $\hat{H} = \widehat{H_0} + \widehat{\Delta m}$.

$$\hat{H}|B_L\rangle = \left(m - \Delta m - \frac{i}{2}\Gamma\right)|B_L\rangle$$

$$\hat{H}|B_H\rangle = \left(m + \Delta m - \frac{i}{2}\Gamma\right)|B_H\rangle$$

Here,

- $m_L = m - \Delta m$
- $m_H = m + \Delta m$
- $\Gamma = \Gamma_L = \Gamma_H$

$$\left\langle B_{\text{decay}} \middle| B^0(\Delta t) \right\rangle = \left\langle B_{\text{decay}} \middle| e^{-i\Delta t \hat{H}} \middle| B^0 \right\rangle$$

$$= e^{-\frac{1}{2}\Gamma\Delta t} e^{-i\Delta t m} \left\langle B_{\text{decay}} \middle| e^{-i\Delta t \widehat{\Delta m}} \middle| B^0 \right\rangle$$

Assuming Δt is order of lifetime of B meson (1/Γ), the condition of weak measurement is:

$$e^{-i\frac{\widehat{\Delta m}}{\Gamma}} \sim 1 - i\,\frac{\widehat{\Delta m}}{\Gamma} \quad \Longrightarrow \quad \frac{\Delta m}{\Gamma} \sim 0$$

Extension of effective lifetime (2)

With $\frac{\Delta m}{\Gamma} \sim 0$ and $A_{\mathrm{w}} = \dfrac{\langle B_{\mathrm{decay}} | \Delta m | B^0 \rangle}{\langle B_{\mathrm{decay}} | B^0 \rangle}$

$$\langle B_{\mathrm{decay}} | B^0(\Delta t) \rangle = e^{-\frac{1}{2}\Gamma \Delta t} e^{-i\Delta t m} \langle B_{\mathrm{decay}} | B^0 \rangle \, e^{-i\Delta t A_{\mathrm{w}}}$$

$$\left| \langle B_{\mathrm{decay}} | B^0(\Delta t) \rangle \right|^2 = e^{-\Gamma \Delta t} \left| \langle B_{\mathrm{decay}} | B^0 \rangle \right|^2 \, e^{2\Delta t \, \mathrm{Im}[A_{\mathrm{w}}]}$$

$$= \boxed{e^{-(\Gamma - 2\Delta t \, \mathrm{Im}[A_{\mathrm{w}}])\Delta t}} \left| \langle B_{\mathrm{decay}} | B^0 \rangle \right|^2$$

The postselection effectively shortens/extends lifetime of B^0.

Extension of effective lifetime (3)

- $\Delta m = \ m_{B_H} - m_{B_L} = 3.3\ \times 10^{-10}$ MeV
- Γ_{B^0} = 4.3 $\times\ 10^{-10}$ MeV (τ = 1.5 $\times\ 10^{-12}$ s)

Δm/Γ = 0.77

Since Δm/Γ is not ~0, the first order calculation is not sufficient.

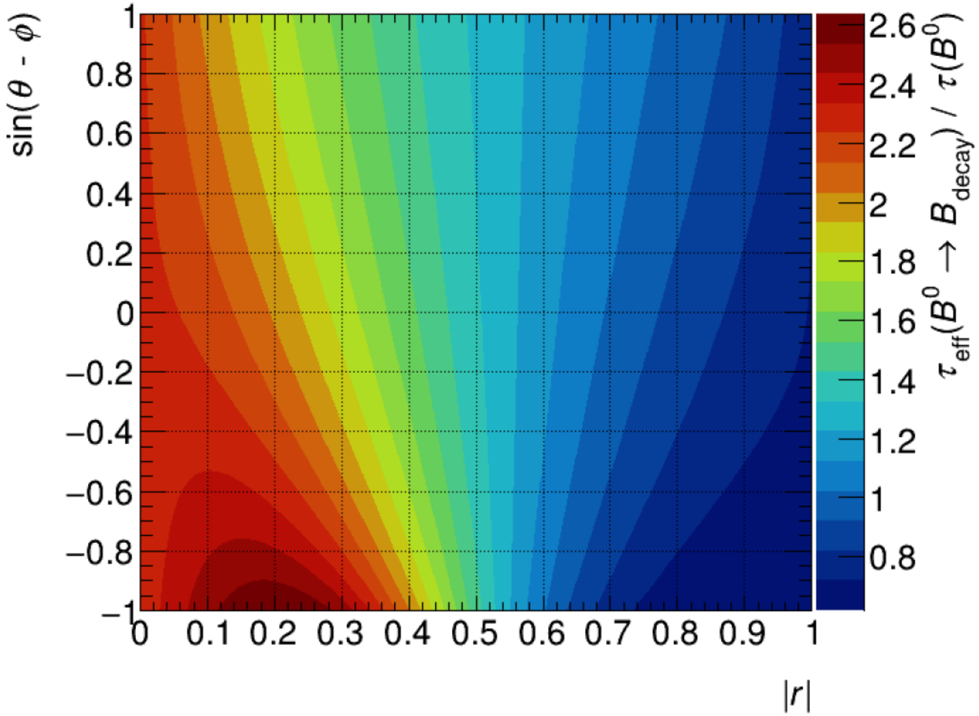
→ Let's calculate the lifetime without approximation.

Extension of effective lifetime (4)

$$\tau_{\mathrm{eff}}(B^0 \to B_{\mathrm{decay}}) = \int_0^\infty d\Delta t'\ \Delta t' P(\Delta t' | B^0 \to B_{\mathrm{decay}})$$

$$A_{\mathrm{w}} = \frac{\sqrt{1-|r|^2}}{|r|}\{\cos(\theta-\varphi) + i\sin(\theta-\varphi)\}$$

$$= \frac{\left(1+|A_{\mathrm{w}}|^2\right)\frac{1}{\Gamma^2} + \left(1-|A_{\mathrm{w}}|^2\right)\frac{\Gamma^2-(\Delta m)^2}{\{\Gamma^2+(\Delta m)^2\}^2} + 4\mathrm{Im}\left[A_{\mathrm{w}}\right]\frac{(\Delta m)\Gamma}{\{\Gamma^2+(\Delta m)^2\}^2}}{\left(1+|A_{\mathrm{w}}|^2\right)\frac{1}{\Gamma} + \left(1-|A_{\mathrm{w}}|^2\right)\frac{\Gamma}{\Gamma^2+(\Delta m)^2} + 2\mathrm{Im}\left[A_{\mathrm{w}}\right]\frac{\Delta m}{\Gamma^2+(\Delta m)^2}}$$



The effective lifetime can be extended 2.6 than $\tau(B^0)$, selecting $(|r|, \sin(\theta-\varphi)) \sim (0.2, -1)$.