A brief Overview on CP violation in Heavy Quark

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Outline

- History of CP violation in Quarks
- Theoretical foundations of CP violations
- Recent Progress (biased)
- Prospect

(3) J_μ has "unit length," i.e., $a^2+b^2=1$.

We then rewrite J_μ as[4]

$$J_\mu = \cos\theta(j_\mu^{(0)} + g_\mu^{(0)}) + \sin\theta(j_\mu^{(1)} + g_\mu^{(1)}), \qquad (2)$$

where $\tan\theta = b/a$. Since J_μ, as well as the baryons and the pseudoscalar mesons, belongs to the octet representation of SU_3, we have relations (in which θ enters as a parameter) between processes with $\Delta S = 0$ and processes with $\Delta S = 1$.

To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$
$$= \tan^2\theta M_K(1 - M_\mu^2/M_K^2)^2/M_\pi(1 - M_\mu^2/M_\pi^2)^2. \qquad (3)$$

From the experimental data, we then get[5,6]

$$\theta = 0.257. \qquad (4)$$

Cabibbo, PRL 10, 531(1963)

$\begin{pmatrix} u \\ d \end{pmatrix}$ (s)

N. Cabibbo 1963

(Cabibbo angle)

W – coupling :

$u \longleftrightarrow d\cos\theta_c + s\sin\theta_c$

$\theta_c : \sim 13{,}04°$

$\cos\theta_c \to 0.974$, $\sin\theta_c \to 0.226$

Cabibbo

1963

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

PRL13,138(1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$ where τ_1 and τ_2 are the K_1^0 and K_2^0 mean lives and R_T is the branching ratio including decay to two π^0. Using $R_T = \frac{3}{2} R$ and the branching ratio quoted above, $|\epsilon| \cong 2.3 \times 10^{-3}$.

Cabibbo
1963

K CPV
1964

Theoretical foundations

Strong eigenstates: $K^0 = d\bar{s}$, $\overline{K^0} = s\bar{d}$,

CP eigenstates:

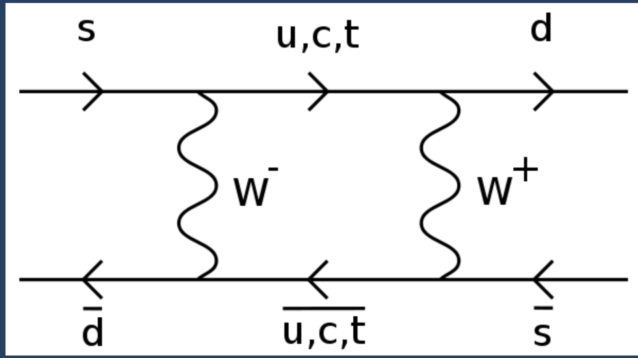
$$K_1 = \frac{1}{\sqrt{2}}\left(K^0 + \overline{K}^0\right)$$

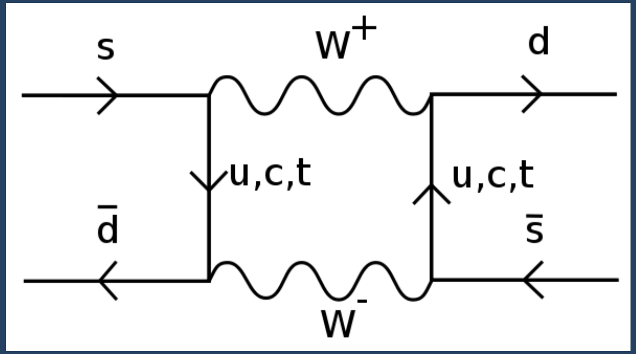
$$K_2 = \frac{1}{\sqrt{2}}\left(K^0 - \overline{K}^0\right)$$

Weak eigenstates:

$$K_S = \frac{K_1 + \varepsilon \cdot K_2}{\sqrt{1+|\varepsilon|^2}}$$

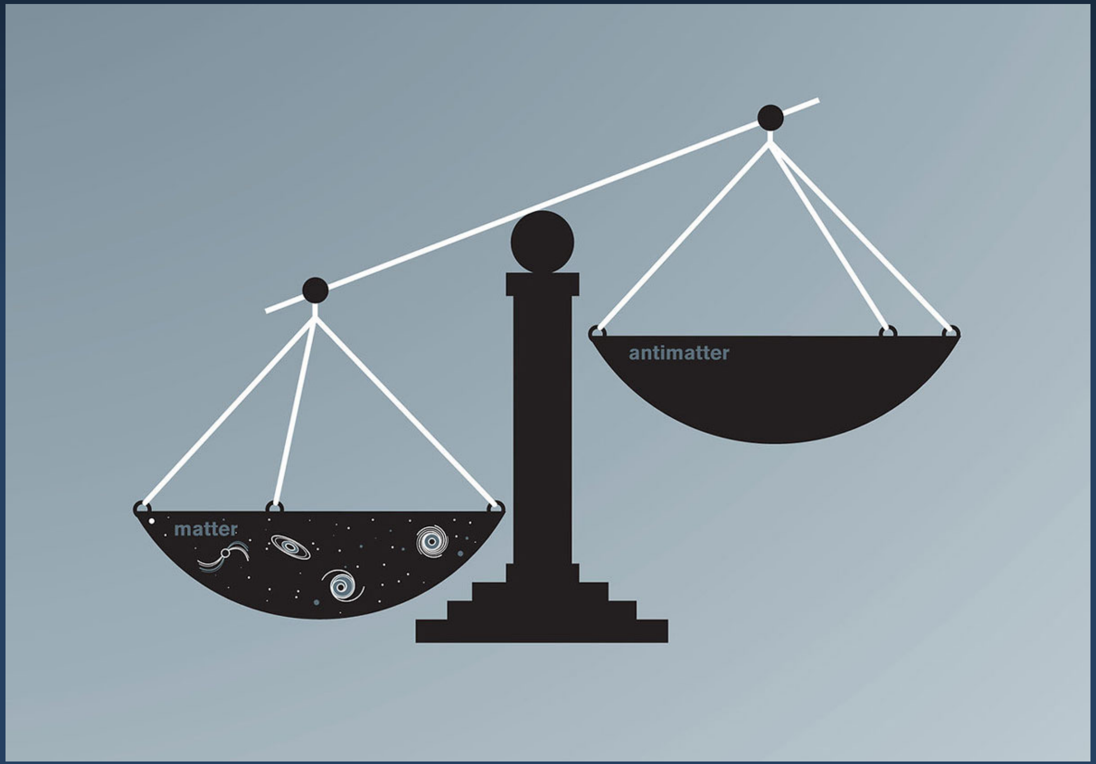
$$K_L = \frac{K_2 + \varepsilon \cdot K_1}{\sqrt{1+|\varepsilon|^2}}$$

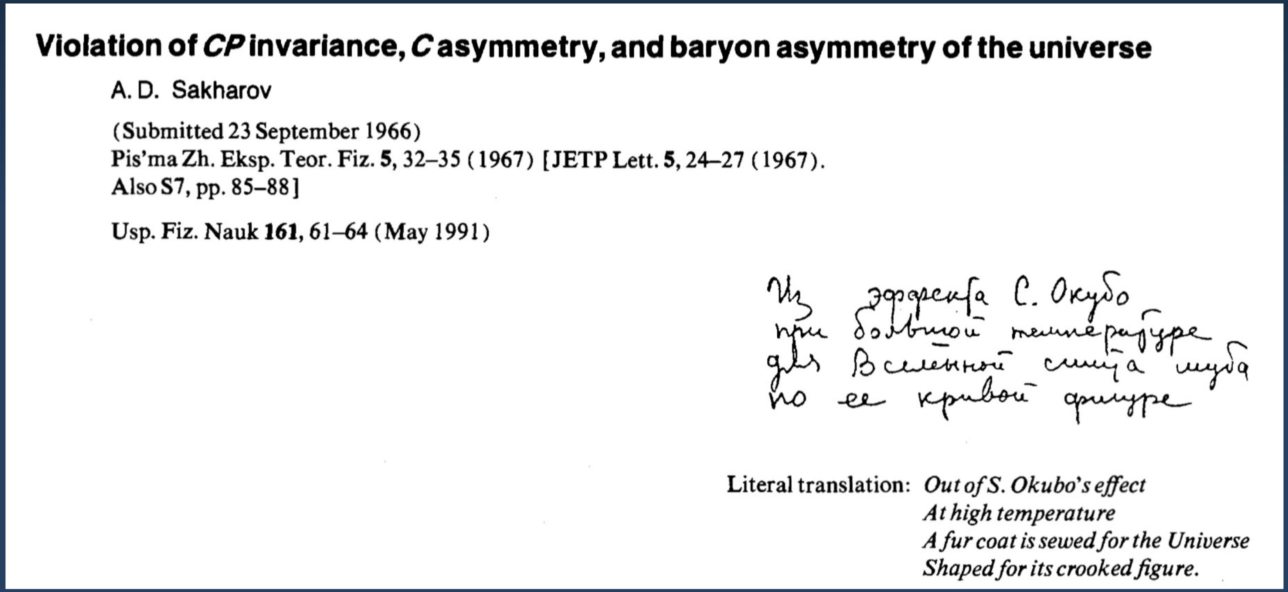




Mixing CPV

$$A_{\mathrm{CP}}^{\mathrm{B}} \equiv \frac{\Gamma(\bar{B}^0(t) \to l^+ \nu_l X) - \Gamma(B^0(t) \to l^- \bar{\nu}_l X)}{\Gamma(\bar{B}^0(t) \to l^+ \nu_l X) + \Gamma(B^0(t) \to l^- \bar{\nu}_l X)}$$





Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

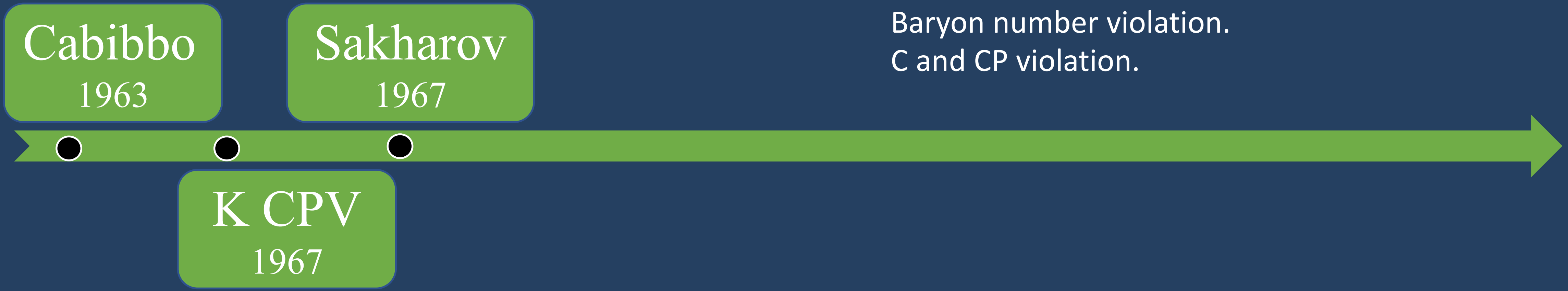
Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Из эффекта С. Окубо
При большой температуре
Для Вселенной сшита шуба
По ее кривой фигуре

Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

3 conditions required to generate a baryon asymmetry:

- Period of departure from thermal equilibrium in the early universe.
- Baryon number violation.
- C and CP violation.



$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

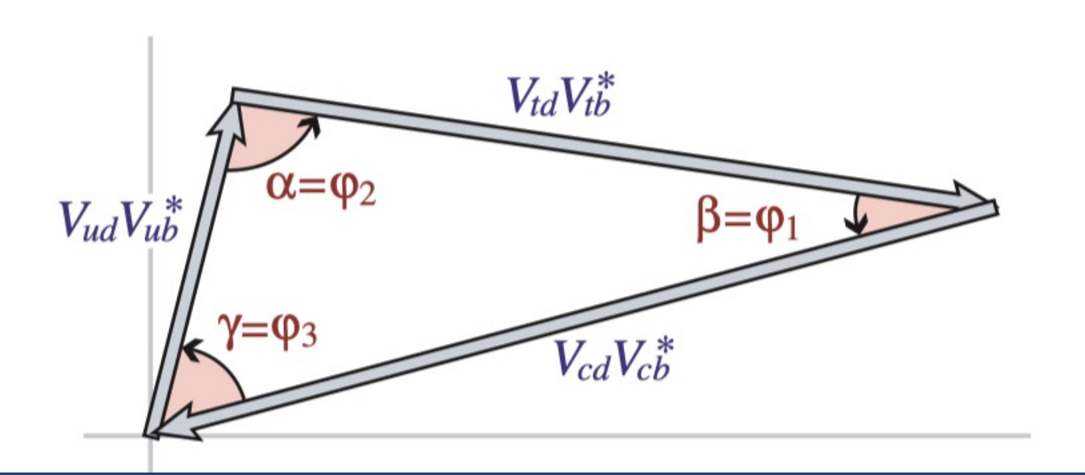
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Prog. Theor. Phys.49, 652 (1973)

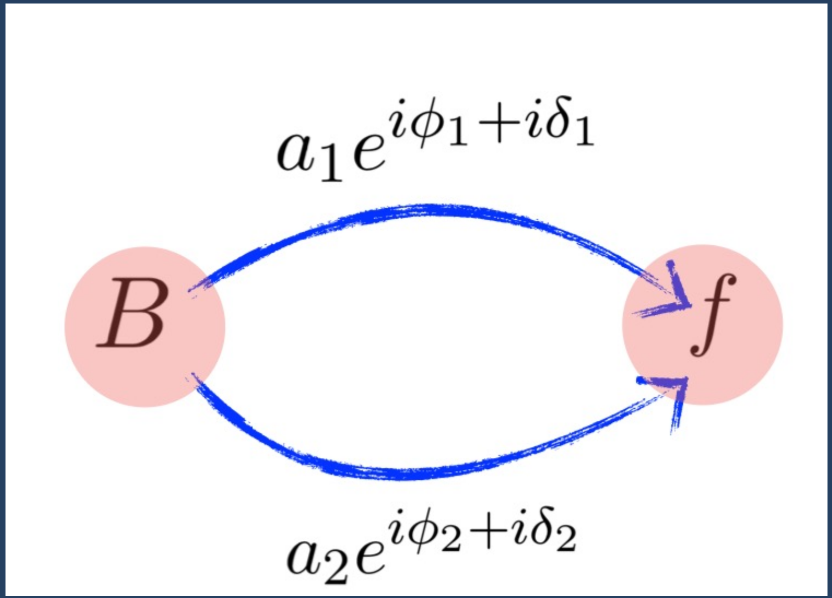
Theoretical foundations

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

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$



Theoretical foundations

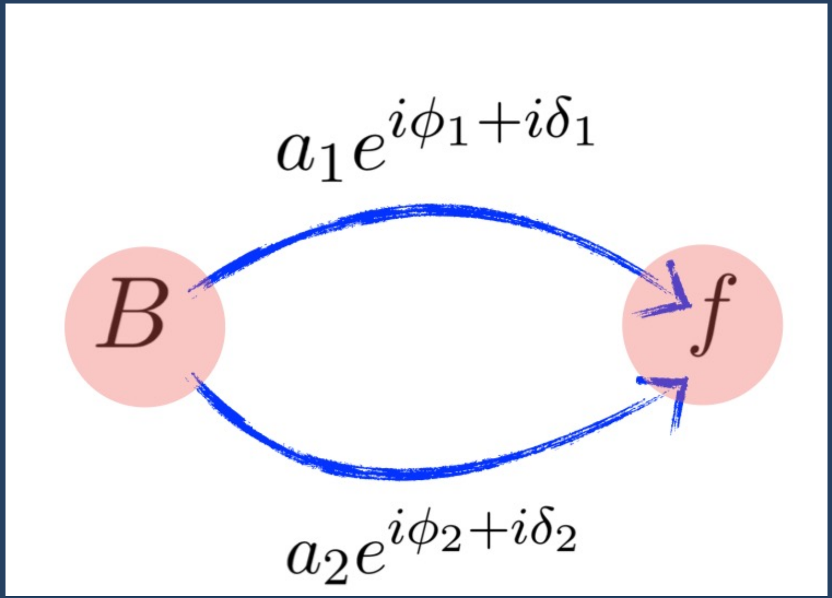


$$\mathcal{A}_f \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{1 - |A_f/\bar{A}_f|^2}{1 - |A_f/\bar{A}_f|^2},$$

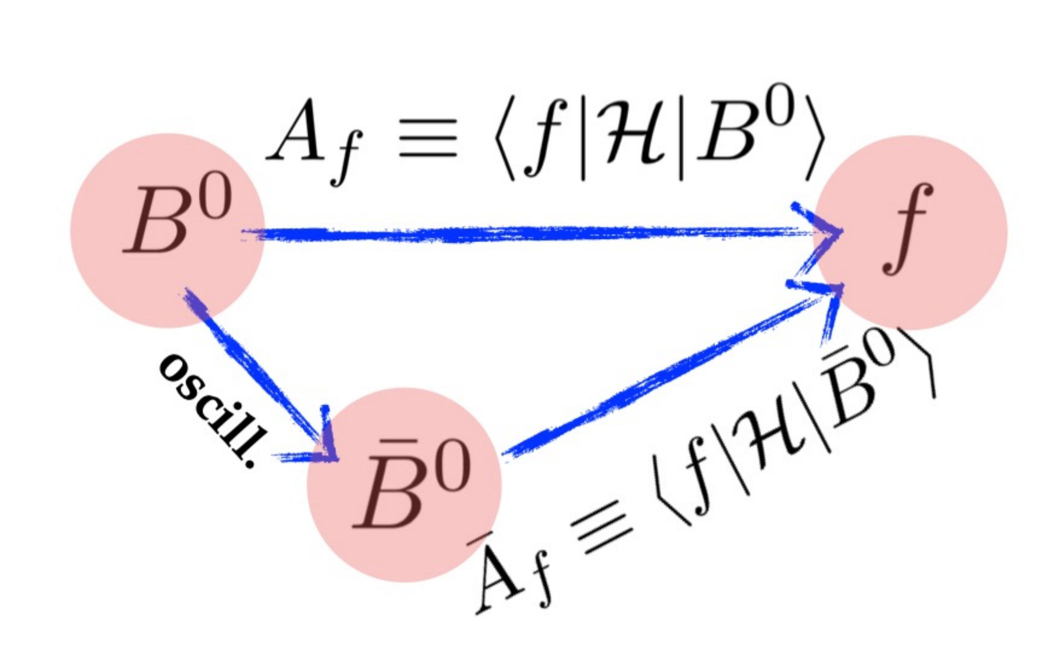
$$A_f = a_1 e^{i\phi_1+i\delta_1} + a_2 e^{i\phi_2+i\delta_2},$$
$$\bar{A}_f = a_1 e^{-i\phi_1+i\delta_1} + a_2 e^{-i\phi_2+i\delta_2}.$$

$$\mathcal{A}_f = \frac{a_2}{a_1} \sin(\phi_2 - \phi_1) \sin(\delta_2 - \delta_1) + \mathcal{O}(a_2^2/a_1^2).$$

Direct CPV



Direct CPV



CPV in interference between decays with and without mixing

Theoretical foundations

$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$$

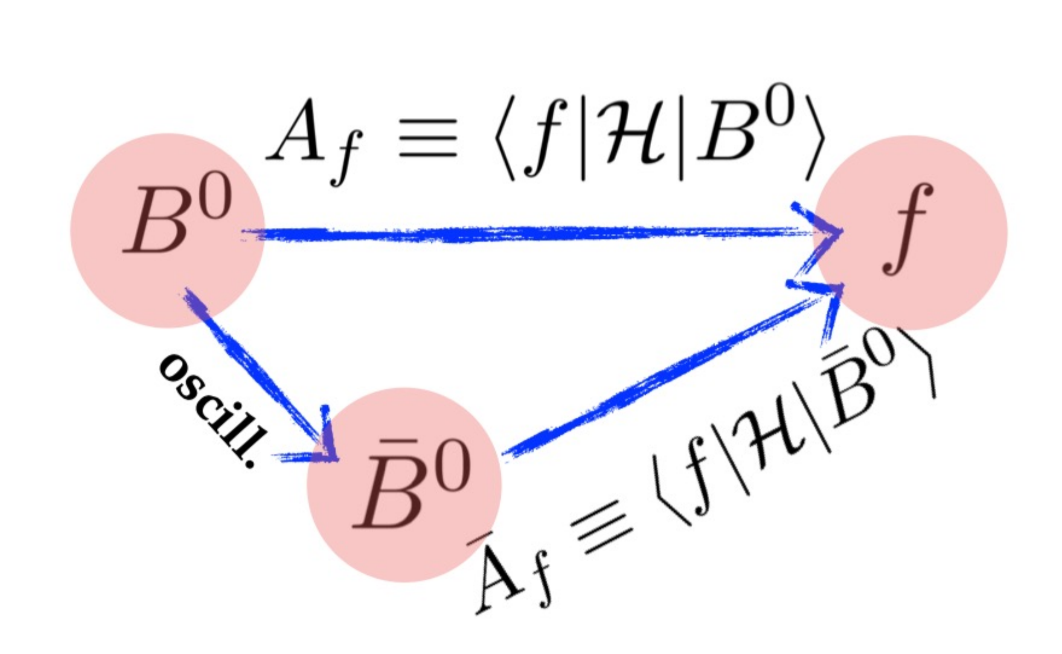
$$i\frac{d}{dt}\begin{pmatrix}|B^0(t)\rangle\\ |\bar{B}^0(t)\rangle\end{pmatrix} = \mathcal{H}\begin{pmatrix}|B^0(t)\rangle\\ |\bar{B}^0(t)\rangle\end{pmatrix} = \begin{pmatrix}M_{11}+i\Gamma_{11}, & M_{12}+i\Gamma_{12}\\ M_{21}+i\Gamma_{21}, & M_{22}+i\Gamma_{22}\end{pmatrix}\cdot\begin{pmatrix}|B^0(t)\rangle\\ |\bar{B}^0(t)\rangle.\end{pmatrix}$$

$$\frac{d}{dt}\Gamma(\bar{B}^0(t)[B^0(t)] \to f_{\rm CP}) \propto e^{-\Gamma t}\left[\frac{1}{2}\left(1+|\lambda_f|^2\right) \pm S_f\sin(\Delta m t) \mp C_f\cos(\Delta m t)\right]$$

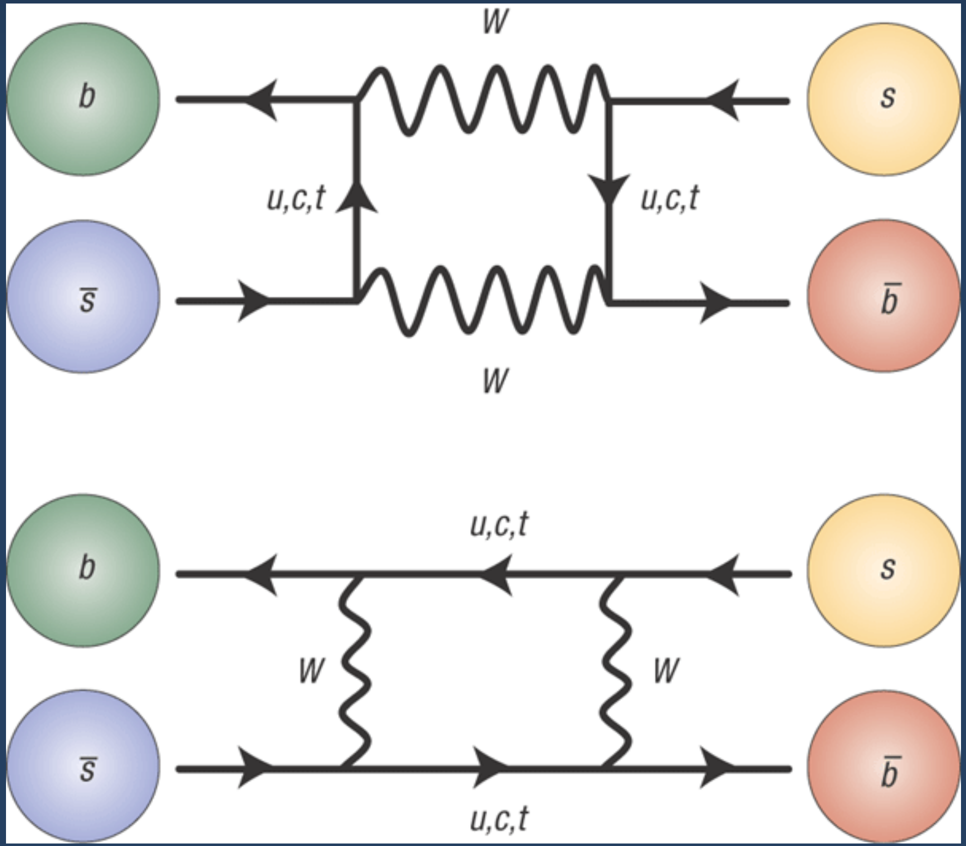
$$\mathcal{A}_{f_{CP}}(t) = S_f\sin(\Delta m t) - C_f\cos(\Delta m t)$$

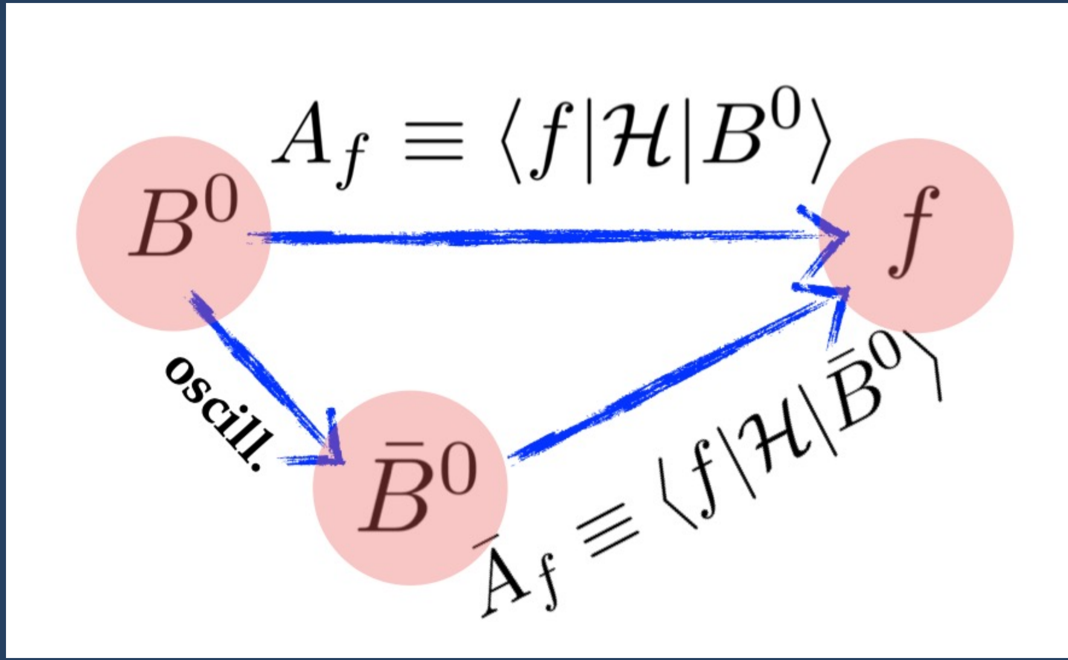
$$S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}, \qquad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}.$$

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}.$$



CPV in interference between decays with and without mixing





CPV in interference between decays with and without mixing

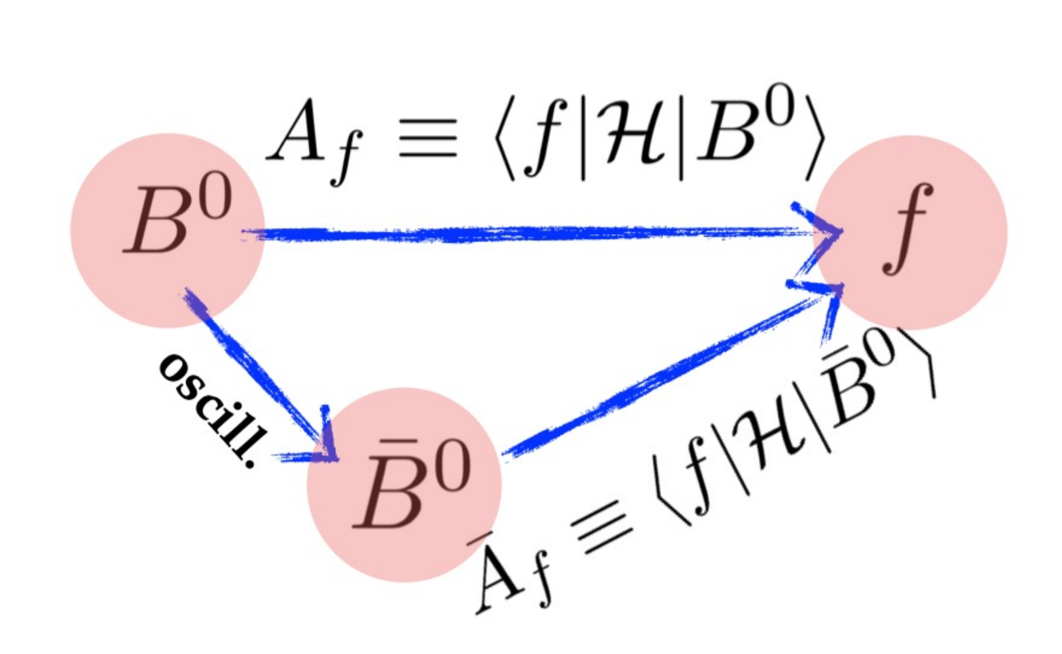
Theoretical foundations

$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{\frac{d}{dt}\Gamma[\bar{B}^0(t) \to f_{\mathrm{CP}}] - \frac{d}{dt}\Gamma[B^0(t) \to f_{\mathrm{CP}}]}{\frac{d}{dt}\Gamma[\bar{B}^0(t) \to f_{\mathrm{CP}}] + \frac{d}{dt}\Gamma[B^0(t) \to f_{\mathrm{CP}}]}$$

$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

$$S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}, \qquad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

$$\frac{q}{p} = e^{-i\phi_B} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}$$



CPV in interference between decays with and without mixing

Theoretical foundations

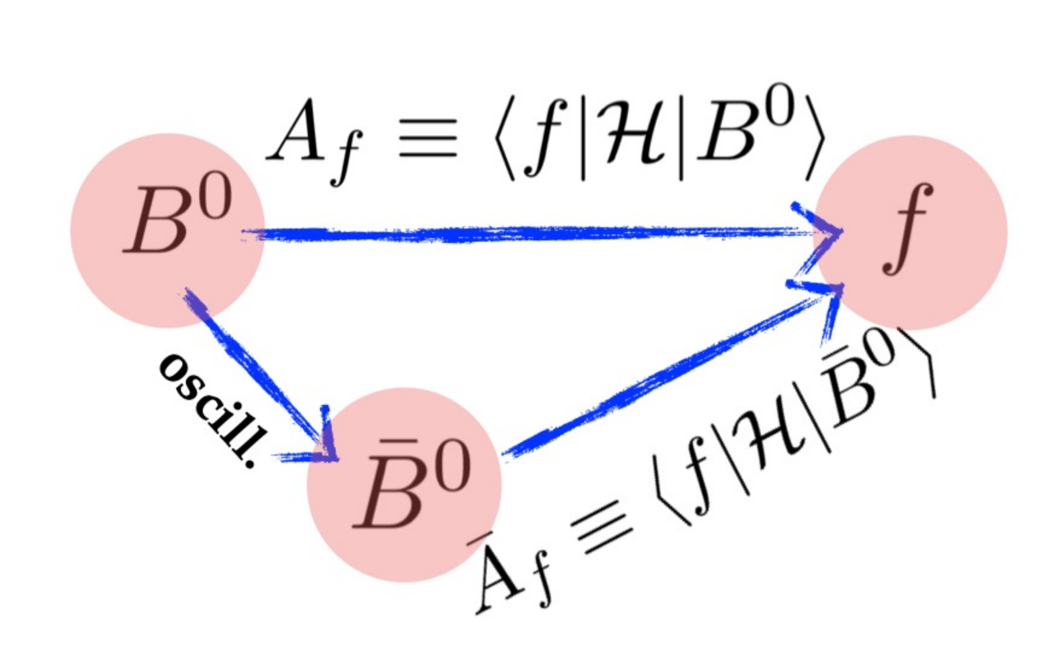
$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

$$S_f \equiv \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}, \qquad C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

$$\frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = \eta_f \frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}} + \cdots$$

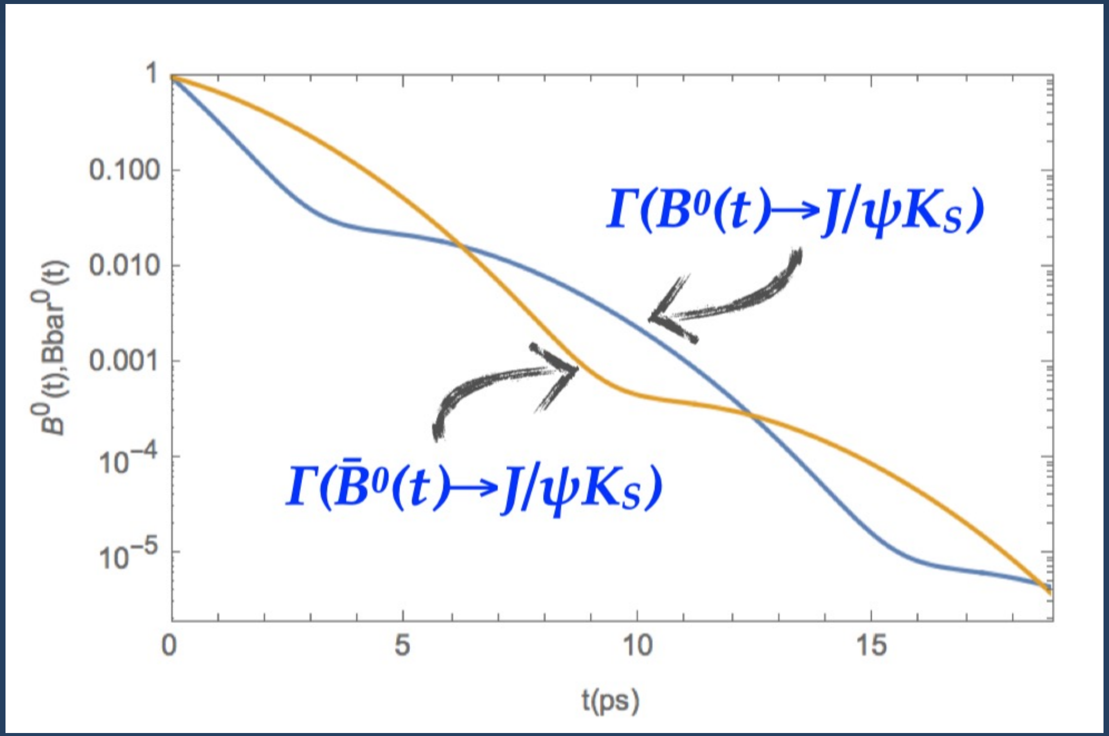
$$\lambda_{J/\psi K_S} = \eta_f \frac{V_{tb}^*V_{td}V_{cb}V_{cs}^*}{V_{tb}V_{td}^*V_{cb}^*V_{cs}} = \eta_f e^{-i2\beta}$$

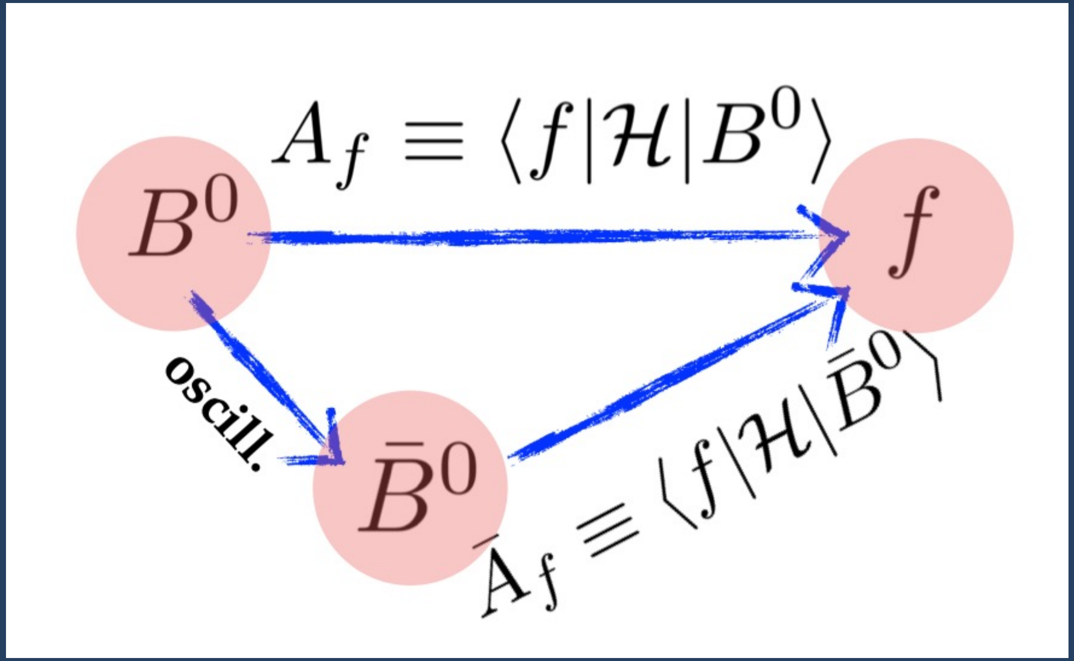
$$\mathrm{Im}\,\lambda_{J/\psi K_S} = \sin 2\beta$$



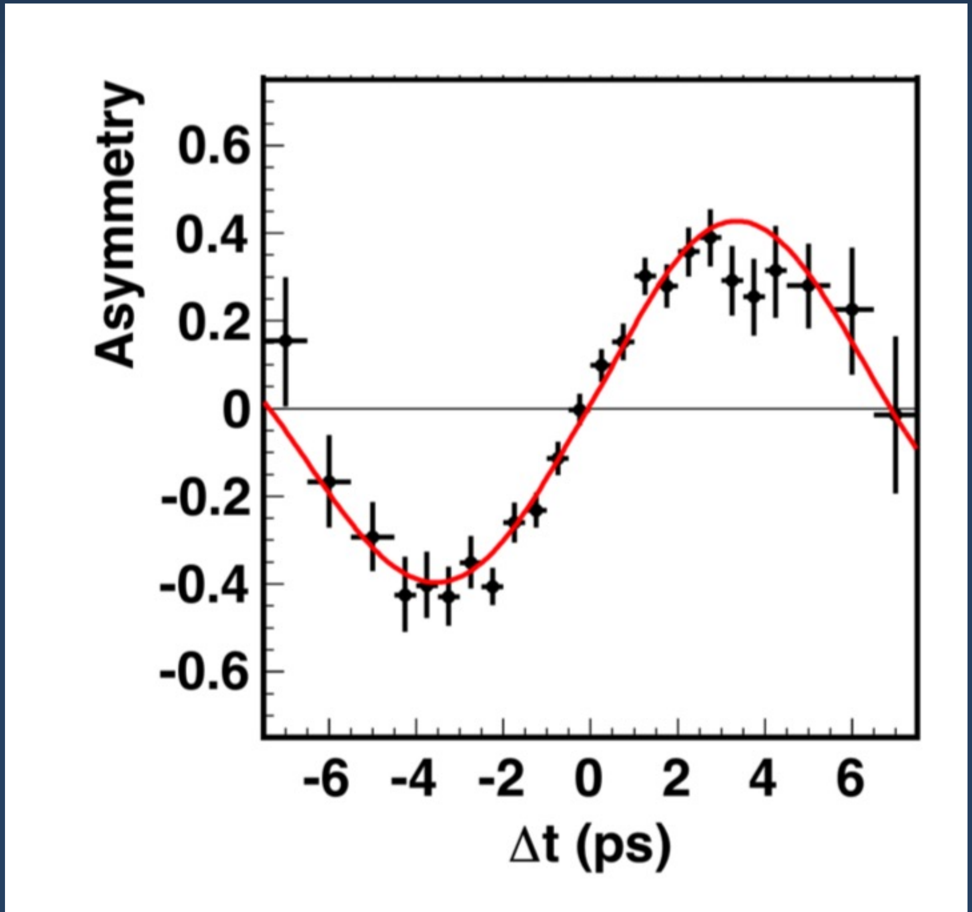
CPV in interference between decays with and without mixing

Theoretical foundations

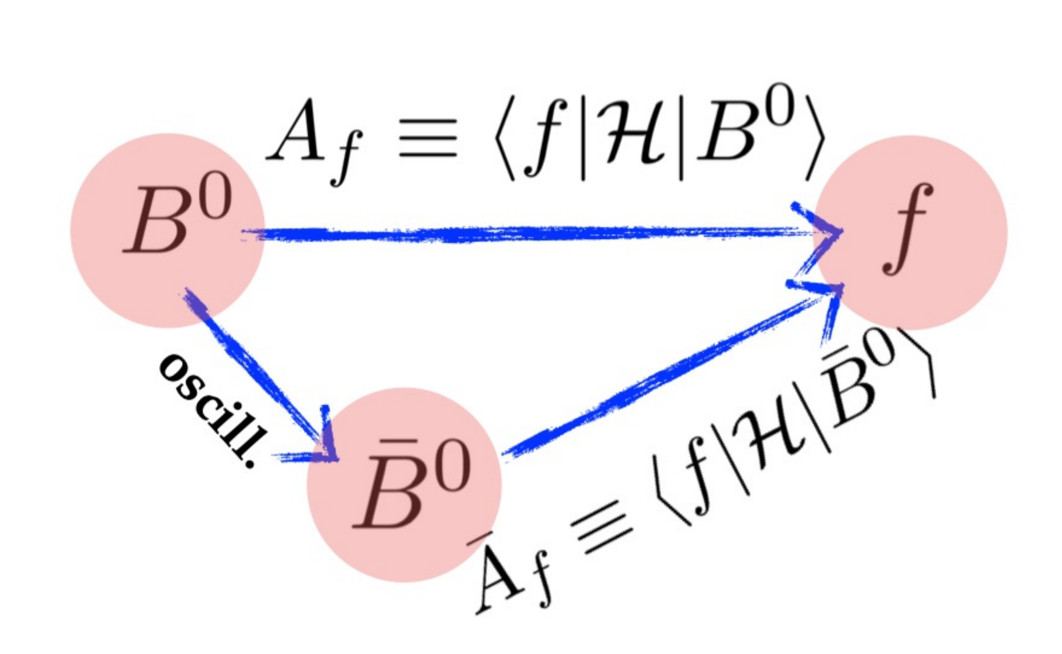




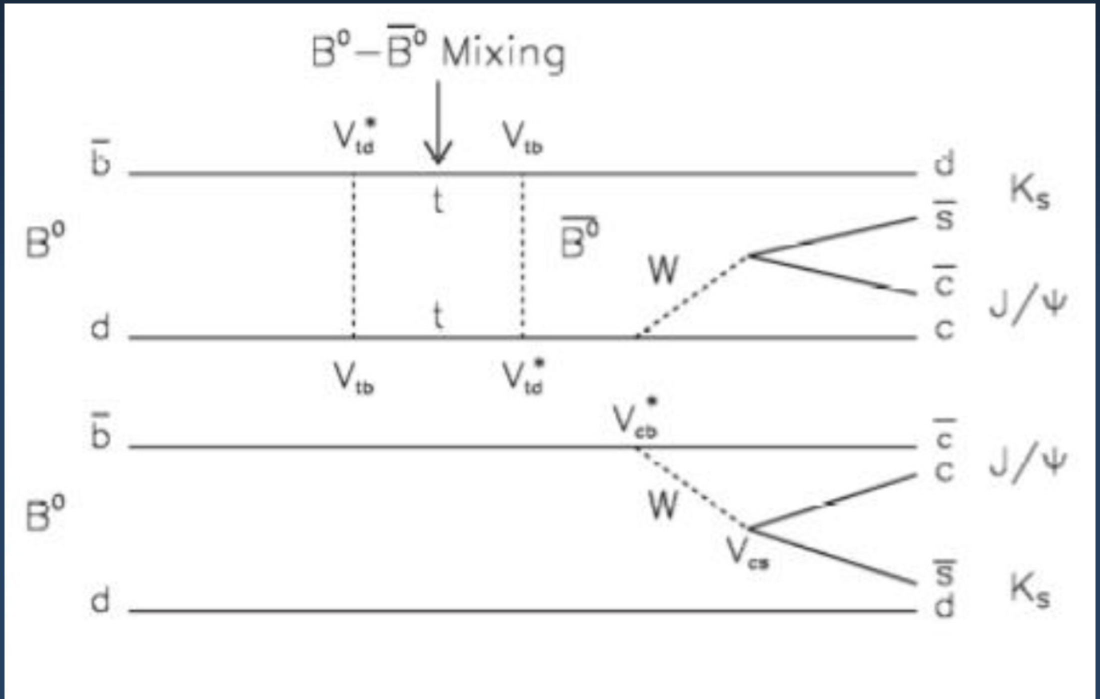
CPV in interference between decays with and without mixing



I. Adachi et al., PRL108, 171802 (2012), 1201.4643



CPV in interference between decays with and without mixing



I. Bigi, A. Sanda

$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

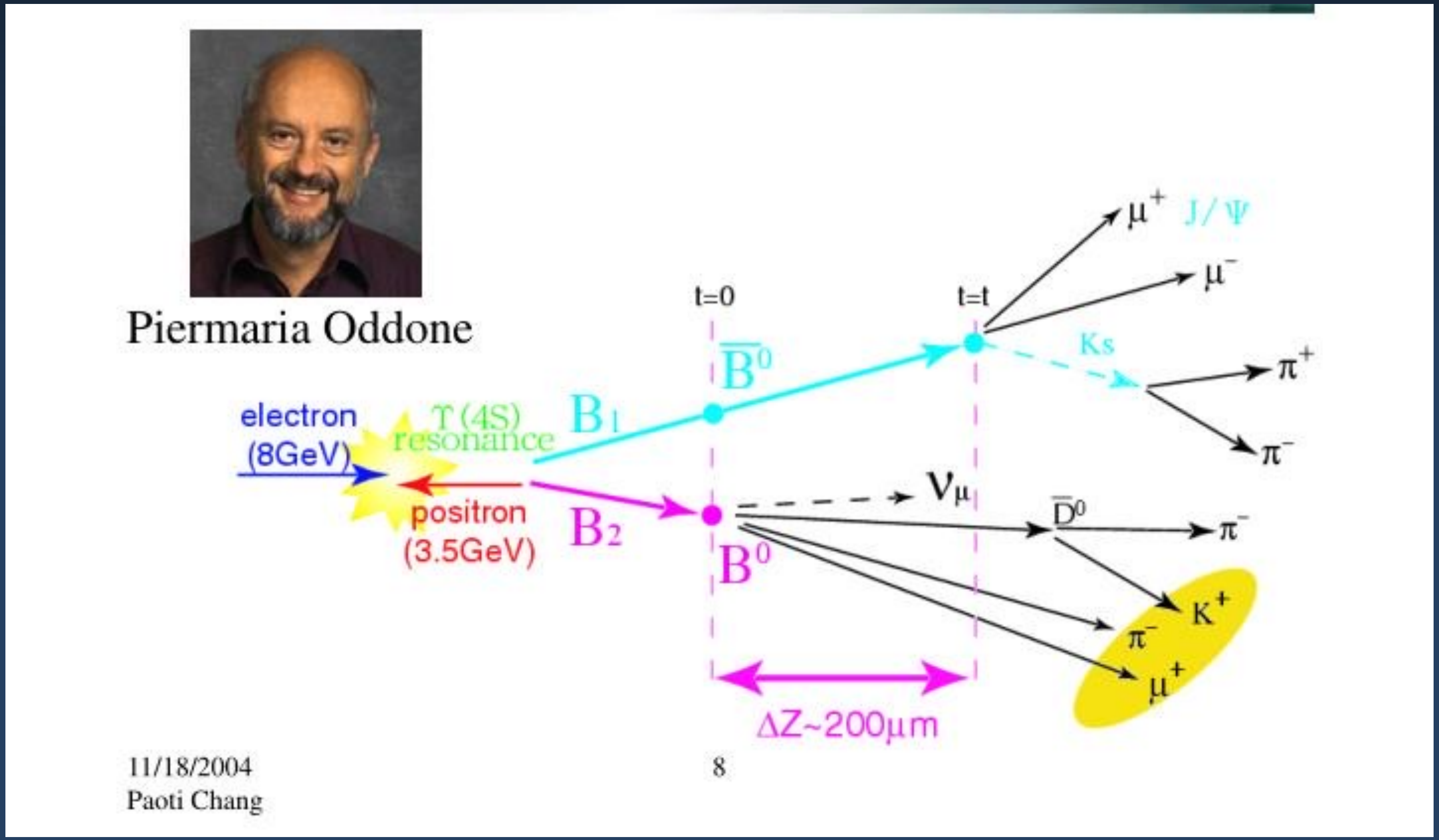
Cabibbo 1963

K CPV 1967

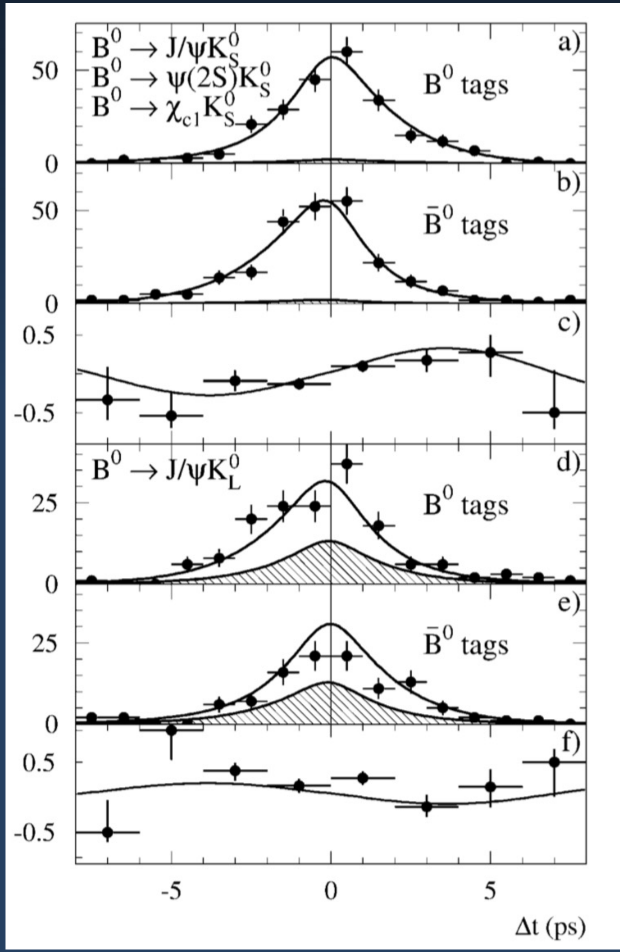
Sakharov 1967

KM 1973

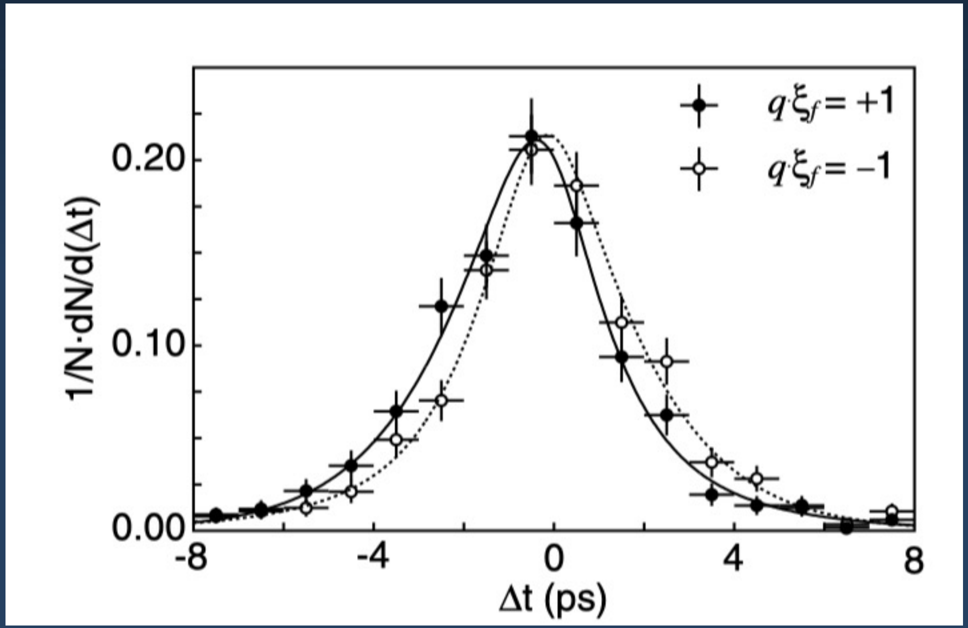
B→ $J/\Psi K$ 1981



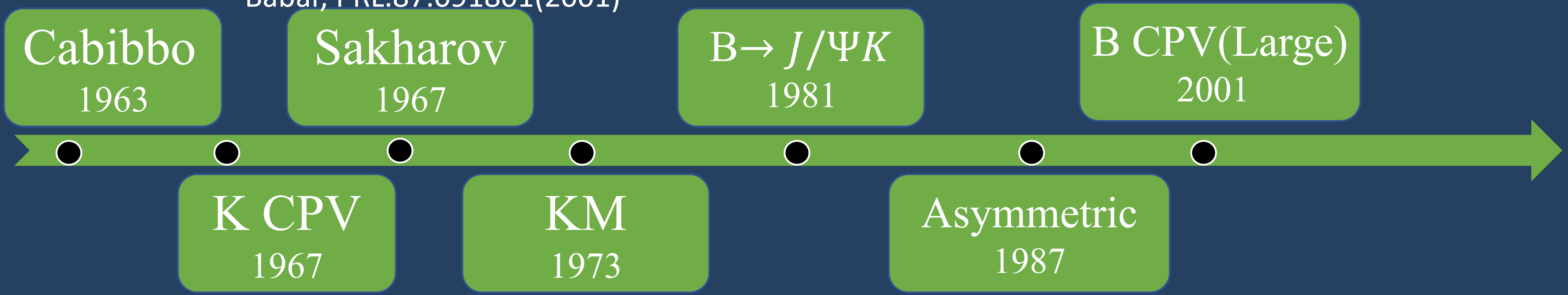
- Cabibbo 1963
- K CPV 1967
- Sakharov 1967
- KM 1973
- B→ $J/\Psi K$ 1981
- Asymmetric 1987

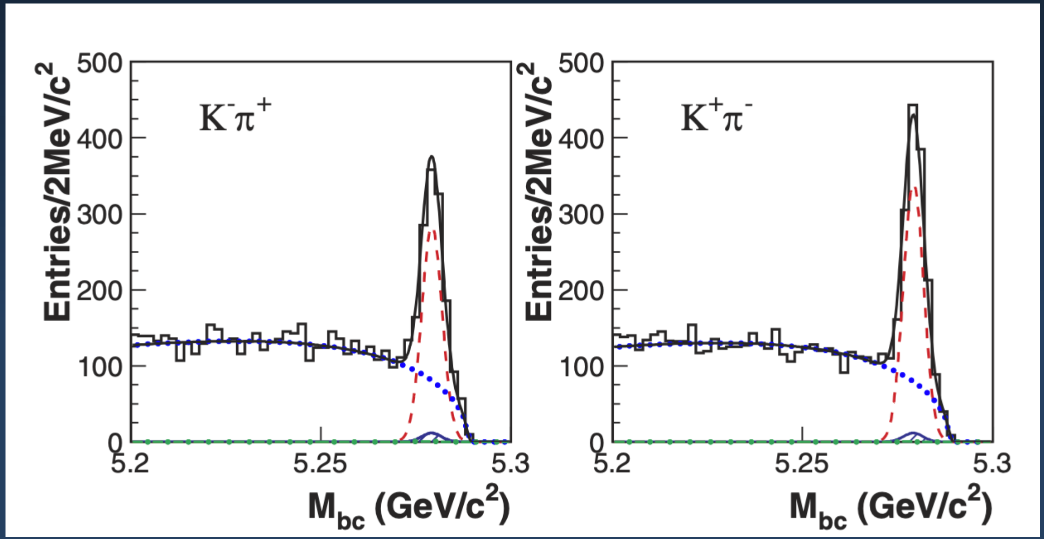


Babar, PRL.87.091801(2001)



Belle, PRL.87.091802(2001)



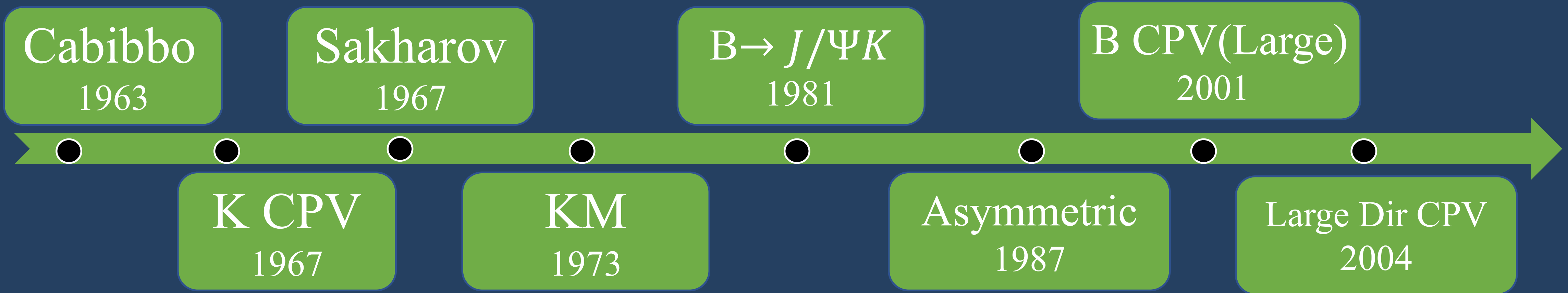


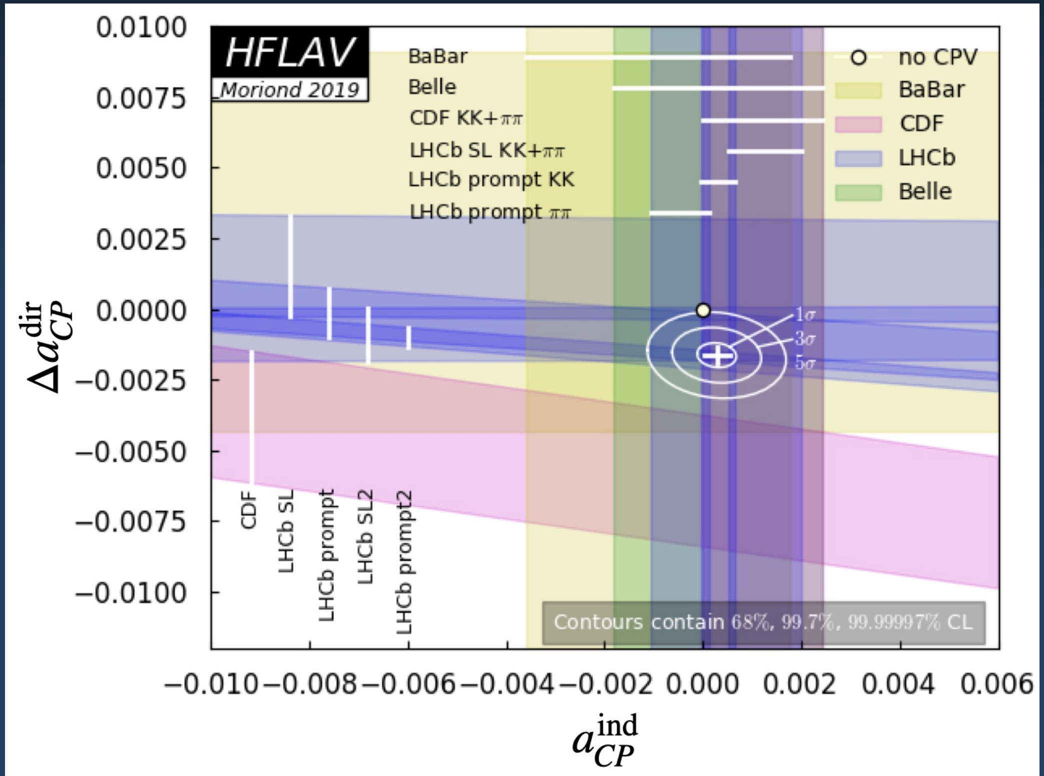
Sample	$N_{B\bar{B}}$	$n_{K\pi}$	$\mathcal{A}_{K\pi}$
1999–2001	21.1	142 ± 15	−0.240 ± 0.102
2002	66.4	479 ± 27	−0.102 ± 0.055
2003	34.1	241 ± 19	−0.109 ± 0.079
2004	104.9	743 ± 33	−0.142 ± 0.044

Babar, PRL93.131801(2004)

Mode	Signal Yield	$\mathcal{A}_{CP}$	Bkg $\mathcal{A}_{CP}$
$K^{\mp}\pi^{\pm}$	2140 ± 53	−0.101 ± 0.025 ± 0.005	−0.001 ± 0.005
$K^{\mp}\pi^0$	728 ± 34	0.04 ± 0.05 ± 0.02	−0.02 ± 0.01
$\pi^{\mp}\pi^0$	315 ± 29	−0.02 ± 0.10 ± 0.01	−0.01 ± 0.01

Belle, PRL93.191802(2004)





Cabibbo 1963

K CPV 1967

Sakharov 1967

KM 1973

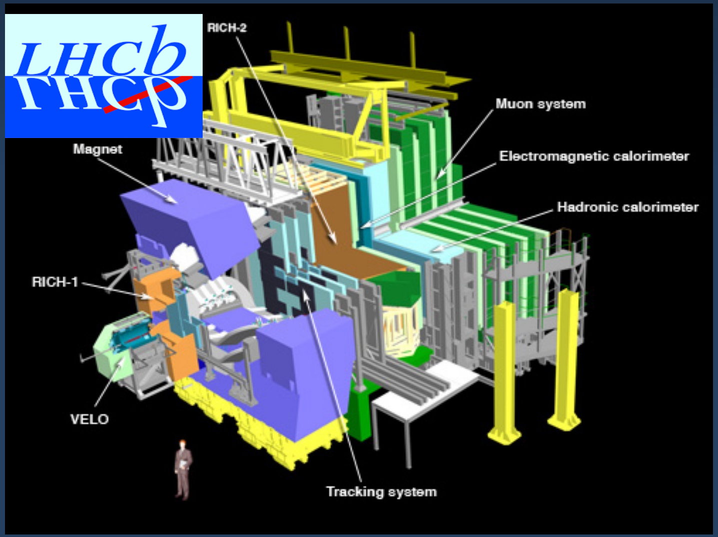
B→ $J/\Psi K$ 1981

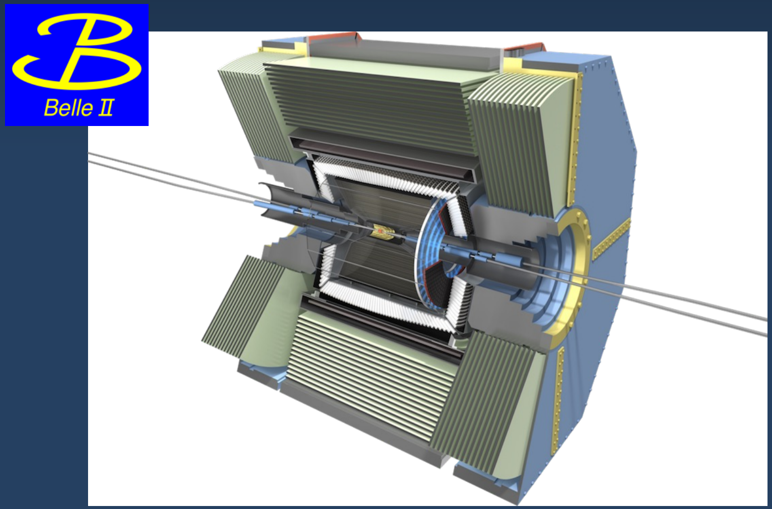
Asymmetric 1987

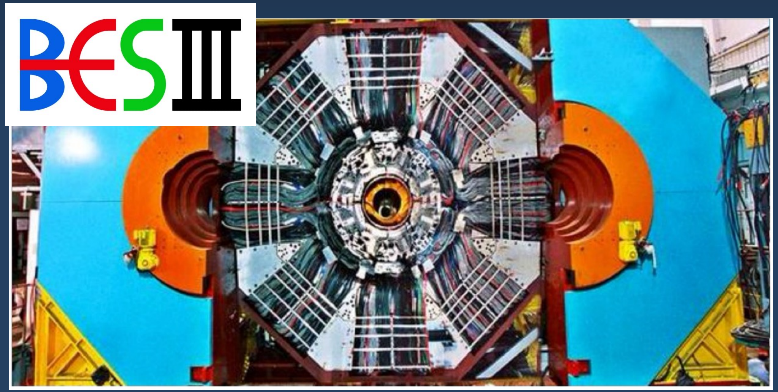
B CPV(Large) 2001

Large Dir CPV 2004

Charm Dir CPV 2019

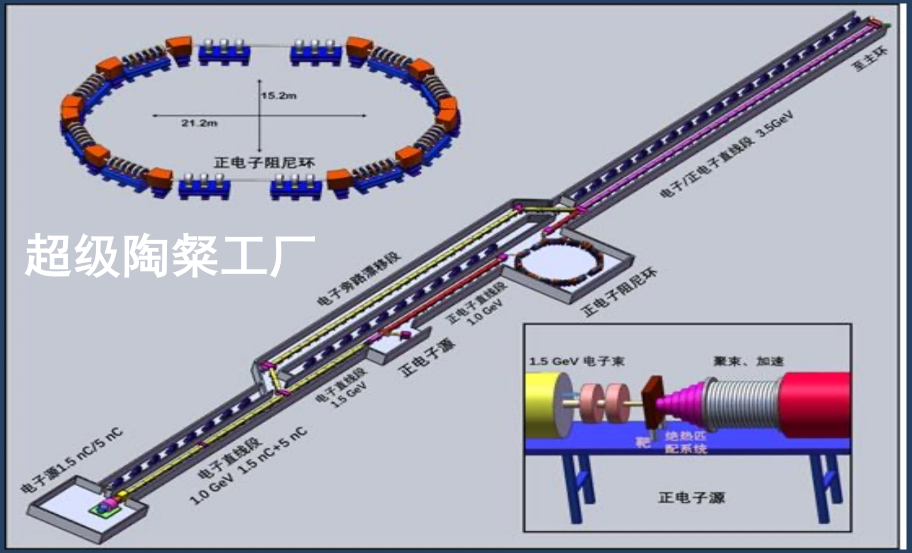






高精度的实验数据对理论计算精度提出了相应的需求

See Wen-bin, Pei-Lian, and Xiaodong’s talks.

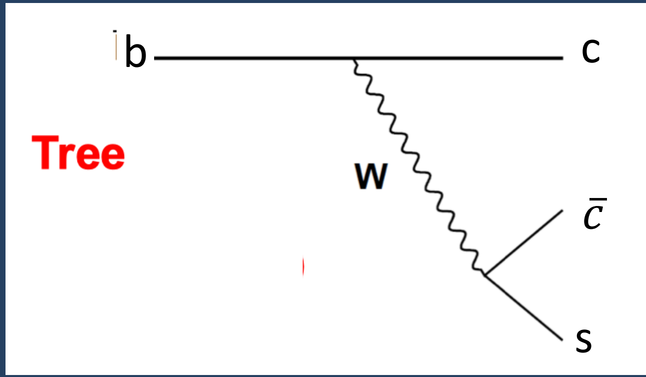


Challenges

$\sin(2\beta) = 0.699 \pm 0.017$

$\beta = (22.2 \pm 0.7)^{\circ}$

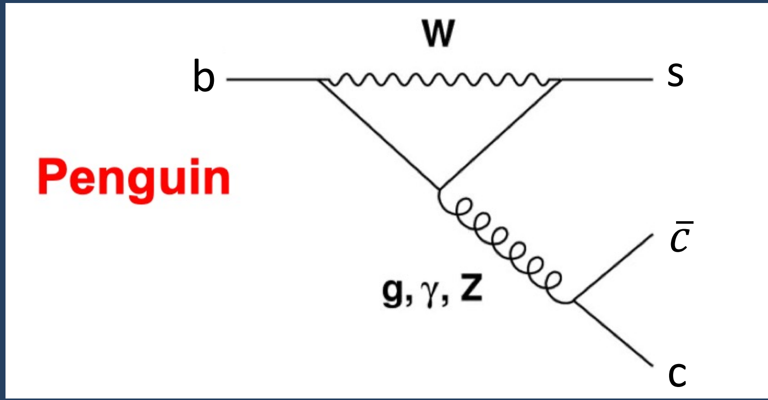
Golden Channel: $B \rightarrow J/\psi K_s$



Tree Amplitudes:

$V_{cb}V_{cs} \sim 40 \times 10^{-3}$

$a_2 \sim 0.1 - 1$

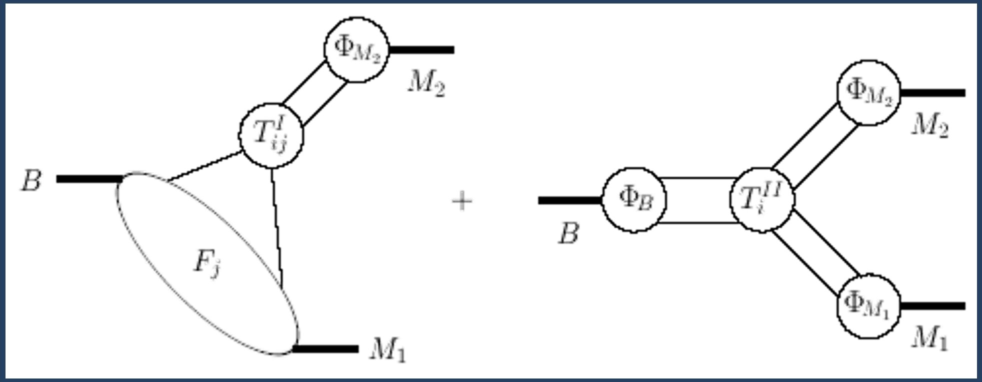


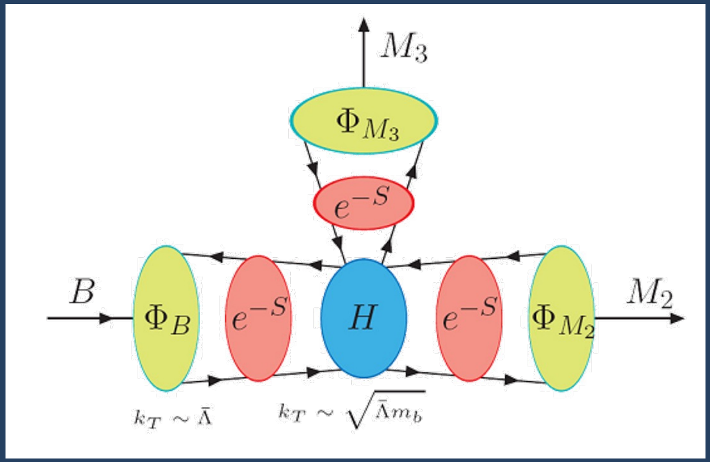
Penguin Amplitudes:

$V_{ub}V_{us} \sim 0.8 \times 10^{-3}$

$a_4 \sim 0.04$

Challenges





$$A(B \to \pi\pi) \propto \phi_\pi \otimes T_I \otimes F^{B\pi} + \phi_\pi \otimes T_{II} \otimes \phi_B \otimes \phi_\pi$$

$$A \sim \int d^4k_1\, d^4k_2\, d^4k_3\, \mathrm{Tr}\,[\, C(t)\, \Phi_B(k_1)\, \Phi_1(k_2)\, \Phi_2(k_3)\, H(k_1,k_2,k_3,t)\,]\, \exp\{-S(t)\}$$

Prospect:

A incomplete list of recent theoretical progress:

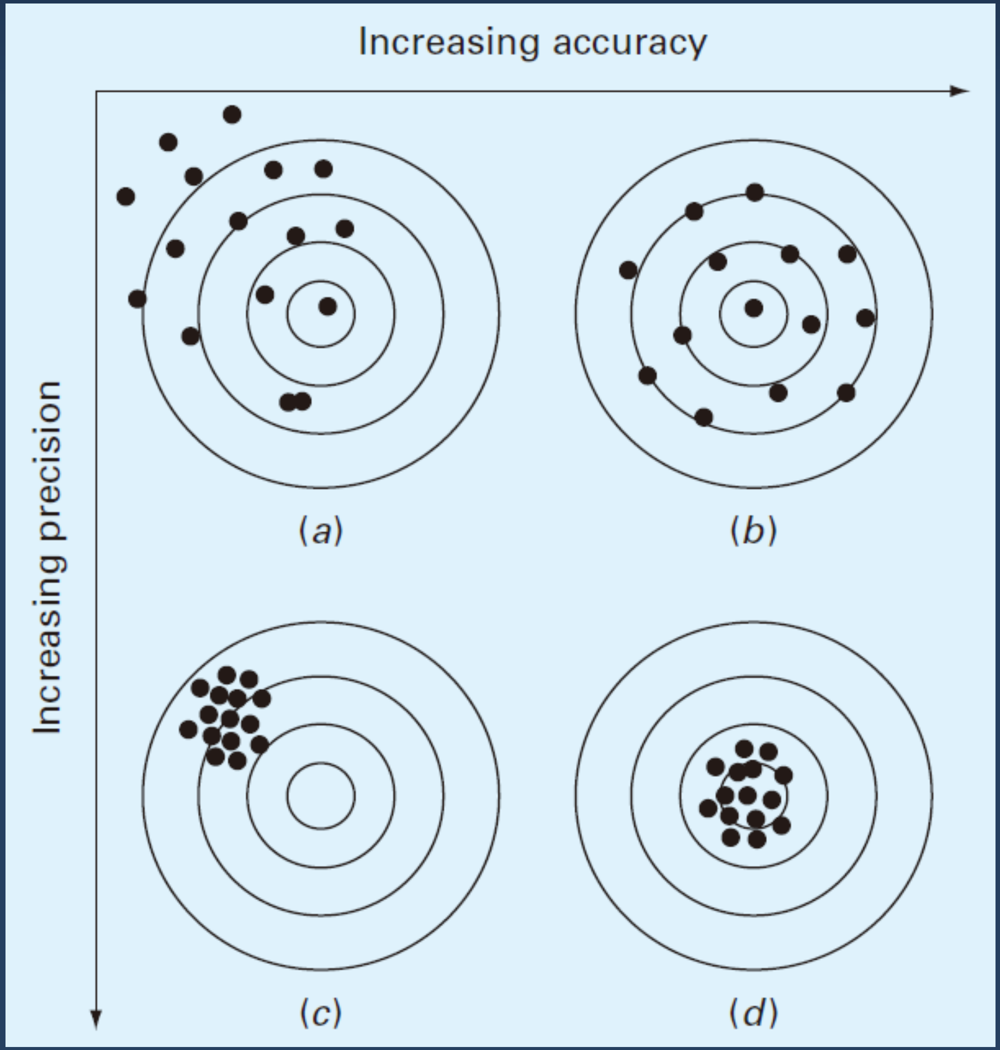
High Precision:

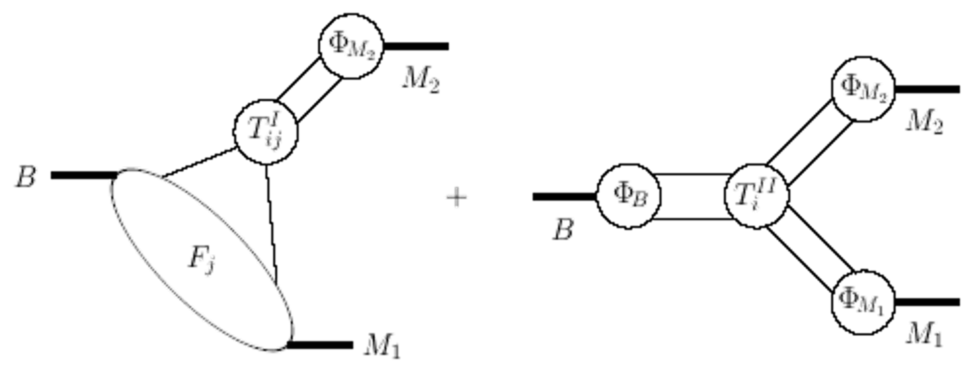
- ✓QCD corrections
- ✓Power corrections vs Factorization
- ✓Low energy Inputs
- ✓。。。

New Observables:

- ✓ Baryon CPV:
- ✓ Multi-body CPV:
- ✓ 。。。

Prospect:

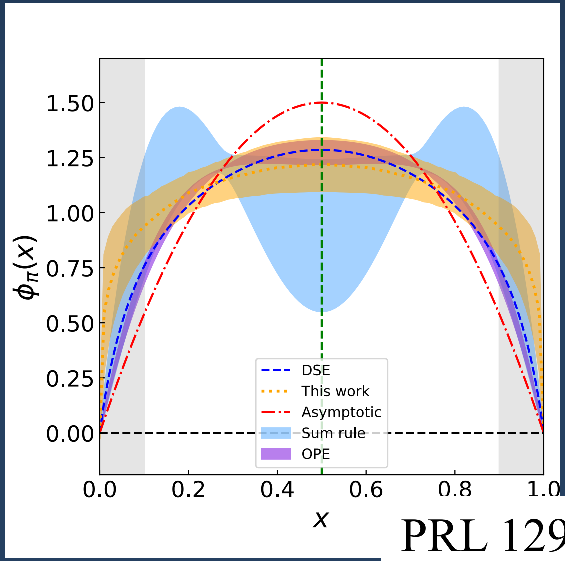


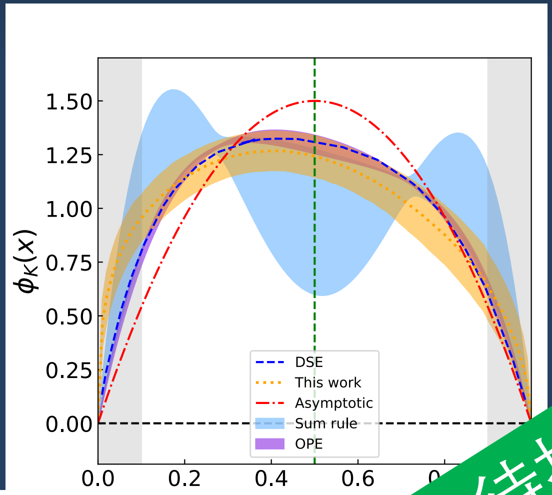


$$A(B \to \pi\pi) \propto \phi_\pi \otimes T_I \otimes F^{B\pi} + \phi_\pi \otimes T_{II} \otimes \phi_B \otimes \phi_\pi$$

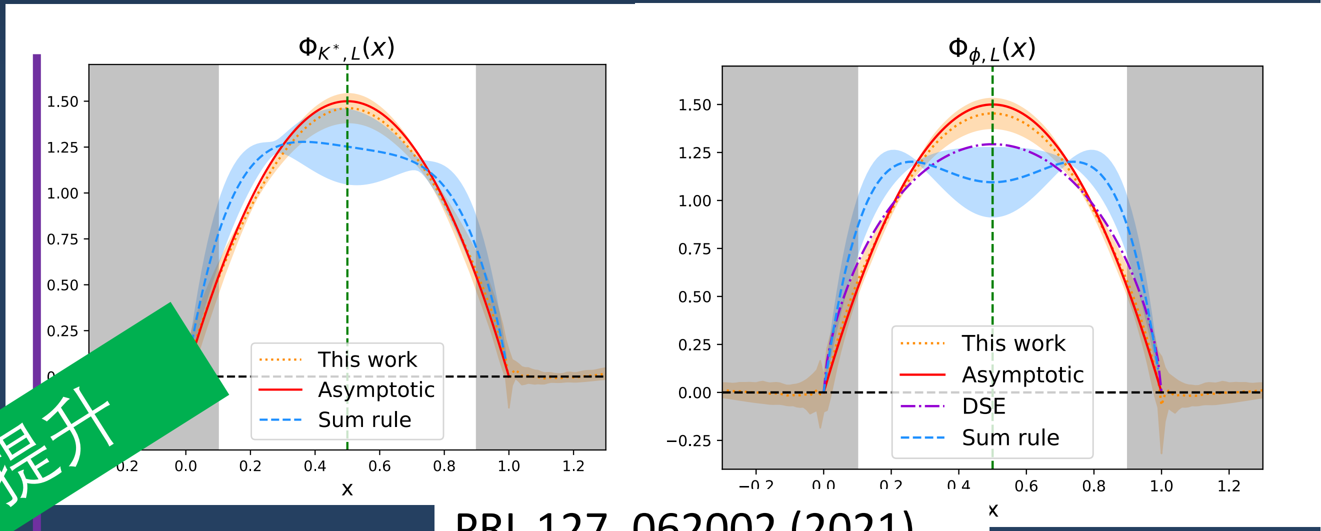
高精度 = 正确 + 精确

Prospect:



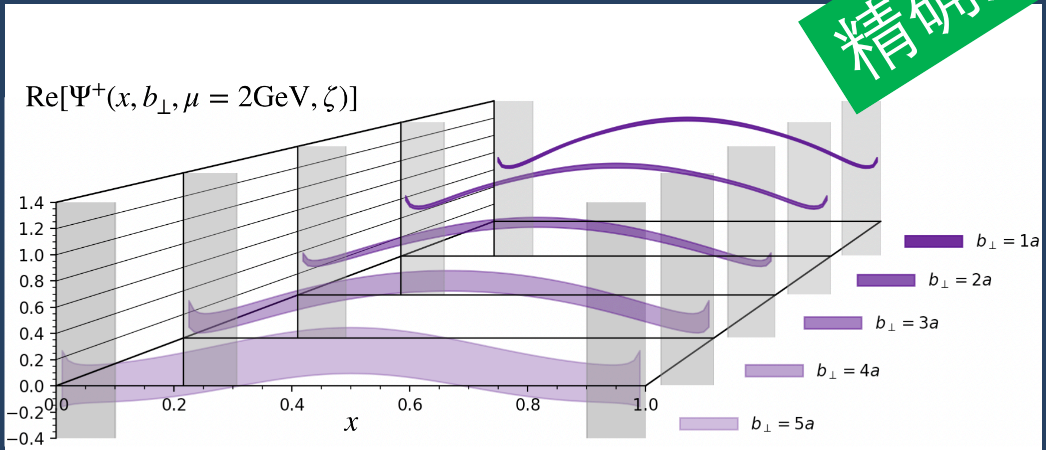


PRL 129, 132001 (2022)

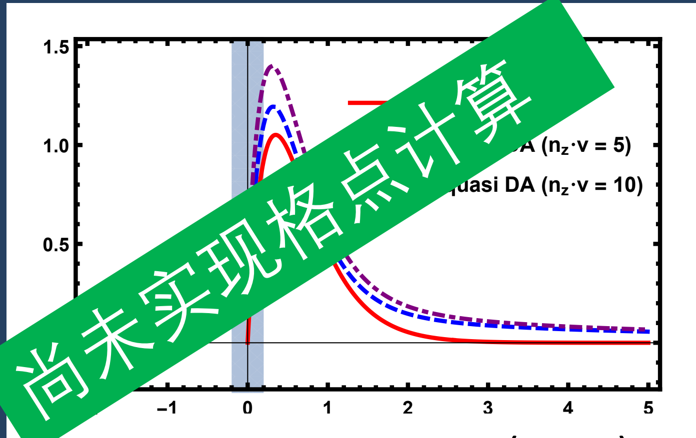


PRL 127, 062002 (2021)

精确度待提升



arXiv: 2302.09961



尚未实现格点计算

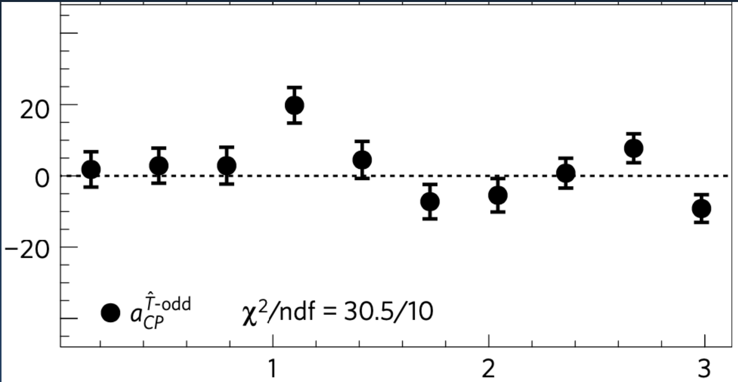
PRD 127, 062002 (2021)

Prospect: Baryon CPV

➢ LHCb实验在重味底夸克重子过程 $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$中发现了$3\sigma$的 CP 破坏迹象

➢ 我国BESIII实验上也测量到目前关于超子CP破坏最严格的上限

➢ 虽未发现重子CP破坏，但实验精度已经达到了 1% 量级



[Nature Phys 2017]

BESIII: $\Lambda \to p\pi$

$A_{CP} = (-0.6 \pm 1.4)\%$

[Nature Phys 2019]

BESIII: $\Xi \to \Lambda\pi$

$A_{CP} = (0.6 \pm 1.4)\%$

[Nature 2022]

LHCb: $\Lambda_b \to p\pi$

$A_{CP} = (-3.5 \pm 2.6)\%$

[PLB 2018]

重子CP破坏的实验研究已取得重要进展

Prospect: Baryon CPV

- 以往寻找底重子CP破坏主要通过两类观测量：
  - 通过衰变宽度定义的直接CP破坏
  - 由动量定义的三重积诱导CP破坏
- 但都未发现重子CP破坏

直接CP破坏

$$A_{CP} = \frac{\Gamma(\Lambda_b) - \Gamma(\overline{\Lambda}_b)}{\Gamma(\Lambda_b) + \Gamma(\overline{\Lambda}_b)}$$

三重积诱导CP破坏

$$C_{\hat{T}} = \vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$$

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$$

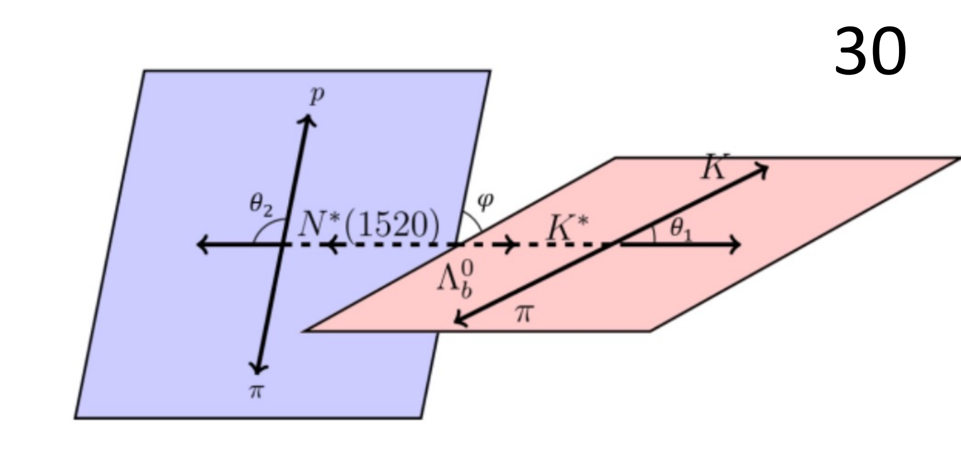
$$A_{CP} = A_{\hat{T}} - \overline{A}_{\hat{T}}$$

Prospect: Baryon CPV

① 用螺旋度振幅方法，推导底重子衰变各类过程的角分布公式，探讨角分布和分波等各类观测量

② 结合PQCD计算振幅，指出寻找重子CP破坏的黄金衰变道和最佳观测量

J.P. Wang, et.al, 2211.07332



$$\frac{d\Gamma}{dc_1\, dc_2\, d\varphi} \propto$$

直接CP破坏

三重积诱导CP破坏

$$- \frac{s_1^2 s_2^2}{\sqrt{3}} \mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right) \sin 2\varphi$$

$$+ \frac{s_1^2 s_2^2}{\sqrt{3}} \mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{-1,-\frac{1}{2}} + \mathcal{H}_{+1,+\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right) \cos 2\varphi$$

$$- \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}} \mathrm{Im}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right) \sin \varphi$$

$$+ \frac{4 s_1 c_1 s_2 c_2}{\sqrt{6}} \mathrm{Re}\left(\mathcal{H}_{+1,+\frac{3}{2}}\mathcal{H}^*_{0,+\frac{1}{2}} + \mathcal{H}_{0,-\frac{1}{2}}\mathcal{H}^*_{-1,-\frac{3}{2}}\right) \cos \varphi$$

存在更多观测量

Summary

CPV in (Heavy) Quarks has played an important role in SM

Great Progresses have been made and we are entering a precision era.

High Precision Prediction vs New Observables

Warning: Small CPV BSM vs SM Uncertainties

Thank you very much!

Backup

Unitarity constraints: the triangles