

A brief Overview on CP violation in Heavy Quark



FIND 系列学术报告

在电弱能标等尺度下寻找CP破缺现象

CP violation at electroweak scale and beyond

Sponsoring Parties for This Workshop:
State Key Laboratory of Particle Detection and Electronics, USTC
Peng Huanwu Center for Fundamental Theory (Hefei)
Center for Particle Science and Technology, USTC
Interdisciplinary Center for Theoretical Study, USTC

Sponsoring Parties for FIND:
Center for Particle Science and Technology, USTC
Research Center of Science Communication, Chinese Academy of Sciences

Introduction:
This is a mini-workshop organized to bring together experimentalists and theorists to promote frontier research on searching for CP violation (CPV) phenomena at electroweak scale and beyond. CPV is a compelling reasoning behind the observed matter-anti-matter asymmetry in the Universe. This workshop will review current CPV studies at different energy scales (EDM/nDM, charm, bottom, electroweak), and discuss the idea of a systematic, direct investigation of CPV at and beyond electroweak scale, in view of the unique, increasing precision data offered by Large Hadron Collider for electroweak physics.

This event is hosted under the workshop series of FIND (Forum for Interdisciplinary Investigations into New Directions at extreme scales), which aims to promote interdisciplinary exchanges on frontiers of scientific research as well as science outreach and communications.

Timetable:
<https://indico.pnp.ustc.edu.cn/event/32/>
August 25 (Arrival Date)
August 26 – August 27 (Scientific Program)
August 28 (Departure Date)

Reminder:
Please register to this event in INDICO if you wish to join either in person or remotely.

Dates:
Aug. 26th – 27th

Remote connection:
ZOOM and Koushare

Scientific Secretaries:
donggongxiu@ustc.edu.cn zhnan@ustc.edu.cn xfchu@ustc.edu.cn

Organization committee:
Yingying Li (USTC, co-chair) Kun Liu (TDLI, co-chair) Nan Lu (USTC) Yusheng Wu (USTC) Lailin Xu (USTC) Hongtao Yang (USTC, co-chair)

Location: ROOM A608, Material Science Building, University of Science and Technology of China

Wei Wang
Shanghai Jiaotong University

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 as⁴

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

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 $K^+ \rightarrow \mu^+ + \nu$ and $\pi^+ \rightarrow \mu^+ + \nu$; we find

$$\begin{aligned} & \Gamma(K^+ \rightarrow \mu\nu) / \Gamma(\pi^+ \rightarrow \mu\nu) \\ &= \tan^2\theta M_K (1 - M_\mu^2/M_K^2)^2 / M_\pi (1 - M_\mu^2/M_\pi^2)^2. \quad (3) \end{aligned}$$

From the experimental data, we then get^{5,6}

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

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

N. Cabibbo 1963

(Cabibbo angle)

W - coupling :

$$u \longleftrightarrow c/\cos\theta_c + s/\sin\theta_c$$

$$\theta_c: \sim 13,04^\circ \quad \begin{array}{cc} \downarrow & \downarrow \\ 0.974 & 0.226 \end{array}$$

Cabibbo
1963

Cabibbo, PRL 10, 531(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 $R = (K_2^0 \rightarrow \pi^+ + \pi^-) / (K_2^0 \rightarrow \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ 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: $K^0 = d\bar{s}, \bar{K}^0 = s\bar{d},$

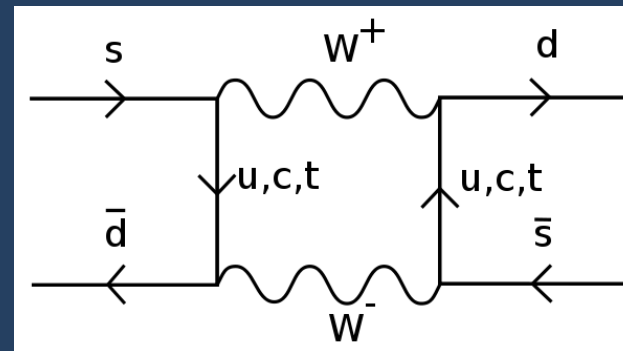
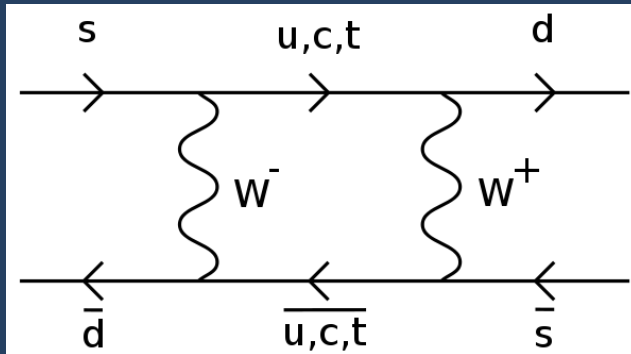
Weak eigenstates:

CP eigenstates: $K_1 = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0)$

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

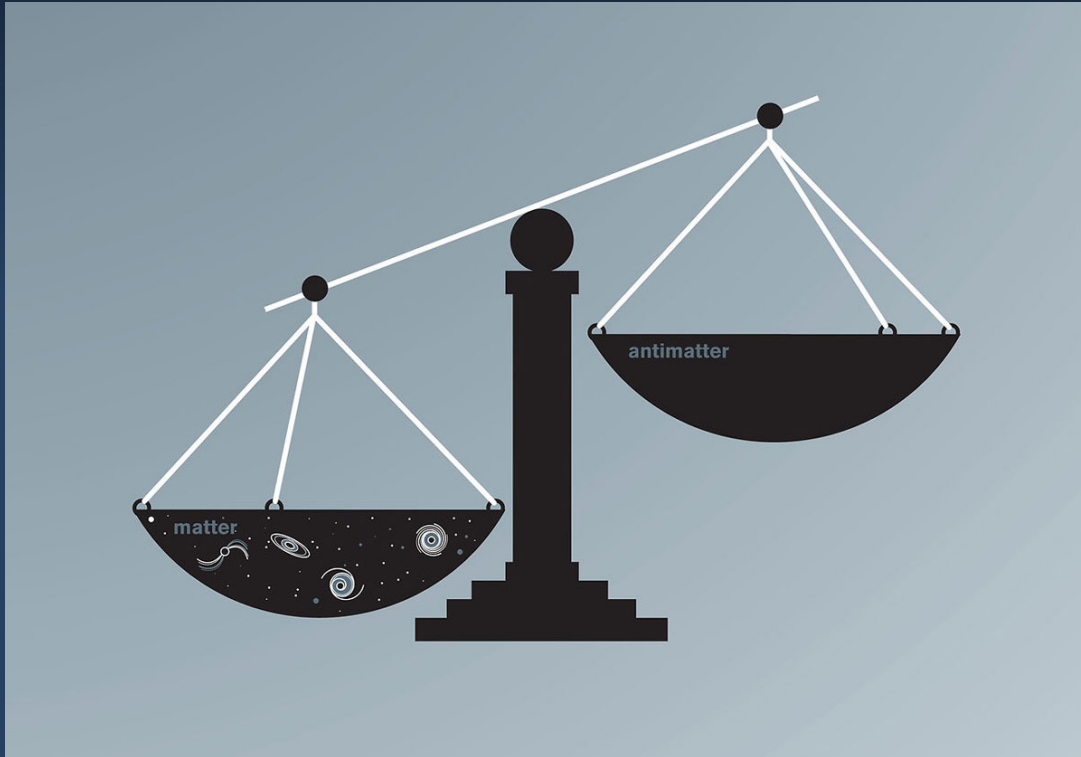
$$K_2 = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0)$$

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



Mixing CPV

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



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 высокой температуре
для Вселенной сшита шуба
но 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.

Cabibbo

1963

Sakharov

1967

K CPV

1967

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

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

Cabibbo
1963

Sakharov
1967

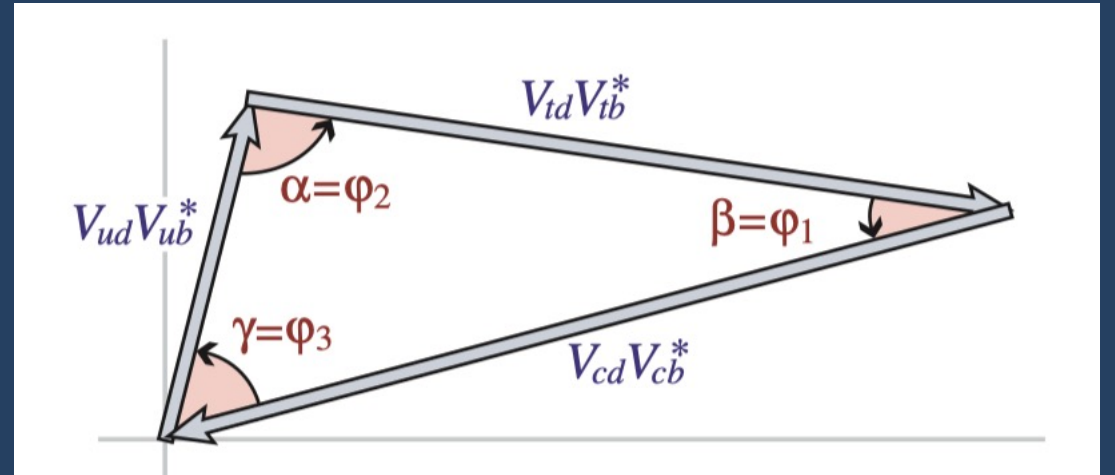
K CPV
1967

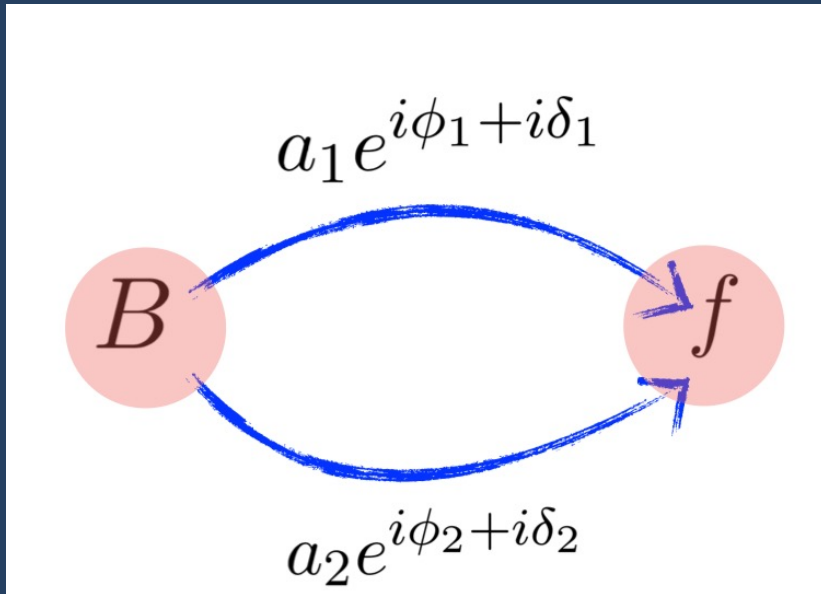
KM
1973

Theoretical foundations

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

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





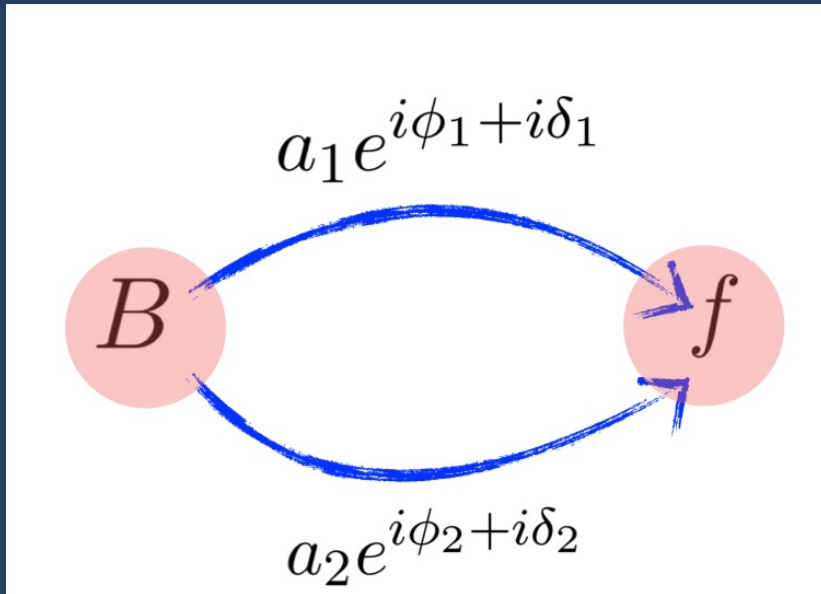
$$A_f \equiv \frac{\Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)}{\Gamma(\bar{B} \rightarrow \bar{f}) + \Gamma(B \rightarrow f)} = \frac{1 - |A_f/\bar{A}_f|^2}{1 + |A_f/\bar{A}_f|^2},$$

$$A_f = a_1 e^{i\phi_1 + i\delta_1} + a_2 e^{i\phi_2 + i\delta_2},$$

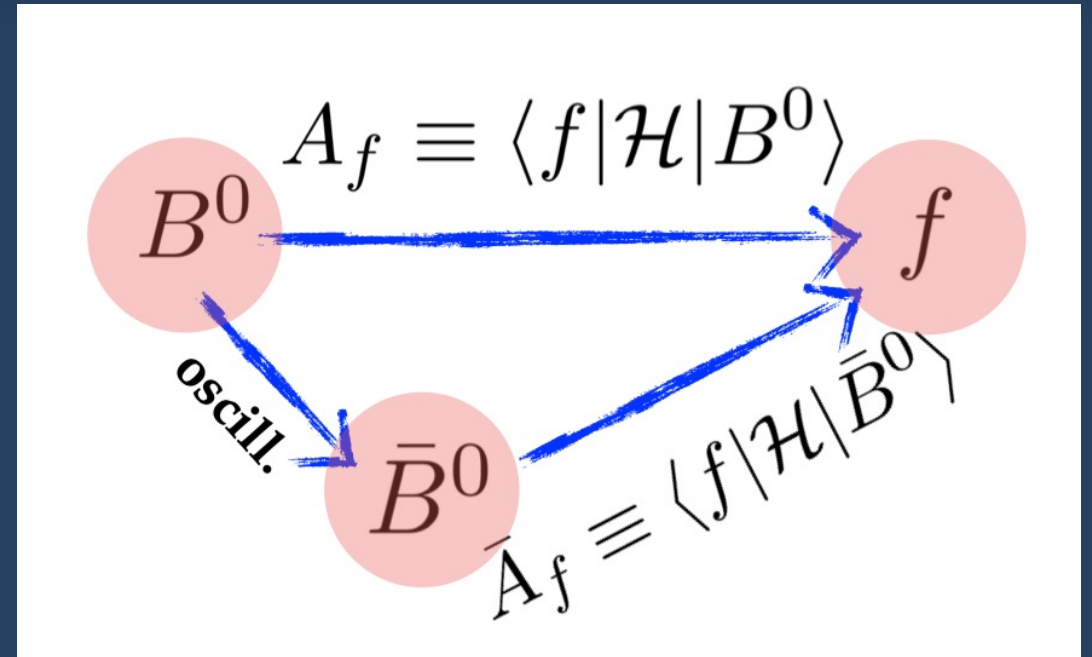
$$\bar{A}_f = a_1 e^{-i\phi_1 + i\delta_1} + a_2 e^{-i\phi_2 + i\delta_2}.$$

Direct CPV

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



Direct CPV



CPV in interference between decays with and without mixing

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

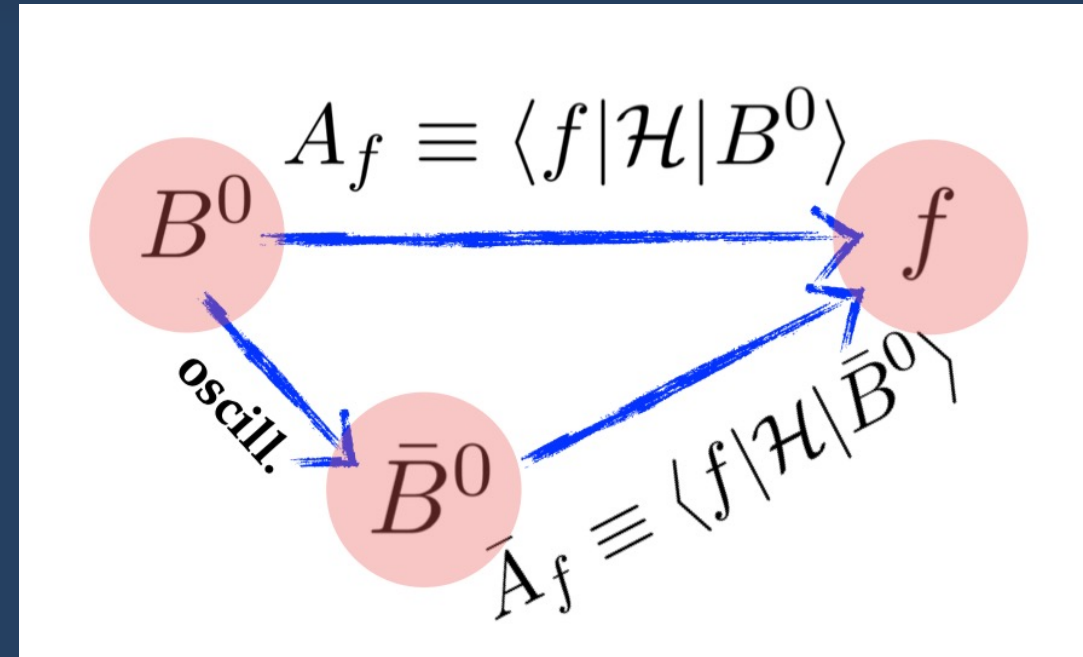
$$i\frac{d}{dt} \begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \mathcal{H} \begin{pmatrix} |B^0(t)\rangle \\ |\bar{B}^0(t)\rangle \end{pmatrix} = \begin{pmatrix} M_{11} + i\Gamma_{11} & M_{12} + i\Gamma_{12} \\ M_{21} + i\Gamma_{21} & M_{22} + i\Gamma_{22} \end{pmatrix} \cdot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

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

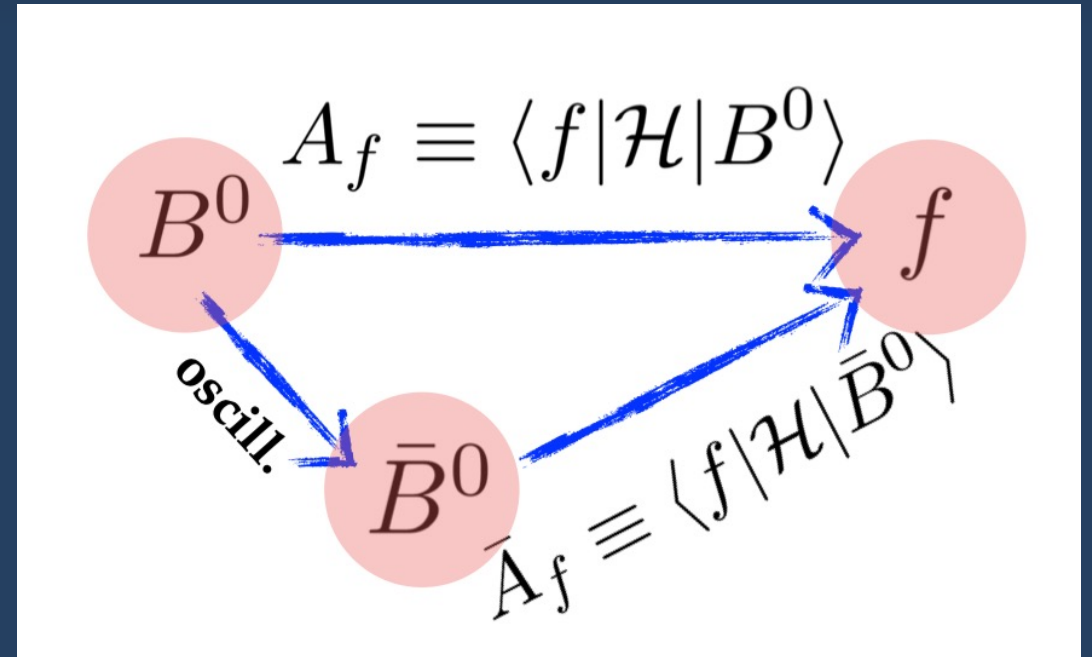
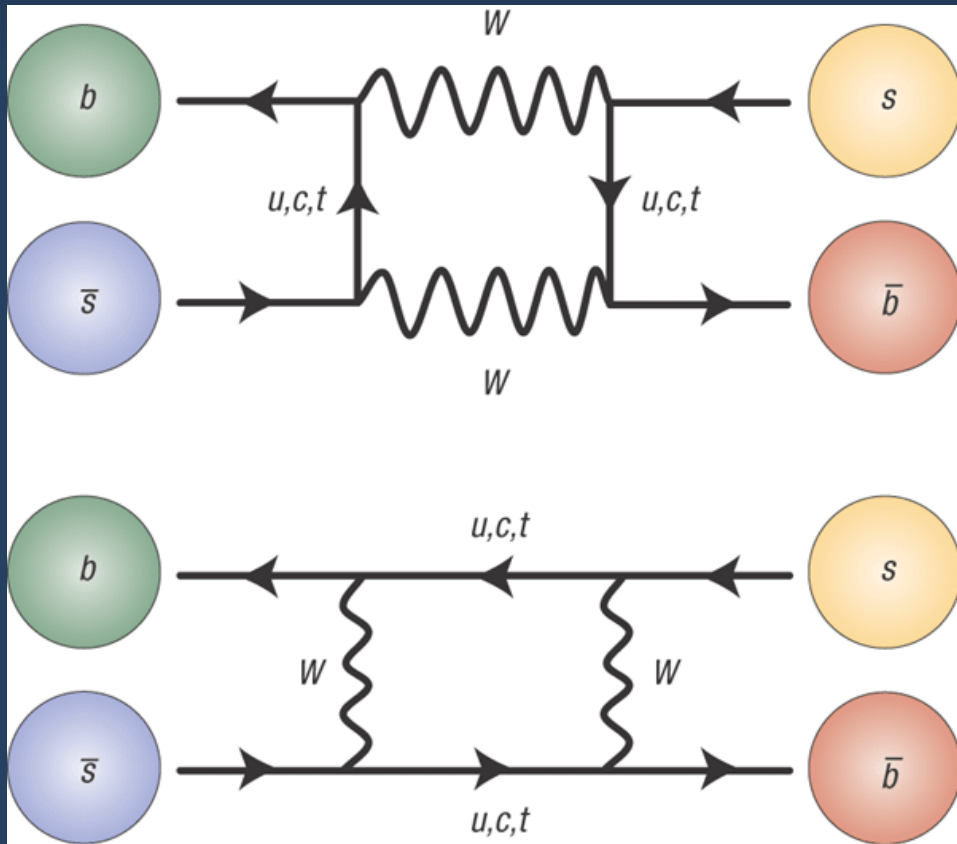
$$\mathcal{A}_{f_{CP}}(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

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

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



CPV in interference between decays with and without mixing



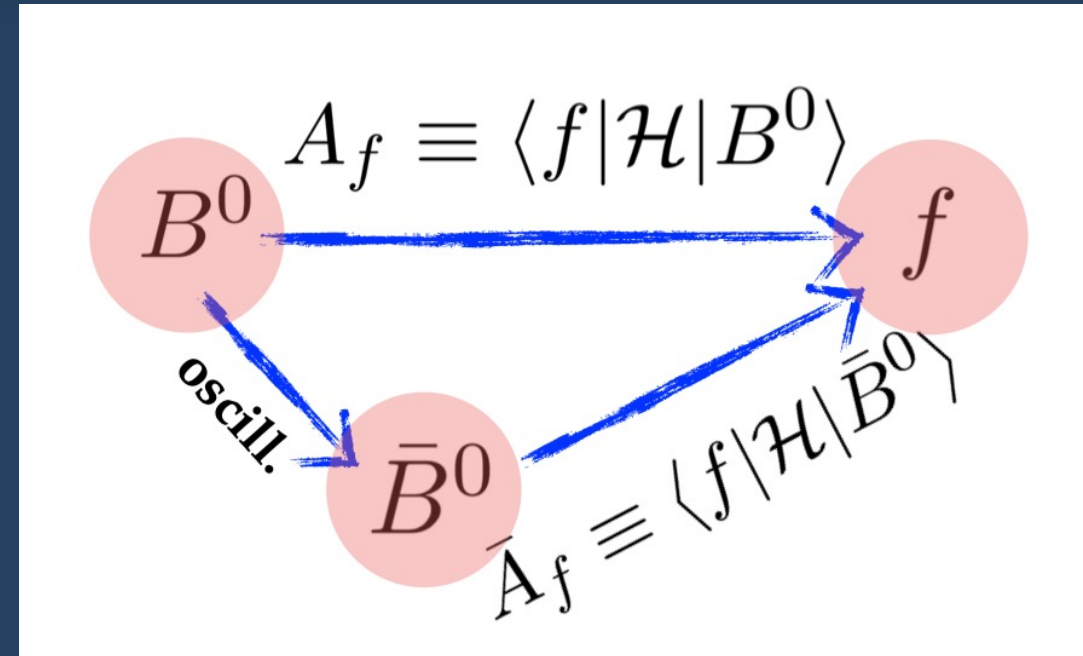
CPV in interference between decays with and without mixing

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

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

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

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



CPV in interference between decays with and without mixing

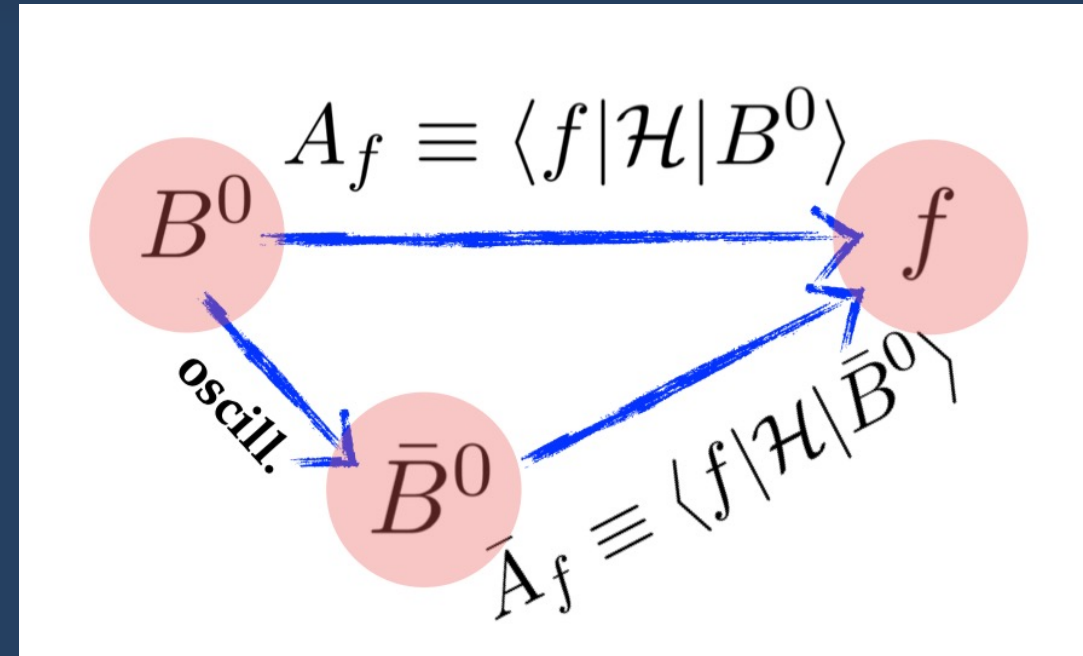
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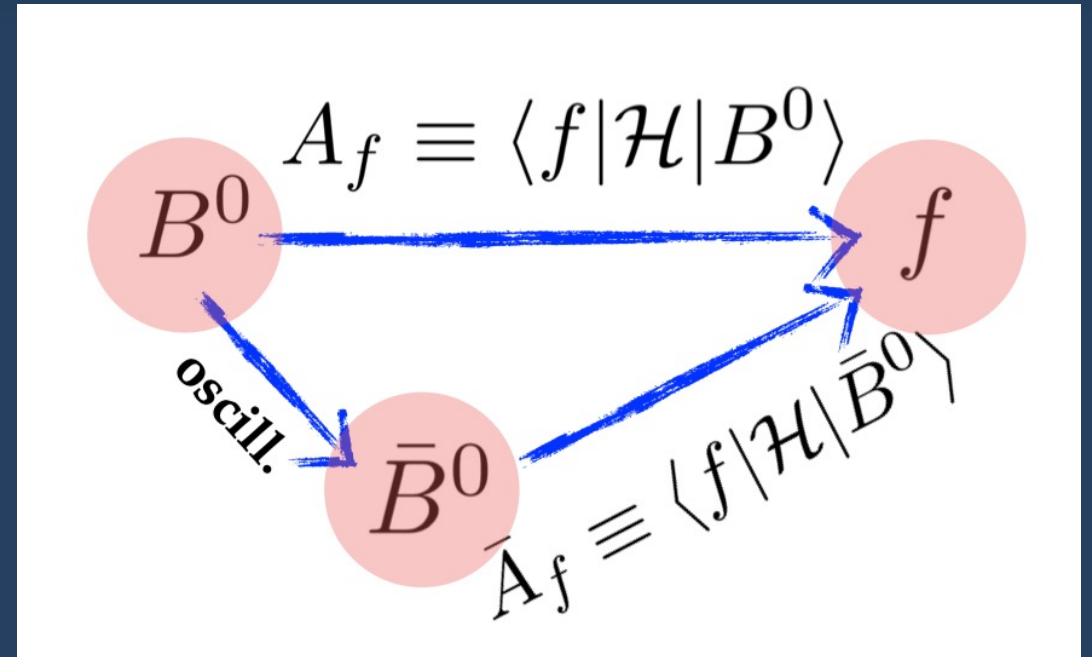
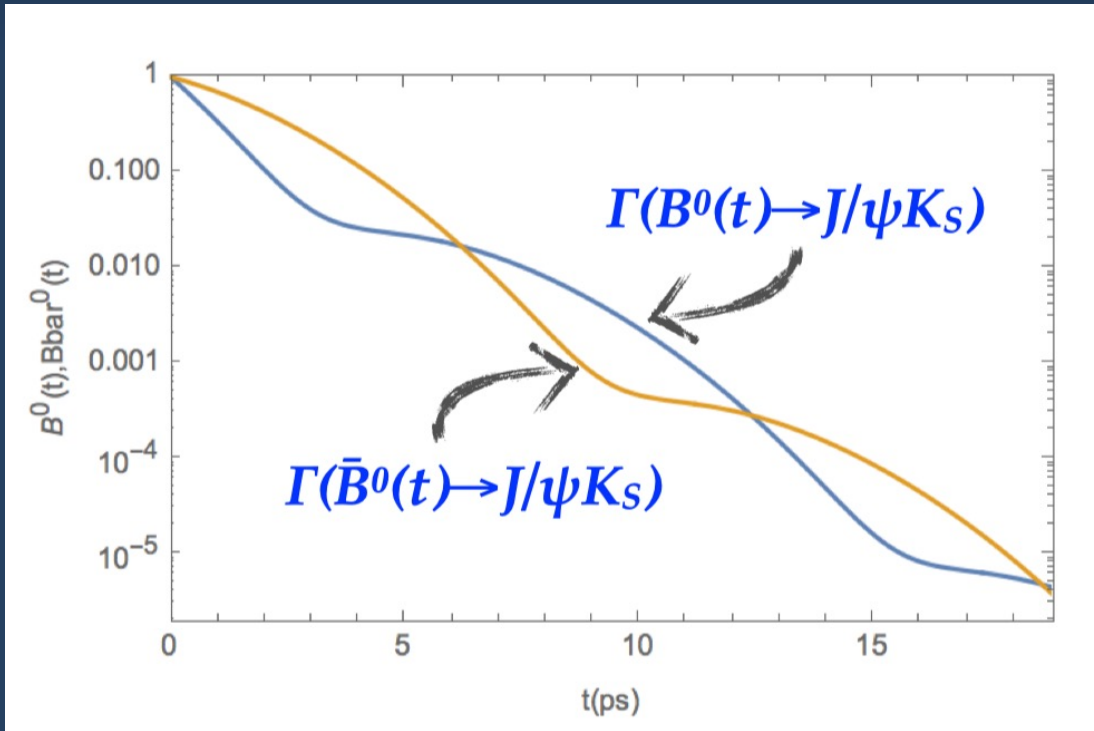
$$\frac{\bar{A}_{J/\psi K_S}}{A_{J/\psi K_S}} = \eta_f \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} + \dots$$

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

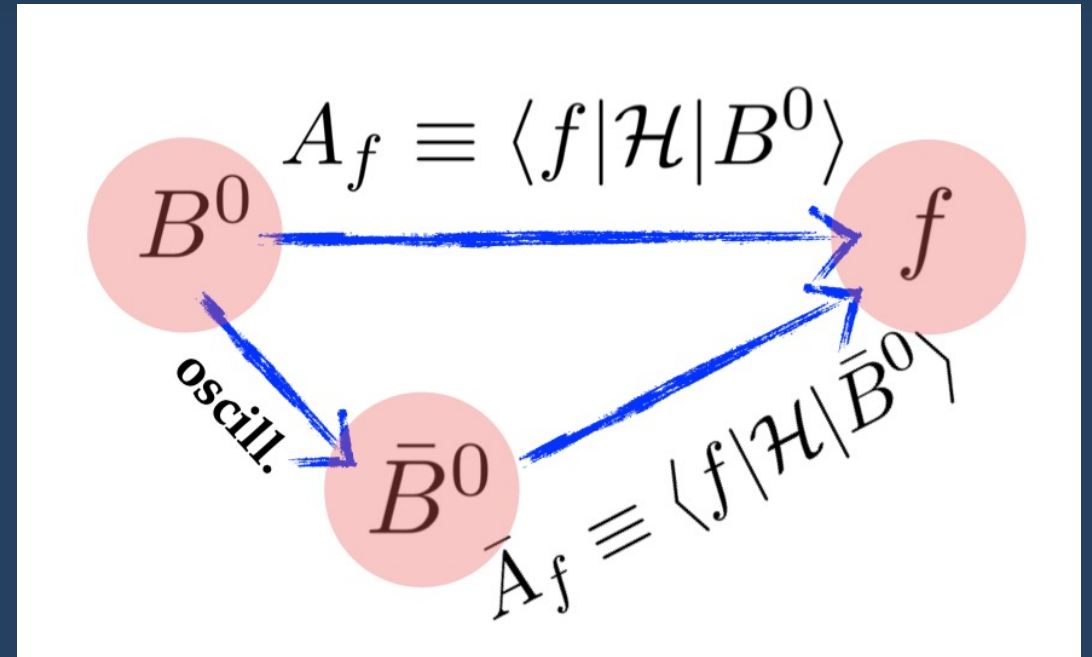
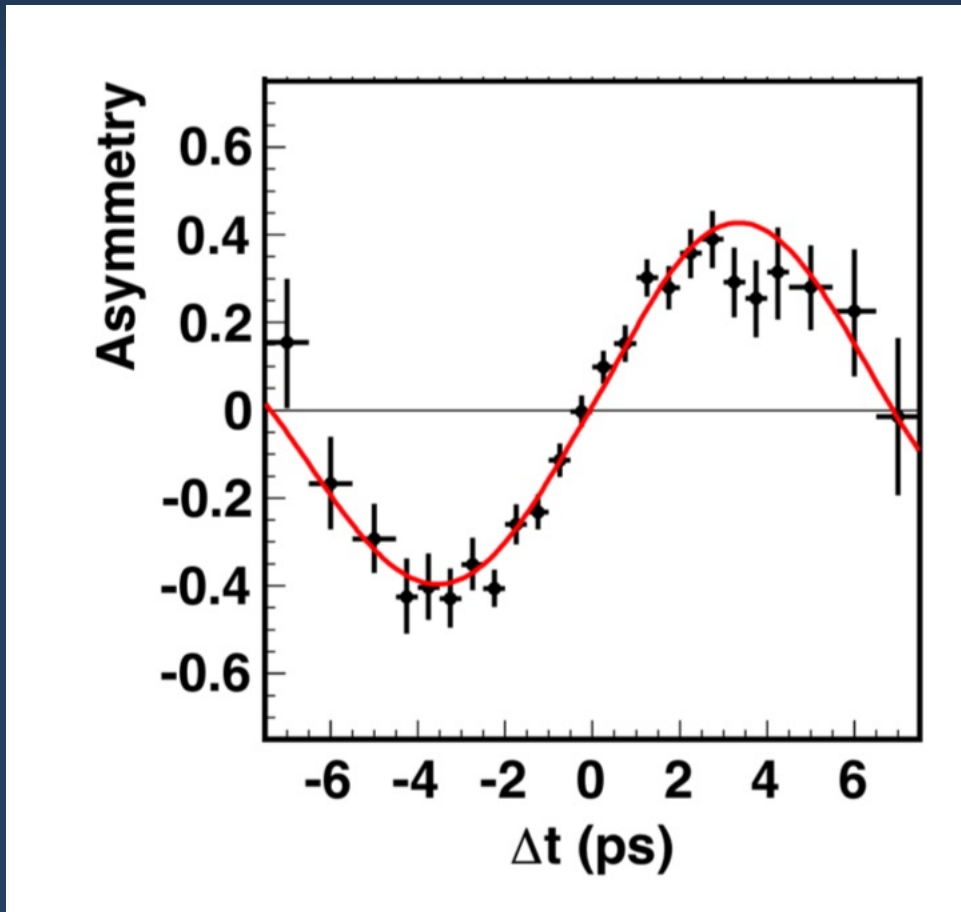
$$\operatorname{Im} \lambda_{J/\psi K_S} = \sin 2\beta$$



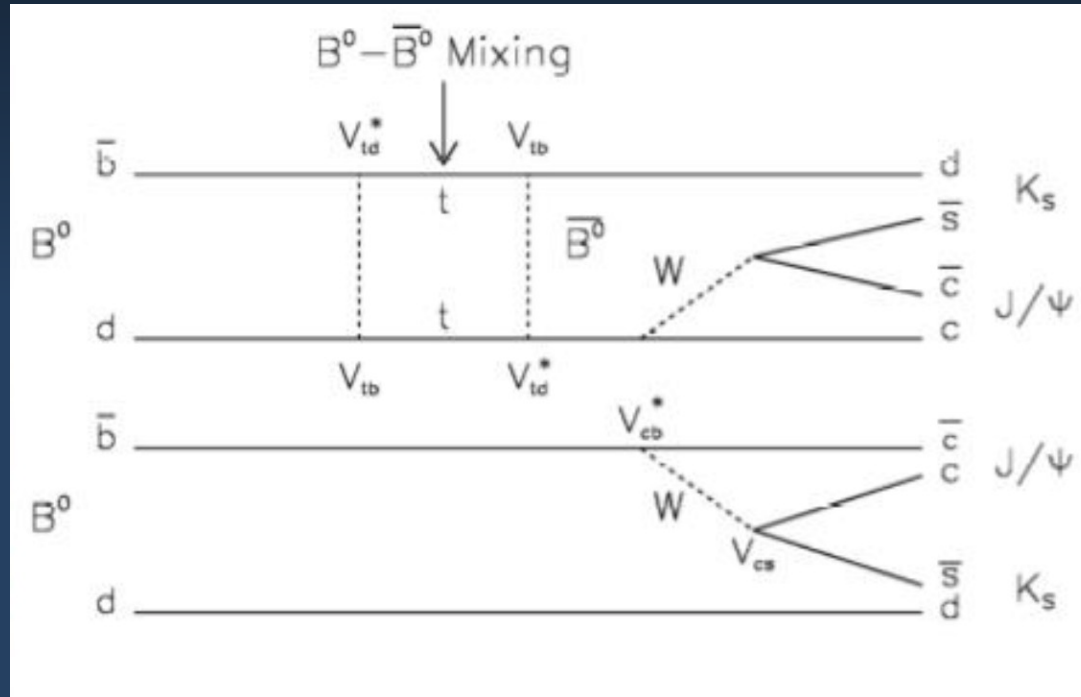
CPV in interference between decays with and without mixing



CPV in interference between decays with and without mixing



CPV in interference between decays with and without mixing



I. Bigi, A. Sanda

$$\mathcal{A}_{fCP}(t) = S_f \sin(\Delta mt) - C_f \cos(\Delta mt)$$

Cabibbo
1963

Sakharov
1967

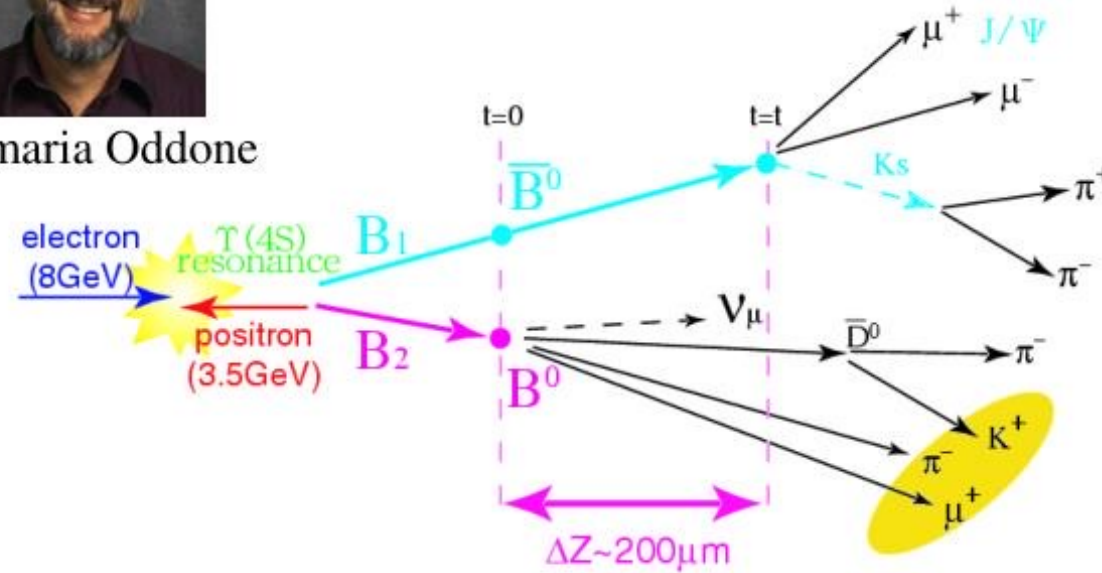
$B \rightarrow J/\psi K$
1981

K CPV
1967

KM
1973



Piermaria Oddone



11/18/2004
Paoti Chang

8

Cabibbo
1963

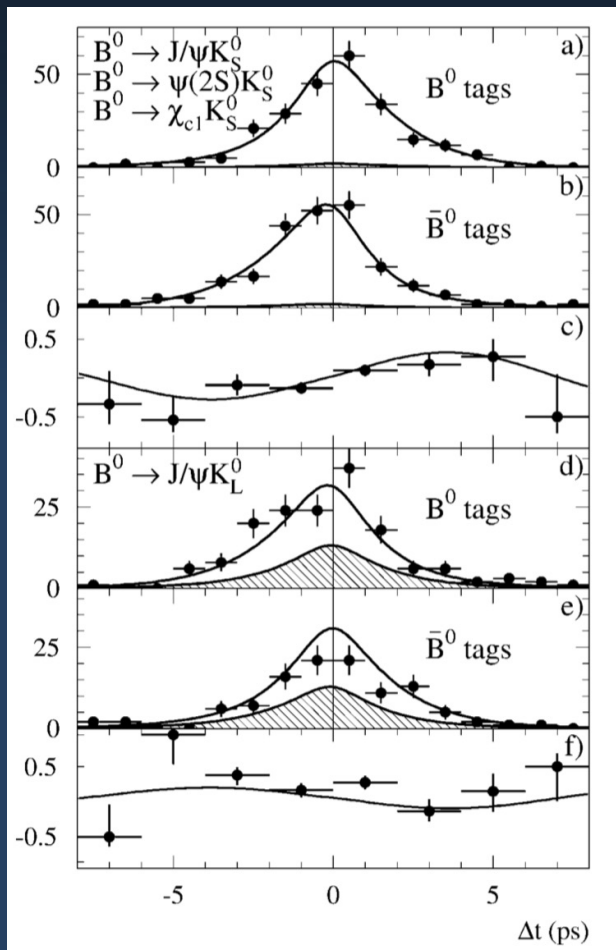
Sakharov
1967

$B \rightarrow J/\Psi K$
1981

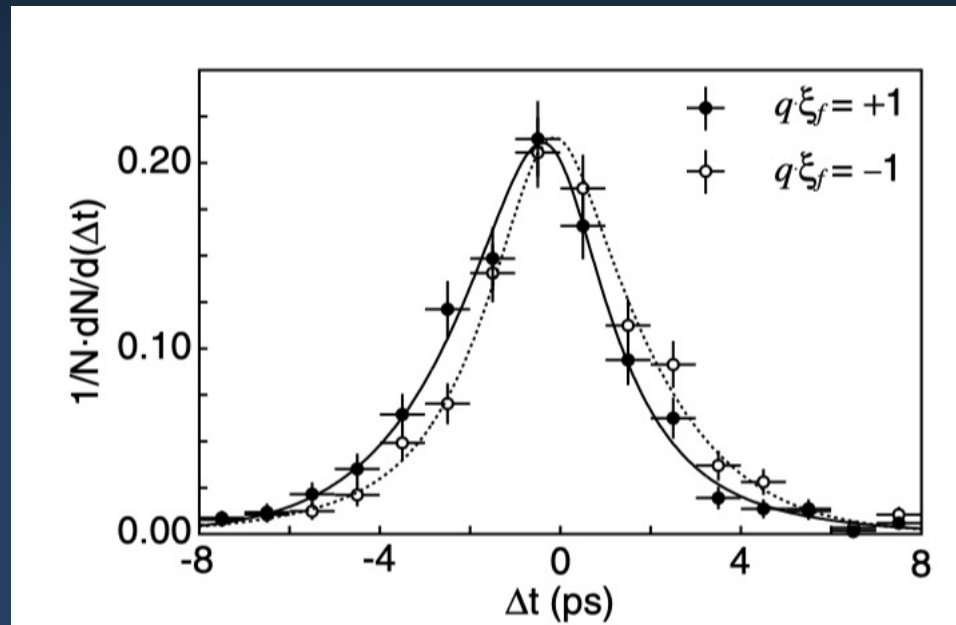
K CPV
1967

KM
1973

Asymmetric
1987



Babar, PRL.87.091801(2001)



Belle, PRL.87.091802(2001)

Cabibbo
1963

Sakharov
1967

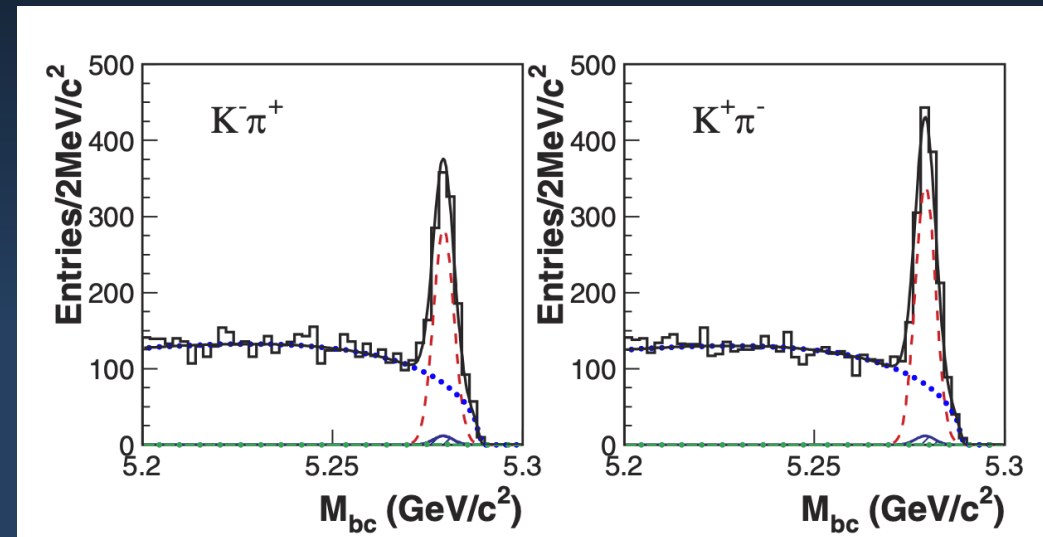
$B \rightarrow J/\Psi K$
1981

B CPV(Large)
2001

K CPV
1967

KM
1973

Asymmetric
1987



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	$-0.101 \pm 0.025 \pm 0.005$	-0.001 ± 0.005
$K^\mp \pi^0$	728 ± 34	$0.04 \pm 0.05 \pm 0.02$	-0.02 ± 0.01
$\pi^\mp \pi^0$	315 ± 29	$-0.02 \pm 0.10 \pm 0.01$	-0.01 ± 0.01

Belle, PRL93.191802(2004)

Cabibbo
1963

Sakharov
1967

$B \rightarrow J/\psi K$
1981

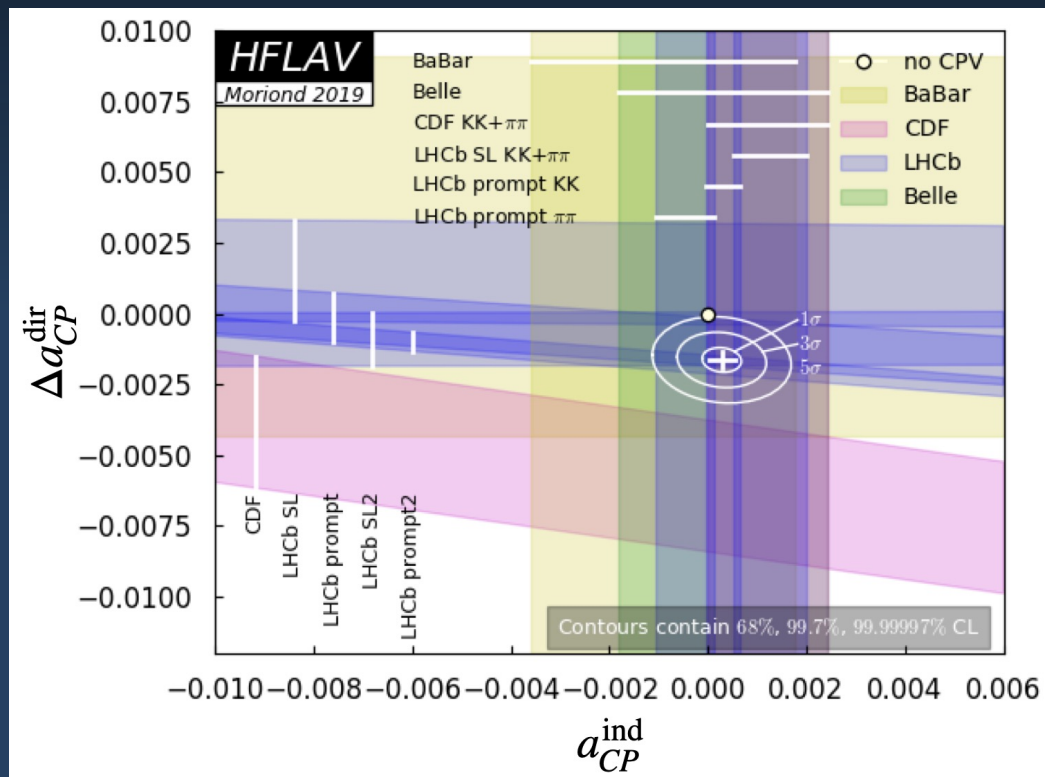
B CPV(Large)
2001

K CPV
1967

KM
1973

Asymmetric
1987

Large Dir CPV
2004



Cabibbo
1963

Sakharov
1967

$B \rightarrow J/\Psi K$
1981

B CPV(Large)
2001

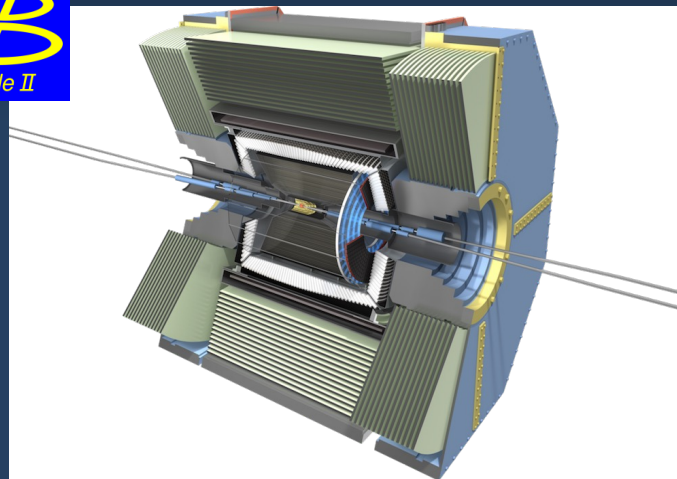
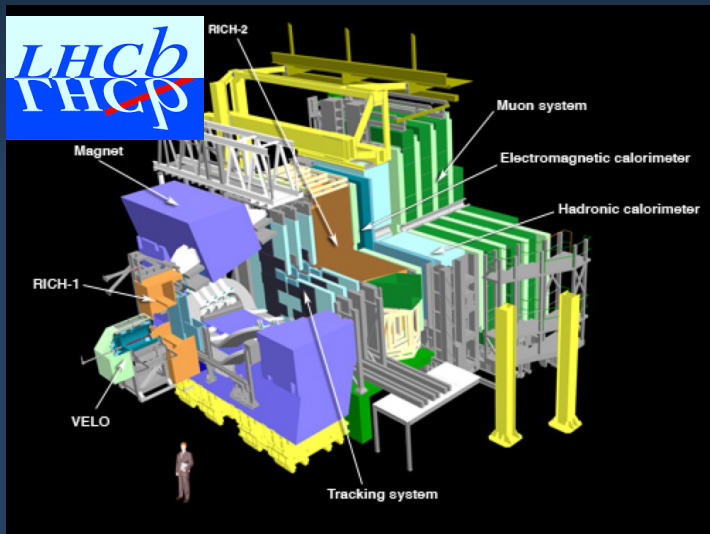
Charm Dir CPV
2019

K CPV
1967

KM
1973

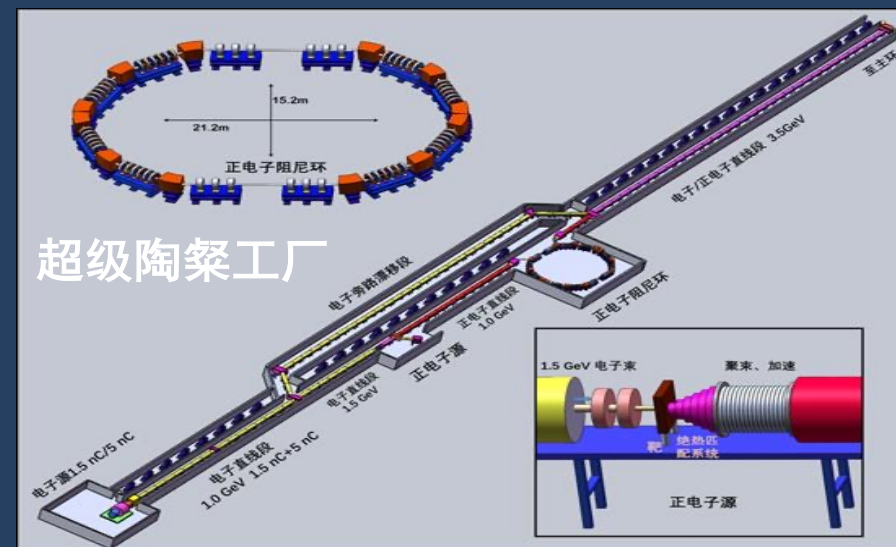
Asymmetric
1987

Large Dir CPV
2004



高精度的实验数据对理论计算精度
提出了相应的需求

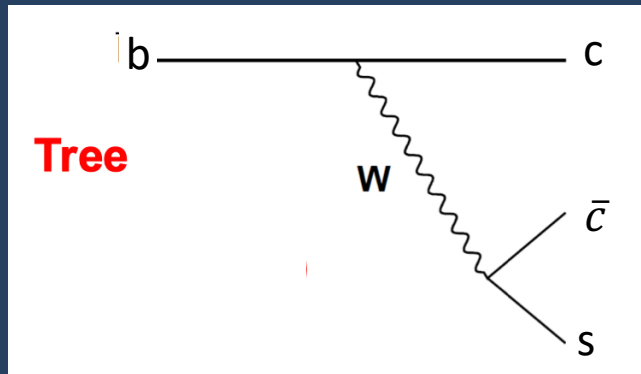
See Wen-bin, Pei-Lian, and Xiaodong's talks.



Challenges

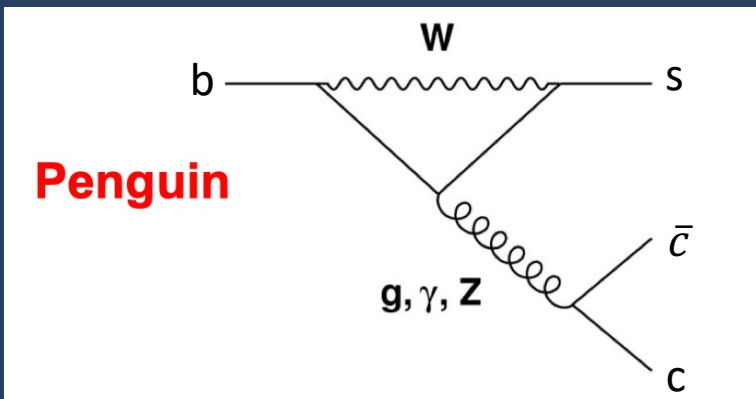
$$\sin(2\beta) = 0.699 \pm 0.017$$
$$\beta = (22.2 \pm 0.7)^\circ$$

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



Tree Amplitudes:

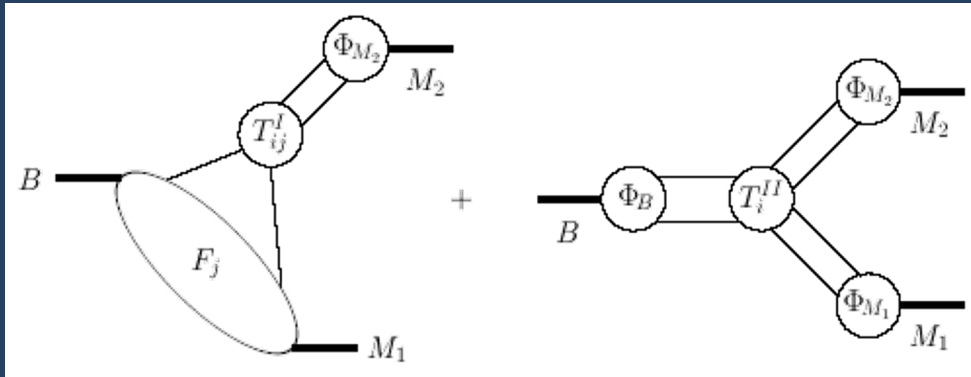
$$V_{cb}V_{cs} \sim 40 \times 10^{-3}$$
$$a_2 \sim 0.1 - 1$$



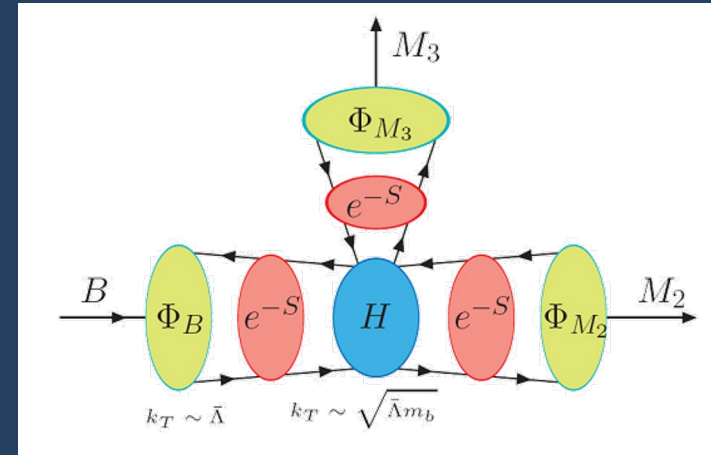
Penguin Amplitudes:

$$V_{ub}V_{us} \sim 0.8 \times 10^{-3}$$
$$a_4 \sim 0.04$$

Challenges



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



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

A incomplete list of recent theoretical progress:

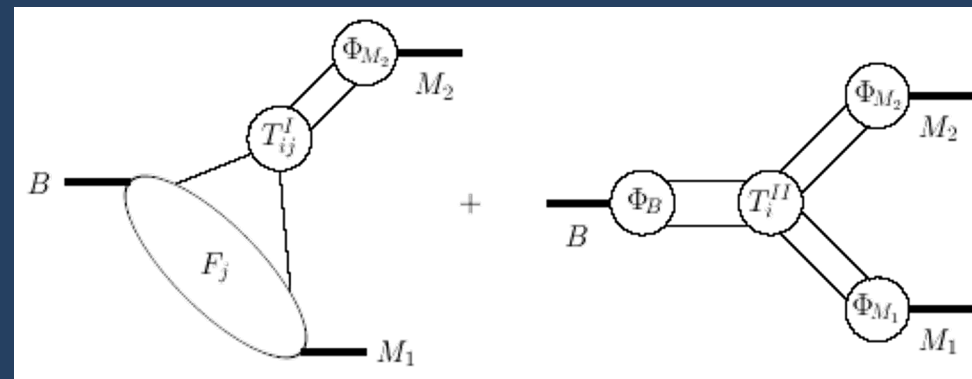
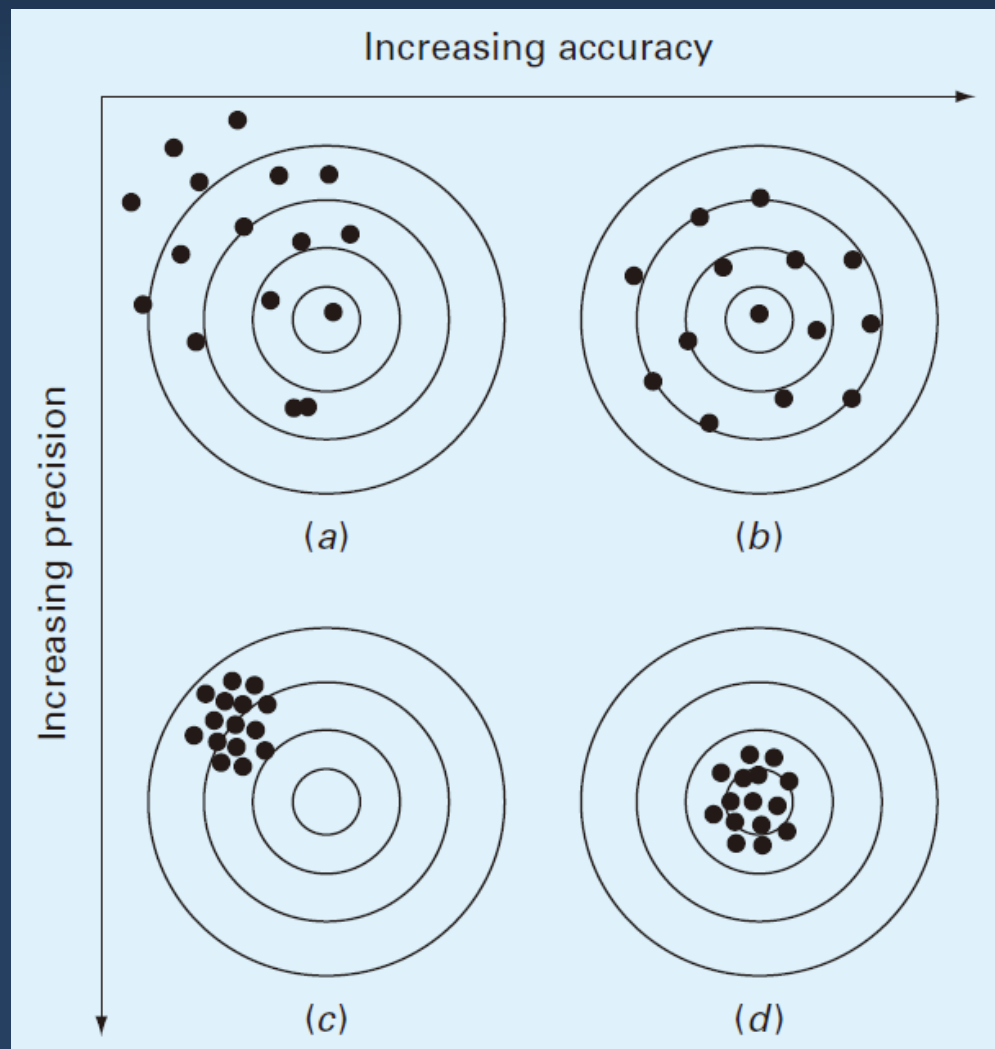
High Precision:

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

New Observables:

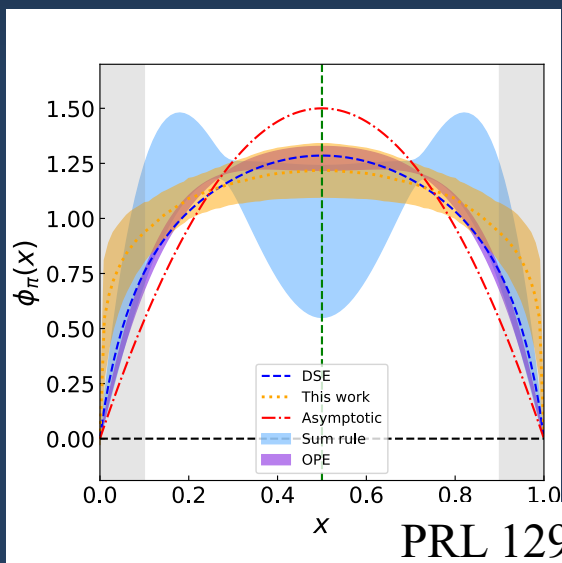
- ✓ Baryon CPV:
- ✓ Multi-body CPV:
- ✓ ○ ○ ○

Prospect:

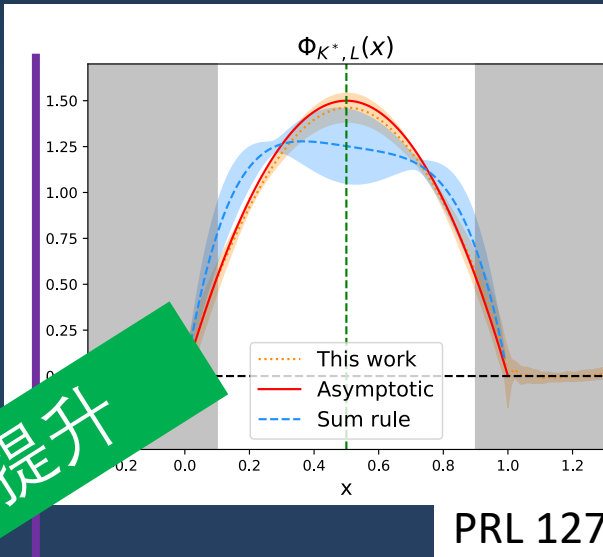
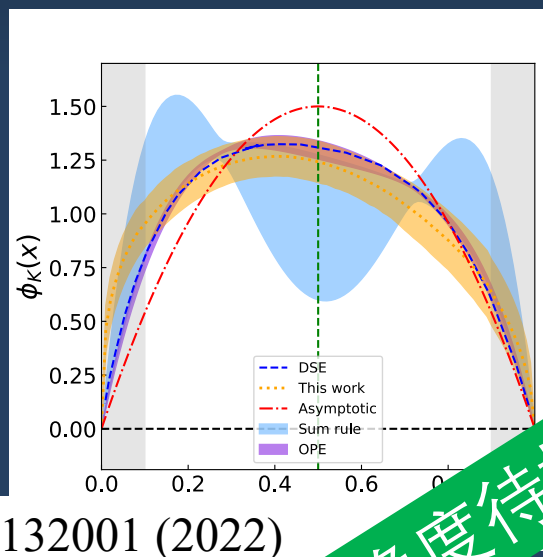


$$A(B \rightarrow \pi\pi) \propto \phi_\pi \otimes T_I \otimes F^{B\pi} + \phi_\pi \otimes T_{II} \otimes \phi_B \otimes \phi_\pi$$

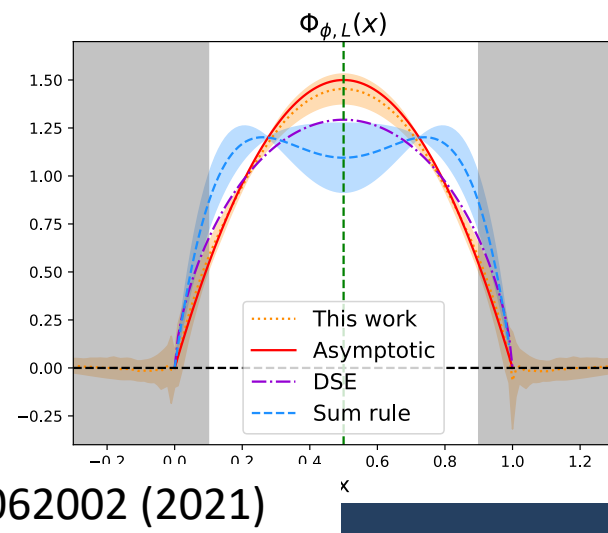
高精度 = 正确 + 精确



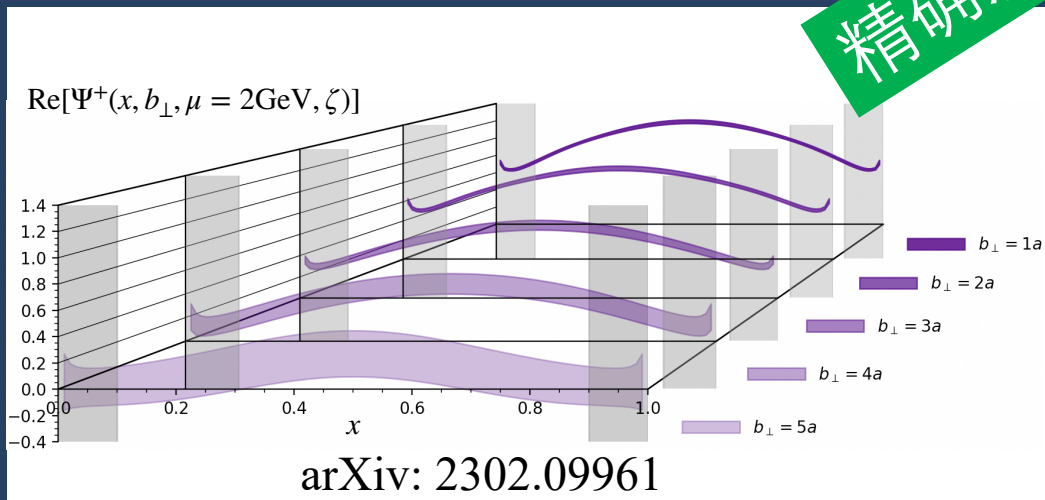
PRL 129, 132001 (2022)



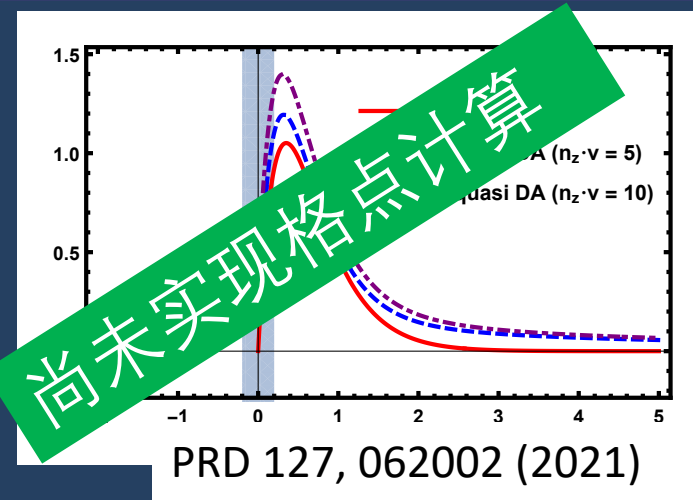
PRL 127, 062002 (2021)



精确度待提升



arXiv: 2302.09961



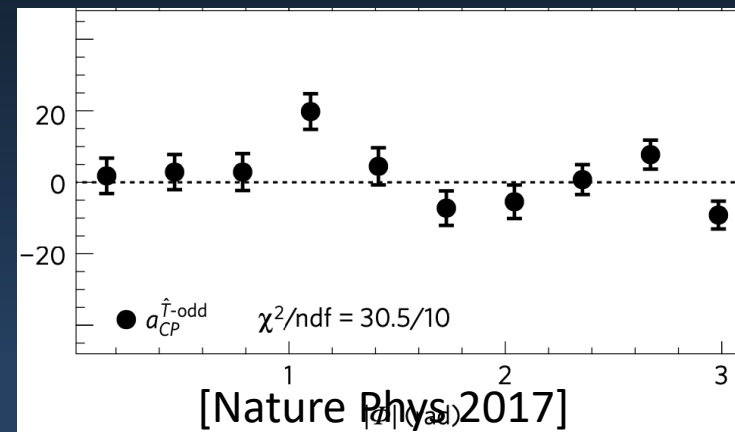
尚未实现格点计算

PRD 127, 062002 (2021)

Prospect: Baryon CPV

- LHCb实验在重味底夸克重子过程 $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ 中发现了 3σ 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

重子CP破坏的实验研究已取得重要进展



BESIII: $\Lambda \rightarrow p\pi$
 $A_{CP} = (-0.6 \pm 1.4)\%$
[Nature Phys 2019]

BESIII: $\Xi \rightarrow \Lambda\pi$
 $A_{CP} = (0.6 \pm 1.4)\%$
[Nature 2022]

LHCb: $\Lambda_b \rightarrow p\pi$
 $A_{CP} = (-3.5 \pm 2.6)\%$
[PLB 2018]

➤ 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

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

三重积诱导CP破坏

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

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

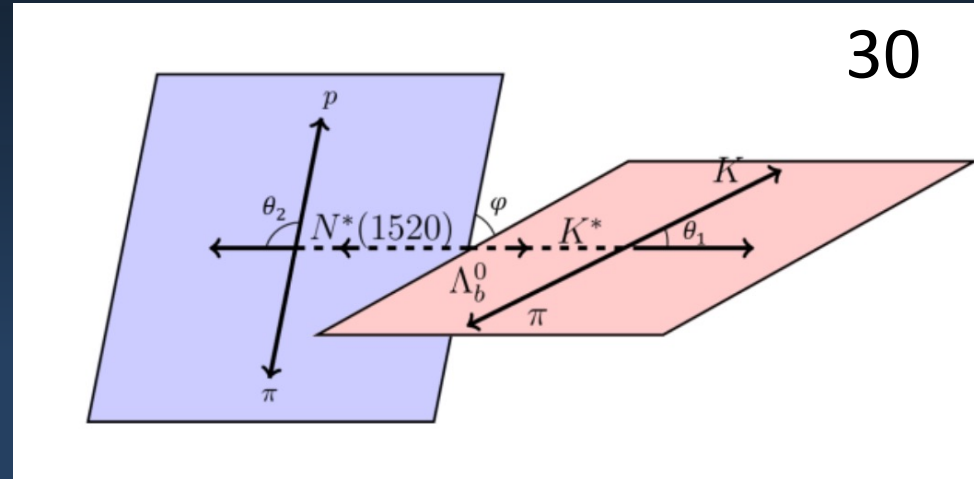
$$A_{CP} = A_{\hat{T}} - \bar{A}_{\hat{T}}$$

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

$$\begin{aligned}
 & - \frac{s_1^2 s_2^2}{\sqrt{3}} \text{Im} \left(\mathcal{H}_{+1,+\frac{3}{2}} \mathcal{H}_{-1,-\frac{1}{2}}^* + \mathcal{H}_{+1,+\frac{1}{2}} \mathcal{H}_{-1,-\frac{3}{2}}^* \right) \sin 2\varphi \\
 & + \frac{s_1^2 s_2^2}{\sqrt{3}} \text{Re} \left(\mathcal{H}_{+1,+\frac{3}{2}} \mathcal{H}_{-1,-\frac{1}{2}}^* + \mathcal{H}_{+1,+\frac{1}{2}} \mathcal{H}_{-1,-\frac{3}{2}}^* \right) \cos 2\varphi \\
 & - \frac{4s_1 c_1 s_2 c_2}{\sqrt{6}} \text{Im} \left(\mathcal{H}_{+1,+\frac{3}{2}} \mathcal{H}_{0,+\frac{1}{2}}^* + \mathcal{H}_{0,-\frac{1}{2}} \mathcal{H}_{-1,-\frac{3}{2}}^* \right) \sin \varphi \\
 & + \frac{4s_1 c_1 s_2 c_2}{\sqrt{6}} \text{Re} \left(\mathcal{H}_{+1,+\frac{3}{2}} \mathcal{H}_{0,+\frac{1}{2}}^* + \mathcal{H}_{0,-\frac{1}{2}} \mathcal{H}_{-1,-\frac{3}{2}}^* \right) \cos \varphi
 \end{aligned}$$

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

