CP Violation in the SM and Beyond

Manuel Wittner, Martin Klassen, Falk Bartels

Motivation and Theoretical Background

C, P & T symmetries   The CKM Formalism   Parameterization of the CKM matrix

Motivation and discrete symmetries

Motivation

CP violation allows for a distinction between matter and anti-matter independent of convention.

It is needed to have an abundance of normal matter over anti-matter. (→ Baryogenesis)

Based on Kooijman & Tuning (2015)

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Parity violation

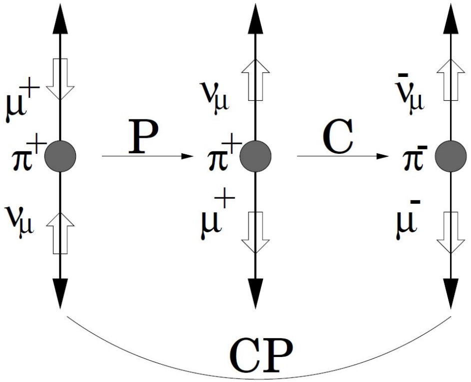
P symmetry ($P\psi(\vec{x}, t) = \psi(-\vec{x}, t)$) has been believed to hold until 1956: Wu-experiment.
→ Decay of Co-60 to Ni-60 in magnetic field shows different decay rates after changing field polarization.
→ Violation of parity.

Based on Kooijman & Tuning (2015)

C violation

Charge conjugation replaces particles with anti-particles and vice versa.

Pion decay:



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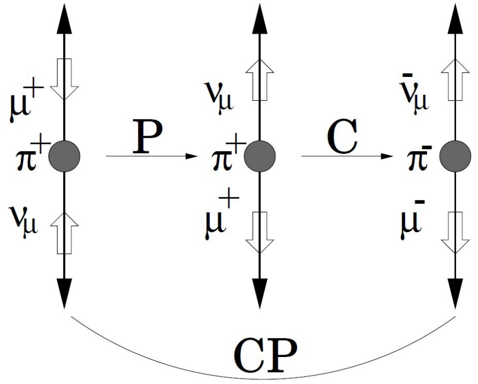

→ Violation of P and C symmetry.

CPT theorem

Lüders & Pauli: "Every **Lorentz invariant**, **causal**, **local** field theory with a **Hamiltonian** that is **bounded from below** is CPT invariant."

CPT invariance implies the existence of antiparticles with the same mass for every mass eigenstate.

C & P symmetries are violated but combined CP symmetry could hold, which is equivalent to time reversal (T) invariance.

Based on Kooijman & Tuning (2015)

CP violation in the standard model

The kinetic term and charged-current interactions

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{kin}} + \mathcal{L}_{\mathrm{Higgs}} + \mathcal{L}_{\mathrm{Yukawa}} + \mathcal{L}_{\mathrm{gauge}}$$

Based on Kooijman & Tuning (2015)

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The kinetic term is

$$\mathcal{L}_{\rm kin} = i\bar{\Psi}(\gamma^\mu D_\mu)\Psi$$

with

$$D_\mu = \partial_\mu + ig_s G^a_\mu \lambda^a + igW^b_\mu \sigma^b + ig' B_\mu Y$$

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and

$$\Psi \mathrel{\widehat{=}} Q_i^{\mathrm{L}}(3,2)_{1/6},\ u_i^{\mathrm{R}}(3,1)_{2/3},\ d_i^{\mathrm{R}}(3,1)_{-1/3},\ L_i^{\mathrm{L}}(1,2)_{-1/2},\ l_i^{\mathrm{R}}(1,1)_{-1}$$

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For example, the left-handed quarks are represented by

$$Q_i^{\mathrm{L}}(3,2,+1/6) = \begin{pmatrix} u_g & u_r & u_b \\ d_g & d_r & d_b \end{pmatrix}_i = \begin{pmatrix} u_g & u_r & u_b \\ d_g & d_r & d_b \end{pmatrix}, \begin{pmatrix} c_g & c_r & c_b \\ s_g & s_r & s_b \end{pmatrix}, \begin{pmatrix} t_g & t_r & t_b \\ b_g & b_r & b_b \end{pmatrix}$$

Through the kinetic term, the fermions couple to the gauge bosons.

Example: charged-current interaction of left-handed quarks

$$\begin{aligned}\mathcal{L}_{\text{kin}} &\supset -g\overline{Q_i^{\text{L}}}\gamma^\mu W_\mu^b \sigma^b Q_i^{\text{L}} \\ &= -g\overline{\begin{pmatrix} u & d \end{pmatrix}_i^{\text{L}}}\gamma^\mu W_\mu^b \sigma^b \begin{pmatrix} u \\ d \end{pmatrix}_i^{\text{L}} \\ &= -g\overline{u_i^{\text{L}}}\gamma^\mu W_\mu^- d_i^{\text{L}} - g\overline{d_i^{\text{L}}}\gamma^\mu W_\mu^+ u_i^{\text{L}}\end{aligned}$$

with

$$W^+ = W^1 - W^2, \qquad W^- = W^1 + W^2$$

→ Interaction between quarks of the same generation.

Based on Kooijman & Tuning (2015)

The Higgs and Yukawa sector

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

where after spontaneous symmetry breaking

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

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The Yukawa terms are given by

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= Y_{ij}\phi\overline{\Psi_i^{\text{L}}}\Psi_j^{\text{R}} + \text{h.c.} \\ &= Y_{ij}\frac{v}{\sqrt{2}}\overline{\Psi_i^{\text{L}}}\Psi_j^{\text{R}} + \text{h.c.} + \text{interaction terms} \\ &= M_{ij}^u\overline{u_i^{\text{L}}}u_j^{\text{R}} + M_{ij}^d\overline{d_i^{\text{L}}}d_j^{\text{R}} + \text{h.c.} + \text{interaction terms}\end{aligned}$$

Based on Kooijman & Tuning (2015)

Now diagonalize the mass matrices to obtain proper masses:

$$M^u_{\text{diag}} = V^u_{\text{L}} M^u V^{u\dagger}_{\text{R}}$$
$$M^d_{\text{diag}} = V^d_{\text{L}} M^d V^{d\dagger}_{\text{R}}$$

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so that

$$\begin{aligned}
\mathcal{L}_{\text{Yukawa}} &\supset \overline{u^{\text{L}}_i} M^u_{ij} u^{\text{R}}_j + \overline{d^{\text{L}}_i} M^d_{ij} d^{\text{R}}_j \\
&= \overline{u^{\text{L}}_i} V^{u\dagger}_{\text{L}} V^u_{\text{L}} M^u_{ij} V^{u\dagger}_{\text{R}} V^u_{\text{R}} u^{\text{R}}_j + \overline{d^{\text{L}}_i} V^{d\dagger}_{\text{L}} V^d_{\text{L}} M^d_{ij} V^{d\dagger}_{\text{R}} V^d_{\text{R}} d^{\text{R}}_j \\
&= \overline{(u^{\text{L}}_{\text{mass}})_i} (M^u_{\text{diag}})_{ij} (u^{\text{R}}_{\text{mass}})_j + \overline{(d^{\text{L}}_{\text{mass}})_i} (M^d_{\text{diag}})_{ij} (d^{\text{R}}_{\text{mass}})_j
\end{aligned}$$

where

$$(u^{\text{L}}_{\text{mass}})_i = (V^u_{\text{L}})_{ij} u^{\text{L}}_j, \qquad (u^{\text{R}}_{\text{mass}})_i = (V^u_{\text{R}})_{ij} u^{\text{R}}_j$$
$$(d^{\text{L}}_{\text{mass}})_i = (V^d_{\text{L}})_{ij} d^{\text{L}}_j, \qquad (d^{\text{R}}_{\text{mass}})_i = (V^d_{\text{R}})_{ij} d^{\text{R}}_j$$

Based on Kooijman & Tuning (2015)

Charged-current sector revisited and the CKM matrix

Now express cc terms through mass eigenstates:

$$\begin{aligned}\mathcal{L}_{\text{kin}} &\supset -g\overline{u_i^{\text{L}}}\gamma^\mu W_\mu^- d_i^{\text{L}} - g\overline{d_i^{\text{L}}}\gamma^\mu W_\mu^+ u_i^{\text{L}} \\ &= -g\overline{(u_{\text{mass}}^{\text{L}})_i}(V_{\text{L}}^u V_{\text{L}}^{d\dagger})_{ij}\gamma^\mu W_\mu^-(d_{\text{mass}}^{\text{L}})_i - g\overline{(d_{\text{mass}}^{\text{L}})_i}(V_{\text{L}}^d V_{\text{L}}^{u\dagger})_{ij}\gamma^\mu W_\mu^+(u_{\text{mass}}^{\text{L}})_i\end{aligned}$$

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This defines the CKM matrix:

$$V_{\text{CKM}} = V_{\text{L}}^u V_{\text{L}}^{d\dagger}$$

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By convention, up-type quarks don't change in the mass basis but down-type are rotated:

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cd} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_{\text{mass}} \\ s_{\text{mass}} \\ t_{\text{mass}} \end{pmatrix}$$

Based on Kooijman & Tuning (2015)

CP violation in the hadron sector

Reminder: the charged-current interaction term is

$$\mathcal{L}_{\text{kin}} \supset -g\overline{(u^{\text{L}}_{\text{mass}})}V_{\text{CKM}}\gamma^{\mu}W^{-}_{\mu}(d^{\text{L}}_{\text{mass}}) - g\overline{(d^{\text{L}}_{\text{mass}})}V^{*}_{\text{CKM}}\gamma^{\mu}W^{+}_{\mu}(u^{\text{L}}_{\text{mass}})$$

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CP violation is strongly related to a complex phase of the CKM matrix:

$$V_{\text{CKM}} \neq V^{*}_{\text{CKM}} \;\Leftrightarrow\; \text{CP violation}$$

Based on Kooijman & Tuning (2015)

Parameterization of the CKM matrix

Number of free parameters

The CKM matrix is a unitary n×n matrix

$$\Rightarrow n^2 \text{ real components}$$

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In total there are

$$(n-1)^2 \text{ free parameters}$$

Based on Kooijman & Tuning (2015)

Parameterization

CKM matrix can be written in terms of three mixing angles and a complex, CP-violating phase:

$$V_{\mathrm{CKM}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\mathrm{e}^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}\mathrm{e}^{i\delta_1 3} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & c_{23} & -s_{23} \end{pmatrix}$$

where

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The absolute values of the components are experimentally given by

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

A. Ceccucci, Z. Ligeti and Y. Sakai (2018)

Experimental Status

CP Violation in Kaon Systems

K^0 and $\overline{K}^0$ are flavor eigenstates

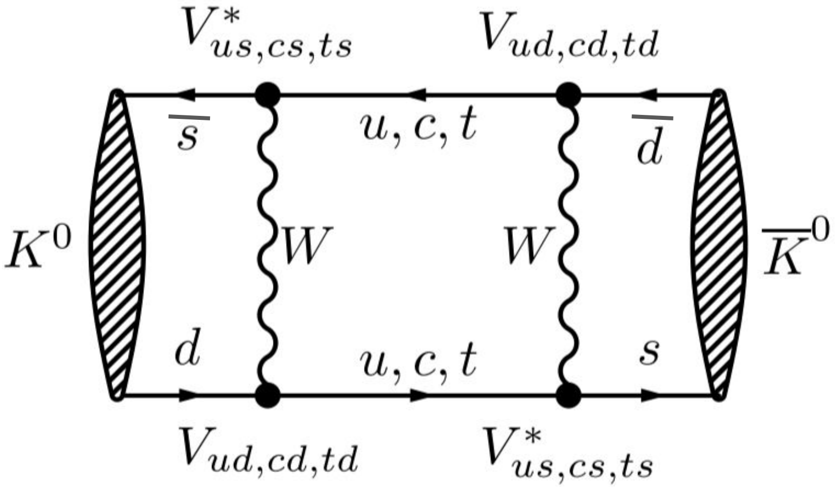
CP eigenstates:

$$|K_1\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle + |\bar{K}^0\rangle) \quad \text{CP = +1}$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle - |\bar{K}^0\rangle) \quad \text{CP = -1}$$

Question: Do K_1 and K_2 correspond

to mass eigenstates K_S and K_L?



CP Violation in Kaon Systems

K_S & K_L have very distinct lifetimes:

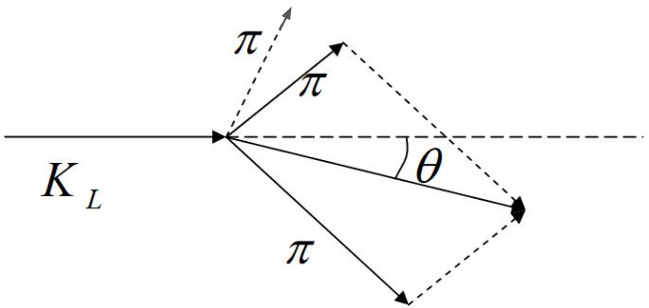
$\tau(K_S) = 0.9 \times 10^{-10}$ s, $\tau(K_L) = 0.5 \times 10^{-7}$ s

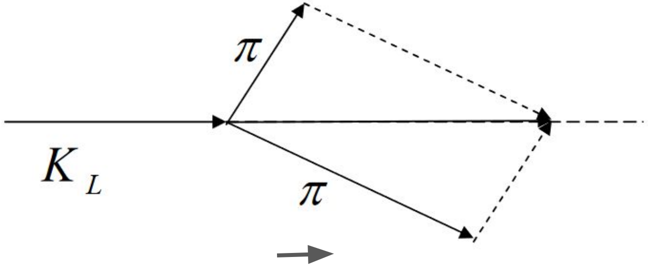
Neutral kaon decays mainly hadronically into pions:

$K_1 \rightarrow \pi\pi$, $K_2 \rightarrow \pi\pi\pi$ as $CP(\pi) = -1$

If K_L can be identified with the CP eigenstate K_2 then $K_L \not\rightarrow \pi\pi$

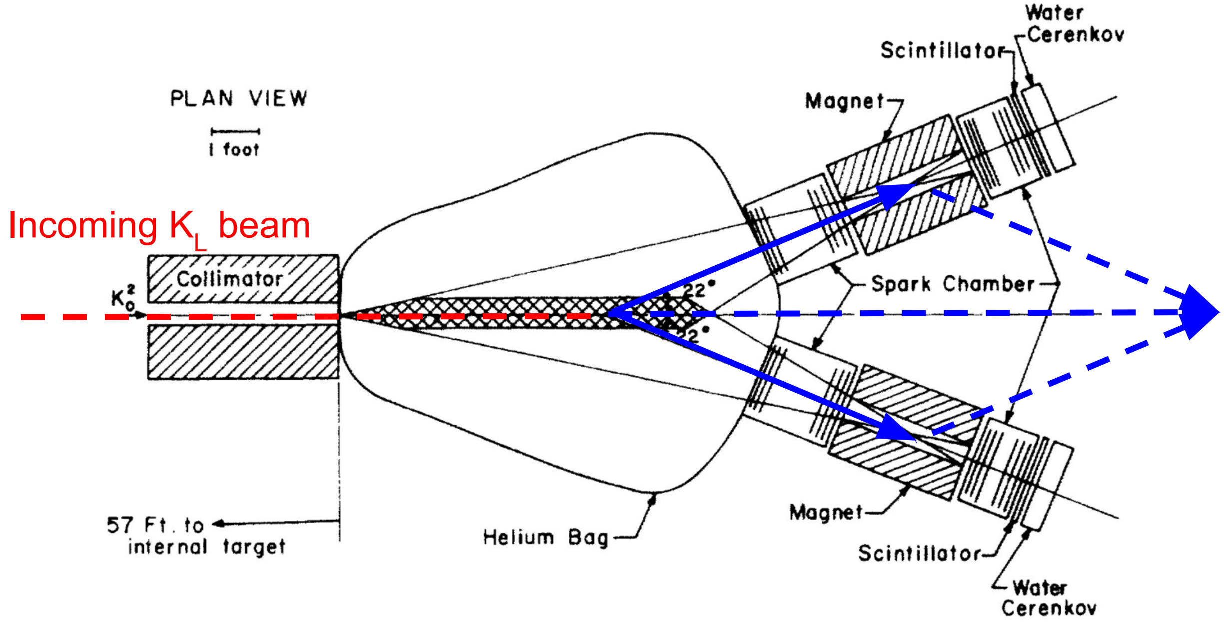
Search strategy:





$K_L \rightarrow \pi\pi$ $\boldsymbol{\theta} = 0$

The Cronin & Fitch Experiment



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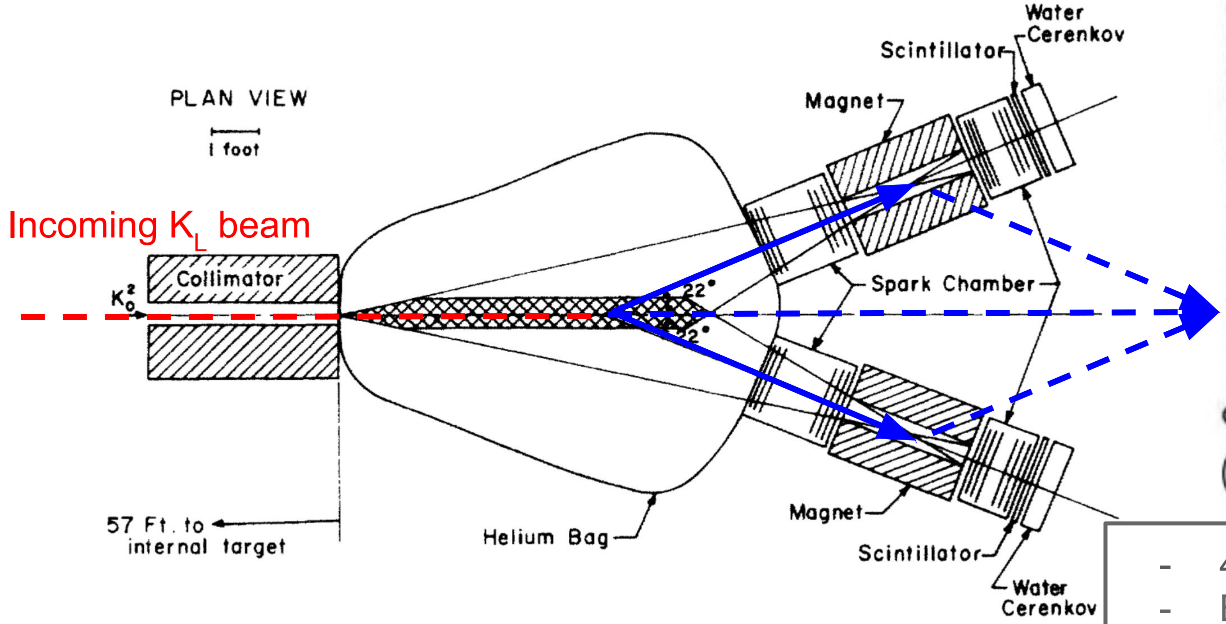
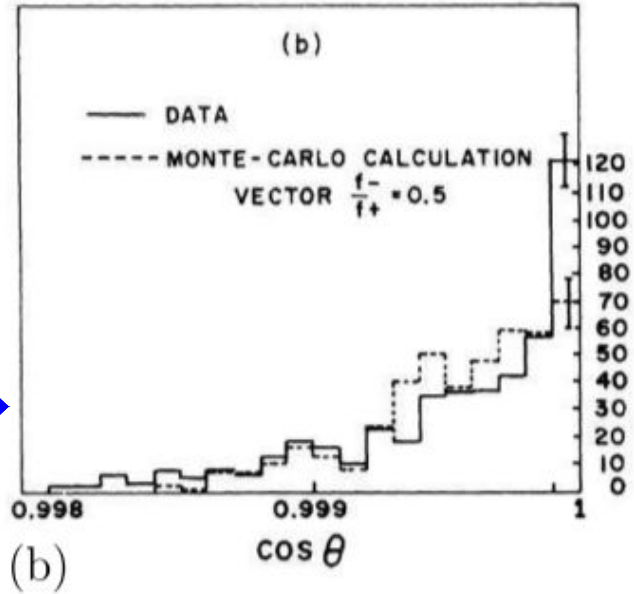




- 49 ± 9 $K_L \to \pi\pi$ events in 22700 decays
- $BR(K_L \to \pi^+\pi^-) = 2.0 \pm 0.4 \times 10^{-3}$
- First observation of CP Violation in weak interaction

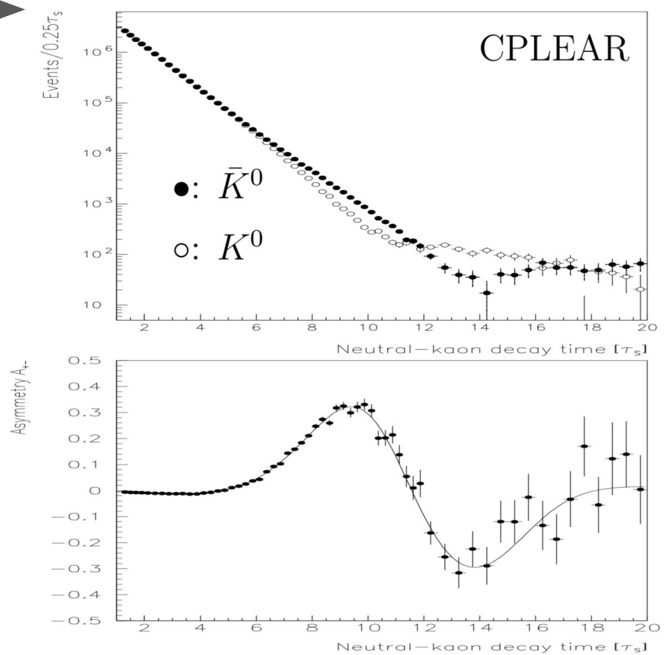
PhysRevLett.13.138

CP Violation in Kaon Systems

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle)$$

indirect CPV

$\bar{p}p \to K^-\pi^+K^0$ and $\bar{p}p \to K^+\pi^-\bar{K}^0$



$$A_{+-} = \frac{\Gamma(\bar{K}^0_{t=0} \to \pi^+\pi^-) - \Gamma(K^0_{t=0} \to \pi^+\pi^-)}{\Gamma(\bar{K}^0_{t=0} \to \pi^+\pi^-) + \Gamma(K^0_{t=0} \to \pi^+\pi^-)}$$

$\to |\varepsilon| = (2.264 \pm 0.035) \times 10^{-3}$

Phys.Lett. B458 (1999)

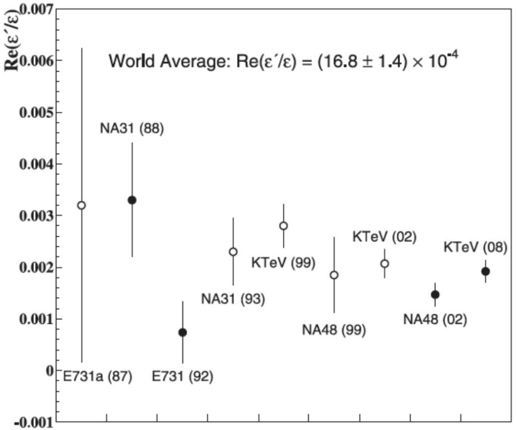
CP Violation in Kaon Systems

$$|K_L\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2\rangle + \epsilon|K_1\rangle)$$

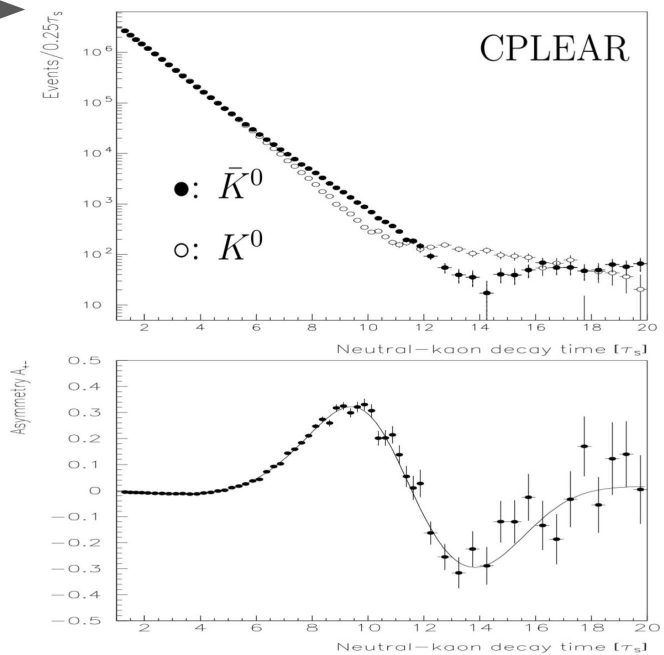
indirect CPV

direct CPV: $\varepsilon' = \Gamma(K_2 \rightarrow \pi\pi) / \Gamma(K_2 \rightarrow \pi\pi\pi)$

$$\Re(\varepsilon'/\varepsilon) = \frac{\Gamma(K_L \rightarrow \pi^0\pi^0) / \Gamma(K_S \rightarrow \pi^0\pi^0)}{\Gamma(K_L \rightarrow \pi^+\pi^-) / \Gamma(K_S \rightarrow \pi^+\pi^-)} \cong 1 - 6\,\Re(\varepsilon'/\varepsilon)$$



$\bar{p}p \rightarrow K^-\pi^+K^0$ and $\bar{p}p \rightarrow K^+\pi^-\bar{K}^0$



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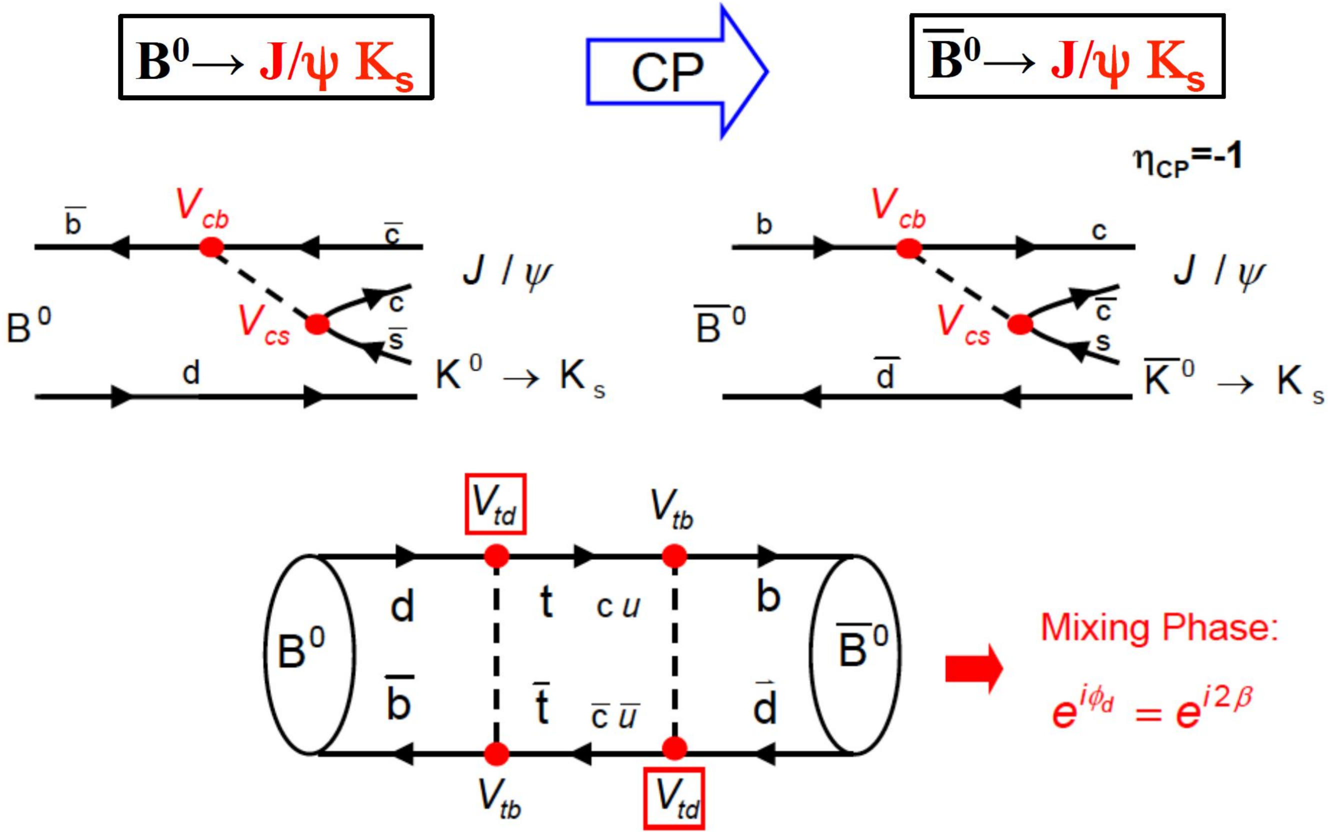
CP Violation in B Mesons

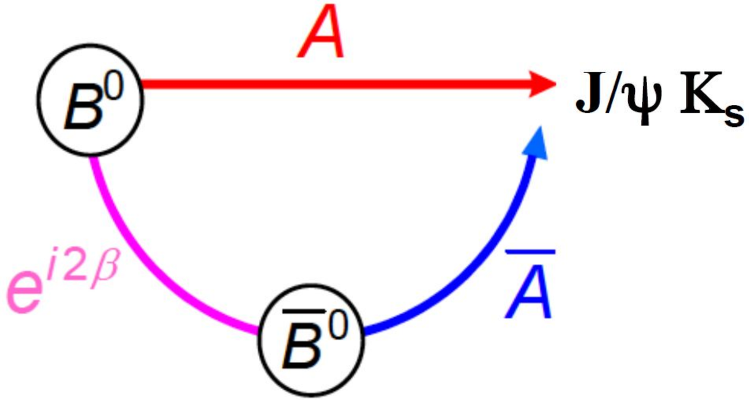


J. Albrecht

CP Violation in B Mesons

$B^0 \to J/\psi\ K_s$ —CP→ $\overline{B}^0 \to J/\psi\ K_s$

$\eta_{CP}=-1$



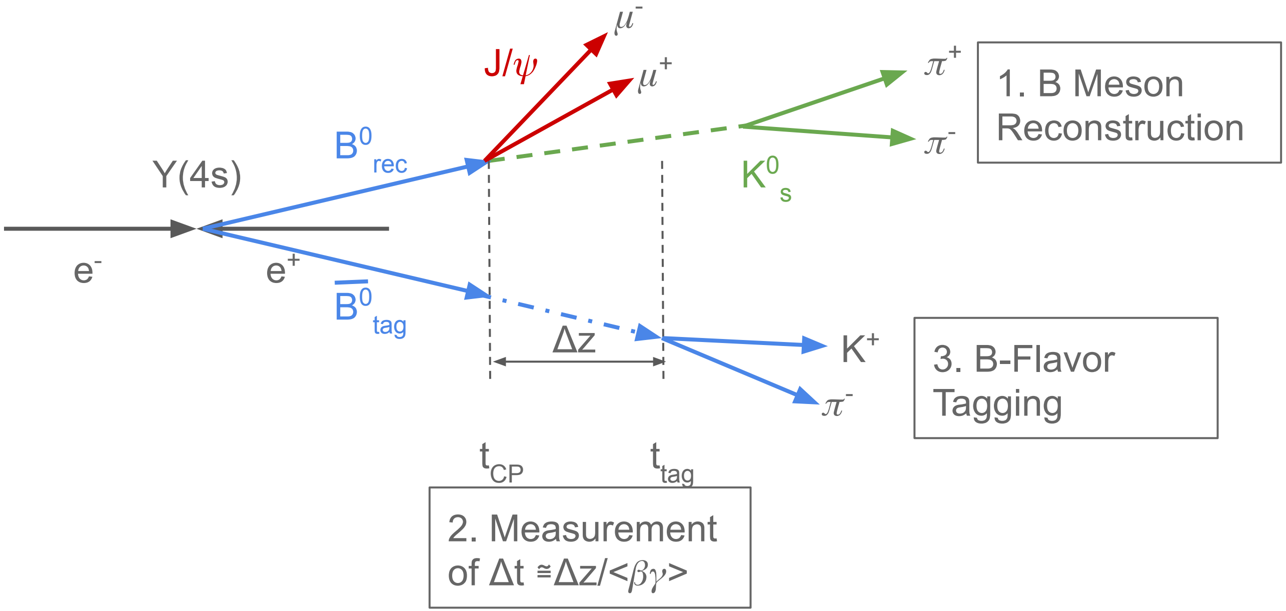
$$\Gamma(B^0 \to J/\psi\, K_s)(t) \neq \Gamma(\overline{B}^0 \to J/\psi\, K_s)(t)$$

Require knowledge about the production flavor of the B meson

J. Albrecht

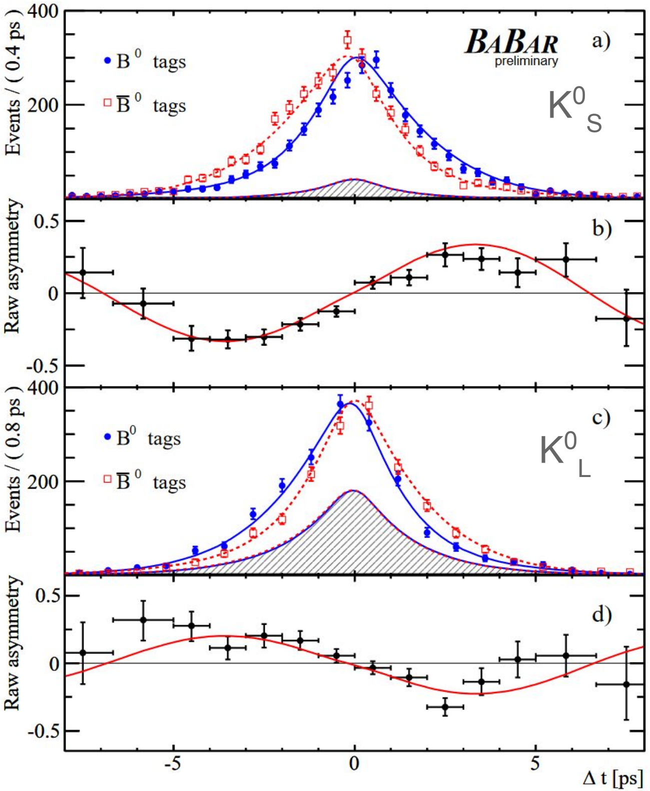
CP Violation in B Mesons

3 steps to measure CP asymmetry in mixing & decay:



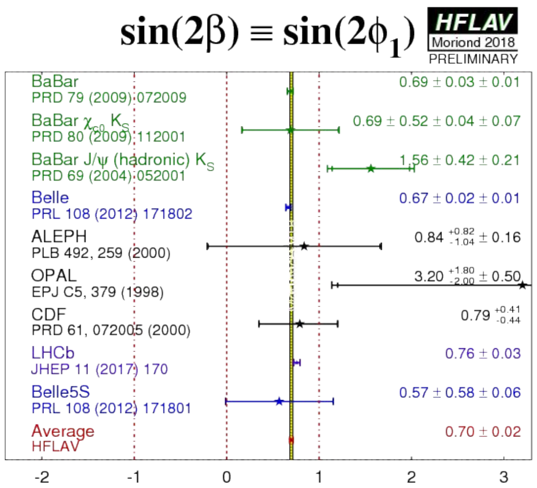
Tagging efficiency	Mistag probability	Dilution
$\varepsilon = \frac{\#\, tagged\ candidates}{\#\, all\ candidates}$	$\omega = \frac{\#\, tagged\ wrong}{\#\, tagged}$	$D = (1 - 2\omega)$

CP Violation in B Mesons



$$A_{CP}(t) \equiv \frac{N(\overline{B}^0(t) \to f) - N(B^0(t) \to f)}{N(\overline{B}^0(t) \to f) + N(B^0(t) \to f)}$$

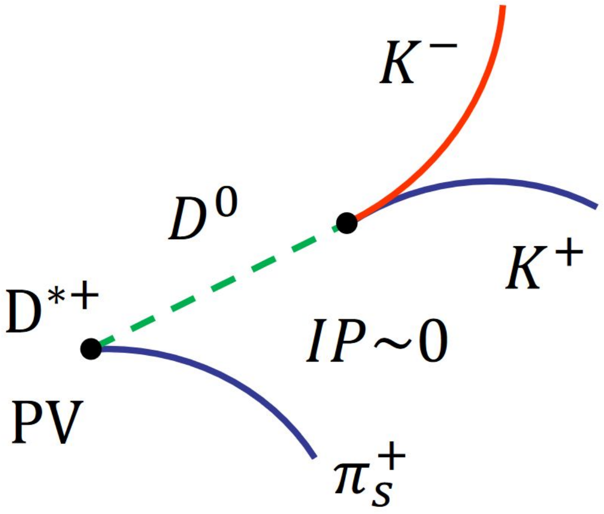
= (1-2w) sin(2β) sin(Δm_dt) with $\epsilon D^2 \cong 30\%$

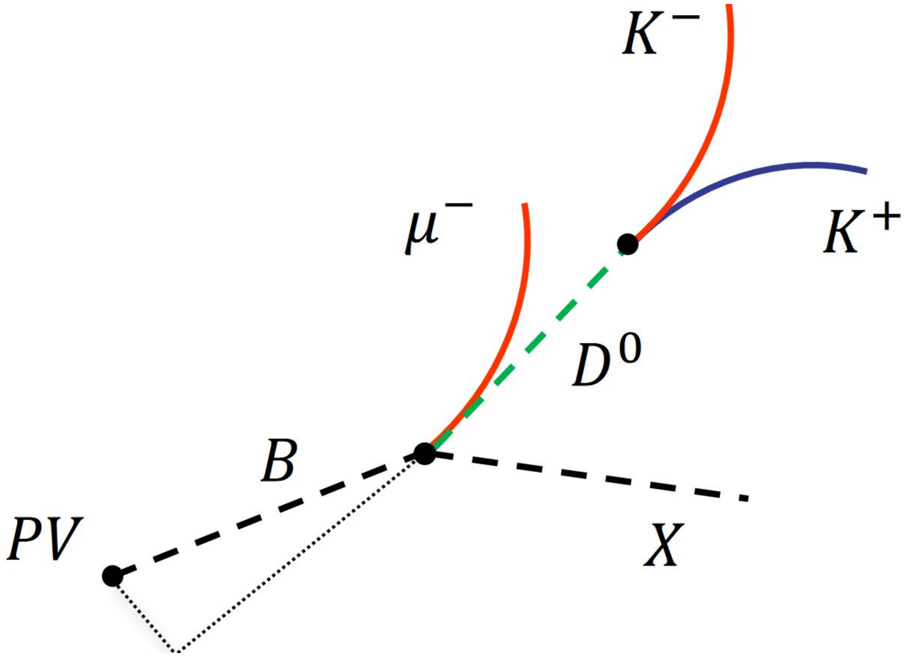


arXiv:hep-ex/0610007

CP Violation in Charm Decays

Two production mechanisms of D^0





Deduce flavor of D^0 at production by charge of the muon or soft pion

A. Carbone

CP Violation in Charm Decays

$$A_{raw}(f) = A_{CP}(f) + A_D(\pi_s^+) + A_P(D^{*+})$$

CP asymmetry

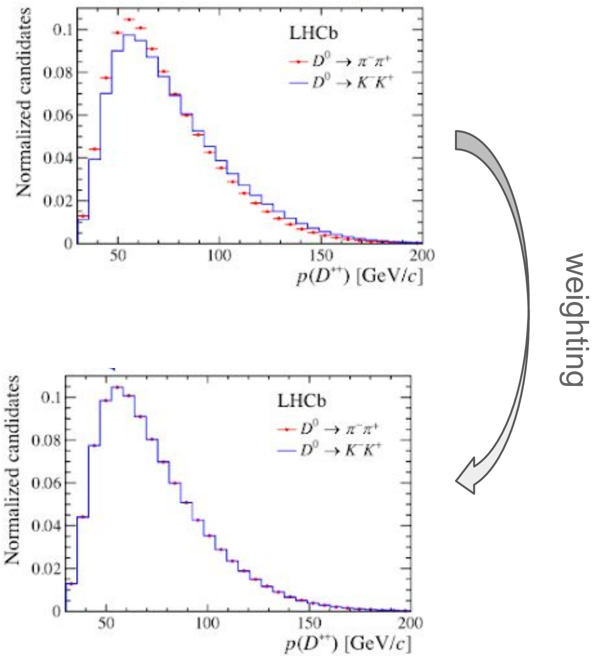
charge-dependent asymmetry in π reconstruction

$D^{*\pm}$ production asymmetry

with $A_{raw}(h^+h^-) = \dfrac{N(D^0 \to h^+h^-) - N(\overline{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\overline{D}^0 \to h^+h^-)}$

Take raw asymmetry difference of $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ to cancel detection asymmetry:

$$\Delta A_{CP} := A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

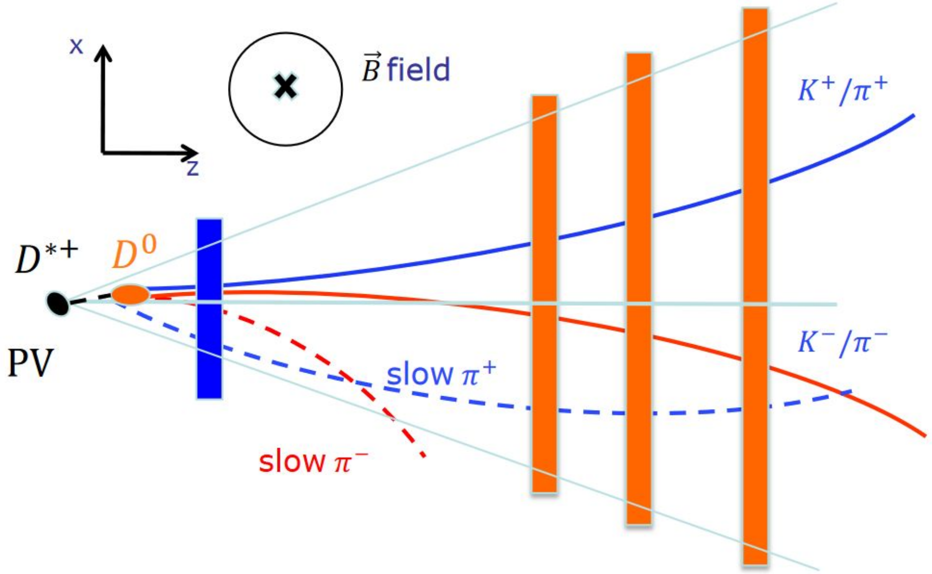


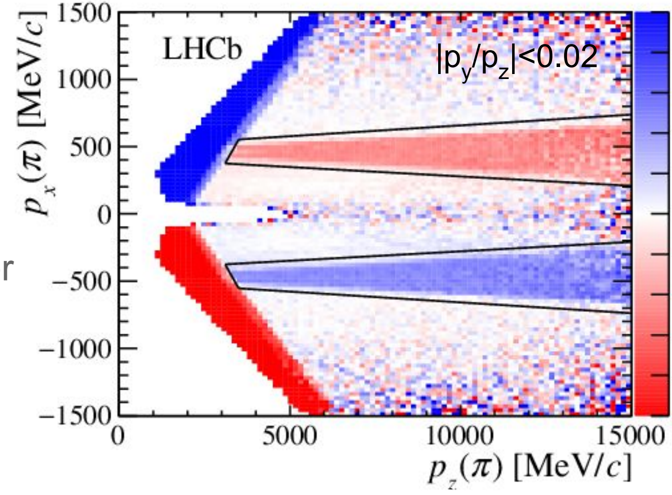
detection & production asymmetries dependent on kinematics
→ apply weighting procedure

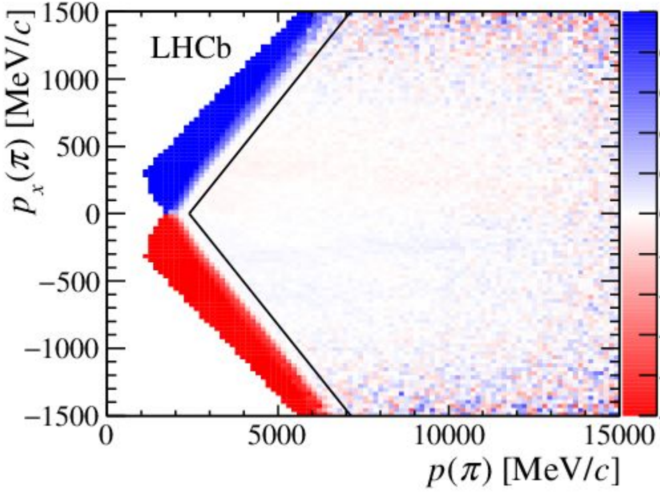
A. Carbone

CP Violation in Charm Decays

Fiducial Selection: In parts of phase space soft pion leaves the detector

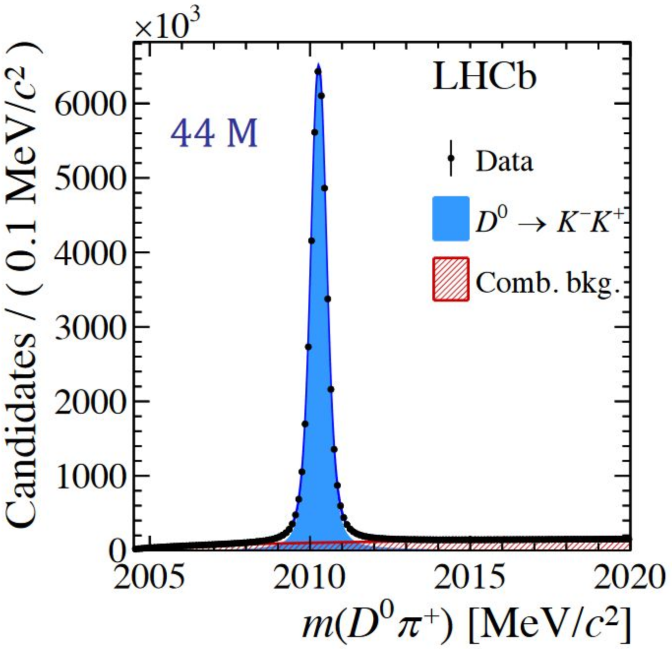


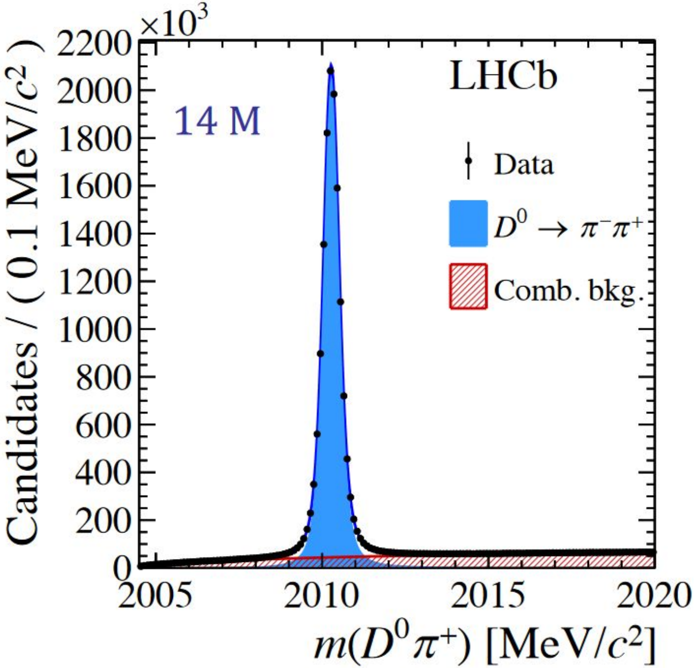




arXiv:1903.08726

CP Violation in Charm Decays





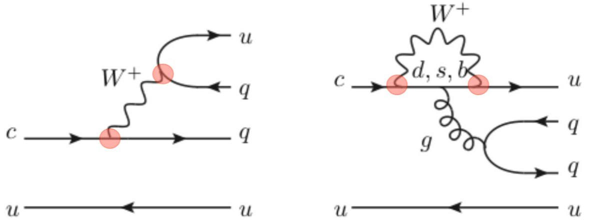
Simultaneous fit to D^0 and $\overline{D}^0$ samples combined with Run1 results gives:
$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$ corresponding to 5.3 σ

arXiv:1903.08726

The 3 Types of CP Violation

1. Direct CPV (in decay):

   with $A=\langle f|H|D^0\rangle$: $\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1$



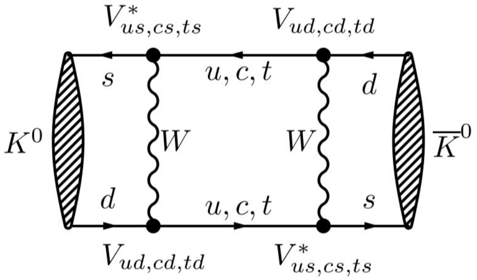
Interference between tree & penguin amplitudes

2. Indirect CPV (in mixing):

   with $|P_1\rangle = p\,|P^0\rangle + q\,|\bar{P}^0\rangle$

   & $|P_2\rangle = p\,|P^0\rangle - q\,|P^0\rangle$

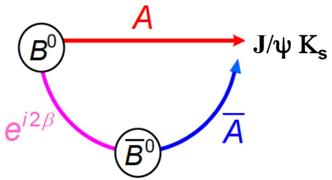
   → CPV if: $\left|\frac{q}{p}\right| \neq 1$



3. CPV in combination of decay and mixing:

   with $\lambda = \eta_{f_{CP}} \left(\frac{q}{p}\right)\left(\frac{\bar{A}_{\bar{f}}}{A_f}\right)$:

   CPV if $|\lambda|=1$ and $\Im m(\lambda)\neq 0$



$\Gamma(B^0 \to J/\psi\, K_s)(t) \neq \Gamma(\overline{B}^0 \to J/\psi\, K_s)(t)$

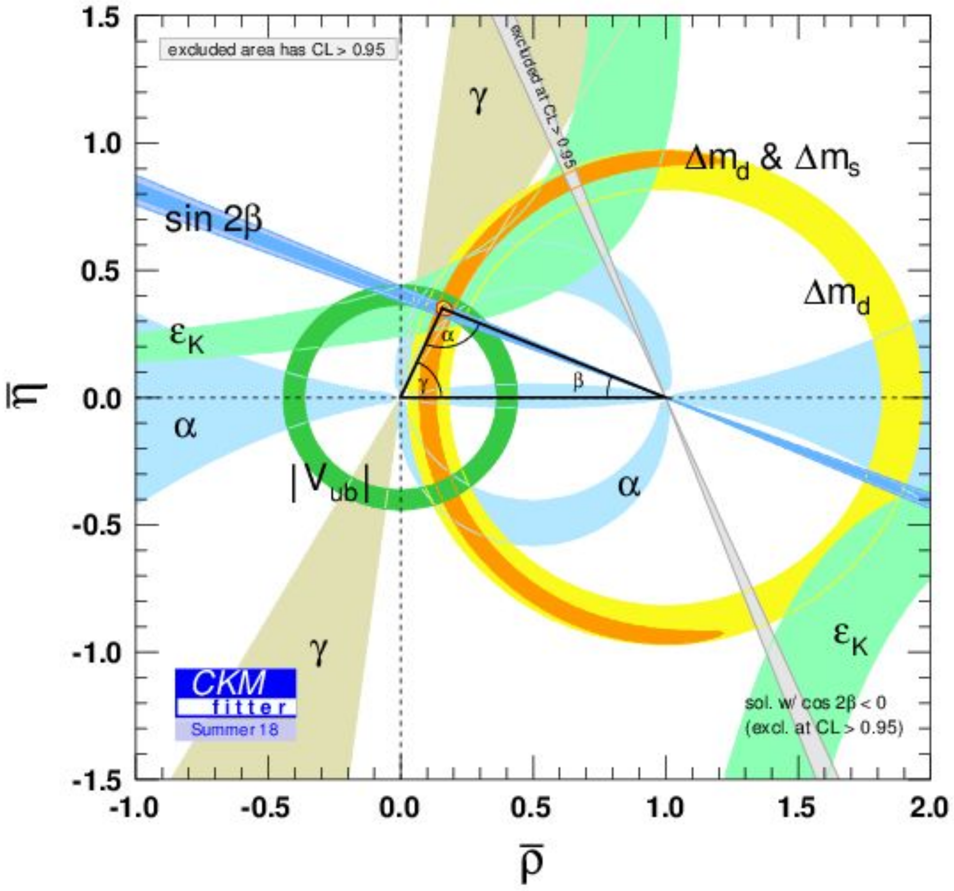
Unitarity Triangle(s)

CKM matrix: unitary transformation between weak and mass basis

$$VV^\dagger = I$$

⇒ weak universality $$\sum_k |V_{ik}|^2 = 1$$

⇒ 6 unitarity triangles $$\sum_k V_{ik}V_{jk}^* = 0$$



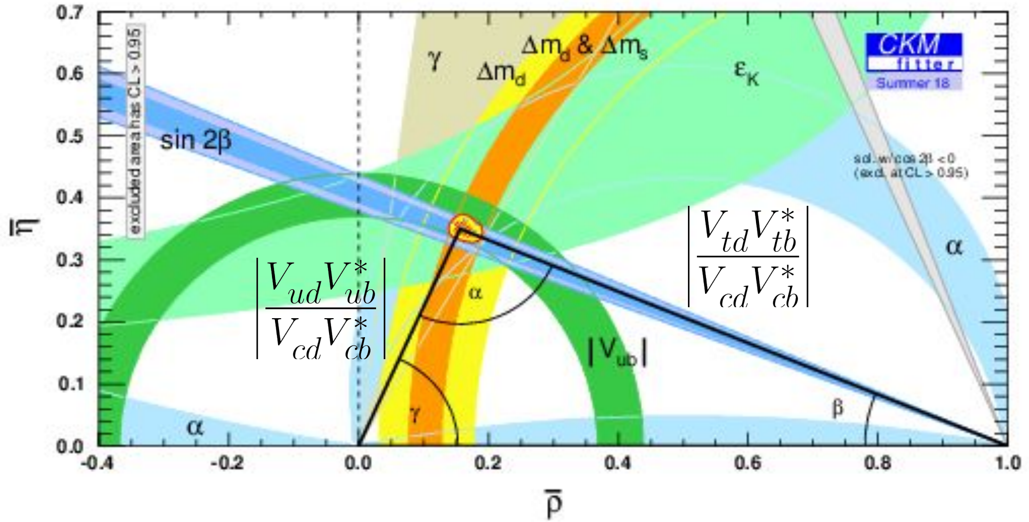
Unitarity Triangle(s)

$\sin(2\beta)$: $B^0 \to J/\Psi\, K_s$ (BaBar, Belle, LHCb)

ε_K: kaon mixing (KLOE)

$|V_{ub}|$: $B \to X_u\, \bar{\nu}\, l$ (BaBar, Belle, CLEO)
Λ_b decays (LHCb)

Δm: B^0 mixing (BaBar)
B_s^0 mixing (LHCb)



Other Sources of CP Violation

Lepton Sector

neutrino mass eigenstates mismatch weak eigenstates

⇒ analogue to CKM matrix: PMNS matrix

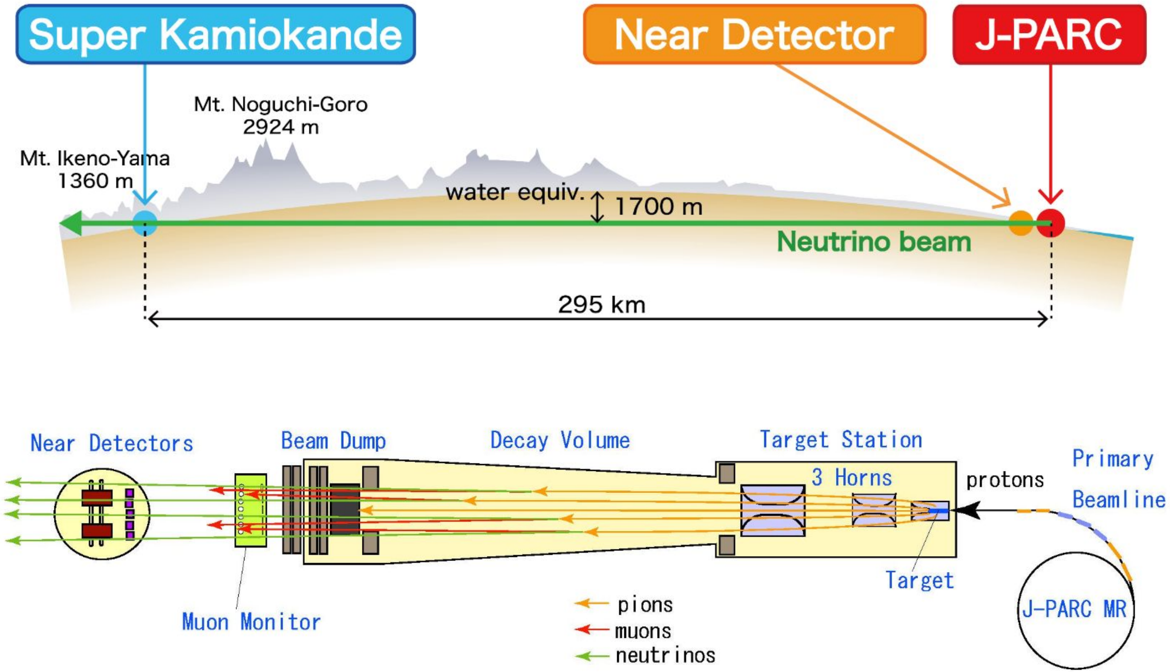
$$|U|_{3\sigma}^{\text{with SK-atm}} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.243 \to 0.490 & 0.473 \to 0.674 & 0.651 \to 0.772 \\ 0.295 \to 0.525 & 0.493 \to 0.688 & 0.618 \to 0.744 \end{pmatrix}$$

NuFIT 4.1: JHEP 01 (2019) 106

CP violating phase still 2σ consistent with CP conservation: $\delta_{CP} = 144^\circ \to 357^\circ$

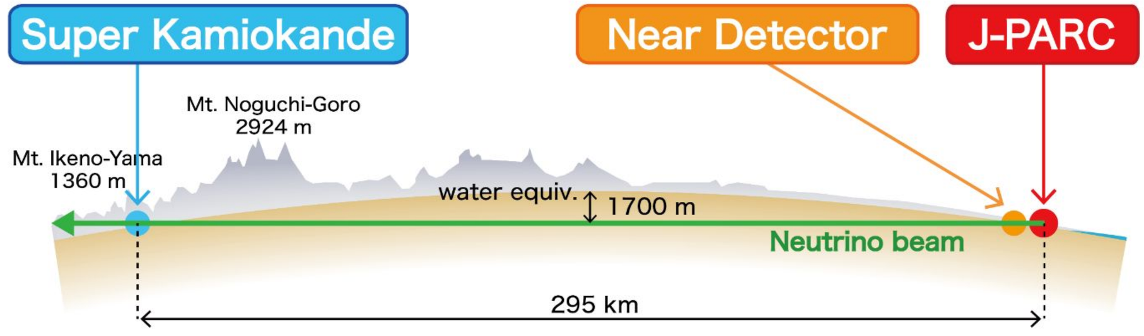
determined at accelerator experiments

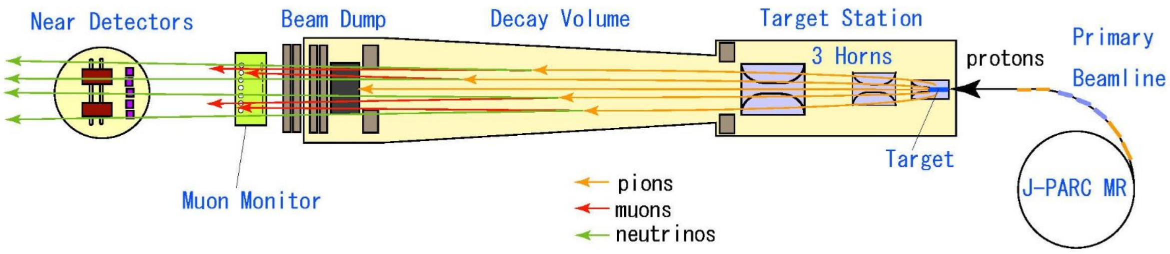
T2K (Tokai to Kamioka) Experiment

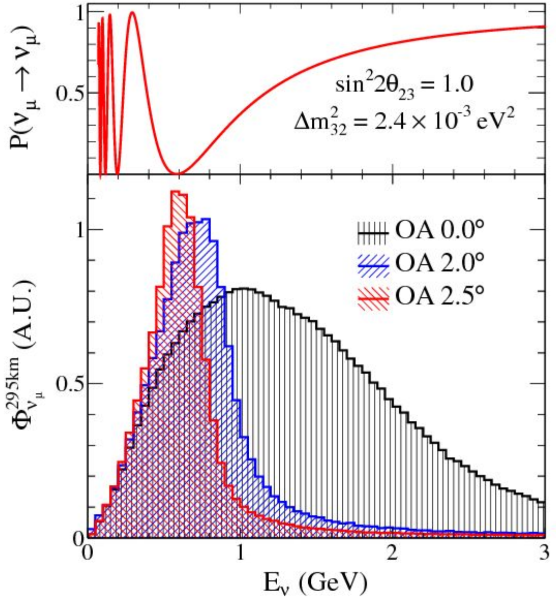


T. Koga

T2K (Tokai to Kamioka) Experiment







arxiv:1211.0469

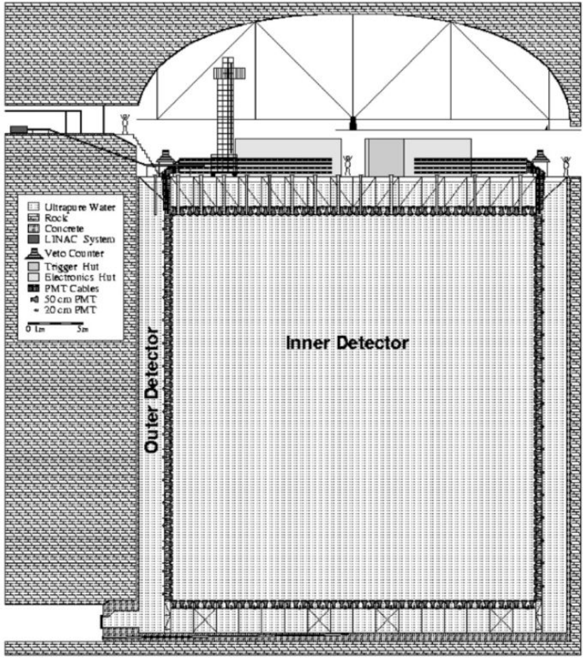
⇒ beam intentionally aimed off detector

T. Koga

Super-Kamiokande Detector

50 kiloton water Cherenkov detector, 11000 PMTs

$\nu_l + n \to l^- + p \quad (\bar{\nu}_l + p \to l^+ + n)$ $\to$ light cone



Super-Kamiokande Detector

50 kiloton water Cherenkov detector, 11000 PMTs

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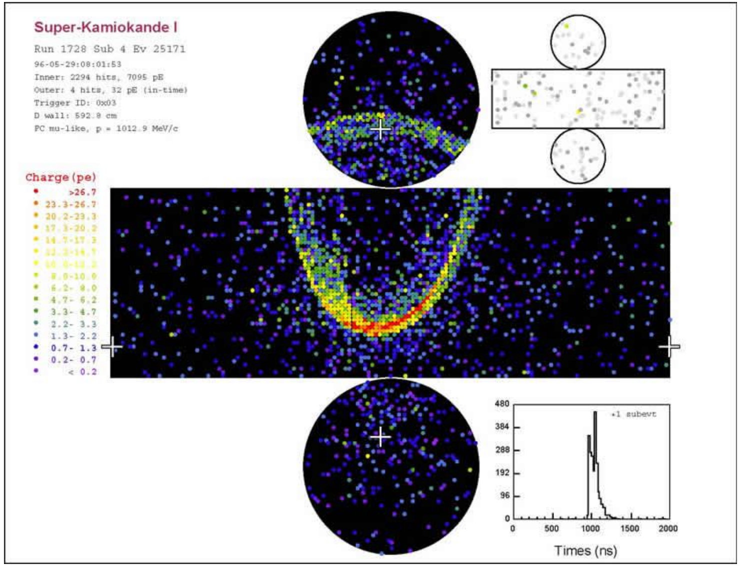
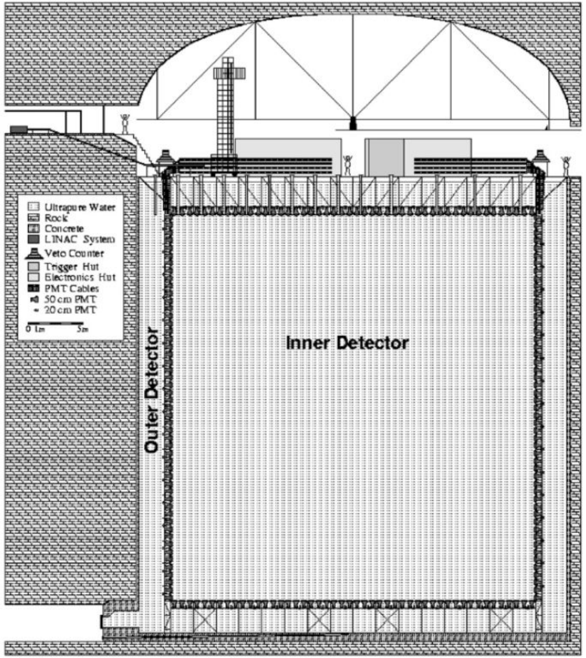




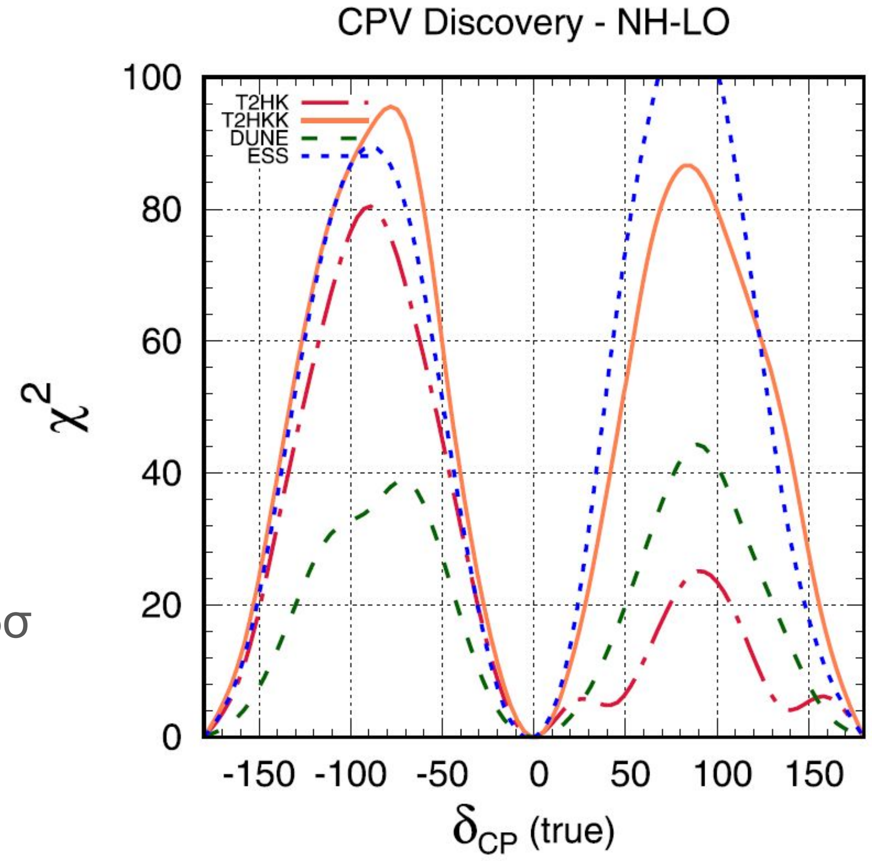
T2HK(K) Experiment

50 kilotons → 260 kilotons (×2)

11000 PMTs → 40000 PMTs (×2)

construction supposed to start 2020

60% of δ_{CP} space could be discovered at 5σ

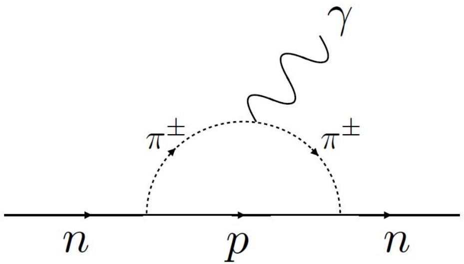


arXiv:1711.11107

CP Violation in QCD

QCD Lagrangian can contain CP violating relative phase $\bar{\theta}$

measurement of neutron electric dipole moment: $\bar{\theta} < 10^{-10}$



⇒ fine tuning problem

suggested solutions:

- CP broken spontaneously, not explicitly
- massless up-quark
- Peccei-Quinn theory:
  global approximate U(1) symmetry broken at scale f_A
  ⇒ axions as pseudo-Nambu-Goldstone bosons

CP Violation in QCD

Neutron Electric Dipole Moment

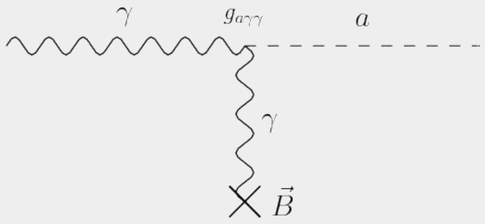
$$h\nu_L = 2\mu_N B \pm 2 d_N E$$

best limit: $|d_N| < 2.9 \times 10^{-26} e\,\mathrm{cm}$

next gen: $|d_N| \sim 10^{-28} e\,\mathrm{cm}$

(e.g. CryoEDM)

Axion / ALPs Search



detectable via Primakoff effect ("light shining through a wall")

IAXO, ALPS II, MADMAX, ...

Summary

- CP violation well measured in meson weak interactions:
  - decay
  - mixing
  - decay + mixing

- Lepton sector has CP violating phase, hint at $\delta_{CP} \neq 0$

- QCD should have CP violating phase, but none observed

Backup

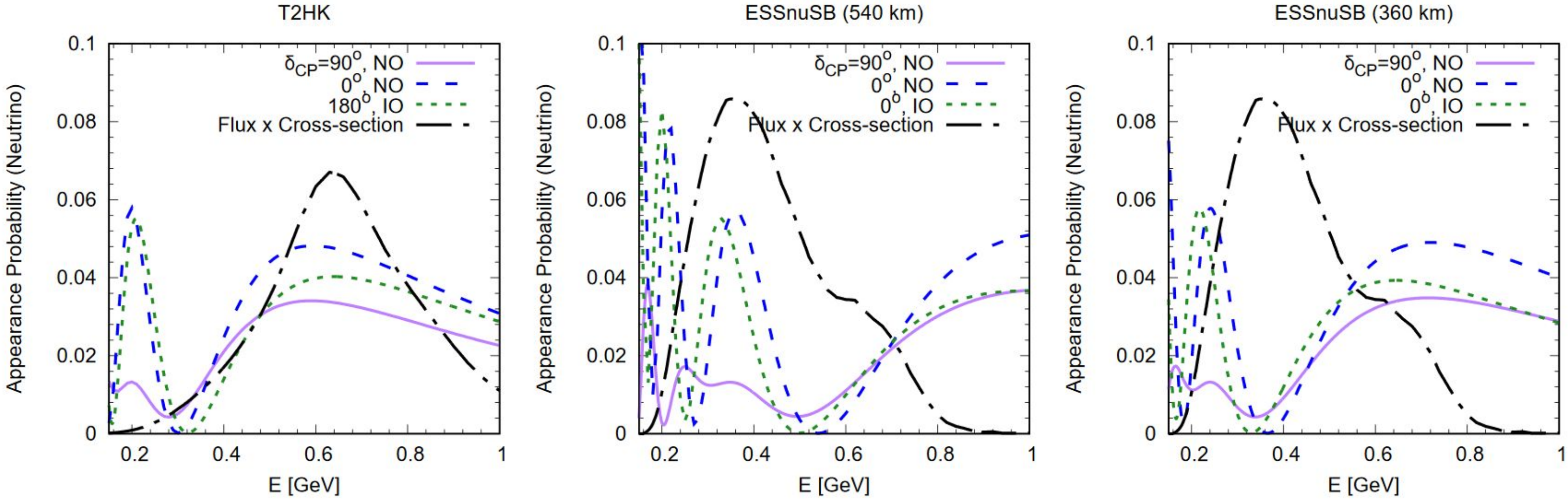
CKM Matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}$$

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

$\lambda = 0.2257^{+0.0009}_{-0.0010}$, $A = 0.814^{+0.021}_{-0.022}$, $\rho = 0.135^{+0.031}_{-0.016}$, and $\eta = 0.349^{+0.015}_{-0.017}$.

TH2K vs ESSnuSB



Peccei-Quinn Theory

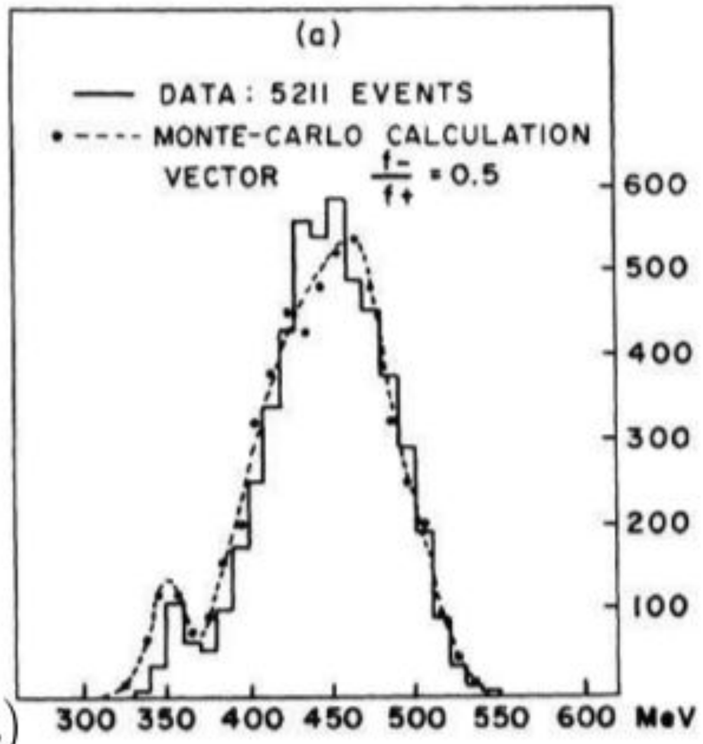
without Peccei-Quinn:

$$\mathcal{L}_{QCD} \supset \bar{\theta}\frac{\alpha_s}{8\pi}G^a\tilde{G}^a$$

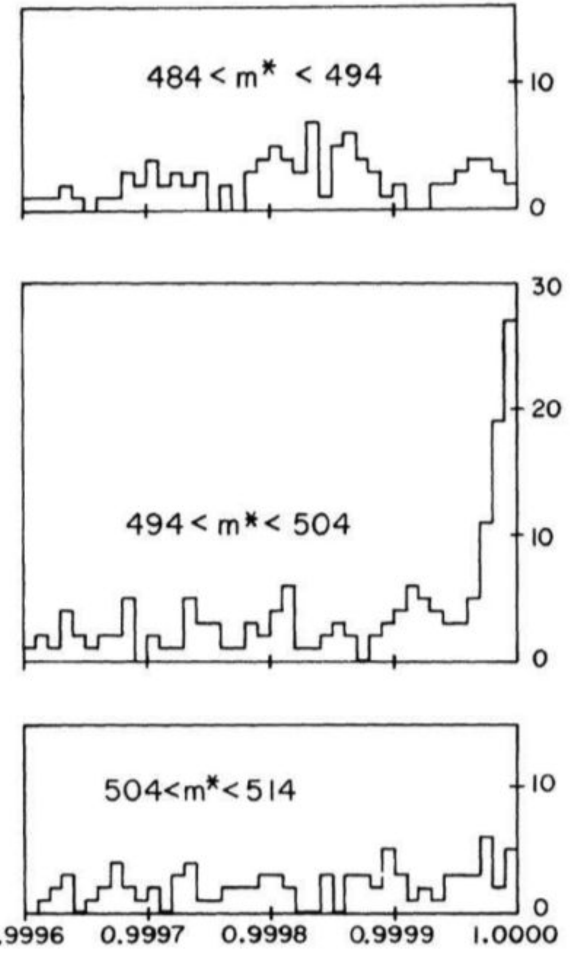
with Peccei-Quinn:

$$\mathcal{L}_{QCD} \supset \left(\frac{\Phi_A}{f_A} - \bar{\theta}\right)\frac{\alpha_s}{8\pi}G^a\tilde{G}^a$$

The Cronin & Fitch Experiment



(a)



(c)
(d)
(e)