Karlsruher Institut für Technologie

Vorlesung:

Teilchenphysik I (Particle Physics I)

V14b: CP Violation

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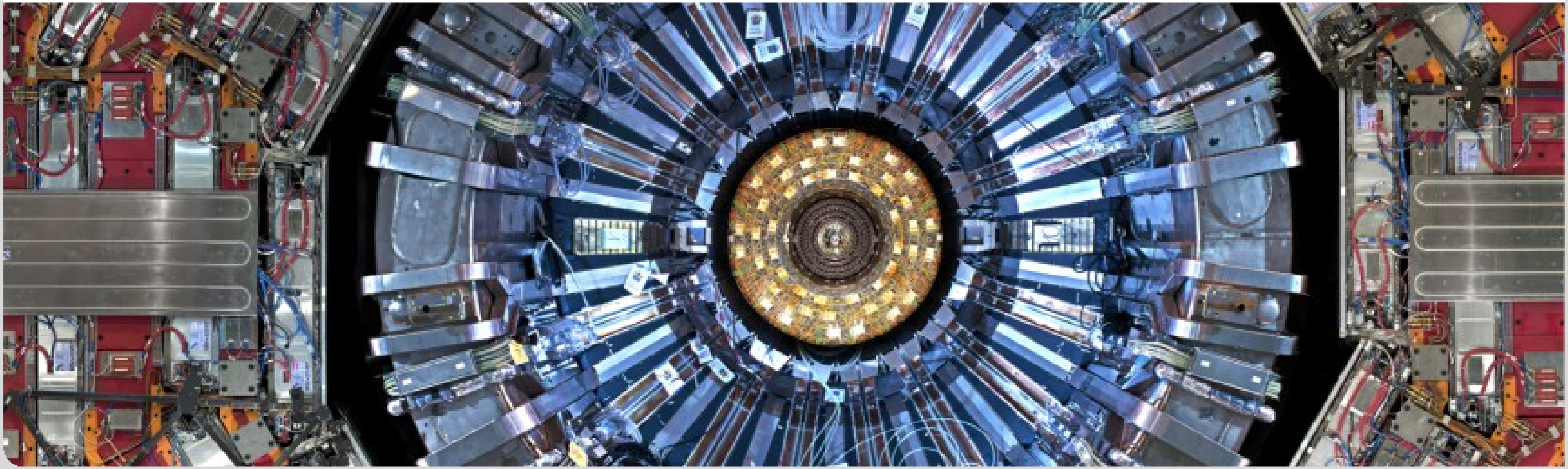
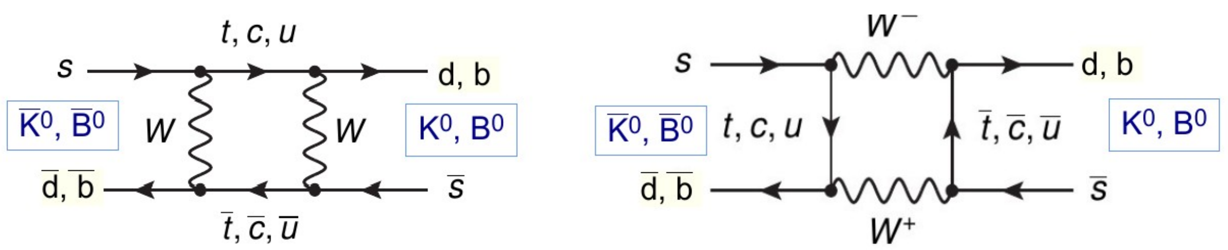


Summary V16: Meson-Anitmeson Mixing

- In the Standard Model, mixing is caused by box diagrams



- Precise determination of meson-anti-meson mixing in
  - (asymmetric) electron-positron colliders operating at the Υ(4s) resonance
  - $b\overline{b}$ production in hadron colliders

  requires precise measurement of decay length differences (→ vertex detecctors) and flavor tagging (→ particle idetification)

- Mixing depends on CKM matrix elements and helps to overconstrain them

- “new” or unknown physics contributes to box loops
  - led to the prediction of new particles (charm quark)
  - allows tests of the validity of the Standard Model

1. History
2. Basics principles
3. Detectors and Accelerators
4. Theoretical Foundations
    1. Relativistic Quantum Mechanics
    2. Quantum Field Theory and symmetries
    3. Elctroweak Symmetry and Higgs Mechanism
5. QCD and Jets
6. Analysis Chain

7. Flavour Physics
    1. Quark mixing and CKM Matrix
    2. Meson-Antimeson Mixing
    3. CP Violation

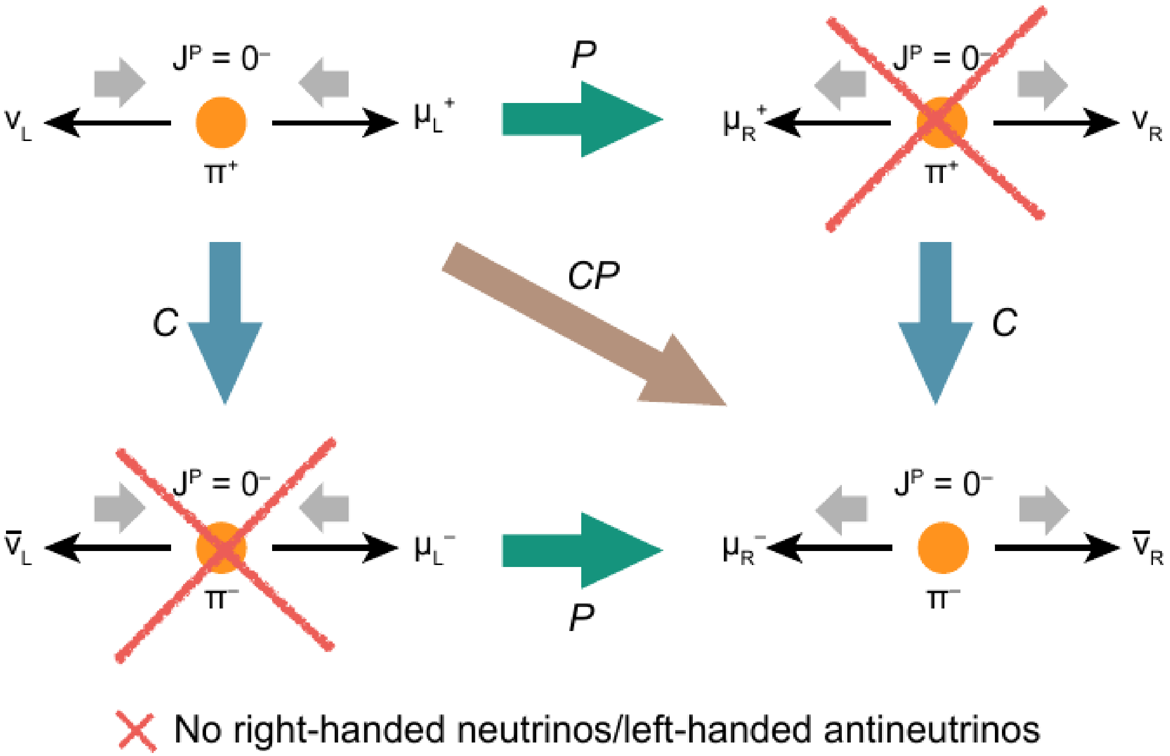
8. Tests of Electroweak Theory
    1. Discoveries
    2. Precicion Physics with Z bosons
    3. W Boson and electroweak fit

Reminder: The CP Symmetry

CP Symmetry:

- Charge conjugation *C*:
  particle ↔ antiparticle
- Parity operation *P*:
  left-handed ↔ right-handed
- Combined *CP* operations:
  left-handed (right-handed) particle ↔ right-handed (left-handed) antiparticle

Example: pion decay

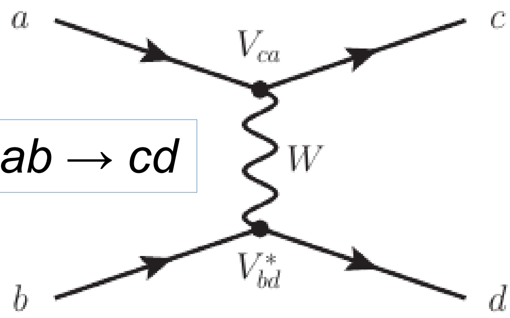


CP symmetry is conserved in the electromagnetic and strong interaction
as mentioned earlier, EW CP violation possible with three flavour generations

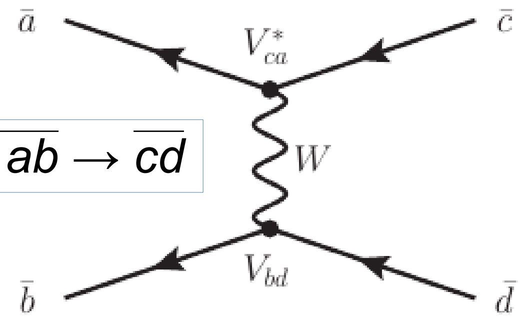
Electroweak CP Violation

charged-current interaction:

$1.\ ab \to cd$



$2.\ \overline{ab} \to \overline{cd}$



- 1. Process with **particles**:

$$\mathcal{M}(ab \to cd) \sim V_{ca} V^*_{bd} \left[\bar{c} \left(\gamma^\mu \frac{1}{2}(1-\gamma_5) \right) a \right] \left[\bar{d} \left(\gamma_\mu \frac{1}{2}(1-\gamma_5) \right) b \right]$$

CP-transformed process:
$$\mathcal{M}_{CP} \sim V_{ca} V^*_{bd} \left[\bar{a} \left(\gamma^\mu \frac{1}{2}(1-\gamma_5) \right) c \right] \left[\bar{b} \left(\gamma_\mu \frac{1}{2}(1-\gamma_5) \right) d \right]$$

- 2. Process with **antiparticles**:

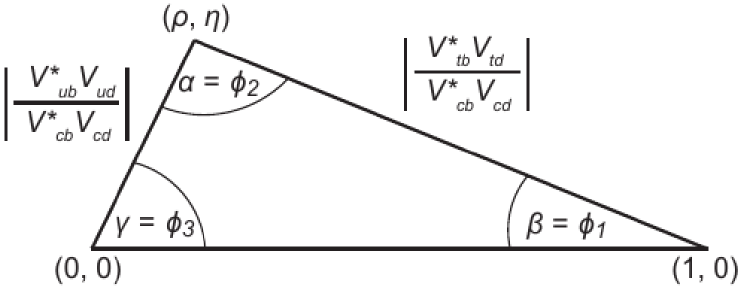
$$\mathcal{M}(\bar{a}\bar{b} \to \bar{c}\bar{d}) = \mathcal{M}(cd \to ab) \sim V^*_{ca} V_{bd} \left[\bar{a} \left(\gamma^\mu \frac{1}{2}(1-\gamma_5) \right) c \right] \left[\bar{b} \left(\gamma_\mu \frac{1}{2}(1-\gamma_5) \right) d \right] = \mathcal{M}^\dagger$$

For real-valued V_{ca}, V_{bd}, the last two relations are identical,
but not if V_{ca}, V_{bd} are complex → **CP Violation**

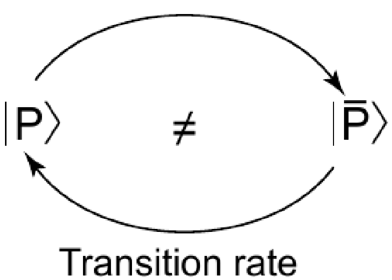
Electroweak CP Violation

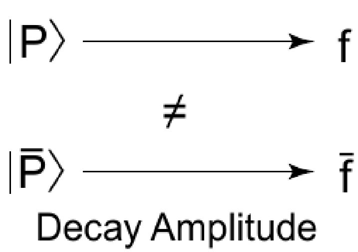
CKM matrix for ≥ quark families generally complex: $\mathcal{M}_{CP} \neq \mathcal{M}^{\dagger}$

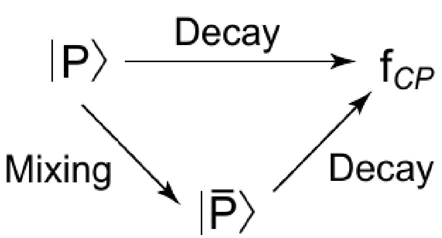
- Necessary requirement for **CP violation in quark mixing**
- Reminder: **area** of unitarity triangle = measure of CP violation
- Experimental question: is complex phase **δ≠0** realized in nature?



Known **mechanisms** for electroweak CP violation:







Indirect CP violation
CP violation through mixing

Direct CP violation

CP violation through interference of mixing and decay

Formalism of CP Violation

Reminder: **time evolution** of strong eigenstates

$$\begin{pmatrix} |P(t)\rangle \\ |\overline{P}(t)\rangle \end{pmatrix} = \begin{pmatrix} g_+(t) & \frac{p}{q} g_-(t) \\ \frac{q}{p} g_-(t) & g_+(t) \end{pmatrix} \begin{pmatrix} |P\rangle \\ |\overline{P}\rangle \end{pmatrix}$$

- **Decay amplitude**: matrix element for decay to final state f

$$A_f = \mathcal{M}(|P\rangle \to f), \quad \overline{A}_f = \mathcal{M}(|\overline{P}\rangle \to \overline{f})$$

- Relevant quantity for CP violation:

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = \left|\frac{q}{p}\right| \left|\frac{\overline{A}_f}{A_f}\right| \exp[i(\phi_{\text{mixing}} - \phi_{\text{decay}})]$$

$|q/p| \neq 1 \to$ CPV through mixing

$|\overline{A}_f/A_f| \neq 1$
$\to$ direct CPV

Phase difference
$\to$ CPV through mixing-decay interference

CP violation is measurable in interference experiments capable of **detecting relative phases** (analogous to double-slit experiment)

CP Violation in Kaon System

K-mesons produced in stron-interaction reactions have a definite quark content:

→ initial K_0 or $\overline{K}_0$ state

These are, however, not the mass eigenstates,
which result from mixing through weak interaction:

- K^0_S („K-short"): proper lifetime $c\tau$ = 2.7 cm, decays mainly into $\pi\pi$
- K^0_L („K-long"): proper lifetime $c\tau$ = 15 m, decays mainly into $\pi\pi\pi$
- Reason for long K^0_L lifetime: $m(\pi\pi\pi) \lesssim m_K$

CP eigenstates:

- Final states with n pions: CP eigenstates with $CP\,|n\cdot\pi\rangle = (-1)^n\,|n\cdot\pi\rangle$
- CP eigenstates of neutral kaons:

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K}_0\rangle\right), \quad |K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K}_0\rangle\right)$$

? Do the observed mass eigenstates, K_S and K_L, correspond to the CP eigenstates, K_1 and K_2 ?

Experimental Answer: no, observation of decay of K_L to 2 pions
→ CP Violation

Discovery of CP Violation

Discovery experiment:

(J. Christenson, J. Cronin, V. Fitch, R. Turlay, PRL 13 (1964) 138)

- Prepare pure K^0_L beam → decays mainly into CP eigenstate $\pi\pi\pi$ (eigenvalue $CP = -1$)
- If decay $K^0_L \to \pi\pi$ ($CP = +1$) is observed → **indirect CP violation** (through mixing of K^0 and $\overline{K}^0$)

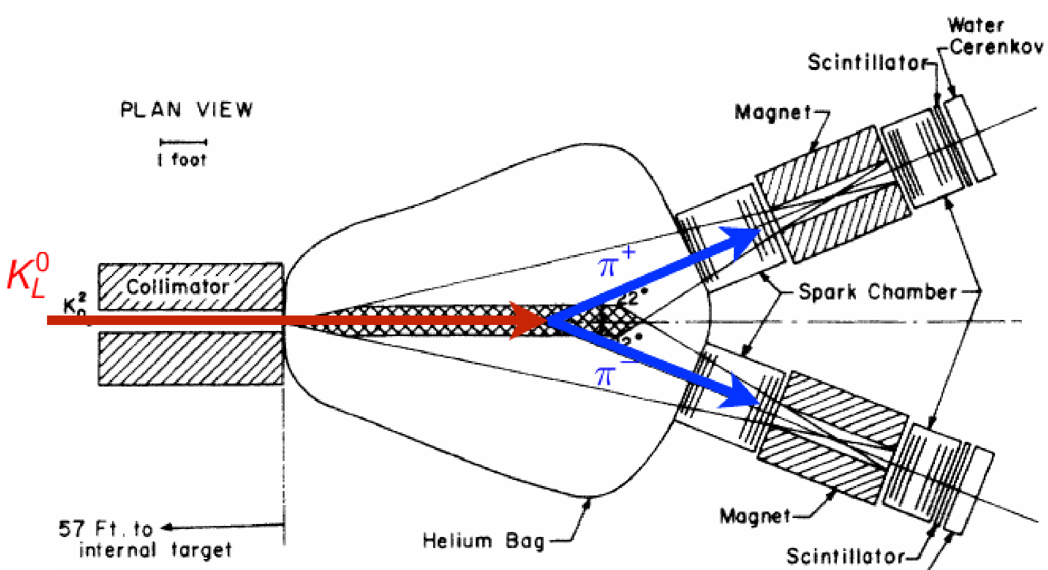
Recipe: how to make a kaon beam

- Direct protons on fixed target → beam of secondary particles
- Remove all charged particles from beam with magnets and collimators → neutral kaon beam
- Let all K^0_S decay (approx. 20 m of decay tunnel): pure $\boldsymbol{K^0_L}$ **beam** (cf. kaon mixing)
- Remark: K^0_S may be **regenerated** due to different strong interaction probabilities of K^0 and $\overline{K}^0$ in matter (→ background, to be controlled)

Discovery of CP Violation: Cronin-Fitch Experiment

Setup: **two-arm spectrometer**

- Measure momentum of $\pi^{\pm}$ (magnetic spectrometer)
- Signal: **invariant ππ mass m* ≈ 498 MeV** and angle of $\pi\pi$ system relative to beam **cos $\theta \approx 1$**



Low-density material
→ reduced regeneration probability

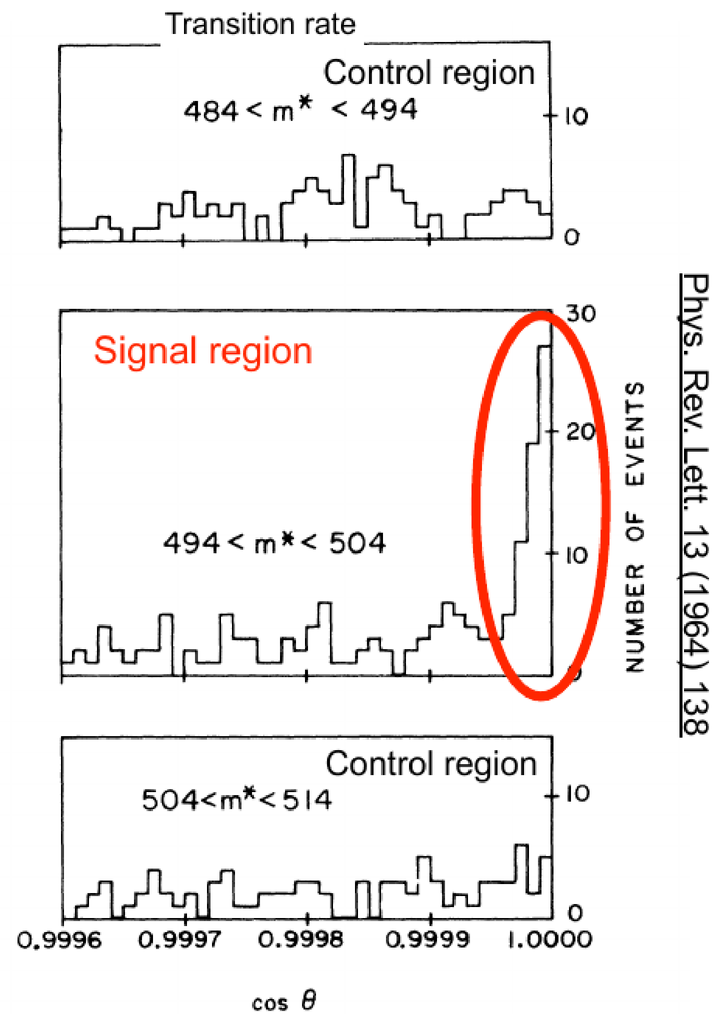
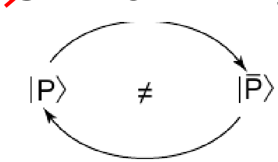


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

~~CP~~ via mixing



CP Violation in Neutral Kaon System

Results of Cronin-Fitch experiment

- 45 ± 9 candidates for decay $K^0_L \to \pi^+\pi^-$ in 22,700 K^0_L decays
- Mass eigenstates K^0_S, K^0_L are **not the same as CP eigenstates**

→ K_1 and K_1 have a small admixture of “wrong” CP state,

$$|K_S^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(|K_1\rangle + \epsilon\,|K_2\rangle\right)$$

$$|K_L^0\rangle = \frac{1}{\sqrt{1+|\epsilon|^2}}\left(\epsilon\,|K_1\rangle + |K_2\rangle\right)$$

With small (complex) parameter ε

value today (PDG 2017): $\mathbf{|\varepsilon| = 2.228(11)\cdot 10^{-3}}$ (→ 10^{-3} effect)

Discovery of Direct CP violation in K system

Direct CP violation in neutral Kaon system described by an additional **parameter ε'**

- Compare $K^0{}_L$ and $K^0{}_S$ decays into two neutral or charged pions

$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} \approx \epsilon + \epsilon', \quad \eta_{00} = \frac{A(K_L^0 \to \pi^0\pi^0)}{A(K_S^0 \to \pi^0\pi^0)} \approx \epsilon - 2\epsilon'$$

- Observable: **double ratio**

$$R = \frac{\Gamma(K_L^0 \to \pi^0\pi^0)/\Gamma(K_S^0 \to \pi^0\pi^0)}{\Gamma(K_L^0 \to \pi^+\pi^-)/\Gamma(K_S^0 \to \pi^+\pi^-)} = \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \approx 1 - 6\,\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$$

Measurement idea of 2nd generation experiments:

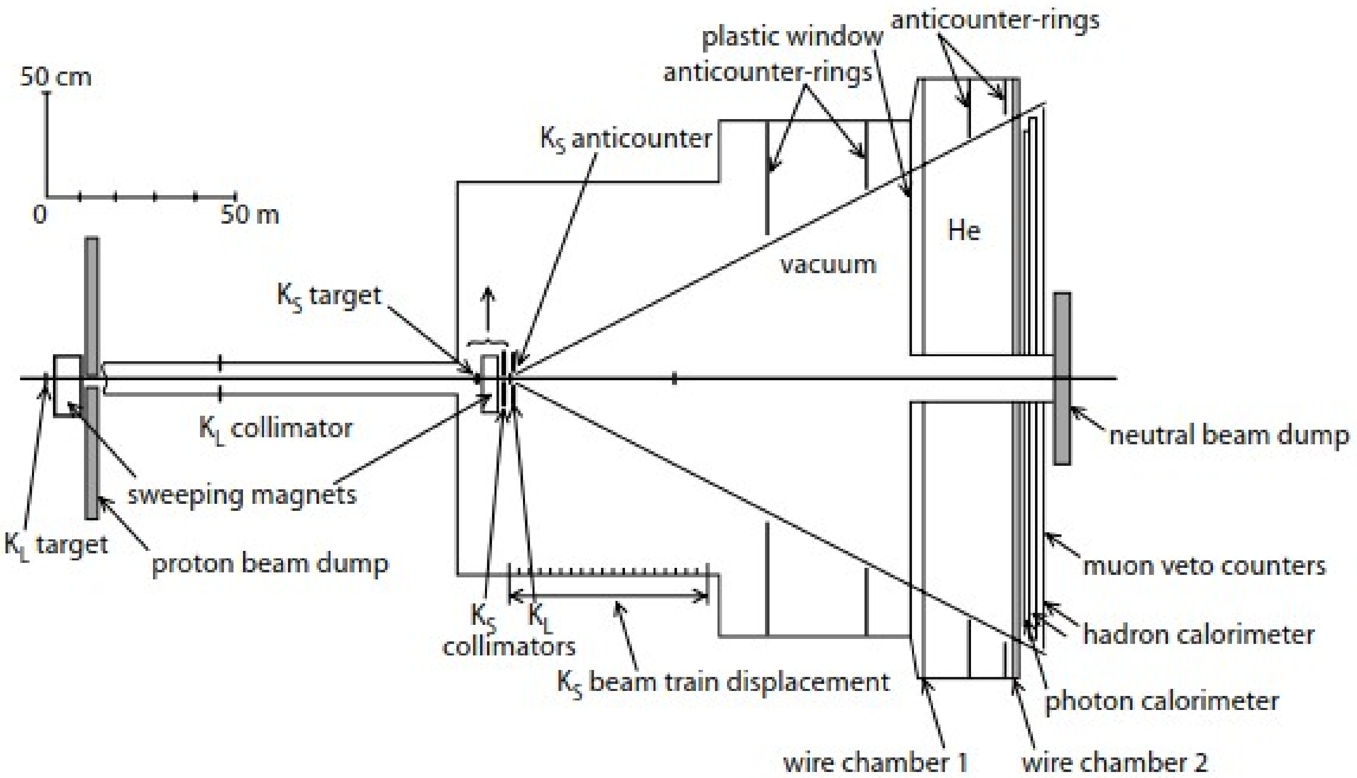
to control systematics, study
- KS and KL beams and
- neutral and charged final states   in the same experiment

- 1980s: NA31 (CERN) → $\varepsilon'/\varepsilon \neq 0$, E731 (Fermilab) → $\varepsilon'/\varepsilon = 0$
- 1990s: NA48 (CERN), KTeV (Fermilab) → $\varepsilon'/\varepsilon \neq 0$

Result (PDG 2017): **Re(ε'/ε) = 1.66(23)·10^{-3}** (→ 10^{-6} effect)

First evidence for direct CP Violation – NA31 (1988)

- K_L and K_S measured in momentum bins at the same location with mobile K_S target reproducing the decay region of K_L
- simulaneous measurement of neutral and charged decays
  - $\pi^{\pm}$ detection in wire chambers
  - detection of photons from π^0 decays in liquid-argon calorimeter and veto-counters
- veto on $e^{\pm}$ and $\mu^{\pm}$ (from semileptonic decays) in calirometers and myon veto



first evidence at 3σ level for direct CP violation

Phys.Lett. B206 (1988) 169-176

CP violation in B decays

interference of two decay amplitudes in $B \rightarrow K\pi$

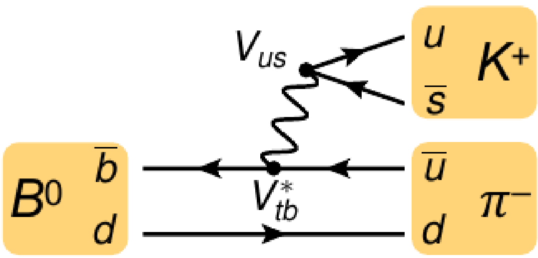
~~CP~~ in decay

$|P\rangle \longrightarrow f$

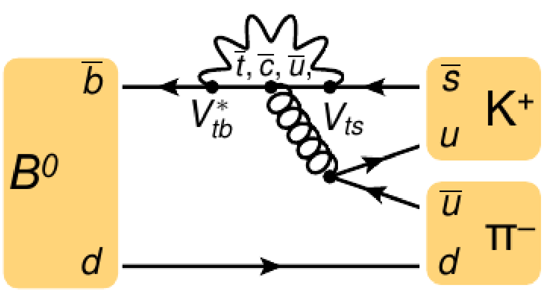
$\neq$

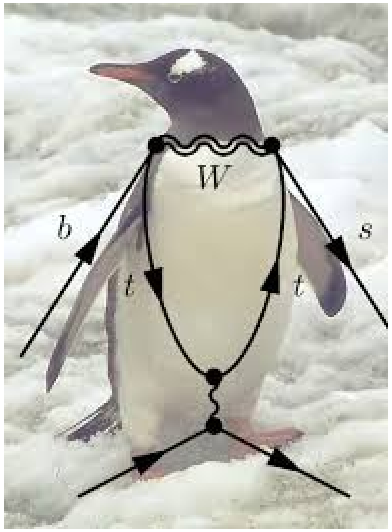
$|\bar{P}\rangle \longrightarrow \bar{f}$

- Tree-level Feynman diagram:



- One-loop diagram (J. Ellis: “penguin diagram”):





wikipedia

CP violation in B decays (2)

$B^0 \rightarrow K\pi$ has small branching fraction:

$\mathrm{B}(B \rightarrow K^+\pi^-) = 1.96(5) \times 10^{-5}$

~~CP~~ in decay

$|P\rangle \longrightarrow f$

$\neq$

$|\bar{P}\rangle \longrightarrow \bar{f}$

CP asymmetry

$$A_{CP} = \frac{N(\overline{B}^0 \rightarrow K^-\pi^+) - N(B^0 \rightarrow K^+\pi^-)}{N(\overline{B}^0 \rightarrow K^-\pi^+) + N(B^0 \rightarrow K^+\pi^-)}$$

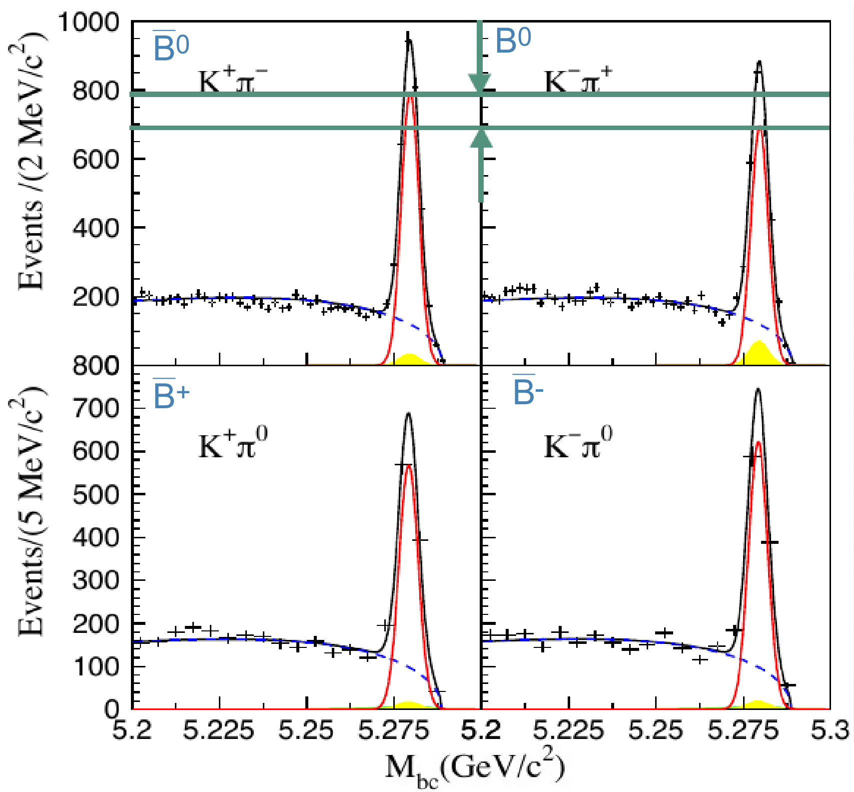
B-meson reconstruction:

- In center-of-mass frame:
  $E_B = E_{\bar{B}} = E^*_{beam}$
- **Beam-constrained mass**:

$$M_{bc} = \sqrt{(E^*_{beam})^2 - (\mathbf{p}^*_B)^2}$$

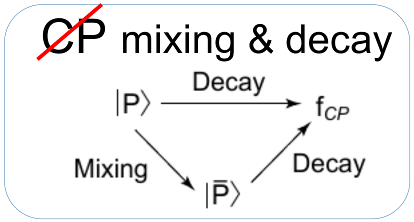
$\mathbf{p}^*_B$: B-meson momentum reconstructed from π and K in center-of-mass frame

Result of Belle Experiment:
CP asymmetry in $K^\pm\pi^\mp$
no signal in $K^\pm\pi^0$



Phys. Rev. D87 (2013) 031103

CP Violation in B system: sin 2β



CP violation through mixing – decay interference

- Particle and antiparticle decay into the same **CP eigenstate *f*$_{CP}$**
- Observable: **time-dependent CP asymmetry**

$$\mathcal{A}_{f_{CP}} = \frac{\frac{d\Gamma}{dt}(|\overline{P}\rangle \to f_{CP}) - \frac{d\Gamma}{dt}(|P\rangle \to f_{CP})}{\frac{d\Gamma}{dt}(|\overline{P}\rangle \to f_{CP}) + \frac{d\Gamma}{dt}(|P\rangle \to f_{CP})} = \frac{2\,\mathrm{Im}(\lambda_f)}{1+|\lambda_f|^2}\sin(\Delta m t) - \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos(\Delta m t)$$

with $\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$

S_f: CPV through interference

C_f (also: A_f): direct CPV

Golden channel: *B*$^0 \to$ *J/ψ K*^0_S

- C_f = 0: no direct CP violation
- Small **theoretical uncertainties** caused by hadronization
- But: small branching fraction 8.73(32)×10^{-4} (PDG 2016)
- Historically: **first observation of CP violation in B-meson system** (BaBar, Belle, 2001)

CP Violation in B system: sin 2β (2)

- λ_f for $B^0 \rightarrow J/\psi\ K^0{}_S$:

$$\lambda_{J/\psi K_S^0} = -\underbrace{\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}}_{B\bar{B}\text{ Mixing}} \cdot \underbrace{\frac{V_{cb}^* V_{cs}}{V_{cb} V_{cs}^*}}_{\text{B Decay}} \cdot \underbrace{\frac{V_{cs}^* V_{cd}}{V_{cs} V_{cd}^*}}_{K\bar{K}\text{ Mixing}}$$

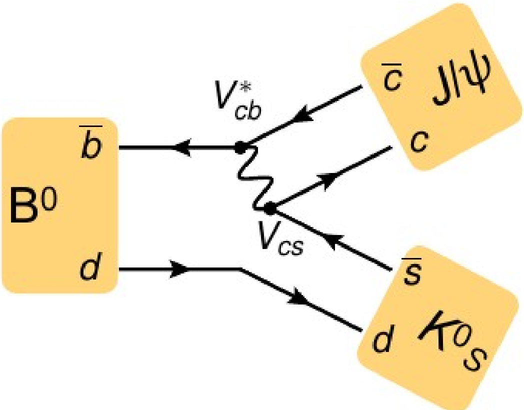
- Wolfenstein parameterization:

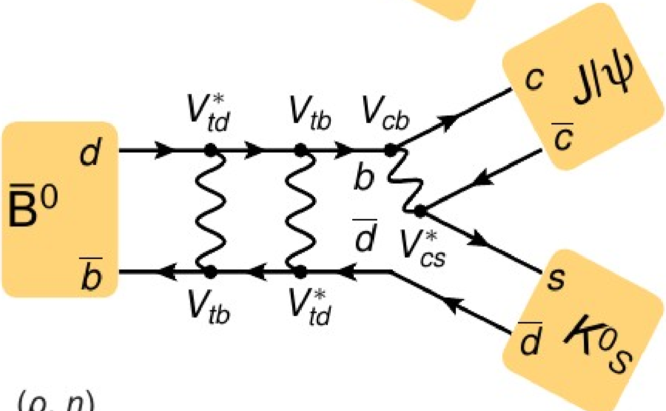
$V_{tb} = 1$; V_{cb}, V_{cs}, V_{cd} real;
complex phase only for V_{td}

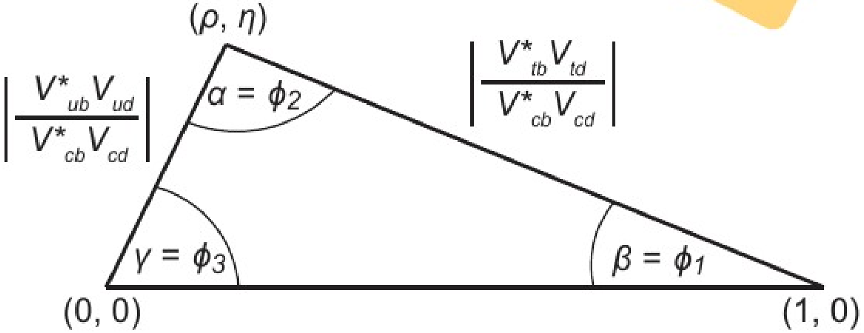
$$\lambda_{J/\psi K_S^0} \approx -\frac{V_{td}}{V_{td}^*} = -\exp[2i \arg(V_{td})]$$

- Mixing-induced CPV ~ Im(λ):

$$\text{Im}\left(\lambda_{J/\psi K_S^0}\right) \approx -\sin[2\arg(V_{td})]$$
$$= -\sin[2\arg(1-\rho-i\eta)]$$
$$= \sin 2\beta \equiv \sin 2\phi_1$$



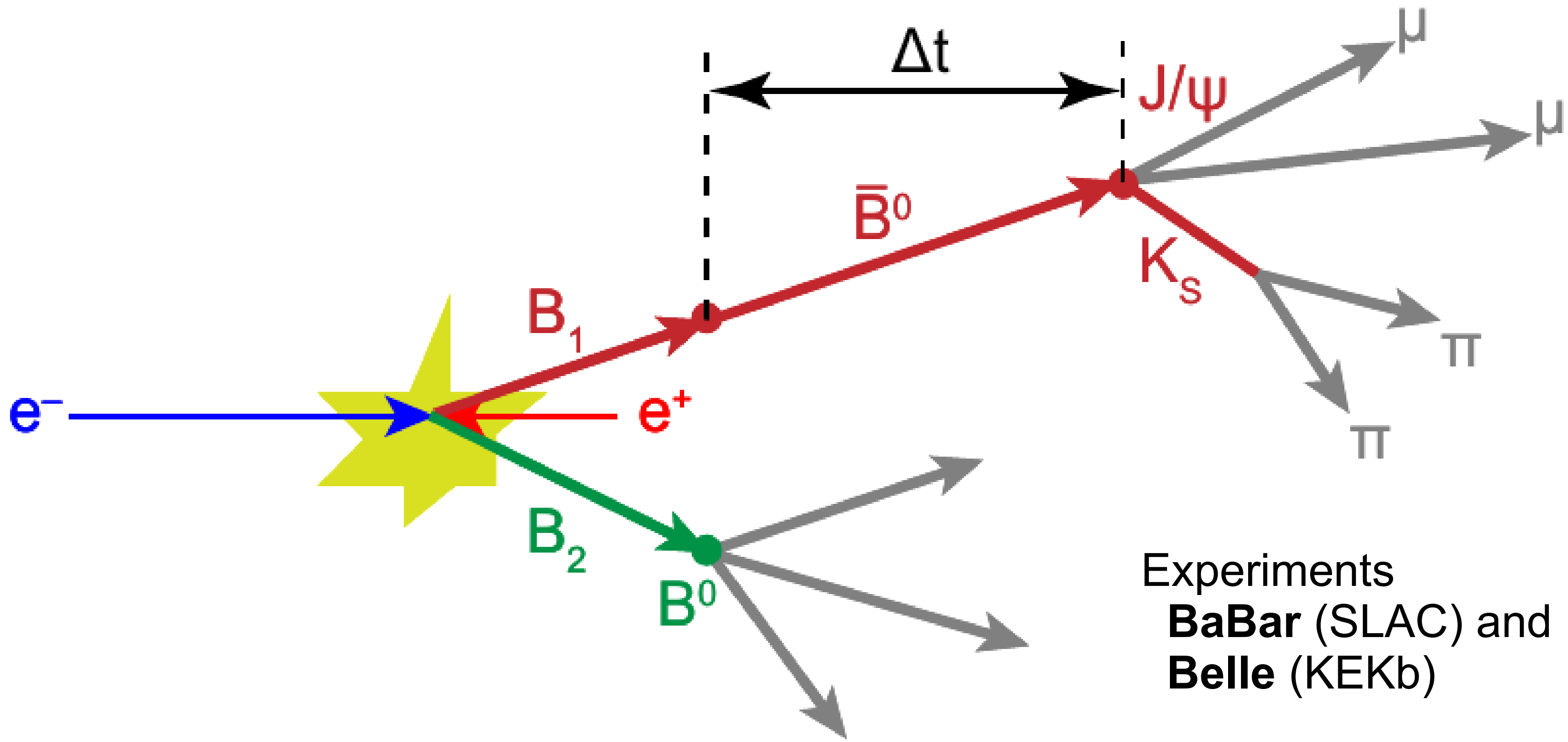




CP Violation in B system: sin 2β (3)

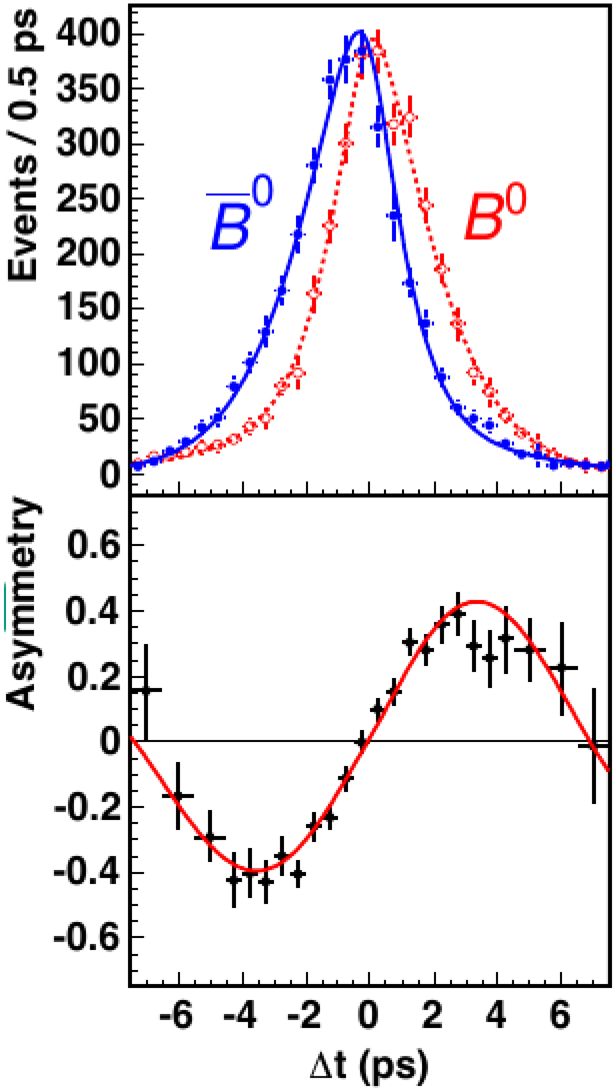
Measurement of **time-dependent CP asymmetry**

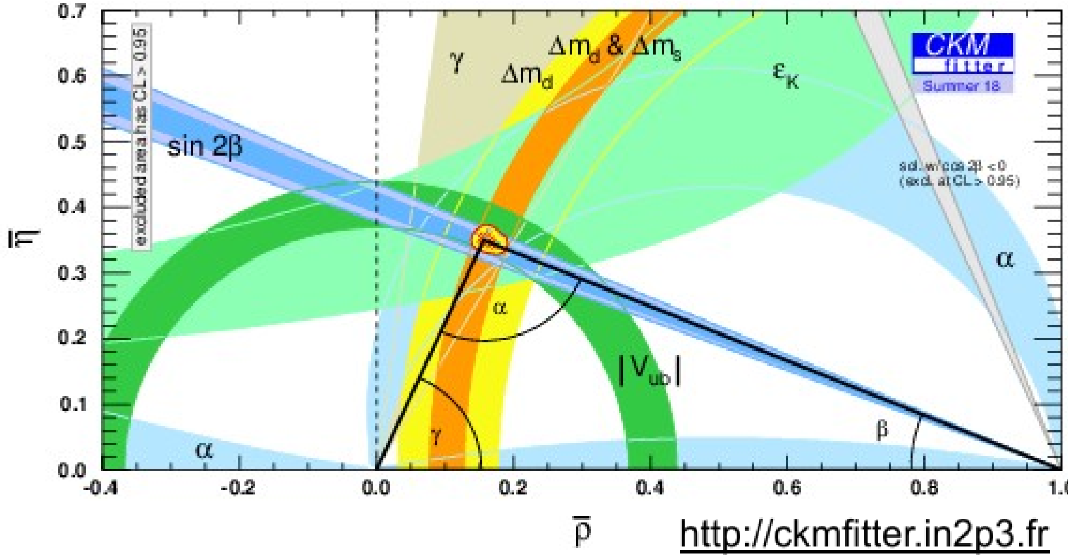
- B_1 flavor at **production**: tag flavor of B_2
- Reconstruct B_1 via **CP eigenstate** $J/\psi\ K^0_S$ in decay $\mu\mu\ \pi\pi$
- Determine lifetime difference Δt via **decay length difference**
- Extract CPV parameter sin 2β from **fit** of CP asymmetry distribution



Experiments
BaBar (SLAC) and
Belle (KEKb)

CP Violation in B system: sin 2β (4)

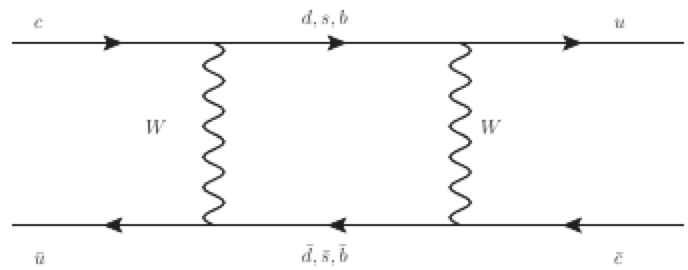




Measurement (Belle 2012):
sin 2β = 0.667(26)

sin 2β measurement significantly helps to **constrain the CKM unitarity triangle**

Latest news: CP violation in D system



Mixing in D-System is very small
(c$\bar{u}$ state, GIM and CKM suppressed)

Discovery channels:

- D^0 , $\bar{D}^0$ $\rightarrow$ K^+K^-
- D^0 , $\bar{D}^0$ $\rightarrow$ $\pi^+\pi^-$

Observable: $$A_{CP}(f;t) \equiv \frac{\Gamma(D^0(t)\to f) - \Gamma(\bar{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\bar{D}^0(t)\to f)}$$

Assuming universality between K and π decay modes,

$\rightarrow$ differenced between K^+K^- and $\pi^+\pi^-$:

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \approx \Delta a_{CP}^{\rm dir} - \frac{\Delta\langle t\rangle}{\tau(D^0)} A_\Gamma$$

Result:

$$\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}$$

largest contribution:

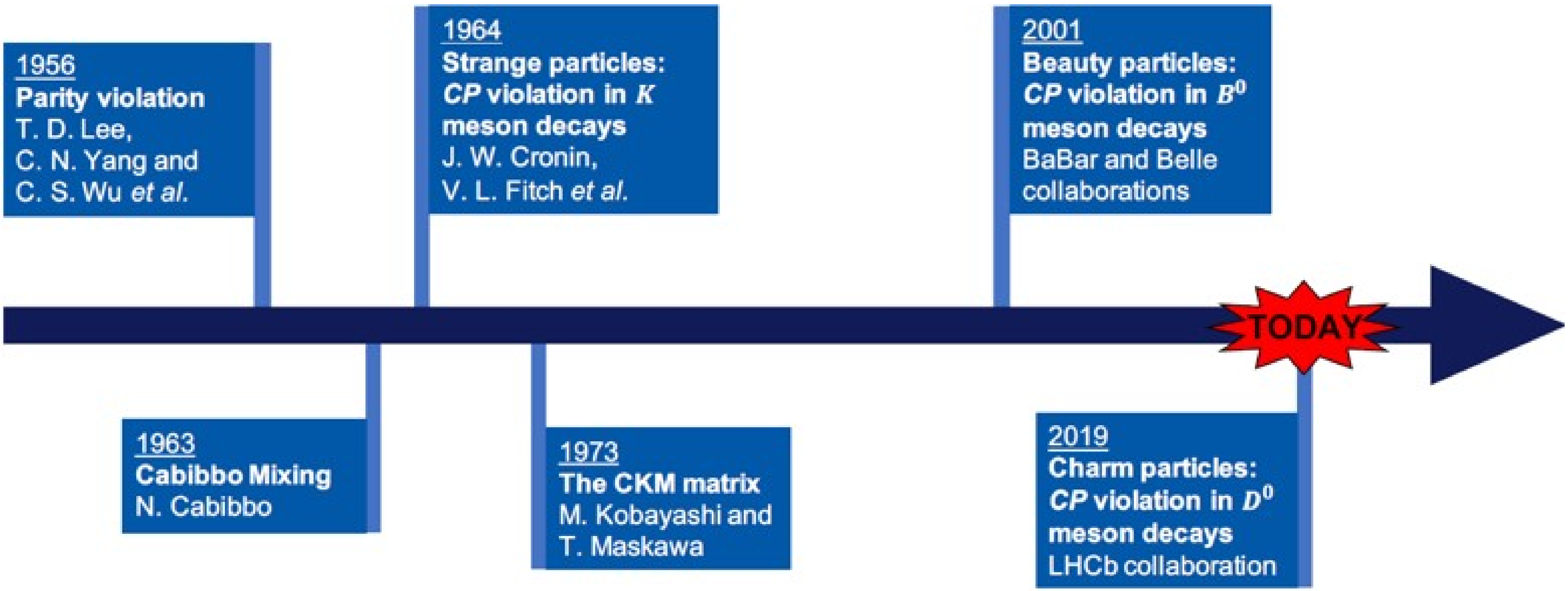
$$\Delta a_{CP}^{\rm dir} = (-15.7 \pm 2.9)\times 10^{-4}$$

Phys. Rev. Lett. 122 (2019) 211803

$\Delta a^{\rm dir}$: direct CP asymmetry
$\Delta\langle t\rangle$: difference between mean decay times K^+K^- and $\pi^+\pi^-$
A_Γ: asymmetry between decay widths

First observation of CP violation in charm system, consistent with expectations from the Standard Model

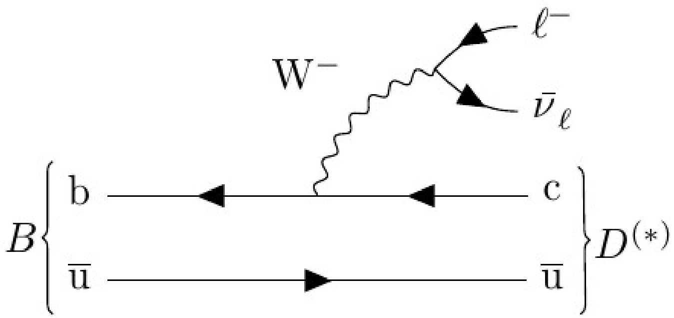
CP Violation: History



http://lhcb-public.web.cern.ch/lhcb-public/Welcome.html#CPVcharm

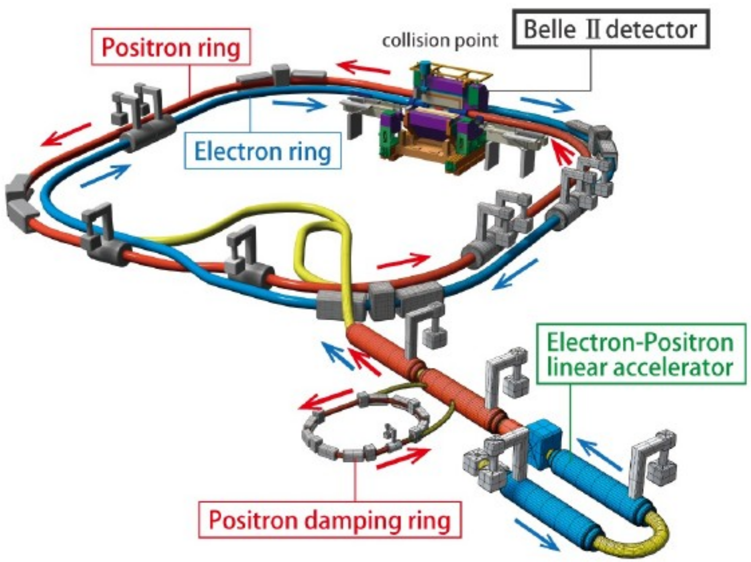
Appetizer: Anomalies in B system

Results of measurements by B-factories and at LHCb show some “tension” wrt. SM:



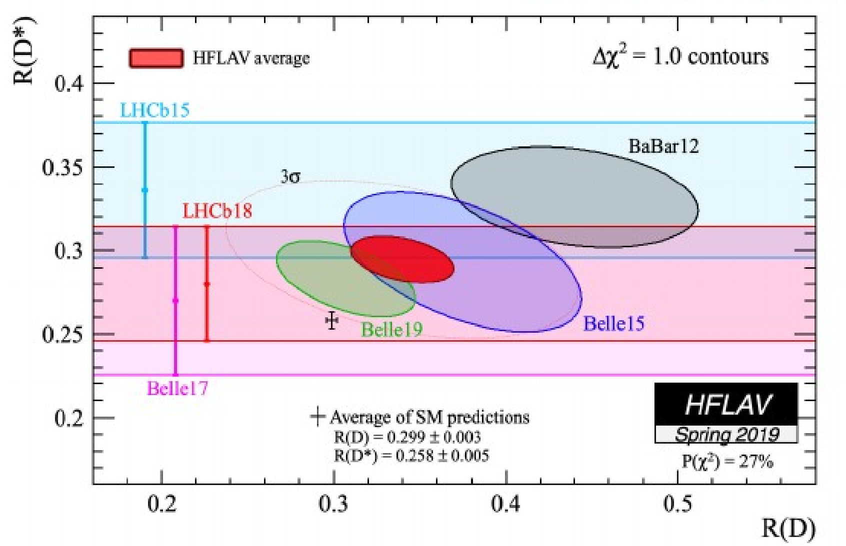
$$\mathcal{R}\left(D^{(*)}\right) = \frac{\mathcal{B}\left(\overline{B}\to D^{(*)}\tau\nu\right)}{\mathcal{B}\left(\overline{B}\to D^{(*)}\ell\nu\right)}$$

The Belle II experiment at the SuperKEKb accelerator in Tsukuba / Japan started data taking last year



strong contributions from KA !

Belle 19 1904.08794



Source: Talk by Pablo Goldenzweig at Planck 2019 conference in Grenada/Spain

Summary V14b: CP violation

- CP symmetry is conserved in electroweak and strong interactions

- CP is violated in the weak interaction
  - indirect: in particle-antiparticle mixing
  - direct: different decay amplitudes for particles and antiparticles
  - through interference of mixing and decay to the same CP eigenstate

- Status 2019: CP violation observed
  - in neutral kaon system
  - in neutral B mesons
  - direct in charged B-mesons
  - difficult to observe in charm sector due to small mixing and long-range QCD effects, discovered by LHCb in 2019 in difference between $D^0, \overline{D}^0 \rightarrow K^+K^-$, $\pi^+\pi^-$

- CP violation in quark sector not strong enough to explain matter dominance in erarly universe; need additional sources of CP violation (QCD ? neutrinos ?)

Appendix: Operators

OperatorParity:

$$P = \gamma^0 \qquad \Psi(-\vec{r}) = P\Psi(\vec{r})$$

Charge Conjugation Operator:

$$C = \mathrm{i}\gamma^2\gamma^0 = \begin{pmatrix} & -\mathrm{i}\sigma^2 \\ -\mathrm{i}\sigma^2 & \end{pmatrix} \qquad \Psi_C = C\bar{\Psi}^T$$

$\rightarrow$

$$CP\Psi(\vec{r},t) = i\gamma^2\gamma^0\Psi(-\vec{r},t)$$

$$\overline{\psi}_1\gamma_\mu\psi_2 \xrightarrow{C} -\psi_1^T C^{-1}\gamma_\mu C\overline{\psi}_2^T = \psi_1^T\gamma_\mu^T\overline{\psi}_2^T = -(\overline{\psi}_2\gamma_\mu\psi_1)^T = -\overline{\psi}_2\gamma_\mu\psi_1$$