CP Violation in K Decay

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Symmetries

- Continuous:

Symmetry trafo		Conserved quantity
Time translation	$\leftrightarrow$	Energy
Spatial translation	$\leftrightarrow$	Linear momentum
Spatial rotation	$\leftrightarrow$	Angular momentum

- Discrete:

Symmetry trafo		Conserved quantity
Charge conjugation	$\leftrightarrow$	η_C
Parity inversion	$\leftrightarrow$	η_P
Time reversal	$\leftrightarrow$	η_T

$\eta_P(AB) = \eta_P(A) \cdot \eta_P(B) \cdot (-1)^l$

Parity transformation (P)

- Inversion of all spatial coordinates:

$$\vec{r} \xrightarrow{\hat{P}} -\vec{r}$$

$$\Rightarrow \vec{p} = m\frac{d\vec{r}}{dt} \xrightarrow{\hat{P}} -\vec{p} \Rightarrow \vec{F} = \frac{d\vec{p}}{dt} \xrightarrow{\hat{P}} -\vec{F}$$

- Axial (pseudo) vector:

$$\vec{L} = \vec{r} \times \vec{p} \xrightarrow{\hat{P}} \vec{L}$$

- Pseudoscalar: $\vec{L} \cdot \vec{p} \xrightarrow{\hat{P}} -\vec{L} \cdot \vec{p}$
- Mirror symmetry $\Rightarrow \left\langle \vec{L} \cdot \vec{p} \right\rangle = 0$

Parity Violation

- 1949/50: $\theta - \tau$ puzzle

  $\theta^+ \rightarrow \pi\pi$ and $\tau^+ \rightarrow \pi\pi\pi$

- 1956: Lee and Yang propose experiments to test parity symmetry in weak interactions

http://smartlemming.com/2009/05/dont-be-the-master-of-spin-on-your-own-performance/

The Wu Experiment (1957)

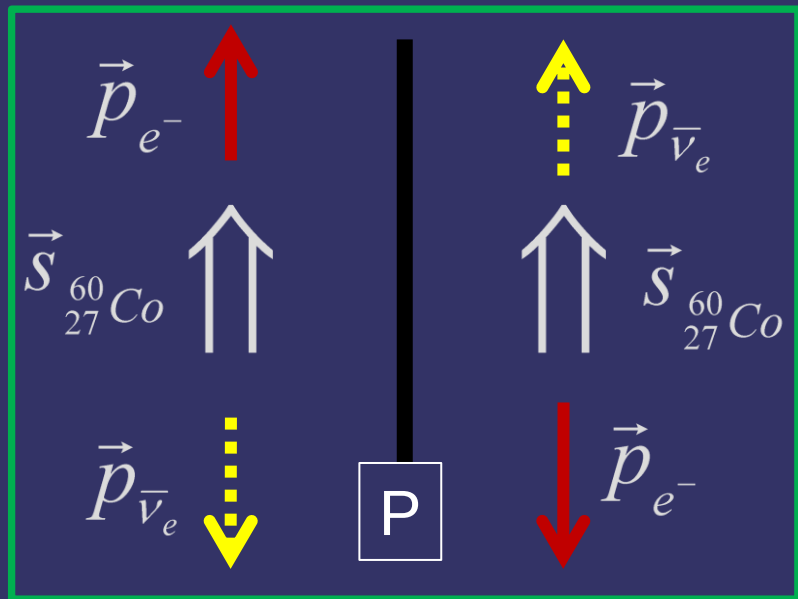
Chien Shiung Wu
(1912-1997)

- Beta decay of polarized Cobalt nuclei:

$$^{60}_{27}\mathrm{Co}_{I=5} \rightarrow {}^{60}_{28}\mathrm{Ni}^{*}_{I=4} + e^{-}_{J=1/2} + \overline{\nu}_{e\ J=1/2}$$

- Parity symmetry => $\left\langle \vec{p}_{e^-} \cdot \vec{s}_{^{60}_{27}Co} \right\rangle = 0$

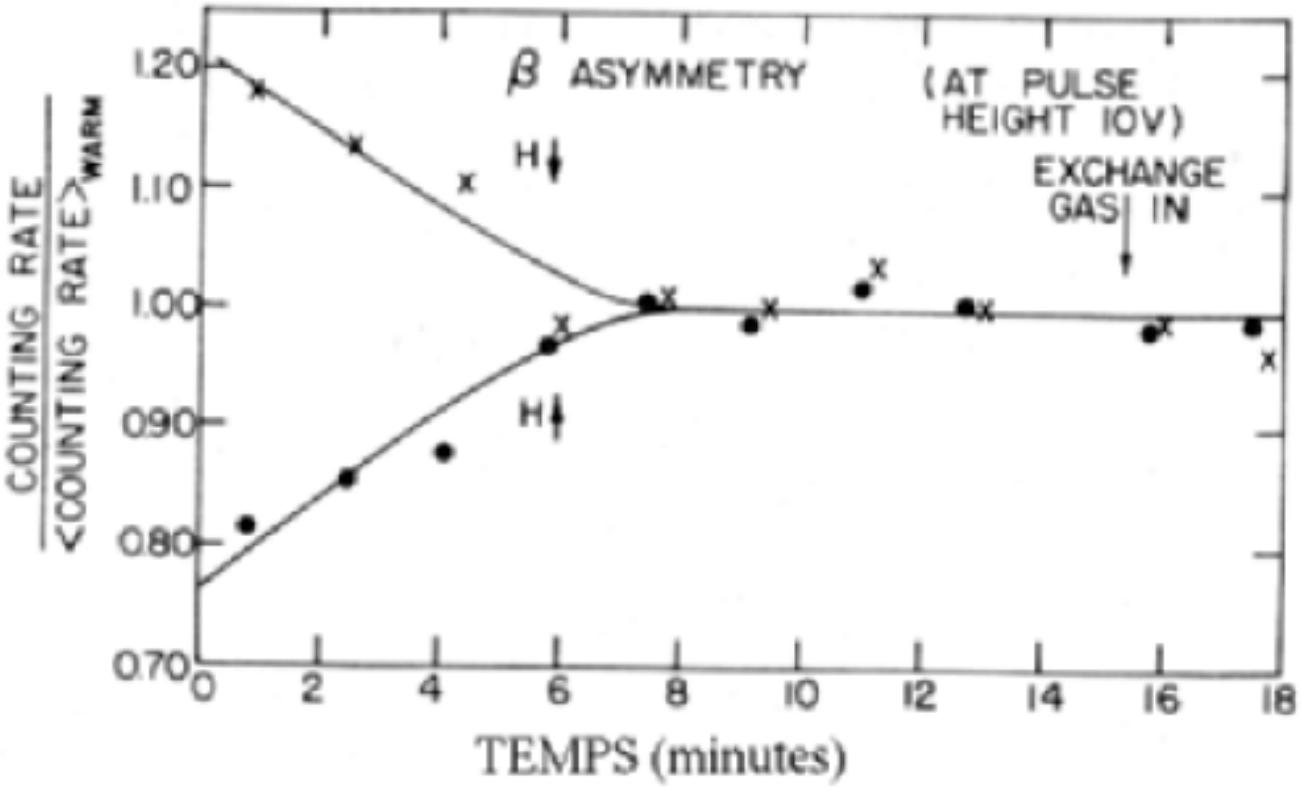
- Result: Electrons are emitted preferentially in the direction opposite to the nucleus spin

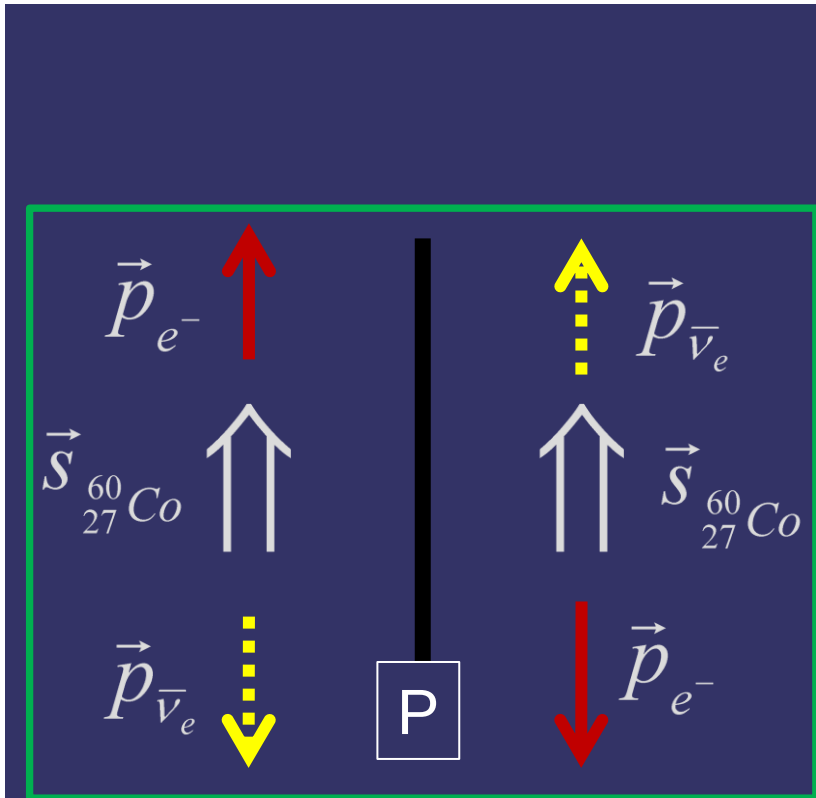


The Wu Experiment (1957)

- Parity symmetry is violated in weak interactions: $\left\langle \vec{p}_{e^-} \cdot \vec{s}_{^{60}_{27}Co} \right\rangle \neq 0$

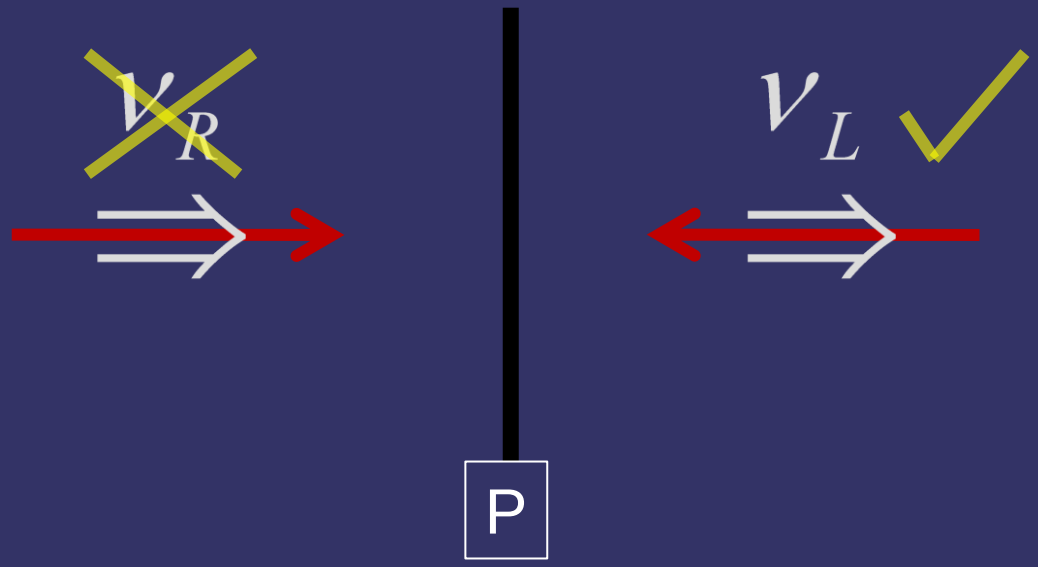
$$^{60}_{27}\mathrm{Co}_{I=5} \rightarrow {}^{60}_{28}\mathrm{Ni}^{*}_{I=4} + e^{-}_{J=1/2} + \bar{\nu}_{e\ J=1/2}$$





Maximal Parity Violation

- W,Z bosons only couple to left-handed particles and right-handed antiparticles
- Maximal Parity Violation in Weak Interactions!



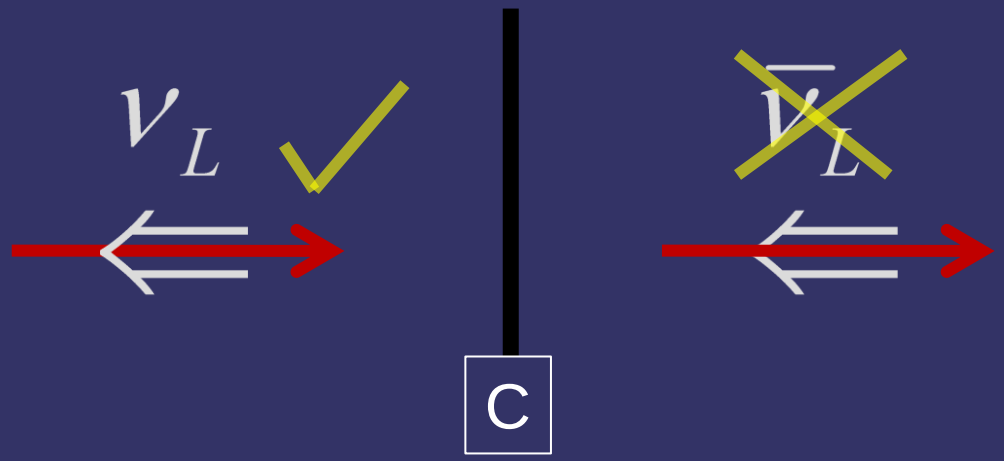
$$H = \frac{\vec{s} \cdot \vec{p}}{|\vec{s}| \cdot |\vec{p}|}$$

Charge Conjugation (C)

- Particle-Antiparticle conjugation

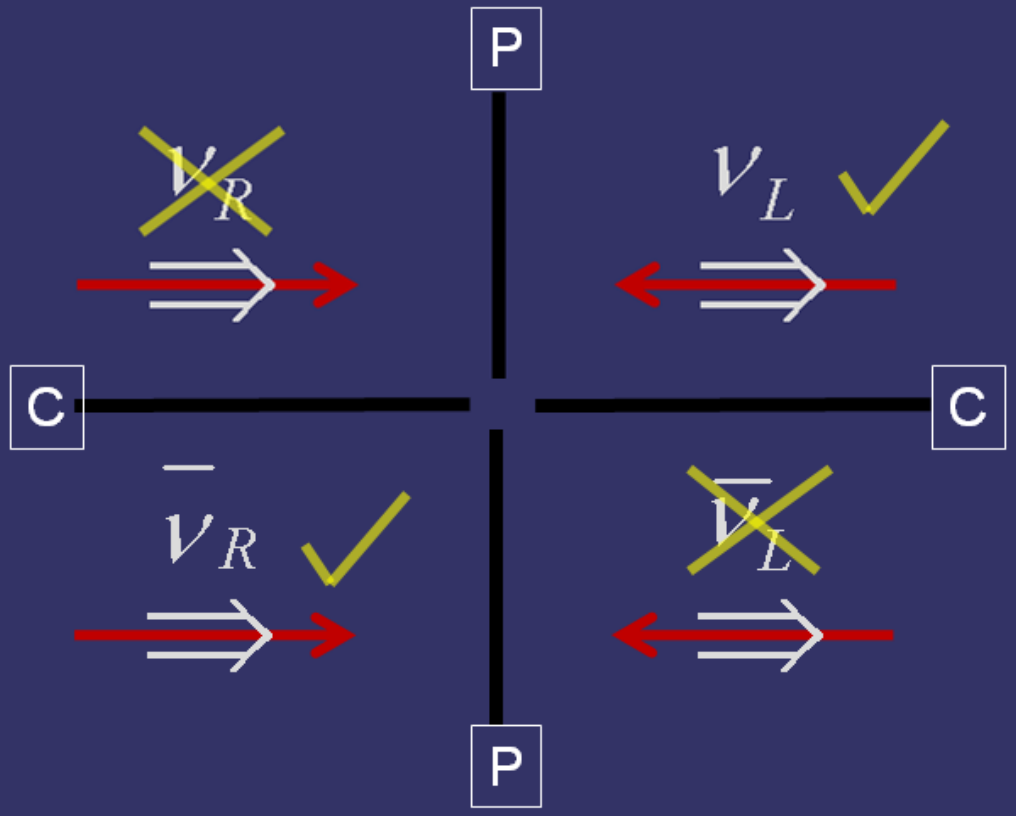
$$q \xrightarrow{\hat{C}} -q$$

- Strong and electromagnetic interactions invariant under C
- Symmetry maximally violated by weak interaction:



CP Invariance

- Landau (1957): CP is the true symmetry of nature



The $K^0 - \overline{K}^0$ system

- Quark content: $K^0 = d\bar{s}$, $\overline{K}^0 = \bar{d}s$
- Spin: s=0
- CP eigenstates: $K_1 = \frac{1}{\sqrt{2}}\left(K^0 + \overline{K}^0\right)$, $K_2 = \frac{1}{\sqrt{2}}\left(K^0 - \overline{K}^0\right)$
- CP conservation in weak decays

$$\Rightarrow \quad K_1 \to \pi\pi \qquad \left(\eta_{CP}(\pi\pi) = \eta_{CP}(\pi)^2 = 1\right)$$

$$K_2 \to \pi\pi\pi \qquad \left(\eta_{CP}(\pi\pi\pi) = \eta_{CP}(\pi)^3 = -1\right)$$

- Pais/Gell-Mann: the known short-lived Kaon ($\tau = 10^{-10}\,s$) must have a long-lived partner

CP Violation

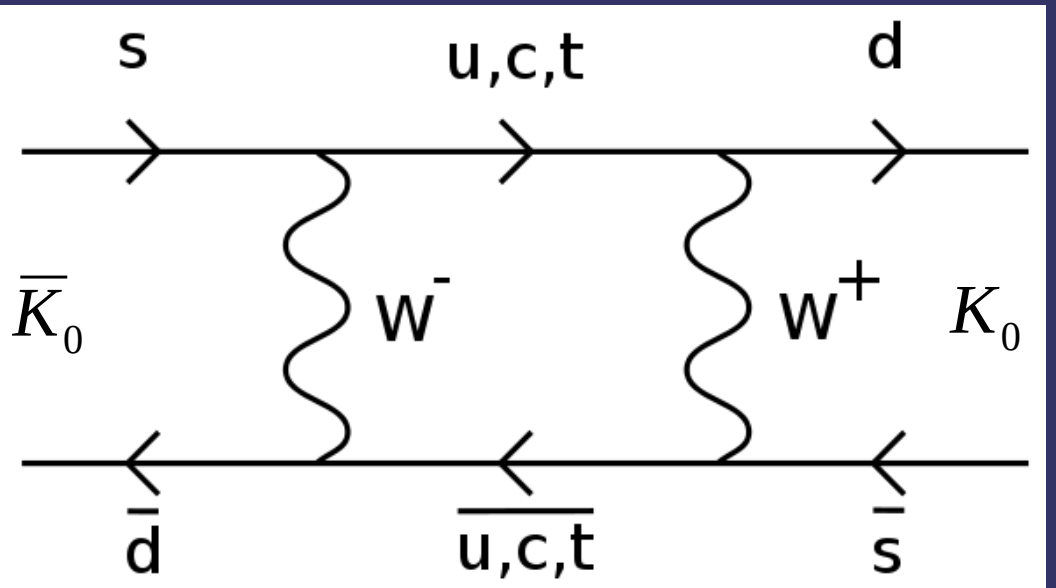
- Adair et al., BNL (1963): Anomalies in K_1 regeneration
- Christenson, Cronin, Fitch, Turlay (1964):

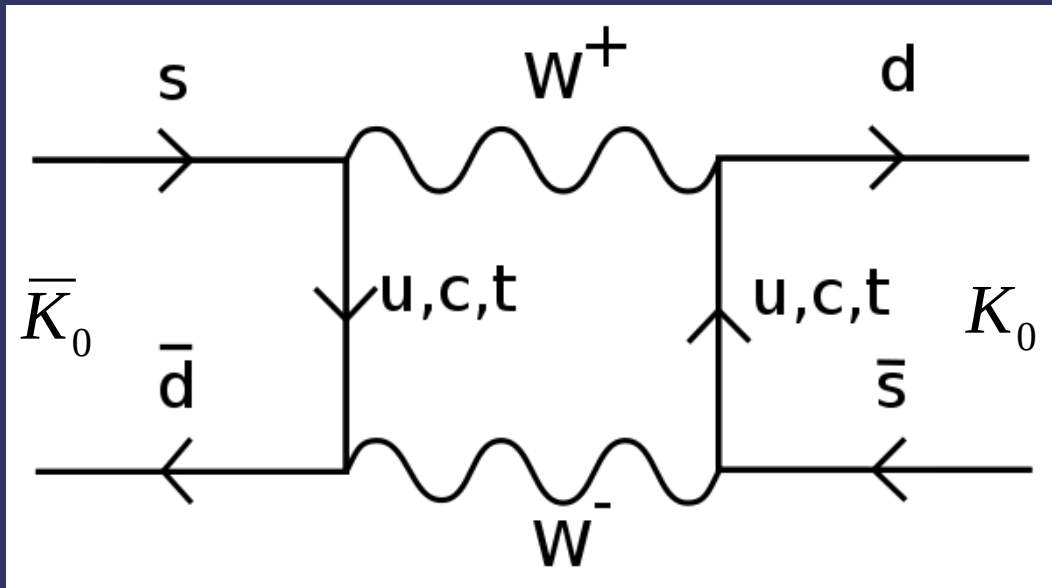
  Long-lived kaon decays into two charged pions!

  $$BR(K_L \to \pi^+\pi^-) \approx 2 \cdot 10^{-3}$$
- CP violation confirmed in the decays $K_L \to \pi^0\pi^0$ and by charge asymmetry in $K_L \to \pi^\pm e^\mp \nu, K_L \to \pi^\pm \mu^\mp \nu$
- Nobel prize in 1980 for Cronin and Fitch

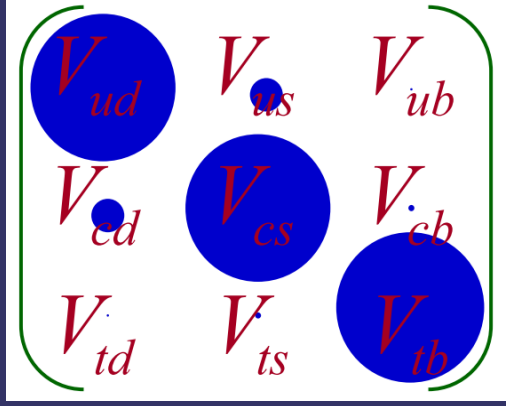
K mixing

- Strong eigenstates: $K^0 = d\bar{s}\,, \quad \bar{K}^0 = \bar{d}s$
- CP eigenstates: $K_1 = \frac{1}{\sqrt{2}}\left(K^0 + \bar{K}^0\right),\ K_2 = \frac{1}{\sqrt{2}}\left(K^0 - \bar{K}^0\right)$
- Weak eigenstates: $K_L = \frac{K_2 + \varepsilon \cdot K_1}{\sqrt{1+|\varepsilon|^2}}\,,\ K_S = \frac{K_1 + \varepsilon \cdot K_2}{\sqrt{1+|\varepsilon|^2}}$





CKM matrix (1973)



- Cabbibo matrix (unitary, 2x2)
  - 4 real parameters – 3 relative phases
  - = 1 Cabbibo angle
- CKM matrix (unitary, 3x3)
  - 9 real parameters – 5 relative phases
  - = 3 Cabbibo angles + one phase
- 6 Quarks make CP violating phase possible!
- Nobel Prize 2008

$$\begin{bmatrix} |\mathrm{d}'\rangle \\ |\mathrm{s}'\rangle \\ |\mathrm{b}'\rangle \end{bmatrix} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} |\mathrm{d}\rangle \\ |\mathrm{s}\rangle \\ |\mathrm{b}\rangle \end{bmatrix}$$

Makoto Kobayashi
1944 –

Toshihide Maskawa
1940 –

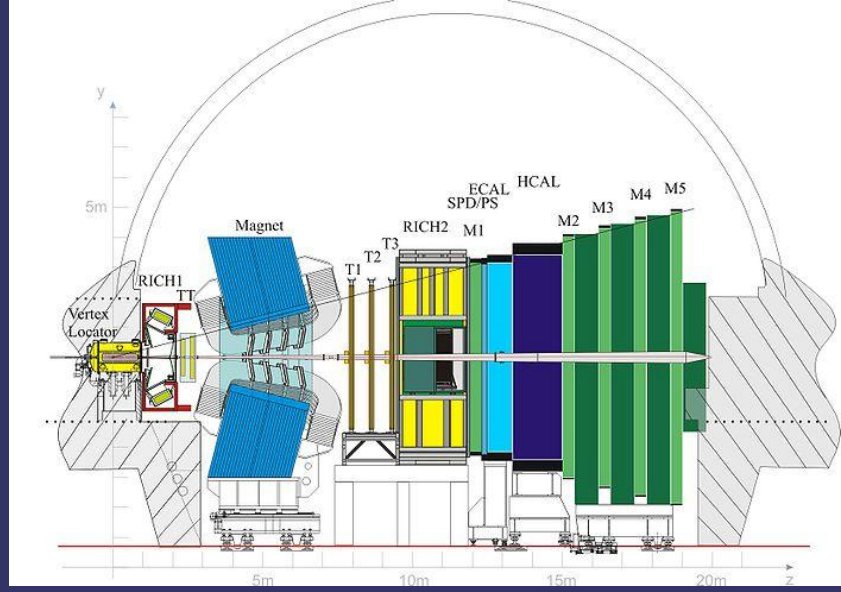
B factories $B_0 = d\bar{b}$

- (HERA-B at DESY in Germany)
- Belle at KEKB in Japan
- BaBar at PEP-II, SLAC, California
- Electron-Positron collisions with $E_{CMS} = 10.58 GeV$

BaBar (B and B-bar)

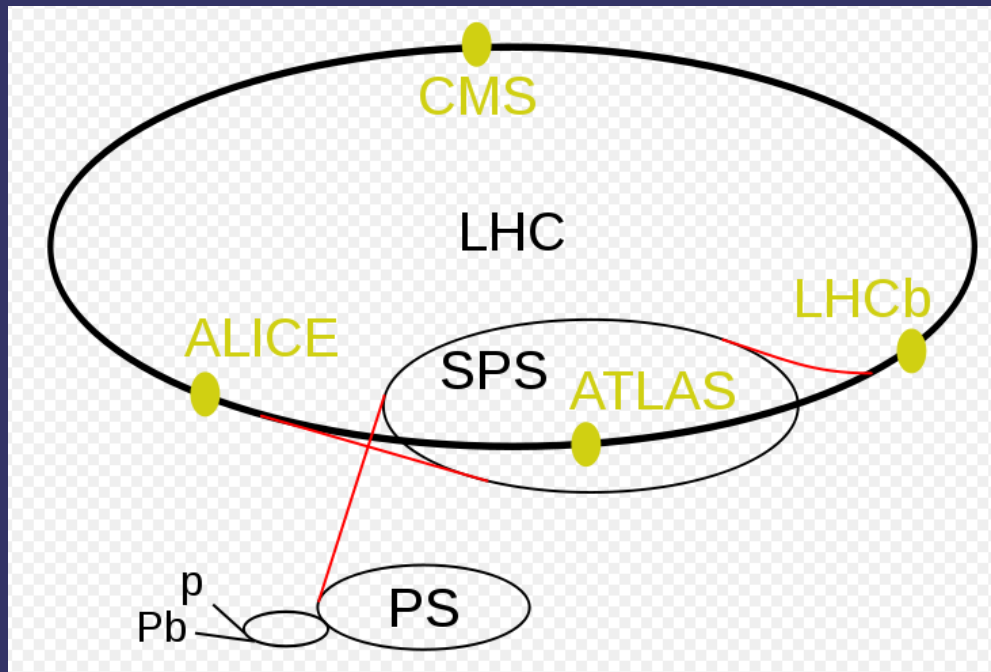
- 2001: First Observation of CP violation outside of the kaon system.
- 2004: Direct CP violation
- 2007: Observation of D mixing

LHCb



- Proton-proton collisions with $E_{CMS} = 14TeV$
- Flavour changing neutral currents
- $B_s^0 = s\bar{b}$ mesons, excited B-mesons, b-baryons
- Data produced at LHC:

  >1 GB/s



Thanks for listening!

References:

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Lecture „**KET**“ by *Bernhard Spaan*:
http://www.physik.uni-dortmund.de/~spaan/KET0910/vl/