CP Violation & Belle

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April 19, 2017

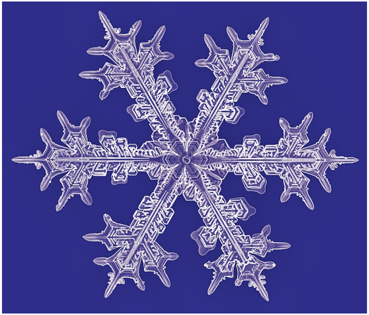
Výjezdní seminář MFF

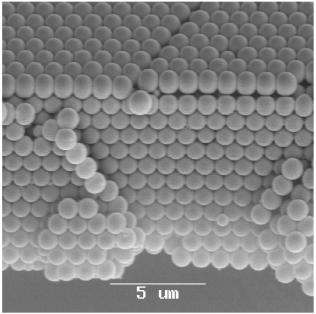
Outline

- Symmetries
- CP Violation
- Belle & Belle II

Disclaimer: This presentation was not intended to be read separately and by itself won't make much sense.

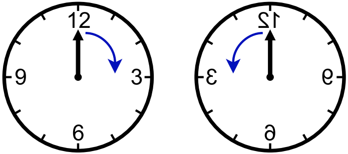
Symmetries





Parity and Charge Symmetry

$$\widehat{\mathrm{P}} : \begin{pmatrix} t \\ x \\ y \\ z \end{pmatrix} \rightarrow \begin{pmatrix} t \\ -x \\ -y \\ -z \end{pmatrix}$$



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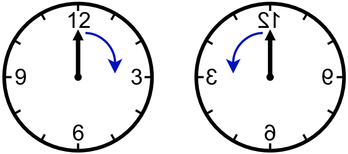

$$\widehat{\mathrm{C}} : e^{-} \rightarrow e^{+}$$

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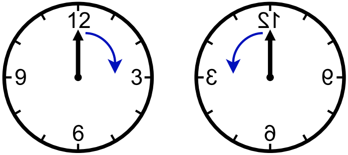

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CP Violation Discovery

$K_L^0 \to \pi^+\pi^- \quad CP(-1) \to CP(+1)$

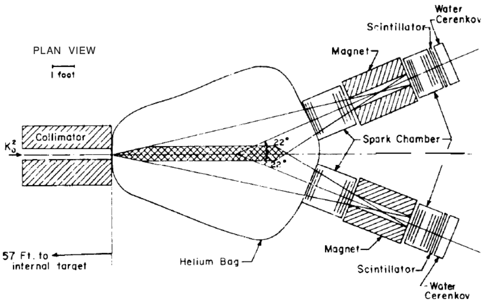


Fig. I. Plan view of the apparatus as located at the A. G. S.

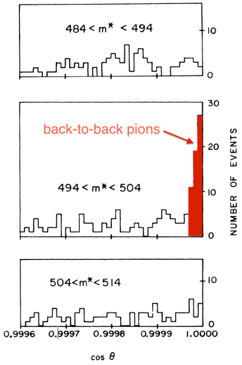
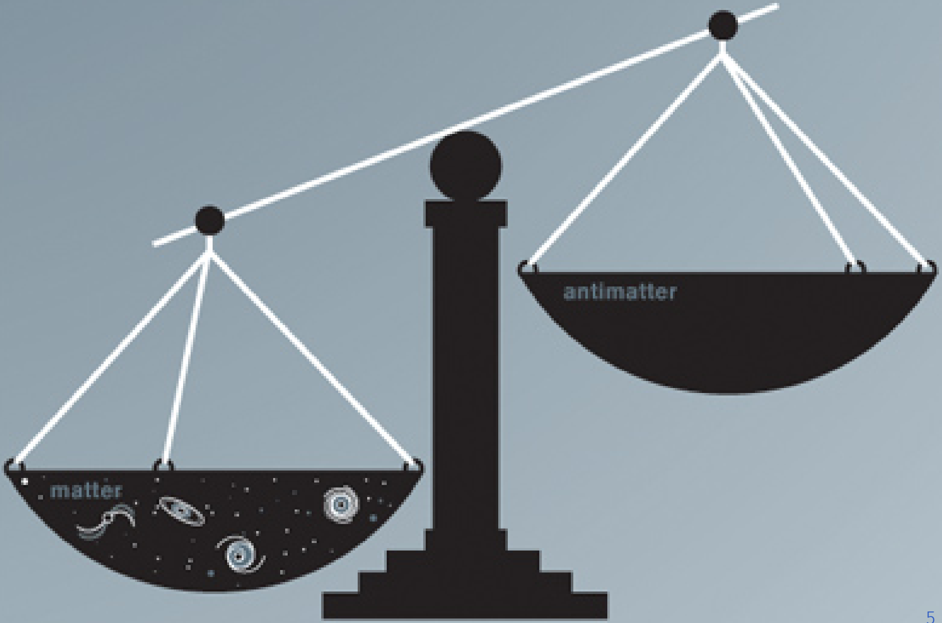


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

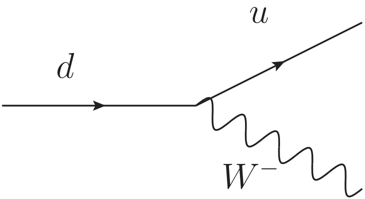
Branching ratio for this CP violating mode: $\epsilon \cong 2.3 \times 10^{-3}$

Cronin&Fitch, 1964, Nobel Prize 1980

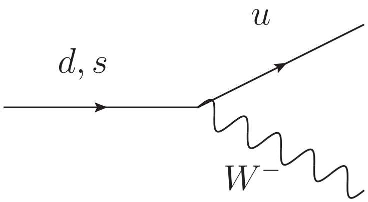
CP Violation en Masse



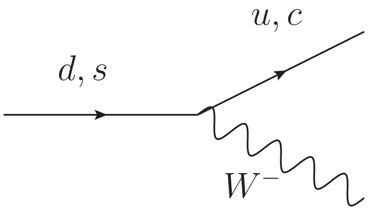
Charged Current



$$\mathcal{L}_{CC} \propto \bar{u}\gamma^\mu \frac{1-\gamma^5}{2} d W^+_\mu + \text{c.c.}$$



$$\mathcal{L}_{CC} \propto \bar{u}\gamma^{\mu}\frac{1-\gamma^5}{2}(V_{ud}d + V_{us}s)W^{+}_{\mu} + c.c.$$



$$\mathcal{L}_{CC} \propto \bar{u}\gamma^\mu \frac{1-\gamma^5}{2}(V_{ud}d + V_{us}s)W^+_\mu$$

$$+ \bar{c}\gamma^\mu \frac{1-\gamma^5}{2}(V_{cd}d + V_{cs}s)W^+_\mu + \text{c.c.} =$$

$$= (\bar{u}\ \bar{c})\gamma^\mu \frac{1-\gamma^5}{2} \begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} W^+_\mu + \text{c.c.}$$

The Matrix

$$\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix}$$

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Counting parameters:

- 4 complex pars. = 8 real ones

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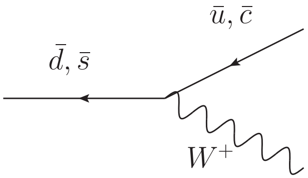
- A phase can be absorbed into each of the quark fields, but the overall phase is irrelevant $\implies -3$ pars.
- We have just one parameter and we can choose the relative phases!

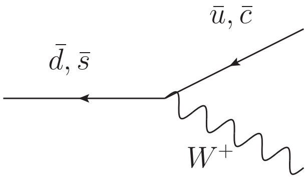
$$\begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$



To get the term relevant for anti-quarks in the same vertex, we need the c.c. part:

$$(\bar{d}\ \bar{s})\gamma^\mu \frac{1-\gamma^5}{2} \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}^\dagger \begin{pmatrix} u \\ c \end{pmatrix} W^-_\mu =$$

$$=(\bar{d}\ \bar{s})\gamma^\mu \frac{1-\gamma^5}{2} \begin{pmatrix} \cos\theta_C & -\sin\theta_C \\ \sin\theta_C & \cos\theta_C \end{pmatrix}^* \begin{pmatrix} u \\ c \end{pmatrix} W^-_\mu$$



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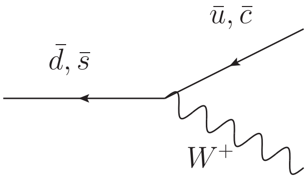

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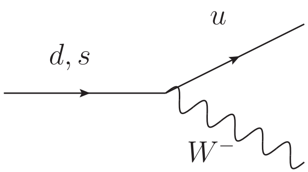
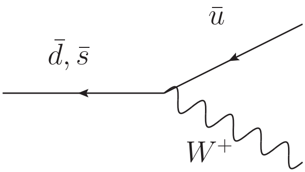
The part that is relevant for, e.g., the u quark is:

$$(\cos\theta_C\bar{d} + \sin\theta_C\bar{s})\gamma^\mu \frac{1-\gamma^5}{2} u W^-_\mu$$



$\bar{u}\gamma^\mu \frac{1-\gamma^5}{2}(\cos\theta_C d + \sin\theta_C s)W^+_\mu$



$(\cos\theta_C \bar{d} + \sin\theta_C \bar{s})\gamma^\mu \frac{1-\gamma^5}{2} u W^-_\mu$

Kobayashi and Maskawa: no CP violation possible with two quark generations, but natural with three

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

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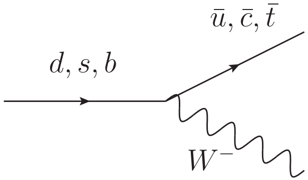
- We have 4 parameters!

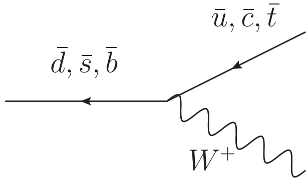
To Be or Not To Be (Real)

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

Can we take V_{CKM} *real*?

- Real unitary matrix = special orthogonal matrix
- $V \in SO(3) \Longrightarrow$ only 3 parameters (rotations in 3D, Euler angles)
- 1 irreducible complex phase

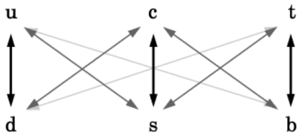




$$(\bar{u}\ \bar{c}\ \bar{t})\gamma^\mu \frac{1-\gamma^5}{2} V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} W_\mu^+ \qquad (\bar{d}\ \bar{s}\ \bar{b})\gamma^\mu \frac{1-\gamma^5}{2} V_{CKM}^\dagger \begin{pmatrix} u \\ c \\ t \end{pmatrix} W_\mu^-$$

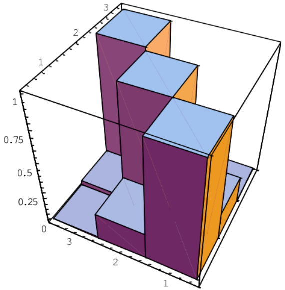
V_{CKM} complex $\Longrightarrow$ Nature treats matter and anti-matter differently

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



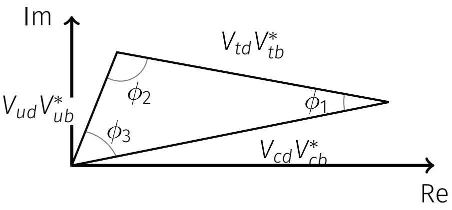
CKM Matrix:

- Encodes quark mixing amplitudes
- Encodes CP violation
- Is almost diagonal



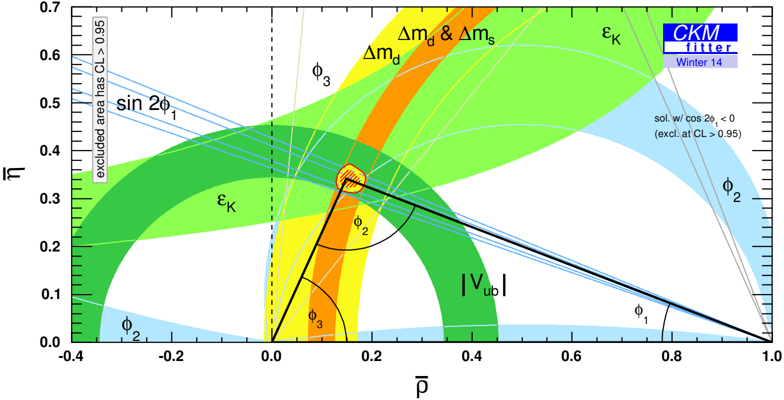
$$\begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

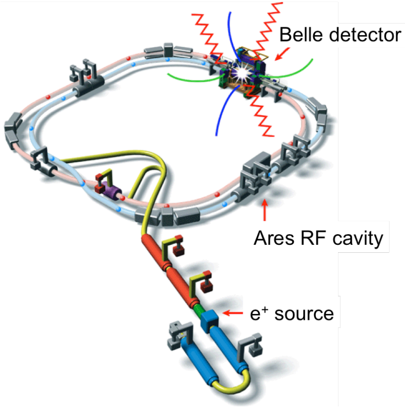
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

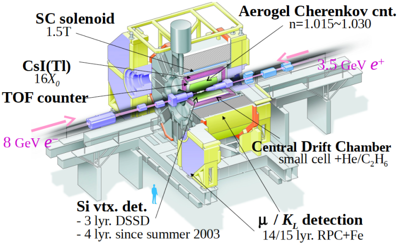


- 2 sides and 3 angles ⇒ heavily overdetermined.
- Are angles consistent with sides?
- Are angles from loop and tree decays consistent?

Unitarity Triangle Fit

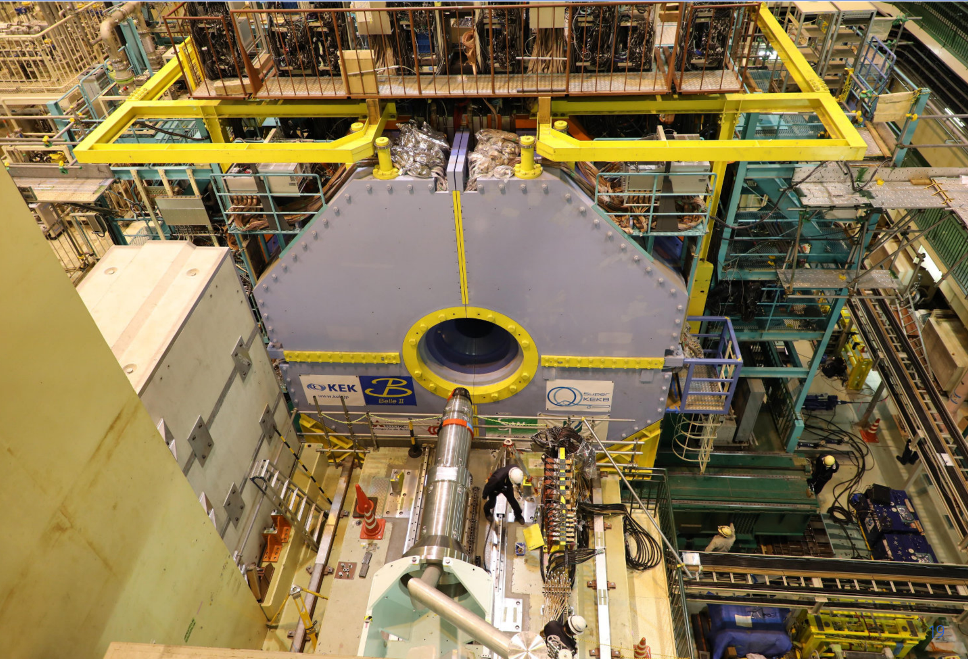






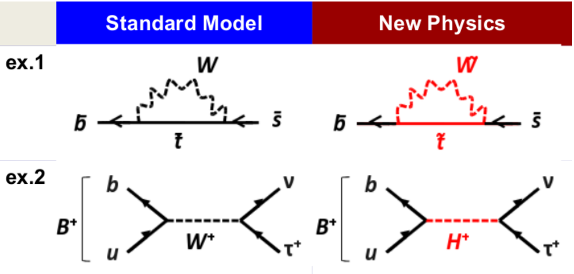
- $\sqrt{s} = 10.58\ \text{GeV} = M[\Upsilon(4S)] \Rightarrow$ B-factory
- Asymmetric e^+e^- collider $\Rightarrow$ enables B decay time measurement
- World's highest luminosity machine $\mathcal{L} = 2.11 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$

Belle II, Last Week...



So far no New Physics (NP) from LHC experiments. There is a possibility that NP scale is $> \sim$10 TeV; out of reach of LHC.

B-factories can search for new particles in a different way:



SuperKEKB/Belle II Motivation

The effect of NP in indirect searches is expected to be tiny and has not been observed so far.
Only several ”anomalous”measurements:

- Unexpectedly large $D^0 - \bar{D}^0$ mixing (although SM has large uncertainties)
- $\mathcal{B}(B \to D^{(*)}\tau\nu)$($\sim 4\sigma$ discrepancy)

Need more precise measurements with more statistics $\Longrightarrow$ Belle II

- 40$\times$ higher luminosity
- Improved particle ID detectors
- Improved vertex detectors

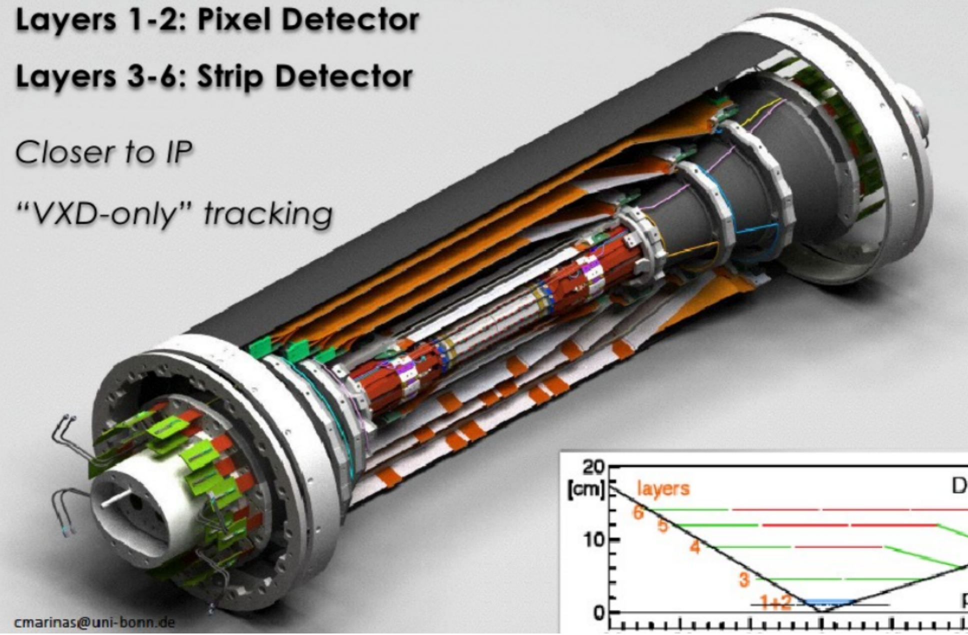
Belle II Vertex Detector

Layers 1-2: Pixel Detector

Layers 3-6: Strip Detector

Closer to IP

“VXD-only” tracking



23 countries, 98 institutions, $\sim$ 700 physicists

7 Czech members (Charles University in Prague, Faculty of Mathematics and Physics), 3 faculty, 4 students. Working mostly on the pixel detector and tracking (as well as some analyses on the Belle data sample).

Prague Belle/Belle II Team

- Zdeněk Doležal
- Peter Kodyš
- Peter Kvasnička

- Tadeáš Bilka
- Daniel Červenkov
- Jakub Kandra
- Michal Krištof

Anyone interested in a Belle/Belle II related

- bachelor
- master
- doctoral
- other

work should contact **Z. Doležal**.

Thank you!