3.2 CP Violation in the Standard Modell

$V_{ub} = |V_{ub}| e^{-i\gamma}$ ← see Wolfenstein parametrization

Quarks

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

$V_{td} = |V_{td}| e^{-i\beta}$

Antiquarks:

$$\begin{pmatrix} \bar{d}' \\ \bar{s}' \\ \bar{b}' \end{pmatrix} = \begin{pmatrix} V^*_{ud} & V^*_{us} & V^*_{ub} \\ V^*_{cd} & V^*_{cs} & V^*_{cb} \\ V^*_{td} & V^*_{ts} & V^*_{tb} \end{pmatrix} \begin{pmatrix} \bar{d} \\ \bar{s} \\ \bar{b} \end{pmatrix}$$

Phase angle≠0: complex CKM matrix

⬇

Different mixing for quarks and anti-quarks

⬇

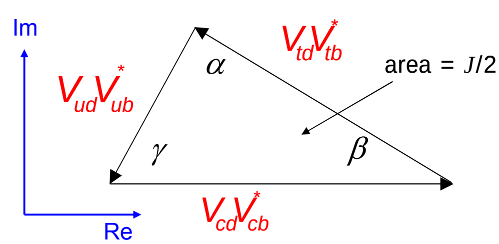
Origin of CP Violation (CPV)

Unitary of CKM matrix: **VV† = 1** → 6 "triangle" relations in complex plane:

$$\left.\begin{array}{l} V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0 \\ V_{td}V^*_{ud} + V_{ts}V^*_{us} + V_{tb}V^*_{ub} = 0 \end{array}\right\}$$

Important for **B$_d$** and **B$_s$** decays

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



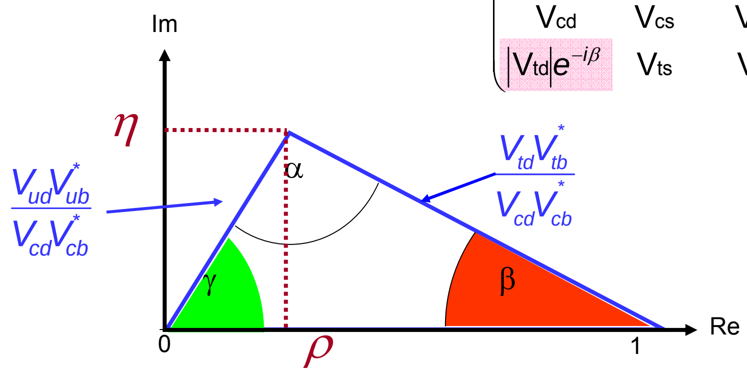
$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

Strength of CPV: Characterized by Jarlskog invariant $J = \mathrm{Im}\left(V_{ij} V_{kl} V^*_{il} V^*_{kj}\right)$

In SM: $J = \mathrm{Im}[V_{us}V_{cb}V^*_{ub}V^*_{cs}] = A^2\lambda^6\eta\left(1-\lambda^2/2\right) + O(\lambda^{10}) \sim 10^{-5}$

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

$$\begin{pmatrix} V_{ud} & V_{us} & |V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ |V_{td}|e^{-i\beta} & V_{ts} & V_{tb} \end{pmatrix}$$

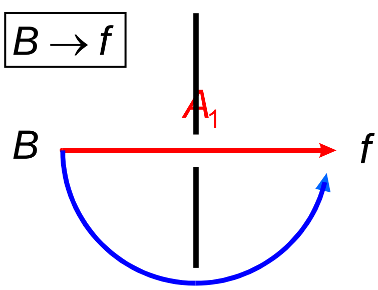


$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right]$ $\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$ $\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$

3.3 Observation of CP Violation

→ Phase measurement
→ Interference experiment

$\boxed{B \to f}$



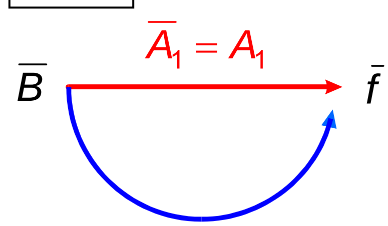
$A_2\, e^{i\phi_{CP}} e^{i\delta}$

Weak and CP invariant phase difference

$|A|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} + \delta)$

CP

$\boxed{\bar{B} \to \bar{f}}$



$\bar{A}_2 = A_2\, e^{-i\phi_{CP}} e^{i\delta}$

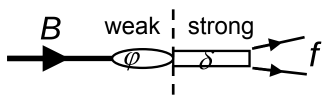
$|\bar{A}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\phi_{CP} - \delta)$

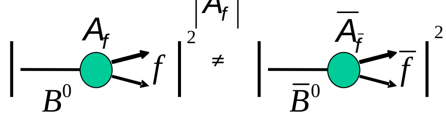
Need two phase differences between A_1 and A_2: Weak difference which changes sign under CP and another phase difference (e.g. strong) which is unchanged.

“3 Ways” of CP violation in meson decays

a) Direct CP violation

$$\left|\frac{\overline{A}_{\bar f}}{A_f}\right| \neq 1$$



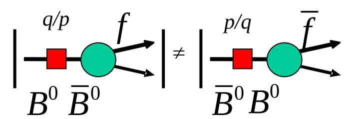


$$A(B \to f) = |A|\, e^{i\varphi}\, e^{i\delta}$$

$$P(\overline{B} \to \bar{f}) \neq P(B \to f)$$

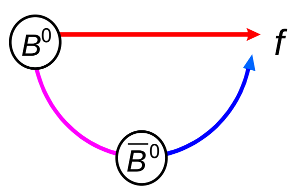
b) CP violation in mixing

$$\left|\frac{q}{p}\right| \neq 1$$



$$P(B^0 \to \overline{B^0}) \neq P(\overline{B^0} \to B^0)$$

c) CP violation through interference of mixed and unmixed amplitudes

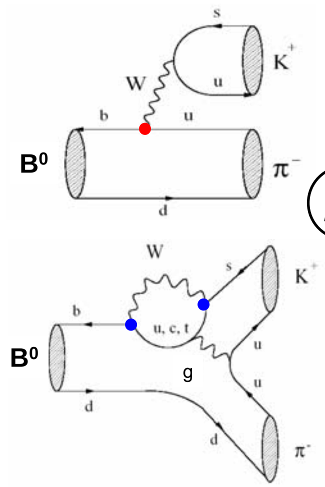


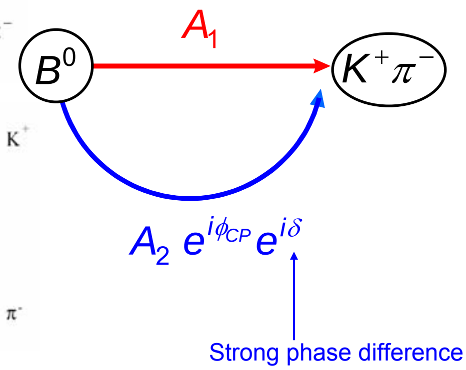
$$\Gamma(B^0_{t=0} \to f)(t) \neq \Gamma(\overline{B}^0_{t=0} \to f)(t)$$

Asymmetrie modulated by $\sim \sin \Delta m t$

Combinations of the 3 ways are possible!

Ad a) Direct CP violation (B system)





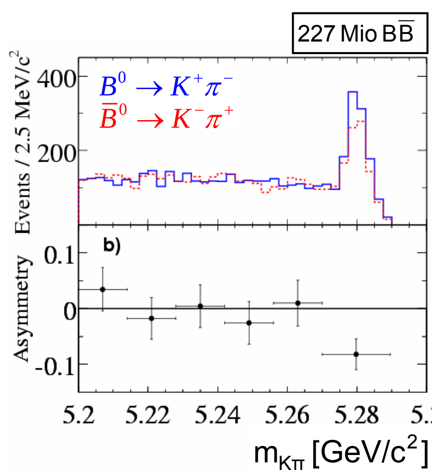
CP Asymmetrie $\quad |\bar{A}|^2 - |A|^2 = 4|A_1||A_2|\sin\phi_{cp}\sin\delta$

$$N(B^0/\bar{B}^0 \to K^\pm\pi^\mp) = 1606 \pm 51$$

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

$$A_{CP} = -0.133 \pm 0.030 \pm 0.009$$

4.2σ



PRL93(2004) 131801.

b) CP (T) violation in mixing

T violation

$$\left|\frac{q}{p}\right| \neq 1 \qquad P(B^0 \to \overline{B}^0) \neq P(\overline{B}^0 \to B^0)$$

$$\eta_m \equiv \frac{q}{p} = \frac{1-\varepsilon}{1+\varepsilon}$$

Reminder:
$$|K_L\rangle = \frac{1}{\sqrt{1+|\varepsilon_K|^2}}\left(|K_2\rangle + \varepsilon_K |K_1\rangle\right)$$

$$A(t) = \frac{P(\overline{B}^0 \to B^0)(t) - P(B^0 \to \overline{B}^0)(t)}{P(\overline{B}^0 \to B^0)(t) + P(B^0 \to \overline{B}^0)(t)} = \frac{1-|q/p|^4}{1+|q/p|^4} \approx \frac{4\,\mathrm{Re}\,\varepsilon}{1+|\varepsilon|^2} \approx 4\,\mathrm{Re}\,\varepsilon$$

Skipped.

Measured using semileptonic decays

$$B^0 \to X^-\ell^+\nu$$
$$\overline{B}^0 \to X^+\ell^-\overline{\nu}$$

$$A_{SL}(t) = \frac{\Gamma(\overline{B}^0_{t=0} \to \overset{B^0}{X\ell^+\nu})(t) - \Gamma(B^0_{t=0} \to \overset{\overline{B}^0}{X\ell^-\overline{\nu}})(t)}{\Gamma(\overline{B}^0_{t=0} \to X\ell^+\nu)(t) + \Gamma(B^0_{t=0} \to X\ell^-\overline{\nu})(t)}$$

B^0 $\overline{B}^0$ System:

HFAG 2004

$$A_{SL} = -0.0026 \pm 0.0067$$
$$\left|\frac{q}{p}\right| = 1.0013 \pm 0.0034$$
$$4\,\mathrm{Re}\,\varepsilon_B = -0.0007 \pm 0.0017$$

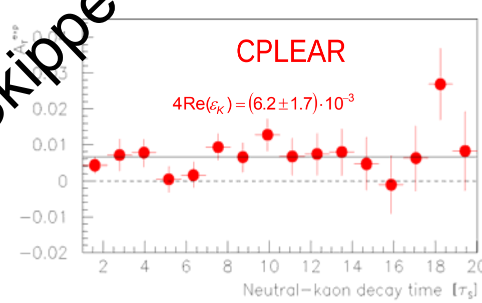
Standard model prediction for B

$$\left|\frac{q}{p}\right| - 1 \approx 4\pi \frac{m_c^2}{m_t^2} \sin\beta \approx 5\times 10^{-4}$$

K^0 $\overline{K}^0$ System:

$$A_{SL}(t) = \frac{\Gamma(\overbrace{\overline{K}^0_{t=0} \to e^+\pi^-\nu_e}^{K^0}) - \Gamma(K^0_{t=0} \to e^-\pi^+\overline{\nu}_e)}{\Gamma(\overline{K}^0_{t=0} \to e^+\pi^-\nu_e) - \Gamma(K^0_{t=0} \to e^-\pi^+\overline{\nu}_e)}(t)$$

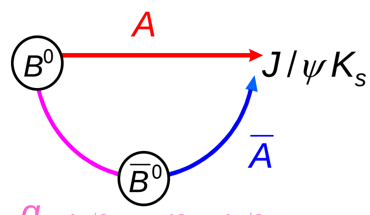
Skipped.



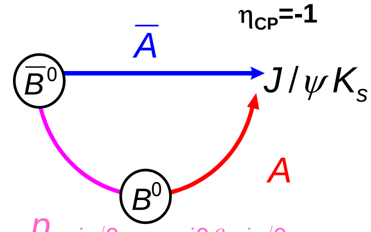
c) CP violation in interference between mixing and decay

$\boxed{B^0 \rightarrow J/\psi K_s}$ CP $\boxed{\overline{B}^0 \rightarrow J/\psi K_s}$

η_{CP}=-1



$$\frac{q}{p}e^{i\pi/2} \sim e^{i2\beta}e^{i\pi/2}$$



$$\frac{p}{q}e^{i\pi/2} \sim e^{-i2\beta}e^{i\pi/2}$$

$$\left|B^0 \rightarrow J/\psi K_s\right\rangle = A\left(f_+(t) + \lambda_{CP} f_-(t)\right)$$

$$\left|\overline{B}^0 \rightarrow J/\psi K_s\right\rangle = \overline{A}\left(f_+(t) + \frac{1}{\lambda_{CP}} f_-(t)\right)$$

$$\lambda_{CP} \equiv \frac{q}{p} \cdot \frac{\overline{A}}{A}$$

Reminder: Mixing

$$\left|B^0\right\rangle = \frac{1}{2p}\left(\left|B_L\right\rangle + \left|B_H\right\rangle\right)$$

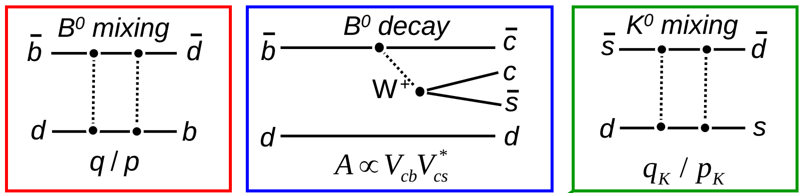
$$\left|\psi_{B^0}(t)\right\rangle = \frac{\left|B_L,t\right\rangle + \left|B_H,t\right\rangle}{2p} = \frac{1}{2p}\left(b_L(t)\cdot\left(p\left|B^0\right\rangle + q\left|\overline{B}^0\right\rangle\right) + b_H(t)\cdot\left(p\left|B^0\right\rangle - q\left|\overline{B}^0\right\rangle\right)\right)$$

$$= f_+(t)\cdot\left|B^0\right\rangle + \frac{q}{p} f_-(t)\cdot\left|\overline{B}^0\right\rangle$$

$$\left|\psi_{\overline{B}^0}(t)\right\rangle = f_+(t)\cdot\left|\overline{B}^0\right\rangle + \frac{p}{q} f_-(t)\cdot\left|B^0\right\rangle \qquad f_\pm(t) = \frac{1}{2}\cdot\left[e^{-im_H t}e^{-\Gamma_H t/2} \pm e^{-im_L t}e^{-\Gamma_L t/2}\right]$$

SM prediction of λ_{CP} for $B^0 \to J/\psi K_S$

$\eta_{CP} = -1$



Same for all $c\bar{c}K^0$ channels

$\frac{q}{p} \sim e^{2i\beta}$

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A} = -\underbrace{\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}}_{} = -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}} = -e^{-2i\beta}$$

Beside V_{td} all other CKM elements are real

$$\boxed{V_{td} \approx |V_{td}| e^{-i\beta}} \Rightarrow \boxed{\begin{array}{c}|\lambda_{CP}| = 1 \\ \mathrm{Im}(\lambda_{CP}) = \sin(2\beta)\end{array}}$$

no direct CPV, no CPV in mixing

Calculation of the time-dependent CP asymmetry

$$\Gamma(B^0 \to f_{CP})(t) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{\left(1+|\lambda_{CP}|^2\right)} \times \left[\frac{1+|\lambda_{CP}|^2}{2} - \mathrm{Im}(\lambda_{CP})\sin(\Delta m_d t) + \frac{1-|\lambda_{CP}|^2}{2}\cos(\Delta m_d t)\right]$$

$$\neq$$

$$\Gamma(\overline{B^0} \to f_{CP})(t) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{\left(1+|\lambda_{CP}|^2\right)} \times \left[\frac{1+|\lambda_{CP}|^2}{2} + \mathrm{Im}(\lambda_{CP})\sin(\Delta m_d t) - \frac{1-|\lambda_{CP}|^2}{2}\cos(\Delta m_d t)\right]$$

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} = \left[S_f \sin(\Delta m_d t) - \underbrace{C_f \cos(\Delta m_d t)}_{\text{negligible}}\right]$$

Time resolved

$$S_f = \frac{2\,\mathrm{Im}\,\lambda_{CP}}{1+|\lambda_{CP}|^2} \qquad C_f = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}$$

Interference
= $\sin 2\beta$ for $B^0 \to J/\psi K_S$

indicates direct CP violation
if $|q/p| \neq 1$

$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(B^0(t) \to f_{CP}) + \Gamma(\overline{B}^0(t) \to f_{CP})} = \sin 2\beta \sin(\Delta m_d t)$$

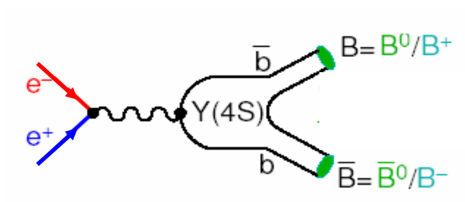
To measure CP violation in B_d system:

- Need many B (several 100 × 10^9)
- Need to know the flavor of the B at t=0
- Need to reconstruct the decay length to measure t

3.4 Measurement of sin2β: Asymmetric $e^+ e^-$ B factory

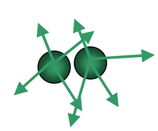
$E_{CMS} = 10.58\,\text{GeV}$

↳ 500 M BB



Symmetric:

$e^- \xrightarrow{5.3\,\text{GeV}} \quad \xleftarrow{5.3\,\text{GeV}} e^+$

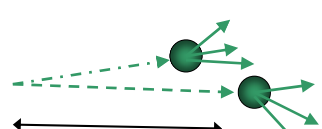


B mesons decay at rest
→ decay length z≈0

Asymmetric:

$e^- \xrightarrow{9\,\text{GeV}} \quad \xleftarrow{3.1\,\text{GeV}} e^+$

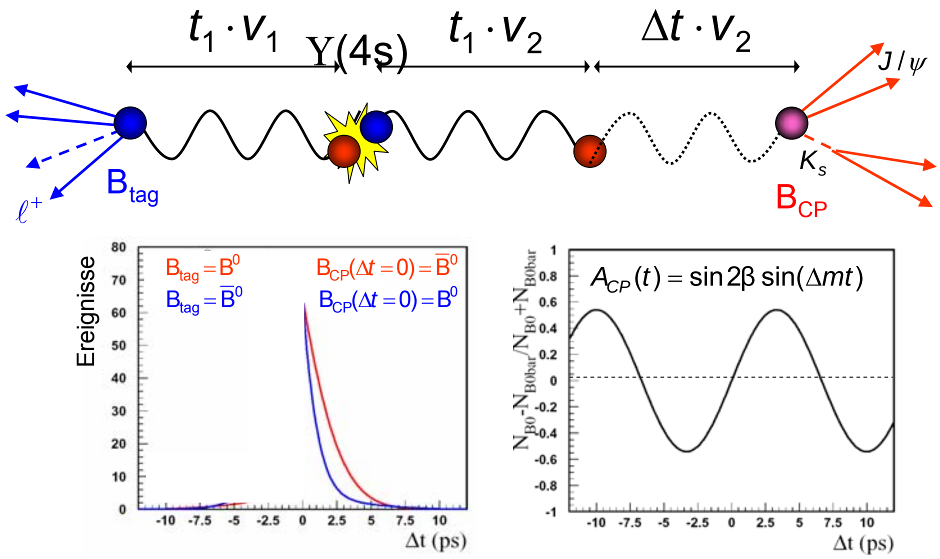
Boost β = 0.56



$z = c\beta\gamma\, t$

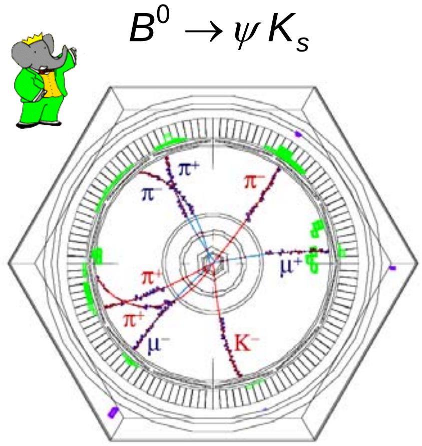
decay length
z≈250μm

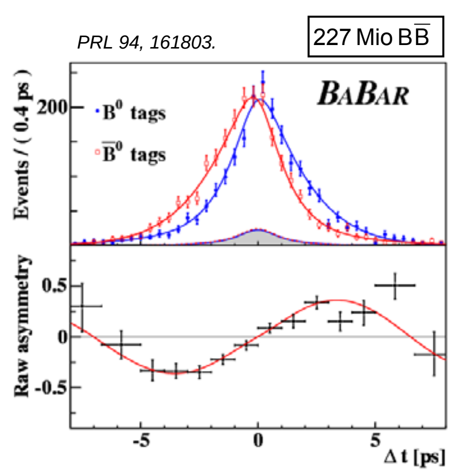
Measurement of sin2β: Coherent oszillation



Measurement of sin2β: Golden decay channel

$$B^0 \rightarrow \psi K_s$$

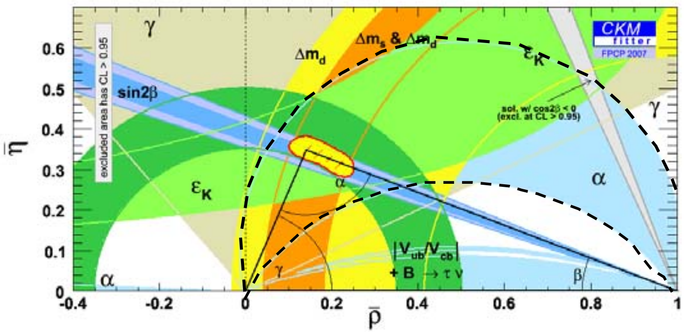




$A_{CP}(t) = \sin 2\beta \sin(\Delta m t)$

$\sin 2\beta = \quad 0.722 \pm 0.040 \pm 0.023$

3.5 Experimental status of the Unitarity Triangle



Standard Model CKM mechanism confirmed

1. Large CP Violation in B decays
2. Large direct CP violation observed
3. CPV parameter related to magnitude of non-CP observables

A triple triumph

3.6 Baryon asymmetry in the universe

Does the Standard Model explain the baryon symmetry in universe?

Andrei D. Sakharov, 1967

- **Baryon number violation**
- **C and CP Violation**
- **Departure from thermal equilibrium**

- **CP violation in quark sector is a factor ~10^{10} to small.**
- **for M_{Higgs}> 114 GeV: Symmetry breaking = 2nd order phase transition**

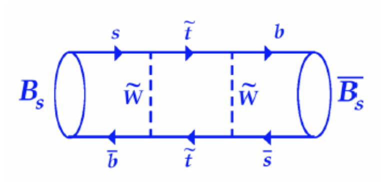
Attractive: Super-symmetric extensions of Standard Model

- **Additional CP violation through supersymmetric particles**
- **Extended Higgs-sector → strong phase transition**

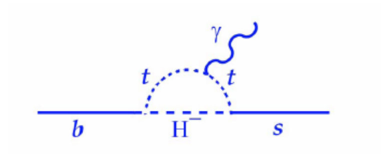
Alternative: Lepto-genesis

3.7 Flavor and CP Physics as probe for New Physics

Aim: Search for New Physics in loop-processes



Box-Diagramms (oscillation)



Penguin amplitudes

➡ Deviation from the Standard Model
Absolute rates und phase dependent CP asymmetries

Complementary to the direct searches for NP by ATLAS/CMS

Historical examples: GIM Mechanism, B Oscillation

Future searches for New Physics

B_s mixing (new phases):

$B_s^0(\overline{B}_s^0) \to J/\psi\,\phi$ $\quad BR \sim 3\times 10^{-5}$ *(visible)*

CP Violation in penguin decays:

$B^0(\overline{B}^0) \to \phi K_s$ $\quad BR \sim 2\cdot 10^{-6}$ *(visible)*

$B_s^0(\overline{B}_s^0) \to \phi\phi$ $\quad BR \sim 10^{-6}$ *(visible)*

Precision meas. of CKM Phase γ:

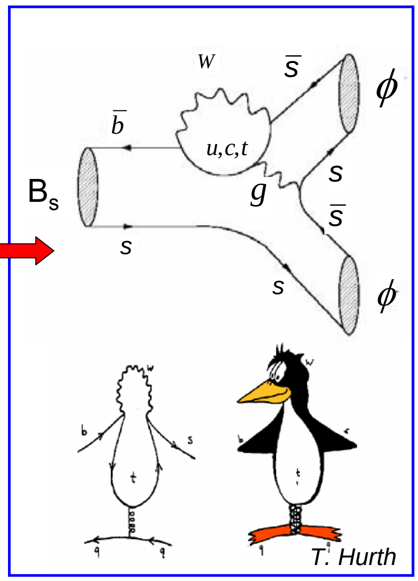
Tree Zerfälle: $B^{\pm,0} \to D^0 K^{\pm,0}$ $\quad BR \sim 10^{-6}$

Loop Zerfälle: $B_s \to D_s K, KK$

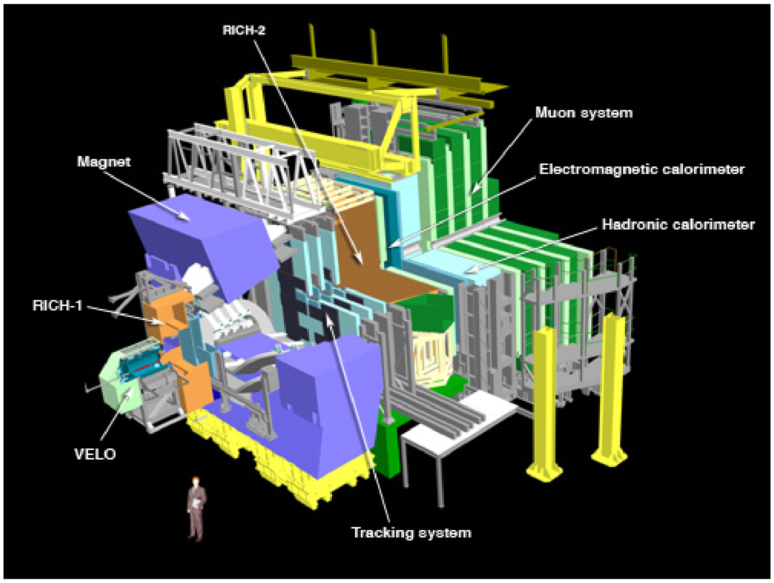
Rare deacys:

$B^0 \to K^{(*)}\ell\ell$ $\quad BR \sim 10^{-6}$

$B^0_{(s)} \to \mu\mu$ $\quad BR \sim 10^{-9}$



LHCb – B Physics at the LHC



B Meson Production at the LHC

LHC

- pp Kollisionen bei $\sqrt{s}$ = 14 TeV

$$\begin{cases} \sigma_{inel} \sim 80 \text{ mb} \\ \sigma_{bb} \sim 500\ \mu\text{b} \end{cases}$$

- Korrelierte Vorwärtsproduktion der bb
- für L ~ 2 x 10^{32} $cm^{-2}s^{-1}$ (defokussierte Strahlen am LHCb IP):

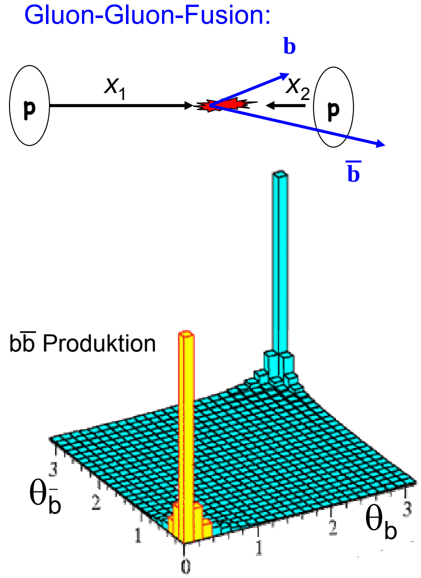
  n = 0.5 IA / BX (ATLAS 5…25)

~10^{12} b $\bar{b}$ Ereignisse/Jahr

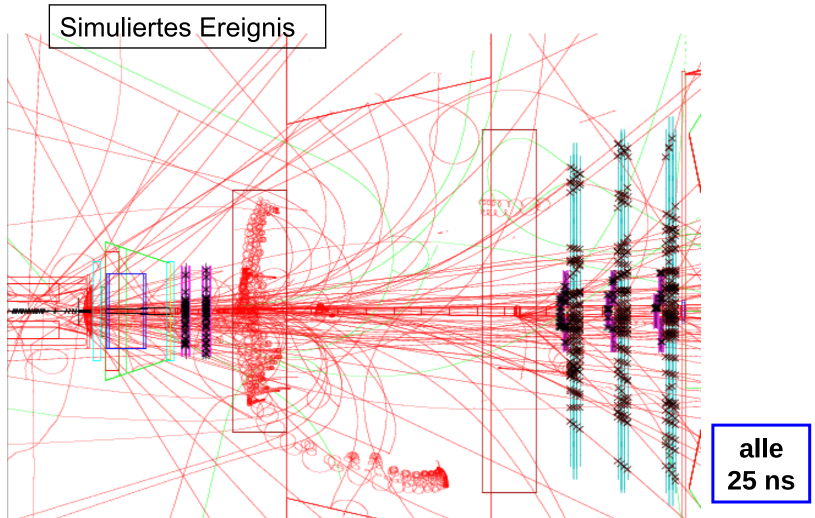
LHCb

- Ein-Arm Vorwärtsspektrometer
  12 mrad < θ < 300 mrad(1.8<η<4.9)

Gluon-Gluon-Fusion:



Typisches B Ereignis in LHCb



- Physik verlangt Rekonstruktion des Zerfalls