Measurement of CP-violation in the $B^0 \to \pi^+\pi^-$ decay at the Belle experiment

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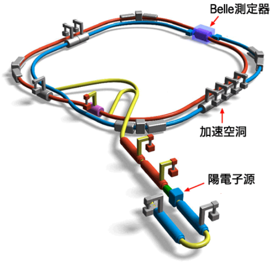
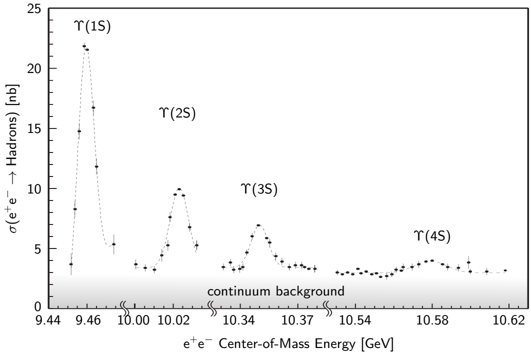
1. motivation
2. analysis procedure
3. Summary

The Belle Experiment



- e^-e^+ storage ring
- $\Upsilon(4S)$ resonance $\to$ exclusive $B\overline{B}$ production



CKM Matrix and the unitarity triangle

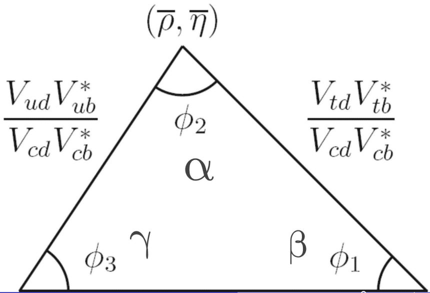
$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{cd} & V_{td} \\ V_{us} & V_{cs} & V_{ts} \\ V_{ub} & V_{cb} & V_{tb} \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

- using the unitarity condition of the CKM matrix $\sum_k V_{ik} V_{jk}^* = 0$
- triangle in complex space
- very small angles in the kaon system, big angles in the B meson system

$\lambda =$ Cabibbo angle

$\lambda \approx 0.23$

$$\underset{\mathcal{O}(\lambda^3)}{V_{ud} V_{ub}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{cd} V_{cb}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{td} V_{tb}^*} = 0$$

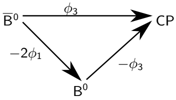


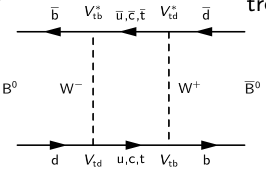
$$\phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

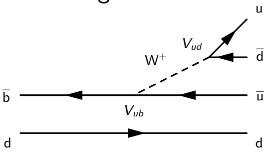
CP-violation and the angle ϕ_2

mixture of B^0



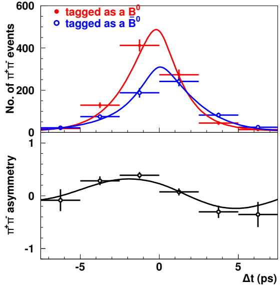


tree level diagram



$$a_{CP}(t) = \frac{\Gamma\left(\overline{\mathrm{B}}^0 \to f_{CP};t\right) - \Gamma\left(\mathrm{B}^0 \to f_{CP};t\right)}{\Gamma\left(\overline{\mathrm{B}}^0 \to f_{CP};t\right) + \Gamma\left(\mathrm{B}^0 \to f_{CP};t\right)} =$$

$$A_{cp}\cos\Delta m_d \Delta t + S_{cp}\sin\Delta m_d \Delta t$$



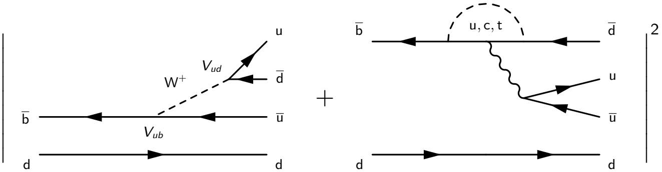
$$\lambda_{CP} = \left(\frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}\right)\cdot\left(\frac{V_{ud}^*V_{ub}}{V_{ud}V_{ub}^*}\right)$$

$$= e^{-i2(\phi_1+\phi_3)}$$

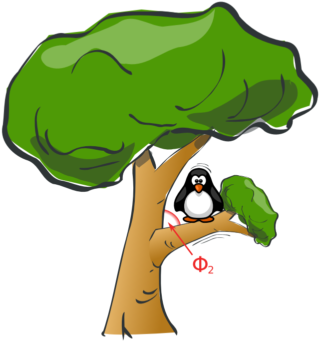
$$= e^{i2(\phi_2)}$$

$$\mathcal{A}_{CP} = \frac{|\lambda_{CP}|^2 - 1}{|\lambda_{CP}|^2 + 1} = 0 \qquad \mathcal{S}_{CP} = \frac{2\,\mathrm{Im}\,\lambda_{CP}}{|\lambda_{CP}|^2+1} = \sin(2\phi_2)$$

The penguin-diagram



- naive estimation shows a strong suppression of the penguin-diagram contribution
- measurement shows direct CP-violation
- we observe: $\phi_2^{eff} = \phi_2 + \Delta\phi_2$



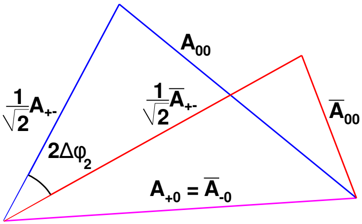
How the penguin distorts the tree level measurement

Elimination of the penguin: isospin analysis

$\phi_2^{eff} = \phi_2 + \Delta\phi_2$
the branching ratios and CP-asymmeries of the following decays needed:

- $\mathcal{B}(\mathrm{B}^0 \to \pi^+\pi^-)$
- $\mathcal{B}(\mathrm{B}^+ \to \pi^+\pi^0)$
- $\mathcal{B}(\mathrm{B}^0 \to \pi^0\pi^0)$
- $\mathcal{A}_{CP}(\mathrm{B}^0 \to \pi^+\pi^-)$
- $\mathcal{A}_{CP}(\mathrm{B}^0 \to \pi^0\pi^0)$
- $\mathcal{S}_{CP}(\mathrm{B}^0 \to \pi^+\pi^-)$

To eliminate the penguin-contributions we use the isospin relations:



$$A^{+0} = \frac{1}{\sqrt{2}}A^{+-} + A^{00},$$
$$A^{-0} = \frac{1}{\sqrt{2}}\bar{A}^{+-} + \bar{A}^{00}.$$

four fold ambiguity

Event reconstruction

$B^0 \to \pi^+\pi^-$ ($B^0 \to K^+\pi^-$, $B^0 \to K^+K^-$)

- combine two particles with oposite charge (pion hypothesis)

$$\Delta E = E_{rec} - E_{beam}$$

$$M_{\text{beam constrained}} = \sqrt{E_{beam}^2 + \vec{p}^{\,2}}$$

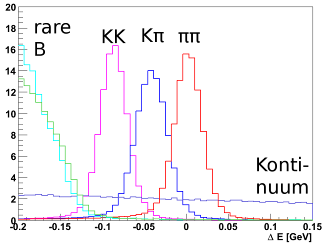
- vertex-fit
- B-tag
  determining the flavour with help of the other $|PB$

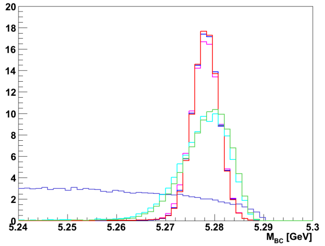
analysis window

- $5.24\,\text{GeV} < M_{BC} < 5.3\,\text{GeV}$
- $-0.2\,\text{GeV} < \Delta E < 0.15\,\text{GeV}$
- electron veto

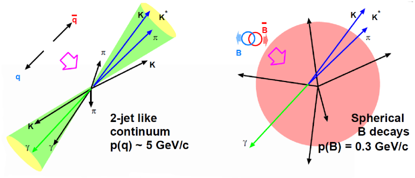
event multiplicity of 1.01

all components normed to an area of 1

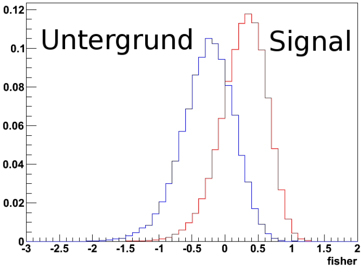




Background supression



construction of a fisher-discriminant from event-shape variables



previous Belle analysis (Ishino et al.)

- cut on the $\frac{b\bar{b}}{q\bar{q}}$ discriminant
- $K\pi$, KK yield from other analysis

new method

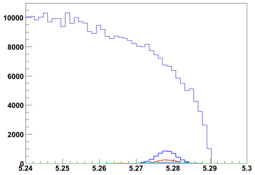
- minimize usage of cuts
- determine $K\pi$, KK yield in same fit

reconstruction efficency $\approx$ 53%

	previous analysis	new analysis	
$B^0\overline{B}^0$ pairs	535 mio.	535 mio.	770 mio.
$\pi^+\pi^-$ events	1464	$\approx$1680	$\approx$2360

Measurement of the yield

$$\mathcal{L} = PDF_{\pi^+\pi^-} Y_{\pi^+\pi^-} \cdot PDF_{K^+\pi^-} Y_{K^+\pi^-} \cdot PDF_{K^+K^-} Y_{K^+K^-} \cdot PDF_{rareB^+} Y_{rareB^+} \cdot PDF_{rareB^0} Y_{rareB^0} \cdot PDF_{q\bar{q}} Y_{q\bar{q}}$$



M_{BC}

extendent maximum likelihood fit

- $\mathcal{B}(B^0 \Rightarrow \pi^+\pi^-)$
- $A_{cp}(\pi^+\pi^-)$
- $S_{cp}(\pi^+\pi^-)$

- $\mathcal{B}(B^0 \Rightarrow K^+\pi^-)$
- $A_{cp}(K^+\pi^-)$

- $\mathcal{B}(B^0 \Rightarrow K^+K^-)$

factorization of the PDF (for uncorrelated data)

$$PDF_{\pi^+\pi^-} = PDF_{\Delta E} \cdot PDF_{M_{BC}} \cdot PDF_{\mathcal{L}^+} \cdot PDF_{\mathcal{L}^-} \cdot PDF_{\text{fisher}} \cdot PDF_{\Delta t} \cdot PDF_{q} \cdot PDF_{\cos\theta}$$

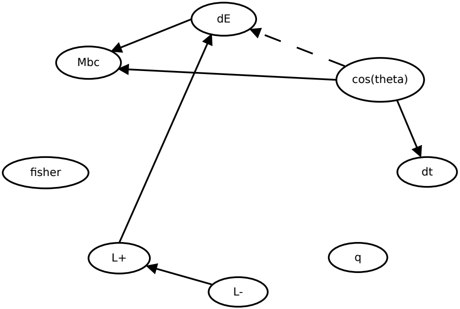
for correlated data we need to model a higher dimensional PDF
$\rightarrow$ e.g. continuum background

Correlations in the K π component

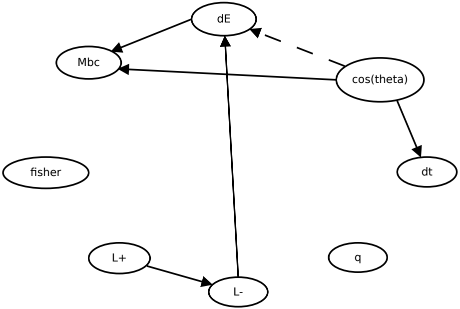
Bayesian Probability networks

- directed acyclic graph
- circles are fit dimensions
- arrows represent a correlation

$B \to K^+\pi^-$



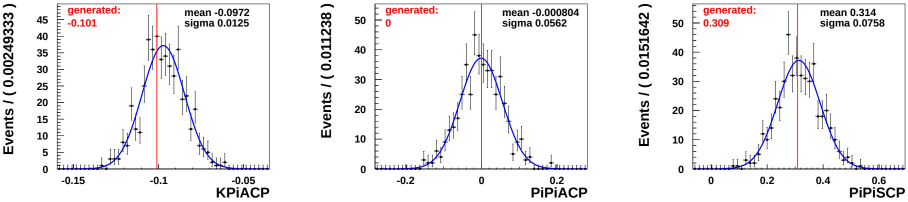
$B \to K^-\pi^+$



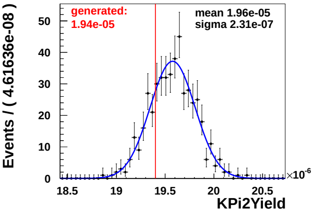
Toy-Monte-Carlo Ensemble tests

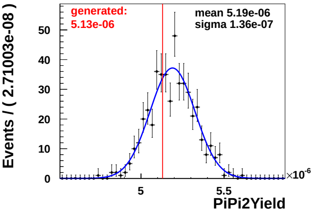
Method

- create pseudo-experiments
- number of events according to our expectations
- full detector simulation for all signal events
- creation of continuum events from PDF
- 500 pseudo-experiments



Branching Ratio pull-distribution

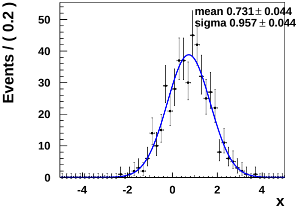


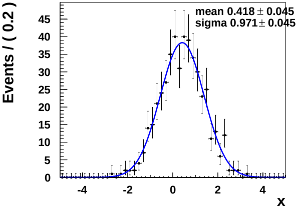


Definition: Pull

$$\text{pull} = \frac{x_{\text{fit}} - x_{\text{gen}}}{\Delta x}$$

- expect Gaussian distribution with mean of 0
- expect a sigma of 1





Summary

summary

- new ansatz for the analysis of $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$ und $B^0 \to K^+K^-$
  "minimal cuts"
- statistical improvement: better method + more luminosity
- model for 6 components and 8 observables each finished
- various methods for corrections of differences between MC and data
- Toy-Monte-Carlo ensemble tests
  estimation of the errors of the fitter

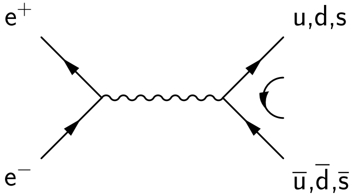
outlook

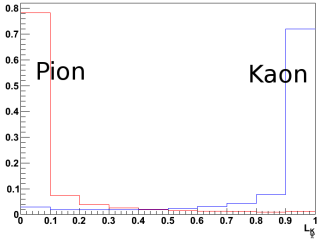
- box opening
- estimation of the systematic errors
- isospin analysis

Backup

Correlations in continuum background

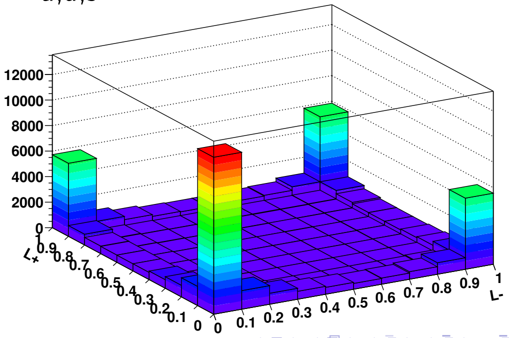
- $\mathcal{L}^+$:= "Likelihood $\frac{K}{\pi}$ of the positiv particle"
- $\mathcal{L}^-$:= "Likelihood $\frac{K}{\pi}$ of the negativ particle"





$$\mathcal{L}^\pm = \frac{PDF(\text{K})}{PDF(\text{K}) + PDF(\pi)}$$

	$\mathcal{L}^+$	$\mathcal{L}^-$	q
$\mathcal{L}^+$	1	16%	-6%
$\mathcal{L}^-$		1	6%
q			1



Zusammenfassung des Analyseverfahren

1. Rekonstruktion von $\pi^+\pi^-$ Monte-Carlo-Ereignissen
2. Erstellen einer Probability Density Function (PDF) für den Kanal $\pi^+\pi^-$
3. Rekonstruction und Erstellung einer PDF für alle Untergrund Kanäle
4. Konstruktion einer globalen PDF und Minimierung von $-2\log\mathcal{L}(PDF)$

Vorhergehende Belle Analyse (Ishino et al.)

- 6 Komponenten im Fit (ΔE, M_{BC}, $\mathcal{L}^+$, $\mathcal{L}^-$, Δt, q)
- Schnitt auf die $\frac{b\bar{b}}{q\bar{q}}$ Discriminante
- Untergrund Yield aus anderen Analysen

Neue Methode

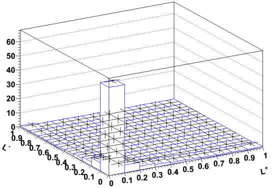
- 8 Komponenten im Fit (ΔE, M_{BC}, $\mathcal{L}^+$, $\mathcal{L}^-$, Δt, q, $F_{\frac{b\bar{b}}{q\bar{q}}}$, $\cos\theta$)
- Vermeidung von Schnitten
- Bestimmung des Untergrunds in gleichem Fit

PID Likelihoods

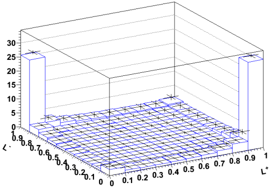
Information in den PID Likelihoods

- Unterscheidung der 3 Signalkanäle
- Messung von A_{CP} bei $\mathrm{B}^0 \to \mathrm{K}^+\pi^-$

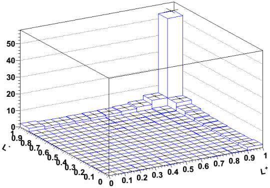
$\mathrm{B}^0 \to \pi^+\pi^-$



$\mathrm{B}^0 \to \mathrm{K}^+\pi^-$



$\mathrm{B}^0 \to \mathrm{K}^+\mathrm{K}^-$



CP Symmetrie

C-Parität

$$C\,|\Phi\rangle = |\bar{\Phi}\rangle$$

Konjugiert alle multiplikativen Quantenzahlen.

- Elektrische Ladung
- Baryonenzahl, Leptonenzahl
- strangeness, charm, beauty, I_3

P-Parität

$$P\,|\Phi\rangle = |\tilde{\Phi}\rangle$$

$$P : \begin{pmatrix} x \\ y \\ z \end{pmatrix} \longrightarrow \begin{pmatrix} -x \\ -y \\ -z \end{pmatrix}$$

Entspricht einer Punktspiegelung am Ursprung in 3 Dimensionen

CP-Parität

$$CP\,|\Phi\rangle = |\bar{\Phi}\rangle$$

Sollte ein Teilchen in sein Antiteilchen überführen ohne die Schwache Wechselwirkung zu brechen. Aber: CP Verletzung 1964 in Kaon Zerfällen gefunden.

CP-Verletzung im Standardmodell

- CP violated in weak interactions
- represented by non-vanishing complex phase in the weak mixing matrix
  (CKM model, Nobel Prize 2008 for Kobayashi & Maskawa)

$$\begin{pmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\mathbf{C}_{CKM}} \begin{pmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{pmatrix}$$

Precision Measurement of CP-Violation

- verification of the CKM model
- search for new sources of CP Violation → New Physics
- B mesons show large CP-Violation, well suited for CP measurements
- high statistics and precision needed to challenge SM