University *of Ljubljana*
Faculty *of Mathematics and Physics*

MEASUREMENT OF $\mathcal{CP}$ VIOLATION IN WEAK DECAYS OF $B^0 \rightarrow K^+\pi^-\pi^0$ WITH THE BELLE DETECTOR

PhD thesis defense

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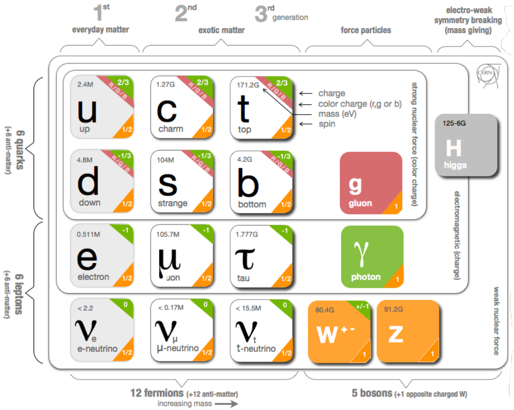
Advisor: Assoc. Prof. Dr. Marko Starič

8 May 2014

The Standard Model

- Theory of electromagnetism, the weak and the strong interaction
- In 2012 the last missing particle (Higgs) discovered.
    - Experimentally exceptionally well confirmed theory



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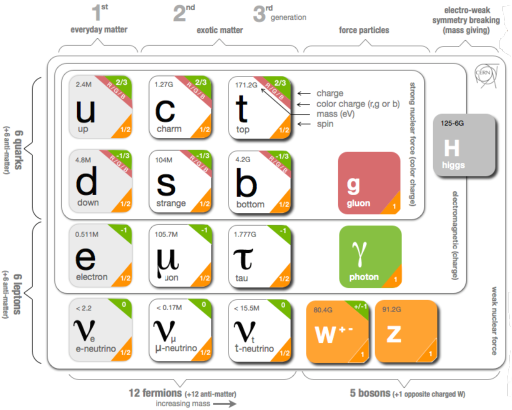


Open Issues

- Hierarchy problem
- Neutrino Masses
- Strong CP problem
- Dark Matter
- Generations of matter
- $\mathcal{CP}$ Violation
- ...

What is $\mathcal{CP}$ Violation?

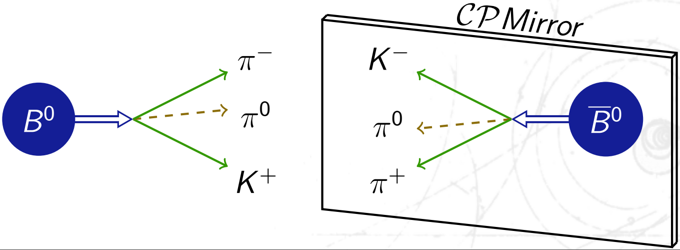
$\mathcal{C}$ – Charge conjugation

$$\mathcal{C}e_L^- \rightarrow e_L^+$$

$\mathcal{P}$ – Parity

$$\mathcal{P}e_L^- \rightarrow e_R^-$$

- Till 1957 believed that $\mathcal{C}$ and $\mathcal{P}$ are conserved
  - $\mathcal{P}$ violation discovered (C.S .Wu 1957)
- The product $\mathcal{CP}$ is conserved (Landau 1957)
  - $\mathcal{CP}$ violation measured; $K_L \rightarrow \pi^+\pi^-$ (Cronin & Fitch 1964)
  - $\mathcal{CP}$ violation measured in B^0 (Belle & *BABAR* 2001)
- $\mathcal{CP}$ violation distinguishes matter from antimatter



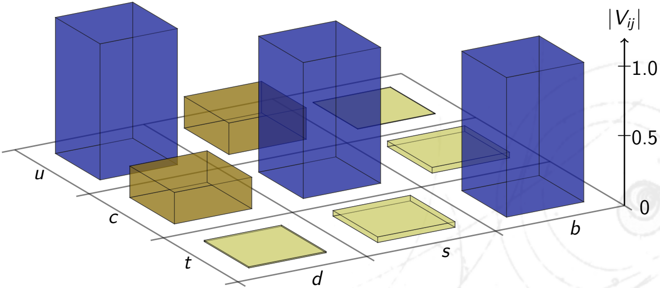
$\mathcal{CP}$ Violation in the SM

- Described by the CKM matrix (Kobayashi & Maskawa 1973)
  - relative misalignment of the Yukawa matrices for the up- and down-type quarks

$$V_{CKM} = V_u V_d$$

V matrices from diagonalisation of mass matrices

- 3×3 unitary matrix (3 angles, 1 complex phase $\rightarrow$ $\mathcal{CP}$ Viol.)
- weak interaction couplings differ for quarks and antiquarks



$\mathcal{CP}$ Violation in the SM

- CKM matrix very hierarchical → Wolfenstein parametrization

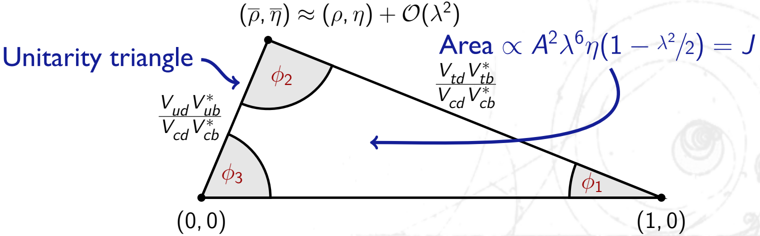
$$V_{CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = 0.225, \quad A = 0.823, \quad \rho = 0.132, \quad \eta = 0.357$$

- Unitarity → six relations represented as triangles in the complex plane

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

- Parameter η describes size of $\mathcal{CP}$ violation in the SM



$\mathcal{CP}$ Violation an Open Issue?

- Sakharov conditions (1967) for Baryogenesis
  1. Baryon number violating interaction $H_{\text{eff}}(\Delta\mathcal{B} \neq 0) \neq 0$
  2. Existence of $\mathcal{CP}$ violating interactions
  3. Departure from thermodynamic equilibrium ($\mathcal{CPT} \to \mathcal{CP}$)
- Baryon asymmetry of the Universe by KM $\mathcal{CP}$ violation

Jarlskog parameter $J = 3 \times 10^{-5}$

Mass difference term

$$\Delta = \frac{n_{\mathcal{B}} - n_{\overline{\mathcal{B}}}}{n_\gamma} \approx \frac{n_{\mathcal{B}}}{n_\gamma} \sim J \; P_u \; P_d \; M^{-12}$$

Mass scale EW $\propto \mathcal{O}(100\text{GeV})$

- SM gives $\Delta \sim \mathcal{O}(10^{-17})$ – Observed value $\Delta \sim \mathcal{O}(10^{-10})$

$\mathcal{CP}$ Violation an Open Issue?

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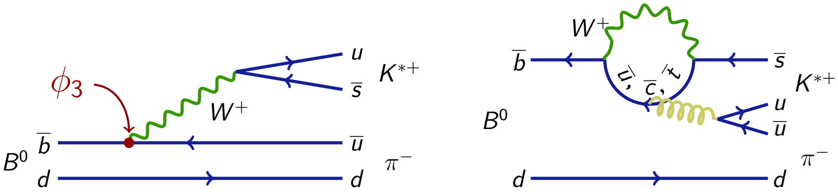
We need more $\mathcal{CP}$ violation!

SM $\mathcal{CP}$ violation insufficient to explain baryon asymmetry
Search for new sources of $\mathcal{CP}$ violation

$\mathcal{CP}$ Violation in $B^0 \to K^+\pi^-\pi^0$

- $B^0 \to K^*\pi \to K^+\pi^-\pi^0$ source of information of ϕ_3
- B^0 decays via $\overline{b} \to \overline{u}u\overline{s}$ tree carry the phase ϕ_3
  - But tree doubly-Cabibbo-suppressed



- Tree sensitive to $V_{ub}^* V_{us} = A\lambda^4(\rho + i\eta)$
- Measure $\mathcal{CP}$ violation through interference of tree and penguin

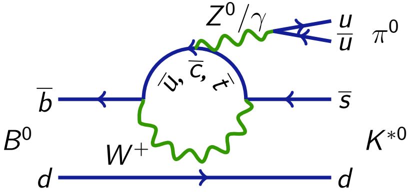
Caveat emptor

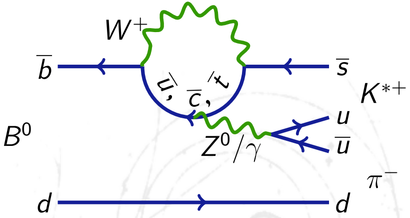
Cabibbo-allowed EWP/QCD penguin contributions $\to$ large dynamical enhancement
Model-independent determination of ϕ_3 impossible

$\mathcal{CP}$ Violation in $B^0 \to K^+\pi^-\pi^0$

What can we do?

- Isospin symmetry of QCD
  - Penguin $\to \Delta I = 0$
  - Eliminate QCD penguins ($\Delta I = 1 \to$ no QCD)
  - Nir 1991
- Linear combination $\Delta I = 1$: $A_{3/2} = -A(K^{*0}\pi^+) + \sqrt{2}A(K^{*+}\pi^0)$
- After isospin decomposition $\Phi_{3/2} \equiv -\frac{1}{2}\arg\left(\frac{\overline{A}_{3/2}}{A_{3/2}}\right) \overset{\cancel{EWP}}{=} \phi_3$
- Phase difference between $K^{*-}\pi^+$ and $K^{*+}\pi^-$ from $B^0 \to K_S\pi^+\pi^-$
- EWP estimated from (Gronau 2006)

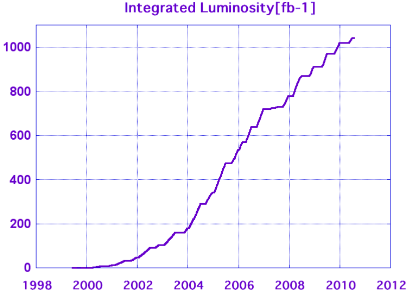


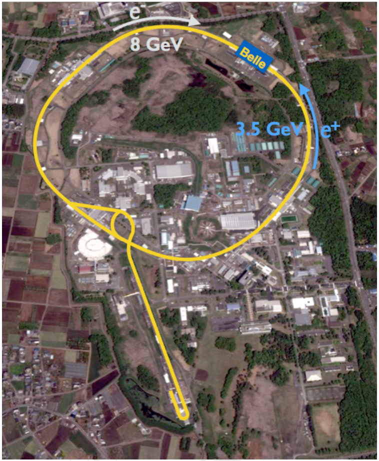


$\propto A\lambda^2\alpha_s$ (QCD)
$\propto A\lambda^2\alpha$ (EW)

KEKB Accelerator

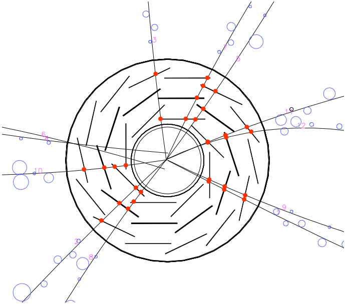
- Operated in Tsukuba, Japan (1999–2010)
- 8 GeV $e^- \rightarrow\leftarrow e^+$ 3.5 GeV

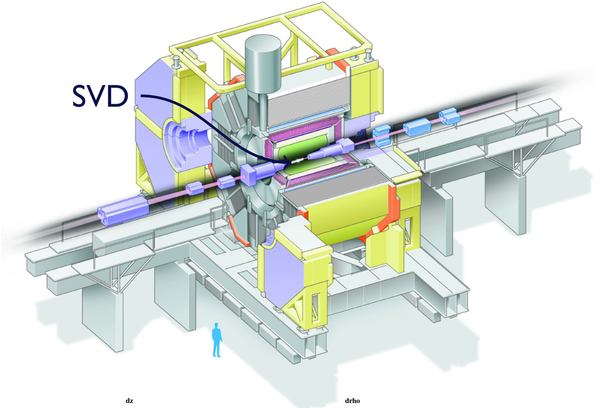




- KEKB took data mostly on $\Upsilon(4S)$
- $\Upsilon(4S)$ decays almost entirely to $B\overline{B}$
- $(772 \pm 11) \times 10^6$ $B\overline{B}$ pairs recorded
- Very clean environment for physics studies

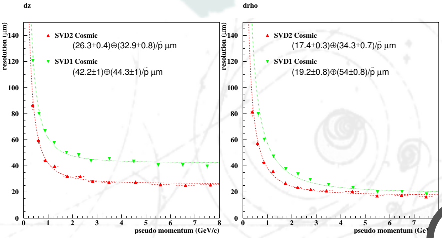
Belle Spectrometer



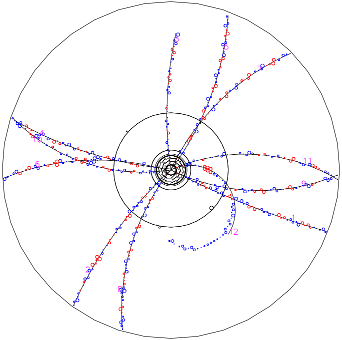


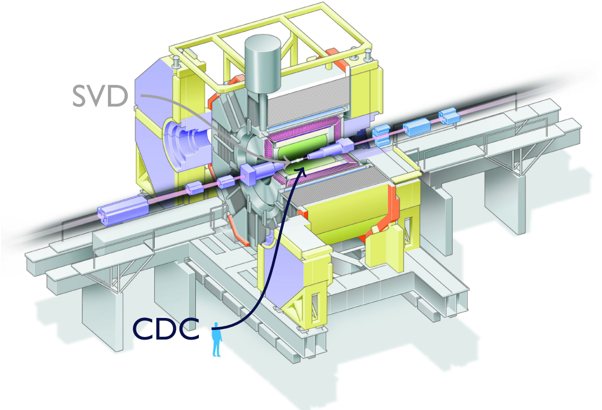
Silicon Vertex Detector (SVD)

- Determination of decay point



Belle Spectrometer



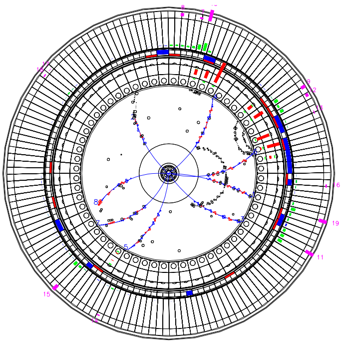


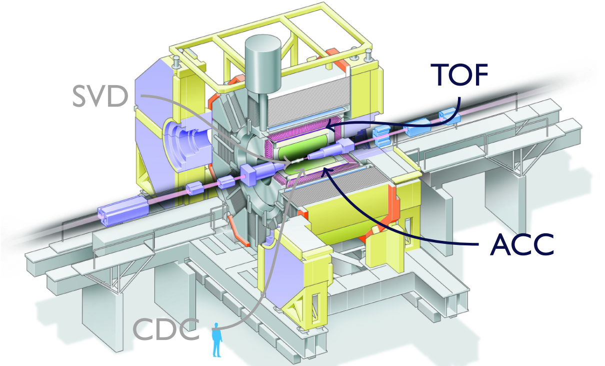
Central Drift Chamber (CDC) – $B = 1.5$ T

- Momentum measurement
- Particle identification

$$\frac{\sigma_{p_T}}{p_T} \sim 0.5\% \sqrt{1 + p_T^2[\mathrm{GeV}/c]}$$

Belle Spectrometer

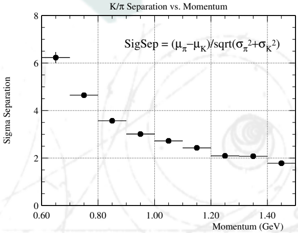




Time-Of-Flight Counter(TOF)

Aerogel Cherenkov Counter (ACC)

- Identification of $K^-, \pi^-, \mu^-, e^-, p$



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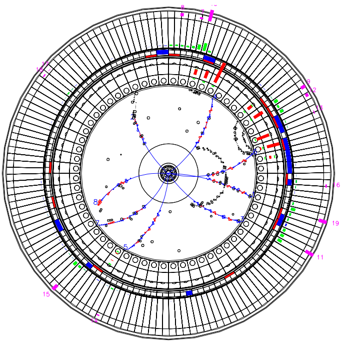
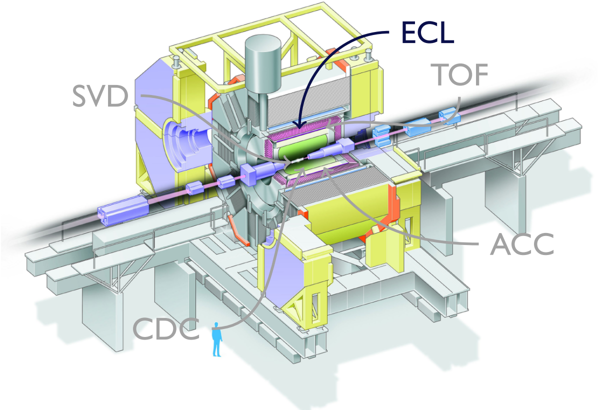
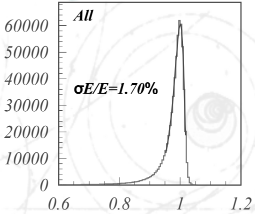




Electromagnetic Calorimeter (ECL)

- Identification of γ and e^-



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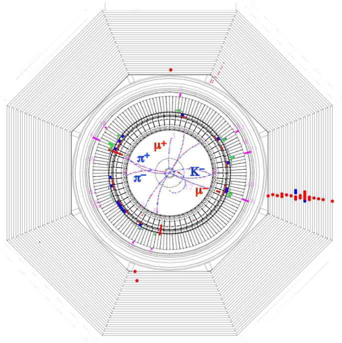
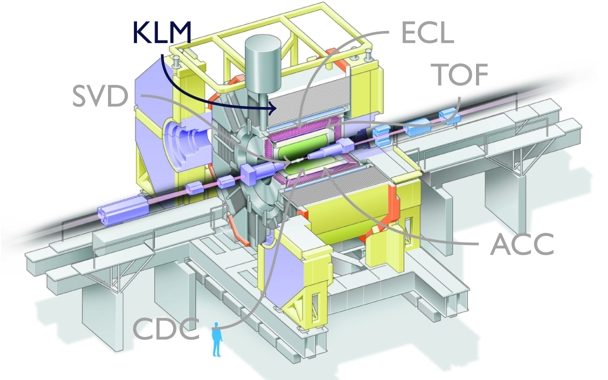
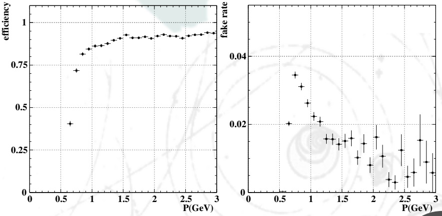


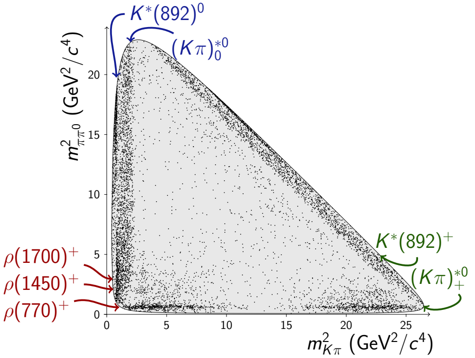


Detection System for K_L Particles and Muons (KLM)



Measurement technique

- $B^0 \to K^+\pi^+\pi^0$ receives contributions from intermediate states
- Measure phases and amplitudes from interference over the available phase-space (Dalitz Plot Analysis)
  - Three-body pseudoscalar decay $\to$ 2 free parameters
    $m^2_{K\pi} = (p_K + p_\pi)^2$ and $m^2_{\pi\pi^0} = (p_\pi + p_{\pi^0})^2$



- Populated as: $d^2\Gamma = \frac{1}{(2\pi)}\frac{1}{32M^3}|\mathcal{M}|^2 \, dm^2_{K\pi} dm^2_{\pi\pi^0}$
- Matrix element defined as: $\mathcal{M} = \sum_k a_k e^{i\phi_k} f_k(m^2_{K\pi}, m^2_{\pi\pi^0})$
- Want to measure a_i and ϕ_i and $A_{\mathcal{CP}} = \frac{\bar{a}_k^2 - a_k^2}{\bar{a}_k^2 + a_k^2}$
- Intermediate states (Fit Fractions – FF)

$$\mathrm{FF}_k = \frac{\int |A_k|^2 dm^2_{K\pi} dm^2_{\pi\pi^0} + \int |\bar{A}_k|^2 dm^2_{K\pi} dm^2_{\pi\pi^0}}{\int \left|\sum_j A_j\right|^2 dm^2_{K\pi} dm^2_{\pi\pi^0} + \int \left|\sum_j \bar{A}_j\right|^2 dm^2_{K\pi} dm^2_{\pi\pi^0}}$$

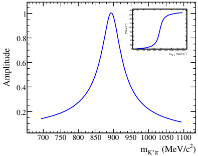
Measurement technique

- Intermediate states: $\rho(770)^-K^+$, $\rho(1450)^-K^+$, $\rho(1700)^-K^+$, $K^*(892)^+\pi^-$, $K^*(892)^0\pi^0$, $(K\pi)_0^{*+}\pi^-$, $(K\pi)_0^{*0}\pi^0$ and non-resonant
  - Need to parametrize their distribution in the Dalitz Plot

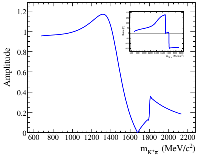
Resonance	Line shape	Parameters
	Spin-J = 1	
$\rho(770)^-$	RBW	$m = 775.26 \pm 0.25$ MeV/c^2 $\Gamma = 147.8 \pm 0.9$ MeV $R = 5.3$ GeV^{-1}
$\rho(1450)^-$	RBW	$m = 1465 \pm 25$ MeV/c^2 $\Gamma = 400 \pm 60$ MeV $R = 5.3$ GeV^{-1}
$\rho(1700)^-$	RBW	$m = 1720 \pm 20$ MeV/c^2 $\Gamma = 250 \pm 100$ MeV $R = 5.3$ GeV^{-1}
$K^*(892)^+$	RBW	$m = 891.66 \pm 0.26$ MeV/c^2 $\Gamma = 50.8 \pm 0.9$ MeV $R = 3.4$ GeV^{-1}
$K^*(892)^0$	RBW	$m = 895.81 \pm 0.19$ MeV/c^2 $\Gamma = 47.4 \pm 0.6$ MeV $R = 3.4$ GeV^{-1}
	Spin-J = 0	
$(K\pi)_0^{*+}$ or $(K\pi)_0^{*0}$	LASS	$m = 1425 \pm 50$ MeV/c^2 $\Gamma = 270 \pm 80$ MeV cutoff $m_{K\pi} = 1800$ MeV/c^2 $a = 2.07 \pm 0.10$ GeV $r = 3.32 \pm 0.34$ GeV
	Non-interfering	
D^0	Gaussian	$m = 1864.86 \pm 0.13$ MeV/c^2
D^+	Gaussian	$m = 1869.62 \pm 0.15$ MeV/c^2

f_k

- Spin-1 $\rightarrow$ Relativistic Breit-Wigner



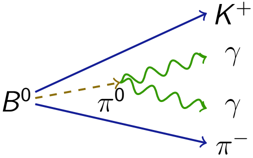
- Spin-0 $\rightarrow$ LASS parametrization



- Non-resonant $\rightarrow$ Flat

Event reconstruction and selection

- Branching fraction $\mathcal{B}r(B^0 \to K^+\pi^-\pi^0) \sim 4 \times 10^{-5}$ (PDG)



- Reconstruct $\pi^0 \to \gamma\gamma$ and combine 4-momentum vectors to final state particle

- Reconstruction criteria to reduce background:
  - π^0 invariant mass & quality of vertex fix
  - Energy difference

$$\Delta E = E_B^* - E_{\text{beam}}^*$$

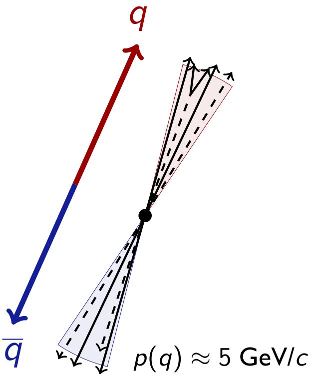
  - Modified beam energy constrained mass (use only direction of π^0) $\to$ less correlation to ΔE

$$M'_{bc} = \sqrt{E_{\text{beam}}^2 - \left(\vec{p}_{K^+} + \vec{p}_{\pi^+} + \left(\frac{\vec{p}_{\pi^0}}{|\vec{p}_{\pi^0}|}\right) \cdot \sqrt{(E_{\text{beam}} - E_{K^+} - E_{\pi^+})^2 - m_{\pi^0}^2}\right)^2}$$

- Best candidate selection:
  - 1st stage: photon asymmetry $A_\gamma = \frac{|E_\gamma^1 - E_\gamma^2|}{E_\gamma^1 + E_\gamma^2}$
  - 2nd stage: best χ^2 from the B^0 vertex fit

Continuum Suppression

- $e^+e^- \to q\overline{q}$ $(q \in \{u, d, s, c\})$ background outweighs signal
  - Topological variables to discriminate signal and background



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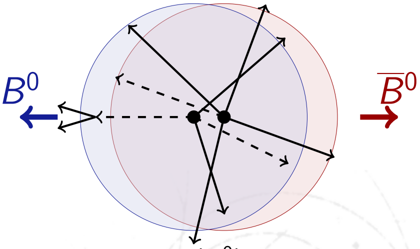

$p(B^0) \approx 0.3$ GeV/c

$e^+e^- \to \Upsilon(4S) \to B\overline{B}$

Continuum Suppression

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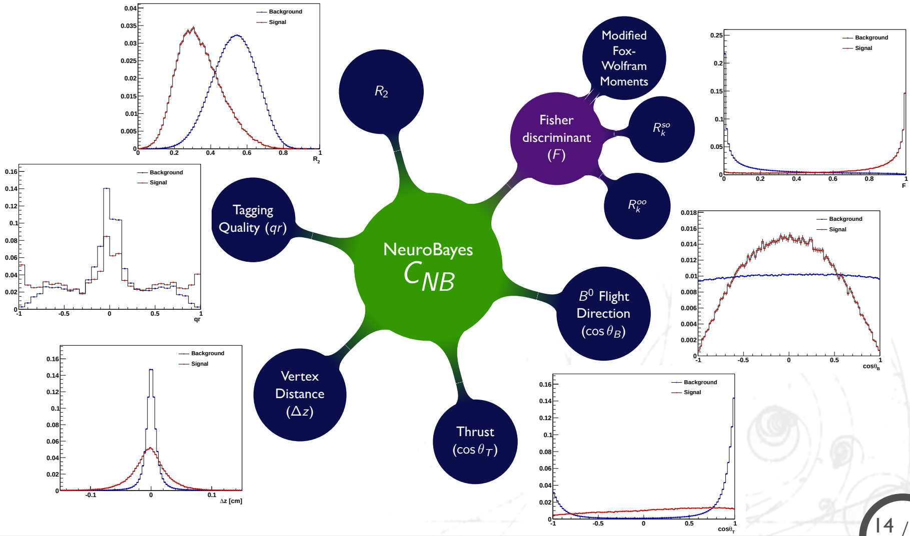
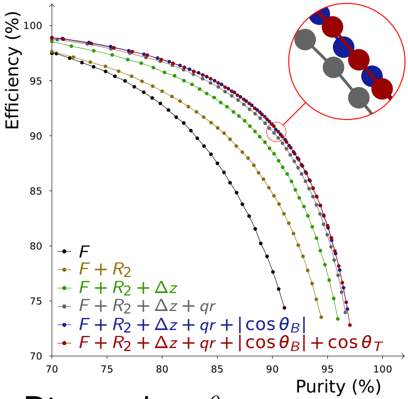
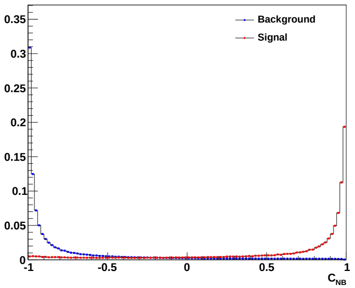


Continuum Suppression Performance

- Test → plot efficiency vs. purity



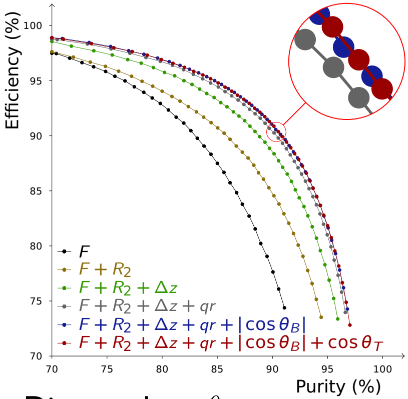
$\mathcal{F} + R_2 + \Delta z + qr + |\cos\theta_B|$



- Disregard $\cos\theta_T$

Continuum Suppression Performance

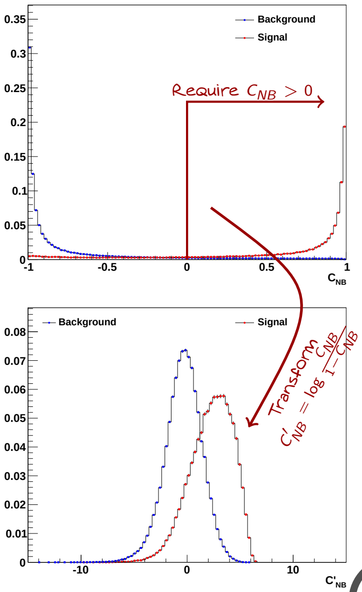
- Test → plot efficiency vs. purity



- Disregard $\cos\theta_T$
- Require $C_{NB} > 0$
- Transform and use for fit

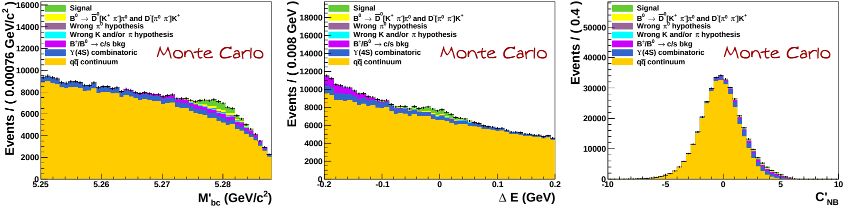
$$C'_{NB} = \log\frac{C_{NB}}{1-C_{NB}}$$

$\mathcal{F} + R_2 + \Delta z + qr + |\cos\theta_B|$



Background Studies

- $C_{NB} > 0$ rejects 92% of $e^+e^- \to q\bar{q}$ and 20% of $B\bar{B}$



Type	Fraction (%)
Signal	2.3
Continuum	87.0
Combinatoric	5.9
Wrong mass hypothesis	0.5
Wrong π^0 hypothesis	0.5
$B^+/B^0 \to c/s$	3.1
Non-interfering	0.8

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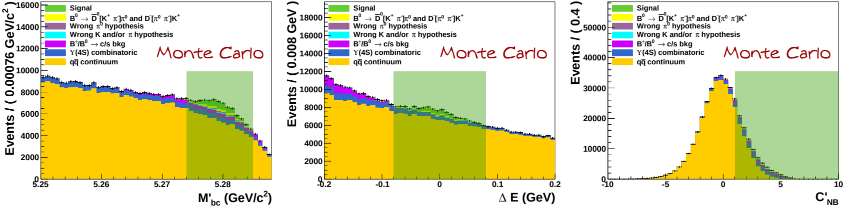


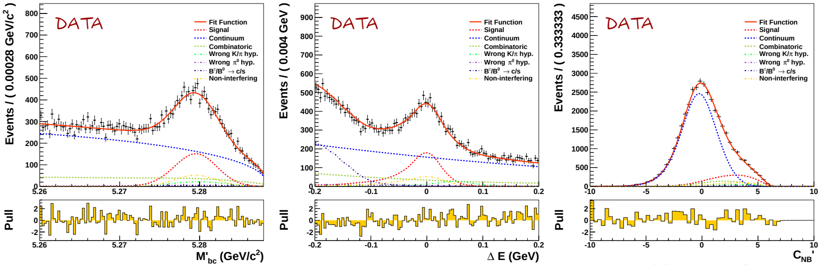
- Signal region: $5.274\ \text{GeV}/c^2 < M'_{bc} < 5.285\ \text{GeV}/c^2$, $|\Delta E| < 0.08$ GeV, $C'_{NB} > 1$

Type	Fraction (%)	Fraction in the signal region (%)
Signal	2.3	27.6
Continuum	87.0	45.1
Combinatoric	5.9	10.8
Wrong mass hypothesis	0.5	4.4
Wrong π^0 hypothesis	0.5	1.7
$B^+/B^0 \rightarrow c/s$	3.1	1.4
Non-interfering	0.8	9.1

$B^0 \to K^+\pi^-\pi^0$ – Fit

- Two step fit
  - 3D fit: determine Continuum, Combinatoric, $B^+/B^0 \to c/s$
  - 6D fit: fix results from 3D fit
  - 6D fit: determine Signal, Wrong mass, Wrong π^0, Non-interfering, Dalitz parameters a_i, $\phi_i \to A_{\mathcal{CP}}$, FF_i

M'_{bc}	modified beam-constrained mass	S/B separation
ΔE	energy difference	S/B separation
C'_{NB}	continuum suppression network output	S/B separation
$m^2_{K\pi}$	$K^+\pi^-$ invariant mass squared	Dalitz
$m^2_{\pi\pi^0}$	$\pi^+\pi^0$ invariant mass squared	Dalitz
Q	charge of primary kaon from B^0	$\mathcal{CP}$

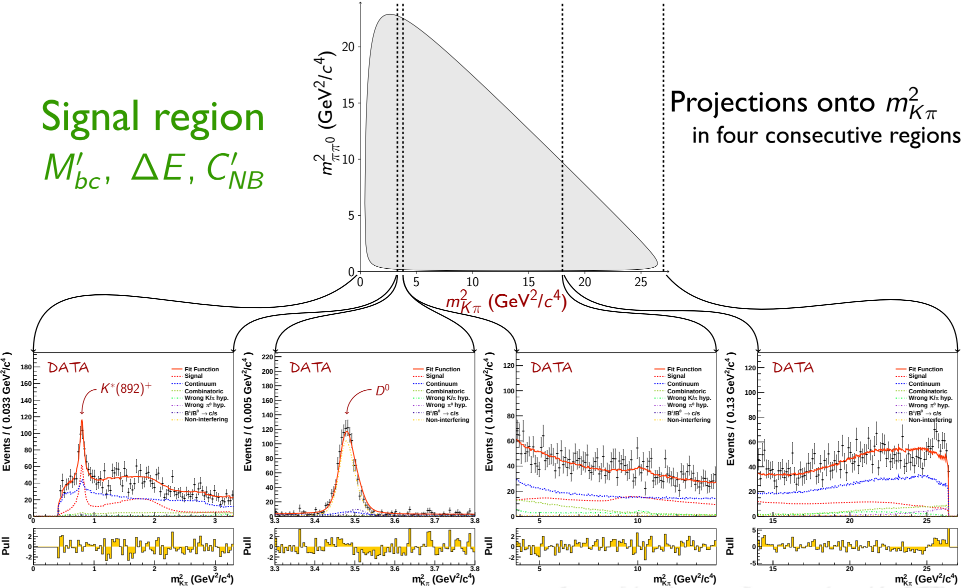


$B^0 \to K^+\pi^-\pi^0$ – Fit (Dalitz plot)

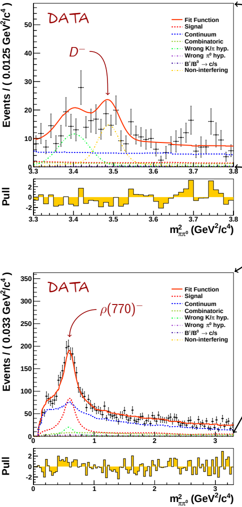
Signal region

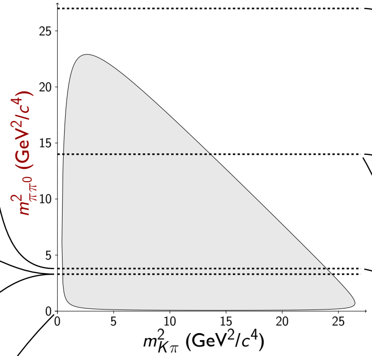
$M'_{bc},\ \Delta E,\ C'_{NB}$

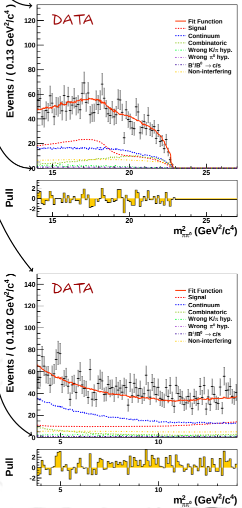
Projections onto $m^2_{K\pi}$ in four consecutive regions



$B^0 \to K^+\pi^-\pi^0$ – Fit (Dalitz plot)







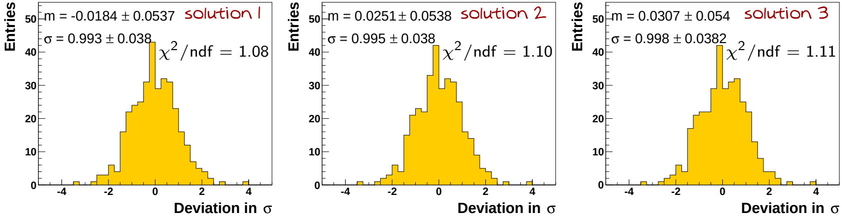
Projections onto $m^2_{\pi\pi^0}$
in four consecutive regions

Signal region

M'_{bc}, ΔE, C'_{NB}

$B^0 \to K^+\pi^-\pi^0$ – Fit (Multiple Solutions)

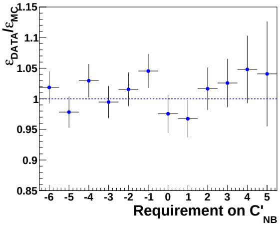
- High dimensionality of parameter space $\to$ no single minimum
- Solution:
  - Repeated 100 times with different starting values of parameters
  - Chosen one order of magnitude smaller and one order of magnitude bigger than expected value and $\phi_i \in [-\pi, \pi]$
- Three solutions found (2D χ^2):



- Most likely separated 3.8σ from second best, and 4.5σ from third best
- Most likely solution taken as result

$B^0 \to K^+\pi^-\pi^0$ – Systematic Uncertainties

- General Branching Fraction uncertainties:
  - Track Reconstruction Efficiency ($\pm 0.35\%$ per charged track)
  - PID Selection ($\pm 2.6\%$ measured from $D^{*+} \to D^0\pi^+ \to (K_S\pi^+\pi^-)\pi^+$)
  - C'_{NB} Dependence
  - MC Statistics and Number of $B\overline{B}$ ($\pm 0.4\%$)



- Dalitz model and PDF related uncertainties:
  - Line Shapes (vary parameters $\pm\sigma$)
  - Dalitz Model ($K_2^*(1430)^0$, $K_2^*(1430)^+$, $K^*(1680)^0$, $K^*(1680)^+$)
  - $B\overline{B}$ Background
  - Continuum Background
  - Asymmetry in the Reconstruction of Charged Tracks

$B^0 \to K^+\pi^-\pi^0$ – Results (1/2)

- Measured branching fraction (no $B^0 \to D^-K^+$ or $B^0 \to D^0\pi^0$)

$$\mathcal{B}r\left(B^0 \to K^+\pi^-\pi^0\right) = (3.65 \pm 0.05(\text{stat.}) \pm 0.18(\text{syst.}))\times 10^{-5}$$

- Signal yield: $5593 \pm 82(\text{stat.}) \pm 285(\text{syst.})$

$$\mathcal{B}r_i = \text{FF}_i \times \frac{N_{sig}}{N_{B\overline{B}}\varepsilon}$$

Amplitude	$\mathcal{B}r[10^{-6}]$	$A_{\mathcal{CP}}$	$\Delta\phi$
$K^*(892)^+\pi^-$	$2.69\pm0.32\pm0.41$	$-0.34\pm0.10\pm0.026$	$-0.12\pm0.22\pm0.20$
$(K\pi)_0^{*+}\pi^-$	$10.5\pm0.54\pm0.73$	$0.00\pm0.12\pm0.016$	$-0.25\pm0.24\pm0.21$
$\rho(770)^-K^+$	$5.56\pm0.33\pm0.43$	$-0.14\pm0.10\pm0.095$	0.0 (fixed)
$\rho(1450)^-K^+$	$2.89\pm0.69\pm0.63$	$0.30\pm0.27\pm0.123$	$0.72\pm0.27\pm0.12$
$\rho(1700)^-K^+$	$1.14\pm0.58\pm0.45$	$-0.28\pm0.36\pm0.126$	$0.52\pm0.25\pm0.19$
$K^*(892)^0\pi^0$	$2.12\pm0.24\pm0.46$	$-0.15\pm0.11\pm0.022$	$0.30\pm0.22\pm0.30$
$(K\pi)_0^{*0}\pi^0$	$4.46\pm0.58\pm0.50$	$-0.16\pm0.10\pm0.014$	$-0.06\pm0.26\pm0.13$
non-resonant	$2.80\pm0.36\pm0.51$	$0.08\pm0.15\pm0.123$	$0.65\pm0.28\pm0.19$

- All $\Delta\phi$ parameters consistent with zero
- Evidence for $\mathcal{CP}$ violation in $B^0 \to K^*(892)^+\pi^-$ (3.3σ)

$B^0 \to K^+\pi^-\pi^0$ – Results (2/2)

- Measured resonance weights and phases of individual resonances

Amplitude	a	$\bar{a}$	ϕ	$\bar{\phi}$
$K^*(892)^+\pi^-$	$1.16 \pm 0.05 \pm 0.048$	$0.80 \pm 0.05 \pm 0.064$	$0.35 \pm 0.16 \pm 0.26$	$0.47 \pm 0.15 \pm 0.14$
$(K\pi)_0^{*+}\pi^-$	$45.91 \pm 1.65 \pm 1.59$	$45.81 \pm 1.74 \pm 1.018$	$-2.43 \pm 0.14 \pm 0.19$	$-2.19 \pm 0.13 \pm 0.12$
$\rho(770)^-K^+$	1.57 (fixed)	$1.35 \pm 0.09 \pm 0.178$	0.0 (fixed)	0.0 (fixed)
$\rho(1450)^-K^+$	$1.65 \pm 0.20 \pm 0.126$	$2.31 \pm 0.18 \pm 0.164$	$2.17 \pm 0.15 \pm 0.29$	$1.13 \pm 0.11 \pm 0.20$
$\rho(1700)^-K^+$	$1.20 \pm 0.16 \pm 0.221$	$0.92 \pm 0.14 \pm 0.205$	$0.59 \pm 0.15 \pm 0.19$	$0.00 \pm 0.17 \pm 0.19$
$K^*(892)^0\pi^0$	$0.93 \pm 0.04 \pm 0.065$	$0.82 \pm 0.04 \pm 0.060$	$0.03 \pm 0.14 \pm 0.16$	$0.21 \pm 0.13 \pm 0.36$
$(K\pi)_0^{*0}\pi^0$	$30.31 \pm 1.32 \pm 1.62$	$25.67 \pm 1.16 \pm 1.197$	$0.04 \pm 0.13 \pm 0.20$	$0.08 \pm 0.14 \pm 0.36$
non-resonant	$14.68 \pm 0.93 \pm 0.667$	$16.12 \pm 0.97 \pm 0.620$	$1.44 \pm 0.12 \pm 0.18$	$0.69 \pm 0.11 \pm 0.15$

- All complex weights have a significance of at least 3σ
  - Dalitz model was chosen adequately
- Data serving as partial input for ϕ_3 determination

Summary

- Perfomed Dalitz analysis of $B^0 \to K^+\pi^-\pi^0$ on full Belle data sample
- Dalitz model used: $\rho(770)^- K^+$, $\rho(1450)^- K^+$, $\rho(1700)^- K^+$, $K^*(892)^+\pi^-$, $K^{*0}(892)\pi^0$, $(K\pi)_0^{*+}\pi^-$, $(K\pi)_0^{*0}\pi^0$ and non-resonant
- Measured branching fraction (no $B^0 \to D^- K^+$ or $B^0 \to D^0\pi^0$)

$$\mathcal{B}r\left(B^0 \to K^+\pi^-\pi^0\right) = (3.65 \pm 0.05(\text{stat.}) \pm 0.18(\text{syst.}))\times 10^{-5}$$

- First evidence for $\mathcal{CP}$ violation

$$A_{\mathcal{CP}}(K^*(892)^+\pi^-) = -0.34 \pm 0.10 \pm 0.026$$

- *BABAR* measurement of $B^0 \to K^+\pi^-\pi^0$

$$A_{\mathcal{CP}}(K^*(892)^+\pi^-) = -0.29 \pm 0.11 \pm 0.02$$

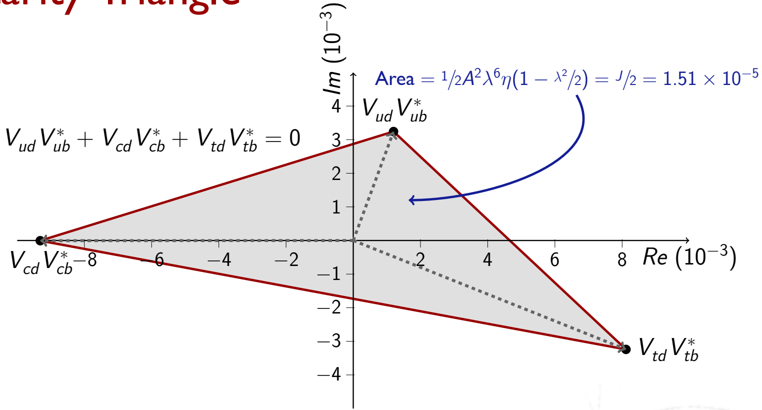
- Measure resonance weights and phases of individual resonances (partial input for ϕ_3 determination)

BACKUP

Background Composition

- Continuum – random $e^+e^- \to q\bar{q}$ ($q \in \{u, d, s, c\}$)
- Combinatoric – tracks from B and $\overline{B}$
- Wrong mass hypothesis
  - 50.0% $B^0 \to \rho^\pm(\to \pi^\pm\pi^0)\pi^\mp$
  - 15.7% $B^0 \to D^-(\to \pi^0\pi^-)\pi^+$
  - 6.0% $B^0 \to K^+K^-\pi^0$
- Wrong π^0 hypothesis
  - 9.0% $B^0 \to \rho^\pm(\to \pi^\pm\pi^0)\pi^\mp$
  - 7.6*% $B^0 \to \rho^-(\to \pi^-\pi^0)K^+$
  - 5.2% $B^- \to \rho(1450)^0(\to \pi^+\pi^-)K^-$
  - 3.6*% $B^0 \to K^*(892)^+(\to K^+\pi^0)\pi^-$
- $B^+/B^0 \to c/s$
  - 60.0% $B^+ \to \rho^+(\to \pi^+\pi^0)\overline{D}^0(\to K^+\pi^-)$
  - 2.7%$B^0 \to \overline{D}^{*0}(\to \overline{D}^0(\to K^+\pi^-)\pi^0)\pi^0$
- Non-interfering
  - 97.6% $B^0 \to D^0(\to K^+\pi^-)\pi^0$
  - 2.4% $B^0 \to D^-(\to \pi^-\pi^0)K^+$

Unitarity Triangle



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9745 & 0.2246 & 0.001230 - 0.003327i \\ -0.2244 - 0.000138i & 0.9734 & 0.04151 \\ 0.008122 - 0.003243i & -0.04073 - 0.000747i & 0.9991 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

$$\bar{\rho} = \rho(1 - \frac{1}{2}\lambda^2) + \left(\frac{1}{2}A^2\rho - \frac{1}{8}\rho - A^2(\rho^2 - \eta^2)\right)\lambda^4 + \mathcal{O}(\lambda^6)$$

$$\bar{\eta} = \eta(1 - \frac{1}{2}\lambda^2) + \left(\frac{1}{2}A^2\eta - \frac{1}{8}\eta - 2A^2\rho\eta\right)\lambda^4 + \mathcal{O}(\lambda^6)$$