CP violation and Standard Model tests in charmless hadronic B decays

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Outline

1. Introduction to the . . .
   - . . . computation of hadronic amplitudes
   - . . . phenomenology of non-leptonic B-decays
   - . . . statistical methods

2. Fit Results
   - SM for $B \to K\pi$ and $B \to K\rho$ system
   - New Physics: Enhanced left-handed Z penguin

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B-Hadron decays are a Multi-scale problem . . .

. . . Typical interaction (IA) scales

electroweak IA	$\gg$	ext. mom'a in B restframe	$\gg$	QCD-bound state effects
$M_W \approx 80$ GeV $M_Z \approx 91$ GeV		$M_B \approx 5$ GeV		$\Lambda_{\rm QCD} \approx 0.5$ GeV

B-Hadron decays are a Multi-scale problem . . .

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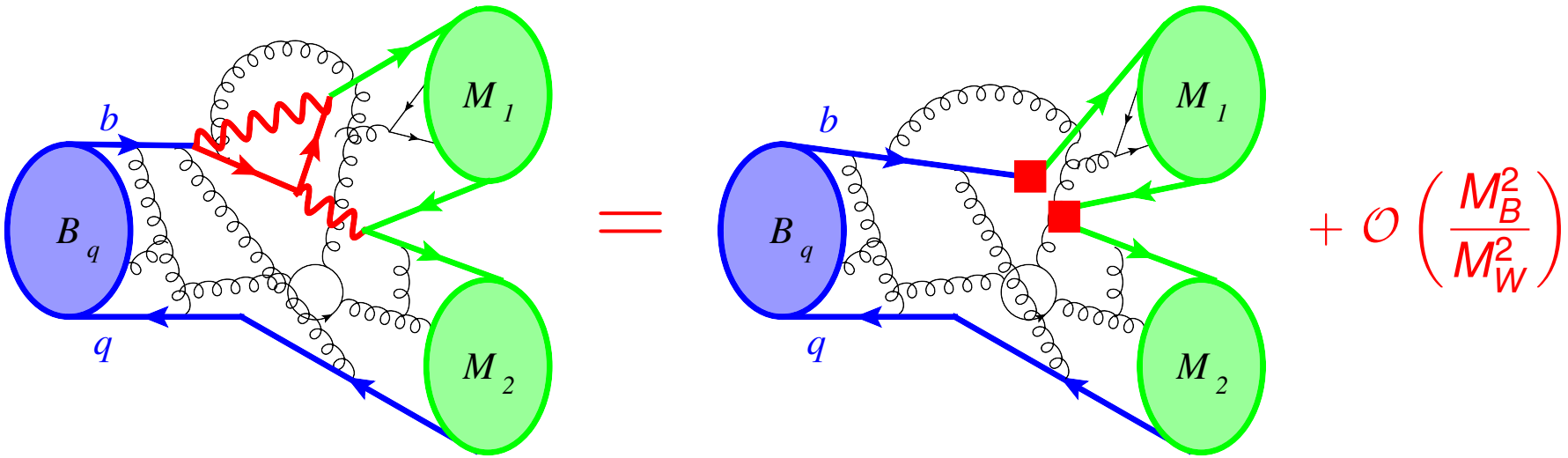
electroweak IA $\gg$

$M_W \approx 80$ GeV
$M_Z \approx 91$ GeV

electroweak IA is "short-distance = local" compared to binding QCD IA

$\Rightarrow$ Effective theory of $|\Delta B| = |\Delta S| = 1$ decays $\Rightarrow$ separation of scales



for charmless hadronic $B \to M_1 M_2$ decays

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$M_W \approx 80$ GeV
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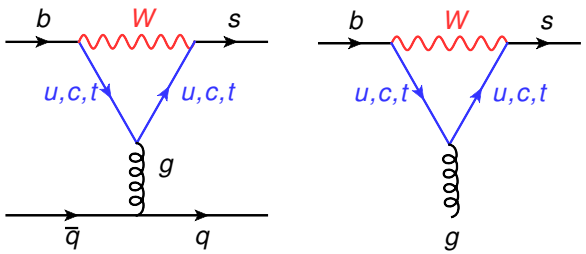
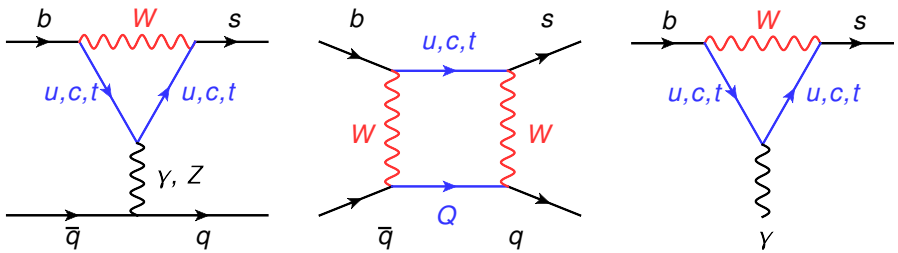
$$H_{\text{eff}}^{|\Delta B|=|\Delta S|=1} = \frac{G_F}{\sqrt{2}} \times \Big[\text{CC} + (\text{QCD-peng} + \mathcal{O}_{8g}) + (\text{QED-peng} + \mathcal{O}_{7g})\Big]$$

CC = charged current

QCD-penguin and chromo-magnetic



QED-penguin and electro-magnetic



tree decays

FCNC decays $\Rightarrow$ sensitive to non-standard virtual heavy states

$\Rightarrow$ factorized into Wilson coefficients C_i of operators $\mathcal{O}_i$

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QCD and QED penguin dominated $|\Delta B| = |\Delta S| = 1$ decays

$B \to PP$ with $PP = K\pi,\ K\eta,\ K\eta'$

$B \to VP$ with $PV = K\rho,\ K\phi,\ K\omega$

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ext. mom'a in B restframe $\gg$ QCD-bound state effects

$M_B \approx 5$ GeV $\qquad$ $\Lambda_{\rm QCD} \approx 0.5$ GeV

QCD factorization a la BBNS [arxiv-hep/0104110, arxiv-hep/0308039]:

matrix elements factorize into perturbative and non-perturbative quantities
by the expansion of gluon momentum transfer $k \sim mb$

$$\langle M_1 M_2 | \, \mathrm{Q}_i \, | B \rangle =$$

$$F^{B\to M_1}(0) f_{M_2} \int_0^1 du \, \mathrm{T}^{\mathrm{I}}_{\mathrm{ij}}(u) \Phi_{M_2}(u) + f_B f_{M_1} f_{M_2} \int_0^1 d\xi dv du \, \mathrm{T}^{\mathrm{II}}_{\mathrm{ij}} \Phi_B(\xi) \Phi_{M_1}(v) \Phi_{M_2}(u) + \mathcal{O}\left(\frac{1}{mb}\right)$$

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non-perturbative input	Form-factor $F_j^{B\to M_1}$
	decay constants f_{M1}, f_B
	LCDA $\Phi_{M_1}(u)$
	inverse momen of LCDA B-meson $\frac{1}{\lambda_B} = \int dw \frac{\Phi_{B_+}(w)}{w}$
perturbative input	quark masses, CKM-elements
model parameter	X_A, X_H

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Can be extracted from

LCSR
[arxiv-hep/0309330]
$\lambda_B \sim 300 - 600$ MeV

hadronic tree decays of B-meson NNLO
$B \to \pi\pi$ [arxiv-hep/0911.3655]
$\lambda_B \sim 200 - 450$ MeV

$B \to \gamma l \nu_l$
[arxiv-hep/1110.3228]
$\lambda_B > 115$ MeV

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Calculation of hard-scattering and weak-annihilation amplitudes involves logarithmically divergent integrals

$$X_H = \int_0^1 \frac{1}{1-x}\Phi(x)dx \to \int_0^1 \frac{1}{1-x+\varepsilon}\Phi(x)dx$$
$$\varepsilon \sim \mathcal{O}(\tfrac{\Lambda}{mb}) \to X_H = (1+\rho_H e^{i\phi_H})\ln\tfrac{\Lambda}{mb}$$

$$X_A = \int_0^1 \frac{1}{1-x}\Phi(x)dx \to \int_0^1 \frac{1}{1-x+\varepsilon}\Phi(x)dx$$
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XA in principle different for each process and operator insertion $XA = XA_i^{M_1}$ . . .
. . . but main contribution comes from QCD-operator $Q_{3,5,6}$ insertions
$\Rightarrow$ assumptions:

$SU(2)_I$ Invarianz of QCD	universal XA for $B \to K\pi(\rho)$!
Fit XA	No scale variation for error estimate needed!

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Phenomenology I - Observables

$B \to (\rho)\pi K$ are dominated by QCD-peng. P_{QCD} and polluted by . . . [arxiv-hep:1011.6319]

topologies	$\to$	suppression factor	$\to$	expansion parameter
tree T		CKM $\times 1/\alpha_s$		$r_T = 0.17^{+0.07}_{-0.06} + 0.03^{+0.03}_{-0.10}\mathrm{i}$
col. sup. tree C		CKM $\times (1/N_C) \times 1/\alpha_s$		$r_C = 0.07^{+0.04}_{-0.06} - 0.01^{+0.03}_{-0.05}\mathrm{i}$
EW peng. P_{EW}		α/α_s		$r_{EW} = 0.13^{+0.05}_{-0.05} + 0.02^{+0.02}_{-0.07}\mathrm{i}$
col. sup. EW peng. P^C_{EW}		$\alpha/\alpha_s \times (1/N_C)$		$r^C_{EW} = 0.04^{+0.02}_{-0.03} - 0.01^{+0.02}_{-0.03}\mathrm{i}$
EW ann. PA_{EW}		$\alpha/\alpha_s \times (\Lambda_{\mathrm{QCD}}/mb)$		$r^A_{EW} = 0.007^{+0.002}_{-0.010} - 0.004^{+0.011}_{-0.003}\mathrm{i}$

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Expanding the amplitude . . .

$$A(B^- \to K^0\pi^-) \sim P\left(1 - \frac{1}{3}r^c_{EW} + \frac{2}{3}r^A_{EW}\right)$$

$$\sqrt{2}A(B^- \to K^-\pi^0) \sim P\left(1 + r_{EW} + \frac{2}{3}r^c_{EW} + \frac{2}{3}r^A_{EW} + (r_T + r_C)e^{\mathrm{i}\gamma}\right)$$

$$A(B^0 \to K^-\pi^+) \sim P\left(1 + \frac{2}{3}r^c_{EW} - \frac{1}{3}r^A_{EW} - r^T e^{\mathrm{i}\gamma}\right)$$

$$\sqrt{2}A(B^0 \to K^0\pi^0) \sim P\left(1 - r_{EW} - \frac{1}{3}r^c_{EW} + \frac{1}{3}r^A_{EW} + r_C e^{\mathrm{i}\gamma}\right)$$

Branching Ratio

Sensitive to real and imaginary parts of expansion parameters

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Expanding Ratios of Branching Ratios . . .

$$R^B_n \equiv \frac{1}{2}\frac{Br(B^0 \to K^-\pi^+)}{Br(B^0 \to K^0\pi^0)} \sim 1 + \mathrm{Re}(r_{EW} + r^c_{EW}) - 2\mathrm{Re}(r_T + r_C)\cos\gamma$$

$$R^K_c \equiv 2\frac{\tau_0}{\tau_-}\frac{Br(B^- \to K^-\pi^0)}{Br(B^0 \to K^-\pi^+)} \sim 1 + \mathrm{Re}(r_{EW}) - 2\mathrm{Re}(r_C)\cos\gamma$$

$$R^\pi_n \equiv \frac{\tau_0}{\tau_-}\frac{Br(B^- \to K^0\pi^-)}{Br(B^0 \to K^-\pi^+)} \sim 1 - 2\mathrm{Re}(r^c_{EW}) - 2\mathrm{Re}(r_T)\cos\gamma$$

Ratios of Branching Ratio

Sensitive to real parts of expansion parameters

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Direct CP-Asymmetries . . .

$$C(B^- \to K^-\pi^0) \sim 2\mathrm{Im}(r_T + r_C)\sin\gamma$$

$$C(B^0 \to K^-\pi^+) \sim 2\mathrm{Im}(r_T)\sin\gamma$$

$$\Delta A_{\mathrm{CP}} \equiv C(B^0 \to K^-\pi^+) - C(B^- \to K^-\pi^0) \sim -2\mathrm{Im}(r_C)\sin\gamma$$

Direct CP-Asy

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Direct CP-Asymmetries $\to K\pi$-puzzle

$$C(B^- \to K^-\pi^0) \sim 2\mathrm{Im}(r_T + r_C)\sin\gamma$$

$$C(B^0 \to K^-\pi^+) \sim 2\mathrm{Im}(r_T)\sin\gamma$$

$\Delta A_{\mathrm{CP}} \overset{\mathrm{exp}}{=} (12.4 \pm 2.3)\%$, $\quad \Delta A_{\mathrm{CP}} \overset{\mathrm{the}}{=} (1.9^{-4.8}_{+5.8})\%$

Direct CP-Asy

Sensitive to imaginary parts of expansion parameters

Phenomenology II - Motivation

Why fitting contributions from weak annihilation?

Expansion in CKM elements	$A(B \to K\pi) = \lambda_c A^c_{K\pi} + \lambda_u A^u_{K\pi}$
Branching Ratio	$Br(B \to K\pi) \sim \lambda_c A^c_{K\pi}$
CP-Asy	$S, C(B \to K\pi) \sim \frac{\lambda_u}{\lambda_c} \frac{A^u_{K\pi}}{A^c_{K\pi}}$

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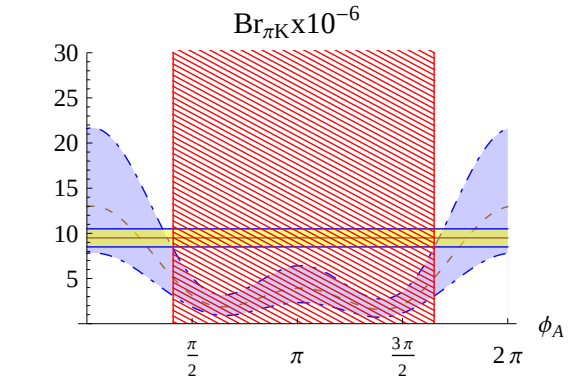

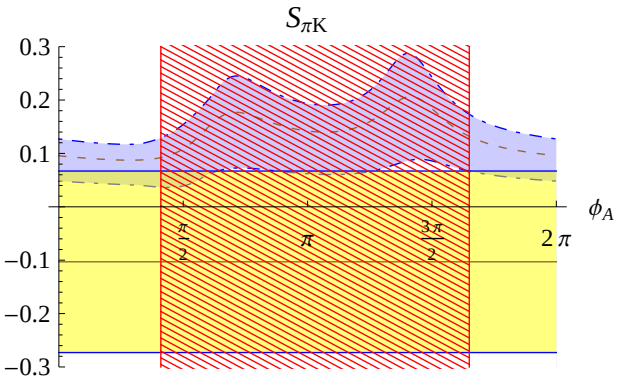

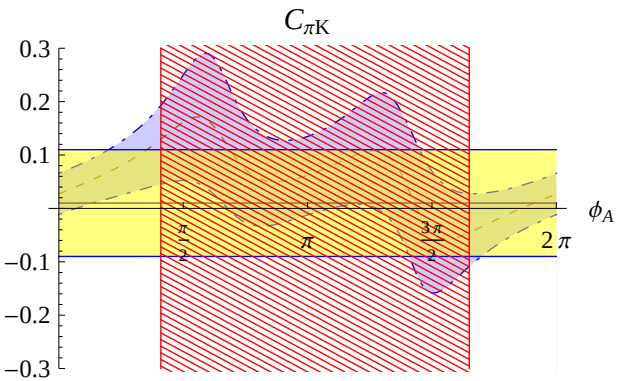

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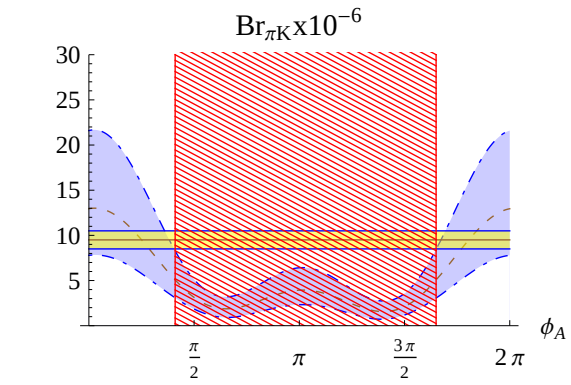
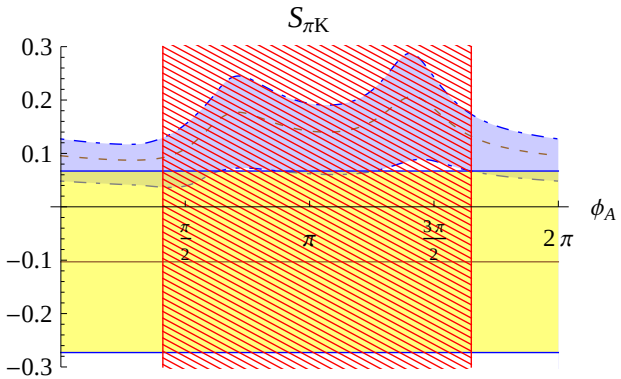
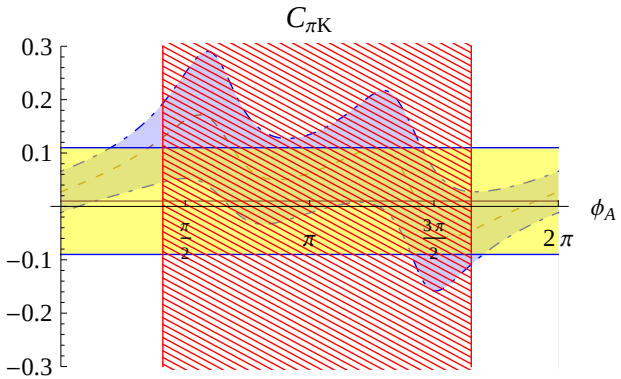
Correlation effects reduces uncertainty up to factor 2

$C^{\text{scan}}(B^0 \to K^0\pi^0) = 0.03^{+0.15}_{-0.09}$ $\quad \Delta S^{\text{scan}}(B^0 \to K^0\pi^0) = 0.10^{+0.12}_{-0.05}$

$C^{\text{fit}}(B^0 \to K^0\pi^0) = 0.03^{+0.10}_{-0.08}$ $\quad \Delta S^{\text{fit}}(B^0 \to K^0\pi^0) = 0.10^{+0.05}_{-0.05}$







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Fit method and treatment of theory uncertainties

Parameters of interest

$$\vec{\theta} = (C_i, X_{A,H}, \lambda_B)$$

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Nuisance parameters

$\vec{\nu}$

1) process-specific

FF's, decay const's,
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sub-leading Λ/m_b,
renorm. scales: $\mu_{b,0}$

2) general

quark masses, CKM, . . .

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Observables

1) observables

$$O(\vec{\theta}, \vec{\nu})$$

depend usually on sub-set of $\vec{\theta}$ and $\vec{\nu}$

2) experimental data for each observable

$$\text{pdf}(O = o)$$

$\Rightarrow$ probability distribution of values o

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Fit strategy: Put theory uncertainties in likelihood using RFit-scheme

$$\chi^2 = \sum_j \begin{cases} \left(\frac{x_j^{\text{the}} - \sigma_j^{\text{the}} - x_j^{\text{exp}}}{\sigma_j^{\text{exp}}} \right)^2 & \text{if } x_j^{\text{exp}} < x_j^{\text{the}} - \sigma_j^{\text{the}} \\ \left(\frac{x_j^{\text{the}} + \sigma_j^{\text{the}} - x_j^{\text{exp}}}{\sigma_j^{\text{exp}}} \right)^2 & \text{if } x_j^{\text{exp}} > x_j^{\text{the}} + \sigma_j^{\text{the}} \\ 0 & \textit{else} \end{cases}$$

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$\Rightarrow$ probability distribution of values o

Fit strategy: Put theory uncertainties in likelihood using RFit-scheme and . . .

- sample $\vec{\theta}$-space (Markov Chains: BAT = Bayesian Analysis Tool)
- theory uncertainties of O_i at each $(\vec{\theta})_i$: vary $\vec{\nu}$ within some ranges $\Rightarrow \sigma_{\text{th}}(O[(\vec{\theta})_i])$
- Find $\Rightarrow$ 68 , 95 & 99 % CL regions of $\vec{\theta}$
- Goodness-of-Fit through p-value estimation

Fit method and treatment of theory uncertainties

Parameters of interest

$$\vec{\theta} = (C_i, X_{A,H}, \lambda_B)$$

Nuisance parameters

$\vec{\nu}$

1) process-specific

FF's, decay const's,
LCDA pmr's,
sub-leading Λ/m_b,
renorm. scales: $\mu_{b,0}$

2) general

quark masses, CKM, . . .

Observables

1) observables

$$O(\vec{\theta}, \vec{\nu})$$

depend usually on sub-set of $\vec{\theta}$ and $\vec{\nu}$

2) experimental data for each observable

$$\text{pdf}(O = o)$$

$\Rightarrow$ probability distribution of values o

Fit strategy: Test different independent sets of observables $O(\vec{\theta}, \vec{\nu})$

BR - Set I	only $BR(B \to K\pi)$
BR - Set II	2 $BR(B \to K\pi)$ 2 Ratios of $BR(B \to K\pi)$
BR - Set III	1 $BR(B \to K\pi)$ 3 Ratios of $BR(B \to K\pi)$

CP - Set I	4 $C(B \to K\pi)$ $S(B \to K\pi)$
CP - Set II	3 $C(B \to K\pi)$ $S(B \to K\pi)$ ΔA_{CP}

Outline

1. Introduction to the . . .
   - . . . computation of hadronic amplitudes
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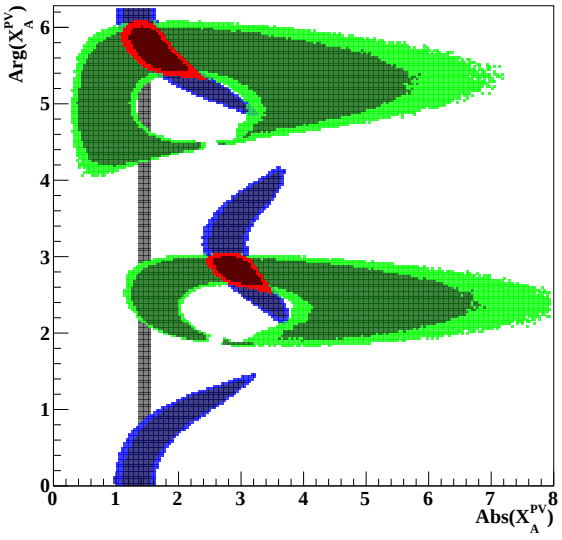
   - . . . statistical methods

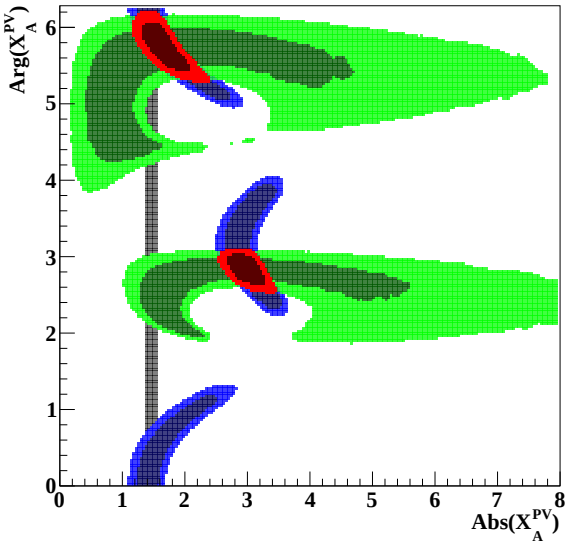
2. Fit Results
   - SM for $B \to K\pi$ and $B \to K\rho$ system
   - New Physics: Enhanced left-handed Z penguin

SM Fit XA $B \to K\rho$ preliminary results

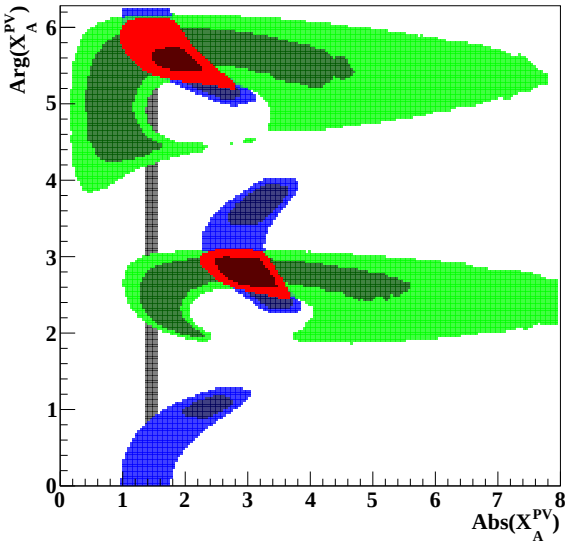
BR-Set I CP Set I @95, 99% CL



BR-Set II CP Set II @95, 99% CL



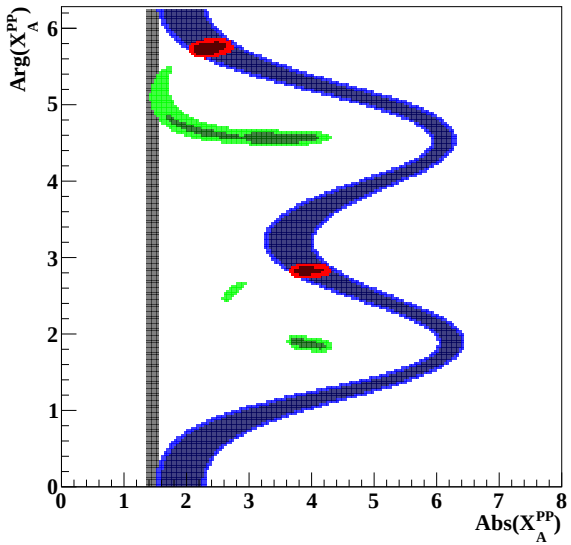
BR-Set III CP Set II @95, 99% CL

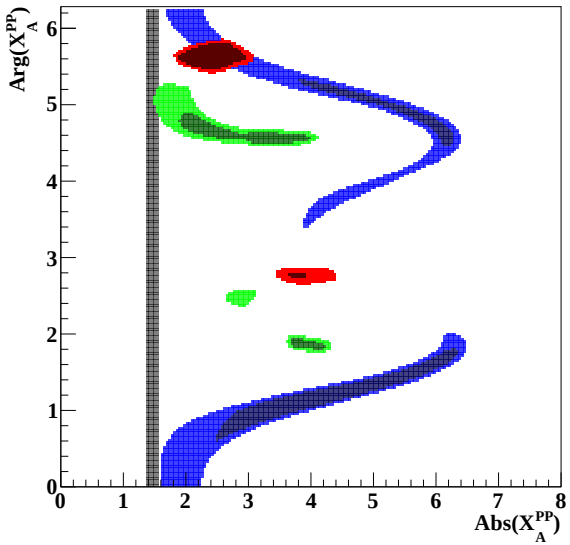


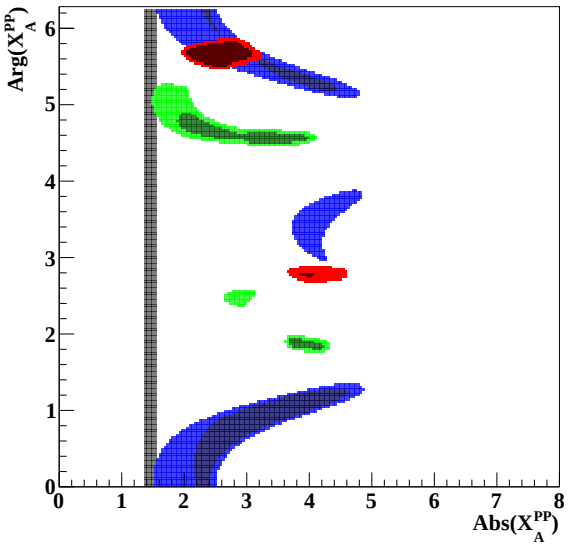
p-Val BestFP	100 % 1.7, 5.6	100% 2.8, 2.9	99% 3.2, 2.7
R_K^c	-	0	0.7σ
$C_{K^+\rho^-}$	0	0	0.2σ
$C_{K^0\rho^+}$	0.7σ	0.7σ	0.7σ
ΔA^{CP}	0	0	-
$S_{K^0\rho^0}$	0	0	-

SM Fit XA $B \to K\pi$ preliminary results

BR-Set I CP Set I @95, 99% CL | BR-Set II CP Set II @95, 99% CL | BR-Set III CP Set II @95, 99% CL







p-Val	23 %	0.7 %	0.7%
BestFP	3.8; 2.8	2.1, 5.7	2.2, 5.7
R_B^n	-	2.9σ	2.8σ
$C_{K^+\pi^0}$	2.3σ	-	-
$C_{K^0\pi^+}$	1.6σ	1.4σ	1.4σ
ΔA^{CP}	-	2.8σ	2.8σ
$S_{K^0\pi^+}$	0.9	1σ	1σ

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Enhanced Z-penguin: Generic Parameterization

Model independent description by the effective Lagrangian

$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \frac{G_f}{2\sqrt{2}} \frac{e}{\pi^2} M_Z^2 c_W s_W \lambda_t \; Z^\mu Z_L \, \bar{s} \gamma_\mu (1 - \gamma_5) b$

with $Z_L \in \mathbb{C}$

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with $Z_L \in \mathbb{C}$

Modification of EW Wilson coeff.

$C_3^{NP}(\mu_W) = -\frac{\alpha}{6\pi} Z_L{}^*$

$C_7^{NP}(\mu_W) = -\frac{2\alpha}{3\pi} s_W^2 Z_L{}^*$

$C_9^{NP}(\mu_W) = \frac{2\alpha}{3\pi} (1 - s_W^2) Z_L{}^*$

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$\Rightarrow$

NP vs QCD

- NP decouples from QCD
- stable fit for XA

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with $Z_L \in \mathbb{C}$

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$$C_9^{NP}(\mu_W) = \frac{2\alpha}{3\pi}(1 - s_W^2) Z_L{}^*$$

$\Rightarrow$

NP vs QCD

- NP decouples from QCD
- stable fit for XA

Modification of Expansion parameter with additional weak phase δ

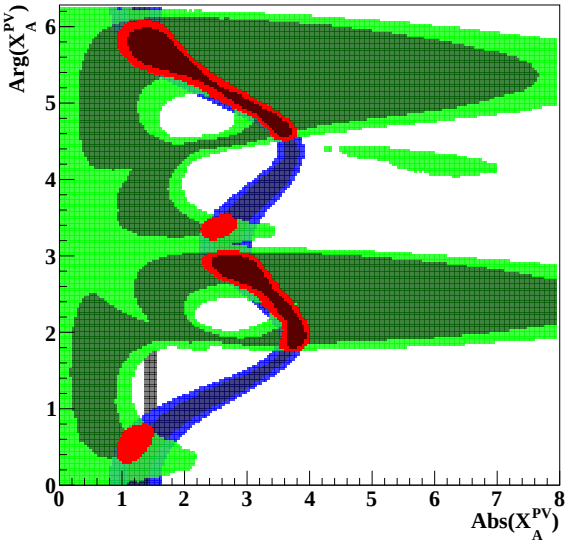
$$r_{EW} \to r_{EW} + r_{EW}^{NP} e^{i\delta}$$

$$r_{EW}^C \to r_{EW}^C + r_{EW}^{C,NP} e^{i\delta}$$

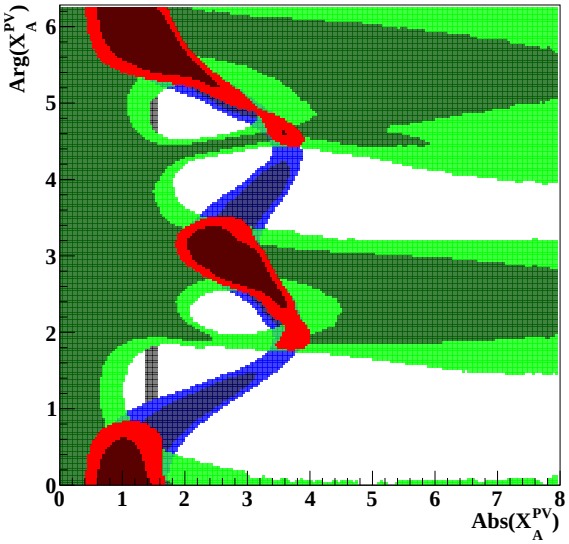
$$r_{EW}^A \to r_{EW}^A + r_{EW}^{A,NP} e^{i\delta}$$

Enhanced Z-penguin $B \to K\rho$ preliminary results

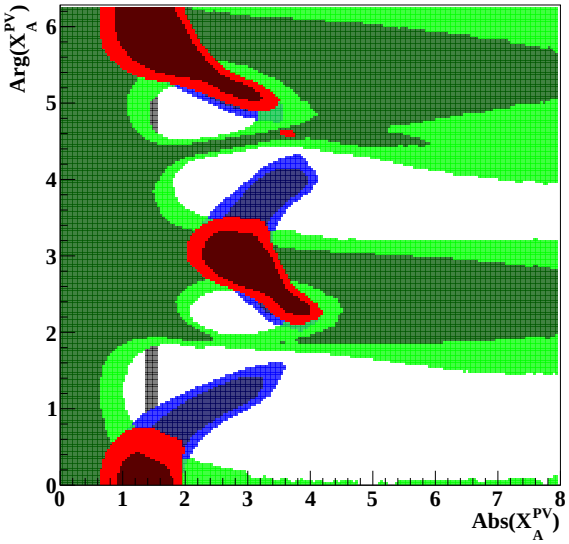
BR-Set I CP Set I @95, 99% CL



BR-Set II CP Set II @95, 99% CL



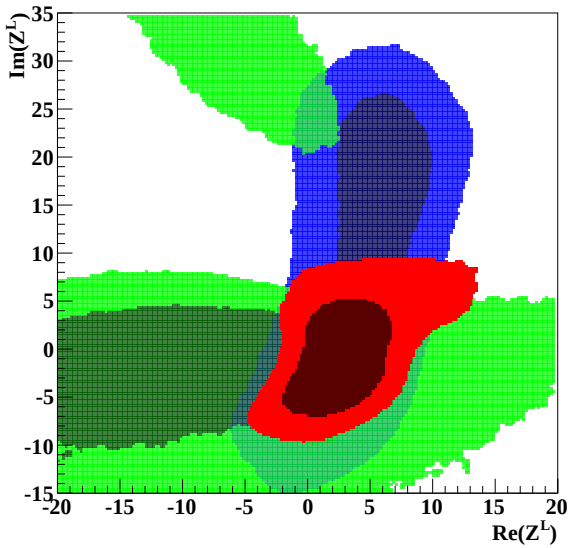
BR-Set III CP Set II @95, 99% CL



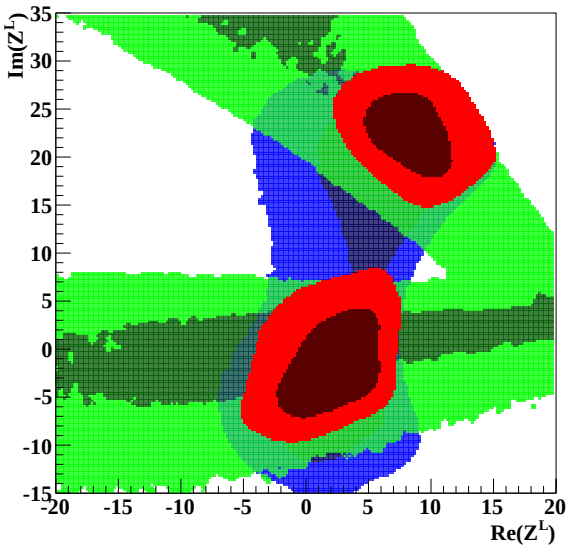
p-Val BestFP	100 % 2.8, 2.8	100% 2.4, 3.2	100% 2.7, 2.8
R_ρ^c	-	0.3σ	0
$C_{K^0\rho^0}$	0.2σ	0.3σ	0
$C_{K^0\rho^+}$	0.5σ	0	0.5σ
ΔA^{CP}	0	0.3σ	0
$S_{K^0\rho^+}$	0	0	0

Enhanced Z-penguin $B \to K\rho$ preliminary results

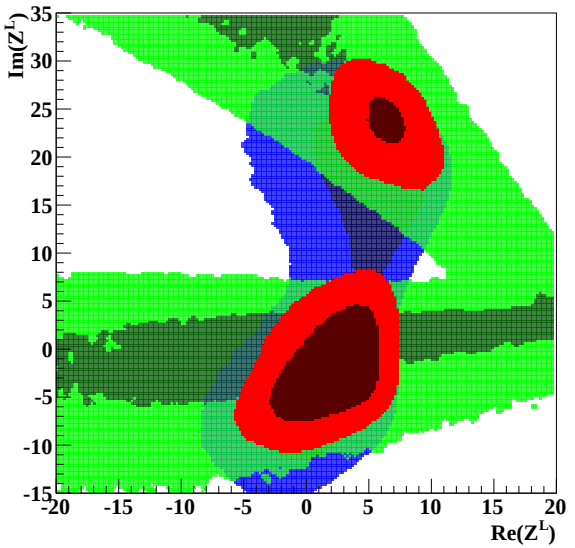
BR-Set I CP Set I @68, 95% CL



BR-Set II CP Set II @68, 95% CL



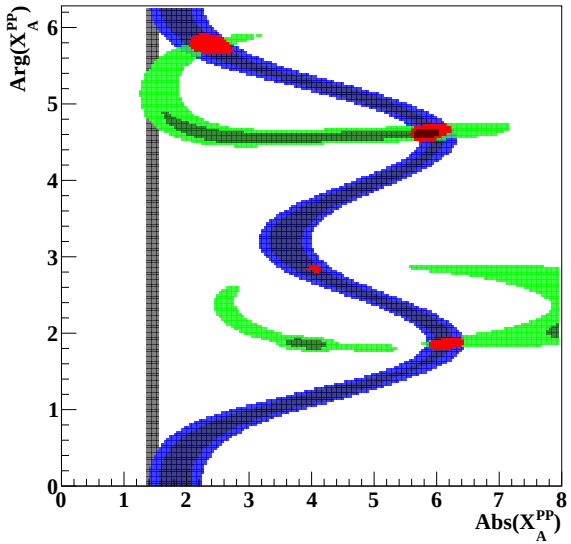
BR-Set III CP Set II @68, 95% CL



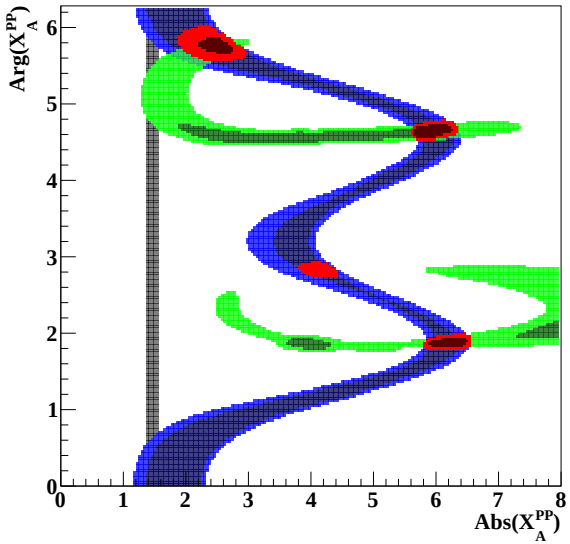
p-Val BestFP	100 % -2.0, -4.1	100% 7.2, 24.2	99% -0.2, -3.7
R_ρ^c	-	0.3σ	0
$C_{K^0\rho^0}$	0.2σ	0.3σ	0
$C_{K^0\rho^+}$	0.5σ	0	0.5σ
ΔA^{CP}	0	0.3σ	0
$S_{K^0\rho^+}$	0	0	0

Enhanced Z-penguin $B \to K\pi$ preliminary results

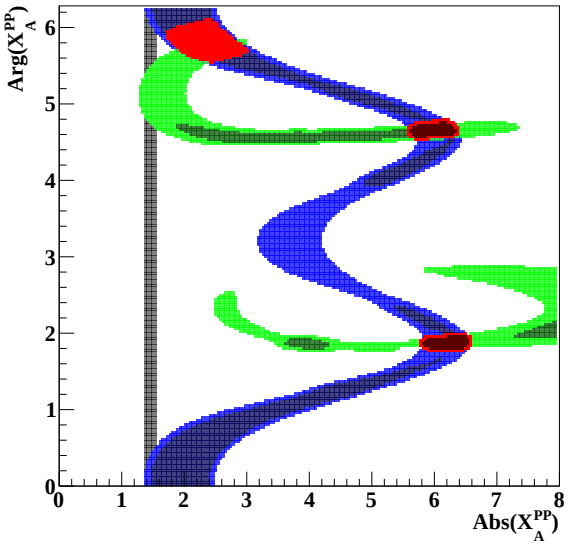
BR-Set I CP Set I @95, 99% CL



BR-Set II CP Set II @95, 99% CL



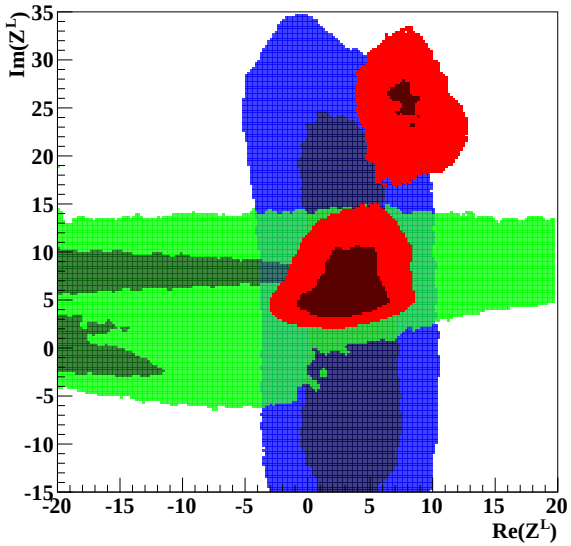
BR-Set III CP Set II @95, 99% CL



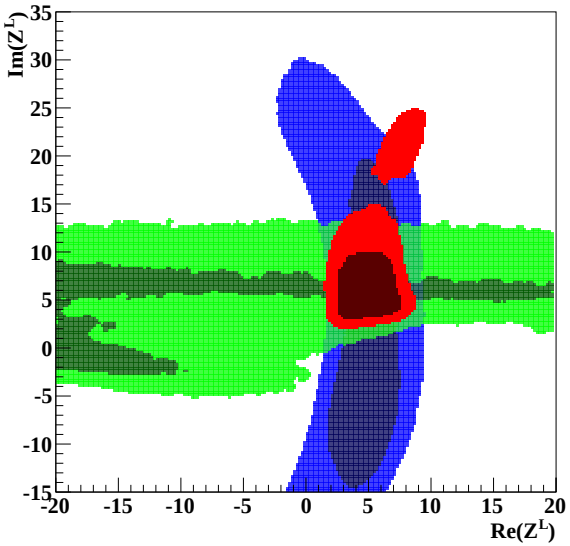
p-Val BestFP	100 % 5.7, 4.6	100% 5.7,4.6	80% 6.5, 1.9
R_B^n	-	0.2σ	0.4σ
R_π^c	-	0.3σ	0.2σ
$C_{K^0\pi^0}$	0	0	0.3σ
$C_{K^0\pi^+}$	0	0	0
ΔA^{CP}	0	0	0.2σ
$S_{K^0\pi^+}$	0	0.4σ	1.4σ

Enhanced Z-penguin $B \to K\pi$ preliminary results

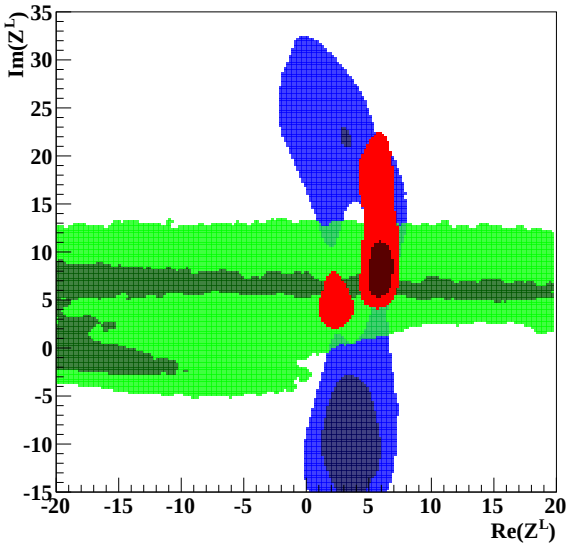
BR-Set I CP Set I @68, 95% CL



BR-Set II CP Set II @68, 95% CL



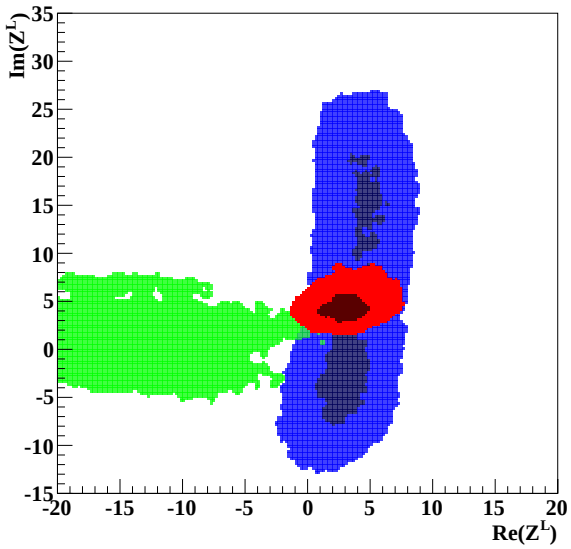
BR-Set III CP Set II @68, 95% CL



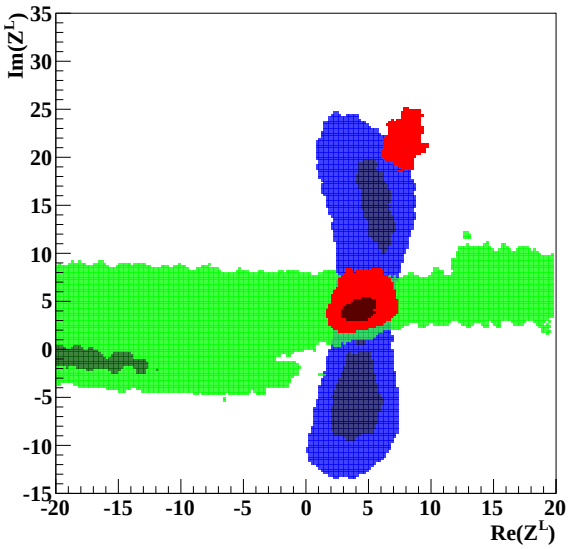
p-Val BestFP	100 % 6.6, 30.6	100% 8.6, 22.2	80% 6.0, 6.6
R_B^h	-	0.2σ	0.4σ
R_π^c	-	0.3σ	0.2σ
$C_{K^0\pi^0}$	0	0	0.3σ
$C_{K^0\pi^+}$	0	0	0
ΔA^{CP}	0	0	0.2σ
$S_{K^0\pi^+}$	0	0.4σ	1.4σ

Enhanced Z-penguin $B \to K(\rho)\pi$ preliminary results

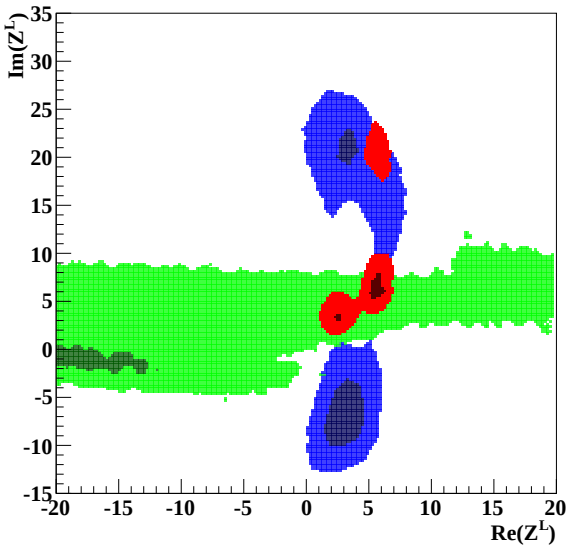
BR-Set I CP Set I @68, 95% CL



BR-Set II CP Set II @68, 95% CL



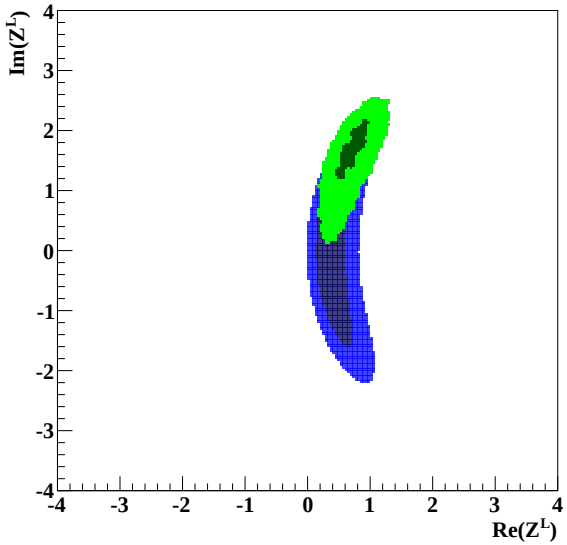
BR-Set III CP Set II @68, 95% CL



p-Val BestFP	100 % 5.3, 25.6	100% 8.6, 22.2	95% 5.9, 19.9
R_ρ^c	-	0.6σ	0.4σ
R_B^n	-	0	1σ
$BR_{K^0\rho^0}$	0.4σ	0	-
$BR_{K^0\rho^+}$	0.5σ	0	0.4σ
$C_{K^0\rho^0}$	1.3σ	0	0.2σ
$C_{K^+\rho^0}$	0.6σ	0	-
$S_{K^0\pi^+}$	0.3σ	0.4σ	1.3σ
$S_{K^0\rho^0}$	0	0	1.3σ

Enhanced Z-penguin $B \to K^{(*)}l^+l^-$ preliminary results

$B \to K^{(*)}l^+l^-$,
$B \to K^{(*)}l^+l^-$ and $B \to K(\rho)\pi$
@68, 95% CL



$B \to K^{(*)}l^+l^-$,
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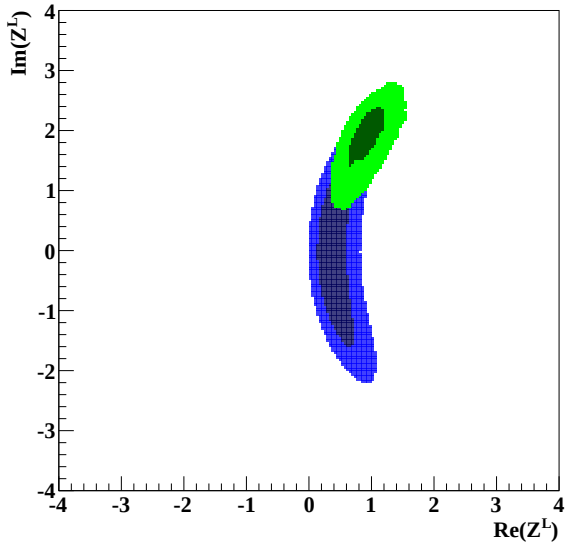
@68, 95% CL



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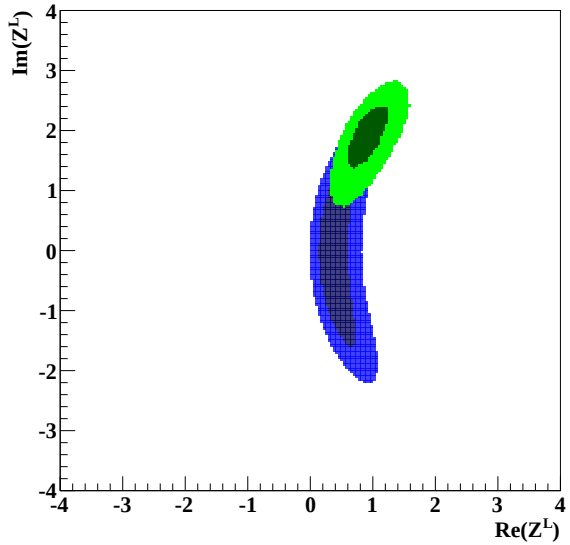

p-Val BestFP	100 % 0.6, 1.5	100% 0.9, 1.9	100% 0.9, 1.9
R_B^n	-	2.1σ	2.1σ
R_π^c	-	1.0σ	1.0σ
$C_{K^+\pi^0}$	1.7σ	-	-
$C_{K^0\pi^+}$	1.7σ	1.8σ	1.8σ
$C_{K^0\rho^+}$	0.7σ	0.7σ	0.8σ
ΔA^{CP}	-	1.4σ	1.4σ
$S_{K^0\pi^0}$	0.6σ	0.6σ	1.3σ
$S_{K^0\rho^0}$	0	0.2σ	1.3σ

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$B \to K^{(*)}l^+l^-$,
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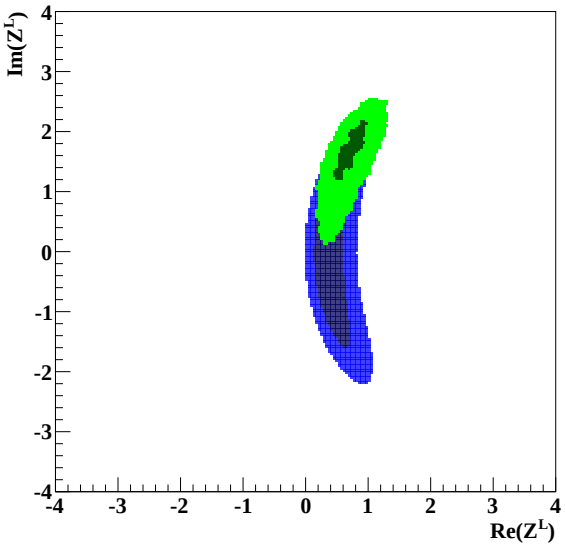

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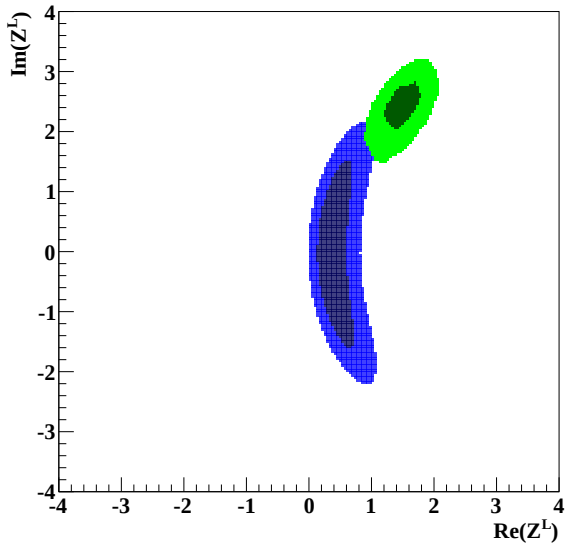

$B \to K^{(*)}l^+l^-$,
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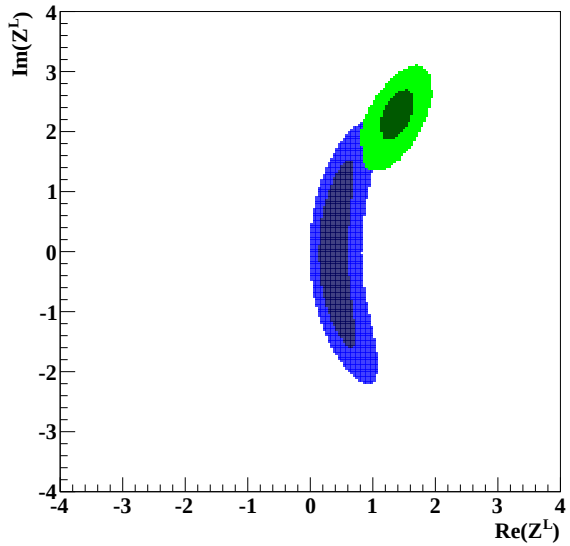
@68, 95% CL



Experimental uncertainties of Ratios of BR had been reduced by a factor of 2!

Conclusions

- Fitting power-suppressed contributions in hadronic B-meson decays reduces theory uncertainty up to a factor of 2
- In our framework, experimental data can not be accommodated by the Standard Model $\rightarrow p = 0.6\%$
- In addition to ΔA_{CP}, tensions in Ratios of Branching Ratios pop up.
  Question to experimentalists:
  - Can systematic uncertainties be reduced by a measurement of Ratios of Branching Ratios?
  - Can it be extracted from the existing Belle and BaBar data?
- Strong constraints from leptonic and semi-leptonic B-meson decays in New Physics scenarios with enhanced $b \rightarrow s$-transition can be further constrained by rich phenomenology of hadronic B-meson decays

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