Search for New Physics in B Decays

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Overview of topics covered:

- $B \to K\pi$ puzzle and a possible solution
- Interesting observables in Semileptonic B Decays
- Hadronic three-body B decays in light of SU(3)$_F$ Symmetry

$B \to K\pi$: The puzzle in short

CP-even phase   CP-odd phase

* Amplitudes: $\mathcal{A} = A_1 + A_2\, e^{i\phi}\, e^{i\delta}$ and $\bar{\mathcal{A}} = A_1 + A_2\, e^{-i\phi}\, e^{i\delta}$

  $\Rightarrow$ CP Asymmetry: $A_{\rm CP} = \dfrac{|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2}{|\bar{\mathcal{A}}|^2 + |\mathcal{A}|^2} \propto \sin(\phi)\sin(\delta)$

* Consider processes:

  $\delta = 0$

  $B^+ \to \pi^0 K^+ \qquad \mathcal{A}^{0+} = -T'\, e^{i\gamma} + P'_{tc} - P'_{EW} \qquad (P'_{EW} \propto T')$

  $B^0_d \to \pi^- K^+ \qquad \mathcal{A}^{-+} = -T'\, e^{i\gamma} + P'_{tc}$

  $\Rightarrow \boxed{A_{\rm CP}(B^+ \to \pi^0 K^+) = A_{\rm CP}(B^0_d \to \pi^- K^+)}$ in *Theory*!

* Experiment:

  $A^{0+}_{\rm CP} = 0.025 \pm 0.016$ 2012.12789

  $A^{-+}_{\rm CP} = -0.084 \pm 0.004$ 1805.06759 $\sim 6.5\sigma$ discrepancy!

$B \to K\pi$: The puzzle

4 $B \to K\pi$ processes with 9 observables

Decay	BR	$A_{\rm CP}$	$S_{\rm CP}$
$B^+ \to \pi^+ K^0$	✓	✓	
$B^+ \to \pi^0 K^+$	✓	✓	
$B_d^0 \to \pi^- K^+$	✓	✓	
$B_d^0 \to \pi^0 K^0$	✓	✓	✓

Fit with several theory parameters (usually) results in a bad fit.

$$
\begin{aligned}
A^{+0} &= -P'_{tc} + P'_{uc} e^{i\gamma} - \frac{1}{3} P'^{C}_{EW} , \\
\sqrt{2} A^{0+} &= -T' e^{i\gamma} - C' e^{i\gamma} + P'_{tc} - P'_{uc} e^{i\gamma} \\
&\quad - P'_{EW} - \frac{2}{3} P'^{C}_{EW} , \\
A^{-+} &= -T' e^{i\gamma} + P'_{tc} - P'_{uc} e^{i\gamma} - \frac{2}{3} P'^{C}_{EW} , \\
\sqrt{2} A^{00} &= -C' e^{i\gamma} - P'_{tc} + P'_{uc} e^{i\gamma} \\
&\quad - P'_{EW} - \frac{1}{3} P'^{C}_{EW} .
\end{aligned}
$$

The $B \to K\pi$ puzzle: A solution (2104.03947)!

* Consider an ALP (2104.03947):

$$\mathcal{L} \supset -\, i \sum_{f=u,d,l} \eta_f \frac{m_f}{f_a} \bar{f}\gamma_5 f a + \ldots$$

  - $\rightarrow$ $m_a \simeq m_{\pi^0}$ and ALP promptly decays to $\gamma\gamma$
  - $\rightarrow$ Mixes with the π^0: $|a\rangle = \sin\theta \left|\pi^0\right\rangle_{\rm phys} + \cos\theta \left|a\right\rangle_{\rm phys}$
  - $\rightarrow$ $B \to K\pi^0$ processes get new contribution: $\mathcal{A} = |\mathcal{A}| e^{i\pi/2}$
    $\sqrt{2}\mathcal{A}^{0+} = \ldots + \mathcal{A}$; $\sqrt{2}\mathcal{A}^{00} = \ldots + \mathcal{A}$
  - $\rightarrow$ Leads to a good fit with $|\mathcal{A}| \sim P'_{EW}$
  - $\rightarrow$ Constraint from $B \to Ka$ ($B \to K$ + invis):
    $$\mathcal{B} \sim 10^{-5} \Rightarrow \sin\theta \sim 0.1 - 0.2$$

* Work in progress: How to detect an ALP with mass close to m_{π^0} in other flavor processes.

Semileptonic B decays: Anomalies

* Ratio anomaly in $B \to D^* \tau\nu / B \to D^* \ell\nu$ ($\sim 3\sigma$)
* Effective 4-body decay with 4 kinematic variables
  – leverage angular observables for NP searches

$$\frac{d^4\Gamma}{dq^2 d\cos\theta^* d\cos\theta_\ell d\chi} \propto \sum_{i=1,\dots 9} I_i(q^2)\ \Omega_i(\theta^*, \theta_\ell, \chi)$$

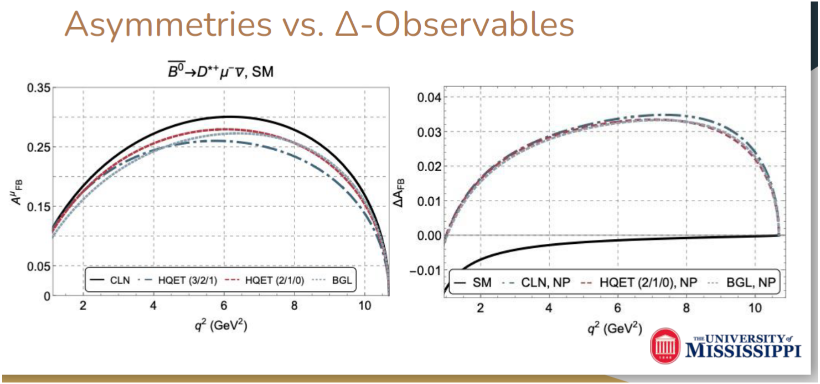
* 2104.02094 indicated new $\sim 4\ \sigma$ anomaly in Belle 2018 data
  - $\to$ Forward-backward asymmetry for lepton: difference in events with $\cos\theta_\ell > 0$ and < 0
  - $\to$ $\Omega_6 \propto \cos\theta_\ell \quad \Rightarrow \quad A_{\rm FB} \propto I_6$
  - $\to$ Measure $A_{\rm FB}$ in both μ^- and e^- channels
  - $\to$ $\Delta A_{\rm FB} = A_{\rm FB}^\mu - A_{\rm FB}^e$ sensitive to NP

B Anomalies: A Monte-Carlo tool (2203.07189)

* Snowmass Contributed Paper on Monte-Carlo event generator: 2203.07189
* Effective Field Theory approach with dimension 6 NP operators:
  $(\bar{b}\Gamma c)(\bar{\mu}\Gamma_L \nu)$ where $\Gamma_L = (1-\gamma^5)/2$
  and $\Gamma =$ Left/Right Scalar/Vector/Tensor
* MC tool based on EvtGen: generates $B \to D^* \ell \nu$ events
  - $\rightarrow$ Obtain $\Delta A_{\rm FB}$ as a function of q^2: distinguish models
  - $\rightarrow$ $\Delta A_{\rm FB}$ free from Form Factor effects
  - $\rightarrow$ Correlated with other Δ observables – such as S_5

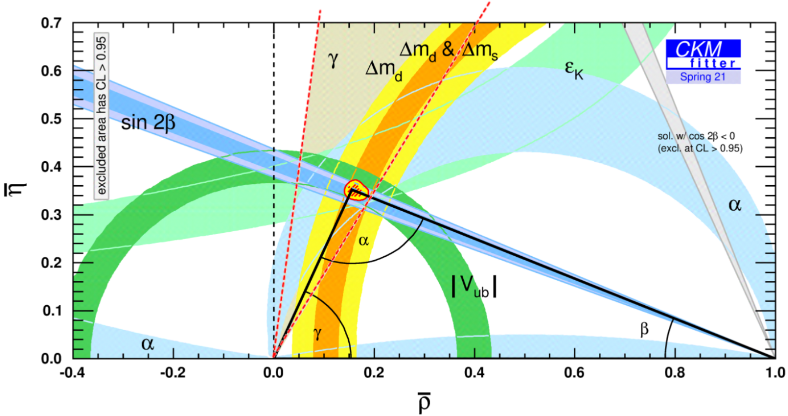
B Anomalies: A Monte-Carlo tool (2203.07189)

* Details in talk by Q. Campagna (BSM IV Session)



Hadronic B Decays: The CKM Angle γ

* Large experimental uncertainty in $\gamma \sim 6^\circ$



* LHCb will significantly reduce this uncertainty over the next decade
* May reveal tension – find corroborating information from other methods

3-body B Decays: Fully-symmetric state

* 1303.0846, 1812.06194 showed that three-body B decays can be used to extract γ

$$
\begin{aligned}
2\mathscr{A}_{\rm fs}(B^0 \to K^+\pi^0\pi^-) &= Be^{i\gamma} - \kappa C \ , \\
\sqrt{2}\mathscr{A}_{\rm fs}(B^0 \to K^0\pi^+\pi^-) &= -De^{i\gamma} - \cancel{\tilde{P}'_{\rm uc}}e^{i\gamma} - A + \kappa D \ , \\
\mathscr{A}_{\rm fs}(B^0 \to K^0K^0\overline{K}^0) &= \cancel{\alpha_{SU(3)}}(\cancel{\tilde{P}'_{\rm uc}}e^{i\gamma} + A) \ , \\
\sqrt{2}\mathscr{A}_{\rm fs}(B^0 \to K^+K^0K^-) &= \cancel{\alpha_{SU(3)}}(-Ce^{i\gamma} - \cancel{\tilde{P}'_{\rm uc}}e^{i\gamma} - A + \kappa B) \ , \\
\text{✗} \quad \sqrt{2}\mathscr{A}_{\rm fs}(B^+ \to K^+\pi^+\pi^-) &= -Ce^{i\gamma} - \cancel{\tilde{P}'_{\rm uc}}e^{i\gamma} - A + \kappa B \ .
\end{aligned}
$$

* Amplitudes are momentum dependent – study on a Dalitz plot
* Unknowns: 4 SU(3) amplitudes (momentum dependent) + γ
* Observables: 9 per Dalitz plot point
* Fit to extract γ

3-body B Decays: Fully-antisymmetric state

* Work in progress with undergraduate student
  - ✓ Find flavor-SU(3) representations of $\langle B| H |PPP\rangle_{\rm FA}$

    $B \to (P_1P_2P_3)_{\rm FA}$ with $|P_1P_2P_3\rangle = -|P_2P_1P_3\rangle$.

Decay	$V_{cb}^*V_{cs}$		$V_{ub}^*V_{us}$						
Amplitude	$B_1^{(FA)}$	$B^{(FA)}$	$A_1^{(FA)}$	$A^{(FA)}$	$R_8^{(FA)}$	$R_{10}^{(FA)}$	$P_8^{(FA)}$	$P_{10^*}^{(FA)}$	$P_{27}^{(FA)}$
$A(B^+ \to K^+\pi^+\pi^-)$	0	$\frac{1}{\sqrt{5}}$	0	$\frac{1}{\sqrt{5}}$	$\frac{1}{\sqrt{15}}$	$-\frac{1}{\sqrt{3}}$	-$\frac{3}{5}$	0	$\frac{3\sqrt{6}}{5}$
$A(B^+ \to K^0\pi^+\pi^0)$	0	$\sqrt{\frac{2}{5}}$	0	$\sqrt{\frac{2}{5}}$	$\sqrt{\frac{2}{15}}$	$\frac{1}{\sqrt{6}}$	$-\frac{3\sqrt{2}}{5}$	0	$\frac{\sqrt{3}}{5}$
$A(B^0 \to K^0\pi^+\pi^-)$	0	$-\frac{1}{\sqrt{5}}$	0	$-\frac{1}{\sqrt{5}}$	$\frac{1}{\sqrt{15}}$	$-\frac{1}{\sqrt{3}}$	-$\frac{1}{5}$	0	$\frac{\sqrt{6}}{5}$
$A(B^0 \to K^+\pi^0\pi^-)$	0	$\sqrt{\frac{2}{5}}$	0	$\sqrt{\frac{2}{5}}$	$-\sqrt{\frac{2}{15}}$	$-\frac{1}{\sqrt{6}}$	$\frac{\sqrt{2}}{5}$	0	$\frac{3\sqrt{3}}{5}$
$A(B^+ \to K^+K^0\bar{K}^0)$	0	$-\frac{1}{\sqrt{5}}$	0	$-\frac{1}{\sqrt{5}}$	$-\frac{1}{\sqrt{15}}$	0	$\frac{3}{5}$	0	$\frac{2\sqrt{6}}{5}$
$A(B^0 \to K^0K^+K^-)$	0	$-\frac{1}{\sqrt{5}}$	0	$-\frac{1}{\sqrt{5}}$	$\frac{1}{\sqrt{15}}$	0	-$\frac{1}{5}$	$\sqrt{2}$	$\frac{\sqrt{6}}{5}$
$\sqrt{2}A(B_s^0 \to \pi^0K^+K^-)$	$-\frac{1}{2\sqrt{6}}$	0	$-\frac{1}{2\sqrt{6}}$	0	$\frac{2}{\sqrt{15}}$	$\frac{1}{2\sqrt{3}}$	$\frac{4}{5}$	-$\frac{1}{\sqrt{2}}$	$-\frac{\sqrt{\frac{3}{2}}}{10}$
$\sqrt{2}A(B_s^0 \to \pi^0K^0\bar{K}^0)$	$-\frac{1}{2\sqrt{6}}$	0	$-\frac{1}{2\sqrt{6}}$	0	$-\frac{2}{\sqrt{15}}$	$-\frac{1}{2\sqrt{3}}$	$-\frac{4}{5}$	$\frac{1}{\sqrt{2}}$	$-\frac{9\sqrt{\frac{3}{2}}}{10}$
$A(B_s^0 \to \pi^-K^+\bar{K}^0)$	$\frac{1}{2\sqrt{6}}$	0	$\frac{1}{2\sqrt{6}}$	0	0	$-\frac{1}{2\sqrt{3}}$	0	$-\frac{1}{\sqrt{2}}$	$\frac{\sqrt{\frac{3}{2}}}{2}$
$A(B_s^0 \to \pi^+K^-K^0)$	$-\frac{1}{2\sqrt{6}}$	0	$-\frac{1}{2\sqrt{6}}$	0	0	$-\frac{1}{2\sqrt{3}}$	0	$-\frac{1}{\sqrt{2}}$	$-\frac{\sqrt{\frac{3}{2}}}{2}$
$\sqrt{2}A(B_s^0 \to \pi^0\pi^+\pi^-)$	$-\frac{1}{\sqrt{6}}$	$\frac{2}{\sqrt{5}}$	$-\frac{1}{\sqrt{6}}$	$\frac{2}{\sqrt{5}}$	0	0	$\frac{6}{5}$	0	$\frac{3\sqrt{\frac{3}{2}}}{5}$

$\rightarrow$ Find reduced set of SU(3) amplitudes

$\rightarrow$ Establish γ extraction method

Outlook

* Several new directions to search for NP in B decays
* With more precision data from experiments expect to find more tensions
* Correlated information from many discrepancies will lead to finding NP

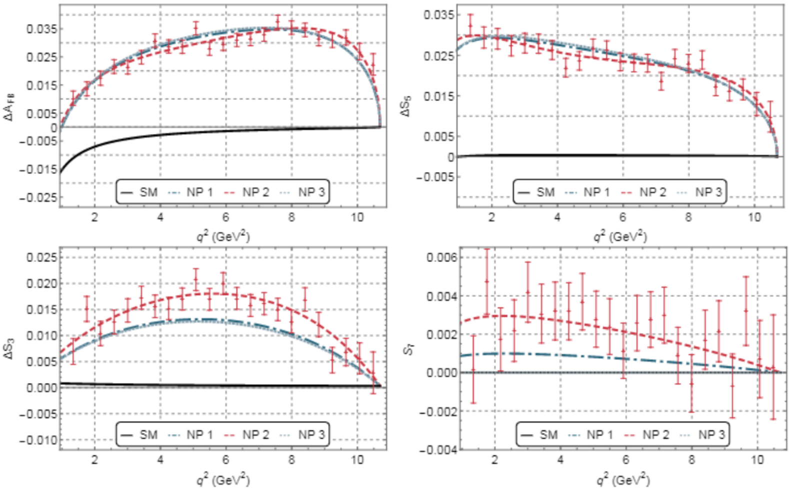
Thank You!

Back-up Slides

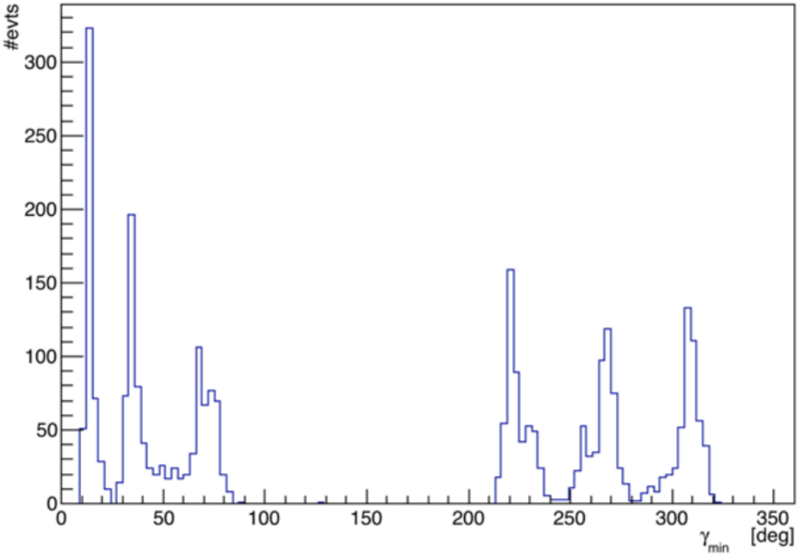
$B \to K\pi$ fit with ALP-π^0 mixing

Parameter	$\|C'\|/\|T'\| = 0.2$
χ^2/dof	3.64/3
p-value	30%
$\|T'\|$	6.4 ± 1.5
$\|P'_{tc}\|$	50.30 ± 0.47
$\|\mathcal{A}\|$	6.4 ± 3.4
$\delta_{C'}$	186 ± 54
$\delta_{Ptc'}$	-18.1 ± 5

$B \to D^* \ell \nu$ angular observables



3-body B Decays: Fully-symmetric state



$B_d^0 \to \pi^- K^+$

$\leftarrow \quad T' \propto V_{ub}^* V_{us}$

$\leftarrow \quad P_{tc} : V_{tb}^* V_{ts} P_t - V_{cb}^* V_{cs} P_c$

$B^+ \to \pi^0 K^+$

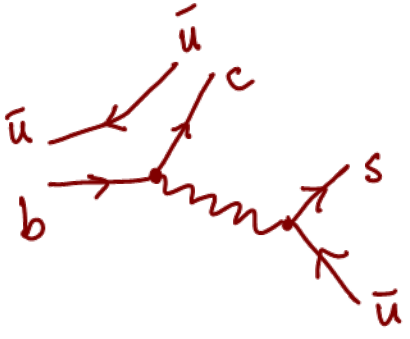
$\leftarrow \quad P_{EW}$

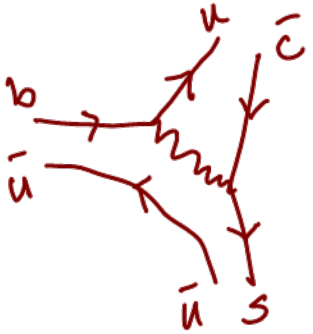
CKM Unitarity:

$$V_{tb}^* V_{ts} + V_{cb}^* V_{cs} + V_{ub}^* V_{us} = 0$$

Direct measurement of γ

$B^- \to D^0 K^-$ vs $B^- \to \bar{D}^0 K^-$





$V_{cb}^* V_{us}$ $\quad$ $V_{ub}^* V_{cs}$

Unknowns: r_B, δ_B, γ

- r_B ← Ratio of magnitudes
- δ_B ← Relative strong phase
- γ ← Weak phase

GLW Method*

$D^0 \to f_{CP}$

$\bar{D}^0 \to f_{CP}$

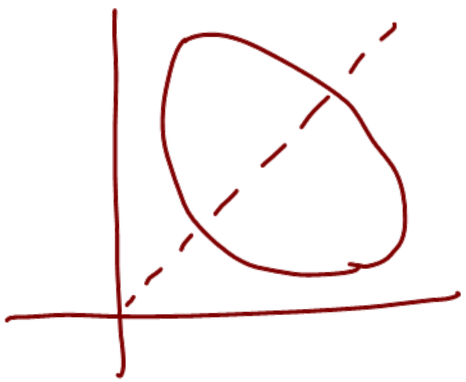
ADS Method

$D^0 \to f$ $\quad$ CF

$\bar{D}^0 \to f$ $\quad$ DCS

GGSZ Method

$D/\bar{D} \to$ Multibody states



$k \geq 2$ bins

$4k$ observables

$2k + 3$ unknowns

Lesson: No QCD input necessary to find γ.