Select puzzles from B decays

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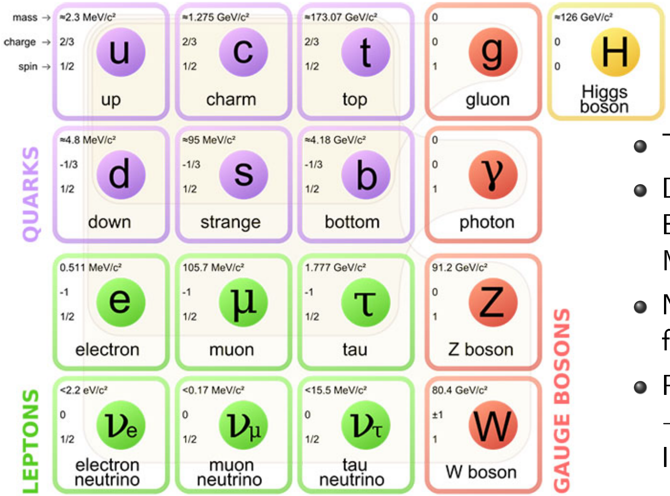
Virtual Talk
http://bit.ly/3mOWxc3

The Standard Model and beyond

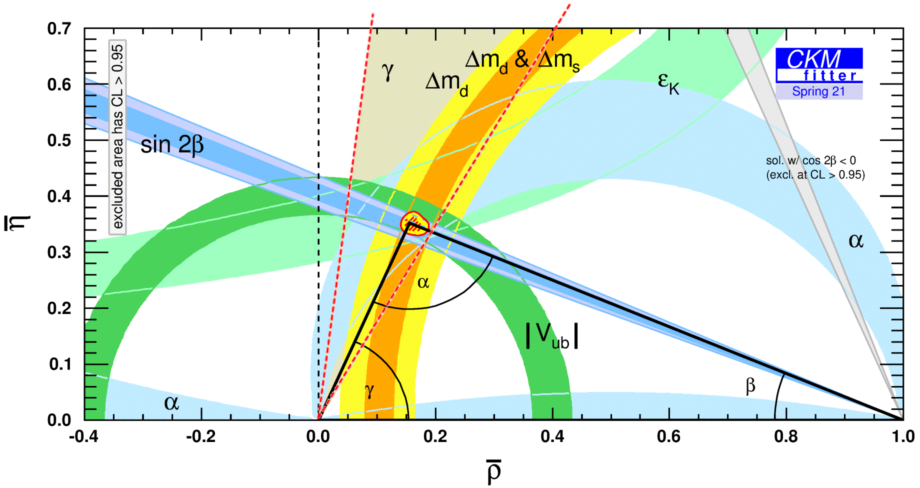


- The Standard Model is incomplete!
- Dark Matter/Dark energy
  Baryon-asymmetry problem
  May require new particles/symmetry
- New physics may be beyond energy frontier reach
- Puzzles/Anomalies
  $\rightarrow$ SM prediction $\neq$ Expt.
  Intensity frontier $\Leftrightarrow$ Energy frontier

Puzzles in Hadronic B decays

- U-spin puzzle
- $B \to K\pi$ puzzle
- $B \to K\pi\pi$ puzzle?

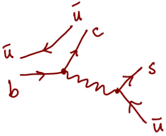
Status of direct measurement of γ

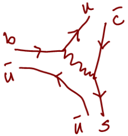


Weak-phase information from tree-level B decays

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*

$D^0 \to f_{CP}$

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

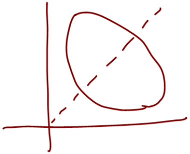
ADS Method

$D^0 \to f$ CF

$\bar{D}^0 \to f$ 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.

Weak-phase information from B decays with tree + loop

- $\mathcal{A}(B \to f) = |a| + |b|e^{i\phi}e^{i\delta} \quad \to \quad \Gamma \propto |\mathcal{A}|^2$

  $\bar{\mathcal{A}}(\bar{B} \to \bar{f}) = |a| + |b|e^{-i\phi}e^{i\delta} \quad \to \quad \bar{\Gamma} \propto |\bar{\mathcal{A}}|^2$

  – 4 parameters: 2 magnitudes ($|a|, |b|$), 1 rel. strong phase (δ), 1 rel. weak phase (ϕ)
- 2 Observables: $\mathcal{B}_{\rm CP} = \dfrac{\Gamma + \bar{\Gamma}}{2\Gamma_B}, \quad C_{\rm CP} = \dfrac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}$ (direct CP asymmetry)

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  B-mixing: $|B\rangle_{\rm mass} = p\,|B\rangle + q\,|\bar{B}\rangle$ with $\lambda = \dfrac{q}{p}\dfrac{\bar{\mathcal{A}}}{\mathcal{A}} \Rightarrow S_f = \dfrac{2{\rm Im}[\lambda]}{1 + |\lambda|^2}$

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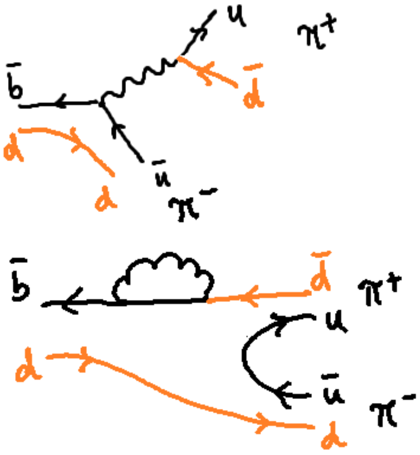
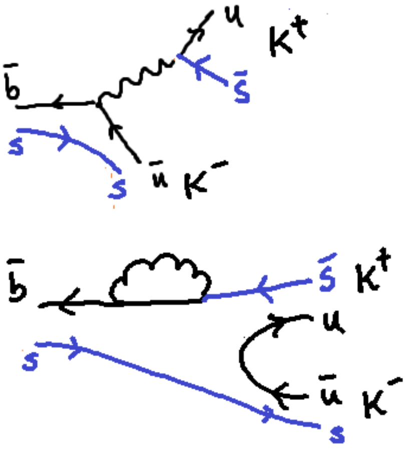
- $C_{\rm CP} = \dfrac{1-|\lambda|^2}{1+|\lambda|^2} \quad \Rightarrow \quad$ Identity: $(C_{\rm CP})^2 + (S_{\rm CP})^2 + (A^{\Delta\Gamma})^2 = 1$ (LHCb:0.85±0.16)

U-spin in hadronic B decays



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



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Weak-phase info using U-spin

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- $|q/p| \approx 1$ for $B^0_{d,s}$ (can check from semileptonic B decays);

  $\arg(q_s/p_s) \approx 2\beta_s$ $\to$ from $B_s \to J/\Psi\phi$

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- Hadronic parameters same for both decays: $(|b/a|, \delta) \leftarrow$ 2 parameters
- Weak decay parameters: $\gamma, \beta_d \leftarrow$ Up to 2 parameters
- $C_{\pi\pi}, C_{KK}, S_{KK}$ sufficient to determine γ + 2 hadronic parameters
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- Data unavailable at the time

> The strategies proposed in this paper are very interesting for "second-generation" B-physics experiments performed at hadron machines, for example LHCb, where the very

Measurement from LHCb and theory progress

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- $C_{KK} = 0.172 \pm 0.031, \;\; S_{KK} = 0.139 \pm 0.032, \;\; C_{\pi\pi} = -0.32 \pm 0.04, \;\; S_{\pi\pi} = -0.64 \pm 0.04$

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- Use β_d $(B_d \to J/\Psi K_s)$, β_s $(B_s \to J/Psi\phi)$

  γ $(B \to DK)$
- Find hadronic parameters for both decays

  $\to$ test U-spin

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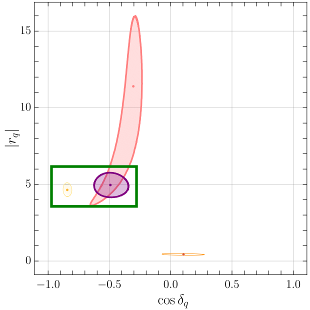
- $\dfrac{|b_s/a_s|}{|b_d/a_d|} = 1.07, \ |a_s/a_d| = 1.26$

  $\to$ (0 - 30%) U-spin breaking

  $(\mathcal{O}(m_s/\Lambda_{\rm QCD}) \sim 30\%, f_K/f_\pi - 1 \sim 20\%)$
- Result: NP + different orders of breaking at play



Other U-spin related decays

- What about other U-spin related decays? BB with others, 2211.06994
- Consider U-spin SU(2) subgroup of flavor SU(3)

  $\to$ quark doublet: (d, s); $\to$ antiquark doublet: $(\bar{s}, -\bar{d})$;

  $\to$ meson doublets: (π^-, K^-), (K^+, π^+), (B_d^0, B_s^0)
- Initial state: B doublet; Final state: Doublet$\times$Doublet = Singlet(0) + Triplet(1)
- 6 decays possible: 3 decays each $\Delta S = 0(b \to d), 1(b \to s)$; 4 U-spin RMEs

Decay	Representation	$\mathcal{B}_{\rm CP}$	$C_{\rm CP}$	$S_{\rm CP}$
$B_d^0 \to \pi^+\pi^-$	$M_{1d}^{1/2} + M_{0d}^{1/2}$	$\sim 10^{-6}$	✓	✓
$B_d^0 \to K^+K^-$	$M_{1d}^{1/2} - M_{0d}^{1/2}$	$\sim 10^{-8}$	?	?
$B_s^0 \to \pi^+K^-$	$2\ M_{1d}^{1/2}$	$\sim 10^{-6}$	✓	
$B_s^0 \to K^+K^-$	$M_{1s}^{1/2} + M_{0s}^{1/2}$	$\sim 10^{-5}$	✓	✓
$B_s^0 \to \pi^+\pi^-$	$M_{1s}^{1/2} - M_{0s}^{1/2}$	$\sim 10^{-7}$	?	?
$B_d^0 \to K^+\pi^-$	$2\ M_{1s}^{1/2}$	$\sim 10^{-5}$	✓	

- Each $M_{xq}^{1/2}$ has two parts
- $M_{xq}^{1/2} = V_{ub}^* V_{uq} T_q^x + V_{cb}^* V_{cq} P_q^x$
- 12 measurements
- 4 yet to be measured
- 2 amplitude triangles:
  $\pi^+\pi^- + K^+K^- = \pi K$

Hints of U-spin breaking

- $\Delta S = 0 \Rightarrow q = d$, $\Delta S = 1 \Rightarrow q = s$

  $\rightarrow$ 7 hadronic parameters $\leftarrow T_q^x, P_q^x$ with $x = 0, 1$

  $\rightarrow$ 6 measurements available ✗

  $\rightarrow$ 2 future measurements $\Rightarrow \gamma$ can be extracted with β_q from independent source

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- Apply U-spin! $\Rightarrow$ 8 parameters (γ + 7 hadronic for both $\Delta S = 0, 1$); 12 measurements ✓

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- Bad Fit! $\chi^2_{\rm min} = 17.8$ for 4 dof. $\gamma = (67.6 \pm 3.4)^\circ$ close to $\gamma_{\rm direct}$
- U-spin relation(s): $-\dfrac{C^s_{\rm CP}\mathcal{B}^s_{\rm CP}\Gamma_s}{C^d_{\rm CP}\mathcal{B}^d_{\rm CP}\Gamma_d} = 1$
- $\mathcal{A}(B^0_d \to \pi^+\pi^-) \approx \mathcal{A}(B^0_s \to \pi^+K^-)$
- $\mathcal{A}(B^0_s \to K^+K^-) \approx \mathcal{A}(B^0_d \to \pi^-K^+)$

$\Delta S = 0$	$\Delta S = 1$	Relation	
$B^0_d \to \pi^+\pi^-$	$B^0_s \to K^+K^-$	2.78±0.66	✓
$B^0_s \to \pi^+K^-$	$B^0_d \to \pi^-K^+$	1.25±0.21	✓
$B^0_s \to \pi^+K^-$	$B^0_s \to K^+K^-$	3.41±0.91	✗
$B^0_d \to \pi^+\pi^-$	$B^0_d \to \pi^-K^+$	1.02±0.12	✗

The U-spin puzzle

- $\mathcal{A}(B_d^0 \to \pi^+\pi^-) \lesssim \mathcal{A}(B_s^0 \to \pi^+K^-)$: $\delta\mathcal{A} \sim (5 \pm 8)\%, \quad \delta\bar{\mathcal{A}} \sim (15 \pm 9)\%$
- $\mathcal{A}(B_s^0 \to K^+K^-) \lesssim \mathcal{A}(B_d^0 \to \pi^-K^+)$: $\delta\mathcal{A} \sim (11 \pm 6)\%, \quad \delta\bar{\mathcal{A}} \sim (19 \pm 5)\%$

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- U-spin triangle: $\mathcal{A}_1 + \mathcal{A}_2 = (1 + X)\mathcal{A}_3 \qquad \leftarrow 2^3 + 1 = 9$ additional parameters!✗

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- Situation: 12 observables available, enforce $\gamma \approx \gamma_{\rm tree}$

  $\Rightarrow$ 7 hadronic parameters at U-spin limit ✓
- Can solve for up to 5 additional parameters: ∞ combinations – try a large sample ✓
- Also test hypothesis γ_1 in $\Delta S = 1$ is different from γ in $\Delta S = 0$

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- Can solve for up to 5 additional parameters: ∞ combinations – try a large sample ✓
- Also test hypothesis γ_1 in $\Delta S = 1$ is different from γ in $\Delta S = 0$
- Results: $|t_0| \sim \mathcal{O}(100\%)$, $\delta_{t_0} \neq 0$ needed; Other $|y_x|$ and $|X|$ small

  $\gamma_1 \neq \gamma$ preferred when γ_1 is included in fits

$$|t_0|\, e^{i\delta_{t_0}} = \frac{T_s^0}{T_d^0} - 1 \qquad M_{0q}^{1/2} = V_{ub}^* V_{uq} T_q^0 + V_{cb}^* V_{cq} P_q^0$$

$\leftarrow$ U-spin puzzle

Summary and other contemporary puzzles

- Reasonably sized U-spin breaking + NP $\leftrightarrow B_d^0 \to \pi^+\pi^-, B_s^0 \to K^+K^-$
- Sizable U-spin breaking needed to explain 6 U-spin related $B_{d,s}^0 \to DD$ (D = Doublet)
- Puzzles seem to involve $B_s^0 \to K^+K^-$ $\to$ need unusually large T_s^0/T_d^0
- Comparable with U-spin breaking in D decays $\sim 173\%$ Schacht, 2207.08539
- $R_{KK}^{ss} = \dfrac{\Gamma(B_s \to K^0\bar{K}^0)}{\Gamma(B_s \to K^+K^-)} \sim 66\%$ expected$\gtrsim 1$ Amhis et al., 2212.03874

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

* 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:

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

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

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

* Experiment:

  $A_{\rm CP}^{0+} = \quad 0.025 \pm 0.016$ 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	$A_{\rm CP}$	$S_{\rm CP}$
$B^+ \to \pi^+ K^0$	✓	✓	
$B^+ \to \pi^0 K^+$	✓	✓	
$B_d^0 \to \pi^- K^+$	✓	✓	
$B_d^0 \to \pi^0 K^0$	✓	✓	✓

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

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

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

* Consider an ALP (2104.03947):

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

→ $m_a \simeq m_{\pi^0}$ and ALP promptly decays to $\gamma\gamma$

→ Mixes with the π^0: $|a\rangle = \sin\theta \left|\pi^0\right\rangle_{\rm phys} + \cos\theta \, |a\rangle_{\rm phys}$

→ $B \to K\pi^0$ processes get new contribution: $\mathcal{A} = |\mathcal{A}| e^{i\pi/2}$
$\sqrt{2}\mathcal{A}^{0+} = \ldots + \mathcal{A}; \qquad \sqrt{2}\mathcal{A}^{00} = \ldots + \mathcal{A}$

→ Leads to a good fit with $|\mathcal{A}| \sim P'_{EW}$

→ Constraint from $B \to Ka$ ($B \to K$ + invis):

$$\mathcal{B} \sim 10^{-5} \Rightarrow \sin\theta \sim 0.1 - 0.2$$

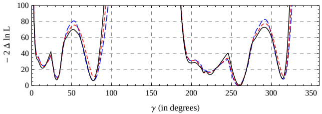
* Work in progress: How to detect an ALP with mass close to m_{π^0} in other flavor processes.

3-body B Decays: Fully-symmetric state

A result

γ from three-body decays

- 3-body final state under SU(3) : $B \to K\pi\pi, K\overline{K}K$
  - $\to$ 6 final state symmetries : permutations of 3 particles
- Fully-symmetric state (Rey-Le Lorier, London, 1109.0881)
  - $\to$ More observables than unknowns $\Rightarrow$ γ can be extracted
  - $\to$ BB, Imbeault, London, 1303.0846



$\to$ SM-like : 77°

$\to$ 32°, 259°, 315°

$K\pi\pi - K\overline{K}K$ puzzle ?

David London's talk in this session!

- Group theory analysis : I-spin, U-spin, SU(3) relations
  - $\to$ BB, Gronau, Imbeault, London, Rosner, 1402.2909

Bhubanjyoti Bhattacharya (UdeM) *Multi-body decays & flavor symmetries* July 30, 2015 2 / 13

$$
\begin{aligned}
2A(B^0 \to K^+\pi^0\pi^-)_{\rm fs} &= be^{i\gamma} - \kappa c\,, \\
\sqrt{2}A(B^0 \to K^0\pi^+\pi^-)_{\rm fs} &= -de^{i\gamma} - \tilde{P}'_{uc}e^{i\gamma} - a + \kappa d\,, \\
\sqrt{2}A(B^+ \to K^+\pi^+\pi^-)_{\rm fs} &= -ce^{i\gamma} - \tilde{P}'_{uc}e^{i\gamma} - a + \kappa b\,, \\
\sqrt{2}A(B^0 \to K^+K^0K^-)_{\rm fs} &= \alpha_{SU(3)}(-ce^{i\gamma} - \tilde{P}'_{uc}e^{i\gamma} - a + \kappa b) \\
A(B^0 \to K^0K^0\bar{K}^0)_{\rm fs} &= \alpha_{SU(3)}(\tilde{P}'_{uc}e^{i\gamma} + a)\,,
\end{aligned}
$$

- BB with others, 1303.0846
- Updated: Bertholet et al., 1812.06194
- N Dalitz points
  $\Rightarrow$ 8N hadronic parameters + γ
- 11N observables
  $\Rightarrow$ γ can be extracted

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	$\frac{1}{\sqrt5}$	0	$\frac{1}{\sqrt5}$	$\frac{1}{\sqrt{15}}$	$-\frac{1}{\sqrt3}$	$-\frac{3}{5}$	0	$\frac{3\sqrt6}{5}$
$A(B^+\to K^0\pi^+\pi^0)$	0	$\sqrt{\frac{2}{5}}$	0	$\sqrt{\frac{2}{5}}$	$\sqrt{\frac{2}{15}}$	$\frac{1}{\sqrt6}$	$-\frac{3\sqrt2}{5}$	0	$\frac{\sqrt3}{5}$
$A(B^0\to K^0\pi^+\pi^-)$	0	$-\frac{1}{\sqrt5}$	0	$-\frac{1}{\sqrt5}$	$\frac{1}{\sqrt{15}}$	$-\frac{1}{\sqrt3}$	$-\frac{1}{5}$	0	$\frac{\sqrt6}{5}$
$A(B^0\to K^+\pi^0\pi^-)$	0	$\sqrt{\frac{2}{5}}$	0	$\sqrt{\frac{2}{5}}$	$-\sqrt{\frac{2}{15}}$	$-\frac{1}{\sqrt6}$	$\frac{\sqrt2}{5}$	0	$\frac{3\sqrt3}{5}$
$A(B^+\to K^+K^0\bar{K}^0)$	0	$-\frac{1}{\sqrt5}$	0	$-\frac{1}{\sqrt5}$	$-\frac{1}{\sqrt{15}}$	0	$\frac{3}{5}$	0	$\frac{2\sqrt6}{5}$
$A(B^0\to K^0K^+K^-)$	0	$-\frac{1}{\sqrt5}$	0	$-\frac{1}{\sqrt5}$	$\frac{1}{\sqrt{15}}$	0	$-\frac{1}{5}$	$\sqrt2$	$\frac{\sqrt6}{5}$
$\sqrt2 A(B_s^0\to\pi^0K^+K^-)$	$-\frac{1}{2\sqrt6}$	0	$-\frac{1}{2\sqrt6}$	0	$\frac{2}{\sqrt{15}}$	$\frac{1}{2\sqrt3}$	$\frac{4}{5}$	$-\frac{1}{\sqrt2}$	$-\frac{\sqrt{\frac{3}{2}}}{10}$
$\sqrt2 A(B_s^0\to\pi^0K^0\bar{K}^0)$	$-\frac{1}{2\sqrt6}$	0	$-\frac{1}{2\sqrt6}$	0	$-\frac{2}{\sqrt{15}}$	$-\frac{1}{2\sqrt3}$	$-\frac{4}{5}$	$\frac{1}{\sqrt2}$	$-\frac{9\sqrt{\frac{3}{2}}}{10}$
$A(B_s^0\to\pi^-K^+\bar{K}^0)$	$\frac{1}{2\sqrt6}$	0	$\frac{1}{2\sqrt6}$	0	0	$-\frac{1}{2\sqrt3}$	0	$-\frac{1}{\sqrt2}$	$\frac{\sqrt{\frac{3}{2}}}{2}$
$A(B_s^0\to\pi^+K^-K^0)$	$-\frac{1}{2\sqrt6}$	0	$-\frac{1}{2\sqrt6}$	0	0	$-\frac{1}{2\sqrt3}$	0	$-\frac{1}{\sqrt2}$	$-\frac{\sqrt{\frac{3}{2}}}{2}$
$\sqrt2 A(B_s^0\to\pi^0\pi^+\pi^-)$	$-\frac{1}{\sqrt6}$	$\frac{2}{\sqrt5}$	$-\frac{1}{\sqrt6}$	$\frac{2}{\sqrt5}$	0	0	$\frac{6}{5}$	0	$\frac{3\sqrt{\frac{3}{2}}}{5}$

→ Find reduced set of SU(3) amplitudes

→ Establish γ extraction method

→ $\gamma_{\rm FS} \neq \gamma_{\rm FA}$

→ $B \to K\pi\pi$ puzzle?

Hadronic B puzzles: Summary

- Emerging cracks in the fabric of flavor symmetries
- Is it simply a lack of understanding of QCD?

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- Is it new physics?

Hadronic B puzzles: Summary

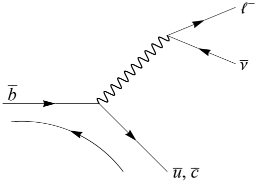
- Emerging cracks in the fabric of flavor symmetries
- Is it simply a lack of understanding of QCD?
- Is it new physics?
- Era of precision physics – lots of data from Belle II and LHCb
- Time will tell if SM can stand its ground
- Future is bright with many areas to explore

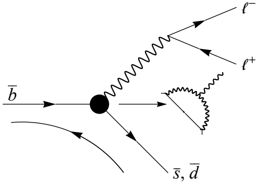
Puzzles in Semileptonic B decays

- $R_{K^{(*)}}$
- $R_{D^{(*)}}$
- ΔA_{FB} and other angular observables

Semileptonic B decays in the Standard Model

- Decay amplitudes may factorize into hadronic and leptonic parts
- Mediated by EW gauge bosons – $W^{\pm}, Z^0, \gamma$





Charged current

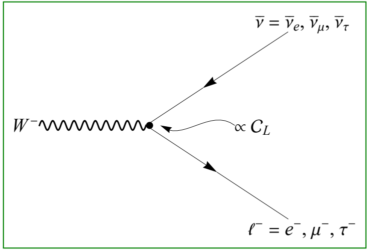
- Tree level; Eg. $B \to D^{(*)}\ell^-\bar{\nu}$
- CKM suppressed ($\lambda \sim 0.2$)
  $\propto V_{cb} \sim \lambda^2$
  $\propto V_{ub} \sim \lambda^3$

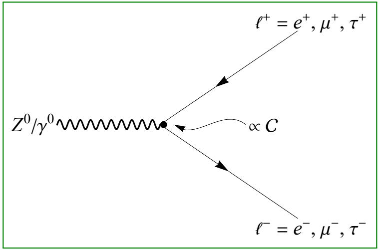
Neutral current

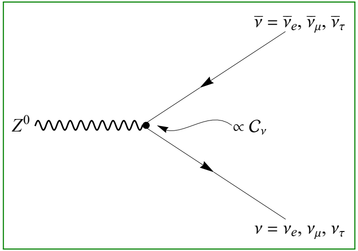
- Loop level; Eg. $B \to K^{(*)}\ell^-\ell^+$
- GIM + CKM Suppression
  $\propto V_{tb}^* V_{ts} \sim \lambda^2$
- Enhancement from top-quark in loop

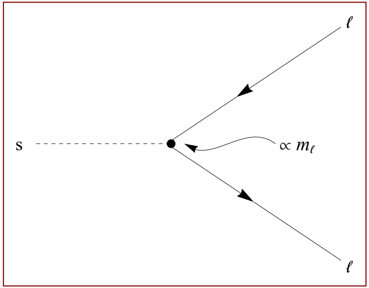
- Ideal for measuring SM parameters (CKM elements)
- Deviations may lead to New Physics discoveries

Lepton-flavor Universality and Violation









- $W^\pm, Z^0, \gamma$ couplings are same for e, μ, τ
- SM Gauge couplings are lepton-flavor universal (LFU)
- Departure from LFU can be a signature of **new physics**

Signatures of LFUV and New Physics

- Experimental measurement

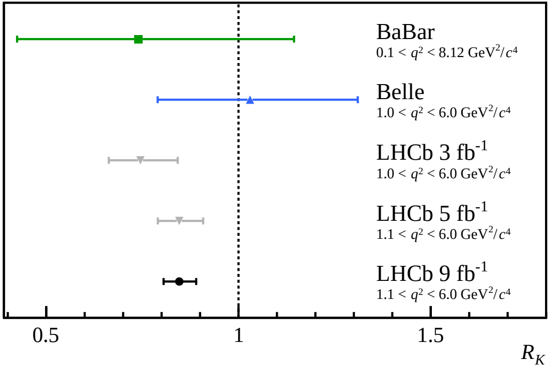
$$\mathcal{B}(B \to K^{(*)}\ell^-\ell^+)_{\rm exp} = \mathcal{B}_{\rm SM}^{\textit{Leading Order}}(1 + \mathcal{O}(\alpha_s))$$

- Leading order result in the Standard Model
- Hadronic corrections
- $\Delta\mathcal{B} = \mathcal{B}_{\rm exp} - \mathcal{B}_{\rm SM}$; Non-zero value could be due to QCD effects
- Hadronic uncertainties cancel in ratio between lepton flavors

$$\left.\frac{\mathcal{B}(B \to K\mu^-\mu^+)}{\mathcal{B}(B \to Ke^-e^+)}\right|_{\rm exp} = \left.\frac{\mathcal{B}(B \to K\mu^-\mu^+)}{\mathcal{B}(B \to Ke^-e^+)}\right|_{\rm SM} \frac{(1 + \mathcal{O}(\alpha_s))}{(1 + \mathcal{O}(\alpha_s))}$$

- $R_K^{\rm exp}$ $\quad R_K^{\rm SM} \sim 1$ Hadronic uncertainties cancel

Ratio anomalies I: R_K

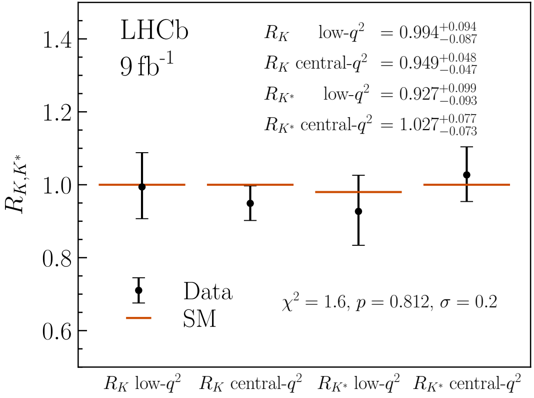


$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathcal{B}(B \to K\mu^-\mu^+)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{\mathcal{B}(B \to Ke^-e^+)}{dq^2} dq^2}$$

$$q^2 = (p_{\mu^+} + p_{\mu^-})^2$$

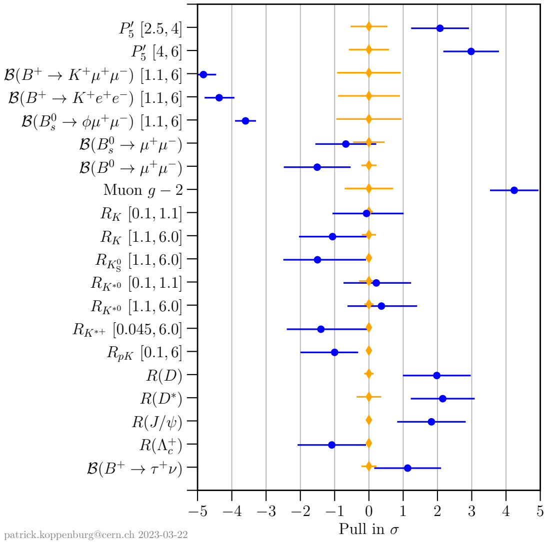
- Results from 2103.11769(LHCb) (Nature Physics)
- SM result $R_K^{[1-6]{\rm GeV}^2} = 1 \pm 0.01$ – clean! (Bordone et al., 1605.07633)

Ratio anomalies I: $R_{K^{(*)}}$



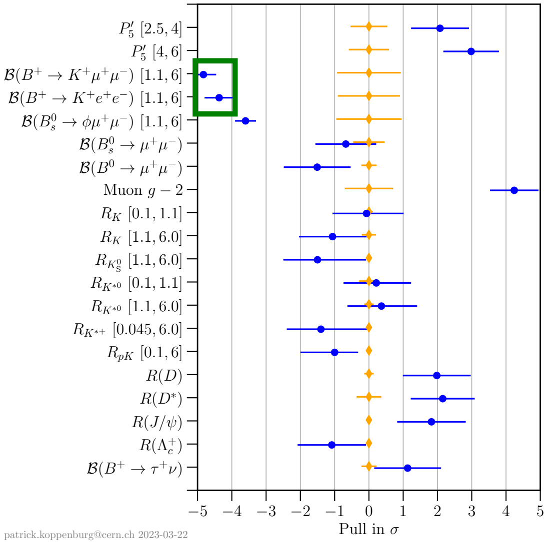
- Latest results from 2212.09153(LHCb)
- Same dataset – systematic shift due to improved understanding of background
- low-q^2: [0.1–1.1] GeV^2
- central-q^2: [1.1–6.0] GeV^2

Many more observables



- From Flavor Anomalies blog by P. Koppenburg (LHCb)
- $\delta^2_{\text{expt.}} + \delta^2_{\text{th}}$ normalized to 1
- SM in Orange shifted so central value is 0
- Expt. in Blue shows number of σ from SM

Many more observables



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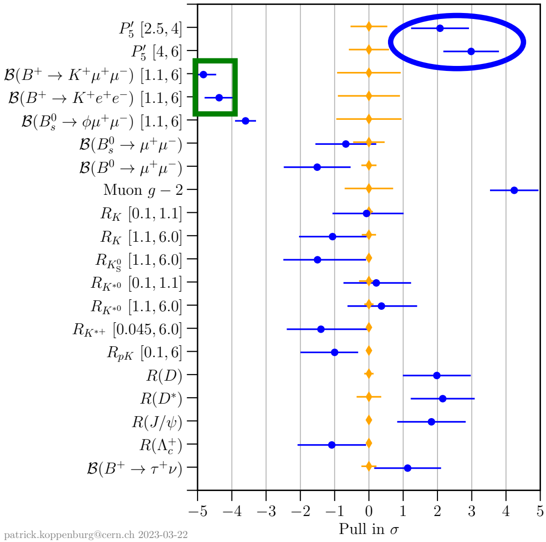
Many more observables



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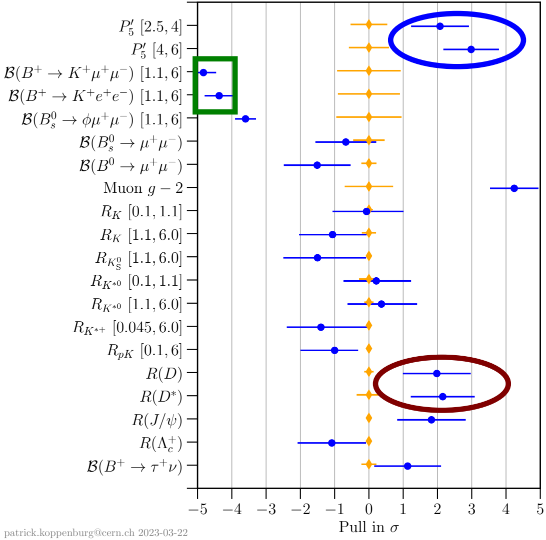
Many more observables



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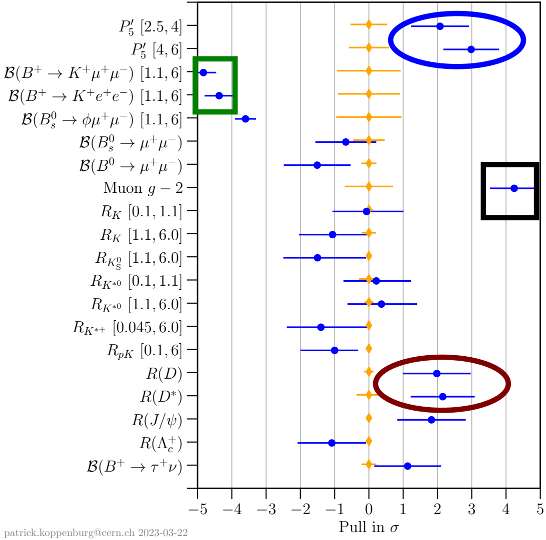
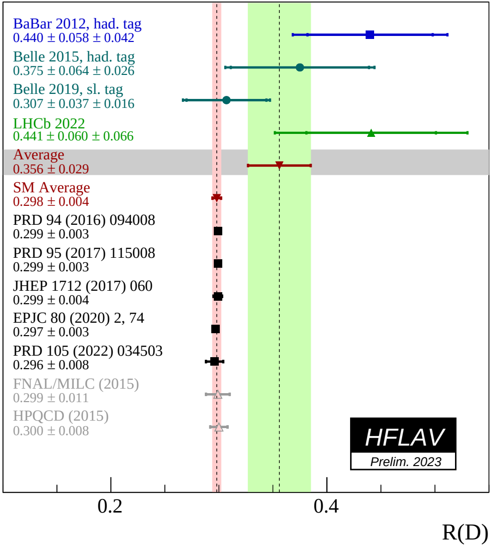
Many more observables



- From Flavor Anomalies blog
  by P. Koppenburg (LHCb)
- $\delta^2_{\text{expt.}} + \delta^2_{\text{th}}$ normalized to 1
- SM in Orange shifted so central value is 0
- Expt. in Blue shows number of σ from SM
- 2023 APS April Meeting talk by B. Kiburg

Ratio anomalies II: R_D



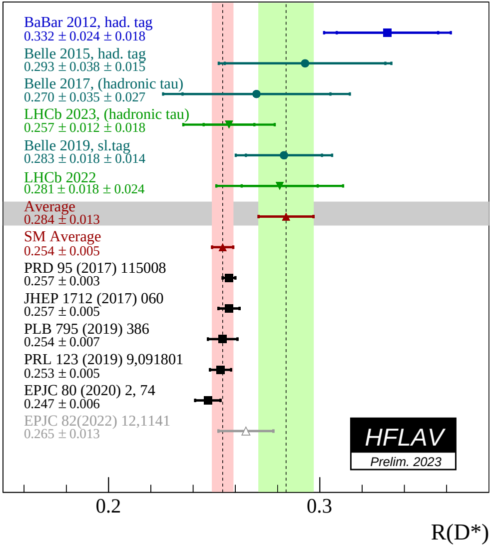
$$R_D = \frac{\mathcal{B}(B \to D\tau^-\bar{\nu})}{\mathcal{B}(B \to D\ell^-\bar{\nu})}$$

- SM Value: 0.298±0.004

  Heavy Flavor Averaging Group

- World Average measurement: 0.356±0.029
- Roughly 2.0σ deviation

Ratio anomalies III: R_{D^*}



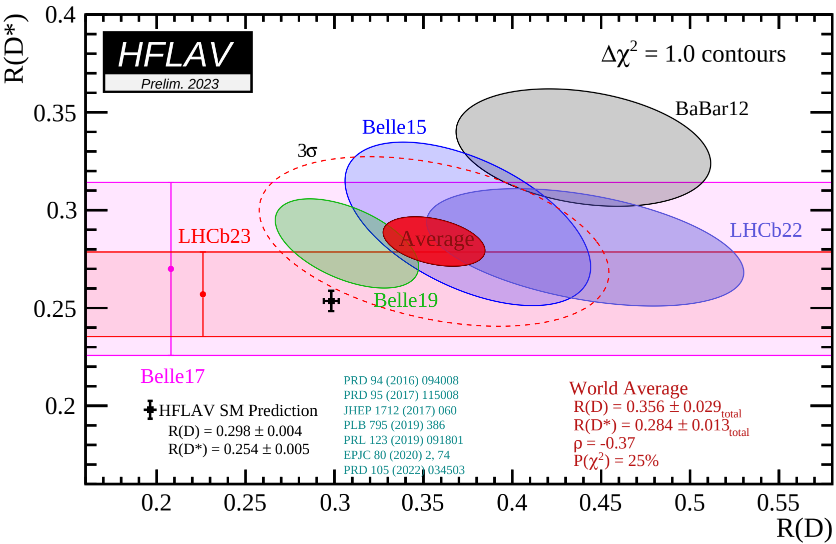
$$R_{D^*} = \frac{\mathcal{B}(B \to D^* \tau^- \bar{\nu})}{\mathcal{B}(B \to D^* \ell^- \bar{\nu})}$$

- SM Value: 0.254 ± 0.005

Heavy Flavor Averaging Group

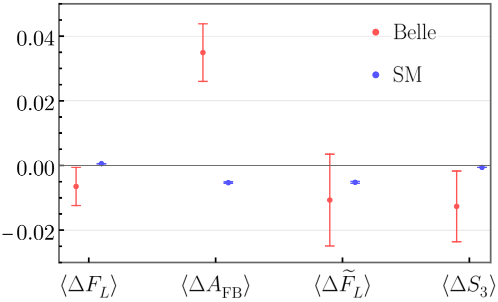
- World Average measurement: 0.284 ± 0.013
- Roughly 2.2σ deviation

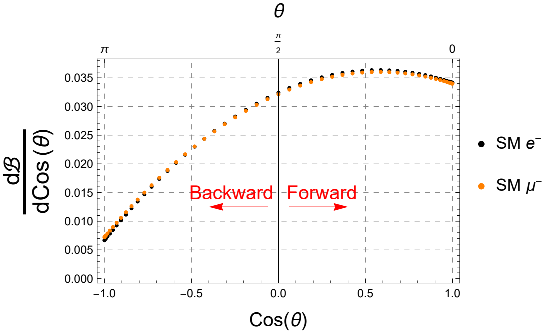
R_D and R_{D^*} combined



New anomaly: ΔA_{FB}

$$\Delta A_{\mathrm{FB}}(B \to D^* \ell^- \bar{\nu}) = A_{\mathrm{FB}}(B \to D^* \mu^- \bar{\nu}) - A_{\mathrm{FB}}(B \to D^* e^- \bar{\nu})$$

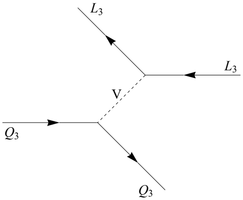


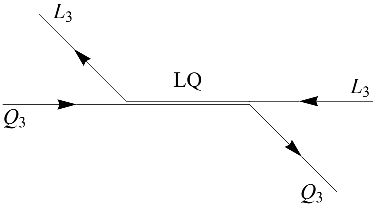


- Bobeth et al. 2104.02094 $\sim 4\sigma >$ SM
- Data from 1809.03210 (Belle 0.71 ab^{-1})
- $A_{FB}^{\mu} = 0.198 \pm 0.012$
  $A_{FB}^{e} = 0.204 \pm 0.012$
- $A_{\mathrm{FB}} = \dfrac{N_F - N_B}{N_F + N_B}$
- q^2 cuts to remove threshold effects
- $\Delta A_{FB} \sim (3.5 \pm 0.9)\%$

New-physics models

- TeV-scale new physics should respect electro-weak symmetry
- Relatively small couplings to first and second generation fermions
  - $\rightarrow$ No new particle seen in direct processes at colliders





New vector bosons (Z')

- Couples to quarks and leptons
- Dimension-4 couplings
- $(\bar{Q}\gamma^\mu Q + \bar{L}\gamma^\mu L)V_\mu$
- Quite constrained (BB with others, 1609.09078)

Leptoquarks

- Six types: Lorentz Scalar/Vector
  SU(2) Singlet/Doublet/Triplet
- Fermion number conserving/violating
- Possible to embed in unification models

Effective field theory approach

- Consider all possible dimension d = 6 four-fermion operators

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} f_{\rm EW} \sum_i C_i\, \mathcal{O}_i$$

$b \to s\ell^+\ell^-$, Neutral Current

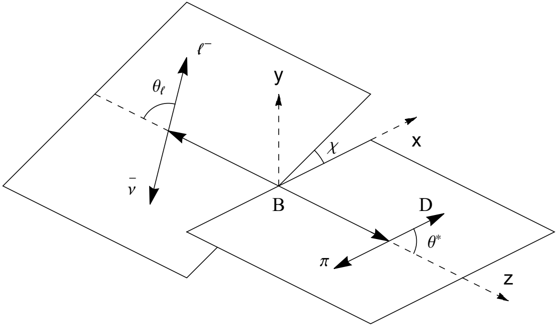
- Eg. $C_9 \to (\bar{s}_L\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$
- SM: $C_7 \sim -0.3, C_9 = -C_{10} \sim 4$
- Several NP WC's: $C_7', C_9', C_{10}', C_S^{(\prime)}, \ldots$
- A NP solution: $\delta C_9^\mu = -\delta C_{10}^\mu \sim -0.4$ (Altmannshofer and Stangl, 2103.13370)
- LFU NP scenario favored since $R_K \sim 1$
- For $\mathcal{O}(1)$ couplings $\Lambda_{\rm NP} \sim 50$ TeV

$b \to c\ell^-\bar{\nu}$, Charged Current

- Eg. $g_L \to (\bar{g}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu \nu_L)$
- SM: $g_L = 1$ only non-zero WC
- NP solution: $g_L^\mu, g_R^\mu \sim 0.1$ for ΔA_{FB} (BB with others, 2206.11283)
- For $\mathcal{O}(1)$ couplings $\Lambda_{\rm NP} \sim 3$ TeV
- $R_{D^{(*)}}$ anomalies require similar g_L^τ (Murgui et al., 1904.09311)

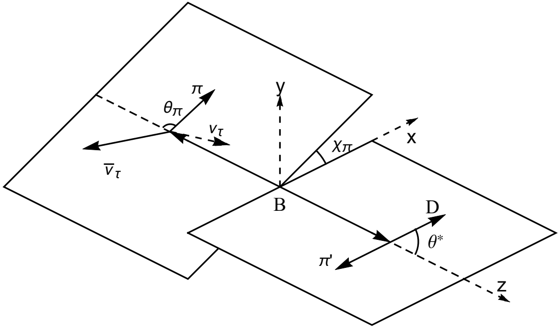
- Simultaneous explanation possible with TeV scale NP – BB with others, 1412.7164

Beyond ratio anomalies



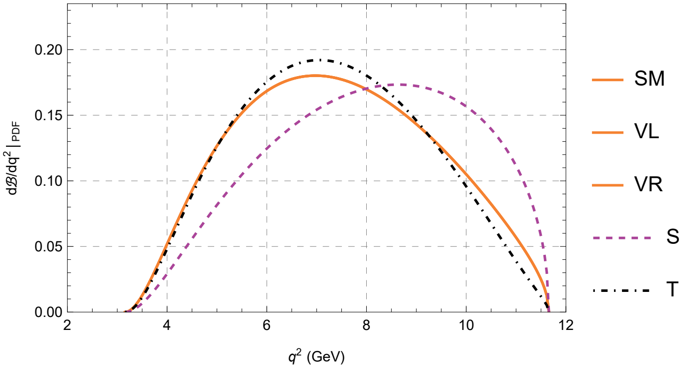
- Multiple measurements + corroborating information to pinpoint NP
- $B \to D\ell\nu$ phase space has two kinematic parameters – $\boxed{q^2}$, θ_ℓ (Bečirević et al.)
- $B \to D^*\ell\nu$ phase space has four kinematic parameters – $\boxed{q^2, \theta^*, \theta_\ell, \chi}$

Beyond ratio anomalies



- Multiple measurements + corroborating information to pinpoint NP
- $B \to D\ell\nu$ phase space has two kinematic parameters – $\boxed{q^2}$, θ_ℓ (Bečirević et al.)
- $B \to D^*\ell\nu$ phase space has four kinematic parameters – $\boxed{q^2, \theta^*, \theta_\ell, \chi}$
- $B \to D^*\tau\nu$, $\tau \to \pi\nu$ phase space has four measurable kinematic parameters: $q^2, \theta^*, \theta_\pi, \chi_\pi$ – BB with others, 2005.03032

Event distribution as a function of q^2: $B \to D\tau^-\bar{\nu}$



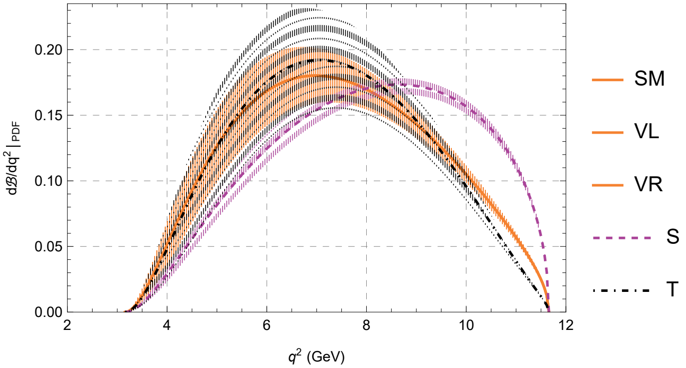
$B \to D\tau^-\bar{\nu}$ differential decay rate vs. q^2

- Relevant NP couplings:

$$
\begin{array}{ll}
V_L & (\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu_L) \\
V_R & (\bar{c}_R\gamma^\mu b_R)(\bar{\ell}_L\gamma_\mu\nu_L) \\
S & (\bar{c}_L b_R + \bar{c}_R b_L)(\bar{\ell}_R\nu_L) \\
T & (\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\ell}_R\sigma_{\mu\nu}\nu_L)
\end{array}
$$

- $g_i^{\mathrm{NP}} = 1$ in figure
  exaggerated for visibility

Event distribution as a function of q^2: $B \to D\tau^-\bar{\nu}$



$B \to D\tau^-\bar{\nu}$ differential decay rate vs. q^2

- Relevant NP couplings:

  V_L $(\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu_L)$

  V_R $(\bar{c}_R\gamma^\mu b_R)(\bar{\ell}_L\gamma_\mu\nu_L)$

  S $(\bar{c}_L b_R + \bar{c}_R b_L)(\bar{\ell}_R\nu_L)$

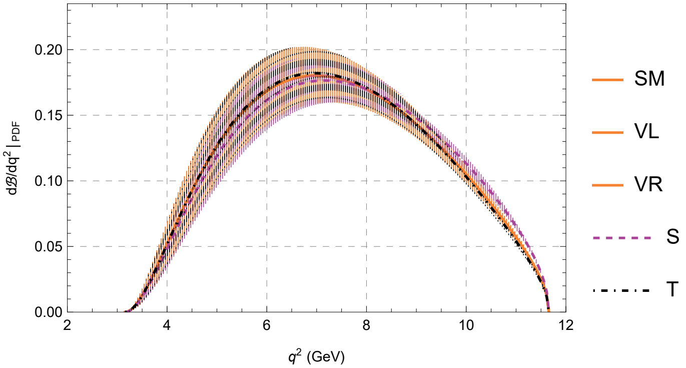
  T $(\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\ell}_R\sigma_{\mu\nu}\nu_L)$

- $g_i^{\rm NP} = 1$ in figure

  exaggerated for visibility

- Form factors and errors from Sakaki et al. 1309.0301

Event distribution as a function of q^2: $B \to D\tau^-\bar{\nu}$



$B \to D\tau^-\bar{\nu}$ differential decay rate vs. q^2

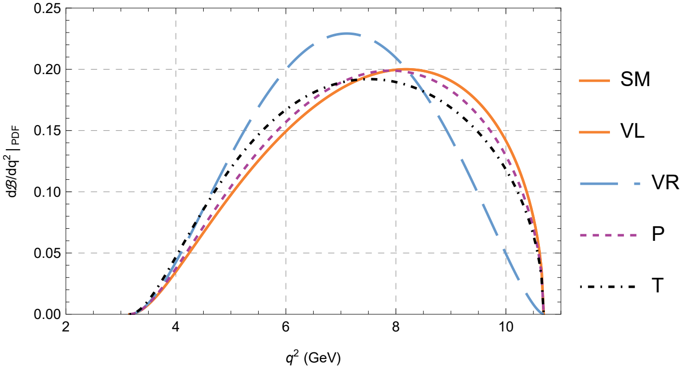
- Relevant NP couplings:

$$\begin{array}{ll} V_L & (\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu_L) \\ V_R & (\bar{c}_R\gamma^\mu b_R)(\bar{\ell}_L\gamma_\mu\nu_L) \\ S & (\bar{c}_L b_R + \bar{c}_R b_L)(\bar{\ell}_R\nu_L) \\ T & (\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\ell}_R\sigma_{\mu\nu}\nu_L) \end{array}$$

- Form factors and errors from Sakaki et al. 1309.0301
- $g_i^{\rm NP} = 0.1$

  Tough to distinguish

Event distribution as a function of q^2: $B \to D^* \tau^- \bar{\nu}$



$B \to D^* \tau^- \bar{\nu}$ differential decay rate vs. q^2

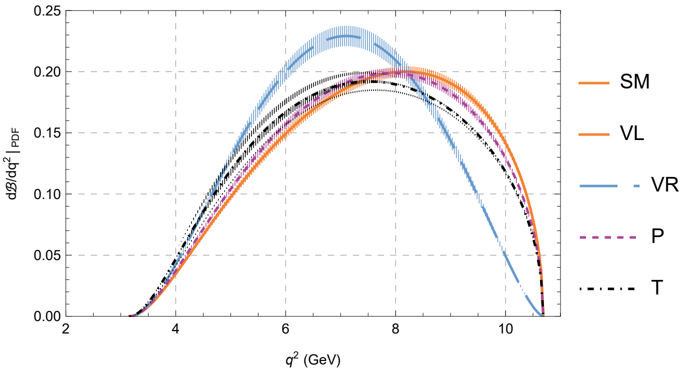
- Relevant NP couplings:

V_L	$(\bar{c}_L \gamma^\mu b_L)(\bar{\ell}_L \gamma_\mu \nu_L)$
V_R	$(\bar{c}_R \gamma^\mu b_R)(\bar{\ell}_L \gamma_\mu \nu_L)$
P	$(\bar{c}_L b_R - \bar{c}_R b_L)(\bar{\ell}_R \nu_L)$
T	$(\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_L)$

- $g_i^{\mathrm{NP}} = 1$ in figure

  exaggerated for visibility

Event distribution as a function of q^2: $B \to D^* \tau^- \bar{\nu}$



$B \to D^* \tau^- \bar{\nu}$ differential decay rate vs. q^2

- Relevant NP couplings:

  $V_L \quad (\bar{c}_L \gamma^\mu b_L)(\bar{\ell}_L \gamma_\mu \nu_L)$

  $V_R \quad (\bar{c}_R \gamma^\mu b_R)(\bar{\ell}_L \gamma_\mu \nu_L)$

  $P \quad (\bar{c}_L b_R - \bar{c}_R b_L)(\bar{\ell}_R \nu_L)$

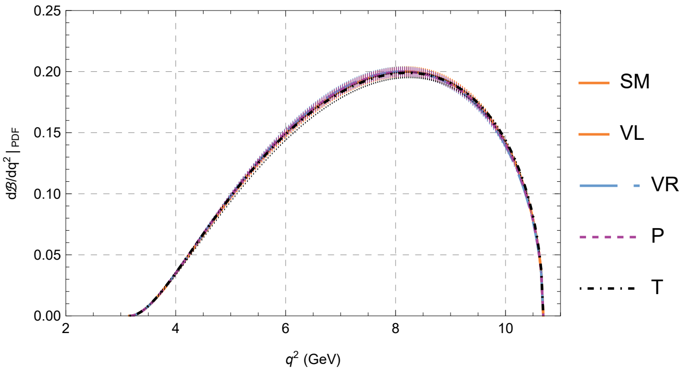
  $T \quad (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_L)$

- $g_i^{\mathrm{NP}} = 1$ in figure

  exaggerated for visibility

- Form factors and errors from Sakaki et al. 1309.0301

Event distribution as a function of q^2: $B \to D^* \tau^- \bar{\nu}$



$B \to D^* \tau^- \bar{\nu}$ differential decay rate vs. q^2

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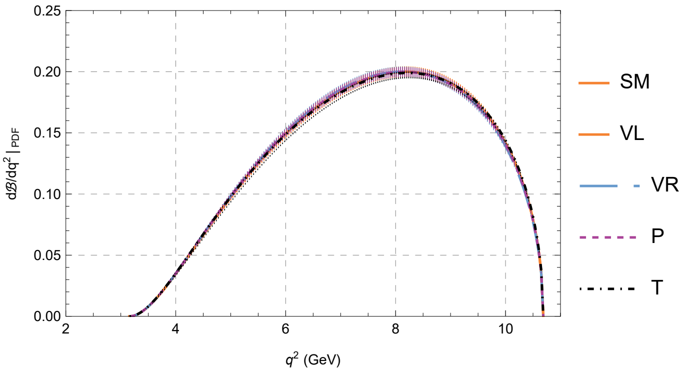

$B \to D^* \tau^- \bar{\nu}$ differential decay rate vs. q^2

- Relevant NP couplings:

$$
\begin{array}{ll}
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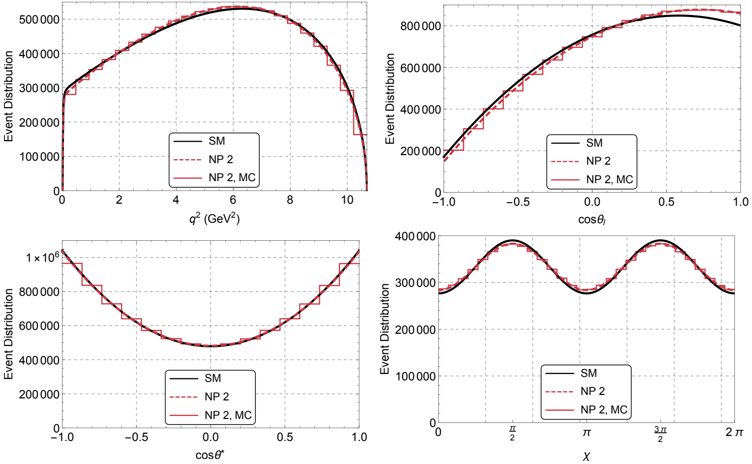
\end{array}
$$

- Form factors and errors from Sakaki et al. 1309.0301
- $g_i^{\rm NP} = 0.1$
  Tough to distinguish

- New tools needed: MonteCarlo generators with SM + NP effects
- MC tools may assist experimental analyses for pinpointing NP

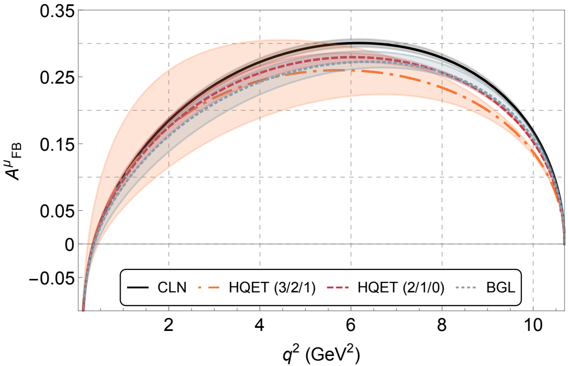
Other distributions for $B \to D^* \mu^- \bar{\nu}$



- $B \to D^* \mu^- \bar{\nu}$ MC Tools
- NP2 model:
  $g_L = 0.08$
  $g_R = 0.09$
  $g_P = 0.6\ i$
- Event distributions:
  vs. q^2
  vs. $\cos\theta_\ell$
  vs. $\cos\theta^*$
  vs. χ

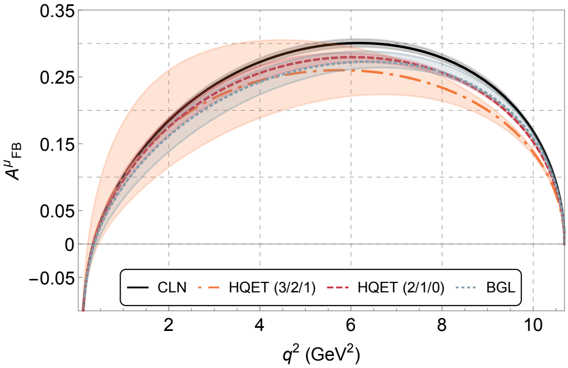
2206.11283, BB with T. Browder, Q. Campagna, A. Datta, S. Dubey, L. Mukherjee, and A. Sibidanov

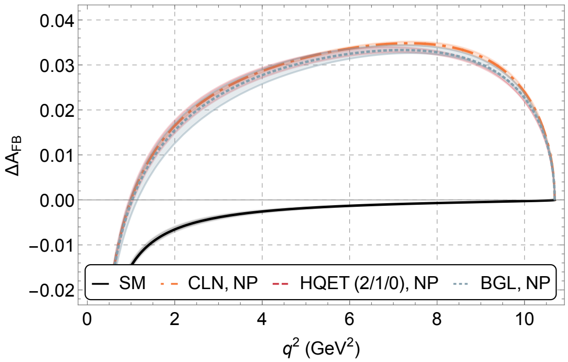
Back to forward-backward asymmetry



- $A^{\mu}_{\rm FB}(q^2)$ with form factor uncertainties
- NP model used:
  $g_L = 0.08,\ g_R = 0.090,\ g_P = 0.6i$

Back to forward-backward asymmetry

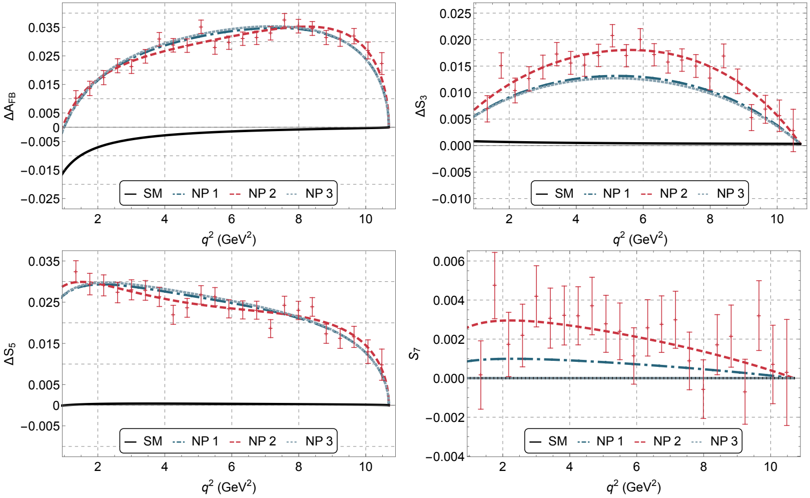




- $A^{\mu}_{\rm FB}(q^2)$ with form factor uncertainties
- NP model used:
  $g_L = 0.08,\ g_R = 0.090,\ g_P = 0.6i$

- $\Delta A_{\rm FB}(q^2) = A^{\mu}_{\rm FB}(q^2) - A^{e}_{\rm FB}(q^2)$
- For $q^2 > 1$ GeV^2, $\Delta A_{FB} < 0$ in SM $\sim \%$
- In NP scenarios, $\Delta A_{FB} > 0$ possible
- Possible to detect NP over FF effects

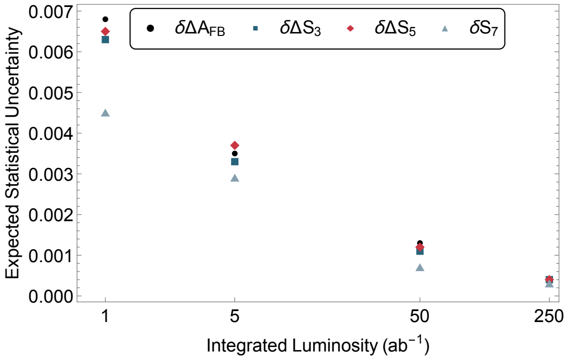
Additional observables with MC Tools



- $X = A_{\rm FB}, S_3, S_5$
- $\Delta X_{\rm SM} \sim 0$
- $S_7^\ell = 0$ in SM
- Non-zero value $\Rightarrow$ NP
- 10M events MC Data ($\sim$ Belle II stats)

Significance and correlations

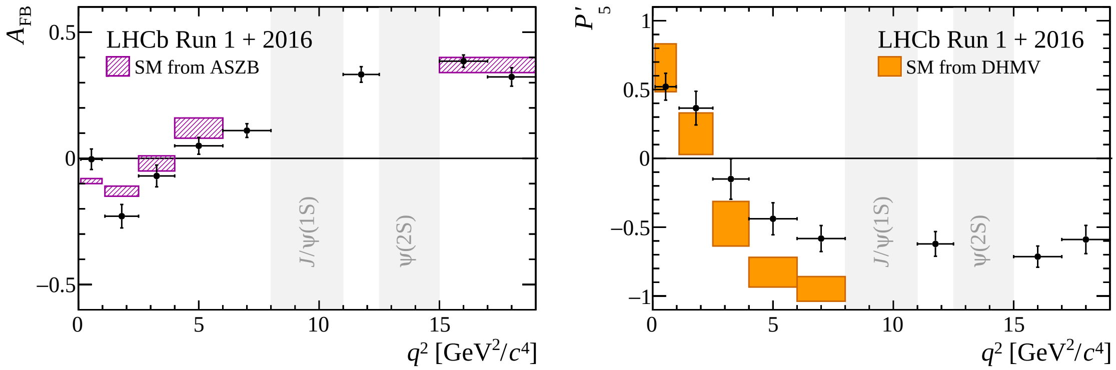
q^2 integrated observables



Observable	Angular Function	NP Dependence	m_ℓ suppression order
A_{FB}	$\cos\theta_\ell$	$\mathrm{Re}\,[g_T g_P^*]$ $\mathrm{Re}\,[(1+g_L-g_R)(1+g_L+g_R)^*]$	$\mathcal{O}(1)$
		$\mathrm{Re}\,[(1+g_L-g_R)g_P^*]$ $\mathrm{Re}\,[g_T(1+g_L-g_R)^*]$ $\mathrm{Re}\,[g_T(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\lvert 1+g_L-g_R\rvert^2$ $\lvert g_T\rvert^2$	$\mathcal{O}(m_\ell^2/q^2)$
S_3	$\sin^2\theta^*\sin^2\theta_\ell\cos 2\chi$	$\lvert 1+g_L+g_R\rvert^2$ $\lvert 1+g_L-g_R\rvert^2$ $\lvert g_T\rvert^2$	$\mathcal{O}(1),\ \mathcal{O}(m_\ell^2/q^2)$
S_5	$\sin 2\theta^*\sin\theta_\ell\cos\chi$	$\mathrm{Re}\,[g_T g_P^*]$	$\mathcal{O}(1)$
		$\lvert 1+g_L-g_R\rvert^2$	$\mathcal{O}(1),\ \mathcal{O}(m_\ell^2/q^2)$
		$\mathrm{Re}\,[(1+g_L-g_R)g_P^*]$ $\mathrm{Re}\,[g_T(1+g_L-g_R)^*]$ $\mathrm{Re}\,[g_T(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\lvert g_T\rvert^2$	$\mathcal{O}(m_\ell^2/q^2)$
S_7	$\sin 2\theta^*\sin\theta_\ell\sin\chi$	$\mathrm{Im}\,[g_P g_T^*]$	$\mathcal{O}(1)$
		$\mathrm{Im}\,[(1+g_L+g_R)g_P^*]$ $\mathrm{Im}\,[(1+g_L-g_R)g_T^*]$	$\mathcal{O}(m_\ell/\sqrt{q^2})$
		$\mathrm{Im}\,[(1+g_L-g_R)(1+g_L+g_R)^*]$	$\mathcal{O}(m_\ell^2/q^2)$

- Stat uncertainty goes down as luminosity increases
- Observables are correlated – multiprong approach for NP searches

Similarities with $B \to K^* \ell^+ \ell^-$



- LHCb results on $B \to K^* \mu + \mu^-$ and plots from 2003.04831
- SM results for $A_{\rm FB}$ from DHMV, 1407.8526
- SM results for P_5' from ASZB, 1411.3161, 1503.05534
- Ongoing efforts using AI to categorize NP – see 2023 APS April Meeting talk by S. Dubey)

Semileptonic anomalies: Summary

- Anomalies in Semileptonic B decays persist
- Ratio anomalies present clean signal for NP
- Precision measurement from LHCb, Belle II may help
- Necessary to go beyond overall ratio anomalies
- With more data, angular observables will become accessible
- Δ observables + correlated deviations $\rightarrow$ path to NP
- Lots more data coming – bright future!

What does AI say about the anomalies?

What is the future of B-decay anomalies?

The future of B-decay anomalies is an active area of research in particle physics. B-decay anomalies refer to deviations from the predictions of the Standard Model of particle physics in the decay of particles containing b quarks, which have been observed in several experiments.

There are ongoing efforts to study these anomalies in more detail, both through the collection of more data at existing experiments and through the construction of new experiments with increased sensitivity. Some of these efforts include the Belle II experiment in Japan, the LHCb experiment at CERN in Switzerland, and the proposed Future Circular Collider (FCC) at CERN.

The ultimate goal of these efforts is to determine whether the observed anomalies are due to statistical fluctuations or whether they represent genuine physics beyond the Standard Model. If the latter is true, it could provide important clues to the nature of dark matter, the origin of matter-antimatter asymmetry in the universe, and other fundamental questions in particle physics.

Overall, the future of B-decay anomalies is bright, as ongoing and future experiments will continue to shed light on these intriguing phenomena and potentially revolutionize our understanding of particle physics.

Chat GPT Outlook:

The Future is Bright!

Thanks!

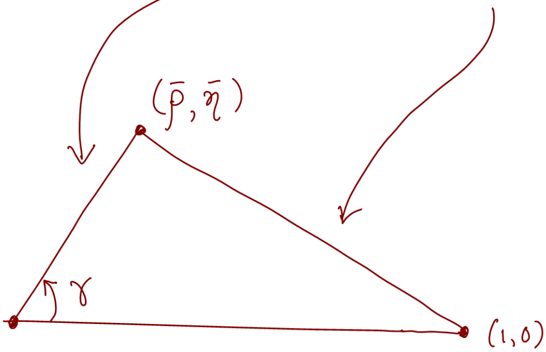
- UG students: J. P. Guévin, N. Payot (UdeM)
  K. LeBlanc, A. Houck (LTU)
- Grad students:
  S. Shivashankara, S. Kamali, J. Waite, Q. Campagna (UMiss)
- Postdocs: R. Watanabe, S. Kumbhakar (UdeM)
  L. Mukherjee (UMiss), S. Dubey, A. Sibidanov (Hawaii)
- Faculty: D. London (UdeM), A. Datta (UMiss)
  D. Marfatia, T. Browder (Hawaii)
- Support orgs: LTU, MIAPP, US National Science Foundation (PHY-2013984)

Back-up Slides

CKM Unitarity Triangle

CKM Unitarity

$$1 + \frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} = 0$$



CP Violation in the angular distribution

- Consider $\hat{n}_X$ as normal unit vector for plane of X decay
- Triple-product (TP) asymmetries $\propto \sin\chi = (\hat{n}_{D^*} \times \hat{n}_{\ell\bar{\nu}}) \cdot \hat{p}_{D^*}$

  See for example Gronau & Rosner, 1107.1232S
- Not all triple-products have to be CP odd!
- Example CP odd (true) TP: $X = \mathrm{Im}(A_a A_b^* - \bar{A}_a \bar{A}_b^*)$

  $\rightarrow$ $\bar{A}$ represents CP conjugate of A

  $\rightarrow$ $\bar{X} = -X \Rightarrow X$ is CP-odd
- In order to observe CP violation

  $\Rightarrow$ measure a non-zero CP-odd TP; X appears in untagged $(\Gamma + \bar{\Gamma})$ distribution
- Details in work done with Datta, Kamali, and London

  $\rightarrow$ 1903.02567

Leptoquark couplings

Type		Fermion number	
Lorentz	SU(2)	Conserving	Lagrangian
scalar	singlet	✗	$(g_{1L}^{ij}\bar{Q}_{iL}^{c}i\sigma_2 L_{jL} + g_{1R}^{ij}\bar{u}_{iR}^{c}\ell_{jR})S_1$
scalar	doublet	✓	$(h_{2L}^{ij}\bar{u}_{iR}L_{jL} + h_{2R}^{ij}\bar{Q}_{iL}i\sigma_2\ell_{jR})R_2$
scalar	triplet	✗	$(g_{3L}^{ij}\bar{Q}_{iL}^{c}i\sigma_2\vec{\sigma}L_{jL})\cdot\vec{S}_3$
vector	singlet	✓	$(h_{1L}^{ij}\bar{Q}_{iL}\gamma^{\mu}L_{jL} + h_{1R}^{ij}\bar{d}_{iR}\gamma^{\mu}\ell_{jR})U_{1\mu}$
vector	doublet	✗	$(g_{2L}^{ij}\bar{d}_{iR}^{c}\gamma_{\mu}L_{jL} + g_{2R}^{ij}\bar{Q}_{iL}^{c}\gamma_{\mu}\ell_{jR})V_2^{\mu}$
vector	triplet	✓	$h_{3L}^{ij}\bar{Q}_{iL}\vec{\sigma}\gamma^{\mu}L_{jL}\cdot\vec{U}_{3\mu}$

Angular observables in $B \to K^* \mu^+ \mu^-$

$$
\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2} \frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K
$$
$$
+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l
$$
$$
-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi
$$
$$
+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi
$$
$$
+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi
$$
$$
+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]
$$

$$
P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}
$$

2003.04831

Angular observables in $B \to D^* \ell^- \bar{\nu}$

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta^*\, d\cos\theta_\ell\, d\chi} = \frac{9}{32\pi} \Big[\left(I_1^s \sin^2\theta^* + I_1^c \cos^2\theta^*\right) + \left(I_2^s \sin^2\theta^* + I_2^c \cos^2\theta^*\right)\cos 2\theta_\ell$$
$$+ I_3 \sin^2\theta^* \sin^2\theta_\ell \cos 2\chi + I_4 \sin 2\theta^* \sin 2\theta_\ell \cos\chi + I_5 \sin 2\theta^* \sin\theta_\ell \cos\chi$$
$$+ \left(I_6^c \cos^2\theta^* + I_6^s \sin^2\theta^*\right)\cos\theta_\ell + I_7 \sin 2\theta^* \sin\theta_\ell \sin\chi$$
$$+ I_8 \sin 2\theta^* \sin 2\theta_\ell \sin\chi + I_9 \sin^2\theta^* \sin^2\theta_\ell \sin 2\chi \Big]\,,$$

2206.11283

Other anomalies

Observable	SM Prediction	Measurement	Source
$R_{J/\psi}^{\tau/\mu}$	0.283 ± 0.048	$0.71 \pm 0.17 \pm 0.18$	Watanabe
$R_{D^*}^{\mu/e}$	~ 1.0	$1.04 \pm 0.05 \pm 0.01$	Belle
$B \to K\nu\bar{\nu}$ $(\times 10^6)$	4.20 ± 0.36	30 ± 16	Buras et al. Belle

- Constrain NP couplings in $SU(2)$ invariant models BB with others
- $B \to K^{(*)}\nu\bar{\nu} \to$ independent path to NP w/o hadronic uncertainties – Browder et al.
- Belle II 250 ab^{-1} $\to \sim 4\%$ error