$8\,\sigma$ tension in $B \to \pi K$: Oasis or mirage?

Anirban Kundu

November 10, 2021
Anomalies 2021, IIT-Hyderabad

University of Calcutta

Notation

The B mesons: $B^+ \equiv u\bar{b}$, $B^- \equiv b\bar{u}$, $B^0 \equiv d\bar{b}$, $\overline{B}^0 \equiv b\bar{d}$

$B \to \pi K$

$B^- \to \pi^0 K^-$	$\Longrightarrow$	$b \to u\bar{u}s\,,\; d\bar{d}s$	Tree and penguin
$B^- \to \pi^- \overline{K}^0$	$\Longrightarrow$	$b \to d\bar{d}s$	Only tree
$\overline{B}^0 \to \pi^+ K^-$	$\Longrightarrow$	$b \to u\bar{u}s$	Only penguin
$\overline{B}^0 \to \pi^0 \overline{K}^0$	$\Longrightarrow$	$b \to u\bar{u}s\,,\; d\bar{d}s$	Tree and penguin

Decay rate asymmetry $\Delta(\pi K) = \Gamma(b) - \Gamma(\bar{b})$

Direct CP asymmetry $$A_{\rm CP}(\pi K) = \frac{\Delta(\pi K)}{\Gamma(b) + \Gamma(\bar{b})}$$

University of Calcutta

$B \to X$ $\overset{CP}{\Longrightarrow}$ $\overline{B} \to \overline{X}$

To have a direct CP asymmetry $A_{\rm CP} \neq 0$, there must be at least two amplitudes with *different* weak and strong phases

$$\begin{aligned} \mathcal{M}(B \to X) &\propto A_1 \exp(i\theta_1)\exp(i\delta_1) + A_2 \exp(i\theta_2)\exp(i\delta_2) \\ \overline{\mathcal{M}}(\overline{B} \to \overline{X}) &\propto A_1 \exp(-i\theta_1)\exp(i\delta_1) + A_2 \exp(-i\theta_2)\exp(i\delta_2) \\ A_{\rm CP} &\propto |\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2 \propto \sin(\theta_1 - \theta_2)\sin(\delta_1 - \delta_2) \end{aligned}$$

Weak phases from CKM, no first principle to calculate strong phases

What amplitudes do we talk about? How to calculate them?

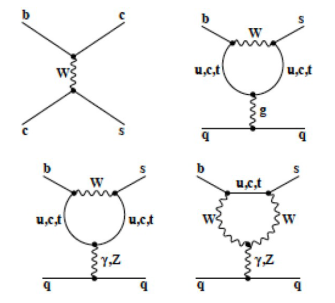
University of Calcutta

Groundwork

- $$\mathcal{H} \sim G_F \times \underbrace{(CKM)}_{V_{qb}V_{qs}^*} \times \underbrace{C(\mu)}_{WC} \times \underbrace{Q}_{4-f}$$

  EFT with 4-fermi operators at $\sim \mathcal{O}(m_b) \ll m_W$.
- These are 4-fermi operators, but while QCD and EM do not differentiate between L and R fermions, weak does.
- All such short-distance corrections are dumped into the WCs.
- $\langle f|Q_i|B\rangle$ involves FF

`Good job from Lattice, QCD SR, LCSR`



Tree, Strong, and EW penguins
BSM may involve more operators

University of Calcutta

1. Current-current:

$$Q_1 = (\bar{u}b)_{8,V-A}(\bar{s}u)_{8,V-A}\,, \quad Q_2 = (\bar{u}b)_{1,V-A}(\bar{s}u)_{1,V-A}$$

2. Strong penguin:

$$Q_{3(5)} = (\bar{s}b)_{1,V-A}\sum_q(\bar{q}q)_{1,V-(+)A}\,, \quad Q_{4(6)} = (\bar{s}b)_{8,V-A}\sum_q(\bar{q}q)_{8,V-(+)A}$$

3. EW penguin:

$$\begin{aligned} Q_{7(9)} &= \frac{3}{2}(\bar{s}b)_{1,V-A}\sum_q e_q(\bar{q}q)_{1,V+(-)A} \\ Q_{8(10)} &= (\bar{s}b)_{8,V-A}\sum_q e_q(\bar{q}q)_{8,V+(-)A} \end{aligned}$$

UNIVERSITY OF CALCUTTA

$$\Delta A_{\rm CP} = A_{\rm CP}(B^+ \to \pi^0 K^+) - A_{\rm CP}(B^0 \to \pi^- K^+)$$

Expected to be close to zero in SM (we'll see why), and

$$\begin{aligned} \Delta A_{\rm CP} &= 0.108 \pm 0.017 \quad \text{(LHCb)} \\ &= 0.112 \pm 0.013 \quad \text{(Global av. after BelleII(21))} \end{aligned}$$

LHCb : 5.4 fb^{-1} @ 13 TeV [LHCb, PRL 2021, 2012.12789]

$8\,\sigma$ tension !!!

How serious is this?

$\Rightarrow$ AK, Patra, Roy, 2106.15633

University of Calcutta

$$\Delta A_{\rm CP} = A_{\rm CP}(B^+ \to \pi^0 K^+) - A_{\rm CP}(B^0 \to \pi^- K^+)$$

Expected to be close to zero in SM (we'll see why), and

$$\begin{aligned} \Delta A_{\rm CP} &= 0.108 \pm 0.017 \quad \text{(LHCb)} \\ &= 0.112 \pm 0.013 \quad \text{(Global av. after BelleII(21))} \end{aligned}$$

LHCb : 5.4 fb^{-1} @ 13 TeV [LHCb, PRL 2021, 2012.12789]

$8\,\sigma$ tension !!!

How serious is this?

$\Rightarrow$ AK, Patra, Roy, 2106.15633

University of Calcutta

Isospin amplitudes

Neubert, JHEP 1999

B is $I = \frac{1}{2}$, πK can be in $I' = \frac{1}{2}$ or $\frac{3}{2}$

$$\begin{array}{ll} \Delta I = 1 & A_{1/2}\ (I' = \tfrac{1}{2}), \quad A_{3/2}\ (I' = \tfrac{3}{2}) \\ \Delta I = 0 & B_{1/2}\ (I' = \tfrac{1}{2}) \end{array}$$

$$\begin{aligned} A(B^+ \to \pi^+ K^0) &= B_{1/2} + A_{1/2} + A_{3/2}\,, \\ A(B^+ \to \pi^0 K^+) &= -\frac{1}{\sqrt{2}}\left(B_{1/2} + A_{1/2}\right) + \sqrt{2}A_{3/2}\,, \\ A(B^0 \to \pi^- K^+) &= -B_{1/2} + A_{1/2} + A_{3/2}\,, \\ A(B^0 \to \pi^0 K^0) &= \frac{1}{\sqrt{2}}\left(B_{1/2} - A_{1/2}\right) + \sqrt{2}A_{3/2}\,. \end{aligned}$$

Each with two indep. CKM combo, so 6 amplitudes and 5 strong phases

Isospin amplitudes

Neubert, JHEP 1999

B is $I = \frac{1}{2}$, πK can be in $I' = \frac{1}{2}$ or $\frac{3}{2}$

$$\begin{array}{ll} \Delta I = 1 & A_{1/2}\ (I' = \tfrac{1}{2})\,, \quad A_{3/2}\ (I' = \tfrac{3}{2}) \\ \Delta I = 0 & B_{1/2}\ (I' = \tfrac{1}{2}) \end{array}$$

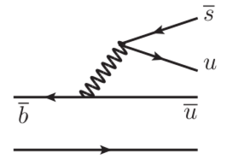
$$\begin{aligned} A(B^+ \to \pi^+ K^0) &= B_{1/2} + A_{1/2} + A_{3/2}\,, \\ A(B^+ \to \pi^0 K^+) &= -\frac{1}{\sqrt{2}}\left(B_{1/2} + A_{1/2}\right) + \sqrt{2}A_{3/2}\,, \\ A(B^0 \to \pi^- K^+) &= -B_{1/2} + A_{1/2} + A_{3/2}\,, \\ A(B^0 \to \pi^0 K^0) &= \frac{1}{\sqrt{2}}\left(B_{1/2} - A_{1/2}\right) + \sqrt{2}A_{3/2}\,. \end{aligned}$$

Each with two indep. CKM combo, so 6 amplitudes and 5 strong phases

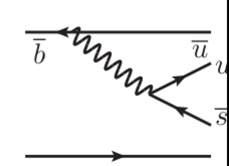
University of Calcutta

Topological amplitudes

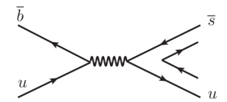
Fleischer, Mannel, Gronau, Rosner, Neubert, 1998



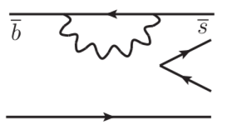
Colour-allowed tree (**T**), $b \to u\bar{u}s$, comes as $\lambda_u T$, with $\lambda_u = V_{us}V_{ub}^* \sim \lambda^4$
$\lambda \approx 0.22$ is the smallness parameter



Colour-suppressed tree (**C**), same as T but $1/N_c$ suppressed



Annihilation (**A**) – much suppressed compared to T or C



Penguin – further subdivided into strong penguin (**P**) and EW penguin (**P**$_{\rm EW}$)

University of Calcutta

More ornithology:

Strong penguins $\Rightarrow$ $P = \lambda_u P_u + \lambda_c P_c + \lambda_t P_t$ $\lambda_q = V_{qs} V_{qb}^*$

But $\lambda_u + \lambda_c + \lambda_t = 0$, so

$$P = \lambda_u (P_u - P_c) + \lambda_t (P_t - P_c) \equiv \lambda_u P_{uc} + \lambda_t P_{tc}$$

We expect a hierarchy $\sim \mathcal{O}(\lambda)$

$$|\lambda_t P_{tc}| > |\lambda_u T| > |\lambda_u C| > |\lambda_u A|, |\lambda_u P_{uc}|$$

Two types of EW penguin amplitudes too: P_{EW} (Col.A) and P_{EW}^C (Col.S)

SU(3) flavour symmetry relates EWP with tree amplitudes.

University of Calcutta

Ornithology continued:

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \left[\lambda_u \underbrace{\left(C_1 \left(\bar{b}u \right) \left(\overline{u}s \right) + C_2 \left(\bar{b}s \right) \left(\overline{u}u \right) \right)}_{(V-A)\otimes(V-A)} - \lambda_t \sum_{i=3}^{10} C_i Q_i \right]$$

Q_{1-2}: tree, Q_{3-6}: strong penguin, Q_9, Q_{10}: non-negligible EWP

$$P_{EW} \pm P_{EW}^{C} = -\frac{3}{2} \frac{C_9 \pm C_{10}}{C_1 \pm C_2} (T \pm C) \, . \qquad \text{(Neubert, Rosner, 1998)}$$

At LL, $q^2 = m_b^2$

$$P_{EW} \sim \kappa T \, , \qquad P_{EW}^{C} \sim \kappa C \, ,$$

$$\kappa = -\frac{3}{2} \frac{C_9 + C_{10}}{C_1 + C_2} \simeq -\frac{3}{2} \frac{C_9 - C_{10}}{C_1 - C_2} \simeq 0.0135 \pm 0.0012 \, .$$

Only within SM !

University of Calcutta

In terms of the topological amplitudes, dominant, subdominant, and negligible

$$\underbrace{\mathcal{A}^{-+}}_{\pi^- K^+} = -\lambda_u (P_{uc} + T) - \lambda_t \left(P_{tc} + \frac{2}{3} P_{EW}^C \right) ,$$

$$\mathcal{A}^{+0} = \lambda_u (P_{uc} + A) + \lambda_t \left(P_{tc} - \frac{1}{3} P_{EW}^C \right) ,$$

$$\sqrt{2}\mathcal{A}^{00} = \lambda_u (P_{uc} - C) + \lambda_t \left(P_{tc} - P_{EW} - \frac{1}{3} P_{EW}^C \right) ,$$

$$\sqrt{2}\mathcal{A}^{0+} = -\lambda_u (T + C + P_{uc} + A) - \lambda_t \left(P_{tc} + P_{EW} + \frac{2}{3} P_{EW}^C \right)$$

$A_{\rm CP}$ comes from T–P_{tc} interference
T and P_{EW} carry the same strong phase, related by κ

University of Calcutta

So we expect

$$A_{\rm CP}(B^0 \to \pi^- K^+) = A_{\rm CP}(B^+ \to \pi^0 K^+)$$

$$\Downarrow$$

$$\Delta A_{\rm CP} \approx 0$$

Depends on neglect of C. Is C negligible?

Another potential observable (~ 0 in SM)

$$\Delta_4 = A_{\rm CP}(\pi^- K^+) + A_{\rm CP}(\pi^+ K^0)\frac{\mathcal{B}(\pi^+ K^0)\tau_0}{\mathcal{B}(\pi^- K^+)\tau_+} - A_{\rm CP}(\pi^0 K^+)\frac{2\mathcal{B}(\pi^0 K^+)\tau_0}{\mathcal{B}(\pi^- K^+)\tau_+} - A_{\rm CP}(\pi^0 K^0)\frac{2\mathcal{B}(\pi^0 K^0)}{\mathcal{B}(\pi^- K^+)}$$

University of Calcutta

Not entirely unexpected ....

Large EWP

$B \to \pi\pi$, $B \to \pi K$ known to be troublesome, related by SU(3)

Hints of possible large EW penguin $\implies$ BSM ! `Nandi and AK, 2004`

Large C

PQCD: $|C/T| \sim 0.5$ for $\pi\pi$, similar for πK `Li and Mishima, PRD 2011`

SCET: $|C/T|$ can be even larger, maybe close to 1 `Bauer et al. 2005`

Not entirely unexpected ....

Large EWP

$B \to \pi\pi$, $B \to \pi K$ known to be troublesome, related by SU(3)

Hints of possible large EW penguin $\Longrightarrow$ BSM ! Nandi and AK, 2004

Large C

PQCD: $|C/T| \sim 0.5$ for $\pi\pi$, similar for πK Li and Mishima, PRD 2011
SCET: $|C/T|$ can be even larger, maybe close to 1 Bauer et al. 2005

1. $|C/T| \leq 0.5$ is still allowed in SM, but not large EWP
2. Large EWP $\Rightarrow \kappa > \kappa_{\rm SM}$, maybe there are two different κs
   $\Longrightarrow \kappa_1 = P_{EW}/T$, $\kappa_2 = P_{EW}^C/C$, beyond-SM

UNIVERSITY OF CALCUTTA

Not entirely unexpected ....

Large EWP

$B \to \pi\pi$, $B \to \pi K$ known to be troublesome, related by SU(3)

Hints of possible large EW penguin $\implies$ BSM ! `Nandi and AK, 2004`

Large C

PQCD: $|C/T| \sim 0.5$ for $\pi\pi$, similar for πK `Li and Mishima, PRD 2011`
SCET: $|C/T|$ can be even larger, maybe close to 1 `Bauer et al. 2005`

1. $|C/T| \leq 0.5$ is still allowed in SM, but not large EWP
2. Large EWP $\Rightarrow \kappa > \kappa_{\rm SM}$, maybe there are two different κs
   $\implies \quad \kappa_1 = P_{EW}/T$, $\kappa_2 = P_{EW}^C/C$, beyond-SM

University of Calcutta

A Bayesian analysis

Also cross-check with frequentist

- Take all data on BR and A_{CP}, no averaging.
- Check for a "good" fit in the "SM-like" region.

What is a good fit?
Which region is SM-like?
What is meant by "no averaging"?

University of Calcutta

A Bayesian analysis

Also cross-check with frequentist

- Take all data on BR and A_{CP}, no averaging.
- Check for a "good" fit in the "SM-like" region.

What is a good fit?
Which region is SM-like?
What is meant by "no averaging"?

University of Calcutta

Modes	Expt.	BR $[10^{-6}]$	Expt.	$A_{\rm CP}$	$S_{\rm CP}$
$B^0 \to \pi^- K^+$	BaBar [5]	19.1(6)(6)	BaBar [9]	$-0.107(16)(^{6}_{4})$	
	Belle [11]	20.00(34)(60)	Belle [11]	−0.069(14)(7)	
	CLEO [74]	$18.0(^{23}_{21})(^{12}_{9})$	CDF [75]	−0.083(13)(4)	
			LHCb [13]	−0.084(4)(3)	
			LHCb [14]	−0.0824(33)(33)	
	Belle-II [15]	18.0(9)(9)	Belle-II [15]	−0.16(5)(1)	
$B^+ \to \pi^0 K^+$	BaBar [7]	13.6(6)(7)	BaBar [7]	0.030(39)(10)	
	Belle [11]	12.62(31)(56)	Belle [11]	0.043(24)(2)	
	CLEO [74]	$12.9(^{24}_{22})(^{12}_{11})$	LHCb [18]	0.025(15)(6)	
	Belle-II [16]	$11.9(^{11}_{10})(^{16}_{11})$	Belle-II [16]	−0.09(9)(3)	
$B^+ \to \pi^+ K^0$	BaBar [6]	23.9(11)(10)	BaBar [6]	−0.029(39)(10)	
	Belle [11]	23.97(53)(71)	Belle [11]	−0.011(21)(6)	
	CLEO [74]	$18.8(^{37}_{33})(^{21}_{18})$	LHCb [12]	−0.022(25)(10)	
	Belle-II [15]	$21.4(^{23}_{22})(16)$	Belle-II [15]	−0.01(8)(5)	
$B^0 \to \pi^0 K^0$	BaBar [9]	10.1(6)(4)	BaBar [8, 76]	−0.13(13)(3)	0.55(20)(3) [8, 76]
	Belle [10]	8.7(5)(6)	Belle [10, 76]	0.14(13)(6)	0.67(31)(8) [10, 76]
	Belle [11]	9.68(46)(50)			
	CLEO [74]	$12.8(^{40}_{33})(^{17}_{14})$			
	Belle-II [17]	$8.5(^{17}_{16})(12)$	Belle-II [17]	$-0.40(^{46}_{44})(4)$	

University of Calcutta

- Free parameters:
  - — P_{tc}, $|T|$, $|C|$, $|A|$, $|P_{uc}|$
  - — Relative phases w.r.t. P_{tc} : δ_T, δ_C, δ_A, $\delta_{P_{uc}}$
  - — κ as a normal prior or a free parameter

10 free parameters

- CKM elements, and β, γ taken as theoretical inputs from HFLAV, with their uncertainties

♠ $|A|$ and $|P_{uc}|$ are suppressed, so should not have much effect on the fits. Same for their associated phases δ_A and $\delta_{P_{uc}}$

University of Calcutta

Different fits (all δs $\in \{0, 2\pi\}$) :

1. Naive:

$$0 \le \kappa \le 0.03\,, \quad -0.3 \le P_{tc} \le 0\,, \quad 0 \le |T| \le 0.5\,, \quad 0 \le |C| \le 0.1$$

   No acceptable fit, $p < 1\%$. Same for higher-order with 4 extra parameters

$$0 \le |A| \le 0.01\,, \quad 0 \le |P_{uc}| \le 0.01$$

2. SM-like:
   Order-2, with P_{tc}, $|T|$, $|C|$, δ_T, δ_C, and $|C| < |T|/2$.
   (i) κ taken as a normal prior 0.014 ± 0.006
   (ii) κ as a free parameter

Different fits (all δs $\in \{0, 2\pi\}$) :

1. Naive:

$$0 \le \kappa \le 0.03\,, \quad -0.3 \le P_{tc} \le 0\,, \quad 0 \le |T| \le 0.5\,, \quad 0 \le |C| \le 0.1$$

   No acceptable fit, $p < 1\%$. Same for higher-order with 4 extra parameters

$$0 \le |A| \le 0.01\,, \quad 0 \le |P_{uc}| \le 0.01$$

2. SM-like:
   Order-2, with P_{tc}, $|T|$, $|C|$, δ_T, δ_C, and $|C| < |T|/2$.
   (i) κ taken as a normal prior 0.014 ± 0.006
   (ii) κ as a free parameter

3. BSM:

$$-0.3 \le P_{tc} \le 0\,, \quad 0 \le |T|, |C| \le 1$$

   κ free, maybe two κs

University of Calcutta

Different fits (all δs $\in \{0, 2\pi\}$) :

1. Naive:

$$0 \le \kappa \le 0.03\,, \quad -0.3 \le P_{tc} \le 0\,, \quad 0 \le |T| \le 0.5\,, \quad 0 \le |C| \le 0.1$$

   No acceptable fit, $p < 1\%$. Same for higher-order with 4 extra parameters

$$0 \le |A| \le 0.01\,, \quad 0 \le |P_{uc}| \le 0.01$$

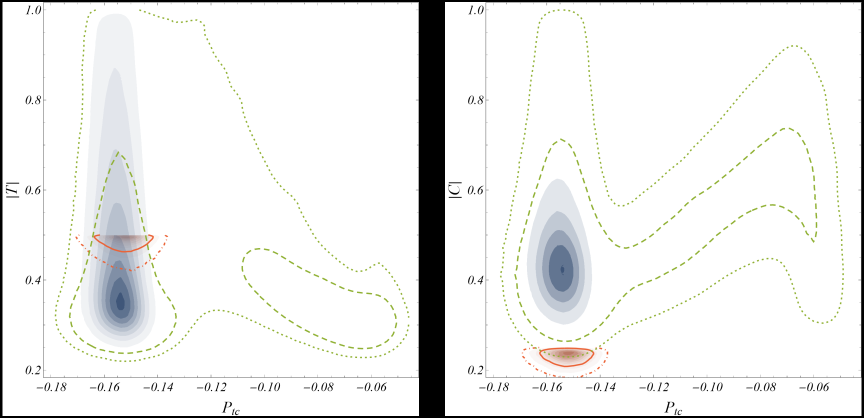
2. SM-like:
   Order-2, with P_{tc}, $|T|$, $|C|$, δ_T, δ_C, and $|C| < |T|/2$.
   (i) κ taken as a normal prior 0.014 ± 0.006
   (ii) κ as a free parameter
3. BSM:

$$-0.3 \le P_{tc} \le 0\,, \quad 0 \le |T|, |C| \le 1$$

   κ free, maybe two κs

UNIVERSITY OF CALCUTTA

More on the “SM-like” region:

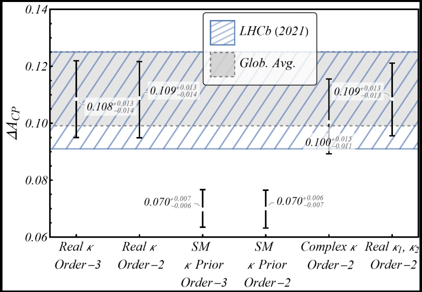


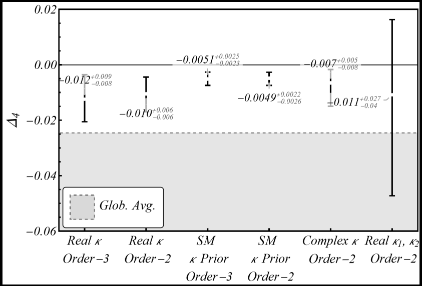
There is an acceptable SM-like fit

Parameters	Priors	Real κ				Complex κ
		SM (κ Prior)		κ Free		
		Order-2	Order-3	Order-2	Order-3	Order-2
κ	0.014(6)	$0.0210(^{44}_{43})$	$0.0210(^{44}_{43})$	$0.028(^{41}_{14})$	$0.029(^{47}_{14})$	$0.048(^{80}_{28})$
$P_{\rm tc}$	-	$-0.1524(^{62}_{65})$	$-0.1524(^{61}_{66})$	$-0.1551(^{66}_{69})$	$-0.1548(^{72}_{70})$	$-0.1534(^{78}_{74})$
$\lvert T \rvert$	-	$0.486(^{11}_{22})$	$0.486(^{11}_{22})$	$0.49(^{28}_{15})$	$0.49(^{29}_{16})$	$0.68(^{22}_{24})$
$\lvert C \rvert$	-	$0.23(^{11}_{18})$	$0.23(^{12}_{18})$	$0.454(^{150}_{83})$	$0.471(^{166}_{94})$	$0.58(^{22}_{16})$
δ_κ	-	-	-	-	-	$0.70(^{71}_{50})$
$\lvert A \rvert$	-	-	$0.0051(^{34}_{35})$	-	$0.047(^{35}_{32})$	-
$\lvert P_{\rm uc} \rvert$	-	-	0.0050(34)	-	$0.049(^{35}_{33})$	-

But more best-fit regions for BSM.

So, SM or BSM?





Δ_4 is not yet that precise

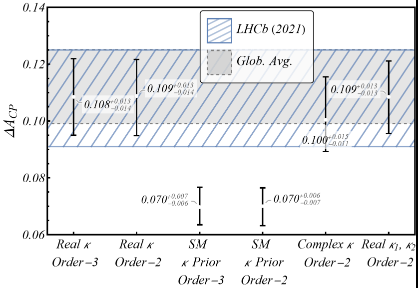
SM-like fits have tension with $\Delta A_{\rm CP}$ but at about 3σ

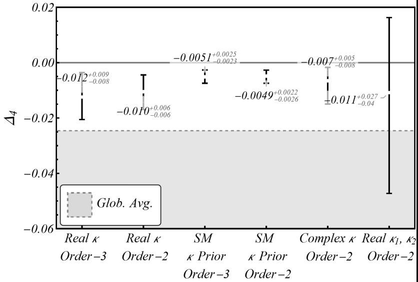
Large κ means something's wrong with EWP $\implies$ BSM?

Thank you !

University of Calcutta

So, SM or BSM?





Δ_4 is not yet that precise
SM-like fits have tension with $\Delta A_{\rm CP}$ but at about 3σ
Large κ means something's wrong with EWP $\implies$ BSM?

Thank you !

University of Calcutta