Solution Solution Solution



Jason Aebischer, Valeriia Lukashenko, Ben Kilminster, <u>Anson Kwok</u>, Zach Polonshy 15/01/25 hkust ias program fp2025



Once upon a time.....

Cosmological measurement shows: (n_{baryon}-n_{anti-baryon})/n_{photon} ~ 10-9 [Matter >> Anti-matter]

Sakharov Condition (within Baryogenesis):

- Baryon number violation
- Interactions out of thermal equilibrium
- <u>C, CP violation</u>

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5)$$

We have CPV in SM! But not enough [Mostly CPV in non-leptonic decay]







Just an example, there are more diagrams

It is FCNC!!! Loop suppressed: BR~8x10⁻⁷ (BR measurement done by LHCb in 2021 [arXiv:2105.14007]) [Leptonic CPV is not yet fully explored]





BSM could introduce CPV in FCNC operators: time-dependent measurements are sensitive to $Im[C_{7,9,10}]$



Just an example, there are more diagrams



Why FCC-ee

FCC-ee at Z-pole

<i>b</i> -hadron	Belle II	LHCb	FCC-ee
$B^0, ar{B}^0$	$5.3 imes 10^{10}$	6×10^{13}	$7.2 imes 10^{11}$
B^{\pm}	$5.6 imes10^{10}$	$6 imes 10^{13}$	$7.2 imes 10^{11}$
$B^0_s, ar{B}^0_s$	$5.7 imes 10^8$	$2 imes 10^{13}$	1.9×10^{11}
B_c^{\pm}		4×10^{11}	1.1×10^9
$\Lambda_b^0,ar{\Lambda}_b^0$		$2 imes 10^{13}$	1.5×10^{11}

In general (you all know better than I do):

Clean

. . .

- Good Flavor Tagging (vs LHCb)
- - Good Vertexing (vs Belle II)

(vs LHCb) Large Stat. (vs Belle II)

Cartoon Diagram of Signal.....



We use Pythia + Delphes (IDEA) for simulating signal & backgrounds

Some Physics of Signal.....

Vertex Fit





Some Physics of Signal....



Resonances

Kinematics





Some Physics of Signal....





Inv. Mass (Dikaon + Dimuon)



Cut Flow.



Cut Flow.

Channel	$B_s^0 \to \phi \mu^+ \mu^-$	$Z \to b \overline{b}$	$Z \to c \bar{c}$
Events at FCC-ee	7.82×10^{4}	9.07×10^{11}	7.22×10^{11}
$N_{ m FS}$	$7.30 imes 10^4$	4.34×10^9	2.82×10^8
N_{χ^2}	$7.19 imes 10^4$	2.15×10^8	$7.25 imes 10^7$
$N_{ \vec{p} }$	4.61×10^4	$5.98 imes 10^7$	$2.25 imes 10^6$
$N_{m_{\phi}}$	4.59×10^4	3.21×10^7	$3.64 imes 10^5$
N_{q^2}	$3.97 imes 10^4$	1.24×10^7	$3.13 imes 10^5$
$N_{m_{B_{e}^{0}}}$	3.93×10^{4}	1.39×10^{3}	2.13×10^{2}

Precision: ~0.5% (vs LHCb: ~2.6%)



Fact Sheet: "Tagging"

Tell they're from B or anti-B

Tag eff.: How often we can tell something Tag Rate: How often we get it right

Uncert. ~ 1/sqrt{Tag Power}

	LEP	Belle II	BaBar	LHCb
P_{tag}	25-30%	30%	30%	6%

Fact Sheet: "Timing"

agg

Time resolution effect: dilution factor (~0.995)

Bs

Function of: PV, SV, Boost [Dominated by SV resolution]





Untagged

Tagged



10





Conclusion (Analysis Part):

Now (we think) we know what we can measure.....

Here's

Theory

$$\begin{split} & \sum_{AL,i} \left\{ \begin{array}{c} s_{1s} = \frac{2 + \beta_{\mu}^{2}}{2} \Im \left(\tilde{A}_{\perp}^{L} A_{\perp}^{L*} + \tilde{A}_{\parallel}^{L} A_{\parallel}^{L*} + \tilde{A}_{\perp}^{R} A_{\perp}^{R*} + \tilde{A}_{\parallel}^{R} A_{\parallel}^{R*} \right) \\ & b_{k} = \left(-0.34(28) - 0.565(76) - 0.676(80) - 0.002(19) - 0.861(74) - 0 \right) , \\ & J_{k} \\$$

Model-independent Way (EFT).....

$$\mathcal{H}^{\text{eff}} \supset -\frac{4G_F V_{tb} V_{ts}^*}{\sqrt{2}} \left(\sum_{i=1}^8 \left(\mathcal{C}_i \mathcal{O}_i + \mathcal{C}'_i \mathcal{O}_i' \right) + \sum_{i=9}^{10} \left(\mathcal{C}_i \mathcal{O}_i^{\mu} + \mathcal{C}'_i \mathcal{O}_i^{\mu'} \right) \right) + \text{h.c.}$$

Want to see how Wilson Coefficients (C_i) deviate from SM value





Connecting EXP-TH (An Example).....

$$C_{\phi\mu\mu} = \frac{\int dq^2 \sum_i \kappa_i \left(J_i(q^2) - \tilde{J}_i(q^2) \right)}{\Gamma + \bar{\Gamma}}, \quad S_{\phi\mu\mu} = -\frac{\int dq^2 \sum_i \kappa_i s_i}{\Gamma + \bar{\Gamma}},$$
$$D_{\phi\mu\mu} = -\frac{\int dq^2 \sum_i \kappa_i h_i}{\Gamma + \bar{\Gamma}},$$

Link observables to J's, h's, s's

$$\begin{split} J_{1s} &= \frac{(2+\beta_{\mu}^{2})}{4} \left(|A_{\perp}^{L}|^{2} + |A_{\parallel}^{R}|^{2} + |A_{\parallel}^{R}|^{2} + |A_{\parallel}^{R}|^{2} \right) + \frac{4m_{\mu}^{2}}{q^{2}} \Re \left(A_{\perp}^{L} A_{\perp}^{R*} + A_{\parallel}^{L} A_{\parallel}^{R*} \right) ,\\ J_{1c} &= |A_{0}^{L}|^{2} + |A_{0}^{R}|^{2} + \frac{4m_{\mu}^{2}}{q^{2}} \left[|A_{t}|^{2} + 2\Re \left(A_{0}^{L} A_{0}^{R*} \right) \right] ,\\ J_{2s} &= \frac{\beta_{\mu}^{2}}{4} \left(|A_{\perp}^{L}|^{2} + |A_{\parallel}^{R}|^{2} + |A_{\perp}^{R}|^{2} + |A_{\parallel}^{R}|^{2} \right) ,\\ J_{2c} &= -\beta_{\mu}^{2} \left(|A_{0}^{L}|^{2} + |A_{0}^{R}|^{2} \right) ,\\ h_{1s} &= \frac{2 + \beta_{\mu}^{2}}{2} \Re \left(\widetilde{A}_{\perp}^{L} A_{\perp}^{L*} + \widetilde{A}_{\parallel}^{L} A_{\parallel}^{L*} + \widetilde{A}_{\perp}^{R} A_{\perp}^{R*} + \widetilde{A}_{\parallel}^{R} A_{\parallel}^{R*} \right) \\ &+ \frac{4m_{\mu}^{2}}{q^{2}} \Re \left(\widetilde{A}_{\perp}^{L} A_{\perp}^{R*} + \widetilde{A}_{\parallel}^{L} A_{\parallel}^{R*} + A_{\perp}^{L} \widetilde{A}_{\perp}^{R*} + A_{\parallel}^{L} \widetilde{A}_{\parallel}^{R*} \right) \\ h_{1c} &= 2\Re \left(\widetilde{A}_{0}^{L} A_{0}^{L*} + \widetilde{A}_{0}^{R} A_{0}^{R*} \right) + \frac{8m_{\mu}^{2}}{q^{2}} \Re \left(\widetilde{A}_{t} A_{t}^{*} + \widetilde{A}_{0}^{L} A_{0}^{R*} + A_{0}^{L} \widetilde{A}_{0}^{R*} \right) \\ h_{2s} &= \frac{\beta_{\mu}^{2}}{2} \Re \left(\widetilde{A}_{\perp}^{L} A_{\perp}^{L*} + \widetilde{A}_{\parallel}^{L} A_{\parallel}^{L*} + \widetilde{A}_{\perp}^{R} A_{\perp}^{R*} + \widetilde{A}_{\parallel}^{R} A_{\parallel}^{R*} \right) \\ h_{2c} &= -2\beta_{\mu}^{2} \Re \left(\widetilde{A}_{0}^{L} A_{0}^{L*} + \widetilde{A}_{0}^{R} A_{0}^{R*} \right) \end{split}$$

Observable as function of C's

$$\begin{split} A_{\perp}^{L,R} &= N\sqrt{2\lambda} \left\{ \begin{pmatrix} C_9 \mp C_{10} \end{pmatrix} \frac{V(q^2)}{m_{B_s^0} + m_{\phi}} + \frac{2m_b}{q^2} C_7 T_1(q^2) \right\} \ , \\ A_{\parallel}^{L,R} &= -N\sqrt{2} \left(m_{B_s^0}^2 - m_{\phi}^2 \right) \left\{ \begin{pmatrix} C_9 \mp C_{10} \end{pmatrix} \frac{A_1(q^2)}{m_{B_s^0} - m_{\phi}} + \frac{2m_b}{q^2} C_7 T_2(q^2) \right\} \ , \\ A_{0}^{L,R} &= -\frac{N}{2m_{\phi}\sqrt{q^2}} \left\{ 2m_b C_7 \cdot \left[\left(m_{B_s^0}^2 + 3m_{\phi}^2 - q^2 \right) T_2(q^2) - \frac{\lambda T_3(q^2)}{m_{B_s^0}^2 - m_{\phi}^2} \right] \right. \\ &+ \left. \begin{pmatrix} C_9 \mp C_{10} \end{pmatrix} \cdot \left[\left(m_{B_s^0}^2 - m_{\phi}^2 - q^2 \right) \left(m_{B_s^0} + m_{\phi} \right) A_1(q^2) - \frac{\lambda A_2(q^2)}{m_{B_s^0} + m_{\phi}} \right] \right\} \\ A_t &= 2N \frac{\sqrt{\lambda}}{\sqrt{q^2}} C_{10} A_0(q^2) \ , \end{split}$$

J's, h's, s's functions of Amplitudes

Our projection is pushing theory limit

Time-Dependent Precision Measurement of $B_s^0 \rightarrow \phi \mu^+ \mu^-$ Decay at FCC-*ee*

Should also apply to SM prediction

Long-distance Effects.....

$$C_7^{\text{eff}} = C_7 - \frac{1}{3}C_3 - \frac{4}{9}C_4 - \frac{20}{3}C_5 - \frac{80}{9}C_6, \quad C_9^{\text{eff}} = C_9 + \frac{Y(q^2)}{Y(q^2)},$$

$$\begin{split} Y(q^2) = & \frac{4}{3}C_3 + \frac{64}{9} + \frac{64}{27}C_6 - \frac{1}{2}h(q^2,0)\left(C_3 + \frac{4}{3}C_4 + 16C_5 + \frac{64}{3}C_6\right) \\ & + h(q^2,m_c)\left(\frac{4}{3}C_1 + C_2 + 6C_3 + 60C_5\right) \\ & - \frac{1}{2}h(q^2,m_b)\left(7C_3 + \frac{4}{3}C_4 + 76C_5 + \frac{64}{3}C_6\right), \\ & h\left(q^2,\frac{q^2x}{4}\right) = -\frac{4}{9}\left(\log\left(\frac{m^2}{\mu^2}\right) - \frac{2}{3} - x\right) \\ & - \frac{4}{9}\left(2+x\right) \times \begin{cases} \sqrt{x-1}\arctan\frac{1}{\sqrt{x-1}} & , x > 1 \\ \sqrt{1-x}\left(\log\frac{1+\sqrt{1-x}}{\sqrt{x}} - \frac{i\pi}{2}\right) & , x \le 1 \end{cases}. \end{split}$$



16

Money Plot (In Construction).....

Complementary: Re and Im parts



Can learn NP up to O(10 TeV) [Stat. only]



With Th. Uncert.: Th. Uncert. » Exp. Uncert.



Money Plot (In Construction).....

0,0,00,0000

 $\Im(\delta C_{10})$

0.0

J(SC.

 $\Re(\delta C_{10})$

-0.2

0.8

Complementary: Re and Im parts Can learn NP up to O(10 TeV) [Stat. only] $\langle B_{\phi\mu\mu} \rangle (c_i = 1)$ (Bduu) (MFV) $\Re(\delta C_7)$ $\tilde{S}_{\phi \mu \mu}$ (c_i = 1) $\tilde{S}_{\phi \mu \mu}$ (c_i = 0.01) \Box $\tilde{S}_{\phi \mu \mu}$ (MFV) $(B_{\phi\mu\mu})^{q^2 \in [1.1, 6.0]}$ Not only we can tell there is NP 3(8C7) R(6C9) We can also tell what kind δC_{10} ncert 3(6C9) (If we see deviation) $\Re(\delta C_{10})$ 20 05 00 05 20 05 00 05 20 05 00 05 20 exp. + th. (Profiled) $\Re(\delta C_7)$ $\Re(\delta C_{10})$ $\Im(\delta C_{10})$ 0.2

2InL

20 20 05

 $\Im(\delta C_7)$

20 20

 $\Im(\delta C_{10})$

Conclusion		
Big Question	Why matter >> antimatter?	
Exact Problem	Do we have CPV from NP	
	(in leptonic rare, FCNC, decay)?	
Vhere do we test it	FCC- <i>ee</i> : Ideal to test rare process!	
	[Clean, Good Vertexing,]	
low to Interpret it	EFT: Tell how (NP) complex phase	
	affects experimental measurements	
What can we learn	Can probe NP up to O(10 TeV)	
	[If th. uncert. suppressed to similar	
	order of magnitude]	
	We should push th. calculation	
How to Interpret it What can we learn	[Clean, Good Vertexing,] EFT: Tell how (NP) complex phase affects experimental measurements Can probe NP up to O(10 TeV) [If th. uncert. suppressed to similar order of magnitude] We should push th. calculation	

Conclusion

Big QuestionWhy matter >> antimatter?Exact ProblemDo we have CPV from NP

There is only one way to find out if it oscillates! MEASURE IT!

[If th. uncert. suppressed to similar order of magnitude] We should push th. calculation

Crew

Theoretical Part Jason Aebischer Experimental Part (Boss) Ben Kilminster Experimental Part Anson Kwok Experimental Part Valeriia Lukashenko Theoretical Part Zach Polonsky

Special Thank Useful Discussions and Feedbacks Franco Grancagnolo Armin Ilg Gino Isidori Lingfeng Li Margherita Primavera We are not supported by these companies





THIS PICTURE MADE UNDER THE JURISDICTION OF



AFFILIATED WITH A.F.L.-C.I.O.-C.L.C.



In Selected Theatres

COLOR BY

But supported by

But supported by



Universität Zürich^{uzH}





What background types do we have?

Z>bb Cascade

- ККµµ don't form a vertex - m(ККµµ) != m(B_s)

Z>bb Comb.

- m(KK) != m(φ)

Signal

Why doing a fit in $m(B_s)$? Leak of simulation samples

Why D_f, C_f measurement is not included?

Not so sensitive compared to S_f

Extra argument vs LHCb: They can measure D_f but not much physics can be told from D_f along.

Binned measurements