Polarisation Fraction in $B \to V_1 V_2$: U-spin constraints and New Physics signatures

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Nonleptonic Decays of Heavy Meson, IPPP Durham
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This talk

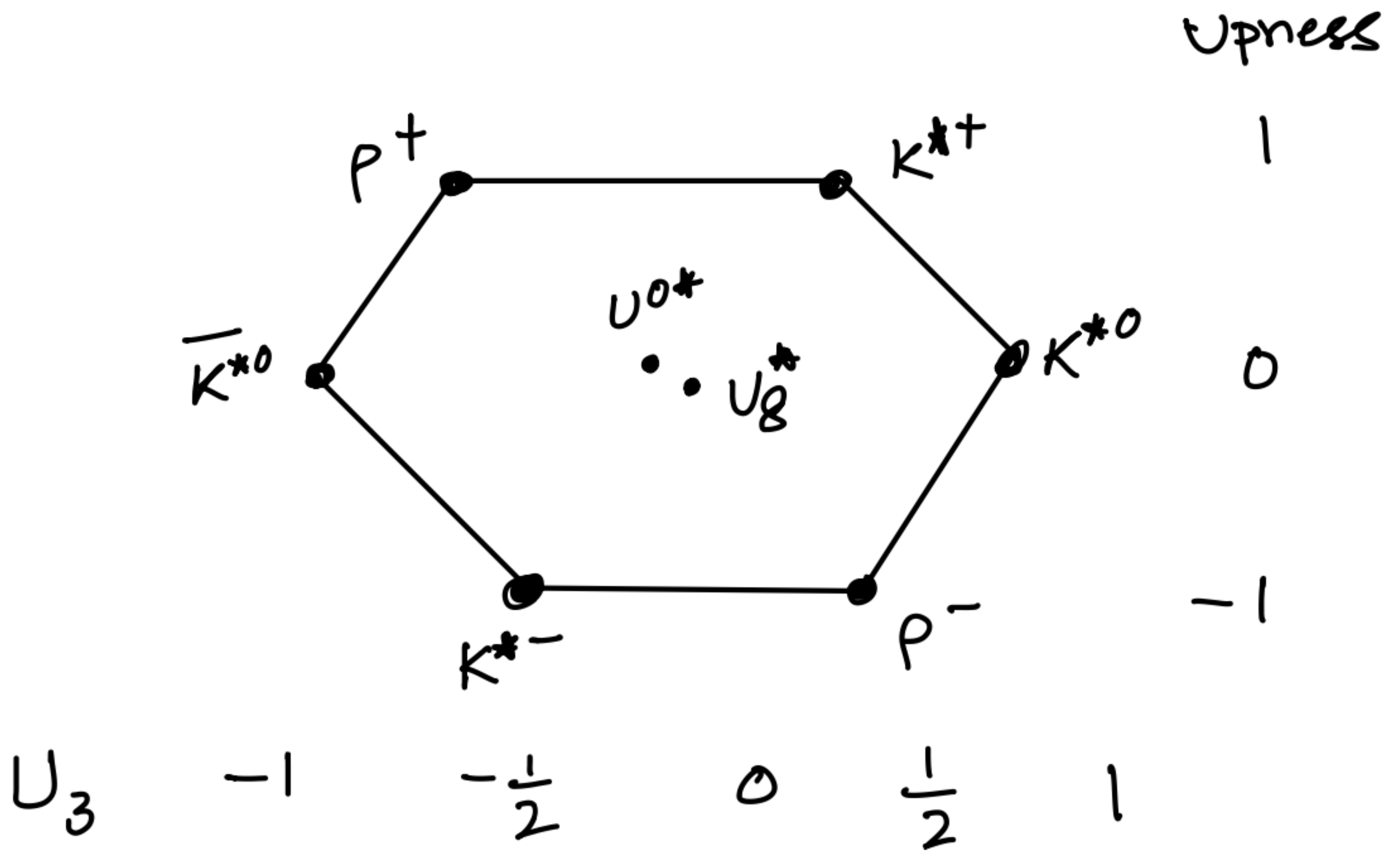
- Charmless B decays to two vector mesons
- Related by U-spin Symmetry
- The SM Fit results $\Longrightarrow$ Large symmetry breaking than SM $\Longrightarrow$ Reasons
- Open questions: How could one explain these?
- Possibility of New Physics
- Experimentally missing quantities

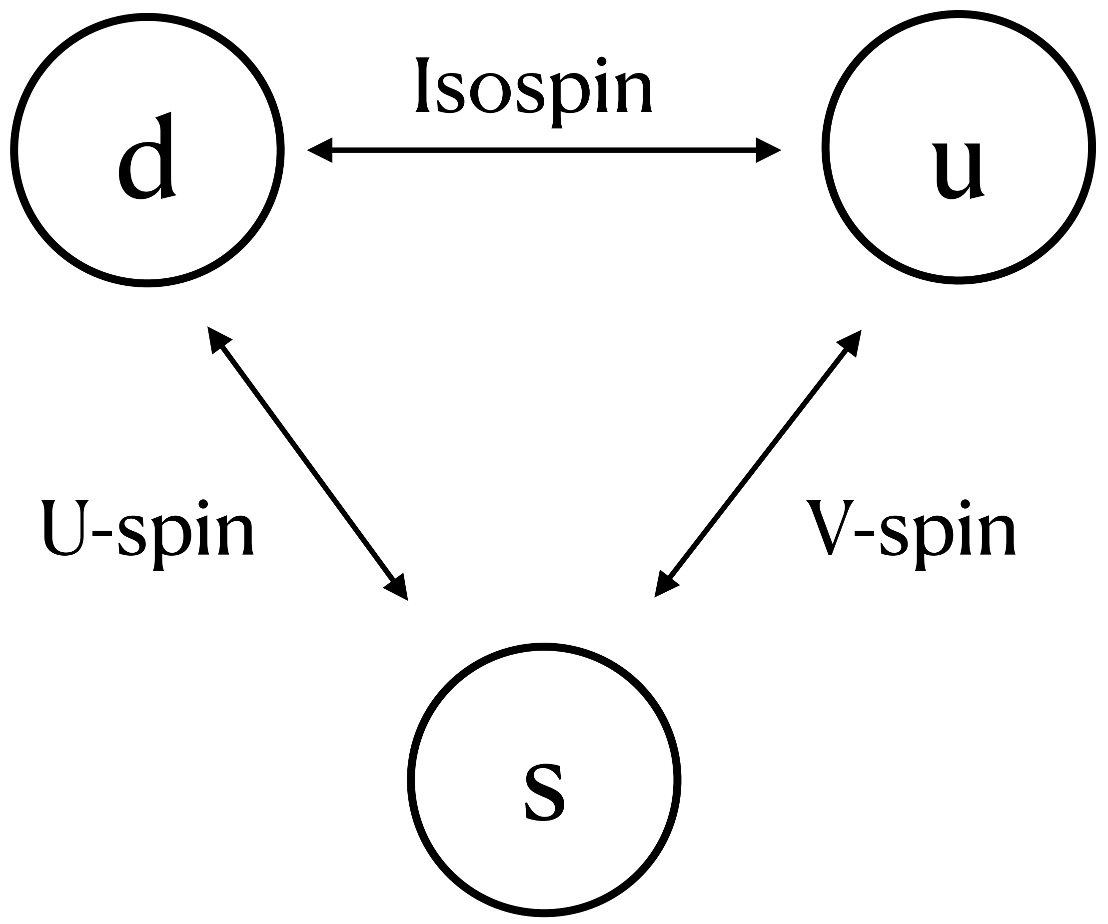
U-spin

Starting point: full flavour group $SU(3)_F$ has three $SU(2)$ subgroups $\Longrightarrow$ Isospin, U-spin and V-spin.

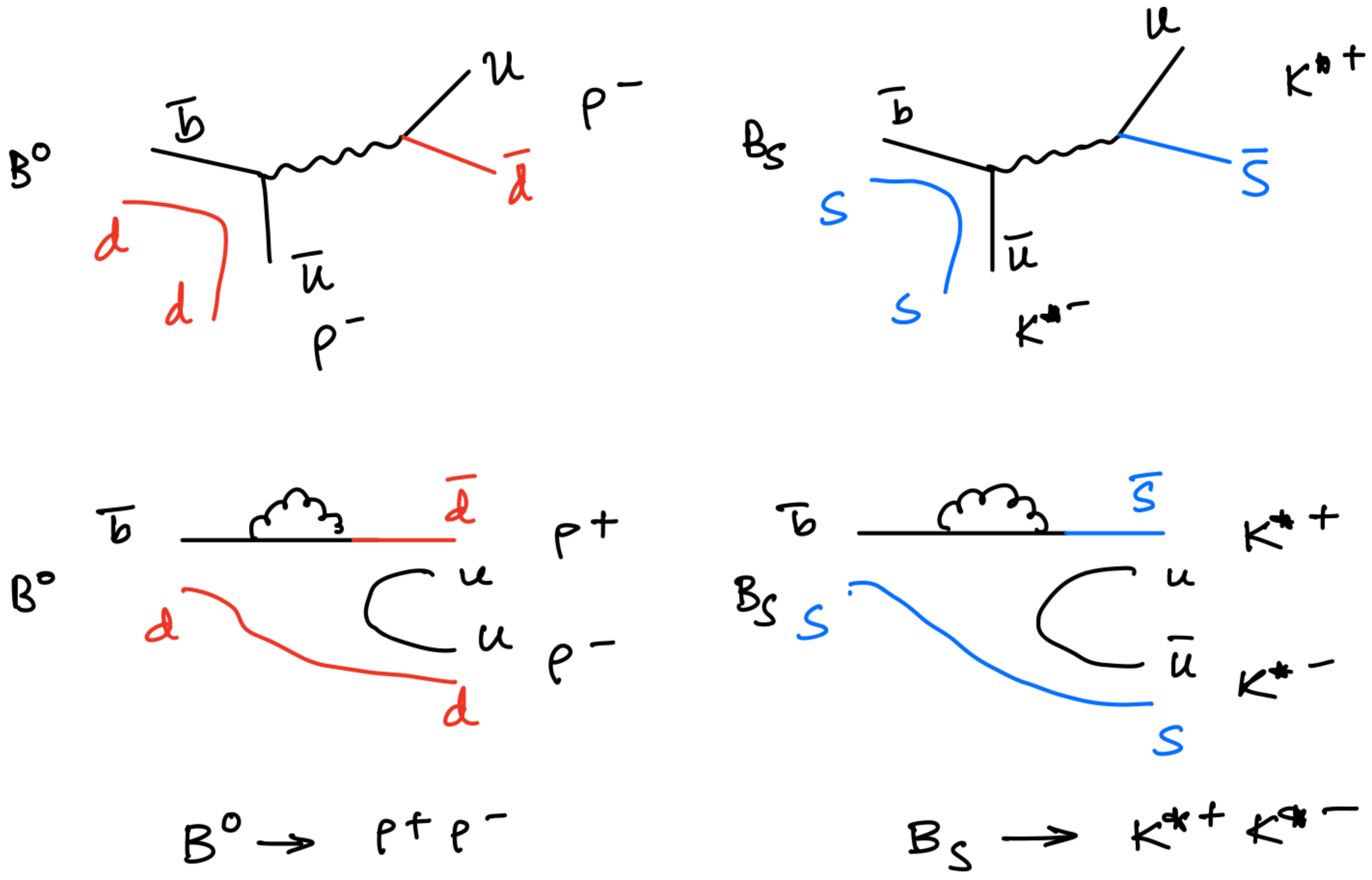
- With $SU(2)_{Uspin}$.

$$\text{Doublet} \begin{pmatrix} d \\ s \end{pmatrix} \quad \text{conjugate} \begin{pmatrix} \bar{s} \\ -\bar{d} \end{pmatrix}$$





U-spin ($d \leftrightarrow s$)



Polarisation Puzzle in $B \to VV$

$\Delta S = 0$	$\Delta S = 1$
$B^+ \to \overline{K^{*0}} K^{*+}$ $\mathscr{B}_{CP} = (0.91 \pm 0.29) \times 10^{-6}$ $f_L = 0.82^{+0.15}_{-0.21}$	$B^+ \to K^{*0} \rho^+$ $\mathscr{B}_{\mathscr{CP}} = (9.2 \pm 1.5) \times 10^{-6}$ $A_{CP} = -0.01 \pm 0.16$ $f_L = 0.48 \pm 0.08$
$B_d \to K^{*0} \overline{K^{*0}}$ $\mathscr{B}_{CP} = (0.83 \pm 0.24) \times 10^{-6}$ $f_L = 0.74 \pm 0.05$	$B_s \to K^{*0} \overline{K^{*0}}$ $\mathscr{B}_{CP} = (11.1 \pm 2.7) \times 10^{-6}$ $f_L = 0.24 \pm 0.04$ $f_\perp = 0.38 \pm 0.12$
$B_d \to \rho^+ \rho^-$ $\mathscr{B}_{CP} = (27.7 \pm 1.9) \times 10^{-6}$ $A_{CP} = 0.00 \pm 0.09$ $S_{CP} = -0.14 \pm 0.13$ $f_L = 0.990^{+0.021}_{-0.019}$	$B_s \to K^{*-} K^{*+}$ (not yet observed)
$B_s \to K^{*-} \rho^+$ (not yet observed)	$B_d \to K^{*+} \rho^-$ $\mathscr{B}_{CP} = (10.3 \pm 2.6) \times 10^{-6}$ $A_{CP} = 0.21 \pm 0.15$ $f_L = 0.38 \pm 0.13$

Facts about Longitudinal Polarisation Fraction

$$f_L(\Delta S = 1) \lesssim 0.50$$

$$f_L(B_d \to K^{*0}\overline{K^{*0}}) = 0.74 \pm 0.05$$

$$f_L(B_s \to K^{*0}\overline{K^{*0}}) = 0.24 \pm 0.04$$

$$\left[\frac{f_L(B_d \to K^{*0}\overline{K^{*0}})}{f_L(B_s \to K^{*0}\overline{K^{*0}})}\right]_{\text{QCDF}} = 1.09^{+0.19}_{-0.08}$$

$$\left[\frac{f_L(B_d \to K^{*0}\overline{K^{*0}})}{f_L(B_s \to K^{*0}\overline{K^{*0}})}\right]_{\text{Exp}} = 3.08 \pm 0.55$$

$\Longrightarrow$ Tension at the level of $\sim 3.5\sigma$

$\Longrightarrow$ Polarisation puzzle in $B_{s,d} \to K^{*0}\overline{K^{*0}}$

U-spin amplitudes

- Initial state is a doublet $[(B^0, B_s^0)]$ or a singlet $[B^+]$

Amplitude = $\langle V_1 V_2 | H_W | B \rangle$

- Here $V_1, V_2 \in \{\rho, K^*\}$. U^{0*} and U_8^* are not useful (not physical particles)
- Quark level decay $b \to qu\bar{u}$ and $b \to q$ ($q = d$ or s) $\Longrightarrow H_W$ has $U = 1/2$ for both $q = d$ and $q = s$
- Using Wigner-Eckart theorem, Helicity amplitudes for $\Delta S = 0$ decays :

$$
\begin{aligned}
A_h(B^+ \to K^{*+}\overline{K^{*0}}) &= -\sqrt{\frac{2}{3}}\left[\lambda_{bd}^u \mathscr{A}_{\frac{1}{2}d}^{u,h} + \lambda_{bd}^c \mathscr{A}_{\frac{1}{2}d}^{c,h}\right] \\
A_h(B_d \to K^{*0}\overline{K^{*0}}) &= -\frac{1}{\sqrt{6}}\left[\lambda_{bd}^u \mathscr{A}_{0d}^{u,h} + \lambda_{bd}^c \mathscr{A}_{0d}^{c,h}\right] - \frac{1}{2}\left[\lambda_{bd}^u \mathscr{A}_{1d}^{u,h} + \lambda_{bd}^c \mathscr{A}_{1d}^{c,h}\right] \\
A_h(B_d \to \rho^+\rho^-) &= \frac{1}{2}\left[\lambda_{bd}^u \mathscr{A}_{0d}^{u,h} + \lambda_{bd}^c \mathscr{A}_{0d}^{c,h}\right] - \frac{1}{2}\left[\lambda_{bd}^u \mathscr{A}_{1d}^{u,h} + \lambda_{bd}^c \mathscr{A}_{1d}^{c,h}\right] \\
A_h(B_s \to \rho^+ K^{*-}) &= \lambda_{bd}^u \mathscr{A}_{1d}^{u,h} + \lambda_{bd}^c \mathscr{A}_{1d}^{c,h}.
\end{aligned}
$$

The amplitudes for $\Delta S = 1$ decays can be obtained replacing d by s .

U-spin RMEs are:

$$
\mathscr{A}_{\frac{1}{2}D}^{p,h} = \left\langle \tfrac{1}{2}; h \middle\| [\mathscr{O}_D^p]^{\frac{1}{2}} \middle\| 0 \right\rangle, \quad \mathscr{A}_{0D}^{p,h} = \left\langle 0; h \middle\| [\mathscr{O}_D^p]^{\frac{1}{2}} \middle\| \tfrac{1}{2} \right\rangle, \quad \mathscr{A}_{1q}^{p,h} = \left\langle 1; h \middle\| [\mathscr{O}_D^p]^{\frac{1}{2}} \middle\| \tfrac{1}{2} \right\rangle,
$$

$h = 0, +, -$

$p = u, c$

SM Analysis

- Do a fit the experimental data $\Longrightarrow$ To examine how well the hypothesis of U-spin symmetry holds up.
- Heavy quark symmetry implies the following hierarchy

$$A_0 : A_- : A_+ \sim 1 : \frac{\Lambda_{\rm QCD}}{m_b} : \left(\frac{\Lambda_{\rm QCD}}{m_b}\right)^2 .$$

- Using naive factorisation we find $\Longrightarrow$ $A_0 : A_- : A_+ \simeq 1 : 0.27 : 0.01$ (We can safely ignore A_+) $\Longrightarrow \frac{A_-}{A_0} \simeq 0.3$
- In the exact U-spin limit, RMEs are equal to each other

$$\mathscr{A}^{p,h}_{\frac{1}{2}d} = \mathscr{A}^{p,h}_{\frac{1}{2}s}, \quad \mathscr{A}^{p,h}_{0d} = \mathscr{A}^{p,h}_{0s}, \quad \mathscr{A}^{p,h}_{1d} = \mathscr{A}^{p,h}_{1s}, \qquad \begin{array}{l} p = u, c \\ h = 0, - \end{array}$$

- This leads to a total 12 hadronic parameters. We choose them to be real.
- With a total 17 measured observables, a fit to the data can be performed.

SM Analysis

Just keeping $A_+ = 0$,

We find that the fit is very good.

$\chi^2/\text{dof} = 3.4/5$

parameters ($h=0$)	best fit	parameters ($h=-$)	best fit
$\mathscr{A}^{u,0}_{\frac{1}{2}d}$	-0.23 ± 0.08	$\mathscr{A}^{u,-}_{\frac{1}{2}d}$	-0.08 ± 0.31
$\mathscr{A}^{c,0}_{\frac{1}{2}d}$	0.08 ± 0.01	$\mathscr{A}^{c,-}_{\frac{1}{2}d}$	-0.08 ± 0.01
$\mathscr{A}^{u,0}_{0d}$	1.91 ± 0.09	$\mathscr{A}^{u,-}_{0d}$	-0.32 ± 0.23
$\mathscr{A}^{c,0}_{0d}$	0.17 ± 0.03	$\mathscr{A}^{c,-}_{0d}$	-0.11 ± 0.03
$\mathscr{A}^{u,0}_{1d}$	-2.02 ± 0.07	$\mathscr{A}^{u,-}_{1d}$	0.08 ± 0.19
$\mathscr{A}^{c,0}_{1d}$	-0.03 ± 0.02	$\mathscr{A}^{c,-}_{1d}$	-0.08 ± 0.01

$$\Delta S = 0: \quad \left|\frac{A_-}{A_0}\right|_{B^+\to\overline{K^{*0}}K^{*+}} = 0.50 \pm 0.87\,, \quad \left|\frac{A_-}{A_0}\right|_{B_d\to K^{*0}\overline{K^{*0}}} = 0.62 \pm 0.48\,, \quad \left|\frac{A_-}{A_0}\right|_{B_d\to\rho^+\rho^-} = 0.10 \pm 0.08\,.$$

$$\Delta S = 1: \quad \left|\frac{A_-}{A_0}\right|_{B^+\to K^{*0}\rho^+} = 1.03 \pm 0.19\,, \quad \left|\frac{A_-}{A_0}\right|_{B_d\to K^{*+}\rho^-} = 1.28 \pm 0.40\,, \quad \left|\frac{A_-}{A_0}\right|_{B_s\to K^{*0}\overline{K^{*0}}} = 1.72 \pm 0.54\,.$$

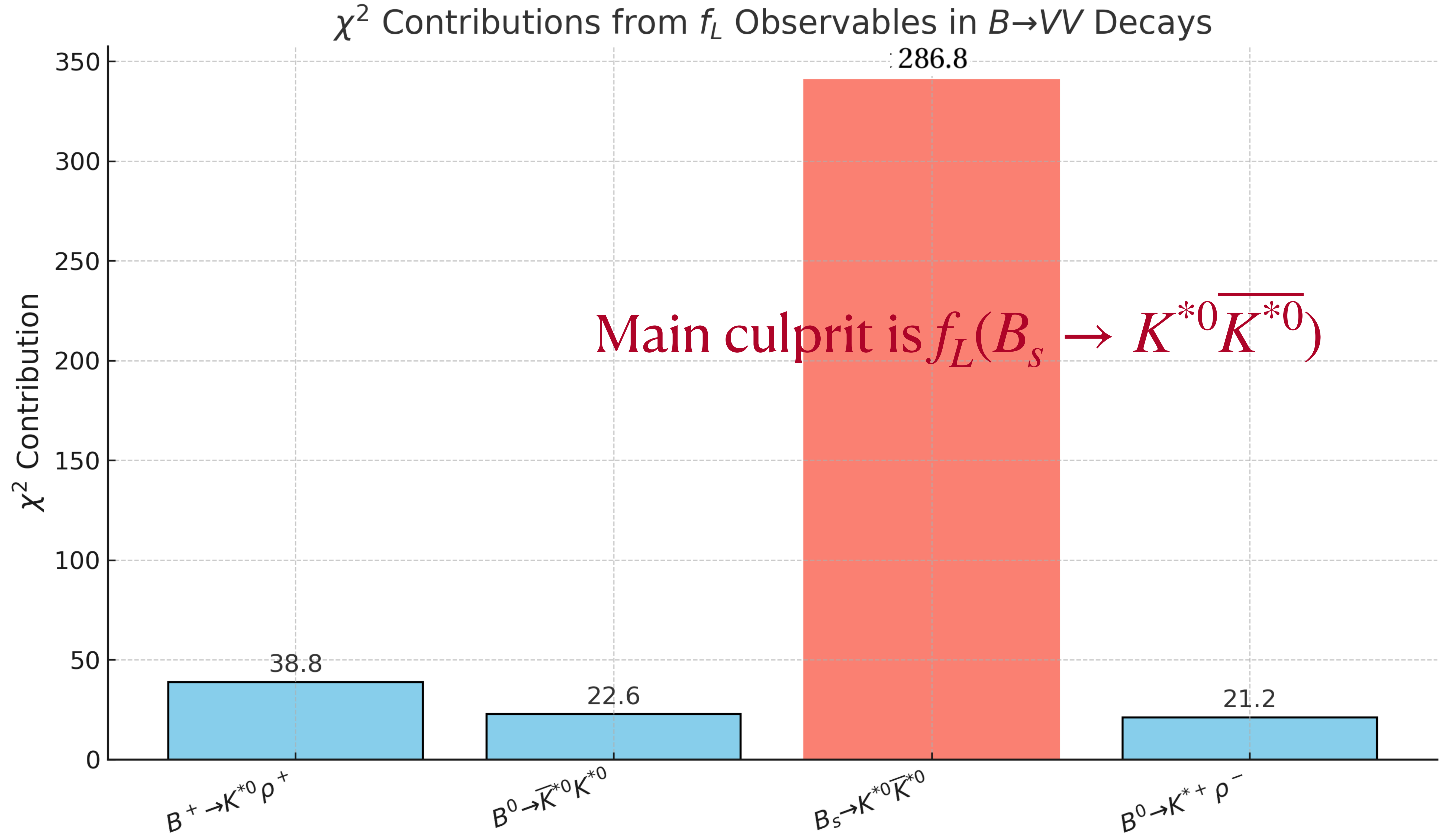
Do not respect the hierarchy!! Breaking Maximally.

Need experimental verification.

SM Analysis

- Now keeping $A_+ = 0$, and set $A_- = 0.3A_0 \Longrightarrow$ 17 measurements and 6 hadronic parameters
- Fit is very poor $\Longrightarrow \chi^2/\mathrm{dof} = 370.5/11$

Parameter	Best fit	Parameter	Best fit	Parameter	Best fit
$\mathscr{A}^u_{\frac{1}{2}d}$	0.19 ± 0.09	$\mathscr{A}^u_{0d}$	-1.89 ± 0.12	$\mathscr{A}^u_{1d}$	1.74 ± 0.10
$\mathscr{A}^c_{\frac{1}{2}d}$	-0.11 ± 0.01	$\mathscr{A}^c_{0d}$	-0.14 ± 0.03	$\mathscr{A}^c_{1d}$	-0.11 ± 0.01



Main culprit is $f_L(B_s \to K^{*0}\overline{K^{*0}})$

U-spin found to be good symmetry if we do not care about the hierarchy and it's badly broken if we rely on the hierarchy.

The SM U-spin breaking is even incapable to reduce the tension.

$$0.7 \leq \frac{\mathscr{A}^{p,h}_{nd}}{\mathscr{A}^{p,h}_{ns}} \leq 1.3 \quad \forall p, h, n,$$

SM Analysis

Keeping $A_+ = 0$, and set $A_- = 0.3A_0$

Parameters ($\Delta S = 0$)	Best fit	Parameter ($\Delta S = 1$)	Best fit
$\mathscr{A}^u_{\frac{1}{2}d}$	0.17 ± 3.50	$\mathscr{A}^u_{\frac{1}{2}s}$	1.70 ± 5.00
$\mathscr{A}^c_{\frac{1}{2}d}$	0.17 ± 0.03	$\mathscr{A}^c_{\frac{1}{2}s}$	0.09 ± 0.07
$\mathscr{A}^u_{0d}$	-1.69 ± 0.72	$\mathscr{A}^u_{0s}$	-5.89 ± 55.84
$\mathscr{A}^c_{0d}$	-0.06 ± 0.93	$\mathscr{A}^c_{0s}$	-0.22 ± 0.32
$\mathscr{A}^u_{1d}$	2.04 ± 0.71	$\mathscr{A}^u_{1s}$	5.20 ± 1.26
$\mathscr{A}^c_{1d}$	0.08 ± 0.93	$\mathscr{A}^c_{1s}$	-0.04 ± 0.25

$\chi^2/\text{dof} = 26.0/2$

$\chi^2/\text{dof} = 343.7/3$

$\chi^2_{f_L}(B_d \to K^{*0}\overline{K^{*0}}) = 22.6$

$\chi^2_{f_L}(B_s \to K^{*0}\overline{K^{*0}}) = 286.8$

BSM Analysis

Assume New Physics in $b \to sq\bar{q}$ transition ($\Delta S = 1$ decays)

$$\begin{aligned}
\text{Vector}: \quad \mathcal{H}_V &= h_v e^{i\zeta_v} \left(\bar{q}_\alpha \gamma_\mu (c_1 + c_2\gamma_5) q_\alpha\right) \left(\bar{s}_\beta \gamma^\mu (c_3 + c_4\gamma_5) b_\beta\right), \\
\text{Scalar}: \quad \mathcal{H}_S &= h_s e^{i\zeta_s} \left(\bar{q}_\alpha (c_1 + c_2\gamma_5) q_\alpha\right) \left(\bar{s}_\beta (c_3 + c_4\gamma_5) b_\beta\right), \\
\text{Tensor}: \quad \mathcal{H}_T &= h_t e^{i\zeta_t} \left(\bar{q}_\alpha \sigma_{\mu\nu} (c_1 + c_2\gamma_5) q_\alpha\right) \left(\bar{s}_\beta \sigma^{\mu\nu} (c_3 + c_4\gamma_5) b_\beta\right).
\end{aligned}$$

Calculate the matrix elements of $B(p) \to V_1(q, \epsilon_1) V_2(k, \epsilon_2)$

$$\mathcal{M} = a\epsilon_1^* . \epsilon_2^* + \frac{b}{m_B^2}(p.\epsilon_1^*)(p.\epsilon_2^*) + i\frac{c}{m_B^2}\varepsilon_{\mu\nu\alpha\beta} p^\mu q^\nu \epsilon_1^\alpha \epsilon_2^\beta,$$

The helicity amplitudes depend on a, b, and c

$$A_\parallel = \sqrt{2}a, \quad A_L = -ax - \frac{m_1 m_2}{m_B^2} b(x^2 - 1), \quad A_\perp = 2\sqrt{2}\frac{m_1 m_2}{m_B^2} c\sqrt{x^2 - 1},$$

Goal: To identify the Lorentz structure of new physics which can reduce the tension

BSM Analysis

U-spin with $\Delta S = 0$ and $\Delta S = 1$ decays

NP type	Lorentz structure	best fit value (h_i)	χ^2/dof
Scalar	$(S-P)\otimes(S-P)$	0.063 ± 0.005	33.8/10
	$(S-P)\otimes(S+P)$	0.211 ± 0.021	70.0/10
	$(S+P)\otimes(S-P)$	0.149 ± 0.011	36.8/10
	$(S+P)\otimes(S+P)$	0.068 ± 0.005	29.7/10
Vector	$(V-A)\otimes(V-A)$	0.093 ± 0.007	41.5/10
	$(V-A)\otimes(V+A)$	0.108 ± 0.008	31.1/10
	$(V+A)\otimes(V-A)$	-0.108 ± 0.008	31.1/10
	$(V+A)\otimes(V+A)$	-0.093 ± 0.007	41.5/10
Tensor	$(T-PT)\otimes(T-PT)$	0.028 ± 0.002	37.6/10
	$(T+PT)\otimes(T+PT)$	0.031 ± 0.002	29.2/10

$\Longrightarrow$

Only $\Delta S = 1$

Three NP Best cases	χ^2/dof
(1) $(V-A)\otimes(V+A)$	2.1/2
(2) $(S+P)\otimes(S+P)$	2.4/2
(3) $(T+PT)\otimes(T+PT)$	2.0/2

f_L

	$(S+P)\otimes(S+P)$	$(V-A)\otimes(V+A)$	$(T+PT)\otimes(T+PT)$
♠ $B_s \to K^{*+}K^{*-}$	0.26 ± 0.09	0.79 ± 0.06	0.32 ± 0.11

The longitudinal polarisation fraction of $B_s \to K^{*+}K^{*-}$ is capable to distinguish these three NP scenarios.

Summary

- There is a tension at the level of $\sim 3.5\sigma$ in the longitudinal polarisation fractions of $B_{s,d} \to K^{*0}\overline{K^{*0}}$ decays which are related by $d \leftrightarrow s$
- In fact the longitudinal polarisation fractions of $\Delta S = 1$ decays are less than 50 % which are much lower than what we expect in the SM.
- The U-spin breaking allowed by the SM can not explain the tension rather it indicates a large U-spin breaking.
- If we disregard the hierarchy between the helicity amplitudes, dictated from naive factorisation and heavy quark limit, the puzzle is resolved.
- Assuming the hierarchy is valid in SM, we find the Lorentz structures of new physics $(V-A)\otimes(V+A)$, $(S+P)\otimes(S+P)$ and $(T+PT)\otimes(T+PT)$ can alleviate the tension in $\Delta S = 1$ decays, particularly in the longitudinal polarisation fraction of $B_s \to K^{*0}\overline{K^{*0}}$.
- There are similar tensions in other hadronic decays (1) $B \to \pi K$ puzzle (2) U-spin puzzle in $B \to PP$ decays (3) $SU(3)_F$ puzzle in $B \to PP$ .....
- If/when the unmeasured decays $B_s \to K^{*-}K^{*+}$ and $B_s \to K^{*-}\rho^{+}$ are measured, this will give us additional information that may help shed light on theses puzzles.

Unmeasured Quantities

$\Delta S = 0$	$\Delta S = 1$
$B^+ \to \overline{K^{*0}} K^{*+}$ $\mathcal{B}_{CP} = (0.91 \pm 0.29) \times 10^{-6}$ $f_L = 0.82^{+0.15}_{-0.21}$	$B^+ \to K^{*0} \rho^+$ $\mathcal{B}_{\mathcal{CP}} = (9.2 \pm 1.5) \times 10^{-6}$ $A_{CP} = -0.01 \pm 0.16$ $f_L = 0.48 \pm 0.08$
$B_d \to K^{*0} \overline{K^{*0}}$ $\mathcal{B}_{CP} = (0.83 \pm 0.24) \times 10^{-6}$ $f_L = 0.74 \pm 0.05$	$B_s \to K^{*0} \overline{K^{*0}}$ $\mathcal{B}_{CP} = (11.1 \pm 2.7) \times 10^{-6}$ $f_L = 0.24 \pm 0.04$ $f_\perp = 0.38 \pm 0.12$
$B_d \to \rho^+ \rho^-$ $\mathcal{B}_{CP} = (27.7 \pm 1.9) \times 10^{-6}$ $A_{CP} = 0.00 \pm 0.09$ $S_{CP} = -0.14 \pm 0.13$ $f_L = 0.990^{+0.021}_{-0.019}$	$B_s \to K^{*-} K^{*+}$ (not yet observed) $\mathcal{B}_{\text{CP}}$ f_L
$B_s \to K^{*-} \rho^+$ (not yet observed) $\mathcal{B}_{\text{CP}}$ f_L	$B_d \to K^{*+} \rho^-$ $\mathcal{B}_{CP} = (10.3 \pm 2.6) \times 10^{-6}$ $A_{CP} = 0.21 \pm 0.15$ $f_L = 0.38 \pm 0.13$

New updated measurements by LHCb 2026

$\Delta S = 0$	$\Delta S = 1$
$B^+ \to \overline{K^{*0}} K^{*+}$ $\mathscr{B}_{CP} = (0.91 \pm 0.29) \times 10^{-6}$ $f_L = 0.82^{+0.15}_{-0.21}$	$B^+ \to K^{*0} \rho^+$ $\mathscr{B}_{CP} = (9.2 \pm 1.5) \times 10^{-6}$ $A_{CP} = -0.01 \pm 0.16$ $f_L = 0.48 \pm 0.08$
$B_d \to K^{*0} \overline{K^{*0}}$ $\mathscr{B}_{CP} = (0.83 \pm 0.24) \times 10^{-6}$ $f_L = 0.600 \pm 0.028$ [17] $f_\perp = 0.24 \pm 0.03$ [17]	$B_s \to K^{*0} \overline{K^{*0}}$ $\mathscr{B}_{CP} = (11.1 \pm 2.7) \times 10^{-6}$ $f_L = 0.159 \pm 0.012$ [17] $f_\perp = 0.500 \pm 0.014$ [17]
$B_d \to \rho^+ \rho^-$ $\mathscr{B}_{CP} = (27.7 \pm 1.9) \times 10^{-6}$ $A_{CP} = 0.00 \pm 0.09$ $S_{CP} = -0.14 \pm 0.13$ $f_L = 0.990^{+0.021}_{-0.019}$	$B_s \to K^{*-} K^{*+}$ (not yet observed)
$B_s \to K^{*-} \rho^+$ (not yet observed)	$B_d \to K^{*+} \rho^-$ $\mathscr{B}_{CP} = (10.3 \pm 2.6) \times 10^{-6}$ $A_{CP} = 0.21 \pm 0.15$ $f_L = 0.38 \pm 0.13$

$$\left[\frac{f_L(B_d \to K^{*0}\overline{K^{*0}})}{f_L(B_s \to K^{*0}\overline{K^{*0}})}\right]_{\rm QCDF} = 1.09^{+0.19}_{-0.08},$$

$$\left[\frac{f_L(B_d \to K^{*0}\overline{K^{*0}})}{f_L(B_s \to K^{*0}\overline{K^{*0}})}\right]_{\rm exp} = 3.77 \pm 0.33,$$

$\Longrightarrow$ Tension at the level of $\sim 7.0\sigma$

Updated Analysis will be available soon!!

Thanks for your attention!