B anomalies

Quark Confinement and the Hadron Spectrum, 2021

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on behalf of the LHCb Collaboration

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Introduction

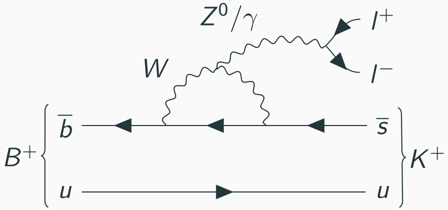
Over the past decade we have observed a coherent set of tensions with SM predictions

- In $b \to sll$ transitions (FCNC)
  - Lepton flavour universality (LFU) ratios such as $R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$
  - Branching fractions of several $b \to (s)ll$ decays.
  - Angular observables from $B \to K^{(*)} \mu^+ \mu^-$, $\Lambda_b \to \Lambda \mu^+ \mu^-$, etc.

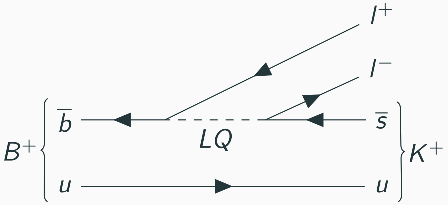
- In $b \to cl\nu$ transitions (Tree level),
  - Lepton flavour universality (LFU) ratios such as $R_{D^{(*)}} = \frac{\mathcal{B}(\overline{B}^0 \to D^{(*)+} \tau^- \overline{\nu})}{\mathcal{B}(\overline{B}^0 \to D^{(*)+} \mu^- \overline{\nu})}$.

Any discrepancy seen in well calculable B-decay measurements is a promising sign of new physics.

- Proceed via Flavour Changing Neutral Current (FCNC) loop processes.
- Have a small SM contribution (10^{-9} to 10^{-6}).
- Measurements done in different regions of dilepton invariant mass squared ($m_{ll}^2 \equiv q^2$) owing to different amplitudes which dominate in different regions.



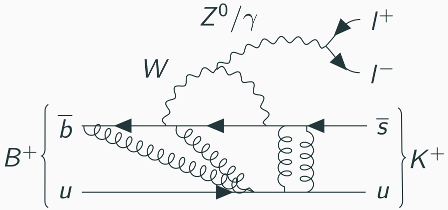
SM Example



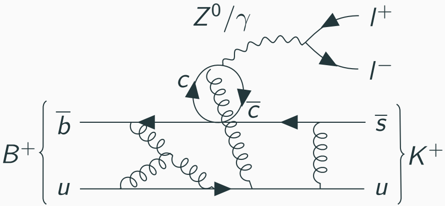
NP Example

Hadronic Effects

- Hadronic effects largest contributor to the theoretical uncertainties.
- BF and angular observables potentially suffer from underestimated hadronic effects.



Local contributions



Non-local contributions

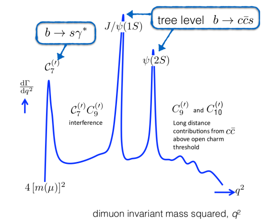
Effective Field Theory

SM Lagrangian rewritten using the Operator Product Expansion method.

$$\mathcal{L}(\Lambda) = \sum_i \mathcal{C}_i \mathcal{O}_i$$

Operator $\mathcal{O}_i$	$B_{s(d)} \to V_{s(d)}\mu^+\mu^-$	$B_{s(d)} \to \mu^+\mu^-$	$B_{s(d)} \to V_{s(d)}\gamma$
$\mathcal{O}_7$ EM	✓		✓
$\mathcal{O}_9$ Vector dilepton	✓		
$\mathcal{O}_{10}$ Axial-vector dilepton	✓	✓	
$\mathcal{O}_{S,P}$ (Pseudo-)Scalar dilepton	(✓)	✓	

- $\mathcal{C}_i$ Wilson Coefficients (perturbative short distance part)
  - Integrates out the heavy physics that can't resolve at some scale Λ.
- $\mathcal{O}_i$ Operators (non-perturbative long-distance part)
  - Accounts for the strong interactions, difficult to calculate reliably.



Forms a complete basis and accounts for SM and NP effects.

Lepton Flavour Universality Tests [$b \to sll$]

- In the SM, coupling of gauge bosons to leptons are independent of lepton flavour.
  - Branching fractions differ only by phase space and helicity-suppression (differences also very tiny).
- Ratios of the form:

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \overset{\text{SM}}{\cong} 1$$

- In SM free from QCD uncertainties affecting other observables O(10^{-4}) uncertainty [JHEP 12 (2007) 040]
- Up to O(1%) QED correction. [EPJC 76 (2016) 8,440]

Any significant deviation is a smoking gun for New Physics!!

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Lepton Flavour Universality Tests [$b \to sll$]

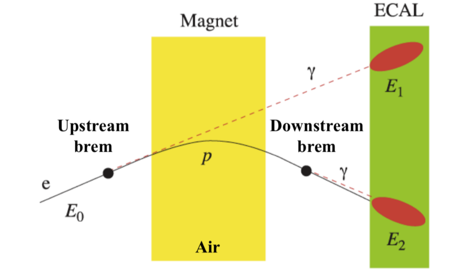
- At LHCb, R_K and R_{K^*} measurements done using a double ratio to cancel out most experimental systematics.

$$R_{K^{(*)}} \equiv \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}J/\psi(\to \mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B \to K^{(*)}e^+e^-)}{\mathcal{B}(B \to K^{(*)}J/\psi(\to e^+e^-))}$$

- Yields calculated from fits to invariant mass of final state particles.
- Detector efficiencies from simulation are calibrated with control channels in data.
- Overall effect of calibrations is a relative shift of R_K by $(+3{\pm}1)\%$.
  [would be 20% without the double ratio method]

LFU Electrons vs muons

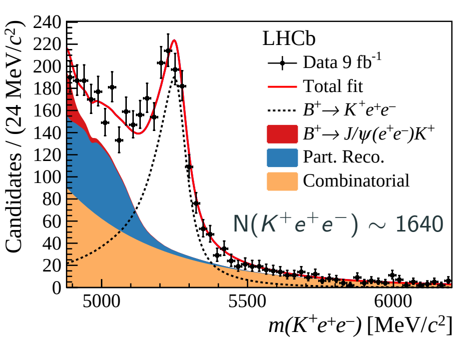
- Electrons loose a large fraction of their energy through Bremsstrahlung in the detector material.

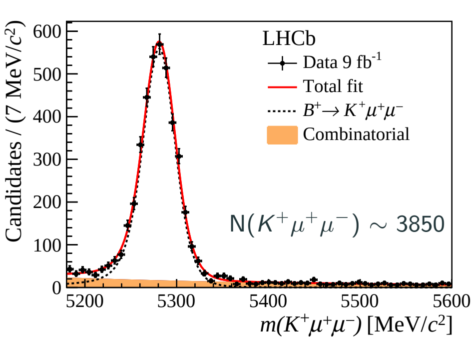


- Most electrons will emit one energetic photon before the magnet.
  - Look for photon clusters in the calorimeter ($E_T > 7$ MeV) compatible with electron direction before magnet.
  - Recover brem energy loss by "adding" the cluster energy back to the electron momentum.

Lepton Flavour Universality Tests [$b \to sll$]

- R_K extracted as a parameter from unbinned maximum likelihood fit to m($K^+\mu^+\mu^-$) and m($K^+e^+e^-$) in $B^+ \to K^+l^+l^-$ and $B \to K^+J/\psi(\to l^+l^-)$ decays. [arXiv:2103.11769]





Dominant Systematic ($\sim$ 1%): Fit model choice and statistics of calibration sample

Total relative systematic of 1.5% $\implies$ Resulting error statistically dominated.

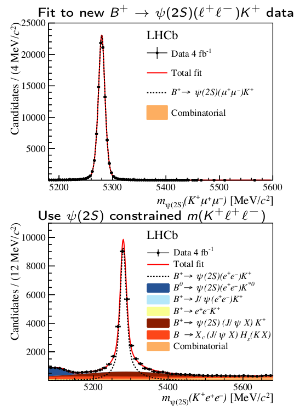
Lepton Flavour Universality Tests [$b \to sll$]

Measurement of $\psi(2S)$ double ratio as a cross-check,

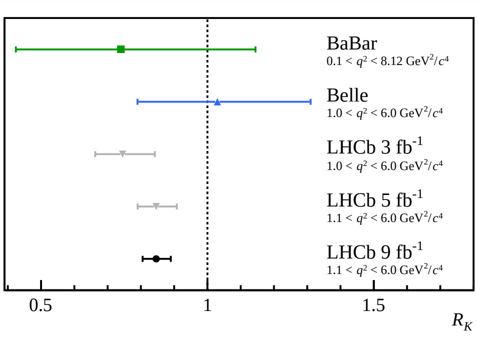
$$R_{\psi(2S)} \equiv \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+\psi(2S)(\to e^+e^-))}{\mathcal{B}(B^+ \to K^+J/\psi(\to e^+e^-))}$$

- Independent validation of double-ratio at q^2 away from J/ψ
- Result well compatible with unity:

$$R_{\psi(2S)} = 0.997 \pm 0.011(\mathrm{stat.} + \mathrm{syst.})$$



Lepton Flavour Universality Tests [$b \to sll$]



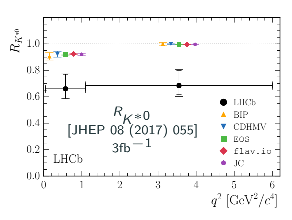
$R_K(1.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4) = 0.846^{+0.042}_{-0.039}(\mathrm{stat.})^{+0.013}_{-0.012}(\mathrm{syst.})$

Evidence of LFU violation at 3.1σ

[BaBar - PRD86 03 2012]

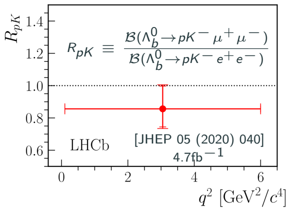
[Belle - JHEP 03 (2021) 105]

[LHCb - arXiv:2103.11769]



$R_{K^{*0}}(0.045 < q^2 < 1.1\ \mathrm{GeV}^2/c^4)$
$0.66^{+0.11}_{-0.07}(\mathrm{stat.}) \pm 0.03(\mathrm{syst.})$

$R_{K^{*0}}(1.1 < q^2 < 1.1\ \mathrm{GeV}^2/c^4)$
$0.69^{+0.11}_{-0.07}(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})$

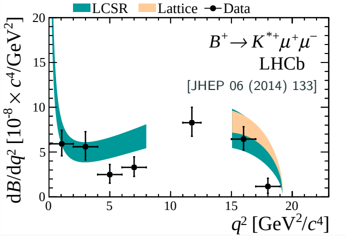


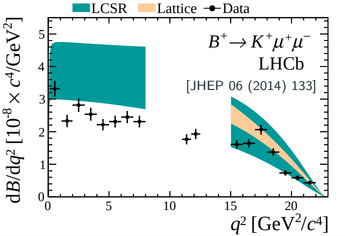
$R^{-1}_{pK}(0.01 < q^2 < 6.0\ \mathrm{GeV}^2/c^4)$
$1.17^{+0.18}_{-0.16}(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})$

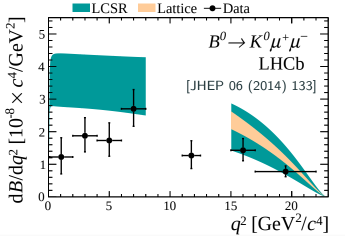
Tensions up to 2.5σ

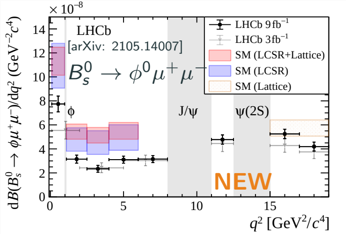
Branching Fractions of $b \to s\mu\mu$ Processes

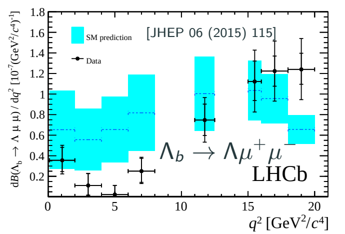
Several measurements show tension with SM predictions at low q^2 ($\sim$ 1 to 7 GeV^2/c^4).

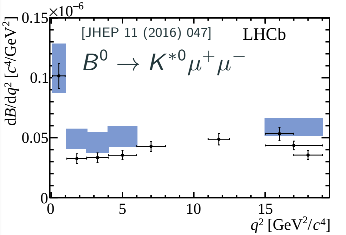










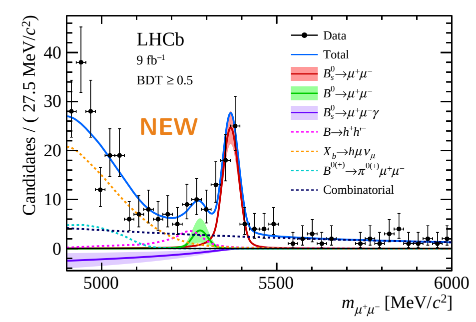


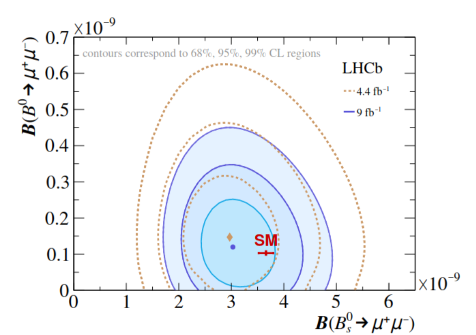
SM predictions limited by large hadronic uncertainties

New $B^0_{(s)} \to \mu^+\mu^-$ measurement

Even rarer that $b \to sll$ as additionally helicity suppressed.

Recent updated measurement of $B^0_{(s)} \to \mu^+\mu^-$ using full LHCb data (9 fb^{-1}) [LHCb-PAPER-2021-007,8].

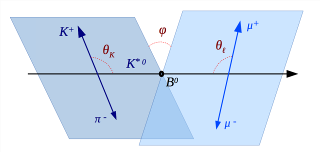




$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.09^{+0.46}_{-0.43}(\mathrm{stat.})^{+0.15}_{-0.11}(\mathrm{syst.})$; $B^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-\gamma$ compatible with background at 1.7σ and 1.5σ

Combine with ATLAS, CMS data- compatible with SM at 2σ.

Results constrain possible NP contributions to scalar, pseudoscalar or axial-vector currents, and thus limit the parameter space of NP models.

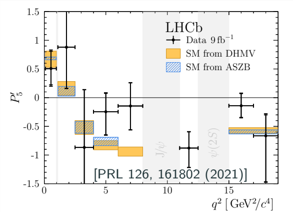


- For $B \to V\mu^+\mu^-$, differential decay rate (see backup) can be described by 3 angles (θ_K, θ_l and ϕ) and q^2.
  - Construct,
    - 2 form factor dependent observables (F_L and A_{FB})
    - 6 form factor independent (at LO) observables (the $P^{(\prime)}$ series) eg: $P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$

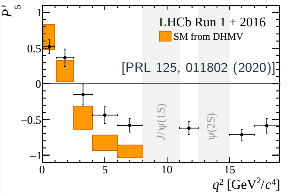
[JHEP 1204 (2012) 104]

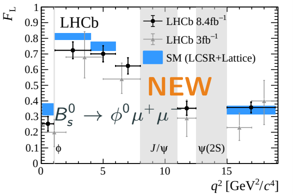
  - Wilson fits to all 8 CP averaged observables with LHCb data shows a $\sim 3\sigma$ tension with SM prediction.

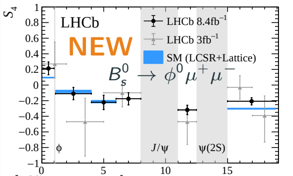
$B^+ \to K^{*+}\mu^+\mu^-$



$B^0 \to K^{*0}\mu^+\mu^-$







[arXiv:2107.13428]

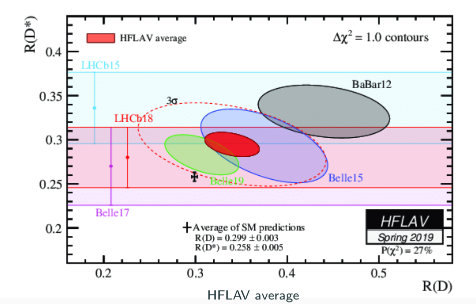
Lepton Flavour Universality Tests [$b \to cl\nu$]

- A further anomaly is seen in LFU ratios in $b \to cl\nu$ decays
    - Good theoretical control due to factorisation of hadronic and leptonic parts.
    - In addition theoretically clean by using ratios such as,

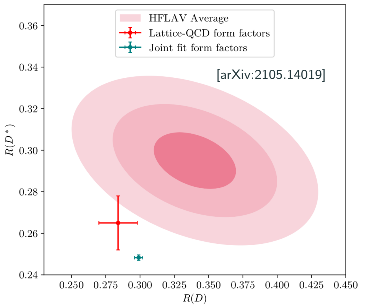
$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\tau^-\overline{\nu})}{\mathcal{B}(\overline{B}^0 \to D^{(*)+}\mu^-\overline{\nu})}; \qquad R_{J/\psi} \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu)}$$

    - Tree-level processes in SM $\implies$ a huge NP effect, comparable to SM needed to be visible.
    - IF NP effect is hierarchical, expect large contribution in τ; smaller μ; and negligible in e modes.
- Possible to make a NP explanantion, coherent with $b \to s\mu\mu$ [EPJC 79 714 (2019)].

- Combination of R_D, R_{D^*} plane from LHCb, Babar and Belle. World average at 3.1σ tension with SM.
- Also have recent updates to Lattice QCD form factors for SM prediction. [arXiv:2105.14019]
- $R_{J/\psi} = 0.71 \pm 0.17(\text{stat.}) \pm 0.18(\text{syst.})$ at 2σ away from SM (3 fb^{-1} LHCb data) [PRL 120, 121801 (2018)]

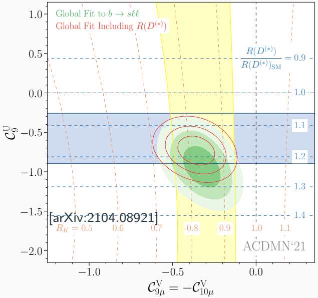


HFLAV average
$R_D = 0.349 \pm 0.027(\text{stat.}) \pm 0.015(\text{syst.})$
$R_{D*} = 0.298 \pm 0.011(\text{stat.}) \pm 0.007(\text{syst.})$



Global Fits

- Global fits performed with different hypotheses of NP models, influencing different Wilson coefficients.
- Measured values of LFU tests precisely what is expected of $C_9^{NP,e} = 0$, $C_9^{NP,\mu} = -1$ i.e. could account for data, BFs and $R_{K^{(*)}}$ by just changing C_9^{μ}.

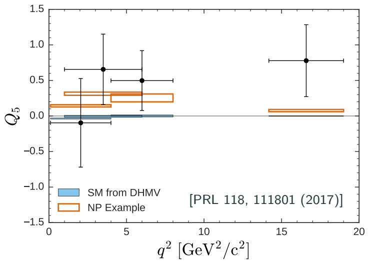


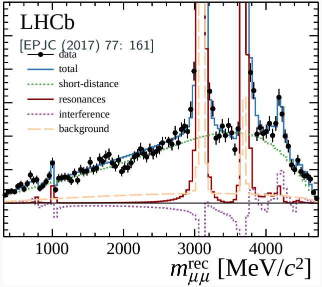
Many alternatives in the market: [arXiv:2012.12207, 2011.01212, 1904.08399, 1903.09578, 1903.10086, 1903.10932 ....]

- Cherry picking observables neglects the look elsewhere effect.
- An attempt to include all observables with sensitivity to $b \to sll$ and conservative theory treatment [arXiv:2104.05631]
  - 3.9σ global significance with respect to any form of heavy NP.

Future Prospects

- R_{K^*}, R_ϕ R_D, R_{D^*}, $R_{J/\psi}$ LHCb update coming soon.
- Full angular analysis of $B \to K^* e^+ e^-$ coming $\to$ measure ratio of $P_5'(\mathrm{e})$ and $P_5'(\mu)$ to get Q_5.
- Measure the effect of $c\bar{c}$ loops with full LHCb data.
- Updating searches for effects expected from $b \to s\tau\tau$ and possibility of seeing LFU violating $b \to s\tau\mu$





Conclusions

- Discrepancies seen in the behaviour of leptons in B decays
- Anomalies studied in 3 ways: LFU tests, BF measurement and angular analysis.
- Evidence of LFU violation at 3.1σ in $b \rightarrow sll$ decays.
- BF measurements in $b \rightarrow s\mu\mu$ lower than SM prediction.
- Tensions seen in observables with form factor uncertainites minimised (P_5').
- Discrepancies also seen in $b \rightarrow cl\nu$ decays.

LHCb Run3 will start very soon and expect to collect 25 fb^{-1}.
Belle II also expected to start soon.
Exciting time as upcoming results will shed more light at the problem.

Backup

R_K efficiency systematics

	$\boldsymbol{R_K}$											
	Run 1			Run 2.1			2017			2018		
	eTOS	hTOS!	TIS!	eTOS	hTOS!	TIS!	eTOS	hTOS!	TIS!	eTOS	hTOS!	TIS!
total	2.18	3.28	2.07	1.50	7.90	2.20	1.28	2.79	2.36	1.33	2.73	2.20
finite size	1.14	2.16	1.70	0.95	1.78	1.77	1.02	2.43	2.09	1.02	2.08	1.95
kinematic weighting	1.15	1.85	0.33	0.72	0.11	0.47	0.54	1.09	0.83	0.56	1.21	0.79
model	0.37	0.22	0.12	0.43	0.24	0.37	0.47	0.26	0.25	0.43	0.23	0.38
smearing	0.42	0.42	0.42	0.23	0.23	0.23	0.14	0.14	0.14	0.34	0.34	0.34
occupancy	1.24	0.56	0.69	0.49	0.33	0.37	0.14	0.33	0.33	0.25	0.45	0.28
tracking	0.53	0.62	0.09	0.47	0.02	0.35	0.14	0.05	0.13	0.16	0.48	0.12
trigger	0.06	1.31	0.77	0.26	1.64	0.43	0.13	0.63	0.53	0.12	0.98	0.27
PID	0.03	0.17	0.14	0.10	0.16	0.11	0.09	0.28	0.23	0.06	0.24	0.07
ECAL constants	0.00	0.00	0.00	0.22	7.50	0.91	0.00	0.00	0.00	0.00	0.00	0.00

Angular distribution

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

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