EFT ANALYSIS OF $b \to s l^+ l^-$ TRANSITIONS

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- Introduction
- EFT for $b \to s\, ll$ fits
- Current status
- Conclusions

Based on M. Ciuchini, M. Fedele, E. Franco, A. Paul, L.S. & M. Valli, arXiv:2110.10126.
See also Geng et al., arXiv:2103.12738, Cornella et al., 2103.16558,
Hurth et al., 2104.10058, Alguerò et al., arXiv:2104.08921

Many thanks to M. Fedele and A. Paul!

$b \to s\ l^+l^-$ decays

- $b \to s l^+ l^-$ transitions are FCNC
  - cannot occur at tree-level in the SM
  - they arise at one loop through penguins and boxes
  - they are particularly sensitive to possible NP contributions
  - since $V_{ub}V_{us}^* \ll V_{cb}V_{cs}^* \approx V_{tb}V_{ts}^*$, top and charm quarks dominate loop contributions

EFT for b → s l^+l^- decays in three steps

1) Assume NP heavier than EW scale:

- NP contributions invariant under SM gauge group
- Can be written in terms of SMEFT operators built with Q_i, u_i, d_i, L_i, e_i, Higgs and SU(3) x SU(2) x U(1) gauge fields:

$$
\begin{aligned}
O^{LQ(1)}_{2223} &= (\bar{L}_2\gamma_\mu L_2)(\bar{Q}_2\gamma^\mu Q_3)\,, \\
O^{LQ(3)}_{2223} &= (\bar{L}_2\gamma_\mu \tau^A L_2)(\bar{Q}_2\gamma^\mu \tau^A Q_3)\,, \\
O^{Qe}_{2322} &= (\bar{Q}_2\gamma_\mu Q_3)(\bar{e}_2\gamma^\mu e_2)\,, \\
O^{Ld}_{2223} &= (\bar{L}_2\gamma_\mu L_2)(\bar{d}_2\gamma^\mu d_3)\,, \\
O^{ed}_{2223} &= (\bar{e}_2\gamma_\mu e_2)(\bar{d}_2\gamma^\mu d_3)\,,
\end{aligned}
$$

+ $L_2, e_2 \to L_1, e_1$

EFT for b → s l⁺l⁻ decays in three steps

2) Expand H around its vev, integrate out $W^\pm$, Z and t:

- W, Z, t & NP contributions can be written in terms of WET operators built with $d^i_{L,R}$, $u^i_{L,R}$, $l^i_{L,R}$, photons & gluons:

$$Q_1^p = (\bar{s}_L \gamma_\mu T^a p_L)(\bar{p}_L \gamma^\mu T^a b_L)\,,$$
$$Q_2^p = (\bar{s}_L \gamma_\mu p_L)(\bar{p}_L \gamma^\mu b_L)\,,$$
$$P_3 = (\bar{s}_L \gamma_\mu b_L) \sum\nolimits_q (\bar{q}\gamma^\mu q)\,,$$
$$P_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum\nolimits_q (\bar{q}\gamma^\mu T^a q)\,,$$
$$P_5 = (\bar{s}_L \gamma_{\mu 1}\gamma_{\mu 2}\gamma_{\mu 3} b_L) \sum\nolimits_q (\bar{q}\gamma^{\mu 1}\gamma^{\mu 2}\gamma^{\mu 3} q)\,,$$
$$P_6 = (\bar{s}_L \gamma_{\mu 1}\gamma_{\mu 2}\gamma_{\mu 3} T^a b_L) \sum\nolimits_q (\bar{q}\gamma^{\mu 1}\gamma^{\mu 2}\gamma^{\mu 3} T^a q)\,,$$
$$Q_{8g} = \sqrt{\frac{\alpha_s}{64\pi^3}} m_b \bar{s}_L \sigma_{\mu\nu} G^{\mu\nu} b_R\,.$$

p=u,c

q=u,d,s,c,b

$$Q_{7\gamma} = \sqrt{\frac{\alpha_e}{64\pi^3}} m_b \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_I$$
$$Q_{9V} = \frac{\alpha_e}{4\pi} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$Q_{10A} = \frac{\alpha_e}{4\pi} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma^5 \ell)\,,$$
$$Q_S = \frac{\alpha_e}{4\pi} (\bar{s}_L b_R)(\bar{\ell}\ell)\,,$$
$$Q_P = \frac{\alpha_e}{4\pi} (\bar{s}_L b_R)(\bar{\ell}\gamma^5 \ell)\,.$$

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NP contributions from SMEFT operators →

$$C_9^{\rm NP} = \frac{\pi v^2}{\alpha_e\lambda_t\Lambda_{\rm NP}^2}\left(C_{2223}^{LQ^{(1)}} + C_{2223}^{LQ^{(3)}} + C_{2322}^{Qe}\right)\,,$$
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Run from EW scale to m_b: C_9 gets a large $\log(M_W^2/m_b^2)$ from mixing with Q_2^c

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p=~~u~~,c

q=~~u,d,s,c,b~~

Small coefficients or doubly Cabibbo suppressed

$$Q_{7\gamma} = \sqrt{\frac{\alpha_e}{64\pi^3}}\, m_b \bar{s}_L\sigma_{\mu\nu}F^{\mu\nu}b_R$$
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$$C_9^{\rm NP} = \frac{\pi v^2}{\alpha_e\lambda_t\Lambda^2_{\rm NP}}\left(C^{LQ^{(1)}}_{2223} + C^{LQ^{(3)}}_{2223} + C^{Qe}_{2322}\right)\,,$$
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EFT for $b \to s\, l^+ l^-$ decays in three steps

3) Compute matrix elements of WET operators:

- $B_s \to \mu\bar{\mu}$ only from $\langle Q_{10} \rangle$, no large logs, very clean
- $B \to K^{(*)}\, l^+ l^-$ from:
  - Q_9, Q_7 and Q_{10} at tree level;
  - $Q_{1,2}^c$ at one loop:
    - $O(4\pi\alpha_s)$ (factorizes in the $m_b \to \infty$ limit, perturbative) or
    - $O(16\pi^2\Lambda/m_b)$ (power correction, nonperturbative)

Charming penguins

THE CHARM CONTRIBUTION

- Computable in the infinite m_b limit (QCDF)
  Bjorken; Beneke, Buchalla, Neubert & Sachrajda; Beneke, Feldmann & Seidel
- In the real world, nonperturbative power corrections due to the intermediate $c\bar{c}s\bar{d}$ state are important Ciuchini et al
- Nonperturbative methods working in Euclidean spacetime (lattice, QCDSR) cannot (yet) cope with rescattering in B decays Maiani & Testa
- Two classes of power corrections:
  - $B \to K^{(*)} + (c\bar{c} \to l^+l^-)$: has known analytic structure in q^2; can be estimated at low q^2 using LCSR Khodjamirian et al; Gubernari et al.
  - $B \to (c\bar{c}s\bar{d}) \to K^{(*)}l^+l^-$, e.g. $B \to (D_s^{(*)}\, D^{(*)}) \to K^{(*)}l^+l$: unrelated to q^2 singularities, no estimate available. Notice: BESIII observes a near-threshold structure in the K recoil in $e^+e^- \to (D_s^{(*)}\, D^{(*)})\, K$ arXiv:2011.07855

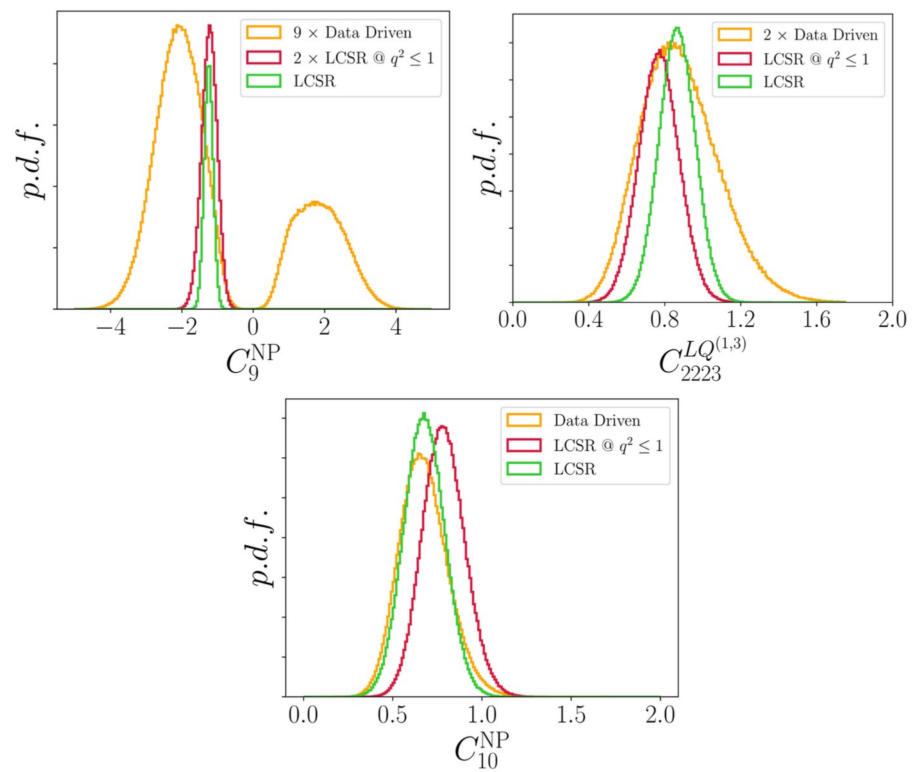
WHAT IS AFFECTED BY CHARMING PENGUINS?

- Charming penguins do not affect observables independent on photon exchange, i.e. on $C_{7,9}$:
  - $BR(B_q \to \ell^+\ell^-)$
- **In the Standard Model**, charming penguins do not affect Lepton Universality (LU) ratio predictions, which are 1 up to lepton mass effects and QED corrections:
  - R_K, R_{K^*}, R_{pK}, …
- Anything else, **including LU ratios beyond the SM**, is affected by charming penguins.

HOW TO PERFORM AN EFT FIT

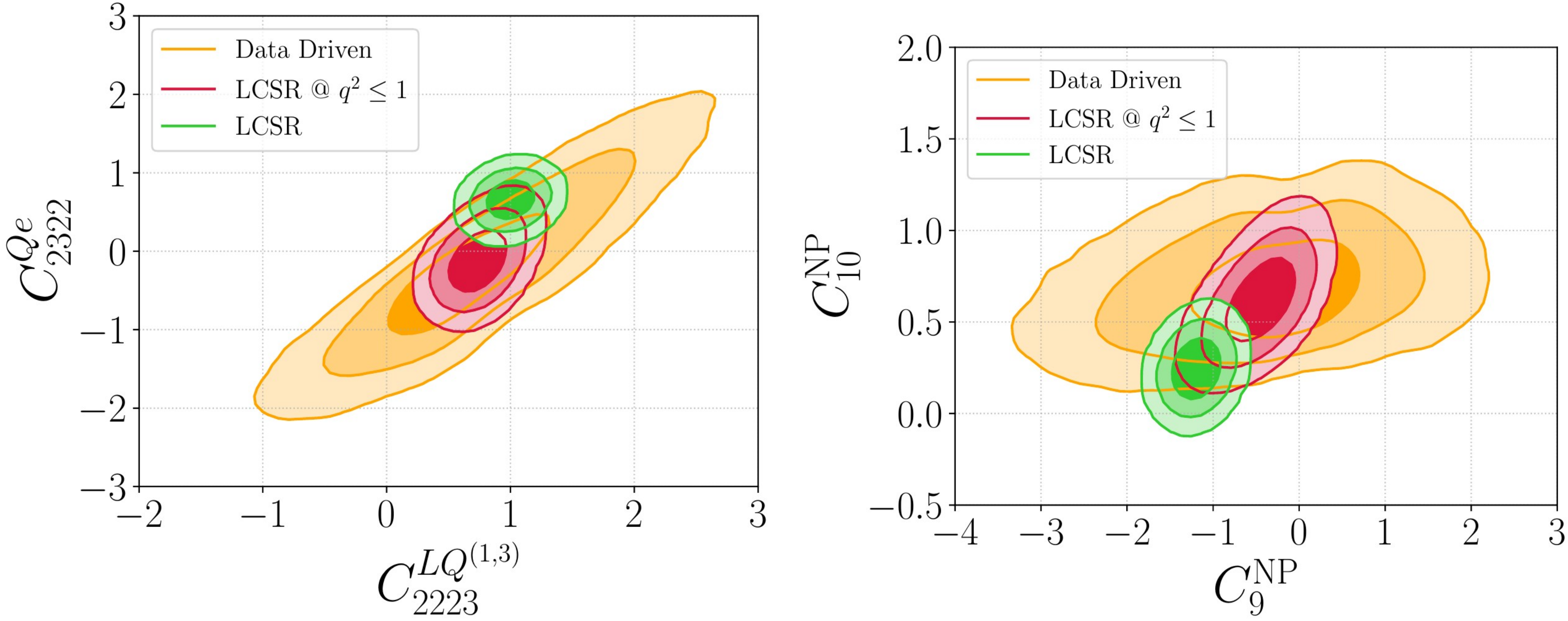
- Current evidence of LUV calls for NP, but LU ratios beyond the SM in general depend on charming penguins: determine simultaneously EFT coefficients and charming penguins from a global fit of all $b \to s l^+ l^-$ observables
  - Fully Data Driven: no assumption about charming penguins (except for Taylor expansion in q^2); equivalent to, but more powerful than, fit of LUV ratios only See also Isidori et al.
  - Partly Model Dependent: assume LCSR result for charming penguins at small q^2 only
  - Fully Model Dependent: assume LCSR result and analytic structure in q^2

ONE-DIMENSIONAL NP SCENARIOS



- Dramatic effect of charming penguins on the C_9^{NP} scenario
- Moderate effect on C^{LQ}, small effect on C_{10}^{NP}
- Using IC=-2<log$\mathscr{L}$>+4$\sigma^2_{\log\mathscr{L}}$, C_9^{NP} is largely preferred using LCSR + analyticity, while C^{LQ} and C_{10}^{NP} are preferred with more conservative assumptions

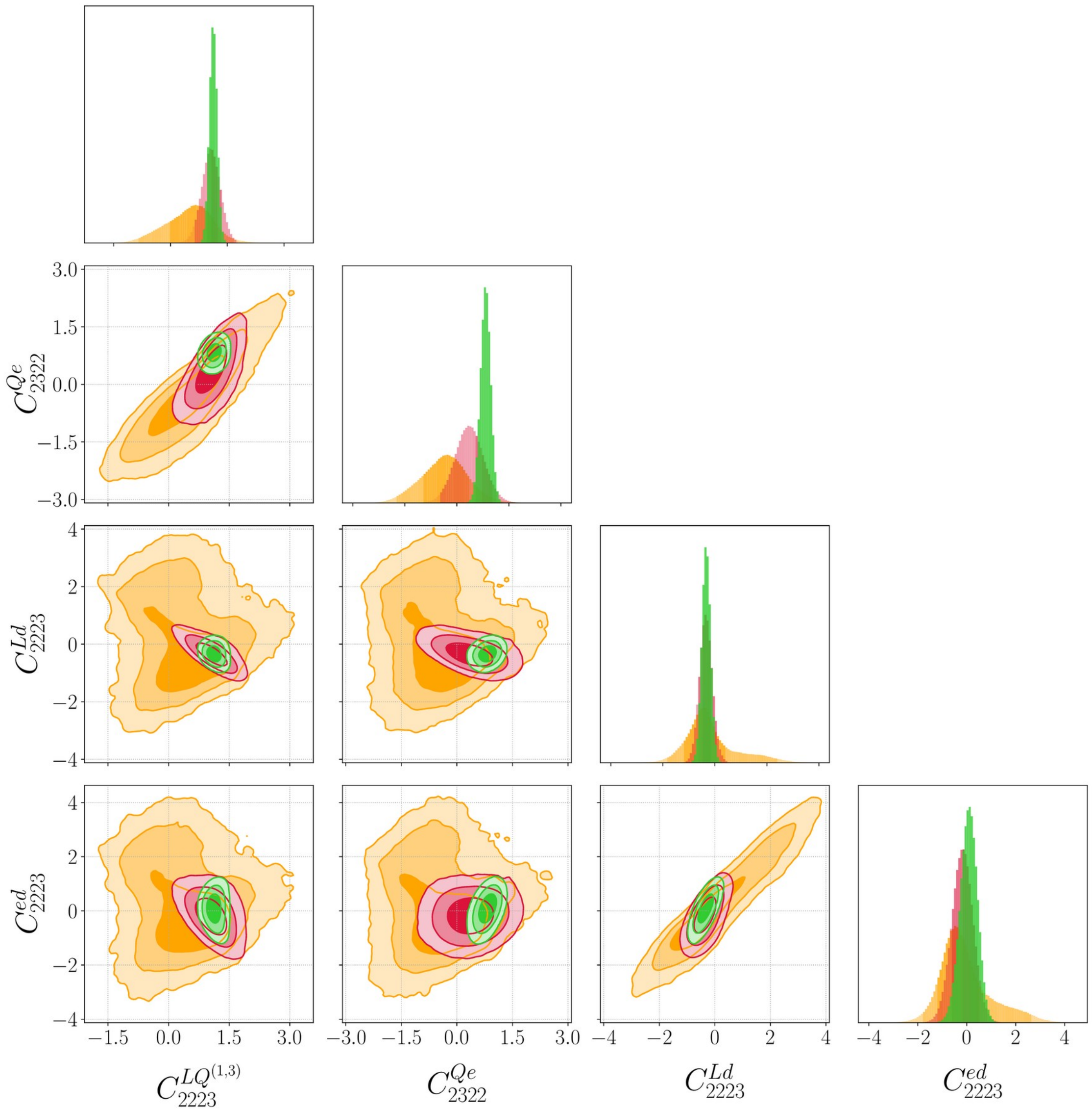
TWO-DIMENSIONAL NP SCENARIOS



Inference on NP coefficients depends on assumptions on charming penguins.

In Data Driven fit, ΔIC similar to 1D C^{LQ} and C_{10}^{NP} scenarios.

FOUR-DIMENSIONAL NP FIT



- Dependence on charming penguins evident
- 4D scenario is favoured using QCDSR + analyticity, disfavoured in Data Driven approach

CONCLUSIONS

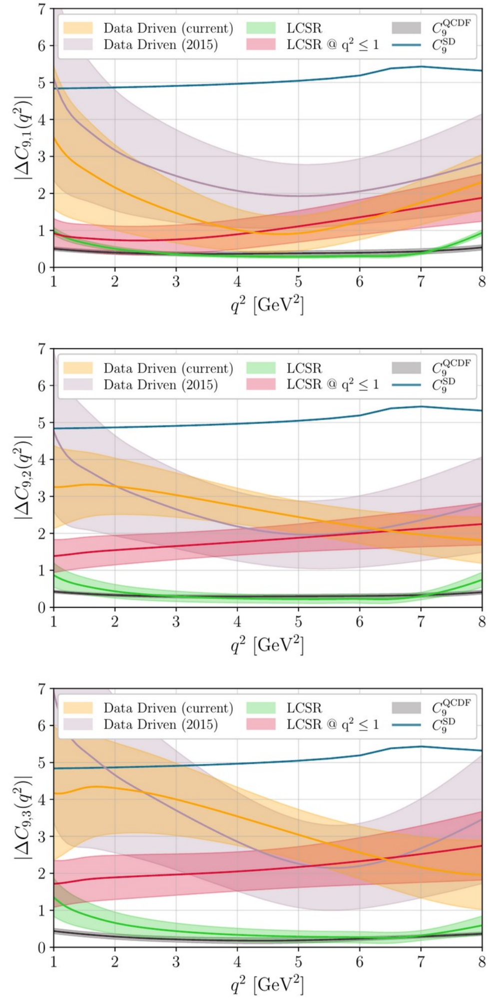
- Evidence for LUV in $b \to s l^+ l^-$ transitions very exciting
- Unbiased NP inference calls for a conservative treatment of charming penguins
- A purely data driven approach is the way to go, already offering remarkable insight on NP thanks to the huge experimental progress
- It's time for a joint th+exp effort to optimize our hunt for NP!

BACKUP

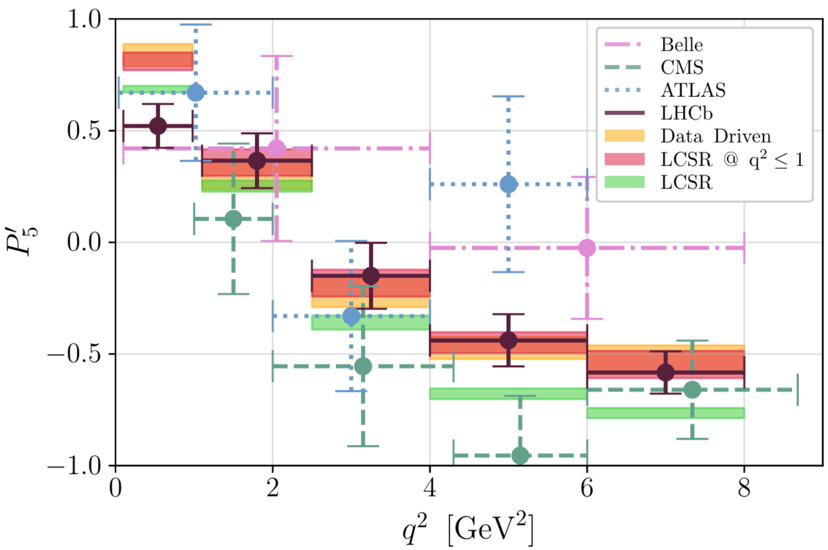
NP scenario	Approach	68% HPDI	ΔIC
A: $C_9^{\rm NP}$	Data Driven	$[-3.04,-1.10]\cup[1.48,1.99]$	$21\cup 13$
	LCSR $q^2\leq 1$	$[-1.44,-1.01]$	43
	LCSR	$[-1.37,-1.12]$	94
B: C_{2223}^{LQ}	Data Driven	$[0.65,1.05]$	38
	LCSR $q^2\leq 1$	$[0.67,0.88]$	60
	LCSR	$[0.77,0.96]$	75
C: $C_{10}^{\rm NP}$	Data Driven	$[0.53,0.79]$	39
	LCSR $q^2\leq 1$	$[0.66,0.90]$	54
	LCSR	$[0.56,0.79]$	20
D: $\{C_{2223}^{LQ},C_{2322}^{Qe}\}$	Data Driven	$\{[0.20,1.03],[-0.82,0.15]\}$	37
	LCSR $q^2\leq 1$	$\{[0.61,0.86],[-0.37,0.11]\}$	57
	LCSR	$\{[0.90,1.10],[0.53,0.79]\}$	96
D: $\{C_9^{\rm NP},C_{10}^{\rm NP}\}$	Data Driven	$\{[-0.81,0.46],[0.51,0.83]\}$	37
	LCSR $q^2\leq 1$	$\{[-0.67,-0.20],[0.47,0.76]\}$	57
	LCSR	$\{[-1.33,-1.06],[0.15,0.34]\}$	96
E: $\{C_{2223}^{LQ},C_{2322}^{Qe},$	Data Driven	$\{[-0.06,1.18],[-0.99,0.35],[-1.30,0.34],[-1.25,0.56]\}$	30
$C_{2223}^{Ld},C_{2223}^{ed}\}$	LCSR $q^2\leq 1$	$\{[0.83,1.32],[-0.05,0.76],[-0.59,-0.10],[-0.58,0.27]\}$	54
	LCSR	$\{[1.03,1.23],[0.69,0.97],[-0.49,-0.17],[-0.25,0.43]\}$	105
E: $\{C_9^{\rm NP},C_{10}^{\rm NP},$	Data Driven	$\{[-1.05,0.75],[0.38,0.81],[-0.57,1.82],[-0.31,0.12]\}$	30
$C_9^{\prime,\rm NP},C_{10}^{\prime,\rm NP}\}$	LCSR $q^2\leq 1$	$\{[-1.45,-0.59],[0.29,0.70],[-0.06,0.82],[-0.37,0.08]\}$	54
	LCSR	$\{[-1.55,-1.27],[0.11,0.31],[-0.17,0.52],[-0.47,-0.14]\}$	105

	Approach	R_K $[1.1,6]$	R_{K^*} $[0.045,1.1]$	R_{K^*} $[1.1,6]$	P_5' $[4,6]$	P_5' $[6,8]$	$B_s\to\mu\mu$ $\times 10^9$
Exp.	-	0.848(42)	0.680(93)	0.71(10)	-0.439(117)	-0.583(095)	2.86(33)
A	Data Driven	0.84(4)	0.86(4)	0.81(13)	-0.47(5)	-0.53(7)	3.58(11)
	LCSR $q^2\leq 1$	0.76(4)	0.89(1)	0.85(3)	-0.44(5)	-0.55(6)	3.58(11)
	LCSR	0.76(2)	0.89(1)	0.83(1)	-0.45(4)	-0.59(4)	3.58(11)
B	Data Driven	0.83(4)	0.85(2)	0.75(5)	-0.48(5)	-0.54(7)	2.64(21)
	LCSR $q^2\leq 1$	0.76(3)	0.86(1)	0.76(3)	-0.46(5)	-0.56(6)	2.74(11)
	LCSR	0.72(3)	0.85(1)	0.74(3)	-0.63(3)	-0.74(2)	2.65(10)
C	Data Driven	0.82(3)	0.86(1)	0.75(5)	-0.49(5)	-0.55(7)	2.56(19)
	LCSR $q^2\leq 1$	0.83(2)	0.85(1)	0.76(3)	-0.48(5)	-0.57(6)	2.40(16)
	LCSR	0.84(3)	0.87(1)	0.74(3)	-0.73(3)	-0.80(2)	2.55(16)
D	Data Driven	0.83(4)	0.85(2)	0.75(6)	-0.49(5)	-0.55(7)	2.58(23)
	LCSR $q^2\leq 1$	0.77(4)	0.85(1)	0.76(3)	-0.47(5)	-0.57(6)	2.67(21)
	LCSR	0.71(3)	0.87(1)	0.77(3)	-0.48(4)	-0.62(4)	3.20(16)
E	Data Driven	0.84(4)	0.82(4)	0.68(8)	-0.48(6)	-0.55(7)	2.54(29)
	LCSR $q^2\leq 1$	0.79(4)	0.81(3)	0.65(8)	-0.47(5)	-0.56(6)	2.64(24)
	LCSR	0.80(4)	0.82(2)	0.67(4)	-0.49(4)	-0.64(4)	2.80(22)

BACKUP

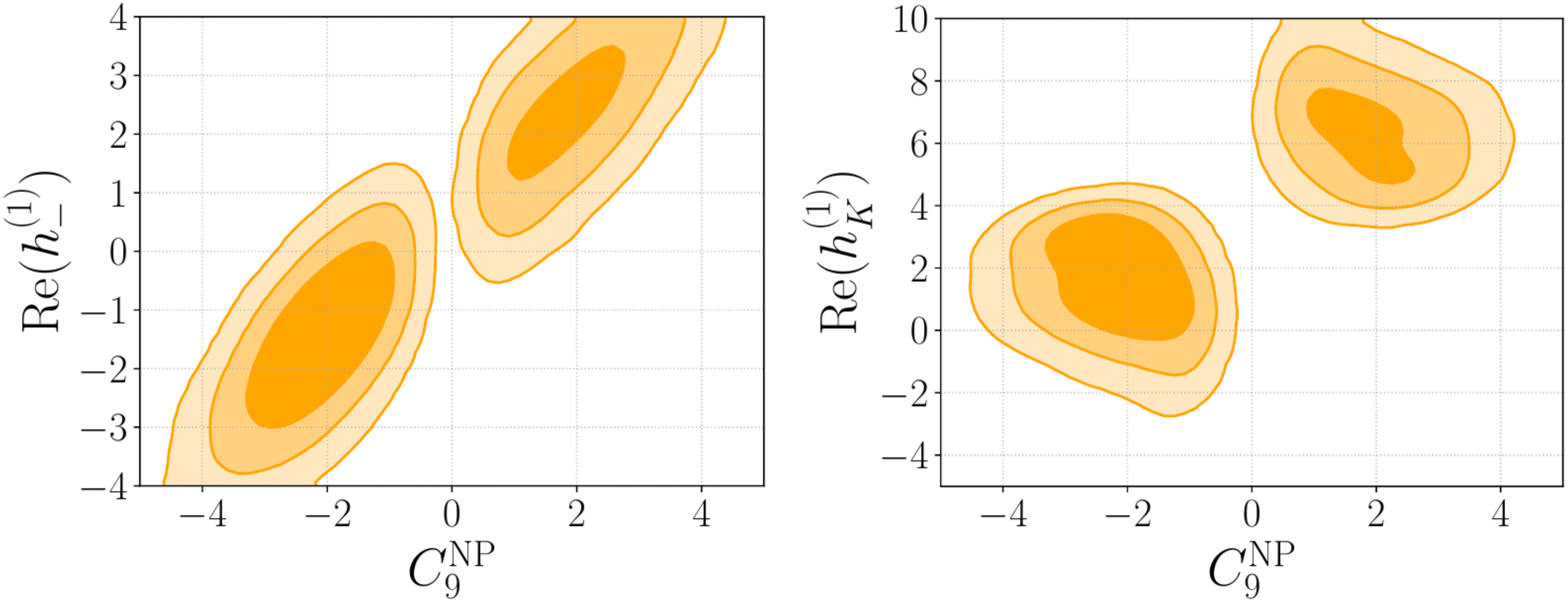


Data Driven (current)
Data Driven (2015)
LCSR
LCSR @ $q^2 \leq 1$
C_9^{QCDF}
C_9^{SD}
$|\Delta C_{9,1}(q^2)|$
$|\Delta C_{9,2}(q^2)|$
$|\Delta C_{9,3}(q^2)|$
q^2 [GeV^2]



Belle
CMS
ATLAS
LHCb
Data Driven
LCSR @ $q^2 \leq 1$
LCSR
P_5'
q^2 [GeV^2]

BACKUP



$\mathrm{Re}(h_-^{(1)})$
4
3
2
1
0
−1
−2
−3
−4
−4
−2
0
2
4
C_9^{NP}
$\mathrm{Re}(h_K^{(1)})$
10
8
6
4
2
0
−2
−4
−4
−2
0
2
4
C_9^{NP}