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

$\cancel{b \to s \ell^+ \ell^-}$ 標準模型理論

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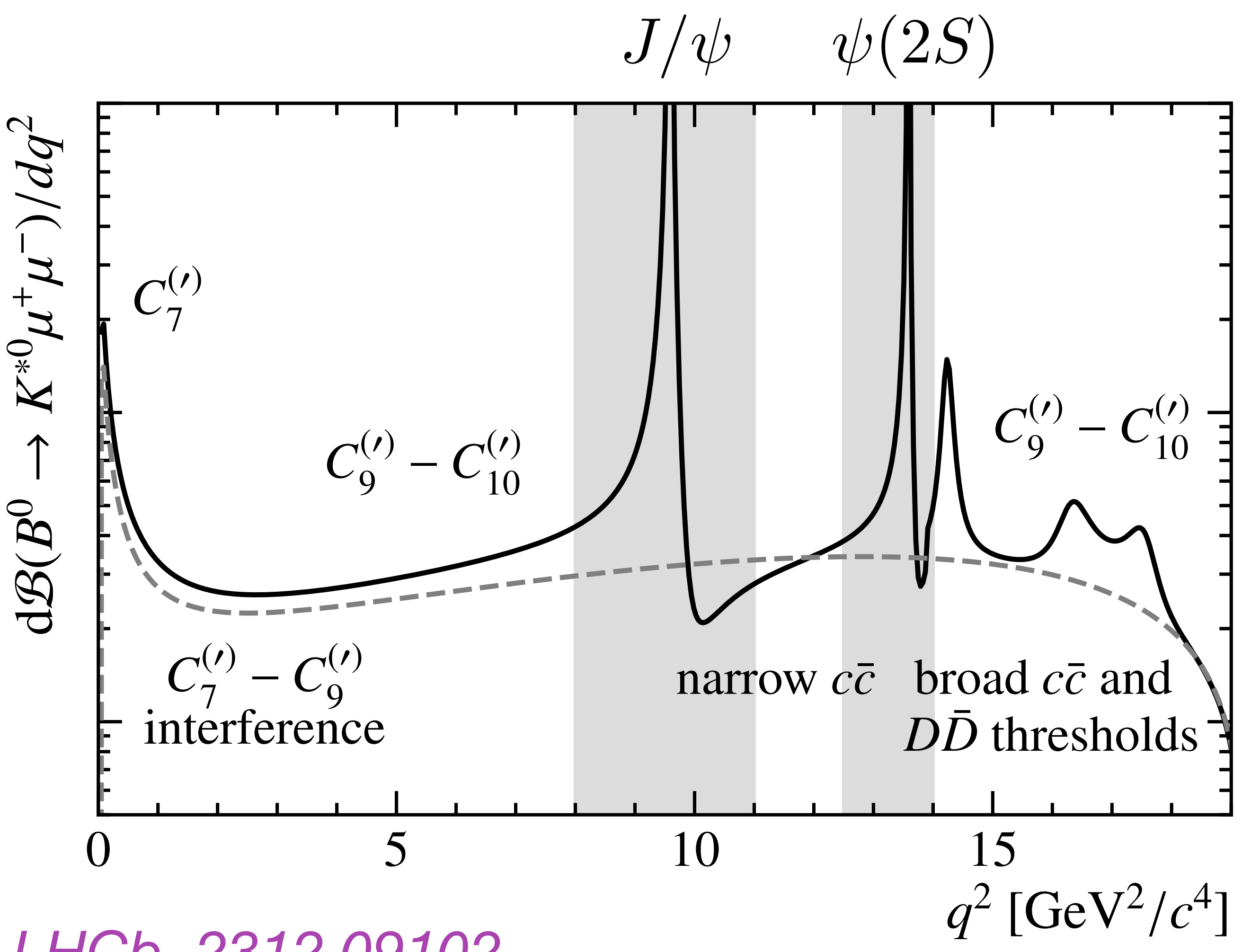
$B \to K^{(*)}\mu^+\mu^-$

✦ Short-distance physics enters through C_9 and C_{10} (and C_7 near q^2=0).

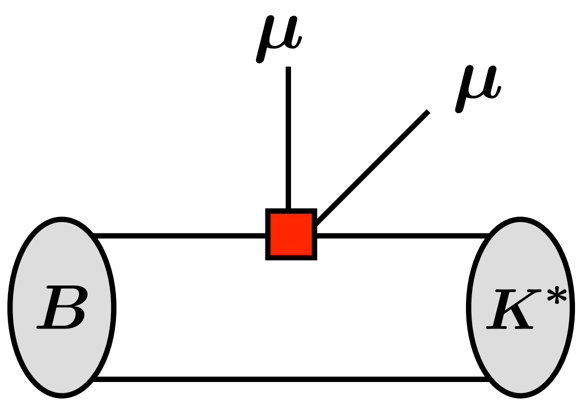


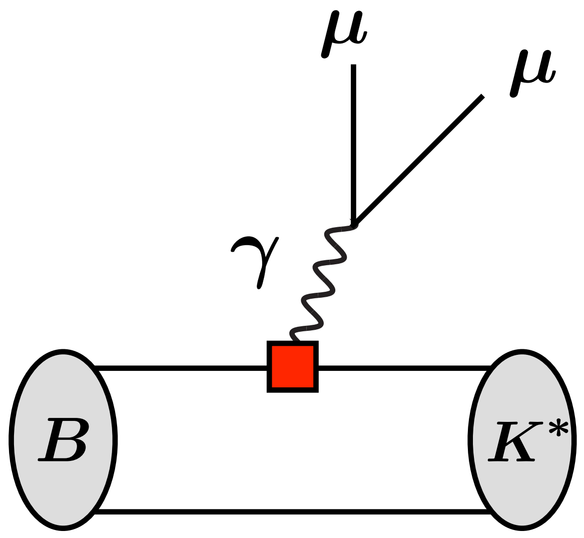
LHCb, 2312.09102

$$\mathcal{O}_9 \sim \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu \ell\right)$$

$$\mathcal{O}_{10} \sim \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu \gamma_5 \ell\right)$$

$$\mathcal{O}_7 \sim m_b\left(\bar{s}\sigma^{\mu\nu} P_R b\right) F_{\mu\nu}$$



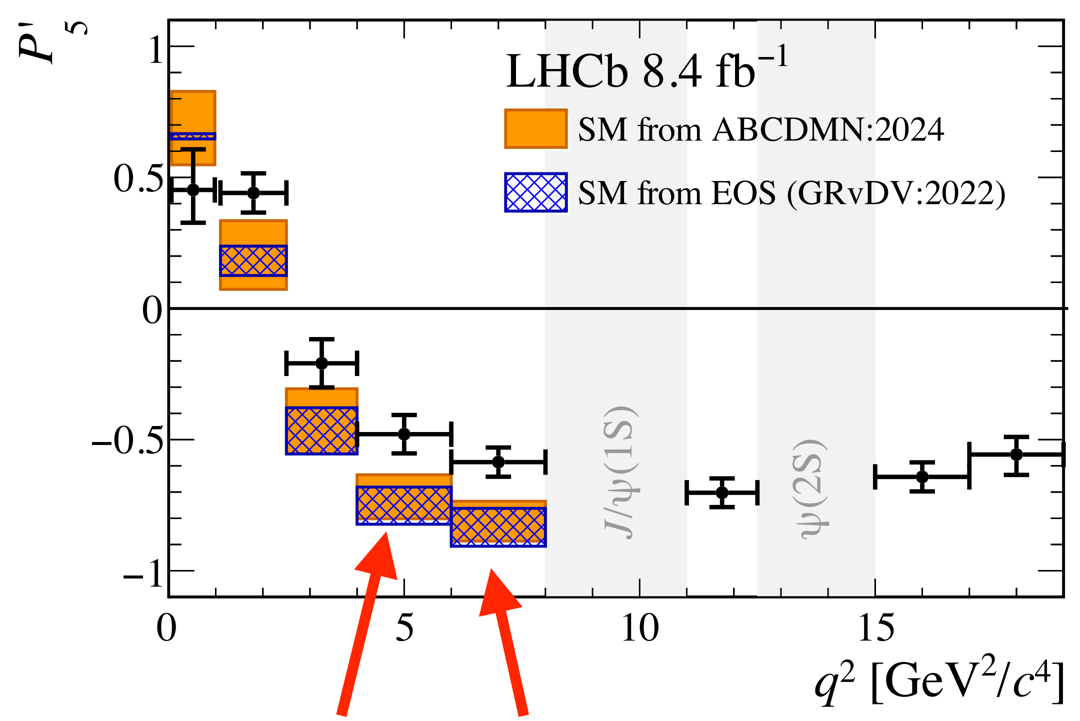


$$\mathcal{C}_9^{\mathrm{SM}}(m_b) \sim 4.3$$

$$\mathcal{C}_{10}^{\mathrm{SM}}(m_b) \sim -4.2$$

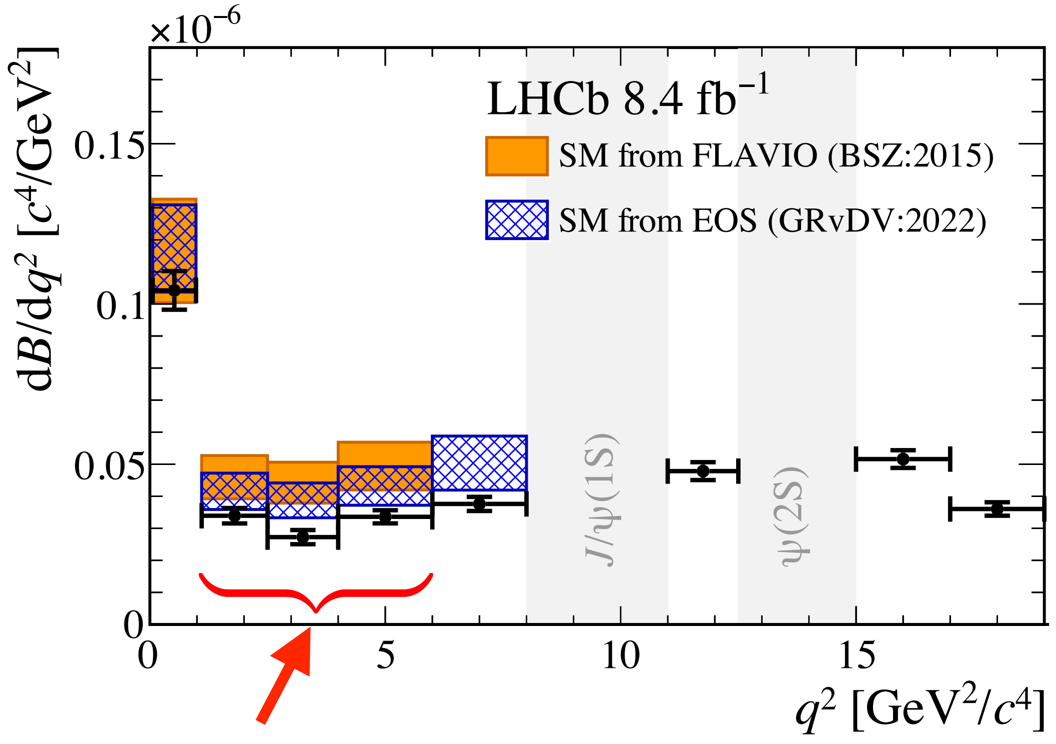
$b \to s$ anomaly?

$P_5'(B^0 \to K^{*0}\mu^+\mu^-)$



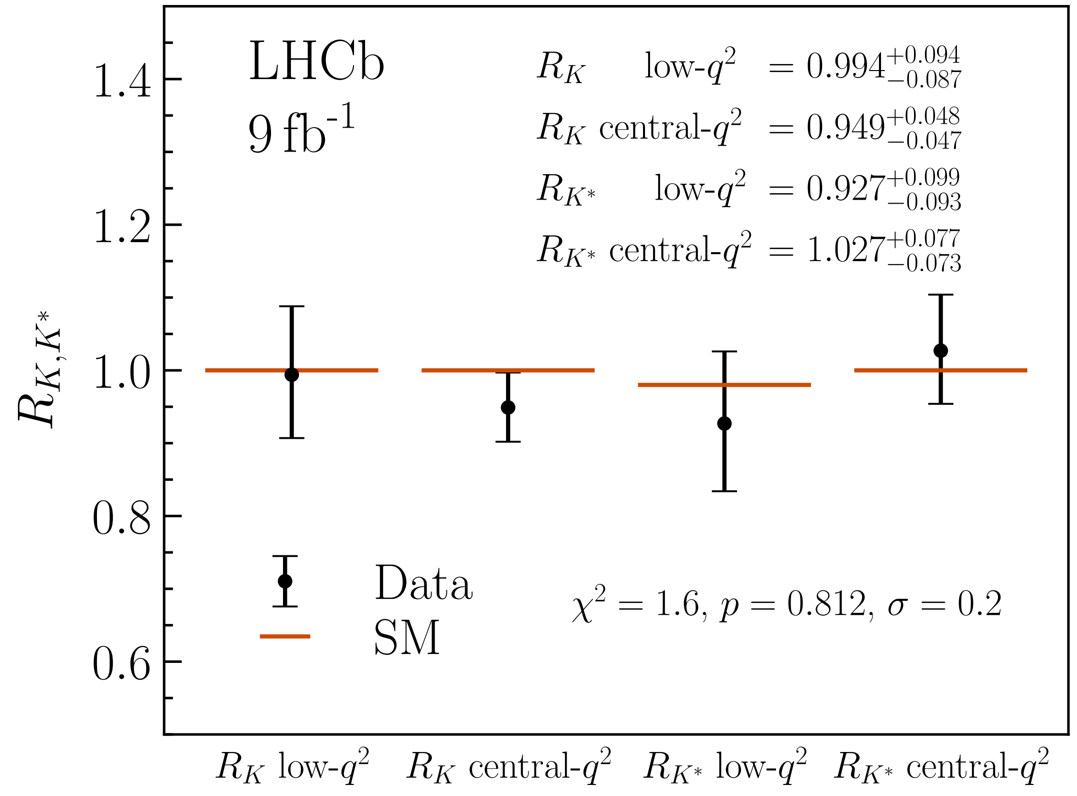
2.1σ, 2.4σ (ABCDMN)
2.6σ, 2.7σ (EOS)

$\mathrm{d}\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)/\mathrm{d}q^2$



2.1σ (FLAVIO)
1.5σ (EOS)

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

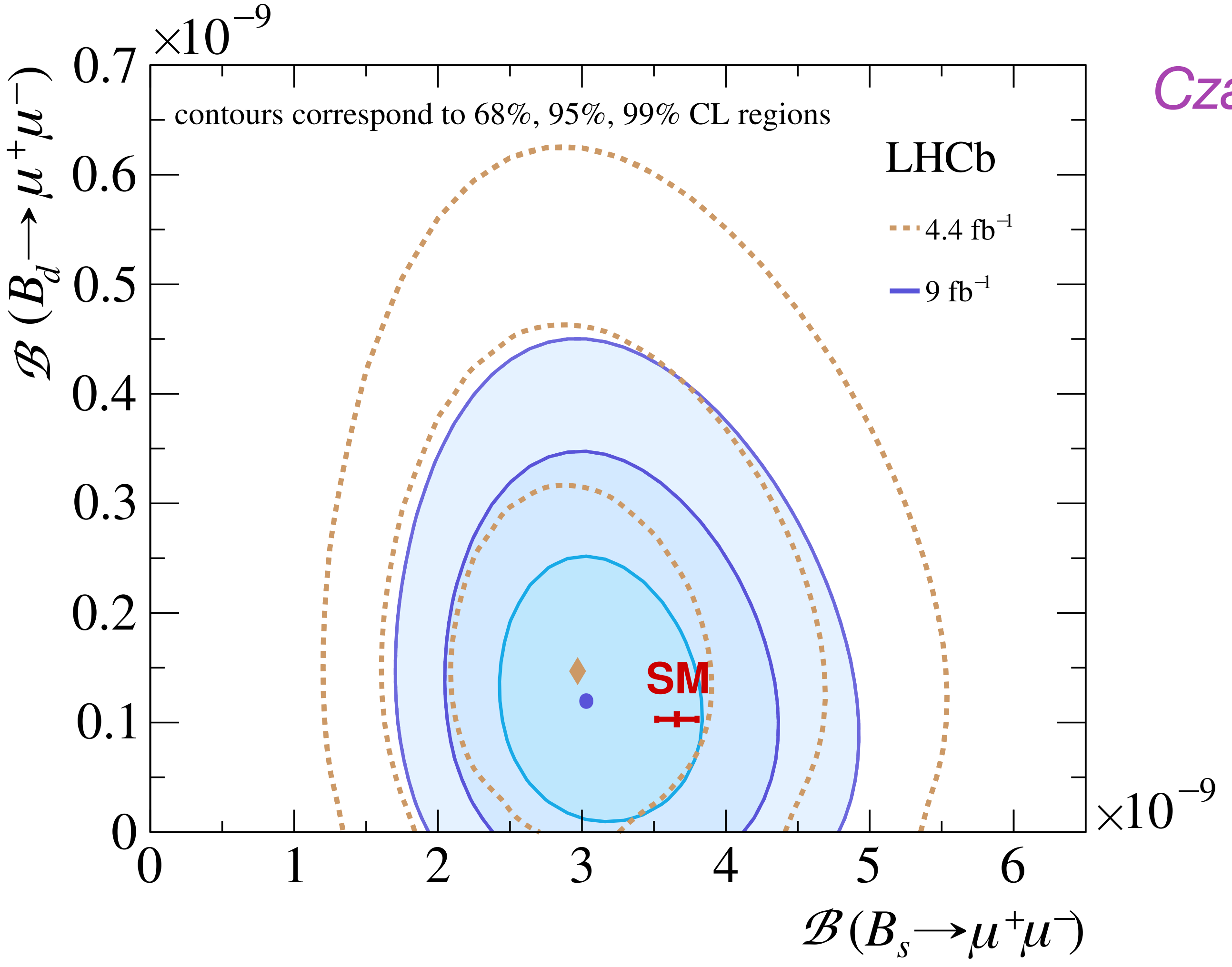


low$-q^2$: [0.1, 1.1] GeV^2
central$-q^2$: [1.1, 6.0] GeV^2

- ✦ P_5' and $\mathrm{d}B/\mathrm{d}q^2$ show tensions with the SM, while $R_{K^{(*)}}$ are compatible with the SM.

LHCb, 2212.09153; 2512.18053

$B_s \to \mu^+\mu^-$: pinning down C_{10}



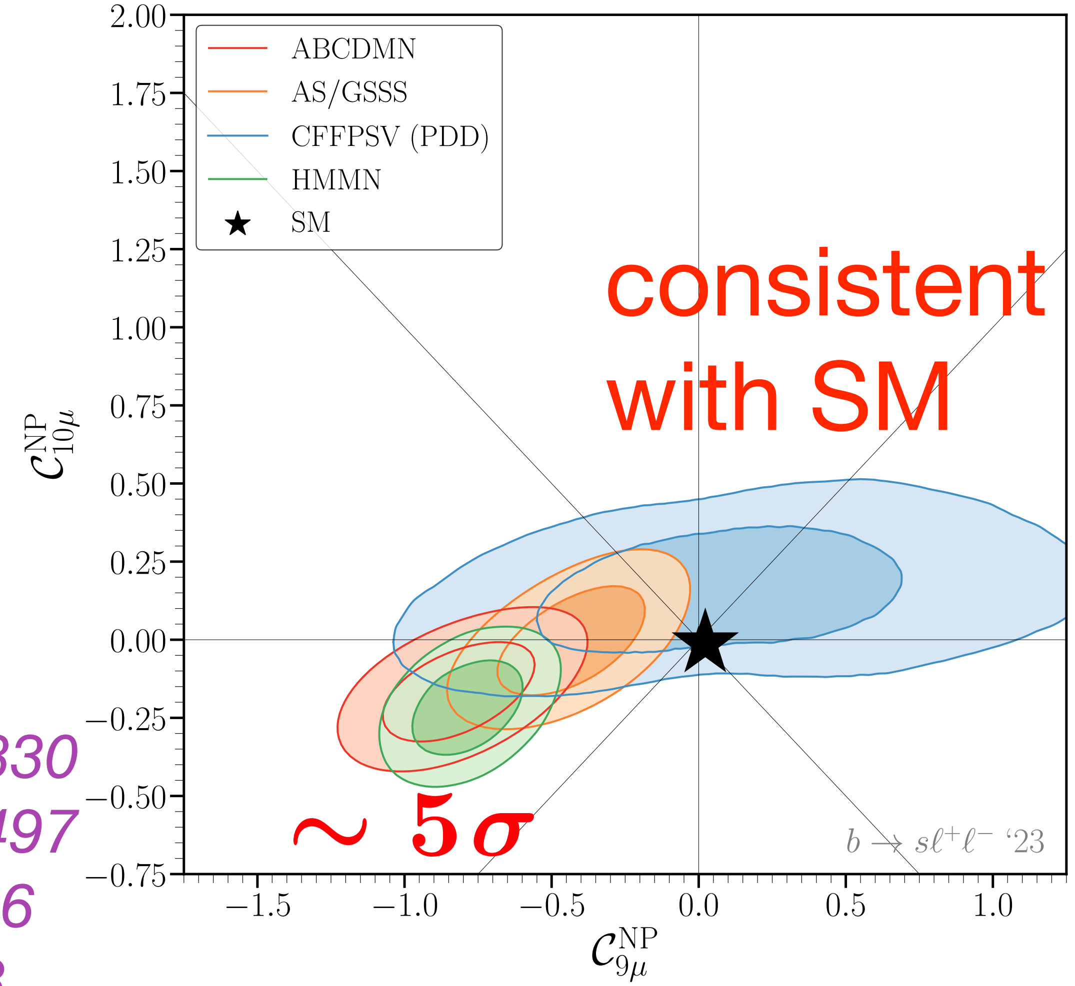
Czaja & Misiak, 2407.03810

$$\mathcal{B}(B_s \to \mu^+\mu^-) \;\propto\; f_{B_s}^2\, |V_{cb}|^2 \left|\frac{V_{tb}^* V_{ts}}{V_{cb}}\right|^2 |C_{10}|^2$$

- ✦ Largest uncertainty is $|V_{cb}|^2$ — inclusive determination is used.
- ✦ Measurement is consistent with SM, and C_{10} is SM-like.

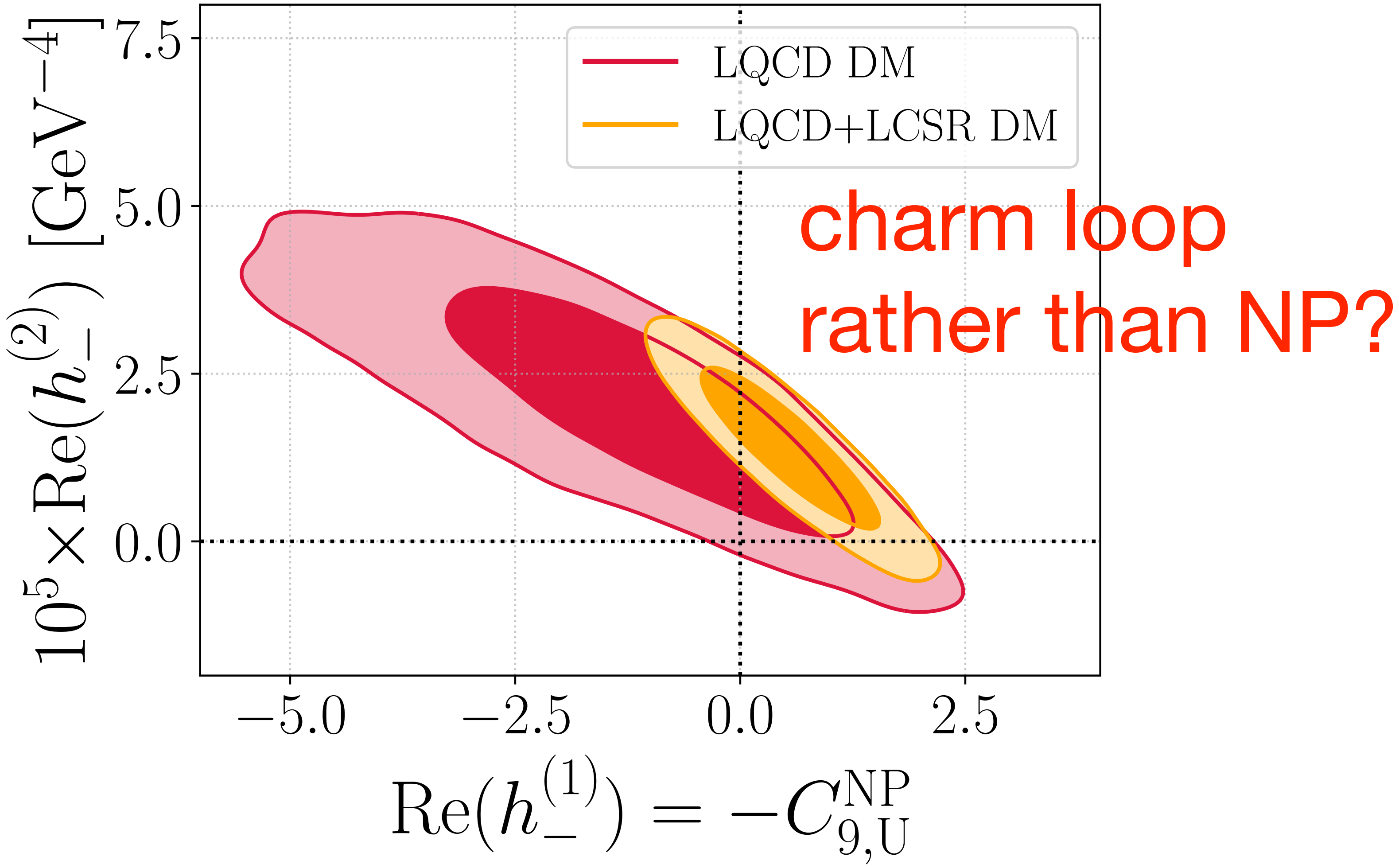
Anomaly or charm loop?

Capdevila et al., 2309.01311



ABCDMN, 2304.07330
AS/GSSS, 2212.10497
CFFPSV, 2212.10516
HMMN, 2104.10058

Ciuchini et al., 2607.03531



✦ $R_{K^{(*)}}$ agree with SM → Re(C_9) deficit is LFU.

✦ Significance depends on the treatment of the non-local charm loop.

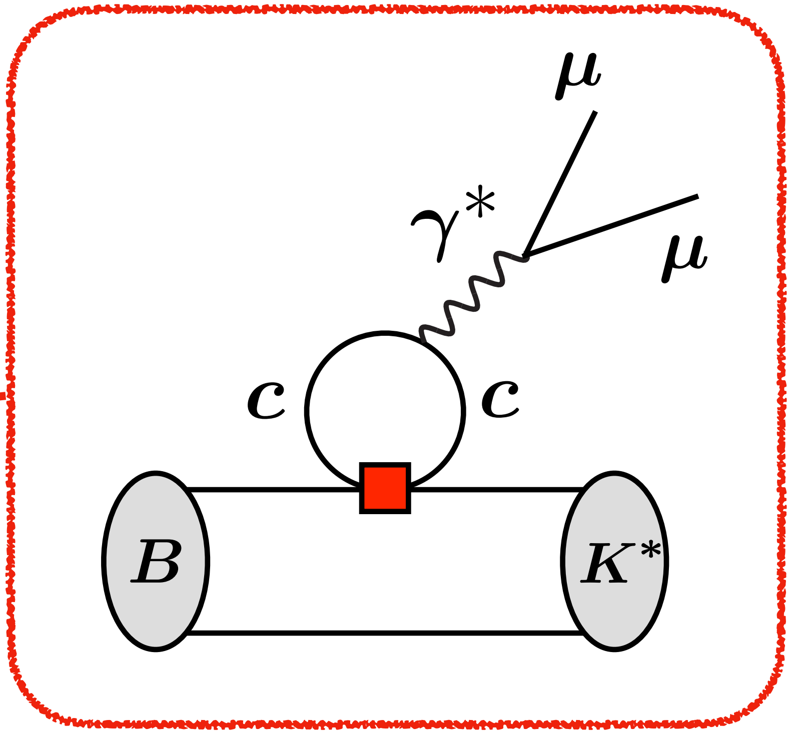
Hadronic inputs

$$L^{\mu}_{V(A)} \equiv \bar{u}_\ell\, \gamma^\mu (\gamma_5)\, v_\ell$$

$$\mathcal{A}(B \to K^{(*)}\ell^+\ell^-)$$
$$= \mathcal{N}\left[(C_9\, L^\mu_V + C_{10}\, L^\mu_A)\, \mathcal{F}^{B\to K^{(*)}}_\mu(q^2) - \frac{L^\mu_V}{q^2}\left(2 i m_b\, C_7\, \mathcal{F}^{B\to K^{(*)}}_{T,\mu}(q^2) + 16\pi^2\, \mathcal{H}^{B\to K^{(*)}}_\mu(q^2)\right)\right]$$

- ✦ Two hadronic inputs
  - Local form factors (FFs):

$$\mathcal{F}^{B\to K^{(*)}}_\mu(q^2) \equiv \langle K^{(*)}|\, \bar{s}\, \gamma_\mu P_L\, b\, |B\rangle$$
$$\mathcal{F}^{B\to K^{(*)}}_{T,\mu}(q^2) \equiv \langle K^{(*)}|\, \bar{s}\, \sigma_{\mu\nu} q^\nu P_R\, b\, |B\rangle$$



  - Non-local charm loop:

$$\mathcal{H}^{B\to K^{(*)}}_\mu(q^2) \equiv i \int d^4x\, e^{iq\cdot x}\, \langle K^{(*)}|\, T\{j^{\text{em}}_\mu(x),\, (C_1\mathcal{O}_1 + C_2\mathcal{O}_2)(0)\}\, |B\rangle$$

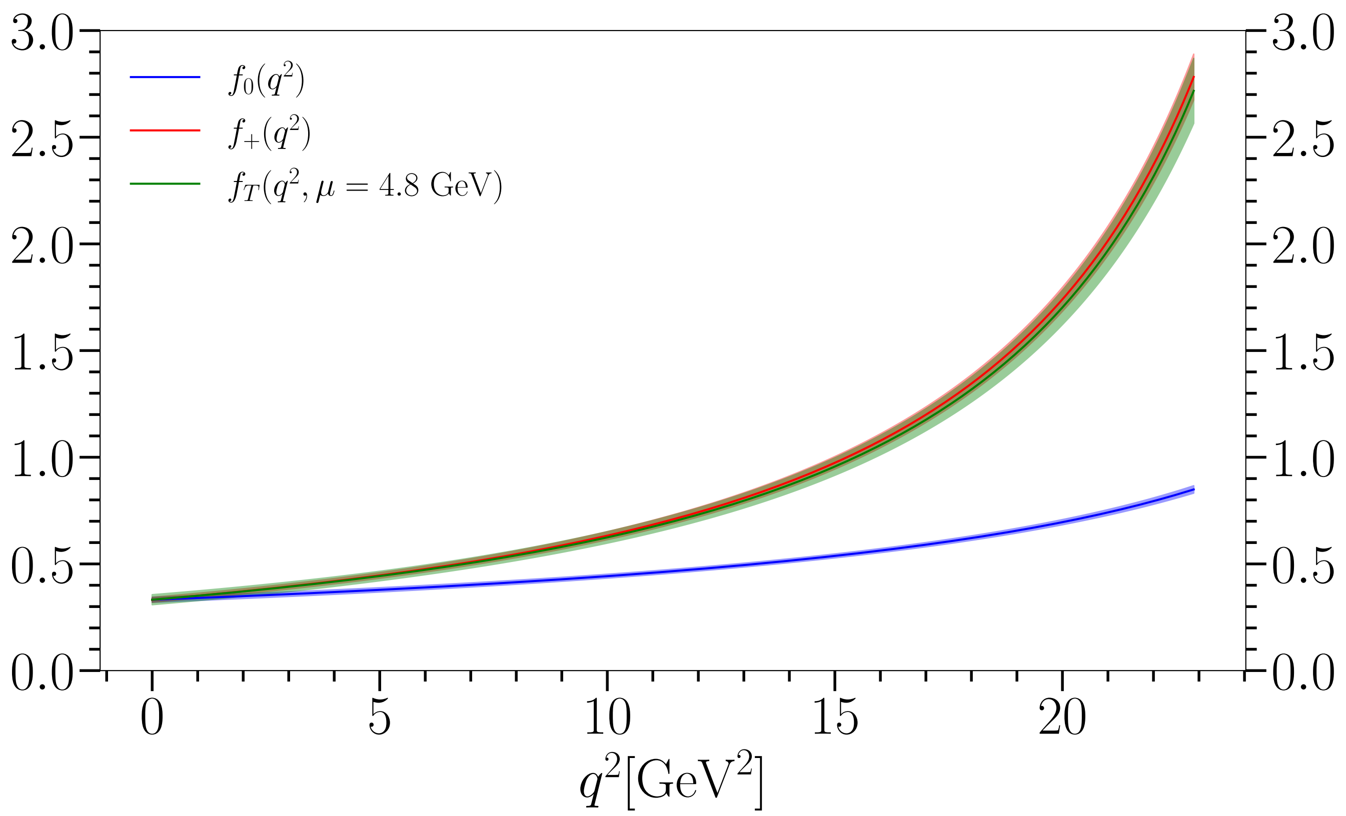
Outline

- Hadronic uncertainties
  - local form factors
  - non-local charm loop
- Disentangling NP and hadronic effects
  - q^2 and channel dependences of C_9
  - absorptive parts / CPV
  - inclusive $B \to X_s \ell^+ \ell^-$
- Summary

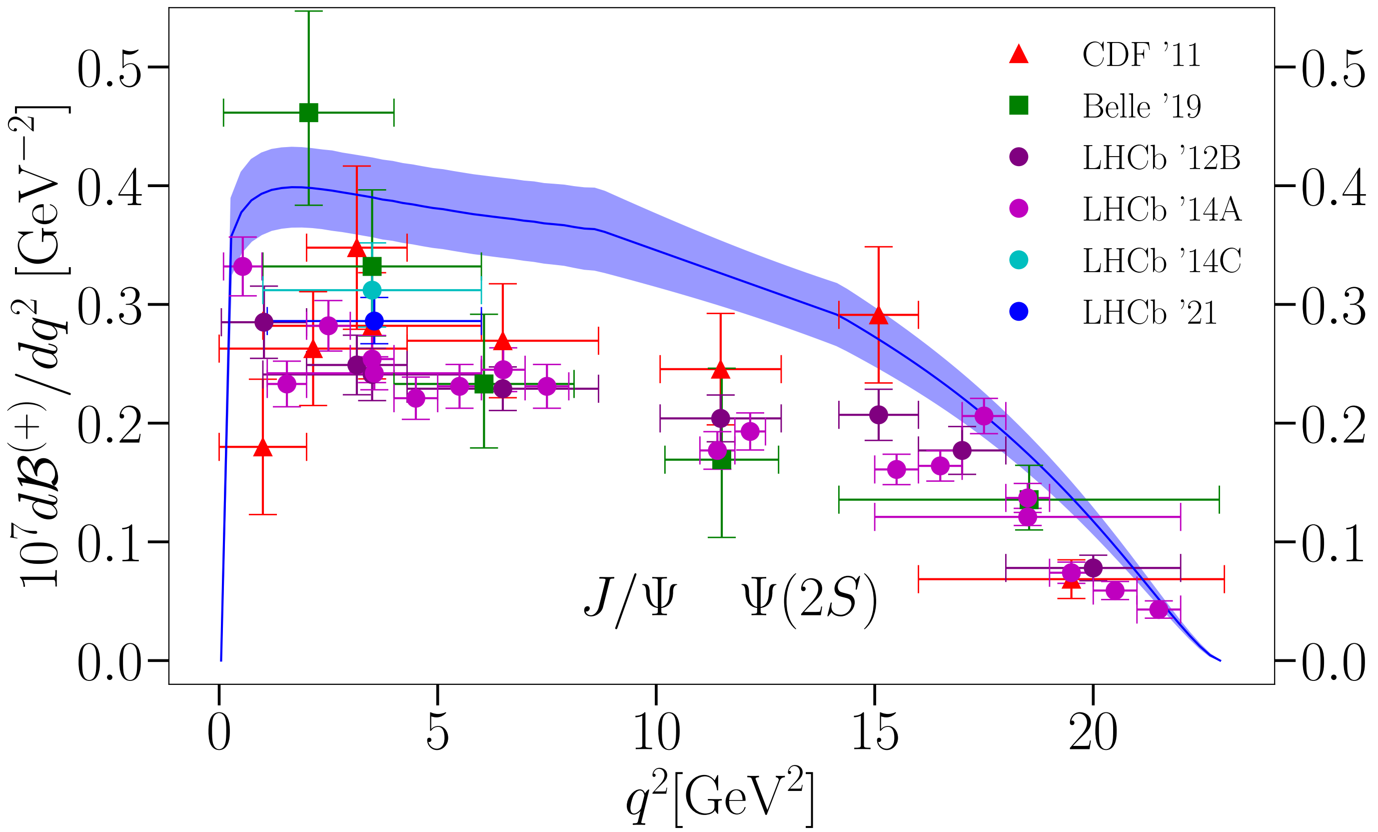
Hadronic uncertainties

- local form factors
- non-local charm loop

$B \to K$



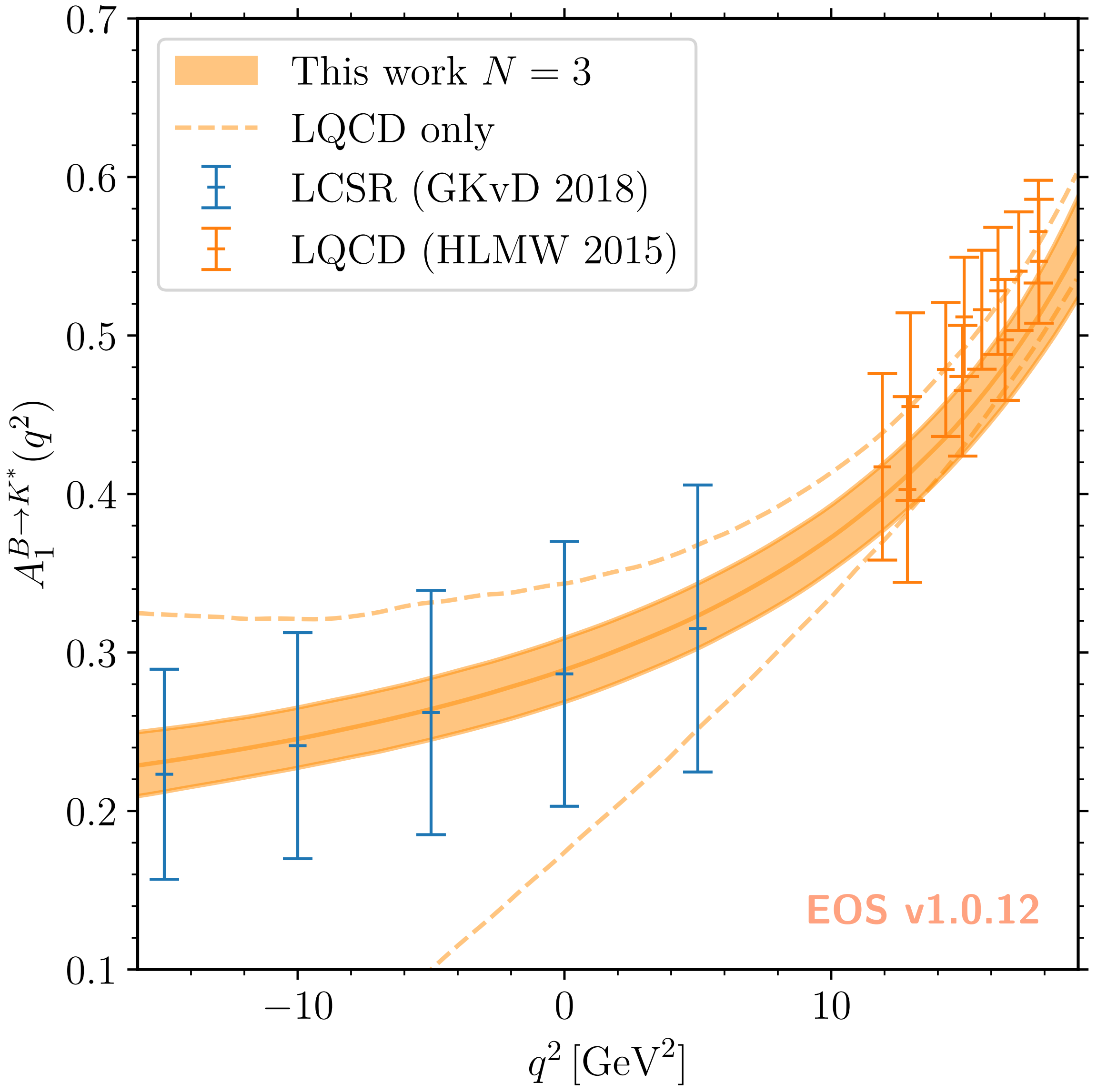
Parrott et al. [HPQCD], 2207.12468



Parrott et al. [HPQCD], 2207.13371

- ✦ Lattice covers **full q^2** with uncertainties <4% for f_0, f_+ and <7% for f_T.
- ✦ $B \to K\mu\mu$: tensions with LHCb up to **4.2σ** at low q^2 and **2.7σ** at high q^2.
- ✦ No independent lattice result of comparable precision yet.

$B \to K^*$



Gubernari et al., 2305.06301

- No lattice at low q² — FFs rely on LCSR.
- Low-q² results are limited by LCSR systematics.
- Lattice treats $K^*(\to K\pi)$ as stable (narrow width), while finite-width effects are estimated at ~10% in the form factors (~20% in rates) in LCSR.

Descotes-Genon et al., 1908.02267

- First finite-width lattice calculations have just started.

Leskovec et al., 2501.00903
Erben et al., 2603.17900

Extrapolation

- $B \to K^*$ FFs must be extrapolated in q^2.
  - **simple z-expansion** (BSZ) — no control of truncation error.

    Bharucha et al., 1503.05534

  - **z-expansion + dispersive bound** (BGL, GRvDV, GG) — unitarity limits the sum of coefficients: $\sum_n |a_n|^2 \leq 1$

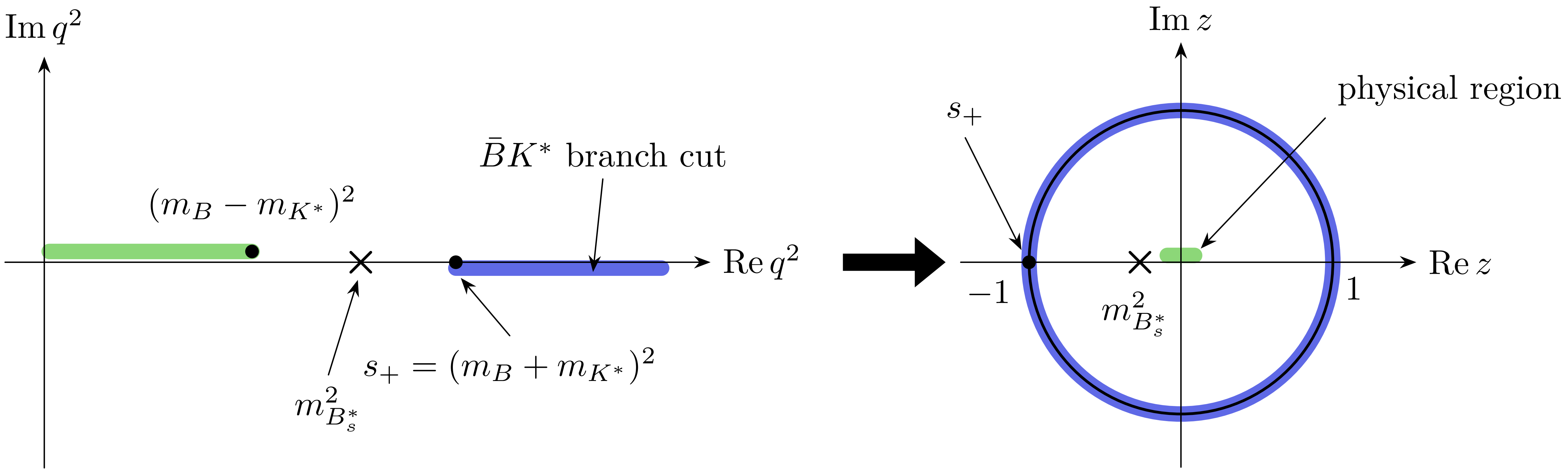
    Boyd et al., hep-ph/9705252
    Gubernari et al., 2305.06301
    Gopal & Gubernari, 2412.04388

  - **dispersive matrix** (DM) — unitarity bound, without truncation.

    Di Carlo et al., 2105.02497
    Ciuchini et al., 2607.03531

Simple z-expansion (BSZ)

✦ Branch cut in q² plane is mapped onto |z|=1 circle.



✦ FFs are expanded as

Bharucha et al., 1503.05534

$$F_i(q^2) = \frac{1}{1 - q^2/m^2_{R,i}} \sum_{k=0}^{N} \alpha^i_k \left[z(q^2) - z(0)\right]^k \qquad \text{e.g., } m_{R,i} = m_{B_s^*} \text{ for } F_i = V$$

z-expansion + dispersive bound (BGL)

- Expand $\mathcal{G}_i(z)$, which is analytic in |z|<1.

Boyd et al., hep-ph/9705252

$$\mathcal{G}_i(z) \;\equiv\; \phi_i(z)\, B_i(z)\, F_i(z) \;=\; \sum_{n=0}^{\infty} a_n\, z^n \quad \longleftrightarrow \quad F_i(z) \;=\; \frac{1}{\phi_i(z)\, B_i(z)} \sum_{n=0}^{\infty} a_n\, z^n$$

- Blaschke factor $B_i(z)$ removes the poles, leaving the modulus on the circle unchanged.

$$B_i(z) = \frac{z - z_p}{1 - z\, z_p}\,, \qquad z_p = z(m_{R,i}^2)\,, \qquad \left|B_i(e^{i\theta})\right| = 1$$

- Outer function $\phi_i(z)$ is a known function, analytic and free of zeros in |z|<1.

$$\left|\phi_i(e^{i\theta})\right|^2 = \frac{2\pi\, w(s)}{\chi_{\mathrm{OPE}}} \left|\frac{ds}{d\theta}\right|$$

z-expansion + dispersive bound (BGL)

- Vacuum correlator of two b→s currents:

$$\Pi^{\mu\nu}(q) = i\int d^4x\, e^{iq\cdot x}\,\langle 0|T\{J^\mu(x)\,J^{\nu\dagger}(0)\}|0\rangle = \left(\frac{q^\mu q^\nu}{q^2} - g^{\mu\nu}\right)\Pi_V^1(q^2) + \frac{q^\mu q^\nu}{q^2}\,\Pi_V^0(q^2)$$

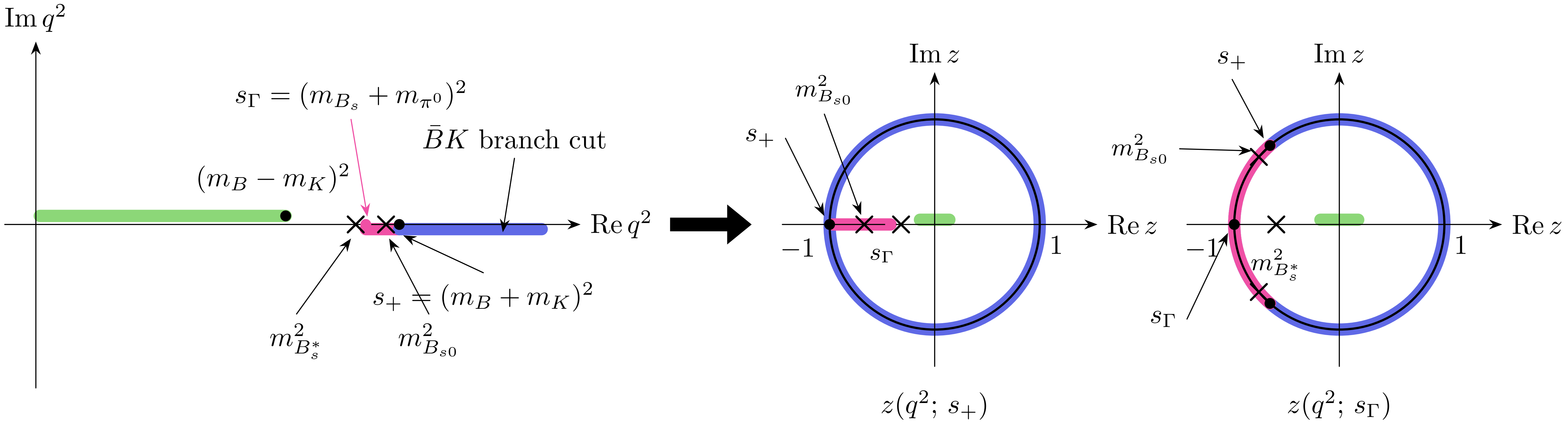
- Compute χ in two ways — OPE at q^2=0 (far below the $\bar{s}$b threshold) and optical theorem:

$$\chi = \underbrace{\frac{1}{k!}\left(\frac{\partial}{\partial q^2}\right)^k \Pi(q^2)\bigg|_{q^2=0}}_{\text{OPE}} = \underbrace{\frac{1}{\pi}\int_{s_+}^{\infty} ds\,\frac{\operatorname{Im}\Pi(s)}{s^{k+1}}}_{\text{optical theorem}}$$

- $\mathbf{Im}\,\boldsymbol{\Pi}(\boldsymbol{s})$ is a positive sum over all intermediate states. Keeping only *BK** and using crossing symmetry:

$$\operatorname{Im}\Pi(s) \geq w(s)\,|F_i(s)|^2 \implies \int_{s_+}^{\infty} ds\, w(s)\,\big|F_i(s)\big|^2 \;\leq\; \chi_{\rm OPE} \implies \sum_{n=0}^{\infty}|a_n|^2 \leq 1$$

Subthreshold cut

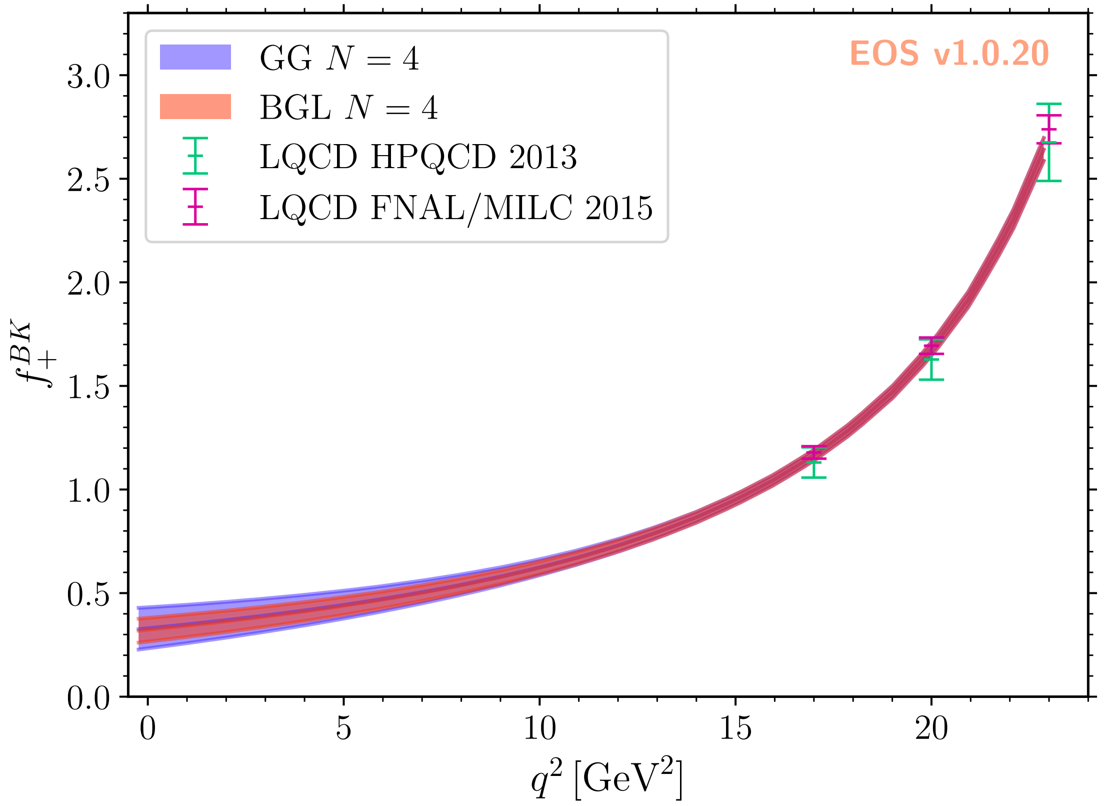


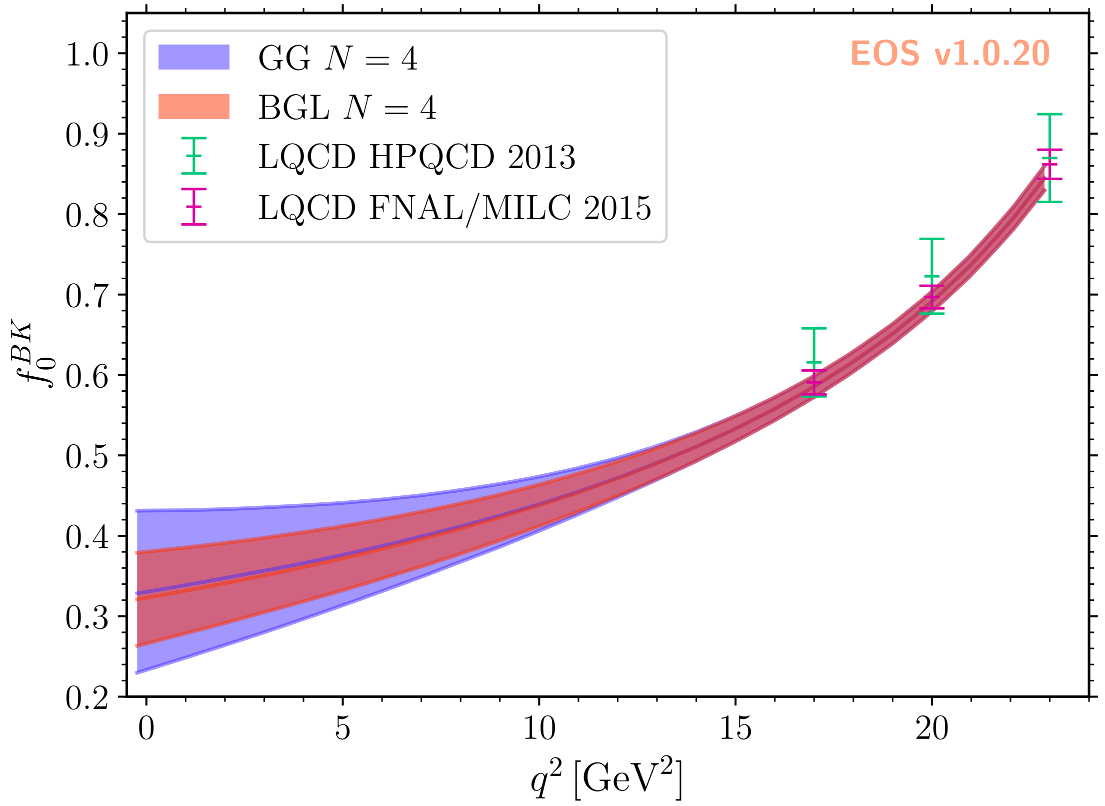
- ✦ Lightest two-particle state is not *BK* but $B_s\pi^0$ (isospin-suppressed).
- ✦ Convergence and $\sum_n |a_n|^2 \leq 1$ are invalidated by the position of the cut — no matter how weak it is.
- ✦ Remap with $z(q^2; s_\Gamma)$ and re-derive the bound:

$$\frac{1}{2\pi}\oint |\mathcal{G}|^2\, d\theta = \underbrace{\int_{\text{image of }[s_+,\infty)}}_{\leq\, \tilde{\chi}_{\text{OPE}}} + \underbrace{\int_{\text{image of }[s_\Gamma, s_+]}}_{\text{positive};\, \leq\, \Delta\chi} \leq\ \tilde{\chi}_{\text{OPE}} + \Delta\chi\,, \qquad \Delta\chi < 1\%\text{ of }\chi_{\text{OPE}}\,.$$

Gopal & Gubernari, 2412.04388

z-expansion + dispersive bound (GG)



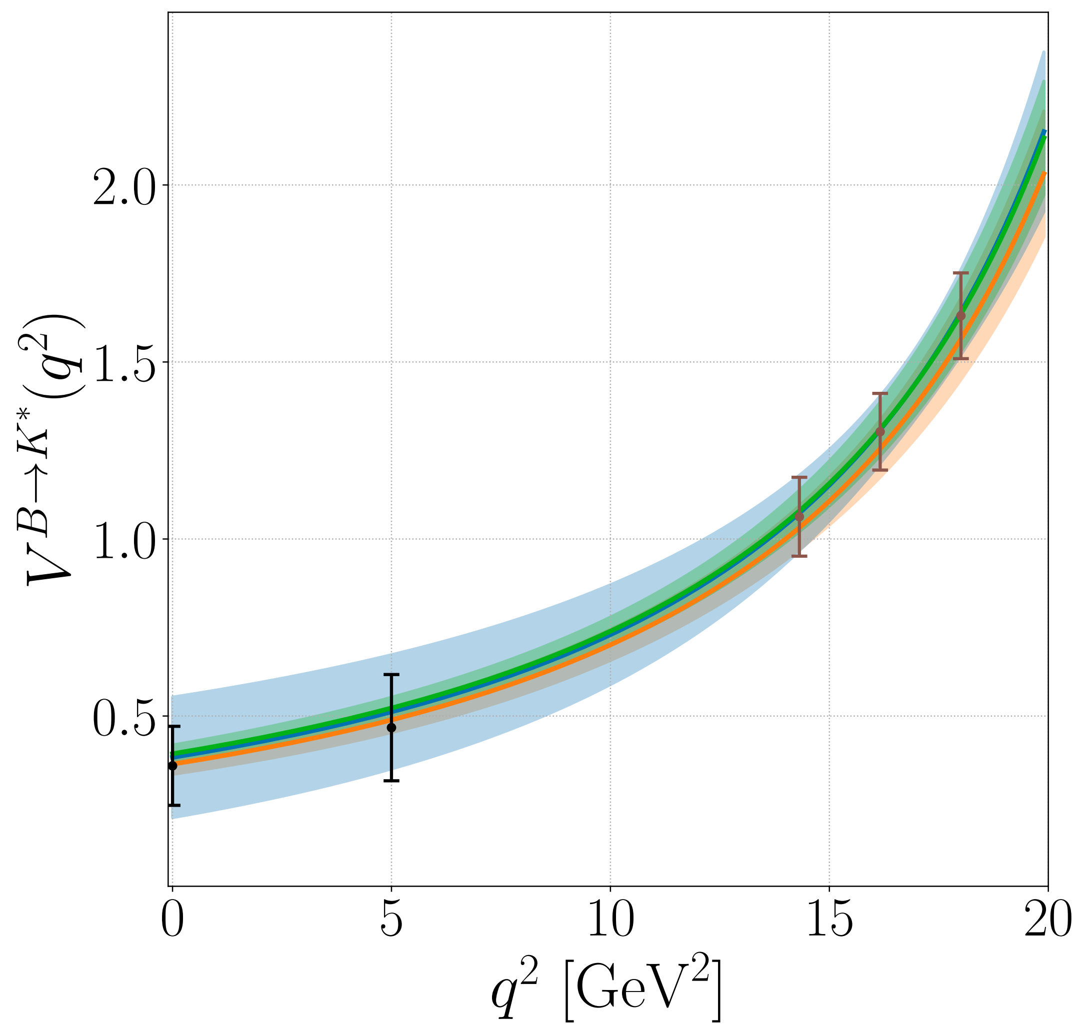


Gopal & Gubernari, 2412.04388
Gubernari, 2605.26213

- ✦ Lattice-only fits without HPQCD 2022, so that the difference is visible.
- ✦ Difference between BGL and GG (incl. subthreshold cut) is moderate for f_+ but substantially larger for f_0, where the interval $[s_\Gamma, s_+]$ contains a subthreshold scalar resonance, associated with a predicted B_{s0}^*.

Dispersive matrix (DM)

- DM combines the unitarity bound with the known FF values directly into two-sided bounds on the FF at any q^2.
- The band is spanned by all functions passing through the inputs and satisfying unitarity — no truncation.
- With LQCD+LCSR inputs, the DM band (green) agrees well with the BGL one (orange).



Di Carlo et al., 2105.02497
Ciuchini et al., 2607.03531
cf. Simula et al., 2509.00412

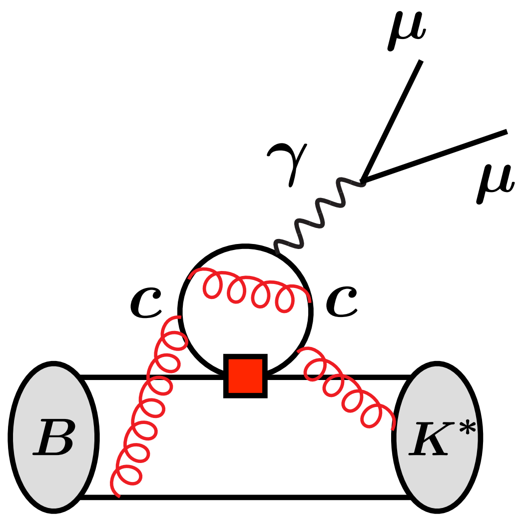
Hadronic uncertainties

- local form factors
- non-local charm loop

Non-local charm loop

$$\mathcal{A}(B \to K^{(*)}\ell^+\ell^-)$$
$$= \mathcal{N}\left[(C_9\, L_V^\mu + C_{10}\, L_A^\mu)\, \mathcal{F}_\mu^{B\to K^{(*)}}(q^2) - \frac{L_V^\mu}{q^2}\left(2 i m_b\, C_7\, \mathcal{F}_{T,\mu}^{B\to K^{(*)}}(q^2) + 16\pi^2\, \mathcal{H}_\mu^{B\to K^{(*)}}(q^2)\right)\right]$$

$$\mathcal{H}_\mu^{B\to K^{(*)}}(q^2) \equiv i\int d^4x\, e^{iq\cdot x}\, \langle K^{(*)}|\, T\{j_\mu^{\rm em}(x),\, (C_1\mathcal{O}_1 + C_2\mathcal{O}_2)(0)\}\, |B\rangle$$



- Narrow charmonia from tree-level $B\to\psi_n K^{(*)}$ dominate the spectrum and interfere with the C_9 term.

- No first-principles calculation over the physical region: the perturbative loop misses the charmonium structure, and there is no lattice result yet.

- q^2-flat part of charm loop is indistinguishable from an NP shift of C_9.

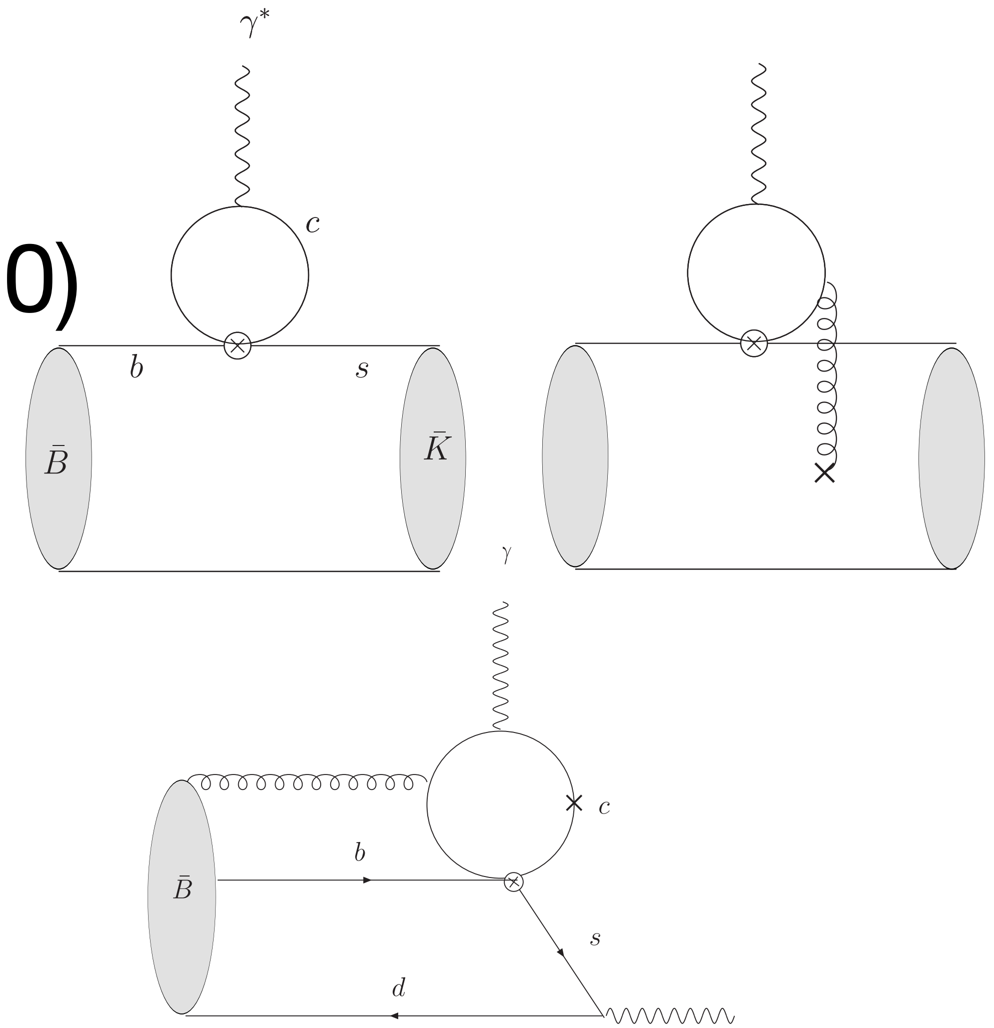
Light-cone OPE calculation

✦ LCOPE, valid for $4m_c^2 - q^2 \gg m_b \Lambda_{\rm had}$ (in practice $q^2<0$):

$$\mathcal{H}_\lambda^c(q^2) \simeq \underbrace{\Delta C_9(q^2)\,\mathcal{F}_\lambda + \Delta C_7(q^2)\,\mathcal{F}_{T,\lambda}}_{\text{leading power: NLO matching}\times\text{local FFs}} + \underbrace{\mathcal{H}_\lambda^{\rm soft}(q^2)}_{\text{soft gluon (3-particle } B\text{-LCDA)}} + \dots$$

- Leading power: 2-loop $\Delta C_{7,9}$.
- Soft gluon by GvDV (2020): ~10^{-2} × KMPW (2010) with the complete 3-particle B-LCDA basis.
- Theory anchor at q^2={-7,-5,-3,-1} GeV^2 — the physical region requires analytic continuation.

Asatrian et al., 1912.09099; Khodjamirian et al., 1006.4945; Gubernari et al., 2011.09813



Three parametrizations

- Three ways to describe $\mathcal{H}_\mu^{B\to K^{(*)}}(q^2)$ in the physical region:
  - **z-expansion + dispersive bound**

    Bobeth et al., 1707.07305; Gubernari et al., 2011.09813; 2206.03797
  - **Subtracted dispersion relation + measured resonances**

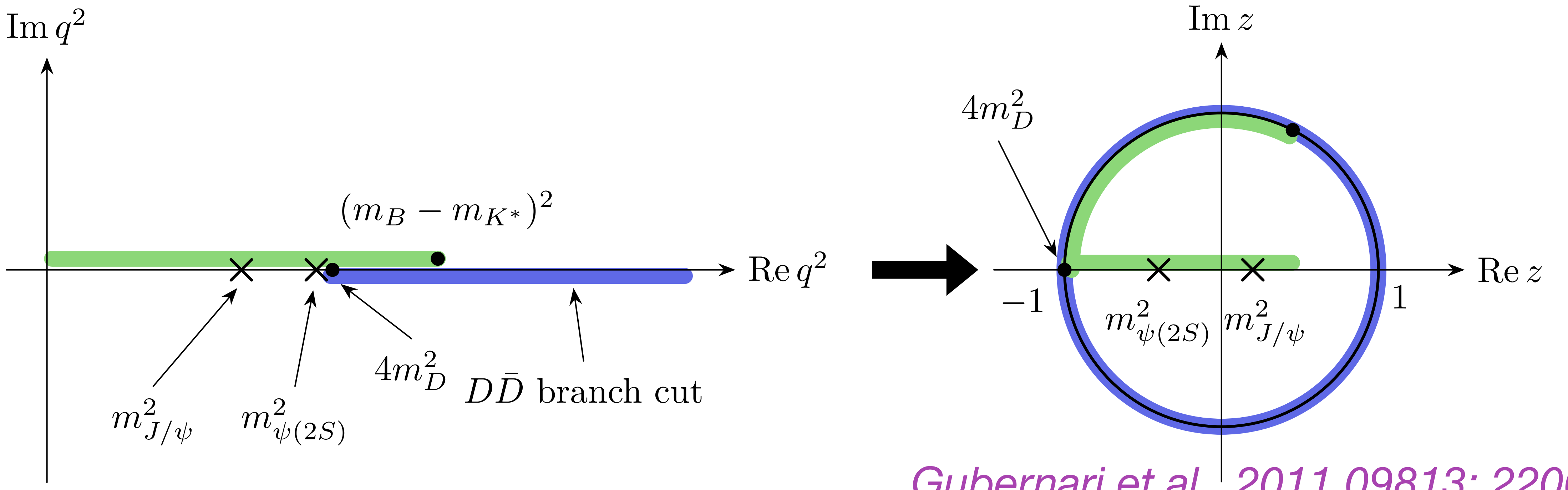
    Cornella et al., 2001.04470; LHCb, 2405.17347; Bordone et al., 2607.09458
  - **Polynomial ansatz** *Ciuchini et al., 1512.07157; 2212.10516; 2607.03531*

z-expansion + dispersive bound

$$\mathcal{H}_\lambda(q^2) = \frac{1}{\phi_\lambda(z)\,\mathcal{P}(z)} \sum_{n=0}^{N} \beta_{\lambda,n}\, p_n(z), \qquad \mathcal{P}(z) = \prod_{\psi = J/\psi,\, \psi(2S)} \frac{z - z_\psi}{1 - z\, z_\psi}$$

$$\sum_n \left\{ 2\left|\beta_{0,n}^{B\to K}\right|^2 + \sum_{\lambda=\perp,\parallel,0} \left[2\left|\beta_{\lambda,n}^{B\to K^*}\right|^2 + \left|\beta_{\lambda,n}^{B_s\to\phi}\right|^2 \right] \right\} < 1$$

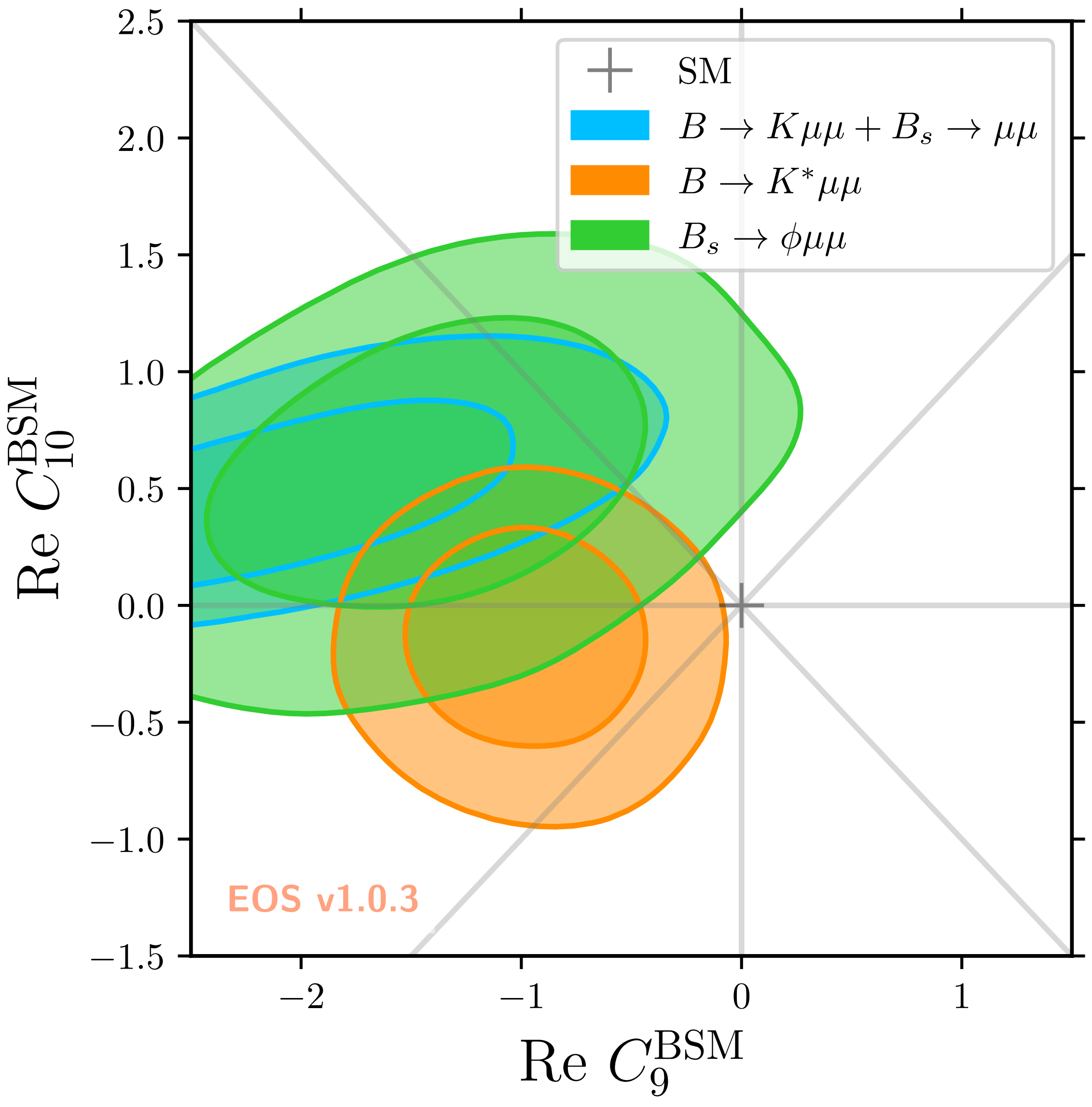
- ✦ The cut is mapped onto the unit circle, the poles into Blaschke factors.
- ✦ The dispersive bound controls the truncation error of the expansion.



Gubernari et al., 2011.09813; 2206.03797

z-expansion + dispersive bound (GRvDV)

- **Inputs**: LCOPE at q^2={-7,-5,-3,-1} GeV^2 + J/ψ residues from rates and polarizations for $B \to J/\psi K^{(*)}$, $B_s \to J/\psi \phi$.
- SM pull: 5.7σ ($B \to K\mu\mu$ + $B_s \to \mu\mu$), 2.7σ ($B \to K^*\mu\mu$), 2.6σ ($B_s \to \phi\mu\mu$).
- (ΔC_9, ΔC_{10}) = (-1.0, +0.4) is compatible with all channels at ~1σ.
- Floating the non-local FFs within the bound is insufficient to restore SM agreement.

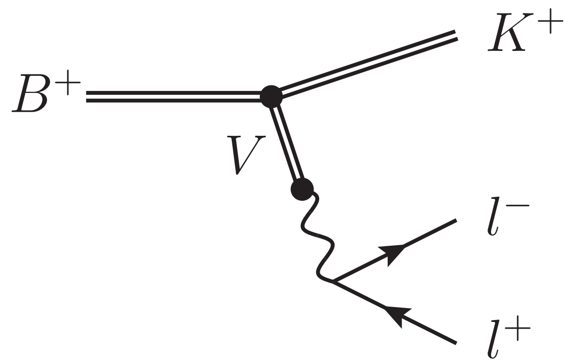


Gubernari et al., 2206.03797

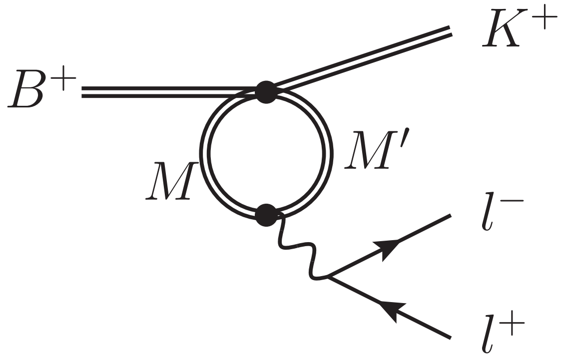
Subtracted dispersion relation + measured resonances

$$\mathcal{C}_9^{\text{eff},\lambda} = \mathcal{C}_9 + Y_\lambda(q^2)\,, \quad Y_\lambda(q^2) = Y_\lambda(q_0^2) + \frac{(q^2-q_0^2)}{\pi}\int_{4m_\mu^2}^{\infty}\frac{\rho_\lambda(s)}{(s-q_0^2)(s-q^2-i\epsilon)}\,\mathrm{d}s$$
$$= Y_\lambda(q_0^2) + \Delta Y_\lambda^{\text{1P}}(q^2) + \Delta Y_\lambda^{\text{2P}}(q^2)$$

- $Y_\lambda(q_0^2 = -4.6\,\text{GeV}^2)$ from 2-loop OPE.
- 1P amplitude is described by BW distribution with magnitude and phase fitted to data.



$$\Delta Y_\lambda^{\text{1P}}(q^2) = \sum_j |H_j^\lambda|\, e^{i\delta_j^\lambda}\, \frac{q^2-q_0^2}{m_j^2-q_0^2}\, \frac{m_j\Gamma_j}{(m_j^2-q^2)-i\,m_j\Gamma_j}$$



- 2P amplitude is described by two-body phase-space function with magnitude and phase fitted to data.

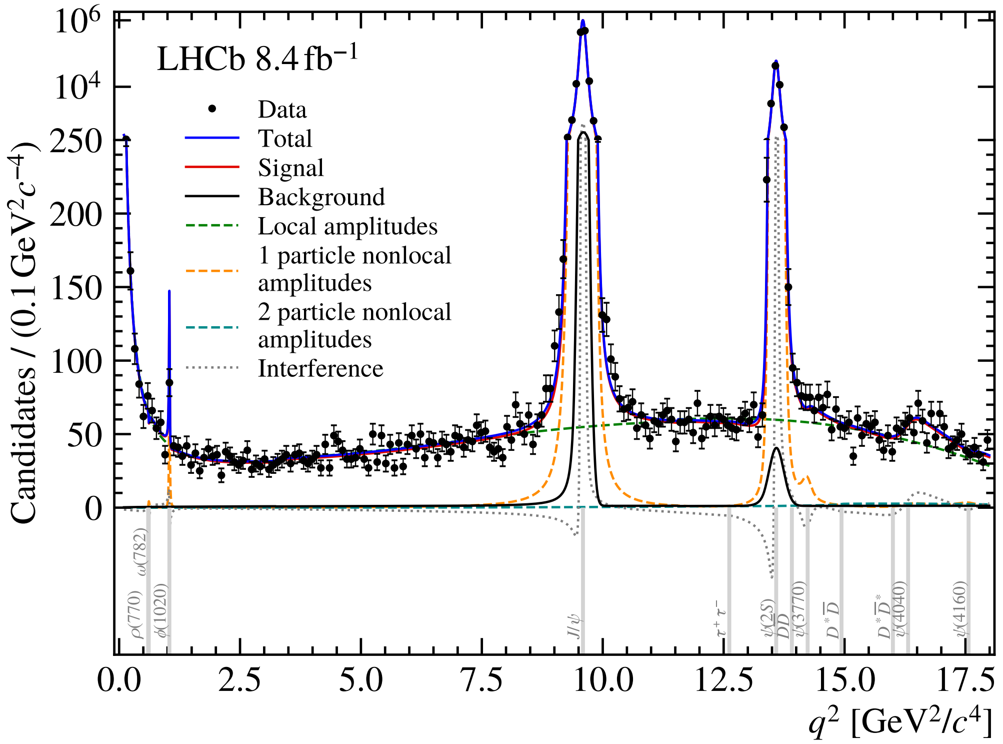
Cornella et al., 2001.04470; LHCb, 2405.17347; Bordone et al., 2607.09458

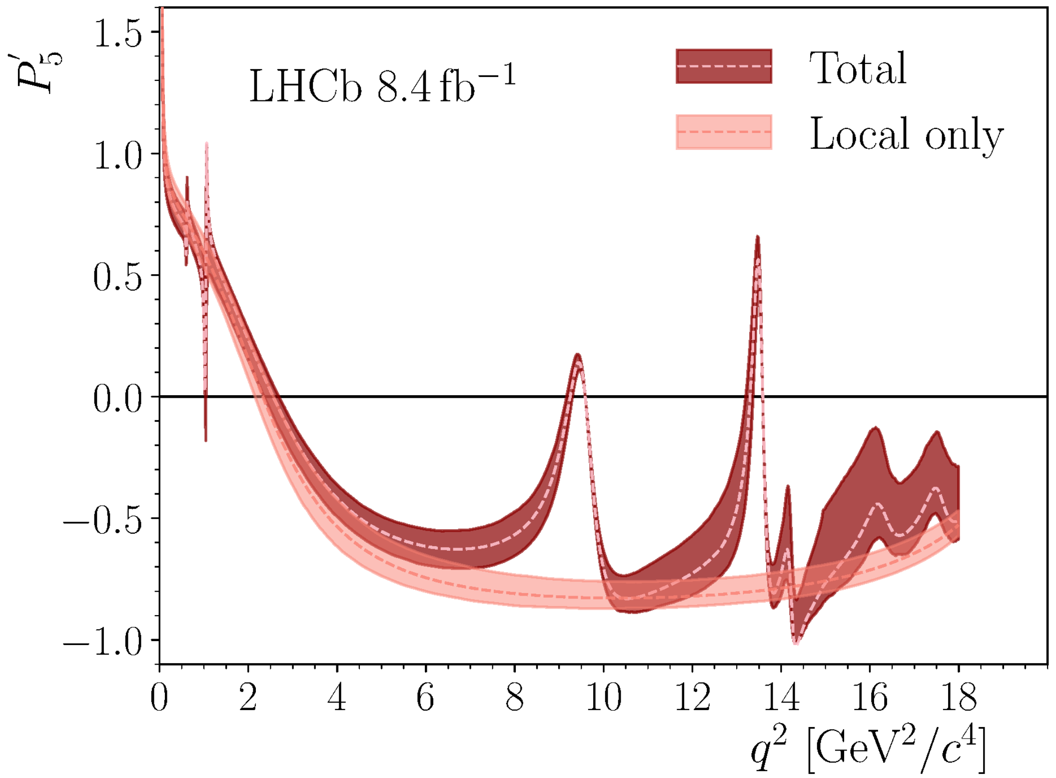
Subtracted dispersion relation + measured resonances (LHCb)

- Fit over the full q^2 range, including the *J/ψ* and *ψ(2S)* peaks: Wilson coefficients and non-local amplitudes determined simultaneously.
- Data prefer larger non-local contributions than theory predictions.
- Non-local contributions play a clear role in P_5', but **a 2.1σ tension** in C_9 persists.

$$\Delta\mathcal{C}_9^{\mathrm{NP}} = -0.71 \pm 0.33$$

LHCb, 2405.17347





Polynomial ansatz

$$h_-(q^2) = \frac{m_b}{8\pi^2 m_B}\,\widetilde{T}_{L-}(q^2)\,h_-^{(0)} + \frac{\widetilde{V}_{L-}(q^2)}{16\pi^2 m_B^2}\,h_-^{(1)}\,q^2 + h_-^{(2)}\,q^4 + \mathcal{O}(q^6)$$

$$\Rightarrow \quad \mathcal{H}_V^- \propto \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\rm SM} - h_-^{(0)}\right)\widetilde{T}_{L-} - 16\pi^2 h_-^{(2)} q^4\right] + \left(C_9^{\rm SM} - h_-^{(1)}\right)\widetilde{V}_{L-}$$

- Low-q^2 expansion (also h_+, h_0, h_K) with complex coefficients.
- No bound, no singularities are built in.
- $\mathrm{Re}(h_-^{(0)})$ and $\mathrm{Re}(h_-^{(1)})$ act as LFU shifts of C_7 and C_9, respectively, while the rest is genuinely hadronic.

Ciuchini et al., 1512.07157; 2212.10516; 2607.03531

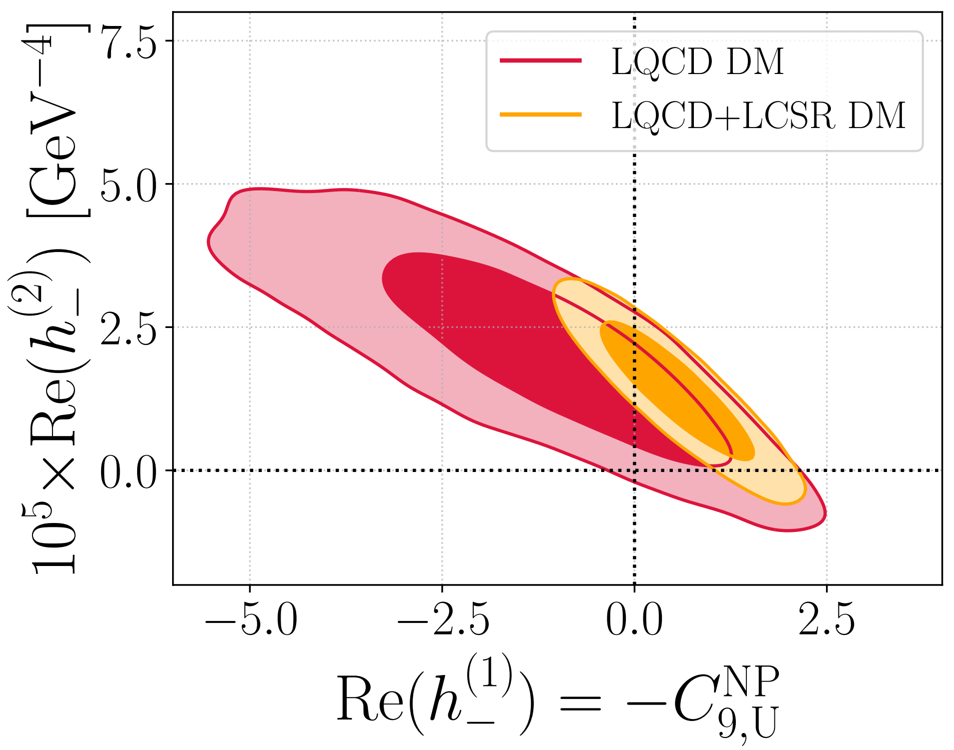
Polynomial ansatz (Rome)

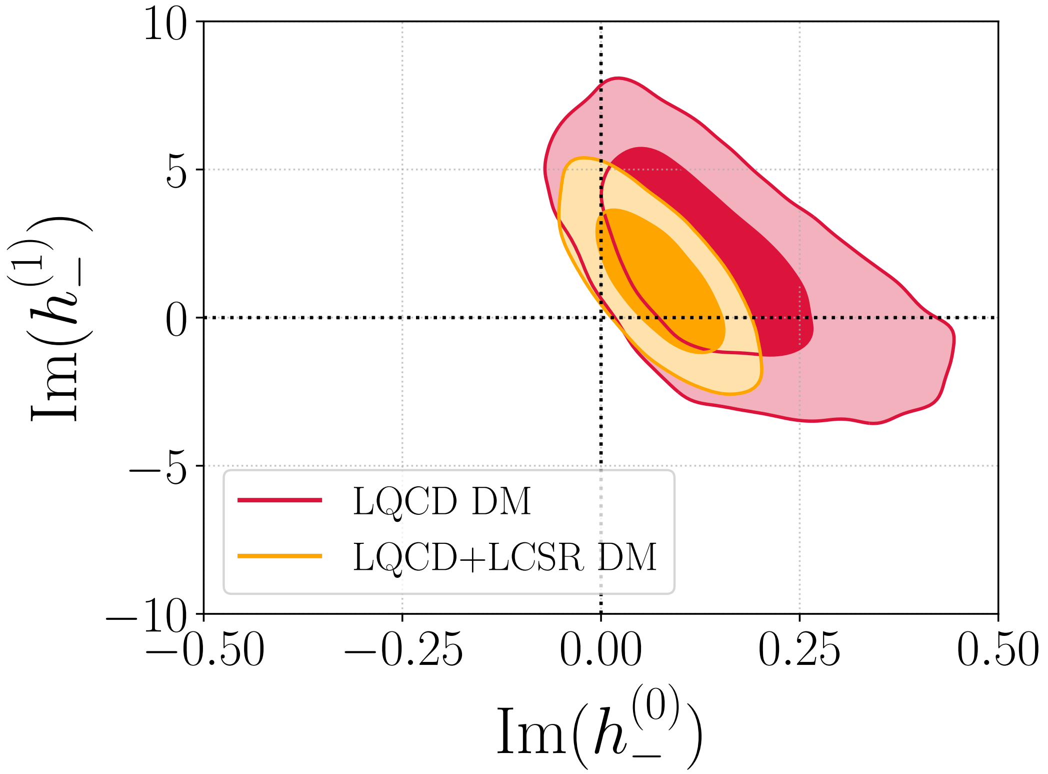
Ciuchini et al., 2607.03531

- No LCOPE inputs at negative q².
- No evidence for NP in C_9 (all $h_\lambda^{(i)}$ floated):

$$\mathrm{Re}\left(h_-^{(1)}\right) = -\Delta C_9 \in [-4.63,\ 1.82] \text{ at } 95\%$$

- Genuinely hadronic coefficients ($\mathrm{Re}(h_-^{(2)})$, imaginary parts) deviate from zero at the 1-2σ level.





Fit results

	GRvDV *Gubernari et al., 2206.03797*	**LHCb** *LHCb, 2405.17347*	**Rome** *Ciuchini et al., 2607.03531*
Parametrization	z-expansion + dispersive bound	Subtracted DR	Polynomial ansatz
Singularities	$D\bar{D}$ cut + $J/\psi, \psi(2S)$ poles (Blaschke)	Cut with explicit resonances (1P BW, 2P phase space)	None (low-q^2 expansion)
Theory input	LCOPE at $q^2 = \{-7, -5, -3, -1\}\,\mathrm{GeV}^2$	Subtraction constant at $q_0^2 = -4.6\,\mathrm{GeV}^2$	None
External data	J/ψ residues from $B \to J/\psi K^{(*)}$, $B_s \to J/\psi \phi$	Resonance masses and widths (PDG)	None
Charm loop from	Prediction (floated within priors)	Data over full q^2, anchored at q_0^2	Data only (flat priors)
ΔC_9 vs charm loop	Separated by prediction	Separated by anchor	Degenerate with $\mathrm{Re}\, h_-^{(1)}$ by construction
SM pull	**5.7σ** ($B \to K\mu\mu$ + $B_s \to \mu\mu$), **2.7σ** ($B \to K^*\mu\mu$)	**2.1σ** ($\Delta C_9^{\mathrm{NP}} = -0.71 \pm 0.33$, $B^0 \to K^{*0}$)	**None**: ΔC_9^{NP} at 95%, $[-1.82, 4.63]$ (LQCD FF), $[-1.82, 0.74]$ (LQCD+LCSR FF)

Caveats

Ciuchini et al., 2212.10516; Mutke et al., 2406.14608; Isidori et al., 2405.17551; 2507.17824; Hoferichter et al., 2604.01284

- **z-expansion + dispersive bound (GRvDV)**
  - Charm-meson rescattering is not in the partonic LCOPE input.
    - ➡ Model estimate: a few % (up to ~20% only if tuned, with strong q^2 dependence).
  - Anomalous branch cuts from charm-meson rescattering are ignored.
    - ➡ Present in the OPE input; hadron-level estimate still absent, expected small.
  - Higher-twist soft-gluon terms are not converged ($B_s \to \phi$). *Alam Khan et al., 2502.08427*
- **Subtracted dispersion relation + measured resonances (LHCb)**
  - Constant-width BW fails for broad charmonia.
  - Subtraction constant $Y(q_0^2)$ is a constant offset to C_9 — degenerate with NP.
- **Polynomial ansatz (Rome)**
  - Low-q^2 only.
  - Conservative, but it gives up in determining NP in C_9.

Disentangling NP and hadronic effects

- q^2 and channel dependences of C_9
- absorptive parts / CPV
- inclusive $B \to X_s \ell^+ \ell^-$

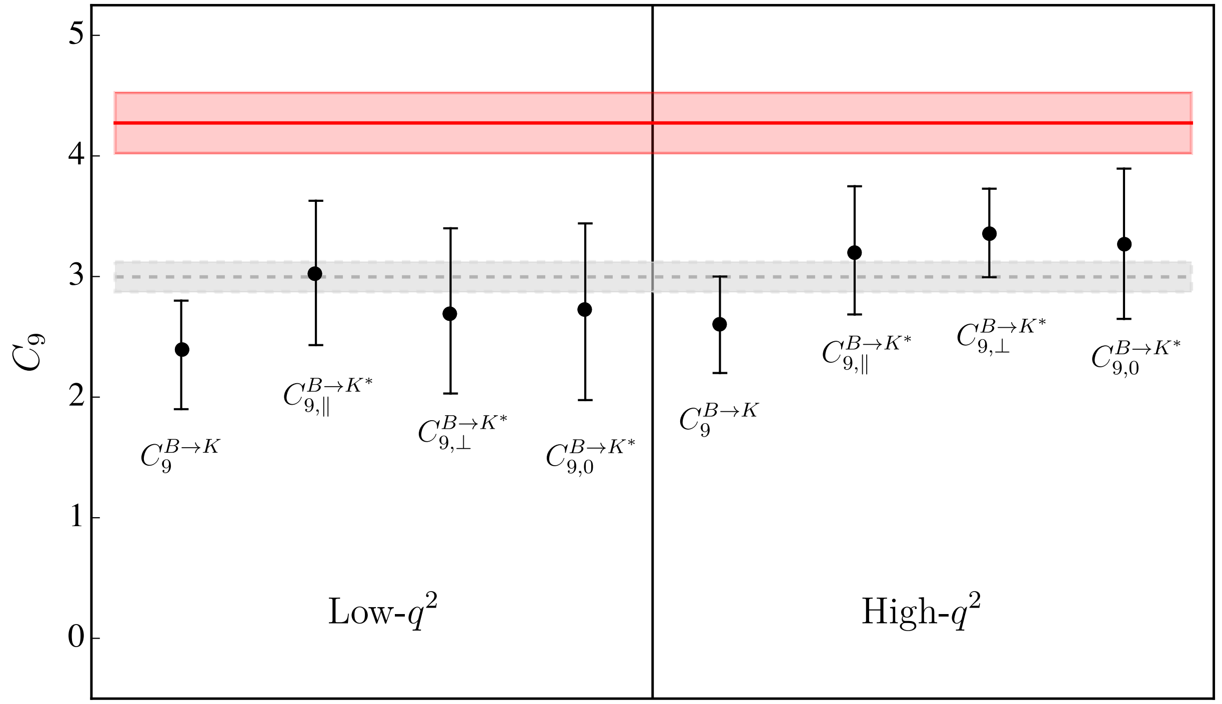
NP vs hadronic effects

- **NP**: a q^2-independent shift in C_9 (can be complex).
- **Hadronic**: generically q^2/channel-dependent, with strong phases.

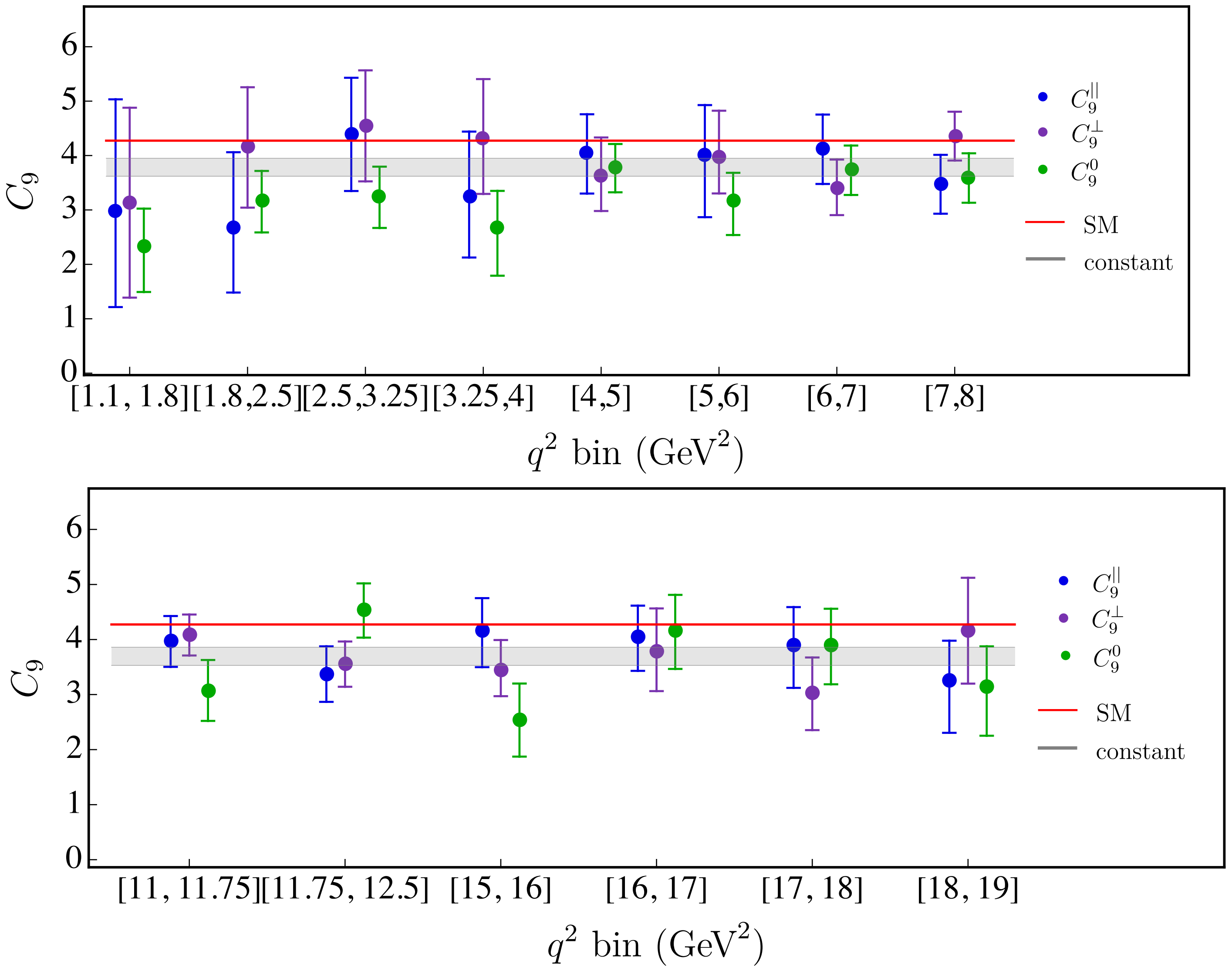
- Three discriminators:
  - **q^2 and channel dependences of C_9**
  - **Absorptive parts / CPV**: strong phases → hadronic
    new weak phases → NP
  - **Inclusive** $B \to X_s \ell^+ \ell^-$

q^2 and channel dependences of C_9

Bordone et al., 2401.18007



Bordone et al., 2607.09458



- ✦ Charm loop from subtracted DR + measured resonances.
- ✦ No significant q^2, channel and helicity dependences.

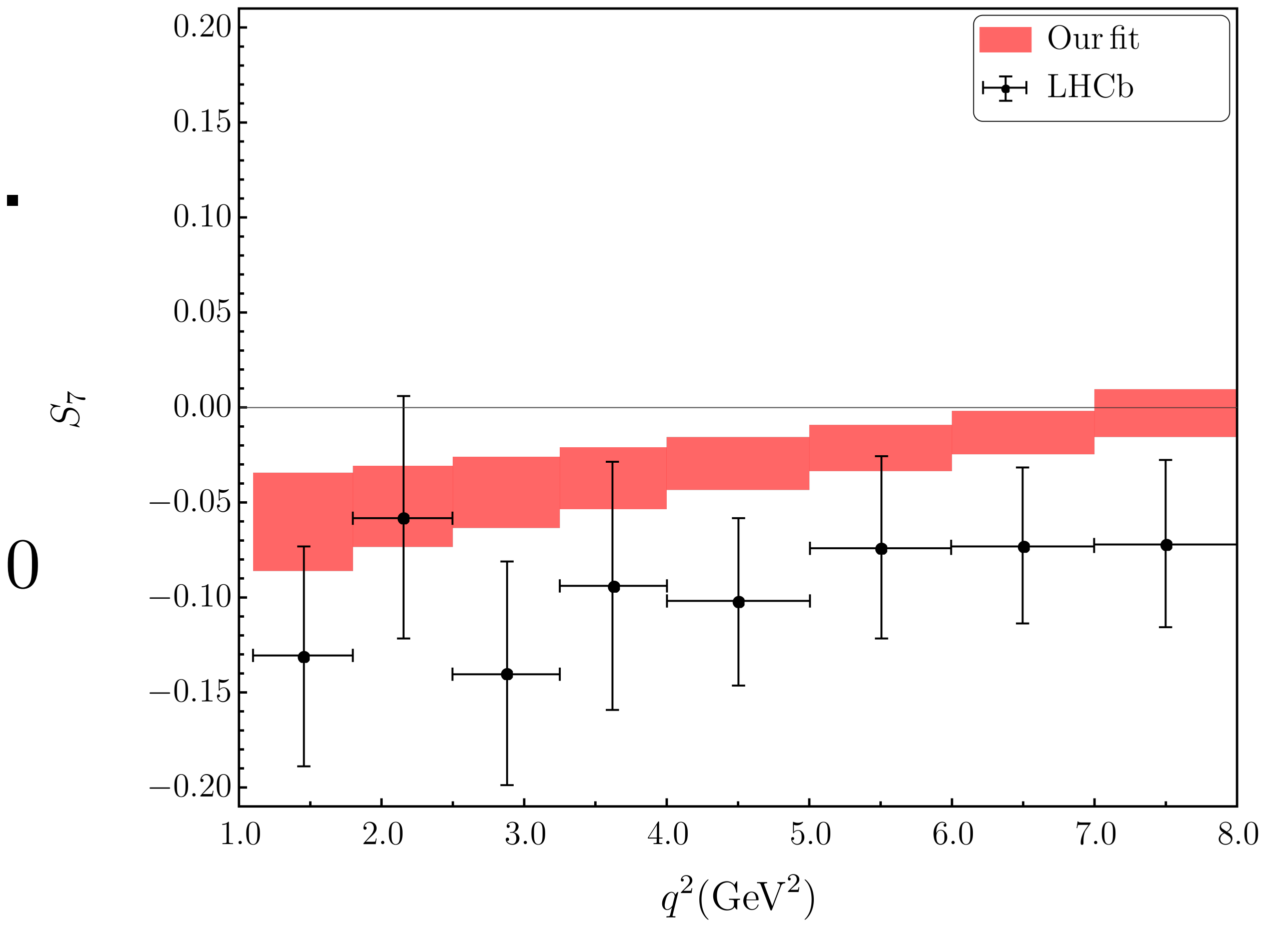
Absorptive parts

Bordone et al., 2607.09458
cf. Altmannshofer et al., 2603.27753

- S_7, S_8, S_9 are proportional to absorptive parts.
- Charm loop from subtracted DR + measured resonances.
- **Postdiction**: S_8, $S_9 \sim 0$, only S_7 nonzero, more precise than data.
- **Sum rule** holds for any absorptive parts in SM and in NP with same operator basis.
  → consistency check of data.

$$\frac{S_7(q^2)}{\kappa_7(q^2)\,\mathrm{Re}(C_{10})} - \frac{S_8(q^2)}{\kappa_8(q^2)\,\mathrm{Re}[C_9(q^2)]} - \frac{S_9(q^2)}{\kappa_9(q^2)\,\mathrm{Re}[C_9(q^2)]} \approx 0$$

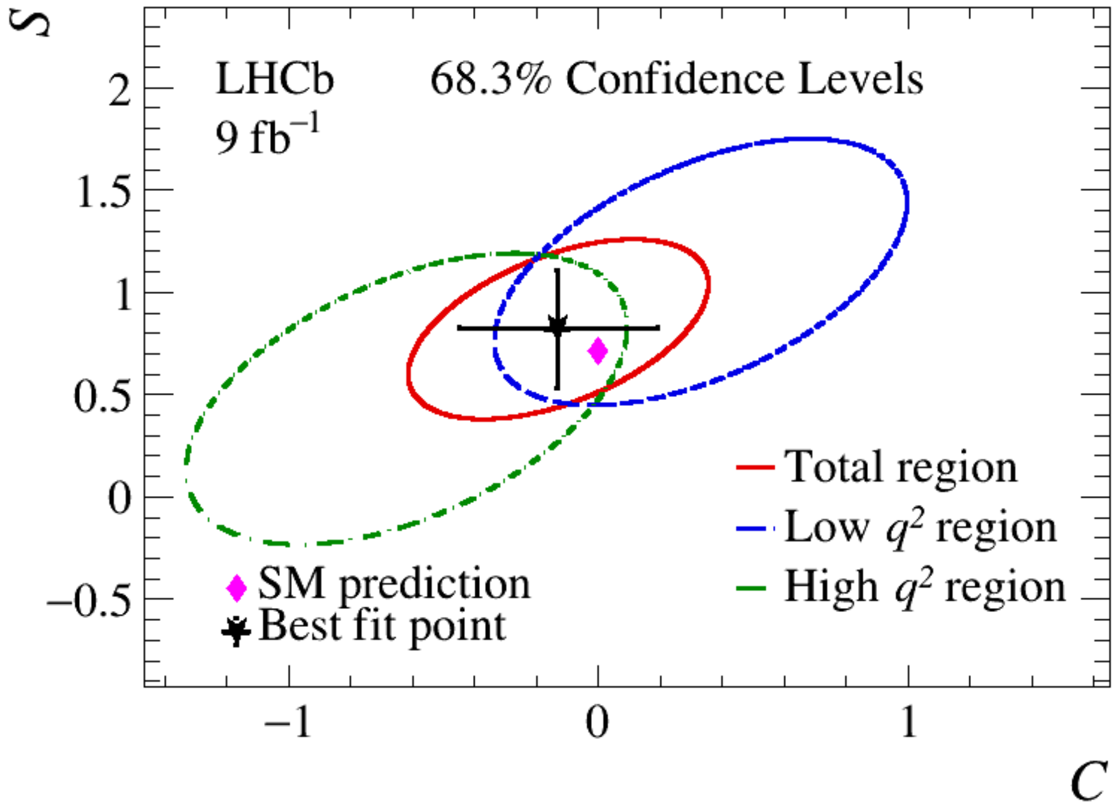
κ_i: kinematic factors, ratios of FFs



CP violation

- ✦ First direct probes of new CPV phases.

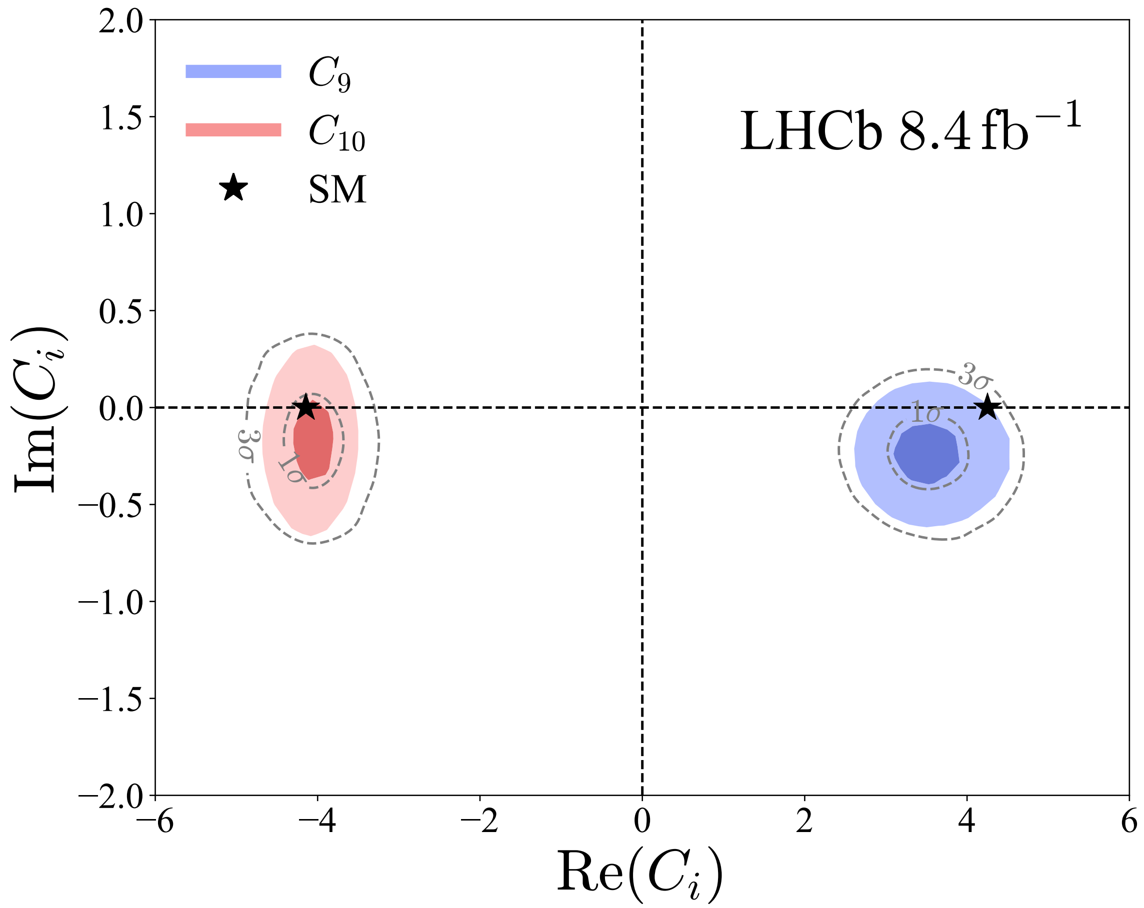
Time-dependent CPV in $B^0 \to K_S \mu^+ \mu^-$



$$S = 0.82 \pm 0.29\,(\text{stat}) \pm 0.05\,(\text{syst})$$
$$C = -0.13 \pm 0.32\,(\text{stat}) \pm 0.04\,(\text{syst})$$

LHCb, 2603.13223

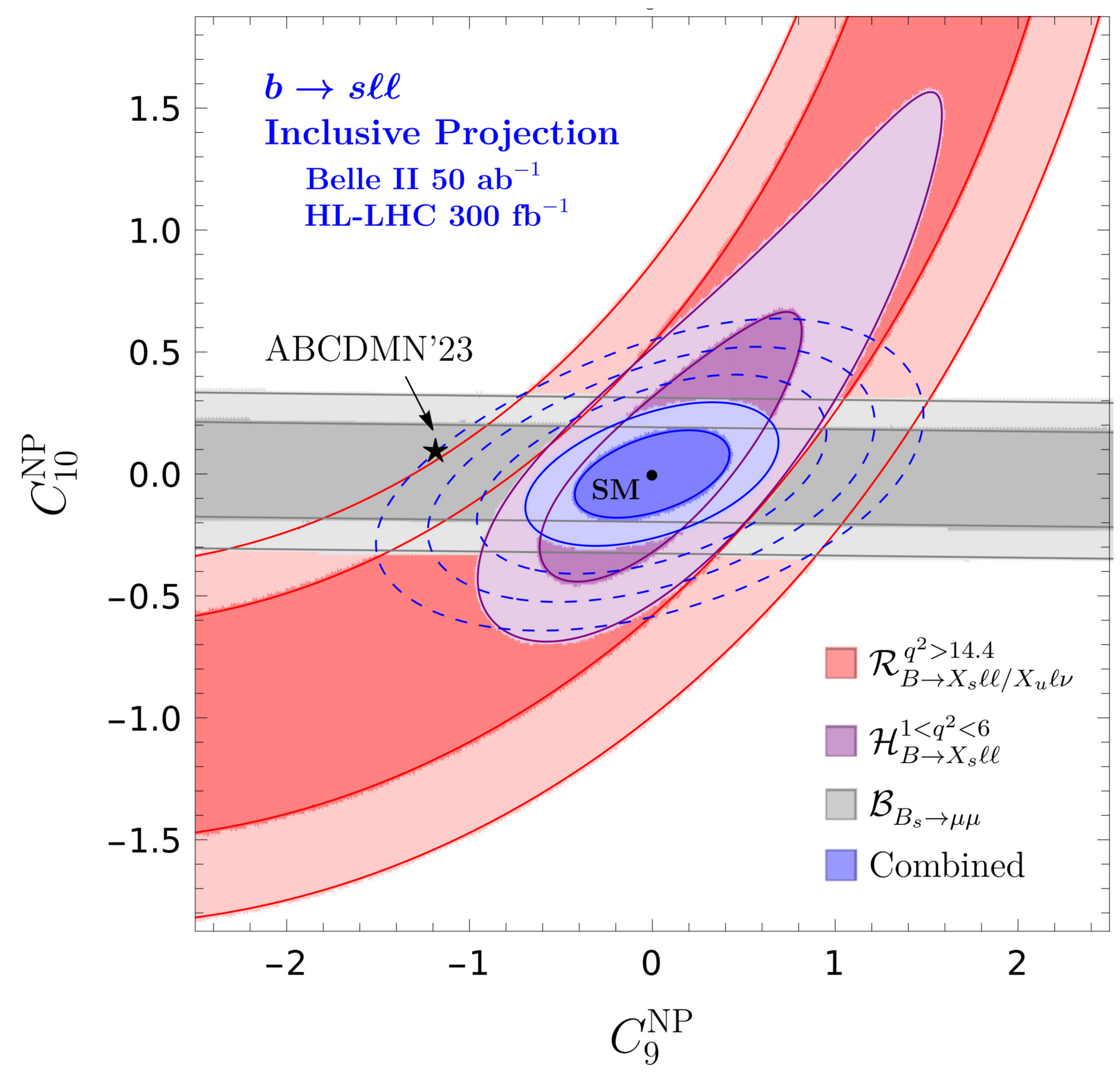
Direct CPV in $B^0 \to K^{*0} \mu^+ \mu^-$



$$\mathrm{Im}(\mathcal{C}_9) = -0.23 \pm 0.11\,(\text{stat}) \pm 0.04\,(\text{syst})$$

LHCb, 2605.07582

Inclusive $B \to X_s \ell^+ \ell^-$



projection centered on SM

Huber et al., 2404.03517

- ✦ Uncontrolled charm-loop part is power-suppressed.
- ✦ SM-like Belle II (50 ab^{-1}) + HL-LHC $B_s \to \mu\mu$ would exclude ΔC_9^{NP}=-1.

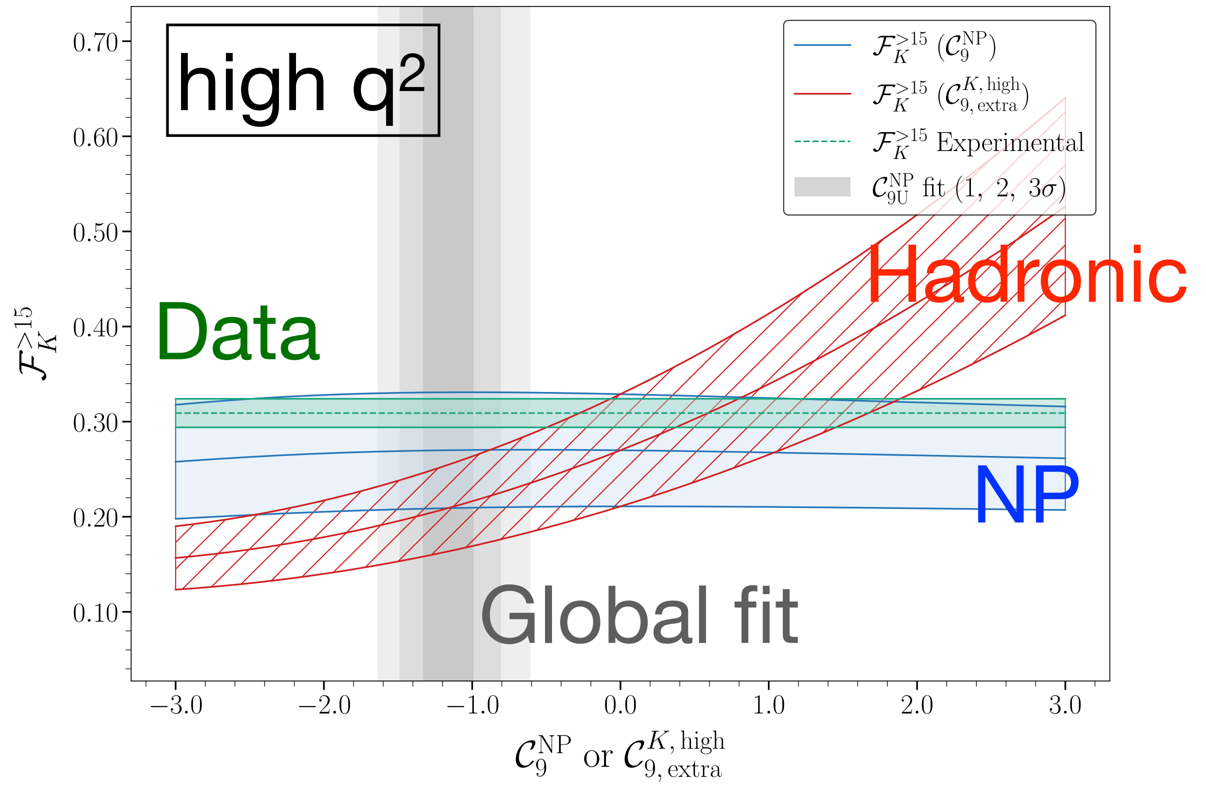
Inclusive $B \to X_s \ell^+ \ell^-$

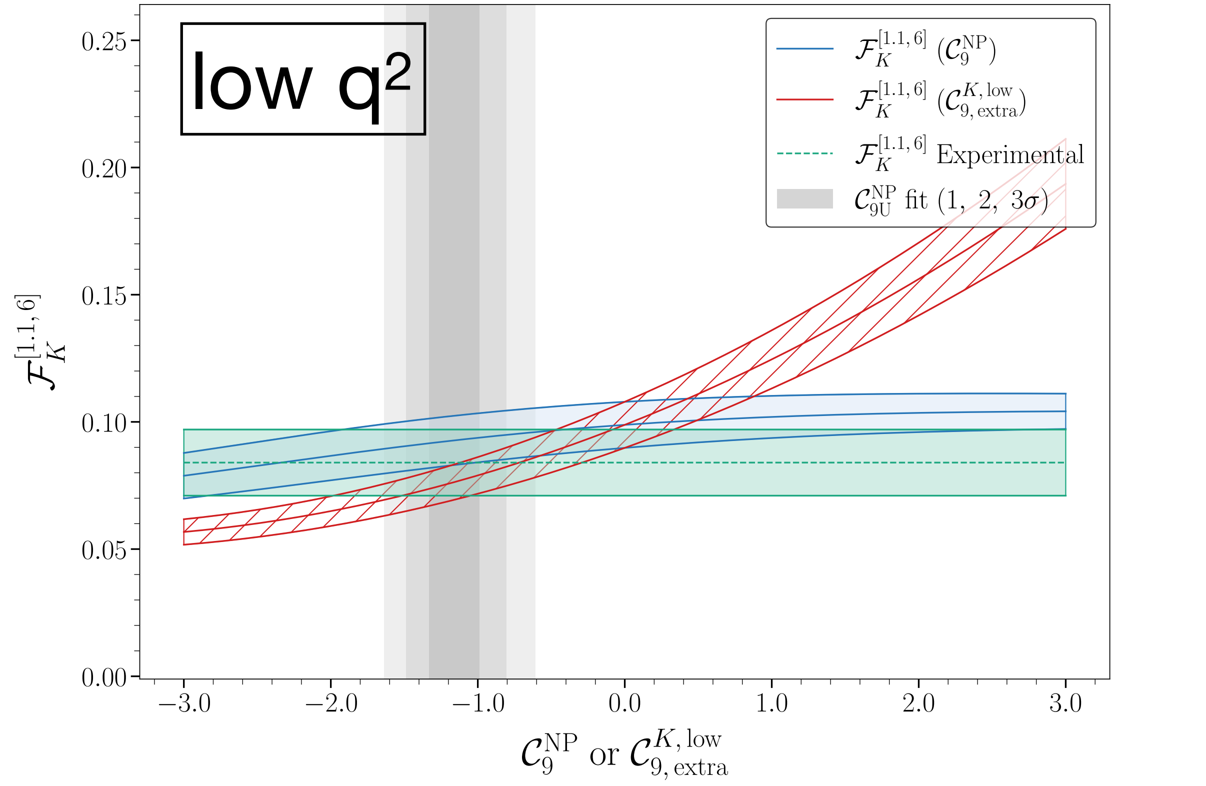
- $F_K = \mathcal{B}(B \to K\mu\mu) / \mathcal{B}(B \to X_s \ell\ell)$: nearly flat under NP — shifted if the deficit is hadronic in the exclusive mode.

- High q^2: inclusive is saturated by K, K^*, $(K\pi)_S$, $K\pi\pi$ → LHCb alone builds F_K; NP preferred at 2.0σ.

- Low q^2: a true inclusive measurement is needed — Belle II ~400 fb^{-1} now; F_K: 15% → ~10% with 1 ab^{-1}.

Alvarez-Cartelle et al., 2605.06567





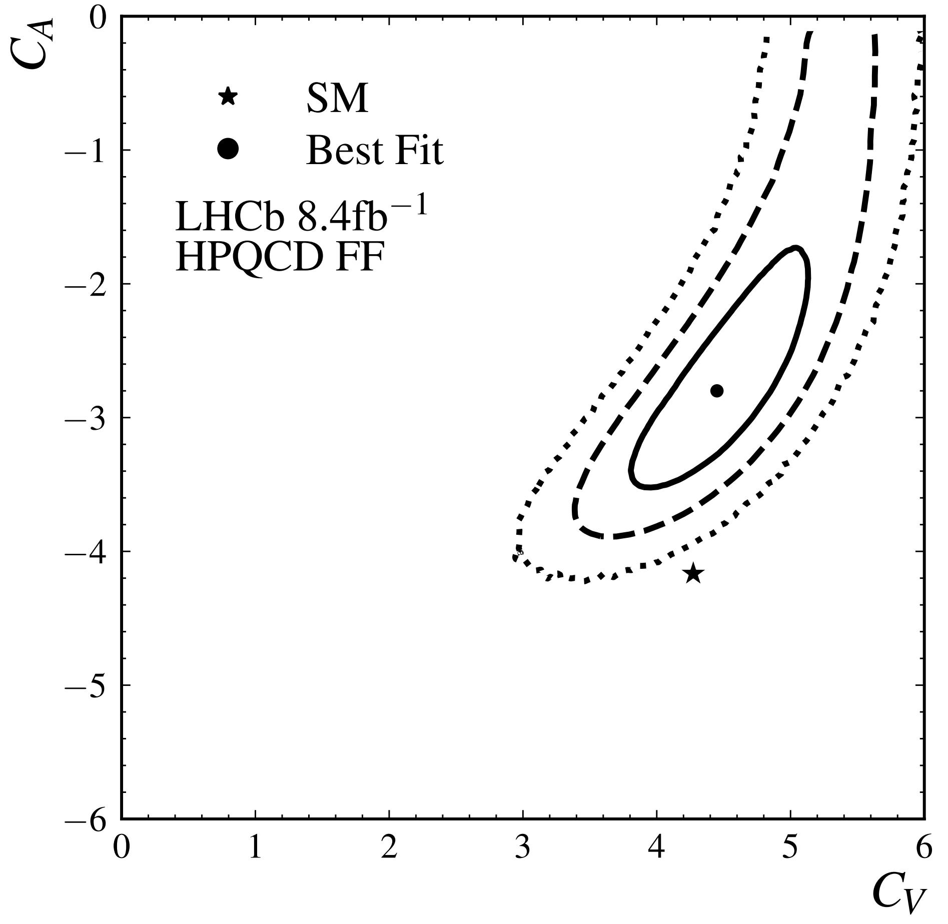
Summary

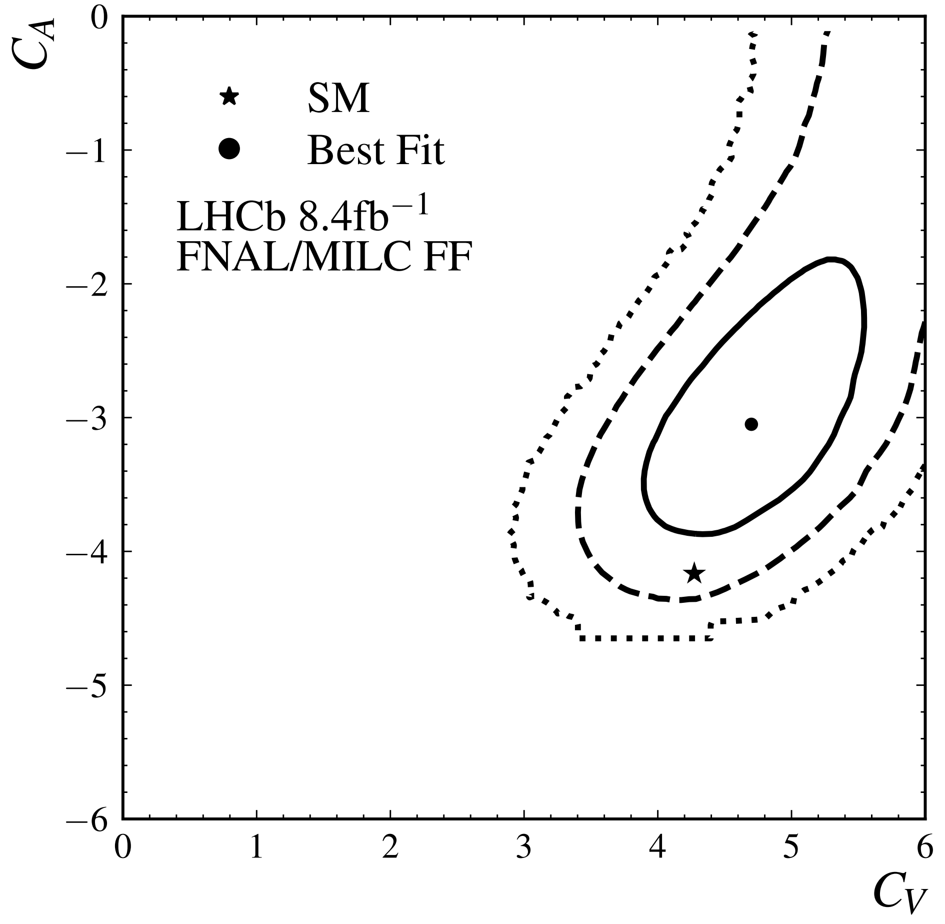
- ✦ C_{10} and $R_{K^{(*)}}$ are SM-like, and consistent with an LFU shift in C_9.
- ✦ All exclusive $B \to K^{(*)}\mu\mu$ analyses find C_9 below the SM value, except for the polynomial ansatz (Rome), where C_9 is consistent with the SM.
- ✦ The significance depends on how much the charm loop is fixed by data.
- ✦ Future tests include q^2 and channel dependences of C_9, absorptive parts, CPV, and inclusive $B \to X_s \ell^+ \ell^-$.
- ✦ A longer-term goal is a lattice QCD computation of the charm loop, for which a theoretical framework has been formulated.

Frezzotti et al., 2508.03655

Backup

$B \to K$



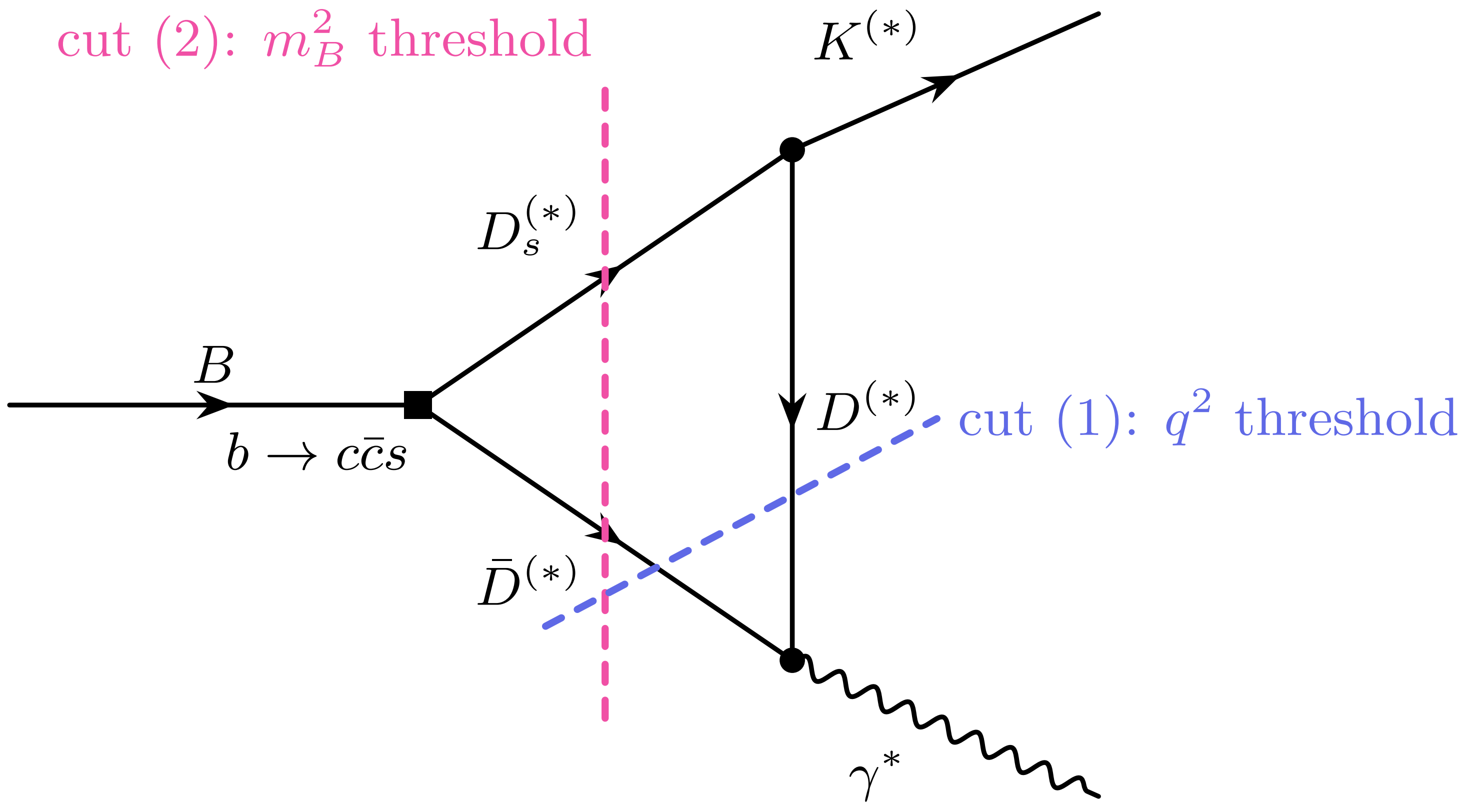


$$C_V \equiv C_9 + C_9'$$
$$C_A \equiv C_{10} + C_{10}'$$

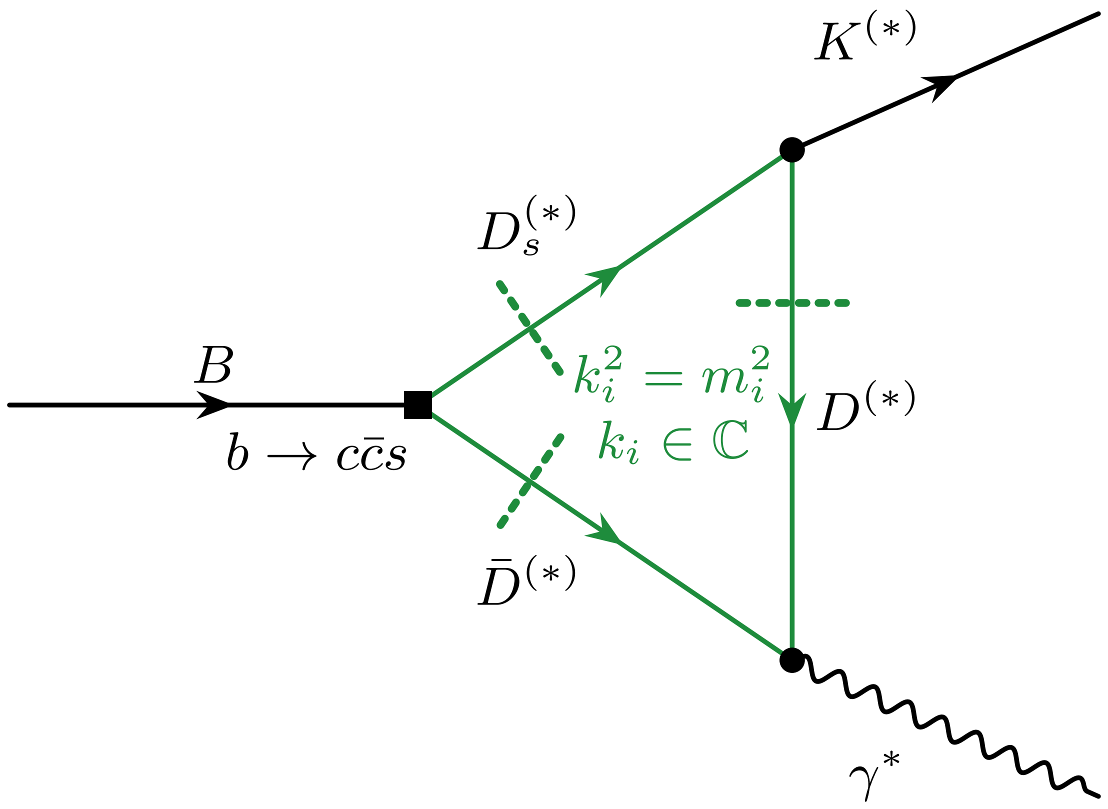
LHCb, 2603.12477
HPQCD, 2207.12468
Fermilab/MILC, 2402.14924

- $B \to K\mu\mu$ unbinned fit: tension with the SM at **4.0σ** with HPQCD FFs, reduced to **1.6σ** with FNAL/MILC FFs (consistent central values, larger uncertainties).

Charm-meson rescattering



(a) two internal lines on shell at real momenta:
normal thresholds (unitarity cuts)



(b) all three internal lines on shell at complex momenta:
leading Landau singularity (anomalous threshold at complex q^2)

Three LHCb analyses

- Same LHCb 8.4 fb^{-1} dataset.
- Significance ranges from 2 to 5σ depending on how much the non-local part is fixed by data.

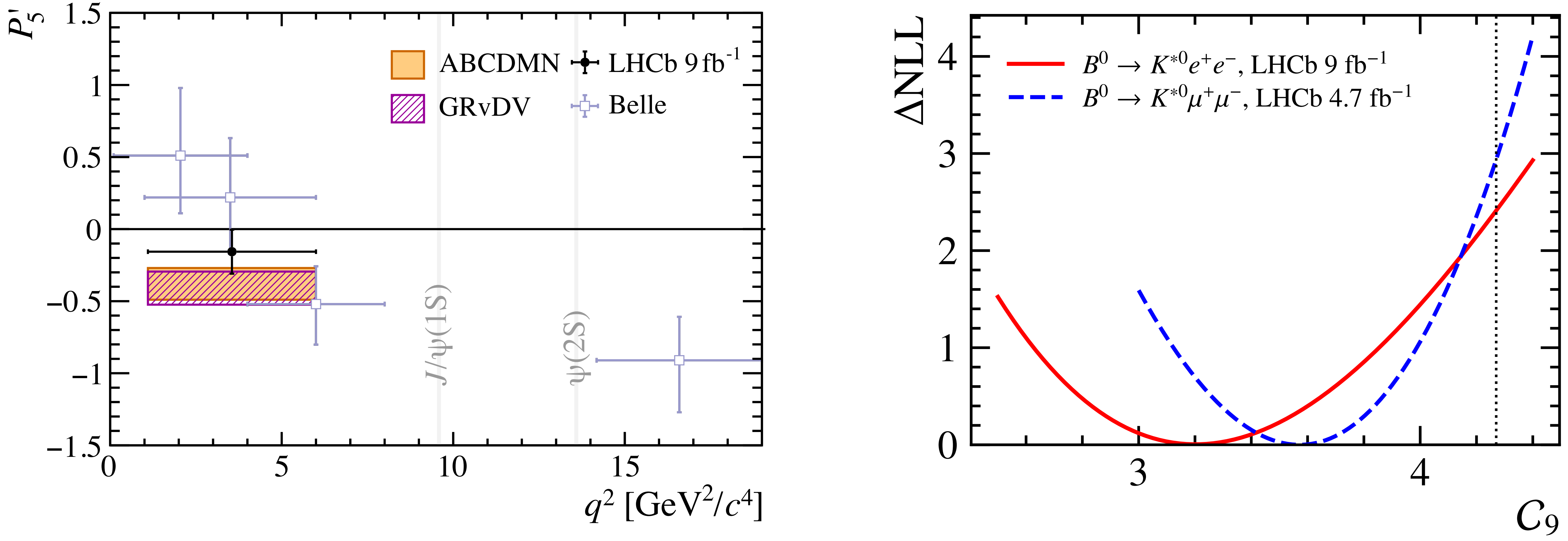
Analysis	non-local $\mathcal{H}_\lambda$	$\Delta C_9^{\rm NP}$	SM pull
binned observables	predicted (flavio/EOS)	$-0.93/-0.94$	3.6–4.1σ (angular $\to$ +BR)
unbinned amplitudes, model-indep.	predicted (flavio)	$-1.17^{+0.21}_{-0.20}$	4.3–4.8σ (baseline $\to$ finer bins)
unbinned amplitude fit, DR model	fitted to data	-0.71 ± 0.33	2.1σ

flavio: QCDf + power-correction nuisances (BSZ15 FFs); EOS: z-expansion + dispersive bound (GRvDV)

LHCb, 2405.17347; 2512.18053; 2608.12215

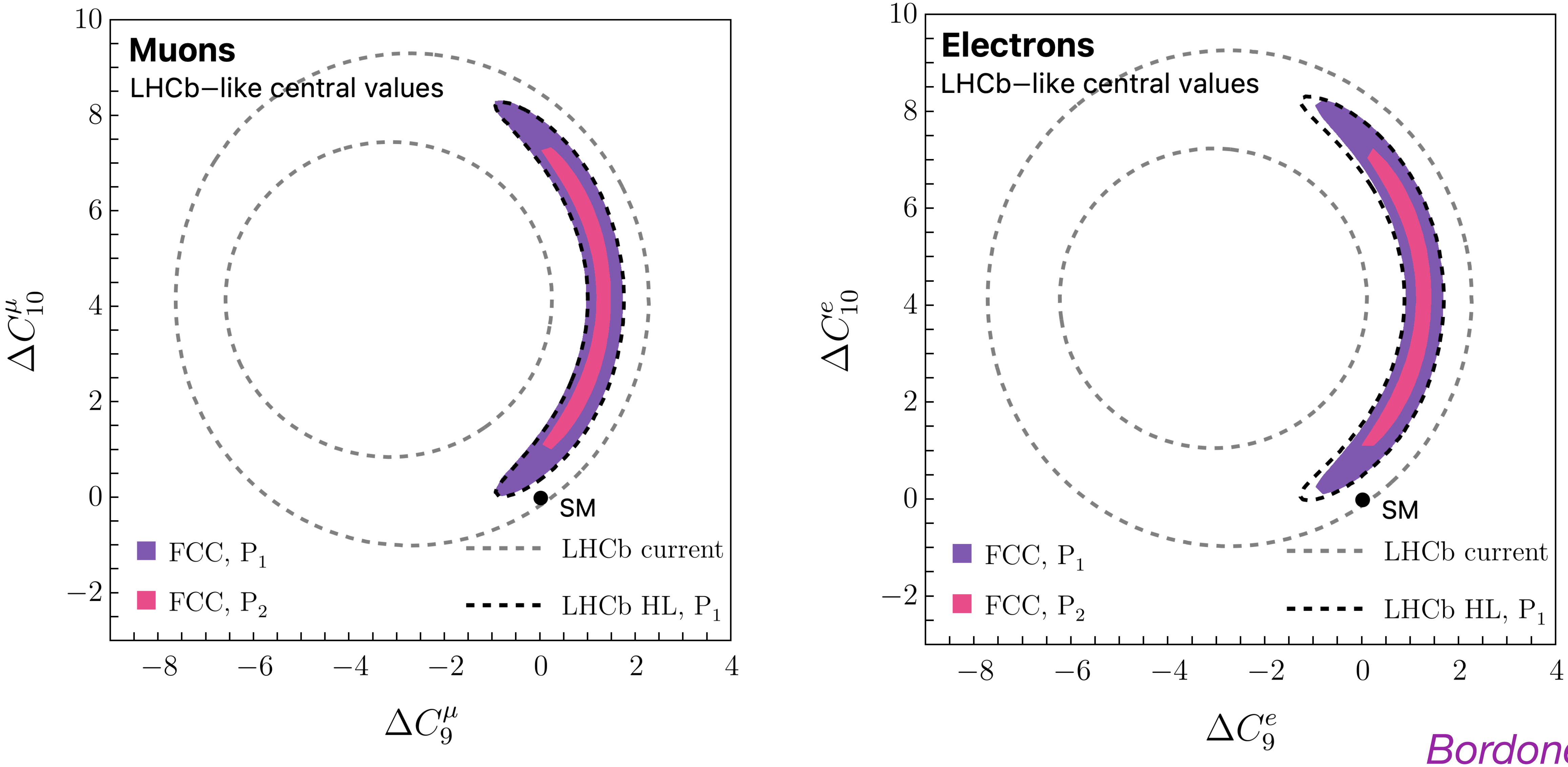
$B \to K^{*0} e^+ e^-$

LHCb, 2502.10291



- LFU NP would generate the same deviations in the electron channel.
- $B \to K^{*0}e^+e^-$ angular analysis is consistent with the SM as well as with the shift seen in $B \to K^{*0}\mu^+\mu^-$.

$\mathcal{B}(B \to K^*\ell^+\ell^-)$ at FCC-ee



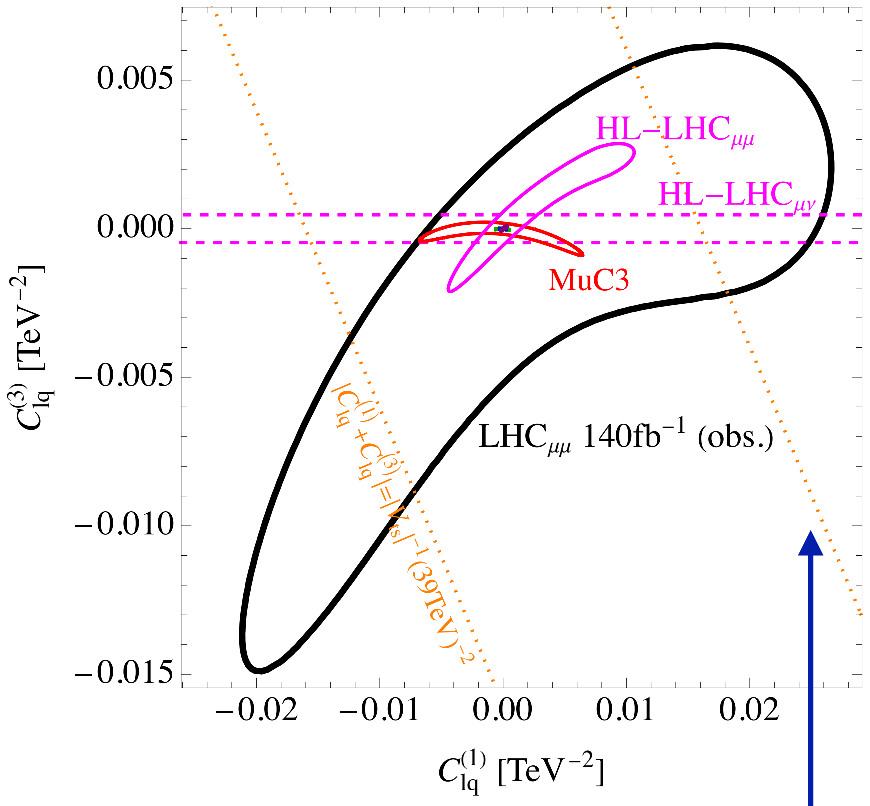
Bordone et al., 2503.22635

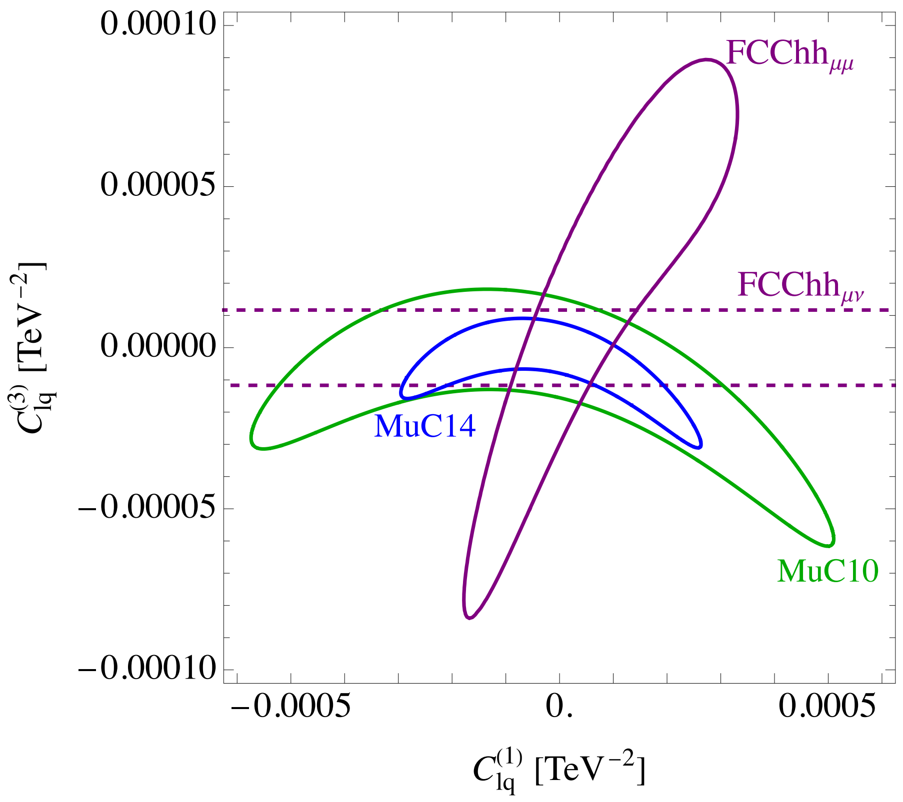
- ✦ P_1, P_2: future theory benchmarks — form-factor and C_7^{eff} uncertainties reduced by factors of 2 and 5, with $|V_{cb}|$ at 1% and 0.5%.
- ✦ Modest improvements in NP sensitivity from HL-LHC to FCC-ee with P_1.

Future colliders

Collider	C.o.m. Energy	Luminosity	Label
LHC Run-2	13 TeV	140 fb^{-1}	LHC
HL-LHC	14 TeV	6 ab^{-1}	HL-LHC
FCC-hh	100 TeV	30 ab^{-1}	FCC-hh
Muon Collider	3 TeV	1 ab^{-1}	MuC3
Muon Collider	10 TeV	10 ab^{-1}	MuC10
Muon Collider	14 TeV	20 ab^{-1}	MuC14

$$[C_{lq}^{(1)}]_{22ij} = C_{lq}^{(1)}\delta_{ij} \text{ and } [C_{lq}^{(3)}]_{22ij} = C_{lq}^{(3)}\delta_{ij}$$



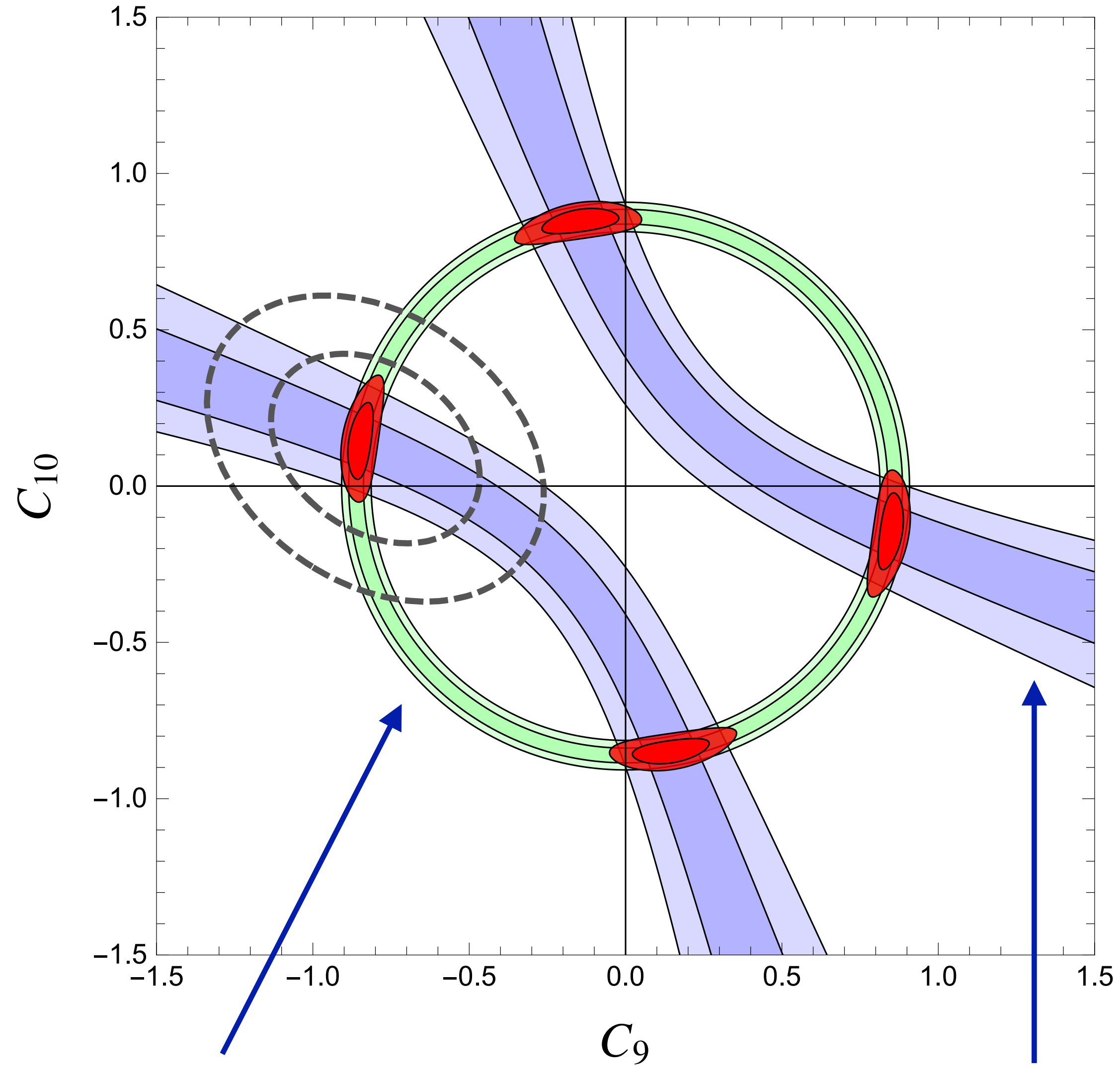


$$|C_{lq}^{(1)} + C_{lq}^{(3)}| = |V_{ts}^{-1}|\,(39\text{TeV})^{-2}$$

Azatov et al., 2205.13552

10 TeV muon collider (1 ab^{-1})

$$\mu^+\mu^- \to b\,s$$



cross section

FB asym.

Altmannshofer et al., 2306.15017
cf. Glioti et al., 2509.08132