(B)eyond the Anomalies

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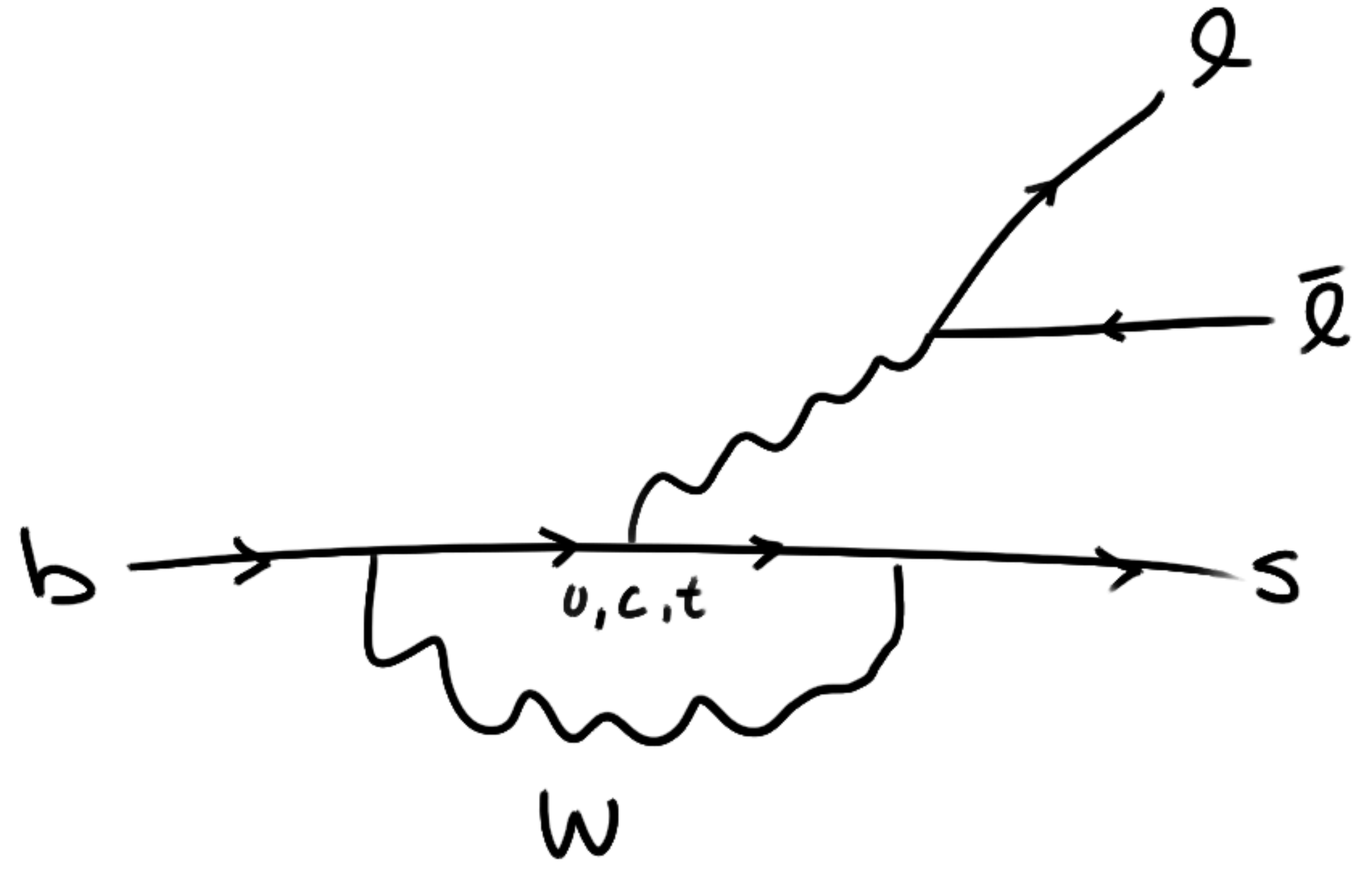
BRDA 2025, October 30

Rare $b \to s\ell\bar{\ell}$ Decays

- FCNC Decays: Loop and GIM/CKM suppressed
  - BSM more competitive with SM rates
- Naive SM Scale:

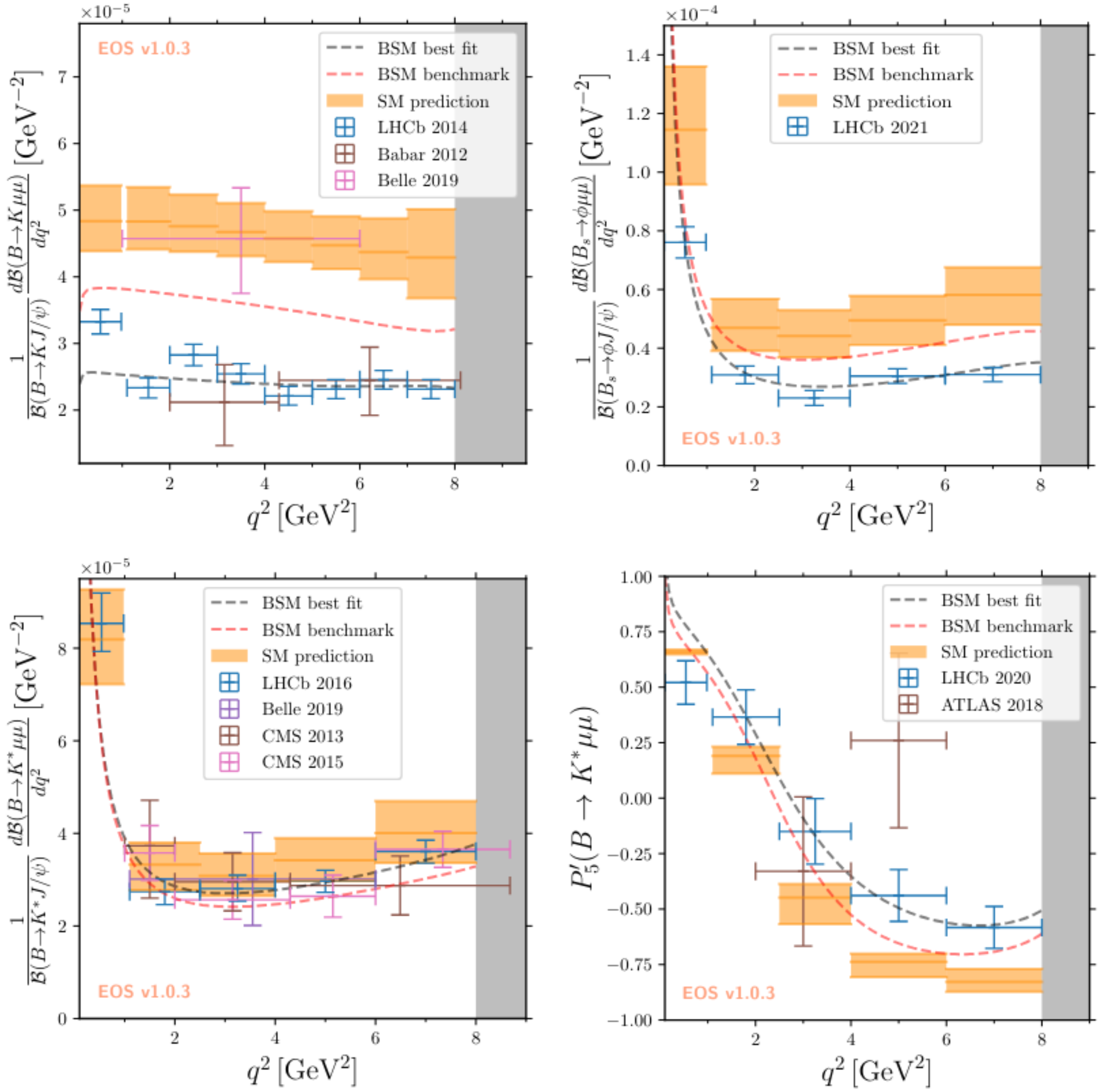
$$\left(\frac{\alpha G_F}{4\pi} V_{tb}^* V_{ts}\right)^{-1/2} \sim 50 \text{ TeV}$$



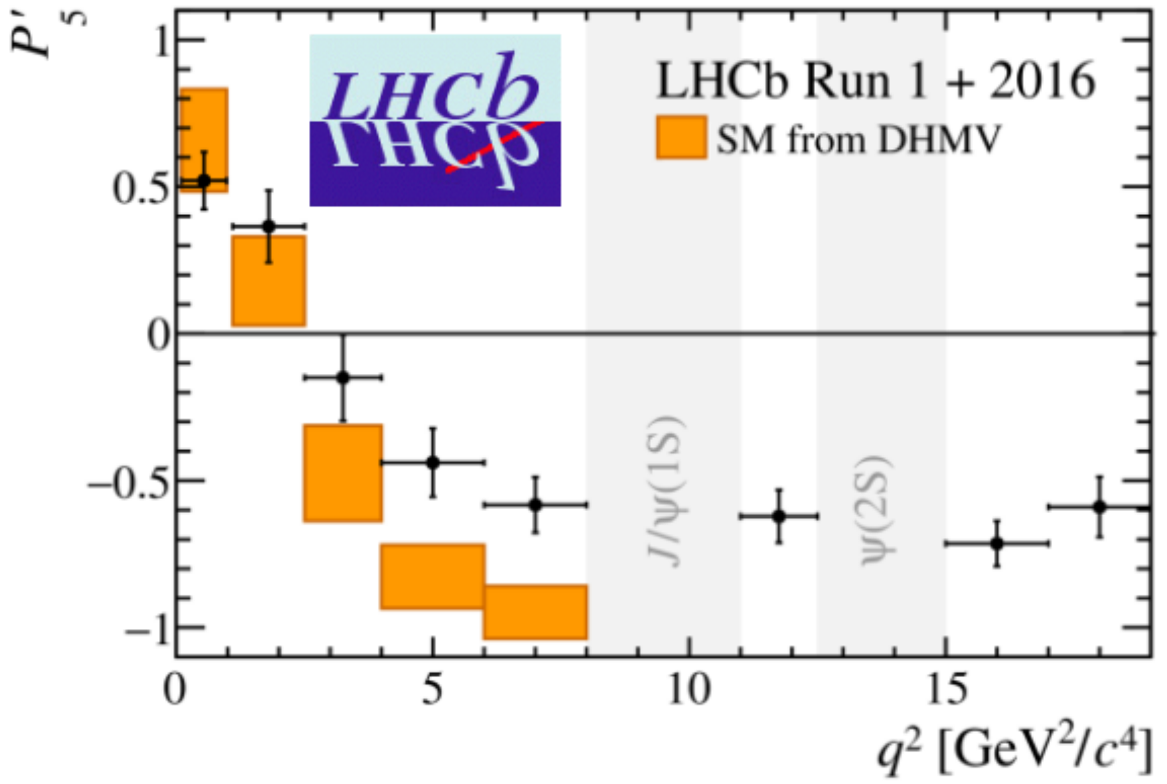
- Several long-standing anomalies in exclusive decays

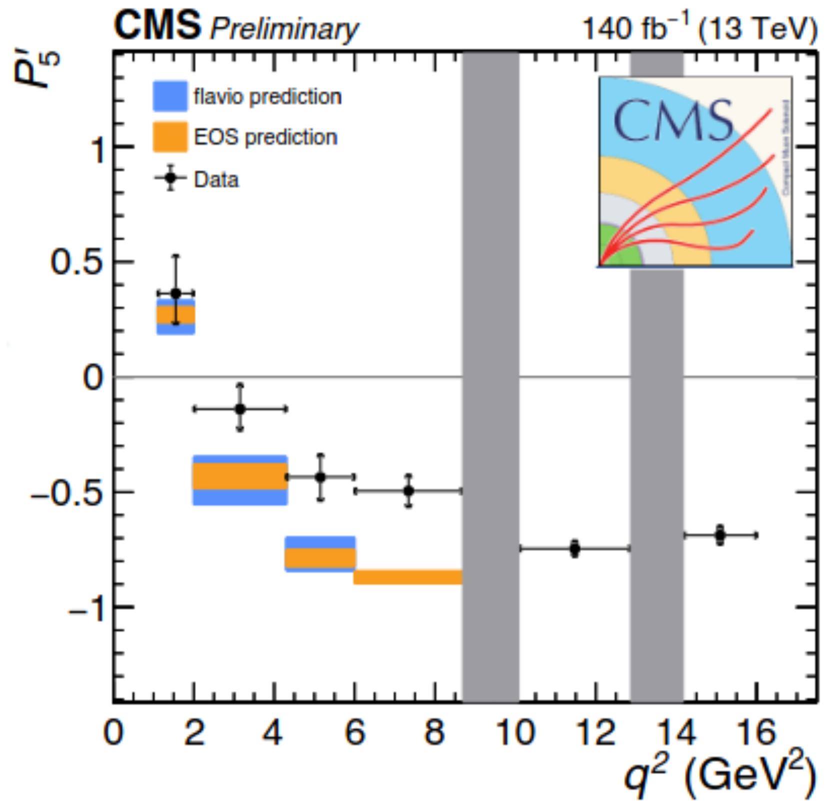
Exclusive-Mode Anomalies

[Gubernari, Reboud, van Dyk, Virto; 2206.03797]



[LHCb; 2003.04831]





[CMS-PAS-BPH-21-002]

Most Relevant Operators

- Short-distance (high energy) and long-distance (low energy) effects separated via OPE

$$\mathcal{H}^{\mathrm{eff}} = \sum_i C_i \mathcal{O}_i$$

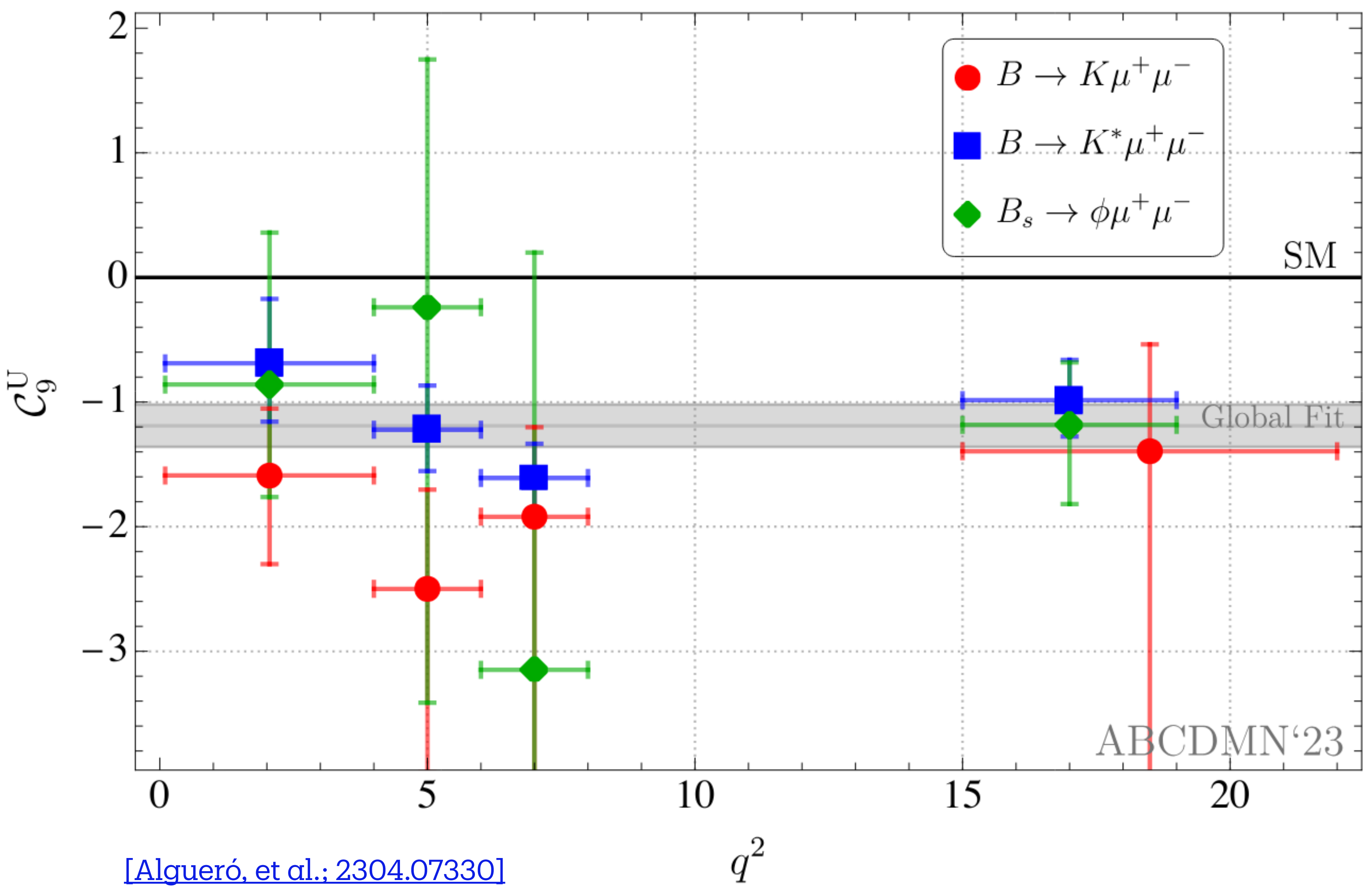
- Most relevant operators generated in SM:

$$\mathcal{O}_7 = \frac{2m_b e}{16\pi^2}(\bar{b}_L \sigma_{\mu\nu} s_L)F^{\mu\nu} \qquad \boxed{\mathcal{O}_9 = \frac{\alpha}{4\pi}(\bar{b}_L \gamma^\mu s_L)(\bar{\ell}\gamma_\mu \ell)} \qquad \mathcal{O}_{10} = \frac{\alpha}{4\pi}(\bar{b}_L \gamma^\mu s_\ell)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

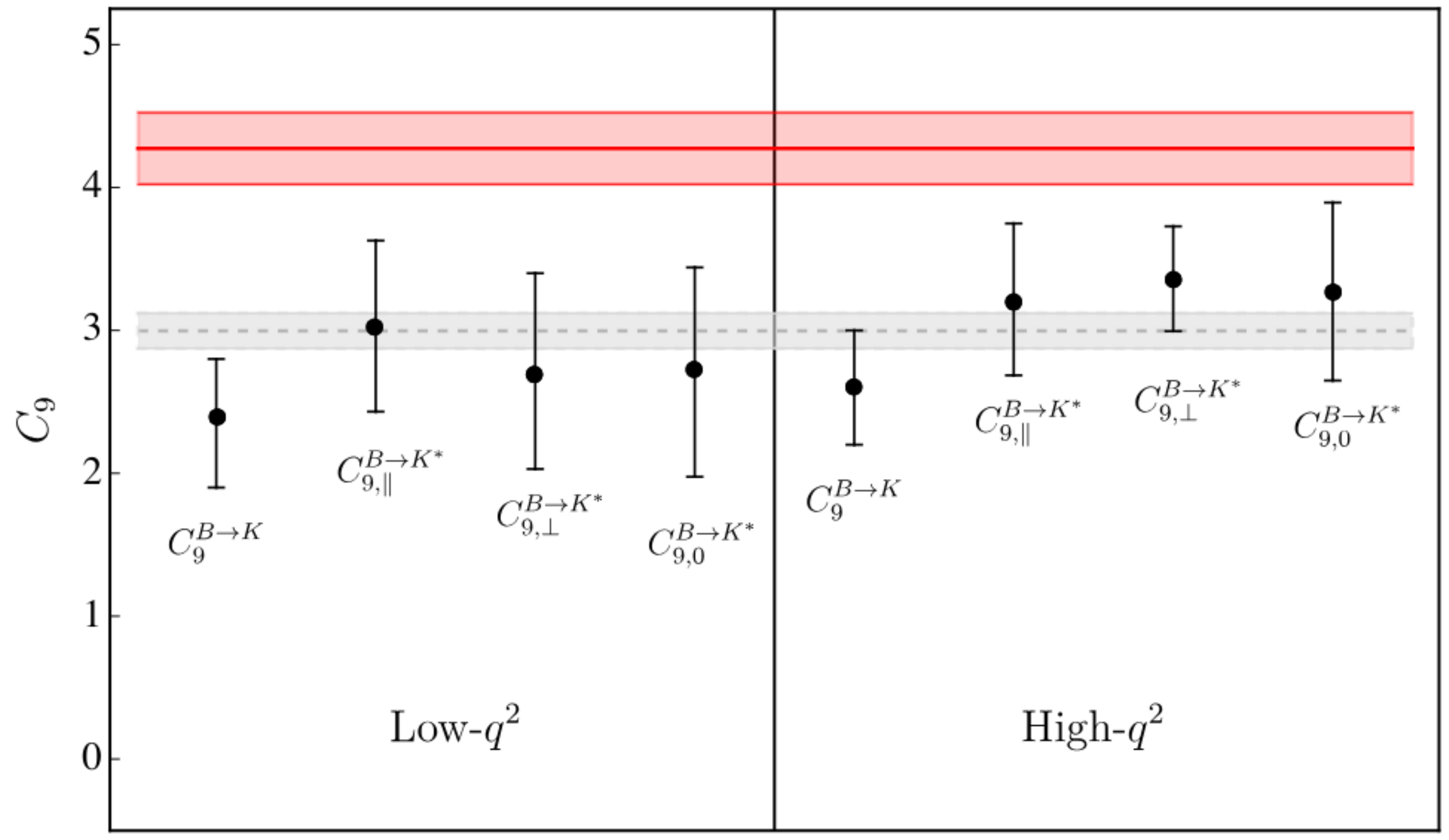
- BSM contributions to C_7 and C_{10} constrained by $b \to s\gamma$ and $B_s \to \mu\mu$, respectively

Exclusive Modes Across q^2

- Heavy BSM physics only enters into SD C_9 — should be q^2-independent



[Algueró, et al.; 2304.07330]



[Bordone, Isidori, Mächler, Tinari; 2401.18007]

- **Data consistent with q^2-independent C_9-like shift**

Hadronic Effects

- Local Matrix Elements: computed using LCSRs/lattice → well understood

[Horgan, Liu, Meinel, Wingate; 1501.00367]
[Parrott, Bouchard, Davis; 2207.12468]
[Bharucha, Straub, Zwicky; 1503.05534]

- Non-Local Matrix Elements can be more difficult

$$H_{M,\mu}(q^2) \sim -i \int d^4x e^{iq\cdot x} \langle M \,|\, T\{j_\mu(x), \mathcal{O}^{cc}_{1,2}(0)\} \,|\, B\rangle$$

$$\mathcal{O}_1 = (\bar{b}^\alpha_L \gamma^\mu c^\beta_L)(\bar{c}^\beta_L \gamma_\mu s^\alpha_L)$$

$$\mathcal{O}_2 = (\bar{b}_L \gamma^\mu c_L)(\bar{c}_L \gamma_\mu s_L)$$

- Problem: can imitate short-distance Wilson Coefficients

$$\epsilon^{\lambda *}_\mu H^\mu_V \propto \boxed{\left(C^{eff}_9 + h^{(1)}_-\right)} \tilde{V}_{L\lambda} + \frac{m_B^2}{q^2}\left\{ \frac{2m_b}{m_B} \boxed{\left(C^{eff}_7 + h^{(0)}_-\right)} \tilde{T}_{L\lambda} + \ldots \right\}$$

[Jäger, Camalich; 1212.2263]
[Ciuchini, et al.; 2110.10126]
...

Hadronic Effects (Continued)

- Non-local MEs have been computed using light-cone OPE for $q^2 < 0$

  [Bobeth, Chrzaszcz, van Dyk, Virto; 1707.07305]
  [Chrzaszcz, et al.; 1805.06378]
  [Gubernari, van Dyk, Virto; 2011.09813]

  - Analytically continued to $q^2 > 0$ with *parameterization* of FFs (model-dependent)
  - *Anomalous branch cuts* in complex-q^2 plane cause complications (quantifying errors)
- Light-quark anomalous branch cuts can contribute up to 10% of non-local ME

  [Mutke, Hoferichter, Kubis; 2406.14608]
- Charm anomalous branch cuts of type which gave smallest effect in $\pi\pi$ rescattering
  - More challenging to actually evaluate (need e.g. $B \to D\bar{D}K^*$, $D - \bar{D}$ interference...)
- Novel parameterization can account for anomalous branch cuts, but similar challenges

  [Gopal, Gubernari; 2412.04488]

LFUV Ratios

- Long-distance effects are entirely blind to lepton flavor

$$R_{K^{(*)}} = \frac{\int dq^2 \frac{d\Gamma(B \to K^{(*)}\mu^+\mu^-)}{dq^2}}{\int dq^2 \frac{d\Gamma(B \to K^{(*)}e^+e^-)}{dq^2}}$$

- $R_{K^{(*)}} \neq 1 \quad \Rightarrow$ anomalies can't be fully from unaccounted-for long-distance physics

$$R_K^{exp} = 0.745^{0.090}_{-0.074} \pm 0.036 \qquad R_{K^*}^{exp} = 0.69^{0.11}_{-0.07} \pm 0.05$$

[LHCb; 1406.6482]

[LHCb; 1705.05802]

LFUV Ratios

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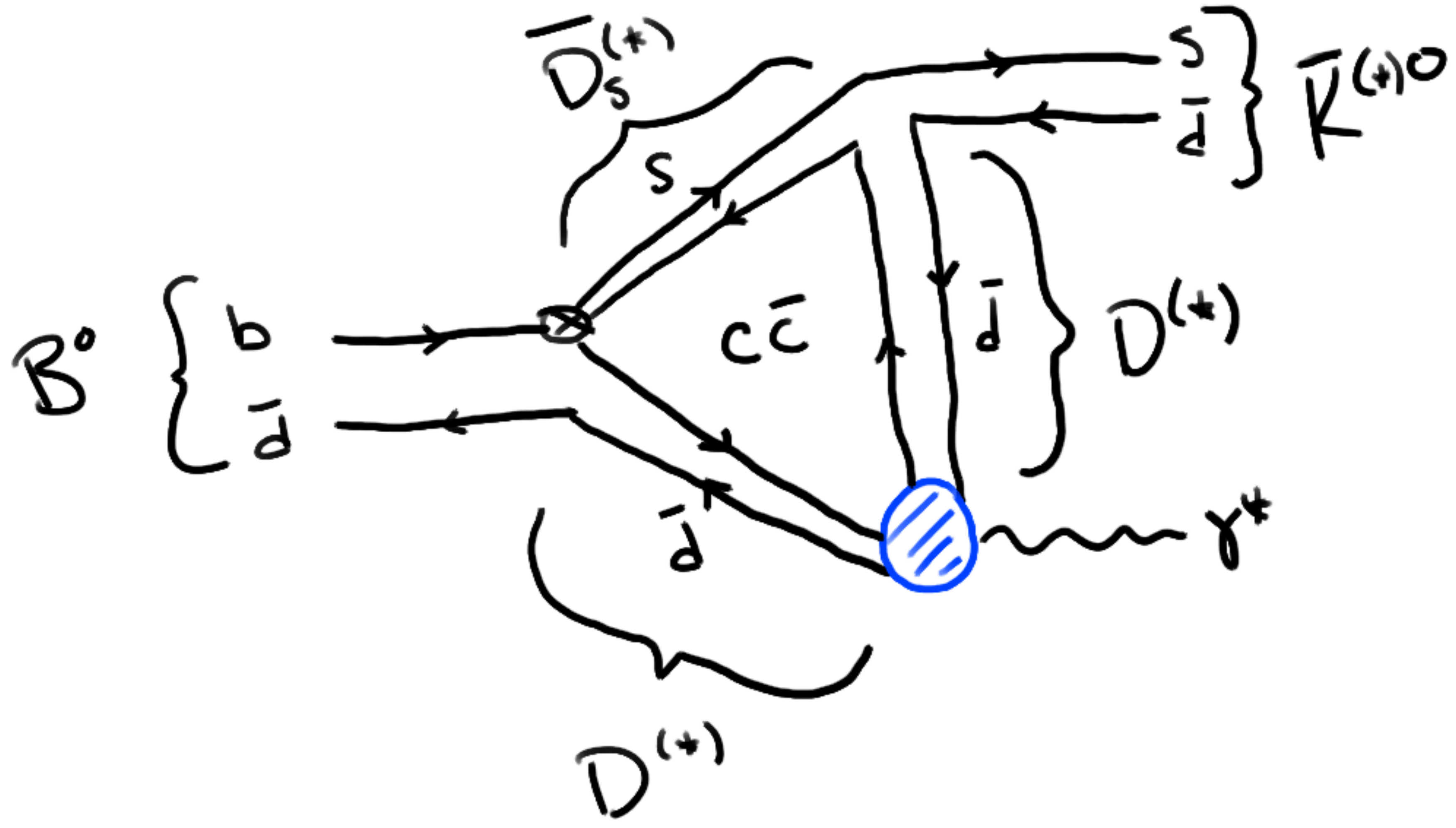
$$R_K^{exp} = 0.994^{0.090\;\;+0.029}_{-0.082-0.027} \qquad\qquad R_{K^*}^{exp} = 0.927^{+0.093+0.036}_{-0.087-0.035}$$

[LHCb; 2212.09152]

"Charming Penguins"

- Anomalous branch cuts can arise from triangle diagrams with bilocal insertions



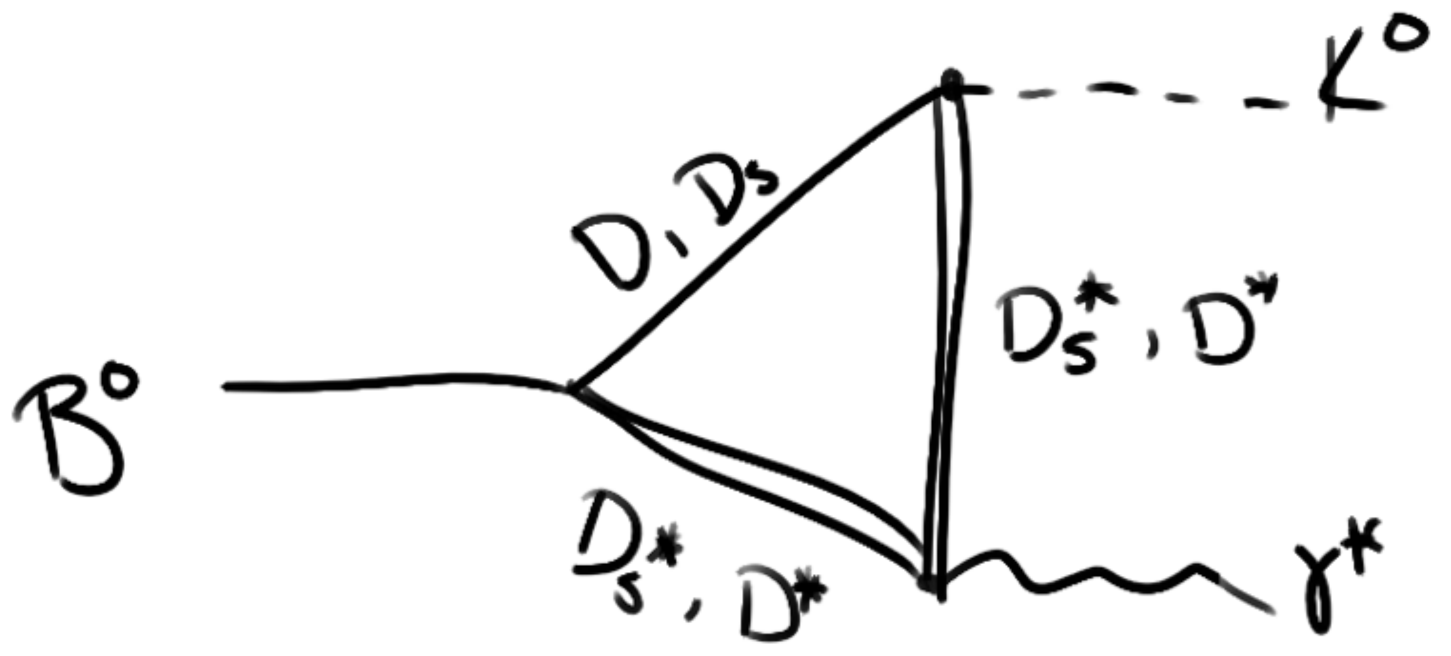
$$H_{M,\mu}(q^2) \sim -i \int d^4x e^{iq\cdot x} \langle M \,|\, T\{j_\mu(x), \mathcal{O}_{1,2}^{cc}(0)\} \,|\, B\rangle$$

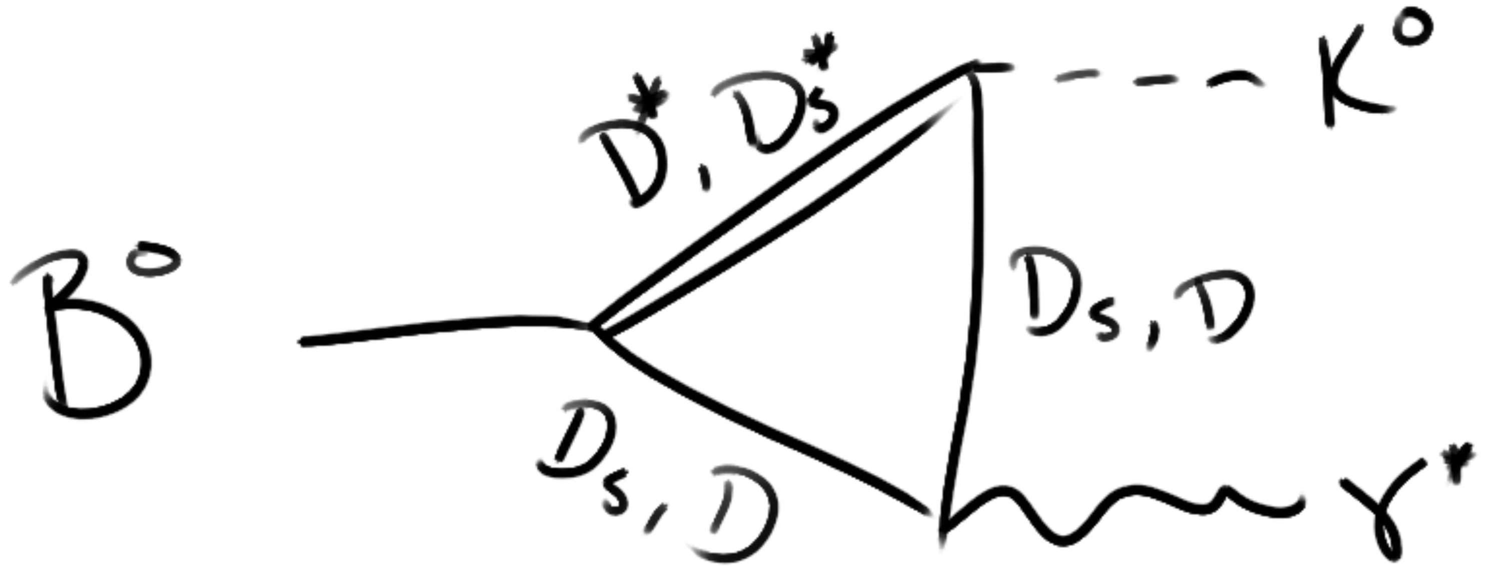
Explicit Estimate

[Isidori, Z.P., Tinari; 2405.17551]

[Isidori, Z.P., Tinari; 2507.17824]

- Evaluate charming penguin contributions to $B^0 \to K^0 \ell \bar{\ell}$ using explicit model of "fundamental" hadrons
  - Interactions from HHChPT (valid in high-q^2)
  - Couplings determined from data
  - Extrapolated with FFs from data/theoretical motivation





Form Factors

Generically gives sizable difference between high- and low-q^2

- $D^{(*)}D^{(*)}\gamma^*$ **Monopole FF (**$e^+e^- \to D_s^+ D_s^-$ **+ HQ symmetry):**

$$F_V(q^2) = \sum_V M_V^2 \frac{y_V e^{i\varphi_V}}{q^2 - M_V^2 + i\sqrt{q^2}\Gamma_V} \qquad F_V(0) = 1$$

[Meng, et al; 2401.13475]

- $DD^*\gamma^*$ **and** $D^*D^*\gamma^*$ **Dipole FF (**$e^+e^- \to DD^*, D^* \to D\gamma$ **+ HQ symmetry):** [Donald, Davies, Koponen, Lepage; 1312.5264]

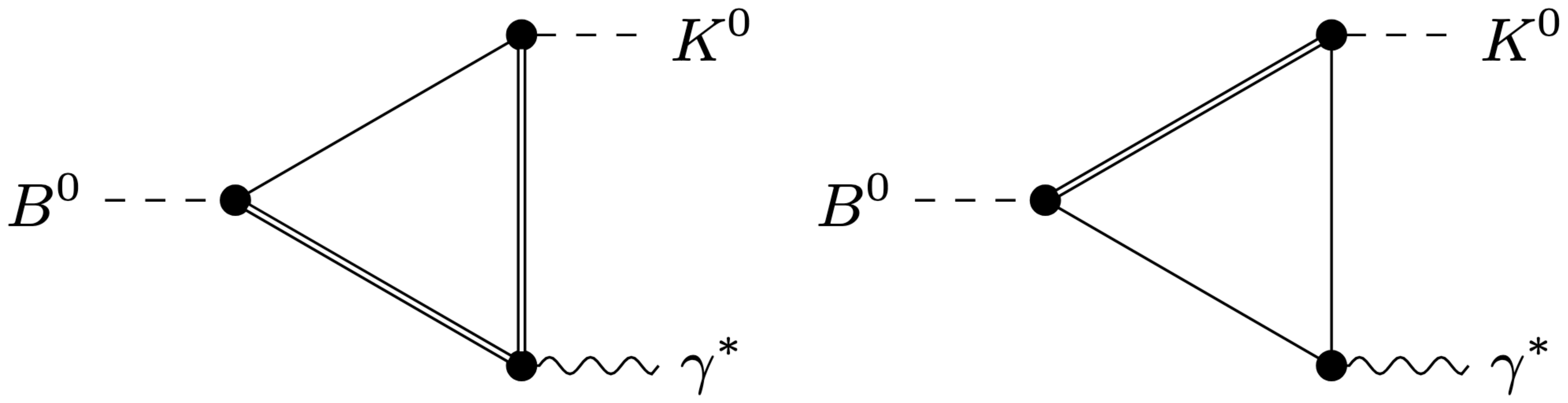
$$g_{dip}(q^2) = \sum_V M_V^2 \frac{\eta_V e^{i\phi_V}}{q^2 - M_V^2 + i\sqrt{q^2}\Gamma_V} \qquad \Gamma(D^* \to D\gamma) = \frac{1}{6\pi m_D^2}|g_{dip}(0)|^2 \frac{(m_{D^*}^2 - m_D^2)^3}{m_{D^*}^3}$$

- $DD^* \to K^0 \ell\bar{\ell}$ **(Unitarity and eliminate soft-Goldstone behavior)**

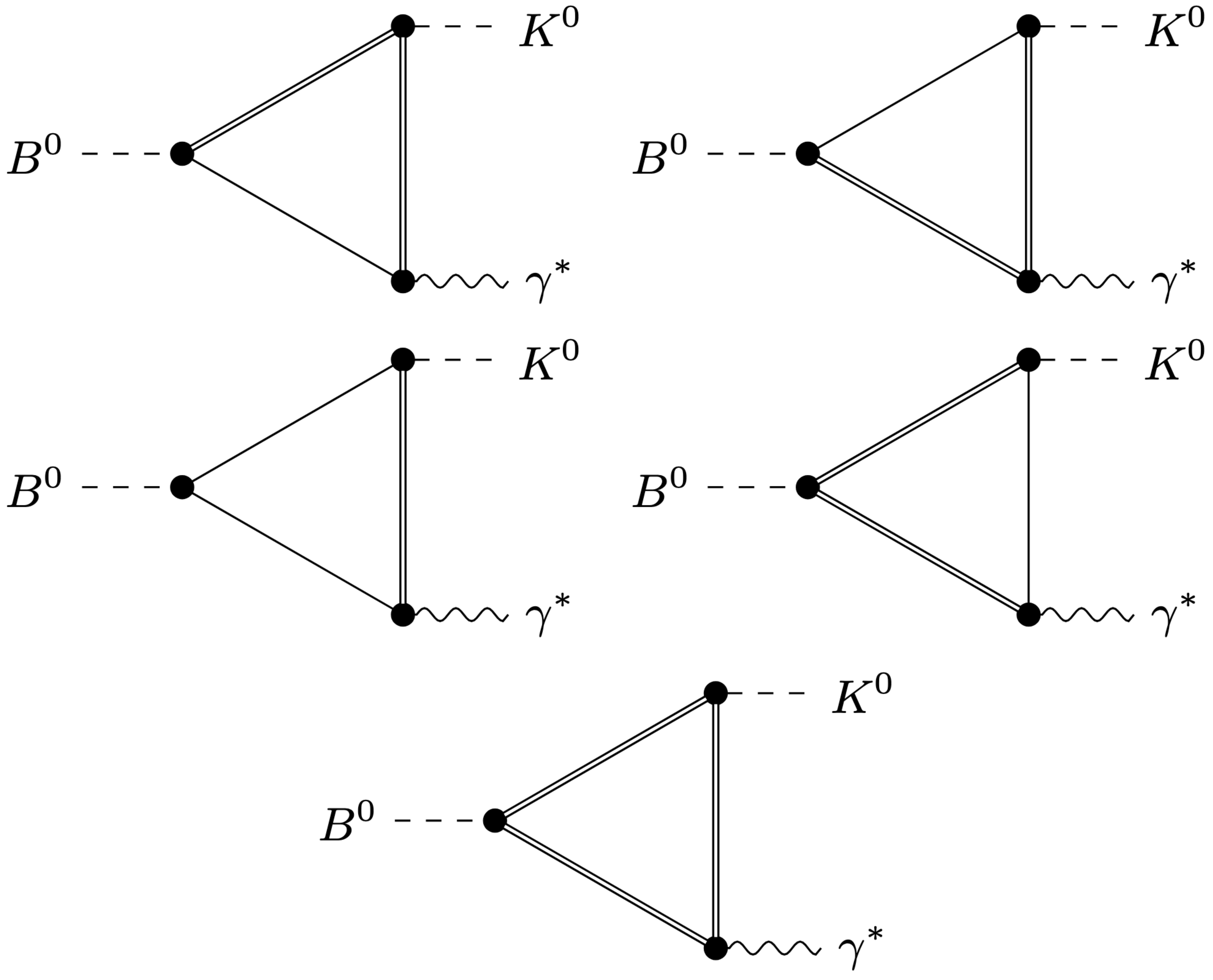
$$\frac{1}{f_K} \to \frac{2m_B}{2m_B f_K + m_B^2 - q^2}$$

Similar to local FF: naturally gives SD-like behavior

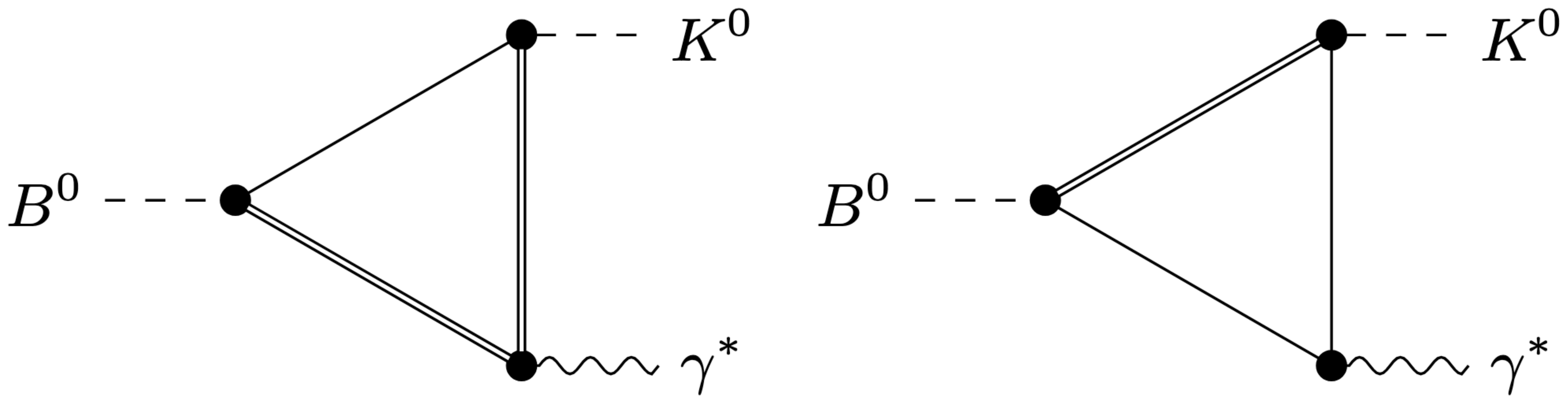
Monopole



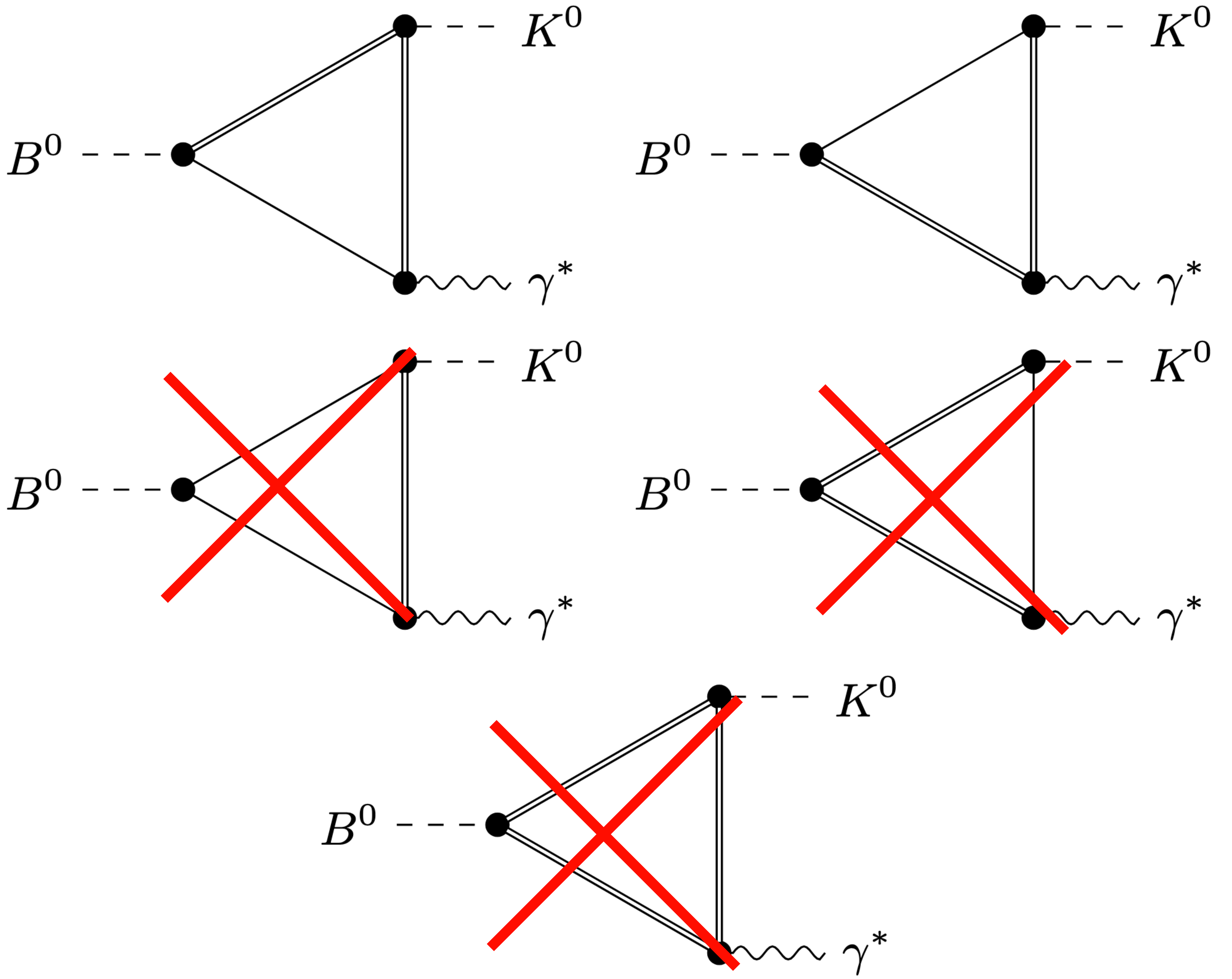
Dipole



Monopole

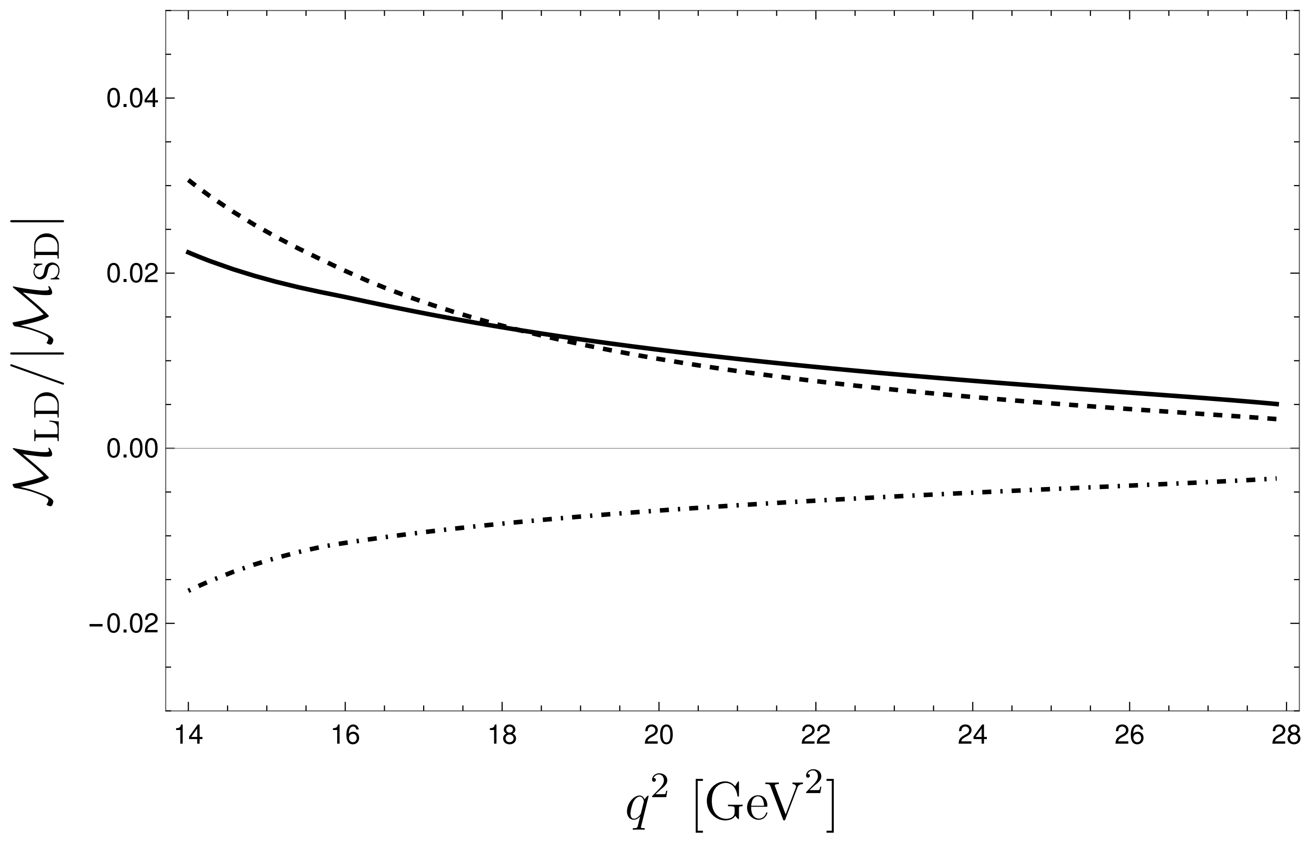


Dipole

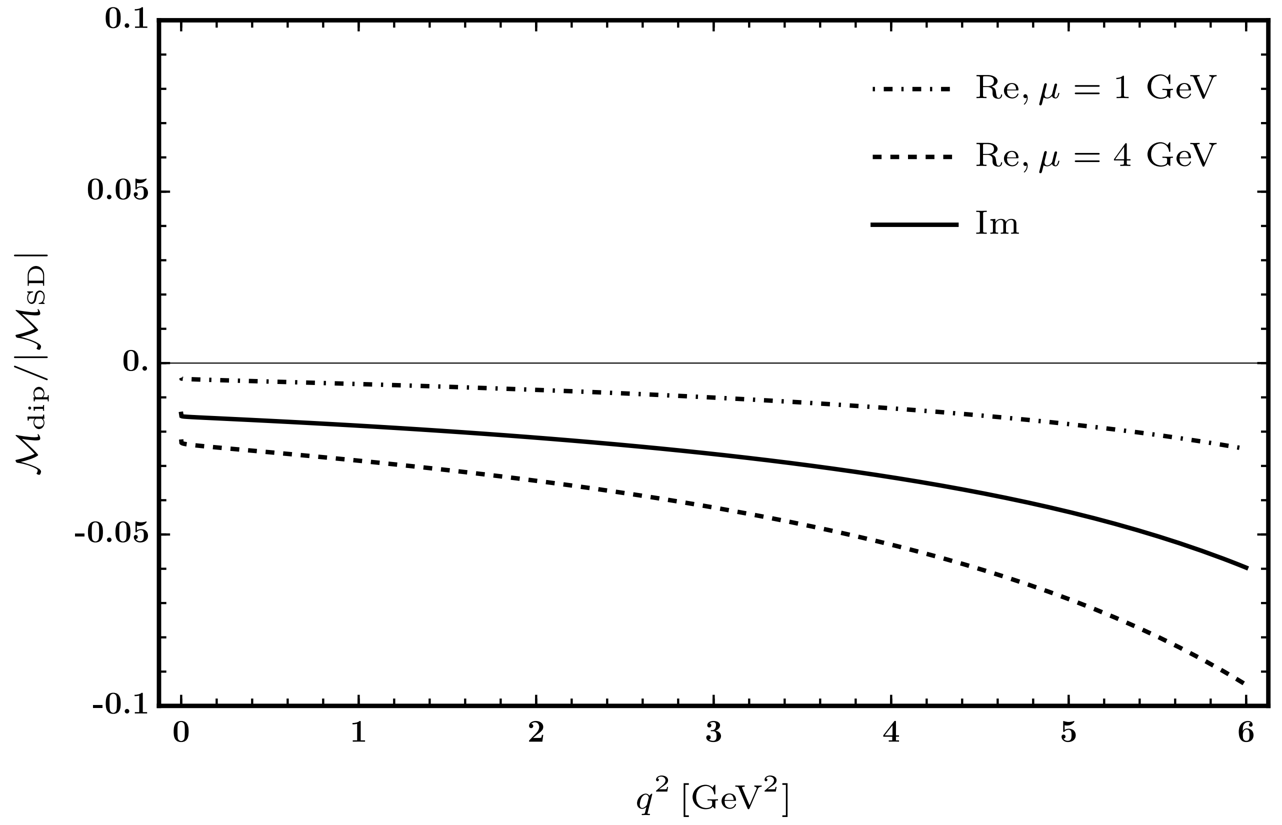


Only depends on one B coupling, g_{DD^*} — pull from $B \to DD^*$ (up to phase)

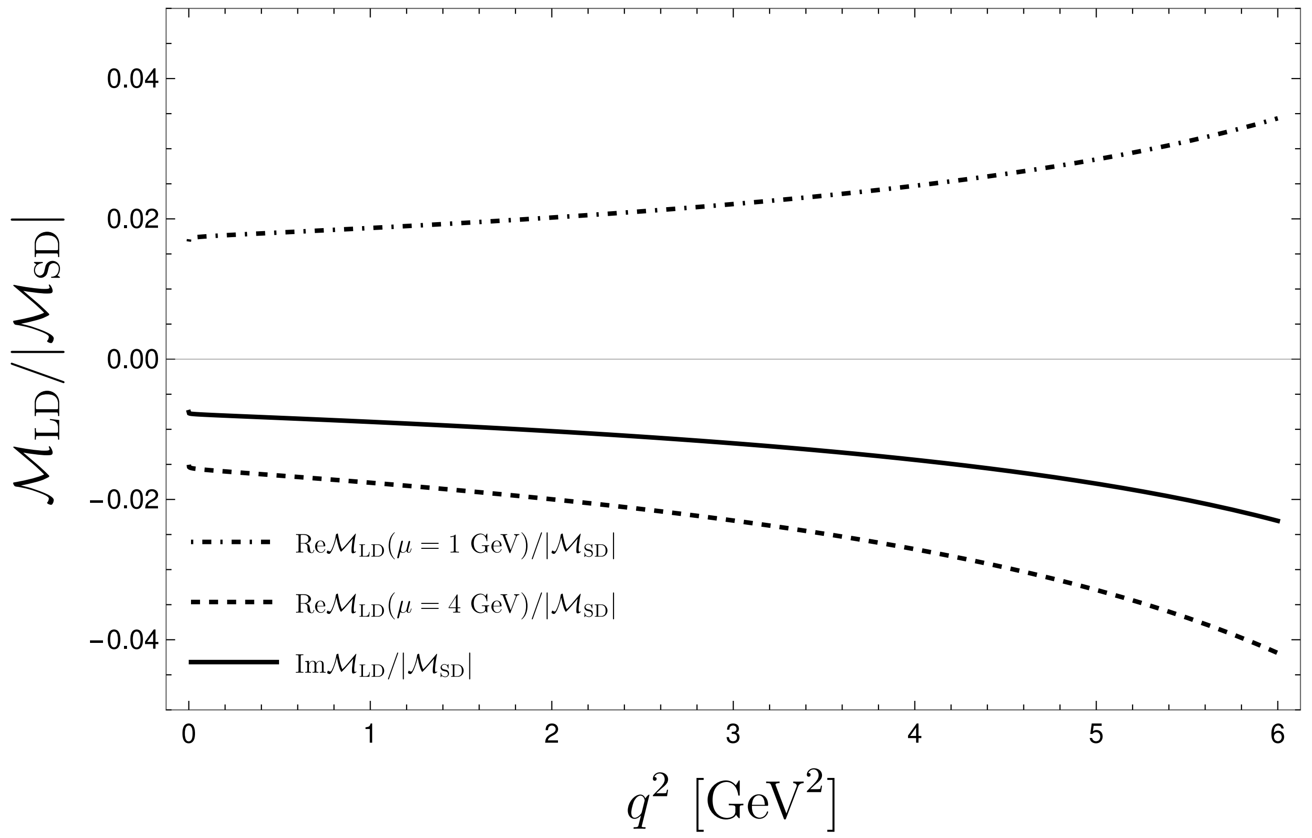
Results



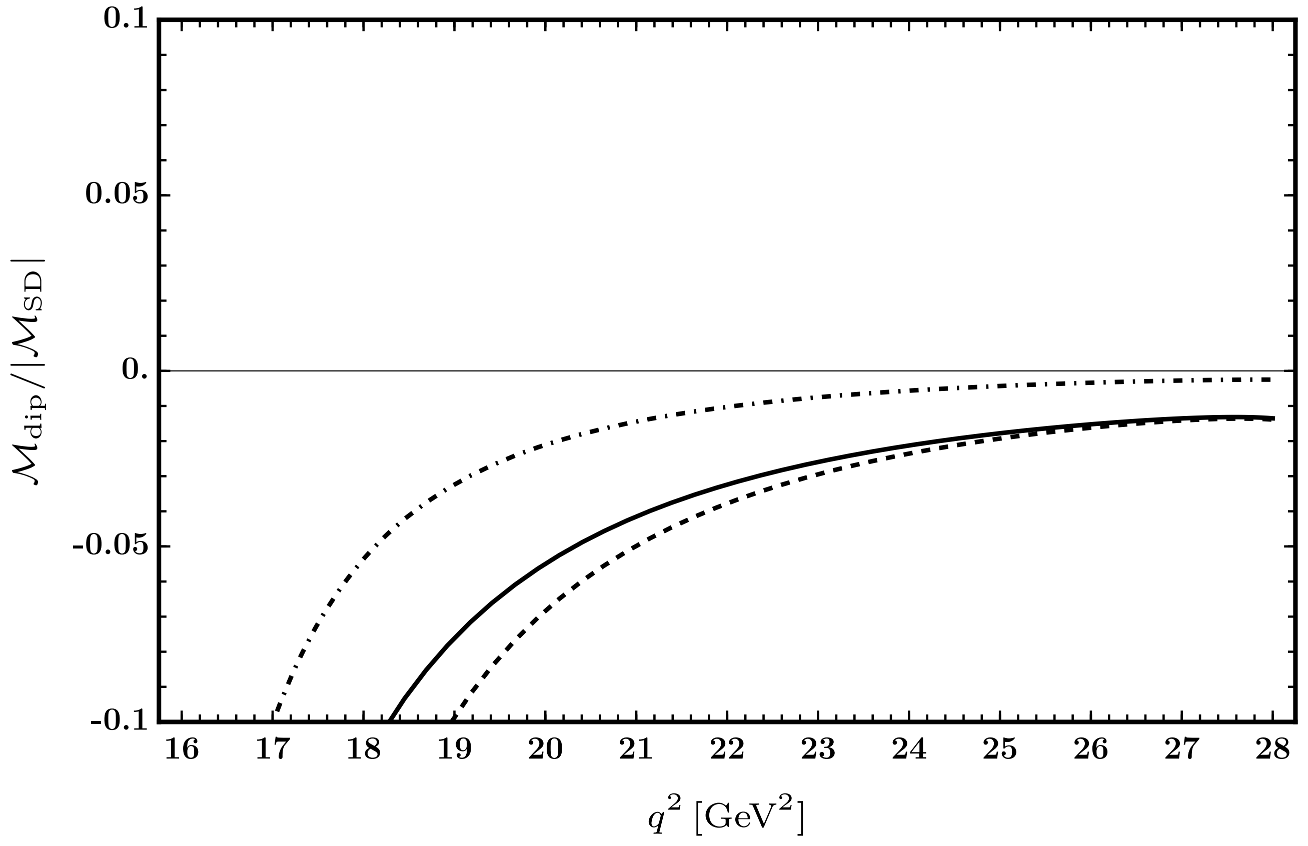
$\mathcal{M}_{\rm LD}/|\mathcal{M}_{\rm SD}|$
0.04
0.02
0.00
−0.02
14 16 18 20 22 24 26 28
q^2 [GeV^2]



Re, $\mu = 1$ GeV
Re, $\mu = 4$ GeV
Im
$\mathcal{M}_{\rm dip}/|\mathcal{M}_{\rm SD}|$
0.1
0.05
0.
−0.05
−0.1
0 1 2 3 4 5 6
q^2 [GeV^2]



$\mathcal{M}_{\rm LD}/|\mathcal{M}_{\rm SD}|$
0.04
0.02
0.00
−0.02
−0.04
Re$\mathcal{M}_{\rm LD}(\mu = 1$ GeV$)/|\mathcal{M}_{\rm SD}|$
Re$\mathcal{M}_{\rm LD}(\mu = 4$ GeV$)/|\mathcal{M}_{\rm SD}|$
Im$\mathcal{M}_{\rm LD}/|\mathcal{M}_{\rm SD}|$
0 1 2 3 4 5 6
q^2 [GeV^2]



$\mathcal{M}_{\rm dip}/|\mathcal{M}_{\rm SD}|$
0.1
0.05
0.
−0.05
−0.1
16 17 18 19 20 21 22 23 24 25 26 27 28
q^2 [GeV^2]

Multiplicity Factor

- Other $c\bar{c}d\bar{s}$ intermediate states can contribute
- Less data available, no HHChPT
- Assumption: gauge-invariant sets of diagrams give similar contributions scaled by "B^0 coupling" ratio

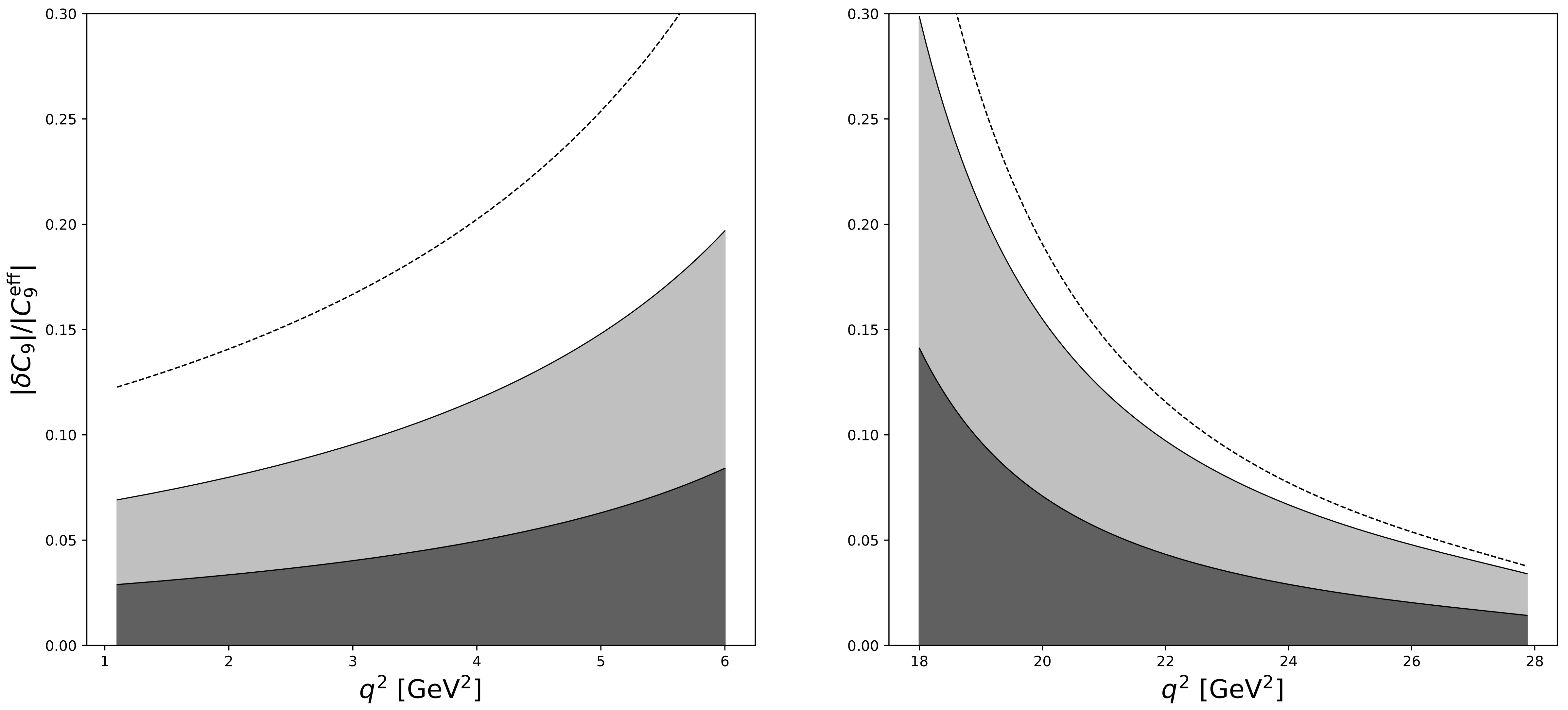
$$\frac{1}{2}\sqrt{\frac{\mathscr{B}(B^0 \to X)}{\mathscr{B}(B^0 \to DD_s^*)}}$$

- *Note: higher resonances are much broader — same contributions to long-distance rescattering?*

B^0 Decay	$\mathcal{B}(B^0 \to X) \times 10^3$
DD	7.2 ± 0.8
$D^* D_s$	8.0 ± 1.1
DD_s^*	7.4 ± 1.6
$D^* D_s^*$	17.7 ± 1.4
$DD_{s1}(2460)$	3.5 ± 1.1
$D^* D_{s1}(2460)$	9.3 ± 2.2
$DD_{s0}^*(2317)$	1.06 ± 0.16
$D^* D_{s0}^*(2317)$	1.5 ± 0.6

J^P	meson state
0^-	$D_{(s)}$
1^-	$D_{(s)}^*$
0^+	$D_0^*(2300)/D_{s0}^*(2317)$
1^+	$\mathrm{D}_1(2430)$ / $\mathrm{D}_{s1}(2460)$

Results



(a) **Natural:** No tuning — δC_9 only given by absorptive part of DD^* contribution

(b) **Multiplicity-Tuned:** Relative phases of all $c\bar{c}d\bar{s}$ states tuned to add coherently

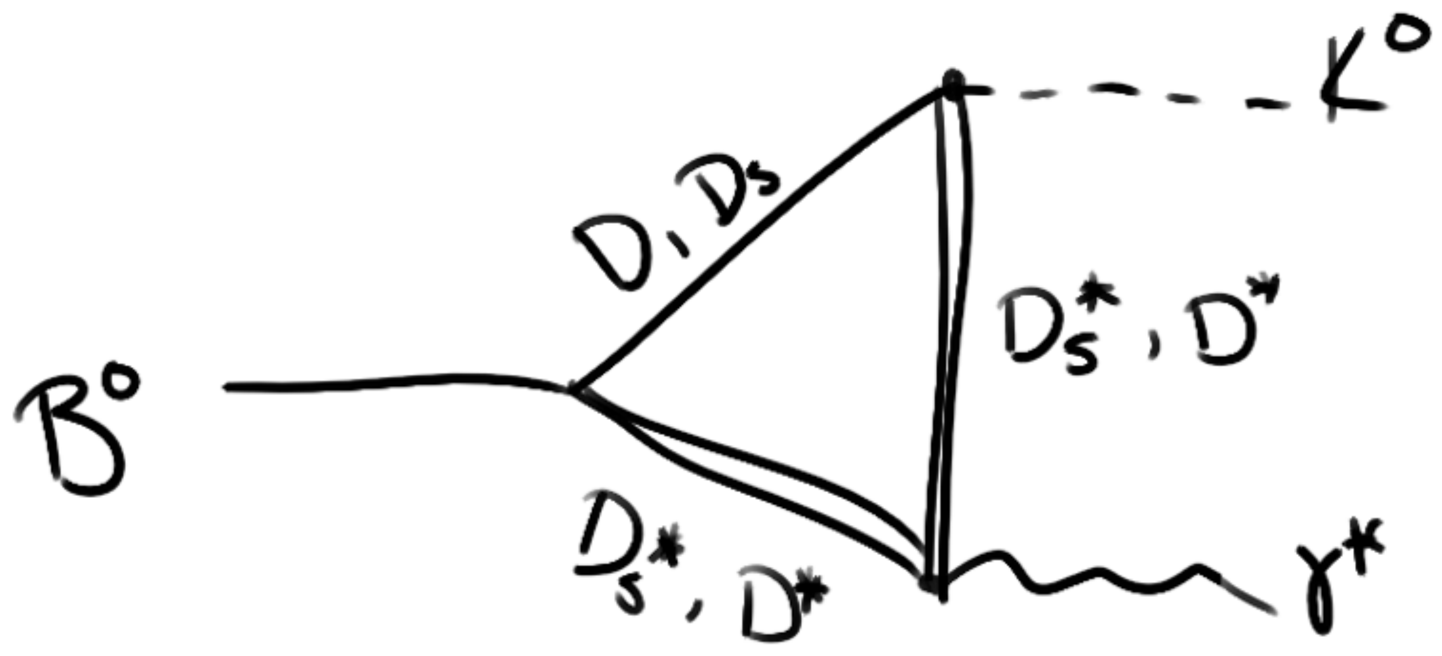
(c) **Fully Tuned:** Tune phases of couplings for max interference with SM C_9

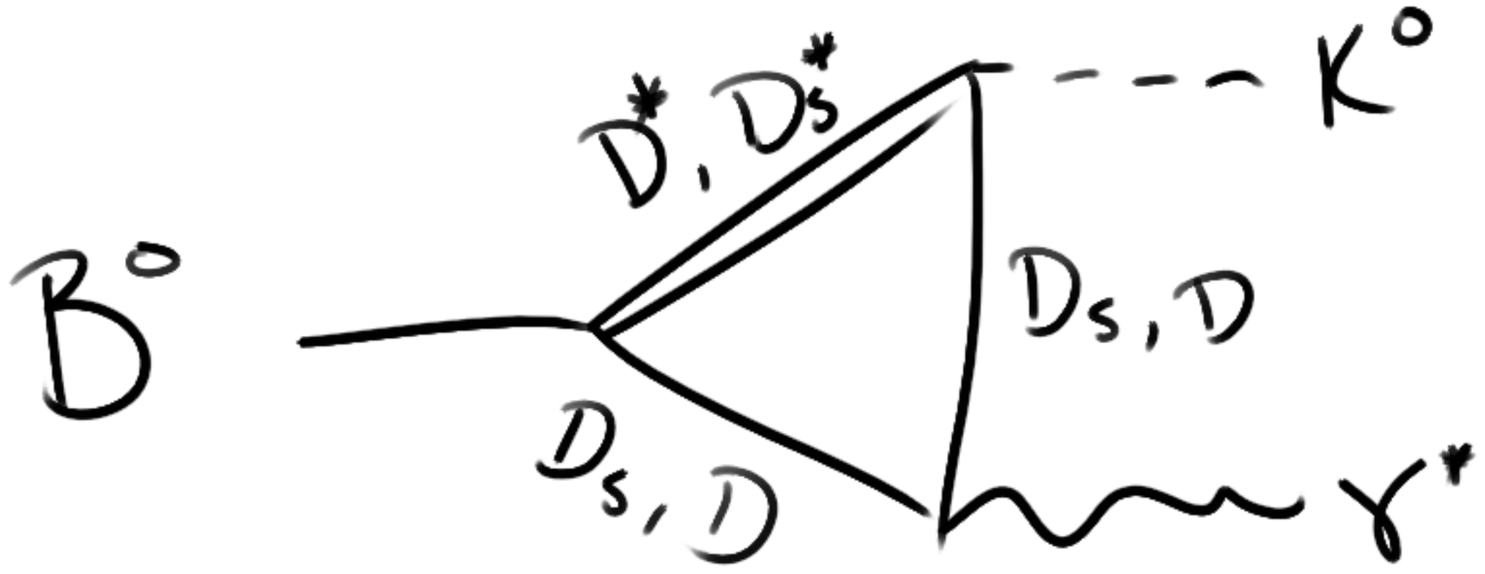
- *Note 1: Calculation most trustworthy near q^2_{max} — HHChPT valid*
- *Note 2: In all cases, neglect phase difference between high- and low-q^2 from monopole FF*

Remarks

- Model-dependent estimate suggests a tension in long-distance interpretation of anomalies:
  - Difficult to simultaneously have a large effect (~20%) and short-distance-like effect
- Emphasizes importance of detailed q^2-dependent future analyses [Beck, Atzeni, Smith; 2503.22549]
- Recent developments could lead to first-principles determination from lattice

[Frezzotti, et al.; 2508.03655]





Inclusive $B \to X_s \ell \bar{\ell}$

Inclusive $B^0 \to X_s \ell \bar{\ell}$

- Calculation uses HQET — matrix elements evaluated using OPE
- **Low-q^2:**
  - Theoretically: OPE converges well: expansion in Λ_{QCD}/m_b
  - Experimentally: More challenging due to many possible final states (B-factories)
- **High-q^2:**
  - Theoretically: OPE converges poorly: expansion in $\Lambda_{QCD}/(m_b - \sqrt{q^2})$
  - Experimentally: Less phase-space — fewer final states (B-fac. + LHCb)

$B \to X_s \ell \bar{\ell}$ at High q^2

- Solution: normalize to $B \to X_u \bar{\ell} \nu$ with same q^2 cut

$$R^{(\ell)}_{incl.}(q_0^2) = \frac{\int_{q_0^2}^{m_B^2} dq^2 \frac{d\Gamma(B \to X_s \bar{\ell} \ell)}{dq^2}}{\int_{q_0^2}^{m_B^2} dq^2 \frac{d\Gamma(B \to X_u \bar{\ell} \nu)}{dq^2}}$$

[Ligeti, Tackmann; 0707.1694]

- Much better OPE convergence — clean extraction from inclusive data on $B \to X_u \bar{\ell} \nu$

Semi-Inclusive vs. Inclusive [Isidori, Z.P, Tinari; 2305.03076]

- Consistency check: sum over exclusive modes— compare to inclusive

- Small phase space — only a few modes dominate:

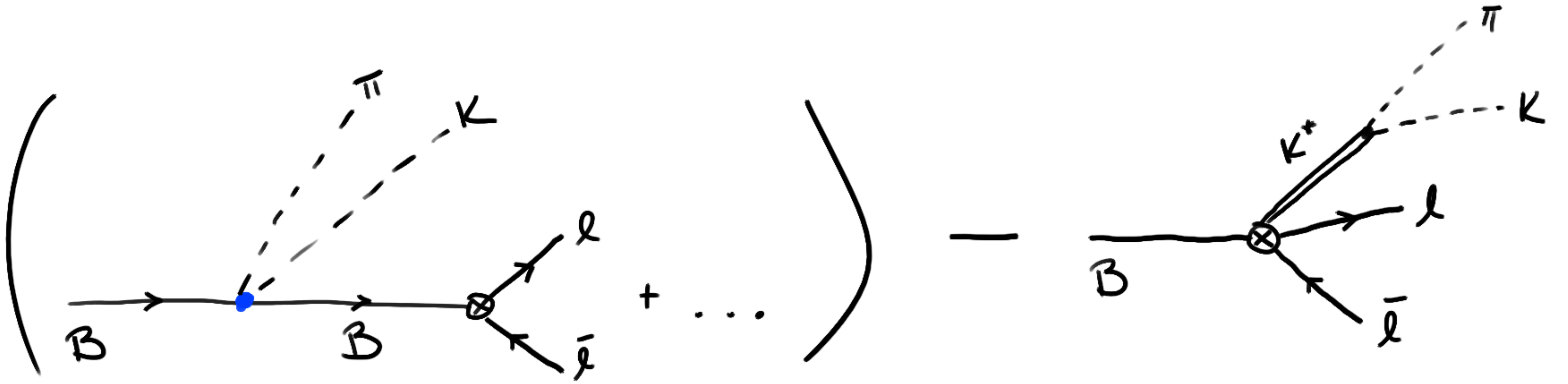
$$B \to K, \qquad B \to K^*, \qquad B \to (K\pi)_{direct}$$

Extracted as normal from lattice FFs

Need to estimate

Estimating $B \to (K\pi)_{direct}$

- High-q^2 $\Rightarrow$ low hadronic recoil: HHChPT valid
- EFT: contains contributions from integrated-out degrees of freedom
  - Full HHChPT calculation will double-count K^* already computed
- Expand near threshold, subtract resonant K^* to obtain mostly s-wave $K\pi$



Comparison with Data

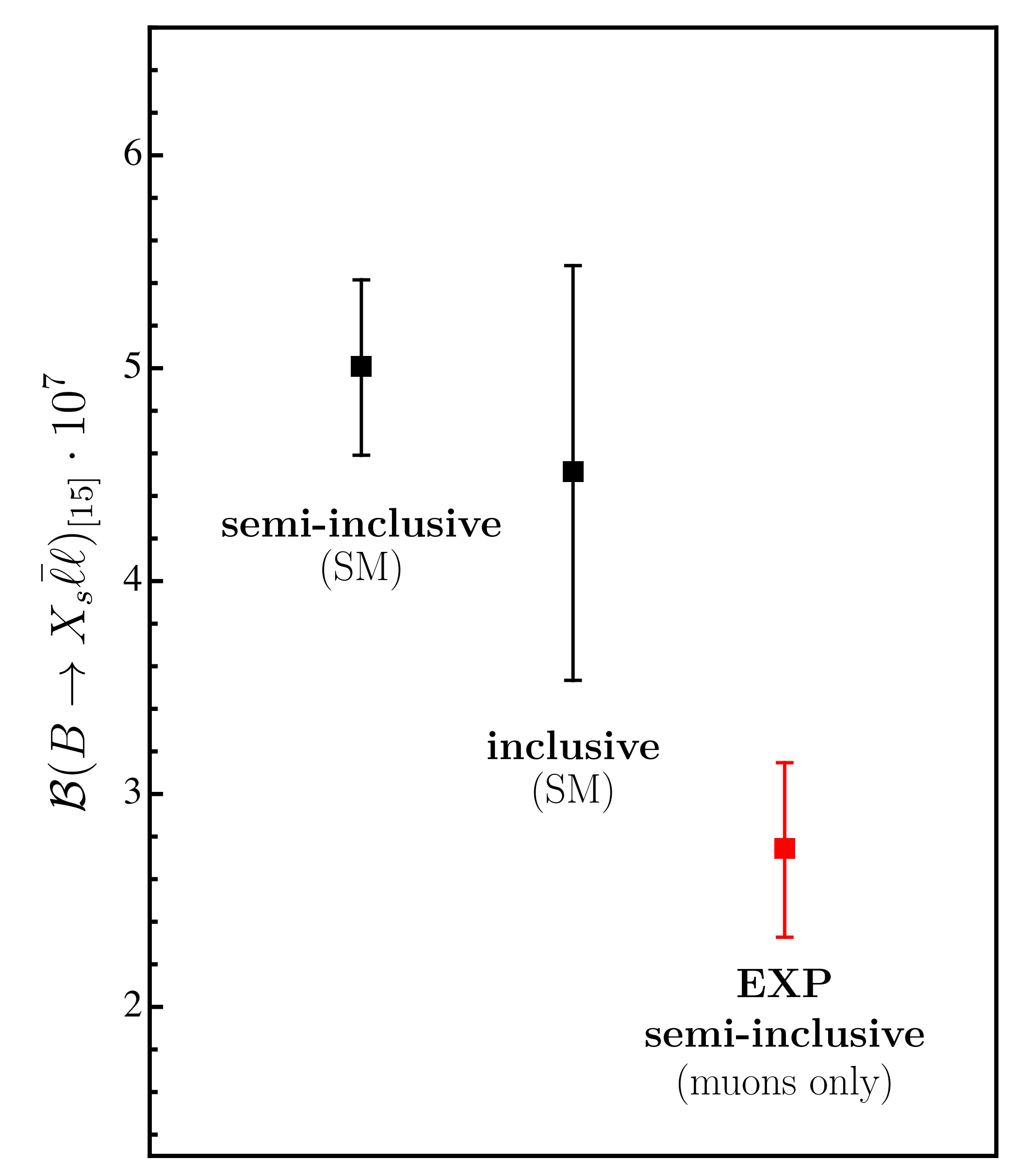
- Define "correction factor"

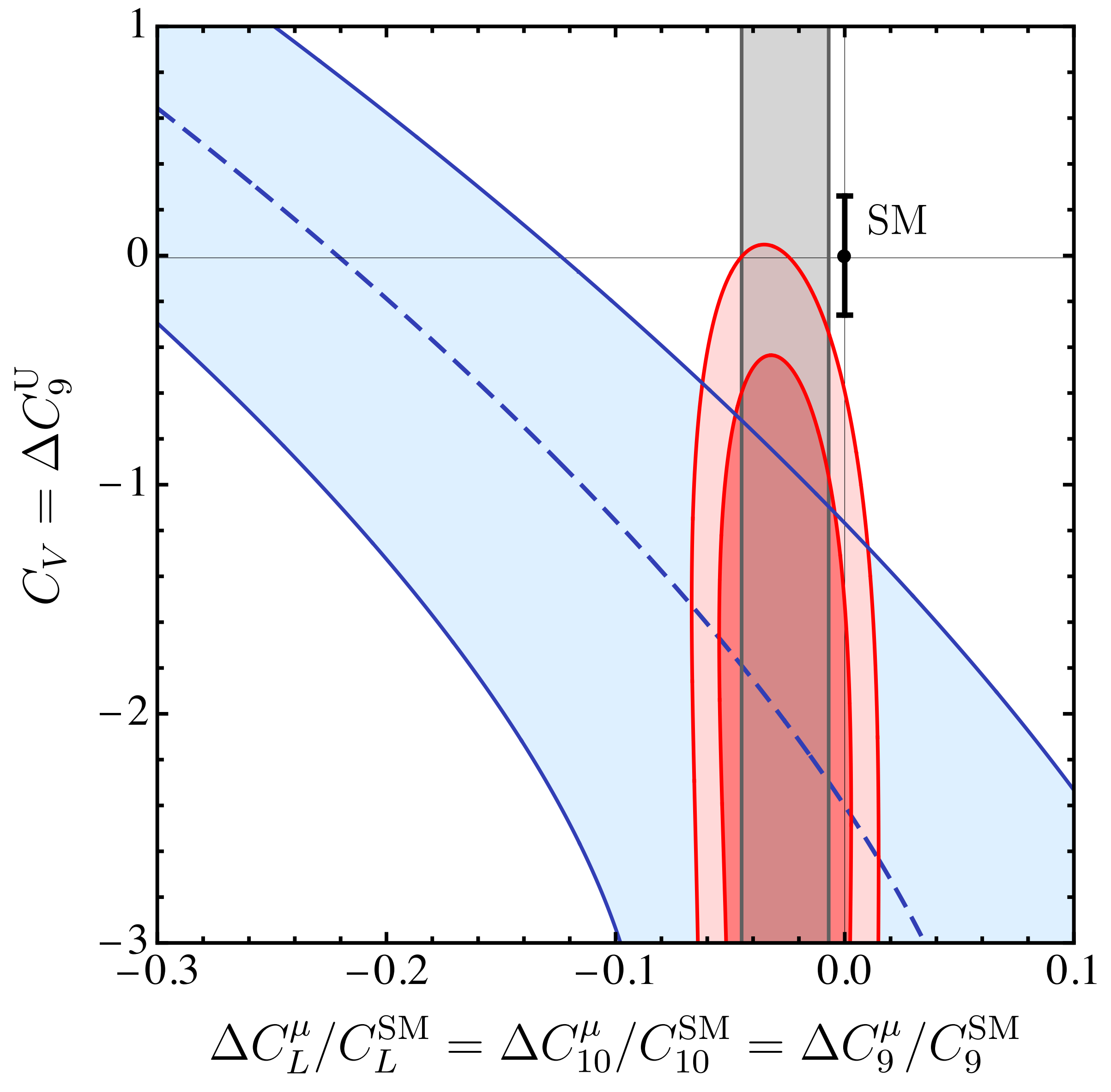
$$\Delta_{K\pi}^{[15]} = \frac{\mathscr{B}(B \to (K\pi)_s)^{th}_{[15]}}{\sum_{M=K,K^*} \mathscr{B}(B \to M)^{th}_{[15]}} = 0.13 \pm 0.06$$

- Determine semi-inclusive LHCb result

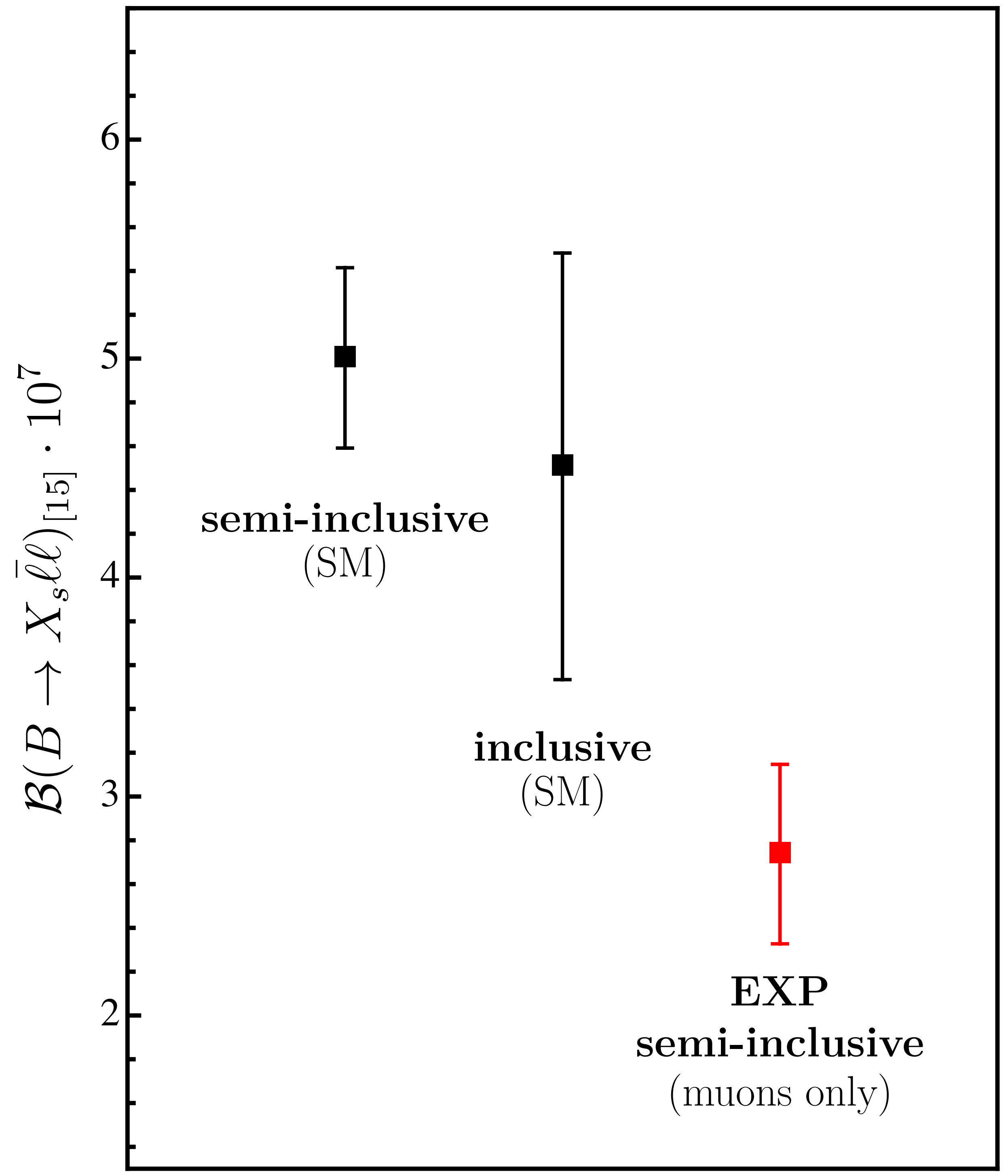
$$\mathscr{B}(B \to X_s \ell \bar{\ell})^{LHCb}_{[15]} = (1 + \Delta_{K\pi}^{[15]}) \sum_{M=K,K^*} \mathscr{B}(B \to M \ell \bar{\ell})^{LHCb}_{[15]}$$

- Theory predictions consistent — tension with data
- Large uncertainty from $\mathscr{B}(B \to Xu\bar{\ell}\nu)_{exp}$

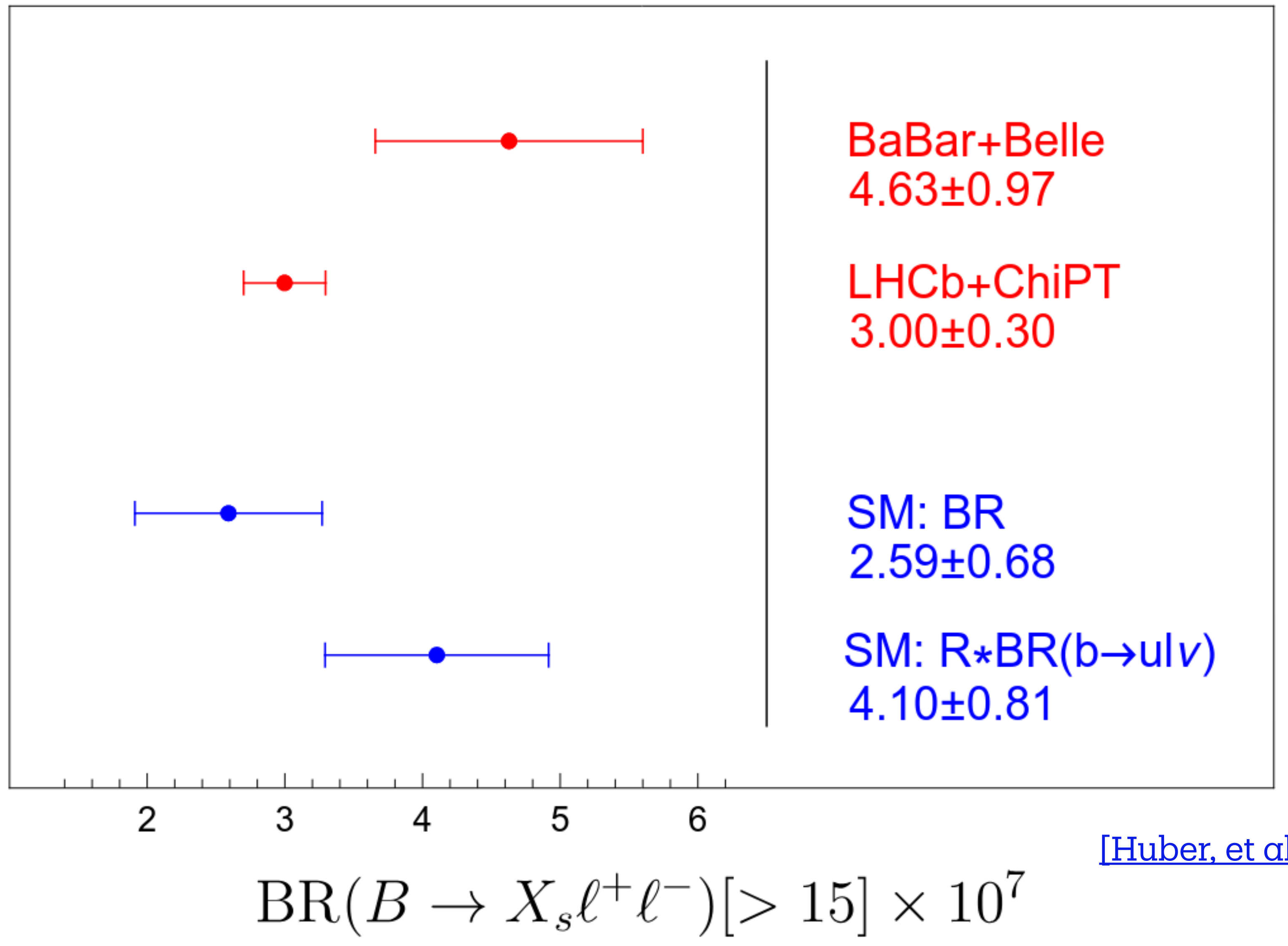




Tweaking the Calculation



[Isidori, Z.P, Tinari; 2305.03076]

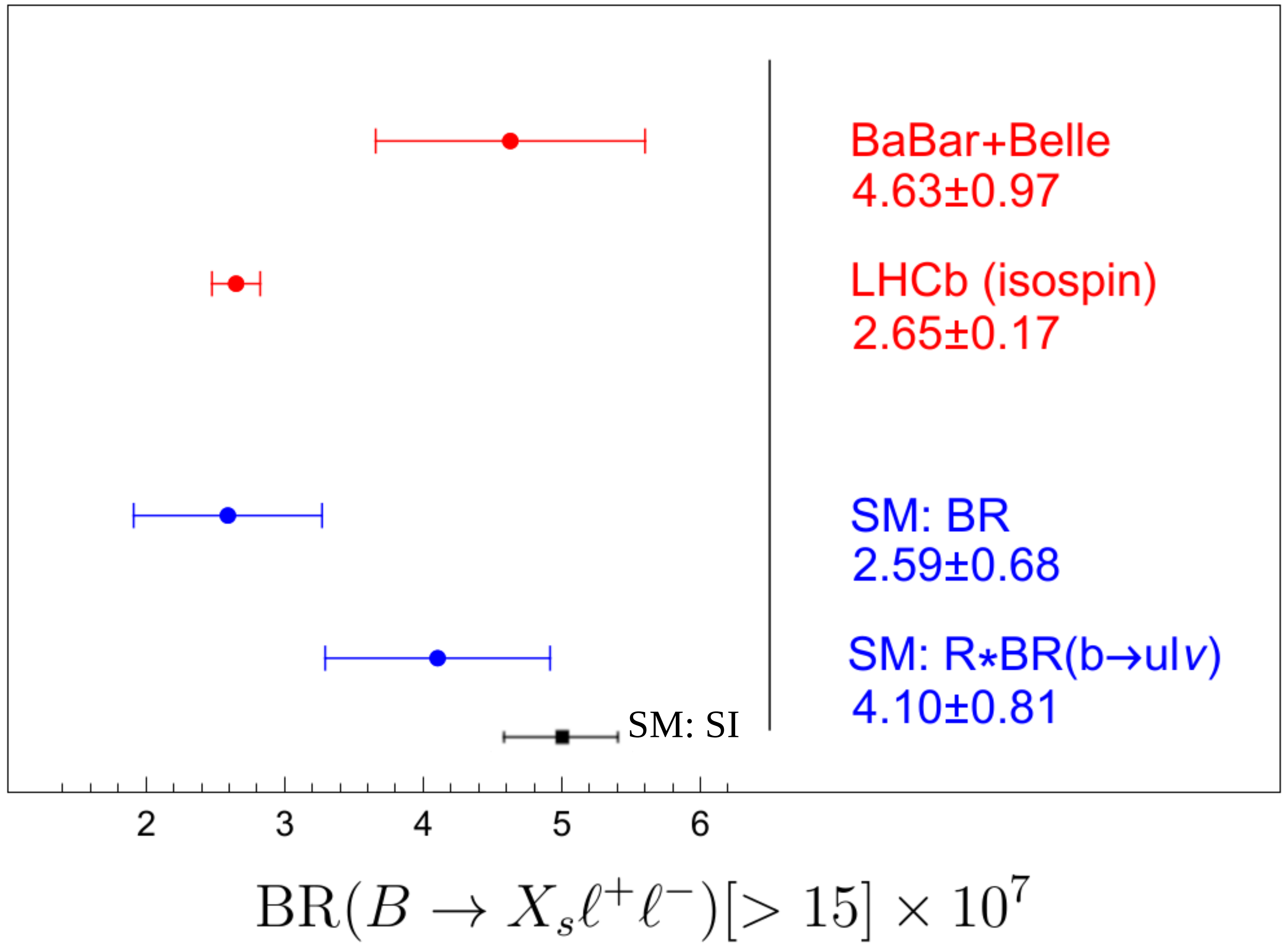


[Huber, et al.; 2404.03517]

- Two-loop QCD effects
- Direct ChPT instead of $\Delta_{K\pi}^{[15]}$
- KS method for off-shell resonances

Final Results

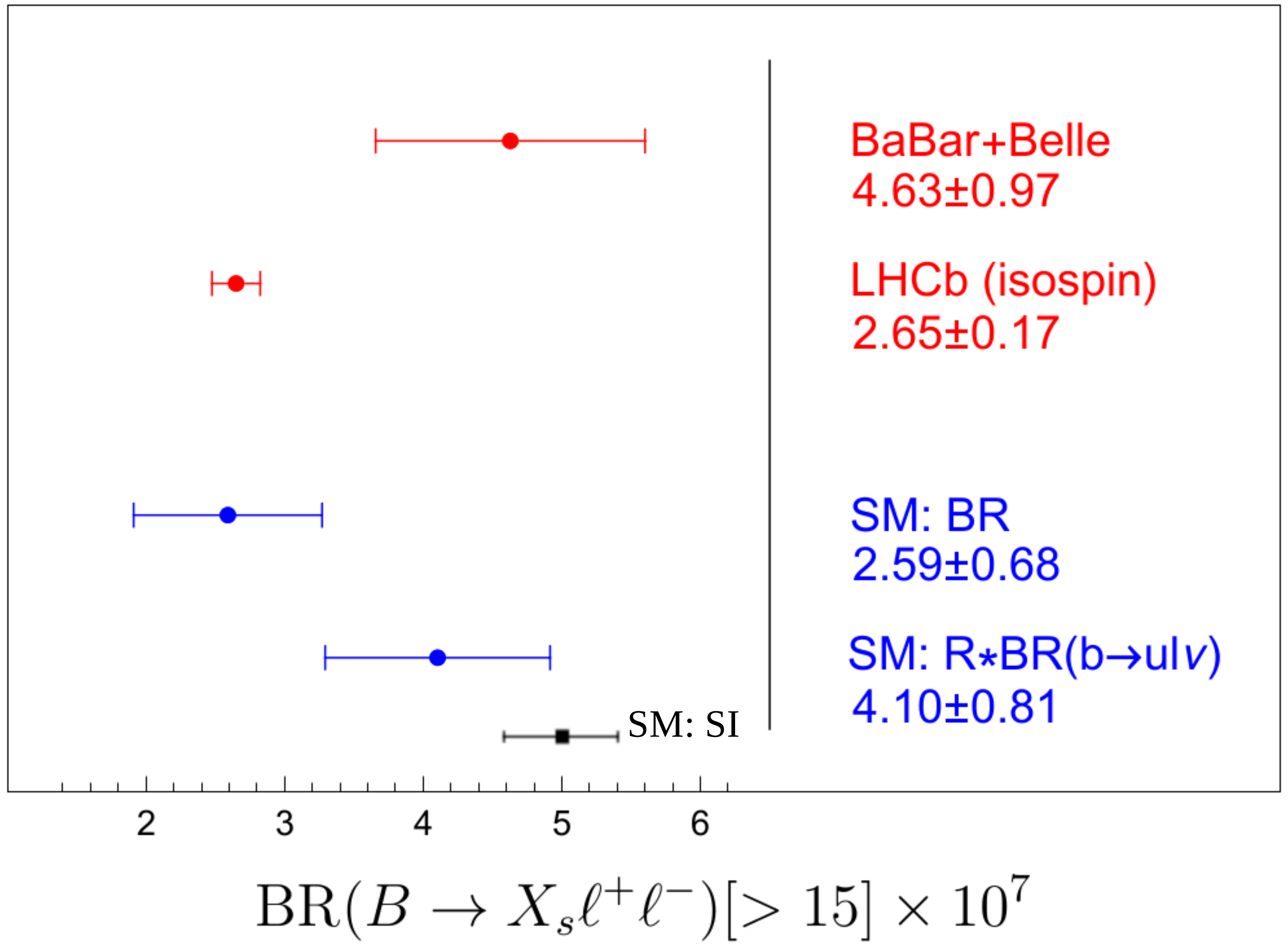
- LHCb has result for $(K\pi)_s$ channel
  [LHCb; 1606.04731]
- Factor of ~6 smaller than ChPT result
- Likely due to threshold enhancement



Remarks

- Large errors → difficult to make definitive statement

- Theory will be improved with future updates of $B \to X_u \bar{\ell} \nu$ and V_{cb}



Looking Forward

Looking Forward

- Exclusive/inclusive and high-/low-q^2 provide highly complementary information

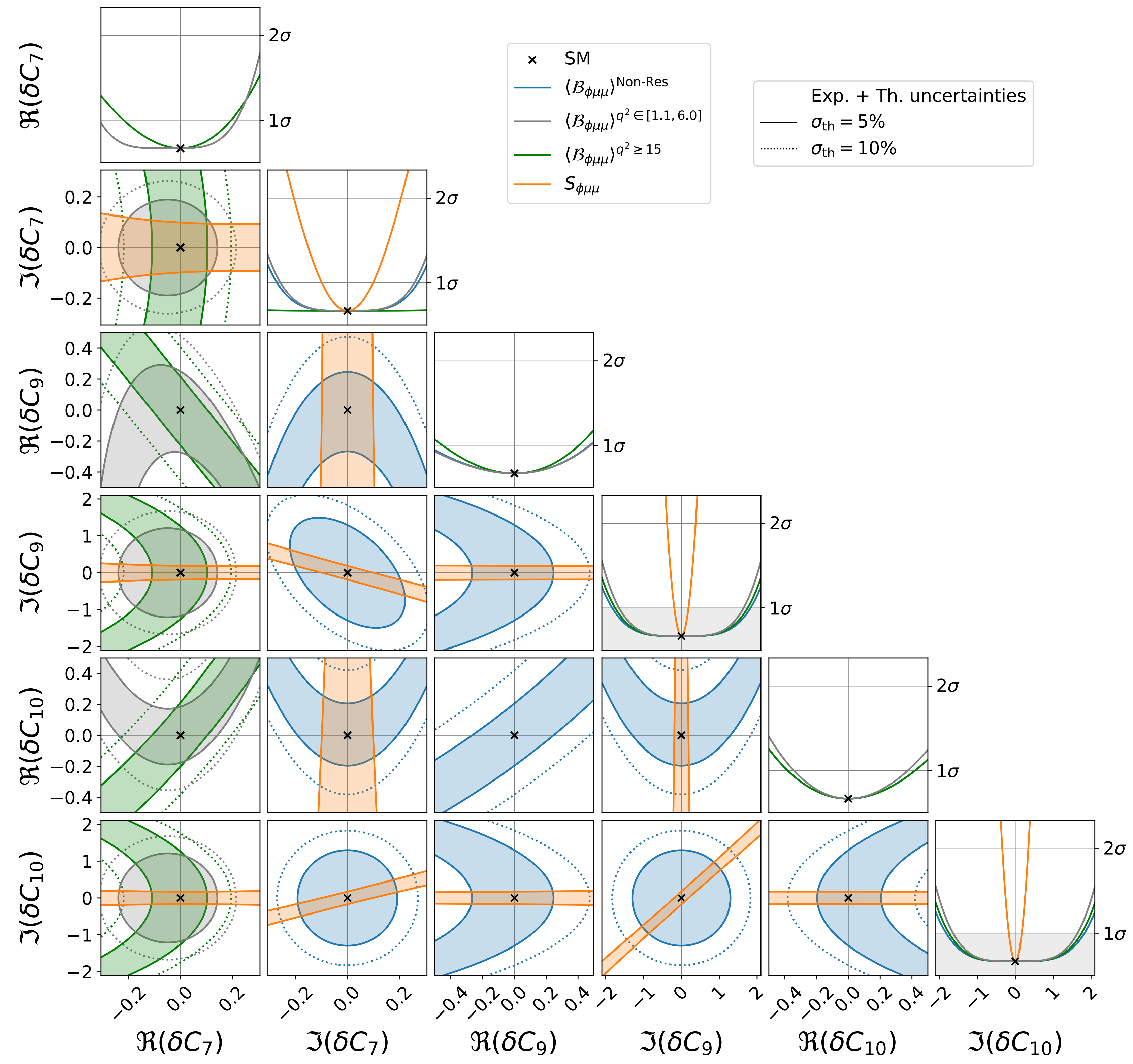
[Bordone, Cornella, Davighi; 2503.22635]

- Exclusive BRs become limited by theoretical errors: CP-violating observables at future colliders

[Fael, Jenkins, Lunghi, Z.P.; 2511(12).XXXXX]

- $b \to s\bar{\nu}\nu$ sensitive to C_9 structure — related by SU(2), without long-distance contamination

- **B-physics is in a very exciting era!**



[Kwok, Z.P., et al.; 2506.08089]

See Patrick's talk!