Inclusive $B \to X_s \ell\ell$ at the LHC

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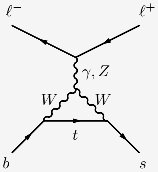
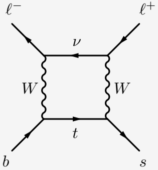
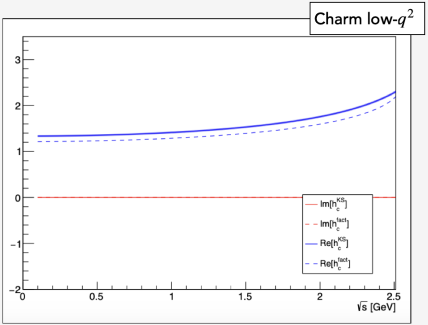
Introduction

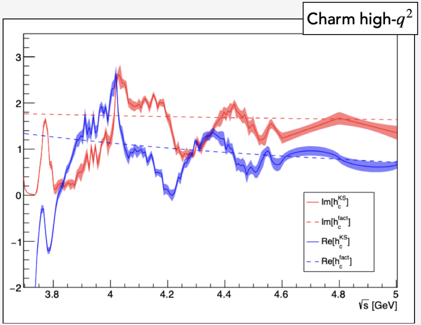
- The CKM+LFU paradigm of the Standard Model should be tested in all semileptonic reactions
- Unique to $b \to s$ (among FCNCs):
  No suppression other than the QED loop factor $\alpha^2/16\pi^2 \sim 10^{-6}$
  - GIM-allowed $m_t \sim M_W$
  - CKM-allowed $|V_{tb}V_{ts}| \sim |V_{cb}|^2$
- The SM contribution is already known to dominate $B \to X_s\gamma$ and $B_s \to \mu\mu$.. the situation for observables sensitive to C_9 is more complex due to $c\bar{c}$ effects

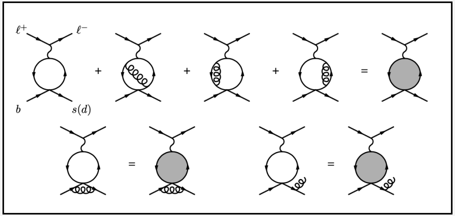




Resonances in $B \to X_s \ell\ell$







Open-charm resonances at high-q^2 and residual effects of the narrow resonances at low-q^2.. Replace factorizable matrix elements with spectral functions (Krüger-Sehgal)

Implementation

Leading order: one loop in RG improved perturbation theory ($C_{1,2}$ and C_9 running)

- Leading power ($m_b \to \infty$)
  - pQCD at NNLO, e.g. two-loop $Q_{1,2} - Q_{7,9}$ interference
  - pQED: $\alpha_e \ln(m_\ell/m_b)$ (collinear radiation) and finite α_e (in branching ratios)
  - Resonances: HVP functions for factorizable four-quark matrix elements
- Power corrections
  - High q^2: Local $1/m_b^2$, $1/m_b^3$ and $1/m_c^2$
  - Low q^2: Nonlocal resolved contributions $1/m_b$ (uncertainty added post-analysis)
- Parametric
  - Default normalization to $B \to X_c \ell \nu$ ($|V_{cb}|^2$ and m_b^5 prefactors cancel)
  - Optional normalization to $B \to X_u \ell \nu$

Power corrections

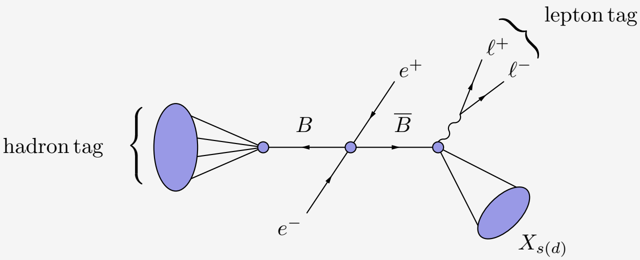
Power corrections dominate the error at high-q^2, in particular four-quark operators which are suppressed in the ratio

$$\mathcal{R}(q_0^2) = \int_{q_0^2}^{M_B^2} dq^2 \frac{d\mathcal{B}(B \to X_s \ell\ell)}{dq^2} \Bigg/ \int_{q_0^2}^{M_B^2} dq^2 \frac{d\mathcal{B}(B \to X_u \ell\nu)}{dq^2}$$

The ratio above offers an indirect determination of the $B \to X_s \ell\ell$ rate in the Standard Model (which relies on measurement of another rare decay)

$$\begin{aligned}\mathcal{B}[>15] &= (2.59 \pm 0.21_{\rm scale} \pm 0.03_{m_t} \pm 0.05_{C,m_c} \pm 0.19_{m_b} \pm 0.004_{\alpha_s} \pm 0.002_{\rm CKM} \\ &\quad \pm 0.04_{\rm BR_{sl}} \pm 0.26_{\rho_1} \pm 0.10_{\lambda_2} \pm 0.54_{f_{u,s}}) \times 10^{-7} \\ &= (2.59 \pm 0.68) \times 10^{-7} \\ \mathcal{R}(15) &= (27.00 \pm 0.25_{\rm scale} \pm 0.30_{m_t} \pm 0.11_{C,m_c} \pm 0.17_{m_b} \pm 0.15_{\alpha_s} \pm 1.16_{\rm CKM} \\ &\quad \pm 0.37_{\rho_1} \pm 0.07_{\lambda_2} \pm 1.43_{f_{u,s}}) \times 10^{-4} \\ &= (27.00 \pm 1.94) \times 10^{-4}\,.\end{aligned}$$

Electromagnetic effects



At the B factories, with a recoiling B, it is possible but not necessary to simulate or measure radiation from the leptons to trigger on $B \to X\ell\ell$.

The "true" q^2 distribution is sensitive to QED logarithms of the lepton mass.

At LHCb, the B momentum must be inferred on the signal side even if there are unmeasured photons..

Results without log-enhanced QED corrections

q^2 range [GeV^2]	$[1, 6]$	$[1, 3.5]$	$[3.5, 6]$
$\mathcal{B}$ $[10^{-7}]$	16.87 ± 1.25	9.17 ± 0.61	7.70 ± 0.65
$\mathcal{H}_T$ $[10^{-7}]$	3.14 ± 0.25	1.49 ± 0.09	1.65 ± 0.17
$\mathcal{H}_L$ $[10^{-7}]$	13.65 ± 1.00	7.63 ± 0.54	6.02 ± 0.49
$\mathcal{H}_A$ $[10^{-7}]$	-0.27 ± 0.21	-1.08 ± 0.08	0.81 ± 0.16

q^2 range [GeV^2]	> 14.4	> 15
$\mathcal{B}$ $[10^{-7}]$	3.04 ± 0.69	2.59 ± 0.68
$\mathcal{R}(q_0^2)$ $[10^{-4}]$	26.02 ± 1.76	27.00 ± 1.94

Results including log-enhanced QED corrections

q^2 range [GeV^2]	$[1,6]$	$[1,3.5]$	$[3.5,6]$
$\mathcal{B}$ [10^{-7}]	17.41 ± 1.31	9.58 ± 0.65	7.83 ± 0.67
$\mathcal{H}_T$ [10^{-7}]	4.77 ± 0.40	2.50 ± 0.18	2.27 ± 0.22
$\mathcal{H}_L$ [10^{-7}]	12.65 ± 0.92	7.085 ± 0.48	5.56 ± 0.45
$\mathcal{H}_A$ [10^{-7}]	-0.10 ± 0.21	-0.989 ± 0.080	0.89 ± 0.16

q^2 range [GeV^2]	> 14.4
$\mathcal{B}$ [10^{-7}]	2.66 ± 0.70
$\mathcal{R}(q_0^2)$ [10^{-4}]	$24.12 \pm 2.01^{\dagger}$

† The denominator of $\mathcal{R}(q_0^2)$ (the $B \to X_u \ell \nu$ rate) does not include log-enhanced QED corrections

Sum over exclusive $B \to K^{(*)}\mu\mu$

Charged ($B^{\pm} \to K^{\pm}\mu\mu$) and neutral ($B^0 \to K^0\mu\mu$) branching ratios ($\times 10^{-7}$) are available from LHCb over a common phase space $q^2 > 15$ GeV^2

	Charged	Neutral	Isospin avg.
$B \to K$	0.85 ± 0.05	0.66 ± 0.11	$0.82 \pm 0.05^{\dagger}$
$B \to K^*$	1.58 ± 0.33	1.74 ± 0.14	$1.72 \pm 0.13^{\dagger}$
$B \to K + K^*$	$2.43 \pm 0.33^{\dagger}$	$2.41 \pm 0.18^{\dagger}$	$\mathbf{2.41 \pm 0.16}^{\dagger}$

† Combinations do not include correlations from common backgrounds

Estimate nonresonant contributions by S-wave $K\pi$ [Isidori et al '23]

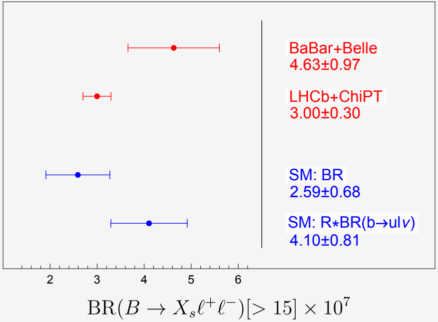
$$\mathcal{B}(B \to (K\pi)_s \ell\ell)[> 15] = \mathbf{0.58 \pm 0.25}$$

Semi-inclusive determination:

$$\mathcal{B}[> 15]_{\mathrm{LHCb+ChiPT}} = \mathbf{3.00 \pm 0.30}$$

$$\mathcal{B}[> 15]^{\text{charged only}}_{\mathrm{LHCb+ChiPT}} = 3.01 \pm 0.43$$

Comparison to Experiment



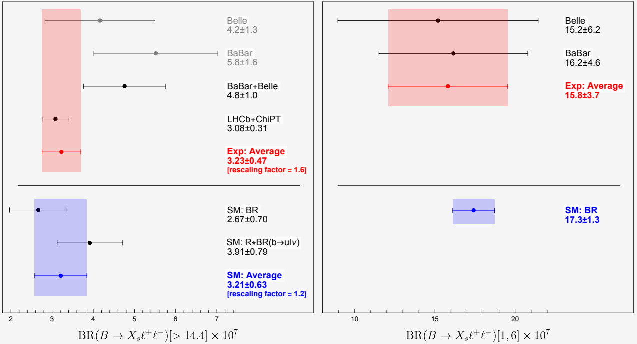
- Interpolated B factory results to LHCb's phase space:
  - BaBar: $q^2 > 14.2$ (e/μ avg)
  - Belle: $q^2 > 14.4$ (e/μ avg)
  - LHCb: $q^2 > 15$ (noQED, μ only)
- Used inclusive theory predictions to correct for phase space and QED
  - $\mathcal{B}[> 14.4]/\mathcal{B}[> 14.2] = 0.96$
  - $\mathcal{B}[> 15]_{\mathrm{noQED}}/\mathcal{B}[> 14.4] = 0.97$

No clear anomaly in the inclusive mode

Our analysis does not reproduce a deficit in the data w.r.t. theory reported by Isidori et al '23

Comparison to Experiment

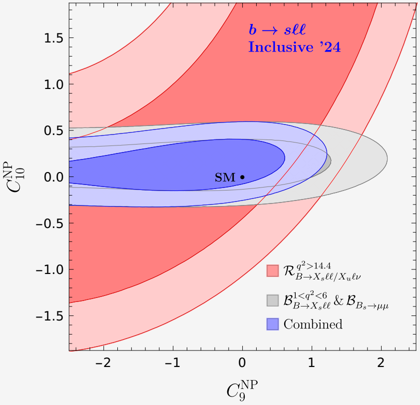
Extrapolated LHCb+ChiPT to Belle's phase space

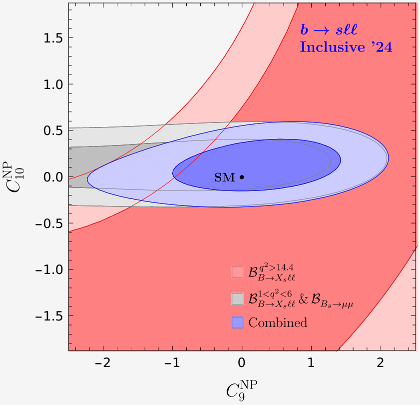


- Direct, indirect theory determinations are in better agreement for $q^2 > 14\,\mathrm{GeV}^2$
- Experimental average is compatible with both theory determinations
- Low-q^2 also in agreement

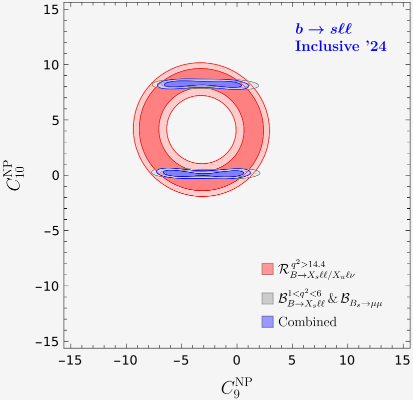
Constraints on C_9 and C_{10}

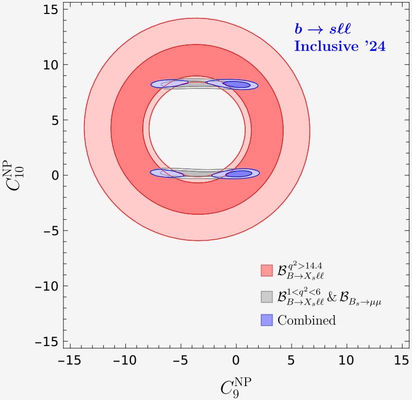
- Three branching ratio constraints: $B \to X_s \ell\ell$ (low-q^2 and high-q^2) and $B_s \to \mu\mu$
- With (left) and without (right) normalization to $B \to X_u \ell\nu$ at high-q^2





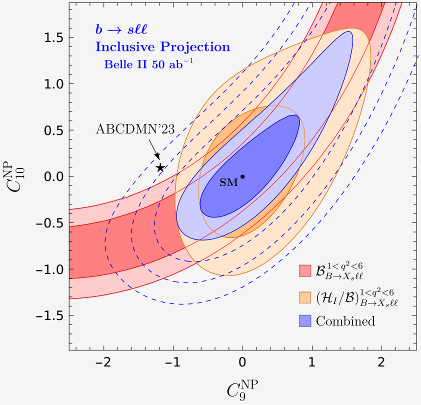
Constraints on C_9 and C_{10} (expanded plane)

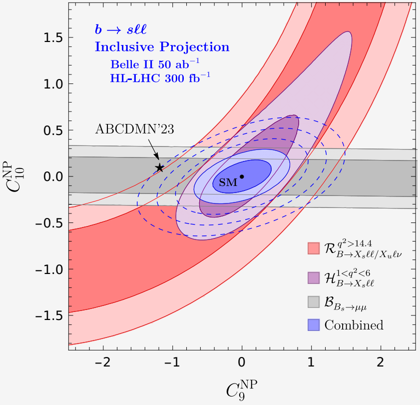




Belle II projections

The angular decomposition in the low-q^2 region would be key to extracting C_9 from inclusive analyses at Belle II





Summary

- We considered the effect of collinear photon radiation in inclusive $B \to X_s \ell\ell$, suitable for analyses at LHCb
- The inclusive theory predictions can also be used to compare LHCb results to the B factories: bounds on C_9 from the inclusive mode are consistent with the SM.

Several directions to progress (before a fully inclusive measurement at Belle II):

- LHCb updates of $B \to K^{(*)}$ at high-q^2
- Closer look at $K\pi$ and $K\pi\pi$ (theory and experiment)
- Updates of power corrections parameters and $B \to X_u \ell\nu$

Inclusive $B \to X_s \ell\ell$ at the LHC

Thank you for listening !
Any Questions ?