Progress in $B \to X_s \ell\ell$ Phenomenology

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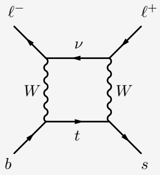
Collaborative Research Center TRR 257
P H
Particle Physics Phenomenology after the Higgs Discovery

TP1 Theoretical Particle Physics

CPPS Center for Particle Physics Siegen

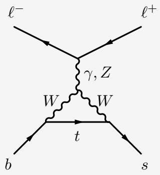
Quirks in Semileptonic Decays

The SM applied to semileptonic decays is remarkably predictive (CKM+LFU) ..
.. but does not explain mass and mixing hierarchies and is phenomenological in this respect



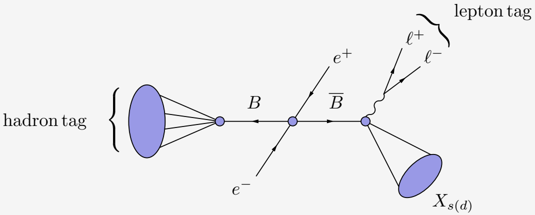
$b \to s$: no suppression other than $\alpha^2/16\pi^2 \sim 10^{-6}$

- GIM-allowed $m_t \sim M_W$
- CKM-allowed $|V_{tb}V_{ts}| \sim |V_{cb}|^2$



Inclusive $B \to X\ell\ell$ at the B factories

Ideal environment for inclusive modes
(recoil tagging or sum-over-exclusive)



Three angular observables with q^2-dependent sensitivity to $C_{9,10}$
[Lee, Ligeti, Stewart, Tackmann 0612156]

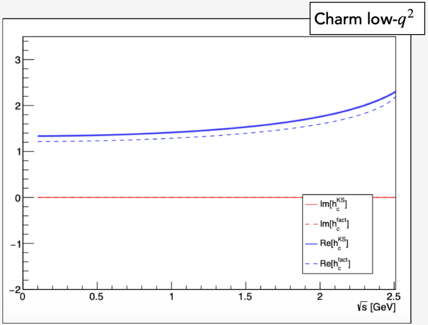
$$\frac{d^3\Gamma}{dq^2\, dM_X\, dz} = \frac{3}{8}\left[(1+z^2)H_T + 2z\, H_A + 2(1-z^2)H_L\right]$$

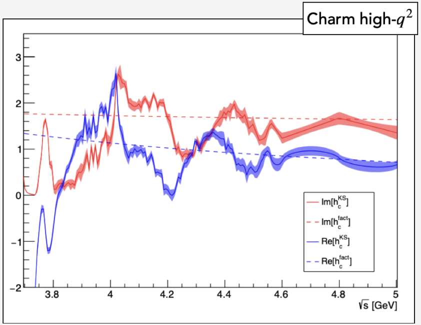
$$H_T \sim 2(1-\hat{q}^2)^2\hat{q}^2\left[\left(C_9 + 2C_7/\hat{q}^2\right)^2 + C_{10}^2\right],$$

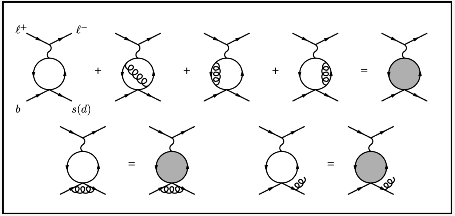
$$H_A \sim -4(1-\hat{q}^2)^2\hat{q}^2\, C_{10}(C_9 + 2C_7/\hat{q}^2),$$

$$H_L \sim (1-\hat{q}^2)^2\left[(C_9 + 2C_7)^2 + C_{10}^2\right]$$

Krüger-Sehgal approach







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 and Sehgal 9603237]

Nonfactorizable amplitudes treated perturbatively (no narrow resonance fudge factors)

Normalization

Power corrections dominate the error at high-q^2, in particular four-quark operators which are suppressed in the ratio [Ligeti, Tackmann 0707.1694]

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

This normalization provides an indirect determination of the $B \to X_s \ell\ell$ rate [Huber, Hurth, Jenkins, Lunghi, Qin, Vos 2404.03517]

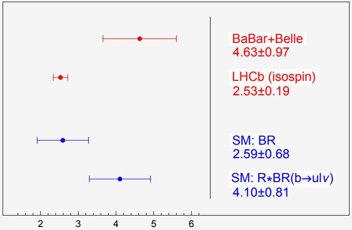
$$\begin{aligned}
\mathcal{B}[>15] &= (2.59 \pm 0.21_{\rm scale} \pm 0.03_{m_t} \pm 0.05_{C,m_c} \pm 0.19_{m_b} \pm 0.004_{\alpha_s} \pm 0.002_{\rm CKM} \\
&\qquad \pm 0.04_{\rm BR_{sl}} \pm 0.26_{\rho_1} \pm 0.10_{\lambda_2} \pm 0.54_{f_{u,s}}) \times 10^{-7} \\
&= (2.59 \pm 0.68) \times 10^{-7} \\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

Comparison to Experiment

	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	$1.72 \pm 0.13^{\dagger}$
$B \to K + K^*$	$2.43 \pm 0.33^{\dagger}$	$2.41 \pm 0.18^{\dagger}$	$\mathbf{2.41 \pm 0.16}^{\dagger}$

[LHCb 1403.8044, 1606.04731, LHCb 1408.1137]

† Our combinations do not include correlations



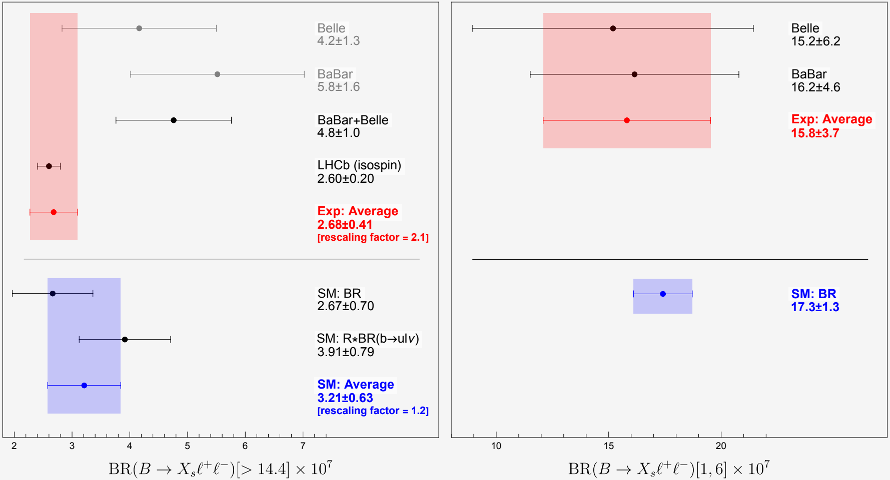
$\mathrm{BR}(B \to X_s \ell^+ \ell^-)[> 15] \times 10^7$

- 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
  - $\mathcal{B}[> 14.4]/\mathcal{B}[> 14.2] = 0.96$
  - $\mathcal{B}[> 15]_{\mathrm{noQED}}/\mathcal{B}[> 14.4] = 0.97$

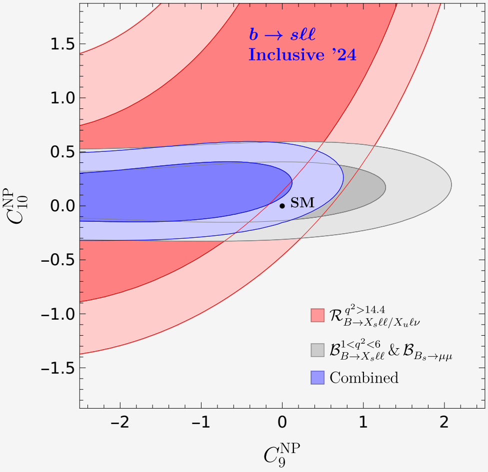
The picture is obscured by a spread of experimental and theoretical determinations
(B factory vs LHCb, direct vs indirect)

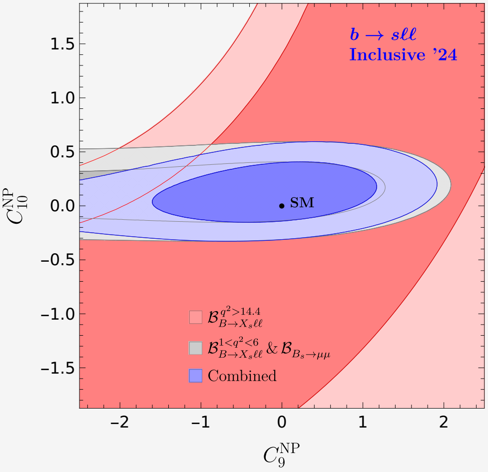
No clear anomaly in the inclusive mode

Comparison to Experiment

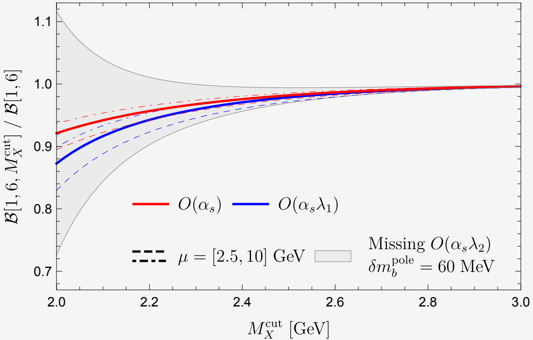


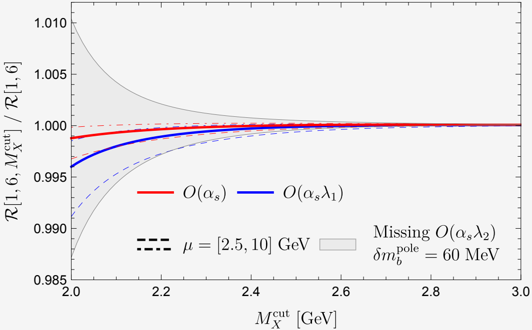
Constraints on SM Coefficients





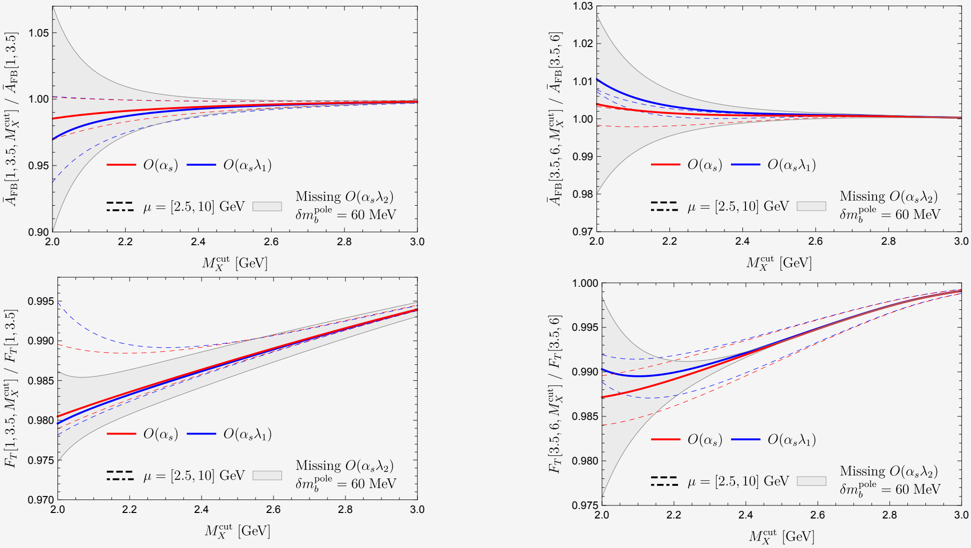
M_X Distribution: Rate



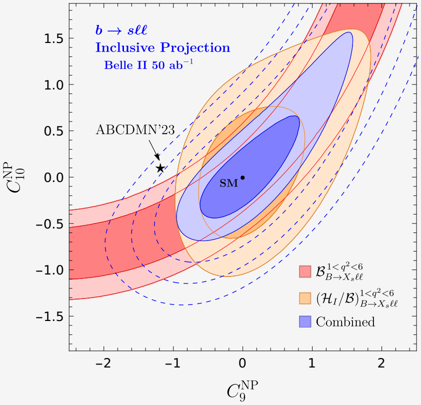


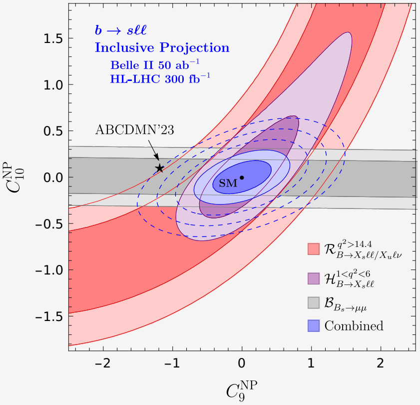
[Huber, Hurth, Jenkins, Lunghi 2306.03134]

M_X Distribution: Angular Observables



Belle II projections





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.

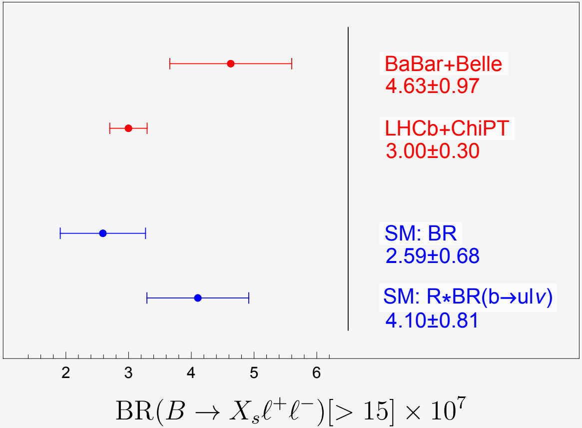
Several directions to progress (before a fully inclusive measurement at Belle II):

- 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 $B \to X_u \ell\nu$

Progress in $B \to X_s \ell\ell$ Phenomenology

Thank you for listening !
Any Questions ?

HHChiPT

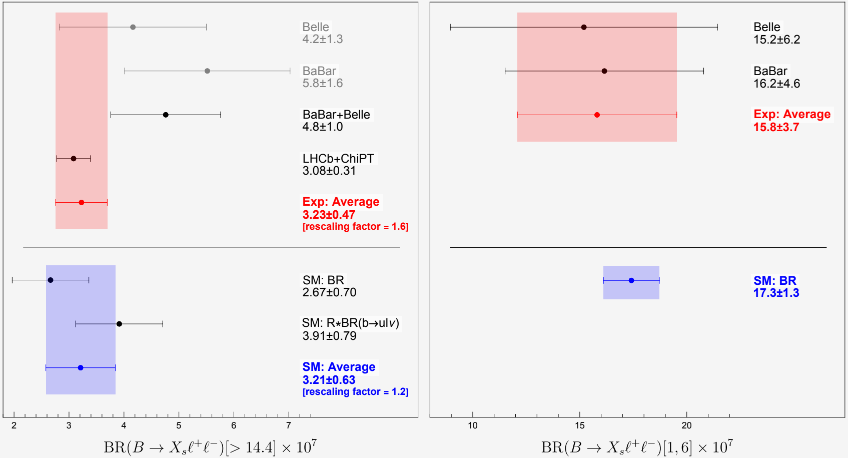


Estimate of nonresonant contributions [2305.03076]

$\mathrm{Br}(B \to (K\pi)_S \ell\ell)[> 15] = (0.58 \pm 0.25) \times 10^{-7}$

This estimate is consistent with and superceded by more precise $B \to K\pi$ and $B \to K\pi\pi$ from LHCb

HHChiPT


Belle
4.2±1.3
BaBar
5.8±1.6
BaBar+Belle
4.8±1.0
LHCb+ChiPT
3.08±0.31
Exp: Average
3.23±0.47
[rescaling factor = 1.6]
SM: BR
2.67±0.70
SM: R∗BR(b→ulν)
3.91±0.79
SM: Average
3.21±0.63
[rescaling factor = 1.2]
2 3 4 5 6 7
$\mathrm{BR}(B \to X_s \ell^+ \ell^-)[> 14.4] \times 10^7$
Belle
15.2±6.2
BaBar
16.2±4.6
Exp: Average
15.8±3.7
SM: BR
17.3±1.3
10 15 20
$\mathrm{BR}(B \to X_s \ell^+ \ell^-)[1,6] \times 10^7$

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

Constraints on SM coefficients (expanded plane)