QED corrections to inclusive $\bar{B} \to X_s \ell^+ \ell^-$ decays

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DFG SFB TRR 257

With E. Lunghi, M. Misiak, D. Wyler, T. Hurth, J. Jenkins, Q. Qin, K. Vos 2005 – ?

"QED corrections to (semi-)leptonic *B* decays", Paris, July 8-9th, 2019

Outline

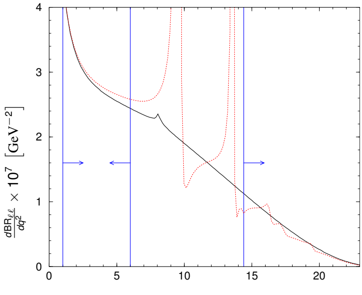
- Observables
- Complementarity between incl. and excl. decays
- NLO QED corrections
- Collinear photons
- Results for $\bar{B} \to X_s \ell^+ \ell^-$
- Preliminary results for $\bar{B} \to X_d \ell^+ \ell^-$
- Conclusion and outlook

Observables

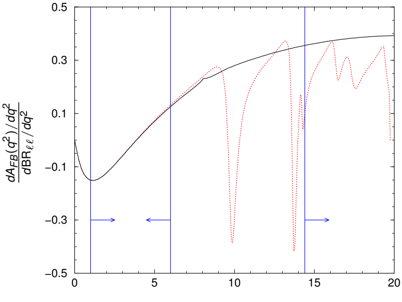
- Double differential decay width ($z = \cos\theta_\ell$) [Lee,Ligeti,Stewart,Tackmann'06]

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

Note: $$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2)\,, \qquad \frac{dA_{\rm FB}}{dq^2} = 3/4\,H_A(q^2)$$



[Ghinculov,Hurth,Isidori,Yao]



[Ghinculov,Hurth,Isidori,Yao]

- Low-q^2 region: $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$
- High-q^2 region: $q^2 > 14.4\,\mathrm{GeV}^2$

Observables

- Dependence of the H_i on WCs

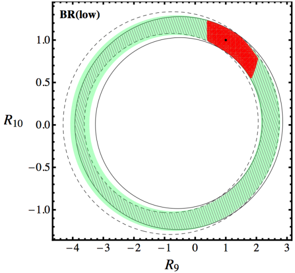
$$H_T(q^2) \propto 2s(1-s)^2 \left[\left| C_9 + \frac{2}{s} C_7 \right|^2 + |C_{10}|^2 \right]$$
$$H_A(q^2) \propto -4s(1-s)^2 \ \mathrm{Re}\left[C_{10} \left(C_9 + \frac{2}{s} C_7 \right) \right]$$
$$H_L(q^2) \propto (1-s)^2 \left[\left| C_9 + 2\, C_7 \right|^2 + |C_{10}|^2 \right]$$

- Consider integrals of H_i over two bins $1 - 3.5$ GeV^2 and $3.5 - 6$ GeV^2
    - H_T suppressed at low-q^2: Factor "s" and small $\left| C_9 + \frac{2}{s} C_7 \right|^2$
- Moreover: zero of H_A in low-q^2 region
- In high-q^2 region: ratio $\mathcal{R}(s_0) = \frac{\int_{\hat{s}_0}^1 \mathrm{d}\hat{s} \ d\Gamma(\bar{B} \to X_s \ell^+ \ell^-)/d\hat{s}}{\int_{\hat{s}_0}^1 \mathrm{d}\hat{s} \ d\Gamma(\bar{B}^0 \to X_u \ell \nu)/d\hat{s}}$ [Ligeti,Tackmann'07]
    - Normalize to semileptonic $\bar{B}^0 \to X_u \ell \nu$ rate with the same cut
- In $\bar{B} \to X_d \, \ell^+ \ell^-$ also CP asymmetry $A_{CP} = \frac{\Gamma(\bar{B} \to X_d \, \ell^+ \ell^-) - \Gamma(B \to X_{\bar{d}} \, \ell^+ \ell^-)}{\Gamma(\bar{B} \to X_d \, \ell^+ \ell^-) + \Gamma(B \to X_{\bar{d}} \, \ell^+ \ell^-)}$

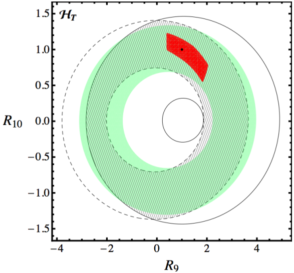
Inclusive $\bar{B} \to X_s \ell^+ \ell^-$: WC sensitivity

[Hurth,Lunghi,TH'15]

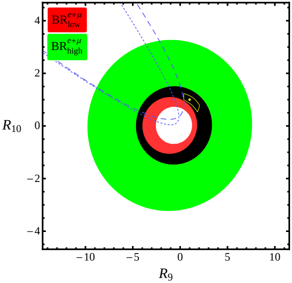
- Study ratios $R_i = \dfrac{C_i(\mu_0)}{C_i^{\rm SM}(\mu_0)}$ in different bins of q^2
- Model-independent constraints on high-scale WCs through angular observables $H_{T,A,L}(q^2)$
- Extrapolation to the full Belle-II statistics (50 ab^{-1})



BR low-q^2



H_T low-q^2



combined

[See also Lee,Ligeti,Stewart,Tackmann'06; K. Flood]

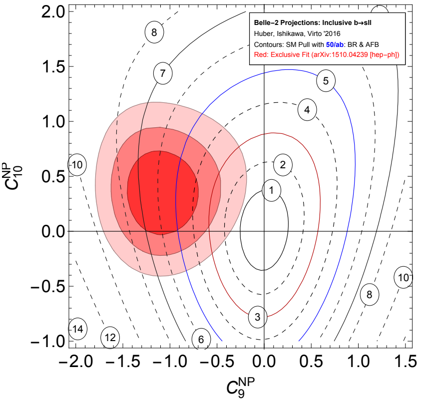
Inclusive vs. exclusive $b \to s\ell^+\ell^-$

- Complementarity of $\bar{B} \to X_s\,\ell^+\ell^-$ and $\bar{B} \to K^{(*)}\,\mu^+\mu^-$
  - Different experimental analysis: LHCb vs. BaBar, Belle (II)
  - Underlying hadronic uncertainties in inclusive mode are quite different and independent of those in exclusive transitions
  - Probing different theoretical approaches when measuring e.g. C_9

- Complementarity study [Ishikawa,Virto,TH: Belle II Physics Book, 1808.10567, sec. 9.4.5]
  - Include BR and $A_{\rm FB}$ in $\bar{B} \to X_s\,\ell^+\ell^-$ with 50/ab.
  - Consider three q^2 bins: $[1, 3.5]$ GeV^2, $[3.5, 6]$ GeV^2, > 14.4 GeV^2
  - derive model-independent constraints on C_9 and C_{10}

Q: If the *true* values for the NP contributions are $C_9^{\rm NP}$ and $C_{10}^{\rm NP}$, with which significance will the Belle II measurements exclude the SM ($C_9^{\rm NP} = C_{10}^{\rm NP} = 0$)?

[Ishikawa,Virto,TH, Belle II physics book, 1808.10567, sec. 9.4.5]



[See also Hurth,Mahmoudi'13; Hurth,Mahmoudi,Neshatpour'14]

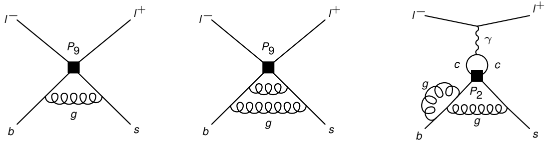
Superimpose the current global fit, dominated by the *exclusive* $b \to s\ell\ell$ measurements

Precision measurements of the $\bar{B} \to X_s\,\ell^+\ell^-$ channel provide important complementary information in the context of global fits.

Perturbative and non-perturbative corrections

$$\Gamma(\bar{B} \to X_s \ell\ell) = \Gamma(b \to X_s \ell\ell) \; + \; \text{power corrections}$$

- Pert. corrections at quark level are known to NNLO QCD + NLO QED
  [Misiak,Buras,Münz,Bobeth,Urban,Asatrian,Asatryan,Greub,Walker,Bobeth,Gambino,Gorbahn,Haisch,Blokland]
  [Czarnecki,Melnikov,Slusarczyk,Bieri,Ghinculov,Hurth,Isidori,Yao,Greub,Pilipp,Schüpbach,Lunghi,TH]
  - Involves diagrams up to three loops



  - Fully differential QCD corrections at NNLO for $P_{9,10}$ also known
    [Brucherseifer,Caola,Melnikov'13]

- $1/m_b^2$, $1/m_b^3$ and $1/m_c^2$ non-pert. corrections
  [Falk,Luke,Savage'93]
  [Ali,Hiller,Handoko,Morozumi'96]
  [Bauer,Burrell'99; Buchalla,Isidori,Rey'97]

- Factorizable $c\bar{c}$ contributions implemented via KS approach [Krüger, Sehgal'96]

Motivation for NLO QED corrections

- Consider differential decay rate (or any of $H_{T,A,L}$)

$$\frac{d\Gamma(\bar{B}\to X_s l^+ l^-)}{d\hat{s}} = \frac{G_F^2 m_b^5 |V_{ts}^* V_{tb}|^2 \alpha_{em}^2(\mu)(1-\hat{s})^2}{768\pi^5} \left\{ \left(4+\frac{8}{\hat{s}}\right)|C_7|^2 + (1+2\hat{s})\left(|C_9|^2+|C_{10}|^2\right) + 12\,\mathrm{Re}\left(C_7\, C_9^*\right) \right\}$$

  - $\pm 4\%$ scale uncertainty: $\alpha_e(m_b) \approx 1/133$ vs. $\alpha_e(m_Z) \approx 1/128.$

- The organisation of the perturbative expansion is screwed since LO = $\alpha_{\rm em}/\alpha_s$
  - Consistent expansion is in α_s and $\kappa = \alpha_{\rm em}/\alpha_s$ [Lunghi,Misiak,Wyler,TH'05]

- Amplitude:

$$\begin{aligned} A &= \kappa\left[A_{LO} + \alpha_s A_{NLO} + \alpha_s^2 A_{NNLO} + \mathcal{O}(\alpha_s^3)\right] \\ &+ \kappa^2\left[A_{LO}^{em} + \alpha_s A_{NLO}^{em} + \alpha_s^2 A_{NNLO}^{em} + \mathcal{O}(\alpha_s^3)\right] + \mathcal{O}(\kappa^3) \end{aligned}$$

  - Accidentially: $A_{LO} \sim \tilde{\alpha}_s A_{NLO}$ and $A_{LO}^{em} \sim \tilde{\alpha}_s A_{NLO}^{em}$

    $\Rightarrow$ quite high terms in the expansion remain numerically important

Details of NLO QED Corrections

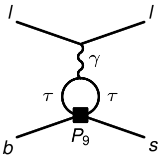
- Calculation of NLO QED corrections is threefold
  - Matching and running calculation [Bobeth,Gambino,Gorbahn,Haisch'03; Lunghi,Misiak,Wyler,TH'05]

    $\Longrightarrow$ see Misiak's talk
  - Matrix elements of the P_i

- Matrix elements of the P_i

- IR finite contributions $$\langle P_i \rangle = H_i^9 \, \langle P_9 \rangle_{\rm tree} + H_i^7 \, \frac{\langle P_7 \rangle_{\rm tree}}{\tilde{\alpha}_s \kappa} + H_i^{10} \, \langle P_{10} \rangle_{\rm tree}$$

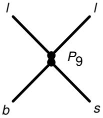
	H_i^9	H_i^7	H_i^{10}
$i = 1, 2$	$\tilde{\alpha}_s \kappa \; f_i(\hat{s}) - \tilde{\alpha}_s^2 \kappa \; F_i^9(\hat{s})$	$-\tilde{\alpha}_s^2 \kappa \; F_i^7(\hat{s})$	0
$i = 3-6, 3Q-6Q, b$	$\tilde{\alpha}_s \kappa \; f_i(\hat{s})$	0	0
$i = 7$	0	$\tilde{\alpha}_s \kappa$	0
$i = 8$	$-\tilde{\alpha}_s^2 \kappa \; F_8^9(\hat{s})$	$-\tilde{\alpha}_s^2 \kappa \; F_8^7(\hat{s})$	0
$i = 9$	$1 + \tilde{\alpha}_s \kappa \; f_9^{\rm pen}(\hat{s})$	0	0
$i = 10$	0	0	1



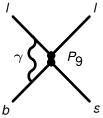
NLO QED Matrix Elements

- IR divergent contributions: Photon-loop corrections to P_9
- Consider massless final state, work in $D = 4 - 2\,\epsilon$ dimensions
- Virtual corrections:

$\int dPS_3 \Big|$

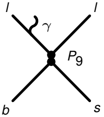


$+ \; 6 \; \times$



$\Big|^2 \quad + \quad$ UV counterterms

- Real corrections: $\int dPS_4 \Big| \; 4 \; \times$



$\Big|^2$

NLO QED Matrix Elements

- Result virtual corrections

$$= \mathcal{O}(\alpha_e^0) + \frac{\alpha_e}{4\pi}\left(\frac{a_1\, Q_d^2 + a_2\, Q_l^2}{\epsilon^2} + \frac{a_3\, Q_d^2 + a_4\, Q_d\, Q_l + a_5\, Q_l^2}{\epsilon} + \text{finite}\right)$$

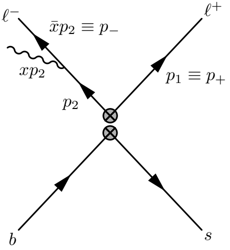
- Result real corrections

$$= \frac{\alpha_e}{4\pi}\left(-\frac{a_1\, Q_d^2 + a_2\, Q_l^2}{\epsilon^2} + \frac{-a_3\, Q_d^2 - a_4\, Q_d\, Q_l + (a_5' - a_5)\, Q_l^2}{\epsilon} + \text{finite}\right)$$

- Residual collinear divergence $\frac{\alpha_e}{4\pi}\frac{a_5'\, Q_l^2}{\epsilon}$
- Observables differential in q^2 are not IR safe w.r.t emission of collinear photons off lepton lines (integrated observables are)

NLO QED Matrix Elements

- Change of from naive dim. reg. to mass regularization: fragmentation (splitting) function $f_\gamma(x, E)$
- Collinear singularity in $f_\gamma(x, E)$ can be regularized with dim. reg. or with lepton mass



$$f_\gamma^{(\epsilon)}(x, E) = 4\tilde{\alpha}_e \left[\frac{1 + (1-x)^2}{x} \left(-\frac{1}{2\epsilon} + \ln \frac{E}{\mu} + \ln(2 - 2x) \right) + \ldots \right]$$

$$f_\gamma^{(m)}(x, E) = 4\tilde{\alpha}_e \left[\frac{1 + (1-x)^2}{x} \left(\ln \frac{E}{m_\ell} + \ln(2 - 2x) \right) + \ldots \right]$$

- Translation of collinear divergence into an electromagnetic logarithm:

$$\frac{\alpha_e}{4\pi} \frac{a_5' \, Q_l^2}{\epsilon} \longrightarrow \frac{\alpha_e}{4\pi} \left[\log\left(\frac{m_b^2}{m_\ell^2} \right) \cdot h(\hat{s}) + k(\hat{s}) \right] \quad \text{with} \quad \int_0^1 d\hat{s} \;\, h(\hat{s}) = 0.$$

NLO QED Matrix Elements

- Additional remarks
  - We do not resum the single electromagnetic logarithm

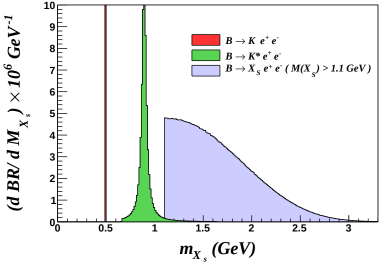
$$\frac{\alpha_e}{4\pi} \log\left(\frac{m_b^2}{m_\ell^2}\right) \sim 0.01 \quad \text{for} \quad \ell = e$$

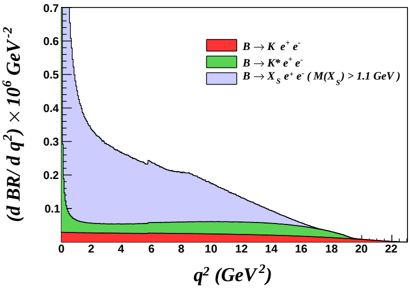
  - We include also log-enhanced corrections to other interferences of $H_{T,A,L}$
    - $|\langle P_7\rangle|^2$, $|\langle P_{10}\rangle|^2$, $Re\left[\langle P_7\rangle \langle P_9\rangle^*\right]$, $Re\left[\langle P_7\rangle \langle P_{10}\rangle^*\right]$, $Re\left[\langle P_9\rangle \langle P_{10}\rangle^*\right]$
    - $\left|\left\langle P_{1,2}^c\right\rangle\right|^2$, $Re\left[\left\langle P_{1,2}^c\right\rangle \left\langle P_{7,9,10}\right\rangle^*\right]$
    - For $b \to d$ also $\left|\left\langle P_{1,2}^u\right\rangle\right|^2$, $Re\left[\left\langle P_{1,2}^u\right\rangle \left\langle P_{7,9,10}\right\rangle^*\right]$, $Re\left[\left\langle P_{1,2}^u\right\rangle \left\langle P_{1,2}^c\right\rangle^*\right]$
  - Presence and size of $\log\left(\frac{m_b^2}{m_\ell^2}\right)$ depends on experimental setup due to finite detector resolution for collinear photons
    - not a problem for muons
    - electron case requires further studies

Collinear photons

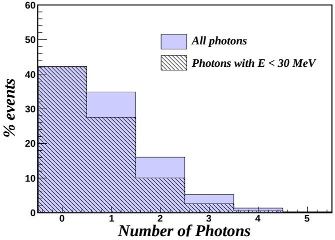
- Size of logs depends on experimental setup
  - $q^2 = (p_{\ell^+} + p_{\ell^-})^2$ vs. $q^2 = (p_{\ell^+} + p_{\ell^-} + p_{\gamma,\mathrm{coll}})^2$
  - To compare to BaBar electron channel our numbers need to be modified

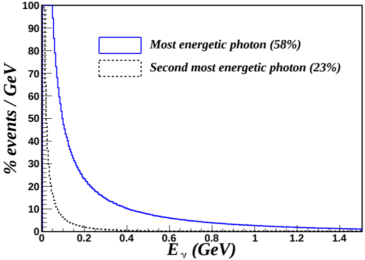
$$\frac{\left[\mathcal{B}_{ee}^{\mathrm{low}}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\mathrm{coll}}}}}{\left[\mathcal{B}_{ee}^{\mathrm{low}}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 1.65\% \qquad \frac{\left[\mathcal{B}_{ee}^{\mathrm{high}}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\mathrm{coll}}}}}{\left[\mathcal{B}_{ee}^{\mathrm{high}}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 6.8\%$$

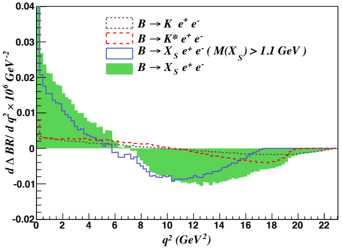


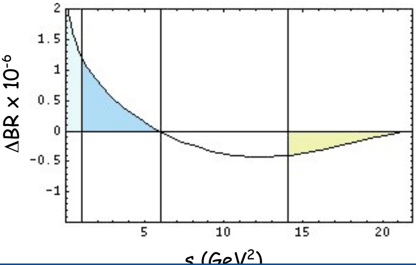


- Validation
  - Generate events (EVTGEN), hadronise (JETSET), add EM radiation (PHOTOS)



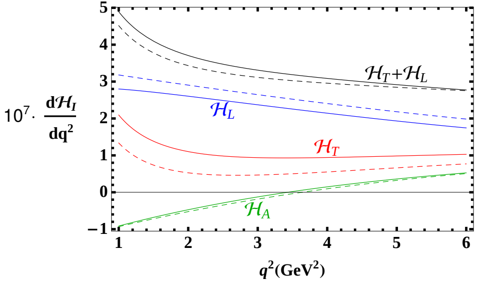


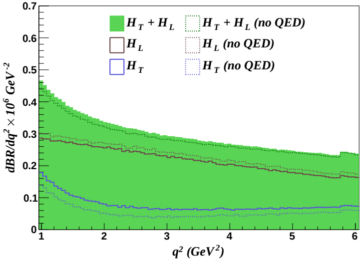




Collinear photons

- QED corrections lift smallness of H_T to a certain extent. Not a breakdown of perturbation theory.





- Radiation of energetic, collinear photons from final state leptons introduces higher powers of z in double differential decay width
  - How to define the H_i ??
    - Use Legendre polynomials for H_T and H_L, Sign(z) for H_A
  - Can construct observables that vanish in absence of QED !!
    - Can use higher Legendre polynomials, e.g. $P_3(z)$ or $P_4(z)$, as projectors to obtain QED-sensitive observables. Experimental sensitivity?

Branching ratio, low-q^2 region

- Branching ratio, integrated over bins in low-q^2 region, in units of 10^{-6}
  - Electron channel

$$\mathcal{B}[1,3.5]_{ee} = 0.93 \pm 0.03_{\text{scale}} \pm 0.01_{m_t} \pm 0.03_{C,m_c} \pm 0.01_{m_b} \pm 0.002_{\alpha_s} \pm 0.003_{\text{CKM}} \pm 0.01_{\text{BR}_{\text{sl}}}$$
$$= 0.93 \pm 0.05$$

$$\mathcal{B}[3.5,6]_{ee} = 0.74 \pm 0.04_{\text{scale}} \pm 0.01_{m_t} \pm 0.03_{C,m_c} \pm 0.01_{m_b} \pm 0.003_{\alpha_s} \pm 0.002_{\text{CKM}} \pm 0.01_{\text{BR}_{\text{sl}}}$$
$$= 0.74 \pm 0.05$$

$$\mathcal{B}[1,6]_{ee} = 1.67 \pm 0.07_{\text{scale}} \pm 0.02_{m_t} \pm 0.06_{C,m_c} \pm 0.02_{m_b} \pm 0.01_{\alpha_s} \pm 0.005_{\text{CKM}} \pm 0.02_{\text{BR}_{\text{sl}}}$$
$$= 1.67 \pm 0.10$$

  - Muon channel

$$\mathcal{B}[1,3.5]_{\mu\mu} = 0.89 \pm 0.03_{\text{scale}} \pm 0.01_{m_t} \pm 0.03_{C,m_c} \pm 0.01_{m_b} \pm 0.002_{\alpha_s} \pm 0.002_{\text{CKM}} \pm 0.01_{\text{BR}_{\text{sl}}}$$
$$= 0.89 \pm 0.05$$

$$\mathcal{B}[3.5,6]_{\mu\mu} = 0.73 \pm 0.04_{\text{scale}} \pm 0.01_{m_t} \pm 0.03_{C,m_c} \pm 0.01_{m_b} \pm 0.003_{\alpha_s} \pm 0.002_{\text{CKM}} \pm 0.01_{\text{BR}_{\text{sl}}}$$
$$= 0.73 \pm 0.05$$

$$\mathcal{B}[1,6]_{\mu\mu} = 1.62 \pm 0.07_{\text{scale}} \pm 0.02_{m_t} \pm 0.05_{C,m_c} \pm 0.02_{m_b} \pm 0.01_{\alpha_s} \pm 0.005_{\text{CKM}} \pm 0.02_{\text{BR}_{\text{sl}}}$$
$$= 1.62 \pm 0.09$$

- Total error $\mathcal{O}(5-7\%)$, dominated by scale uncertainty.
- Log-enhanced QED corrections $\sim 2\%$ in muon case.

Zero of H_A (FBA)

- Forward-backward asymmetry (or H_A) has a zero in low-q^2 region
- Electron channel

$$
\begin{aligned}
(q_0^2)_{ee} =& (3.46 \pm 0.10_{\text{scale}} \pm 0.001_{m_t} \pm 0.02_{C,m_c} \pm 0.06_{m_b} \pm 0.02_{\alpha_s})\ \text{GeV}^2 \\
=& (3.46 \pm 0.11)\ \text{GeV}^2
\end{aligned}
$$

- Muon channel

$$
\begin{aligned}
(q_0^2)_{\mu\mu} =& (3.58 \pm 0.10_{\text{scale}} \pm 0.001_{m_t} \pm 0.02_{C,m_c} \pm 0.06_{m_b} \pm 0.02_{\alpha_s})\ \text{GeV}^2 \\
=& (3.58 \pm 0.12)\ \text{GeV}^2
\end{aligned}
$$

- Parametric and perturbative uncertainty at $\mathcal{O}(3-4\%)$

High-q^2 region

- Branching ratio, integrated over high-q^2 region, in units of 10^{-7}
  - Electron channel

$$\begin{aligned}\mathcal{B}[>14.4]_{ee} =& 2.20 \pm 0.30_{\text{scale}} \pm 0.03_{m_t} \pm 0.06_{C,m_c} \pm 0.16_{m_b} \pm 0.003_{\alpha_s} \pm 0.01_{\text{CKM}} \pm 0.03_{\text{BR}_{\text{sl}}} \\ & \pm 0.12_{\lambda_2} \pm 0.48_{\rho_1} \pm 0.36_{f_s} \pm 0.05_{f_u} \\ =& 2.20 \pm 0.70\end{aligned}$$

  - Muon channel

$$\begin{aligned}\mathcal{B}[>14.4]_{\mu\mu} =& 2.53 \pm 0.29_{\text{scale}} \pm 0.03_{m_t} \pm 0.07_{C,m_c} \pm 0.18_{m_b} \pm 0.003_{\alpha_s} \pm 0.01_{\text{CKM}} \pm 0.03_{\text{BR}_{\text{sl}}} \\ & \pm 0.12_{\lambda_2} \pm 0.48_{\rho_1} \pm 0.36_{f_s} \pm 0.05_{f_u} \\ =& 2.53 \pm 0.70\end{aligned}$$

- Total error $\mathcal{O}(30\%)$

High-q^2 region

- Ratio $\mathcal{R}(q^2_{\rm min})$, integrated over high-$q^2$ region, in units of 10^{-3}
  - Electron channel

$$\begin{aligned}\mathcal{R}(14.4)_{ee} =& 2.25 \pm 0.12_{\rm scale} \pm 0.03_{m_t} \pm 0.02_{C,m_c} \pm 0.01_{m_b} \pm 0.01_{\alpha_s} \pm 0.20_{\rm CKM} \\ & \pm 0.02_{\lambda_2} \pm 0.14_{\rho_1} \pm 0.08_{f_u^0+f_s} \pm 0.12_{f_u^0-f_s} \\ =& 2.25 \pm 0.31\end{aligned}$$

  - Muon channel

$$\begin{aligned}\mathcal{R}(14.4)_{\mu\mu} =& 2.62 \pm 0.09_{\rm scale} \pm 0.03_{m_t} \pm 0.01_{C,m_c} \pm 0.01_{m_b} \pm 0.01_{\alpha_s} \pm 0.23_{\rm CKM} \\ & \pm 0.0002_{\lambda_2} \pm 0.09_{\rho_1} \pm 0.04_{f_u^0+f_s} \pm 0.12_{f_u^0-f_s} \\ =& 2.62 \pm 0.30\end{aligned}$$

- Total error $\mathcal{O}(10 - 15\%)$.
  - Uncertainties due to power corrections significantly reduced
  - Largest source of error are CKM elements (V_{ub})

[for full set of numbers, see Hurth,Lunghi,TH 1503.04849]

What's new in $\bar{B} \to X_d \, \ell^+ \ell^-$?

[Hurth,Jenkins,Lunghi,Qin,Vos,TH in prep.]

- Five-particle contributions [Qin,Vos,TH'18]
- Revisit resonances
- Investigate background from cascade decays such as $B \to X_1 (c\bar{c} \to X_2 \ell^+ \ell^-)$
- Resolved contributions [Hurth,Fickinger,Turczyk,Benzke'17]
- Revisit input parameters
- Include also Log-enhanced QED corrections from $P^u_{1,2}$

Preliminary results, low-q^2 region

[Hurth,Jenkins,Lunghi,Qin,Vos,TH in prep.]

- Numbers still preliminary

$$\mathcal{B}(\bar{B} \to X_d e^+ e^-)[1,6] = (7.79 \pm 0.36_{\rm scale} \pm 0.14_{CKM}) \times 10^{-8}$$
$$\mathcal{B}(\bar{B} \to X_d e^+ e^-)[1,3.5] = (4.32 \pm 0.17_{\rm scale} \pm 0.08_{CKM}) \times 10^{-8}$$
$$\mathcal{B}(\bar{B} \to X_d e^+ e^-)[3.5,6] = (3.47 \pm 0.20_{\rm scale} \pm 0.06_{CKM}) \times 10^{-8}$$

$$\mathcal{B}(\bar{B} \to X_d \mu^+ \mu^-)[1,6] = (7.57 \pm 0.34_{\rm scale} \pm 0.14_{CKM}) \times 10^{-8}$$
$$\mathcal{B}(\bar{B} \to X_d \mu^+ \mu^-)[1,3.5] = (4.16 \pm 0.15_{\rm scale} \pm 0.08_{CKM}) \times 10^{-8}$$
$$\mathcal{B}(\bar{B} \to X_d \mu^+ \mu^-)[3.5,6] = (3.41 \pm 0.19_{\rm scale} \pm 0.06_{CKM}) \times 10^{-8}$$

$$A_{CP}(\bar{B} \to X_d e^+ e^-)[1,6] = (1.4 \pm 0.7_{\rm scale} \pm 0.03_{CKM})\%$$
$$A_{CP}(\bar{B} \to X_d e^+ e^-)[1,3.5] = (1.5 \pm 0.3_{\rm scale} \pm 0.05_{CKM})\%$$
$$A_{CP}(\bar{B} \to X_d e^+ e^-)[3.5,6] = (1.4 \pm 1.6_{\rm scale} \pm 0.04_{CKM})\%$$

$$A_{CP}(\bar{B} \to X_d \mu^+ \mu^-)[1,6] = (1.3 \pm 0.7_{\rm scale} \pm 0.04_{CKM})\%$$
$$A_{CP}(\bar{B} \to X_d \mu^+ \mu^-)[1,3.5] = (1.3 \pm 0.4_{\rm scale} \pm 0.04_{CKM})\%$$
$$A_{CP}(\bar{B} \to X_d \mu^+ \mu^-)[3.5,6] = (1.4 \pm 1.6_{\rm scale} \pm 0.04_{CKM})\%$$

Preliminary results, high-q^2 region

[Hurth,Jenkins,Lunghi,Qin,Vos,TH in prep.]

- Numbers still preliminary

$$\mathcal{B}(\bar{B} \to X_d e^+ e^-)[> 14.4] = (0.97 \pm 0.12_{\text{scale}} \pm 0.24_{f_{NV}} \pm 0.09_{CKM}) \times 10^{-8}$$
$$\mathcal{B}(\bar{B} \to X_d \mu^+ \mu^-)[> 14.4] = (1.12 \pm 0.12_{\text{scale}} \pm 0.23_{f_{NV}} \pm 0.09_{CKM}) \times 10^{-8}$$

$$A_{CP}(\bar{B} \to X_d e^+ e^-)[> 14.4] = (-1.7 \pm 0.1_{\text{scale}} \pm 0.5_{f_{NV}} \pm 7.6_{CKM})\%$$
$$A_{CP}(\bar{B} \to X_d \mu^+ \mu^-)[> 14.4] = (-1.6 \pm 0.2_{\text{scale}} \pm 0.4_{f_{NV}} \pm 6.7_{CKM})\%$$

$$R(0)(\bar{B} \to X_d e^+ e^-)[14.4] = (0.95 \pm 0.02_{\text{scale}} \pm 0.05_{f_{NV}}) \times 10^{-4}$$
$$R(0)(\bar{B} \to X_d \mu^+ \mu^-)[14.4] = (1.11 \pm 0.01_{\text{scale}} \pm 0.02_{f_{NV}}) \times 10^{-4}$$

Conclusion and outlook

- Complementarity to $\bar{B} \to X_s \gamma$ and $\bar{B} \to K^{(*)} \mu^+ \mu^-$ crucial in the search for NP
- We present the SM theory predictions for inclusive $\bar{B} \to X_{s(d)} \ell^+ \ell^-$ decays
  - Perform thorough investigation of QED corrections (collinear photons)
- To-do list
  - Extend pheno to $\bar{B} \to X_s \ell^+ \ell^-$: All angular observables, NP analysis, RH currents, complementarity w/ exclusive $B \to K^{(*)} \ell^+ \ell^-$, ...
  - MC study of collinear photons for Belle II
  - Further investigate the effects of an $M_{X_{s(d)}}$-cut at low q^2
    [Lee,Ligeti,Stewart,Tackmann'06; Lee,Tackmann'08; Hurth,Fickinger,Turczyk,Benzke'17]
  - Study effects of lepton-flavour universality violation, e.g. in observable

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