Developments in Exclusive $b \to s\ell^+\ell^-$ Decays

Danny van Dyk

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Motivation

Basics of the $|\Delta B| = |\Delta S| = 1$ Effective Field Theory

Overview of Exclusive $b \to s\ell^+\ell^-$ Decays

Development: $\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$

Development: Charmonium Resonances in $B \to K\ell^+\ell^-$

Conclusion

Motivation

Search for effects of physics beyond the Standard Model

- the Standard Model of particle physics describes nature very well
- however: beyond SM physics seems likely, since the SM ...
  - ...does not allow for neutrino oscillations
  - ...has no candidate for dark matter
  - ...has no explanation for the emergence of different flavours
- consequence: search for the effects of new physics, either ...
  - ...*directly*, i.e., in the production of new particles at very high energies
  - ...*indirectly*, i.e., as loop effects in e.g. b-quark decays

Top-down vs. bottom-up in flavour physics

Top-down

- start with a New Physics model
- calculate effects on observables
- constrain model parameters from data

Bottom-up

- for a given process: categorize all possible effects of new physics
- introduce *effective* couplings $\mathcal{C}_i$, and determine their SM values
- constrain $\mathcal{C}_i$ from data
- *if* deviations from SM expectations are found, search for a model or models that can explain these specific deviations

Bottom-up and Effective Field Theories

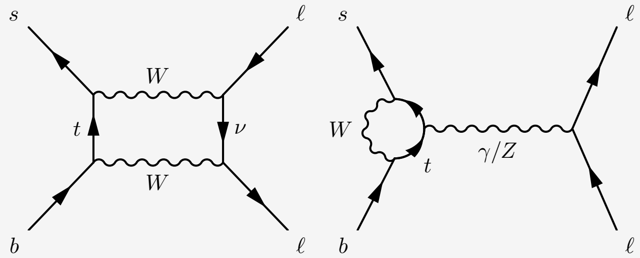
- effective field theories (EFTs) describe the same effects up to a limiting scale μ as the respective full field theory but uses fewer degrees of freedom
  - example 4-fermi theory: includes the dynamics of leptons and neutrino as in the SM – in particular the μ decay – but W is not a dynamical degree of freedom

- effective field theories are very compatible with the bottom-up approach
  - example 4-fermi theory: operator $[\bar{e}\gamma_\rho(1-\gamma_5)\nu_e]\,[\bar{\nu}_\mu\gamma^\rho(1-\gamma_5)\mu]$ has effective coupling G_F
  - natural extension: introduce further operators with anomalous spin structures (i.e. beyond the SM)
  - constrain their *additional* effective couplings from data (4-fermi: Michel parameter studies)

Basics of the $|\Delta B| = |\Delta S| = 1$ Effective Field Theory

$b \to s\ell^+\ell^-$ Transitions

- $b \to s\ell^+\ell^-$ is a flavour-changing neutral current (FCNC)
  - forbidden at *tree level* in the SM
  - leading term arises at the *one-loop level*
  - examples:

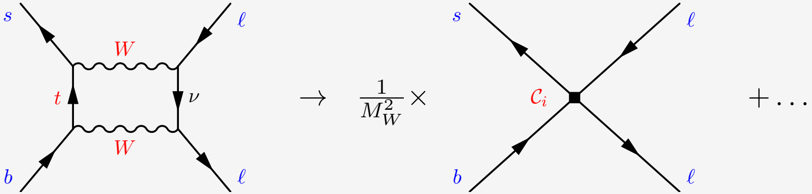


Effective Field Theory for $b \to s\ell^+\ell^-$ FCNCs

- remove heavy fields (SM: t, W, Z, beyond: ?) as dynamical degrees of freedom
  - technical term: *to integrate out*
  - new 4-fermion operators emerge with currents at different coordinates
  - non-local effective field theory, described by effective hamiltonian $\mathcal{H}^{\text{eff}}$
- expand $\mathcal{H}^{\text{eff}}$ in terms of *local* operators (OPE)
  - illustration at hand of W propagator:

$$\frac{1}{M_W^2 - p^2} = \frac{1}{M_W^2}\left[1 + \frac{p^2}{M_W^2} + O\left(\frac{p^4}{M_W^4}\right)\right]$$

  - focus on leading-power term only
  - next-to-leading-power suppressed by $p^2/M_W^2 \simeq 4 \cdot 10^{-3}$



Effective Hamiltonian

- "universal" $b \to s$ effective Hamiltonian

$$\mathcal{H}^{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\left[V_{tb}V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i + O\left(V_{ub}V_{us}^*\right)\right] + \text{h.c.}$$

- describes all $b \to s$ transitions, including
  - $b \to sc\bar{c}$
  - $b \to s\gamma$
  - $b \to s\ell^+\ell^-$
- model-independent correlations between observables

Some $b \to s\ell^+\ell^-$, $b \to s\gamma$ modes

$B \to K^*\ell^+\ell^-$	$B \to K\ell^+\ell^-$	$B_s \to \mu^+\mu^-$
$B \to K^*\gamma$	$B \to X_s\ell^+\ell^-$	$B \to X_s\gamma$

exclusive decay modes: final state is fully specified

Effective Operators

Radiative and semileptonic operators

$$\mathcal{O}_{7(7')} = \frac{e m_b}{4\pi}[\bar{s}\sigma^{\mu\nu}P_{R(L)}b]F_{\mu\nu}$$

$$\mathcal{O}_{9(9')} = \frac{\alpha_e}{4\pi}[\bar{s}\gamma^\mu P_{L(R)}b][\bar{\ell}\gamma_\mu \ell]$$

$$\mathcal{O}_{10(10')} = \frac{\alpha_e}{4\pi}[\bar{s}\gamma^\mu P_{L(R)}b][\bar{\ell}\gamma_\mu \gamma_5 \ell]$$

- $\mathcal{O}_{7,9,10}$ dominantly contribute to $b \to s\ell^+\ell^-$ in the SM
- couplings of $\mathcal{O}_{7'}$ small, $\mathcal{O}_{9',10'}$ vanish in the SM
- suppressing spin structures other than $V \pm A$

Four-quark operators

dominant background

$$\mathcal{O}_1 = [\bar{c}\gamma^\mu T^a P_L b][\bar{s}\gamma_\mu T^a c] \quad \mathcal{O}_2 = [\bar{c}\gamma^\mu P_L b][\bar{s}\gamma_\mu c]$$

$O(1)$ Wilson coefficients, contribute α_e suppressed via off-shell photon

Renormalization Group Equations

- evaluate hadronic matrix elements $\langle \mathcal{O}_i \rangle$ at $\mu_b \simeq m_b$
  - typical scale for the problem
  - $\alpha_s(m_b)$ still reasonably small $\Rightarrow$ perturbation series under control
- match (that is 'read off') $\mathcal{C}_i$ at scale $\mu_0 \simeq M_W, m_t$
  - $\mathcal{C}_{7,9,10}$ emerge at one-loop order, $\mathcal{C}_2$ at tree level
  - α_e and α_s corrections under control
- however, $\mathcal{C}_i(\mu_0)\langle \mathcal{O}_i \rangle_{\mu_b}$ wildly inacurate
- solution: Renormalization Group Improved Perturbation Theory

$$\mathcal{C}_i(\mu_0) \to \mathcal{C}_i(\mu_b) = \sum_j [U(\mu_b, \mu_0)]_{ij} \, \mathcal{C}_j(\mu_0)$$

  next-to-next-to-leading-logarithm (N^{2}LL) result
  - resums large logarithms $\alpha_s^n \ln^m(\mu_b/\mu_0)$, $2 \geq n - m \geq 0$
  - electroweak corrections start to play important role
    [Bobeth/Gorbahn/Stamou 1311.1348]
  - $\mathcal{C}_{10}$ matching now computed to α_s^2
    [Hermann/Misiak/Steinhauser 1311.1347]

Overview of Exclusive $b \to s\ell^+\ell^-$ Decays

Wilson coefficients and amplitudes

at $\mu = 4.2\,\mathrm{GeV}$ to NNLL accuracy

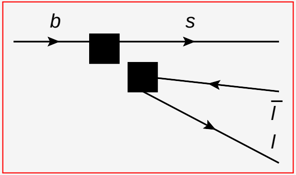
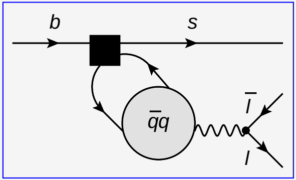
$\mathcal{C}_7$	$\mathcal{C}_9$	$\mathcal{C}_{10}$	$\mathcal{C}_1$	$\mathcal{C}_2$
-0.34	$+4.27$	-4.17	-0.29	$+1.01$

typically, the $b \to s\ell^+\ell^-$ decay amplitudes looks like

$$\mathcal{A} \propto \left[\mathcal{C}_9 \pm \mathcal{C}_{10} + \frac{2m_b^2}{q^2}\frac{F_T(q^2)}{F(q^2)}\mathcal{C}_7\right] F(q^2) + \left[\mathcal{C}_2 - \frac{\mathcal{C}_1}{6}\right] F_{\bar{c}c} \ldots$$

with hadronic matrix elements, F, F_T and $F_{\bar{c}c}$

schematically:

$\mathcal{A} \sim$  $+$ 

Comparison of Exclusive Decays

decay	# kin. variables	# hadr. matr. elem.†	sensitivity	
$B_s \to \ell^+\ell^-$	0	1 constant	$\mathcal{C}_{10(')}$	
$B \to K\ell^+\ell^-$	2	1+1 form factors	$\mathcal{C}_{7(')}, \mathcal{C}_{9(')}, \mathcal{C}_{10(')}$	$\leftarrow$
$B \to K^*\ell^+\ell^-$	4	3+3 form factors	$\mathcal{C}_{7(')}, \mathcal{C}_{9(')}, \mathcal{C}_{10(')}$	
$\Lambda_b \to \Lambda\ell^+\ell^-$	4	4+4 form factors	$\mathcal{C}_{7(')}, \mathcal{C}_{9(')}, \mathcal{C}_{10(')}$	$\leftarrow$

- will focus on semileptonic decays
  - with increasing # of kinematic variables, the # of observables rises (good)
  - however: # of hadronic matrix elements rises too (bad)
- each exclusive decay has its own *individual set* of hadronic matrix elements
  - for semileptonic decays with one final statehadron, had. mat. elements are functions of only q^2: dilepton mass squared

†: for naivly factorizing amplitudes

(for semileptonic decays, massless leptons are assumed)

Optimized Observables

- design observables that e.g. probe right-chiral leptons
  - amplitude $\mathcal{A}$ can be decomposed w/ respect to lepton chirality
  - left-chiral leptons: $\mathcal{A}_L \propto \mathcal{C}_9 - \mathcal{C}_{10}$
  - right-chiral leptons: $\mathcal{A}_R \propto \mathcal{C}_9 + \mathcal{C}_{10} \ll \mathcal{C}_{9,10}$!
- several groups working on optimal bases of angular observables, with focus on $B \to K^* \ell^+ \ell^-$ decays
- aims
  - reduce form factor uncertainties at low q^2: P_i'
    [Descotes-Genon/Matias/Virto 1303.5794 and references therein]
  - reduce form factor uncertainties at high q^2: $H_T^{(i)}$
    [Bobeth/Hiller/DvD 1212.2321 and references therein]
  - extract form factor ratios from data
    [Bobeth/Hiller/DvD 1006.5013, 1212.2321]

Pollution by $\bar{c}c$ States

all exclusive $b \to s\ell^+\ell^-$ processes face severe problem of hadronic ($\bar{c}c$) resonances in dilepton spectrum

- hadronic operators give rise to $b \to s\bar{c}c$, hadronizes to $H_b \to X_s\psi(n)[\to \ell^+\ell^-]$
- systematically include effects via *hadronic two-point function* $\mathcal{T}(q^2)$

$$C_7\langle\mathcal{O}_7\rangle \to \mathcal{T}(q^2)$$

- different approaches to obtain $\mathcal{T}(q^2)$, depending on kinematics
- methods and their domain of validity
  - small $q^2 \ll m_b^2$: QCD-improv. Factorization (QCDF)
    [Beneke/Feldmann/Seidel hep-ph/0106067 and hep-ph/0412400]
  - large $q^2 \simeq m_b^2$: Operator Product Expansion (OPE)
    [Grinstein/Pirjol hep-ph/0404250, Beylich/Buchalla/Feldmann 1101.5118]
  - all q^2: hadronic dispersion relation (model-dependent)
    [Khodjamirian et al. 1006.4945, 1211.0234, Lyon/Zwicky 1406.0566]

reviewing these works is another talk; some details in the backups

State of Model-Independent Analysis

[Beaujean/Bobeth/DvD Eur.Phys.J. C74 (2014) 2897 (Err. ibid)]

does not yet include today's preprint by Altmannshofer and Straub

Model-Independent Framework

Definition of model-independent for the purpose of this work:

Basis of Operators $\mathcal{O}_i$

- include as many $\mathcal{O}_i$ beyond SM as needed/as few as possible
- balancing act, test statistically if choice of basis describes data well!

Wilson Coefficients $\mathcal{C}_i$

- treat $\mathcal{C}_i$ as uncorrelated, generalized couplings
- constrain their values from data
- model builders: confront new physics models with constraints

Fit Scenarios

SM(ν-only)

- fix $\mathcal{C}_{7,9,10}$ to SM values (NNLL)
- fix $\mathcal{C}_{7'} = m_s/m_b\,\mathcal{C}_7$, fix $\mathcal{C}_{9',10'} = 0$
- fit nuisance parameters, use informative priors
  - form factors: light-cone sum rules [Khodjamirian/Mannel/Pivovarov/Wang '10]
  - power corrections: power-counting assumptions
  - CKM: tree-level fit [UTfit]
  - quark masses [PDG]

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Fit Scenarios

SM+SM′ Basis

- fit $\mathcal{C}_{7,9,10}$
- fit $\mathcal{C}_{7',9',10'}$
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  - power corrections: power-counting assumptions
  - CKM: tree-level fit [UTfit]
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Sensitivity to Fit Parameters

Wilson coefficients

	$\mathcal{C}_{7(')}$	$\mathcal{C}_{9(')}$	$\mathcal{C}_{10(')}$	93 individual measurements	experiments
$B_s \to \mu^+\mu^-$	–	–	✓	CP-avg. time-int. BR	CMS,LHCb
$B \to X_s\gamma$	✓	–	–	CP-avg. BR	BaBar,Belle,CLEO
$B \to X_s\ell^+\ell^-$	✓	✓	✓	CP-avg. BR	BaBar,Belle
$B \to K^*\gamma$	✓	–	–	CP-avg. BR + 2 time-dep. CP asymm.	BaBar,Belle,CLEO
$B \to K^*\ell^+\ell^-$	✓	✓	✓	CP-avg. BR + 7 angular observables	ATLAS,BaBar,Belle,CDF,CMS,LHCb
$B \to K\ell^+\ell^-$	✓	✓	✓	CP-avg. BR	BaBar,Belle,CDF,LHCb

Form factors

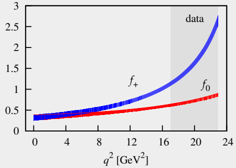
- interplay between $B \to X_s\{\gamma, \ell^+\ell^-\}$ and $B \to K^*\{\gamma, \ell^+\ell^-\}$
- some $B \to K^*\ell^+\ell^-$ obs. form-factor insensitive by construction
- some $B \to K^*\ell^+\ell^-$ obs. dominantly sensitive to form factor ratios

Further Theory Constraints

Form factors from lattice QCD (LQCD)

[HPQCD arxiv:1306.2384]

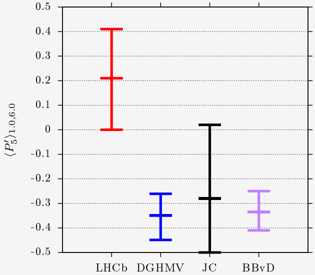
- $B \to K$ form factors available from LQCD
  - data only at high q^2: $17 – 23\,\mathrm{GeV}^2$
  - no data points given
- reproduce 3 data points from z-parametrization
  - $q^2 \in \{17,\ 20,\ 23\}\,\mathrm{GeV}^2$
  - use as constraint, incl. covariance matrix



$B \to K^*$ Form factor (FF) relation at $q^2 = 0$

- FF $V, A_1 \propto \xi_\perp + \dots$ [Charles et al. hep-ph/9901378]
  - no α_s corrections [Burdmann/Hiller hep-ph/0011266, Beneke/Feldmann hep-ph/0008255]
  - Large Energy Limit: $V(0) = (1.33 \pm 0.4) \times A_1(0)$
- LCSR constraint: $\xi_\parallel(0) = 0.10^{+0.03}_{-0.02}$, to avoid $\xi_\parallel(q^2) \propto A_0(q^2) < 0$.
- see also FF fits by [Hambrock/Hiller/Schacht/Zwicky 1308.4379]

- **LHCb** measurement [1308.1707]
  - not considering data at $6\,\mathrm{GeV}^2 \leq q^2 \leq 14\,\mathrm{GeV}^2$
  - deviation from SM prediction in form factor-free obs. $\langle P_5' \rangle_{[1,6]}$
  - LHCb uses one SM prediction (**DGHMV**) [Descotes-Genon/Hurth/Matias/Virto 1303.5794]



- however: further SM prediction exist, much larger uncertainty (**JC**) [Jäger/Camalich 1212.2263]
- our take on SM prediction $\langle P_5' \rangle_{[1,6]} = -0.34^{+0.09}_{-0.08}$ (**BBvD**) however, also consider later slides

difference: treatment of unknown power corrections (form factor corrections, $\bar{c}c$ resonances)

Results SM(ν-only)

Goodness of fit

- largest pulls at best-fit point

  -3.4σ $\langle F_L \rangle_{[1,6]}$, BaBar 2012

  -2.5σ $\langle F_L \rangle_{[1,6]}$, ATLAS 2013

  -2.4σ $\langle P_4' \rangle_{[14.18,16]}$, LHCb 2013

  $+2.6\sigma$ $\langle \mathcal{B} \rangle_{[16,19.21]}$, Belle 2009

  $+2.1\sigma$ $\langle A_{\mathsf{FB}} \rangle_{[16,19]}$, ATLAS 2013

- obtain p value of 0.12

Summary

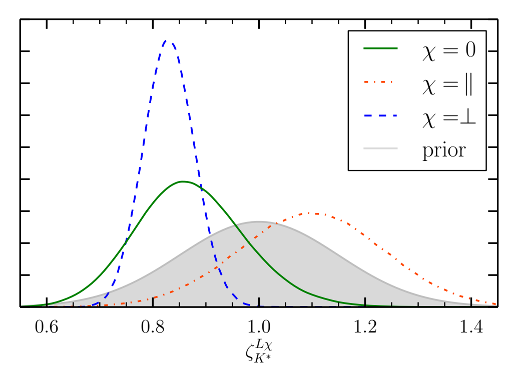
- good fit, no New Physics signal
- we find power corrections on top of QCDF results at large recoil

Parametrization of Power Corrections @ Large Recoil

- six parameters $\zeta_\chi^{L(R)}$ for the $[1, 6]$ bin

$$A_\chi^{L(R)}(q^2) \mapsto \zeta_\chi^{L(R)} A_\chi^{L(R)}(q^2)\,, \quad \chi = \perp, \parallel, 0$$

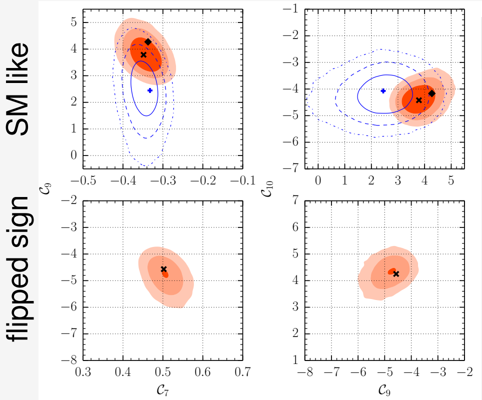
- on top of QCDF correction to transversity amplitudes



- tension diluted by parameters $\zeta_\chi^{L(R)}$
- shift by $\simeq -20\%$ for $\zeta_{\perp,\parallel}^L$
- shift by $\simeq +10\%$ for ζ_0^L
- few percents for ζ_χ^R

improved understanding of power corrections desirable

Results (SM Basis)



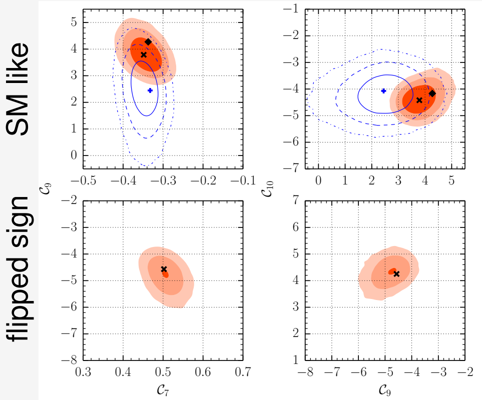
◆: Standard Model, ×: best-fit point

red-shaded areas: regions of 68%, 95%, 99% prob., full dataset

blue solid lines: regions of 68%, 95%, 99% prob., selection

post HEP'13 (selection)

- with $B \to X_s\{\gamma, \ell^+\ell^-\}$
- $B_s \to \mu^+\mu^-$ from LHCb and CMS
- same data as [Descotes-Genon/Matias/Virto 1307.5683] exclusive decays limited:
  - only $B \to K^*\ell^+\ell^-$!
  - only LHCb data!
  - only $q^2 \in [1, 6]\mathrm{GeV}^2$
- best-fit point similar to [Descotes-Genon et al. 1307.5683]
  - less tension, only $\sim 2.5\sigma$
  - $\mathcal{C}_9 - \mathcal{C}_9^{\mathrm{SM}} \simeq -1.7 \pm 0.7$



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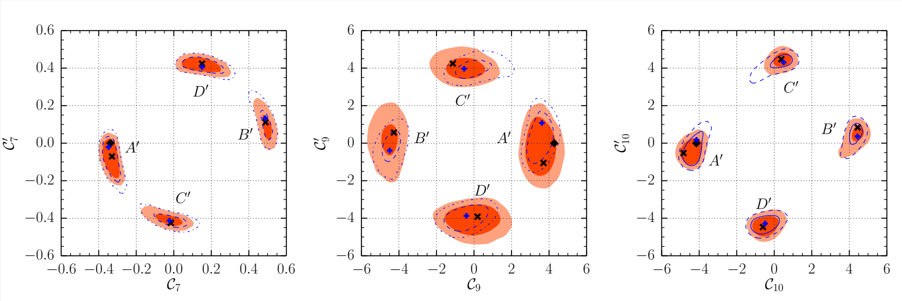
post HEP'13 (full)

- SM-like uncertainty reduced by ~ 2 compared to 2012
- SM at the border of 1σ
- flipped-sign barely allowed at 1σ $(26\%$ of evidence)
- cannot confirm NP findings
  - in $(\mathcal{C}_7, \mathcal{C}_9)$ [Descotes-Genon et al. 1307.5683]
- $\zeta_\chi^{L(R)}$ as in SM(ν-only)
- p value: 0.12 (@SM-like sol.)

Results (SM+SM′ Basis)



◆: Standard Model, ×: best-fit points, (light-) red: 68% CL (95% CL) for full dataset

- four solutions A' through D'
  - A' = SM like, 37% of ev.
  - D' = SM↔SM', 34% of ev.
  - B', C' suppressed: 14% and 15% of evidence
- for A' (SM-like sol.)
  - p value 0.07
  - $\mathcal{C}_9 - \mathcal{C}_9^{\mathrm{SM}} = -0.8 \pm 0.4$
  - 1.8σ deviation from SM
  - $\zeta_\chi^{L(R)}$ decrease wrt. SM(ν-only) and SM basis

(Statistical) Model Comparison

- model comparison using Bayes factor
  - compare scenarios only at SM-like solution $A(')$
  - adjust priors to contain only $A(')$
- results
  - SM(ν-only) wins over SM basis: odds of 48:1 (43:1 with lattice inputs)
  - SM(ν-only) wins over SM+SM$'$ basis: odds of 401:1 (143:1 with lattice inputs)
  - SM(ν-only) draws against highly-spec. scenario where NP only enters $\mathcal{C}_{9(9')}$

Development: $\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$

[based on Böer/Feldmann/DvD 1410.2115]

Why $\Lambda_b \to \Lambda$

$B \to K^* \ell^+ \ell^-$ is being measured with increasing precision. Why spend effort on $\Lambda_b \to \Lambda$?

pro arguments, sorted from weakest to strongest

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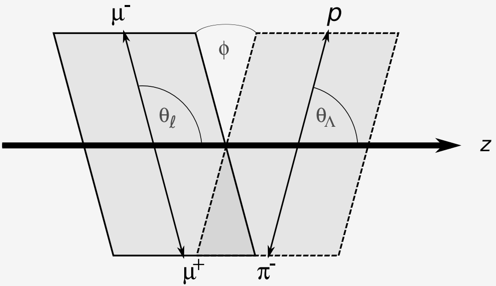
- fewer hadronic matrix elements (2 in HQET limit, 1 in SCET limit)
- doubly weak decay: complementary constraints on $b \to s\ell^+\ell^-$ physics with respect to $B \to K^*\ell^+\ell^-$

Kinematics and Decay Topology

$$\Lambda_b(p) \to \Lambda(k)\,[\to N(k_1)\,\pi(k_2)]\,\ell^+(q_1)\,\ell^-(q_2)$$



3 independent decay angles

- $\cos\theta_\Lambda \sim \bar{k}\cdot q$
- $\cos\theta_\ell \sim k\cdot\bar{q}$
- $\cos\phi \sim \bar{k}\cdot\bar{q}$

only for unpolarized Λ_b

Momenta

$$q = q_1 + q_2$$
$$\bar{q} = q_1 - q_2$$
$$k = k_1 + k_2$$
$$\bar{k} = k_1 - k_2$$

$\Lambda_b \to \Lambda$ Hadronic Matrix Elements

In General

- using (overall 10) helicity form factors (FFs) [compare Feldmann/Yip 1111.1844]

  schematically: $\varepsilon^\dagger(\lambda) \cdot \langle \Lambda | \Gamma | \Lambda_b \rangle \sim f_\lambda^\Gamma(q^2)$

- for lepton mass $m_\ell \to 0$ this reduces to 8 independent FFs
- results for all FFs expected from the lattice in the long run

Within HQET

- heavy quark spin symmmetry reduces matrix elements to 2 FFs at leading power
- known from Lattice QCD [Detmold/Lin/Meinel/Wingate 1212.4827]

Within SCET

applicable when $E_\Lambda = O(m_b)$

- matrix elements reduce further to 1 single FF
- estimates from SCET sum rules [Feldmann/Yip 1111.1844]

$\Lambda \to N\pi$ Hadronic Matrix Element

- $\Lambda \to N\pi$ is a parity-violating weak decay
- branching fraction $\mathcal{B}[\Lambda \to N\pi] = (99.7 \pm 0.1)\%$ [PDG, our naive average]

- equations of motions reduce independent matrix elements to 2
- we choose to express them through
  - decay width Γ_Λ
  - parity-violating coupling α

- within small width approximation, Γ_Λ cancels
- α well known from experiment: $\alpha_{p\pi^-} = 0.642 \pm 0.013$ [PDG average]

Angular Distribution of $\Lambda_b \to \Lambda[\to N\pi]\ell^+\ell^-$

we define the angular distribution as

$$\frac{8\pi}{3}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2\,\mathrm{dcos}\,\theta_\ell\,\mathrm{dcos}\,\theta_\Lambda\,\mathrm{d}\phi} \equiv K(q^2, \cos\theta_\ell, \cos\theta_\Lambda, \phi)$$

when considering only SM and chirality-flipped operators

$$\begin{aligned}
K = 1\,&\left(K_{1ss}\sin^2\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1c}\cos\theta_\ell\right)\\
+\cos\theta_\Lambda\,&\left(K_{2ss}\sin^2\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2c}\cos\theta_\ell\right)\\
+\sin\theta_\Lambda\sin\phi\,&\left(K_{3sc}\sin\theta_\ell\cos\theta_\ell + K_{3s}\sin\theta_\ell\right)\\
+\sin\theta_\Lambda\cos\phi\,&\left(K_{4sc}\sin\theta_\ell\cos\theta_\ell + K_{4s}\sin\theta_\ell\right)
\end{aligned}$$

no further observables possible up to mass-dimension six $\qquad K_n \equiv K_n(q^2)$

Angular Observables

- matrix elements parametrized through 8 transversity amplitudes $A^{\lambda}_{\chi_M}$

$$A^R_{\perp_1}\,,\ A^R_{\|_1}\,,\ A^R_{\perp_0}\,,\ A^R_{\|_0}\,,\ \text{and } (R \leftrightarrow L)$$

λ dilepton chirality

χ transversity state, similar as in $B \to K^* \ell^+ \ell^-$

M |third component| of dilepton angular momentum

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  - λ dilepton chirality
  - χ transversity state, similar as in $B \to K^* \ell^+ \ell^-$
  - M |third component| of dilepton angular momentum

- express angular observables through transversity amplitudes, e.g.

$$K_{1cc} = \frac{1}{2}\left[|A^R_{\perp_1}|^2 + |A^R_{\parallel_1}|^2 + (R \leftrightarrow L)\right]$$
$$K_{2c} = \frac{\alpha}{2}\left[|A^R_{\perp_1}|^2 + |A^R_{\parallel_1}|^2 - (R \leftrightarrow L)\right]$$
$$\vdots$$

full list in the backups

Simple Observables

start with integrated decay width

$$\Gamma = 2K_{1ss} + K_{1cc}$$

define further observables X as weighted (ω_X) integrals

$$X = \frac{1}{\Gamma} \int \frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_\ell \,\mathrm{d}\cos\theta_\Lambda \,\mathrm{d}\phi} \omega_X(\cos\theta_\ell, \cos\theta_\Lambda, \phi) \mathrm{d}\cos\theta_\ell \,\mathrm{d}\cos\theta_\Lambda \,\mathrm{d}\phi$$

A leptonic forward-backward asymmetry

$$A_{\mathrm{FB}}^\ell = \frac{3}{2} \frac{K_{1c}}{2K_{1ss} + K_{1cc}} \qquad \text{with } \omega_{A_{\mathrm{FB}}^\ell} = \mathrm{sign}\cos\theta_\ell$$

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B fraction of longitudinal dilepton pairs

$$F_0 = \frac{2K_{1ss} - K_{1cc}}{2K_{1ss} + K_{1cc}} \qquad \text{with } \omega_{F_0} = 2 - 5\cos^2\theta_\ell$$

Simple Observables

start with integrated decay width

$$\Gamma = 2K_{1ss} + K_{1cc}$$

define further observables X as weighted (ω_X) integrals

$$X = \frac{1}{\Gamma}\int \frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_\Lambda\,\mathrm{d}\phi}\omega_X(\cos\theta_\ell, \cos\theta_\Lambda, \phi)\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_\Lambda\,\mathrm{d}\phi$$

C hadronic forward-backward asymmetry

$$A_{\mathrm{FB}}^{\Lambda} = \frac{1}{2}\frac{2K_{2ss} + K_{2cc}}{2K_{1ss} + K_{1cc}} \qquad \text{with } \omega_{A_{\mathrm{FB}}^{\ell}} = \operatorname{sign}\cos\theta_\Lambda$$

Simple Observables

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$$\Gamma = 2K_{1ss} + K_{1cc}$$

define further observables X as weighted (ω_X) integrals

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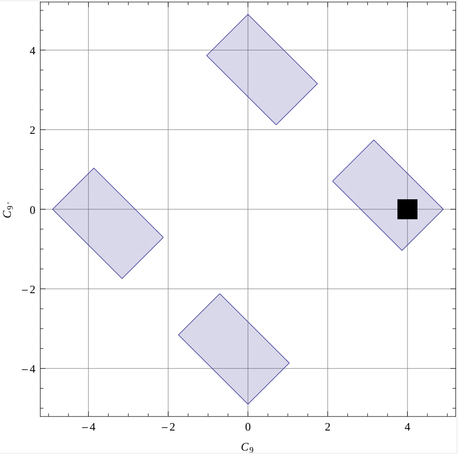
D combined forward-backward asymmetry

$$A_{\text{FB}}^{\ell\Lambda} = \frac{3}{4}\frac{K_{2c}}{2K_{1ss} + K_{1cc}} \qquad \text{with } \omega_{A_{\text{FB}}^{\ell}} = \text{sign}\cos\theta_\Lambda \; \text{sign}\cos\theta_\ell$$

New Types of Constraints

assume $\mathcal{C}_{9(9')}$ free floating, and $\mathcal{C}_{10(10')} = \mathcal{C}^{\mathrm{SM}}_{10(10')} \simeq (-4, 0)$



- existing constraints
  - $\rho_1^\pm$ blue banded constraints

black square: SM point

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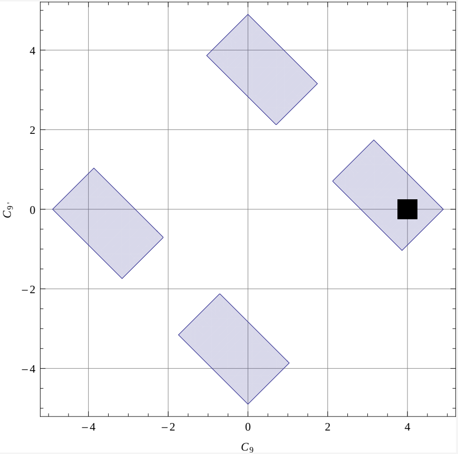

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  - ρ_2 insensitive (not shown)

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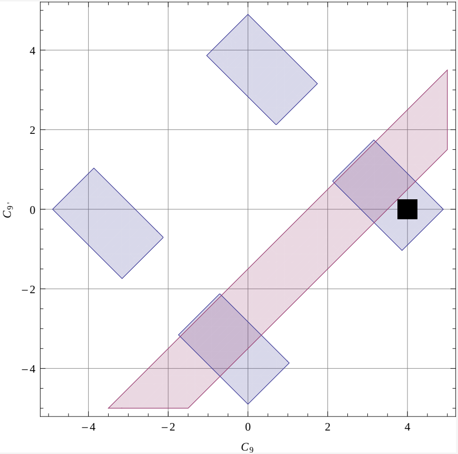

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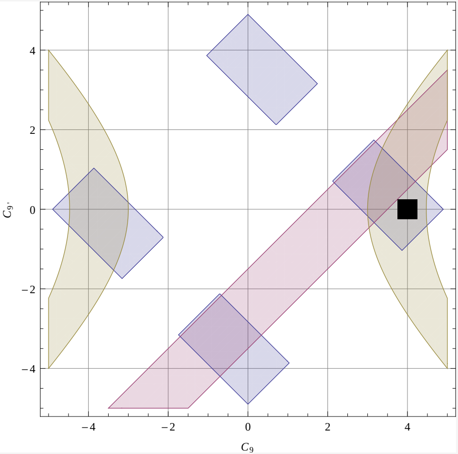


- existing constraints
  - $\rho_1^{\pm}$ blue banded constraints
  - ρ_2 insensitive (not shown)
- new constraints
  - ρ_3^{-} purple banded constraints
  - ρ_4 gold hyperbolic constraint

black square: SM point

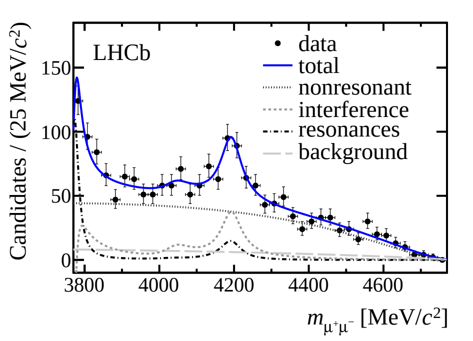
Development: Charmonium Resonances in $B \to K\ell^+\ell^-$

Experimental Situation

- in 2013 LHCb announced observation of a resonance beyond $\psi(3770)$ in dilepton spectrum of $B^+ \to K^+\mu^+\mu^-$ [LHCb 1307.7595]
- to paraphrase Douglas Adams:

"this made a lot of people very irritated and has been widely regarded as a bad move"

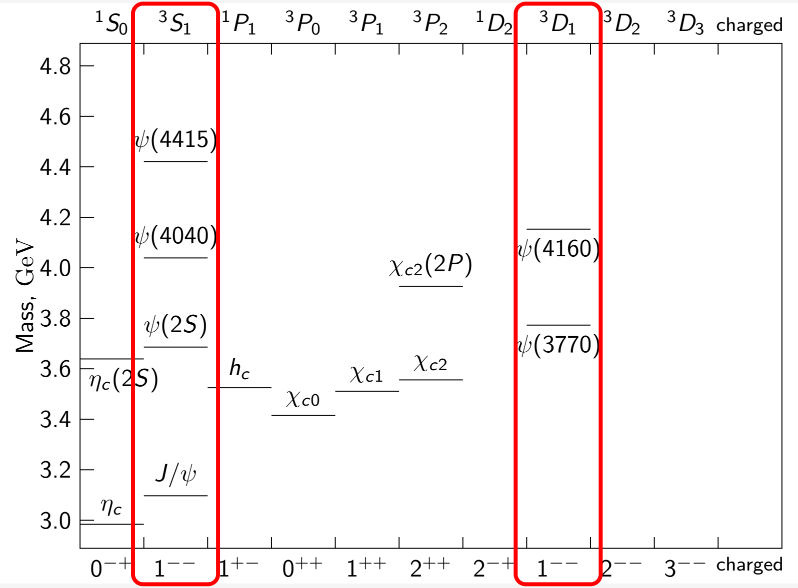
experiment performed **model-dependent** decomposition



- theory side did never claim absence of resonances in low recoil region
  - LHCb's non-resonant curve $\neq$ OPE prediction
- same resonances as in $e^+e^- \to hadrons$ expected in $B \to K^{(*)}\ell^+\ell^-$ spetrum

Known Charmonia with $J^P = 1^-$

apologies, cannot find source of plots



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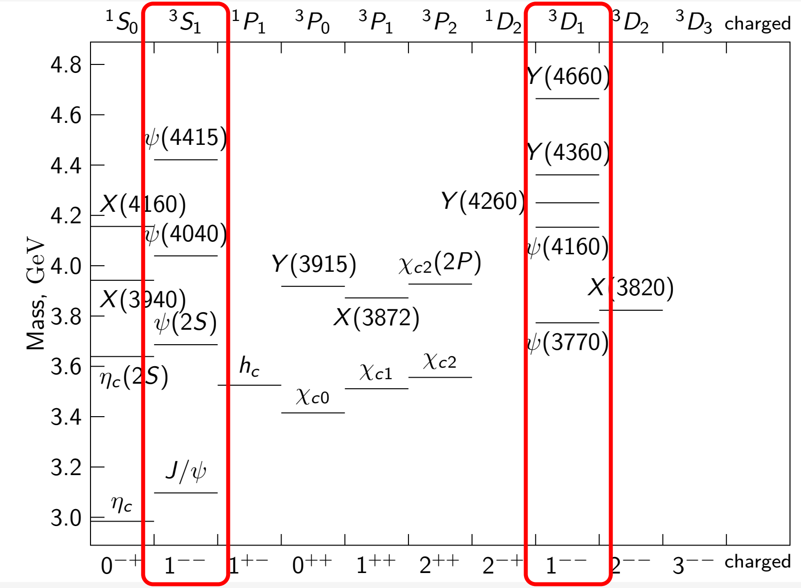

Open Questions

- where are the other resonances beside $\psi(4160)$?
- to what extent is quark-hadron duality violated?
  - $B \to K^* \ell^+ \ell^-$ to the rescue!
  - what is the value of $H_T^{(1)}$?
  - what is the value of S_7?
- can we learn more about the q^2 spectrum when combining exclusive $b \to s\ell^+\ell^-$ data?

Conclusion

Summary and Outlook

- exclusive $b \to s\ell^+\ell^-$ decays are interesting channels to probe for new physics effects and to simultaneously understand "old physics"
- data has become very precise; we have already started to infer hadronic physics from data
  - however: disentangling right-handed currents from $\bar{c}c$ contributions will be difficult
- measurements in the decay channel $\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$ will be helpful
  - will offer novel types of new physics constraints
  - on account of different hadronic matrix element, it will either confirm or challenge the current results offered in the mesonic decay channels
- increasing precision in $B \to K\ell^+\ell^-$ will need to be met by further understanding of the charmonium spectrum
  - we might need to reconsider *modelling* the spectrum
- not discussed:
  - $B \to K\pi\ell^+\ell^-$ [Das/Jung/Hiller/Shires 1406.6681], $B_s \to \phi\ell^+\ell^-$, ...

Backup Slides

Large Recoil (I)

QCD Factorization (QCDF) + Soft Collinear Effective Theory (SCET)

- calculate $\bar{q}q$ loops perturbatively, expand in $1/m_b$, $1/E_{K^*}$
- relate matrix elements to universal hadronic quantities:
  - Light Cone Distribution Amplitudes (LCDAs)
  - form factors
  - decay constants

[Beneke/Feldmann '00, Beneke/Feldmann/Seidel '01 & '04]

Light Cone Sum Rules (LCSR)

- calculate $\langle \bar{c}c \rangle$, $\langle \bar{c}cG \rangle$ on the light cone for $q^2 \ll 4m_c^2$
- achieves resummation of soft gluon effects
- use analycity of amplitude to relate results to $q^2 < M_{\psi'}^2$
- uses many of the same inputs as QCDF+SCET

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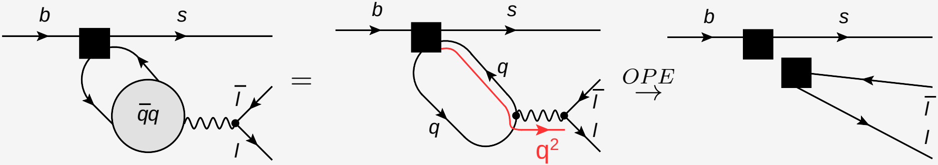
[Beneke/Feldmann '00, Beneke/Feldmann/Seidel '01 & '04]

Combination of QCDF+SCET and LCSR Results

- not yet!
  - no studies yet to find impact on optimized observables at large recoil!
  - LCSR results are not included in following discussion

Low Recoil OPE [Grinstein/Pirjol '04, Beylich/Buchalla/Feldmann '11]

$$i \int \mathrm{d}^4 x e^{iqx} \langle \bar{K}^* | T\{\mathcal{O}_i(0), j_\mu^{\text{e.m.}}(x)\} | \bar{B} \rangle = \sum_{j,k} \mathcal{C}_{i,j,k}(q^2/m_b^2, \mu) \langle \mathcal{O}_j{}^{(k)} \rangle_\mu$$



Operators

- $k = 3$ form factors, α_s corrections known, absorbed into effective Wilson coefficients $\mathcal{C}_{7,9} \to \mathcal{C}_{7,9}^{\text{eff}}$
- $k = 4$ absent
- $k = 5$ $\Lambda^2/m_b^2 \sim 2\%$ corrections, first new had. matrix elements explicitly: $< 1\%$ for $q^2 = 15\text{GeV}^2$ [Beylich/Buchalla/Feldmann]

$\Lambda_b \to \Lambda(\to N\pi)\ell^+\ell^-$ Angular Observables

$$K_{1ss} = \frac{1}{4}\left[|A_{\perp_1}^R|^2 + |A_{\|_1}^R|^2 + 2|A_{\perp_0}^R|^2 + 2|A_{\|_0}^R|^2 + (R \leftrightarrow L)\right]$$

$$K_{1cc} = \frac{1}{2}\left[|A_{\perp_1}^R|^2 + |A_{\|_1}^R|^2 + (R \leftrightarrow L)\right]$$

$$K_{1c} = -\,\text{Re}\left(A_{\perp_1}^R A_{\|_1}^{*R} - (R \leftrightarrow L)\right)$$

$$K_{2ss} = -\frac{\alpha}{2}\,\text{Re}\left(A_{\perp_1}^R A_{\|_1}^{*R} + 2A_{\perp_0}^R A_{\|_0}^{*R} + (R \leftrightarrow L)\right)$$

$$K_{2cc} = -\alpha\,\text{Re}\left(A_{\perp_1}^R A_{\|_1}^{*R} + (R \leftrightarrow L)\right)$$

$$K_{2c} = \frac{\alpha}{2}\left[|A_{\perp_1}^R|^2 + |A_{\|_1}^R|^2 - (R \leftrightarrow L)\right]$$

$$K_{3sc} = -\frac{\alpha}{\sqrt{2}}\,\text{Im}\left(A_{\perp_1}^R A_{\perp_0}^{*R} - A_{\|_1}^R A_{\|_0}^{*R} + (R \leftrightarrow L)\right)$$

$$K_{3s} = -\frac{\alpha}{\sqrt{2}}\,\text{Im}\left(A_{\perp_1}^R A_{\|_0}^{*R} - A_{\|_1}^R A_{\perp_0}^{*R} + (R \leftrightarrow L)\right)$$

$$K_{4sc} = \frac{\alpha}{\sqrt{2}}\,\text{Re}\left(A_{\perp_1}^R A_{\perp_0}^{*R} - A_{\|_1}^R A_{\|_0}^{*R} + (R \leftrightarrow L)\right)$$

$$K_{4s} = \frac{\alpha}{\sqrt{2}}\,\text{Re}\left(A_{\perp_1}^R A_{\|_0}^{*R} - A_{\|_1}^R A_{\perp_0}^{*R} - (R \leftrightarrow L)\right)$$

$$A_{\perp_1}^{L(R)} = -2NC_+^{L(R)} f_\perp^V \sqrt{s_-} \qquad A_{\|_1}^{L(R)} = +2NC_-^{L(R)} f_\perp^A \sqrt{s_+}$$

$$A_{\perp_0}^{L(R)} = +\sqrt{2}NC_+^{L(R)} f_0^V \frac{m_{\Lambda_b} + m_\Lambda}{\sqrt{q^2}} \sqrt{s_-} \qquad A_{\|_0}^{L(R)} = -\sqrt{2}NC_-^{L(R)} f_0^A \frac{m_{\Lambda_b} - m_\Lambda}{\sqrt{q^2}} \sqrt{}$$

with $s_\pm = (m_{\Lambda_b} \pm m_\Lambda)^2 - q^2$

$$C_+^{R(L)} = \left((\mathcal{C}_9 + \mathcal{C}_{9'}) + \frac{2\kappa m_b m_{\Lambda_b}}{q^2}(\mathcal{C}_7 + \mathcal{C}_{7'}) \pm (\mathcal{C}_{10} + \mathcal{C}_{10'})\right)$$

$$C_-^{R(L)} = \left((\mathcal{C}_9 - \mathcal{C}_{9'}) + \frac{2\kappa m_b m_{\Lambda_b}}{q^2}(\mathcal{C}_7 - \mathcal{C}_{7'}) \pm (\mathcal{C}_{10} - \mathcal{C}_{10'})\right)$$

κ as in [Grinstein/Pirjol hep-ph/0404250]

At Low Recoil: ρs when $q^2 = O\left(m_b^2\right)$

$$
\begin{aligned}
\rho_1^\pm &= |\mathcal{C}_{79} \pm \mathcal{C}_{7'9'}|^2 + |\mathcal{C}_{10} \pm \mathcal{C}_{10'}|^2 \\
\rho_2 &= \text{Re}\,(\mathcal{C}_{79}\mathcal{C}_{10}^* - \mathcal{C}_{7'9'}\mathcal{C}_{10'}^*) - i\,\text{Im}\,(\mathcal{C}_{79}\mathcal{C}_{7'9'}^* + \mathcal{C}_{10}\mathcal{C}_{10'}^*) \\
\rho_3^\pm &= 2\,\text{Re}\,((\mathcal{C}_{79} \pm \mathcal{C}_{7'9'})(\mathcal{C}_{10} \pm \mathcal{C}_{10'})^*) \\
\rho_4 &= \left(|\mathcal{C}_{79}|^2 - |\mathcal{C}_{7'9'}|^2 + |\mathcal{C}_{10}|^2 - |\mathcal{C}_{10'}|^2\right) - i\,\text{Im}\,(\mathcal{C}_{79}\mathcal{C}_{10'}^* - \mathcal{C}_{7'9'}\mathcal{C}_{10}^*)\ .
\end{aligned}
$$