Kstar Kstar Project Overview

MWAPP Group Meeting

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Outline

NP in the Weak Phase

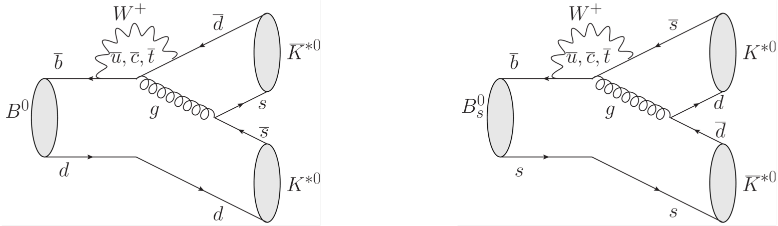
- Interested in CPV in (charmless) $B \to VV$ decays
- Want to search for New Physics in weak phase ϕ_s
- Measured phase, $\phi_s^{\rm meas}$ looks like

$$\phi_s^{\rm meas} = -2\beta_s + \delta\phi_s^{\rm SM} + \phi_s^{\rm NP} \tag{1}$$

- β_s very precisely predicted in the SM but sub-dominant loop-process contribution $\delta\phi_s^{\rm SM}$ is unknown so how can we disentangle $\phi_s^{\rm NP}$?

$B^0_{(s)} \to K^{*0}\overline{K}^{*0}$

- This project specifically is looking at: $B^0_{(s)} \to K^*(892)^0\overline{K}^*(892)^0$ decays[1] where the $K^{*0}(\overline{K}^{*0})$ is reconstructed as $K^+\pi^-(K^-\pi^+)$
- This is a mediated by penguin diagrams so loop-contributions from u, c and t



R. Aaij *et al.* (LHCb Collaboration), JHEP **2019**, 32 (2019)

[1] M. Ciuchini, M. Pierini and L. Silvestrini, PRL **100**, 031802 (2008)

Amplitudes

- Exploit unitarity of CKM matrix to re-write amplitudes of final states in terms of two amplitudes:

$$A(B^0 \to K^{*0}\overline{K}^{*0}) = |\lambda_{ud}|e^{i\gamma}P_{uc} + |\lambda_{td}|e^{-i\beta}P_{tc}, \tag{2}$$

$$A(B_s^0 \to K^{*0}\overline{K}^{*0}) = |\lambda_{us}|e^{i\gamma}P'_{uc} - |\lambda_{ts}|e^{-i\beta_s}P'_{tc}, \tag{3}$$

- where $\lambda_{qq'} = V_{qb}^* V_{qq'}$, β, γ are the usual CKM phases, $\beta_s = \arg(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*})$ and $P_{qq'} = P_q - P_{q'}$ with P_q the contribution related to quark q.
- Eqn. 3: first term much smaller than second but need to know its impact in high precision analysis
- Eqn. 2: both terms approx. the same size so maximally sensitive to pollution of $P_{uc}^{(\prime)}$ which also affects Eqn. 3

U-Spin

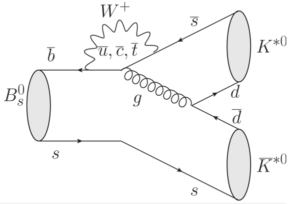
- Assuming perfect U-spin symmetry i.e. exchange $s \Leftrightarrow d$, $P_{uc} = P'_{uc}$, $P_{tc} = P'_{tc}$
- This decay is (almost) unique: U-spin symmetry to change between B^0 and B_s^0 leaves the final state invariant
- Use this U-spin symmetry in simultaneous analysis of the two modes[2]
- The polluting sub-leading first term in $A(B_s^0 \to K^{*0}\overline{K}^{*0})$ can be disentangled, allowing an in principle unambiguous measurement of ϕ_s^{NP}
- Requires a time-dependent CP-Asymmetry measurement
- A time-dependent amplitude analysis has been performed for the B_s^0 mode and a time-integrated for both modes with LHCb Run 1 data [3]

[2] M. Ciuchini, M. Pierini and L. Silvestrini, PRL **100**, 031802 (2008), S. Descotes-Genon, J. Matias and J. Virto Phys. Rev. D **85** 034010 (2012)

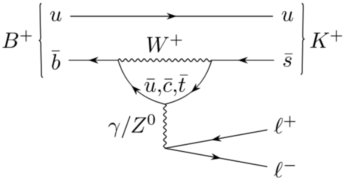
[3] R. Aaij *et al.* (LHCb Collaboration), JHEP **2019**, 32 (2019), R. Aaij *et al.* (LHCb Collaboration), JHEP **2018**, 140 (2018)

Anomalies in $b \to s$ Transitions

- Recent LHCb measurements suggest a deviation from the SM in $b \to s\ell^+\ell^-$ transitions e.g. R_K in $B^+ \to K^+\mu^-\mu^+$ vs $B^+ \to K^+e^-e^+$ decays at 3.1σ tension with the SM
- What about $b \to s\bar{q}q$ vs. $b \to d\bar{q}q$ transitions?
- $B^0 \to K^{*0}\overline{K}^{*0}$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$ very similar to some of these $b \to s\ell^+\ell^-$ transitions i.e. loop diagrams but mediated by gluons instead of electroweak bosons
- But, hadronic uncertainties much harder to model than relatively 'clean' leptonic ones



R. Aaij *et al.* (LHCb Collaboration), JHEP **2019**, 32 (2019)



arXiv:2103.11769

The 'L' Observable

- Similar to e.g. R_K analysis, want to exploit a ratio of branching fractions to cancel some systematics
- In this case, use U-spin symmetry to construct a similar ratio observable denoted $L_{K^{*0}\overline{K}^{*0}}$ [4]

$$L_{K^{*0}\overline{K}^{*0}} = G\frac{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}\frac{f_L^{B_s^0\to K^{*0}\overline{K}^{*0}}}{f_L^{B^0\to K^{*0}\overline{K}^{*0}}} \quad (4)$$

- Where G is a phase-space factor, $\mathcal{B}(X)$ is the branching fraction for decay X and f_L^X is the longitudinal polarisation fraction of decay X

[4] M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brune, JHEP **2021**, 66 (2021)

The 'L' Observable

- Spin-0 pseudoscalar $\rightarrow$ two spin-1 vectors
- Decay amplitude therefore sum of a longitudinal helicity amplitude A^0 and two transversely polarised amplitudes A^+ and A^-
- Naively, we expect $A^0 >> A^+ >> A^-$
- Significant hadronic uncertainties on the transverse components, so $L_{K^{*0}\overline{K}^{*0}}$ is constructed such that it only depends on the longitudinal polarisation which is less affected
- Theory predictions suggest a large longitudinal polarisation fraction for $B \rightarrow VV$ decays such as this

Longitudinal Polarisation Fractions

- f_L has been measured for both decays at LHCb previously in a time-integrated amplitude analysis[5]

$$f_L^{B^0\to K^{*0}\overline{K}^{*0}} = 0.724 \pm 0.051\ (\text{stat.}) \pm 0.016\ (\text{syst.}) \quad (5)$$

$$f_L^{B^0_s\to K^{*0}\overline{K}^{*0}} = 0.240 \pm 0.031\ (\text{stat.}) \pm 0.025\ (\text{syst.}) \quad (6)$$

- Can see that $f_L^{B^0\to K^{*0}\overline{K}^{*0}}$ agrees well with a strong longitudinal polarisation fraction whereas $f_L^{B^0_s\to K^{*0}\overline{K}^{*0}}$ is not strongly polarised and suggests a tension with the SM QCDF prediction[6] of $f_L^{B^0_s\to K^{*0}\overline{K}^{*0}} = 0.63^{+0.42}_{-0.29}$
- This tension in its own right is interesting and should be investigated further

[5] R. Aaij *et al.* (LHCb Collaboration), JHEP **2019**, 32 (2019)
[6] M. Beneke, J. Rohrer and D. Yang, Nucl. Phys. B **774**, 64 (2007)

The 'L' Observable

- Using the previous analyses, can start to construct $L_{K^{*0}\overline{K}^{*0}}$ and compare to theory predictions[7]:

Assumption	$L_{K^{*0}\overline{K}^{*0}}$	Tension
Experiment	4.43 ± 0.92	-
Naive $SU(3)$	23^{+16}_{-12}	1.9σ
Factorised $SU(3)$	$19.2^{+9.3}_{-6.5}$	3.0σ
QCD Factorised	$19.5^{+9.3}_{-6.8}$	2.6σ

- Value from experiment seems lower than theory predictions — suggests a deficit of $b \to s$ w.r.t $b \to d$ similar to the deficit of $b \to s\mu^+\mu^-$ w.r.t $b \to se^+e^-$
- Dominant sources of error for theory $L_{K^{*0}\overline{K}^{*0}}$ values are the form factors $A_0^{B_s^0 \to K^{*0}\overline{K}^{*0}}$ and $A_0^{B^0 \to K^{*0}\overline{K}^{*0}}$ with (-28%, +33%) and (-22%, +32%) respectively

[7] M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brune, JHEP **2021**, 66 (2021)

Possible NP Explanations for $L_{K^{*0}\overline{K}^{*0}}$

- Using the weak-effective theory, can determine sensitivity of $L_{K^{*0}\overline{K}^{*0}}$ to different Wilson Coefficients[8]
- Find there are three dominant coefficients: $\mathcal{C}^c_{1q}$, $\mathcal{C}_{4q}$ and $\mathcal{C}^{\text{eff}}_{8gq}$
- These coefficents correspond to the following operators[9]:

$\mathcal{O}^p_{1s}$	$\bar{p}\gamma_\mu(1-\gamma_5)b\ \bar{s}\gamma_\mu(1-\gamma_5)p$	SM tree-level W-boson exchange
$\mathcal{O}_{4s}$	$\bar{s}_i\gamma_\mu(1-\gamma_5)b_j\ \sum_q \bar{q}_j\gamma_\mu(1-\gamma_5)q_i$	QCD Penguin
$\mathcal{O}_{8gs}$	$-\frac{g_s}{8\pi^2}m_b\bar{s}\sigma_{\mu\nu}(1+\gamma_5)G^{\mu\nu}b$	Chromomagnetic dipole

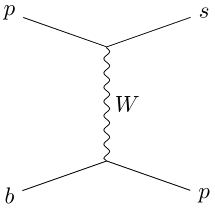
- with i, j colour indices, and a summation over $q = u, d, s, c, b$ implied

[8] M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brune, JHEP **2021**, 66 (2021)

[9] M. Beneke, G. Buchalla, M. Neubert, C. T. Sachrajda, Nucl. Phys. B **606** 245 (2001)

Wilson Coefficients

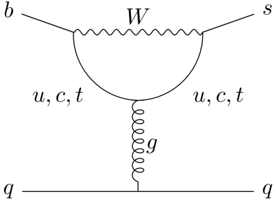
- Can look at some SM diagrams that generate these operators[10]
- Use shorthand $\bar{q}_1\gamma_\mu(1 \pm \gamma_5)q_2 = (\bar{q}_1 q_2)_{V\pm A}$



$\mathcal{O}^p_{1s}$

$(\bar{p}b)_{V-A}(\bar{s}p)_{V-A}$

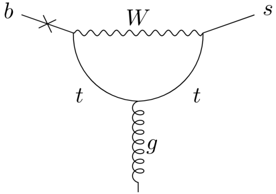
W-boson exchange



$\mathcal{O}_{4s}$

$(\bar{s}_i b_j)_{V-A}\sum_q(\bar{q}_j q_i)_{V-A}$

QCD Penguin



$\mathcal{O}_{8gs}$

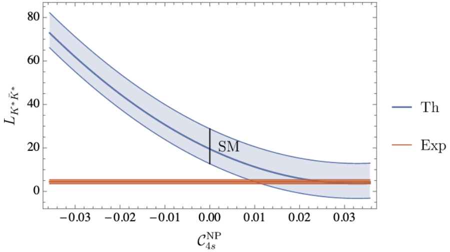
$-\frac{g_s}{8\pi^2}m_b\bar{s}\sigma_{\mu\nu}(1+\gamma_5)G^{\mu\nu}b$

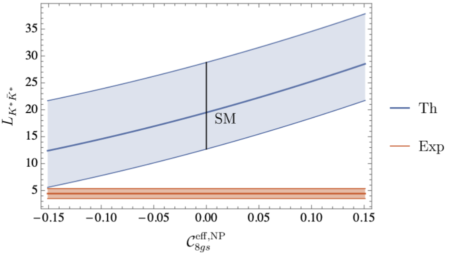
Chromomagnetic dipole

[10] G. Buchalla, A. J. Buras and M. E. Lautenbacher, Rev. Mod. Phys. **68** 1125 (1996) and arXiv:hep-ph/0512222

Possible NP Explanations for $L_{K^{*0}\overline{K}^{*0}}$

- NP contribution needed from $\mathcal{C}_{1q}^{c}$ is too large given bounds from other studies, leaving $\mathcal{C}_{4q}$ and $\mathcal{C}_{8gq}^{\text{eff}}$ as the dominant contenders
- $\mathcal{C}_{4q}$ needs ≈25% NP contribution to reduce tension of $L_{K^{*0}\overline{K}^{*0}}$ to 1σ
- $\mathcal{C}_{8gq}^{\text{eff}}$ needs about 100% of SM — large but not impossible
- Can see from plots below how large theory uncertainty is compared to experimental





M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brune, JHEP **2021**, 66 (2021)

Possible NP Explanations for $L_{K^{*0}\overline{K}^{*0}}$

- NP considered here could come from $\mathcal{C}_{4q}$, $\mathcal{C}_{8gq}^{\text{eff}}$ or a mixture of both
- One suggestion for $\mathcal{C}_{4q}$ is a Kaluza-Klein gluon
  - But, requires significant fine-tuning with $B_s^0 - \overline{B}_s^0$ mixing
  - If fine-tuning accepted, model can provide single explanation for $L_{K^{*0}\overline{K}^{*0}}$ and $b \to s\ell^+\ell^-$ transitions as KK gluon contribution has same sign as Z' w.r.t the SM
- Alternatively, can consider $\mathcal{C}_{8gq}^{\text{eff}}$ where the NP contribution could be explained by requiring two vector-like quarks and an additional neutral scalar
  - This also has a possible connection to $b \to s\ell^+\ell^-$ transitions as this model could be extended with a vector-like lepton to cover $b \to s\ell^+\ell^-$ anomalies
- Perhaps some collaboration interest here? We are looking at the experimental side, would be great to collaborate on the phenomenological side

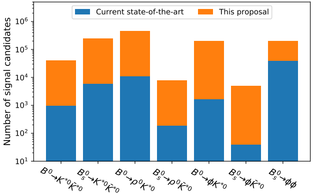
What we want to do

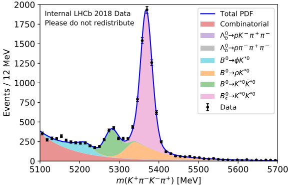
- Start with a time-integrated amplitude analysis using full Run 1 + Run 2 datasets
- Use simultaneous analysis of $B^0 \to K^{*0}\overline{K}^{*0}$ $B_s^0 \to K^{*0}\overline{K}^{*0}$ to make first direct measurement of $L_{K^{*0}\overline{K}^{*0}}$
- Then, begin work on time-dependent flavour-tagged analysis to make first simultaneous measurement of ϕ_s in B^0 and B_s^0 decays
- Collaborating with LHCb colleagues at Universidade de Santiago de Compostela on $B_{(s)}^0 \to K^{*0}\overline{K}^{*0}$ analysis
- Matt Kenzie new ERC grant (Oct. 2022 for 5 years) to probe related modes $B_{(s)}^0 \to \overset{(-)}{K}{}^{*0}\rho^0$ and $B_{(s)}^0 \to \overset{(-)}{K}{}^{*0}\phi$ which will be complementary and will add to the phenomenological picture — will $L_{K^{*0}\phi}$ and $L_{K^{*0}\rho^0}$ show the same trend as $L_{K^{*0}\overline{K}^{*0}}$?

What's been done so far

- Work on HLT2 Upgrade to write and test some lines for $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ and related decays $B^0_{(s)} \to \overset{(-)}{K}{}^{*0}\rho^0$ and $B^0_{(s)} \to \overset{(-)}{K}{}^{*0}\phi$ ready for Run 3
- Producing tuples (using Analysis Productions) from LHCb collision and MC data:
  - Data 2011-2018
  - Signal MC 2017-2018 (bug in 2011-2016 MC samples, need to re-run)
  - Background MC 2011-2018
- Now beginning the pre-selection, particle identification calibration (PIDCorr) workflow

From Matt Kenzie's ERC research proposal — please do not redistribute





Summary

- $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decays provide a unique way to measure the weak phase and look for unambiguous NP contributions
- Previous analyses suggests hints of tension to the SM in the ratio of the B^0 vs B^0_s modes to the common $K^{*0}\overline{K}^{*0}$ final state
    - Characterised by $L_{K^{*0}\overline{K}^{*0}}$, has large theory uncertainties dominated by the $A_0^{B_s^0}$, $A_0^{B^0}$
    - Some explanations of this discrepancy suggest a possible connection to the recent $b \to s\ell^+\ell^-$ anomalies
- We will use full Run 1 and Run 2 datasets to perform a time-integrated simultaneous amplitude analysis of $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ to make the first direct measurement of $L_{K^{*0}\overline{K}^{*0}}$
- Will then build on this to perform a time-dependent flavour-tagged analysis to make the first simultaneous measurement of ϕ_s in B^0 and B^0_s decays
- So far, some work on HLT2 Upgrade lines and getting the tuples ready to start the selection

Backup Slides

References

- 1,2 M. Ciuchini, M. Pierini and L. Silvestrini, PRL **100**, 031802 (2008) arXiv:hep-ph/0703137
- 2 S. Descotes-Genon, J. Matias and J. Virto Phys. Rev. D **85** 034010 (2012) arXiv:2011.07867
- 4,7,8 M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brune, JHEP **2021**, 66 (2021) arXiv:2011.07867
- 3,5 R. Aaij *et al.* (LHCb Collaboration), JHEP **2019**, 32 (2019) arXiv:1905.06662
- 3 R. Aaij *et al.* (LHCb Collaboration), JHEP **2018**, 140 (2018) arXiv:1712.08683
- 6 M. Beneke, J. Rohrer and D. Yang, Nucl. Phys. B **774**, 64 (2007) arXiv:hep-ph/0612290
- 9 M. Beneke, G. Buchalla, M. Neubert, C. T. Sachrajda, Nucl. Phys. B **606** 245 (2001) arXiv:hep-ph/0104110
- 10 G. Buchalla, A. J. Buras and M. E. Lautenbacher, Rev. Mod. Phys. **68** 1125 (1996) arXiv:hep-ph/9512380
- 10 arXiv:hep-ph/0512222

- Eqn. 2 $|\lambda_{ud}|$ and $|\lambda_{td}|$ order of $\mathcal{O}(\lambda^3)$ with $\lambda \approx 0.2$ CKM suppression factor
- Eqn. 3 $|\lambda_{us}| \sim \mathcal{O}(\lambda^4)$ and $|\lambda_{ts}| \sim \mathcal{O}(\lambda^2)$

$$L_{K^{*0}\overline{K}^{*0}} = G\frac{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})}\frac{f_L^{B_s^0 \to K^{*0}\overline{K}^{*0}}}{f_L^{B^0 \to K^{*0}\overline{K}^{*0}}} = \frac{|A_0^s|^2 + |\bar{A}_0^s|^2}{|A_0^d|^2 + |\bar{A}_0^d|^2} \quad (7)$$

- with phase space factor G:

$$G = \frac{g_{b\to d}}{g_{b\to s}} \quad (8)$$

- and

$$g_{b\to q} = \omega\sqrt{[M_{B_Q}^2 - \Sigma_{V_1V_2}][M_{B_Q}^2 - \Delta_{V_1V_2}]} \quad (9)$$

- with $\omega = \tau_{B_Q}/(16\pi M_{B_Q}^3)$, $\Sigma_{ab} = (m_a + m_b)^2$ and $\Delta_{ab} = (m_a - m_b)^2$ and all quantities CP-averaged

- Relative Error budget (cropped Table 2) from S. Descotes-Genon, J. Matias and J. Virto Phys. Rev. D **85** 034010 (2012)

Input	$L_{K^*\bar{K}^*}$
f_{K^*}	$(-0.1\%, +0.1\%)$
$A_0^{B_d}$	$(-22\%, +32\%)$
$A_0^{B_s}$	$(-28\%, +33\%)$
λ_{B_d}	$(-0.6\%, +0.2\%)$
$\alpha_2^{K^*}$	$(-0.1\%, +0.1\%)$
X_H	$(-0.2\%, +0.2\%)$
X_A	$(-4.3\%, +4.4\%)$
κ	$(-1.4\%, +2.2\%)$
Others	$(-1.3\%, +1.1\%)$

NP Assumptions

- M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brune, JHEP **2021**:
- From global-fits to the $b \to s\ell^+\ell^-$, only considered SM operators ($\mathcal{O}_i$) or chirally-flipped ($\widetilde{\mathcal{O}}_i$) ones where $V - A$ and $V + A$ are swapped
- Means NP in longitudinal amplitudes would enter as $\mathcal{C}_i^{\mathrm{NP}} - \widetilde{\mathcal{C}}_i$
- Only the values of Wilson Coefficients change, the structure of the hadronic matrix elements is assumed to stay the same
- Assume no other additional NP phases such that Wilson Coefficients are real-valued

- M. Algueró, A. Crivellin, S. Descotes-Genon, J. Matias and M. Novoa-Brune, JHEP **2021**:
- $\mathcal{C}_{1s}^{c}$ would need NP contribution of $\sim 60\%$ of SM to get $L_{K^{*0}\overline{K}^{*0}}$ discrepancy down to 1σ
- Global constraints [11] suggest only room for $\mathcal{O}(10\%)$ of SM contribution to $\mathcal{C}_{1s}^{c}$ (and possibly tighter than that)
- $\mathcal{C}^{4s}$ not greatly constrained and incidentally the $\sim 25\%$ needed is about the same as is needed to $\mathcal{C}_9$ for $b \to s\ell^+\ell^-$
- $\sim 100\%$ needed for $\mathcal{C}_{8gs}^{\text{eff}}$ (surprisingly) okay
    - Allowed within current bounds
    - Difficult to get precise bound for $\mathcal{C}_{8gs}^{\text{eff}}$ as constraints from $b \to s\gamma$ and $b \to d\gamma$ actually constrain combination of $\mathcal{C}_{8gs}^{\text{eff}}$ and $\mathcal{C}_{7\gamma s}^{\text{eff}} = \mathcal{C}_{7\gamma} - \frac{1}{3}\mathcal{C}_5 - \mathcal{C}_6$ and so effects in $\mathcal{C}_{8gs}^{\text{eff}}$ and $\mathcal{C}_{7\gamma s}^{\text{eff}}$ can cancel each other

[11] A. Lenz and G. Tetlalmatzi-Xolocotzi, JHEP **07** 177 (2020) arXiv:1912.07621

- List of operators where $\mathcal{O}^p_{1,2}$ are current-current (W boson), $\mathcal{O}_{3,\ldots,6}$ are QCD penguin operators, $\mathcal{O}_{7,\ldots,10}$ are electroweak penguin operators, $\mathcal{O}_{7\gamma}$ is electromagnetic dipole operator and $\mathcal{O}_{8g}$ is chromomagnetic dipole operator
- From S. Descotes-Genon, J. Matias and J. Virto Phys. Rev. D **85** 034010 (2012) and M. Beneke, G. Buchalla, M. Neubert, C. T. Sachrajda, Nucl. Phys. B **606** 245 (2001)

- $\mathcal{O}^p_{1s} = (\bar{p}b)_{V-A}(\bar{s}p)_{V-A}$
- $\mathcal{O}^p_{2s} = (\bar{p}_i b_j)_{V-A}(\bar{s}_j p_i)_{V-A}$
- $\mathcal{O}_{3s} = (\bar{s}b)_{V-A}\sum_q(\bar{q}q)_{V-A}$
- $\mathcal{O}_{4s} = (\bar{s}_i b_j)_{V-A}\sum_q(\bar{q}_j q_i)_{V-A}$
- $\mathcal{O}_{5s} = (\bar{s}b)_{V-A}\sum_q(\bar{q}q)_{V+A}$
- $\mathcal{O}_{6s} = (\bar{s}_i b_j)_{V-A}\sum_q(\bar{q}_j q_i)_{V+A}$
- $\mathcal{O}_{7s} = (\bar{s}b)_{V-A}\sum_q \frac{3}{2}e_q(\bar{q}q)_{V+A}$
- $\mathcal{O}_{8s} = (\bar{s}_i b_j)_{V-A}\sum_q \frac{3}{2}e_q(\bar{q}_j q_i)_{V+A}$
- $\mathcal{O}_{9s} = (\bar{s}b)_{V-A}\sum_q \frac{3}{2}e_q(\bar{q}q)_{V-A}$
- $\mathcal{O}_{10s} = (\bar{s}_i b_j)_{V-A}\sum_q \frac{3}{2}e_q(\bar{q}_j q_i)_{V-A}$
- $\mathcal{O}_{7\gamma s} = -\frac{e}{8\pi^2} m_b \bar{s}\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu}b$
- $\mathcal{O}_{8gs} = -\frac{g_s}{8\pi^2} m_b \bar{s}\sigma_{\mu\nu}(1+\gamma_5)G^{\mu\nu}b$

- with e_q electric charge of the quarks
- Define $\mathcal{C}^{\rm eff}_{8g} = \mathcal{C}_{8g} + \mathcal{C}_5$