$B \to V\gamma$

Beyond QCD Facorization

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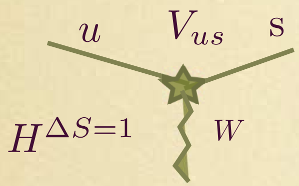
Flavour Physics at IPPP -- IPPP steering Committee

Overview

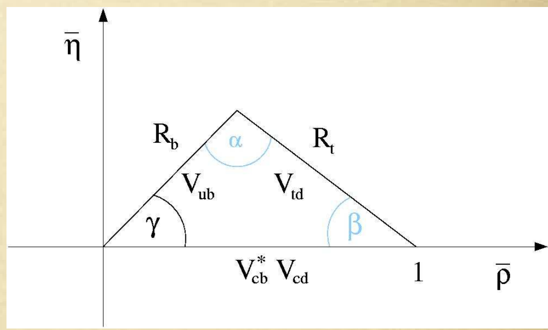
- B-physics CKM-matrix generalities
- Exclusive decays H_{eff}
- Hadronic matrix elements – Distribution Amplitudes
- Overview of our activities
- Focus $B \to V\gamma$ beyond QCD factorization
- Particular focus on time dep. CP-asymmetry

The Quark-Sector



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \delta & \delta^3 \\ \delta & 1 & \delta^2 \\ \delta^3 & \delta^2 & 1 \end{pmatrix} \quad \text{hierarchy :} \quad \delta \sim 0.2$$

absolute values



- V arbitrary **unitary** matrix

  9 parameters (5=6-1 absorbed in phases of quarks)
  $\Rightarrow$ 4 parameters $\sim$ 3 rotation & 1 complex pahse

- $(CP)\mathcal{L}^{\text{weak}}(CP)^\dagger = \mathcal{L}^{\text{weak}} \;\Leftrightarrow\; V_{\alpha\beta} = V^*_{\alpha\beta}$ CP-violation

- unitarity $VV^\dagger = 1$, 9 conditions among B_d^0 triangle

$$V_{du}V_{ub}^* + V_{dc}V_{cb}^* + V_{dt}V_{tb}^* = 0$$

  known as the CKM-triangle (B_s^0 and K^0 triangles too flat)

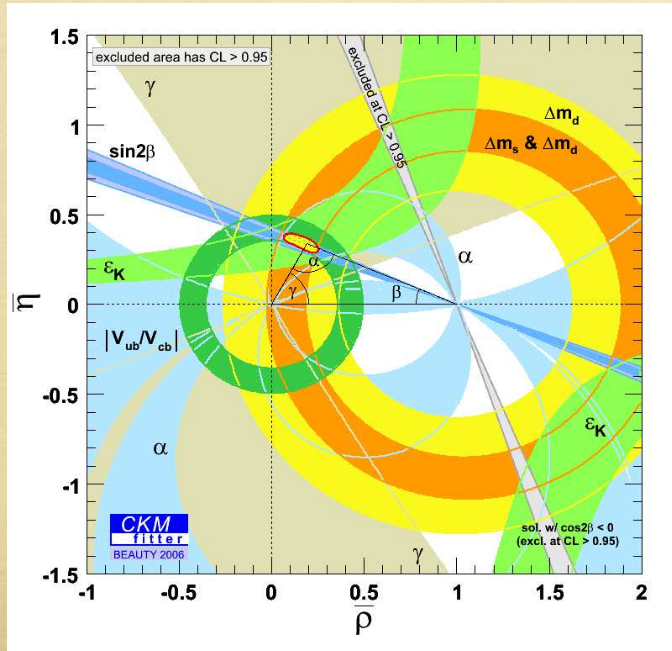
- CP violation $\leftrightarrow$ non-zero area triangle

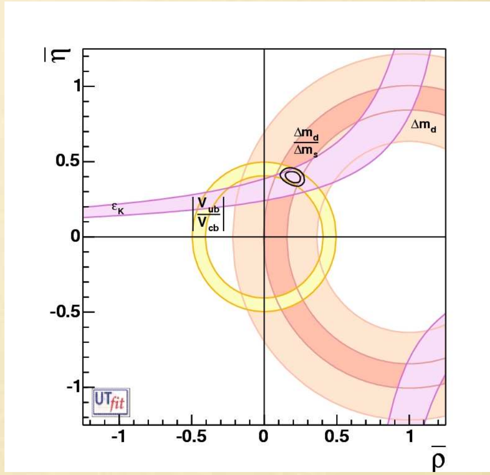
- only established source of CP-viol SM (MNS neutrinos ?)

Measuring CKM - B-Factories 1999-

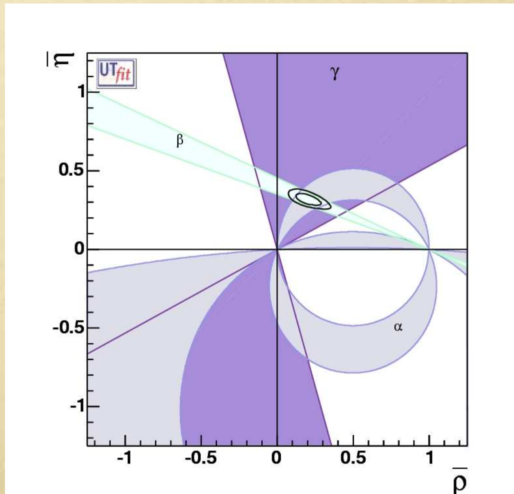
Results:

1. CKM mechanism works
   - triangle overconstrained
   - describes CP-viol. mesons quant.
2. Not enough Baryogenesis ($\sim 10^{10}$)
   $\rightarrow$ T.Underwood's talk





From Sides (CP-cons.)



From Angles (CP-viol.)

Challenge for Theory

Relate observables to fund. parameters (Hadronization)

$$\Gamma(B \to \pi e \nu), \Delta M_s \qquad \leftrightarrow \qquad m_b, V_{\rm ub}, V_{\rm ts}$$

A few simple examples

- $A_{\rm CP}(B \to J/\Psi K_s) \sim \sin(2\beta)\sin(\Delta M t)$ Bigi & Sanda 81
- $|V_{\rm ub}|^{-2} \sim \int dq^2 |f_+(q^2)|^2$ one single form factor !

Exclusive Decays $B \to X\,Y \quad \leftrightarrow \quad \langle XY|H_{\rm eff}|B\rangle$

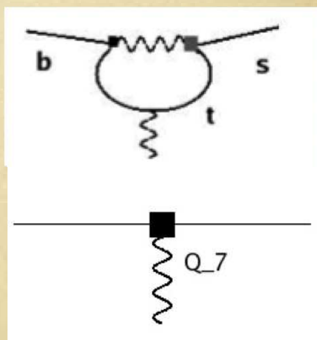
	$H_{\rm eff}$	remark	type
$B \to \pi e \nu$	$(\bar{b}u)_{V-A}$	tree – level	semileptonic
$\bar{B} \to K^*\gamma$	$(\bar{b}\sigma\cdot F s)_{V+A} + \dots$	FCNC	semileptonic
$B \to \pi\pi$	$(\bar{b}u)_{V-A}(\bar{d}u)_{V-A}$	tree – level	non – leptonic

Exploit hierarchy of scales

$\Lambda_{\rm QCD}$ (0.2) — $\sqrt{\Lambda m_b}$ (1) — m_b (5) — M_W (80GeV) → new Physics ?

- M_W to m_b described pert. QCD $\Rightarrow$ concretely apply Wilsonian picture

$$H_{\rm eff} = \sum \underbrace{C_i(\mu)}_{\rm UV}\,\underbrace{O_i(\mu)}_{\rm IR}$$



Q_i operators (above), $\mu \sim m_b$ factorisation scale ... steps:

1. matching scale M_W (initial condition)
2. RNG-running scale $C_i \sim L^{\gamma_i}$ ... γ_i anomal. dim → calc.
3. evaluate $\langle XY|Q_i(\mu)B\rangle$ "domain of expertise"

Matrix elements: semilept. form factors

- Parametrize matrix element grounds Lorentz-covariane

$$\langle \pi(p)|\bar{b}\gamma_\mu(1-\gamma_5)q|B\rangle = 2p_\mu f_+(q^2) \qquad 0 < q^2 < (m_B - m_\pi)^2$$

Heavy-light (no sym. light-light or heavy-heavy) $\Rightarrow$ non-pert object

Methods:

1. Light-Cone Sum Rules small $q^2 \leftrightarrow E_\pi$ large, pion LC
2. Lattice-QCD large $q^2 \leftrightarrow E_\pi$ small, pion o/w not resolved by lattice

are complementary

- LCSR are QCD sum-rules

$$\begin{array}{rcl} \text{OPE} & \leftrightarrow & \text{LC}-\text{OPE} \\ \text{Cond}: \ \langle \bar{q}q \rangle & \leftrightarrow & \text{DistributionAmplitudes}: \quad \phi_\pi(u) \end{array}$$

- Leading part the form factor in LCSR

$$f_+^{B\to\pi} \sim f_\pi(1 + O(1)\, a_2(\pi)\ldots) + \ldots$$

a_2 moment DA

Meson Distribution Amplitudes (DA)

- relevant exclusive processes at large momentum transfer (LC)
- most important DA $\leftrightarrow$ minimal number of partons

$$\langle \pi(p)|\bar{q}(x)\gamma_\mu\gamma_5 q(0)|0\rangle = i f_\pi p_\mu \int e^{iupx}\phi_\pi(u) + O(x^2, m_\pi^2)$$

  - called twist-2, twist = dim - spin = 3 -1
    correction: higher Fock states, dev. from LC
  - variable u : col. momentum fraction of corr. quark in meson

- QCD e.o.m. different DA related

$$\partial_\mu \bar{q}(x)\gamma_\mu s(-x) = -i\int_{-1}^{1} dv\, v\bar{q}(x)x_\alpha g G^{\alpha\mu}(vx)\gamma_\mu s(-x) - (m_s+m_q)\bar{q}(x)i(\gamma_5)s(-x)$$

  Wilson lines omitted, take matrix elements

- what to do $\phi_\pi(u)$?

A. models obeying theor. & exp. constraints

B. expand in Eigenfunction of evolution kernel

$$\phi_\pi(u,\mu) = 6u(1-u)(1+\sum_{n\geq 1} a_n(\mu,\pi)\, C_n^{3/2}(2u-1))$$

- a_n Gegenbauer moments
- C_n Gegenbauer pol. rep. collinear $SL(2,R) \in S0(4,2)$ conformal
- asymptotic part $6u(1-u)$ exact from perturbative QCD

- Why good expansion ?

1. convolution smooth kernel $\int duT(u)C_n(u)$ decreasing (C_n n nodes)
2. det. of a_n indicate $a_0 \equiv 1 > |a_1| > |a_2| \dots$
   "consistent" with $\gamma_{n+1} > \gamma_n$ conformal hierarchy

- **Determination ?**

a. fit to experiment .. (contam. other hadr. uncert.)

b. calculate from local matrix element (Fourier inversion)

  * QCD sum rules
  * lattice QCD (new efforts)

Overview results (selected)

1. calculation of all weak and penguin form factors $B \to (P, V)$ from LCSR
   PRD 71, 14015 and PRD 71, 14029 2005 Ball RZ

   $$|V_{\rm ub}|^{\rm HFAG}_{\rm BZ} = 3.38 \pm 0.12^{+0.56}_{-0.37}\, 10^{-3}$$

   Open parenthesis (NP ?)

   $$|V_{\rm ub}|_{\rm CKM-fit} = 3.5 \pm 0.18\, 10^{-3} \qquad |V_{\rm ub}|^{\rm DGE}_{\rm incl} = 4.46 \pm 0.2 \pm 0.2\, 10^{-3}$$

2. Kaon DA $K, K^{*,\parallel}, K^{*,\perp}$ emph. SU(3)-break.
   PLB 633,289 2006, JHEP 0602:034 2006 Ball RZ

   $$a_1(K) = 0.06 \pm 0.03, \quad a_1^{\parallel}(K^*) = 0.03 \pm 0.02, \quad a_1^{\perp}(K^*) = 0.04 \pm 0.03.$$

   Later QCDSF/HPQCD & QCDSF same values advert. smaller uncert.

3. apply these results $B \to V\gamma$
   JHEP 0604:046,2006, PLB B642:478 RZ Ball
   all new hep-ph/0612081 Ball Jones RZ topic rest

$B \to V\gamma$ beyond QCD Factorisation

- whole zoo: $B \to (\rho^{(0,+)}, \omega, K^{*,(0,+)})$ and $B_s \to (\bar{K}^*, \phi)$
- FCNC new physics hidden loops ?
- $\mathcal{B}(b \to X_s\gamma)_{\text{incl}}$ no hints NP
- history

1993 $B \to K^*\gamma$ CLEO

2005 $B \to \rho\gamma$ Belle (BaBar 2006)

200x $B_s \to (\bar{K}^*, \phi)\gamma$ LHCb

$$\mathcal{H}_{\text{eff}}^{(d,s)} = \frac{G_F}{\sqrt{2}} \sum_{U=u,c} \underbrace{\lambda_U^{(d,s)}}_{\text{CKM}} \left[C_1 Q_1 + C_2 Q_2 + \sum_{i=3,\ldots,8} C_i Q_i \right] + \text{BSM}$$

Effective Hamiltonian (OPE-description), CKM-factors $\lambda_t^s = V_{\text{bt}} V_{\text{ts}}^*$

$$Q_1{}^{U} = (\bar{s}_i U_j)_{V-A} (\bar{U}_j b_i)_{V-A} \qquad Q_2{}^{U} = (\bar{s} U)_{V-A} (\bar{U} b)_{V-A}$$

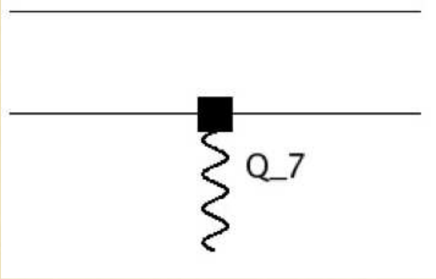
$$Q_3 = (\bar{s} b)_{V-A} \sum_q (\bar{q} q)_{V-A} \qquad Q_4 = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$

$$Q_5 = (\bar{s} b)_{V-A} \sum_q (\bar{q} q)_{V+A} \qquad Q_6 = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A}$$

$$Q_7 = \frac{e}{8\pi^2} m_b \, \bar{s}_i \sigma^{\mu\nu} (1 + \gamma_5) b_i \, F_{\mu\nu} \qquad Q_8 = \frac{g}{8\pi^2} m_b \, \bar{s}_i \sigma^{\mu\nu} (1 + \gamma_5) T_{ij}^a b_j \, G_{\mu\nu}^a$$

- C_i Wilson Coeff. NLO α_s (NNLO first estimate) from "inclusive people"
- C_7 leading $1/m_b$ and α_s $b \to (d,s)\gamma$, add $O(m_s)$-part later
- C_2 $1/m_b$ (power)-correction in $b \to (d,s)\gamma$, but $C_2 \sim C_7$
- $Q_2{}^{U}$-flavour sensitive, discr. final state

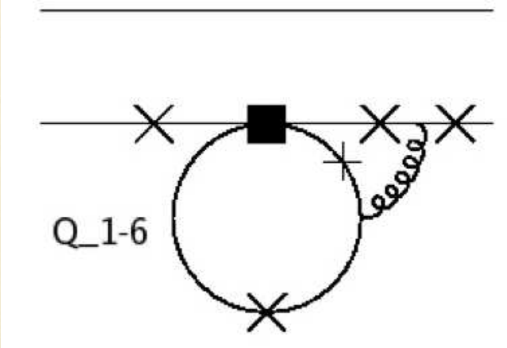
- At $O(\alpha_s^0)$, LO $1/m_b$ only electric penguin



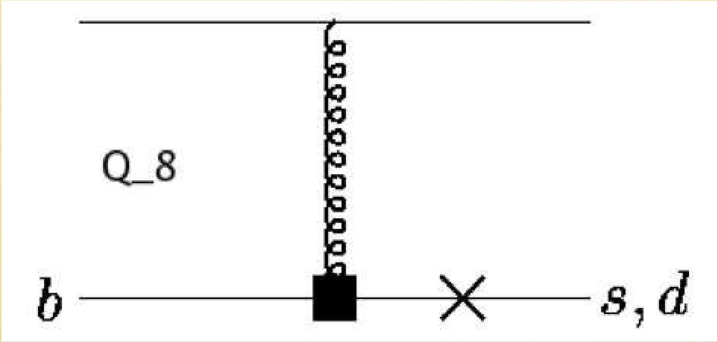
$$\langle V\gamma|\underbrace{\bar{b}\sigma\cdot F(1+\gamma_5)q}_{Q_7}|B\rangle = kin.T_1(0) \quad \text{FF from LCSR}$$

- At $O(\alpha_s)$, LO $1/mb$ **QCD factorization**
  (Bosch et al, Beneke et al, Ali et al 01):

$$\begin{aligned}\langle V\gamma|Q_i|B\rangle &= T_i^I F(B\to V_\perp) + \int_0^1 d\xi du\, \phi_B(\xi)\phi_{V_\perp}(u)T_i^{II}(\xi,u) + O\left(\Lambda/m_b\right) \\ &= \#\langle V\gamma|Q_7|B\rangle + O(\Lambda/m_b)\end{aligned}$$



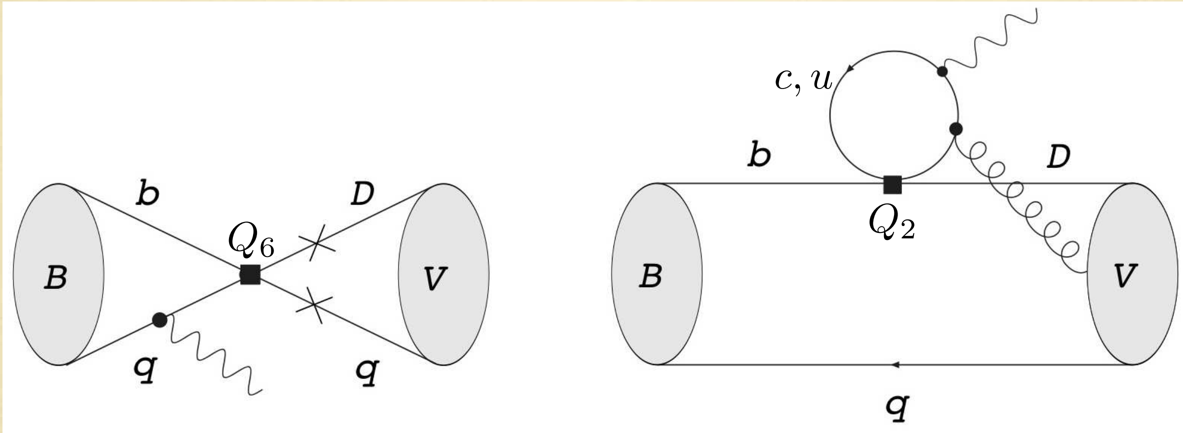
Ex. hard-vertex, T^I



Ex. hard-spectator, T^{II}

Beyond QCD Factorization

power supressed non-factorizable contribution

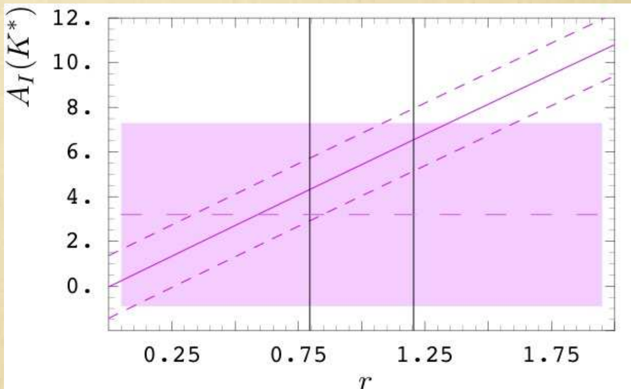


annihilation (drives isospin break.) c, u-loops (Time-dep CP asymmetry)

- $\mathcal{B}(B \to V\gamma) \sim 20(30)\%$
- Isospin asymmetries
  - (ρ^0, ρ^+) depend angle γ
  - (K^{*0}, K^{*+}) .. interesting
- $R \equiv \frac{B(B\to(\rho,\omega)\gamma)}{B(B\to K^*\gamma)} \sim \left|\frac{V_{\rm td}}{V_{\rm ts}}\right|^2$ red. uncert.

  extract $|V_{\rm td}/V_{\rm ts}|^{BJZ}_{\rm BaBar} = 0.199(22)(14)$

  compare $|V_{\rm td}/V_{\rm ts}|^{\Delta M_s}_{\rm CDF} = 0.206(8)$



$r = C_6/C_6^{\rm SM}$

Time dependent CP asymmetry

- Key idea $\bar{B}^0$ decay $(V{-}A)$-int.produce predominantly left handed photons
  Beyond SM anything possible .. enhanced $m_{\rm NP}/m_b$
- $$A_{CP} = \frac{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) - \Gamma(B^0(t) \to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) + \Gamma(B^0(t) \to K^{*0}\gamma)} = S\sin(\Delta m_B t) - C\cos(\Delta m_B t)\,,$$
- Gronau,Attwood & Soni 97 since LO operator

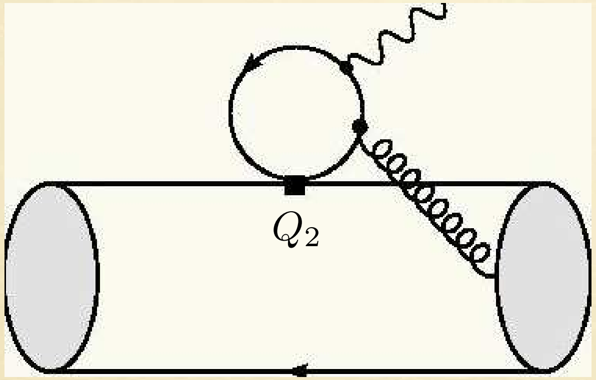
$$Q_7 = \frac{e}{8\pi^2}\left[m_b \bar{s}\sigma_{\mu\nu}(1+\gamma_5)b + m_s \bar{s}\sigma_{\mu\nu}(1-\gamma_5)b\right] F^{\mu\nu} \equiv Q_7^L + \frac{m_s}{m_b} Q_7^R$$

Time dependent CP asymmetry $(\sim L \cdot R/L^2$

$$S^{{\rm SM},s_R}_{K^*\gamma} = -\sin(2\beta)\,\frac{m_s}{m_b}\,(2 + O(\alpha_s)) \sim (2-3)\%$$

  - $O(\alpha_s)$-correction calculable QCD-F
  - $\mathcal{B} \sim (L^2 + R^2)/L^2$ right-handed "not sizable" $O(m_s^2/m_b^2)$

- Grinstein et al 04 futher contribution from soft gluon emission, c-loop from Q_2^c (QCD V-interaction)



non-factorizable

- SCET based analysis resorts to dimensional estimate of matrix element and obtain

$$|S_{K^*\gamma}^{\mathrm{SM,soft\ gluons}}| = 2\sin(2\beta)\left|\frac{C_2}{3C_7}\right|\frac{\Lambda_{\mathrm{QCD}}}{m_b} \approx 0.06\,.$$

reach conclusion: $S_{K^*\gamma}^{\mathrm{SM}} \sim 10\%$ with large uncertainties

Quantitative Analysis

- idea: on-shell photon, c-quark heavy perform a local OPE

$$
\begin{aligned}
Q_F &= i e^{*\mu} \int d^4x e^{iqx}\, \mathrm{T}\left\{[\bar{c}(x)\gamma_\mu c(x)]\, Q_2^c(0)\right\} \\
&= -\frac{1}{48\pi^2 m_c^2}(D^\rho F^{\alpha\beta})[\bar{s}\gamma_\rho(1-\gamma_5) g \widetilde{G}^a_{\alpha\beta}\frac{\lambda^a}{2}\, b] + \ldots
\end{aligned}
$$

- Remains calculate matrix element $\langle K^*(p,\eta)\gamma(q,e)|Q_F|B\rangle = L\,\mathrm{kin}_1 + \tilde{L}\,\mathrm{kin}_2$
- use LCSR (generous uncertainty, 3-particle DA, $1/m_c$-corrections)

$$
S^{\mathrm{SM,soft\ gluons}}_{K^*\gamma} = -2\sin(2\beta)\left(-\frac{C_2}{C_7}\frac{L-\tilde{L}}{36 m_b m_c^2 T_1^{B\to K^*}(0)}\right) = 0.5 \pm 1\%
$$

$$
\Rightarrow S^{\mathrm{SM}} = -2.2 \pm 1.2^{+0}_{-1_{\alpha_s}}\,\%
$$

$$
\begin{aligned}
S_{\mathrm{BaBar}} &= -21 \pm 40\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\% \qquad \text{BaBar} \qquad (232\cdot 10^6\ B\bar{B}\ \text{pairs}), \\
S_{\mathrm{Belle}} &= -32^{+36}_{-33}\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\% \qquad \text{Belle} \qquad (535\cdot 10^6\ B\bar{B}\ \text{pairs}),
\end{aligned}
$$

and $S_{\mathrm{HFAG}} = -28 \pm 26\%$ waiting for BaBar update !

Other transitions:

- Results in all transitions, $S(\phi\gamma)$ LHCb !!

$$
\begin{aligned}
S(\rho\gamma) &= \quad (\underbrace{0.01}_{m_D/m_b} + \underbrace{0.02}_{\text{LD WA}} + \underbrace{0.20}_{\text{soft } g} \pm 1.6)\% &&= \quad (0.2 \pm 1.6)\%\,,\\
S(\omega\gamma) &= \quad (0.01 - 0.08 + 0.22 \pm 1.7)\% &&= \quad (0.1 \pm 1.7)\%\,,\\
S(K^*\gamma) &= -(2.9 - 0 + 0.6 \pm 1.6)\% &&= -(2.3 \pm 1.6)\%\,,\\
S(\bar{K}^*\gamma) &= \quad (0.12 + 0.03 + 0.11 \pm 1.3)\% &&= \quad (0.3 \pm 1.3)\%\,,\\
S(\phi\gamma) &= -(0.5 - 0 - 5.3 \pm 8.2) \times 10^{-2}\,\% &&= -(0.1 \pm 0.1)\%\,.
\end{aligned}
$$

- $b \to d$ transitions CKM-hierarchy demands u-quark loops !
  Problem because photon momentum $q^2 = 0$
- Method devised to calculate it: key ingredients:
  1. calculate off-shell photon q^2 deep euclidian
  2. use dispersion relation (make sure no subtraction terms)
  3. estimate the non-perturbative $s \in [0, \text{cont}]$ part of the spectral function with LCSR and $s \in [\text{cont}, \infty[$ by analtyic continuation above threshold

Epilogue

Efforts in

1. form factors from LCSR
2. distribution amplitudes (DA)
3. new methods (light-quark loops)

led to

a. CKM-determination (tree-level) $|V_{\rm ub}|$

b. "CKM-determination" (loop-induced) $|V_{\rm td}/V_{\rm ts}|$

c. plenty observables $B \to V\gamma$ for NP

most exciting $S_{V\gamma}$ time-dep. CP asymmetry

d. The future: $B \to K^* l^+ l^-$ (LHCb), even more obsevables, continue programme, hadr. param. and new methods valuable

In particular NP associated prod γ_R in $B \to V\gamma$

$$\mathcal{B}(B \to V\gamma) \sim 1 + (R/L)^2 \qquad S_V\gamma \sim R/L$$

Look at all possible observables ! Do not get discouraged by $\mathcal{B}(b- > X_s)_{\rm incl}$!