The On-Shell Story

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ERC Ideas: NPFlavour

INFN, Sezione di Roma. Roma, Italy.

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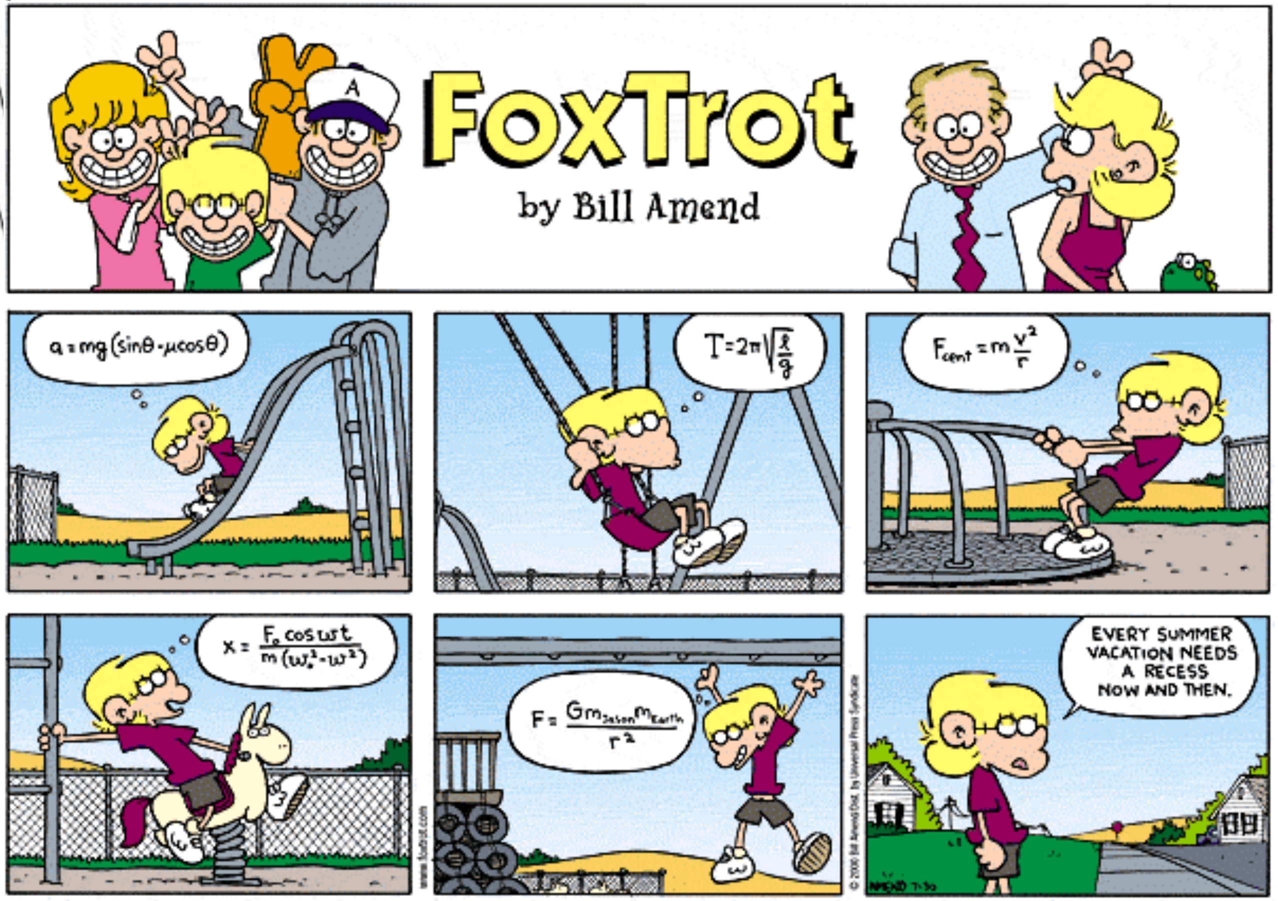
Elba. May 30th 2017.

the most complicated calculation ...

vs.



summary

- ✓ the matter covered here is less general than advertised
- ✓ I will mostly cover asymmetries and branching fractions of exclusive decays (honorary mention of some inclusive channels too…)
- ✓ my survey of literature will be limited
- ✓ my survey of numerical results will be limited
- ✓ I will shamelessly promote `HEPfit` and how we can extract hadronic uncertainties from data
- ✓ I will also promote flavio and send the bill to the developer later
- ✓ I will discuss mostly SM with honorary mentions of extension to BSM
- ✓ I do not qualify as an expert in QCD, yet…

some details...

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

$$a_{7L}^{c,u} = C_7 + O(\alpha_s, 1/m_b) \qquad a_{7R}^{c} = \frac{m_s}{m_b} C_7 + O\left(\frac{1}{m_b}, \frac{\alpha_s}{m_b}\right)$$

- ✓ the leading order in expansion is factorized and a pure short distance contribution
- ✓ the contributions at $1/m_b$ do not factorize and are commonly classified as power correction estimated using various techniques
- ✓ the right handed contribution from the SM is helicity suppressed but is the essential ingredient for the non-zero value of certain observables like the mixing induced photon polarization asymmetries.
- ✓ a priori, there is no reason why this suppression should be manifest in new dynamics

$$\bar{\mathcal{A}}_{L(R)} \equiv \frac{G_F}{\sqrt{2}}\left(\lambda_u a_{7L(R)}^u + \lambda_c a_{7L(R)}^c\right)\langle \bar{K}^* \gamma_{L(R)} | Q_7^{L(R)} | \bar{B}\rangle$$

$$\boxed{\lambda_u \sim \lambda^4} \quad \boxed{\lambda_c \sim \lambda^2}$$

$$\langle \bar{K}^*(p,\eta)\gamma_{L(R)}(q,e)|Q_7^{L(R)}|\bar{B}\rangle \equiv -\frac{e}{2\pi^2} m_b T_1^{B\to K^*}(0) S_{L(R)}$$

in addition to branching fractions...

$$A_{\mathrm{CP}}(B_q(t) \to V\gamma) = \frac{\Gamma(\bar{B}_q(t) \to \bar{V}\gamma) - \Gamma(B_q(t) \to V\gamma)}{\Gamma(\bar{B}_q(t) \to \bar{V}\gamma) + \Gamma(B_q(t) \to V\gamma)} = \frac{S(B_q \to V\gamma)\sin(\Delta M_q t) + A_{\mathrm{CP}}(B_q \to V\gamma)\cos(\Delta M_q t)}{\cosh(y_q t/\tau_{B_q}) - A_{\Delta\Gamma}(B_q \to V\gamma)\sinh(y_q t/\tau_{B_q})}$$

$$\overline{\mathrm{BR}}(B_s \to \phi\gamma) = \left[\frac{1 - A_{\Delta\Gamma}(B_s \to \phi\gamma)\, y_s}{1 - y_s^2}\right] \mathrm{BR}(B_s \to \phi\gamma)$$

$$A_{CP} = \frac{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) - \Gamma(B^0(t) \to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) + \Gamma(B^0(t) \to K^{*0}\gamma)} = S\sin(\Delta m_B t) - C\cos(\Delta m_B t)$$

$$\bar{\mathcal{A}}_{L(R)} = \mathcal{A}(\bar{B}^0 \to \bar{K}^{*0}\gamma_{L(R)}) \qquad \mathcal{A}_{L(R)} = \mathcal{A}(B^0 \to K^{*0}\gamma_{L(R)})$$

$$\boxed{S = \frac{2\,\mathrm{Im}\left(\frac{q}{p}(\mathcal{A}_L^*\bar{\mathcal{A}}_L + \mathcal{A}_R^*\bar{\mathcal{A}}_R)\right)}{|\mathcal{A}_L|^2 + |\mathcal{A}_R|^2 + |\bar{\mathcal{A}}_L|^2 + |\bar{\mathcal{A}}_R|^2}}$$

$$S^{\mathrm{SM},s_R} = -\sin(2\beta)\,\frac{m_s}{m_b}\,(2 + O(\alpha_s))$$

$$\boxed{C = \frac{|\mathcal{A}_L|^2 + |\mathcal{A}_R|^2 - |\bar{\mathcal{A}}_L|^2 - |\bar{\mathcal{A}}_R|^2}{|\mathcal{A}_L|^2 + |\mathcal{A}_R|^2 + |\bar{\mathcal{A}}_L|^2 + |\bar{\mathcal{A}}_R|^2}}$$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^*}{M_{12}}} = e^{-2i\beta}$$

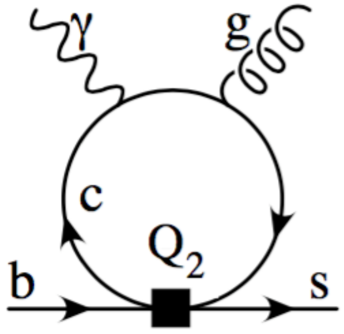
$$\boxed{S_{K^*\gamma}^{\mathrm{SM},m_s} = -2\sin 2\beta\frac{m_s}{m_b} = -0.0249 \pm 0.0016}$$

the charm loop

computation done with QCDF

A. Ali and A. Y. Parkhomenko, Eur. Phys. J. C **23** (2002) 89 [arXiv:hep-ph/0105302];
M. Beneke, T. Feldmann and D. Seidel, Eur. Phys. J. C **41** (2005) 173 [arXiv:hep-ph/0412400];
T. Becher, R. J. Hill and M. Neubert, Phys. Rev. D **72** (2005) 094017 [arXiv:hep-ph/0503263].

S. W. Bosch and G. Buchalla, Nucl. Phys. B **621** (2002) 459 [arXiv:hep-ph/0106081] and JHEP **0501** (2005) 035 [arXiv:hep-ph/0408231].



computation done with QCD sum rules

P. Ball and R. Zwicky, Phys. Lett. **B642**, 478 (2006), arXiv:hep-ph/0609037 [hep-ph].
A. Khodjamirian, R. Ruckl, G. Stoll, and D. Wyler, Phys. Lett. **B402**, 167 (1997), arXiv:hep-ph/9702318 [hep-ph].
M. B. Voloshin, Phys. Lett. **B397**, 275 (1997), arXiv:hep-ph/9612483 [hep-ph].

$$S^{\mathrm{SM},s_R} = -0.027 \pm 0.006(m_{s,b}) \pm 0.001(\sin(2\beta)) \qquad S^{\mathrm{SM,soft\ gluons}} = -2\sin(2\beta)\left(-\frac{C_2}{C_7}\frac{L-\tilde{L}}{36 m_b m_c^2 T_1^{B\to K^*}(0)}\right) = 0.005 \pm 0.01$$

$$\boxed{S^{\mathrm{SM}} = S^{\mathrm{SM},s_R} + S^{\mathrm{SM,soft\ gluons}} = -0.022 \pm 0.015^{+0}_{-0.01}}$$

computation done with pQCD sum rules on the light cone

M. Matsumori and A. I. Sanda, Phys. Rev. **D73**, 114022 (2006), arXiv:hep-ph/0512175 [hep-ph].

$$\boxed{S^{\mathrm{SM}}_{K^*\gamma} = -(3.5 \pm 1.7) \times 10^{-2}}$$

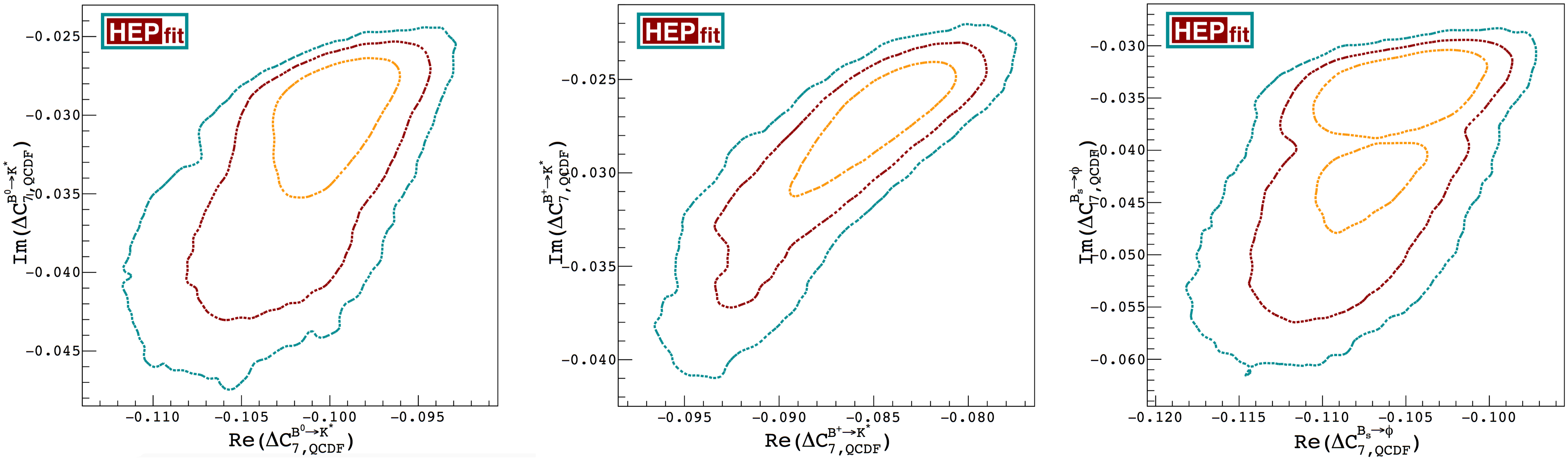
estimate using SCET

B. Grinstein and D. Pirjol, Phys. Rev. **D73**, 014013 (2006), arXiv:hep-ph/0510104 [hep-ph].
B. Grinstein, Y. Grossman, Z. Ligeti, and D. Pirjol, Phys. Rev. **D71**, 011504 (2005), arXiv:hep-ph/0412019 [hep-ph]

$$\boxed{S_{K^*\gamma} \sim 10\%}$$

leading QCDF corrections

Compare to C_7 = 0.3 in SM



68%
95%
99%

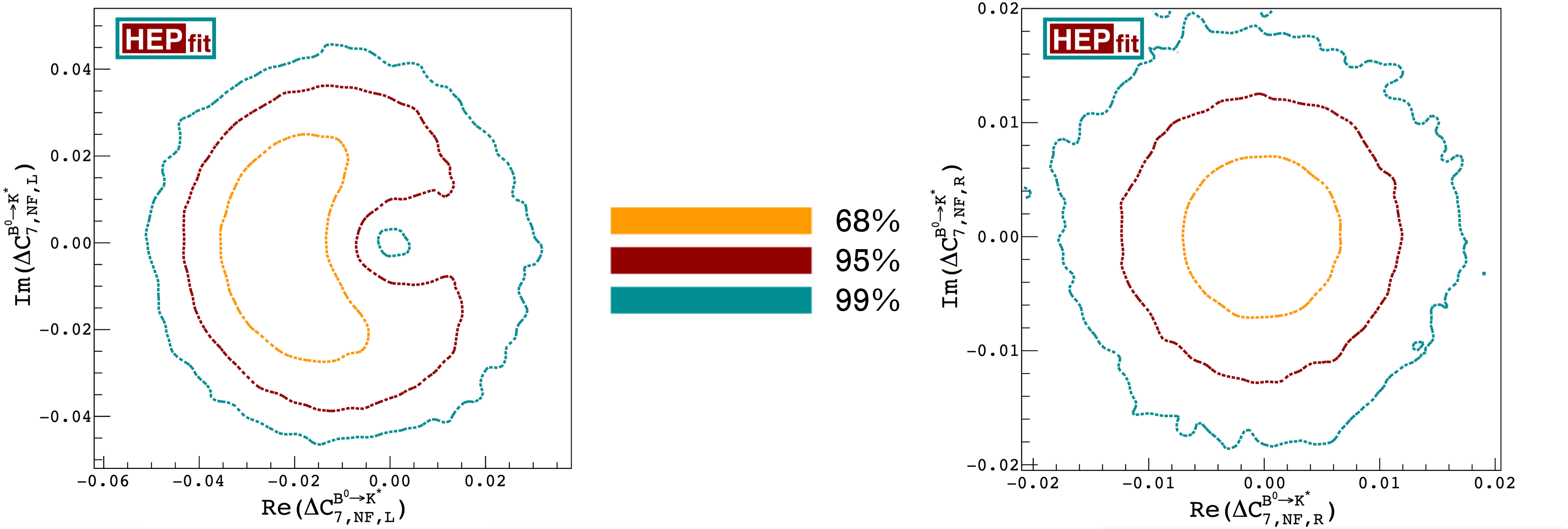
	$B^0 \to K^*\gamma$	$B^+ \to K^*\gamma$	$B_s \to \phi\gamma$
Vertex corrections		$-(7.8 \pm 1.0) - (1.1 \pm 0.3)i$	
Spectator scattering Q_{1-6}	$-0.7 - 1.3i$	$-0.7 - 1.3i$	$-0.7 - 1.7i$
Spectator scattering Q_8	-0.3	-0.3	-0.4
Weak annihilation	-0.4	$+0.9$	-0.5

Contributions to ΔC_7 in units of 10^{-2} for the three decays.

A. Paul, D.M. Straub, *"Constraints on new physics from radiative B decays"*, JHEP 1704 (2017) 027 [arXiv:1608.02556].

sub-leading non-factorizable corrections

Compare to C_7 = 0.3 in SM



$$C_7^{\rm eff} + \Delta C_7 = C_7^{\rm eff} + \frac{h_L}{T_1(0)}$$

$$h_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2}\int d^4x e^{iqx}\langle \bar{K}^*|T\{j^\mu_{\rm em}(x)\mathcal{H}_{\rm eff}^{\rm had}(0)\}|\bar{B}\rangle$$
$$= h_\lambda^{(0)} + q^2 h_\lambda^{(1)} + q^4 h_\lambda^{(2)}\,,$$

P. Ball, G. W. Jones, and R. Zwicky, *$B \to V\gamma$ beyond QCD factorisation*, *Phys. Rev.* **D75** (2007) 054004, [hep-ph/0612081].

F. Muheim, Y. Xie, and R. Zwicky, *Exploiting the width difference in $B_s \to \phi\gamma$*, *Phys. Lett.* **B664** (2008) 174–179, [arXiv:0802.0876].

A. Khodjamirian, T. Mannel, A. A. Pivovarov, and Y. M. Wang, *Charm-loop effect in $B \to K^{(*)}\ell^+\ell^-$ and $B \to K^*\gamma$*, *JHEP* **09** (2010) 089, [arXiv:1006.4945].

the form factors

LCSR:

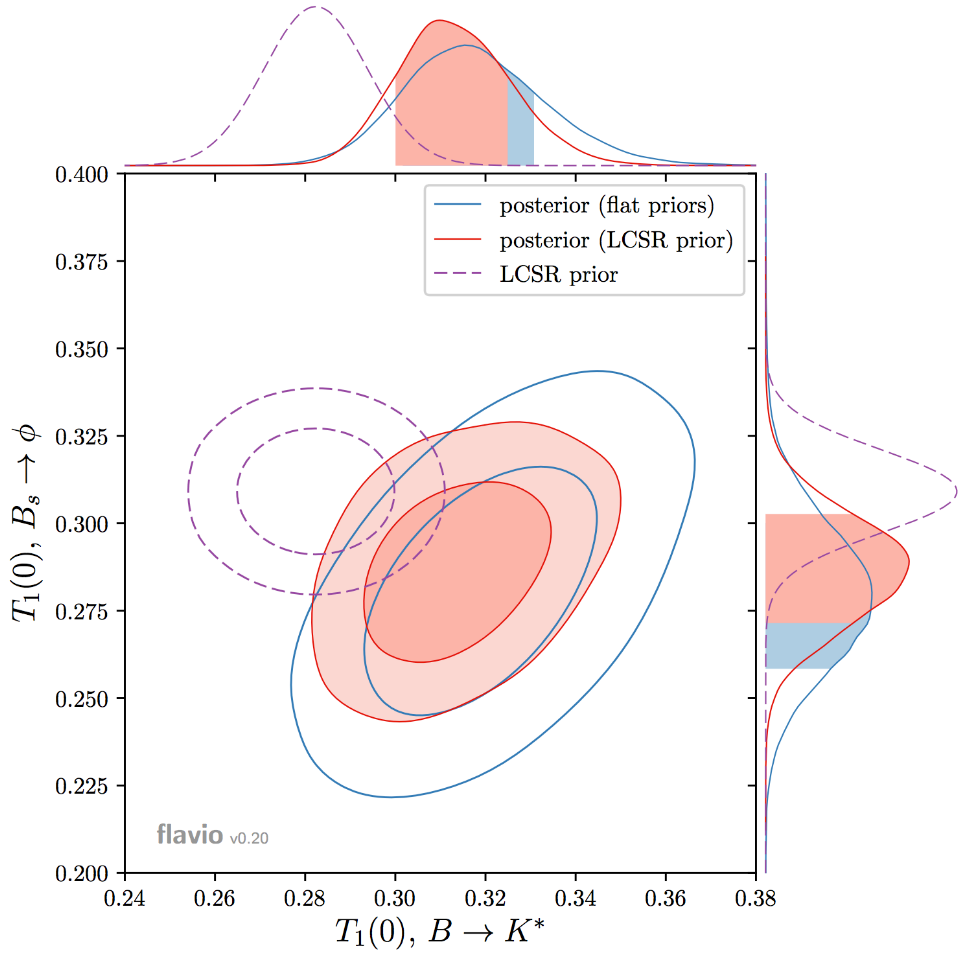
$$T_1(0) = 0.282 \pm 0.031 \qquad \text{for } B \to K^*\gamma\,,$$
$$T_1(0) = 0.309 \pm 0.027 \qquad \text{for } B_s \to \phi\gamma\,,$$

LCSR + Lattice:

$$T_1(0) = 0.312 \pm 0.027 \qquad \text{for } B \to K^*\gamma\,,$$
$$T_1(0) = 0.299 \pm 0.012 \qquad \text{for } B_s \to \phi\gamma\,.$$

fit to experimental data:

$$T_1(0) = 0.316^{+0.016}_{-0.015} \qquad \text{for } B \to K^*\gamma\,,$$
$$T_1(0) = 0.280^{+0.020}_{-0.022} \qquad \text{for } B_s \to \phi\gamma\,.$$



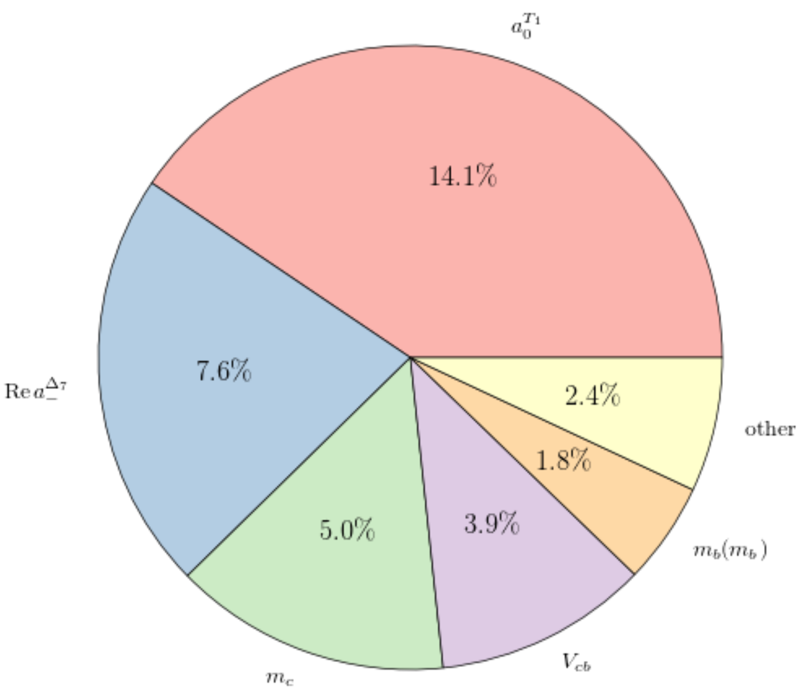
A. Paul, D.M. Straub, *"Constraints on new physics from radiative B decays"*, JHEP 1704 (2017) 027 [arXiv:1608.02556].

some experimental numbers

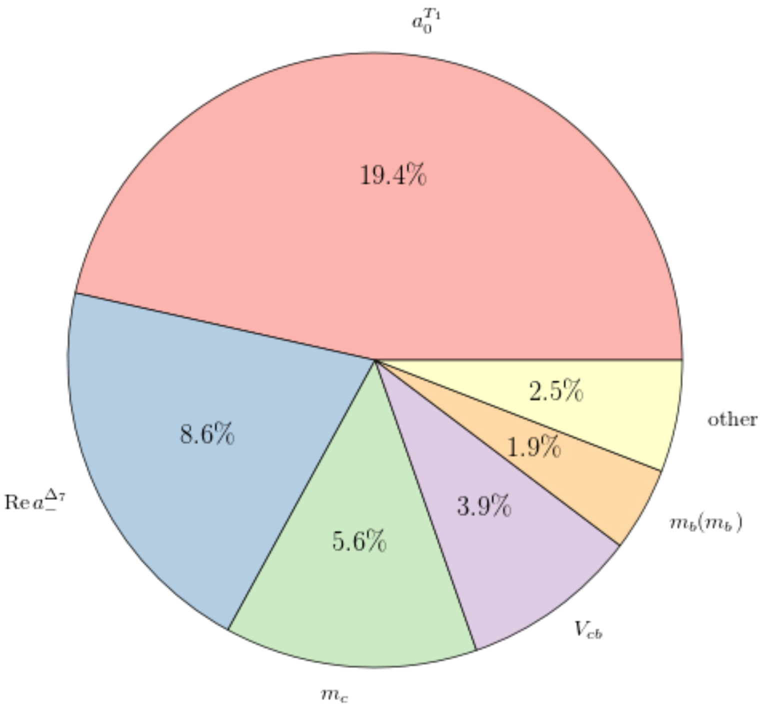
$10^4 \times \mathrm{BR}(B \to X_s\gamma)_{E_\gamma > 1.6\,\mathrm{GeV}}$	3.27 ± 0.14
$10^5 \times \mathrm{BR}(B^+ \to K^*\gamma)$	4.21 ± 0.18
$10^5 \times \mathrm{BR}(B^0 \to K^*\gamma)$	4.33 ± 0.15
$10^5 \times \overline{\mathrm{BR}}(B_s \to \phi\gamma)$	3.5 ± 0.4
$S(B^0 \to K^*\gamma)$	-0.16 ± 0.22
$A_{\mathrm{CP}}(B^0 \to K^*\gamma)$	-0.002 ± 0.015
$A_{\Delta\Gamma}(B_s \to \phi\gamma)$	-1.0 ± 0.5

error budget in the branching fractions

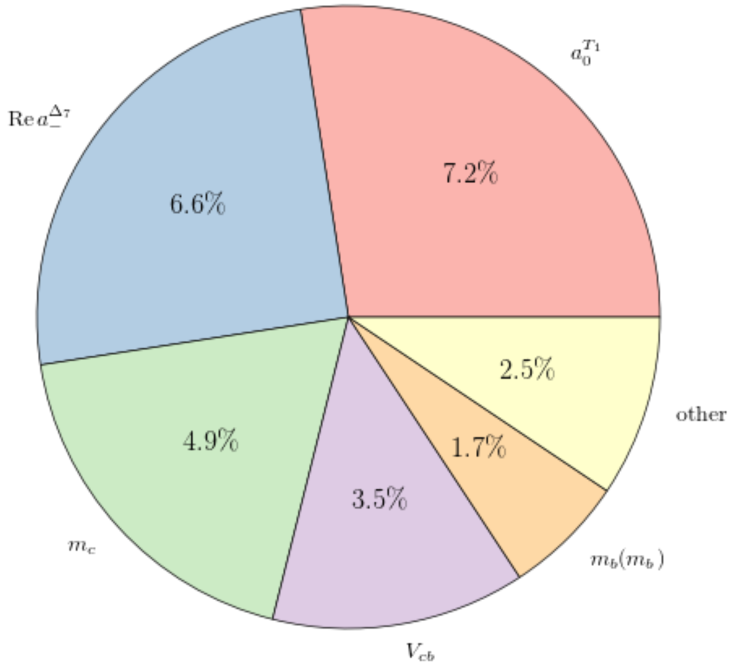
$BR(B^0 \to K^*\gamma) = 4.207\text{E-}05 \pm 9.095\text{E-}06$



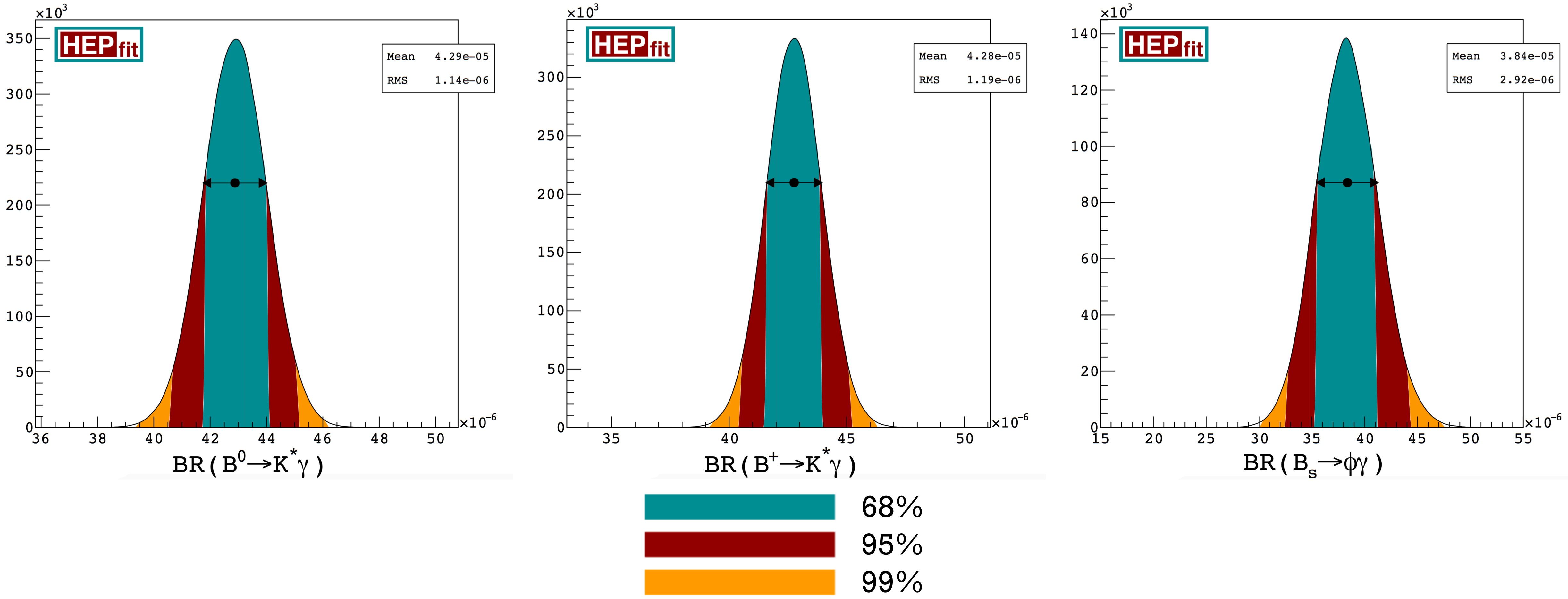
$BR(B^+ \to K^*\gamma) = 4.182\text{E-}05 \pm 8.703\text{E-}06$



$BR(B_s \to \phi\gamma) = 4.062\text{E-}05 \pm 5.171\text{E-}06$



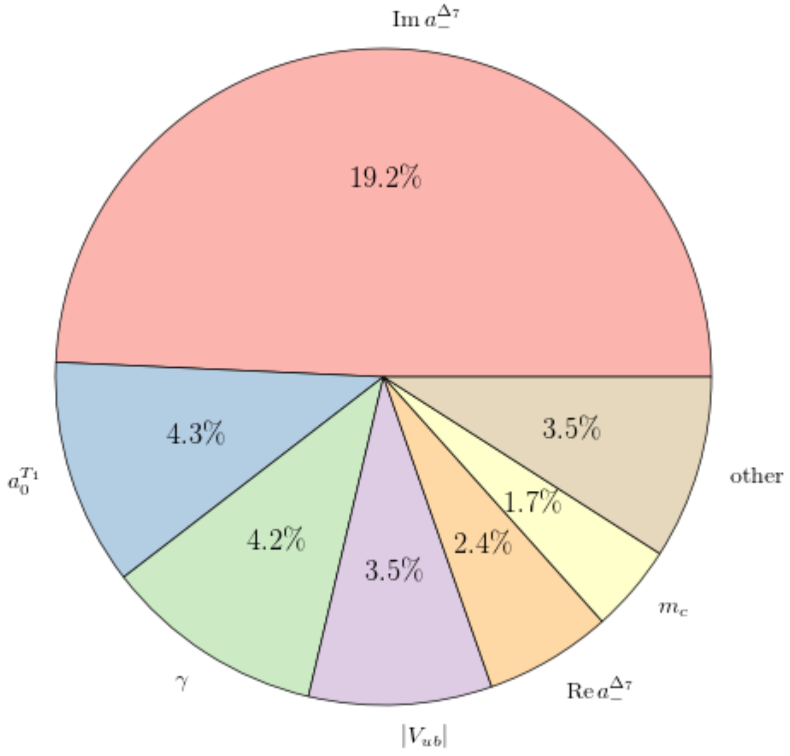
fit to the branching fractions measurements



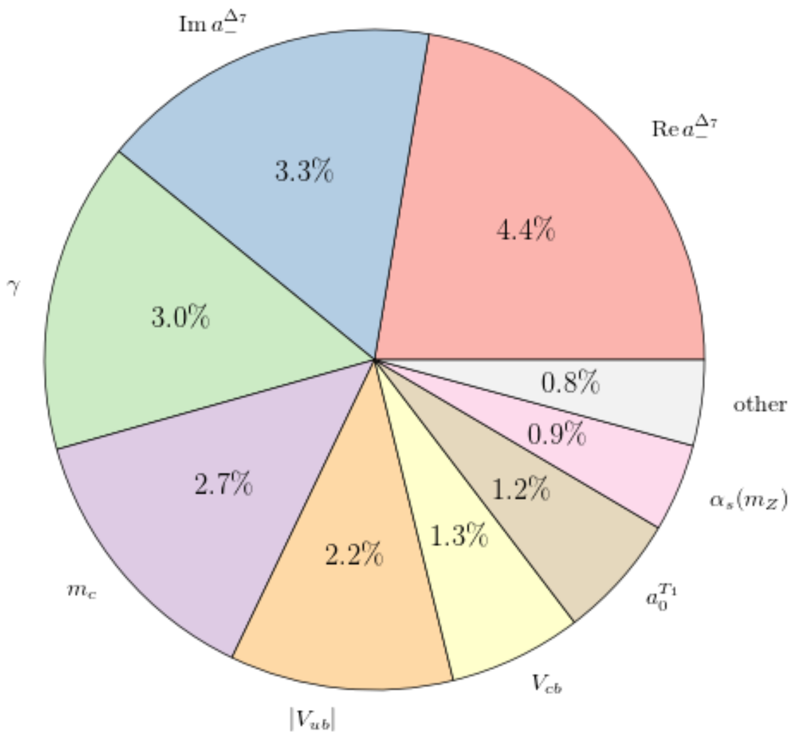
x-axis shows experimental mean +/- 5 s.d.

error budget in the CP asymmetries

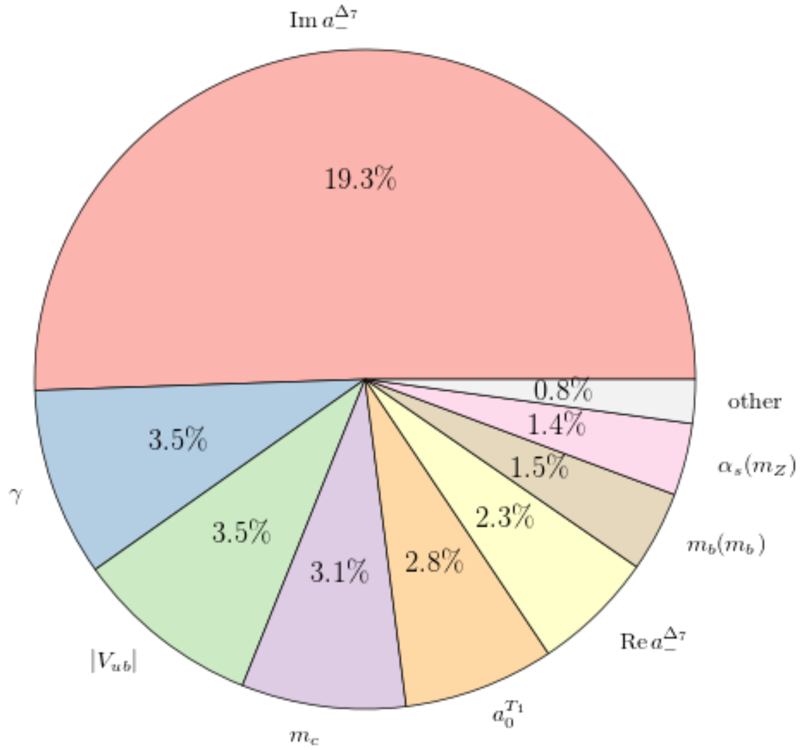
$A_{CP}(B^0 \to K^*\gamma) = 3.556\text{E-}03 \pm 6.986\text{E-}04$



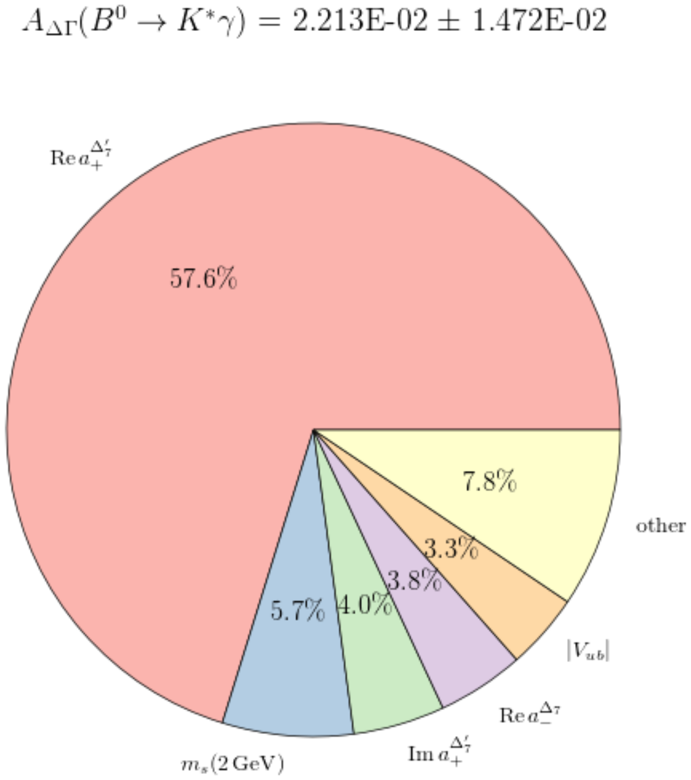
$A_{CP}(B^+ \to K^*\gamma) = 5.332\text{E-}03 \pm 4.308\text{E-}04$



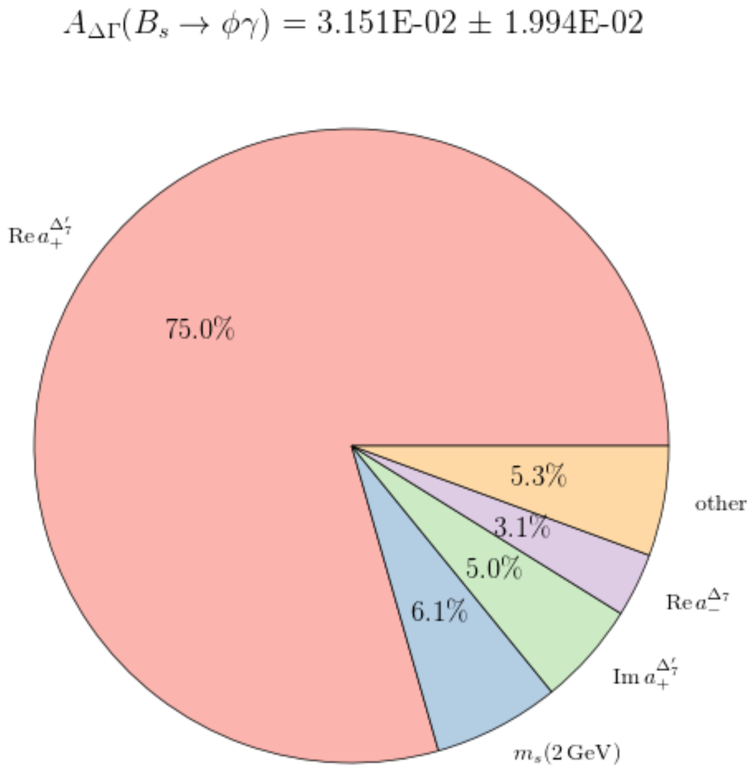
$A_{CP}(B_s \to \phi\gamma) = 3.016\text{E-}03 \pm 6.118\text{E-}04$



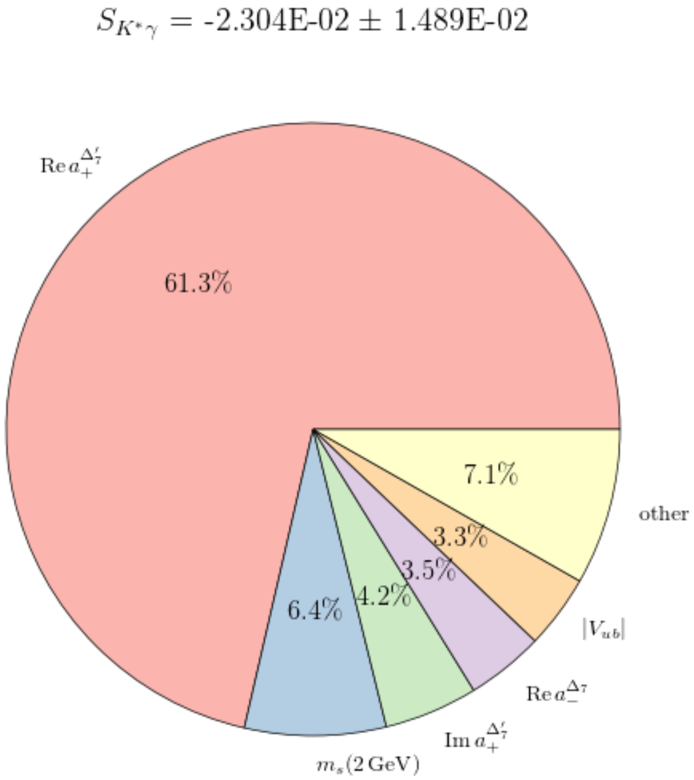
and finally...



$A_{\Delta\Gamma}(B^0 \to K^*\gamma)$ = 2.213E-02 ± 1.472E-02
$\mathrm{Re}\,a_+^{\Delta_7'}$
57.6%
7.8%
other
3.3%
3.8%
5.7%
4.0%
$|V_{ub}|$
$\mathrm{Re}\,a_-^{\Delta_7}$
$\mathrm{Im}\,a_+^{\Delta_7'}$
$m_s(2\,\mathrm{GeV})$



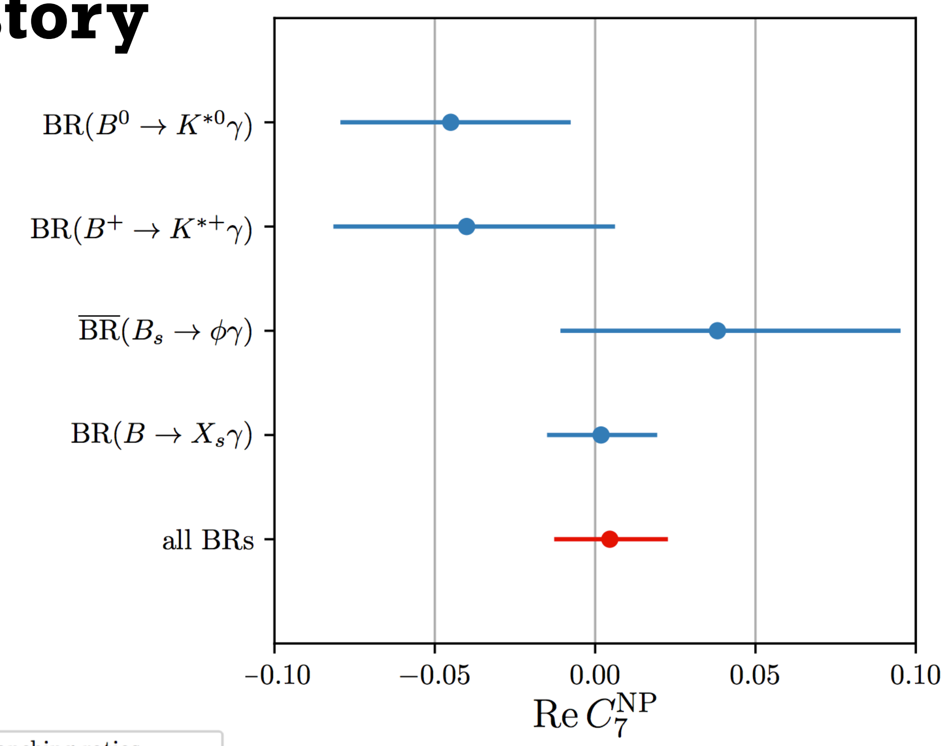
$A_{\Delta\Gamma}(B_s \to \phi\gamma)$ = 3.151E-02 ± 1.994E-02
$\mathrm{Re}\,a_+^{\Delta_7'}$
75.0%
5.3%
other
3.1%
5.0%
6.1%
$\mathrm{Re}\,a_-^{\Delta_7}$
$\mathrm{Im}\,a_+^{\Delta_7'}$
$m_s(2\,\mathrm{GeV})$



$S_{K^*\gamma}$ = -2.304E-02 ± 1.489E-02
$\mathrm{Re}\,a_+^{\Delta_7'}$
61.3%
7.1%
other
3.3%
3.5%
4.2%
6.4%
$|V_{ub}|$
$\mathrm{Re}\,a_-^{\Delta_7}$
$\mathrm{Im}\,a_+^{\Delta_7'}$
$m_s(2\,\mathrm{GeV})$

the new physics story

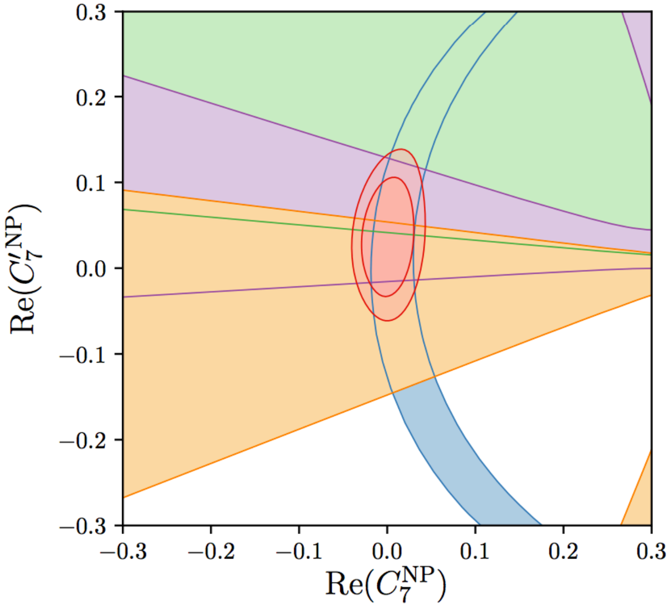
$$\mathrm{Re}\, C_7^{\mathrm{NP}}(\mu_b) \in \begin{cases} [-0.018, 0.012] & @\ 1\sigma, \\ [-0.032, 0.027] & @\ 2\sigma, \end{cases}$$

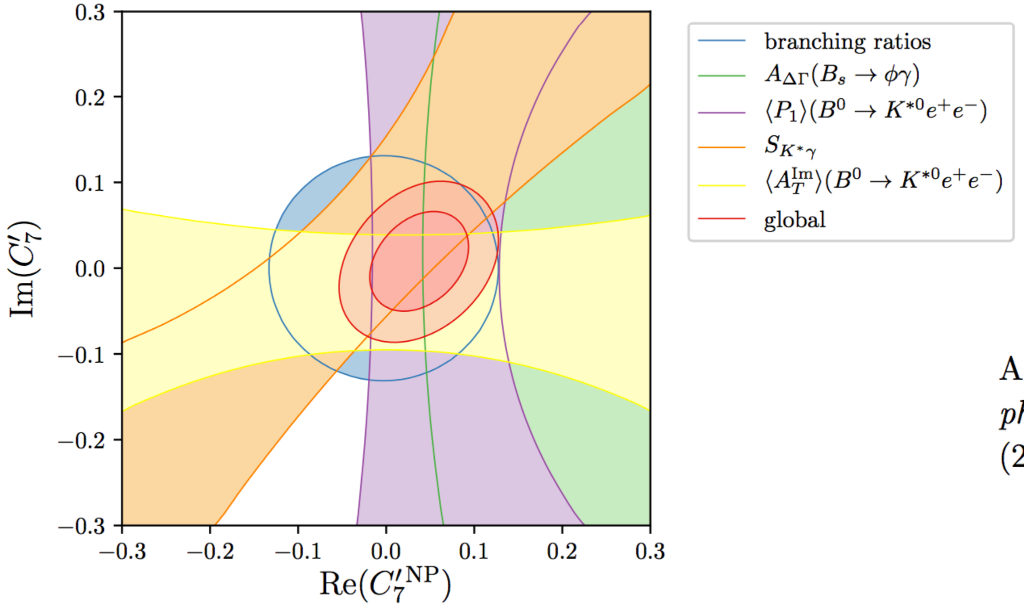


$$\mathrm{Im}\, C_7^{\mathrm{NP}}(\mu_b) \in [-0.064, 0.094] \times \left[\frac{-0.027}{\mathrm{Im}\,\Delta C_7}\right] \qquad @\ 95\%\ \text{C.L.} \quad \text{from } A_{\mathrm{CP}}(B \to K^*\gamma)$$

$$\begin{pmatrix} \mathrm{Re}\, C_7^{\prime\mathrm{NP}}(\mu_b) \\ \mathrm{Im}\, C_7^{\prime}(\mu_b) \end{pmatrix} = \begin{pmatrix} 0.018 \pm 0.037 \\ 0.001 \pm 0.037 \end{pmatrix}, \qquad \rho = 0.34 \qquad (\text{without } A_{\Delta\Gamma}),$$

$$\begin{pmatrix} \mathrm{Re}\, C_7^{\prime\mathrm{NP}}(\mu_b) \\ \mathrm{Im}\, C_7^{\prime}(\mu_b) \end{pmatrix} = \begin{pmatrix} 0.038 \pm 0.035 \\ 0.006 \pm 0.036 \end{pmatrix}, \qquad \rho = 0.29 \qquad (\text{with } A_{\Delta\Gamma}),$$





A. Paul, D.M. Straub, *"Constraints on new physics from radiative B decays"*, JHEP 1704 (2017) 027 [arXiv:1608.02556].

questions for the future upgrade

- ✓ Can measurements of photon polarization be made at O(SM) or better?
- ✓ What can be done that Belle II cannot do, maybe baryonic modes?
- ✓ If NP is not yet found, what can be done to constrain parametrizations of long distance effects?

Thank you…!!

To my Mother and Father, who showed me what I could do,

and to Ikaros, who showed me what I could not.

“To know what no one else does, what a pleasure it can be!”

– adopted from the words of

Eugene Wigner.