Radiative and Semileptonic rare *B* decays

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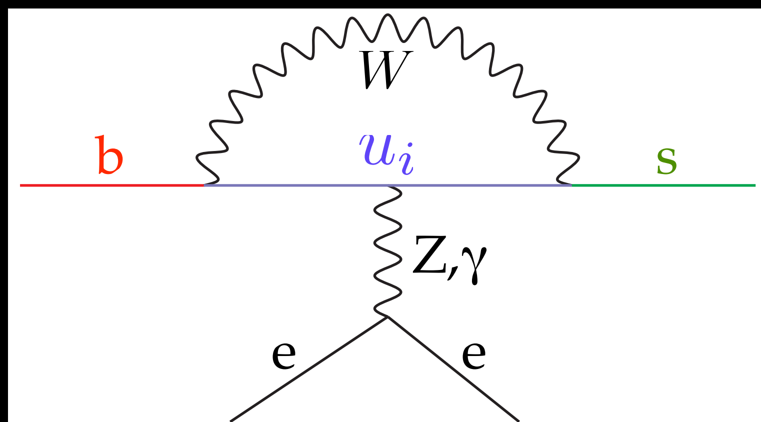
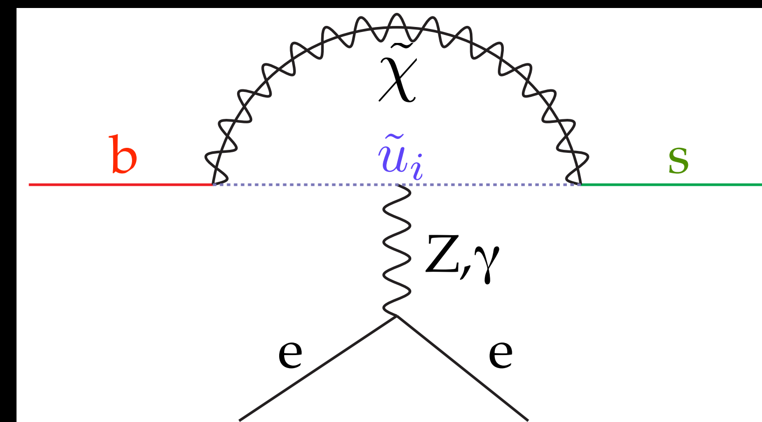
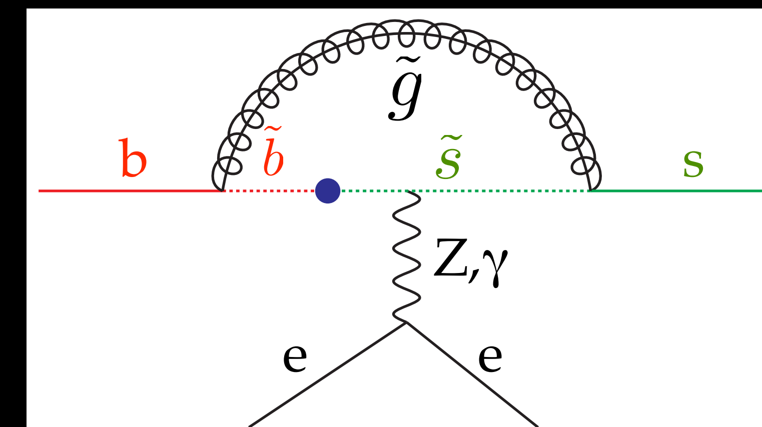
Outline

- Introduction
- Inclusive: $B \to X_{d,s}\gamma$ and $B \to X_s \ell^+ \ell^-$
- Exclusive: $B \to (K^*, \rho, \omega)\gamma$ and $B \to (K, K^*)\ell^+ \ell^-$
- Outlook

What can we learn?

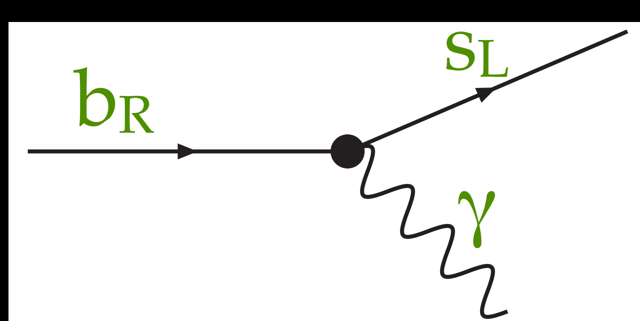




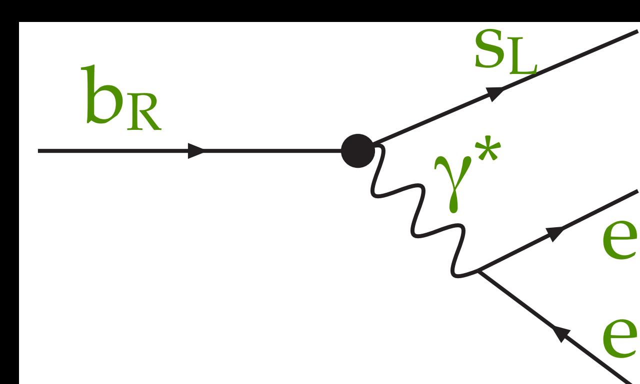


SM	MFV	generic
$V_{tb} V_{ts}$	$V_{tb} V_{ts}$	δ_{bs}
	mass scale	mass scale

- Complementarity between $b \to s\gamma$ and $b \to s\ell^+\ell^-$:



vs



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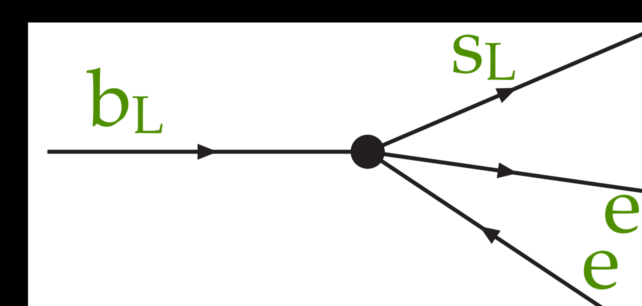
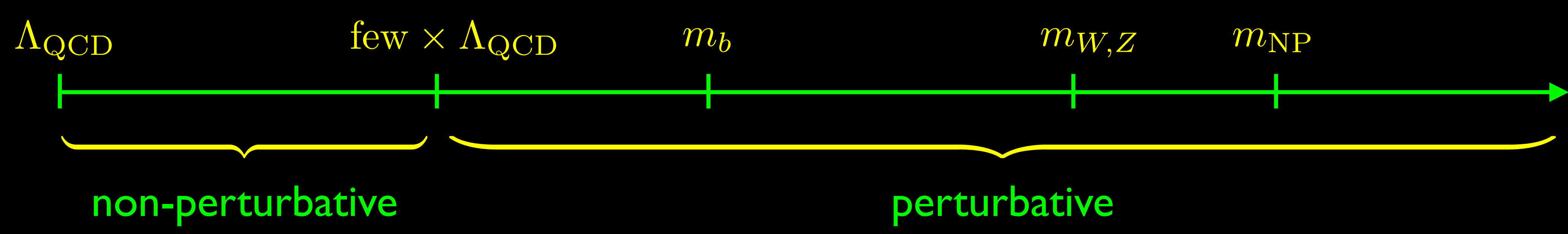


Effective Lagrangian

$$\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \left[\sum_{i=1}^{10} C_i Q_i + \frac{V_{ub} V_{uq}^*}{V_{tb} V_{tq}^*} \sum_{i=1}^{2} C_i (Q_i - Q_i^u) + \underbrace{\sum_{i=3}^{6} C_{iQ} Q_{iQ} + C_b Q_b}_{\text{for QED corrections}} \right]$$



$$\begin{aligned} Q_1 &= (\bar{q}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \\ Q_2 &= (\bar{q}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L) \end{aligned}$$

$$\begin{aligned} Q_1^u &= (\bar{q}_L \gamma_\mu T^a u_L)(\bar{c}_L \gamma^\mu T^a b_L) \\ Q_2^u &= (\bar{q}_L \gamma_\mu u_L)(\bar{c}_L \gamma^\mu b_L) \end{aligned}$$

$$\begin{aligned} Q_7 &= \frac{e}{16\pi^2} m_b (\bar{q}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} \\ Q_8 &= \frac{g}{16\pi^2} m_b (\bar{q}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu} \end{aligned}$$

$$\begin{aligned} Q_3 &= (\bar{q}_L \gamma_\mu b_L) \sum (\bar{q} \gamma^\mu q) \\ Q_4 &= (\bar{q}_L \gamma_\mu T^a b_L) \sum (\bar{q} \gamma^\mu T^a q) \\ Q_5 &= (\bar{q}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} b_L) \sum (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} q) \\ Q_6 &= (\bar{q}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} T^a b_L) \sum (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} T^a q) \end{aligned}$$

$$\begin{aligned} Q_9 &= (\bar{q}_L \gamma_\mu b_L) \sum (\bar{\ell} \gamma^\mu \ell) \\ Q_{10} &= (\bar{q}_L \gamma_\mu b_L) \sum (\bar{\ell} \gamma^\mu \gamma_5 \ell) \end{aligned}$$

Inclusive channels

General considerations

$$\Gamma\left[\bar{B}\to X_s(\gamma,\ell^+\ell^-)\right]=\Gamma\left[\bar{b}\to X_s(\gamma,\ell^+\ell^-)\right]+O\left(\frac{\Lambda^2_{QCD}}{m_b^2},\frac{\Lambda^2_{QCD}}{m_c^2},\ldots\right)$$

local OPE, optical theorem
quark-hadron duality

HQET

Phase space cuts introduce sensitivity to new scales, the rate becomes less inclusive and new non-perturbative effects appear

(I) $E_\gamma > E_0 = [1.7, 2.0]\mathrm{GeV}$ to suppress backgrounds: *simple OPE, SCET, DGE*

(II) $q^2=(p_{\ell^+}+p_{\ell^-})^2$ cuts to remove $c\bar{c}$ resonances. OPE breaks down at $q^2\sim m_b^2$. In the high q^2 region expansion parameter is $\Lambda_{QCD}/(m_b-\sqrt{q^2})$

(III) $M_{X_s} < [1.8, 2]\mathrm{GeV}$ to remove $b\to c\ell^-\bar{\nu}\to s\ell^-\ell^+\bar{\nu}\nu$ background: Fermi motion, SCET

Status of $B \to X_s \gamma$

- Present status:

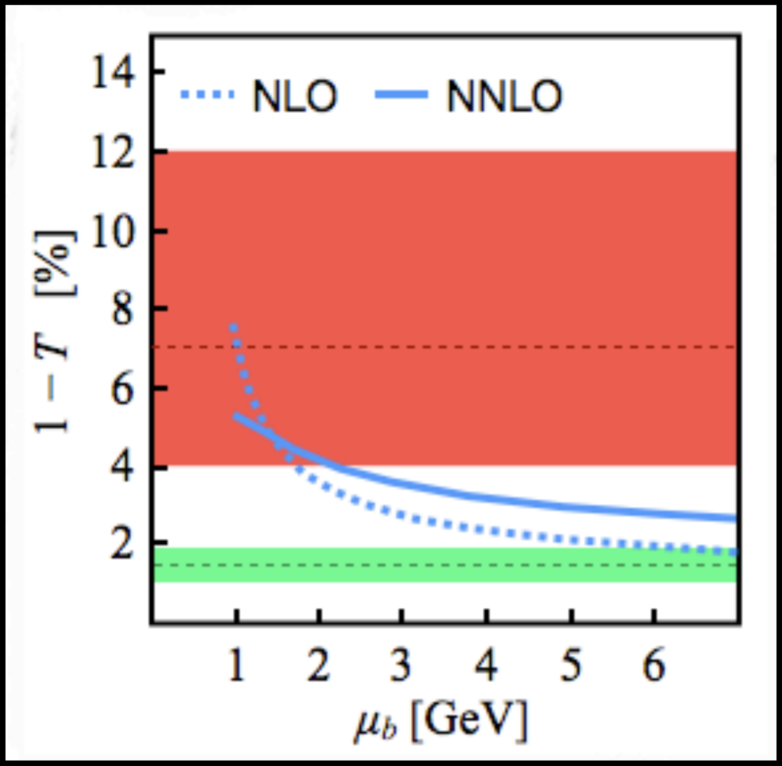
$$1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha_e) + \mathcal{O}\left(\frac{\Lambda^2}{m_b^2}\right) + \mathcal{O}\left(\frac{\Lambda^2}{m_c^2}\right) + \mathcal{O}\left(\alpha_s \frac{\Lambda}{m_b}\right)$$

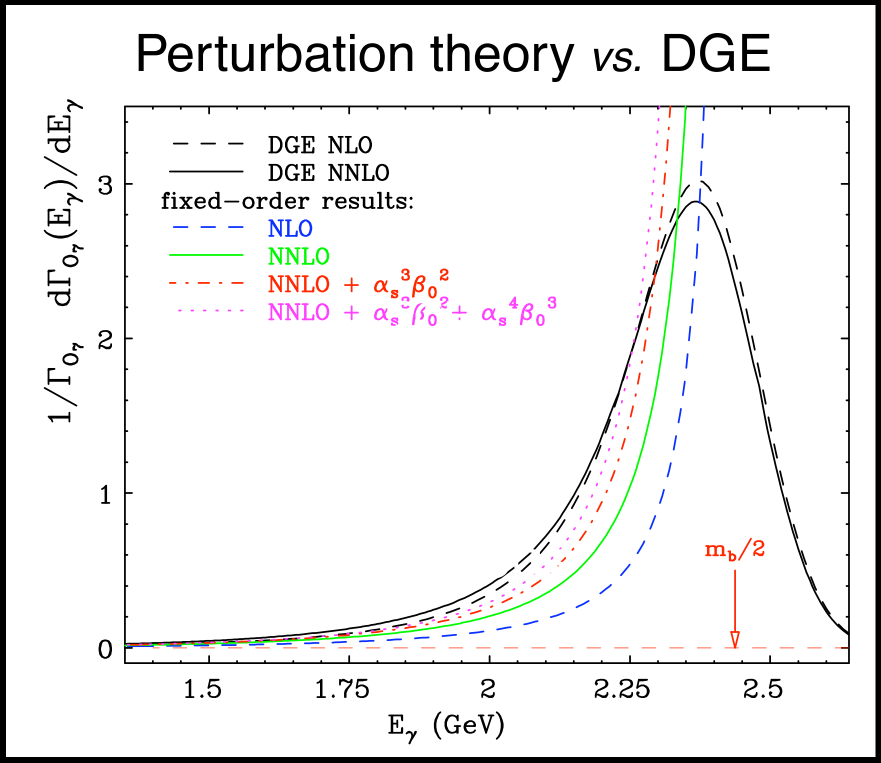
30% *10%* *5%* *1%* *3%* *O(5%)*

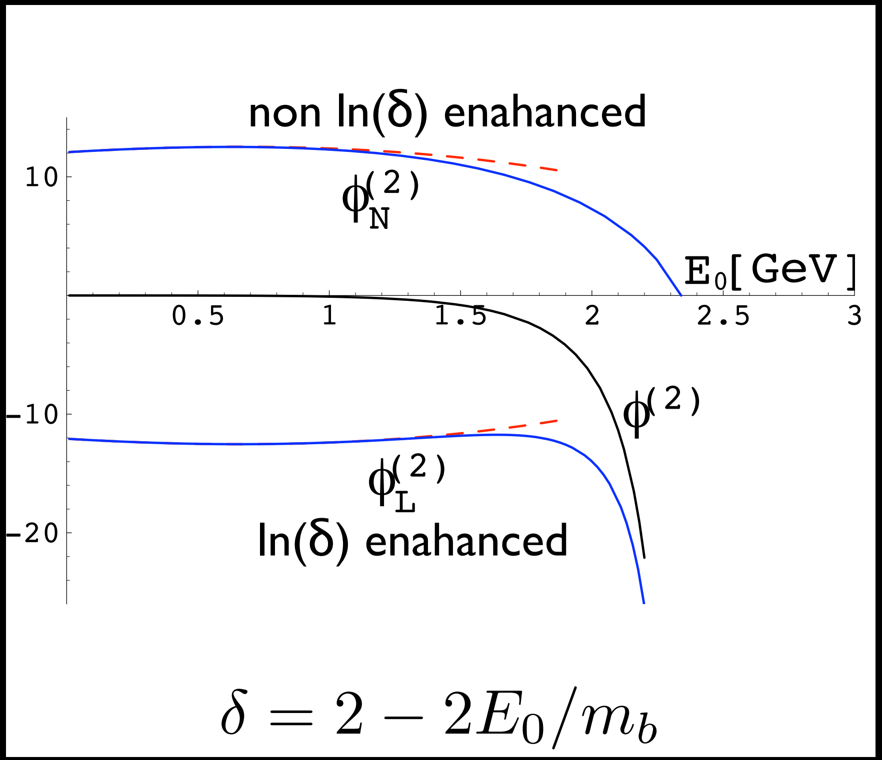
- For $E_\gamma > E_0 = 1\mathrm{GeV}$ the OPE is trusted

- $T = \dfrac{\Gamma(E_\gamma > 1.6\ \mathrm{GeV})}{\Gamma(E_\gamma > 1\ \mathrm{GeV})} = \begin{cases} 0.96 \pm 0.01 \\ 0.93^{+0.03}_{-0.05} \pm 0.02 \pm 0.02 \\ 0.0984 \pm 0.003 \end{cases}$

0.96 ± 0.01	OPE	[Misiak et al.]
$0.93^{+0.03}_{-0.05} \pm 0.02 \pm 0.02$	SCET	[Becher, Neubert]
0.0984 ± 0.003	DGE	[Andersen, Gardi]







$B \to X_{d,s}\gamma$: SM predictions

- *b→s*

$$\mathrm{BR}(B \to X_s\gamma)^{E_\gamma > 1.6\ \mathrm{GeV}}_{\mathrm{SM}} = \begin{cases} (3.15 \pm 0.23) \times 10^{-4} \\ (2.98 \pm 0.26) \times 10^{-4} \end{cases}$$

[Misiak et al.]
[Becher, Neubert]

$$\mathrm{BR}(B \to X_s\gamma)^{E_\gamma > 1.6\ \mathrm{GeV}}_{\mathrm{exp}} = (3.52 \pm 0.25) \times 10^{-4}$$

[CLEO, BaBar, Belle]

$$A_{\mathrm{CP}}(B \to X_s\gamma)_{\mathrm{SM}} = (0.4 \pm 0.2)\ \%$$

[Hurth,EL,Porod]

$$A_{\mathrm{CP}}(B \to X_s\gamma)_{\mathrm{exp}} = (12 \pm 30 \pm 18)\ \%$$

[BaBar]

- *b→d*

$$\mathrm{BR}(B \to X_d\gamma)^{E_\gamma > 1.6\ \mathrm{GeV}}_{\mathrm{SM}} = (1.36 \pm 0.25) \times 10^{-6}$$

[Hurth,EL,Porod]

$$\begin{aligned}\mathrm{BR}(B \to X_d\gamma)^{E_\gamma > 1.6\ \mathrm{GeV}}_{\mathrm{exp}} &= (0.033 \pm 0.016) \times \mathrm{BR}(B \to X_s\gamma) \\ &= (11.6 \pm 5.7) \times 10^{-6}\end{aligned}$$

[BaBar]

$$A_{\mathrm{CP}}(B \to X_d\gamma)_{\mathrm{SM}} = -(10.2 \pm 4.6)\ \%$$

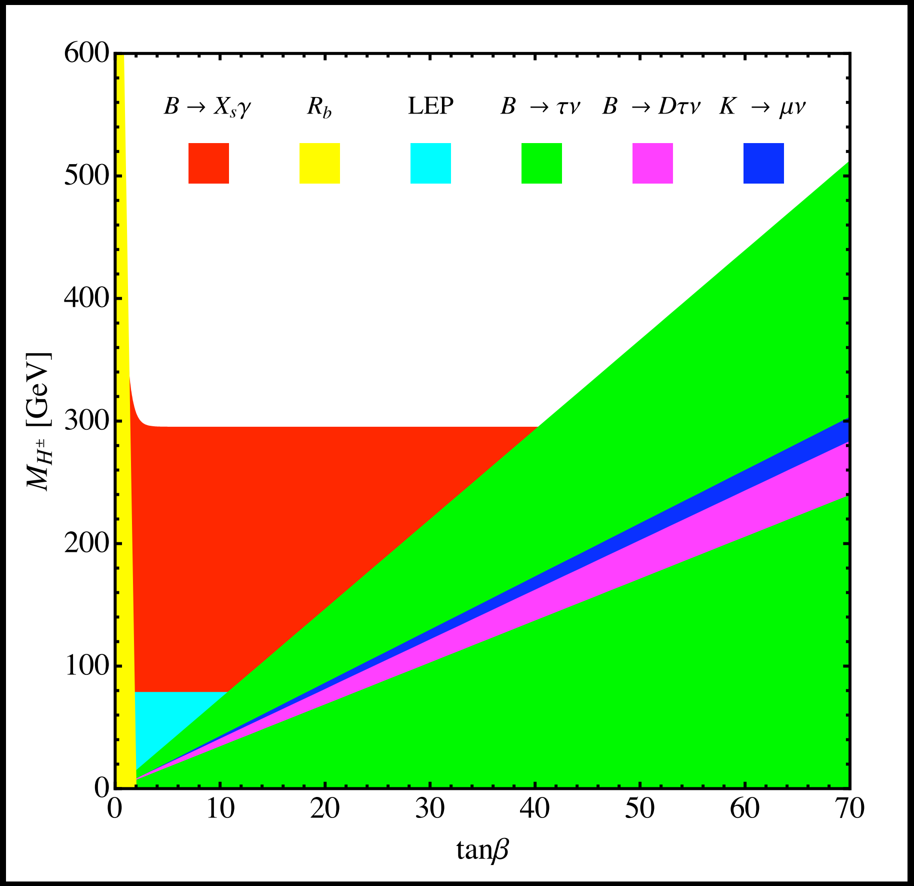
[Hurth,EL,Porod]

- *b→d/s (untagged)*

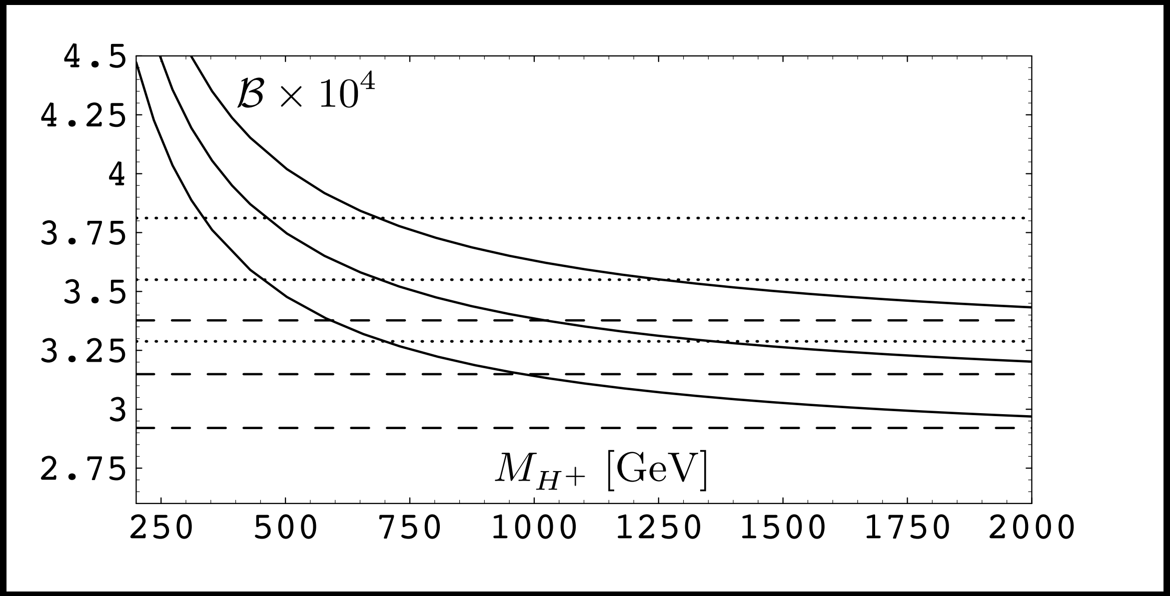
$$A_{\mathrm{CP}}(B \to X_{d,s}\gamma)_{\mathrm{SM}} = \frac{A_{CP}^{b\to s\gamma} + \frac{\Gamma_d}{\Gamma_s} A_{CP}^{b\to d\gamma}}{1 + \Gamma_d/\Gamma_s} \sim 0$$

$B \to X_s\gamma$: impact on NP

- Two Higgs Doublet Model



[Haisch]

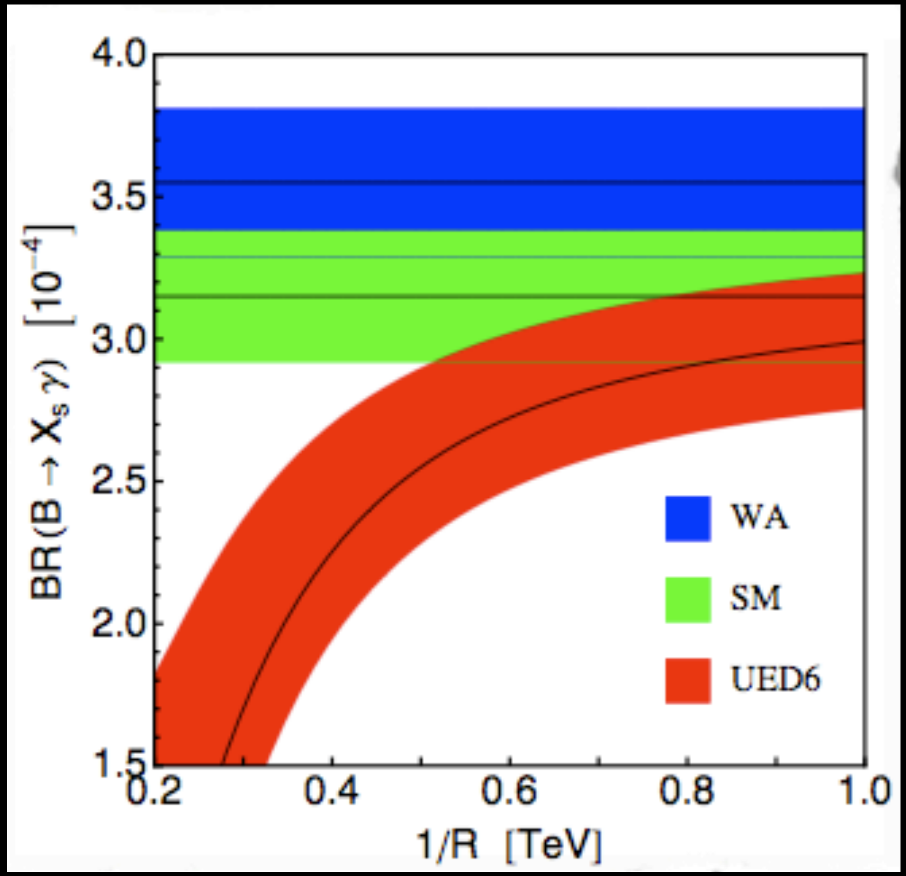


[Misiak et al.]

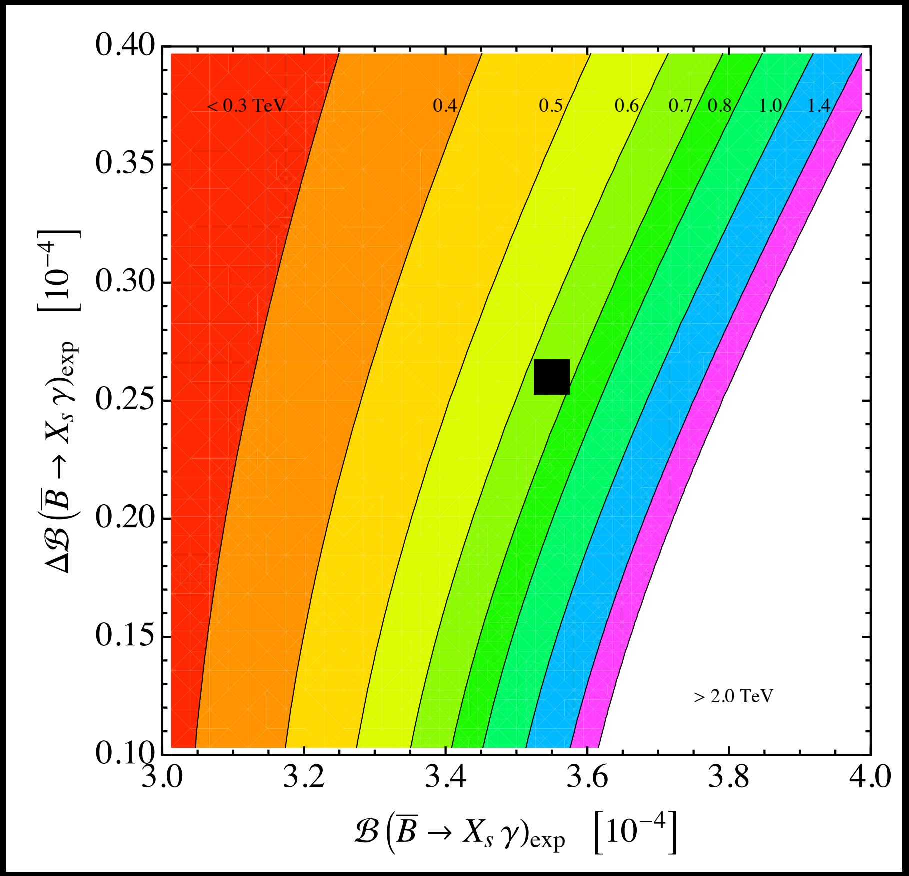
- M_{H+} > 300 GeV
- largely independent of tan(β)
- positive interference between SM and $H^\pm$ contributions

$B \to X_s\gamma$: impact on NP

- Two Universal Extra Dimension



[Haisch, Freitas]

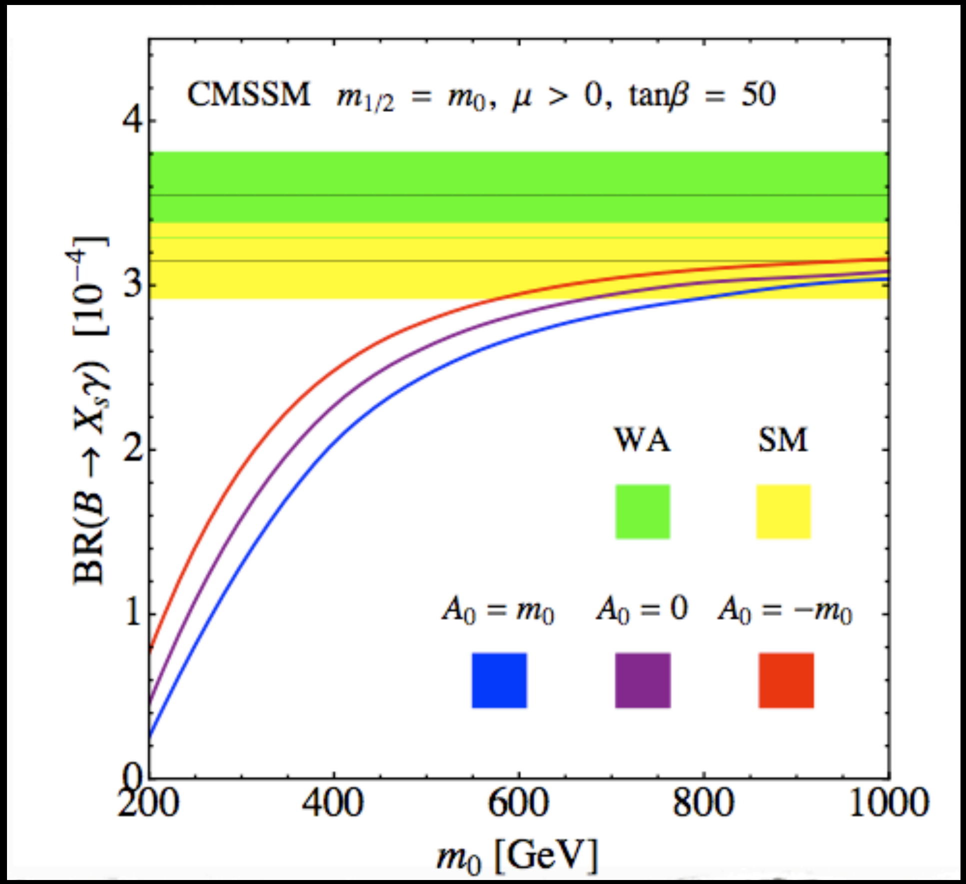


[Haisch, Freitas]

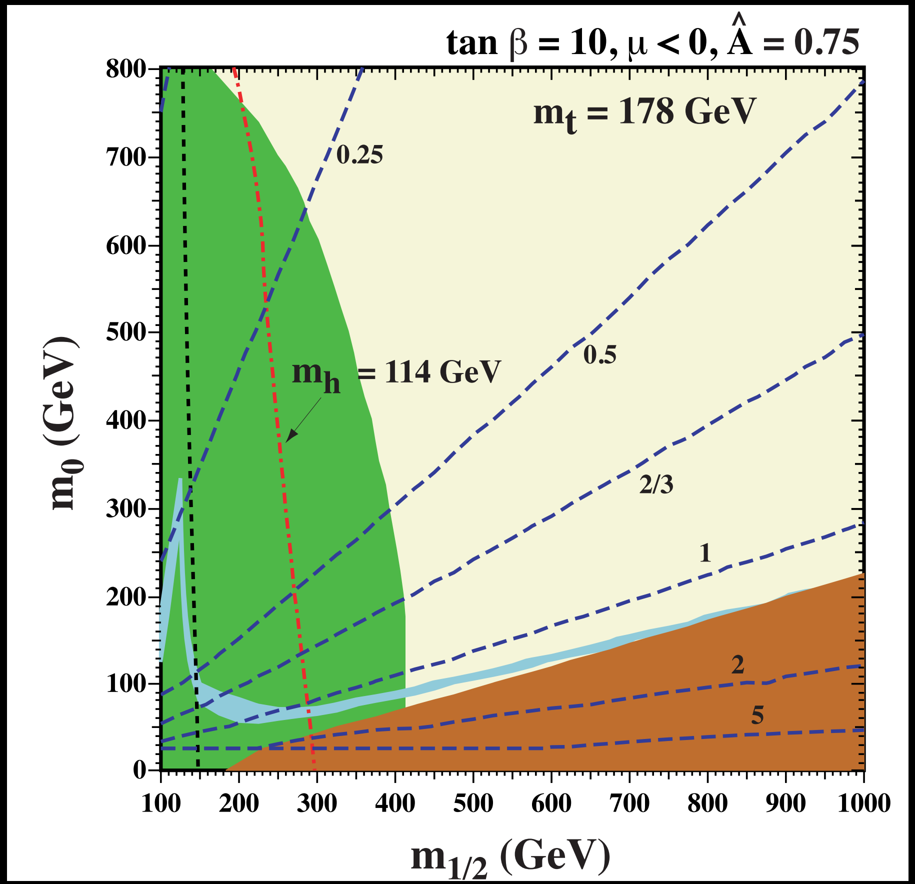
- BR is always suppressed with respect to the SM
- Bound on compactification scale: $R^{-1} > 650$ GeV
- Dark matter constrain favors $R^{-1} < 600$ GeV

$B \to X_s\gamma$: impact on NP

- Flavor blind MSSM



[Straub; Olive, Velasco-Sevilla]



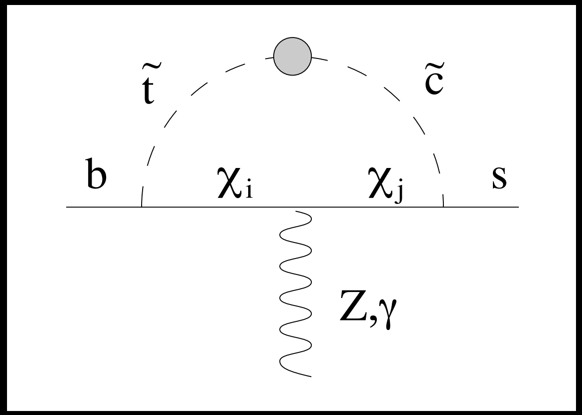
[Ellis et al.]

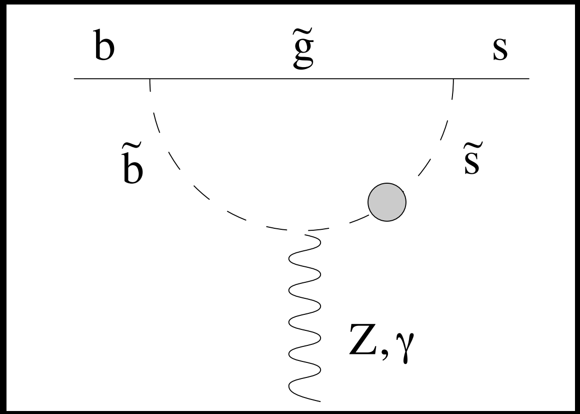
- Relative sign of $\chi^{\pm}$ and $H^{\pm}$ contributions is $-\mathrm{sign}(\mu)$
- Strength of constrain varies over the parameter space

$B \to X_s\gamma$: impact on NP

- Most general MSSM
- Parametrize non-minimal sources of flavor violation in terms of mass insertions in the squark mass matrices

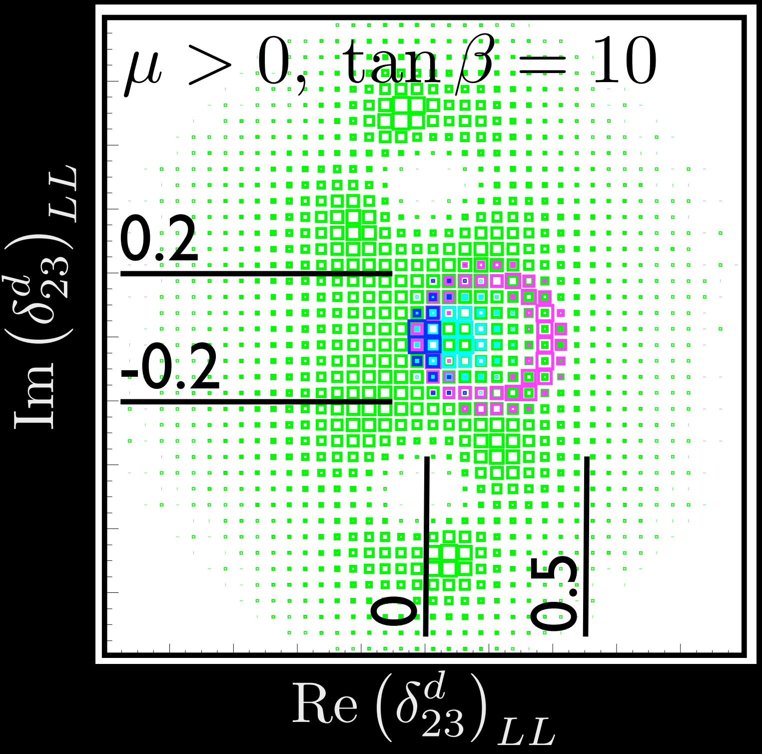
$$\left(\delta_{23}^{u,d}\right)_{AB} = \frac{\left(m_{23}^{u,d}\right)^2_{AB}}{M_{\rm sq}^2}$$

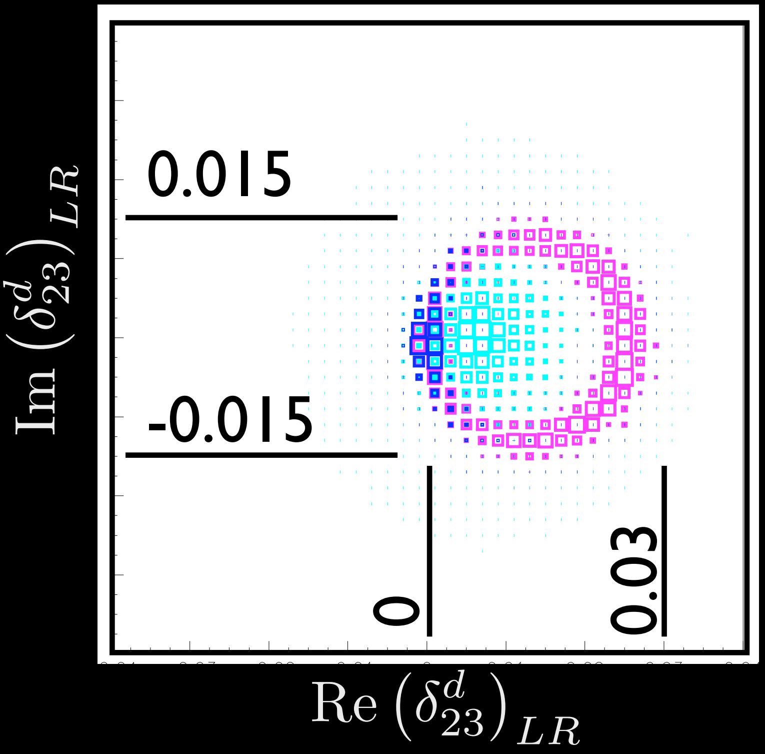




- Constraints on LR insertions at the 10^{-3} level because of chiral enhancement ($m_{\tilde{g},\chi^\pm}/m_b$)

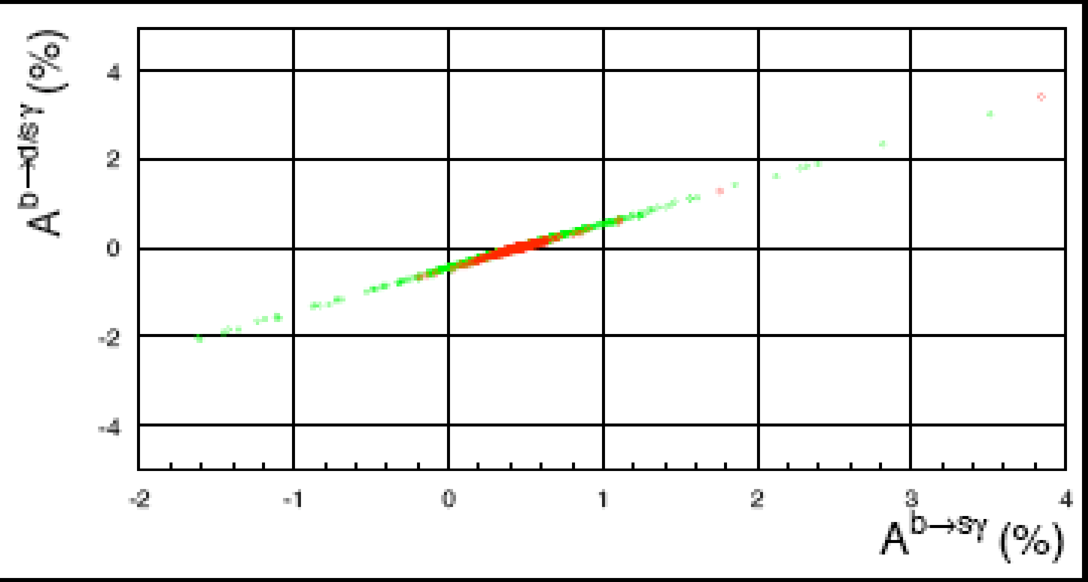
[Silvestrini]





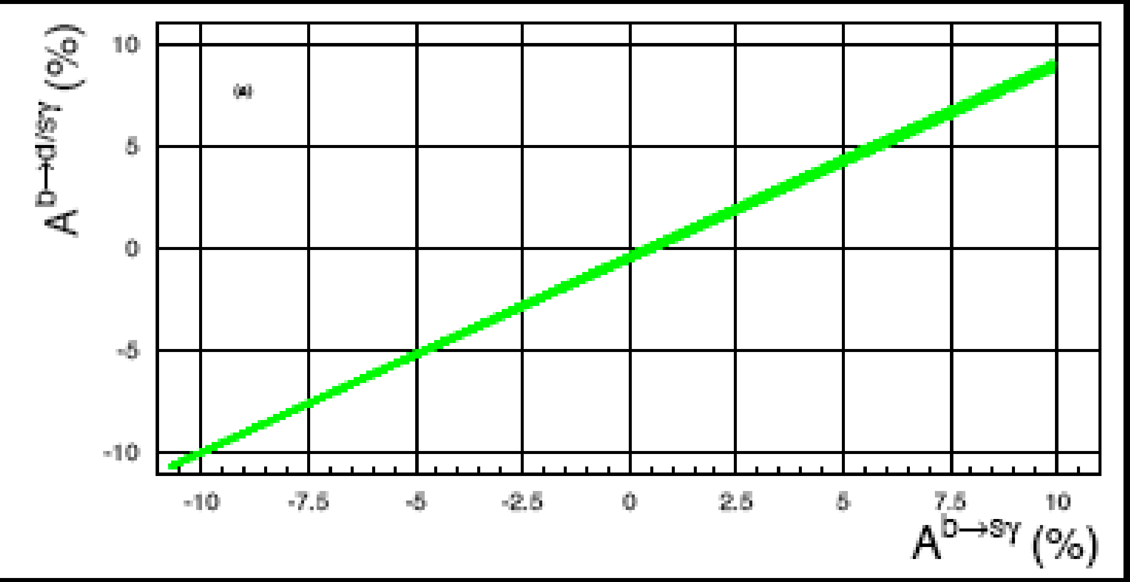
$B \to X_s\gamma$: impact on NP

- Untagged CP asymmetry



[EL, Hurth, Porod]

MFV



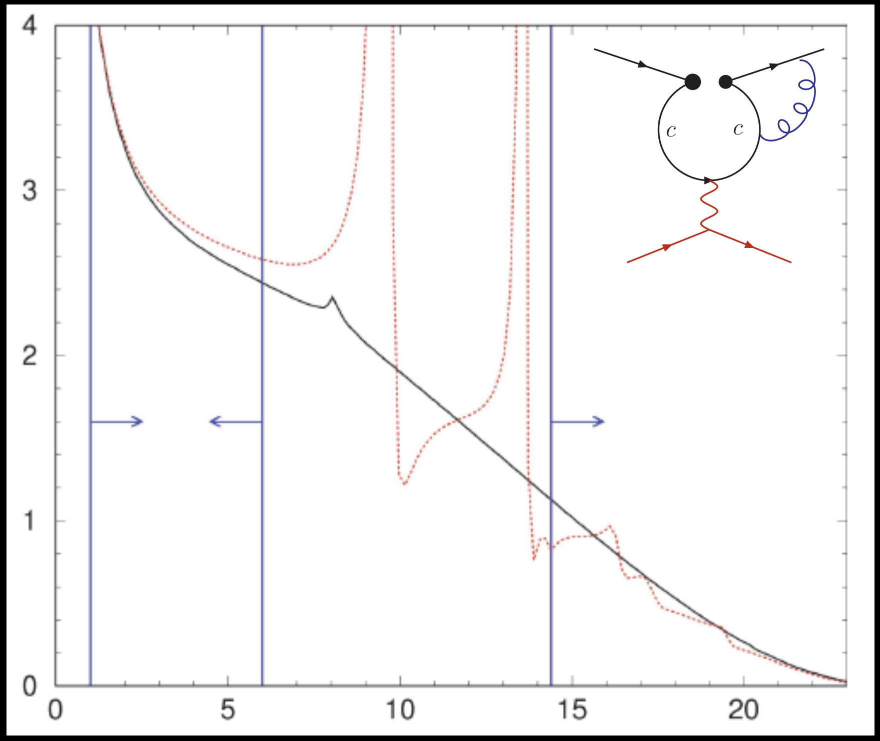
[EL, Hurth, Porod]

Model Independent Analysis

- Very clean test for new CP violating phases
- Experimental sensitivity at super-B factoriescan reach the 0.3% level

Status of $B \to X_s \ell^+ \ell^-$

- NNLO QCD and NLO EW corrections are known
- Issue with QED collinear logs: theory prediction depends on experimental treatment of energetic collinear photons
- q^2 cut
- M_X cut

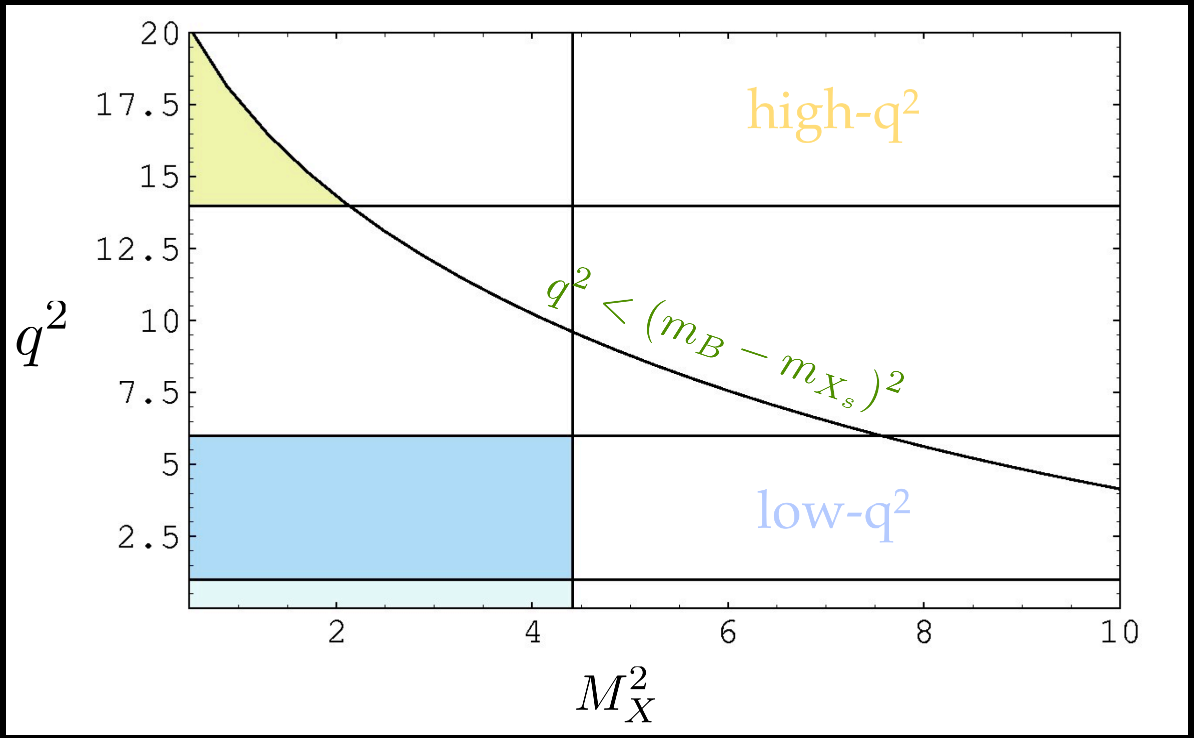


Three regions:

0.04 GeV^2 < q^2 < 1 GeV^2

1 GeV^2 < q^2 < 6 GeV^2

q^2 > 14.4 GeV^2



Calculated using Fermi motion or SCET. Non-perturbative effects strongly reduced in:

$\Gamma^{\mathrm{cut}}(B \to X_s \ell^+ \ell^-)/\Gamma^{\mathrm{cut}}(B \to X_u \ell \bar{\nu})$

$B \to X_s \ell^+ \ell^-$: SM predictions

- Branching ratio

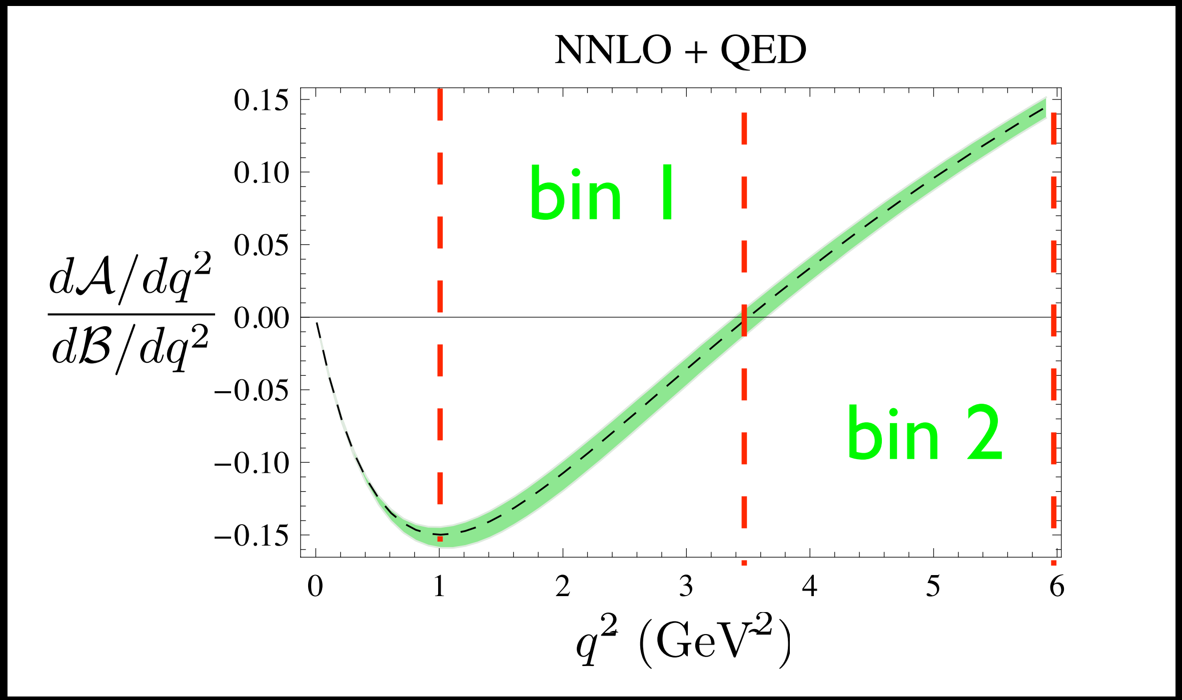
$$\mathrm{BR}(B \to X_s \ell^+ \ell^-)^{\mathrm{SM}}_{\mathrm{low}-q^2} = (1.59 \pm 0.11) \times 10^{-6}$$ [Huber, EL, Misik, Wyler]

$$\mathrm{BR}(B \to X_s \ell^+ \ell^-)^{\mathrm{exp}}_{\mathrm{low}-q^2} = (1.60 \pm 0.51) \times 10^{-6}$$ [BaBar, Belle]

$$\mathrm{BR}(B \to X_s \ell^+ \ell^-)^{\mathrm{SM}}_{\mathrm{high}-q^2} = (2.40^{+0.69}_{-0.62}) \times 10^{-7}$$ ← largest source of uncertainty are m_b^{-3} power corrections [Huber, Hurth, EL]

$$\mathrm{BR}(B \to X_s \ell^+ \ell^-)^{\mathrm{exp}}_{\mathrm{high}-q^2} = (4.4 \pm 1.2) \times 10^{-7}$$ [BaBar, Belle]

- Forward-backward asymmetry



[Huber, Hurth, EL]

- location of the zero:

$$q_0^2 = (3.50 \pm 0.12)\ \mathrm{GeV}^2$$

- Integrated observables:

$$(\bar{\mathcal{A}}_{\ell\ell})_{\mathrm{low}} = [1.5 \pm 0.9]\%$$

$$(\bar{\mathcal{A}}_{\ell\ell})_{\mathrm{bin1}} = [-9.1 \pm 0.9]\%$$

$$(\bar{\mathcal{A}}_{\ell\ell})_{\mathrm{bin2}} = [7.8 \pm 0.8]\%$$

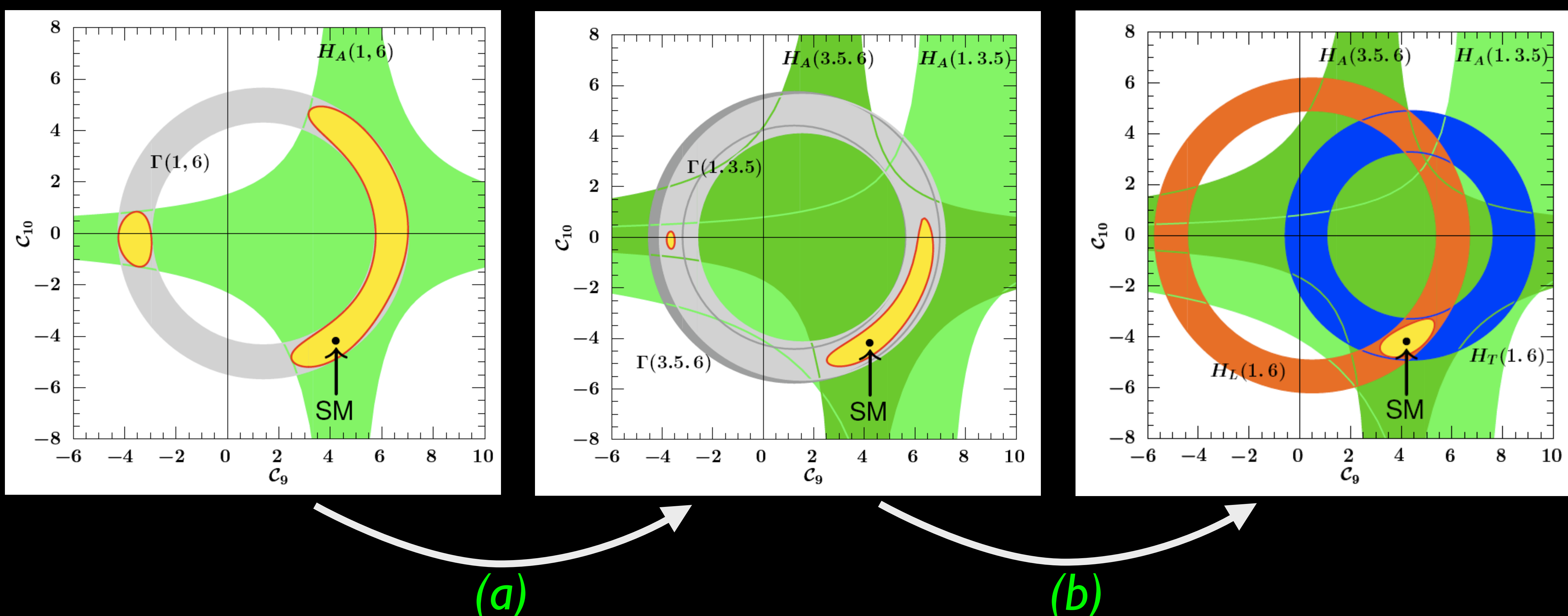
$B \to X_s \ell^+ \ell^-$: new observables

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

$$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2) \qquad \frac{d\mathcal{A}_{FB}}{dq^2} = \frac{3}{4}H_A(q^2) \qquad z = \cos\theta_\ell$$

- Wilson coefficient determination is improved by *(a)* splitting the FB asymmetry in two bins and *(b)* extracting separately H_T and H_L:

[Lee, Ligeti, Stewart, Tackmann]



$B \to X_s \ell^+ \ell^-$: reducing the errors

- Sensitivity to OPE breakdown in the high-q^2 region can be attenuated by considering:

$$\mathcal{R}(q_0^2) = \frac{\displaystyle\int_{\hat{q}_0^2}^{1} \mathrm{d}\hat{q}^2 \, \frac{\mathrm{d}\Gamma(\bar{B} \to X_s \ell^+ \ell^-)}{\mathrm{d}\hat{q}^2}}{\displaystyle\int_{\hat{q}^2}^{1} \mathrm{d}\hat{q}^2 \, \frac{\mathrm{d}\Gamma(\bar{B}^0 \to X_u \ell \nu)}{\mathrm{d}\hat{q}^2}}$$

[Ligeti, Tackmann]

- Size of power corrections strongly reduced
- In the SM we find: $\mathcal{R}(14.4\ \mathrm{GeV}^2) = (2.29 \pm 0.30) \times 10^{-3}$ [Huber, Hurth, EL]
- Error is reduced from ~30% to ~13%
- Largest source of uncertainty is V_{ub}
- Procedure already possible using present experimental data
- Separation of neutral and charged semileptonic b→u decays important to control WA contributions.

$B \to X_s \ell^+ \ell^-$: impact on NP

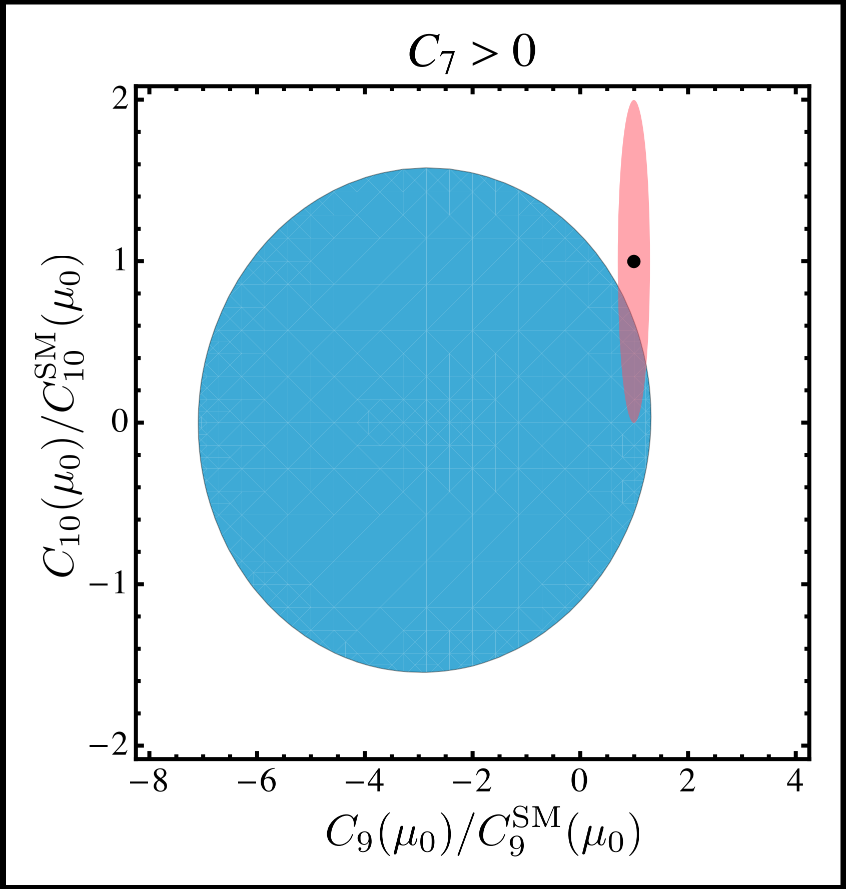
- Scenarios with $C_7 \sim -C_7^{\rm SM}$ are disfavored at the 2.7σ level:

[Gambino, Haisch, Misiak]
[Huber, Hurth, EL]

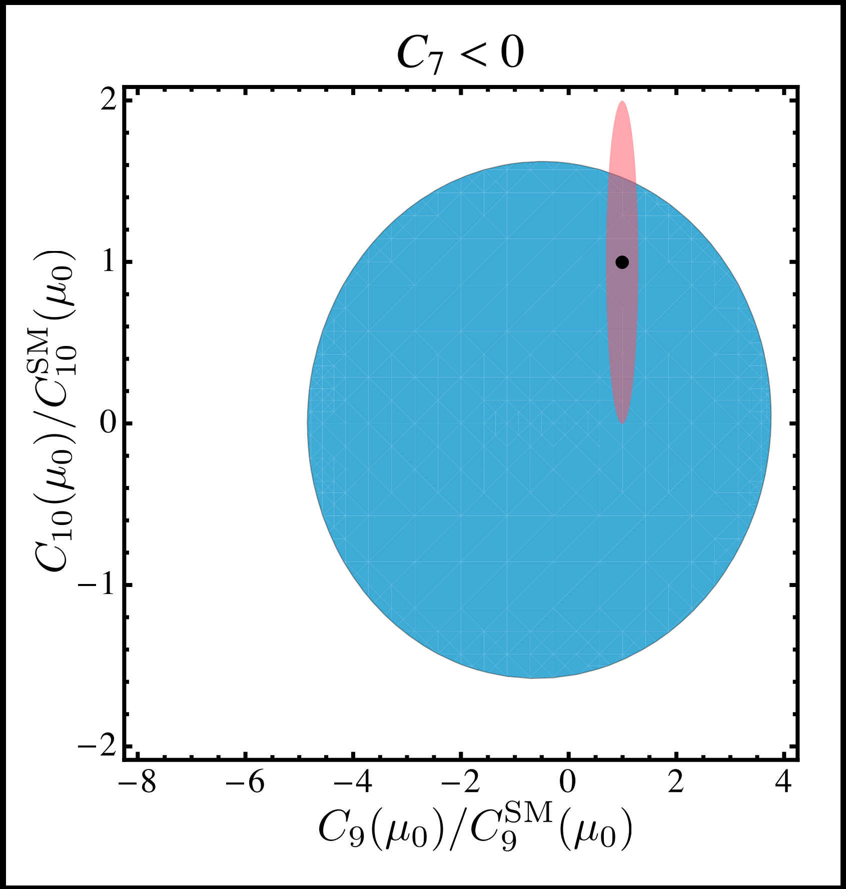
$$\mathrm{BR}(\bar{B} \to X_s \ell^+ \ell^-)^{\rm NP}_{{\rm low}-q^2} = (3.11 \pm 0.22) \times 10^{-6}$$

$$\mathrm{BR}(B \to X_s \ell^+ \ell^-)^{\rm exp}_{{\rm low}-q^2} = (1.60 \pm 0.51) \times 10^{-6}$$

- In presence of non-MFV new physics (e.g. most general MSSM) they become viable:



[EL]



[EL]

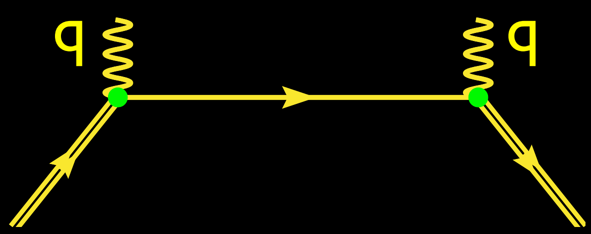
Exclusive channels

Theory

$$\mathcal{A}(B \to K^* \ell^+ \ell^-) = C_i \langle K^* \ell^+ \ell^- | O_i | B \rangle$$
$$= C_i \, \bar{\ell} \Gamma_1^i \ell \underbrace{\langle K^*(p_{K^*}, \epsilon_{K^*}) | \bar{s} \Gamma_2^i b | B(p_B) \rangle}_{\text{form factors}} + \cdots$$

hard spectator interactions

- Lorentz decomposition of form factors in terms of p_{K^*}, p_B and ε_{K^*}
- Form factors are functions of $q^2 = (p_B - p_{K^*})^2$
- Several approaches to the calculation of the form factors:
  - QCD-factorization [Ali, Parkhomenko; Bosch, Buchalla; Beneke, Feldmann, Seidel]
  - QCD-factorization + resummation (SCET) [Chay, Kim; Grinstein, Grossman, Ligeti; Becher, Hill, Neubert]
  - Light-cone QCD sum rules [Ball, Jones, Zwicky]
  - pQCD [Keum, Matsumori, Sanda, Yang]
- We will focus on QCDF/SCET approaches:
  - only work if q^2 is small (for radiative decays q^2=0)
  - for large q^2 the final state meson is soft and no expansion is possible



QCD factorization

$$\langle K_a^* \ell^+ \ell^- | H_{eff} | B \rangle = T_a^I(q^2)\zeta_a(q^2) + \sum_{\pm} \int_0^\infty \frac{d\omega}{\omega} \phi_\pm^B(\omega) \int_0^1 du\ \phi_{K^*}^a(u) T_{a,\pm}^{II}(\omega, u, q^2)$$

hard scattering (m_b^2)

soft form factors (Λ^2)

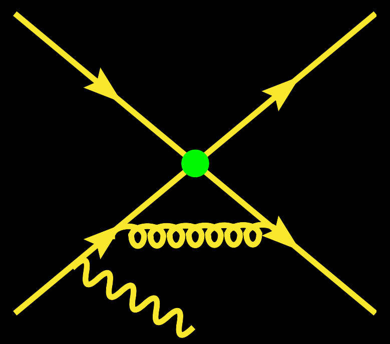
light-cone wave functions (Λ^2)

hard scattering (m_b^2)
jet function (Λm_b)

- Includes effects of all operators (not only O_7, O_9, O_{10})
- Systematic expansion in α_s
- Expansion in $\Lambda/m_b \sim 10\%$
- The 10 FFs in full QCD are reduced to 3 in QCDF at leading power
- Two options:
  1. Use lattice/LCSR calculations to extract the soft form factors
  2. Use lattice/LCSR results directly (to automatically include some sets of power corrections)

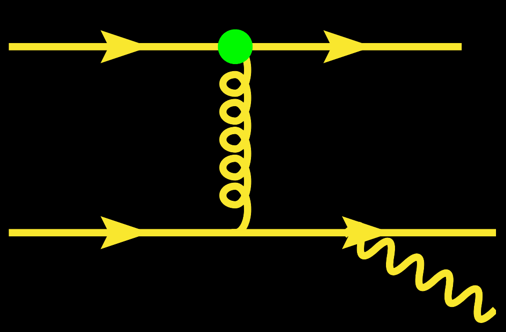
Annihilation

- Appear at the subleading power
- Relevant for B→ρ: proportional to $V_{ub}V_{ud}^*/(V_{cb}V_{cd}^*) \sim O(1)$
- Also impact CP and Isospin asymmetries in B→K*
- Some annihilation diagrams are factorizable (e.g. $O_{1,2}$):



All divergences can be absorbed in the LCDA
Convolutions are convergent
[Ali, Parkhomenko, Pecjak]

- Other are not (O_8):



Some convolutions are divergent and imply a breakdown of factorization:

- cut-off? [Kagan, Neubert]
- zero-bin subtraction? [Ligeti, Manohar]
- subleading form factors?

$B \to K^*\gamma$: SM predictions

- Branching ratio [Ali, Parkhomenko, Pecjak]

$$\mathrm{BR}(B \to K^*\gamma)_{\mathrm{SM}} = (4.6 \pm 1.2_{\xi_{K^*}} \pm 0.4_{m_c} \pm 0.2_{\lambda_B} \pm 0.1_{\mu}) \times 10^{-5}$$

$$\mathrm{BR}(B \to K^*\gamma)_{\mathrm{exp}} = (4.18 \pm 0.17) \times 10^{-5}$$ [BaBar, Belle]

  - vertex and hard-spectator corrections involving $O_{7,8}$ are known at NNLO
  - vertex corrections involving $O_{1,2}$ are known at NNLO in the BLM limit
  - hard-spectator corrections involving $O_{1,2}$ are known at NLO

- Isospin asymmetry

$$\mathcal{A}_I(B \to K^*\gamma)_{\mathrm{SM}} = (5.4 \pm 1.4)\ \%$$ [Ball, Jones, Zwicky]

$$\mathcal{A}_I(B \to K^*\gamma)_{\mathrm{exp}} = (3 \pm 4)\ \%$$ [BaBar, Belle]

  - Sensitive to NP contributions to O_6
  - Requires understanding of annihilation topologies

$B \to K^*\gamma$: SM predictions

- Time dependent CPA: $S_{K^*\gamma} = -\frac{2|r|}{1+|r|^2} \sin\left(2\beta - \arg(C_7^{(0)} C_7')\right)$

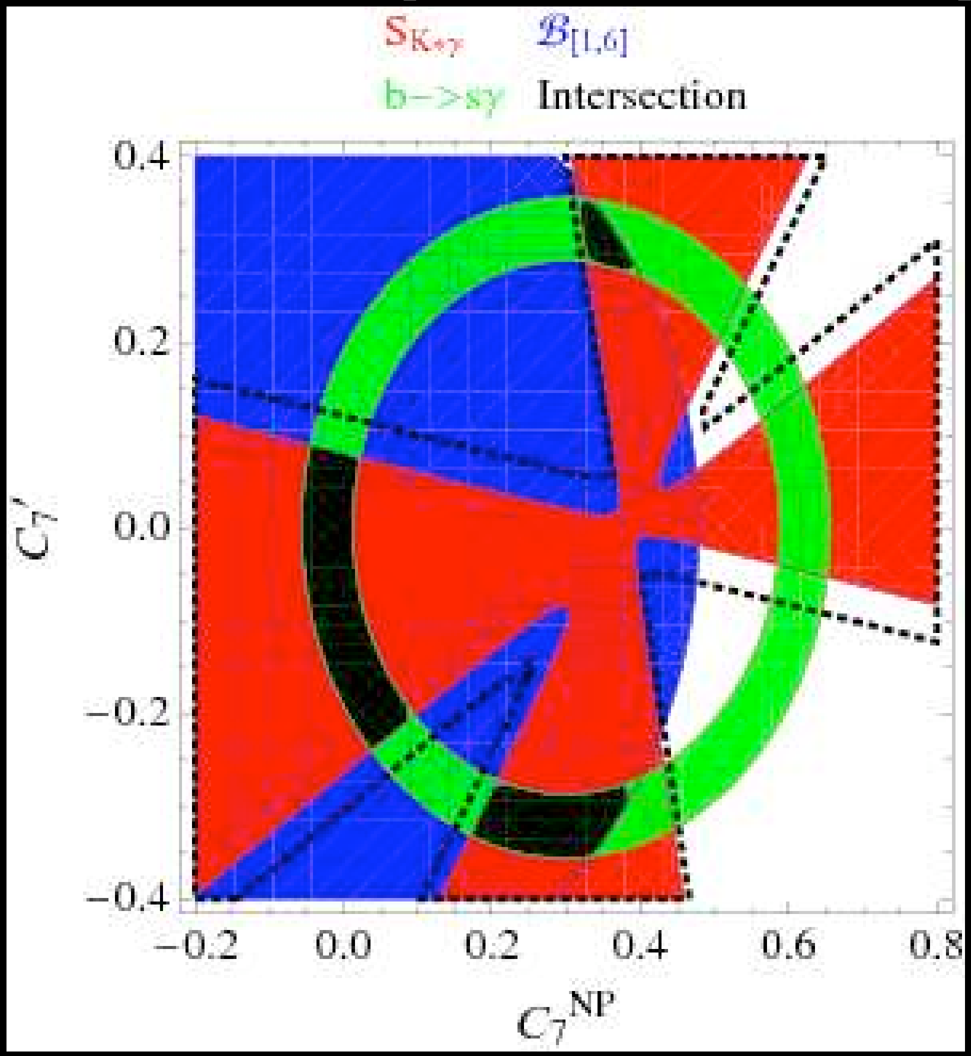
$$r = C_7'/C_7^{(0)}$$

- Predictions: $S_{K^*\gamma}^{\rm SM} = \left(-2.8^{+0.4}_{-0.5}\right)\ \%$

$$S_{K^*\gamma}^{\rm exp} = (-3 \pm 29)\ \%$$

- Sensitive to opposite chirality operator O7':

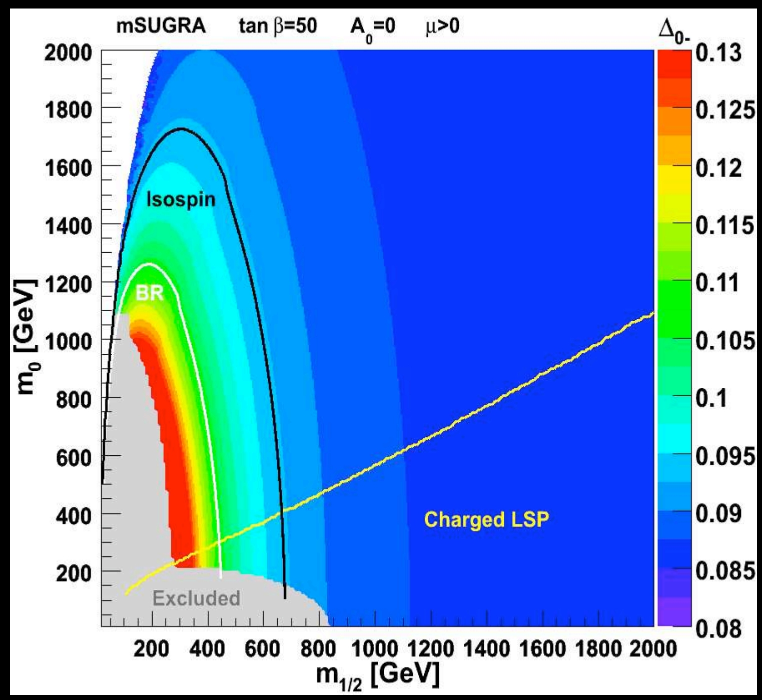
[Bobeth, Hiller, Piranishvili]



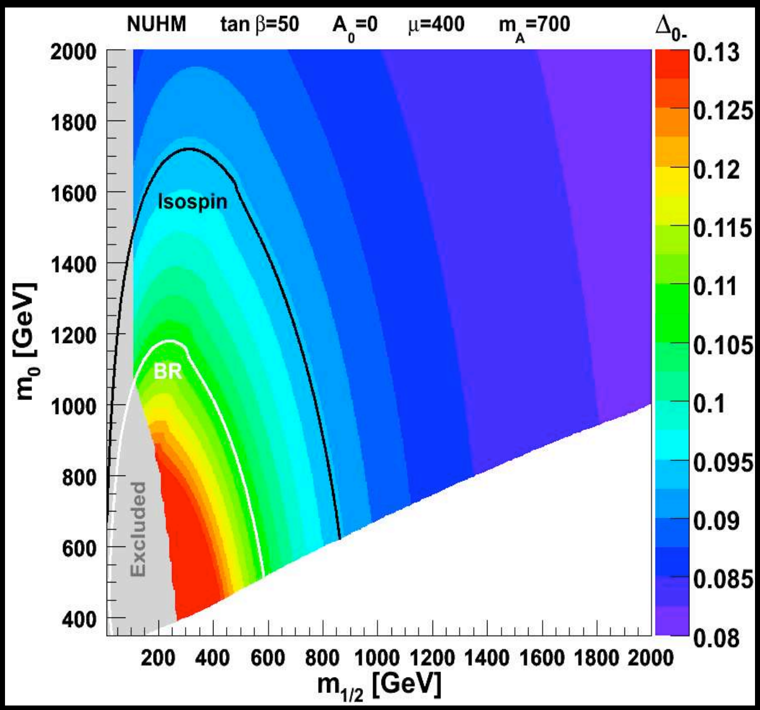
$A_I(B \to K^*\gamma)$: impact on NP

- The B→K*γ isospin asymmetry provides stronger constraints than the B→X_sγ BR ones in some parts of the MSSM parameter space: [Mahmoudi]

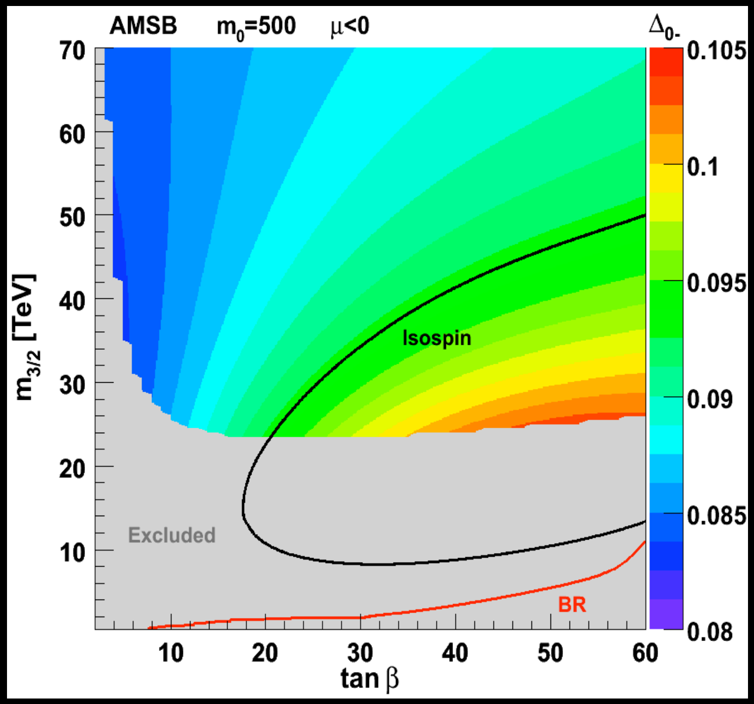
mSugra



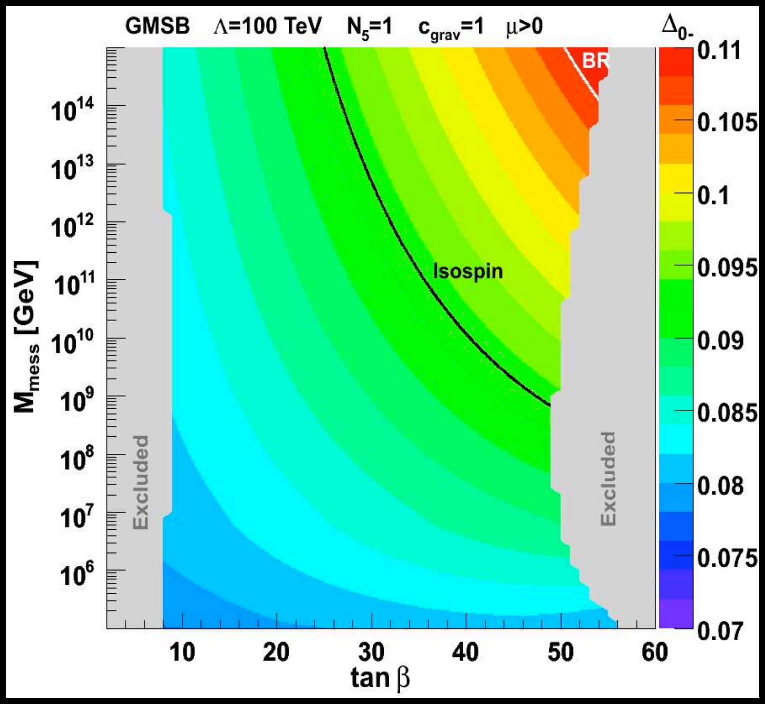
NUHM



AMSB



GMSB



$B \to (\rho, \omega)\gamma$: impact on UT fits

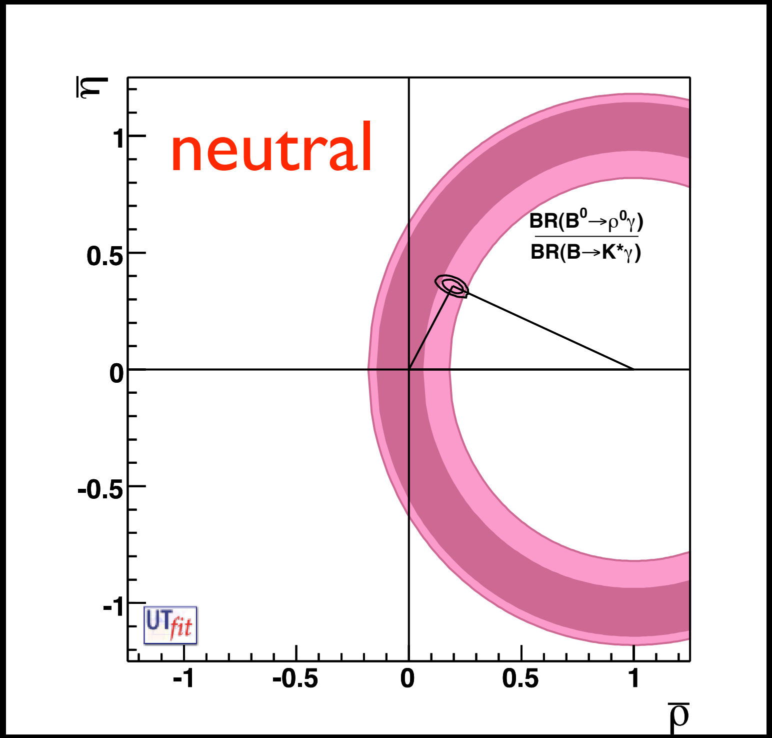
- In QCDF one finds:

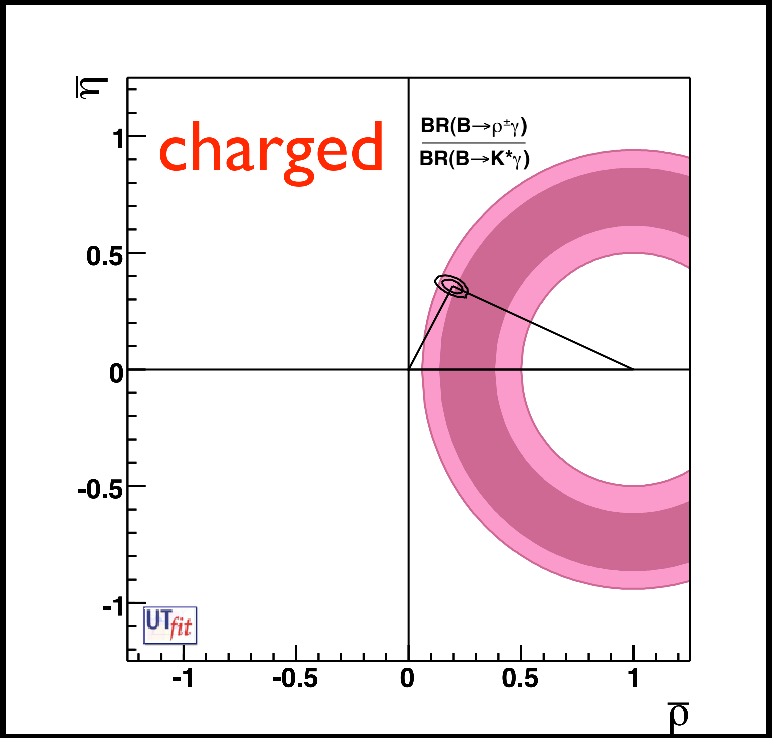
$$\frac{\mathrm{BR}(B \to \rho\gamma)}{\mathrm{BR}(B \to K^*\gamma)} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{1}{\xi_\rho^2}\left[1 + \Delta R\right]$$

- ΔR ~ 0.1 is calculated
- Utilizing form factor ratio from LCSR [Ball Jones Zwicky]:

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.192 \pm 0.016_{\mathrm{exp}} \pm 0.014_{\mathrm{th}}$$

- Impact on unitarity triangle fit [UTfit]:

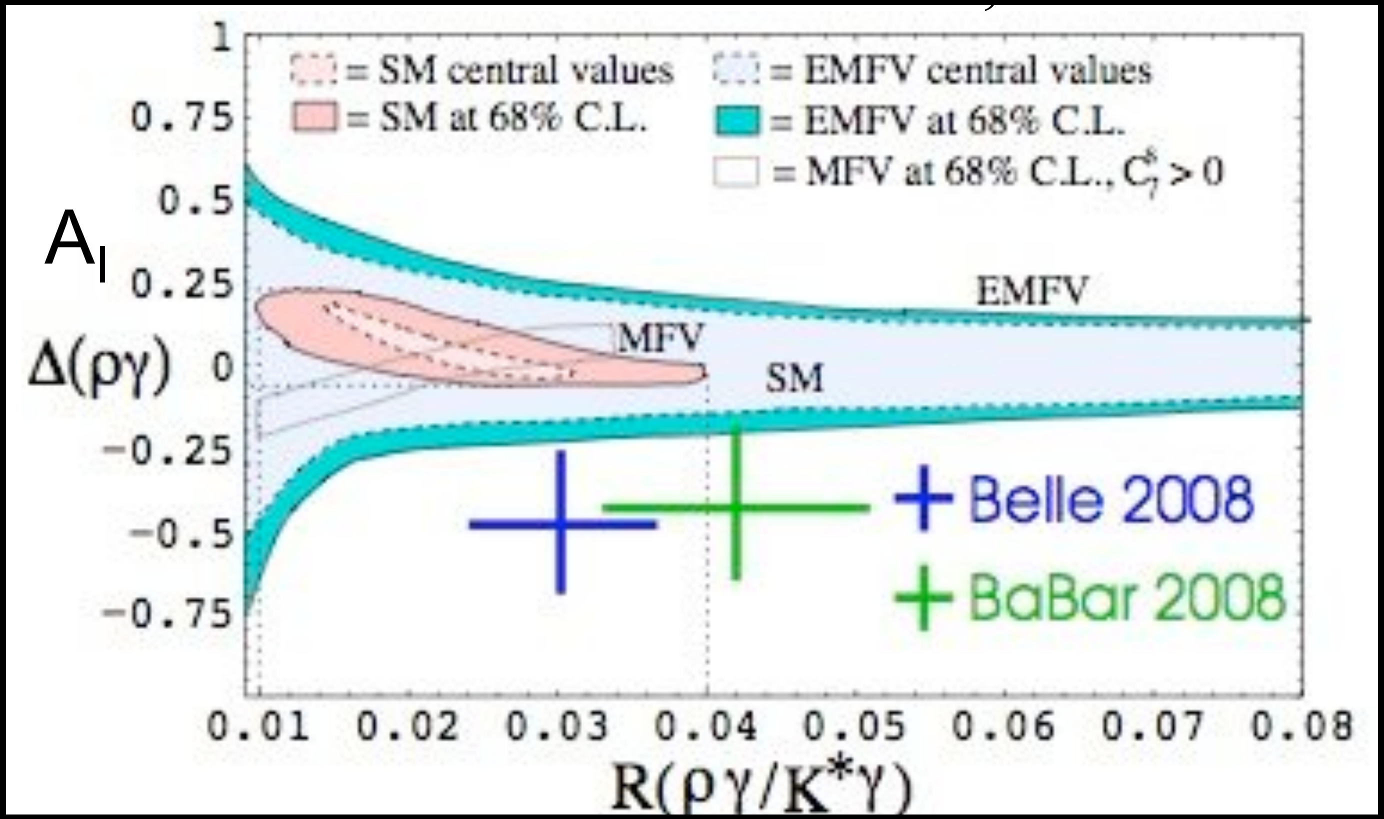




Isospin asymmetry in $B \to \rho\gamma$

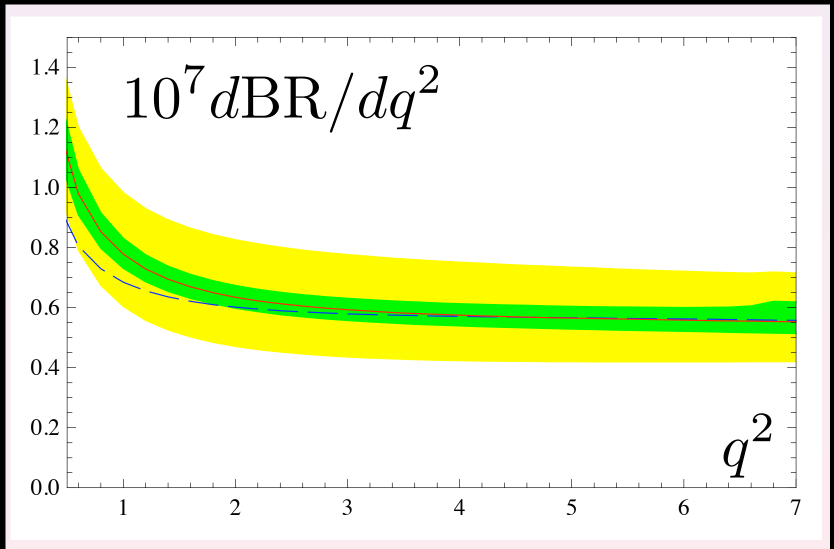
$$\mathcal{A}_I(B \to \rho\gamma) = \frac{\Gamma(B^\pm \to \rho^\pm\gamma)}{2\,\Gamma(B^0 \to \rho^0\gamma)} - 1$$

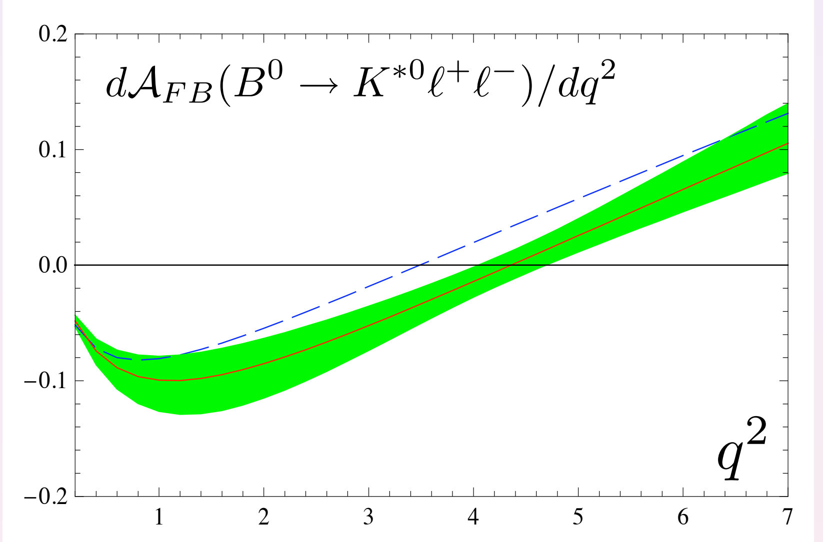
- Impact on various MSSM models:

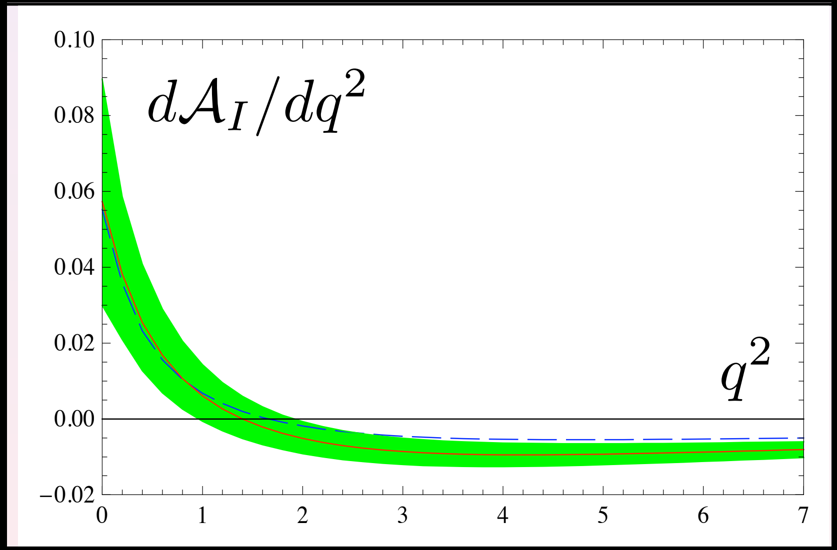


[Ali, EL]

$B \to K^* \ell^+ \ell^-$: SM predictions







$$\mathrm{BR}(B \to K^* \ell^+ \ell^-)^{\mathrm{low}}_{\mathrm{SM}} = 3.01^{+0.36}_{-0.28} \times 10^{-7} \times \left(\frac{A_0(4\ \mathrm{GeV}^2)}{0.66}\right)^2$$

$$\mathrm{BR}(B \to K^* \ell^+ \ell^-)^{\mathrm{low}}_{\mathrm{exp}} = (1.49^{+0.45}_{-0.40} \pm 0.12) \times 10^{-7}$$ [Belle]

$$\mathrm{BR}(B \to K^* \ell^+ \ell^-)^{[0.1,7.02]}_{\mathrm{SM}} = 4.69^{+0.71}_{-0.53} \times 10^{-7} \times \left(\frac{A_0(4\ \mathrm{GeV}^2)}{0.66}\right)^2$$

$$\mathrm{BR}(B \to K^* \ell^+ \ell^-)^{[0.1,7.02]}_{\mathrm{exp}} = (4.3^{+1.1}_{-1.0} \pm 0.3) \times 10^{-7}$$ [BaBar]

$$(q_0^2)_{\mathrm{SM}} = \begin{cases} 4.36^{+0.33}_{-0.31}\ \mathrm{GeV}^2 & \text{neutral} \\ 4.15 \pm 0.27\ \mathrm{GeV}^2 & \text{charged} \end{cases}$$

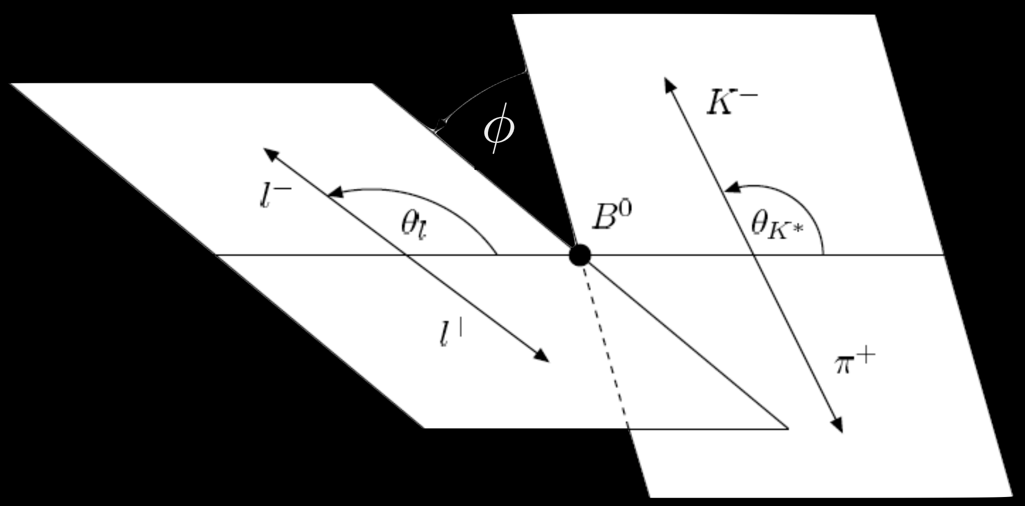
As for inclusive modes, it is important to split the integrated FB asymmetry in 2 bins

$$(\mathcal{A}_I)^{\mathrm{low}}_{\mathrm{SM}} = (0.7 \pm 0.3)\ \%$$

$$(\mathcal{A}_I)^{\mathrm{low}}_{\mathrm{exp}} = (0.33^{+0.37}_{-0.43} \pm 0.05)\ \%$$ [Belle]

$$(\mathcal{A}_I)^{\mathrm{low}}_{\mathrm{exp}} = (-0.25^{+0.20}_{-0.18} \pm 0.03)\ \%$$ [BaBar]

$B \to K^* \ell^+ \ell^-$: angular analysis



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_{K^*}\, d\phi} \propto$$

$$I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*})\cos 2\theta_\ell$$
$$+ I_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos\phi$$
$$+ I_5 \sin 2\theta_{K^*} \sin\theta_\ell \cos\phi$$
$$+ (I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*})\cos\theta_\ell + I_7 \sin 2\theta_{K^*} \sin\theta_\ell \sin\phi$$
$$+ I_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_{K^*} \sin^2\theta_\ell \sin 2\phi$$

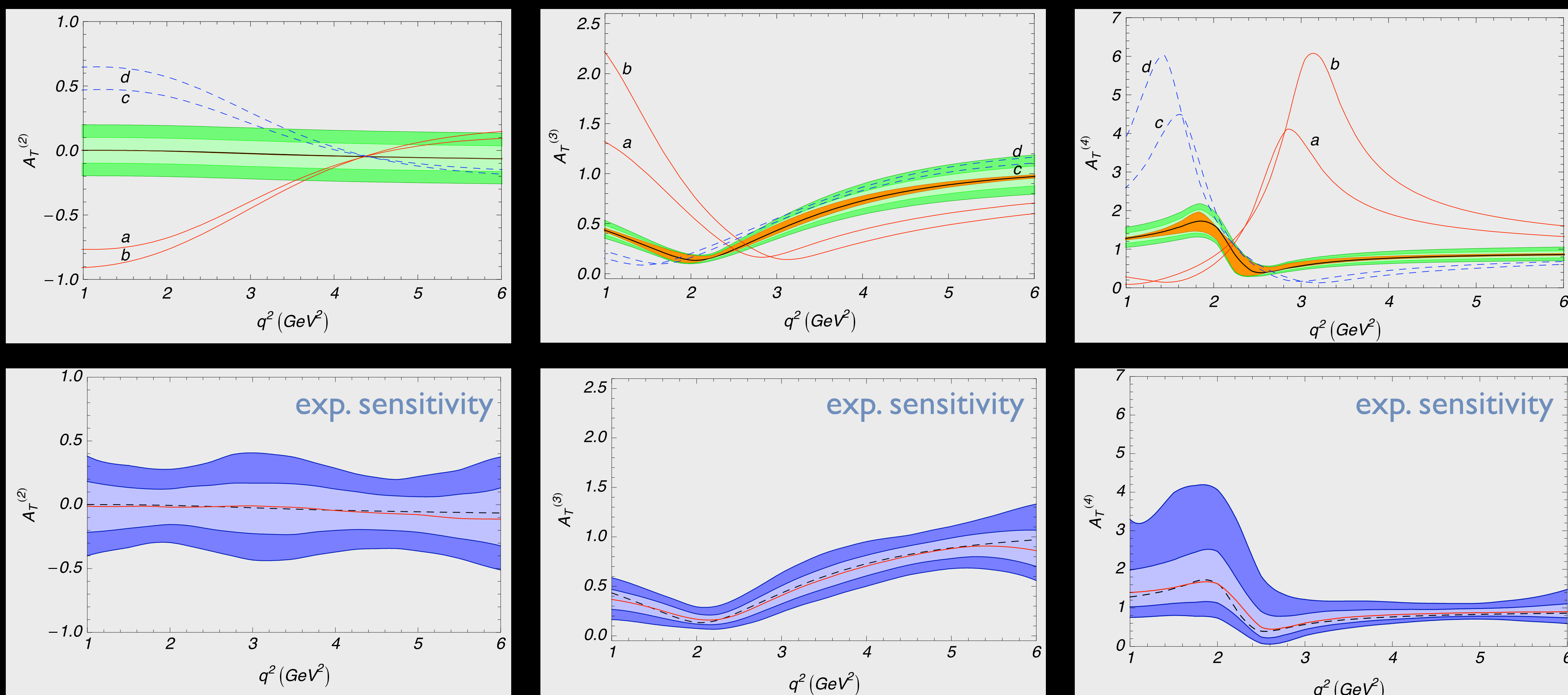
- Differential width is summed over spins of final state particles
- In absence of scalar operators I_6^c vanishes
- Only 9 of the remaining I_i^a are independent and are a function of 6 complex amplitudes: $A_{\perp L/R},\ A_{\parallel L/R},\ A_{0L/R}$
- There are three symmetries that act on these amplitudes: not everything you can build out of the A_i is observable
- Define 12 symmetries and 12 asymmetries (bar = CP conjugation):

$$S_i^{(a)} = \frac{I_i^{(a)} + \bar{I}_i^{(a)}}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}} \qquad A_i^{(a)} = \frac{I_i^{(a)} - \bar{I}_i^{(a)}}{\frac{d(\Gamma+\bar{\Gamma})}{dq^2}}$$

$B \to K^* \ell^+ \ell^-$: impact on NP

- Most interesting observables:
  [Kruger, Matias; EL, Matias; Egede, Hurth, Matias, Ramon, Reece]

$$A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2} \qquad A_T^{(3)} = \frac{|A_{0L}A^*_{\parallel L} + A_{0R}A^*_{\parallel R}|}{|A_0|\,|A_\perp|} \qquad A_T^{(4)} = \frac{|A_{0L}A^*_{\perp L} - A_{0R}A^*_{\perp R}|}{|A_{0L}A^*_{\parallel L} + A_{0R}A^*_{\parallel R}|}$$



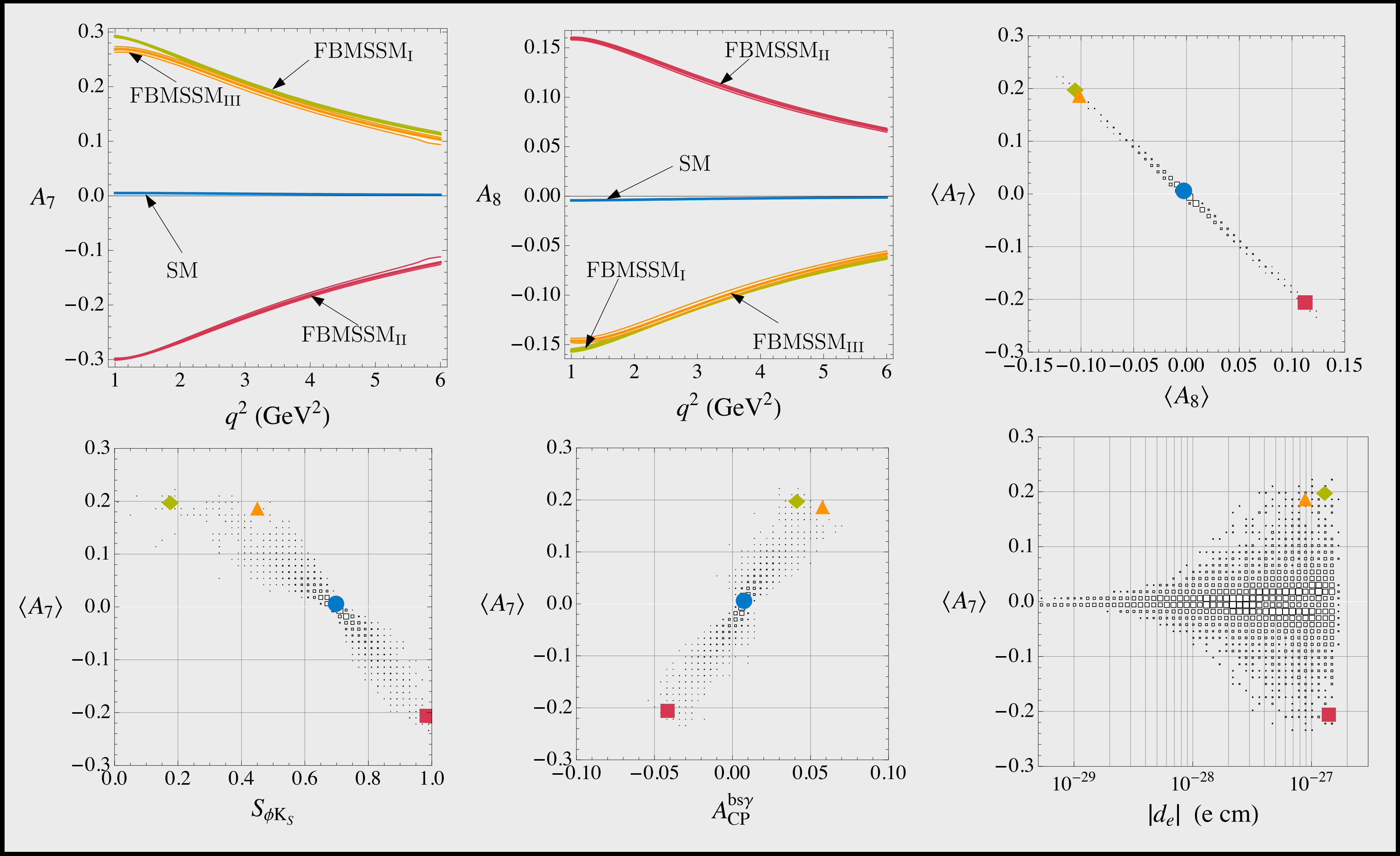
[Egede, Hurth, Matias, Ramon, Reece]

- *Scenarios a-d* corresponds to MSSM scenarios with $(\delta^d_{LR})_{32} \neq 0$

$B \to K^* \ell^+ \ell^-$: impact on NP

- The $A_T^{(i)}$ can be expressed in terms of the S_i^a
- Additional interesting effects on $A_{7,8}$

[Altmannshofer, Ball, Bharucha, Buras, Straub, Wick]



- Flavor Blind MSSM scenarios:

[Bartl, Gajdosik, EL, Masiero, Porod, Stremintzer, Vives]

Scenario	$\tan\beta$	m_A	$m_{\tilde{g}}$	$m_{\tilde{Q}}$	$m_{\tilde{U}}$	$A_{\tilde{t}}$	μ	$\mathrm{Arg}(\mu A_{\tilde{t}})$	
FBMSSM$_\mathrm{I}$	40	400	700	380	700	900	150	$-45°$	$\mathrm{Im}C_7 < 0$
FBMSSM$_\mathrm{II}$	40	400	700	380	700	900	150	$50°$	$\mathrm{Im}C_7 > 0$

$B \to K\ell^+\ell^-$: impact on NP

$$\frac{1}{\Gamma(B \to K\ell\ell)} \frac{d\Gamma(B \to K\ell\ell)}{d\cos\theta} = \frac{3}{4}(1 - F_H^\ell)(1 - \cos^2\theta) + \frac{1}{2} F_H^\ell + \mathcal{A}_{\rm FB}^\ell \cos\theta$$

$$R_K = \frac{\Gamma(B \to K\mu\mu)}{\Gamma(B \to Kee)}$$

- In the SM: $F_H^\ell \simeq \mathcal{A}_{\rm FB}^\ell \simeq R_K - 1 \simeq O(m_\ell/m_b)$
- In presence of NP in scalar/pseudoscalar (Scenarios 1-3) and in tensor operators (Scenario 4) deviations are possible:

Observable	Sc I	Sc II	Sc III	Sc IV
F_H^e	< 0.39	$-$	< 0.56	< 0.13
F_H^μ	$[0.013, 0.035]$	$[0.018, 0.032]$	$[0.013, 0.56]$	$[0.014, 0.18]$
R_K	$[0.61, 1.01]$	$[0.996, 1.01]$	$[0.44, 2.21]$	$[0.93, 1.10]$
$\mathcal{B}_e\,[10^{-7}]$	$[1.91, 3.14]$	$-$	$[1.91, 4.36]$	$[1.91, 2.00]$
$\mathcal{B}_\mu\,[10^{-7}]$	$[1.90, 1.94]$	$[1.90, 1.93]$	$[1.90, 4.26]$	$[1.87, 2.10]$
$A_{\rm FB}^e\,[\%]$	$[-0.02, 0.02]$	$-$	$[-0.02, 0.02]$	$[-0.02, 0.02]$
$A_{\rm FB}^\mu\,[\%]$	$[-0.6, 0.6]$	$[-0.5, 0.3]$	$[-4.46, 4.46]$	$[-3.1, 3.1]$

[Bobeth, Hiller, Piranishvili]

- The strongest constrain on the WCs comes from $B_s \to \mu\mu$

Outlook

- Inclusive modes:
  - $B \to X_s \gamma$ spectrum needs better understanding for both the SM prediction and for the extraction of m_b
  - Experimental treatment of collinear QED logs is still not completely implemented in theory predictions
  - Separate $b \to sll$ low-q^2 observables in two bins (1-3.5 and 3.5-6 GeV^2)

- Exclusive modes:
  - Theory is sound in the low-q^2 region
  - Isospin asymmetry in $B \to K^* \gamma$ has a very strong sensitivity to NP
  - Plethora of CP and angular distributions in $B \to K^* ll$ and $B \to Kll$ offer sensitivity to MFV and non-MFV extensions of the SM