B Physics @ ATLAS – Theory

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- flavour violation, as far as we understand, happens in the scalar sector:
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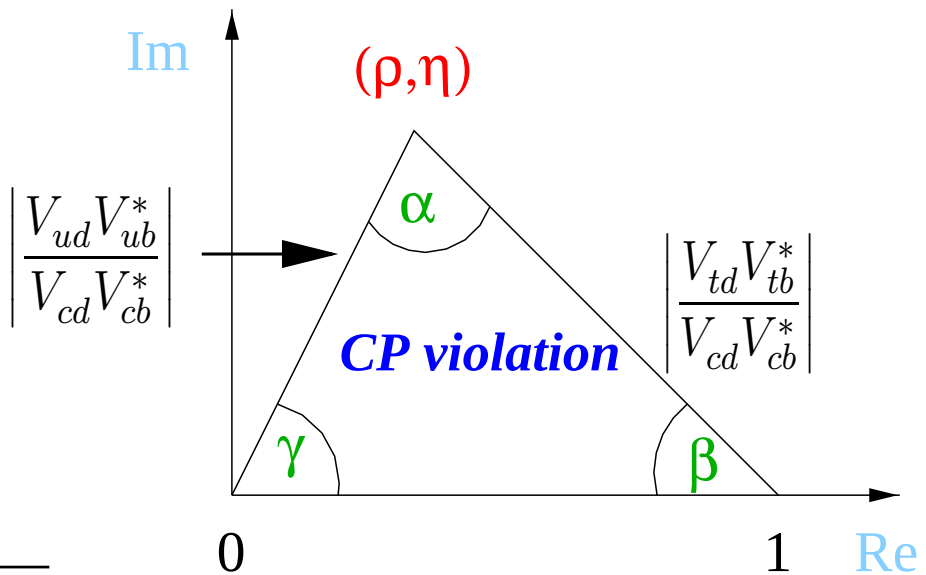
- hence:
  a complete understanding of EW symmetry breaking necessarily includes a complete understanding of flavour violation

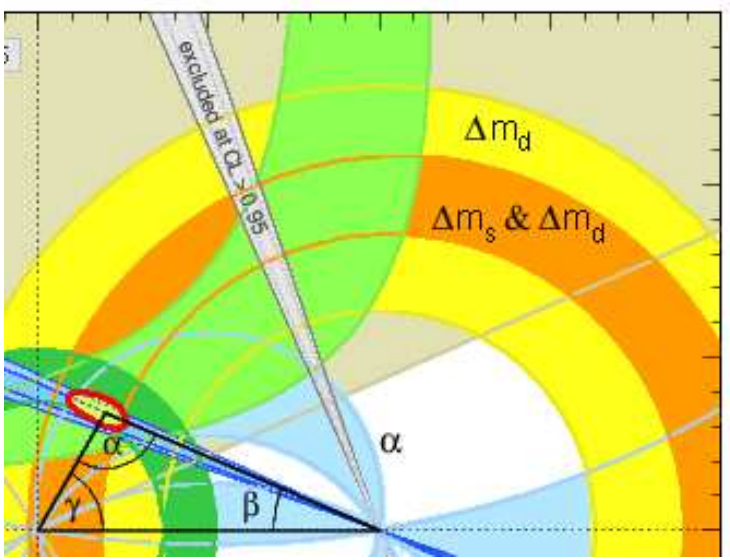
FV in the SM: CKM matrix and Unitarity Triangle

- UT summarizes salient features of SM heavy flavour physics

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$

- unitarity: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0.$





Where is B Physics now?

- BaBar and Belle opened era of precision measurements in B physics and provided/continue to provide plethora of data
- CDF/D0 now measuring B_s/Λ_b processes not accessible at B factories (B_s mixing!)
- bottom line:
  within present exp./th. accuracy, CKM picture appears to be consistent with observed flavour/CP violation
- Where to go from here?
  - theory: postulate of minimal flavour violation (MFV):
    NP provides no new sources of flavour violation
    (that is: NP only modifies short-distance amplitudes by $O(1)$)
    But why??? Flavour violation originates in scalar sector of SM (plus extensions).
    And how??? MSSM: if MFV imposed at a certain scale, it will be broken by EW radiative corrections

    ($b \to s\gamma$: Degrassi/Gambino/Slavich 06)

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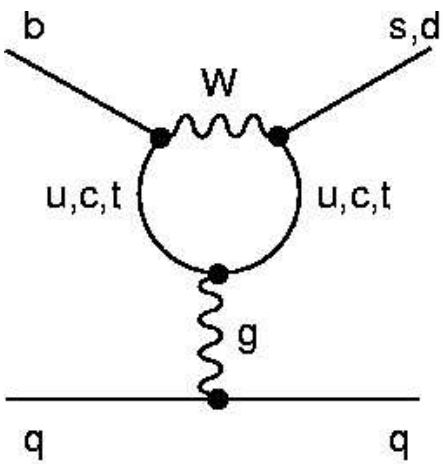
    ($b \to s\gamma$: Degrassi/Gambino/Slavich 06)
  - conclusion: search for small deviations from SM:
    need clean predictions from theory and lots and lots of clean B decays
  - particularly useful: null (or quasi null) tests:
    observables that are forbidden or expected to be small in the SM (Gershon/Soni 06)

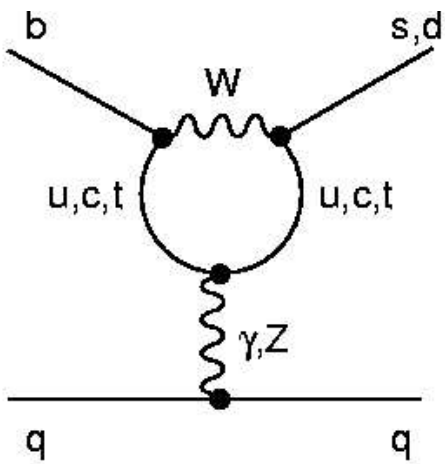
Examples of (Quasi) Null Tests

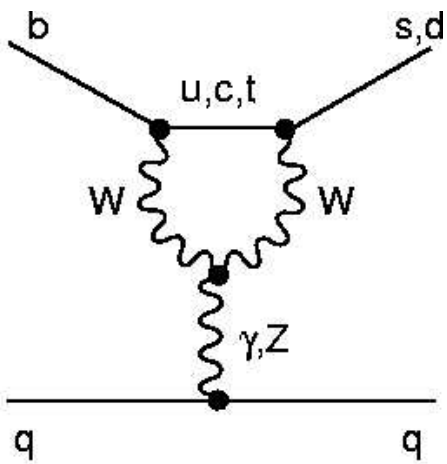
- time-dependent CP asymmetry in penguin-dominated modes ($B \to \phi K_S$ vs. $B \to J/\psi K_S$) (NP in FCNC)
- time-dependent CP asymmetry in $B_d \to K^*(K_S\pi)\gamma$ or $B_s \to \phi\gamma$ (e.g. left-right symmetric models)
- time-dependent CP asymmetry in $B_s \to J/\psi\phi$ (NP in B_s mixing)
- direct CP asymmetry in $B^+ \to \pi^+\pi^0$ (enhanced EW penguins)
- forward-backward asymmetry in $B \to K\ell\ell$ (e.g. Higgs penguins)
- zero in forward-backward asymmetry in $B \to K^*\ell\ell$
- $B \to D^{(*)}\mu\nu_\mu$ vs. $B \to D^{(*)}\tau\nu_\tau$ (charged Higgs etc.)
- transverse τ polarisation in semileptonic decays (charged Higgs etc.)
- ...

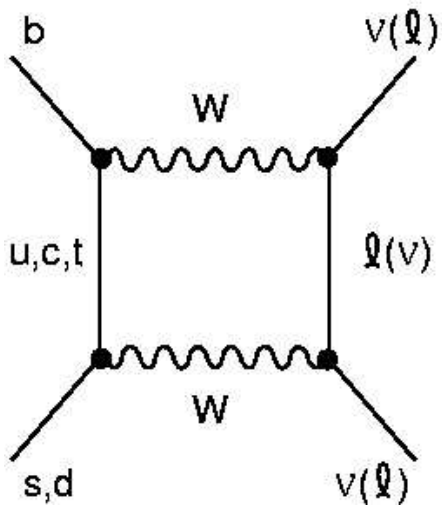
A Quick Reminder of FCNC

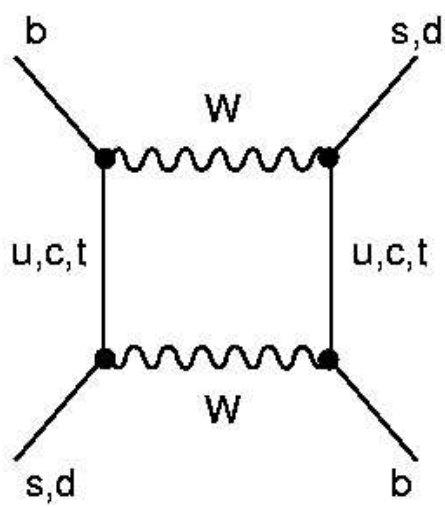
It so happens that all our examples involve $b \to s\gamma$ and $b \to s\ell\ell$. In the SM, these are loop induced.

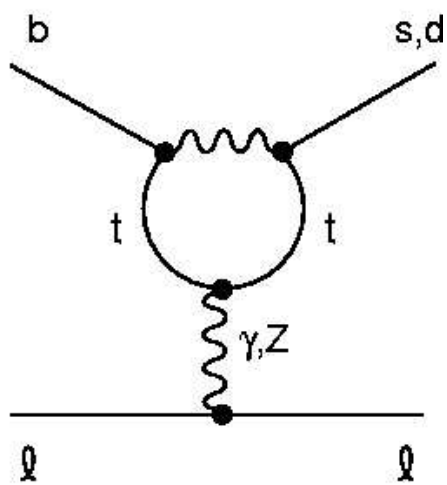












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- in SUSY, possibly large contributions from e.g. squark/gluino loops (with coupling α_s!):
  not seen: $B(b \to s\gamma)$ in very good agreement with SM prediction ($\sim 5\%$ exp., 10% th. error): SUSY (NP) flavour problem
- SUSY contribution vanishes if squarks degenerate in mass (that is: if soft SUSY breaking terms flavour independent)
- this is one of the motivations for MFV!

A Quick Reminder of FCNC

It so happens that all our examples involve $b \to s\gamma$ and $b \to s\ell\ell$. In the SM, these are loop induced.
$b \to s\ell\ell$ comes in various hadronic channels:

- $B_s \to \ell\ell$, $B_{u,d} \to K^{(*)}\ell\ell$, $B_s \to \phi\ell\ell$, $\Lambda_b \to \Lambda\ell\ell$.
  The short-distance physics is always the same!
  That is: there are strong correlations between these processes – which are not fully explored yet.

$b \to d\gamma$, $b \to d\ell\ell$ is more difficult to tackle:

- in the SM, rates are suppressed by roughly a factor $|V_{td}/V_{ts}|^2 \approx 1/100$.
  $B \to (\rho, \omega)\gamma$ was first observed by B factories in 2005, whereas $B \to K^*\gamma$ was seen by CLEO in 1993!
- theoretical treatment of $B_u \to \rho^-\gamma$ etc. more difficult than that of $B_d \to \rho^0\gamma$ etc. due to tree-level weak annihilation diagrams
  (which are doubly CKM suppressed for $b \to s$)

A Quick Reminder of FCNC

Theoretical input needed:

- For inclusive decays (probably not ATLAS' first choice):
  - QCD perturbation theory + heavy quark expansion (+ shape functions or variants for spectra)
- For exclusive decays:
  - QCD factorisation or SCET (to consistently include radiative corrections)
  - form factors of $B \to K$ etc. transitions
    - non-perturbative methods, in particular QCD sum rules on the light-cone and lattice
    - would actually be nice to have high resolution experimental spectra of $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$ to check calculations of form factor shapes!

CP Asymmetry in $B_d \to K^*\gamma$ ($B_s \to \phi\gamma$)

(Atwood/Gronau/Soni 97, Grinstein/Pirjol 05, Ball/Zwicky 06)

- $b \to s\gamma$ is actually either $b_R \to s_L\gamma_L$ (with, in the SM, a helicity factor m_b) or $b_L \to s_R\gamma_R$ (with, in the SM, a helicity factor m_s): γ dominantly left-polarised, γ_R suppressed by m_s/m_b
- entails a small time-dependent CP asymmetry (interference of γ_L/γ_R amplitudes):

$$\begin{aligned} A_{\rm CP} &= \frac{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) - \Gamma(B^0(t) \to K^{*0}\gamma)}{\Gamma(\bar{B}^0(t) \to \bar{K}^{*0}\gamma) + \Gamma(B^0(t) \to K^{*0}\gamma)} \\ &\approx -2\frac{m_s}{m_b}\sin(2\beta)\sin(\Delta m_B t) \approx -3\% \cdot \sin(\Delta m_B t) \end{aligned}$$

  ($K^*, \bar{K}^*$ observed as CP eigenstate $K_S\pi$)

- helicity suppression removed by NP if spin flip can occur on virtual line (e.g. left-right symmetric model, MSSM): factor $m_{\rm virtual}/m_b$ instead of m_s/m_b

CP Asymmetry in $B_d \to K^*\gamma$ ($B_s \to \phi\gamma$)

Caveat emptor! No helicity suppression in 3-parton process $b \to s\gamma g$.

Contributes to $B \to K^*\gamma$ if B or K^* in 3-particle quark-antiquark-gluon state configuration.

Estimated to increase $A_{\rm CP}$ to $\sim 10\%$ (Grinstein/Pirjol 05, using SCET).

Is that sound?

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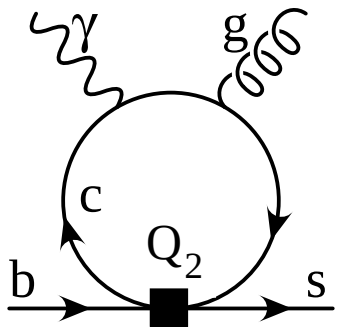
Soft gluons abundant everywhere – if 3-particle configurations of hadrons were that important, most form factor calculations (quark model/lattice) would be pretty wrong (as they neglect these contributions).

Exception: QCD sum rules on the light-cone, where these terms are included and are found to be small.

CP Asymmetry in $B_d \to K^*\gamma$ ($B_s \to \phi\gamma$)

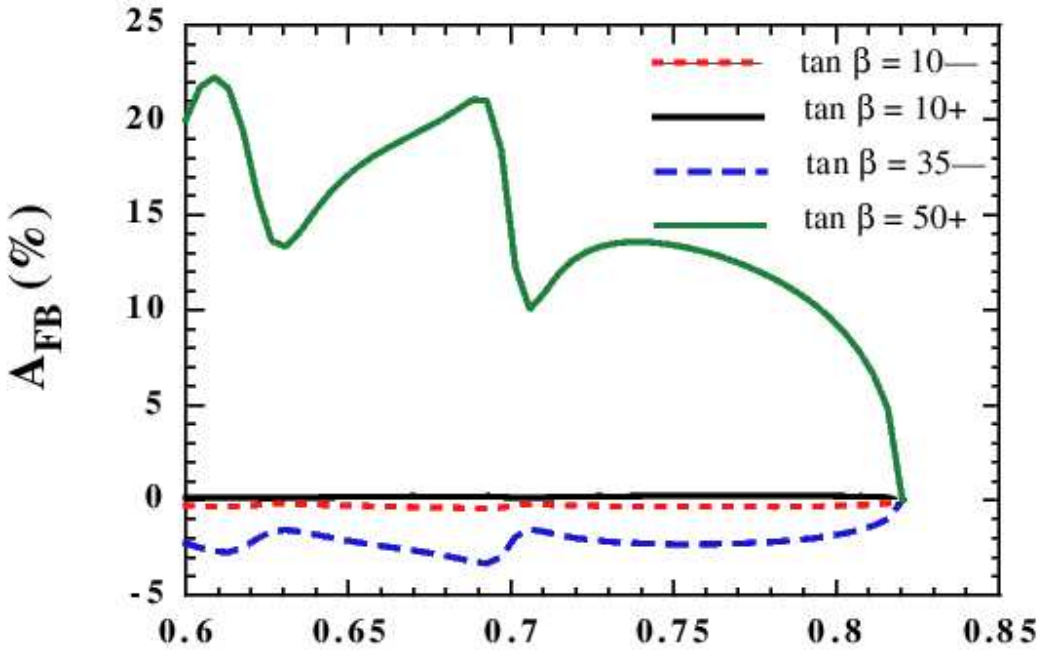
Can one do better?



- calculate effective operator for soft-gluon emission in $1/m_c$ expansion
- calculate relevant matrix elements from QCD sum rules on the light-cone
- yields $A_{\rm CP} = -(2 \pm 2)\% \, \sin(\Delta m_B t)$ (Ball/Zwicky 06)
- CP asymmetry in $B_d \to K^*\gamma$ remains near perfect null test of SM!
- $B_s \to \phi\gamma$ more feasible for LHCb (ATLAS/CMS?). Should yield very similar result (Ball/Zwicky, in prep)

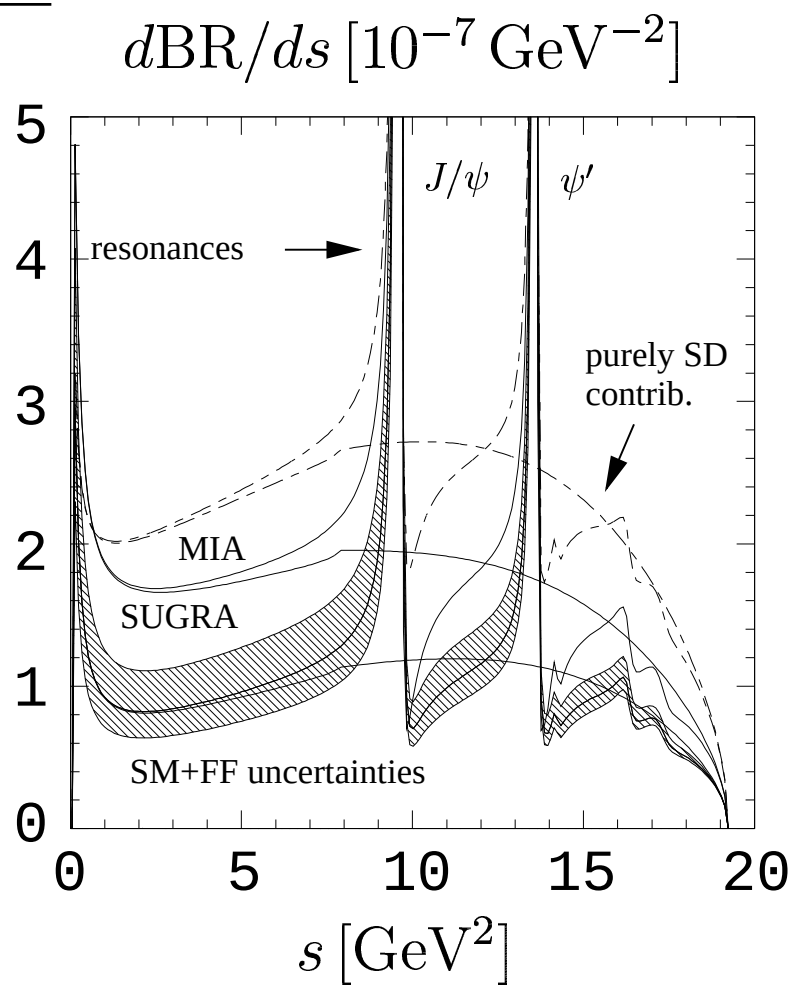
FB Asymmetry in $B \to K\ell\ell$

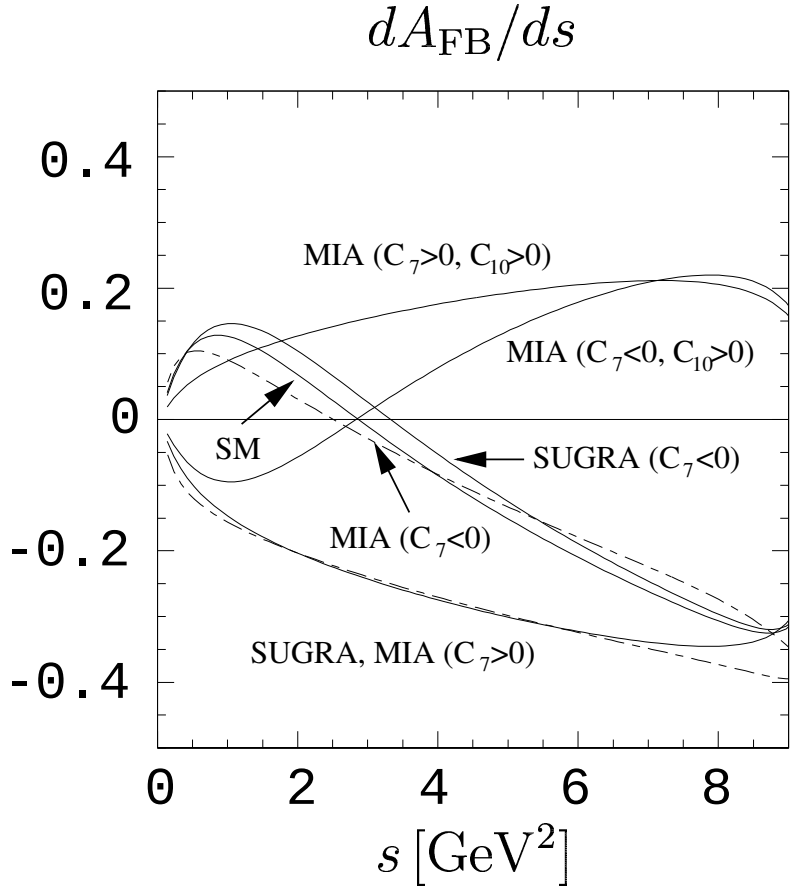
- vanishes in SM, is due to scalar exchange in BSM: Higgs penguins and similar (in MSSM, effect $\propto \tan\beta^n$ with $n = 2, 3$)
- SUSY with large $\tan\beta$: need $\ell = \tau$ to get large asymmetries $\sim 10\%$
- but maybe there is some non-SUSY NP around?



(Demir/Olive/Voloshin 02)

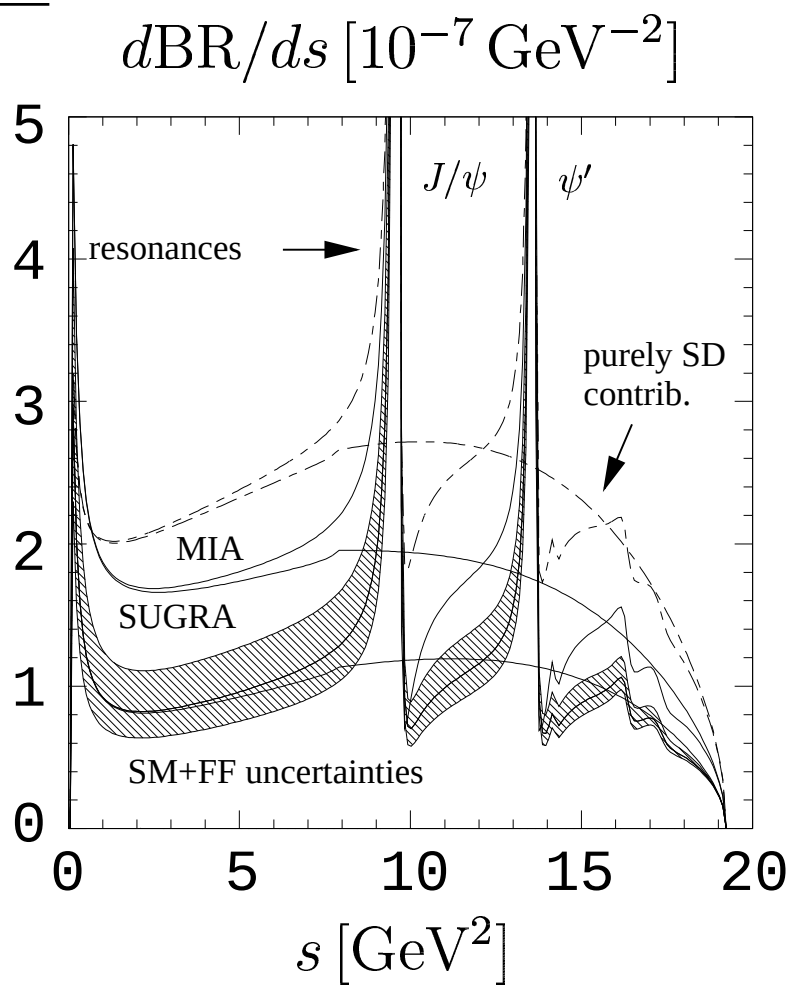
FB Asymmetry in $B \longrightarrow K^* \ell\ell$

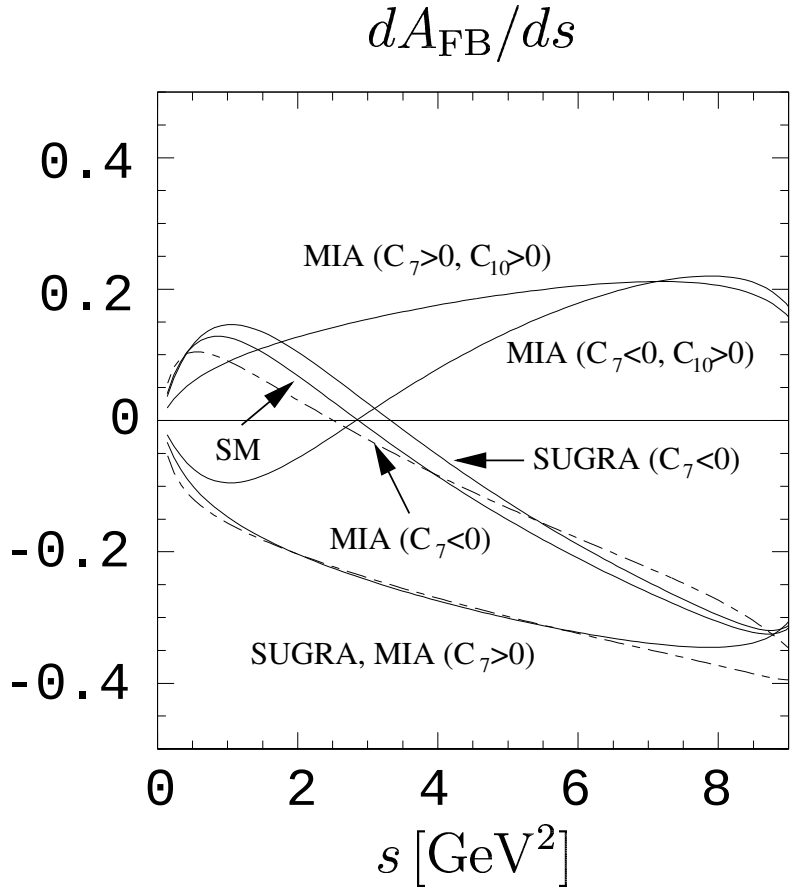




- FB wrt/ angle $\theta = \sphericalangle(\vec{p}_B, \vec{p}_{\mu^+})$ in CMS of dilepton pair

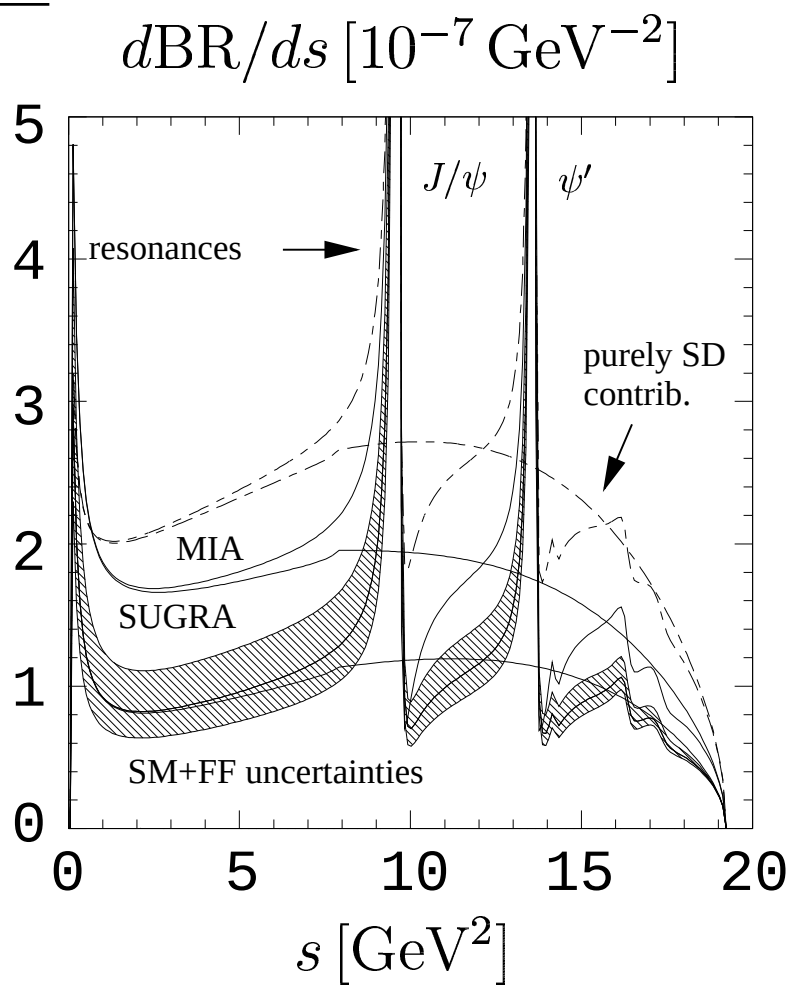
FB Asymmetry in $B \to K^* \ell\ell$

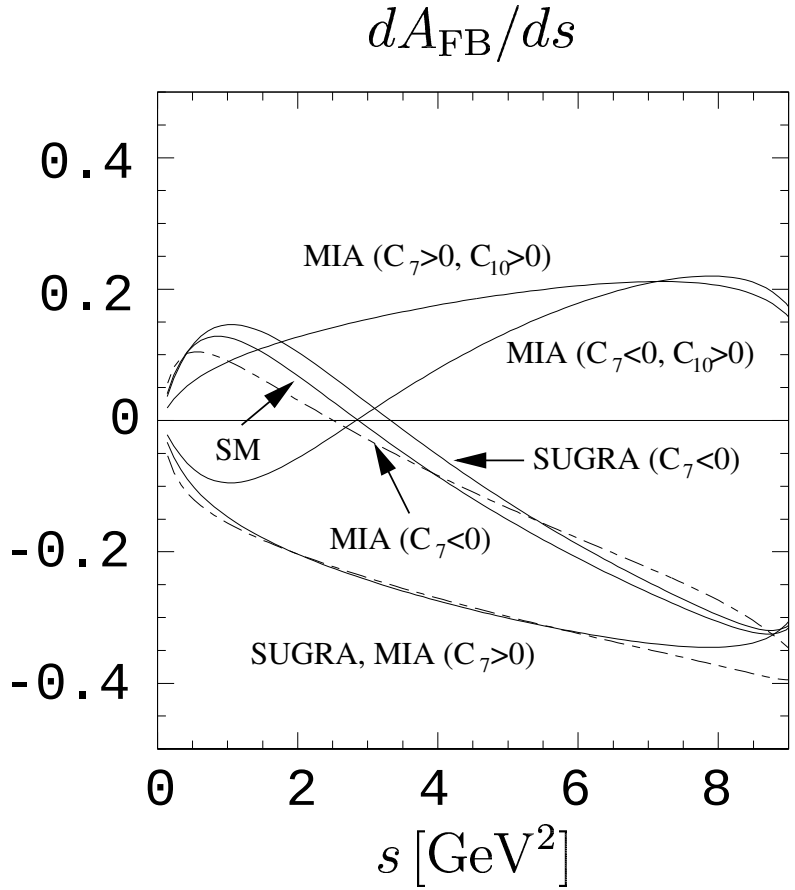




- dA_{FB}/ds has zero in SM, position determined by short-distance coefficients and form factors

FB Asymmetry in $B \to K^* \ell\ell$

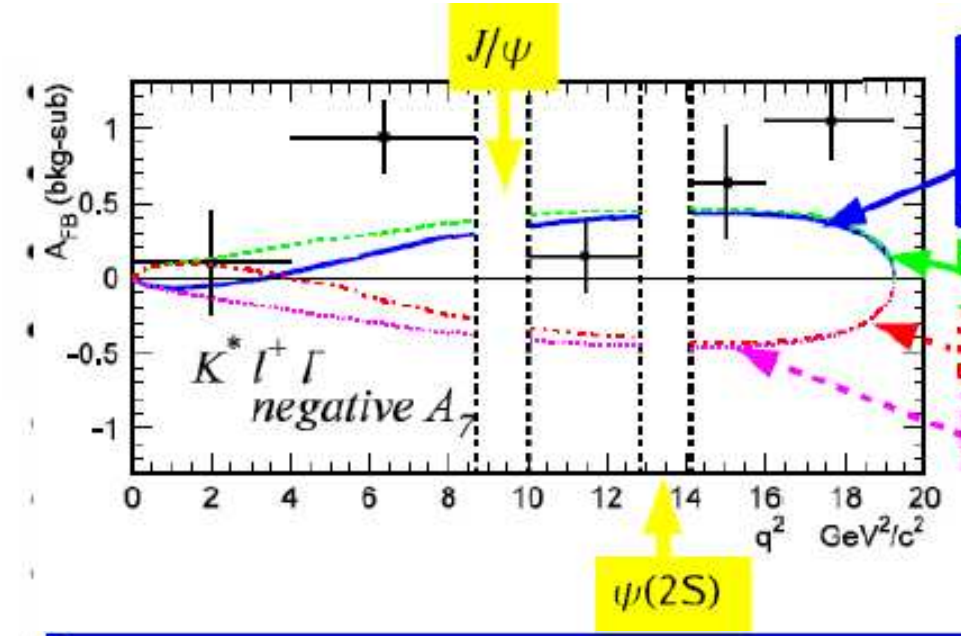




- part of hadronic uncertainties cancels in FB asymmetry

FB Asymmetry in $B \to K^* \ell\ell$

Belle data (presented by J. Berryhill (BaBar), Moriond 06):



fix $A_7 = -0.330$; $A_{FB} > 0$ at 3.4σ

$A_{FB}^{\text{bkg-sub}}(B \to K^* \ell\ell) = 0.56 \pm 0.13$ (stat.)

$A_7 A_{10}$ sign flipped | slightly worse fit, but OK

Both $A_7 A_{10}$ and $A_9 A_{10}$ signs flipped

$A_9 A_{10}$ sign flipped

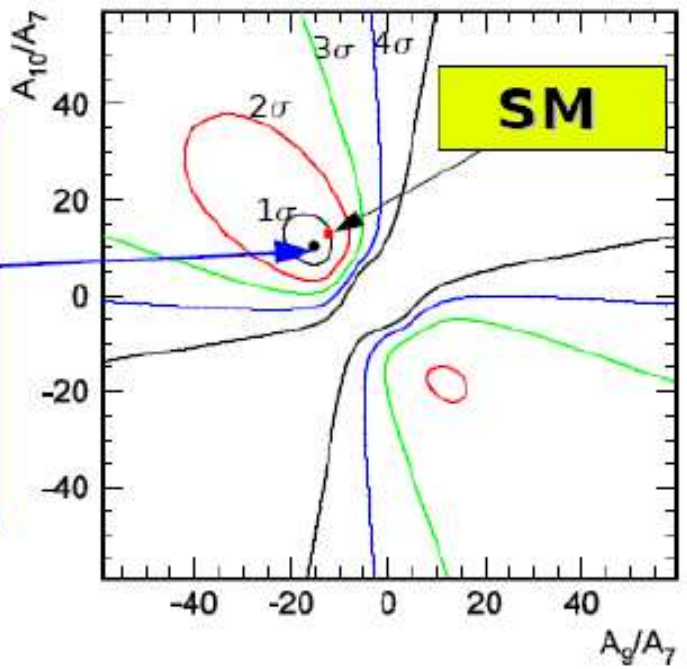
} excluded!

Wilson coefficients:

$A_9/A_7 = -15.3^{+3.4}_{-4.8} \pm 1.1$

$A_{10}/A_7 = 10.3^{+5.2}_{-3.5} \pm 1.8$ (A_7^{SM})

$-1401 < A_9 A_{10} / A_7^2 < -26.4$ (any A_7)



SM: $A_9/A_7 = -12.3$, $A_{10}/A_7 = 12.8$.

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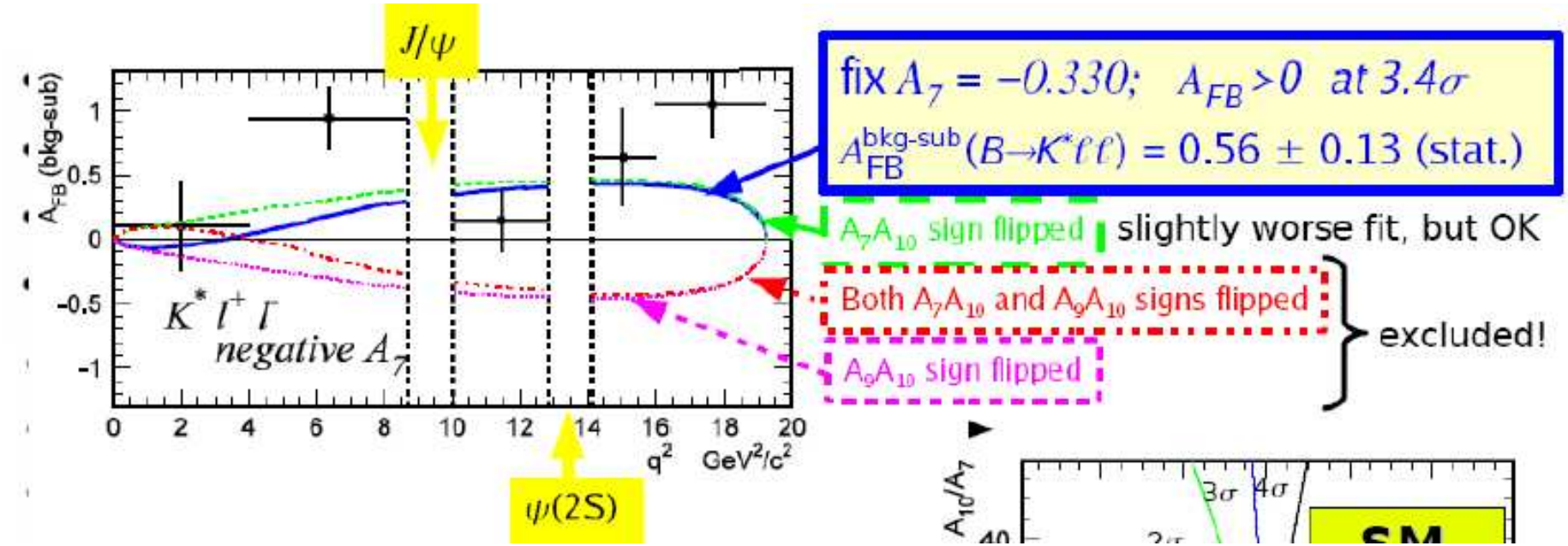

The fitted values for $A_{7,9,10}$ may actually be wrong: QCD factorisation does not work at large q^2 (unknown $O(\alpha_s)$, $1/m_b$ corrections). Better to rely on data at small $q^2 < 8\,\mathrm{GeV}^2$ only, where theory is better.

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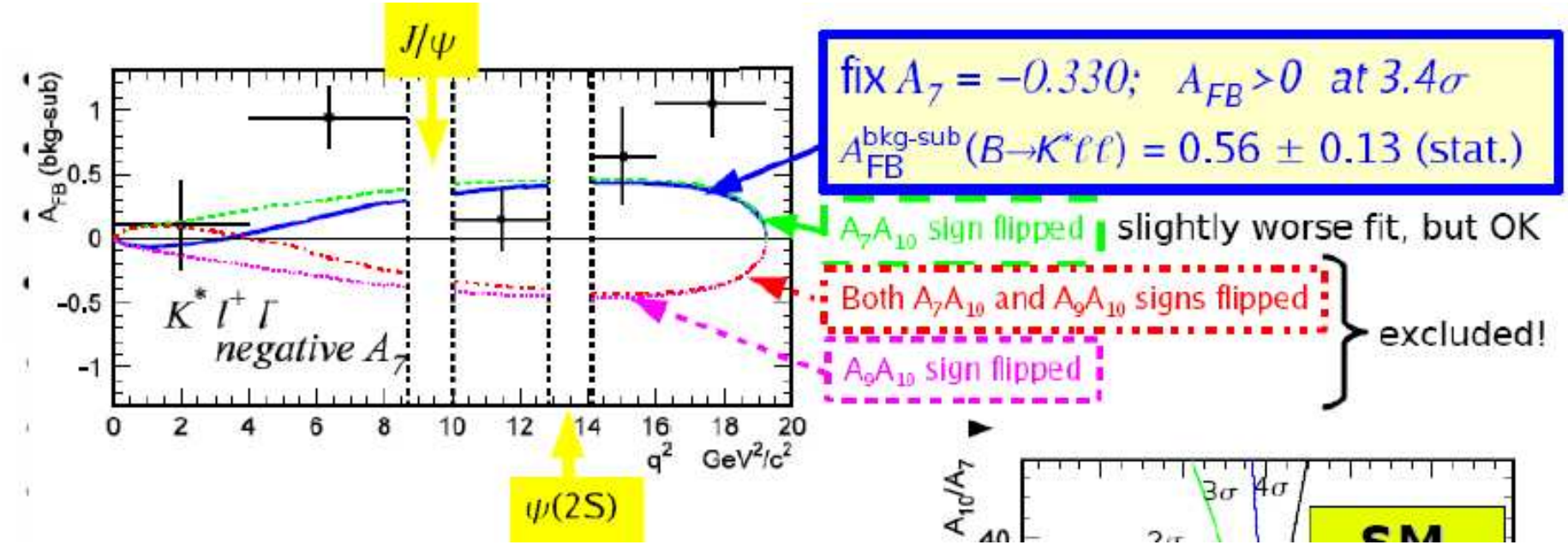
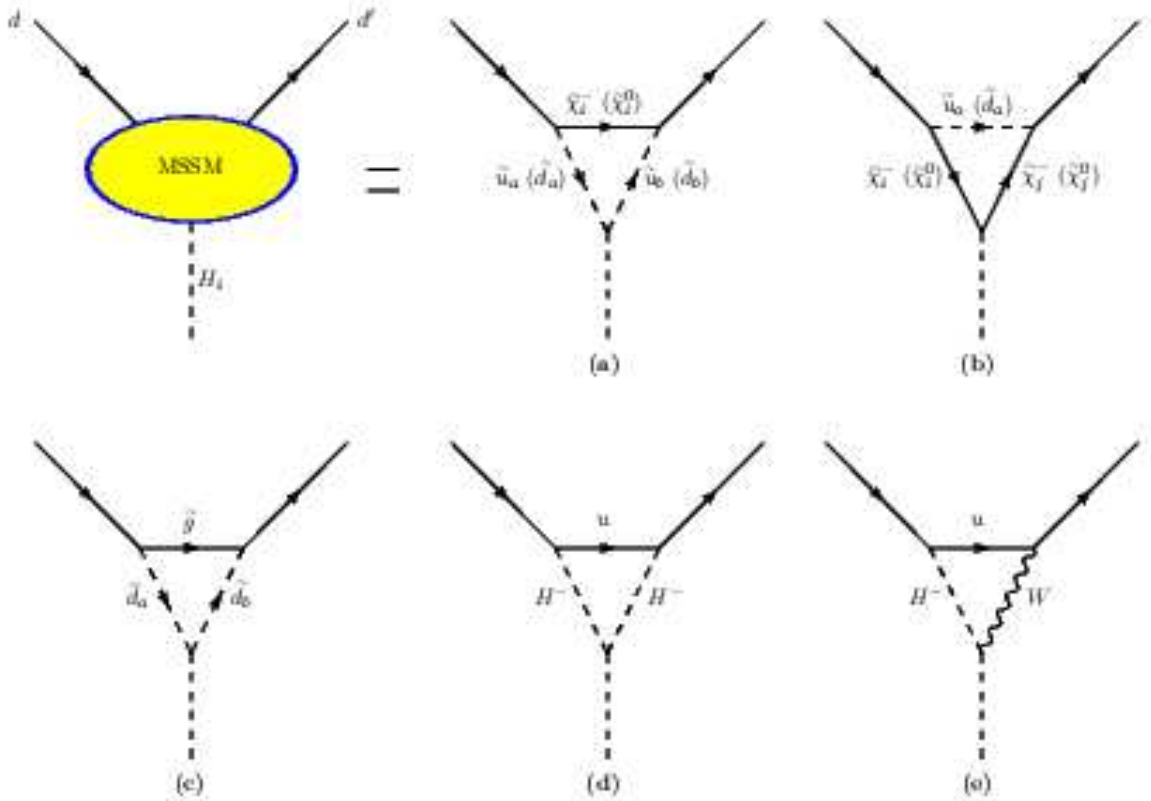


In any case, a reanalysis using recent form factor updates and a clean separation of leading and sub-leading (in $1/m_b$) terms would be timely & useful. (Ball/NN/Zwicky, planned)

And, not to forget, an analysis of all exclusive $b \to s\gamma$, $b \to s\ell\ell$ with an eye on mutual correlations.

$B_s \longrightarrow \mu^+\mu^-$

- GIM and helicity suppressed in SM, predicted BR: $4 \cdot 10^{-9}$
- current exp. bound: $8 \cdot 10^{-8}$ (CDF)
- SUSY Higgs penguins enhance BR with $\tan^6 \beta$



Dedes 03

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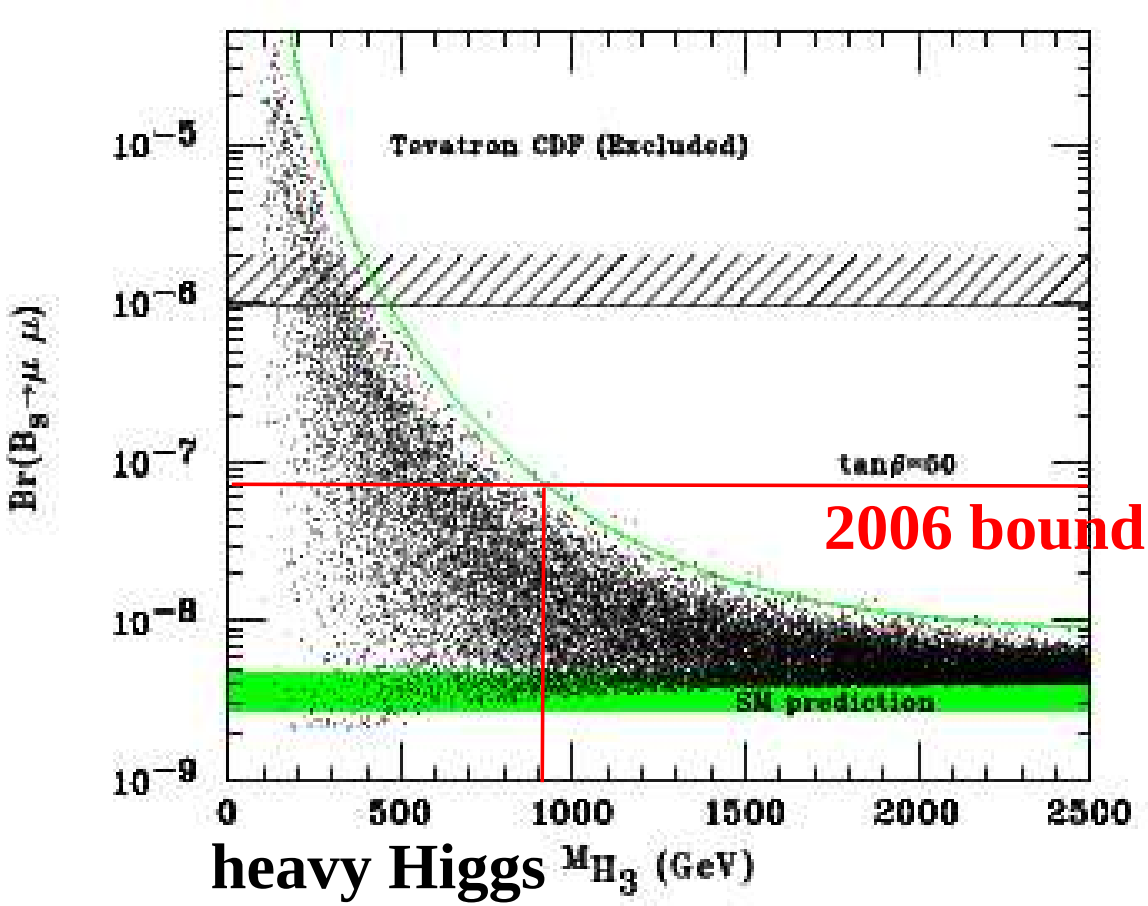

Still a factor of 20 for NP to hide!

Dedes 03

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The ultimate Higgs penguin: $B_s \to e\mu$:

Higgs induced FCNC + Higgs mediated lepton flavour violation!

Current bound on BR: $6 \cdot 10^{-6}$ (CDF).

Summary & Conclusions

- B physics @ LHC probes scalar sector of SM and BSM
- complementary to Higgs searches
- no huge deviations from SM (CKM) mechanism of flavour violation observed so far
- motivates postulate of Minimal Flavour Violation:
  NP contaings no new sources of flavour violation, modification of SM short-distance coefficients by $O(1)$ (at most)
- still plenty of space for NP in, e.g., B_s mixing and $b \to s$ transitions
- otherwise, look for small deviations from SM predictions/null tests of SM
- homework for theorists: work out correlation between exclusive $b \to s$ processes
- looking forward to precise measurements of $b \to s\ell\ell$ @ ATLAS!