Towards New Frontiers in Precision B Physics: Theoretical Challenges and Perspectives

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- Setting the Stage
- Focus on two major lines of research in B Physics @ LHC:
  - Rare decays: $B_s^0 \to \mu^+\mu^-$
  - CP violation: $B_s^0 \to J/\psi\phi \quad + \quad$ other modes.
- Conclusions & Outlook

Setting the Stage

Quark Flavour Physics & CP Violation

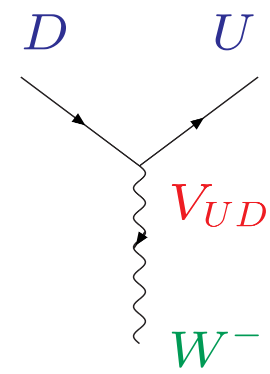
$\rightarrow$ $\boxed{\text{key players in the history of the Standard Model (SM):}}$

- 1963: concept of flavour mixing [Cabibbo].
- 1964: discovery of CP violation in $K_{\rm L} \to \pi^+\pi^-$ [Christenson *et al.*].
- 1970: introduction of the charm quark to suppress the flavour-changing neutral currents (FCNCs) [Glashow, Iliopoulos & Maiani].
- 1973: quark-flavour mixing with 3 generations allows us to accommodate CP violation in the SM [Kobayashi & Maskawa].
- 1974: estimate of the charm-quark mass with the help of the K^0–$\bar{K}^0$ mixing frequency [Gaillard & Lee].
- 1980s: the large top-quark mass was first suggested by the large B^0–$\bar{B}^0$ mixing seen by ARGUS (DESY) and UA1 (CERN).

flavour physics has since continued to progress ...

Quark-Flavour Physics in a Nutshell

- Quark-flavour mixing in the SM: $\to$ rich phenomenology

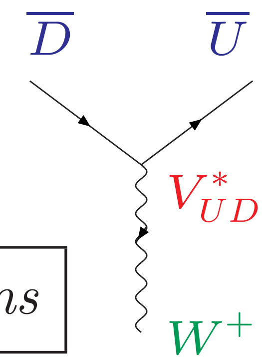


$$\left.\begin{array}{c}\text{flavour}\\ \text{eigen-}\\ \text{states}\end{array}\right\} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} \left\{\begin{array}{c}\text{mass}\\ \text{eigen-}\\ \text{states}\end{array}\right.$$

quark-mixing matrix, also known as

Cabibbo–Kobayashi–Maskawa matrix $\hat{V}_{\rm CKM}$

$\to$ *unitary* and *complex* matrix



$\Rightarrow$ $\boxed{\textit{encoded in weak decays of } K,\ D \textit{ and } B \textit{ mesons}}$

[antiquark–quark boundstates $\bar{q}Q$ with $Q{=}s$, c and b]

- The *key problem:* strong interactions $\to$ $\boxed{\text{“hadronic” uncertainties}}$

  – The theory is formulated in terms of quarks, while flavour-physics experiments use their QCD bound states, i.e. B, D and K mesons.

  – In the calculations of the relevant transition amplitudes, we encounter process-dependent, *non-perturbative “hadronic” parameters!?*

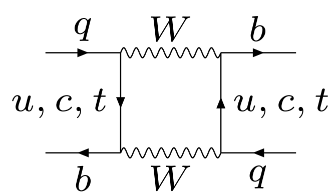
    [$\to$ lattice QCD: lots of progress for some parameters, but still challenging...]

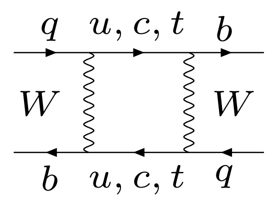
Particularly Interesting Flavour Probe: B Mesons

- Charged B mesons: $B^+ \sim u\,\bar{b} \qquad B^- \sim \bar{u}\,b$
  $B_c^+ \sim c\,\bar{b} \qquad B_c^- \sim \bar{c}\,b$

- Neutral B mesons: $B_d^0 \sim d\,\bar{b} \qquad \bar{B}_d^0 \sim \bar{d}\,b$
  $B_s^0 \sim s\,\bar{b} \qquad \bar{B}_s^0 \sim \bar{s}\,b$

  – B_q^0–$\bar{B}_q^0$ mixing: $\rightarrow$ *Quantum Mechanics*





$$\Rightarrow \quad \boxed{|B_q(t)\rangle = a(t)|B_q^0\rangle + b(t)|\bar{B}_q^0\rangle\ :}$$

  $*$ Schrödinger equation $\Rightarrow$ mass eigenstates:

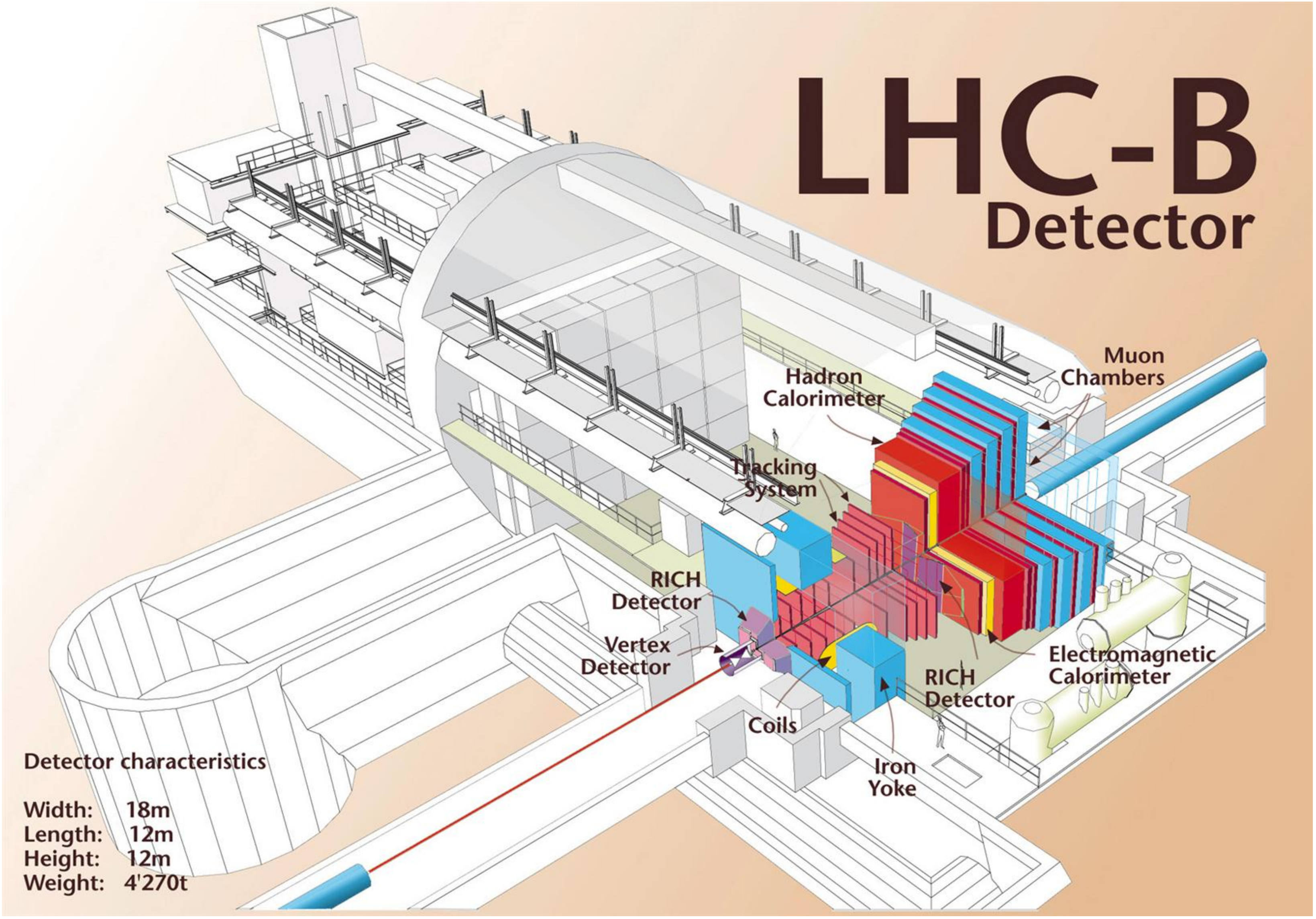
$$\boxed{\Delta M_q \equiv M_{\rm H}^{(q)} - M_{\rm L}^{(q)}, \quad \Delta\Gamma_q \equiv \Gamma_{\rm L}^{(q)} - \Gamma_{\rm H}^{(q)}}$$

  $*$ Decay rates: $\Gamma(\overset{(-)}{B_q^0}(t) \rightarrow \overset{(-)}{f})$:

$$\cos(\Delta M_q t)\ \&\ \sin(\Delta M_q t) \ \rightarrow\ \text{oscillations!}$$

- Outstanding features of the B-meson system for testing the SM:
  - Simplifications through the large b-quark mass $m_b \sim 5\,\text{GeV} \gg \Lambda_{\text{QCD}}$.
  - Offers various strategies to eliminate the hadronic uncertainties and to determine the hadronic parameters from the data.
  - Tests of SM relations that could be spoiled by physics beyond the SM.
  - Strongly suppressed "rare" decays, absent at the SM tree level.
- The last decade was governed by the e^+e^- B factories with the BaBar (SLAC) and Belle (KEK) experiments and B results from the Tevatron:
  - *CP-violating phenomena in B-meson decays could be established.*
  - The *interplay with theory* resulted in many new insights.
- But large territory of the B landscape was left essentially unexplored:

$\boxed{B_s \text{ system}}$ $\rightarrow$ *major target of another LHC experiment:* $\boxed{\text{LHCb}}$



[Further information: `http://lhcb-public.web.cern.ch/lhcb-public/`]

Hope for New Physics (NP) ...

- We have indications that the SM *cannot* be complete:
  - Neutrino masses $\neq 0$: suggest see-saw mechanism, GUT scenarios ...
  - Baryon asymmetry of the Universe (SM cannot generate it ...)
  - The long-standing problem of dark matter (?)

- Fundamental theoretical questions/problems:
  - Hierarchy problem
  - Fine-tuning problem $\rightarrow$ $\boxed{\text{suggest NP in the TeV regime (!?)}}$

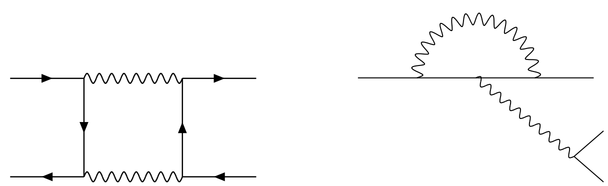
- Popular specific models for physics beyond the SM:
  - Supersymmetry (SUSY)
  - Universal extra dimension (UED)
  - Warped extra dimension (WED)
  - Little Higgs models (LH, with T parity LHT)
  - Z' models
  - ... $\rightarrow$ $\boxed{\text{new sources of flavour \& CP violation}}$

How to Search for Physics Beyond the SM?

- Search for *direct* signals of NP: $\Rightarrow$ $\boxed{\text{physics @ ATLAS} \oplus \text{CMS}}$
  - Produce new particles (e.g. squarks, gauge bosons, ...) at colliders;
  - Study the decays of the new particles in general purpose detectors ...

$\rightarrow$ *high-energy frontier*

- Search for *indirect* footprints of NP: $\Rightarrow$ $\boxed{B \text{ (flavour) physics @ LHCb}}$
  - Sensitivity to NP effects through *virtual quantum effects:*

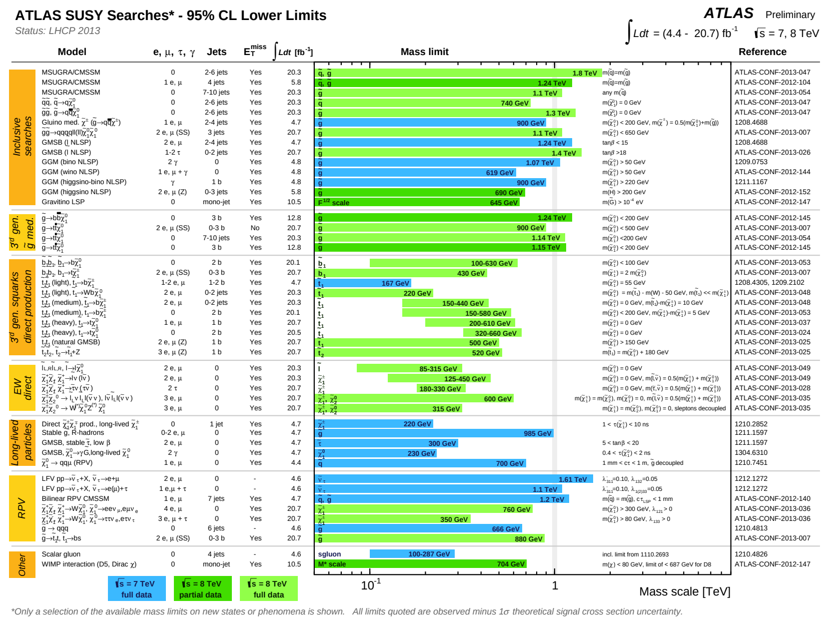


$\rightarrow$ *high-precision frontier* $\rightarrow$ $\boxed{\text{focus of this talk}}$

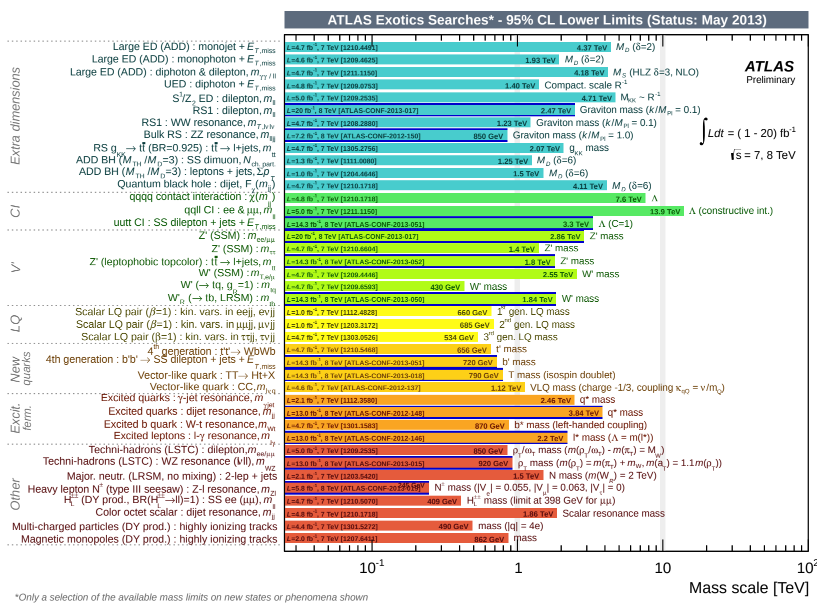
$\Rightarrow$ $\boxed{\text{expect synergy between both avenues to search for NP}}$

News from the LHC High-Energy Frontier

- Examples of NP searches @ ATLAS: $\rightarrow$ *no signals* (CMS similar)
  - SUSY:

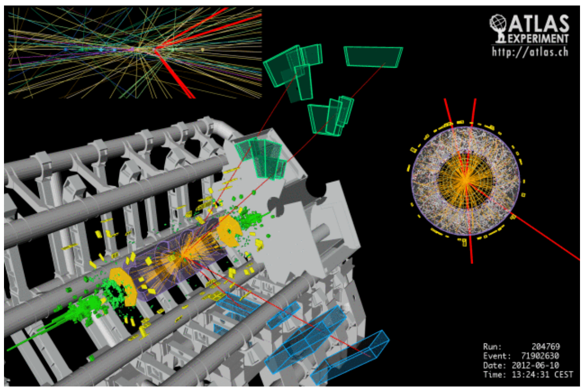


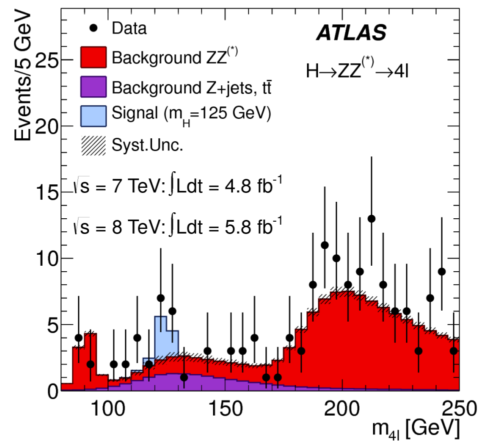
  - Exotics:

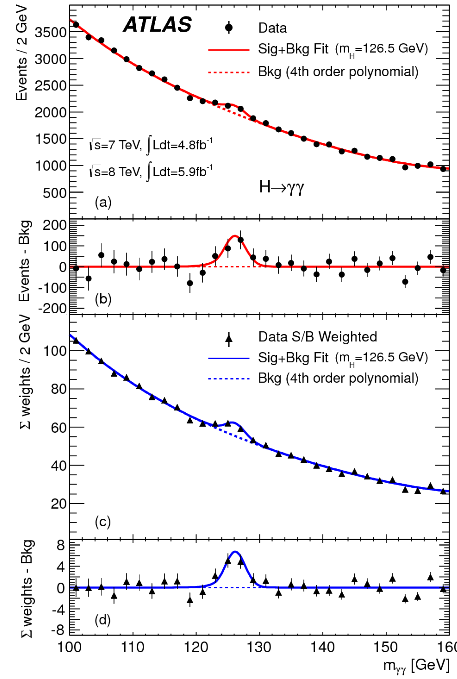


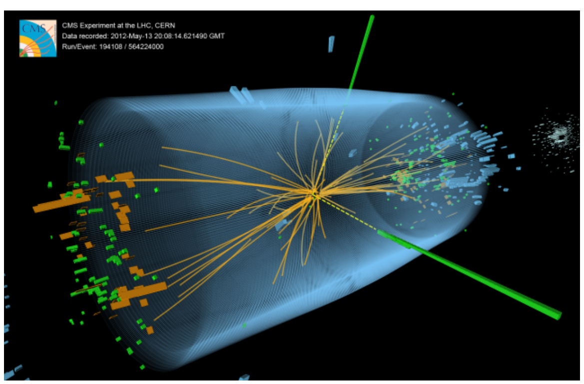
... but “Higgs-like” particle @ ATLAS and CMS!

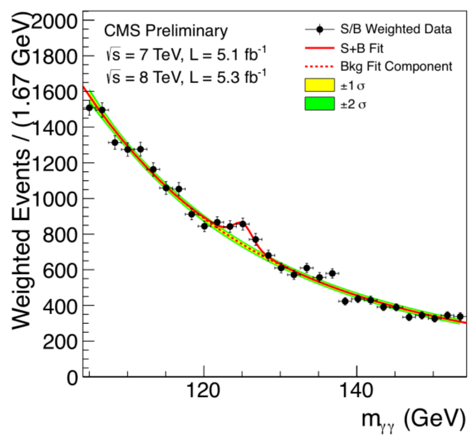
- The last missing SM piece (?): some results ...

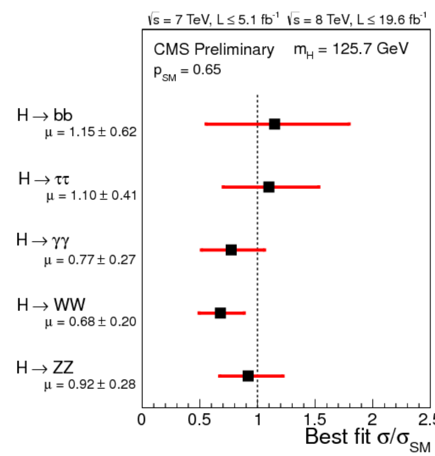












Where Do We Stand?

- News from Physics @ LHC: $\rightarrow$ discovery of "Higgs-like" particle, but ...
  - No SM deviations seen at ATLAS and CMS.
  - No solid evidence for NP in the flavour sector, just a few "puzzles" and "tensions" with the SM ...

- Implications for the structure of NP:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}(\varphi_{\rm NP}, g_{\rm NP}, m_{\rm NP}, ...)$$

  - Large characteristic NP scale $\Lambda_{\rm NP}$, i.e. not just $\sim$ TeV, which would be bad news for the direct searches at ATLAS and CMS, or (and?) ...
  - Symmetries prevent large NP effects in FCNCs and the flavour sector; most prominent example: *Minimal Flavour Violation (MFV).*

- Much more is yet to come: ...

... but prepare to deal with "smallish/challenging" NP effects!

Remainder of this talk:

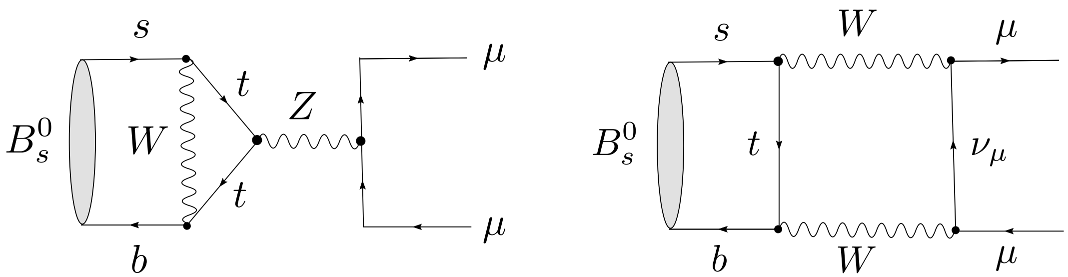
$\rightarrow$ focus on two *key topics:*

- Rare B decays: new aspects of $B_s^0 \to \mu^+\mu^-$
- Precision studies of CP violation in B decays

$$\boxed{B_s^0 \to \mu^+\mu^-}$$

General Features

- Situation in the SM: $\rightarrow$ only loop contributions:



  - Moreover: helicity suppression $\rightarrow$ BR $\propto m_\mu^2$

$$\Rightarrow \boxed{\text{strongly suppressed decay}}$$

- Hadronic sector: $\rightarrow$ very simple, only the B_s decay constant F_{B_s} enters:

$$\langle 0|\bar{b}\gamma_5\gamma_\mu s|B_s^0(p)\rangle = iF_{B_s}p_\mu$$

$$\Rightarrow \boxed{B_s^0 \rightarrow \mu^+\mu^- \text{ belongs to the cleanest rare } B \text{ decays}}$$

SM Prediction(s) of the $B_s \to \mu^+\mu^-$ Branching Ratio

- Parametric dependence on the relevant input parameters:

  [Refers to the "theoretical" branching ratio, see discussion below]

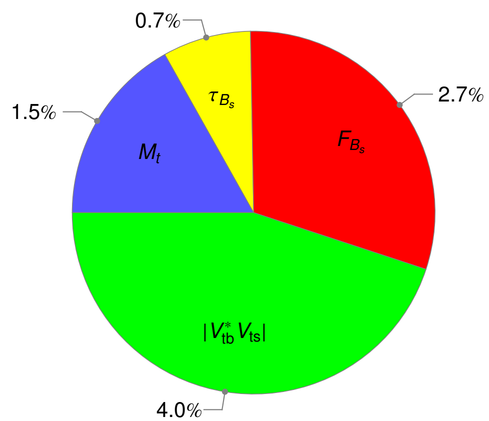
$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.25 \times 10^{-9} \times \left[\frac{M_t}{173.2\,\mathrm{GeV}}\right]^{3.07} \left[\frac{F_{B_s}}{225\,\mathrm{MeV}}\right]^2 \left[\frac{\tau_{B_s}}{1.500\mathrm{ps}}\right] \left|\frac{V_{tb}^* V_{ts}}{0.0405}\right|^2$$

[Buras, Girrbach, Guadagnoli & Isidori (2012); address also soft photon corrections]

- Most relevant recent changes:
  - New lattice picture [Dowdall *et al.*, arXiv:1302.2644]: $F_{B_s} = (225 \pm 3)$ MeV
  - Experiment [Heavy Flavour Averaging Group (HFAG)]: $\tau_{B_s} = 1.503(10)$ ps

$$\Rightarrow \boxed{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.25 \pm 0.17) \times 10^{-9}}$$

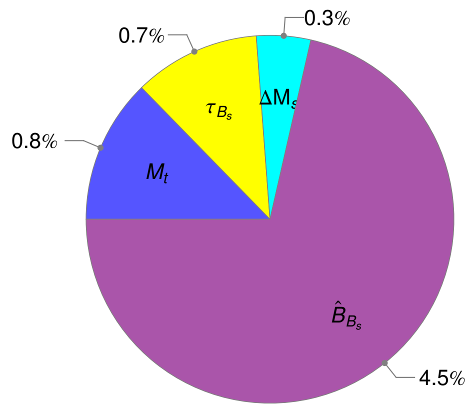
[A.J. Buras, R.F., J. Girrbach & R. Knegjens (2013)]



- While the small lattice QCD error on F_{B_s} is expected to be consolidated soon, the decrease of the error in $|V_{ts}|$ appears to be much harder:

  $\Rightarrow$ use B_s mass difference ΔM_s for normalization [A.J. Buras (2003)]:

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.38 \times 10^{-9} \times \left[\frac{M_t}{173.2\,\mathrm{GeV}}\right]^{1.6} \left[\frac{\tau_{B_s}}{1.500\mathrm{ps}}\right] \left[\frac{1.33}{\hat{B}_{B_s}}\right] \left[\frac{\Delta M_s}{17.72/\mathrm{ps}}\right]$$



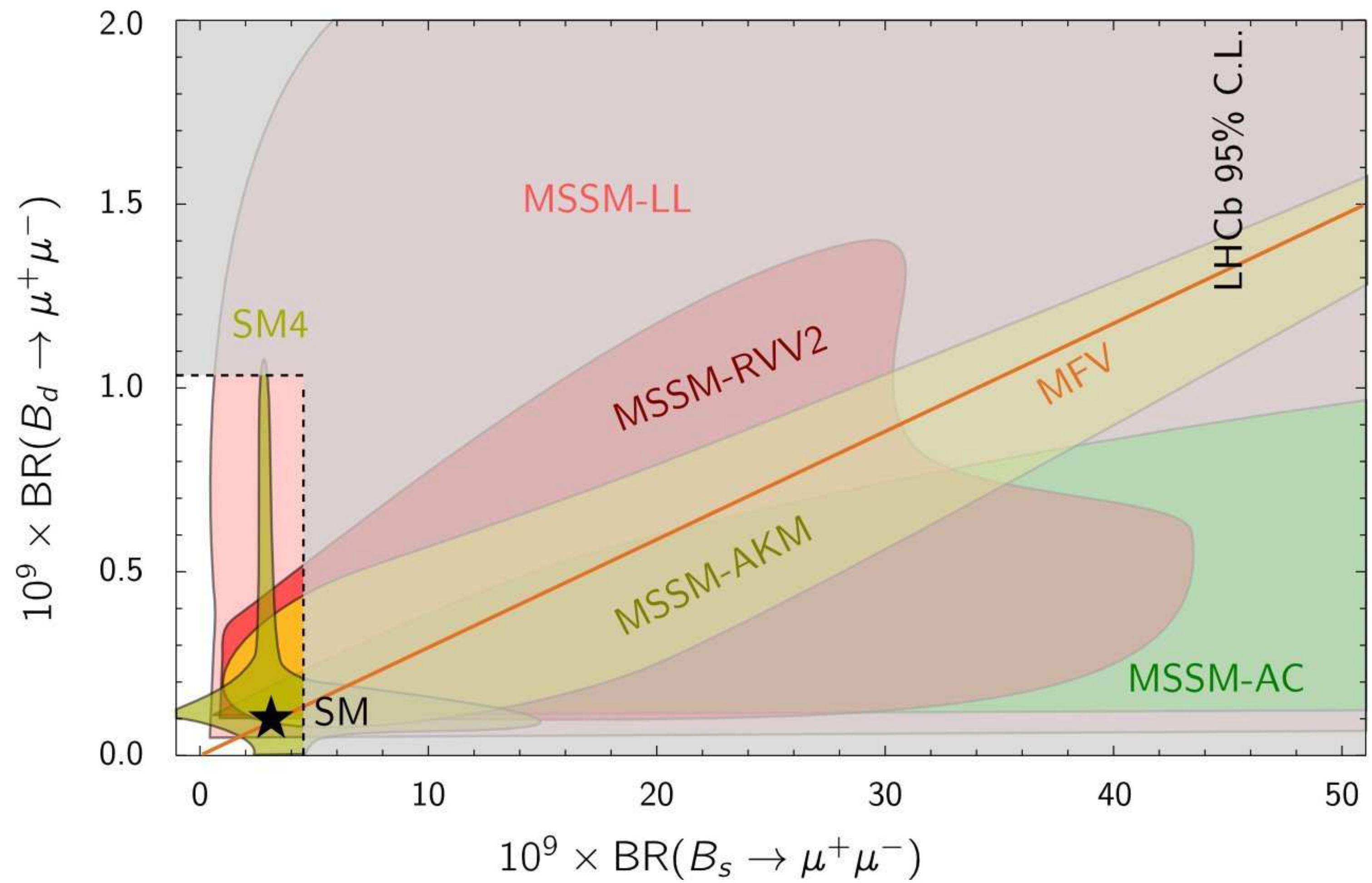
- Comments:
  - Assumes that there are no NP contributions to ΔM_s.
  - Prefer to use $\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.25 \pm 0.17) \times 10^{-9}$ as discussed above as the best estimate of the theoretical SM branching ratio.

[A.J. Buras, R.F., J. Girrbach & R. Knegjens (2013)]

Impact of NP on the $B_{s(d)} \to \mu^+\mu^-$ Branching Ratios

- May (in principle ...) enhance the branching ratios significantly:

  $\to$ illustration in different supersymmetric flavour models:



[D. Straub (2010); A.J. Buras & J. Girrbach (2012)]

Current Experimental Status of $B_s \to \mu^+\mu^-$

- Tevatron: $\to$ *"legacy"* ...
  - DØ (2013): BR$(B_s \to \mu^+\mu^-) < 15 \times 10^{-9}$ (95% C.L.)
  - CDF (2013): BR$(B_s \to \mu^+\mu^-) < 31 \times 10^{-9}$ (95% C.L.)

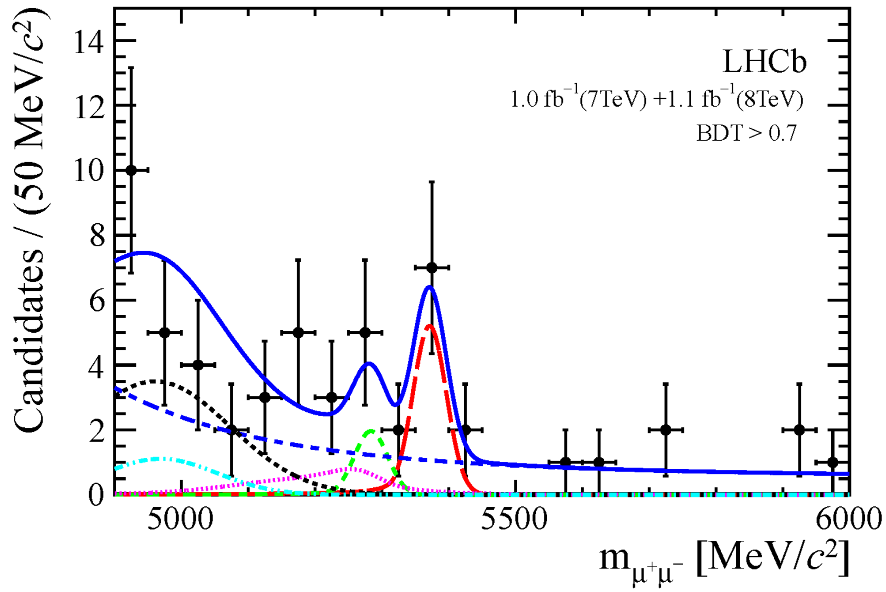
- Large Hardon Collider: $\to$ *future* ...
  - ATLAS (2012): BR$(B_s \to \mu^+\mu^-) < 22 \times 10^{-9}$ (95% C.L.)
  - CMS (2012): BR$(B_s \to \mu^+\mu^-) < 7.7 \times 10^{-9}$ (95% C.L.)
  - Finally *first evidence* for $B_s \to \mu^+\mu^-$ @ LHCb (2012):

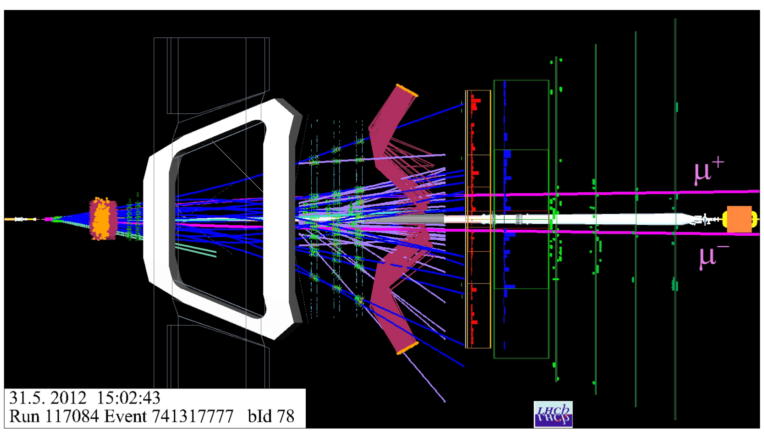
$$\boxed{\text{BR}(B_s \to \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}}$$

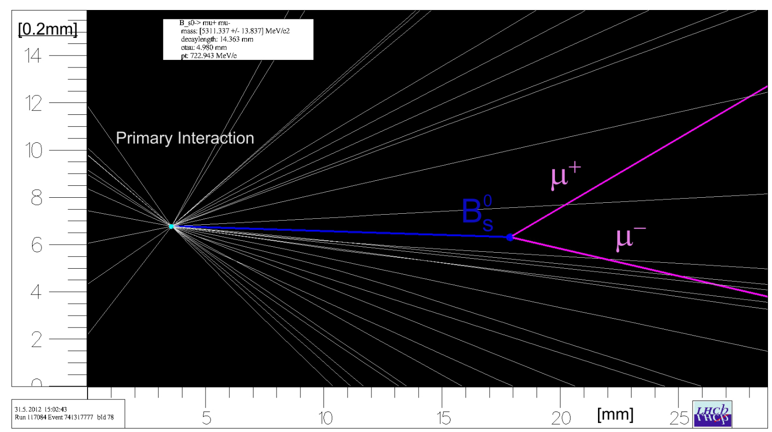
$\Rightarrow$ *falls into the SM regime although the error is still very large ...*

- Note: *the* limiting factor for the BR$(B_s \to \mu^+\mu^-)$ measurement – and all B_s branching ratios – is the ratio of f_s/f_d fragmentation functions.

[Details: R.F., Serra & Tuning (2010); Fermilab Lattice & MILC Collaborations (2012)]







- <u>Comment:</u> $\text{BR}(B_d \to \mu^+\mu^-)|_{\text{LHCb}} < 9.4 \times 10^{-10}$ (95% C.L.)

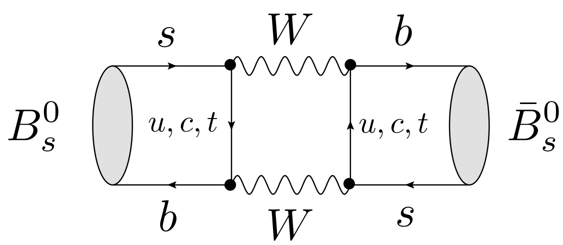
[Review of experimental $B_{s,d} \to \mu^+\mu^-$ analyses: J. Albrecht (2012)]

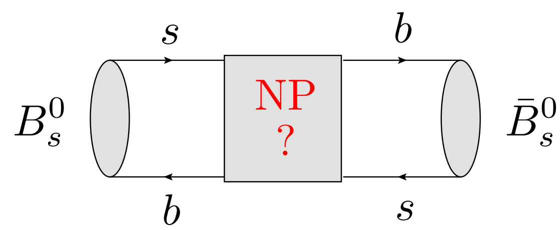
$\boxed{\text{Recent Development:}}$

$\diamond$ Concerning a – seemingly – unrelated topic:

$\rightarrow$ *Interlude* ...

B_s^0–$\bar{B}_s^0$ Mixing & $\Delta\Gamma_s$





- Quantum mechanics: $\Rightarrow \quad |B_s(t)\rangle = a(t)|B_s^0\rangle + b(t)|\bar{B}_s^0\rangle$
  - Mass eigenstates: $\Delta M_s \equiv M_{\mathrm{H}}^{(s)} - M_{\mathrm{L}}^{(s)}, \quad \Delta\Gamma_s \equiv \Gamma_{\mathrm{L}}^{(s)} - \Gamma_{\mathrm{H}}^{(s)}$
  - Time-dependent decay rates: $\Gamma(B_s^0(t) \to f), \quad \Gamma(\bar{B}_s^0(t) \to f)$

- Key feature of the B_s-meson system: $\boxed{\Delta\Gamma_s \neq 0}$
  - Expected theoretically since decades [Recent review: A. Lenz (2012)].
  - Established by LHCb at the $6\,\sigma$ level [LHCb-CONF-2012-002]:

$$y_s \equiv \frac{\Delta\Gamma_s}{2\,\Gamma_s} \equiv \frac{\Gamma_{\mathrm{L}}^{(s)} - \Gamma_{\mathrm{H}}^{(s)}}{2\,\Gamma_s} = 0.088 \pm 0.014$$

$$\tau_{B_s}^{-1} \equiv \Gamma_s \equiv \frac{\Gamma_{\mathrm{L}}^{(s)} + \Gamma_{\mathrm{H}}^{(s)}}{2} = (0.6580 \pm 0.0085)\ \text{ps}^{-1}$$

B_s Branching Ratios:

- $\Delta\Gamma_s \neq 0 \Rightarrow$ *special care* has to be taken when dealing with the concept of a branching ratio ...

- How to *convert* measured "experimental" B_s branching ratios into "theoretical" B_s branching ratios?

[De Bruyn, R.F., Knegjens, Koppenburg, Merk and Tuning
Phys. Rev. **D 86** (2012) 014027 [arXiv:1204.1735 [hep-ph]]]

Experiment vs. Theory

- Untagged B_s decay rate: $\to$ *sum of two exponentials:*

$$\langle\Gamma(B_s(t)\to f)\rangle \equiv \Gamma(B^0_s(t)\to f)+\Gamma(\bar{B}^0_s(t)\to f) = R^f_{\rm H}e^{-\Gamma^{(s)}_{\rm H}t}+R^f_{\rm L}e^{-\Gamma^{(s)}_{\rm L}t}$$

$$= \left(R^f_{\rm H}+R^f_{\rm L}\right)e^{-\Gamma_s t}\left[\cosh\left(\frac{y_s\, t}{\tau_{B_s}}\right)+\mathcal{A}^f_{\Delta\Gamma}\sinh\left(\frac{y_s\, t}{\tau_{B_s}}\right)\right]$$

- "Experimental" branching ratio: [I. Dunietz, R.F. & U. Nierste (2001)]

$$\mathrm{BR}\,(B_s\to f)_{\rm exp}\equiv\frac{1}{2}\int_0^\infty\langle\Gamma(B_s(t)\to f)\rangle\,dt$$

$$=\frac{1}{2}\left[\frac{R^f_{\rm H}}{\Gamma^{(s)}_{\rm H}}+\frac{R^f_{\rm L}}{\Gamma^{(s)}_{\rm L}}\right]=\frac{\tau_{B_s}}{2}\left(R^f_{\rm H}+R^f_{\rm L}\right)\left[\frac{1+\mathcal{A}^f_{\Delta\Gamma}\,y_s}{1-y_s^2}\right] \qquad (6)$$

- "Theoretical" branching ratio: [R.F. (1999); S. Faller, R.F. & T. Mannel (2008); ...]

$$\mathrm{BR}\,(B_s\to f)_{\rm theo}\equiv\frac{\tau_{B_s}}{2}\langle\Gamma(B^0_s(t)\to f)\rangle\Big|_{t=0}=\frac{\tau_{B_s}}{2}\left(R^f_{\rm H}+R^f_{\rm L}\right) \qquad (8)$$

  – By considering $t=0$, the effect of B^0_s–$\bar{B}^0_s$ mixing is "switched off".

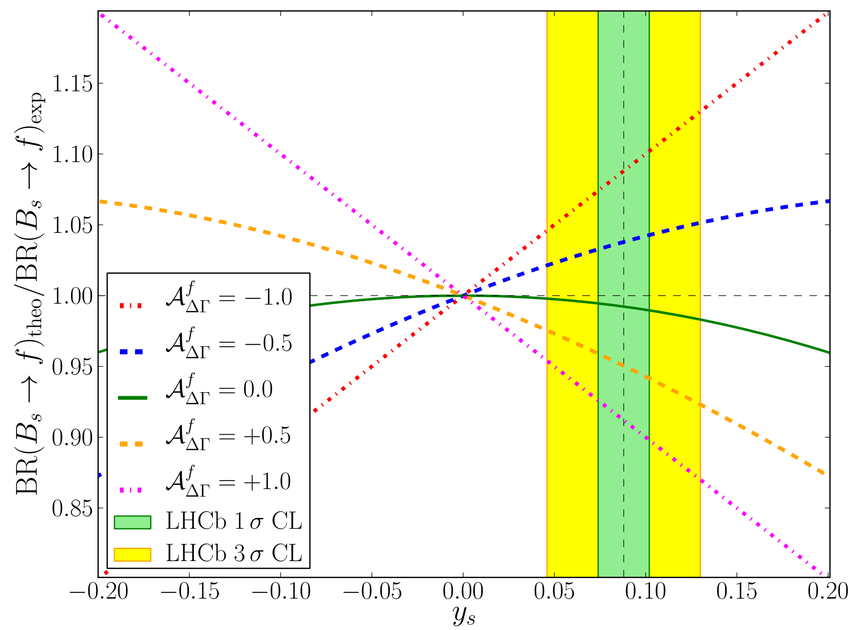
  – The advantage of this definition is that it allows a straightforward comparison with the BRs of B^0_d or B^+_u mesons by means of $SU(3)_{\rm F}$.

Conversion of B_s Decay Branching Ratios

- Relation between $\mathrm{BR}\,(B_s \to f)_{\rm theo}$ and the measured $\mathrm{BR}\,(B_s \to f)_{\rm exp}$:

$$\mathrm{BR}\,(B_s \to f)_{\rm theo} = \left[\frac{1-y_s^2}{1+\mathcal{A}^f_{\Delta\Gamma}\, y_s}\right] \mathrm{BR}\,(B_s \to f)_{\rm exp} \tag{9}$$

- While $y_s = 0.088 \pm 0.014$ has been measured, $\mathcal{A}^f_{\Delta\Gamma}$ depends on the considered decay and generally involves non-perturbative parameters:



$\Rightarrow$ $\boxed{\text{differences can be as large as } \mathcal{O}(10\%) \text{ for the current value of } y_s}$

- Compilation of theoretical estimates for specific B_s decays:

$B_s \to f$	$\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$	$\mathcal{A}^f_{\Delta\Gamma}(\mathrm{SM})$	$\mathrm{BR}\,(B_s \to f)_{\mathrm{theo}}\,/\mathrm{BR}\,(B_s \to f)_{\mathrm{exp}}$ From Eq. (9)	From Eq. (11)
$J/\psi f_0(980)$	$(1.29^{+0.40}_{-0.28}) \times 10^{-4}$ [18]	0.9984 ± 0.0021 [14]	0.912 ± 0.014	0.890 ± 0.082 [6]
$J/\psi K_{\mathrm{S}}$	$(3.5 \pm 0.8) \times 10^{-5}$ [7]	0.84 ± 0.17 [15]	0.924 ± 0.018	N/A
$D_s^- \pi^+$	$(3.01 \pm 0.34) \times 10^{-3}$ [9]	0 (exact)	0.992 ± 0.003	N/A
K^+K^-	$(3.5 \pm 0.7) \times 10^{-5}$ [18]	-0.972 ± 0.012 [13]	1.085 ± 0.014	1.042 ± 0.033 [19]
$D_s^+ D_s^-$	$(1.04^{+0.29}_{-0.26}) \times 10^{-2}$ [18]	-0.995 ± 0.013 [16]	1.088 ± 0.014	N/A

TABLE I: Factors for converting $\mathrm{BR}\,(B_s \to f)_{\mathrm{exp}}$ (see (6)) into $\mathrm{BR}\,(B_s \to f)_{\mathrm{theo}}$ (see (8)) by means of Eq. (9) with theoretical estimates for $\mathcal{A}^f_{\Delta\Gamma}$. Whenever effective lifetime information is available, the corrections are also calculated using Eq. (11).

How can we avoid theoretical input? $\to$

- Effective B_s decay lifetimes:

$$\tau_f \equiv \frac{\int_0^\infty t\,\langle\Gamma(B_s(t) \to f)\rangle\,dt}{\int_0^\infty \langle\Gamma(B_s(t) \to f)\rangle\,dt} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1+2\,\mathcal{A}^f_{\Delta\Gamma}y_s+y_s^2}{1+\mathcal{A}^f_{\Delta\Gamma}y_s}\right]$$

$$\Rightarrow \boxed{\mathrm{BR}\,(B_s \to f)_{\mathrm{theo}} = \left[2-\left(1-y_s^2\right)\tau_f/\tau_{B_s}\right]\mathrm{BR}\,(B_s \to f)_{\mathrm{exp}}} \qquad (11)$$

$\to$ *advocate the use of this relation for Particle Listings.*

Key B_s Decay: $B_s \to \mu^+\mu^-$

- Experimental BR falls into the SM regime ...
- What is the impact of $\Delta\Gamma_s \neq 0$ on this channel?

$\to$ *Opens actually a new window for New Physics*

[De Bruyn, R.F., Knegjens, Koppenburg, Merk, Pellegrino and Tuning
Phys. Rev. Lett. **109** (2012) 041801 [arXiv:1204.1737 [hep-ph]]]

The General $B_s \to \mu^+\mu^-$ Amplitudes

- Low-energy effective Hamiltonian for $\bar{B}^0_s \to \mu^+\mu^-$: $\boxed{\text{SM} \oplus \text{NP}}$

$$\mathcal{H}_{\text{eff}} = -\frac{G_{\text{F}}}{\sqrt{2}\pi} V_{ts}^* V_{tb} \alpha \left[C_{10} O_{10} + C_S O_S + C_P O_P + C'_{10} O'_{10} + C'_S O'_S + C'_P O'_P \right]$$

[G_{F}: Fermi's constant, $V_{qq'}$: CKM matrix elements, α: QED fine structure constant]

- Four-fermion operators, with $P_{L,R} \equiv (1 \mp \gamma_5)/2$ and b-quark mass m_b:

$$\begin{array}{rclrcl} O_{10} & = & (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell), & O'_{10} & = & (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell) \\ O_S & = & m_b(\bar{s}P_R b)(\bar{\ell}\ell), & O'_S & = & m_b(\bar{s}P_L b)(\bar{\ell}\ell) \\ O_P & = & m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell), & O'_P & = & m_b(\bar{s}P_L b)(\bar{\ell}\gamma_5\ell) \end{array}$$

[Only operators with non-vanishing $\bar{B}^0_s \to \mu^+\mu^-$ matrix elements are included]

- The Wilson coefficients C_i, C'_i encode the short-distance physics:
  - SM case: only $C_{10} \neq 0$, and is given by the *real* coefficient C_{10}^{SM}.
  - *Outstanding feature of* $\bar{B}^0_s \to \mu^+\mu^-$: sensitivity to (pseudo-)scalar lepton densities $\to O_{(P)S}$, $O'_{(P)S}$; WCs are still largely unconstrained.

[W. Altmannshofer, P. Paradisi & D. Straub (2011) $\to$ model-independent NP analysis]

$\rightarrow$ *convenient to go to the rest frame of the decaying $\bar{B}_s^0$ meson:*

- Distinguish between the $\mu_{\rm L}^+\mu_{\rm L}^-$ and $\mu_{\rm R}^+\mu_{\rm R}^-$ helicity configurations:

$$|(\mu_{\rm L}^+\mu_{\rm L}^-)_{\rm CP}\rangle \equiv (\mathcal{CP})|\mu_{\rm L}^+\mu_{\rm L}^-\rangle = e^{i\phi_{\rm CP}(\mu\mu)}|\mu_{\rm R}^+\mu_{\rm R}^-\rangle$$

[$e^{i\phi_{\rm CP}(\mu\mu)}$ is a convention-dependent phase factor $\rightarrow$ cancels in observables]

- General expression for the decay amplitude [$\eta_{\rm L}=+1$, $\eta_{\rm R}=-1$]:

$$A(\bar{B}_s^0\to\mu_\lambda^+\mu_\lambda^-) = \langle\mu_\lambda^-\mu_\lambda^+|\mathcal{H}_{\rm eff}|\bar{B}_s^0\rangle = -\frac{G_{\rm F}}{\sqrt{2}\pi}V_{ts}^*V_{tb}\alpha$$

$$\times F_{B_s}M_{B_s}m_\mu C_{10}^{\rm SM}e^{i\phi_{\rm CP}(\mu\mu)(1-\eta_\lambda)/2}\left[\eta_\lambda P+S\right]$$

- Combination of Wilson coefficient functions [CP-violating phases $\varphi_{P,S}$]:

$$P\equiv|P|e^{i\varphi_P}\equiv\frac{C_{10}-C_{10}'}{C_{10}^{\rm SM}}+\frac{M_{B_s}^2}{2\,m_\mu}\left(\frac{m_b}{m_b+m_s}\right)\left(\frac{C_P-C_P'}{C_{10}^{\rm SM}}\right)\xrightarrow{\rm SM}1$$

$$S\equiv|S|e^{i\varphi_S}\equiv\sqrt{1-4\frac{m_\mu^2}{M_{B_s}^2}}\frac{M_{B_s}^2}{2\,m_\mu}\left(\frac{m_b}{m_b+m_s}\right)\left(\frac{C_S-C_S'}{C_{10}^{\rm SM}}\right)\xrightarrow{\rm SM}0$$

[F_{B_s}: B_s decay constant, M_{B_s}: B_s mass, m_μ: muon mass, m_s: strange-quark mass]

The $B_s \to \mu^+\mu^-$ Observables

- Key quantity for calculating the CP asymmetries and the untagged rate:

$$\xi_\lambda \equiv -e^{-i\phi_s}\left[e^{i\phi_{\mathrm{CP}}(B_s)}\frac{A(\bar{B}^0_s \to \mu^+_\lambda\mu^-_\lambda)}{A(B^0_s \to \mu^+_\lambda\mu^-_\lambda)}\right]$$

$\Rightarrow A(B^0_s \to \mu^+_\lambda\mu^-_\lambda) = \langle \mu^-_\lambda\mu^+_\lambda|\mathcal{H}^\dagger_{\mathrm{eff}}|B^0_s\rangle$ is also needed ...

- Using $(\mathcal{CP})^\dagger(\mathcal{CP}) = \hat{1}$ and $(\mathcal{CP})|B^0_s\rangle = e^{i\phi_{\mathrm{CP}}(B_s)}|\bar{B}^0_s\rangle$ yields:

$$A(B^0_s \to \mu^+_\lambda\mu^-_\lambda) = -\frac{G_{\mathrm{F}}}{\sqrt{2}\pi}V_{ts}V^*_{tb}\alpha f_{B_s}M_{B_s}m_\mu C^{\mathrm{SM}}_{10}$$

$$\times\, e^{i[\phi_{\mathrm{CP}}(B_s)+\phi_{\mathrm{CP}}(\mu\mu)(1-\eta_\lambda)/2]}\left[-\eta_\lambda P^* + S^*\right]$$

- The convention-dependent phases cancel in ξ_λ $[\eta_{\mathrm{L}} = +1,\ \eta_{\mathrm{R}} = -1]$:

$$\xi_\lambda = -\left[\frac{+\eta_\lambda P + S}{-\eta_\lambda P^* + S^*}\right] \quad \Rightarrow \quad \boxed{\xi_{\mathrm{L}}\xi^*_{\mathrm{R}} = \xi_{\mathrm{R}}\xi^*_{\mathrm{L}} = 1}$$

CP Asymmetries:

- Time-dependent rate asymmetry: $\rightarrow$ *requires tagging of* B_s^0 *and* $\bar{B}_s^0$*:*

$$\frac{\Gamma(B_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)-\Gamma(\bar{B}_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)}{\Gamma(B_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)+\Gamma(\bar{B}_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)}=\frac{C_\lambda\cos(\Delta M_s t)+S_\lambda\sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s})+\mathcal{A}_{\Delta\Gamma}^\lambda\sinh(y_s t/\tau_{B_s})}$$

- Observables: $\rightarrow$ *theoretically clean (no dependence on* F_{B_s}*):*

$$C_\lambda\equiv\frac{1-|\xi_\lambda|^2}{1+|\xi_\lambda|^2}=-\eta_\lambda\left[\frac{2|PS|\cos(\varphi_P-\varphi_S)}{|P|^2+|S|^2}\right]\xrightarrow{\text{SM}}0$$

$$S_\lambda\equiv\frac{2\,\mathrm{Im}\,\xi_\lambda}{1+|\xi_\lambda|^2}=\frac{|P|^2\sin(2\varphi_P-\phi_s^{\rm NP})-|S|^2\sin(2\varphi_S-\phi_s^{\rm NP})}{|P|^2+|S|^2}\xrightarrow{\text{SM}}0$$

$$\mathcal{A}_{\Delta\Gamma}^\lambda\equiv\frac{2\,\mathrm{Re}\,\xi_\lambda}{1+|\xi_\lambda|^2}=\frac{|P|^2\cos(2\varphi_P-\phi_s^{\rm NP})-|S|^2\cos(2\varphi_S-\phi_s^{\rm NP})}{|P|^2+|S|^2}\xrightarrow{\text{SM}}1$$

[$\phi_s^{\rm NP}$ is the NP component of the B_s^0–$\bar{B}_s^0$ mixing phase $\phi_s=-2\lambda^2\eta+\phi_s^{\rm NP}$]

- Note: $\mathcal{S}_{\mu\mu}\equiv S_\lambda$, $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}\equiv\mathcal{A}_{\Delta\Gamma}^\lambda$ are *independent* of the muon helicity λ.

- Difficult to measure the muon helicity: $\Rightarrow$ *consider the following rates:*

$$\Gamma(\overset{(-)}{B}{}^0_s(t) \to \mu^+\mu^-) \equiv \sum_{\lambda=\mathrm{L,R}} \Gamma(\overset{(-)}{B}{}^0_s(t) \to \mu^+_\lambda \mu^-_\lambda)$$

- Corresponding CP-violating rate asymmetry: $\to$ $C_\lambda \propto \eta_\lambda$ *terms cancel:*

$$\frac{\Gamma(B^0_s(t) \to \mu^+\mu^-) - \Gamma(\bar{B}^0_s(t) \to \mu^+\mu^-)}{\Gamma(B^0_s(t) \to \mu^+\mu^-) + \Gamma(\bar{B}^0_s(t) \to \mu^+\mu^-)} = \frac{\mathcal{S}_{\mu\mu} \sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s}) + \mathcal{A}^{\mu\mu}_{\Delta\Gamma} \sinh(y_s t/\tau_{B_s})}$$

- Practical comments:
  - It would be most interesting to measure this CP asymmetry as a non-zero value would signal CP-violating NP phases [$\to$ see below].
  - Unfortunately, this is challenging in view of the tiny branching ratio and as B^0_s, $\bar{B}^0_s$ *tagging* and time information are required.

[Previous studies of CP asymmetries of $B^0_{s,d} \to \ell^+\ell^-$ (assuming $\Delta\Gamma_s = 0$):
Huang and Liao (2002); Dedes and Pilaftsis (2002), Chankowski *et al.* (2005)]

Untagged Rate and Branching Ratio:

- The first measurement concerns the "experimental" branching ratio:

$$\mathrm{BR}\left(B_s \to \mu^+\mu^-\right)_{\rm exp} \equiv \overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) \equiv \frac{1}{2}\int_0^\infty \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle \, dt$$

$\to$ *time-integrated untagged rate*, involving

$$\langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle \equiv \Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)$$

$$\propto e^{-t/\tau_{B_s}}\left[\cosh(y_s t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu}\sinh(y_s t/\tau_{B_s})\right]$$

- Conversion into the "theoretical" branching ratio (referring to $t=0$):

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \left[\frac{1-y_s^2}{1+\mathcal{A}_{\Delta\Gamma}^{\mu\mu}\, y_s}\right]\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$$

- The observable $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ depends on NP and is hence unknown:

$$\mathcal{A}_{\Delta\Gamma}^{\mu\mu} \in [-1,+1] \quad \Rightarrow \quad \textit{two options:}$$

(i) Add an extra error to the experimental branching ratio:

$$\Delta\mathrm{BR}(B_s \to \mu^+\mu^-)|_{y_s} = \pm y_s \overline{\mathrm{BR}}(B_s \to \mu^+\mu^-).$$

(ii) $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}|_{\mathrm{SM}} = +1$ gives a *new SM reference value* for the comparison with the time-integrated experimental branching ratio $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$:

$\Rightarrow$ rescale BR$(B_s \to \mu^+\mu^-)_{\mathrm{SM}}$ by $1/(1-y_s)$:

$$\boxed{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.56 \pm 0.18) \times 10^{-9}}$$

[Updated numerics from: A.J. Buras, R.F., J. Girrbach & R. Knegjens (2013)]

Effective $B_s \to \mu^+\mu^-$ Lifetime:

$\diamond$ *Collecting more and more data* $\oplus$ *include decay time information* $\Rightarrow$

- Access to the effective $B_s \to \mu^+\mu^-$ lifetime:

$$\tau_{\mu\mu} \equiv \frac{\int_0^\infty t\, \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle\, dt}{\int_0^\infty \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle\, dt}$$

- $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ can then be extracted: $\quad \mathcal{A}_{\Delta\Gamma}^{\mu\mu} = \frac{1}{y_s}\left[\frac{(1-y_s^2)\tau_{\mu\mu} - (1+y_s^2)\tau_{B_s}}{2\tau_{B_s} - (1-y_s^2)\tau_{\mu\mu}}\right]$

- Finally, extraction of the "theoretical" BR: $\to$ *clean expression:*

$$\mathrm{BR}\left(B_s \to \mu^+\mu^-\right) = \underbrace{\left[2 - \left(1 - y_s^2\right)\frac{\tau_{\mu\mu}}{\tau_{B_s}}\right]\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)}_{\to \text{ only measurable quantities}}$$

– It is *crucial* that $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ does *not* depend on the muon helicity.

$\Rightarrow$ $\boxed{\text{Interesting new measurement for the high-luminosity LHC upgrade!}}$

- Authors have started to include the effect of $\Delta\Gamma_s$ in analyses of the constraints on NP that are implied by BR$(B_s \to \mu^+\mu^-)_{\rm exp}$:

W. Altmannshofer, M. Carena, N. R. Shah and F. Yu, "Indirect Probes of the MSSM after the Higgs Discovery," arXiv:1211.1976 [hep-ph]

A. J. Buras, F. De Fazio and J. Girrbach, "The Anatomy of Z' and Z with Flavour Changing Neutral Currents in the Flavour Precision Era," arXiv:1211.1896 [hep-ph]

O. Buchmueller, R. Cavanaugh, M. Citron, A. De Roeck, M. J. Dolan, J. R. Ellis, H. Flächer and S. Heinemeyer *et al.*, "The CMSSM and NUHM1 in Light of 7 TeV LHC, $B_s \to \mu^+\mu^-$ and XENON100 Data," arXiv:1207.7315 [hep-ph]

T. Hurth and F. Mahmoudi, "The Minimal Flavour Violation benchmark in view of the latest LHCb data," arXiv:1207.0688 [hep-ph]

W. Altmannshofer and D. M. Straub, "Cornering New Physics in $b \to s$ Transitions," arXiv:1206.0273 [hep-ph]

D. Becirevic, N. Kosnik, F. Mescia and E. Schneider, "Complementarity of the constraints on New Physics from $B_s \to \mu^+\mu^-$ and from $B \to K\ell^+\ell^-$ decays," arXiv:1205.5811 [hep-ph]

F. Mahmoudi, S. Neshatpour and J. Orloff, "Supersymmetric constraints from $B_s \to \mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ observables," arXiv:1205.1845 [hep-ph]

...

Probing New Physics:

$$\rightarrow \left\{ \begin{array}{l} \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \text{ and } \mathcal{S}_{\mu\mu} \text{ exhibit NP sensitivity} \\ \text{that is complementary to the BR} \end{array} \right.$$

- "Disclaimer":
  - Assume that the B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s will be precisely known by the time the $B_s \to \mu^+\mu^-$ measurements can be made $\Rightarrow$ fixes ϕ_s^{NP}.
  - LHCb result for current $B_s \to J/\psi\phi$ data: $\phi_s = -(0.06 \pm 5.99)^\circ$.

[Detailed analysis: A.J. Buras, R.F., J. Girrbach & R. Knegjens (2013)]

Branching Ratio Information

- Useful to introduce the following ratio:

$$\overline{R} \equiv \frac{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)}{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = \left[\frac{1 + \mathcal{A}_{\Delta\Gamma}^{\mu\mu}\, y_s}{1 + y_s}\right] (|P|^2 + |S|^2)$$

$$= \left[\frac{1 + y_s \cos(2\varphi_P - \phi_s^{\mathrm{NP}})}{1 + y_s}\right] |P|^2 + \left[\frac{1 - y_s \cos(2\varphi_S - \phi_s^{\mathrm{NP}})}{1 + y_s}\right] |S|^2$$

  – Current situation: $\overline{R} = 0.90^{+0.42}_{-0.34} \in [0.30, 1.80]$ (95% C.L).

  – $\overline{R}$ does not allow a separation of the P and S contributions:

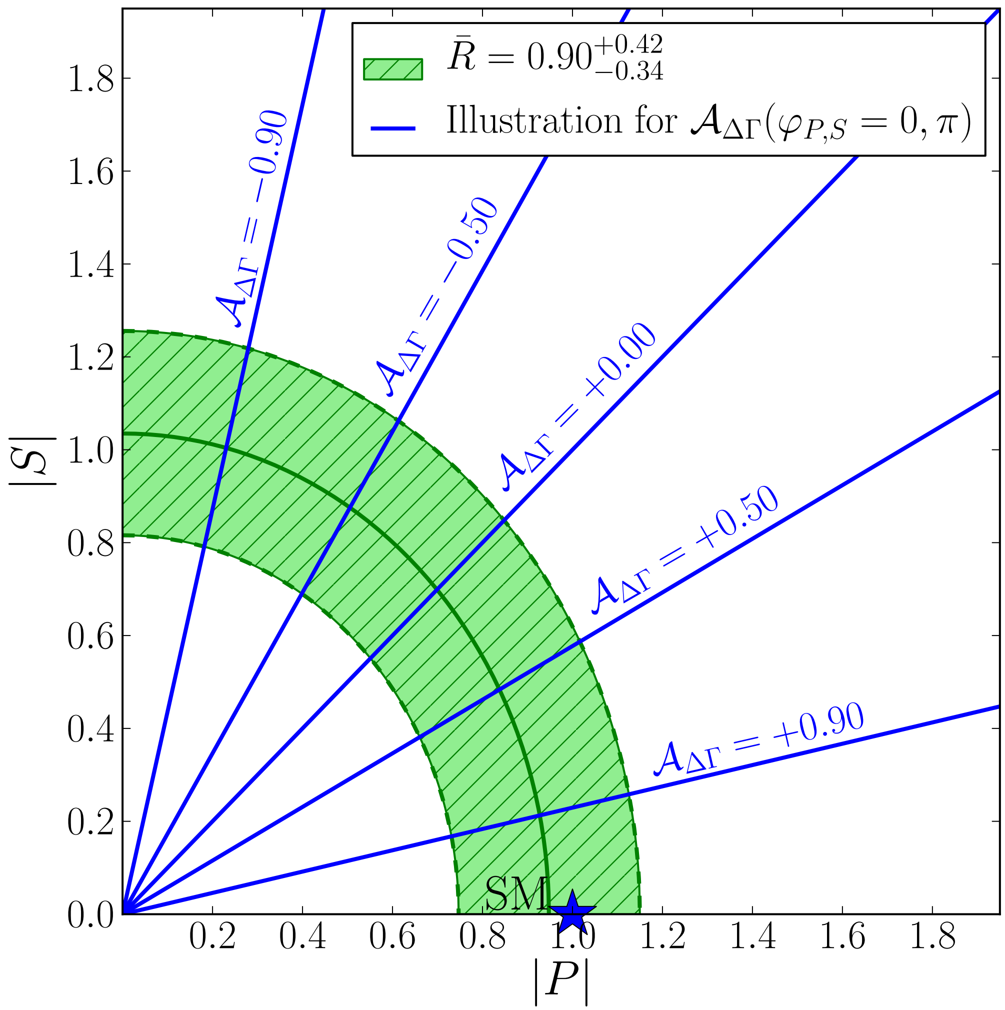
$\Rightarrow$ large NP could be present, even if $\overline{R}$ is close to $\overline{R}_{\mathrm{SM}} = 1$.

- Further information from the measurement of $\tau_{\mu\mu}$ yielding $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$:

$$|S| = |P| \sqrt{\frac{\cos(2\varphi_P - \phi_s^{\mathrm{NP}}) - \mathcal{A}_{\Delta\Gamma}^{\mu\mu}}{\cos(2\varphi_S - \phi_s^{\mathrm{NP}}) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu}}}$$

$\Rightarrow$ offers a new window for NP in $B_s \to \mu^+\mu^-$

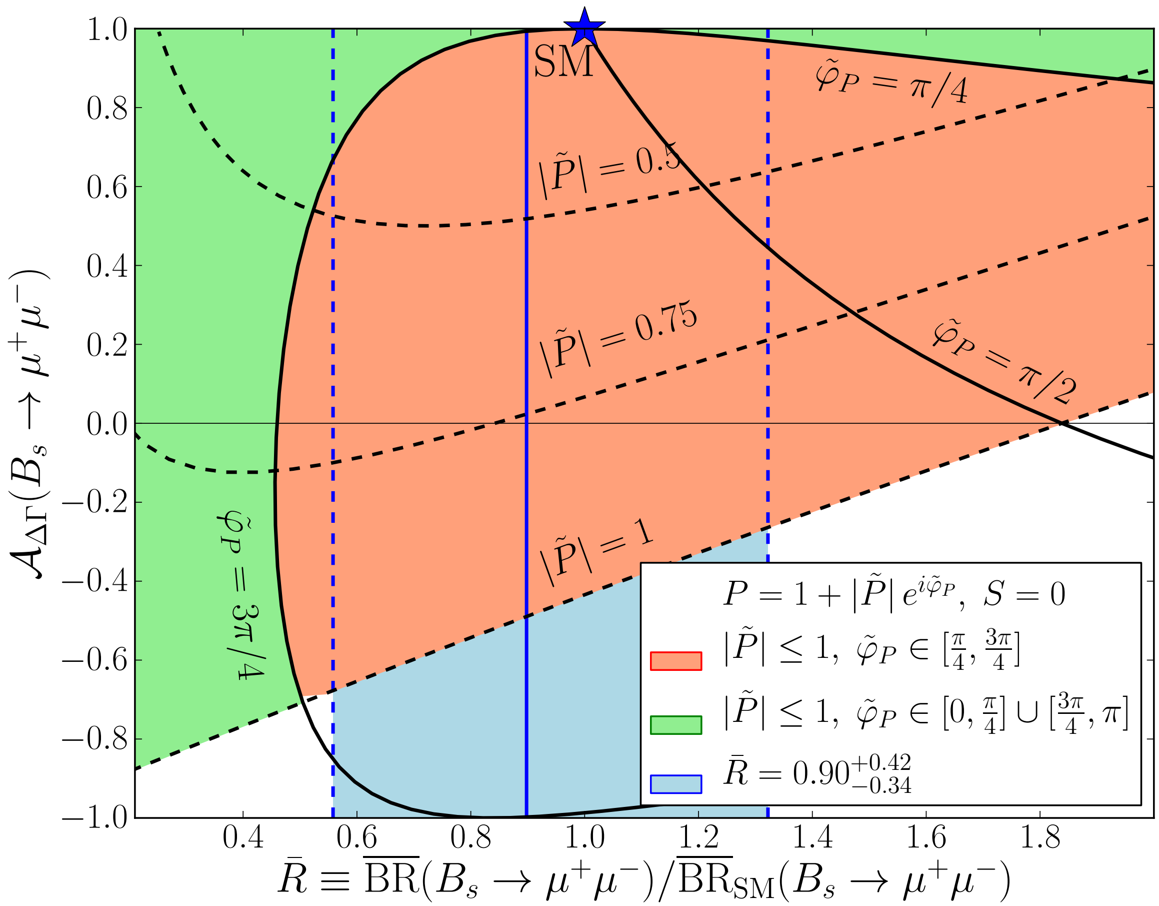
- Current constraints in the $|P|$–$|S|$ plane and illustration of those following from a future measurement of the $B_s \to \mu^+\mu^-$ lifetime yielding $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$:



[Assumes no NP phases for the $\mathcal{A}_{\Delta\Gamma}$ curves (e.g. MFV without flavour-blind phases)]

Scenario with $P = 1 + \tilde{P}$ ($\tilde{P}$ Free) and $S = 0$

$\Rightarrow$ *no new scalar operators:*

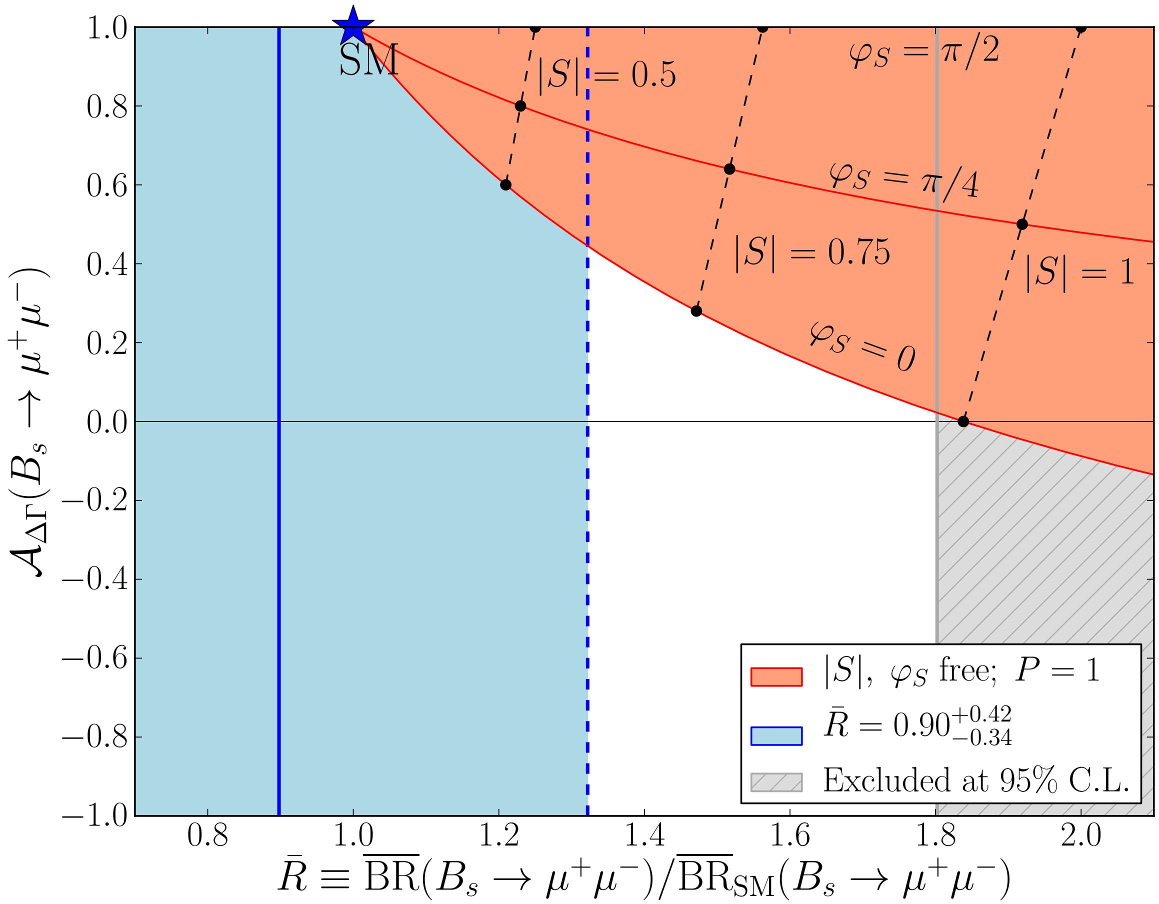


- Deviation of $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ from SM value $+1$ requires CP-violating NP phases.

[Examples of specific models: CMFV, LHT, 4G, RSc, Z']

Scenario with $P = 1$ and S Free:

$\Rightarrow$ *only new scalar operators:*

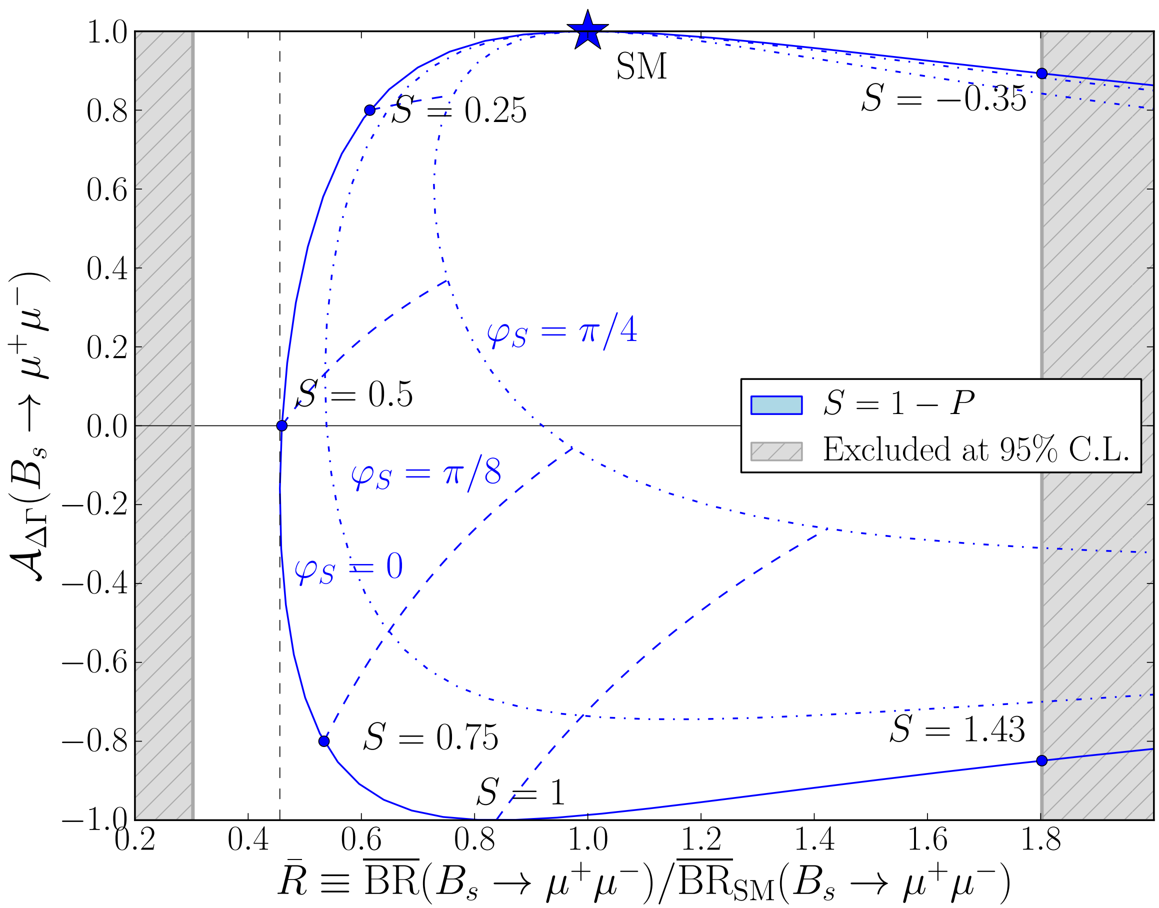


- $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ may differ from its SM value $+1$ without new CP-violating phases.
- $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) \geq \overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}$
- Experimental constraint: $\mathcal{A}_{\Delta\Gamma}^{\mu\mu} > 0$.

[Example of specific model: 2HDM (scalar H^0 dominance)]

Scenario with $P \pm S = 1$

$\Rightarrow P = 1 + \tilde{P}$, $S = \pm\tilde{P}$ (e.g. $C_S = -C_P$):



- Can access the full range of $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ without new CP-violating phases.
- *Lower bound:* $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) \geq \frac{1}{2}(1 - y_s)\,\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}$

[Examples: Decoupled 2HDM/MSSM ($M_{H^0} \approx M_{A^0} \gg M_{h^0}$)]

Detailed Analyses in Specific NP Models

- Tree-Level Neutral Gauge Boson Exchange:

$$\mathcal{L}_{\rm FCNC}(Z') = \left[\Delta_L^{sb}(Z')(\bar{s}\gamma_\mu P_L b) + \Delta_R^{sb}(Z')(\bar{s}\gamma_\mu P_R b)\right] Z'^{\mu}$$

$$\mathcal{L}_{\ell\bar{\ell}}(Z') = \left[\Delta_L^{\ell\ell}(Z')(\bar{\ell}\gamma_\mu P_L \ell) + \Delta_R^{\ell\ell}(Z')(\bar{\ell}\gamma_\mu P_R \ell)\right] Z'^{\mu}$$

  - Left-handed Scheme (LHS) with complex $\Delta_L^{bs} \neq 0$ and $\Delta_R^{bs} = 0$
  - Right-handed Scheme (RHS) with complex $\Delta_R^{bs} \neq 0$ and $\Delta_L^{bs} = 0$
  - Left-Right symmetric Scheme (LRS) with complex $\Delta_L^{bs} = \Delta_R^{bs} \neq 0$
  - Left-Right asymmetric Scheme (ALRS) with complex $\Delta_L^{bs} = -\Delta_R^{bs} \neq 0$

- Tree-Level Neutral (Pseudo)Scalar Exchange:

$$\mathcal{L}_{\rm FCNC}(H) = \left[\Delta_L^{sb}(H)(\bar{s}P_L b) + \Delta_R^{sb}(H)(\bar{s}P_R b)\right] H$$

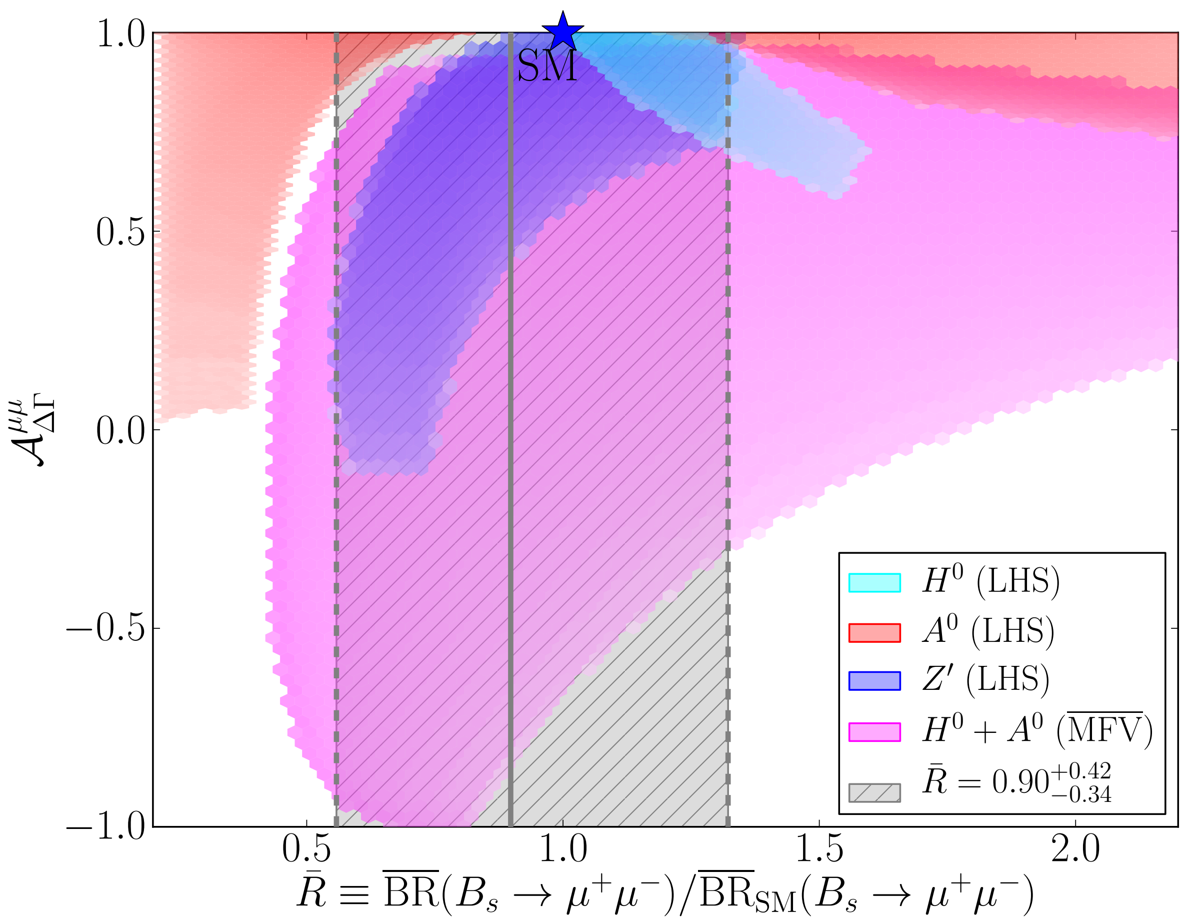
- Tree-Level Neutral Scalar+Pseudoscalar Exchange:

$$\begin{aligned}\mathcal{L}_{\rm FCNC}(H^0, A^0) = \quad & \left[\Delta_L^{sb}(H^0)(\bar{s}P_L b) + \Delta_R^{sb}(H^0)(\bar{s}P_R b)\right] H^0 \\ & + \left[\Delta_L^{sb}(A^0)(\bar{s}P_L b) + \Delta_R^{sb}(A^0)(\bar{s}P_R b)\right] A^0\end{aligned}$$

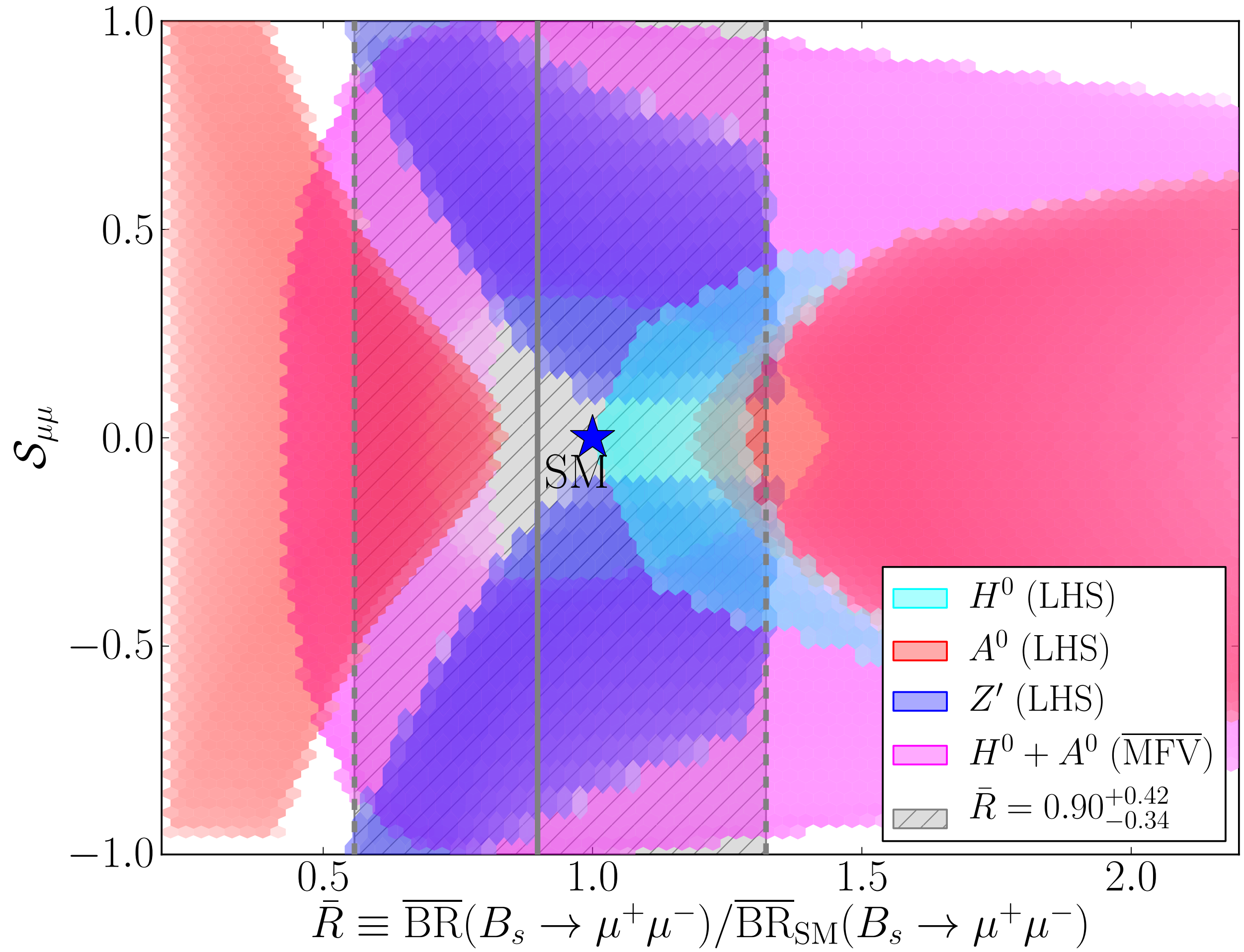
$\rightarrow$ take constraints on B_s^0–$\bar{B}_s^0$ mixing into account [Buras et al. (2013)]

Correlations between Observables

- $\underline{\overline{R}\text{–}\mathcal{A}^{\mu\mu}_{\Delta\Gamma}\text{ plane:}}$ $\rightarrow$ only *untagged* observables



- $\overline{R}$–$\mathcal{S}_{\mu\mu}$ plane: $\rightarrow$ requires *tagging* for CP asymmetry $\mathcal{S}_{\mu\mu}$



– Interesting relation with $\mathcal{A}^{\mu\mu}_{\Delta\Gamma}$:

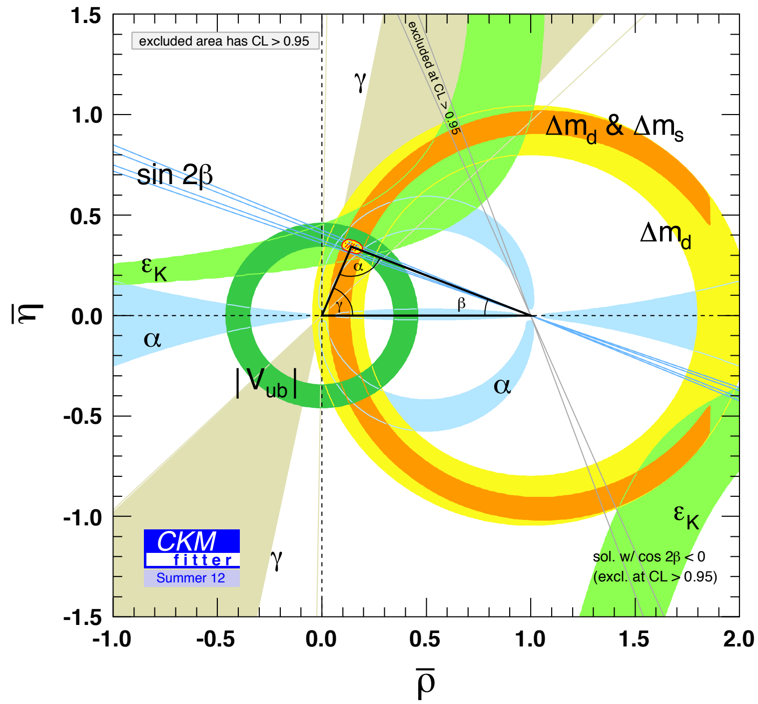
$$|\mathcal{S}_{\mu\mu}|^2 + |\mathcal{A}^{\mu\mu}_{\Delta\Gamma}|^2 = 1 - \left[\frac{2|PS|\cos(\varphi_P - \varphi_S)}{|P|^2 + |S|^2}\right]^2$$

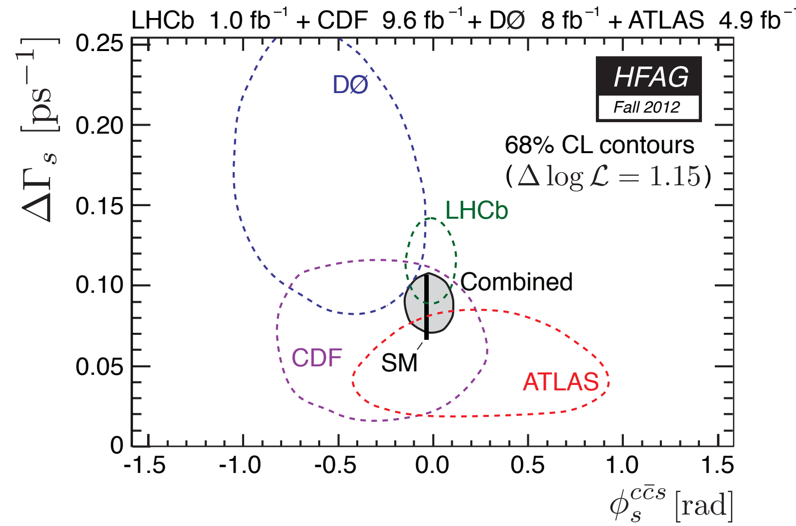
Precision Studies

of

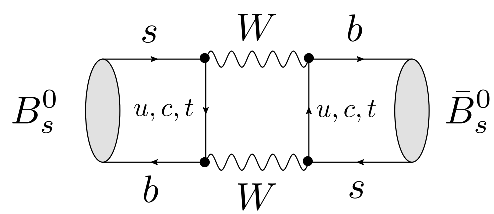
CP Violation

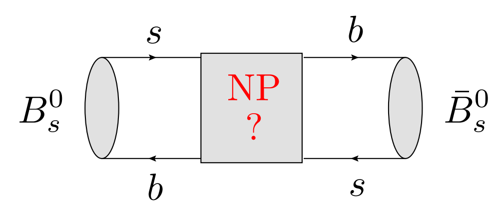
Experimental Situation





- B_s^0–$\bar{B}_s^0$ mixing phase:





$$\boxed{\phi_s^{c\bar{c}s} \equiv \phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} = -2\lambda^2\eta + \phi_s^{\rm NP}}$$

- HFAG average:

$$\phi_s = -(2.5^{+4.8}_{-5.2})^\circ \quad \text{vs.} \quad \phi_s^{\rm SM} = -(2.08 \pm 0.09)^\circ$$

Towards New Frontiers ...

- Crucial for resolving smallish effects of NP:

  – Have a critical look at theoretical analyses and their approximations:

  $\rightarrow$ key issue: $\boxed{\text{strong interactions: } \rightarrow \text{ "hadronic" effects}}$

  – Match the experimental and theoretical precisions.

- Key decays for exploring CP violation:

$$B_d \to J/\psi K_{\mathrm{S}},\ B_s \to J/\psi\phi,\ B_s \to J/\psi f_0(980)$$

  – Allow measurements of the $B^0_{d,s}$–$\bar{B}^0_{d,s}$ mixing phases $\phi_{d,s}$.

  – Uncertainties from doubly Cabibbo-suppressed *penguin* contributions.

  – These effects are usually neglected; we cannot reliably calculate them...

$\Rightarrow$ $\boxed{\text{How big are they \& how can they be controlled?}}$

"Penguin Hunting"

- Marseille Penguin (!):

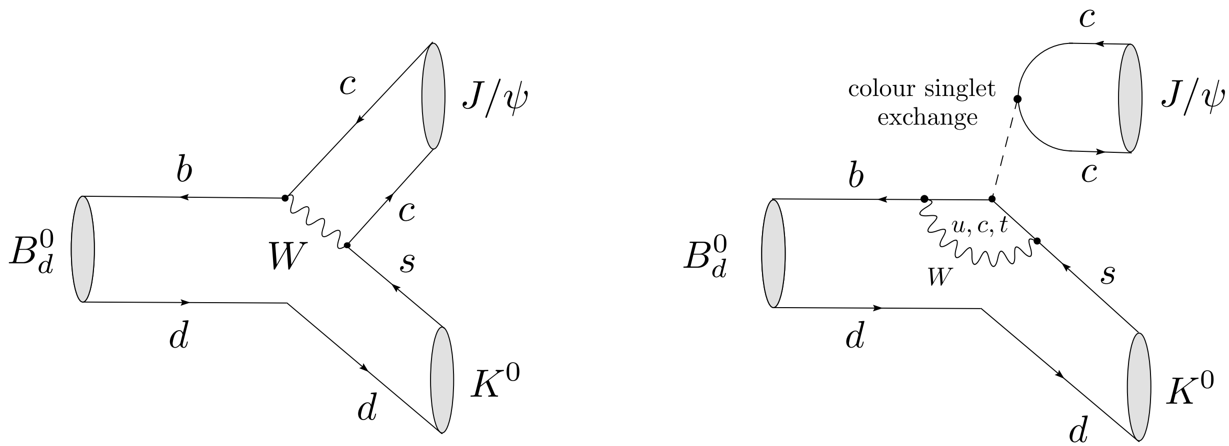
$\rightarrow$ Musée des civilisations de l'Europe et de la Méditerranée

$$\boxed{B_d^0 \to J/\psi K_{\rm S} \oplus B_s^0 \to J/\psi K_{\rm S}}$$

Current picture of the penguin parameters?

[Thanks to Kristof De Bruyn for plots/numerics; work in progress.]

The Decay $B_d \to J/\psi K_S$



- Decay amplitude in the SM:

$$A(B_d^0 \to J/\psi\, K_S) = \lambda_c^{(s)} \left[A_T^{(c)'} + A_P^{(c)'} \right] + \lambda_u^{(s)} A_P^{(u)'} + \lambda_t^{(s)} A_P^{t'}$$

- Unitarity of the CKM matrix: $\Rightarrow\ \lambda_t^{(s)} = -\lambda_c^{(s)} - \lambda_u^{(s)} \quad [\lambda_q^{(s)} \equiv V_{qs} V_{qb}^*]$:

$$\Rightarrow \quad \boxed{A(B_d^0 \to J/\psi\, K_S) = \left(1 - \lambda^2/2\right) \mathcal{A}' \left[1 + \epsilon\, a' e^{i\theta'} e^{i\gamma} \right]}$$

$$\mathcal{A}' \equiv \lambda^2 A \left[A_T^{(c)'} + A_P^{(c)'} - A_P^{(t)'} \right], \qquad a' e^{i\theta'} \equiv R_b \left[\frac{A_P^{(u)'} - A_P^{(t)'}}{A_T^{(c)'} + A_P^{(c)'} - A_P^{(t)'}} \right]$$

$$A \equiv |V_{cb}|/\lambda^2 \sim 0.8, \ \ R_b \equiv \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right| \sim 0.5, \ \ \epsilon \equiv \frac{\lambda^2}{1 - \lambda^2} = 0.053$$

- Time-dependent CP asymmetry (CP-odd final state):

$$\frac{\Gamma(B^0_d(t)\to J/\psi K_{\rm S})-\Gamma(\bar B^0_d(t)\to J/\psi K_{\rm S})}{\Gamma(B^0_d(t)\to J/\psi K_{\rm S})+\Gamma(\bar B^0_d(t)\to J/\psi K_{\rm S})}$$

$$= C(B_d\to J/\psi K_{\rm S})\cos(\Delta M_d t) - S(B_d\to J/\psi K_{\rm S})\sin(\Delta M_d t)$$

- CP-violating observables: $[\phi_d = 2\beta + \phi_d^{\rm NP} \to B^0_d$–$\bar B^0_d$ mixing phase]

$$C(B_d\to J/\psi K_{\rm S}) = -\frac{2\epsilon a\sin\theta\sin\gamma}{1+2\epsilon a\cos\theta\cos\gamma+\epsilon^2a^2}$$

$$\frac{S(B_d\to J/\psi K_{\rm S})}{\sqrt{1-C(B_d\to J/\psi K_{\rm S})^2}} = \sin(\phi_d+\Delta\phi_d)$$

$$\sin\Delta\phi_d = \frac{2\epsilon a'\cos\theta'\sin\gamma+\epsilon^2a'^2\sin2\gamma}{(1+2\epsilon a'\cos\theta'\cos\gamma+\epsilon^2a'^2)\sqrt{1-C(B_d\to J/\psi K_{\rm S})^2}}$$

$$\cos\Delta\phi_d = \frac{1+2\epsilon a'\cos\theta\cos\gamma+\epsilon^2a'^2\cos2\gamma}{(1+2\epsilon a'\cos\theta'\cos\gamma+\epsilon^2a'^2)\sqrt{1-C(B_d\to J/\psi K_{\rm S})^2}}$$

[Faller, R.F., Jung & Mannel (2008)]

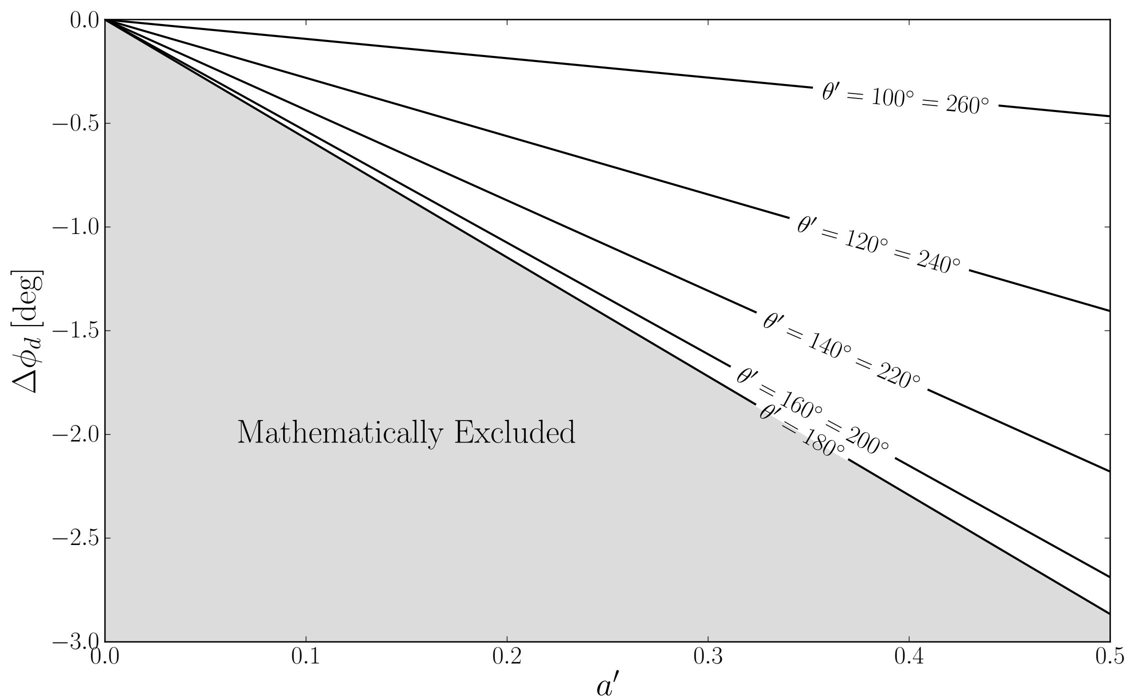
- Current experimental status: [HFAG]

$$S(B_d \to J/\psi K_{\rm S}) = 0.665 \pm 0.024$$

$$C(J/\psi K_{\rm S}) = 0.024 \pm 0.026 \quad \Rightarrow \quad \sqrt{1 - C(J/\psi K_{\rm S})^2} = 0.99971^{+0.00029}_{-0.00096}$$

$$\Rightarrow \boxed{S(B_d \to J/\psi K_{\rm S}) = \sin(\phi_d + \Delta\phi_d) = 0.665 \pm 0.024}$$

- Illustration of the impact of the penguin topologies: $a' e^{i\theta'} \sim R_b \left[\frac{\text{“pen”}}{\text{“tree”}}\right]$



How can we control $\Delta\phi_d$?

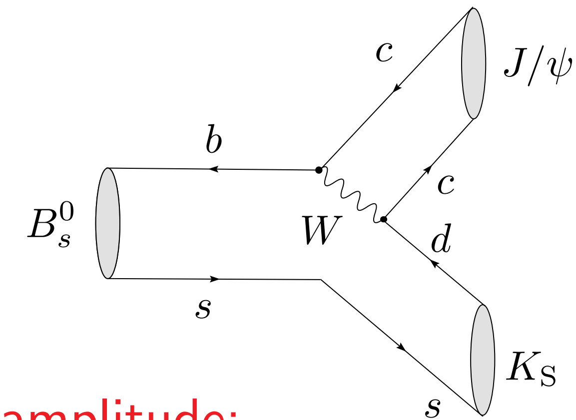
$$\tan\Delta\phi_d = \frac{2\epsilon a'\cos\theta'\sin\gamma + \epsilon^2 a'^2\sin 2\gamma}{1 + 2\epsilon a'\cos\theta\cos\gamma + \epsilon^2 a'^2\cos 2\gamma}$$

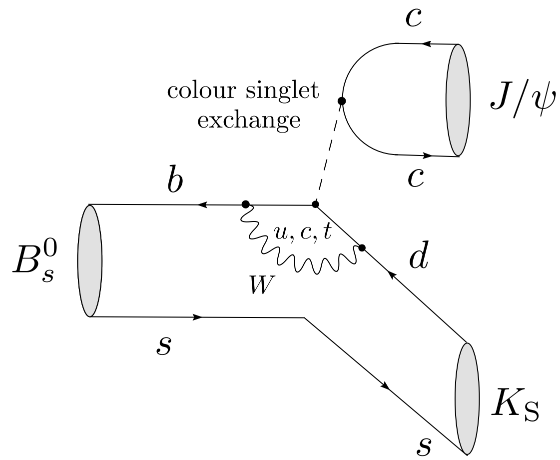
$\rightarrow$ hadronic parameters a', θ' cannot be calculated:

$\Rightarrow$ use control channel(s): $B_s^0 \to J\psi K_{\rm S} \oplus U$-spin symmetry

[R.F., Eur. Phys. J. C **10** (1999) 299 [hep-ph/9903455]]

The Decay $B_s \to J/\psi K_{\mathrm{S}}$





- Decay amplitude:

$$A(B_s^0 \to J/\psi\, K_{\mathrm{S}}) = \lambda_c^{(d)} \left[A_{\mathrm{T}}^{(c)} + A_{\mathrm{P}}^{(c)} \right] + \lambda_u^{(d)} A_{\mathrm{P}}^{(u)} + \lambda_t^{(d)} A_{\mathrm{P}}^{t}$$

- Unitarity of the CKM matrix: $\lambda_t^{(d)} = -\lambda_c^{(d)} - \lambda_u^{(d)}$

$$\Rightarrow \boxed{A(B_s^0 \to J/\psi\, K_{\mathrm{S}}) = -\lambda\, \mathcal{A} \left[1 - a e^{i\theta} e^{i\gamma} \right]}$$

$$\mathcal{A} \equiv \lambda^2 A \left[A_{\mathrm{T}}^{(c)} + A_{\mathrm{P}}^{(c)} - A_{\mathrm{P}}^{(t)} \right], \quad a e^{i\theta} \equiv R_b \left[\frac{A_{\mathrm{P}}^{(u)} - A_{\mathrm{P}}^{(t)}}{A_{\mathrm{T}}^{(c)} + A_{\mathrm{P}}^{(c)} - A_{\mathrm{P}}^{(t)}} \right]$$

- In contrast to $B_d^0 \to J/\psi K_{\mathrm{S}}$, $a e^{i\theta}$ is *not* suppressed by $\epsilon = 0.05$:

$\Rightarrow$ penguin effects are “magnified”!

- Useful quantity: $[\Phi^s_{J/\psi K_S}$, $\Phi^d_{J/\psi K_S}$: phase-space factors]

$$H \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2 \left[\frac{\tau_{B_d}\Phi^d_{J/\psi K_S}}{\tau_{B_s}\Phi^s_{J/\psi K_S}}\right] \frac{\mathrm{BR}\,(B_s \to J/\psi K_S)_{\rm theo}}{\mathrm{BR}(B_d \to J/\psi K_S)_{\rm theo}}$$

$$= \frac{1 - 2a\cos\theta\cos\gamma + a^2}{1 + 2\epsilon a'\cos\theta'\cos\gamma + \epsilon^2 a'^2}$$

- Further $B_s^0 \to J/\psi K_S$ observables from *tagged* time-dependent rates:

$$\frac{\Gamma(B^0_s(t) \to J/\psi K_S) - \Gamma(\bar{B}^0_s(t) \to J/\psi K_S)}{\Gamma(B^0_s(t) \to J/\psi K_S) + \Gamma(\bar{B}^0_s(t) \to J/\psi K_S)}$$
$$= \frac{C(B_s \to J/\psi K_S)\cos(\Delta M_s t) - S(B_s \to J/\psi K_S)\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}(B_s \to J/\psi K_S)\sinh(\Delta\Gamma_s t/2)}$$

$$\Rightarrow \quad C, \quad S, \quad \mathcal{A}_{\Delta\Gamma}$$

– Note that these observables are not independent: $C^2 + S^2 + \mathcal{A}^2_{\Delta\Gamma} = 1$.

Extraction of γ and Penguin Parameters

- U-spin flavour symmetry:

$$a = a', \quad \theta = \theta'$$

$$\Rightarrow \qquad \mathcal{A}' = \mathcal{A}$$

- Observables:

$$\begin{aligned} H &= \text{function}(a, \theta, \gamma) \\ C(B_s \to J/\psi K_S) &= \text{function}(a, \theta, \gamma) \\ S(B_s \to J/\psi K_S) &= \text{function}(a, \theta, \gamma; \phi_s) \end{aligned}$$

$$\Rightarrow \boxed{\gamma,\ a \text{ and } \theta \text{ can be extracted from the 3 observables}}$$

[ϕ_s denotes the B_s^0–$\bar{B}_s^0$ mixing phase, with $\phi_s^{\rm SM} = -2\lambda^2\eta \sim -2^\circ$]

- Change of of focus of interest since 1999:
  - Extraction of γ @ LHCb is feasible but probably not competitive ...
  - Assume that γ is know $\Rightarrow$ clean determination of the penguin parameters a, θ from C and S (further info from H).

[R.F. (1999); De Bruyn, R.F. & Koppenburg (2010)] through

$$\Gamma(B(t) \to f) + \Gamma(\overline{B}(t) \to f) = \mathrm{PhSp} \times |\mathcal{N}|^2 \times \left[R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t}\right], \quad (28)$$

where PhSp denotes an appropriate, straightforwardly calculable phase-space factor. Consequently, the overall normalization $|\mathcal{N}|^2$ is required in order to determine R. In the case of the decay $B_s \to J/\psi K_S$, this normalization can be fixed through the CP-averaged $B_d \to J/\psi K_S$ rate with the help of the U-spin symmetry.

In the case of $B_d \to J/\psi K_S$, we have

$$\mathcal{N} = \left(1 - \frac{\lambda^2}{2}\right)\mathcal{A}', \quad b = \epsilon a',$$
$$\rho = \theta' + 180^\circ, \quad \text{with} \quad \epsilon \equiv \frac{\lambda^2}{1-\lambda^2}, \quad (29)$$

whereas we have in the $B_s \to J/\psi K_S$ case

$$\mathcal{N} = -\lambda \mathcal{A}, \quad b = a, \quad \rho = \theta. \quad (30)$$

Consequently, we obtain

$$H \equiv \frac{1}{\epsilon}\left(\frac{|\mathcal{A}'|}{|\mathcal{A}|}\right)^2 \left[\frac{M_{B_d}\Phi(M_{J/\psi}/M_{B_d}, M_K/M_{B_d})}{M_{B_s}\Phi(M_{J/\psi}/M_{B_s}, M_K/M_{B_s})}\right]^3 \frac{\langle\Gamma\rangle}{\langle\Gamma'\rangle}$$
$$= \frac{1 - 2a\cos\theta\cos\gamma + a^2}{1 + 2\epsilon a'\cos\theta'\cos\gamma + \epsilon^2 a'^2}, \quad (31)$$

where

in the case of $B_d \to J/\psi K_S$. Since the value of the CP-violating parameter ε_K of the neutral kaon system is small, ϕ_K can only be affected by very contrived models of new physics [14].

An important by-product of the strategy described above is that the quantities a' and θ' allow us to take into account the penguin contributions in the determination of β from $B_d \to J/\psi K_S$, which are presumably very small because of the Cabibbo suppression of $\lambda^2/(1-\lambda^2)$ in (3). Moreover, using (34), we obtain an interesting relation between the direct CP asymmetries arising in the modes $B_d \to J/\psi K_S$ and $B_s \to J/\psi K_S$ and their CP-averaged rates:

$$\frac{\mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_d \to J/\psi K_S)}{\mathcal{A}^{\mathrm{dir}}_{\mathrm{CP}}(B_s \to J/\psi K_S)} = -\epsilon H \quad (35)$$
$$= -\left(\frac{|\mathcal{A}'|}{|\mathcal{A}|}\right)^2 \left[\frac{M_{B_d}\Phi(M_{J/\psi}/M_{B_d}, M_K/M_{B_d})}{M_{B_s}\Phi(M_{J/\psi}/M_{B_s}, M_K/M_{B_s})}\right]^3 \frac{\langle\Gamma\rangle}{\langle\Gamma'\rangle}.$$

An analogous relation holds also between the $B^\pm \to \pi^\pm K$ and $B^\pm \to K^\pm K$ CP-violating asymmetries [11,12]. At "second-generation" B-physics experiments at hadron machines, for instance at LHCb, the sensitivity may be good enough to resolve a direct CP asymmetry in $B_d \to J/\psi K_S$. In view of the impressive accuracy that can be achieved in the era of such experiments, it is also an important issue to think about the theoretical accuracy of the determination of β from $B_d \to J/\psi K_S$. The approach discussed above allows us to control these – presumably very small – hadronic uncertainties with the help of $B_s \to J/\psi K_S$.

Current information on the penguin parameters?

- $B_s^0 \to J/\psi K_{\rm S}$ observed by CDF and LHCb, but no CP violation yet ...
- Use data for decays with a CKM structure similar to $B_s^0 \to J/\psi K_{\rm S}$:

$$B_d^0 \to J/\psi \pi^0, \; B^+ \to J/\psi \pi^+$$

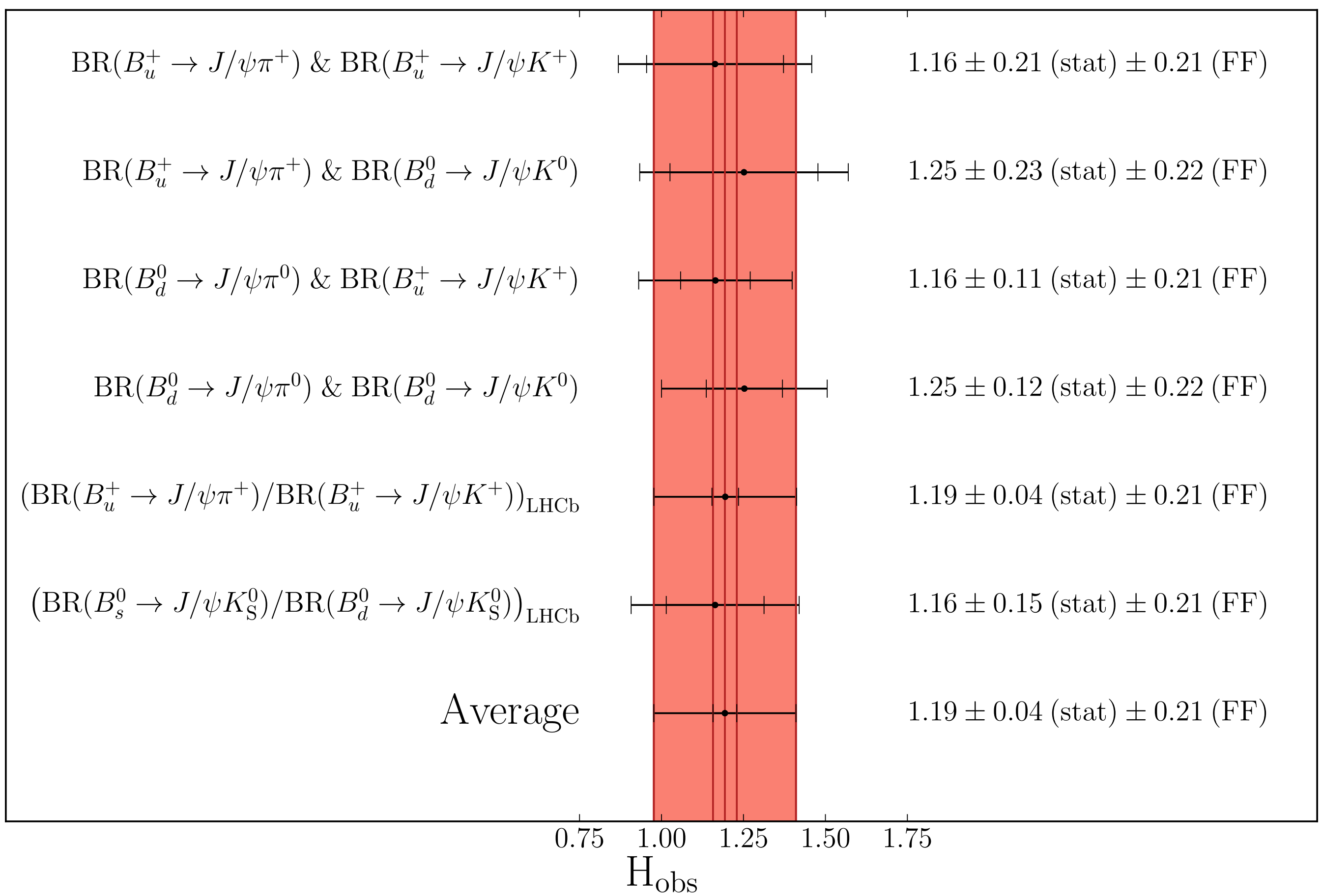
... and complement them with data for $B_d^0 \to J/\psi K^0$, $B^+ \to J/\psi K^+$.

Work in progress with K. De Bruyn & P. Koppenburg
see also Ciuchini, Pierini & Silvestrini (2005);
Faller, R.F., Jung & Mannel (2008);
Jung (2012)

Compilation of H Observables

- BR ratios, including factorizable $SU(3)$-breaking corrections:

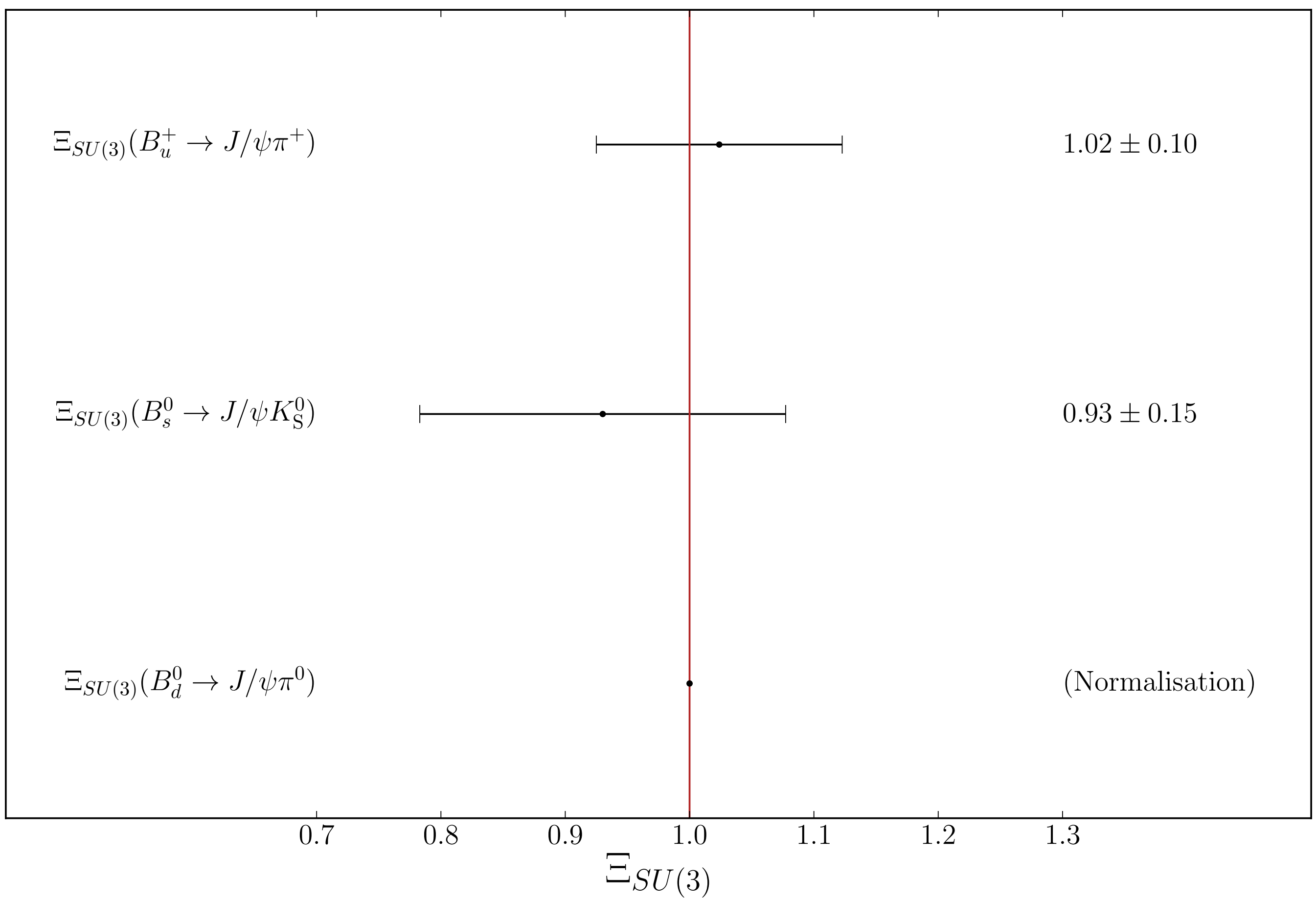
$$H \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{A}'}{\mathcal{A}}\right|^2 \left[\frac{\tau_{B_d}\Phi^d_{J/\psi K_S}}{\tau_{B_s}\Phi^s_{J/\psi K_S}}\right] \frac{\mathrm{BR}\left(B_s \to J/\psi K_S\right)_{\mathrm{theo}}}{\mathrm{BR}(B_d \to J/\psi K_S)_{\mathrm{theo}}}$$



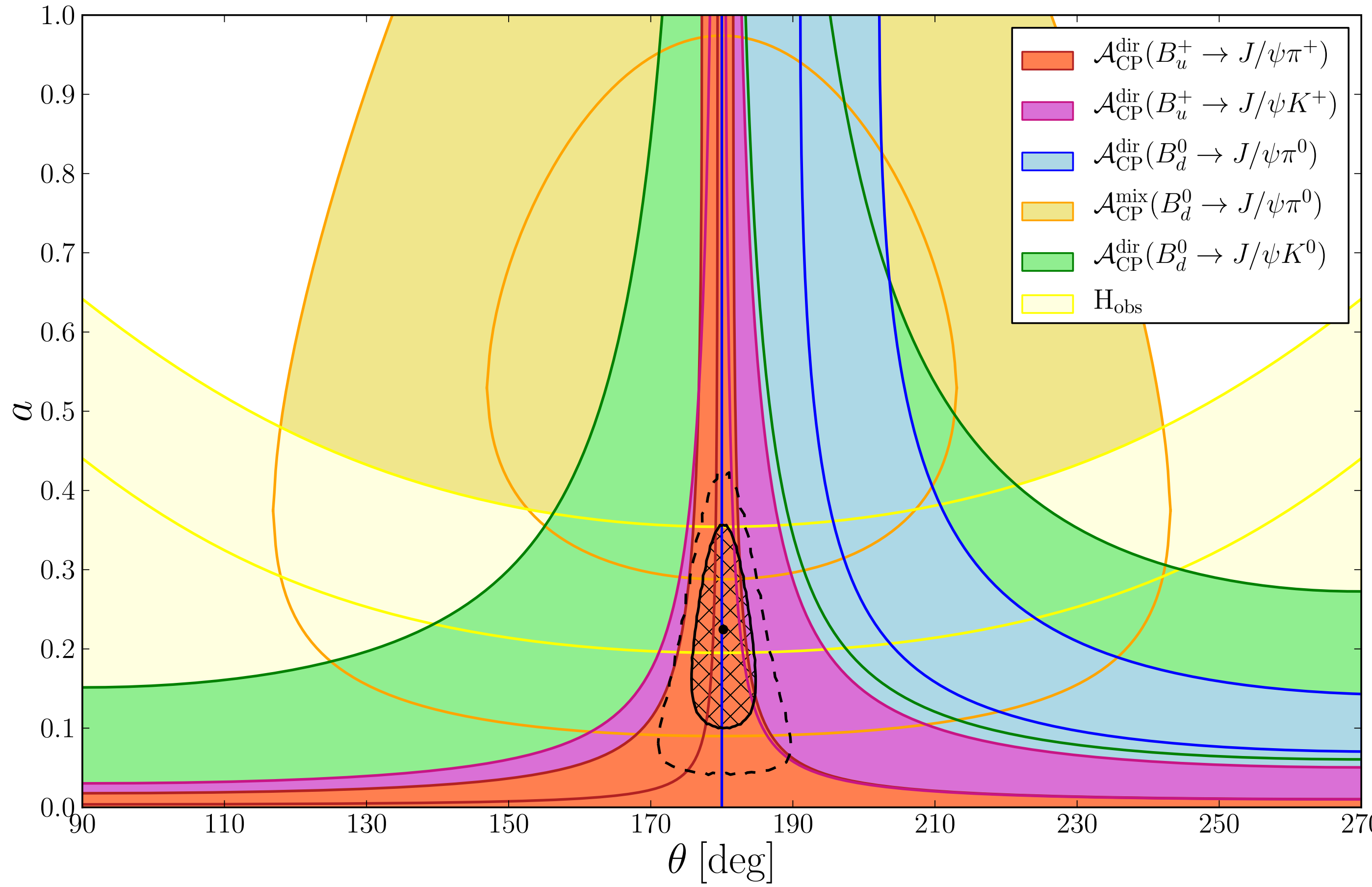
$SU(3)$ Tests

- Neglecting penguin annihilation & exchange topologies:

$$\Xi_{SU(3)} \equiv \frac{\mathrm{BR}(B_s^0 \to J/\psi \bar{K}^0)_{\rm theo}}{2\mathrm{BR}(B_d^0 \to J/\psi \pi^0)_{\rm theo}} \frac{\tau_{B_d}}{\tau_{B_s}} \frac{\Phi^d_{J/\psi\pi^0}}{\Phi^s_{J/\psi K_{\rm S}}} \xrightarrow{SU(3)} 1$$



Constraints on Penguin Parameters

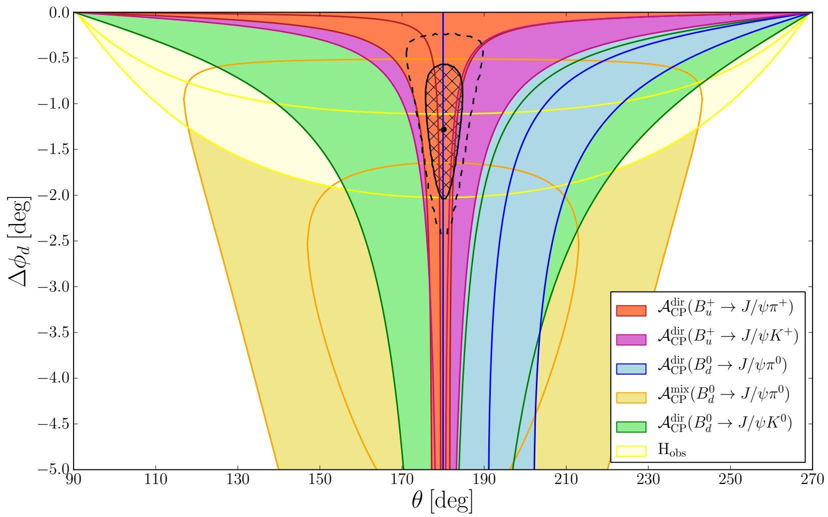


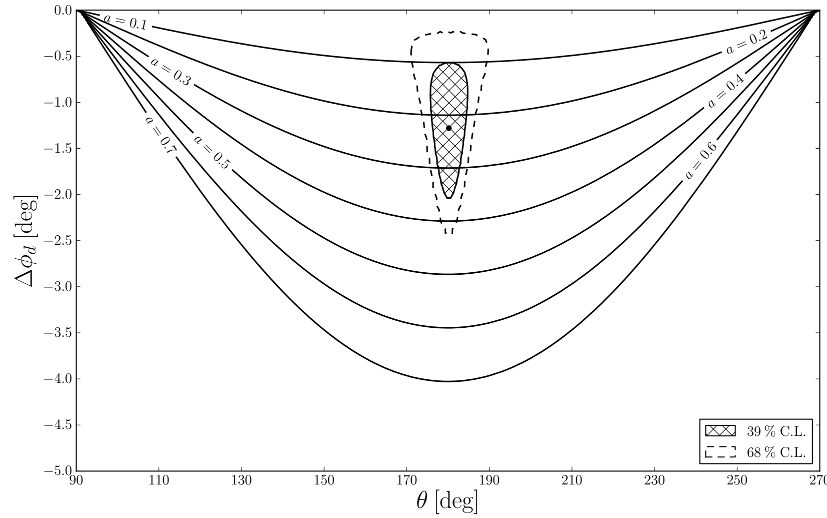
[39% and 68% C.L.]

$$\boxed{a = 0.22 \pm 0.13, \quad \theta = (180.2 \pm 4.5)^\circ}$$ [1σ ranges]

[Comparison with Faller, R.F., Jung & Mannel ('08): $a \in [0.15, 0.67]$, $\theta \in [174, 213]^\circ$]

Constraints on $\Delta\phi_d$





$$\boxed{\Delta\phi_d = -(1.28 \pm 0.74)^\circ}$$

$$S(B_d \to J/\psi K_{\rm S}) = \sin(\phi_d + \Delta\phi_d) = 0.665 \pm 0.024 \Rightarrow$$

$$\phi_d + \Delta\phi_d = (41.7 \pm 1.7)^\circ \Rightarrow$$

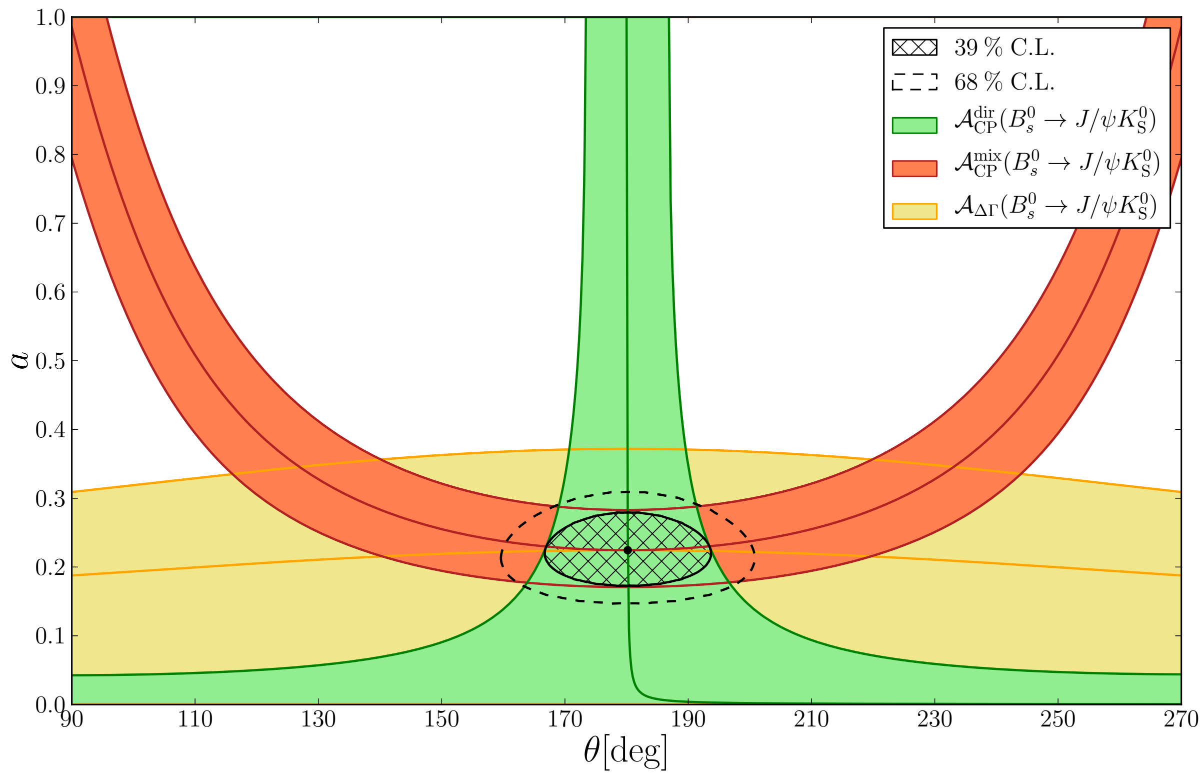
$$\phi_d = (43.0 \pm 1.7|_S \pm 0.7|_{\Delta\phi_d})^\circ = (43.0 \pm 1.8)^\circ$$

- Situation is similar in the extraction of ϕ_s from $B_s \to J/\psi\phi$ ...
- LHCb strategy document [arXiv:1208.3355]:

  $\to$ theory uncertainty of ϕ_s measurement quoted as $\sim 0.003 = 0.17^\circ$!?

Prospects for LHCb Upgrade

- Extrapolation from toy study (i.e. not official LHCb):



- Comments:
  - This determination of a and θ is theoretically clean.
  - Relation to a', θ' (enter $B_d \to J/\psi K_{\rm S}$) through U-spin symmetry.

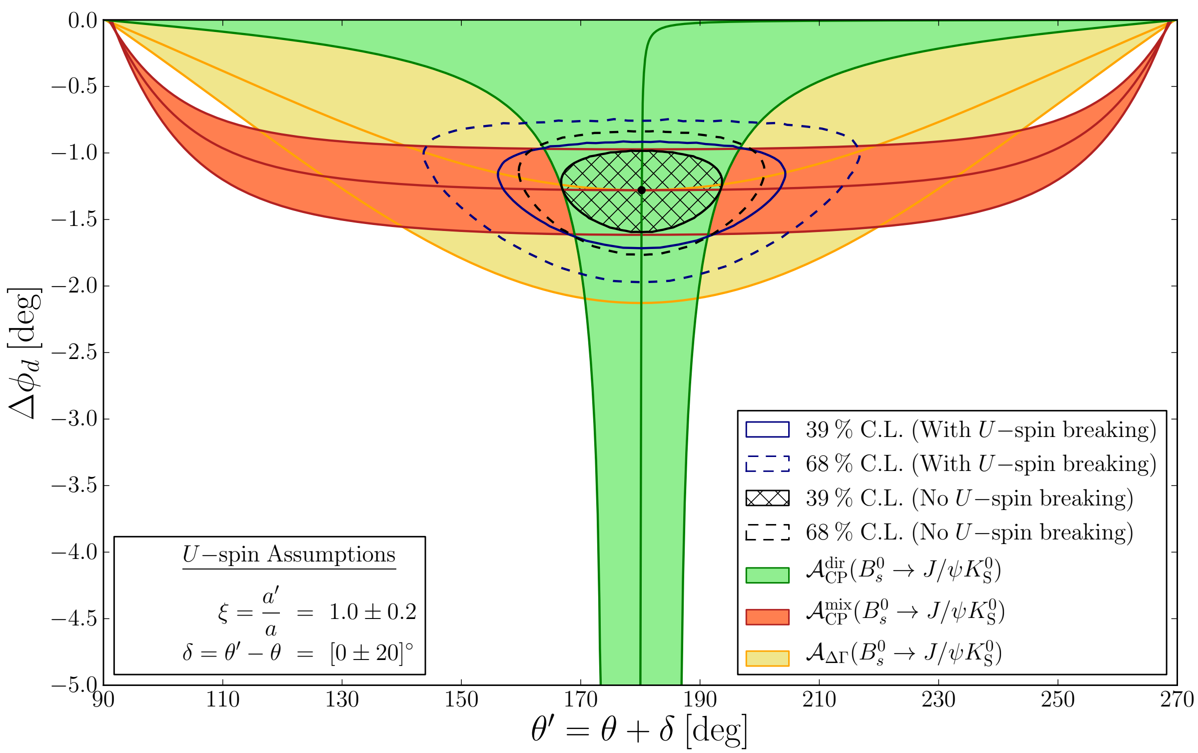
[Update of De Bruyn, R.F. & Koppenburg (2010)]

... Conversion into $\Delta\phi_d$

- Use U-spin symmetry between $B_s^0 \to J/\psi K_S$ and $B_d^0 \to J/\psi K_S$:

$$a' = a, \quad \theta' = \theta$$

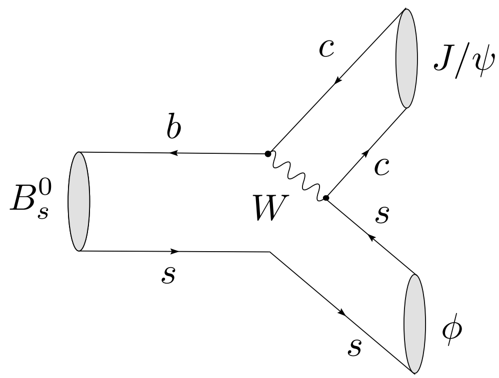
$$\Rightarrow \tan\Delta\phi_d = \frac{2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma}{1 + 2\epsilon a' \cos\theta \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma}$$

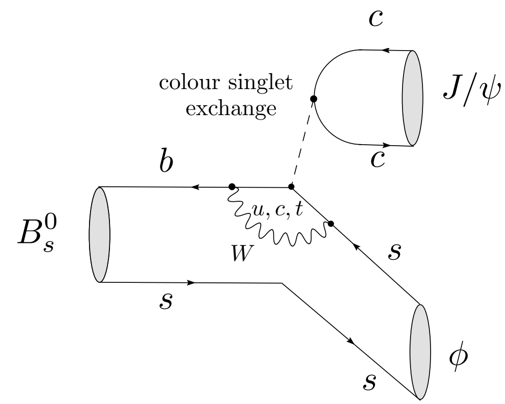


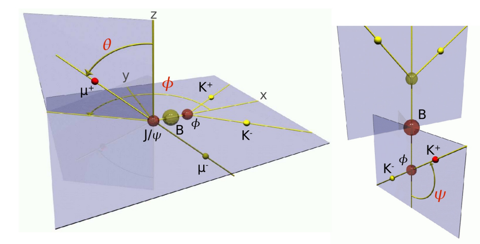
$$\boxed{B_s \to J/\psi\phi\text{:}}$$

$\Rightarrow$ B_s counterpart of $B_d \to J/\psi K_{\mathrm{S}}$

CP Violation in $B_s \to J/\psi\phi$







- Final state is mixture of CP-odd and CP-even states:

  $\to$ disentangle through $J/\psi[\to \mu^+\mu^-]\phi[\to\ K^+K^-]$ angular distribution

- Impact of SM penguin contributions (which are usually neglected):

$$A(B_s^0 \to (J/\psi\phi)_f) \propto \mathcal{A}_f \left[1 + \lambda^2(a_f e^{i\theta_f})e^{i\gamma}\right]$$

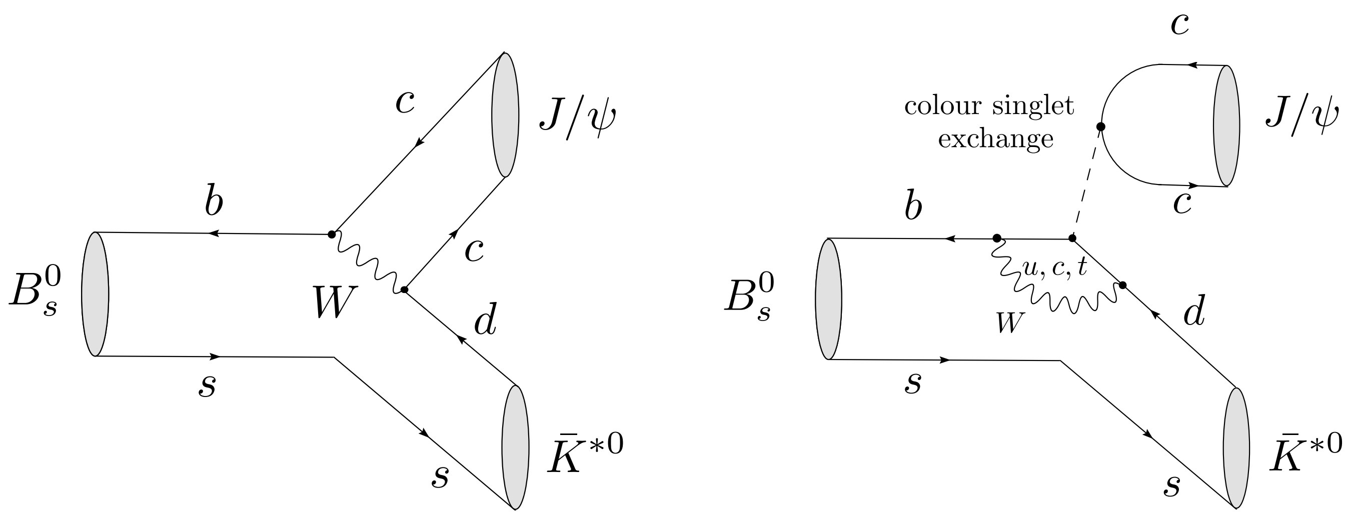
$$\mathcal{A}_{\mathrm{CP},f}^{\mathrm{mix}} = \sin\phi_s \ \to\ \sin(\phi_s + \Delta\phi_s^f)$$

- Smallish B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s (indicated by data ...):

  $\Rightarrow\ \ \Delta\phi_s^f$ at the 1° level would have a significant impact ...

[Faller, R.F. & Mannel (2008)]

Control Channel: $B_s^0 \to J/\psi \bar{K}^{*0}$



- Decay amplitude: $$A(B_s^0 \to (J/\psi \bar{K}^{*0})_f) = \lambda \mathcal{A}'_f \left[1 - a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

  – Neglect PA and E topologies [upper bound on $\mathrm{BR}(B_d^0 \to J/\psi\phi) \Rightarrow |E + PA|/|T| \lesssim 0.1$] and use the $SU(3)$ flavour symmetry:

$$\Rightarrow \quad |\mathcal{A}_f| = |\mathcal{A}'_f| \quad \text{and} \quad a_f = a'_f, \quad \theta_f = \theta'_f.$$

- Implementation: $\to$ no mixing-induced CP in $B_s^0 \to J/\psi \bar{K}^{*0}$, but ...

  – Untagged rate measurement $\oplus$ direct CP violation.

  – Angular analysis is required to disentangle final states $f \in \{0, \|, \perp\}$.

Comments

- $B_s^0 \to J/\psi \bar{K}^{*0}$ was observed by CDF and LHCb [arXiv:1208.0738]:

  - Branching ratio $(4.4^{+0.5}_{-0.4} \pm 0.8) \times 10^{-5}$ agrees well with the prediction $(4.6 \pm 0.4) \times 10^{-5}$ from $B_d \to J/\psi \rho^0$ [Faller, R.F. & Mannel (2008)].

  - Polarization fractions agree well with those of $B_d^0 \to J/\psi K^{*0}$.

$$\Rightarrow \boxed{\text{look forward to future data...}}$$

- Sensitivity at the LHCb upgrade ($50\,\mathrm{fb}^{-1}$) [arXiv:1208.3355]:

$$\Delta\phi_s|_{\rm exp} \sim 0.008 = 0.46^\circ$$

  - Theoretical uncertainty quoted as $\Delta\phi_s|_{\rm theo} \sim 0.003 = 0.17^\circ$ (!), ...
  - Data for $B \to J/\psi\pi, J/\psi K$ decays with a similar dynamics:

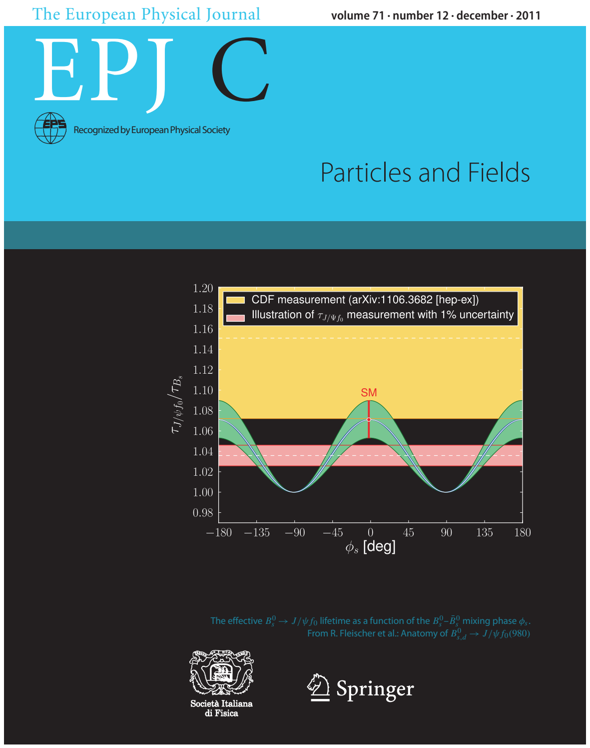
$$\Delta\phi_d = -(1.28 \pm 0.74)^\circ$$

  - Such phase shifts may mimic New Physics: $\mathcal{A}_{\rm CP,f}^{\rm mix} = \sin(\phi_s + \Delta\phi_s^f)$

$$\Rightarrow \boxed{\text{we have to get a handle on the penguin effects ...}}$$

$B_s \to J/\psi f_0(980)$:

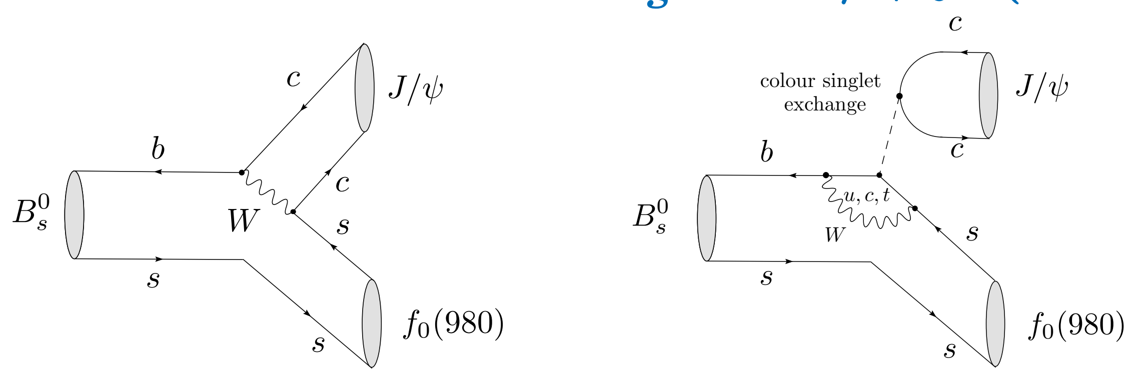
$\to$ interesting new decay



Detailed analysis: R.F., R. Knegjens & G. Ricciardi, arXiv:1109.1112 [hep-ph];

see also arXiv:1110.5490 [hep-ph], giving a discussion of $B_{s,d} \to J/\psi \eta^{(\prime)}$

General Features of $B_s^0 \to J/\psi f_0(980)$



- $f_0(980)$ is a scalar $J^{PC} = 0^{++}$ state: $\Rightarrow$ no angular analysis is required!
- Dominant mode: $B_s^0 \to J/\psi f_0$ with $f_0 \to \pi^+\pi^-$.
- Observation of $B_s^0 \to J/\psi f_0$ at LHCb, Belle, DØ and CDF:

$$R_{f_0/\phi} \equiv \frac{\mathrm{BR}(B_s^0 \to J/\psi f_0; f_0 \to \pi^+\pi^-)}{\mathrm{BR}(B_s^0 \to J/\psi \phi; \phi \to K^+K^-)} \sim 0.25$$

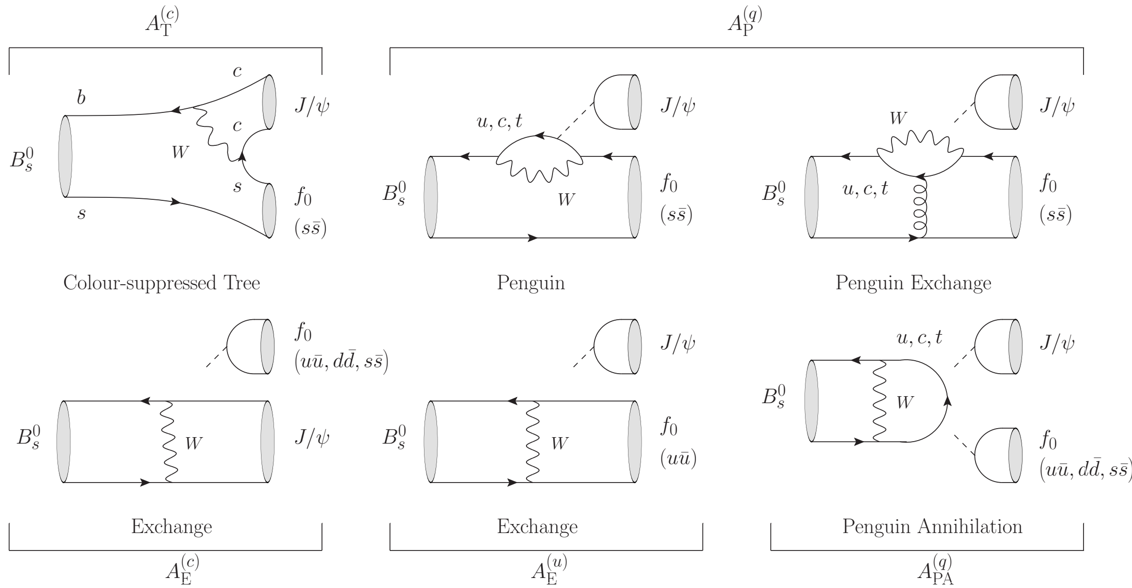
... but as no angular analysis is required:

$\Rightarrow$ $\boxed{B_s^0 \to J/\psi f_0 \text{ offers an interesting alternative to } B_s^0 \to J/\psi \phi}$

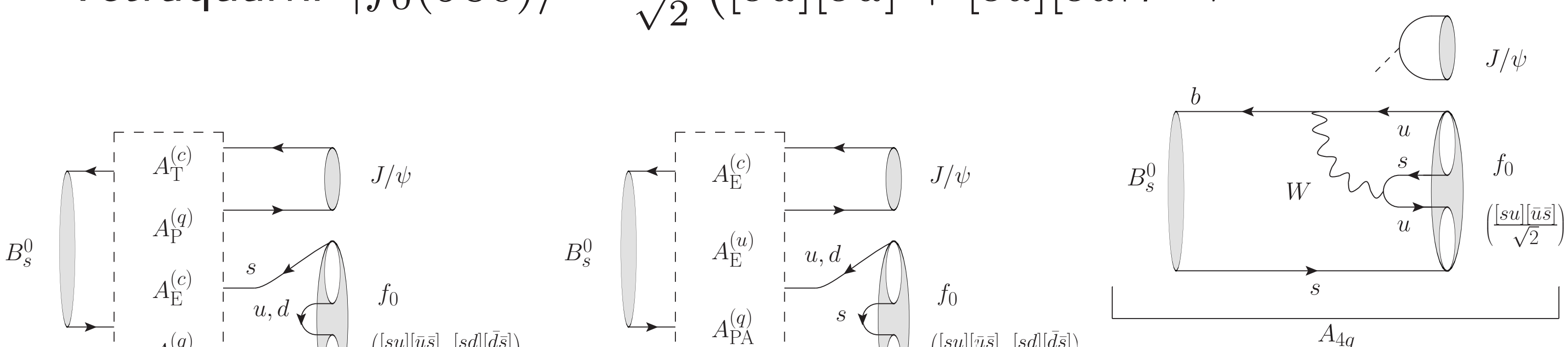
[S. Stone & L. Zhang (2009)]

Theoretical Uncertainties?

- Decay topologies:



- The composition of the $f_0(980$ is still poorly known: $\rightarrow$ 2 benchmarks:
  - Quark–antiquark: $|f_0(980)\rangle = \cos\varphi_{\mathrm{M}}|s\bar{s}\rangle + \sin\varphi_{\mathrm{M}}\frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)$
  - Tetraquark: $|f_0(980)\rangle = \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right) \rightarrow$



no counterpart in $q\bar{q}$!

[R.F., R. Knegjens & G. Ricciardi, arXiv:1109.1112 [hep-ph]]

Amplitude Structure of $B_s^0 \to J/\psi f_0$

- General SM parametrization:

$$A(B_s^0 \to J/\psi f_0) \propto \left[1 + \epsilon\, b e^{i\vartheta} e^{i\gamma}\right] \quad \text{with} \quad \epsilon \equiv \lambda^2/(1-\lambda^2)$$

- Here we have introduced a CP-conserving hadronic parameter:

$$b e^{i\vartheta} \equiv R_b \left[\frac{A_{\mathrm{P}}^{(ut)} + A_{\mathrm{E}}^{(u)} + A_{\mathrm{PA}}^{(ut)}}{A_{\mathrm{T}}^{(c)} + A_{\mathrm{P}}^{(ct)} + A_{\mathrm{E}}^{(c)} + A_{\mathrm{PA}}^{(ct)}} \right]$$

$\to$ hadron dynamics (?), *but enters in a doubly Cabibbo-suppressed way*

- Characteristic hadronic phase shift:

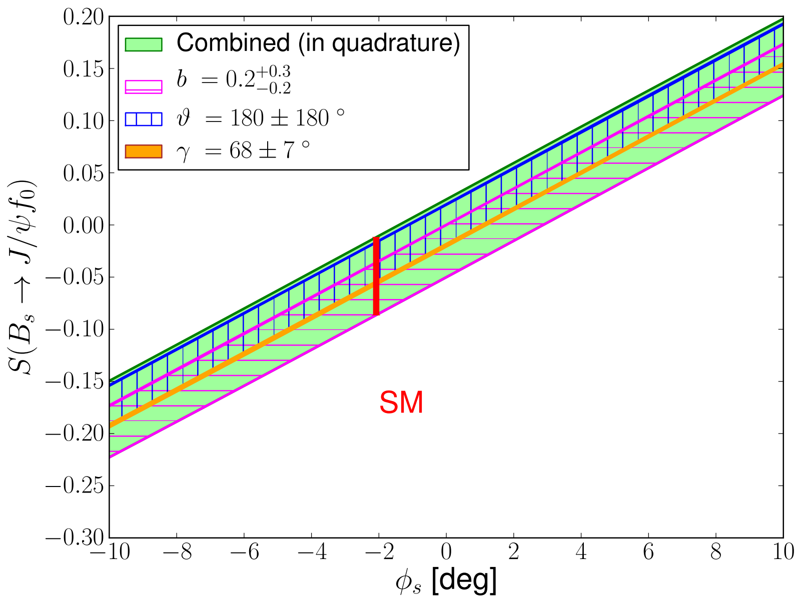
$$\tan \Delta\phi_{J/\psi f_0} = \frac{2\epsilon b \cos\vartheta \sin\gamma + \epsilon^2 b^2 \sin 2\gamma}{1 + 2\epsilon b \cos\vartheta \cos\gamma + \epsilon^2 b^2 \cos 2\gamma}$$

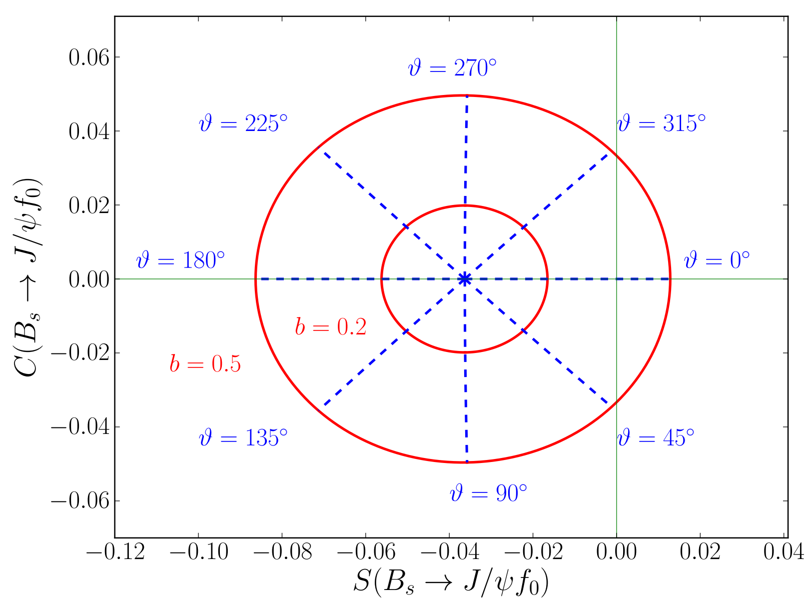
– Conservative range for $be^{i\theta}$: $0 \leq b \leq 0.5$, $0^\circ \leq \vartheta \leq 360^\circ \quad \Rightarrow$

$$\Delta\phi_{J/\psi f_0} \in [-2.9^\circ, 2.8^\circ]$$

CP Violation in $B_s^0 \to J/\psi f_0$

$$\frac{\Gamma(B_s(t) \to J/\psi f_0) - \Gamma(\bar{B}_s(t) \to J/\psi f_0)}{\Gamma(B_s(t) \to J/\psi f_0) + \Gamma(\bar{B}_s(t) \to J/\psi f_0)} = \frac{C\cos(\Delta M_s t) - S\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s t/2) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s t/2)}$$





- Mixing-induced CP asymmetry: $\boxed{S = \sqrt{1 - C^2}\sin(\phi_s + \Delta\phi)}$
  - Naïve SM value: $(\sin\phi_s)|_{\rm SM} = -0.036 \pm 0.002$;
  - Allowing for hadronic effects: $S(B_s^0 \to J/\psi f_0)\big|_{\rm SM} \in [-0.086, -0.012]$

Comments

- Should smallish CPV $-0.1 \lesssim S \lesssim 0$ be found:

$\Rightarrow$ $\boxed{\text{crucial to constrain hadronic corrections to disentangle NP from SM}}$

- LHCb result for ϕ_s from $B_s^0 \to J/\psi f_0$:

$$\phi_s = -(25 \pm 25 \pm 1)^\circ, \text{ corrsponds to } S = -0.43^{+0.43}_{-0.34}.$$

  – Hadronic corrections were not taken into account; still some way to go until we may eventually enter the limiting range $-0.1 \lesssim S \lesssim 0$:

$$S = \sqrt{1 - C^2}\sin(\phi_s + \Delta\phi); \quad \Delta\phi_{J/\psi f_0} \in [-2.9^\circ, 2.8^\circ]$$

  – LHCb [arXiv:1208.3355]: theory uncertainty of $\sim 0.01 = 0.57^\circ$!?

- Average with $B_s^0 \to J/\psi\phi$:
  – Increase of exp. precision: average is problematic because of hadronic effects and their different impact on $B_s^0 \to J/\psi f_0$ and $B_s^0 \to J/\psi\phi$.
  – It will actually be interesting to compare the individual measurements.

[Remember discussions about averages for CP asymmetries in $b \to s$ penguin modes]

Control Channel: $B_d^0 \to J/\psi f_0(980)$

- Leading contributions emerge from the $d\bar{d}$ component of the $f_0(980)$:

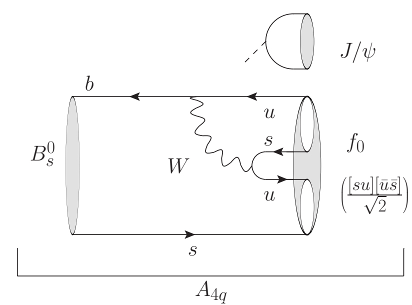
$$A(B_d^0 \to J/\psi f_0) = -\lambda \mathcal{A}' \left[1 - b' e^{i\vartheta'} e^{i\gamma}\right]$$

- Measurement of branching ratio and CP-violating asymmetries:

$$\Rightarrow \boxed{b' \text{ and } \vartheta' \text{ can be (cleanly) determined}}$$

- Relation to the b and ϑ hadronic parameters of $B_s^0 \to J/\psi f_0$:
  - $q\bar{q}$ interpretation of the $f_0(980)$: $\to b \approx b'$, $\vartheta \approx \vartheta'$ through $SU(3)$ if mixing angle is significantly different from $0°$ or $180°$.
  - Tetraquark description: topology contributing to $B_s^0 \to J/\psi f_0$ does not have a counterpart in $B_s^0 \to J/\psi f_0$ $\to$ how important is it!?

$$\to \boxed{\text{hadronic } f_0 \text{ structure !?}}$$



- Branching ratio:
  - 4q estimate: BR$(B_d^0 \to J/\psi f_0; f_0 \to \pi^+\pi^-) \sim (1\text{–}3) \times 10^{-6}$
  - 1st LHCb analysis [arXiv:1301.5347 [hep-ex]]: $< 1.1 \times 10^{-6}$ (90% C.L.)

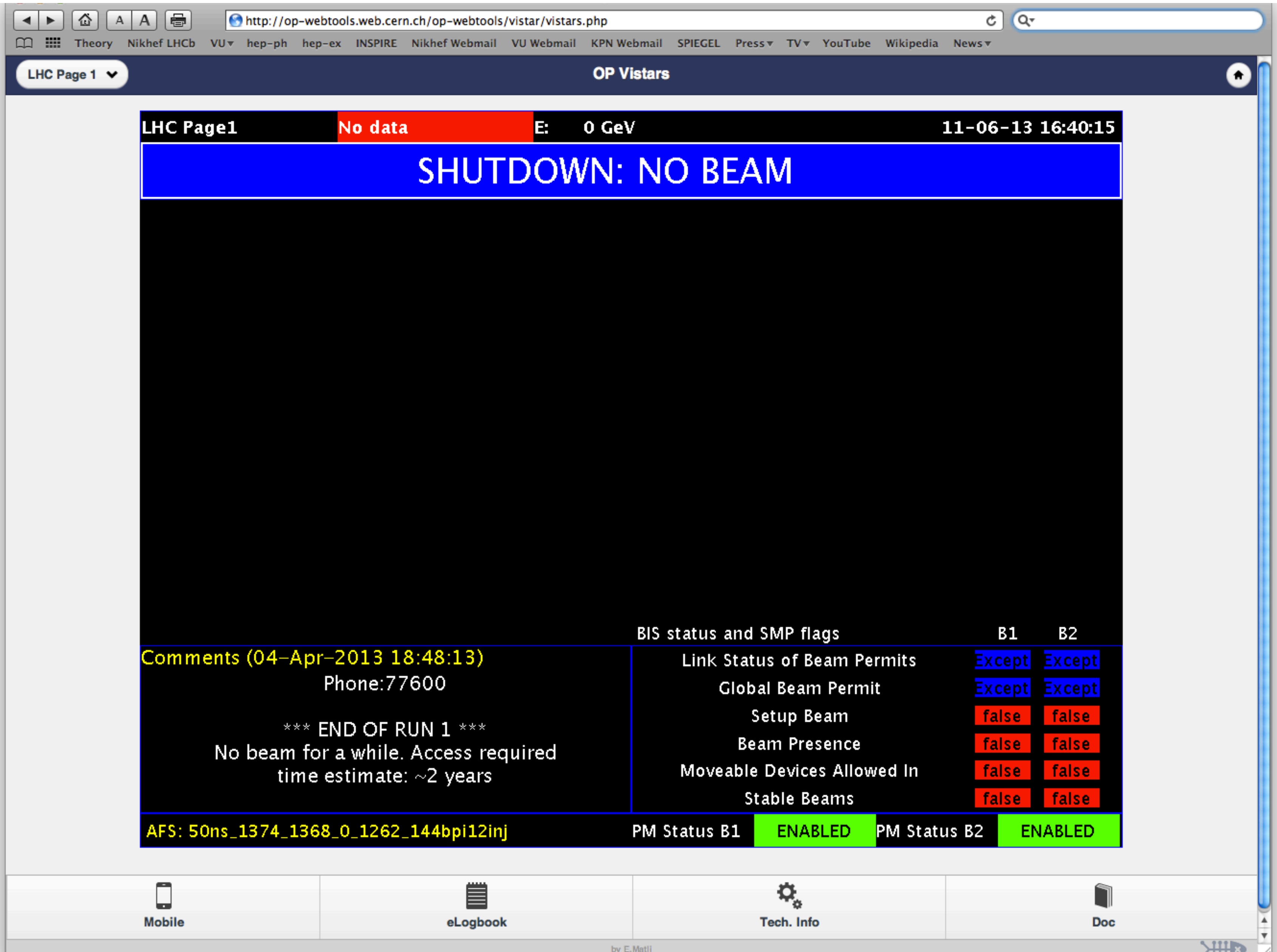
[Details: R.F., R. Knegjens & G. Ricciardi, arXiv:1109.1112 [hep-ph]]

$\boxed{\text{Conclusions \& Outlook}}$

$\diamond$ New Frontiers in Precision Physics:

- Still no signals for New Physics @ LHC:
  - Impressive (also frustrating ...), but more is yet to come!
  - Prepare to deal with "smallish" NP effects:

$\Rightarrow$ $\boxed{\text{Match experimental with theoretical precision!}}$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LHC Page 1
OP Vistars
LHC Page1
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SHUTDOWN: NO BEAM
BIS status and SMP flags
B1
B2
Comments (04-Apr-2013 18:48:13)
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time estimate: ~2 years
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Except
Global Beam Permit
Except
Except
Setup Beam
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false
Beam Presence
false
false
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