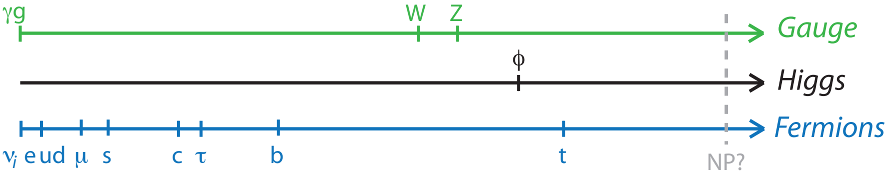
Heavy flavours: a theoretical introduction

Sébastien Descotes-Genon

Laboratoire de Physique Théorique
CNRS & Université Paris-Sud 11, 91405 Orsay, France

LHC France 2013 (Annecy)
3 April 2013

Why flavour ?



Gauge part $\mathcal{L}_{gauge}(A_a, \Psi_j)$

- Highly symmetric (gauge symmetry, flavour symmetry)
- Well-tested experimentally (electroweak precision tests)
- Stable with respect to quantum corrections

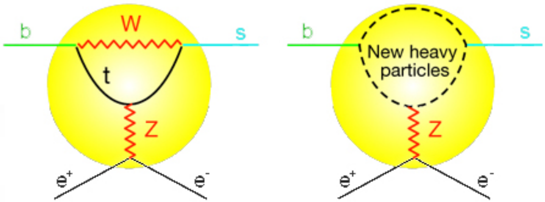
Higgs part $\mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$

- Ad hoc potential
- Dynamics not fully tested (structure of Higgs potential ?)
- Not stable w.r.t quantum corrections
- Origin of flavour structure of the Standard Model

due to Yukawa couplings $Y^{ij}\psi^i_L\psi^j_R\phi$

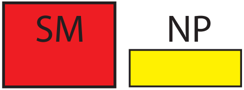
The flavour game

- Dynamics of flavours under electroweak processes
- "Low"-energy experiments (generally below *b*-quark mass) probing flavour structure:
  - structure of Yukawa couplings
  - strength of CP violation
  - origin of mass hierarchy
- Quantum sensitivity (through loops) to structure and scales of higher energies: electroweak scale, top quark, New Physics ?

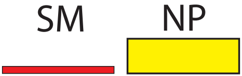


Different processes for different goals

SM expected to be dominant (tree-dominated processes)
Metrology of SM



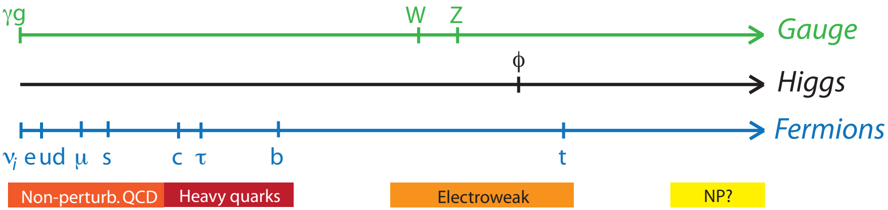
SM and NP competing (loop-dominated processes)
Constraints on NP



SM zero or very small (SM symmetry forbidden proc.)
Smoking guns of NP

Last two categories hinge on theorists' beliefs concerning the size of NP and experimental measurements. . .

A multi-scale problem

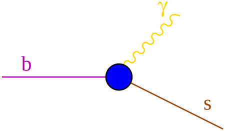


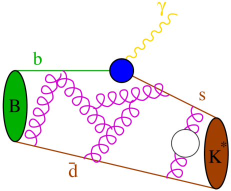
- Tough multi-scale challenge with 3 interactions intertwined
- Separation of scale

  effective Hamiltonian (Λ_{EW} vs m_b), effective theories (m_b vs Λ_{QCD})
- Main theoretical problem from hadronisation of quarks into hadrons: description/parametrisation in terms of QCD quantities

  decay constants, form factors, bag parameters...
- QCD in non-perturbative regime ! but theory tools to assess them

Theoretical tools for QCD



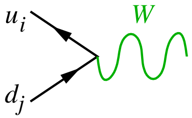


$\langle K^*(k,\varepsilon)\bar{s}\gamma_\mu(1-\gamma_5)b|\bar{B}(p)\rangle$
$= \epsilon_{\mu\nu\rho\sigma} \times 2V(q^2)/(m_B + m_{K^*})$
$\quad -i\varepsilon^*_{K^*,\mu}(m_B + m_{K^*})A_1(q^2) + \dots$

4 form factors
depending on γ virtuality

- lattice QCD (discretised version of the theory)
  - progress in computational power (1% accuracy in view)
  - access to final-state interactions for two meson states, start tackling unstable particles under strong interaction
- heavy-flavour effective theories
  - Expansion in Λ_{QCD}/m_b to exploit heavy-quark symmetry
  - Separation of soft (universal) and hard (process-dependent)
  - Simplification in terms of soft form factors (all $B \to K^* : 7 \to 2$)
- sum rules
  - Duality between hadron and quark in specific energy range
  - Different energy window from lattice QCD
  - Difficult to assess corrections due to duality violations

Misalignment of up-type and down-type Yukawa couplings
$\Longrightarrow$weak interaction not diagonal in mass eigenstates



$$\frac{g}{\sqrt{2}}\,\bar{u}_{Li}\,V_{ij}\gamma^\mu d_{Lj}\,W^+_\mu + \text{h.c.}$$

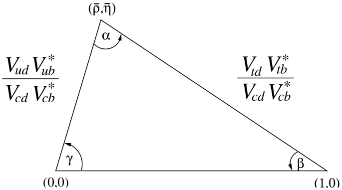
unitary Cabibbo-Kobayashi-Maskawa matrix

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

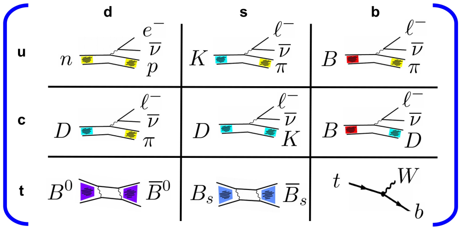
1 complex phase (for $\eta \neq 0$) source of CP-violation in the quark sector

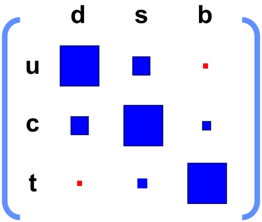
(small but non-squashed)
B-meson triangle (bd)

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$



SM: Constraining the CKM matrix

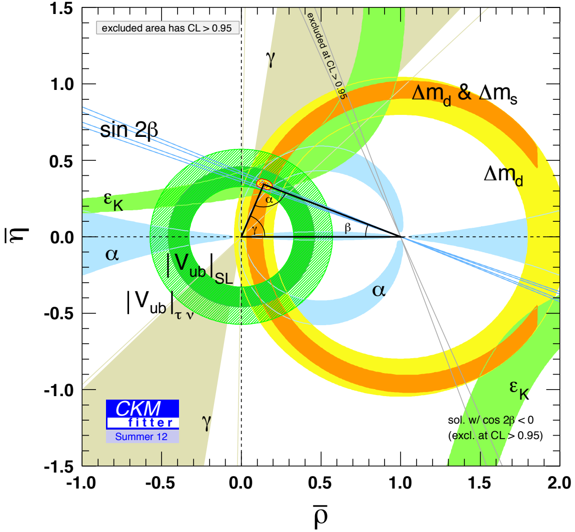
V = 



- CP-invariance of QCD to build hadronic-indep. CP-violating asym. or to determine hadronic inputs from data
- Lattice inputs (mostly) for CP-conserving quantities
- Statistical framework to combine data and assess uncertainites

	Exp. uncert.		Theoretical uncertainties	
Tree	$B \to DK$	γ	$B(b) \to D(c)\ell\nu$	$\lvert V_{cb}\rvert$ vs form factor (OPE)
			$B(b) \to \pi(u)\ell\nu$	$\lvert V_{ub}\rvert$ vs form factor (OPE)
			$M \to \ell\nu$	$\lvert V_{UD}\rvert$ vs f_M (decay cst)
Loop	$B \to J/\Psi K_s$	β	ϵ_K (K mixing)	$(\bar\rho, \bar\eta)$ vs B_K (bag parameter)
	$B \to \pi\pi, \rho\rho$	α	$\Delta m_d, \Delta m_s$ (B_d, B_s mixings)	$\lvert V_{tb}V_{tq}\rvert$ vs $f_B^2 B_B$ (bag param)

SM: The current status of CKM



$|V_{ud}|, |V_{us}|, |V_{cb}|, |V_{ub}|_{SL}$

$B \to \tau\nu$

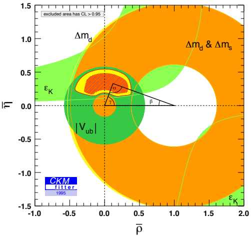
$\Delta m_d, \Delta m_s, \epsilon_K$

$\alpha, \sin 2\beta, \gamma$

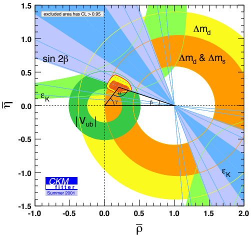
$$A = 0.802^{+0.029}_{-0.011}$$
$$\lambda = 0.2254^{+0.0006}_{-0.0010}$$
$$\bar{\rho} = 0.140^{+0.027}_{-0.026}$$
$$\bar{\eta} = 0.343^{+0.015}_{-0.015}$$

(68% CL)

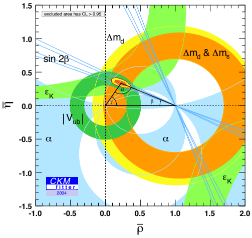
SM: Two decades of CKM



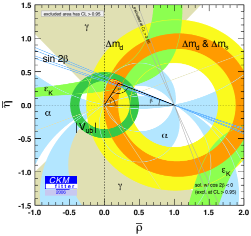
1995



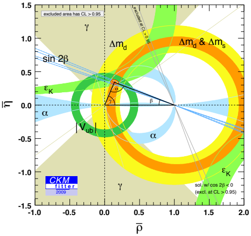
2001



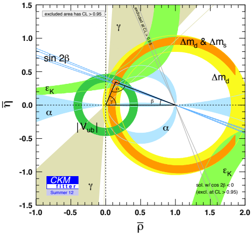
2004



2006

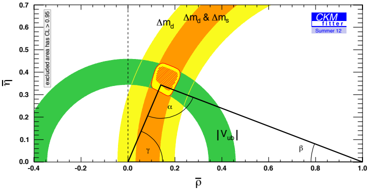


2009

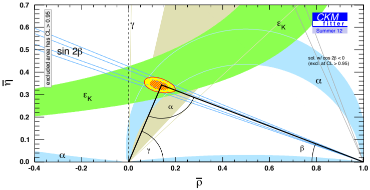


2013

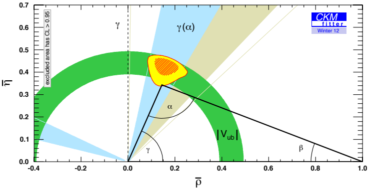
SM: A very consistent description of flavour



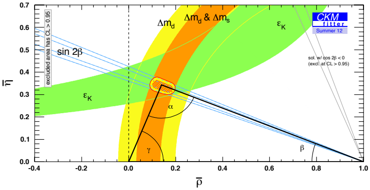
CP allowed only



CP violating only



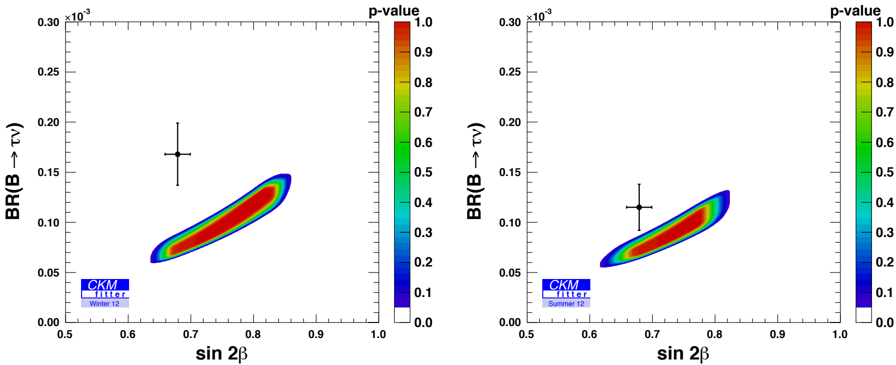
Tree only



Loop only

Validity of Kobayashi-Maskawa picture of *CP* violation

SM: A discrepancy dies away



- There *used to be* a significant discrepancy for $B \to \tau\nu$ or $\sin(2\beta)$

  2.8σ [Moriond 12] $\to$ 1.6σ [ICHEP 12]

- New Belle result with hadronic tag for $Br(B \to \tau\nu)$ changing WA $(1.68 \pm 0.31) \cdot 10^{-3}$ [Moriond12] $\to$ $(1.15 \pm 0.23) \cdot 10^{-3}$ [ICHEP12]
- Brings pure QCD (no CKM) ratio $d\Gamma(B \to \pi\ell\nu)/dq^2/Br(B \to \tau\nu)$ closer to theoretical estimates (sum rules)

From SM to NP

SM = effective low-energy theory from
an underlying, more fundamental and yet unknown, theory

As long as we stay at low energies, below the scale Λ of new particles

$$\mathcal{L} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \Psi_j)$$

In Higgs potential, new operators O_n, suppressed by powers of Λ

- Describe impact of New Physics on "low-energy" physics
- Made of SM fields, compatible with its symmetries,
  e.g., effective neutrino mass term $(g^{ij}/\Lambda)\psi_L^i \psi_L^{Tj} \phi\phi^T$

- New d.o.f. and energy scale of NP ? High-energy experiments
- Symmetries and structure ? High-precision experiments

SM+NP $\simeq$ SM

Operator	Bounds on Λ in TeV ($c_n = 1$) Re	Im	Bounds on c_n ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

[Isidori, Nir, Perez]

Neutral meson mixing ($\Delta F = 2$) is enough to constrain NP with

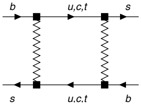
- A significant mass gap [not too large ?]
- Weak couplings with close-to-SM pattern of flavour violation
- Some mixture of the two ? [not too close ?]

- Explains the popularity (success ?) of Minimal Flavour Violation (only source of flavour violation stems from Yukawa couplings)
- Hints of a more specific structure ? $\Longrightarrow$ Current effort

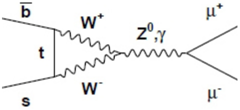
NP: Flavour-Changing Neutral Currents

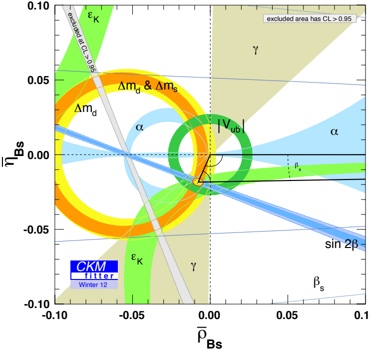
Forbidden in SM at tree level, so good place for NP to show up in loops

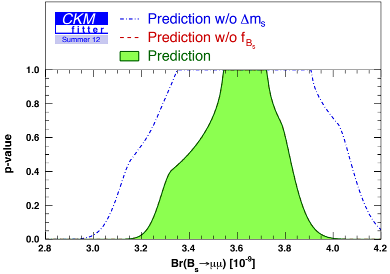
$\Delta F = 2$: B_s mixing



$\Delta F = 1$: $B_s \to \mu\mu$



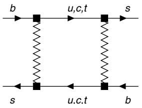




$$Br^{th}_{SM} = (3.63^{+0.21}_{-0.34}) \cdot 10^{-9}$$

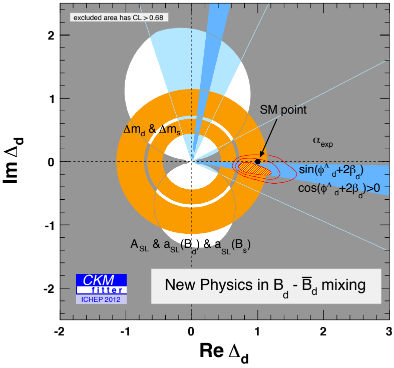
Agree well with SM, as probed by LHCb (B_s) and before, by B-factories

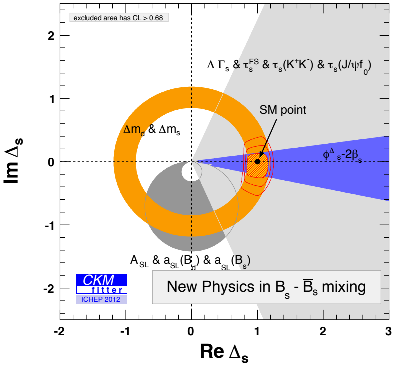
NP: Constraining power of flavour physics



Model-indep. fit to NP in $\Delta F = 2$ processes only
to fit $B_q \leftrightarrow \bar{B}_q$ mixing matrix $M_q^{12} = M_q^{12;SM} \times \Delta_q$

[Lenz, Nierste et al.]





Overall good agreement with SM, but still some room left for NP
DØ result on dimuon asymmetry hard to explain [3.3 σ pull]

NP under scrutiny

Room for NP	Charged current (SM tree)	Neutral current (SM loops)
NP needed ?	$B \to D(^*)\tau\nu$	$A_{sl}, A_I(B \to K\mu\mu)$
Unclear	$A_{CP}(D \to PP)$	$B \to K(^*)\ell\ell, B \to V\gamma$
NP constrained	$B \to \tau\nu$	$B_s \to J/\psi\phi, B_s \to \mu\mu$

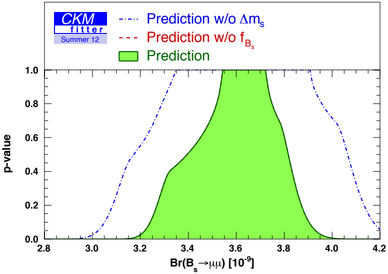
Ongoing theoretical effort

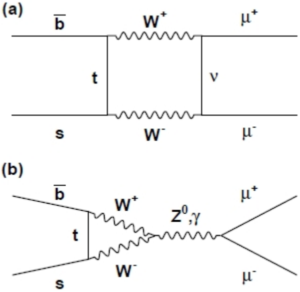
- Better understand hadronic issues: form factors (lattice QCD, sum rules, effective theories), final-state interaction (factorisation)
- Design obs. more sensitive to NP and less to hadronic inputs (angular obs. in $B \to D(^*)\tau\nu$, $B \to K(^*)\ell\ell$, $B \to V\gamma$ polarisation)
- Explore both model-independent approach (eff. Hamitlonian) and model-dependent (two-Higgs doublet, 4th gen., left-right sym.)
- ...at least for models with interesting pattern of flavour violation, more and more together with constraints on Higgs processes

Need for close interplay between theory and experiment, but also between electroweak and heavy flavour scales !

Back-up

$B_s \to \mu\mu$ (1)





$$Br(B_s \to \mu^+\mu^-) = \tau_{B_s} \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2\theta_W}\right)^2 f_{B_s}^2 m_{B_s} m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} |V_{tb}^* V_{ts}|^2 \eta_Y^2 Y^2(m_t/M_W)$$

- LHCb: $Br(B_s \to \mu\mu)_{\rm exp} = (3.2^{+1.5}_{-1.2}) \cdot 10^{-9}$
- NLO prediction from global fit: $Br(B_s \to \mu\mu)_{\rm th} = (3.63^{+0.21}_{-0.34}) \cdot 10^{-9}$
- Global fit constraints $|V_{tb}^* V_{ts}|$, but also f_{B_s}

$B_s \to \mu\mu$ (2)

- Comparing theoretical and experimental predictions
  - Theoretically: CP-average at fixed $t = 0$
  - Experimentally: CP-average integrated over t (including B_s mixing)

[SDG et al, De Bruyn et al]

$$Br(B_s \to f)_{th} = \frac{1 - y_s^2}{1 + A^f_{\Delta\Gamma} y_s} Br(B_s \to f)_{exp,untag} \qquad y_s = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

$$\Gamma(B_s(t) \to f) + \Gamma(\bar{B}_s(t) \to f) = e^{-\Gamma_H t/2}(1 + A^f_{\Delta\Gamma}) + e^{-\Gamma_L t/2}(1 - A^f_{\Delta\Gamma})$$

In SM: $A^{\mu\mu}_{\Delta\Gamma} = 1, Br(B_s \to \mu\mu)_{th} \simeq 0.91 \cdot Br(B_s \to \mu\mu)_{exp}$

[De Bruyn et al]

- Choice of inputs and higher orders

$$Br(B_s \to \mu\mu)_{th} = (3.23 \pm 0.14 \pm 0.23) \cdot 10^{-9}$$ [Buras et al]

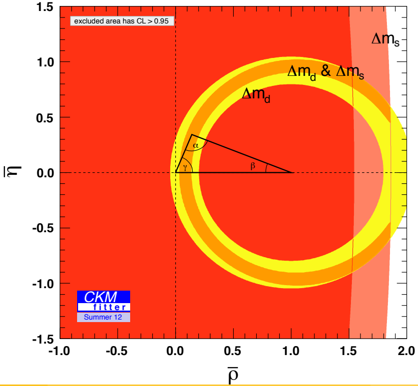
$$Br(B_s \to \mu\mu)_{th} = (3.63^{+0.21}_{-0.34}) \cdot 10^{-9}$$ [CKMfitter]

  - mainly $m_t^{\bar{MS}}$ from $m_t^{\rm pole}$ @ NLO or N^{3}LO
  - f_{B_s} from lattice average or (very) constrained by global fit (Δm_s)
  - Including part of NLO electroweak corrections (large-m_t) or not

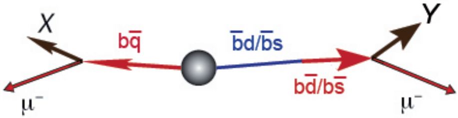
The mended Δm_d and Δm_s ring

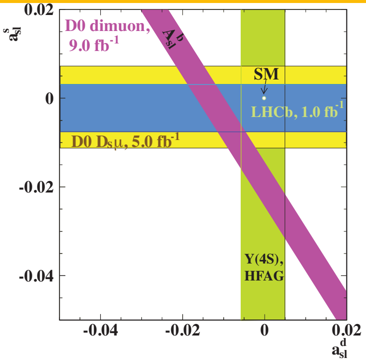
- Changed bag parameters in $\Delta m_{d,s} \propto |V_{td,s}|^2 f_{B_{d,s}} B^2_{B_{d,s}}$
- Bound on $\bar\rho$ from Δm_s hidden by our choice of contours

$$|V_{td}|^2 = A^2\lambda^6[(1-\bar\rho)^2+\bar\eta^2+O(\lambda^4)]$$
$$|V_{ts}|^2 = A^2\lambda^4[1-\lambda^2(1-2\bar\rho)+O(\lambda^4)]$$



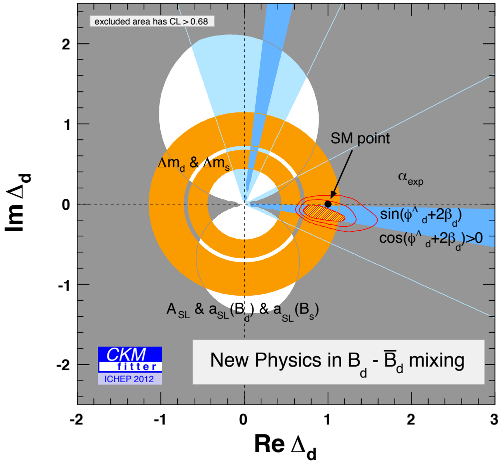
A_{SL} and $a_{SL}^{d,s}$





- Same-sign dimuon charge asym. $A_{SL} = (-0.85\pm0.28)\%$ [CDF, DØ] linear combination of a_{SL}^d and a_{SL}^s, disagrees with SM:
  $A_{SL}^{SM} = -(0.020 \pm 0.003)\%$ [Lenz,Nierste 11]
- Individual semileptonic asyms. from $B_q \to D_q \mu X$ OK with SM
  $a_{SL}^d = (0.38 \pm 0.36)\%$ [B-factories, Tevatron]
  $a_{SL}^s = (-0.22 \pm 0.52)\%$ [DØ, LHCb]

B_d mixing



[Constraints @ 68% CL]

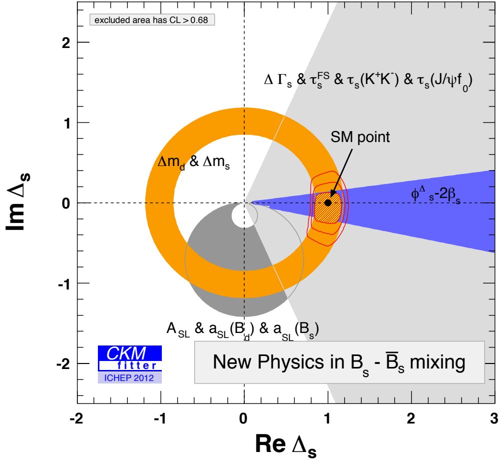
- Dominant constraint from β and Δm_d
- New a^d_{SL} yields weaker suppression of 2nd solution
- New $BR(B \to \tau\nu)$ from Belle brings world average close to SM

$$B(B \to \tau\nu)^{SM} = (0.72^{+0.11}_{-0.08}) \cdot 10^{-4}$$
$$B(B \to \tau\nu)^{\exp} = (1.15 \pm 0.23) \cdot 10^{-4}$$

- Still room for NP in Δ_d

2D SM hypothesis ($\Delta_d = 1 + i \cdot 0$): 1.6 σ

B_s mixing



[Constraints @ 68% CL]

- Dominant constraints from Δm_s and ϕ_s (LHCb)
- LHCb $\Delta\Gamma_s > 0$ kills 2nd solution
- Disagreement with SM driven by A_{SL} alone
- and in disagreement with ϕ_s, which favours SM situation
- still room for NP in Δ_s

2D SM hypothesis ($\Delta_s = 1 + i \cdot 0$): 0.2 σ