B-meson mixing
A tale of two discrepancies (and a half)

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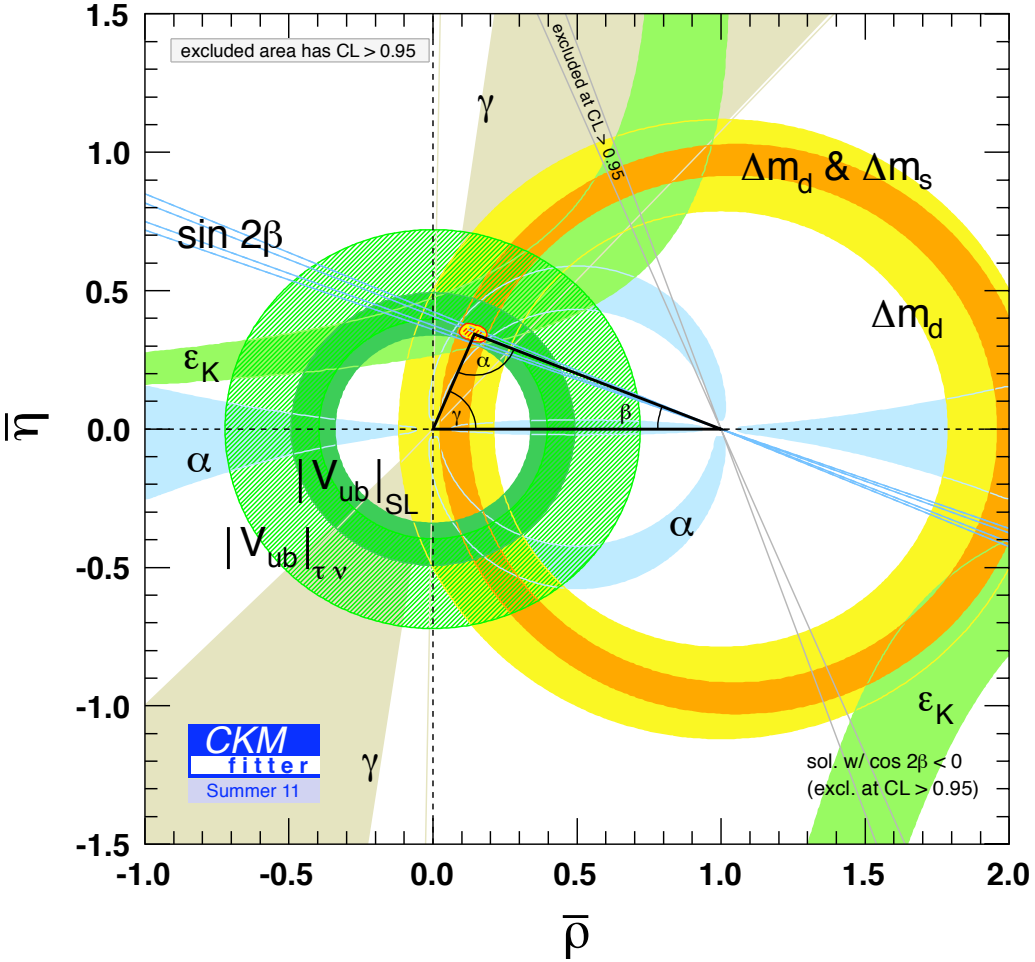
very good agreement of many constraints on CP violation



SM mechanism for CP-violation encoded in CKM matrix describes efficiently B_d

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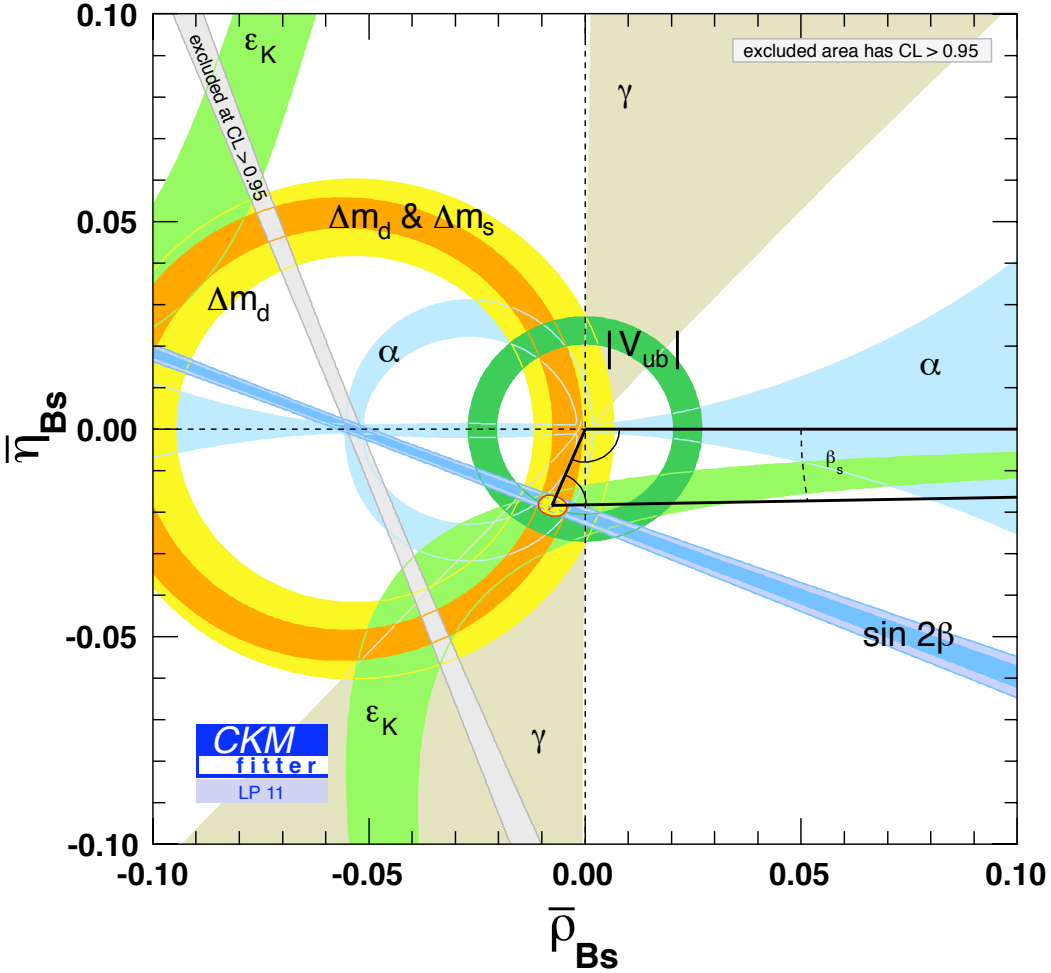

SM mechanism for CP-violation encoded in CKM matrix describes efficiently B_d and B_s systems ?

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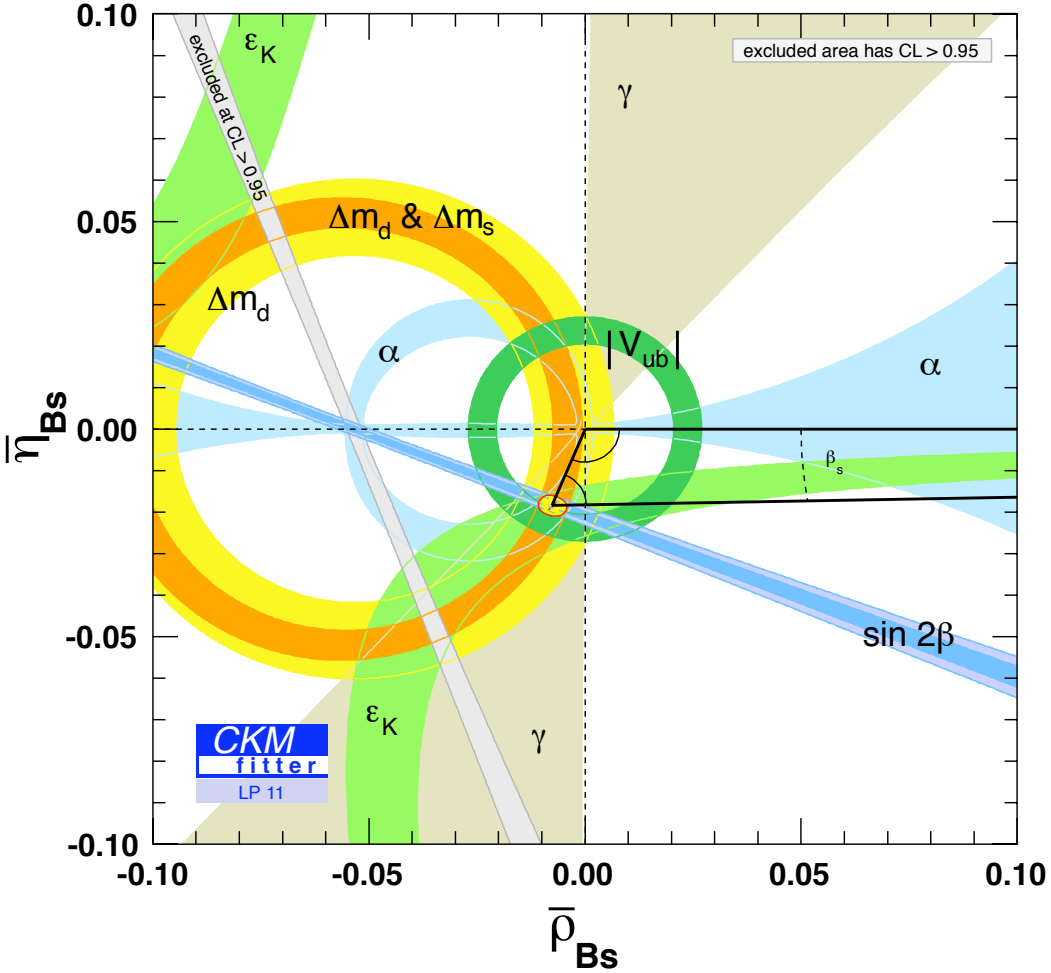


SM mechanism for CP-violation encoded in CKM matrix describes efficiently B_d and B_s systems ?

Not exactly:

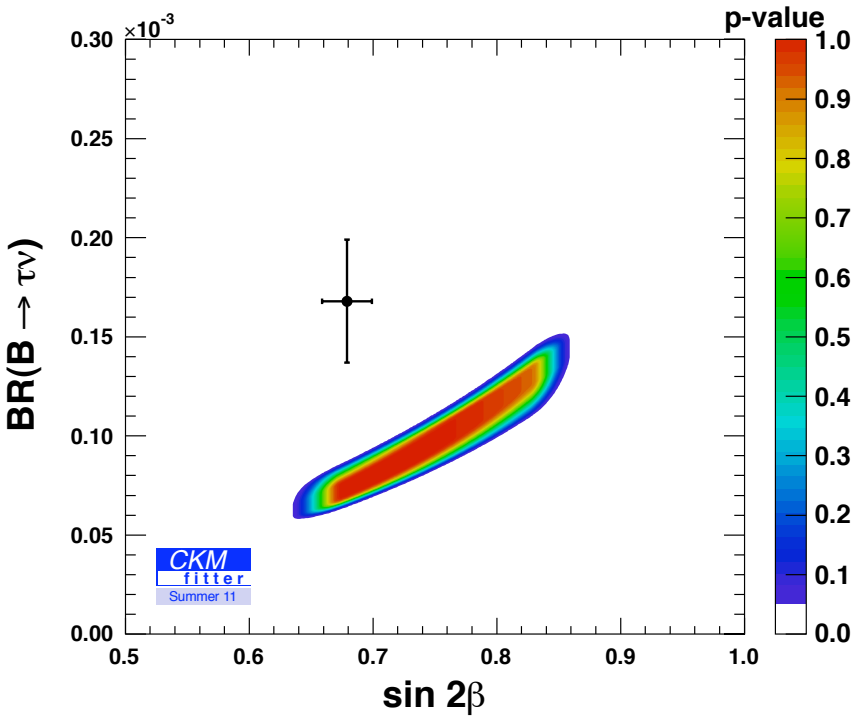
- $\sin(2\beta)$ vs $B \to \tau\nu$
- A_{SL}
- $(\beta_s, \Delta\Gamma_s)$ (?)

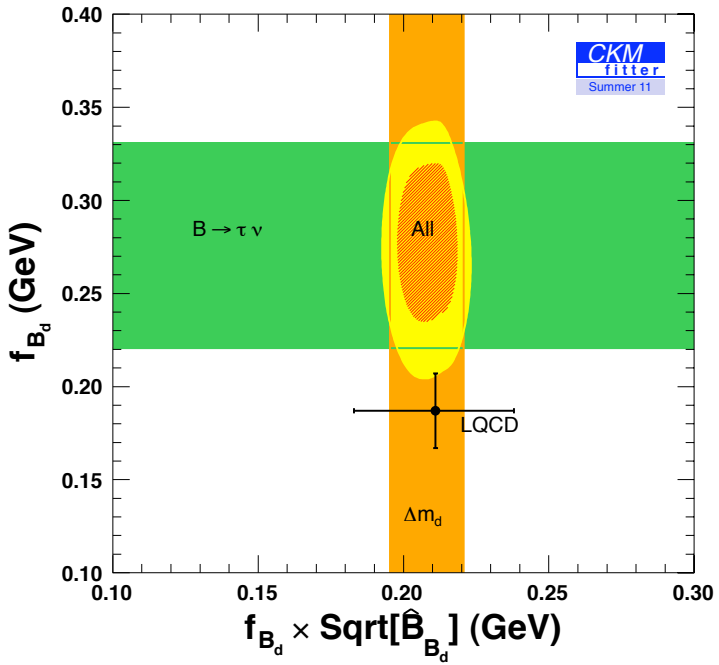
discrepancies related to meson mixing

1st Discrepancy: $\sin(2\beta)$ vs $B \to \tau\nu$

Global fit χ^2_{min} drops by 2.7σ (2.8σ) if $\sin 2\beta_{c\bar{c}}$ ($B \to \tau\nu$) removed

Babar, Belle

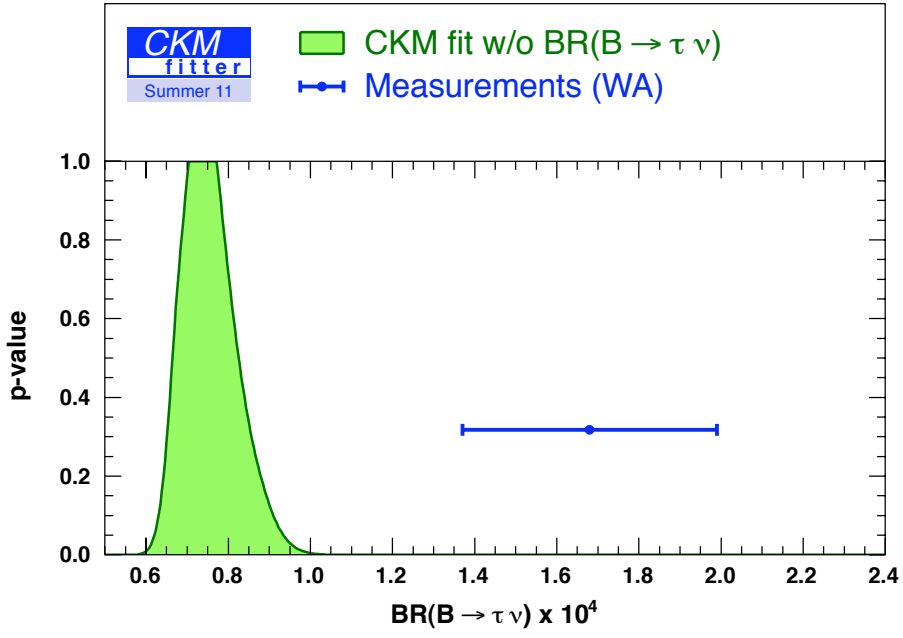


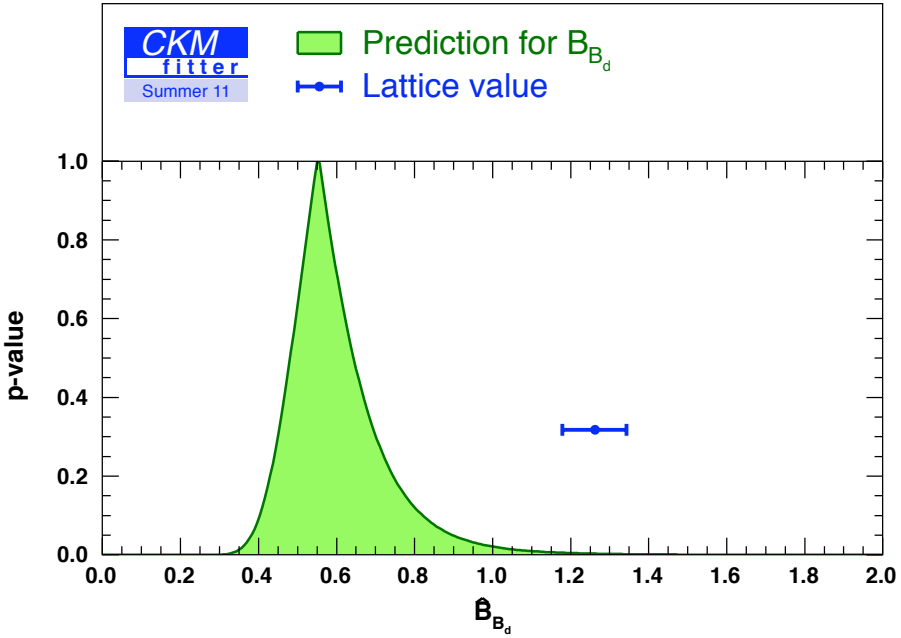


Issue *not only* the value of f_{B_d} since 2.8σ discrepancy from

$$\frac{B(B \to \tau\nu)}{\Delta m_d} = \frac{3\pi}{4} \frac{m_\tau^2 \tau_B}{m_W^2 \eta_B S[x_t]} \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \frac{\sin^2\beta}{\sin^2(\alpha+\beta)} \frac{1}{|V_{ud}|^2 B_{B_d}}$$

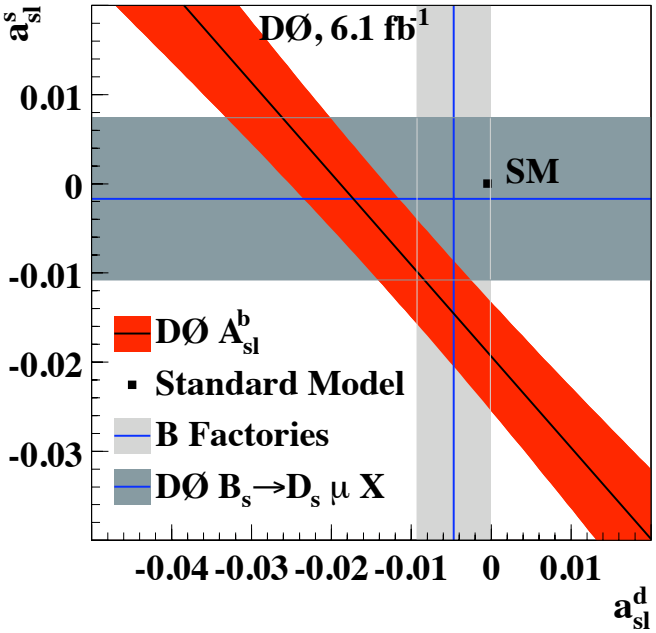
1st Discrepancy: $\sin(2\beta)$ vs $B \to \tau\nu$

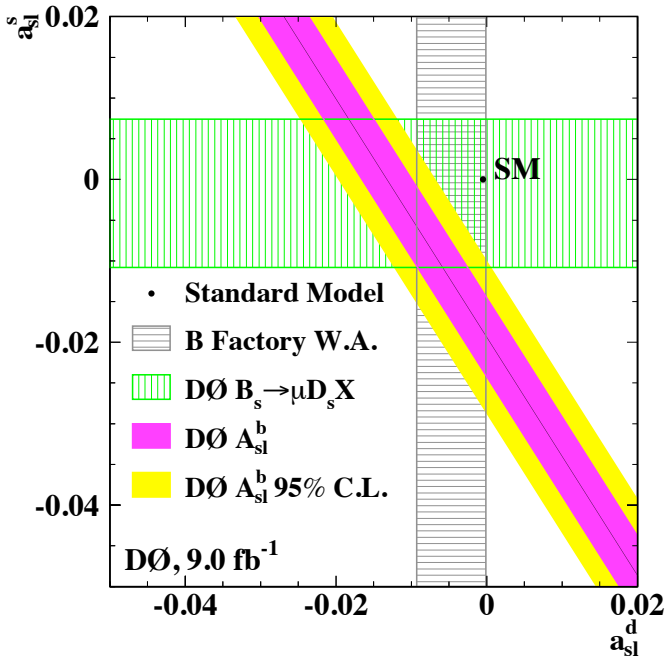




- Change in measured $Br(B \to \tau\nu)$ (2.6 σ) ?
- Correlated change in lattice values for f_{B_d} (2.6 σ) and B_{B_d} (2.7 σ) ?
- New physics in decay (charged Higgs) or in mixing ?

2nd Discrepancy: A_{SL}





- Same-sign dimuon charge asymmetry yields A_{SL} CDF, DØ

$$A_{\rm SL} = (-8.5\pm2.8)\cdot10^{-3}(2010) \to (-7.87\pm1.72\pm0.93)\cdot10^{-3}(2011)$$

- Linear comb. of semileptonic (flavour specific) asym. for $B_{d,s}$

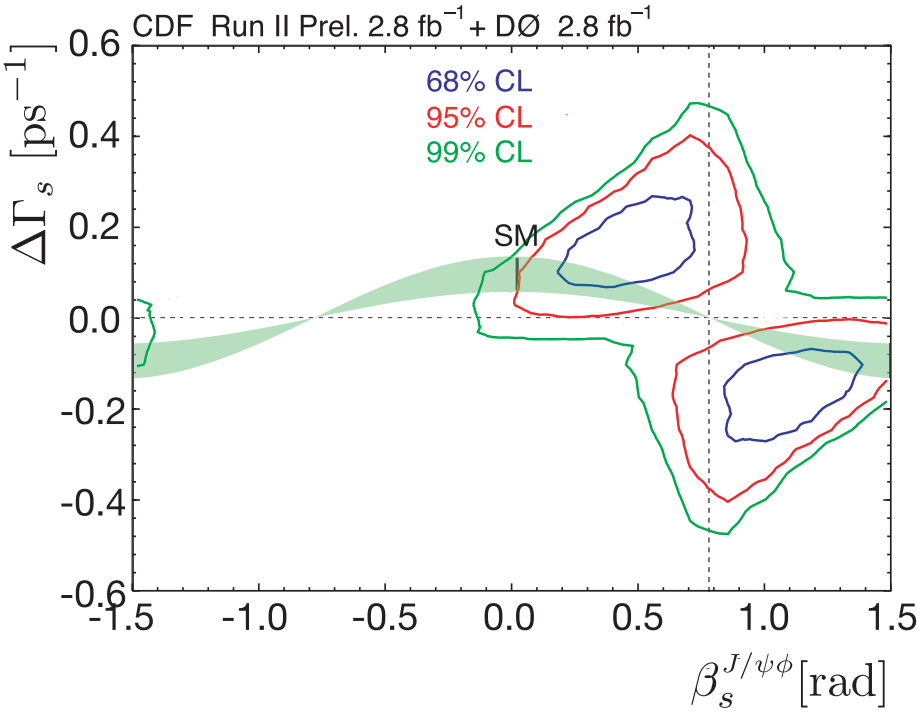
$$a^q_{SL} = \frac{\Gamma(\bar{B}_q(t)\to\ell^+\nu X) - \Gamma(B_q(t)\to\ell^-\nu X)}{\Gamma(\bar{B}_q(t)\to\ell^+\nu X) + \Gamma(B_q(t)\to\ell^-\nu X)} \neq 0 \Longrightarrow \text{CPV in mixing}$$

- SM expectation $A_{SL} = -(2.0\pm0.3)\cdot10^{-4}$ [Lenz, Nierste 11]

3rd Discrepancy: ϕ_{Bs} ?

Angular analysis of $B_s \to J/\psi\phi$ to measure ϕ_{Bs}

In SM, $\phi_{Bs} \to -2\beta_s = 2arg(V_{cs}V_{cb}^*/V_{ts}V_{tb}^*) = -2.09^\circ \pm 0.09^\circ$



- 2010 CDF/DØ $\phi_{Bs} \in [-67.6^\circ, -30.9^\circ] U [-148.9^\circ, -111.1^\circ]$

3rd Discrepancy: ϕ_{Bs} ?

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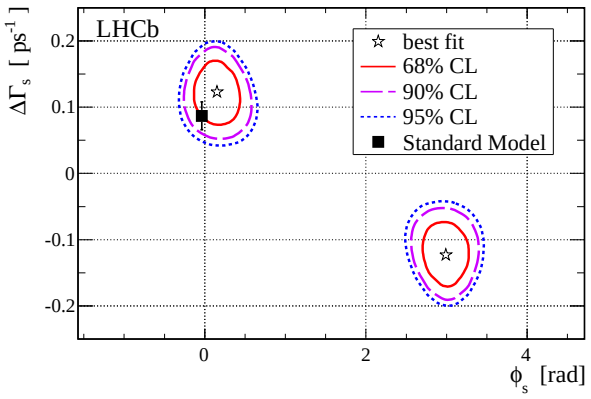
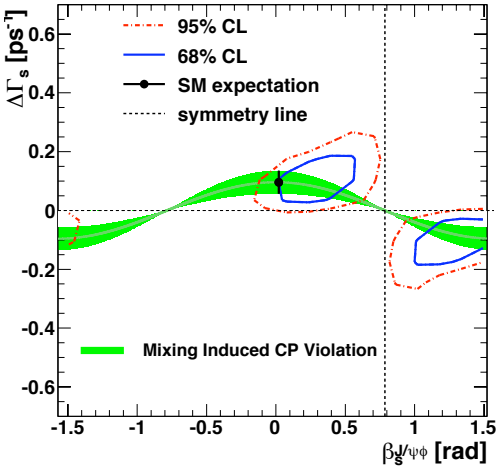
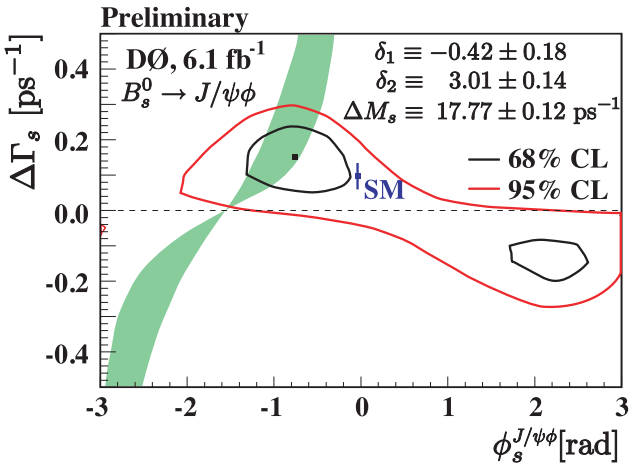
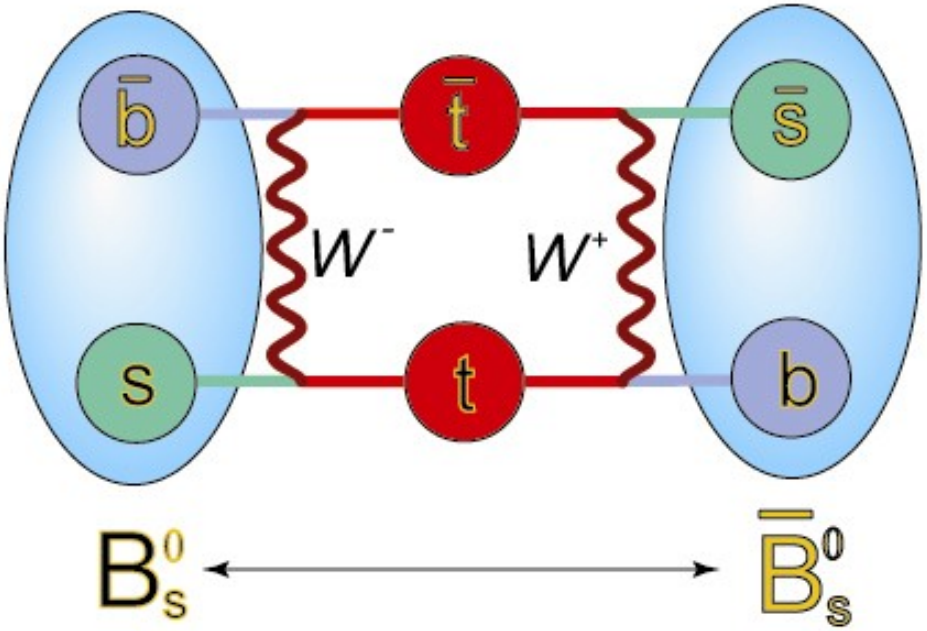






- 2010 CDF/DØ $\phi_{Bs} \in [-67.6^\circ, -30.9^\circ] U [-148.9^\circ, -111.1^\circ]$
- 2011 a series of contradictory results
  - DØ (6.1 fb^{-1}): $\phi_{Bs} = -43.5^\circ {}^{+21.8^\circ}_{-20.6^\circ} \pm 1.2^\circ$
  - LHCb $J/\psi f_0$ (0.41 fb^{-1}): $\phi_{Bs} = -25.2^\circ \pm 25.2^\circ \pm 1.2^\circ$
  - LHCb $J/\psi\phi$ (0.37 fb^{-1}): $\phi_{Bs} = 8.6^\circ \pm 10.3^\circ \pm 3.4^\circ$
  - CDF (5.2 fb^{-1}): $\phi_{Bs} \in [-59.6^\circ, -2.3^\circ]$
- here: combine available LHCb and CDF ($\phi_{Bs}, \Delta\Gamma_s$) likelihoods

Meson mixing and SM



$B - \bar{B}$ system

$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(M^q - \frac{i}{2}\Gamma^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

- Non-hermitian Hamiltonian (only 2 states) but M and Γ hermitian
- Mixing due to non-diagonal terms $M^q_{12} - i\Gamma^q_{12}/2$

$\Longrightarrow$Diagonalisation: physical $|B^q_{H,L}\rangle = p|B_q\rangle \mp q|\bar{B}_q\rangle$

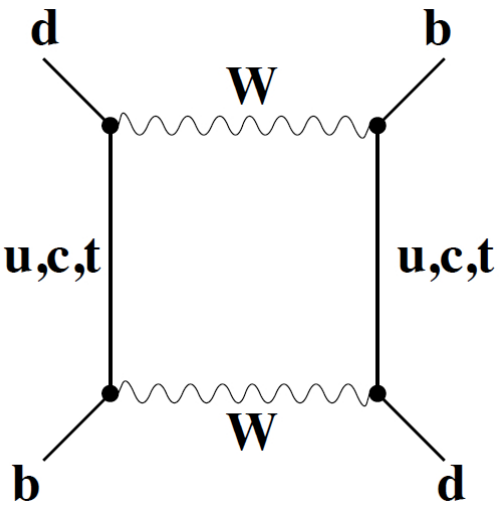
of masses $M^q_{H,L}$, widths $\Gamma^q_{H,L}$

In terms of M^q_{12}, $|\Gamma^q_{12}|$ and $\phi_q = arg\left(-\frac{M^q_{12}}{\Gamma^q_{12}}\right)$ [using $|\Gamma^q_{12}| \ll |M^q_{12}|$]

- Mass difference $\Delta M_q = M^q_H - M^q_L \simeq 2|M^q_{12}|$
- Width difference $\Delta\Gamma_q = \Gamma^q_L - \Gamma^q_H \simeq 2|\Gamma^q_{12}|\cos(\phi_q)$
- Asym $a_{SL} = \dfrac{\Gamma(\bar{B}_q(t) \to \ell^+\nu X) - \Gamma(B_q(t) \to \ell^-\nu X)}{\Gamma(\bar{B}_q(t) \to \ell^+\nu X) + \Gamma(B_q(t) \to \ell^-\nu X)} \simeq \dfrac{|\Gamma^q_{12}|}{|M^q_{12}|}\sin\phi_q$

Phase from mixing in time-dep analysis $q/p \simeq -M^{q*}_{12}/|M^q_{12}| = -e^{-i\phi_{B_q}}$

SM neutral-meson mixing



Neutral $B\bar{B}$ mixing in Standard Model described by box diagrams

$$A_{\Delta B=2} = \sum_{q,q'=u,c,t} (V_{qb}^* V_{qd})(V_{q'b}^* V_{q'd}) A_{qq'}$$

$$A_{\Delta B=2} = \sum_{q=u,c,t} V_{qb}^* V_{qd} [V_{tb}^* V_{td} [A_{tq} - A_{uq}] + V_{cb}^* V_{cd} [A_{cq} - A_{uq}]]$$

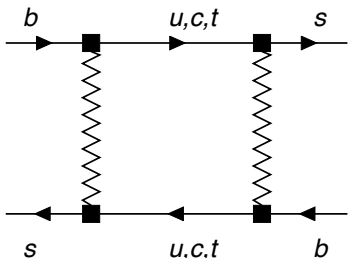
$$A_{qq'} \propto \frac{g^4}{16\pi^2 m_W^2} \left[c^{st} + \frac{m_q m_q'}{m_W^2} + \ldots \right] \langle \bar{B} | (\bar{b}_L \gamma_\mu d_L)^2 | B \rangle$$

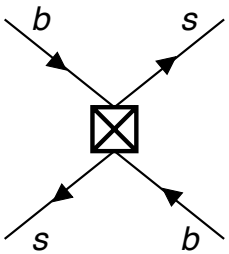
c^{st} killed by GIM, and hierarchy of masses and CKM matrix elements:

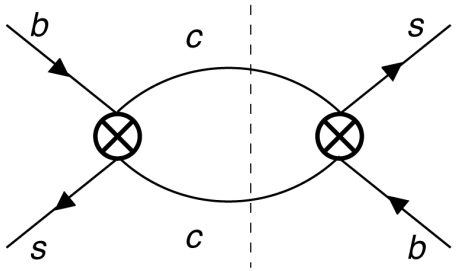
$$A_{\Delta B=2} \propto (V_{tb}^* V_{td})^2 \frac{g^4 m_t^2}{16\pi^2 m_W^4} \langle \bar{B} | (\bar{b}_L \gamma_\mu d_L)^2 | B \rangle + \ldots$$

Computing neutral mixing in SM at NLO

Effective Hamiltonian approach (integrate out heavy W, Z, t)





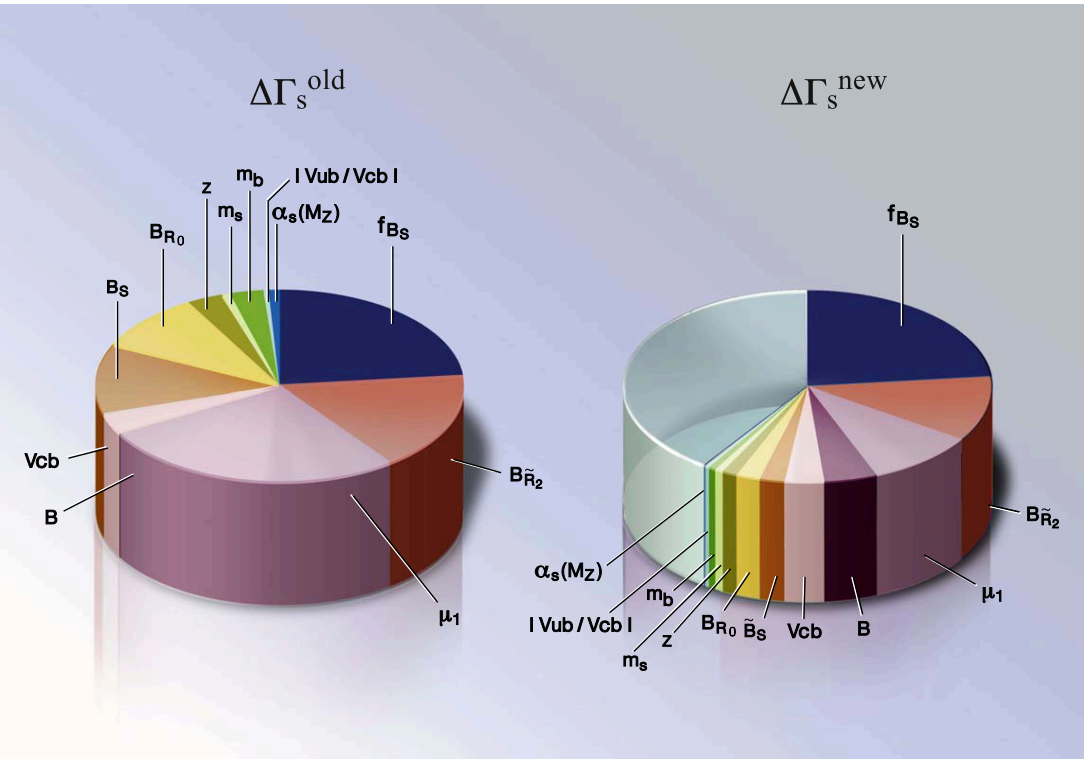


$$A_{\Delta B=2} = \langle \bar{B}|\mathcal{H}_{\rm eff}^{\Delta B=2}|B\rangle - \frac{1}{2}\int d^4x d^4y \langle \bar{B}|T\mathcal{H}_{\rm eff}^{\Delta B=1}(x)\mathcal{H}_{\rm eff}^{\Delta B=1}(y)|B\rangle$$

- M_{12}^q dominated by dispersive part of top boxes [Re[loops]]
  - related to heavy virtual states
  - one operator at LO: $Q = \bar{q}_L\gamma_\mu b_L \bar{q}_L\gamma^\mu b_L$
  - in SM, $arg(M_{12}^q)$ CKM phase: $\phi_{B_d} = 2\beta, \phi_{B_s} = -2\beta_s$
- Γ_{12}^q dominated by absorptive part of charm boxes [Im[loops]]
  [Beneke et al 1996-03, Ciuchini et al. 03]
  - common B and $\bar{B}$ decay channels into final states with $c\bar{c}$ pair
  - non local contribution, computed assuming quark-hadron duality and expanded in $1/m_b$ and α_s series of local operators
  - two operators at LO: Q and $\tilde{Q}_S = \bar{q}_L^\alpha b_R^\beta \bar{q}_L^\beta b_R^\alpha$

Uncertainties

Choice of operators Q and $\tilde{Q}_S$ important to compute Γ_{12}
depending mainly on Q, taming $1/m_b$-corrections



[Nierste and Lenz 2006]

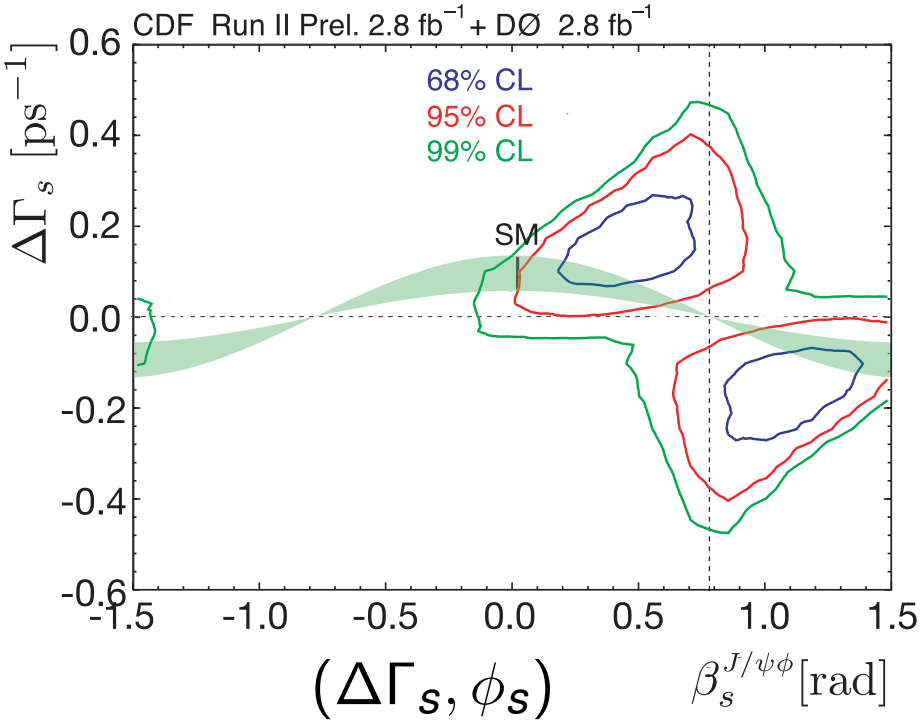
- B and $\tilde{B}_S$ normalised contrib. from Q and $\tilde{Q}_S$ (bag params.)
- m_b^{pow}, B_{1/m_b} $1/m_b$-suppressed, unknown contrib.
- μ renormalisation scale $O(m_b)$

$$\Delta\Gamma_s = f[f_{Bs}, B, \tilde{B}_S; \mu, m_b^{pow}, B_{1/m_b} \ldots]$$

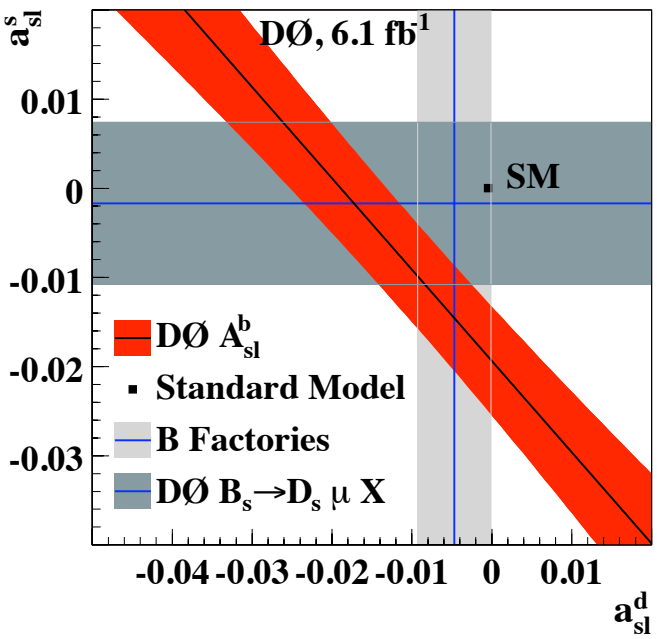
$$\Delta\Gamma_s/\Delta M_s = f[\tilde{B}_S/B; B_{1/m_b}, m_b^{pow}, \mu, \bar{m}_c \ldots]$$

$$a_{SL}^s = f[\tilde{B}_S/B; |V_{ub}/V_{cb}|, \gamma, \mu, \bar{m}_c, B_{1/m_b} \ldots]$$

Three discrepancies in 2010



$(\Delta\Gamma_s, \phi_s)$

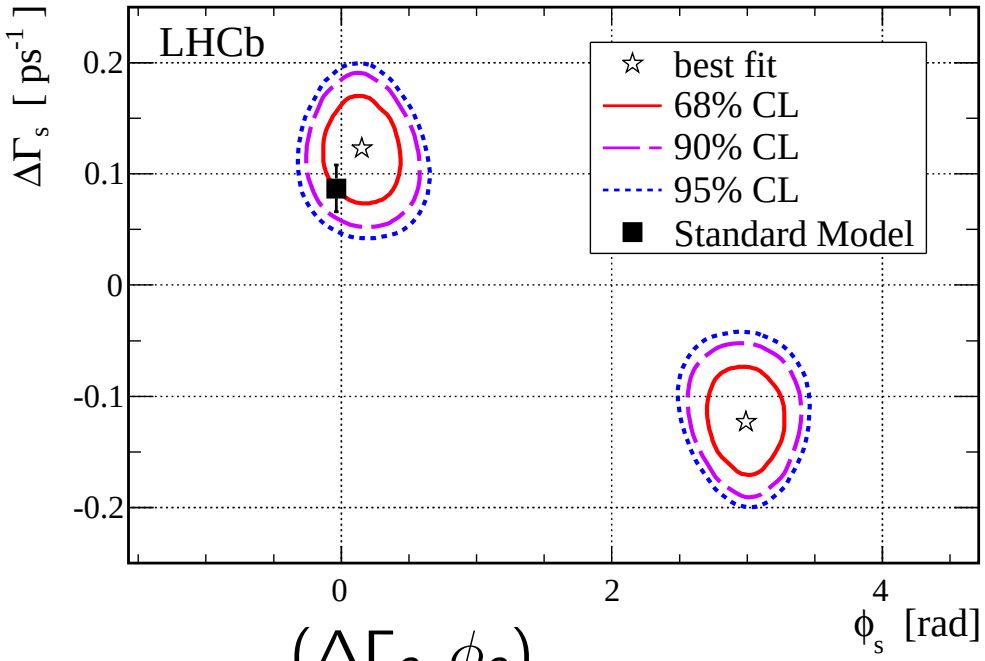


Linear comb of a^d_{SL} and a^s_{SL}

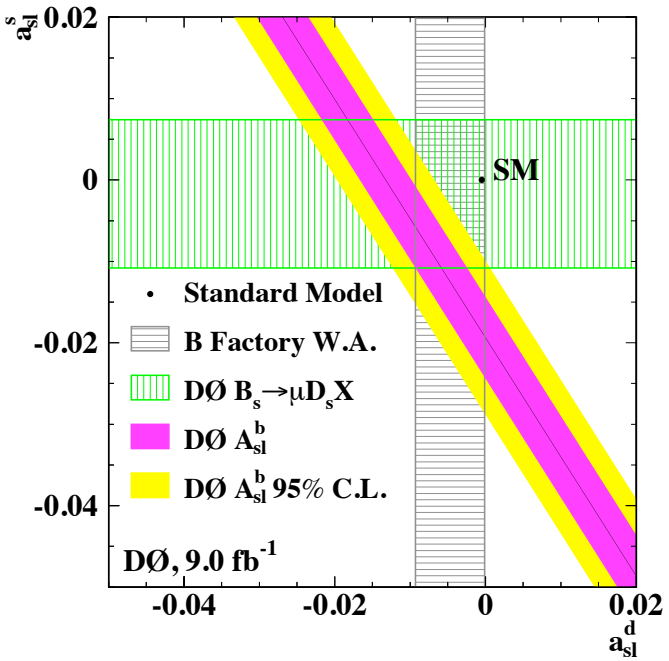
- $B \to \tau\nu$ vs $\sin 2\beta$ — 1D constraint : 2.6 σ
- β_s from $B_s \to J/\psi\phi$ and τ_{FS} (null test) — 1D constraint : 2.1 σ
- A_{SL} (null test) — 1D constraint : 2.9 σ

[ICHEP10 $(\beta_s, \Delta\Gamma_s)$ not included, since no CDF/DØ updated average]

Two discrepancies in 2011



$(\Delta\Gamma_s, \phi_s)$



Linear comb of a^d_{SL} and a^s_{SL}

- $B \to \tau\nu$ vs $\sin 2\beta$ — 1D constraint : 2.8 σ
- β_s from $B_s \to J/\psi\phi$ and τ_{FS} (null test) — 1D constraint : 1.0 σ
- A_{SL} (null test) — 1D constraint : 3.7 σ

[CDF/LHCb $(\beta_s, \Delta\Gamma_s)$ average from $B_s \to J/\psi\phi$]

Meson mixing and NP

New Physics in $\Delta F = 2$

Since discrepancies for meson-mixing observables,
why not New Physics only in $\Delta F = 2$ processes ?

- M_{12} dominated by (virtual) top boxes
  [affected by NP, e.g., if heavy new particles in the box]
- Γ_{12} dominated by tree decays into (real) charm states
  [affected by NP if changes in (constrained) tree-level decays]
- Tree level (4 diff flavours) processes not affected by New Physics

Model-independent parametrisation under the assumption that NP only changes modulus and phase of M_{12}^d and M_{12}^s

$$M_{12}^q = (M_{12}^q)_{SM} \times \Delta_q \qquad \Delta_q = |\Delta_q| e^{i\phi_q^\Delta}$$

[A. Lenz et al., Phys.Rev. D83 (2011) 036004, update in prep.]

Three different NP scenarios for eff. Hamiltonian

- Minimal Flavour Violat. with small bottom Yukawa coupling (sc II)

$$H^{|\Delta B|=2} = (V_{tq}^* V_{tb})^2 CQ + h.c. \qquad C \text{ real}$$

$\Delta_d = \Delta_s$ real, related to K-meson mixing

- MFV with large bottom Yukawa coupling (sc III)

$$H^{|\Delta B|=2} = (V_{tq}^* V_{tb})^2 [CQ + C_S Q_S + \tilde{C}_S \tilde{Q}_S] + h.c.$$

$\Delta_d = \Delta_s$ complex, unrelated to K-meson mixing

- Non Minimal Flavour Violation (sc I)

$$H^{|\Delta B|=2} = (V_{tq}^* V_{tb})^2 C_q Q + h.c.$$

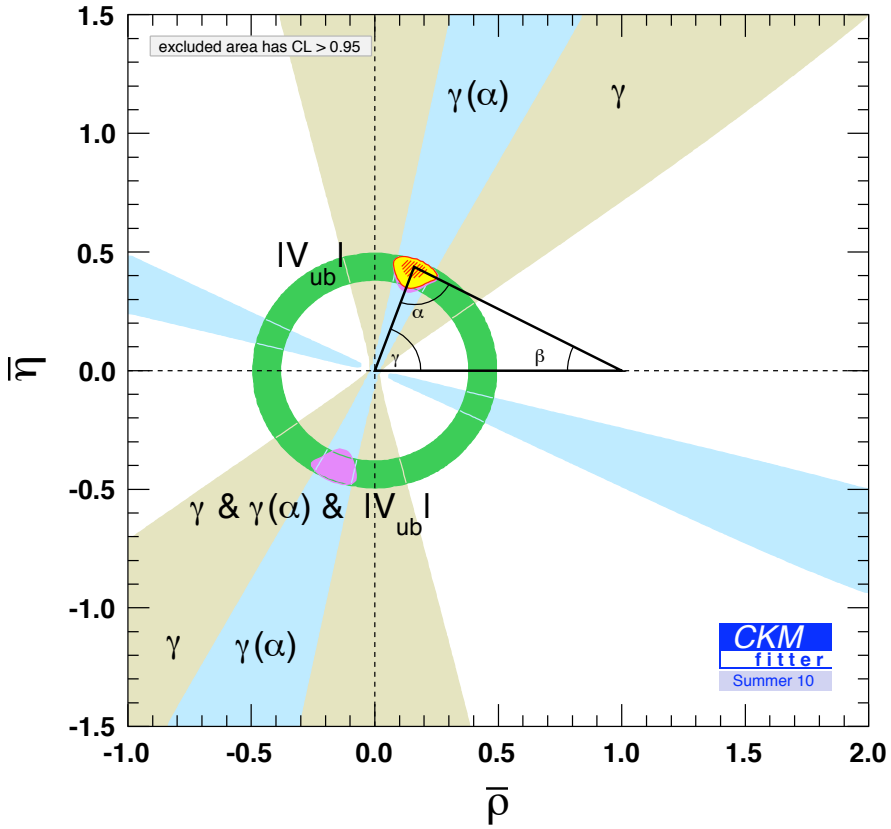
Δ_d, Δ_s complex independent, unrelated to K-meson mixing

$\Longrightarrow$Will focus mainly on the latter scenario in the following

Fixing the CKM part

Observables not affected by NP, used to fix CKM :

$|V_{ud}|$, $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$, γ and $\gamma(\alpha) \equiv \pi - \alpha - \beta$ (ϕ_{B_d} cancels)



Observables affected by NP, used to determine Δ_d, Δ_s

- Neutral-meson oscillation Δm_d, Δm_s
- Lifetime difference $\Delta\Gamma_d$
- Time-dep asymmetries related to $\phi_{B_d} = 2\beta + \phi_d^\Delta$, $\phi_{B_s} = -2\beta_s + \phi_s^\Delta$
- Semileptonic asymmetries a_{SL}^d, a_{SL}^s, A_{SL}
- $\alpha = \pi - \beta - \gamma - \phi_d^\Delta/2$ (interference between decay and mixing)

Some of the theoretical inputs

- B_d, B_s, f_{B_d}, f_{B_d} parameters : our average of unquenched 2 and 2+1 lattice estimates
- Bag parameters for scalar operators from quenched lattice estimate [Becirevic et al. 2002, ongoing work from MILC]

$$\tilde{B}'^s_S(m_b)/\tilde{B}'^d_S(m_b) = 1.00 \pm 0.03 \quad \tilde{B}'^s_S(m_b) = 1.40 \pm 0.13$$

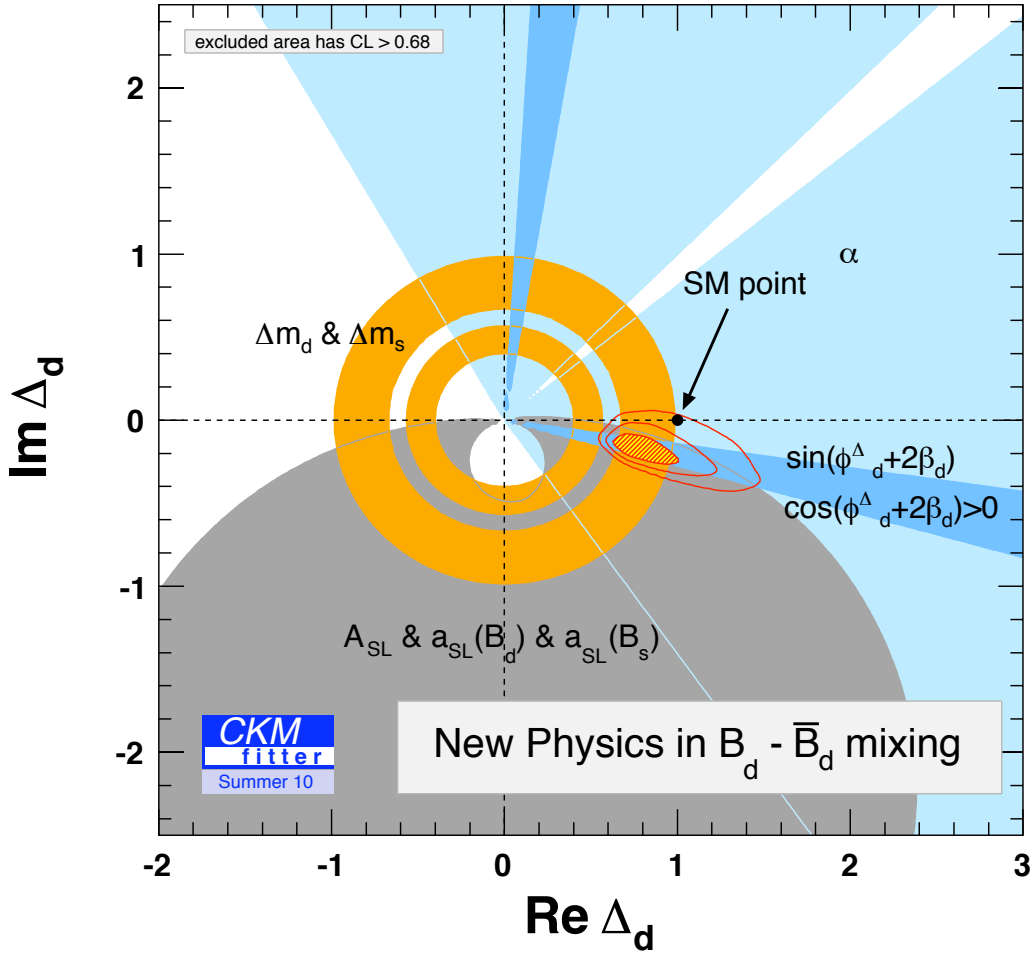
- $1/m_b$ suppressed operators: bag parameters (vacuum insertion approximation) and power correction scale

$$B_{Ri}(m_b) = 1.0 \pm 0.5 \qquad m_b^{\rm pow} = 4.70 \pm 0.10$$

- charm quark mass from $\sigma(e^+e^- \to c\bar{c})$ sum rules to 3- and 4-loops [Steinhauser and Kühn 2001-04, Jamin and Hoang 2004]

$$\bar{m}_c(\bar{m}_c) = 1.286 \pm 0.013 \pm 0.040 \text{ GeV}$$

B_d mixing (in 2010)

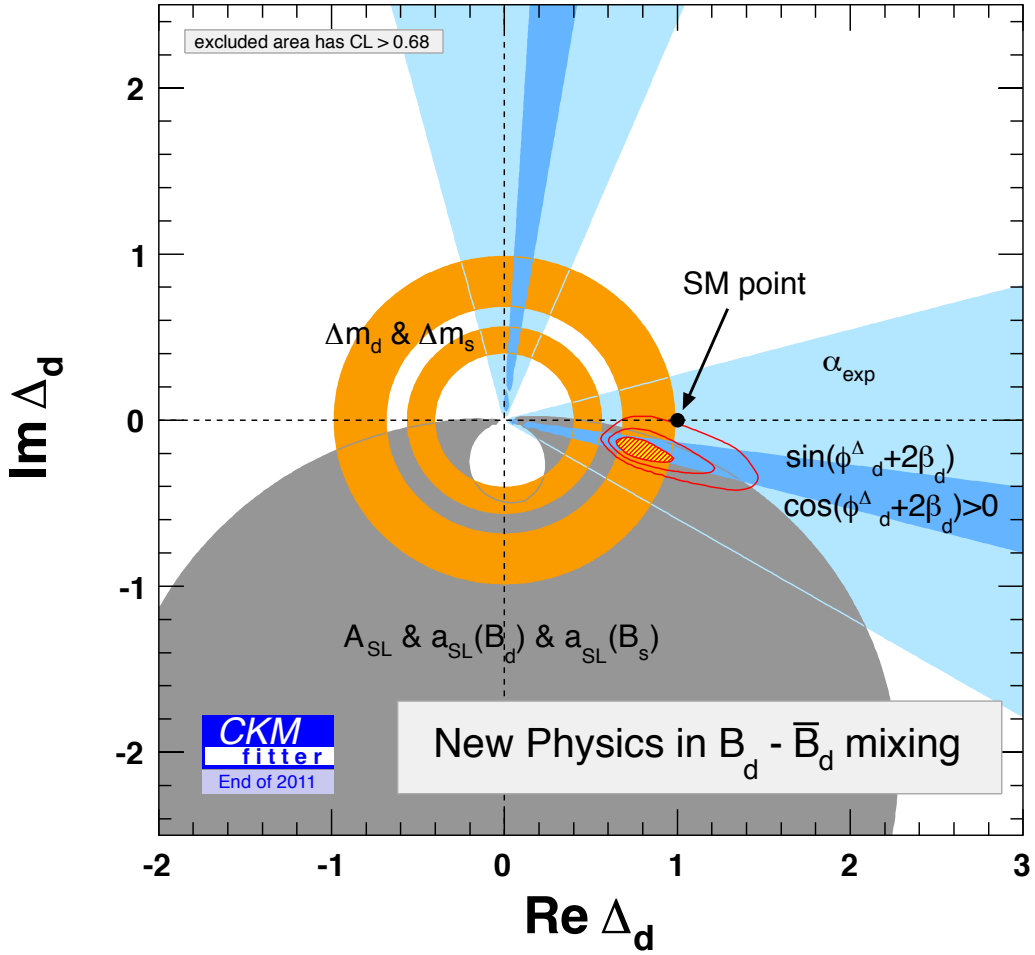


[Constraints 68% CL]

- Dominant const from β and Δm_d (2 rings from 2 sol for apex)
- Tension from $Br(B \to \tau\nu)$ shifts β constraint from real axis
- Disagreement with SM driven in same dir by $Br(B \to \tau\nu)$ and A_{SL}

2D SM hypothesis ($\Delta_d = 1 + i \cdot 0$): 2.7 σ

B_d mixing (in 2011)

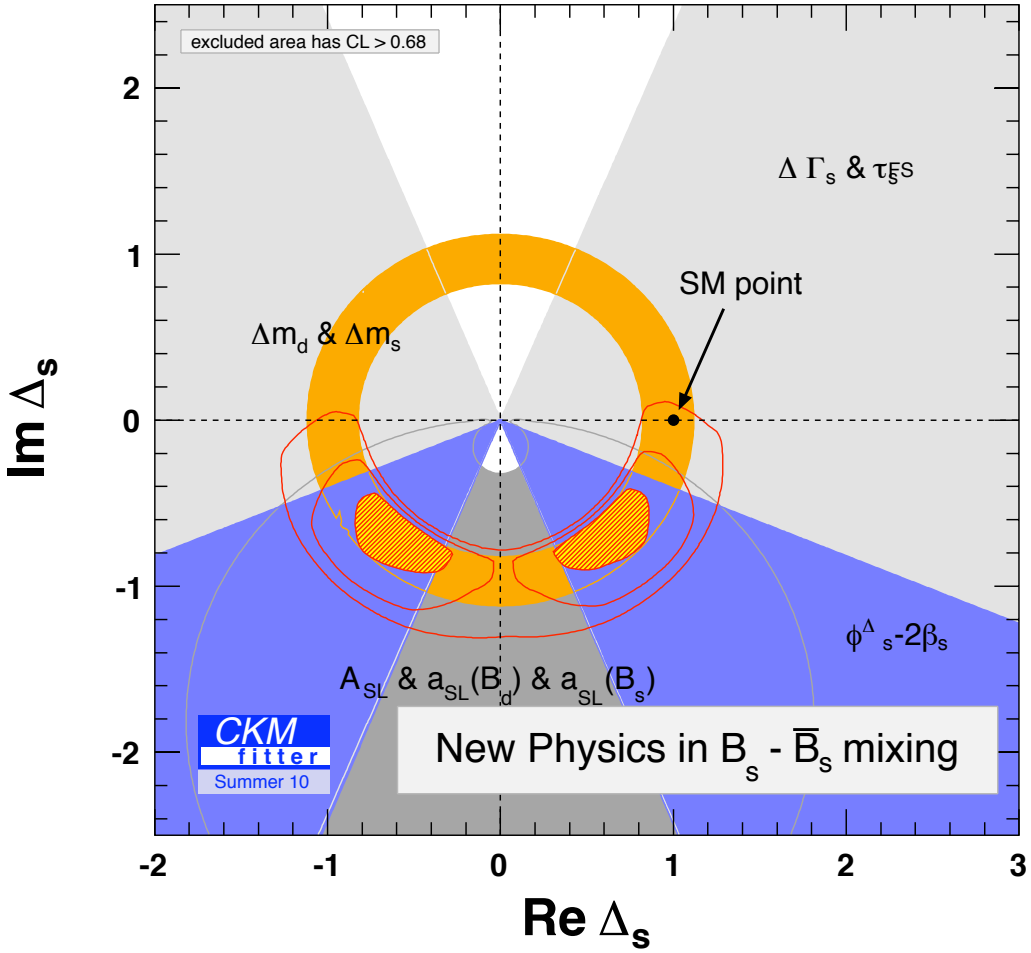


[Constraints 68% CL]

- Dominant const from β and Δm_d
- Tension from $Br(B \to \tau\nu)$ shifts β constraint from real axis
- Disagreement with SM driven in same dir by $Br(B \to \tau\nu)$ and A_{SL}
- Improvement of γ, and thus contraint from $\alpha = \pi - \beta - \gamma - \phi_d^{\Delta}/2$

2D SM hypothesis ($\Delta_d = 1 + i \cdot 0$): 3.2 σ

B_s mixing (in 2010)

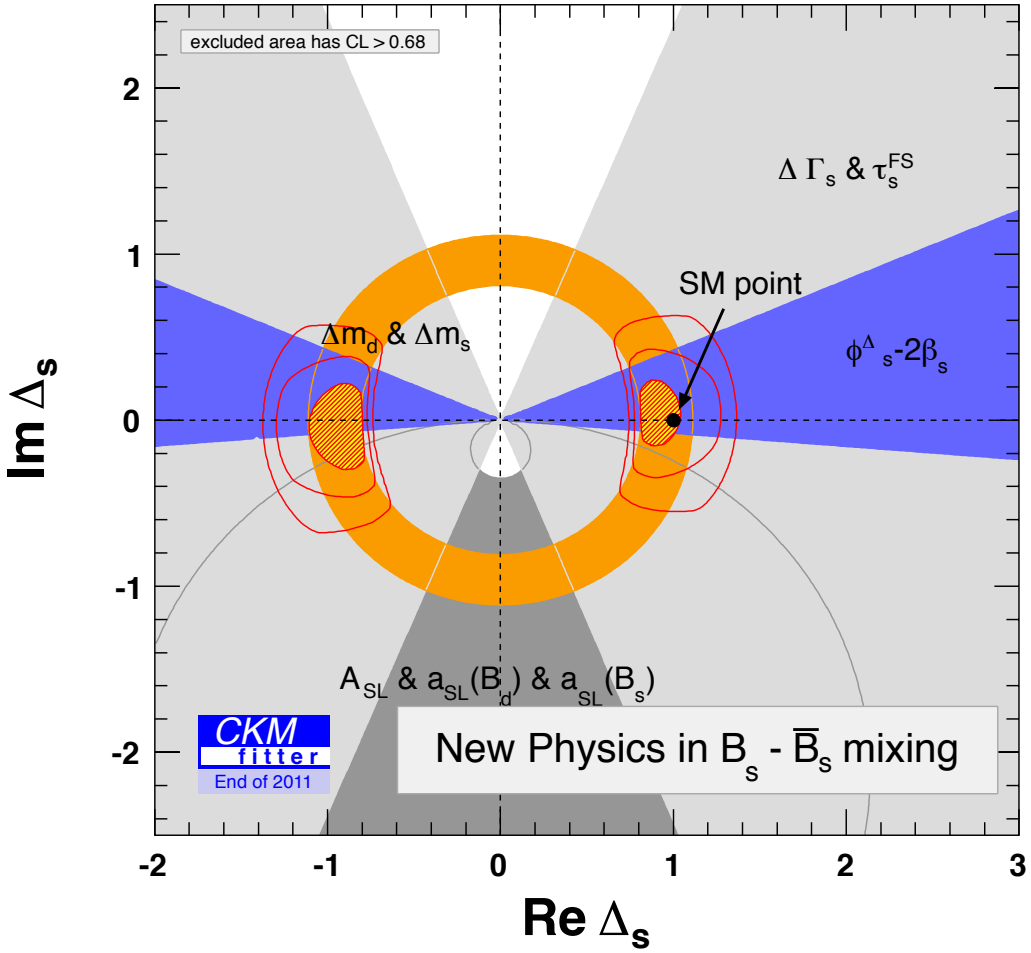


[Constraints 68% CL]

- Dominant constraints from Δm_s and ϕ_s
- Disagreement with SM driven by ϕ_s and A_{SL}
- In the same direction as for B_d mixing

2D SM hypothesis ($\Delta_s = 1 + i \cdot 0$): 2.7 σ

B_s mixing (in 2011)

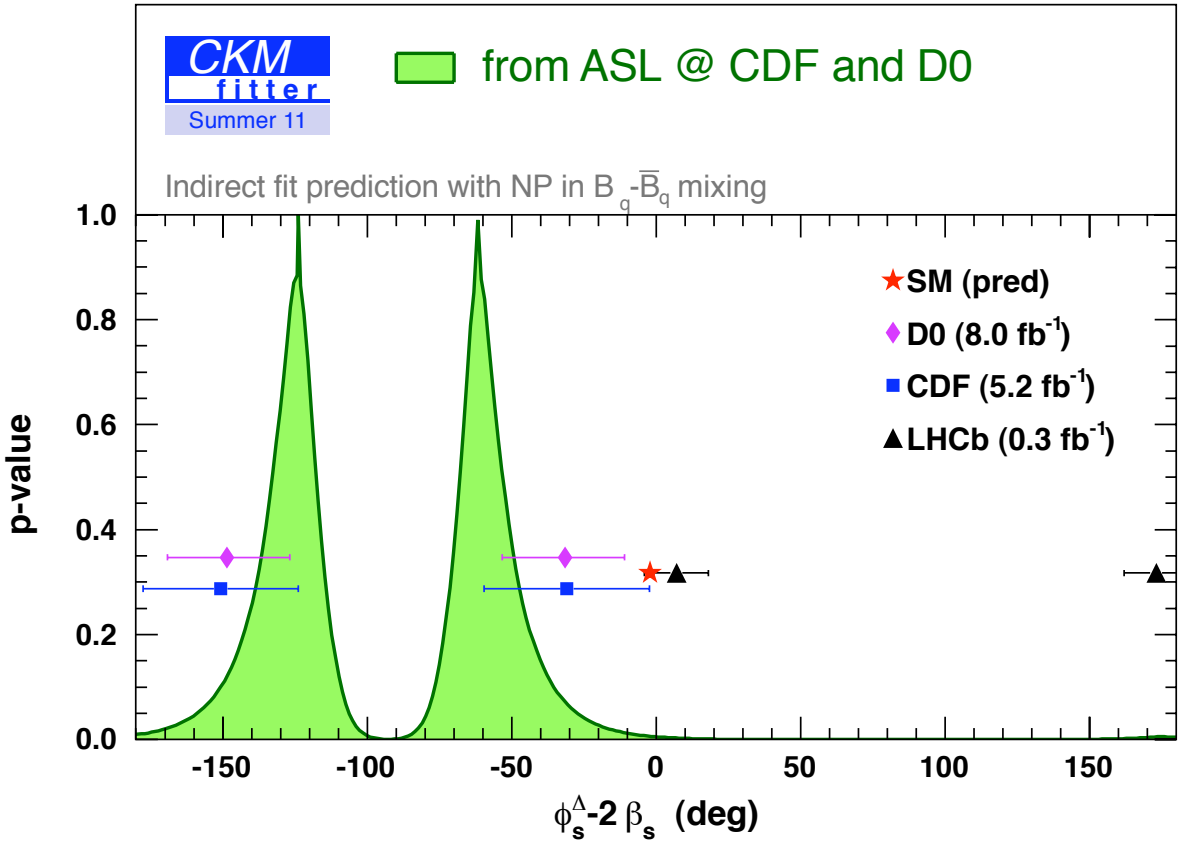


[Constraints 68% CL]

- Dominant constraints from Δm_s and ϕ_s
- Disagreement with SM driven by A_{SL} alone
- and in mild disagreement with ϕ_s, which favours SM situation

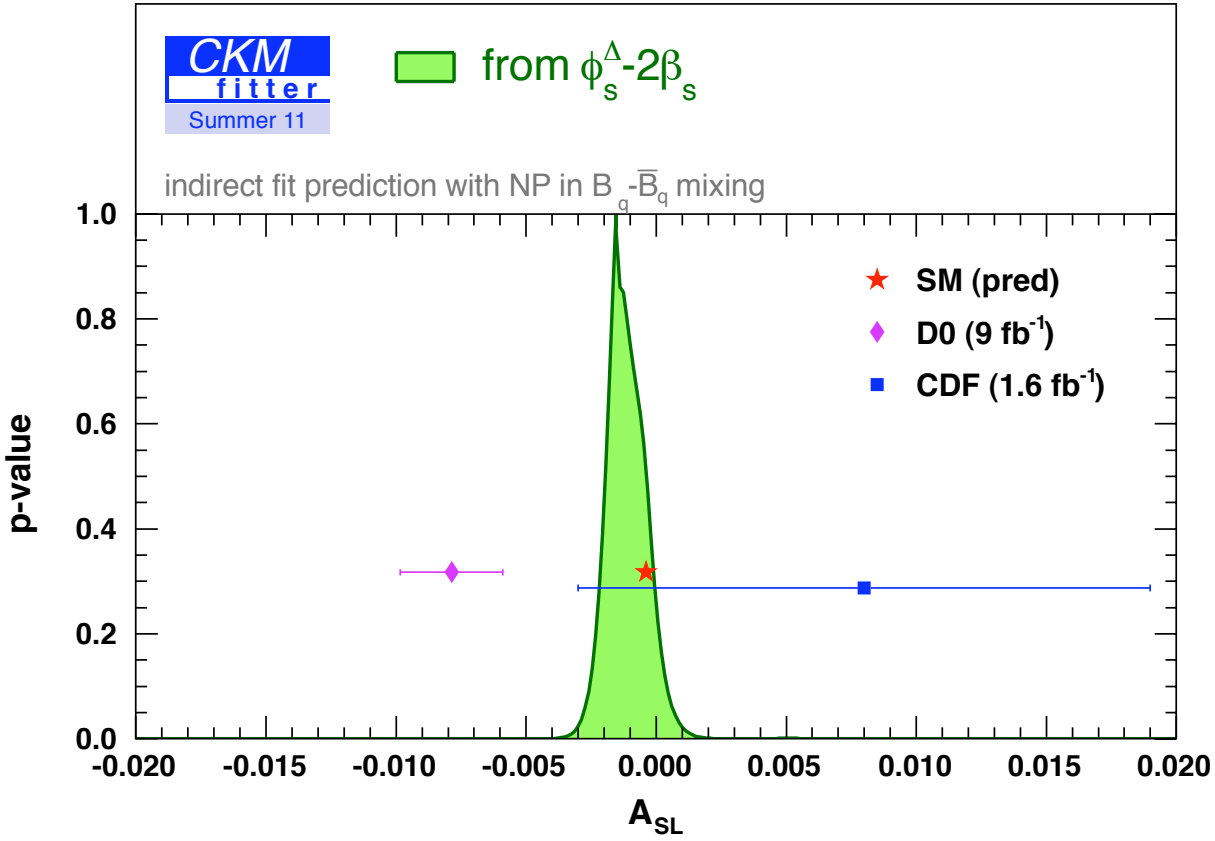
2D SM hypothesis ($\Delta_s = 1 + i \cdot 0$): 0.8σ

Prediction for ϕ_s



$$\phi_s^\Delta - 2\beta_s = (-123.9^{+9.0}_{-13.6})^\circ \qquad \text{or} \qquad (-61.8^{+13.4}_{-8.9})^\circ$$

Prediction for A_{SL}



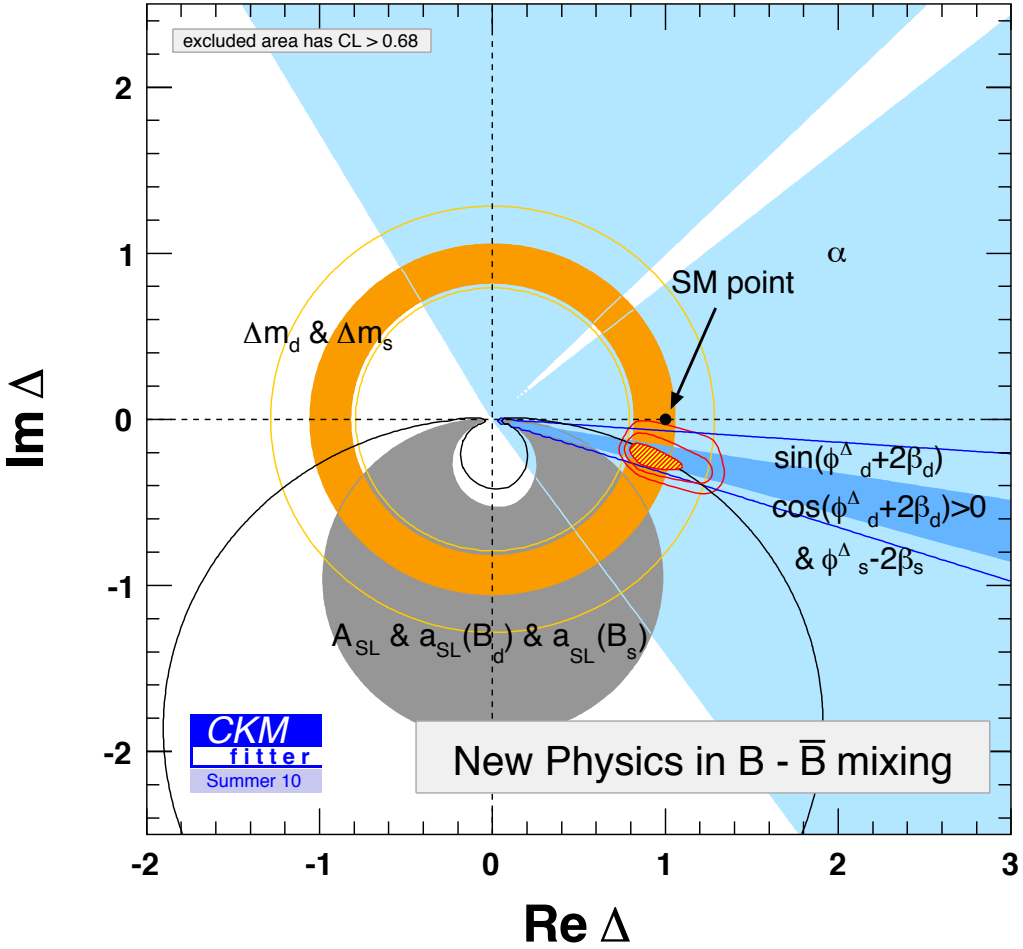
$$A_{SL} = (-15.5^{+14.3}_{-5.9}) \cdot 10^{-4}$$

Pulls

Quantity	SM	Sc. I
$\phi_d^\Delta + 2\beta$	2.7 σ	2.0 σ
$\phi_s^\Delta - 2\beta_s$	1.0 σ	2.7 σ
Δm_d	1.0 σ	2.5 σ
Δm_s	0.0 σ	2.7 σ
$A_{\rm SL}$	3.7 σ	2.9 σ
$a_{\rm SL}^d$	0.9 σ	0.2 σ
$a_{\rm SL}^s$	0.2 σ	0.2 σ
$\Delta\Gamma_s$	0.0 σ	0.7 σ
$\mathcal{B}(B \to \tau\nu)$	2.8 σ	0.7 σ
$\mathcal{B}(B \to \tau\nu)$, $A_{\rm SL}$	4.6 σ	2.6 σ
$\phi_s^\Delta - 2\beta_s$, $A_{\rm SL}$	3.4 σ	2.5 σ
$\mathcal{B}(B \to \tau\nu)$, $\phi_s^\Delta - 2\beta_s$, $A_{\rm SL}$	4.1 σ	2.2 σ

- Deviation between measurement and prediction (w/o meas.) in given model
- If given the possibility, Sc. I tries to accomodate measurements by modifying ϕ_s, A_{SL} or $\Delta m_{d,s}$ (tiny $|\Delta_{d,s}|$)
- But not able to accomodate $\mathcal{B}(B \to \tau\nu)$, $\phi_s^\Delta - 2\beta_s$, $A_{\rm SL}$ at the same time

Another case: Scenario III (in 2010)

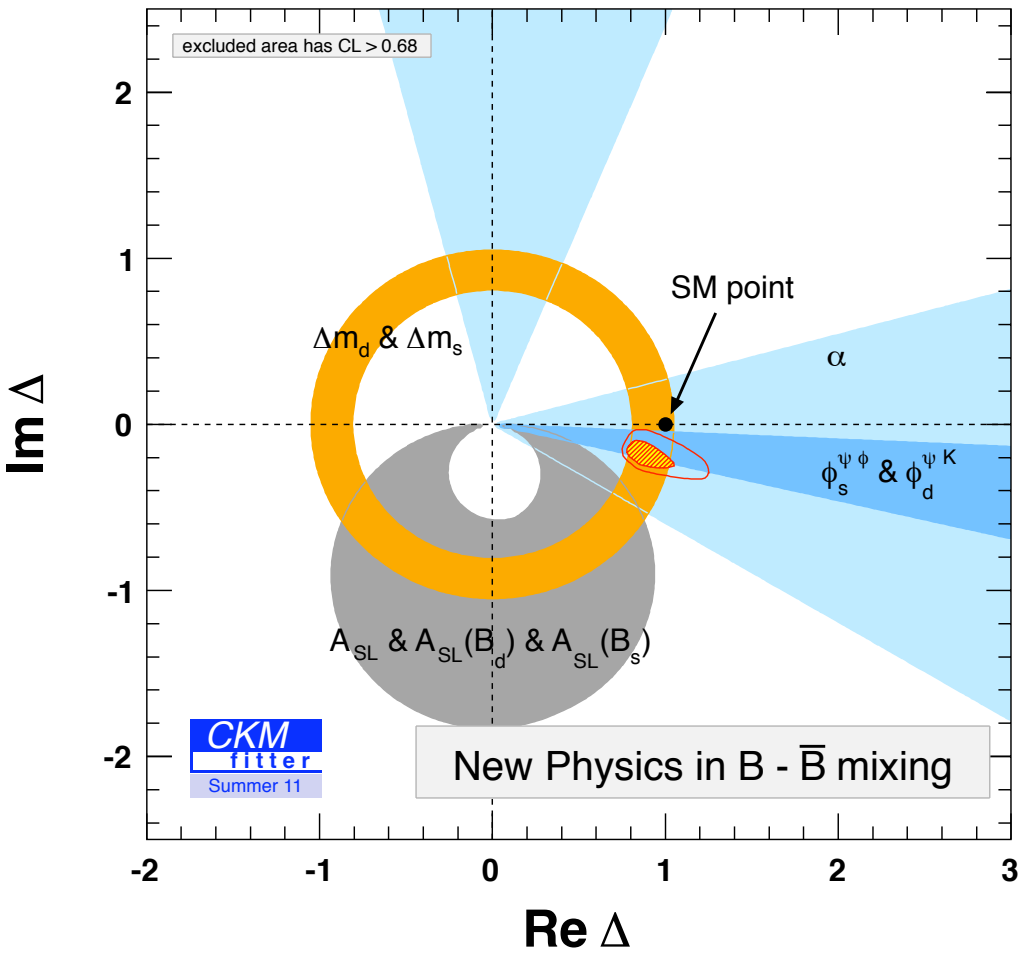


[Constraints 68% CL]

- Minimal Flavour Violation with large bottom Yukawa coupling
- $\Delta_d = \Delta_s = \Delta$ complex
- All three discrepancies in the same direction

2D SM hypothesis ($\Delta = 1 + i \cdot 0$): 3.3σ

Another case: Scenario III (in 2011)



[Constraints 68% CL]

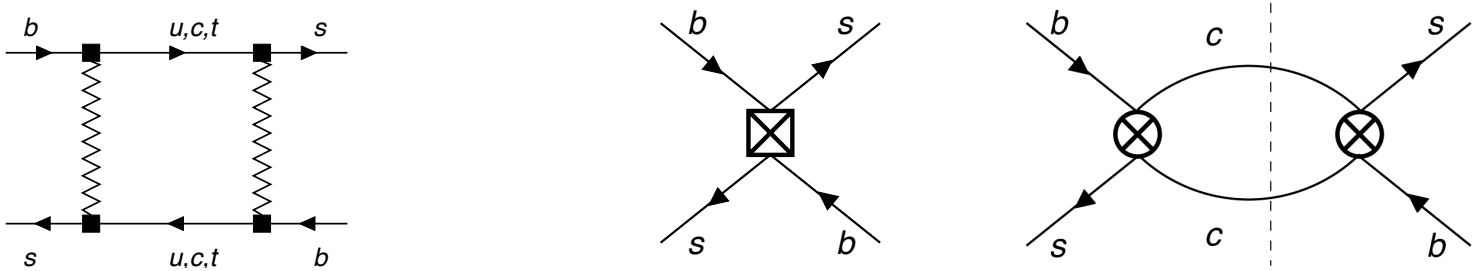
- Minimal Flavour Violation with large bottom Yukawa coupling
- $\Delta_d = \Delta_s = \Delta$ complex
- discrepancy among data more acute in this scenario: A_{SL} in one direction, $B_s \to J/\psi\phi$ in another, with $\sin(2\beta)$ standing in the middle

2D SM hypothesis ($\Delta = 1 + i \cdot 0$): 2.7σ

New physics also in Γ_{12}^s ?

$$\Delta M_s = 2|M_{12}^s| \qquad \Delta\Gamma_s = 2|\Gamma_{12}^s|\cos(\phi_s) \qquad a_{SL}^s = \frac{\Gamma_{12}^s}{M_{12}^s}\sin(\phi_s)$$

Could solve A_{SL}, but significant deviation of $\Delta\Gamma_s$ w.r.t. SM



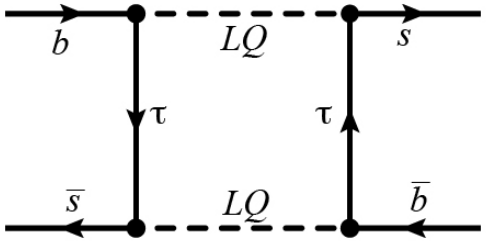
$$A_{\Delta B=2} = \langle \bar{B}|\mathcal{H}_{\rm eff}^{\Delta B=2}|B\rangle - \frac{1}{2}\int d^4x d^4y \langle \bar{B}|T\mathcal{H}_{\rm eff}^{\Delta B=1}(x)\mathcal{H}_{\rm eff}^{\Delta B=1}(y)|B\rangle$$

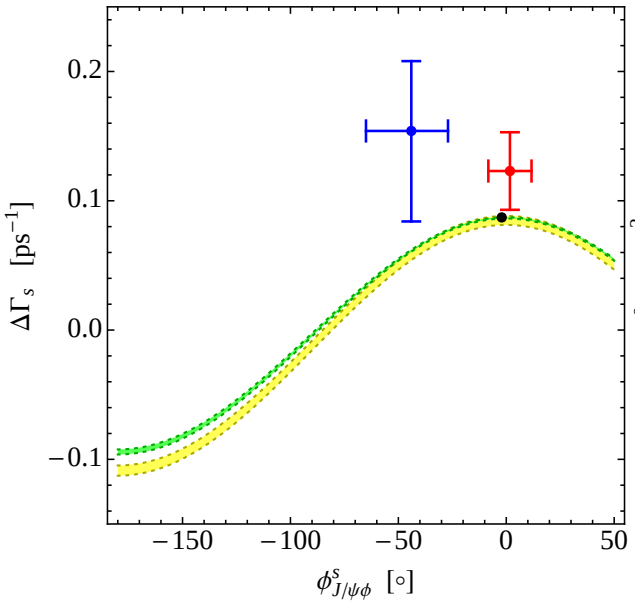
- Change in $b \to c\bar{c}s$ modes or new decay mode competing in Γ_{12}^s would affect Γ_s^{11} and thus Γ_s (in good agreement with SM)
- Change in $b \to c\bar{c}s$ modes affects also $B_d \to J/\psi K_s$ and $B_s \to J/\psi\phi$ and thus determination of B_d, B_s mixing angles
- Change in Γ_{12}^s impacts M_{12}^s (same box diagams with same particles) and thus ΔM_s (in good agreement with SM)

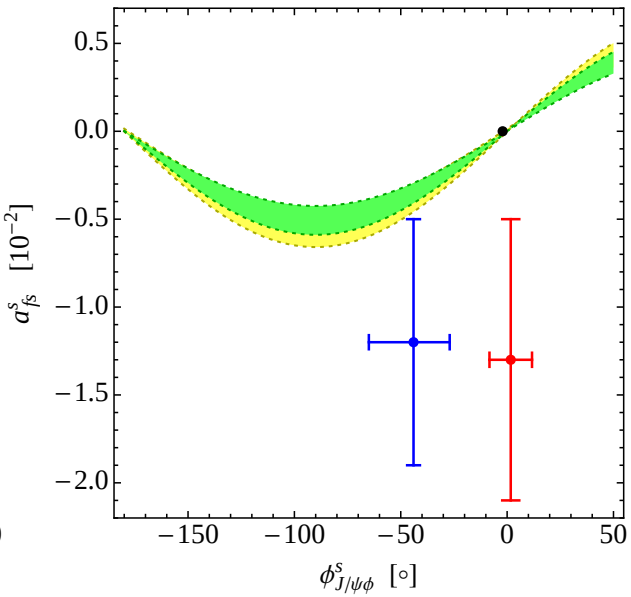
No model-independent way of connecting $\Gamma_{12}^s, \Gamma_{11}^s, M_{12}^s$

Example of New Physics in Γ_{12}^s (Haisch, Bobeth 11)

- $\tau\bar{\tau}$ intermediate states due to NP $(\bar{b}s)(\bar{\tau}\tau)$ operators ?
- Eff. Hamiltonian analysis of $b \to s\gamma$, $b \to s\ell^+\ell^-$, $b \to s\gamma\gamma$: room for scalar or vector ops. able to enhance $|\Gamma_{12}^s|$ by 30-40%







- But M_{12}^s and Γ_{12}^s correlated in specific models (e.g., $SU(2)$ singlet scalar leptoquark) making it difficult to accomodate all data
- General problem for $(M_{12}^s)_{NP}/(\Gamma_{12}^s)_{NP}$ real, linking ΔM_s, $\Delta\Gamma_s$, a_{SL}^s [weakest ΔM_s constraint if light NP scale or GIM-like mechanism]

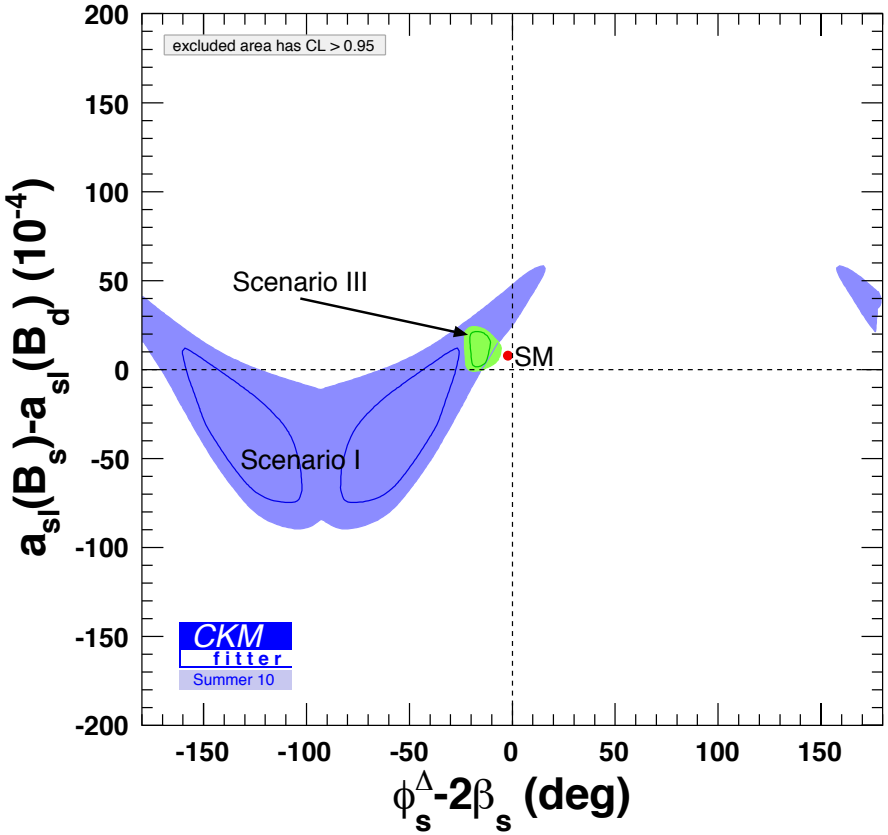
NP in $\Delta B = 2$ not enough ? Or A_{SL} the problem ?

Only $\Delta F = 2$?

Checking NP in $\Delta F = 2$ only

- General relationship among observables under this hypothesis [Grossman, Nir, Perez 09]

$$\frac{y}{x} = \frac{1 - |q|/|p|}{\tan\phi_s} \Longrightarrow a^s_{SL} = \pm 2 \left|\frac{y}{x}\right| \tan(\beta_s^{\psi\phi}) \qquad x = \frac{\Delta m}{\Gamma}, y = \frac{\Delta\Gamma}{2\Gamma}$$



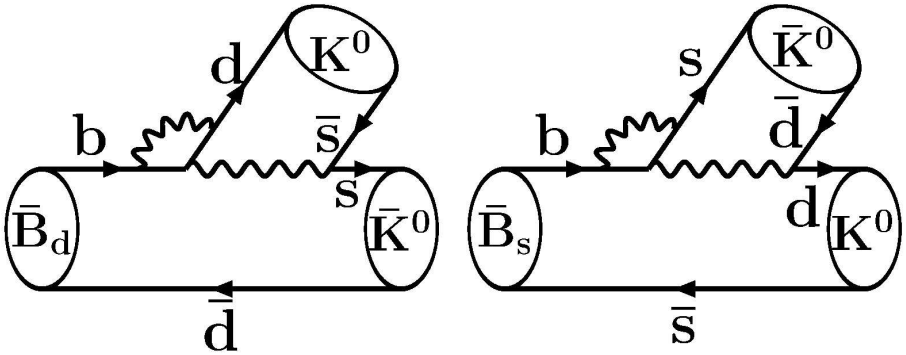
- New observables under fairly general scenarios (Sc. I,II,III) [A. Lenz et al., Phys.Rev. D83 (2011) 036004]
- Additional theoretical assumptions to cross-check specific channels [SDG, J. Matias, J. Virto, arXiv:1111.4882]

Interesting penguin-mediated decays

Consider tree and penguin decomposition of $B_Q \to K^0 \bar{K}^0$ $(Q = d, s)$

$$\bar{A} \equiv A(\bar{B}_Q \to K^0 \bar{K}^0) = V_{ub} V_{uq}^* T + V_{cb} V_{cq}^* P$$

$$A \equiv A(B_Q \to K^0 \bar{K}^0) = V_{ub}^* V_{uq} T + V_{cb}^* V_{cq} P \qquad q = Q$$



Only penguin diagrams

no contrib. from W-exch. $(O_{1,2})$

Difference between tree and penguin from u, c, t quarks in loop

$\Longrightarrow \delta = T - P$ dominated by short-distance physics computed fairly accurately within QCD factorisation (exp. in α_s, $1/m_b$)

$$\delta(B_d \to K^0 \bar{K}^0) = (1.09 \pm 0.43) \cdot 10^{-7} + i(-3.02 \pm 0.97) \cdot 10^{-7} \mathrm{GeV}$$

$$\delta(B_s \to K^0 \bar{K}^0) = (1.03 \pm 0.41) \cdot 10^{-7} + i(-2.85 \pm 0.93) \cdot 10^{-7} \mathrm{GeV}$$

Various penguin-mediated modes of interest

Channel	$\lvert\delta\rvert$ (10^{-7} GeV)
$B_d \to K\bar{K}$	(3.23 ± 1.16)
$B_s \to \bar{K}K$	(3.05 ± 1.11)
$B_d \to K\phi$	(2.32 ± 1.00)
$B_d \to K\bar{K}^*$	(2.29 ± 0.93)
$B_d \to K^*\bar{K}$	(0.41 ± 0.60)
$B_s \to \bar{K}K^*$	(2.16 ± 0.89)
$B_s \to \bar{K}^*K$	(0.36 ± 0.53)
$B_d \to K^*\bar{K}^*$	(1.85 ± 0.93)
$B_s \to \bar{K}^*K^*$	(1.62 ± 0.81)
$B_d \to K^*\phi$	(1.92 ± 1.03)
$B_s \to \phi K^*$	(1.87 ± 0.94)
$B_s \to \phi\phi$	(3.86 ± 2.09)

- Penguin modes for B_Q decaying through $b \to q$ transition ($Q, q = d, s$)
- For VV modes, only observables for a longitudinally polarised final states (transverse polar. are $1/m_b$-suppressed, only modelled in QCD factorisation)
- Which requires one to translate measurements into "longitudinal observables" (BR, asymmetries)

Relating $\delta = T - P$ and observables

In terms of $A \equiv A(B_Q \to M_1 M_2)$ and $\bar{A} \equiv A(\bar{B}_Q \to M_1 M_2)$

- $b \to q$ penguin mediated decay into state of CP-parity η_f
- $BR = g_{ps}(|A|^2 + |\bar{A}|^2)/2$ with g_{ps} phase space factor
- 3 CP asymmetries with $A_{\rm dir}^2 + A_{\rm mix}^2 + A_{\Delta\Gamma}^2 = 1$

$$A_{\rm dir} \equiv \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \qquad A_{\rm mix} + iA_{\Delta\Gamma} \equiv -2\eta_f \frac{e^{-i\phi_{B_Q}} A^* \bar{A}}{|A|^2 + |\bar{A}|^2}$$

Relating $\delta = T - P$ and observables

In terms of $A \equiv A(B_Q \to M_1 M_2)$ and $\bar{A} \equiv A(\bar{B}_Q \to M_1 M_2)$

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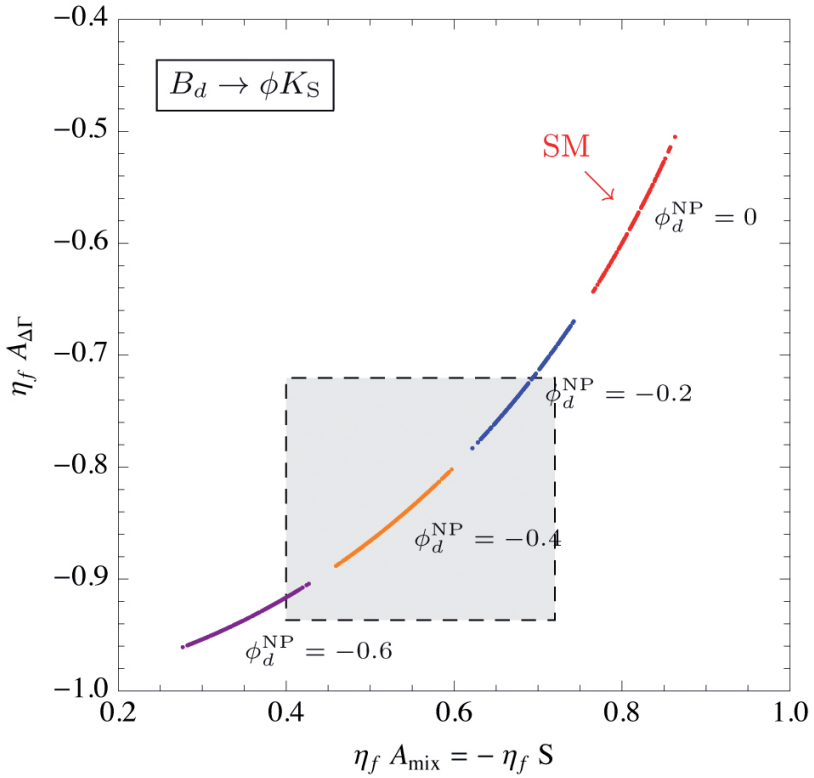
$$A_{\rm dir} \equiv \frac{|A|^2 - |\bar{A}|^2}{|A|^2 + |\bar{A}|^2} \qquad A_{\rm mix} + iA_{\Delta\Gamma} \equiv -2\eta_f \frac{e^{-i\phi_{B_Q}} A^* \bar{A}}{|A|^2 + |\bar{A}|^2}$$

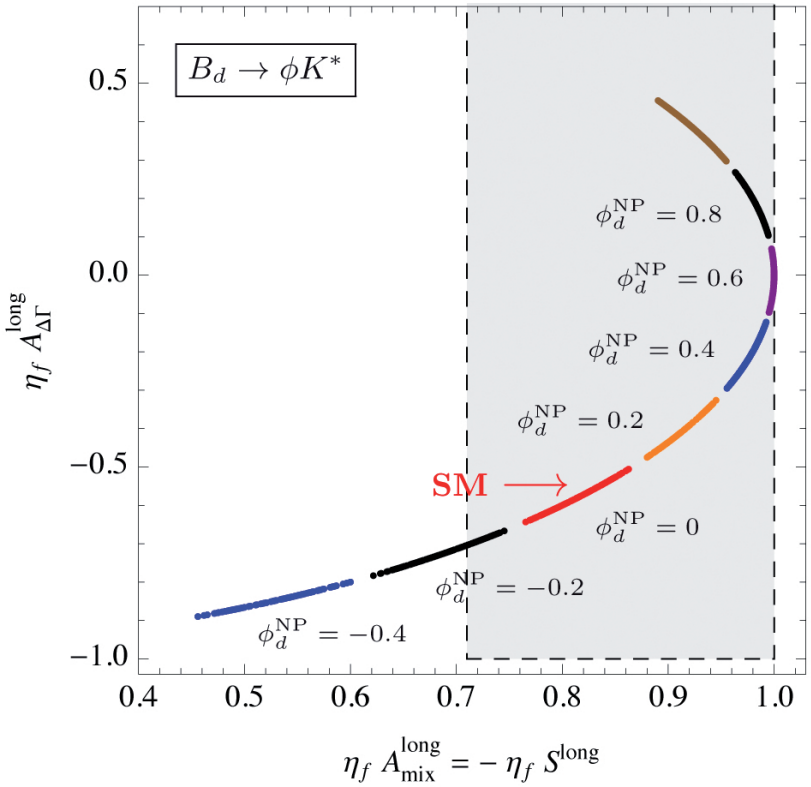
Assuming NP affects only phase in B_Q mixing ($\Delta_Q = e^{i\phi_Q^\Delta}$)

$$2g_{ps}|\delta|^2 |V_{cb}V_{cq}^*|^2 \sin^2\beta_q = BR(1 - \eta_f \sin\Phi_{Qq} A_{\rm mix} + \eta_f \cos\Phi_{Qq} A_{\Delta\Gamma})$$

- $\Phi_{Qq} = 2\beta_Q - 2\beta_q + \phi_Q^{\rm NP}$ $\qquad (\phi_d^{\rm NP} = \phi_d^\Delta,\ \phi_s^{\rm NP} = -\phi_s^\Delta)$,
- Constraint on $A_{\rm dir}$ (near zero) for a solution $\phi_Q^{\rm NP}$ to exist
- Determine $\phi_Q^{\rm NP}$ from $|\delta|$, BR, $A_{\rm mix}$ (and CKM from tree decays)

Illustration for two measured modes

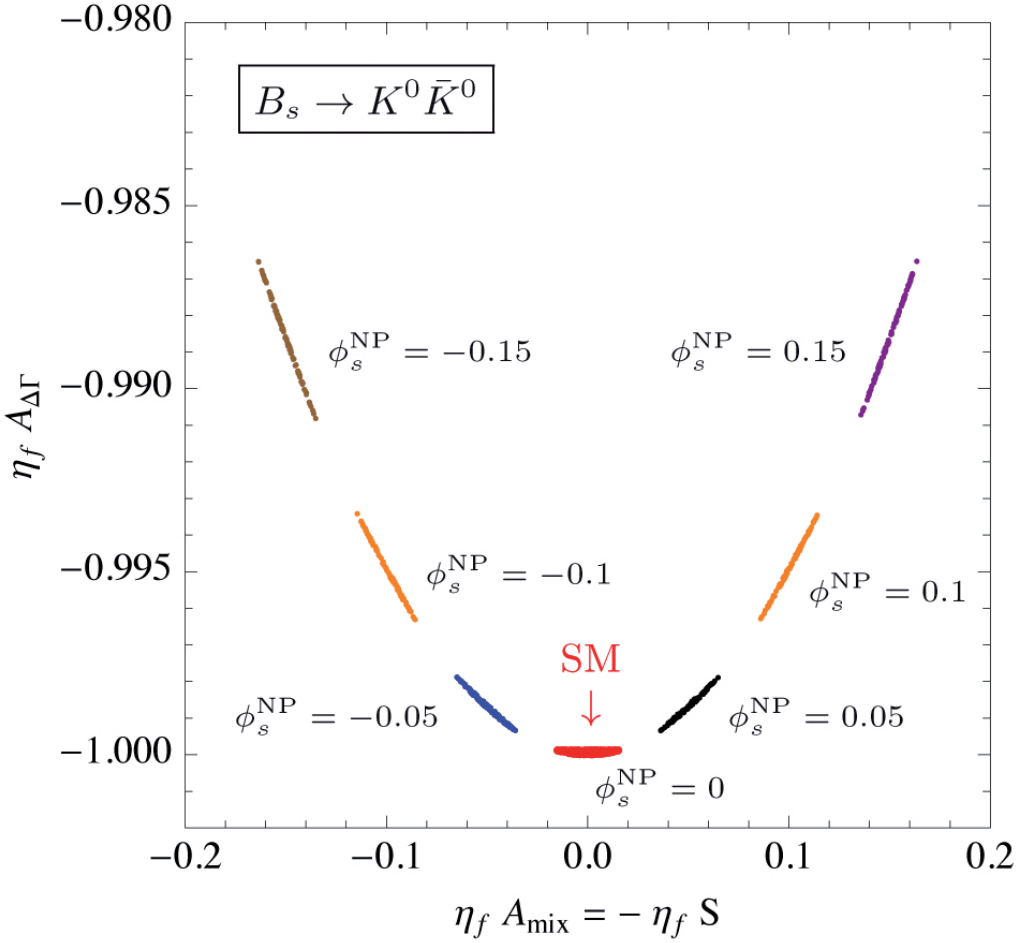




$B_d \to \phi K_s$ $\qquad$ $B_d \to \phi K^*$

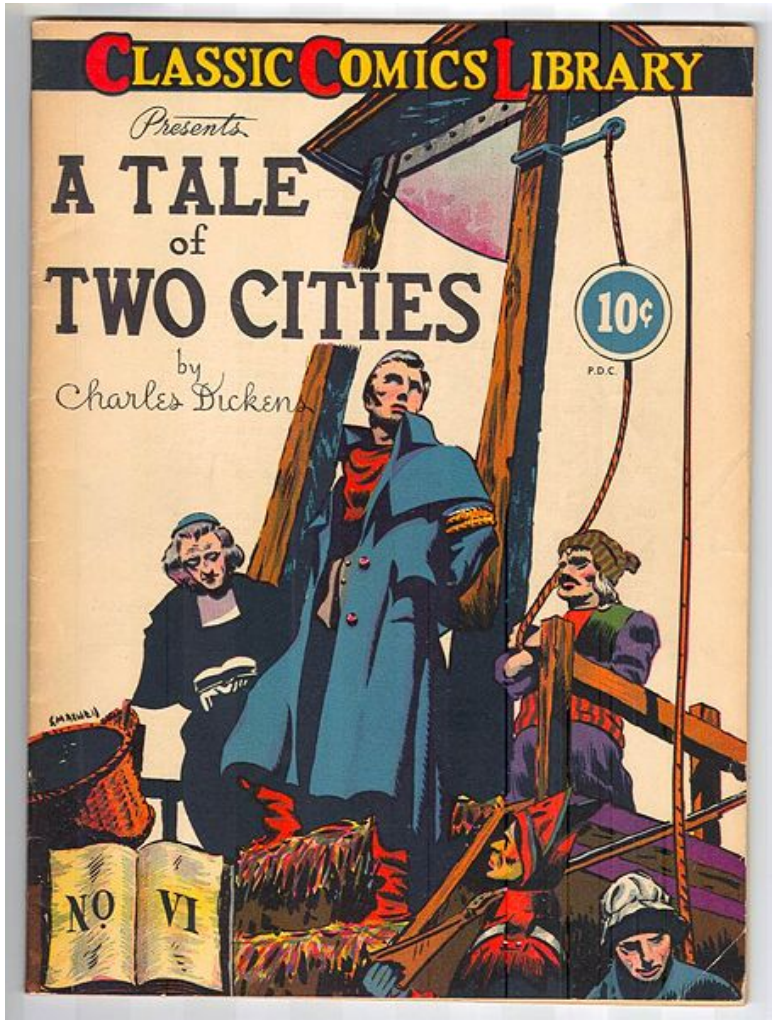
- $(A_{\rm mix}, A_{\Delta\Gamma} = \pm\sqrt{1 - A_{\rm mix}^2 - A_{\rm dir}^2})$ asymmetries at 1 σ in grey box
- $\phi_d^{NP}(\phi K_S) = -0.36 \pm 0.22$ rad, $\phi_d^{NP}(\phi K^*) = 0.33 \pm 0.90$ rad

Illustration for $B_s \to K_0 \bar{K}_0$



- Estimate of BR from $B_d \to K_0 \bar{K}_0$ + $SU(3)$ flavour symmetry

The end of the tale



Conclusions

Interesting hints of NP in $\Delta F = 2$

- $Br(B \to \tau\nu)$ vs $\sin 2\beta$ [$B \to \tau\nu$ cross-check ?]
- A_{SL} [separate a^d_{SL} and a^s_{SL} ?]
- β_s ? [higher statistics ? other modes ?]

Scenarios of NP in $\Delta F = 2$

- Conflict between current A_{SL} and ϕ_s not solved by NP in M_{12} only
- Could be solved by NP in Γ^s_{12}, but affects other SM-compatible observables in mixing ($\Delta M_s, \Delta\Gamma_s, \Gamma_s$) as well as in $b \to s$ decays
- No model-indep. connection, but correlations in specific models

Cross-checks through penguin-mediated decays [prospects ?]

- Interesting laboratory to probe NP in mixing phase
- Theory input restricted to QCDF computation of $T - P$
- Alternative determination of ϕ^{NP}_Q from (longitudinal) BR and $A_{\rm mix}$

More

CKM fitter

CKMFITTER

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Plots & Results
Specific Studies

Talks & Writeups
Publications

CKMfitter Group

Code

Contact

CKMfitter global fit results as of Lepton Photon 11:

- Wolfenstein parameters
- UT angles and sides
- UT_s angle and apex
- CKM elements
- Theory parameters
- Rare branching fractions (B→lν, B→ll)

For a more extensive discussion, please read the summary of inputs and results.

Wolfenstein parameters and Jarlskog invariant:

Observable	Central ± 1 σ	± 2 σ	± 3 σ
A	0.801 [+0.026 -0.014]	0.801 [+0.036 -0.022]	0.801 [+0.046 -0.029]
λ	0.22539 [+0.00062 -0.00095]	0.2254 [+0.0010 -0.0019]	0.2254 [+0.0014 -0.0027]
ρbar	0.144 [+0.023 -0.026]	0.144 [+0.038 -0.046]	0.144 [+0.048 -0.057]
ηbar	0.343 [+0.015 -0.014]	0.343 [+0.030 -0.025]	0.343 [+0.045 -0.033]
J [10^{-5}]	2.884 [+0.253 -0.053]	2.884 [+0.400 -0.098]	2.88 [+0.55 -0.14]

UT angles and sides:

Observable	Central ± 1 σ	± 2 σ	± 3 σ
sin 2α	-0.03 [+0.14 -0.12]	-0.03 [+0.25 -0.21]	-0.03 [+0.31 -0.26]
sin 2α (meas. not in the fit)	-0.10 [+0.18 -0.12]	-0.10 [+0.34 -0.17]	-0.10 [+0.40 -0.22]
sin 2β	0.691 [+0.020 -0.020]	0.691 [+0.040 -0.034]	0.691 [+0.060 -0.047]
sin 2β (meas. not in the fit)	0.830 [+0.013 -0.033]	0.830 [+0.025 -0.098]	0.830 [+0.037 -0.170]
α [deg]	90.9 [+3.5 -4.1]	90.9 [+6.0 -7.2]	90.9 [+7.5 -8.9]
α [deg] (meas. not in the fit)	92.9 [+3.6 -5.1]	92.9 [+5.0 -9.8]	92.9 [+6.4 -11.7]
α [deg] (dir. meas.)	89.0 [+4.4 -4.2]	89.0 [+9.1 -8.4] || 178.3 [+2.2 -5.6] || -1.8 [+6.6 -5.6]	89 [+21 -13] || 178.3 [+2.5 -13.8] || -2 [+14 -14]
β [deg]	21.84 [+0.80 -0.76]	21.8 [+1.6 -1.3]	21.8 [+2.5 -1.8]
β [deg] (meas. not in the fit)	28.06 [+0.67 -1.62]	28.1 [+1.4 -4.5]	28.1 [+2.0 -7.4]
β [deg] (dir. meas.)	21.38 [+0.79 -0.77]	21.4 [+1.6 -1.5]	21.4 [+2.4 -2.3]

More plots and results available on http://ckmfitter.in2p3.fr

J. Charles, Theory
O. Deschamps, LHCb
SDG, Theory
R. Itoh, Belle
A. Jantsch, ATLAS
H. Lacker, ATLAS
A. Menzel, ATLAS
S. Monteil, LHCb
V. Niess, LHCb
J. Ocariz, BaBar
S. T'Jampens, LHCb
V. Tisserand, BaBar/LHCb
K. Trabelsi, Belle

Back-up

Inputs of the SM global fit

CKM fitter

CKM matrix within a frequentist framework ($\simeq \chi^2$ minimum)
+ specific scheme for theory errors (Rfit)

data = weak $\otimes$ QCD

$\Longrightarrow$Need for hadronic inputs (often lattice) with good theoretical control

$\lvert V_{ud}\rvert$	superallowed β decays	PRC79, 055502 (2009)
$\lvert V_{us}\rvert$	$K_{\ell 3}$ (Flavianet Kaon WG)	$f_+(0) = 0.963 \pm 0.003 \pm 0.005$
	$K_{\ell 2}, \tau \to K\nu_\tau$	$f_K = 156.3 \pm 0.3 \pm 1.9$ MeV
$\lvert V_{us}\rvert/\lvert V_{ud}\rvert$	$K_{\ell 2}/\pi_{\ell 2}, \tau \to K\nu_\tau/\tau \to \pi\nu_\tau$	$f_K/f_\pi = 1.1985 \pm 0.0013 \pm 0.0019$
ϵ_K	PDG 08	$\hat{B}_K = 0.732 \pm 0.004 \pm 0.036$
$\lvert V_{ub}\rvert$	inclusive and exclusive	$\lvert V_{ub}\rvert \cdot 10^3 = 3.92 \pm 0.09 \pm 0.45$
$\lvert V_{cb}\rvert$	inclusive and exclusive	$\lvert V_{cb}\rvert \cdot 10^3 = 40.89 \pm 0.38 \pm 0.59$
Δm_d	last WA B_d-$\bar{B}_d$ mixing	$B_{B_s}/B_{B_d} = 1.024 \pm 0.013 \pm 0.015$
Δm_s	last WA B_s-$\bar{B}_s$ mixing	$B_{B_s} = 1.291 \pm 0.025 \pm 0.035$
β	last WA $J/\psi K^{(*)}$	
α	last WA $\pi\pi, \rho\pi, \rho\rho$	isospin
γ	last WA $B \to D^{(*)}K^{(*)}$	GLW/ADS/GGSZ
$B \to \tau\nu$	$(1.68 \pm 0.31) \cdot 10^{-4}$	$f_{B_s}/f_{B_d} = 1.235 \pm 0.008 \pm 0.033$
		$f_{B_s} = 231 \pm 3 \pm 15$ MeV

Lattice averages

Consistent averages of lattice results for hadronic quantities needed

$\Longrightarrow$ we perform our own averages

Lattice averages

Consistent averages of lattice results for hadronic quantities needed

$\Longrightarrow$ we perform our own averages

- Collecting lattice results
  - only unquenched results with 2 or 2+1 dynamical fermions
  - papers and proceedings (but not preliminary results)
- Splitting error estimates into stat and syst
  - Stat : essentially related to size of gauge conf
  - Syst : fermion action, $a \to 0$, $L \to \infty$, mass extrapolations...
    added linearly when error budget available
- Potential problems
  - proceedings not always followed by peer-reviewed papers
  - some syst estimates controversial within lattice community (staggered action, extrapolations...)

Averaging procedure

"Educated Rfit" used to combine the results, with different treament of statistical and systematic errors

- product of (Gaussian + Rfit) likelihoods for central value
- product of Gaussian (stat) likelihoods for stat uncertainty
- syst uncertainty of the combination

= the one of the most precise method

Conservative, algorithmic procedure with internal logic for syst

- the present state of art cannot allow us to reach a better theoretical accuracy than the best of all estimates
  (combining 2 methods with similar syst does not reduce the intrinsic uncertainty encoded as a systematic)
- best estimate should not be penalized by less precise methods
  (opposed, e.g., to combined syst = dispersion of central values)

Our average for $B_K^{\bar{M}S}(2\text{ GeV})$

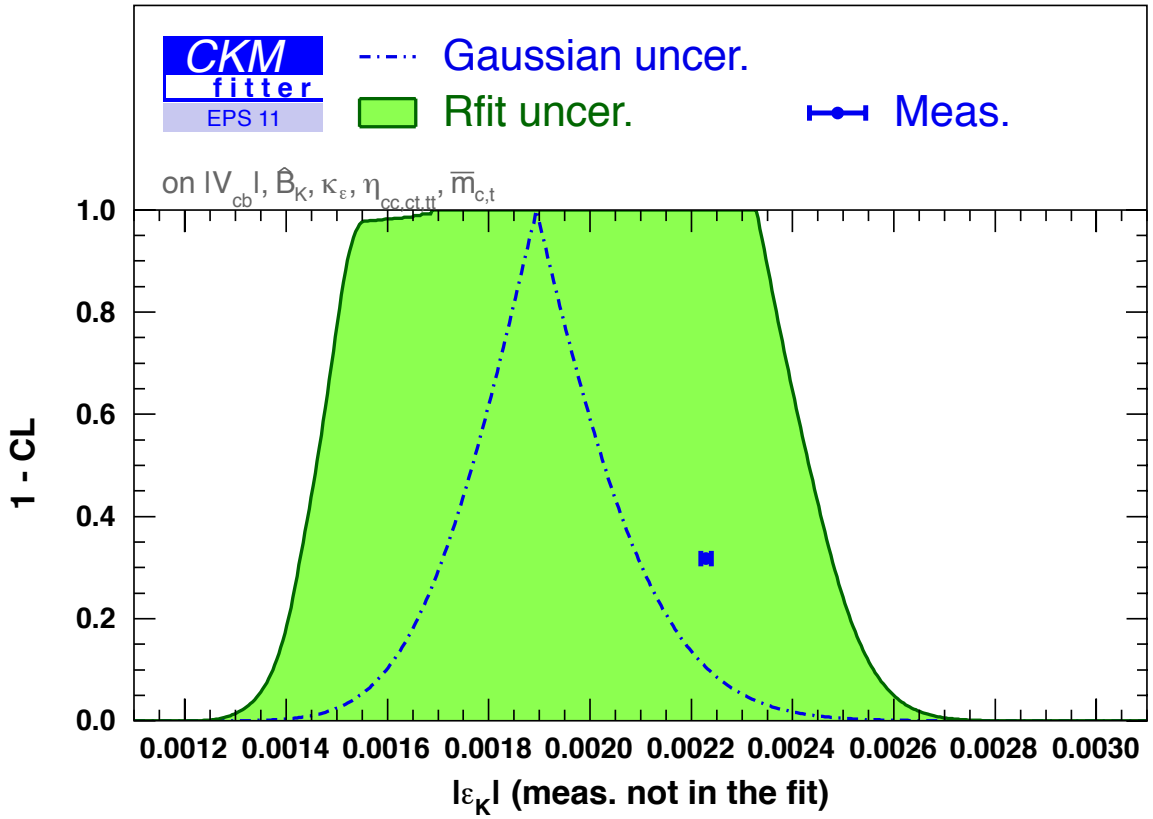
Reference	N_f	Mean	Stat	Syst
JLQCD08	2	0.537	0.004	0.072
ETMC10	2	0.532	0.019	0.026
HPQCD/UKQCD06	2+1	0.618	0.018	0.179
ALVdW09	2+1	0.527	0.006	0.035
RBC/UKQCD10	2+1	0.549	0.005	0.038
BSW10	2+1	0.523	0.007	0.039
Our average		0.534	0.003	0.026
Our average for $\hat{B}_K$		0.732	0.004	0.036

- Other values proposed: 0.737 ± 0.020 (`latticeaverages.org`)
- Method used for B_d and B_s decay constants, bag parameters, form factors...

$K - \bar{K}$ mixing in the SM

Impact of the statistical treatment of theoretical inputs on ϵ_K

$$\kappa_\epsilon, |V_{cb}|, \hat{B}_K, \eta_{ct,cc,tt}, \bar{m}_{c,t}$$



- Gaussian error: 1.6 σ discrepancy
- Rfit error: no discrepancy

$|V_{ub}|$ inclusive and exclusive

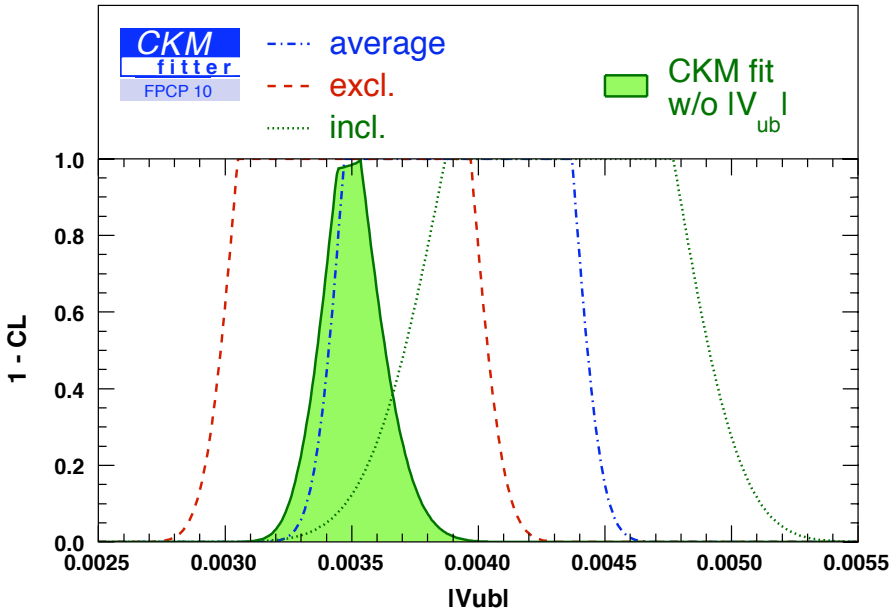
Two ways of getting $|V_{ub}|$:

- Inclusive : $b \to u\ell\nu$ + Operator Product Expansion
- Exclusive : $B \to \pi\ell\nu$ + Form factors

$$|V_{ub}|_{inc} = 4.32^{+0.21}_{-0.24} \pm 0.45$$
$$|V_{ub}|_{exc} = 3.51 \pm 0.10 \pm 0.46$$

$$|V_{ub}|_{ave} = 3.92 \pm 0.09 \pm 0.45$$

with all values $\times 10^{-3}$



Tension depends on statistical treatment:

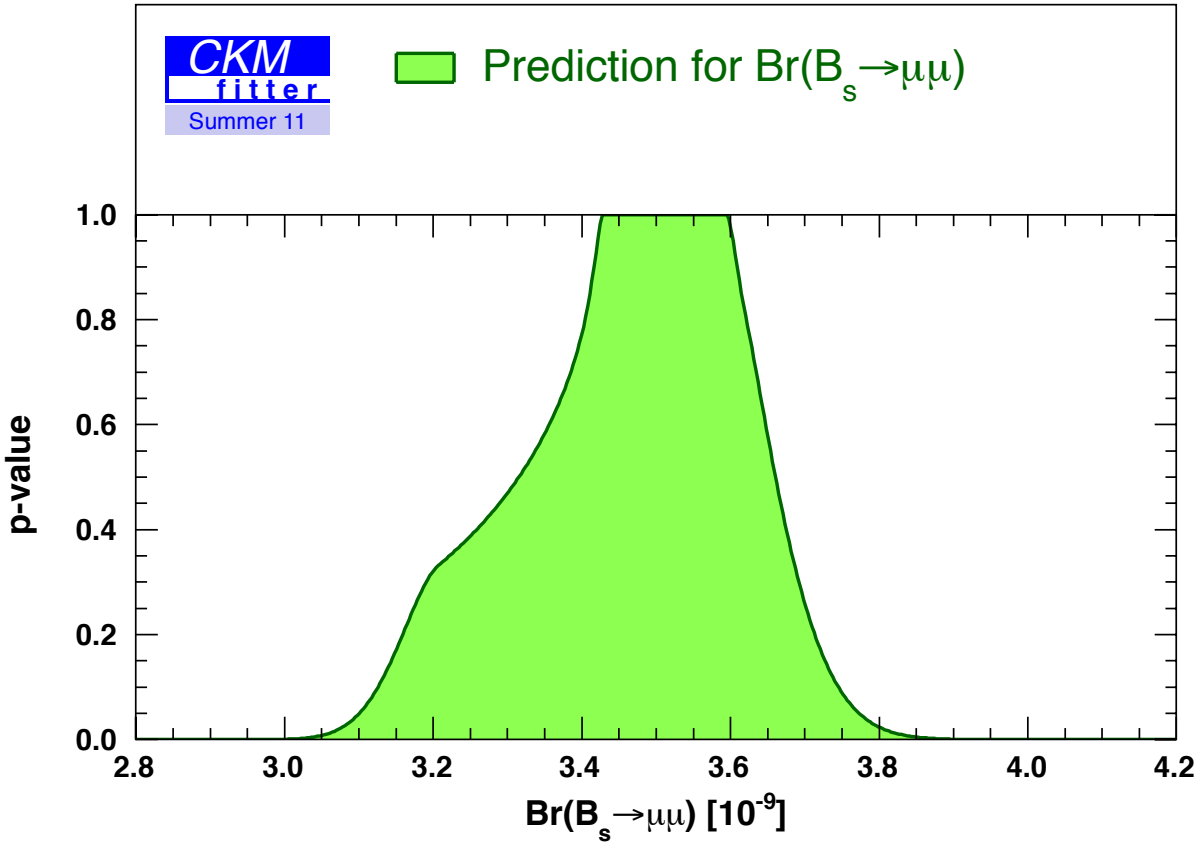
- discrepancy solved once systematics combined in Educated Rfit
- same problem for $|V_{cb}|$

A few predictions for Scenario I

Quantity	1σ
$\mathrm{Re}(\Delta_d)$	$0.757^{+0.132}_{-0.083}$
$\mathrm{Im}(\Delta_d)$	$-0.181^{+0.053}_{-0.045}$
$\mathrm{Re}(\Delta_s)$	$-0.895^{+0.082}_{-0.120}$ *or* $0.895^{+0.020}_{-0.018}$
$\mathrm{Im}(\Delta_s)$	$-0.04^{+0.17}_{-0.17}$
$\phi_d^\Delta + 2\beta$ [deg] (!)	$17.^{+13.}_{-11.}$
$\phi_s^\Delta - 2\beta_s$ [deg] (!)	$-123.9^{+9.0}_{-13.6}$ *or* $-61.8^{+13.4}_{-8.9}$
A_{SL} $[10^{-4}]$ (!)	$-15.5^{+14.3}_{-5.9}$
a^d_{SL} $[10^{-4}]$ (!)	$-35.8^{+6.9}_{-4.6}$
a^s_{SL} $[10^{-4}]$ (!)	$-3.^{+11.}_{-13.}$
$\Delta\Gamma_s[\mathrm{ps}^{-1}]$ (!)	$-0.169^{+0.080}_{-0.023}$ *or* $0.168^{+0.041}_{-0.112}$
$B \to \tau\nu$ $[10^{-4}]$ (!)	$1.471^{+0.075}_{-0.261}$

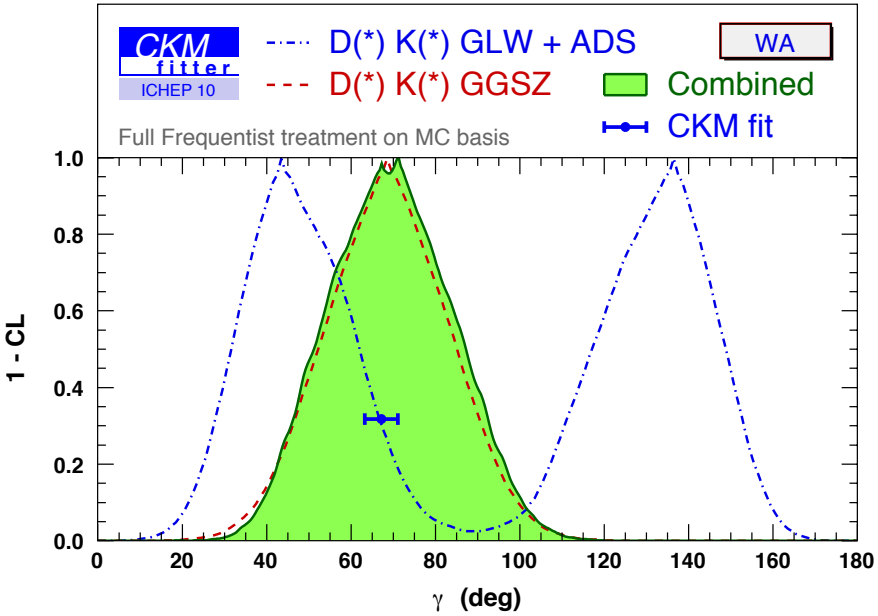
- (!): the prediction is made without including the measurement
- Warning: non-Gaussian tails for some observables

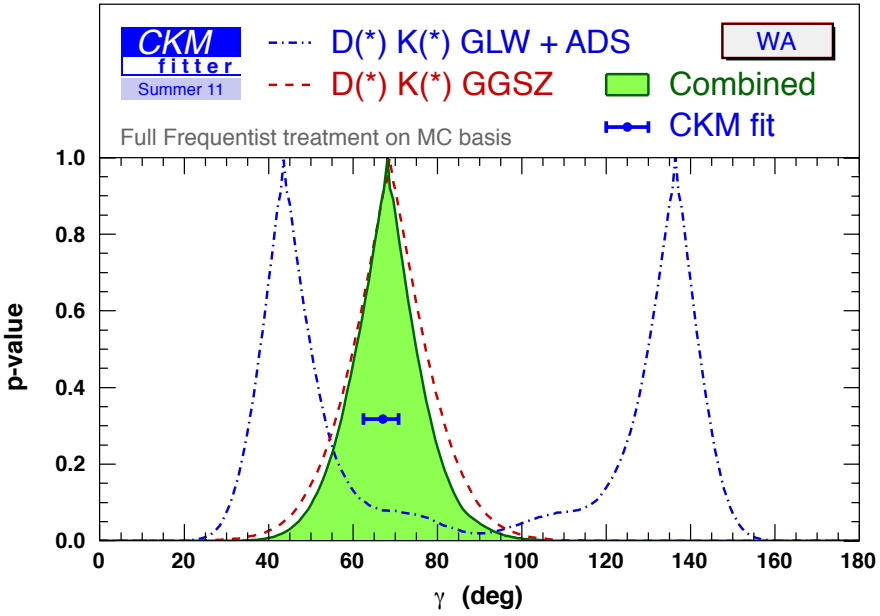
$B_s \to \mu\mu$ in SM



$$Br(B_s \to \mu\mu) = (3.51^{+0.18}_{-0.31}) \cdot 10^{-9}$$

γ





$$\gamma[\text{meas}, 2010] = (71^{+21}_{-25})^\circ \qquad \gamma[\text{meas}, 2011] = (68^{+10}_{-11})^\circ$$

- Update in ADS inputs from Belle, CDF
- Better control over nuisance parameters in statistical treatment

Longitudinal observables ($B_d \to \phi K^*$)

- A_0 decay amplitude for B_Q into a longitudinally polarised pair, $\bar{A}_0$ its CP conjugate
- Longitudinal BR: $Br^{\rm long} = g\frac{|A_0|^2+|\bar{A}_0|^2}{2}$ with $g = g_{ps}$ phase space
- Asymmetries: $A^{\rm long}_{\rm dir} = \frac{|A_0|^2-|\bar{A}_0|^2}{|A_0|^2+|\bar{A}_0|^2}$ $\quad A^{\rm long}_{\Delta\Gamma} + iA^{\rm long}_{\rm mix} = -2\eta_0 \frac{e^{-i\phi_{B_Q}} A_0^* \bar{A}_0}{|A_0|^2+|\bar{A}_0|^2}$

– $(+)$ superscript for B_d ($\bar{B}_d$) observables of $B_d \to \phi K^*$ [Babar]

$$Br^+ = \frac{\bar{\Gamma}}{\Gamma_{\rm tot}} = g\sum_\lambda |\bar{A}_\lambda|^2,\ Br^- = \frac{\Gamma}{\Gamma_{\rm tot}} = g\sum_\lambda |A_\lambda|^2,\ f_L^+ = \frac{|\bar{A}_0|^2}{\sum_\lambda |\bar{A}_\lambda|^2}\ ,\ f_L^- = \frac{|A_0|^2}{\sum_\lambda |A_\lambda|^2}$$

$$Br = \frac{1}{2}\frac{1}{\Gamma_{\rm total}}\left(\bar{\Gamma}+\Gamma\right), \quad \mathcal{A}_{CP} = \frac{\bar{\Gamma}-\Gamma}{\bar{\Gamma}+\Gamma}, \quad f_L = \frac{1}{2}\left(f_L^+ + f_L^-\right), \quad \mathcal{A}^0_{CP} = \frac{f_L^+ - f_L^-}{f_L^+ + f_L^-}$$

Dictionnary w.r.t. longitudinal observables

$$Br^{\rm long} = Br \cdot f_L \cdot [1 + \mathcal{A}^0_{CP}\cdot \mathcal{A}_{CP}], \qquad A^{\rm long}_{\rm mix} = \eta\sqrt{1-(A^{\rm long}_{\rm dir})^2}\sin(2\beta + \arg(A_0/\bar{A}_0))$$

$$A^{\rm long}_{\rm dir} = -\frac{\mathcal{A}^0_{CP}+\mathcal{A}_{CP}}{1+\mathcal{A}^0_{CP}\cdot\mathcal{A}_{CP}}, \qquad A^{\rm long}_{\Delta\Gamma} = -\eta\sqrt{1-(A^{\rm long}_{\rm dir})^2}\cos(2\beta + \arg(A_0/\bar{A}_0))$$

with $\arg(A_0/\bar{A}_0) = 2\Delta\delta_0 + 2\Delta\phi_0$ measured