Hints of New Physics in Flavor Interactions

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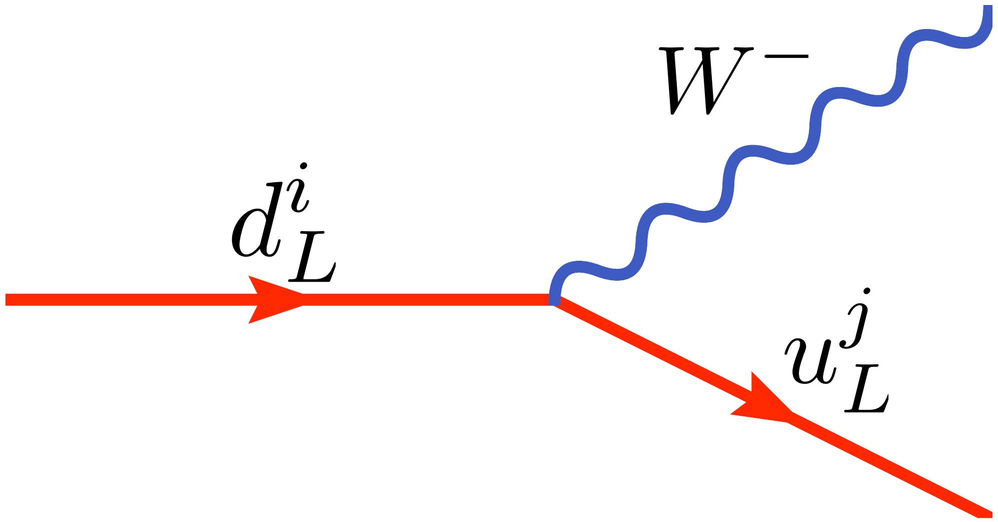
Fermilab

Outline

- Unitarity Triangle: *new phase in B_d mixing?*
- $B \to (\phi, \eta')K_S$: *new phase in $b \to s\bar{s}s$ amplitudes?*
- $B_s \to J/\psi\ \phi$: *new phase in B_s mixing?*
- $D_s \to \ell\nu$

The Cabibbo-Kobayashi-Maskawa matrix



$\propto V_{ji}$

Wolfenstein parametrization (λ, A, ρ, η ~ O(1)):

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$$-A\lambda^2\left(1 - \frac{1-2\rho}{2}\lambda^2 + i\,\eta\lambda^2\right)$$

λ: β-decay, $K \to \pi l \nu$, $D \to (\pi, K) l \nu$, $\nu N \to \mu X$, ...

ρ,η: $B \to \pi l \nu$, $B \to X_u l \nu$
CP violation

$$\begin{pmatrix} \boxed{\begin{matrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{matrix}} & \begin{matrix} \boxed{V_{ub}} \\ \boxed{V_{cb}} \end{matrix} \\ \boxed{V_{td}} \quad \boxed{V_{ts}} & \boxed{V_{tb}} \end{pmatrix}$$

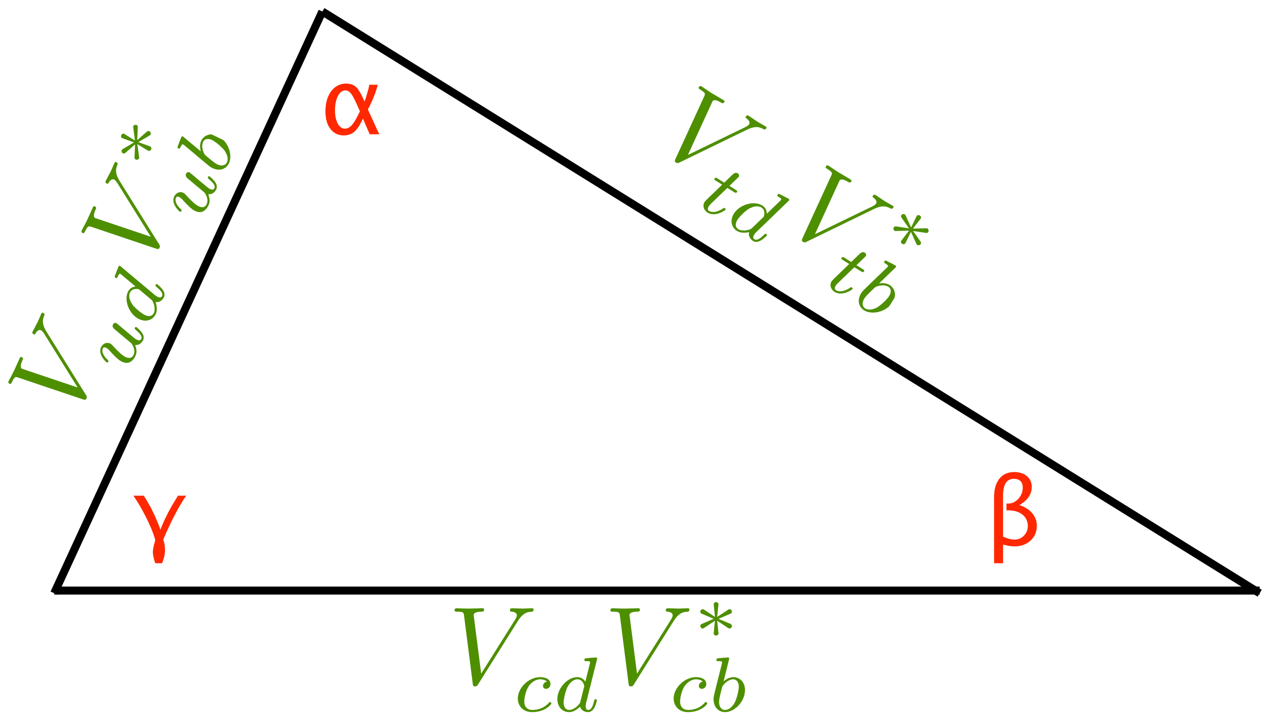
A: $B \to D^{(*)} l \nu$, $B \to X_c l \nu$

=1: $t \to Wb$ (single top)

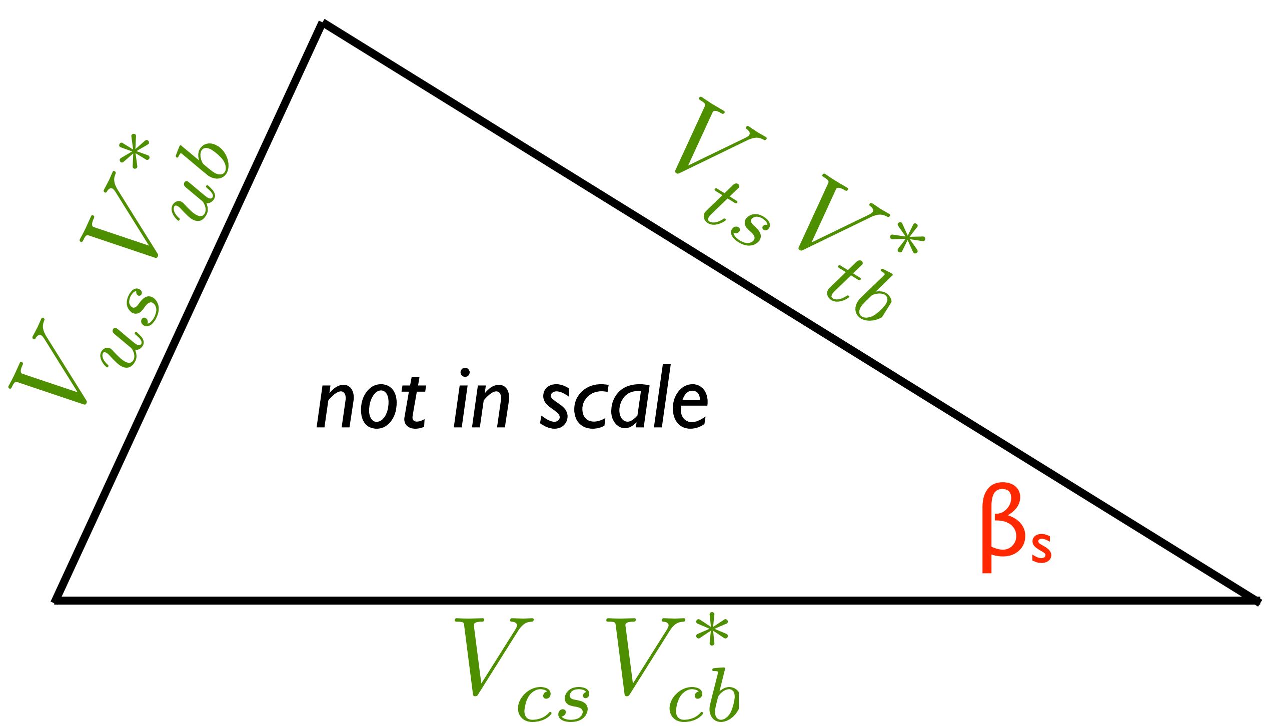
A: no direct meas. ($B \to X_s \gamma$, ΔM_{Bs}, ...)

ρ,η: no direct meas. (ΔM_{Bd}, CP violation)

Unitarity Triangles:

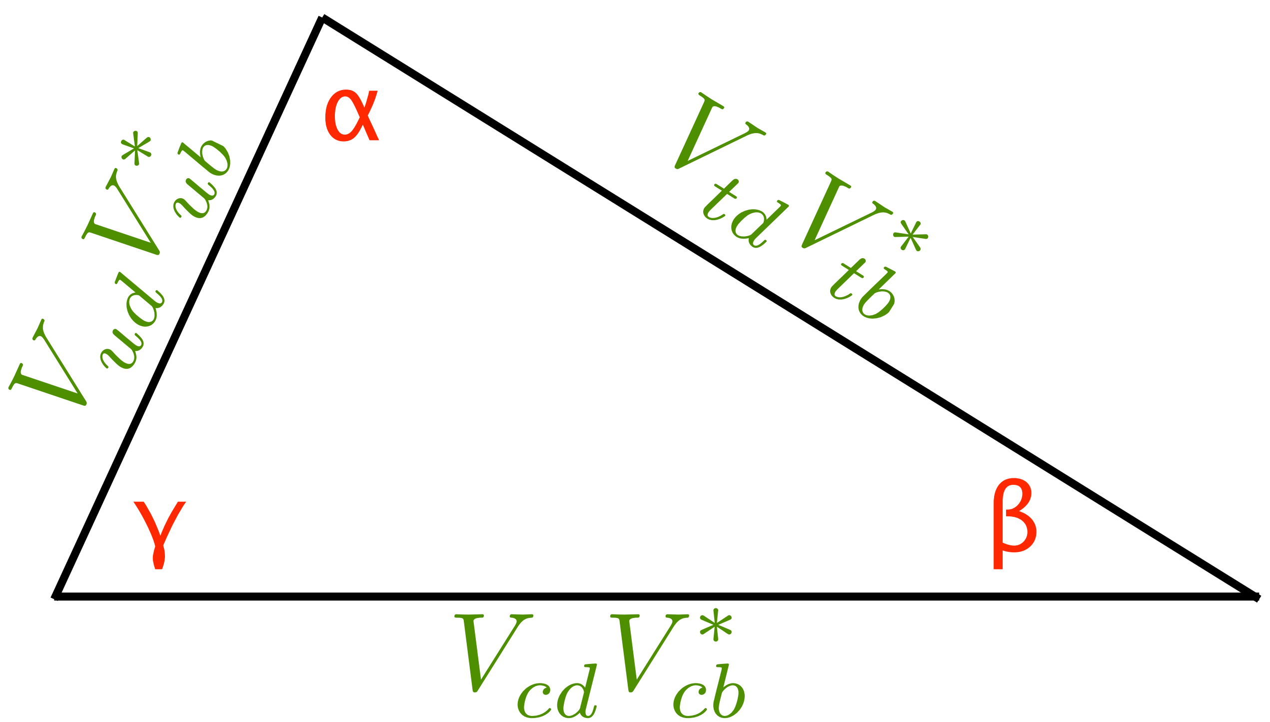


$$
\begin{aligned}
V_{td} &= |V_{td}|\; e^{-i\beta} \\
V_{ub} &= |V_{ub}|\; e^{-i\gamma}
\end{aligned}
$$



$$\beta_s = \arg(V_{ts}) = \eta\lambda^2 + O(\lambda^4)$$

Unitarity Triangles:



$$
\begin{aligned}
V_{td} &= |V_{td}|\ e^{-i\beta} \\
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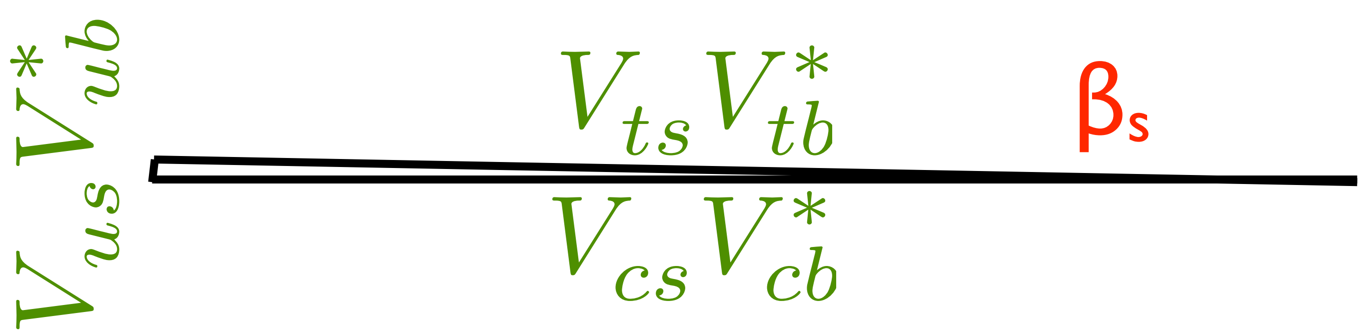
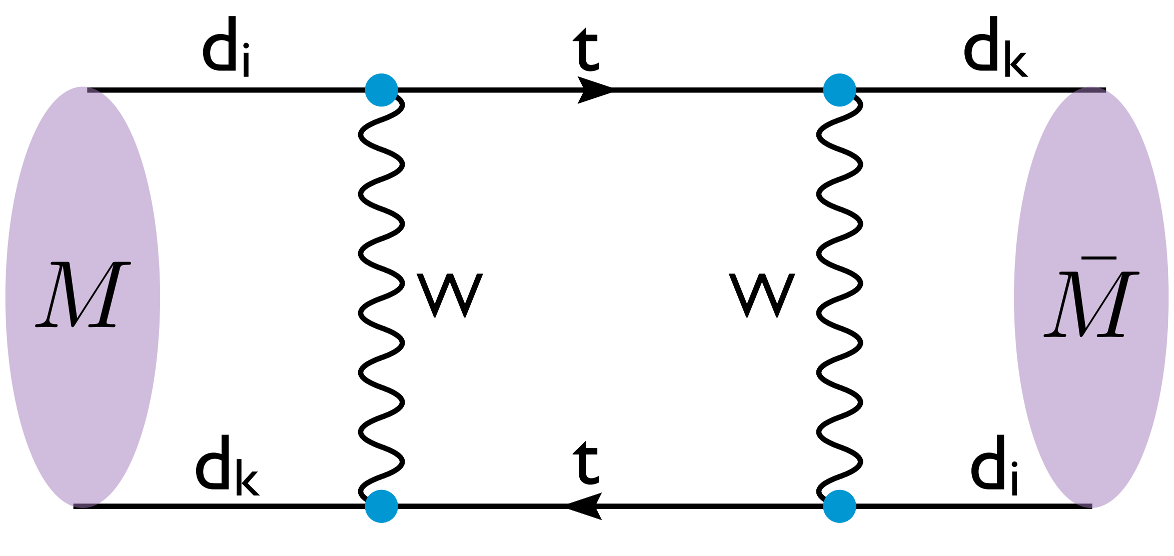
\end{aligned}
$$

$$\beta_s = \arg(V_{ts}) = \eta\lambda^2 + O(\lambda^4)$$



Meson Mixing



$$\propto (V_{tk} V_{ti}^*)^2$$

- The meson-antimeson amplitude can be written as:

$$M_{12} - \frac{i}{2}\Gamma_{12}$$

Possibly dominated by perturbative physics

Usually dominated by long distance effects

K system (ε_K)

- In the Standard Model we have:

$$\varepsilon_K = e^{i\phi_\varepsilon} \sin\phi_\varepsilon \left(\frac{\mathrm{Im} M_{12}^K}{\Delta M_K} + \frac{\mathrm{Im}\; A\left(K \to [\pi\pi]_{I=0}\right)}{\mathrm{Re}\; A\left(K \to [\pi\pi]_{I=0}\right)} \right)$$

$$\begin{aligned} |\varepsilon_K| \quad &= \quad \kappa_\varepsilon C_\varepsilon \hat{B}_K \left|V_{cb}\right|^2 \lambda^2 \eta \Big(\left|V_{cb}\right|^2 (1-\bar{\rho}) \eta_{tt} S_0(x_t) \\ &\qquad + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c \Big) \end{aligned}$$

- Note the strong dependence on V_{cb}.
- $\hat{B}_K$ is a non-perturbative matrix element that has to calculated using lattice-QCD
- $\kappa_\epsilon = 0.92 \pm 0.02$

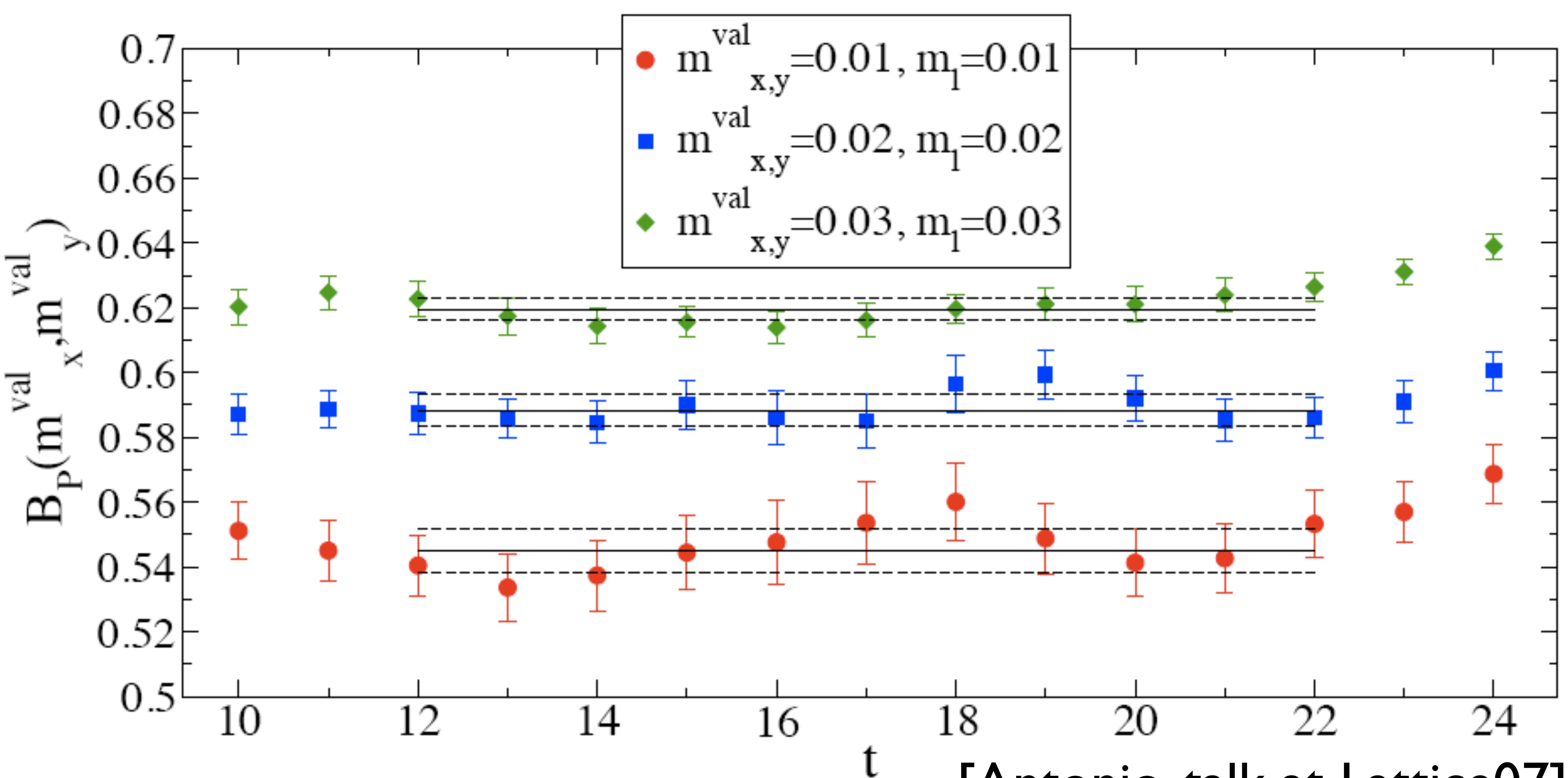
[Buras, Guadagnoli]

K system (ε_K)

- We use the most recent calculation from RBC and UKQCD (2+1 Domain Wall Fermions):

$$\hat{B}_K = 0.720 \pm 0.013 \pm 0.037$$

- Some caution is required due to lack of statistics:



[Antonio, talk at Lattice07]

B_q system

- Consider the ratio $\Delta M_{Bs}/\Delta M_{Bd}$

$$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \frac{m_{B_s}}{m_{B_d}} \frac{\hat{B}_s f_{B_s}^2}{\hat{B}_d f_{B_d}^2} \left| \frac{V_{ts}}{V_{td}} \right|^2 \equiv \frac{m_{B_s}}{m_{B_d}} \xi^2 \left| \frac{V_{ts}}{V_{td}} \right|^2$$

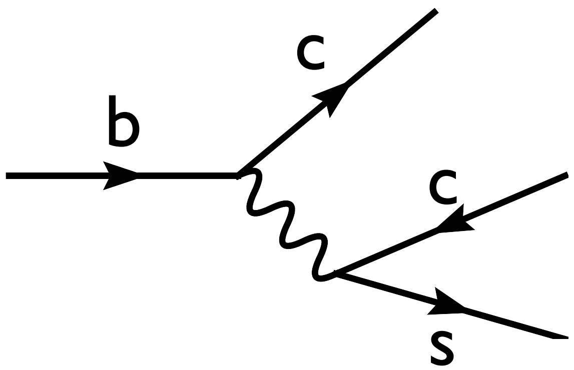
- No dependence on A (V_{cb})
- Lattice ratio (ξ) is better known (even though a fully dynamical determination is still missing):

$$\xi = 1.20 \pm 0.06$$

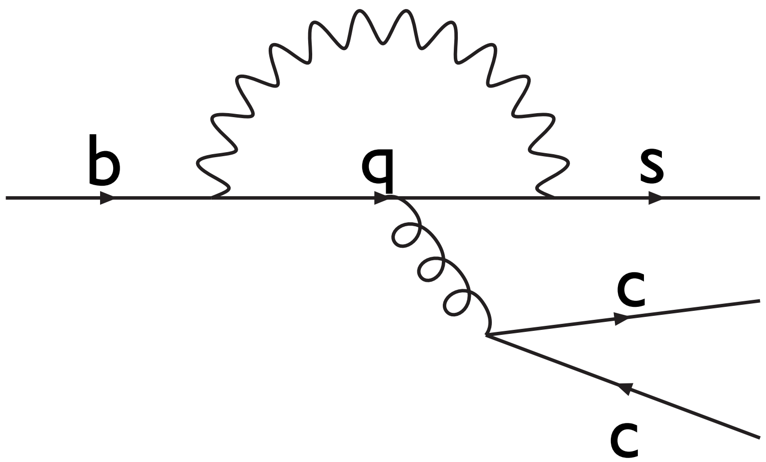
- In several NP models, this ratio is not affected

Time dependent CP asymmetries:

- $B \to J/\psi K_S$



$\propto V_{cb}V_{cs}^*$



$\propto V_{qb}V_{qs}^*$

$$\mathcal{A}_{c\bar{c}s} = (T + P^c - P^t)V_{cb}V_{cs}^* + \underbrace{(P^u - P^t)V_{ub}V_{us}^*}_{\text{loop \& CKM}}$$

- $B \to (\phi, \eta')K_S$

$$\mathcal{A}_{s\bar{s}s} = (P^c - P^t)V_{cb}V_{cs}^* + \underbrace{(P^u - P^t)V_{ub}V_{us}^*}_{\text{CKM only}}$$

These asymmetries measure:

$$a_f = \eta_f \sin 2(\theta_M + \theta_A^f)$$

where θ_M is the phase in the mixing amplitude and θ_A^f is the overall phase of the B→f amplitude.

We have:
$$\begin{aligned} \theta_M &= \beta + \theta_d \\ \theta_A^f &= (\theta_A^f)_{\rm SM} + (\theta_A^f)_{\rm NP} \end{aligned}$$

In the SM:
$$(\theta_A^f)_{\rm SM} \simeq \left\{ \begin{array}{ll} 0.1\% & \text{in } B \to J/\psi K_S \\ \underbrace{(1 \div 10)\%}_{\text{Naive estimate}} & \text{in } b \to s\bar{s}s \end{array} \right.$$

In QCD factorization we have:

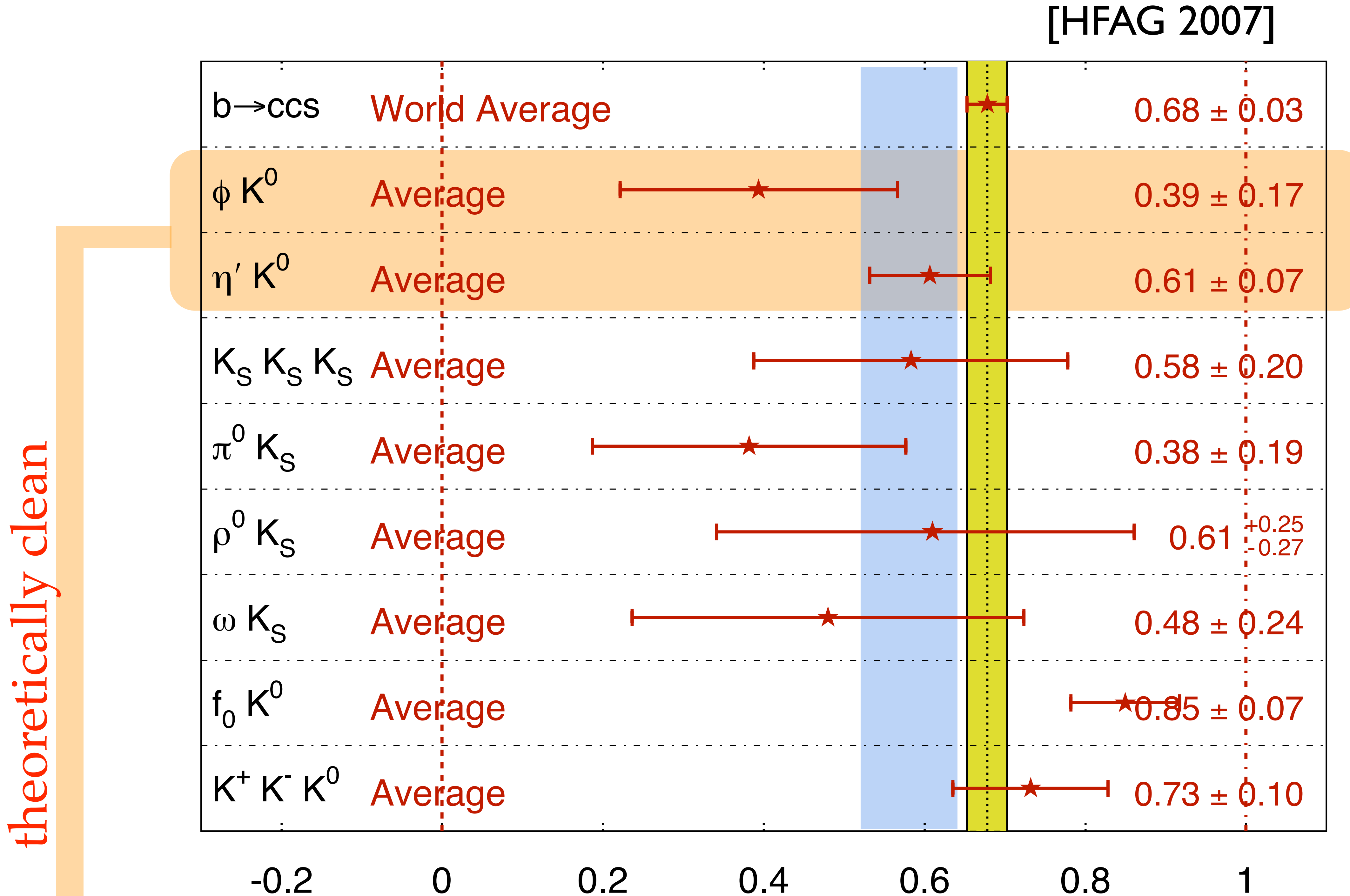
$$\begin{aligned}\Delta a_f &\equiv a_f - \sin 2\beta \\ &= 2\left|\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\right| \cos 2\beta \;\sin\gamma \;\mathrm{Re}\left(\frac{a_f^u}{a_f^c}\right)\end{aligned}$$

0.025

In particular for the ϕ and η' final states one finds:

$$\begin{aligned}\Delta a_\phi &= 0.02 \pm 0.01 \\ \Delta a_{\eta'} &= 0.01 \pm 0.01\end{aligned}$$

[Beneke, Neubert]



new phase in B mixing

$$\text{Average (ccs):} \quad \sin 2(\beta + \theta_d) = 0.681 \pm 0.025$$

$$\text{Average (sss):} \quad \sin 2(\beta + \theta_d + \theta_A) = 0.58 \pm 0.06$$

new phase in the b→sss amplitude

Updated inputs:

$$\xi = 1.20 \pm 0.06$$

$$\hat{B}_K = 0.72 \pm 0.04$$

B→D*lν form factor from lattice-QCD (2+1 dynamical staggered fermions)

$$|V_{cb}| \times 10^3 = \begin{cases} 38.7 \pm 1.1 & \text{excl} \\ 41.7 \pm 0.7 & \text{incl} \end{cases} \implies 2.3\,\sigma \text{ discrepancy}$$

$B \to X_c l\nu$ moments

B→πlν form factor from lattice-QCD (2+1 dynamical staggered fermions)

$$|V_{ub}| \times 10^4 = \begin{cases} 37.8 \pm 5.2 & \text{excl} \\ 37.0 \pm 3.2 & \text{incl} \end{cases}$$

[Neubert, no b→sγ]

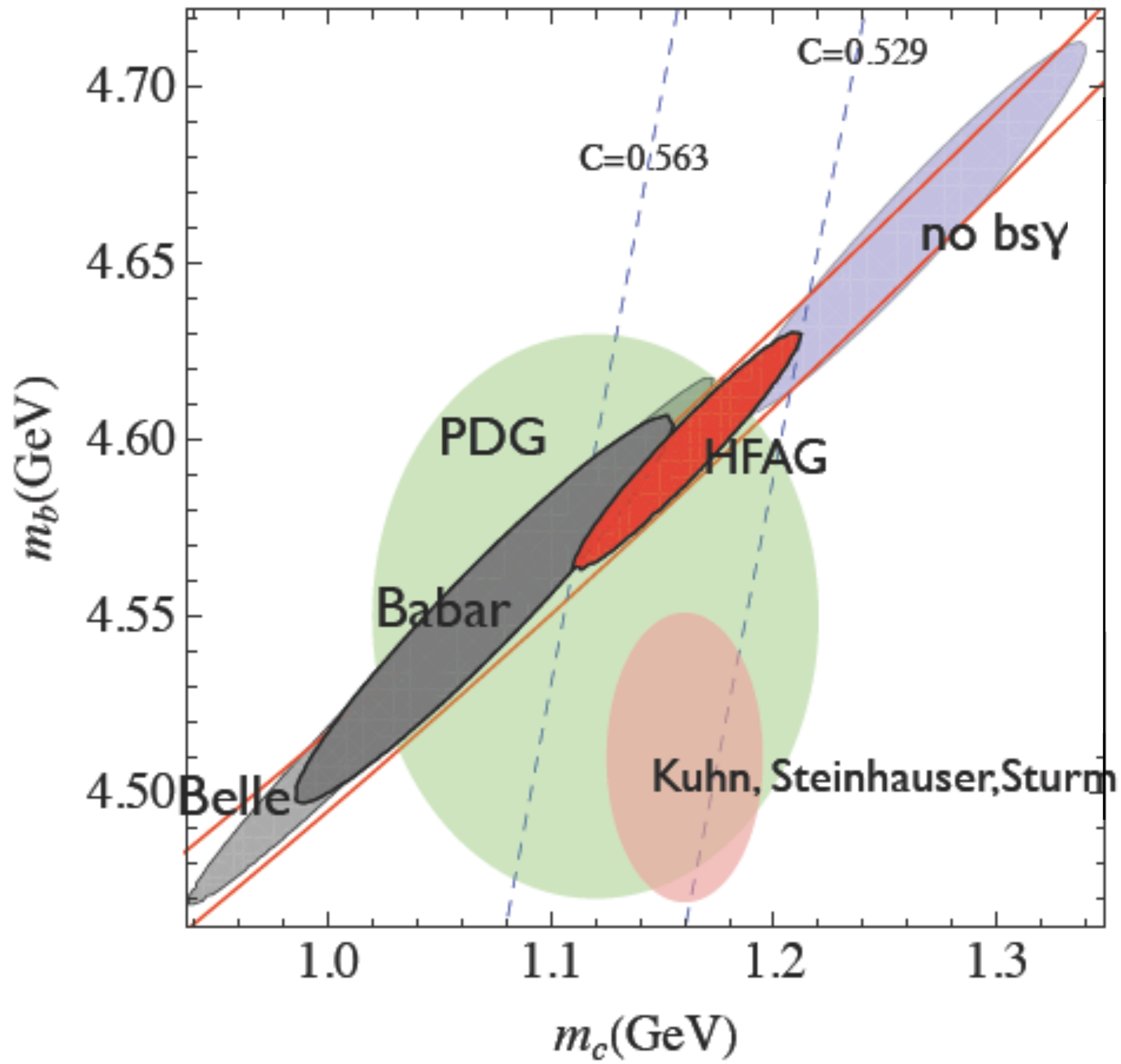
$B \to X_u l\nu$ moments (severe phase space cuts, large mb dependence)

V_{cb} inclusive

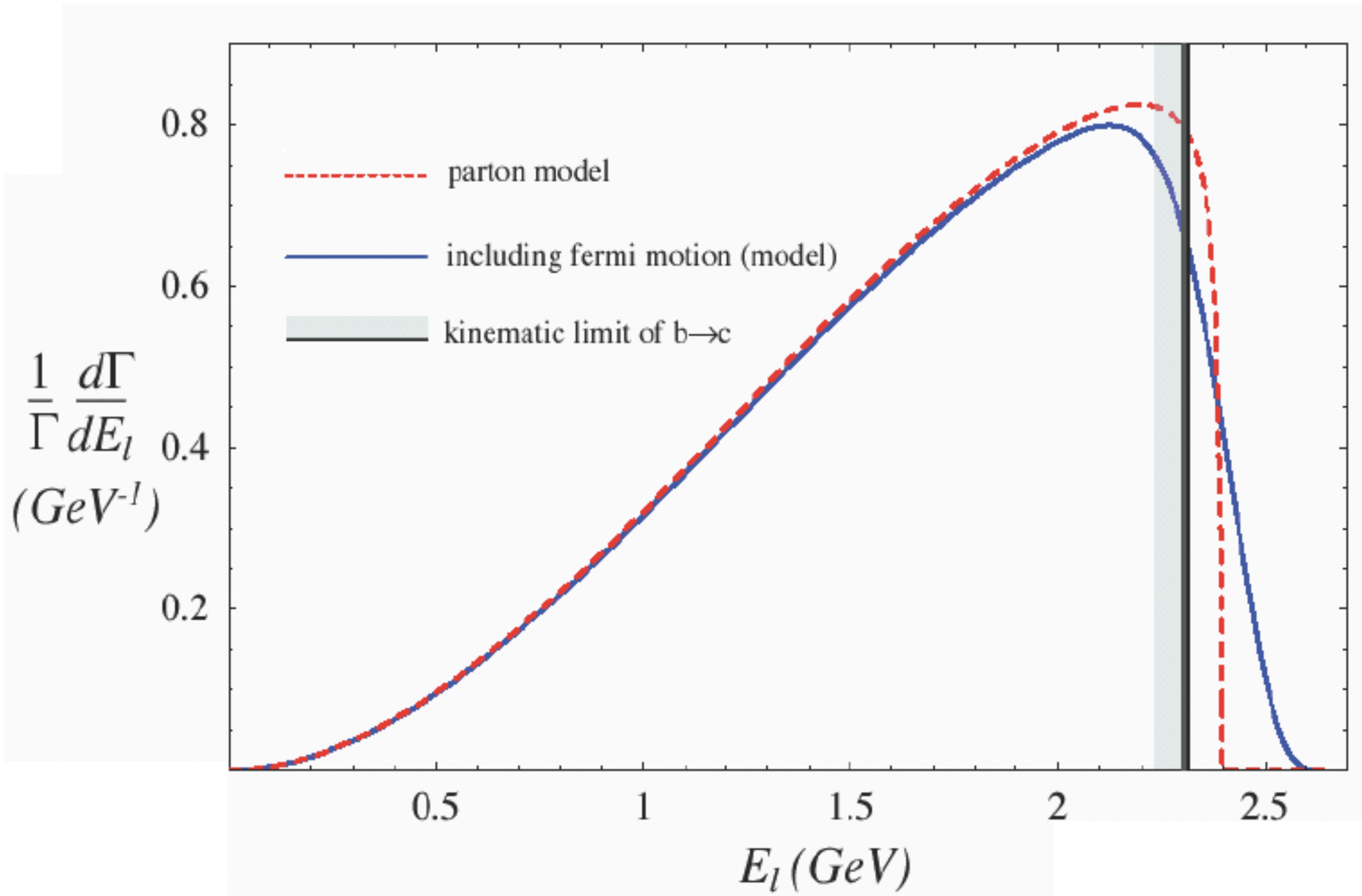
- Inclusion of $b \rightarrow s\gamma$ has strong impact on quark masses but not on V_{cb}

- Missing perturbative corrections might help. Full NNLO (α_s^2) and α_s/m_b^2 not included in the global fit yet

- m_b value is relevant for V_{ub}



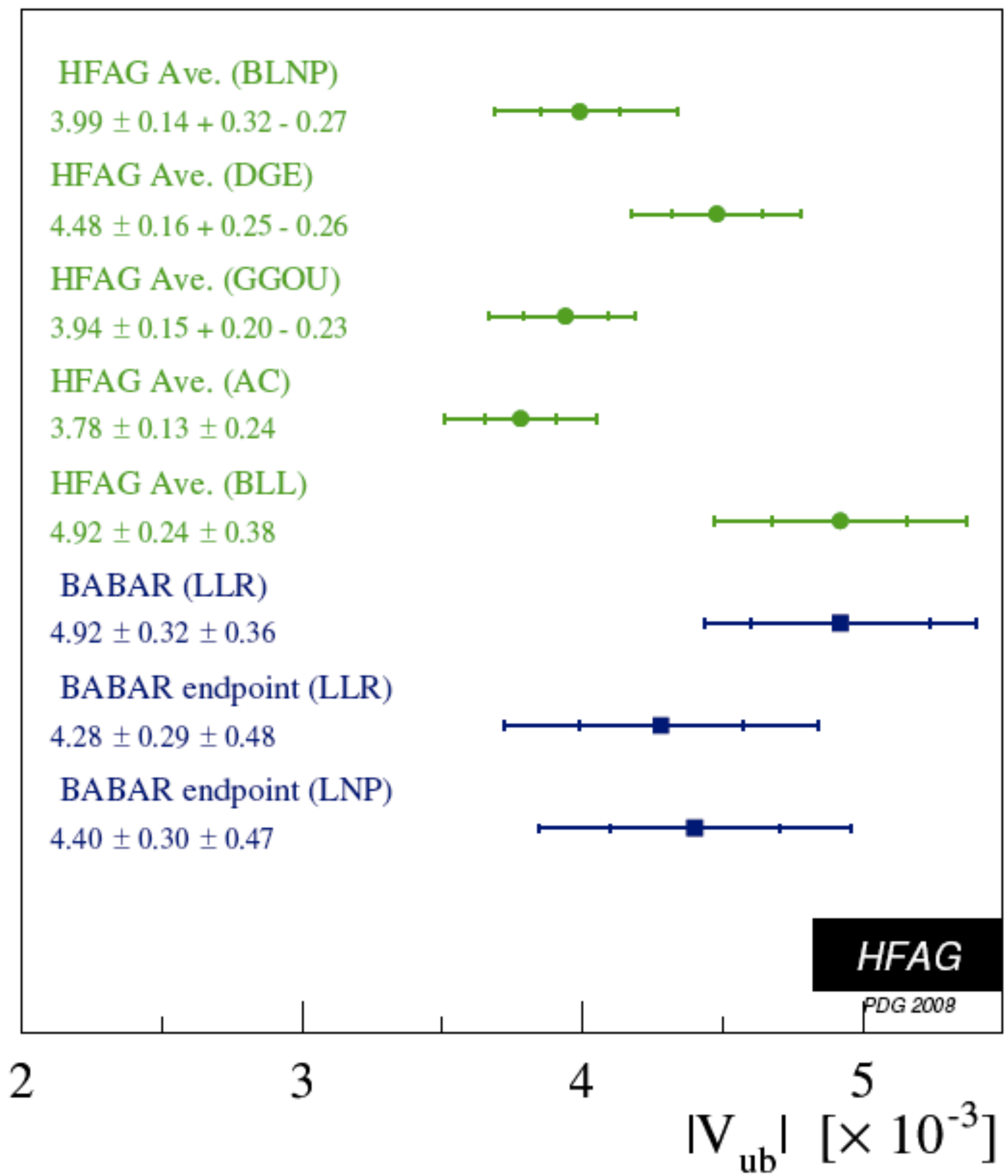
V_{ub} inclusive



- ⋆ Higher $m_b \Rightarrow$ lower V_{ub}
- ⋆ We adopt Neubert's approach (no $b \to s\gamma$)

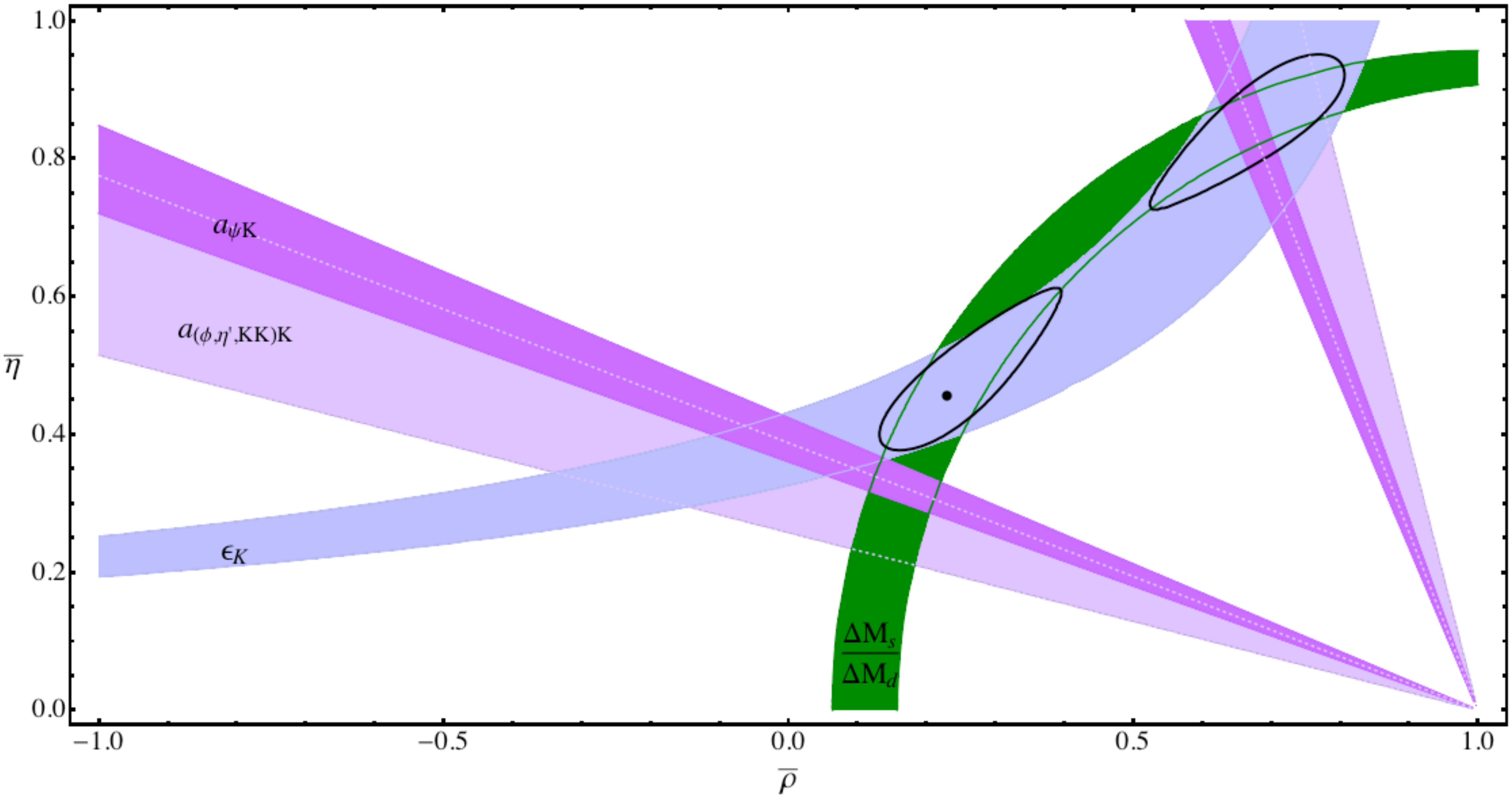
$$V_{ub} = (37.0 \pm 3.2) \times 10^{-4}$$

Still some confusion remains....



Extraction of sin(2β) without using |V_{ub}|

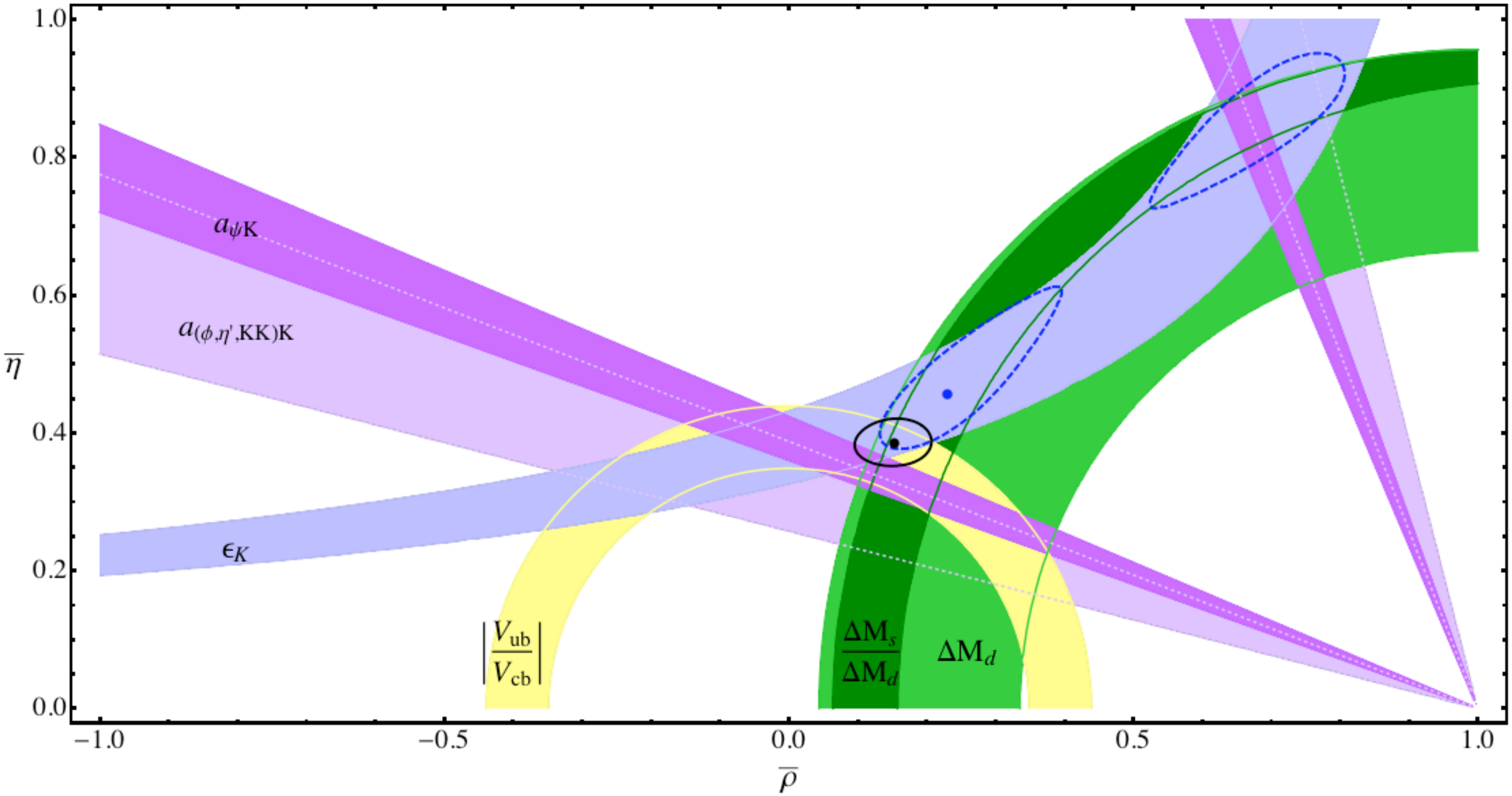
[Lunghi, Soni]



$$[\sin(2\beta)]^{\text{prediction}}_{\text{no } V_{ub}} = 0.87 \pm 0.09$$

Extraction of sin(2β) with $|V_{ub}|$

[Lunghi, Soni]



$$[\sin(2\beta)]^{\text{prediction}}_{\text{full fit}} = 0.75 \pm 0.04$$

Direct vs indirect sin(2β)

mode	experiment	no V_{ub} 0.87 ± 0.09	with V_{ub} 0.75 ± 0.04
$a_{\psi K_S}$	0.681 ± 0.025	$2.1\ \sigma$	$1.7\ \sigma$
$a_{\phi K_S}$	0.39 ± 0.17	$2.5\ \sigma$	$2.1\ \sigma$
$a_{\eta' K_S}$	0.61 ± 0.07	$2.3\ \sigma$	$1.8\ \sigma$
$a_{(\phi+\eta')K_S}$	0.58 ± 0.06	$2.7\ \sigma$	$2.5\ \sigma$

- Discrepancies do not depend critically on the inclusion of V_{ub}
- Our V_{ub} independent result points towards new physics phases in the B_d system (both in *B* mixing and in $b \to s\bar{s}s$ amplitudes)

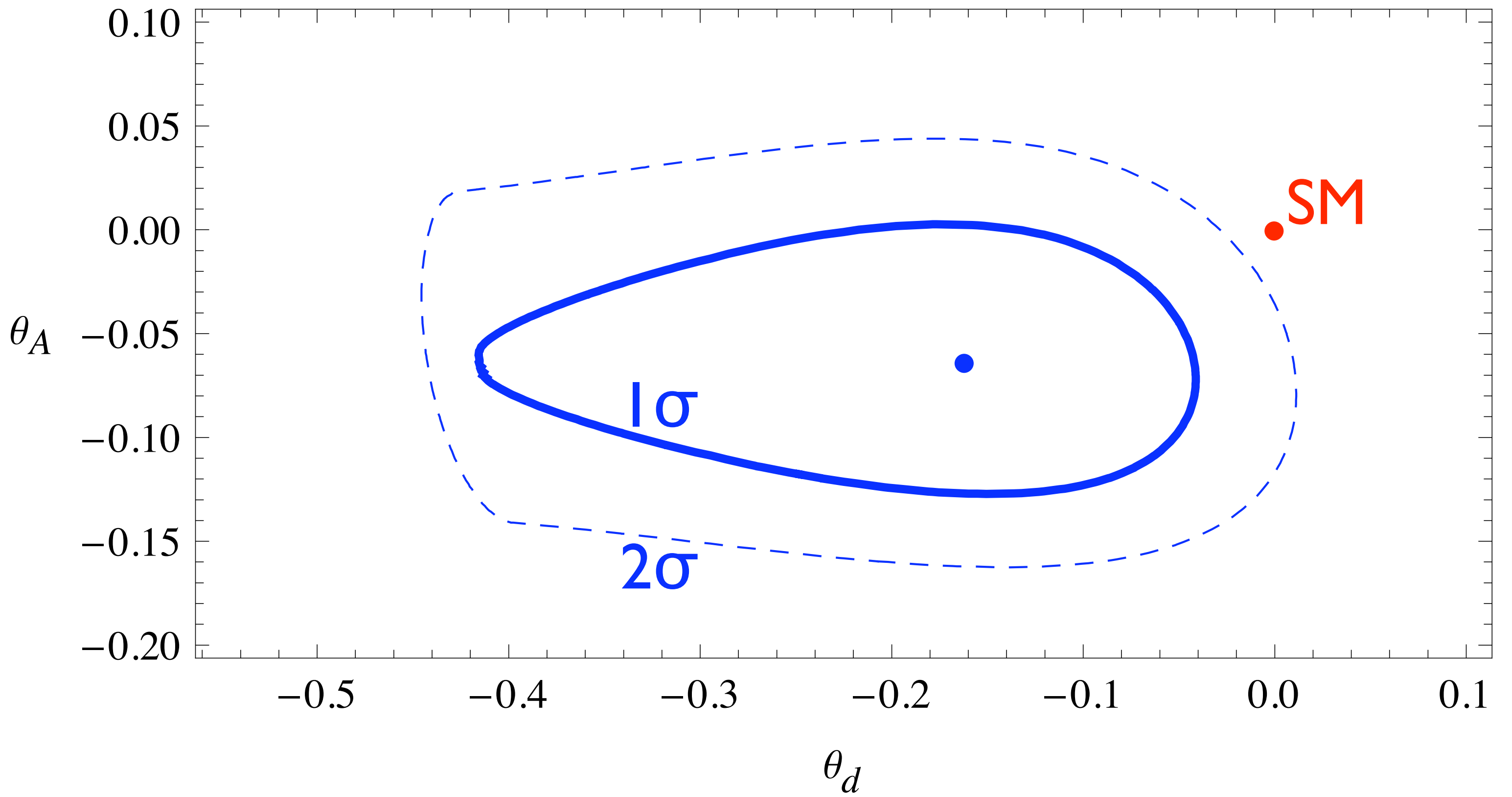
Assuming no new physics in ε_K and $\Delta M_{B_s}/\Delta M_{B_d}$:

$$
\begin{aligned}
a_{c\bar{c}s} &= \sin 2(\beta + \theta_d) \\
a_{s\bar{s}s} &= \sin 2(\beta + \theta_d + \theta_A)
\end{aligned}
$$

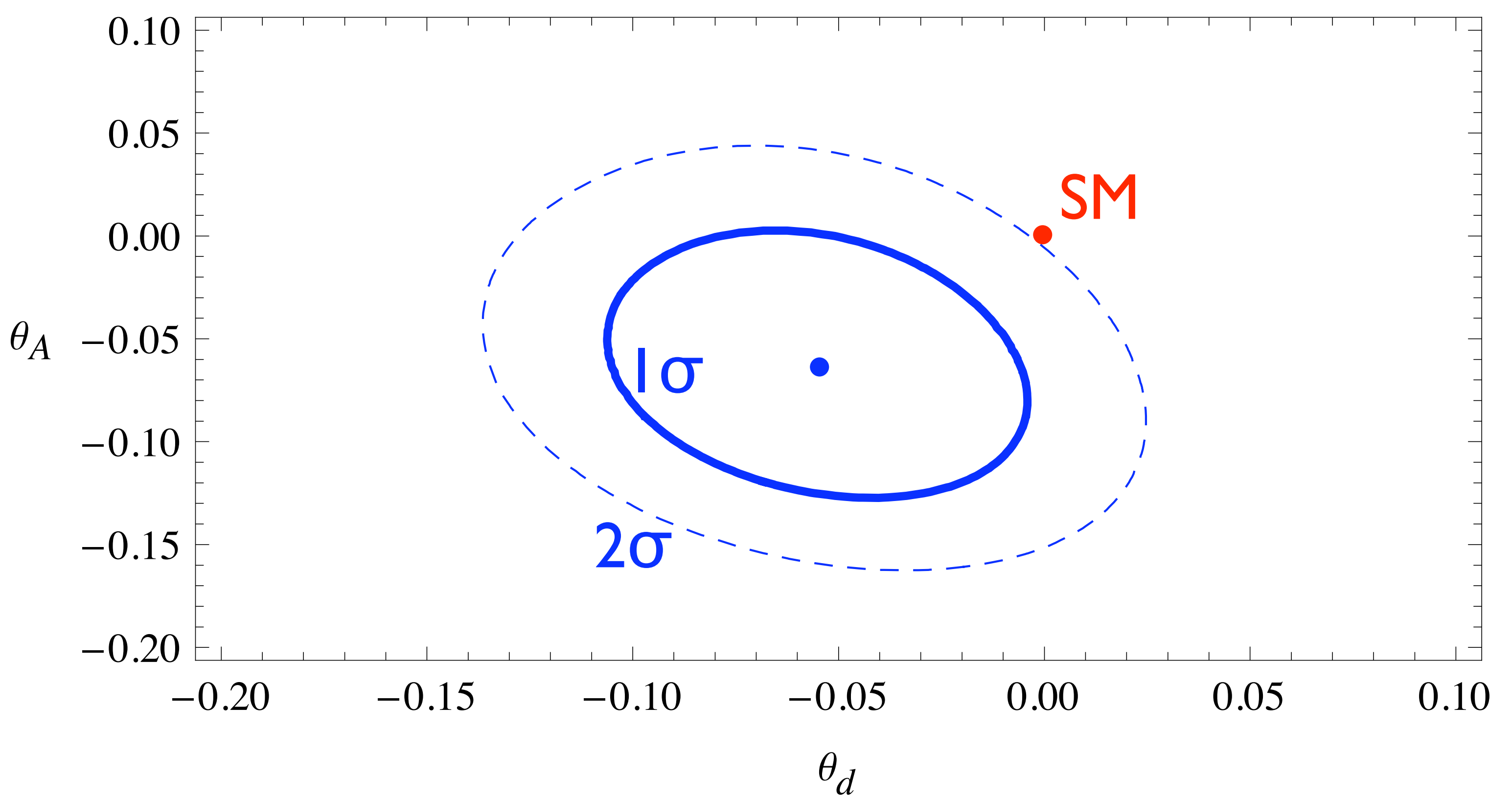
From the UT fit one finds:

$$
\begin{aligned}
\theta_A &= -0.06 \pm 0.04 = -(3.4 \pm 2.3)^{\text{o}} \\
\theta_d &= \begin{cases} -\left(0.16^{+0.12}_{-0.08}\right) = -\left(9.2^{+6.9}_{-4.6}\right)^{\text{o}} & \text{no } V_{ub} \\ -(0.055 \pm 0.03) = -(3.2 \pm 1.7)^{\text{o}} & \text{with } V_{ub} \end{cases}
\end{aligned}
$$

$\theta_d < 0$ at 95% C.L.



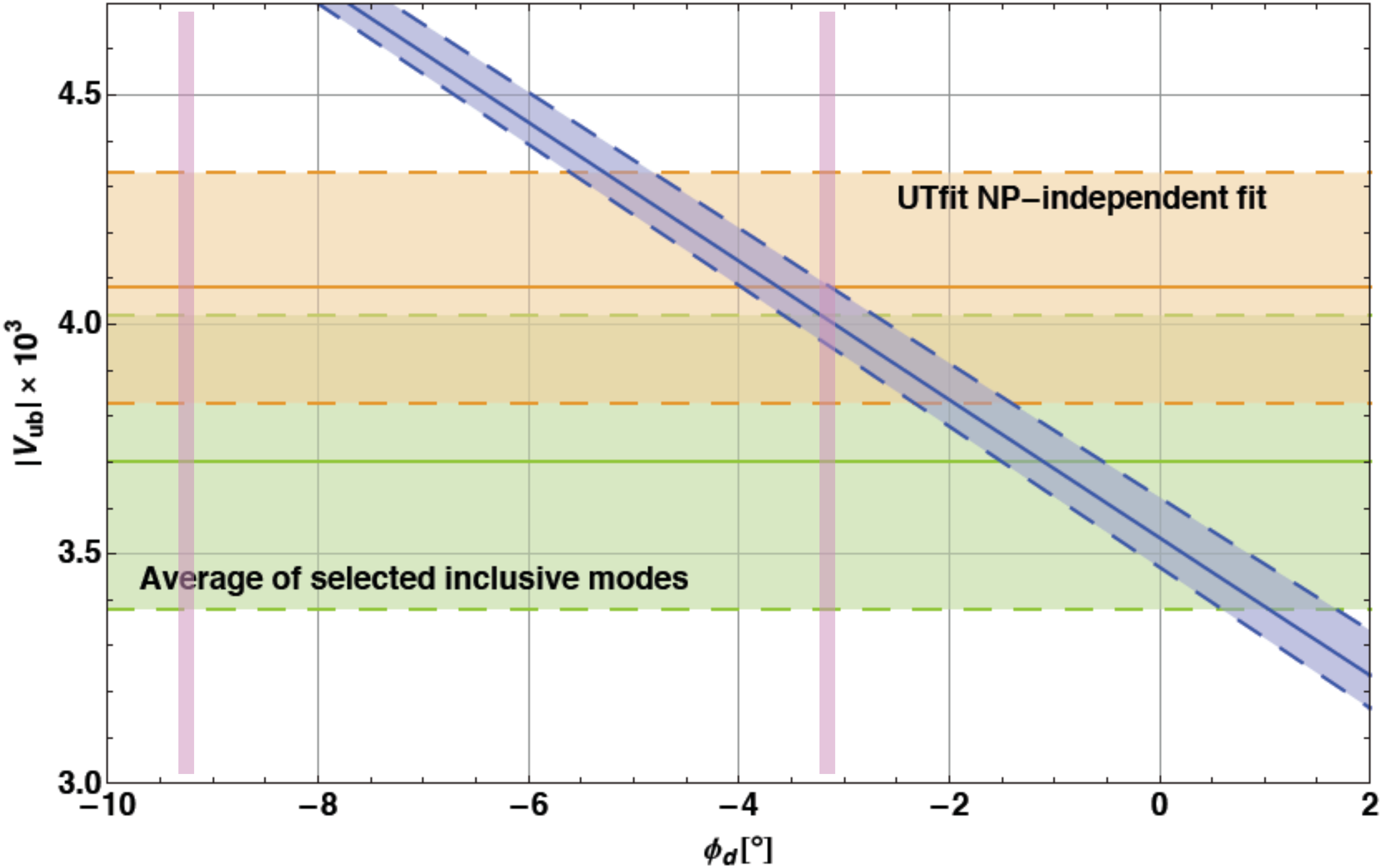
no V_{ub}



with V_{ub}

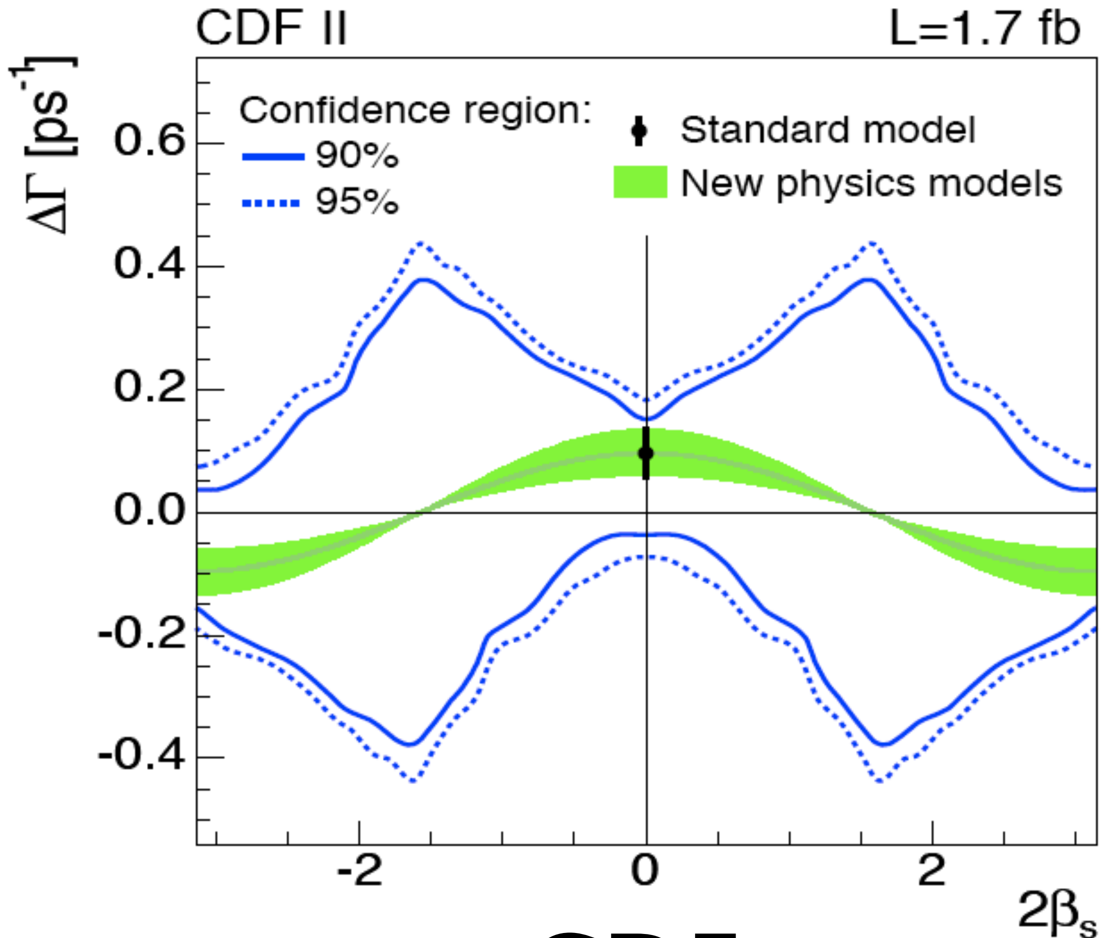
Compatibility check: V_{ub}

[Buras, Guadagnoli]

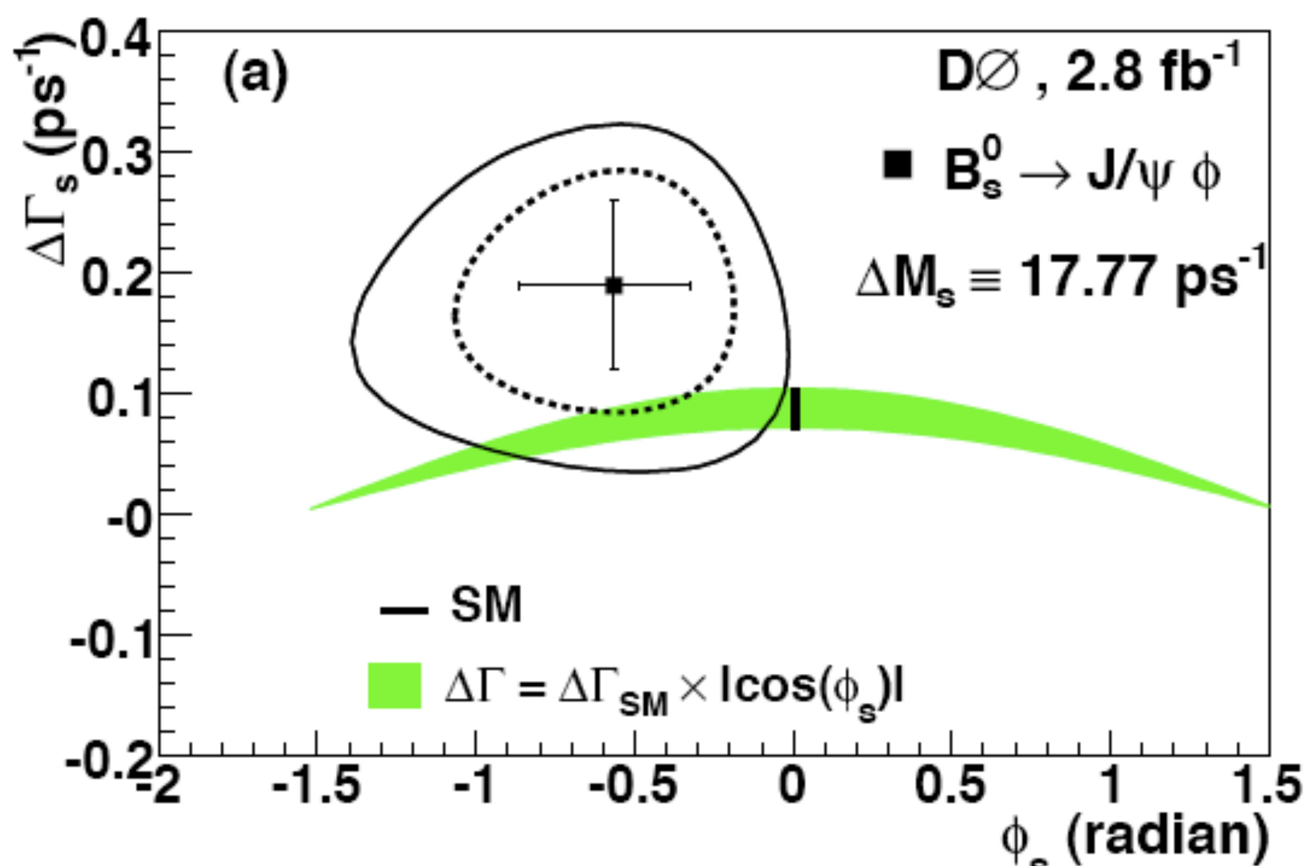


New physics in B_s mixing?

- Recent CDF and D0 measurements of mixing induced CP violation in $B \to J/\psi\phi$ point towards a sizable phase in the B_s mixing amplitude



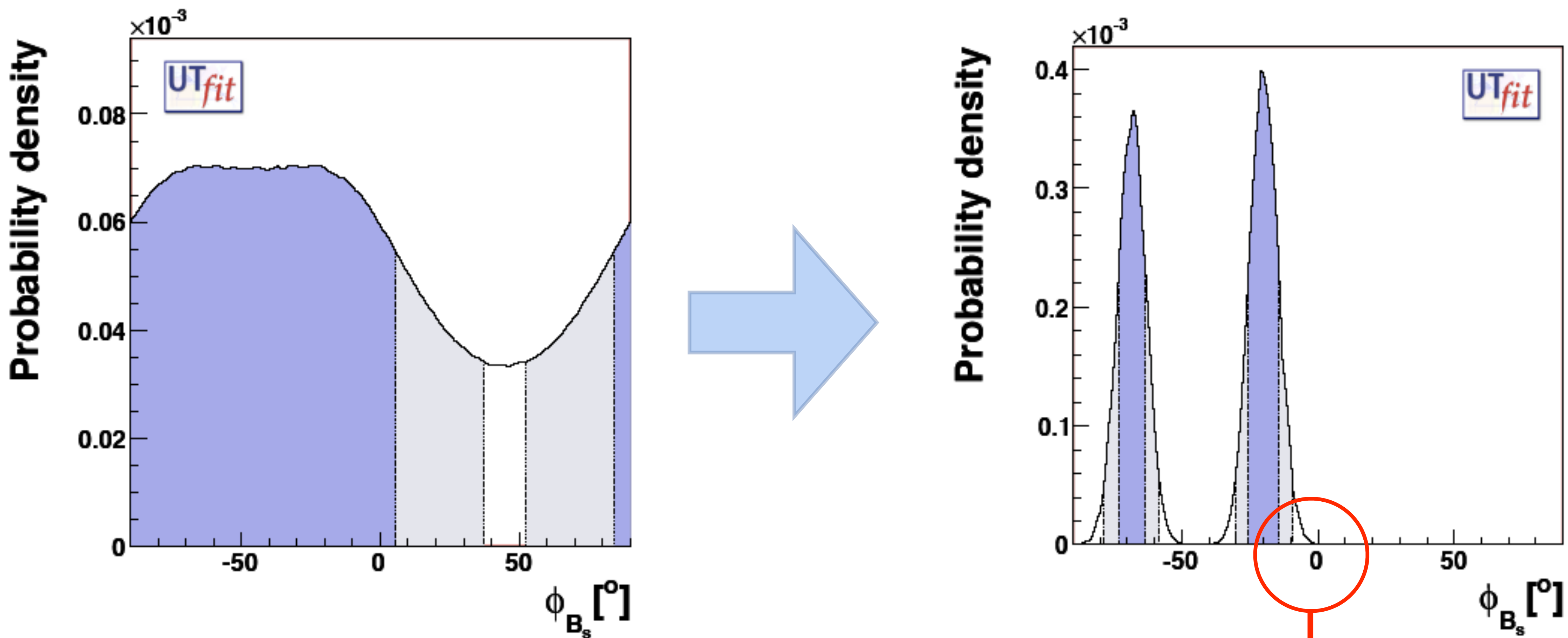
CDF



D0

New physics in B_s mixing?

- UTfit *attempted* a first combination of all data
- ***Issue***: D0 invokes SU(3) to relate strong phases in the K* and Φ final states. This is *wrong* because of the singlet component in Φ.



$\neq 0$ at 3.7σ

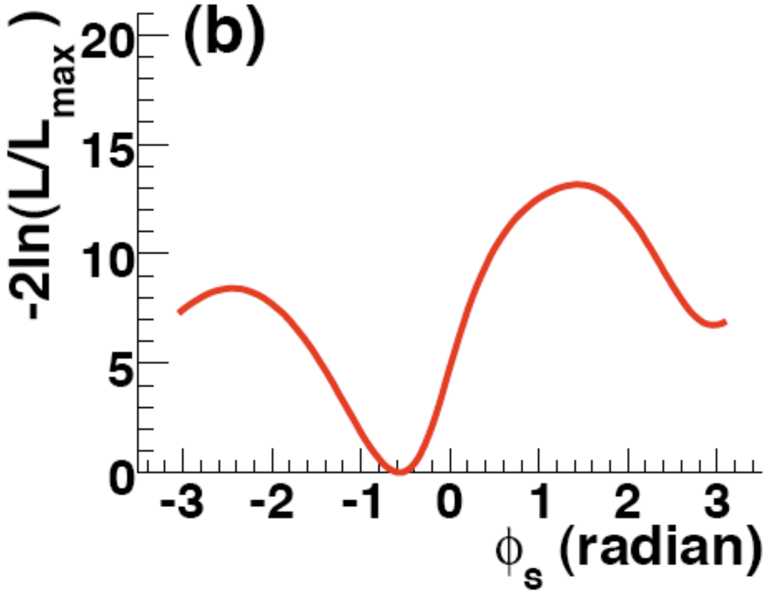
New physics in B_s mixing?

- Statistical approach of UTfit is questionable
- The assumption of gaussian D0 errors leads to:

$$\phi_{B_s} \equiv \phi_s + \beta_s = \begin{cases} (-19.9 \pm 5.6)^{\mathrm{o}} \\ (-68.2 \pm 4.9)^{\mathrm{o}} \end{cases}$$

- Using the original D0 likelihood, they obtain:

$$-88^{\mathrm{o}} < \phi_{B_s} < 0^{\mathrm{o}} \;\; \text{at } 3\ \sigma$$



- HFAG combination to appear soon

B_s-B_d connection

- In many NP models corrections to the B_d and B_s amplitudes are identical:

$$(M_{12})_q = (M_{12})_q^{\rm SM} \; r^2 \; e^{i2\phi}$$

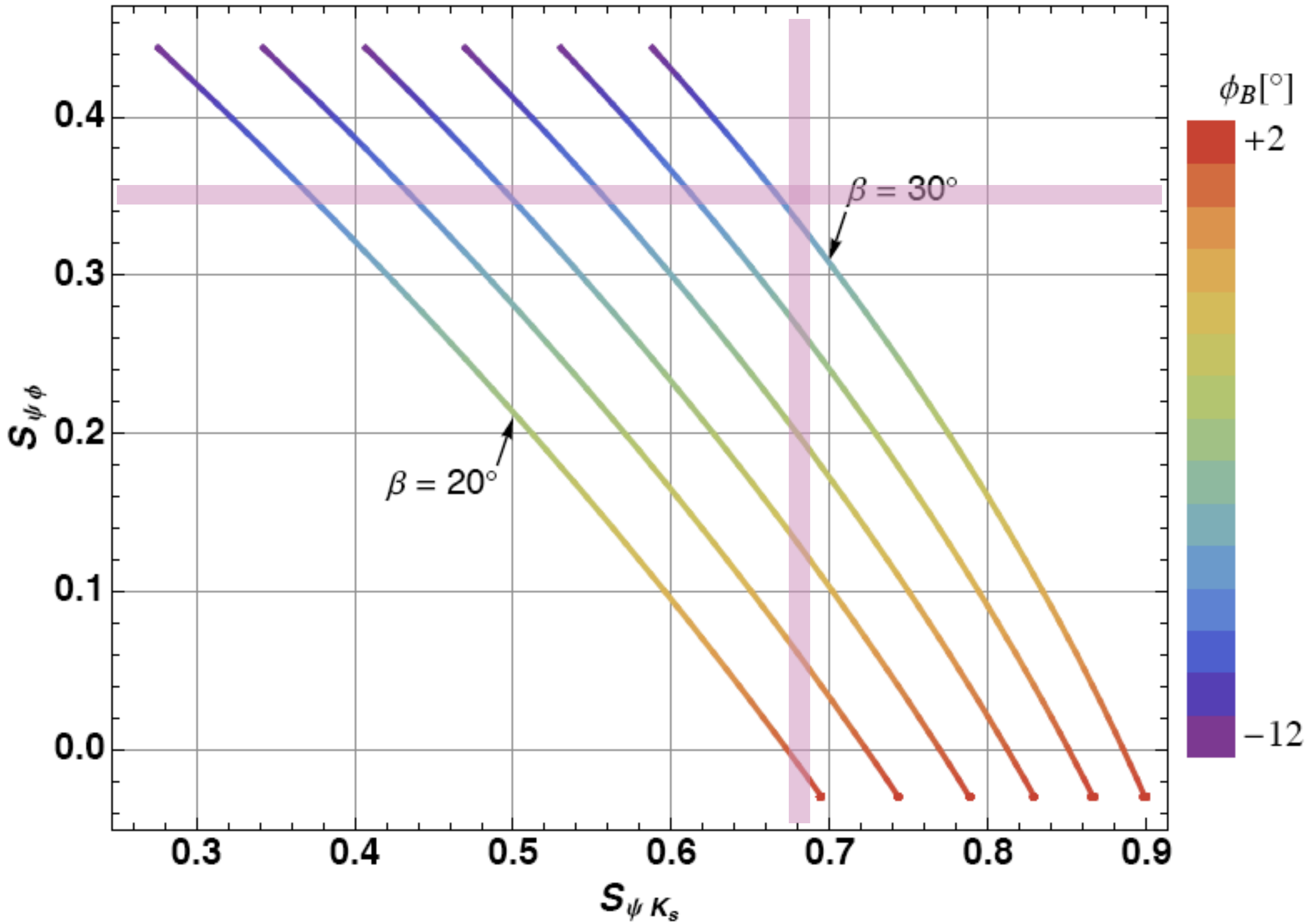
- In this case we have:

$$\phi_d = \phi_s \sim -9^{\rm o} \Longrightarrow \left\{ \begin{array}{c} \sin(2\beta) \simeq 0.87 \\ a_{\psi K} \simeq 0.68 \\ a_{\psi\phi} \simeq -0.36 \end{array} \right.$$

- As a consequence one would expect a large V_{ub}

B_s-B_d connection

[Buras,Guadagnoli]



CP asymmetries in B→Kπ

- Experiment:
$$\begin{aligned} A_{CP}(B^- \to K^-\pi^0) &= (5.0 \pm 2.5)\,\% \\ A_{CP}(\bar{B}^0 \to K^-\pi^+) &= (-9.7 \pm 1.2)\,\% \\ (\Delta A_{CP})_{\rm exp} &= (14.7 \pm 2.8)\% \end{aligned}$$

- In QCD factorization one gets:

$$\begin{aligned} A_{CP}(B^- \to K^-\pi^0) &= \left(7.1^{+1.7+2.0+0.8+9.0}_{-1.8-2.0-0.6-9.7}\right)\% \\ A_{CP}(\bar{B}^0 \to K^-\pi^+) &= \left(4.5^{+1.1+2.2+0.5+8.7}_{-1.1-2.5-0.6-9.5}\right)\%\,, \end{aligned}$$

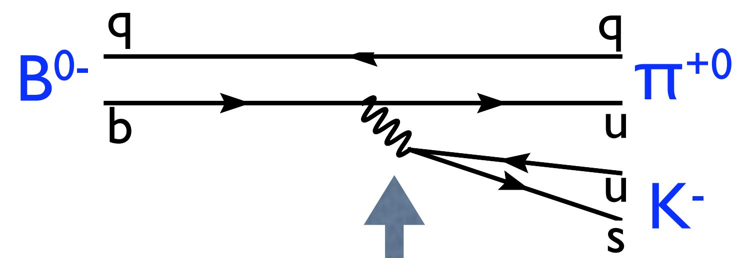
$$(\Delta A_{CP})_{\rm th} = (2.1 \pm 1.6)\%$$

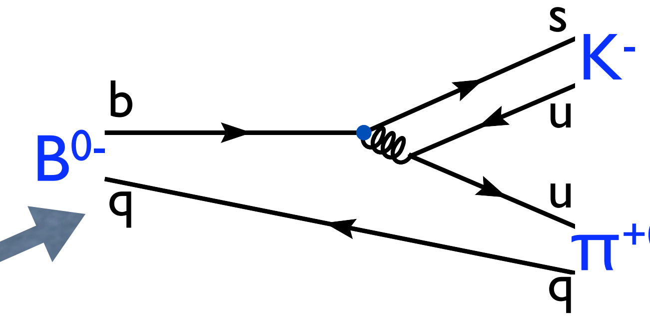
- Difference:

$$(\Delta A_{CP})_{\rm exp} - (\Delta A_{CP})_{\rm th} = 12.6 \pm 3.2 \Longrightarrow 3.9\ \sigma$$

CP asymmetries in B→Kπ

- Amplitudes in QCD factorization:

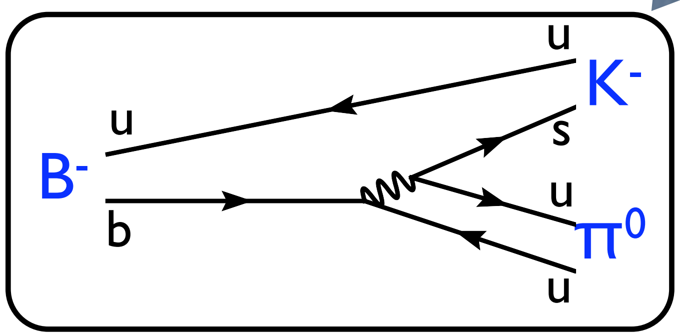


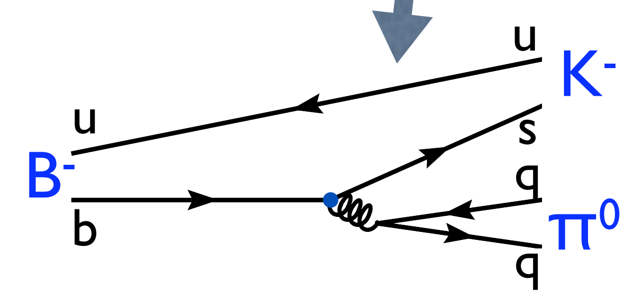


$$\mathcal{A}_{\bar B^0\to\pi^+K^-} = A_{\pi\bar K}\sum_{p=u,c}\lambda_p^{(s)}\left[\delta_{pu}\alpha_1+\hat\alpha_4^p\right]$$

$$\sqrt{2}\mathcal{A}_{B^-\to\pi^0K^-} = \mathcal{A}_{\bar B^0\to\pi^+K^-} + A_{\bar K\pi}\sum_{p=u,c}\lambda_p^{(s)}\left[\delta_{pu}\alpha_2+\delta_{pc}\frac{3}{2}\alpha^c_{3,EW}\right]$$

color suppressed ←
[Gronau,Rosner]





- NP contributions to the QCD and EW penguin
- Correlation between B→Kπ and B→(Φ,η')K$_S$

Possible New Physics scenario

- V_{ub} turns out to be large (4.4×10^{-4})
- V_{cb}, V_{ub}, ε_K and $\Delta M_{Bs}/\Delta M_{Bd}$ determine $\sin(2\beta) \sim 0.87$
- The difference between $\sin(2\beta)$ and the CP asymmetry in $B \rightarrow J/\psi K_S$ is due to a universal new physics contribution that is also responsible for generating $\phi_s \sim -9°$
- The difference between the asymmetries in the $(\phi, \eta')K_S$ and $J/\psi K_S$ modes is due to additional NP contributions to the QCD and EW penguins
- These effects also explain the $B \rightarrow K\pi$ puzzle

New Physics in the second generation?

- The width for $D_s \to \ell\nu$ in the SM is

$$\Gamma(D_s \to \ell\nu) = \frac{m_{D_s}}{8\pi} \left|G_F V_{cs}^* m_\ell\right| f_{D_s}^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2$$

- f_{Ds} is *extracted from data* and *lattice-QCD*:

$$\begin{aligned} (f_{D_s})_{\rm exp} &= (269.6 \pm 8.3)\ \mathrm{MeV} \quad \text{[CLEO, BaBar, Belle]} \\ (f_{D_s})_{\rm QCD} &= (241 \pm 3)\ \mathrm{MeV} \quad \text{[HPQCD]} \end{aligned}$$

- Same effect in $\mu\nu$ and $\tau\nu$ final states

- The discrepancy is at the 3.2 σ level

- Independent cross check of the lattice result needed

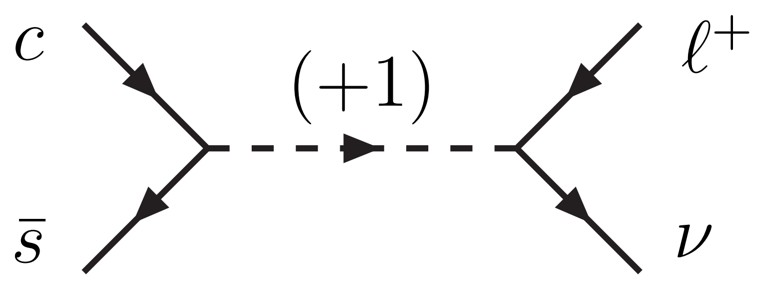
New Physics in the second generation?

- $$\frac{C_A^\ell}{M^2}\,(\bar{s}\gamma_\mu\gamma_5 c)\,(\bar{\nu}_L\gamma^\mu\ell_L) + \frac{C_P^\ell}{M^2}\,(\bar{s}\gamma_5 c)\,(\bar{\nu}_L\ell_R)$$

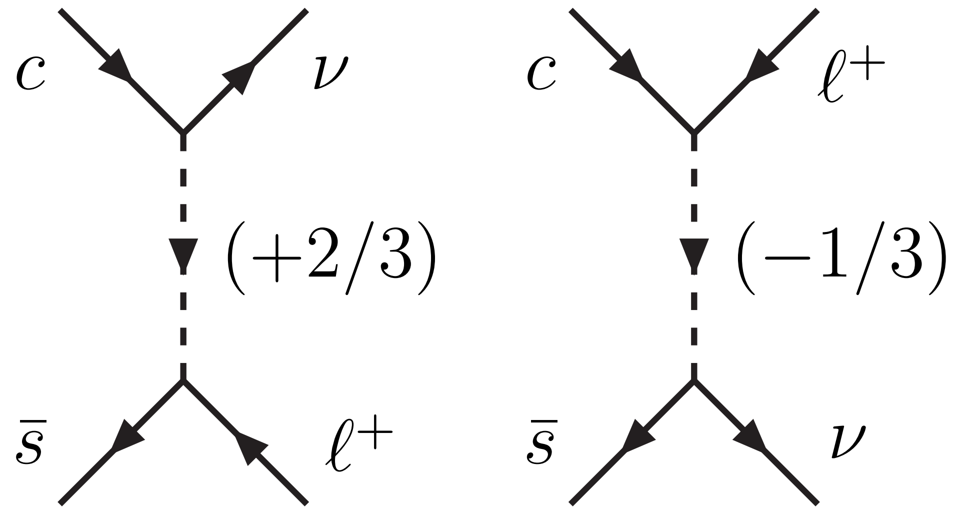
$$\frac{M}{(\mathrm{Re}\,C_A^\ell)^{1/2}} \gtrsim \begin{cases} 710\ \mathrm{GeV} & \text{for } \ell=\tau \\ 850\ \mathrm{GeV} & \text{for } \ell=\mu \end{cases}$$

$$\frac{M}{(\mathrm{Re}\,C_P^\ell)^{1/2}} \gtrsim \begin{cases} 920\ \mathrm{GeV} & \text{for } \ell=\tau \\ 4500\ \mathrm{GeV} & \text{for } \ell=\mu \end{cases}$$

- Explicit models are exotic:



Charged Higgs
(favored)



Leptoquarks

[Dobrescu, Kronfeld]

Conclusions

- Our theoretical understanding of QCD issues related to the UT analysis has improved dramatically (lattice-QCD, perturbative and non-perturbative effects)
- *Large* new physics effects are hinted by:
  - ★ UT fit (new lattice-QCD results)
  - ★ CP asymmetries in $b \to sss$ modes
  - ★ Model independent analyses of $B \to \psi\phi$
  - ★ $D_s \to l\nu$, asymmetries in $B \to K^{*}\mu\mu$, $(g-2)_\mu$
- Key role of V_{ub}
- We might be on the brink of discovery New Physics!