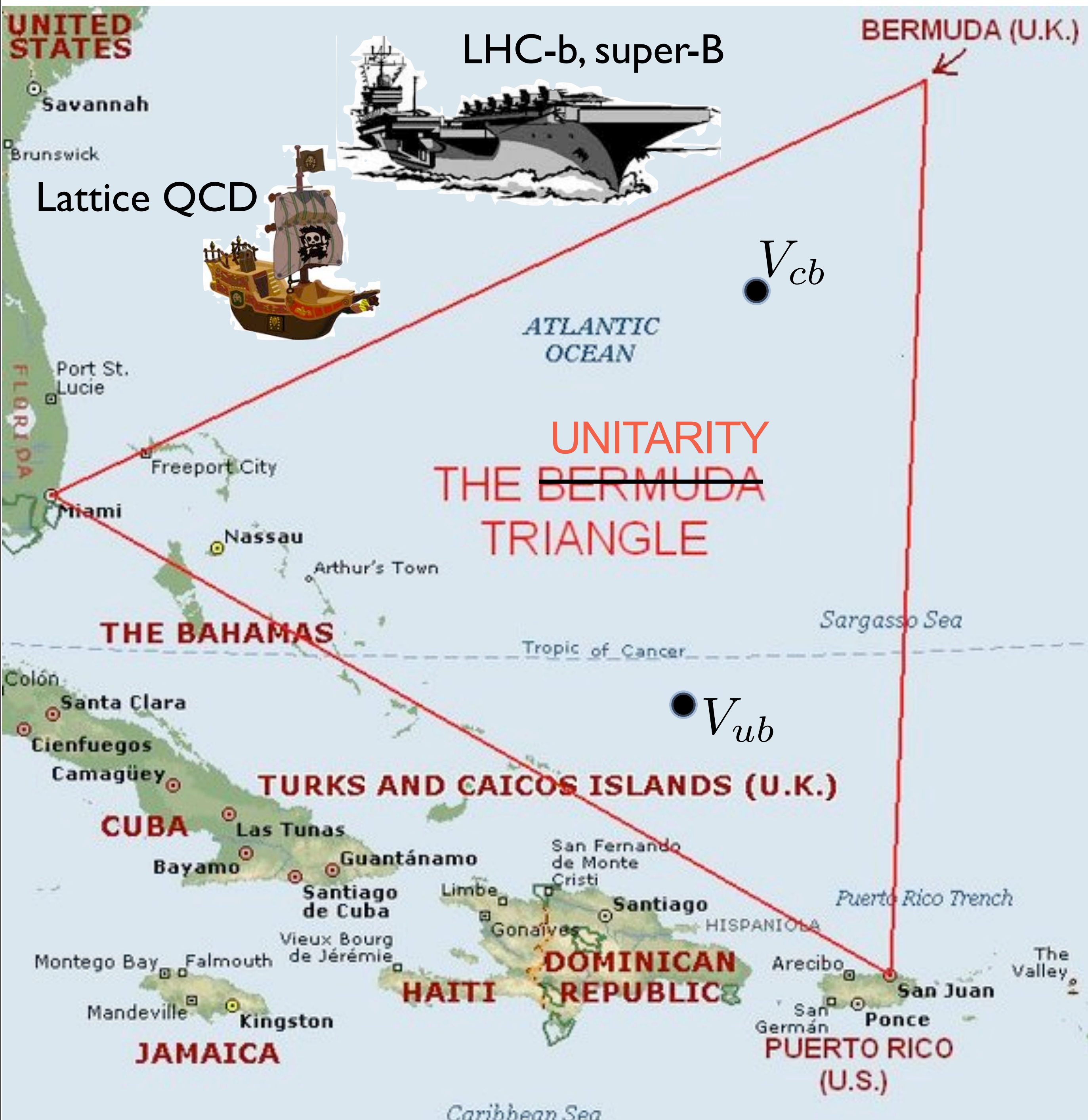

Lessons for New Physics from CKM studies

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Indiana University

E.L. and A. Soni, *0707.0212*
E.L. and A. Soni, *0803.4340*
E.L. and A. Soni, *0903.5059*
J. Laiho, E.L., R. Van de Water: 0910.2928
E.L. and A. Soni, *0912.0002*
E.L. and A. Soni, *1010.6069*
J. Laiho, E.L., R. Van de Water: 1102.3917
www.latticeaverages.org

The Cabibbo✷-Kobayashi★-Maskawa★ matrix

Gauge interactions do not violate flavor:

$$\mathcal{L}_{\text{Gauge}} = \sum_{\psi,a,b} \bar{\psi}_a (i\partial\!\!\!/ - gA\!\!\!/\, \delta^{ab})\psi_b$$

Yukawa interactions (mass) violate flavor:

$$\mathcal{L}_{\text{Yukawa}} = \sum_{\psi,a,b} \bar{\psi}_{La}\, H\, Y^{ab} \psi_{Rb} = \bar{Q}_L H Y_U u_R + \bar{Q}_L H Y_D d_R + \bar{L}_L H Y_E E_R$$

The Yukawas are complex 3x3 matrices:

$$\boxed{Y_U = U_L Y_U^{\text{diag}} U_R, \quad Y_D = D_L Y_D^{\text{diag}} D_R, \quad Y_E = E_L Y_E^{\text{diag}} E_R}$$

huge potential for NP effects (MFV?)

From *Gauge* to *Mass* eigenstates

- neutral currents:

$$\bar{u}_L^0 Z\!\!\!/\, u_L^0 \Longrightarrow \bar{u}_L Z\!\!\!/\, U_L U_L^\dagger u_L = \bar{u}_L Z\!\!\!/\, u_L$$

- charged currents:

$$\bar{u}_L^0 W\!\!\!\!/\, d_L^0 \Longrightarrow \bar{u}_L W\!\!\!\!/\, U_L D_L^\dagger d_L = \bar{u}_L W\!\!\!\!/\, V_{\text{CKM}} d_L$$

✷ = Virtual Nobel Laureate
★ = Real Nobel Laureate

The Cabibbo✹-Kobayashi★-Maskawa★ matrix

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}, ...)

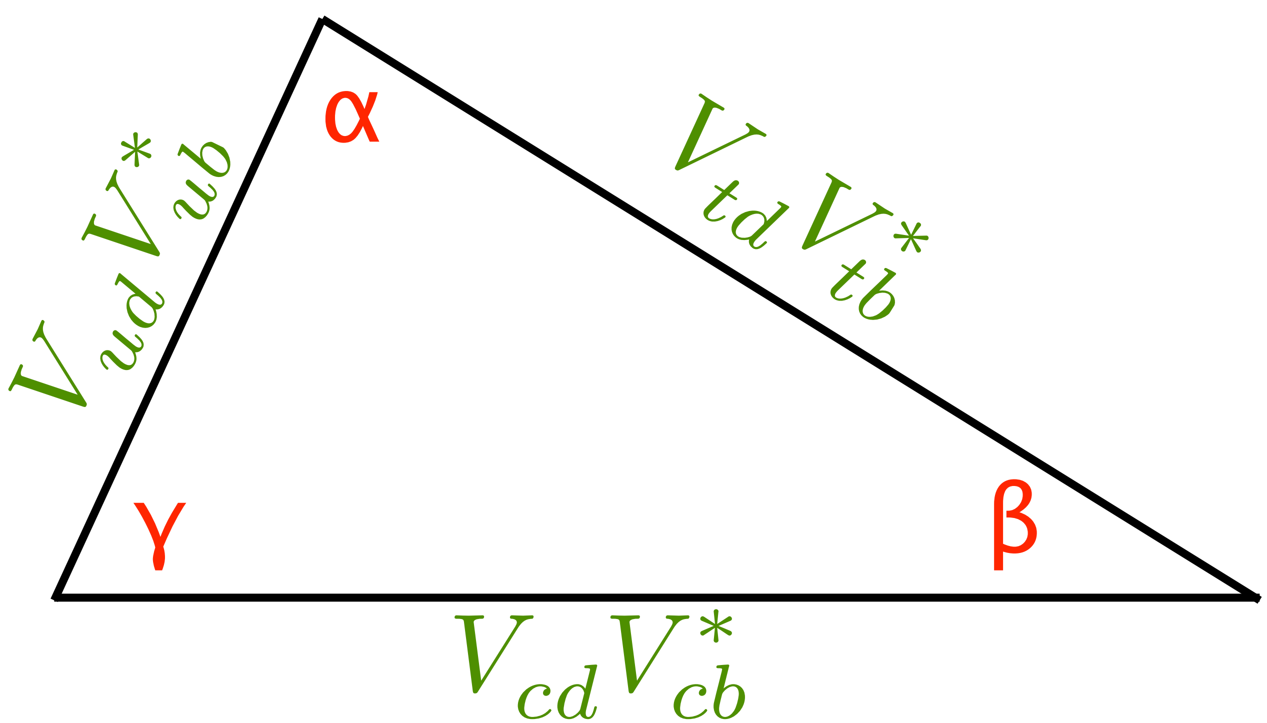
ρ,η: no direct meas. (ΔM_{Bd}, CP violation, K mixing)

Wolfenstein parametrization:
$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

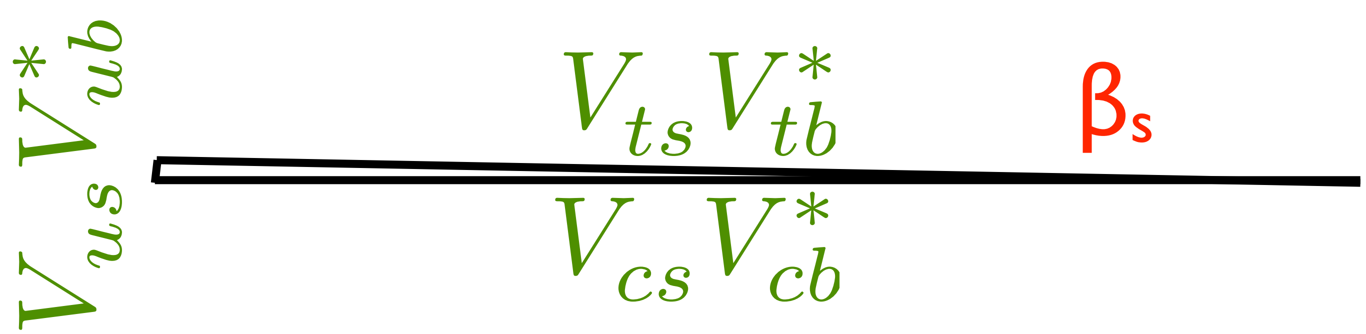
✹ = Virtual Nobel Laureate
★ = Real Nobel Laureate

The Cabibbo✹-Kobayashi★-Maskawa★ matrix

Unitarity Triangles:

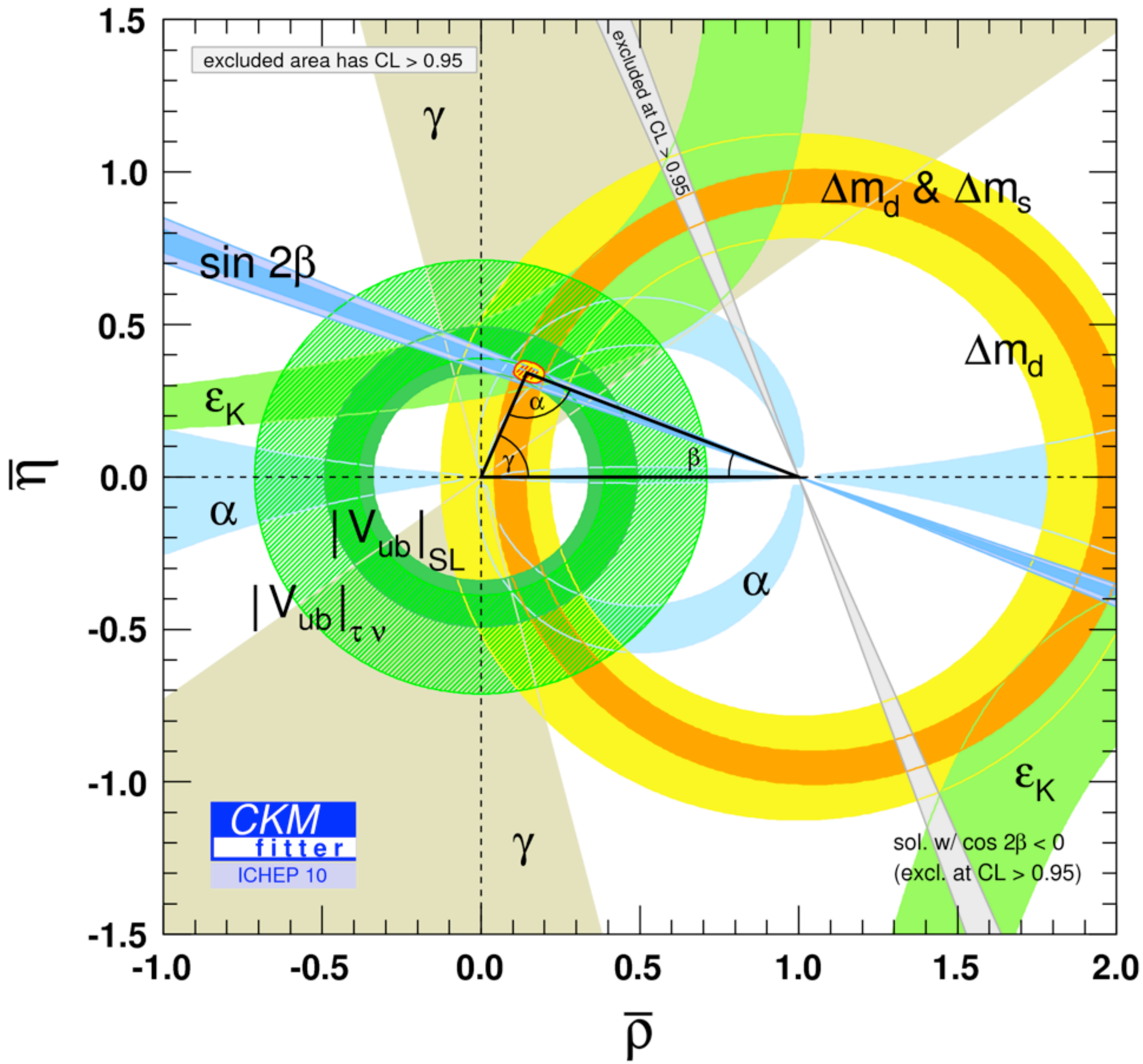


$$V_{td} = |V_{td}|\ e^{-i\beta}$$
$$V_{ub} = |V_{ub}|\ e^{-i\gamma}$$



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

The Unitarity Triangle Fit



ε_K: CP violation in K mixing

α: time dependent A_{CP} in $B\rightarrow(\pi\pi,\rho\rho,\rho\pi)$ modes (*large penguin pollution removed with isospin analysis*)

β: time dependent A_{CP} in $B\rightarrow J/\psi\, K$ and related modes (*very clean*)

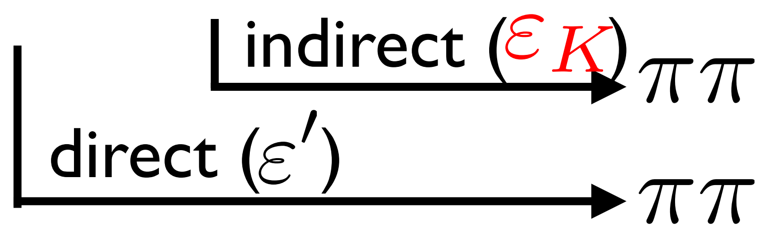
γ: $B\rightarrow D^{(*)}K^{(*)}$ decays (*model independent studies - separation of D-meson flavor and CP eigenstates*)

The Unitarity Triangle Fit

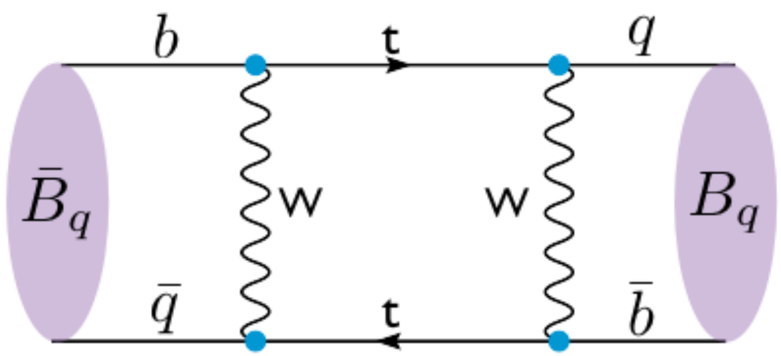
- Mass and CP eigenstates of K mesons differ:

$$\begin{cases} K_S & \sim K_1 + \bar{\varepsilon} K_2 \\ K_L & \sim K_2 + \bar{\varepsilon} K_1 \end{cases}$$

$$K_L \sim K_2 + \bar{\varepsilon} K_1$$

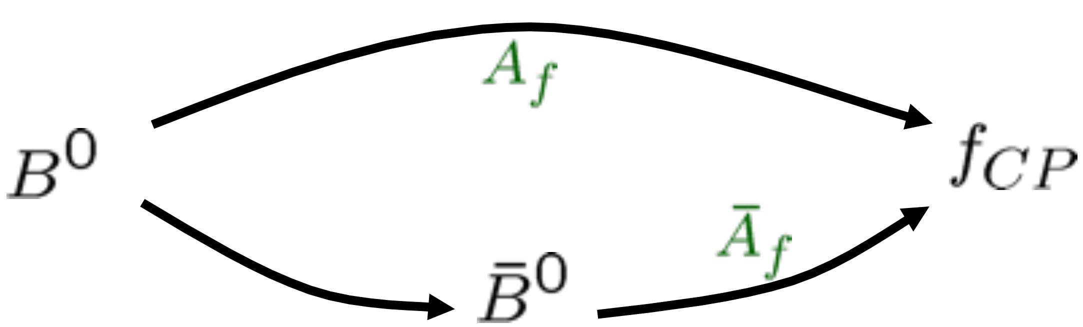


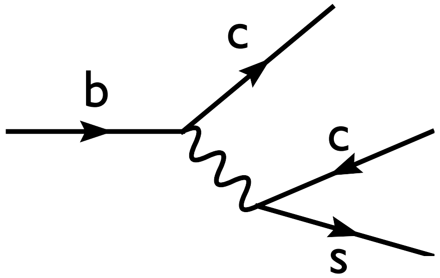
- $B - \bar{B}$ mass difference:



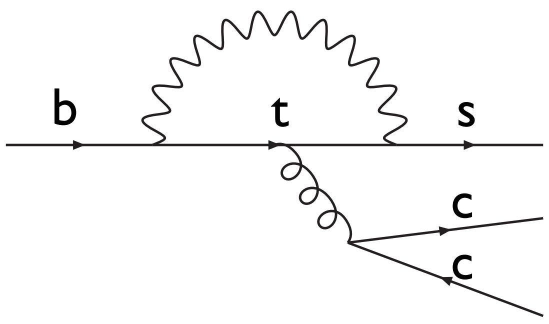
$$\propto \left(V_{tb} V_{tq}^*\right)^2 \; f_{B_q}^2 \hat{B}_q$$

- Time dependent CP asymmetries: $\Gamma(\bar{B}^0_{\rm phys}(t) \to f_{CP}) \neq \Gamma(B^0_{\rm phys}(t) \to f_{CP})$





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



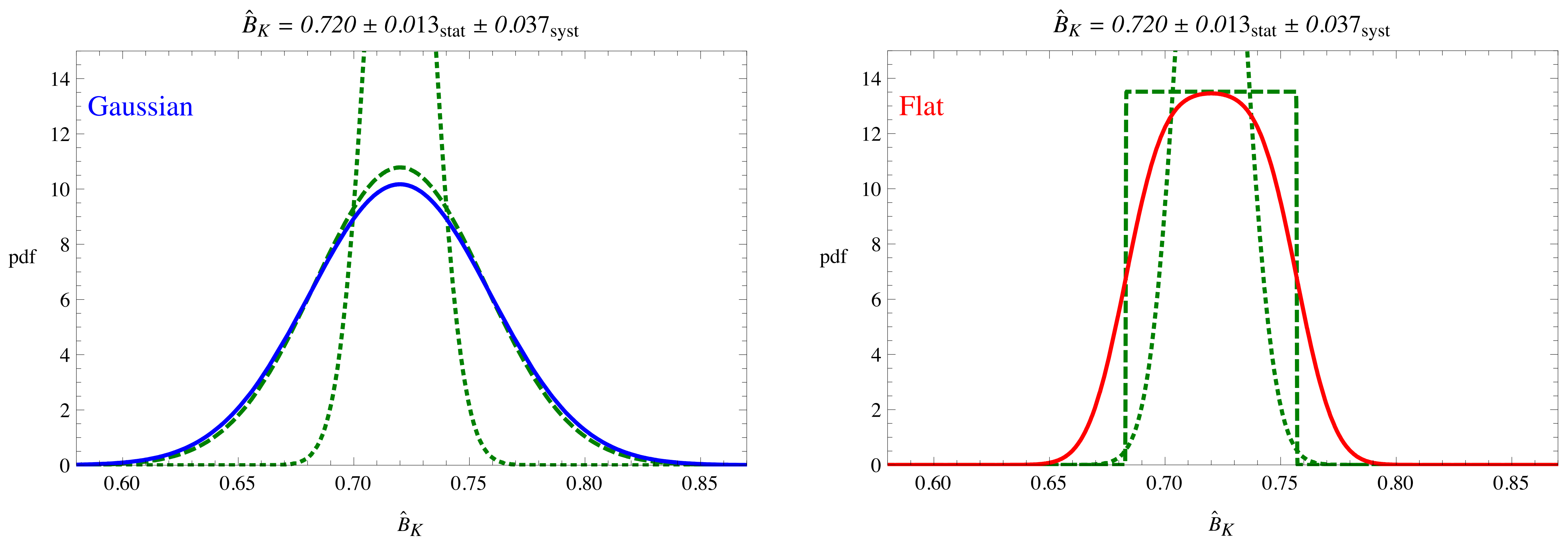
$V_{tb} V_{ts}^* = -V_{cb} V_{cs}^* - V_{ub} V_{us}^*$

Treatment of lattice inputs and errors

- Lattice QCD presently delivers *2+1 flavors* determinations *for all the quantities* that enter the fit to the UT
- Results from different lattice collaborations are often correlated
  - MILC gauge configurations: f_{Bd}, f_{Bs}, ξ, V_{ub}, V_{cb}, f_K
  - use of the same theoretical tools: B_K, V_{cb}
  - experimental data: V_{ub}
- It becomes important to take these correlation into account when combining saveral lattice results [Laiho,EL,Van de Water, 0910.2928 Laiho,EL,Van de Water, 1102.3917]
- We assume all errors to be normally distributed
- Updated averages at: http://www.latticeaverages.org

Comments on systematic uncertainties

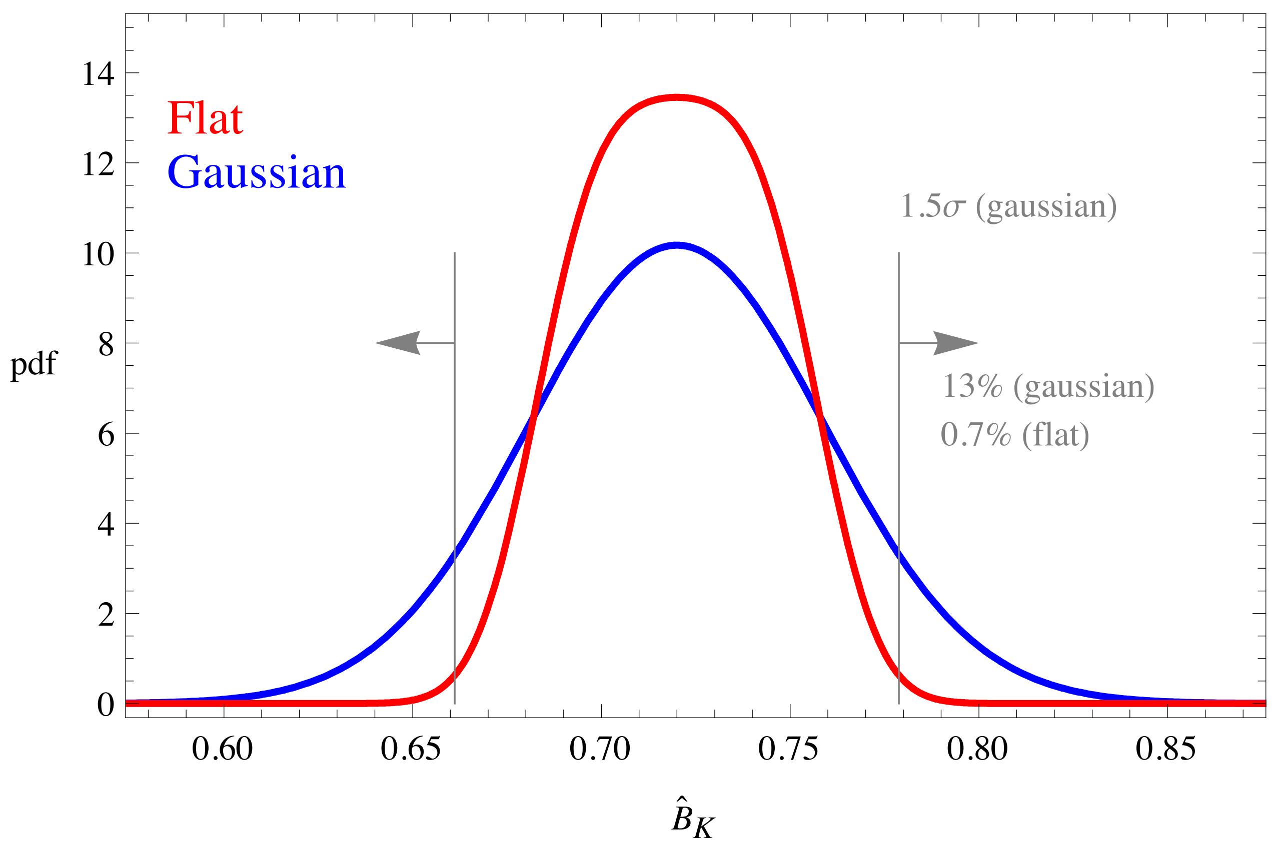
- We treat all systematic uncertainties as gaussian
- Most relevant systematic errors come from lattice QCD (B_K,ξ) and are obtained by adding in quadrature several different sources of uncertainty
- Gaussian treatment seems a fairly conservative choice



Comments on systematic uncertainties

- We treat all systematic uncertainties as gaussian
- Most relevant systematic errors come from lattice QCD (B_K,ξ) and are obtained by adding in quadrature several different sources of uncertainty
- Gaussian treatment seems a fairly conservative choice

$\hat{B}_K = 0.720 \pm 0.013_{\rm stat} \pm 0.037_{\rm syst}$



Determining A

- Can be extracted by tree-level processes ($b \to c l \nu$)

- ΔM_{B_s} is conventionally used only to normalize ΔM_{B_d} but it should be noted that it provides an independent determination of *A* (that might be subject to NP effects):

$$\Delta M_{B_s} \propto f_{B_s}^2 \hat{B}_{B_s} A^2 \lambda^4$$

- Other processes are very sensitive to *A* but also display a strong ρ-η and NP dependence and are therefore usually discussed in the framework of a Unitarity Triangle fit:

$$|\varepsilon_K| \propto \hat{B}_K \, \kappa_\varepsilon \, A^4 \lambda^{10} \eta(\rho - 1)$$

$$\mathrm{BR}(B \to \tau\nu) \propto f_B^2 A^2 \lambda^6 (\rho^2 + \eta^2)$$

Note on ε_K (K mixing)

- Mass and CP eigenstates are different:

$$K_S \sim K_1 + \bar{\varepsilon} K_2 \qquad\qquad K_L \sim K_2 + \bar{\varepsilon} K_1$$

- K_L can decay into the CP even $(\pi\pi)_{I=0}$ final state through its tiny K_1 component:

$$\varepsilon_K = \frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})}$$

$$K_L \sim K_2 + \bar{\varepsilon} K_1$$

$$\bar{\varepsilon} K_1 \xrightarrow{\text{indirect }(\varepsilon)} \pi\pi \qquad K_2 \xrightarrow{\text{direct }(\varepsilon')} \pi\pi$$

Note on ε_K:

$$\varepsilon_K \quad = \quad \underbrace{e^{i\phi_\varepsilon} \sin\phi_\varepsilon \left(\frac{\mathrm{Im} M_{12}^K}{\Delta M_K} + \frac{\mathrm{Im} A_0}{\mathrm{Re} A_0} \right)}_{\kappa_\varepsilon}$$

from experiment

mostly short distance + χPT

long distance (use ε'/ε)

K mixing (ε_K)

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

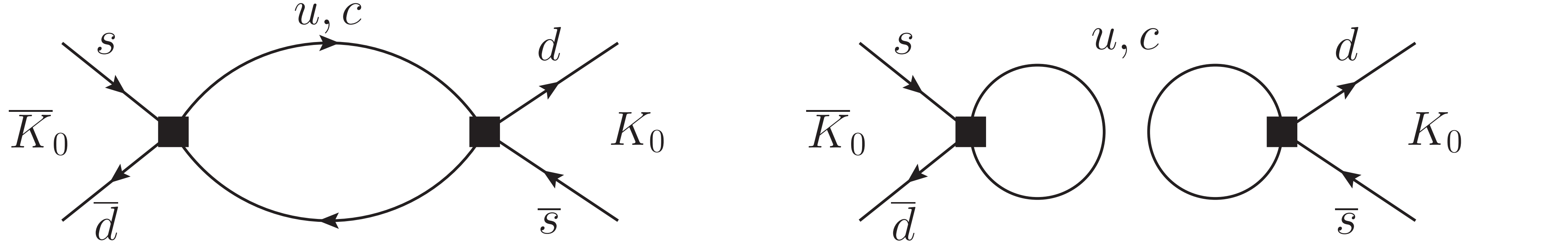
- Experimentally one has: $\phi_\varepsilon = (43.51 \pm 0.05)^o$
- ImA_0/ReA_0 can be extracted from experimental data on ε'/ε and theoretical calculation of isospin breaking corrections:
  - $\mathrm{Re}(\varepsilon'_K/\varepsilon_K)_{\mathrm{exp}} \sim \frac{\omega}{\sqrt{2}|\varepsilon_K|} \left(\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0} \right)$ [PDG]
  - $\mathrm{Im}A_2 = (-7.9 \pm 4.2) \times 10^{-13}$ GeV [RBC/UK-QCD] 1st unquenched attempt!
- Combining everything:

$$\kappa_\varepsilon = 0.92 \pm 0.01$$

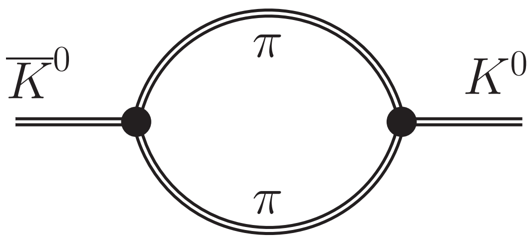
[Laiho,EL,Van de Water]

K mixing (ε_K)

- Buras, Guadagnoli & Isidori pointed out that also M_{12}^K receives non-local corrections with two insertions of the ΔS=1 Lagrangian:



- Using CHPT they obtain a conservative estimate of these effects. Combining the latter with our determination of ImA₀ we obtain:



$$\kappa_\varepsilon = 0.94 \pm 0.017$$

-6% !

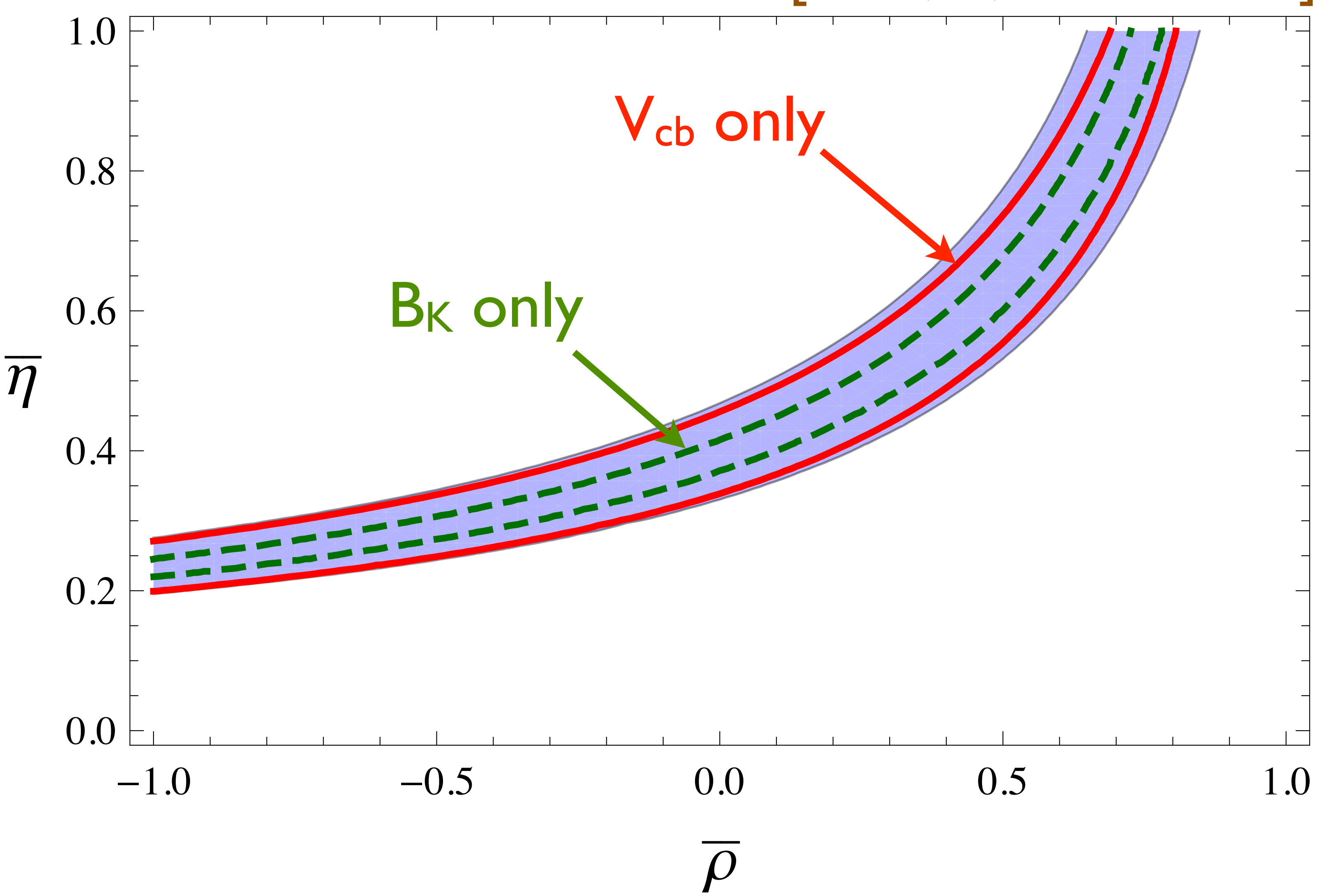
[Laiho,EL,Van de Water;
Buras, Guadagnoli, Isidori]

K mixing (ε_K)

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

- Error budget:

[Laiho,EL,van de Water]



All other uncertainties have negligible impact on the combined error

Central value of κ_ε is important

$B \to \tau\nu$

$$\mathrm{BR}(B \to \tau\nu) = \frac{G_F^2 m_\tau^2 m_{B^+}}{8\pi\Gamma_{B^+}} \left(1 - m_\tau^2/m_{B^+}^2\right)^2 \; f_B^2 \; |V_{ub}|^2$$

- Lattice inputs: $\hat{B}_d,\ \xi,\ f_{B_s}\sqrt{\hat{B}_s} \quad \Longrightarrow \quad f_{B_d} = \frac{f_{B_s}\hat{B}_s^{1/2}}{\xi \hat{B}_d}$
  - ***Using f_B directly is not recommended because of the large correlation between f_B and ξ***
  - ***As a consistency check we can compare direct and indirect determinations of f_B***
- Babar and Belle published measurements using semileptonic and hadronic tags (to reconstruct the recoiling B meson):

$$\mathrm{BR}(B \to \tau\nu)_{\mathrm{exp}} = (1.68 \pm 0.31) \times 10^{-6}$$

- In NP models with a charged Higgs (2HDM, MSSM,..):

$$\mathrm{BR}(B \to \tau\nu)^{\mathrm{NP}} = \mathrm{BR}(B \to \tau\nu)^{\mathrm{SM}} \underbrace{\left(1 - \frac{\tan^2\beta\, m_{B^+}^2}{m_{H^+}^2 (1 + \epsilon_0 \tan\beta)}\right)^2}_{r_H}$$

V_{cb}

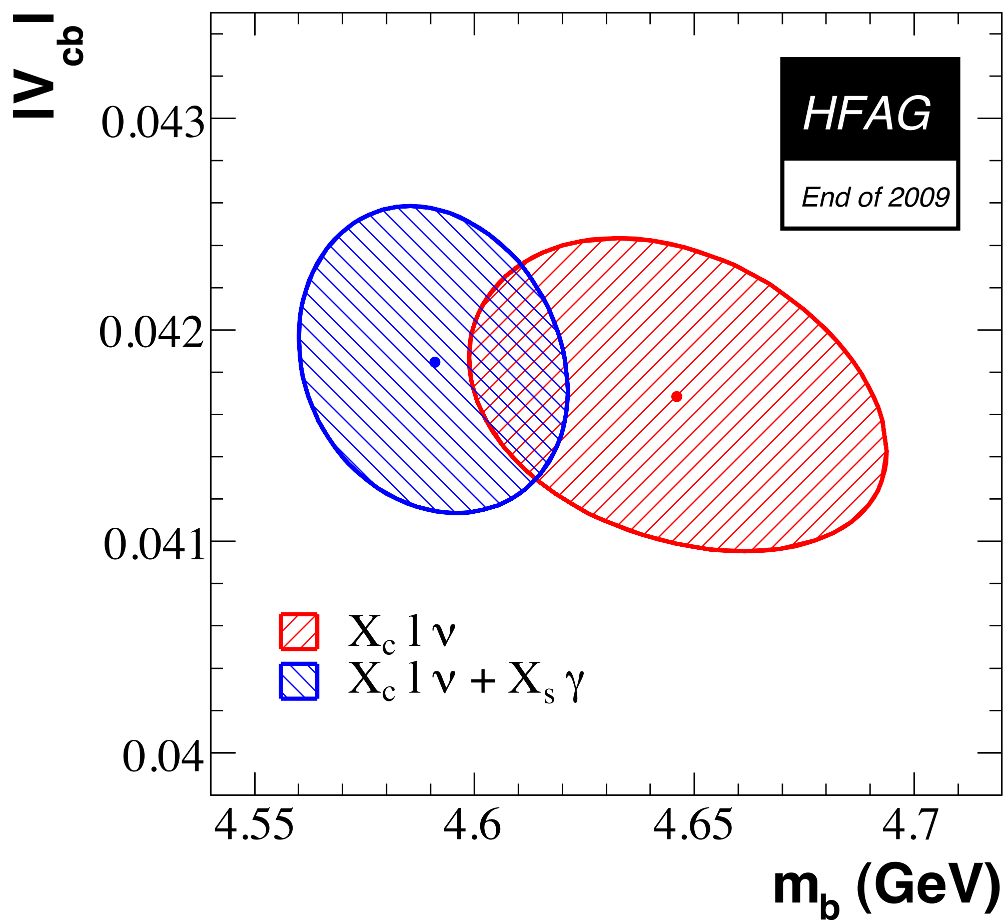
- Exclusive from $B \to D^{(*)} l\nu$. Using form factor from lattice QCD (2+1 dynamical staggered fermions) one finds:

  $$|V_{cb}| = (39.5 \pm 1.0) \times 10^{-3}$$

  [FNAL/MILC]
  [average: Laiho, EL, Van de Water]

  [exp. error on $B \to D^*$ rescaled to account for the large $\chi^2/\mathrm{dof} = 39/21$]

- Inclusive from global fit of $B \to X_c l\nu$ moments. [Büchmuller, Flächer]



- Inclusion of $b \to s\gamma$ has strong impact on quark masses but not on V_{cb}
- NNLO in α_s and $O(1/m_b^4)$ known
- $O(\alpha_s/m_b^2)$ corrections partially known
- Issue of m_b is relevant for V_{ub}

$$|V_{cb}| = (41.68 \pm 0.73) \times 10^{-3}$$

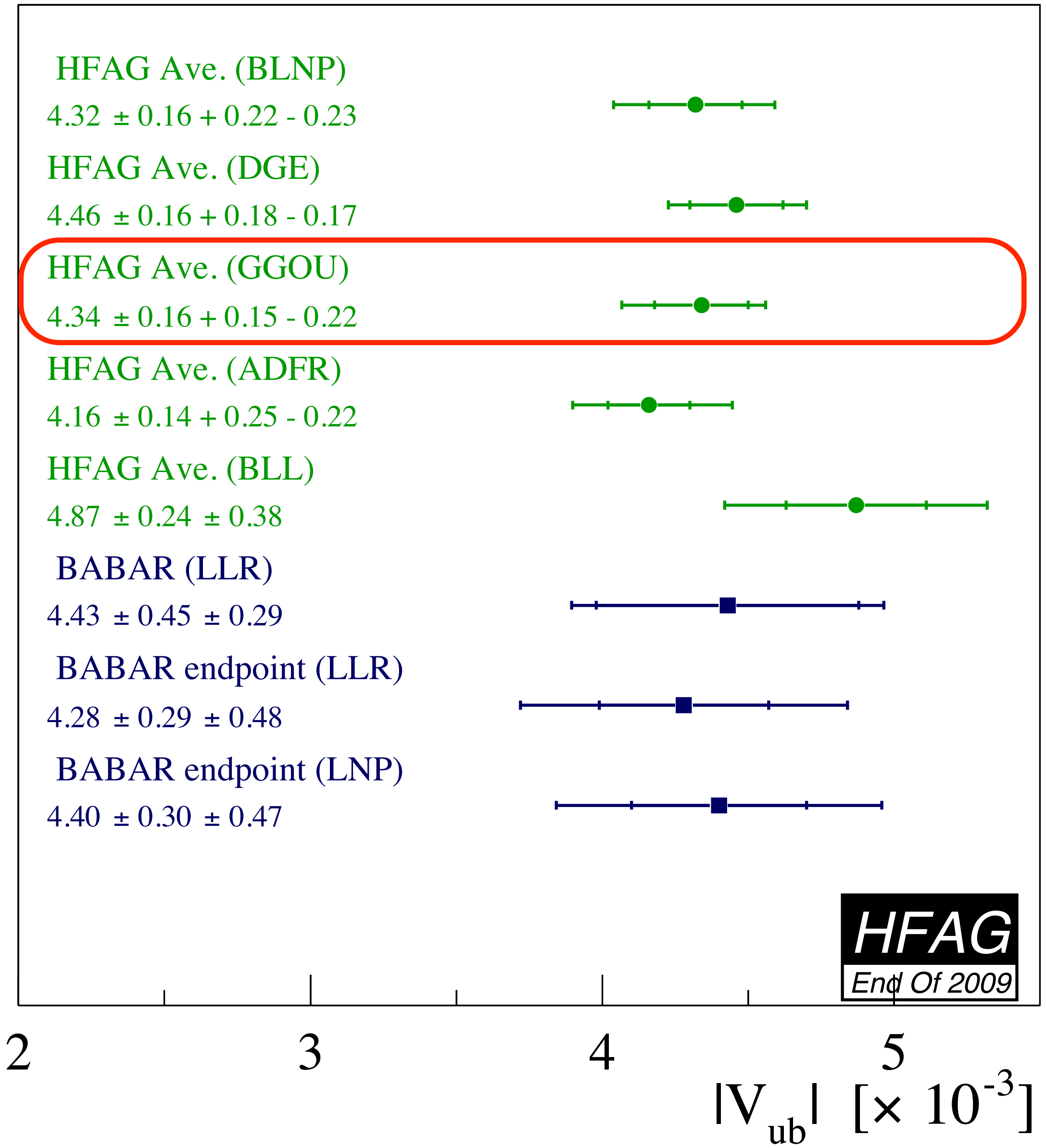
1.7σ discrepancy between inclusive and exclusive

V_{ub}

- Exclusive from B→πlν: $|V_{ub}| = (3.12 \pm 0.26) \times 10^{-3}$

[HPQCD, FNAL/MILC]
[average:Laiho,EL,Van de Water]

- Inclusive from global fit of $B \to X_u l\nu$ moments



Legend:
BLNP = Bosch, Lange, Neubert, Paz
DGE = Andersen, Gardi
GGOU = Gambino,Giordano,Ossola,Uraltsev
ADFR = Aglietti, Di Lodovico, Ferrera, Ricciardi
BLL = Bauer, Ligeti, Luke
LLR = Leibovich, Low, Rothstein
LNP = Lange, Neubert, Paz

3.3σ discrepancy between inclusive and exclusive (!)

We will add a 10% "model" uncertainty to the GGOU result (but ...)

Inputs to the fit: summary

$\lvert V_{cb}\rvert_{\rm excl} = (39.5 \pm 1.0) \times 10^{-3}$	$\lvert V_{ub}\rvert_{\rm excl} = (3.12 \pm 0.26) \times 10^{-3}$
$\hat B_K = 0.737 \pm 0.020$	$\kappa_\varepsilon = 0.94 \pm 0.02$
$f_B = (207.8 \pm 8.3)$ MeV	$f_{B_s} = (252.3 \pm 8.2)$ MeV
$\hat B_{B_d} = 1.26 \pm 0.11$	$\hat B_{B_s} = 1.33 \pm 0.06$
$f_{B_d}\sqrt{\hat B_{B_d}} = (233 \pm 14)$ MeV	$f_{B_s}\sqrt{\hat B_{B_s}} = (291 \pm 11)$ MeV
$\xi \equiv f_{B_s}\sqrt{\hat B_s}/(f_{B_d}\sqrt{\hat B_d}) = 1.237 \pm 0.032$	$f_{B_s}/f_{B_d} = 1.215 \pm 0.019$
$\lvert V_{cb}\rvert_{\rm incl} = (41.68 \pm 0.44 \pm 0.09) \times 10^{-3}$	$\alpha = (89.5 \pm 4.3)^\circ$
$\lvert V_{ub}\rvert_{\rm incl} = (4.34 \pm 0.16^{+0.15}_{-0.22}) \times 10^{-3}$	$\eta_1 = 1.51 \pm 0.24$
${\rm BR}(B \to \tau\nu) = (1.68 \pm 0.31) \times 10^{-4}$	$S_{\psi K_S} = 0.668 \pm 0.023$
$\Delta m_{B_d} = (0.507 \pm 0.005)\ {\rm ps}^{-1}$	$\gamma = (78 \pm 12)^\circ$
$\Delta m_{B_s} = (17.77 \pm 0.10 \pm 0.07)\ {\rm ps}^{-1}$	$\eta_2 = 0.5765 \pm 0.0065$
$m_{t,pole} = (172.4 \pm 1.2)$ GeV	$\eta_3 = 0.494 \pm 0.046$
$m_c(m_c) = (1.268 \pm 0.009)$ GeV	$\eta_B = 0.551 \pm 0.007$
$\varepsilon_K = (2.229 \pm 0.012) \times 10^{-3}$	$\lambda = 0.2255 \pm 0.0007$

very small hadronic uncertainties

www.latticeaverages.org

2+1 Flavor Lattice QCD Averages

For use in determinations of CKM matrix elements, Unitarity Triangle fits, and other flavor physics phenomenology

Introduction
Methodology
Lattice Averages
Fit Results and Plots
Papers and Talks
Contact Info

Lattice Averages for FPCP 2010 and Lattice 2010

If you use these results in proceedings or publications, please cite our original publication (Laiho, Lunghi, & Van de Water, Phys.Rev.D81:034503,2010) as well as this webpage.

Note on the correlations between the various lattice calculations

For each quantity we quote the average that we obtain (in which statistic and systematic errors have been combined) and the statistic component of the total error (in round brackets in the stat error column).

Table of contents:

Light meson decay constants:

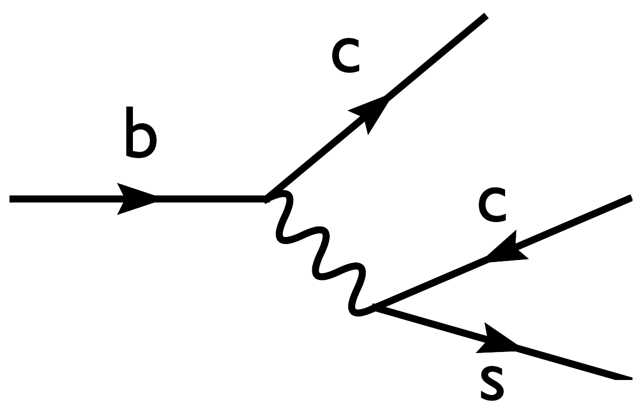
	f_π (MeV)	$(\delta f_\pi)_{stat}$	$(\delta f_\pi)_{syst}$
Aubin, Laiho, Van de Water '08	129.1	1.9	4.0
HPQCD/UKQCD '10 *	132	1	2
MILC '10	129.2	0.4	1.4
RBC/UKQCD '10	124	2	5
Average: (129.5 ± 1.7) MeV		(0.52)	

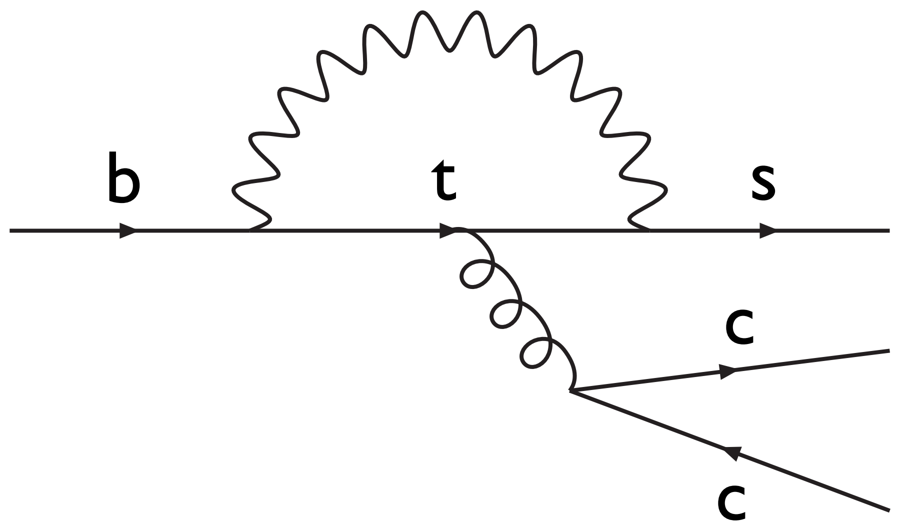
* Although the HPQCD collaboration recently updated their result for f_π in a publication focusing on f_{Ds}, they did not present a new error budget. Since the only change from their previous publication was in the determination of r_1, most of the errors did not

www.latticeaverages.org

Time dependent CP asymmetry in $B \to J/\psi K_S$

- Penguin polluting effects are CKM (10^{-2}) and loop suppressed:





$$V_{cb}V_{cs}^* \qquad V_{tb}V_{ts}^* = -V_{cb}V_{cs}^* - V_{ub}V_{us}^*$$

- It is a clean measurement of the B_d mixing phase (*assuming no NP corrections to the Tree amplitude*):

Hadronic uncertainties in $S_{\psi K}$

- The small penguin pollution can be extracted in the SU(3) limit from time-dependent studies of $B_s \to \psi K$ and $B \to \psi \pi^0$ [Fleischer] [Faller, Jung, Fleischer, Mannel]
- Using a conservative approach about SU(3) effects one finds:

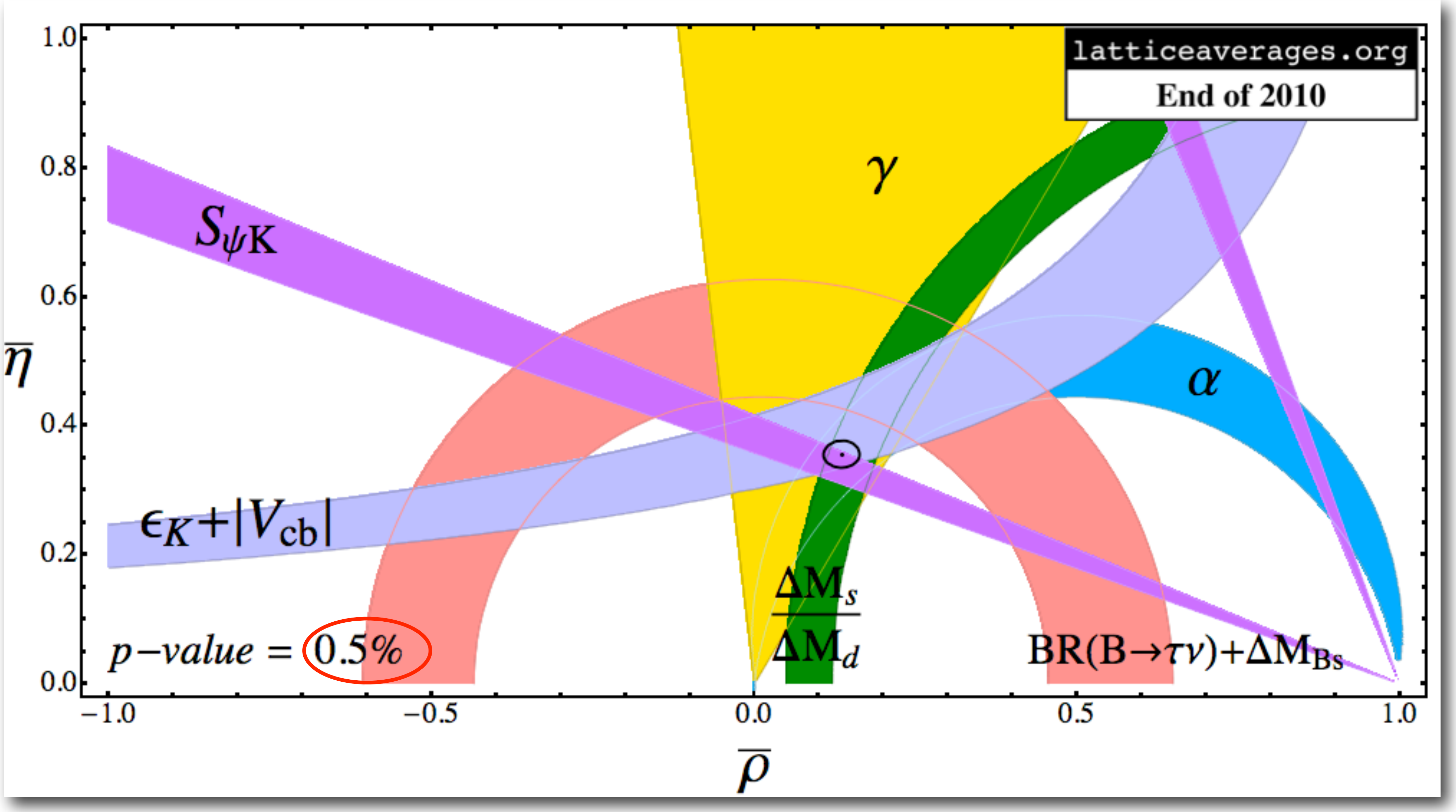
$$|\Delta S_{\psi K}| < 0.02$$

- Quantitative studies based on QCD factorization, pQCD and rescattering effects yield effects that are one order of magnitude smaller
- We conclude that presently one should not use $B \to \psi \pi^0$ decays as sole handle on hadronic uncertainties on $S_{\psi K}$
- Improved measurements of $B \to \psi \pi^0$ (at super-B) and of $B_s \to \psi K$ (at LHC-b) will allow to keep this uncertainty under control

Current fit to the unitarity triangle (removing V_{ub})

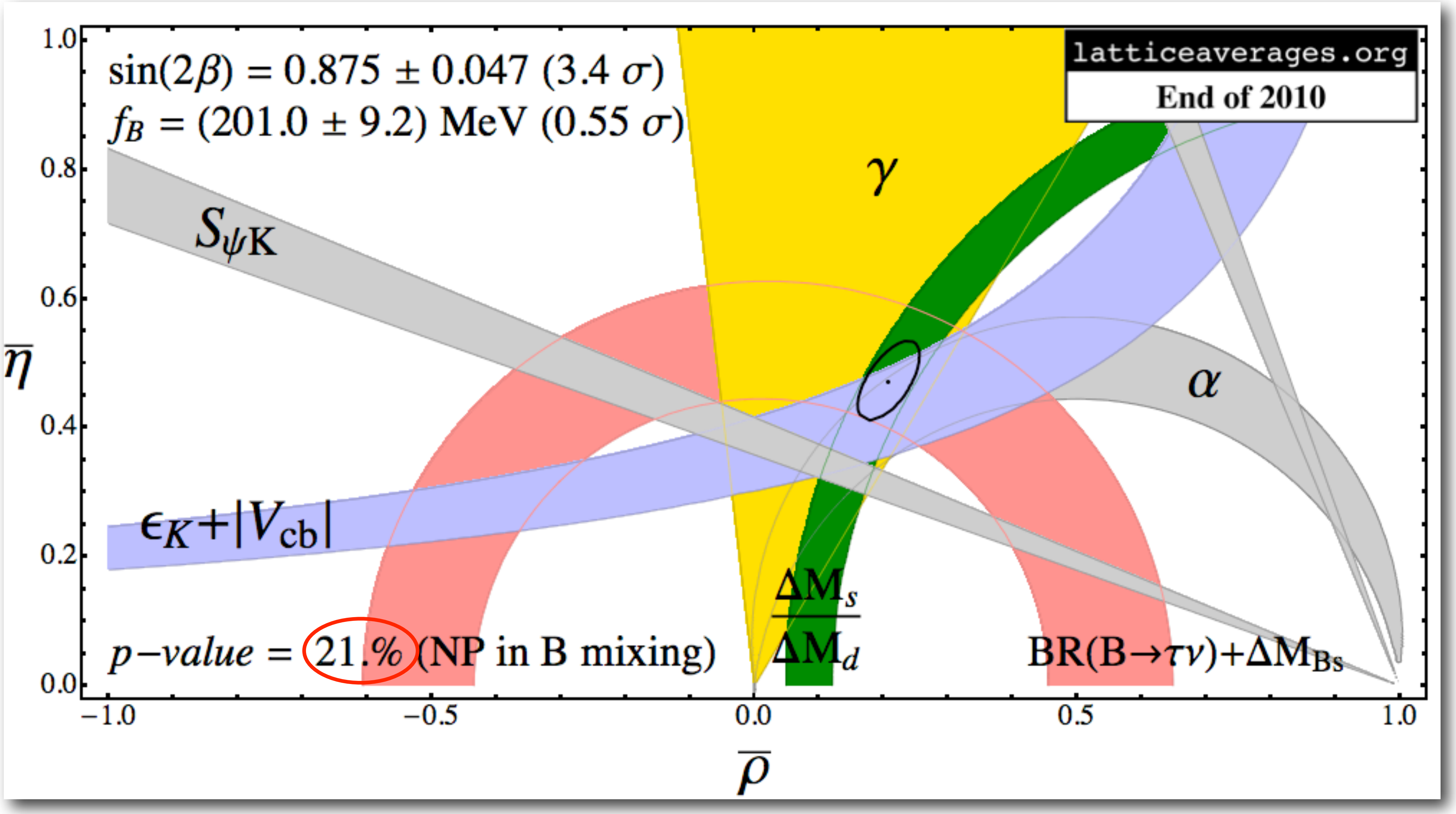
[Lunghi,Soni 0803.4340 and 0903.5059]

- V_{ub} is the \begin{personal opinion} most controversial \end{personal opinion} input



- Every single remaining input is on very solid exp/th ground

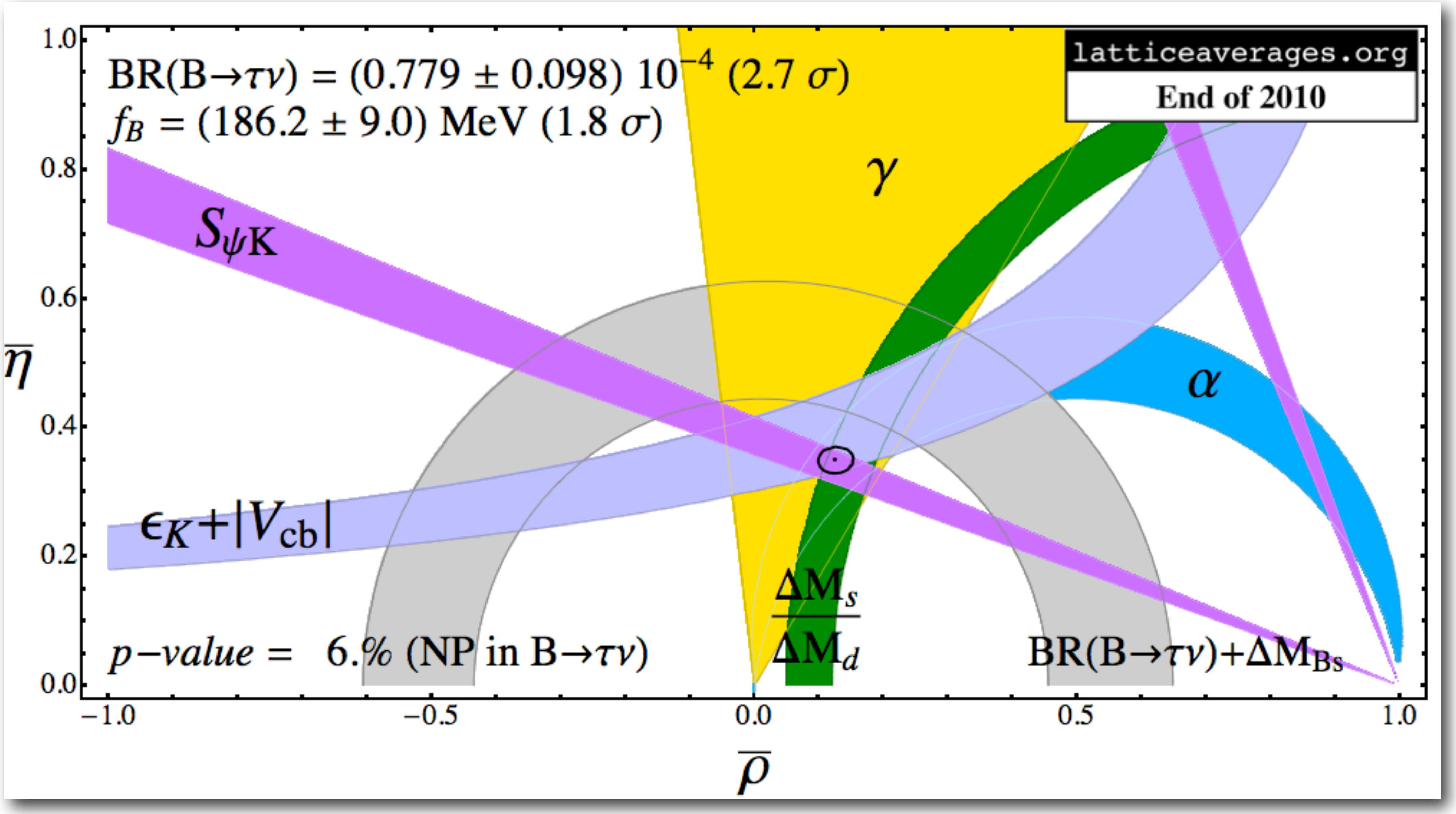
Current fit to the unitarity triangle (removing V_{ub})



$$[\sin 2\beta]_{\rm fit} = 0.875 \pm 0.047 \quad \Rightarrow \quad 3.4\,\sigma$$

$$[f_B]_{\rm fit} = (201.0 \pm 9.2)\ \text{MeV} \quad \Rightarrow \quad 0.6\,\sigma$$

Current fit to the unitarity triangle (removing V_{ub})



$$[BR(B \to \tau\nu)]_{\rm fit} = (0.779 \pm 0.098) \times 10^{-4} \quad \Rightarrow \quad 2.7\,\sigma$$

$$[f_B]_{\rm fit} = (186.2 \pm 9.0)\ \mathrm{MeV} \quad \Rightarrow \quad 1.9\,\sigma$$

Removing V_{ub} and V_{cb}

[Lunghi,Soni 0912.002]

- The use of V_{cb} seems to be necessary in order to use K mixing to constrain the UT:

$$\Delta M_{B_s} = \chi_s\, f_{B_s}^2 \hat{B}_{B_s} A^2 \lambda^4$$

$$|\varepsilon_K| = 2\chi_\varepsilon \hat{B}_K \kappa_\varepsilon\, \eta\lambda^6 \Big(A^4\lambda^4(\rho-1)\eta_2 S_0(x_t) + A^2 \big(\eta_3 S_0(x_c,x_t) - \eta_1 S_0(x_c)\big)\Big)$$

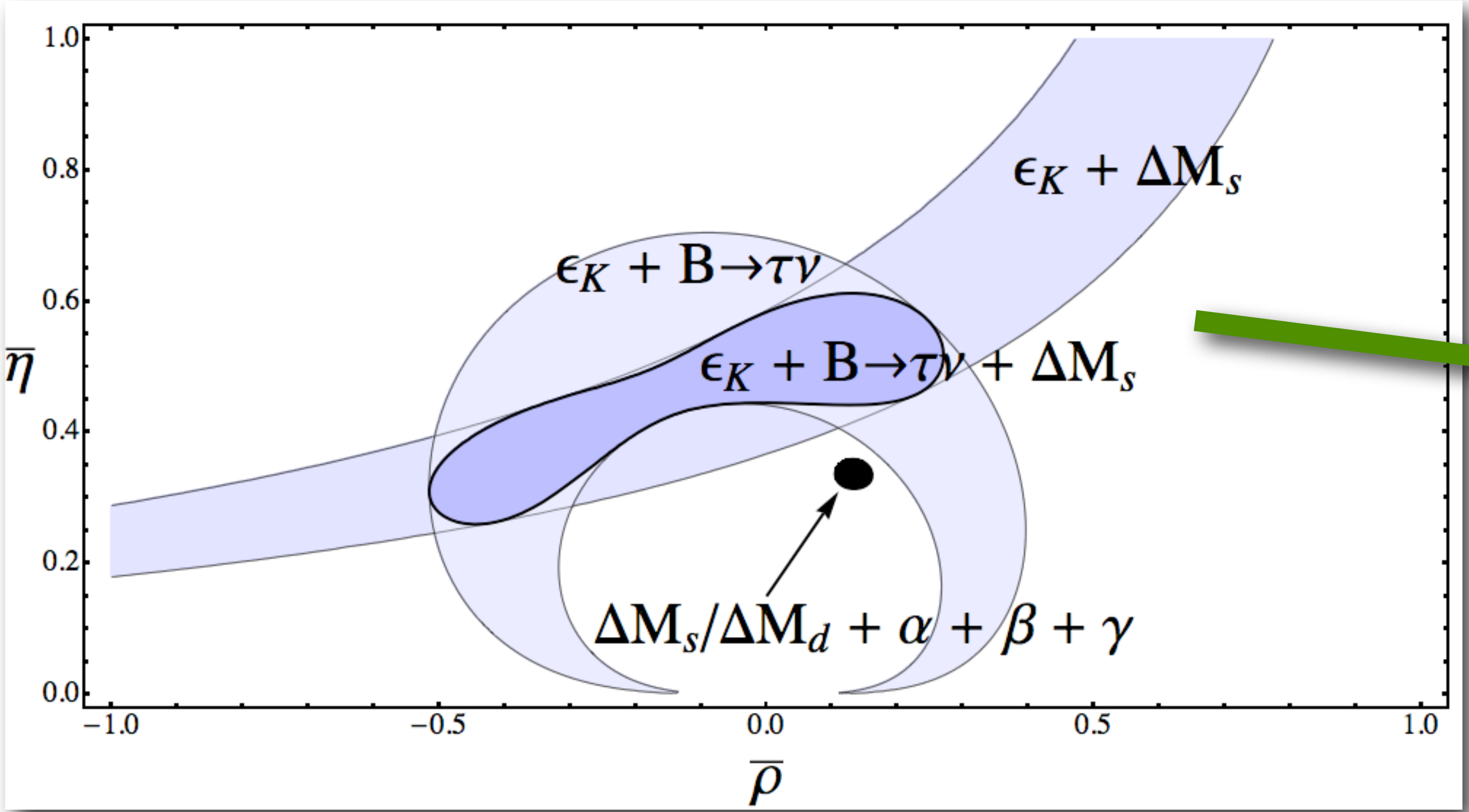
$$\mathrm{BR}(B\to\tau\nu) = \chi_\tau f_B^2 A^2 \lambda^6 (\rho^2+\eta^2)$$

- The interplay of these constraints allows to drop V_{cb} while still constraining new physics in K mixing:

$$\begin{aligned} |\varepsilon_K| &\propto \hat{B}_K\, (f_{B_s}\hat{B}_s^{1/2})^{-4}\, f(\rho,\eta) \\ |\varepsilon_K| &\propto \hat{B}_K\, \mathrm{BR}(B\to\tau\nu)^2\, f_B^{-4}\, g(\rho,\eta) \end{aligned}$$

Removing V_{cb} !

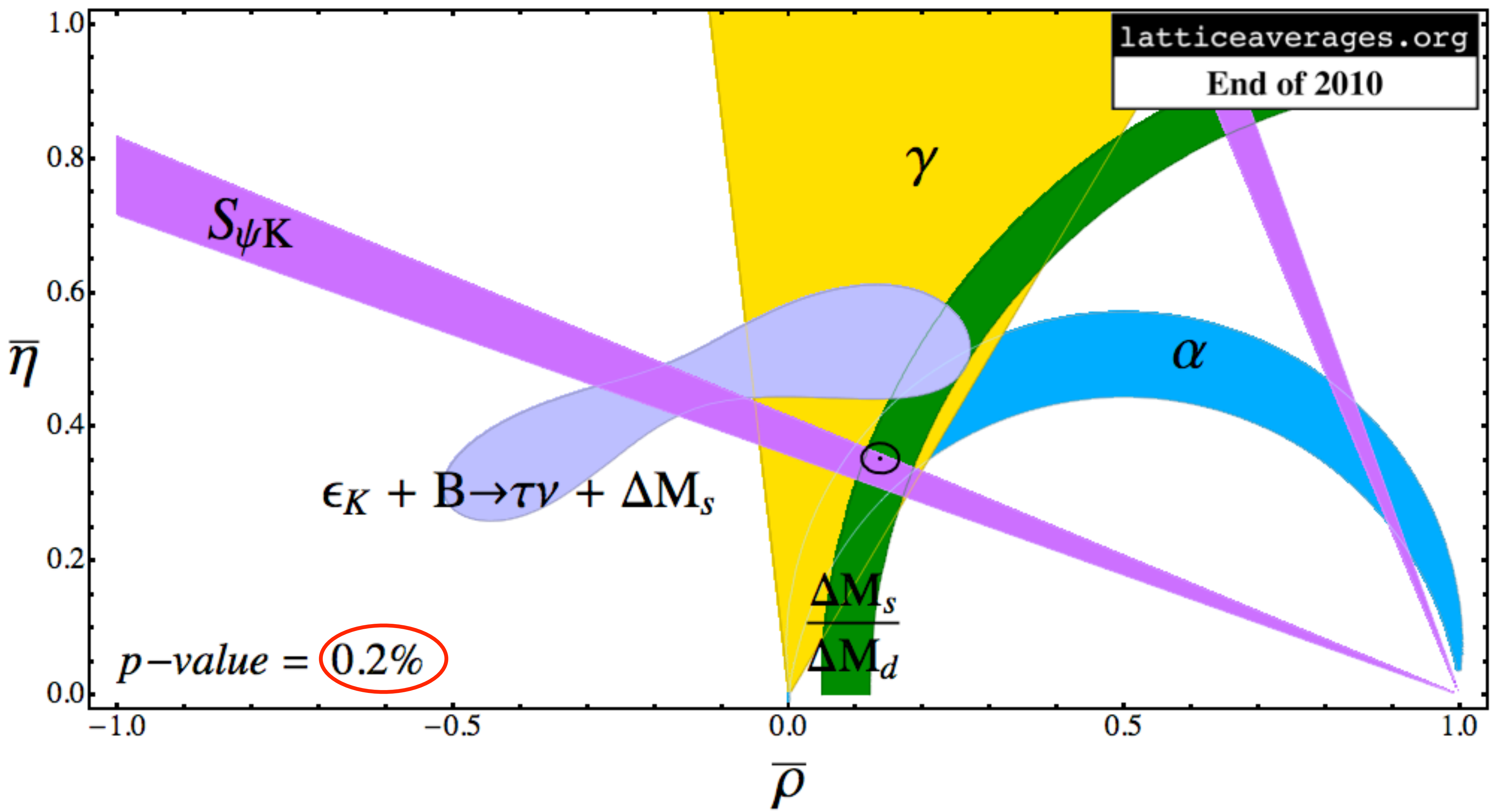
- The use of V_{cb} seems to be necessary in order to use K mixing to constrain the UT:



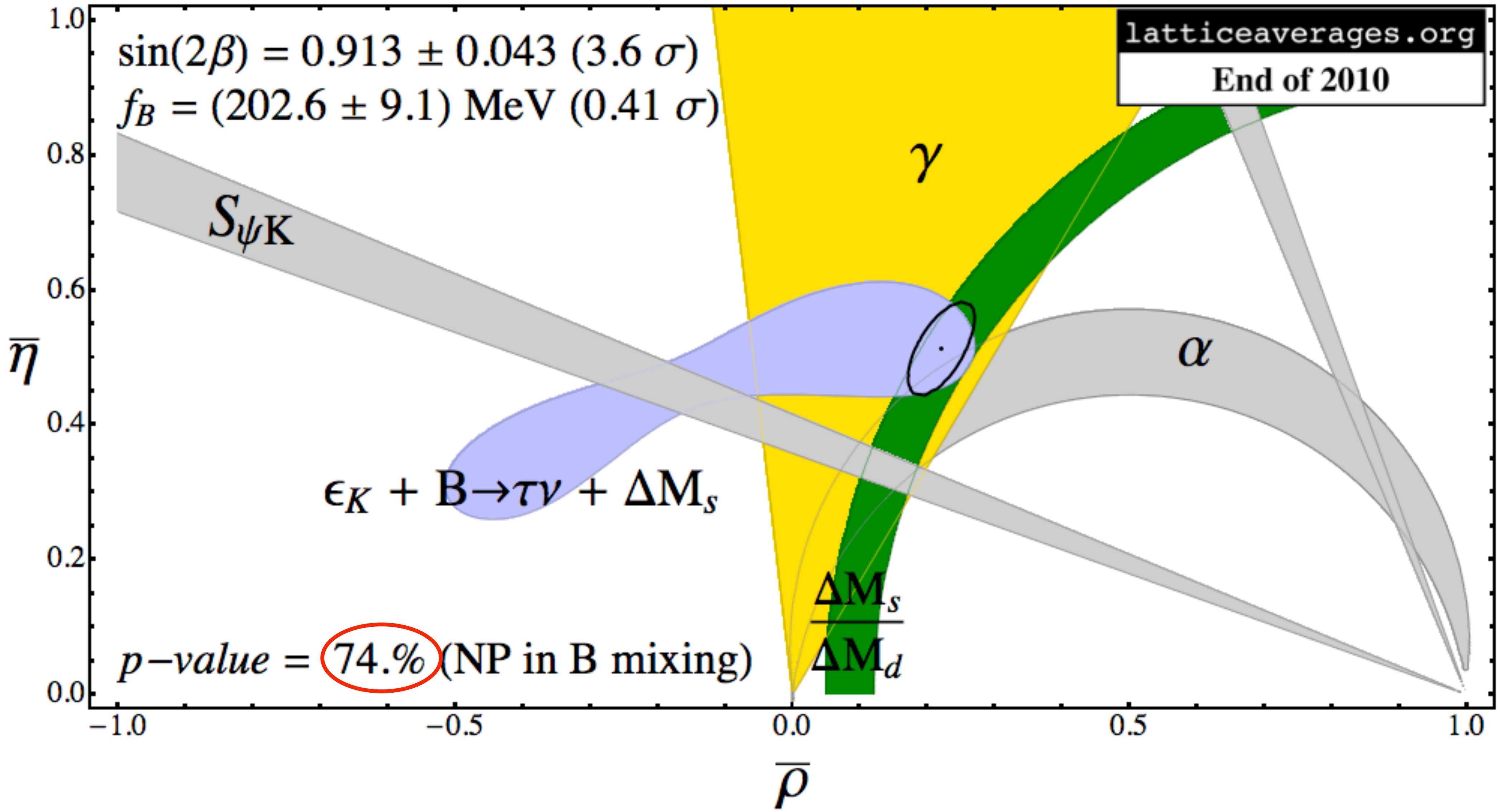
ρ-η topology of the constraint makes it relevant despite large errors on B→τν

X :	$\hat{B}_K$	$\vert V_{cb}\vert$	$f_{B_s}\hat{B}_s^{1/2}$	$\mathrm{BR}(B\to\tau\nu)$	f_B
δX :	3.7%	2.5%	4.7%	21%	5%
$\delta\varepsilon_K$:	3.7%	10%	18.9%	42%	20%

Removing V_{ub} and V_{cb}



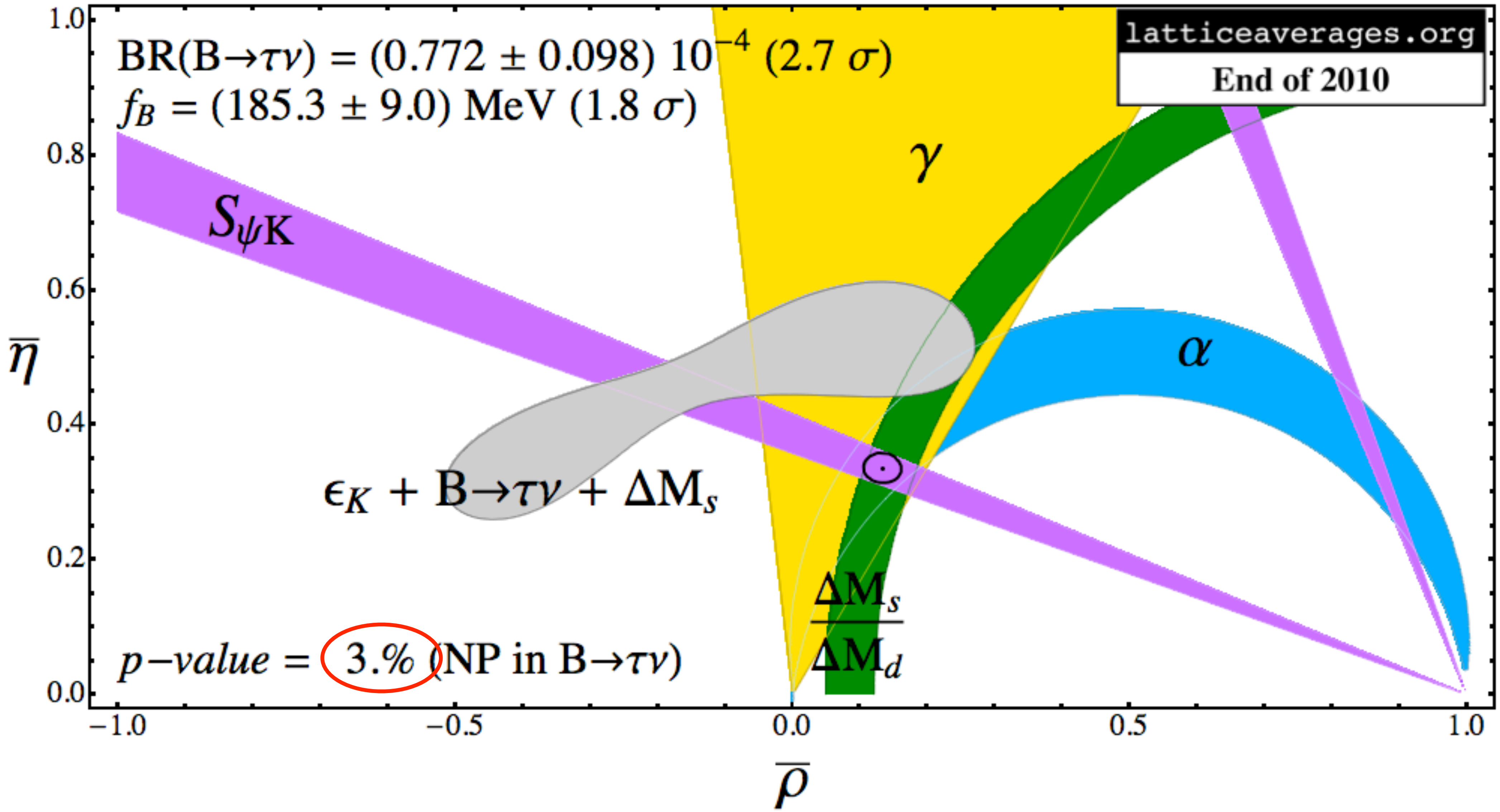
Removing V_{ub} and V_{cb}



$$[\sin 2\beta]_{\rm fit} = 0.9013 \pm 0.043 \quad \Rightarrow \quad 3.6\,\sigma$$

$$[f_B]_{\rm fit} = (202.6 \pm 9.1)\ \mathrm{MeV} \quad \Rightarrow \quad 0.4\,\sigma$$

Removing V_{ub} and V_{cb}



$$[BR(B \to \tau\nu)]_{\text{fit}} = (0.772 \pm 0.098) \times 10^{-4} \quad \Rightarrow \quad 2.7\,\sigma$$

$$[f_B]_{\text{fit}} = (185.3 \pm 9.0)\ \text{MeV} \quad \Rightarrow \quad 1.8\,\sigma$$

Model Independent Interpretation

- The tension in the UT fit can be interpreted as evidence for new physics contributions to ε_K, to B_d *mixing* and to $B \to \tau\nu$:

$$\begin{aligned} \varepsilon_K &= \varepsilon_K^{\rm SM} C_\varepsilon \\ M_{12} &= M_{12}^{\rm SM}\, e^{2i\phi_d}\, r_d^2 \\ {\rm BR}(B \to \tau\nu) &= r_H {\rm BR}(B \to \tau\nu)^{\rm SM} \end{aligned}$$

- This implies:

$$\begin{aligned} S_{\psi K_s} &= \sin 2(\beta + \phi_d) \\ \sin 2\alpha_{\rm eff} &= \sin 2(\alpha - \phi_d) \\ \Delta M_{B_d} &= (\Delta M_{B_d})^{\rm SM}\, r_d^2 \end{aligned}$$

Model Independent Interpretation

- NP in B mixing (*marginalizing over r_d*):

$$(\theta_d)_{\rm fit} = \begin{cases} -(8.4 \pm 3.0)^o & (3.1\sigma) \\ -(11.2 \pm 3.1)^o & (3.7\sigma) \end{cases} \qquad (\sin 2\beta)_{\rm fit} = \begin{cases} 0.875 \pm 0.047 & (3.4\sigma) \\ 0.913 \pm 0.043 & (3.6\sigma) \end{cases}$$

- NP in K mixing:

$$(C_\varepsilon)_{\rm fit} = \begin{cases} 1.25 \pm 0.13 & (2.1\sigma) \\ 1.55 \pm 0.24 & (2.7\sigma) \end{cases}$$

$$p_{\rm SM} = \begin{cases} 0.5\% & \text{no } V_{ub} \\ 0.2\% & \text{no } V_{qb} \end{cases}$$

- NP in B→τν:

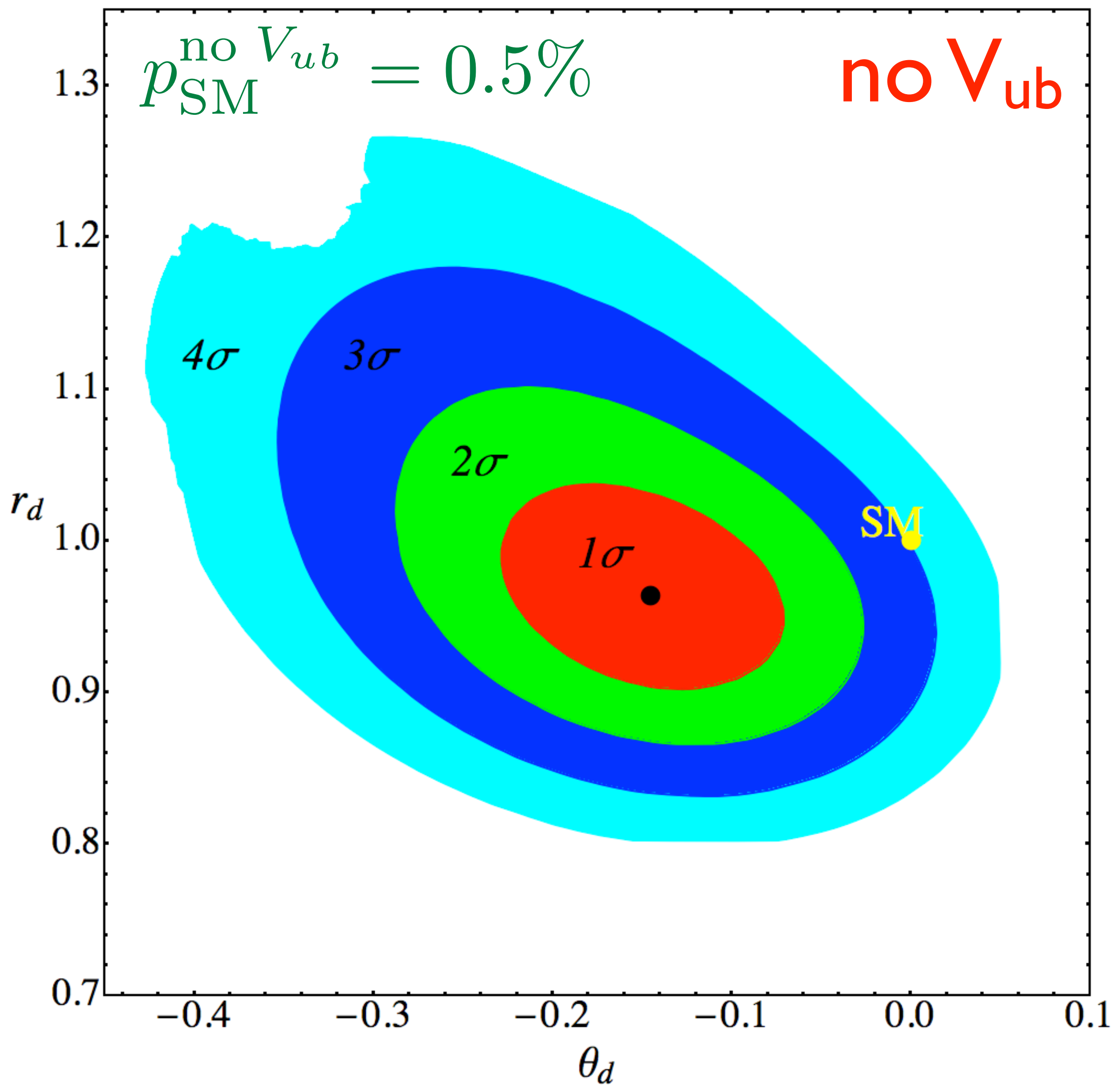
$$(r_H)_{\rm fit} = \begin{cases} 2.20 \pm 0.49 & (2.8\sigma) \\ 2.22 \pm 0.49 & (2.8\sigma) \end{cases}$$

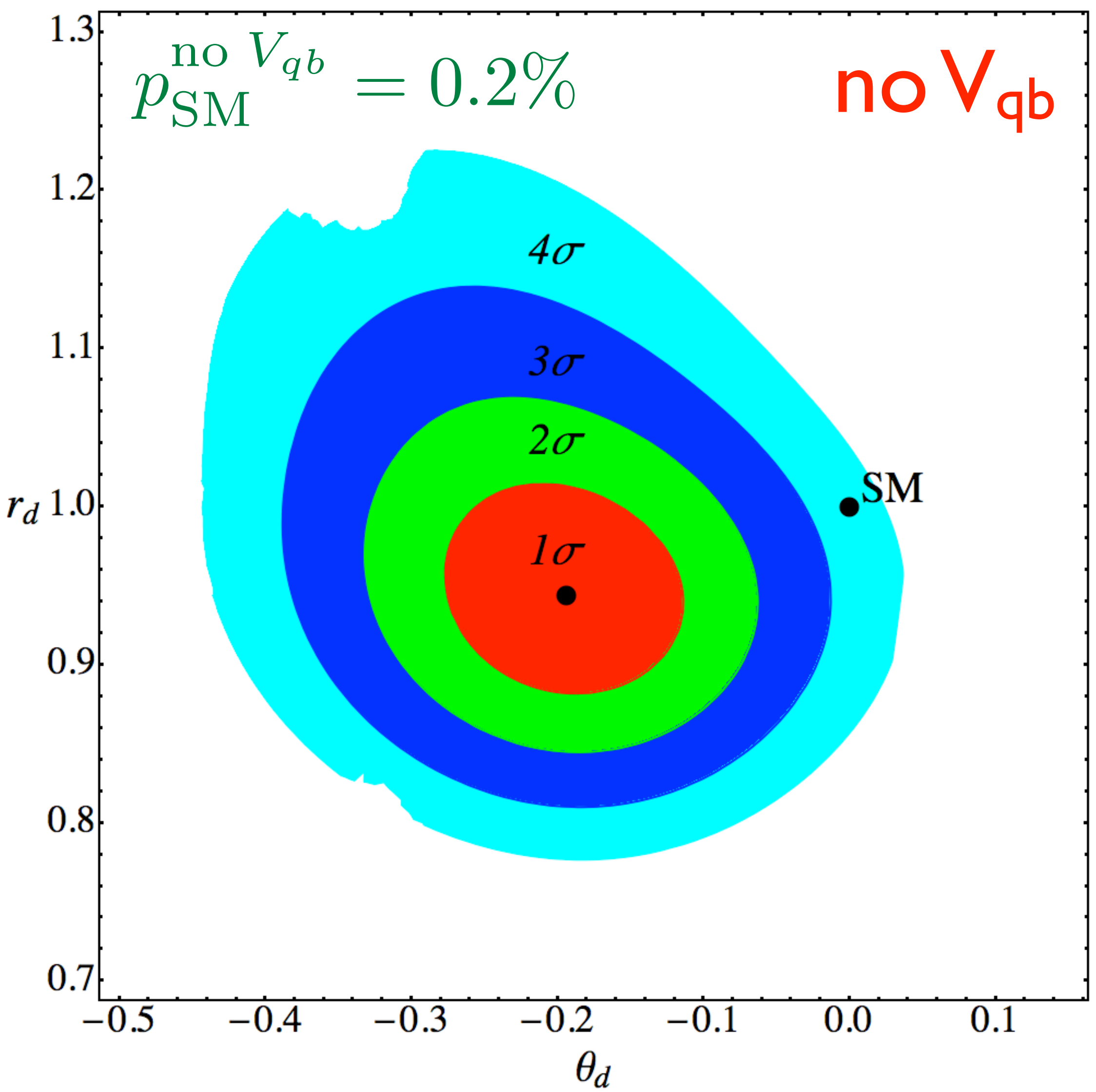
$$[{\rm BR}(B \to \tau\nu)]_{\rm fit} = \begin{cases} (0.779 \pm 0.098) \times 10^{-4} & (2.7\sigma) \\ (0.772 \pm 0.098) \times 10^{-4} & (2.7\sigma) \end{cases}$$

Hard to reconcile with H^+ effects:
in "natural" configurations $r_H<1$
(see also B→Dτν)

Model Independent Interpretation

- NP in B mixing (2 dimensional [θ_d,r_d] contours)





- One dimensional r_d ranges compatible with $r_d = 1$

Super-B expectations

- Reducing uncertainties on Bs mixing and B→τν :

δ_τ	δ_s	$p_{\rm SM}$	$\theta_d \pm \delta\theta_d$	$p_{\theta d}$	$\delta\theta_d/\theta_d$
18%	3.9%	0.25%	-11.2 ± 3.1	74.%	3.7σ
18%	2.5%	0.012%	-11.5 ± 2.9	71.%	4.3σ
18%	1%	0.000017%	-11.9 ± 2.7	67.%	5.2σ
10%	3.9%	0.0014%	-10.9 ± 2.3	74.%	4.8σ
3%	3.9%	0.000015%	-10.7 ± 1.9	73.%	5.7σ
10%	2.5%	0.000083%	-11.0 ± 2.3	69.%	5.2σ
10%	1%	2.26e-7%	-11.3 ± 2.2	63.%	5.8σ
3%	2.5%	9.59e-7%	-10.8 ± 1.9	68.%	5.9σ
3%	1%	3.89e-9%	-10.9 ± 1.8	60.%	6.3σ

$\delta_\tau = \delta \mathrm{BR}(B \to \tau\nu)$ $\qquad$ $\delta_s = \delta(f_{B_s}\sqrt{B_s})$

- Even modest improvements on B→τν have tremendous impact on the UT fit (10/50 ab^{-1} ⇒ δ_τ = 10/3%)

- Interplay between B_s mixing and B→τν can result in a 6σ effect

Operator Level Analysis

- Effective Hamiltonian for B_d mixing:

$$\mathcal{H}_{\rm eff} = \frac{G_F^2 m_W^2}{16\pi^2} (V_{tb}V_{td}^*)^2 \left(\sum_{i=1}^{5} C_i O_i + \sum_{i=1}^{3} \tilde{C}_i \tilde{O}_i \right)$$

$$\begin{aligned}
O_1 &= (\bar{d}_L \gamma_\mu b_L)(\bar{d}_L \gamma_\mu b_L) & \tilde{O}_1 &= (\bar{d}_R \gamma_\mu b_R)(\bar{d}_R \gamma_\mu b_R) \\
O_2 &= (\bar{d}_R b_L)(\bar{d}_R b_L) & \tilde{O}_2 &= (\bar{d}_L b_R)(\bar{d}_L b_R) \\
O_3 &= (\bar{d}_R^\alpha b_L^\beta)(\bar{d}_R^\beta b_L^\alpha) & \tilde{O}_3 &= (\bar{d}_L^\alpha b_R^\beta)(\bar{d}_L^\beta b_R^\alpha) \\
O_4 &= (\bar{d}_R b_L)(\bar{d}_L b_R) & O_5 &= (\bar{d}_R^\alpha b_L^\beta)(\bar{d}_L^\beta b_R^\alpha) \ .
\end{aligned}$$

- Parametrization of New Physics effects:

$$\mathcal{H}_{\rm eff} = \frac{G_F^2 m_W^4}{16\pi^2} (V_{tb}V_{td}^*)^2 \, C_1^{\rm SM} \left(\frac{1}{m_W^2} - \frac{e^{i\varphi}}{\Lambda^2} \right) O_1$$

- Analogue expressions for K mixing

Operator Level Analysis: *Mixing*

- The contribution of the LR operator O_4 to K mixing is strongly enhanced ($\mu_L \sim 2\ \mathrm{GeV}$, $\mu_H \sim m_t$):

O(1)

$$
\begin{aligned}
C_1(\mu_L)\langle K|O_1(\mu_L)|K\rangle &\simeq 0.8\, C_1(\mu_H)\, \frac{1}{3} f_K^2 m_K B_1(\mu_L) \\
C_4(\mu_L)\langle K|O_4(\mu_L)|K\rangle &\simeq 3.7\, C_4(\mu_H)\, \frac{1}{4} \left(\frac{m_K}{m_s(\mu_L)+m_d(\mu_L)} \right)^2 f_K^2 m_K B_4(\mu_L)
\end{aligned}
$$

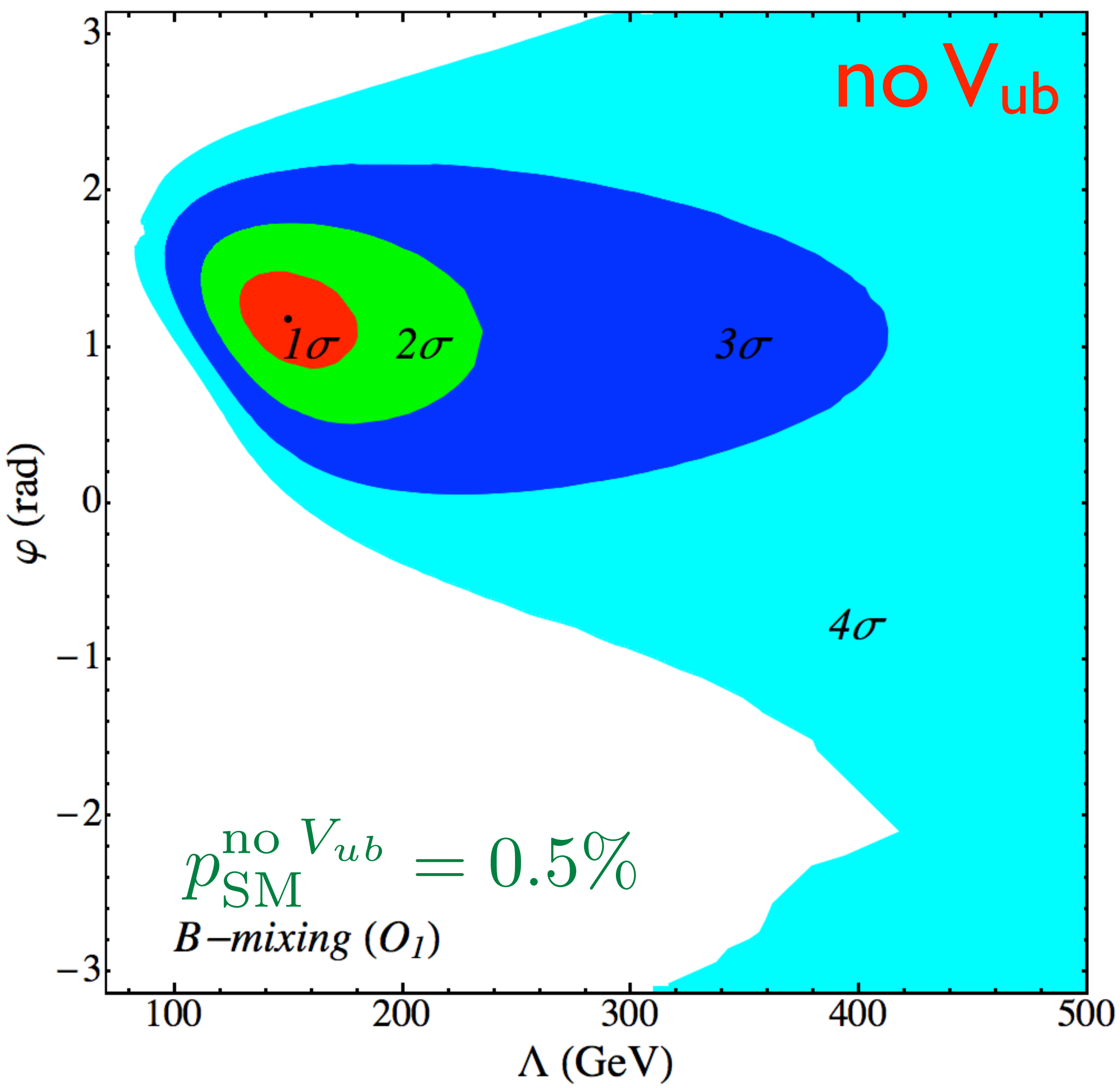
running from μ_H to μ_L chiral enhancement

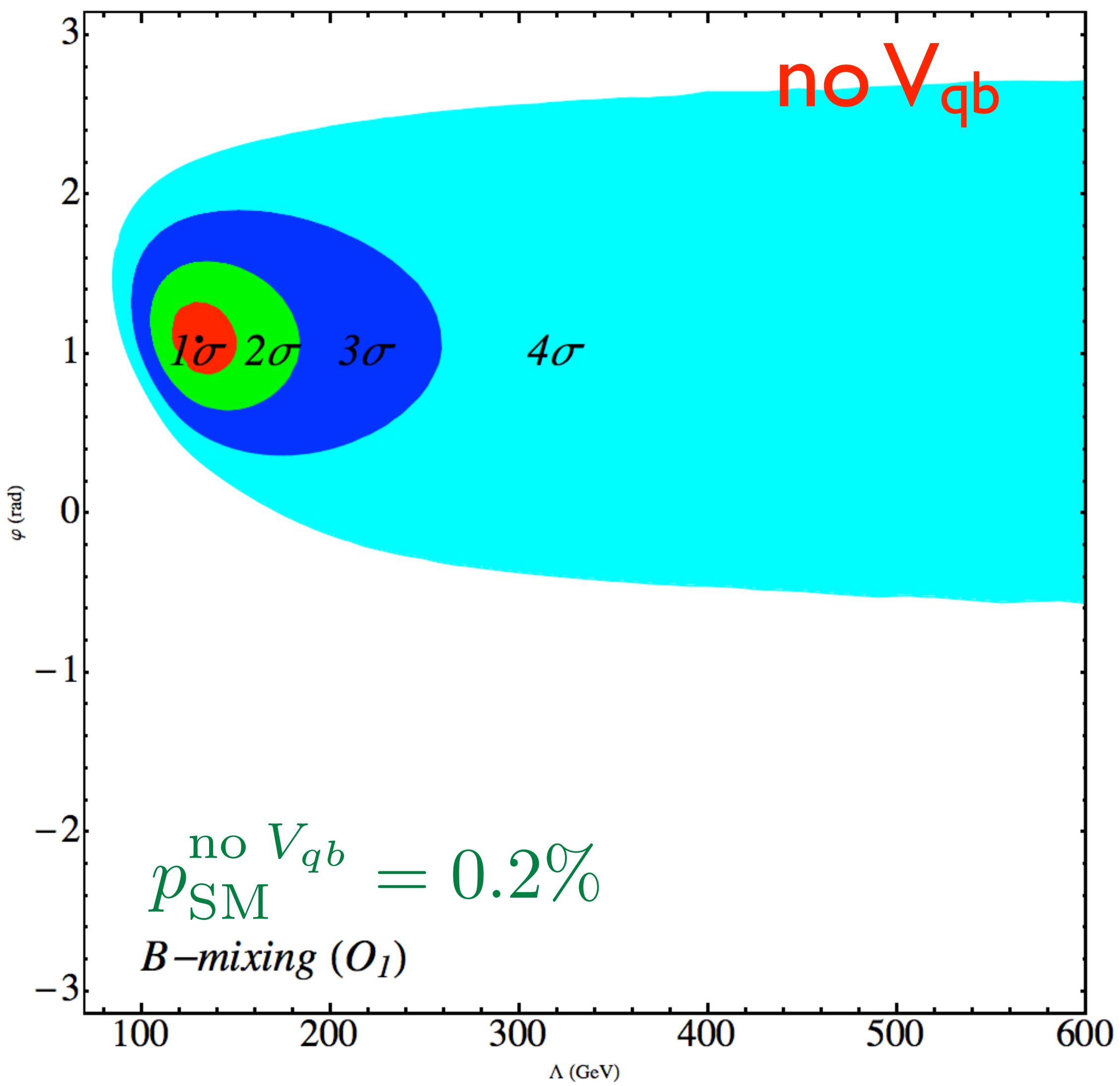
$$
\frac{C_4(\mu_L)\langle K|O_4(\mu_L)|K\rangle}{C_1(\mu_L)\langle K|O_1(\mu_L)|K\rangle} \simeq (65 \pm 14)\, \frac{B_4(\mu_L)}{B_1(\mu_L)} \frac{C_4(\mu_H)}{C_1(\mu_H)}
$$

- No analogous enhancement in B_q mixing

Operator Level Analysis: *B_d Mixing*

- 2 dimensional [Λ,φ] contours:

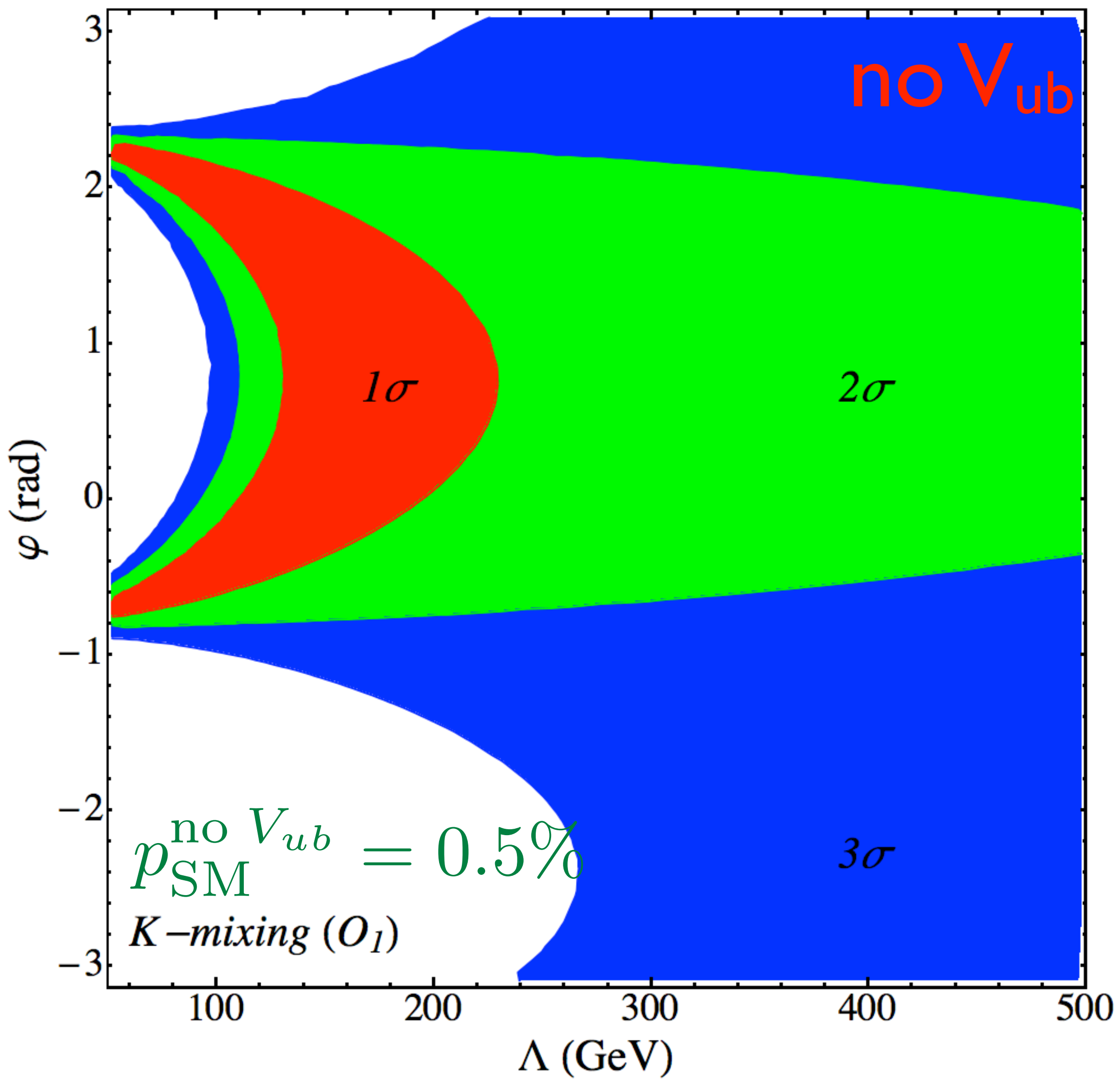


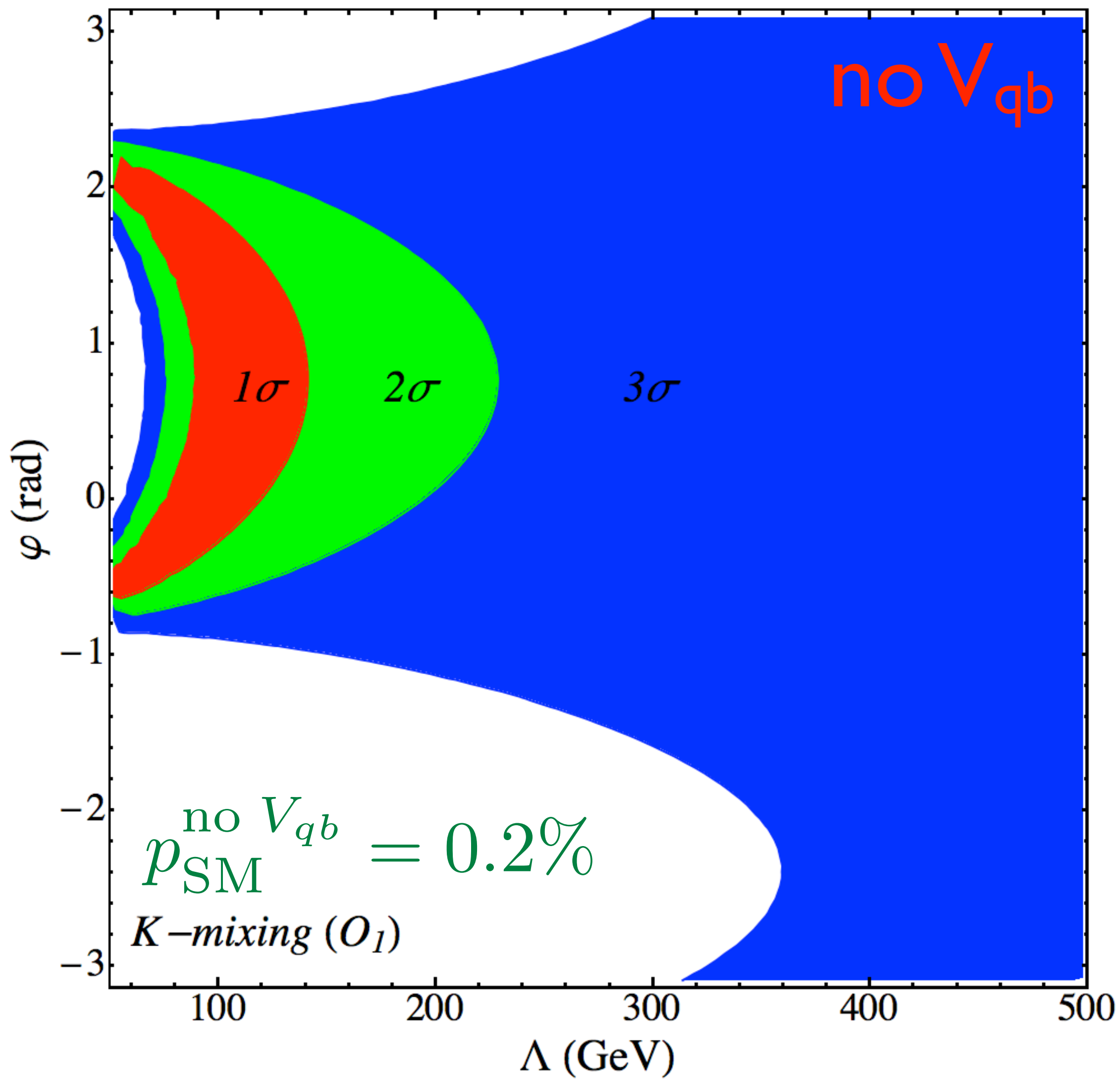


- Lower limit on Λ induced by $\Delta M_{B_s}/\Delta M_{B_d}$
- Projections of contours yield the one-dimensional nσ regions
- *Fit points to Λ in the few hundred GeV range and O(1) phase*

Operator Level Analysis: *K Mixing*

- 2 dimensional [Λ,φ] contours (O_1):

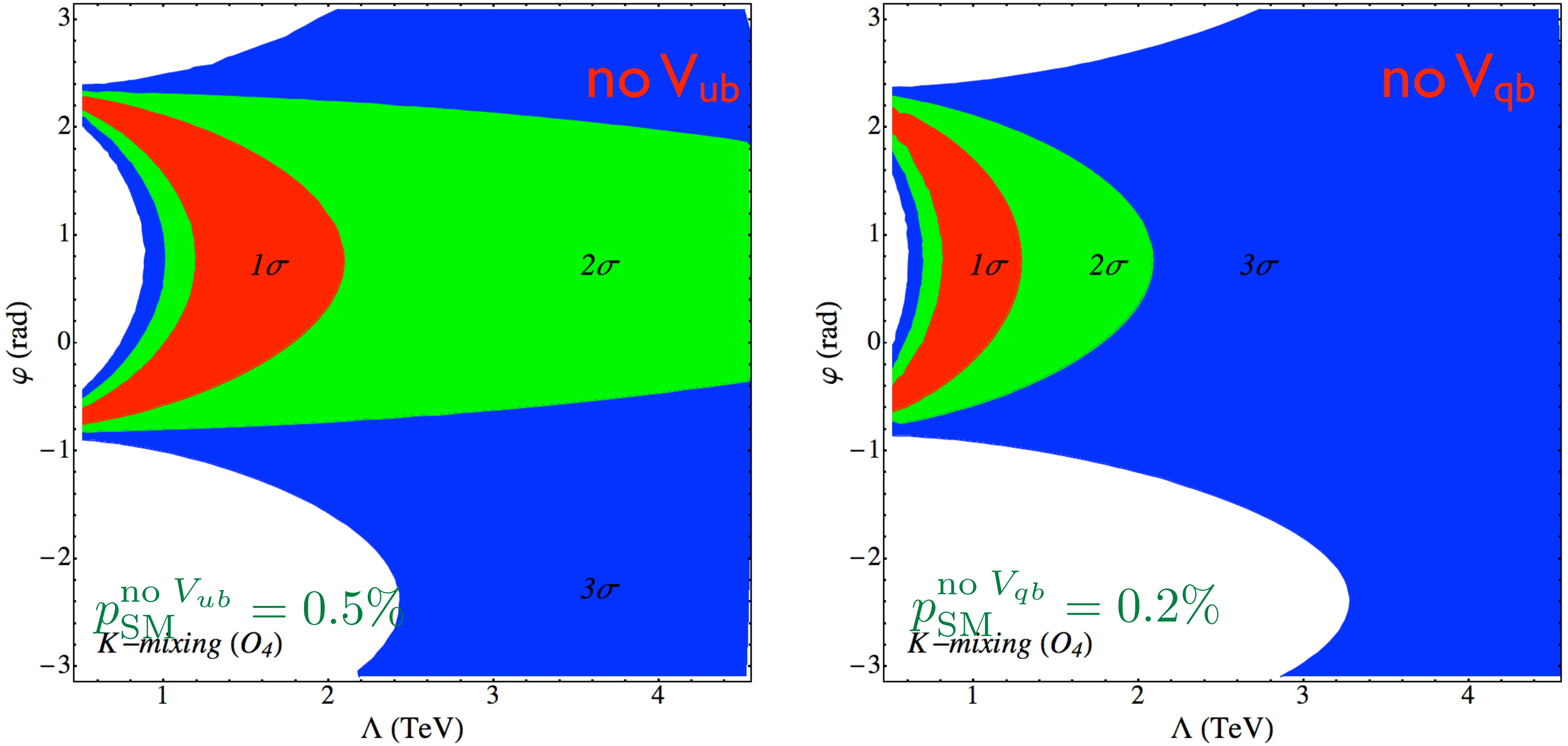




- No lower limit on Λ: fitting one parameter only (C_ε)
- *Fit points to Λ in the few hundred GeV range and O(1) phase; fine tuning allow lower masses*

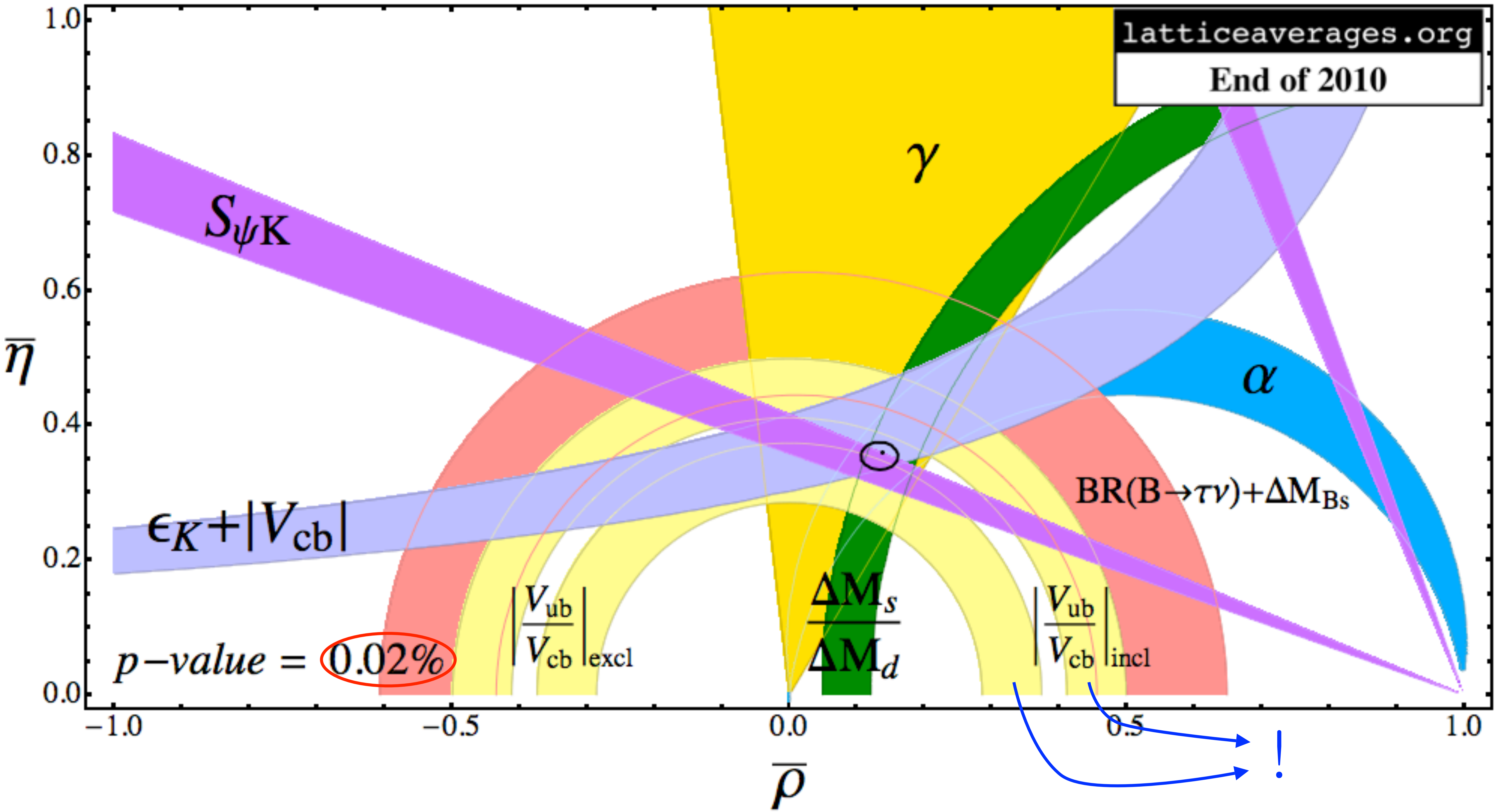
Operator Level Analysis: *K Mixing*

- 2 dimensional [Λ,φ] contours (O_4):



- No lower limit on Λ: fitting one parameter only (C_ε)
- *Fit points to Λ in the few TeV range and O(1) phase; fine tuning allow lower masses*

Including V_{ub}



New Physics in Vub

- The 3.3 discrepancy between inclusive and exclusive V_{ub} could be a hint for new physics in right-handed currents:
  [Chen, Nam; Crivellin; Buras, Gemmler, Isidori; EL, Soni (in preparation)]

$$V_{ub} u_L \not{W} b_L \implies V_{ub}(u_L \not{W} b_L + \xi\, u_R \not{W} b_R)$$

- Impact on semileptonic decays (B and π are pseudoscalars):

$$|V_{ub}|_{\text{incl}} \implies (1+|\xi|^2)|V_{ub}|_{\text{incl}}$$
$$|V_{ub}|_{\text{excl}} \implies |1+\xi|\ |V_{ub}|_{\text{excl}}$$
$$\text{BR}(B\to\tau\nu) \implies |1-\xi|^2 \text{BR}(B\to\tau\nu)$$

- Direct extraction of ξ from semileptonic decays (and f_B) yields:

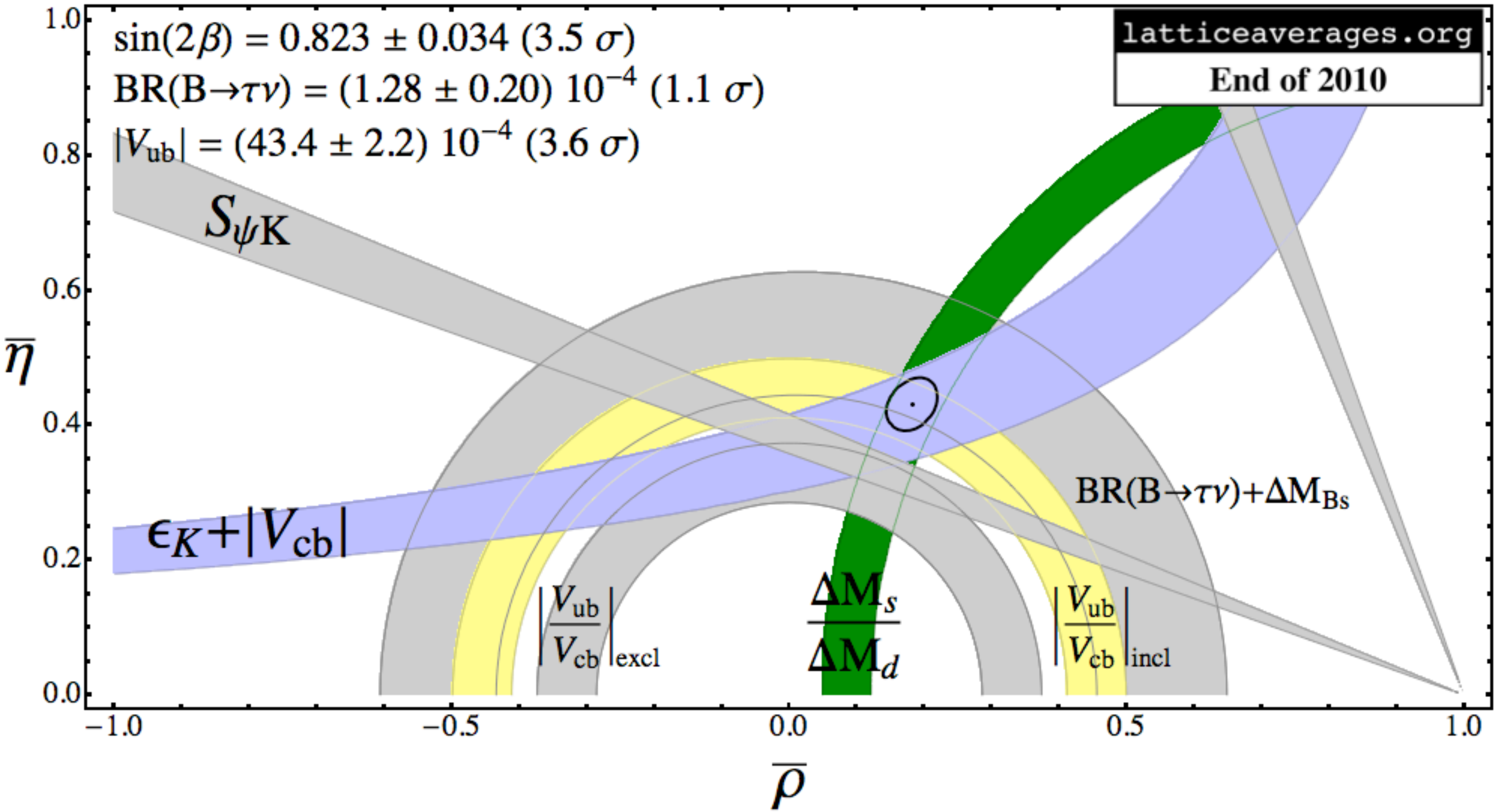
$$\xi_{\text{direct}} = -0.223 \pm 0.065 \quad (3.4\sigma)$$

New Physics in Vub

- Including the rest of the fit and allowing for new physics in B_d mixing we obtain we have a total of three phenomenological parameters (we take ξ to be real):

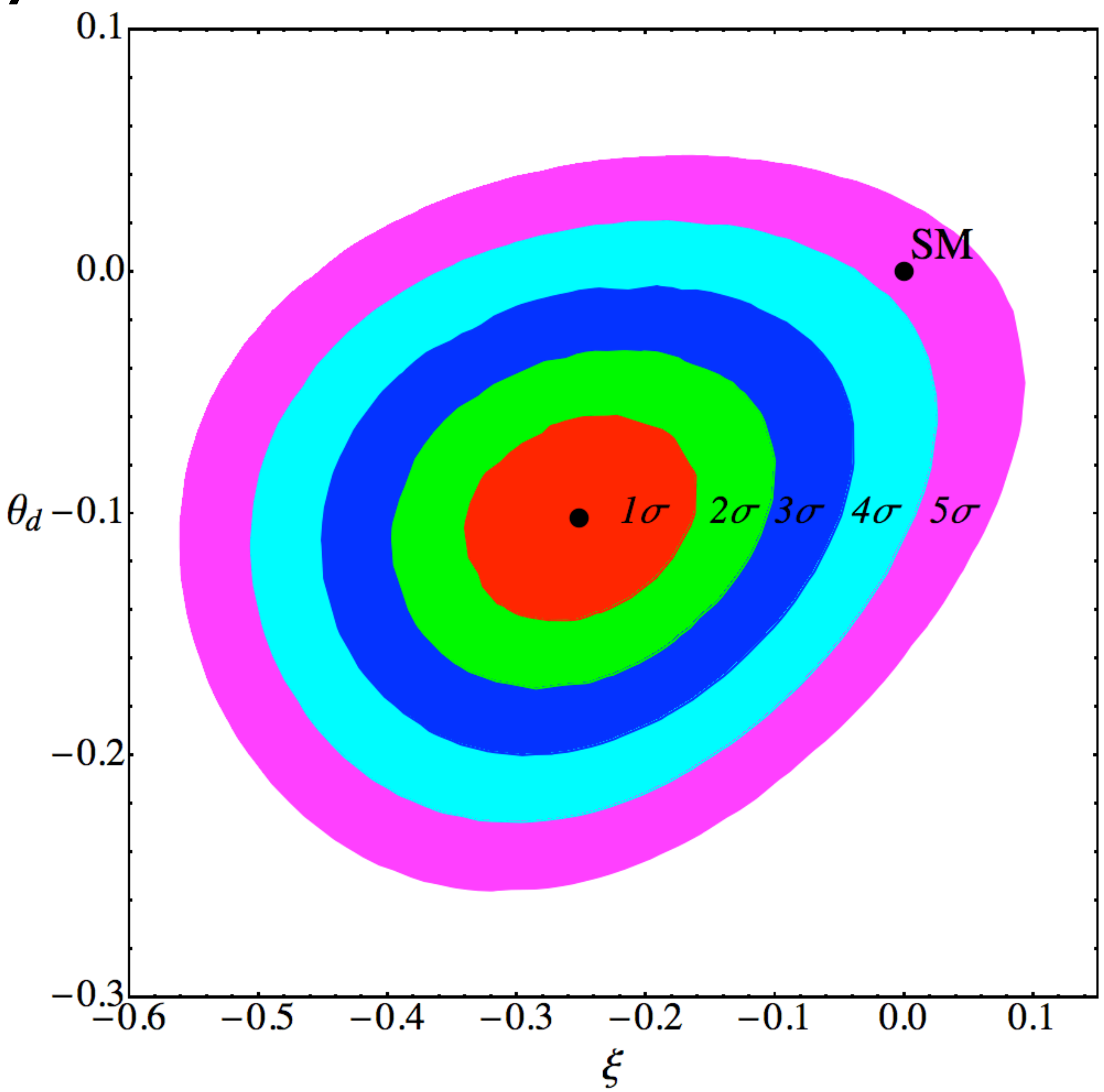
$$
\begin{aligned}
|V_{ub}|_{\rm incl} &\Longrightarrow (1+|\xi|^2)|V_{ub}|_{\rm incl} \\
|V_{ub}|_{\rm excl} &\Longrightarrow |1+\xi|\ |V_{ub}|_{\rm excl} \\
{\rm BR}(B\to\tau\nu) &\Longrightarrow |1-\xi|^2{\rm BR}(B\to\tau\nu) \\
S_{\psi K} &\Longrightarrow \sin 2(\beta+\theta_d) \\
\Delta M_{B_d} &\Longrightarrow r_d^2\Delta M_{B_d} \\
\alpha_{\rho\rho} &\Longrightarrow \alpha_{\rho\rho}-\theta_d+\arg(1+\xi)
\end{aligned}
$$

Including V_{ub}



New Physics in Vub

- The result of the fit to the unitarity triangle in which we simultaneously allow ξ, r_d and θ_d to vary independently yields:



$$\xi = -0.251 \pm 0.059 \quad (4.0\,\sigma)$$
$$\theta_d = -0.102, 0.028 \quad (3.4\,\sigma)$$
$$r_d = 0.978 \pm 0.045 \quad (0.5\,\sigma)$$

$|Vub|_{incl}$ strenghten the case for NP in B_d mixing, this in turns implies a larger effect in $|Vub|_{excl}$

Final Messages

- *Unquenched Lattice-QCD + correlations → hint for a breakdown of the CKM paradigm at 3.x σ level*
- Most probable culprit is B_d mixing (B→τν & K mixing also possible)
- *Determinations of V_{ub} are a problem (3.3σ). Solution:*
  - *ignore (more theoretical work to understand QCD)*
  - *take seriously (new physics in right-handed currents)*
  - *Vub is not necessary to overconstrain the fit (i.e. its temporary exclusion allows to cast the UT fit as a clean & high-precision tool to identify NP)*
- Super-B precision on B→τν & improvements on $f_{B_s}\sqrt{B_s}$ will test the SM at the 5σ level
- Interpretation in terms of new physics points to *O(1)* phases and mass scales in the few hundred GeV range

Back-up Slides

K mixing (ε_K)

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

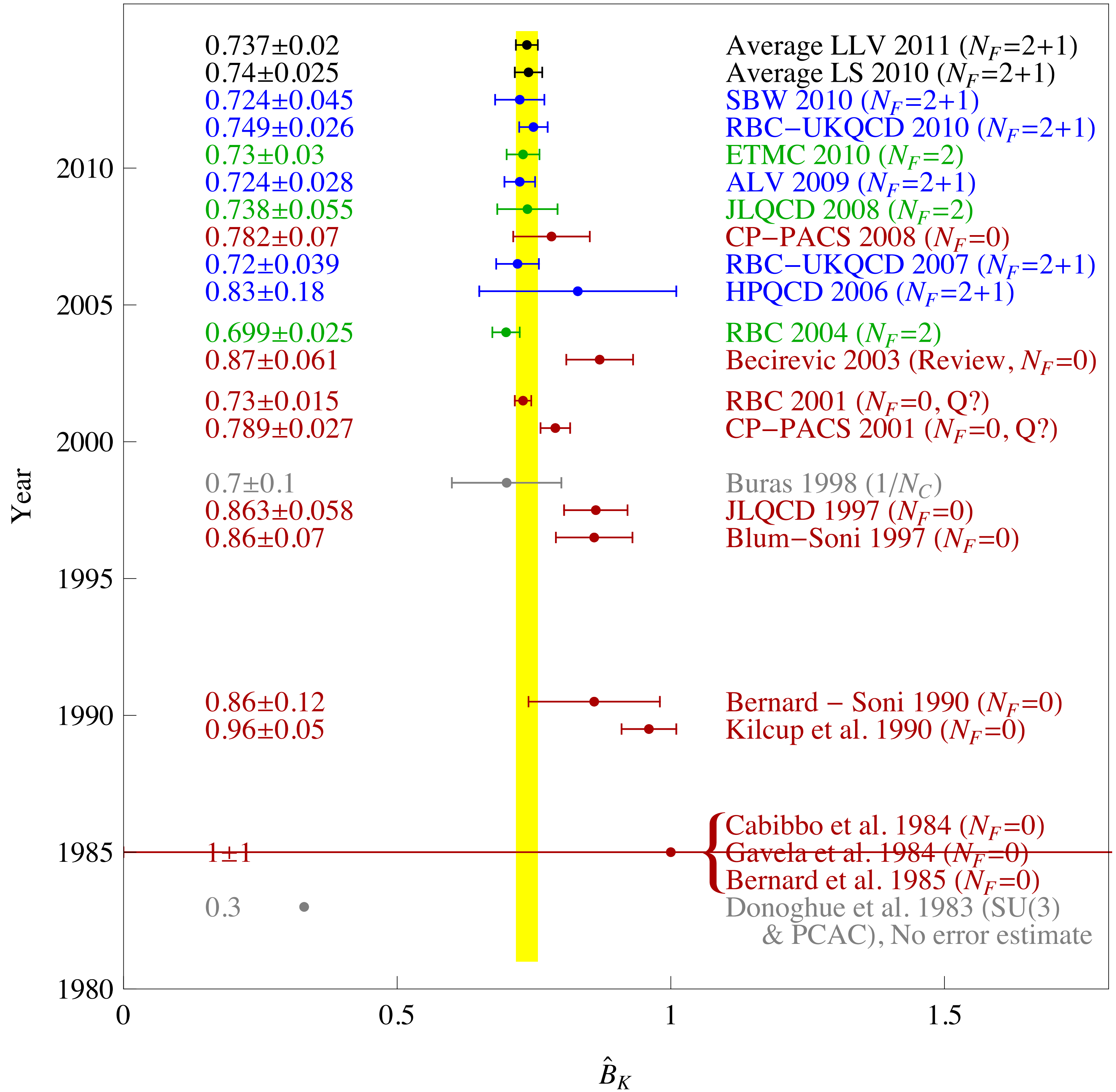
- Note the quartic dependence on V_{cb}: $|V_{cb}|^4 \sim A^4 \lambda^8$
- Critical input from lattice QCD

$$\langle K^0 | \mathcal{O}_{VV+AA}(\mu) | \bar{K}^0 \rangle = \frac{8}{3} f_K^2 M_K^2 B_K(\mu)$$

	B_K	$(\delta B_K)_{stat}$	$(\delta B_K)_{syst}$
Aubin, Laiho, Van de Water '09	0.724	0.008	0.029
HPQCD/UKQCD '06	0.83	0.02	0.18
RBC/UKQCD '10	0.749	0.007	0.026
Seoul, BNL, Washington '10	0.724	0.012	0.043
Average: 0.737 ± 0.020		(0.0056)	

$$\hat{B}_K = 0.737 \pm 0.020$$

History of BK



K mixing (ε_K)

- Alternative calculations of κ_ε
  - Large Nc + some quenched lattice results:

$$\kappa_\varepsilon = 0.92 \pm 0.02$$

[Andryiash,Ovanesyan,Vysotsky; Nierste; Buras,Jamin; Bardeen,Buras,Gerard; Buras,Guadagnoli]

  - Quenched lattice QCD:

Quenched	$\mathrm{Im}A_2 \times 10^{13}$ GeV
RBC '01 [51]	-12.6
CP-PACS '01 [52]	-9.1
SPQ$_{\mathrm{CD}}$R '04 [53]	-5.5
Babich et al '06 [54]	-9.2
Yamazaki '08 [55]	-11.8
Average	$\boxed{-9.6 \pm 9.6}$

very conservative

$$\kappa_\varepsilon = 0.92 \pm 0.02$$

[Laiho,EL,Van de Water]

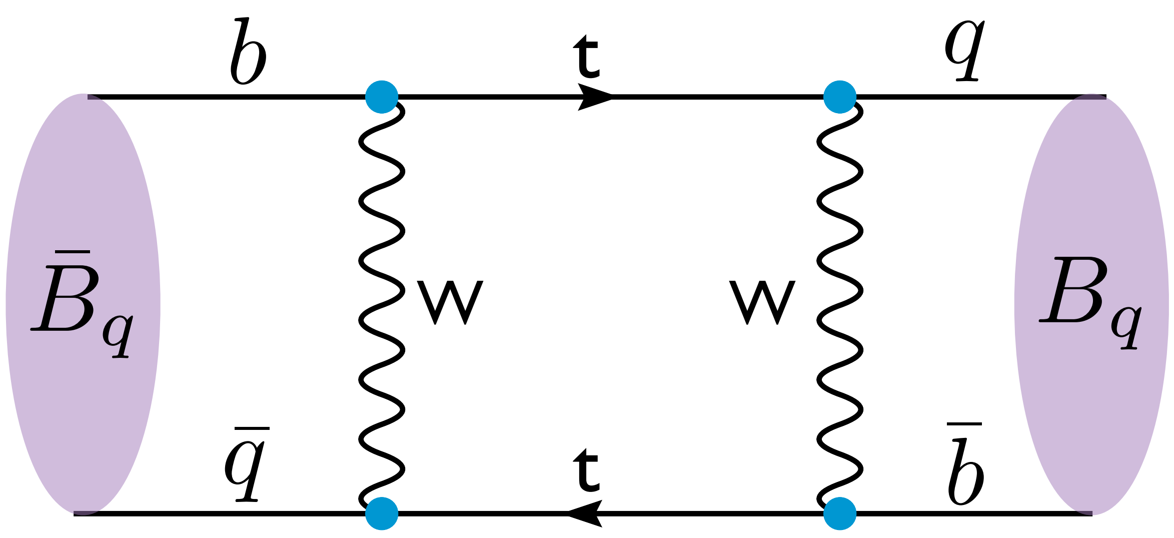
Excellent consistency of all determinations

B_q mixing

- Ratio of the B_s and B_d mass differences:

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

- No dependence on V_{cb}



- Two unquenched determinations:
  - FNAL/MILC: $\xi = 1.205 \pm 0.036 \pm 0.037$
  - HPQCD: $\xi = 1.258 \pm 0.025 \pm 0.021$
  - RBC/UKQCD: $\xi = 1.13 \pm 0.06 \pm 0.10$

- Average: $\xi = 1.237 \pm 0.032$

B_q mixing

- In the fit we utilize only ξ and $f_{B_s}\sqrt{B_s}$
- There is only one unquenched determination of the B_s matrix element from HPQCD but there are two determinations of f_{Bs} (FNAL/MILC and HPQCD):

	f_B (MeV)	$(\delta f_B)_{stat}$	$(\delta f_B)_{syst}$
FNAL/MILC '10	212	6	6
HPQCD '09	190	7	11
Average: (205 ± 12) MeV		(6.4)	
	f_{B_s} (MeV)	$(\delta f_{B_s})_{stat}$	$(\delta f_{B_s})_{syst}$
FNAL/MILC '10	256	6	6
HPQCD '09	231	5	14
Average: (250 ± 12) MeV		(5.4)	

+

	B_{Bd}	δB_{Bd}
HPQCD '09	1.26	0.11
Average: 1.26 ± 0.11		
	B_{Bs}	δB_{Bs}
HPQCD '09	1.33	0.06
Average: 1.33 ± 0.06		

$$f_B = (205 \pm 12)\ \mathrm{MeV}$$

$$f_{B_s}\sqrt{B_s} = (288 \pm 15)\ \mathrm{MeV}$$

HPQCD alone finds (266 ± 18) MeV

Three types of CP violation

- Mixing (mass and CP eigenstates are different)

$$\Gamma(\bar{B}^0_{\rm phys}(t) \to \ell^+ \nu X) \neq \Gamma(B^0_{\rm phys}(t) \to \ell^- \bar{\nu} X)$$

- Decay

$$\Gamma(B^+ \to f^+) \neq \Gamma(B^- \to f^-)$$

- Interference in decays with and without mixing

$$\Gamma(\bar{B}^0_{\rm phys}(t) \to f_{CP}) \neq \Gamma(B^0_{\rm phys}(t) \to f_{CP})$$

Time dependent CP asymmetry in $b \to s\bar{s}s$

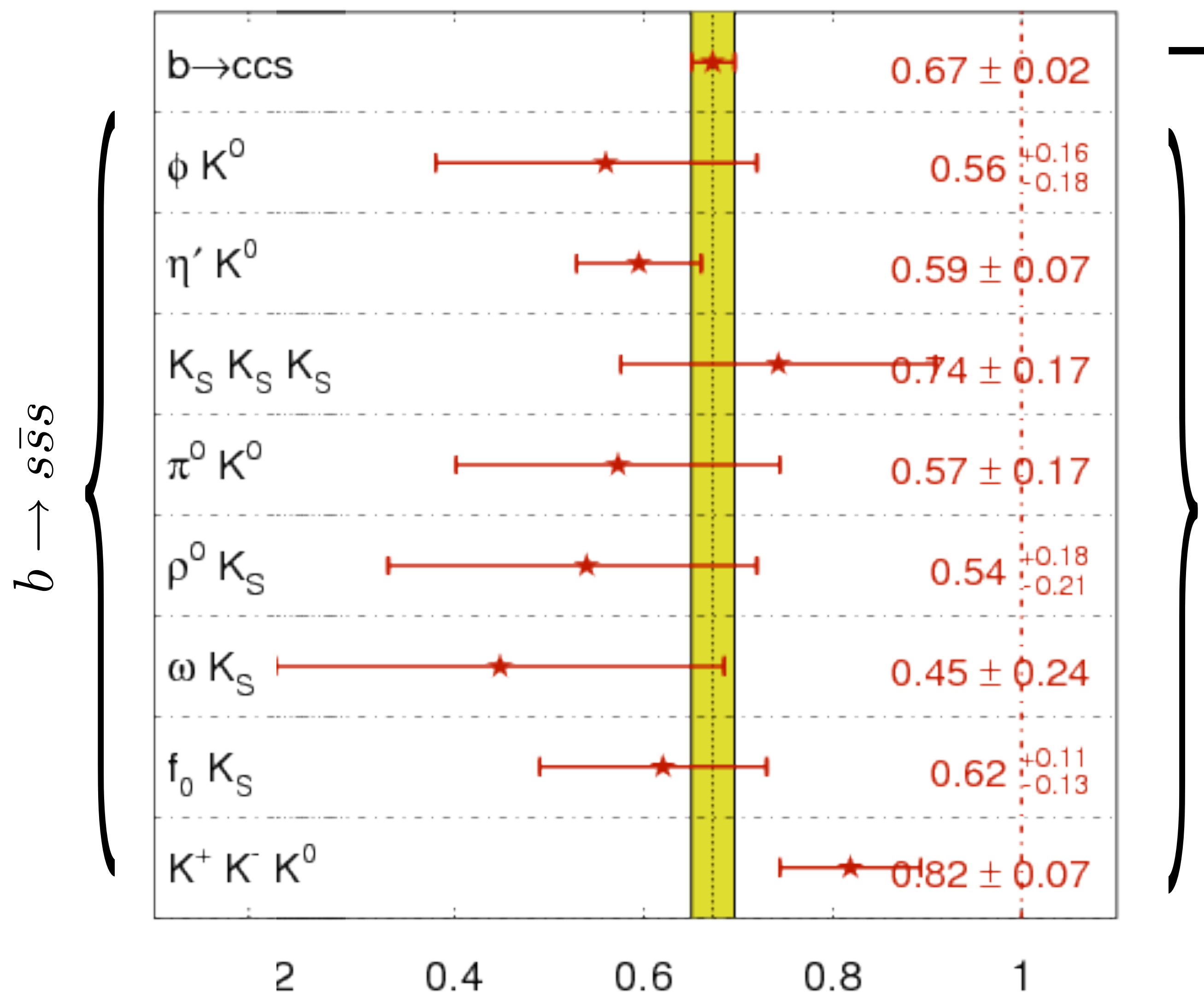
- No tree-level contribution
- There is no loop suppression of the sub-dominant CKM combination: uncertainty is (1-10)%

$$\mathcal{A} = (P^c - P^t)V_{cb}V_{cs}^* + (P^u - P^t)V_{ub}V_{us}^*$$

- Analyses in the framework of QCD factorization (SCET) and PQCD conclude that some modes *should* be very clean: $B \to \phi K_S$
  $B \to \eta' K_S$

Time dependent CP asymmetry in $b \to q\bar{q}s$

[HFAG 2010]



$$\to S_{\psi K_s} = \sin 2(\underbrace{\beta}_{\arg(V_{td}^*)} + \theta_d) + O(0.1\%)$$

In QCDF:

$$\Delta S_f \equiv S_f - \sin 2(\beta + \theta_d)$$

$$= 2 \underbrace{\left| \frac{V_{ub} V_{us}^*}{V_{cb} V_{cs}^*} \right|}_{0.025} \cos 2\beta \, \sin\gamma \, \mathrm{Re}\left(\frac{a_f^u}{a_f^c} \right)$$

$$\Delta S_\phi = 0.03 \pm 0.01$$ [Beneke,Neubert]

$$\Delta S_{\eta'} = 0.01 \pm 0.025$$ [EL, Soni]

Other approaches find similar results [Chen,Chua,Soni; Buchalla,Hiller,Nir,Raz]

- We will consider the asymmetries in the $J/\psi,\ \phi,\ \eta'$ modes
- A case can be made for the $K_s K_s K_s$ final state [Cheng,Chua,Soni]

New Physics in penguin amplitudes

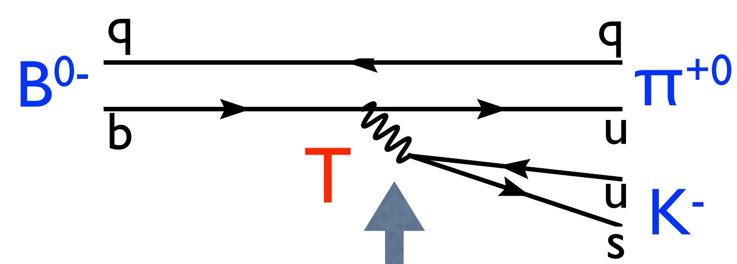
- Proper treatment of new physics effects in penguin amplitudes is better implemented with NP contributions to the *QCD* and *EW penguin* operators
- Correlation between the $b \to s\bar{s}s$ and Kπ asymmetries:

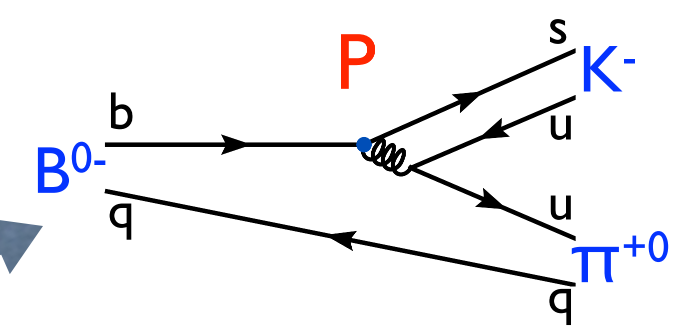
$$A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+) = \begin{cases} (14.8 \pm 2.8)\ \% & \text{exp} \\ (2.2 \pm 2.4)\ \% & \text{QCDF} \end{cases}$$

- QCDF result very stable under variation of all the inputs
- Possible issue with large color suppressed contributions to the $K^-\pi^0$ final state

CP asymmetries in B→Kπ

- Amplitudes in QCD factorization:

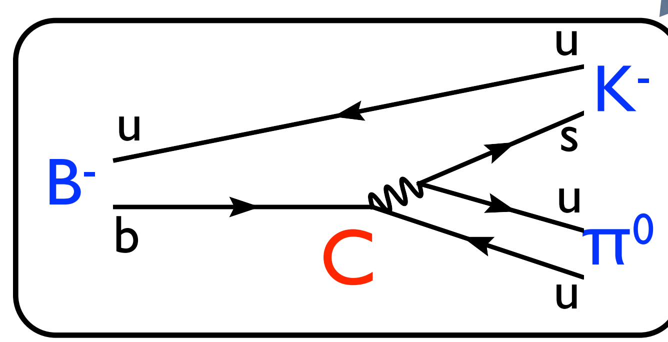


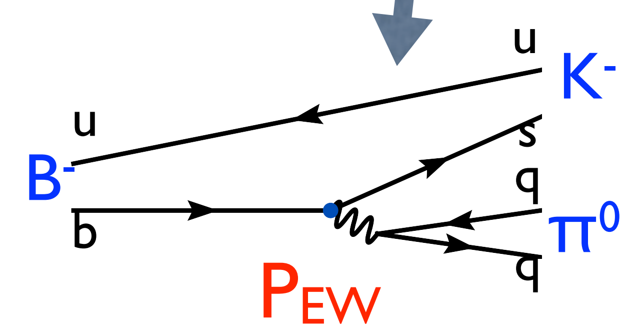


$$\mathcal{A}_{\bar B^0\to\pi^+K^-} = A_{\pi\bar K}\sum_{q=u,c} V_{qb}V_{qs}^*\,[\delta_{qu}\alpha_1+\hat\alpha_4^q]$$

$$\sqrt{2}\mathcal{A}_{B^-\to\pi^0K^-} = \mathcal{A}_{\bar B^0\to\pi^+K^-} + A_{\bar K\pi}\sum_{q=u,c}V_{qb}V_{qs}^*\left[\delta_{qu}\alpha_2+\delta_{qc}\frac{3}{2}\alpha^c_{3,EW}\right]$$

color suppressed
[Gronau,Rosner] ←



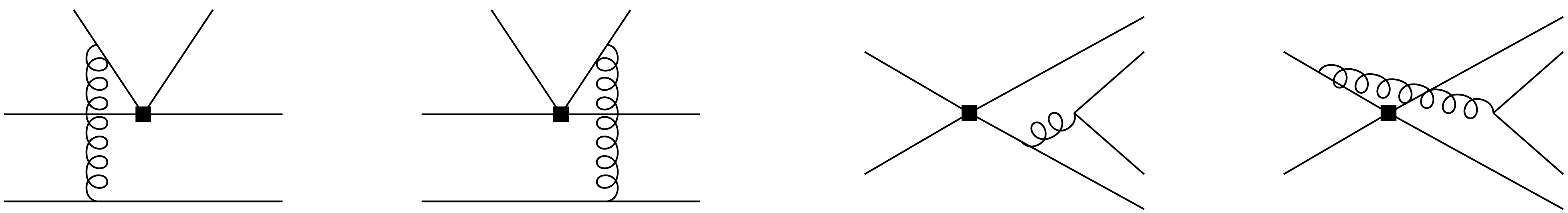


- We get: $\frac{P}{T}\simeq 0.20,\ \boxed{\frac{C}{T}\simeq 0.16},\ \frac{P_{\rm EW}}{T}\simeq 0.47$

fits yield C/T ~ 0.6

CP asymmetries in B→Kπ

- In QCDF: $A_{CP}(B^- \to K^- \pi^0) - A_{CP}(\bar{B}^0 \to K^- \pi^+) = (2.2 \pm 2.4)\ \%$
- Dominant sources of uncertainties
  - light-cone wave function parameters: $\alpha_1^K,\ \alpha_2^K,\ \alpha_2^\pi,\ \lambda_B$
  - end-point singularities: $\rho_H,\ \varphi_H,\ \rho_A,\ \varphi_A$



$$X_H = \left(1 + \rho_H\, e^{i\varphi_H}\right) \log \frac{m_B}{\Lambda}$$

hard scattering

$$X_A = \left(1 + \rho_A\, e^{i\varphi_A}\right) \log \frac{m_B}{\Lambda}$$

weak annihilation

- NP contributions to the QCD and EW penguin

Operator Level Analysis: $b \to s$ amplitudes

- Effective Hamiltonian:

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left(\sum_{i=1}^{6} C_i(\mu) O_i(\mu) + \sum_{i=3}^{6} C_{iQ}(\mu) O_i(\mu) \right)$$

$$\boxed{Q_4 \;=\; (\bar{s}_L \gamma^\mu T^a b_L) \sum_q (\bar{q} \gamma_\mu T^a q) \qquad Q_{3Q} \;=\; (\bar{s}_L \gamma^\mu b_L) \sum_q Q_q \, (\bar{q} \gamma_\mu q)}$$

likely to receive NP corrections

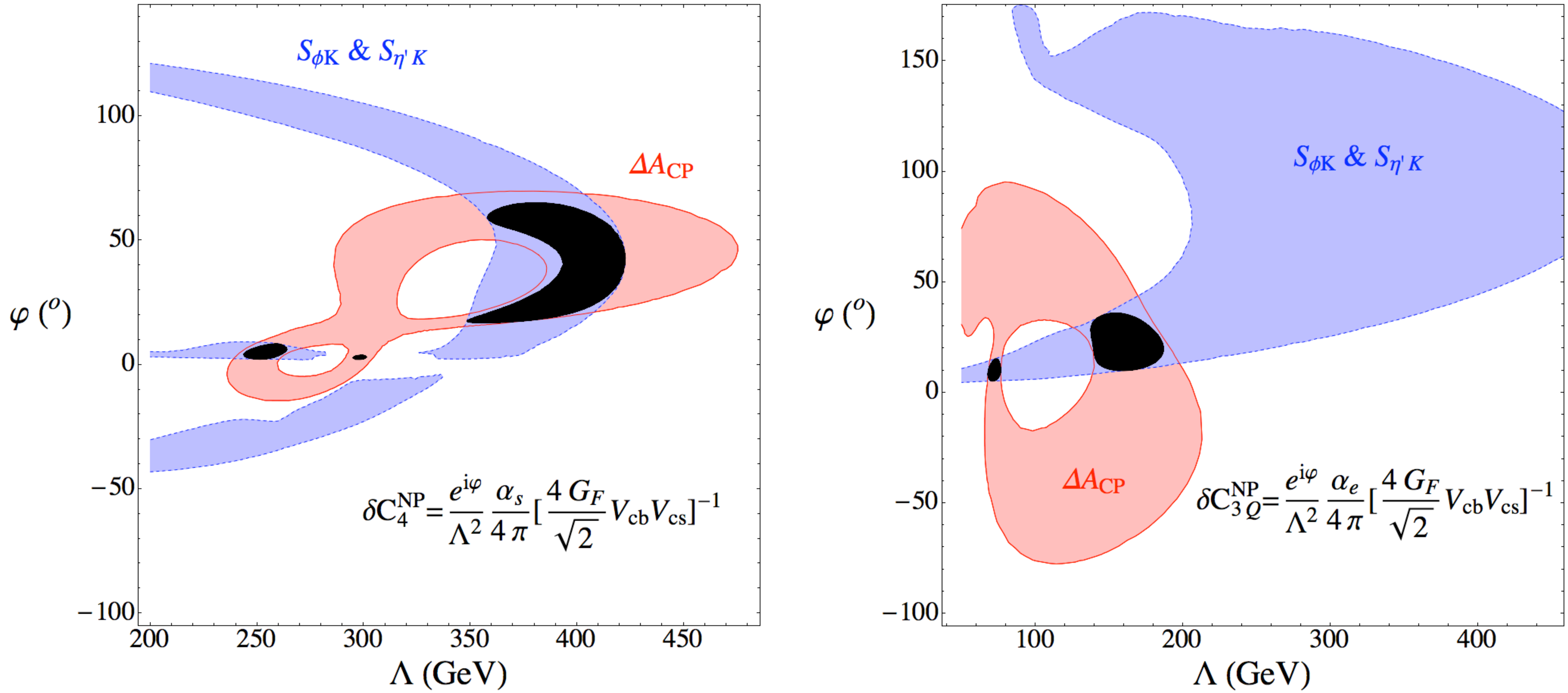
- Assume the following parametrization of NP effects:

$$\delta C_{4,3Q}(\mu_0) = \frac{\alpha_{s,e}}{4\pi} \frac{e^{i\varphi}}{\Lambda^2} \left[\frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \right]^{-1}$$

loop suppression + QED/QCD penguin $g_{s,e}$ dependence

Effective mass scale that absorbs NP couplings

Operator Level Analysis: $b \to s$ amplitudes



$\Lambda \sim [350 \div 420]$ GeV $\qquad$ $\Lambda \sim [140 \div 190]$ GeV

Model Independent Interpretation

- The tension in the UT fit can be interpreted as evidence for new physics contributions to ε_K and to the phases of *B_d mixing* and of $b \to s$ *amplitudes*:

$$\begin{aligned} \varepsilon_K &= \varepsilon_K^{\rm SM} C_\varepsilon \\ M_{12} &= M_{12}^{\rm SM}\, e^{2i\phi_d}\, r_d^2 \\ A(b \to s\bar{s}s) &= [A(b \to s\bar{s}s)]_{\rm SM}\, e^{i\theta_A} \end{aligned}$$

- This implies:

$$\begin{aligned} S_{\psi K_s} &= \sin 2(\beta + \phi_d) \\ \sin 2\alpha_{\rm eff} &= \sin 2(\alpha - \phi_d) \\ \Delta M_{B_d} &= (\Delta M_{B_d})^{\rm SM}\, r_d^2 \\ a_{(\phi,\eta')K_s} &= \sin 2(\beta + \phi_d + \theta_A) \end{aligned}$$

- In general NP will affect in different ways the various $b \to s$ channels