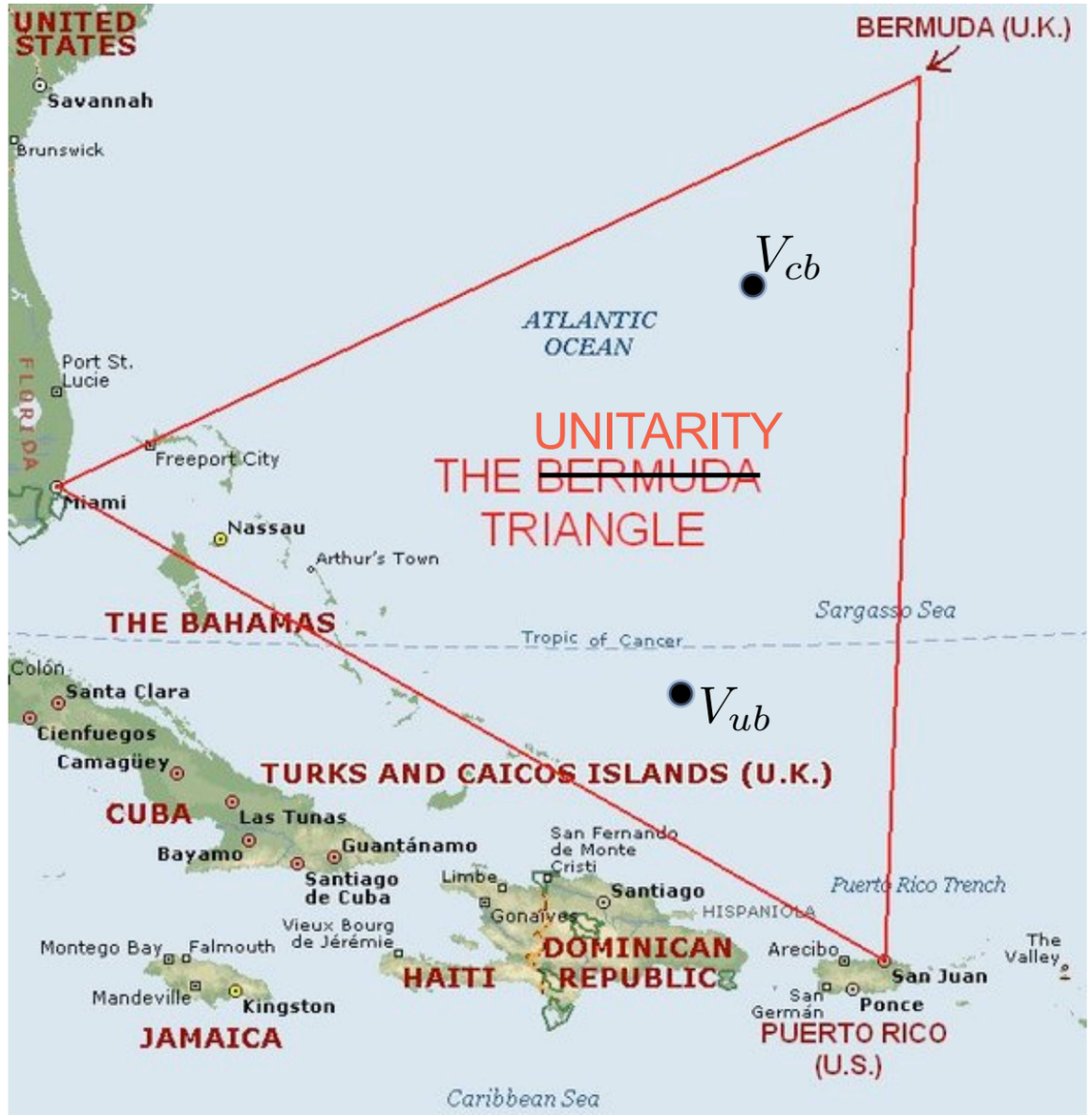
High Precision Flavor Physics



Enrico Lunghi
Indiana University

E.L. and A. Soni: *0707.0212, 0803.4340, 0903.5059*
J. Laiho, E.L., R. Van de Water: 0910.2928

The Cabibbo✹-Kobayashi★-Maskawa★ matrix

Gauge interactions do not violate flavor:

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

ψ, a, b → family indices

ψ → fermion type

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:

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

✹ = Virtual Nobel Laureate
★ = Real Nobel Laureate

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From *Gauge* to *Mass* eigenstates

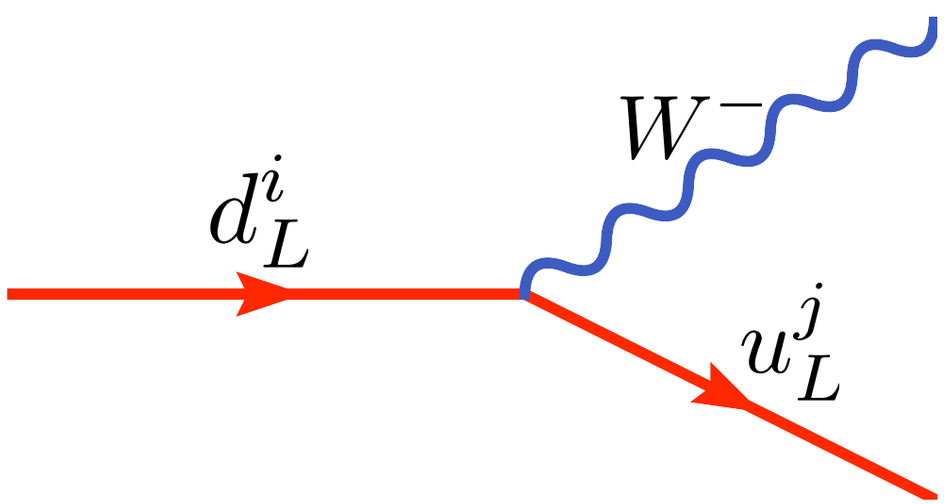
- neutral currents:

$$\bar{u}_L^0 \not{Z}\, u_L^0 \Longrightarrow \bar{u}_L \not{Z}\, U_L U_L^\dagger u_L = \bar{u}_L \not{Z}\, u_L$$

- charged currents:

$$\bar{u}_L^0 \not{W}\, d_L^0 \Longrightarrow \bar{u}_L \not{W}\, U_L D_L^\dagger d_L = \bar{u}_L \not{W}\, V_{\mathrm{CKM}} d_L$$

3 angles + 1 phase



$\propto V_{ji}$

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The Cabibbo✹-Kobayashi★-Maskawa★ matrix

Standard parametrization (θ_{12}, θ_{23}, θ_{13}, δ):

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$
- $\theta_{13} << \theta_{23} << \theta_{12}, \delta \sim O(1)$

Wolfenstein parametrization (λ, A, ρ, η):

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

- $\lambda, A, \rho, \eta \sim O(1)$

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The Cabibbo✹-Kobayashi★-Maskawa★ matrix

λ: β-decay, K→πlν, D→(π,K)lν, νN→μX, ...

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

ρ,η: B→πlν, B→X_ulν
CP violation

A: B→$D^{(*)}$lν, B→X_clν

=1: t→Wb (single top)

A: no direct meas. (B→X_sγ, ΔM_{Bs}, ...)

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

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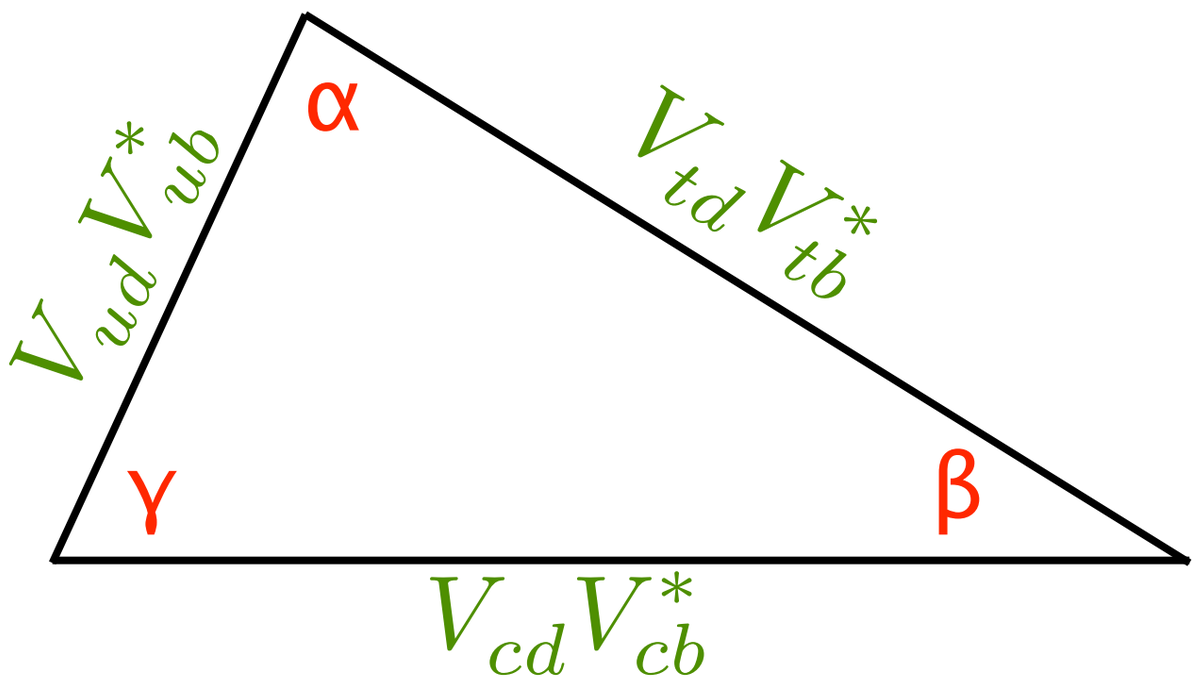
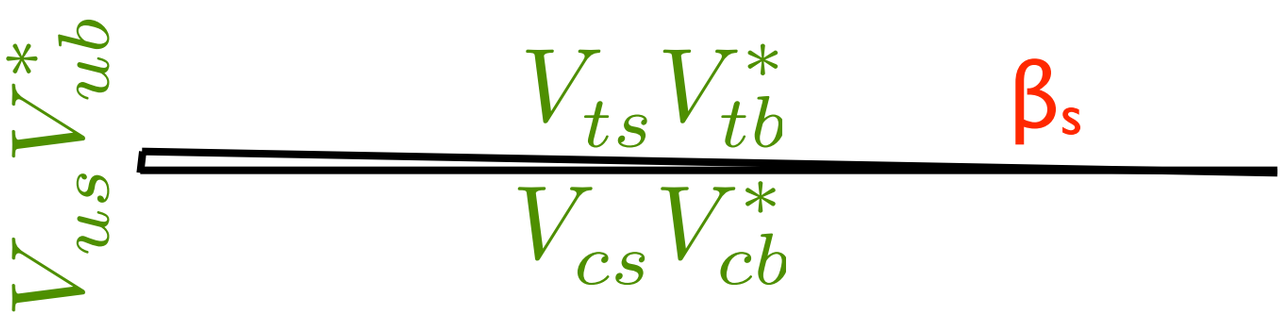
The Cabibbo✹-Kobayashi★-Maskawa★ matrix

Unitarity Triangles:



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



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

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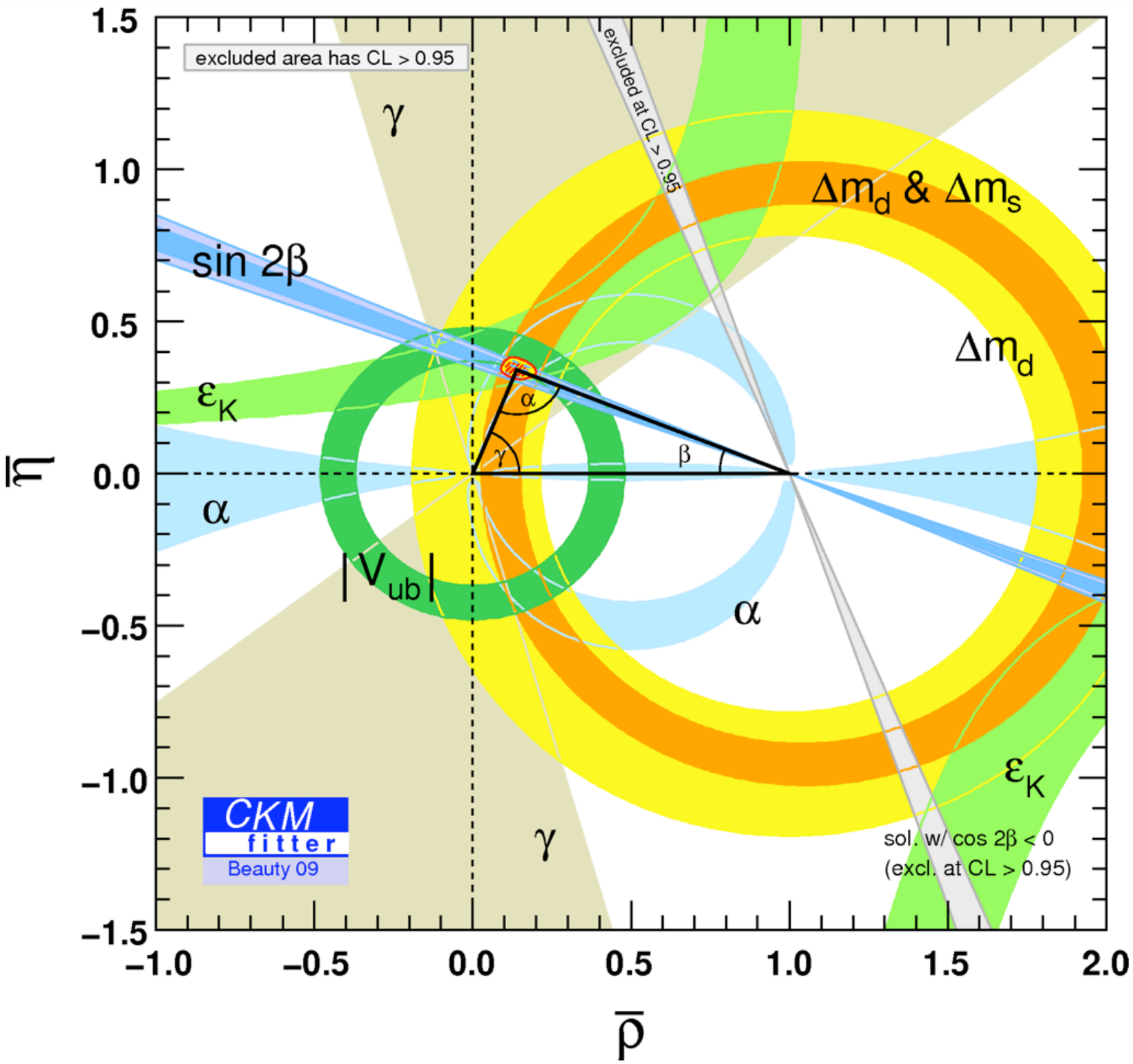
The Unitarity Triangle Fit



ε_K: CP violation in K mixing

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

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

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

Treatment of lattice inputs and errors

- Lattice QCD presently delivers *2+1 flavors* (aka unquenched) determinations *for all the quantities* that enter the fit to the UT
- Results coming 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]
- We assume all errors to be normally distributed (!)

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

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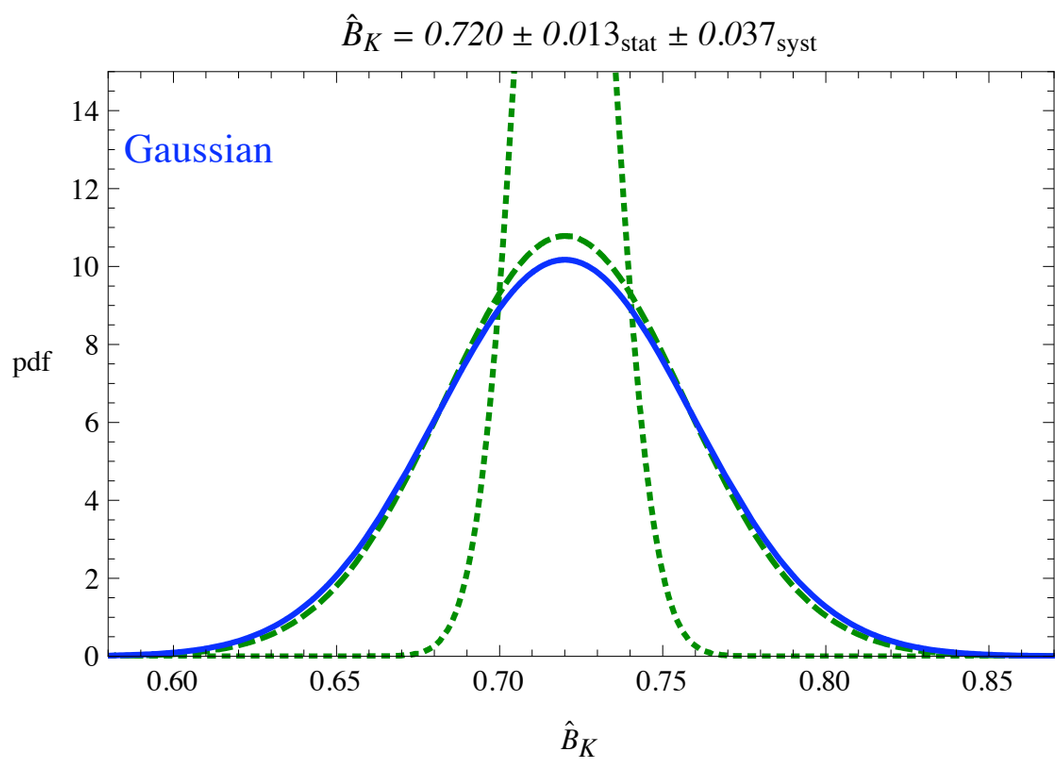

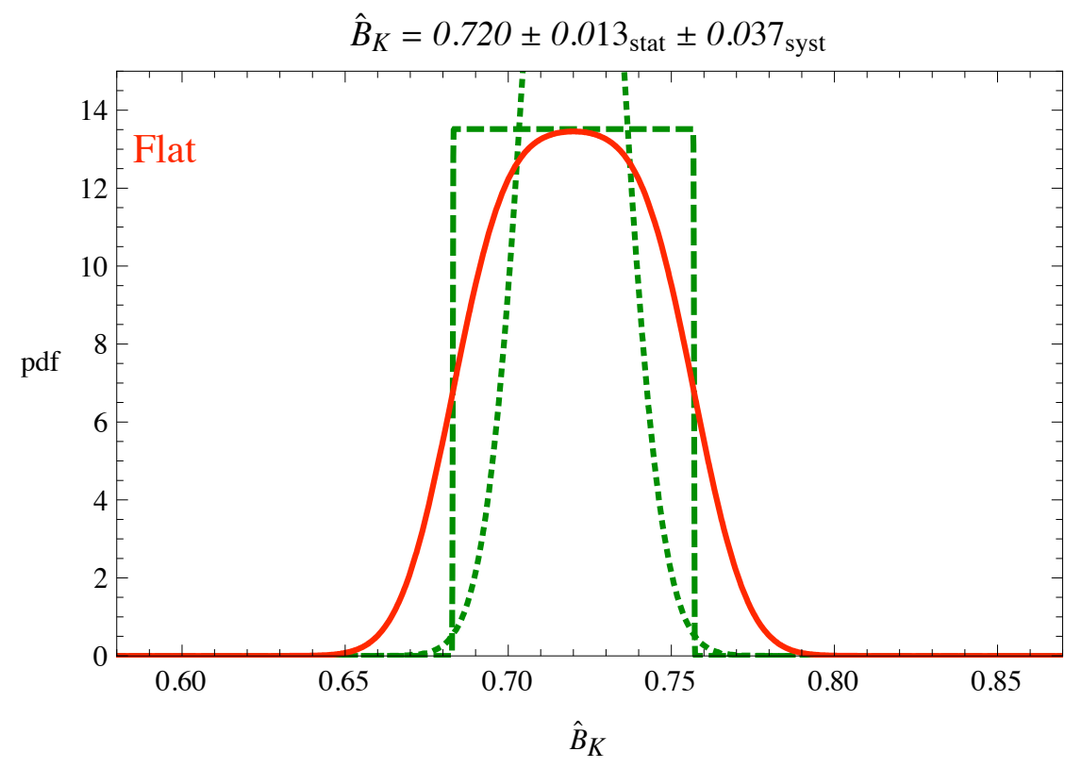

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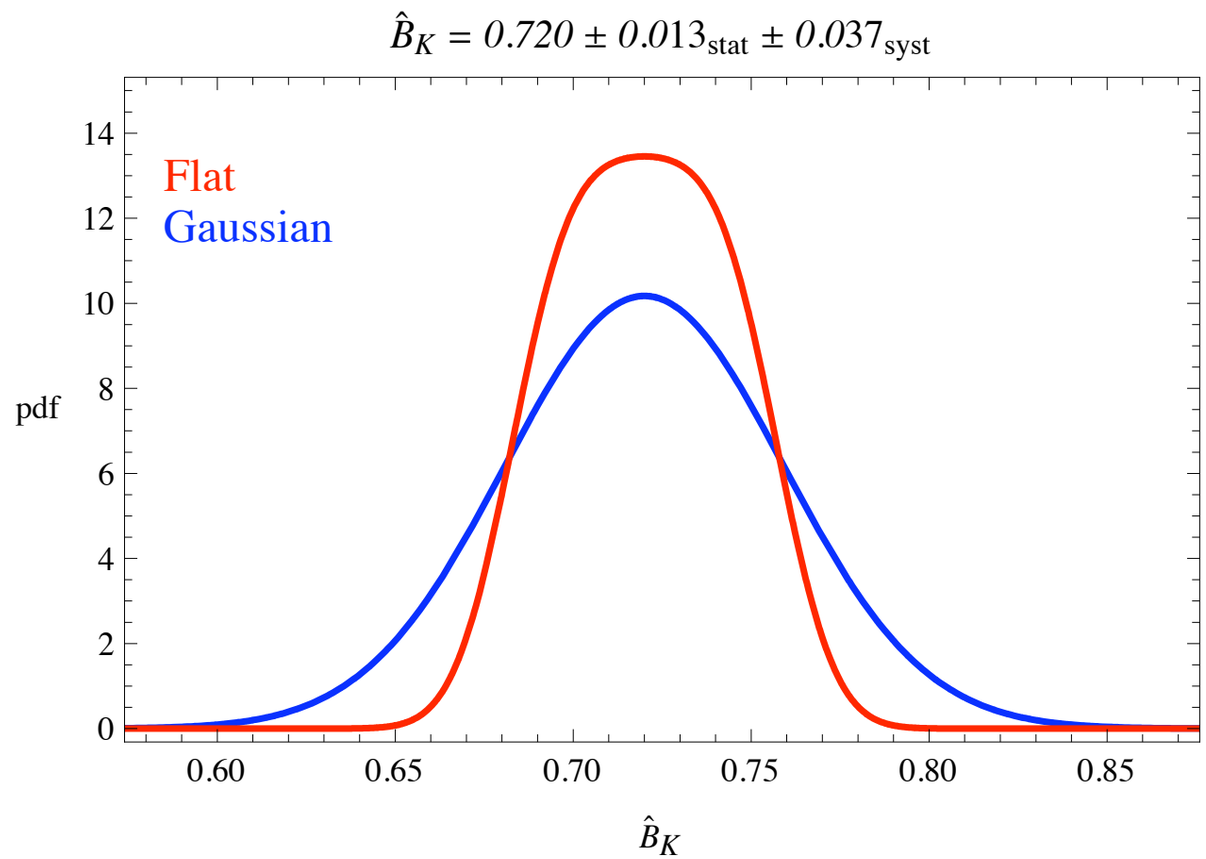

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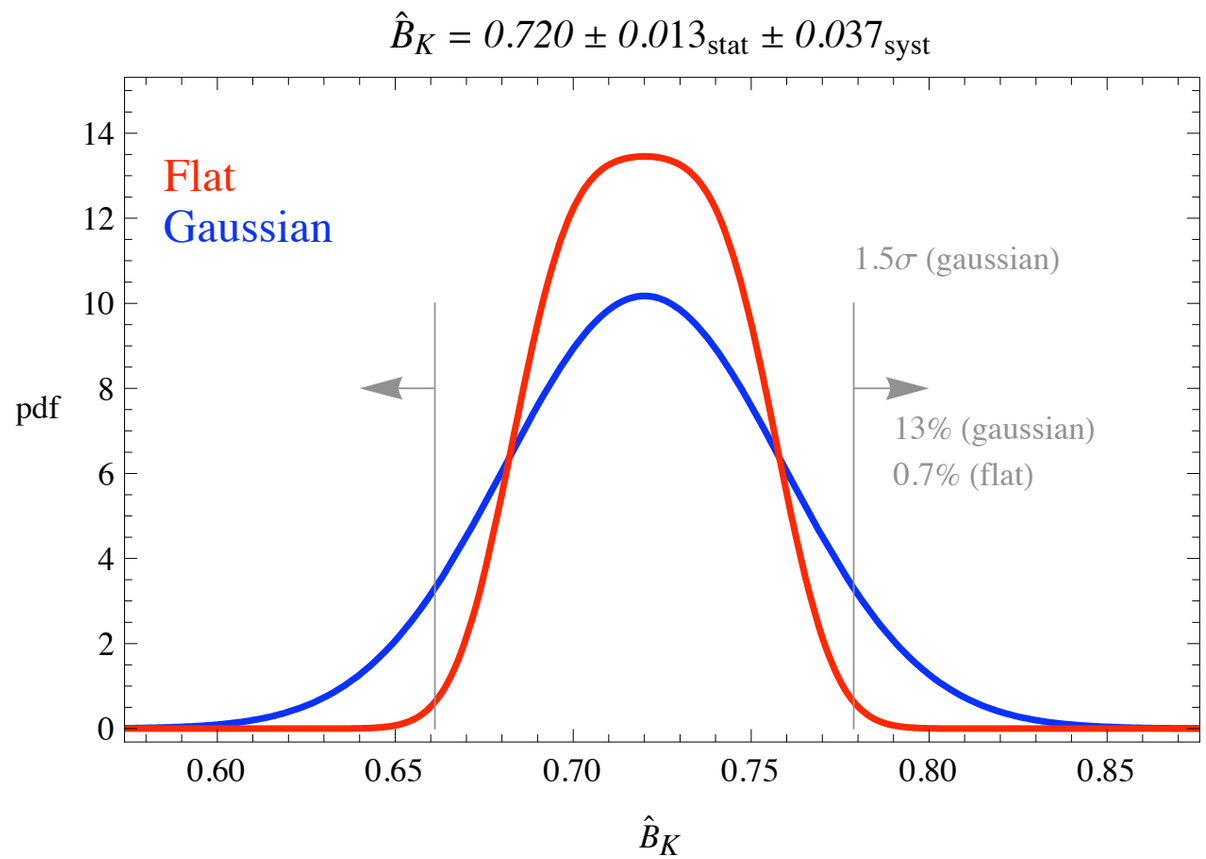
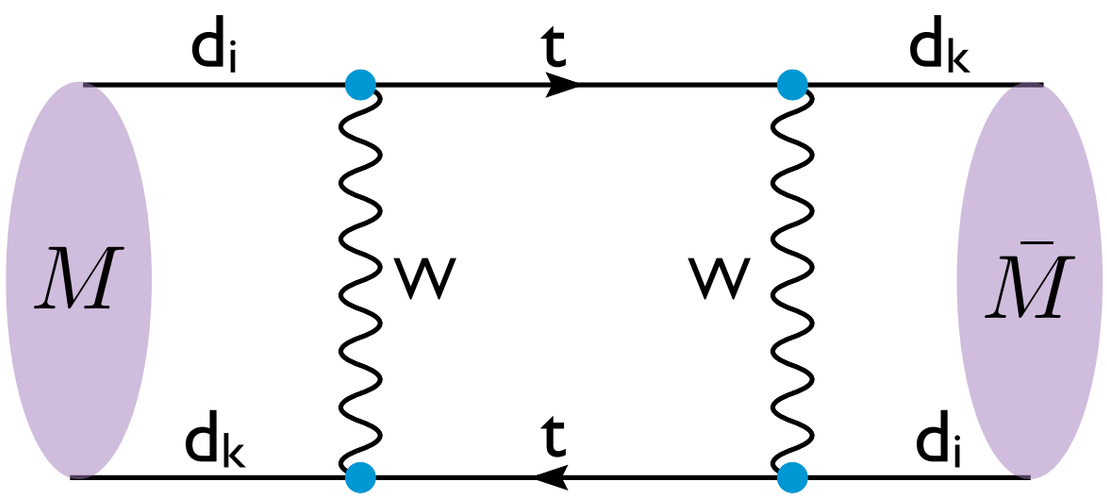


Meson Mixing



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

- The meson-antimeson amplitude can be written as:

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

Dominated by perturbative physics

Dominated by long distance effects

K mixing (ε_K)

- Mass and CP eigenstates are different:

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

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

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

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

indirect (ε) $\longrightarrow$ $\pi\pi$

direct (ε') $\longrightarrow$ $\pi\pi$

K mixing (ε_K)

$$
\begin{aligned}
\varepsilon_K &= \frac{A(K_L \to (\pi\pi)_{I=0})}{A(K_S \to (\pi\pi)_{I=0})} \\
&= e^{i\phi_\varepsilon} \sin\phi_\varepsilon \left(\frac{\mathrm{Im} M_{12}^K}{\Delta M_K} + \frac{\mathrm{Im} A_0}{\mathrm{Re} A_0} \right) \\
&= e^{i\phi_\varepsilon} \kappa_\varepsilon C_\varepsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \eta \Big(|V_{cb}|^2 (1-\bar{\rho}) + \eta_{tt} S_0(x_t) \\
&\quad + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c \Big)
\end{aligned}
$$

Γ_{12}^K

- Critical inputs:
  - $\hat{B}_K$ from lattice QCD
  - $|V_{cb}|$ from inclusive and exclusive $b \to c\ell\nu$ decays
  - κ_ε in the SM from $(\varepsilon'_K/\varepsilon_K)_{\mathrm{exp}}$ and lattice QCD

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]
  - $\mathrm{Im}A_2 = (-7.9 \pm 4.2) \times 10^{-13}\ \mathrm{GeV}$ [RBC/UK-QCD] 1st unquenched attempt!
- Combining everything:

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

[Laiho,EL,Van de Water]

K mixing (ε_K)

- 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	-9.6 ± 9.6

very conservative

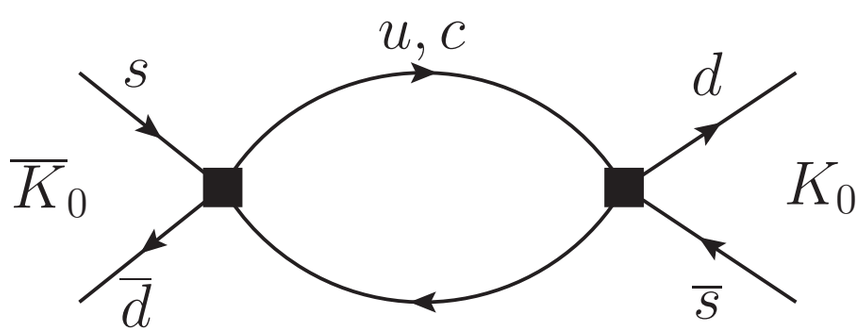
$$\kappa_\varepsilon = 0.92 \pm 0.02$$

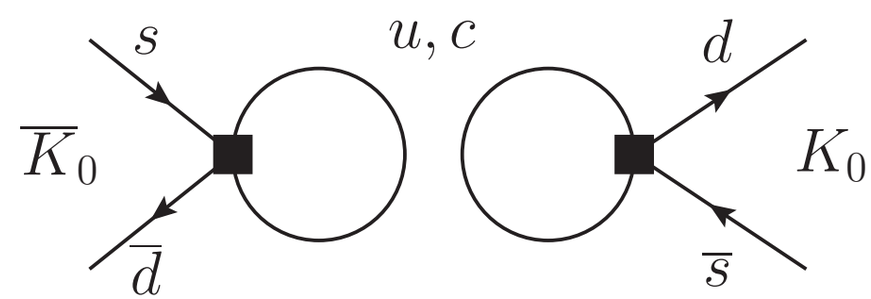
[Laiho,EL,Van de Water]

Excellent consistency of all determinations

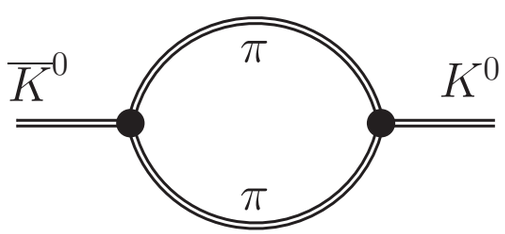
K mixing (ε_K)

- 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 $\mathrm{Im}A_0$ we obtain:



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

-6% !

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

K mixing (ε_K)

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

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

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

		$\widehat{B}_K$	$(\delta\widehat{B}_K)_{\rm stat}$	$(\delta\widehat{B}_K)_{\rm syst}$
	HPQCD/UKQCD '06 [17]	0.83	0.02	0.18
2+1 DW fermions →	RBC/UKQCD '07 [18]	0.720	0.013	0.037
2+1 DW valence fermions and 2+1 staggered sea configurations ↗	Aubin, Laiho & Van de Water '09 [19]	0.724	0.008	0.028
	Average	0.725 ± 0.026		

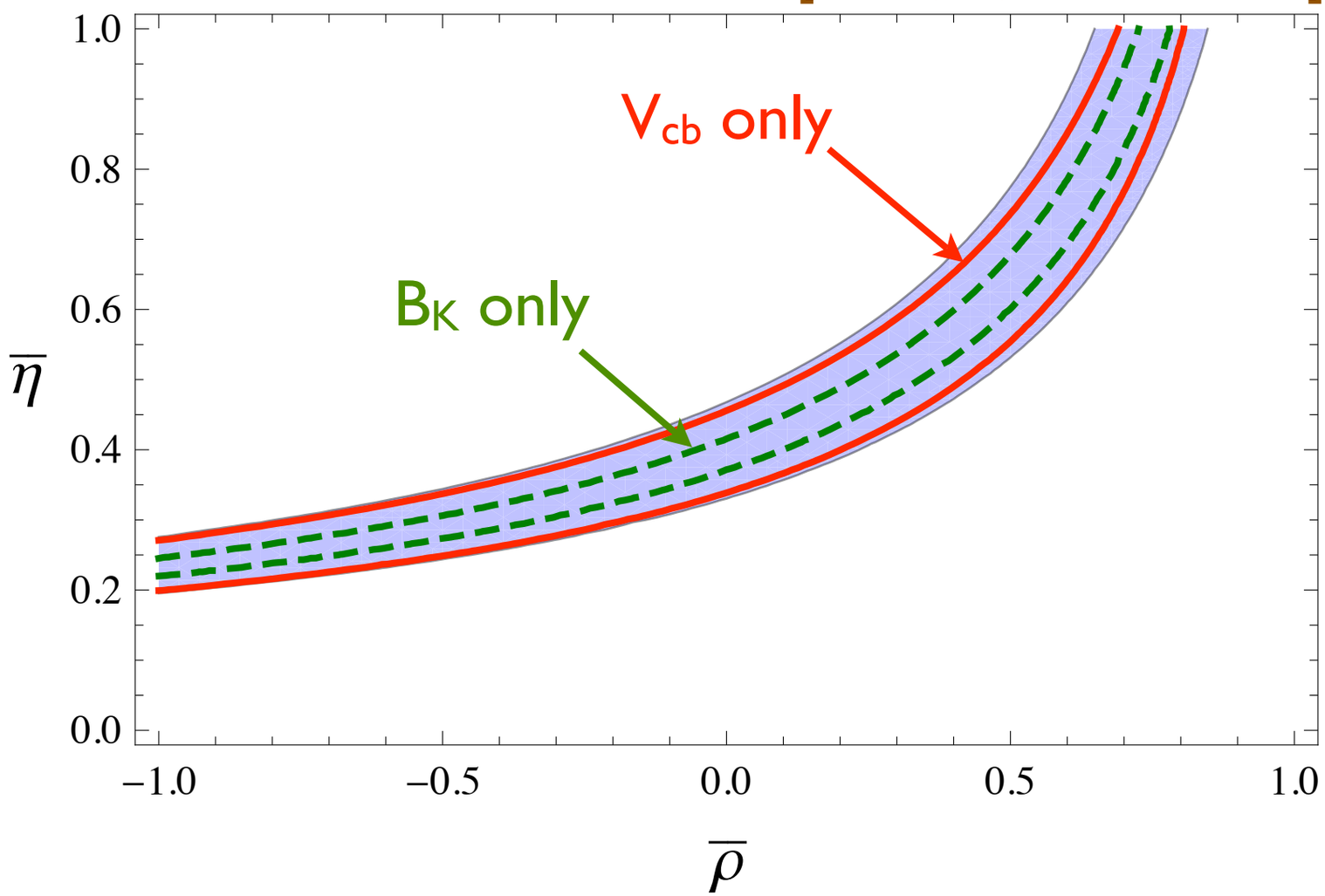
$$\hat{B}_K = 0.725 \pm 0.026$$

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_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: $\xi = 1.258 \pm 0.025 \pm 0.021$

- Average: $\xi = 1.243 \pm 0.034$

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)	$(\delta f_B)_{\rm stat}$	$(\delta f_B)_{\rm syst}$
FNAL/MILC '08 [28]	195	7	9
HPQCD '09 [29]	190	7	11
Average	192.8 ± 9.9		

	f_{B_s}(MeV)	$(\delta f_{B_s})_{\rm stat}$	$(\delta f_{B_s})_{\rm syst}$
FNAL/MILC '08 [28]	243	6	9
HPQCD '09 [29]	231	5	14
Average	238.8 ± 9.5		

+

	$\widehat{B}_{B_d}$	$\widehat{B}_{B_s}$
HPQCD '09 [29]	1.26 ± 0.11	1.33 ± 0.06

$$f_B = (192.8 \pm 9.9)\ \text{MeV}$$

$$f_{B_s}\sqrt{B_s} = (275 \pm 13)\ \text{MeV}$$

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

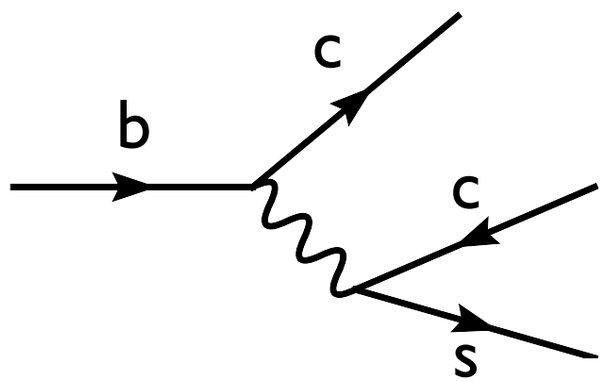
$$\Gamma(B^+ \to f^+) \neq \Gamma(B^- \to f^-)$$

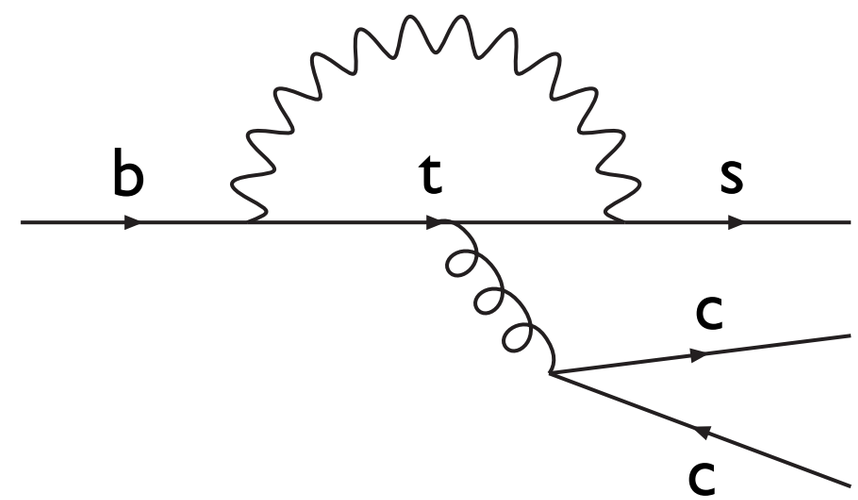
- Interference in decays with and without mixing

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

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

- 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*):

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

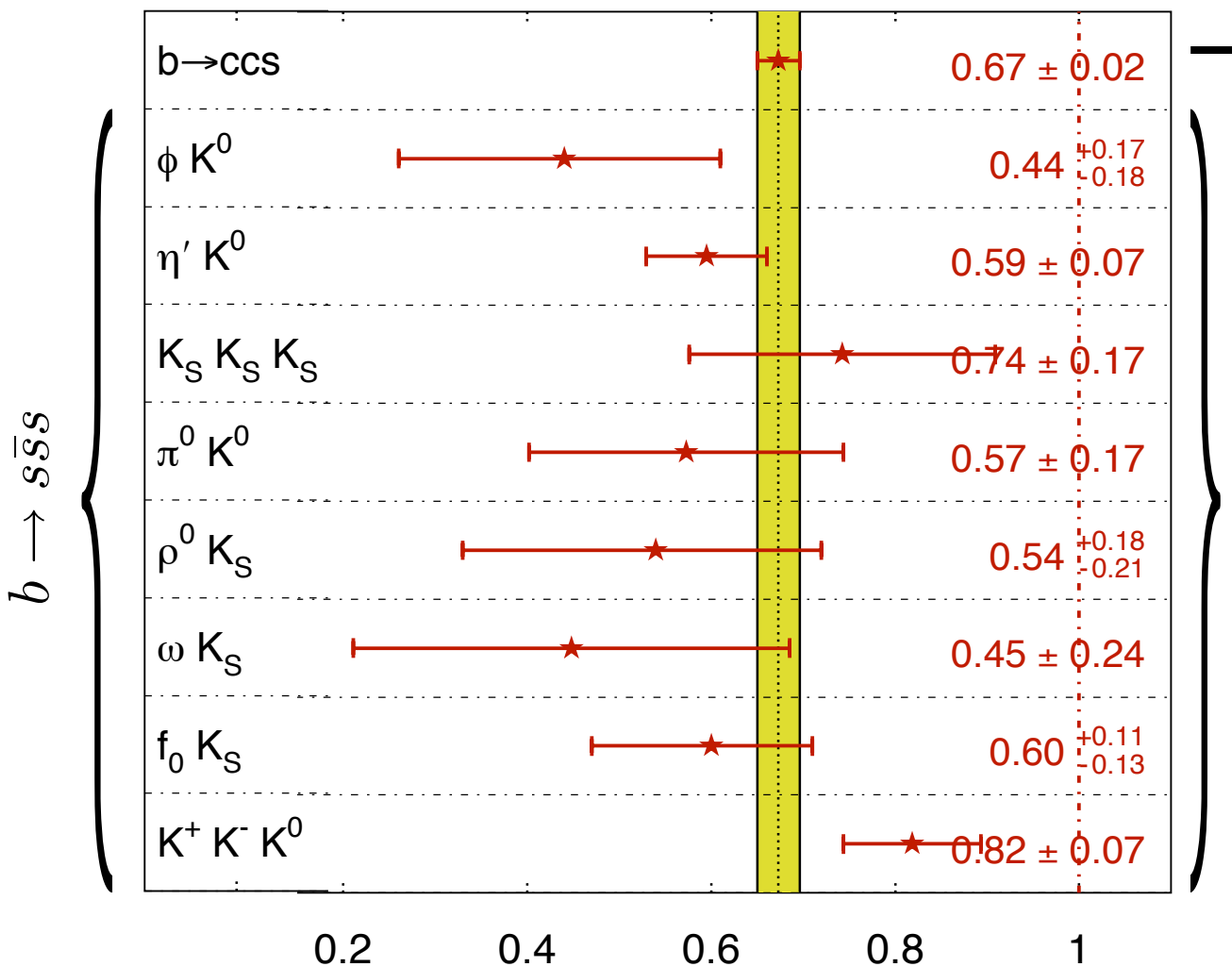
- No tree-level contribution
- There is no loop suppression of the sub-dominant CKM combination: uncertainty is (1-10)%

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

- 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 2009]



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

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]

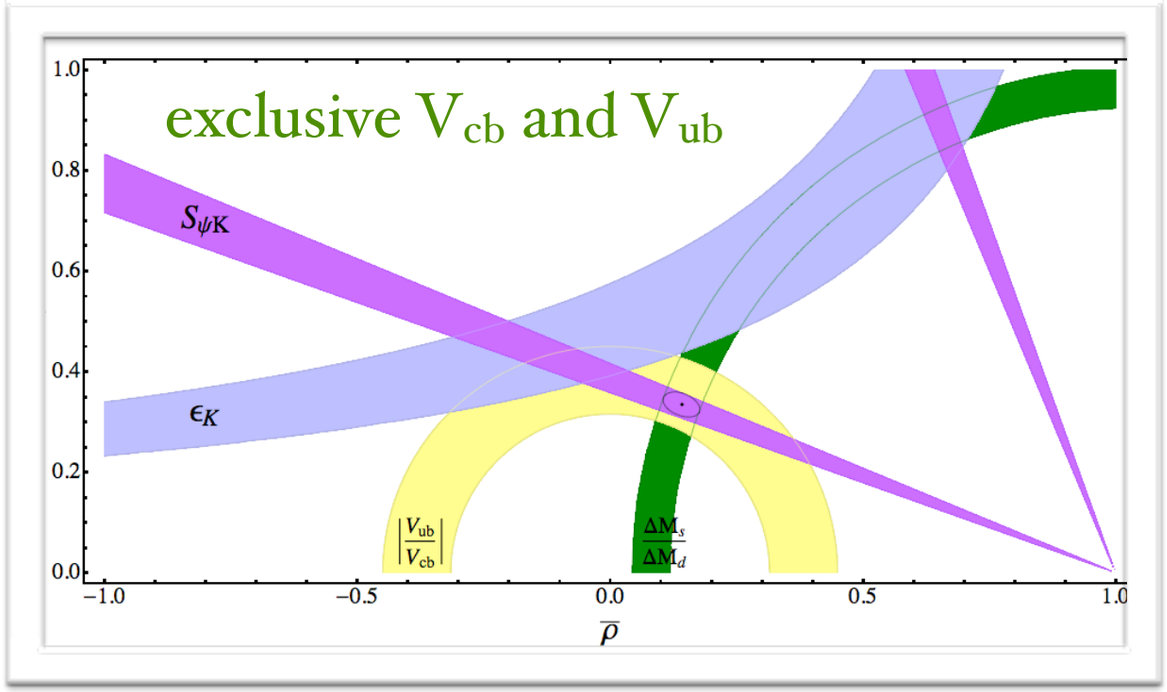
- We will consider the asymmetries in the $J/\psi,\ \phi,\ \eta'$ modes
- A case can be made for the $K_s K_s K_s$ final state [Cheng,Chua,Soni]

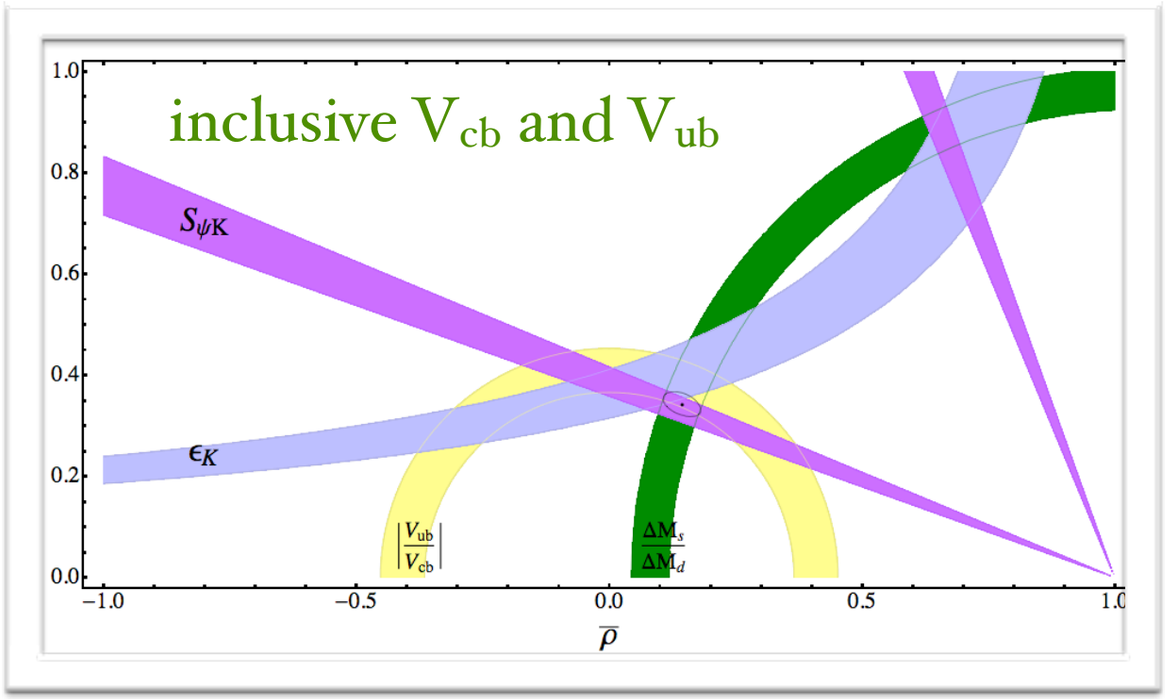
The role of V_{ub} and V_{cb}

- Inclusive and exclusive determinations of V_{cb} and V_{ub} are about 2σ apart

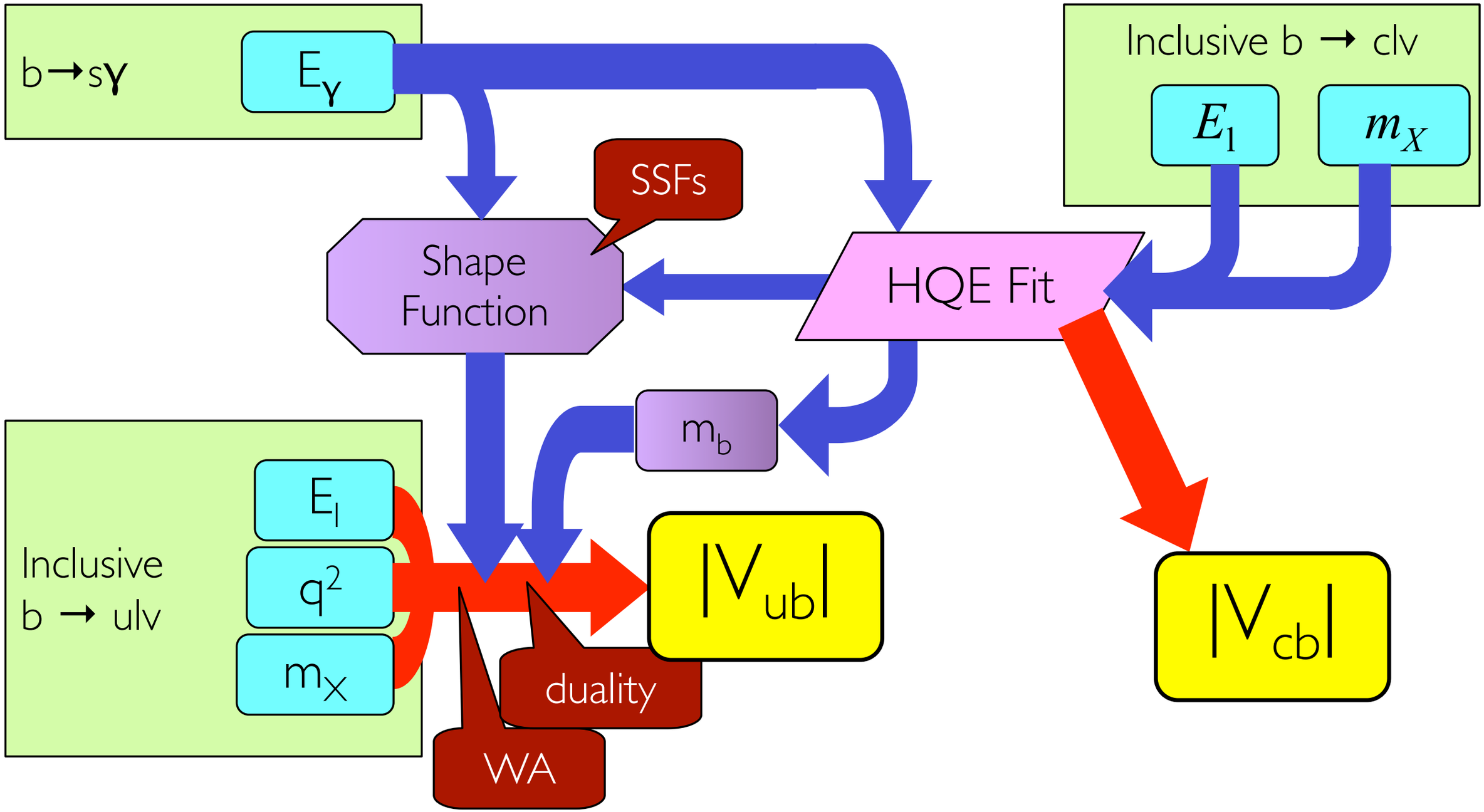
- V_{cb} is quite essential to establish the presence of NP in the UT

- V_{ub} is measured at tree-level and is not sensitive to NP. Its value is important to distinguish between NP in K or B mixing





Interplay between $b \to s\gamma$, V_{cb} and V_{ub}



[Phillip Urquijo]

V_{cb}

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

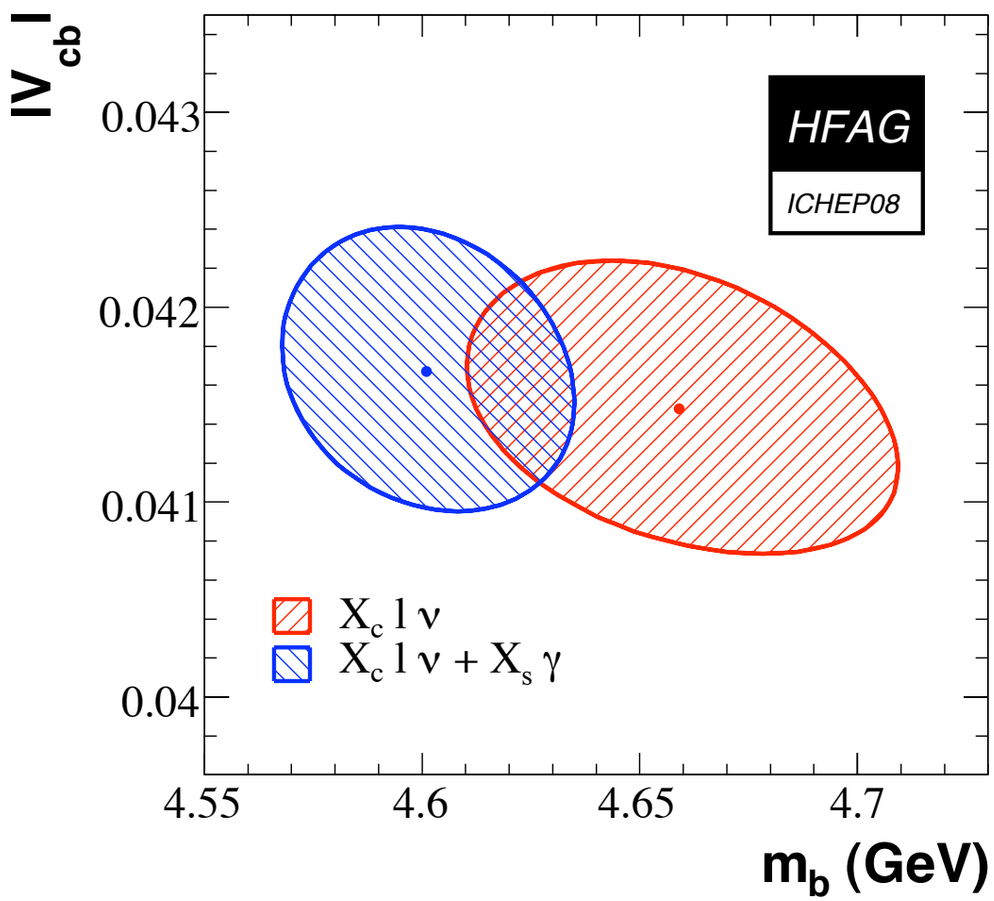
  [FNAL/MILC]

  $|V_{cb}| = (38.6 \pm 1.2) \times 10^{-3}$

  [average:Laiho,EL,Van de Water]

  [exp. error on $B \to D^*$ rescaled to account for the large χ^2/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
  - Calculation of $O(\alpha_s/m_b^2)$ under way
  - Issue of m_b is relevant for V_{ub}

  $|V_{cb}| = (41.31 \pm 0.76) \times 10^{-3}$

  2σ discrepancy between inclusive and exclusive

V_{ub}

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

$$|V_{ub}| = (3.42 \pm 0.37) \times 10^{-3}$$ [HPQCD, FNAL/MILC]

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

$$|V_{ub}| = \left(4.03 \pm 0.15_{\rm exp}{}^{+0.20}_{-0.25}{}_{\rm th}\right) 10^{-3}$$ [Gambino,Giordano,Ossola, Uraltsev (GGOU)]

$$|V_{ub}| = \left(4.25 \pm 0.15_{\rm exp}{}^{+0.21}_{-0.17}{}_{\rm th}\right) 10^{-3}$$ [Andersen,Gardi (DGE)]

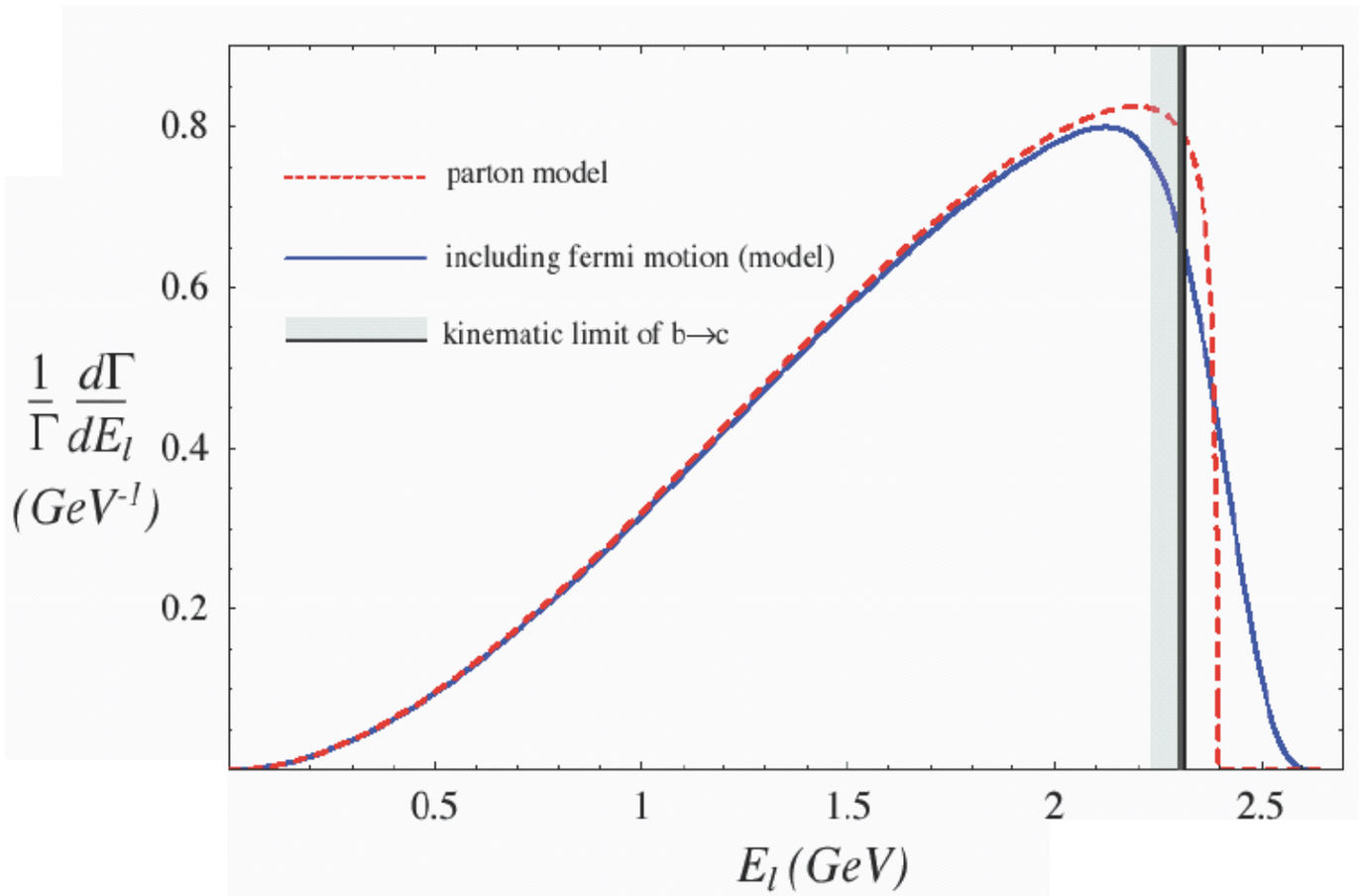
$$|V_{ub}| = \left(4.06 \pm 0.15_{\rm exp}{}^{+0.25}_{-0.27}{}_{\rm th}\right) 10^{-3}$$ [Bosch,Lange,Neubert,Paz (BLNP)]

$$|V_{ub}| = (4.87 \pm 0.24_{\rm exp} \pm 0.38_{\rm th}) 10^{-3}$$ [Bauer,Ligeti,Luke (BLL)]

1.3σ discrepancy between inclusive and exclusive

Trouble with V_{ub} inclusive

- It is really not an inclusive determination: cuts eliminate vast majority of the phase space



- Very strong dependence on m_b (higher $m_b \Rightarrow$ lower V_{ub})

$B \to \tau\nu$

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

- Only lattice input: $f_B = (192.8 \pm 9.9)\ \mathrm{MeV}$
- Babar and Belle published measurements using semileptonic and hadronic tags (to reconstruct the recoiling B meson):

  $\mathrm{BR}(B \to \tau\nu)_{\mathrm{exp}} = (1.74 \pm 0.37) \times 10^{-6}$

  [Note that both HFAG09 and PDG09 do not include the most up-to-date BaBar semileptonic tag analysis and present (1.43±0.37) x 10^{-6}]

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

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

Inputs to the fit: summary

$\hat{B}_K = 0.725 \pm 0.026$

$\kappa_\varepsilon = 0.94 \pm 0.017$

$\xi = 1.243 \pm 0.034$

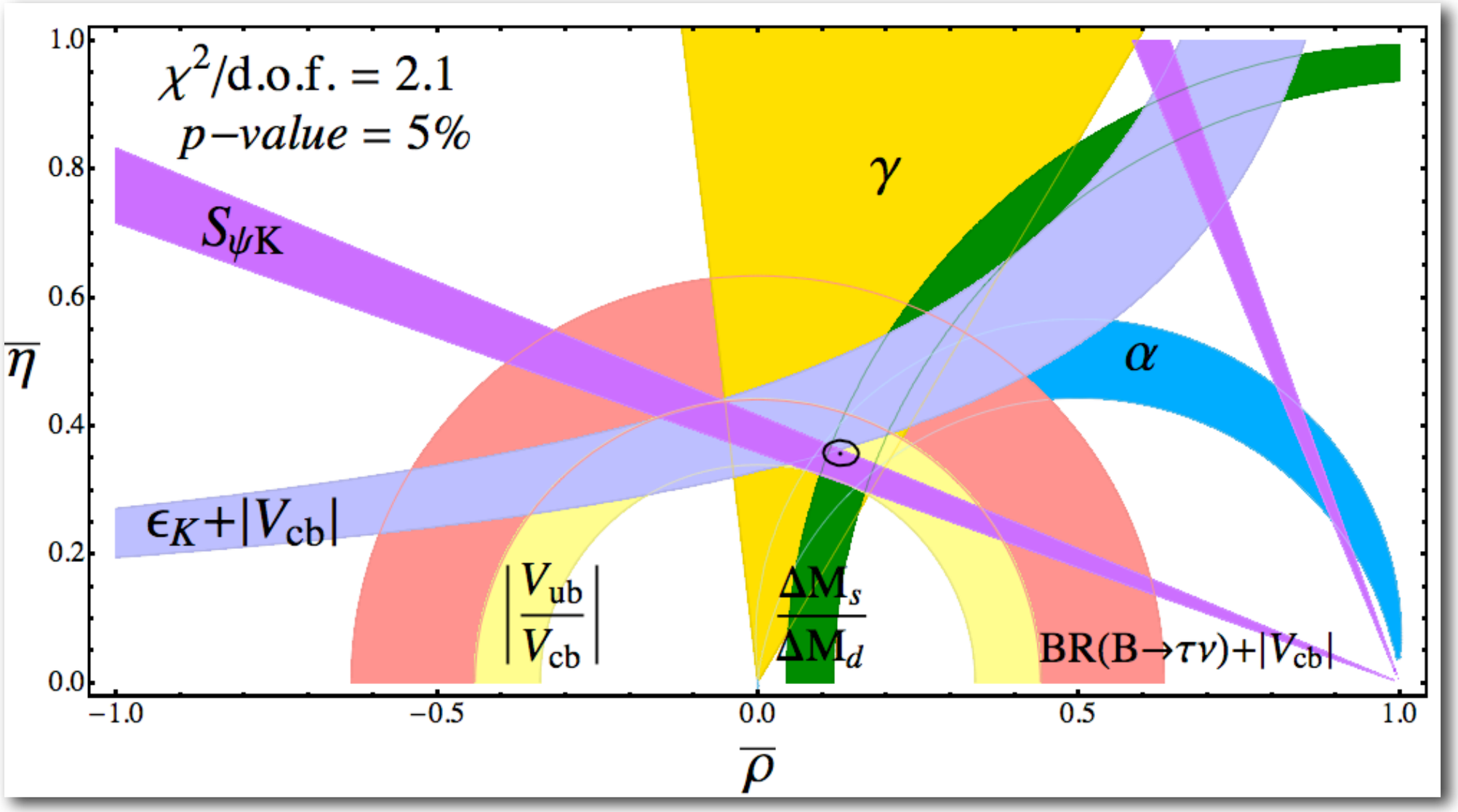
$f_{B_s}\sqrt{\hat{B}_s} = (275 \pm 13)$ MeV

$$\left.\begin{array}{l} |V_{cb}|_{\rm excl} = (38.6 \pm 1.2) \times 10^{-3} \\ |V_{cb}|_{\rm incl} = (41.31 \pm 0.76) \times 10^{-3} \end{array}\right\} (40.3 \pm 1.0) \times 10^{-3}$$

$$\left.\begin{array}{l} |V_{ub}|_{\rm excl} = (34.2 \pm 3.7) \times 10^{-4} \\ |V_{ub}|_{\rm incl} = (40.1 \pm 2.7 \pm 4.0) \times 10^{-4} \end{array}\right\} (36.4 \pm 3.0) \times 10^{-4}$$

$\Delta m_{B_d} = (0.507 \pm 0.005)$ ps^{-1}	$\Delta m_{B_s} = (17.77 \pm 0.10 \pm 0.07)$ ps^{-1}
$\alpha = (89.5 \pm 4.3)^{\rm o}$	$\gamma = (78 \pm 12)^{\rm o}$
$\eta_1 = 1.51 \pm 0.24$	$m_{t,pole} = (172.4 \pm 1.2)$ GeV
$\eta_2 = 0.5765 \pm 0.0065$	$m_c(m_c) = (1.268 \pm 0.009)$ GeV
$\eta_3 = 0.47 \pm 0.04$	$\varepsilon_K = (2.229 \pm 0.012) \times 10^{-3}$
$\eta_B = 0.551 \pm 0.007$	$\lambda = 0.2255 \pm 0.0007$
$S_{\psi K_S} = 0.672 \pm 0.024$	$f_K = (155.8 \pm 1.7)$ MeV

Current fit to the unitarity triangle



$$[\sin 2\beta]_{\rm fit} = 0.774 \pm 0.035 \quad \Rightarrow \quad 2.4\ \sigma$$

$$[BR(B \to \tau\nu]_{\rm fit} = (0.85 \pm 0.11) \times 10^{-4} \quad \Rightarrow \quad 2.4\ \sigma$$

$$[\hat{B}_K]_{\rm fit} = 0.895 \pm 0.090 \quad \Rightarrow \quad 1.8\ \sigma$$

Model Independent Interpretation

- The tension in the UT fit can be interpreted as evidence for new physics contributions to ε_K 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:

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

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

Model Independent Interpretation

- NP in B mixing:

$$(\theta_d)_{\rm fit} = \begin{cases} -(4.4 \pm 1.8)^o \ (2.4\sigma, p = 37\%) & |V_{cb}|_{\rm tot} \\ -(6.0 \pm 1.9)^o \ (3.1\sigma, p = 27\%) & |V_{cb}|_{\rm excl} \\ -(3.4 \pm 1.7)^o \ (2.2\sigma, p = 35\%) & |V_{cb}|_{\rm incl} \end{cases}$$

Slightly favored

- NP in K mixing:

$$(C_\varepsilon)_{\rm fit} = \begin{cases} 1.24 \pm 0.13 \ (1.8\sigma, p = 18\%) & |V_{cb}|_{\rm tot} \\ 1.36 \pm 0.15 \ (2.3\sigma, p = 11\%) & |V_{cb}|_{\rm excl} \\ 1.15 \pm 0.11 \ (1.4\sigma, p = 20\%) & |V_{cb}|_{\rm incl} \end{cases}$$

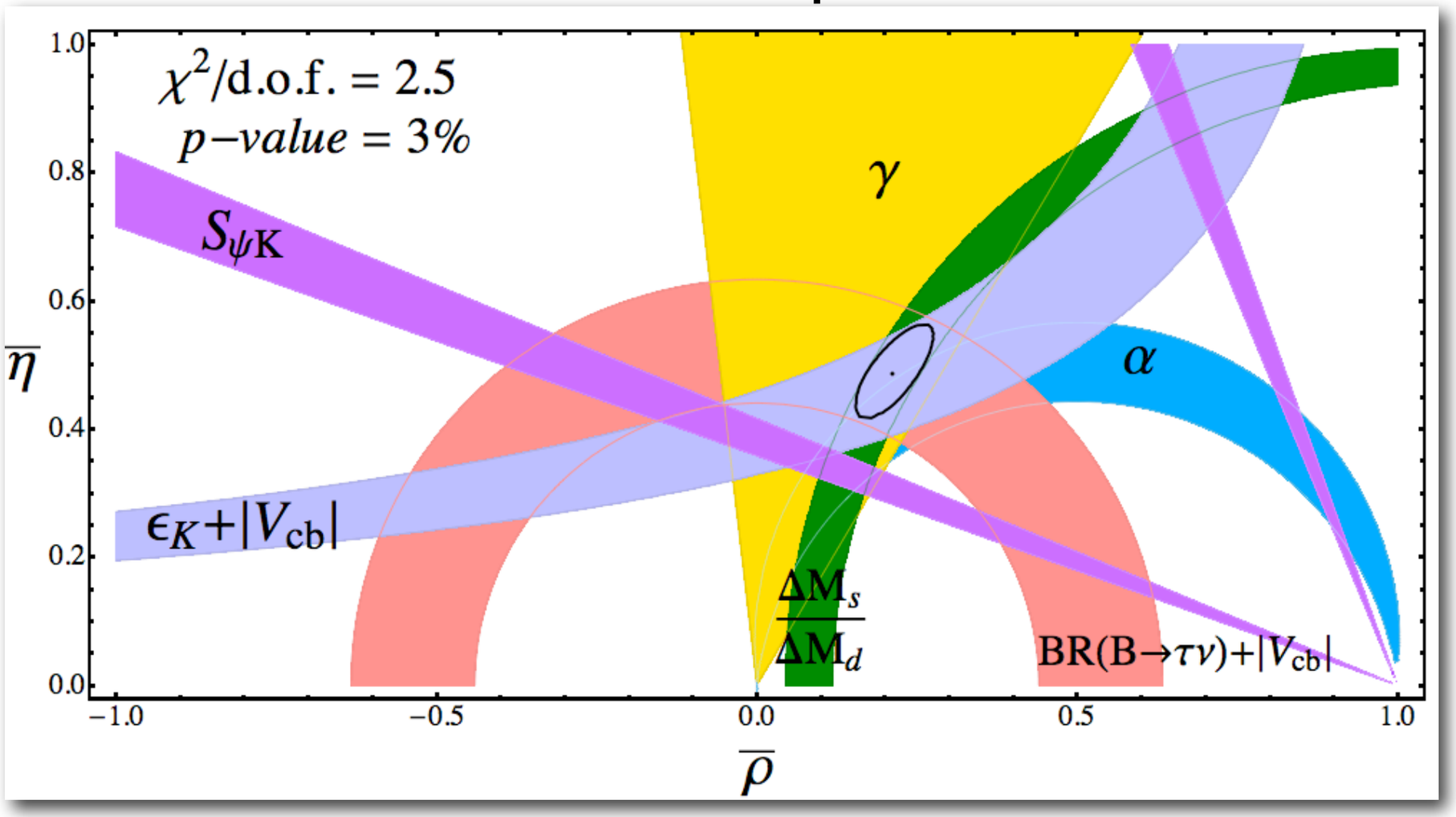
- NP in B→τν:

$$(r_H)_{\rm fit} = \begin{cases} 2.06 \pm 0.48 \ (2.2\sigma, p = 35\%) & |V_{cb}|_{\rm tot} \\ 2.05 \pm 0.48 \ (2.2\sigma, p = 6\%) & |V_{cb}|_{\rm excl} \\ 2.07 \pm 0.48 \ (2.2\sigma, p = 58\%) & |V_{cb}|_{\rm incl} \end{cases}$$

Difficult to reconcile with a charged Higgs effect (but... see new BaBar results)

Removing V_{ub}

- V_{ub} is the most controversial input to the fit



$$[\sin 2\beta]_{\rm fit} = 0.774 \pm 0.035 \quad \Rightarrow \quad 3.2\ \sigma$$

$$[BR(B \to \tau\nu]_{\rm fit} = (0.85 \pm 0.11) \times 10^{-4} \quad \Rightarrow \quad 2.4\ \sigma$$

$$[\hat{B}_K]_{\rm fit} = 0.902 \pm 0.091 \quad \Rightarrow \quad 1.9\ \sigma$$

Removing V_{ub} : Model Independent Interpretation

- NP in B mixing:

$$(\theta_d)_{\rm fit} = -(10.0 \pm 3.4)^o \implies (2.9\sigma, 82\%)$$

Favored

- NP in K mixing:

$$(C_\varepsilon)_{\rm fit} = 1.25 \pm 0.13 \implies (1.8\sigma, 18\%)$$

- NP in B→τν:

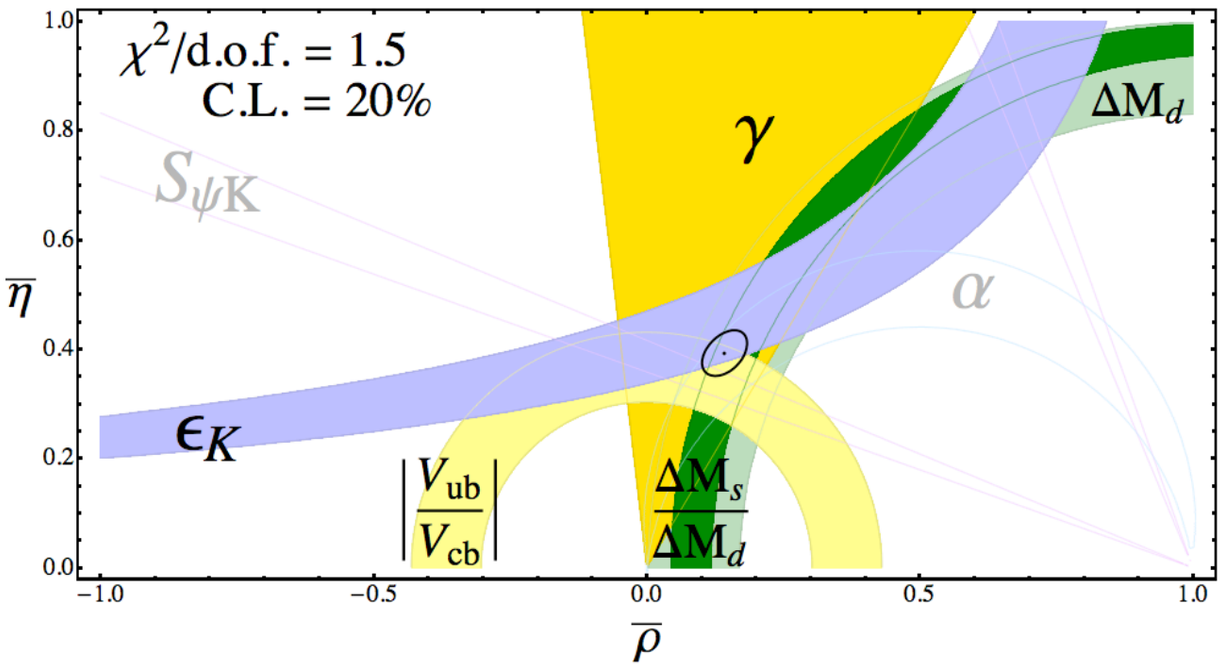
$$(r_H)_{\rm fit} = 2.09 \pm 0.49 \implies (2.2\sigma, 27\%)$$

Difficult to reconcile with a charged Higgs effect (but... see new BaBar results)

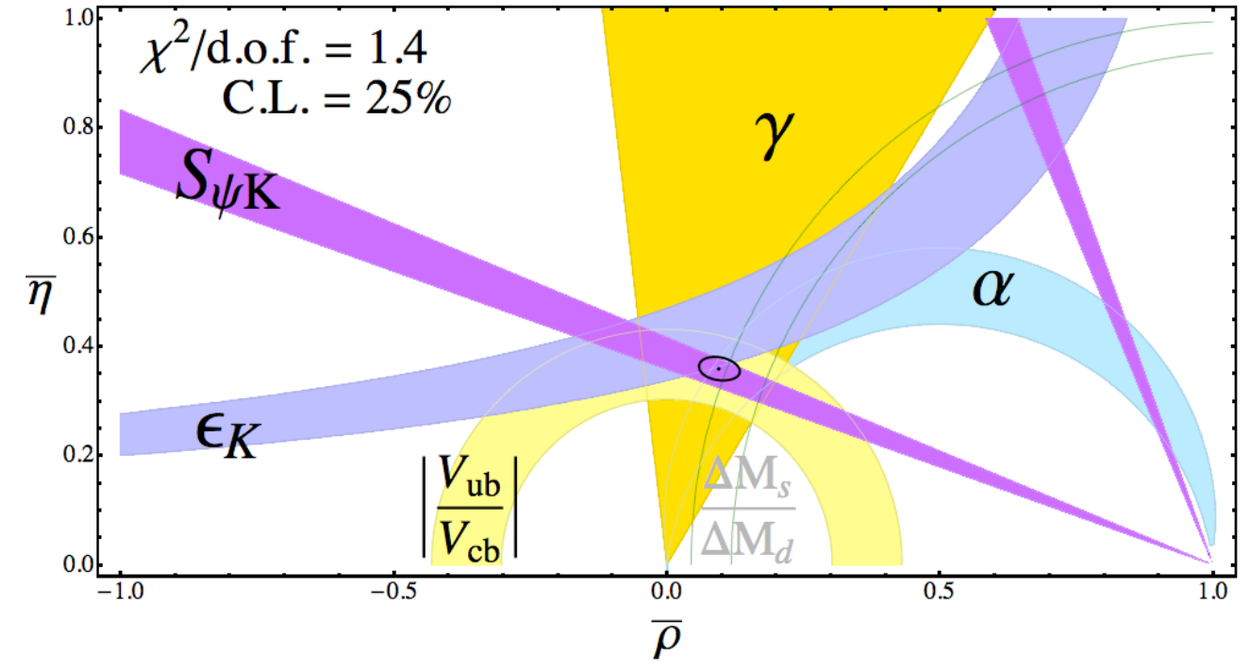
★ *Non trivial agreement between ε_K, B→τν, γ and ΔMs/ΔMd favors scenarios with NP in B_d mixing.*

Removing $B \to \tau\nu$ *(but why?)*

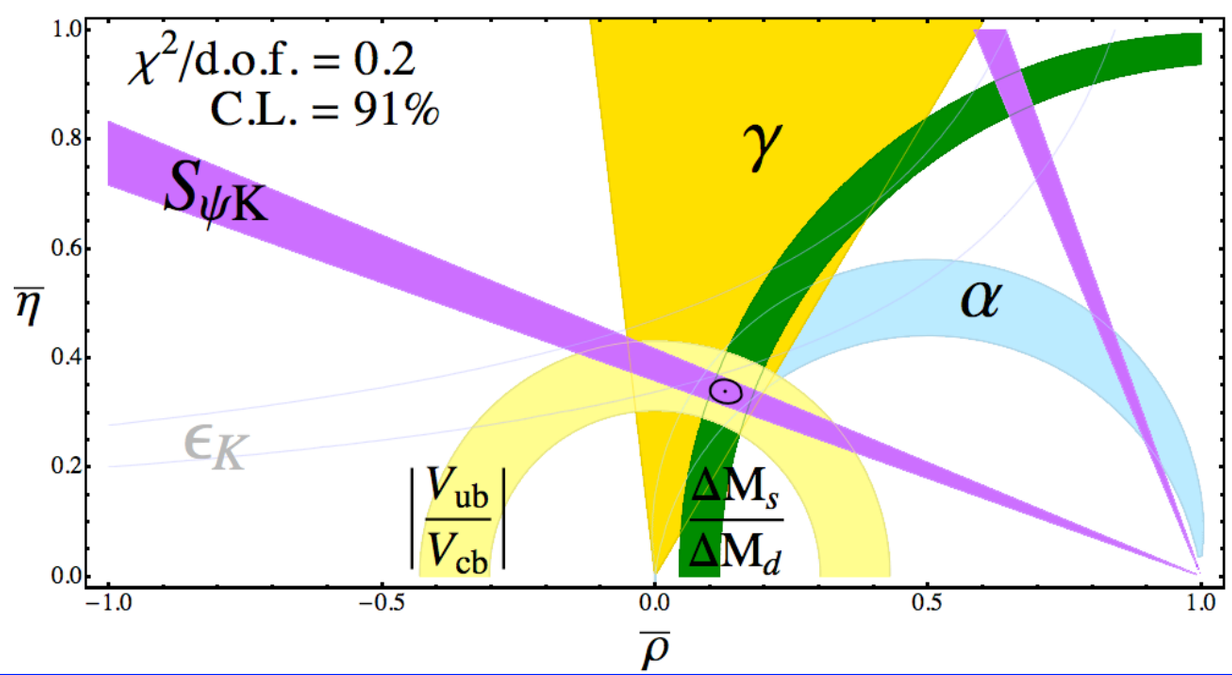
NP in $\arg\left(M_{12}^{d}\right)$



NP in $\left|M_{12}^{d}\right|$



NP in ε_K



preferred

Removing V_{ub} and V_{cb} ?

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

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

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

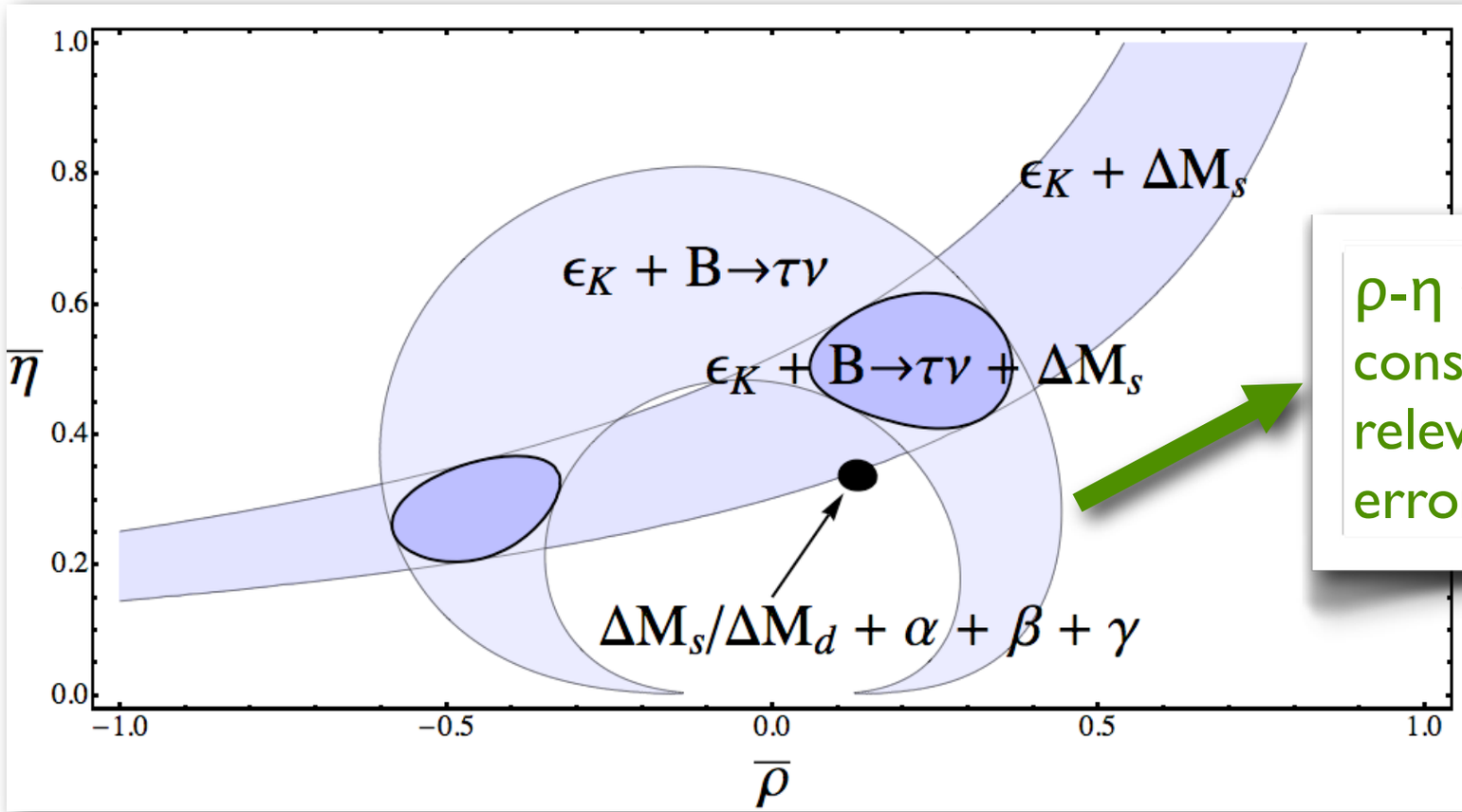
$$\mathrm{BR}(B \to \tau\nu) = \chi_\tau f_B^2 A^2 \lambda^6 (\rho^2 + \eta^2)$$

- 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:

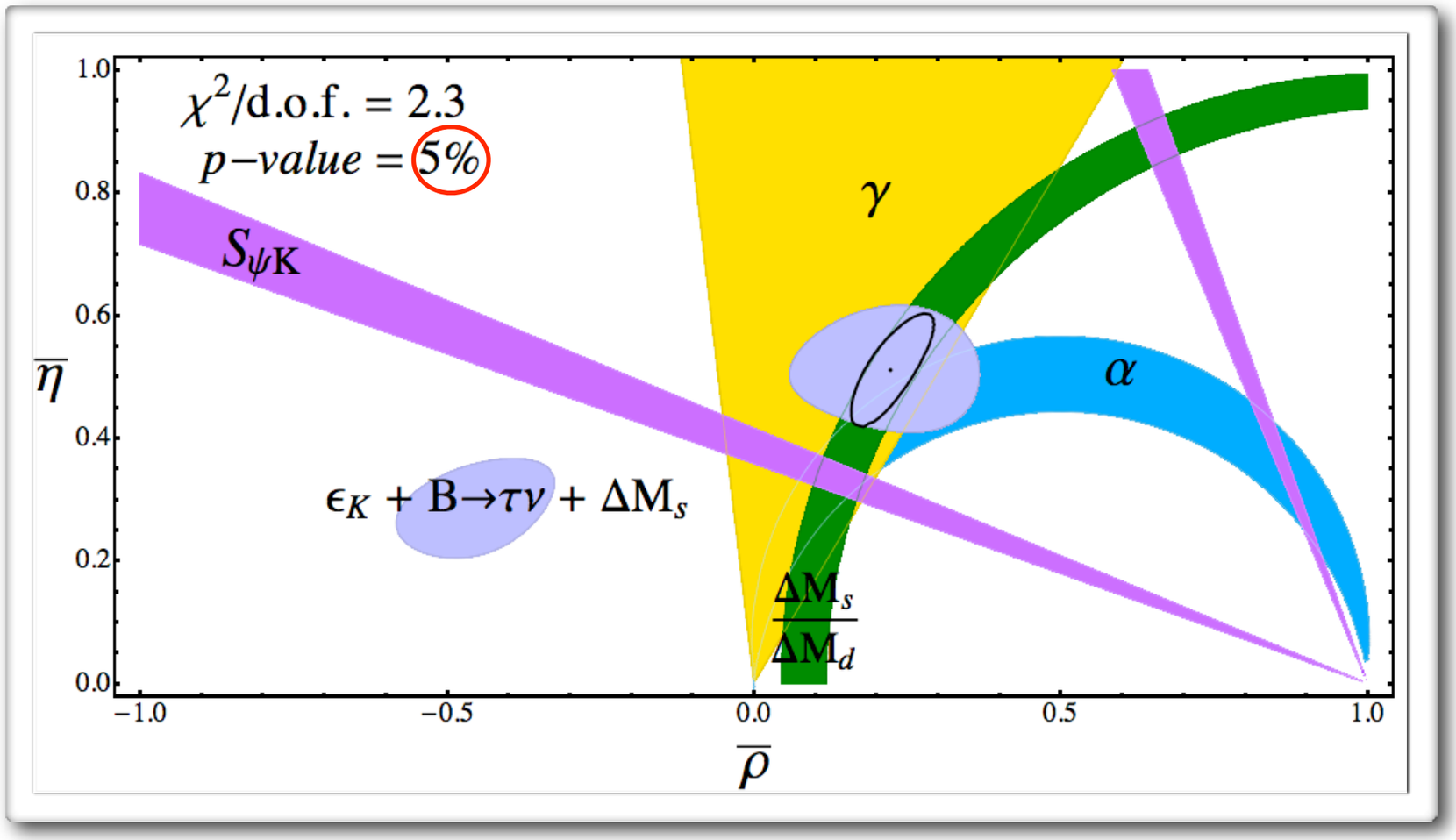


ρ-η topology of the constraint makes it relevant despite large errors on B→τν

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

Removing V_{cb} !

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

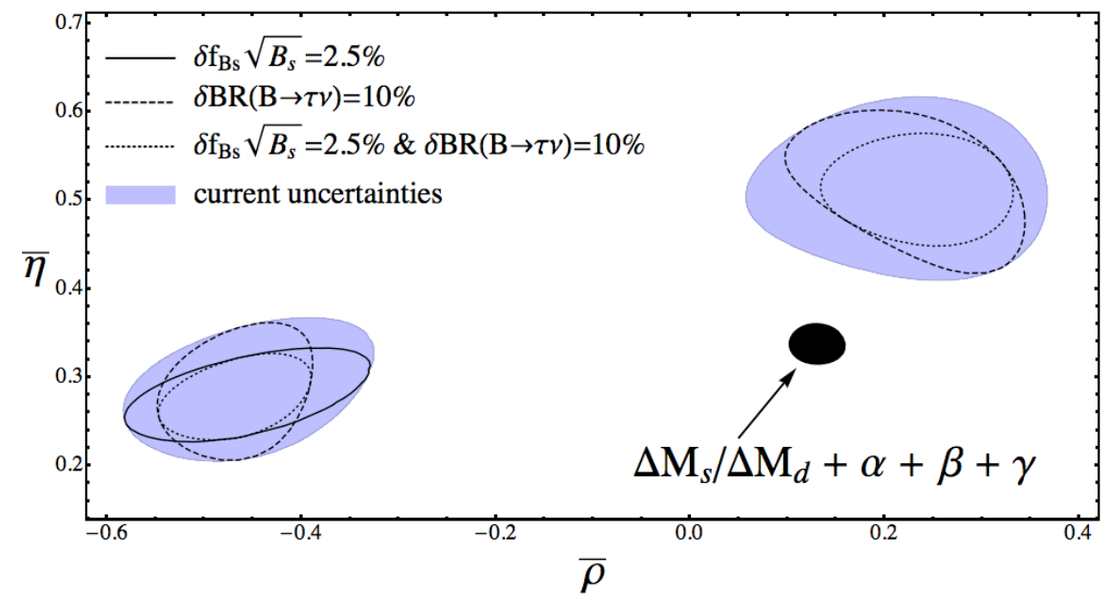


$$
\begin{aligned}
|\varepsilon_K^{\rm NP}| &= C_\varepsilon\, |\varepsilon_K^{\rm SM}| \\
M_{12}^{d,\rm NP} &= e^{i\theta_d}\, M_{12}^{d,\rm SM} \\
{\rm BR}(B\to\tau\nu)^{\rm NP} &= r_H\, {\rm BR}(B\to\tau\nu)^{\rm SM}
\end{aligned}
\quad\Rightarrow\quad
\begin{aligned}
C_\varepsilon^{{\rm no}V_{qb}} &= 1.21\pm 0.22 \quad\Rightarrow\ (1.0\sigma, p=8\%) \\
\theta_d^{{\rm no}V_{qb}} &= -(11.4\pm 2.7)^{\rm o} \Rightarrow\ (2.7\sigma, p=85\%) \\
r_H^{{\rm no}V_{qb}} &= 2.1\pm 0.5 \quad\Rightarrow\ (2.2\sigma, p=50\%)
\end{aligned}
$$

SuperB expectations...

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

δ_τ	δ_s	p_{SM}	$\theta_d \pm \delta\theta_d$	p_{θ_d}	$\theta_d/\delta\theta_d$
*20%	*4.6%	5%	$-(11.4 \pm 4.2)^\circ$	85%	2.7σ
*20%	2.5%	1.1%	$-(11.2 \pm 3.7)^\circ$	85%	3.1σ
*20%	1%	0.08%	$-(11.0 \pm 3.1)^\circ$	85%	3.5σ
10%	*4.6%	0.03%	$-(12.2 \pm 3.0)^\circ$	84%	4.1σ
3%	*4.6%	10^{-5}%	$-(12.5 \pm 2.4)^\circ$	84%	5.2σ
10%	2.5%	0.005%	$-(11.9 \pm 2.7)^\circ$	83%	4.4σ
10%	1%	0.0003%	$-(11.7 \pm 2.5)^\circ$	82%	4.7σ
3%	2.5%	10^{-6}%	$-(12.3 \pm 2.2)^\circ$	82%	5.5σ
3%	1%	4×10^{-8}%	$-(12.0 \pm 2.0)^\circ$	81%	5.9σ



- Even modest improvements on B→τν have tremendous impact on the UT fit: L = 10(50)ab^{-1} → δ_τ = 10(3)%
- Interplay between Bs mixing and B→τν can result in a > 5σ effect
- The fit is completely clean

Operator Level Analysis: *Mixing*

- Effective Hamiltonian for B_d mixing:

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

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

- B_s mixing (d→s), K mixing (b→s & s→d)
- Parametrization of New Physics effects:

$$\delta C_{1,4}^{B_q,K}(\mu_0) = -\frac{1}{G_F^2 m_W^2} \frac{e^{i\varphi}}{\Lambda^2}$$

  - *Retain loop and CKM suppression*

Operator Level Analysis: *Mixing*

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

$$C_1(\mu_L)\langle K|O_1(\mu_L)|K\rangle \simeq 0.8\, C_1(\mu_H)\, \frac{1}{3} f_K^2 m_K B_1(\mu_L)$$

$$C_4(\mu_L)\langle K|O_4(\mu_L)|K\rangle \simeq 3.7\, C_4(\mu_H)\, \frac{1}{4} \left(\frac{m_K}{m_s(\mu_L)+m_d(\mu_L)}\right)^2 f_K^2 m_K B_4(\mu_L)$$

O(1)

running from μ_H to μ_L

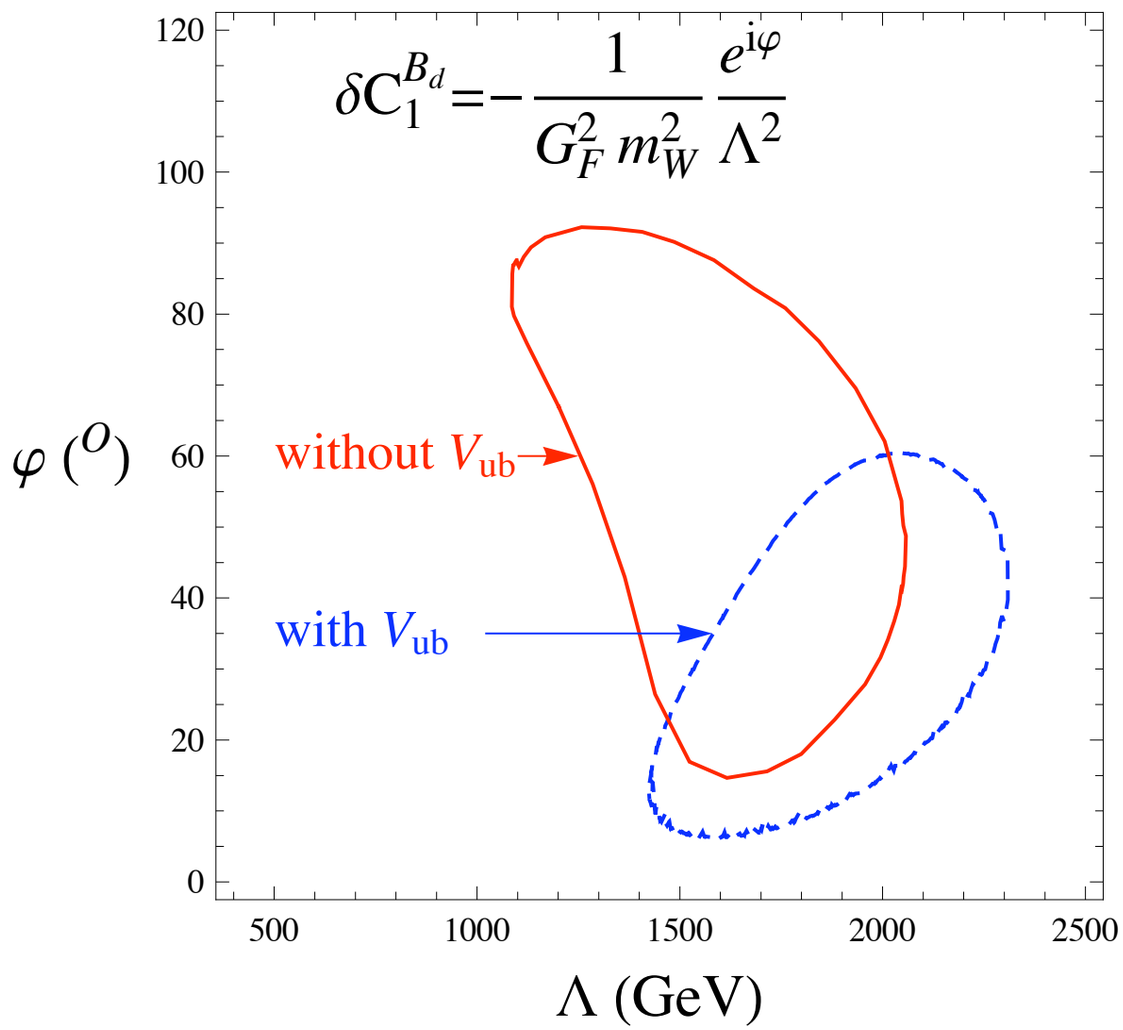
chiral enhancement

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

- No analogous enhancement in B_q mixing

Operator Level Analysis: B_d *Mixing*

- New Physics in B_d mixing only: $\delta C_1^{B_s} = \delta C_1^K = 0$
- Effects on $a_{\psi K}$ <u>*and*</u> $\Delta M_{B_s}/\Delta M_{B_d}$

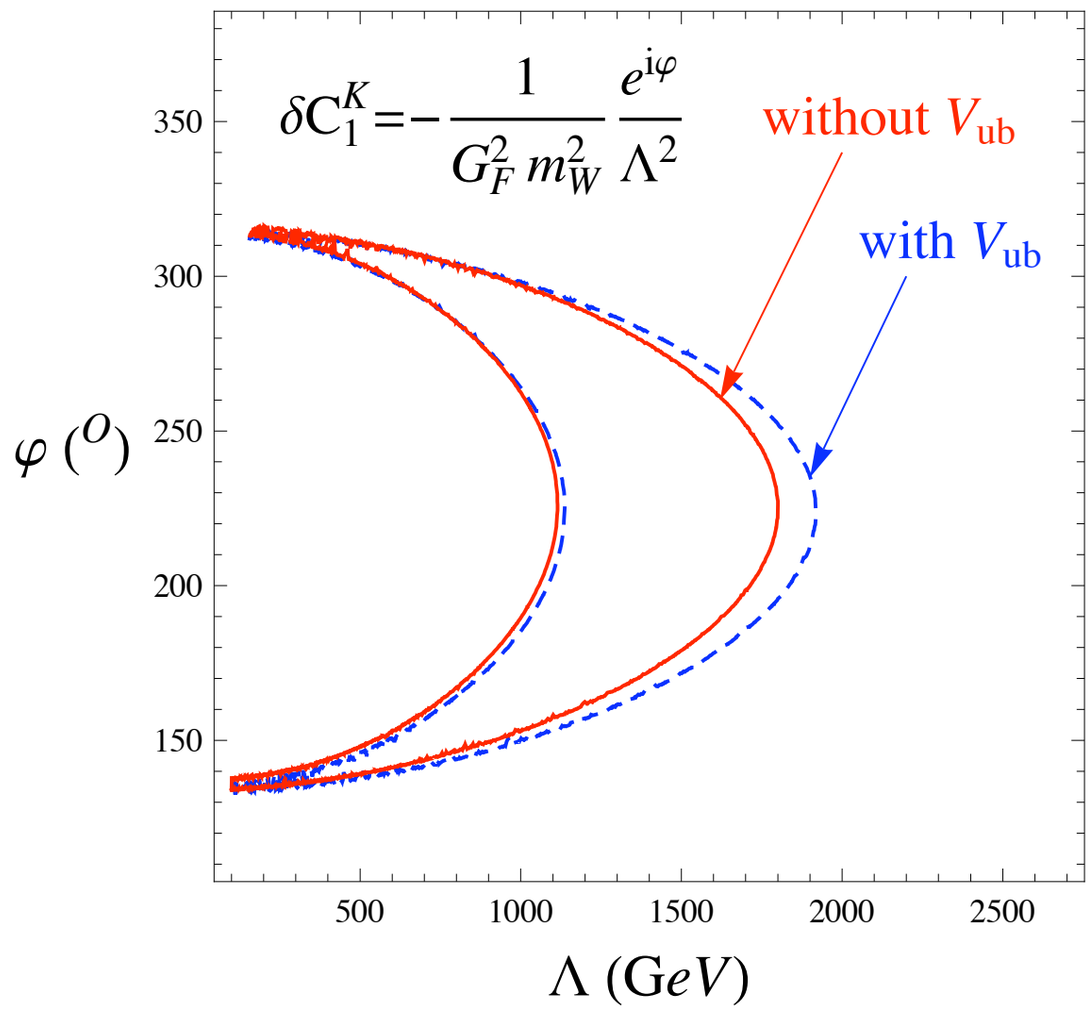


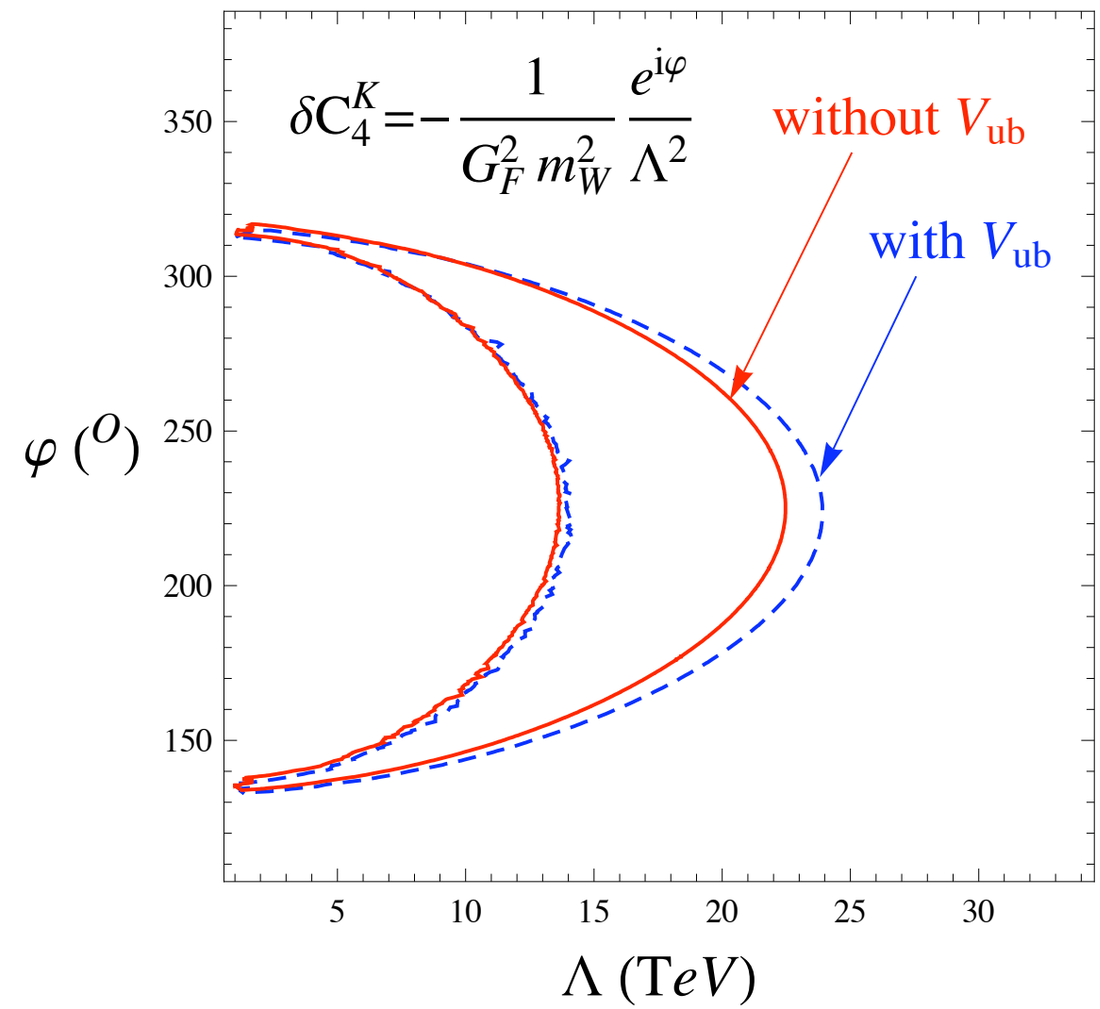
$$\Lambda \sim [1.1 \div 2.3] \text{ TeV}$$

- Lower limit on Λ induced by $\Delta M_{B_s}/\Delta M_{B_d}$

Operator Level Analysis: *K Mixing*

- New Physics in K mixing only: $\delta C_1^{B_s} = \delta C_1^{B_d} = 0$





$\Lambda \sim [1.1 \div 1.9]$ TeV

$\Lambda \sim [14 \div 24]$ TeV

NP in penguin amplitudes

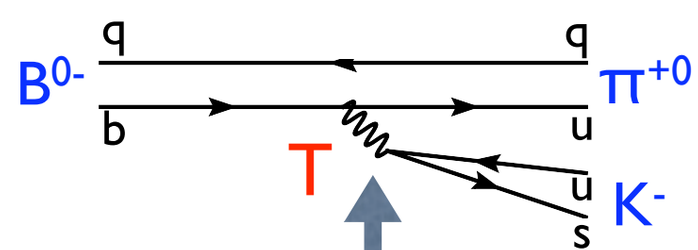
- Proper treatment of new physics effects in penguin amplitudes is better implemented with NP contributions to the *QCD* and *EW penguin* operators
- Correlation between the $b \to s\bar{s}s$ and Kπ asymmetries:

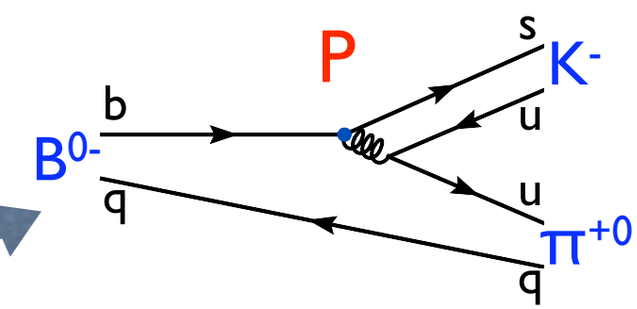
$$A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+) = \begin{cases} (14.8 \pm 2.8)\ \% & \text{exp} \\ (2.2 \pm 2.4)\ \% & \text{QCDF} \end{cases}$$

- 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:

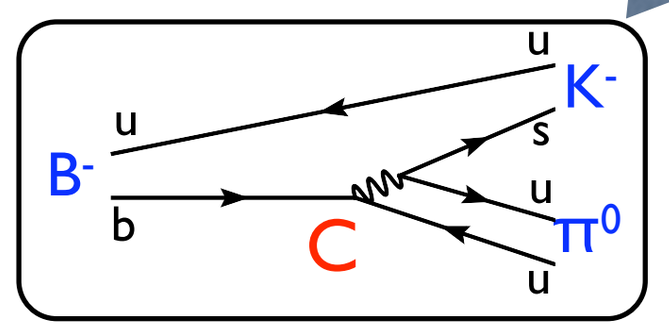


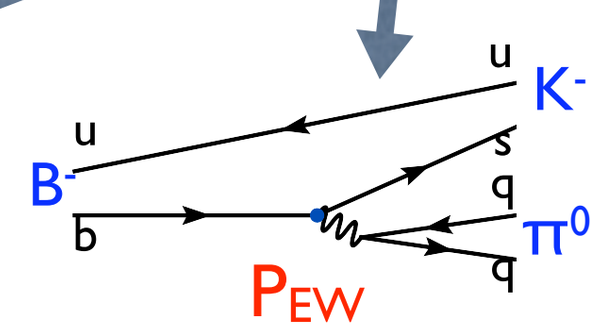


$$\mathcal{A}_{\bar{B}^0\to\pi^+K^-} = A_{\pi\bar{K}} \sum_{q=u,c} V_{qb}V_{qs}^* \left[\delta_{qu}\alpha_1 + \hat{\alpha}_4^q\right]$$

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

color suppressed
[Gronau,Rosner]



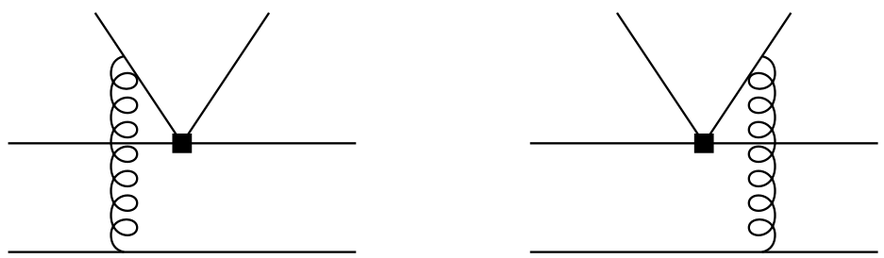


- We get: $\frac{P}{T} \simeq 0.20, \boxed{\frac{C}{T} \simeq 0.16}, \frac{P_{\rm EW}}{T} \simeq 0.47$

fits yield C/T ~ 0.6

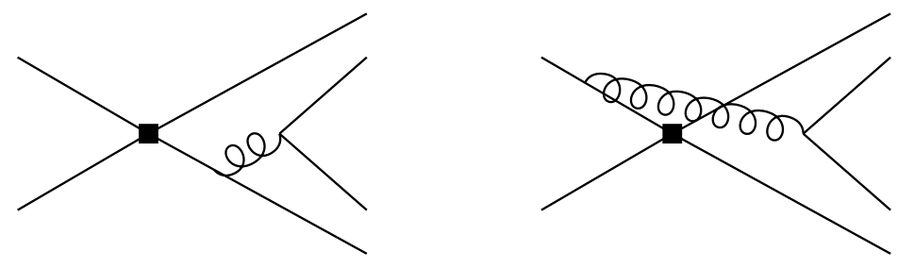
CP asymmetries in B→Kπ

- 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:

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

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

likely to receive NP corrections

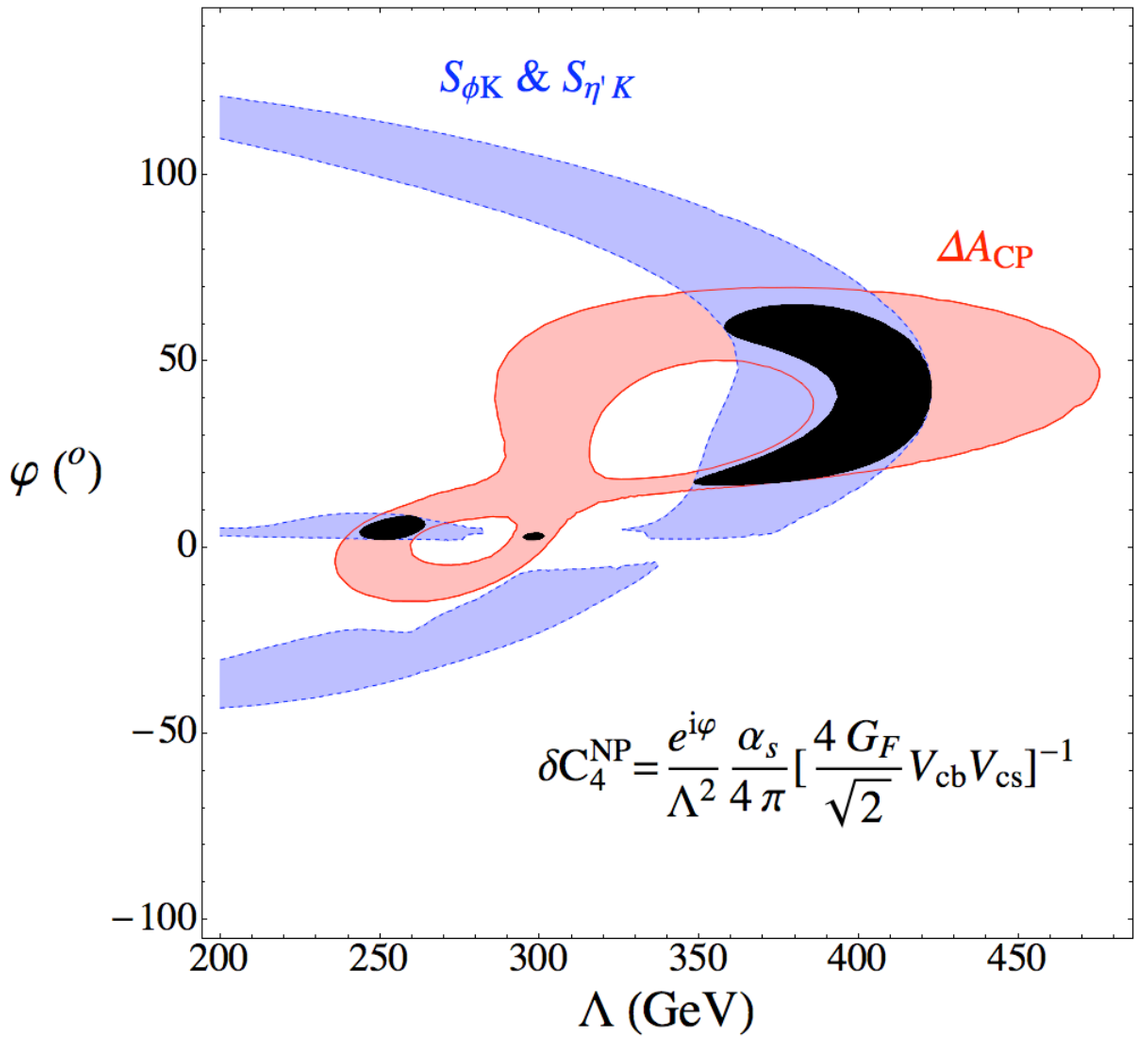
- Assume the following parametrization of NP effects:

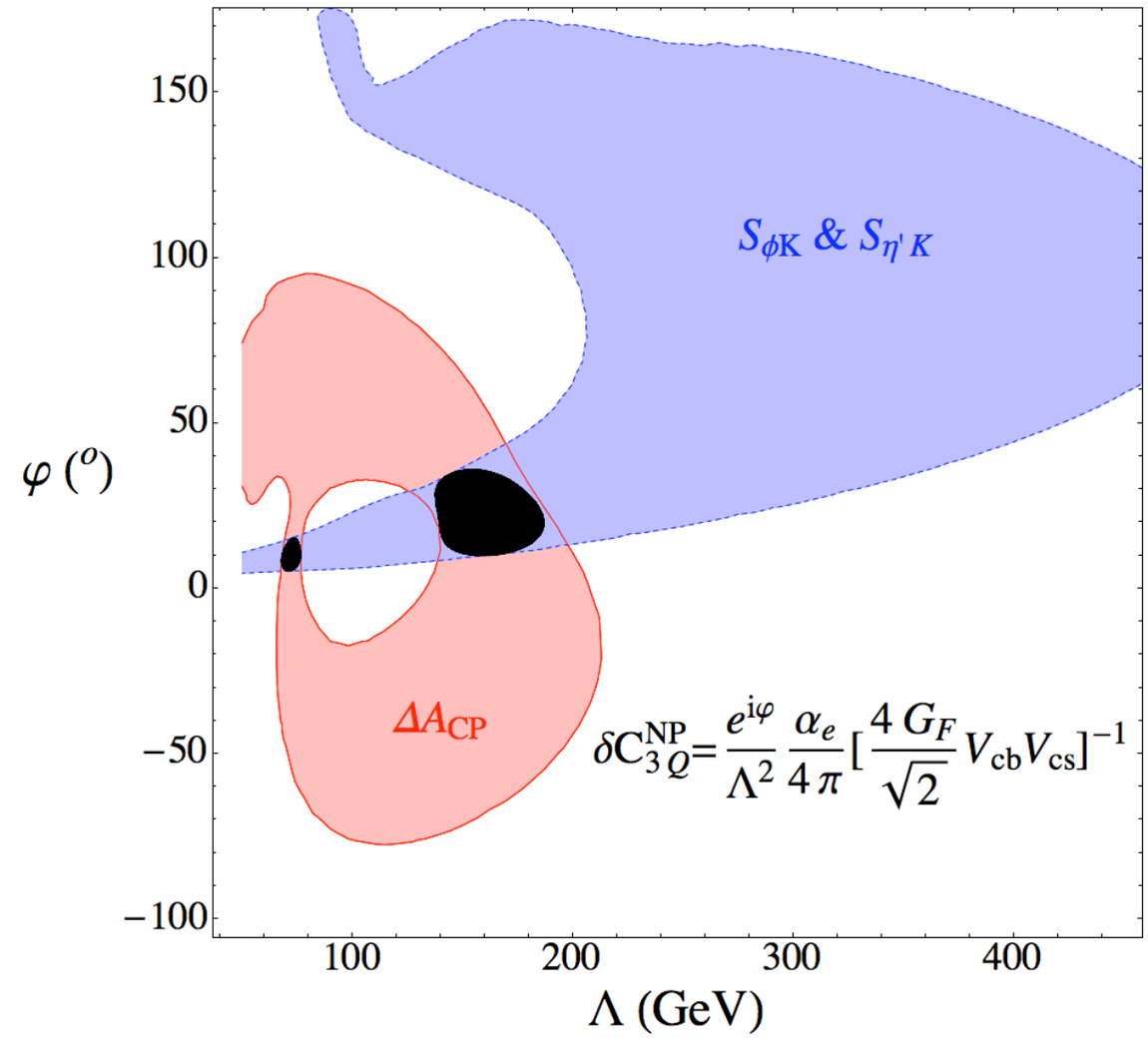
$$\delta C_{4,3Q}(\mu_0) = \frac{\alpha_{s,e}}{4\pi} \frac{e^{i\varphi}}{\Lambda^2} \left[\frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \right]^{-1}$$

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

$\Lambda \sim [140 \div 190]$ GeV

Conclusions

- Recent lattice QCD (B_K, ξ, ...) → possible NP in the UT fit
- We need better understanding of inclusive V_{ub} and V_{cb}
- This "tension" in the UT fit can be explained by a new phase in B_d/K mixing
- As long as V_{xb} determinations remain problematic, removing semileptonic decays allows to cast the UT fit as a clean & high-precision tool to identify new physics
- Super-B level precision on $B \to \tau\nu$ coupled with improvements on the lattice determination of $f_{B_s}\sqrt{B_s}$ can test the SM at the 5σ level

Conclusions (cont'd)

- Hints of NP in $b \to s$ amplitudes (CP asymmetries in $(\Phi,\eta',\pi)K$ final states) and *B_s mixing*
- Typical *upper bounds* on NP scales are in the TeV range:

	Λ	$\varphi(°)$
$A(b \to s)$	O_4: [250÷430] GeV O_{3Q}: [90÷200] GeV	O_4: [0,70] O_{3Q}: [0,30]
B_d mixing	[1.1÷2.3] TeV	10÷90
K mixing	LL: [1.1÷1.9] TeV LR: [14÷24] TeV	130÷320
B_d=B_s mixing	[1÷2] TeV	10÷70