Interplay of Lattice QCD and Experiment in CKM Physics

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Outline

- Flavor violation in the Standard Model
- Determining the CKM
  - 1st↔2nd: λ
  - 2nd↔3rd: A
  - 1st↔3rd: ρ and η
- Status of CKM fits, hints for NP and future prospects
- $B \to K^{(*)}$ processes
- Conclusions

The Cabibbo✹-Kobayashi★-Maskawa★ matrix

Gauge interactions do not violate flavor:

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

Yukawa interactions (mass) violate flavor:

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

The Yukawas are complex 3x3 matrices:

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

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:

$$\bar u_L^0 W\!\!\!\!/ \, d_L^0 \Longrightarrow \bar u_L W\!\!\!\!/ \, U_L D_L^\dagger d_L = \bar u_L W\!\!\!\!/ \, V_{\rm CKM} d_L$$

✹ = 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

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

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

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

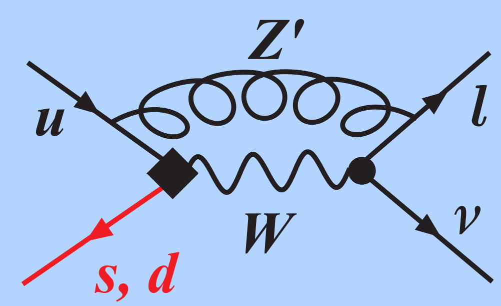
1st ↔ 2nd family (no K mixing)

- V_{ud}: nuclear β decays ($0^+ \to 0^+$), $\pi \to \ell\nu\ (\pi_{\ell 2})$
- V_{us}: $K \to \ell\nu\ (K_{\ell 2}),\ K \to \pi\ell\nu\ (K_{\ell 3})$

$\Big\}\ f_K,\ f_\pi,\ f_+(0)$

- Important for phenomenology
  - GF universality (1st row unitarity):

$$G_{\rm CKM} = G_\mu \left[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2\right]^{1/2}$$

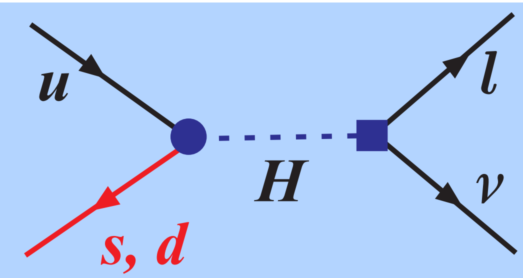


$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + 0.01\lambda\ell n\ X/(X-1)$$
$$X = m_{Z'}^2/m_W^2$$

  - combination proportional to $\Gamma(K_{\ell 2})/(\Gamma(\pi_{\ell 2})\Gamma(K_{\ell 3}))$:

$$R_{\ell 23} = \left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})} \right|$$

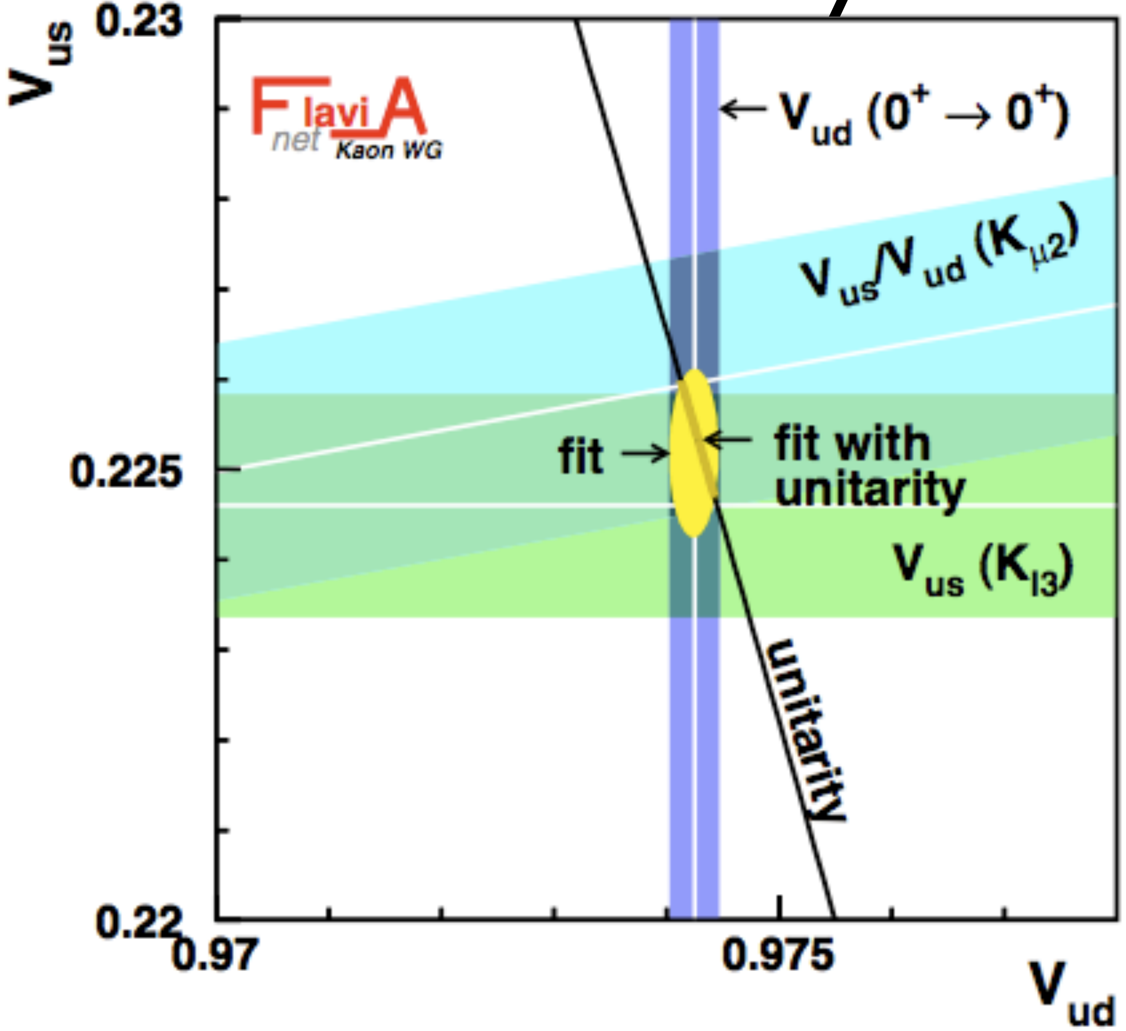
(depends only on $f_K/(f_\pi f_+(0))$)



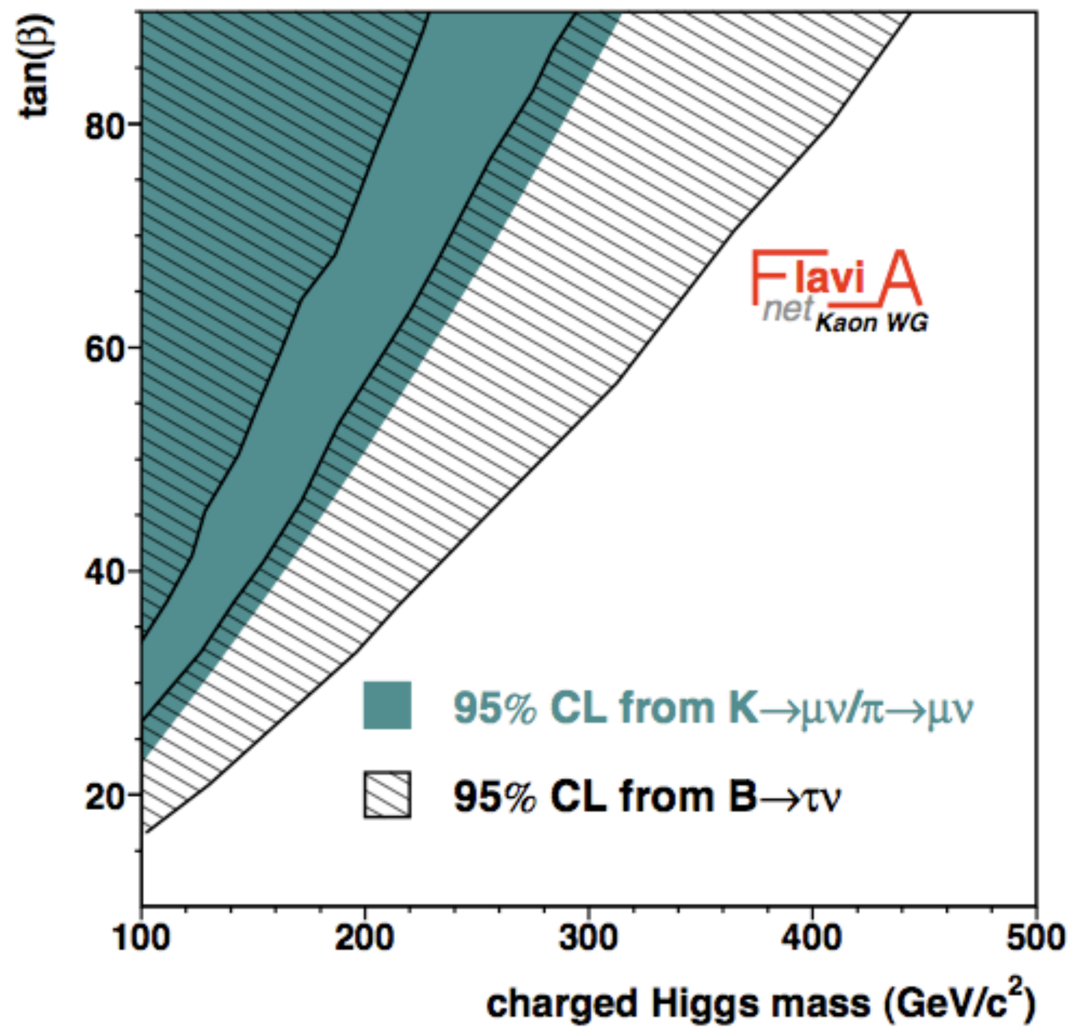
$$R_{l23} = \left| 1 - \frac{m_{K^+}^2}{M_{H^+}^2}\left(1 - \frac{m_d}{m_s}\right)\frac{\tan^2\beta}{1 + \epsilon_0 \tan\beta} \right|$$

1st ↔ 2nd family (no K mixing)

Unitarity:



$R_{\ell 23}$:



- Error bands dominated by lattice uncertainties:

$$f_+(0) = 0.964(5) \quad \text{RBC} + \text{UKQCD}\ N_f = 2+1$$

$$\frac{f_K}{f_\pi} = \begin{cases} 1.197(^{+7}_{-13}) & \text{MILC}\ (N_f = 2+1) \\ 1.189(7) & \text{HPQCD}\ (N_f = 2+1) \end{cases}$$

2nd ↔ 3rd family: determining A

- Can be extracted by tree-level processes (b→clν)

- $\Delta M B_s$ is conventionally used only to normalize $\Delta M B_d$ 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:

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

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

V_{cb}

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

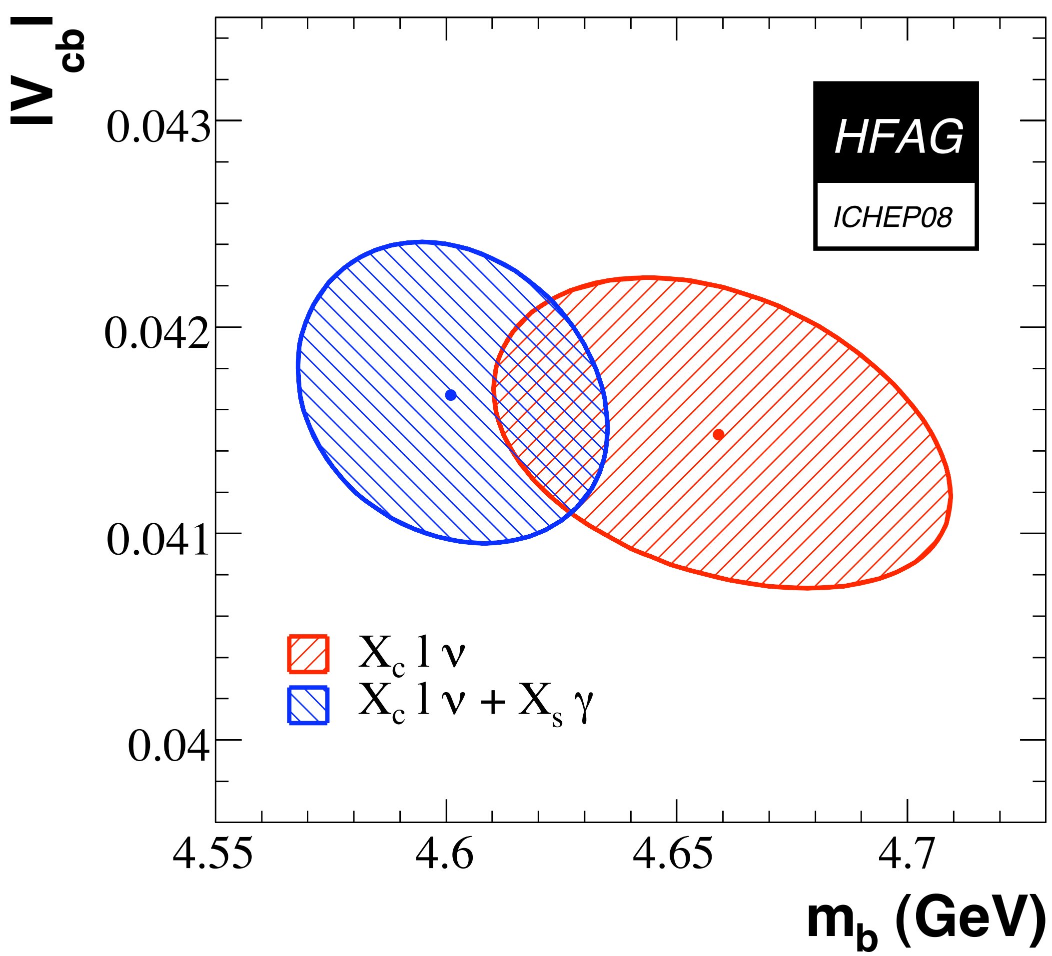
[FNAL/MILC]

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

[average:Laiho,EL,Van de Water]

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

- 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

B_s mixing

- 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		

+

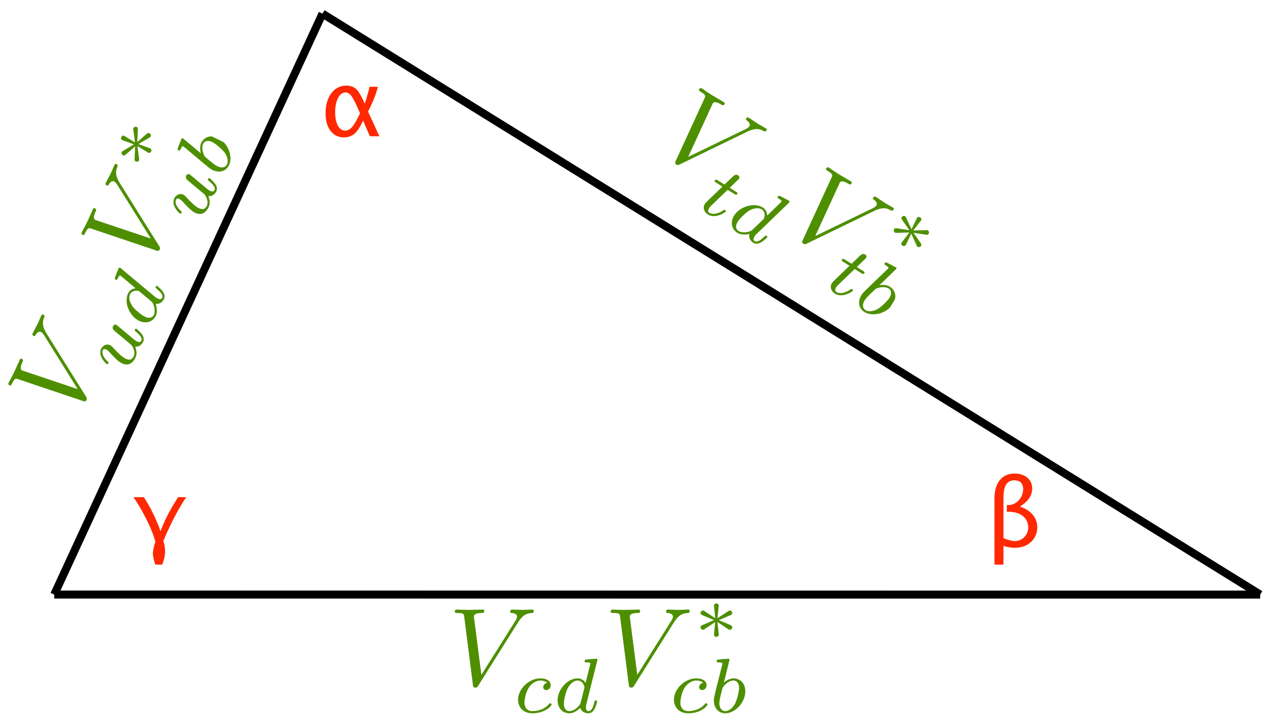
	$\widehat{B}_{B_d}$	$\widehat{B}_{B_s}$
HPQCD '09 [29]	1.26 ± 0.11	1.33 ± 0.06

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

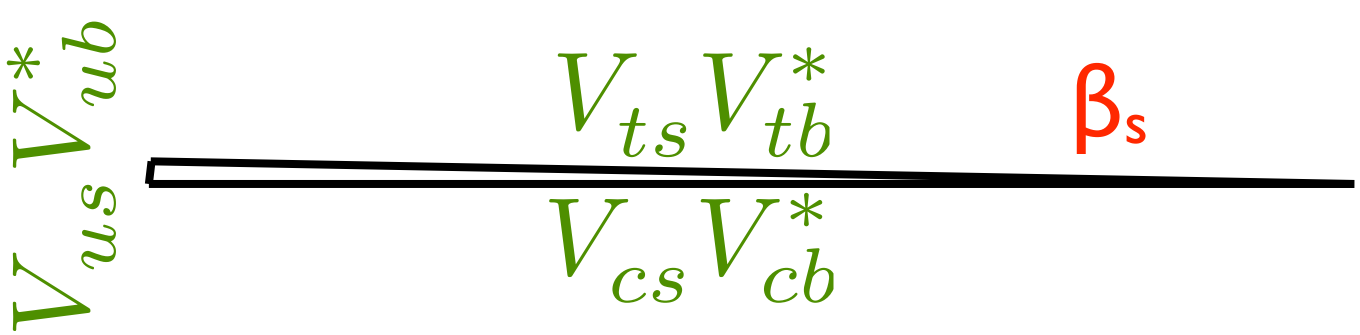
$$f_{B_s}\sqrt{B_s} = (275 \pm 13)\ \text{MeV}$$

HPQCD alone finds (266 ± 18) MeV

1st ↔ 3rd family: ρ and η

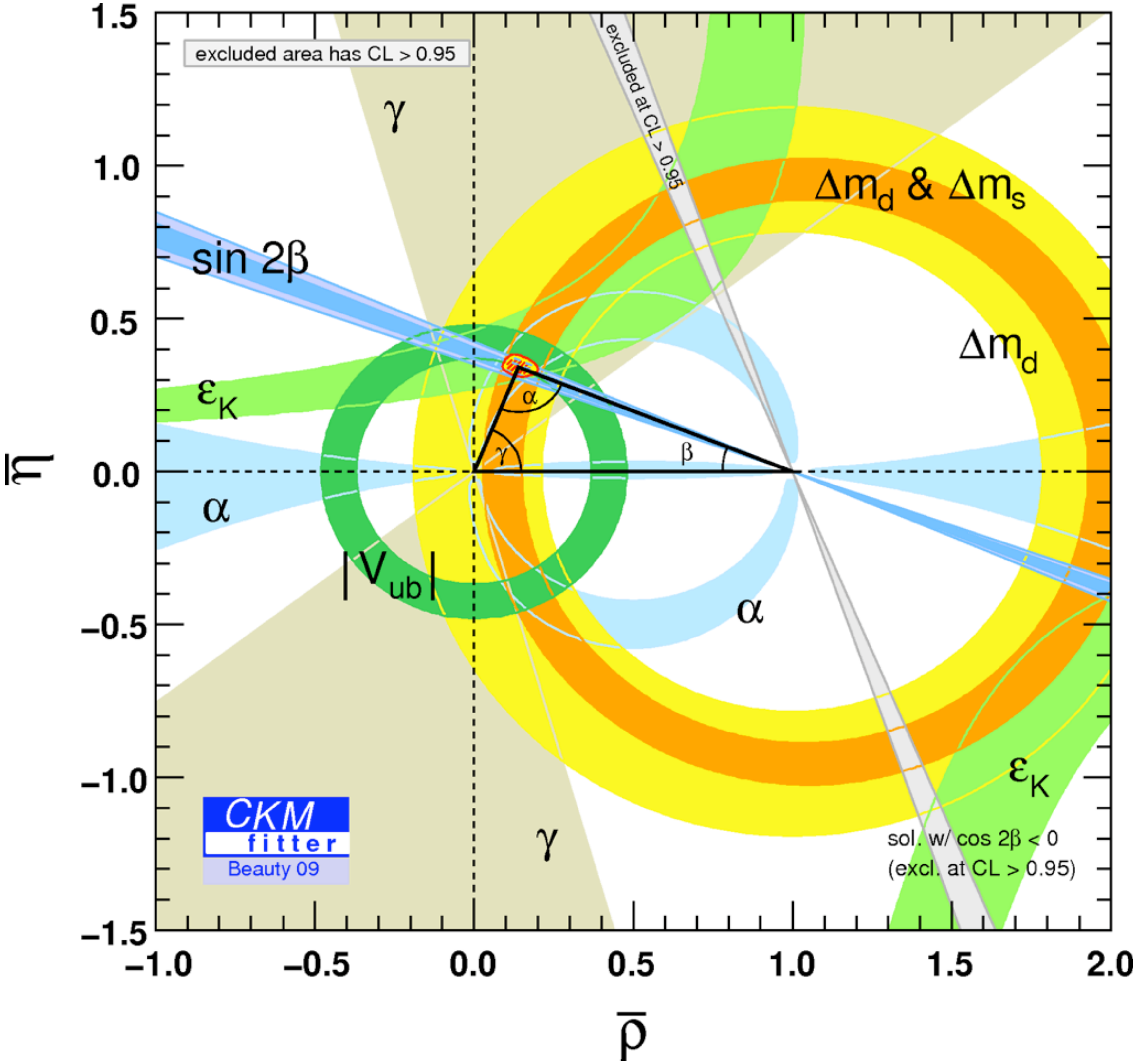


$$V_{td} = |V_{td}|\ e^{-i\beta}$$
$$V_{ub} = |V_{ub}|\ e^{-i\gamma}$$



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

The Unitarity Triangle Fit



ε_K: CP violation in K mixing

α: time dependent A_{CP} in B→(ππ,ρρ,ρπ) modes (*large penguin pollution removed with isospin analysis*)

β: time dependent A_{CP} in B→J/ψ K and related modes (*very clean*)

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

K mixing (ε_K)

$$\Gamma_{12}^K$$

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

- 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 $(\varepsilon'_K/\varepsilon_K)_{\exp}$ and lattice QCD

K mixing (ε_K)

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

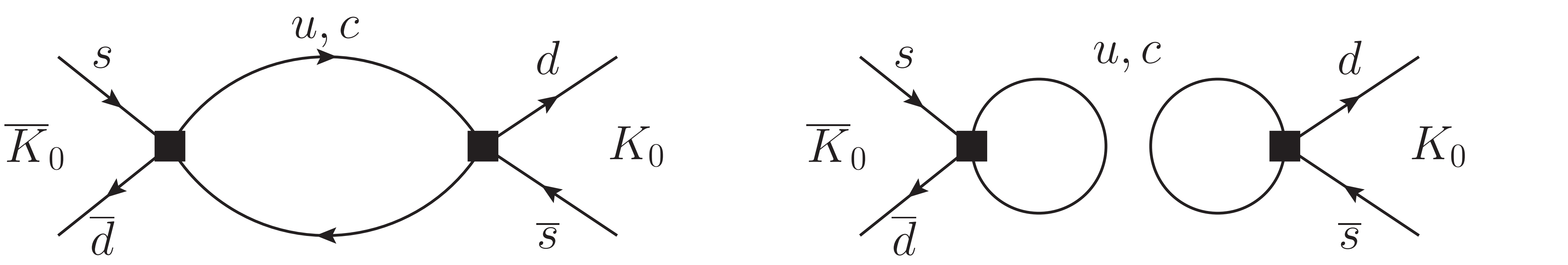
- Experimentally one has: $\phi_\varepsilon = (43.51 \pm 0.05)^o$
- ImA_0/ReA_0 can be extracted from experimental data on ε'/ε and theoretical calculation of isospin breaking corrections:
  - $\mathrm{Re}(\varepsilon'_K/\varepsilon_K)_{\mathrm{exp}} \sim \frac{\omega}{\sqrt{2}|\varepsilon_K|}\left(\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2}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

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

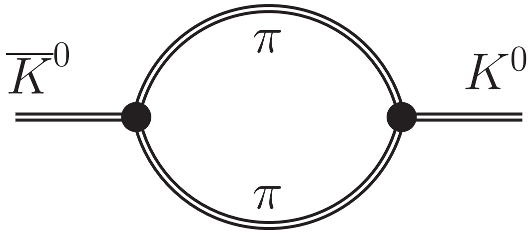
[Laiho,EL,Van de Water]

K mixing (ε_K)

- 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 ImA$_0$ 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		

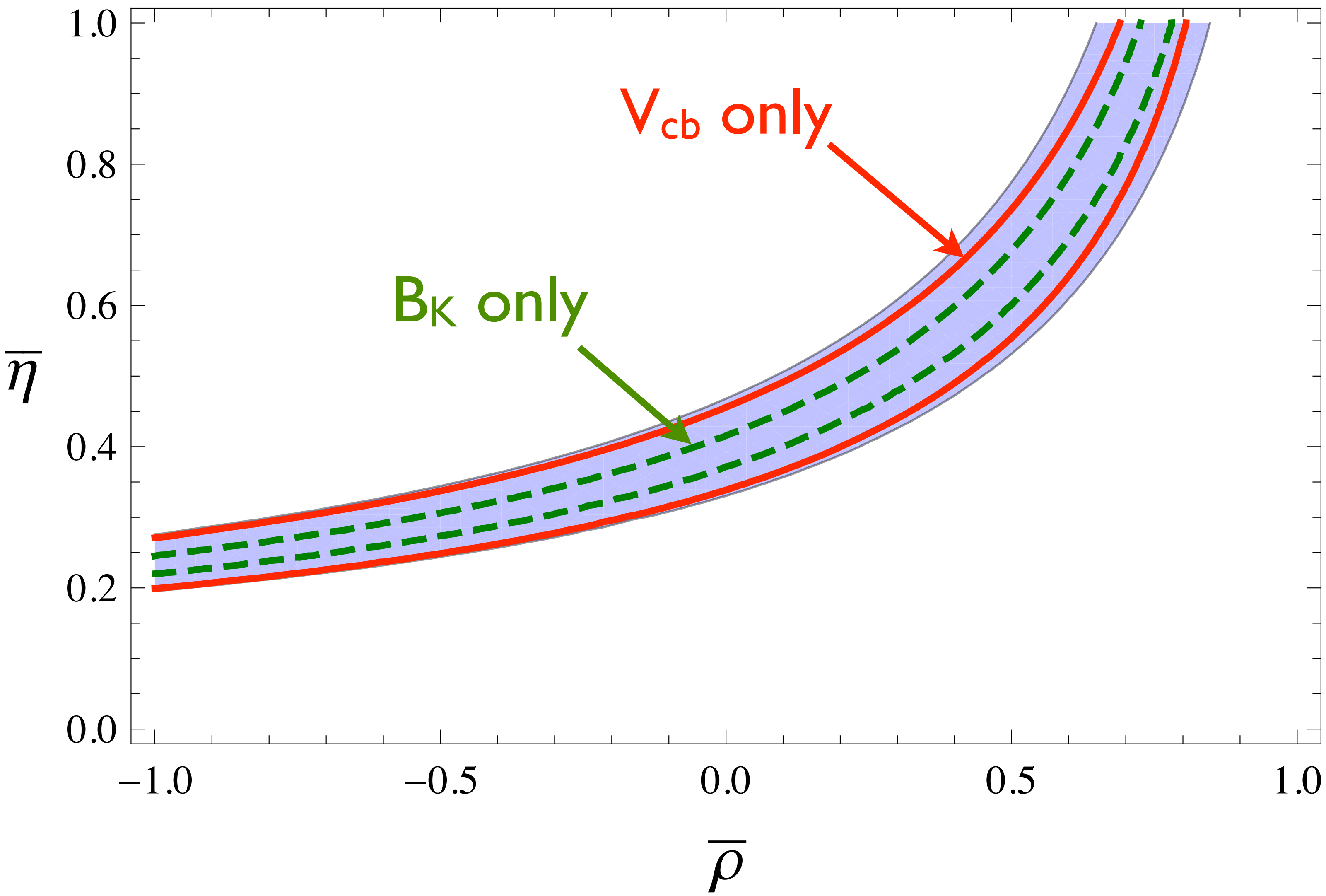
$$\hat{B}_K = 0.725 \pm 0.026$$

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: $\xi = 1.243 \pm 0.034$

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)]

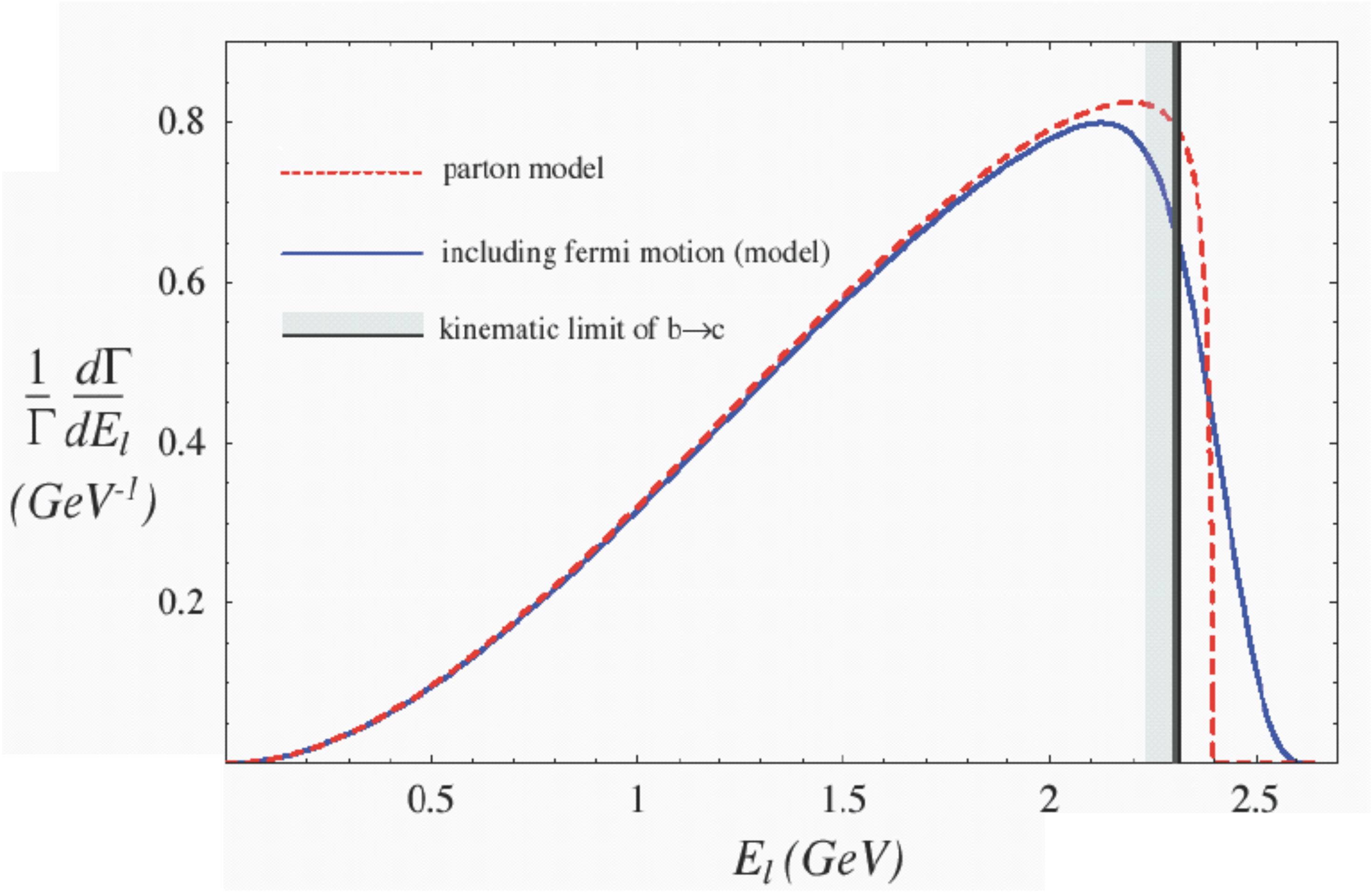
$$|V_{ub}| = \left(4.06 \pm 0.15_{\rm exp}{}^{+0.25}_{-0.27}{}_{\rm th}\right) 10^{-3}$$ [Bosch,Lange,Neubert,Paz (BLNP)]

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

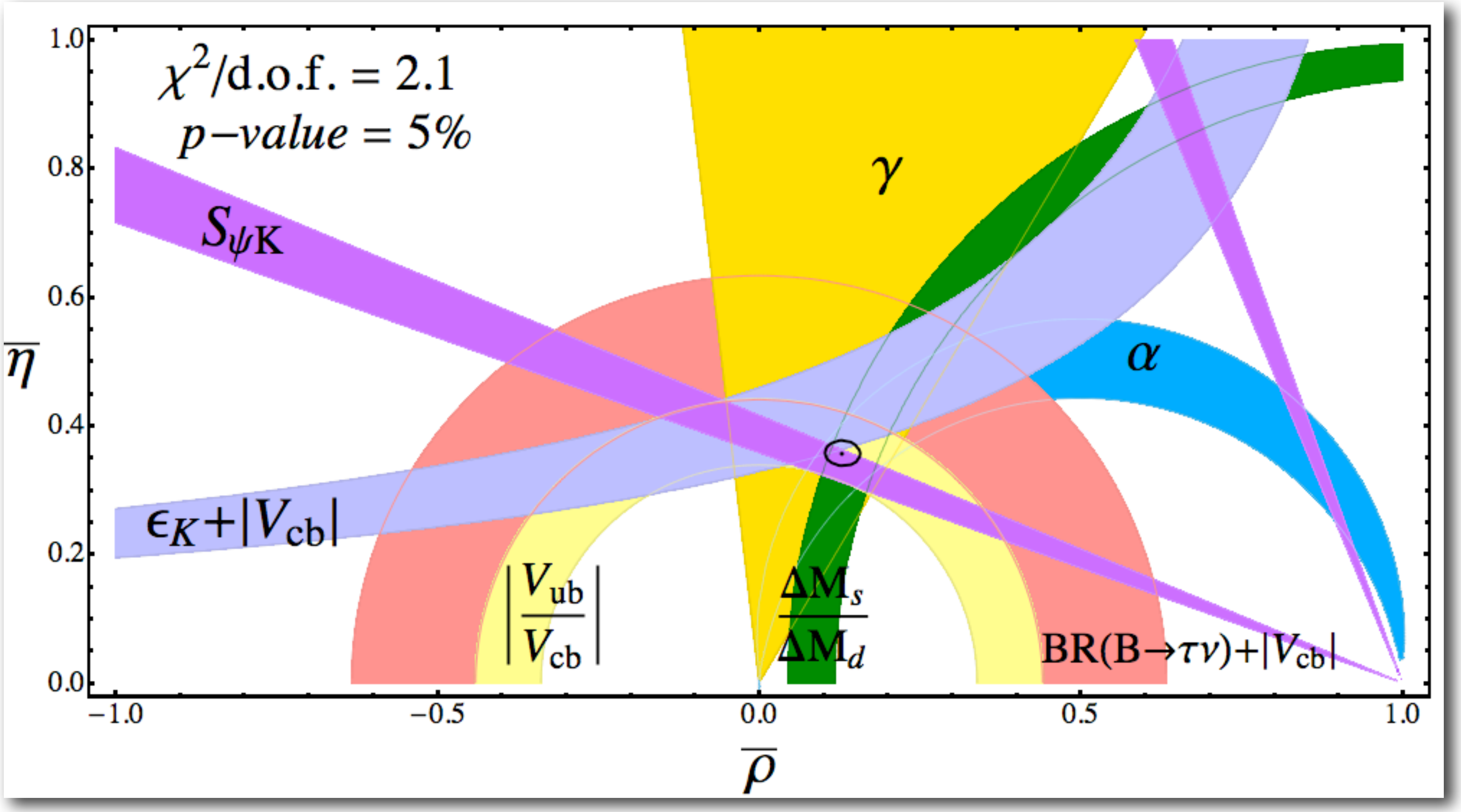
$$\left.\begin{array}{l}|V_{cb}|_{\text{excl}} = (38.6 \pm 1.2) \times 10^{-3} \\ |V_{cb}|_{\text{incl}} = (41.31 \pm 0.76) \times 10^{-3}\end{array}\right\}(40.3 \pm 1.0) \times 10^{-3}$$

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

additional theory uncertainty

$\Delta m_{B_d} = (0.507 \pm 0.005)\ \text{ps}^{-1}$	$\Delta m_{B_s} = (17.77 \pm 0.10 \pm 0.07)\ \text{ps}^{-1}$
$\alpha = (89.5 \pm 4.3)^{\text{o}}$	$\gamma = (78 \pm 12)^{\text{o}}$
$\eta_1 = 1.51 \pm 0.24$	$m_{t,pole} = (172.4 \pm 1.2)$ 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*:

$$\begin{aligned} \varepsilon_K &= \varepsilon_K^{\mathrm{SM}} C_\varepsilon \\ M_{12} &= M_{12}^{\mathrm{SM}}\, e^{2i\phi_d} \end{aligned}$$

- This implies:

$$\begin{aligned} a_{\psi K_s} &= \sin 2(\beta + \phi_d) \\ \sin 2\alpha_{\mathrm{eff}} &= \sin 2(\alpha - \phi_d) \\ \mathrm{BR}(B \to \tau\nu)^{\mathrm{NP}} &= \mathrm{BR}(B \to \tau\nu)^{\mathrm{SM}}\; r_H \end{aligned}$$

- I don’t entertain here NP in the $|M_{12}|$ because it cannot explain the tension in the UT fit

Model Independent Interpretation

- NP in B mixing:

$$(\theta_d)_{\rm fit} = -(4.4 \pm 1.8)^o \quad (2.4\sigma, p = 37\%)$$

Slightly favored

- NP in K mixing:

$$(C_\varepsilon)_{\rm fit} = 1.24 \pm 0.13 \quad (1.8\sigma, p = 18\%)$$

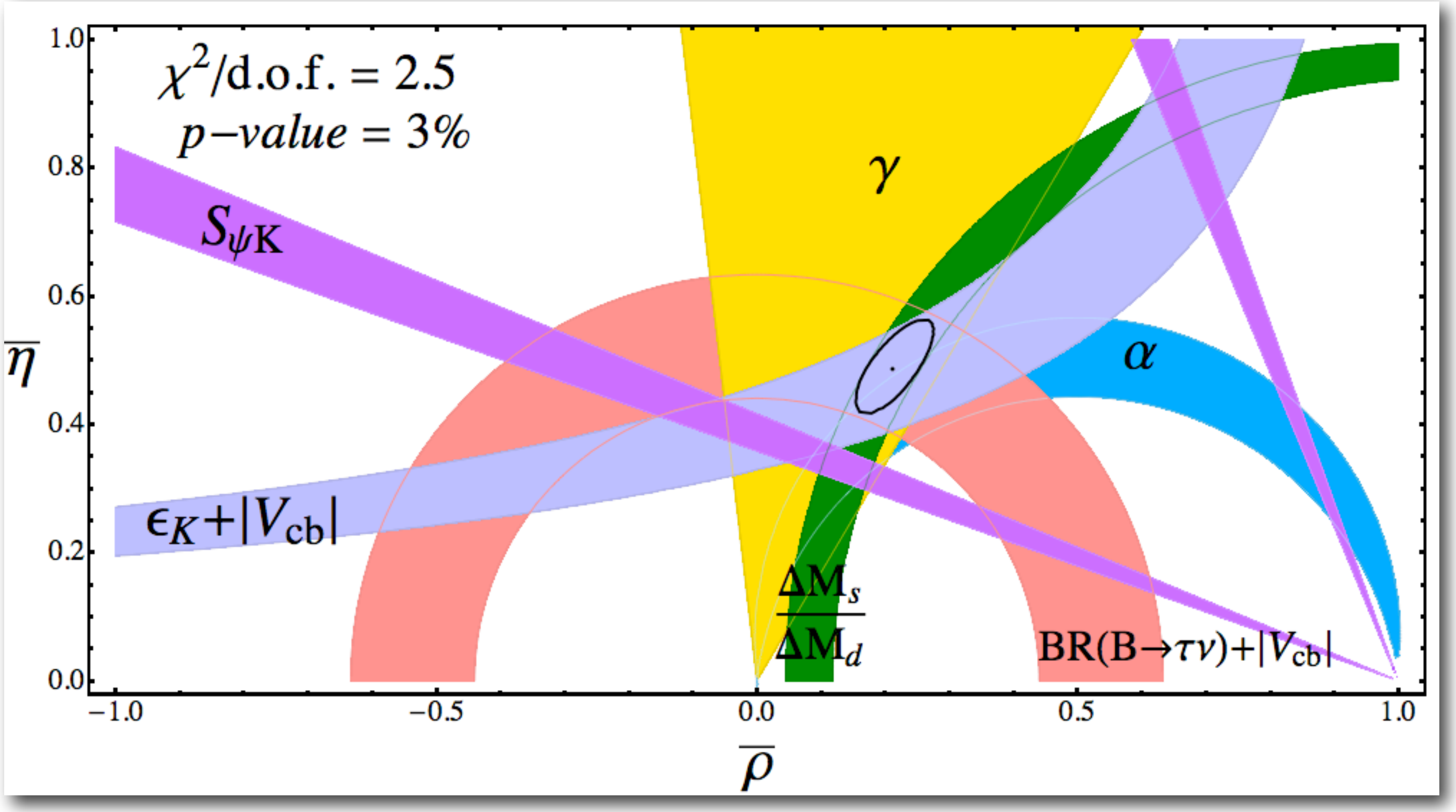
- NP in B→τν:

$$(r_H)_{\rm fit} = 2.06 \pm 0.48 \ (2.2\sigma, p = 35\%)$$

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 V_{ub} and V_{cb} ?

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

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

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

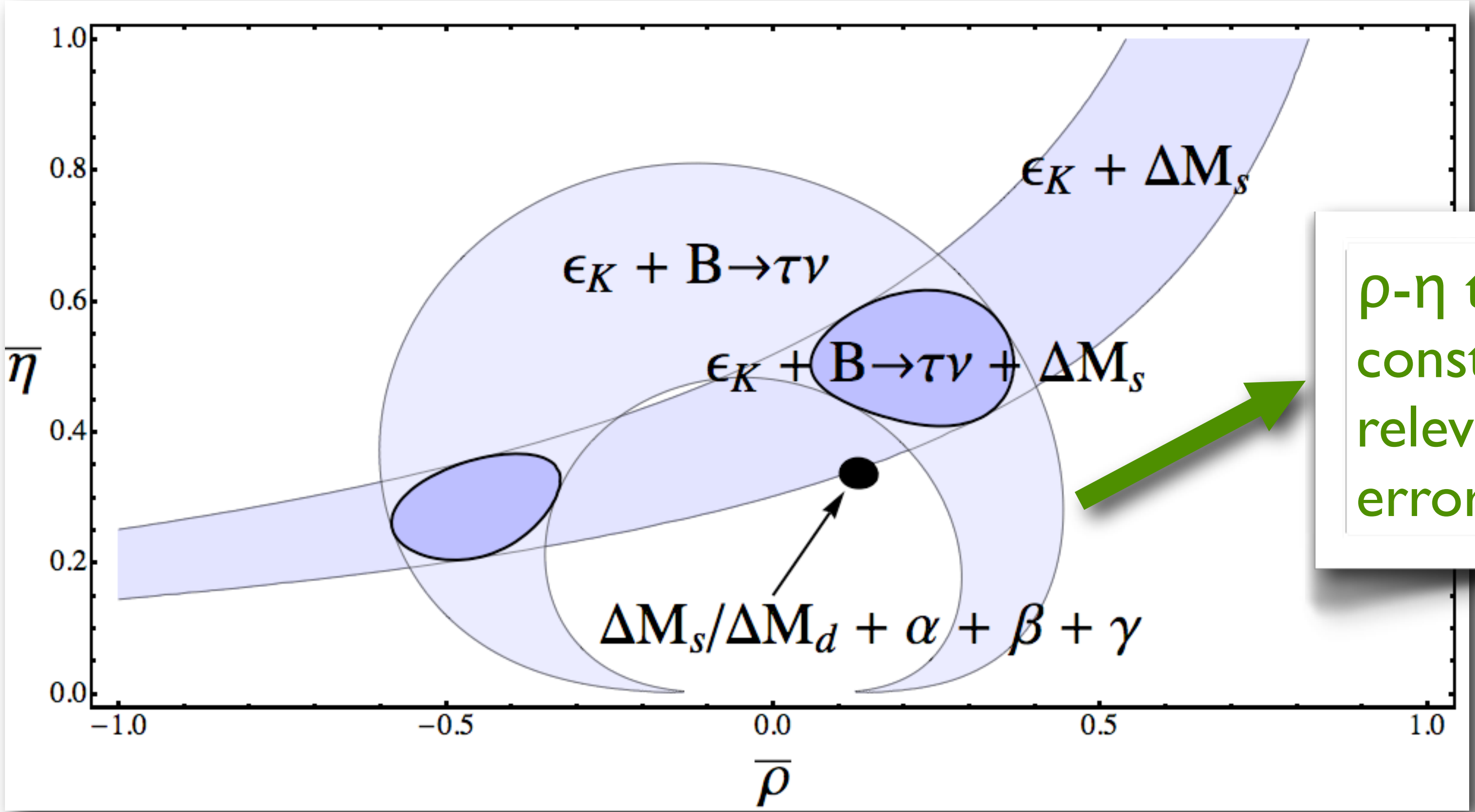
$$\mathrm{BR}(B \to \tau\nu) = \chi_\tau f_B^2 A^2 \lambda^6 (\rho^2 + \eta^2)$$

- 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
$\delta X:$	3.7%	2.5%	4.7%	21%	5%
$\delta\varepsilon_K:$	3.7%	10%	18.9%	42%	20%

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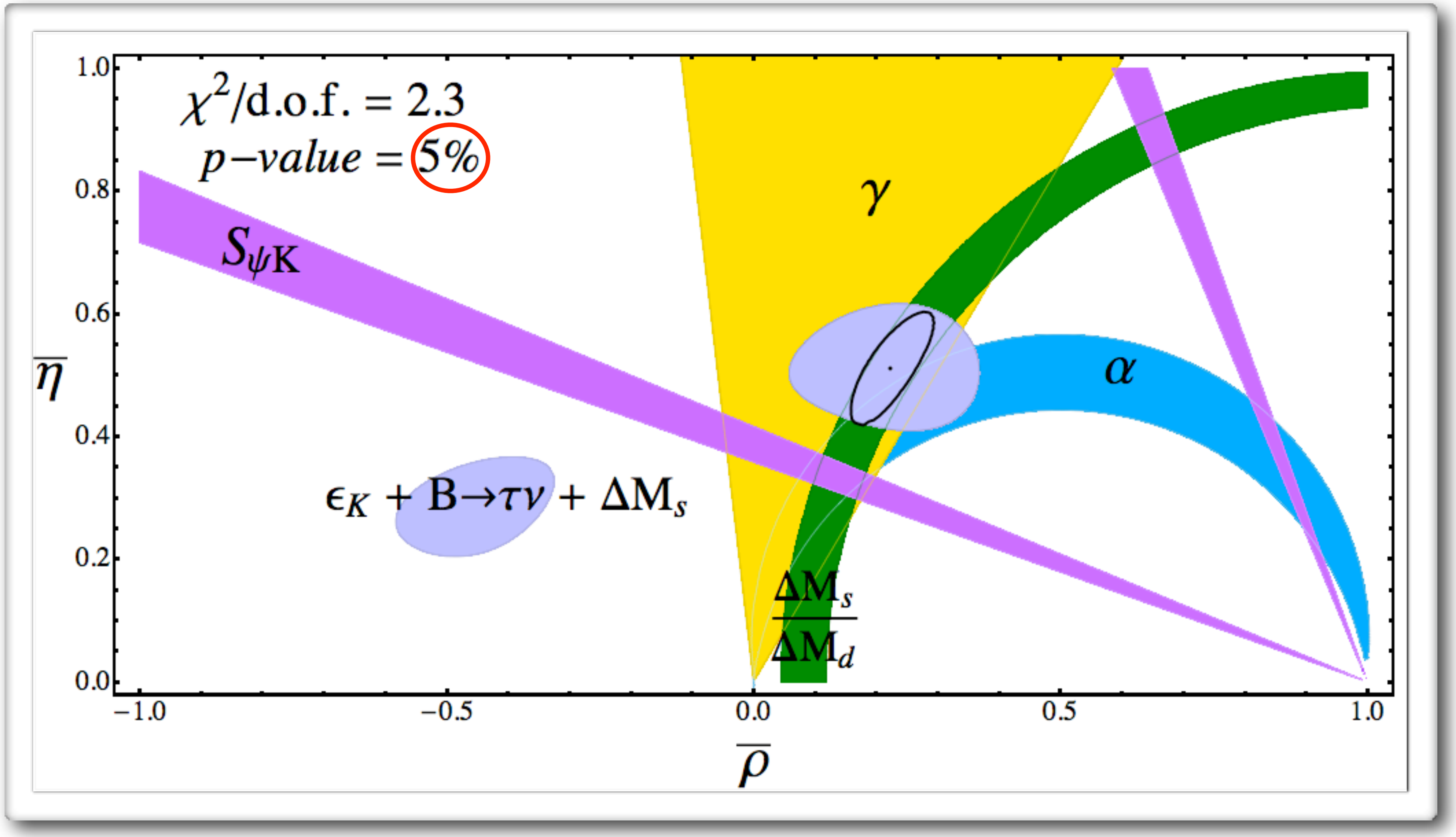


$$C_\varepsilon^{\mathrm{no}V_{qb}} = 1.21 \pm 0.22 \Rightarrow (1.0\sigma, p = 8\%)$$

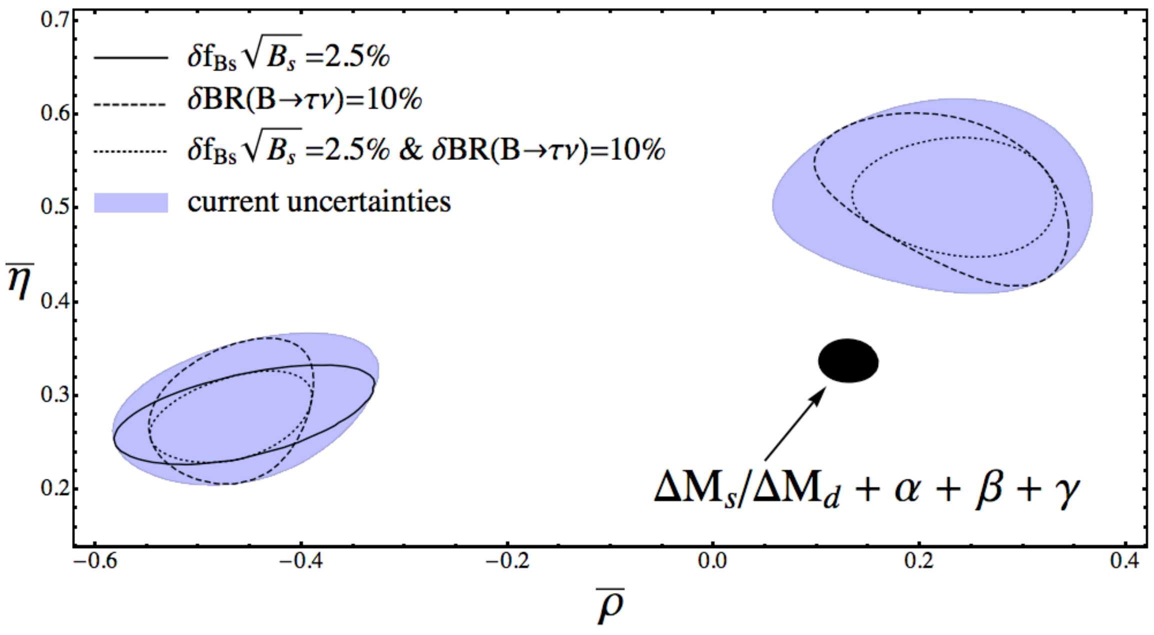
$$\theta_d^{\mathrm{no}V_{qb}} = -(11.4 \pm 2.7)^{\mathrm{o}} \Rightarrow (2.7\sigma, p = 85\%)$$

$$r_H^{\mathrm{no}V_{qb}} = 2.1 \pm 0.5 \Rightarrow (2.2\sigma, p = 50\%)$$

Super-B expectations...

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

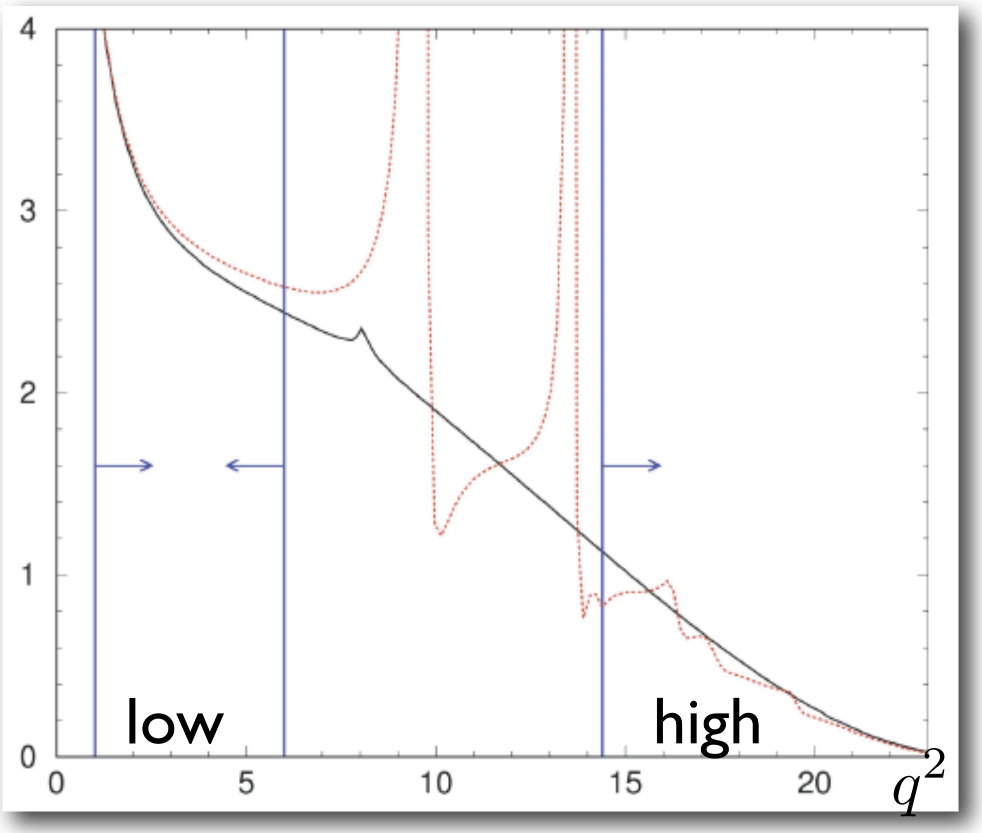
δ_τ	δ_s	$p_{\rm SM}$	$\theta_d \pm \delta\theta_d$	p_{θ_d}	$\theta_d/\delta\theta_d$
*20%	*4.6%	5%	$-(11.4 \pm 4.2)^o$	85%	2.7σ
*20%	2.5%	1.1%	$-(11.2 \pm 3.7)^o$	85%	3.1σ
*20%	1%	0.08%	$-(11.0 \pm 3.1)^o$	85%	3.5σ
10%	*4.6%	0.03%	$-(12.2 \pm 3.0)^o$	84%	4.1σ
3%	*4.6%	10^{-5}%	$-(12.5 \pm 2.4)^o$	84%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

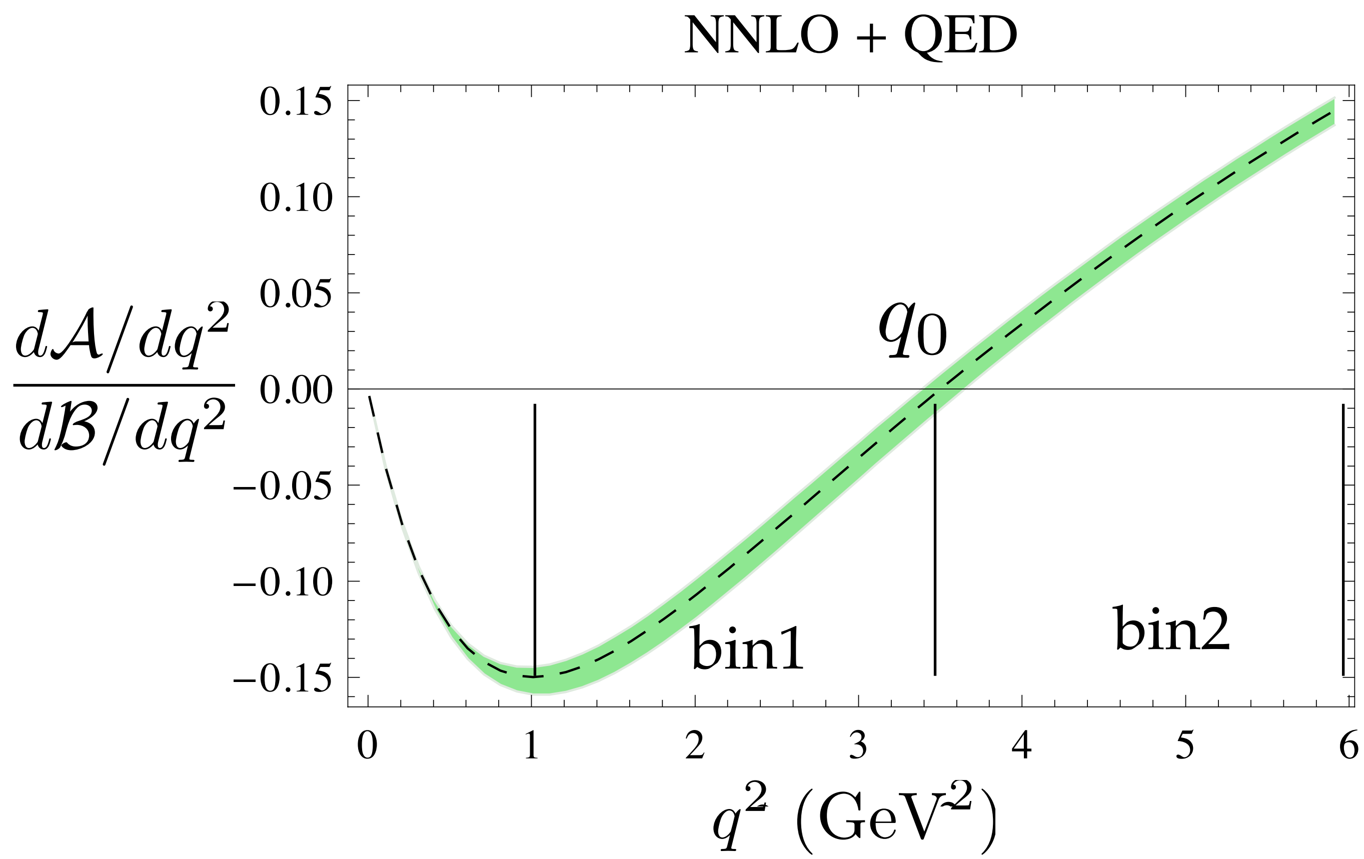


- Even modest improvements on B→τν have tremendous impact on the UT fit: L = 10(50)ab^{-1} → δ_τ = 10(3)%
- Interplay between Bs mixing and B→τν can result in a > 5σ effect
- The fit is completely clean

B→K*ll

- b→sll decays are very sensitive to NP and they are part of the B-factories, Tevatron, LHC-b and Super-B programs
- Inclusive B→X$_s$ll decays are very clean but can only be studied in a B-factory environment:





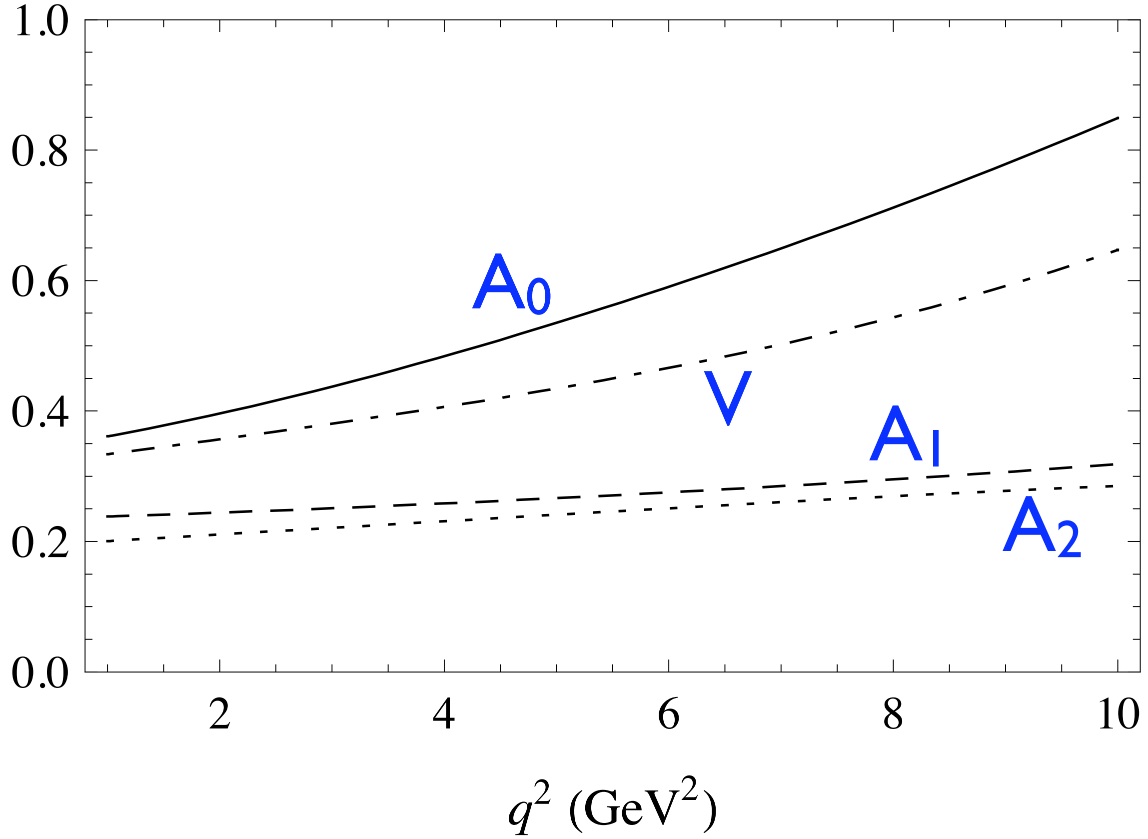
$$\mathcal{B}^{\rm low}_{\mu\mu} = (1.59 \pm 0.14) \times 10^{-6}$$
$$(\mathcal{B}^{\rm low}_{\ell\ell})_{\rm exp} = (1.60 \pm 0.51) \times 10^{-6}$$

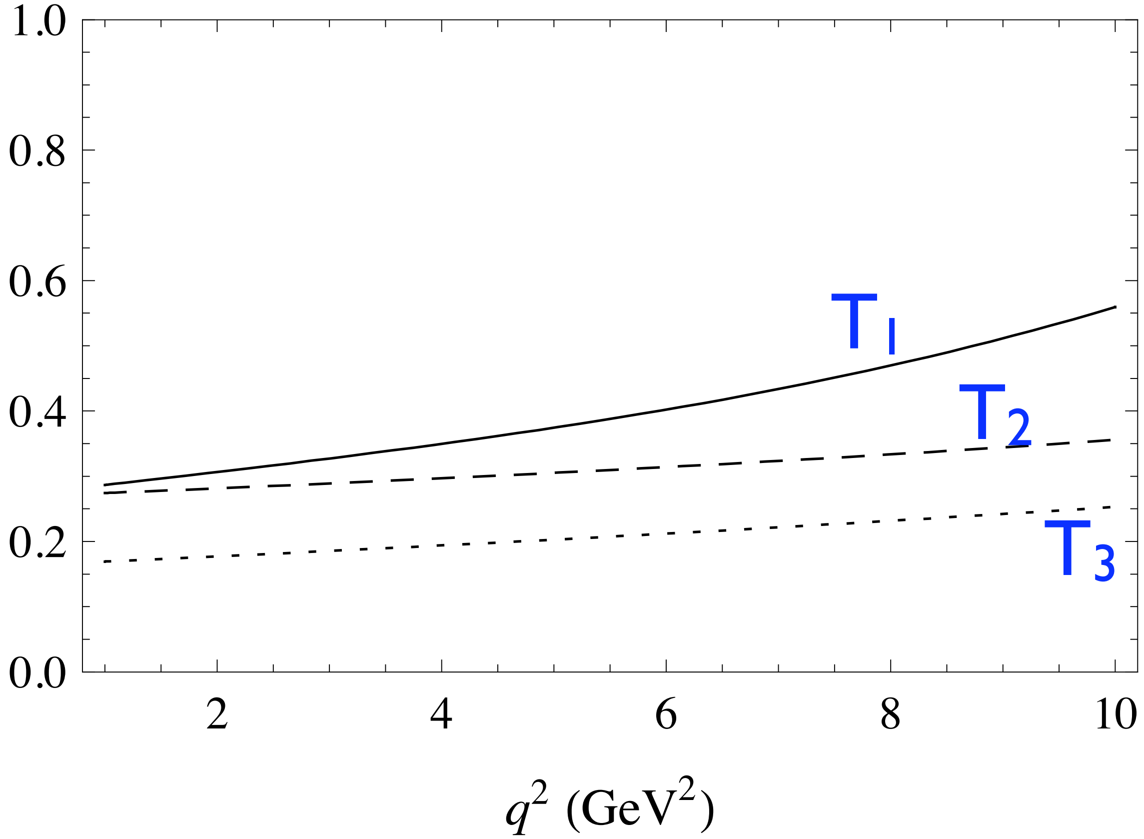
$$(\bar{\mathcal{A}}_{\mu\mu})_{\rm bin1} = [-9.1 \pm 0.9]\%$$
$$(\bar{\mathcal{A}}_{\mu\mu})_{\rm bin2} = [7.8 \pm 0.8]\%$$

$$(q_0^2)_{\mu\mu} = (3.50 \pm 0.12)\ {\rm GeV}^2$$

B→K*ll

- Exclusive transitions can be studied in hadronic experiments but suffer from largish theory uncertainties:
  - power corrections (appear in the QCDF/SCET approach)
  - B→K* form factors (presently from LCSR)

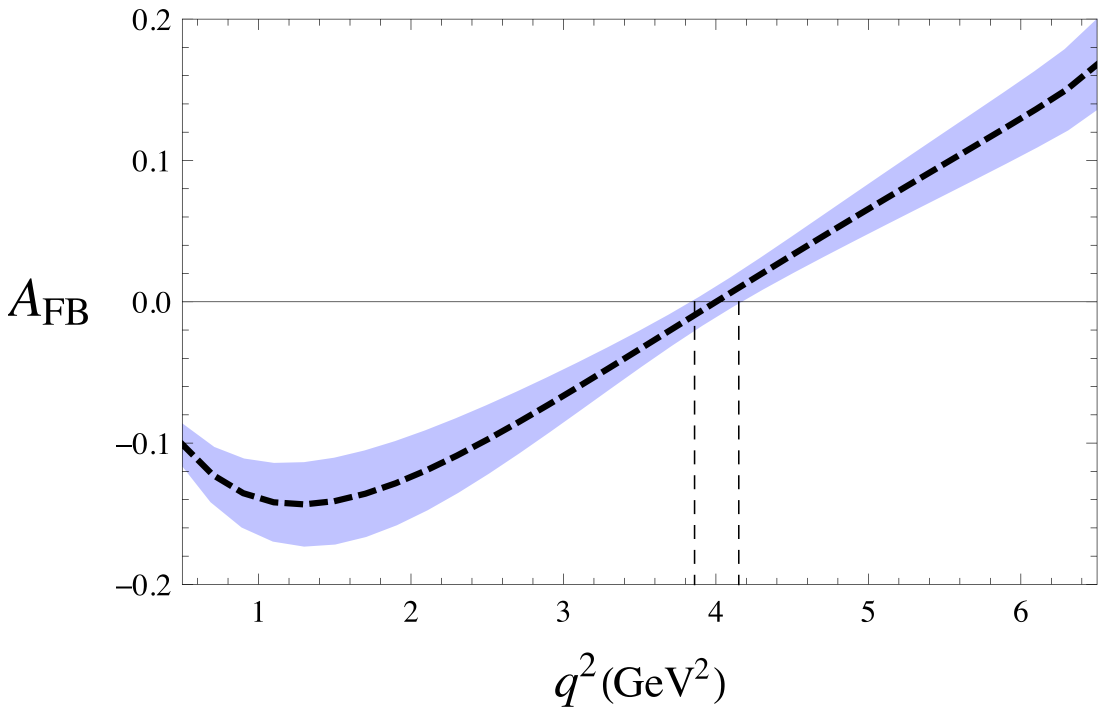




[Ball,Zwicky]

B→K*ll

- The FF's are the dominant source of uncertainty on the calculation of asymmetries (forward-backward, isospin, CP):



$$q_0^2 = (4.0 \pm 0.12)\ \mathrm{GeV}^2$$
$$A_{FB}^{[1,4]} = -0.09 \pm 0.02 \quad (22\%)$$
$$A_{FB}^{[4,6]} = 0.066 \pm 0.015 \quad (23\%)$$

- Error band controlled by the q^2=0 value of the FF's:

$A_0(0)$	$A_1(0)$	$A_2(0)$	$V(0)$
0.333 ± 0.033	0.233 ± 0.038	0.190 ± 0.039	0.311 ± 0.037

$T_1(0)$	$T_3(0)$	$\xi_\parallel(0)$	$\xi_\perp(0)$
0.268 ± 0.045	0.162 ± 0.023	0.118 ± 0.008	0.266 ± 0.032

lattice results for these form factors at any q^2 value are invaluable!!

The shopping list

- ☑ f_K/f_π, $f_+(0)$
- ☑ $B \to D^{(*)}$ form factors at the inclusive level of precision
- ☑ $B \to \pi$ form factors (not clear inclusive prospects)
- ☑ $f_{B_s}\sqrt{B_s}$: becomes essential if the $b \to c$ problem persists
- ☑ f_B: important for $B \to \tau\nu$ (critical if 3-10% precision is reached)
- ☑ $B \to K^{(*)}$ form factors: cornerstone of a big part of present (Babar, Belle, CDF, D0) and future (LHCb) experimental flavor studies
- ☑ $B \to \gamma$ form factor at small q^2: important to determine the B meson wave function (λ_B) using QCDF in $B \to \gamma l \nu$

Backup slides

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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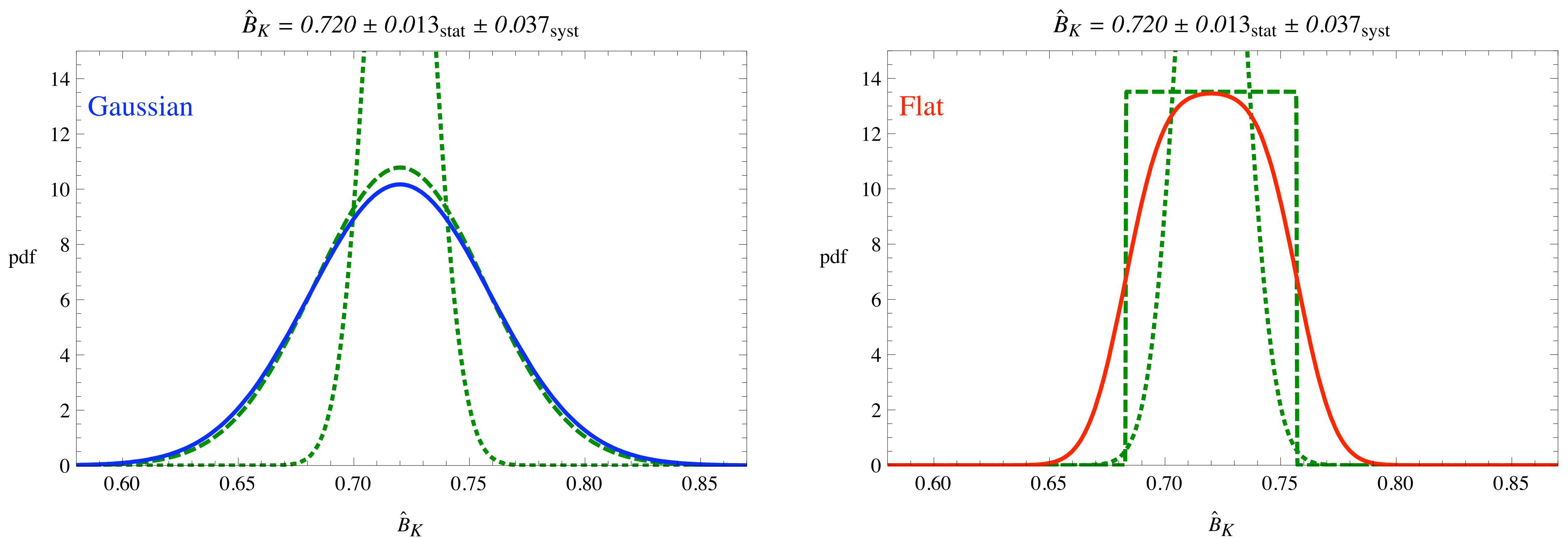

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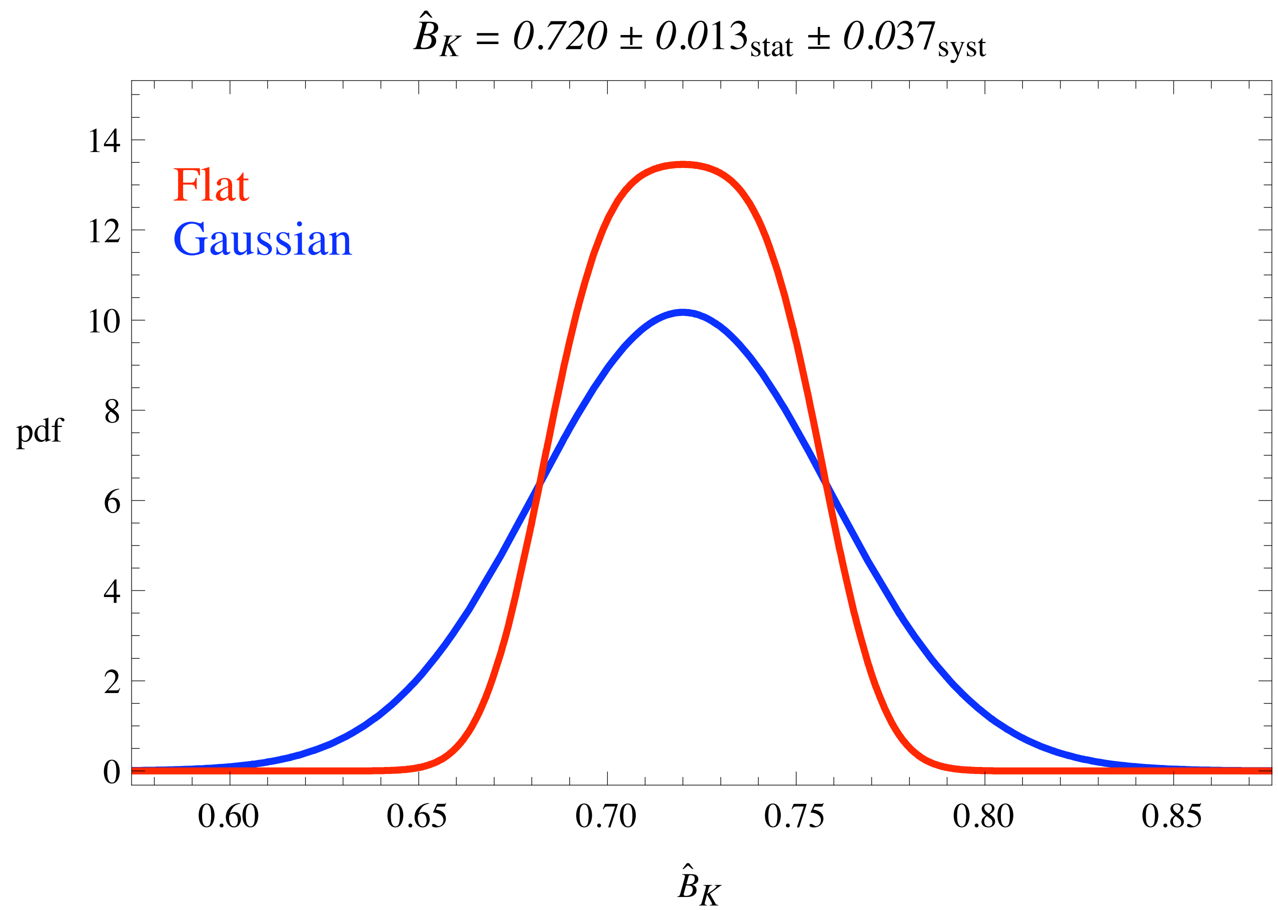

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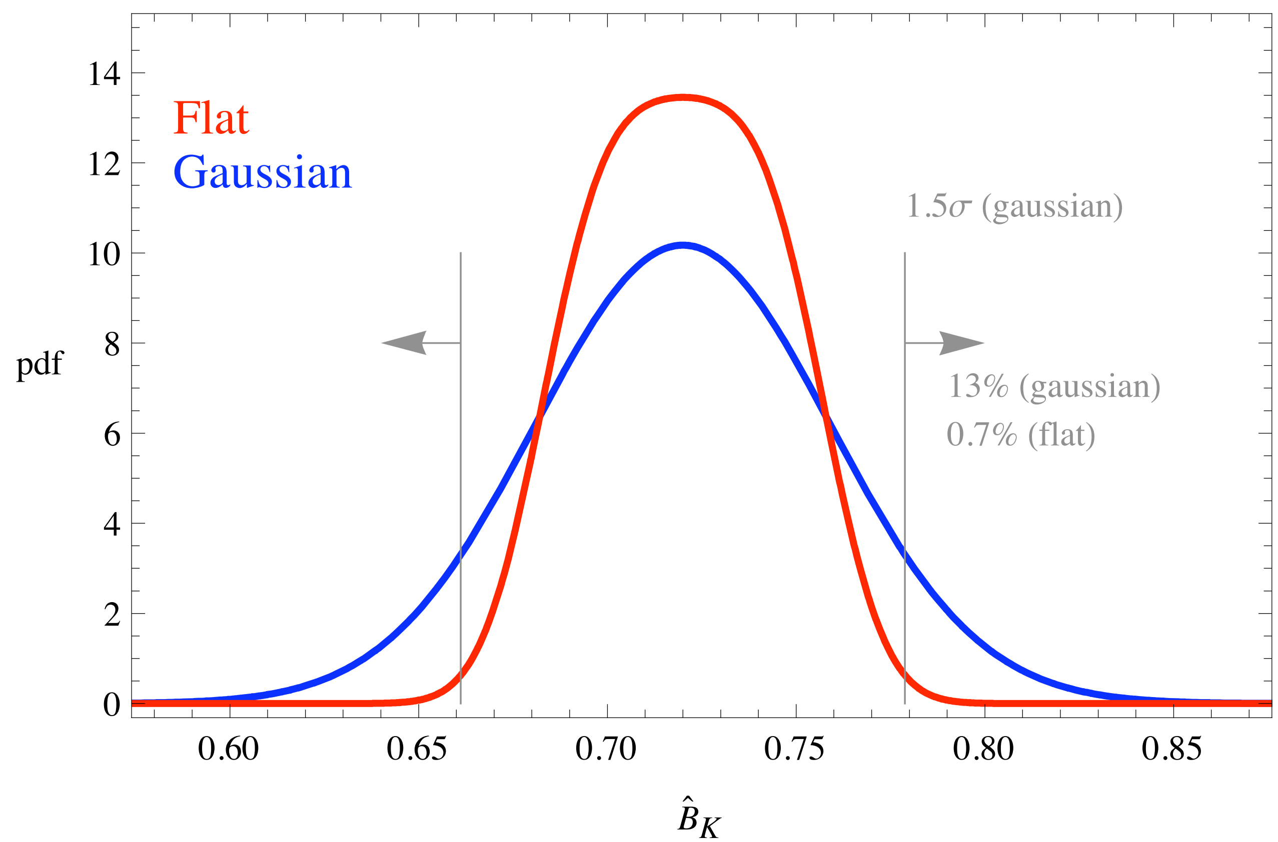
$\hat{B}_K = 0.720 \pm 0.013_{\rm stat} \pm 0.037_{\rm syst}$



Three types of CP violation

- Mixing (mass and CP eigenstates are different)

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

- Decay

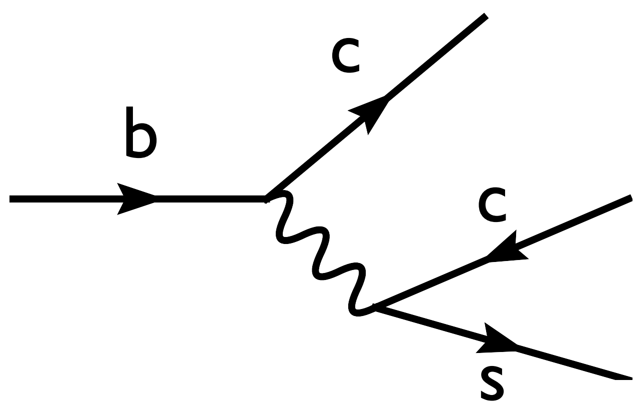
$$\Gamma(B^+ \to f^+) \neq \Gamma(B^- \to f^-)$$

- Interference in decays with and without mixing

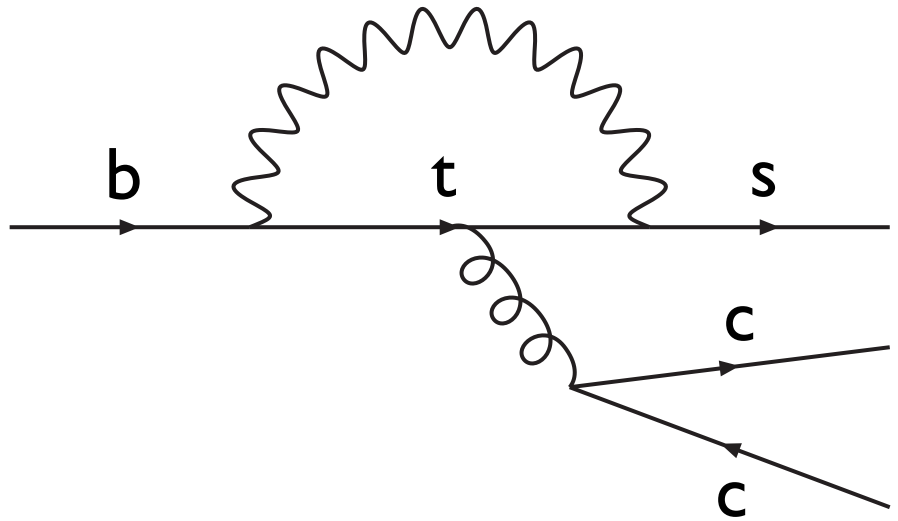
$$\Gamma(\bar{B}^0_{\text{phys}}(t) \to f_{CP}) \neq \Gamma(B^0_{\text{phys}}(t) \to f_{CP})$$

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

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



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



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

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

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

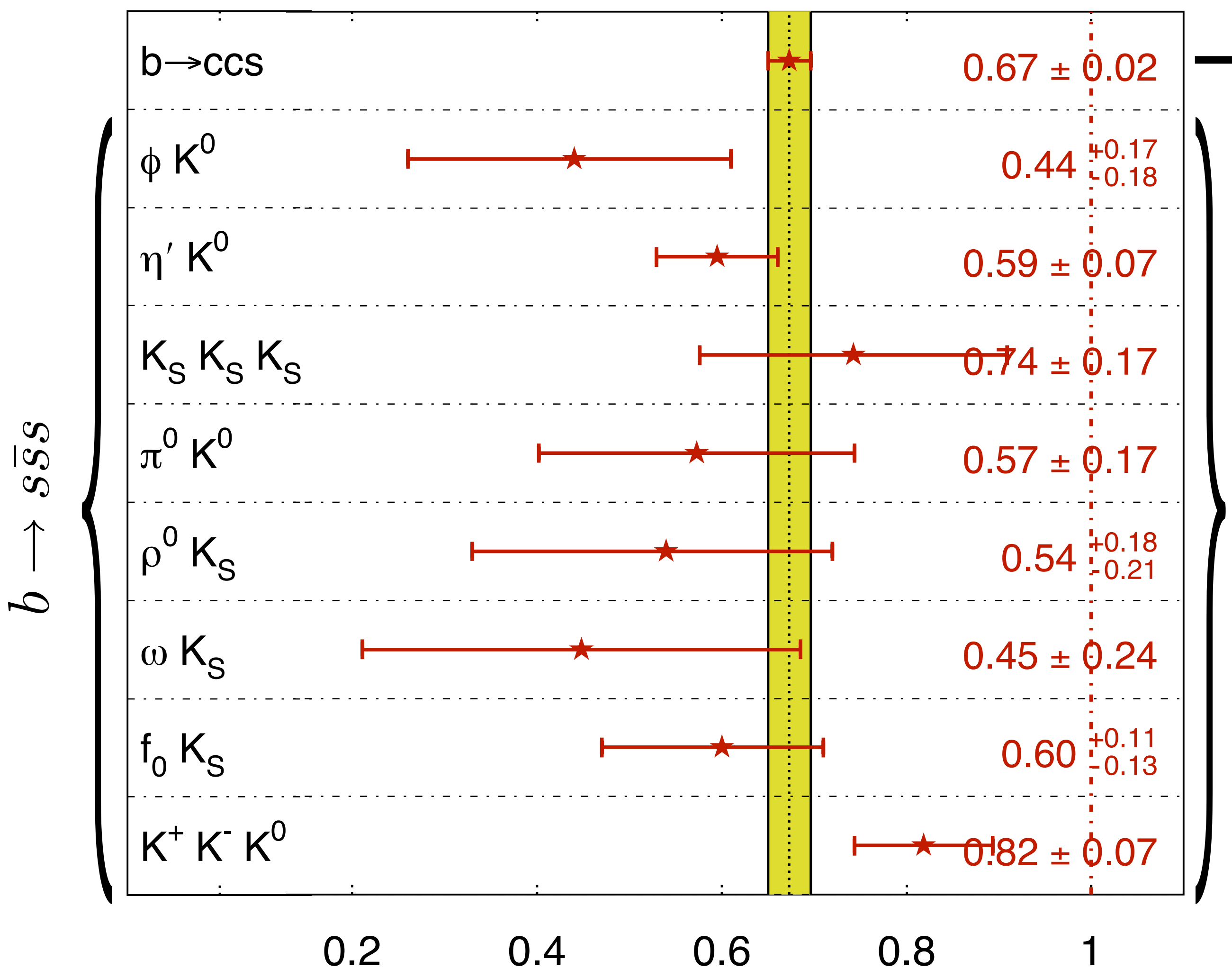
- No tree-level contribution
- There is no loop suppression of the sub-dominant CKM combination: uncertainty is (1-10)%

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

- 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]



$$S_{\psi K_s} = \sin 2(\beta + \theta_d) + O(0.1\%)$$

θ_d: $\arg(V_{td}^*)$

In QCDF:

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

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

$$\Delta S_\phi = 0.03 \pm 0.01 \qquad \text{[Beneke,Neubert]}$$

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

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]