Lessons for New Physics from CKM studies

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F**lavor **P**hysics and **CP** violation, **2010
Università di Torino, May 25-28, 2010

Outline

- Flavor violation in the Standard Model
- Inputs to the unitarity triangle analysis
- Status of CKM fits: role of V_{ub},V_{cb} and $B\to\tau\nu$
- Parametrization of NP in K/B-mixing and $B\to\tau\nu$ and fit
- Interpretation in terms of complex NP coefficients
- Super-B/LHCb prospects
- Conclusions

The Cabibbo✹-Kobayashi★-Maskawa★ matrix

Gauge interactions do not violate flavor:

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

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:

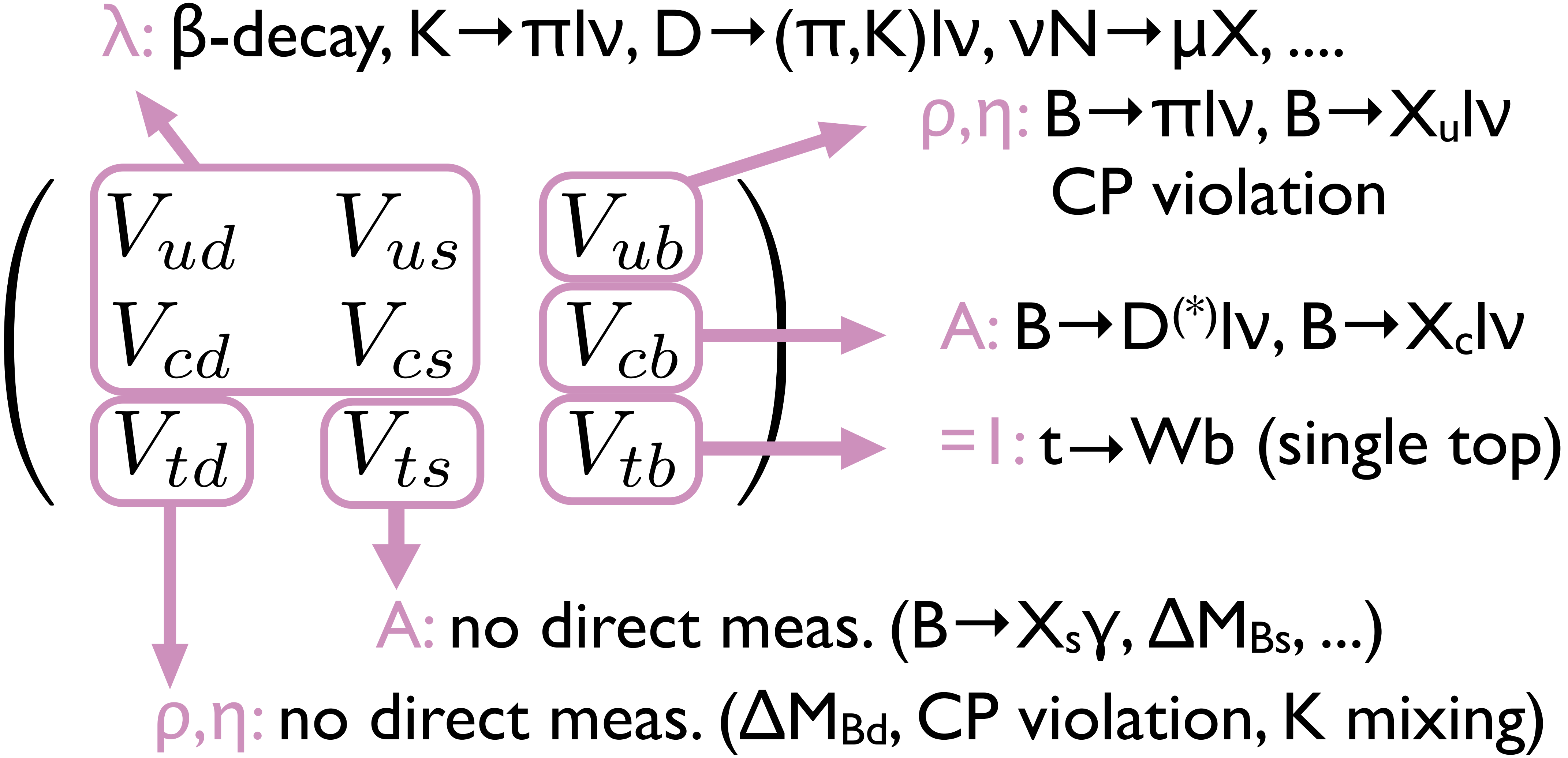
$$\bar u_L^0 Z\!\!\!/\, u_L^0 \Longrightarrow \bar u_L Z\!\!\!/\, U_L U_L^\dagger u_L = \bar u_L Z\!\!\!/\, u_L$$

- 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→πlν, D→(π,K)lν, νN→μX, ...

ρ,η: B→πlν, B→X_ulν
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→$D^{(*)}$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)

Wolfenstein parametrization:

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

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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]
- We assume all errors to be normally distributed
- Updated averages at: http://www.latticeaverages.org

Determining *A*

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

- 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:

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

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

Observables included in the fit

- $|V_{ub}|$ and $|V_{cb}|$ from inclusive and exclusive semileptonic decays
- B_d and B_s mass differences: ξ and $f_{B_s}\hat{B}_s^{1/2}$
- α and γ from $B \to (\pi\pi, \rho\rho, \rho\pi, D^{(*)}K^{(*)})$
- $\mathrm{BR}(B \to \tau\nu)$: $\hat{B}_d$ ($f_{B_d} = f_{B_s}\hat{B}_s^{1/2}/(\xi\hat{B}_d)$)
- $S_{\psi K} = \sin 2\beta$
- $\varepsilon_K : \hat{B}_K , \kappa_\varepsilon$

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)

Inputs to the fit: summary

$$\hat{B}_K = 0.720 \pm 0.025$$

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

$$\xi = 1.237 \pm 0.032$$

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

$$\hat{B}_d = 1.26 \pm 0.11$$

$$\left.\begin{aligned} |V_{cb}|_{\mathrm{excl}} &= (39.0 \pm 1.2) \times 10^{-3} \\ |V_{cb}|_{\mathrm{incl}} &= (41.31 \pm 0.76) \times 10^{-3} \end{aligned}\right\} (40.43 \pm 0.86) \times 10^{-3}$$

1.7σ tension
(error rescaled)

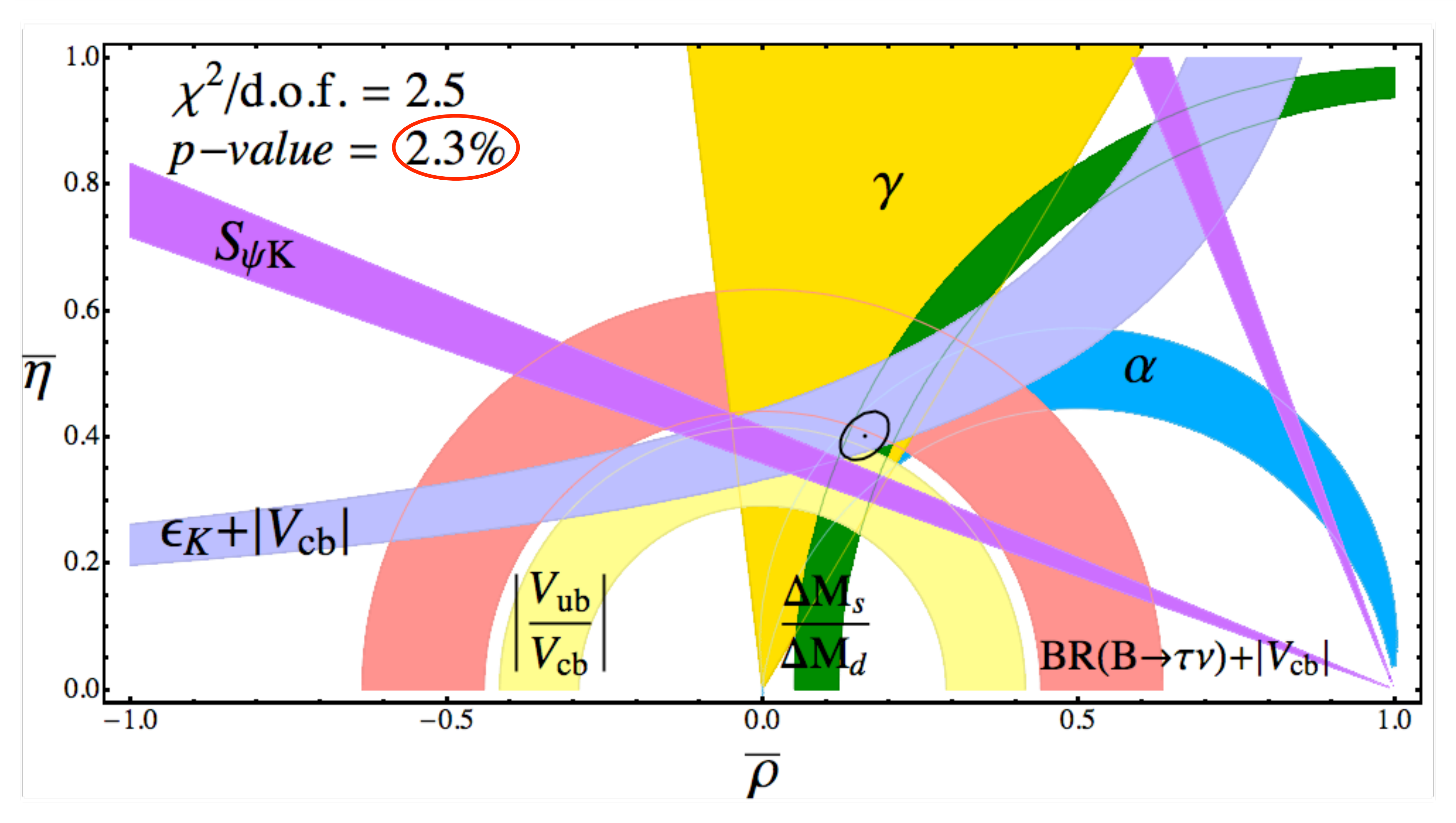
$$\left.\begin{aligned} |V_{ub}|_{\mathrm{excl}} &= (30.9 \pm 3.3) \times 10^{-4} \\ |V_{ub}|_{\mathrm{incl}} &= (40.1 \pm 2.7 \pm 4.0) \times 10^{-4} \end{aligned}\right\} (33.0 \pm 3.7) \times 10^{-4}$$

1.6σ tension
(error rescaled)

additional theory uncertainty

$$\begin{array}{ll}
\Delta m_{B_d} = (0.507 \pm 0.005)\ \mathrm{ps}^{-1} & \Delta m_{B_s} = (17.77 \pm 0.10 \pm 0.07)\ \mathrm{ps}^{-1} \\
\alpha = (89.1 \pm 4.4)^{\mathrm{o}} & \gamma = (78 \pm 12)^{\mathrm{o}} \\
\eta_1 = 1.51 \pm 0.24 & m_{t,pole} = (172.4 \pm 1.2)\ \mathrm{GeV} \\
\eta_2 = 0.5765 \pm 0.0065 & m_c(m_c) = (1.268 \pm 0.009)\ \mathrm{GeV} \\
\eta_3 = 0.47 \pm 0.04 & \varepsilon_K = (2.229 \pm 0.012) \times 10^{-3} \\
\eta_B = 0.551 \pm 0.007 & \lambda = 0.2255 \pm 0.0007 \\
S_{\psi K_S} = 0.672 \pm 0.024 & f_K = (156.1 \pm 1.2)\ \mathrm{MeV} \\
\mathrm{BR}(B \to \tau\nu) = (1.74 \pm 0.35) \times 10^{-4} &
\end{array}$$

Current fit to the unitarity triangle



$$[\sin 2\beta]_{\rm fit} = 0.774 \pm 0.038 \quad \Rightarrow \quad 2.2\,\sigma$$

$$[BR(B \to \tau\nu)]_{\rm fit} = (0.773 \pm 0.095) \times 10^{-4} \quad \Rightarrow \quad 2.7\,\sigma$$

$$[\hat{B}_K]_{\rm fit} = 0.918 \pm 0.086 \quad \Rightarrow \quad 2.4\,\sigma$$

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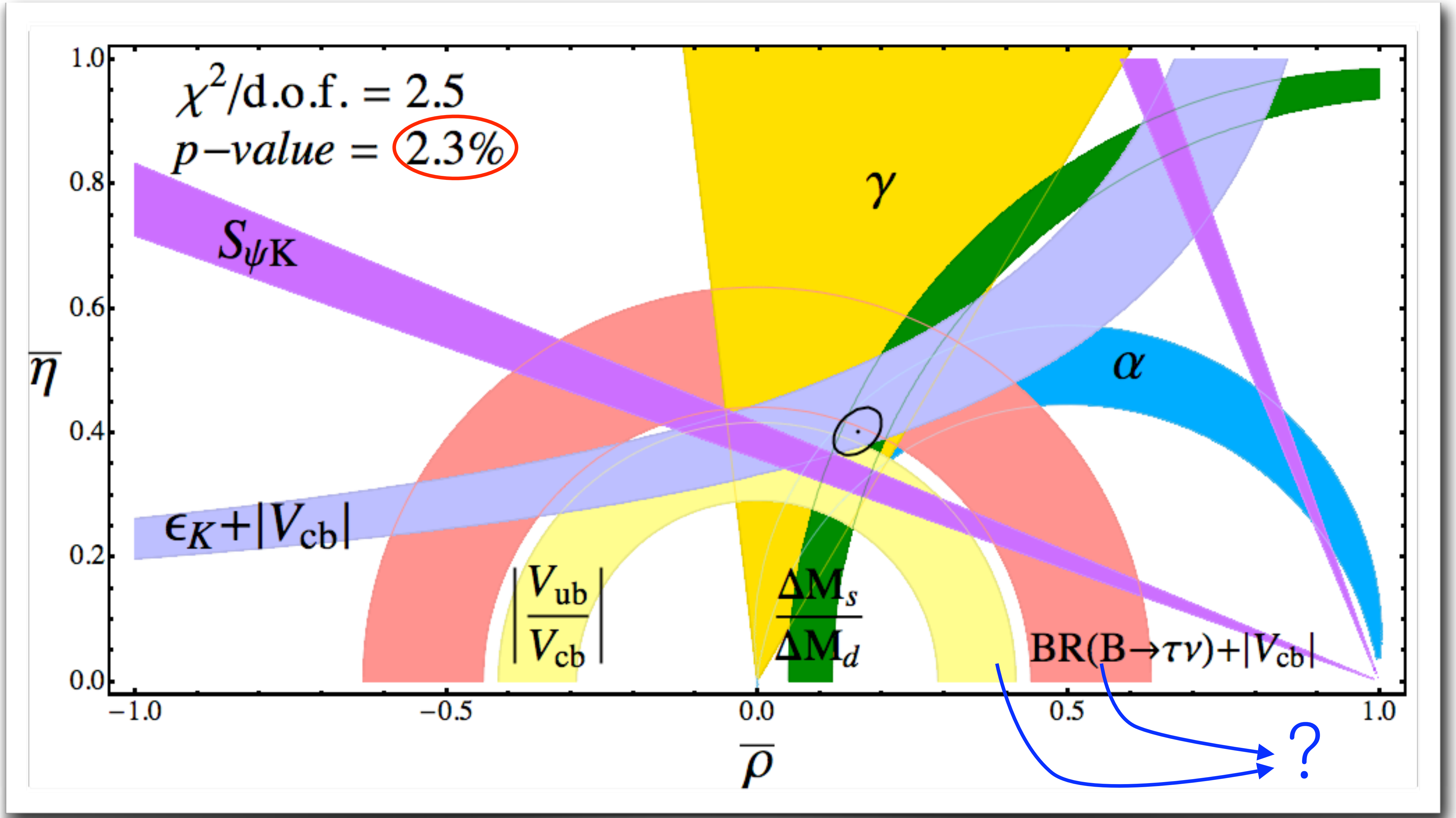

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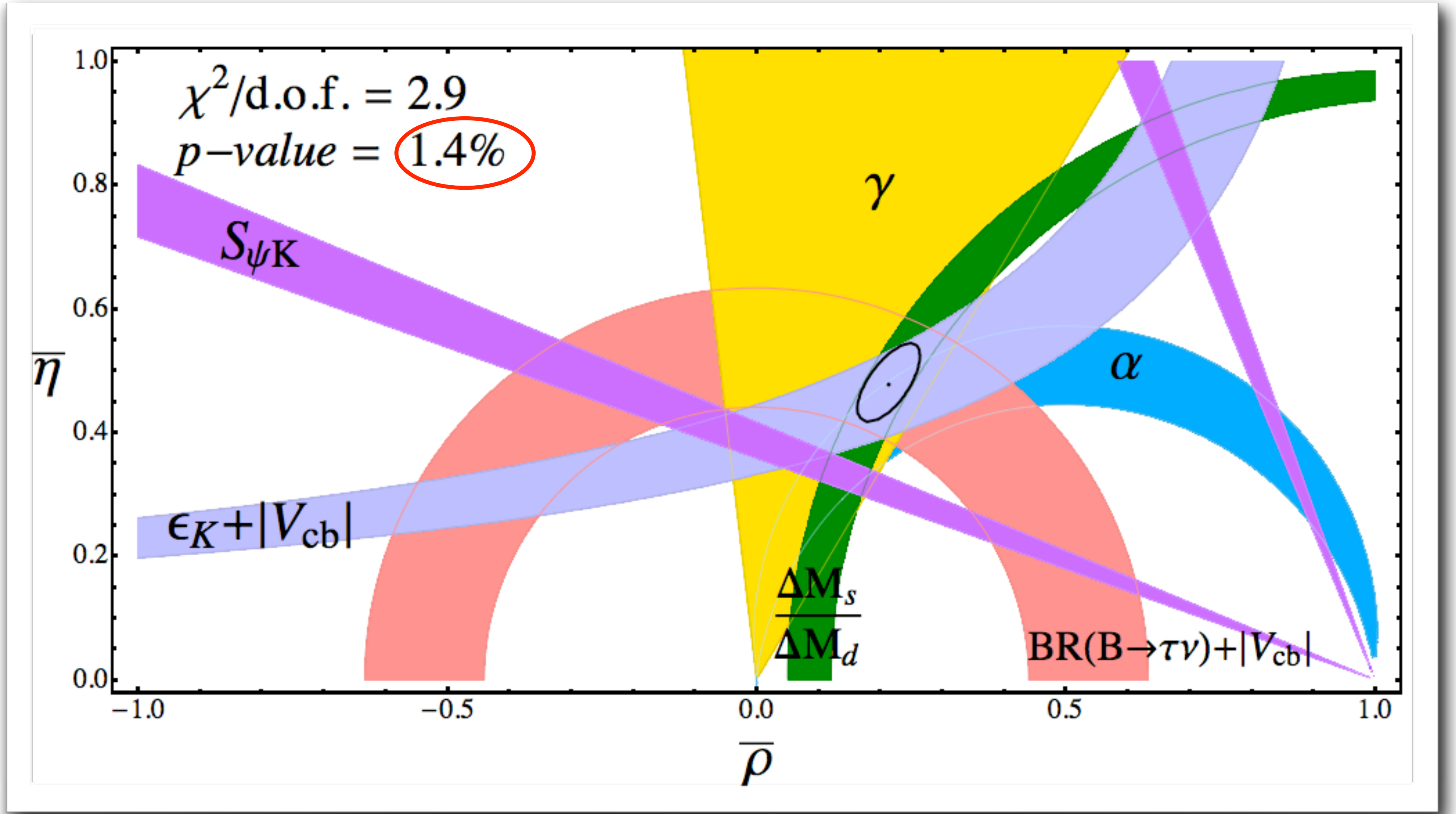
Removing V_{ub}

[Lunghi,Soni 0803.4340 and 0903.5059]

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



$$[\sin 2\beta]_{\rm fit} = 0.862 \pm 0.045 \quad \Rightarrow \quad 3.3\ \sigma$$

$$[BR(B \to \tau\nu)]_{\rm fit} = (0.784 \pm 0.098) \times 10^{-4} \quad \Rightarrow \quad 2.6\ \sigma$$

$$[\hat{B}_K]_{\rm fit} = 0.914 \pm 0.086 \quad \Rightarrow \quad 2.4\ \sigma$$

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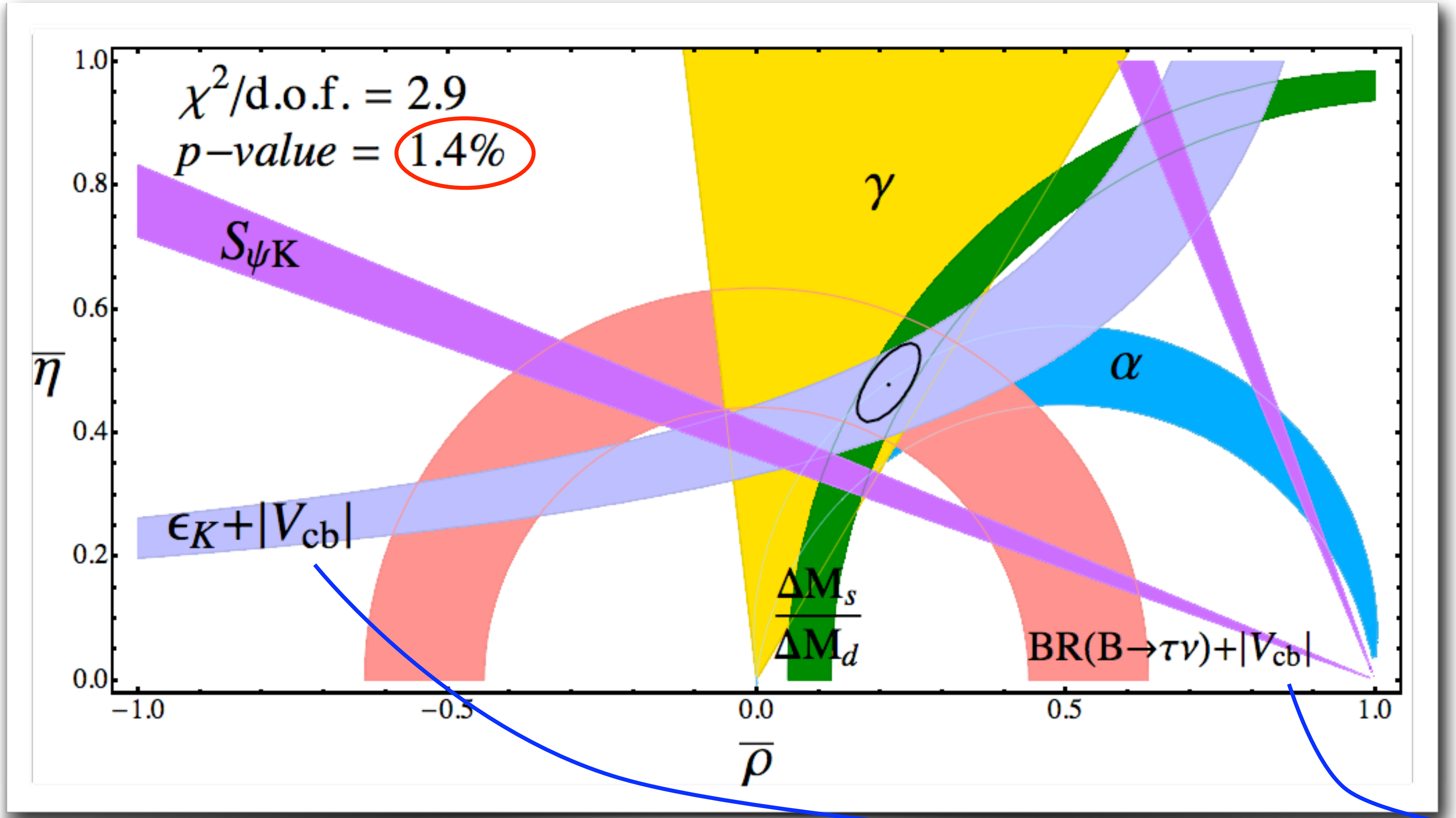

?

disturbing 1.7σ problem

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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:

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

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

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

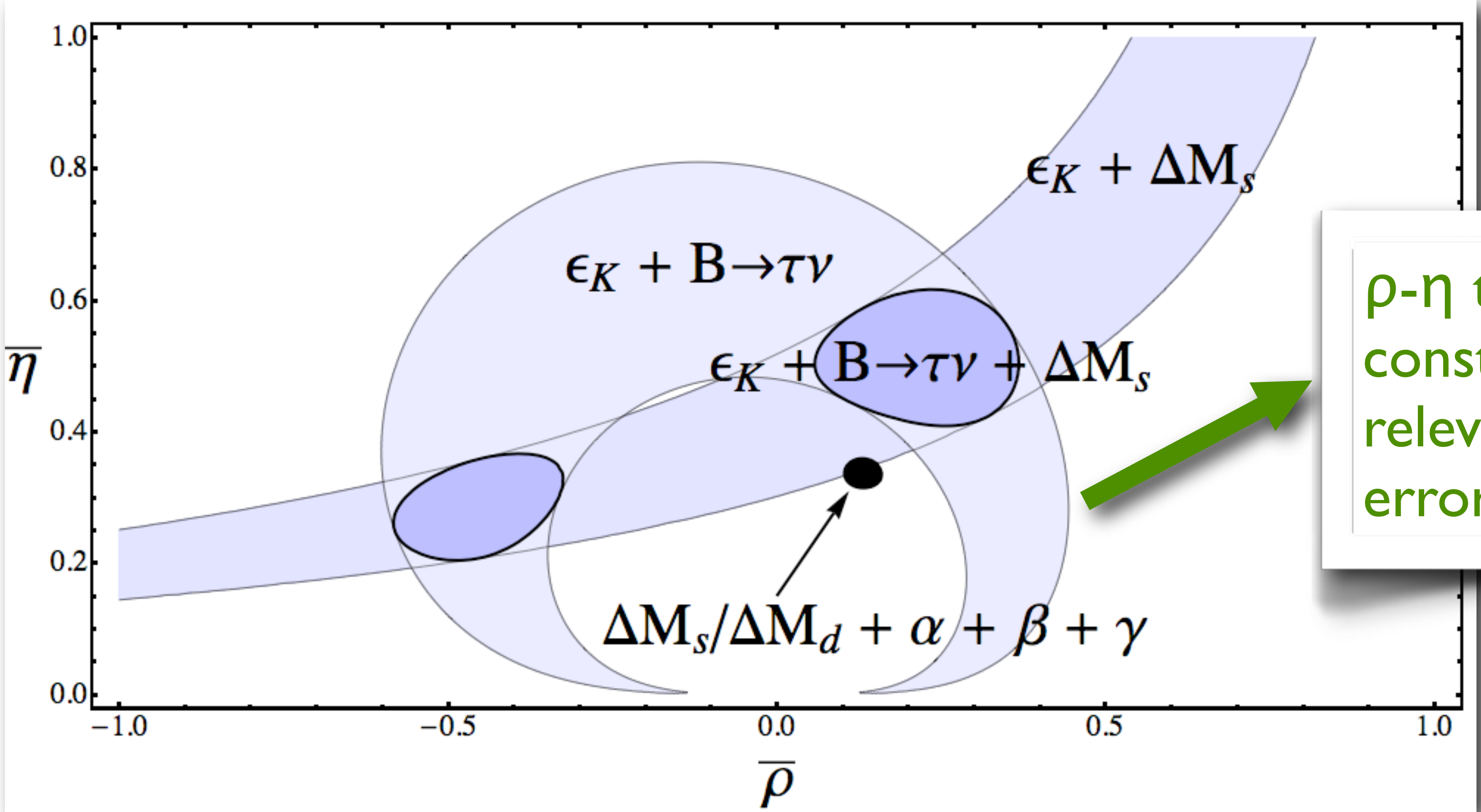
- The interplay of these constraints allows to drop V_{cb} while still constraining new physics in K mixing:

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

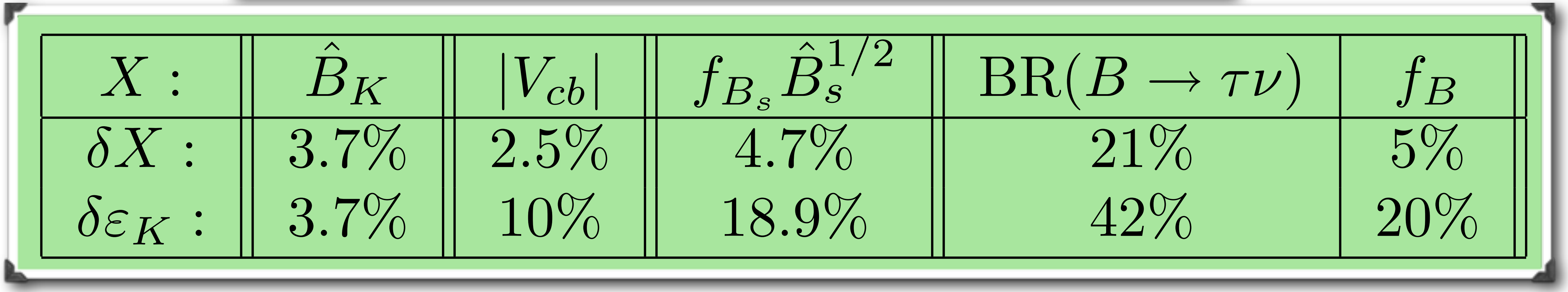
Removing V_{cb} !

[Lunghi,Soni 0912.002]

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



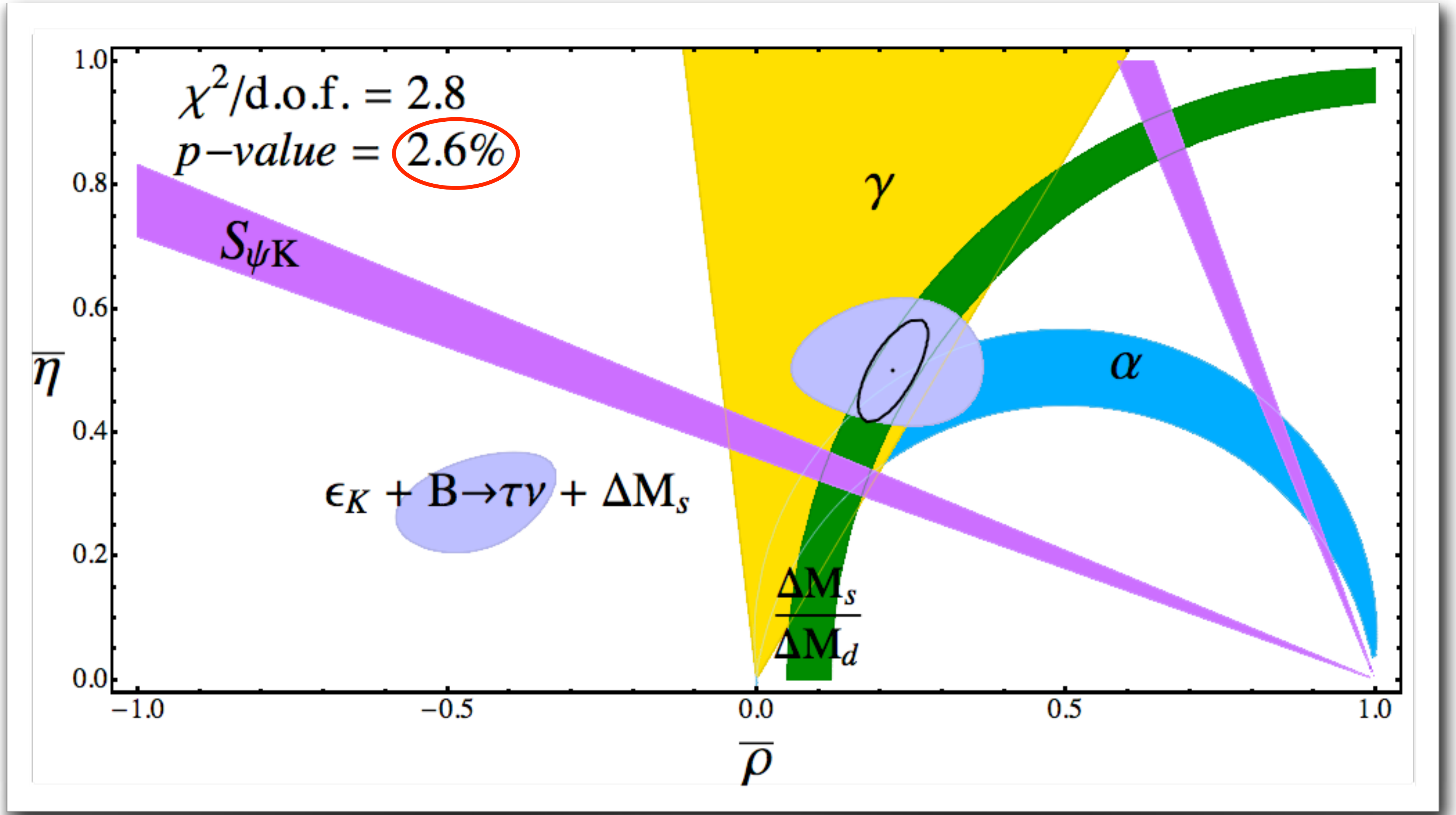
ρ-η topology of the constraint makes it relevant despite large errors on B→τν



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

Removing V_{cb} !

[Lunghi,Soni 0912.002]



$$[\sin 2\beta]_{\rm fit} = 0.863 \pm 0.051 \quad \Rightarrow \quad 2.8\ \sigma$$

$$[BR(B \to \tau\nu]_{\rm fit} = (0.763 \pm 0.098) \times 10^{-4} \quad \Rightarrow \quad 2.7\ \sigma$$

$$[\hat{B}_K]_{\rm fit} = 0.970 \pm 0.17 \quad \Rightarrow \quad 1.6\ \sigma$$

$$|V_{cb}|_{\rm fit} = (42.6 \pm 0.8) \times 10^{-3} \quad \Rightarrow \quad 1.7\ \sigma$$

Model Independent Interpretation

- The tension can be interpreted as NP in *B$_d$/K mixing* or B→τν:

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

- For NP in B$_d$ mixing:

$$\begin{aligned} a_{\psi K_s} &= \sin 2(\beta+\phi_d) \\ \sin 2\alpha_{\rm eff} &= \sin 2(\alpha-\phi_d) \\ X_{sd} &= X_{sd}^{\rm SM}\, r_d^{-2} \end{aligned}$$

- For NP in B→τν:

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

Model Independent Interpretation

- NP in B mixing (*marginalizing over r$_d$*):

$$(\theta_d)_{\rm fit} = \begin{cases} -(3.8 \pm 1.9)^o & (2.1\sigma, p = 11\%) \text{ complete fit} \\ -(8.8 \pm 3.1)^o & (3.2\sigma, p = 68\%) \text{ no } V_{ub} \\ -(10.5 \pm 3.5)^o & (3.0\sigma, p = 76\%) \text{ no } V_{qb} \end{cases}$$

$$p_{\rm SM} = 2.3\%$$
$$p_{\rm SM}^{{\rm no}\ V_{ub}} = 1.4\%$$
$$p_{\rm SM}^{{\rm no}\ V_{qb}} = 2.6\%$$

- NP in K mixing:

$$(C_\varepsilon)_{\rm fit} = \begin{cases} 1.28 \pm 0.13 & (2.4\sigma, p = 12\%) \text{ complete fit} \\ 1.27 \pm 0.13 & (2.4\sigma, p = 7\%) \text{ no } V_{ub} \\ 1.35 \pm 0.23 & (1.6\sigma, p = 4\%) \text{ no } V_{qb} \end{cases}$$

- NP in B→τν:

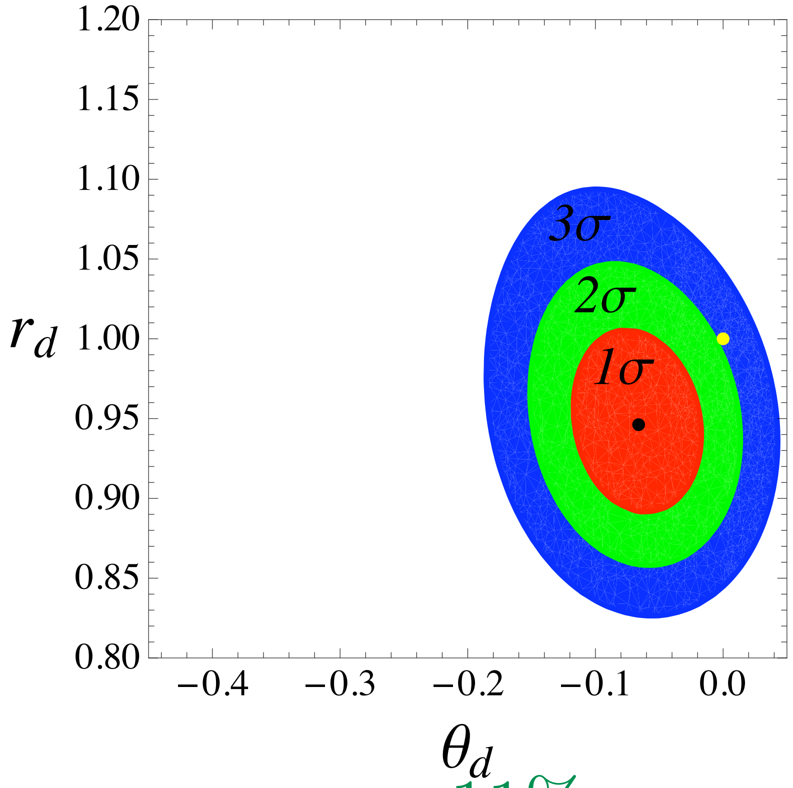
$$(r_H)_{\rm fit} = \begin{cases} 2.30 \pm 0.53 & (2.7\sigma, p = 19\%) \text{ complete fit} \\ 2.27 \pm 0.53 & (2.7\sigma, p = 12\%) \text{ no } V_{ub} \\ 2.33 \pm 0.55 & (2.7\sigma, p = 30\%) \text{ no } V_{qb} \end{cases}$$

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)

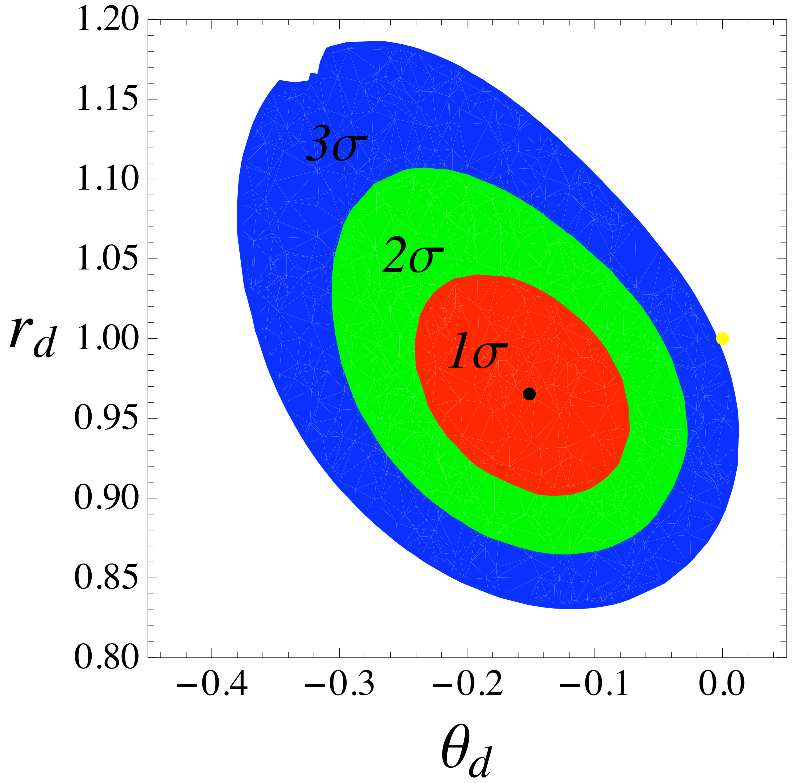
full fit:



$p = 11\%$

$p_{\rm SM} = 2.3\%$

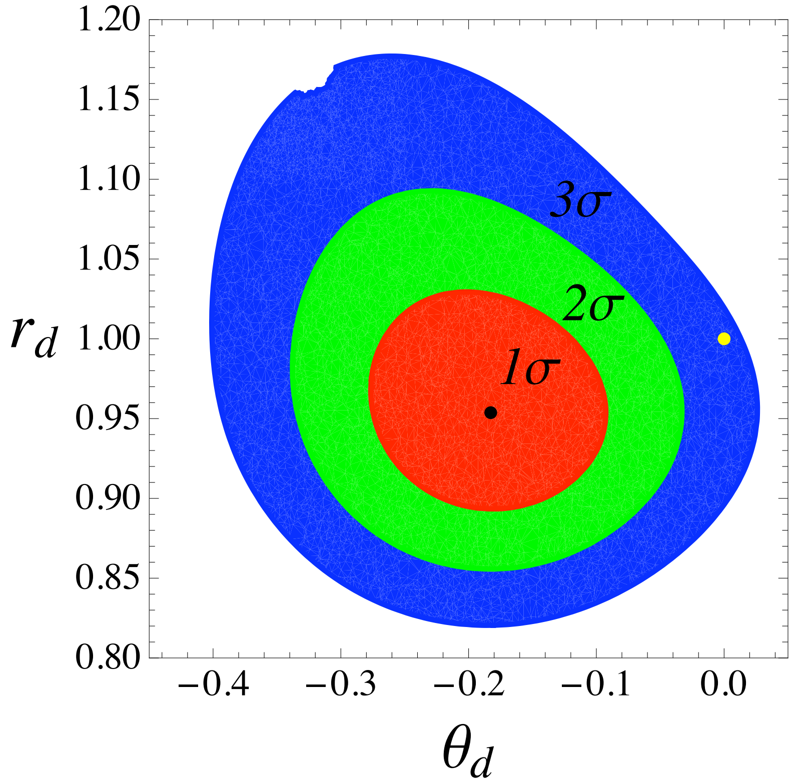
no V_{ub}



$p = 68\%$

$p_{\rm SM}^{\text{no } V_{ub}} = 1.4\%$

no V_{qb}



$p = 76\%$

$p_{\rm SM}^{\text{no } V_{qb}} = 2.6\%$

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

Super-B expectations

- Reducing uncertainties on Bs mixing and $B \to \tau\nu$:

δ_τ	δ_s	$p_{\rm SM}$	$\theta_d \pm \delta\theta_d$	p_{θ_d}	$\theta_d/\delta\theta_d$
$^*20\%$	$^*4.6\%$	2.6%	$-(10.6 \pm 3.5)^{\rm o}$	75%	3.0σ
$^*20\%$	2.5%	0.6%	$-(10.2 \pm 3.3)^{\rm o}$	71%	3.4σ
$^*20\%$	1%	$3 \times 10^{-2}\%$	$-(9.9 \pm 3.0)^{\rm o}$	69%	3.9σ
10%	$^*4.6\%$	$6 \times 10^{-3}\%$	$-(10.9 \pm 2.4)^{\rm o}$	74%	4.7σ
3%	$^*4.6\%$	$4 \times 10^{-5}\%$	$-(11.0 \pm 2.0)^{\rm o}$	74%	5.6σ
10%	2.5%	$1.4 \times 10^{-3}\%$	$-(10.7 \pm 2.4)^{\rm o}$	69%	4.8σ
10%	1%	$1.2 \times 10^{-4}\%$	$-(10.5 \pm 2.4)^{\rm o}$	64%	5.1σ
3%	2.5%	$1.1 \times 10^{-5}\%$	$-(10.9 \pm 2.0)^{\rm o}$	68%	5.7σ
3%	1%	$4 \times 10^{-6}\%$	$-(10.8 \pm 2.0)^{\rm o}$	62%	5.8σ

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

- Even modest improvements on $B \to \tau\nu$ have tremendous impact on the UT fit (10/50 ab^{-1} ⇒ δ_τ = 10/3%)
- Interplay between B_s mixing and $B \to \tau\nu$ can result in a 5σ effect

Operator Level Analysis

- Effective Hamiltonian for B$_d$ mixing:

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

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

- Parametrization of New Physics effects:

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

- Analogue expressions for K mixing

Operator Level Analysis: *Mixing*

- The contribution of the LR operator O4 to K mixing is strongly enhanced ($\mu_L \sim 2\ \mathrm{GeV}$, $\mu_H \sim m_t$):

O(1)

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

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

running from μH to μL

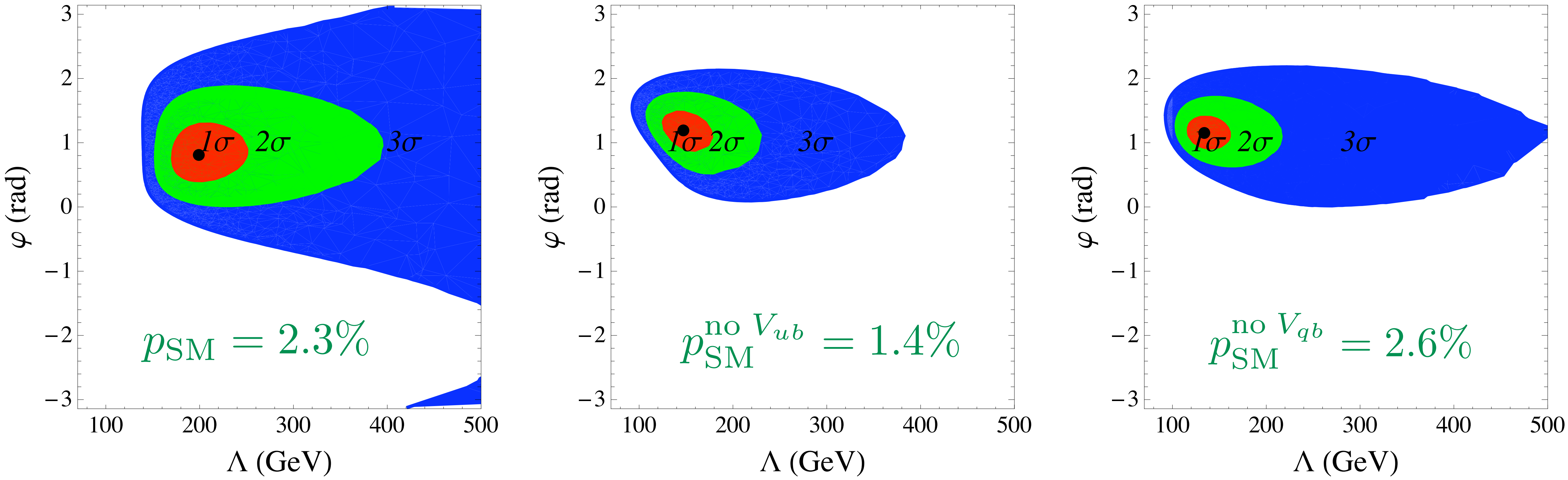
chiral enhancement

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

- No analogous enhancement in B_q mixing

Operator Level Analysis: *B_d Mixing*

- 2 dimensional [Λ,φ] contours:



full fit:

no V_{ub}

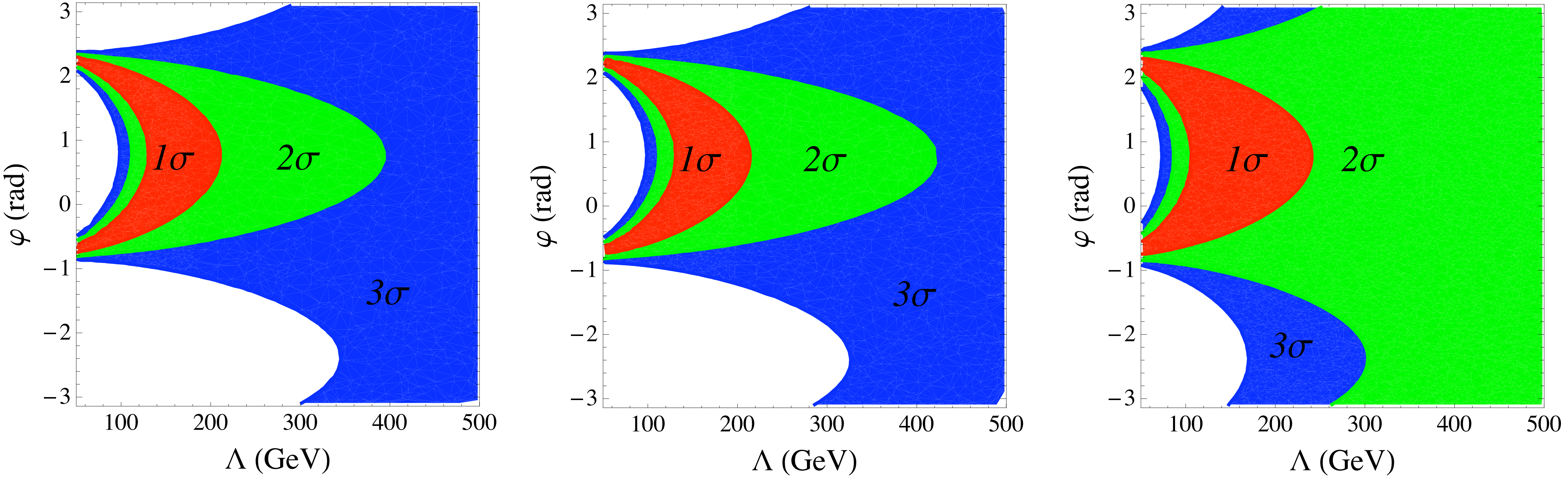
no V_{qb}

- 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):

full fit: no V_{ub} no V_{qb}



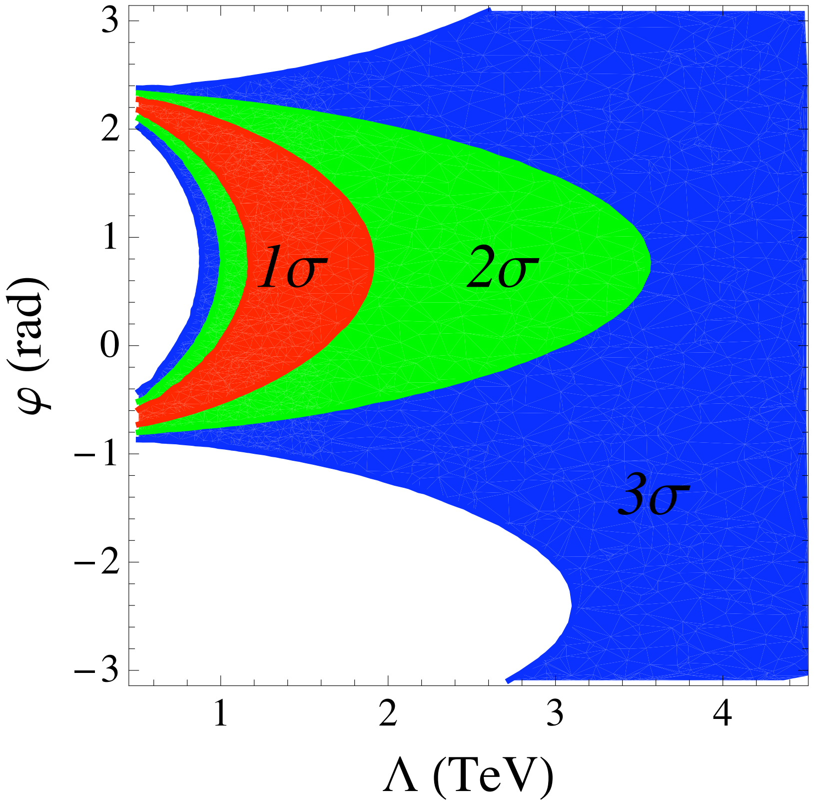
$p_{\rm SM} = 2.3\%$ $p_{\rm SM}^{{\rm no}\ V_{ub}} = 1.4\%$ $p_{\rm SM}^{{\rm no}\ V_{qb}} = 2.6\%$

- 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):

full fit:



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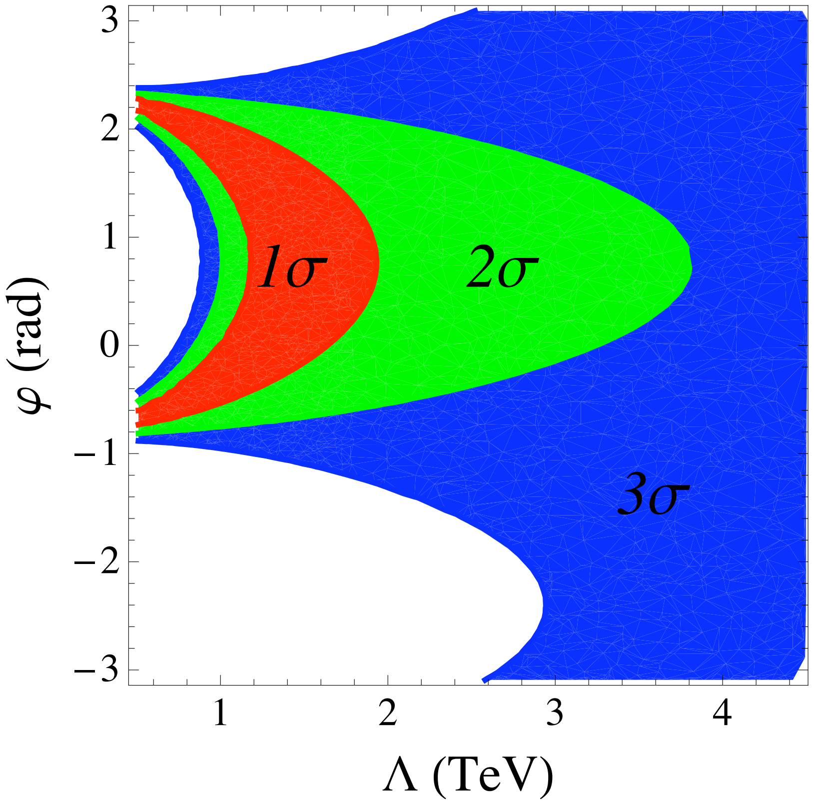
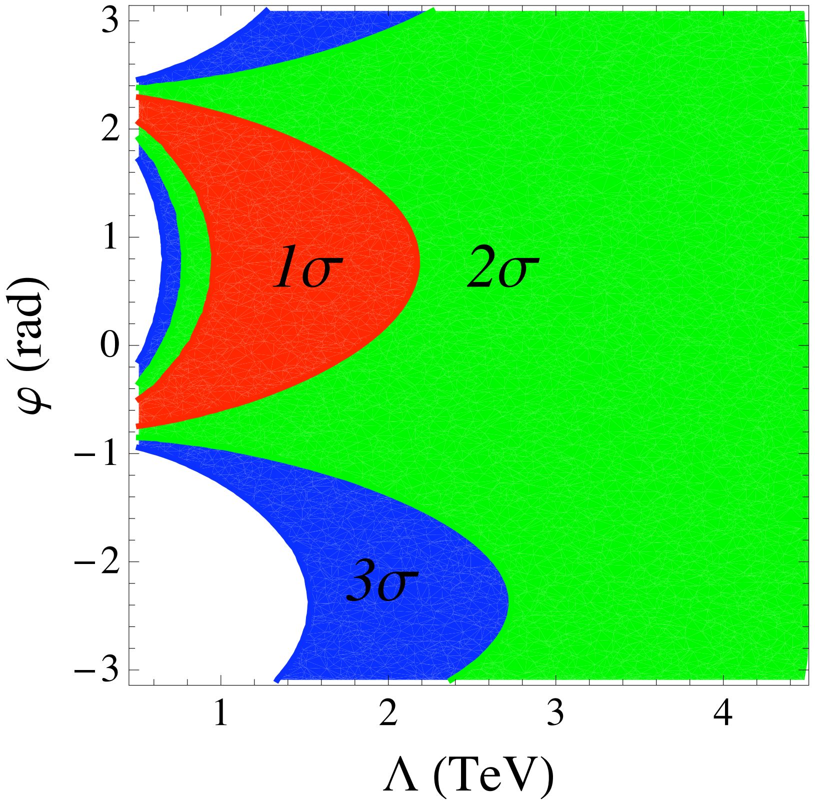


$p_{\rm SM}^{{\rm no}\ V_{ub}} = 1.4\%$

no V_{qb}



$p_{\rm SM}^{{\rm no}\ V_{qb}} = 2.6\%$

- 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*

Conclusions

- *Using 2+1 lattice QCD → hint for NP in the UT fit (~3σ)*
- *We need better understanding of inclusive V_{ub} and V_{cb}*
- The tension in the UT fit could be explained by *new physics in B_d mixing* (preferred), K mixing or B→τν
- As long as V_{qb} determinations remain problematic, *removing semileptonic decays allows to cast the UT fit as a clean & high-precision tool to identify new physics*
- Super-B precision on B→τν coupled with improvements on the lattice determination of $f_{B_s}\sqrt{B_s}$ can test the SM at the 5σ level
- Interpretation of this tension in terms of SM like new physics contribution point to masses in the *few hundred GeV range and complex couplings with O(1) phases*.

Backup slides

Comments on systematic uncertainties

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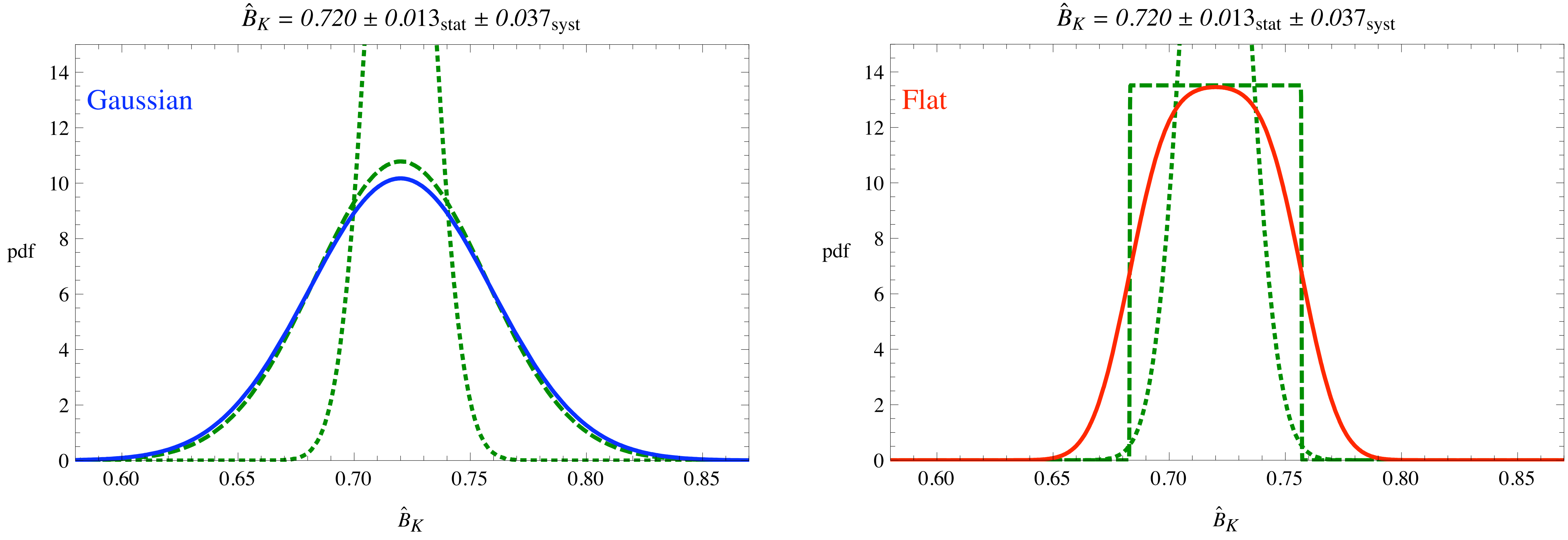

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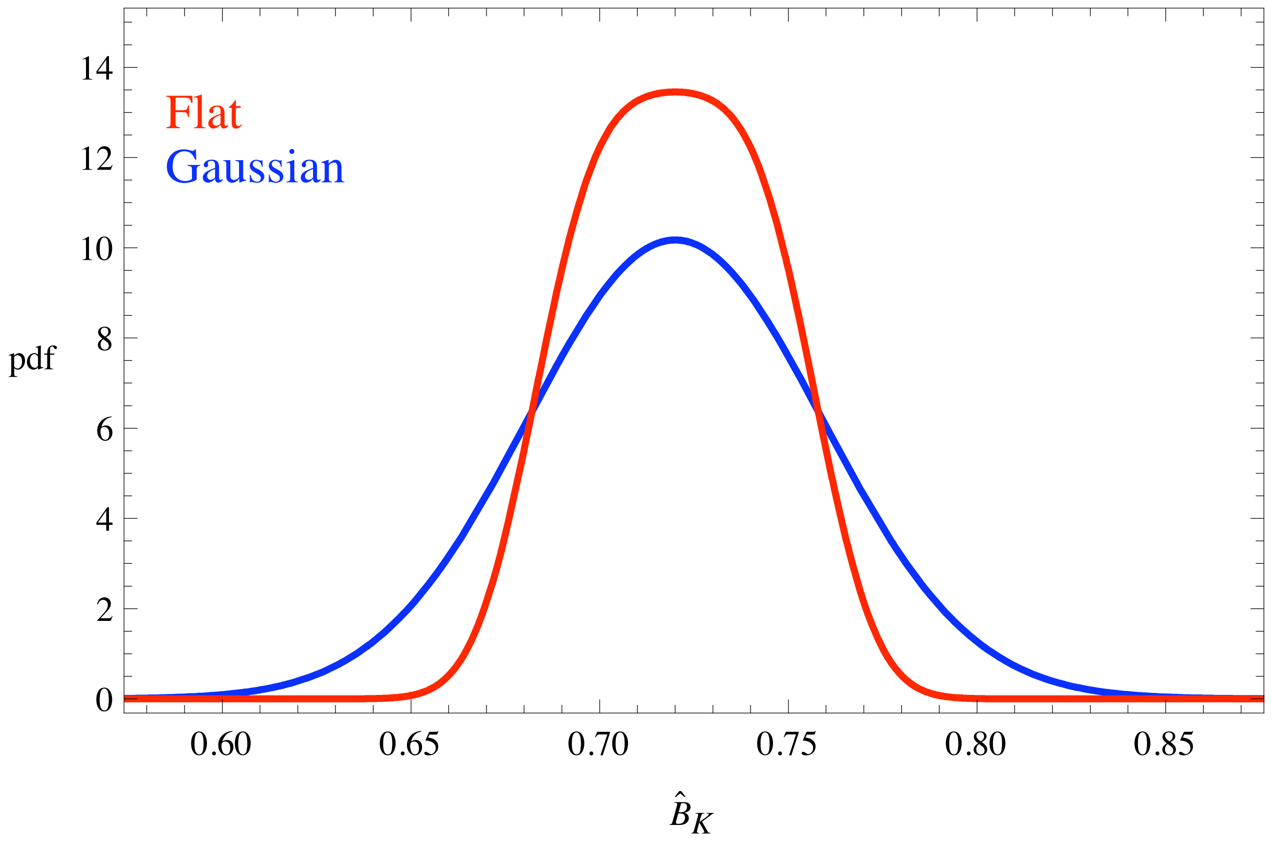
$\hat{B}_K = 0.720 \pm 0.013_{\text{stat}} \pm 0.037_{\text{syst}}$



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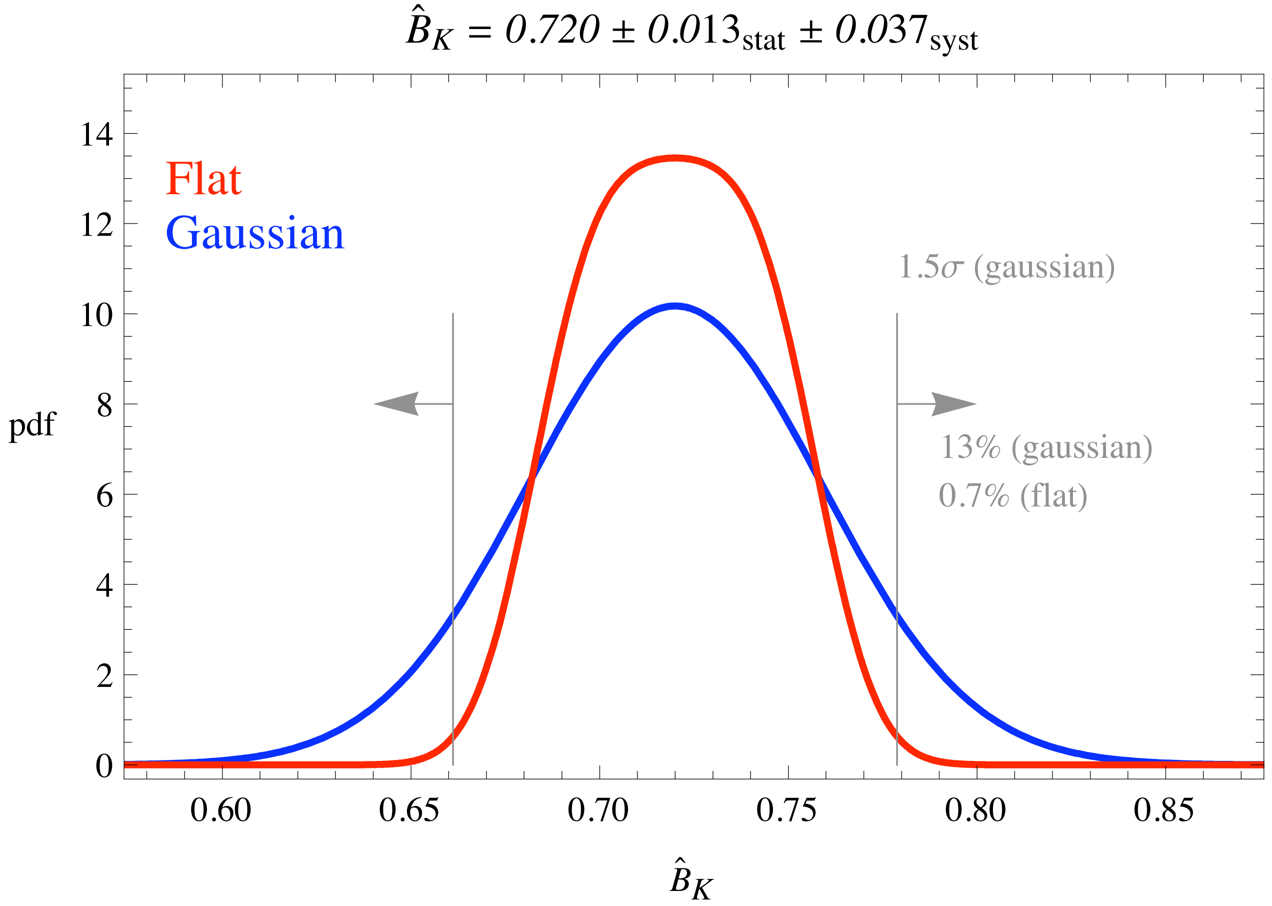
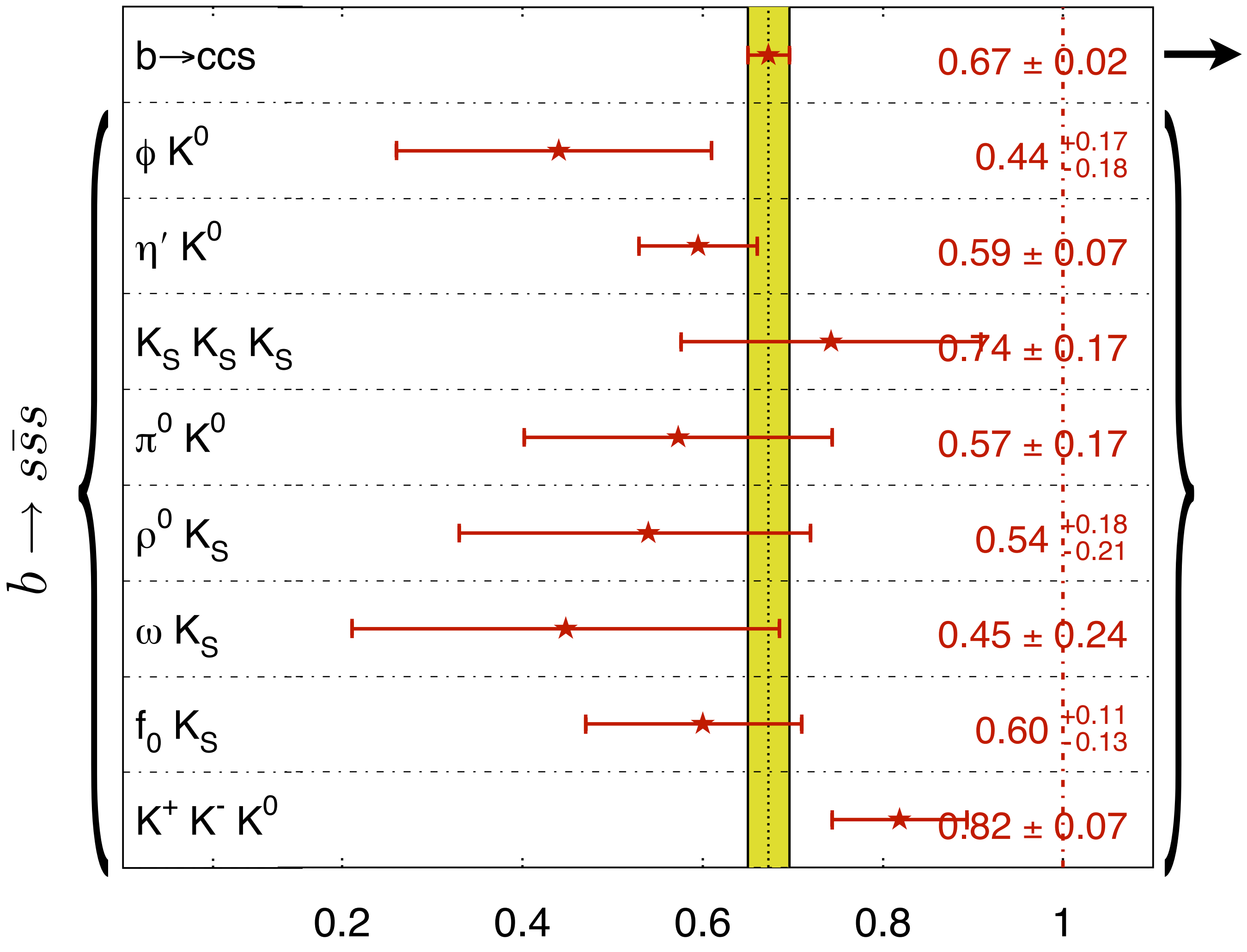


Time dependent CP asymmetry in $b \to q\bar{q}s$

[HFAG 2009]



$$\longrightarrow S_{\psi K_s} = \sin 2(\overset{\arg(V_{td}^*)}{\overset{\uparrow}{\beta}} + \theta_d) + O(0.1\%)$$

In QCDF:

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

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

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

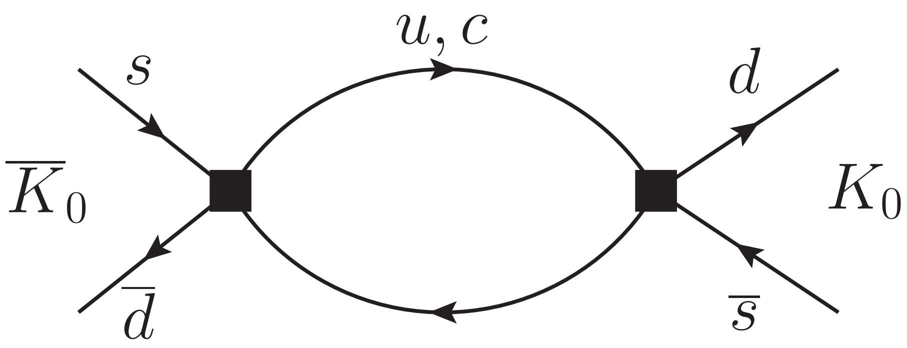
$$\Delta S_{\eta'} = 0.01 \pm 0.025$$ [EL, Soni]

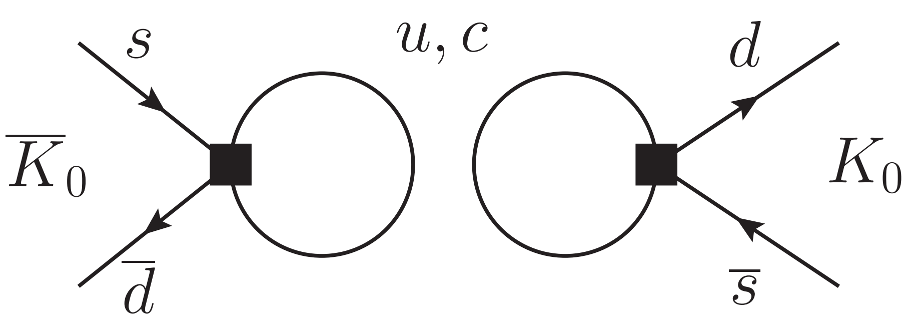
Other approaches find similar results
[Chen,Chua,Soni; Buchalla,Hiller,Nir,Raz]

- 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]

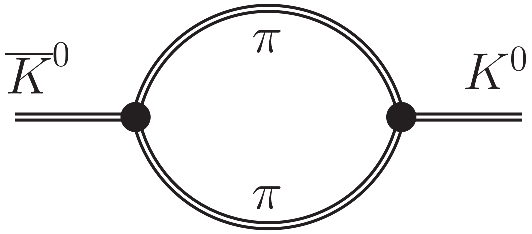
K mixing (ε_K)

- 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]