Hints for *New* Physics in *Flavor* Physics and CP violation

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E.L. and A. Soni: *0707.0212, 0803.4340, 0903.5059*
J. Laiho, E.L., R. van de Water: *in preparation*

Outline

- A critical review of the UT fit:
  - New formula for ε_K — [Andriyash,Ovanesyan,Vysotsky] [Buras,Guadagnoli] [Laiho,EL,van de Water]
  - The role of V_{cb} and V_{ub}
  - Updated inputs
- The UT fit and what it suggests about new physics:
  - NP in *B_d mixing* and in *$b \to s$ amplitudes* — [EL,Soni]
  - NP in *K mixing* and in *$b \to s$ amplitudes* — [Buras,Guadagnoli] [EL,Soni]
- Operator Analysis of New Physics effects — [EL,Soni]
- Conclusions

K mixing

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

- 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 (quenched) lattice QCD

K mixing

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

- Experimentally one has: $\phi_\varepsilon = (43.51 \pm 0.05)^o$
- $\mathrm{Im}A_0/\mathrm{Re}A_0$ 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]
  - $\mathrm{Im}A_2 = (-9.6 \pm 9.6) \times 10^{-13}\ \mathrm{GeV}$ [RBC, CP-PACS, SPQcdR, Babich, Yamazaki]

    conservative error estimate
- Combining everything:

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

[Andryiash,Ovanesyan,Vysotsky; Nierste; Buras,Jamin; Bardeen,Buras,Gerard; Buras,Guadagnoli; Laiho,EL,van de Water]

K mixing

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

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

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

  - RBC/UKQCD (2+1domain wall fermions): $\hat{B}_K = 0.720 \pm 0.013 \pm 0.037$
  - Aubin, Laiho, van de Water (2+1 domain wall valence quarks + MILC staggered gauge configurations): $\hat{B}_K = 0.724 \pm 0.008 \pm 0.028$
  - The average reads†:

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

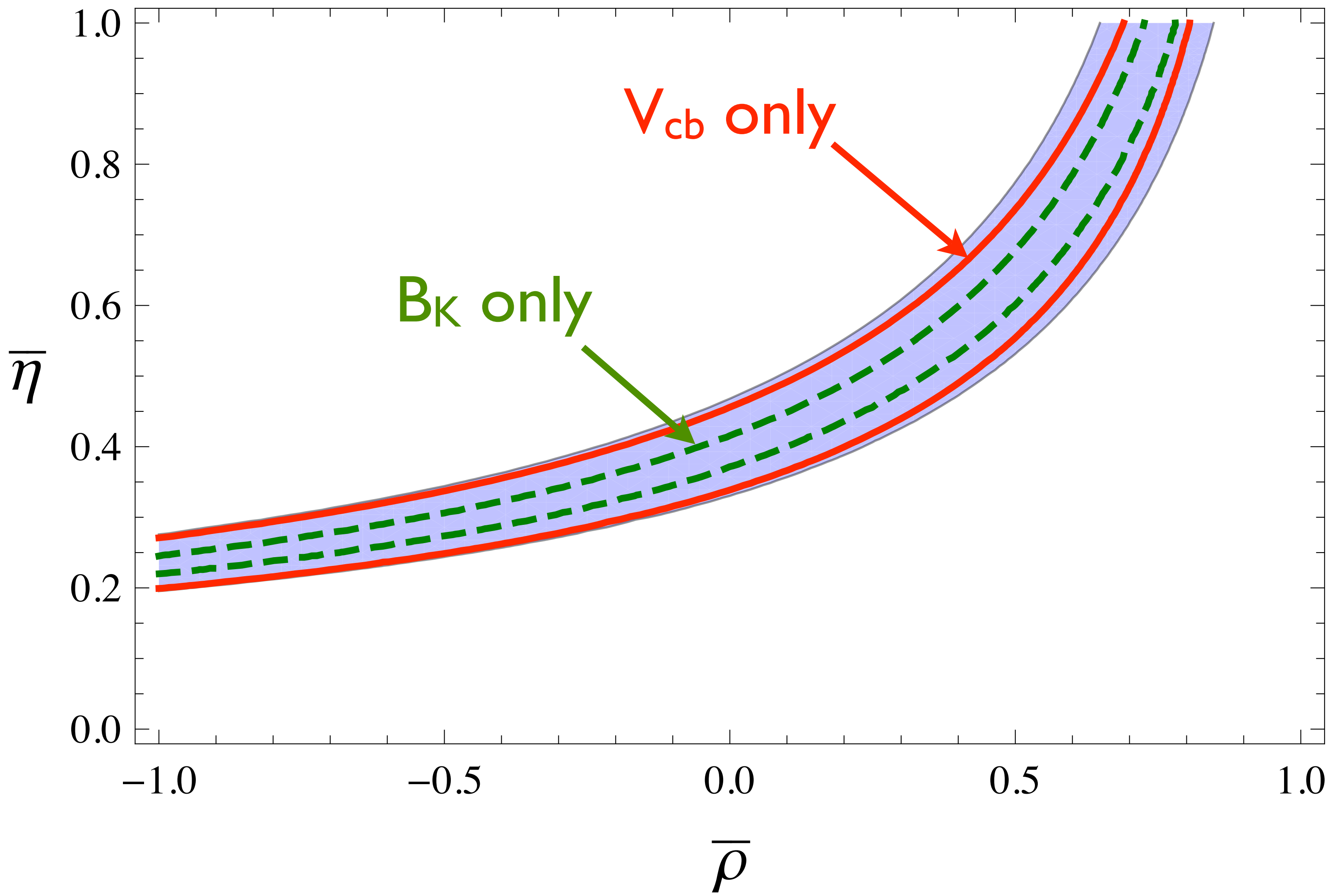
  - † *we include an older HPQCD/UKQCD determination and we take correlations into account* [Laiho,EL,van de Water]

K mixing

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

- Error budget:

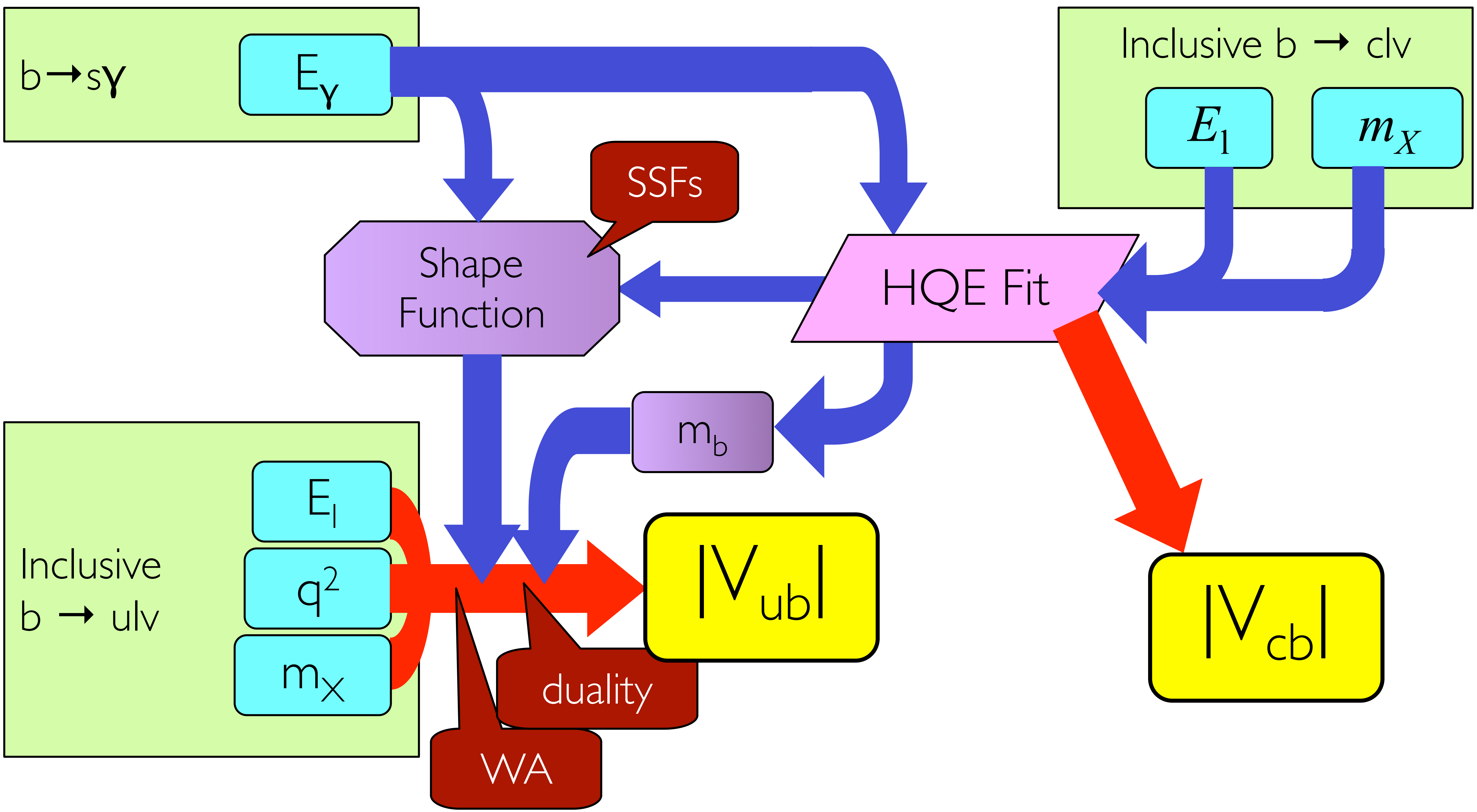
[Laiho,EL,van de Water]



All other uncertainties have negligible impact on the combined error

Central value of κ_ε is important

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



[Phillip Urquijo]

V_{cb}

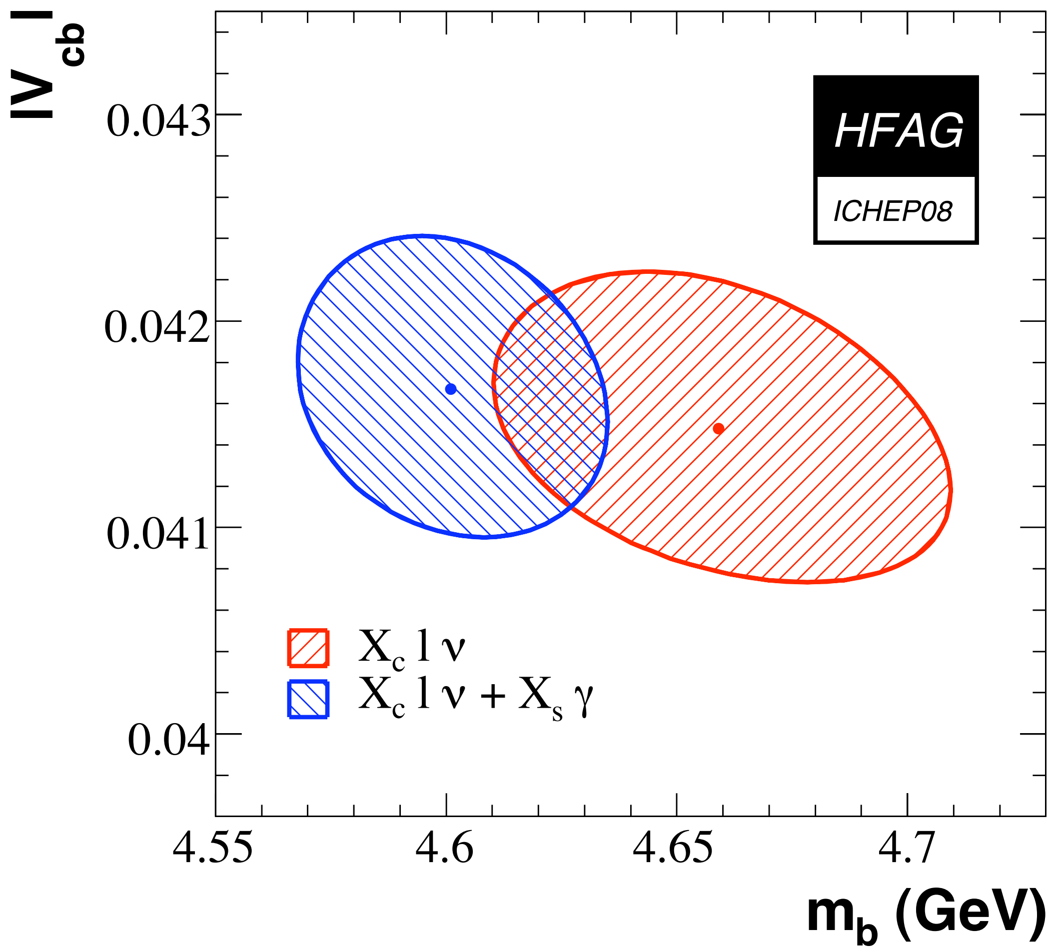
- Exclusive from $B \to D^{(*)} l\nu$. Using form factor from lattice QCD (2+1 dynamical staggered fermions) one finds:

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

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

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

- 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}

$$|V_{cb}| = (41.48 \pm 0.75) \times 10^{-3}$$

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:

$$|V_{ub}| = (3.42 \pm 0.37) \times 10^{-4}$$ [HPQCD, FNAL/MILC]

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

$$|V_{ub}| = \left(3.96 \pm 0.15_{\rm exp}{}^{+0.20}_{-0.23}{}_{\rm th}\right) 10^{-3}$$ [Gambino,Giordano,Ossola, Uraltsev (GGOU)]

$$|V_{ub}| = \left(4.26 \pm 0.14_{\rm exp}{}^{+0.19}_{-0.13}{}_{\rm th}\right) 10^{-3}$$ [Andersen,Gardi (DGE)]

$$|V_{ub}| = \left(4.32 \pm 0.16_{\rm exp}{}^{+0.32}_{-0.27}{}_{\rm th}\right) 10^{-3}$$ [Bosch,Lange,Neubert,Paz (BLNP)]

1.2σ discrepancy between inclusive and exclusive

B_q mixing

- We consider the ratio of the B_s and B_d mass differences:

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

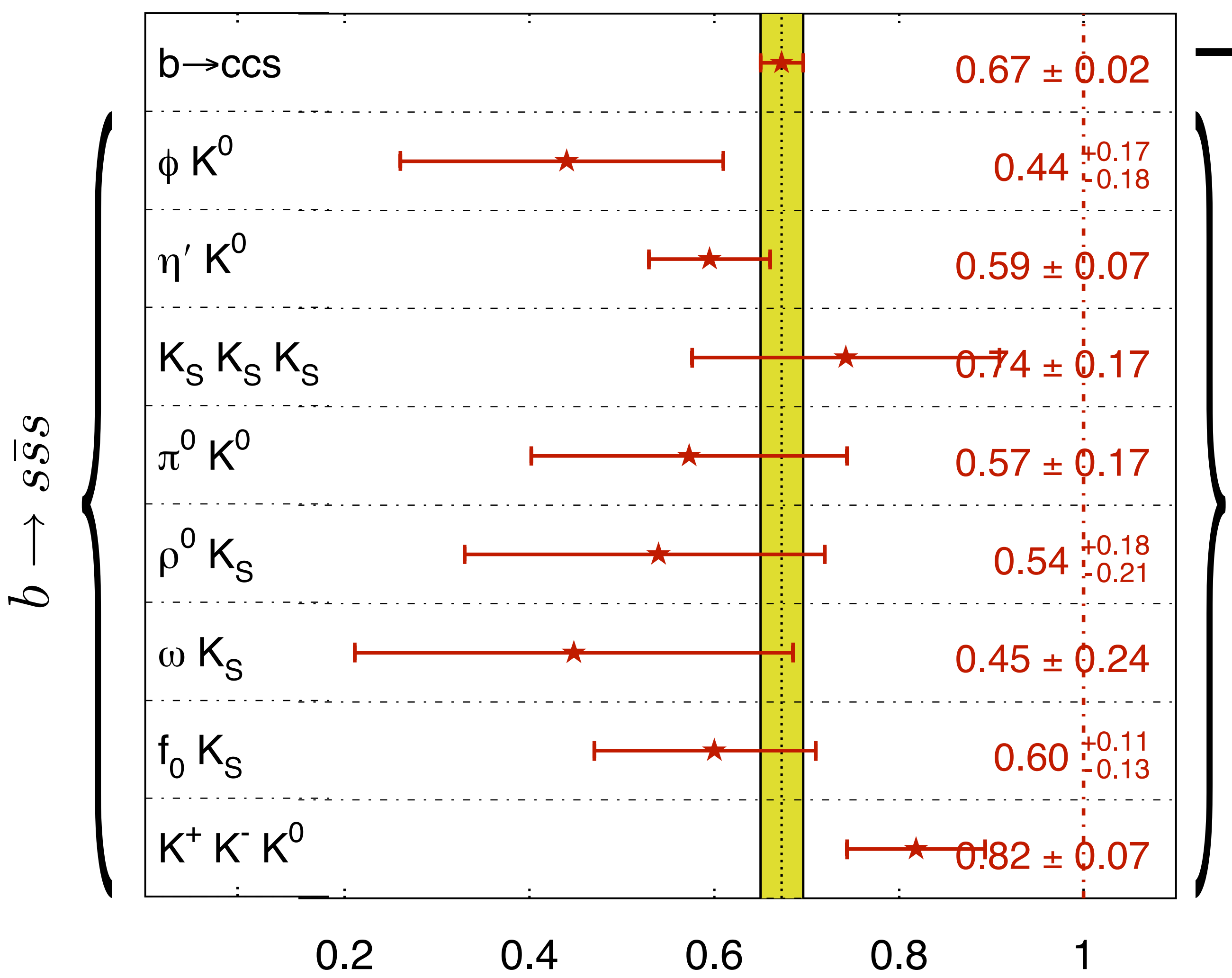
- No dependence on V_{cb}

- 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: $\xi = 1.243 \pm 0.028$

$\sin(2\beta)$

[HFAG 2008]



$$\rightarrow a_{\psi K_s} = \sin(2\underset{\arg(V_{td}^*)}{\underset{\uparrow}{\beta}}) + O(0.1\%)$$

In QCDF:

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

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

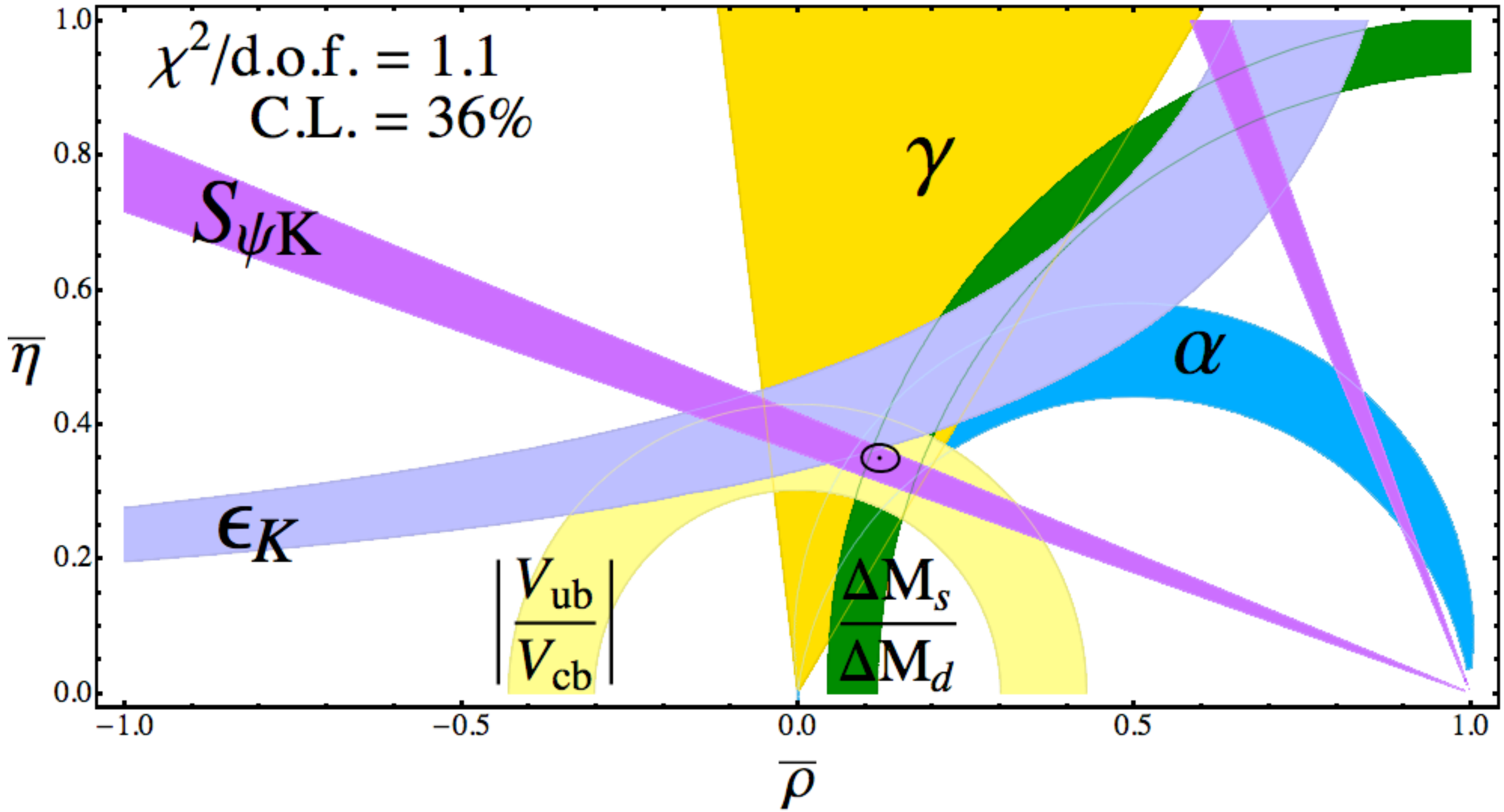
$$\Delta a_\phi = 0.03 \pm 0.01 \qquad \text{[Beneke,Neubert]}$$

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

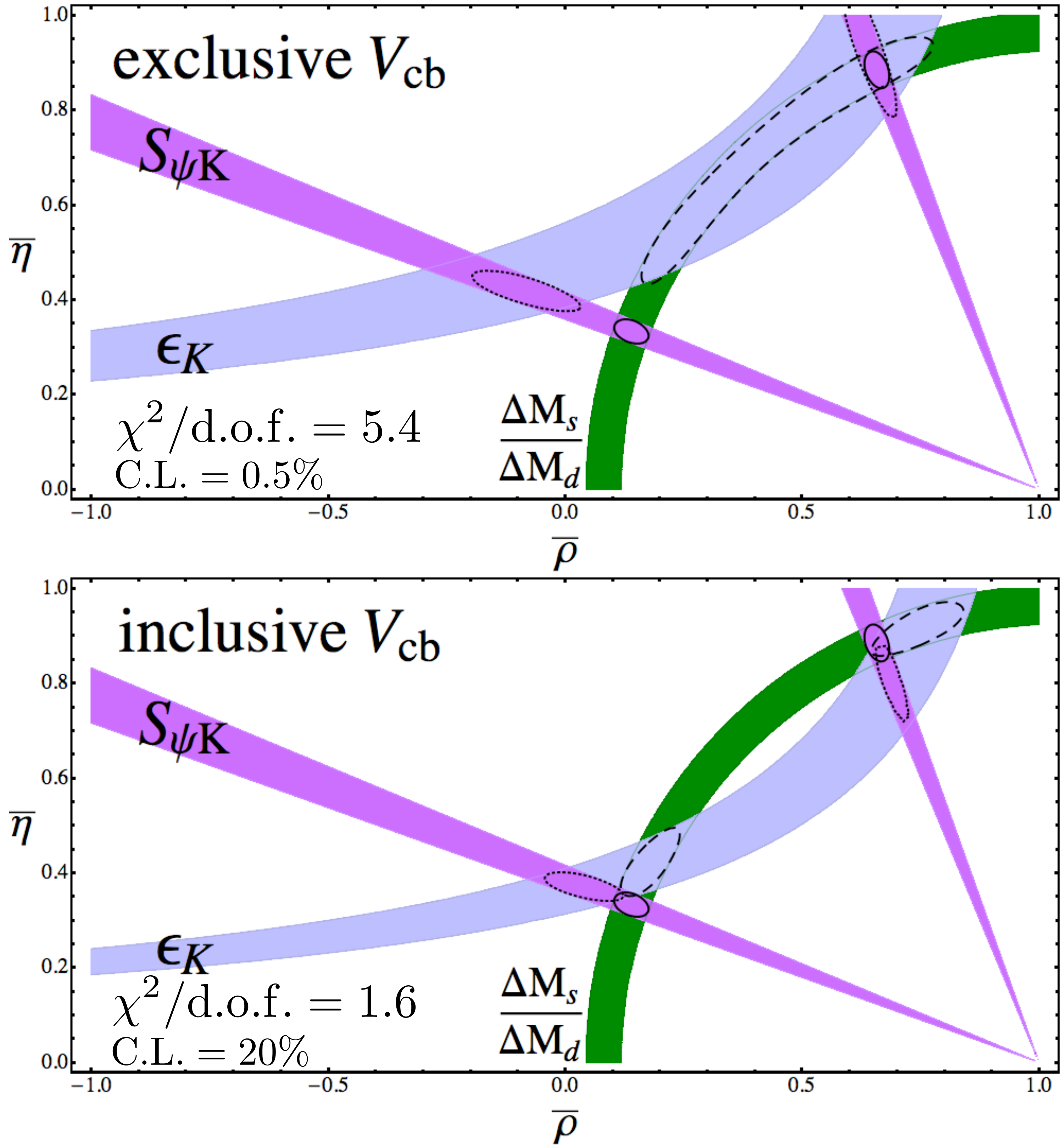
Other approaches find similar results [Chen,Chua,Soni; Buchalla,Hiller,Nir,Raz]

- 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]

Current fit to the unitarity triangle

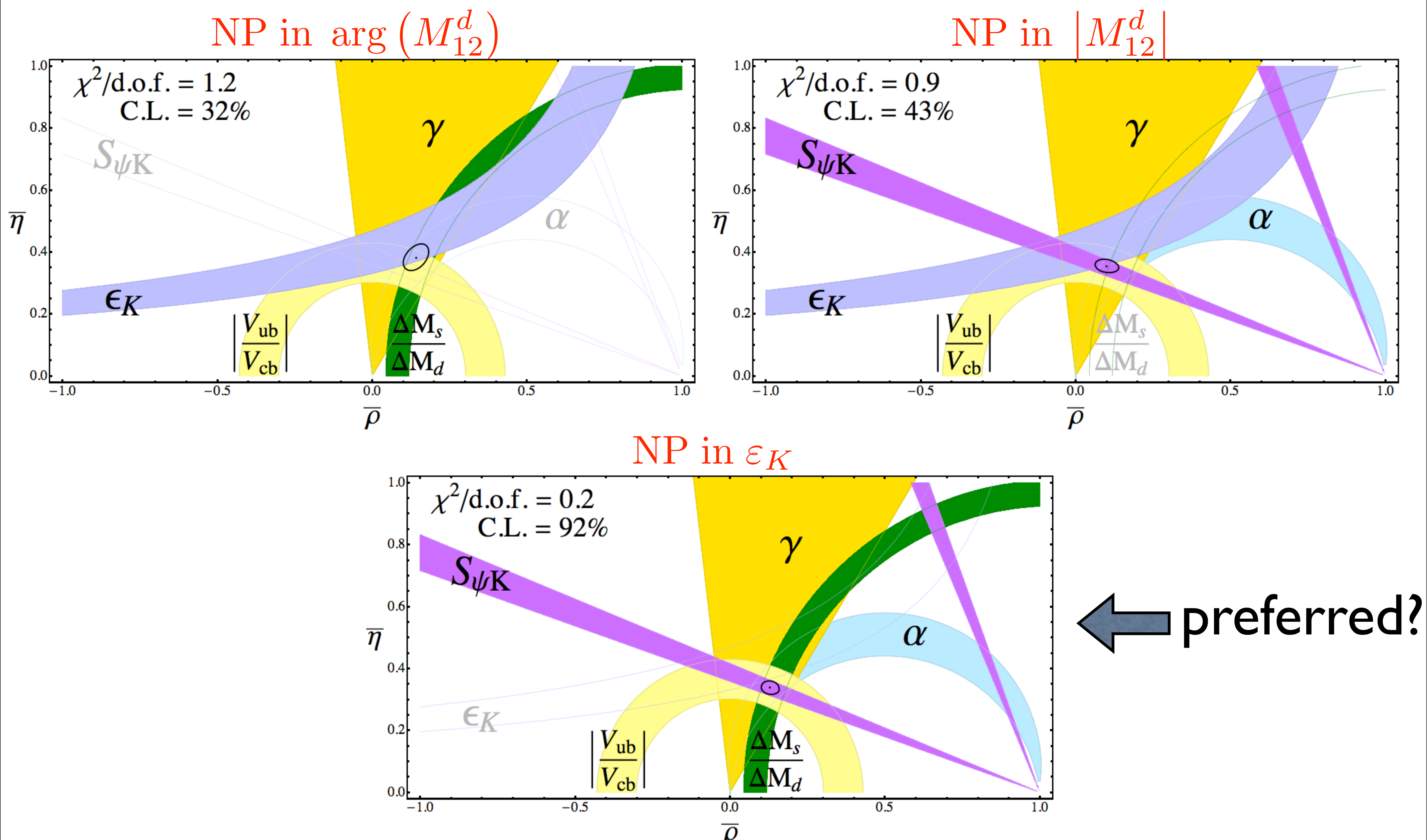


Heart of the problem



- Exclusive V_{cb} triggers a very serious tension in the fit
- No preference between scenarios with new physics in K or B_d mixing
- The tie is broken by the inclusion of additional constraints (α, γ, V_{ub})

Heart of the problem



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*:

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

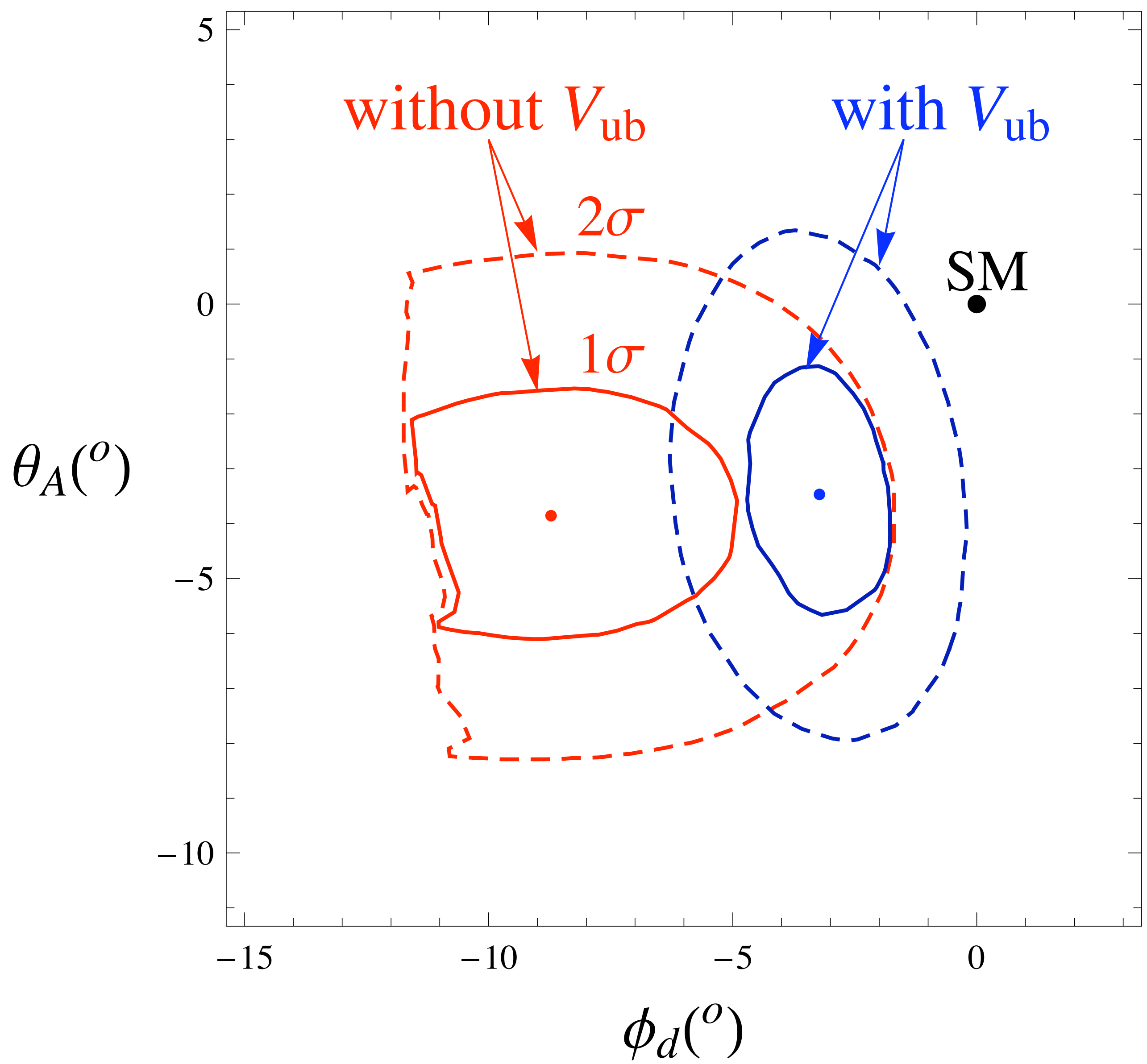
- This implies:

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

- In general NP will affect in different ways the various $b \to s$ channels [*I will discuss this possibility in the operator level analysis*]

Model Independent Analysis: B_d

- $C_\varepsilon = 1:$

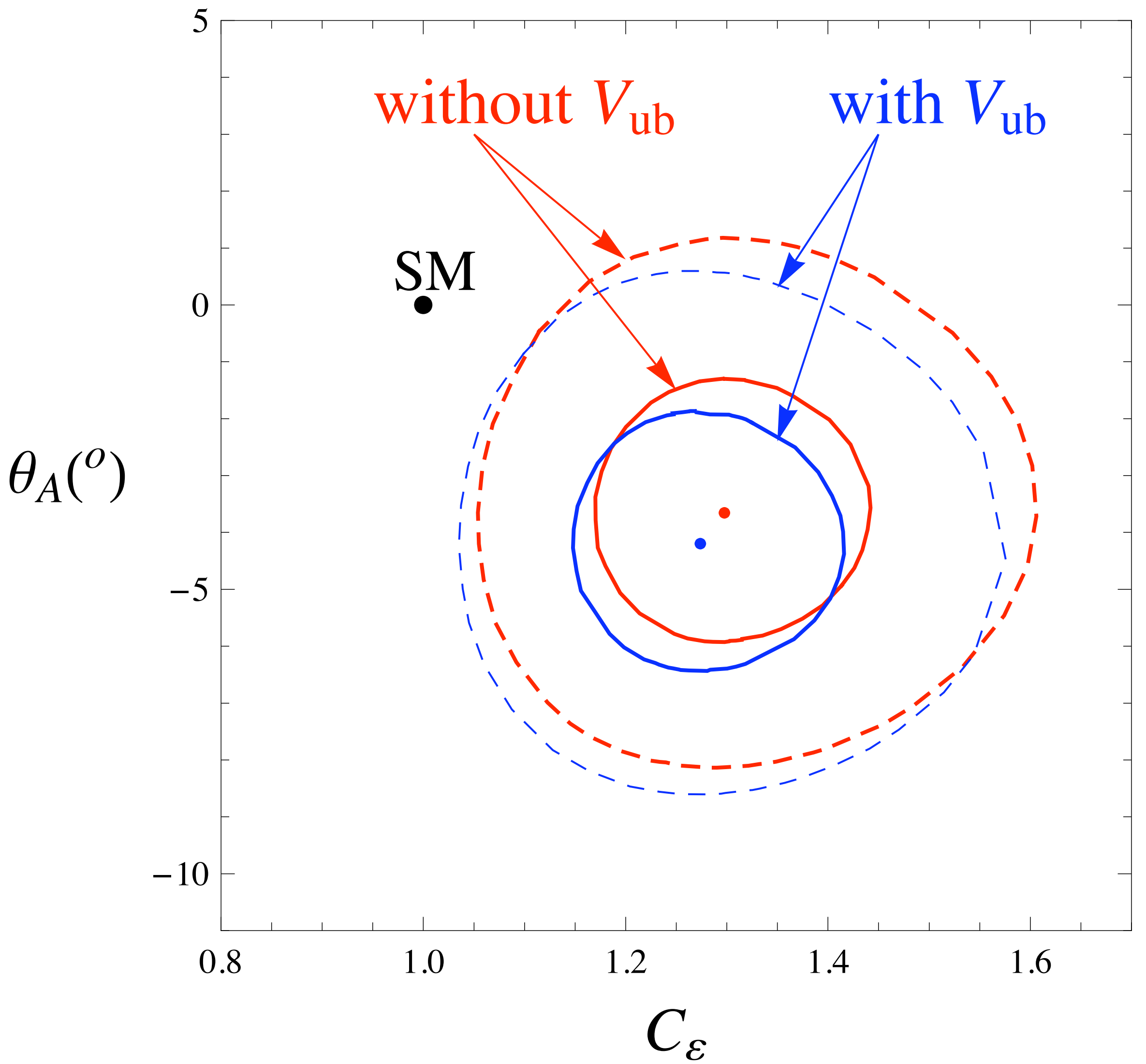


- **Comparison:** $$\phi_d = \begin{cases} (-7.3 \pm 4.3)^\circ & \text{without } V_{ub} \\ (-2.8 \pm 2.1)^\circ & \text{with } V_{ub} \end{cases}$$

$$\theta_A = (-3.6 \pm 2.5)^\circ$$

Model Independent Analysis: *K*

- Alternative solution to the stress in the UT fit is NP in ε_K [Buras,Guadagnoli]
- A new phase in penguin amplitudes (θ_A) is still required
- Assuming $\phi_d = 0$ we find:



$$C_\varepsilon = 1.28 \pm 0.15$$

$$\theta_A = (-3.9 \pm 2.4)^{\mathrm{o}}$$

Correlation with other observables

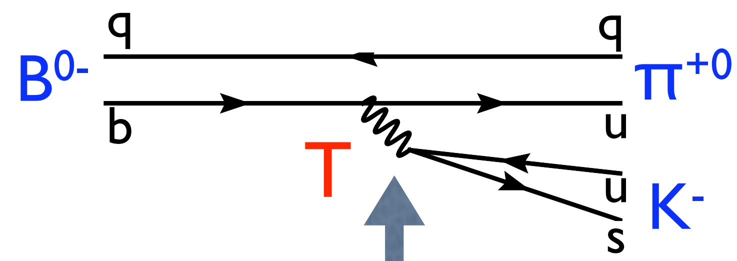
- Proper treatment of new physics effects in penguin amplitudes is better implemented with NP contributions to the *QCD* and *EW penguin* operators
- Correlation between the $b \to s\bar{s}s$ and Kπ asymmetries:

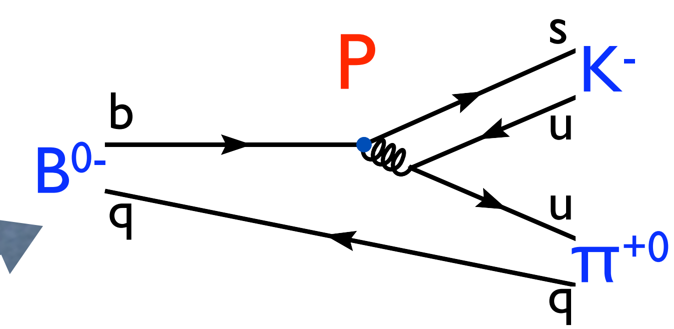
$$A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+) = \begin{cases} (14.8 \pm 2.8)\ \% & \text{exp} \\ (2.2 \pm 2.4)\ \% & \text{QCDF} \end{cases}$$

- 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:

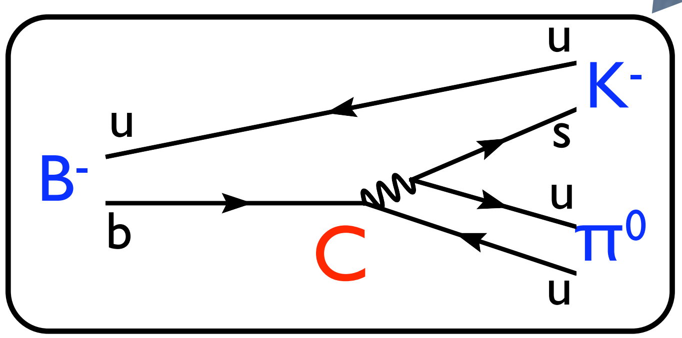


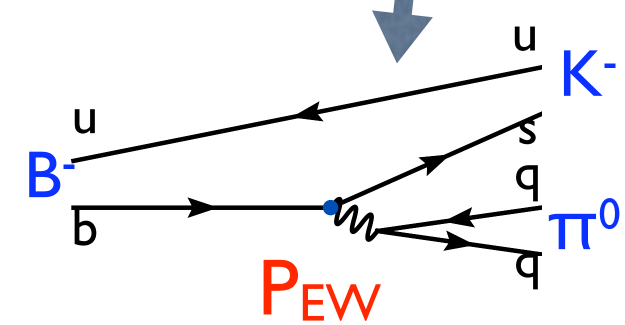


$$\mathcal{A}_{\bar{B}^0\to\pi^+K^-} = A_{\pi\bar{K}}\sum_{p=u,c}\lambda_p^{(s)}\left[\delta_{pu}\alpha_1+\hat{\alpha}_4^p\right]$$

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

color suppressed ←
[Gronau,Rosner]



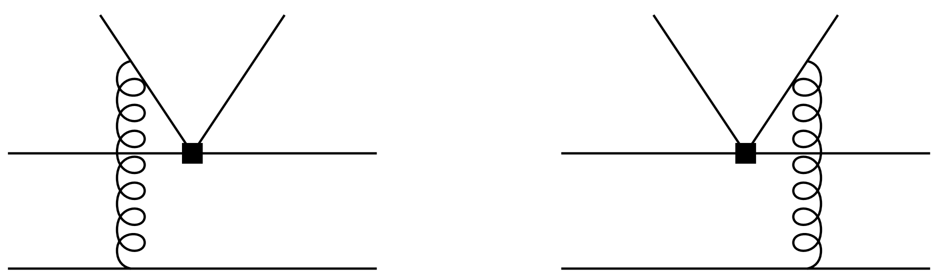


- We get: $\frac{P}{T}\simeq 0.20,\ \boxed{\frac{C}{T}\simeq 0.16},\ \frac{P_{\rm EW}}{T}\simeq 0.47$

fits yield C/T ~ 0.6

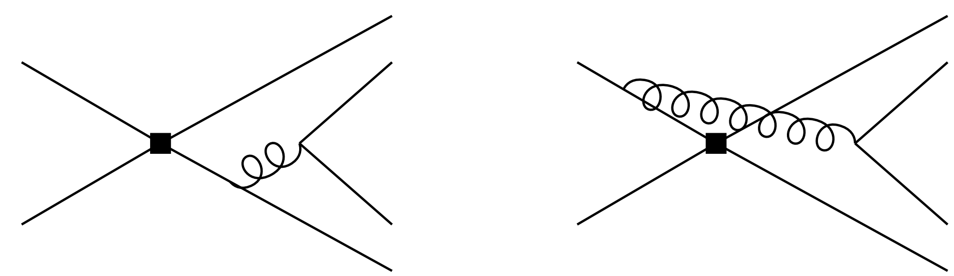
CP asymmetries in B→Kπ

- 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:

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

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

likely to receive NP corrections

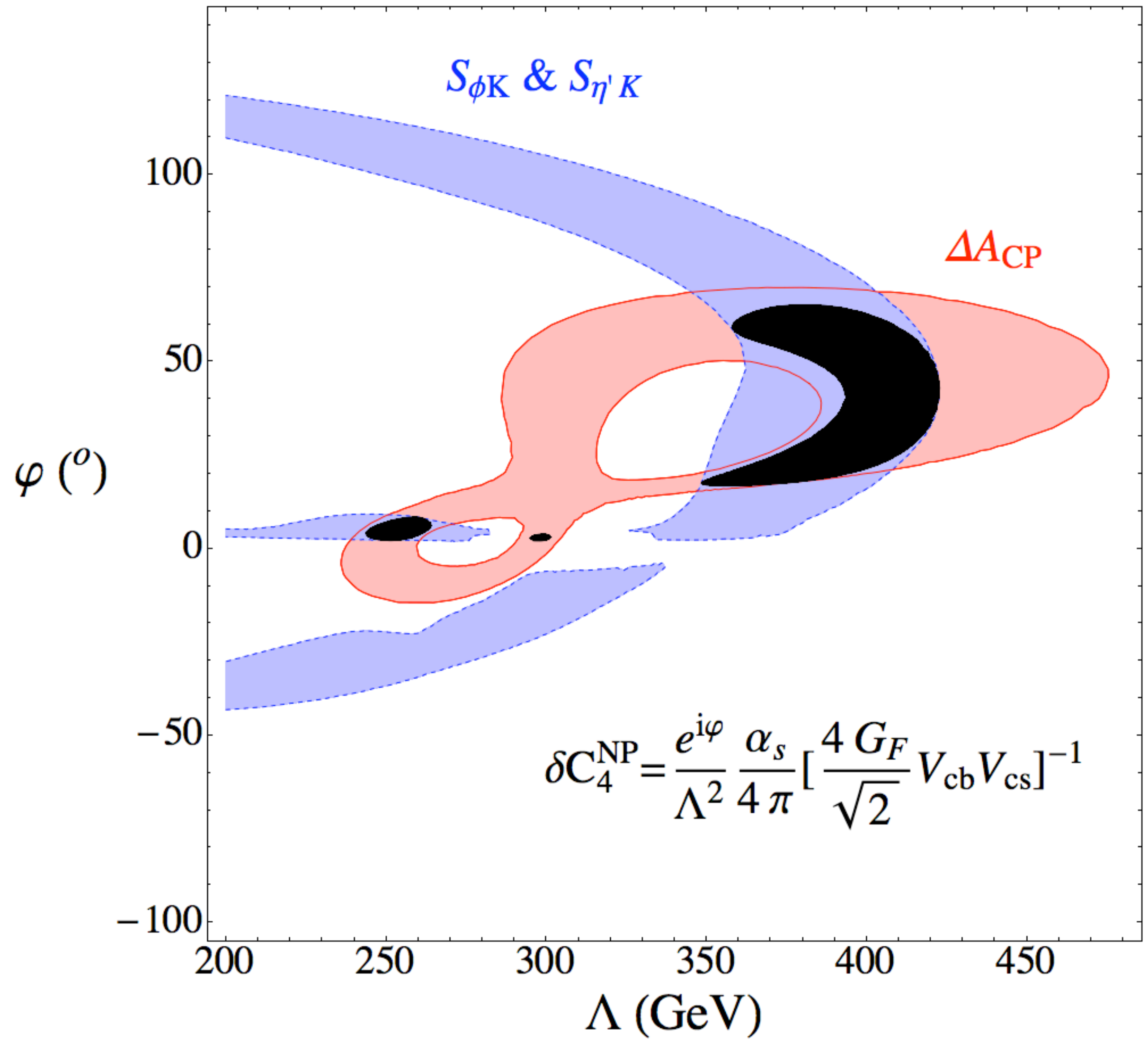
- Assume the following parametrization of NP effects:

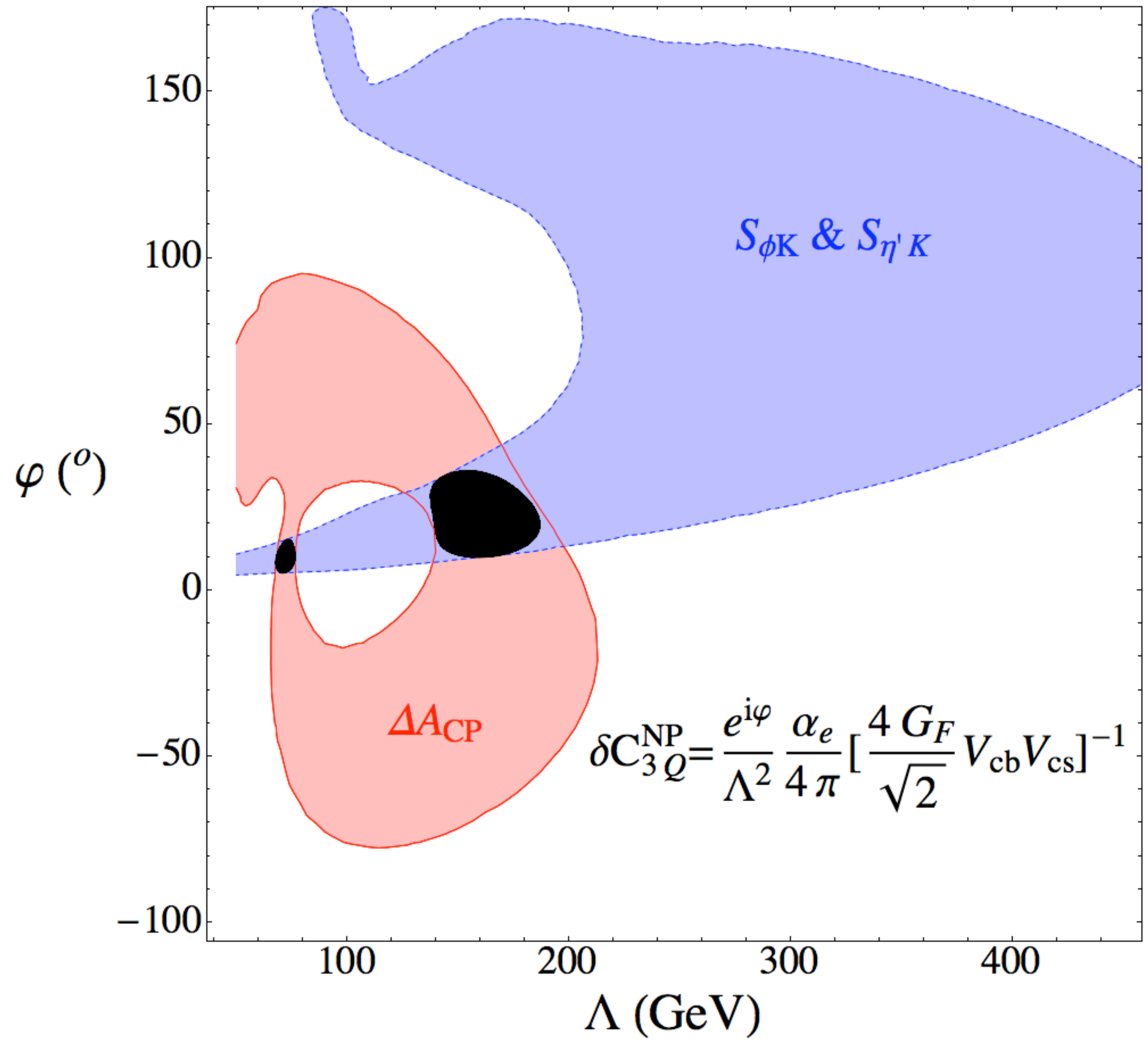
$$\delta C_{4,3Q}(\mu_0) = \frac{\alpha_{s,e}}{4\pi} \frac{e^{i\varphi}}{\Lambda^2} \left[\frac{4G_F}{\sqrt{2}} V_{cb} V_{cs}^* \right]^{-1}$$

loop suppression + QED/QCD penguin g_s,e dependence

Effective mass scale that absorbs NP couplings

Operator Level Analysis: $b \to s$ amplitudes





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

Operator Level Analysis: *Mixing*

- Effective Hamiltonian for B_d mixing:

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

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

- B_s mixing ($d \to s$), K mixing ($b \to s$ & $s \to d$)
- 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 ($\mu_L \sim 2\ \mathrm{GeV}$, $\mu_H \sim m_t$):

$O(1)$

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

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

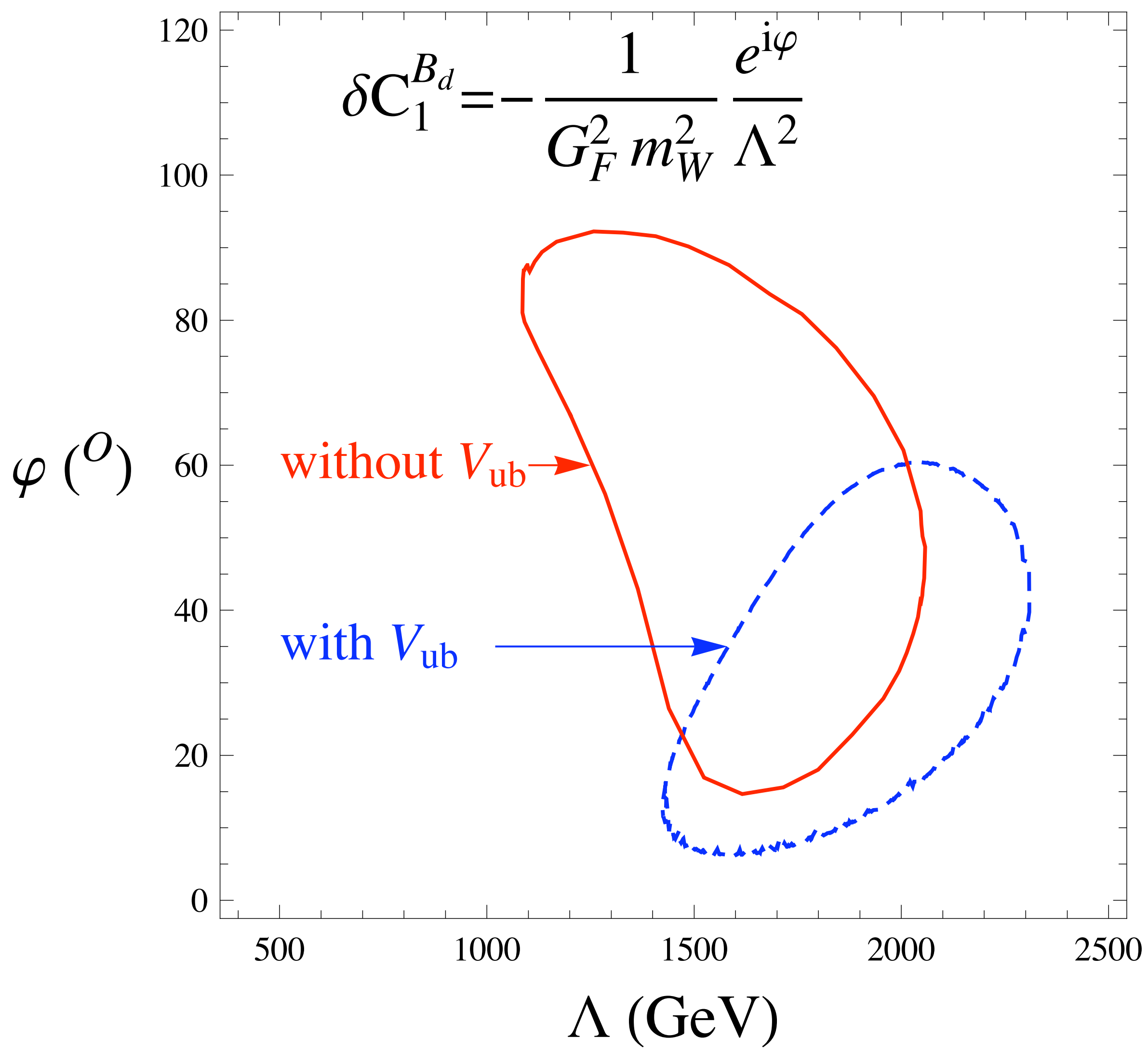
running from μ_H to μ_L chiral enhancement

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

- No analogous enhancement in B_q mixing

Operator Level Analysis: *B_d Mixing*

- 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> $\Delta M_{B_s}/\Delta M_{B_d}$

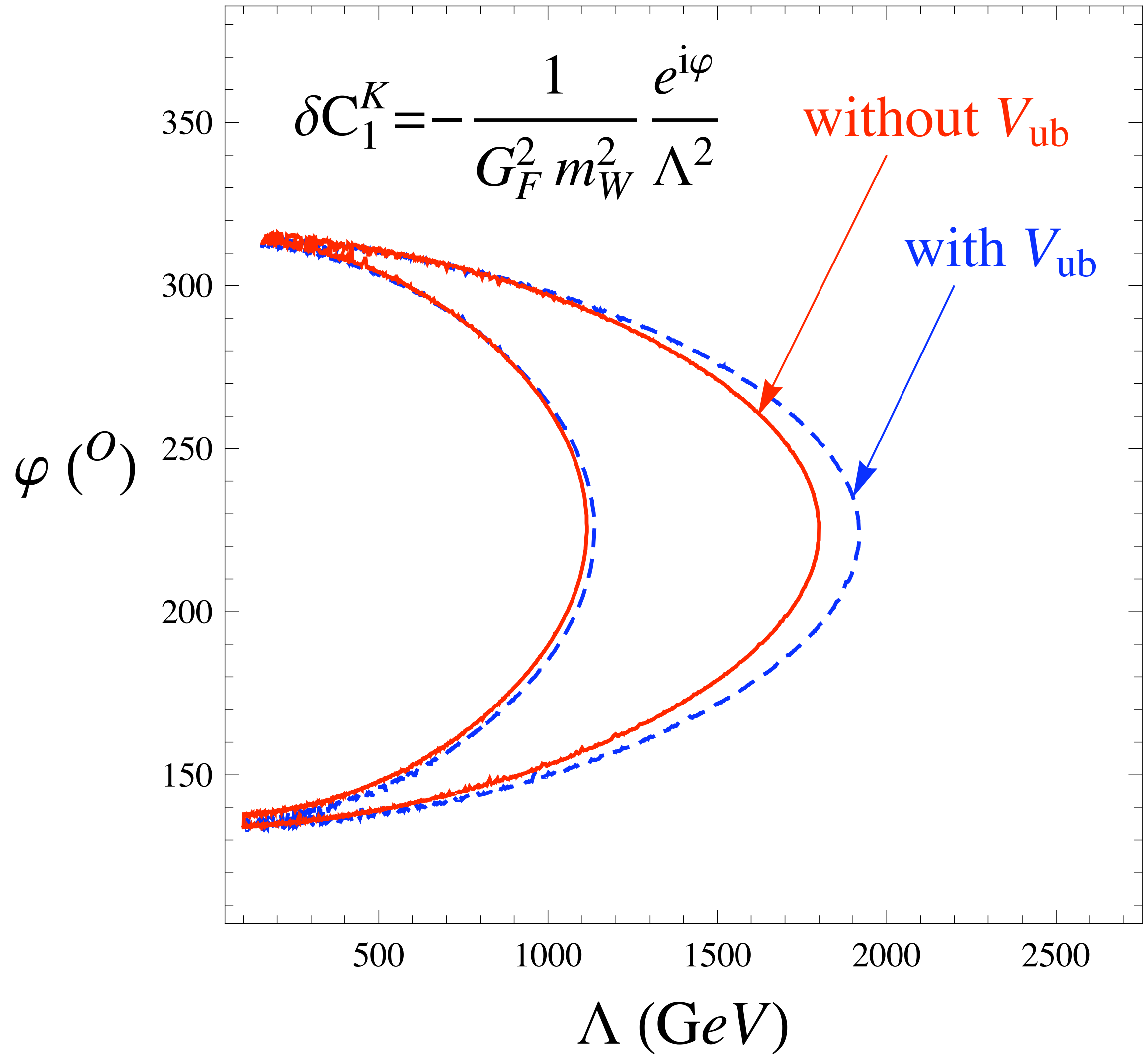


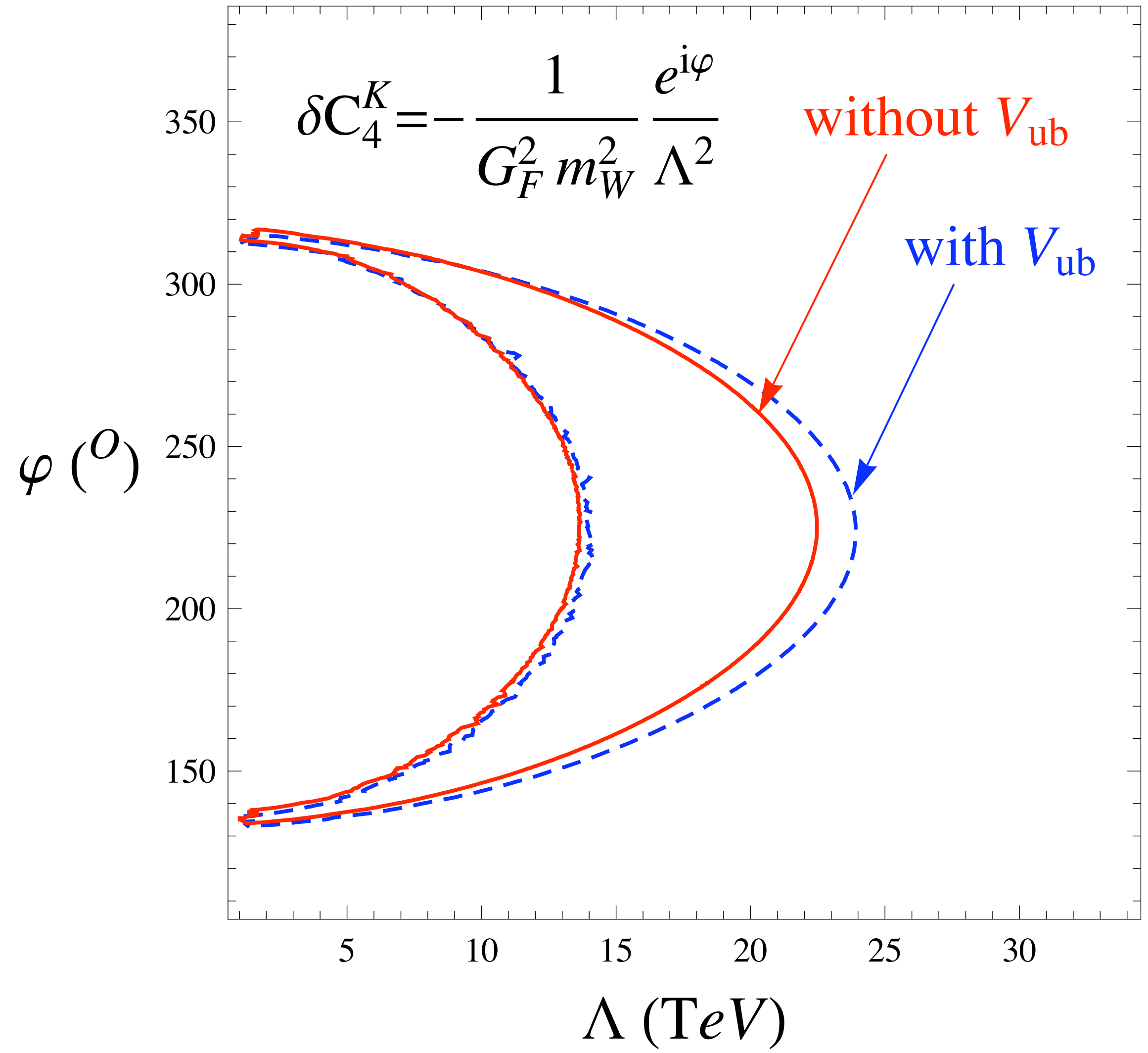
$\Lambda \sim [1.1 \div 2.3]$ TeV

- 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: $\delta C_1^{B_s} = \delta C_1^{B_d} = 0$

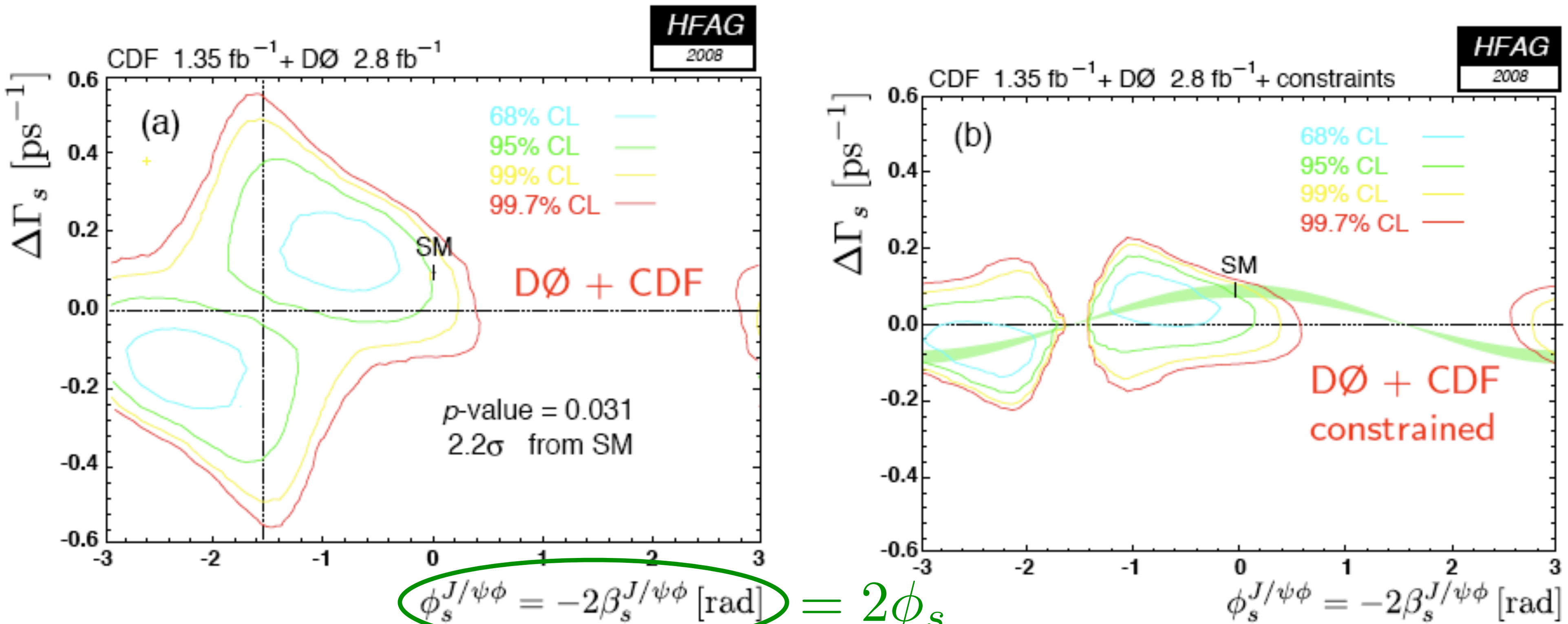




$$\Lambda \sim [1.1 \div 1.9]\ \mathrm{TeV} \qquad \Lambda \sim [14 \div 24]\ \mathrm{TeV}$$

Operator Level Analysis: *B_d and B_s Mixing*

- Interesting possibility: *New Physics contributions to Bd and Bs mixing identical up to CKM factors*
- In our notation: $\delta C_1^K = 0$ and $\delta C_1^{B_s} = \delta C_1^{B_d}$
- New Physics in $a_{\psi K}$ and $a_{\psi\phi}$ ($\Delta M_{B_s}/\Delta M_{B_d}$ unaffected)

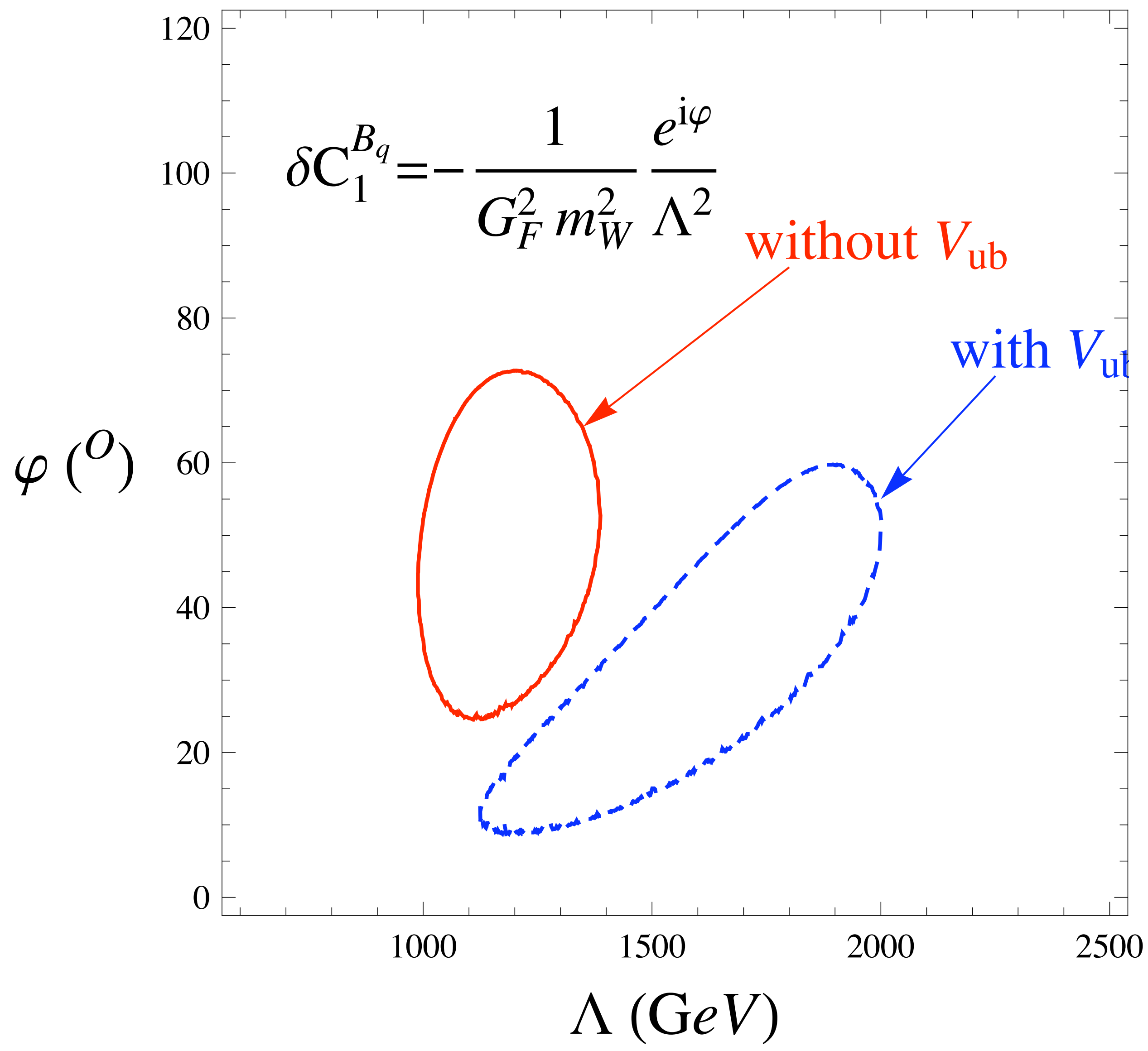


$= 2\phi_s$

- HFAG: $\phi_s = -(22 \pm 10)^o \cup -(68 \pm 10)^o$

Operator Level Analysis: *B_d and B_s Mixing*

- In our notation: $\delta C_1^K = 0$ and $\delta C_1^{B_s} = \delta C_1^{B_d}$
- New Physics in $a_{\psi K}$ and $a_{\psi\phi}$ ($\Delta M_{B_s}/\Delta M_{B_d}$ unaffected)



$$\Lambda \sim \begin{cases} [0.9 \div 1.4]\ \text{TeV} & \text{without } \mathrm{V_{ub}} \\ [1.1 \div 2.0]\ \text{TeV} & \text{with } \mathrm{V_{ub}} \end{cases}$$

Conclusions

- Recent lattice QCD (B_K, V_{cb}, V_{ub}, 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:
  - *new phase in penguin b→s amplitudes and in B_d/K mixing*
- Correlation with NP signals in *B_s mixing* and in the *Kπ system*
- Typical *upper bounds* on NP scales are in the TeV range:

	Λ	φ(°)
A(b→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

Backup Slides

Lattice average: B_K

[Laiho,EL,van de Water]

	$\widehat{B}_K$		
Ref.	mean	stat.	sys.
HPQCD/UKQCD '06 [3]	0.83	0.02	0.18
RBC/UKQCD '07 [4]	0.720	0.013	0.037
Aubin, Laiho & Van de Water '09 [5]	0.724	0.008	0.028
Average	0.725 ± 0.026		

- RBC/UKQCD (domain wall) and AVL (valence: domain wall; gauge: staggered) dominate the average
- We assume independent stat errors
- both use the same 1-loop perturbation theory to convert from RI-MOM to MSbar → truncation error is assumed 100% correlated

Lattice average: ξ

[Laiho,EL,van de Water]

		ξ	
Ref.	mean	stat.	sys.
FNAL/MILC '08 [11]	1.205	0.036	0.037
HPQCD '09 [12]	1.258	0.025	0.021
Average	1.243 ± 0.028		

- Both use staggered fermions and the same MILC configs
- We assume 100% correlation between the stat errors

Lattice average: V_{cb}

[Laiho,EL,van de Water]

	$\lvert V_{cb}\rvert \times 10^3$		
Ref.	mean	exp.	theo.
$B \to D\ell\nu$: FNAL/MILC '04 [19] + HFAG ICHEP '08 [16]	39.1	1.4	0.9
$B \to D^*\ell\nu$: FNAL/MILC '08 [20] + HFAG ICHEP '08 [16]	38.3	0.5	1.0
Average	38.6 ± 1.2		

- In the average, the exp uncertainty on $B \to D_*$ is rescaled by $\sqrt{\chi^2/\text{dof}} = \sqrt{39/21} = 1.4$
- We assume 100% correlation between the theory errors (same ensembles, same lattice actions, same methods)

Lattice average: V_{ub}

[Laiho,EL,van de Water]

Ref.	mean	exp.	theo.
		$\|V_{ub}\| \times 10^3$	
HPQCD '06 [15] + HFAG ICHEP '08 [16]	3.40	0.20	$^{+0.59}_{-0.39}$
FNAL/MILC '08 [17] + BABAR '06 [18]	3.38	~ 0.20	~ 0.29
Average	3.42 ± 0.37		

- Both use staggered fermions and the same MILC configs
- We assume 100% correlation between the stat errors
- We also assume 100% correlation between exp errors (conservative assumption)

Comments on systematic uncertainties

- We treat all systematic uncertainties as gaussian
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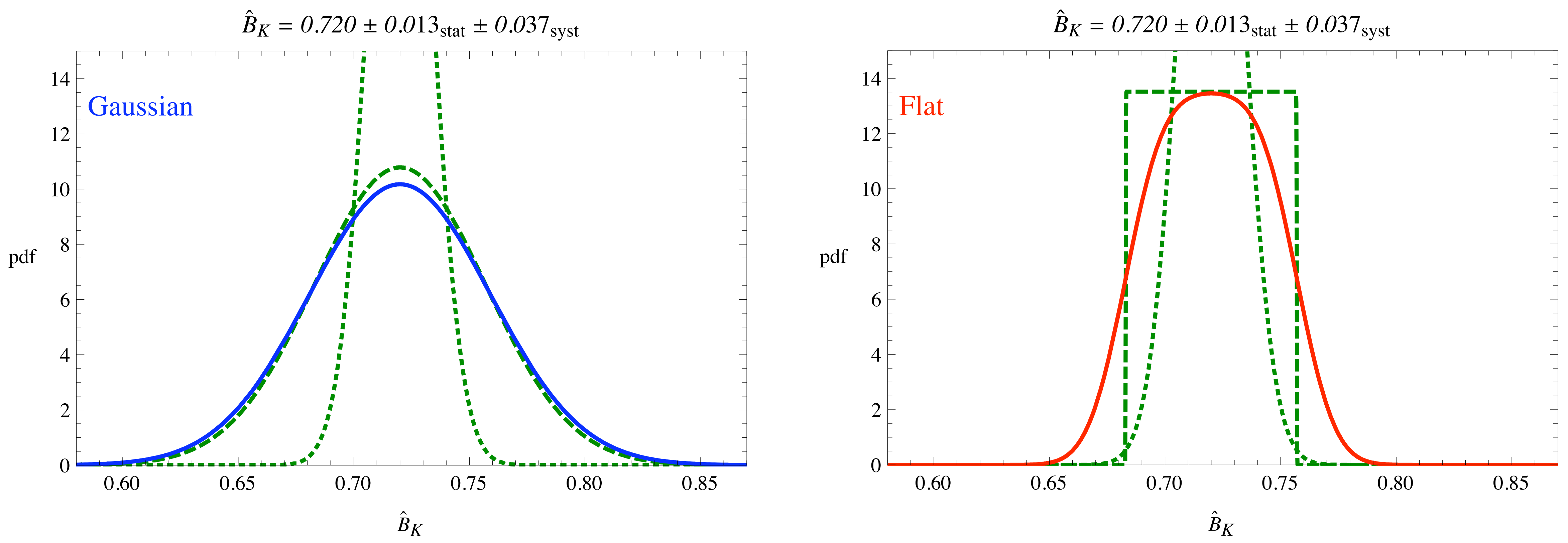

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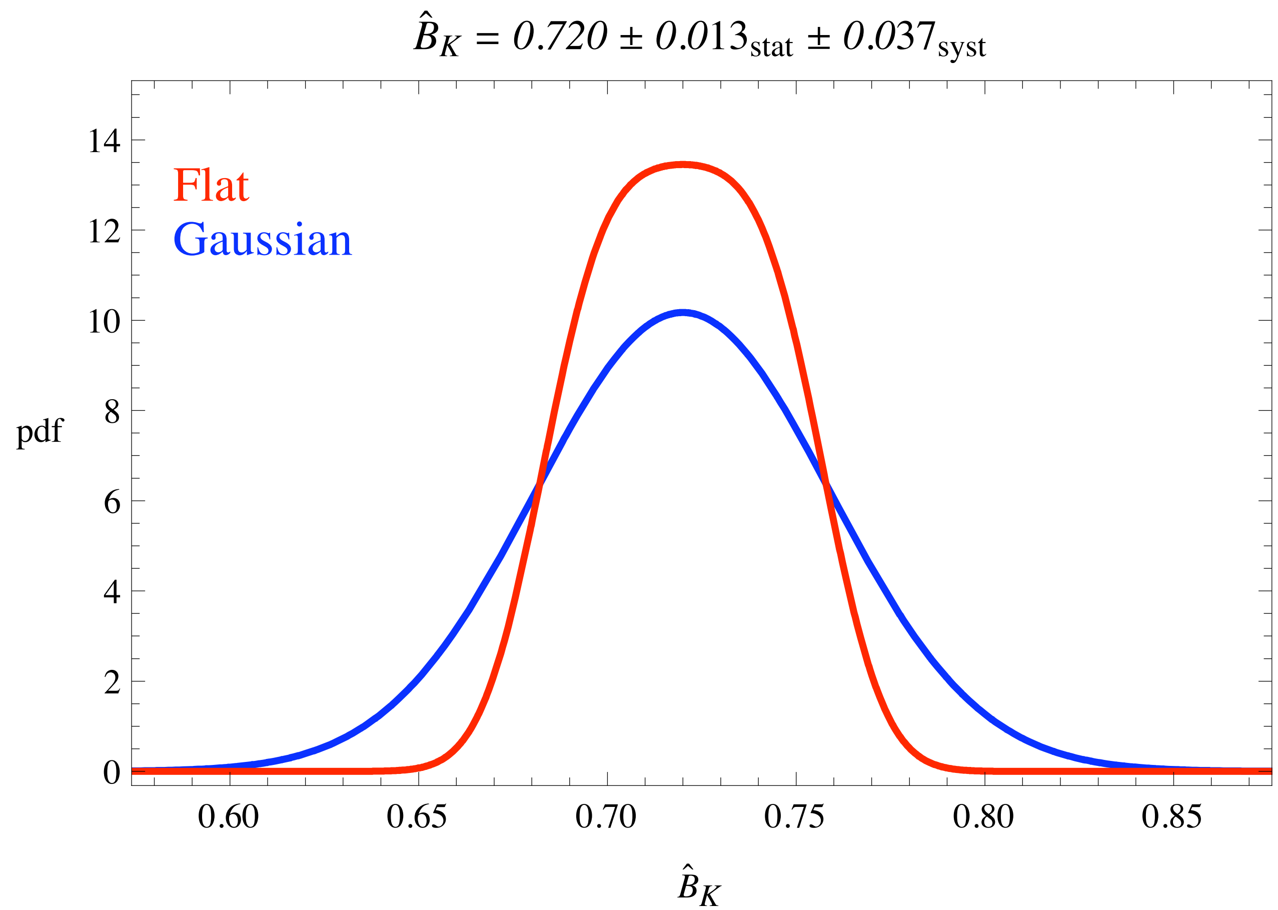

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