Global analysis of meson mixings and EW precision observables in SM4

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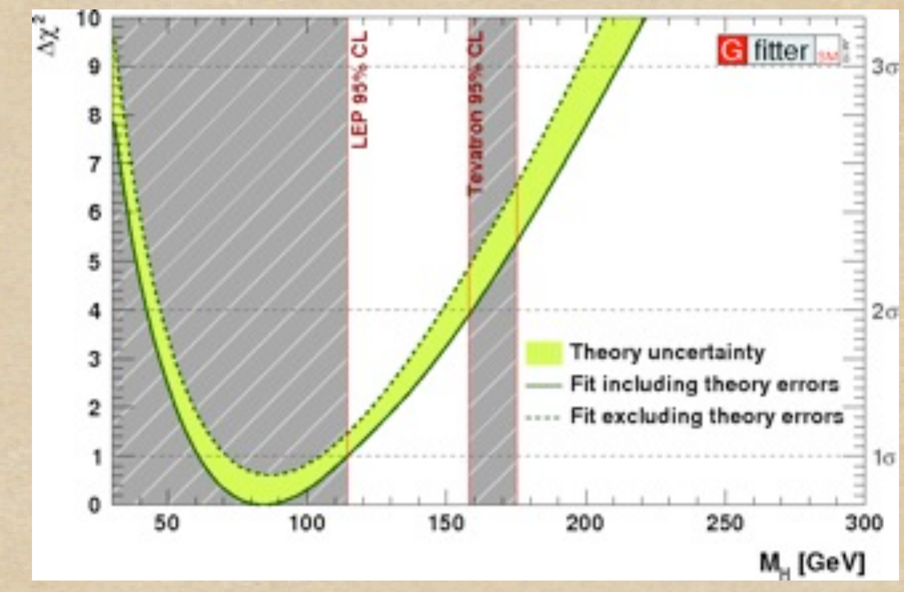
Motivation for another replication of fermions

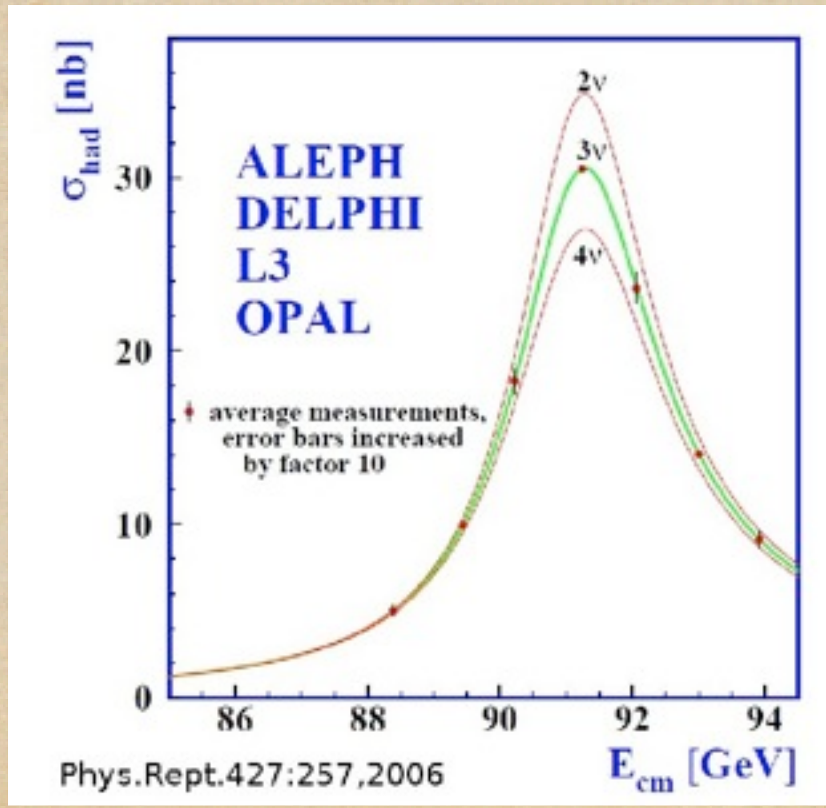
- Relax tension with m_H direct lower bound



- 2 new CP violating phases for electroweak baryogenesis [G.Hou] $n_B/s \simeq 5 \times 10^{-10}$

- Large Yukawa couplings of new fermions - possible dynamical explanation of EWSB

- Neutrinos are heavier than $m_Z/2$



- Current bounds

$m_{t'} > 338\,\text{GeV}$ CDF

$m_{b'} > 361\,\text{GeV}$ CMS

$m_{\ell'} > 100\,\text{GeV}$

$m_{\nu'} > 90\,\text{GeV}$ LEP

Bounds depend on partial BR's, thus on CKM, PMNS

Wednesday, April 20, 2011

Framework

Fourth generation masses run as $300\,\text{GeV} < m_{t'},\, m_{b'} < 600\,\text{GeV}$

Higgs mass fixed at 117 GeV at this stage. $100\,\text{GeV} < m_{\nu'},\, m_{\ell'} < 600\,\text{GeV}$

Higher values are perfectly possible but without improvement in the overall agreement with observables

Direct lower bounds from LEP, Tevatron, LHC

Yukawa couplings perturbativity

CKM matrix contains 3 new angles and 2 new phases

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) & A\lambda^3(\rho_1-i\eta_1) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 & A\lambda^2(\rho_2-i\eta_2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1-A^2{\rho_3}^2\lambda^2/2 & A\rho_3\lambda \\ A\lambda^3(\rho_1-\rho_2-i\eta_1+i\eta_2) & -A\lambda^2(\rho_2+i\eta_2) & -A\rho_3\lambda & 1-(A\rho_3)^2\lambda^2/2 \end{pmatrix} + \mathcal{O}(\lambda^3)$$

Cabibbo angle power counting inspired by 3x3 unitarity measurements

$$|V_{ub'}|^2 = 1-|V_{ud}|^2-|V_{us}|^2-|V_{ub}|^2 = 0.00001 \pm 0.0011\,,$$
$$|V_{cb'}|^2 = 1-|V_{cd}|^2-|V_{cs}|^2-|V_{cb}|^2 = -0.002 \pm 0.027\,,$$
$$|V_{tb'}|^2 < 1-|V_{tb}|^2, \qquad |V_{tb}| = 0.88 \pm 0.07\,.$$

Electroweak precision observables

Oblique parameters: effect of heavy fermions in gauge boson self-energies

$$S_4 = \frac{2}{3\pi}\left[1 - 1/2\log\frac{m_{t'}}{m_{b'}} - 1/2\log\frac{m_{\ell'}}{m_{\nu'}}\right]$$

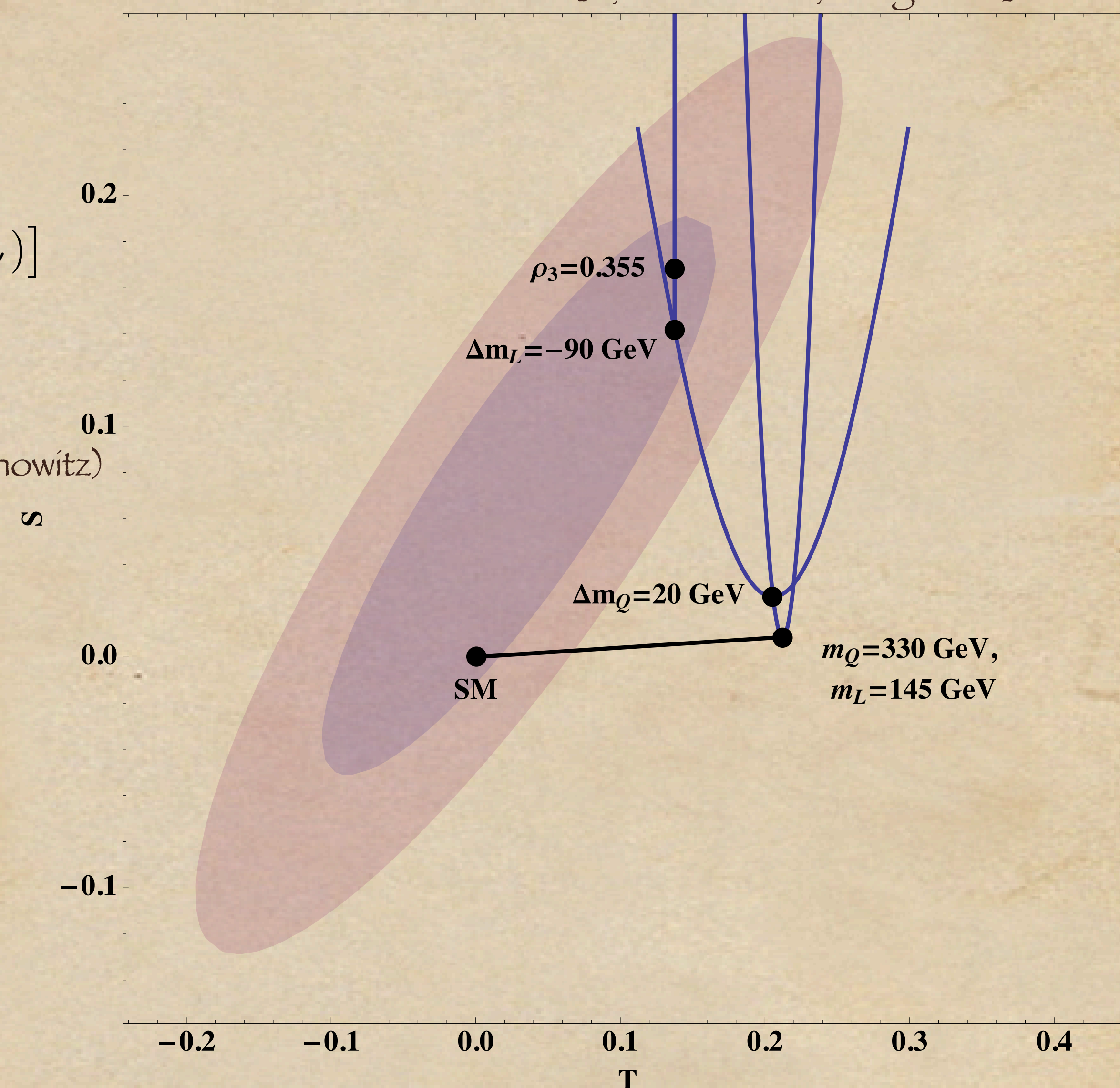
$$T_4 = \frac{3}{16\pi x_w(1-x_w)m_Z^2}\left[m_{t'}^2 + m_{b'}^2 - |V_{t'b'}|^2 F_T(m_{t'}^2, m_{b'}^2)\right] + \frac{1}{16\pi x_w(1-x_w)m_Z^2}\left[m_{\ell'}^2 + m_{\nu'}^2 - F_T(m_{\nu'}^2, m_{\ell'}^2)\right]$$

$$U_4 \simeq 0$$

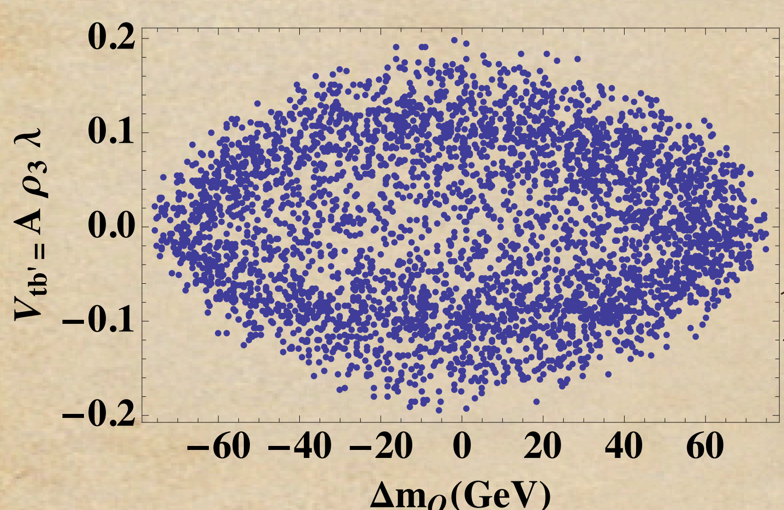
(Peskin, Takeuchi; Lenz; Chanowitz)

$$\mathrm{Cov}_{S,T} = \begin{pmatrix} 0.0081 & 0.006264 \\ 0.006264 & 0.0064 \end{pmatrix}$$

[S,T from Erler, Langacker]



$$V_{t'b'} \approx 1 - V_{tb'}^2/2 \approx 1 - A^2\rho_3^2\lambda^2/2$$



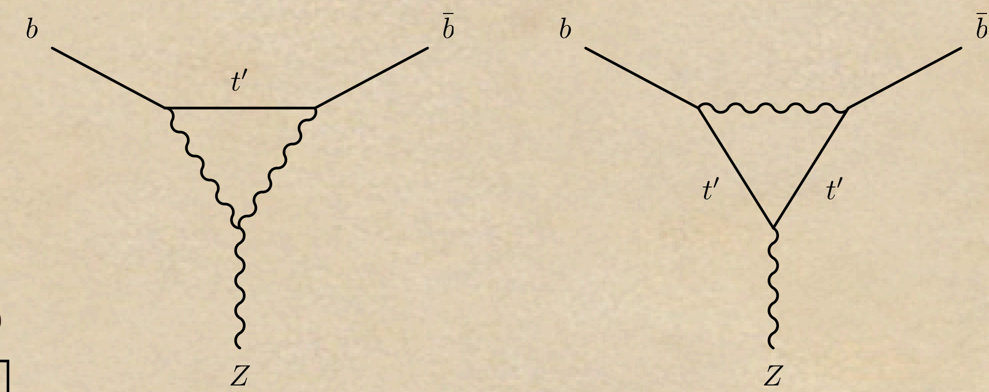
Preferred small 3-4 mixing ($V_{tb'}$)

Points are inside the 2σ contour in the S-T plane

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) & A\lambda^3(\rho_1 - i\eta_1) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 & A\lambda^2(\rho_2 - i\eta_2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 - A^2\rho_3{}^2\lambda^2/2 & A\rho_3\lambda \\ A\lambda^3(\rho_1 - \rho_2 - i\eta_1 + i\eta_2) & -A\lambda^2(\rho_2 + i\eta_2) & -A\rho_3\lambda & 1-(A\rho_3)^2\lambda^2/2 \end{pmatrix}$$

Electroweak precision observables

Zbb non-decoupling vertex correction



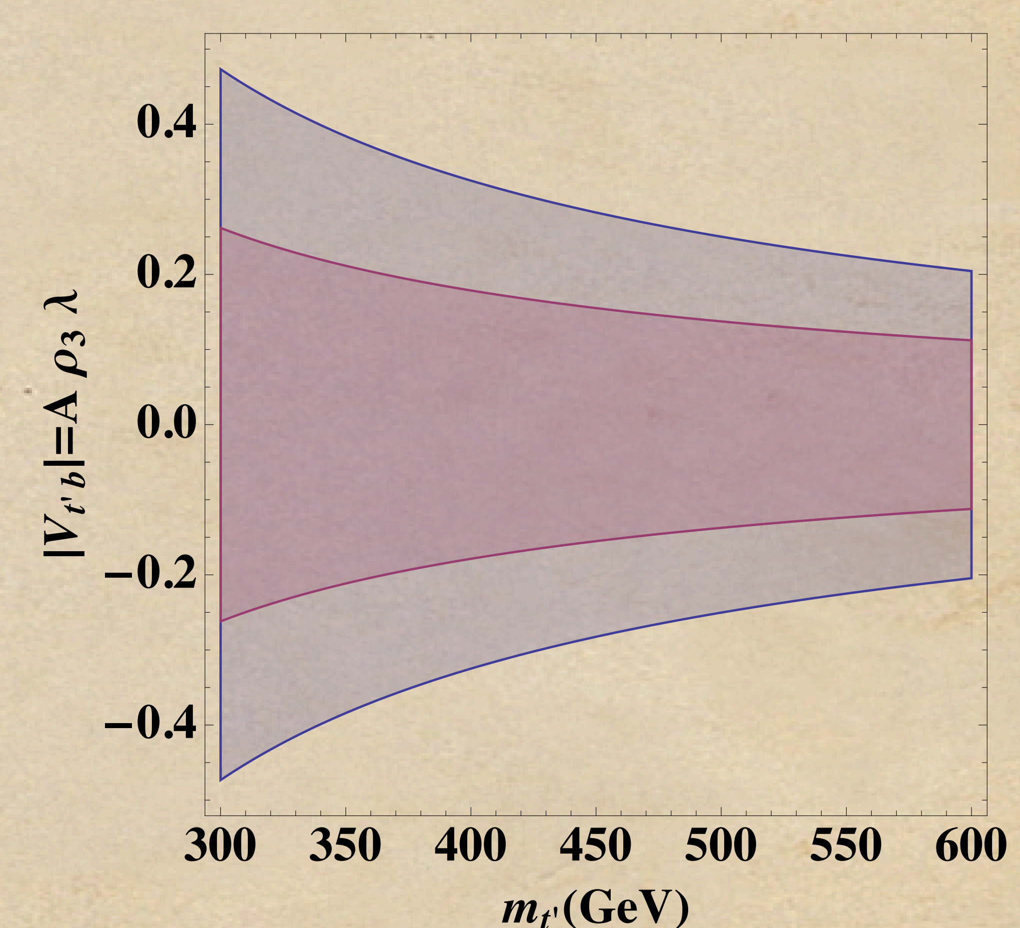
$$R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$$

$$\Gamma(Z \to b\bar{b}) = \# m_Z(1+\delta_b)$$

(Bernabeu; Yanir)

$$\delta_b \approx 10^{-2}\left[(-\frac{m_t^2}{2m_Z^2}+0.2)|V_{tb}|^2 + (-\frac{m_{t'}^2}{2m_Z^2}+0.2)^2|V_{t'b}|^2\right]$$

Probes 3-4 mixing and $m_{t'}$, ρ_3 must not be too large



V_{tb} measurement in single top production

not EWP per-se but directly probes ρ_3

$$V_{tb} = 1-(A\rho_3\lambda)^2/2 \qquad V_{tb} = 0.88 \pm 0.07$$

Requires ρ_3 not too small. (ρ_3 ≈0 is 1.7σ away from the central value)

Meson mixing observables

Probe of CKM and individual quark mass scales.

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) & A\lambda^3(\rho_1 - i\eta_1) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 & A\lambda^2(\rho_2 - i\eta_2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 - A^2{\rho_3}^2\lambda^2/2 & A\rho_3\lambda \\ A\lambda^3(\rho_1 - \rho_2 - i\eta_1 + i\eta_2) & -A\lambda^2(\rho_2 + i\eta_2) & -A\rho_3\lambda & 1-(A\rho_3)^2\lambda^2/2 \end{pmatrix} \quad \Delta m_D$$

ϵ_K $\quad$ Δm_s $\quad$ $\sin 2\beta_s$ $\quad$ Δm_d $\quad$ $\sin 2\beta$

$(m_{b'})$

$(m_{t'})$ ← EWP

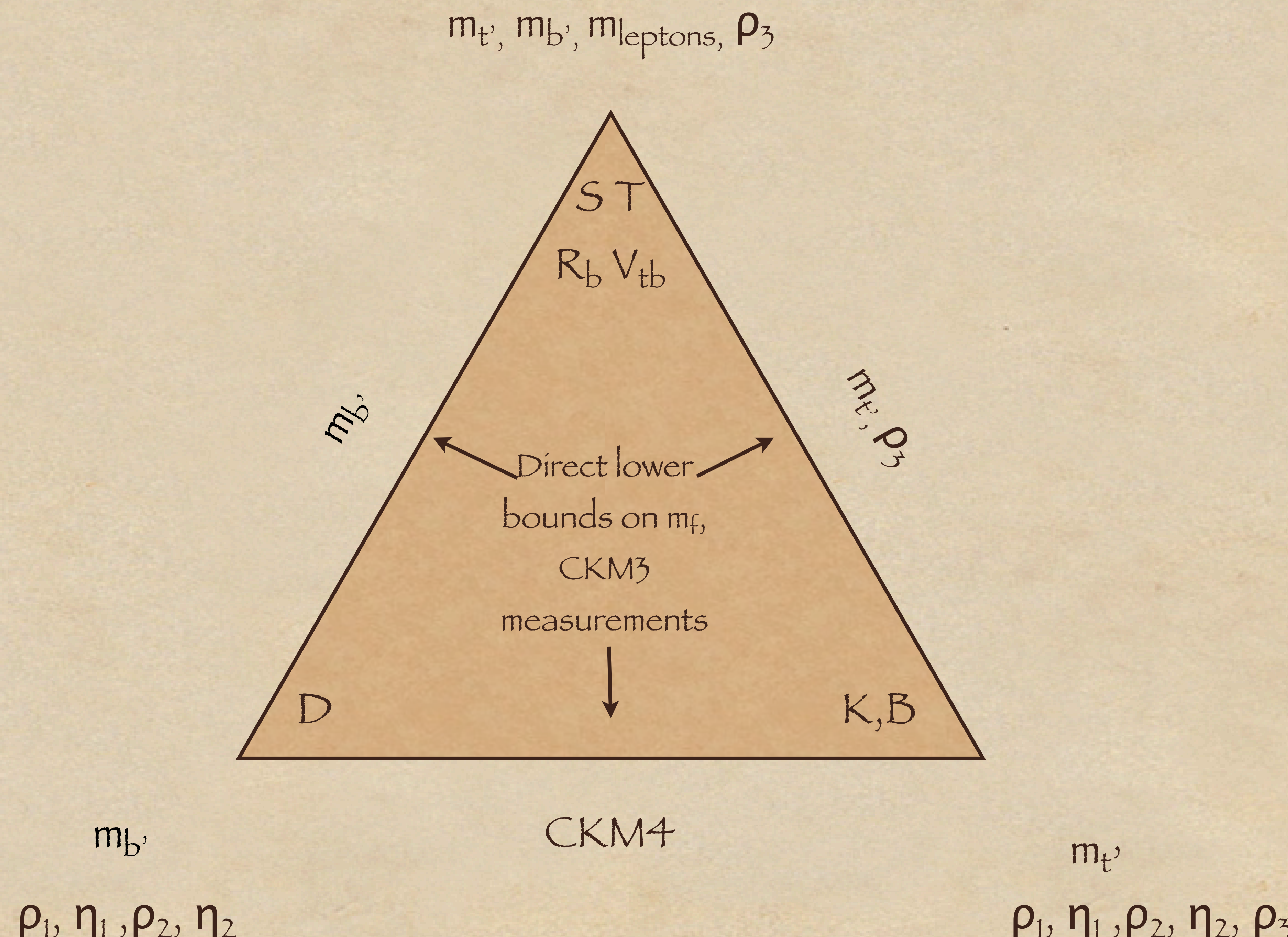
K and B mixing observables are sensitive to $m_{t'}$.

Theoretically reliable, e.g.

$$\xi_{sd}^2 \frac{m_{B_s}}{m_{B_d}} \left| \frac{\eta_t (V_{tb}V_{ts}^*)^2 S_0(x_t) + \eta_{t'}(V_{t'b}V_{t's}^*)^2 S_0(x_{t'}) + 2\eta_{tT} V_{tb}V_{ts}^* V_{t'b}V_{t's}^* S_0(x_t, x_{t'})}{\eta_t (V_{tb}V_{td}^*)^2 S_0(x_t) + \eta_{t'}(V_{t'b}V_{t'd}^*)^2 S_0(x_{t'}) + 2\eta_{tT} V_{tb}V_{td}^* V_{t'b}V_{t'd}^* S_0(x_t, x_{t'})} \right| = \frac{\Delta m_s}{\Delta m_d}\bigg|_{\rm exp}$$

D mixing is sensitive to $m_{b'}$, however, difficult to assign statistical significance of measured mass splitting due to poor theoretical knowledge of long distance physics.

A global view



Global fit

To quantify the impact of meson mixing observables.

Similar analyses done by [Alok 2010; Lenz 2010]

Observables (15):

$S = 0.03 \pm 0.09, \quad T = 0.07 \pm 0.08$

$R_b = 0.216 \pm 0.001$

$V_{tb} = 0.88 \pm 0.07$

EWP and/or driven by ρ_3

$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \end{pmatrix} \quad \gamma$

Tree-level quantities, primarily sensitive to CKM3 (PDG values)

ϵ_K, $\sin 2\beta$

Δm_s, $\dfrac{\Delta m_s}{\Delta m_d}$

FCNC observables, very sensitive to new CKM parameters

Write down Gaussian χ^2 for each observable as $[o(y)-o_{exp}]^2/\sigma_{exp}^2$

Mass splitting in charm sector is treated as a “kinematical” constraint

$$M_{12} = M_{12}^{\rm LD} + M_{12}^{\rm LD,b'} + M_{12}^{\rm b'} \qquad |M_{12,D}^{b'}| < 3|M_{12,D}^{\rm exp}|$$

Note that factor “3” is arbitrary, but conservative.

[Lenz; Golowich]

Global fit parameters

Model parameters (13): $m_{t'},\ m_{b'},\ m_{\nu'},\ m_{\ell'}$ $\lambda,\ A,\ \rho,\ \eta,\ \rho_{1,2,3},\ \eta_{1,2}$

Theoretical (nuisance) parameters:

$\eta_c = 1.43(23)$ [Herrlich, Nierste]

$\eta_{ct} = 0.496(47)$ [Brod, Gorbahn]

$\eta_t = 0.5765(65)$ [Buras, Jamin, Weisz]

$\hat{B}_K = 0.725(26)$ [latticeaverages.com]

$f_K = 156.1(8)\,\mathrm{MeV}$

$\kappa_\epsilon = 0.94(2)$ [Buras, Guadagnoli]

$\eta_B = 0.55(1)$

$\xi = 1.237(32)$ [latticeaverages.com]

$f_{B_s}\sqrt{\hat{B}_{B_s}} = 270(30)\,\mathrm{MeV}$ [Lubicz, Tarantino]

Theoretical parameters freely slide within their allowed ranges and do not contribute to χ^2. Similar to CKMFitter's RFit, except that we do not add statistical error tails. (preliminary)

D mixing theoretical parameters' errors are irrelevant when compared to arbitrariness in interpretation of the experimental Δm_D.

Interpretation of fit results

1. Global minimum of χ^2, χ^2_{min}, determines the overall quality of the fit.

n_{DOF} = 15-13 = 2 degrees of freedom

$$\begin{aligned} \chi^2_{n_{\rm DOF}=2} &\leq 2.3 \qquad 1\sigma \\ &\leq 6.2 \qquad 2\sigma \\ &\leq 11.8 \qquad 3\sigma \end{aligned}$$

Assumption of parabolic (Gaussian) behavior around minimum. To improve, resort to MC and determine confidence levels pseudoexperimentally.

2. Assuming model is correct, we find allowed range of its model parameter "y_1" by considering

$$\Delta\chi^2(y_1) = \min_{\{y2,\, y3,\, \ldots\}} [\chi^2(y_1, y_2, \ldots) - \chi^2_{min}]$$

$\Delta\chi^2(y_1)$ at "best" value of y_1 is 0,

$$\text{N-}\sigma \text{ region} = \{y_1\,;\,\Delta\chi^2(y_1) \leq N^2\}$$

Global minimum

(preliminary)

$\chi^2_{min} \approx 8.60$

$\approx 2.84 + 2.14 + 1.89 + 1.46 + \ldots$

$V_{tb} \quad R_b \quad V_{cs} \quad S, T$

$n_{DOF} \approx 2$ ⟷ 2.5 σ fluctuation (p-value ≈ 1.4%)

Significance of fluctuation is expected to decrease once we include additional observables.

$m_{t'} \approx 325\,\mathrm{GeV}$	$\lambda \approx 0.22515$	$\rho_1 \sim 0.3$
$m_{b'} \approx 305\,\mathrm{GeV}$	$A \approx 0.802$	$\eta_1 \sim 1.4$
$m_{\nu'} \approx 100\,\mathrm{GeV}$	$\rho \approx 0.14$	$\rho_2 \sim -0.1$
$m_{\ell'} \approx 190\,\mathrm{GeV}$	$\eta \approx 0.40$	$\eta_2 \sim 0.3$
		$\rho_3 \sim 0.3$

Mass splittings (see also Lenz's talk)

4th generation doublets can both be degenerate

Weakly preferred

$m_{l'} > m_{\nu'}$

$m_{t'} > m_{b'}$

Equally possible

$m_{t'} \to m_{b'}\, W$

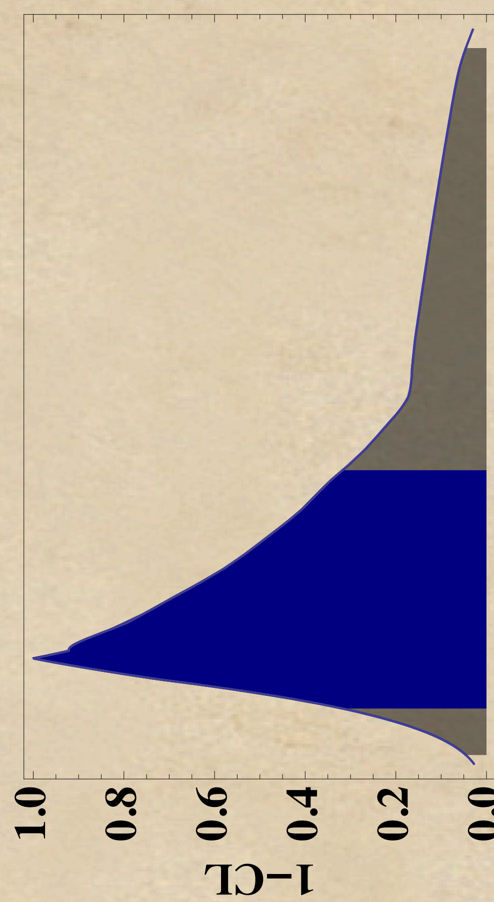
$m_{b'} \to m_{t'}\, W$

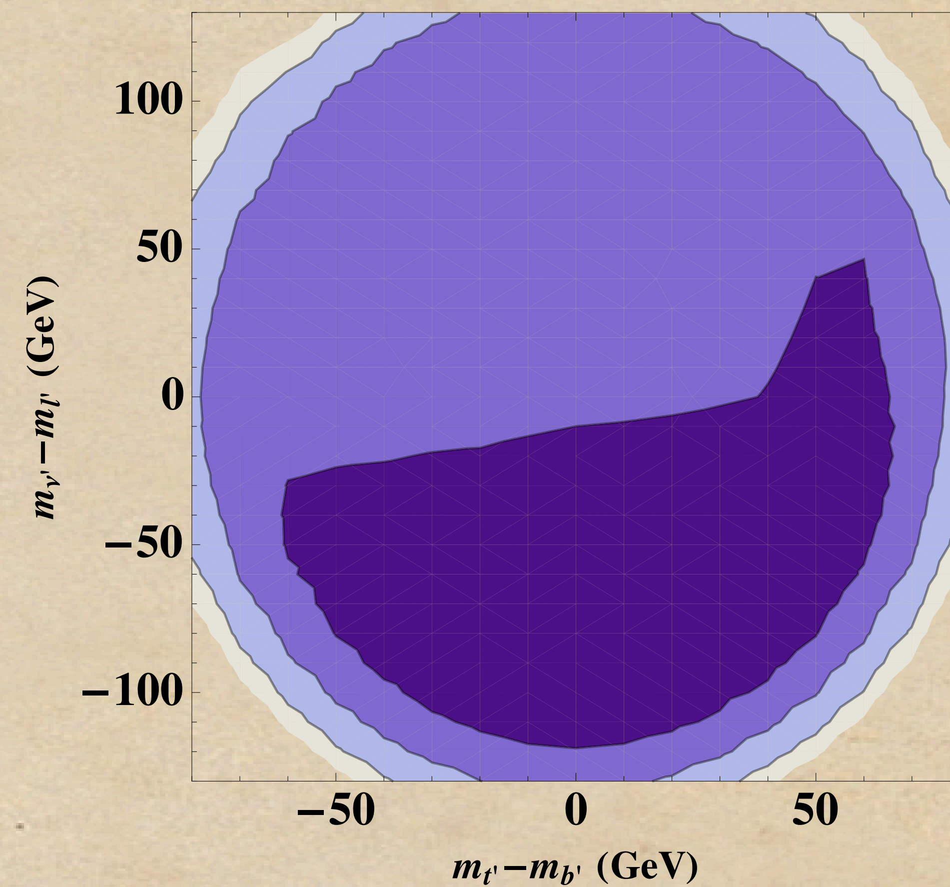
Much broader range than the commonly used optimal point, without taking into account CKM angles

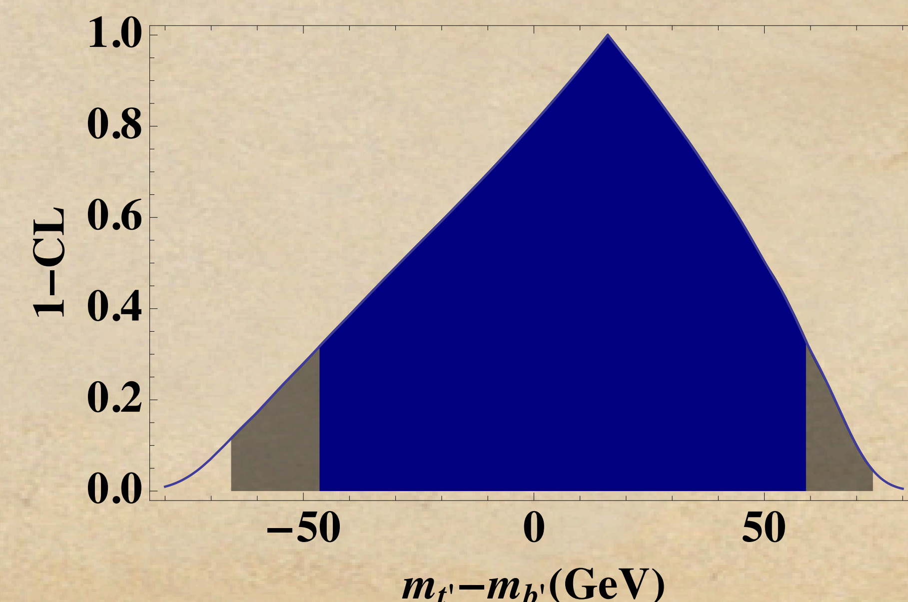
$$m_{\ell'} - m_{\nu'} \approx 30 - 60\,\mathrm{GeV}$$

$$m_{t'} - m_{b'} \approx 50\,\mathrm{GeV}$$

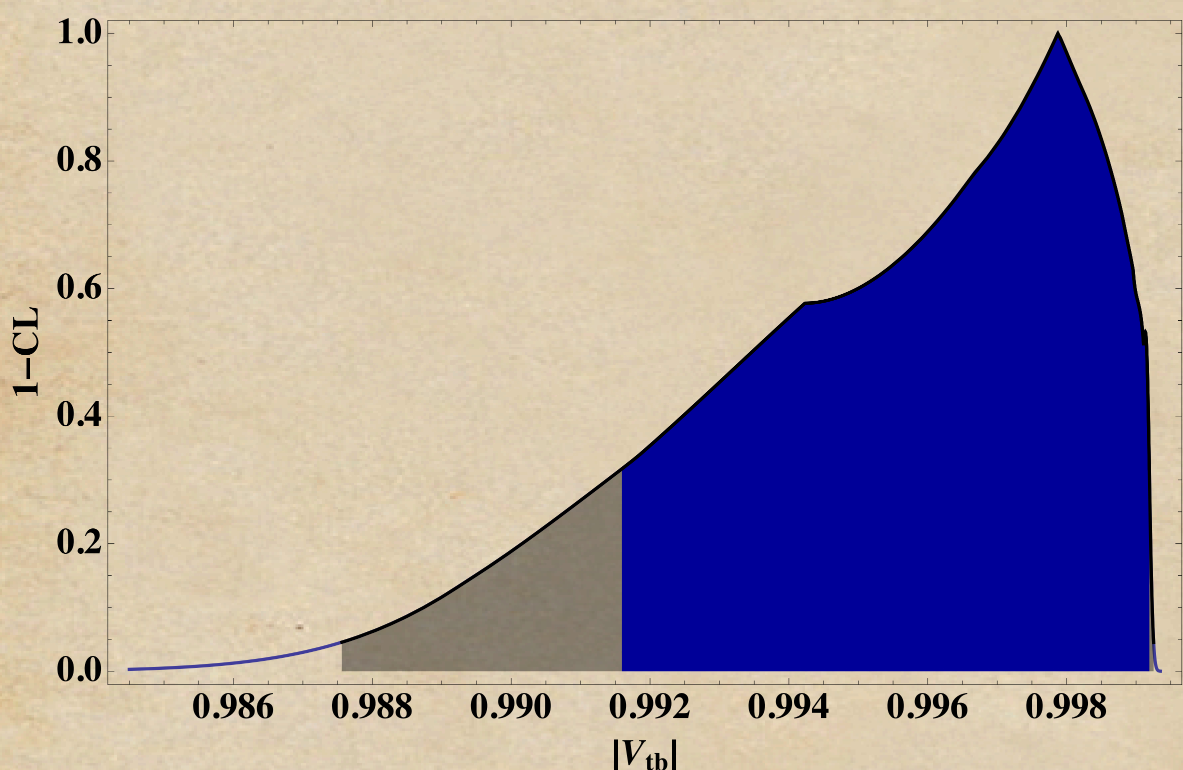
[Kribs,2007]

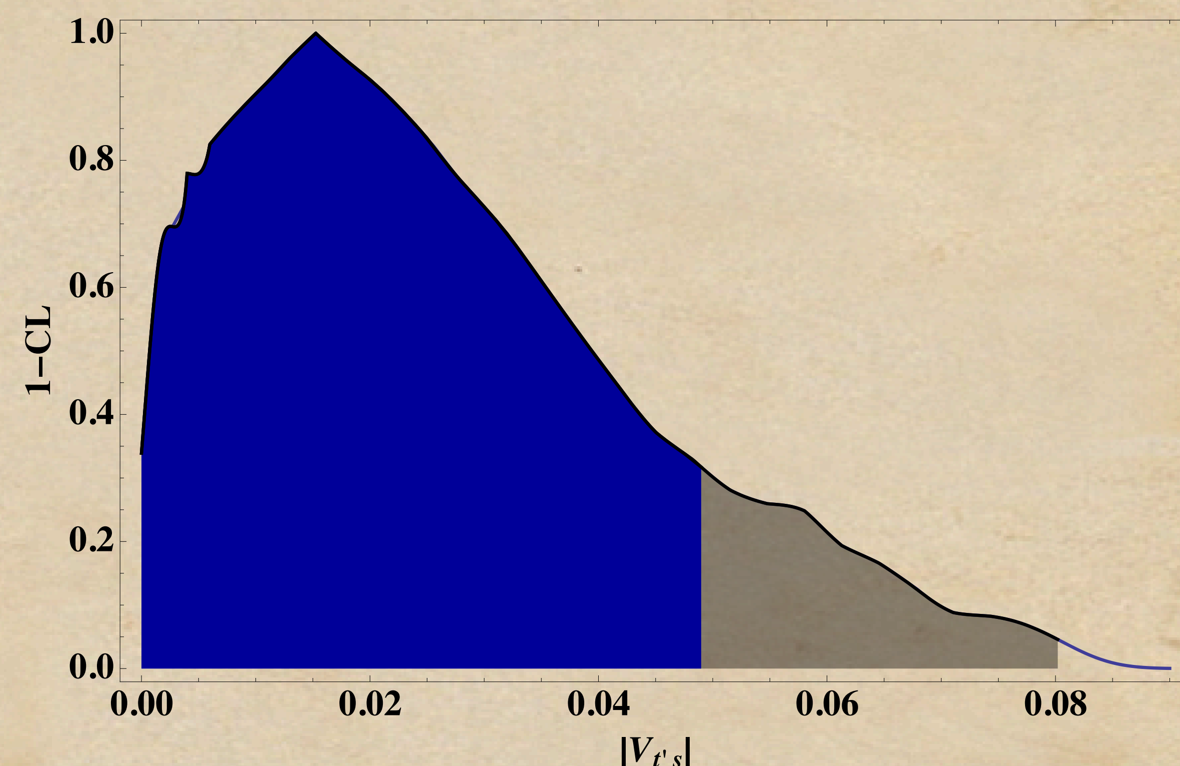






CKM elements predictions





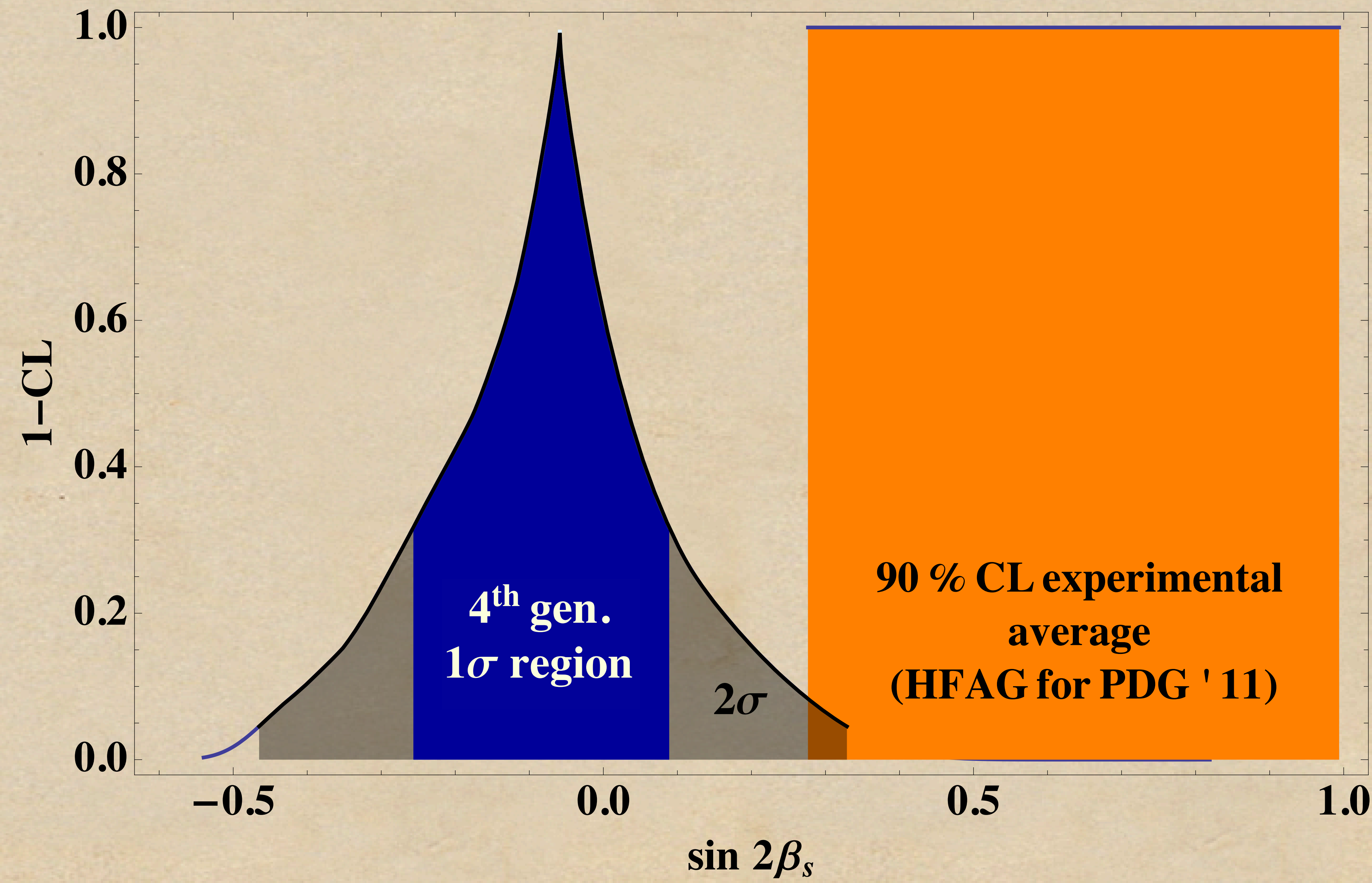
$1-(A\rho_3\lambda)^2/2$

$A\lambda^2(\rho_2+i\eta_2)$

Expansion of CKM stable.

Important for direct searches
t' -> q W. [Flacco et al, PRL105]

Prediction of sin $2\beta_s$



Conclusion

- EW data favors mass splitting in both quark and leptonic sectors
- Crucial degree of freedom is the 3-4 mixing, allowing much wider range of masses and splittings, and opening portal to flavor physics
- Flavor observables are talking to EW observables via 3-4 mixing and quark masses.

Conclusion

- Minimal set of relevant observables ($n_{DOF} = 2$) strongly constrains CKM elements.
- Very large phases in B_s mixing are unlikely
- Study of constraints in ($m_{t'}$, $V_{t'q}$) and ($m_{b'}$, $V_{qb'}$) planes is underway