Revisit of Flavor and CPV Data with Heavy t' and b'

Chien-Yi Ma（馬鑑一）
National Taiwan University, Taipei, Taiwan

In collaboration with W.S. Hou

2nd Workshop on Beyond 3 Generation Standard Model
--- New Fermions at the Crossroads of Tevatron and LHC

14-16 January, 2010 NTU, Taipei, Taiwan

Large sin $2\Phi_{Bs}$?

SM predicts sin $2\Phi_{Bs}$ (also denoted –sin $2\beta_s$) ~ –0.04.
Latest constrained fit by HFAG is 2.2 σ away from SM.
[Barberio et al. arXiv:0808.1297]

4 generation (SM4) introduce *t* ' to interfere with *t* in box diagrams

$$M_{12} = \frac{G_F^2\, M_W^2}{12\,\pi^2}\, m_{B_s} \left(f_{B_s}\sqrt{\hat{B}_{B_s}}\right)^2 (\lambda_t^2\, \eta\, S_0(x_t) + \eta'\, \lambda_{t'}^2\, S_0(x_{t'}) + 2\,\tilde{\eta}\, \lambda_t\, \lambda_{t'}\, \tilde{S}_0(x_t, x_{t'}))$$

SM4 makes SM triangle into quadrangle

$$V^*_{us}V_{ub} + V^*_{cs}V_{cb} + V^*_{ts}V_{tb} + V^*_{t's}V_{t'b} = 0$$

Combine

Δm_{Bs} [box diagram]

$\mathcal{B}(b \to s\ell\ell)$ [Z penguin diagram]

to determine $V^*_{t's}V_{t'b}$

Use parametrization matrix

[Hou, Soni and Steger PLB **192** (1987)]

1st Row

$$V_{ud} = -c_{13}\, s_{14}\, s_{12}\, s_{24}\, e^{i\,\Phi_{sb} - i\,\Phi_d} - s_{13}\, c_{24}\, s_{14}\, s_{34}\, e^{-i\,\Phi_d - i\,\phi_3} + c_{14}\, c_{13}\, c_{12}$$

$$V_{us} = c_{13}\, c_{24}\, s_{12} - s_{13}\, s_{34}\, s_{24}\, e^{-i\,\Phi_{sb} - i\,\phi_3}$$

$$V_{ub} = s_{13}\, c_{34}\, e^{-i\,\phi_3}$$

$$V_{ub'} = c_{14}\, c_{13}\, s_{12}\, s_{24}\, e^{i\,\Phi_{sb}} + c_{13}\, c_{12}\, s_{14}\, e^{i\,\Phi_d} + s_{13}\, c_{14}\, c_{24}\, e^{-i\,\phi_3}\, s_{34}$$

4th Row

$$V_{t'd} = -c_{34}\, c_{24}\, s_{14}\, e^{-i\,\Phi_d}$$

$$V_{t's} = -c_{34}\, s_{24}\, e^{-i\,\Phi_{sb}}$$

$$V_{t'b} = -s_{34}$$

$$V_{t'b'} = c_{14}\, c_{34}\, c_{24}$$

2nd Row

$$V_{cd} = s_{14}\, s_{13}\, s_{12}\, s_{24}\, s_{23}\, e^{i\,\Phi_{sb} - i\,\Phi_d + i\,\phi_3} - c_{12}\, c_{23}\, s_{14}\, s_{24}\, e^{i\,\Phi_{sb} - i\,\Phi_d} - c_{13}\, c_{24}\, s_{14}\, s_{34}\, s_{23}\, e^{-i\,\Phi_d} - c_{14}\, c_{12}\, e^{i\,\phi_3}\, s_{13}\, s_{23} - c_{14}\, c_{23}\, s_{12}$$

$$V_{cs} = -c_{13}\, s_{34}\, s_{24}\, s_{23}\, e^{-i\,\Phi_{sb}} - c_{24}\, e^{i\,\phi_3}\, s_{13}\, s_{12}\, s_{23} + c_{12}\, c_{24}\, c_{23}$$

$$V_{cb} = c_{13}\, c_{34}\, s_{23}$$

$$V_{cb'} = -c_{14}\, s_{13}\, s_{12}\, s_{24}\, s_{23}\, e^{i\,\Phi_{sb} + i\,\phi_3} + c_{14}\, c_{12}\, c_{23}\, s_{24}\, e^{i\,\Phi_{sb}} - c_{12}\, s_{14}\, s_{13}\, s_{23}\, e^{i\,\Phi_d + i\,\phi_3} - c_{23}\, s_{14}\, s_{12}\, e^{i\,\Phi_d} + c_{14}\, c_{13}\, c_{24}\, s_{34}\, s_{23}$$

3rd Row

$$V_{td} = c_{23}\, s_{14}\, s_{13}\, s_{12}\, s_{24}\, e^{i\,\Phi_{sb} - i\,\Phi_d + i\,\phi_3} + c_{12}\, s_{14}\, s_{24}\, s_{23}\, e^{i\,\Phi_{sb} - i\,\Phi_d} - c_{13}\, c_{24}\, c_{23}\, s_{14}\, s_{34}\, e^{-i\,\Phi_d} + c_{14}\, s_{12}\, s_{23} - c_{14}\, c_{12}\, c_{23}\, e^{i\,\phi_3}\, s_{13}$$

$$V_{ts} = -c_{13}\, c_{23}\, s_{34}\, s_{24}\, e^{-i\,\Phi_{sb}} - c_{12}\, c_{24}\, s_{23} - c_{24}\, c_{23}\, e^{i\,\phi_3}\, s_{13}\, s_{12}$$

$$V_{tb} = c_{13}\, c_{34}\, c_{23}$$

$$V_{tb'} = -c_{14}\, c_{23}\, s_{13}\, s_{12}\, s_{24}\, e^{i\,\Phi_{sb} + i\,\phi_3} - c_{14}\, c_{12}\, s_{24}\, s_{23}\, e^{i\,\Phi_{sb}} - c_{12}\, c_{23}\, s_{14}\, s_{13}\, e^{i\,\Phi_d + i\,\phi_3} + s_{14}\, s_{12}\, s_{23}\, e^{i\,\Phi_d} + c_{14}\, c_{13}\, c_{24}\, c_{23}\, s_{34}$$

Hou, Nagashima and Soddu

[PRD**72**(2005),PRD**76**(2007)]

illustrated the case $m_{t'}$ = 300 GEV using

$f_{Bs}\sqrt{B_{Bs}}$ = 295 MEV

Get $\sin 2\Phi_{Bs} \sim -0.50 - -0.70$

What's new in our recent study ?

Trivial Change

1. $m_{t'}$ = 300 GEV → 500 GEV (unitarity bound)

[Chanowitz et al. PLB**78**(1978)]

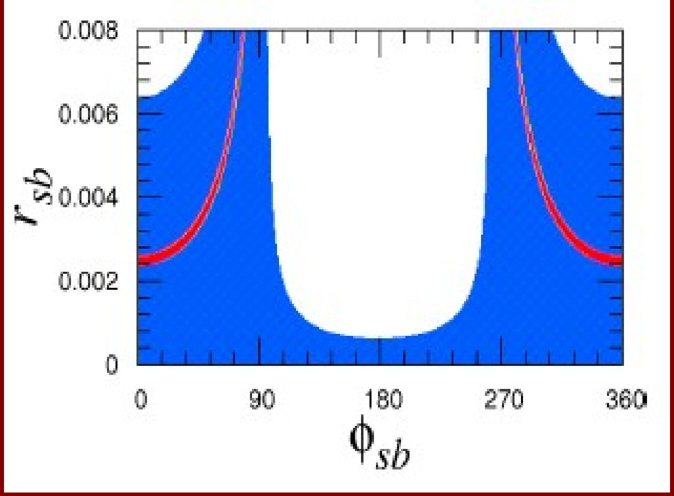
2. $f_{Bs}\sqrt{B_{Bs}}$ = 295 MEV → 266(18) MEV

[Gamiz et al. HPQCD PRD**80**(2009)]

Nontrivial New Analysis

1. *D* – *D* mixing constraint
2. Electroweak precision global fit

$$V^*_{t's} V_{t'b} \equiv r_{sb}\, e^{i\varphi_{sb}}$$

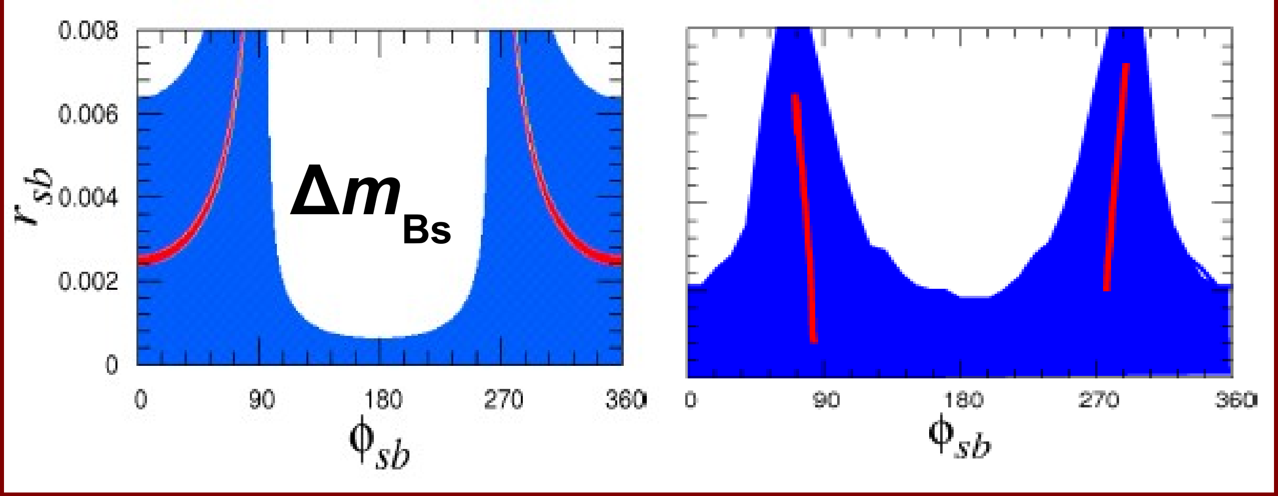


$(\Delta m_{B_s})^{\mathrm{exp}} = (17.77 \pm 0.12)\ \mathrm{ps}^{-1}$

$f_{B_s}\sqrt{B_{B_s}} =$ 266(18) MEV

$$M_{12} = \frac{G_F^2\, M_W^2}{12\,\pi^2}\, m_{B_s} \left(f_{B_s} \sqrt{\hat{B}_{B_s}} \right)^2 \left(\lambda_t^2\, \eta\, S_0(x_t) + \eta'\, \lambda_{t'}^2\, S_0(x_{t'}) + 2\,\tilde{\eta}\, \lambda_t\, \lambda_{t'}\, \tilde{S}_0(x_t, x_{t'}) \right)$$

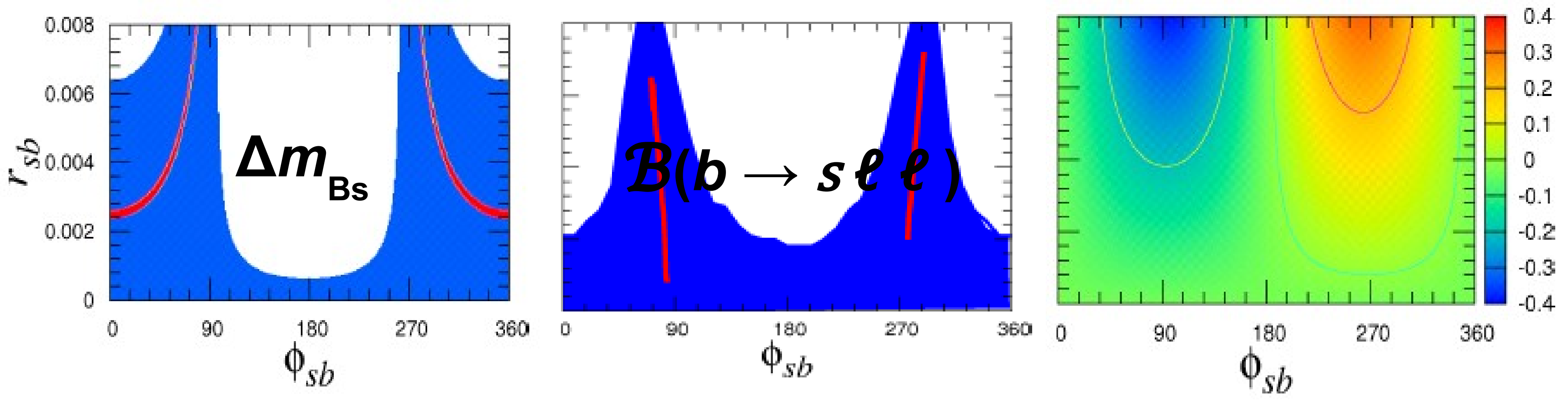
$$V^*_{t's} V_{t'b} \equiv r_{sb}\, e^{i\varphi_{sb}}$$



Calculation using [Bobeth *et al.* NPB(2000)]

$$\mathcal{B}^{exp}(b \to s\ell\ell) = (4.5 \pm 1.0) \times 10^{-6}$$

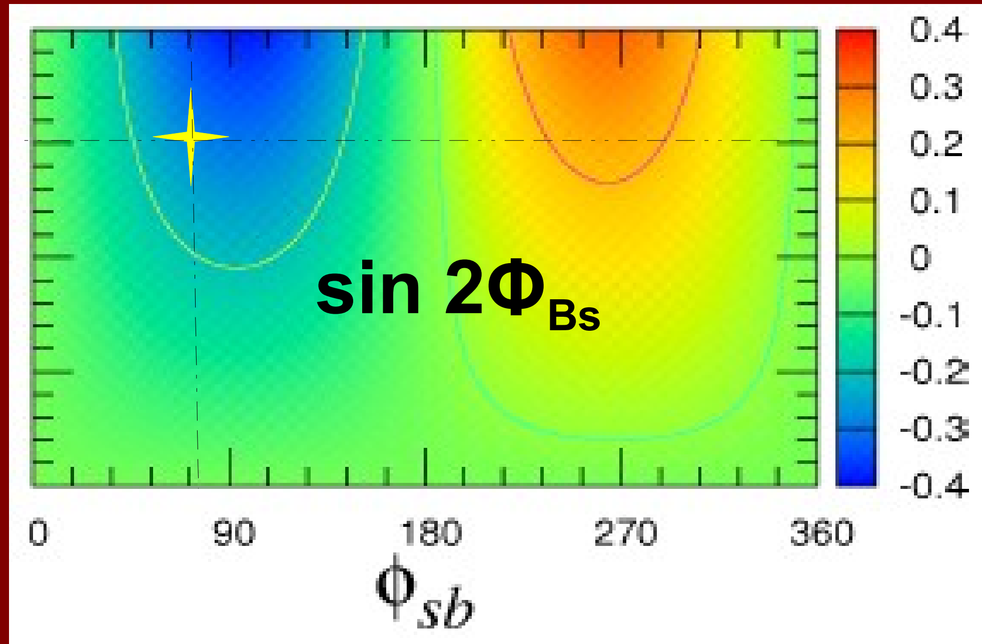
$V^*_{t's} V_{t'b} \equiv r_{sb}\, e^{i\varphi_{sb}}$



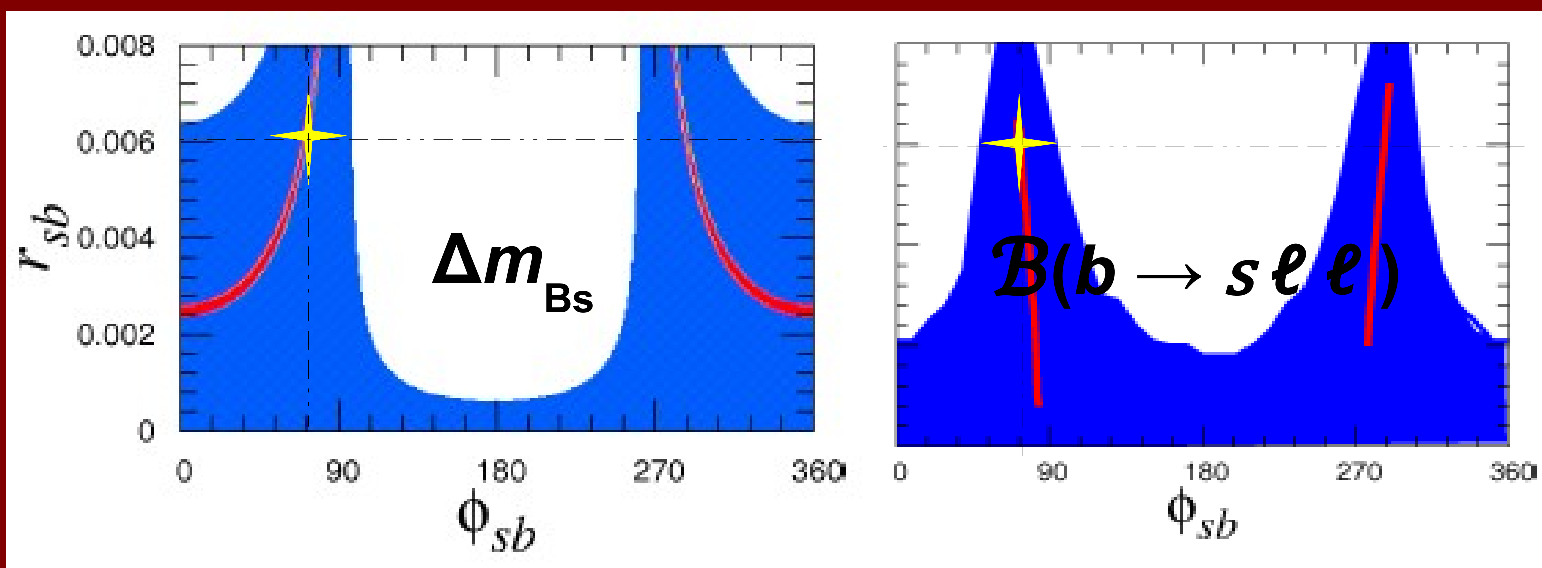
$\sin 2\Phi_{Bs} = \mathrm{Im}(M_{12}) / |M_{12}|$

$$M_{12} = \frac{G_F^2\, M_W^2}{12\,\pi^2}\, m_{B_s} \left(f_{B_s} \sqrt{\hat{B}_{B_s}}\right)^2 (\lambda_t^2\, \eta\, S_0(x_t) + \eta'\, \lambda_{t'}^2\, S_0(x_{t'}) + 2\,\tilde{\eta}\, \lambda_t\, \lambda_{t'}\, \tilde{S}_0(x_t, x_{t'}))$$

r_{sb} = 0.006,
φ_{sb} = 75°,
sin 2Φ_{Bs} = – 0.33



SMALLER sin 2Φ_{Bs} STILL POSSIBLE



$$\begin{matrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{matrix}$$

$$V^*_{t's}\, V_{t'b} = 0.006\, e^{i\,75^\circ}$$

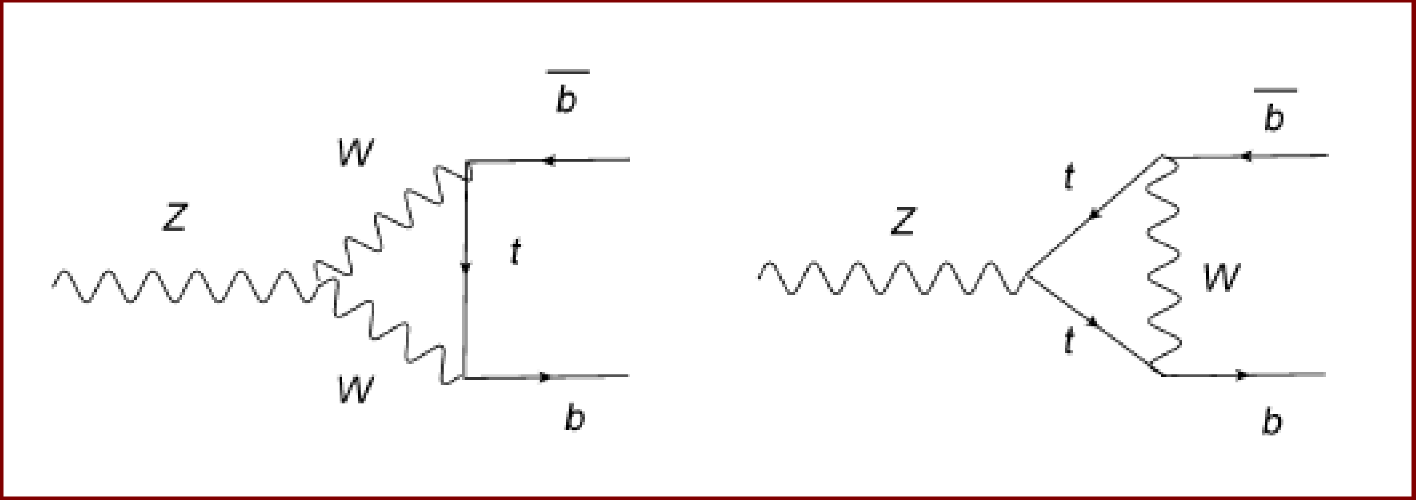
$$V_{t's} = ? \qquad V_{t'b} = ?$$

Upper Bound on $|V_{t'b}|$

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

$|V_{t'b}| < 0.13$ ($m_{t'}$ = 500 GEV)

[Yanir, JHEP06(2002)]



What is Lower Bound on $|V_{t'b}|$?

Constraint from $\mathcal{B}^{exp}(K^+ \to \pi^+ \nu\bar{\nu}) = (1.73^{+1.15}_{-0.33}) \times 10^{-10}$

[Artamonov *et al.* PRL**101**(2008)]

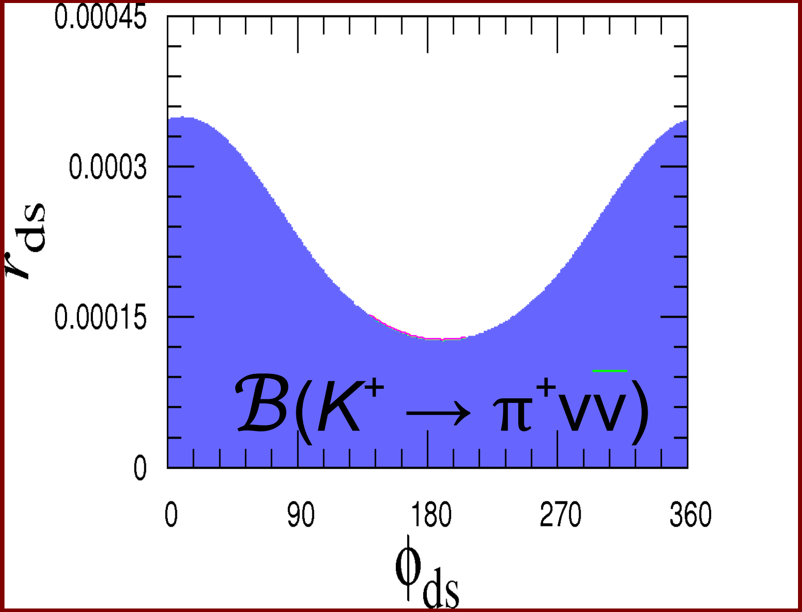
V_{ud} V_{us} V_{ub} $V_{ub'}$

V_{cd} V_{cs} V_{cb} $V_{cb'}$

V_{td} V_{ts} V_{tb} $V_{tb'}$

$V_{t'd}$ $V_{t's}$ $V_{t'b}$ $V_{t'b'}$

$V^*_{t'd} V_{t's} = r_{ds}\, e^{i\varphi_{ds}}$



UPPER BOUND

$$\kappa_+ |V_{us}|^{-5} \left|\lambda_c^{ds} |V_{us}|^4 P_c + \lambda_t^{ds} \eta_t X_0(x_t) + \lambda_{t'}^{ds} \eta_{t'} X_0(x_{t'})\right|^2 < 3.6 \times 10^{-10} \text{ (90\% CL)},$$

Constraint from *D-D* mixing

V_{ud} V_{us} V_{ub} $V_{ub'}$

V_{cd} V_{cs} V_{cb} $V_{cb'}$

V_{td} V V V

$V_{t'd}$

UPPER BOUND

$|V^*_{ub'} V_{cb'}| < 0.0021$

for $m_{b'}$ = 480 GEV

$$M_{12}^{D^0} \propto \lambda_s^2 + 2\lambda_s \lambda_b S(x_s, x_b) + \lambda_b^2 S_0(x_b) + LD$$
$$+ 2\lambda_s \lambda_{b'} S(x_s, x_{b'}) + 2\lambda_b \lambda_{b'} S(x_b, x_{b'}) + LD$$
$$+ \lambda_{b'}^2 S_0(x_{b'}),$$

$(\lambda_{b'} = V^*_{ub'} V_{cb'})$

Neglect all terms, except $\lambda^2_{b'} S_0(x_{b'})$,

equate this term with $x_D^{exp} = 9.1\times 10^{-3}$

accommodate *LD* by a factor of 3

[Golowich *et al*. PRD**76**(2007),
Bobrowski, Lenz *et al*. PRD**79**(2009)]

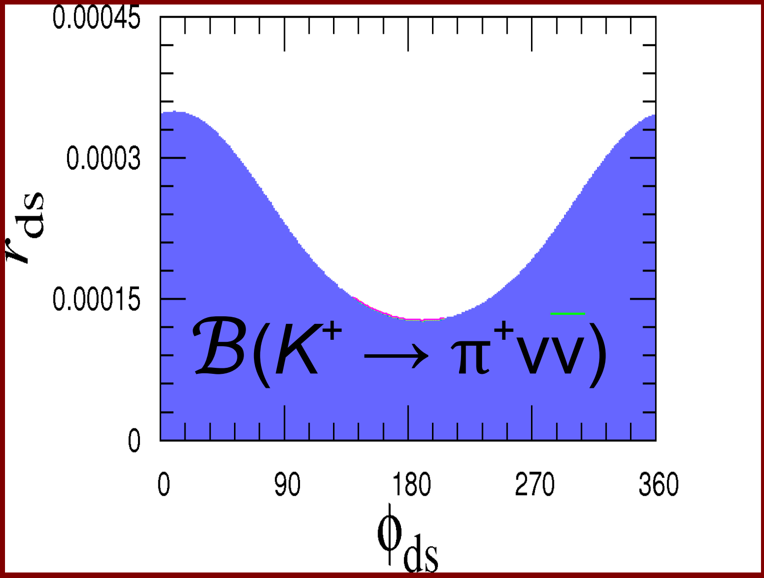
$$V_{ub'} = c_{13}c_{12}s_{14}e^{i\Phi_d} + c_{14}c_{13}s_{12}s_{24}e^{i\Phi_{sb}} + s_{13}s_{34}c_{14}c_{24}e^{-\phi_3}$$

V_{ud}	V_{us}	V_{ub}	$V_{ub'}$
V_{cd}	V_{cs}	V_{cb}	$V_{cb'}$
$V_{t'd}$	$V_{t's}$	$V_{t'b}$	$V_{t'b'}$

? $|V^*_{ub'}V_{cb'}| <$ 0.0021

for $m_{b'} = 480$ GEV

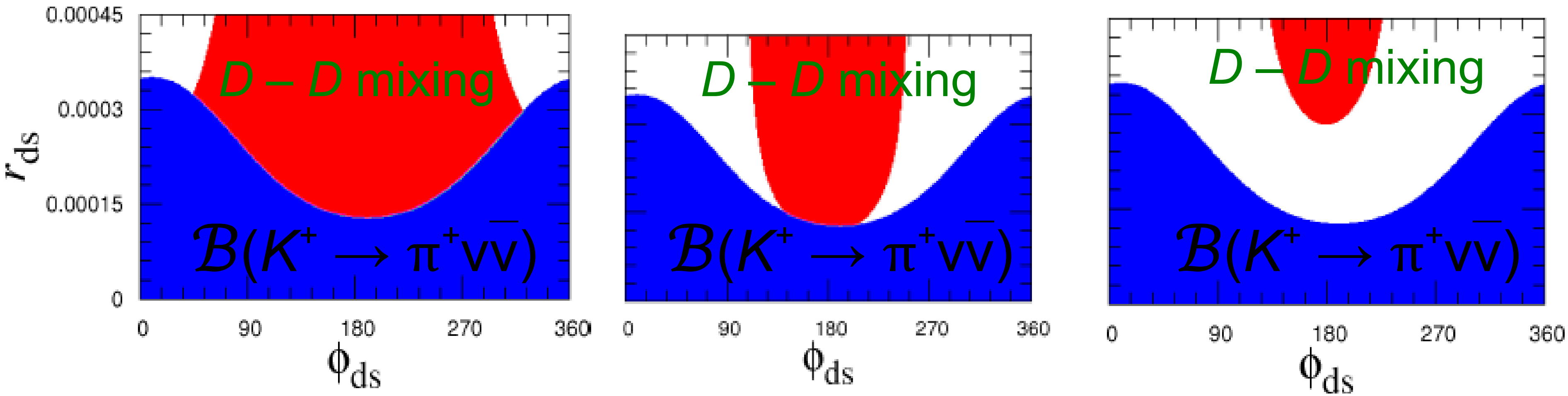
Fix $V^*_{t's}V_{t'b} = 0.006\ e^{i\ 75^\circ}$



$$V_{t'd} = -c_{34}\,c_{24}\,s_{14}\,e^{-i\,\Phi_d} \qquad V_{t's} = -c_{34}\,s_{24}\,e^{-i\,\Phi_{sb}} \qquad V_{t'b} = -s_{34}$$

$$\kappa_+|V_{us}|^{-5}\left|\lambda_c^{ds}|V_{us}|^4P_c + \lambda_t^{ds}\eta_tX_0(x_t)\ + \lambda_{t'}^{ds}\eta_{t'}X_0(x_{t'})\right|^2 < 3.6\times10^{-10}\ (90\%\ \mathrm{CL}),$$

Lower Bound on $|V_{t'b}|$



$|V_{t'b}| = 0.065$ $|V_{t'b}| = 0.060$ $|V_{t'b}| = 0.058$

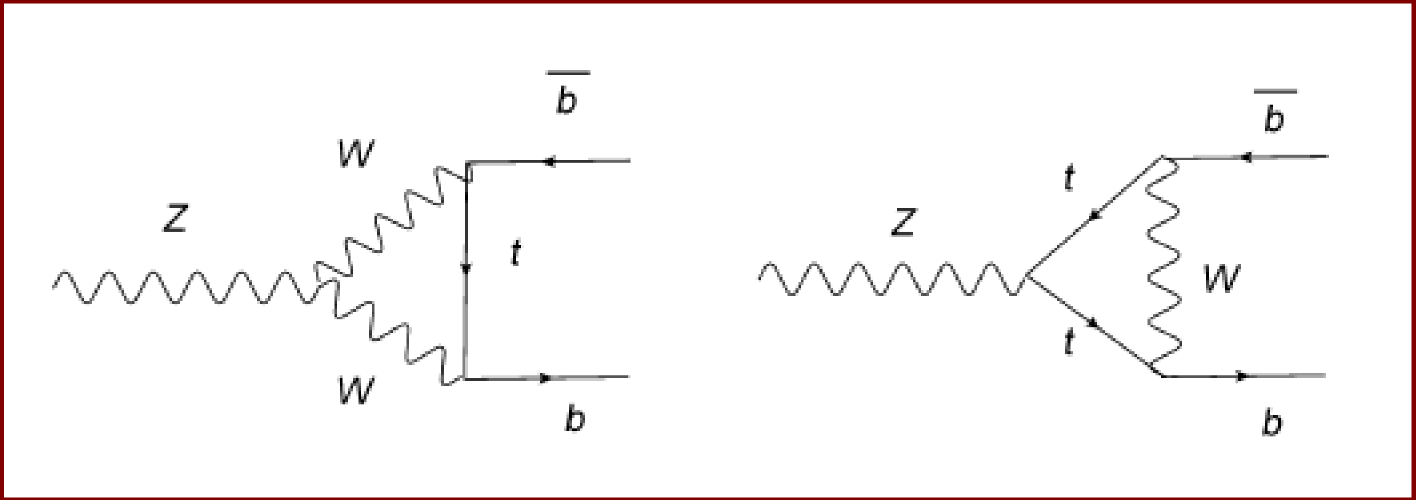
$|V_{t'b}| > 0.06$

Electroweak precision global fit

[Chanowitz, PRD**79**(2009)]

$$S_4 = \frac{N_C}{6\pi}\left(1 - \frac{1}{3}\ln\frac{x_1}{x_2}\right)$$

$$T_4 = \frac{1}{8\pi x_W(1-x_W)}\left\{3\left[F_{t'b'} + s_{34}^2(F_{t'b} + F_{tb'} - F_{tb} - F_{t'b'})\right] + F_{l_4\nu_4}\right\} + \frac{3}{8\pi x_W(1-x_W)}\left[|V_{t's}|^2 F_{t's} + |V_{cb'}|^2 F_{cb'}\right].$$



Electroweak precision global fit

[Maksymyk *et al.* PRD**50**(1994)]

$$M_W^2 = \left(M_W^{\rm SM}\right)^2 \left[1 - \frac{\alpha \Delta S}{2(c_w^2 - s_w^2)} + \frac{c_w^2 \alpha \Delta T}{(c_w^2 - s_w^2)}\right],$$

$$\Gamma_W = \Gamma_W^{\rm SM} \left[1 - \frac{\alpha \Delta S}{2(c_w^2 - s_w^2)} + \frac{c_w^2 \alpha \Delta T}{(c_w^2 - s_w^2)}\right],$$

$$\sin^2\theta_{\rm eff}^{\rm lept} = \sin^2\theta_{\rm eff}^{\rm lept\ SM} \left[1 + \frac{\alpha \Delta S}{4 s_w^2 (c_w^2 - s_w^2)} - \frac{c_w^2 \alpha \Delta T}{(c_w^2 - s_w^2)}\right],$$

$$\Gamma(Z \to \nu\bar{\nu}) = \Gamma^{\rm SM}(Z \to \nu\bar{\nu}) \left[1 + \alpha \Delta T\right].$$

Electroweak precision global fit

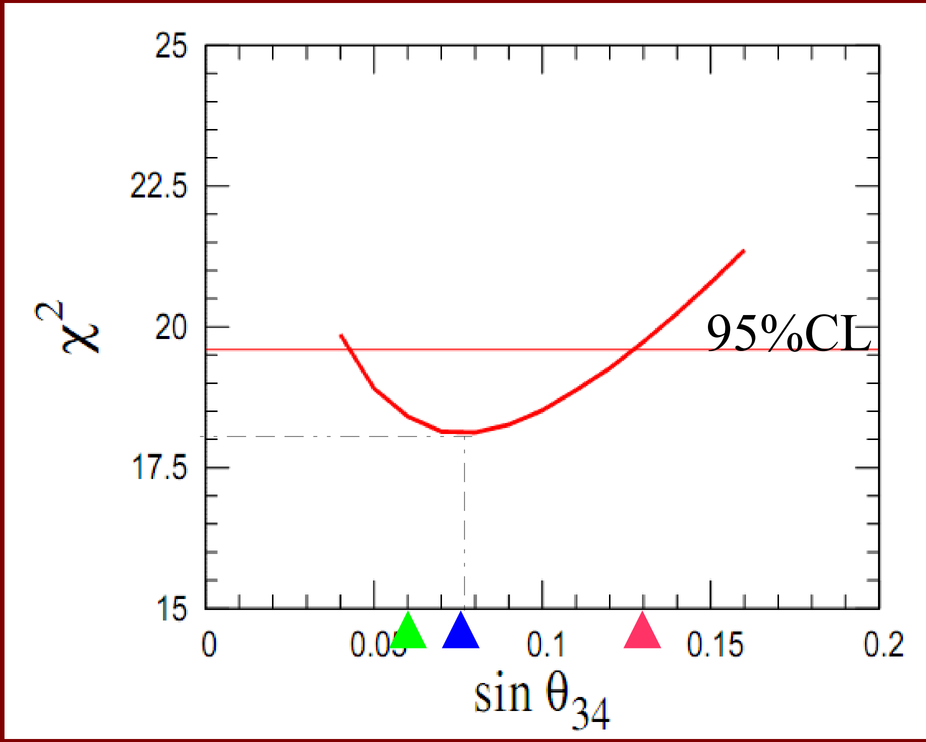
	Measurement with Total error	SM4 Chanowitz' Fit	SM4 Chanowitz's Fit (reproduce)
$\Delta\alpha^{(5)}_{\rm had}(m_Z^2)$	0.02758±0.00035	0.02732	0.02732
m_Z[GeV]	91.1875±0.0021	—-	91.1875
Γ_Z[GeV]	2.4952±0.0023	2.4988	2.4983
$\sigma^0_{\rm had}$[nb]	41.540±0.037	41.487	41.489
R^0_ℓ	20.767±0.025	20.726	20.716
$A^{0,\ell}_{\rm FB}$	0.01714±0.00095	0.01592	0.0160
$\mathcal{A}_\ell(P_\tau)$	0.1465±0.0032	0.1457	0.1459
$\mathcal{A}_\ell$(SLD)	0.1513±0.0021	0.1457	0.1459
R^0_b	0.21629±0.00066	0.21547	0.21549
R^0_c	0.1721±0.0030	0.1723	0.1723
$A^{0,b}_{\rm FB}$	0.0992±0.0016	0.1021	0.1022
$A^{0,c}_{\rm FB}$	0.0707±0.0035	0.0729	0.0730
$\mathcal{A}_b$	0.923±0.020	0.934	0.934
$\mathcal{A}_c$	0.670±0.027	0.667	0.667
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324±0.0012	0.23169	0.2317
m_t[GeV]	172.6±1.4	172.3	172.3
m_W[GeV]	80.398±0.025	80.413	80.410
$\alpha_s(m_Z)$		0.1186	0.1186
M_H		810	810
		$s_{34} = 0.15$	$s_{34} = 0.15$
		$\Delta T = 0.48$	$\Delta T = 0.49$
		$\Delta S = 0.15$	$\Delta S = 0.15$
		$\chi^2 = 20.9$	$\chi^2 = 21.4$

Use m_H, m_t, $\Delta\alpha_5$, α_S, m_Z to fit 17 observables

12 degrees of freedom to each four-family fit.

Electroweak precision global fit
Using ZFITTER6.4.2

- ▲ Upper bound from $Z \to bb$
- ▲ Best global fit
- ▲ Lower bound from *D-D* mixing



Fix $V^*_{t's} V_{t'b} = 0.006\, e^{i\,75^\circ}$

$V_{t'b} = -s_{34}$

V_{ud}	V_{us}	V_{ub}	$V_{ub'}$
V_{cd}	V_{cs}	V_{cb}	$V_{cb'}$
$V_{t\,d}$	$V_{t\,s}$	$V_{t\,b}$	$V_{tb'}$
$V_{t'd}$	$-0.06e^{-i75^{o}}$	-0.10	$V_{t'b'}$

?

$$V^*_{t's}\, V_{t'b} = 0.006\, e^{i\,75^{\circ}}$$

From $\mathcal{B}$ $(K_L \to \pi^0 \nu\bar{\nu})$ to $\sin 2\Phi_D$

Current Bound

$\mathcal{B}^{exp}(K_L \to \pi^0 \nu\nu) < 6.7 \times 10^{-8}$

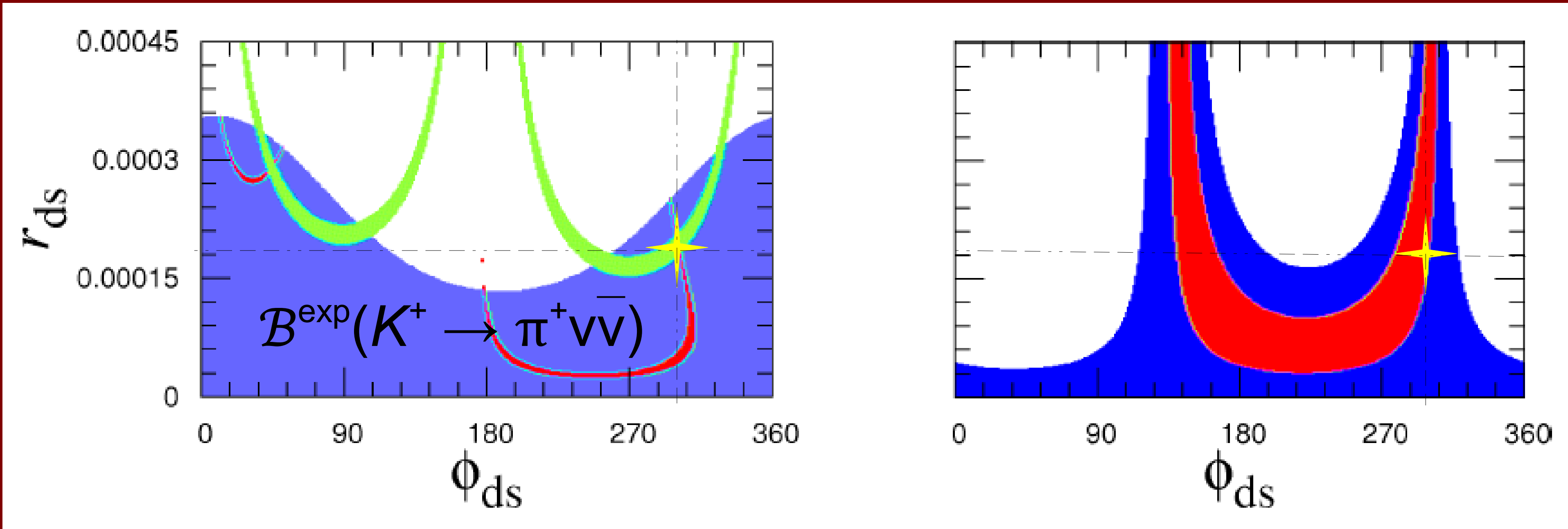
[E391a Collab. PRL**100** (2008)]

KOTO(E14) will have a three-year run beginning in 2011.

Suppose $\mathcal{B}(K_L \to \pi^0 \nu\nu) \sim 1.00 \times 10^{-9}$

There will be $O(100)$ events observed.

$V^*_{t'd} V_{t's} \equiv r_{ds}\ e^{i\varphi_{ds}}$



$(\varepsilon_K)^{exp} = (2.229 \pm 0.012) \times 10^{-3}$

[PDG PLB(2008)]

$(\sin 2\Phi_{Bd})^{exp} = 0.672 \pm 0.023$

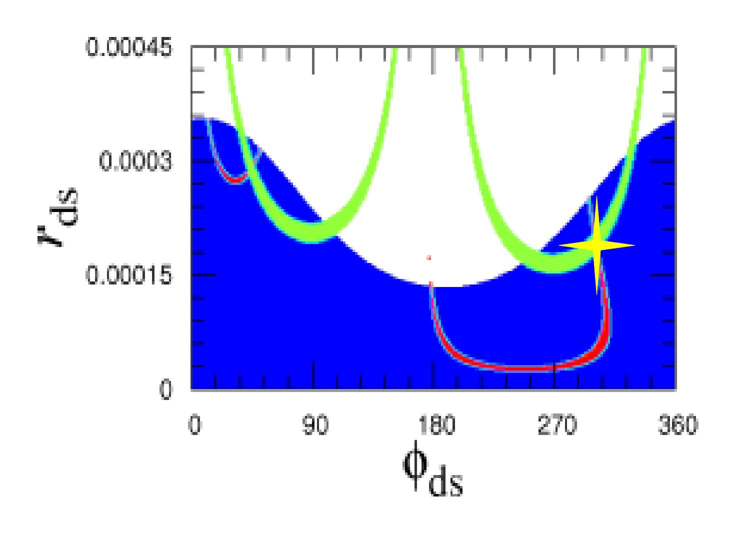
[HFAG arXiv:0704.3575(2008)]

$\mathcal{B}(K_L \to \pi^0 \nu\nu) \sim (1.00 \pm 0.14) \times 10^{-9}$ $(\sin 2\Phi_{Bd})^{exp} = 0.672 \pm 0.008$

From $\mathcal{B}(K_L \rightarrow \pi^0 \nu\bar{\nu})$ to $\sin 2\Phi_D$

V_{ud}	V_{us}	V_{ub}	$V_{ub'}$
V_{cd}	V_{cs}	V_{cb}	$V_{cb'}$
V_{td}	V_{ts}	V_{tb}	$V_{tb'}$
$V_{t'd}$	$-0.06e^{-i75^o}$	-0.10	$V_{t'b'}$

$$V^*_{t'd}V_{t's} \equiv r_{ds}\, e^{i\varphi_{ds}}$$



$$V_{t'd} = -\ 0.003167\ e^{-i18^o}$$

From $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ to $\sin 2\Phi_D$

$(\lambda_{b'} = V^*_{ub'} V_{cb'})$

$$M_{12}^{D^0} = \frac{G_F^2 M_W^2 m_D}{12\pi^2} f_D^2 B_D \eta(m_c, M_W) \times (\lambda_{b'}^2 + R_{LD}) S_0(x_{b'}),$$

Take R_{LD} real for illustration and $m_{b'} = 460^{+30}_{-30}$ GEV

real R_{LD} scenario $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) = 10^{-9}$ $\varepsilon_K = 2.229 \times 10^{-3}$	$V_{t'd} = -0.003167\, e^{-i18^\circ}$
$x_D = 9.1 \times 10^{-3}$ $m_{t'} = 500$ GeV $m_{b'} = 460^{+30}_{-30}$ GeV $V_{t'b} = -0.10$ $V_{t's} = -0.06\, e^{-i75^\circ}$	$\lambda_{b'}^2 = (8.017 + 2.142\, i) \times 10^{-7}$ $\lvert\lambda_{b'}^2 + R_{LD}\rvert = (16.15^{-1.59}_{+1.86}) \times 10^{-7}$ $\sin 2\Phi_D = 0.133^{+0.014}_{-0.014}$ $\cos 2\Phi_D = \pm(0.991^{-0.002}_{+0.002})$

Conclusion

For $f_{B_s}\sqrt{B_{B_s}}$ = 266(18) MEV, $m_{t'}$=500 GEV

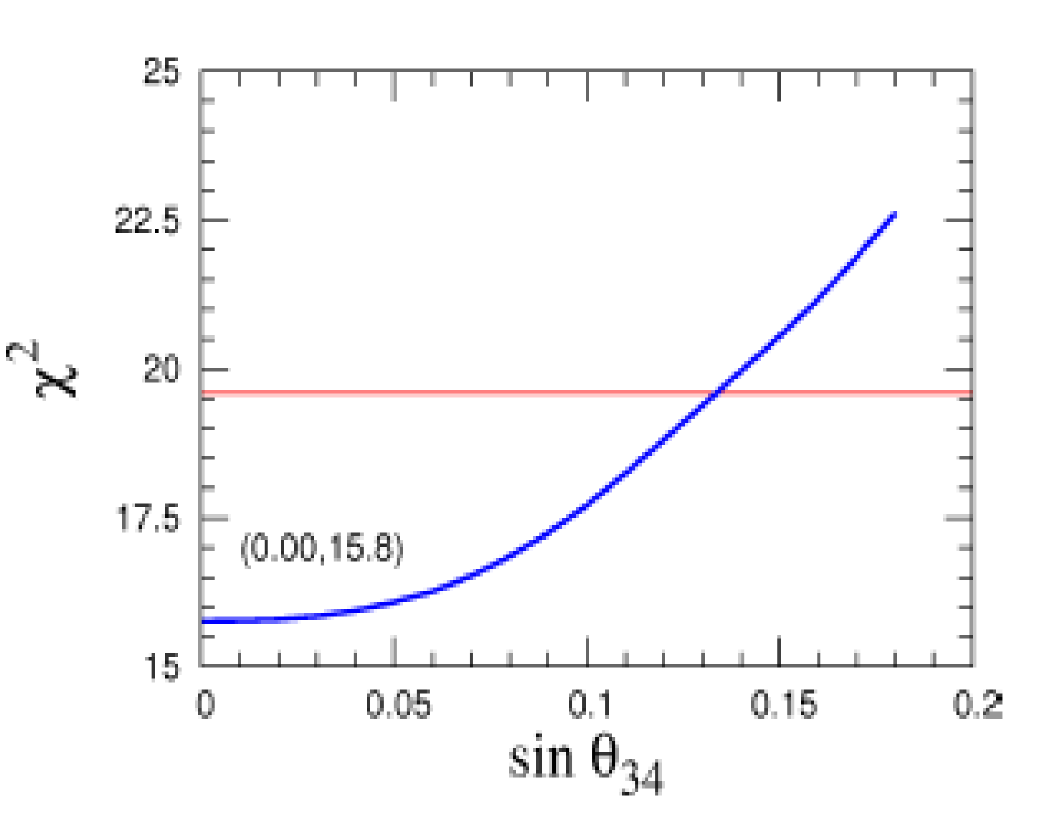
I. For $V^*_{t's}V_{t'b}=0.006\, e^{i\,75^\circ}$, $|V_{t'b}|<0.13$ on $Z \to bb$, $|V_{t'b}|>0.06$ on *D-D* mixing , best global fit at $|V_{t'b}|=0.08$

II. $\sin 2\Phi_{B_s} \sim -0.33 \in [0.00, -0.40]$,

Larger $m_{t'}$ implies larger $\sin 2\Phi_{B_s}$

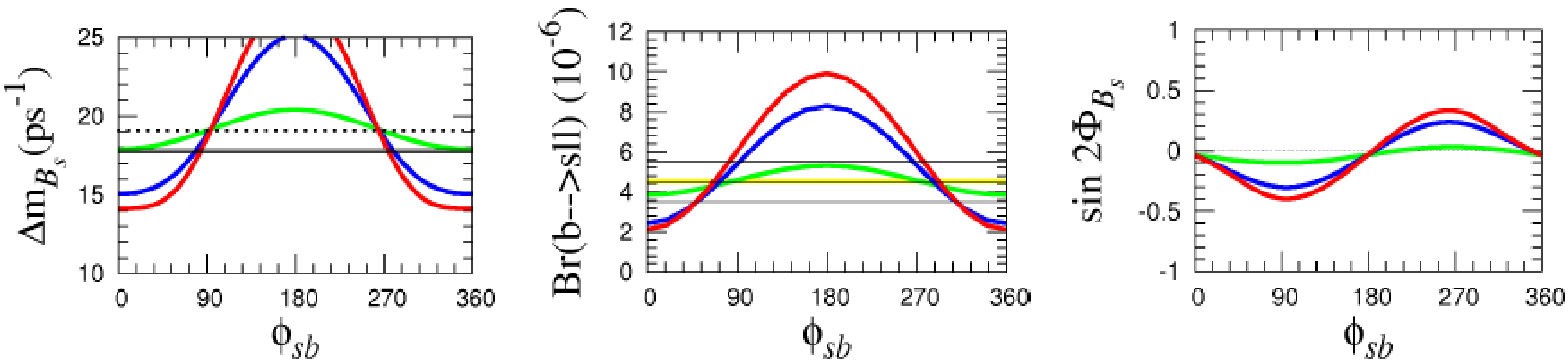
III. Future measurement $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ and $\sin 2\Phi_{B_d}$ can determine $V_{t'd}$.

Back Up



25
22.5
20
17.5
15
χ^2
(0.00,15.8)
0
0.05
0.1
0.15
0.2
$\sin\theta_{34}$

$V^*_{t's} V_{t'b} \equiv r_{sb}\, e^{i\varphi_{sb}}$



$r_{sb} = 0.006,$

$\varphi_{sb} = 75^\circ,$

$\sin 2\Phi_{B_s} = -0.33$

(central-value scenario)

facility in Frascati and $K \to \pi \nu \bar{\nu}$ experiments like NA62 and KOTO.

B^0

$I(J^P) = \frac{1}{2}(0^-)$

I, J, P need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^0} = 5279.50 \pm 0.30$ MeV

$m_{B^0} - m_{B^\pm} = 0.33 \pm 0.06$ MeV

Mean life $\tau_{B^0} = (1.525 \pm 0.009) \times 10^{-12}$ s

$c\tau = 457.2\ \mu$m

$\tau_{B^+}/\tau_{B^0} = 1.071 \pm 0.009$ (direct measurements)

Mode	BABAR	Belle
$J/\psi K^0_S$	$0.657 \pm 0.036 \pm 0.012$	0.643 ± 0.038
$J/\psi K^0_L$	$0.694 \pm 0.061 \pm 0.031$	0.641 ± 0.057

C. Amsler et al. (Particle Data Group), Physics Letters B667, 1 (2008)

$S_{J/\psi(nS)K^0}\ (B^0 \to J/\psi(nS) K^0) = 0.658 \pm 0.024$

From x_D to $\mathcal{B}\,(K_L \to \pi^0 \nu\bar{\nu})$

Short-distance dominance limit (R_{LD}=0)

and $m_{b'}=460^{+30}_{-30}$ GEV

$$x_D = 9.1 \times 10^{-3}$$
$$m_{t'} = 500 \text{ GeV}$$
$$m_{b'} = 460^{+30}_{-30} \text{ GeV}$$

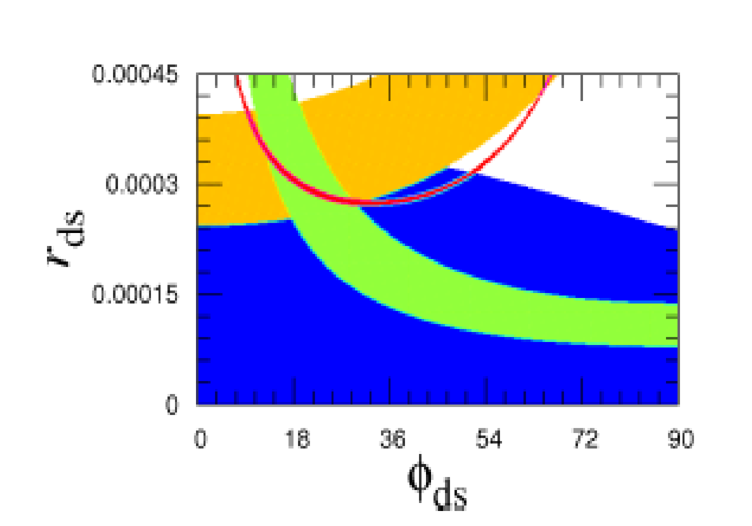
$$M_{12}^{D^0} = \frac{G_F^2 M_W^2 m_D}{12\pi^2} f_D^2 B_D \eta(m_c, M_W) \times (\lambda_{b'}^2 + R_{LD}) S_0(x_{b'}),$$

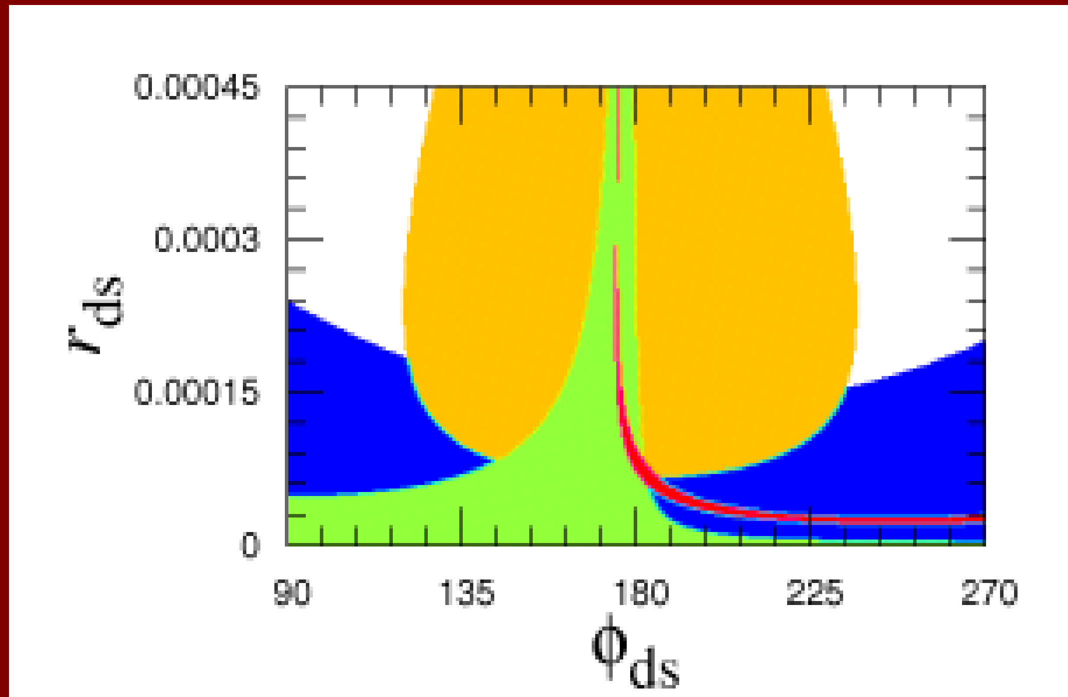
$\mathcal{B}^{exp}(K^+ \to \pi^+ \nu\bar{\nu})$

x_D^{exp}

ε_K^{exp}

$\mathcal{B}\,(K_L \to \pi^0 \nu\bar{\nu}) = (0.4\sim1.0) \times 10^{-9}$





In the long-distance dominated case of $D - \bar{D}$ mixing, *e.g.* $|R_{LD}| > 10|\lambda_{b'}^2|$ for$(m_{t'}, m_{b'}) = (500, 460^{+30}_{-30})$ GeV, we have $|V^*_{ub'}V_{cb'}| < 4 \times 10^{-4}$. Then we can see that $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) < 2 \times 10^{-11}$, as shown in Fig. 7(R).

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ \left| \frac{\lambda_c^{ds}}{|V_{us}|} P_c + \frac{\lambda_t^{ds}}{|V_{us}|^5} \eta_t X_0(x_t) + \frac{\lambda_{t'}^{ds}}{|V_{us}|^5} \eta_{t'} X_0(x_{t'}) \right|^2 ,$$

$$\kappa_+ = (4.84 \pm 0.06) \times 10^{-11} \times (0.224/|V_{us}|)^8$$

It is interesting to see what are the implications for the CPV decay $K_L \to \pi^0 \nu\bar{\nu}$. The formula for $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ is analogous to Eq. (11), except [15] the change of κ_+ to $\kappa_L = (2.12 \pm 0.03) \times 10^{-10} \times (|V_{us}|/0.224)^8$, and taking only the imaginary part for the various CKM products.

$$M_{12} = M_{12}^{\mathrm{SM}} e^{i\phi_M^{\mathrm{SM}}} + M_{12}^{\mathrm{NP}} e^{i\phi_M^{\mathrm{NP}}}$$

$$\sin \phi_{12}^{D} = \left| \frac{M_{12}^{\mathrm{NP}}}{M_{12}} \right| \sin(\phi_M^{\mathrm{NP}} - \phi_M^{\mathrm{SM}})$$

$$\frac{\mathrm{Im}(M_{12}^{\mathrm{NP}})}{|M_{12}|} \in [-0.06, +0.10] \quad (1\sigma)$$

$$\begin{aligned} \frac{\mathrm{Im}(M_{12}^{\mathrm{NP}})}{|M_{12}|} &\in [-0.11, +0.08] \quad (1\sigma)\,, \\ &\in [-0.30, +0.30] \quad (95\%\,\mathrm{CL}) \end{aligned}$$

$$\frac{\mathrm{Im}(M_{12}^{\mathrm{NP}})}{|M_{12}|} \in [-0.01, +0.15]$$

$$|\mathrm{Im}(M_{12}^{\mathrm{NP}})/M_{12}| \le 0.30 \text{ at } 95\% \text{ CL.}$$