Constraints on CKM matrix elements within a fourth generation

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Work within CKMfitter group

Acknowledgement: Discussion with Bobrowski, Lenz, Riedl und Rohrwild

Implementation of 4^{th} generation in CKMfitter

- First studies (H. Lacker) presented at 1^{st} workshop at CERN (2008) using a simplified analysis technique by sampling the CKM parameter space
- Spring 2009: Implementation in CKMfitter started (Andreas Menzel, HU Berlin)
- Exact unitary parametrisations:

  PMNS: 1. Botella & Chau, PLB 168 (1986) 97

  CKM: 1. Botella & Chau 2. Wolfenstein-inspired (Jerome Charles)

- Inputs implemented/used:

  1) Leptonic & semileptonic treelevel decays (allowing for PMNS matrix dependence)

  2) W-decays (allowing for PMNS matrix dependence)

  3) R and $|V_{tb}|$ (allowing for deviation in G_F for sizeable 4^{th} gen. off-diagonal PMNS)

  4) $\epsilon_K, \Delta m_d, \Delta m_s$ (with some simplifications in perturbative QCD corrections)

  5) γ (as discussed later on)

  6) S and T allowing for CKM element dependence (final tests, not shown here)

Tree level constraints with CKMfitter

Directly measured matrix elements:

$$\left|V^{4\times4}_{CKM}\right| = \begin{pmatrix} 0.97418 & 0.2255 & 0.0039 & <0.035 \\ 0.22 & >0.83 & 0.041 & <0.52 \\ <0.052 & <0.28 & >0.78 & <0.62 \\ <0.11 & <0.52 & <0.63 & >0.73 \end{pmatrix}$$

Limits @ ~2σ

Limiting: * $|V_{tb}|$ from single top not well constrained yet

* $|V_{cs}|$ from semileptonic D-decays: still large theoretical error (FF)

$W^+ \to l^+ \nu_l,\ u \bar{d}',\ c \bar{s}'$

$$\frac{\Gamma(W\to l\,\nu)}{\Gamma(W\to All)} \approx \frac{1}{3+3\sum\limits_{i=u,c}\sum\limits_{j=d,s,b}\left|V_{ij}\right|^2(1+\alpha_s(M_W)/\pi)}$$

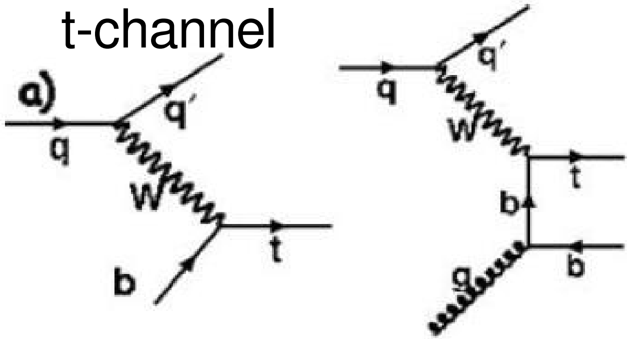
Directly measured matrix elements including W-decays:

$$\left|V^{4\times4}_{CKM}\right| = \begin{pmatrix} 0.97418 & 0.2253 & 0.0043 & <0.046 \\ 0.224 & 0.973 & 0.041 & <0.20 \\ <0.045 & <0.125 & >0.78 & <0.63 \\ <0.075 & <0.21 & <0.63 & >0.78 \end{pmatrix}$$

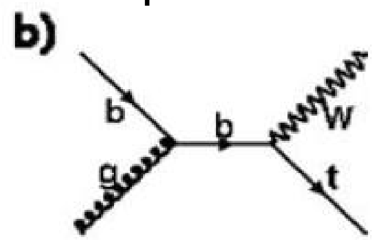
Limits @ ~2σ

Single Top

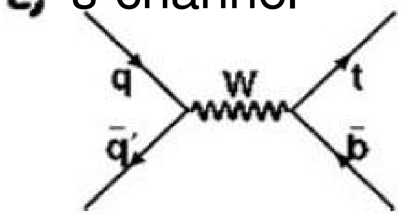
t-channel



Wt production



c) s-channel

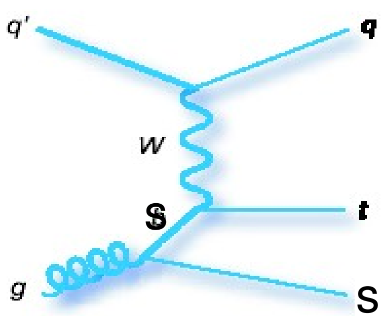


If $\sigma_{meas} \neq \sigma_{theo}$:

$|V_{tb}|<1$ (4^{th} gen.) or other NP

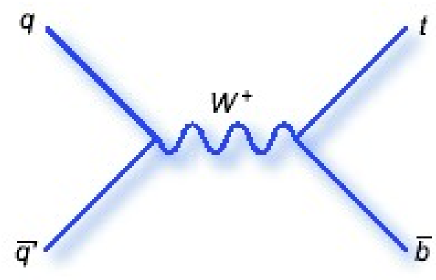
$\sigma(N_{gen}=4) > \sigma(N_{gen}=3)$ possible

even if $|V_{tb}|<1$ if $|V_{ts}|$ is sizeable !



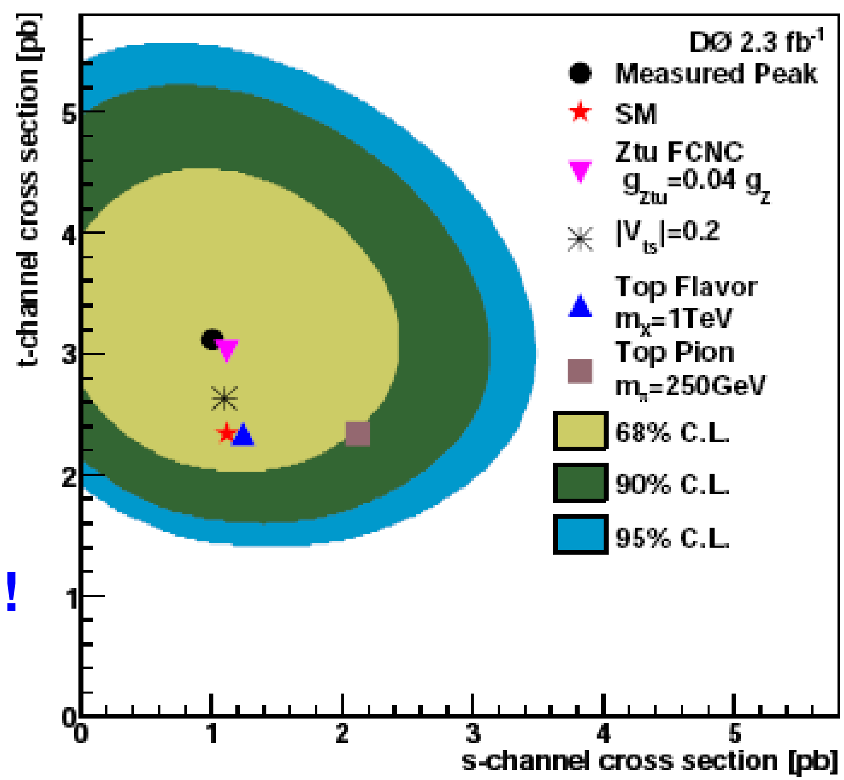
t-channel enhanced

PDF(s) >> PDF(b)



s-channel suppressed:

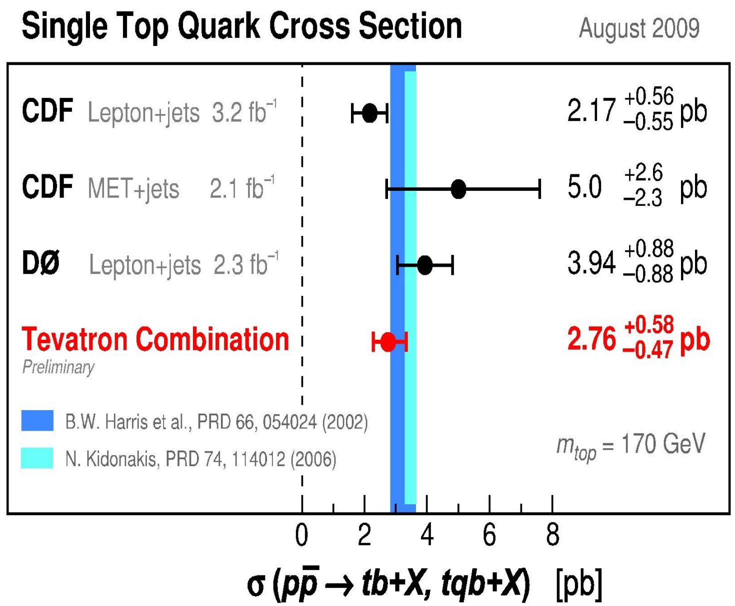
$|V_{tb}| <1$

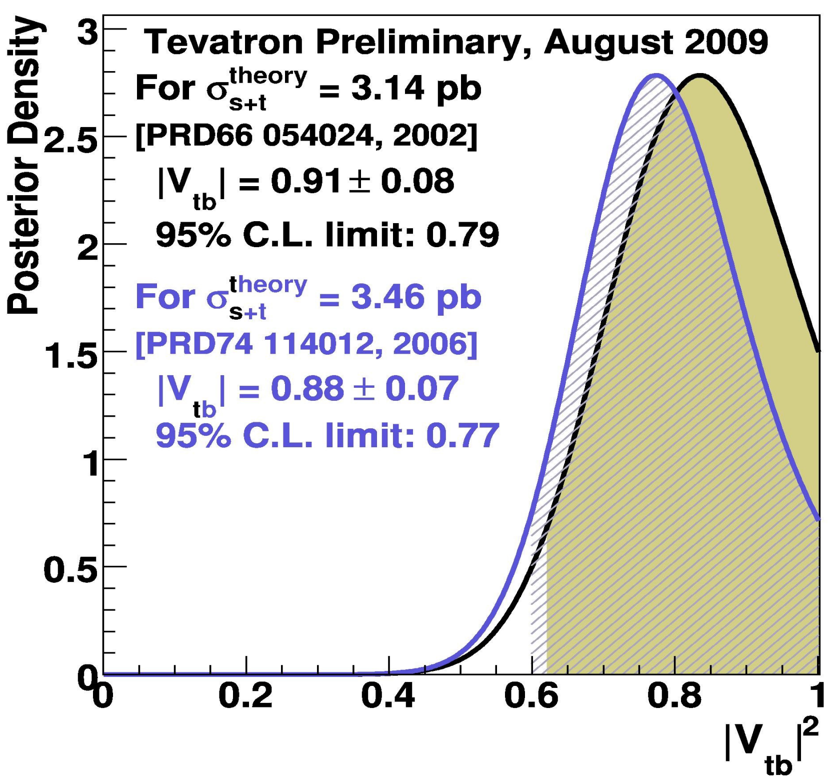


=> Combined $|V_{td}|$&$|V_{ts}|$&$|V_{tb}|$ extraction needed!

Simplified proposal: Alwall et al. , EPJ C49, 791 (2007)

Single Top





- **Cross section measurement, respectively, extraction of $|V_{tb}|$ assumes t→Wb to be dominant (--> b-tagging)**

- **Relevant BR:** $R=\dfrac{\Gamma(t\to W+b)}{\Gamma(t\to W+q)}=\dfrac{|V_{tb}|^2}{|V_{td}|^2+|V_{ts}|^2+|V_{tb}|^2}$

  determined in ttbar events by measuring 0, 1, ≥2 tagged b-jet rates

- **Best measurement by D0:** $R=0.97^{+0.09}_{+0.08}$ **(PRL 100, 192003 (2008))**

- **One extracts rather** $|V_{tb}|\dfrac{|V_{tb}|}{\sqrt{|V_{td}|^2+|V_{ts}|^2+|V_{tb}|^2}}$

  than $|V_{tb}|$ **!**

Reminder: the G_F problem

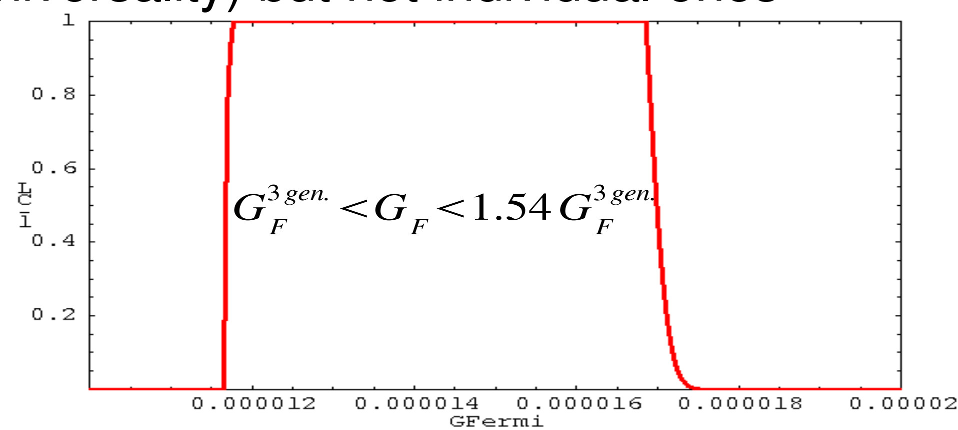
Within 4th generation scenario: G_F not any more well determined by μ-decay

$$\Gamma(\mu^- \to e^- \bar{\nu}_e \nu_\mu) \propto G_F^2 \sum_{i=1,2,3} |U_{\mu i}|^2 \sum_{k=1,2,3} |U_{ek}|^2$$

$$\Gamma(\tau^- \to l^- \bar{\nu}_l \nu_\tau) \propto G_F^2 \sum_{i=1,2,3} |U_{\tau i}|^2 \sum_{k=1,2,3} |U_{lk}|^2 \qquad l = e/\mu$$

=> Ratios of PMNS elements well constrained (universality) but not individual ones

$$|U^{4\times4}| = \begin{pmatrix} * & * & * & <0.57 \\ * & * & * & <0.57 \\ * & * & * & <0.57 \\ <1.00 & <0.99 & <0.99 & >0.17 \end{pmatrix}$$



=> CKM elements not well constrained any more: $\Gamma(\beta\text{-}decay) \propto G_F^2 \sum_{k=1,2,3} |U_{ek}|^2 \; |V_{ud}|^2$

$$|V_{CKM}^{4\times4}| = \begin{pmatrix} \begin{matrix}<0.977\\>0.80\end{matrix} & \begin{matrix}<0.226\\>0.183\end{matrix} & \begin{matrix}<0.0046\\>0.0022\end{matrix} & <0.57 \\ \begin{matrix}<0.249\\>0.174\end{matrix} & \begin{matrix}<0.977\\>0.796\end{matrix} & \begin{matrix}<0.0419\\>0.0325\end{matrix} & <0.57 \\ <0.47 & <0.48 & >0.54 & <0.65 \\ <0.47 & <0.49 & <0.82 & >0.31 \end{pmatrix}$$

only ratios like $K_{\mu 2}/\pi_{\mu 2}$

=> Combined CKM, PMNS & e.w. precision fit needed (M_W & $\Gamma(Z \to ll)$ depend on G_F @LO)

Loop Observables

- B_d and B_s oscillation frequencies:

$$\Delta m_d = \frac{G_F^2 m_W^2 f_{B_d}^2 B_d m_{B_d}}{6\pi^2} \left| \lambda_t^{bd\,2} \eta_t^B S_0(x_t) + \lambda_{t'}^{bd\,2} \eta_{t'}^B S_0(x_{t'}) + 2\lambda_t^{bd} \lambda_{t'}^{bd} \eta_{tt'}^B S_0(x_t, x_{t'}) \right|$$

$$\Delta m_s = \frac{G_F^2 m_W^2 f_{B_s}^2 B_s m_{B_s}}{6\pi^2} \left| \lambda_t^{bs2} \eta_t^B S_0(x_t) + \lambda_{t'}^{bs2} \eta_{t'}^B S_0(x_{t'}) + 2\lambda_t^{bs} \lambda_{t'}^{bs} \eta_{tt'}^B S_0(x_t, x_{t'}) \right|$$

- CP violation in neutral kaon system:

$$\epsilon_K = \kappa_\epsilon \frac{G_F^2 m_W^2 f_K^2 B_K m_K}{12\sqrt{2}\pi^2 \Delta m_K} \Im [\lambda_c^{sd*2} \eta_c^K S_0(x_c) + \lambda_t^{sd*2} \eta_t^K S_0(x_t) + \lambda_{t'}^{sd*2} \eta_{t'}^K S_0(x_{t'}) +$$

$$2\lambda_c^{sd*} \lambda_t^{sd*} \eta_{ct}^K S_0(x_t, x_{t'}) + 2\lambda_c^{sd} \lambda_{t'}^{sd*} \eta_{ct'}^K S_0(x_c, x_{t'}) + 2\lambda_t^{sd*} \lambda_{t'}^{sd*} \eta_{tt'}^K S_0(x_t, x_{t'})]$$

$$\lambda_q^{bd} = V_{qd} V_{qb}^*, \lambda_q^{bs} = V_{qs} V_{qb}^*, \lambda_q^{sd} = V_{qs} V_{qd}^*,$$

Loop Observables

Directly measured matrix elements including W-decays:

$$\left|V_{CKM}^{4\times4}\right| = \begin{pmatrix} 0.97418 & 0.2253 & 0.0043 & <0.046 \\ 0.224 & 0.973 & 0.041 & <0.20 \\ <0.045 & <0.125 & >0.78 & <0.63 \\ <0.075 & <0.21 & <0.63 & >0.78 \end{pmatrix}$$

Limits @ ~2σ

Directly measured matrix elements & $\epsilon_K, \Delta m_d, \Delta m_s$ assuming $m_{t'} > 300$ GeV:

$$\left|V_{CKM}^{4\times4}\right| = \begin{pmatrix} 0.97418 & 0.2253 & 0.0043 & <0.046 \\ 0.224 & 0.973 & 0.041 & <0.20 \\ <0.038 & {<0.123 \atop >0.021} & >0.78 & <0.63 \\ <0.074 & <0.20 & <0.63 & >0.78 \end{pmatrix}$$

Limits @ ~2σ

- Small effect: Quite some freedom in varying $V_{td}V_{tb}^*$ and $(m_{t'}/m_t)V_{t'd}V_{t'b}^*$

  $V_{ts}V_{tb}^*$ $(m_{t'}/m_t)V_{t's}V_{t'b}^*$

  $V_{td}V_{ts}^*$ $(m_{t'}/m_t)V_{t'd}V_{t's}^*$

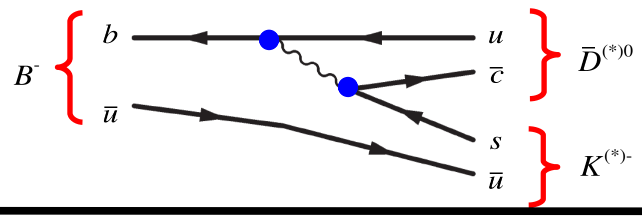
  given the large theory errors

  ---> UT angle measurements needed

UT angles: "γ"

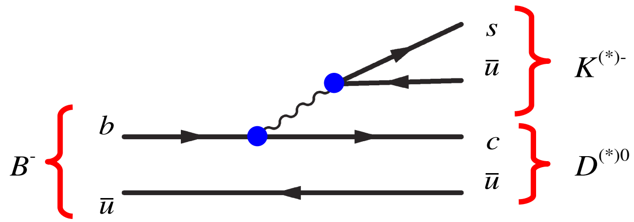
***CP* violation in decay in:** $b \rightarrow c\,\bar{u}\,s\,,\,u\,\bar{c}\,s$

$r_B =$ (upper diagram) / (lower diagram)



$\propto V_{ub} V_{cs}^{*}$

$\approx 0.1 - 0.3$



$\propto V_{cb} V_{us}^{*}$

CKM phase difference: γ	strong phase difference: δ

$r_B\,,\delta$: for each final state $D^{(*)}K^{(*)}$

«GLW» ***D^0*-decay into *CP*-eigenstates**

Gronau-London; Gronau-Wyler (1991)

«ADS» $\bar{D}^0 \rightarrow K^+\pi$ **(fav.) &** $D^0 \rightarrow K^+\pi$ **(disfav.)**

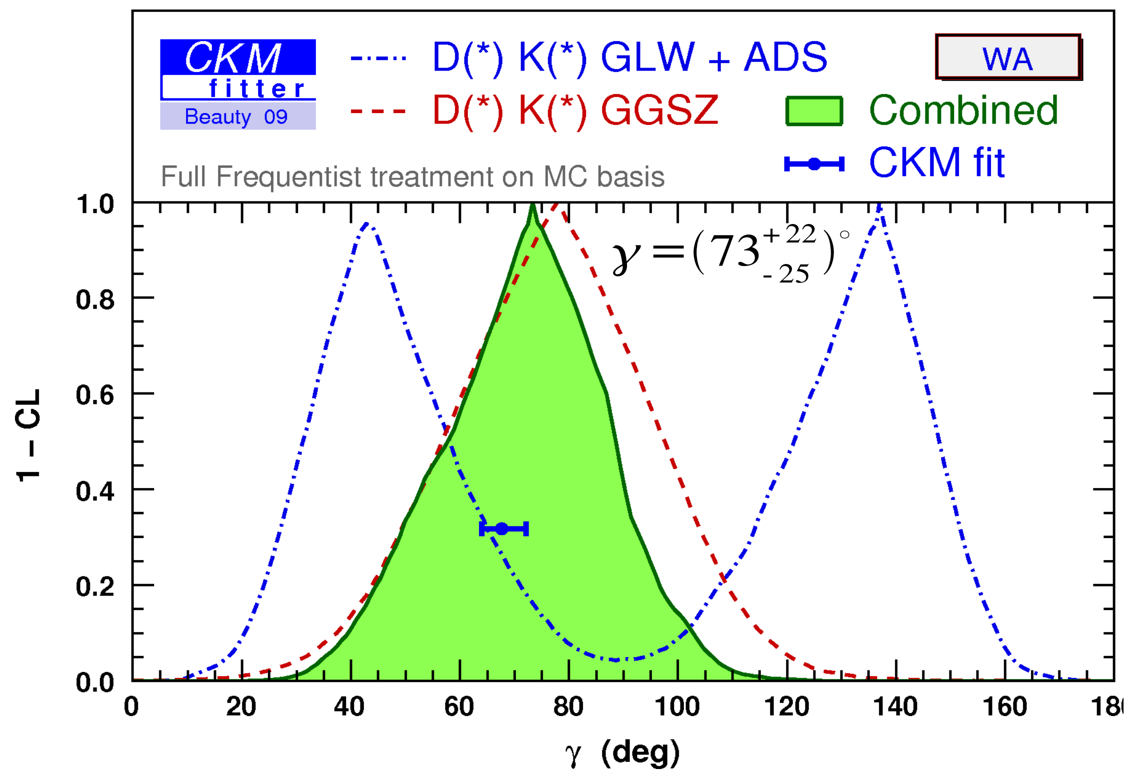
Atwood-Dunietz-Soni (1997)

«GGSZ» $D^0 \rightarrow K_S\,\pi^+\pi^-$ **(Dalitz plot)**

Bondar (Belle, 2002)

Giri-Grossman-Soffer-Zupan (2003)

=> Syst.: Dalitz model; C̸P in D-decays



UT angles: "γ"

- Problem within 4th generation scenario:

$\gamma = Arg\left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$ but the following CKM element combinations appear in

weak decay or
also K-$\bar{K}$ mixing

1) GLW

a) $D^0 \to K^+ K^-$ $\quad - Arg\left(\frac{V_{us} V_{cb}^*}{V_{cs} V_{ub}^*} \frac{V_{cs} V_{us}^*}{V_{us} V_{cs}^*} \right) = \gamma - \pi - Arg\left(\frac{V_{ud} V_{us}^*}{V_{cd} V_{cs}^*} \right)$

b) $D^0 \to \pi^+ \pi^-$ $\quad - Arg\left(\frac{V_{us} V_{cb}^*}{V_{cs} V_{ub}^*} \frac{V_{cd} V_{ud}^*}{V_{ud} V_{cd}^*} \right) = \gamma - \pi + Arg\left(\frac{V_{ud} V_{us}^*}{V_{cd} V_{cs}^*} \right)$

c) $D^0 \to K_S \pi^0$ etc. $\quad - Arg\left(\frac{V_{us} V_{cb}^*}{V_{cs} V_{ub}^*} \frac{V_{cs} V_{us}^*}{V_{us} V_{cs}^*} \right) = \gamma - \pi - Arg\left(\frac{V_{ud} V_{us}^*}{V_{cd} V_{cs}^*} \right)$

3SM: π to very good approximation

4 SM: ? (next slide)

2) ADS: $D^0 \to K^+ \pi^-$ $\quad - Arg\left(\frac{V_{us} V_{cb}^*}{V_{cd} V_{us}^*} \frac{V_{cd} V_{us}^*}{V_{ud} V_{cs}^*} \right) = \gamma - \pi$

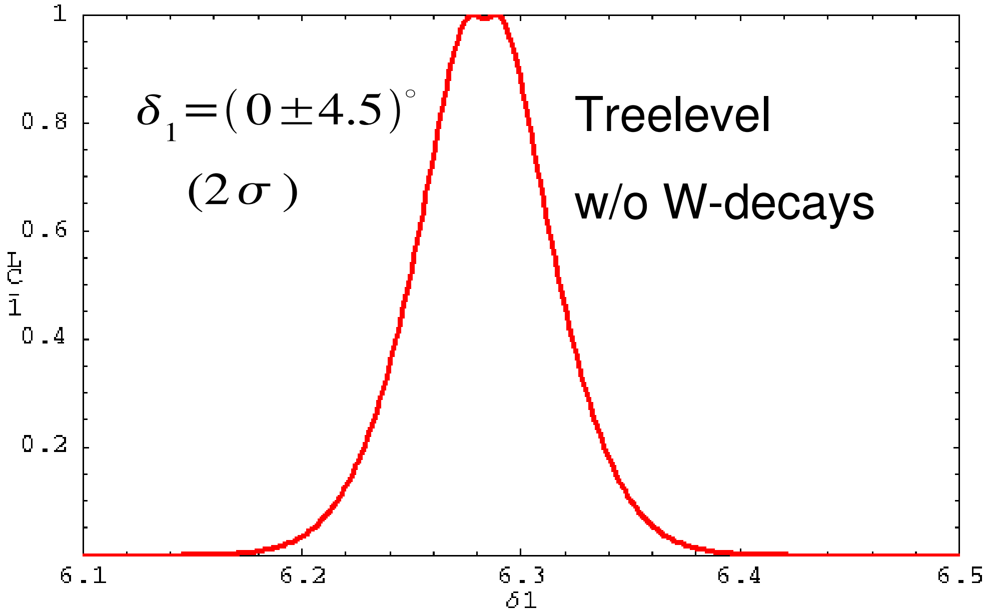
3) Dalitz

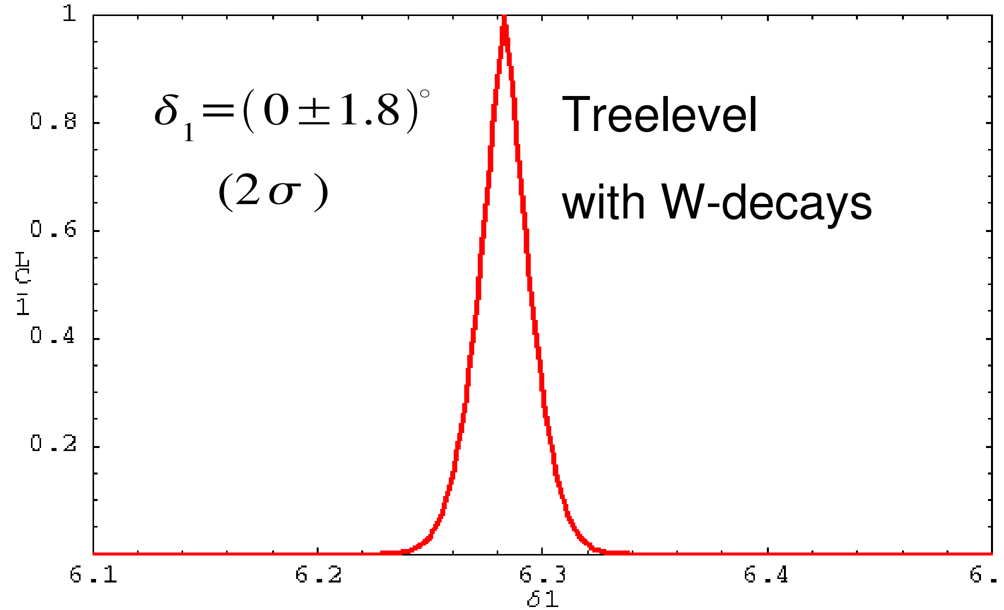
Analogous possibilities depending on final state in Dalitz plane

UT angles: "γ"

Define $\delta_1 = Arg\left(\frac{V_{ud}V_{us}^*}{V_{cd}V_{cs}^*}\right) + \pi$ => Fit for deviation from $2\pi \hat{=} 0$ within 4th generation scenario

(Already considered in Kurimoto & Tomita, Prog.Theor.Phys. 98 (1997) 967; sign error in eq. (18))





=> γ-extraction in ADS and GLW within 4th generation scenario

like in 3-generation scenario to a very good approximation (1° systematics @ 1σ)

Should be analogous in Dalitz plot analysis but not thought through in detail yet

UT angles: “β” from B→ J/ψ $K^0/\bar{K}^0$

- Usually, only NP in mixing studied: $\sin(2\beta)\rightarrow\sin(2\beta-2\theta_d),\ \frac{M_{12}}{M_{12}^{SM}}=e^{-2\theta_d},\ \beta=Arg\left(-\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right)$

=> 4th generation: $2\theta_d=-arg\left(1+\frac{\lambda_{t'}^{bd\,2}\eta_{t'}^{B}S_0(x_{t'})+2\lambda_t^{bd}\lambda_{t'}^{bd}\eta_{tt'}^{B}S_0(x_t,x_{t'})}{\lambda_t^{bd2}\eta_t^{B}S_0(x_t)}\right)$

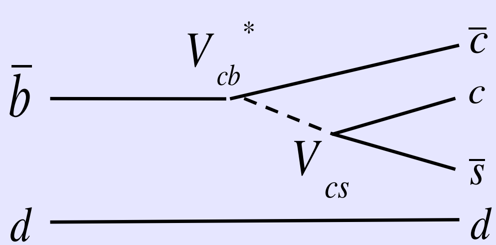
- Complications with 4th generation:

1) K-$\bar{K}$ mixing => $\sin(2\beta-2\theta_d)\rightarrow\sin(2\beta-2\theta_d+2\delta_1)$ mit $\delta_1=Arg\left(\frac{V_{ud}V_{us}^*}{V_{cd}V_{cs}^*}\right)+\pi$

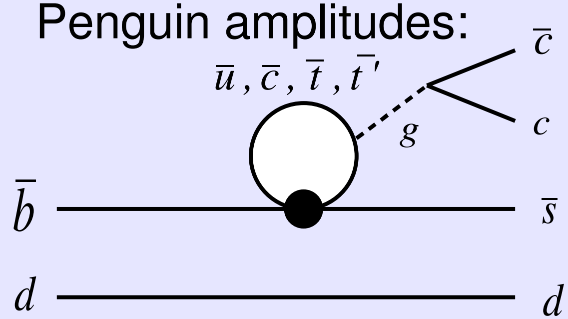
Experimental precision on ”β” of 1° ~ constraint on δ_1 !

2) Decay amplitudes

Leading tree amplitude: $V_{cs}V_{cb}^*T$



Penguin amplitudes:



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

$V_{ts}V_{tb}^*P_{tu}$

$V_{t's}V_{t'b}^*P_{t'u}$

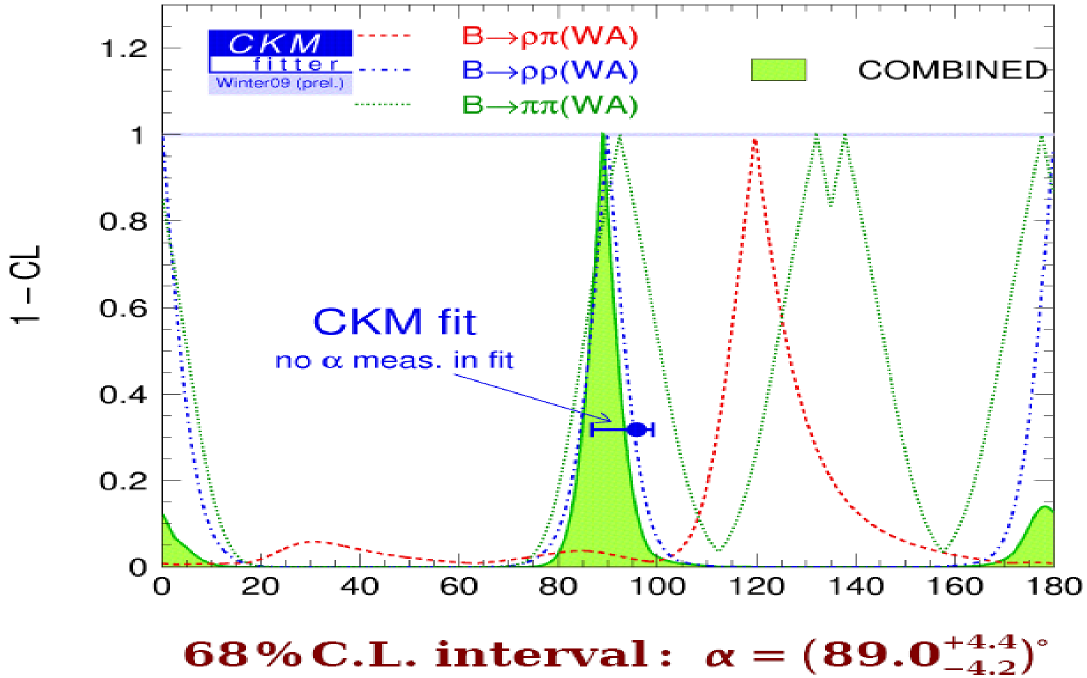
- Weak phases of t- & t'-penguin = weak phase of c-penguin?
- Current 4th generation constraints: $\left|V_{cs}V_{cb}^*\right|<<\left|V_{ts}V_{tb}^*\right|,\left|V_{t's}V_{t'b}^*\right|$

=> q/p not any more pure phase => decay amplitudes & phases to be included or to be constrained using J/ψ h decays?

UT angles: "α" from $B \to \pi\pi, \rho\rho, \rho\pi/\pi\pi\pi$

Assumption: Isospin symmetry of strong interactions => QCD penguin eliminated

"β" measured =>"α" determines "γ" if no NP in ΔI=3/2-ampl. - independent of NP in mixing!



$$\alpha = Arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

Isospin violation from P_{EW} taken into account:

$$\frac{P_{EW}}{T^{+0}} \approx -\frac{3}{2}\frac{C_9^t + C_{10}^t}{C_1 + C_2} = +(1.35 \pm 0.12)10^{-2}$$

Buras & Fleischer, EPJ C11, 93 (1999)

Neubert & Rosner, PLB 441, 403 (1998); PRL 81, 5076 (1998)

Effect: O(1.5°)

P_{EW} with 4[th] generation could be much larger: $\frac{P_{EW}}{T^{+0}} \approx \frac{3}{2}\left[\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\frac{C_9^t + C_{10}^t}{C_1 + C_2} + \frac{V_{t'd}V_{t'b}^*}{V_{ud}V_{ub}^*}\frac{C_9^{t'} + C_{10}^{t'}}{C_1 + C_2}\right]$

1. t and t' CKM factors could be larger than in 3SM and of same order
2. $C_9^{t'} + C_{10}^{t'} \overset{m_{t'}=600\,GeV}{\approx} 3.6(C_9^t + C_{10}^t)$ (estimates according to m_t dependence quoted in
3. $C_8^{t'} \overset{m_{t'}=600\,GeV}{\approx} C_{10}^t$ Buchalla, Buras, Lautenbacher, RMP 68, 1164 (1996))

=> α-extraction will be more involved and expect a significantly larger uncertainty

Summary

- CKMfitter: 4^{th} generation implementation underway (H. Lacker, A. Menzel)
- Tree level: Leptonic & semileptonic decays implemented ($W \to l\nu$!)
- Single top & R: Combined analysis with extraction of $|V_{td}|$&$|V_{ts}|$&$|V_{tb}|$ needed
  (collaboration started: H. Lacker, F. Maltoni & W. Wagner)
- G_F-problem: Combined CKM, PMNS and e.w. precision fit needed
  (collaboration started: H. Lacker, A. Menzel, A. Lenz, & U. Nierste)
- $\epsilon_K, \Delta m_d, \Delta m_s$: Improves constraints on $|V_{td}|$, $|V_{ts}|$, $|V_{t'd}|$ & $|V_{t's}|$ slightly
- "γ"-extraction: Looks similar to 3SM (uncertainty from δ_1 ~1° thanks to $W \to l\nu$)
- "β"-extraction: * Additional uncertainty from δ_1 ~1°
  * Quantifying effect from t- & t'-penguin (maybe with J/ψ h) ?
- "α"-extraction: Taking into account P_{EW} (to be done) will increase uncertainty substantially and will introduce explicit dependency on $m_{t'}$

Single Top

Directly measured matrix elements including W-decays:

$$\left|V_{CKM}^{4\times 4}\right| = \begin{pmatrix} 0.97418 & 0.2253 & 0.0043 & <0.046 \\ 0.224 & 0.973 & 0.041 & <0.20 \\ <0.045 & <0.125 & >0.78 & <0.63 \\ <0.075 & <0.21 & <0.63 & >0.78 \end{pmatrix}$$

Limits @ ~2σ

Directly measured matrix elements including W-decays w/o $|V_{tb}|$ but with R:

$$\left|V_{CKM}^{4\times 4}\right| = \begin{pmatrix} 0.97418 & 0.2253 & 0.0043 & <0.046 \\ 0.224 & 0.973 & 0.041 & <0.20 \\ <0.068 & <0.18 & <1 & <1 \\ <0.074 & <0.21 & <1 & <1 \end{pmatrix}$$

Limits @ ~2σ

UT angles: "γ"

Directly measured matrix elements & $\epsilon_K, \Delta m_d, \Delta m_s$ assuming $m_{t'} > 300$ GeV:

$$|V_{CKM}^{4\times4}| = \begin{pmatrix} 0.97418 & 0.2253 & 0.0043 & <0.046 \\ 0.224 & 0.973 & 0.041 & <0.20 \\ <0.038 & {<0.123 \atop >0.021} & >0.78 & <0.63 \\ <0.074 & <0.20 & <0.63 & >0.78 \end{pmatrix}$$

Limits @ ~2σ

Directly measured matrix elements & $\epsilon_K, \Delta m_d, \Delta m_s$ assuming $m_{t'} > 300$ GeV & current γ input:

$$|V_{CKM}^{4\times4}| = \begin{pmatrix} 0.97418 & 0.2253 & 0.0043 & <0.046 \\ 0.224 & 0.973 & 0.041 & <0.20 \\ {<0.037 \atop >0.006} & {<0.124 \atop >0.021} & >0.78 & <0.63 \\ <0.074 & <0.20 & <0.63 & >0.78 \end{pmatrix}$$

Limits @ ~2σ

- Lower bound on $|V_{td}|$: Easily understood when thinking in 3x3-scenario

  $|V_{td}|$ & γ depend strongly on ρ and η, but not $|V_{ts}|$